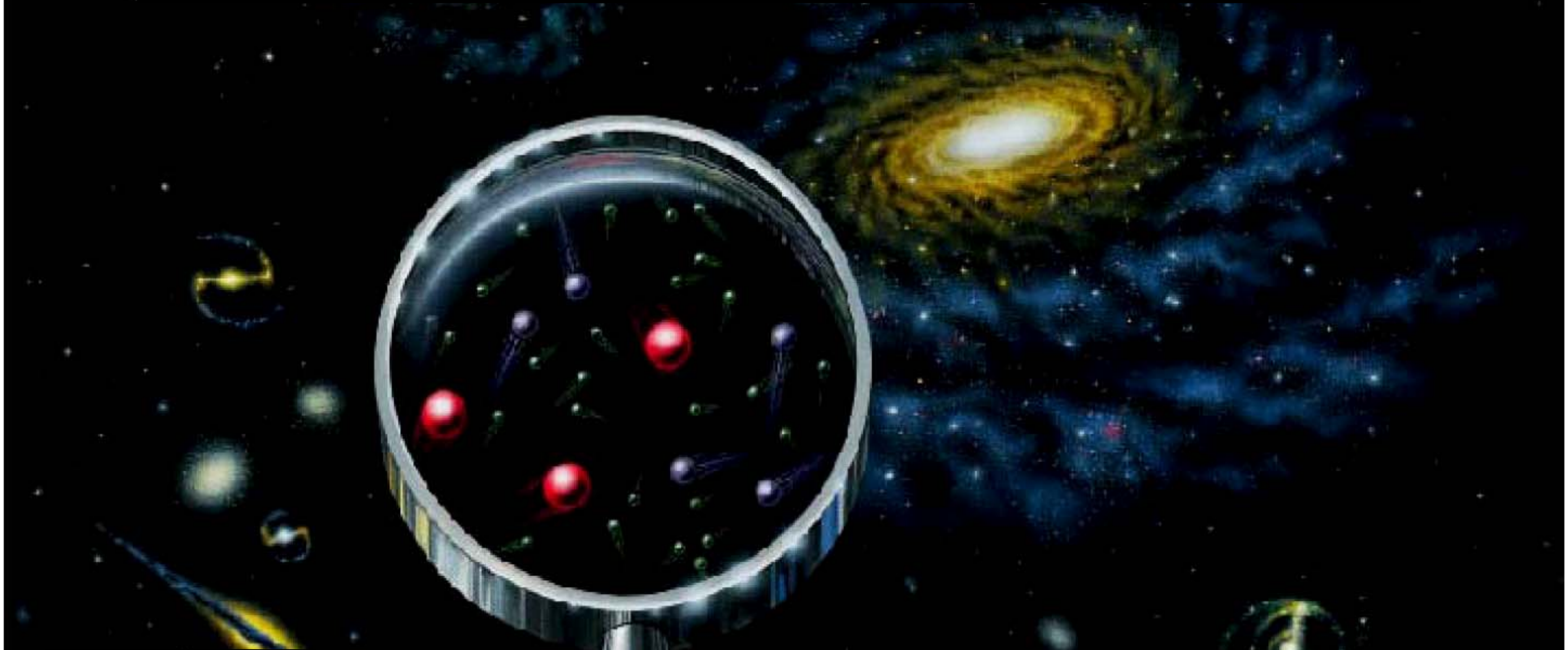
Astroparticle Physics and High-Energy Physics



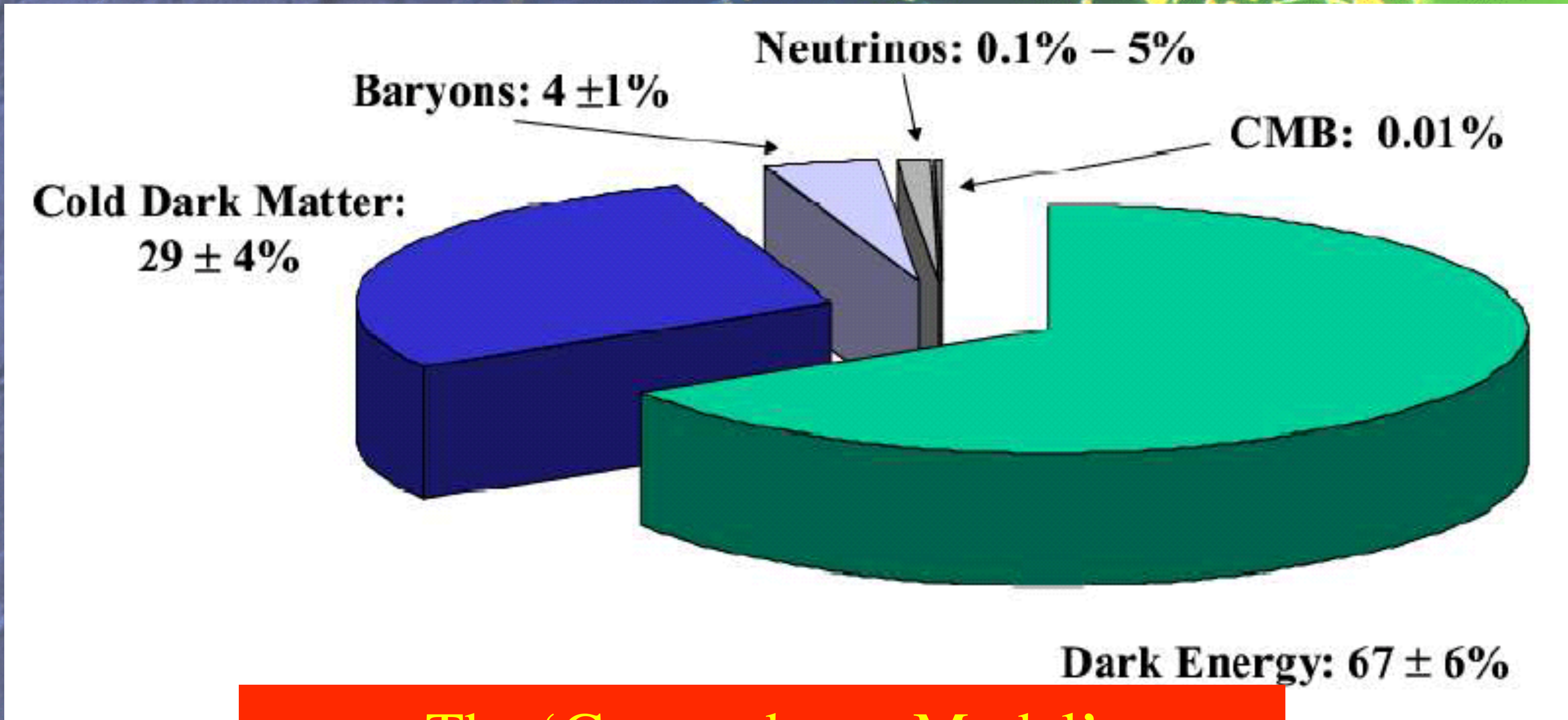
CHIPP, EPFL
June 3rd, 2009
John Ellis

Links between particle physics, astrophysics and cosmology

Dual Aspects of Astroparticles

- Use high-energy particles to study astrophysics and cosmology
  - e.g., GRBs, AGNs, …
- Use astrophysics and cosmology to study particle physics
  - e.g., dark matter, UHECRs
- **As a particle physicist, more motivated by the latter**

A Strange Recipe for a Universe



The 'Concordance Model'
prompted by astrophysics & cosmology

Open Cosmological Questions

- Where did the matter come from?

  1 proton for every 1,000,000,000 photons
- What is the dark matter?

  Much more than the normal matter
- What is the dark energy?

  Even more than the dark matter
- Why is the Universe so big and old?

  Mechanism for cosmological inflation

Need particle physics to answer these questions

The Very Early Universe

- Size: a → zero
- Age: t → zero
- Temperature: T → large

  $T \sim 1/a$, $t \sim 1/T^2$
- Energies: $E \sim T$
- Rough magnitudes:

  T ~ 10,000,000,000 degrees

  E ~ 1 MeV ~ mass of electron

  t ~ 1 second

Need particle physics to describe earlier history

The ‘Standard Model’

= Cosmic DNA

The matter particles

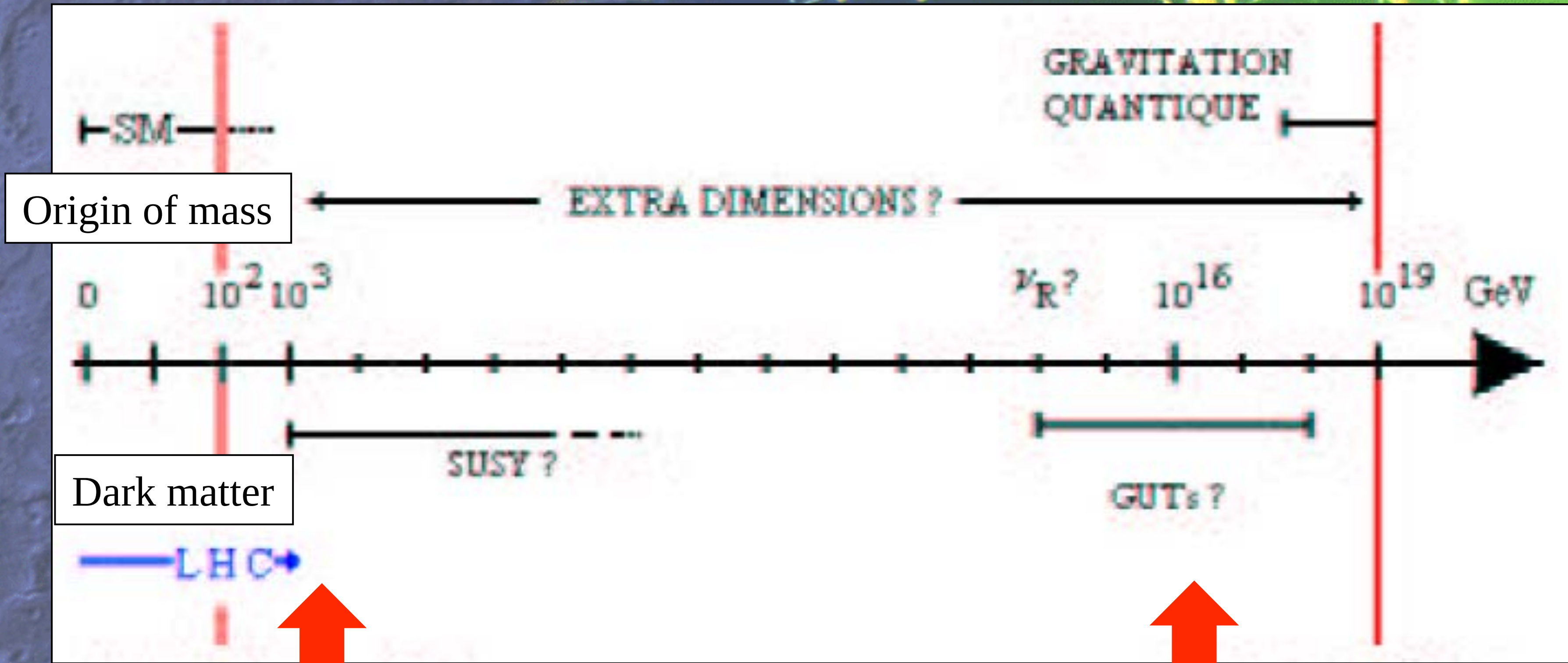
The fundamental interactions

Gravitation electromagnetism weak nuclear force strong nuclear force

Open Questions beyond the Standard Model

- What is the origin of particle masses? LHC
  due to a Higgs boson?
- Why so many types of matter particles? LHC
- What is the dark matter in the Universe? LHC
- Unification of fundamental forces? LHC
- Quantum theory of gravity? LHC

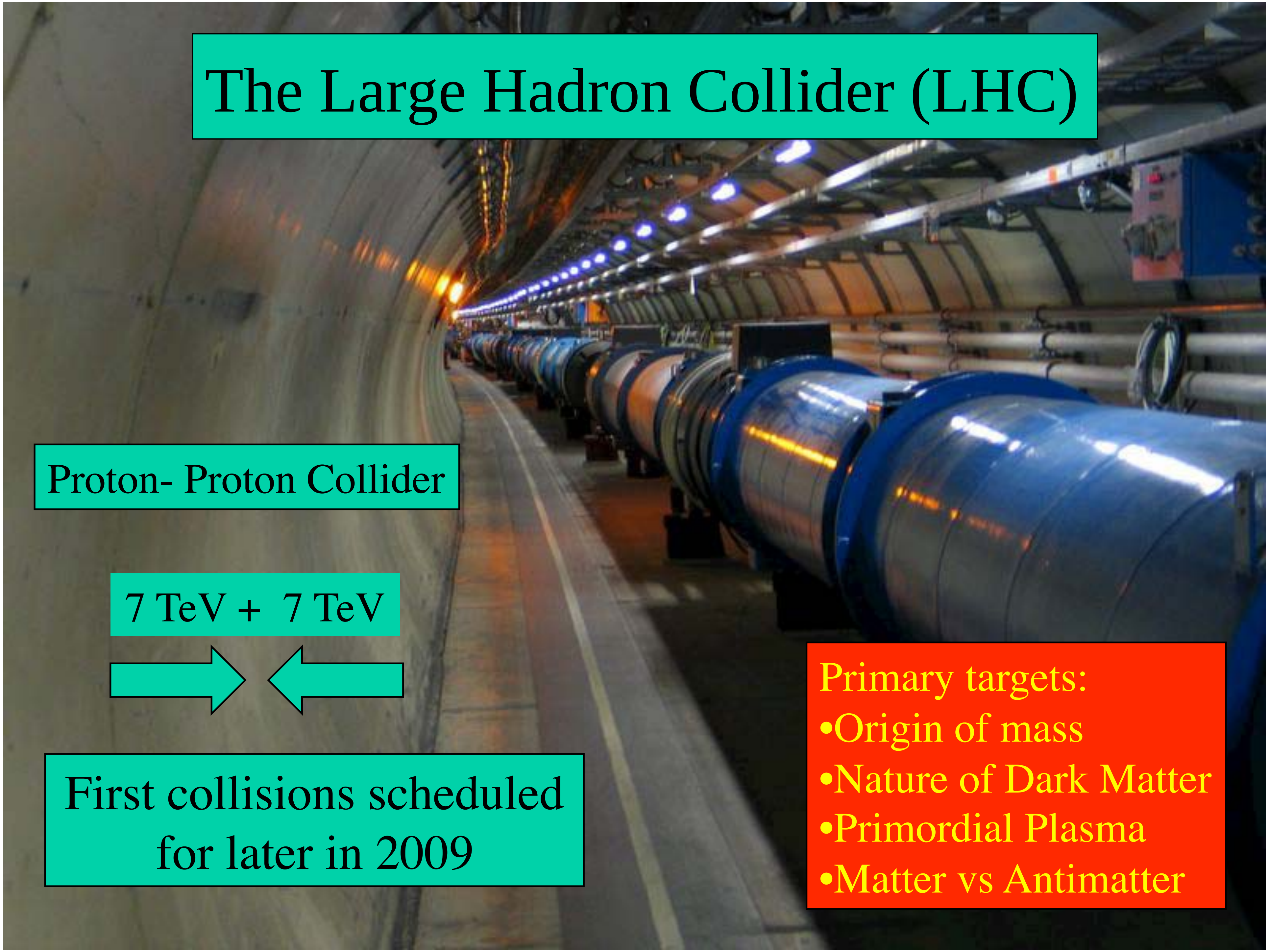
At what Energy is the New Physics?



A lot accessible directly to the LHC

Some accessible indirectly via astrophysics and cosmology

The Large Hadron Collider (LHC)



Proton- Proton Collider

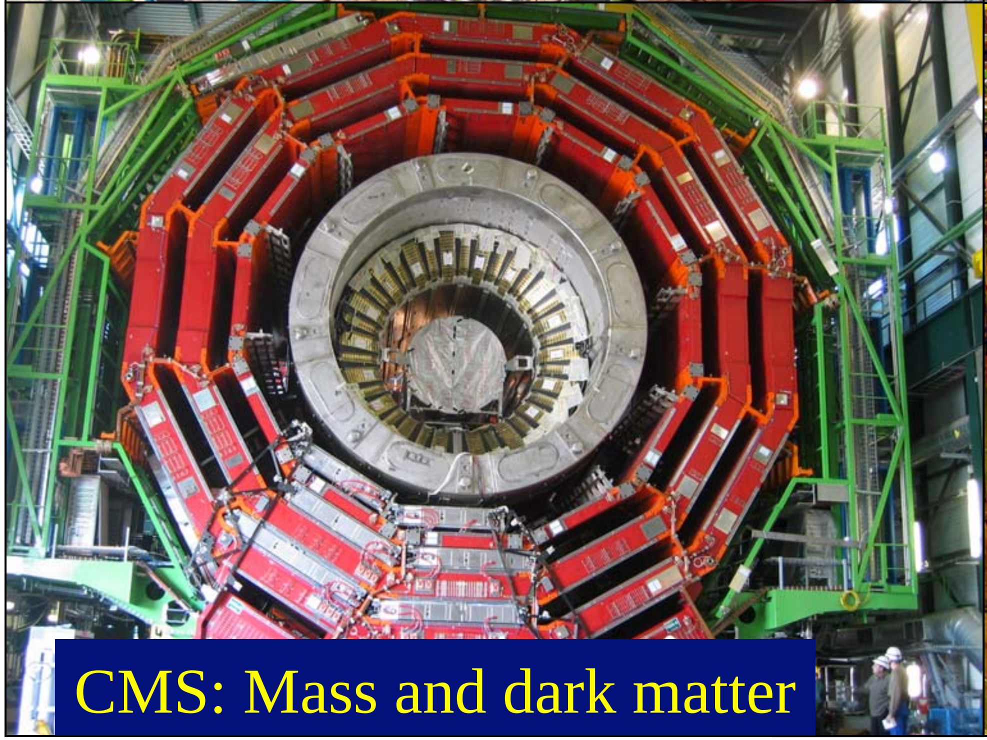
7 TeV + 7 TeV

First collisions scheduled for later in 2009

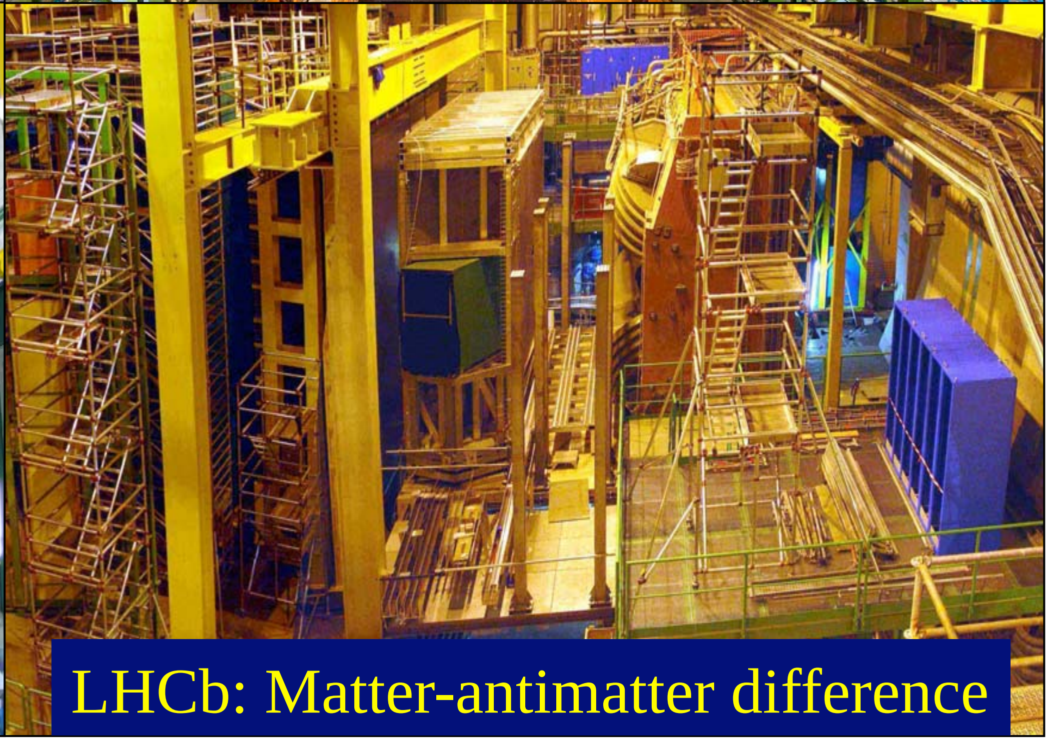
Primary targets:
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter

ALICE: Primordial cosmic plasma

ATLAS: Mass and dark matter



CMS: Mass and dark matter



LHCb: Matter-antimatter difference

The State of the Higgs: May 2009

- Direct search limit from LEP:

  $m_H > 114.4$ GeV

- Electroweak fit sensitive to m_t

  (Now $m_t = 173.1 \pm 1.3$ GeV)

- Best-fit value for Higgs mass:

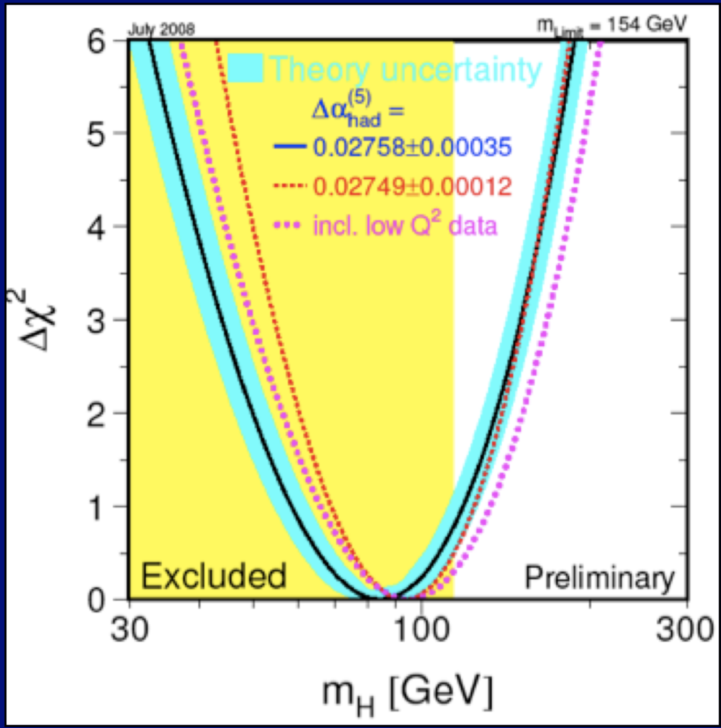
  $m_H = 84^{+34}_{-26}$ GeV

- 95% confidence-level upper limit:

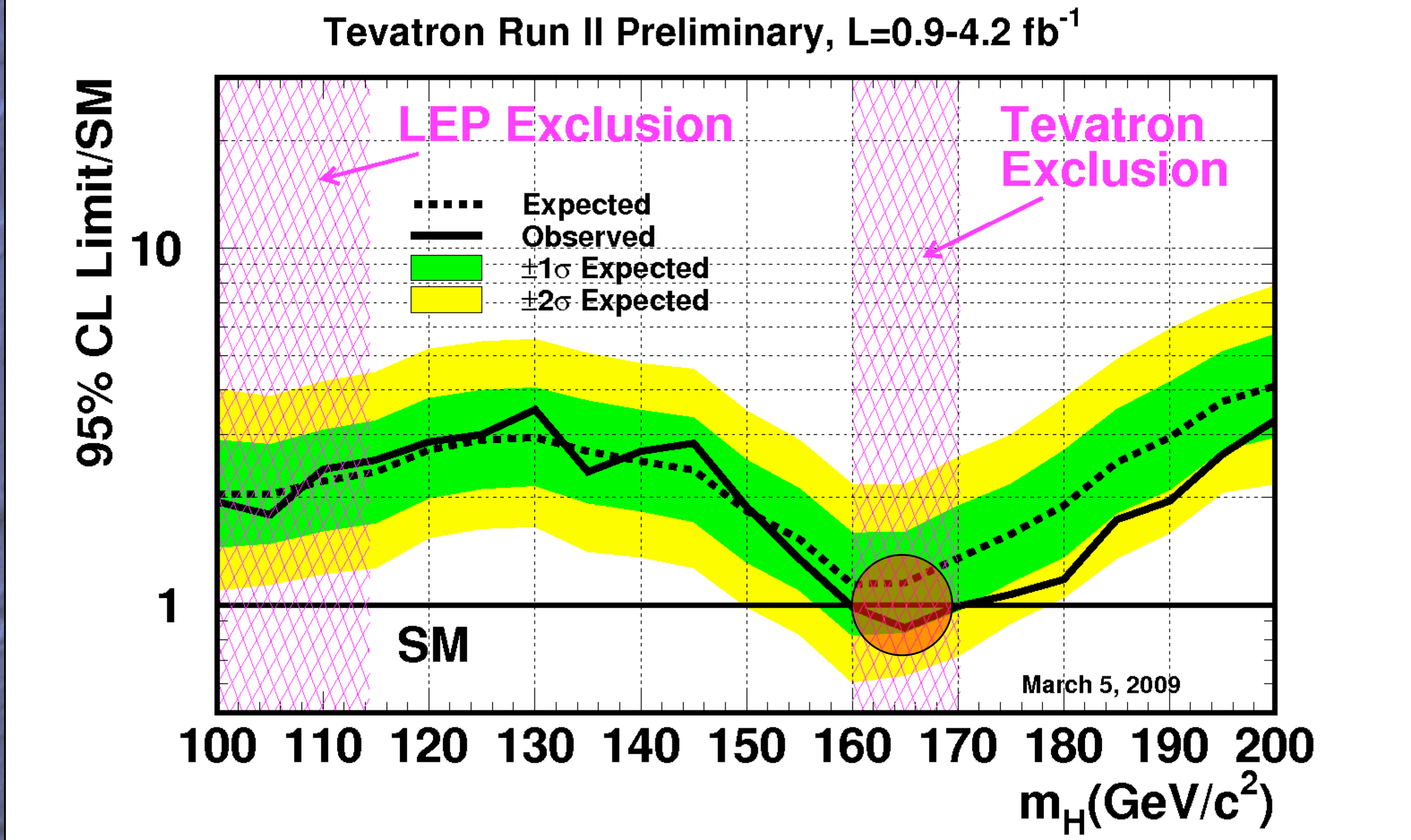
  $m_H < 154$ GeV, or 185 GeV including direct limit

- Tevatron exclusion:

  $m_H < 160$ GeV or > 170 GeV

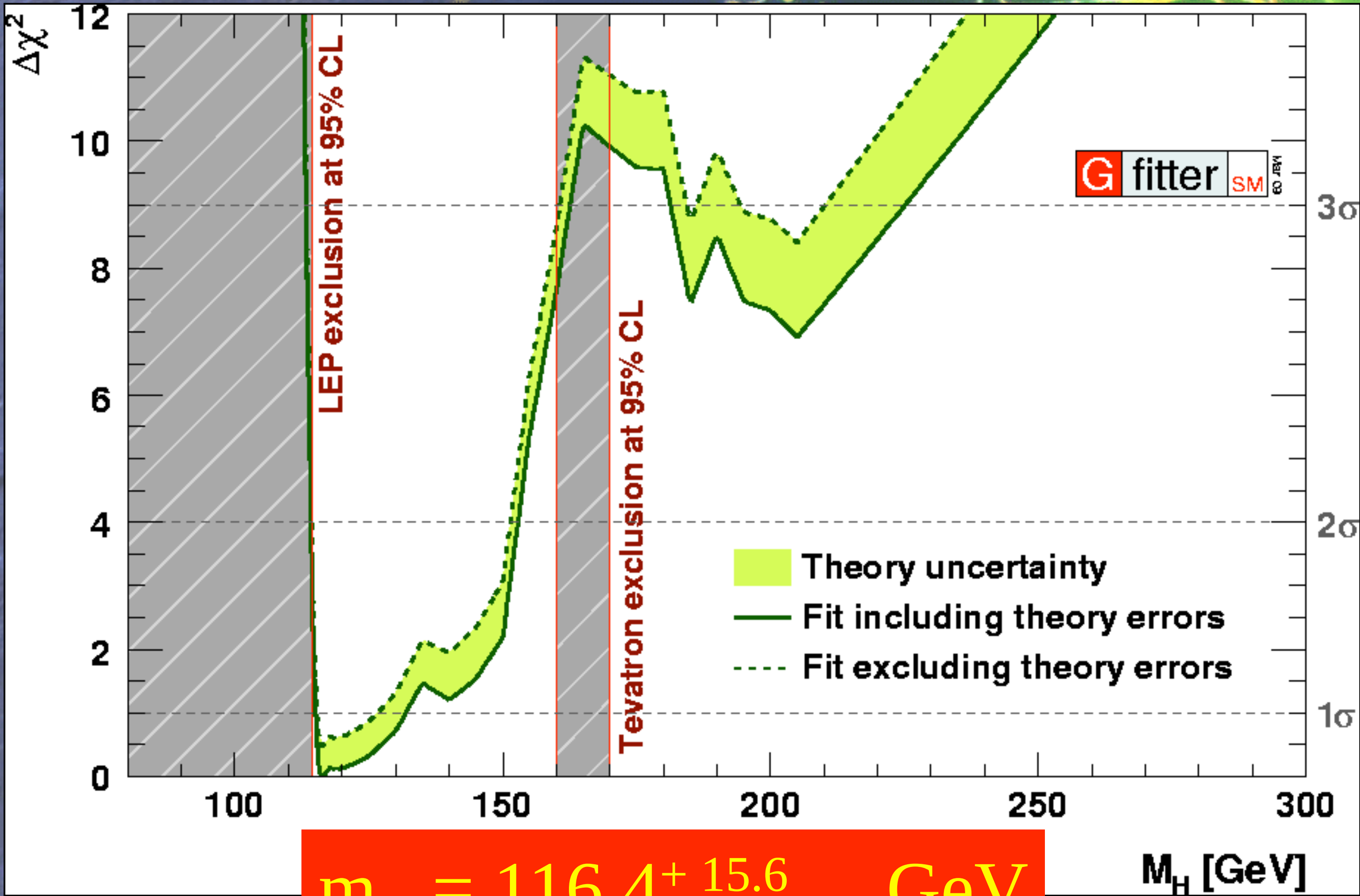


Higgs Search @ Tevatron



Tevatron excludes Higgs between 160 & 170 GeV

Combining the Higgs Information

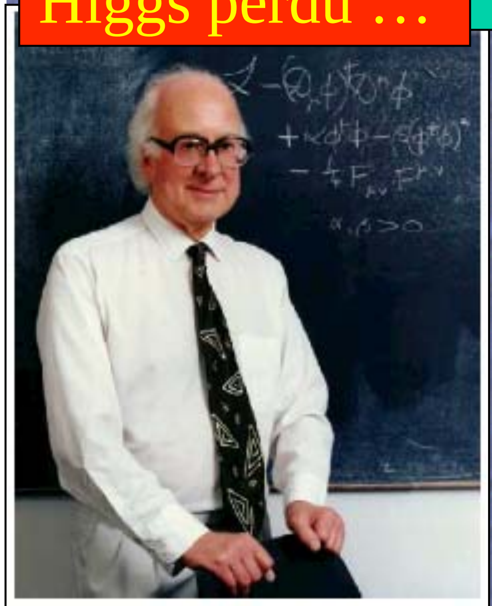


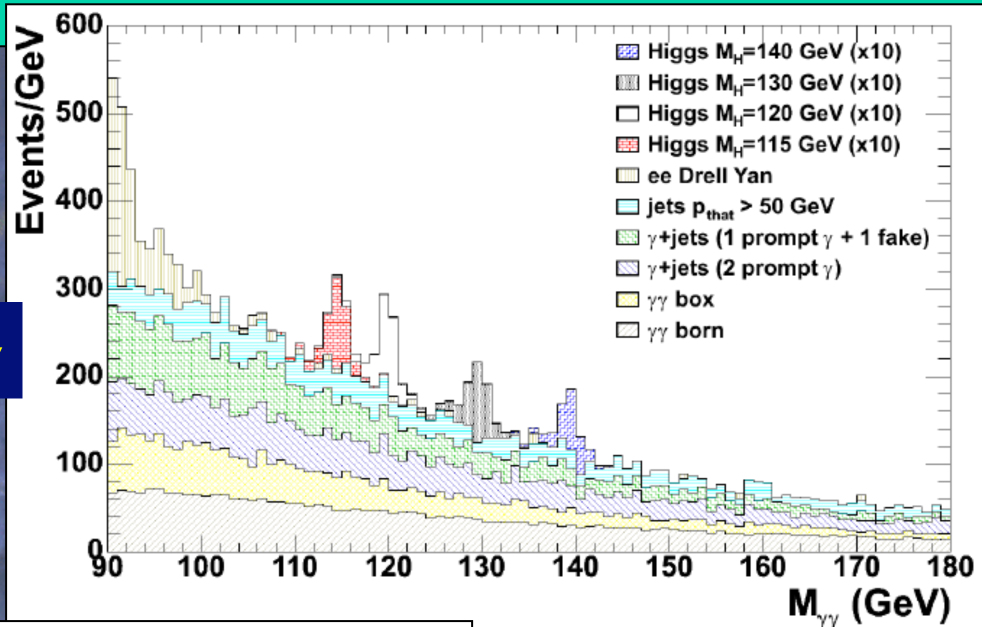
$m_H = 116.4^{+15.6}_{-1.3}$ GeV

Simulation of Higgs Boson @ LHC

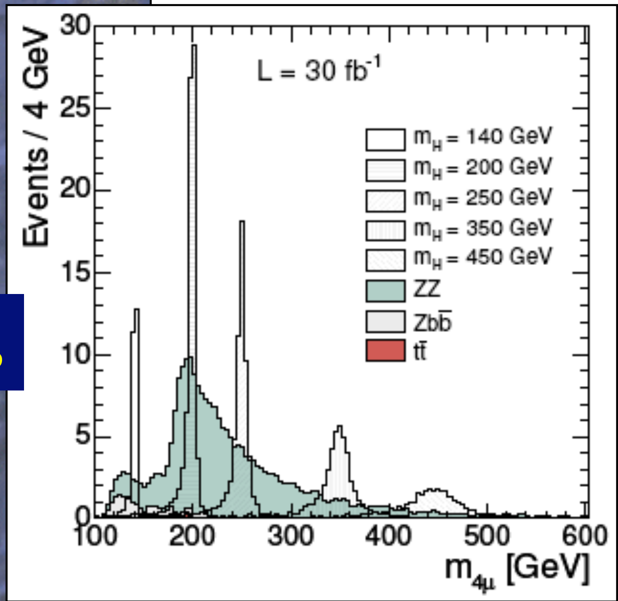
A la recherche du Higgs perdu …

Some Sample Higgs Signals

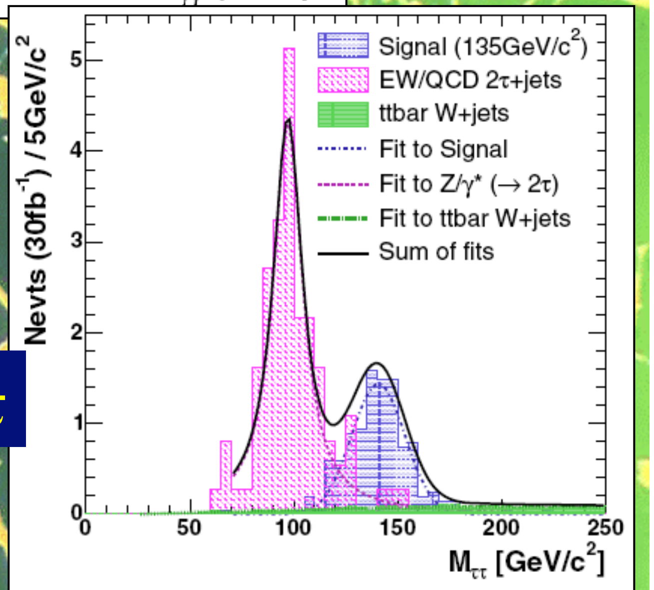




γγ

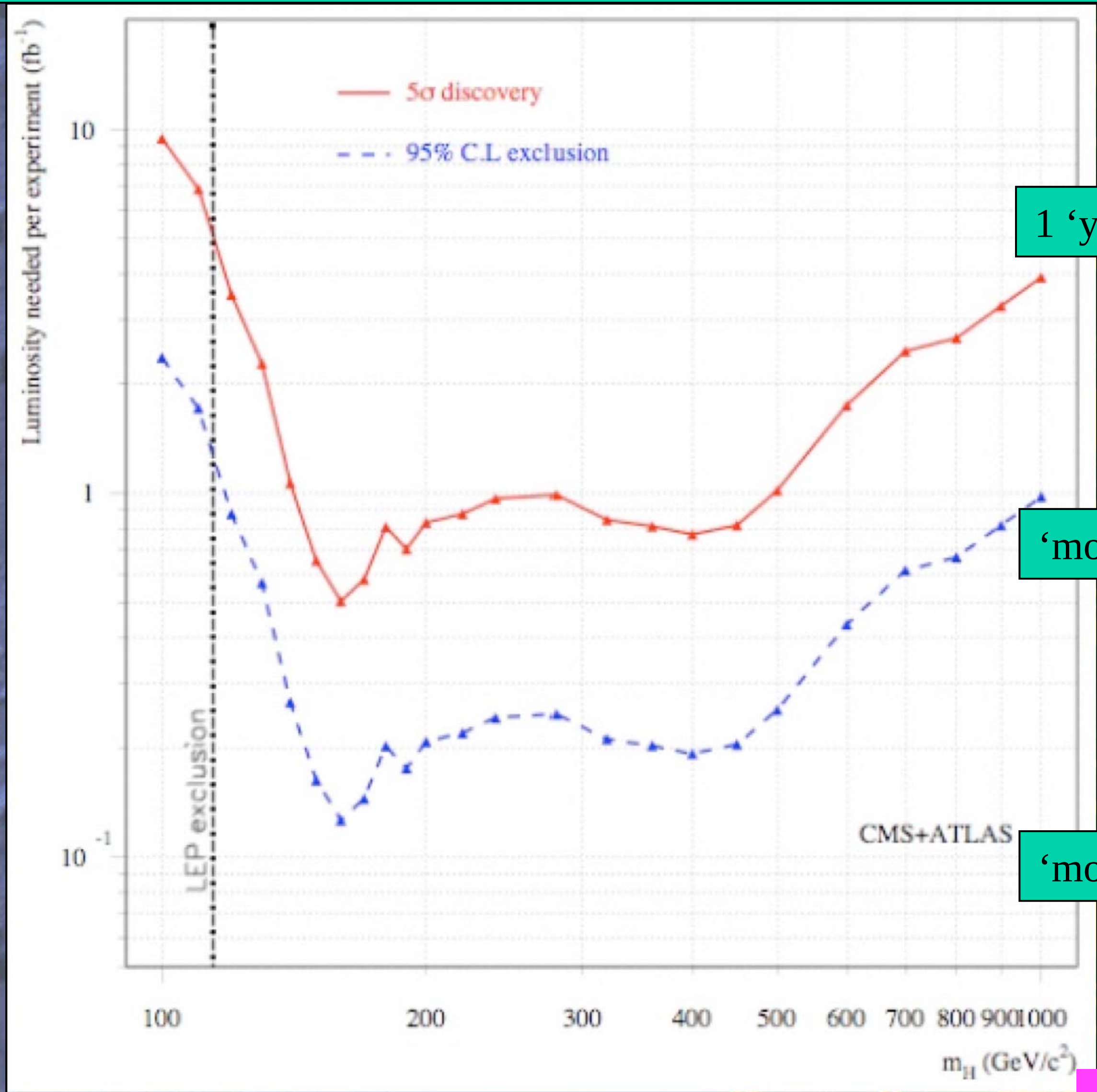


ZZ* -> 4 leptons



ττ

When will the LHC discover the Higgs boson?



