Dark Matter search

III International Pontecorvo Neutrino Physics School
Alushta, September 2007

R. Bernabei
Univ. and INFN Roma Tor Vergata

Interdisciplinary field: Particle Cosmology

Particle Physics
studies on nature
at smallest scale

Cosmology
studies on nature
at largest scale

to investigate the initial condition when the fundamental particles and forces produced the perturbation in the cosmic density field

↔

to investigate the origin and the evolution of the largest-scale structure

Possibility to investigate physics beyond the Standard Model

Early Universe →

Ultimate particle accelerator?

The Dark Side of the Universe: experimental evidences ...

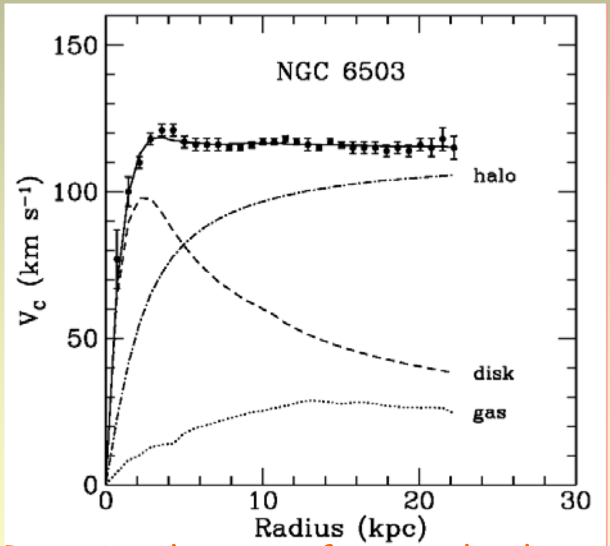
COMA Cluster

First evidence and confirmations:

1933 F. Zwicky: studying dispersion velocity of Coma galaxies

1936 S. Smith: studying the Virgo cluster

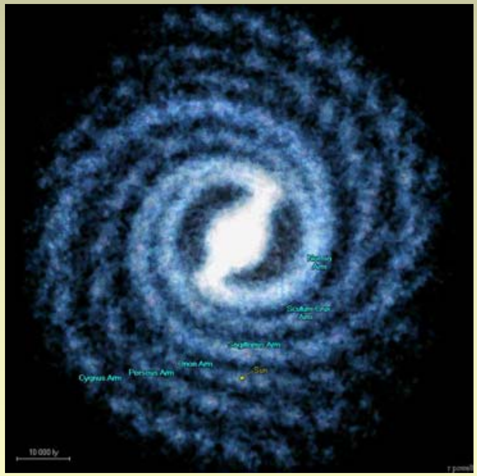
1974 two groups: systematical analysis of mass *density* vs *distance from center* in many galaxies



Rotational curve of a spiral galaxy

Other experimental evidences

- ✓ from LMC motion around Galaxy
- ✓ from X-ray emitting gases surrounding elliptical galaxies
- ✓ from hot intergalactic plasma velocity distribution in clusters



Milky Way

$\mathbf{M}_{\text{visible Universe}} \ll \mathbf{M}_{\text{gravitational effect}} \Rightarrow$ about 90% of the mass is DARK

From cosmology...

Standard cosmology + Standard inflationary scenario $\Rightarrow$ $\Omega = \rho/\rho_c = 1$

$$\rho_c = \frac{3H_0^2}{8\pi G} = 1.88 \cdot h^2 \cdot 10^{-29}\, g/cm^3$$

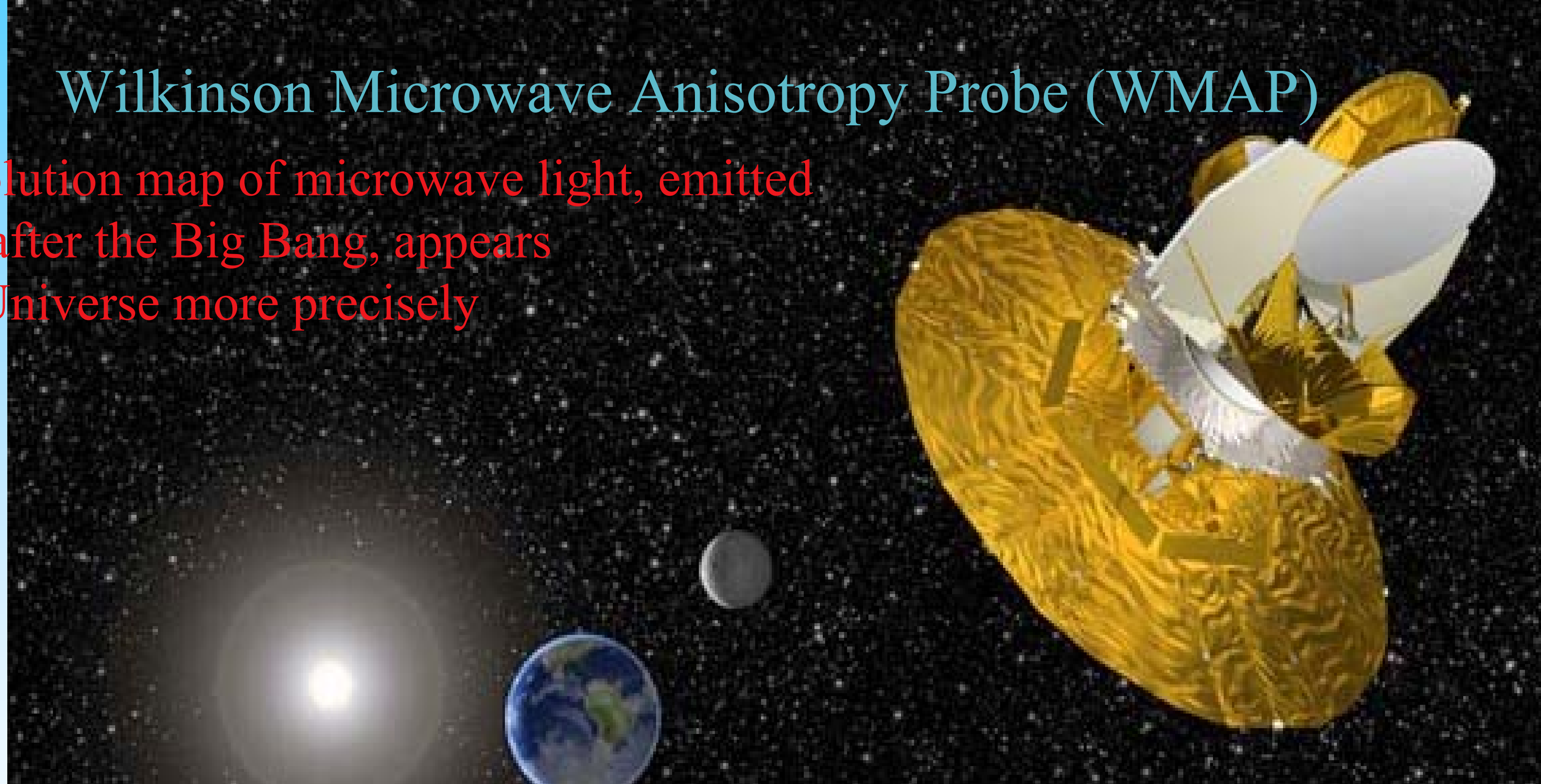
Cosmological Constant $\Lambda \neq 0$ $\Rightarrow$ Ω (Luminous+Dark Matter) $= 0.5 - 0.1$

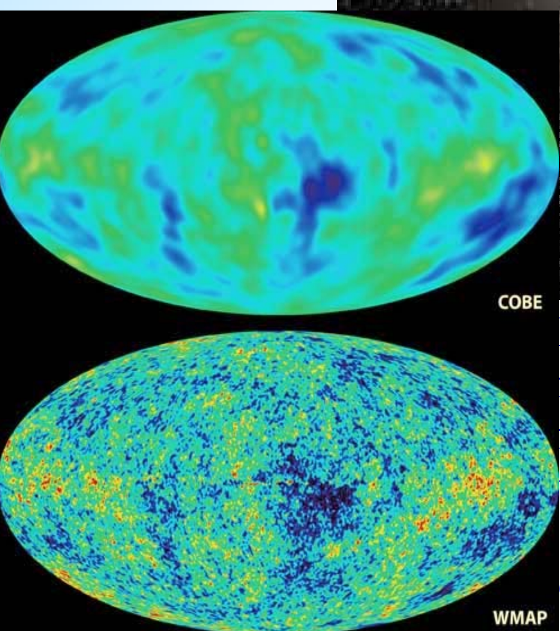
...and from observations

	R (kpc)	$\Omega = \rho/\rho_c$
•Visible part of galaxies	10	~0.007
•Galactic haloes	50 - 100	~0.02 - ~0,2
•Clusters	10^3 - 10^4	~0.2
•Collapse on Virgo cluster	10^4	~0.2
•Collapse on large scale	$3 \cdot 10^4$	~ 0.2 - ~1
•IRAS measurements on large scale velocity flow	10^5	~1

Wilkinson Microwave Anisotropy Probe (WMAP)

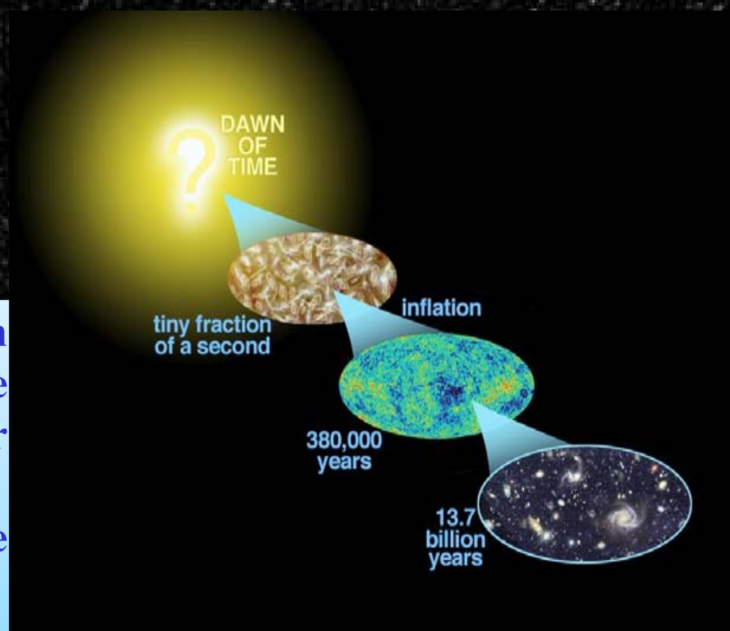
New high-resolution map of microwave light, emitted 380000 years after the Big Bang, appears to define our Universe more precisely



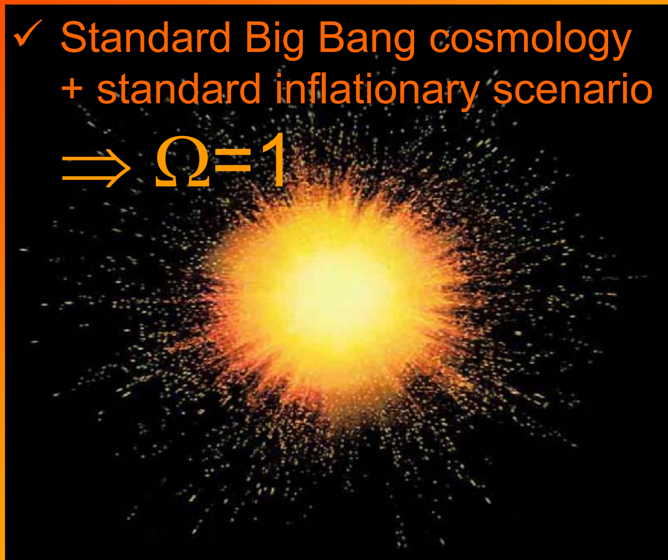


An all-sky image of the infant Universe 380000 years after the Big Bang.

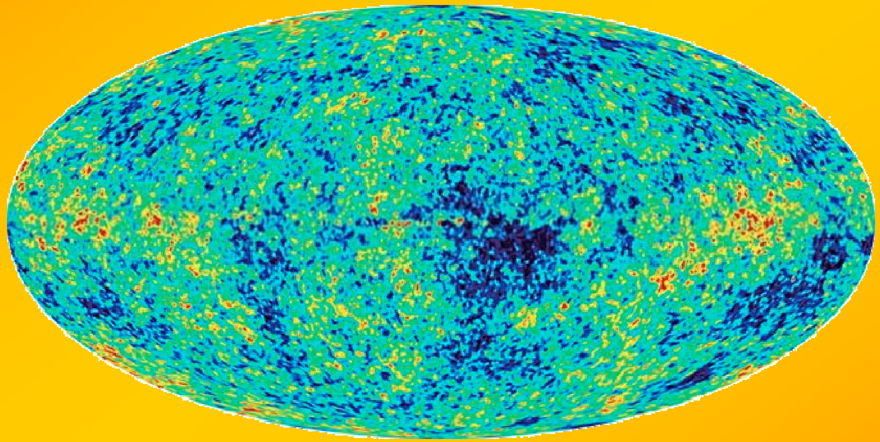
In 1992, NASA's COBE mission firstly detected tiny temperature fluctuations (shown as color variations).
The WMAP image brings the COBE image into sharp focus.



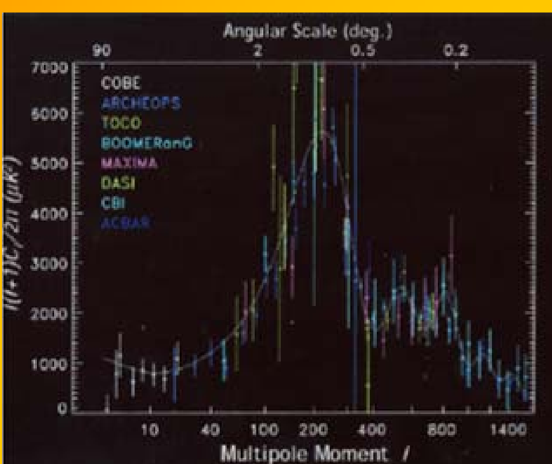
... and support from cosmology



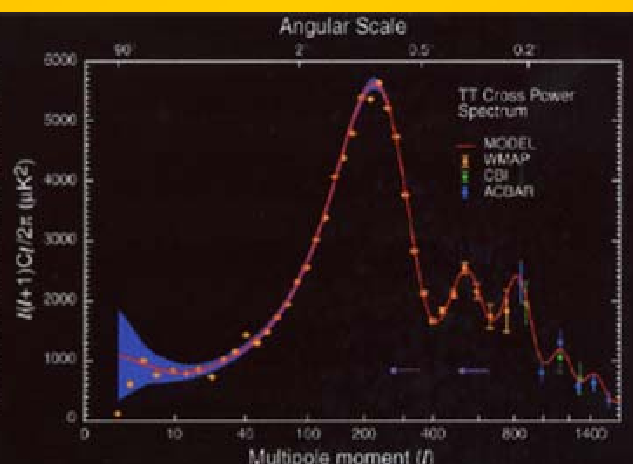
Power Spectrum: CMB measurements



before WMAP



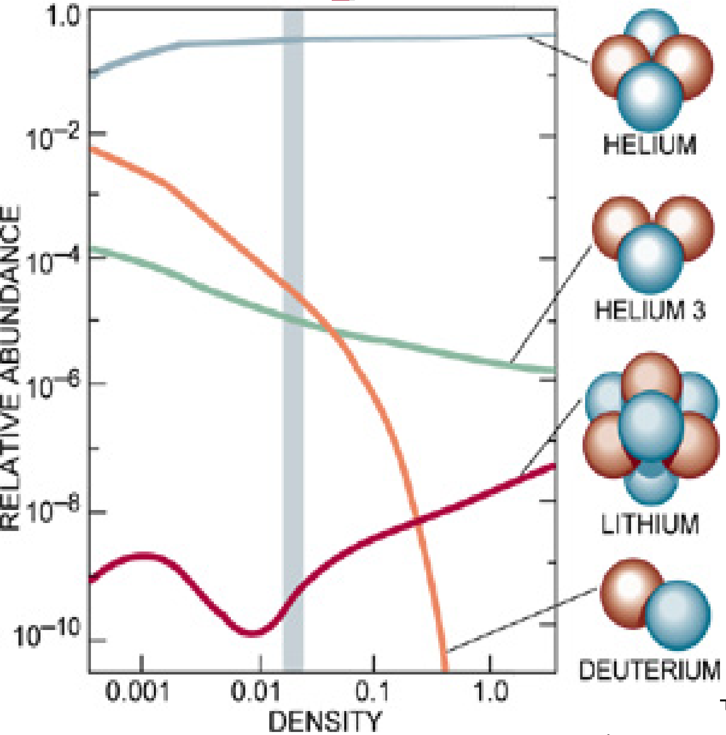
WMAP data

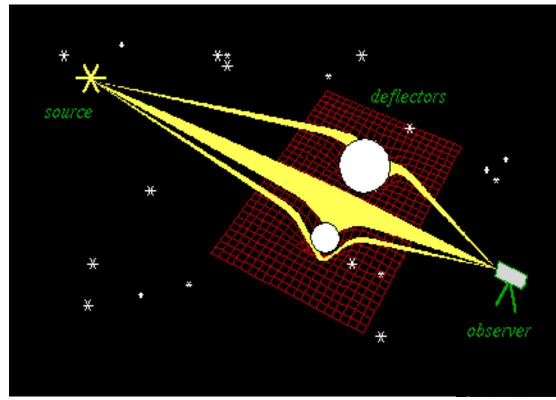


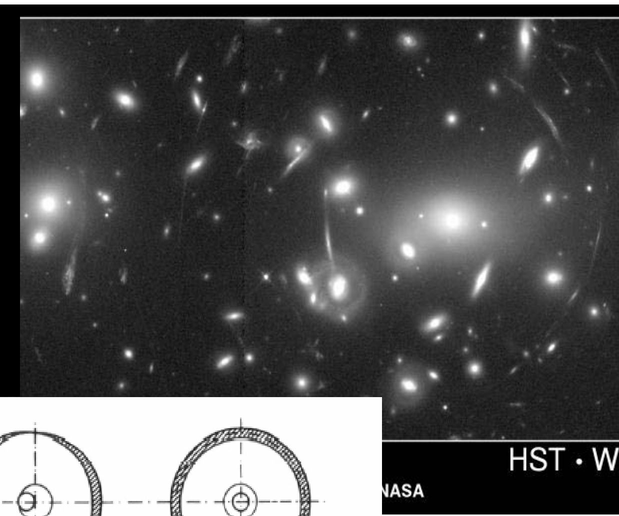
The dynamical evolution of the Universe depends on the quantity and kind of mass and energy densities. The curvature radius of the Universe is related to Ω .

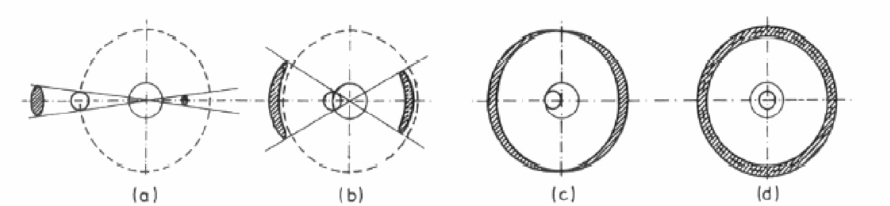
A significant presence of Cold Dark Matter is necessary to reproduce the present cosmological observation

Nucleosynthesis + searching for barionic D.M.



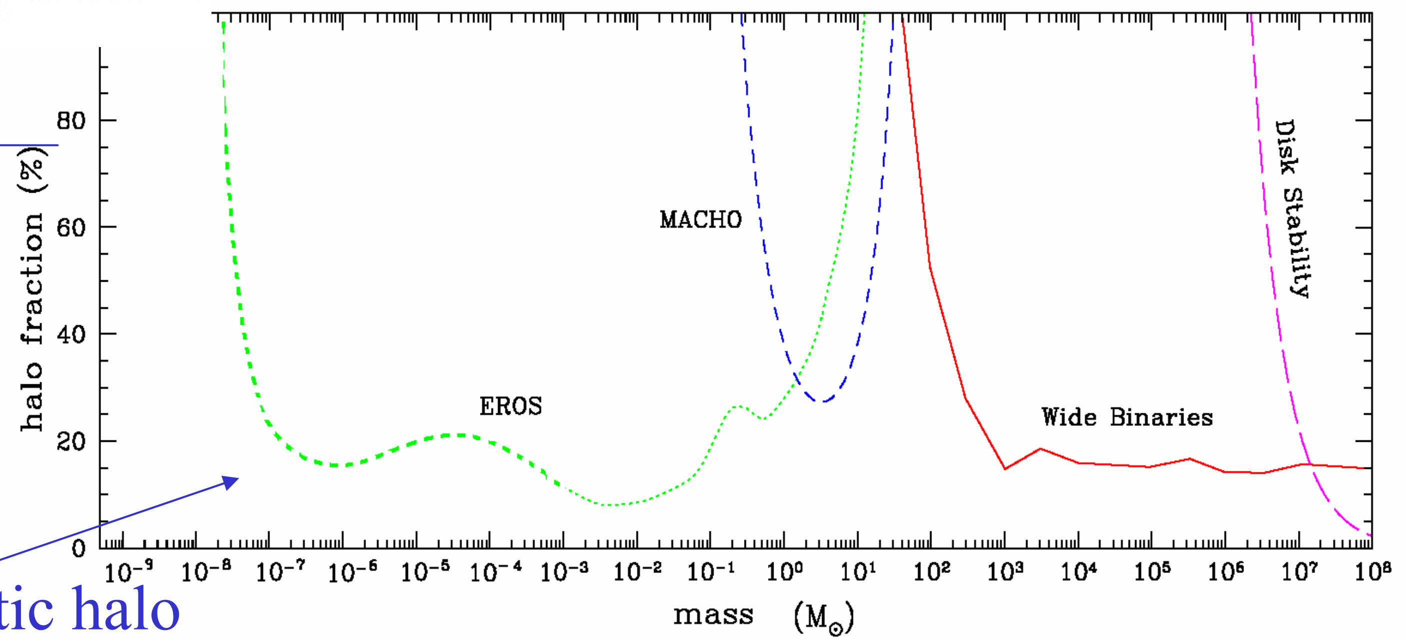






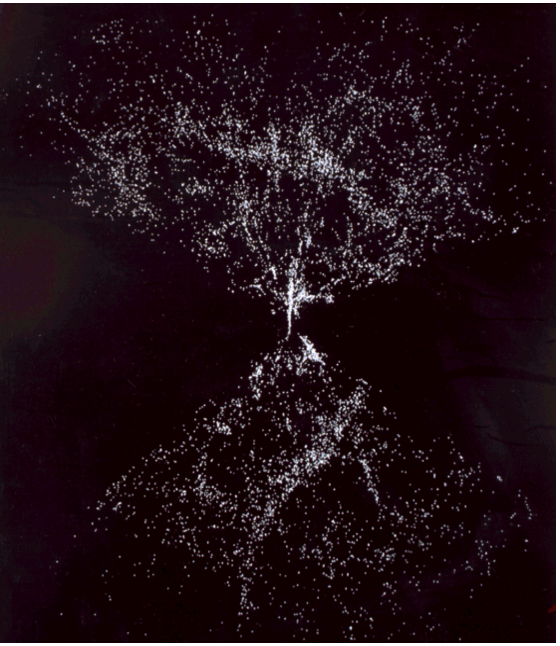
$$\Omega_b h^2 \approx 0.02$$

MACHOs: non luminous astrophysical compact objects (brown dwarf, faint stairs, planets)

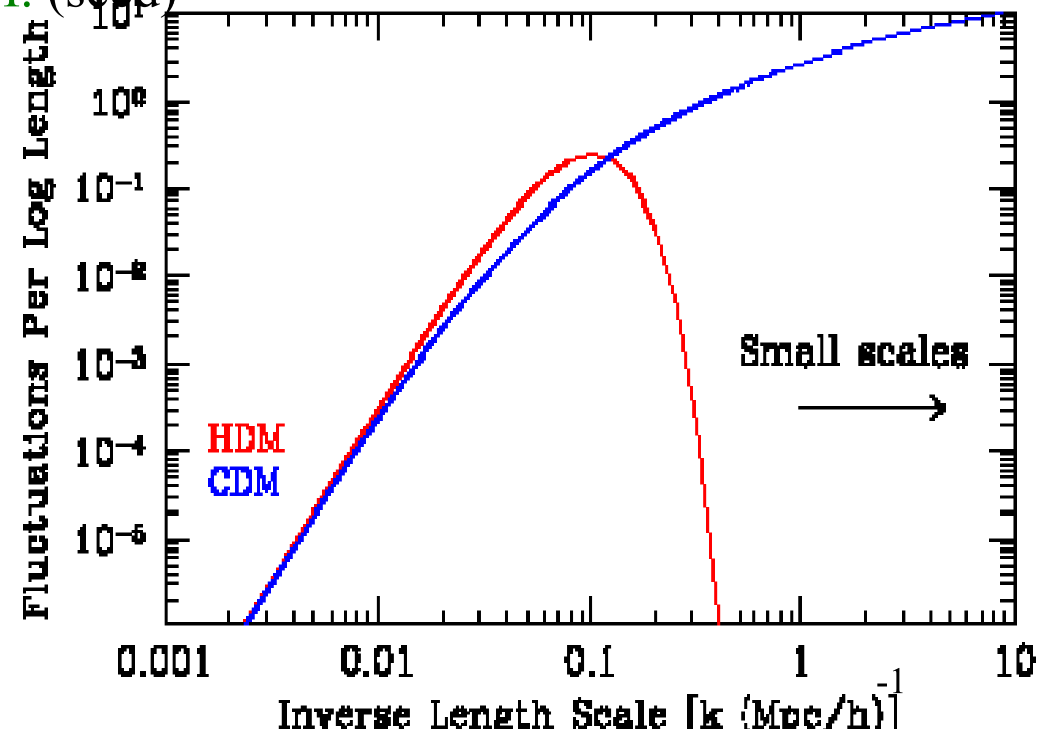


< 10% of the galactic halo

Structure formation in the Universe and nature of the non baryonic D.M.



To obtain the pattern of the present large scale structures from the evolution of the primordial perturbations is necessary to assume the existence of non baryonic D.M., that is of particles relicts from Big-Bang. In this scenario, the structures observed at present have been originated by the "gravitational trapping" of the baryonic matter by the non baryonic D.M. (seed)



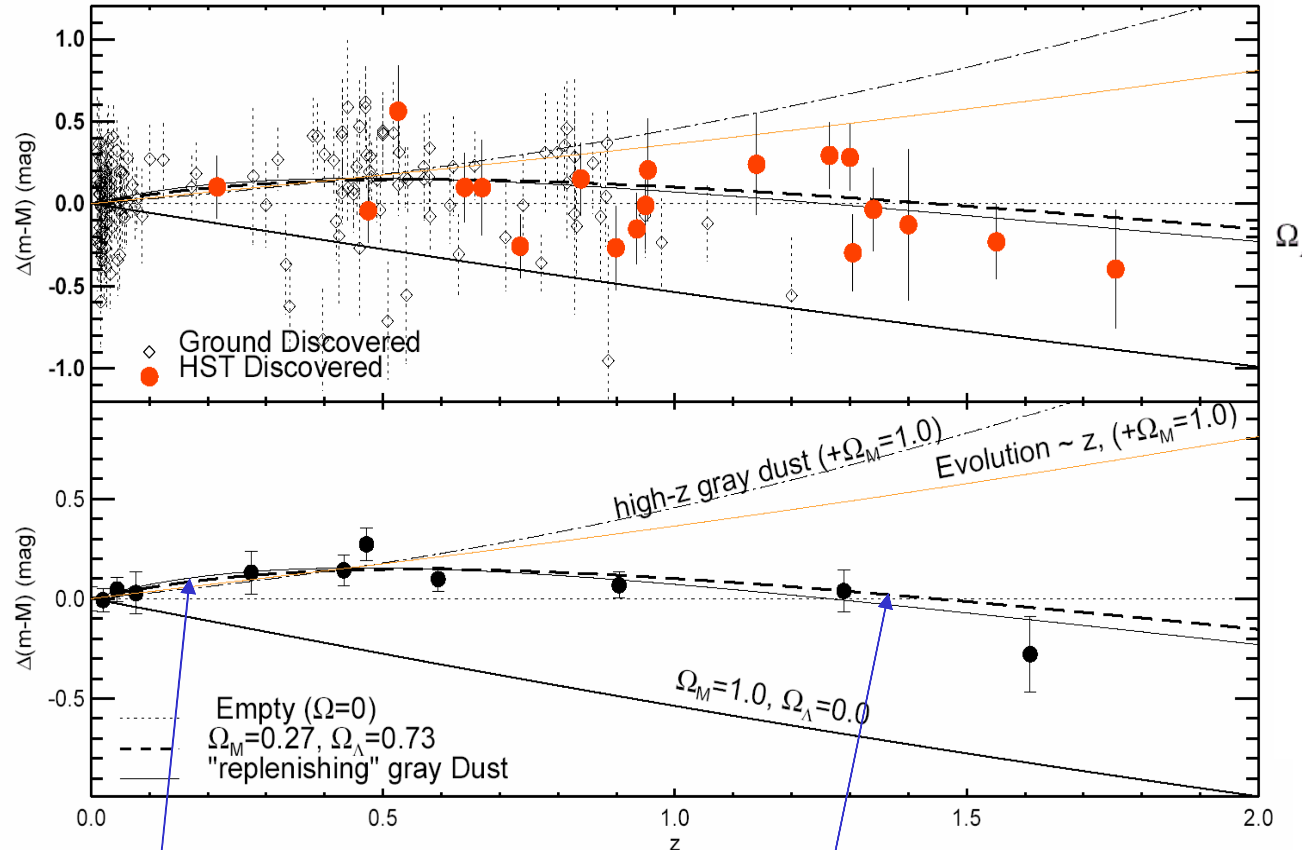
HDM scenario (light massive ν …): particles relativistic at decoupling time

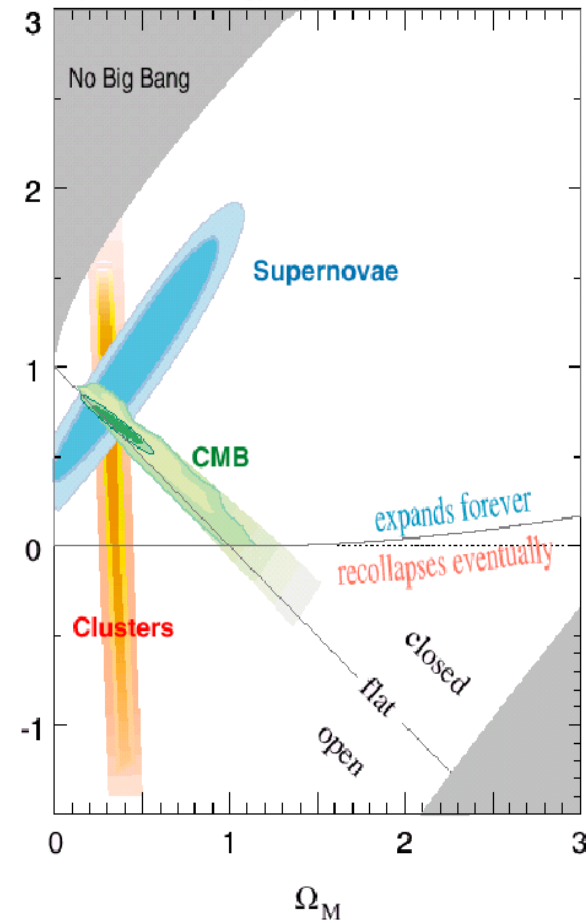
CDM scenario (WIMPs, axions ...): particles non-relativistic at decoupling time

But HDM does not produce small scale structure !

COSMOLOGICAL CONSTANT?

SN Ia standard candle





Accelerating Universe dominated by Λ

Decelerating Universe dominated by (dark) matter

$$\Omega_\Lambda \approx 0.73; \quad \Omega_M \approx 0.27$$

~ 90% of the matter in the Universe is non barionic

A cosmological constant?

Quantum gravity would predict its value to be 10^{120} times the observed value, perhaps it could be zero only in the presence of an unknown symmetry.
A vacuum energy? Does it evolve with time? A quintessence field?

The dark energy? A mystery

Cosmology

About it :
1) It should emit/absorb no light
2) It should have negative pressure, with magnitude comparable to its energy density in order to produce accelerated expansion
3) It should be "approximately" homogeneous
4) It should not interfere with production of structure but it could decide the future of Universe

Particle physics

A direct remnant of string theory ??

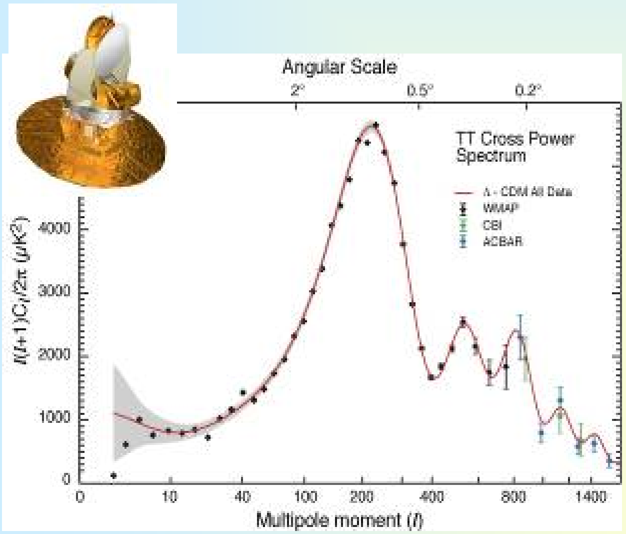
Are dark matter and dark energy connected through axion physics?

Is there a case of "vacuum energy" or "quintessence" in particle physics?

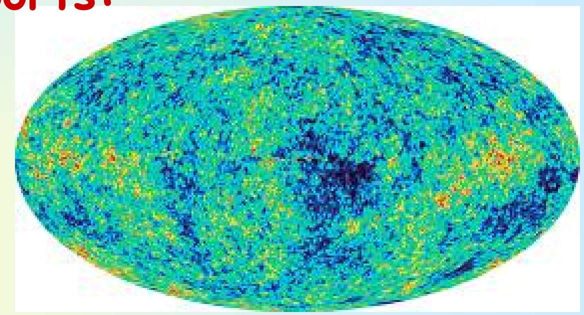
If elementary particles could couple to quintessence field , there could be exoti signatures detectable at accelerator and by astrophysical experiments

The Dark Side of the Universe: experimental evidences ...

From larger scale ...



"Precision" cosmology supports:



Flat Universe:

$\Omega = 1.02 \pm 0.02$

"Concordance" model:

$\Omega_\Lambda \sim 73\%$ from SN1A

$\Omega_{CDM} \sim 23\%$

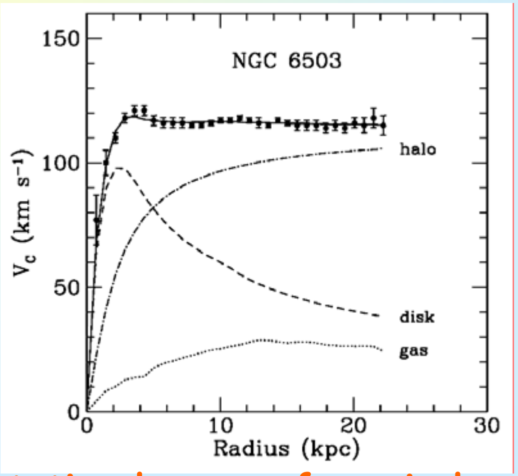
$\Omega_b \sim 4\%$

$\Omega_\nu < 1\ \%$

... to galaxy scale

Open questions:

- Composition?
- Right halo model and parameters?
- Multicomponent also in the particle part?
- Related nuclear and particle physics?
- Non thermalized components?
- Caustics and clumpiness?
- ....



