Particle Physics: Hints from Cosmology

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COSMOLOGY

- Consistent picture of present and early Universe
- But to large extent orthogonal to existing knowledge in particle physics

Major problems with the Standard Model:

Dark Matter and Baryon Asymmetry of the Universe

- Dark matter:

  “Seen” in galxies, galaxy clusters

  Has strong effect on Cosmic Microwave Background anisotropies

  Bottom line

$$\rho_{DM} = (0.2 - 0.25) \cdot \rho_{total}$$

- Dark matter absolutely crucial for structure formation

CMB anisotropies: baryon density perturbations at recombination, $T = 3000$ K

$$\delta_B \equiv \left(\frac{\delta\rho_B}{\rho_B}\right)_{rec} \simeq \left(\frac{\delta T}{T}\right)_{CMB} = (\text{a few}) \cdot 10^{-5}$$

Matter perturbations grow as $\frac{\delta\rho}{\rho}(t) \propto T^{-1}$

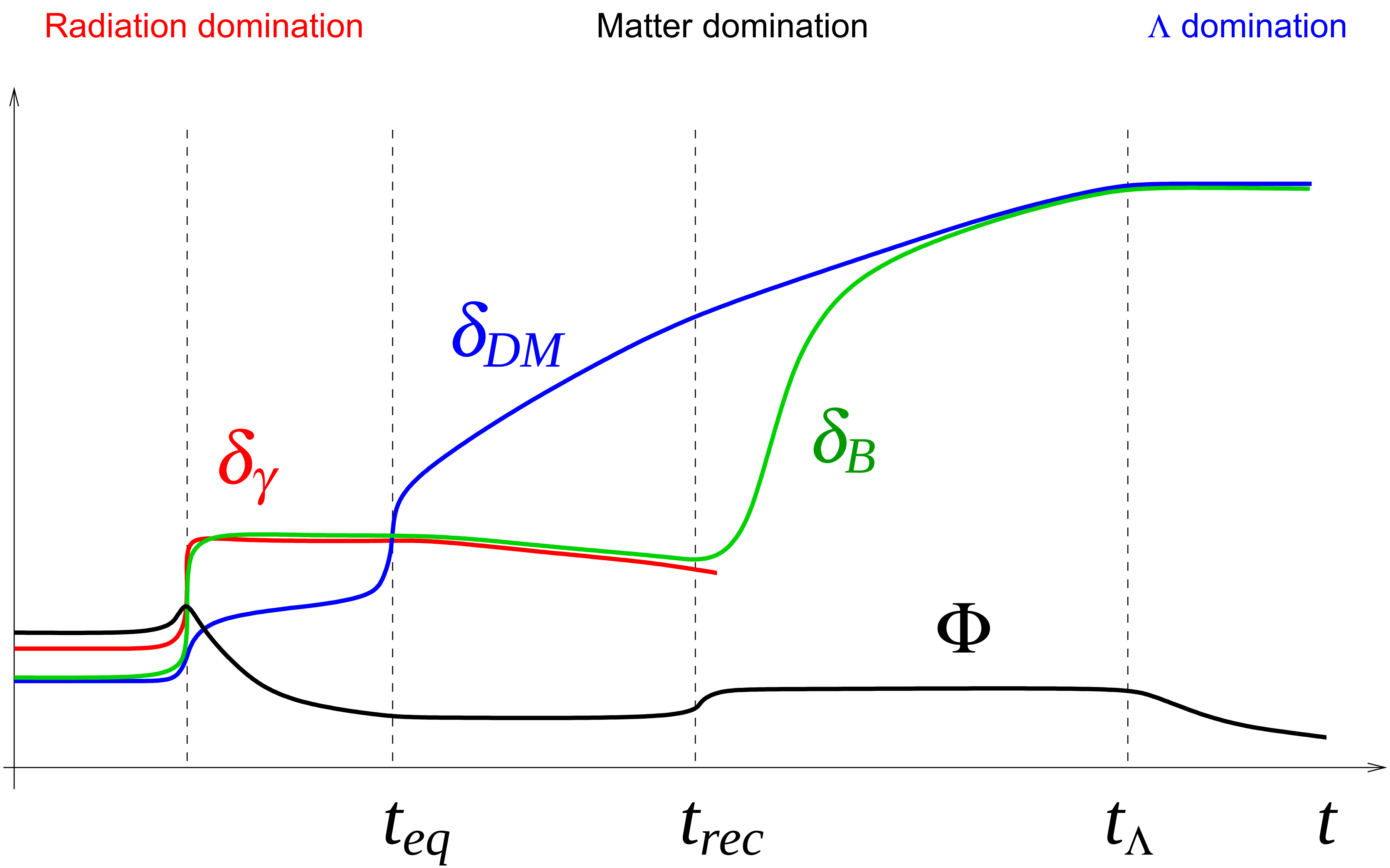
Perturbations in baryonic matter grow after recombination only.
If not for dark matter,

$$\left(\frac{\delta\rho}{\rho}\right)_{today} = 1100 \times (\text{a few}) \cdot 10^{-5} = (\text{a few}) \cdot 10^{-2}$$

No galaxies, no stars...

Perturbations in dark matter start to grow much earlier

Growth of perturbations (linear regime)



Baryon asymmetry of the Universe

- There is matter and no antimatter in the present Universe.
- Baryon-to-photon ratio, almost constant in time:

$$\eta_B \equiv \frac{n_B}{n_\gamma} = 6 \cdot 10^{-10}$$

What's the problem?

Early Universe ($T > 10^{12}$ K $= 100$ MeV):
creation and annihilation of quark-antiquark pairs $\Rightarrow$