1 'year' @ 10^{33}

'month' @ 10^{33}

'month' @ 10^{32}

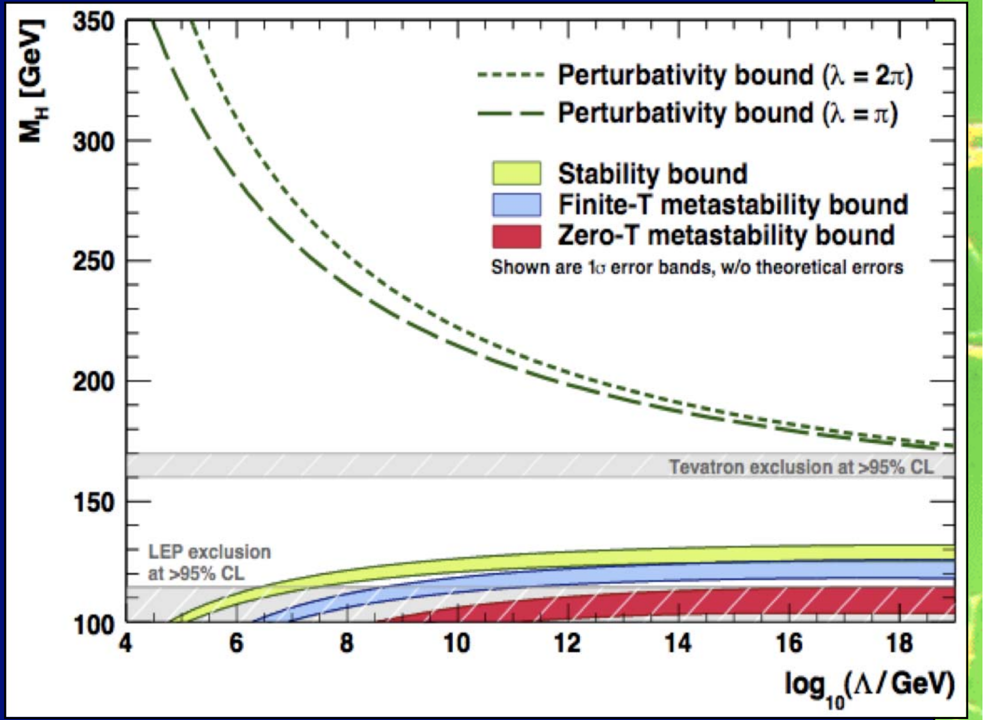
Blaising, JE et al: 2006

The Stakes in the Higgs Search

- How is particle symmetry broken?
- Is there an elementary scalar field?
- What is the fate of the Standard Model?
- Did mass appear when the Universe was a picosecond old?
- Did Higgs help create the matter in the Universe?
- Did a related inflaton make the Universe so big and old?
- Why is there so little dark energy?
- What is the fate of the Universe?

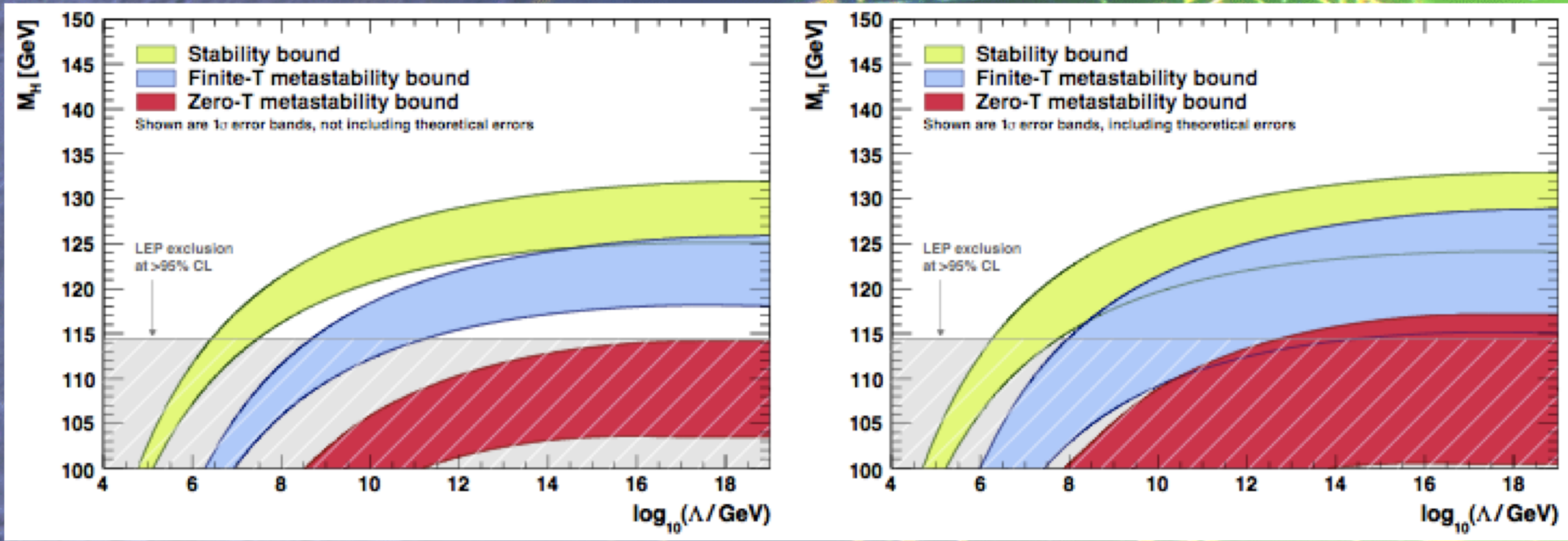
Theoretical Constraints on Higgs Mass

- Large → large self-coupling → blow up at low energy scale Λ due to renormalization
- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable



- Bounds on Higgs mass depend on Λ

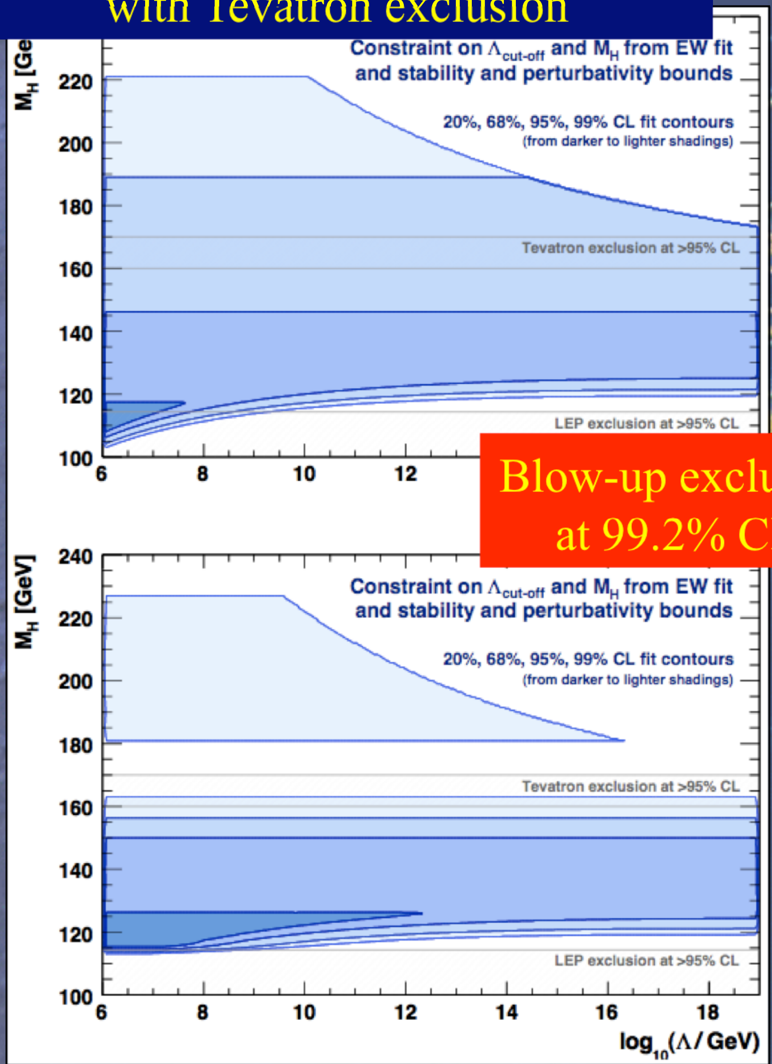
Zoom on Low-Mass Region



- Lower bound for stable vacuum
- Lower bound for stability at finite T
- Lower bound for stability at zero T

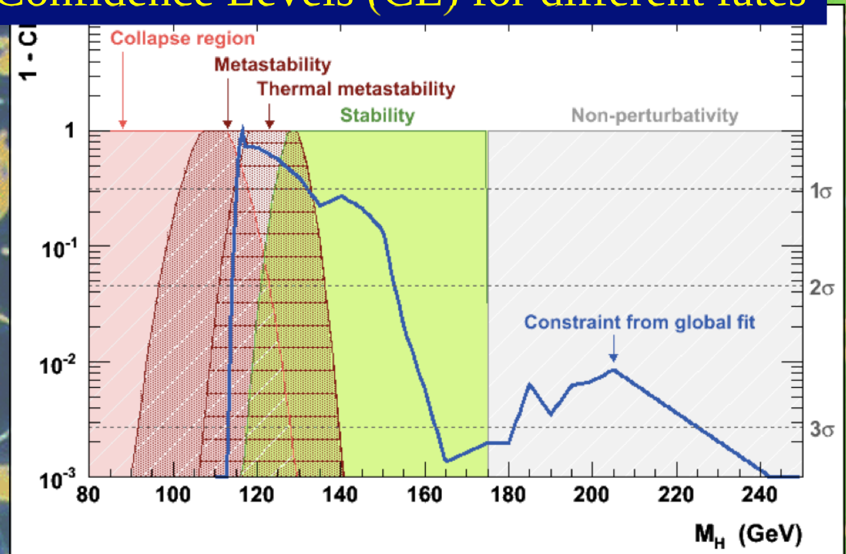
What is the probable fate of the SM?

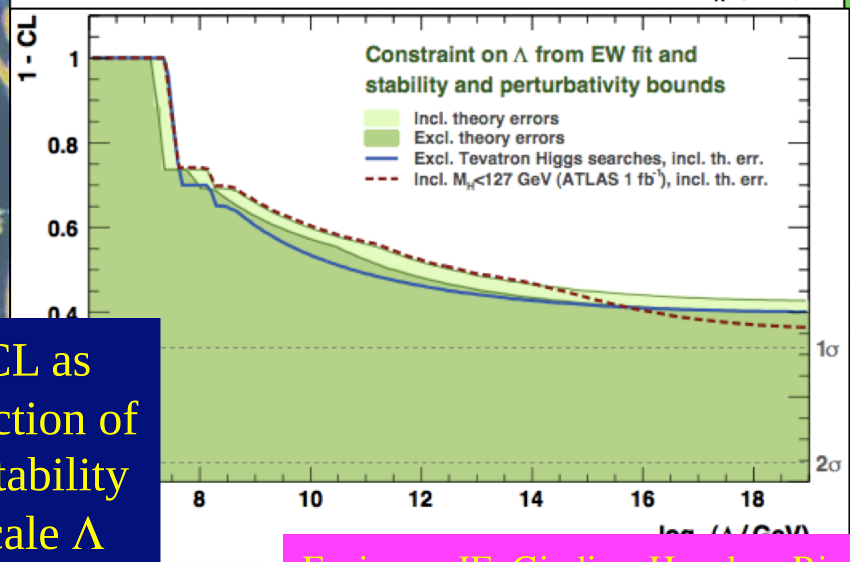
Confidence Levels (CL) without/ with Tevatron exclusion



Blow-up excluded at 99.2% CL

Confidence Levels (CL) for different fates



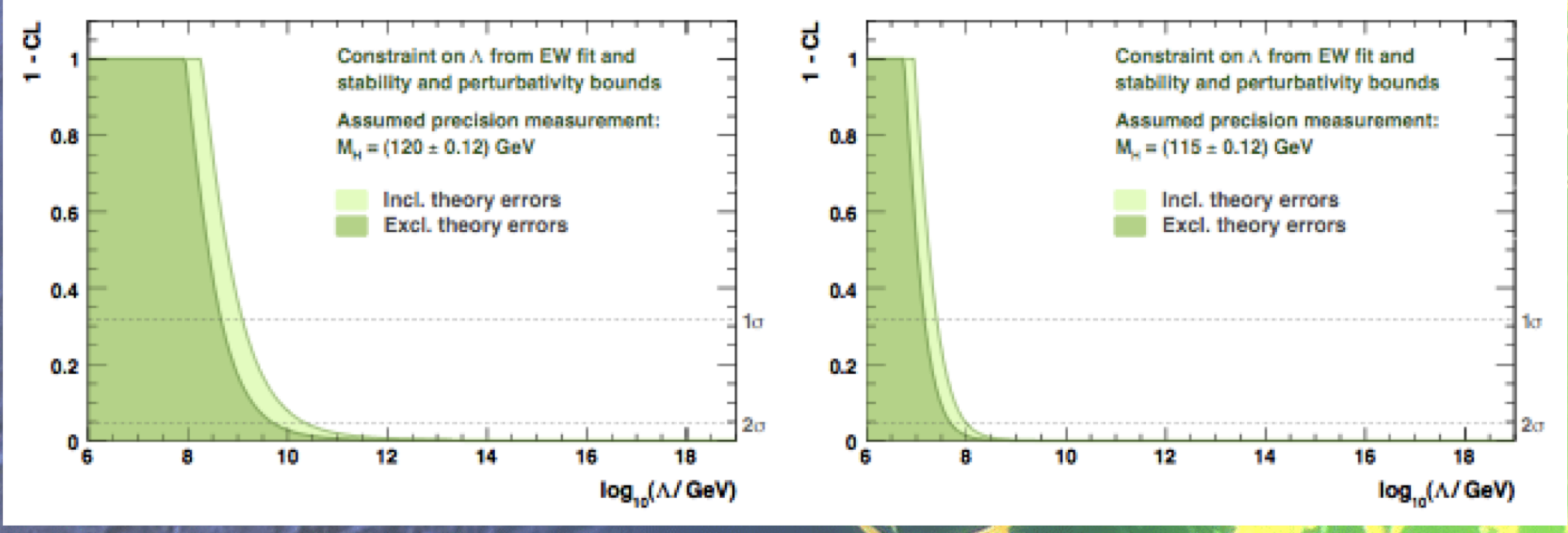


CL as function of instability scale Λ

Espinosa, JE, Giudice, Hoecker, Riotto

The LHC will tell Fate of the Universe

Examples with LHC measurement of m_H = 120 or 115 GeV



Espinosa, JE, Giudice, Hoecker, Riotto

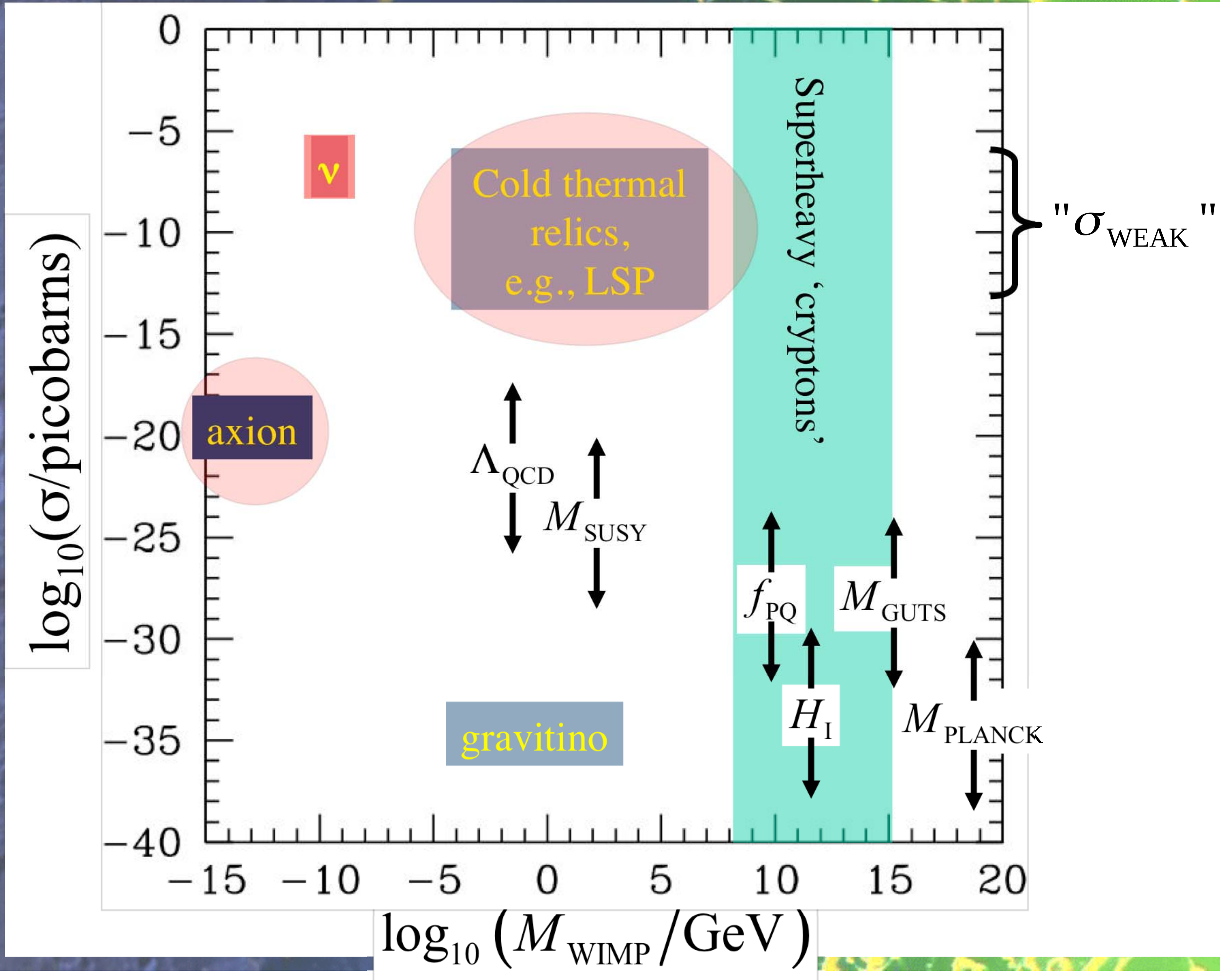
Comments on Dark Energy

- Many orders of magnitude smaller than expected contributions from ‘known’ physics: 10^{-48} GeV^4

