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**

Supersymmetry Algebra

- Simply stated:

$$\begin{aligned} Q|Boson> &= |Fermion> \\ Q|Fermion> &= |Boson> \end{aligned}$$

- Spinorial charges obey algebra:

$$\begin{aligned} [P^\mu, Q_\alpha] &= 0 = [P^\mu, \bar{Q}^{\dot{\alpha}}] \\ \{Q_\alpha, \bar{Q}_{\dot{\beta}}\} &= 2(\sigma_\mu)_{\alpha\dot{\beta}} P^\mu \\ \{Q_\alpha, Q_\beta\} &= \{\bar{Q}^{\dot{\alpha}}, \bar{Q}^{\dot{\beta}}\} = 0 \end{aligned}$$

- Only possible symmetry of S-matrix that combines particles of different spins
- Supermultiplets: chiral (0, 1/2), vector (1/2, 1)

Simplest Supersymmetric Field Theory

- Free scalar boson and free spin-1/2 fermion:

$$S = \int d^4x \ \mathcal{L}_{scalaire} + \mathcal{L}_{fermion}$$
$$\mathcal{L}_{scalaire} = -\partial^\mu \phi \, \partial_\mu \phi^*$$
$$\mathcal{L}_{fermion} = -i\psi^\dagger \bar{\sigma}^\mu \, \partial_\mu \psi$$

- Transform boson to fermion:

$$\delta\phi = \epsilon^\alpha \psi_\alpha \quad \text{et} \quad \delta\phi^* = \bar{\epsilon}_{\dot{\alpha}} \, \bar{\psi}^{\dot{\alpha}}$$
$$\Rightarrow \delta\mathcal{L}_{scalaire} = -\epsilon^\alpha \, (\partial^\mu \psi_\alpha) \, \partial_\mu \phi^* - \partial^\mu \phi \, \bar{\epsilon}_{\dot{\alpha}} \, (\partial_\mu \bar{\psi}^{\dot{\alpha}})$$

- Fermion to boson: $\delta\psi_\alpha = i(\sigma^\mu \epsilon^\dagger)_\alpha \, \partial_\mu \phi \quad \text{et} \quad \delta\bar{\psi}^{\dot{\alpha}} = -i(\epsilon \, \sigma^\mu)^{\dot{\alpha}} \, \partial_\mu \phi^*$
- Lagrangian changes by total derivative: action $A = \int d^4x \, L(x)$ invariant
- Supersymmetry: QQ = P $\phi \to \psi \to \partial\phi, \quad \psi \to \partial\phi \to \partial\psi$

Supersymmetry with Interactions

- General form: $L = L_0 - V(\phi^i, \phi_j^*) - \frac{1}{2} M_{ij}(\phi, \phi^*) \bar{\psi}^{ci} \psi^j$
- Variation includes: $\frac{\partial M}{\partial \phi^*} \psi^* \bar{\psi}^c \psi$ $\frac{\partial M_{ij}}{\partial \phi^k} \bar{E} \psi^k \bar{\psi}^{ci} \psi^j$
- Cannot cancel, so $M = M(\phi)$ symmetric $M_{ij} = \frac{\partial W}{\partial \phi^i \partial \phi^j}$
- Cancel variation in potential:

$$\frac{\partial V}{\partial \phi^i} \bar{E} \psi^I + (\mathrm{Herm.Conj.}) \longrightarrow V = |\frac{\partial W}{\partial \phi^i}|^2$$

- Final form:

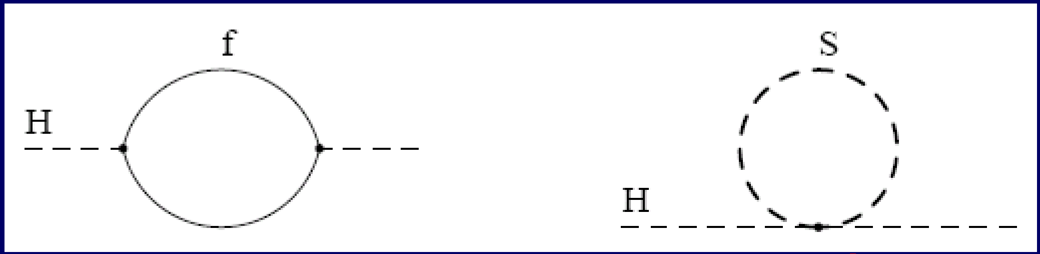
$$L = i\bar{\psi}_i \gamma_\mu \partial^\mu \psi^i + |\partial_\mu \phi^i|^2 - |\frac{\partial W}{\partial \phi^i}|^2 - \frac{1}{2} \frac{\partial^2 W}{\partial \phi^i \partial^j} \bar{\psi}^{ci} \partial \psi^j + (\mathrm{Herm.Conj.})$$

- Simple case:

$$W = \frac{\lambda}{3} \phi^3 + \frac{m}{2} \phi^2 \qquad L = i\bar{\psi} \gamma_\mu \partial^\mu \psi + |\partial_\mu \phi|^2 - |m\phi + \lambda \phi^2|^2 - m\bar{\psi}^c \psi - \lambda \phi \bar{\psi}^c \psi.$$

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:



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

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

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

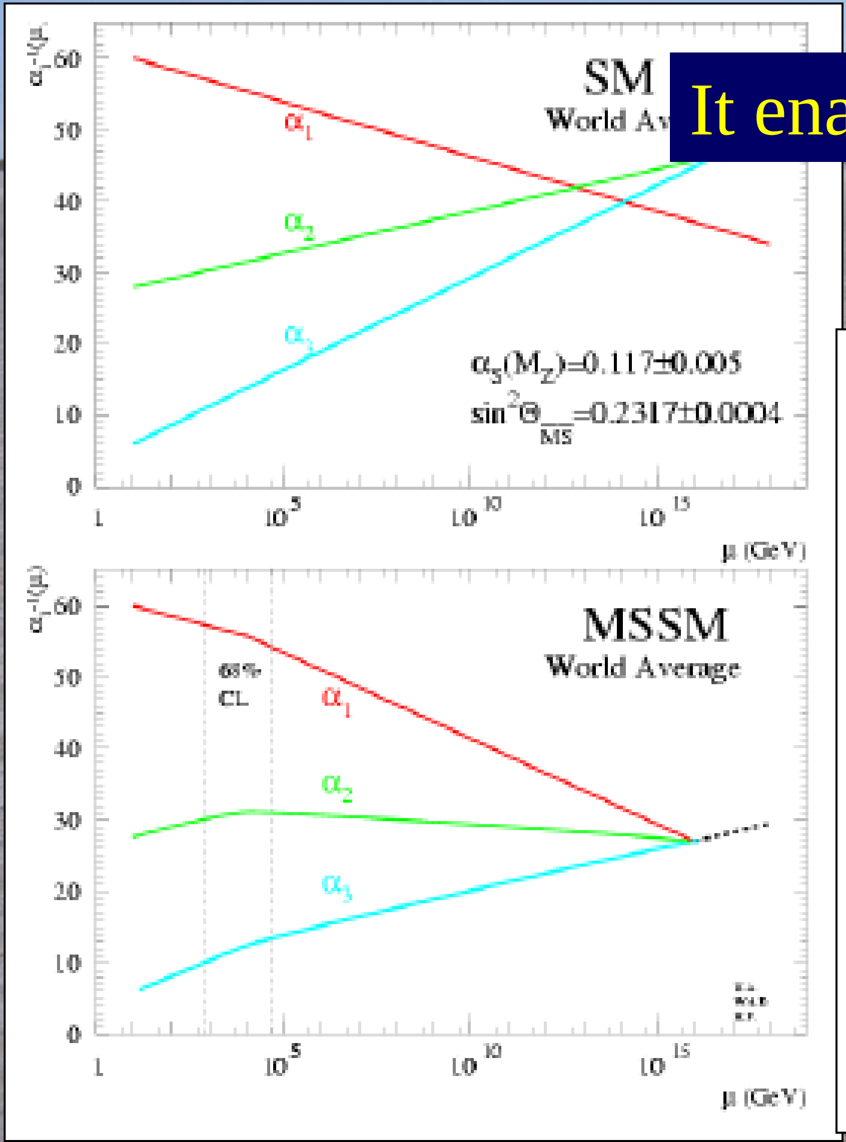
- Leading divergence cancelled if

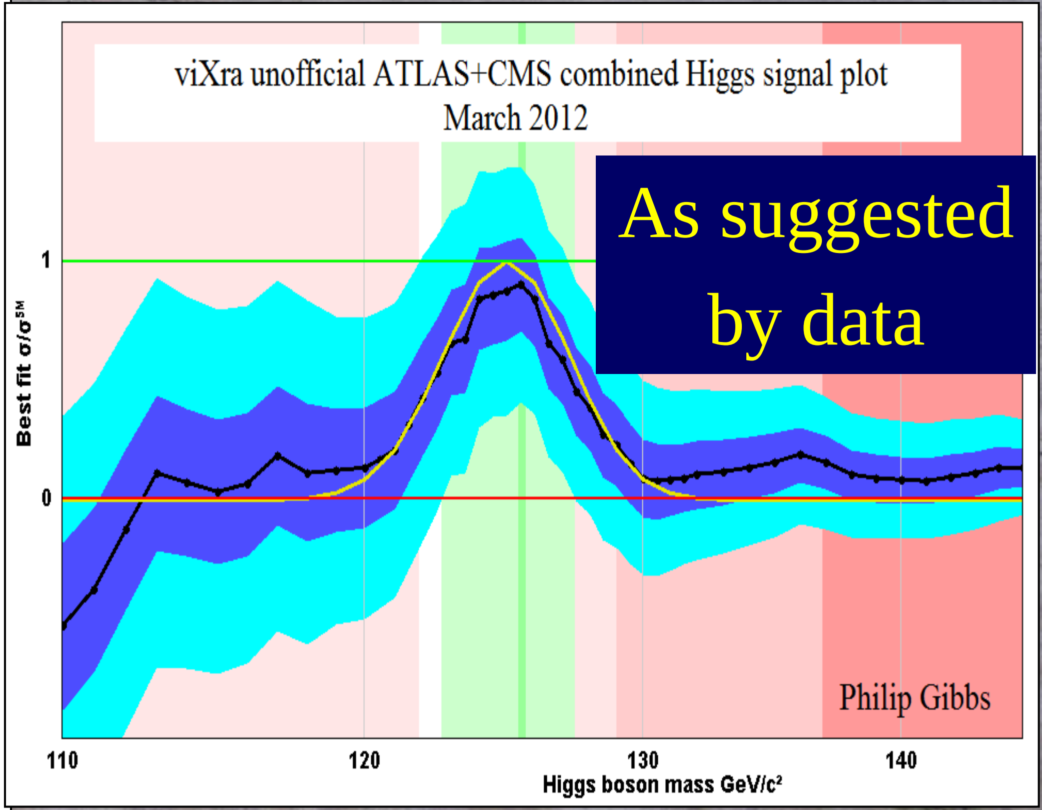
$\lambda_S = y_f^2$ • x 2 **Supersymmetry!**

Other Reasons to like Susy

It enables the gauge couplings to unify

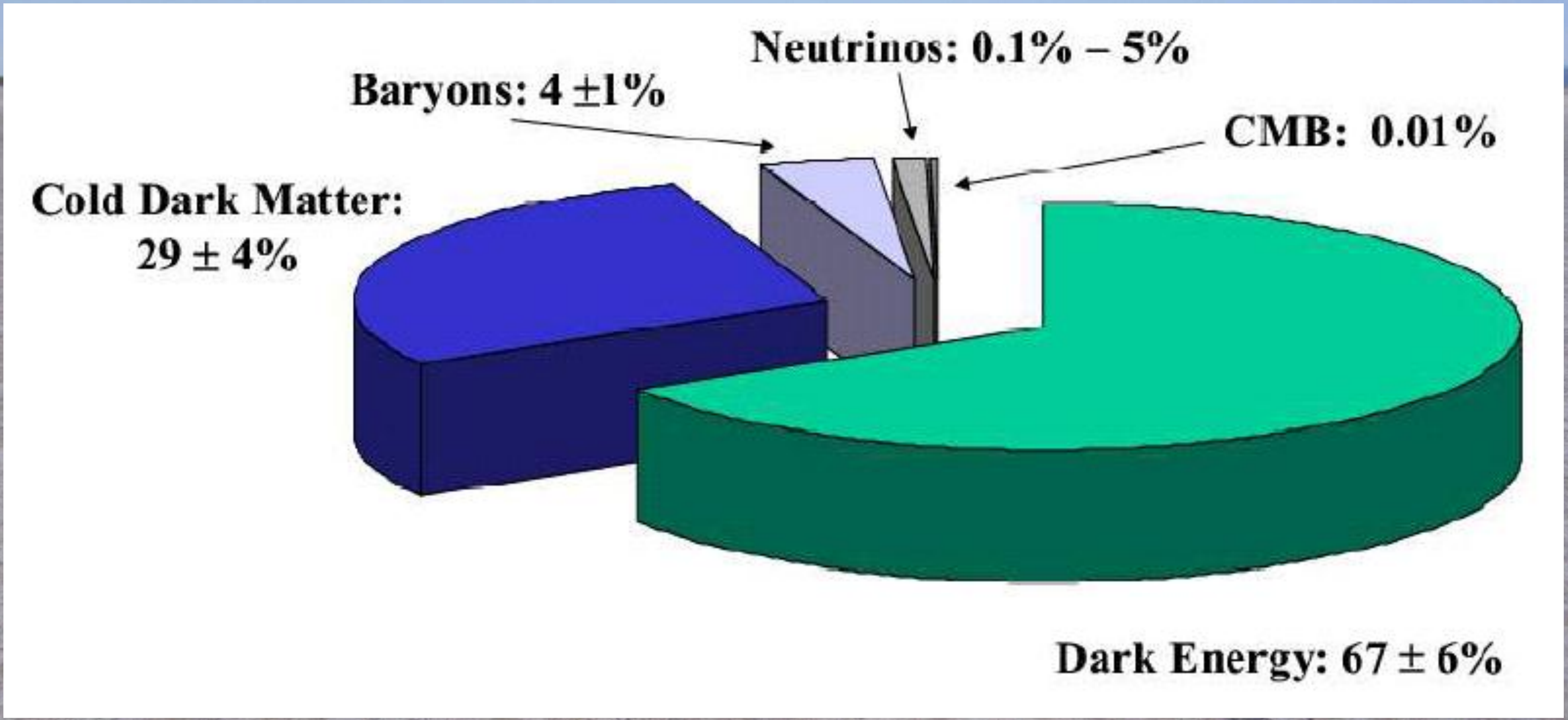
It predicts $m_H < 130$ GeV





As suggested by data

Strange Recipe for a Universe



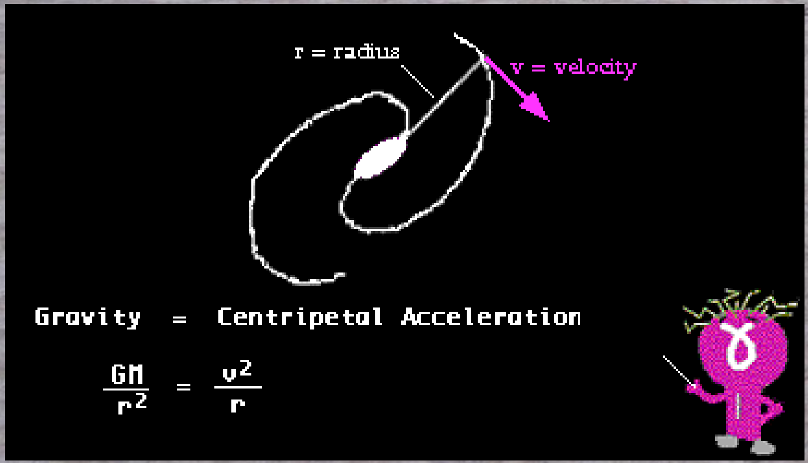
- The 'Standard Model' of the Universe
- indicated by astrophysics and cosmology

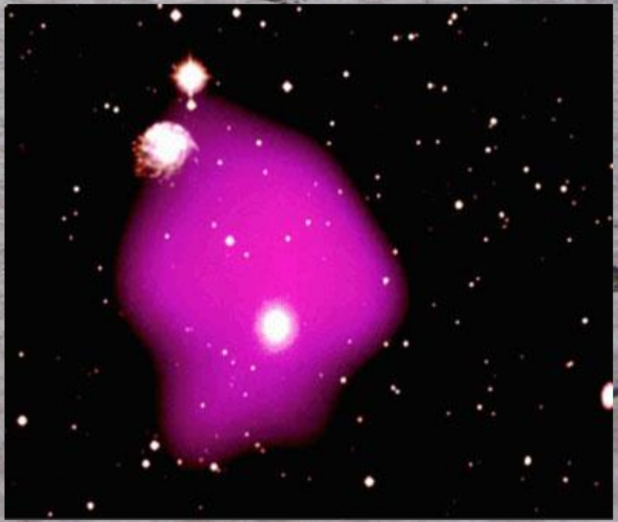
Evidence for Dark Matter

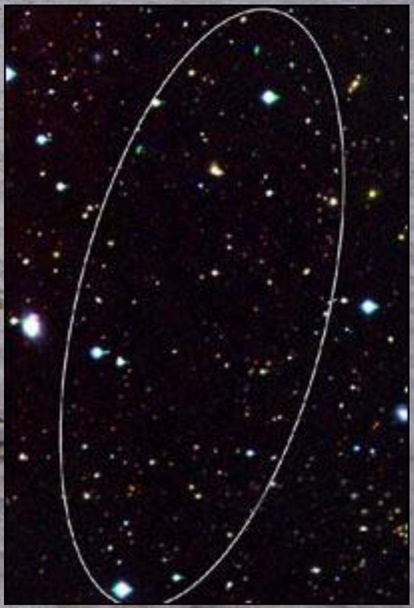
•Galaxies rotate more rapidly
•than allowed by centripetal
•force due to visible matter