Rotational curve of a spiral galaxy

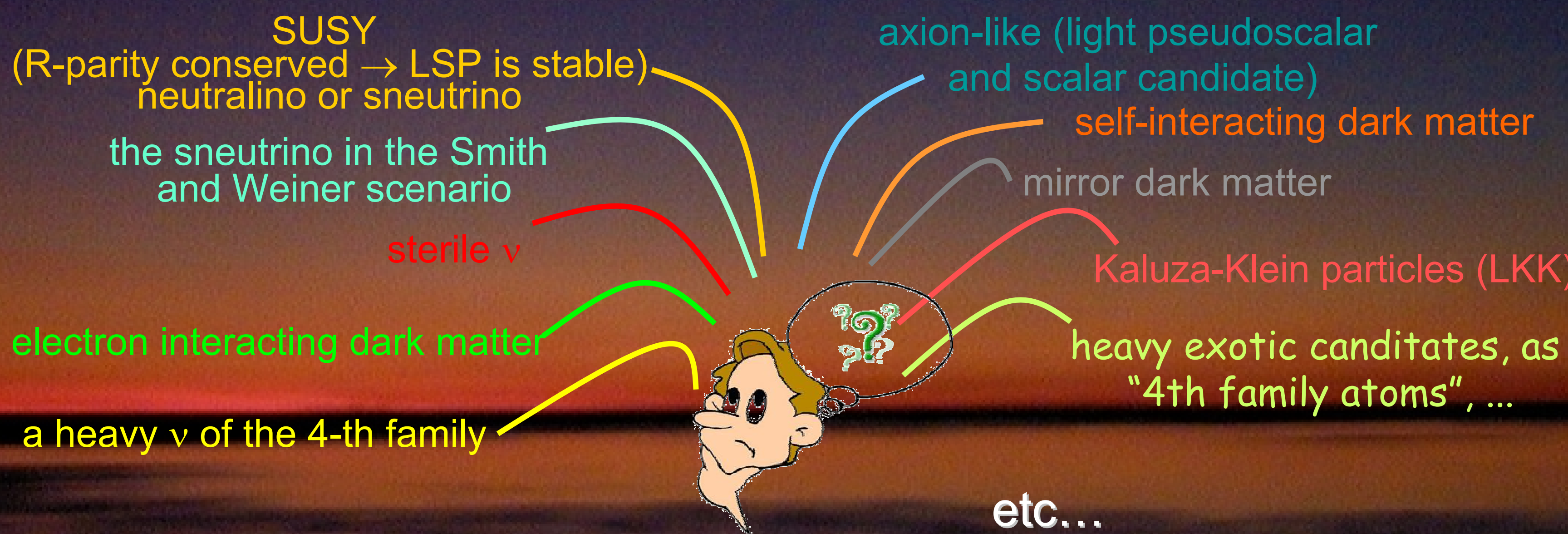
Relic DM particles from primordial Universe

Heavy candidates:

- In thermal equilibrium in the early stage of Universe
- Non relativistic at decoupling time:
  $<\sigma_{ann} \cdot v> \sim 10^{-26}/\Omega_{WIMP}h^2 \ cm^3 s^{-1} \rightarrow \sigma_{ordinary\ matter} \sim \sigma_{weak}$
- Expected flux: $\Phi \sim 10^7 \cdot (GeV/m_W)\ cm^{-2}\ s^{-1}$
  $(0.2 < \rho_{halo} < 1.7\ GeV\ cm^{-3})$
- Form a dissipationless gas trapped in the gravitational field of the Galaxy ($v \sim 10^{-3}c$)
- Neutral, massive, stable (or with half life ~ age of Universe) and weakly interacting

Light candidates:

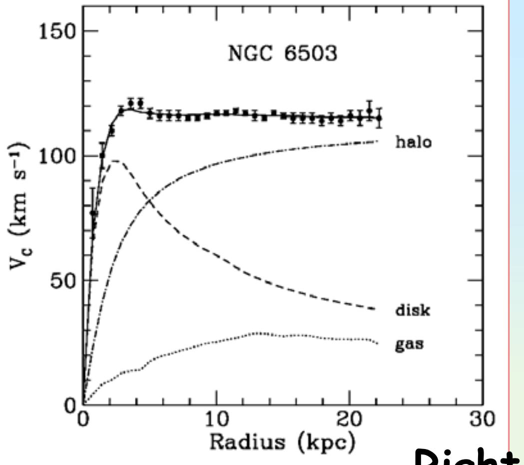
axion, sterile neutrino, axion-like particles cold or warm DM



+ multi-component halo?

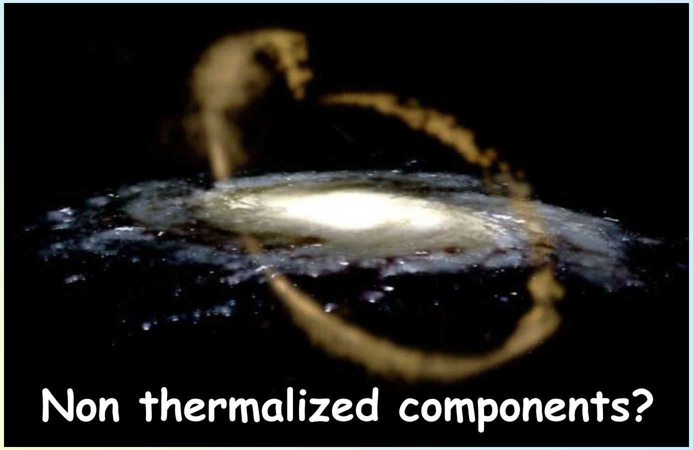
even a suitable particle not yet foreseen by theories

Relic DM particles in the galactic halo:



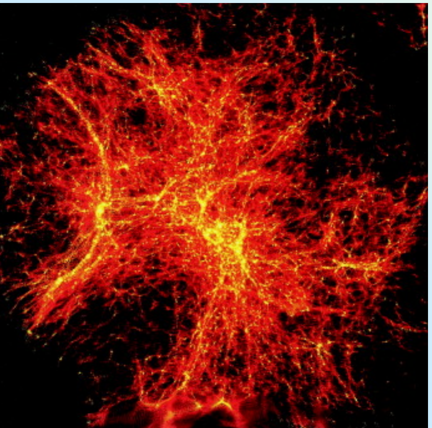
Open questions:

Right halo model and parameters?

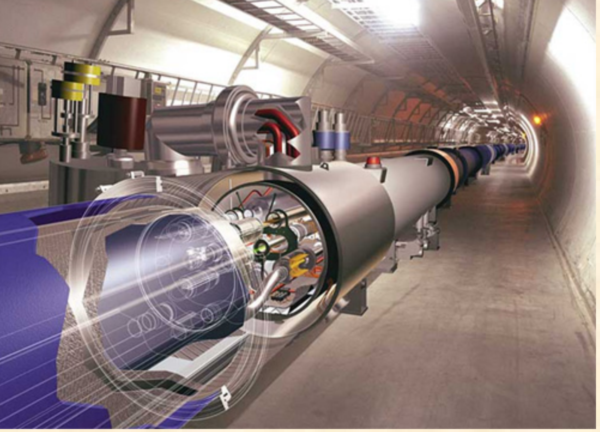


- Composition? Multicomponent also in the particle part? (Related nuclear and particle physics)

clumpiness?



etc…

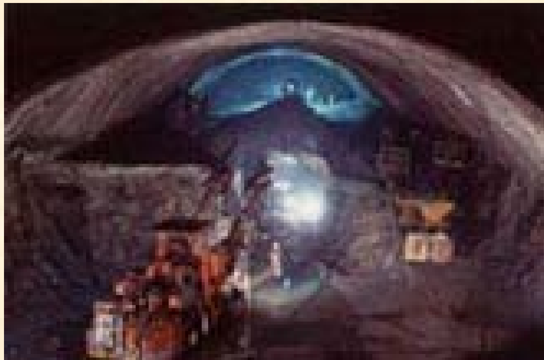


What accelerators can do:
to demostrate the existence of some of the possible DM candidates

What accelerators cannot do:
To credit that a certain particle is the Dark Matter solution or the “single” Dark Matter particle solution…

+ DM candidates and scenarios exist (even for neutralino candidate) on which accelerators cannot give any information

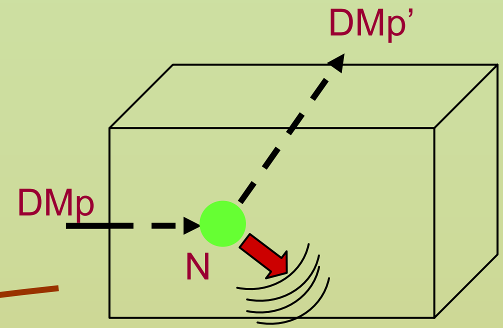
DM direct detection method using a model independent approach



Some direct detection processes:

- Scatterings on nuclei

  → detection of nuclear recoil energy

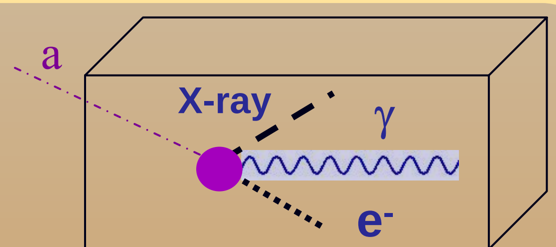


- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

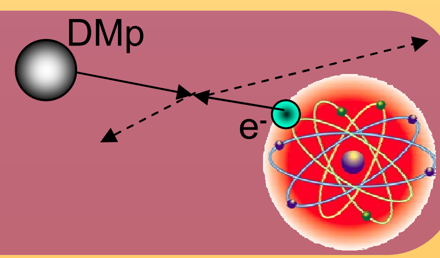
- Conversion of particle into electromagnetic radiation

  → detection of γ, X-rays, e⁻



- Interaction only on atomic electrons

  → detection of e.m. radiation

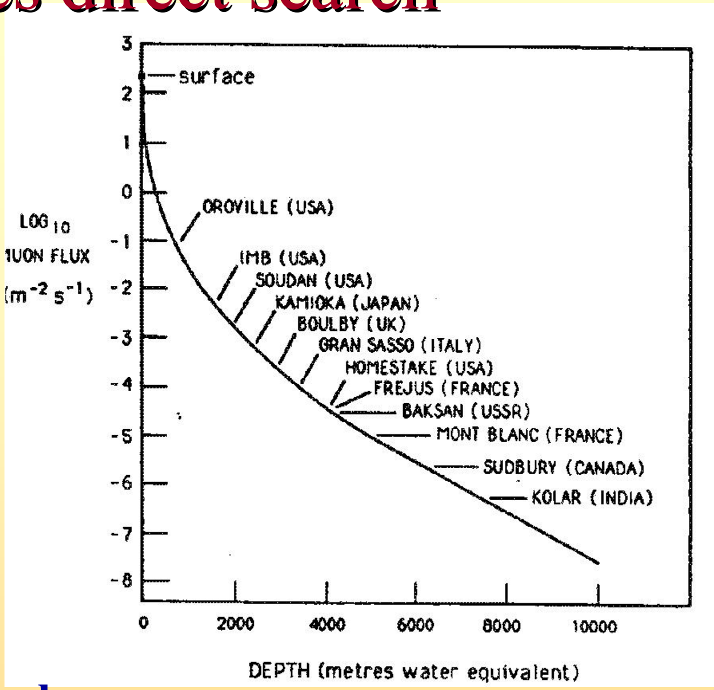


- **… and more**

e.g. signals from these candidates are completely lost in experiments based on “rejection procedures” of the electromagnetic component of their counting rate

Goals for Dark Matter particles direct search

- Underground site
- Low bckg hard shields against γ's, neutrons
- Lowering bckg: selection of materials, purifications, growing techniques, ...
- Rn removal systems



Background sources

- Background at LNGS:

muons → **0.6 μ/(m²h)**

neutrons → **$1.08\cdot10^{-6}$ n/(cm²s) thermal**

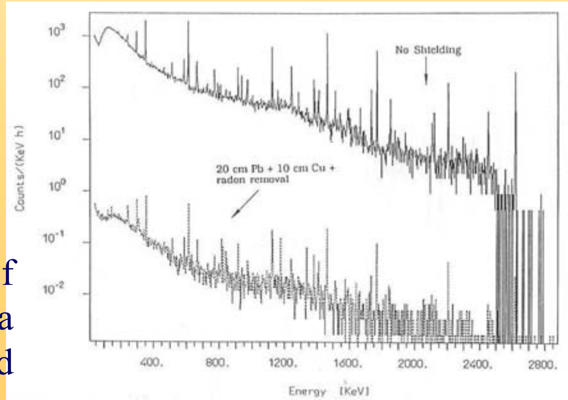
$1.98\cdot10^{-6}$ n/(cm²s) epithermal

$0.09\cdot10^{-6}$ n/(cm²s) fast (>2.5 MeV)

Radon in the hall → **≈30 Bq/m³**

- Internal Background:

selected materials (Ge, NaI, AAS, MS, ...)



Example of the effect of a passive shield

Shielding

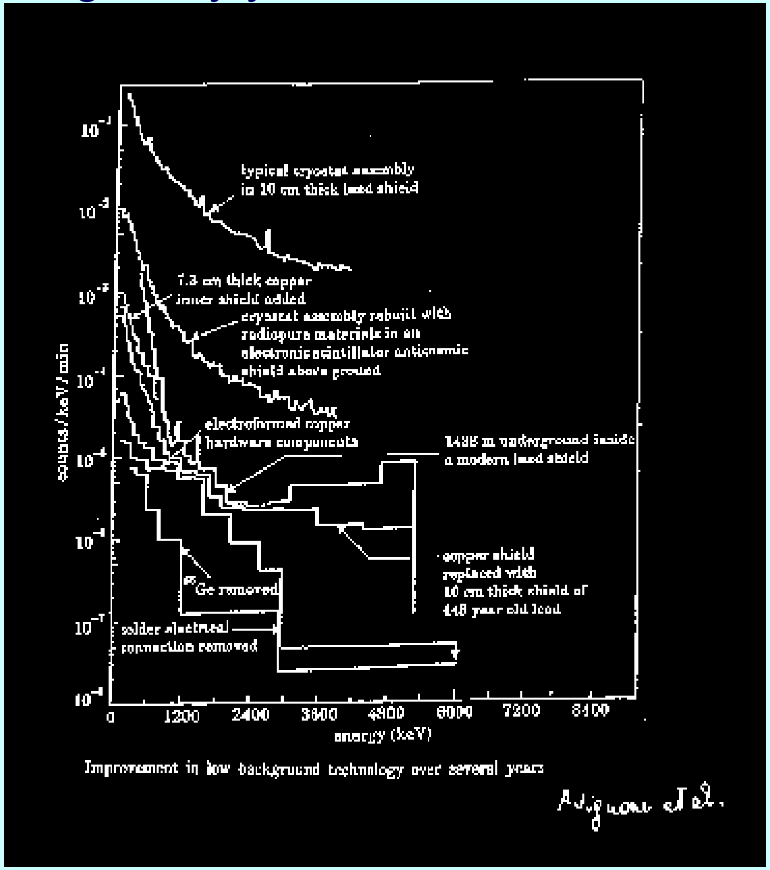
Passive shield: Lead (Boliden [< 30 Bq/kg from ^{210}Pb], LC2 [<0.3 Bq/kg from ^{210}Pb], lead from old roman galena), OFHC Copper, Neutron shield (low A materials, n-absorber foils)

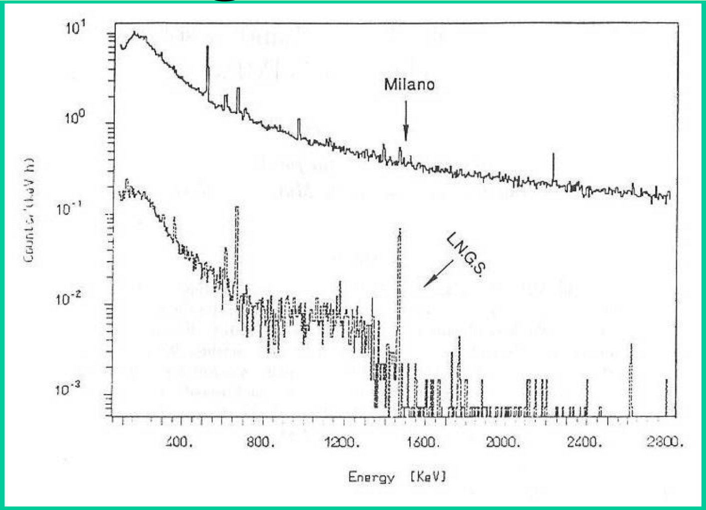
Active shield: Low radio-activity NaI(Tl) surrounding the detectors

etc.

Lowering the background

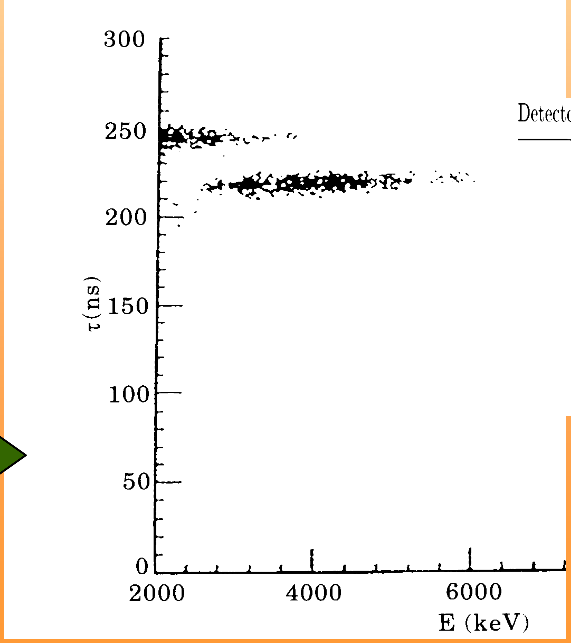
Example of background reduction during many years of work





Reduction from the underground site

U/Th residual contamination in the DAMA/NaI set-up (≈100 kg highly radiopure NaI(Tl))

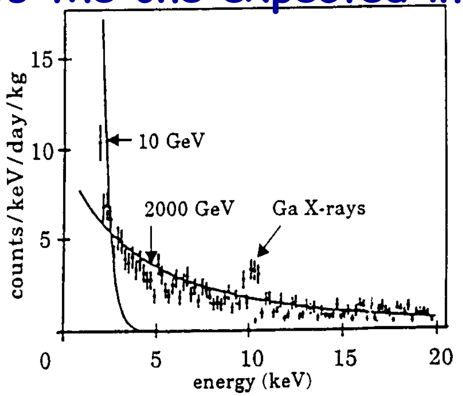


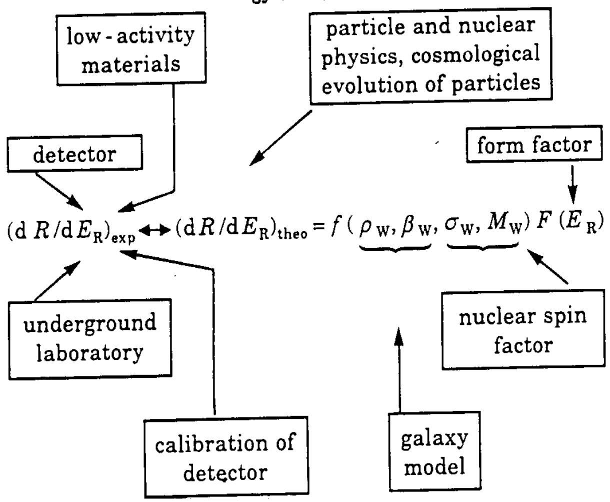
Detector	U + Th (ppt)
1	6.5
2	8.8
3	8.2
4	11.6
5	9.9
6	11.3
7	15.3
8	3.8
9	3.8

Further, improvements from chemical/physical purification of the powders (about 250 kg highly radiopure NaI(Tl), DAMA/LIBRA)

The "traditional" approach

• Experimental energy distribution (with or without bckg rejection)
vs the one expected in a given model framework

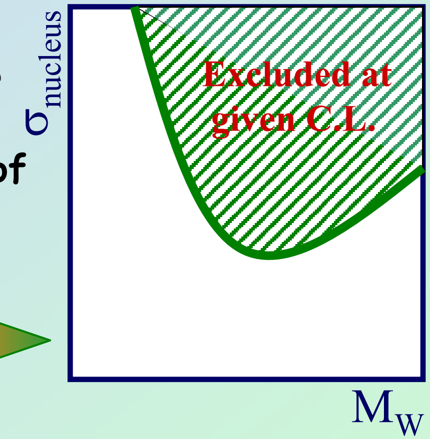




several assumptions and modeling required +

experimental and theoretical uncertainties generally not included in calculations (see later in the model dependent discussion)

Exclusion plot for a fixed set of assumptions and of expt and theor.parameters values



by additional model: σ_p

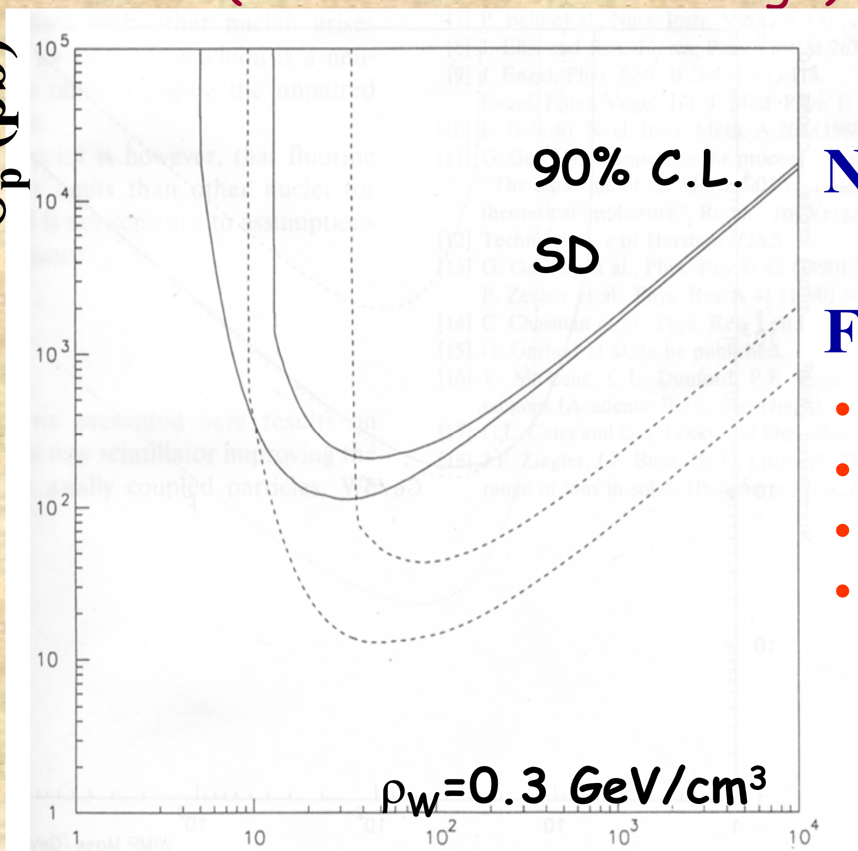
An exclusion plot not an absolute limit. When different target nuclei, no absolute comparison possible.

To have potentiality of discovery a *model independent signature* is needed

- No discovery potentiality
- Uncertainties in the exclusion plots and in their comparison
- Warning: limitations in the recoil/background discrimination

Example

effect on the exclusion plot when changing even just the value of a single parameter (inside its allowed range) within the same model framework



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- Top curves: v_0=180 km/s; v_{esc}=500 km/s
- Lower curves: v_0=250 km/s; v_{esc}=1000 km/s
- v_0 affects mainly the overall rate
- v_{esc} affects mostly the lower mass region

Similar effect are found for every nucleus and interaction type changing assumptions and/or expt/theoretical parameters. Thus, exclusion plots given under a single fixed set of assumptions and parameters values

No "universal" validity!

Limitations in selection/rejection procedures of the electromagnetic component of the counting rate

1. Pulse Shape Discrimination (τ of the pulse depends on the particle) in scintillators (NaI(Tl), LXe, CsI…)

2. Heat/Ionization (Ge,Si)

3. Heat/Scintillation (CaF_2(Eu), $CaWO_4$)

4. Double phase liquid noble gas

1. Limitations in PSD in scintillators from temperature controlling level in each specific expt assembling (+possible systematics peculiar of the given expt)

2. Limitations in bolometers from the identification of the two sensitive volumes, efficiency of the required coincidences, stability of the selection windows, quenching factors, etc. (+ possible systematics peculiar of given expt) → analogous or even worse situation for double phase liquid noble gas detectors

In all kinds of techniques: end-range α's, unshielded environmental neutrons, fission fragments, etc. fully mimic DM induced recoils

↓

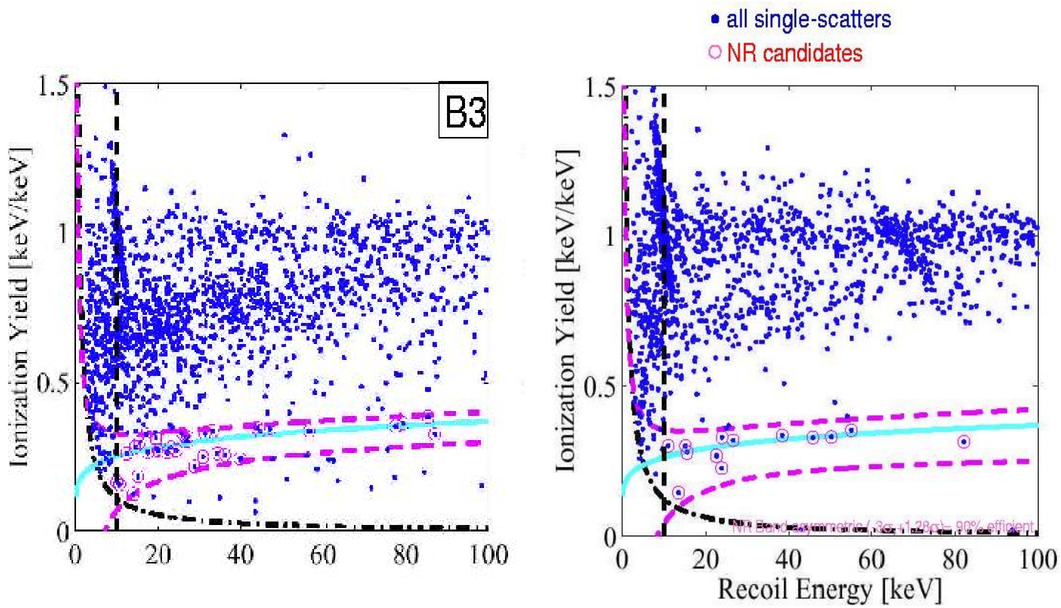
Always not a DM signature + no sensitivity to various candidates and scenarios

Some examples from CDMS-I

- Stanford site, shallow depth: 10 m underground
- Huge initial counting rates →hardware μ-anticoincidence

- 1999 - 10.6 kg d (48 kg d available) Ge BLIP; one detector not used.

Some examples of detectors data



- Knowledge and control of the: "physical" energy threshold, energy scale, Y scale, q.f., sensitive volumes, efficiencies, coincidence eff. for the two signals, energy calibrations, … + stability with time of all these quantities

- Due to small number of events to deal after selection, small fluctuations of parameters (energy, Y scales, noises, …) and of tails of the distributions can play a significant role

- rejection procedure of so-called surface electrons applied in addition to heat/ion rejection

4 events in the "recoil/recoil-like" window claimed after the huge "surface electrons" rejection procedures for selected period and detector , defined as "mainly neutrons"

CDMS II at Soudan

astro-ph/0405033

Exposure about 10^4 times smaller than DAMA/NaI

19.4 kg d exposure

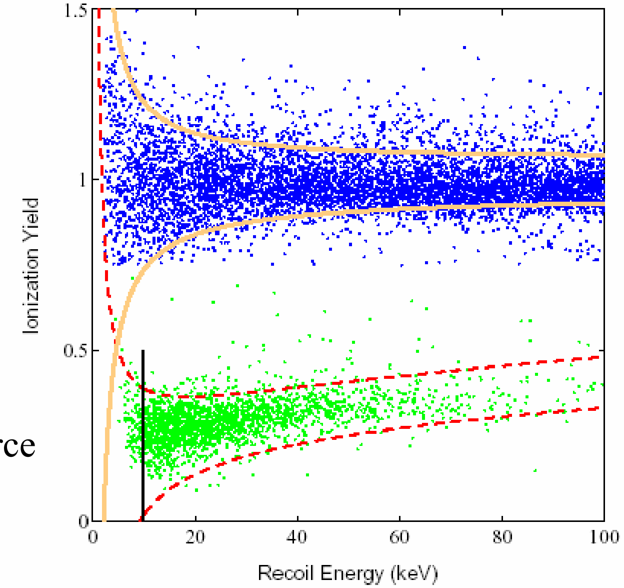
3 x 250 g crystals

See comments

in the slide on

Edelweiss

source



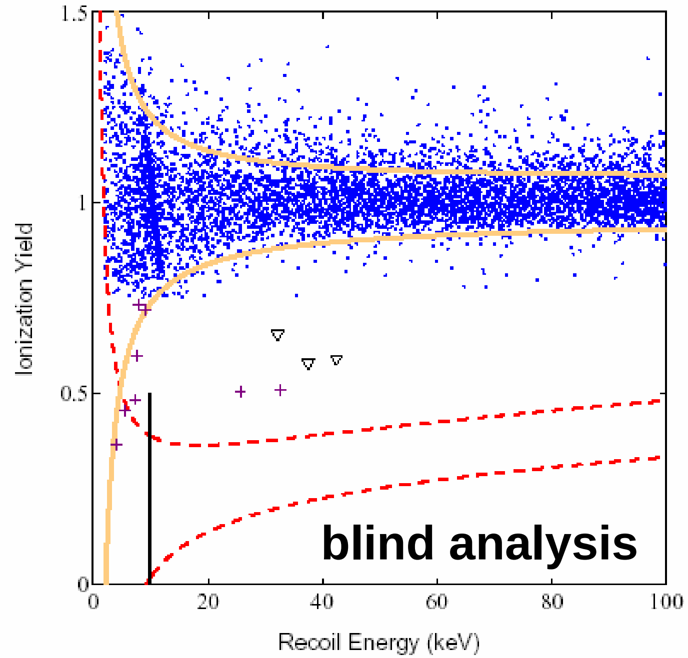


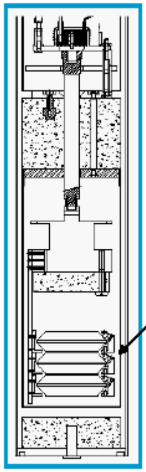
FIG. 4: Ionization yield versus recoil energy for WIMP-search data from Z2 (triangle), Z3, and Z5 (+) in Tower 1, using the same yield-dependent cuts and showing the same curves as in Fig. 1. Above an ionization yield of 0.75, the events from all three detectors are drawn as identical points in order to show the 10.4 keV Ga line from neutron activation of Ge.

Non-blind analysis: 1 event in the “recoil/recoil-like” window

1kg stage of EDELWEISS I : 3 * 320 g Ge.

Cu screens without Roman Pb lateral shield
1[st] data taking: Fall 2000, 1 detector mounted and used – 3kg.d
2[nd] data taking : Spring 2002, 1 detector used out of 3 – 8.6 kg.d
3[rd] data taking : October 2002 - March 2003, 3 detect. - 19 kg.d

Exposure about 10^4 times smaller than DAMA/NaI



4[th] data taking : April -Nov 2003, 3 detectors - 30 kg.d

May 2002
GGA1,GeAl9,GeAl10
October 2002
GGA3, GSA1, GSA3

320 g detector

But: quenching factor assumed 1 (the only measured value in NIMA507(2003)643 is compatible with all: 0.87±0.10stat ± 10syst). What about if less?

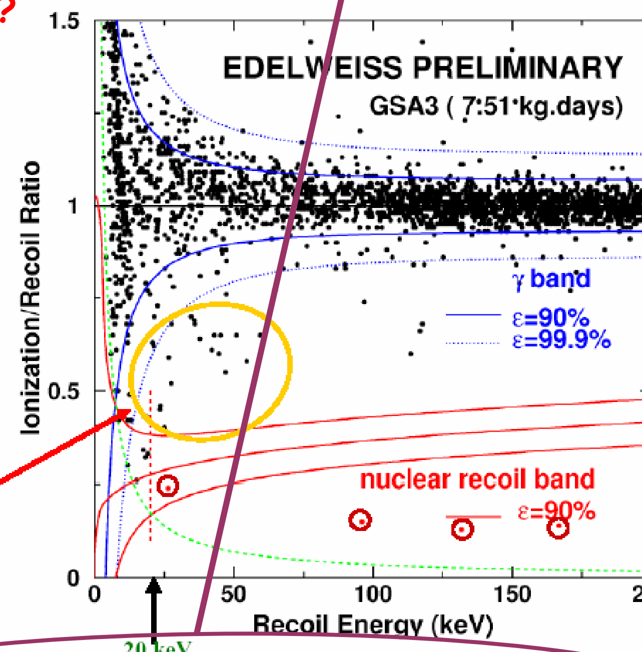
Also for future claimed sensitivities: which is the limit from systematics of this approach?

FEW COMMENTS:

- **very small exposure released with respect to many years of the experiment**
- **bckg rejection technique and associated uncertainties full under control (e.g. bulk response, pre-rejection of so-called surface electrons, quenching factors,..)? Are the two sensitive volumes (for ionization and bolometer signals) exactly identical?**
- **What about the needed continuous monitoring of rejection windows stability, energy scale and threshold, overall detection efficiency, calibration..?**
- **Set-up activation during neutron calibration**
- **Starting from a high background level**

- « Noisy » episode ?

-Events in red (1 inside and 3 outside the neutron zone) all arriving within an interval of a few days out of 90 days total acq time



What about spilling of these events with 10 times more exposure ?

NB : 100 % efficiency at true nuclear recoil energy threshold

Experiments using liquid noble gases

- Single phase: LXe,LAr, LNe $\rightarrow$ scintillation, ionization
- Dual phase liquid /gas $\rightarrow$ scintillation + scintillation

Electromagnetic component of the counting rate reduction

in single phase detector:

- pulse shape discrimination γ/recoils from the UV scintillation photons

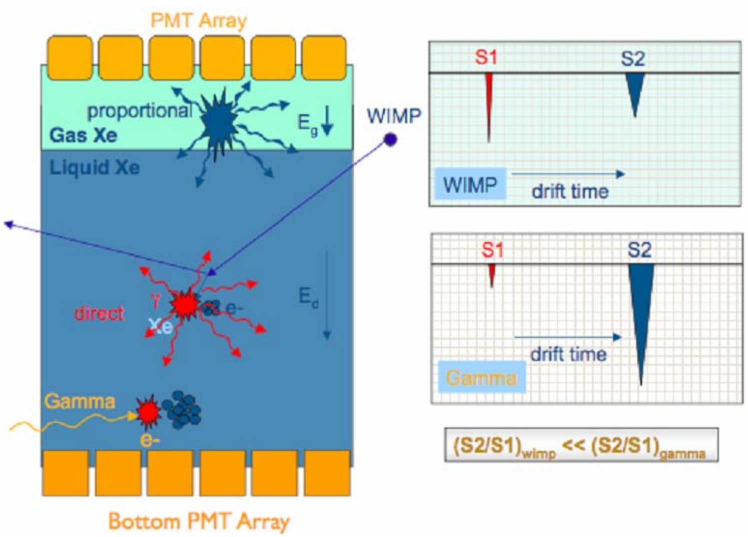
DAMA/LXe

ZEPLIN-I

DAMA/LXe: low background developments and applications to dark matter investigation (since N.Cim. A 103 (1990) 767)

in dual phase detector (old technique by XELTPC):

- prompt signal (S1): UV photons from excitation and ionisation
- delayed signal (S2): e^- drifted into gas phase and secondary scintillation due to ionization in electric field

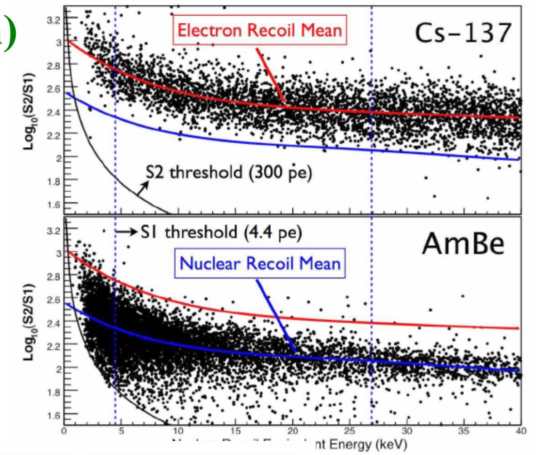


XENON10, WARP, ZEPLIN-II

Recent results of a liquid noble gas experiment: XENON10

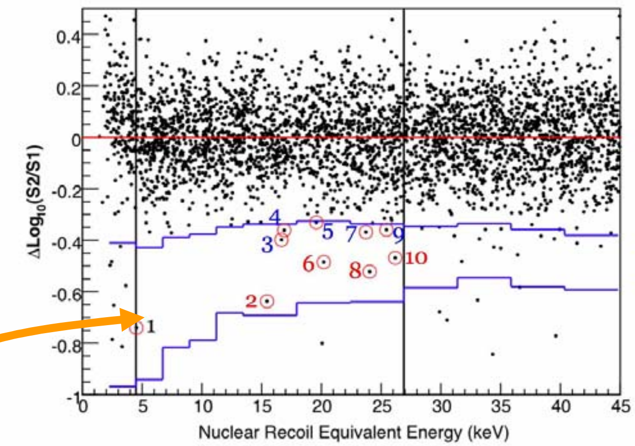
(arXiv:0706.0039)

Experimental site: Gran Sasso (1400 m depth)
Target material: ^{nat}Xe
Target mass: ≈5.4 kg (tot: 15 kg)
Used exposure: 136 kg × day



Many cuts are applied, each of them can introduce systematics. The systematics can be variable along the data taking period; can they and the related efficiencies be suitably evaluated in short period calibration ?