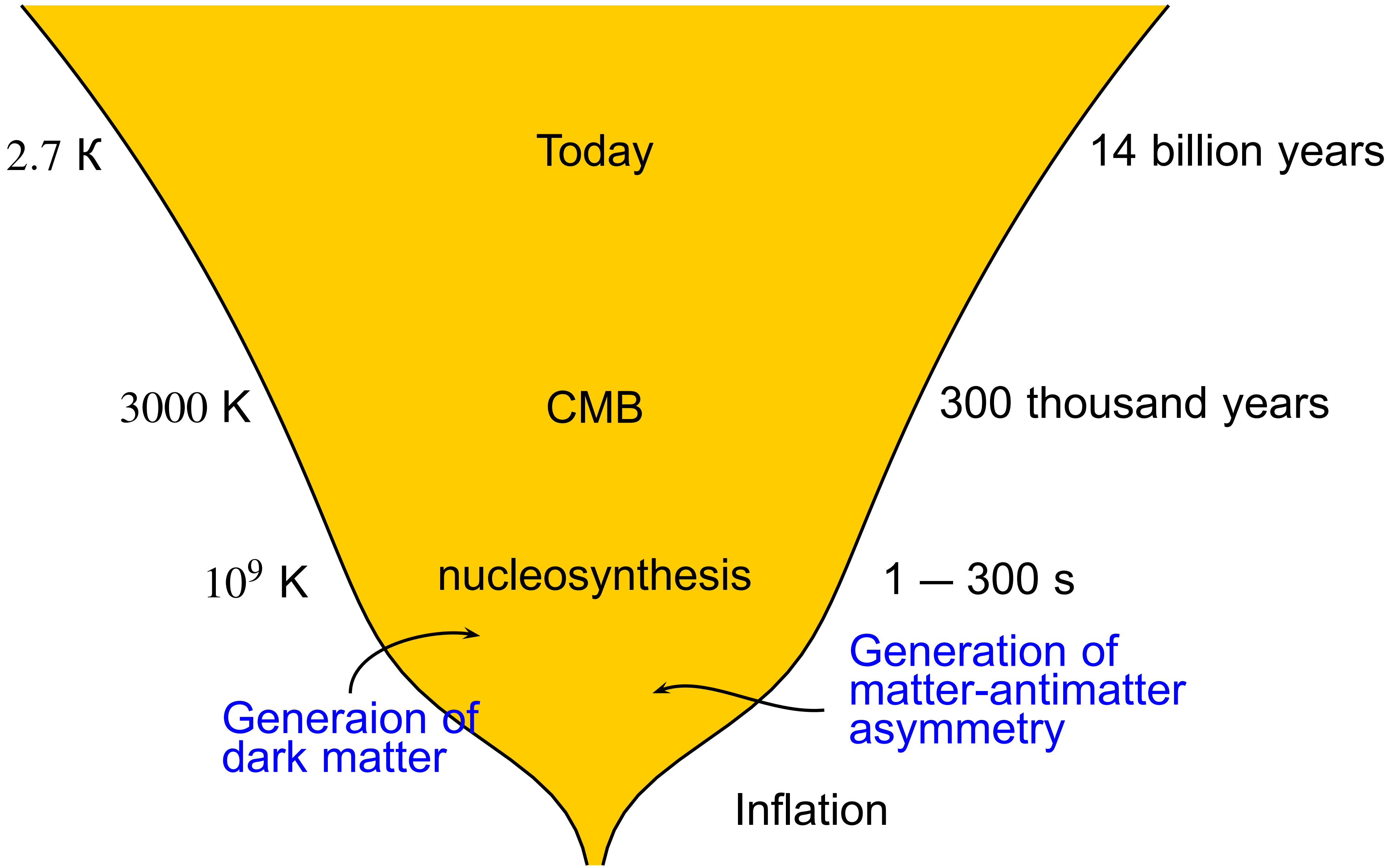
$$n_q, n_{\bar{q}} \approx n_\gamma$$

Hence

$$\frac{n_q - n_{\bar{q}}}{n_q + n_{\bar{q}}} \sim 10^{-9}$$

How was this excess generated in the course of the cosmological evolution?

Sakharov'67, Kuzmin'70



2.7 K
Today
14 billion years
3000 K
CMB
300 thousand years
10^9 K
nucleosynthesis
1 — 300 s
Generation of
matter-antimatter
asymmetry
Generaion of
dark matter
Inflation

Best guess for dark matter: WIMP

- New neutral stable (on cosmological scale) heavy particle
  - Does not exist in the Standard Model
  - Stability: new conserved quantum number $\Longleftrightarrow$ new symmetry
- Pair produced in early Universe at $T \simeq M$, pair-annihilate at $T < M$, freeze out at $T \sim M/30$
  - Calculable in terms of mass (log dependence) and annihilation cross section ($1/\sigma$ dependence)
- To have right present abundance:
  - Mass range: $(10 - 1000)$ GeV
  - Strength of interactions $\simeq$ weak force: annihilation cross section $= (1 \div 2) \cdot 10^{-36}$ cm^2

Just in LHC range

Life may not be that simple

Clouds over CDM

Numerical simulations of structure formation with CDM show

- Too many dwarf galaxies

  A few hundred satellites of a galaxy like ours —

  Much less observed so far

  Kauffmann et.al.'93; Klypin et.al.'99;
  Moore et.al.'99;...; Madau et.al.'08

- Too low angular momenta of spiral galaxies
- Too high density in galactic centers ("cusps")
- Not crisis yet

  But what if one really needs to suppress small structures?