QCD:	$\Lambda_{QCD}^4 \sim 10^{-4}$ GeV^4
Higgs:	$m_W^4 \sim 10^{8}$ GeV^4
Broken susy:	$m_{susy}^4 \sim 10^{12}$ GeV^4
GUT:	$m_{GUT}^4 \sim 10^{64}$ GeV^4
Quantum Gravity:	$m_P^4 \sim 10^{76}$ GeV^4

- Need new physics!
- A great challenge for string theory

Particle Dark Matter Candidates

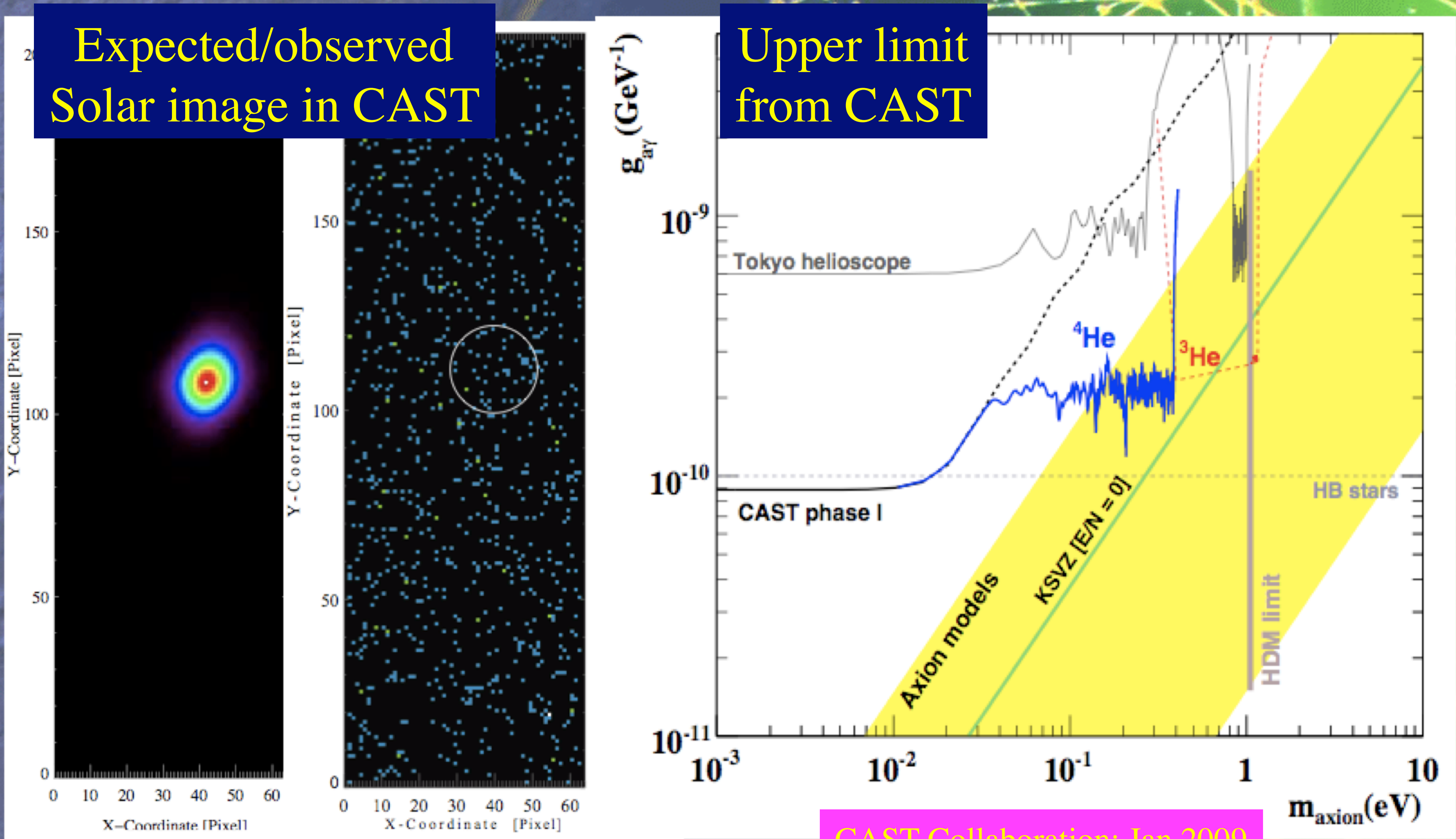


CAST Experiment at CERN

- Search for solar axions(*) converting to photons
- Uses decomissioned LHC test magnet

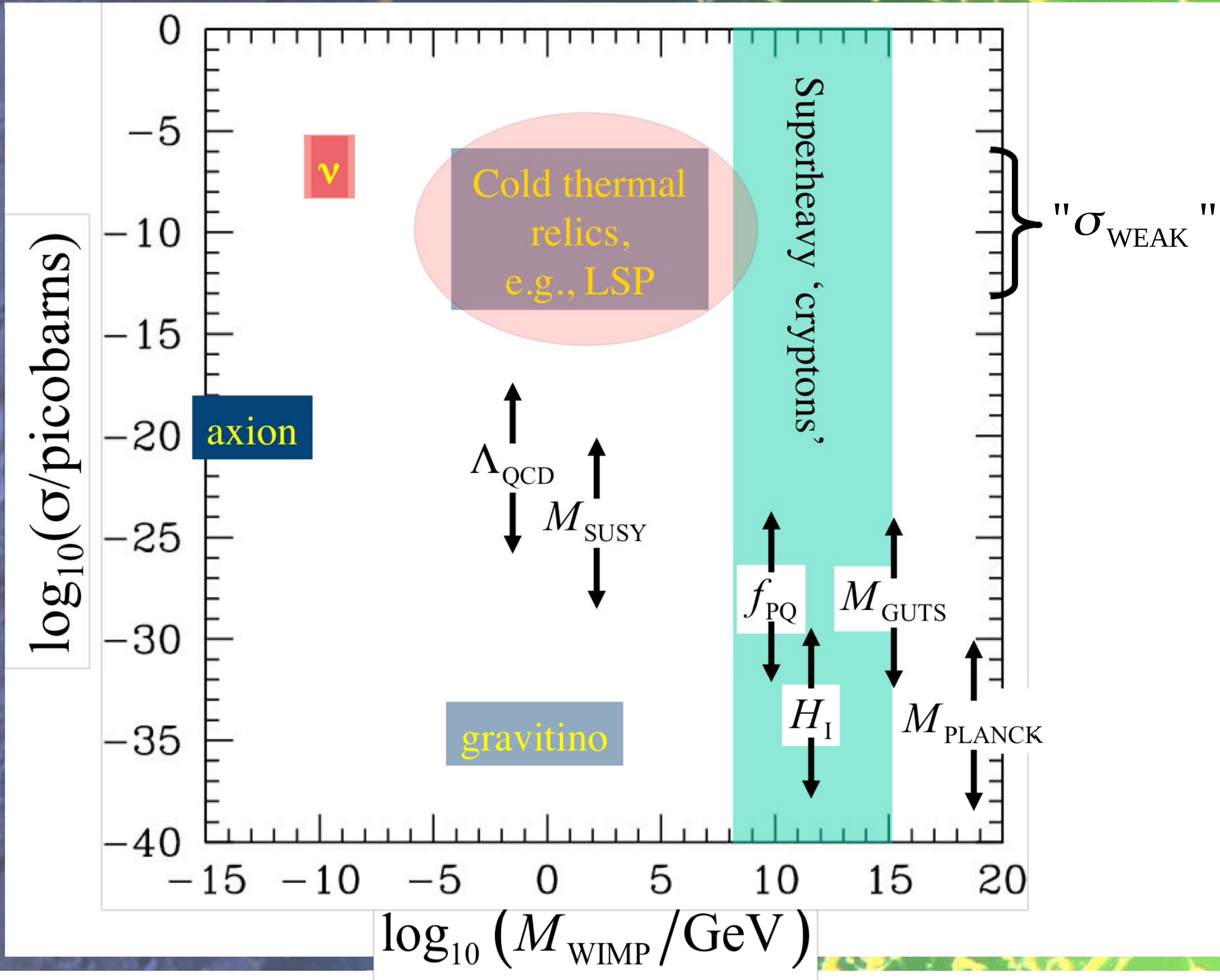
(*) Spinless particle invented to preserve matter-antimatter symmetry in nuclear forces

Looking for Axions with the CAST Experiment at CERN



CAST Collaboration: Jan 2009

Particle Dark Matter Candidates



Supersymmetry?

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

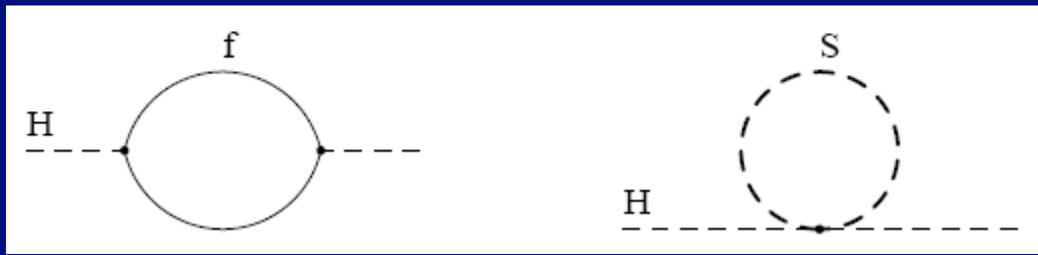
  0 - ½ - 1 - 3/2 - 2

  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**

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 Standard Model (MSSM)

- Particles + spartners

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

- 2 Higgs doublets, coupling μ, ratio of v.e.v.'s = $\tan\beta$
- Unknown supersymmetry-breaking parameters:
  - Scalar masses m_0, gaugino masses $m_{1/2}$,
  - trilinear soft couplings A_λ, bilinear soft coupling B_μ
- Assume universality? constrained MSSM = CMSSM
  - Single m_0, single $m_{1/2}$, single A_λ, B_μ: not string?
- Not the same as minimal supergravity (mSUGRA)
- Gravitino mass, additional relations

$$m_{3/2} = m_0, \; B_\mu = A_\lambda - m_0$$

Constraints on Supersymmetry

- Absence of sparticles at LEP, Tevatron

  selectron, chargino > 100 GeV

  squarks, gluino > 250 GeV

- Indirect constraints

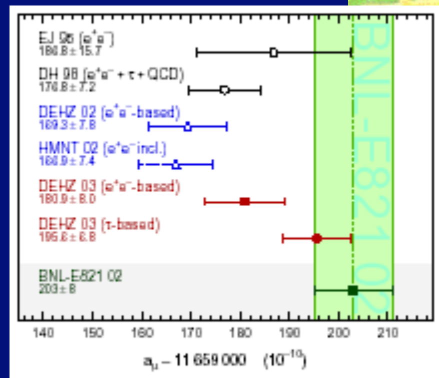
  Higgs > 114 GeV, b -> s γ

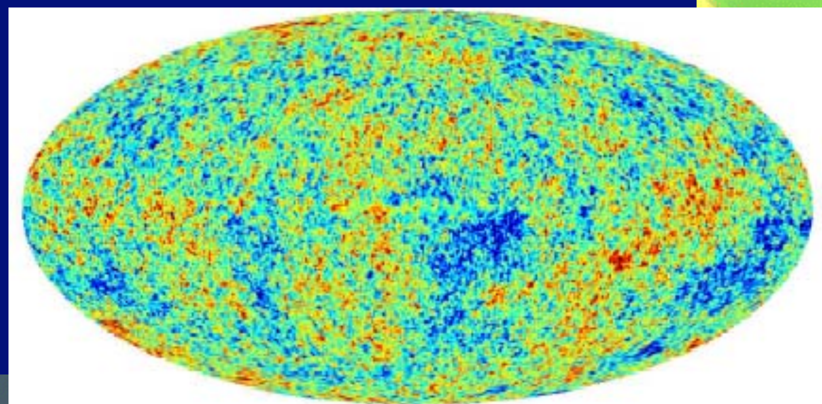
- Density of dark matter

  lightest sparticle χ:

WMAP: $0.094 < \Omega_\chi h^2 < 0.124$

g_μ - 2





Current Constraints on CMSSM

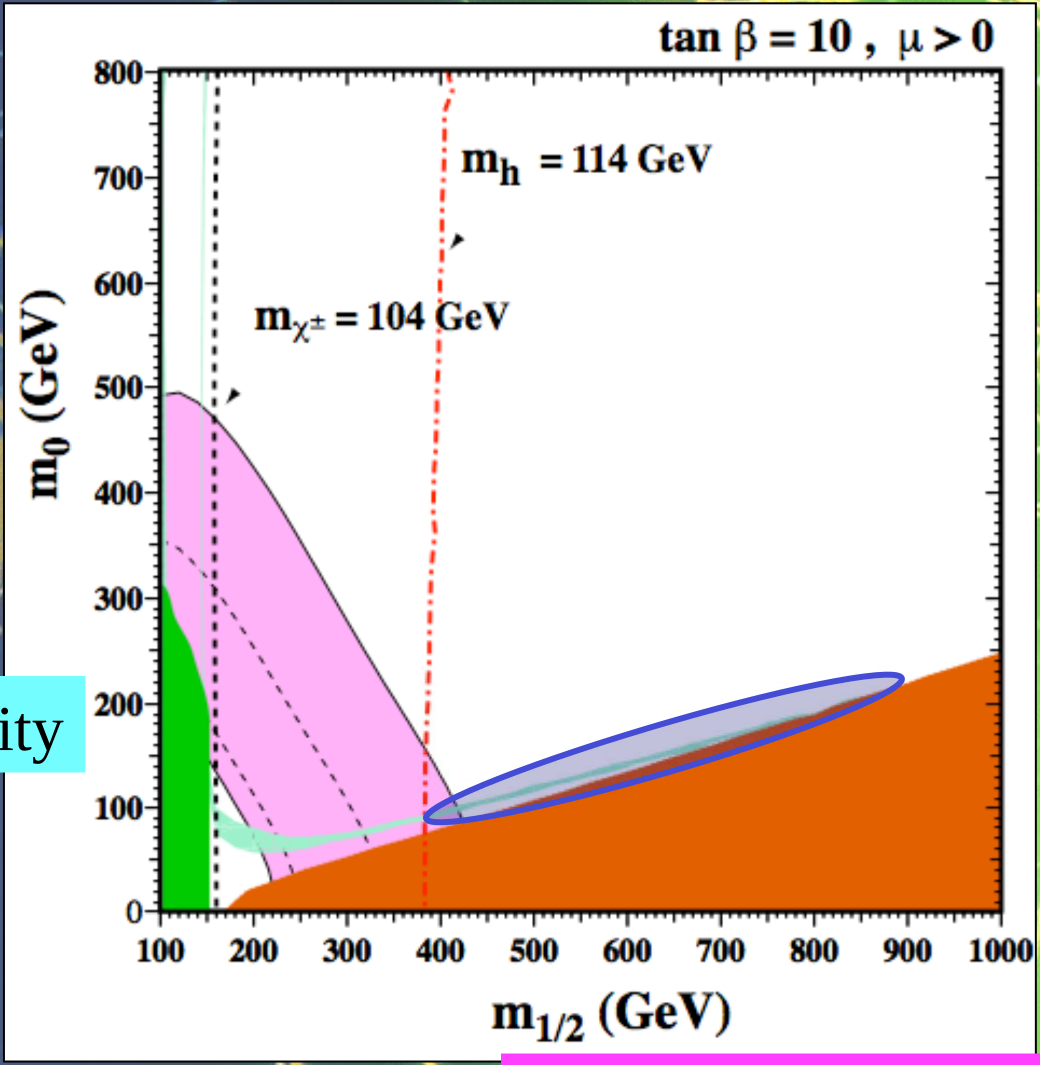
Assuming the lightest sparticle is a neutralino

