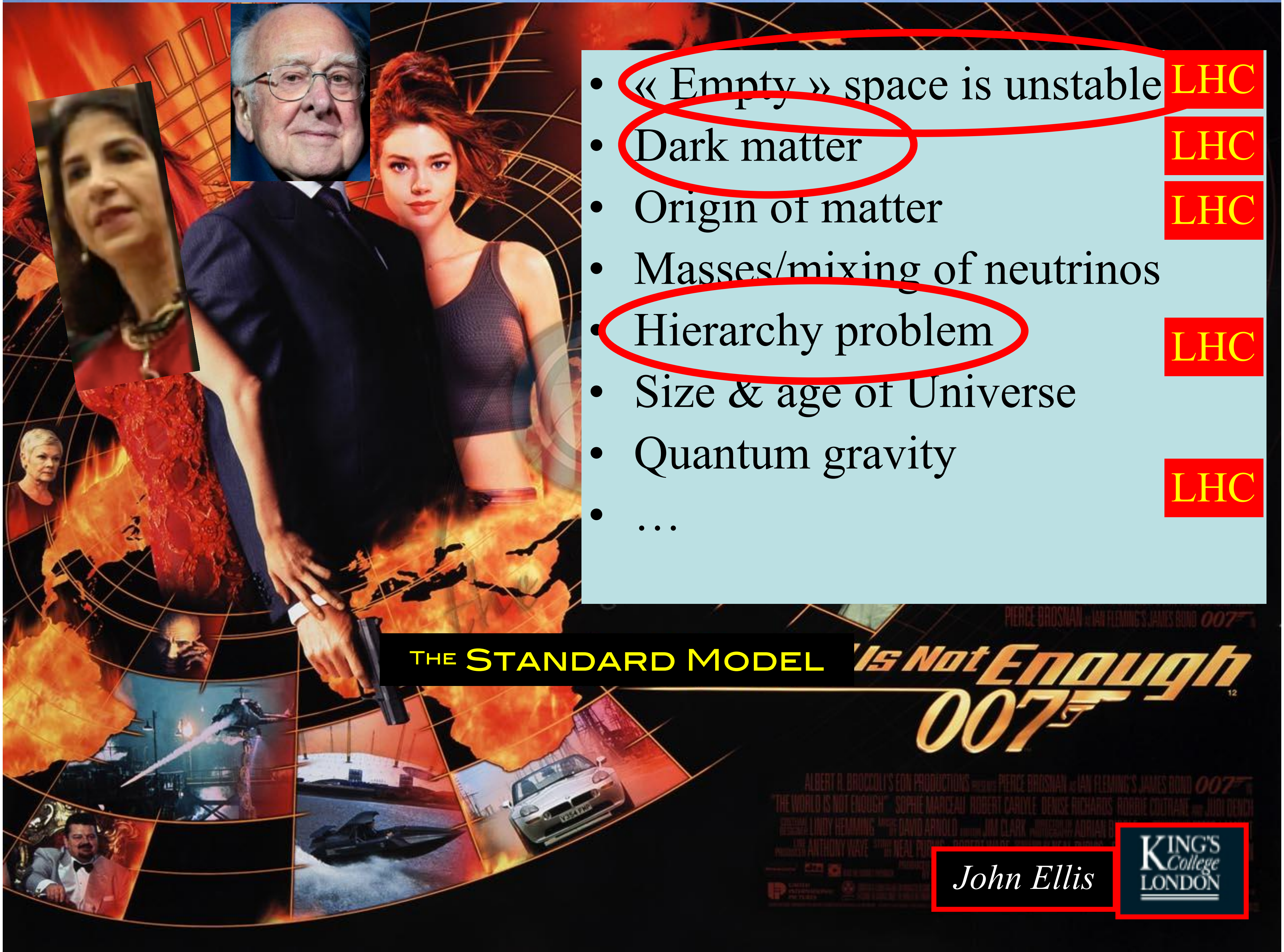
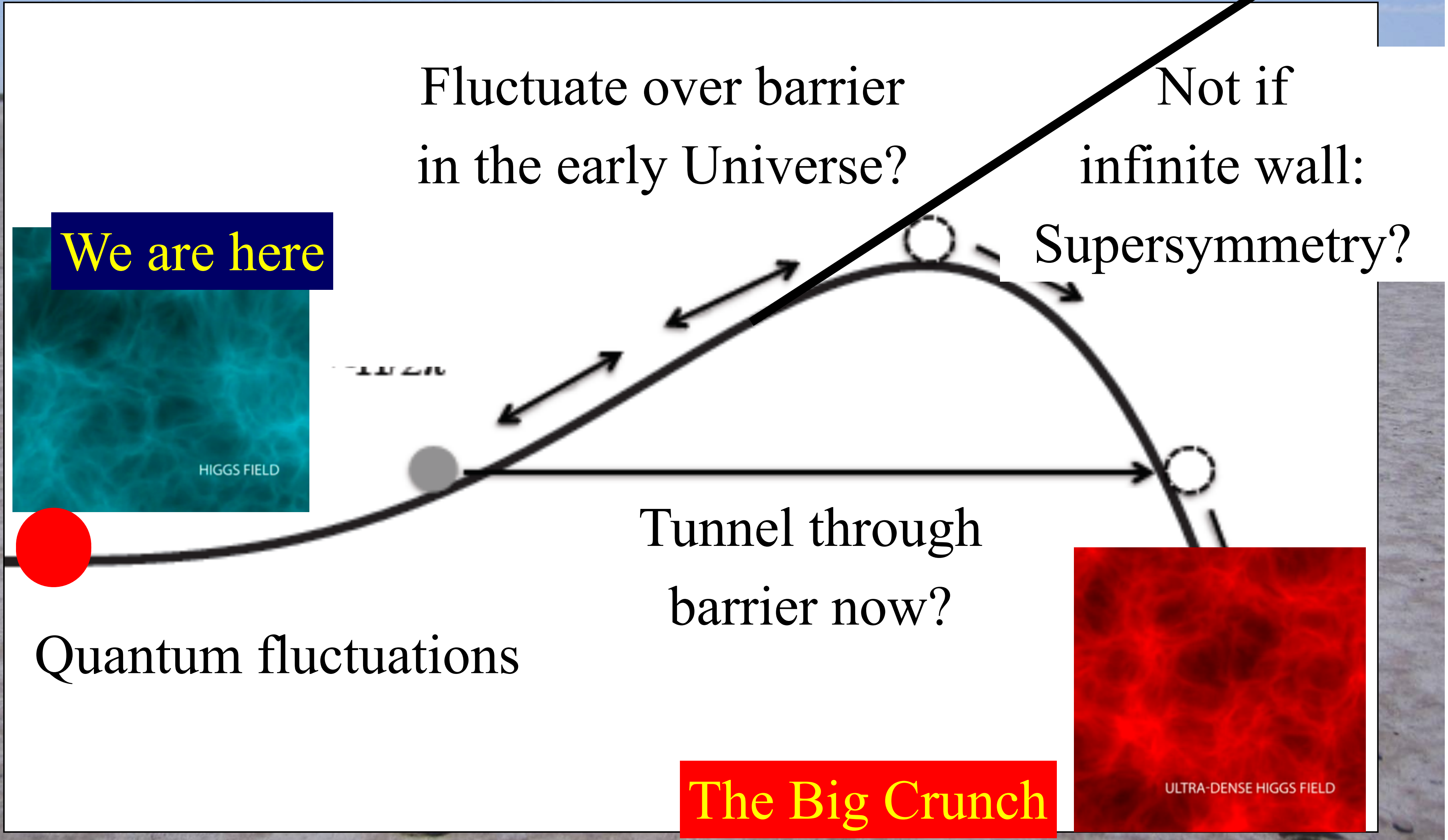
- « Empty » space is unstable LHC
- Dark matter LHC
- Origin of matter LHC
- Masses/mixing of neutrinos
- Hierarchy problem LHC
- Size & age of Universe
- Quantum gravity LHC
- …



THE STANDARD MODEL

John Ellis
KING'S College LONDON

Should it have Collapsed already?



Fluctuate over barrier
in the early Universe?

Not if
infinite wall:
Supersymmetry?

We are here

Quantum fluctuations

Tunnel through
barrier now?

The Big Crunch

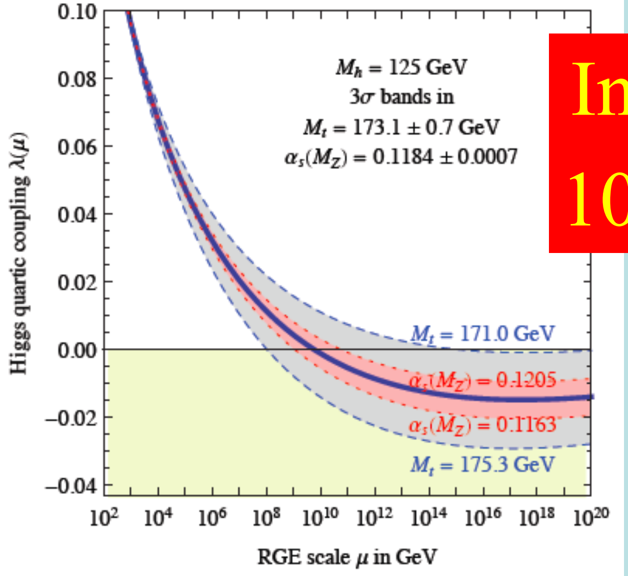
Theoretical Constraints on Higgs Mass

- Large M_h → large self-coupling → blow up at low-energy scale Λ due to renormalization

$$\lambda(Q) = \frac{\lambda(v)}{1 - \frac{3}{4\pi^2}\lambda(v)\log\frac{Q^2}{v^2}}$$

$$\lambda(Q) = \lambda(v) - \frac{3m_t^4}{2\pi^2 v^4}\log\frac{Q}{v}$$

- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable

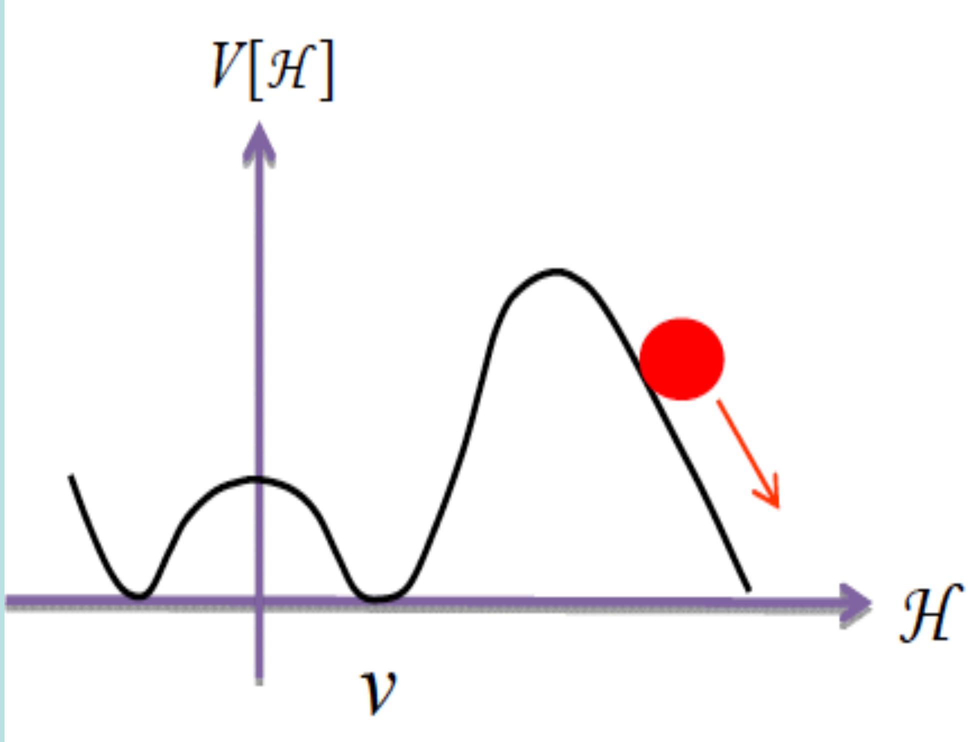


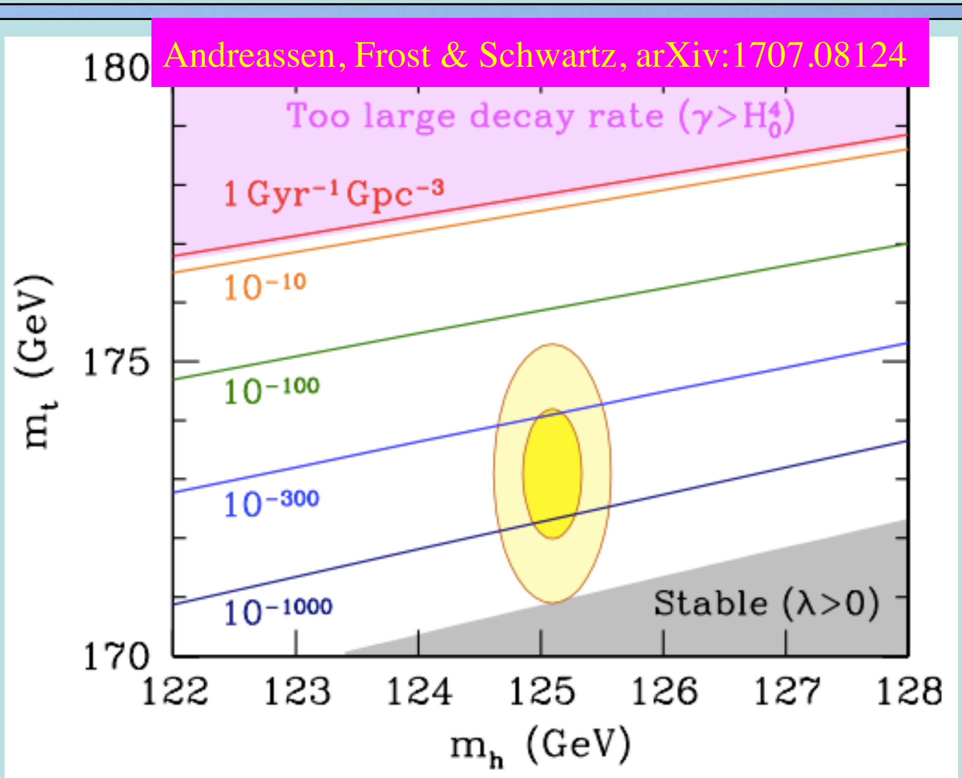
Instability @ $10^{11.4\pm0.8}$ GeV

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio & Strumia, arXiv:1307.3536

- Vacuum could be stabilized by **Supersymmetry**

Vacuum Instability in the Standard Model




Andreassen, Frost & Schwartz, arXiv:1707.08124

- Sensitive to α_s as well as m_t and M_H
- Instability scale:

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio & Strumia, arXiv:1307.3536

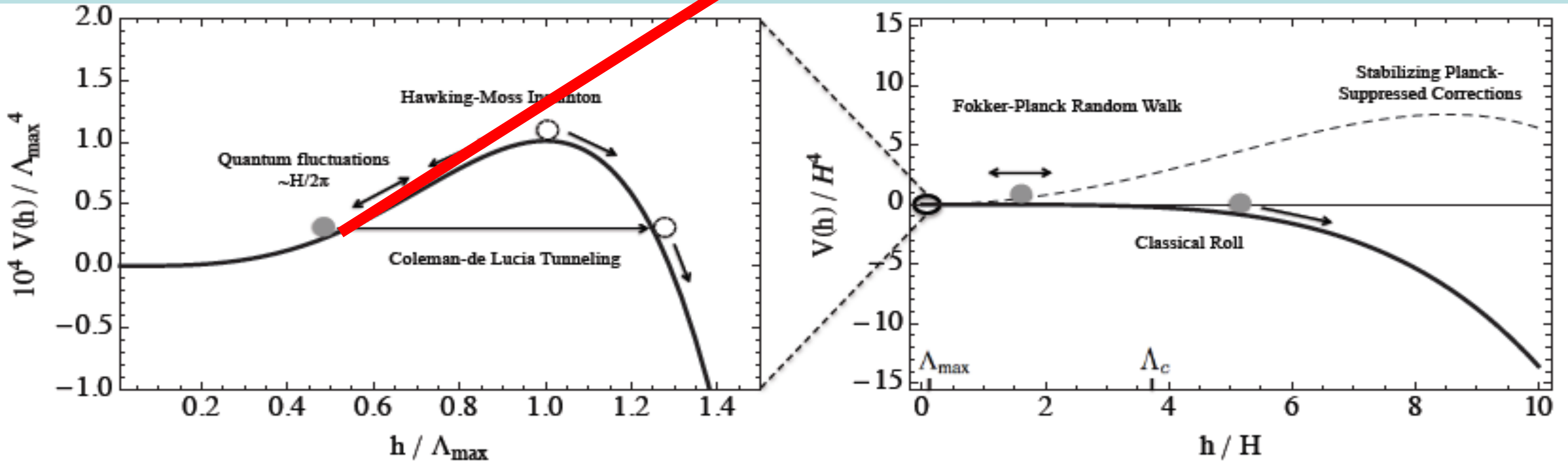
$$\log_{10}\frac{\Lambda_I}{\text{GeV}} = 11.3 + 1.0\left(\frac{M_h}{\text{GeV}} - 125.66\right) - 1.2\left(\frac{M_t}{\text{GeV}} - 173.10\right) + 0.4\,\frac{\alpha_3(M_Z) - 0.1184}{0.0007}$$

$m_t = 172.47 \pm 0.35$ GeV → $\log_{10}(\Lambda/\text{GeV}) = 11.4 \pm 0.8$

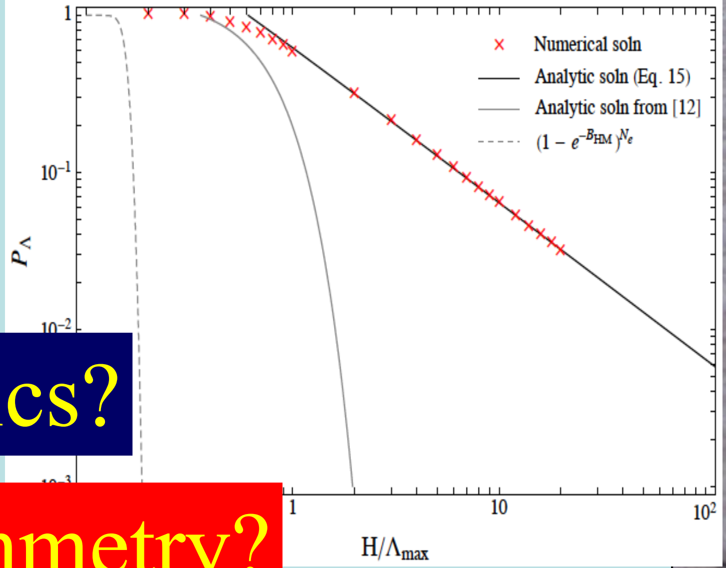
Instability during Inflation?