High initial velocities of DM particles $\Longrightarrow$ Warm dark matter

Free streaming

At time t free streaming length

$$l_{fs}(t) \sim v(t) \cdot t \,, \qquad v = \frac{p}{m}$$

At radiation-matter equality (beginning of rapid growth of perturbations),

$$l_{fs}(t_{eq}) \sim \frac{p}{T} \frac{T_{eq} t_{eq}}{m}$$

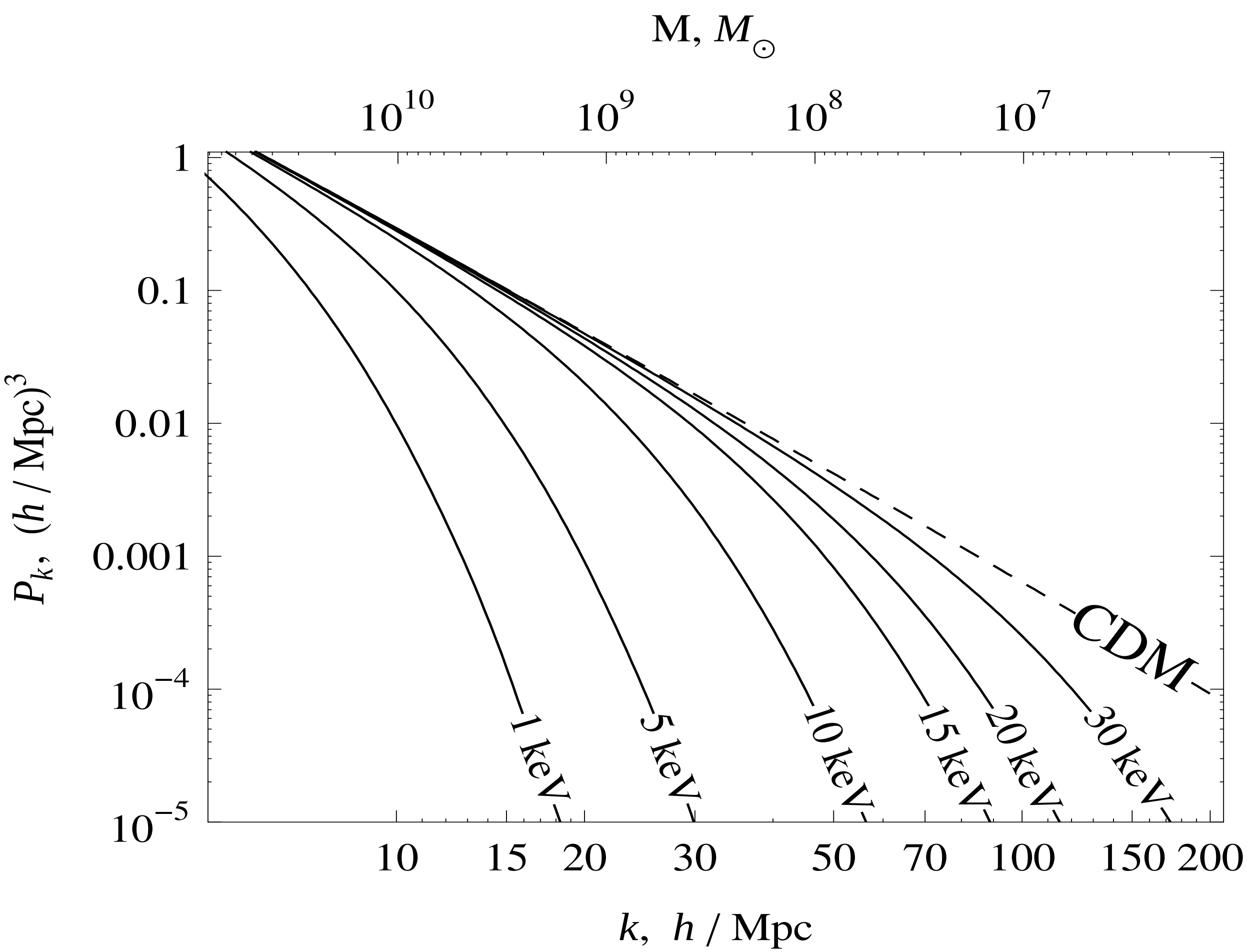
Perturbations at smaller scales are suppressed.

- $\frac{p}{T} \simeq 3$ (if relativistic thremal-like distribution at decoupling)
- $z_{eq} \simeq 3000$, $T_{eq} \simeq 1$ eV, $t_{eq} \simeq 60$ kyr $\simeq 20$ kpc $\Longrightarrow$

Suppression of objects of mass

$$M \lesssim \rho_{DM} \cdot \frac{4}{3} \pi l_0^3 \sim 10^9 M_\odot \cdot \left(\frac{1 \text{ keV}}{m} \right)^3$$

Power spectrum of perturbations



Assuming thermal primordial distribution normalized to $\Omega_{DM} \simeq 0.2$.

Warm dark matter: additional argument

Tremaine, Gunn
Hogan, Dalcanton;
Boyanovsky et.al., ...

- Initial phase space density of dark matter particles: $f(\vec{p})$, independent of $\vec{x}$.

  Fermions:

  $$f(\vec{p}) \leq \frac{1}{(2\pi)^3} \quad \text{by Pauli principle}$$

  Not more than one particle in quantum unit of phase space volume $\Delta\vec{x}\Delta\vec{p} = (2\pi\hbar)^3$.

  NB: Thermal distribution: $f_{max} = \frac{1}{2(2\pi)^3}$

  Expect maximum initial phase space density somewhat below $(2\pi)^{-3}$

- Non-dissipative motion of particles, gravitatonal interactions only: particles tend to penetrate into empty parts of phase space $\Longrightarrow$ coarse grained distribution decreases in time; maximum phase space density also decreases in time.

But not by many orders of magnitude

$$\frac{\text{initial phase space density}}{\text{present phase space density}} = \frac{f}{f_0} = \Delta$$

with

$$\Delta \simeq 10 \div 1000$$

- Observable:

$$Q(\vec{x}) = \frac{\rho_{DM}(\vec{x})}{\langle v_{||}^2 \rangle^{3/2}}$$

$\rho_{DM}(\vec{x}) \Longleftrightarrow$ gravitational potential
$\langle v_{||}^2 \rangle \Longleftrightarrow$ velocities of stars along line of sight.

Assume dark matter particles have same velocities as stars (e.g., virialized)

$$Q \simeq m^4 \frac{n(\vec{x})}{\langle \frac{1}{3} p^2 \rangle^{3/2}} \simeq 3^{3/2} m^4 f_0(\vec{x}, \vec{p})$$

- Estimator of primordial phase space density:

$$f \simeq \Delta \frac{Q}{3^{3/2} m^4}$$

- Largest observed: dwarf galaxies

$$Q_{max} = \left(3 \cdot 10^{-3} \div 2 \cdot 10^{-2}\right) \frac{M_\odot/\text{pc}^3}{\text{km/s}}$$

With $M_\odot \simeq 1 \cdot 10^{63}$ keV, 1 pc$= 1.5 \cdot 10^{26}$ keV^{-1}, km/s$= 3 \cdot 10^{-6}$

$$\begin{aligned} Q_{max} &= 0.2 \text{ keV}^4 \\ &\simeq 3^{3/2}\Delta^{-1} \cdot m^4 f_{max} \simeq 3^{3/2}\Delta^{-1} \cdot m^4 \frac{\#}{(2\pi)^3} \end{aligned}$$

If maximum observed Q indeed estimates the largest phase space density of DM particles in the present Universe, then

$$m \sim (1 \div 10) \cdot \text{keV}$$

Gravitinos as WDM candidates

Gorbunov, Khmelnitsky, VR' 08

- Mass $m_{3/2} \simeq F/M_{Pl}$
  $\sqrt{F}$ = SUSY breaking scale.
  $\Longrightarrow$ Gravitinos light for low SUSY breaking scale.
  E.g. gauge mediation