Excluded because stau LSP

Excluded by b → s gamma

WMAP constraint on relic density

Preferred (?) by latest g - 2

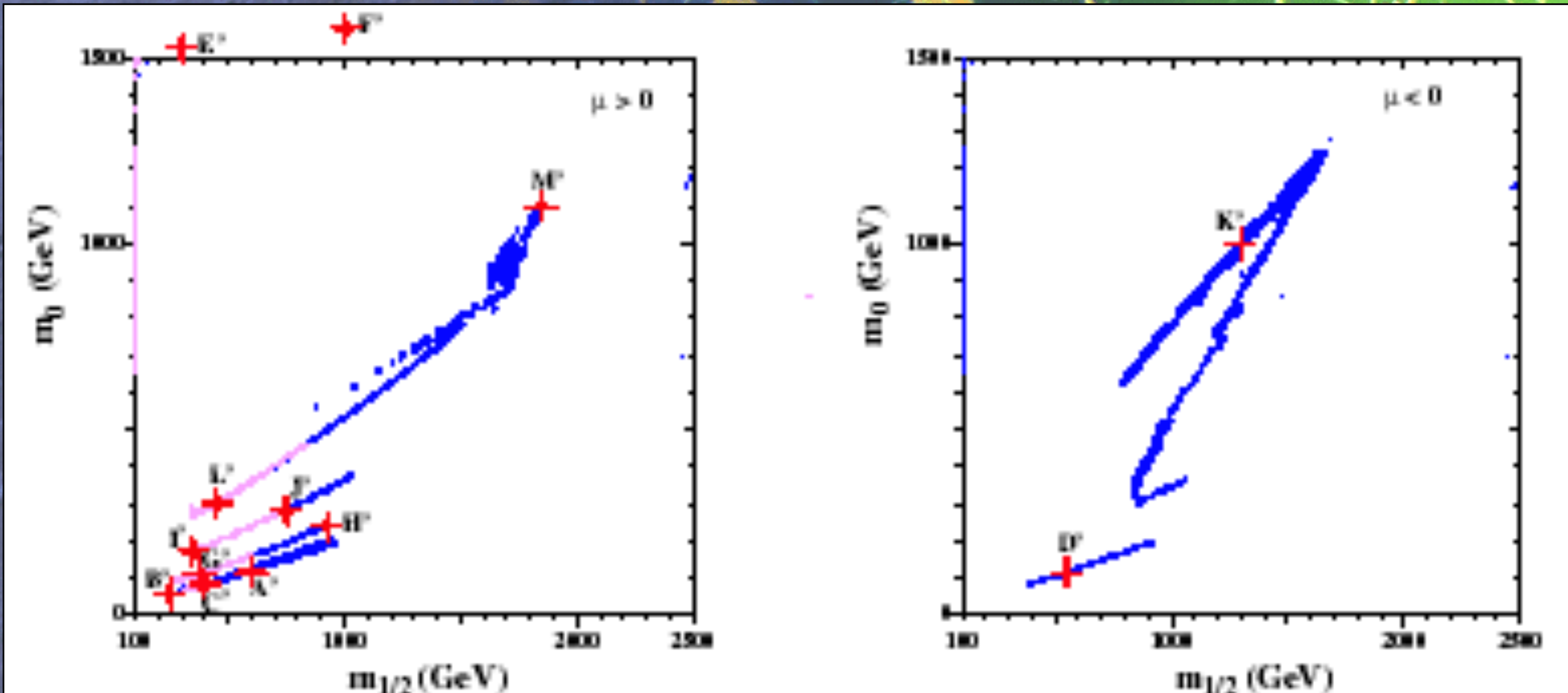


JE + Olive + Santoso + Spanos

Supersymmetric Parameter Space

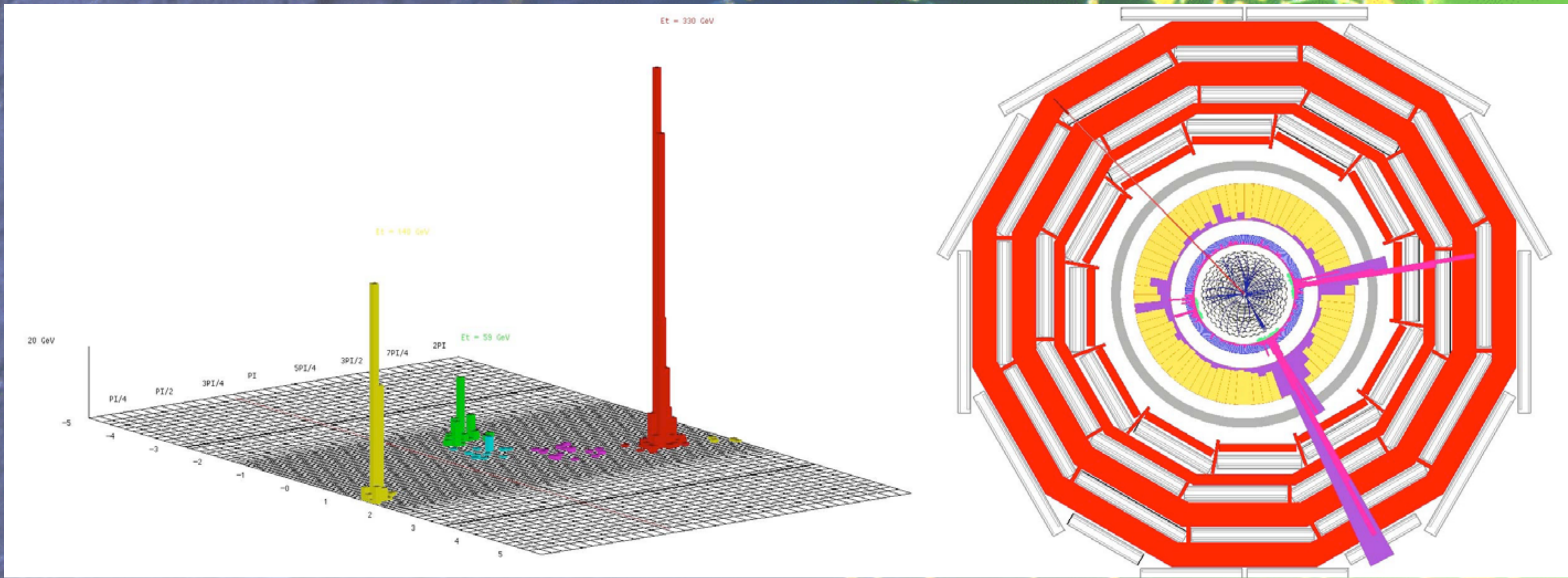
Lines in susy space allowed by accelerators, WMAP data

Specific benchmark points along WMAP lines



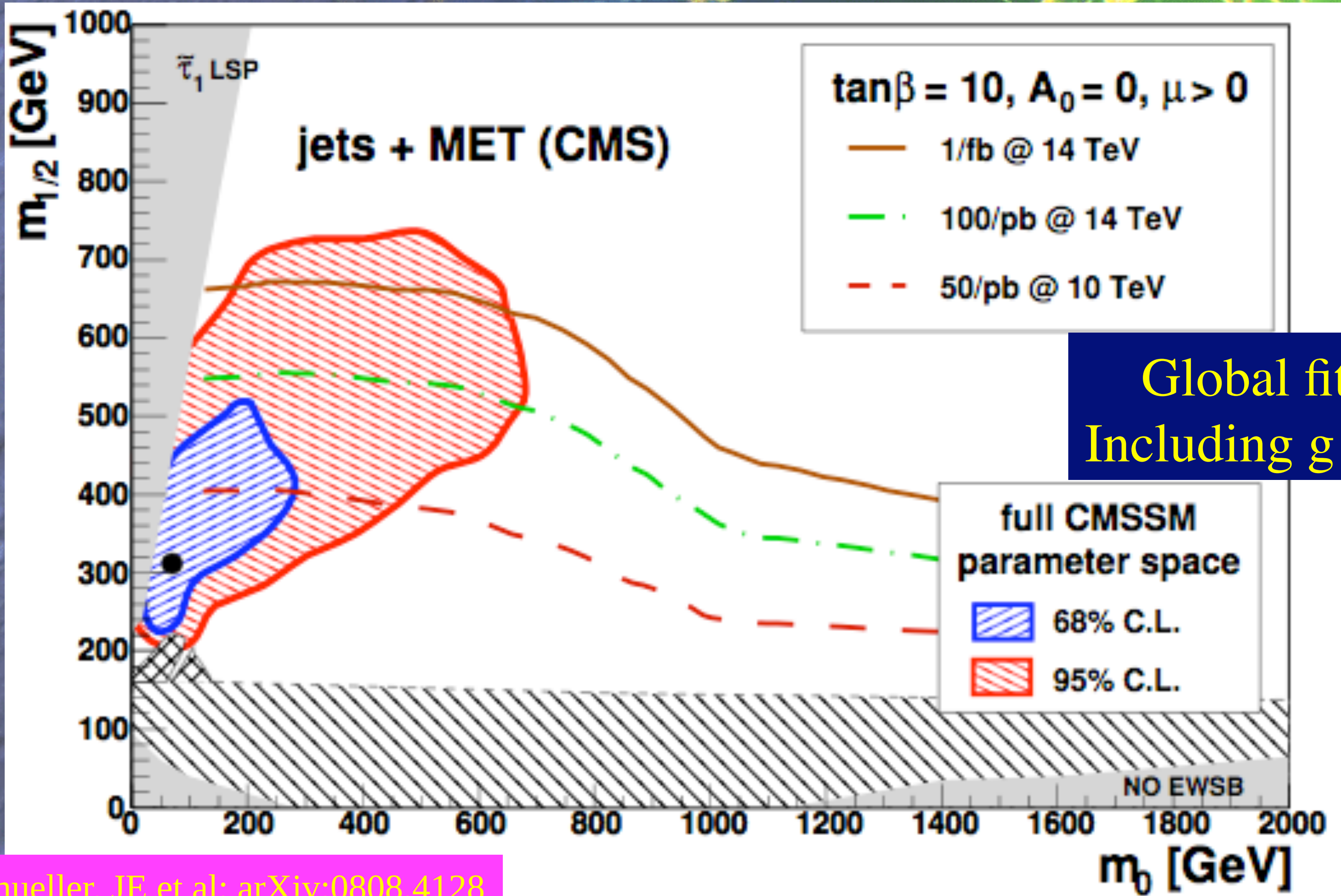
Battaglia, De Roeck, Gianotti, JE, Olive, Pape

Classic Supersymmetric Signature



Missing transverse energy
carried away by dark matter particles

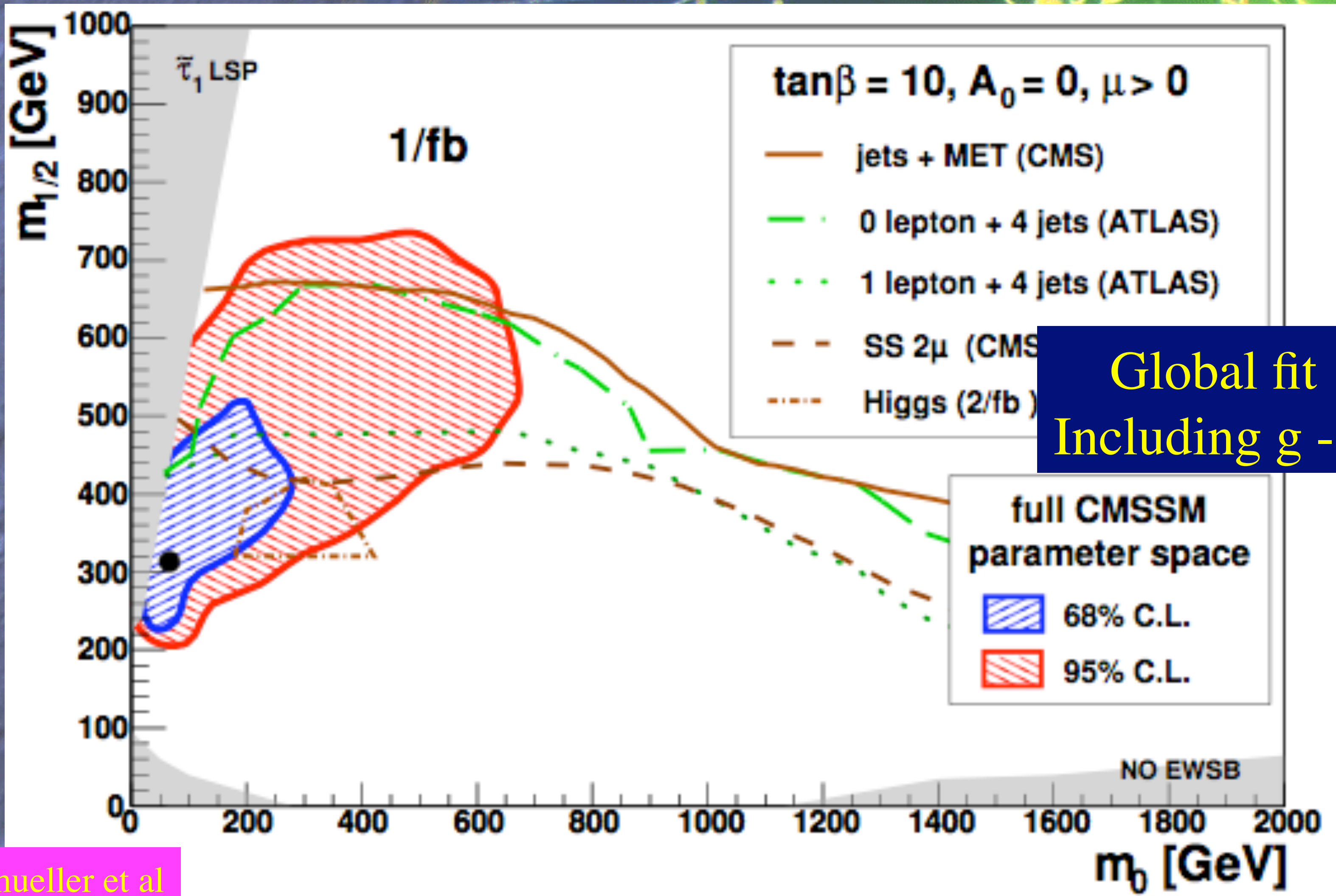
How Soon Might the CMSSM be Detected?