Hook, Kearney, Shakya & Zurek: arXiv:1404.5953

- Do inflation fluctuations drive us over the hill?



- Then Fokker-Planck evolution
- Do AdS regions eat us?
  - – Disaster if so



Stabilize vacuum with BSM physics?

“Build a wall” with supersymmetry?

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

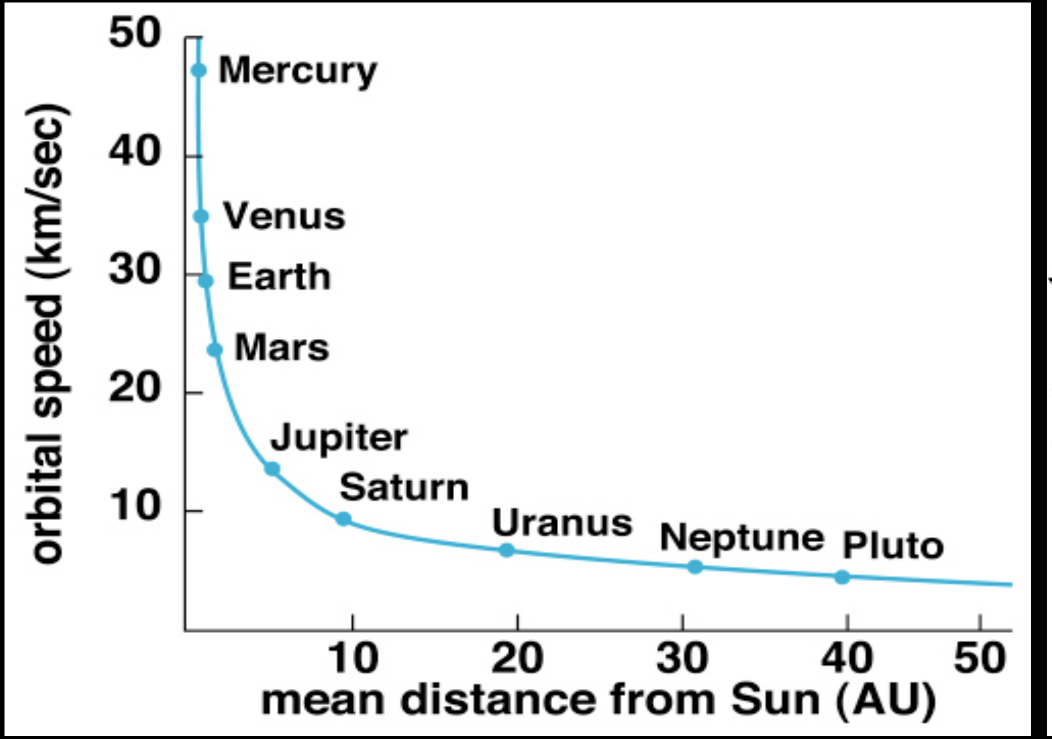
- Measured by Vera Rubin
- The stars also orbit ‘too quickly’
- Her observations also required a stronger gravitational field than provided by the visible matter

Scanned at the American Institute of Physics

- **Further strong evidence for dark matter**
- Also:
  - Structure formation, cosmic background radiation, …

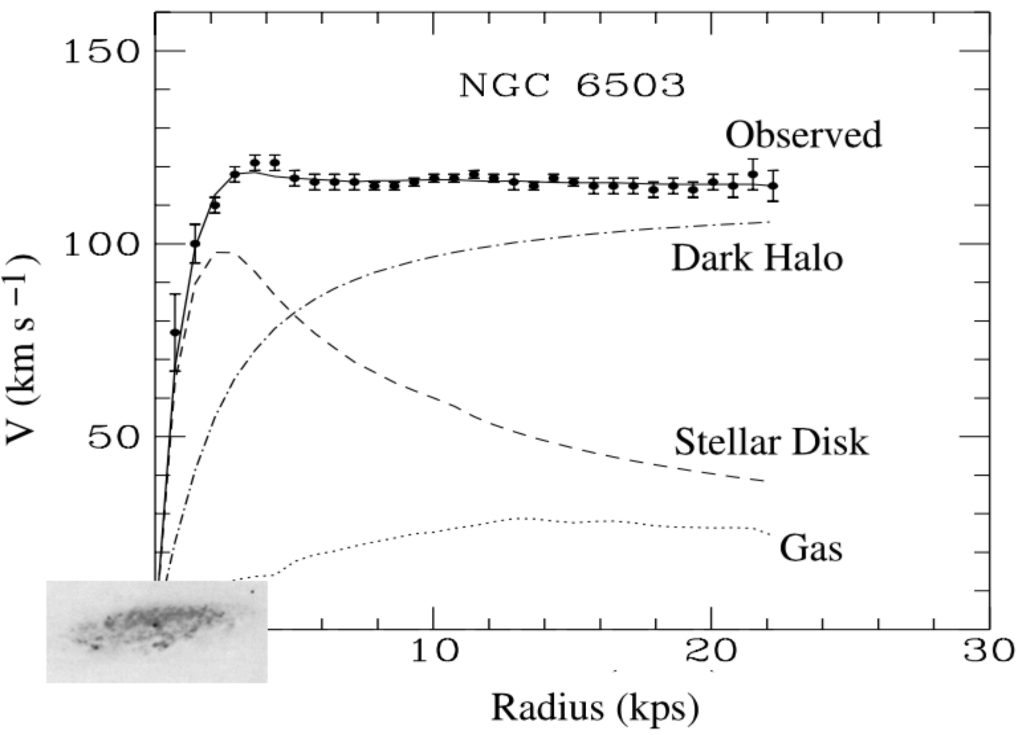
Rotation Curves

- In the Solar System



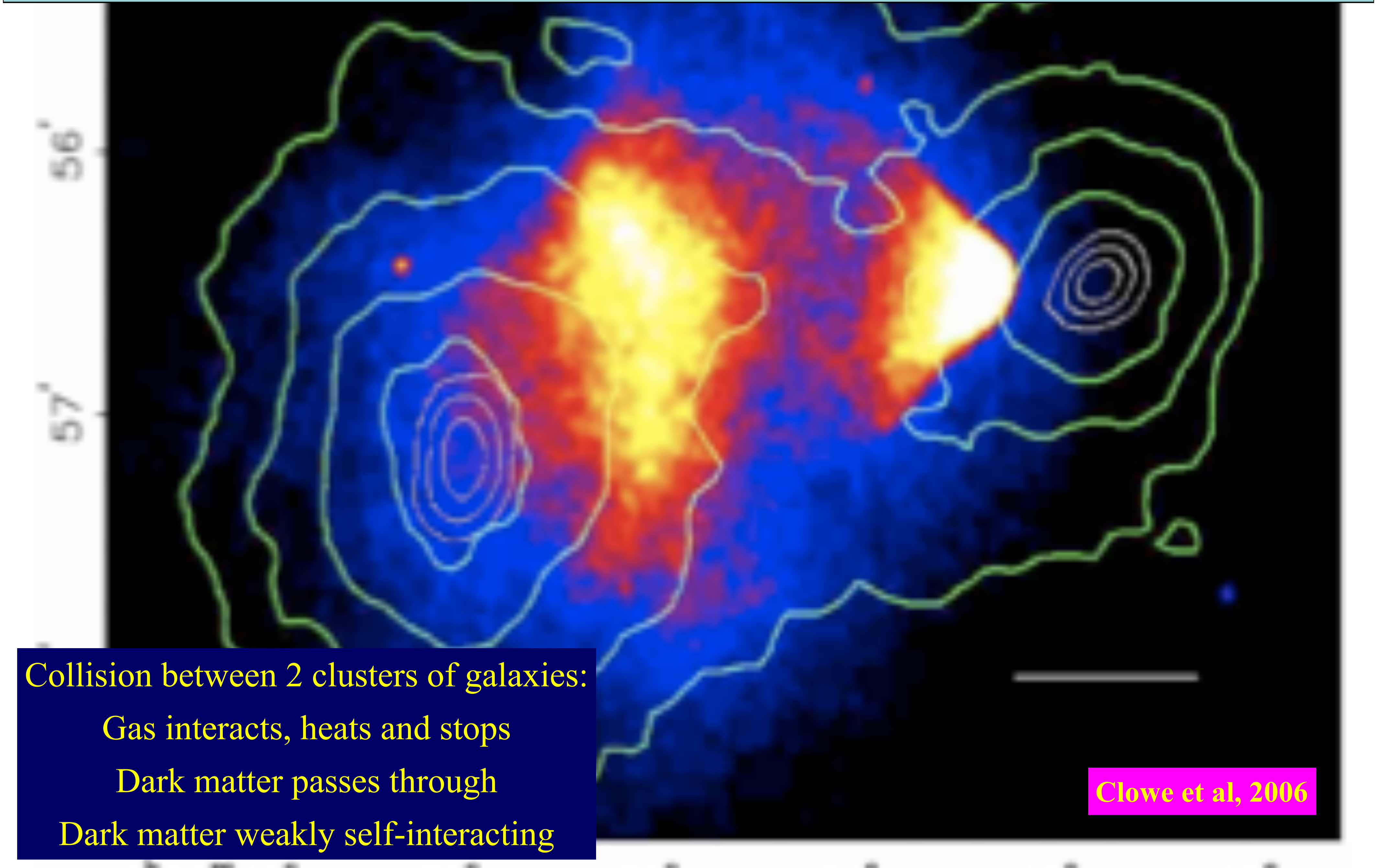
- The velocities decrease with distance from Sun
- Mass lumped at centre

- In galaxies



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

Biggest Collider in the Universe?



Collision between 2 clusters of galaxies:

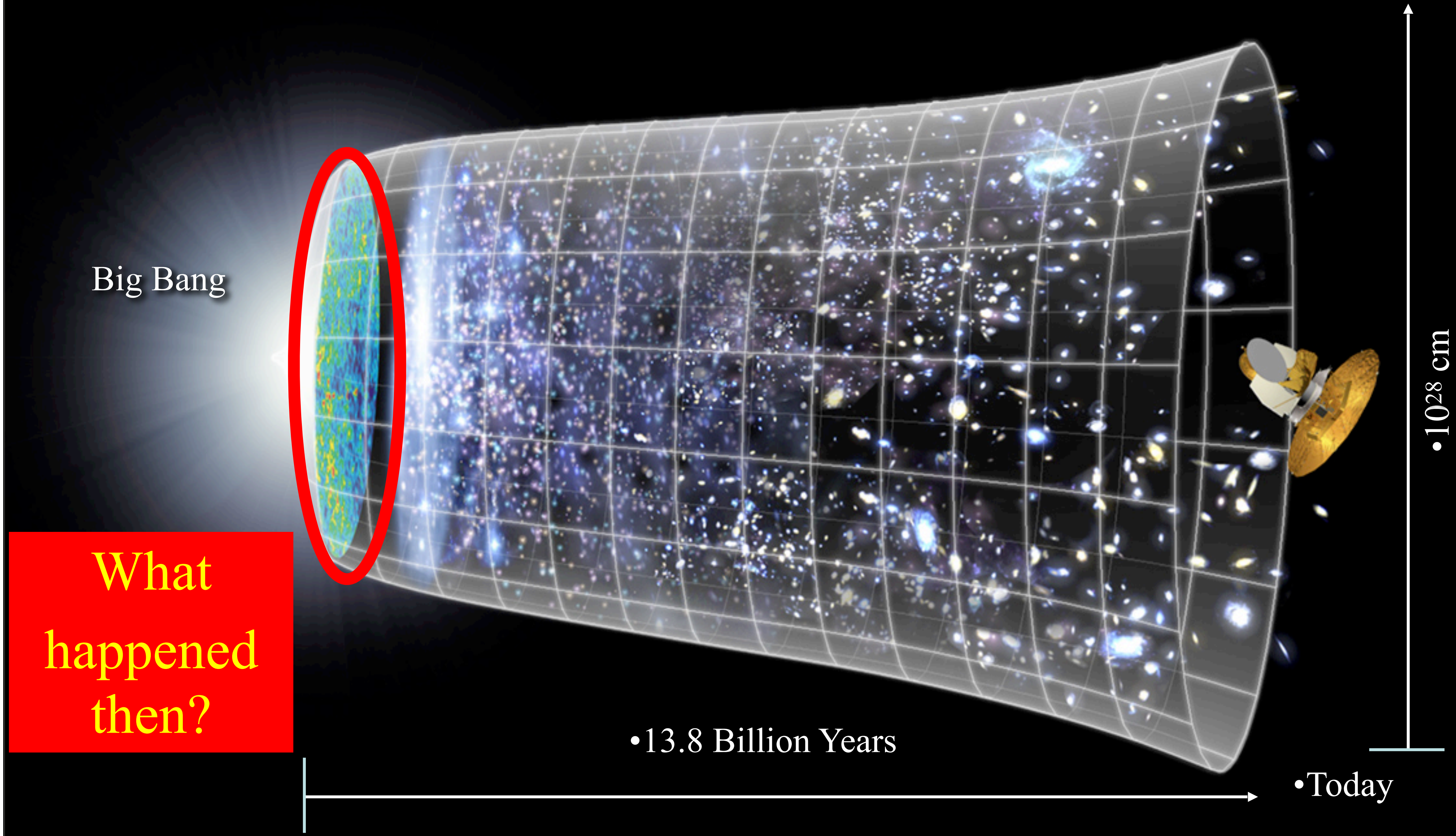
Gas interacts, heats and stops

Dark matter passes through

Dark matter weakly self-interacting

Clowe et al, 2006

Evolution of the Universe



Big Bang

What happened then?