- Light gravitino = LSP $\Longrightarrow$ Stable

- Decay width of superpartners into gravitino + SM particles

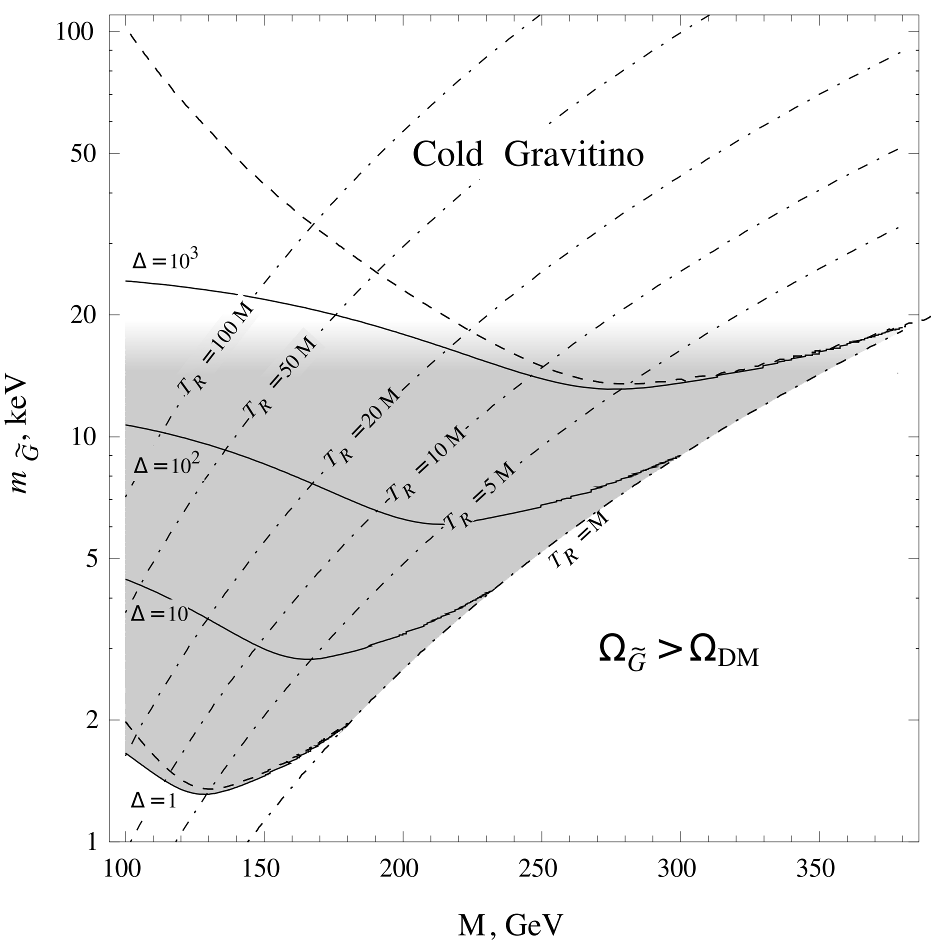
$$\Gamma_{\tilde{S}} \simeq \frac{M_{\tilde{S}}^5}{F^2} = \frac{M_{\tilde{S}}^5}{6\, m_{3/2}^2 M_{Pl}^2}$$

$M_{\tilde{S}}$ = mass of superpartner $\tilde{S}$

- Heavy superpartners $\Longrightarrow$ gravitinos overproduced in the Universe

Need light superpartners

Superpartner mass range



To summarize:

- Gravitinos are still warm dark matter candidates
- Possible only if superpartners are light,

$$M \lesssim 300 \text{ GeV}$$

Will soon be ruled out (or confirmed) by LHC

Competitor: strile neutrino

Gorbunov, Khmelnitsky, VR' 08

- Simplest production mechanism: via active-sterile mixing.

Dodelson, Widrow; Dolgov, Hansen; Asaka et.al.

Almost thermal primordial spectrum normalized to $\Omega_{DM} \simeq 0.2$

$$f(p) = \frac{g_{\nu_s}}{(2\pi)^3} \frac{\beta}{\mathrm{e}^{p/T_\nu} + 1}$$

$\Omega_\nu = \Omega_{DM} \Longrightarrow$

$$\beta = 10^{-2} \left(\frac{1\ \mathrm{keV}}{m} \right) \propto \sin^2 2\theta$$

Phase space bound:

Also: Boyarsky et. al.

$$m^4 f_{max} > \# \cdot Q_{max} \qquad \Longrightarrow$$

$$m > 5.7 \text{ keV} \quad \Longrightarrow \quad \sin^2 2\theta = (\text{a few}) \cdot 10^{-9}$$

Similar to, and independent from Ly-α bounds.

Ly-α: Abazajan; Seljak et.al.; Viel et.al.

$m > 10 \div 28$ keV

Tension with X-ray limits:

$$\nu_s \to \nu\gamma \quad \text{in cosmos}$$

$$m < 4 \text{ keV}$$

Boyarsky et. al.; Riemen-Sorensen et.al., Watson et.al.; Abazajan et.al.

X-ray astronomy: way to discover sterile neutrinos, if they are dark matter particles

Baryon asymmetry: Sakharov conditions

To generate baryon asymmetry, three necessary conditions should be met at the same cosmological epoch:

- B-violation
- C- and CP-violation:
  microscopic physics discriminates between matter and antimatter
- Thermal inequilibrium

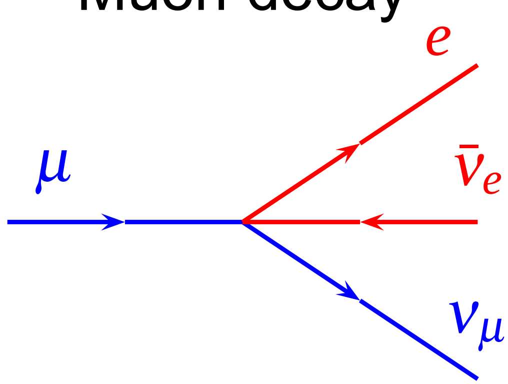
Conservation laws in the Standard Model

- Energy, momentum
- Baryon number $(N_q - N_{\bar{q}})$ ← proton is stable, $\tau_p > 10^{33}$ years!
- Lepton numbers

$L_e = (N_{e^-} + N_{\nu_e}) - (N_{e^+} + N_{\bar{\nu}_e})$

$L_\mu \;, \quad L_\tau$

Muon decay



$\mu \not\to e\gamma \,, \quad$ Br $< 10^{-11}$

Matter-antimatter asymmetry cannot be explained within the Standard Model

BUT

Baryon number is violated in electroweak interactions.