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

•Even a
• ‘dark galaxy’
•without stars

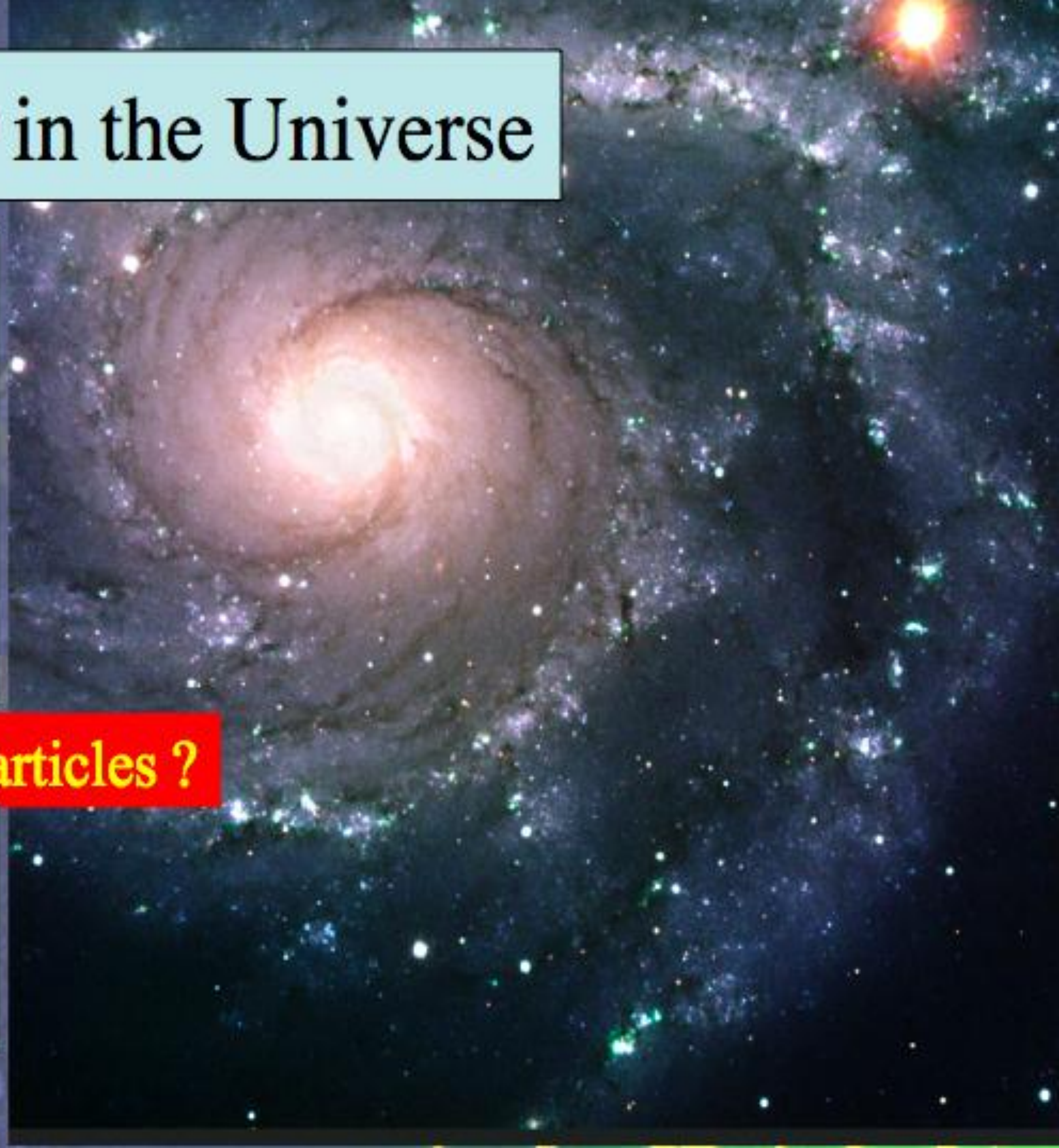






Dark Matter in the Universe

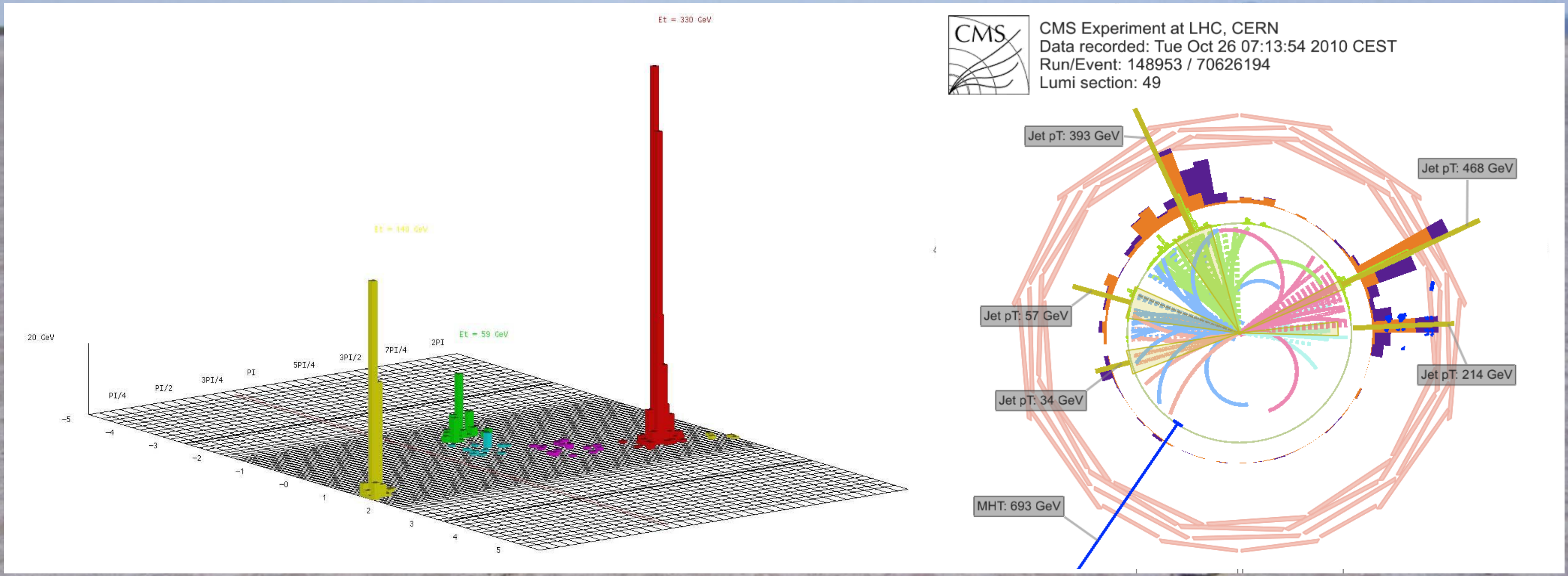
Astronomers say that most of the matter in the Universe is invisible Dark Matter



Supersymmetric particles ?

We shall look for them with the LHC

Supersymmetric Signature @ LHC



- Missing transverse energy
- carried away by dark matter particles

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

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

Possible Nature of LSP

- 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)

Minimal Supersymmetric Extension of Standard Model (MSSM)

- Particles + spartners

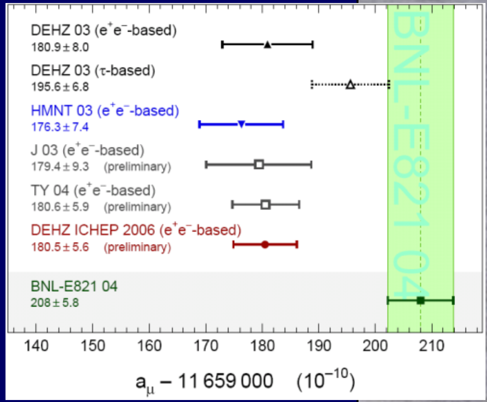
$$\begin{pmatrix} \frac{1}{2} \\ 0 \end{pmatrix} \; e.g., \; \begin{pmatrix} \ell \; (lepton) \\ \tilde{\ell} \; (slepton) \end{pmatrix} or \begin{pmatrix} q \; (quark) \\ \tilde{q} \; (squark) \end{pmatrix} \begin{pmatrix} 1 \\ \frac{1}{2} \end{pmatrix} \; e.g., \; \begin{pmatrix} \gamma \; (photon)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

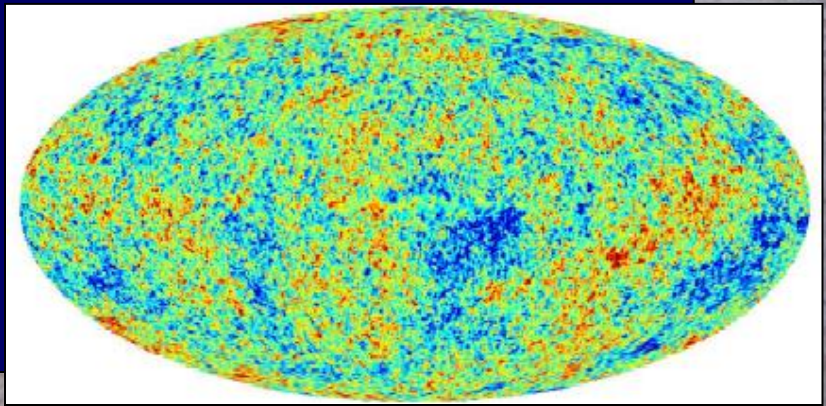
- 2 Higgs doublets, coupling μ, ratio of v.e.v.'s = $\tan\beta$
- Unknown supersymmetry-breaking parameters:
  - Scalar masses m_0, gaugino masses $m_{1/2}$,
  - trilinear soft couplings A_λ, bilinear soft coupling B_μ
- Often assume universality:
  - Single m_0, single $m_{1/2}$, single A_λ, B_μ: not string?
- Called constrained* MSSM = CMSSM (* at what scale?)
- Minimal supergravity (mSUGRA) predicts gravitino mass: $m_{3/2} = m_0$ and relation: $B_\mu = A_\lambda - m_0$

Constraints on Supersymmetry

- Absence of sparticles at LEP, Tevatron
  - selectron, chargino > 100 GeV
  - squarks, gluino > 400 GeV
- Indirect constraints
  - Higgs > 114 GeV, $b \to s\,\gamma$
- Density of dark matter
  - lightest sparticle χ:
  - $0.094 < \Omega_\chi h^2 < 0.124$

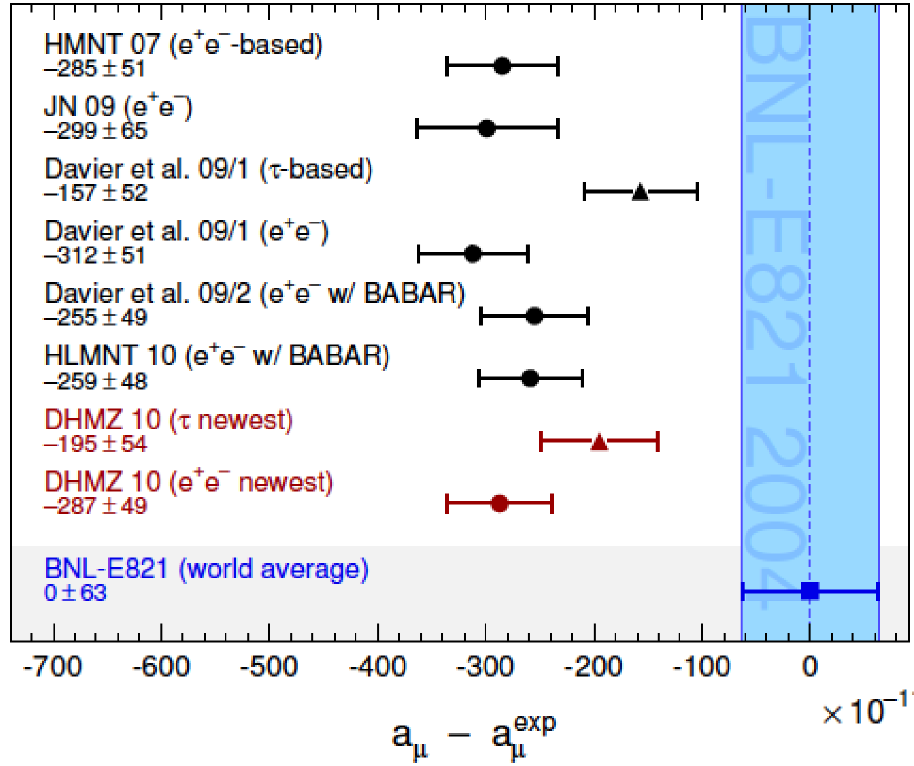
3 σ effect in $g_\mu - 2$?

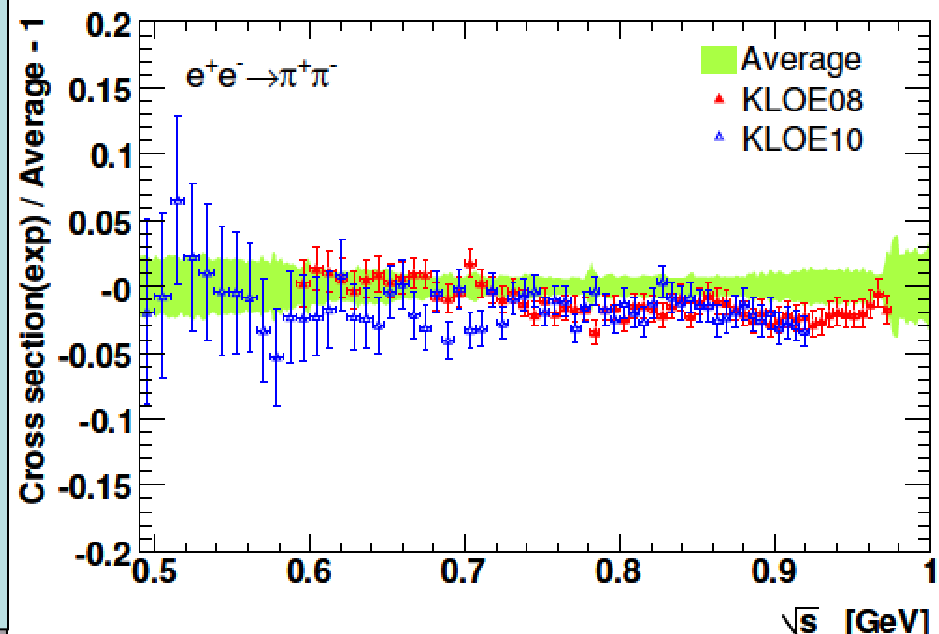




Quo Vadis g_μ - 2?