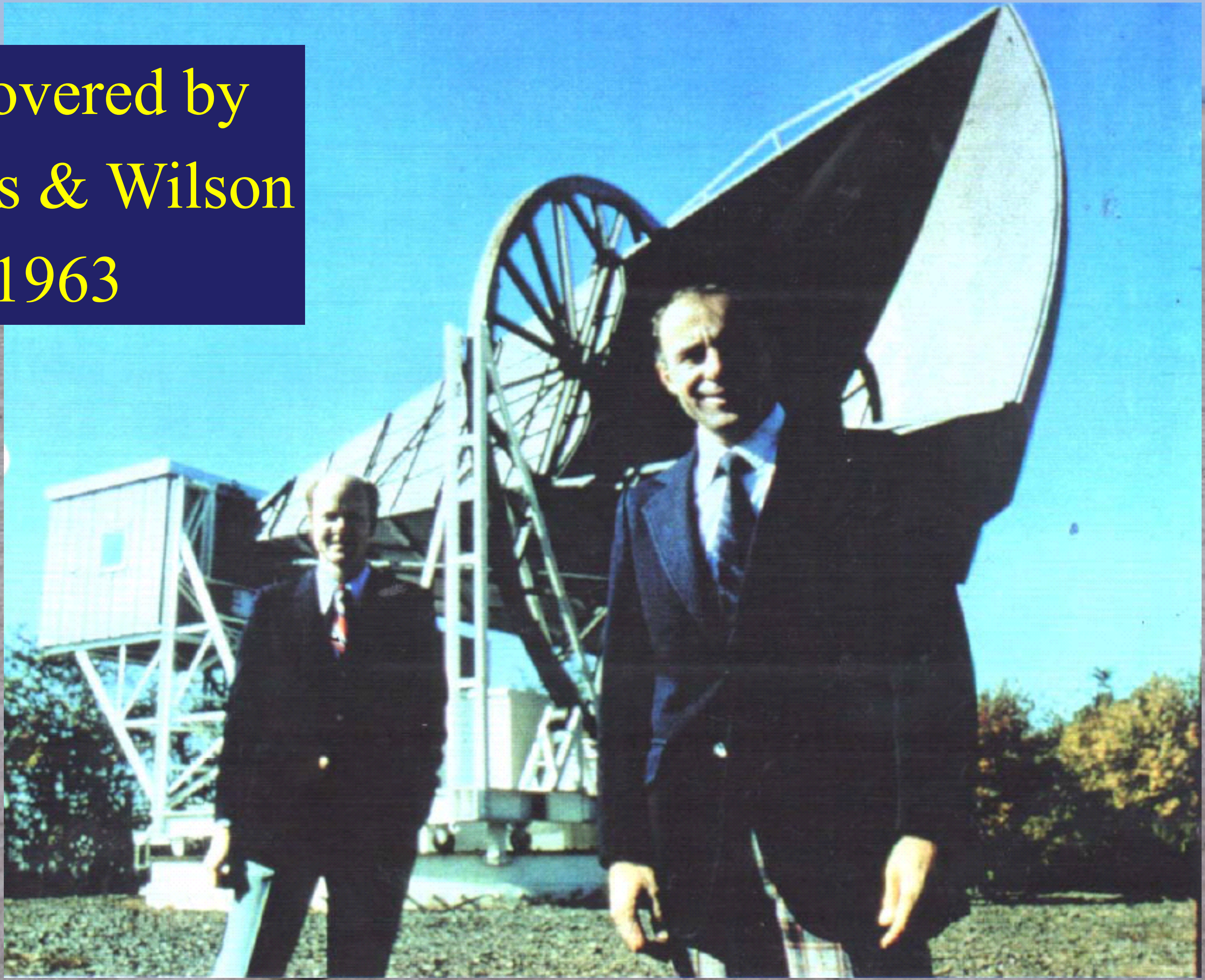
•13.8 Billion Years

•Today

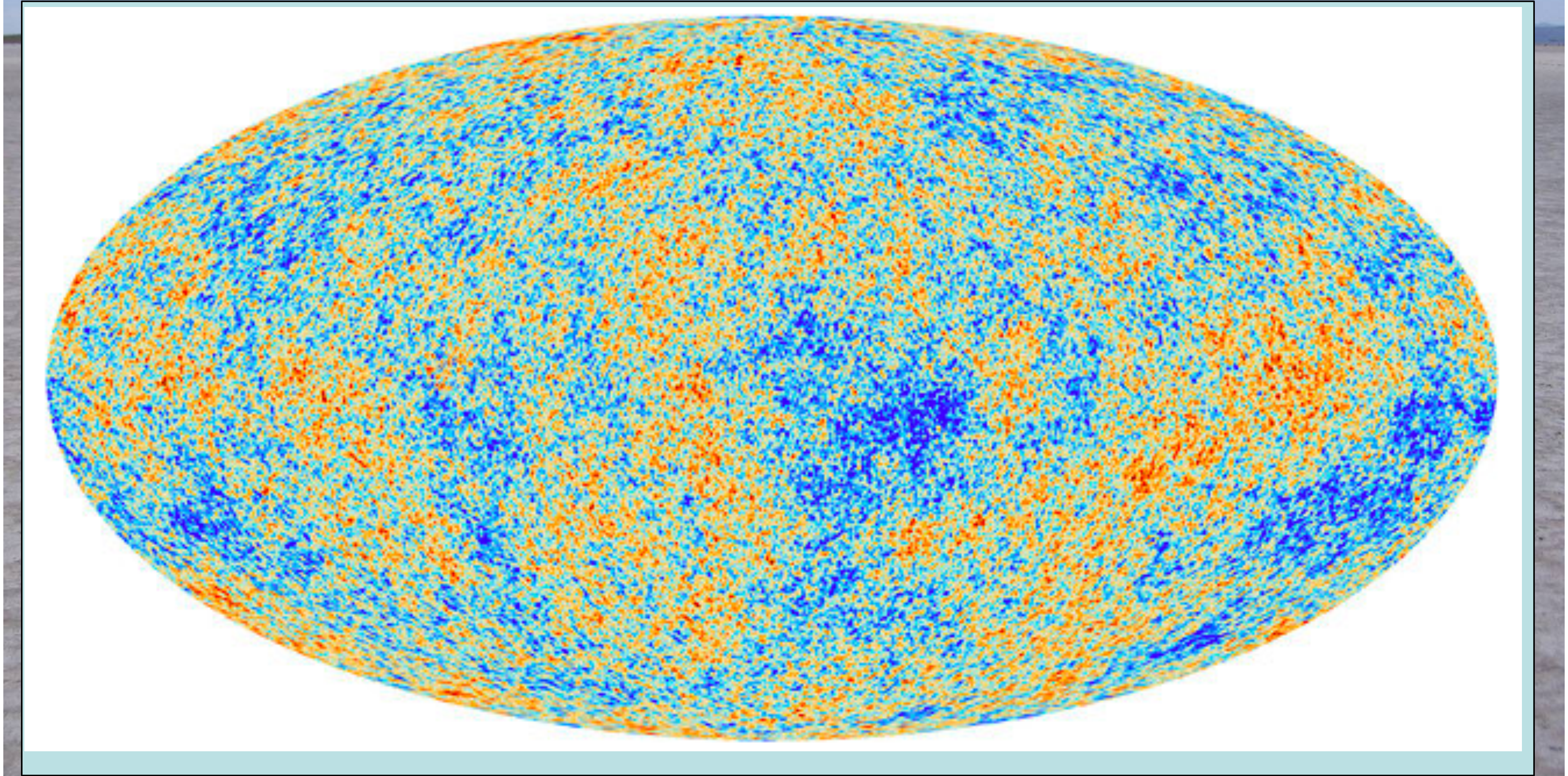
•10^{28} cm

The Cosmic Microwave Background

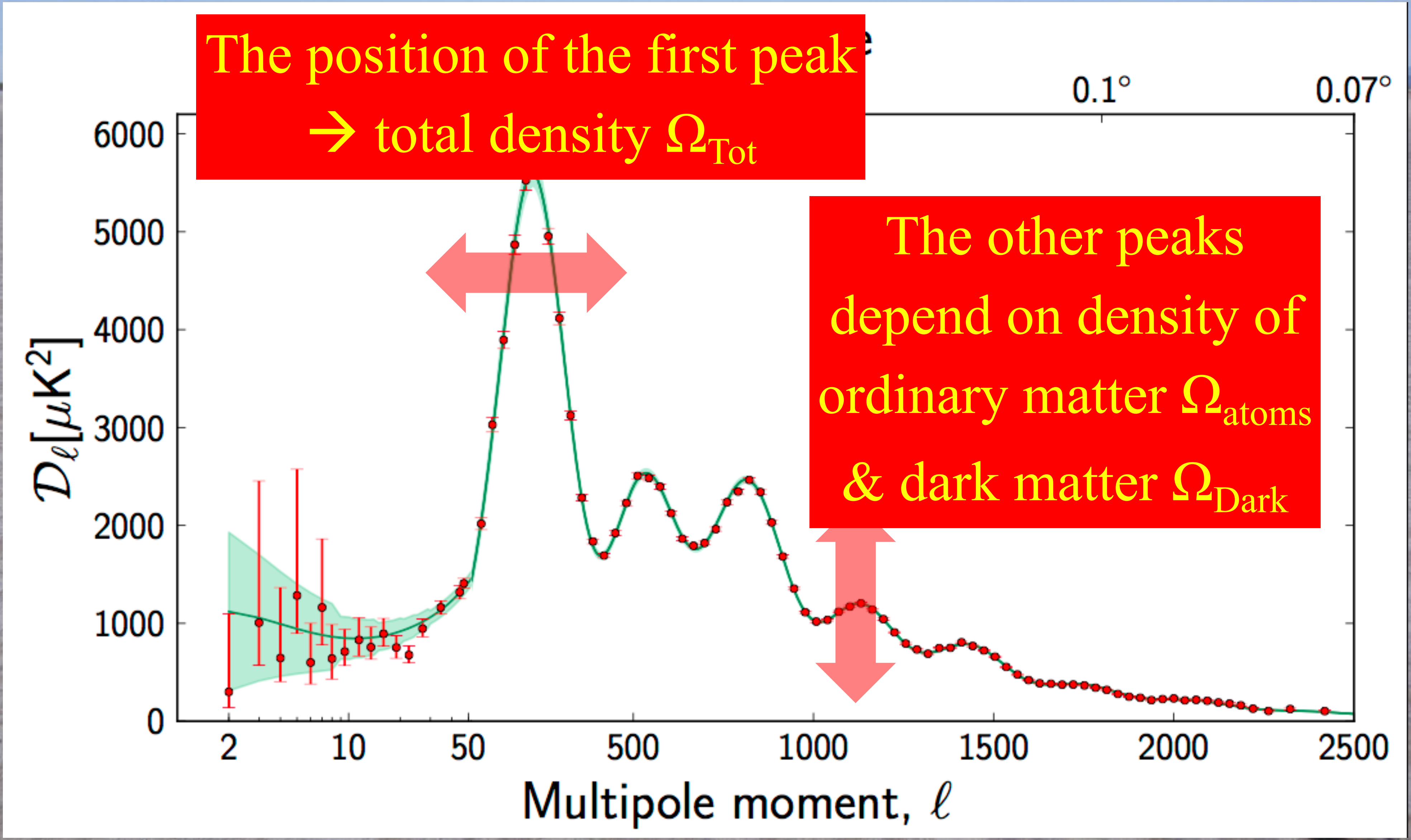
Discovered by
Penzias & Wilson
1963



Cosmological Microwave Background as seen by Planck Satellite



The Spectrum of Fluctuations in the Cosmic Microwave Background

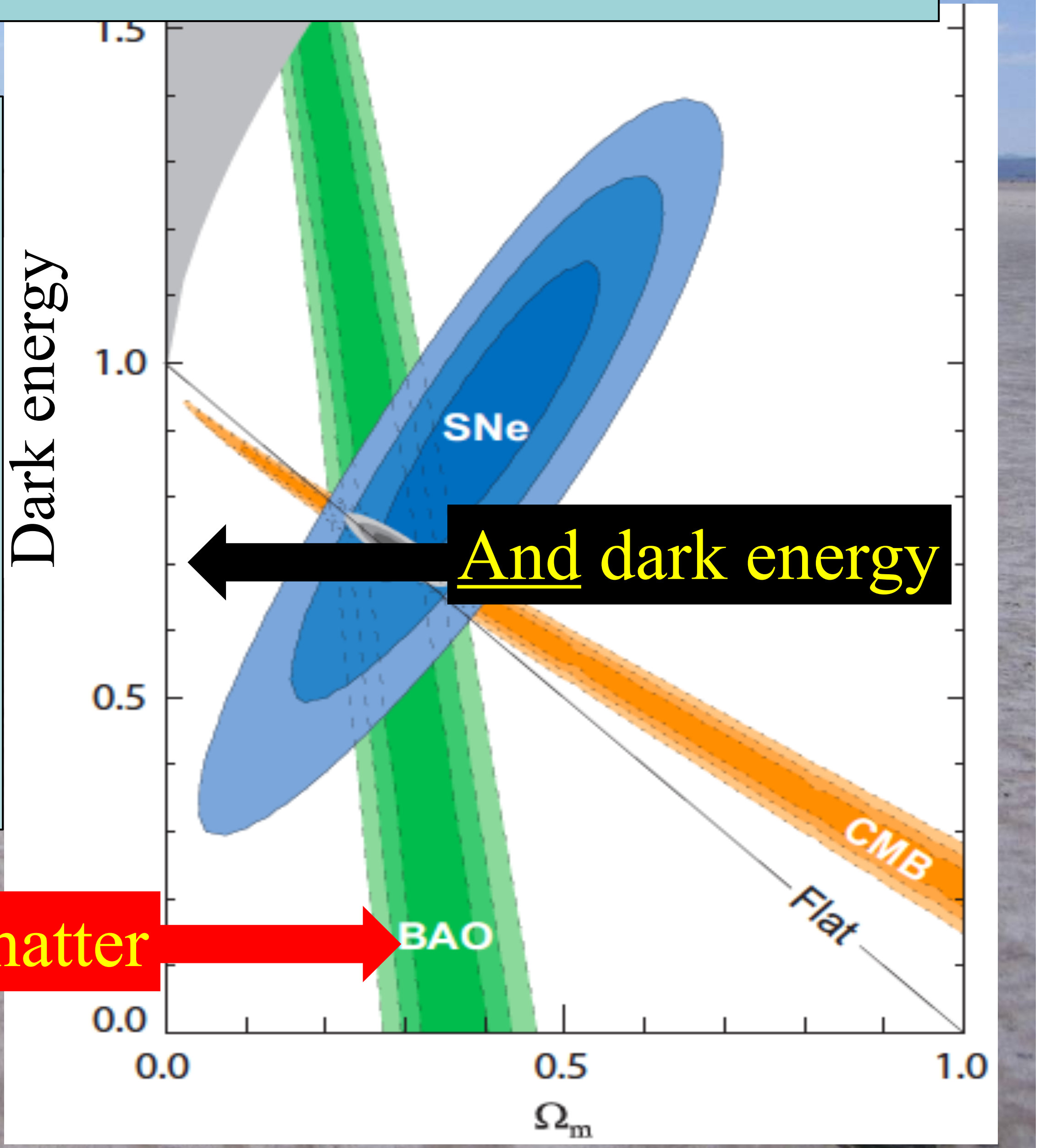


The position of the first peak
→ total density Ω_{Tot}

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

The Content of the Universe

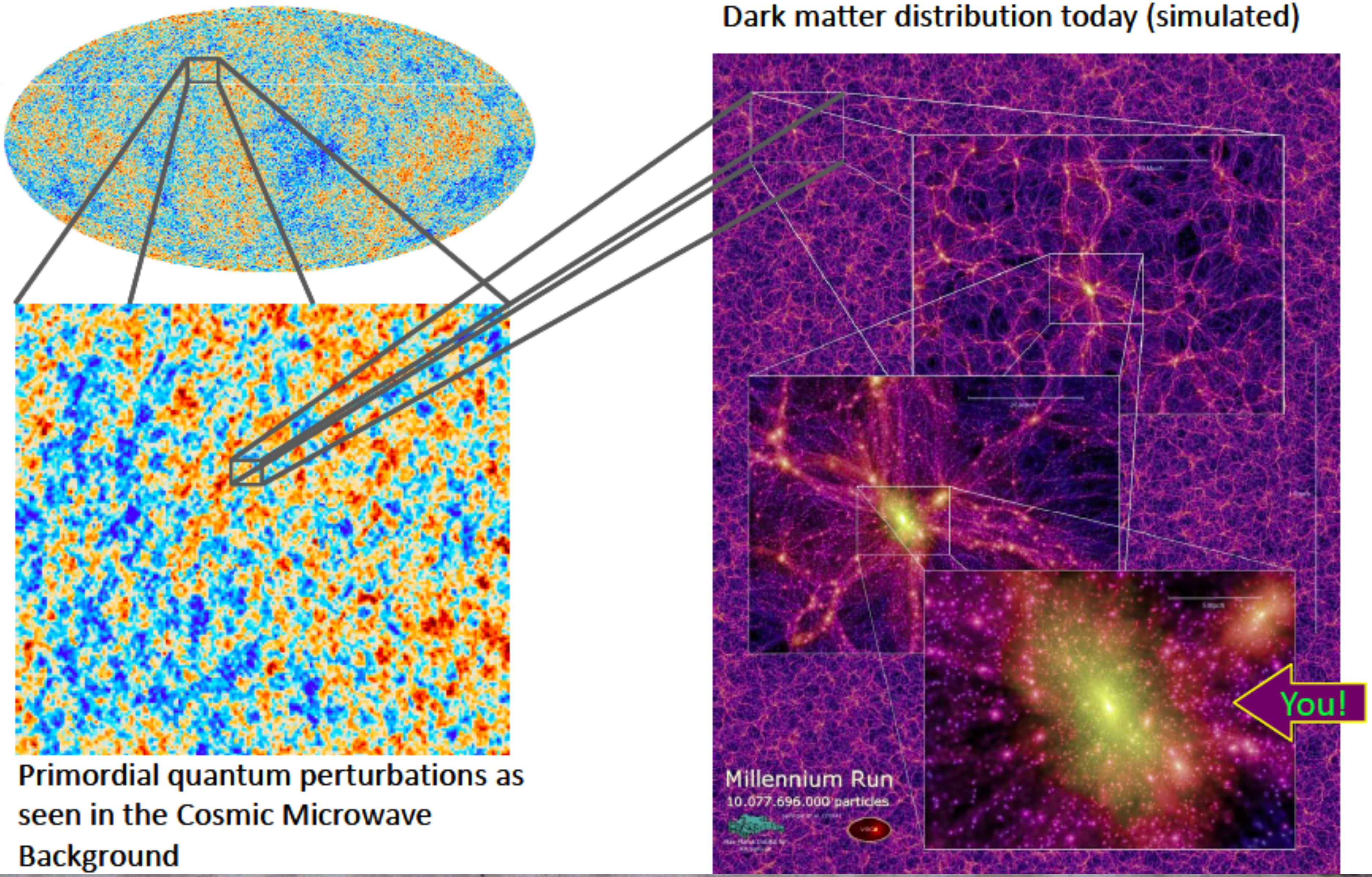
- According to
  - Microwave background
  - Supernovae
  - Structures (galaxies, clusters, …) in the Universe