Non-perturbative effect, requires large fluctuations
of W-and Z-boson fields

At zero temprature rate suppressed by tunneling exponent:

$$e^{-\frac{16\pi^2}{g_W^2}} \sim 10^{-165}$$

High temperatures: large thermal fluctuations (“sphalerons”).

B-violation rapid as compared to cosmological expansion at high temperatures, $T \gtrsim 100$ GeV.

PROBLEM:

Universe expands slowly. Expansion time at $T \sim 100$ GeV

$$H^{-1} \sim 10^{-10} \text{ s}$$

Too large to have deviations from thermal equilibrium?

The only chance: 1st order phase transition, highly inequilibrium process

Electroweak symmetry is broken in vacuo,
restored at high temperatures

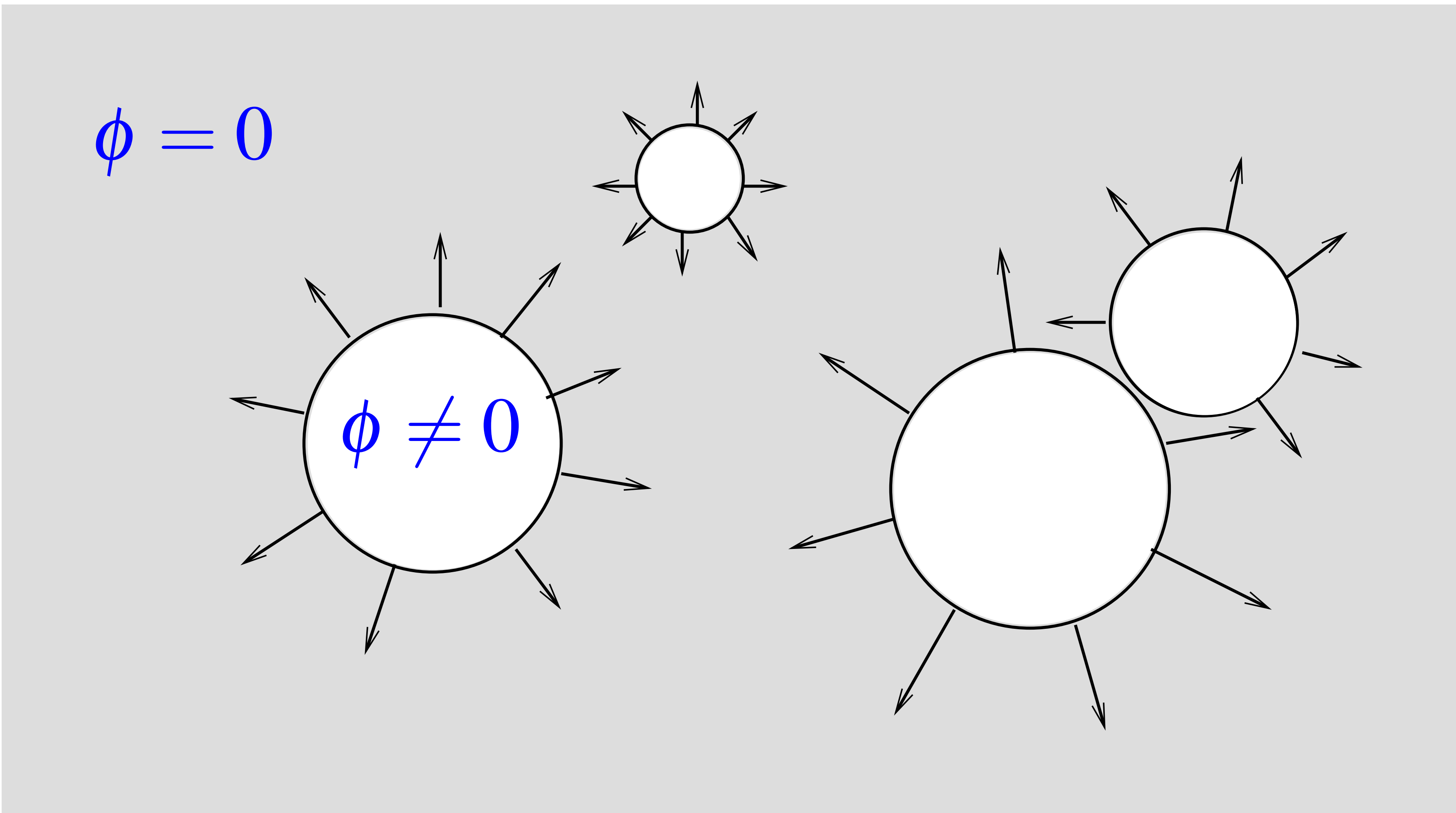
Transition may in principle be 1st order

1st order phase transition occurs from supercooled state via spontaneous creation of bubbles of new (broken) phase in old (unbroken) phase.

Bubbles then expand at $v \sim 0.1c$

Bubbles born microscopic, $r \sim 10^{-16}$ cm, grow to macroscopic size, $r \sim 0.1 H^{-1} \sim$ mm, before their walls collide

Boiling Universe, strongly out of thermal equilibrium



$\phi = 0$
$\phi \neq 0$

Does this really happen?

Not in Standard Model

Standard Model fully calculable

- No phase transition at all; smooth crossover
- Also: way too small CP-violation

What can make EW mechanism work?

- Extra fields/particles
  - Should interact strongly with Higgs(es)
  - Should be present in plasma at $T \sim 100$ GeV

  $\Longrightarrow$ not much heavier than 300 GeV

- Plus extra source of CP-violation.

  Better in Higgs sector $\Longrightarrow$ Several Higgs fields

More generally, electroweak baryogenesis at $T \sim 100$ GeV requires complex dynamics in electroweak symmetry breaking sector