2 photoel./keV
2 kevee threshold claimed!
+q.f?
(see also calibration data)



50% efficiency

Cuts Explanation

QC0: Basic quality cuts	QC1: Fiducial volume cuts	QC2: High level cuts
Designed to remove noisy events, events with unphysical parameters or events which are not interesting for a WIMP search	Because of the high stopping power of LXe, fiducialization is a very effective way of reducing background.	Cuts based on the distribution of the S1 signal on the top and bottom PMTs. They are designed to remove events with anomalous or unusual S1 patterns
■ S1 coincidence cut ■ S1 single peak cut ■ S2 saturation cut ■ S2 single peak cut ■ S2 width cut ■ S2 χ^2 cut	■ $r < 80$ mm ■ $15\,\mu s < dt < 65\,\mu s$	■ S1 top-bottom asymmetry cut ■ S1 top RMS cut ■ S1 bottom RMS cut

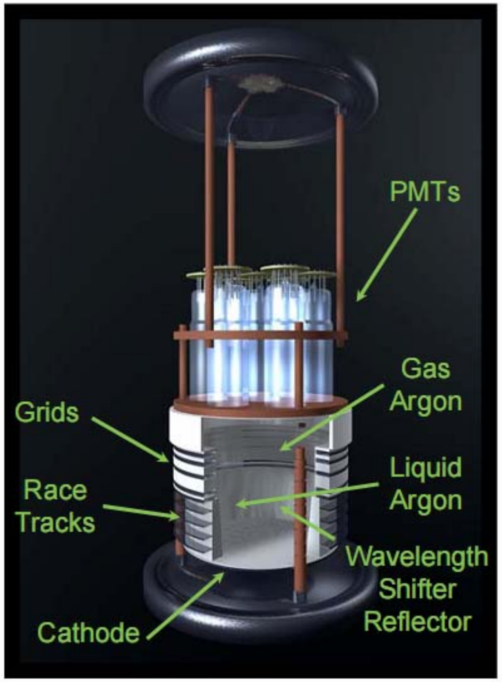
see Guillaume Plante, Columbia, APS Talk

Noble Liquids / Dark Matter — Rick Gaitskell, Brown University, DOE

- **Ten events survives the many cuts (efficiencies for all the cuts?+trigger level of single PMT?...).**
- **Some speculations about their nature.**
- **Has the (intrinsic) limitations of the method been reached?**

Recent results of a liquid noble gas experiment: WARP

(arXiv:0701286)

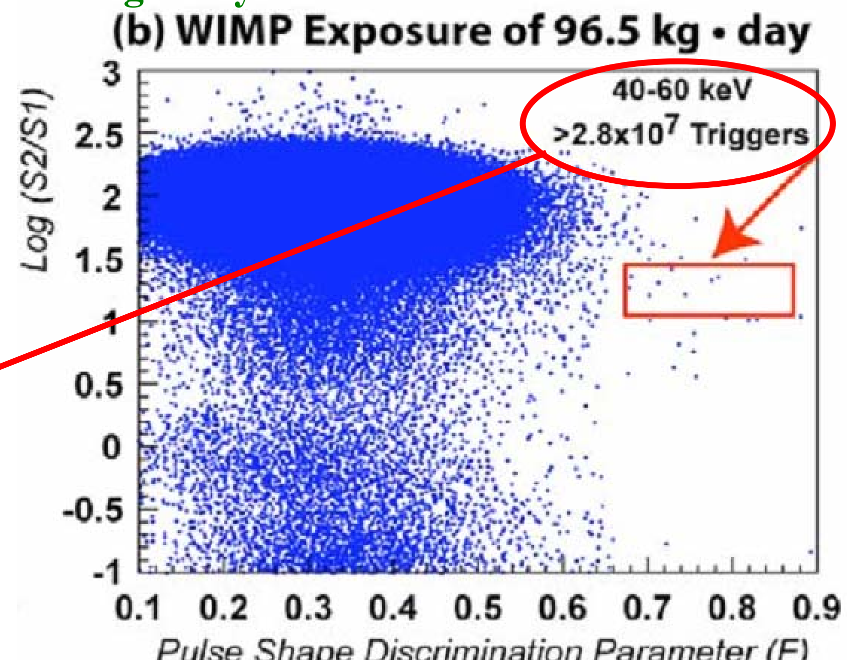


Experimental site: Gran Sasso (1400 m depth)

Target material: ^{nat}Ar

Target volume: ≈2.3 liters

Used exposure: 96.5 kg × day



Integral Rate = 3×10^5 cpd/kg

Energy threshold and scale

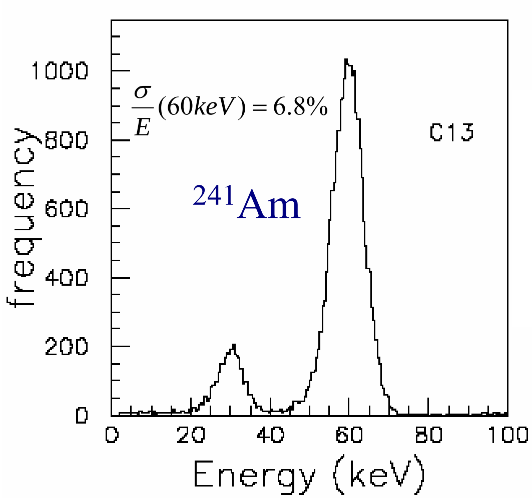
But cautious actitude:

Many cuts are applied, each of them can introduce systematics. The systematics can be variable along the data taking period; can they and the related efficiencies be suitably evaluated in short period calibration ?

- **Eight events survives the many cuts (efficiencies for all the cuts?+trigger level of single PMT?...). .**
- **Some speculations about their nature.**
- **Has the (intrinsic) limitations of the method been reached?**

Examples of energy resolutions: comparison with NaI(Tl)

NaI(Tl)



astro-ph/0603131, Jan 2007

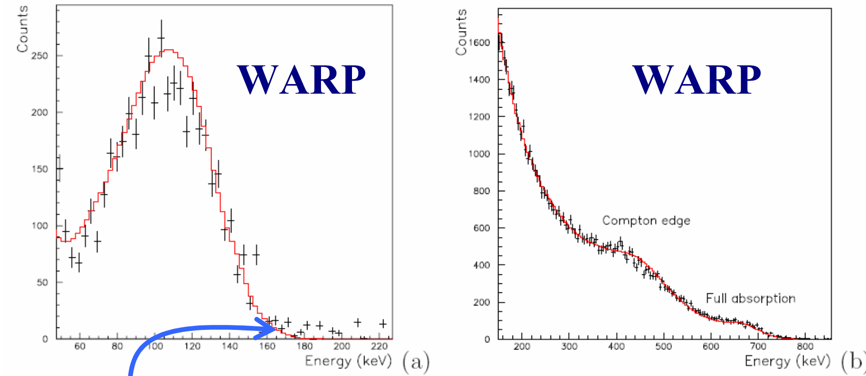


Fig. 2. Energy spectra taken with external γ-ray sources, superimposed with the corresponding Monte Carlo simulations. (a) ^{57}Co source (E = 122 keV, B.R. 85.6%, and 136 keV, B.R. 10.7%), (b) ^{137}Cs source (E = 662 keV).

subtraction of the spectrum ?

ZEPLIN-II

arXiv:astro-ph/0701858v2

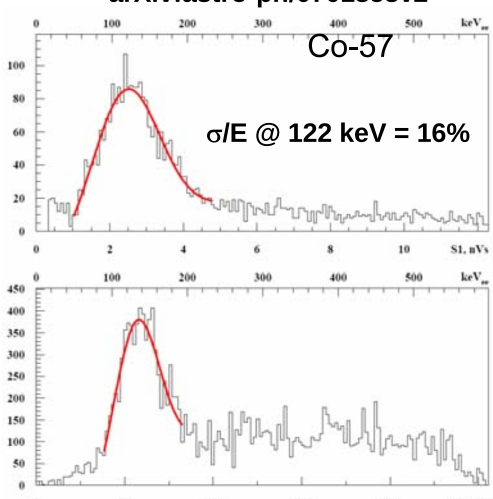


Fig. 5. Typical energy spectra for ^{57}Co γ-ray calibrations, showing S1 spectrum (upper) and S2 spectrum (lower). The fits are double Gaussian fits which incorporate both the 122 keV and 136 keV lines in the ^{57}Co γ-ray spectrum. The energy resolution of the detector is derived from the width of the S1 peak, coupled with calibration measurements at other line energies.

XENON10 XENON10

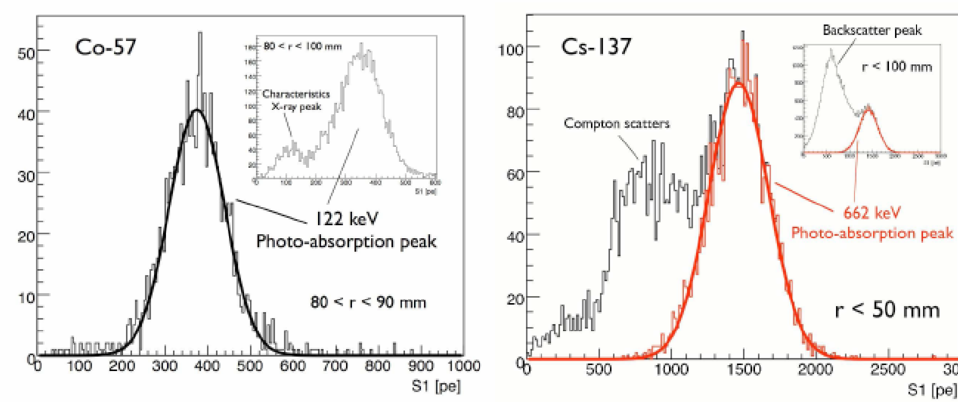


Figure 3. (left) S1 scintillation spectrum from a ^{57}Co calibration. The light yield for the 122 keV photo-absorption peak is 3.1 p.e./keV. (right) S1 scintillation spectrum from a ^{137}Cs calibration. The light yield for the 662 keV photo-absorption peak is 2.2 p.e./keV.

… disuniformity of the two-phases detectors: intrinsic limit?

tor after the WIMP search data taking. The $S1$ and $S2$ response from the ^{131m}Xe 164 keV gamma rays, which interact uniformly within the detector, were used to correct the position dependence of the two signals.

position dependent correction on S1 and S2 signals with maps obtained from activated Xe XENON10 astro-ph0706.0039v1.

where $a_0 = 9.5$ keV, $a_1 = 1.2$ keV and $a_2 = 0.04$. The three terms take into account the effects from non-uniform light collection (a_2 term), statistical

effects of non-uniform light collection accounted in WARP (astro-ph/0603131v2)

To convert the observed pulse height (in mV or photoelectrons) to electron equivalent energy for each event we calibrate with one or more gamma sources of known energy. We used ^{57}Co (122 keV) and ^{137}Cs (660 keV) sources placed under the xenon vessel. The ^{137}Cs source gave a measured light yield 25% lower than the ^{57}Co. Since previous laboratory work [7] had shown a response linear with energy, this difference is due to a position-dependent light collection, the

A geometrical correction is performed via a "rebinning matrix" evaluated by MonteCarlo in ZEPLINI Astroparticle Phys. 23(2005)444.

E being the γ-ray energy in keV. This has the effect of mixing the events between energy bins, which can at the final stage of analysis be accounted for by applying a compensating rebinning matrix to the energy-binned spectral terms, as shown in detail in [7].

Thus the WIMP-nucleon cross-section limit setting procedure is

(1) Apply an energy resolution correction as described in greater detail in a previous paper [7], by numerically applying the resolution rebinning matrix to the vector of binned spectral terms given by the right hand side of (1)

[7] G. J. Alner *et al.* (2005) *Astroparticle Phys.* **23(5)**, 444–462

the position dependent correction is still applied in ZEPLINII astro-ph/0701858v2

A model independent signature is needed

Directionality Correlation of Dark Matter impinging direction with Earth's galactic motion due to the distribution of Dark Matter particles velocities

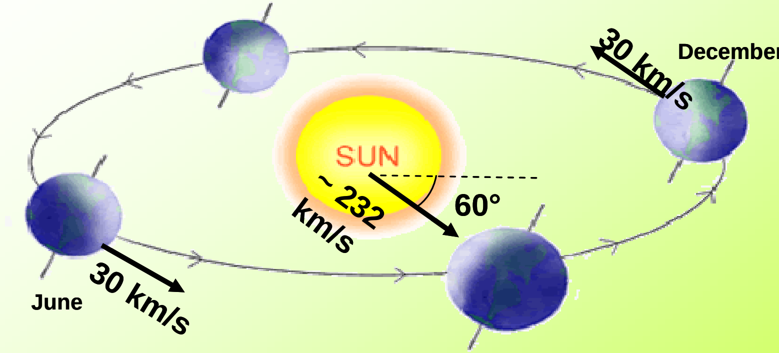
very hard to realize

Annual modulation Annual variation of the interaction rate due to Earth motion around the Sun.

at present the only feasible one

Diurnal modulation Daily variation of the interaction rate due to different Earth depth crossed by the Dark Matter particles

only for high σ

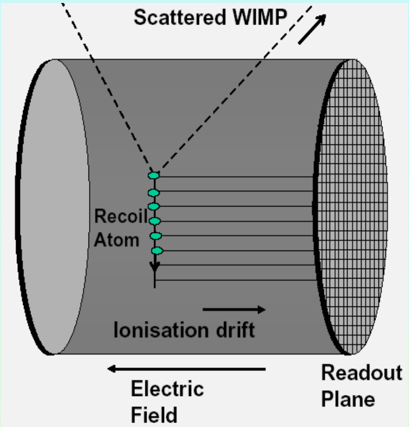


- Just for recoils: due to the statistical nature of all the discrimination procedures and to the related systematics, the annual modulation signature cannot be applied with the "discrimination".
- Other candidates are lost by "discrimination".

Directionality

- Correlation of the track of the nuclear recoil with Earth's motion in the Galactic halo (thus holds just for some DM candidates)

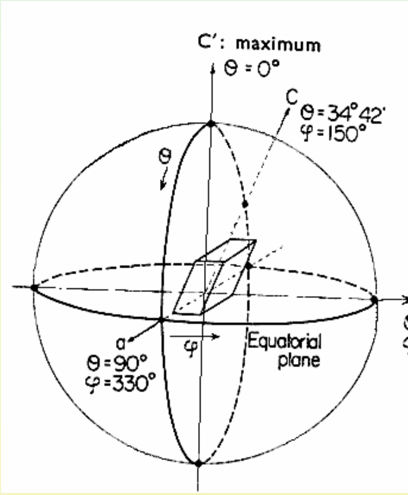
- Hard to realize if the track has to be detected: e.g. in low pressure TPC (old Saclay R&D).



A directional WIMP detector with organic anisotropic scintillator?

DAMA, N.Cim.15C(1992)475, EPJC28 (2003)203 (some tests also by UKDMC,Tokyo)

Crystals as anthracene, $C_{14}H_{10}$ and stilbene $C_{14}H_{12}$

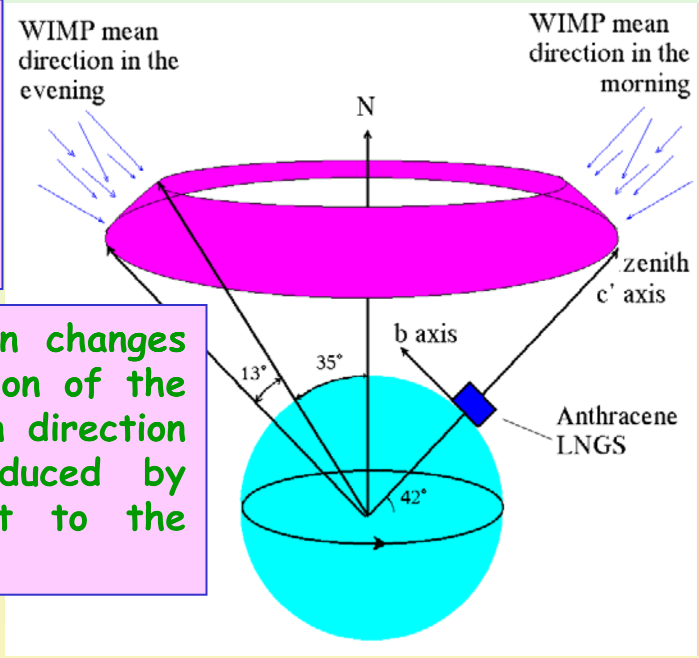


$$\frac{q^{c'}}{q^{b}} \approx 1.5$$

$$\frac{q^{c'}}{q^{a}} \approx 1.2$$

Example: Light response of anthracene relative to heavy ionizing particles depends on their impinging direction with respect to the crystal axes.

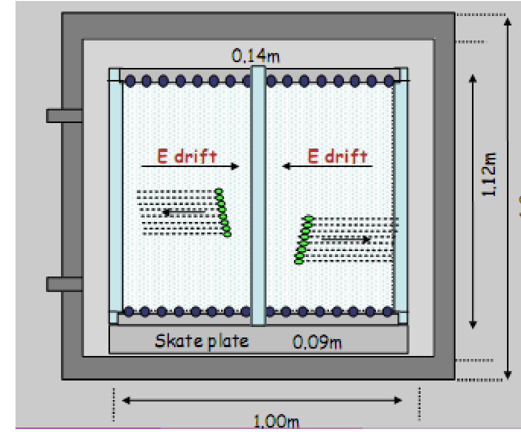
The diurnal Earth rotation changes the mean impinging direction of the WIMP flux (and the mean direction of the recoil nuclei induced by WIMP) with the respect to the crystal axes.



- light anisotropy for recoil nuclei and no anisotropy for electrons;
- anisotropy greater at low energy.

DRIFT-IIa

- Experimental site: Boulby mine
- Possible identification of some Dark Matter candidates by exploiting the non-isotropic recoil distribution correlated to the Earth position with to the Sun
- dE/dx discrimination between gammas and neutrons

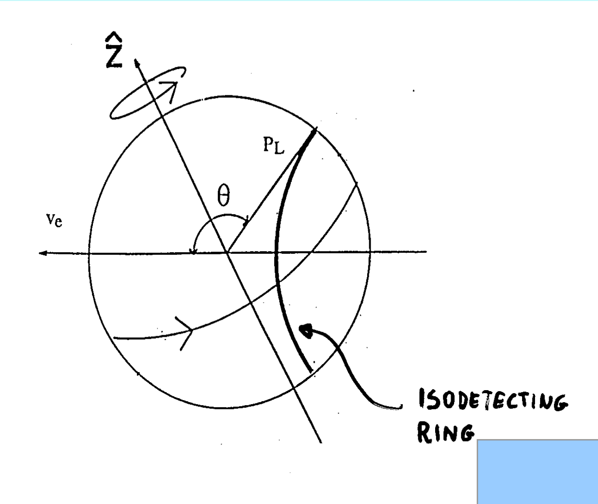


- 1 m³ active volume - back to back MWPCs
- Gas fill $\boxed{\text{40 Torr } CS_2 \Rightarrow \text{167 g of target gas}}$
- 2 mm pitch anode wires left and right
- Grid wires read out for Δy measurement
- Veto regions around outside
- Central cathode made from 20 μm diameter wires at 2 mm pitch
- Drift field 624 V/cm
- Modular design for modest scale-up

After an exposure of 10.2 kg x days a population of nuclear recoils (interpreted as due to the decay of unexpected ^{222}Rn daughter nuclei, present in the chamber) has been observed.

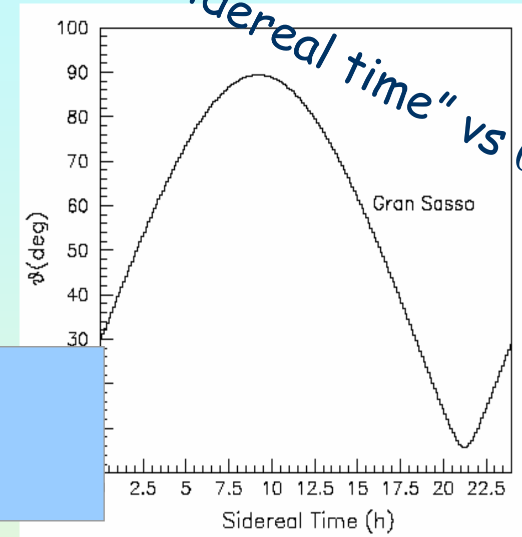
The diurnal modulation

Collar et al., PLB275(1992)181

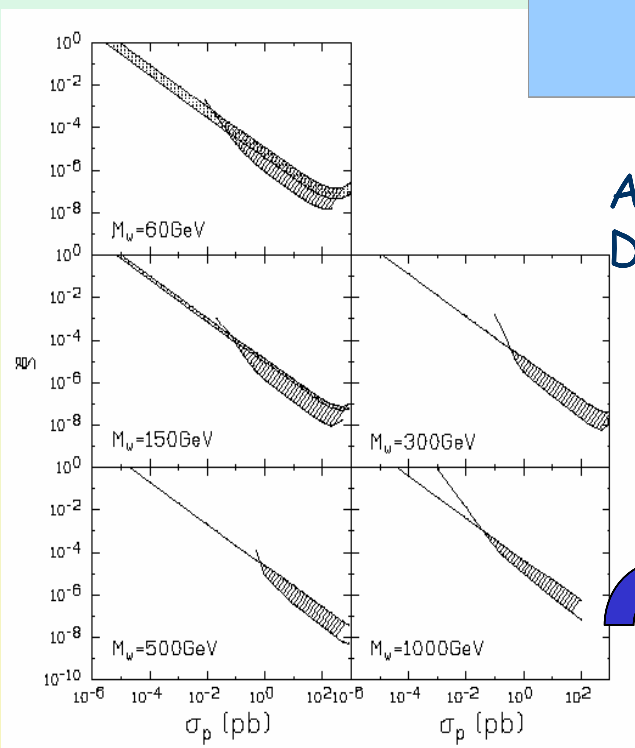


Daily variation of the interaction rate due to different Earth depth crossed by the WIMPs

"Sidereal time" vs θ



Only for large cross sections



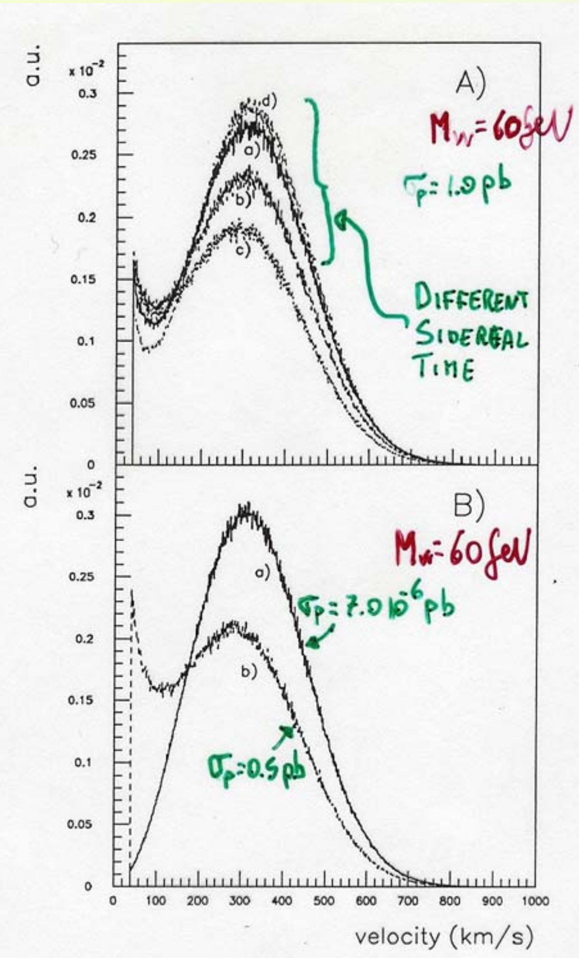
An example: investigation of possible diurnal modulation in DAMA/NaI-2 data (N.Cim. A112(1999)1541): 14962 kg d

Absence of rate diurnal variation at that sensitivity excludes the presence of high σ_p DMp component (with small ξ)

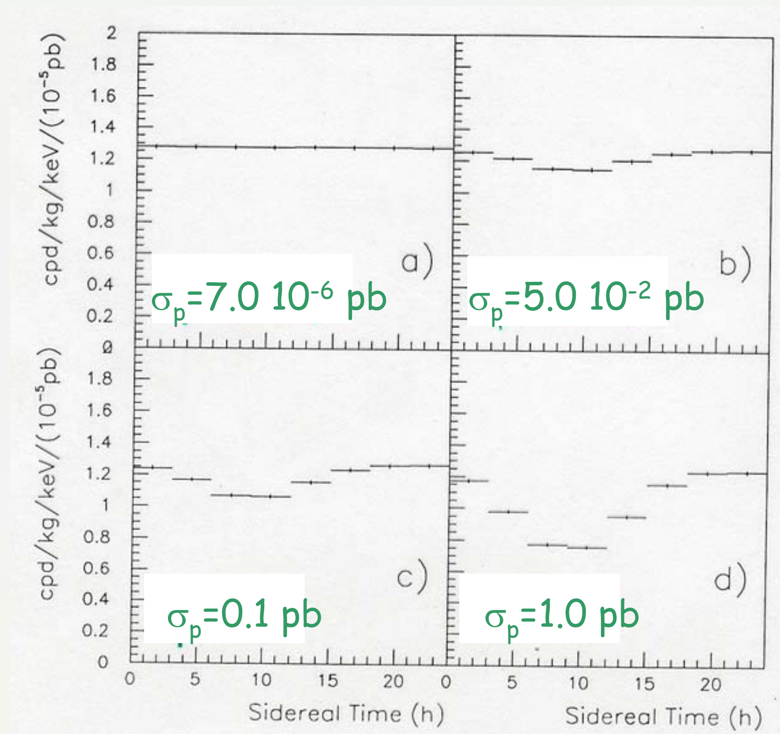
Limits on halo fraction (ξ) vs σ_p for SI case in a given model

For a given simplified model

Velocity distributions (MonteCarlo)



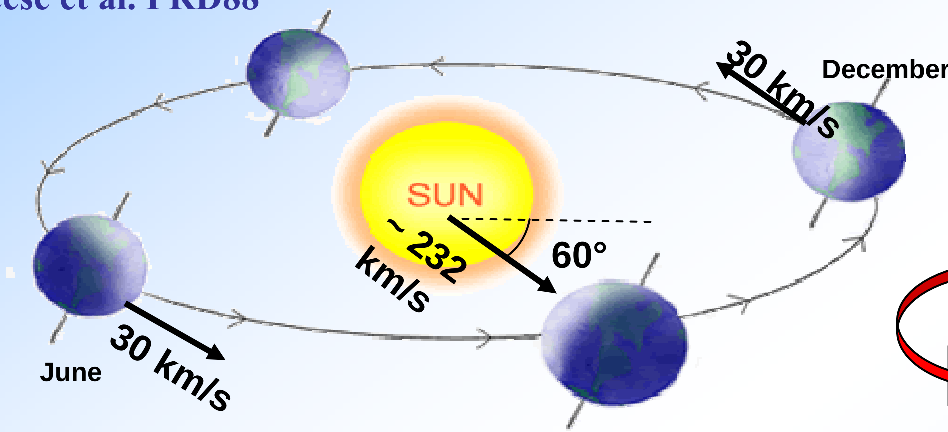
Example of expected rate [2,6] keV for the particular case of M_w=60 GeV



The annual modulation: a model independent signature for the investigation of Dark Matter particles component in the galactic halo

With the present technology, the annual modulation is the main model independent signature for the DM signal. Although the modulation effect is expected to be relatively small **a suitable large-mass, low-radioactive set-up with an efficient control of the running conditions would point out its presence.**

Drukier, Freese, Spergel PRD86
Freese et al. PRD88



- v_{sun} ~ 232 km/s (Sun velocity in the halo)
- v_{orb} = 30 km/s (Earth velocity around the Sun)
- $\gamma = \pi/3$
- $\omega = 2\pi/T$ T = 1 year
- t_0 = 2[nd] June (when $v_\oplus$ is maximum)

$$v_\oplus(t) = v_{sun} + v_{orb} \cos\gamma \cos[\omega(t-t_0)]$$

$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \cong S_{0,k} + S_{m,k} \cos[\omega(t-t_0)]$$

Expected rate in given energy bin changes because the annual motion of the Earth around the Sun moving in the Galaxy

Requirements of the annual modulation

1) Modulated rate according cosine
2) In a definite low energy range
3) With a proper period (1 year)
4) With proper phase (about 2 June)
5) For single hit events in a multi-detector set-up
6) With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions, but it can be larger in case of some possible scenarios

To mimic this signature, spurious effects and side reactions must not only - obviously - be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

Competitiveness of NaI(Tl) set-up

- High duty cycle
- Well known technology
- Large mass possible
- "Ecological clean" set-up; no safety problems
- Cheaper than every other considered technique
- Small underground space needed
- High radiopurity by selections, chem./phys. purifications, protocols reachable
- Well controlled operational condition feasible
- Routine calibrations feasible down to keV range in the same conditions as the production runs
- Neither re-purification procedures nor cooling down/warming up (reproducibility, stability, ...)
- Absence of microphonic noise + effective noise rejection at threshold (τ of NaI(Tl) pulses hundreds ns, while τ of noise pulses tens ns)
- High light response (5.5 -7.5 ph.e./keV)
- Sensitive to SI, SD, SI&SD couplings and to other existing scenarios, on the contrary of many other proposed target-nuclei
- Sensitive to both high (by Iodine target) and low mass (by Na target) candidates
- Effective investigation of the annual modulation signature feasible in all the needed aspects
- PSD feasible at reasonable level
- etc.

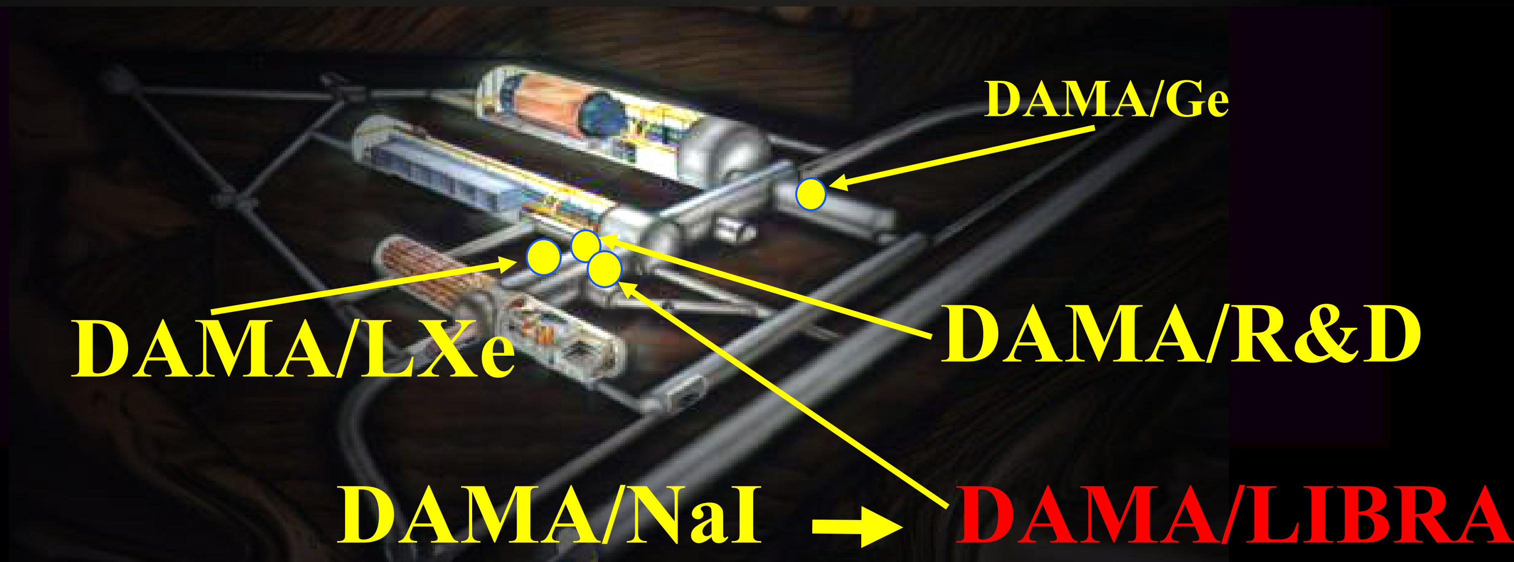
A low background NaI(Tl) also allows the study of several other rare processes :
possible processes violating the Pauli exclusion principle, CNC processes in ^{23}Na and ^{127}I, electron stability, nucleon and di-nucleon decay into invisible channels, neutral SIMP and nuclearites search, solar axion search, ...

High benefits/cost

Roma Tor Vergata, Roma La Sapienza, LNGS, IHEP/Beijing

+ by-products and small scale expts.: INR-Kiev
+ neutron meas.: ENEA-Frascati

& in some studies on ββ decays (DST-MAE project):
IIT Kharagpur, India



DAMA/LXe: results on rare processes

NIMA482(2002)728

Dark Matter Investigation

- Limits on recoils investigating the DMp-^{129}Xe elastic scattering by means of PSD — PLB436(1998)379
- Limits on DMp-^{129}Xe inelastic scattering — PLB387(1996)222, NJP2(2000)15.1
- Neutron calibration — PLB436(1998)379, EPJdirectC11(2001)1
- ^{129}Xe *vs* ^{136}Xe by using PSD $\rightarrow$ SD *vs* SI signals to increase the sensitivity on the SD component — foreseen/in progress

Other rare processes:

- Electron decay into invisible channels — Astrop.Phys5(1996)217
- Nuclear level excitation of ^{129}Xe during CNC processes — PLB465(1999)315
- N, NN decay into invisible channels in ^{129}Xe — PLB493(2000)12
- Electron decay: $e^- \rightarrow \nu_e \gamma$ — PRD61(2000)117301
- 2β decay in ^{136}Xe — Xenon01
- 2β decay in ^{134}Xe — PLB527(2002)182
- Improved results on 2β in ^{134}Xe, ^{136}Xe — PLB546(2002)23
- CNC decay ^{136}Xe $\rightarrow$ ^{136}Cs — Beyond the Desert (2003) 365
- N, NN, NNN decay into invisible channels in ^{136}Xe — EPJA27 s01 (2006) 35

DAMA/R&D set-up: results on rare processes

- Particle Dark Matter search with CaF_2(Eu) — NPB563(1999)97, Astrop.Phys.7(1997)73

- 2β decay in ^{136}Ce and in ^{142}Ce — Il Nuov.Cim.A110(1997)189
- $2EC2\nu$ ^{40}Ca decay — Astrop. Phys. 7(1999)73
- 2β decay in ^{46}Ca and in ^{40}Ca — NPB563(1999)97
- $2\beta^+$ decay in ^{106}Cd — Astrop.Phys.10(1999)115
- 2β and β decay in ^{48}Ca — NPA705(2002)29
- $2EC2\nu$ in ^{136}Ce, in ^{138}Ce and α decay in ^{142}Ce — NIMA498(2003)352
- $2\beta^+ 0\nu$ and EC $\beta^+ 0\nu$ decay in ^{130}Ba — NIMA525(2004)535
- Cluster decay in $LaCl_3$(Ce) — NIMA555(2005)270
- CNC decay ^{139}La $\rightarrow$ ^{139}Ce — UJP51(2006)1037
- α decay of natural Eu — NPA789(2007)15

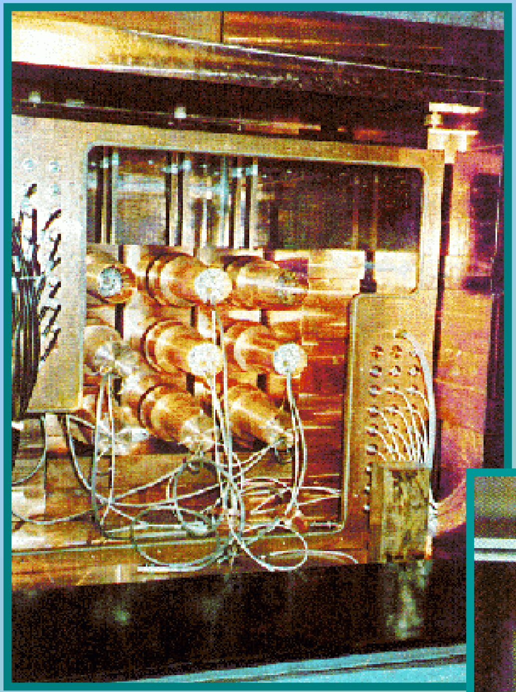
DAMA/Ge & LNGS Ge facility

- RDs on highly radiopure NaI(Tl) set-up;
- several RDs on low background PMTs;
- qualification of many materials
- measurements with a $Li_6Eu(BO_3)_3$ crystal (NIMA572(2007)734)
- measurements with ^{100}Mo sample investigating some double beta decay mode in progress in the 4π low-background HP Ge facility of LNGS (to appear on Nucl. Phys. and Atomic Energy)

+ Many other meas. already scheduled for near future

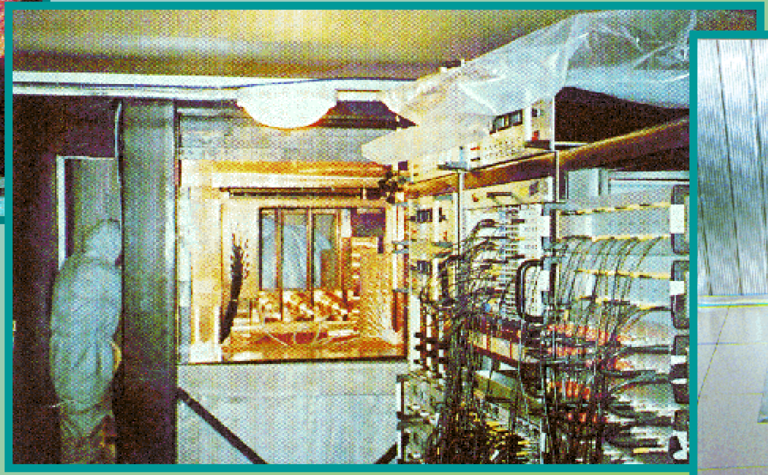
DAMA/NaI(Tl)~100 kg

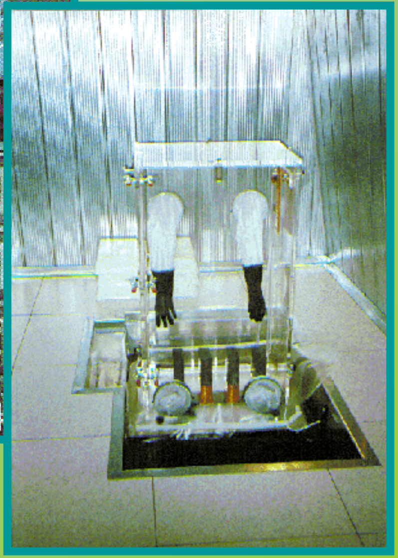
Performances: N.Cim.A112(1999)545-575, EPJC18(2000)283, Riv.N.Cim.26 n. 1(2003)1-73, IJMPD13(2004)2127



Results on rare processes:

- Possible Pauli exclusion principle violation — PLB408(1997)439
- CNC processes — PRC60(1999)065501
- Electron stability and non-paulian transitions in Iodine atoms (by L-shell) — PLB460(1999)235
- Search for solar axions — PLB515(2001)6
- Exotic Matter search — EPJdirect C14(2002)1
- Search for superdense nuclear matter — EPJA23(2005)7
- Search for heavy clusters decays — EPJA24(2005)51





Results on DM particles:

- PSD — PLB389(1996)757
- Investigation on diurnal effect — N.Cim.A112(1999)1541
- Exotic Dark Matter search — PRL83(1999)4918
- Annual Modulation Signature
  PLB424(1998)195, PLB450(1999)448, PRD61(1999)023512, PLB480(2000)23,EPJ C18(2000)283, PLB509(2001)197, EPJ C23 (2002)61, PRD66(2002)043503, Riv.N.Cim.26 n.1 (2003)1-73, IJMPD13(2004)2127, IJMPA21(2006)1445, EPJC47(2006)263, IJMPA22(2007)3155 + other works in progress....

data taking completed on July 2002
(still producing results)

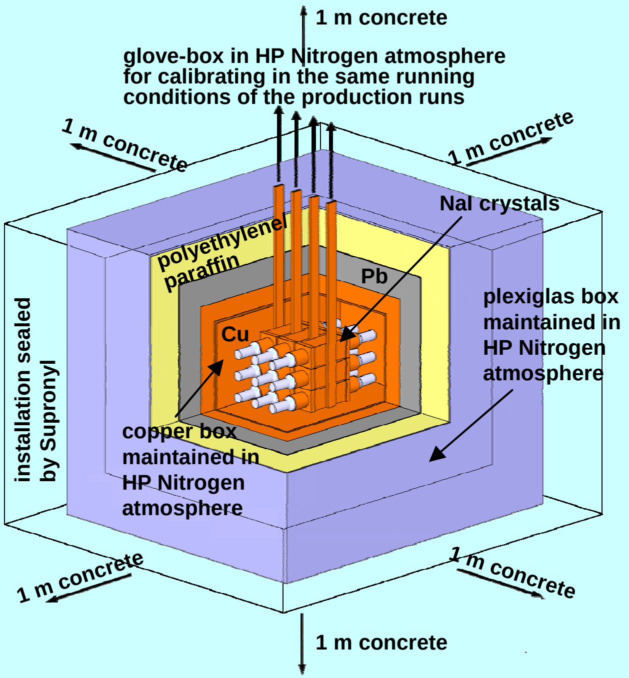
total exposure collected in 7 annual cycles 107731 kg×d

Main Features of DAMA/NaI

Il Nuovo Cim. A112 (1999) 545-575, EPJC18(2000)283,
Riv. N. Cim. 26 n.1 (2003)1-73, IJMPD13(2004)2127

- Reduced standard contaminants (e.g. U/Th of order of ppt) by material selection and growth/handling protocols.
- PMTs: Each crystal coupled - through 10cm long tetrasil-B light guides acting as optical windows - to 2 low background EMI9265B53/FL (special development) 3” diameter PMTs working in coincidence.
- Detectors inside a sealed highly radiopure Cu box maintained in HP Nitrogen atmosphere in slight overpressure
- Very low radioactive shields: 10 cm of highly radiopure Cu, 15 cm of highly radiopure Pb + shield from neutrons: Cd foils + 10-40 cm polyethylene/paraffin+ ~ 1 m concrete (from GS rock) moderator largely surrounding the set-up
- Installation sealed: A plexiglas box encloses the whole shield and is also maintained in HP Nitrogen atmosphere in slight overpressure. Walls, floor, etc. of inner installation sealed by Supronyl (2×10^{-11} cm^2/s permeability).Three levels of sealing from environmental air.
- Installation in air conditioning + huge heat capacity of shield
- Calibration in the same running conditions as the production runs down to keV region.
- Energy and threshold: Each PMT works at single photoelectron level. Energy threshold of the expt: 2 keV (from X-ray and Compton electron calibrations in the keV range and from the features of the noise rejection and efficiencies). Data collected from low energy up to MeV region, despite the hardware optimization was done for the low energy
- Pulse shape recorded over 3250 ns by Transient Digitizers.
- Monitoring and alarm system continuously operating by self-controlled computer processes.

