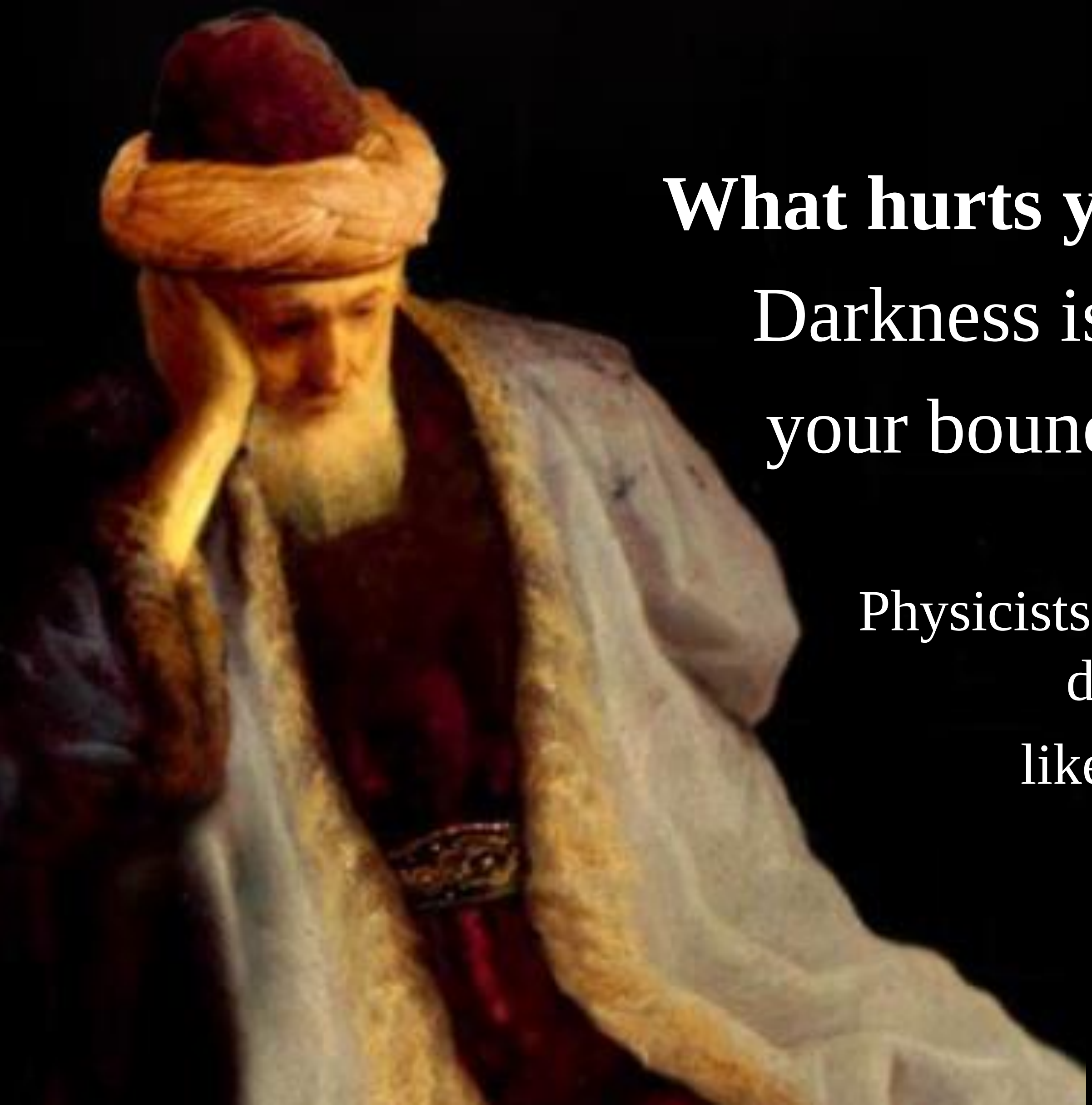
The Dark Side of the Universe



What hurts you, blesses you.

Darkness is your candle,

your boundaries are your quest

Physicists are attracted by what they do not understand,

like moths by a candle

John Ellis

KING'S College LONDON

The ‘Standard Model’

Describes all the VISIBLE matter in the Universe

But what about the INVISIBLE dark matter?

Summary of the Standard Model

- Particles and SU(3) × SU(2) × U(1) quantum numbers:

L_L	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$	$(\mathbf{1},\mathbf{2},-1)$
E_R	$e_R^- , \mu_R^- , \tau_R^-$	$(\mathbf{1},\mathbf{1},-2)$
Q_L	$\begin{pmatrix} u \\ d \end{pmatrix}_L , \begin{pmatrix} c \\ s \end{pmatrix}_L , \begin{pmatrix} t \\ b \end{pmatrix}_L$	$(\mathbf{3},\mathbf{2},+1/3)$
U_R	u_R , c_R , t_R	$(\mathbf{3},\mathbf{1},+4/3)$
D_R	d_R , s_R , b_R	$(\mathbf{3},\mathbf{1},-2/3)$

- Lagrangian:

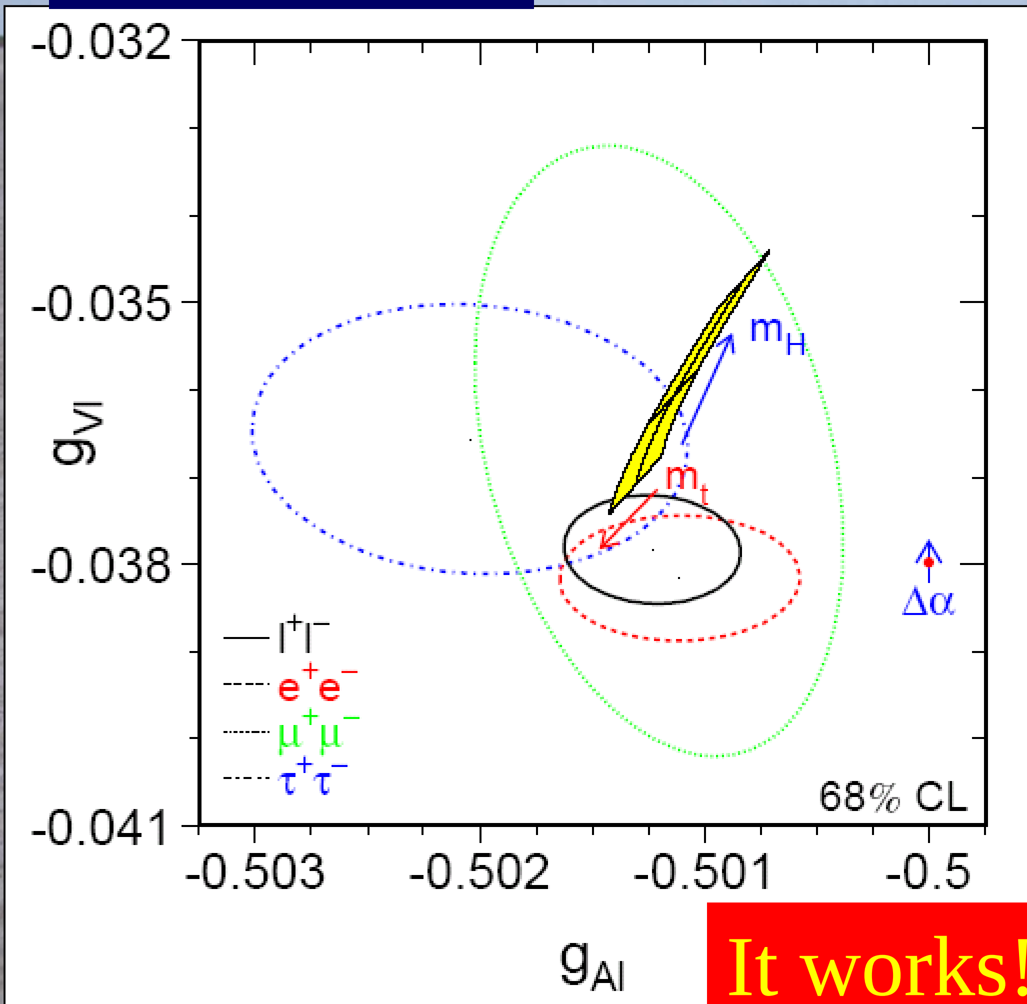
$$\begin{aligned} \mathcal{L} &= -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} && \text{gauge interactions} \\ &+ i\bar{\psi}\, \not{D} \psi + h.c. && \text{matter fermions} \\ &+ \psi_i y_{ij} \psi_j \phi + h.c. && \text{Yukawa interactions} \\ &+ |D_\mu \phi|^2 - V(\phi) && \text{Higgs potential} \end{aligned}$$

Many tests

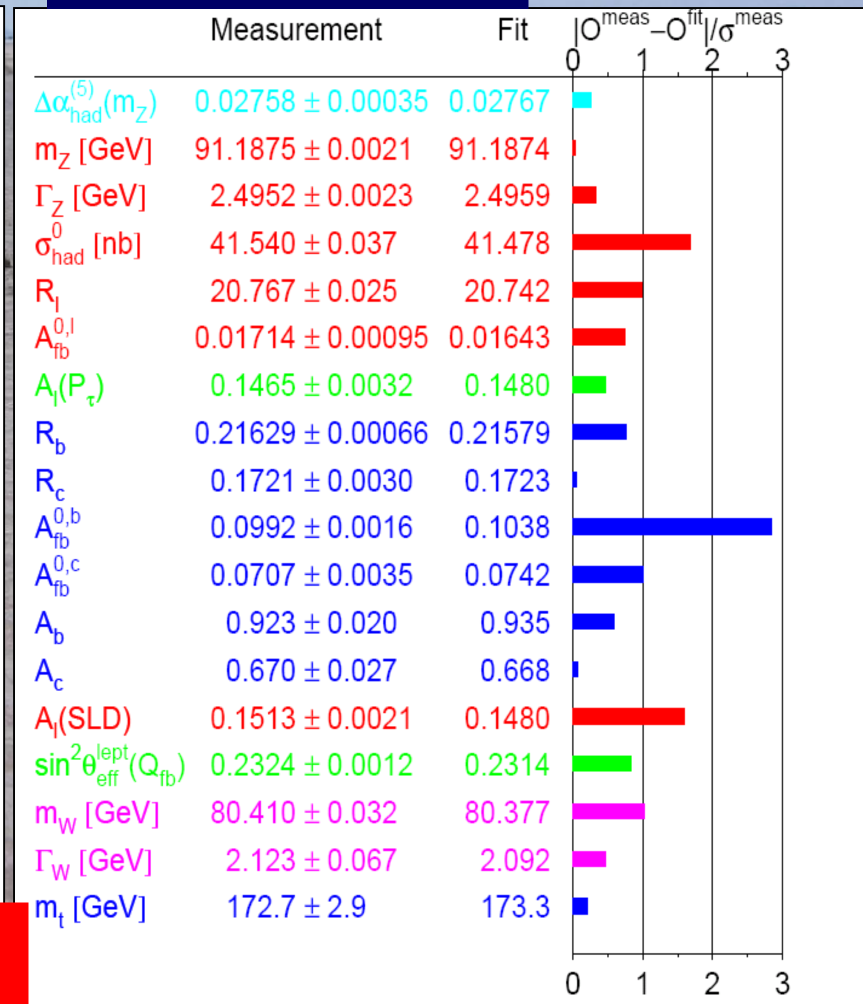
Checked only recently

Precision Tests of the Standard Model

Lepton couplings



Pulls in global fit



It works!

A Phenomenological Profile of the Higgs Boson

- First attempt at systematic survey

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

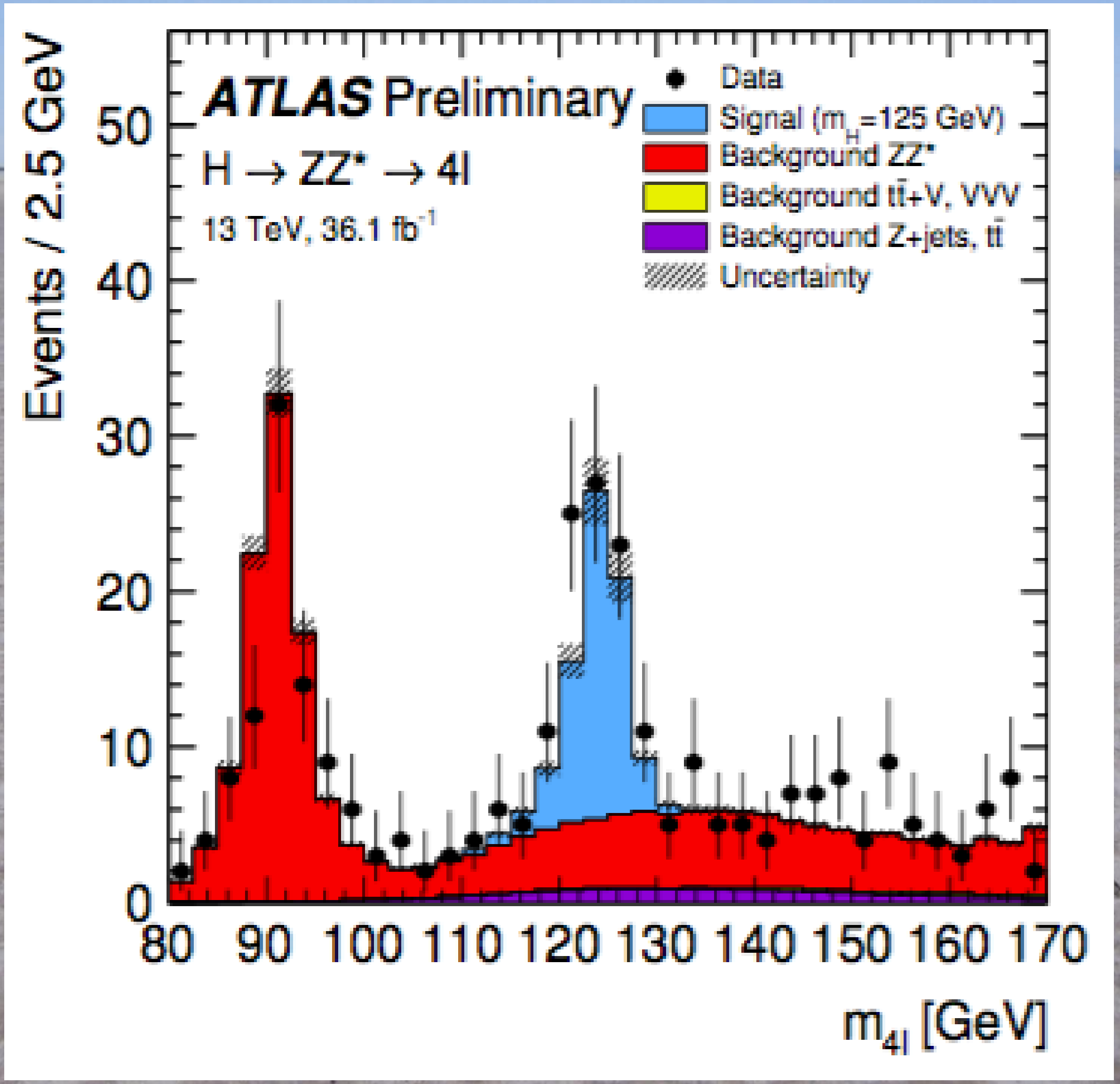
John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