at $E \sim (\text{a few}) \cdot 100$ GeV ,   LHC range

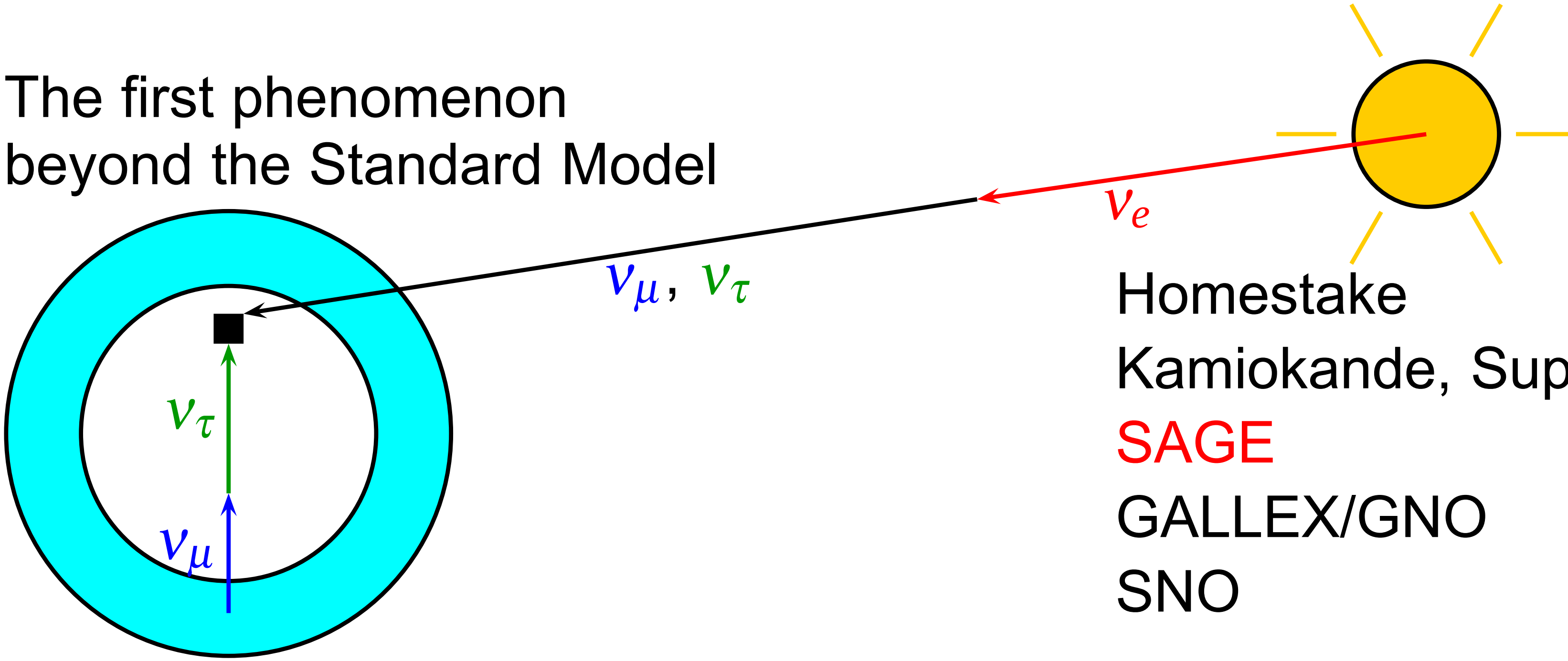
Is EW the only appealing scenario?

By no means!

— Leptogenesis

Key: neutrino oscillations

The first phenomenon
beyond the Standard Model



Homestake
Kamiokande, Super-K
SAGE
GALLEX/GNO
SNO

Super–K
Accelerator ν_μ: K2K

Reactor $\bar{\nu}_e$: KamLAND

Lepton numbers are not conserved
In principle, this is sufficient to generate baryon asymmetry.

Scenario:

Generation of lepton asymmetry due to new interactions at temperatures $10^8 - 10^{10}$ GeV

$$\Downarrow$$

reprocessing of lepton asymmetry into baryon asymmetry in interactions of leptons and quarks at high temperatures within the Standard Model.

Neutrino masses in right ballpark

Prospects

- Neutrino masses $\Longleftrightarrow$ role of neutrino in the Universe
- CP-violation in neutrino sector $\Longleftrightarrow$ asymmetry between matter and antimatter

To conclude

Particle physics may well discover things crucial for our existence

Dark matter
Dynamics behind baryon asymmetry

Quite possibly not particular ones discussed here

May find something even more profound

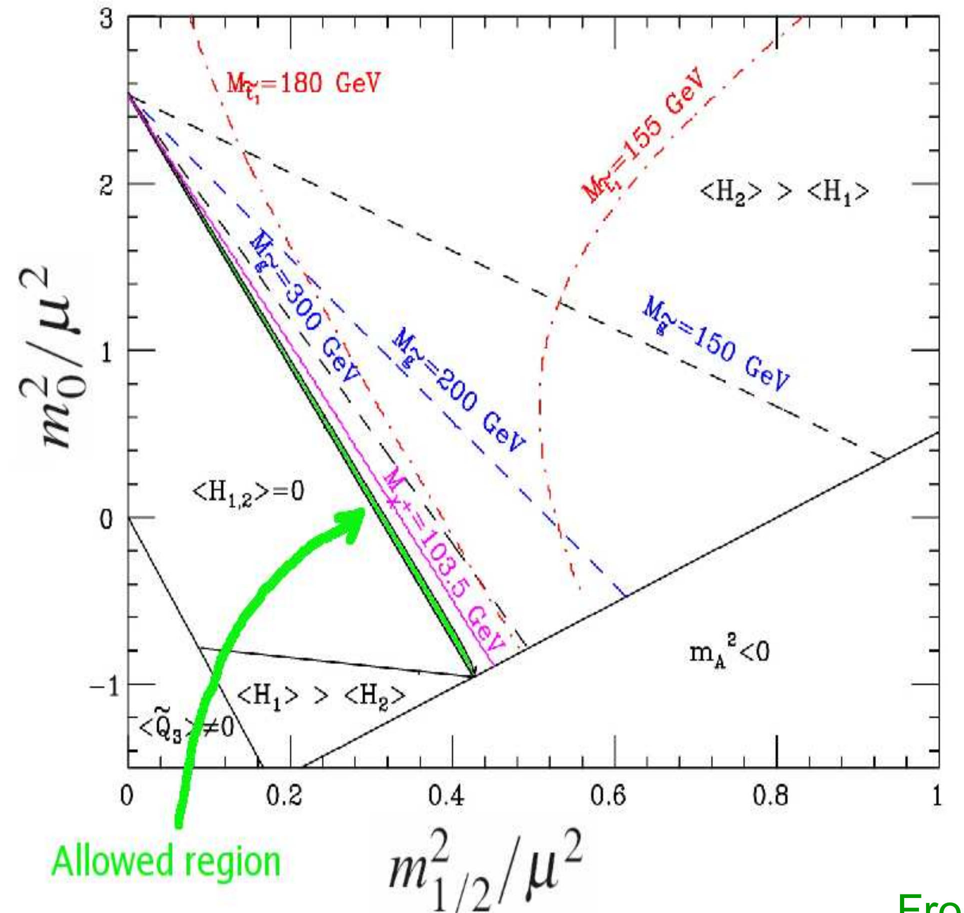
Like extra dimensions/TeV-scale gravity

Quite possibly something else

And in any case the landscape of physics, cosmology included, will change in near future