And dark energy

There is dark matter

Perturbations Generate Structures



Planck

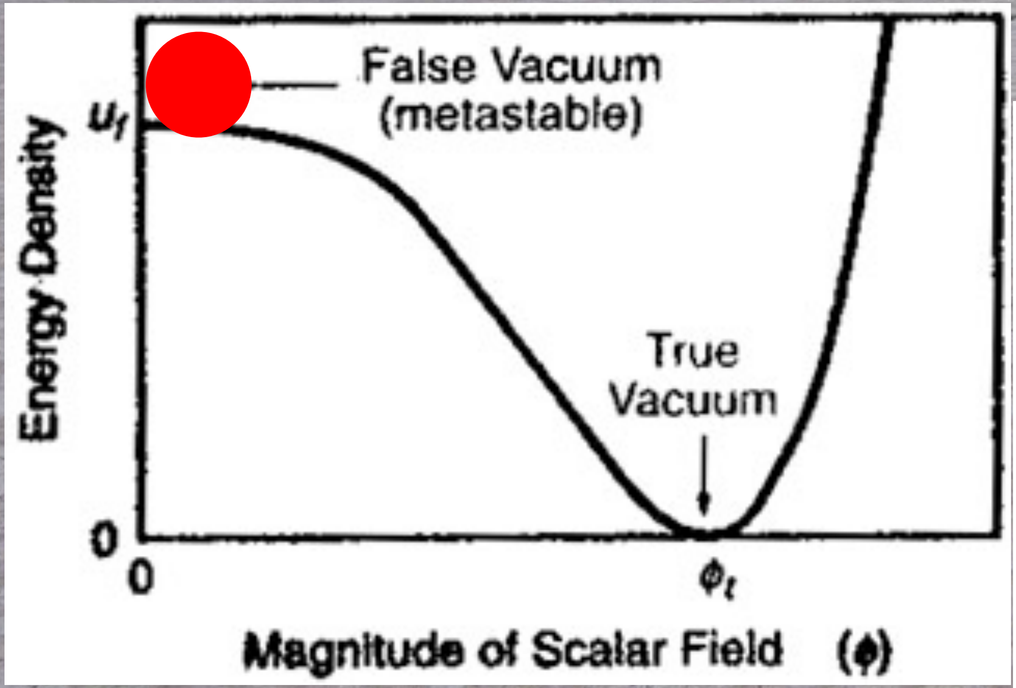
Dark matter distribution today (simulated)

Primordial quantum perturbations as seen in the Cosmic Microwave Background

The Origin of Structures in the Universe

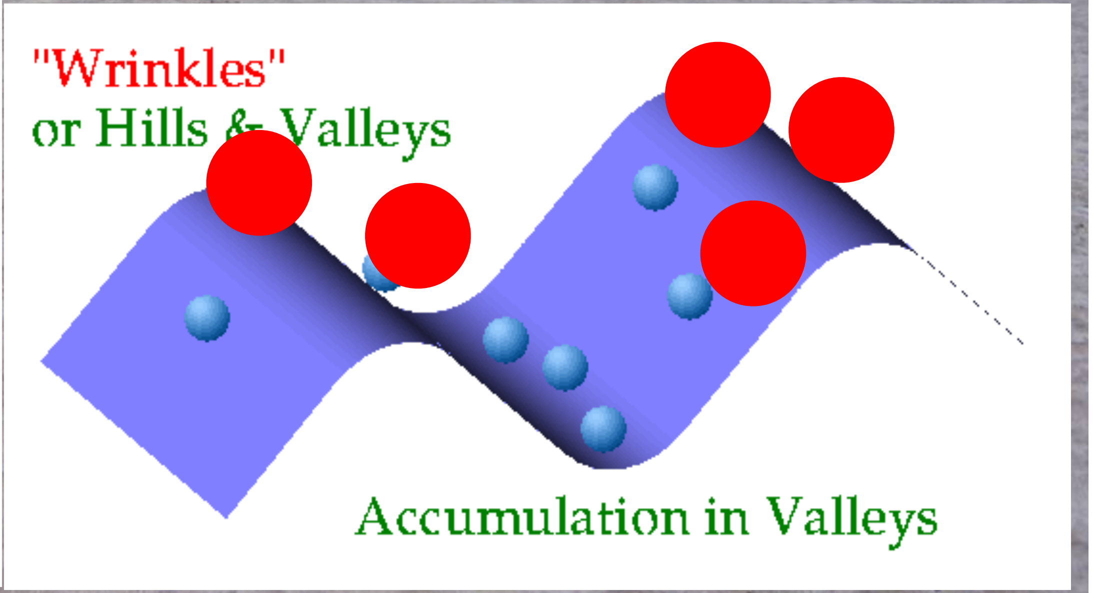
Small primordial quantum fluctuations:

$\sim 1/10^5$



Become density fluctuations

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



Become structures in Universe

A Successful Theory of the Formation of Structures in the Universe

Dark matter:

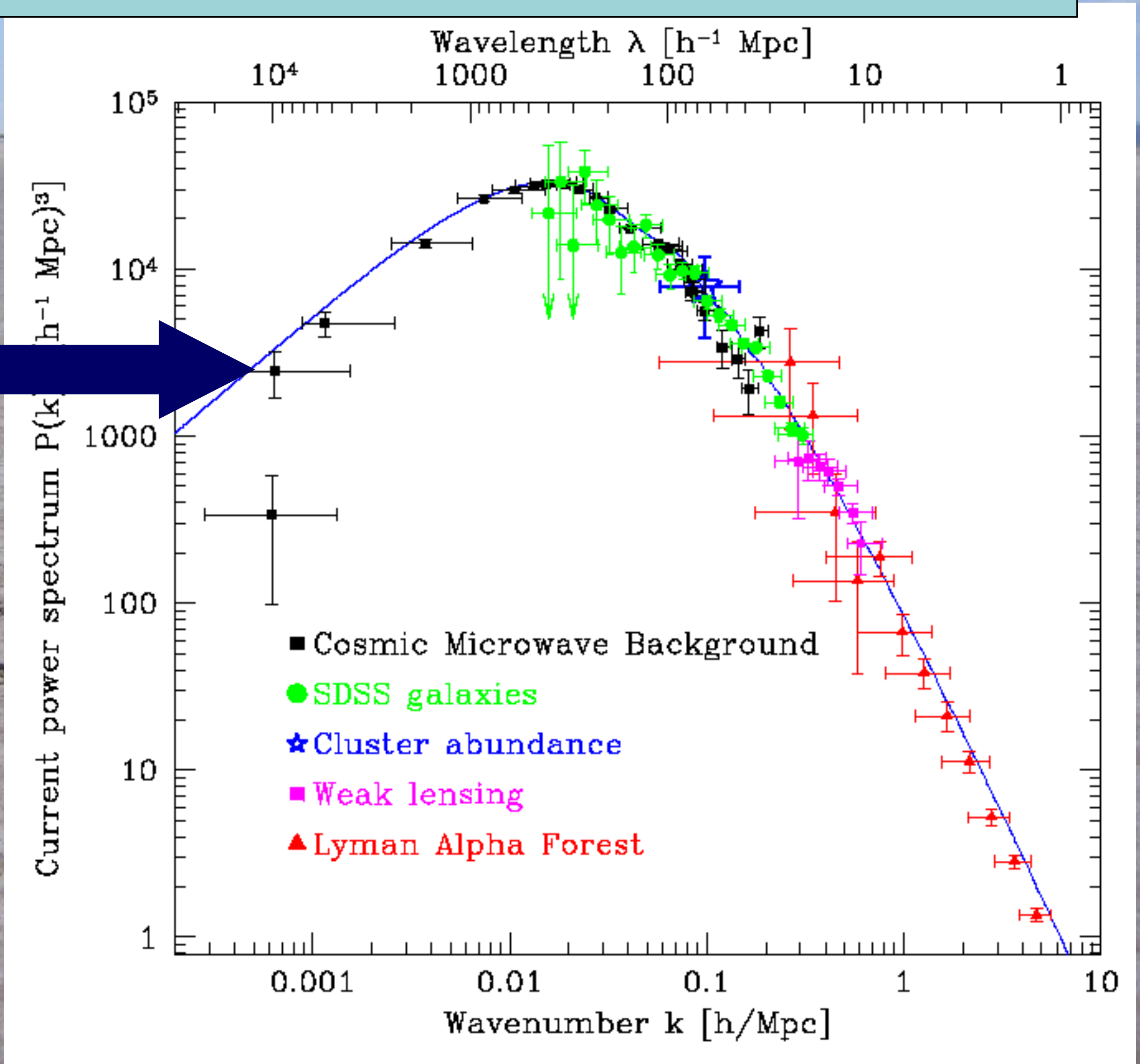
$\Omega_{CDM} \sim 0.25$,

Visible matter:

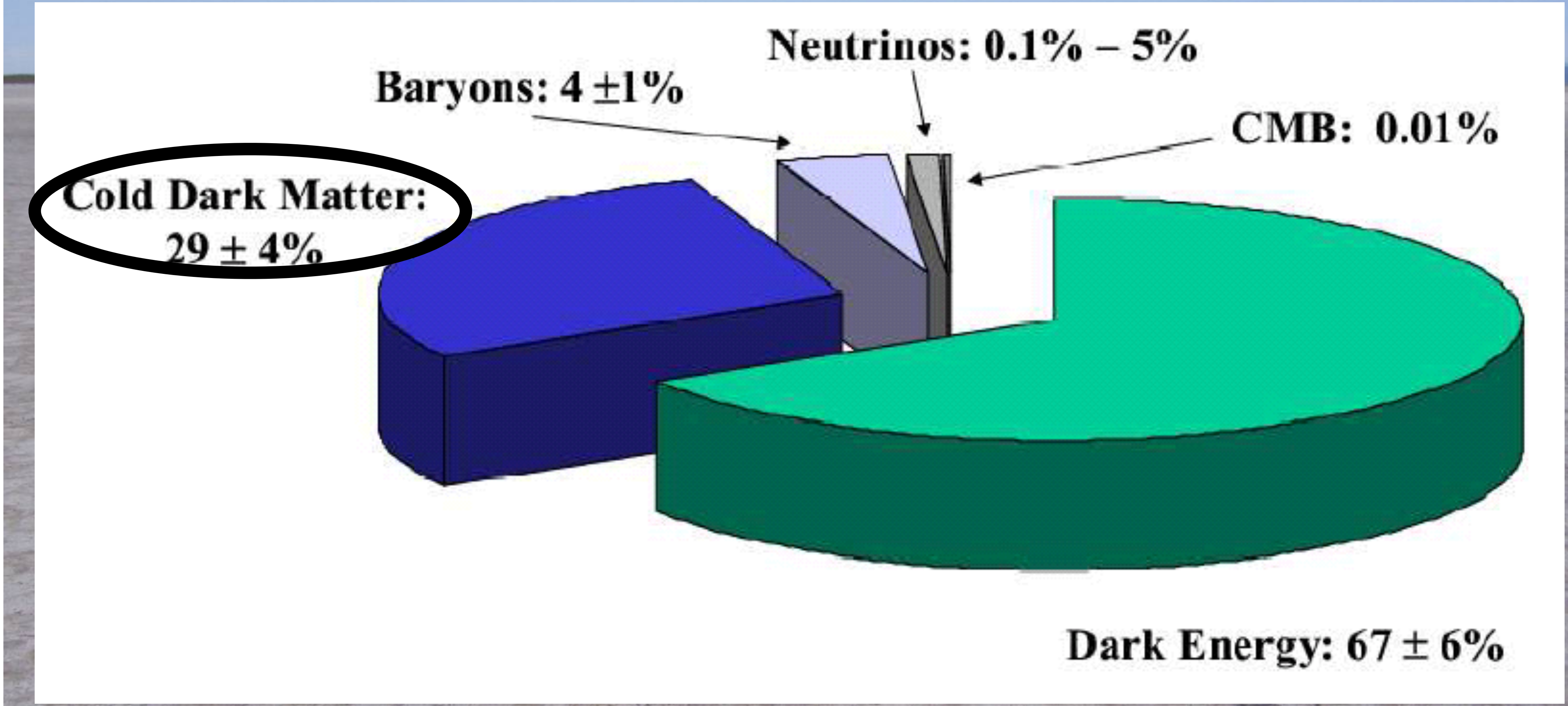
$\Omega_b \sim 0.05$,

Dark energy:

$\Omega_\Lambda \sim 0.7$



Strange Recipe for a Universe

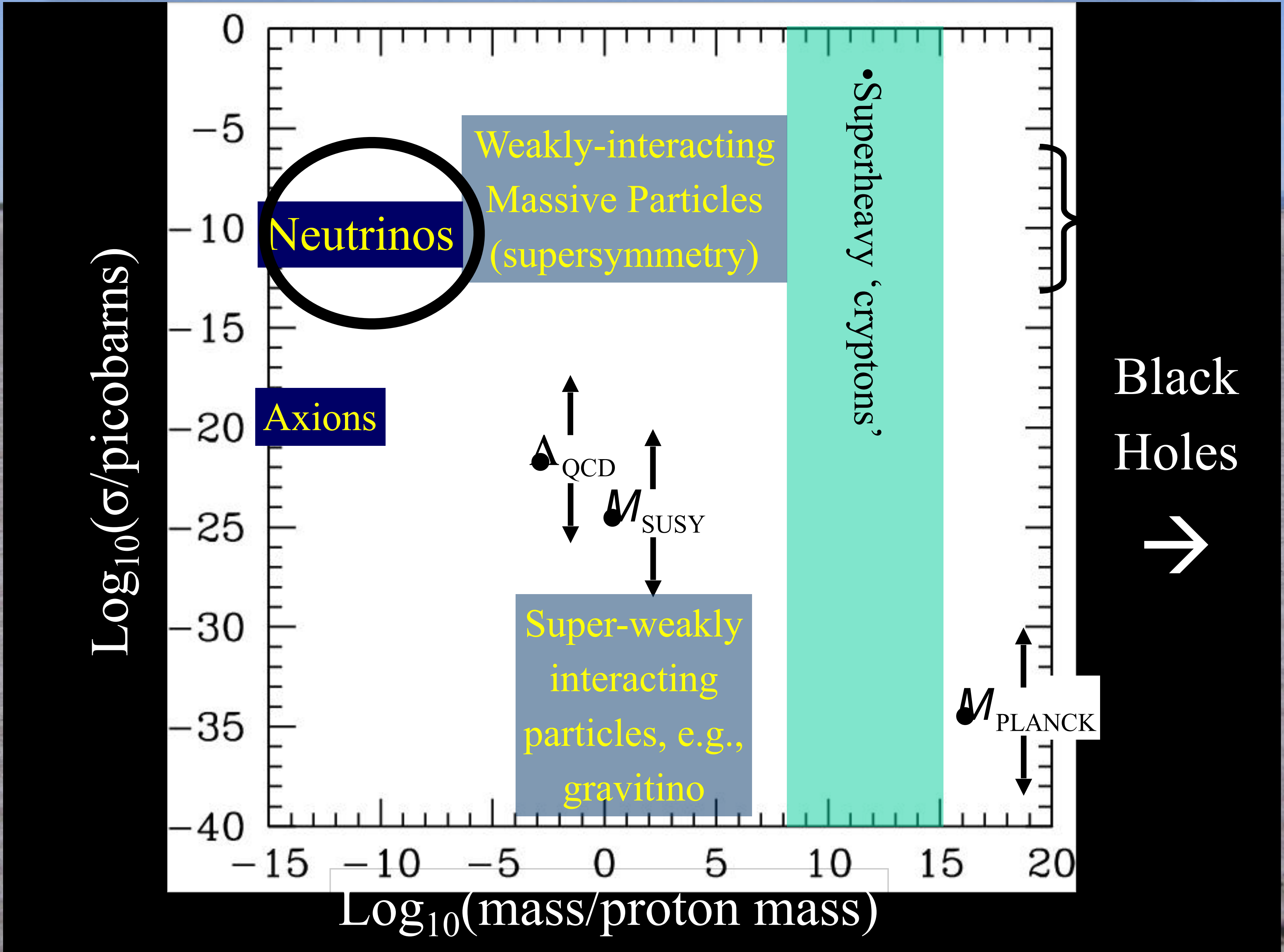


The ‘Standard Model’ of the Universe indicated by astrophysics and cosmology

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, …

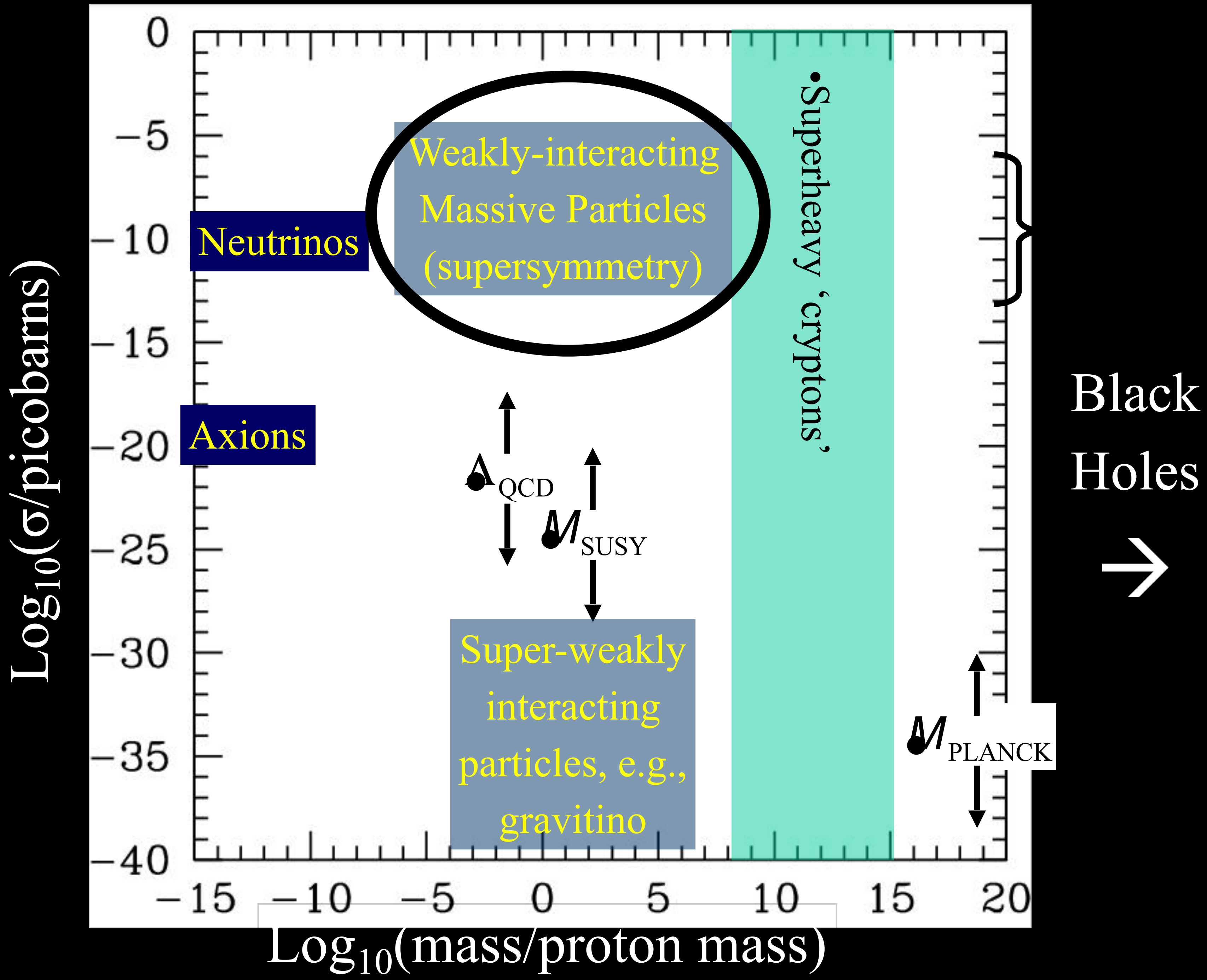
Particle Dark Matter Candidates



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? **Sterile neutrinos?**

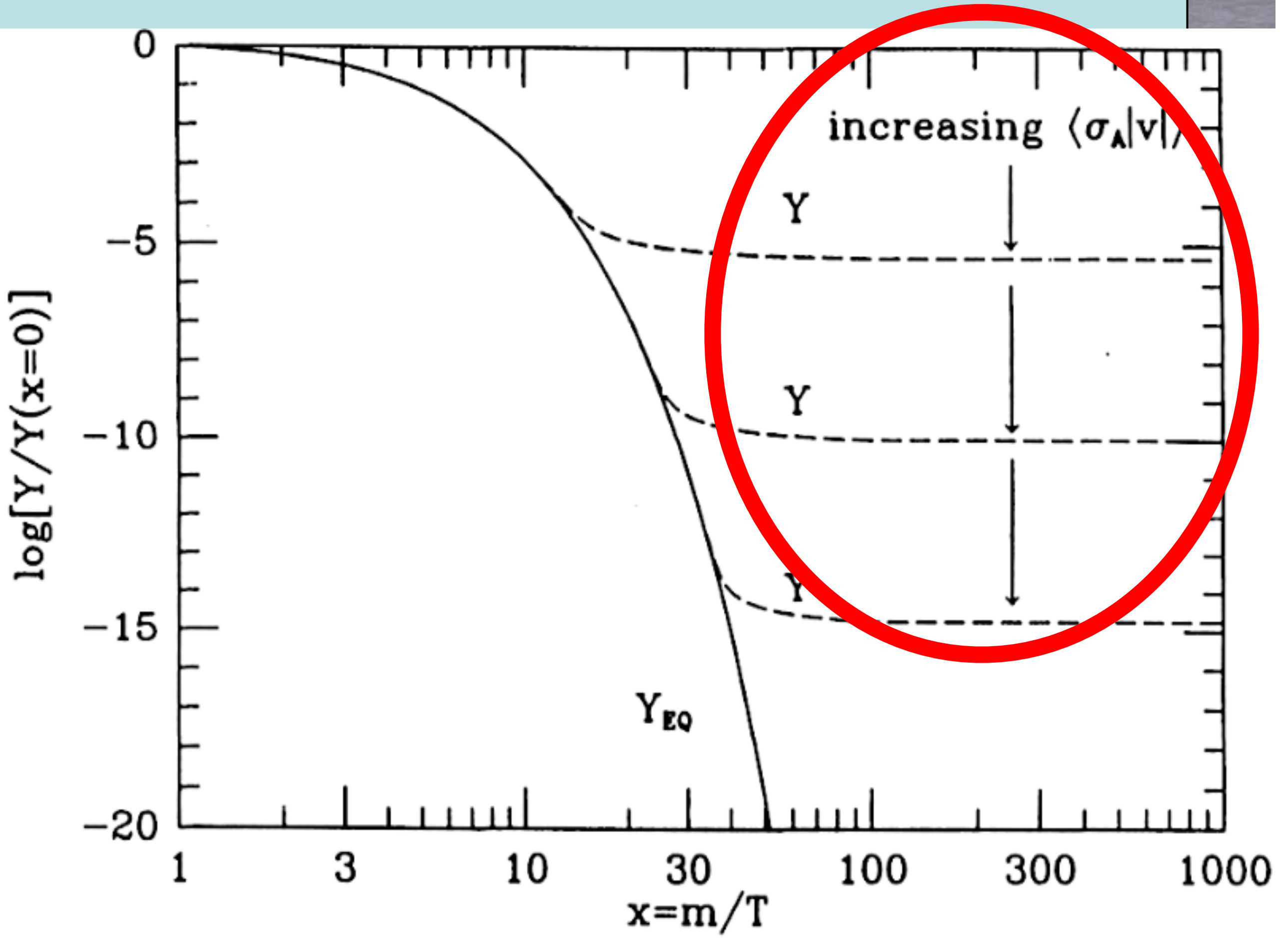
Particle Dark Matter Candidates



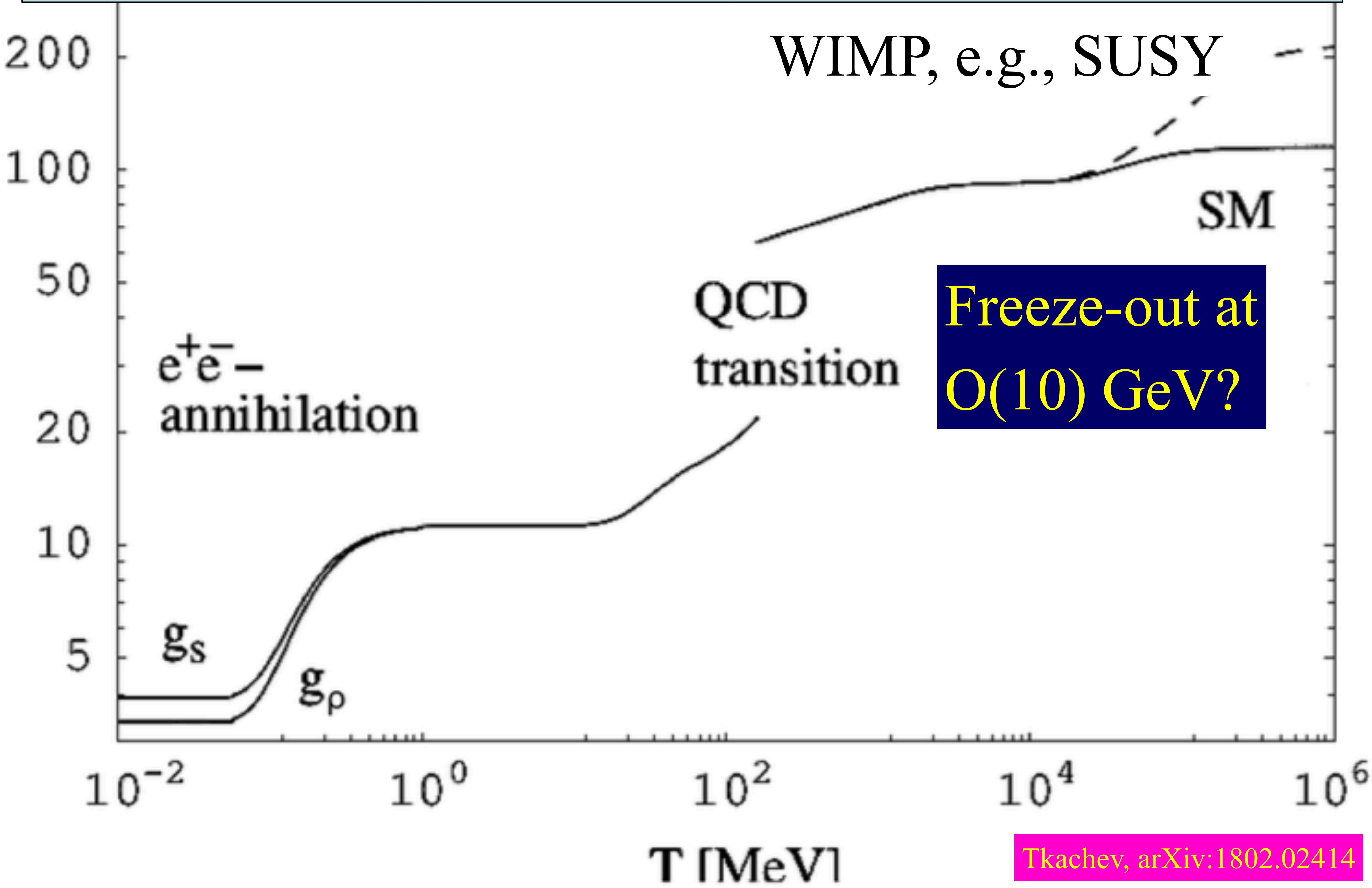
Weakly-Interacting Massive Particles (WIMPs)

- 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

Tkachev, arXiv:1802.02414



‘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:

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

- Generic annihilation cross-section:

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

- Generic relic mass:

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

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

- 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**

We still believe in supersymmetry

You must be joking!

What lies beyond the Standard Model?

Supersymmetry

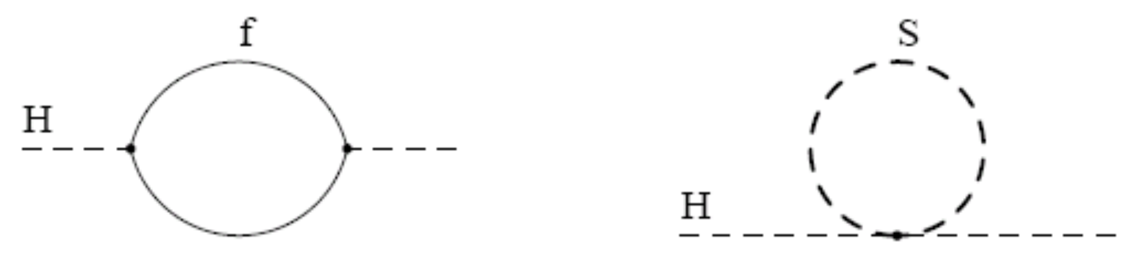
New motivations
From LHC Run 1

- **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**

Naturalness of hierarchy of mass scales

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:



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

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

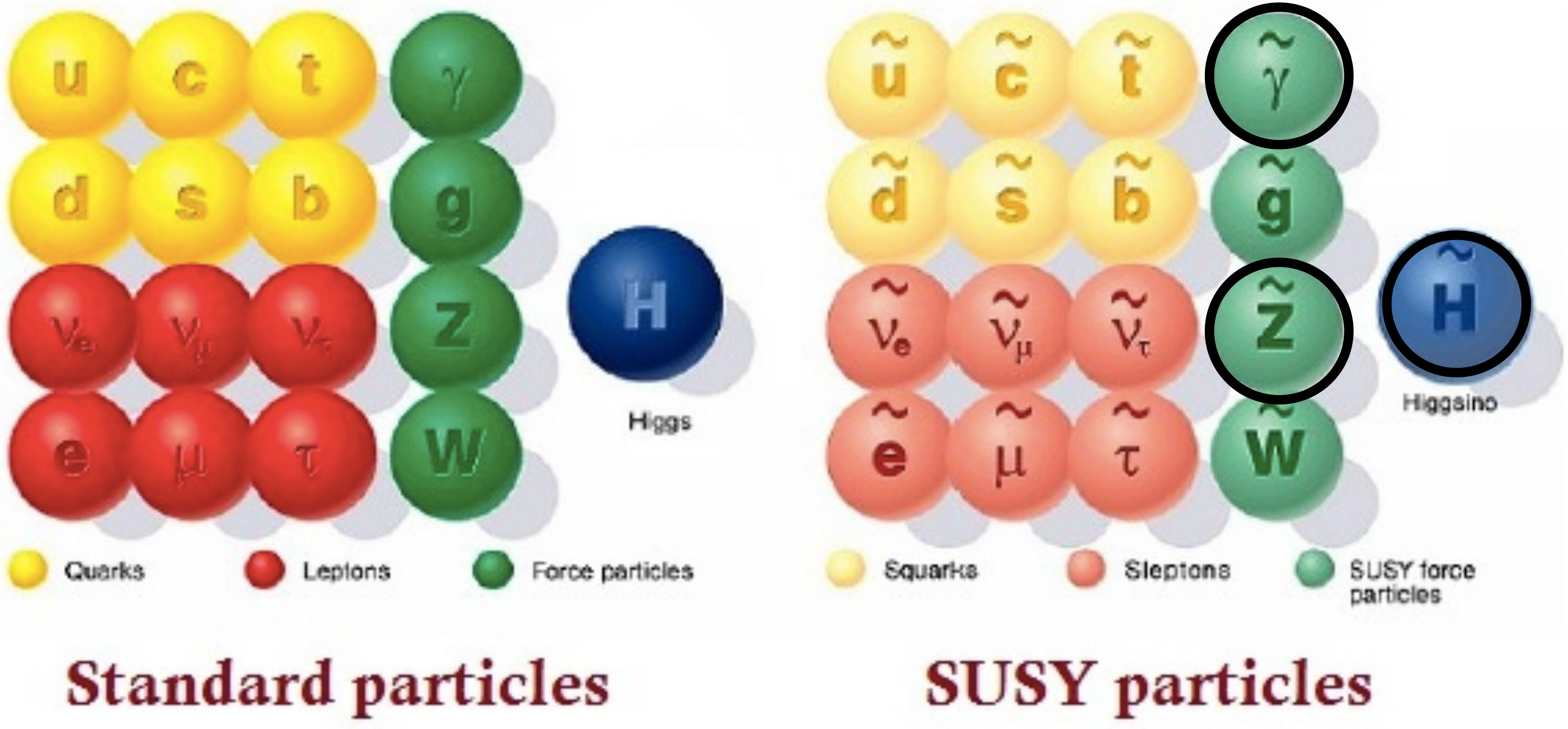
$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + \ldots]$$

- Leading divergence cancelled if

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

Minimal Supersymmetric Extension of the Standard Model

Dark Matter?