Global fit
Including g - 2

O.Buchmueller, JE et al: arXiv:0808.4128

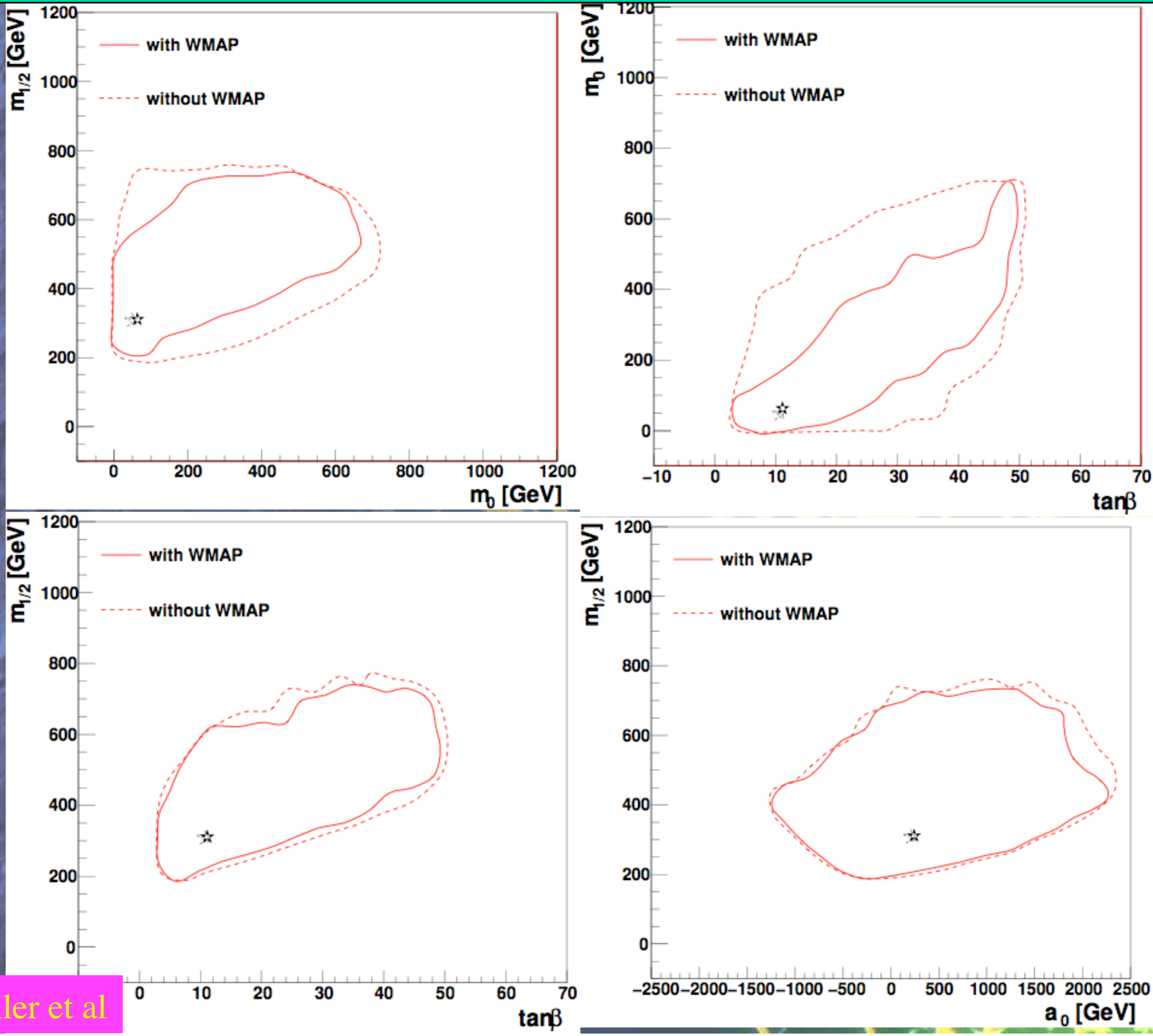
CMSSM with 1/fb of LHC Data



Global fit Including g - 2

O.Buchmueller et al

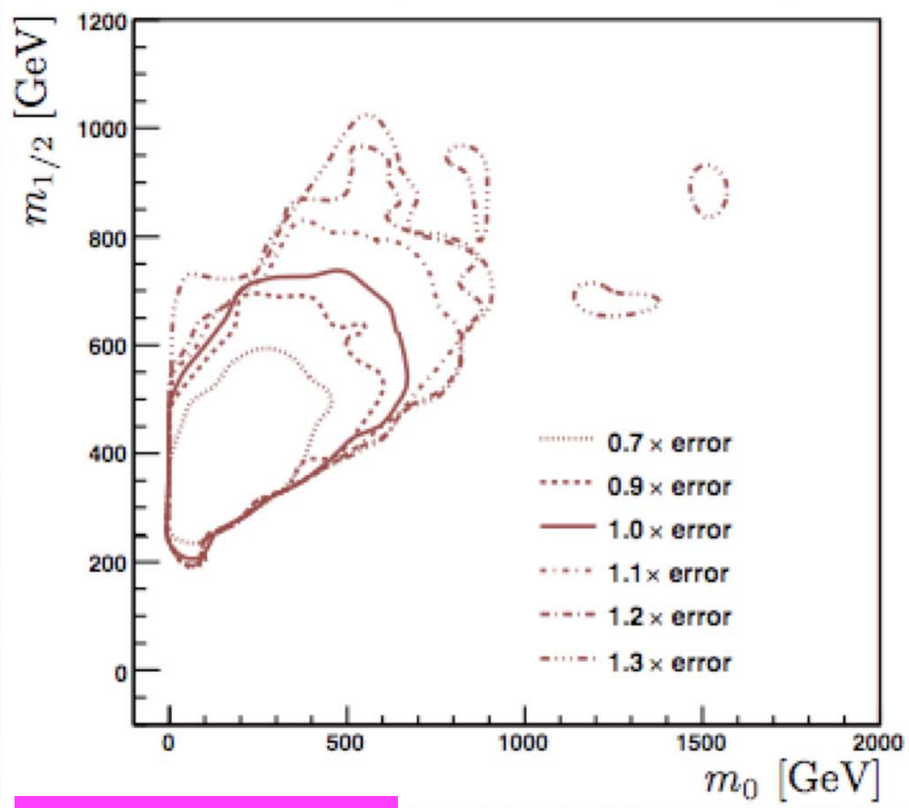
(In)Sensitivity to Dark Matter Density



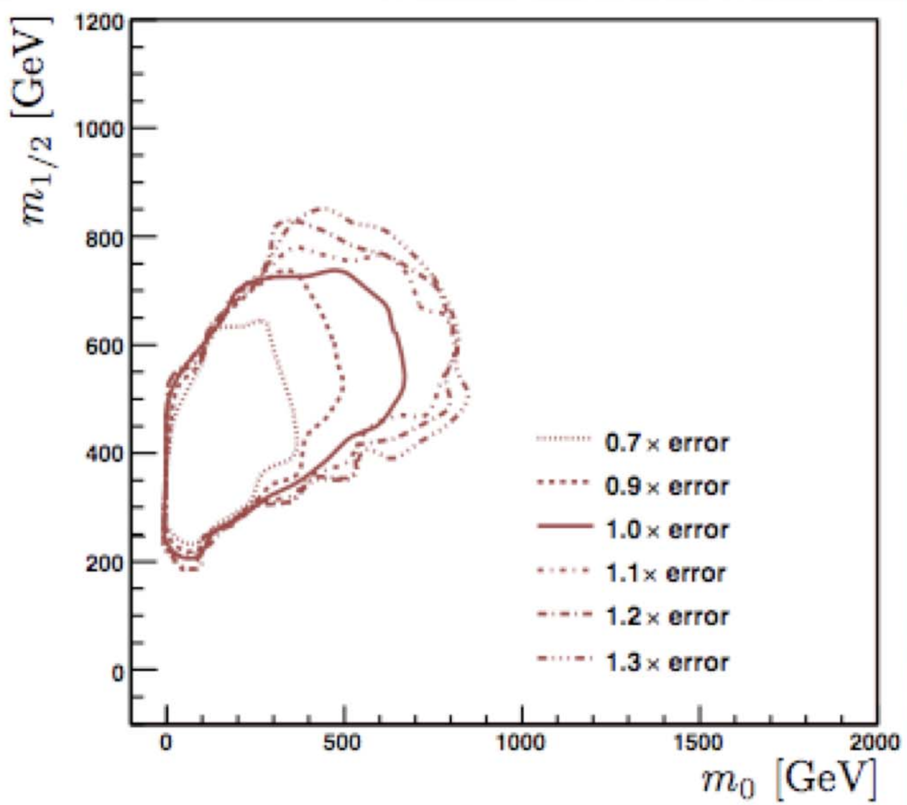
O.Buchmueller et al

Sensitivity to Uncertainties

g_μ - 2



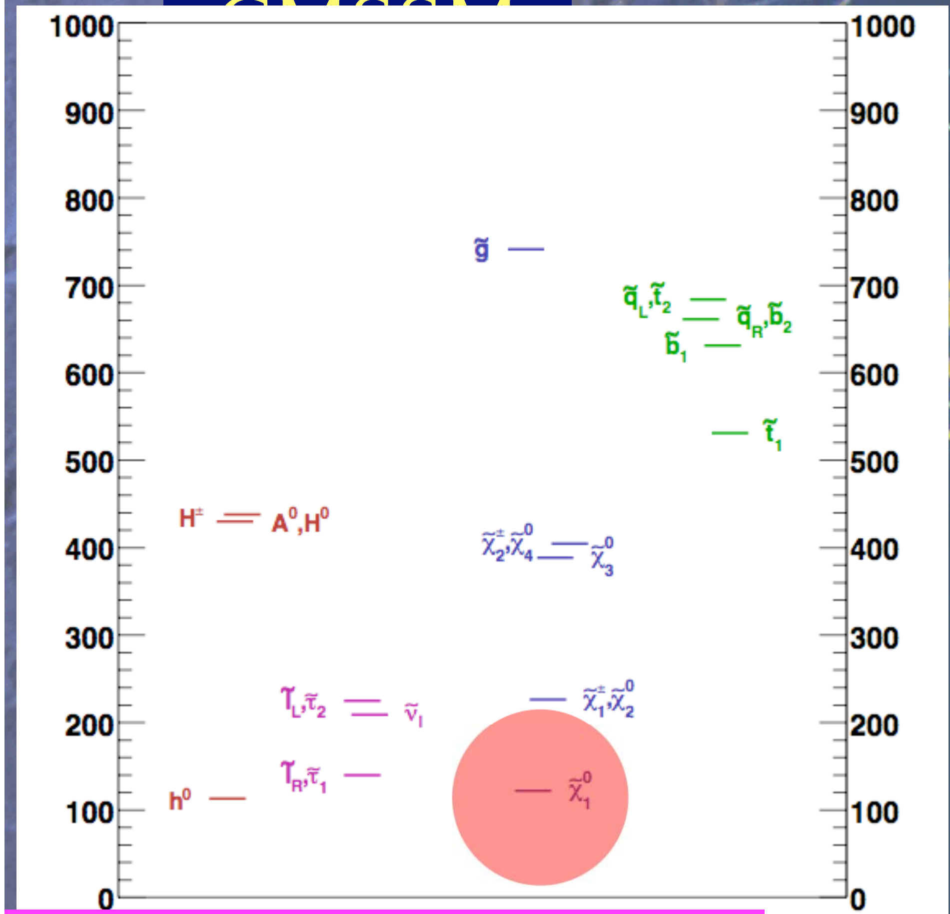
$b \to s\gamma$



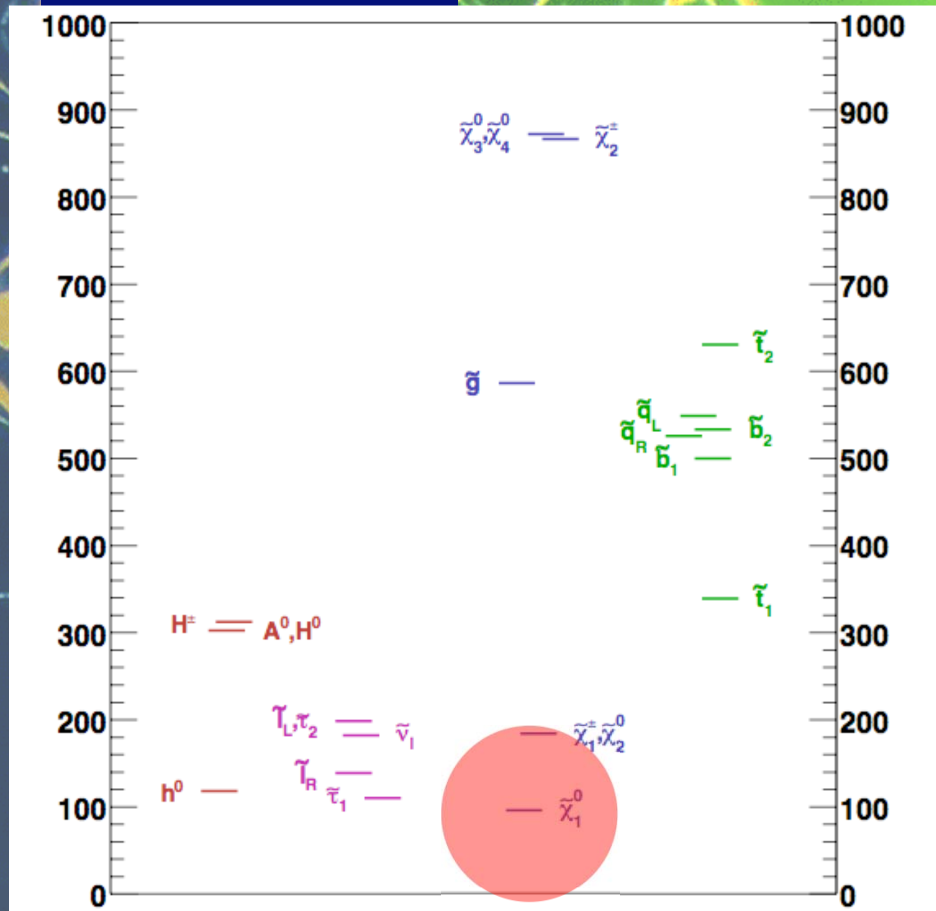
O.Buchmueller et al

Best-Fit Spectra

CMSSM



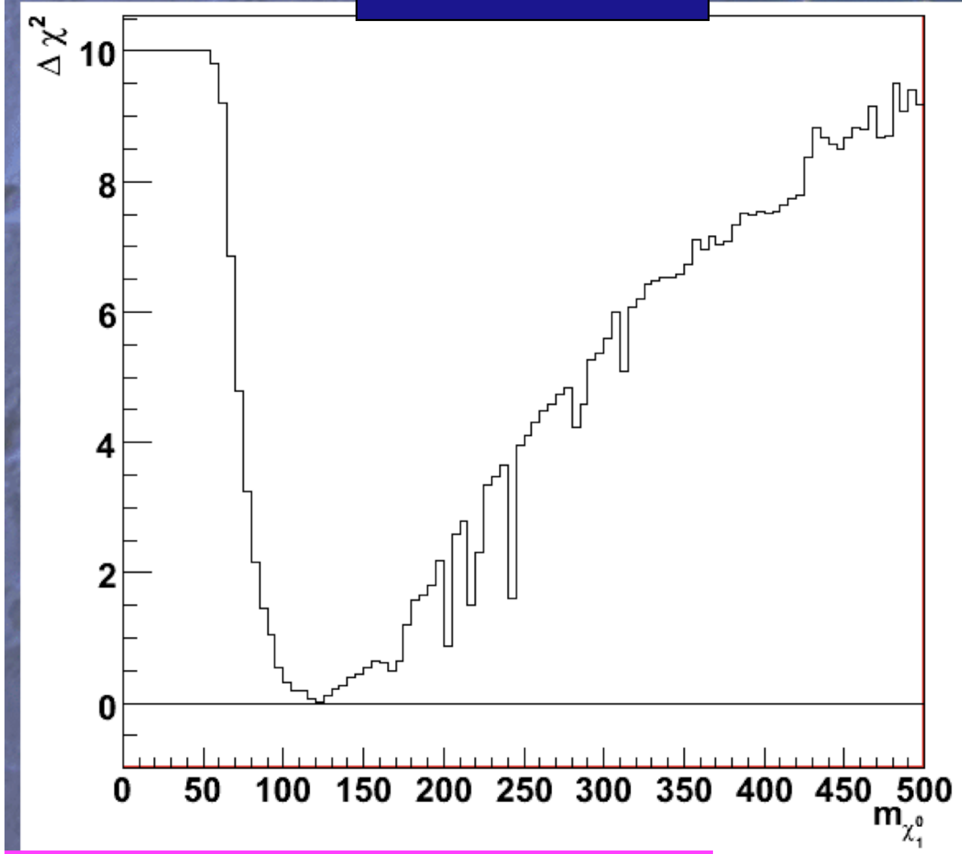
NUHM1



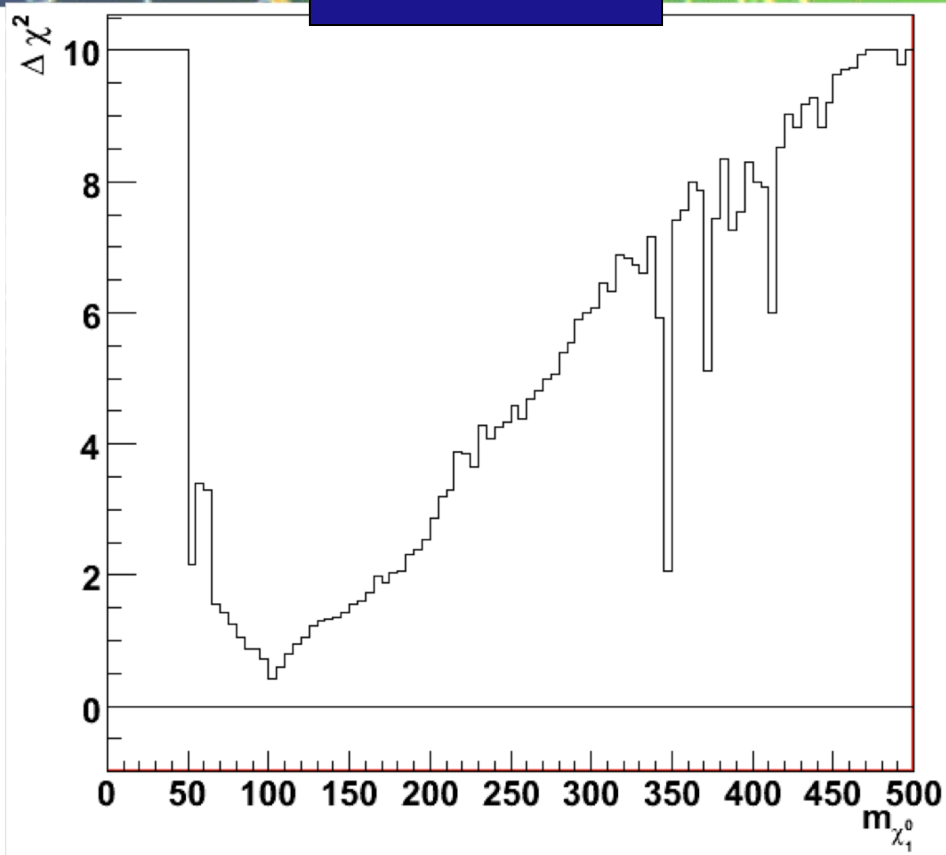
O.Buchmueller, JE et al: arXiv:0808.4128

Likelihood Function for Neutralino Mass

CMSSM



NUHM1



O.Buchmueller, JE et al: in preparation

Strategies for Detecting Supersymmetric Dark Matter

- Annihilation in galactic halo

  $\chi - \chi \rightarrow$ antiprotons, positrons, …?

- Annihilation in galactic centre

  $\chi - \chi \rightarrow \gamma + \ldots ?$

- Annihilation in core of Sun or Earth

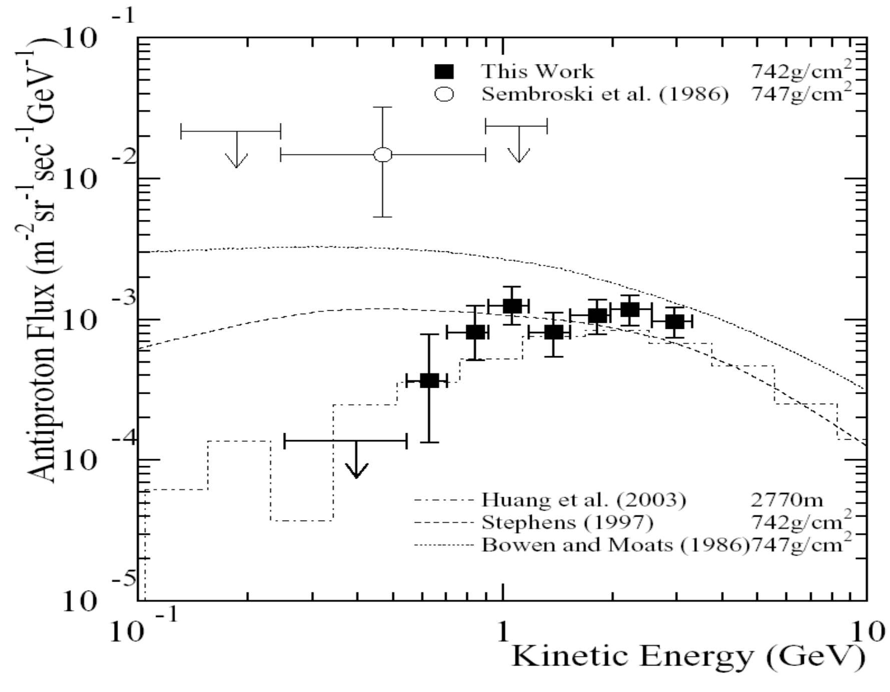
  $\chi - \chi \rightarrow \nu + \ldots \rightarrow \mu + \ldots$

- Scattering on nucleus in laboratory

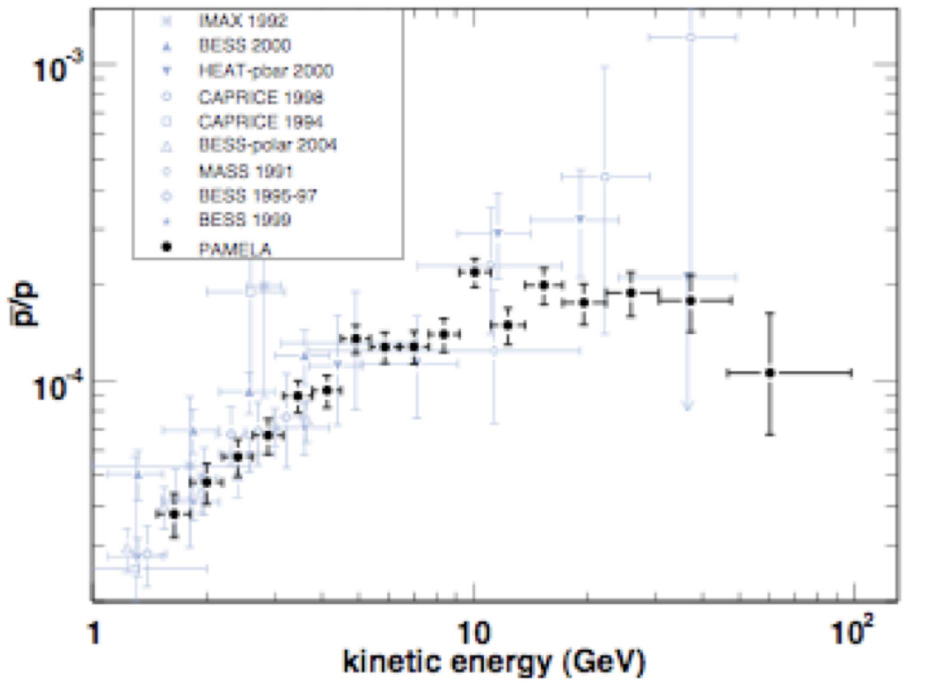
  $\chi + A \rightarrow \chi + A$

Antiproton Measurements

Previous Measurements



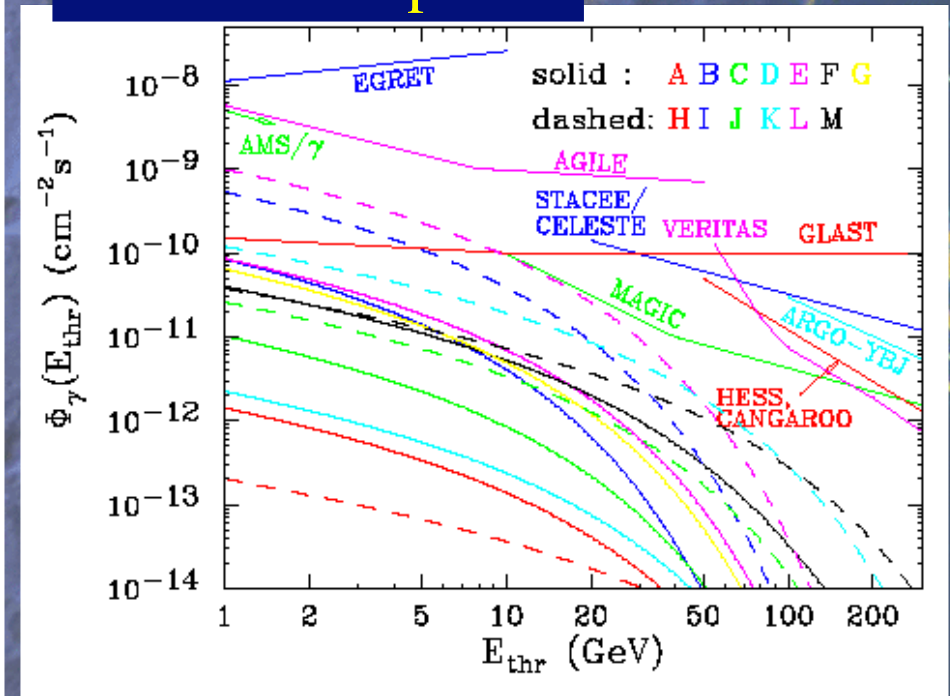
PAMELA Measurements



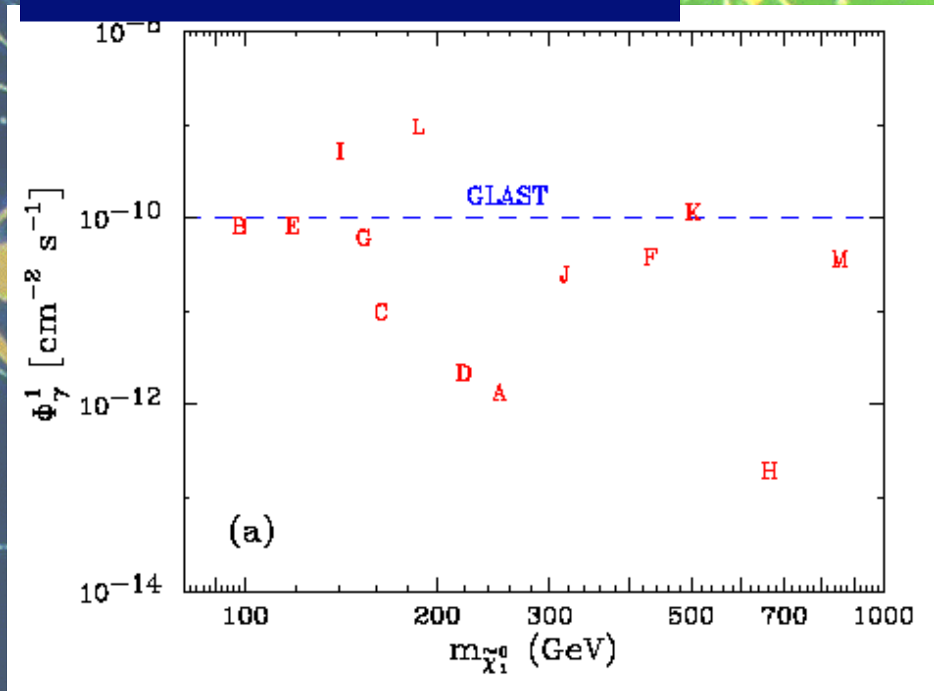
Boezio et al: arXiv:0810.3508

Annihilations in Galactic Centre

Benchmark spectra



Benchmarks → GLAST

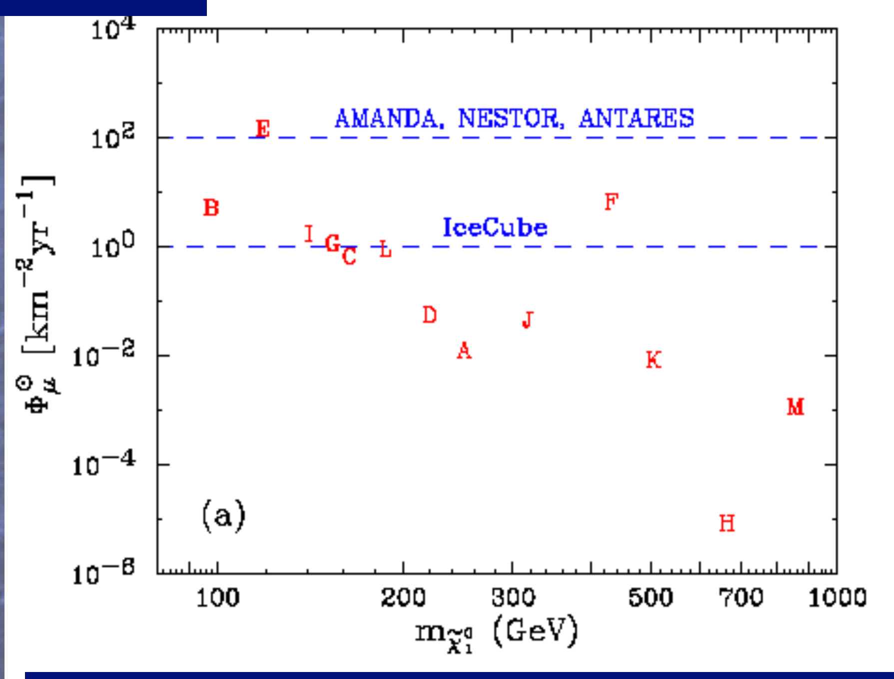


Enhancement of rate uncertain by factor > 100!