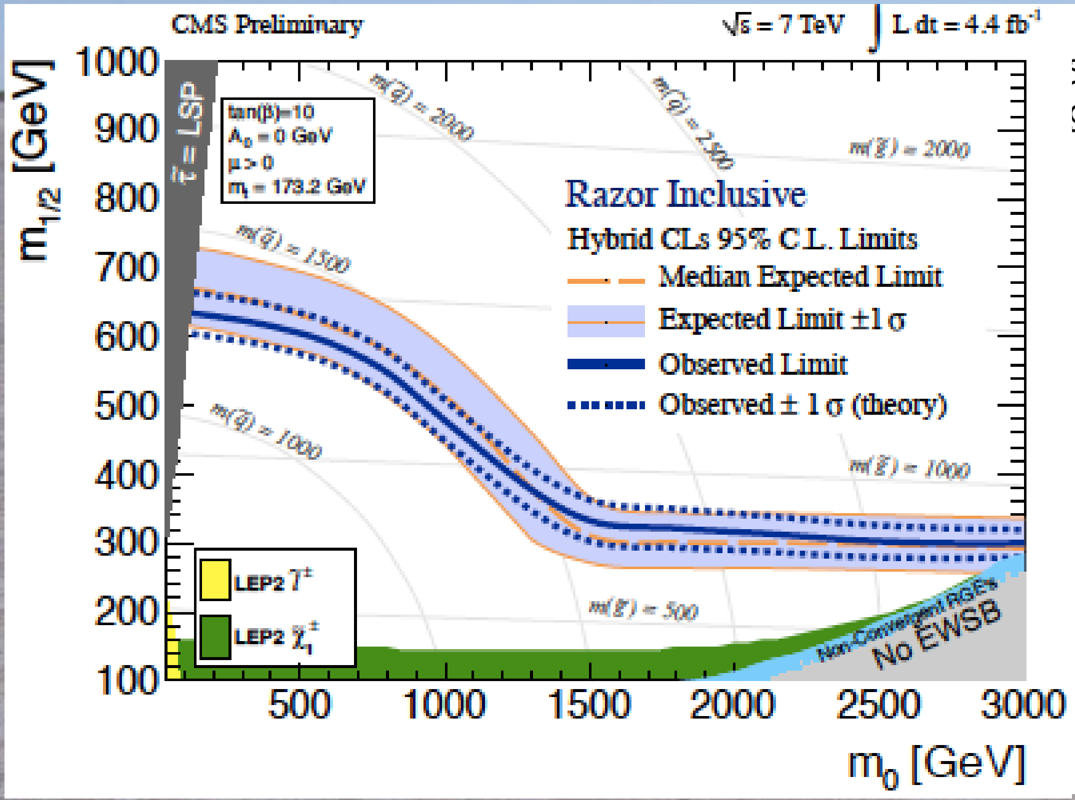
- Strong discrepancy between BNL experiment and e^+e^- data:
  - now ~ 3.6 σ
  - Better agreement between e^+e^- experiments
- Increased discrepancy between BNL experiment and τ decay data
  - now ~ 2.4 σ
  - Convergence between e^+e^- experiments and τ decay
- **More credibility?**

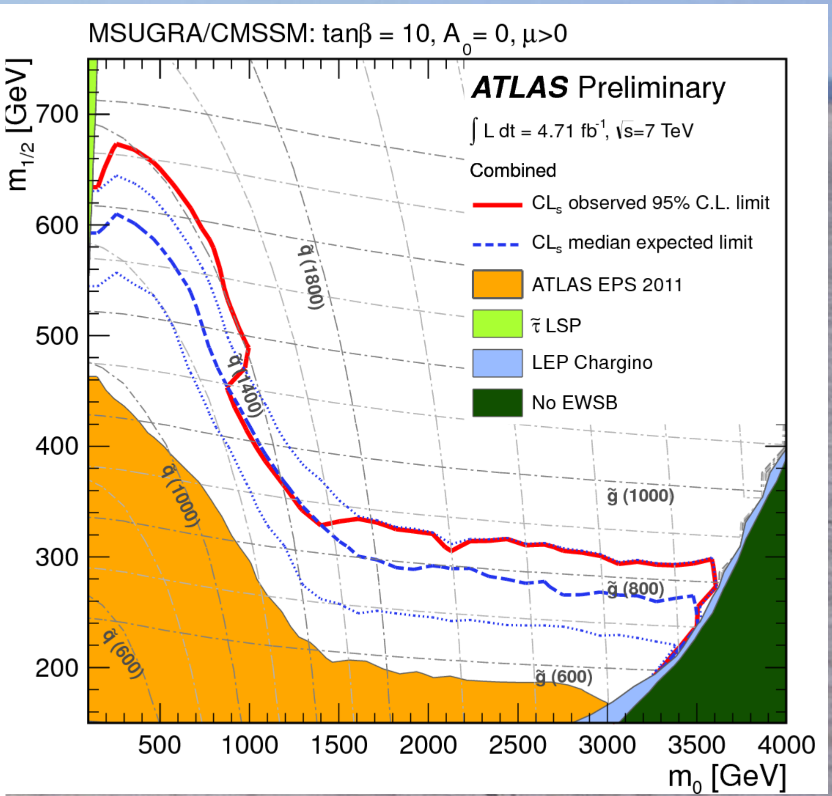




The treadmill continues!

Searches with ~ 5/fb





Jets + missing energy

Impact of LHC on the CMSSM

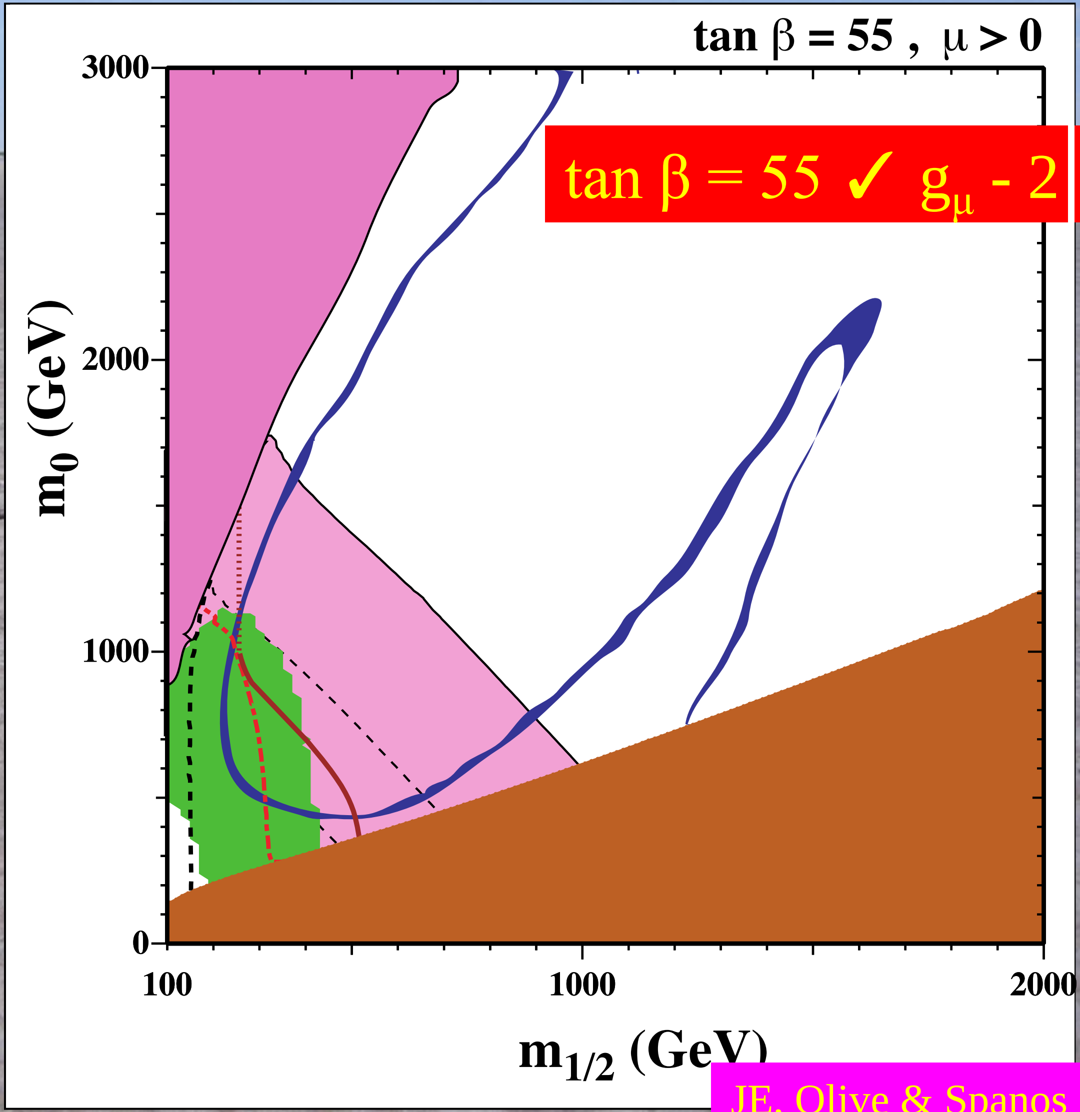
Assuming the lightest sparticle is a neutralino

Excluded because stau LSP

Excluded by b → s gamma

WMAP constraint on CDM density

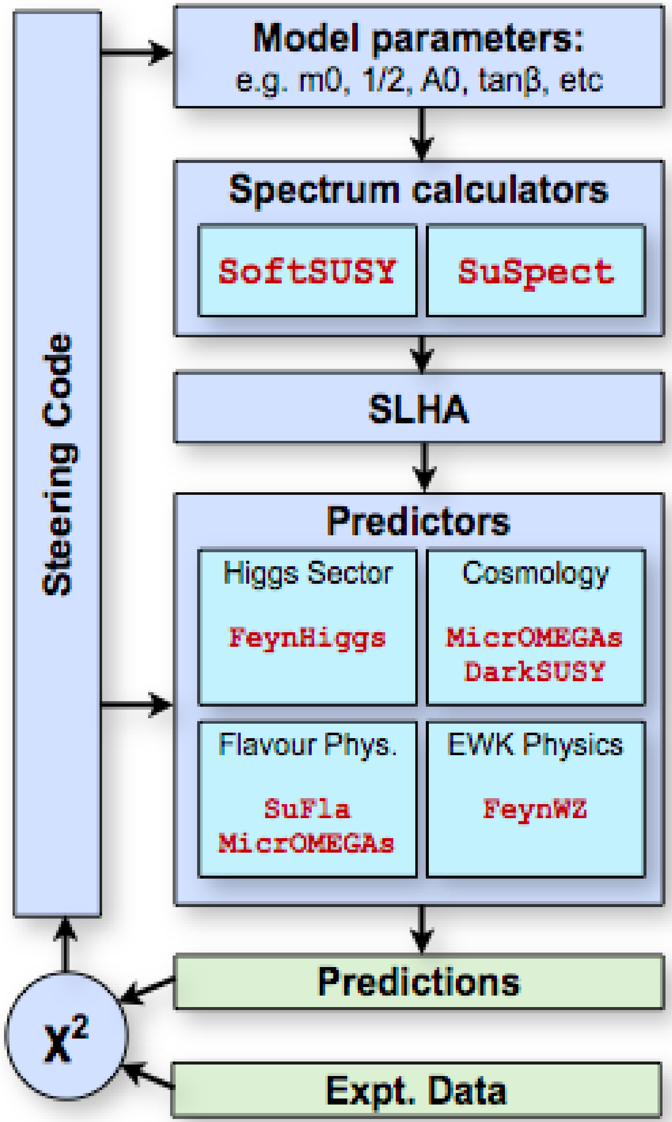
Preferred (?) by latest g - 2



JE, Olive & Spanos

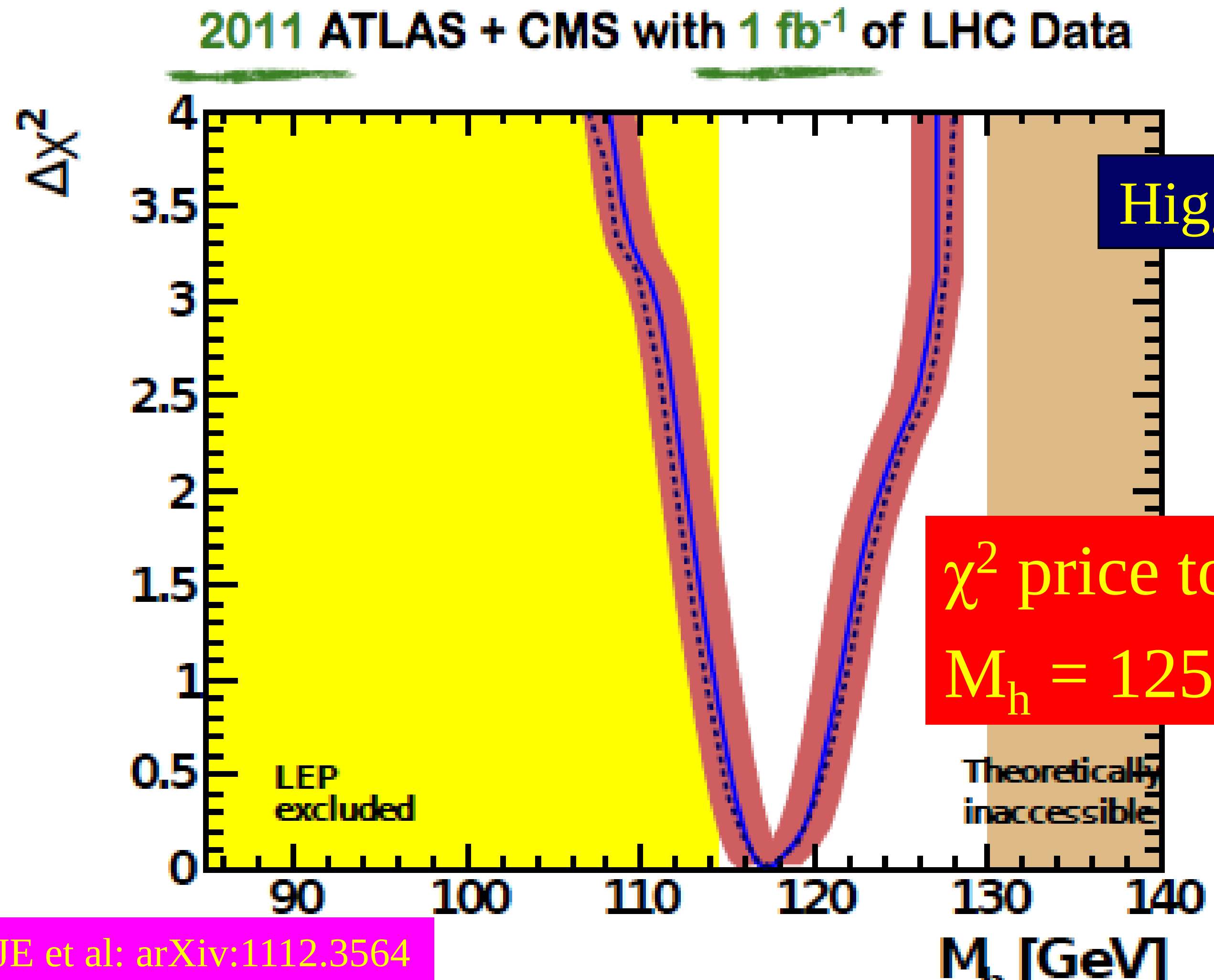
MasterCode

- Combines diverse set of tools
  - different codes : all state-of-the-art
    - Electroweak Precision (FeynWZ)
    - Flavour (SuFla, micrOMEGAs)
    - Cold Dark Matter (DarkSUSY, micrOMEGAs)
    - Other low energy (FeynHiggs)
    - Higgs (FeynHiggs)
  - different precisions (one-loop, two-loop, etc)
  - different languages (Fortran, C++, English, German, Italian, etc)
  - different people (theorists, experimentalists)
- Compatibility is crucial! Ensured by
  - close collaboration of tools authors
  - standard interfaces



O. Buchmueller, R. Cavanaugh, D. Colling, A. de Roeck, M.J. Dolan, J.R. Ellis, H. Flaecher, S. Heinemeyer, G. Isidori, D. Martinez Santos, K.A. Olive, S. Rogerson, F.J. Ronga, G. Weiglein

Post-LHC, Post-XENON100



Higgs mass

χ^2 price to pay if M_h = 125 GeV is ~ 2

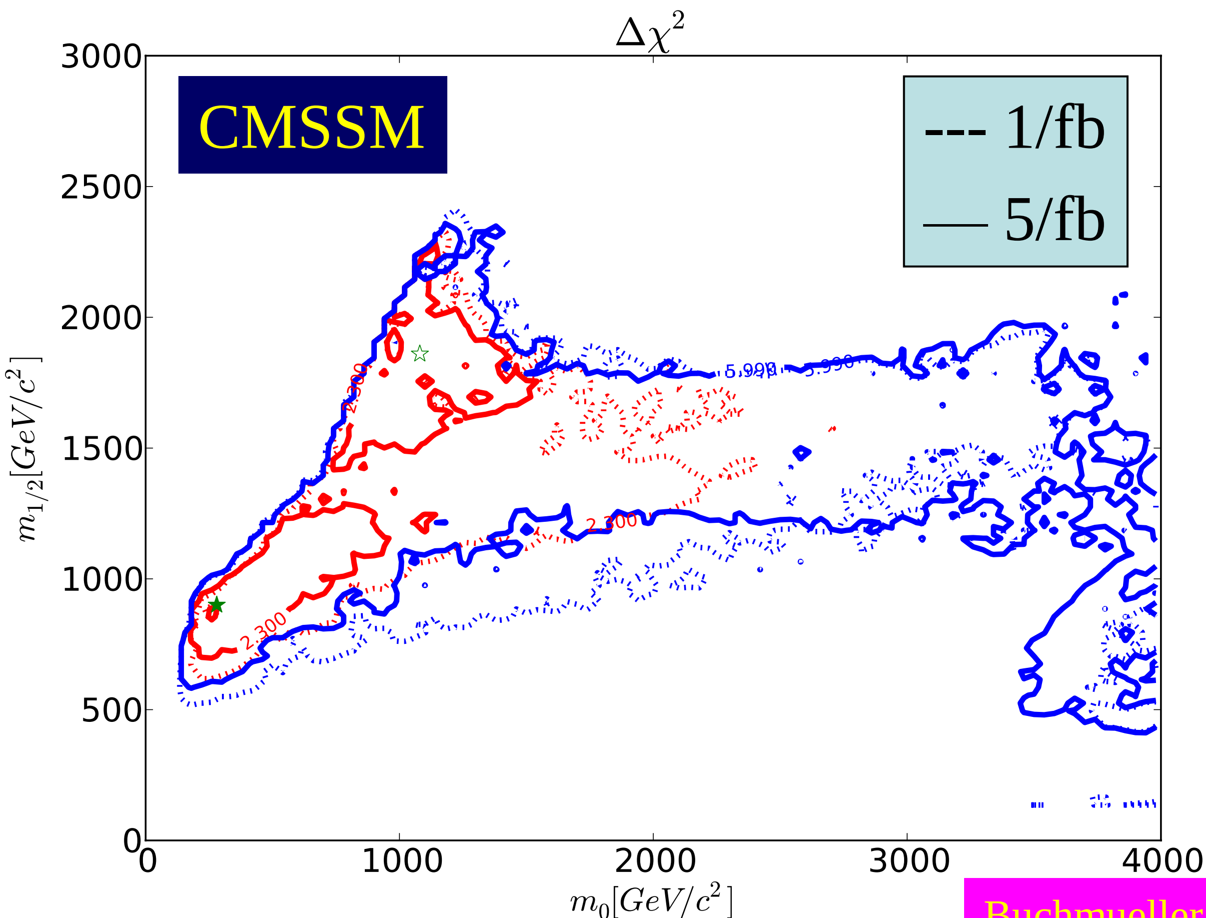
Buchmueller, JE et al: arXiv:1112.3564

Favoured values of M_h ~ 119 GeV:

Range consistent with evidence from LHC !