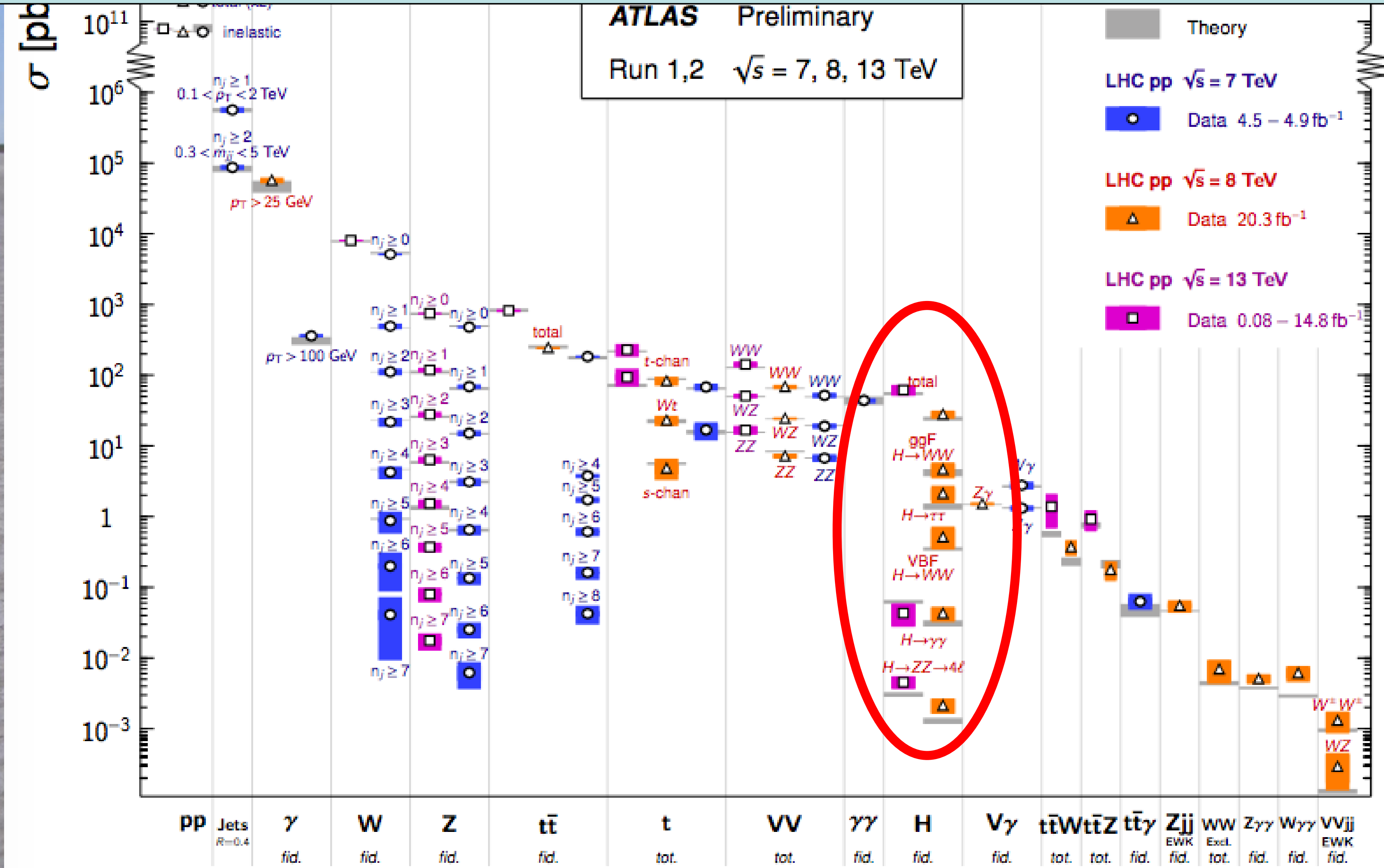
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

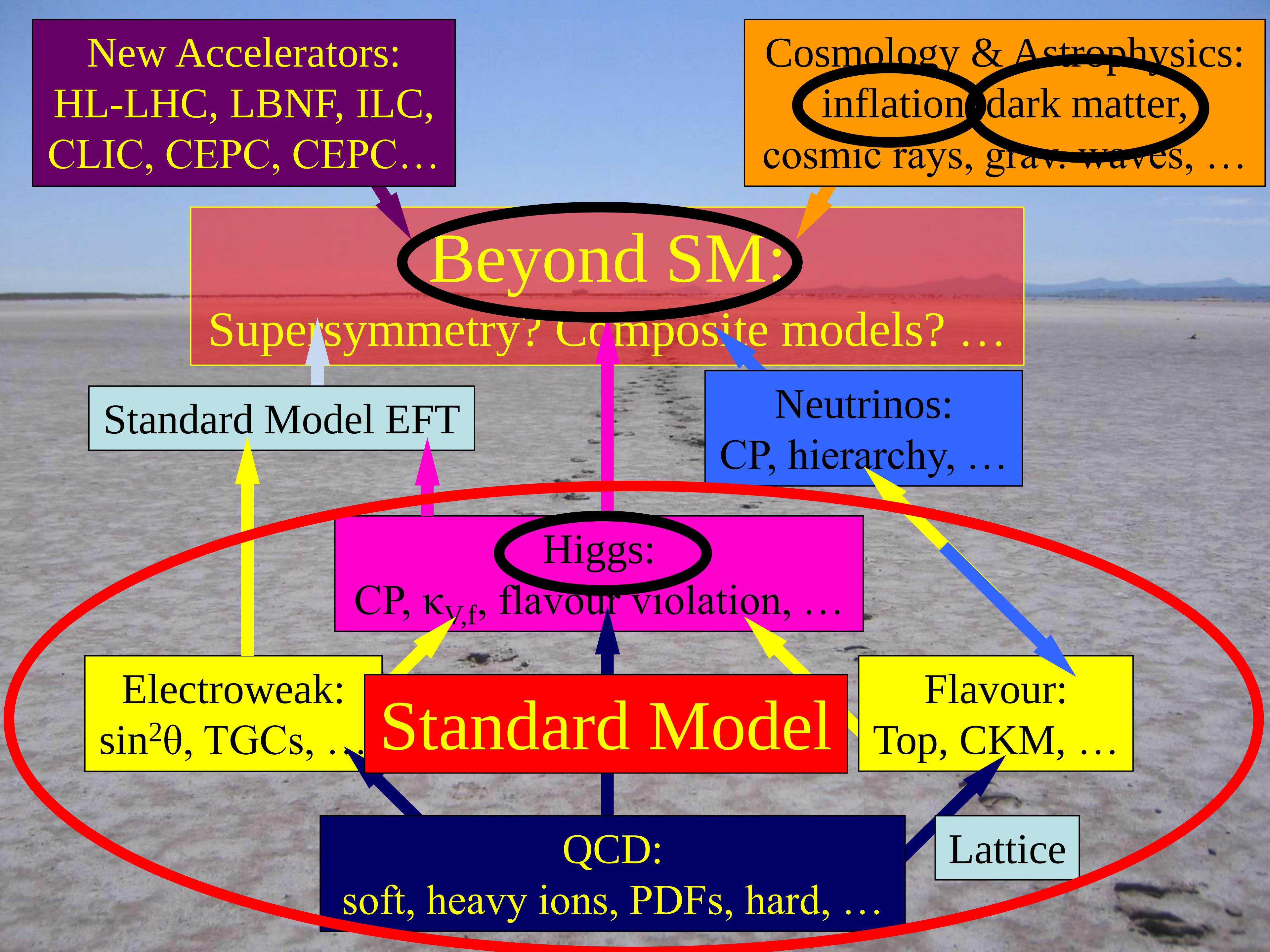
How the Higgs Signal Grew



“Stairway to Heaven”

Standard Model Cross-Sections @ LHC




New Accelerators:
HL-LHC, LBNF, ILC,
CLIC, CEPC, CEPC…
Cosmology & Astrophysics:
inflation, dark matter,
cosmic rays, grav. waves, …
Beyond SM:
Supersymmetry? Composite models? …
Standard Model EFT
Neutrinos:
CP, hierarchy, …
Higgs:
CP, $\kappa_{V,f}$, flavour violation, …
Electroweak:
$\sin^2\theta$, TGCs, …
Standard Model
Flavour:
Top, CKM, …
QCD:
soft, heavy ions, PDFs, hard, …
Lattice

- « Empty » space is unsta SUSY
- Dark matter SUSY
- Origin of matter SUSY
- Masses of neutrinos
- Hierarchy problem SUSY
- Inflation SUSY
- Quantum gravity SUSY
- …

The Standard Model

The Dark Matter Hypothesis

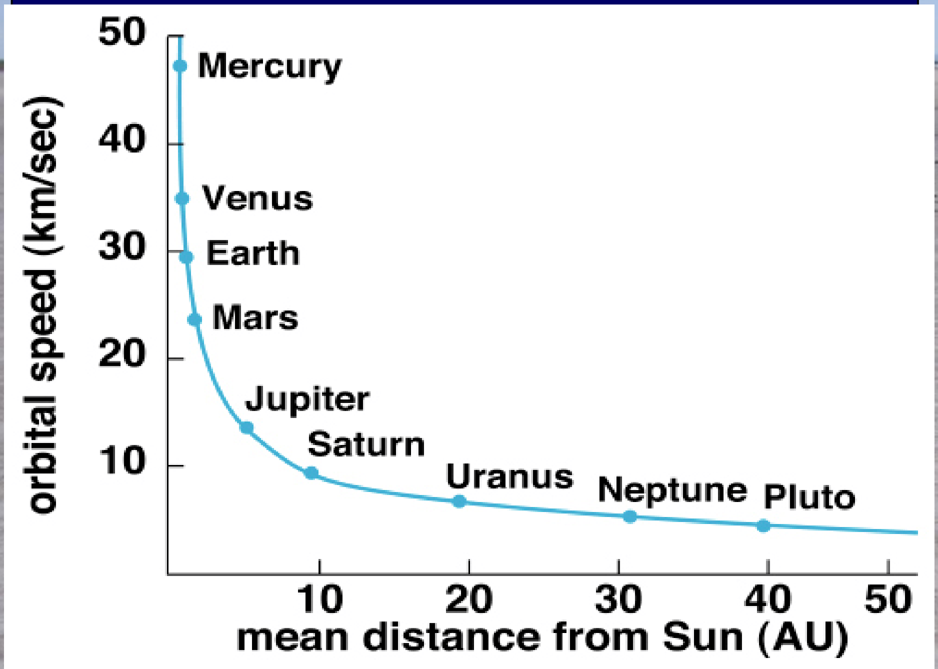
- Proposed by Fritz Zwicky, based on observations of the Coma galaxy cluster
- The galaxies move too quickly
- The observations require a stronger gravitational field than provided by the visible matter
- **Dark matter?**

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
- **Further strong evidence for dark matter**

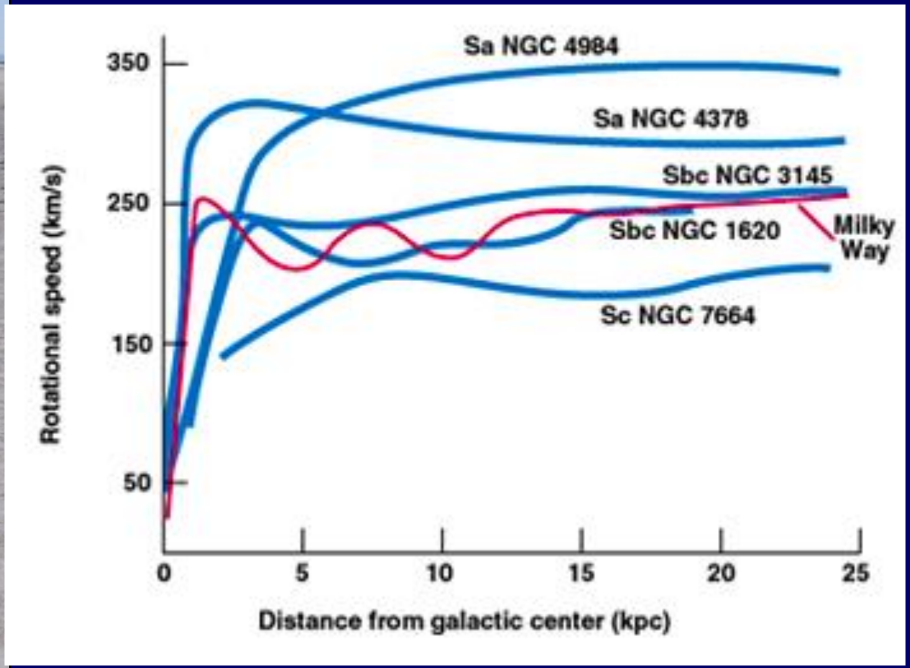
Rotation Curves

- In the Solar System



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

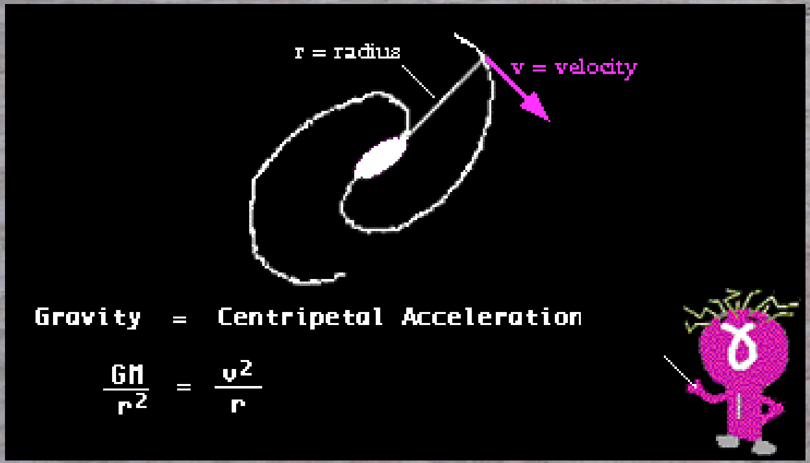
- In galaxies



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

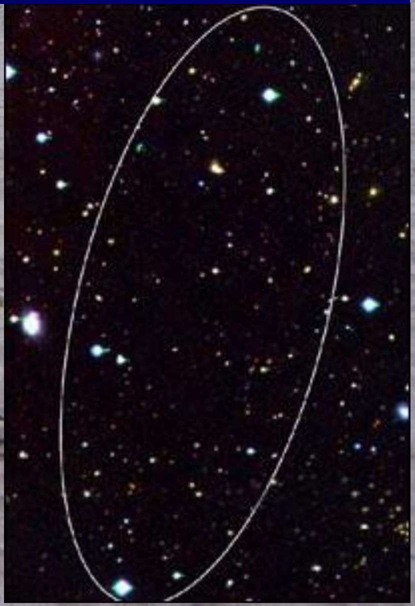
More Evidence for Dark Matter

Galaxies rotate more rapidly than allowed by centripetal force due to visible matter



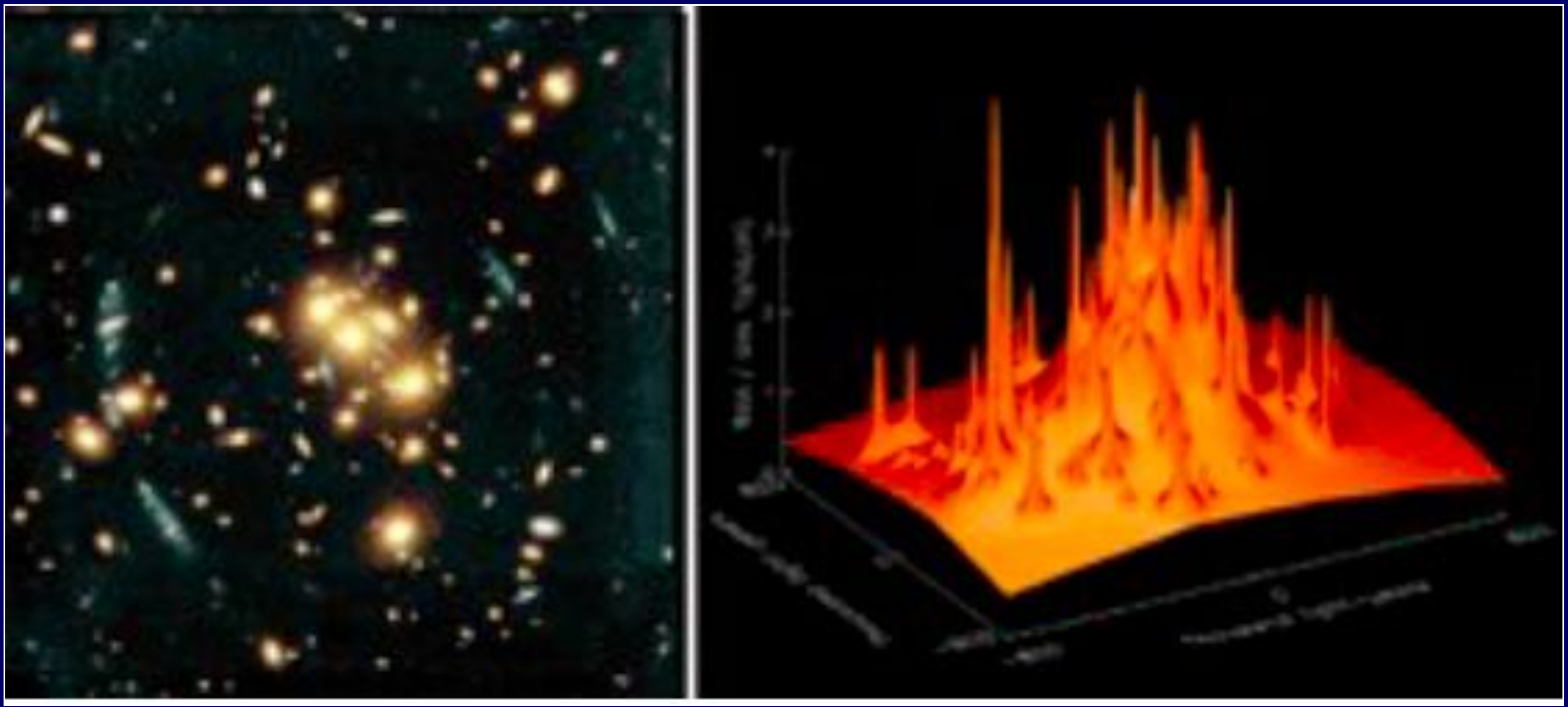
X-ray emitting gas held in place by extra dark matter