Minimal Supersymmetric Extension of 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

Parameters of the Standard Model

- Gauge sector:
  - 3 gauge couplings: g_3, g_2, g'
  - 1 strong CP-violating phase

Unification?

- Yukawa interactions:
  - 3 charge-lepton masses
  - 6 quark masses
  - 4 CKM angles and phase
- Higgs sector:
  - 2 parameters: μ, λ

Mass?

- **Total: 19 parameters**

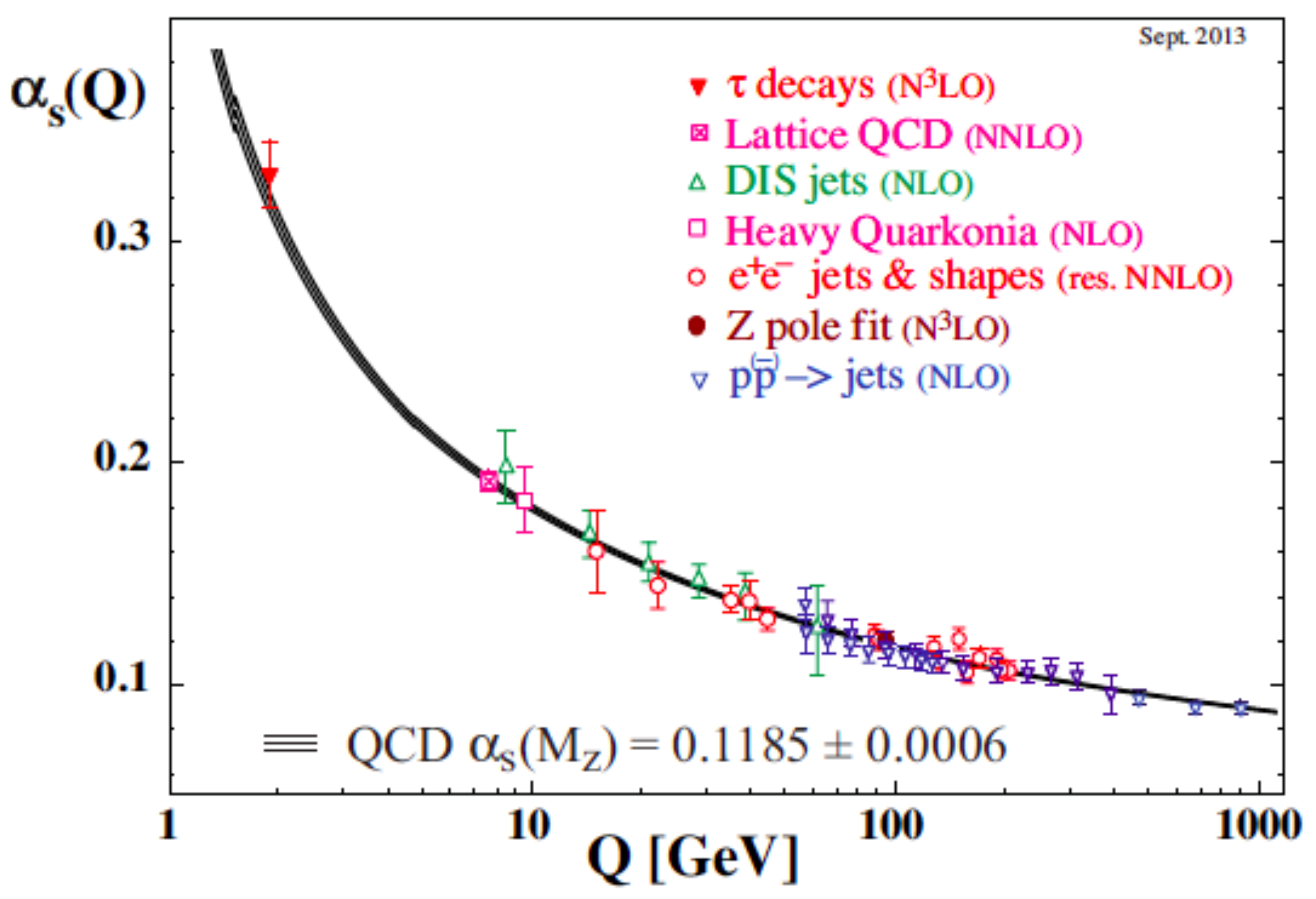
Towards Grand Unification

Pati & Salam
Georgi & Glashow
Georgi, Quinn & Weinberg

- 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**

Towards Grand Unification

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

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

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

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

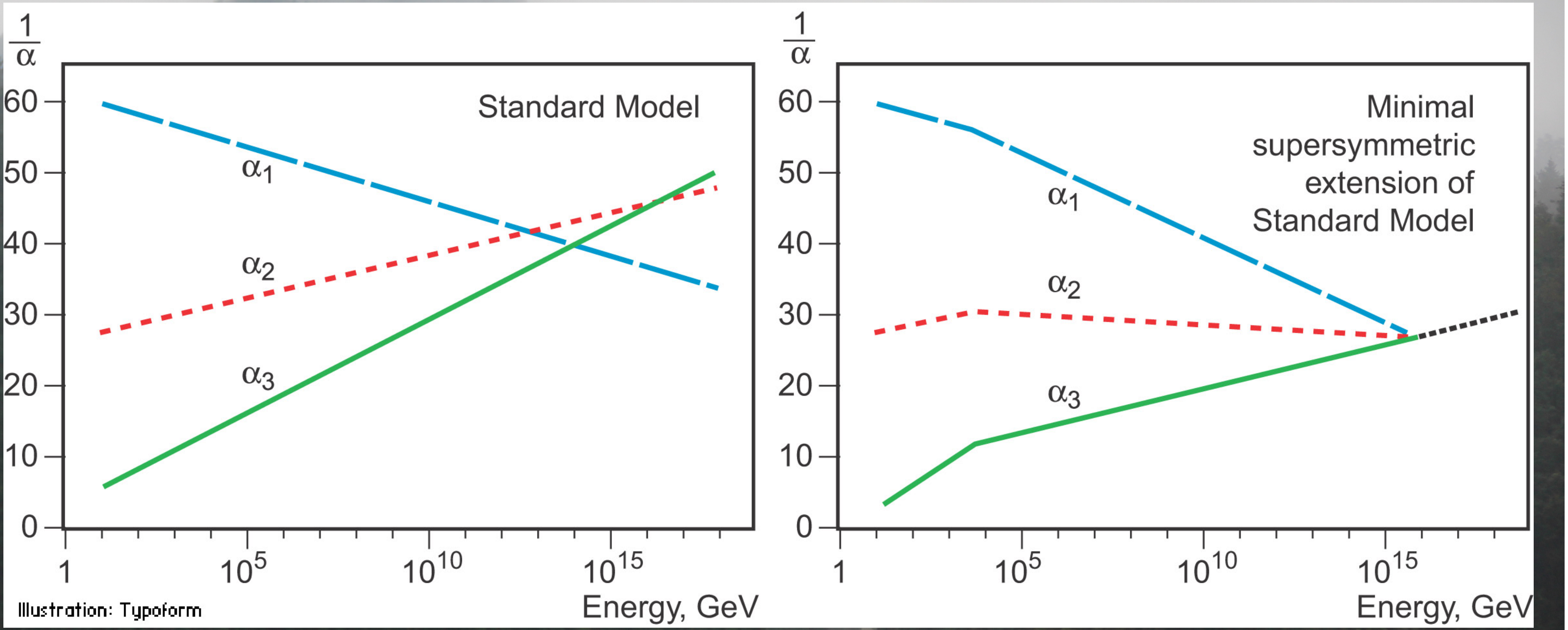
$$b_{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & -\frac{136}{3} & 0 \\ 0 & 0 & -102 \end{pmatrix} + N_g \begin{pmatrix} \frac{19}{15} & \frac{3}{5} & \frac{44}{15} \\ \frac{1}{5} & \frac{49}{3} & 4 \\ \frac{4}{30} & \frac{3}{2} & \frac{76}{3} \end{pmatrix} + N_H \begin{pmatrix} \frac{9}{50} & \frac{9}{10}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

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

1974

Georgi, Quinn & Weinberg

Grand Unification of Couplings



Almost works with just Standard Model particles
Better with supersymmetric particles

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:

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

- Data:

$$\boxed{x = \frac{1}{6.92\pm0.07}}$$

1974

Georgi & Glashow

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

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

- “Explain” “random” quantum numbers
- **Renormalization prediction** $\sin^2\theta_W \simeq 0.22$

Lightest Supersymmetric Particle

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

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

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

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

  Sparticles produced in pairs

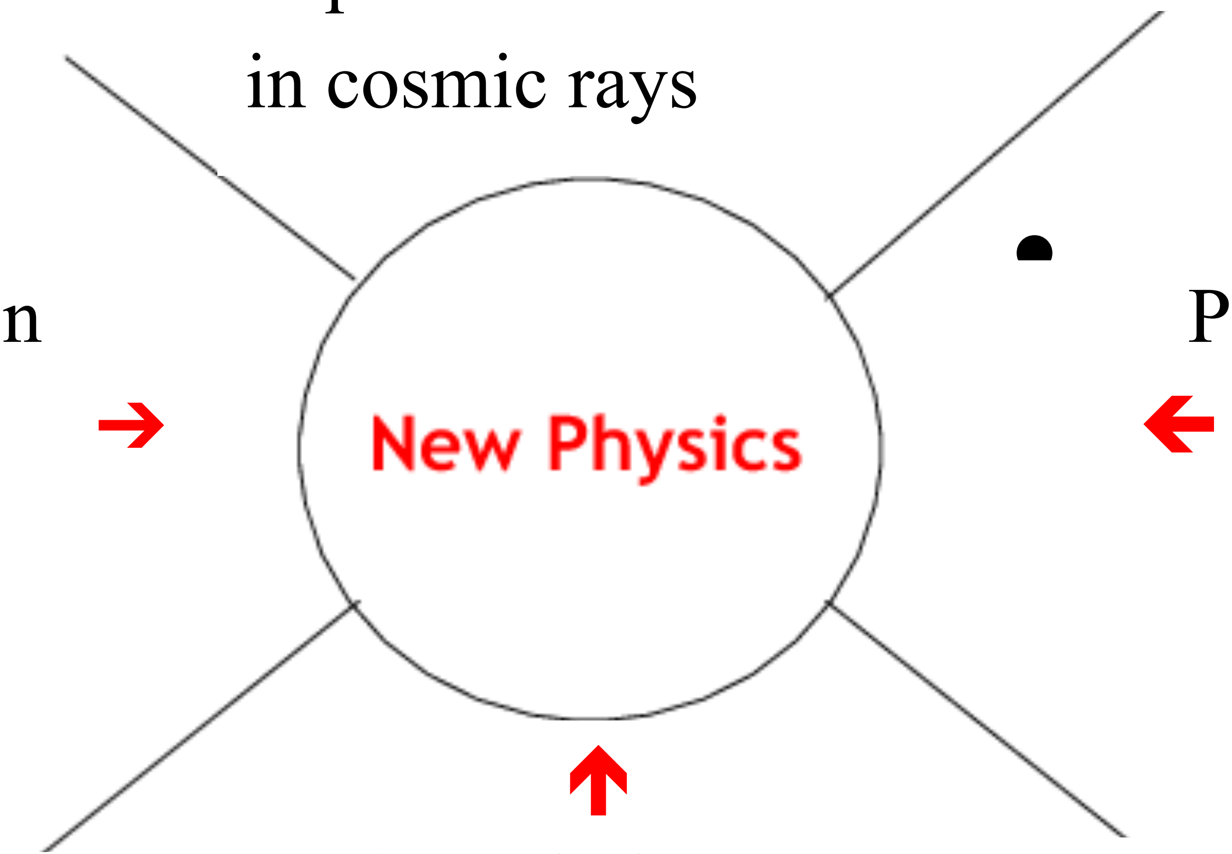
  Heavier sparticles → lighter sparticles

- **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)

