What lies beyond the Standard Model?

Supersymmetry

New motivations
From LHC Run 1

- Stabilize electroweak vacuum
- Successful prediction for Higgs mass
  - Should be < 130 GeV in simple models
- Successful predictions for couplings
  - Should be within few % of SM values
- Naturalness, GUTs, string, …, **dark matter**

Early Russian & Ukrainian Papers

Mat. Sbornik
Tom 82 (124) (1970), No. 3

Math. USSR Sbornik
Vol. 11 (1970), No. 3

LIE GROUPS WITH COMMUTING AND ANTICOMMUTING PARAMETERS

F. A. BEREZIN AND G. I. KAC

UDC 519.46

Abstract. In this paper we study analogs of Lie algebras and formal Lie grou
of groups differ from usual Lie groups, roughly speaking, in that they admit antic
parameters. The analogs of Lie algebras differ from usual Lie algebras by proper
tator. In the definition of these objects an essential role is played by the gradient
ial they become Lie groups and algebras in the usual sense. To these generalize
over classical theorems on the connection between Lie groups and algebras and t
tation theory.

EXTENSION OF THE ALGEBRA OF POINCARE GROUP GENERATORS AND VIOLATION OF P INVARIANCE

Yu.A. Gol'fand and E.P. Likhtman
Physics Institute, USSR Academy of Sciences

Submitted 10 March 1971
ZhETF Pis. Red. 13, No. 8, 452 - 455 (20 April 1971)

POSSIBLE UNIVERSAL NEUTRINO INTERACTION

D.V. Volkov and V.P. Akulov
Physico-technical Institute, Ukrainian Academy of Sciences

Submitted 13 October 1972
ZhETF Pis. Red. 16, No. 11, 621 - 624 (5 December 1972)

PHYSICS LETTERS 3 September 1973

IS THE NEUTRINO A GOLDSTONE PARTICLE?

D.V. VOLKOV and V.P. AKULOV
Physico-Technical Institute, Academy of Sciences of the Ukrainian SSR, Kharkov 108, USSR

Received 5 March 1973

GAUGE FIELDS FOR SYMMETRY GROUP WITH SPINOR PARAMETERS

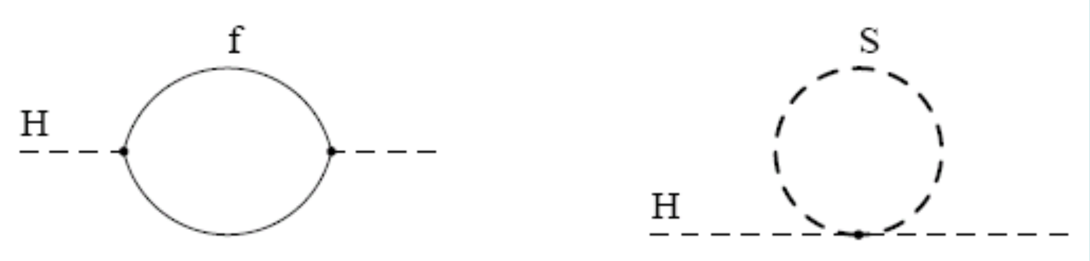
D. V. Volkov and V. A. Soroka

The inclusion of gauge fields for a symmetry group containing anticommuting parameters is considered. The Higgs effect is discussed for Goldstone fields with spin 1/2.

Naturalness of hierarchy of mass scales

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:



- Each is quadratically divergent: $\int^{\Lambda} d^4k/k^2$

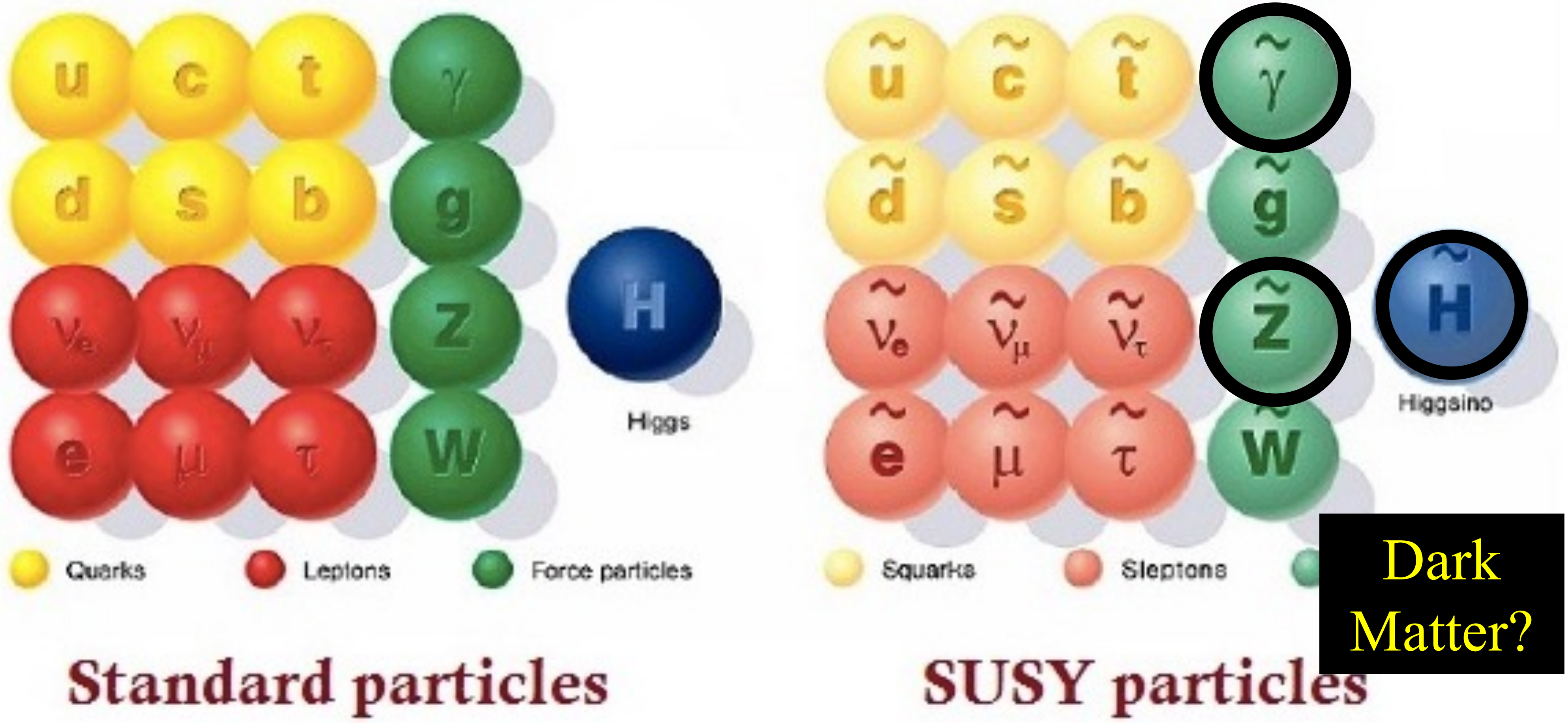
$$\Delta m_H^2 = -\frac{{y_f}^2}{16\pi^2}[2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f) + \ldots]$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + \ldots]$$

- Leading divergence cancelled if

$$\lambda_S = y_f^2 \times 2$$ **Supersymmetry!**

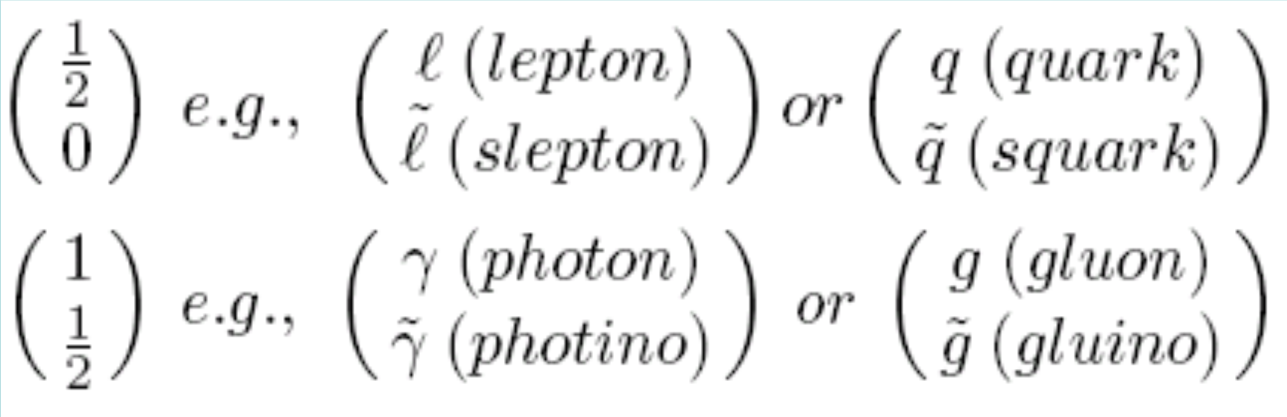
Minimal Supersymmetric Extension of the Standard Model



Dark Matter?

Minimal Supersymmetric Extension of the Standard Model (MSSM)

- Double up the known particles:



$$\begin{pmatrix} \frac{1}{2} \\ 0 \end{pmatrix} \; e.g., \; \begin{pmatrix} \ell\ (lepton) \\ \tilde{\ell}\ (slepton) \end{pmatrix} \; or \; \begin{pmatrix} q\ (quark) \\ \tilde{q}\ (squark) \end{pmatrix}$$

$$\begin{pmatrix} 1 \\ \frac{1}{2} \end{pmatrix} \; e.g., \; \begin{pmatrix} \gamma\ (photon) \\ \tilde{\gamma}\ (photino) \end{pmatrix} \; or \; \begin{pmatrix} g\ (gluon) \\ \tilde{g}\ (gluino) \end{pmatrix}$$

- Two Higgs doublets
  - 5 physical Higgs bosons:
  - 3 neutral, 2 charged
- Lightest neutral supersymmetric Higgs looks like the single Higgs in the Standard Model

1990/1

Higgs Bosons in Supersymmetry

- Need 2 complex Higgs doublets
  (cancel anomalies, form of SUSY couplings)
- 8 – 3 = 5 physical Higgs bosons
  Scalars h, H; pseudoscalar A; charged $H^{\pm}$
- Lightest Higgs < M_Z at tree level:

$$M^2_{\mathrm{H,h}} = \frac{1}{2}\left[M^2_{\mathrm{A}} + M^2_{\mathrm{Z}} \pm \sqrt{(M^2_{\mathrm{A}} + M^2_{\mathrm{Z}})^2 - 4M^2_{\mathrm{Z}}M^2_{\mathrm{A}}\cos^2 2\beta}\right]$$

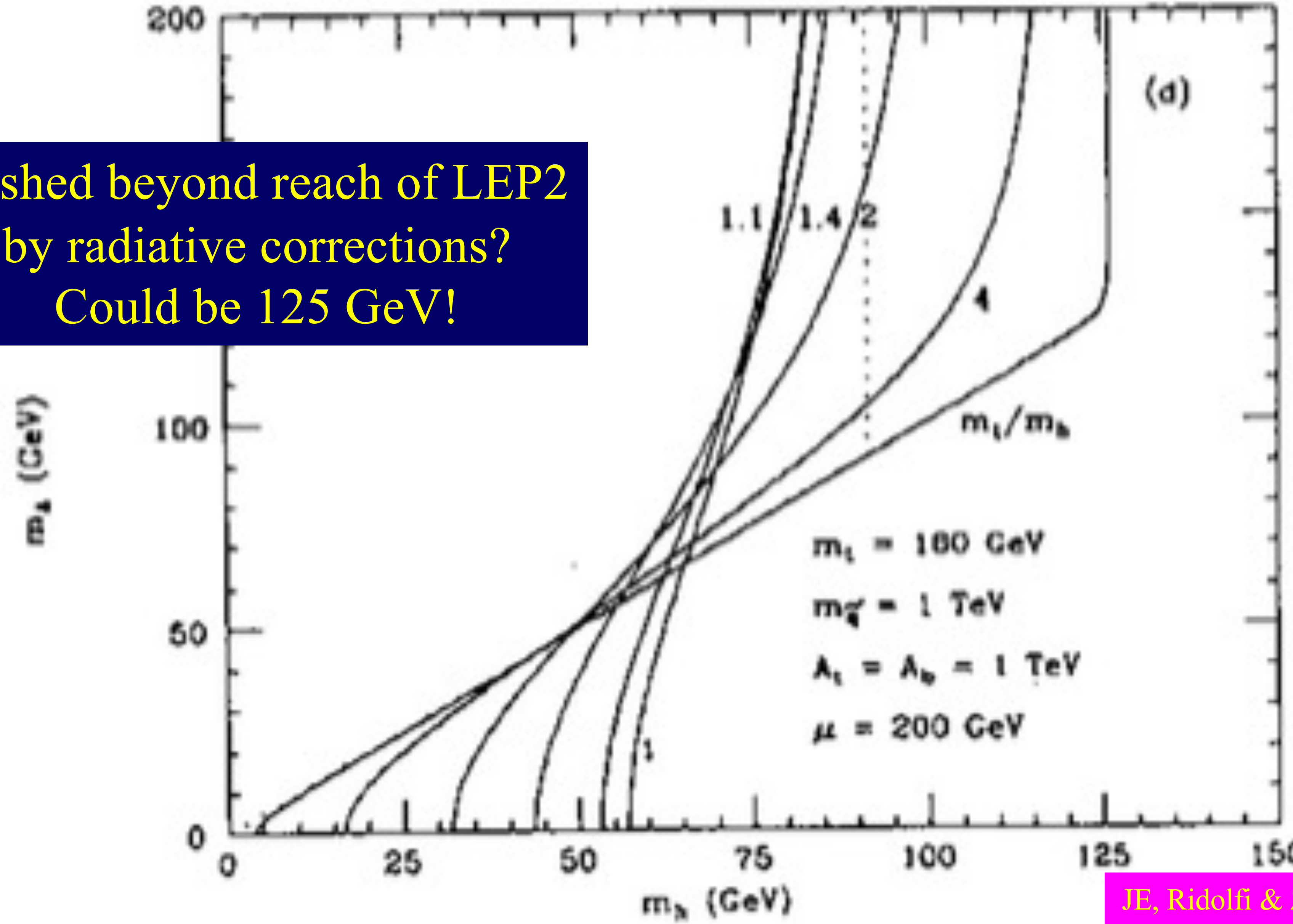
- Important radiative corrections to mass:

$$G_\mu m_{\mathrm{t}}^4 \ln\left(\frac{m_{\tilde{\mathrm{t}}_1} m_{\tilde{\mathrm{t}}_2}}{m_{\mathrm{t}}^2}\right) \quad \Delta M_H\big|_{TH} \sim 1.5\ \mathrm{GeV}$$