Post-LHC, Post-XENON100

2011 ATLAS + CMS with 5 fb^{-1} of LHC Data



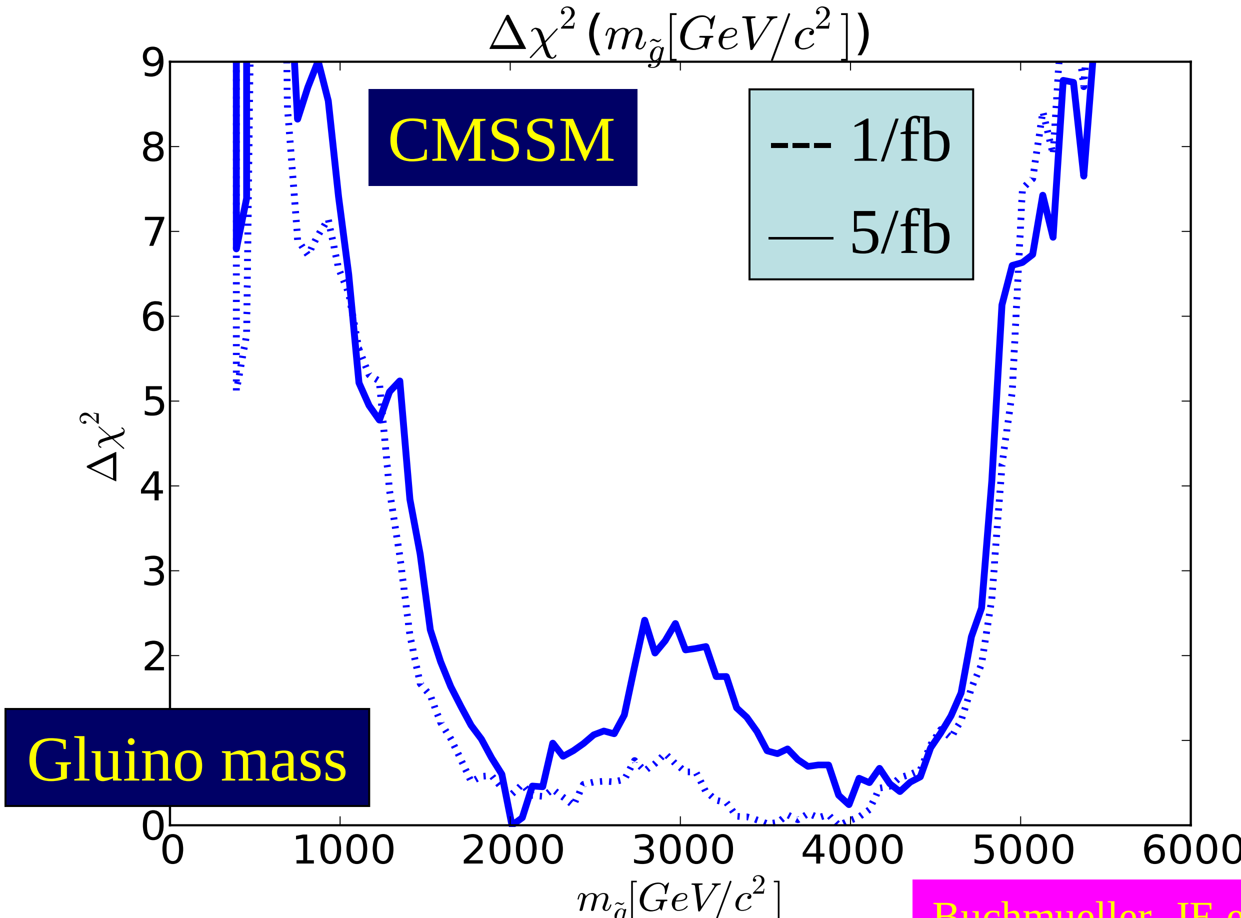
Buchmueller, JE et al: to appear

Red and blue curves represent $\Delta\chi^2$ from global minimum, located at ☆

p-value of CMSSM ~ 10%

Post-LHC, Post-XENON100

2011 ATLAS + CMS with 5 fb^{-1} of LHC Data

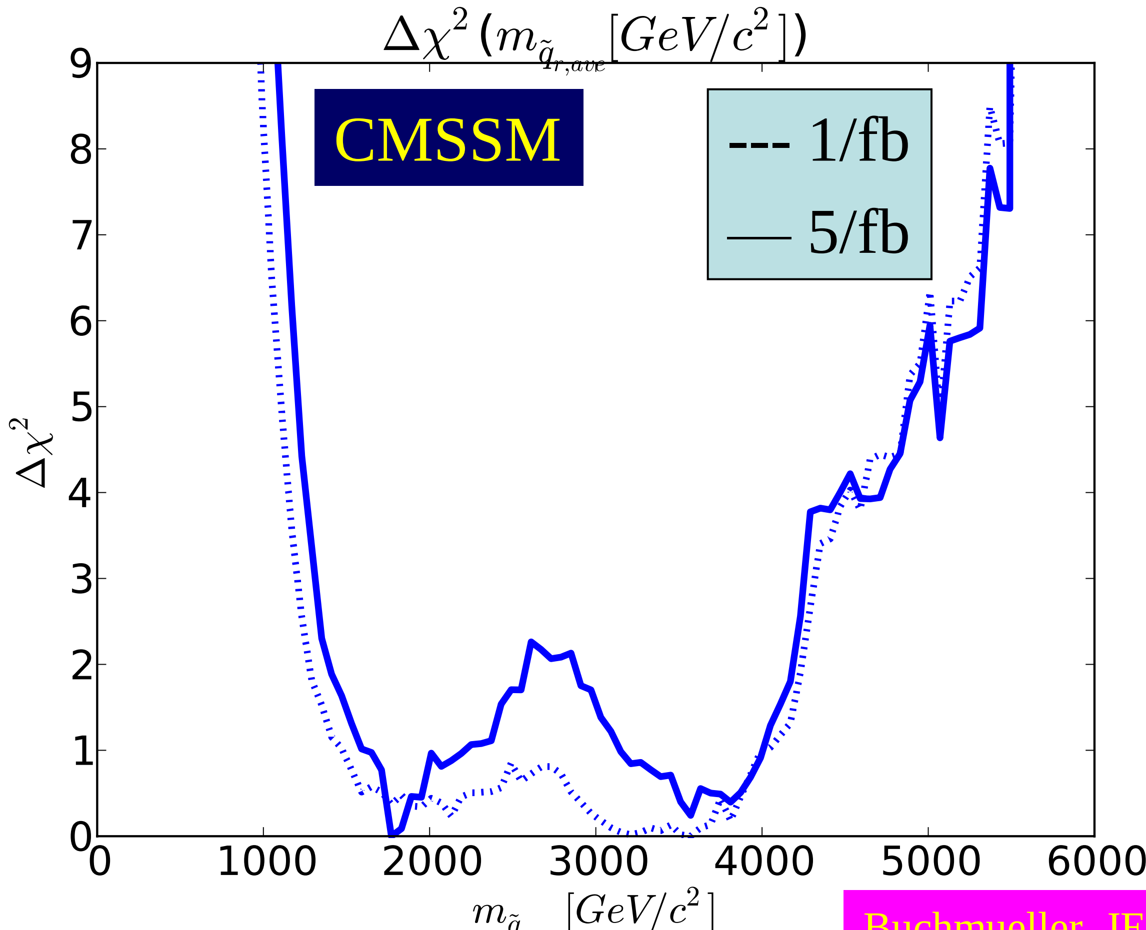


Buchmueller, JE et al: to appear

Favoured values of gluino mass significantly above pre-LHC, > 1.5 TeV

Post-LHC, Post-XENON100

2011 ATLAS + CMS with 5 fb^{-1} of LHC Data



Buchmueller, JE et al: to appear

1

Favoured values of squark mass significantly above pre-LHC, > 1.5 TeV

Strategies for Detecting Supersymmetric Dark Matter

- Scattering on nucleus in laboratory

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

- Annihilation in core of Sun or Earth

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

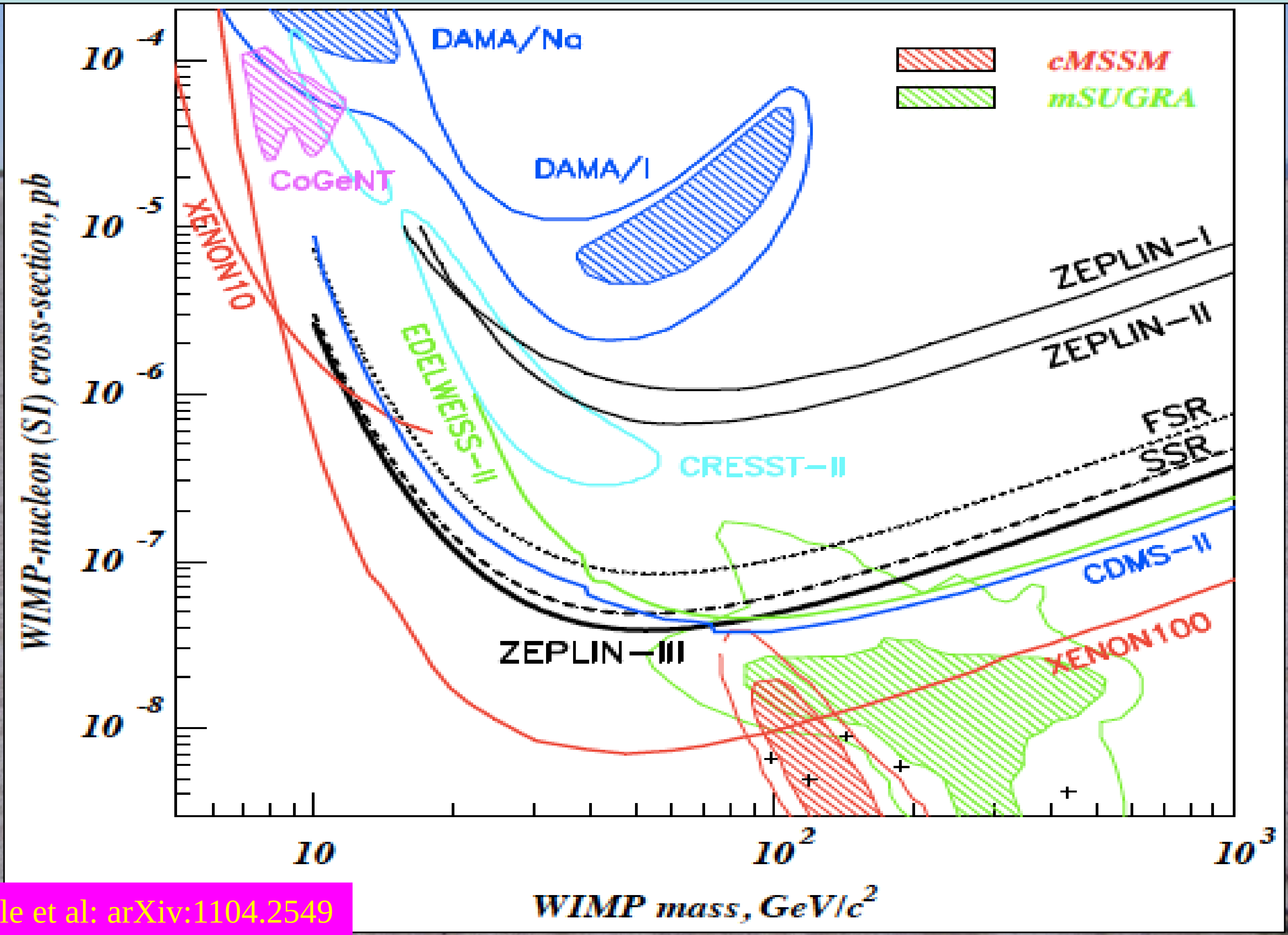
- Annihilation in galactic halo

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

- Annihilation in galactic centre

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

XENON100 & other Experiments

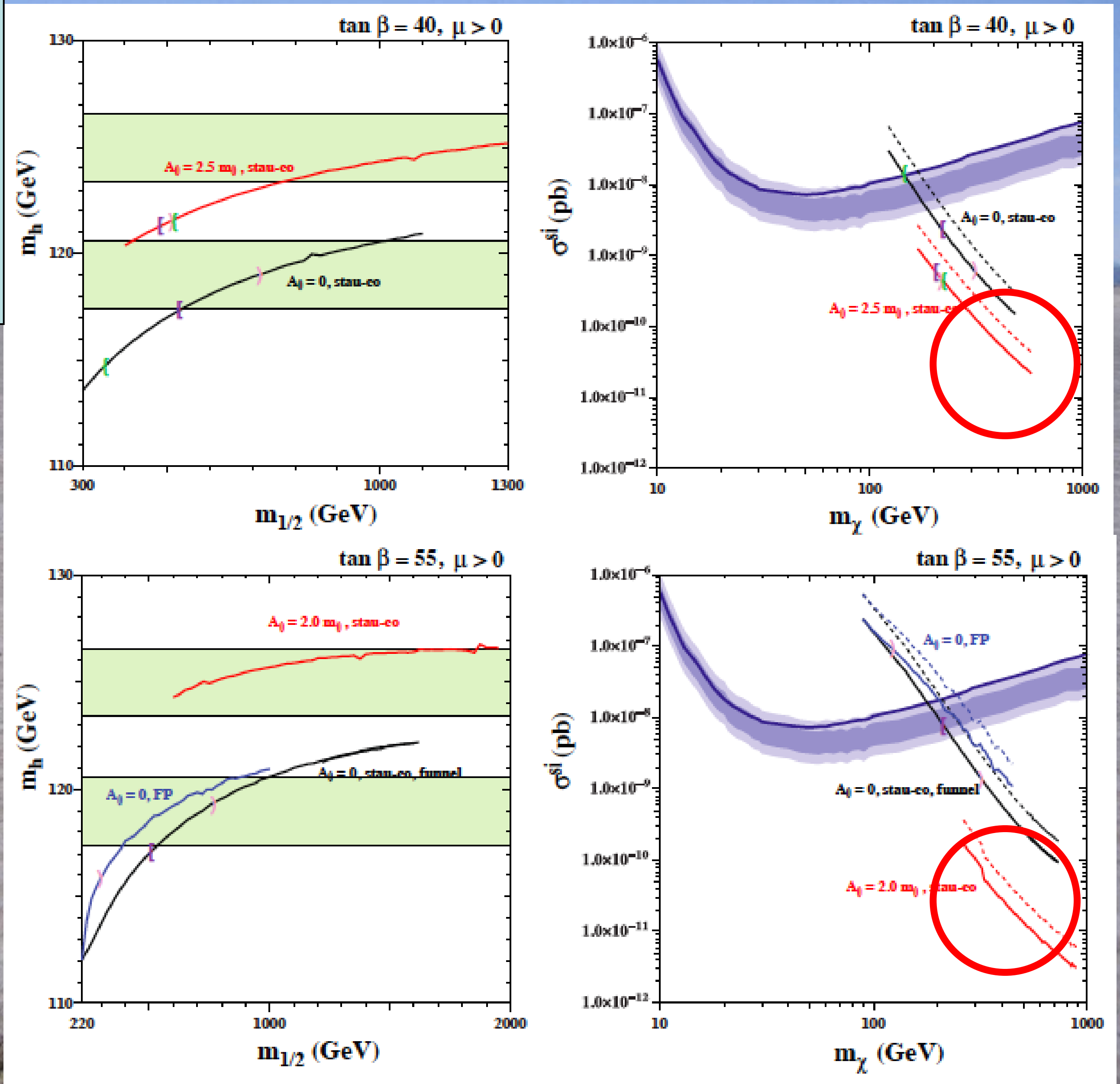


Aprile et al: arXiv:1104.2549

Impact of m_H =125 GeV

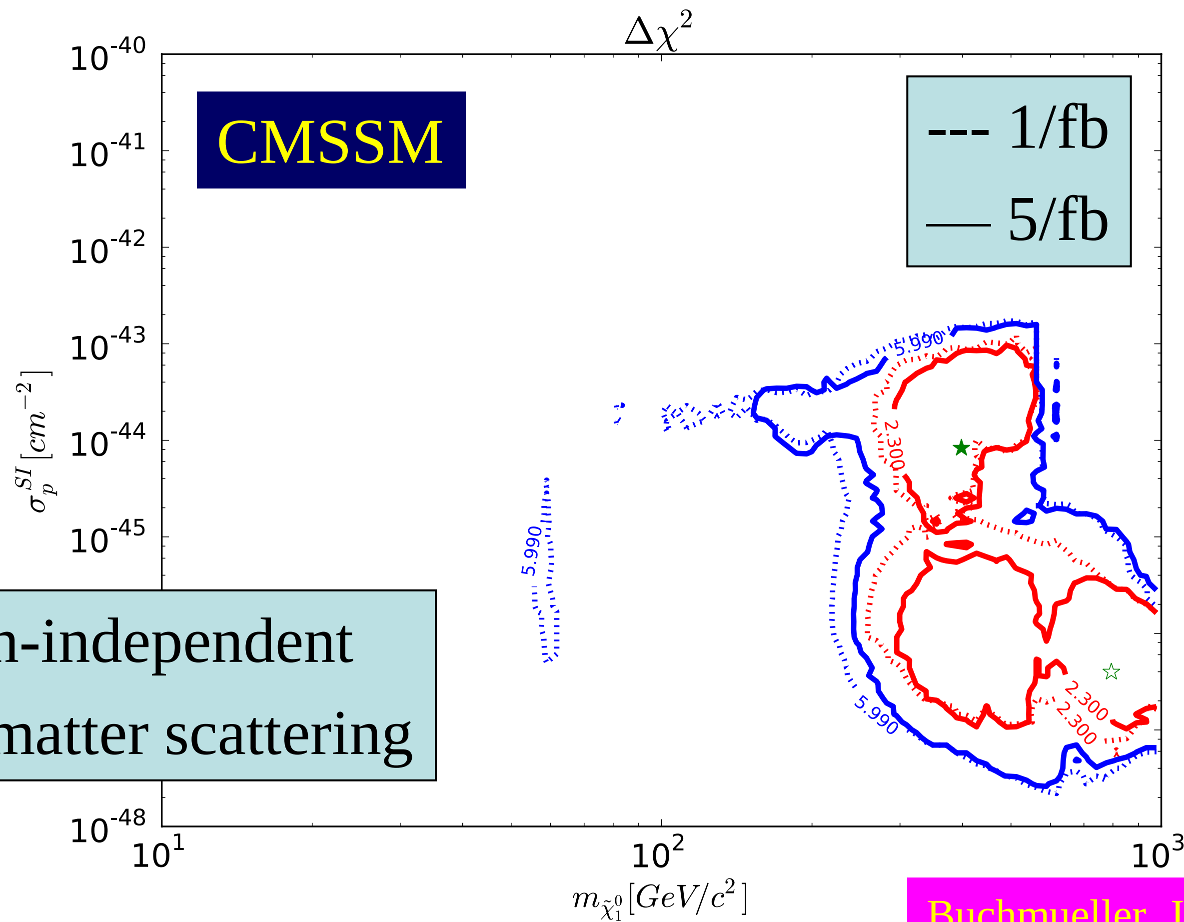
- Need large $m_{1/2}$
- Prefer big tan β
- Non-zero A_0
- **Predict small dark matter scattering rate**