Even a ‘dark galaxy’ without stars



Gravitational Lensing

- Reveal all the matter

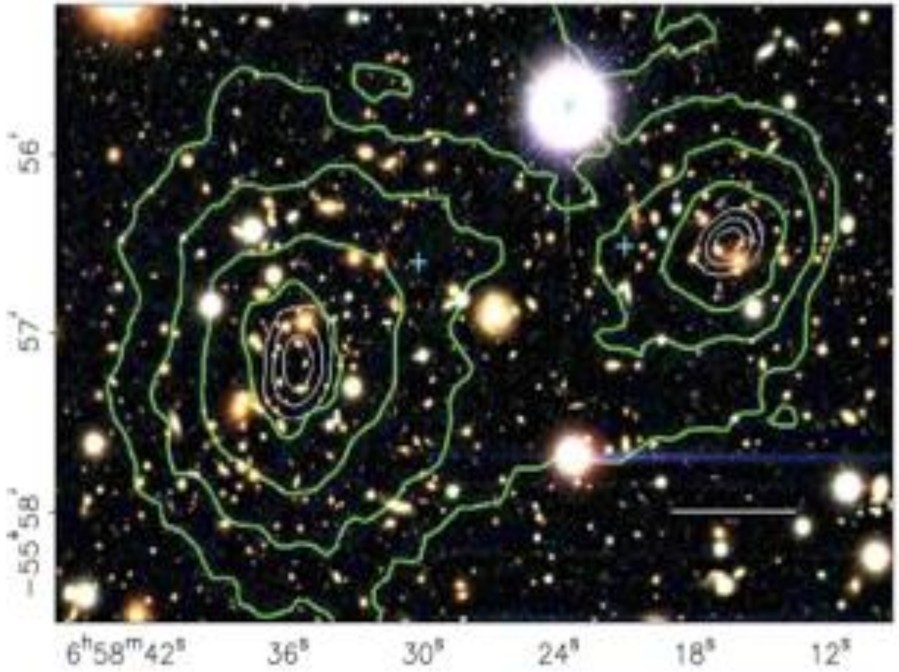


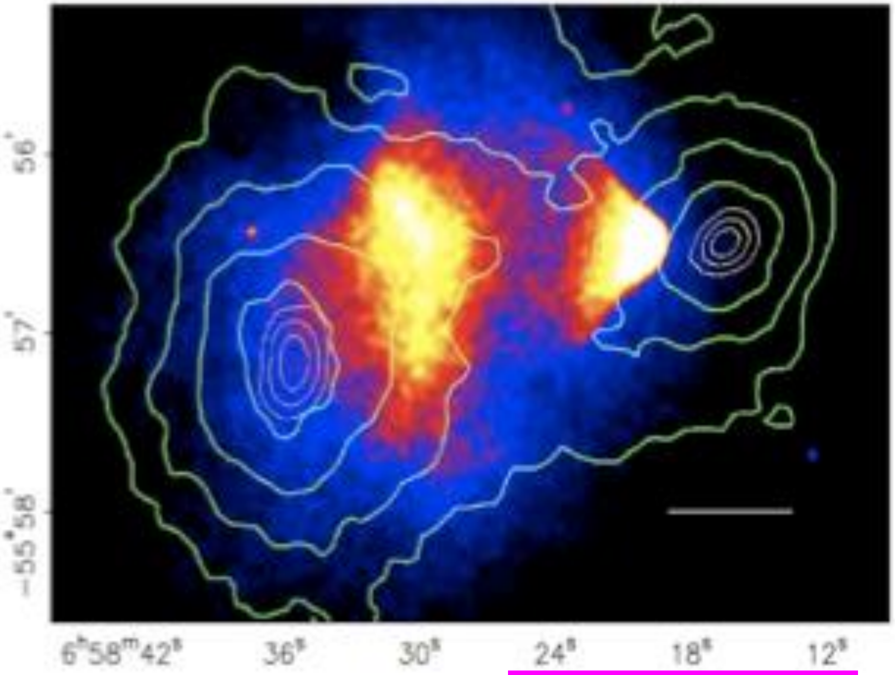
- Galaxies = peaks on a background of dark matter

More Evidence for Dark Matter

Collision between
2 clusters of galaxies:
Dark matter passes through

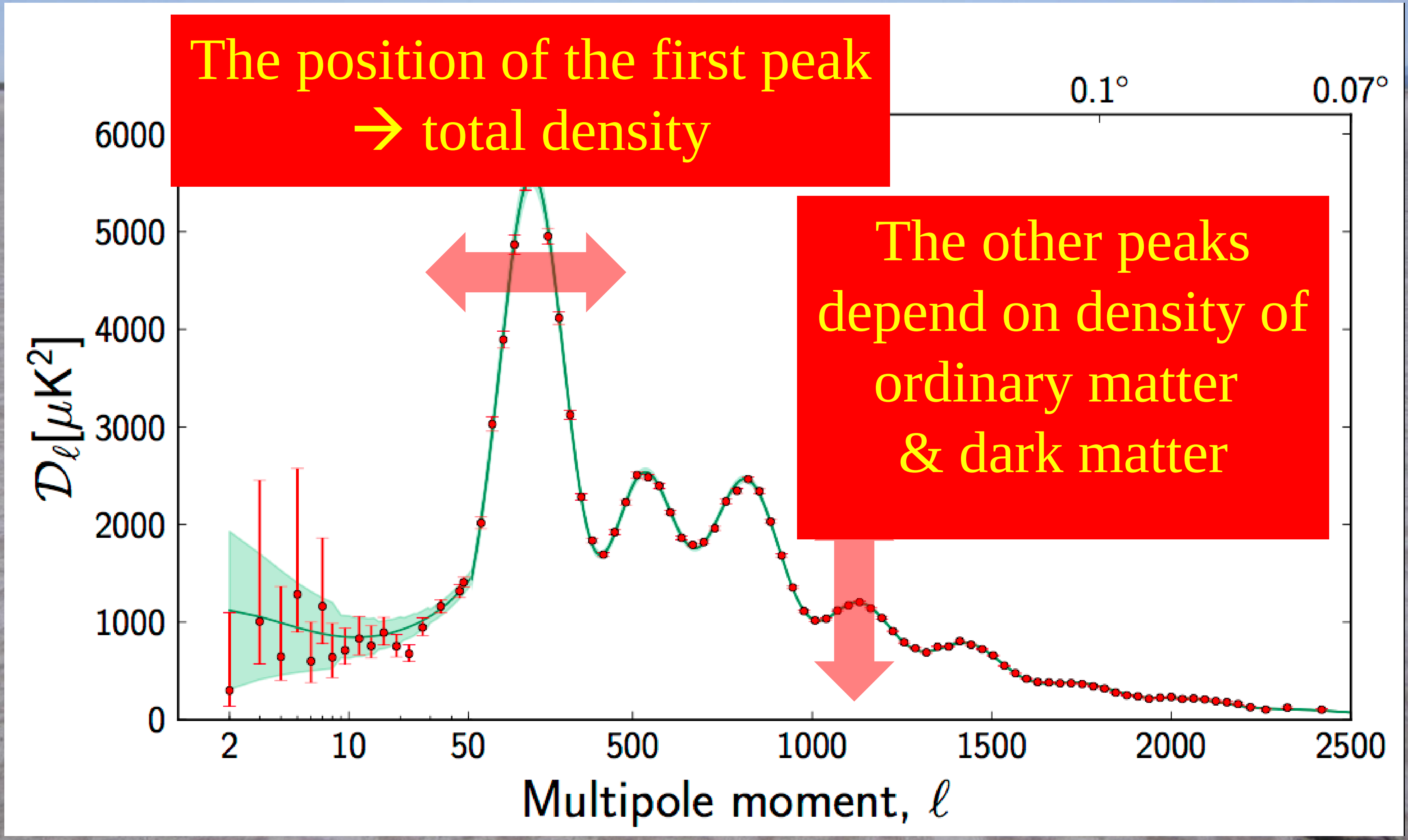
Collision between
2 clusters of galaxies:
Gas interacts, heats and stops