JE, Ridolfi & Zwirner,
Haber & Hempfling
Okada, Yamaguchi & Yanagida

1990/1

Higgs Mass in Supersymmetry



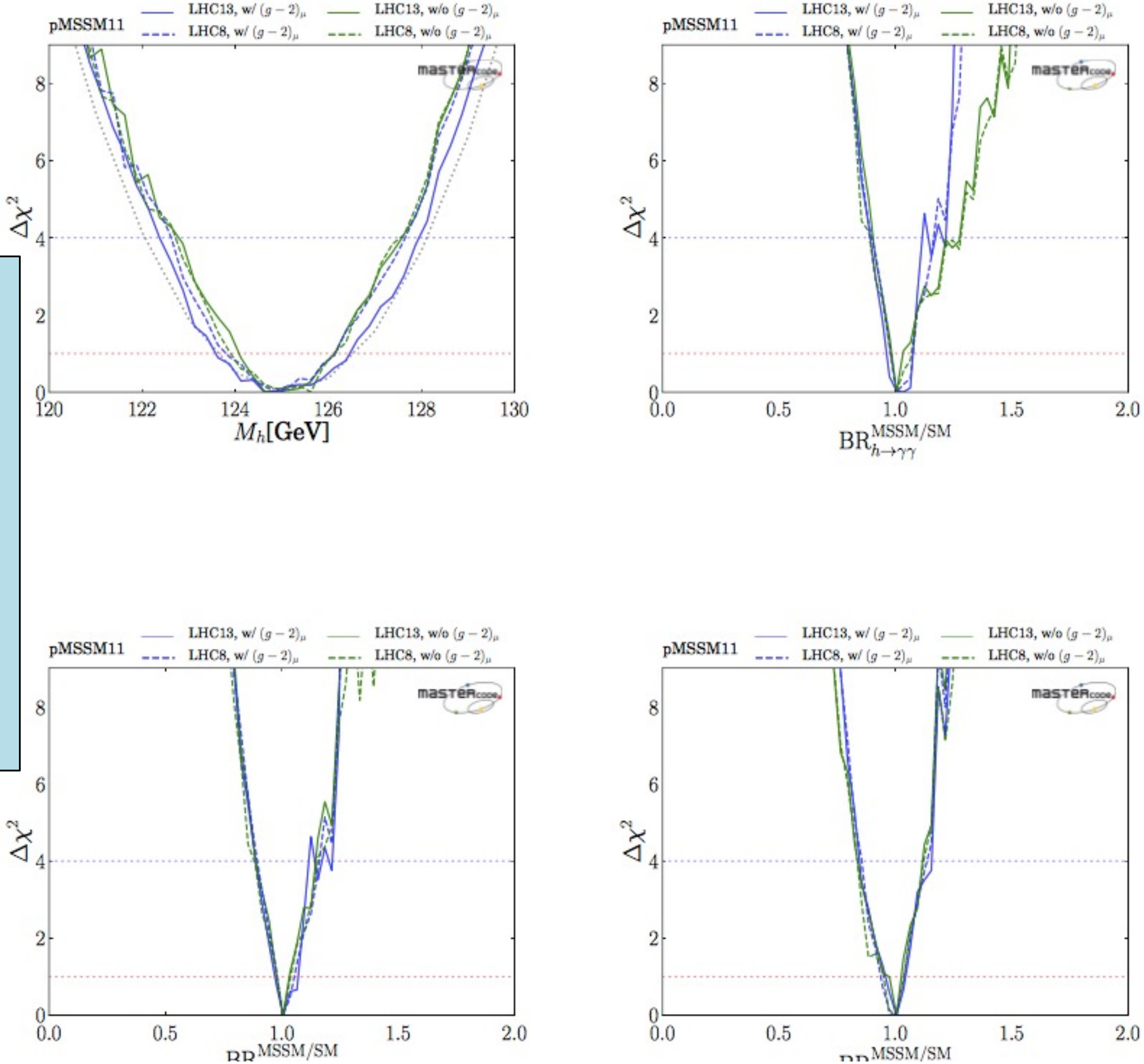
Pushed beyond reach of LEP2
by radiative corrections?
Could be 125 GeV!

JE, Ridolfi & Zwirner;
Haber & Hempfling

Higgs properties in the pMSSM

Fit with g_μ-2

Fit without g_μ-2



- No issue with measured Higgs mass
- Central values of decay BRs similar to SM
- Substantial deviations possible
- Opportunity for LHC!

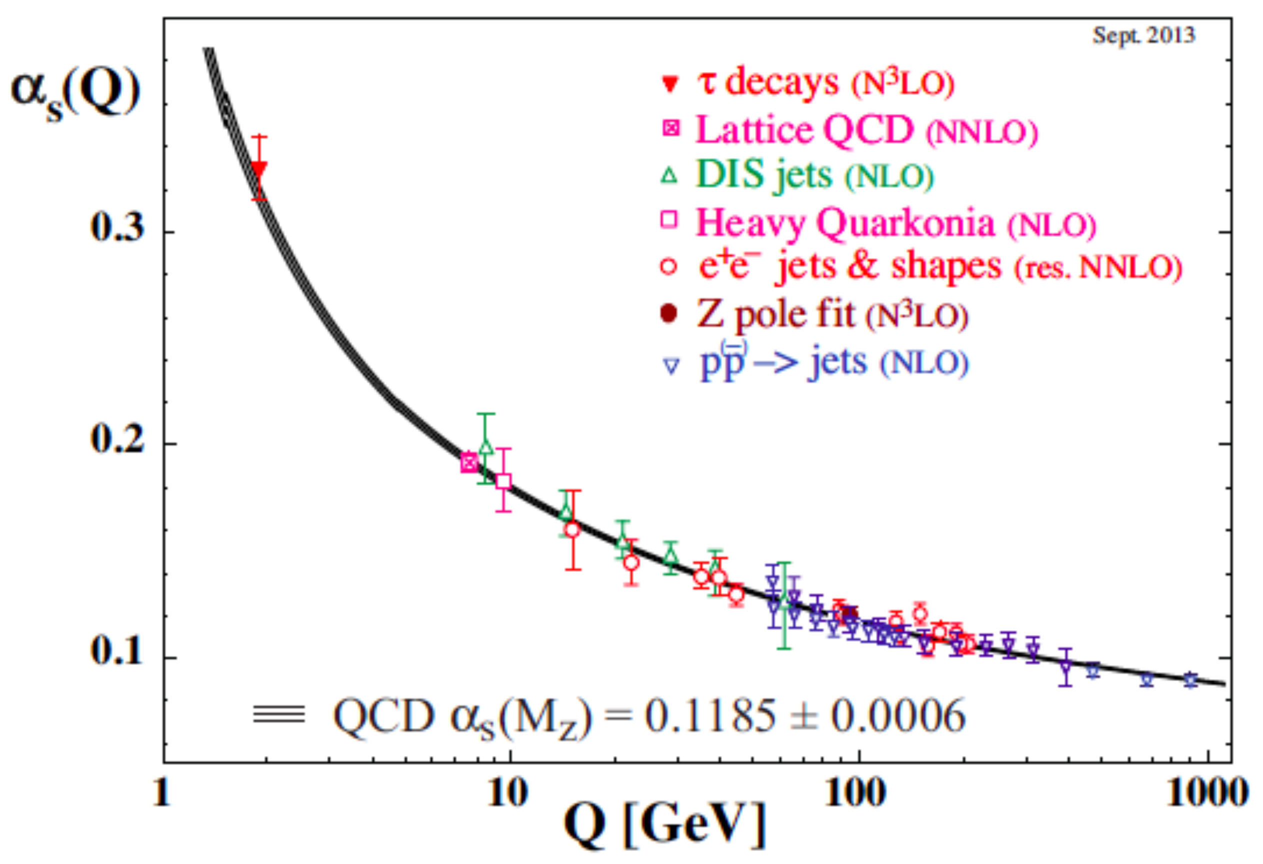
Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

Towards Grand Unification

- The three Standard Model gauge couplings are different: $g_3 >> g_2$, g
- Ratio $\sin^2\theta_W \equiv \frac{g'^2}{g'^2+g_2^2}$ is free parameter in Standard Model
- All couplings vary energy scale, calculable using renormalisation group
- Best known is decrease of $\alpha_s \equiv \frac{g_3^2}{4\pi}$," asymptotic freedom"
- Offers prospect of unifying couplings at high energy, as in simple group structure, and predicting $\sin^2\theta_W$

Strong Coupling “Constant”

- … is not constant: weaker at higher energies



- **Asymptotic freedom**

Grand Unification

- At one-loop order without/**with** supersymmetry:

$$b_i = \begin{pmatrix} 0 \\ -\frac{22}{3} \\ -11 \end{pmatrix} + N_g \begin{pmatrix} \frac{4}{3} \\ \frac{4}{3} \\ \frac{4}{3} \end{pmatrix} + N_H \begin{pmatrix} \frac{1}{10} \\ \frac{1}{6} \\ 0 \end{pmatrix}$$

$$\boxed{b_i = \begin{pmatrix} 0 \\ -6 \\ -9 \end{pmatrix} + N_g \begin{pmatrix} 2 \\ 2 \\ 2 \end{pmatrix} + N_H \begin{pmatrix} \frac{3}{10} \\ frac12 \\ 0 \end{pmatrix}}$$

$$b_{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & -\frac{136}{3} & 0 \\ 0 & 0 & -102 \end{pmatrix} + N_g \begin{pmatrix} \frac{19}{15} & \frac{3}{5} & \frac{44}{15} \\ \frac{1}{5} & \frac{49}{3} & 4 \\ \frac{4}{30} & \frac{3}{2} & \frac{76}{3} \end{pmatrix} + N_H \begin{pmatrix} \frac{9}{50} & \frac{9}{10} & 0 \\ \frac{3}{10} & \frac{13}{6} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\boxed{b_{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & -24 & 0 \\ 0 & 0 & -54 \end{pmatrix} + N_g \begin{pmatrix} \frac{38}{15} & \frac{6}{5} & \frac{88}{15} \\ \frac{2}{5} & 14 & 8 \\ \frac{11}{5} & 3 & \frac{68}{3} \end{pmatrix} + N_H \begin{pmatrix} \frac{9}{50} & \frac{9}{10} & 0 \\ \frac{3}{10} & \frac{7}{2} & 0 \\ 0 & 0 & 0 \end{pmatrix}}$$

Grand Unification of Couplings

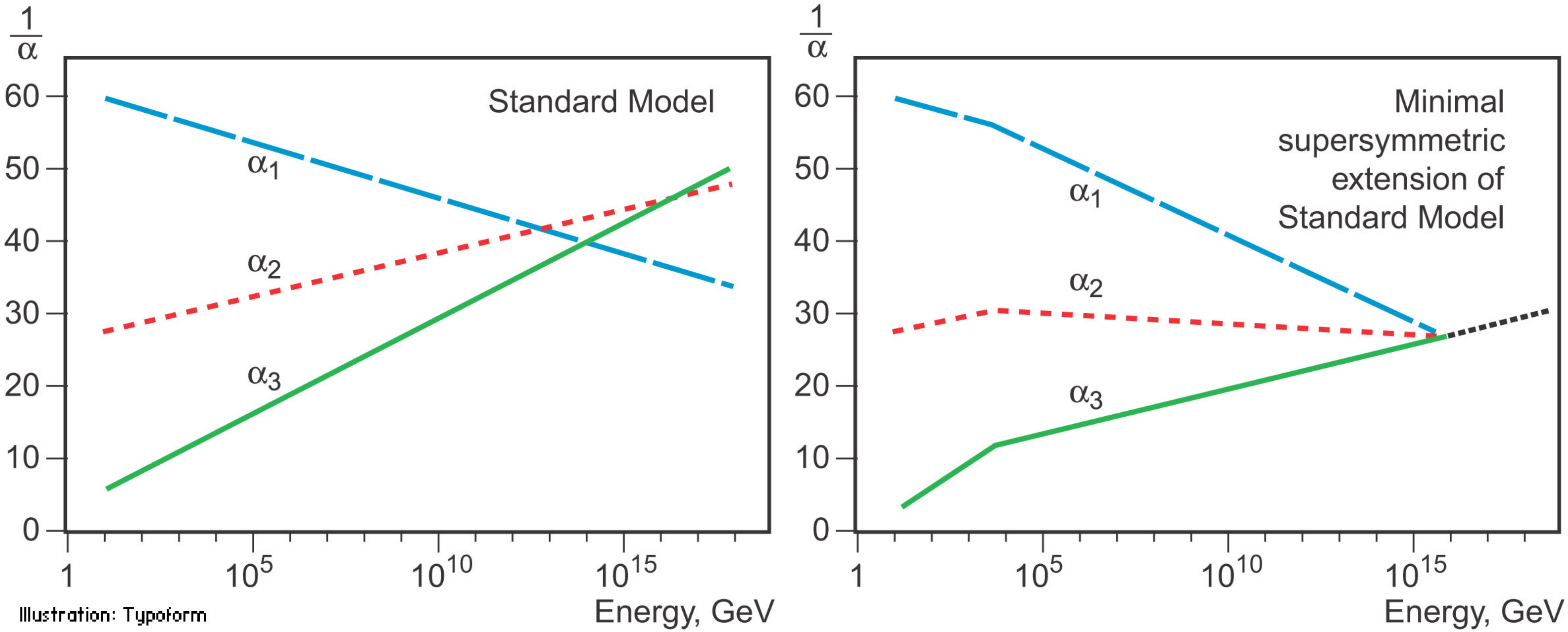


Illustration: Typoform

Almost works with just Standard Model particles

Better with supersymmetric particles

Simplest Grand Unified Theory

- Electromagnetic charge embedded in simple group: charge quantized

$$\sum_{q,\ell} Q_i = 3Q_u + 3Q_d + Q_e = 0$$

- Minimal model: SU(5)
- Fermions of a single generation accommodated

$$\bar{5} : (\psi_i)_L = \begin{pmatrix} \bar{d}_1 \\ \bar{d}_2 \\ \bar{d}_3 \\ e^- \\ -\nu_e \end{pmatrix}_L \quad 10 : (\chi^{ij})_L = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & \bar{u}_3 & -\bar{u}_2 & u_1 & d_1 \\ -\bar{u}_3 & 0 & \bar{u}_1 & u_2 & d_2 \\ u_2 & -\bar{u}_1 & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^+ \\ -d_1 & -d_2 & -d_3 & -e^+ & 0 \end{pmatrix}_L$$

- “Explain” “random” quantum numbers
- **Renormalization prediction $\sin^2\theta_W \simeq 0.23$**

1991

Electroweak Mixing Angle

- Related to ratio of SU(2), U(1) couplings:

$$\sin^2\theta(m_Z) = \frac{g'^2}{g_2^2 + g'^2} = \frac{3}{5}\,\frac{g_1^2(m_Z)}{g_2^2(m_Z) + \frac{3}{5}g_1^2(m_Z)}$$

- At one loop:

$$\sin^2\theta(m_Z) = \frac{1}{1+8x}\left[3x + \frac{\alpha_{em}(m_Z)}{\alpha_3(m_Z)}\right] = \frac{1}{5}\left(\frac{b_2 - b_3}{b_1 - b_2}\right)$$

- One-loop coefficients w’out/**with** supersymmetry:

$$\begin{array}{rcl|lcl}
\frac{4}{3}N_G - 11 & \leftarrow & b_3 & \rightarrow & 2N_G - 9 & = -3 \\
\frac{1}{6}N_H + \frac{4}{3}N_G - \frac{22}{3} & \leftarrow & b_2 & \rightarrow & \frac{1}{2}N_H + 2N_G - 6 & = +1 \\
\frac{1}{10}N_H + \frac{4}{3}N_G & \leftarrow & b_1 & \rightarrow & \frac{3}{10}N_H + 2N_G & = \frac{33}{5} \\
\frac{23}{218} = 0.1055 & \leftarrow & x & \rightarrow & \frac{1}{7}. &
\end{array}$$