JE, Olive : arXiv:1202.3262



Post-LHC, Post-XENON100

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data



Spin-independent
Dark matter scattering

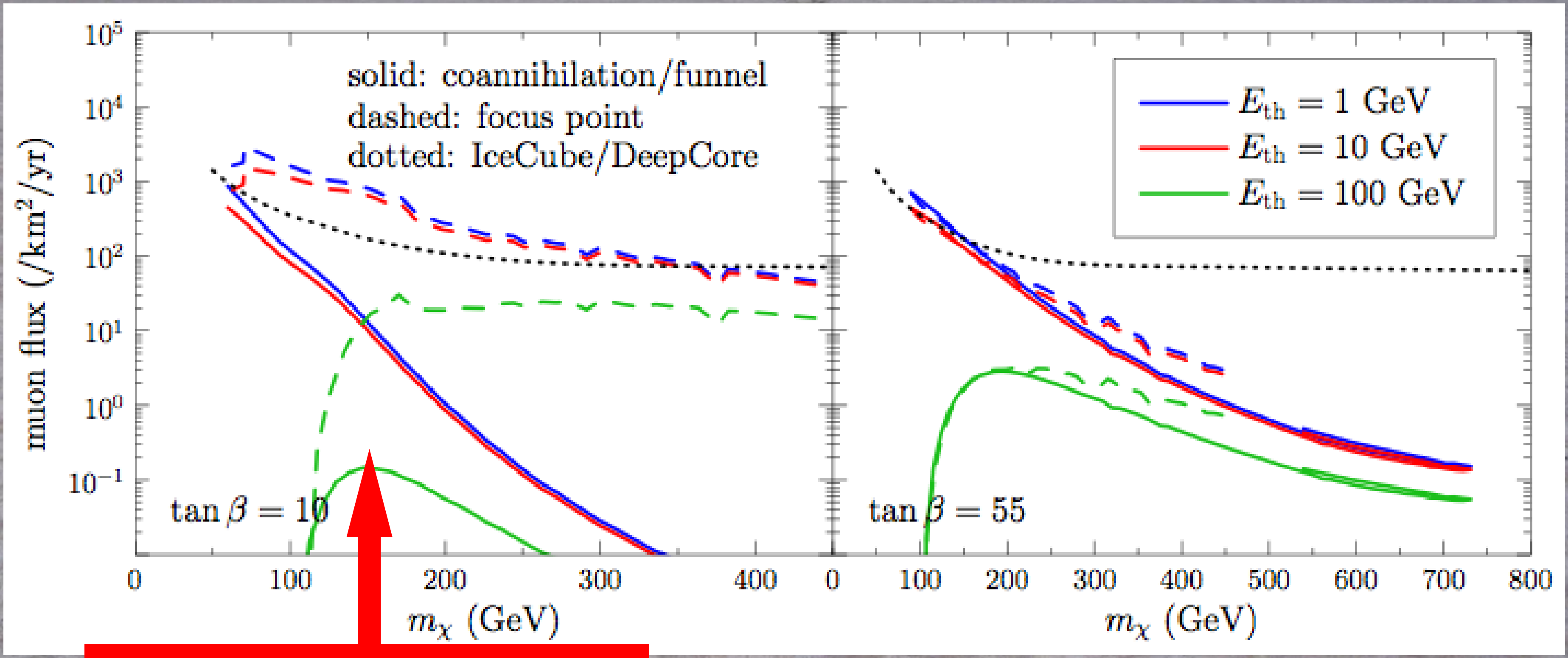
1

Buchmueller, JE et al, to appear

Favoured dark matter scattering rate
well below XENON100 limit

Neutrino Fluxes from CMSSM Dark Matter Annihilation in Sun

Fluxes along WMAP strips

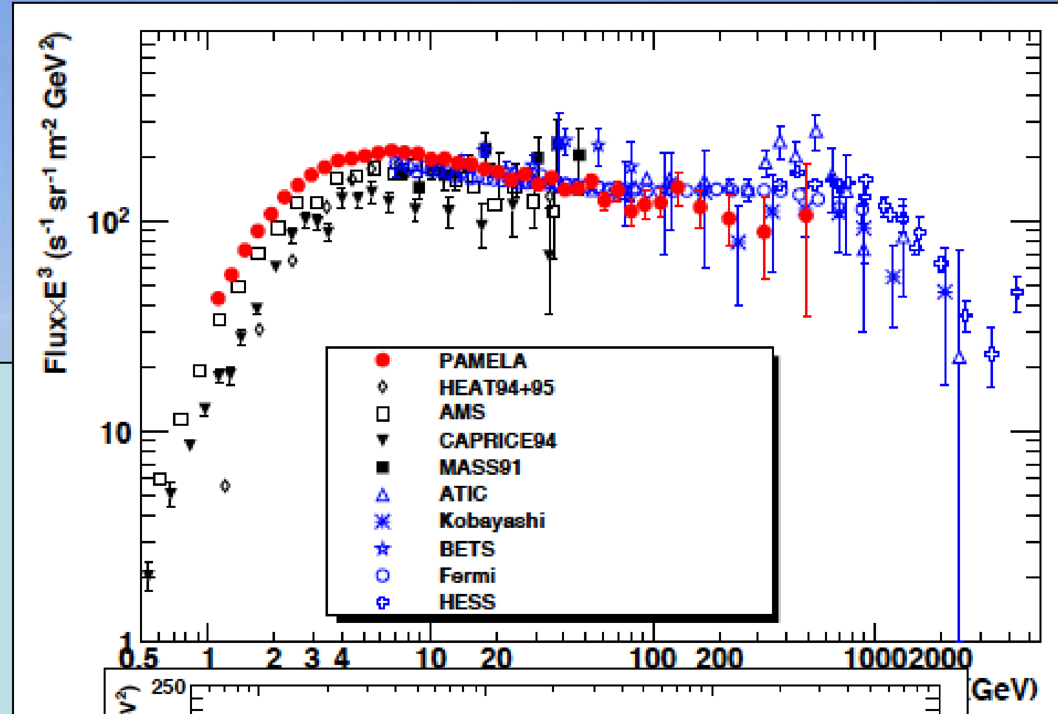


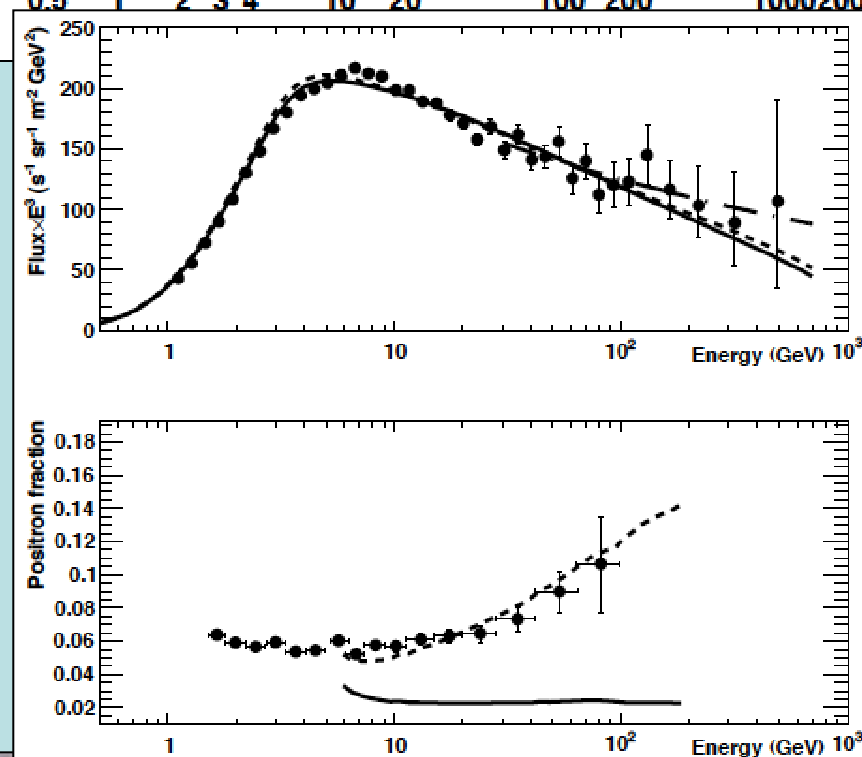
LHC mass limit

JE, Olive & Savage: arXiv:0912.3137

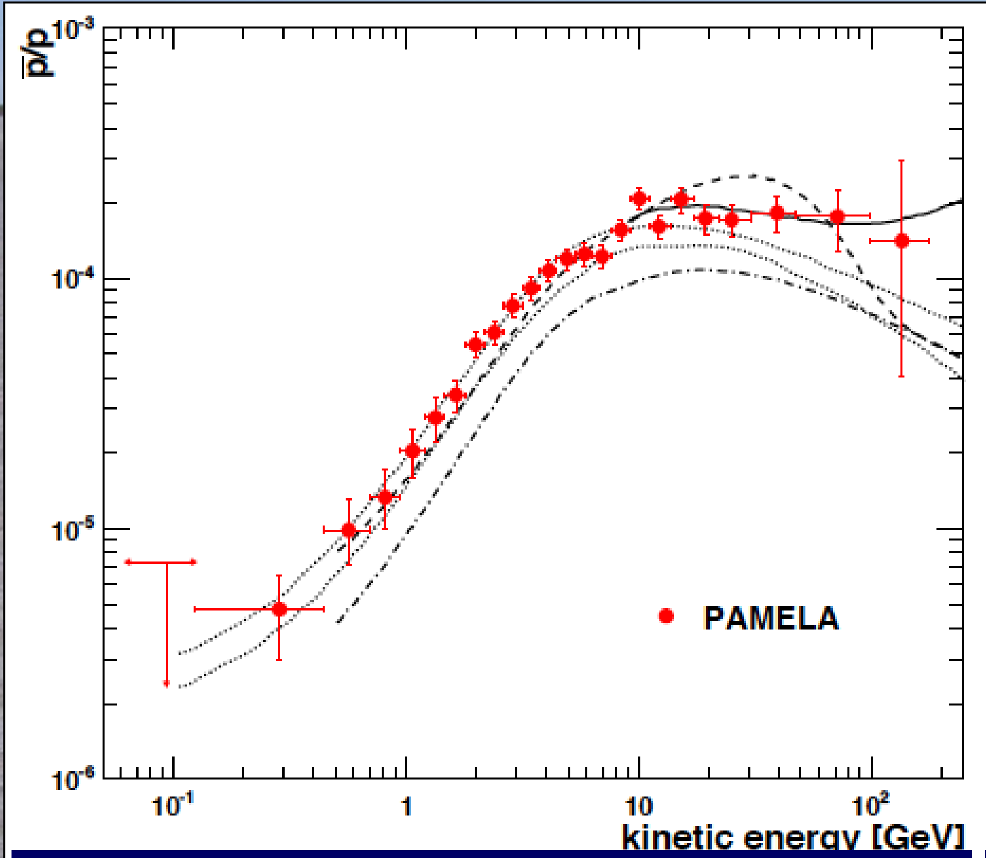
Anomalies in e^+/e^- Spectra?

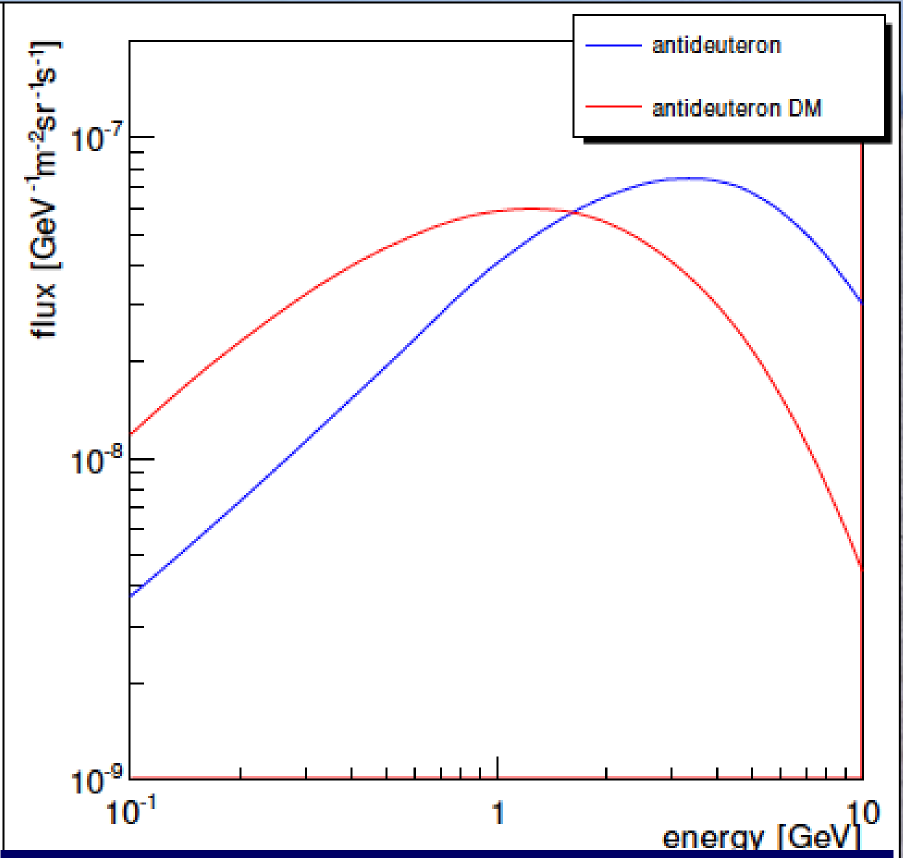
- Shoulder in $e^+ + e^-$ spectrum?
- Rising e^+/e^- ratio
- Uncertainties in cosmic-ray production, propagation?
- Nearby sources?
- SUSY interpretation difficult, unnecessary?





Antiprotons and Antideuterons from Dark Matter Annihilation?