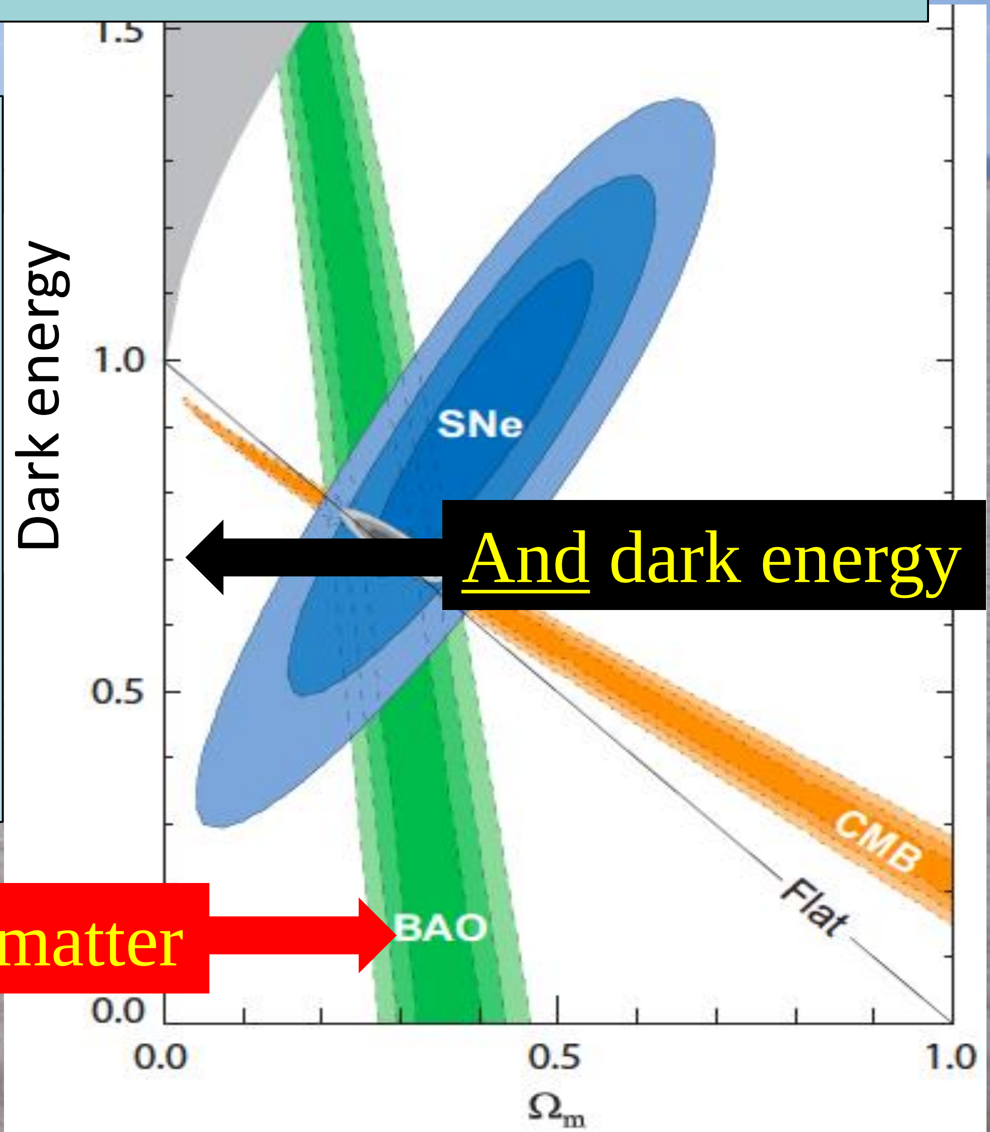
Clowe et al, 2006

The Spectrum of Fluctuations in the Cosmic Microwave Background



The Content of the Universe

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



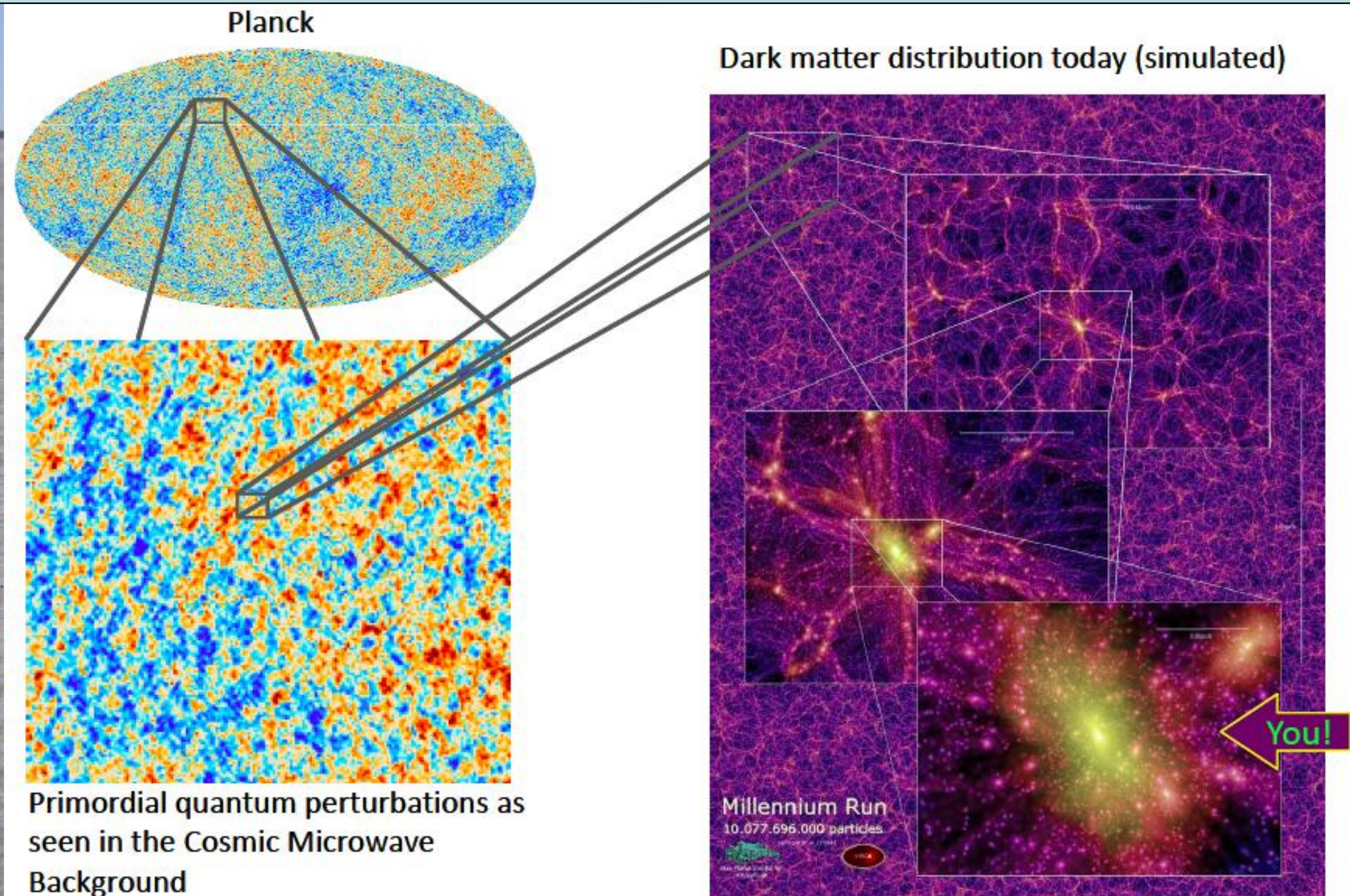
And dark energy

There is dark matter

Dark Energy

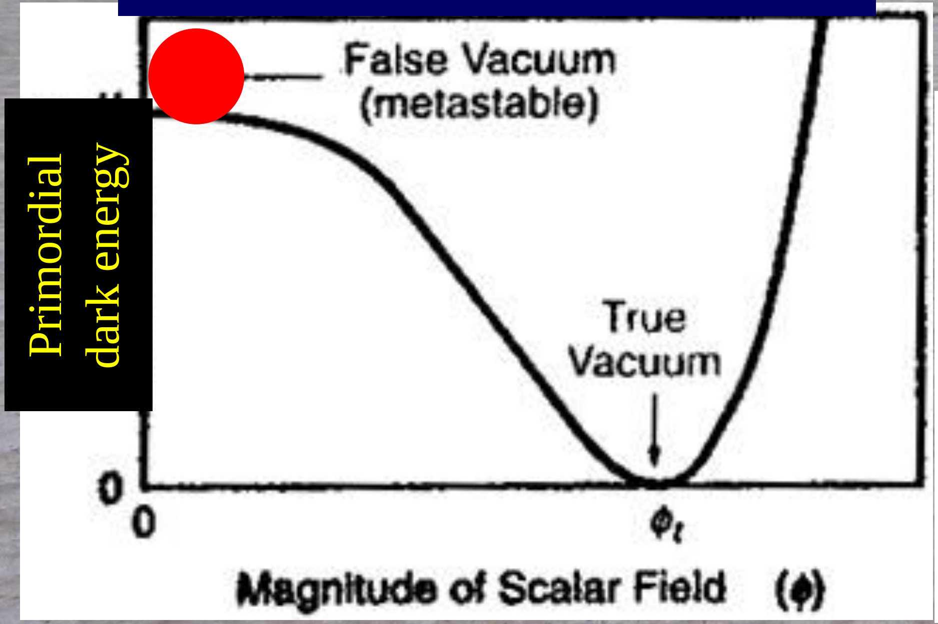
- Energy density spread throughout space
- Not clustered like matter in galaxies, etc.
- Apparently ~ constant for billions of years
- Expect in many theories of fundamental physics, e.g., Higgs
- Mystery is why it is so small

Perturbations Generate Structures



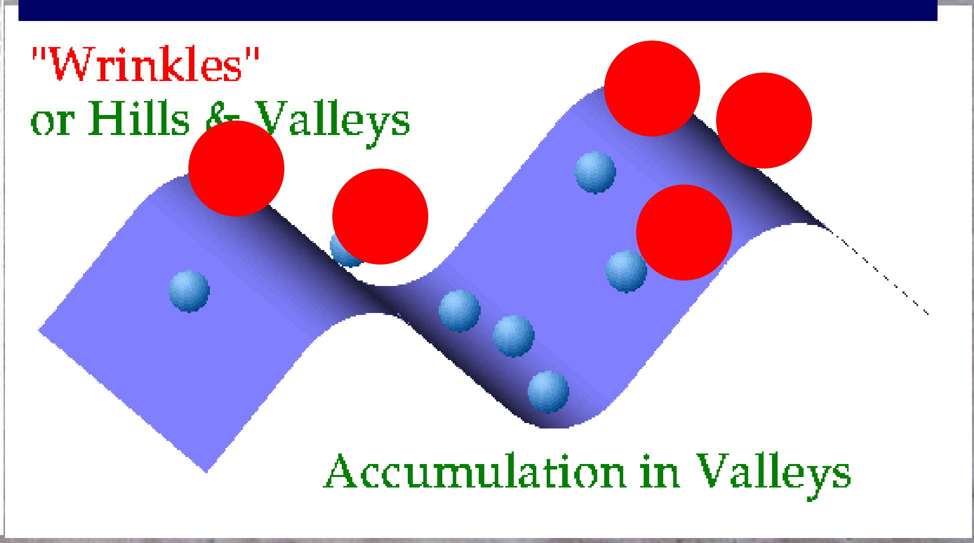
The Origin of Structures in the Universe

Small primordial quantum fluctuations:
~ $1/10^5$



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:

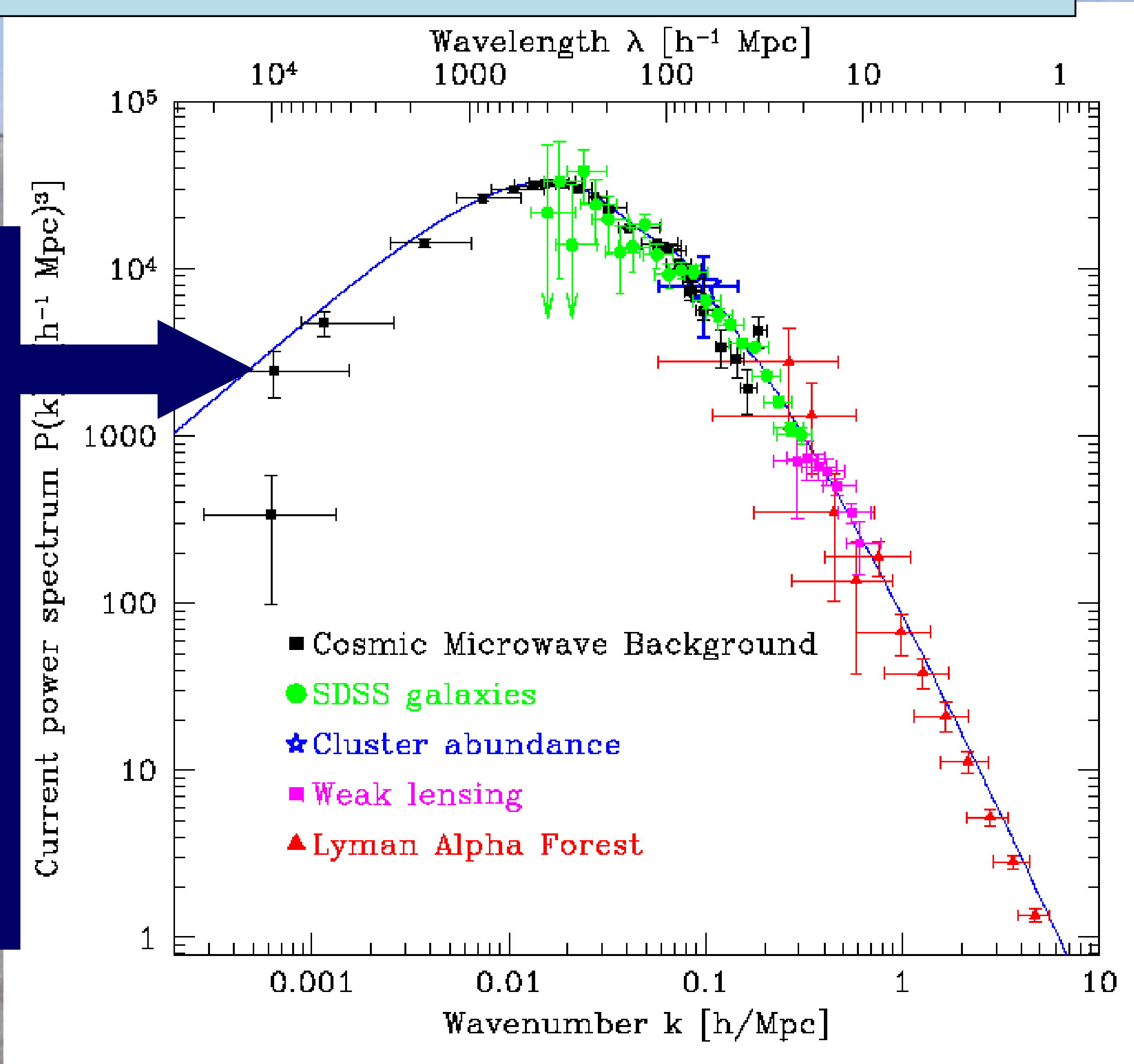
$\Omega_{CDM} \sim 0.25,$

visible matter:

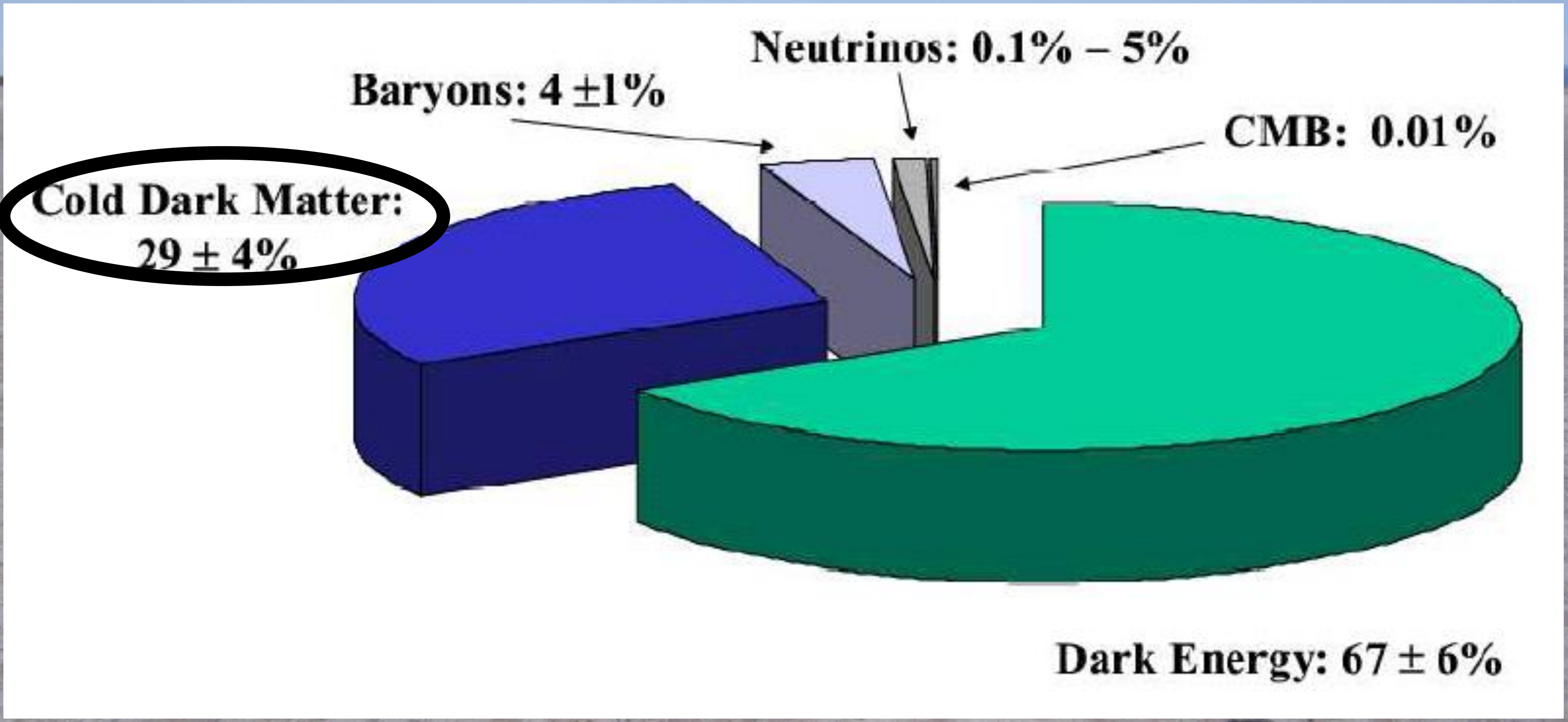
$\Omega_b \sim 0.05,$

Dark energy:

$\Omega_\Lambda \sim 0.7$



Strange Recipe for a Universe



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

Dark Matter in the Universe

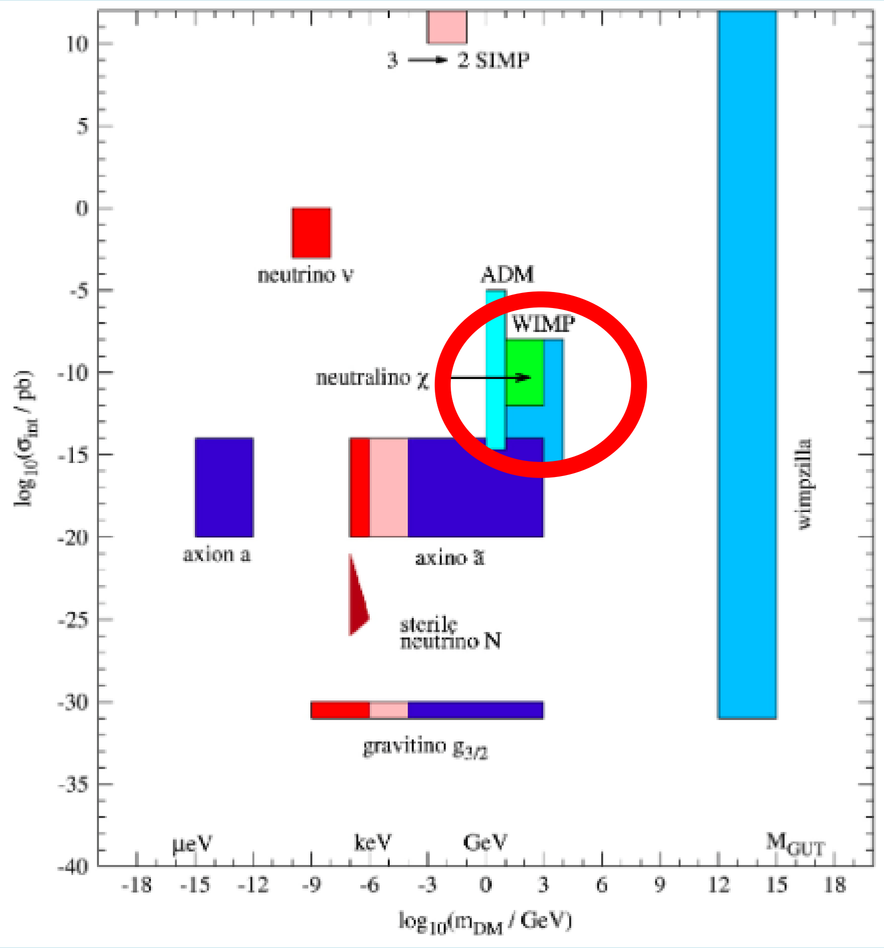
Astronomers say that most of the matter in the Universe is invisible Dark Matter

Weakly-interacting massive particles (WIMPs)?