+ electronics and DAQ fully renewed in summer 2000



Simplified schema

Main procedures of the DAMA data taking for the DMp annual modulation signature

- data taking of each annual cycle starts from autumn/winter (when $\cos\omega(t-t_0)\approx0$) toward summer (maximum expected).
- routine calibrations for energy scale determination, for acceptance windows efficiencies by means of radioactive sources each ~ 10 days collecting typically ~10^5 evts/keV/detector + intrinsic calibration + periodical Compton calibrations, etc.
- continuous on-line monitoring of all the running parameters with automatic alarm to operator if any out of allowed range.

The model independent result

Riv. N. Cim. 26 n.1. (2003) 1-73, IJMPD13(2004)2127

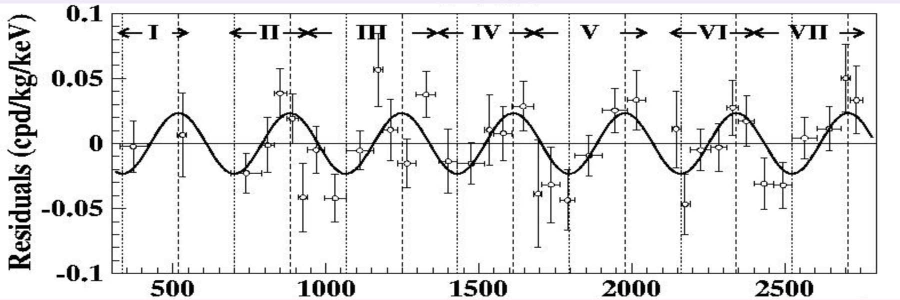
Annual modulation of the rate: DAMA/NaI 7 annual cycles

experimental single-hit residuals rate vs time and energy

107731 kg · d

$A\cos[\omega(t-t_0)]$; continuous lines: t_0 = 152.5 d, T = 1.00 y

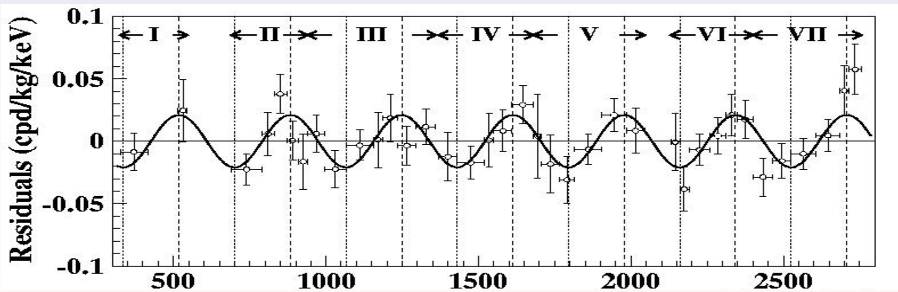
2-4 keV



fit: A=(0.0233 ± 0.0047) cpd/kg/keV

Time (day)

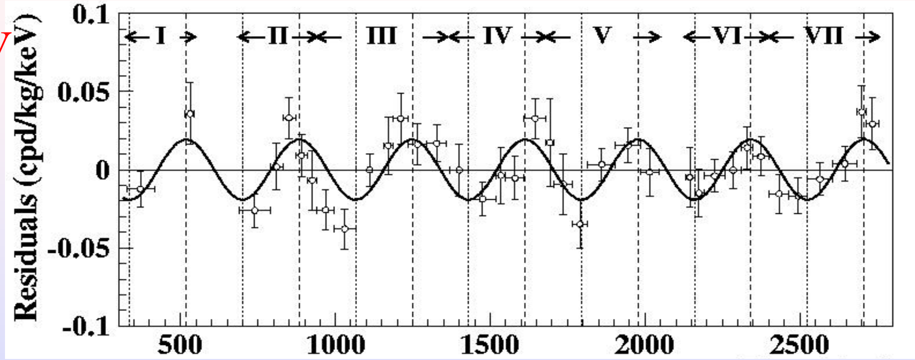
2-5 keV



fit: A = (0.0210 ± 0.0038) cpd/kg/keV

Time (day)

2-6 keV



Time (day)

Absence of modulation? No

χ^2/dof=71/37 → P(A=0)=$7\cdot 10^{-4}$

fit: A = (0.0192 ± 0.0031) cpd/kg/keV

fit (all parameters free):

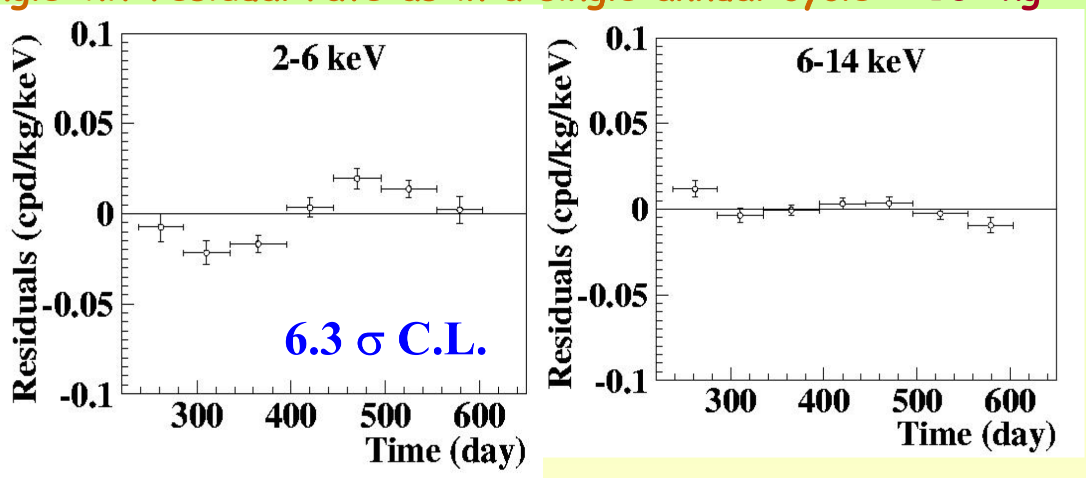
A = (0.0200 ± 0.0032) cpd/kg/keV;

t_0 = (140 ± 22) d ; T = (1.00 ± 0.01) y

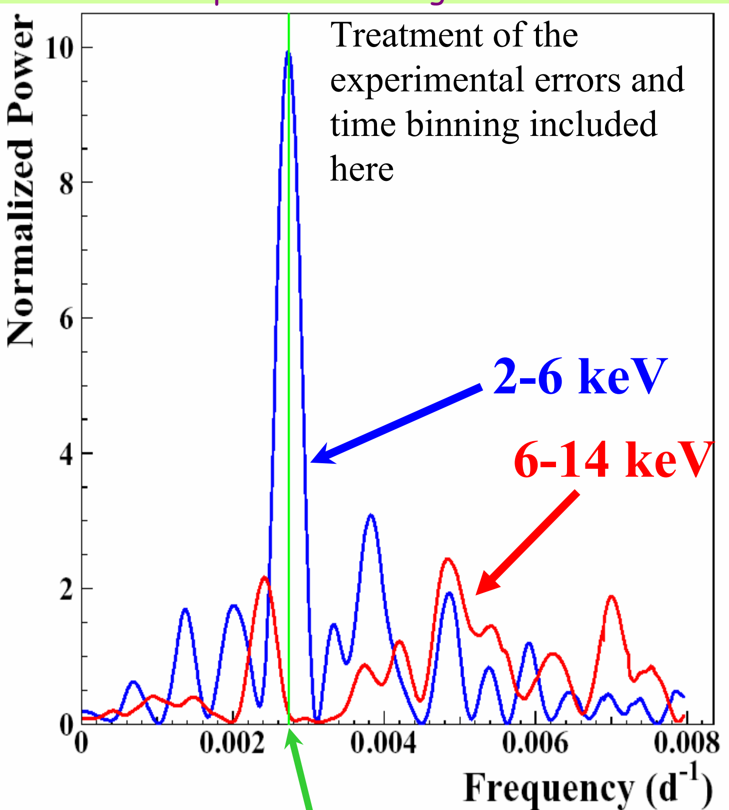
The data favor the presence of a modulated behavior with proper features at 6.3σ C.L.

Low energy vs higher energy

Single-hit residual rate as in a single annual cycle ≈ 10^5 kg × day



Power spectrum of single-hit residuals



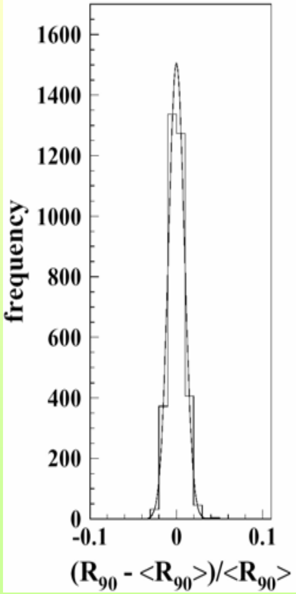
fixing t_0 = 152.5 day and T = 1.00 y, the modulation amplitude:

A=(0.0195 ± 0.0031) cpd/kg/keV A= -(0.0009 ± 0.0019) cpd/kg/keV

Principal mode in the 2-6 keV region → 2.737 · 10^{-3} d^{-1} ≈ 1 y^{-1}

Not present in the 6-14 keV region (only aliasing peaks)

- Clear modulation present in the lowest energy region: from the energy threshold, 2 keV, to 6 keV.



No modulation found:

- in the 6-14 keV energy regions
- in other energy regions closer to that where the effect is observed e.g.: mod. ampl. (6-10 keV): -(0.0076 ±0.0065), (0.0012±0.0059) and (0.0035±0.0058) cpd/kg/keV for DAMA/NaI-5,DAMA/NaI-6 and DAMA/NaI-7; statistically consistent with zero
- in the integral rate above 90 keV, e.g.: mod. ampl.: (0.09±0.32), (0.06±0.33) and -(0.03±0.32) cpd/kg for DAMA/NaI-5, DAMA/NaI-6 and DAMA/NaI-7; statistically consistent with zero + if a modulation present in the whole energy spectrum at the level found in the lowest energy region → R_{90} ~ tens cpd/kg → ~ 100 σ far away

Multiple-hits events in the region of the signal

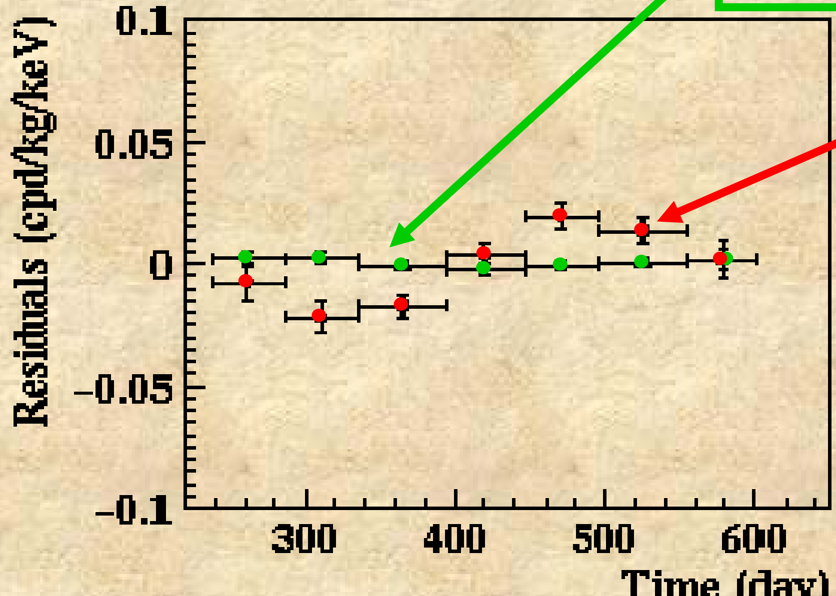
- In DAMA/NaI-6 and 7 each detector has its own TD (multiplexer system removed) → pulse profiles of multiple-hits events (multiplicity > 1) also acquired (total exposure: 33834 kg d).
- The same hardware and software procedures as the ones followed for single-hit events

→ just one difference: events induced by Dark Matter particles do not belong to this class of events, that is: multiple-hits events = Dark Matter particles events "switched off"

- **2-6 keV residuals**

Residuals for multiple-hits events (DAMA/NaI-6 and 7)

Mod ampl. = $-(3.9 \pm 7.9) \cdot 10^{-4}$ cpd/kg/keV

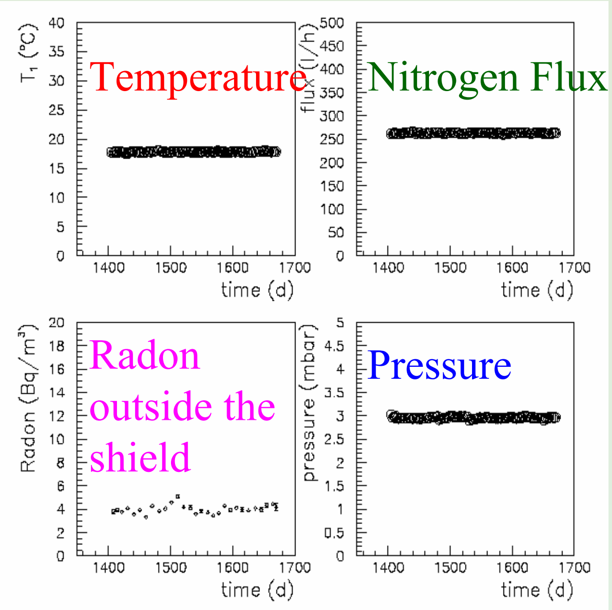


Residuals for single-hit events (DAMA/NaI 7 annual cycles)

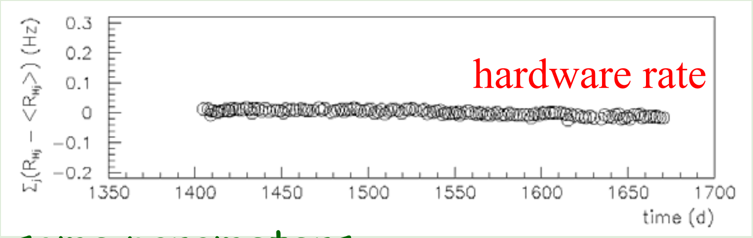
Mod ampl. = (0.0195 ± 0.0031) cpd/kg/keV

This result offers an additional strong support for the presence of Dark Matter particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

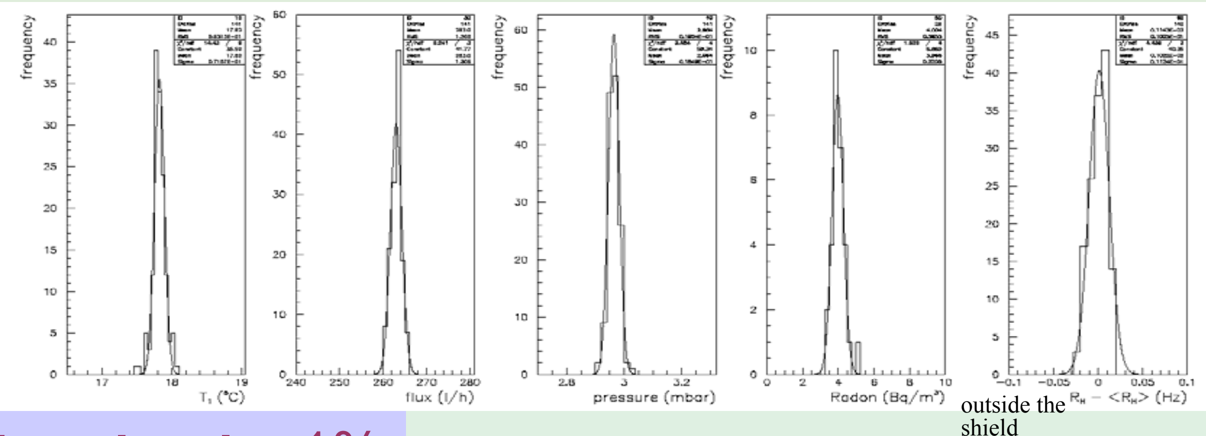
Running conditions



an example: DAMA/NaI-6



Distribution of some parameters



Running conditions stable at level < 1%

Modulation amplitudes obtained by fitting the time behaviours of main running parameters, acquired with the production data, when including a modulation term as in the Dark Matter particles case.

	DAMA/NaI-5	DAMA/NaI-6	DAMA/NaI-7
Temperature	$-(0.033 \pm 0.050)°C$	$(0.021 \pm 0.055)°C$	$-(0.030 \pm 0.056)°C$
Flux	(0.03 ± 0.08) l/h	(0.05 ± 0.14) l/h	(0.07 ± 0.14) l/h
Pressure	$-(0.6 \pm 1.7)10^{-3}$ mbar	$(0.5 \pm 2.5)10^{-3}$ mbar	$(0.2 \pm 2.8)10^{-3}$ mbar
Radon	$-(0.09 \pm 0.17)$ Bq/m^3	(0.06 ± 0.14) Bq/m^3	$-(0.02 \pm 0.03)$ Bq/m^3
Hardware rate	$(0.10 \pm 0.17)10^{-2}$ Hz	$-(0.09 \pm 0.19)10^{-2}$ Hz	$-(0.22 \pm 0.19)10^{-2}$ Hz

All the measured amplitudes well compatible with zero
+ none can account for the observed effect

(to mimic such signature, spurious effects and side reactions must not only be able to account for the whole observed modulation amplitude, but also simultaneously satisfy all the 6 requirements)

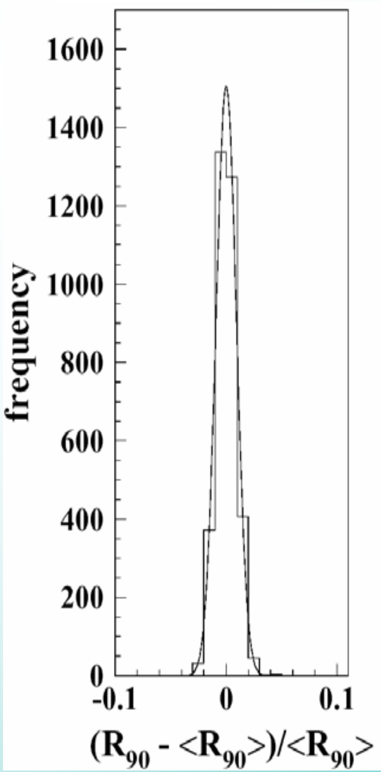
[for details and for the other annual cycles see for example: PLB424(1998)195, PLB450(1999)448, PLB480(2000)23, RNC26(2003)1-73, EPJC18(2000)283, IJMPD13(2004)2127]

Can a hypothetical background modulation account for the observed effect?

Integral rate at higher energy (above 90 keV), R_{90}

- R_{90} percentage variations with respect to their mean values for single crystal in the DAMA/NaI-5,6,7 running periods

  → cumulative gaussian behaviour with $\sigma \approx 0.9\%$, fully accounted by statistical considerations



- Fitting the behaviour with time, adding a term modulated according period and phase expected for Dark Matter particles:

Period	Mod. Ampl.
DAMA/NaI-5	(0.09±0.32) cpd/kg
DAMA/NaI-6	(0.06±0.33) cpd/kg
DAMA/NaI-7	-(0.03±0.32) cpd/kg

→consistent with zero + if a modulation present in the whole energy spectrum at the level found in the lowest energy region → R_{90} ~ tens cpd/kg → ~ 100 σ far away

Energy regions closer to that where the effect is observed e.g.:

Mod. Ampl. (6-10 keV): -(0.0076 ± 0.0065), (0.0012 ± 0.0059) and (0.0035 ± 0.0058) cpd/kg/keV for DAMA/NaI-5, DAMA/NaI-6 and DAMA/NaI-7; → they can be considered statistically consistent with zero

In the same energy region where the effect is observed:

no modulation of the multiple-hits events (see elsewhere)

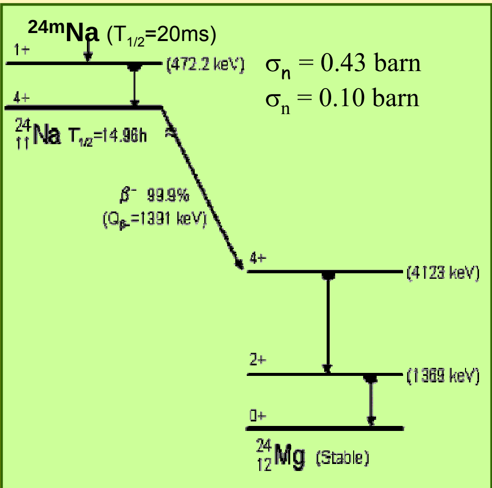
No modulation in the background:
these results also account for the bckg component due to neutrons

Can a possible thermal neutron modulation account for the observed effect?

NO

- Thermal neutrons flux measured at LNGS :

$\Phi_n = 1.08\ 10^{-6}$ n cm^{-2} s^{-1} (N.Cim.A101(1989)959)
(cautiously adopted here and in all the DAMA calculations)



- Experimental limit on the neutrons flux "*surviving*" the neutron shield in the DAMA/NaI set-up:
  - less sensitive approach: studying some neutron activation channels (N.Cim.A112(1999)545):

    $\Phi_n < 5.9\ 10^{-6}$ n cm^{-2} s^{-1}
  - more sensitive approach: studying triple coincidences able to give evidence for the possible presence of ^{24}Na from neutron activation (derivable from EPJA24(2005)51):

    $\Phi_n < 4.0\ 10^{-7}$ n cm^{-2} s^{-1}

Evaluation of the expected effect:

- Capture rate = $\Phi_n\ \sigma_n\ N_T$ = 0.17 capture/d/kg • $\Phi_n/(10^{-6}$ n cm^{-2} s$^{-1})$
- For ex., neutron capture in ^{23}Na: ^{23}Na(n,γ)^{24}Na; ^{23}Na(n,γ)^{24m}Na

HYPOTHESIS: assuming very cautiously $\Phi_n=10^{-6}$ n cm^{-2} s^{-1} and a 10% thermal neutron modulation:

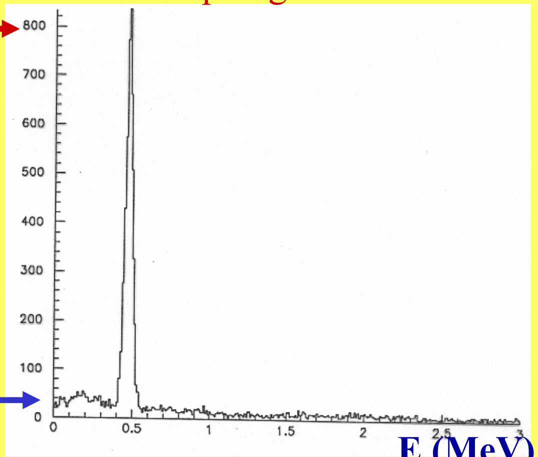
$\Rightarrow$ $S_m^{(\text{thermal n})} < 10^{-5}$ cpd/kg/keV (< 0.05% S_m^{observed}) $\Leftarrow$

MC simulation of the process

When $\Phi_n = 10^{-6}$ n cm^{-2} s^{-1}:

$7 \cdot 10^{-5}$ cpd/kg/keV

$1.4 \cdot 10^{-3}$ cpd/kg/keV



In all the cases of neutron captures (^{24}Na, ^{128}I, ...) a possible thermal n modulation induces a variation in all the energy spectrum

Already excluded also by R_{90} analysis, etc.

Can a possible fast neutron modulation account for the observed effect?

NO

In the estimate of the possible effect of the neutron background cautiously not included the 1m concrete moderator, which almost completely surrounds (mostly outside the barrack) the passive shield

Measured fast neutron flux @ LNGS:
$\Phi_n = 0.9\ 10^{-7}$ n cm^{-2} s^{-1} (Astropart.Phys.4 (1995),23)

By MC: differential counting rate above 2 keV ≈ 10^{-3} cpd/kg/keV

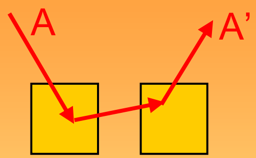
HYPOTHESIS: Assuming - very cautiously - a 10% neutron modulation: ⇒ $S_m^{(fast\ n)} < 10^{-4}$ cpd/kg/keV (< 0.5% $S_m^{observed}$)

Moreover, a possible fast n modulation would induce:

- a variation in all the energy spectrum (steady environmental fast neutrons always accompained by thermalized component)
  - already excluded also by R_{90}
- a modulation amplitude for multiple-hit events different from zero
  - already excluded by the multiple-hit events (see also elsewhere)

Thus, a possible 5% neutron modulation (ICARUS TM03-01) cannot quantitatively contribute to the DAMA/NaI observed signal, even if the neutron flux would be assumed 100 times larger than measured by various authors over more than 15 years @ LNGS

What we can also learn from the multiple/single hit rates. A toy model



$$R_{\text{mult}} = R_{\text{single}} \cdot \left\langle \frac{N_T \sigma_T}{4\pi r^2} \right\rangle$$

What about the nuclear cross sections of the particle (*A*) responsible of the modulation in the single-hit rate and not in the multiple-hit rate?

$$N_T \sigma_T = N_{Na} \sigma_{Na} + N_I \sigma_I = N \cdot (\sigma_{Na} + \sigma_I)$$

The 8 NaI(Tl) detectors in (anti-)coincidence have 3.1×10^{26} nuclei of Na and 3.1×10^{26} nuclei of Iodine. *N*= 3.1×10^{26}

$$R_{\text{mult}} \approx R_{\text{single}} \cdot \frac{N \cdot (\sigma_{Na} + \sigma_I)}{4\pi \cdot r_{med}^2}$$

r_{med} ~ *10-15 cm*

Therefore, the ratio of the modulation amplitudes is:

$$\frac{A_{mult}}{A_{\text{single}}} \approx \frac{N \cdot (\sigma_{Na} + \sigma_I)}{4\pi \cdot r_{med}^2}$$

From the experimental data: $A_{mult} \approx -(4 \pm 8) \cdot 10^{-4} \text{ cpd/kg/keV} < 10^{-3} \text{ cpd/kg/keV};$

$$A_{\text{single}} \approx 2 \cdot 10^{-2} \text{ cpd/kg/keV};$$

Hence: $\frac{A_{mult}}{A_{\text{single}}} < 5 \cdot 10^{-2}$

In conclusion, the particle (*A*) responsible of the modulation in the single-hit rate and not in the multiple-hit rate must have:

$$\sigma_{Na} + \sigma_I < 0.2 \text{ barn}$$

Since for fast neutrons the sum of the two cross sections (weighted by 1/E, ENDF/B-VI) is about 4 barns:

It (*A*) cannot be a fast neutron

Summary of the results obtained in the investigations of possible systematics or side reactions

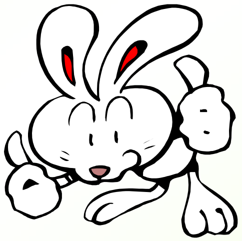
(see for details Riv. N. Cim. 26 n. 1 (2003) 1-73, IJMPD13(2004)2127 and references therein)

Source	Main comment	Cautious upper limit (90%C.L.)
RADON	installation excluded by external Rn +3 levels of sealing in HP Nitrogen atmosphere, etc	$<0.2\%\ S_m^{obs}$
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded +etc.	$<0.5\%\ S_m^{obs}$
NOISE	Effective noise rejection near threshold (τ_{noise}~ tens ns, τ_{NaI} ~ hundreds ns; etc.)	$<1\%\ S_m^{obs}$
ENERGY SCALE	X-rays + Periodical calibrations in the same running conditions + continuous monitoring of ^{210}Pb peak	$<1\%\ S_m^{obs}$
EFFICIENCIES	Regularly measured by dedicated calibrations	$<1\%\ S_m^{obs}$
BACKGROUND	No modulation observed above 6 keV + this limit includes possible effect of thermal and fast neutrons + no modulation observed in the multiple-hits events in 2-6 keV region	$<0.5\%\ S_m^{obs}$
SIDE REACTIONS	Muon flux variation measured by MACRO	$<0.3\%\ S_m^{obs}$

+ even if larger they cannot satisfy all the requirements of annual modulation signature

Thus, they can not mimic the observed annual modulation effect

The positive and model independent result of DAMA/NaI



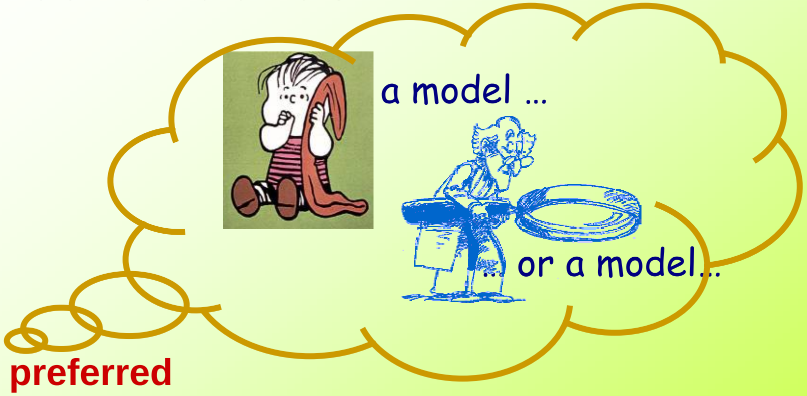
- Presence of modulation for 7 annual cycles at ~6.3σ C.L. with the proper distinctive features of the signature; all the features satisfied by the data over 7 independent experiments of 1 year each one
- Absence of known sources of possible systematics and side processes able to quantitatively account for the observed effect and to contemporaneously satisfy the many peculiarities of the signature

No other experiment whose result can be directly compared in model independent way is available so far

To investigate the nature and coupling with ordinary matter of the possible DM candidate(s), effective energy and time correlation analysis of the events has to be performed within given model frameworks

Corollary quests for candidates

- **astrophysical models: ρ_{DM}, velocity distribution and its parameters**
- **nuclear and particle Physics models**
- **experimental parameters**

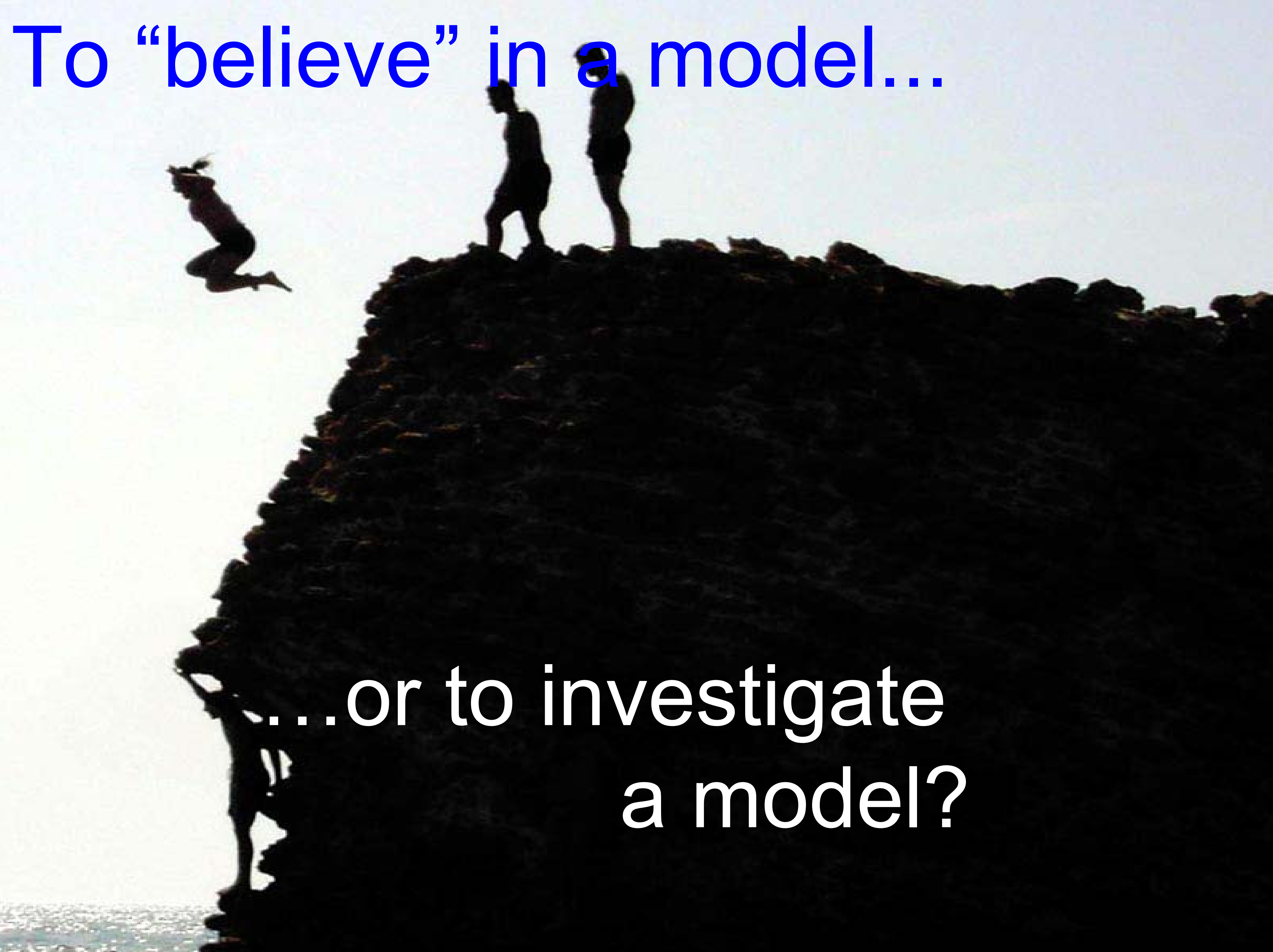


e.g. for WIMP class particles: SI, SD, mixed SI&SD, preferred inelastic, scaling laws on cross sections, form factors and related parameters, spin factors, halo models, etc.