- Data: $\boxed{x = \frac{1}{6.92 \pm 0.07}}$

JE, Kelley & Nanopoulos

1991

LEP Data Consistent with Supersymmetric Grand Unification

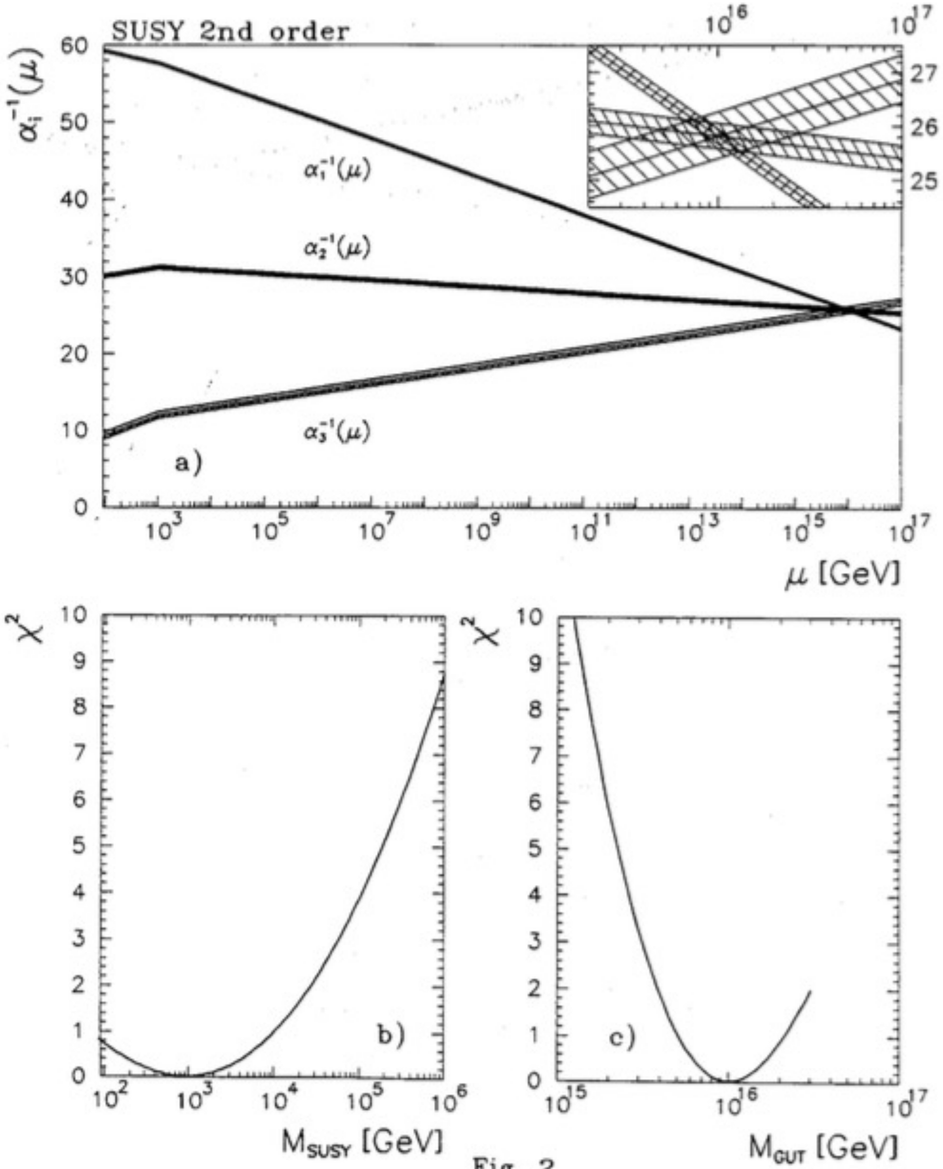
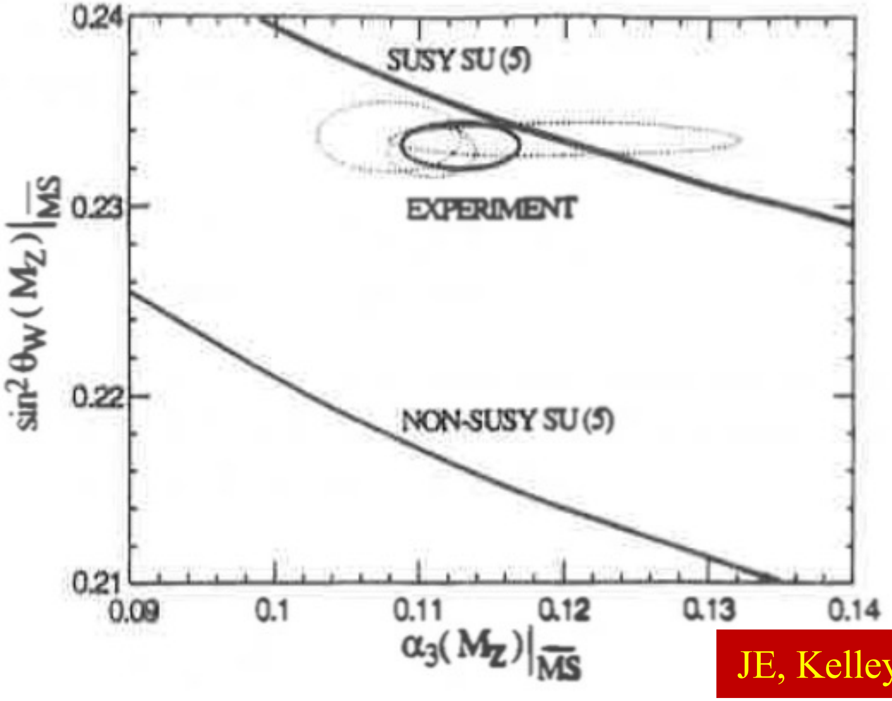


Fig. 2

Amaldi, de Boer & Furstenau



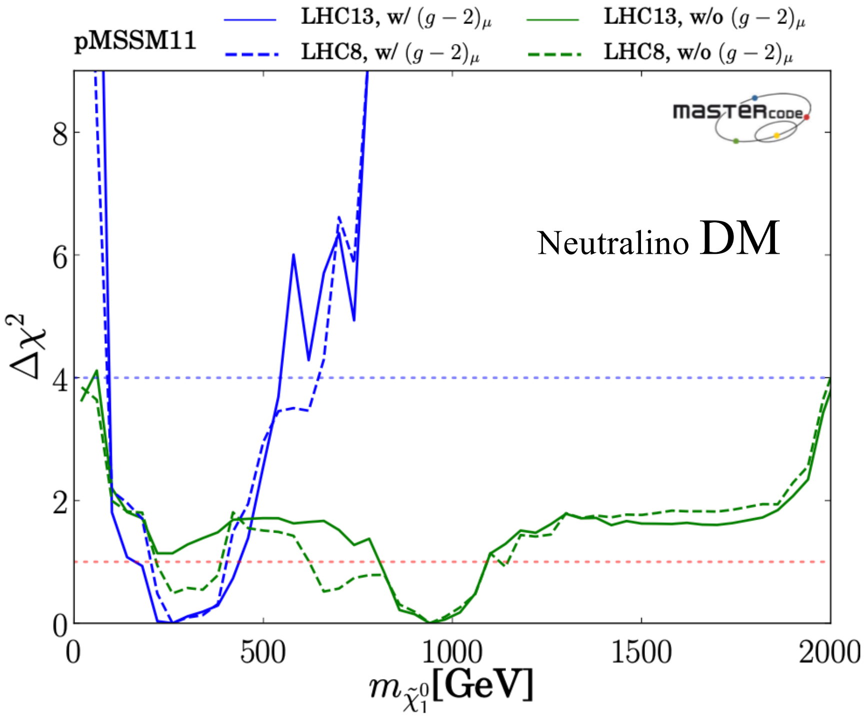
JE, Kelley & Nanopoulos

Supersymmetry Breaking

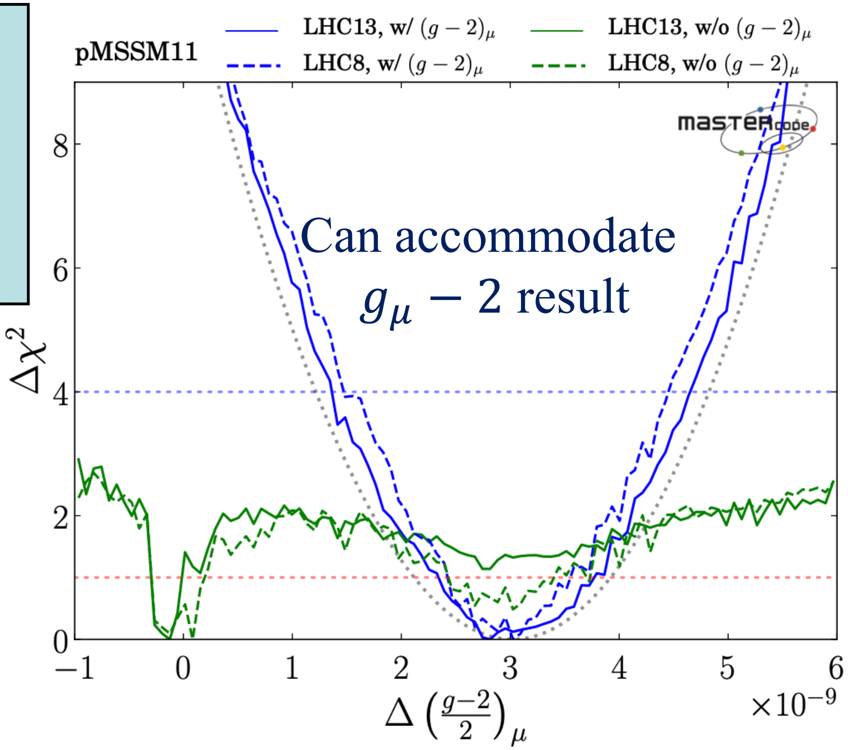
- Supersymmetry must be broken, many models, no clear guidance from theory
- Assume universality at GUT scale? (CMSSM)
  - Renormalisation effects increase $\tilde{q}$ masses relative to $\tilde{\ell}$, $\tilde{g}$ mass relative to $\tilde{W}^{\pm}$
  - Lighter stop squark may have $m_{\tilde{t}_1} < m_{\tilde{q}}$
  - Renormalization can drive $m_H^2 < 0$, enabling spontaneous gauge symmetry breaking
- Alternatively: treat particle masses as free parameters (pMSSM)

$g_\mu - 2$ in Phenomenological Supersymmetry (pMSSM11)

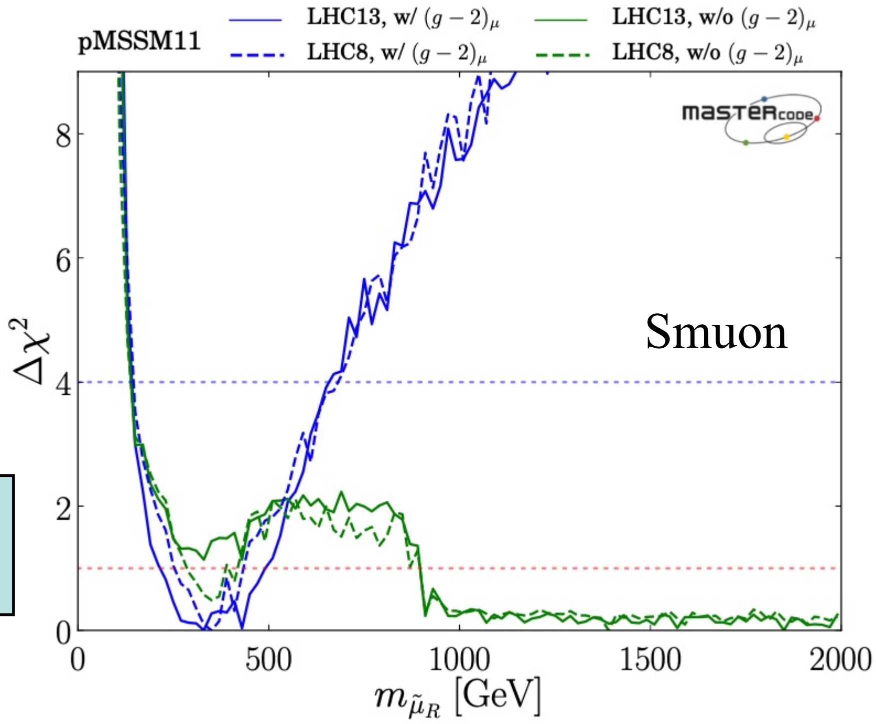
No relation between squark/gluino masses and slepton/neutralino masses



Neutralino DM



Can accommodate $g_\mu - 2$ result



Smuon

No problem accommodating BNL/FNAL result
Neutralino DM, smuon masses ~ 300/400 GeV

MasterCode, E. Bagnaschi, …, JE et al, arXiv:1710.11091

Mass Renormalizations

- **Assuming universality at the GUT scale**
- Gaugino masses:
  - $M_a = (\alpha_a / \alpha_{GUT})\, m_{1/2}$, e.g., $\rightarrow M_2 / M_3 = \alpha_2 / \alpha_3$
- Squark and slepton masses:
  - Squark mass^2: $m_0^2 + 6\, m_{1/2}^2$
  - Left-handed slepton mass^2: $m_0^2 + 0.5\, m_{1/2}^2$
  - Right-handed slepton mass^2: $m_0^2 + 0.15\, m_{1/2}^2$
- Minimal flavour violation (MFV):
  - Flavour mixing of squarks and sleptons induced by CKM, neutrino mixing

Renormalization of Susy Breaking Parameters

- After cancellation of quadratic divergences: renormalized logarithmically:

  gaugino masses: d M_a/dt ~ β_a M_a

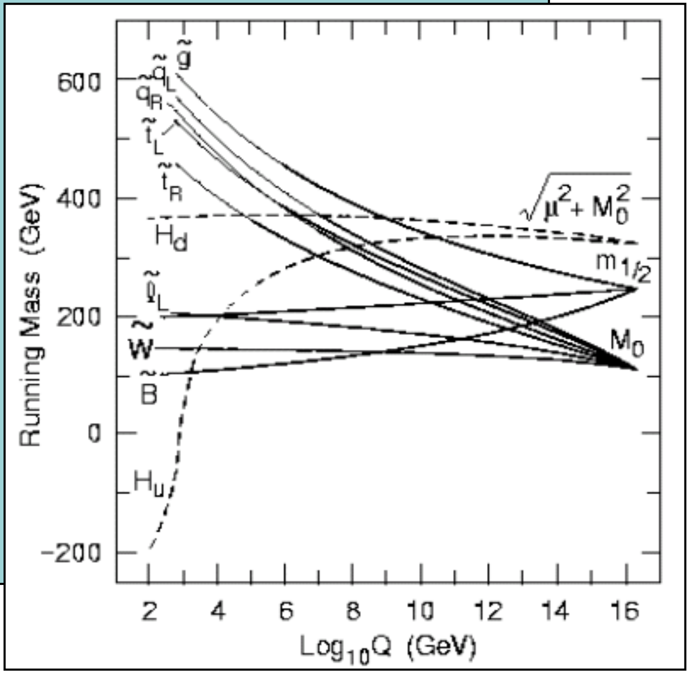
  scalar masses^2: $$\frac{\partial m_{0_i}^2}{\partial t} = \frac{1}{16\pi^2}[\lambda^2(m_0^2 + A_\lambda^2) - g_a^2 M_a^2]$$

- Assuming universal input parameters (CMSSM)
- Solutions at low energy scales Q:

$$M_a\,(Q) = (\alpha_a/\ \alpha_{GUT})\ m_{1/2}$$

$$m_{0_i}^2 = m_0^2 + C_i m_{1/2}^2$$

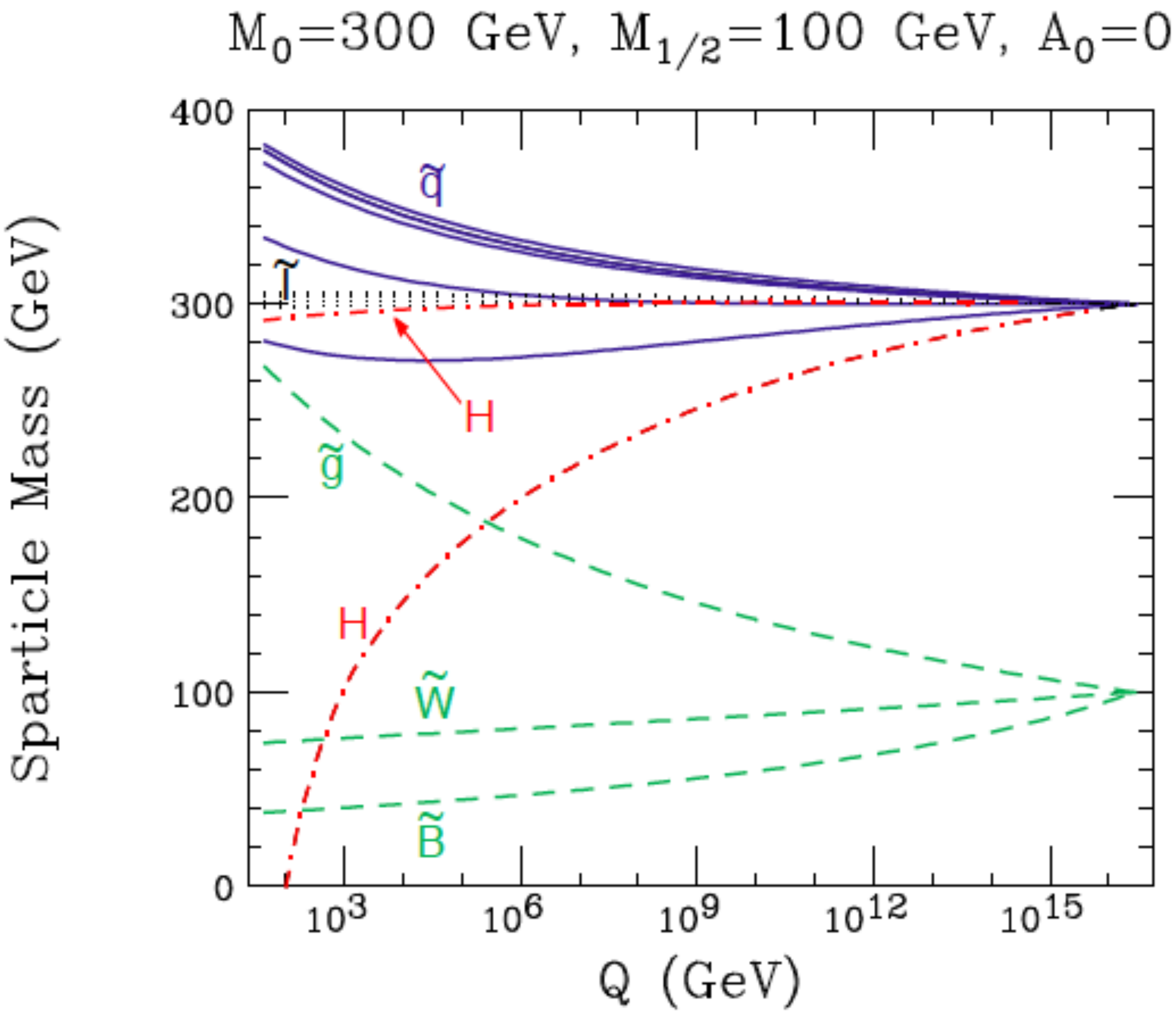
- Gluino heavier than photino, wino
- Squarks heavier than sleptons