Searching for them at the LHC

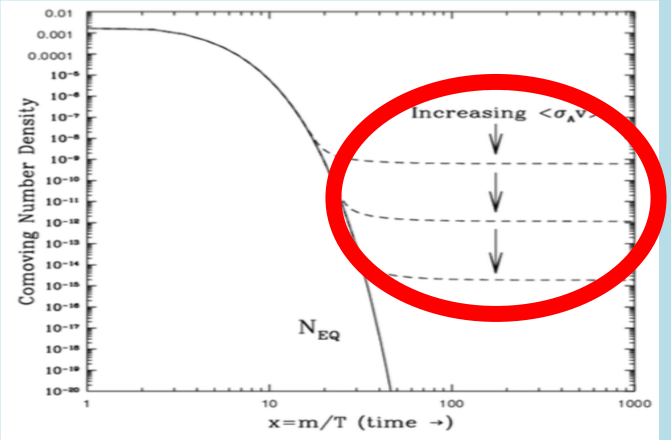
Candidates for Dark Matter

- Large range of possible masses and interactions

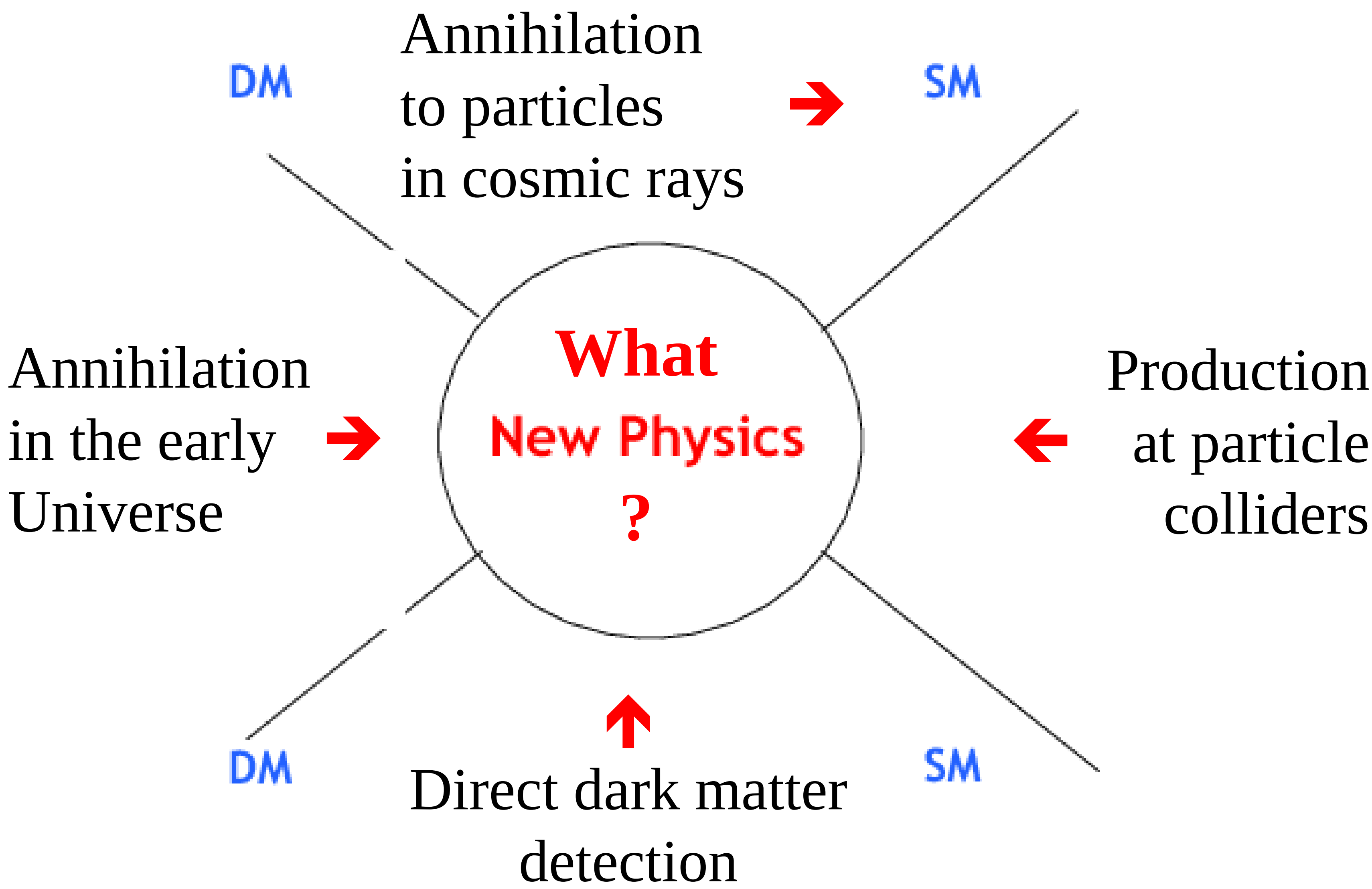


WIMPs: relic particles in thermal equilibrium in early Universe

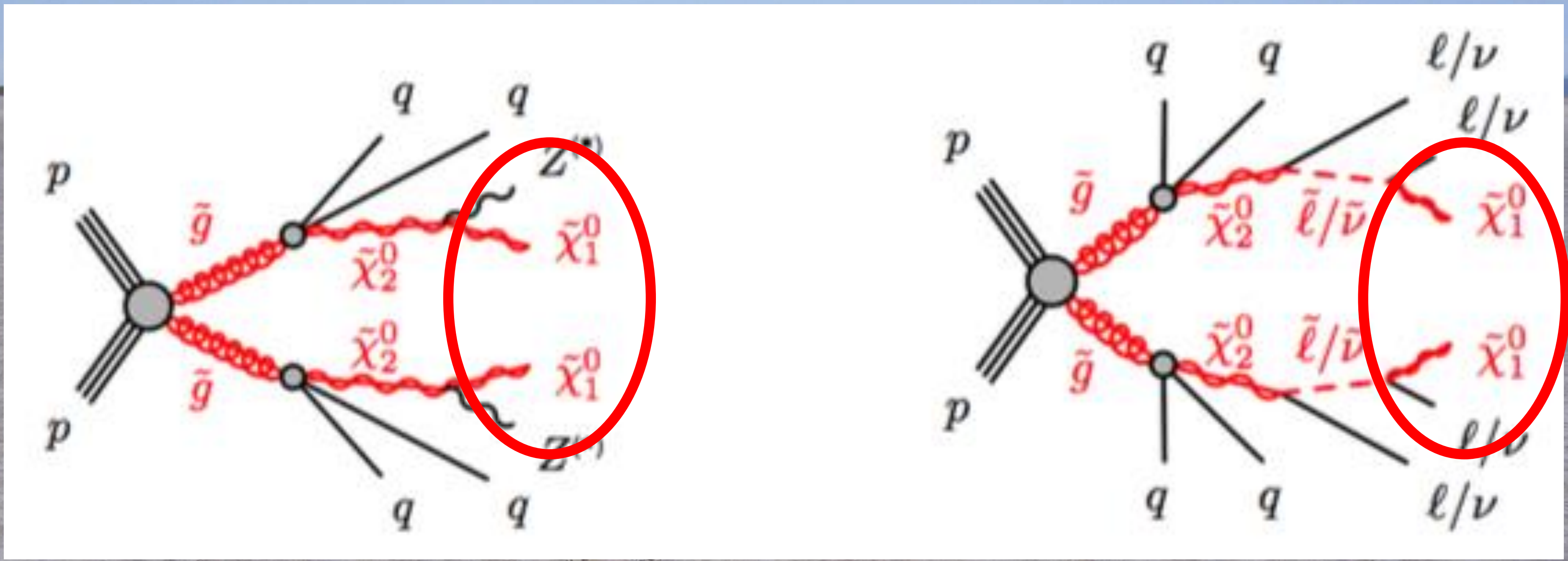
Density freezes out as Universe expands



Searches for Dark Matter

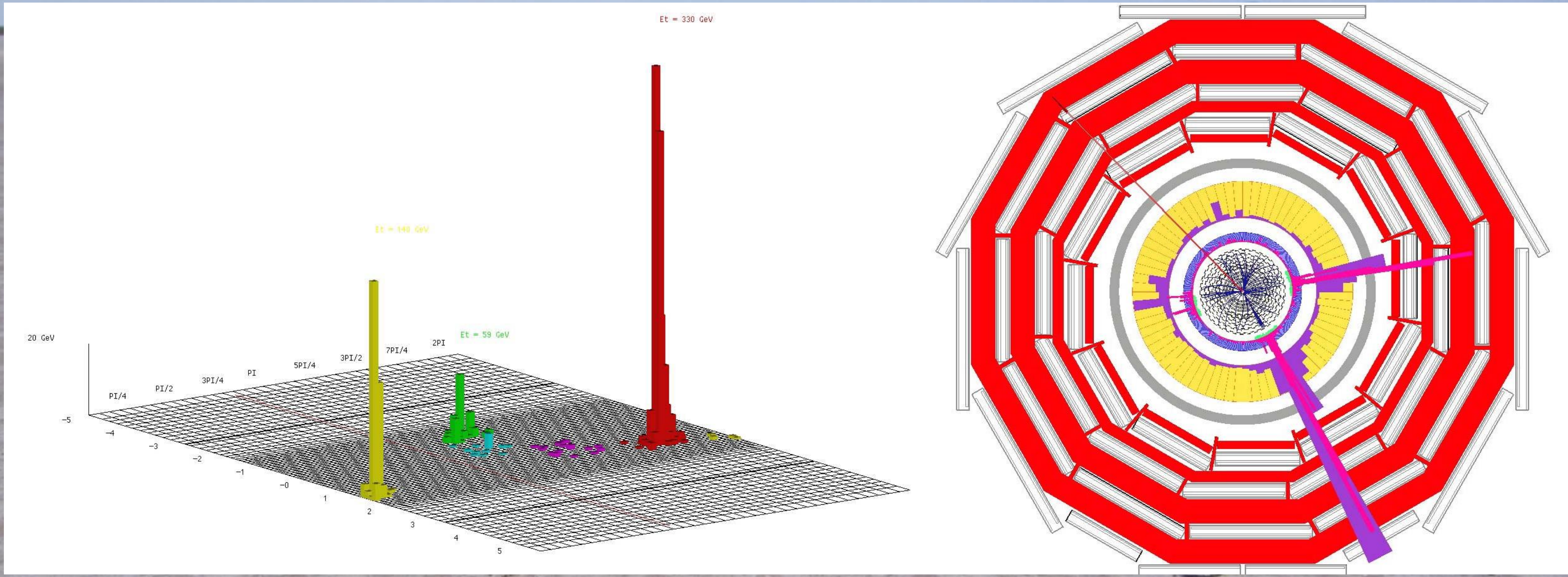


Dark Matter Searches at the LHC



Missing transverse energy
carried away by dark matter particles

Classic Dark Matter Signature

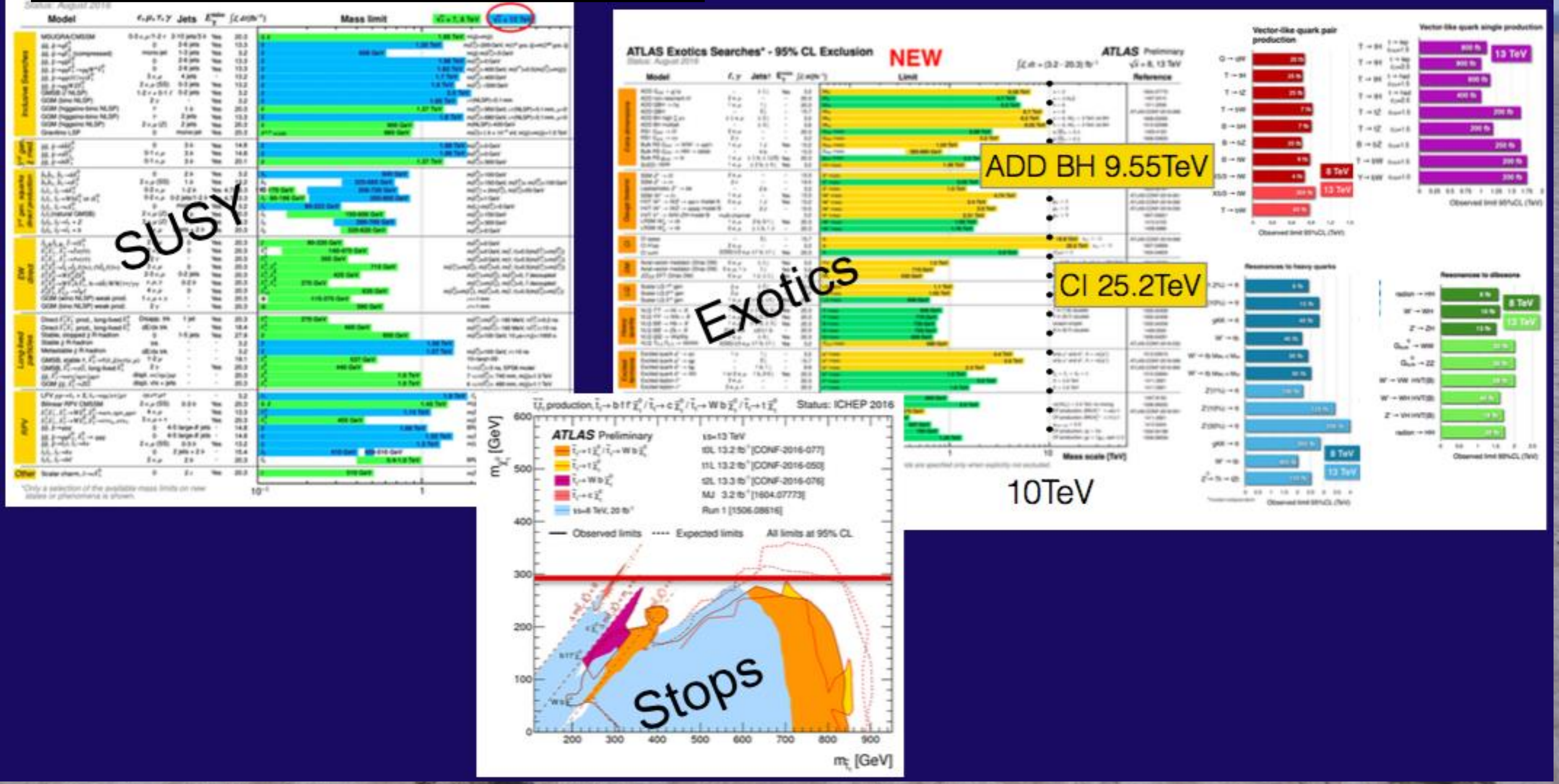


Missing transverse energy
carried away by dark matter particles

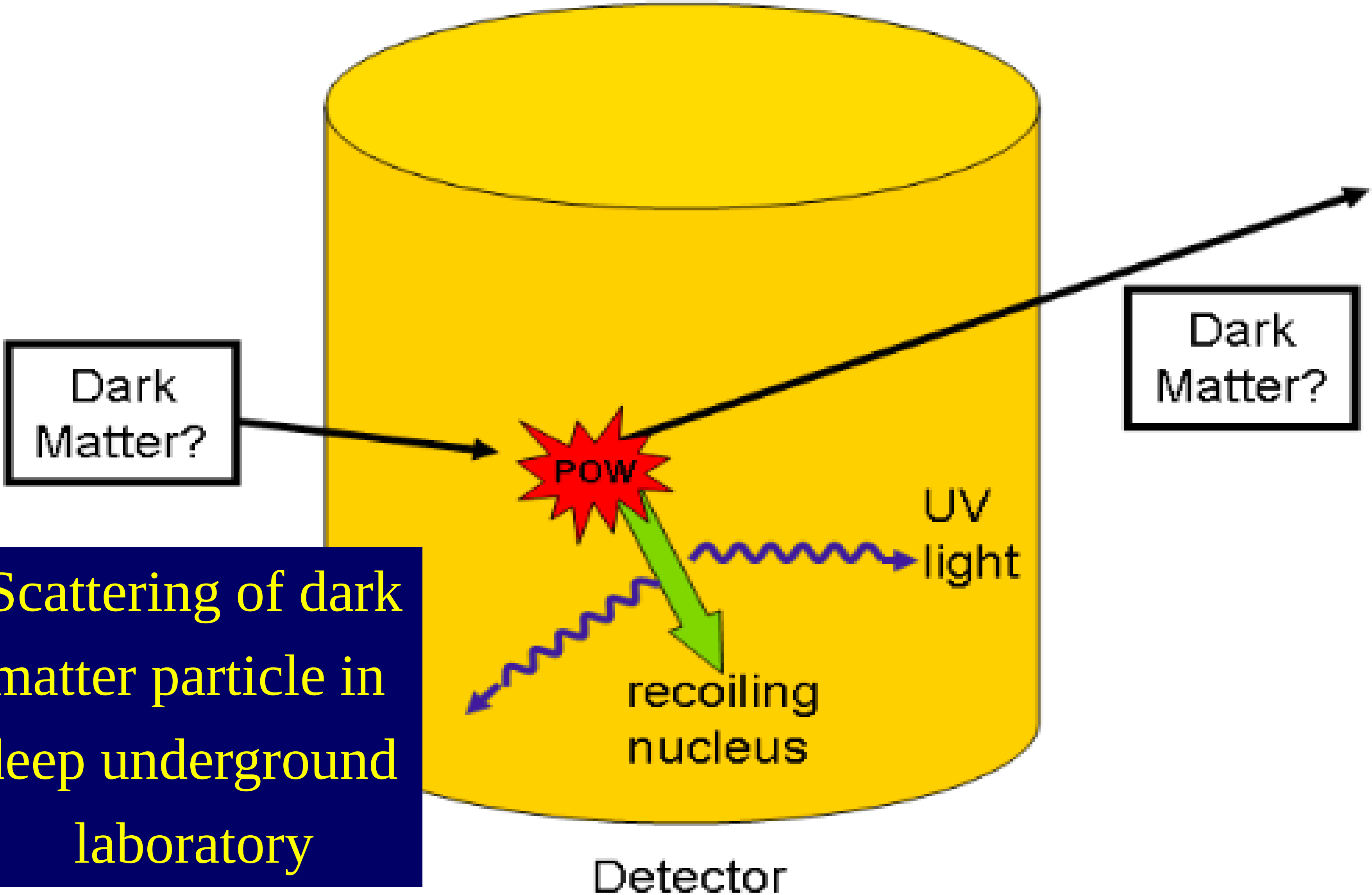
Nothing (yet) at the LHC

No dark matter WIMPs

Nothing else, either



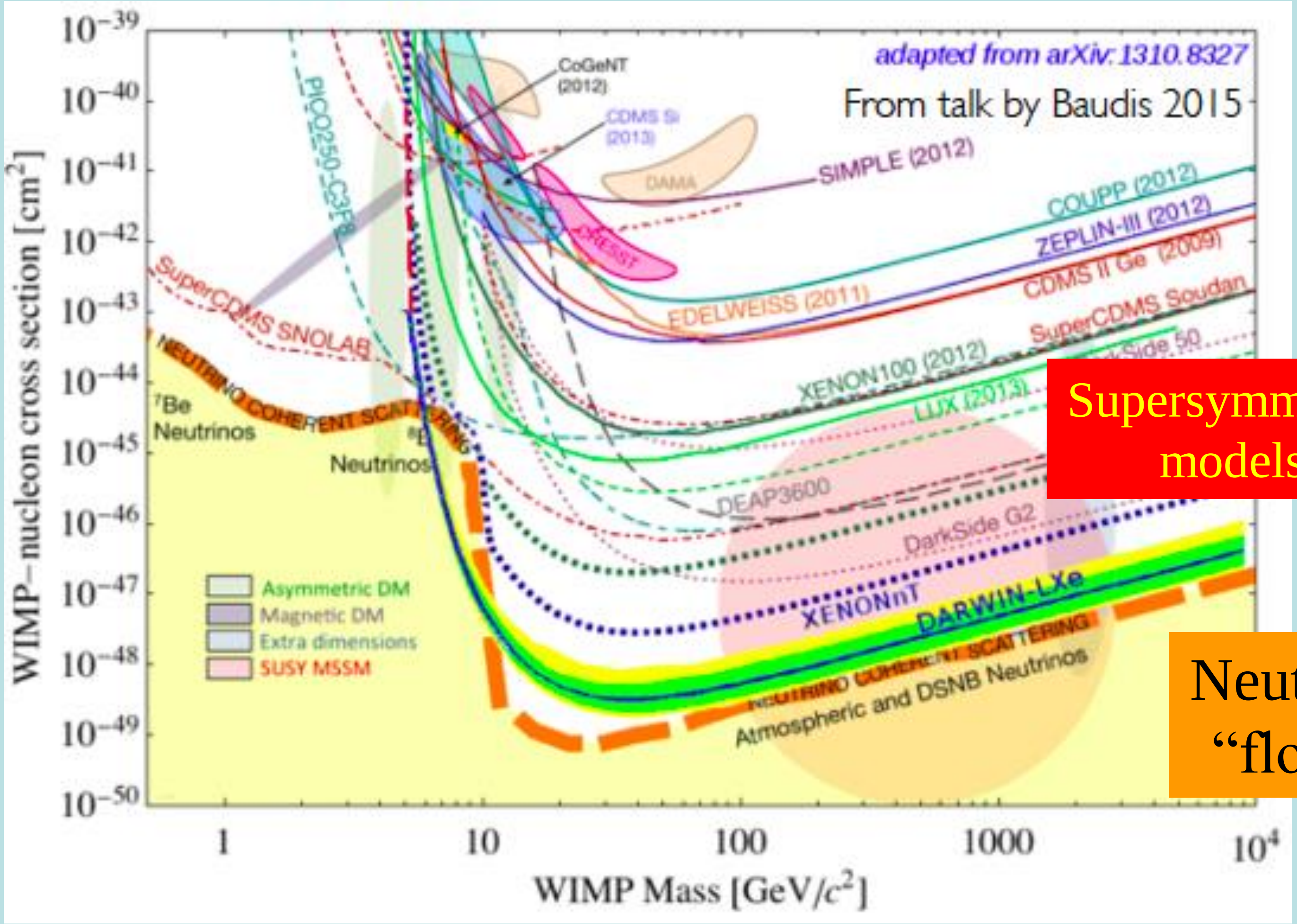
Direct Dark Matter Detection



Scattering of dark matter particle in deep underground laboratory

Direct Dark Matter Searches

- Compilation of present and future sensitivities

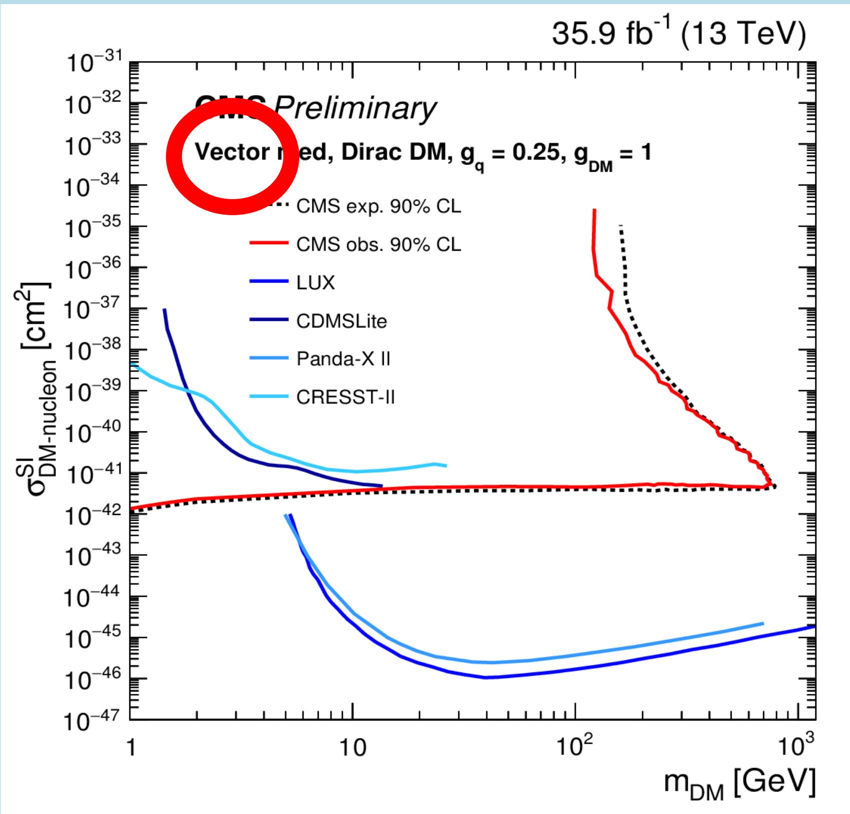


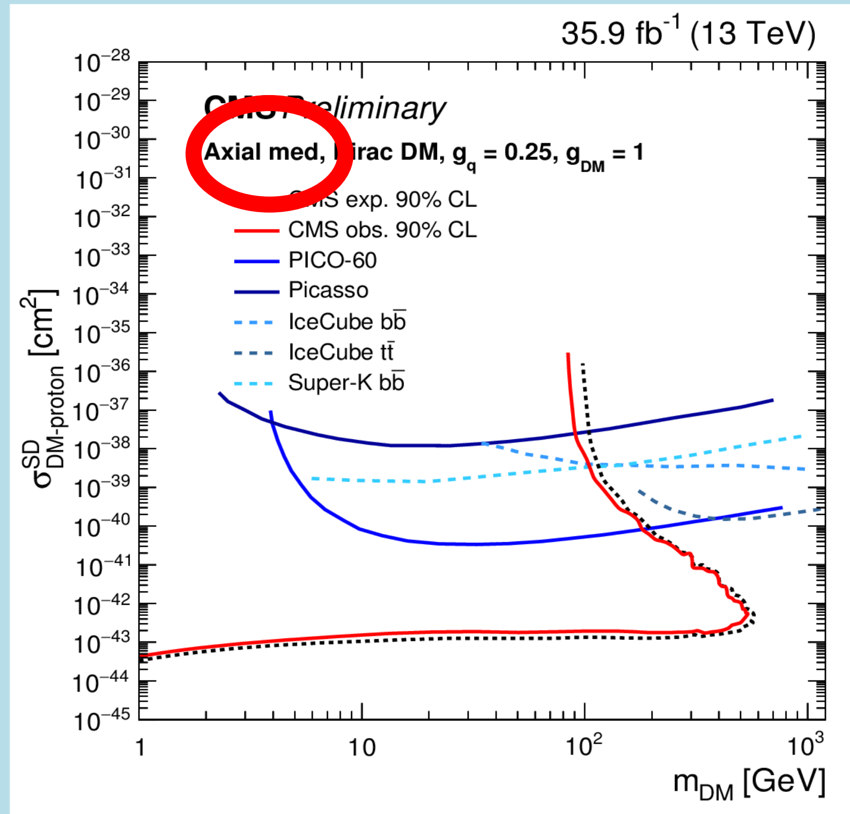
Supersymmetric models

Neutrino “floor”

LHC vs Direct DM Searches

- Compilation of sensitivities to annihilations via Z’





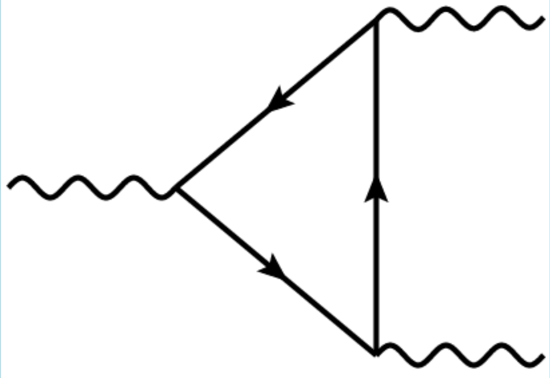
- LHC **loses** for vector, except small m_{DM}
- LHC **wins** for axial, except large m_{DM}

Model dependence

Simplified Dark Matter Models