Searches for WIMP Dark Matter



Dark Matter

Annihilation
to particles
in cosmic rays →

Standard Model

Annihilation
in the early
Universe →

New Physics

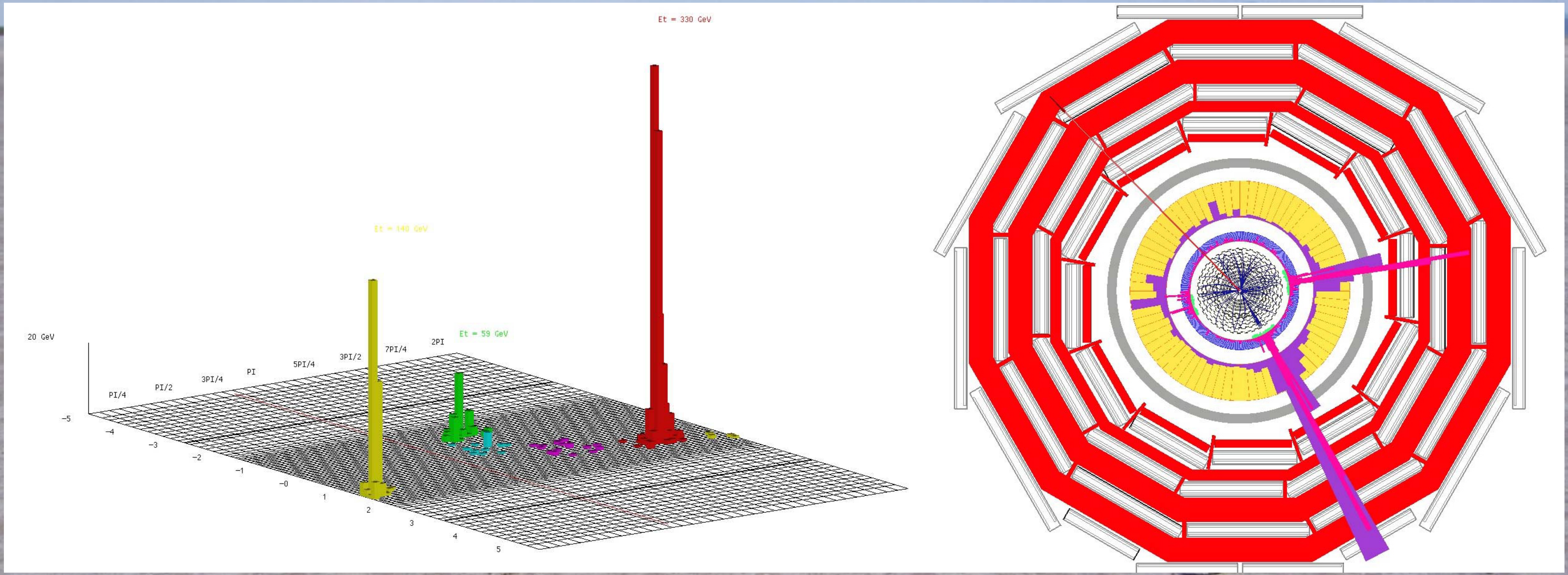
Production
← at
particle
colliders

↑
Direct dark matter
detection

Dark Matter

Standard Model

Classic LHC Dark Matter Signature

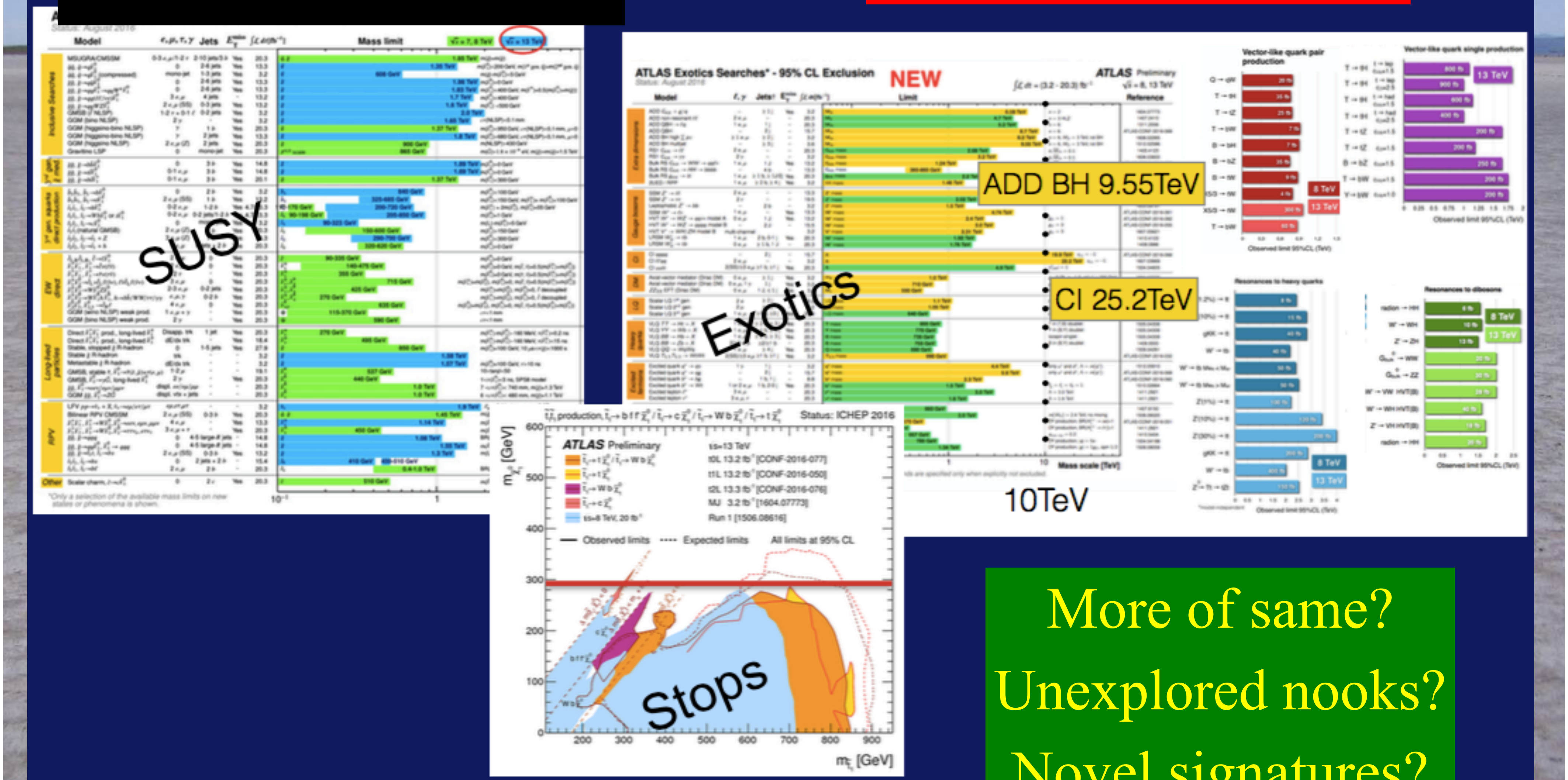


Missing transverse energy
carried away by dark matter particles

Nothing (yet) at the LHC

No supersymmetry

Nothing else, either



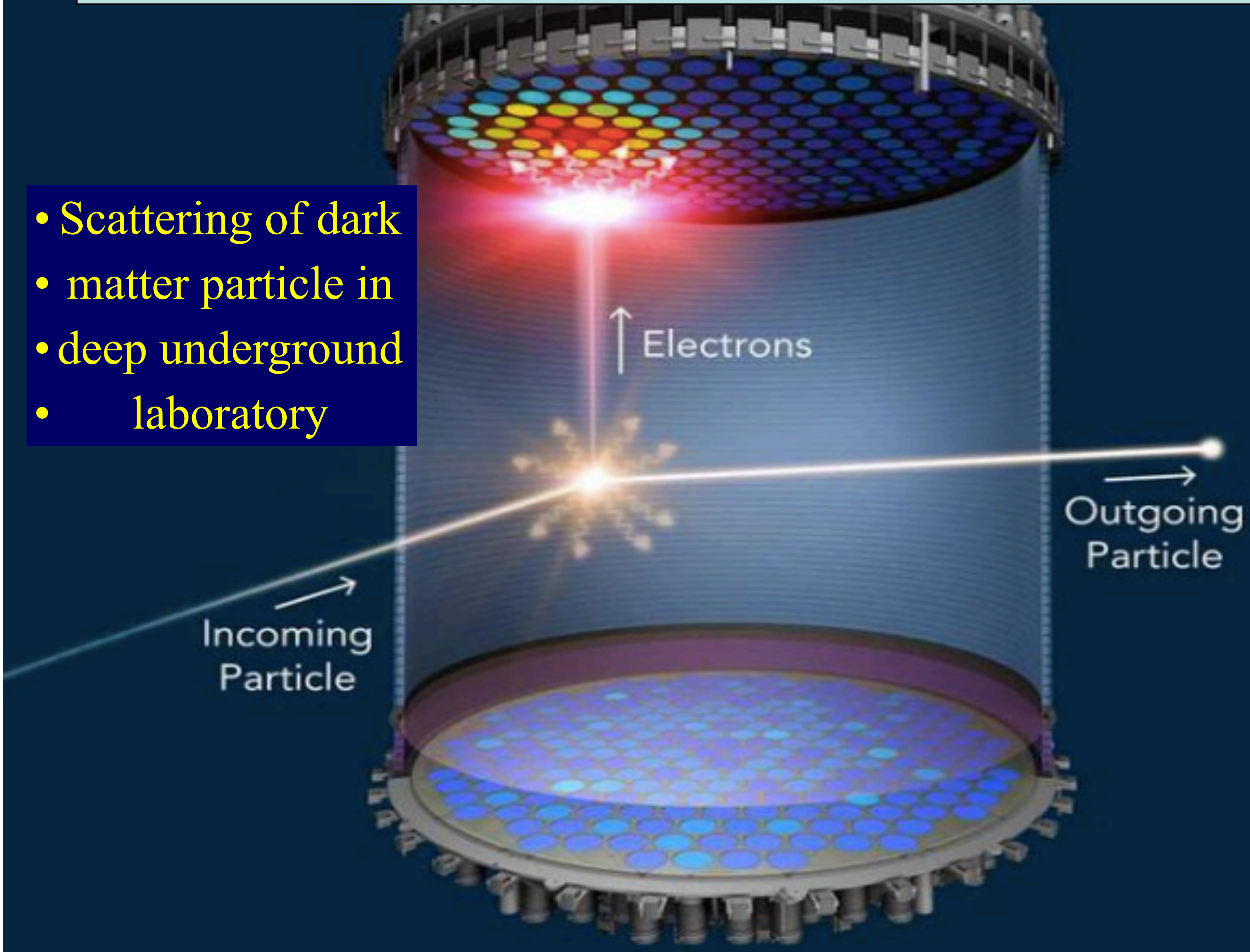
More of same?

Unexplored nooks?

Novel signatures?

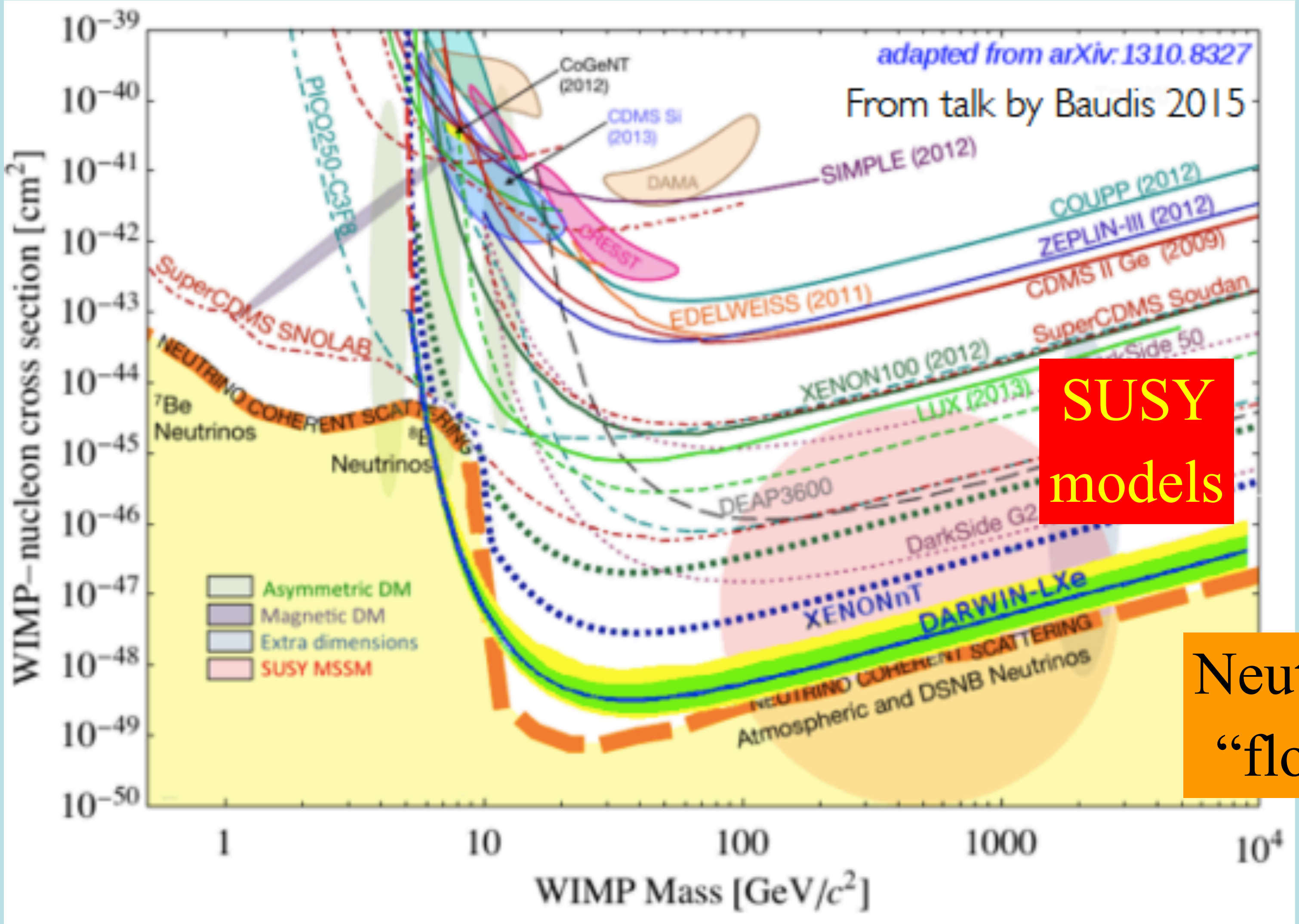
Direct Dark Matter Detection

- Scattering of dark
- matter particle in
- deep underground
- laboratory



Direct Dark Matter Searches

- Compilation of present and future sensitivities



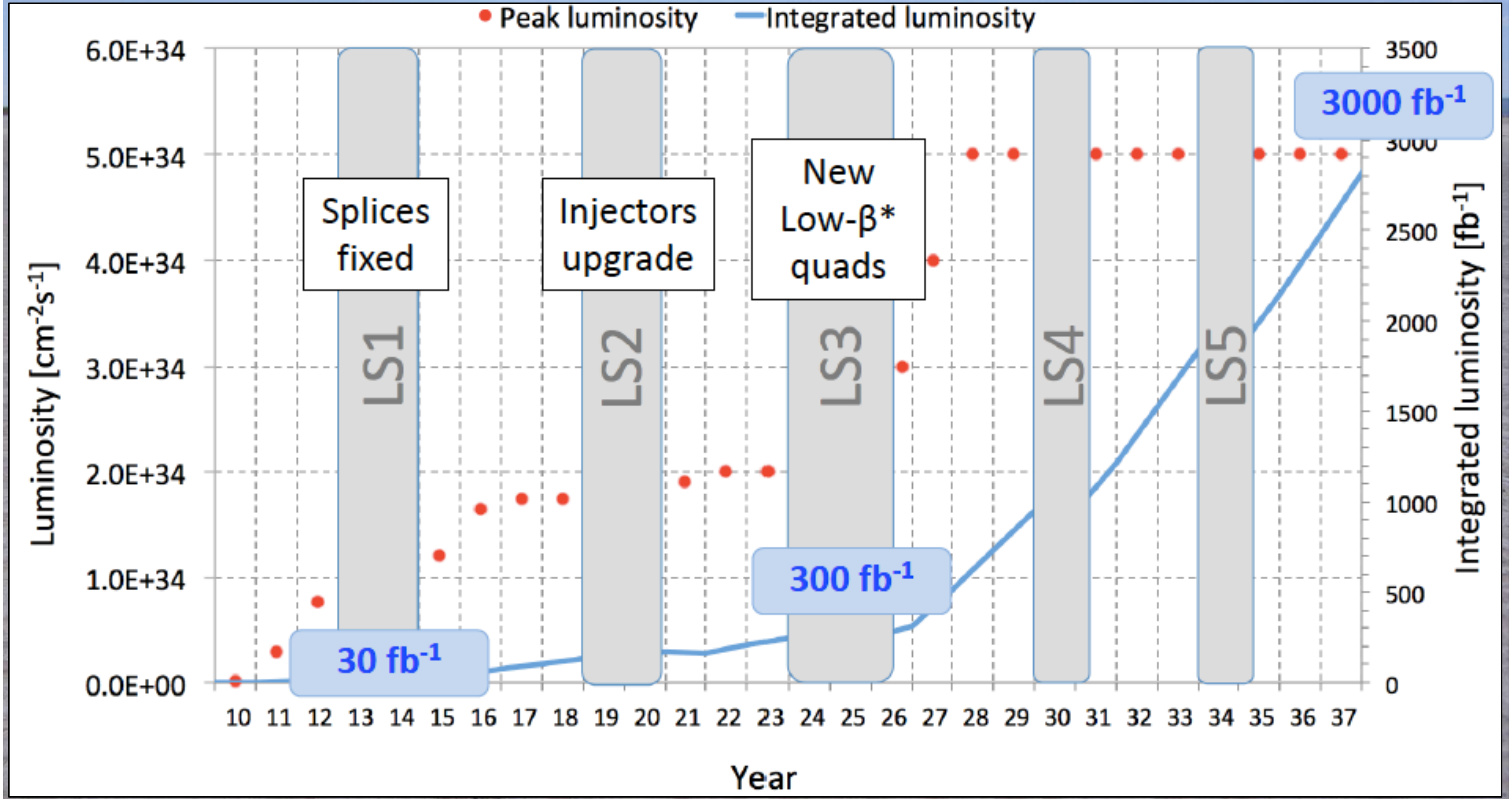
adapted from arXiv:1310.8327

From talk by Baudis 2015

SUSY models

Neutrino “floor”