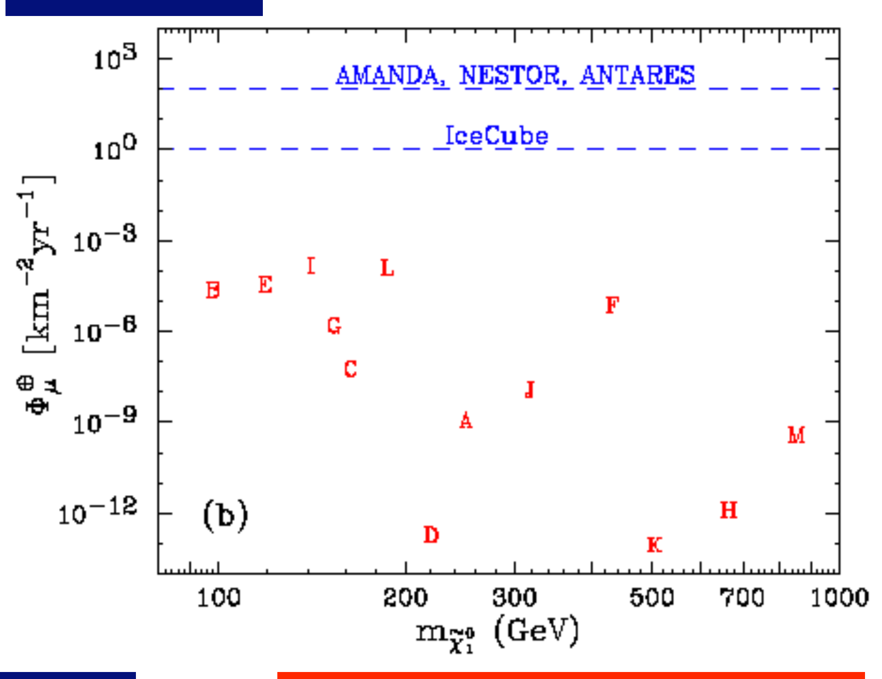
JE + Feng + Ferstl + Matchev + Olive

Annihilations in Solar System …

… Sun



… Earth



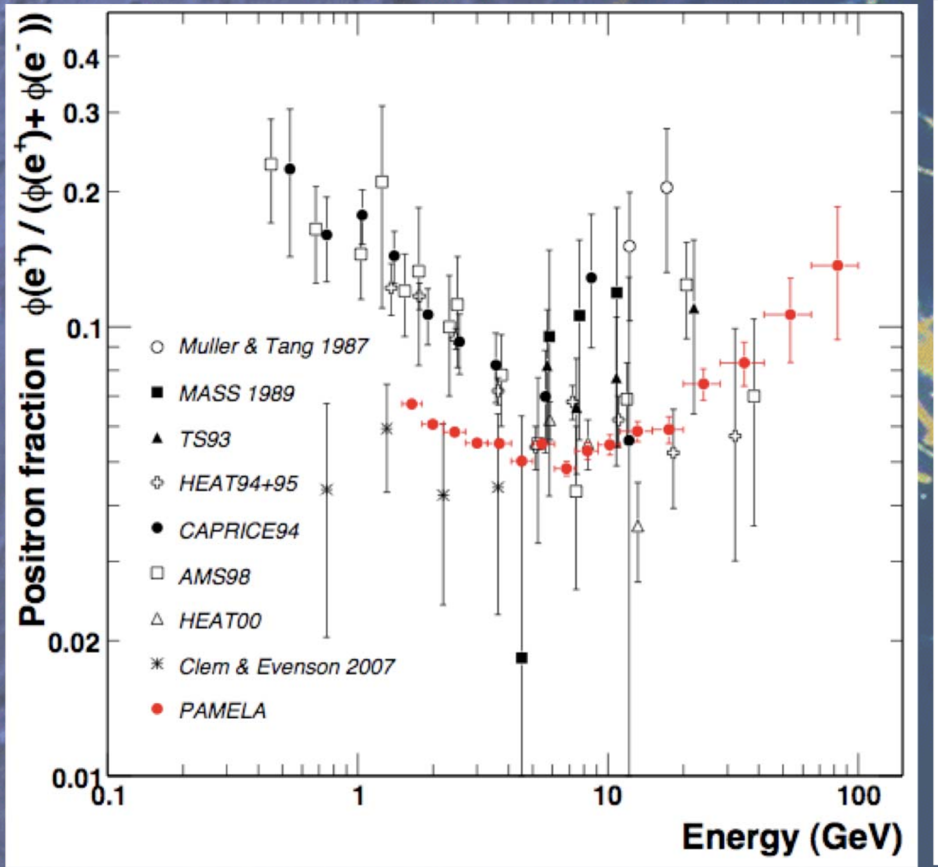
Prospective experimental sensitivities

Benchmark scenarios

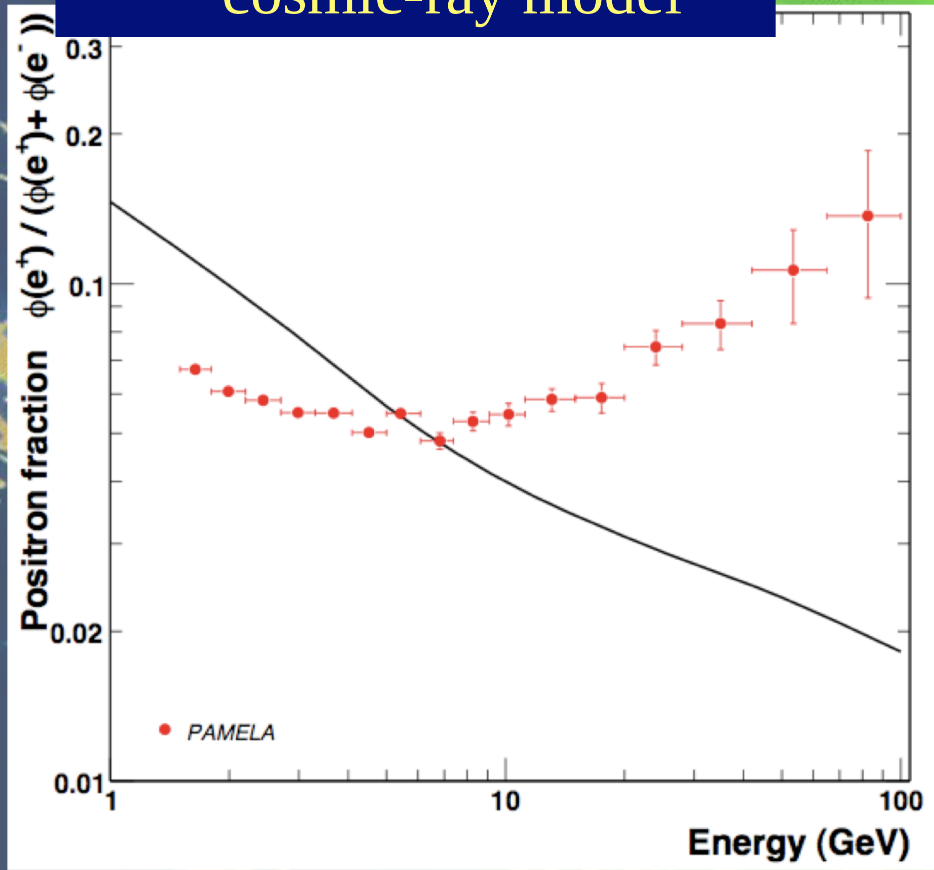
JE + Feng + Ferstl + Matchev + Olive

Positron/Electron Measurements

Compilation of measurements



Comparison with standard cosmic-ray model

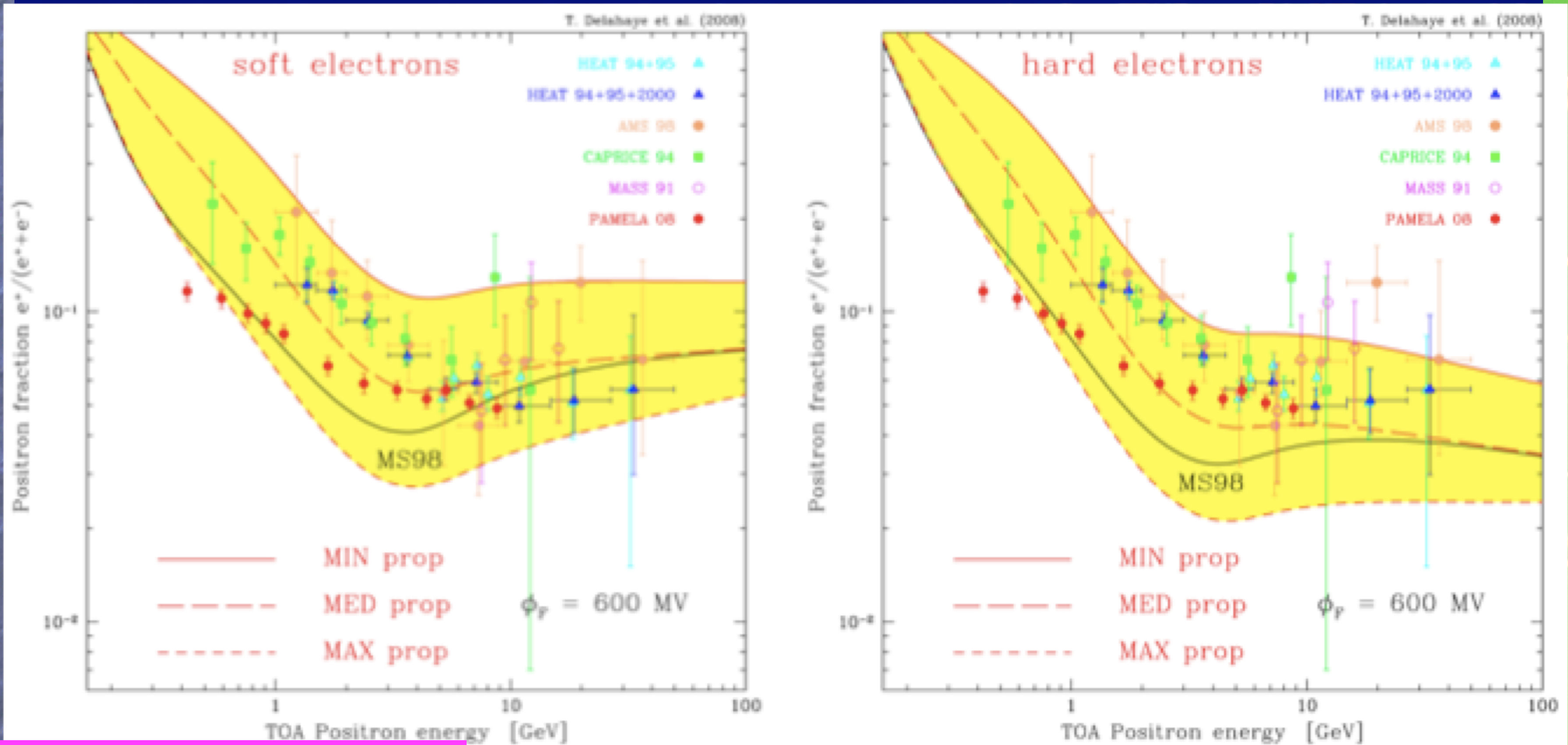


PAMELA: Adriani et al.

Moskalenko & Strong

Galactic Secondary Positron Flux

- Update Moskalenko & Strong using new nuclear cross sections
- Include theoretical uncertainties
- Independent model of cosmic-ray propagation

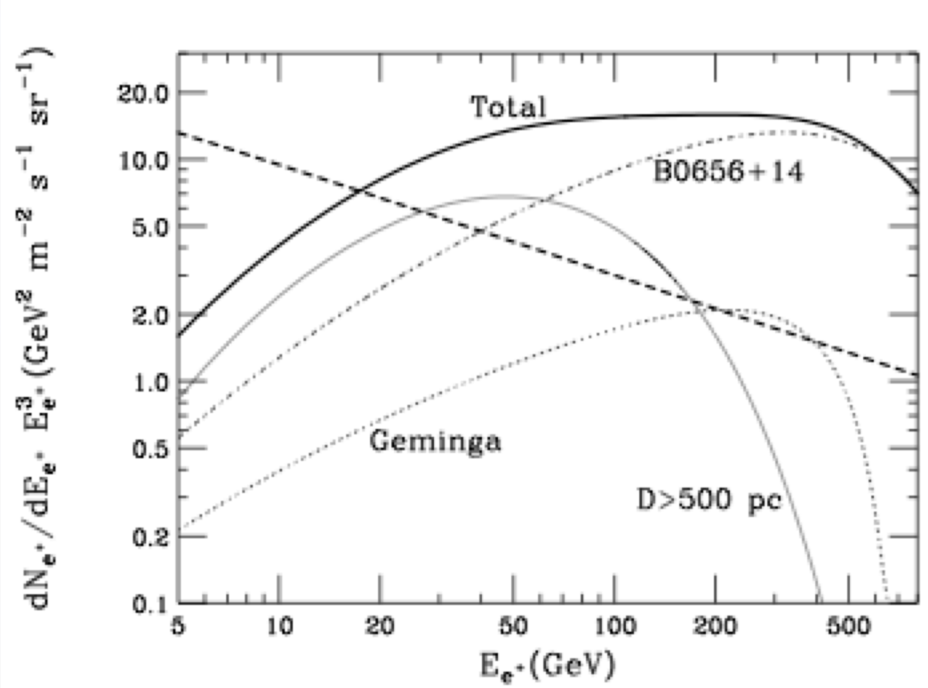


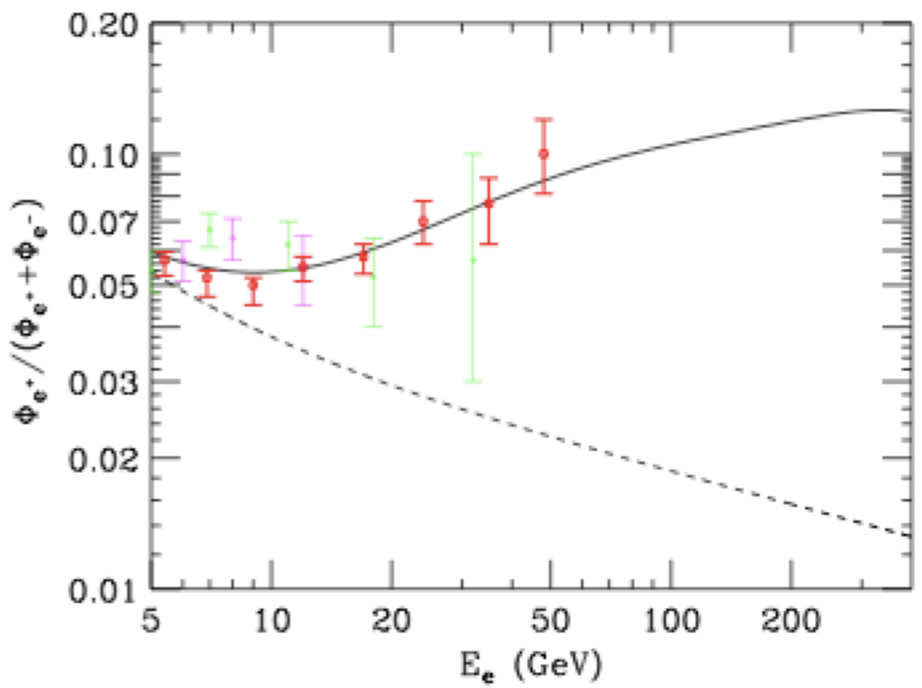
Delahaye et al: arXiv:0809.5268

Pulsars as Sources of Positrons

- Important contributions from both sources
  - Geminga, B0656+14, …

  and from distant pulsars (> 500 pcs)
- Nearby sources would generate small but significant dipole anisotropy in electron spectrum

