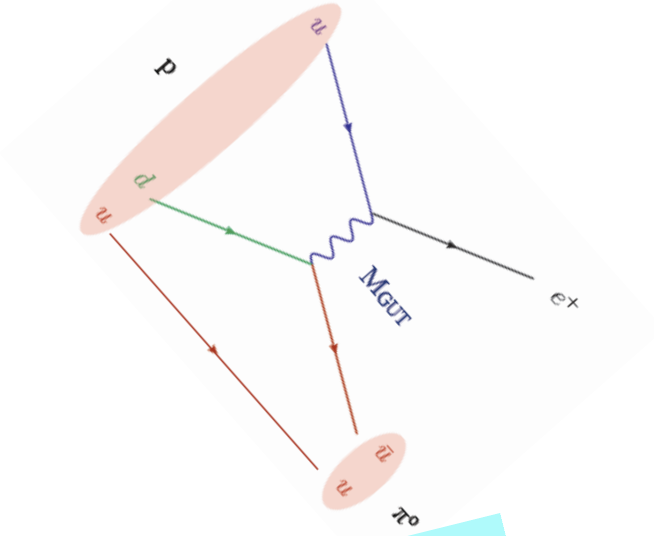
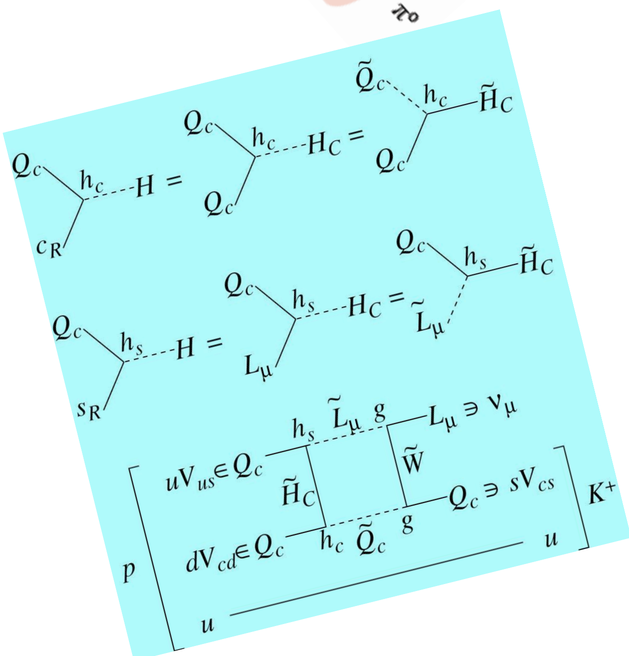
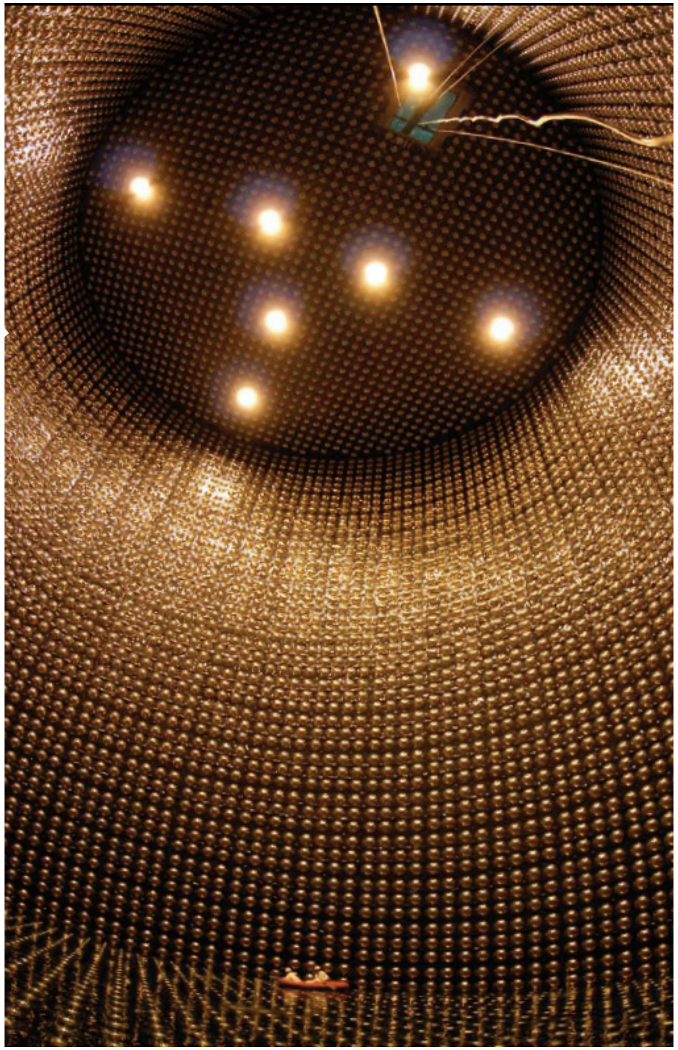
Theory for non-accelerator particle physics







$$\mathcal{M}_{\tilde{\chi}^0_{1,2,3,4}} = \begin{pmatrix} M_1 & 0 & -\frac{g' v_1}{\sqrt{2}} & +\frac{g' v_2}{\sqrt{2}} \\ 0 & M_2 & +\frac{g v_1}{\sqrt{2}} & -\frac{g v_2}{\sqrt{2}} \\ -\frac{g' v_1}{\sqrt{2}} & +\frac{g v_1}{\sqrt{2}} & 0 & -\mu \\ +\frac{g' v_2}{\sqrt{2}} & -\frac{g v_2}{\sqrt{2}} & -\mu & 0 \end{pmatrix}$$