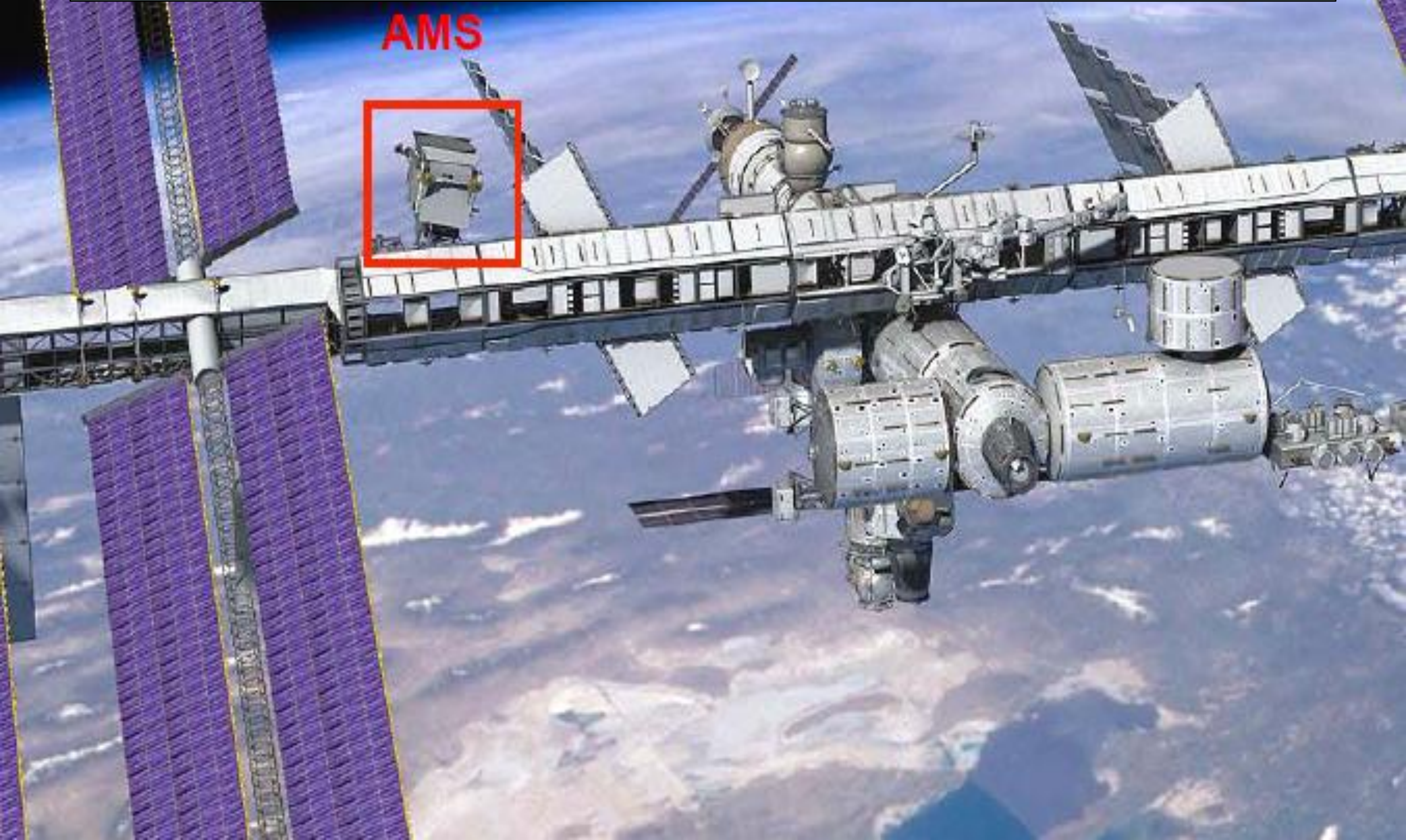




··· standard cosmic rays
--- possible supersymmetric model
— including production at source

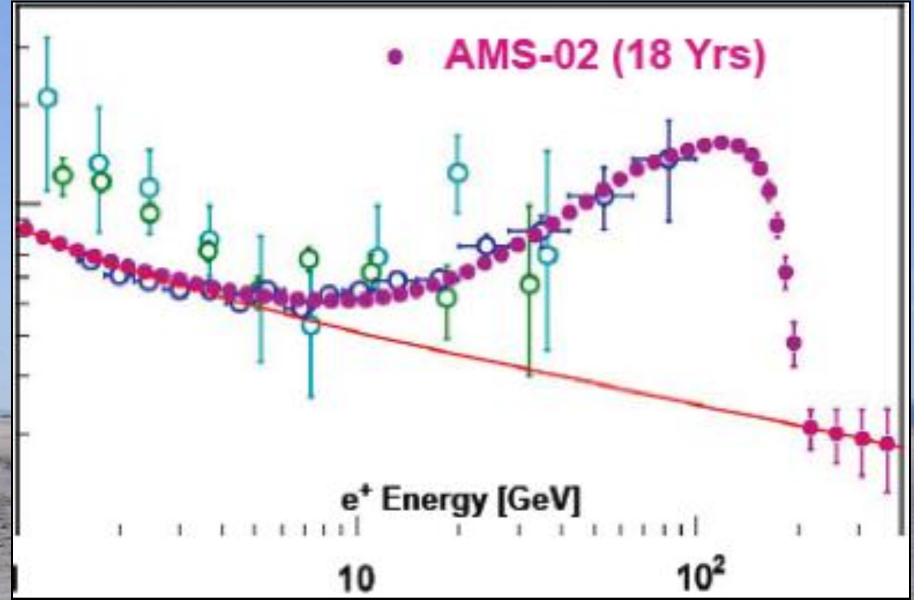
Antideuterons could provide another window of opportunity?

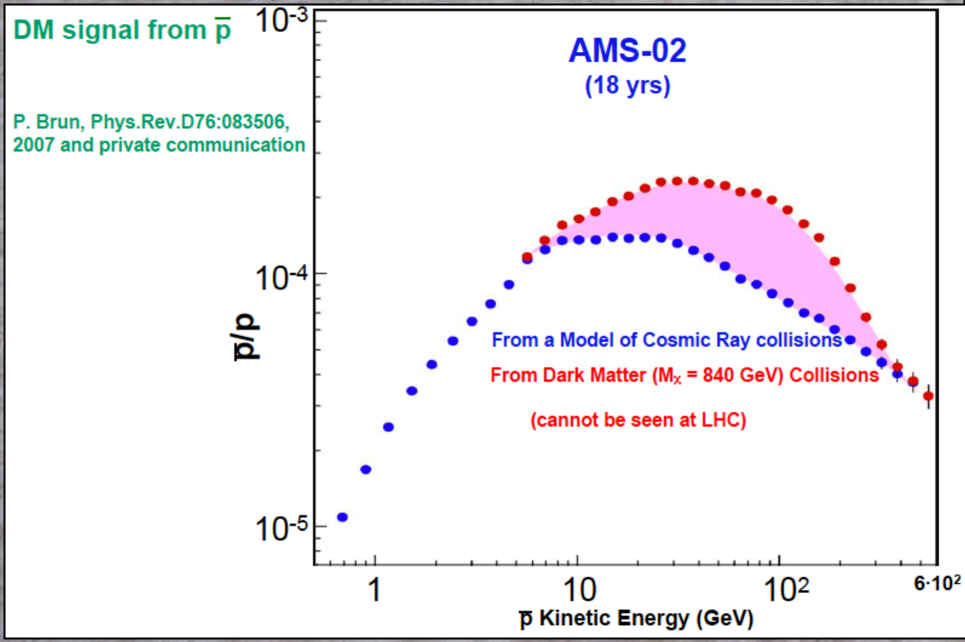
AMS-02 on the International Space Station (ISS)

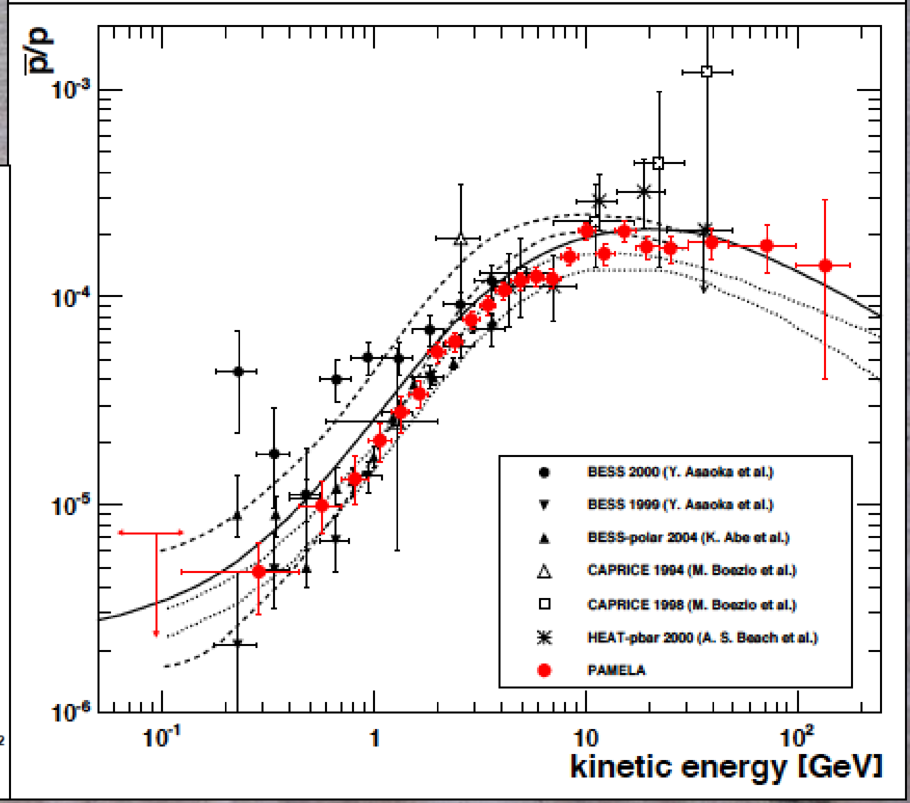


AMS-02 and Dark Matter

- Measurement of e^+ spectrum to higher E
- Precision measurement of antiproton spectrum







Quantum Gravity & String

The Scales of Quantum Gravity

- The Planck length (G = Newton constant):

$$\ell_{\mathrm{P}} = \left(\frac{\hbar\, G}{c^3}\right)^{3/2} = 1.6 \times 10^{-33}\ \mathrm{cm}$$

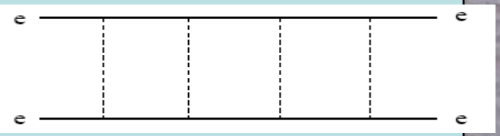
- The Planck mass:

$$m_{\mathrm{P}} = \left(\frac{\hbar\, c}{G}\right)^{1/2} = 1.2 \times 10^{19}\ \mathrm{GeV}/c^2$$

- Graviton exchange becomes strong when E ~ m_P:

  amplitude $\sim (m/m_P)^2 \rightarrow (E/m_P)^2 \sim 1$

- Multi-graviton exchange important:



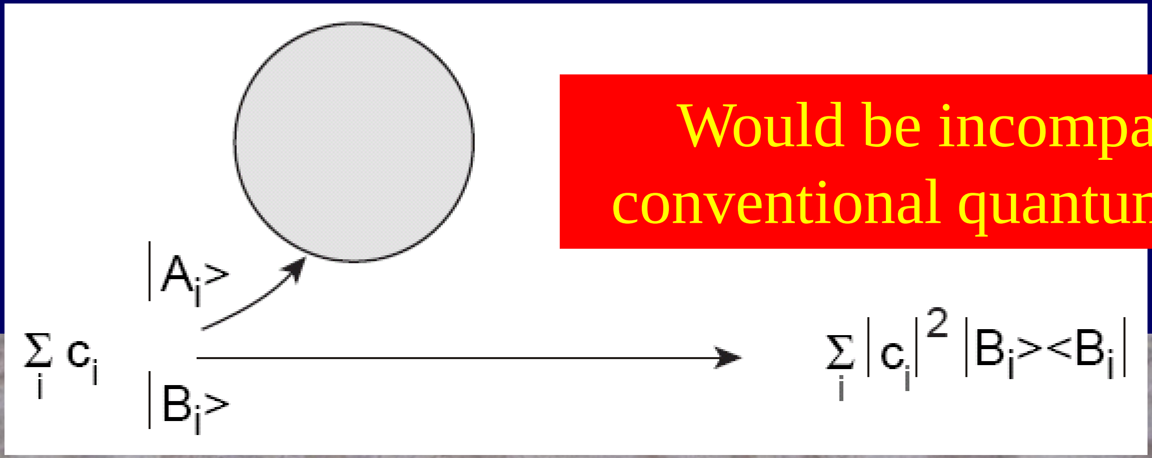
need quantum theory of gravity!

Problems of Quantum Gravity

- Gravity grows with energy: $\sigma_G \sim E^2/m_P^4$
- Two-graviton exchange is infinite:

$$\int^{\Lambda\to\infty} d^4k \left(\frac{1}{k^2}\right) \leftrightarrow \int_{1/\Lambda\to 0} d^4x \left(\frac{1}{x^6}\right) \sim \Lambda^2 \to \infty$$

- **Gravity is a non-renormalizable theory**
- Pure states evolve to mixed states?



Would be incompatible with conventional quantum mechanics

String Theory

- Point-like particles → extended objects
- Simplest possibility: lengths of string
  - Open and/or closed
- Quantum consistency fixes # dimensions:
  - Bosonic string: 26, superstring: 10
- **Must compactify extra dimensions:**

  scale ~ $1/m_P$?

Could they be larger?

How large could extra Dimensions be?

- 1/TeV?

  could break supersymmetry, electroweak

- micron?

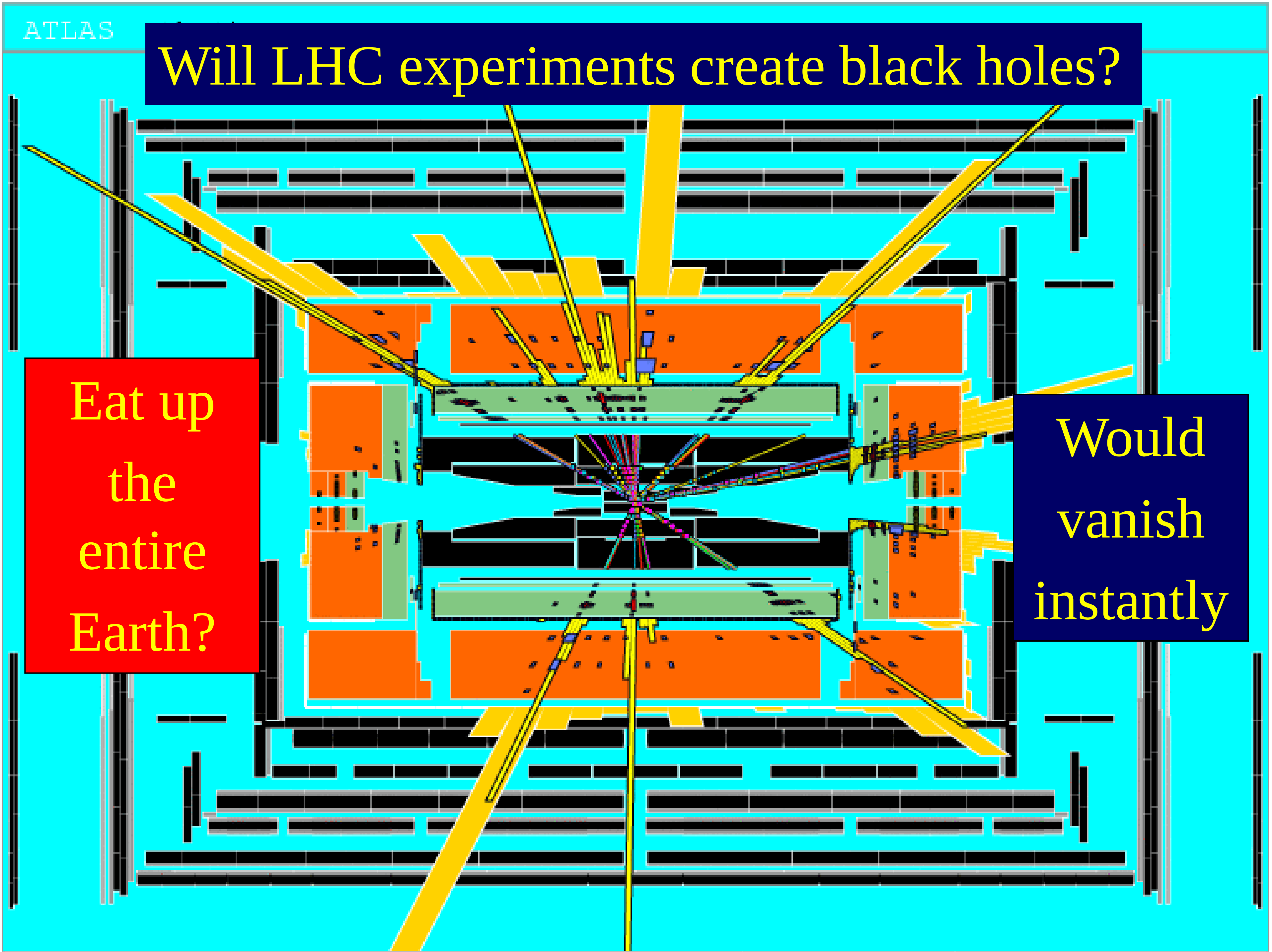
  can rewrite hierarchy problem

- Infinite?