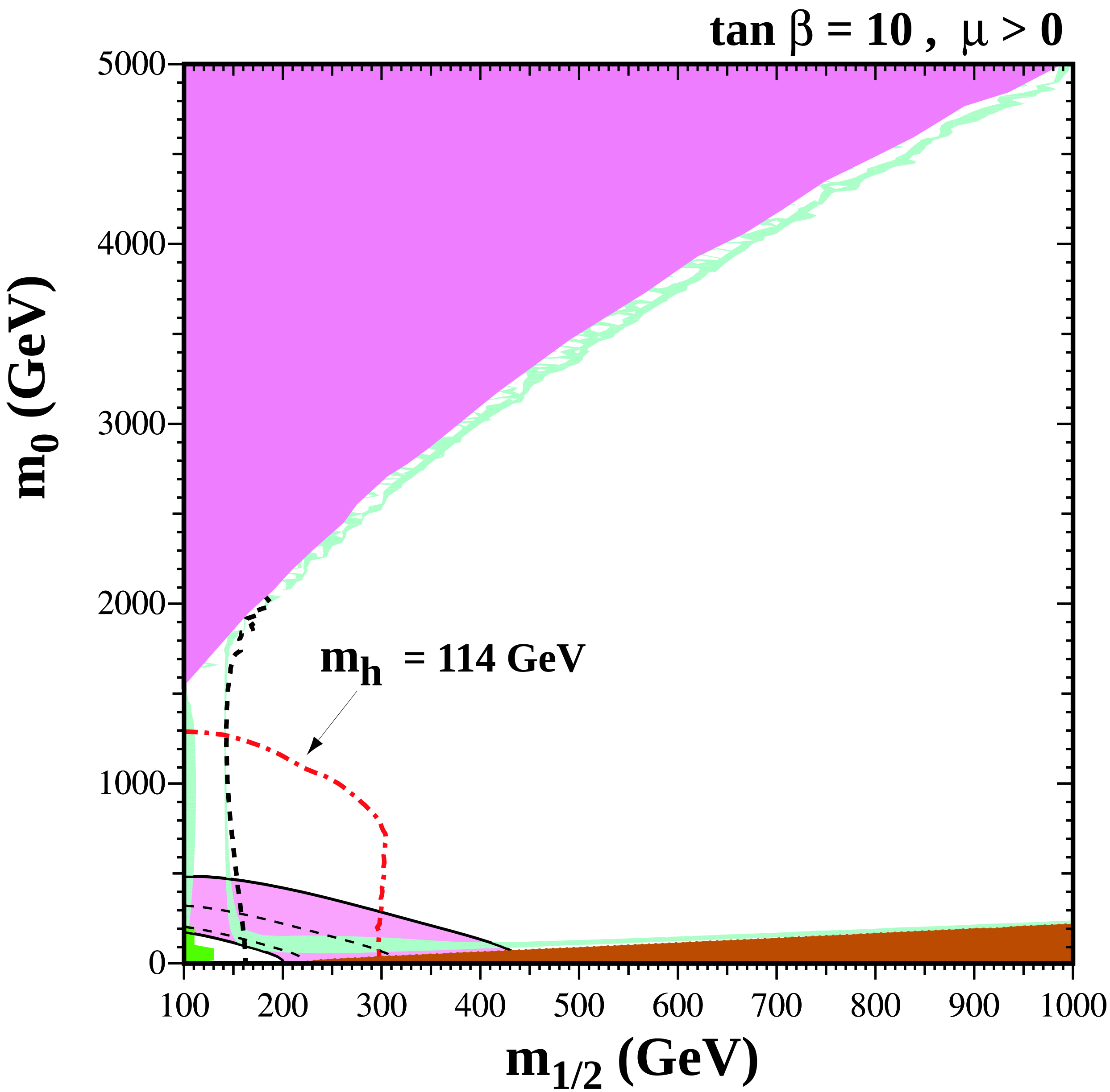
Warning: supersymmetric models are already constrained experimentally