+ different scenarios

+ multi-component halo?

THUS uncertainties on models and comparisons


To “believe” in a model...
…or to investigate
a model?

DM particle-nucleus elastic scattering -I

SI+SD differential cross sections:

$$\frac{d\sigma}{dE_R}(v,E_R)=\left(\frac{d\sigma}{dE_R}\right)_{SI}+\left(\frac{d\sigma}{dE_R}\right)_{SD}=$$

$$\frac{2G_F^2 m_N}{\pi v^2}\left\{\left[Zg_p+(A-Z)g_n\right]^2 F_{SI}^2(E_R)+8\frac{J+1}{J}\left[a_p\langle S_p\rangle+a_n\langle S_n\rangle\right]^2 F_{SD}^2(E_R)\right\}$$

$g_{p,n}$($a_{p,n}$) effective DM particle-nucleon couplings

$\langle S_{p,n}\rangle$ nucleon spin in the nucleus

$F^2(E_R)$ nuclear form factors

m_{Wp} reduced DM particle-nucleon mass

Generalized SI/SD DM particle-nucleon cross sections:

$$\sigma_{SI}=\frac{4}{\pi}G_F^2 m_{Wp}^2 g^2 \qquad \sigma_{SD}=\frac{32}{\pi}\frac{3}{4}G_F^2 m_{Wp}^2 \bar{a}^2$$

where:

$$\begin{cases} g=\dfrac{g_p+g_n}{2}\bullet\left[1-\dfrac{g_p-g_n}{g_p+g_n}\left(1-\dfrac{2Z}{A}\right)\right] \\ \bar{a}=\sqrt{a_p^2+a_n^2} \qquad tg\theta=\dfrac{a_n}{a_p} \end{cases}$$

g: independent on the used target nucleus since Z/A nearly constant for the nuclei typically used

Differential energy distribution:

$$\frac{dR}{dE_R}=N_T\frac{\rho_W}{m_W}\int_{v_{\min}(E_R)}^{v_{\max}}\frac{d\sigma}{dE_R}(v,E_R)vf(v)dv=N_T\frac{\rho_W m_N}{2m_W m_{Wp}^2}\cdot\Sigma(E_R)\cdot I(E_R)$$

N_T: number of target nuclei

$$\Sigma(E_R)=\left\{A^2\sigma_{SI}F_{SI}^2(E_R)+\frac{4}{3}\frac{J+1}{J}\sigma_{SD}\left[\langle S_p\rangle\cos\theta+\langle S_n\rangle\sin\theta\right]^2 F_{SD}^2(E_R)\right\}$$

f(v): DM particle velocity distribution in the Earth frame (**it depends on v_e**)

$v_e=v_{sun}+v_{orb}\cos\omega t$

$$I(E_R)=\int_{v_{\min}(E_R)}^{v_{\max}}\frac{f(v)}{v}dv \qquad v_{\min}=\sqrt{\frac{m_N E_R}{2m_{WN}^2}}$$

minimal velocity providing E_R recoil energy

v_{max}: maximal DM particle velocity in the Earth frame

The inelastic DM – nucleus interaction: $W + N \rightarrow W^* + N$

- **DM particle candidate suggested by D. Smith and N. Weiner (PRD64(2001)043502)**
- **Two mass states χ_+ , χ_- with δ mass splitting**
- **Kinematical constraint for the inelastic scattering of χ_- on a nucleus with mass m_N becomes increasingly severe for low m_N**

$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

Ex. m_W =100 GeV

m_N	μ
70	41
130	57

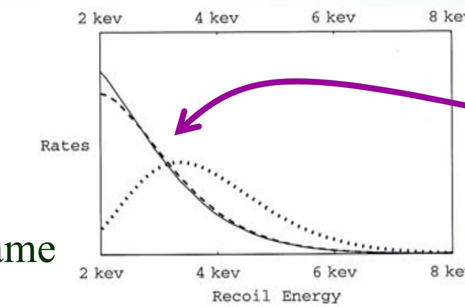
Differential energy distribution for SI interaction:

$$\frac{d\sigma}{d\Omega^*} = \frac{G_F^2 m_{WN}^2}{\pi^2}\left[Zg_p + (A-Z)g_n\right]^2 F_{SI}^2(q^2)\cdot\sqrt{1-\frac{v_{thr}^2}{v^2}}$$

$g_{p,n}$ effective DM particle-nucleon couplings

$d\Omega^*$ differential solid angle in the DM-nucleon c.m. frame

q^2 = squared threee-momentum transfer



Normalized modulation (S_m) as a function of energy for ordinary WIMP scenario (solid), inelastic WIMP scenario with $\delta = 100$keV (dashed), and inelastic WIMP scenario with $\delta = 150$keV (dotted), all with $m_\chi = 60$GeV.

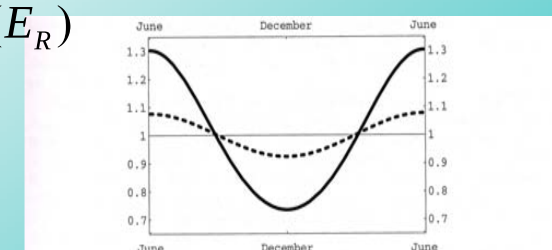
S_m/S_0 enhanced with respect to the elastic scattering case

Nucleus recoil energy:

$$E_R = \frac{2m_{WN}^2 v^2}{m_N}\cdot\frac{1-\frac{v_{thr}^2}{2v^2}-\sqrt{1-\frac{v_{thr}^2}{v^2}}\cdot\cos\theta^*}{2} \qquad \frac{d\sigma}{dE_R} = \frac{2G_F^2 m_N}{\pi v^2}\left[Zg_p + (A-Z)g_n\right]^2 F_{SI}^2(E_R)$$

Differential energy distribution:

$$\frac{dR}{dE_R} = N_T\frac{\rho_W}{m_W}\int_{v_{min}}^{v_{max}}\frac{d\sigma}{dE_R}(v,E_R)vf(v)dv \qquad v_{min}(E_R) = \sqrt{\frac{m_N E_R}{2m_{WN}^2}}\cdot\left(1+\frac{m_{WN}\delta}{m_N E_R}\right)$$



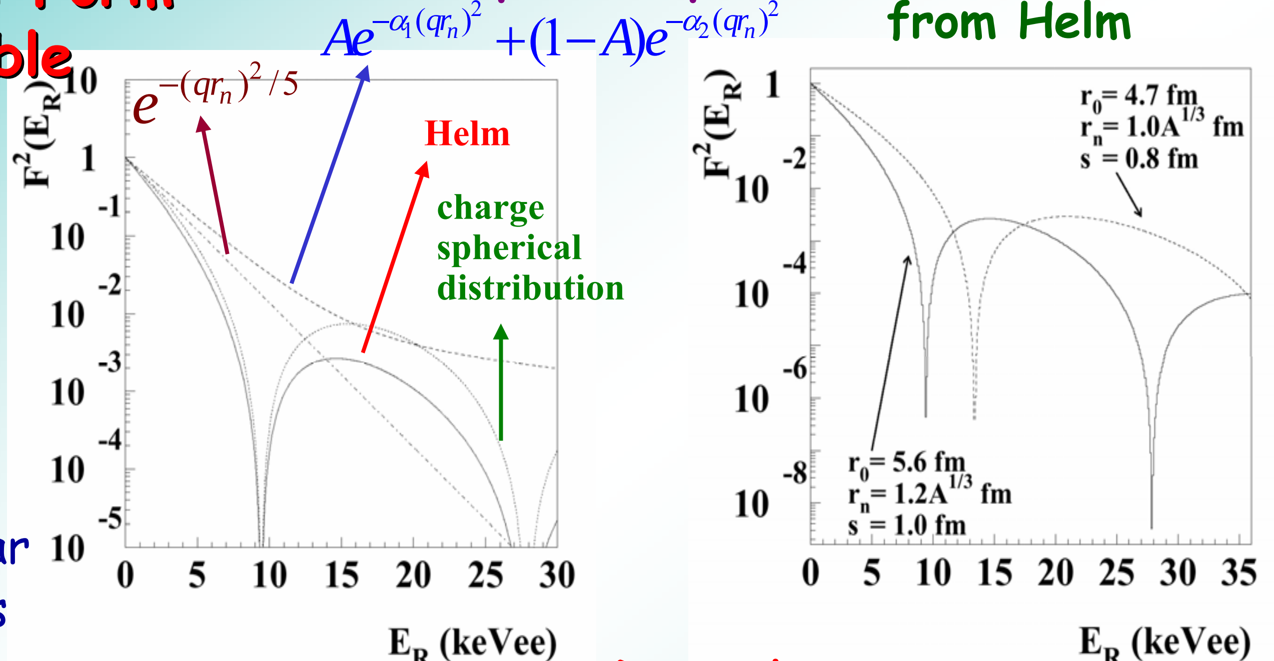
Annual modulation of event rate with average normalized to one in the inelastic WIMP scenario (solid line) and standard WIMP scenario (dashed), with $\delta = 100$keV and $m_\chi = 50$GeV.

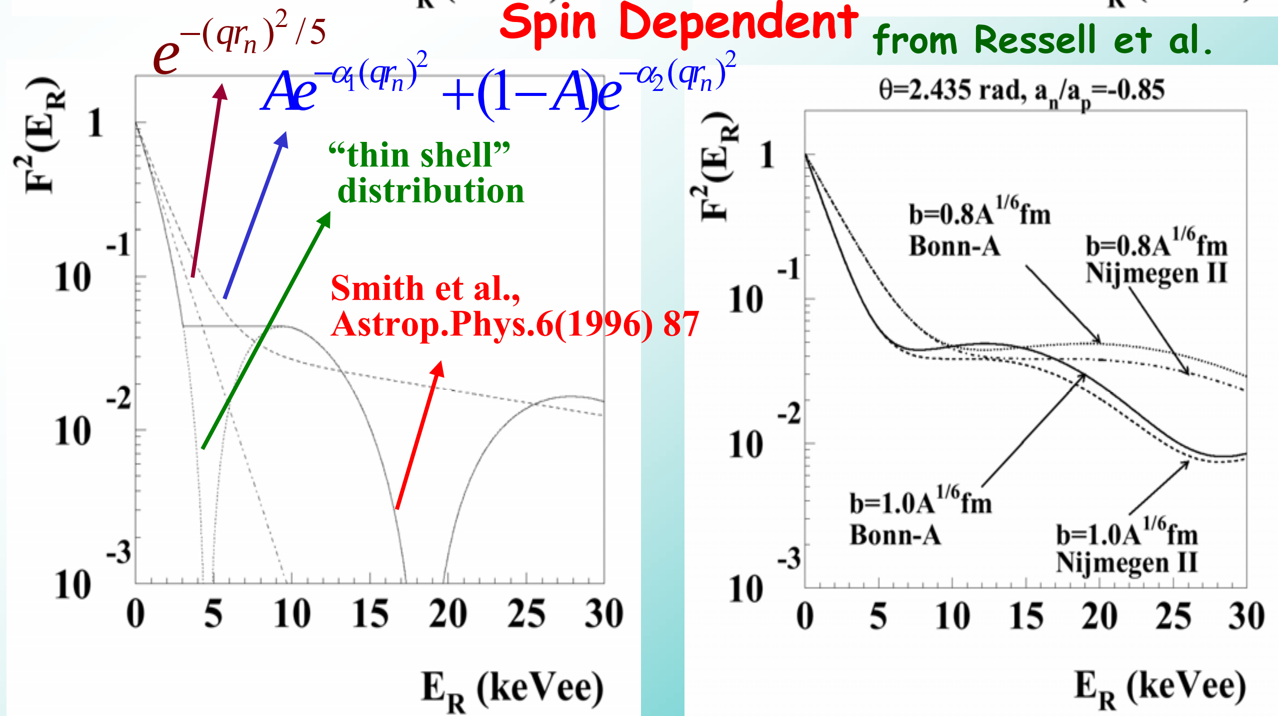
Examples of different Form Factor for ^{127}I available in literature

- Take into account the structure of target nuclei
- In SD form factor: no decoupling between nuclear and Dark Matter particles degrees of freedom; dependence on nuclear potential.

Similar situation for all the target nuclei considered in the field

Spin Independent





The Spin Factor

Spin Factors for some target-nuclei calculated in simple different models

Target-Nucleus	single particle	odd group	Comment
^{29}Si	0.750	0.063	Neutron is the unpaired nucleon
^{73}Ge	0.306	0.065	
^{129}Xe	0.750	0.124	
^{131}Xe	0.150	0.055	
^{1}H	0.750	0.750	Proton is the unpaired nucleon
^{19}F	0.750	0.647	
^{23}Na	0.350	0.041	
^{27}Al	0.350	0.087	
^{69}Ga	0.417	0.021	
^{71}Ga	0.417	0.089	
^{75}As	0.417	0.000	
^{127}I	0.250	0.023	

Spin factor $= \Lambda^2 J(J+1)/a_x^2$

($a_x = a_n$ or a_p depending on the unpaired nucleon)

Spin Factors calculated on the basis of Ressell et al. for some of the possible θ values considering some target nuclei and two different nuclear potentials

Target-Nucleus / nuclear potential	θ=0	$\theta=\pi/4$	$\theta=\pi/2$	θ=2.435 (pure Z_0 coupling)
^{23}Na	0.102	0.060	0.001	0.051
^{127}I/Bonn A	0.134	0.103	0.008	0.049
^{127}I/Nijmegen II	0.175	0.122	0.006	0.073
^{129}Xe/Bonn A	0.002	0.225	0.387	0.135
^{129}Xe/Nijmegen II	0.001	0.145	0.270	0.103
^{131}Xe/Bonn A	0.000	0.046	0.086	0.033
^{131}Xe/Nijmegen II	0.000	0.044	0.078	0.029
^{125}Te/Bonn A	0.000	0.124	0.247	0.103
^{125}Te/Nijmegen II	0.000	0.156	0.313	0.132

Spin factor $= \Lambda^2 J(J+1)/\bar{a}^2$

$$tg\theta = \frac{a_n}{a_p} \qquad (0 \leq \theta < \pi)$$

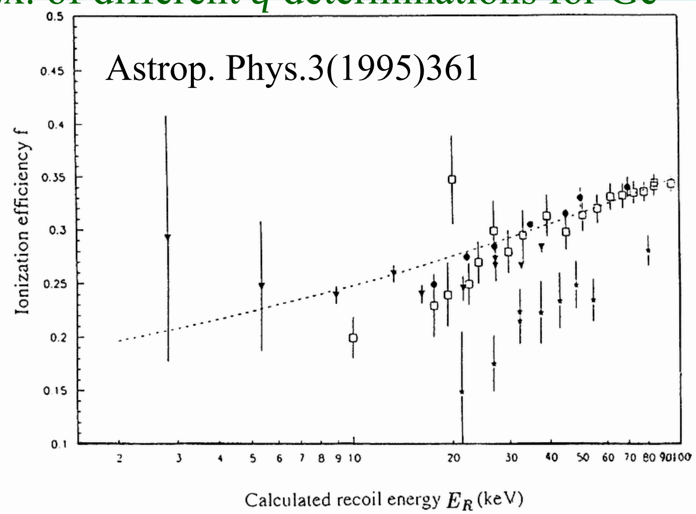
Large differences in the measured counting rate can be expected:

- **when using target nuclei sensitive to the SD component of the interaction (such as e.g. ^{23}Na and ^{127}I) with the respect to those largely insensitive to such a coupling (such as e.g. ^{nat}Ge, ^{nat}Si, ^{nat}Ar, ^{nat}Ca, ^{nat}W, ^{nat}O);**
- **when using different target nuclei although all – in principle – sensitive to such a coupling, depending on the unpaired nucleon (compare e.g. odd spin isotopes of Xe, Te, Ge, Si, W with the ^{23}Na and ^{127}I cases).**

Quenching factor

Quenching factors, q, measured by neutron sources or by neutron beams for some detectors and nuclei

Ex. of different q determinations for Ge



- differences are often present in different experimental determinations of q for the same nuclei in the same kind of detector
- e.g. in doped scintillators q depends on dopant and on the impurities/trace contaminants; in LXe e.g.on trace impurities, on initial UHV, on presence of degassing/releasing materials in the Xe, on thermodynamical conditions, on possibly applied electric field, etc.
- Some time increases at low energy in scintillators (dL/dx)

... and more

recoil/electron response ratio measured with a neutron source or at a neutron generator

Nucleus/Detector	Recoil Energy (keV)	q	Reference
NaI(Tl)	(6.5-97)	(0.30 ± 0.01) for Na	[46]
	(22-330)	(0.09 ± 0.01) for I	[46]
	(20-80)	(0.25 ± 0.03) for Na	[119]
	(40-100)	(0.08 ± 0.02) for I	[119]
	(4-252)	(0.275 ± 0.018) for Na	[120]
	(10-71)	(0.086 ± 0.007) for I	[120]
	(5-100)	(0.4 ± 0.2) for Na	[121]
	(40-300)	(0.05 ± 0.02) for I	[121]
CaF_2(Eu)	(30-100)	(0.06-0.11) for Ca	[120]
	(10-100)	(0.08-0.17) for F	[120]
	(90-130)	(0.049 ± 0.005) for Ca	[45]
	(75-270)	(0.069 ± 0.005) for F	[45]
	(53-192)	(0.11-0.20) for F	[122]
	(25-91)	(0.09-0.23) for Ca	[122]
CsI(Tl)	(25-150)	(0.15-0.07)	[123]
	(10-65)	(0.17-0.12)	[124]
	(10-65)	(0.22-0.12)	[125]
CsI(Na)	(10-40)	(0.10-0.07)	[125]
Ge	(3-18)	(0.29-0.23)	[126]
	(21-50)	(0.14-0.24)	[127]
	(10-80)	(0.18-0.34)	[128]
	(20-70)	(0.24-0.33)	[129]
Si	(5-22)	(0.23-0.42)	[130]
	22	(0.32 ± 0.10)	[131]
Liquid Xe	(30-70)	(0.46 ± 0.10)	[72]
	(40-70)	(0.18 ± 0.03)	[132]
	(40-70)	(0.22 ± 0.01)	[133]
Bolometers	-	**assumed** 1 (see also NIMA507(2003)643))	

Consistent Halo Models

- Isothermal sphere ⇒ very simple but unphysical halo model; generally not considered
- Several approaches different from the isothermal sphere model: Vergados PR83(1998)3597, PRD62(2000)023519; Belli et al. PRD61(2000)023512; PRD66(2002)043503; Ullio & Kamionkowski JHEP03(2001)049; Green PRD63(2001) 043005, Vergados & Owen astroph/0203293, etc.

Models accounted in the following

(Riv. N. Cim. 26 n.1 (2003)1-73 and previously in PRD66(2002)043503)

Class A: spherical ρ_{DM}, isotropic velocity dispersion		
A0	Isothermal Sphere	
A1	Evans' logarithmic [101]	$R_c = 5$ kpc
A2	Evans' power-law [102]	$R_c = 16$ kpc, $\beta = 0.7$
A3	Evans' power-law [102]	$R_c = 2$ kpc, $\beta = -0.1$
A4	Jaffe [103]	$\alpha = 1,\ \beta = 4,\ \gamma = 2,\ a = 160$ kpc
A5	NFW [104]	$\alpha = 1,\ \beta = 3,\ \gamma = 1,\ a = 20$ kpc
A6	Moore et al. [105]	$\alpha = 1.5,\ \beta = 3,\ \gamma = 1.5,\ a = 28$ kpc
A7	Kravtsov et al. [106]	$\alpha = 2,\ \beta = 3,\ \gamma = 0.4,\ a = 10$ kpc
Class B: spherical ρ_{DM}, non–isotropic velocity dispersion (Osipkov–Merrit, $\beta_0 = 0.4$)		
B1	Evans' logarithmic	$R_c = 5$ kpc
B2	Evans' power-law	$R_c = 16$ kpc, $\beta = 0.7$
B3	Evans' power-law	$R_c = 2$ kpc, $\beta = -0.1$
B4	Jaffe	$\alpha = 1,\ \beta = 4,\ \gamma = 2,\ a = 160$ kpc
B5	NFW	$\alpha = 1,\ \beta = 3,\ \gamma = 1,\ a = 20$ kpc
B6	Moore et al.	$\alpha = 1.5,\ \beta = 3,\ \gamma = 1.5,\ a = 28$ kpc
B7	Kravtsov et al.	$\alpha = 2,\ \beta = 3,\ \gamma = 0.4,\ a = 10$ kpc
Class C: Axisymmetric ρ_{DM}		
C1	Evans' logarithmic	$R_c = 0,\ q = 1/\sqrt{2}$
C2	Evans' logarithmic	$R_c = 5$ kpc, $q = 1/\sqrt{2}$
C3	Evans' power-law	$R_c = 16$ kpc, $q = 0.95,\ \beta = 0.9$
C4	Evans' power-law	$R_c = 2$ kpc, $q = 1/\sqrt{2},\ \beta = -0.1$
Class D: Triaxial ρ_{DM} [107] (q = 0.8, p = 0.9)		
D1	Earth on maj. axis, rad. anis.	$\delta = -1.78$
D2	Earth on maj. axis, tang. anis.	$\delta = 16$
D3	Earth on interm. axis, rad. anis.	$\delta = -1.78$
D4	Earth on interm. axis, tang. anis.	$\delta = 16$

- **Needed quantities**
  - → DM local density $\rho_0 = \rho_{DM}(R_0 = 8.5\ \mathrm{kpc})$
  - → local velocity $v_0 = v_{rot}(R_0 = 8.5\mathrm{kpc})$
  - → velocity distribution $f(\vec{v})$

- **Allowed ranges of ρ_0 (GeV/cm^3) have been evaluated for v_0=170,220,270 km/s, for each considered halo density profile and taking into account the astrophysical constraints:**

$$v_0 = (220 \pm 50) km \cdot s^{-1}$$
$$1 \cdot 10^{10} M_\oplus \le M_{vis} \le 6 \cdot 10^{10} M_\oplus$$
$$0.8 \cdot v_0 \le v_{rot}(r = 100kpc) \le 1.2 \cdot v_0$$

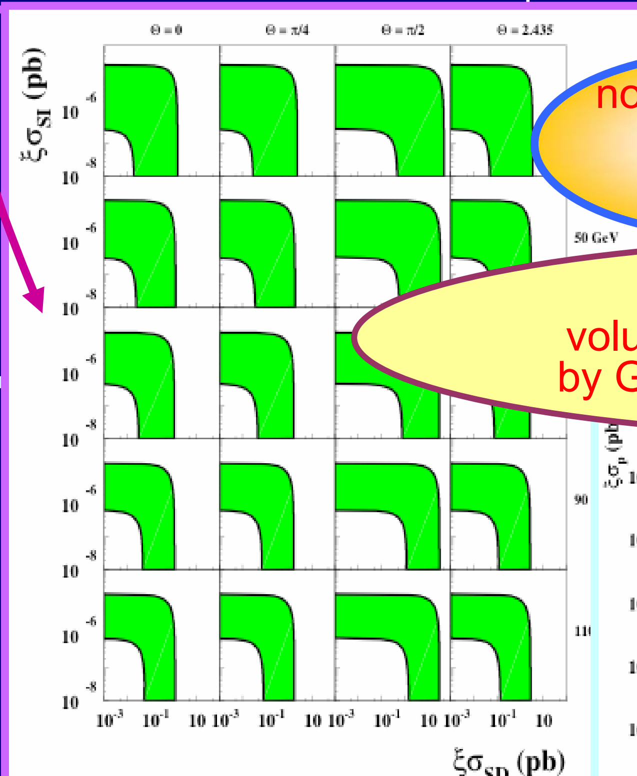
NOT YET EXHAUSTIVE AT ALL

Few examples of corollary quests for the WIMP class in given scenarios

(Riv. N.Cim. vol.26 n.1. (2003) 1-73, IJMPD13(2004)2127)

DM particle with elastic SI&SD interactions

(Na and I are fully sensitive to SD interaction, on the contrary of e.g. Ge and Si) Examples of slices of the allowed volume in the space ($\xi\sigma_{SI}$, $\xi\sigma_{SD}$, m_W, θ) for some of the possible θ ($tg\theta = a_n/a_p$ with $0 \le \theta < \pi$) and m_W



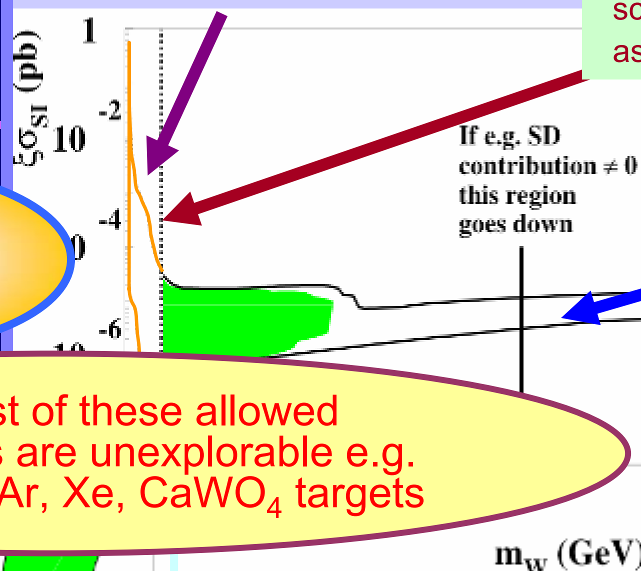
not exhaustive + different scenarios

Already most of these allowed volumes/regions are unexplorable e.g. by Ge, Si, TeO_2, Ar, Xe, $CaWO_4$ targets

DM particle with dominant SI coupling

Region of interest for a neutralino in supersymmetric schemes where assumption on gaugino-mass unification at GUT is released and for "generic" DM particle

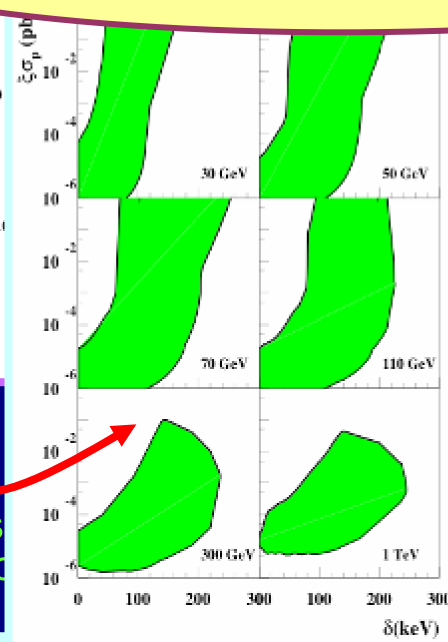
Model dependent lower bound on neutralino mass as derived from LEP data in supersymmetric schemes based on GUT assumptions (DPP2003)



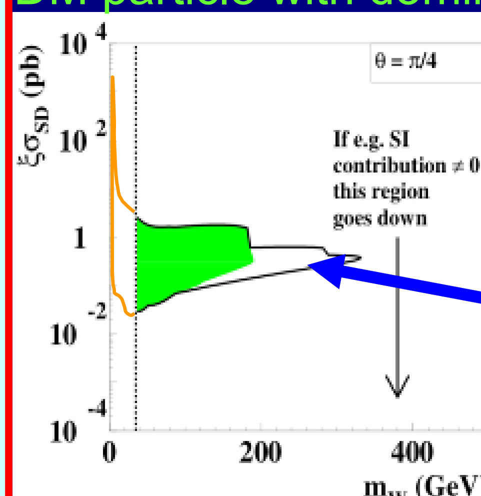
higher mass region allowed for low v_0, every set of parameters' values and the halo models: Evans' logarithmic C1 and C2 co-rotating, triaxial D2 and D4 non-rotating, Evans power-law B3 in setA

DM particle with preferred inelastic interaction:

$W + N \rightarrow W^* + N$ (S_m/S_0 enhanced): examples of slices of the allowed volume in the space ($\xi\sigma_p$, m_W, δ) [e.g. Ge disfavoured]



DM particle with dominant SD coupling

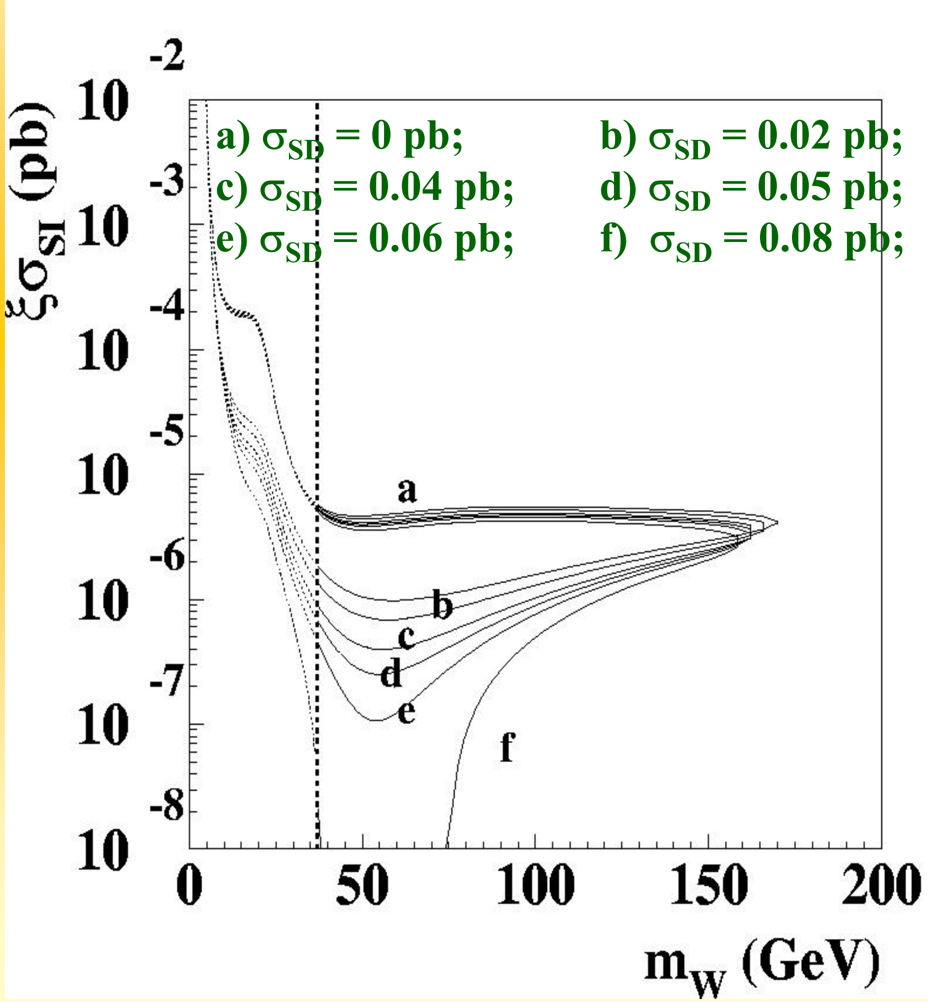


volume allowed in the space (m_W, $\xi\sigma_{SD}$, θ); here example of a slice for $\theta = \pi/4$ ($0 \le \theta < \pi$)

Regions above 200 GeV allowed for low v_0, for every set of parameters' values and for Evans' logarithmic C2 co-rotating halo models

An example of the effect induced by a non-zero SD component on the allowed SI regions

- Example obtained considering Evans' logarithmic axisymmetric C2 halo model with v_0 = 170 km/s, ρ_0 max at a given set of parameters
- The different regions refer to different SD contributions with $\theta=0$



A small SD contribution $\Rightarrow$ drastically moves the allowed region in the plane (m_W, $\xi\sigma_{SI}$) towards lower SI cross sections ($\xi\sigma_{SI} < 10^{-6}$ pb)

Similar effect for whatever considered model framework

- There is no meaning in bare comparison between regions allowed in experiments sensitive to SD coupling and exclusion plots achieved by experiments that are not.
- The same is when comparing regions allowed by experiments whose target-nuclei have unpaired proton with exclusion plots quoted by experiments using target-nuclei with unpaired neutron where $\theta \approx 0$ or $\theta \approx \pi$.

Supersymmetric expectations in MSSM

- Assuming for the neutralino a dominant purely SI coupling
- when releasing the gaugino mass unification at GUT scale:
  $M_1/M_2 \neq 0.5$ (<);

(where M_1 and M_2 U(1) and SU(2) gaugino masses)

low mass configurations are obtained

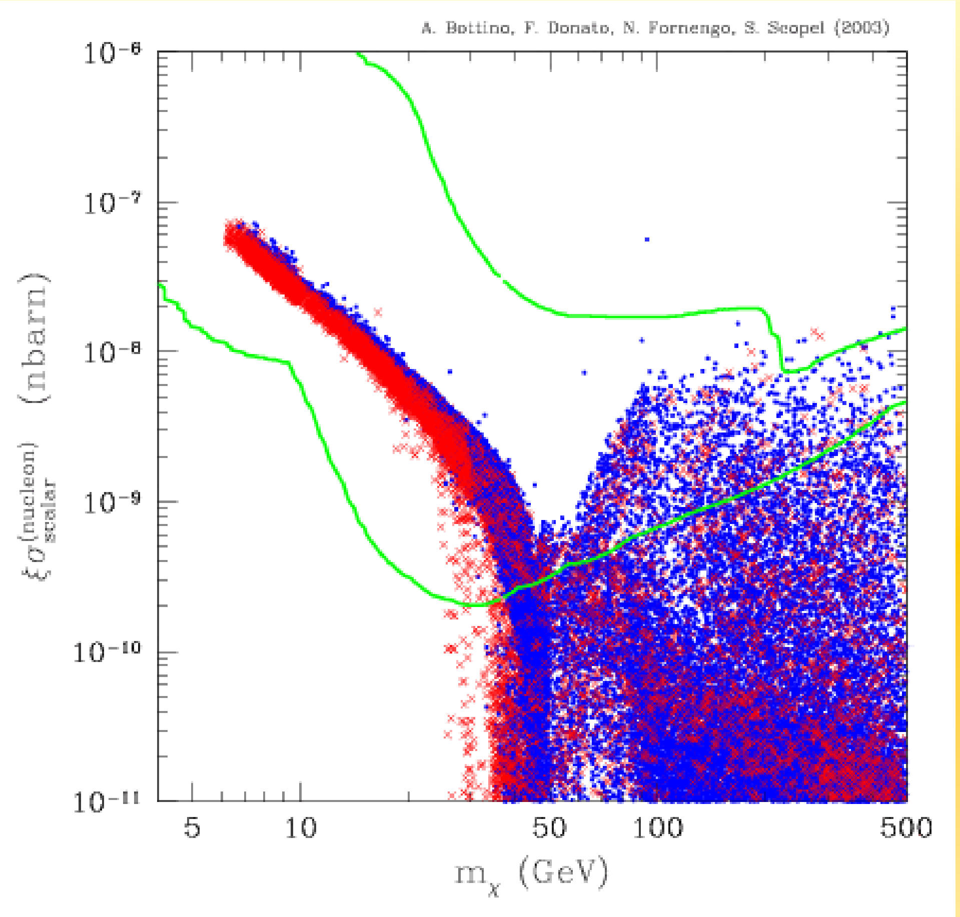


figure taken from PRD69(2004)037302

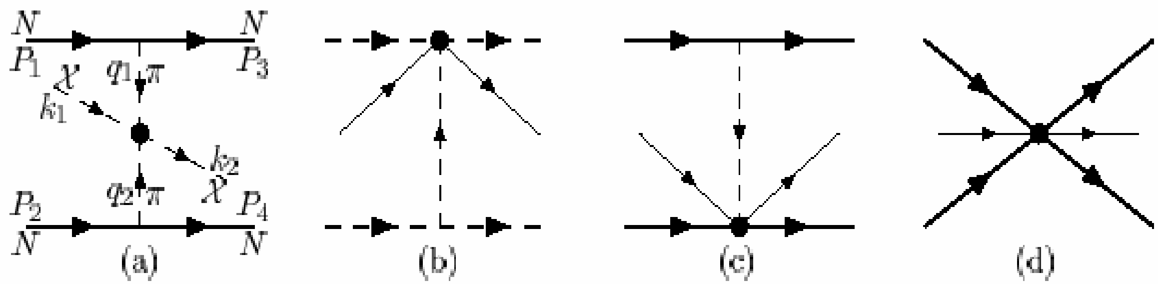
scatter plot of theoretical configurations vs DAMA/NaI allowed region in the given model frameworks for the total DAMA/NaI exposure (area inside the green line);

(for previous DAMA/NaI partial exposure see PRD68(2003)043506)

... either other uncertainties or new models?

Two-nucleon currents from pion exchange in the nucleus:

FIG. 1: Two-nucleon diagrams that contribute to WIMP-nucleus scattering where the WIMP is generally denoted by $\mathcal{X}$. Graph (a) is of $\mathcal{O}(1/q^2)$, graphs (b) and (c) are of $\mathcal{O}(1/q)$ while the contact term of graph (d) is of $\mathcal{O}(1)$. The exchange diagrams are not included. The filled circles represent the non-standard model vertices.



"In supersymmetric models, the one-nucleon current generically produces roughly equal SI couplings to the proton and neutron [5], which results in a SI amplitude that is proportional to the atomic number of the nucleus. Inclusion of the two-nucleon contributions could change this picture since such contributions might cancel against the one-nucleon contributions. If the ratio of the two-nucleon matrix element to the atomic number varies from one nucleus to the next so will the degree of the cancellation. Thus, when the two-current contribution is taken into account, a dark-matter candidate that appears in DAMA but not in other searches [14] is conceivable for a WIMP with SI interactions even within the framework of the MSSM…"

Prezeau, Kamionkowski, Vogel et al., PRL91(2003)231301

$\sigma_A \propto \mu^2 A^2 (1+\varepsilon_A)$

$\varepsilon_A = 0$ "usually"

$\varepsilon_A \approx \pm 1$ here in some nuclei?