- Involve bosonic mediator particles of spin 0 or 1
- The latter are gauge bosons of some U(1)' with vector and/or axial-vector couplings
- Consistency of theory requires cancellation of anomalous triangle diagrams
- Standard Model has

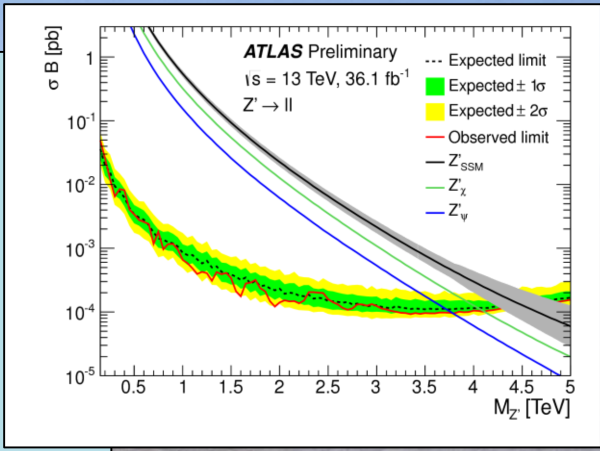
  quark-lepton cancellation
- Should be re-examined in models with extra fermions and/or gauge bosons

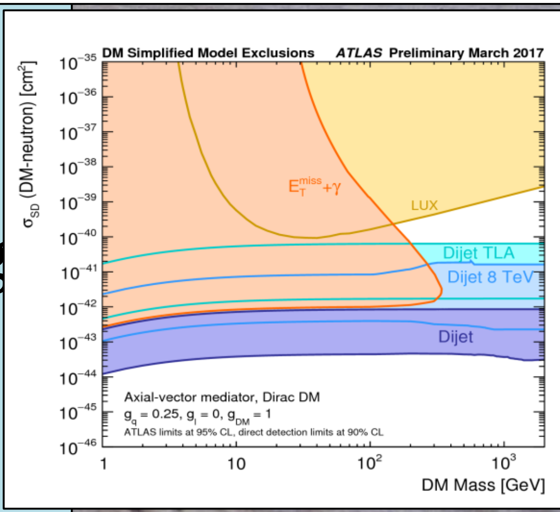


JE, Fairbairn & Tunney, arXiv:1704.03850

Simplified Dark Matter Models

- Mass of Z' boson > about 3 TeV if produced by 1st generation quarks and decays to leptons
- Impact of direct DM searches reduced if
  - DM particle has axial Z' coupling
  - DM particle has axial nuclear coupling
  - DM particle decouples from 1st/2nd generation
- What anomaly-free U(1)' models are compatible with these desiderata?





Anomaly-Free Dark Matter Models are not so Simple

JE, Fairbairn & Tunney, arXiv:1704.03850

- If a single DM fermion and generation-independent U(1)’ charges for SM particles:
  - The SM leptons must have non-zero U(1)’ charges
  - The DM particle has vector U(1)’ coupling
- If DM fermion has axial coupling:
  - Must have 2nd ‘dark’ fermion
  - Z’ still leptophilic
- Leptophobic models need DM particle + ≥ 2 other dark particles with different U(1)’ charges
- **Interesting experimental signatures?**

Supersymmetry?