mSUGRA

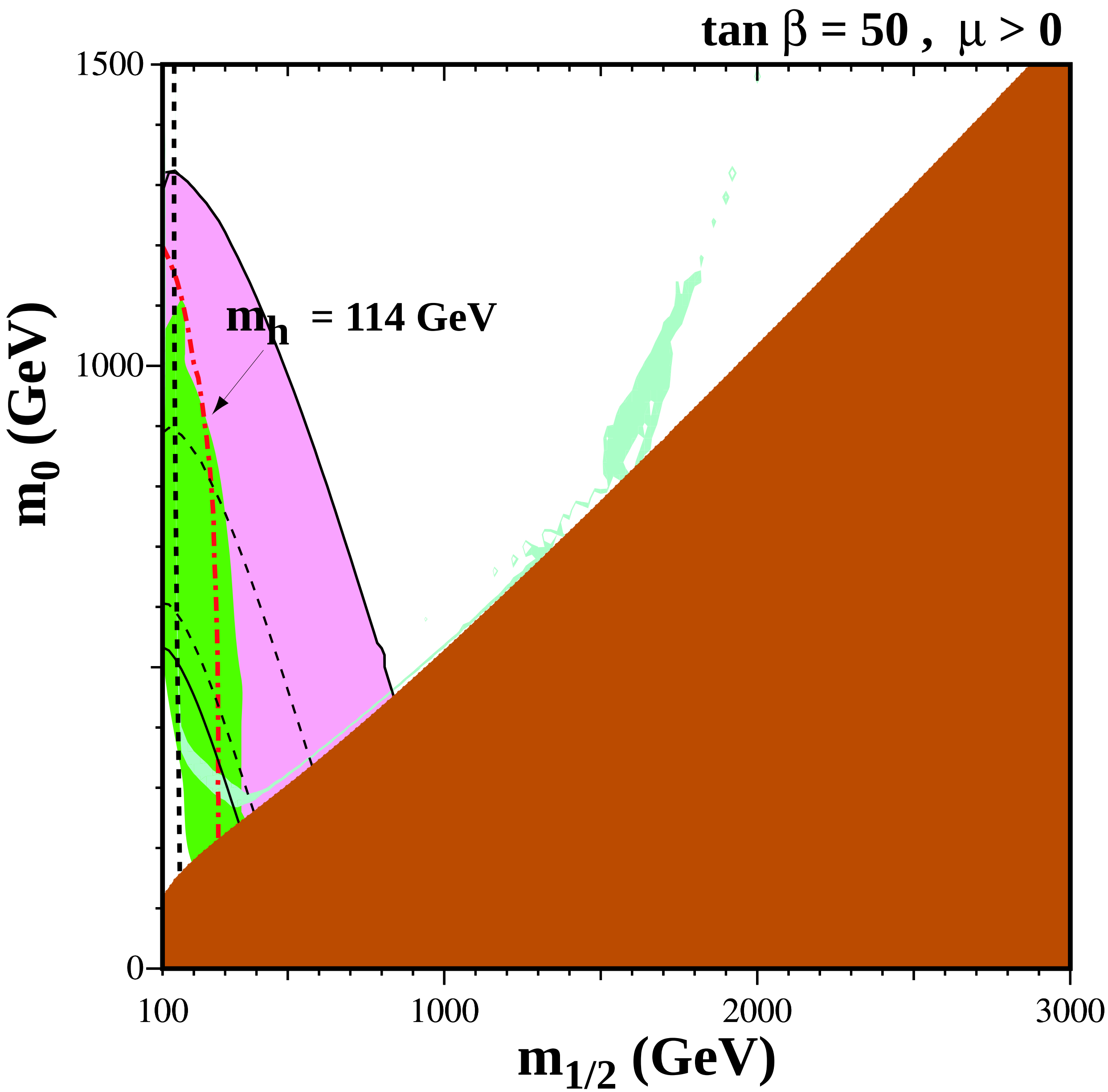


From Giudice, Rattazzi' 06

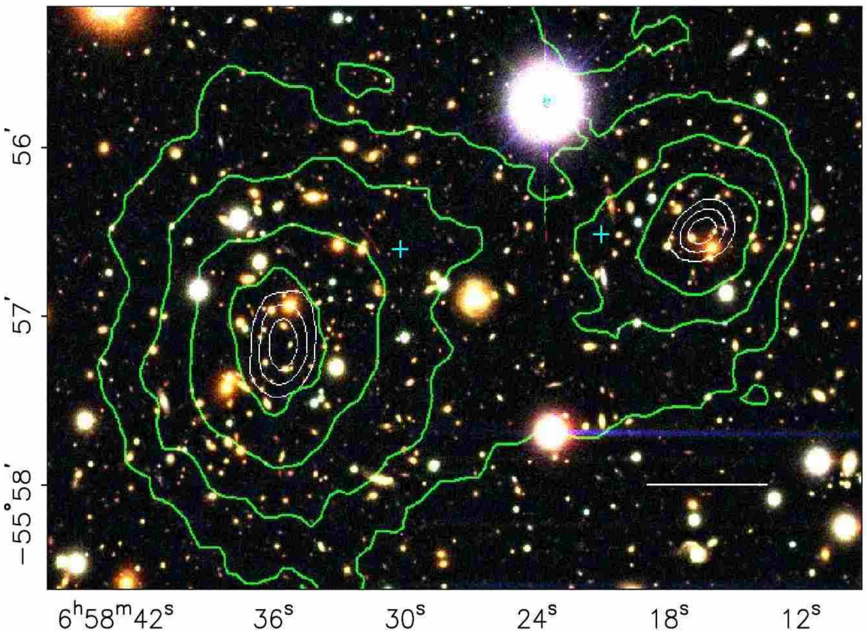
mSUGRA at fairly low $\tan\beta$

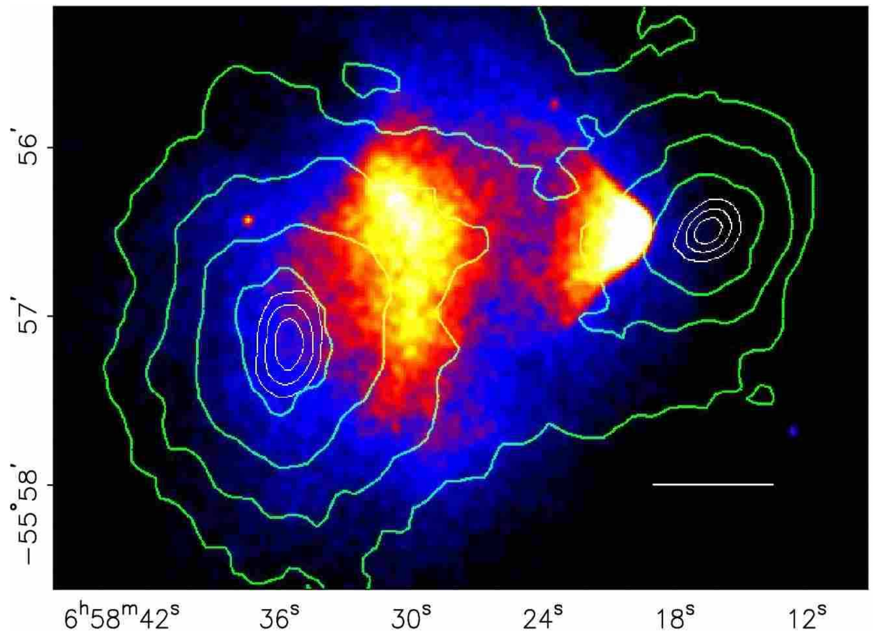


Larger $\tan\beta$ is better



Bullet cluster 1E0657-558





But cosmology may be telling us something different – and unpleasant

Both particle physics and Universe appear heavily fine tuned

- Friendly fine-tunings
  - Dark energy density $\sim (10^{-3}\ \text{eV})^4$

    Just right for galaxies to get formed
  - Primordial density perturbations $\frac{\delta\rho}{\rho} \sim 10^{-5}$

    Just right to form stars

    but not supermassive galaxies w/o planets
  - Dark matter sufficient to produce structure

Also

  - Light quark masses and α_{EM}

    Just right for $m_n > m_p$

    but stable nuclei
  - Many more...

Is the electroweak scale a friendly fine-tuning?

Anthropic principle/environmentalism

"Our location in the Universe
is neccessarily priviledged to
the extent of being compatible
with our existence as observers"

Brandon Carter'1974

Fig

Recent support from "string landscape"

We exist where couplings/masses are right

Problem: never know which parameters are environmental and which derive from underlying physics

Disappointing, but may be true

May gain support from LHC, if not enough new physics to solve the gauge hierarchy problem

横山　操「グランド キャニオン」1961