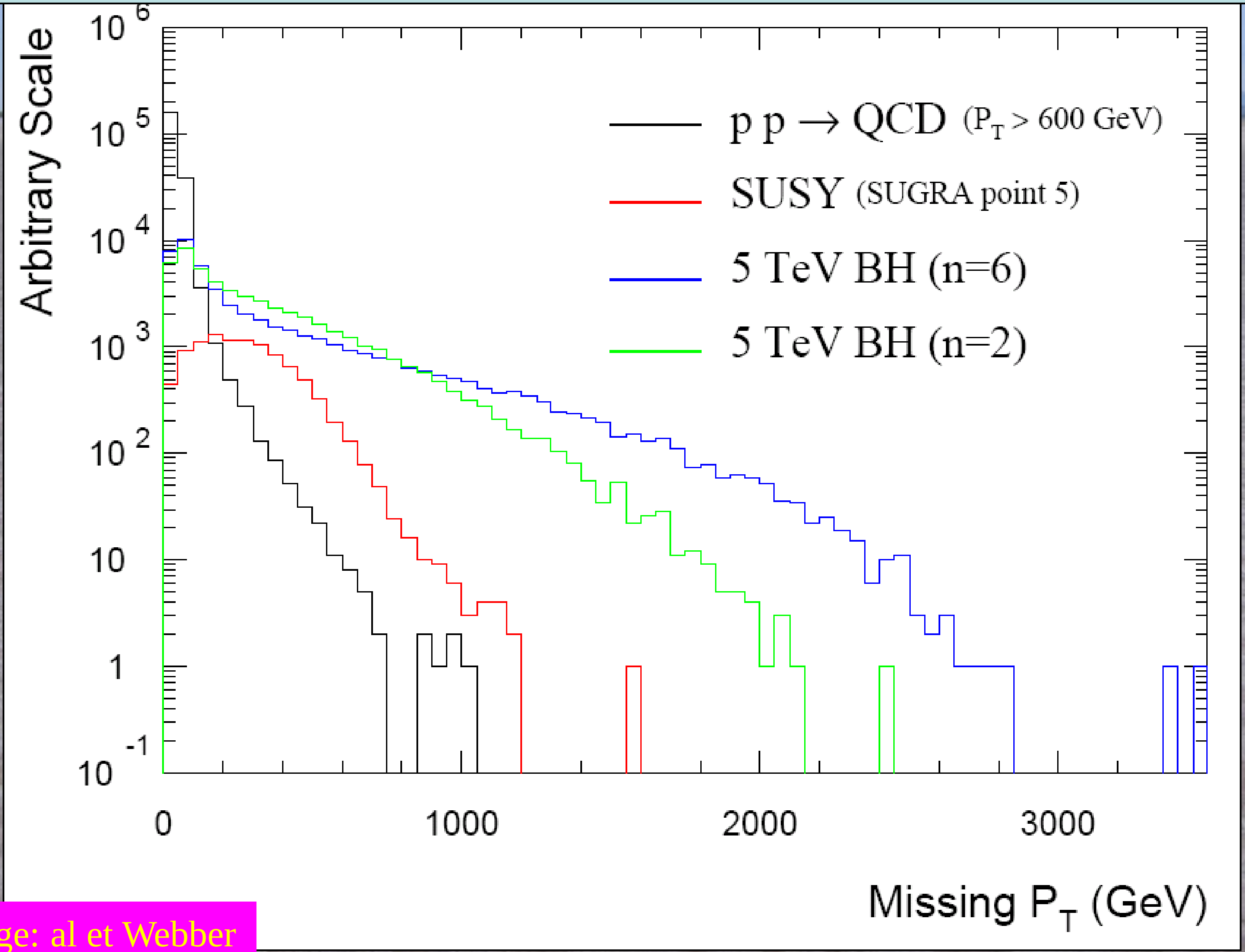
  warped compactifications

- **Look for black holes, Kaluza-Klein excitations @ colliders?**

Will LHC experiments create black holes?

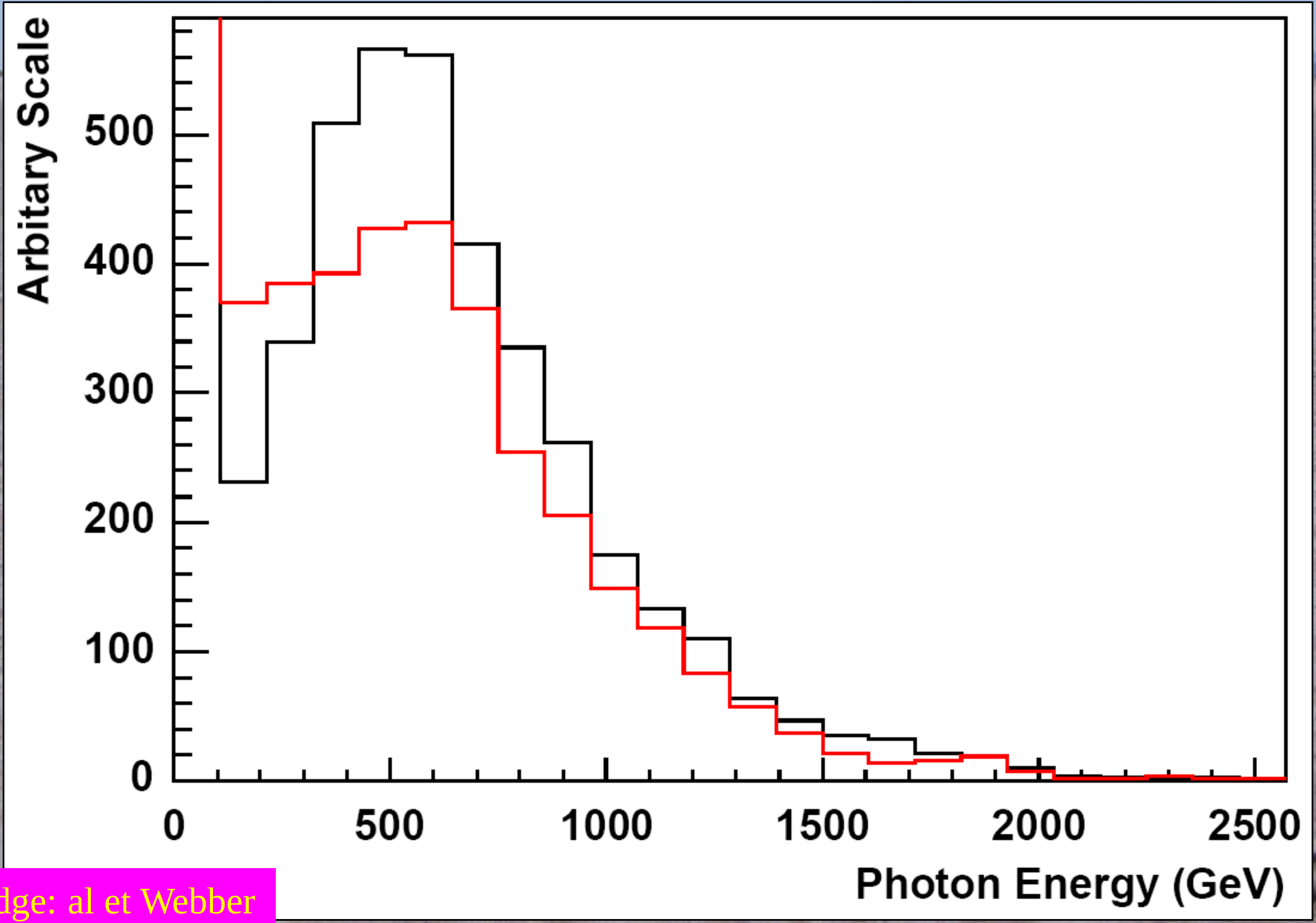


Black Hole Production @ LHC



Cambridge: al et Webber

Black Hole Decay Spectrum



Cambridge: al et Webber

No black holes yet!

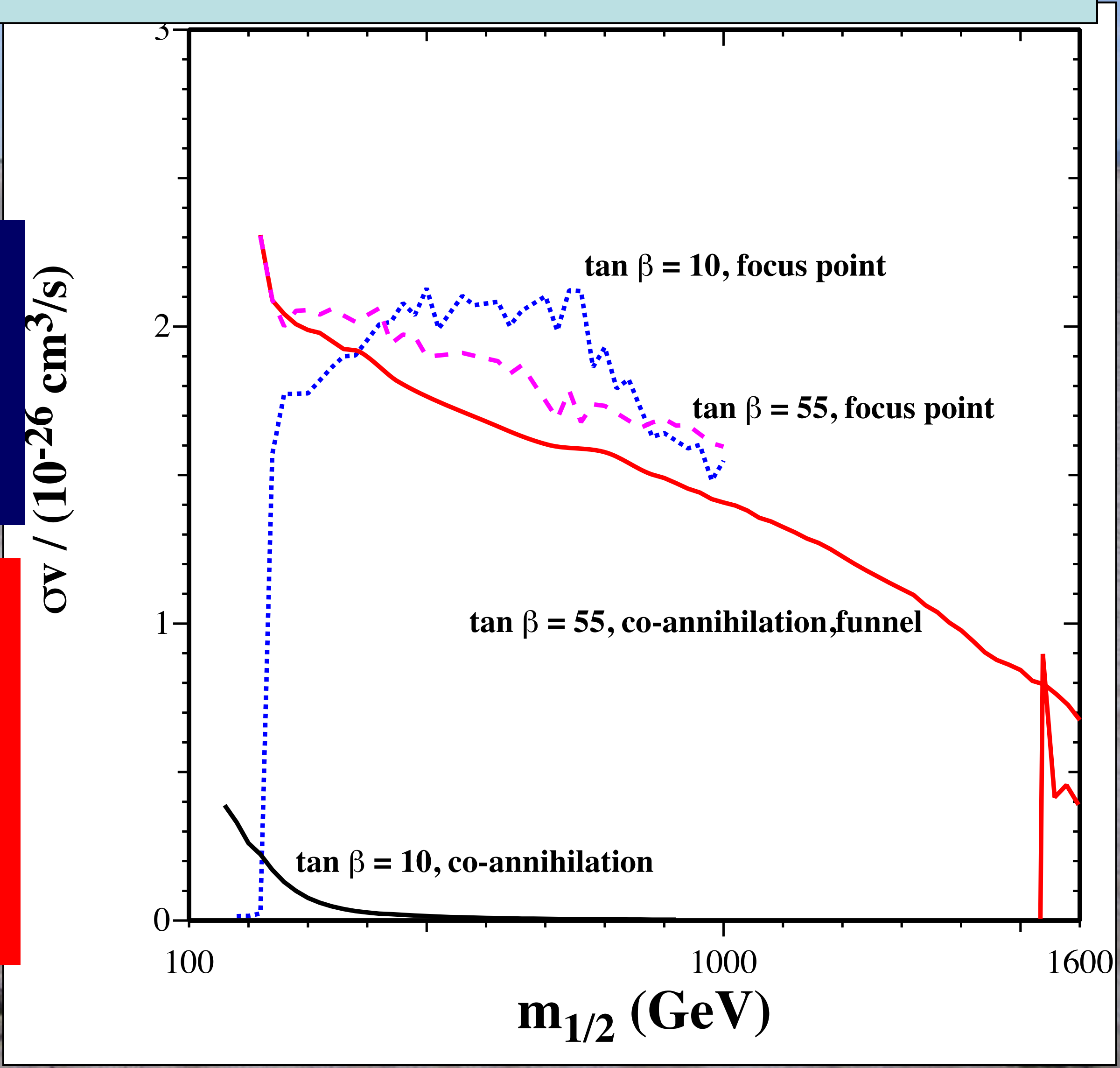
The LHC may revolutionize physics …

… and change our view of the Universe

Neutralino Annihilation Rates

Small in coannihilation strip @ small tan β

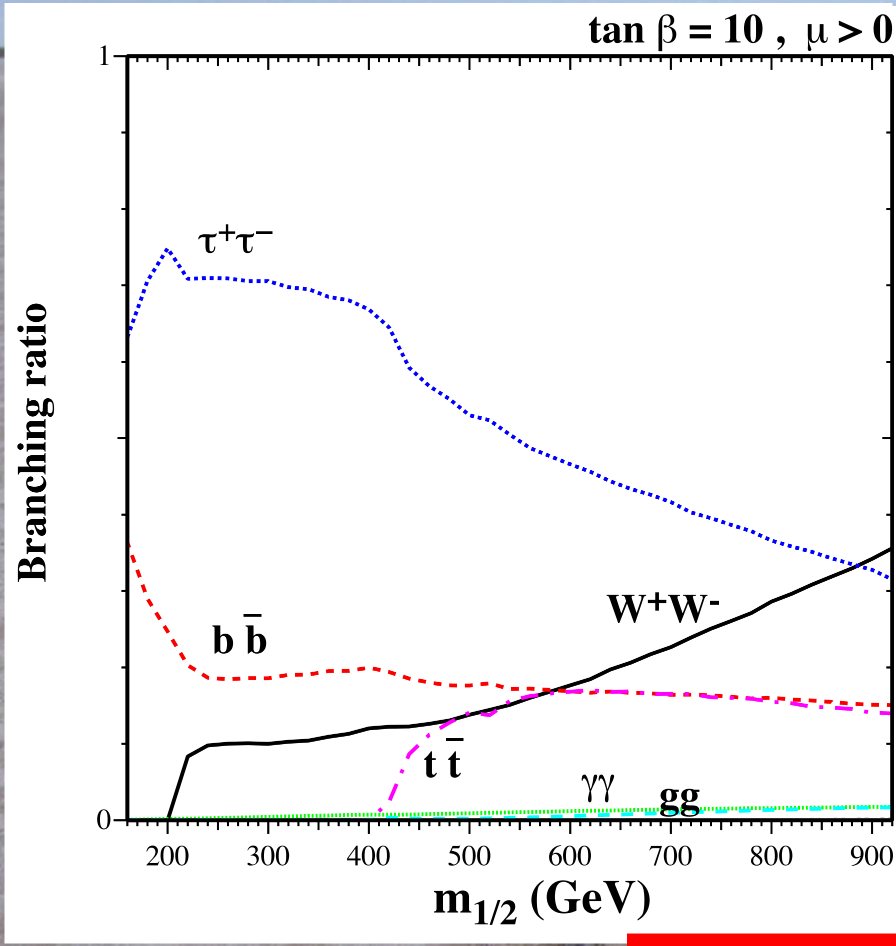
Constraints potentially along focus-point strip and @ large tan β

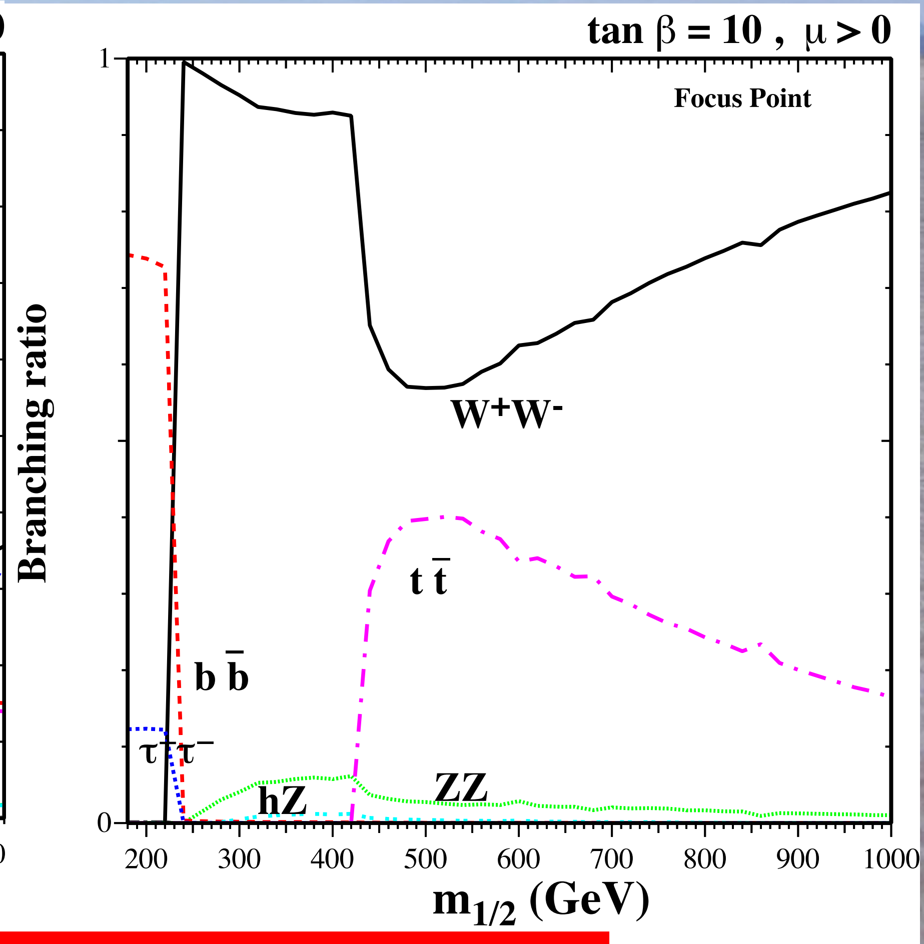


JE, Olive & Spanos

Annihilation Branching Fractions

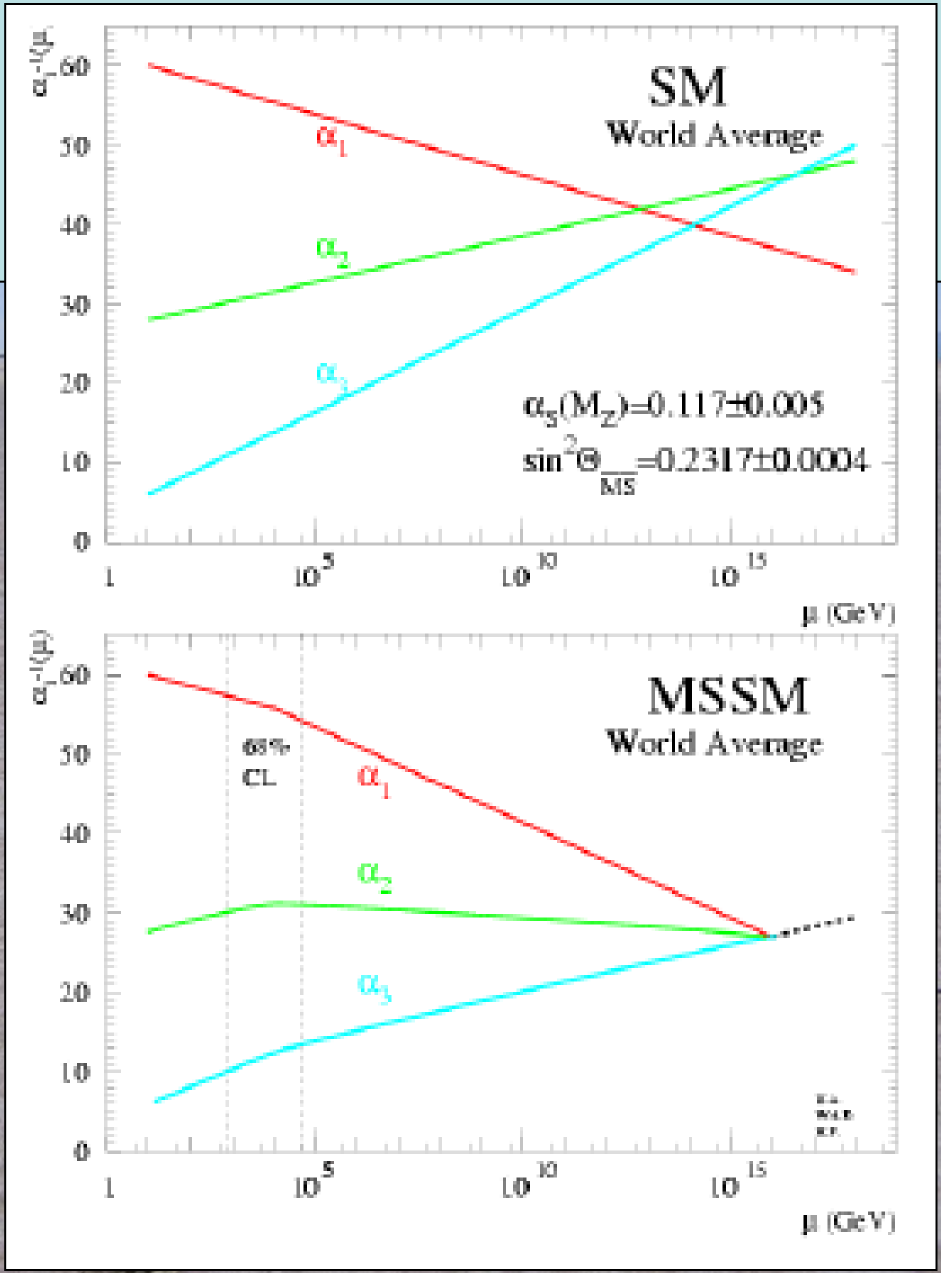
Vary in different regions of parameter space





JE, Olive & Spanos

Must be modelled correctly



SM
World Average
α_1
α_2
α_3
$\alpha_s(M_Z)=0.117\pm0.005$
$\sin^2\Theta_{\overline{MS}}=0.2317\pm0.0004$
$\alpha_i^{-1}(\mu)$
μ (GeV)
MSSM
World Average
68% CL

How to Grand Unify?