Electroweak Symmetry Breaking

Could be driven by radiative corrections due to top quark

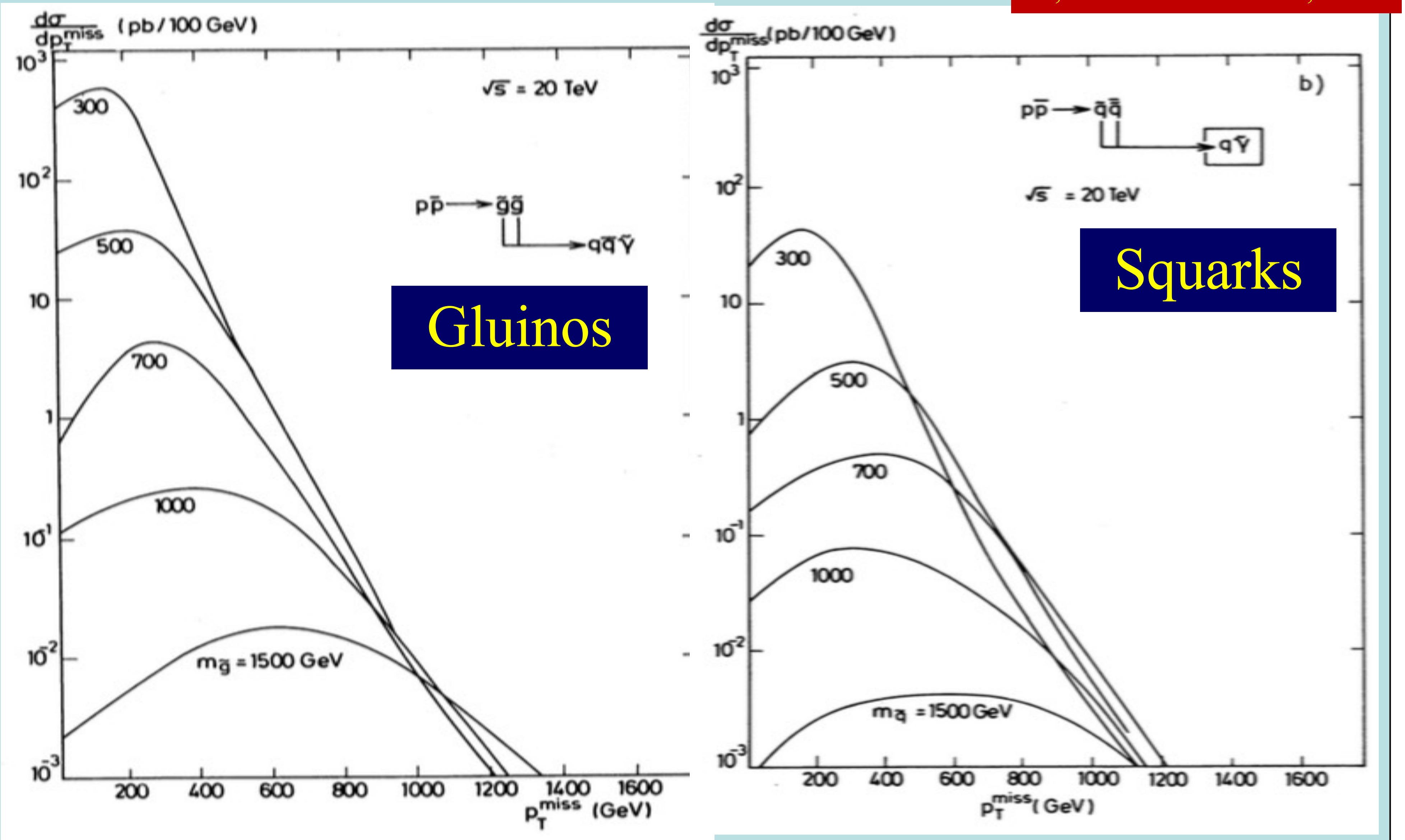
A bonus: supersymmetry may explain why $\mu^2 < 0$



1984

A Preview of Supersymmetry @ LHC

JE, Gelmini & Kowalski, 1984



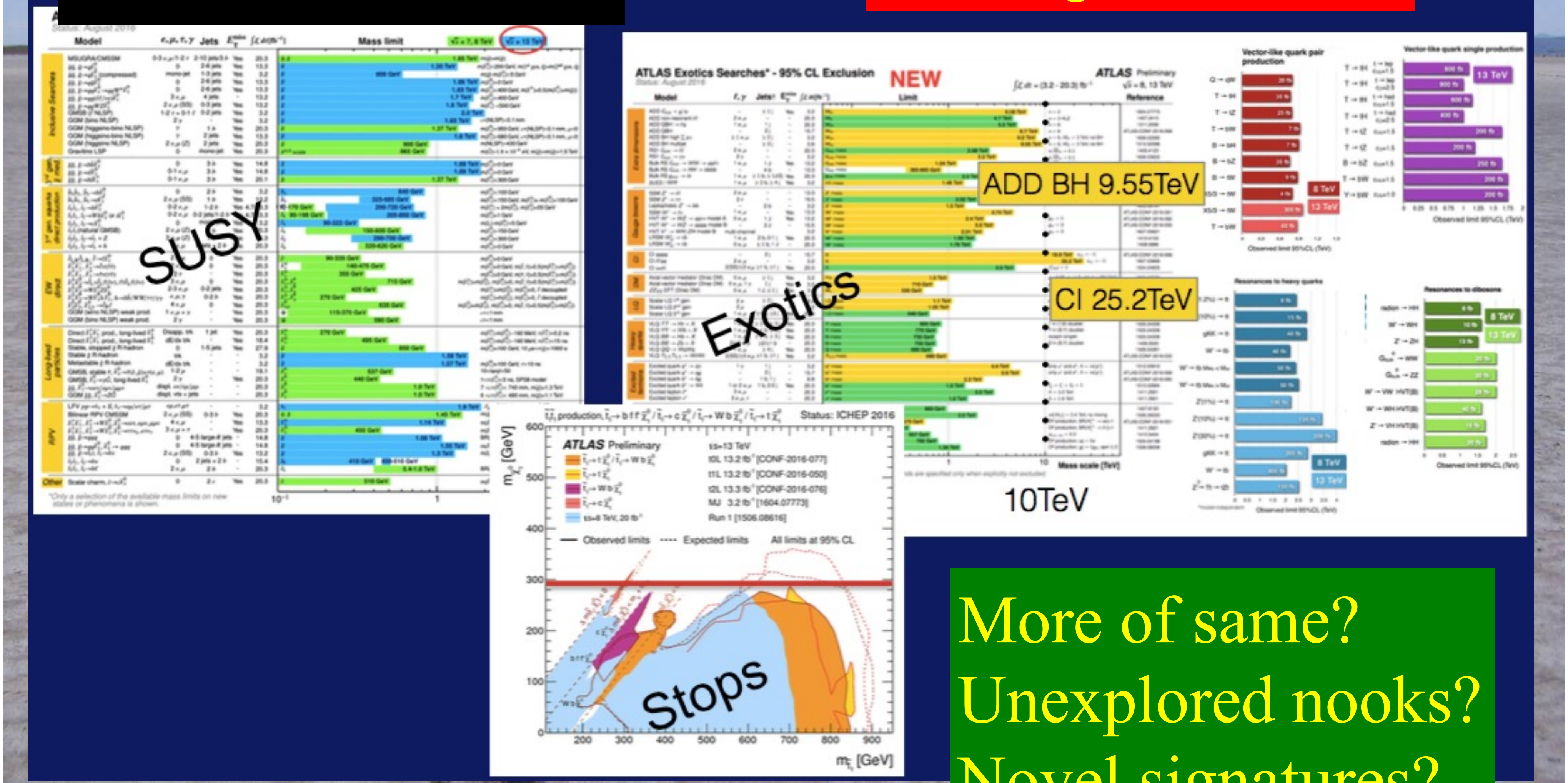
Gluinos

Squarks

Nothing (yet) at the LHC

No supersymmetry

Nothing else, either



More of same?
Unexplored nooks?
Novel signatures?

Lightest Supersymmetric Particle

- Stable in many models because of conservation of R parity:

  $R = (-1)^{2S - L + 3B}$

  where S = spin, L = lepton #, B = baryon #

- Particles have R = +1, sparticles R = -1:

  Sparticles produced in pairs

  Heavier sparticles → lighter sparticles

- **Lightest supersymmetric particle (LSP) stable**

Lightest Sparticle as Dark Matter?

- No strong or electromagnetic interactions
  - **Otherwise would bind to matter**
  - **Detectable as anomalous heavy nucleus**
- Possible weakly-interacting scandidates
  - **Sneutrino**
    - (Excluded by LEP, direct searches)
  - **Lightest neutralino χ** (partner of Z, H, γ)
  - **Gravitino**
    - (nightmare for detection)

The Dark Matter Hypothesis

- Proposed by Fritz Zwicky, based on observations of the Coma galaxy cluster
- The galaxies move too quickly
- The observations require a stronger gravitational field than provided by the visible matter
- **Dark matter?**

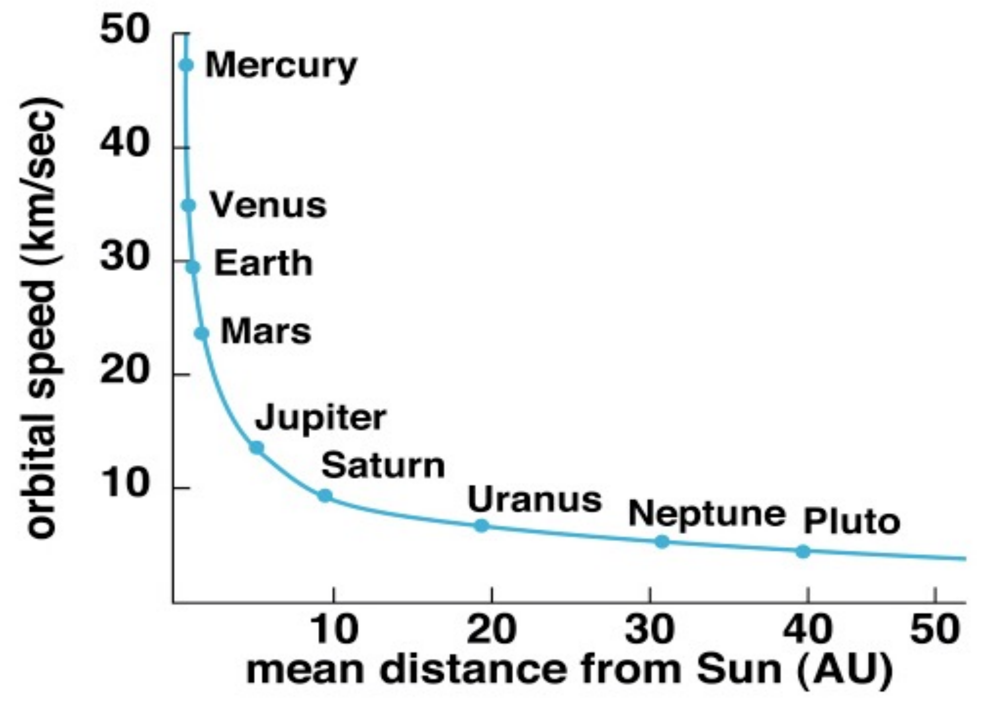
The Rotation Curves of Galaxies

Scanned at the American Institute of Physics

- Measured by Vera Rubin
- The stars also orbit 'too quickly'
- Her observations also required a stronger gravitational field than provided by the visible matter
- **Further strong evidence for dark matter**
- Also:
  - Structure formation, cosmic background radiation, …