- Would unify matter particles and force particles
- Related particles spinning at different rates

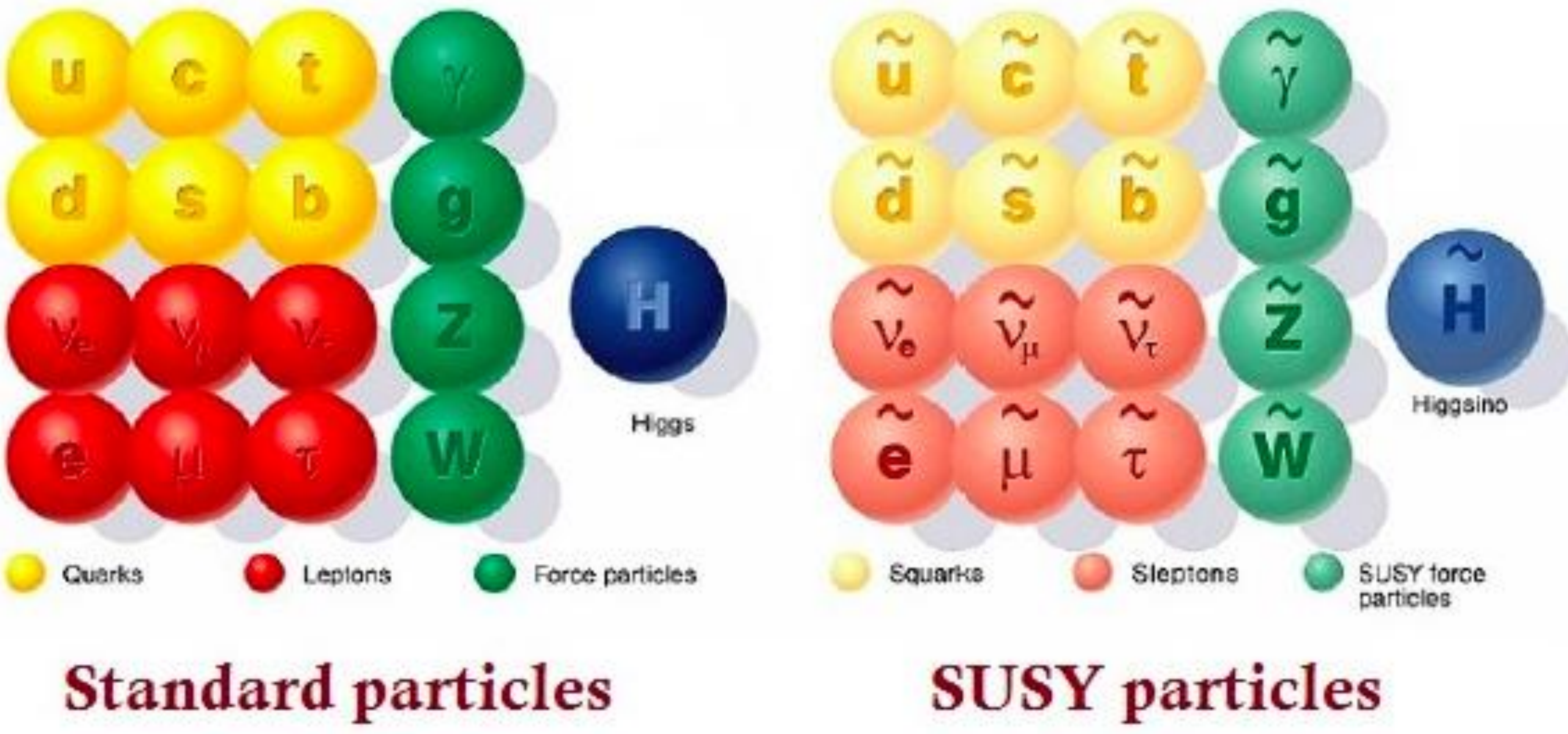
0 - ½ - 1 - 3/2 - 2

Higgs - Electron - Photon - Gravitino - Graviton

(Every particle is a 'ballet dancer')

- Would help fix particle masses
- Would help unify forces
- Predicts light Higgs boson
- **Could provide dark matter for the astrophysicists and cosmologists**

Minimal Supersymmetric Extension of the Standard Model



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)

Nuclear Physics B238 (1984) 453–476

SUPERSYMMETRIC RELICS FROM THE BIG BANG*

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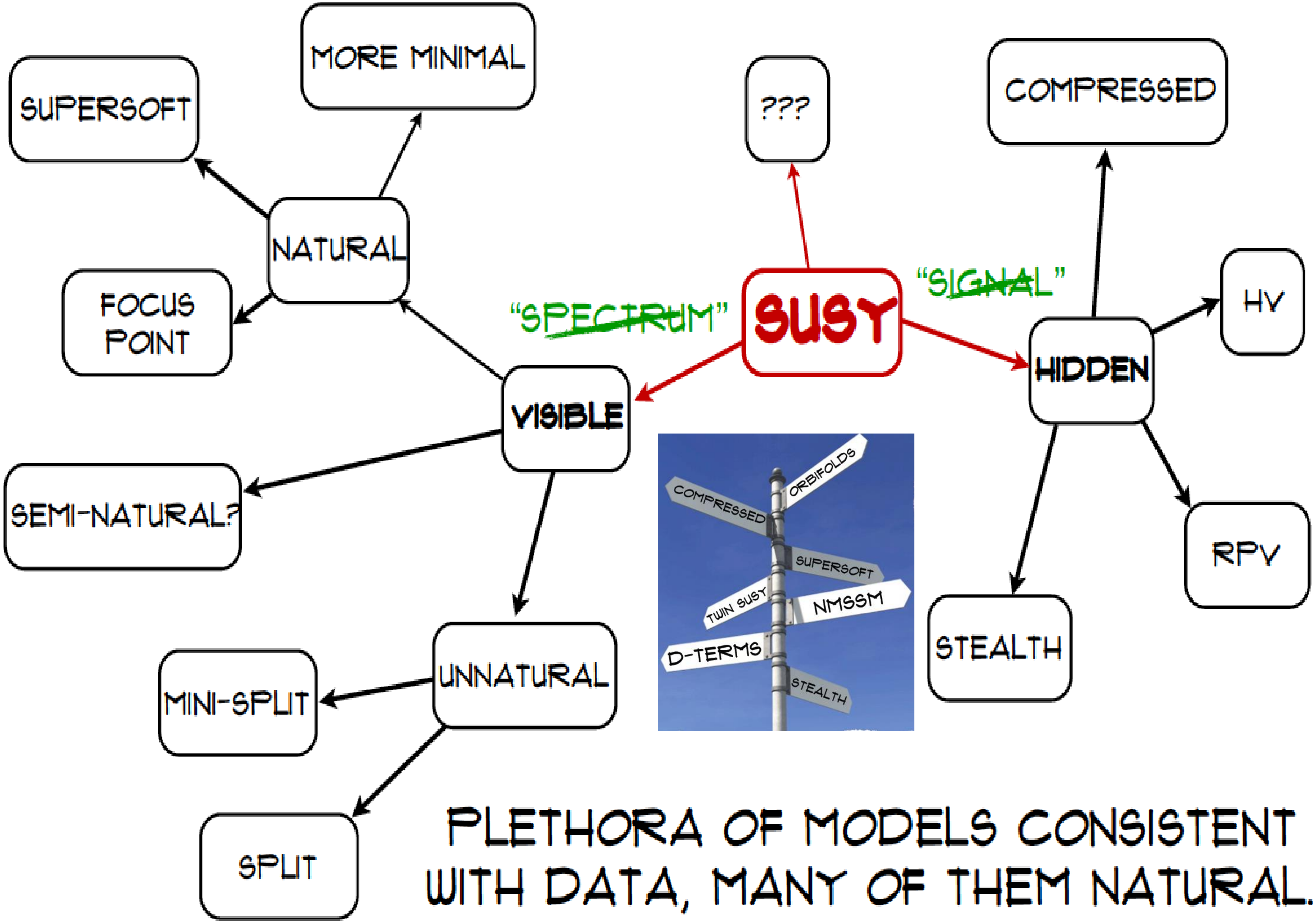
CERN, CH-1211 Geneva 23, Switzerland

Received 16 September 1983
(Revised 15 December 1983)

We consider the cosmological constraints on supersymmetric theories with a new, stable particle. Circumstantial evidence points to a neutral gauge/Higgs fermion as the best candidate for this particle, and we derive bounds on the parameters in the lagrangian which govern its mass and couplings. One favored possibility is that the lightest neutral supersymmetric particle is predominantly a photino $\tilde{\gamma}$ with mass above $\frac{1}{2}$ GeV, while another is that the lightest neutral supersymmetric particle is a Higgs fermion with mass above 5 GeV or less than O(100) eV. We also point out that a gravitino mass of 10 to 100 GeV implies that the temperature after completion of an inflationary phase cannot be above 10^{14} GeV, and probably not above 3×10^{12} GeV. This imposes constraints on mechanisms for generating the baryon number of the universe.



PLETHORA OF MODELS CONSISTENT WITH DATA, MANY OF THEM NATURAL. WHERE DOES THE DATA POINT US?

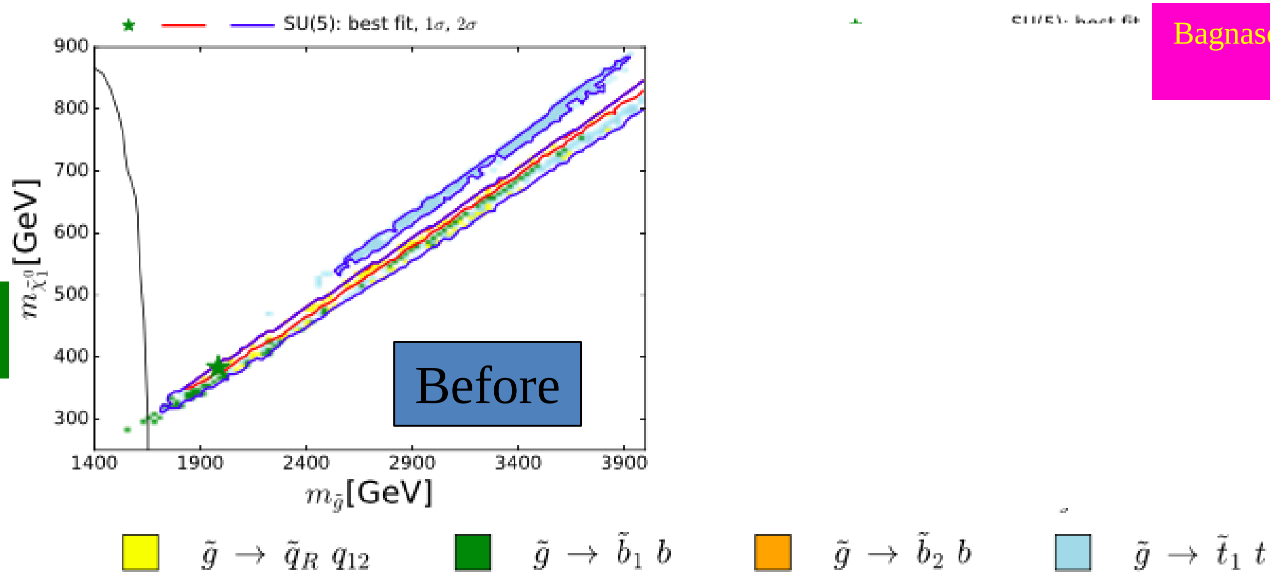
Craig@LHCP

Impact of 13 TeV Data so far

SU(5) GUT

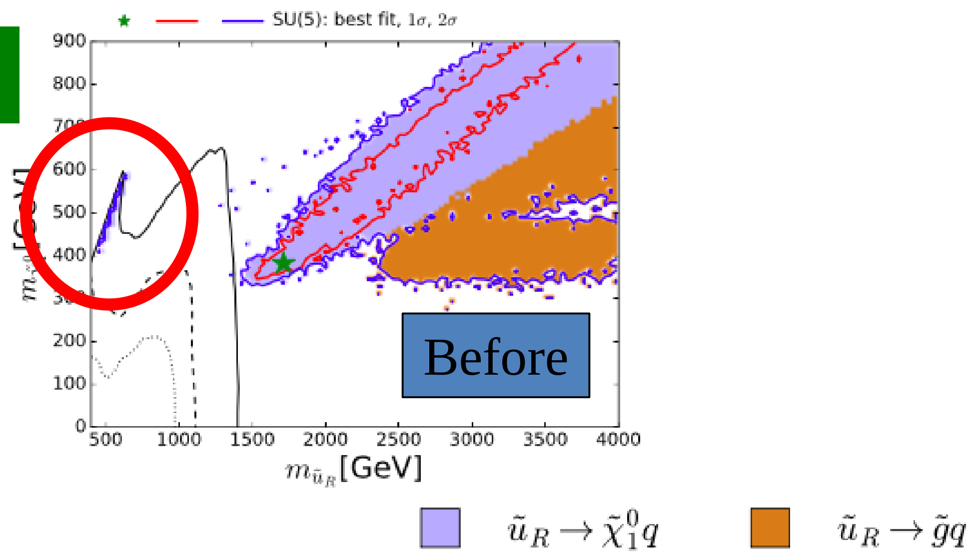
Bagnaschi, Costa, Sakurai, JE et al: arXiv:1610.10084

Gluino



Important to take decay branching ratios into account

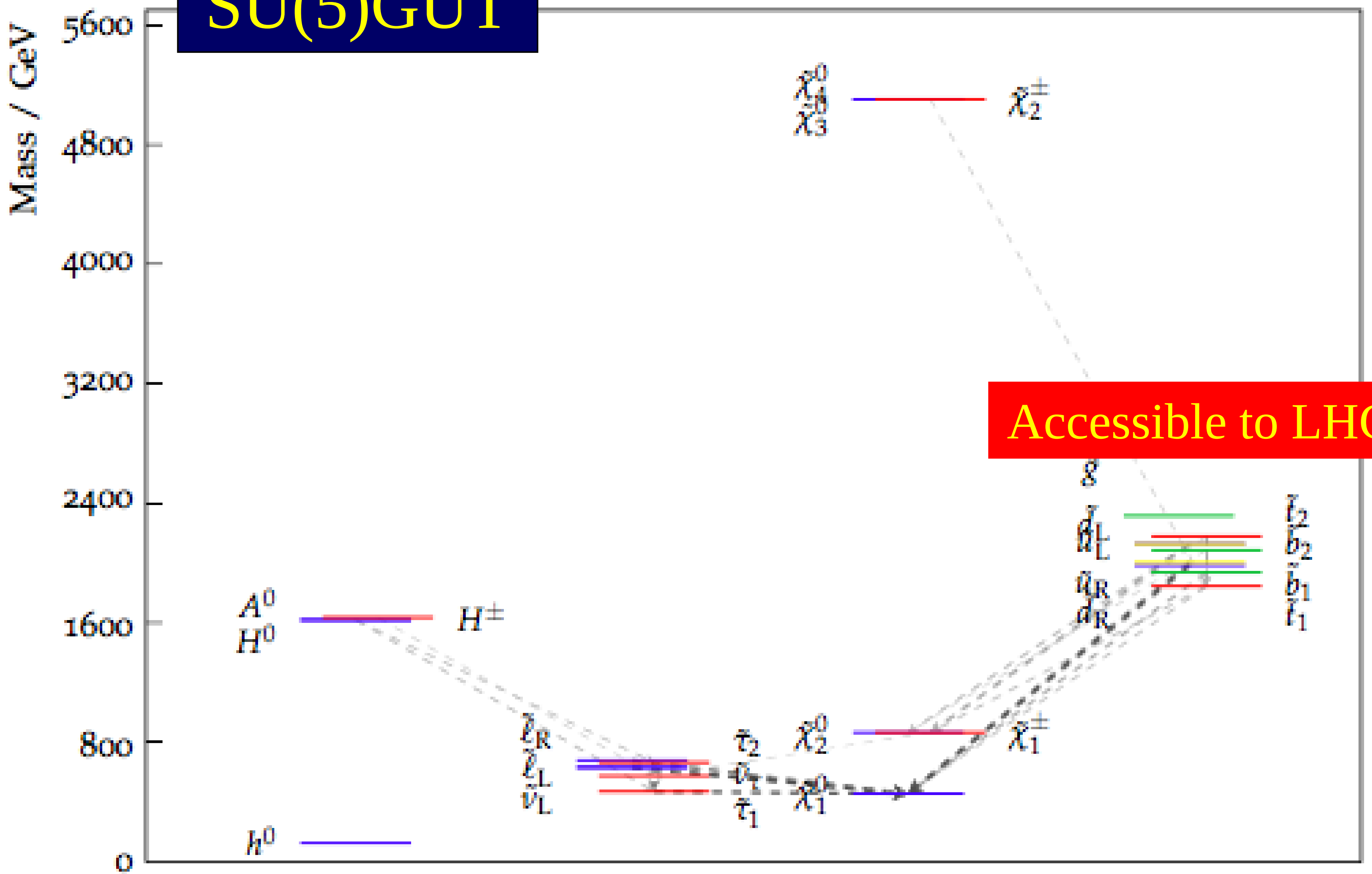
Squark



Light up, charm squarks?