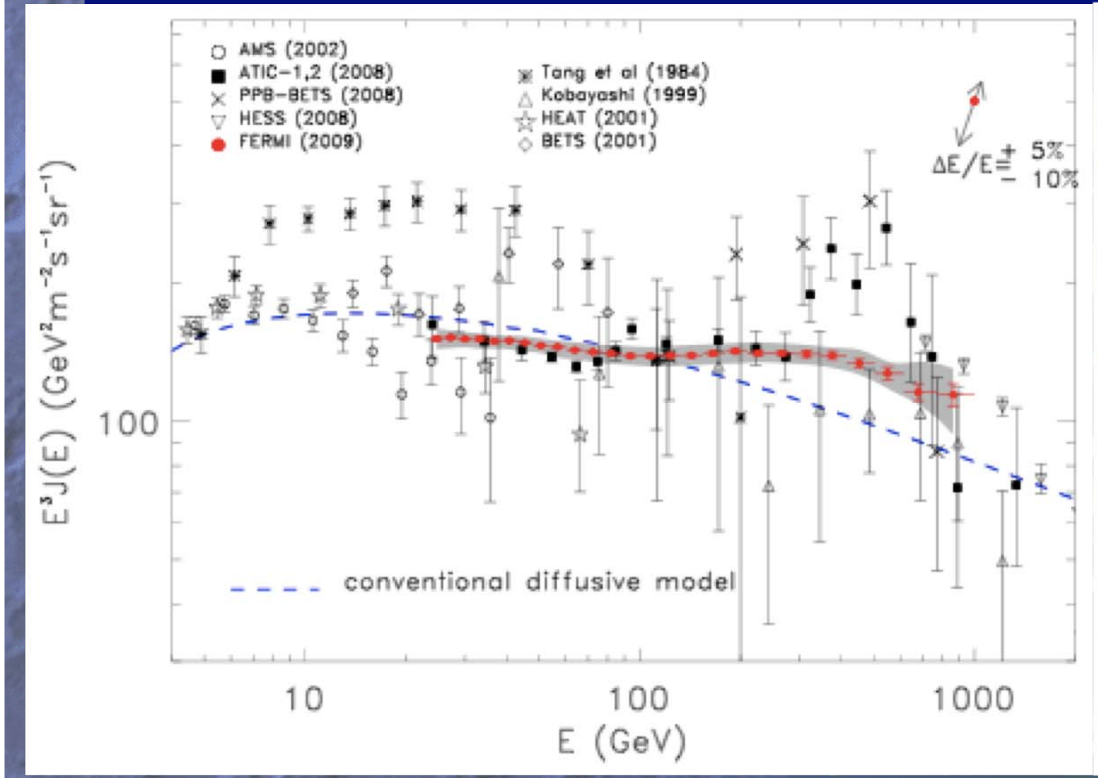


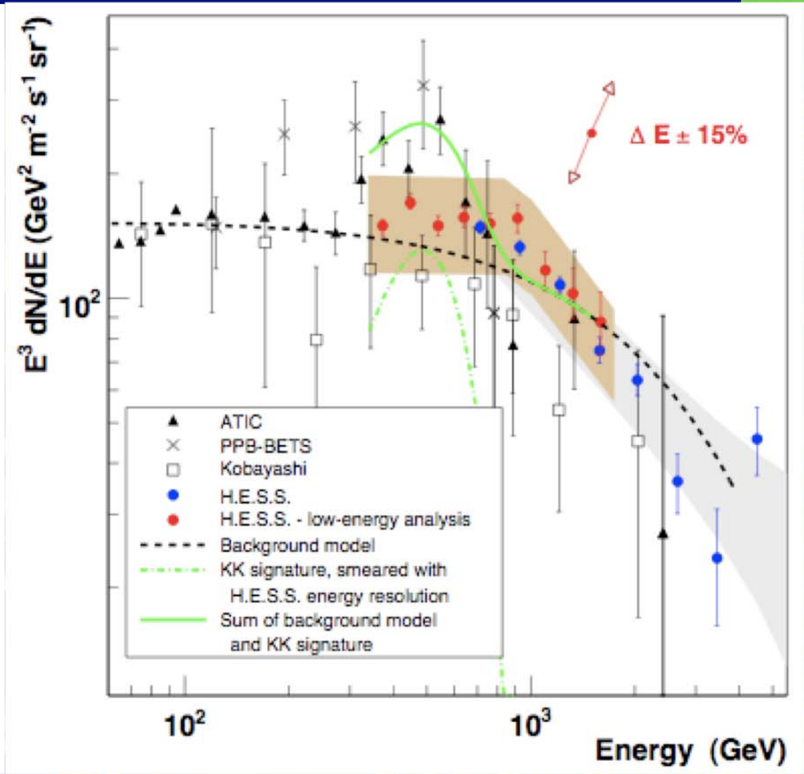


Hooper et al: arXiv:0810.1527

Electron + Positron Spectrum

- Previous data (ATIC) suggested an anomaly
- Not confirmed by Fermi and HESS

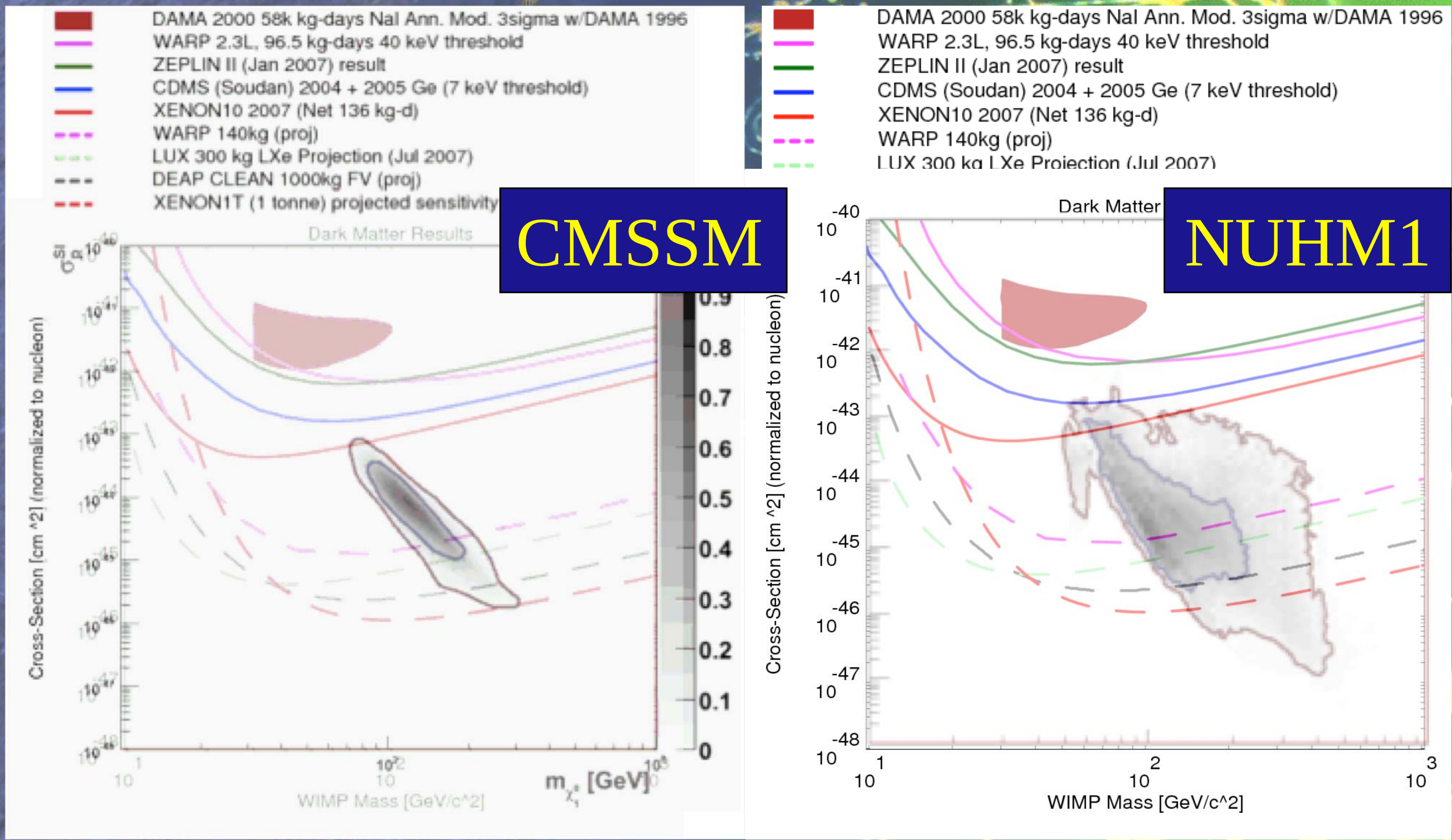




Fermi: arXiv:0905.0025

HESS: arXiv:0905.0105

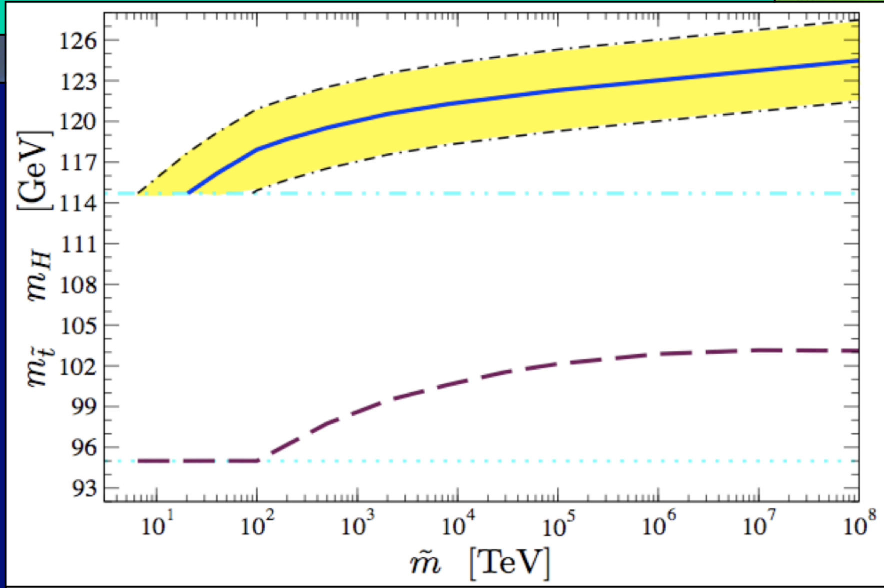
Elastic Scattering Cross Sections

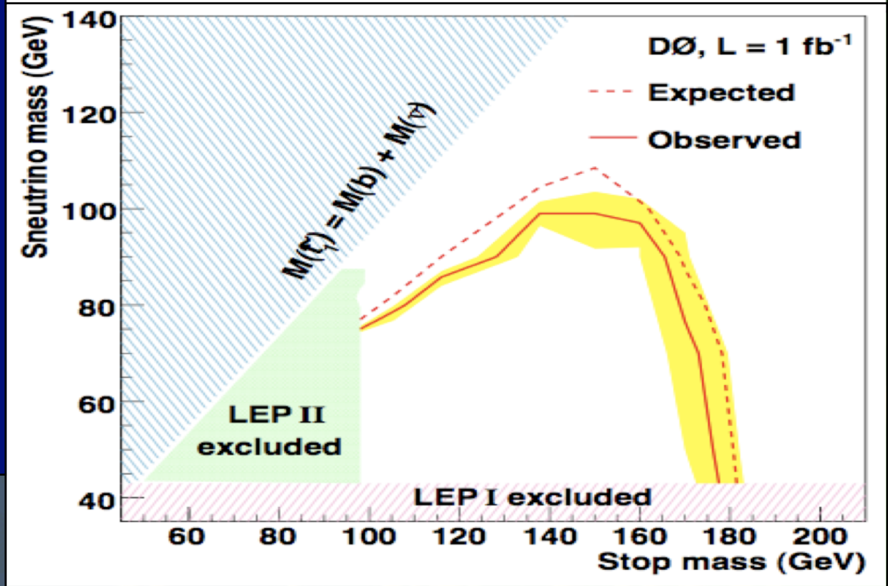


O.Buchmueller, JE et al: in preparation

SUSY Electroweak Baryogenesis?

- Exploit phases in SUSY model
- Require light stop for first-order electroweak transition
- Higgs and stop masses tightly constrained by theory and experiment



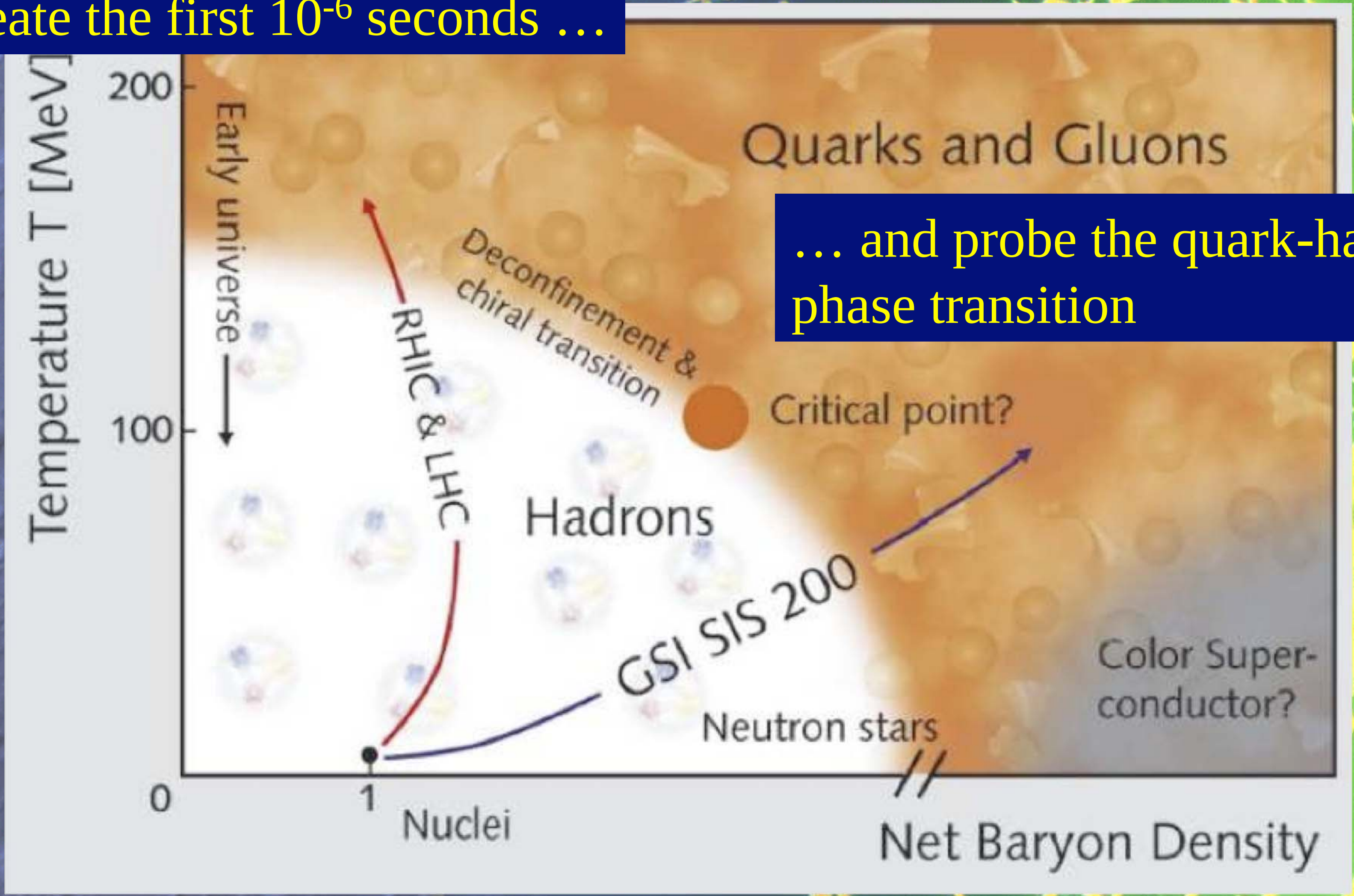


Carena, Nardini, Quiros and Wagner: arXiv:0809.3760

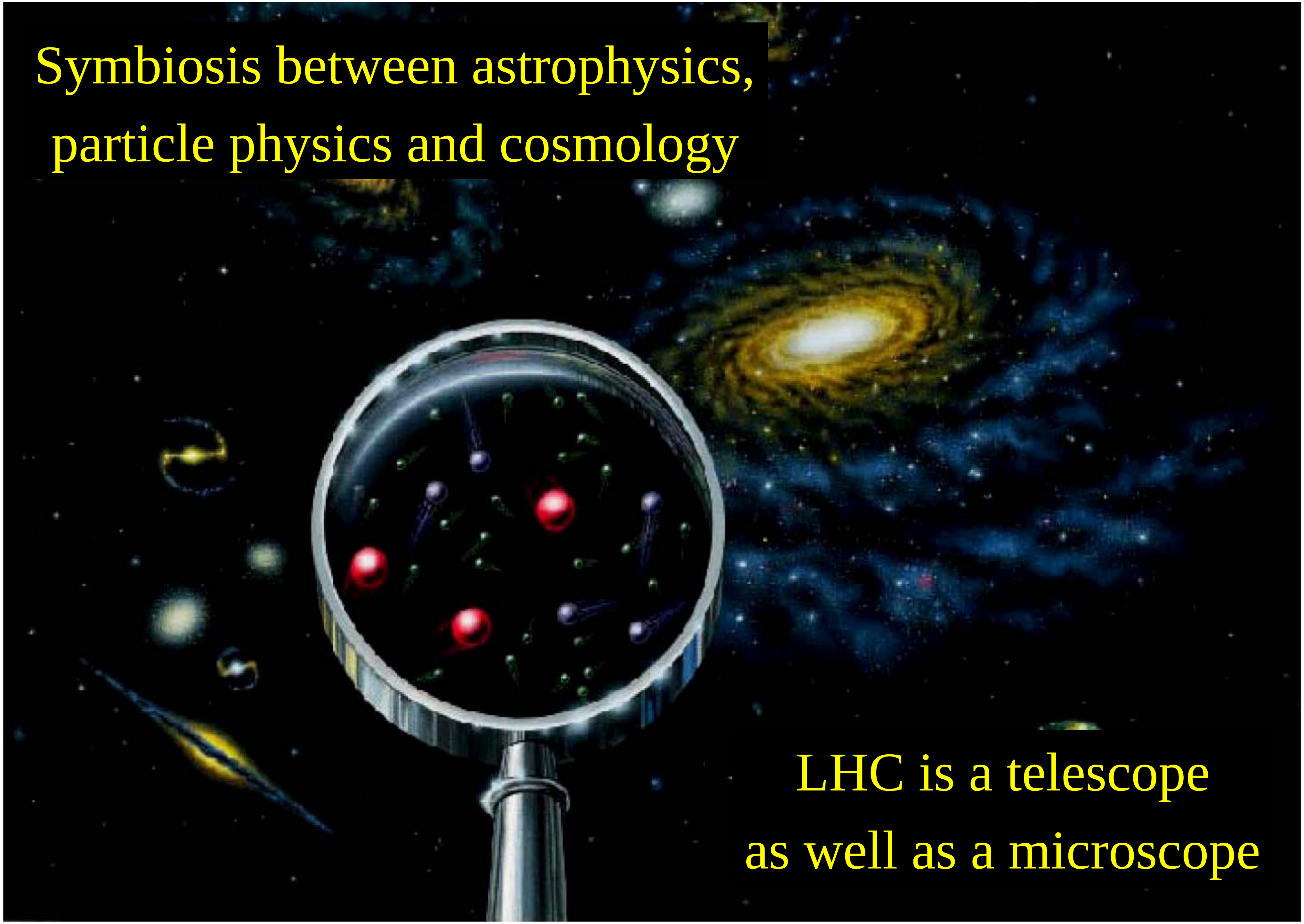
Collide heavy nuclei at high energies to create …

Hot and Dense Hadronic Matter

Recreate the first 10^{-6} seconds …



… and probe the quark-hadron phase transition


Symbiosis between astrophysics,
particle physics and cosmology
LHC is a telescope
as well as a microscope