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma_{\rm ann} v \rangle \left(n_\chi^2 - n_{\chi,{\rm eq}}^2\right)$$

Subir Sarkar

University of Oxford

PPAP meeting, University of Birmingham, 15 July 2009

… significant overlap in physics priorities with the **Particle Astrophysics Panel (PAAP)**

e.g. the following were the key questions addressed by **ApPEC,** the **Astroparticle Physics European Coordination** committee

What is the universe made of?

Do protons last for ever?

What are the properties of neutrinos … and their role in cosmic evolution?

What can neutrinos tell us about the interior of the Sun and Earth, and about supernova explosions?

What is the origin of cosmic rays? How does the sky look at extreme energies?

What is the nature of gravity? Can we detect gravitational waves? What can they tell us about violent cosmic processes?

Since neutrino physics has been discussed already, I will focus on **dark matter & nucleon decay**

ASPERA

ApPEC
Astroparticle Physics European Coordination

ASTRONET
TOWARDS A STRATEGIC PLAN FOR EUROPEAN ASTRONOMY

CERN

courtesey:
Stavros Katsanevas

What are the fundamental conservation laws in Nature?

"One is tempted to conclude that the only fundamental conservation laws left in physics are the gauge symmetries: Lorentz invariance and SU(3)×SU(2)×U(1). But then what about baryon and lepton conservation? They appear to be exact and unbroken, but they are surely not exact unbroken gauge symmetries, because we do not see the effects of a long-range vector field coupled to baryon or lepton number. The peculiar position of baryon and lepton conservation in today's physics suggests that baryon and lepton conservation may go the way of the other non-gauge symmetries, and turn out to be only approximate consequences of the gauge symmetries and renormalizability."

Steven Weinberg (1980)

P	Violated by weak interactions (1956)
CP	Violated by weak interactions (1956)
C	Violated by weak interactions (1964)
T	Violated by weak interactions (1999)
L	$0\nu\beta\beta$ decay?
B	Proton decay?
(***R***-parity	?)

The Standard $SU(3)_c \times SU(2)_L \times U(1)_Y$ Model as an *effective* field theory
… exact up to some high energy 'cut-off' scale M

Higgs mass divergence

$$\mathcal{L}_{\text{eff}} = M^4 + M^2\Phi^2$$ **super-renormalisable**

$$+ \; (D\Phi)^2 + \bar{\Psi}\, \not{D}\Psi + F^2 + \bar{\Psi}\Psi\Phi + \Phi^2$$ renormalisable

$$+ \; \frac{\bar{\Psi}\Psi\Phi\Phi}{M} + \frac{\bar{\Psi}\Psi\bar{\Psi}\Psi}{M^2} + \ldots$$ non-renormalisable

Neutrino mass *Proton decay*

New physics beyond the SM (which can violate lepton and baryon #)
→ non-renormalisable operators which are *suppressed* by powers of M

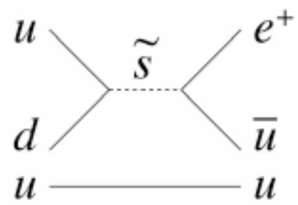
Naturally explains why neutrino mass, proton decay, ... are suppressed

But as M is raised, the effects of the super-renormalisable operators are exacerbated!

Solution for Higgs mass divergence → 'softly broken' supersymmetry at M ~ 1 TeV

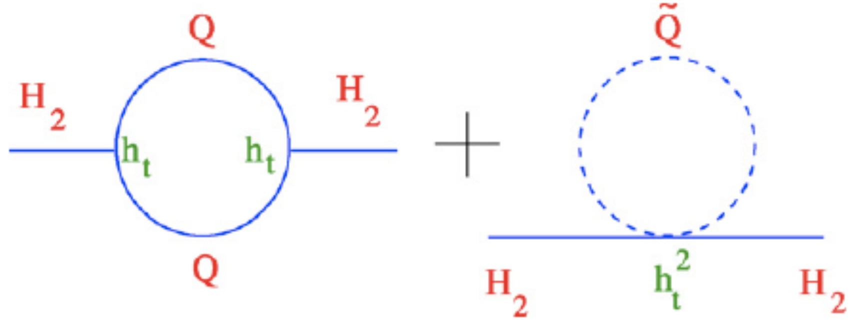
However supersymmetry violates B & L at the renormalisable level: $W = udd + QdL + LLe + Lh_u$