- Exploit logarithmic evolution of gauge couplings:

$$\frac{dg_a^2}{dt} = b_a \frac{g_a^4}{16\pi^2} + \ldots \quad \longrightarrow \quad \frac{m_{GUT}}{m_W} = \exp\left(\mathcal{O}\left(\frac{1}{\alpha_{em}}\right)\right)$$

- Combination measurable at low energies:

$$\sin^2\theta_W(m_Z) = \frac{g'^2}{g_2^2 + g'^2} = \frac{3}{5}\frac{g_1^2(m_Z)}{g_2^2(m_Z) + \frac{3}{5}g_1^2(m_Z)} = \frac{1}{1+8x}[3x + \frac{\alpha_{em}(m_Z)}{\alpha_3(m_Z)}] \quad x \equiv \frac{1}{5}(\frac{b_2 - b_3}{b_1 - b_2})$$

- Values in SM and MSSM:

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

- Experiment:

$$\alpha_{em} = \frac{1}{128};\ \alpha_3(m_Z) = 0.119 \pm 0.003,\ \sin^2\theta_W(m_Z) = 0.2315 \longrightarrow \boxed{x = \frac{1}{6.92 \pm 0.07}}$$

MSSM Calculation

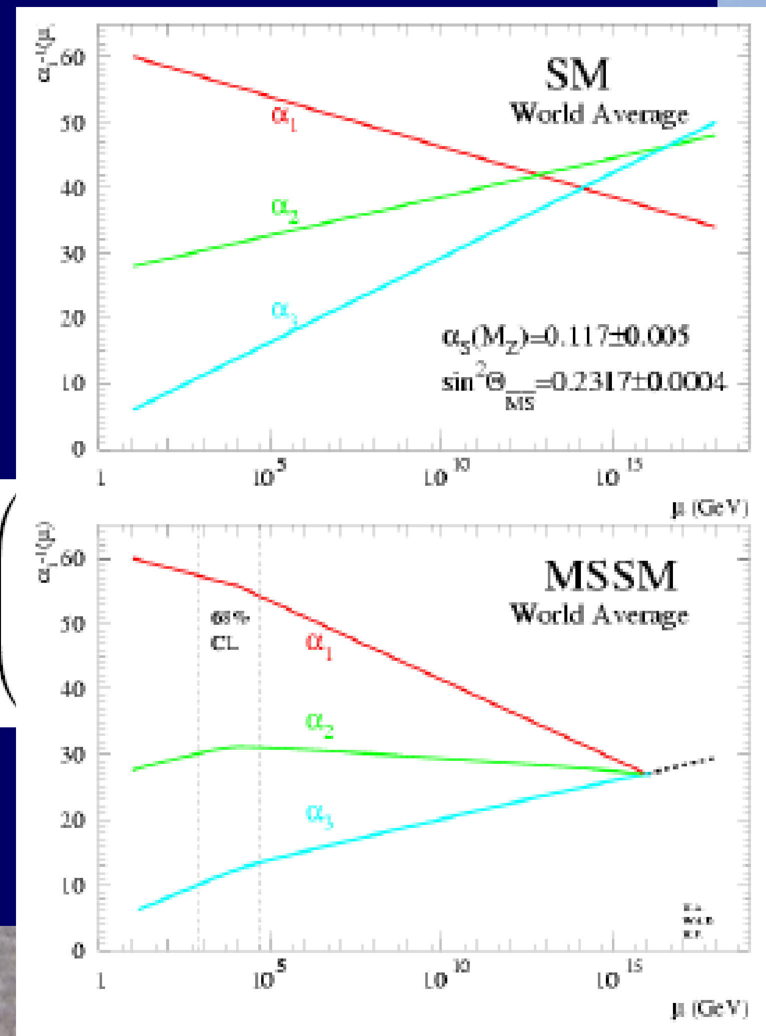
- At one loop:

$$b_i = \begin{pmatrix} 0 \\ -6 \\ -9 \end{pmatrix} + N_g \begin{pmatrix} 2 \\ 2 \\ 2 \end{pmatrix} + N_H \begin{pmatrix} \frac{3}{10} \\ \frac{1}{2} \\ 0 \end{pmatrix}$$

- Two loops:

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

- Results are stable



Particles in SU(5)

- Gauge bosons:

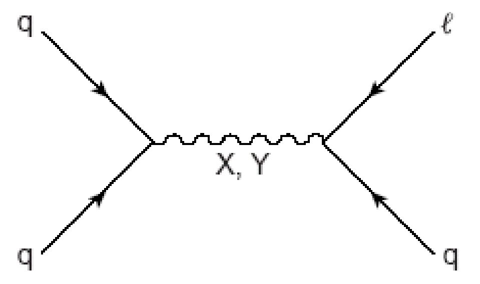
$$\begin{pmatrix} & & & \vdots & \bar{X} & \bar{Y} \\ & g_{1,\ldots,8} & & \vdots & \bar{X} & \bar{Y} \\ & & & \vdots & \bar{X} & \bar{Y} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ X & X & X & \vdots & & \\ & & & \vdots & W_{1,2,3} & \\ Y & Y & Y & \vdots & & \end{pmatrix}$$

- Matter particles: $\underline{\bar{5}} = (\bar{3},1) + (1,2)\ , \quad \underline{10} = (3,2) + (\bar{3},1) + (1,2)$

$$\bar{F} = \begin{pmatrix} d_R^c \\ d_Y^c \\ d_B^c \\ \cdots \\ -e^- \\ \nu_e \end{pmatrix}_L \ , \quad T = \begin{pmatrix} 0 & u_B^c & -u_Y^c & \vdots & -u_R & -d_R \\ -u_B^c & 0 & u_R^c & \vdots & -u_Y & -d_Y \\ u_Y^c & -u_R^c & 0 & \vdots & -u_B & -d_B \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ u_R & u_Y & u_B & \vdots & 0 & -e^c \\ d_R & d_Y & d_B & \vdots & e^c & 0 \end{pmatrix}_L$$

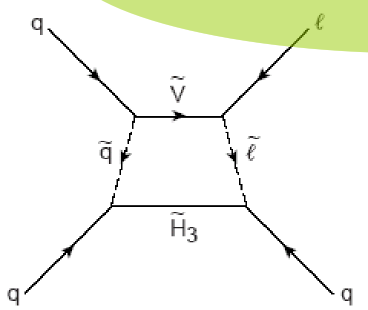
Proton Decays in GUTs

- Decay diagram in non-supersymmetric SU(5)



$A \sim 1/m_X^2$

- Decay diagram in supersymmetric SU(5)



$A \sim 1/m_X \, m_{squark}$

Experimental limits

p DECAY MODES	Partial mean life (10^{30} years)	Confidence level
Antilepton + meson		
$N \to e^+\pi$	> 158 (n), > 1600 (p)	90%
$N \to \mu^+\pi$	> 100 (n), > 473 (p)	90%
$N \to \nu\pi$	> 112 (n), > 25 (p)	90%
$p \to e^+\eta$	> 313	90%
$p \to \mu^+\eta$	> 126	90%
$n \to \nu\eta$	> 158	90%
$N \to e^+\rho$	> 217 (n), > 75 (p)	90%
$N \to \mu^+\rho$	> 228 (n), > 110 (p)	90%
$N \to \nu\rho$	> 19 (n), > 162 (p)	90%
$p \to e^+\omega$	> 107	90%
$p \to \mu^+\omega$	> 117	90%
$n \to \nu\omega$	> 108	90%
$N \to e^+K$	> 17 (n), > 150 (p)	90%
$p \to e^+K^0_S$	> 120	90%
$p \to e^+K^0_L$	> 51	90%
$N \to \mu^+K$	> 26 (n), > 120 (p)	90%
$p \to \mu^+K^0_S$	> 150	90%
$p \to \mu^+K^0_L$	> 83	90%
$N \to \nu K$	> 86 (n), > 670 (p)	90%
$n \to \nu K^0_S$	> 51	90%

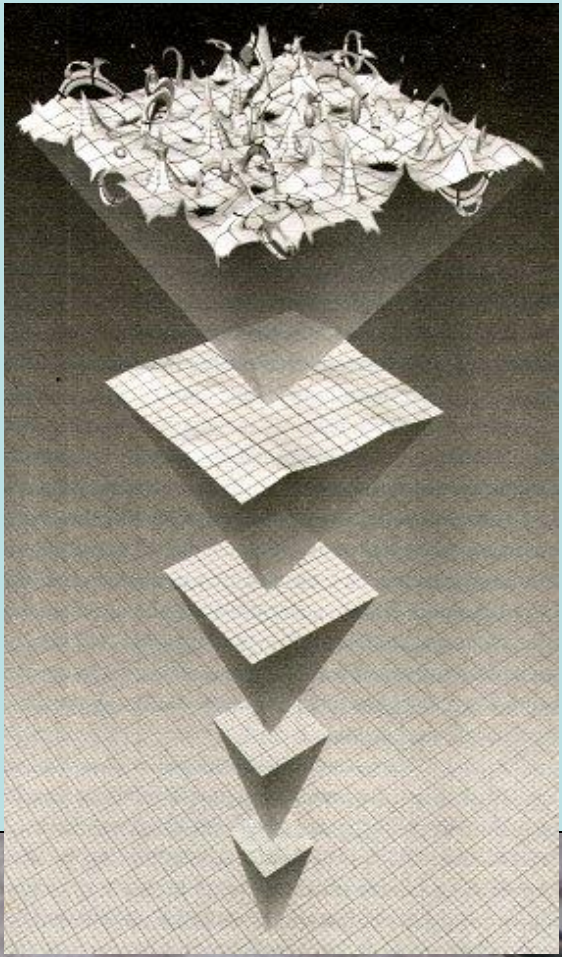
Reconciling General Relativity and Quantum Mechanics

- Unfinished business of 20th-century physics
- Primary task of 21st-century physics
- One or the other – or both – must be modified?
- Modification of quantum mechanics?
- Violation of CPT?
- Modification of Lorentz invariance?
- Breakdown of equivalence principle?
- Search for distinctive signature not allowed in quantum field theory

Nature of QG Vacuum

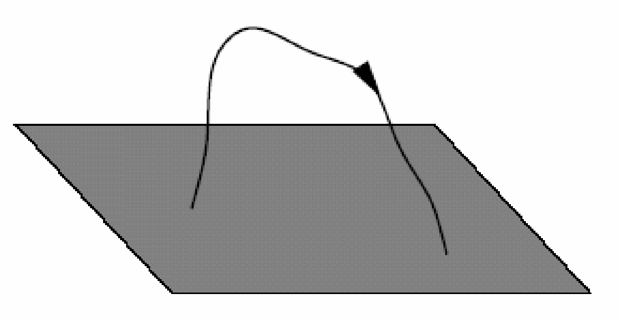
- Expect quantum fluctuations in fabric of space-time
- In natural Planckian units:

  $\Delta E, \Delta x, \Delta t, \Delta\chi \sim 1$
- Fluctuations in energy, space, time, topology of order unity
- **Space-time foam**
- **Manifestations?**



Non-Perturbative String = M Theory

- Solitonic 'lumps' = balls of string $m \propto \frac{1}{g_s}$
- Appear with various dimensions: 'D-branes'

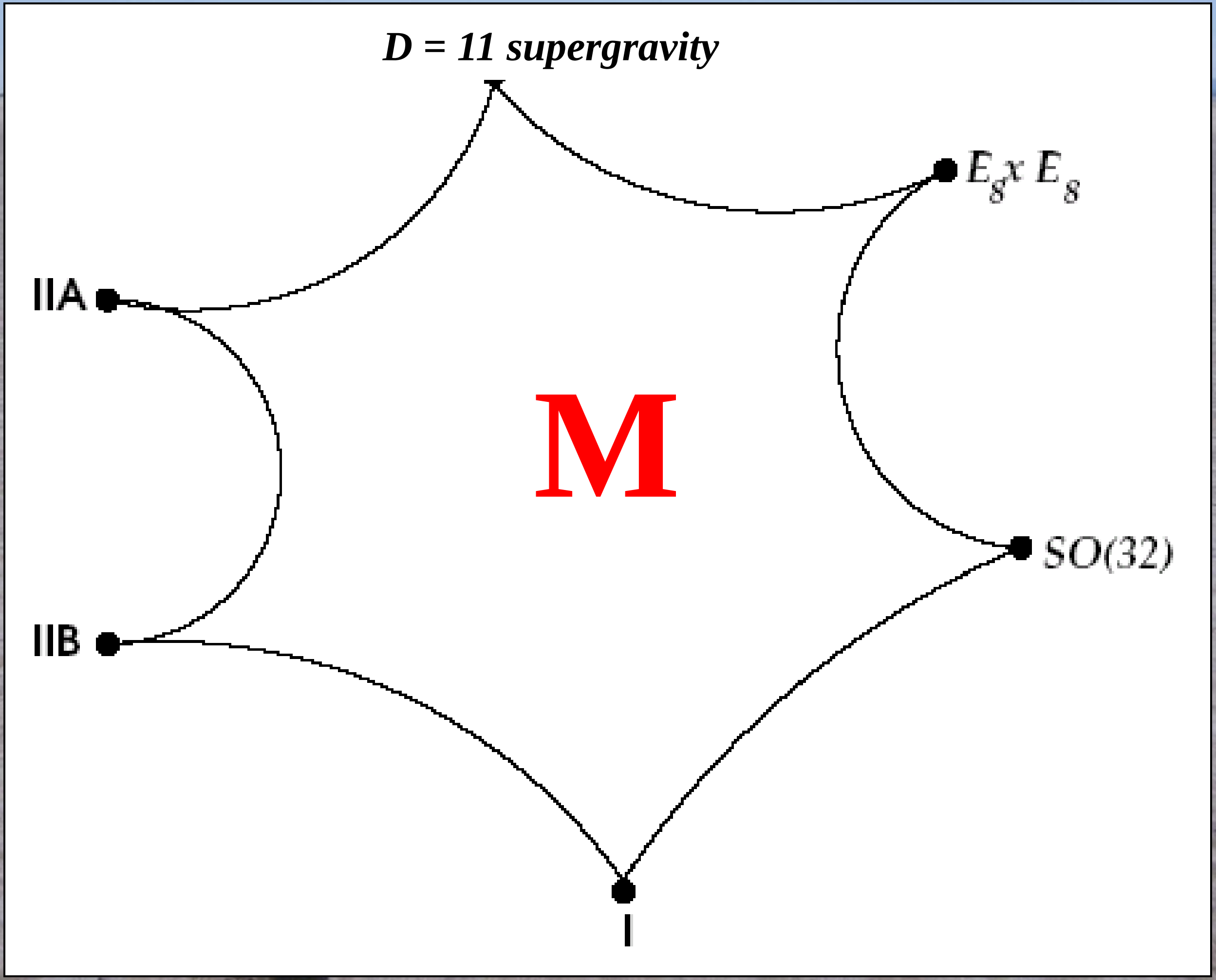


- Can regard string coupling as extra 'dimension'

  11-dimensional M theory

- Includes different string models in various limits
- New ways to get extra gauge symmetries

All Different String Theories are Related



String Landscape?

- Millions (billions?) of manifolds for string compactification
- Each has dozens (hundreds) of topological cycles
- Fluxes through cycles each have O(10) possible values
- Enormous number of possible vacua
- Maybe one of them has small vacuum energy?
- How does Universe choose?
- If it happens to choose small vacuum energy, why not also choose small m_W?
- **No need for supersymmetry?**