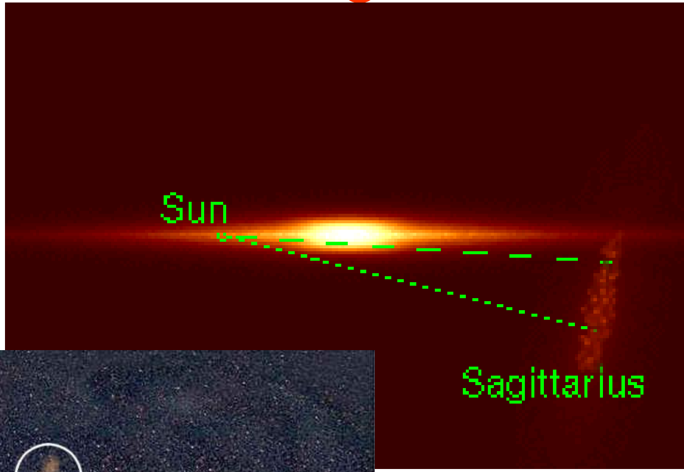
Different scaling laws for a DM particle with SI interactions even within the framework of the MSSM?

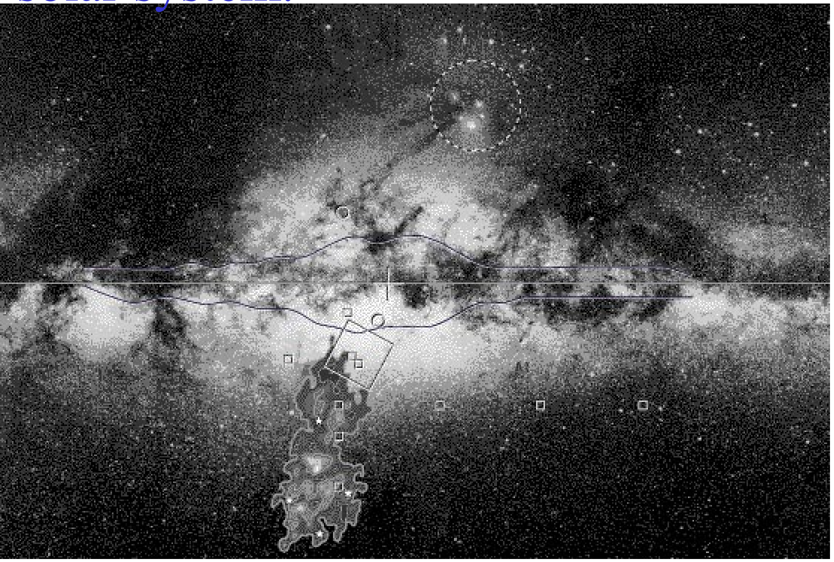
+

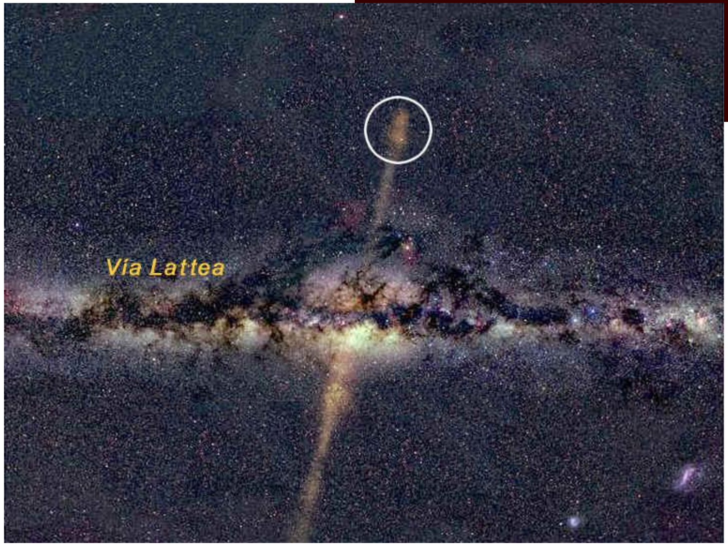
Different Form Factors, e.g. the recently proposed by Gondolo et al. hep-ph/0608035

The Sagittarius Dwarf Elliptical Galaxy and the Dark Matter galactic halo

In 1994 –1995 a new object: the "Sagittarius Dwarf Elliptical Galaxy", has been observed in the vicinity of the Milky Way, in the direction of the galactic center and in the opposite position with respect to the solar system.



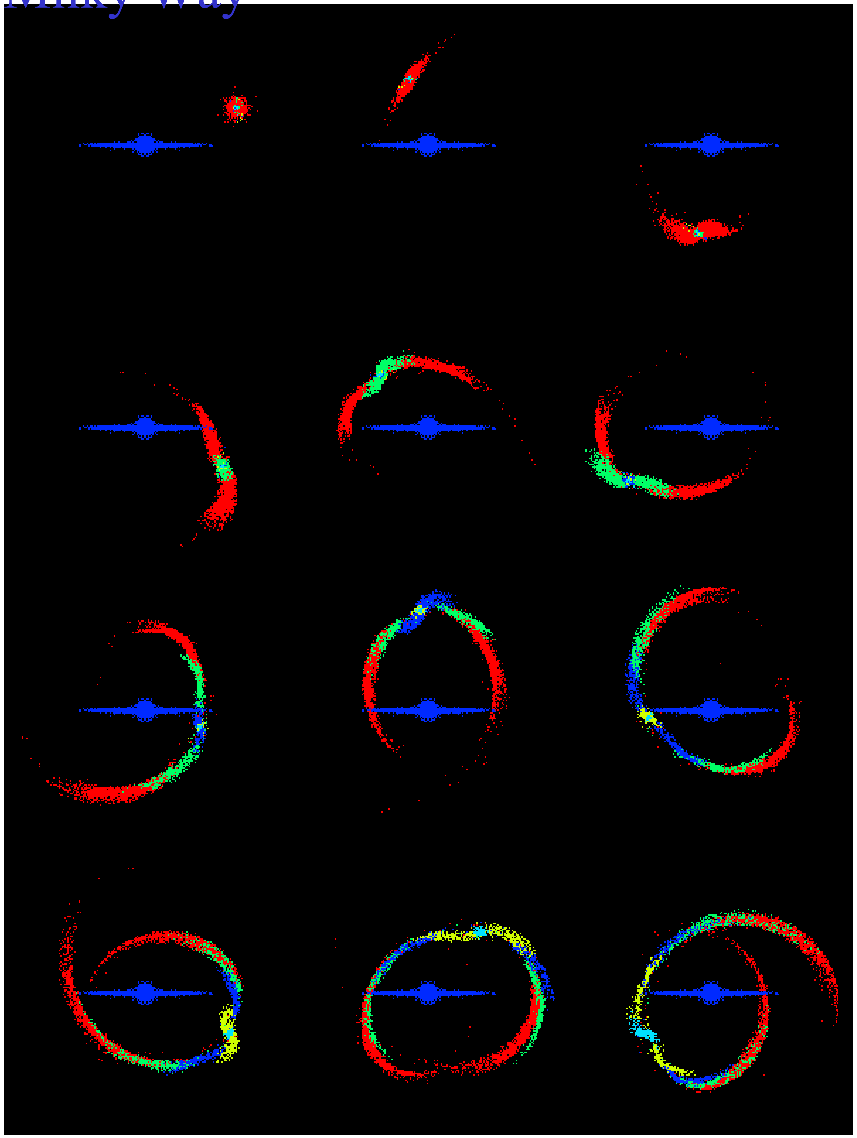




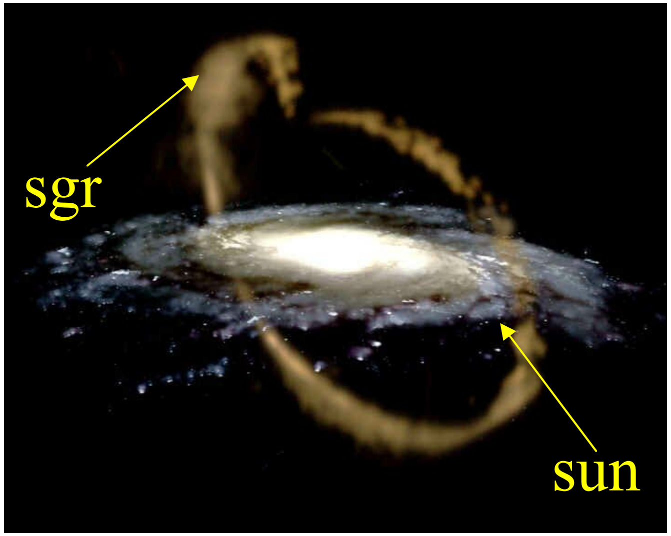
The motion direction of the Sagittarius DEG was well different than that of the other luminous objects in the Milky Way and, thus, it has been discovered that the observed stars belong to this dwarf galaxy satellite of the Milky Way, which is going to be captured.

This dwarf galaxy has a very long shape because of the tidal strengths suffered during about 10 revolutions around the Milky Way.

Simulation of the deformation of the SagDEG due to the tidal strengths during its revolutions around the Milky Way



The Sun is at about 2 kiloparsec from the center of the main tail



A particle Dark Matter flux from the dark halo of SagDEG, with a velocity of about 300 km/s perpendicular to our galactic plane, is expected.

Estimated density: [1 - 80] 10^{-3} GeV/cm^3

that is (0.3-25)% of the local density.

A multi-component Dark Matter galactic halo?

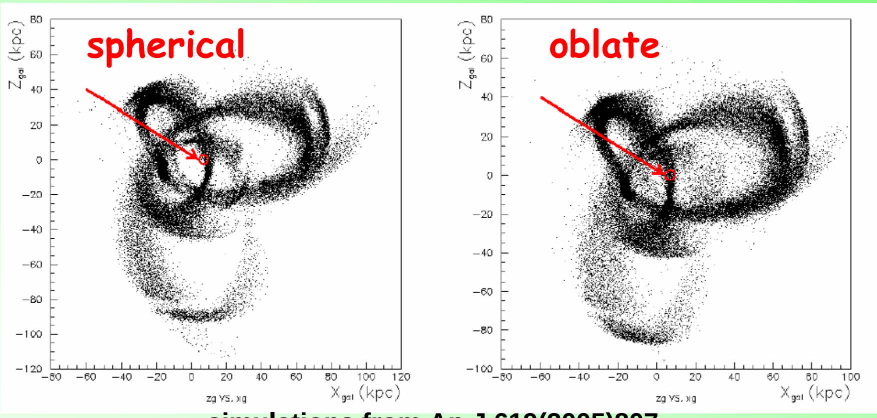
Other contributing satellite DEGs can exist?

Investigating halo substructures by underground expt

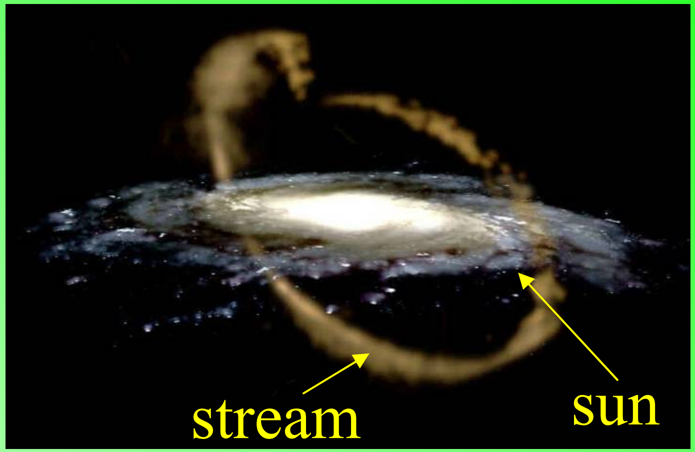
through annual modulation signature

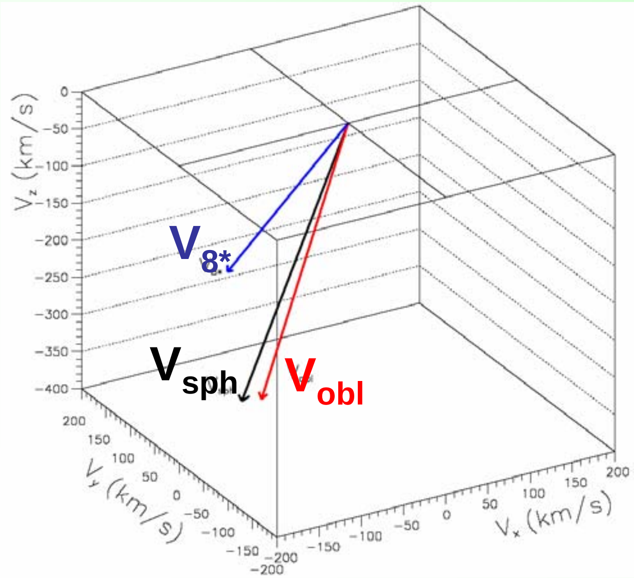
EPJC47(2006)263

Possible contributions due to the tidal stream of Sagittarius Dwarf satellite (SagDEG) galaxy of Milky Way



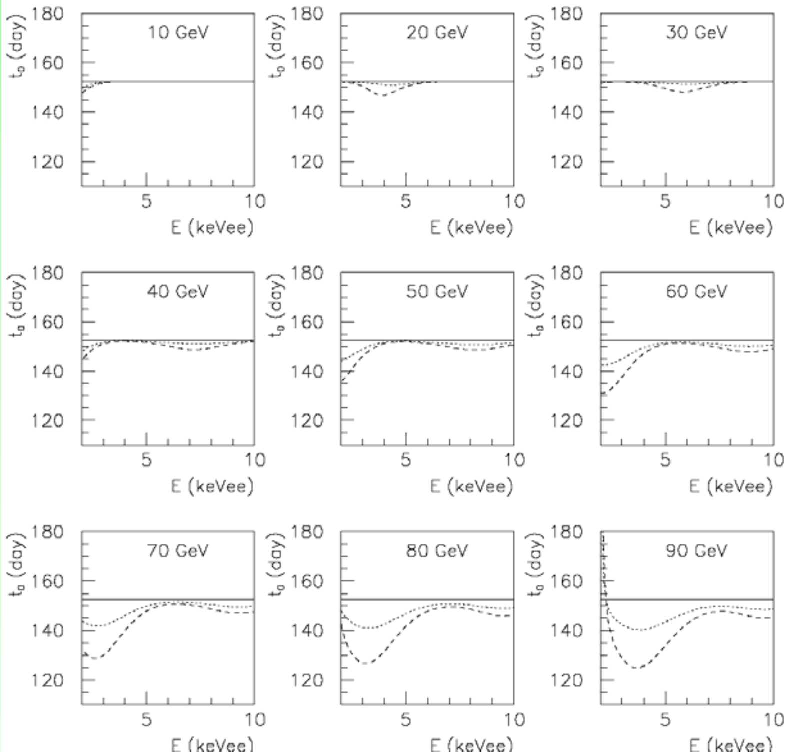
simulations from Ap.J.619(2005)807





V_{8*} from 8 local stars: PRD71(2005)043516

Examples of the effect of SagDEG tail on the phase of the annual modulation signal



Investigating the effect of SagDEG contribution for WIMPs

EPJC47(2006)263

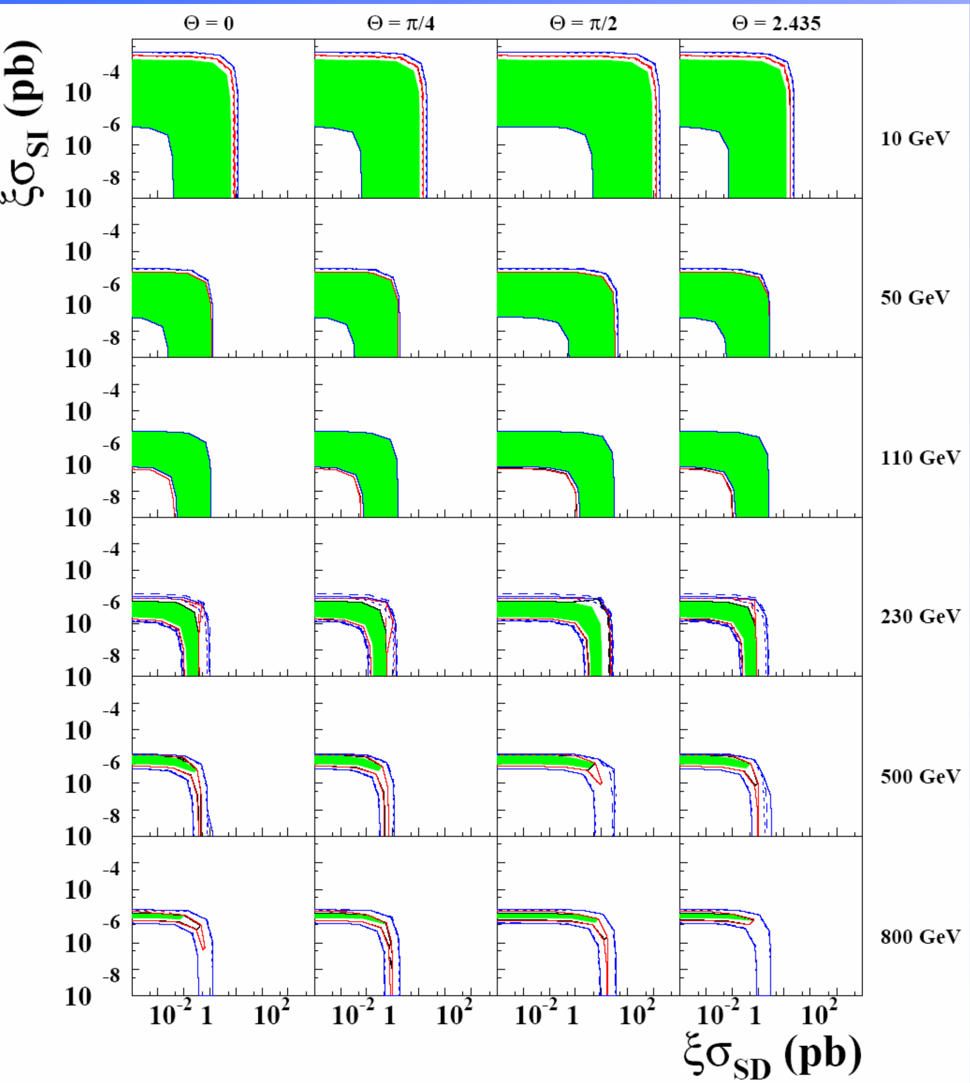
DAMA/NaI: seven annual cycles 107731 kg d

for different SagDEG velocity dispersions (20-40-60 km/s)

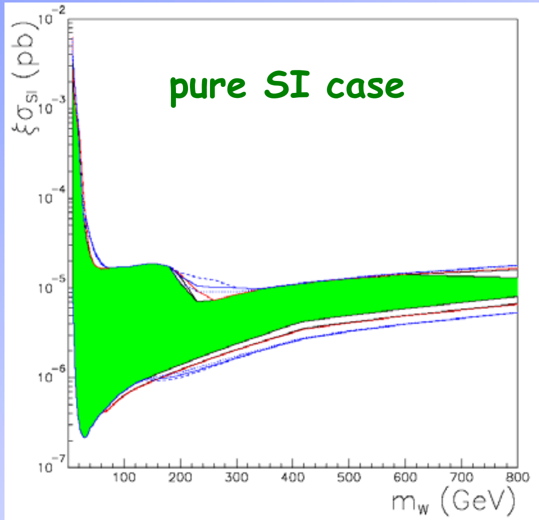
ρ_{SagDEG} < 0.1 GeV cm^{-3} (bound by M/L ratio considerations)

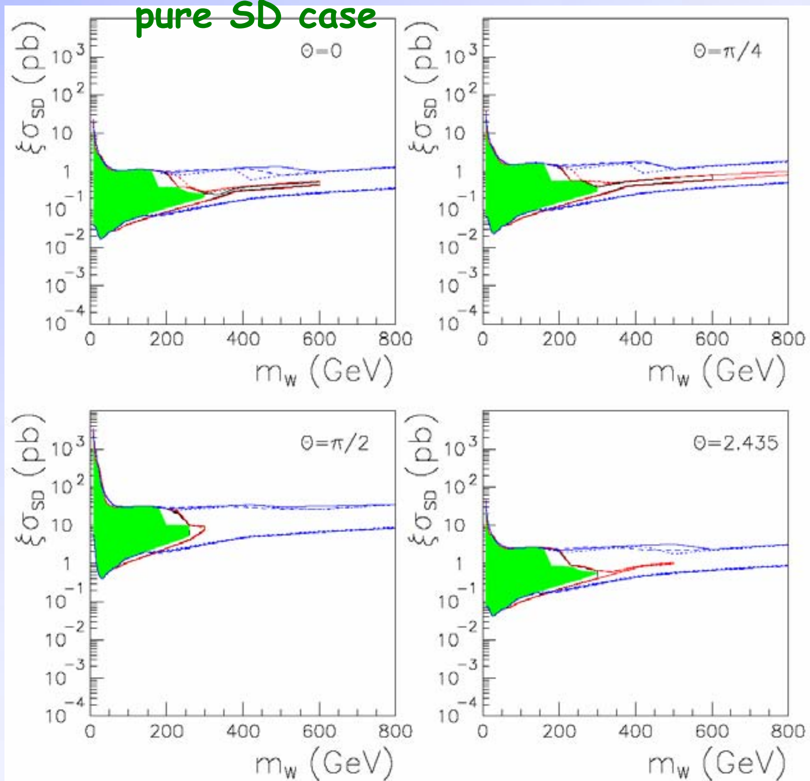
SOME EXAMPLES

mixed SI&SD case



green area: no SagDEG

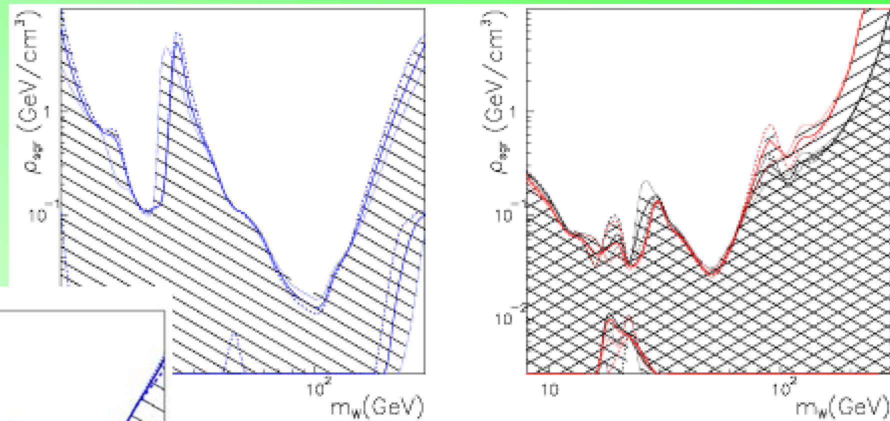


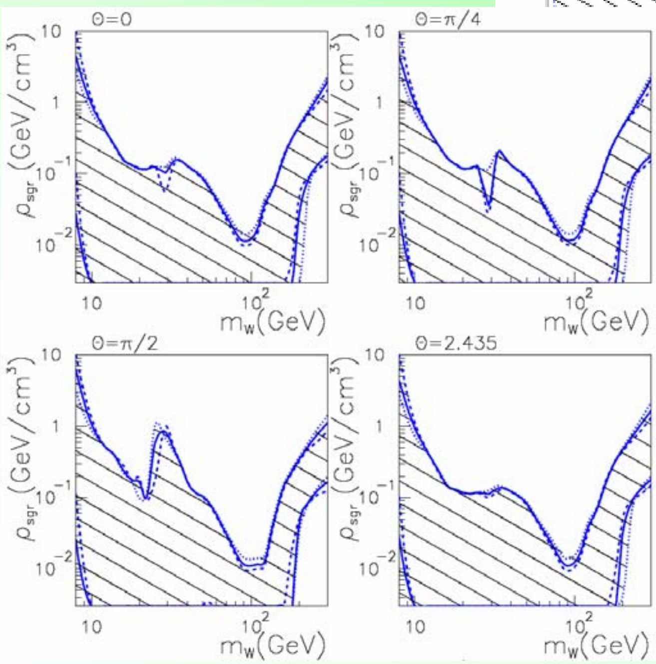


Constraining the SagDEG stream by DAMA/NaI

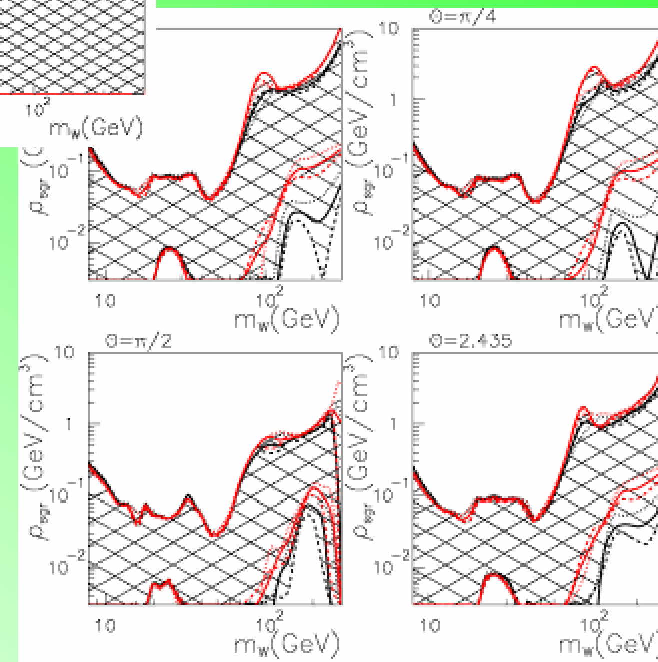
for different SagDEG velocity dispersions (20-40-60 km/s) EPJC47(2006)263

pure SI case





pure SD case



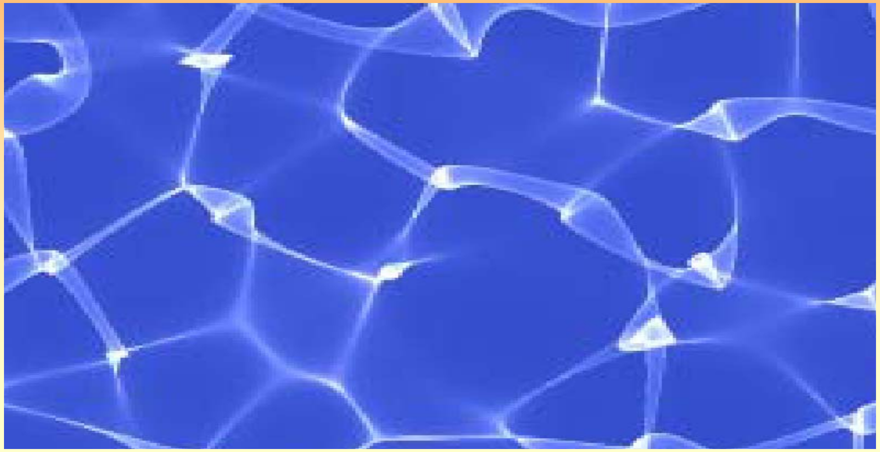
This analysis shows the possibility to investigate local halo features by annual modulation signature already at the level of sensitivity provided by DAMA/NaI, allowing to reach sensitivity to SagDEG density comparable with M/L evaluations.

The higher sensitivity of DAMA/LIBRA will allow to more effectively investigate the presence and the contributions of streams in the galactic halo

… other astrophysical scenarios?

Possible other (beyond SagDEG) non-thermalized component in the galactic halo?

In the galactic halo, fluxes of Dark Matter particles with dispersion velocity relatively low are expected :



Possible presence of caustic rings

⇒ streams of Dark Matter particles

P. Sikivie, Fu-Sin Ling et al. astro-ph/0405231

Interesting scenarios for DAMA

Effect on $|S_m/S_o|$ respect to "usually" adopted halo models?

Effect on the phase of annual modulation signature?

Other dark matter stream from satellite galaxy of Milky Way close to the Sun?

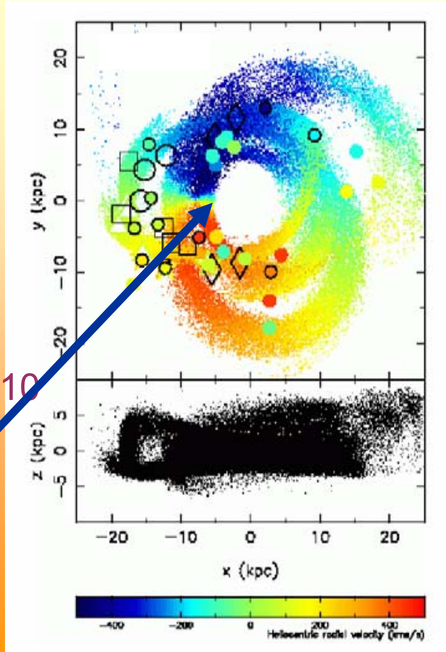
.....very likely....

Can be guess that spiral galaxy like Milky Way have been formed capturing close satellite galaxy as Sgr, Canis Major, ecc…

Canis Major simulation:

astro-ph/0311010

Position of the Sun: (-8,0,0) kpc



Investigating electromagnetic contributions in searches for WIMP candidates

IJMPA 22 (2007) 3155

Ionization and the excitation of bound atomic electrons induced by the presence of a recoiling atomic nucleus in the case of the WIMP-nucleus elastic scattering (named hereafter Migdal effect)

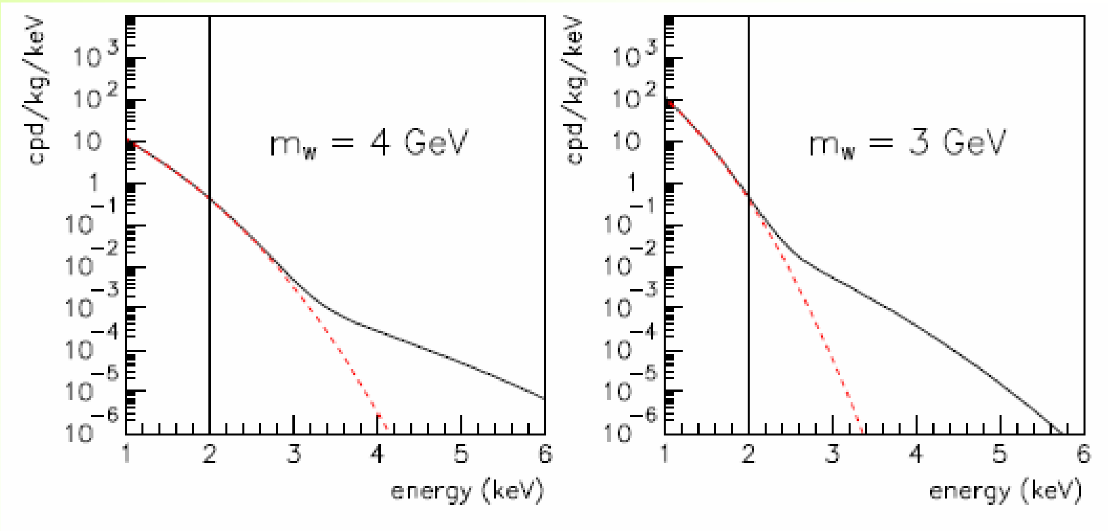
→ **the recoiling nucleus can "shake off" some of the atomic electrons**

→ **recoil signal + e.m. contribution made of the escaping electron, X-rays, Auger electrons arising from the rearrangement of the atomic shells**

→ **e.m. radiation fully contained in a detector of suitable size**

The effect is well known since long time

Example



accounting for Migdal effect

Without Migdal effect

Adopted assumptions in the examples:

- i) **WIMP with dominant SI coupling and with $\sigma \propto A^2$;**
- ii) **non-rotating Evanslogarithmic galactic halo model with R_c=5kpc, v_0=170 km/s, ρ_0= 0,42 GeV cm^{-3}**
- iii) **form factors and q of ^{23}Na and ^{127}I as in case C of Riv.N.Cim 26 n1 (2003)1**

Although the effect of the inclusion of the Migdal effect appears quite small:

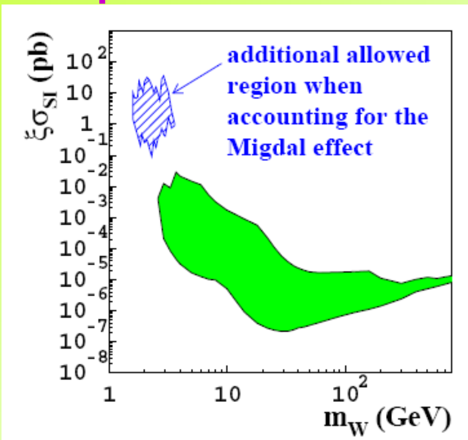
- **the unquenched nature of the e.m. contribution**
- **the behaviour of the energy distribution for nuclear recoils induced by WIMP-nucleus elastic scatterings**
- **etc.**

can give an appreciable impact at low WIMP masses

Examples of the impact of the accounting for the e.m. contribution to the detection of WIMP candidates

IJMPA 22 (2007) 3155

Example of a WIMP with dominant SI coupling

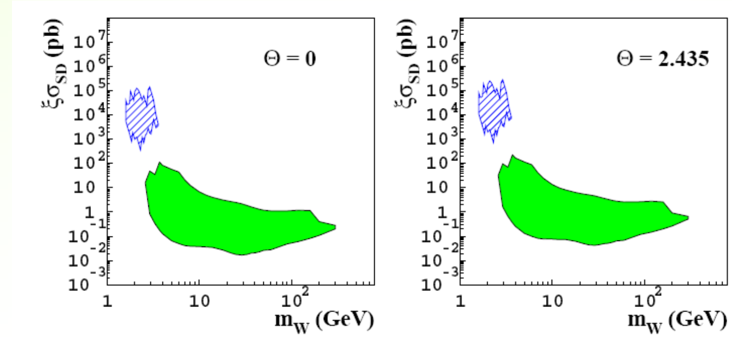


Region allowed in the ($\xi\sigma_{SI}$;m_W) plane in the considered model frameworks for pure SI coupling;

WARNING:
1) to point out just the impact of the Migdal effect the SagDEG contribution have not been included here.

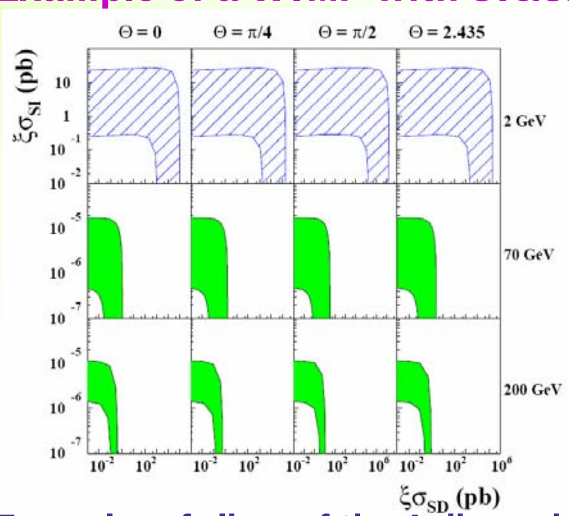
2) considered frameworks as in Riv.N.Cim 26 n1 (2003)1

Example of a WIMP with dominant SD coupling



Two slices of the 3-dimensional allowed volume ($\xi\sigma_{SI}$;m_W; θ) in the considered model frameworks for pure SD coupling

Example of a WIMP with SI&SD coupling



Examples of slices of the 4-dimensional allowed volume ($\xi\sigma_{SI}$; $\xi\sigma_{SD}$; m_W; θ) in the considered model frameworks

GeV mass DM particle candidates have been widely proposed in literature in order to account not only for the DM component of the Universe but also other cosmological and particle physics topics (Baryon Asymmetry, discrepancies between observations and LCDM model on the small scale structure, etc.)

Among DM GeV mass condidates: 1) H dibarion (predicted in Standard Model); 2) a real scalar field in extended Standard Model; 3) the light photino early proposed in models with low-energy supersimmetry; 4) the very light neutralino in Next-to-MSSM model; 5) the mirror deuterium in frameworks where mirror dark matter interations with ordinary matter are dominated by very heavy particles; ...

Further uncertainties in the quest for WIMPs: the case of the recoils' quenching

ROM2F/2007/15, to appear

arXiv:0706.3095

- ***In crystals, ions move in a different manner than that in amorphous materials.***
- In the case of motion along crystallographic axes and planes, a channeling effect is possible, which is manifested in an anomalously deep penetration of ions into the target.

Channeling effect in crystals

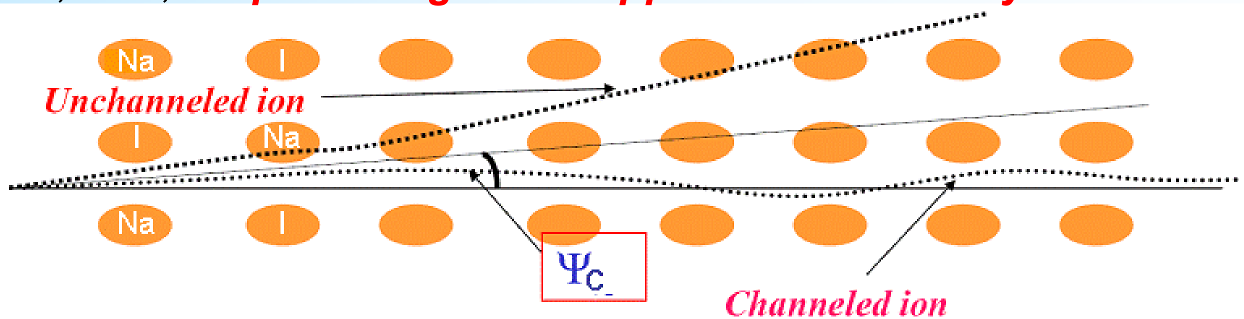
Well-known effect, discovered on 1957, when a deep penetration of $^{134}Cs^{+}$ ions into a Ge crystal to a depth $\lambda_c \approx 10^3$ Å was measured (according to SRIM, a 4 keV Cs^{+} ion would penetrate into amorphous Ge to a depth $\lambda_a = 44$ Å, $S_n/S_e = 32$ and $q=0.03$). Within a channel, mostly electronic stopping takes place (in the given example, $\lambda_c \approx \lambda_a/q \approx 1450$ Å).