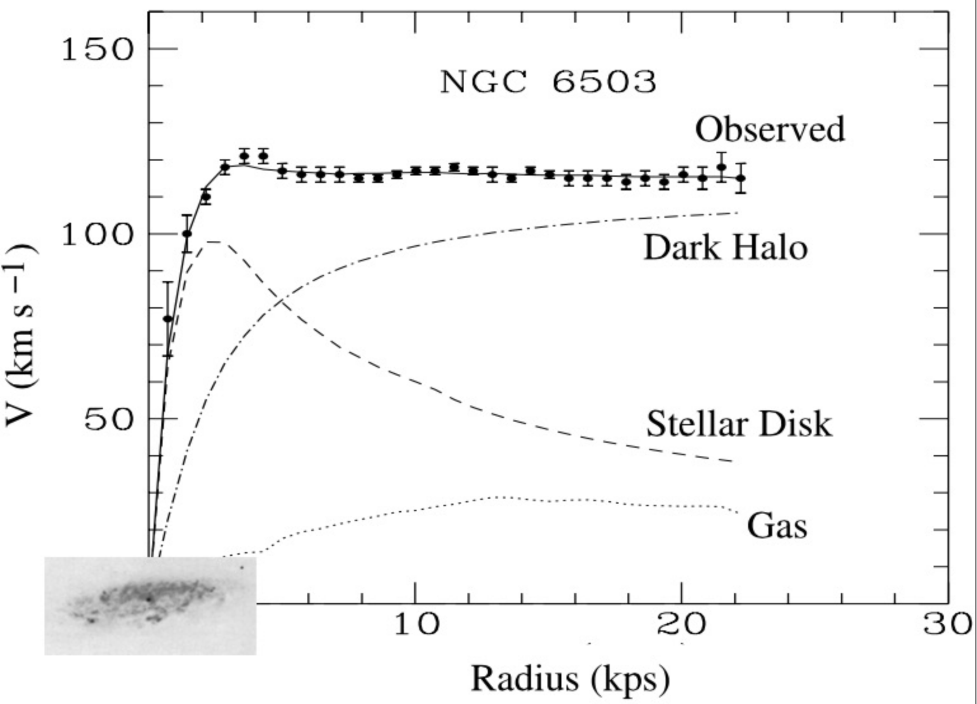
Galactic Rotation Curves

- In the Solar System



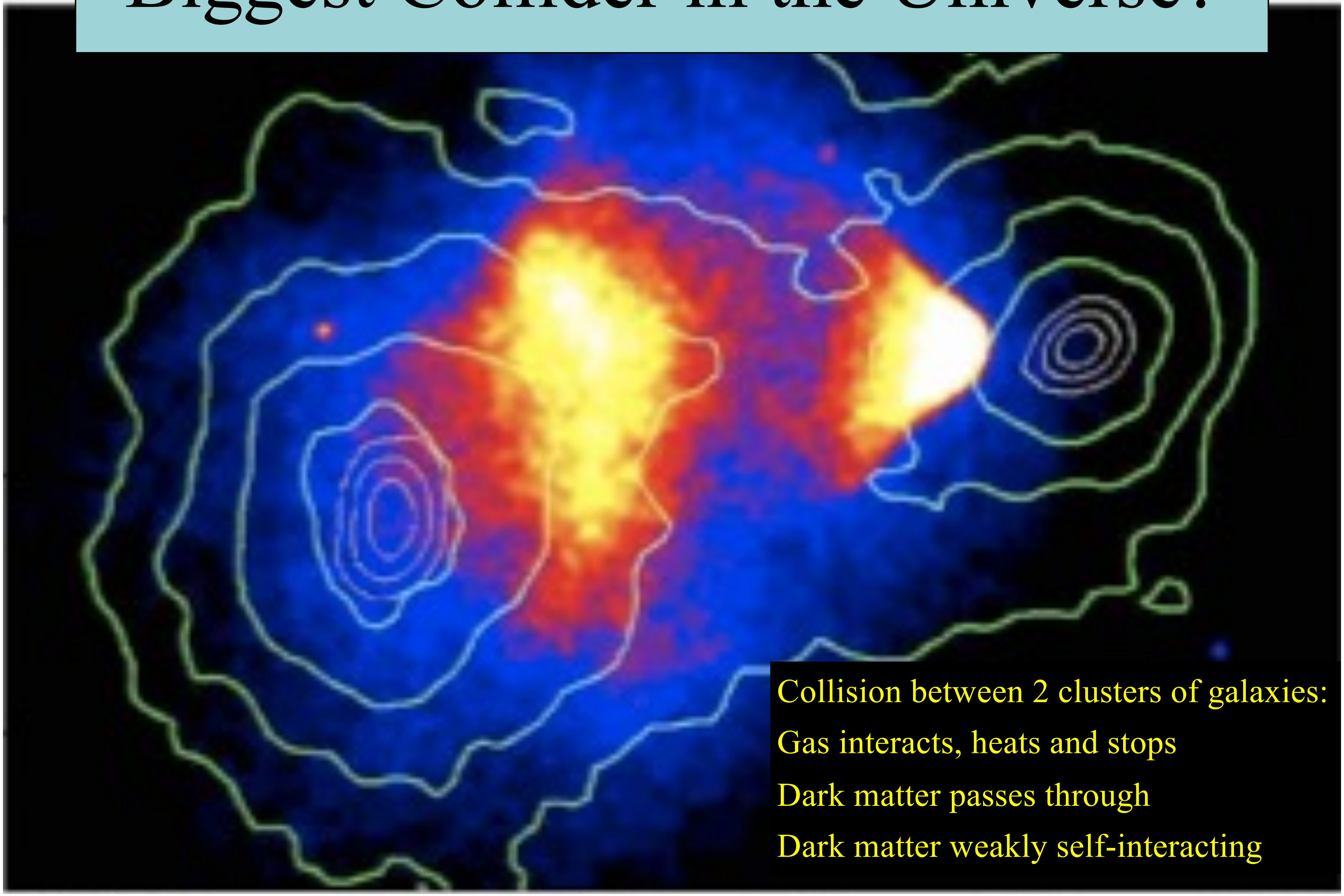
- The velocities decrease with distance from Sun
- Mass lumped at centre

- In galaxies



- The velocities do not decrease with distance
- Dark matter spread out

Biggest Collider in the Universe?



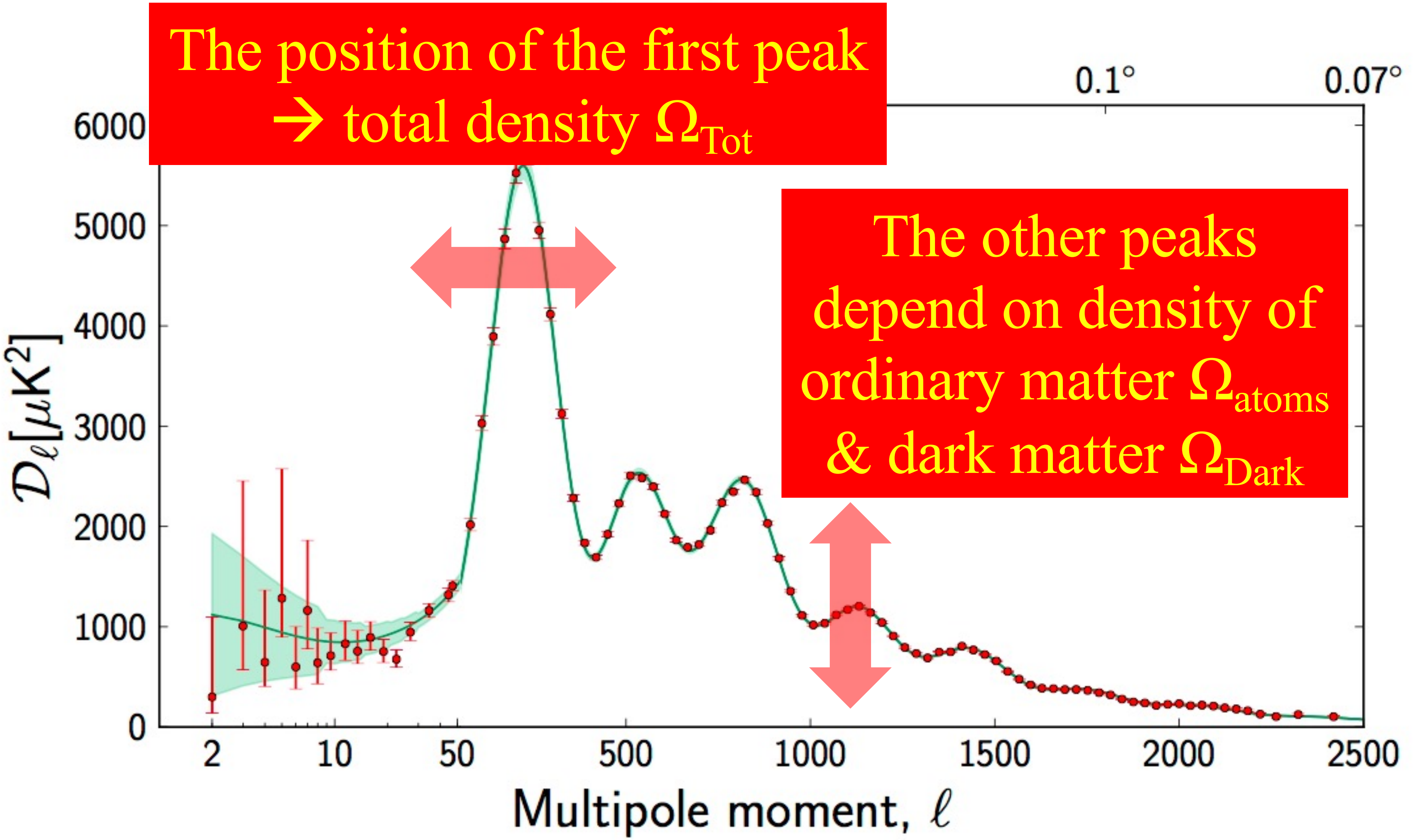
Collision between 2 clusters of galaxies:

Gas interacts, heats and stops

Dark matter passes through

Dark matter weakly self-interacting

The Spectrum of Fluctuations in the Cosmic Microwave Background

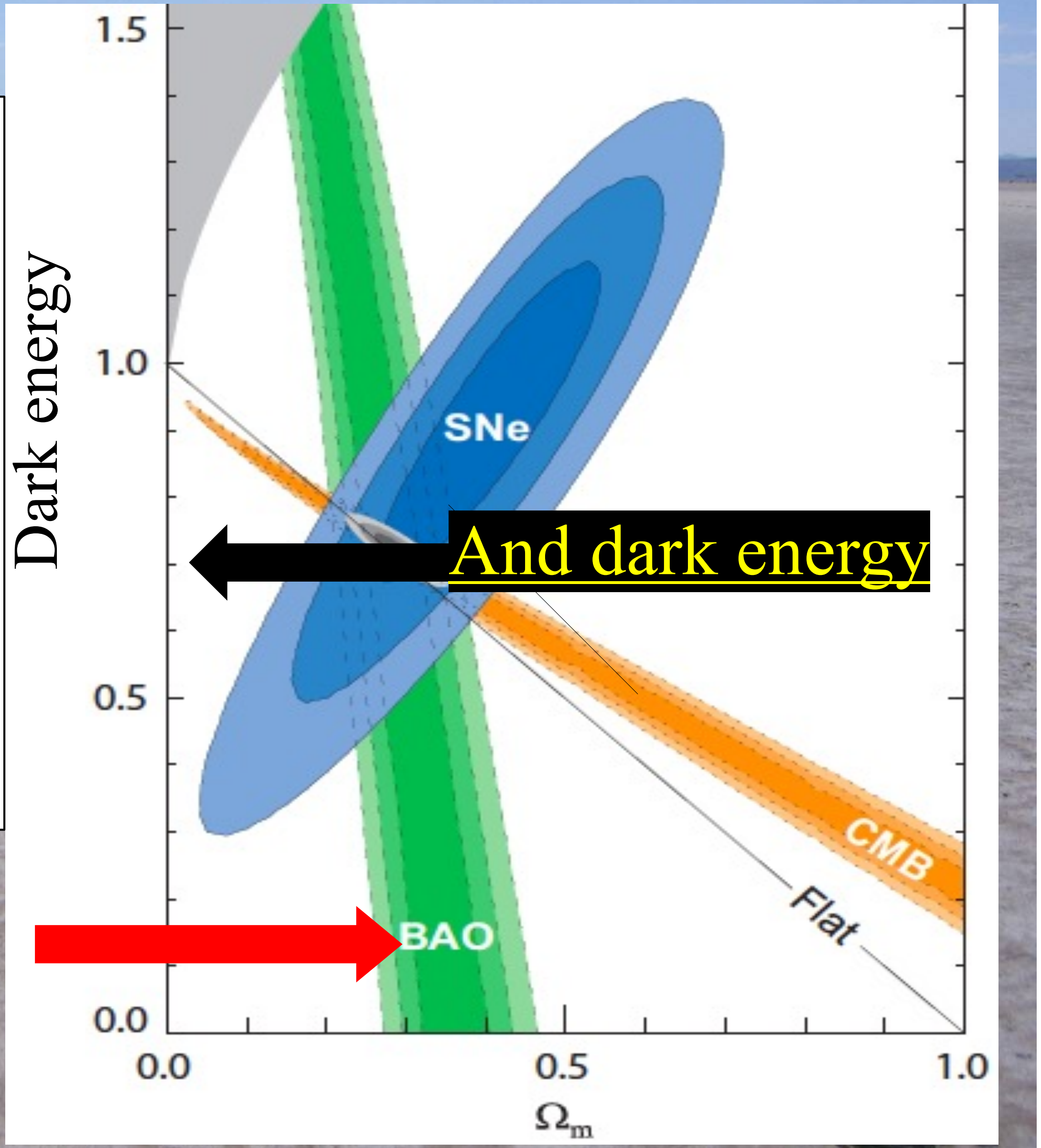


The position of the first peak
→ total density Ω_{Tot}

The other peaks
depend on density of
ordinary matter Ω_{atoms}
& dark matter Ω_{Dark}

The Content of the Universe

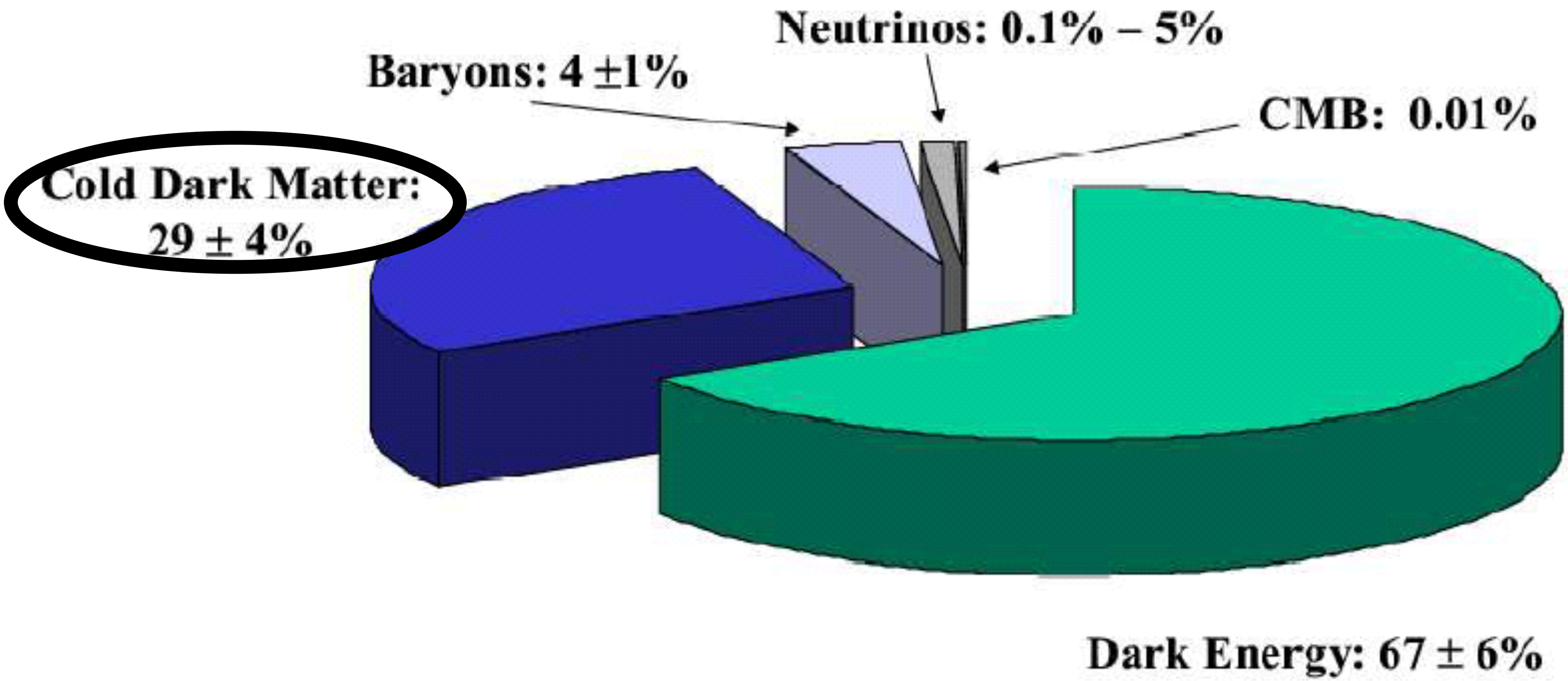
- According to
  - Microwave background
  - Supernovae
  - Structures (galaxies, clusters, …) in the Universe