Best-Fit Sparticle Spectrum

SU(5)GUT



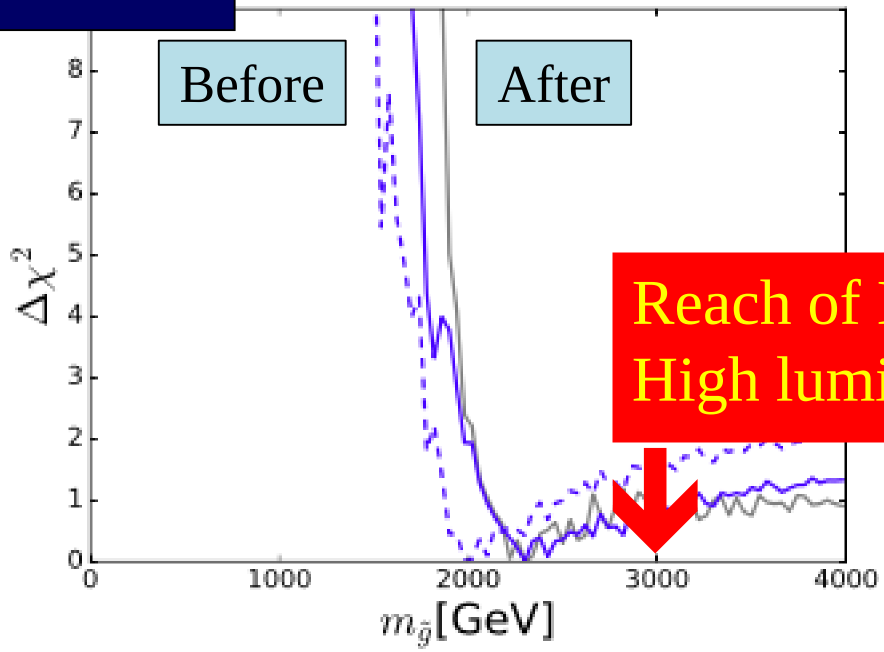
Accessible to LHC?

Bagnaschi, Costa, Sakurai, JE et al: arXiv:1610.10084

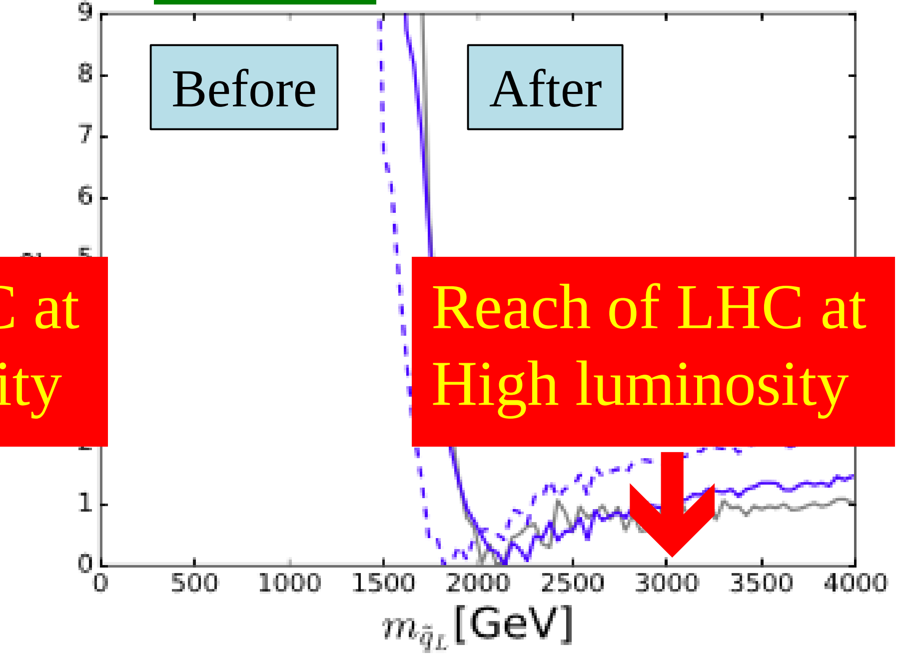
Impact of 13 TeV Data so far

SU(5) GUT

Gluino



Squark

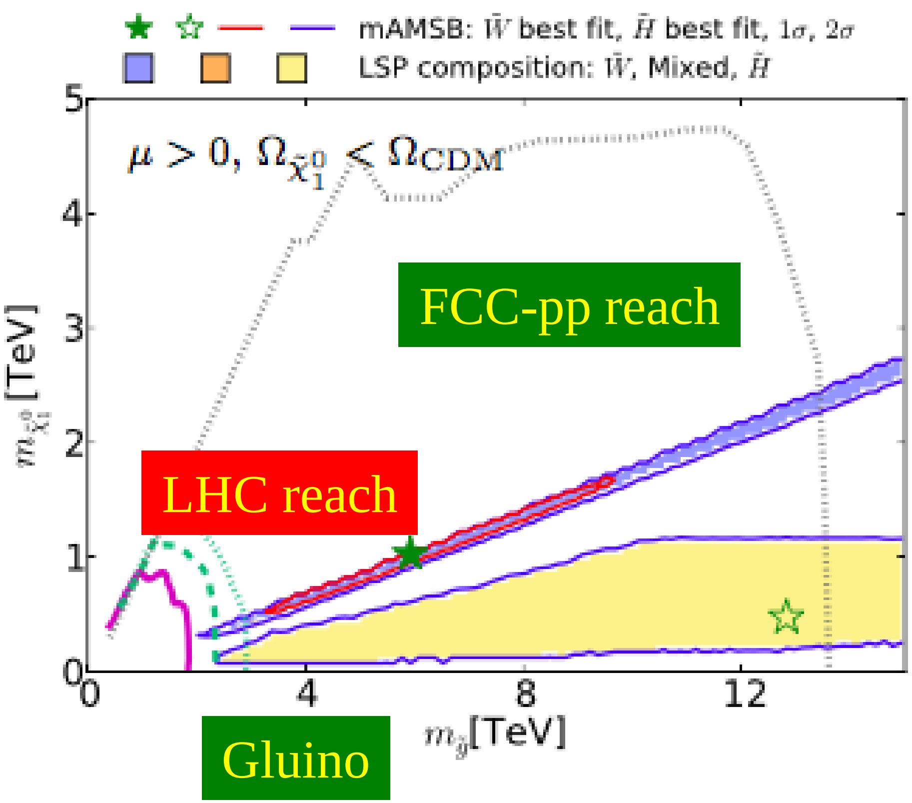


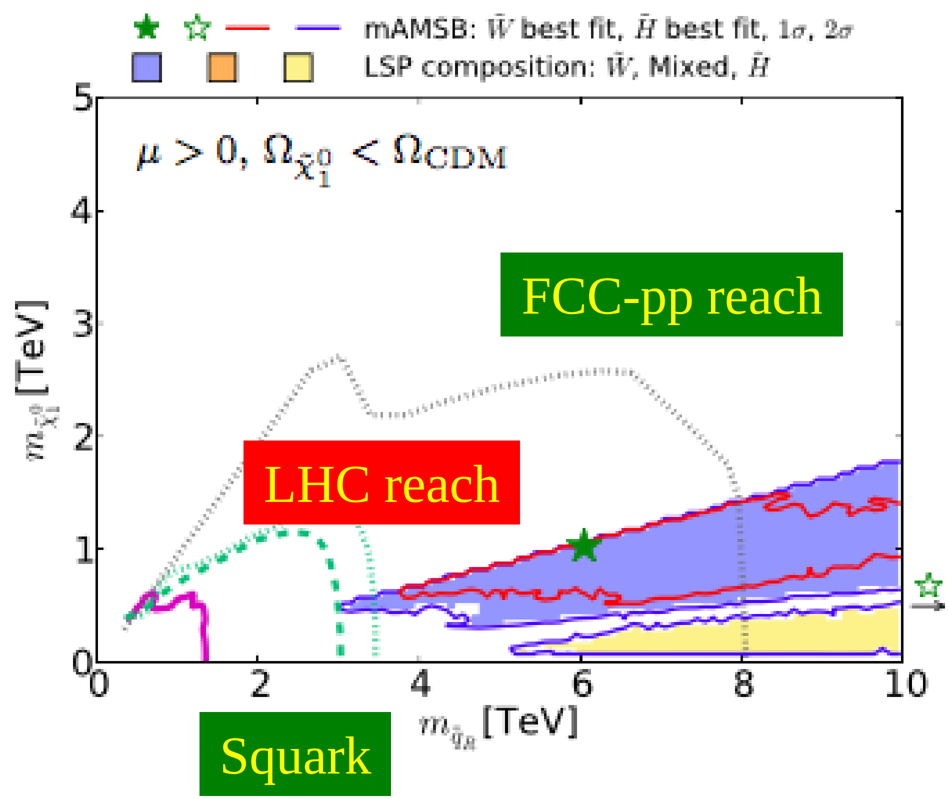
Limited impact of first 13/fb of 13 TeV data
Plenty of room for supersymmetry in future LHC runs
No guarantees!

Bagnaschi, Costa, Sakurai, JE et al: arXiv:1610.10084

Minimal Anomaly-Mediated Supersymmetry-Breaking Model

LSP some of the dark matter



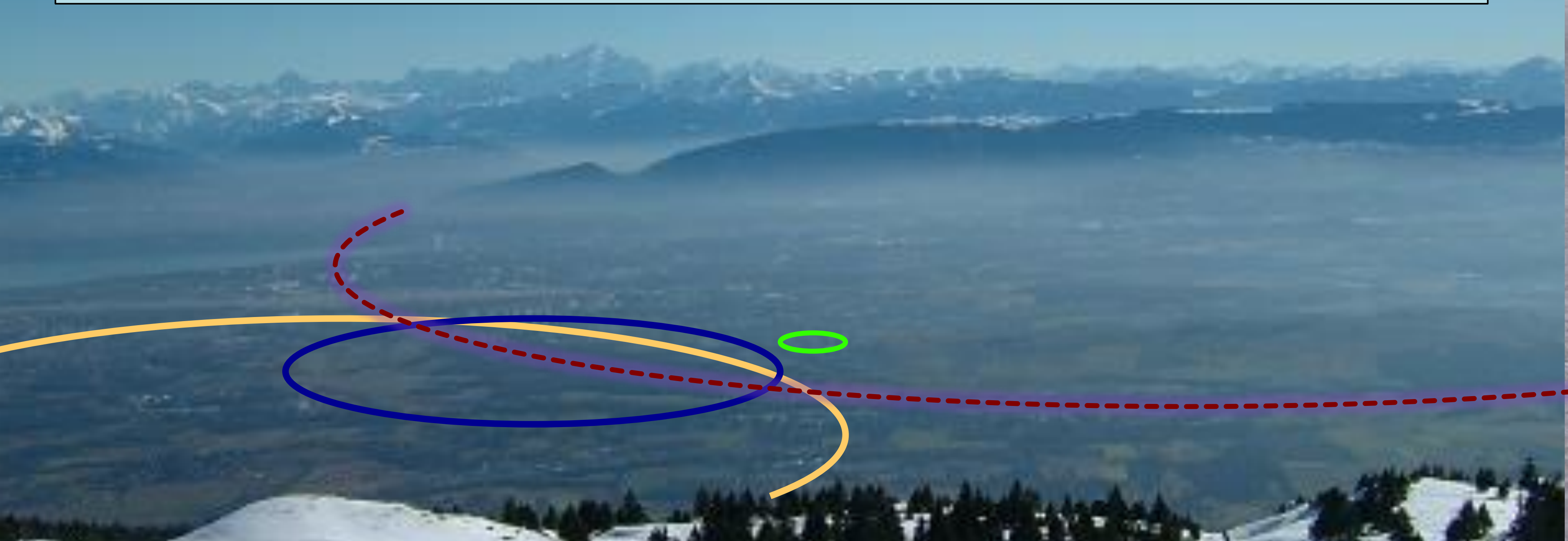


Wino Dark Matter

Higgsino Dark Matter

Bagnaschi, Borsato, Sakurai, JE et al: arXiv:1612.05210

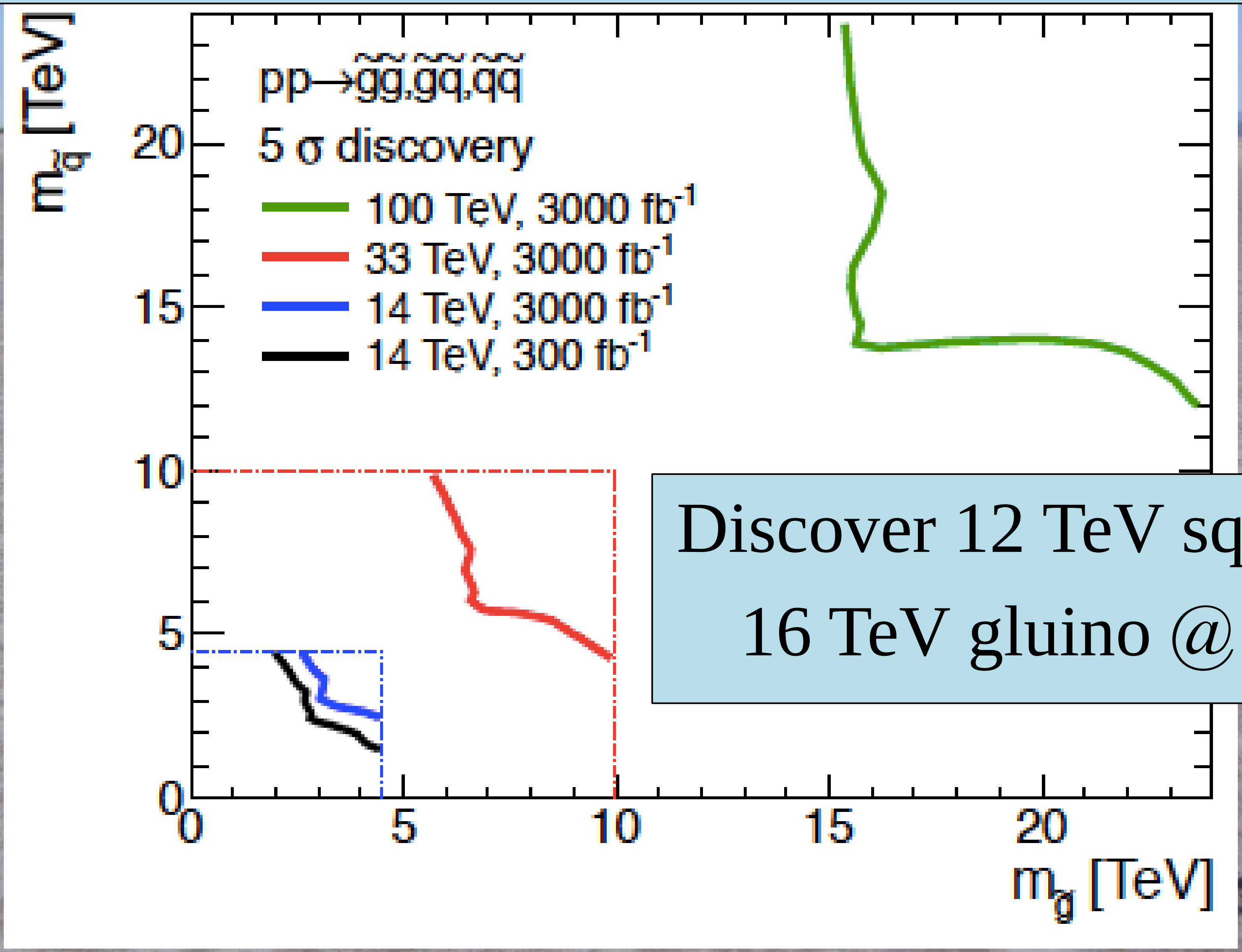
Future Circular Colliders



The vision:

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

Squark-Gluino Plane



Discover 12 TeV squark, 16 TeV gluino @ 5σ

Summary

- Dark matter is the most pressing evidence for physics beyond the Standard Model
- It may be provided by particles within reach of current/forthcoming experiments
- Competition/complementarity between astrophysical and cosmological experiments
- Supersymmetry is a favoured candidate for dark matter
- **We should also think outside the "superbox"**