- Occurs in **crystalline** materials due to correlated collisions of ions with target atoms.
- Steering of the ions through the open channels can result in **ranges several times the maximum range** in no-steering directions or in **amorphous materials**.
- **Electronic losses** determine the range and there is very little straggling.
- When a low-energy ion goes into a channel, its energy losses are mainly due to the electronic contributions. This implies that a channeled ion transfers its energy mainly to electrons rather than to the nuclei in the lattice and, thus, its ***quenching factor approaches the unity***.

$$R_{ion}(E) \approx R_{el.}(E)$$

$$L_{ion} \approx L_{el}$$

$$q(E) \approx 1$$



Modeling the channeling effect: critical angles for channeling

J. Lindhard, Mat. Fys. Medd. K. Dan. Vidensk. Selsk. 34 (1965) 1.

Axial channeling. Lindhard's channeling theory treats channeling of low energy, high mass ions as a separate case from high energy, low mass ions. For low energy, high mass ions (recoiling nuclei) Lindhard's critical angle Ψ_c is given by:

$$\Psi_c = \sqrt{\frac{C a_{TF}}{d\sqrt{2}}\Psi_1}$$

$C^2=3$, d is the interatomic spacing in the crystal along the channeling direction. The characteristic angle Ψ_1 is defined as:

$$\Psi_1 = \sqrt{\frac{2Z_1Z_2e^2}{E_R d}}$$

Z_1 and Z_2 are the atomic numbers of the projectile (recoil nucleus) and target atoms, respectively, E_R is the recoiling nucleus energy, e is the electronic charge and a_{TF} the Thomas-Fermi radius

This equation is valid for $\Psi_1 > \Psi_{1,\lim} = \frac{a_{TF}}{d} \longrightarrow E_R < E_{\lim} = \frac{2\,Z_1\,Z_2\,e^2\,d}{a_{TF}^2}$ more than 150 keV for NaI(Tl)

The critical angles should not depend on the temperature

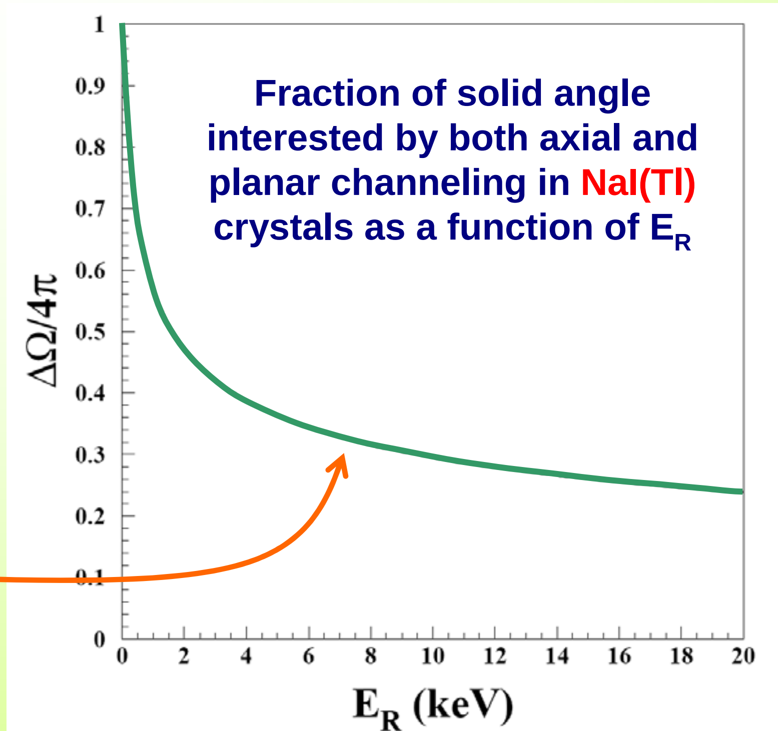
At higher energy, the critical angle is: $C\Psi_1$

Planar channeling. $\theta_{pl} = a_{TF}\cdot\sqrt{Nd_p}\cdot\left(\frac{Z_1Z_2e^2}{E\cdot a_{TF}}\right)^{1/3}$

N is the atomic number density, d_p is the inter-plane spacing.

At higher energy, the critical angle is: $\theta_{pl} = a_{TF}\cdot\sqrt{Nd_p}\cdot\left(\frac{2Z_1Z_2e^2C}{E\cdot a_{TF}}\right)^{1/2}$

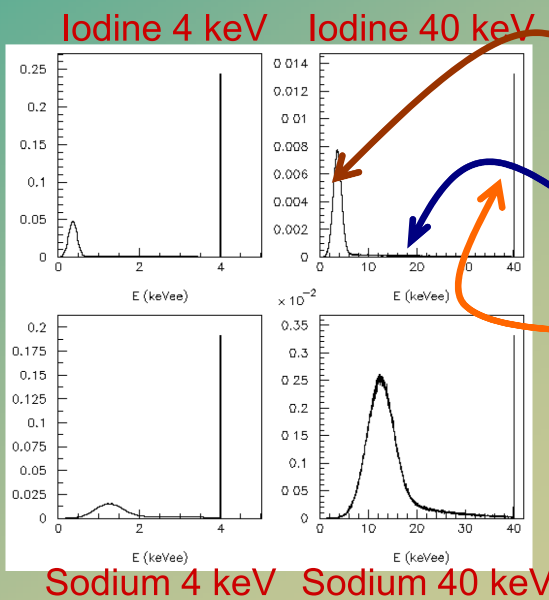
Axial channeling considering the lower index crystallographic axes: <100>, <110>, <111> and planes: {100}, {110}, {111}



Modeling the channeling effect:

Examples of light responses

ROM2F/2007/15, to appear



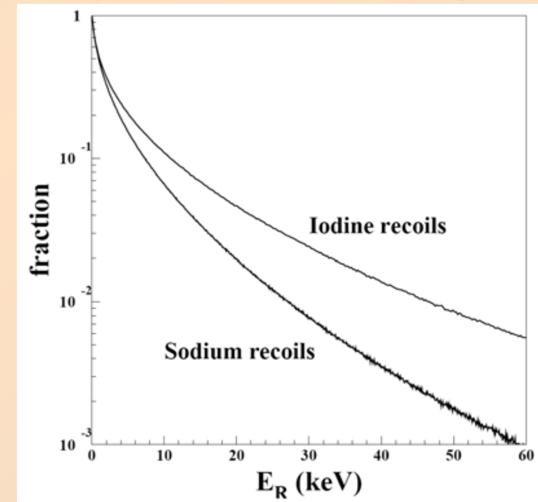
No energy resolution

Quenched peak with the straggling effect

Dechanneled events

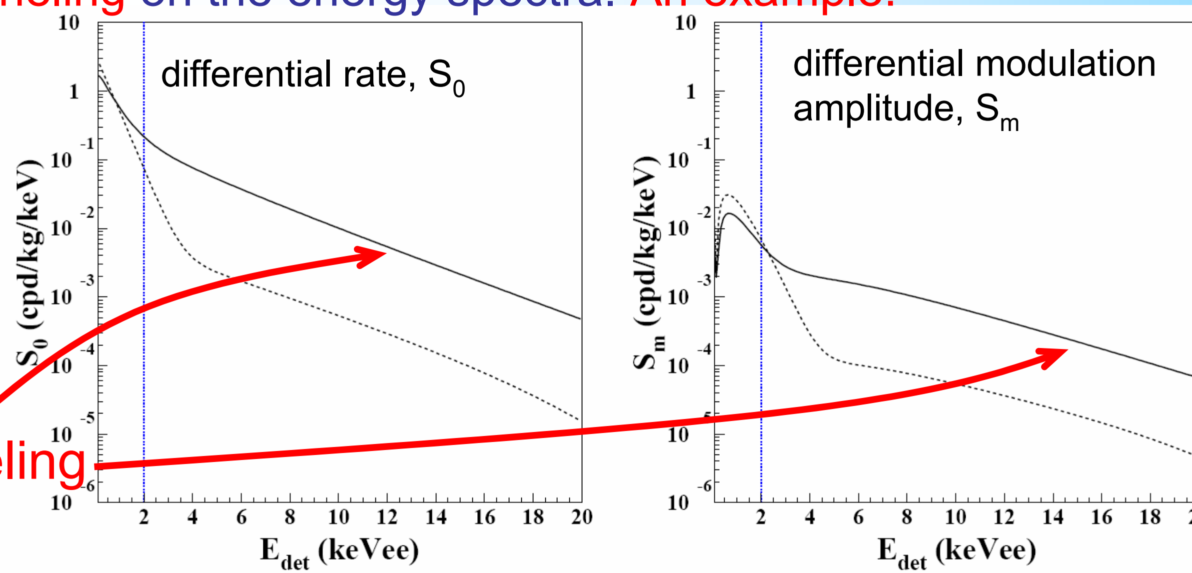
Channeled events (q≈1)

Fraction of events with q ~ 1 (channeled events)



The effect of channeling on the energy spectra. An example:

- NaI(Tl) (as those of DAMA)
- m_W=20 GeV
- pure SI
- $\sigma_{SI}=10^{-6}$ pb
- halo model A5
- NFW, v_0=220 km/s, ρ_{max}
- FF parameters and q factors at the mean values (case A in RNC26(2003)1)



channeling

What about the neutron calibrations of NaI(Tl) detectors?

MEASUREMENT OF THE SCINTILLATION EFFICIENCY OF Na RECOILS IN NaI(Tl) DOWN TO 10 keV NUCLEAR RECOIL ENERGY RELEVANT TO DARK MATTER SEARCHES

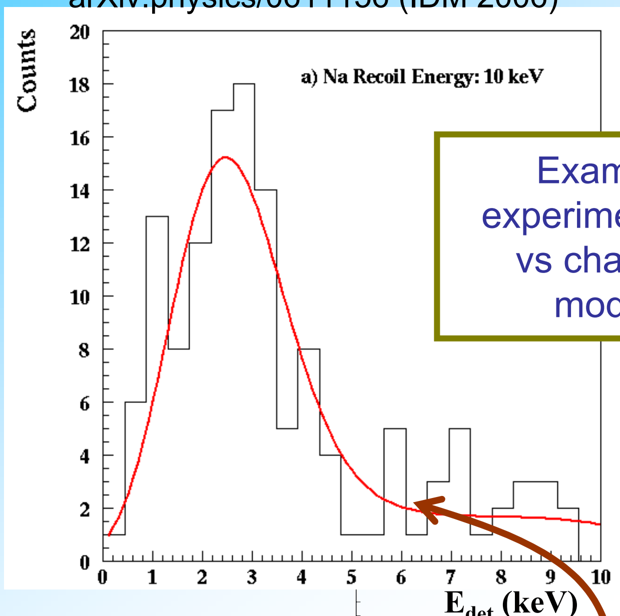
H. CHAGANI*, P. MAJEWSKI**, E. J. DAW, V. A. KUDRYAVTSEV, and N. J. C. SPOONER

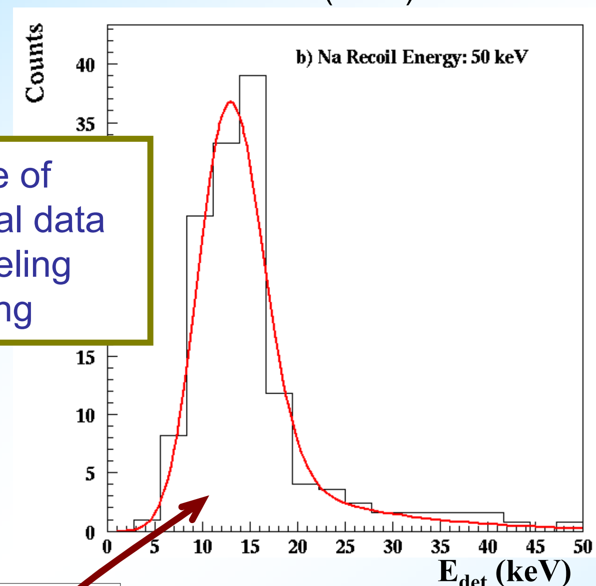
arXiv:physics/0611156 (IDM 2006)

SICANE: a Detector Array for the Measurement of Nuclear Recoil Quenching Factors using a Monoenergetic Neutron Beam

NIMA 507 (2003) 643

ROM2F/2007/15, to appear

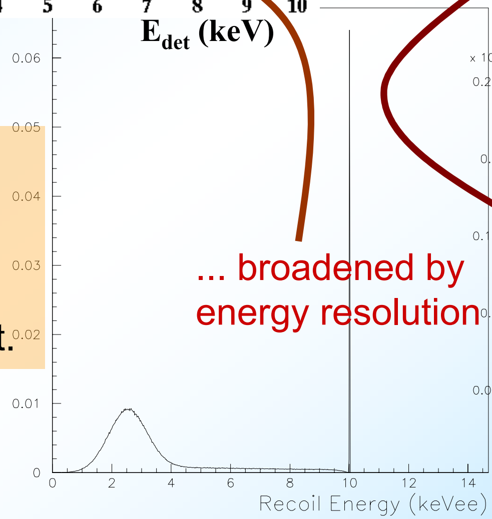


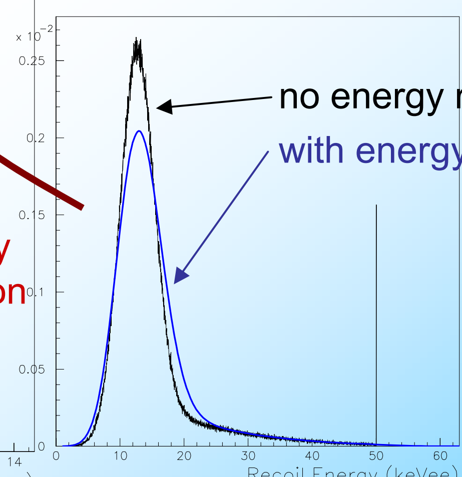


Example of experimental data vs channeling modeling

- **neutron data can contain channeled events**
- **but – owing to the low-statistics of these measurements and to the small effect looked for – they cannot be identified**
- **At higher energy and for Iodine recoils the channeling effect becomes less important and gives more suppressed contributions in the neutron scattering data**

Detector responses to 10keV and 50keV Na recoils in NaI(Tl) taking into account the channeling effect.





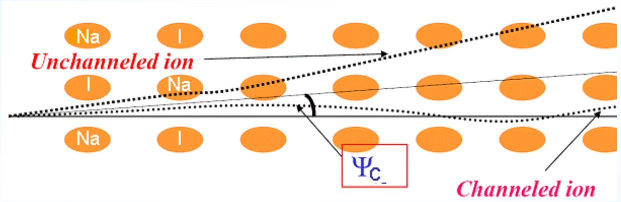
... broadened by energy resolution

no energy res.

with energy res.

Therefore, there is no hope to identify the channeling effect in the already-collected neutron data on NaI(Tl)

... while the accounting of the channeling effect can give a significant impact in the sensitivities of the Dark Matter direct detection methods when WIMP (or WIMP-like) candidates are considered.



Effect for DM direct detection experiments

- Lower cross sections explorable for WIMP and WIMP-like candidates by crystal scintillators, such as ***NaI(Tl)*** (up to more than a factor 10 in some mass range), lower recoil energy thresholds, lower mass thresholds, ...

- The same holds for purely ionization detectors, as ***Ge*** (HD-Moscow – like).

- Loss of sensitivity when PSD is used in crystal scintillators (***KIMS***); in fact, the channeled events ($q \approx 1$) are probably lost.

- No enhancement on ***liquid noble gas*** expts (DAMA/LXe, WARP, XENON10, ZEPLIN, ...).

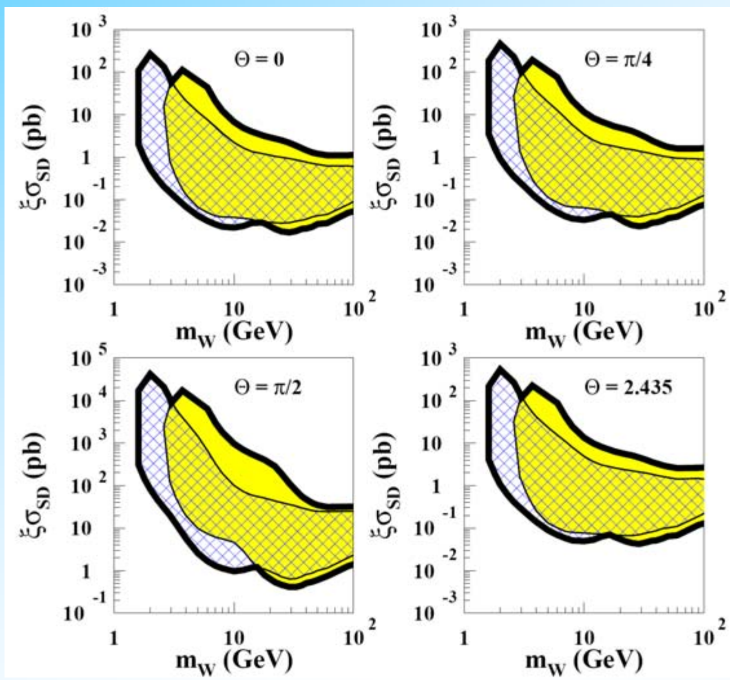
- No enhancement for ***bolometer double read-out*** expts; on the contrary some loss of sensitivity is expected since events (those with $q_{ion} \approx 1$) are lost by applying the discrimination procedures based on $q_{ion} \ll 1$.

Some examples of accounting for the channeling effect on the DAMA/NaI allowed regions

ROM2F/2007/15, to appear

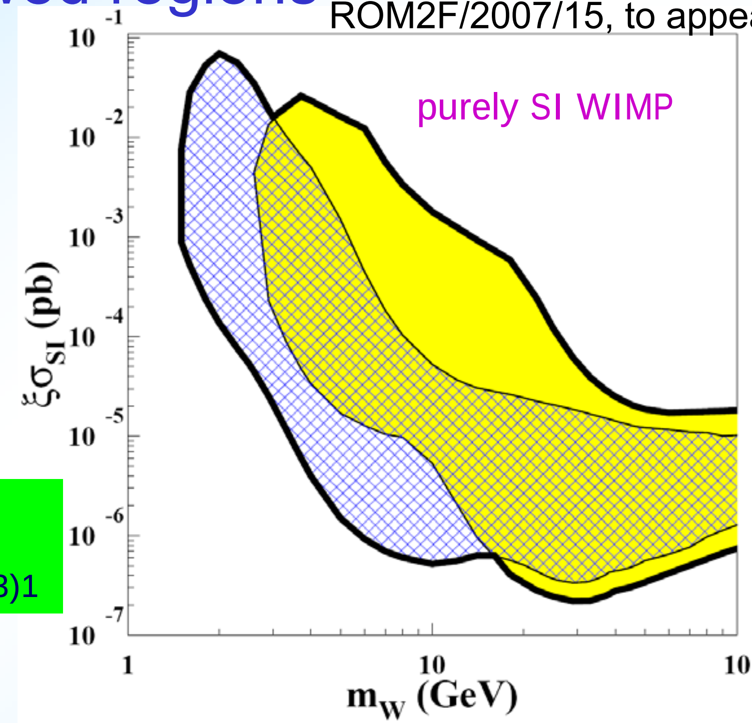
• the modeling in some given frameworks

purely SD WIMP



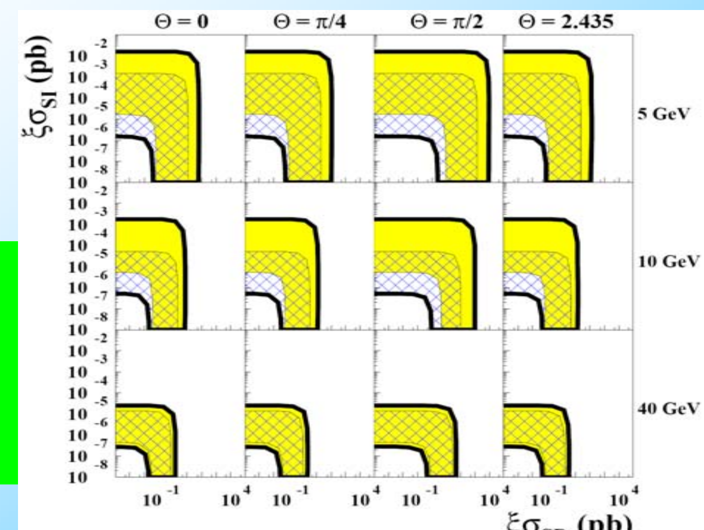
with

without channeling



for details on model frameworks see Riv.N.Cim 26 n1 (2003)1

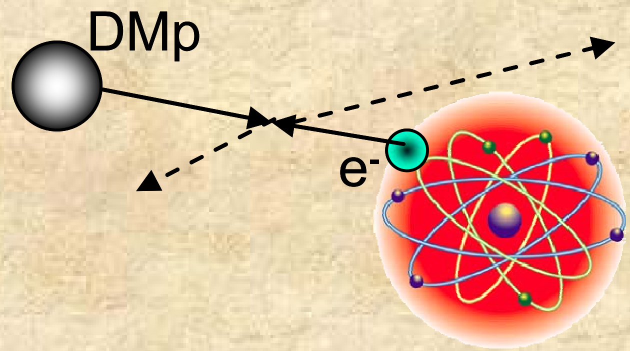
SI & SD WIMP



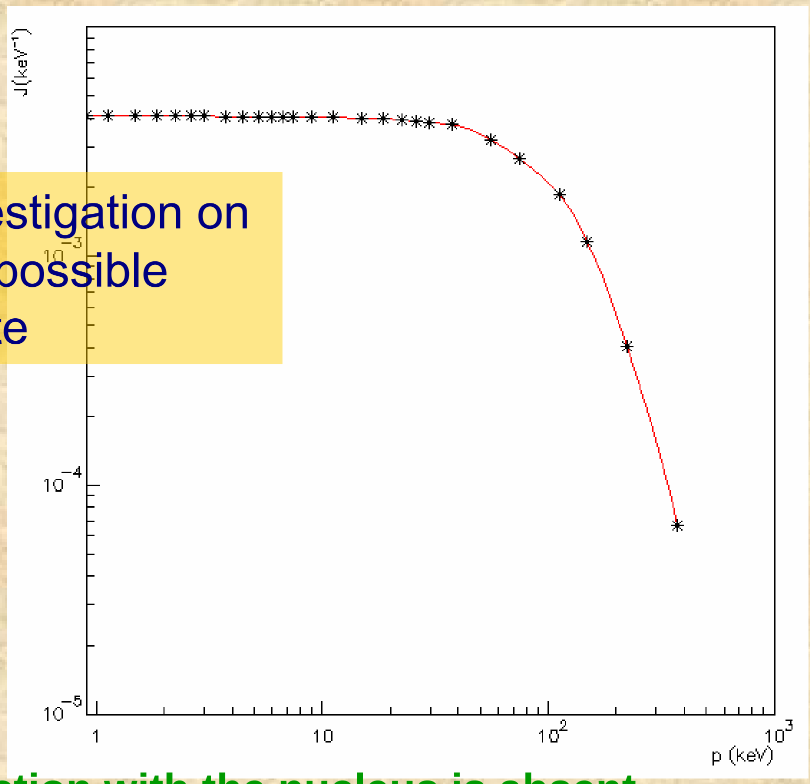
WARNING:

- to point out just the impact of the channeling effect the Migdal and SagDEG contributions have not been included here.
- the slices of the volumes shown here are focused just in the low mass region where the channeling effect is more effective

In advanced phase of investigation: electron interacting DM



- The electron in the atom is not at rest.
- There is a very-small but not-zero probability to have electrons with momenta of ≈ MeV/c.
- Ex.: Compton profile for the 1s electron of Iodine:



For relativistic electrons:

$$E_{\max} \approx \beta_{DM}\, p$$

towards an investigation on the sterile ν as possible further candidate

where, β_{DM}~10^{-3} is the DM velocity and *p* is the electron momentum. Thus, when *p* is of order of MeV/c, scattered electrons with keV energy can be produced

→ They can be detectable.

→ The modulation is expected, due to β_{DM} dependence.

Although the probability of interacting with a ≈MeV momentum atomic electrons is very tiny, this process can be the **only detection method when the interaction with the nucleus is absent.**

Candidates interacting only with electrons are expected, e.g.:

- in theories that foreseen leptonic colour interactions: $SU(3)_\ell \times SU(3)_c \times SU(2)_L \times U(1)$ broken at low energy.
- in models where they interact through a neutral current light (MeV scale) U boson.

Another class of DM candidates:
light bosonic particles

IJMPA21(2006)1445

The detection is based on the total conversion of the absorbed mass into electromagnetic radiation.

In these processes the target nuclear recoil is negligible and not involved in the detection process (i.e. signals from these candidates are lost in experiments applying rejection procedures of the electromagnetic contribution, as CDMS, Edelweiss,CRESST, WARP, Xenon,...)

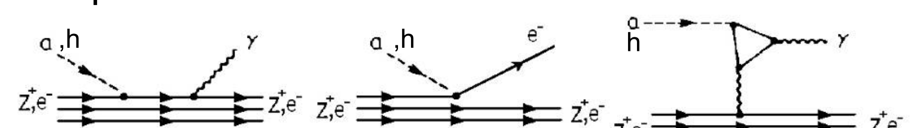
Axion-like particles: similar phenomenology with ordinary matter as the axion, but significantly different values for mass and coupling constants allowed.

A wide literature is available and various candidate particles have been and can be considered + similar candidate can explain several astrophysical observations (AP23(2003)145)

A complete data analysis of the total 107731 kgxday exposure from DAMA/NaI has been performed for pseudoscalar (a) and scalar (h) candidates in some of the possible scenarios.

They can account for the DAMA/NaI observed effect as well as candidates belonging to the WIMPs class

Main processes involved in the detection:



Compton-like — Axioelectric or Photoelectric-like — Primakoff

	Compton-like	Axioelectric or Photoelectric-like	Primakoff
a	S_0	S_0,S_m	S_0,S_m
h	S_0,S_m	S_0	S_0,S_m

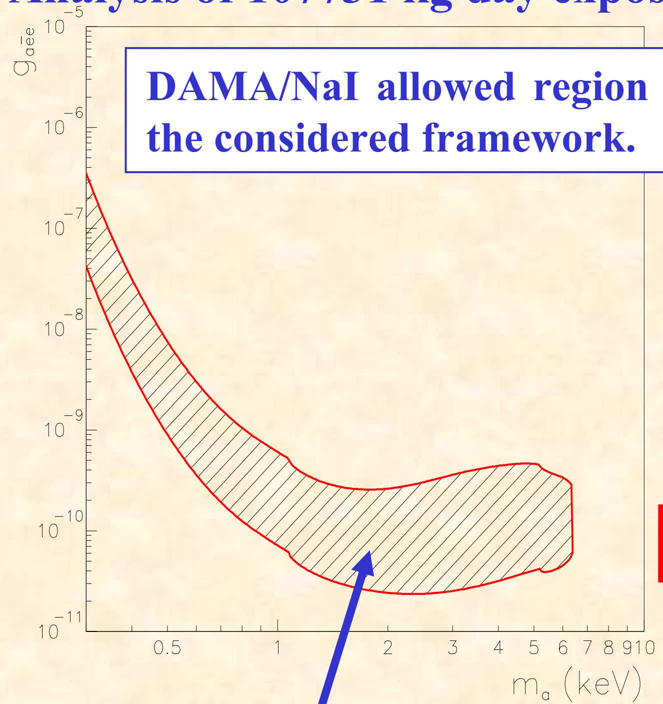
Pseudoscalar case:

IJMPA21(2006)1445

Analysis of 107731 kg day exposure from DAMA/NaI.

Considered dark halo models as in refs.:

Riv.N.Cim. 26 n.1. (2003) 1-73
IJMPD 13 (2004) 2127



DAMA/NaI allowed region in the considered framework.

region almost indipendent on other fermion coupling values.

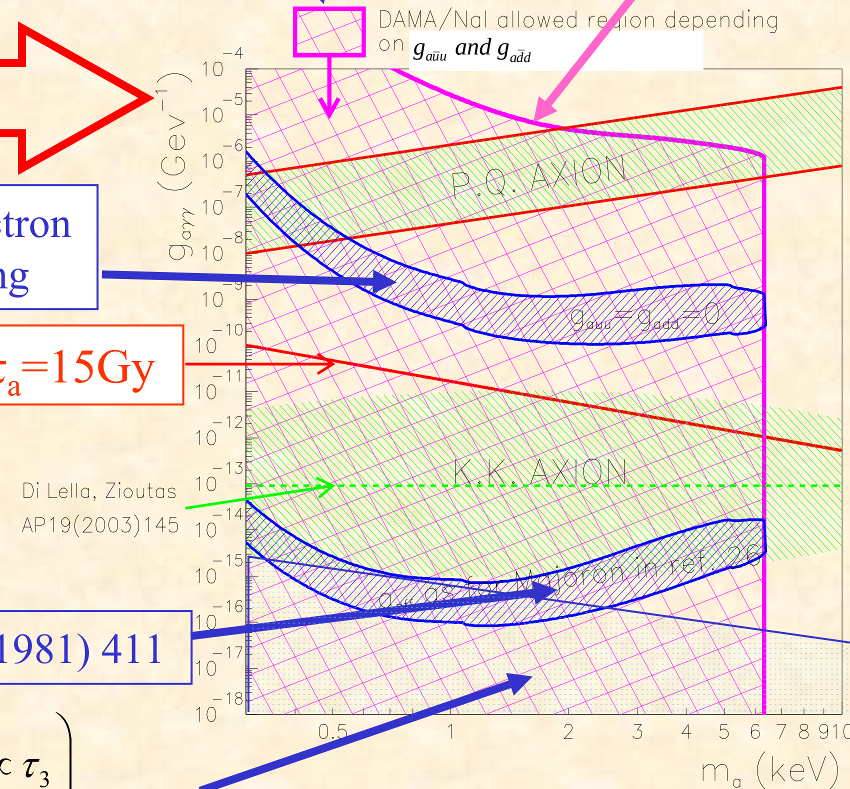
All these configurations are allowed by DAMA/NaI depending on the relative contributions of charged fermion couplings

coupling model

Maximum allowed photon coupling

Only electron coupling

τ_a=15Gy



Also this can account for the DAMA/NaI observed effect

coupling to photons vanish at first order:

majoron as in PLB 99 (1981) 411

UHECR [3] **PRD64(2001)096005**

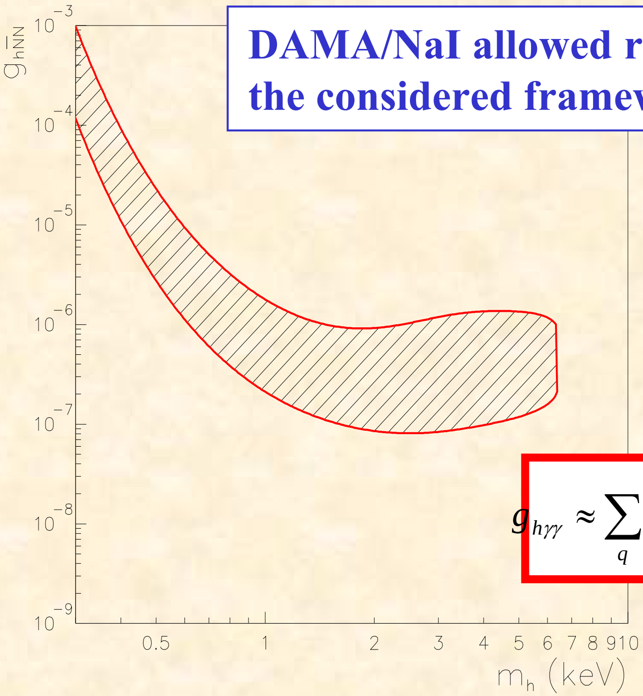
$$g_{a\gamma\gamma} \approx \frac{\alpha}{\pi}\left[\frac{g_{a\bar{e}e}}{m_e} + 3\frac{\tfrac{1}{9}\, g_{a\bar{d}d}}{m_d} + 3\frac{\tfrac{4}{9}\, g_{a\bar{u}u}}{m_u}\right] \approx 0 \qquad \left(\frac{g_{a\bar{e}e}}{m_e} = \frac{g_{a\bar{d}d}}{m_d} = -\frac{g_{a\bar{u}u}}{m_u} \propto \tau_3\right)$$

h

Scalar case:

IJMPA21(2006)1445

Analysis of 107731 kg day exposure from DAMA/NaI.



DAMA/NaI allowed region in the considered framework.

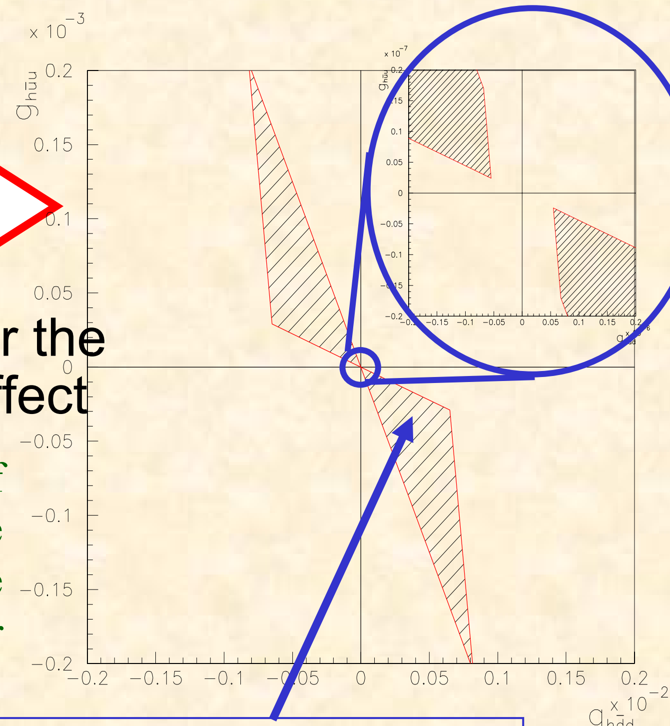
$$g_{h\bar{N}N} = \left(g_{h\bar{u}u} + 2g_{h\bar{d}d}\right) + \frac{Z}{A}\left(g_{h\bar{u}u} - g_{h\bar{d}d}\right)$$

Considered dark halo models as in ref:

Riv.N.Cim. 26 n.1. (2003) 1-73
IJMPD 13 (2004) 2127

Just an example: all the couplings to quarks of the same order ↔ lifetime dominated by u & d loops:

$$g_{h\gamma\gamma} \approx \sum_q -\frac{2}{3}\frac{\alpha\, Q_q^2\, g_{h\bar{q}q}}{\pi\, m_q} \approx -2\frac{\alpha}{\pi}\left[\frac{\frac{4}{9} g_{h\bar{u}u}}{m_u} + \frac{\frac{1}{9} g_{h\bar{d}d}}{m_d}\right]$$



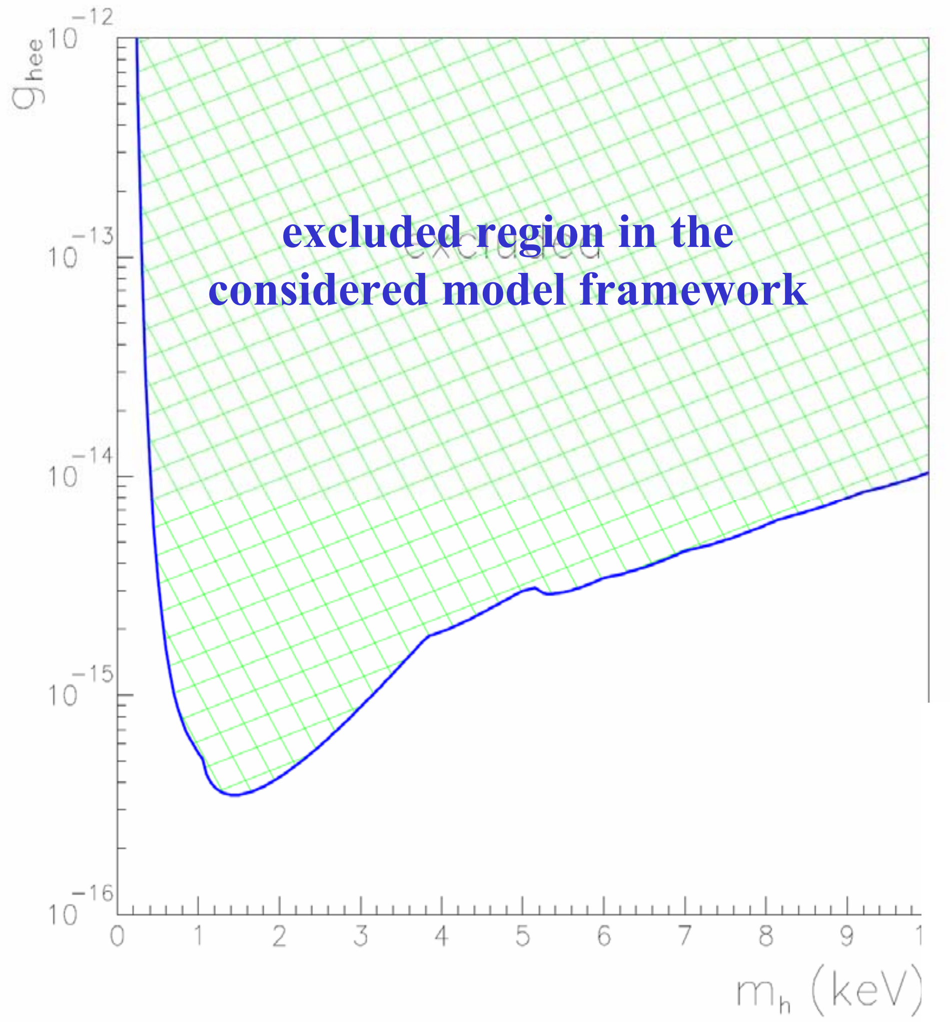
Also this can account for the DAMA/NaI observed effect

Many other configurations of cosmological interest are possible depending on the values of the couplings to other quarks and to gluons….