And dark energy

There is dark matter

Strange Recipe for a Universe

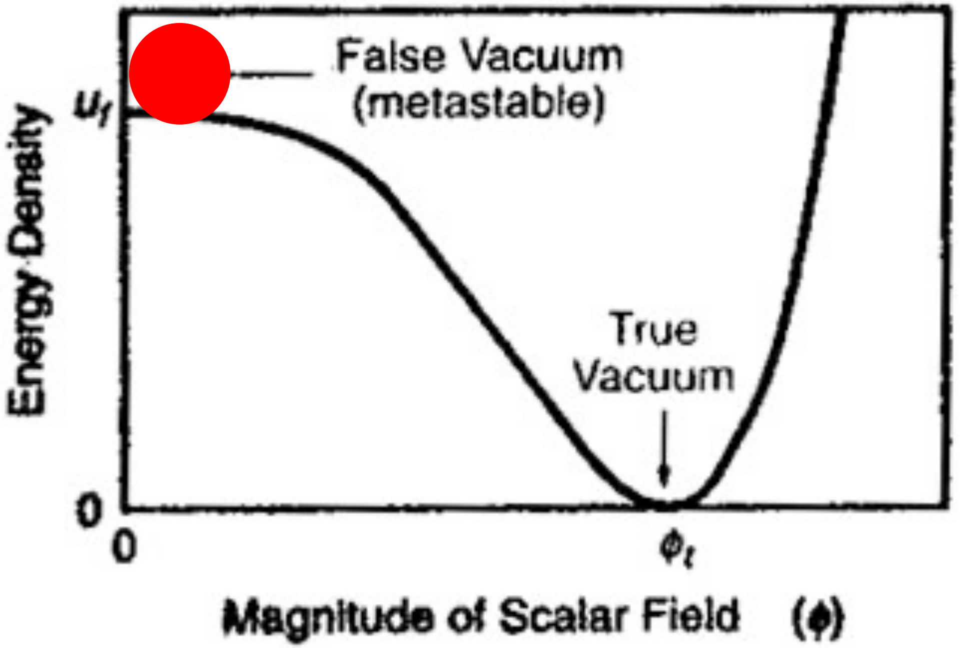


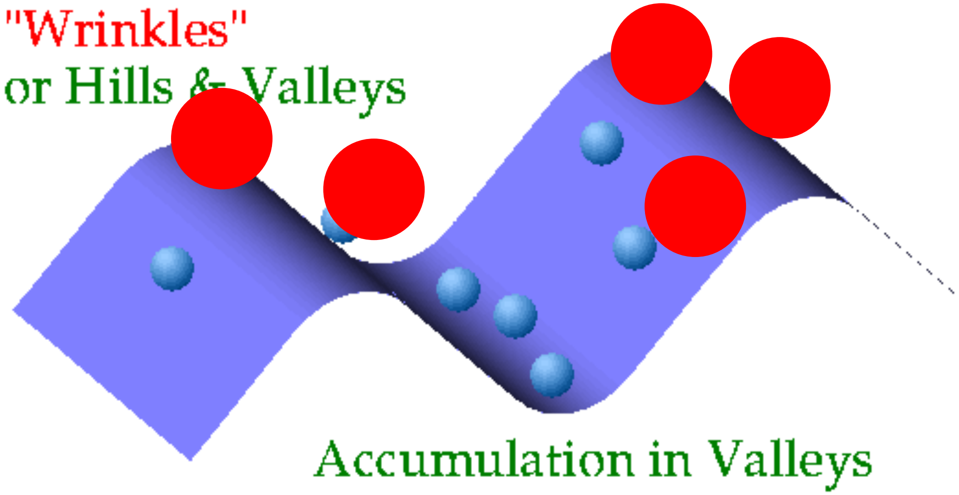
The 'Standard Model' of the Universe indicated by astrophysics and cosmology

The Origin of Structures in the Universe

Small primordial quantum fluctuations:
$\sim 1/10^5$

Gravitational instability:
dark matter falls into the gravitational potential wells, visible matter follows

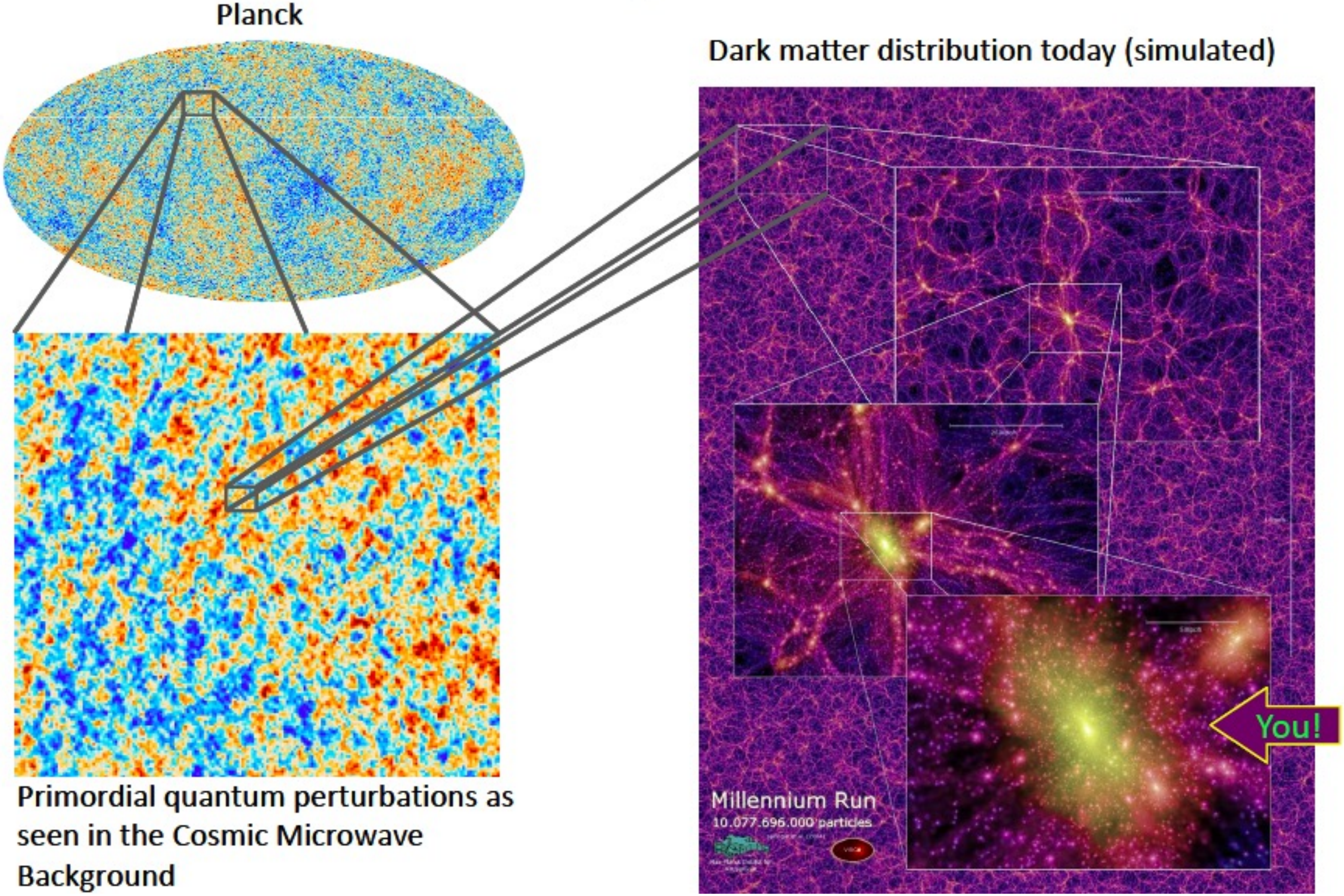




Become density fluctuations

Become structures in Universe

Dark Matter Generated Structures



Dark matter distribution today (simulated)

Primordial quantum perturbations as seen in the Cosmic Microwave Background

A Successful Theory of the Formation of Structures in the Universe

Dark matter:

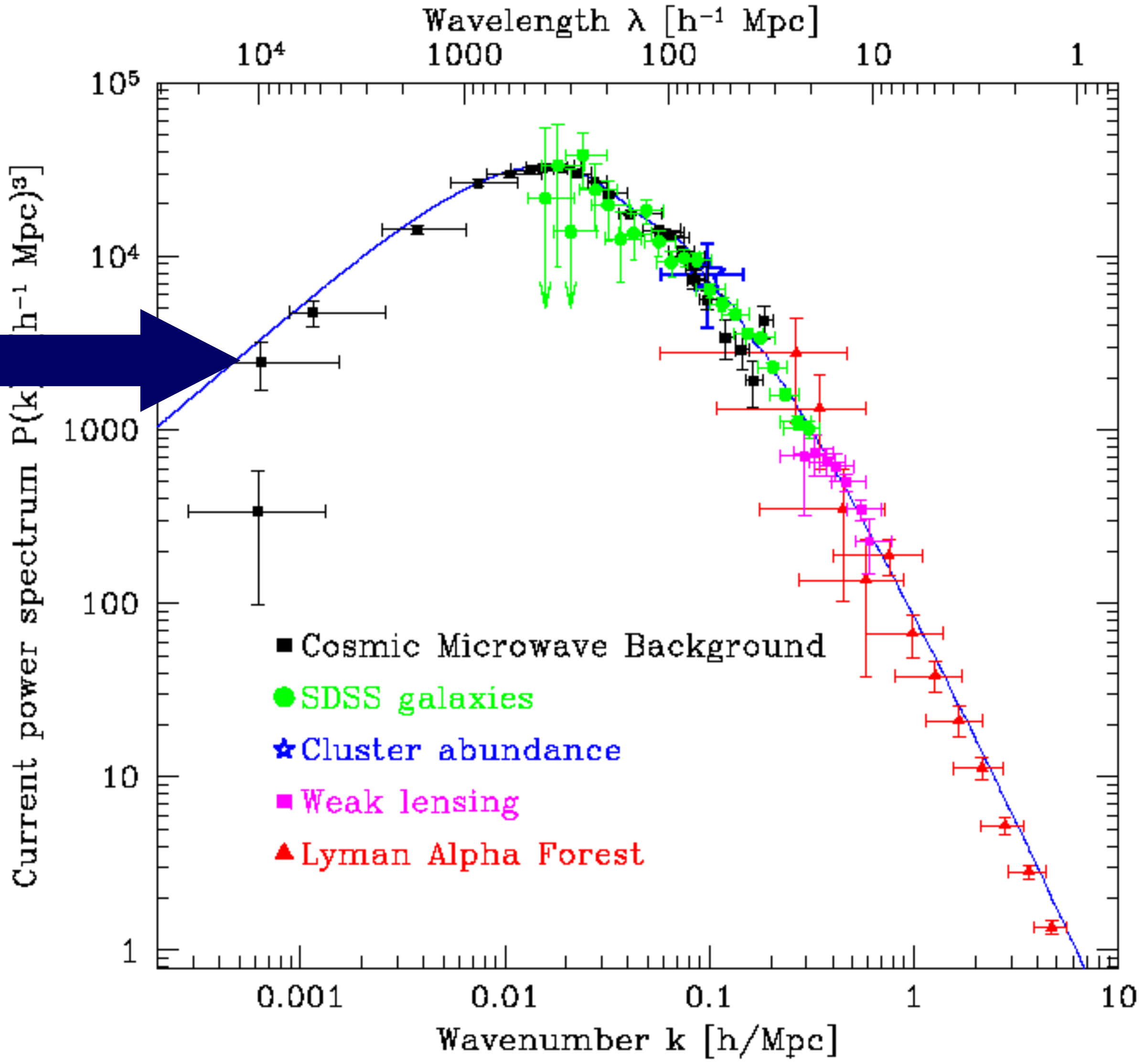
$\Omega_{CDM} \sim 0.25$,

Visible matter:

$\Omega_b \sim 0.05$,

Dark energy:

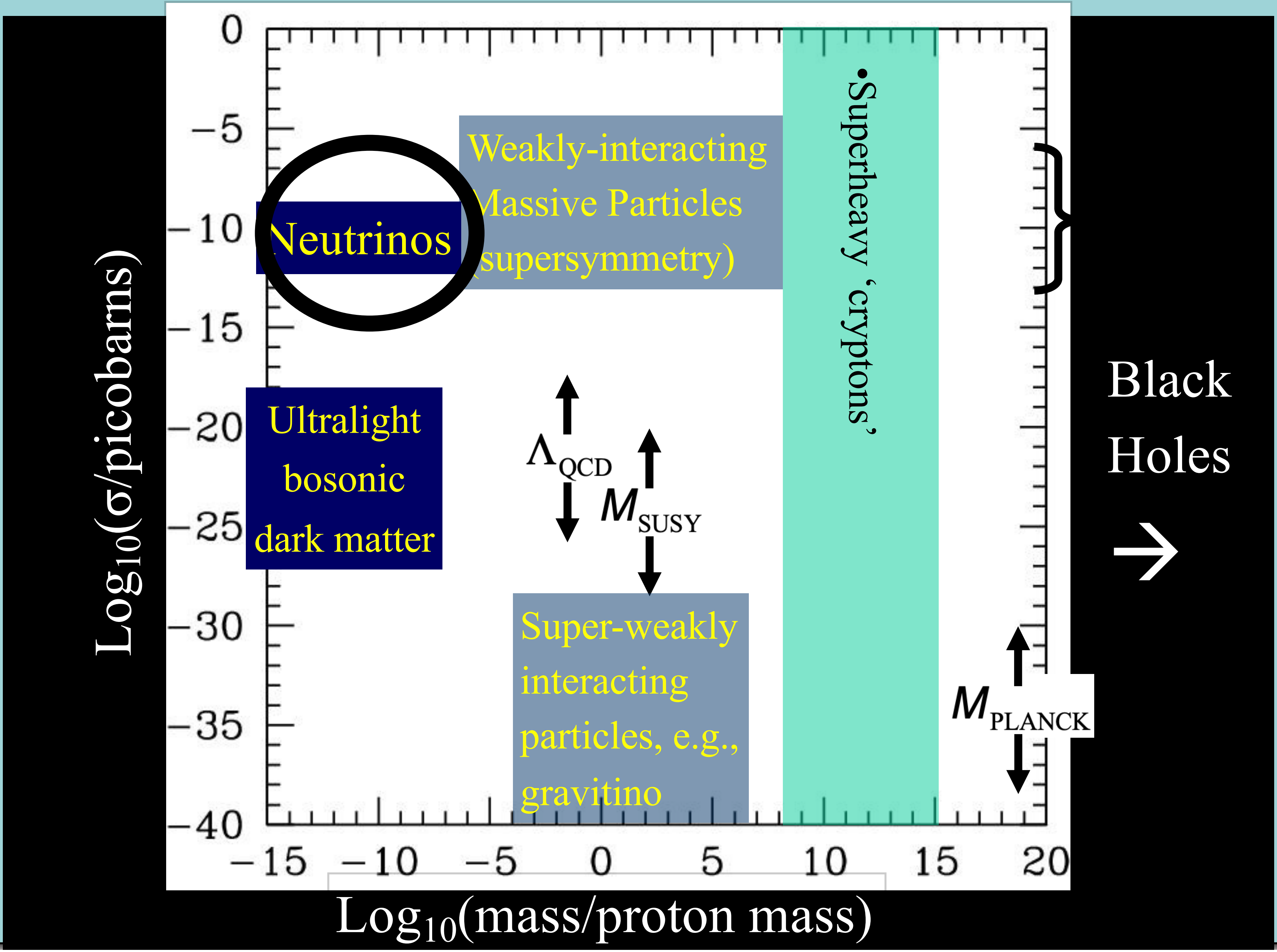
$\Omega_\Lambda \sim 0.7$



Properties of Dark Matter

- Should not have (much) electric charge
  - Otherwise we would have seen it
- Should interact weakly with ordinary matter
  - Otherwise we would have detected it, either directly or astrophysically
- Should not be too light
  - Needed for forming and holding together structures in the Universe: galaxies, clusters, …