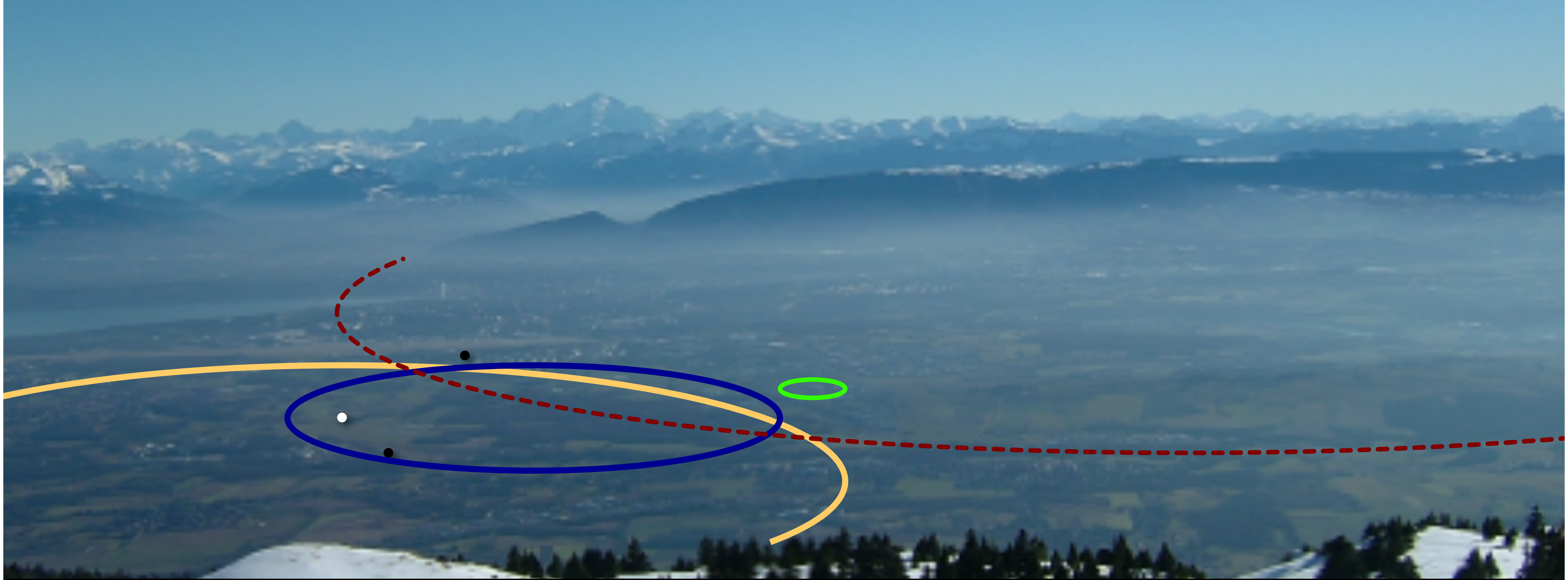
The LHC in Future Years



CEPC-SPPC

Preliminary Conceptual Design Report

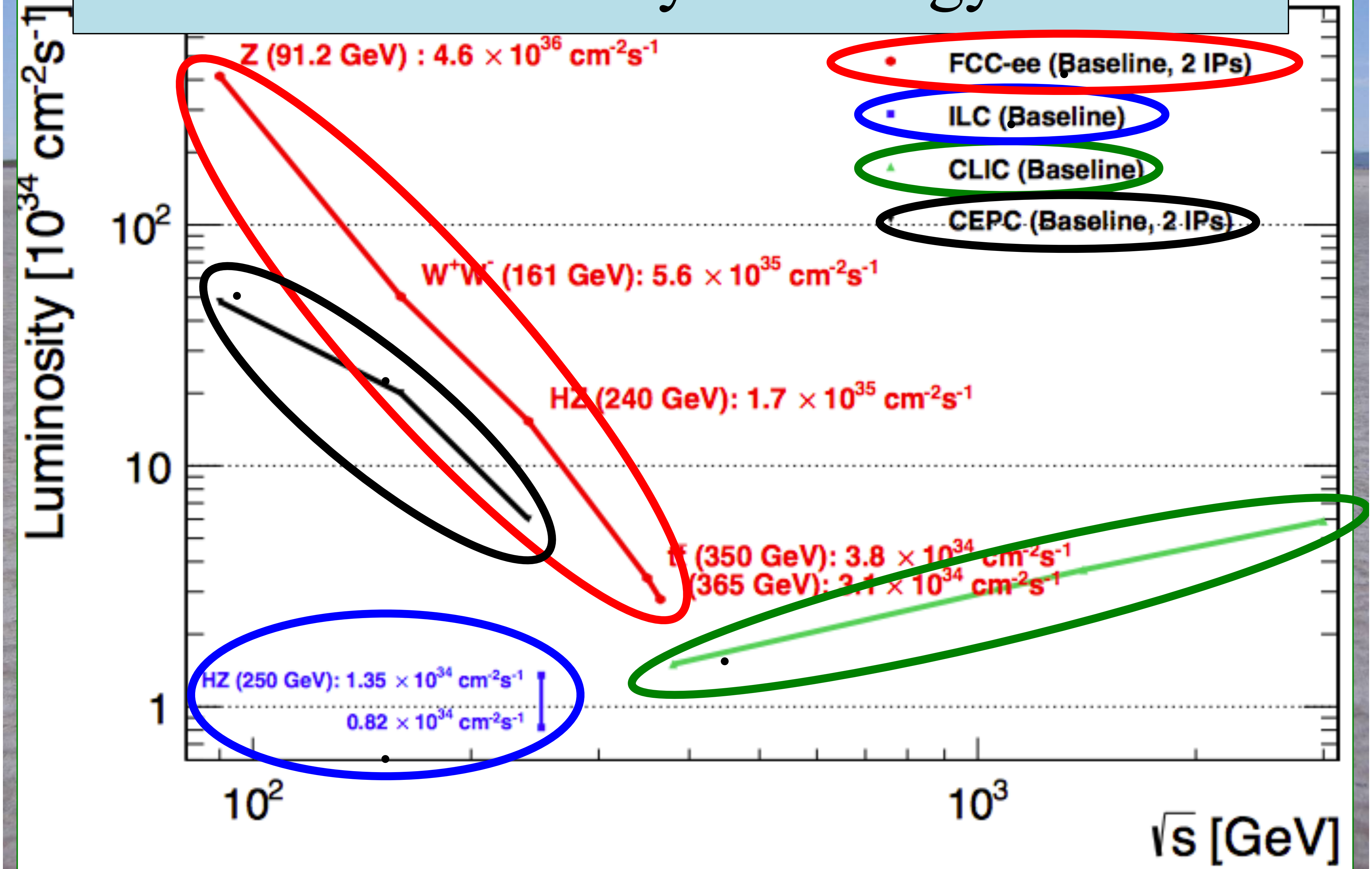
Future Circular Colliders?



The vision:

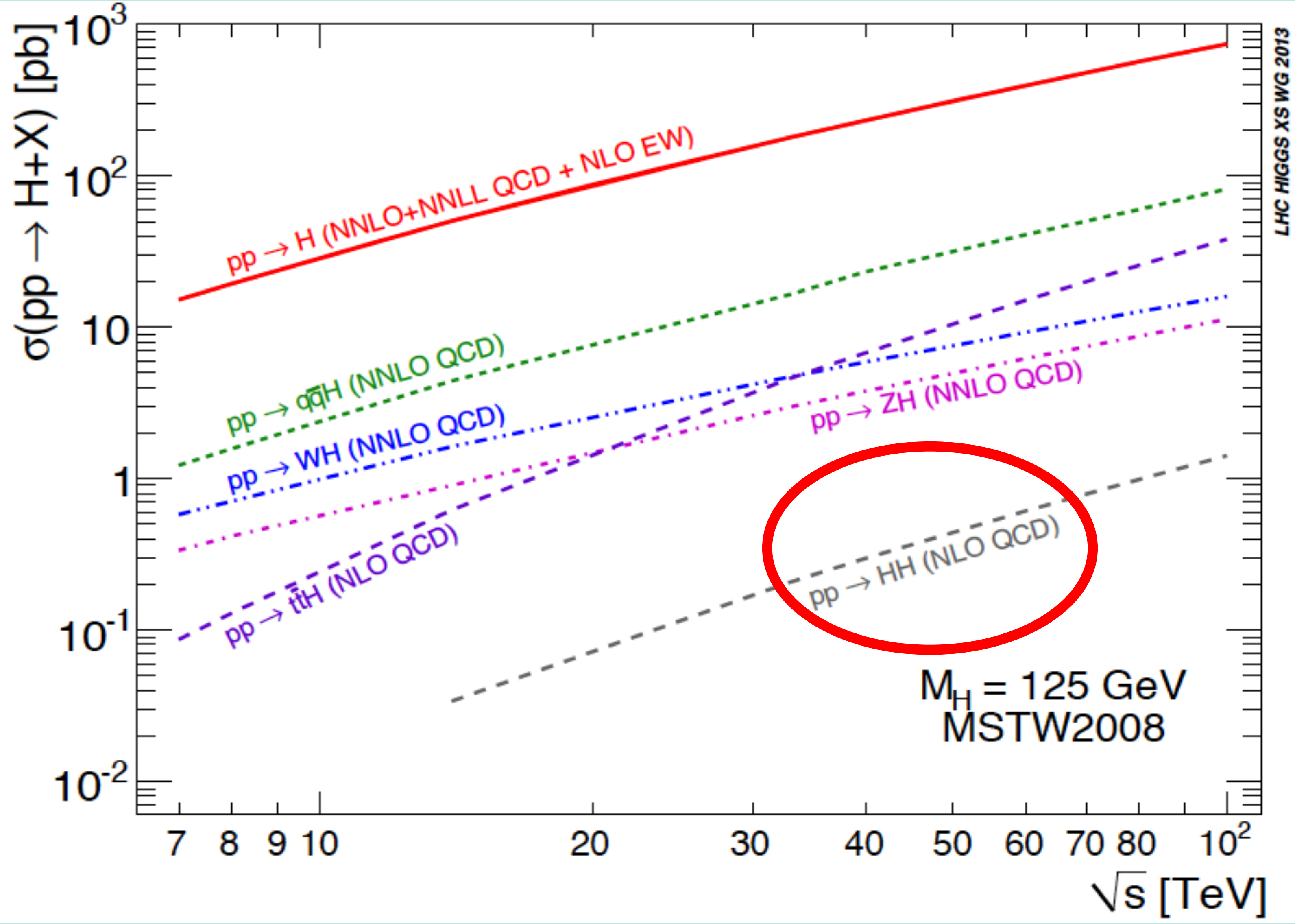
explore 10 TeV scale directly (100 TeV pp) + indirectly (e^+e^-)

Projected e+e- Colliders: Luminosity vs Energy

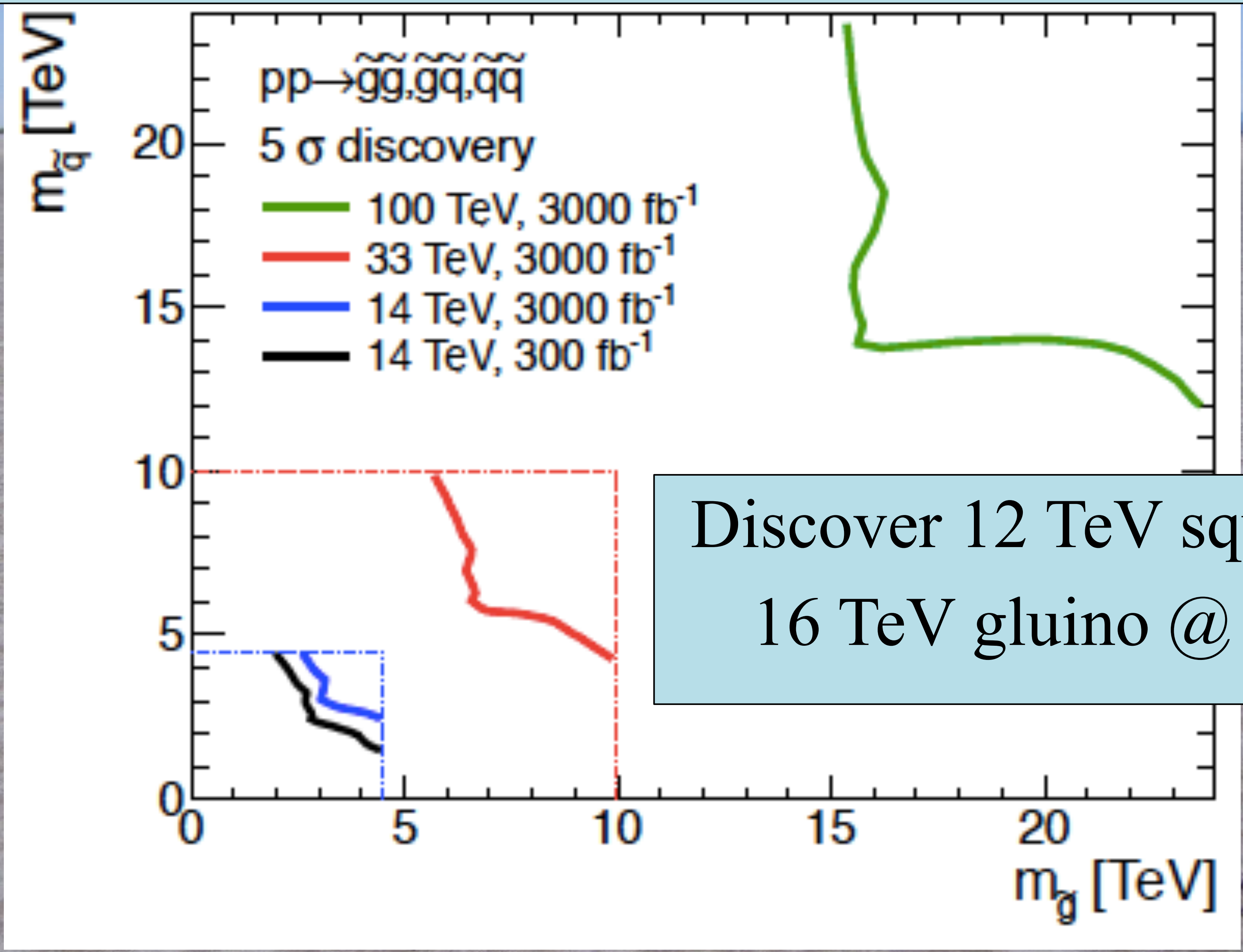


Higgs Cross Sections

- At the LHC and beyond:

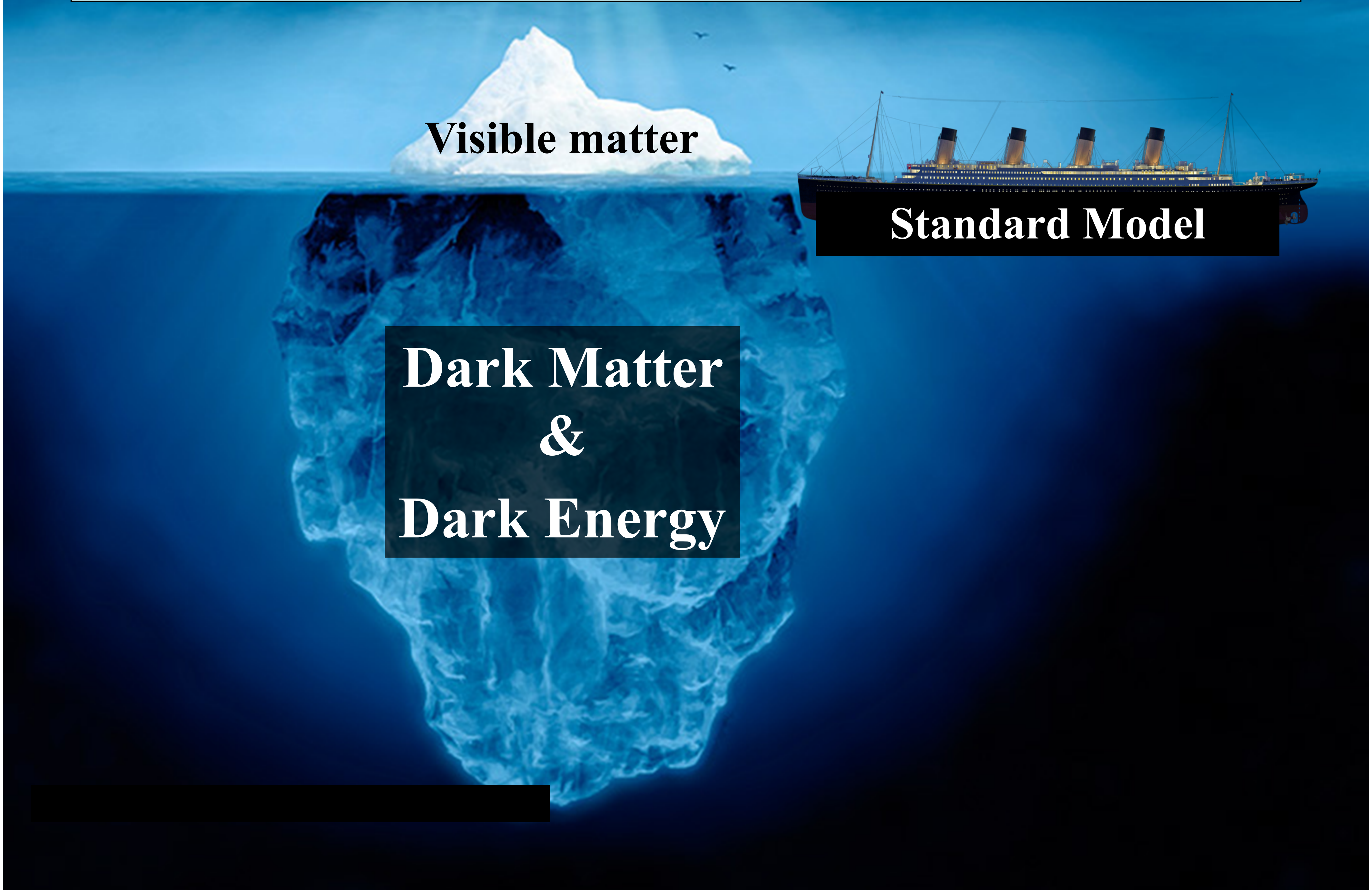


Squark-Gluino Plane



Discover 12 TeV squark, 16 TeV gluino @ 5σ

Summary



[redacted]