- **Annual modulation signature present for a scalar particle with pure coupling to hadronic matter (possible gluon coupling at tree level?).**
- **Compton-like to nucleus conversion is the dominant process for particle with cosmological lifetime.**

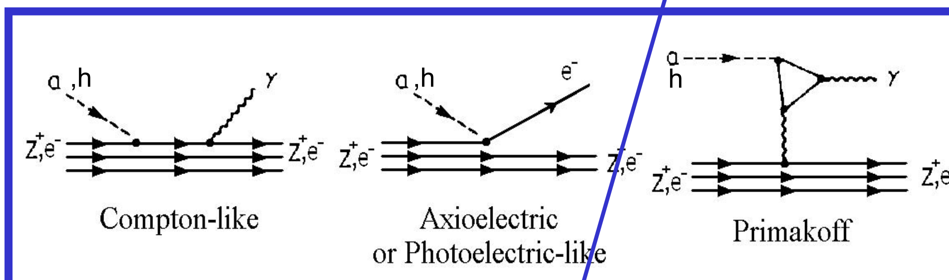
- **Allowed by DAMA/NaI (for m_h > 0.3 keV)**
- **τ_h > 15 Gy (lifetime of cosmological interest)**
- **m_u = 3.0 ± 1.5 MeV m_d = 6.0 ± 2.0 MeV**

Scalar case:



For scalar case the photoelectric –like effect is the dominant process but have not the modulated component:

A coupling to electrons can be excluded from data in this scenario.



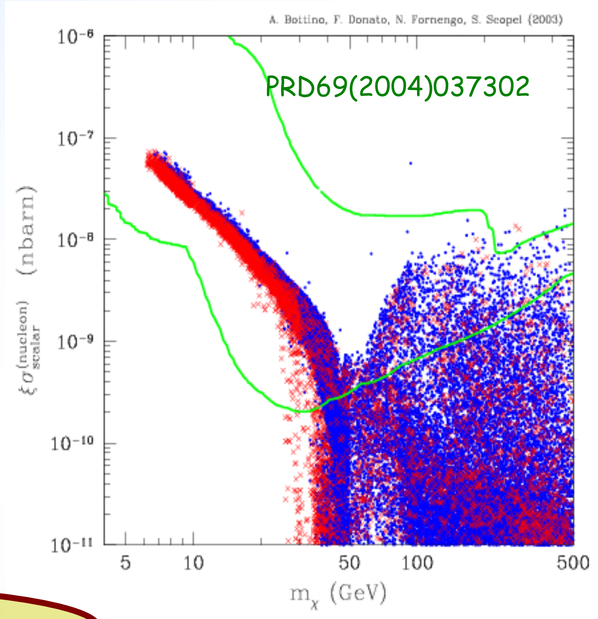
a	S_0	S_0,S_m	S_0,S_m
h	S_0,S_m	S_0	S_0,S_m

h

DAMA/NaI vs ...

... supersymmetric expectations in MSSM

- Assuming for the neutralino a dominant purely SI coupling
- when releasing the gaugino mass unification at GUT scale: $M_1/M_2 \neq 0.5$ (<); (where M_1 and M_2 U(1) and SU(2) gaugino masses) low mass configurations are obtained



scatter plot of theoretical configurations vs DAMA/NaI allowed region in the given model frameworks for the total DAMA/NaI exposure (area inside the green line)

... other DM candidate particles, as (see literature)

the sneutrino in the Smith and Weiner scenario

+

self-interacting dark matter

mirror dark matter

a heavy ν of the 4-th family

Kaluza-Klein particles (LKK)

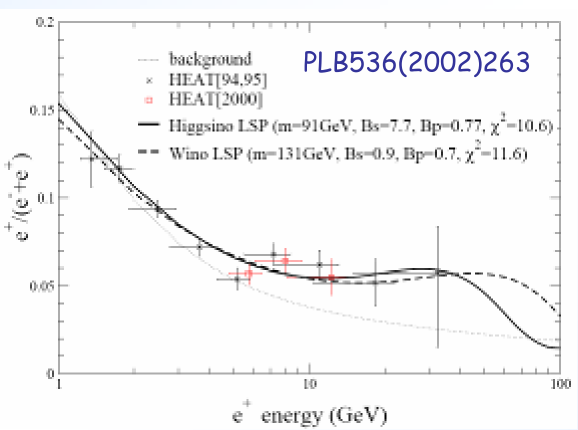
... and more

heavy exotic canditates, as "4th family atoms", ...

light bosons

compatibility

... indirect searches of DM particles in the space



- Positron excess (see e.g. HEAT)
- Excess of Diffuse Galactic Gamma Rays for energies above 1 GeV in the galactic disk and for all sky directions (see EGRET).

interpretation, evidence itself, derived m_W and cross sections depend e.g. on bckg modeling, on DM spatial velocity distribution in the galactic halo, etc.

Hints from indirect searches are not in conflict with DAMA/NaI

Indirect detection

Dark Matter particles may accumulate in Sun/Earth, in galactic halo

↓

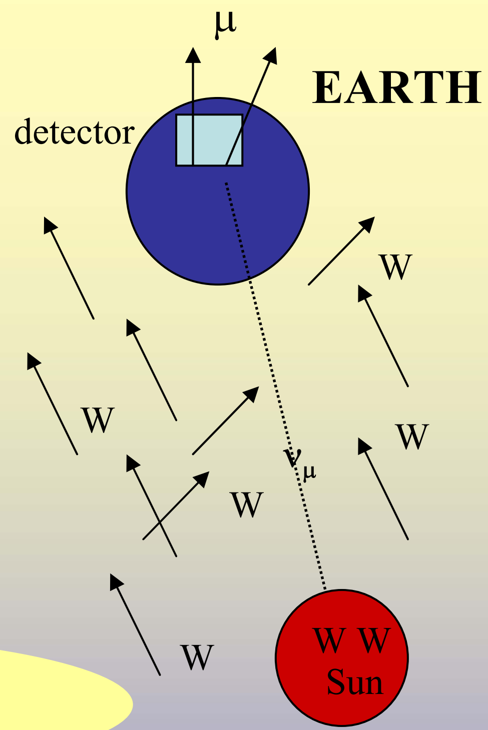
annihilate

↓

high energy neutrinos, γ's, anti-p and e^+

↓

Search for an excess over a (not well known) background



antimatter signature

- **Search for antimatter excess in cosmic rays**
- **Space detectors**

ν_μ signature

- **Best signature from ν_μ producing up-ward going μ**
- **Underground, underwater, underice detectors**

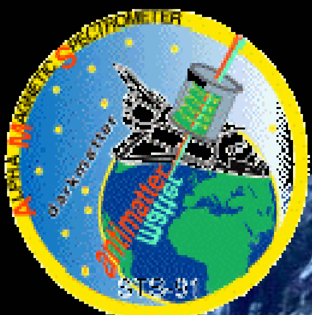
γ signature

- **Search for quasi-monoenergetic γ's in cosmic rays**
- **Space detectors**

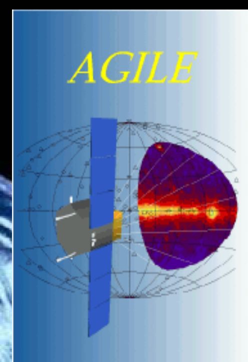
The results depend on the background modeling and on the astrophysical, particle and nuclear Physics assumptions

Experiments with INFN components which plan possible indirect Dark Matter searches

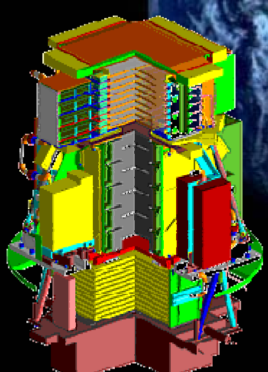
… In the space



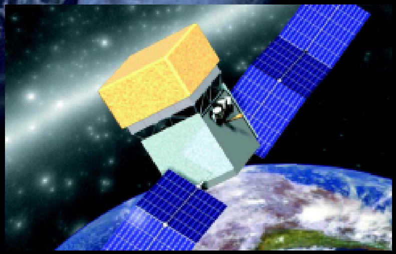
AMS



AGILE



PAMELA



GLAST

… Under the sea

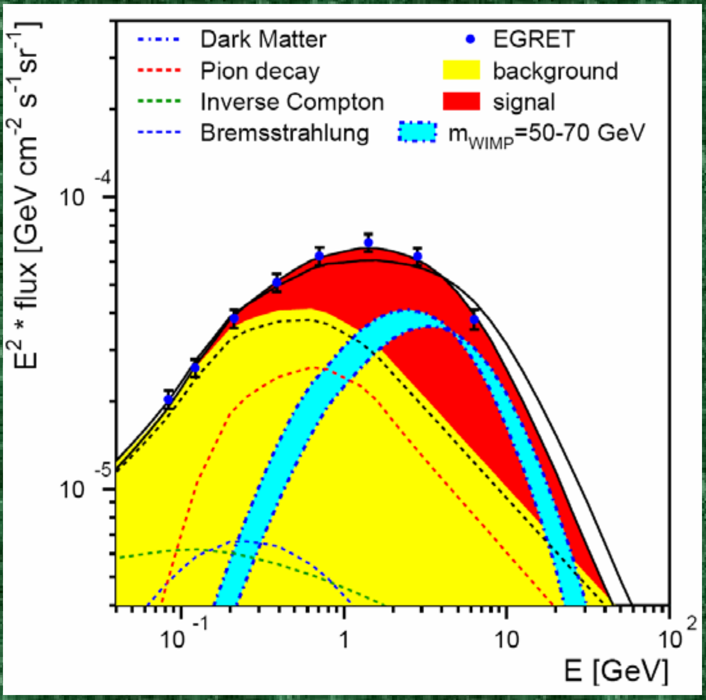
ANTARES

NEMO

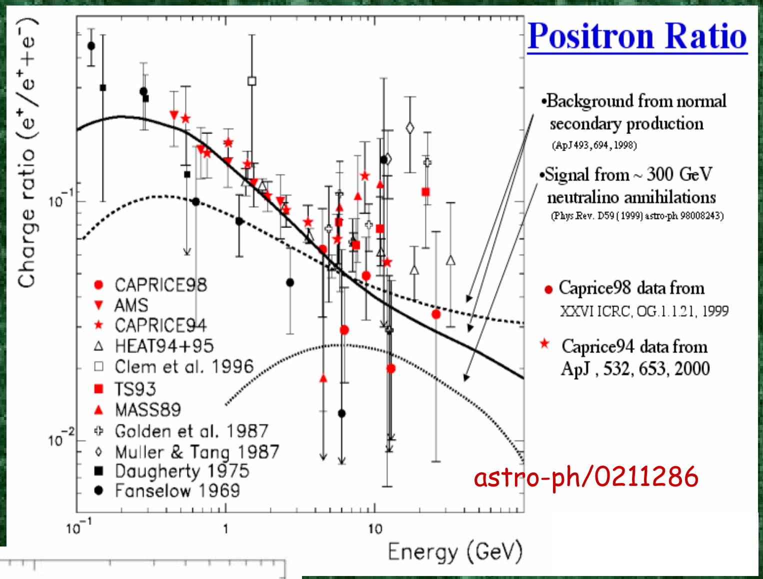
What about the indirect searches of DM particles in the space?

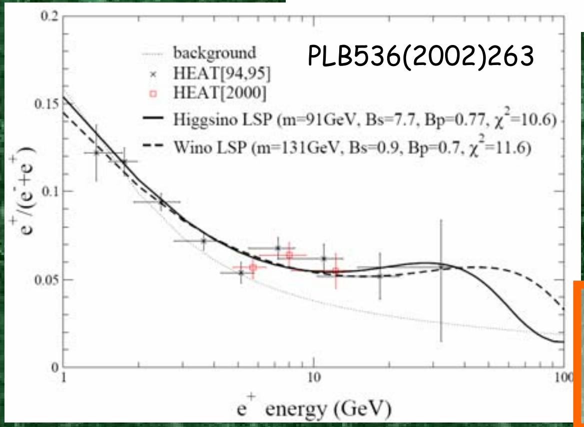
It was noticed that the EGRET data show an excess of gamma ray fluxes for energies above 1 GeV in the galactic disk and for all sky directions.

The EGRET Excess of Diffuse Galactic Gamma Rays



EGRET data, W.de Boer, hep-ph/0508108





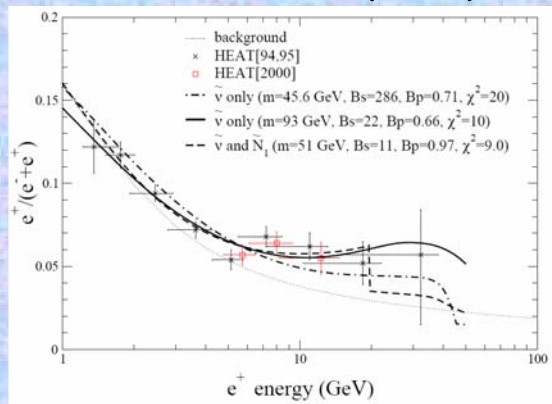
interpretation, evidence itself, derived m_W and cross sections depend e.g. on bckg modeling, on DM spatial velocity distribution in the galactic halo, etc.

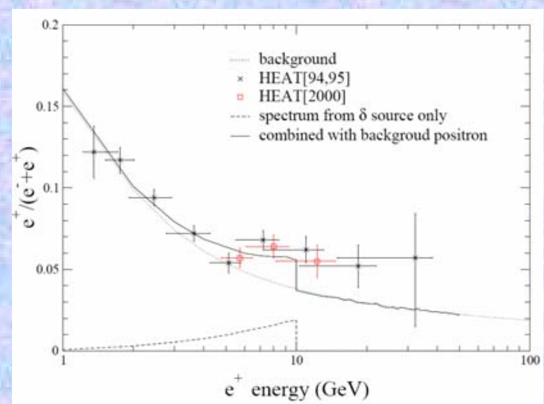
Hints from indirect searches are not in conflict with DAMA/NaI

... not only neutralino, but also e.g. ...

... sneutrino, ...

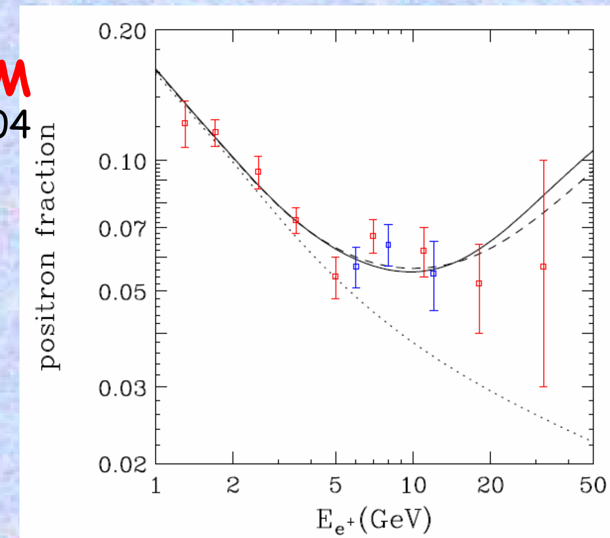
PLB536(2002)263





... or Kaluza-Klein DM

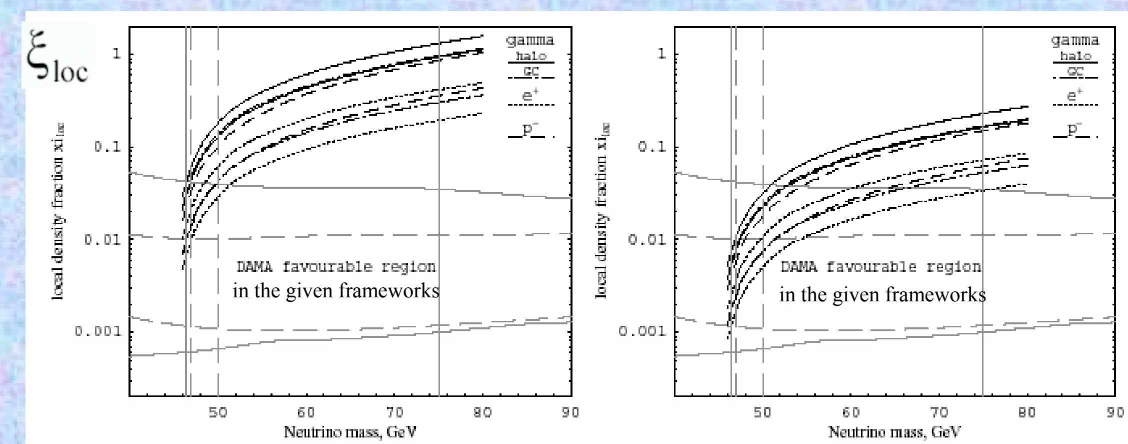
PRD70(2004)115004



... or neutrino of 4th family

hep-ph/0411093

Example of joint analysis of DAMA/NaI and positron/gamma's excess in the space in the light of two DM particle components in the halo



FAQ: ... DAMA/NaI "excluded" by some others ?

OBVIOUSLY NO

They give a single model dependent result using other target
DAMA/NaI gives a model independent result using ^{23}Na and ^{127}I targets

No direct model independent comparison possible

Even "assuming" their expt. results as they claim ... e.g.:

Case of DM particle scatterings on target-nuclei

- In general? OBVIOUSLY NO

The results are fully "decoupled" either because of the different sensitivities to the various kinds of candidates, interactions and particle mass, or simply taking into account the large uncertainties in the astrophysical (realistic and consistent halo models, presence of non-thermalized components, particle velocity distribution, particle density in the halo, ...), nuclear (scaling laws, FFs, SF) and particle physics assumptions and in all the instrumental quantities (quenching factors, energy resolution, efficiency, ...) and theor. parameters.

…and more

- At least in the purely SI coupling they only consider? OBVIOUSLY NO

still room for compatibility either at low DM particle mass or simply accounting for the large uncertainties in the astrophysical, nuclear and particle physics assumptions and in all the expt. and theor. parameters; … and more

Case of bosonic candidate (full conversion into electromagnetic radiation) and of whatever e.m. component

- These candidates are lost by these expts. OBVIOUSLY NO

….and more

+ they usually quote in an uncorrect, partial and unupdated way the implications of the DAMA/NaI model independent result; they release orders of magnitude lower exposures, etc.

Some of the real limitations in the sensitivities claimed (just for "nuclear recoil-like" events, purely SI interactions under a single arbitrary set of expt. and theor. assumptions) by expts applying so far "multiple" procedures to "reduce" the e.m. component of their – generally huge - counting rate, and insensitive to annual modulation signature:

e.g.:

- Physical energy threshold unproved by suitable source calibrations
- Energy scale only "extrapolated" from higher energy, etc.
- Stability of the running parameters unproved
- Stability of the "rejection" windows unproved
- Marginal exposure released generally after years underground
- Efficiencies in each of the many applied "procedures" not proved and illusory overestimated
- Analyses of systematics in each of the many applied procedures not proved at the needed level
- Etc. etc.

At the end of all their "subtractions" if they find events which still remains, they call them "unknown background" …… → they recognize an intrinsic no potentiality of discovery of their approach …

The new DAMA/LIBRA set-up ~250 kg NaI(Tl)
(Large sodium Iodide Bulk for RAre processes)

As a result of a second generation R&D for more radiopure NaI(Tl) by exploiting new chemical/physical radiopurification techniques

(all operations involving crystals and PMTs - including photos - in HP Nitrogen atmosphere)

improving installation and environment

Cu etching with super- and ultra-pure HCl solutions, dried and sealed in HP N_2

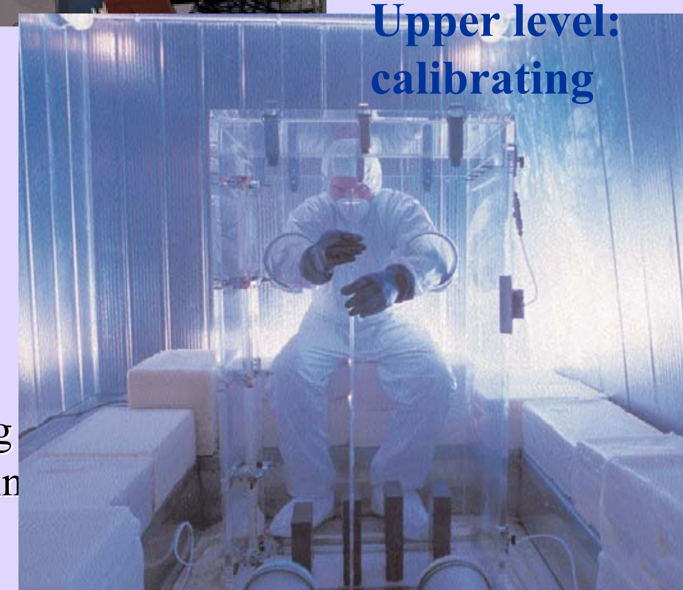
Further on DAMA/LIBRA installation

working under the passive shield before installing the paraffin

view with shielding completed

verifying Cd foils

installing DAMA/LIBRA electronics



Upper level: calibrating

Particular thanks to the Fire Department staff, inside LNGS, for having never left us alone during all the works on the installation performed in HP N_2 atmosphere.

An example: the Cu etching

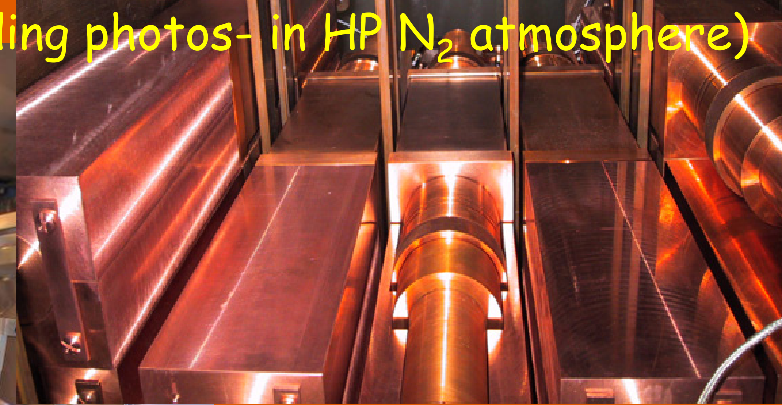
- The Cu etching was performed in a clean room following a devoted protocol:

vessel I: pre-washing of the brick in iper-pure water
vessel II: washing in 1.5l of HCl 3M super-pure
vessel III: first rinse with iper-pure water (bath)
vessel IV: second rinse with iper-pure water (current)
vessel V: washing in 1.5l of HCl 0.5M ultra-pure
vessel VI: first rinse with iper-pure water (bath)
vessel VII: second rinse with iper-pure water (current)
vessel VIII: third rinse with iper-pure water (current)
bricks dried with selected clean towels and HP N_2 flux
bricks sealed in two envelopes (one inside the other) flowed and filled with HP N_2

- Very clean materials (teflon and high purity OFHC copper, selected vessels and gloves) were used. Special tools were also used to help managing the bricks to minimize the contact with gloves.
- The residual contaminants in HCl used in solution with iper-pure water are certified by the producer; in particular standard contaminants are quoted: 10 ppb for ^{nat}K and 1 ppb or U/Th for super-pure HCl and 100 ppt of ^{nat}K and 1 ppt for U/Th in case of ultra-pure HCl.
- For each brick the bath was changed and after each step the solution of the bath was analysed with ICP-MS technique.
- Residual contaminants were checked in order to optimize the choice of the materials (in particular for gloves) and the cleaning procedure. After cleaning, each brick was stored underground.

(all operations involving crystals and PMTs -including photos- in HP N_2 atmosphere)

installing DAMA/LIBRA detectors

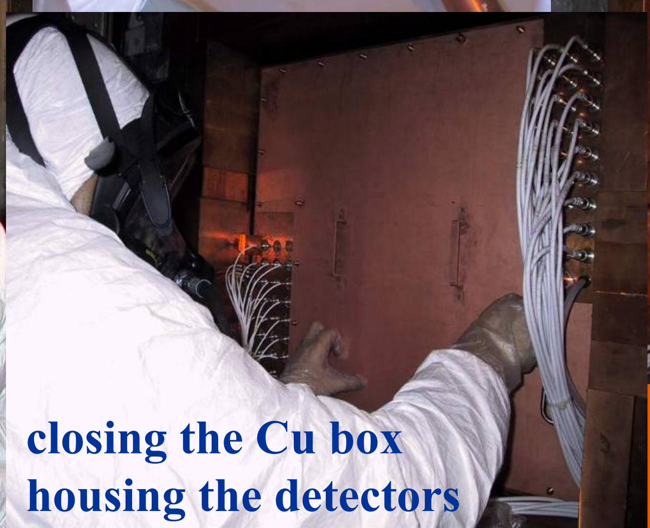


detectors during installation; in the central and right up detectors the new shaped Cu shield surrounding light guides (acting also as optical windows) and PMTs was not yet applied

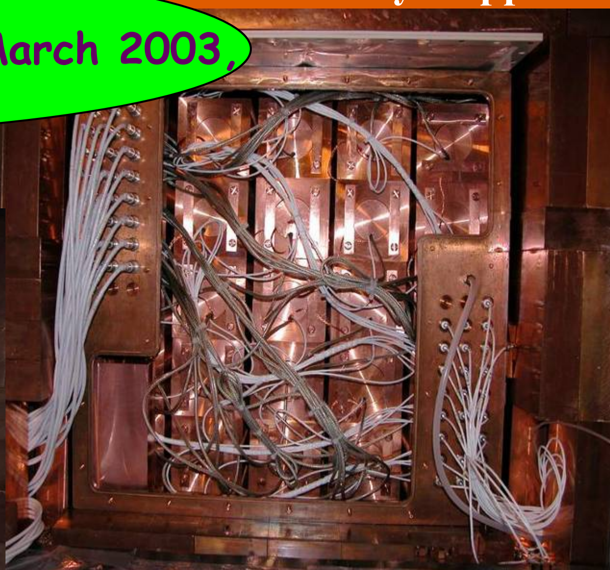
assembling a DAMA/ LIBRA detector

DAMA/LIBRA started operations on March 2003,

filling the inner Cu box with further shield



closing the Cu box housing the detectors



view at end of detectors' installation in the Cu box

DAMA/LIBRA

- <u>Data collected up to March 2007:</u>

  exposure: of order of 1.5 x 10^5 kg x d

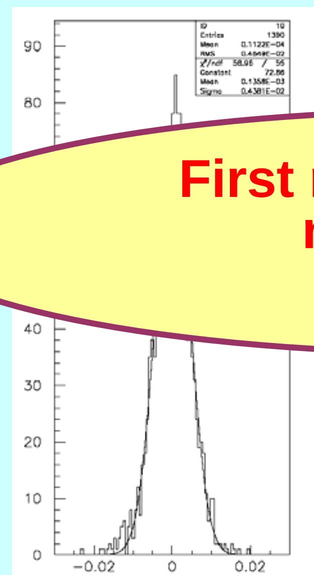
  calibrations: acquired ≈ 40 M events of sources

  acceptance window eff: acquired ≈ 2 M ev/keV

  continuously running

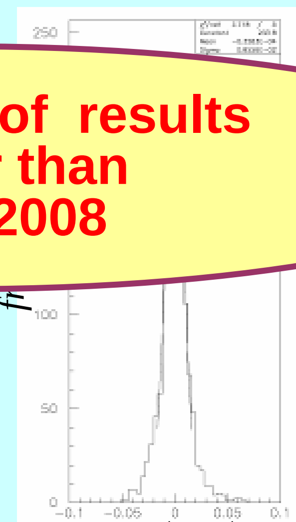
Examples: here from March 2003 to August 2005

Stability of the low energy calibration factors



$$\frac{tdcal - \langle tdcal \rangle}{\langle tdcal \rangle}$$

Stability of the high energy calibration factors



$$\frac{f_{HE} - \langle f_{HE} \rangle}{\langle f_{HE} \rangle}$$

First release of results not later than end of 2008

all operations involving crystals and PMTs -including photos- in HP N_2 atmosphere

- <u>Model independent analysis already concluded almost in all the aspects on an exposure of</u>

  ≈ 0.40 ton × year [(α–β²) = 0.537]

+ in progress

Aims of possible DAMA/1 ton for Dark Matter

We proposed in 1996

Goals of 1 ton NaI detector:

- Extremely high C.L. for the model independent ... gnal
- Model independent investigation on other ... ularities of the signal
- High exposure for the investigation an... of different astrophysical, nuclear and particle ... s models

R&Ds in progress

Improved sensitivity a... mpetitiveness in DM investigation wit... ect to DAMA/LIBRA

- Further investigation on Dark Matter candida... (further on neutralino, bosonic DM, mirror ... inelastic DM, neutrino of 4th family, etc.)

✓ high exposure can allow to disantan... ong the different astrophysical, nuclear an... cle physics models (nature of the candidate ... plings, inelastic interaction, particle co... ersion processes, …, form factors, spin-factors ... nd more on new scenarios)

✓ scaling laws and cross sections

✓ multi-componente DM particles halo?

+

- Further investigation on astrophysical models:

✓ velocity and position distribution of DM particles in the galactic halo

✓ effects due to:

i) satellite galaxies (as Sagittarius and Canis Major Dwarves) tidal "streams";

ii) caustics in the halo;

iii) gravitational focusing effect of the Sun enhancing the DM flow ("spike" and "skirt");

iv) possible structures as clumpiness with small scale size;

+ second-order effects

Some scintillation detector experiments either in preparation or at R&D stage

KIMS:

Experimental site:	Yangyang und. lab. (depth 700m)
Detector:	4 CsI(Tl) scintillators of 8.7 kg mantained at 0°C
Exposure:	3409 kg x day

(arXiv:0704.0423v2)

PSD to discriminate
γ,e^- / nuclear recoils

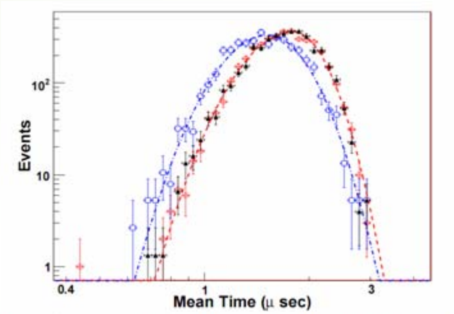
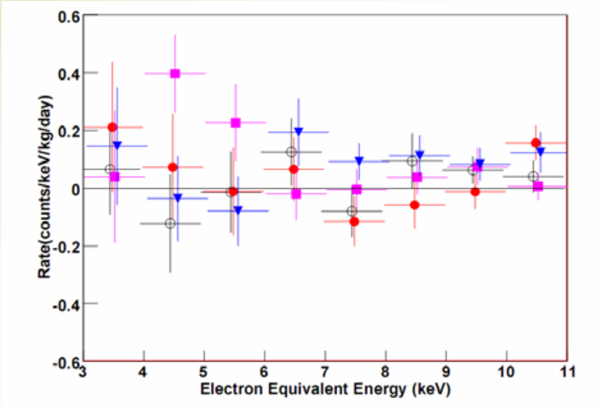


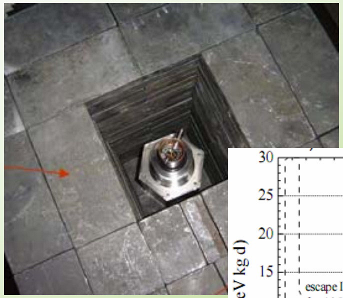
FIG. 1: (color online). MT distribution of NR events (open squares), ER events (open circles) and WIMP search data (filled triangles) of S0501A crystal in the 5-6 keV range. Fitted PDF functions are overlayed. χ^2/DOF =0.8 and 1.3 with DOF=38 and 35 for NR and ER events respectively.

Extracted Nuclear Recoils event rates of the CsI(Tl) crystals



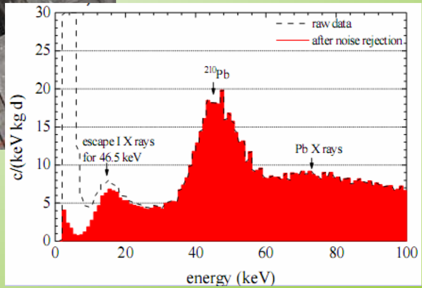
- **Energy spectra after data handling and cuts: about 10 cpd/kg/keV at 3 keV.**
- **Level of background still high. Cesium presence.**

ANAIS: NaI(Tl) scintillator for studying annual modulation signature in Canfranc laboratory



Home-made efforts to improve old detectors.

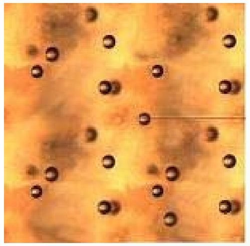
Example of a prototype:

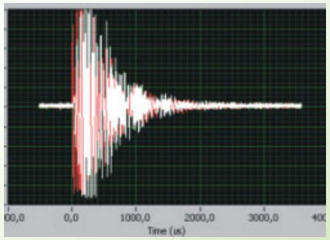


Some alternative techniques for direct detection experiments

PICASSO 3 kg

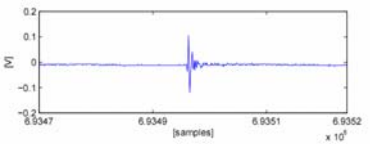
fluorine loaded active superheated liquid C_4F_{10} dispersed in the form of 50-100 μm diameter droplets in a polymerized or viscous medium





- 32 detectors, 3 kg of C_4F_{10}
- 288 acoustic channels
- First detectors installed at SNOLAB
- Data taking ongoing

SIMPLE: a freon-loaded superheated droplet detector (CF_3I)

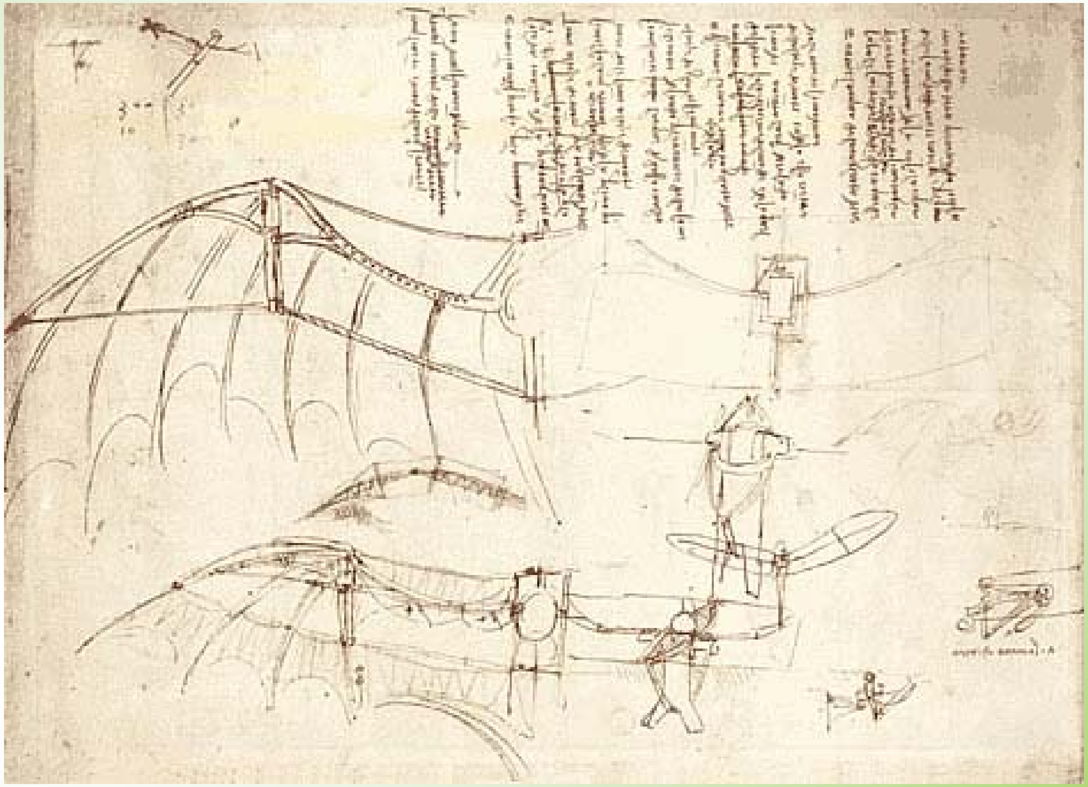


First results from a prototype submitted on april 2007

the superheated droplet detectors

Conclusions

- The model independent signature, the development of highly radiopure set-up, the wide sensitivity to candidate particles and physical scenarios by NaI(Tl) offers a definite strategy to reliably investigate Dark Matter particles in the galactic halo
- A model independent evidence of Dark matter particles in the galactic halo pointed out by DAMA/NaI at 6.3 σ C.L.; soon new results from DAMA/LIBRA. Further R&D in progress towards possible DAMA/1ton, proposed in 1996
- Other solid experimental results by different target materials would – at least at some extent – contribute to disentangle among different astrophysical scenarios and the nuclear and particle physics models



Felix qui potuit rerum cognoscere causas (Virgilio, Georgiche, lI, 489)