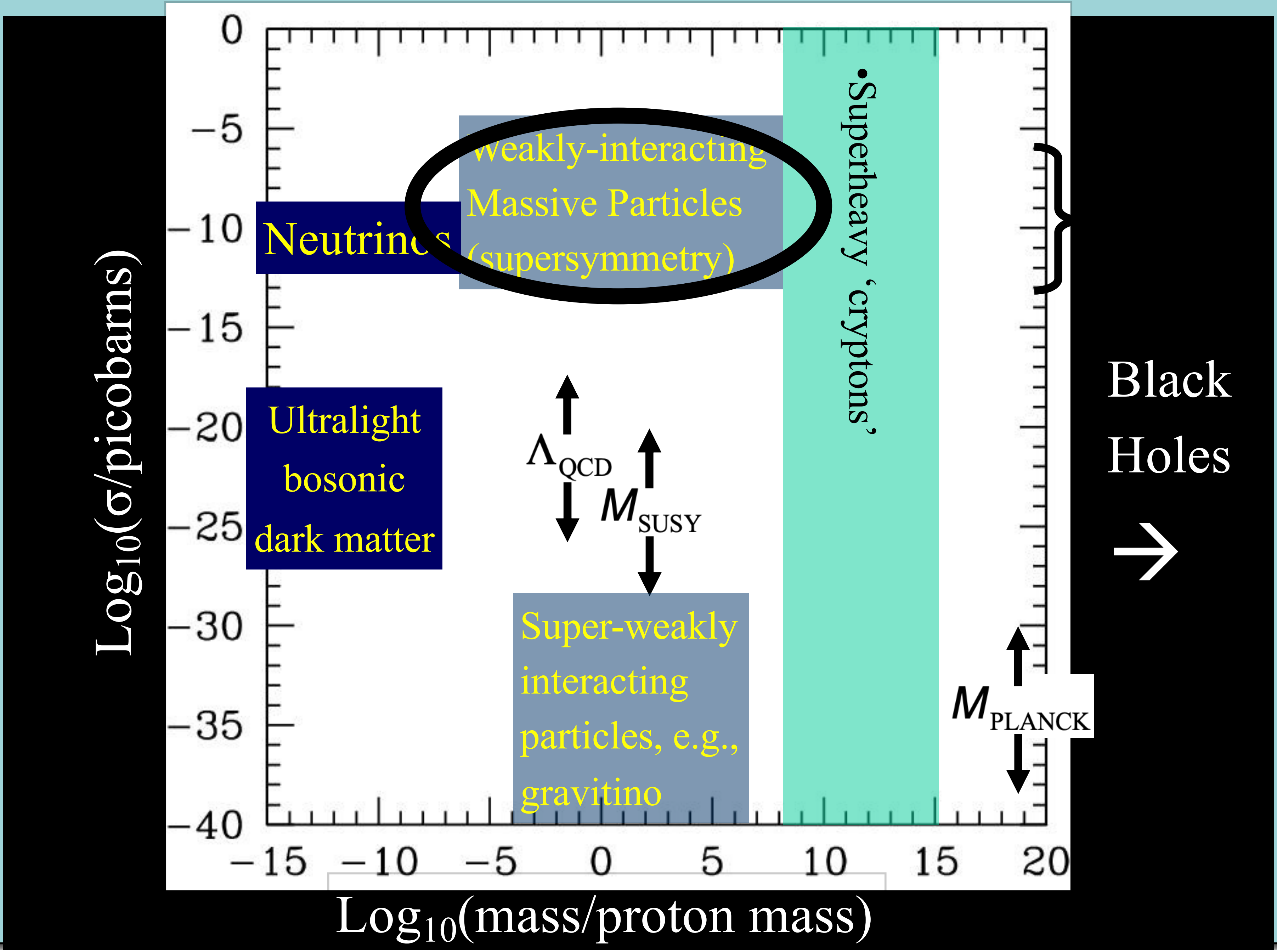
Particle Dark Matter Candidates



Neutrinos

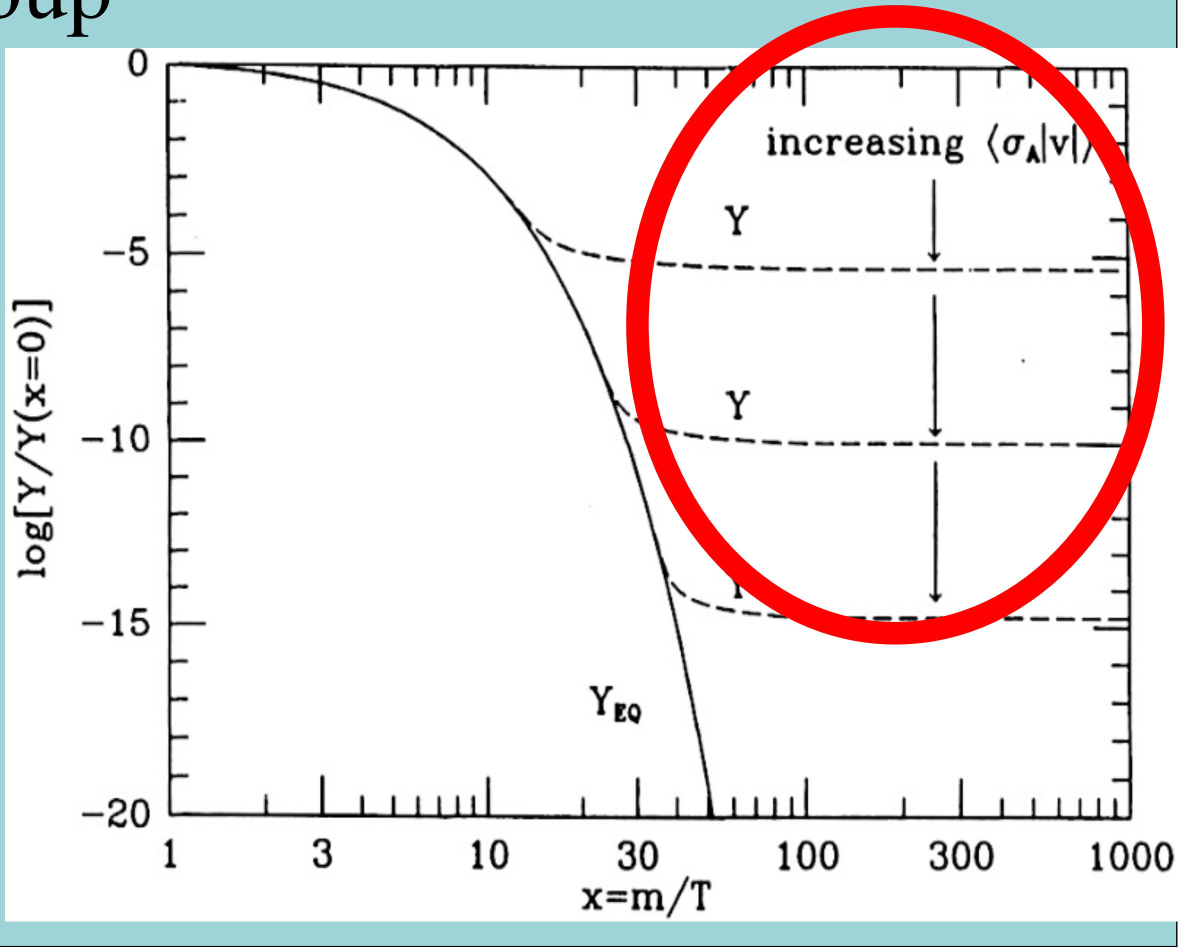
- They exist! ☺️
- They have weak interactions ☺️
- They have masses ☺️
  - As indicated by neutrino oscillations
- But their masses are very small ☹️
  - < 1 eV (= 1/1000,000,000 of proton mass)
- Not able to grow all structures in Universe ☹️
  - (run away from small structures)
- Maybe some other neutrinos beyond the Standard Model?

Particle Dark Matter Candidates

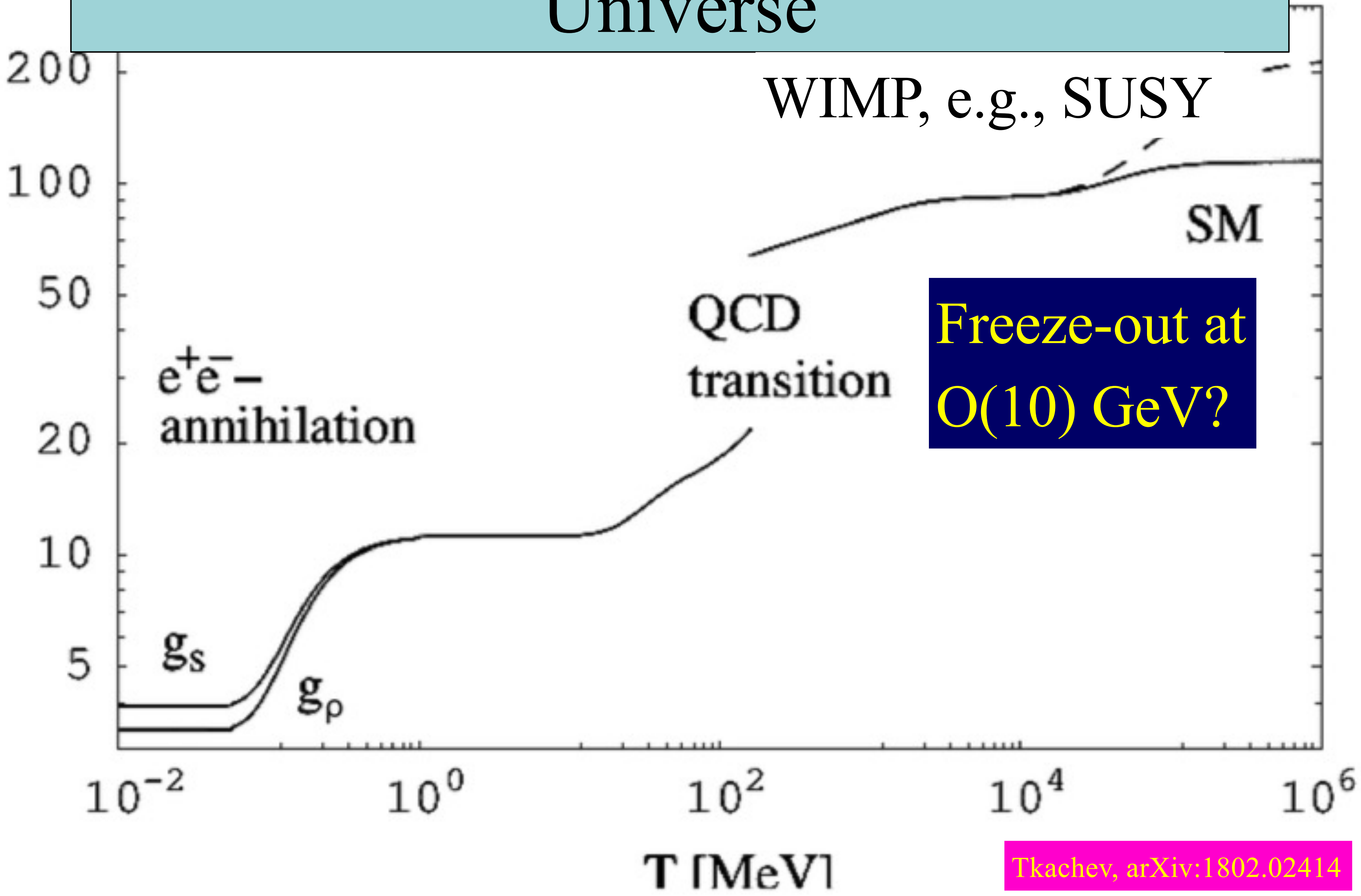


Weakly-Interacting Massive Particles (WIMPs)

- Expected to have been numerous in the primordial Universe when it was a fraction of a second old, full of a primordial hot soup
- Would have cooled down as Universe expanded
- Interactions would have weakened
- WIMPs decoupled from visible matter
- “Freeze-out”
- Larger σ → lower Y



‘Standard’ Thermal History of Early Universe



WIMP, e.g., SUSY

Freeze-out at O(10) GeV?

Tkachev, arXiv:1802.02414

The WIMP 'Miracle'

- The TeV scale from cosmology:

$$\mathrm{TeV} \simeq \sqrt{M_{\mathrm{Pl}} \times 2.7\,\mathrm{K}}$$

- Generic density from freeze-out:

$$\Omega_\chi h_0^2 \simeq \frac{1}{10^3 \langle \sigma v \rangle} \frac{1}{M_{\mathrm{Pl}} \times 2.7\,\mathrm{K}} \simeq \frac{1}{10^3 \langle \sigma v \rangle} \frac{1}{\mathrm{TeV}^2}$$

- Generic annihilation cross-section:

$$\sigma v \simeq \frac{c\alpha^2}{m^2}$$

- Generic relic mass:

$$m \simeq \sqrt{M_{\mathrm{Pl}} \times 2.7\,\mathrm{K}}\; 16\alpha\sqrt{C} \sqrt{\frac{\Omega_\chi h_0^2}{0.25}}$$

$$\simeq \mathrm{TeV}\; 16\alpha\sqrt{C} \sqrt{\frac{\Omega_\chi h_0^2}{0.25}} .$$

- Putting the numbers in:

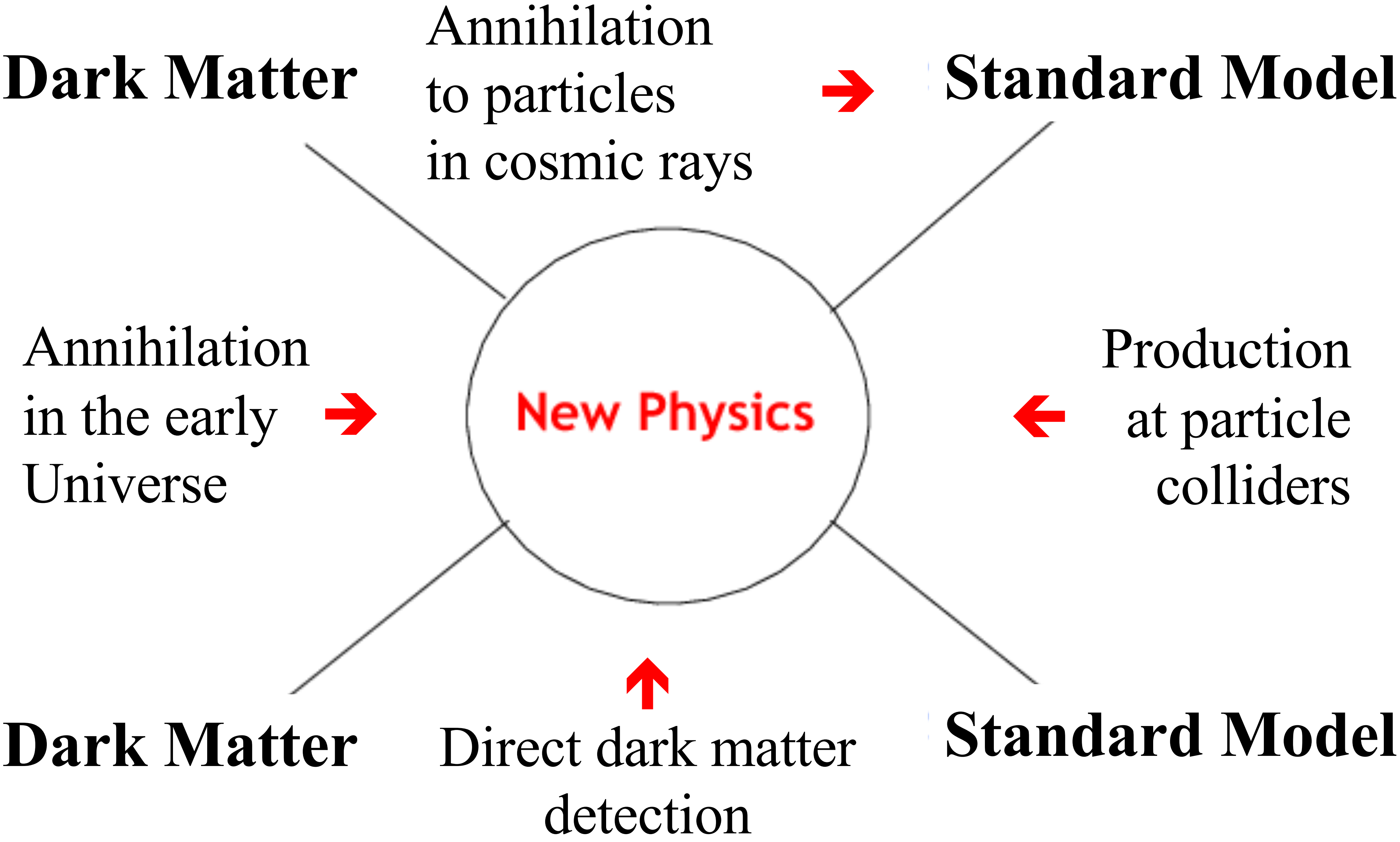
$$m \lesssim \tfrac{1}{2}\sqrt{10C}\,\mathrm{TeV} \lesssim 5\,\mathrm{TeV}$$

Dimopoulos, PLB246, 347 (1990)

WIMP Candidates

- Could have right density if weigh 100 to 1000 GeV (accessible to LHC experiments?)
- Present in many extensions of Standard Model
- Particularly in attempts to understand strength of weak interactions, mass of Higgs boson
- Examples:
  - Extra dimensions of space
  - **Supersymmetry** ♥

Searches for Dark Matter



Dark Matter

Annihilation to particles in cosmic rays →

Standard Model

Annihilation in the early Universe →

New Physics

← Production at particle colliders

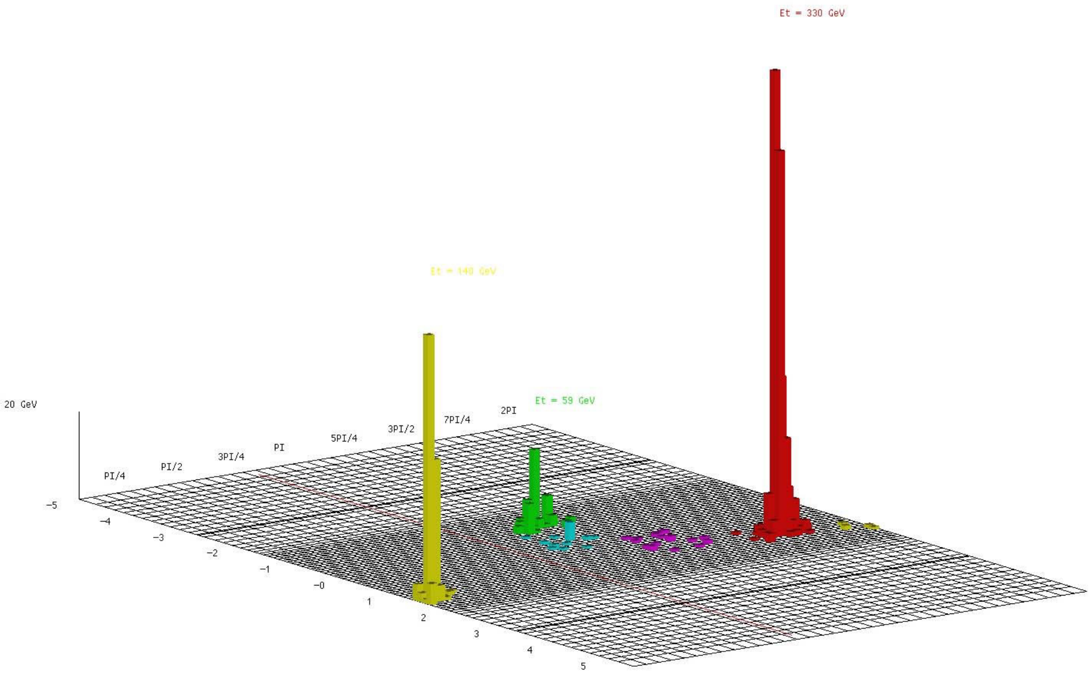
↑

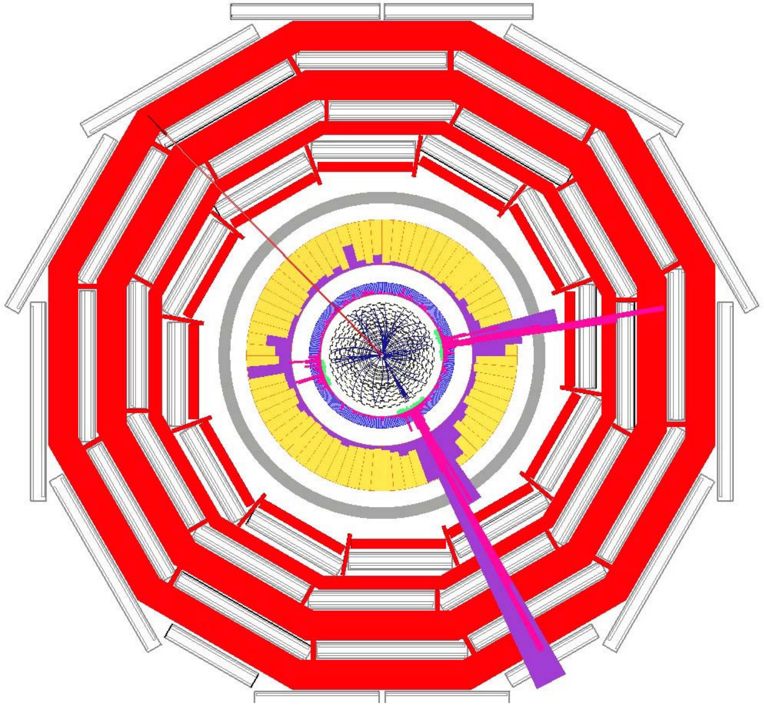
Dark Matter

Direct dark matter detection

Standard Model

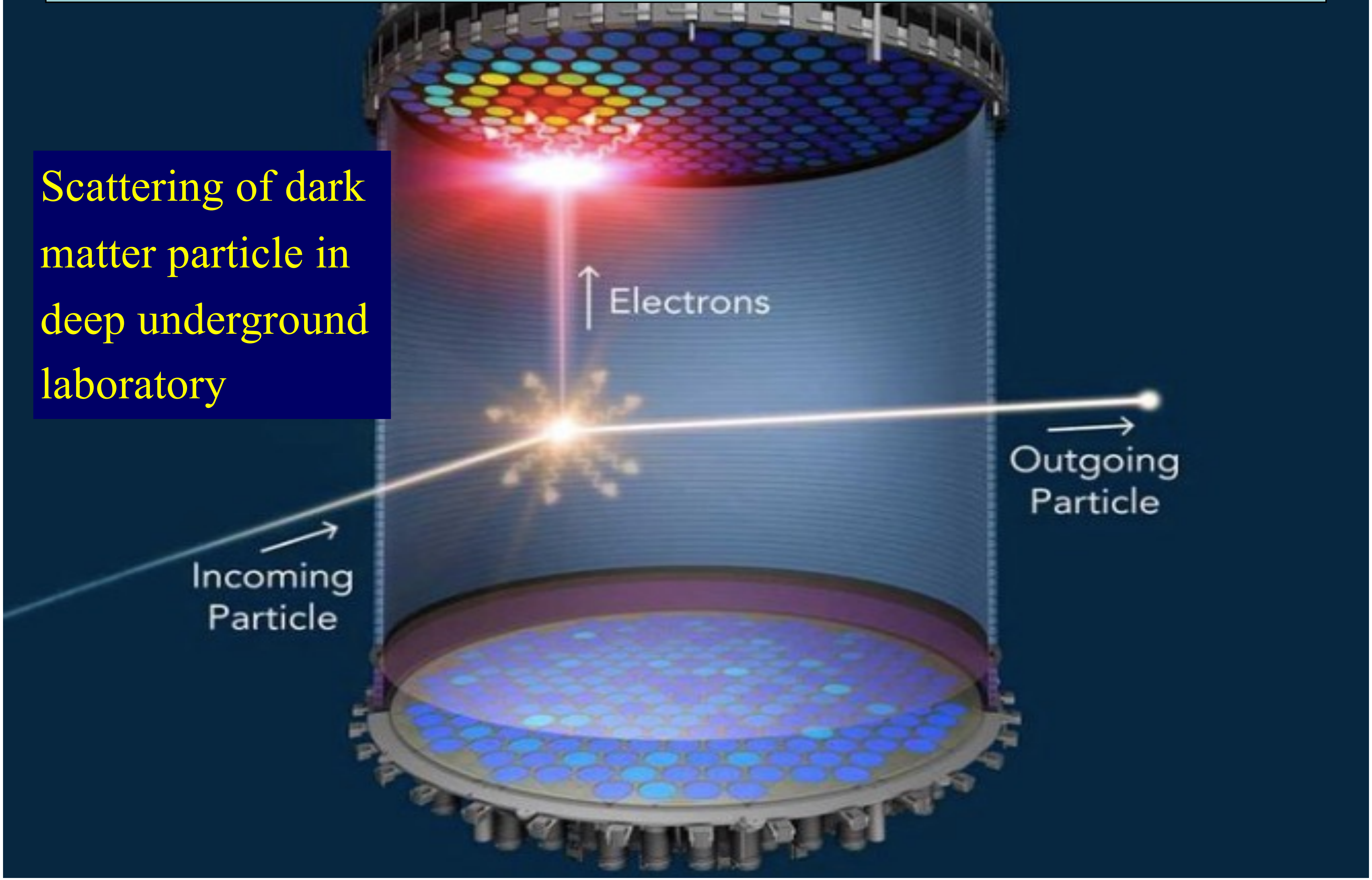
Classic Dark Matter Signature





Missing transverse energy
carried away by dark matter particles

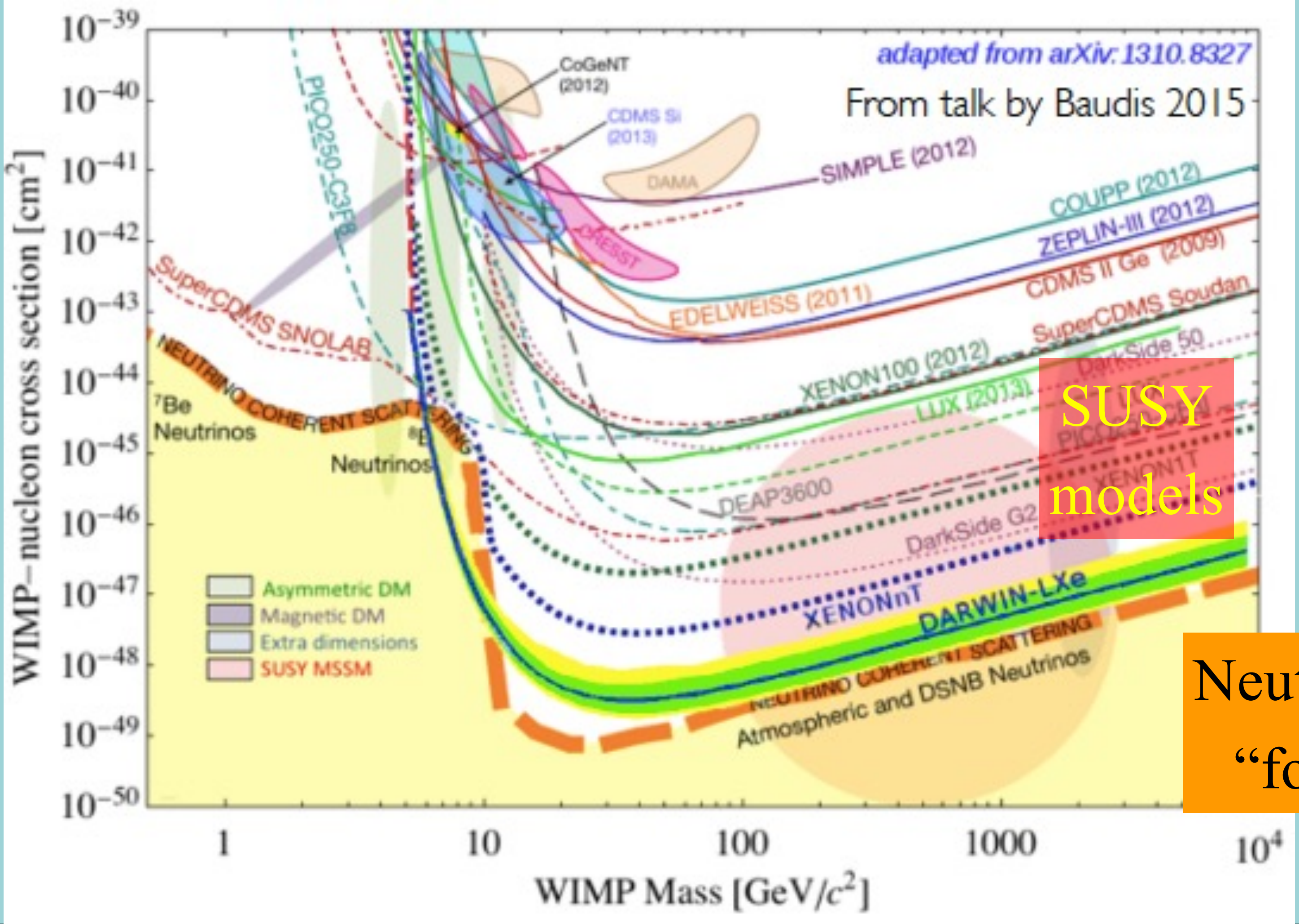
Direct Dark Matter Detection



Scattering of dark matter particle in deep underground laboratory

Direct Dark Matter Searches

- Compilation of present and future sensitivities

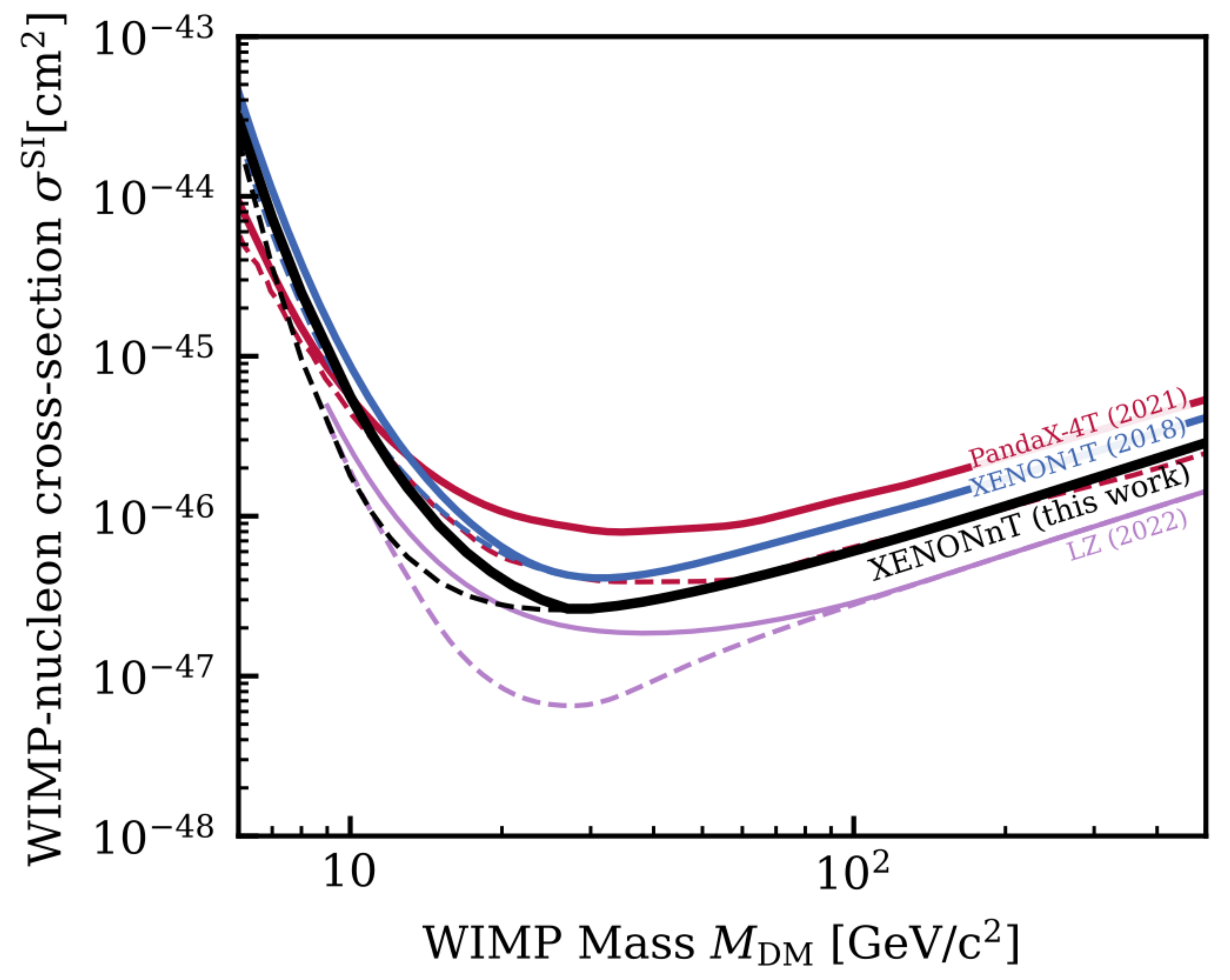


SUSY models

Neutrino “fog”

Direct Dark Matter Searches

- Latest experimental results



We still believe in supersymmetry

You must be joking