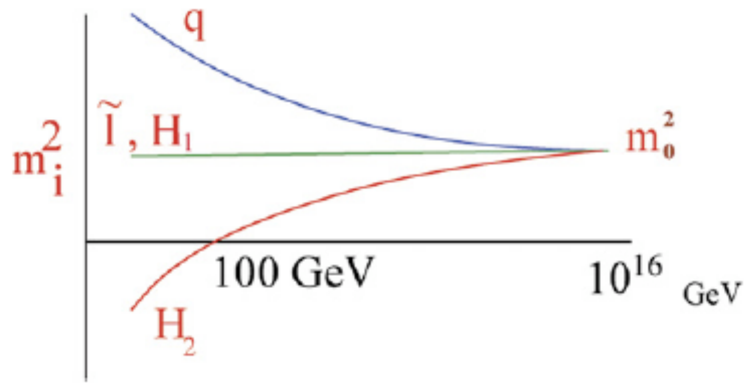
So the proton will decay *too rapidly* unless
R*-parity → $(-1)^{3B+L+2S}$ is *conserved



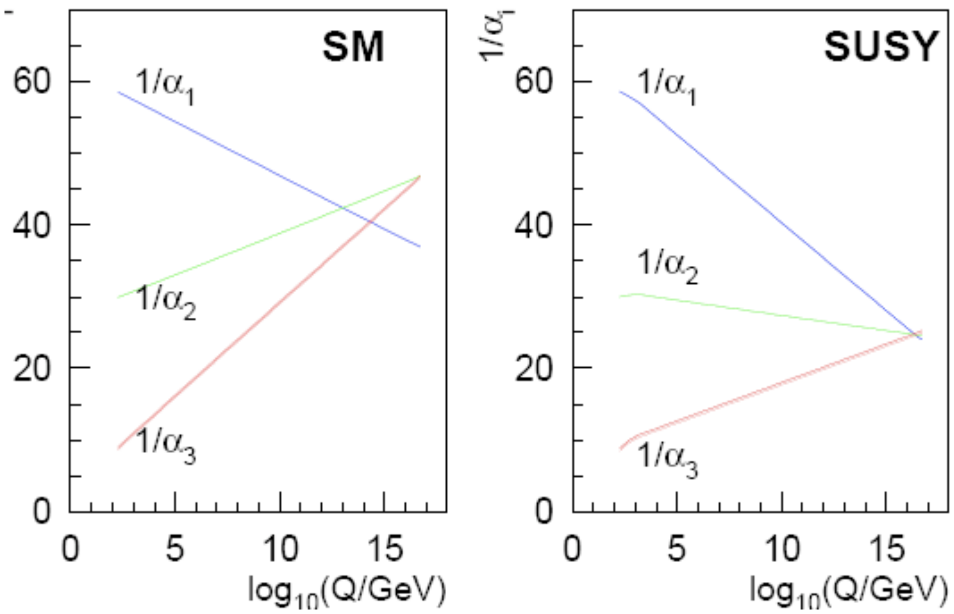
$\tau_p \sim m_{sq}^4/m_p^5 \sim 10^{-12}$ s

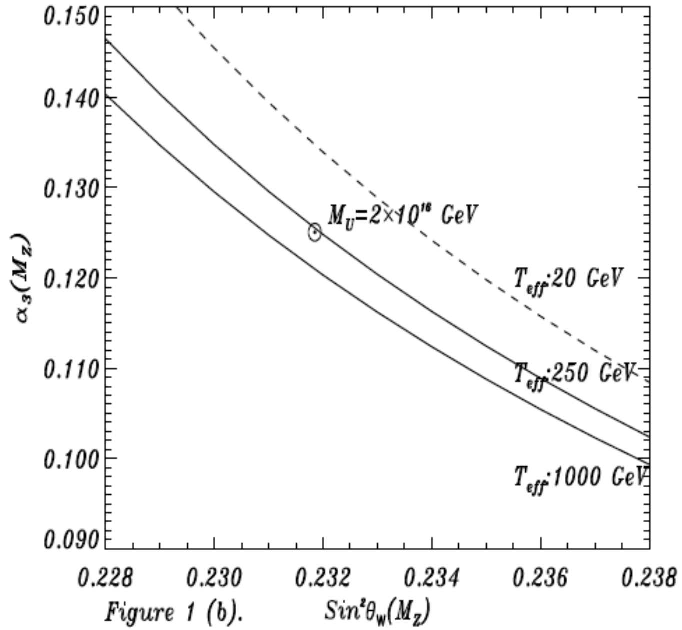
If there are indeed supersymmetric partners of all known particles with masses ~ Fermi scale, radiative corrections can naturally trigger $SU(2)_L \times U(1)_Y$ breaking *and* enable unification of gauge couplings





Ibanez, Ross (1981)

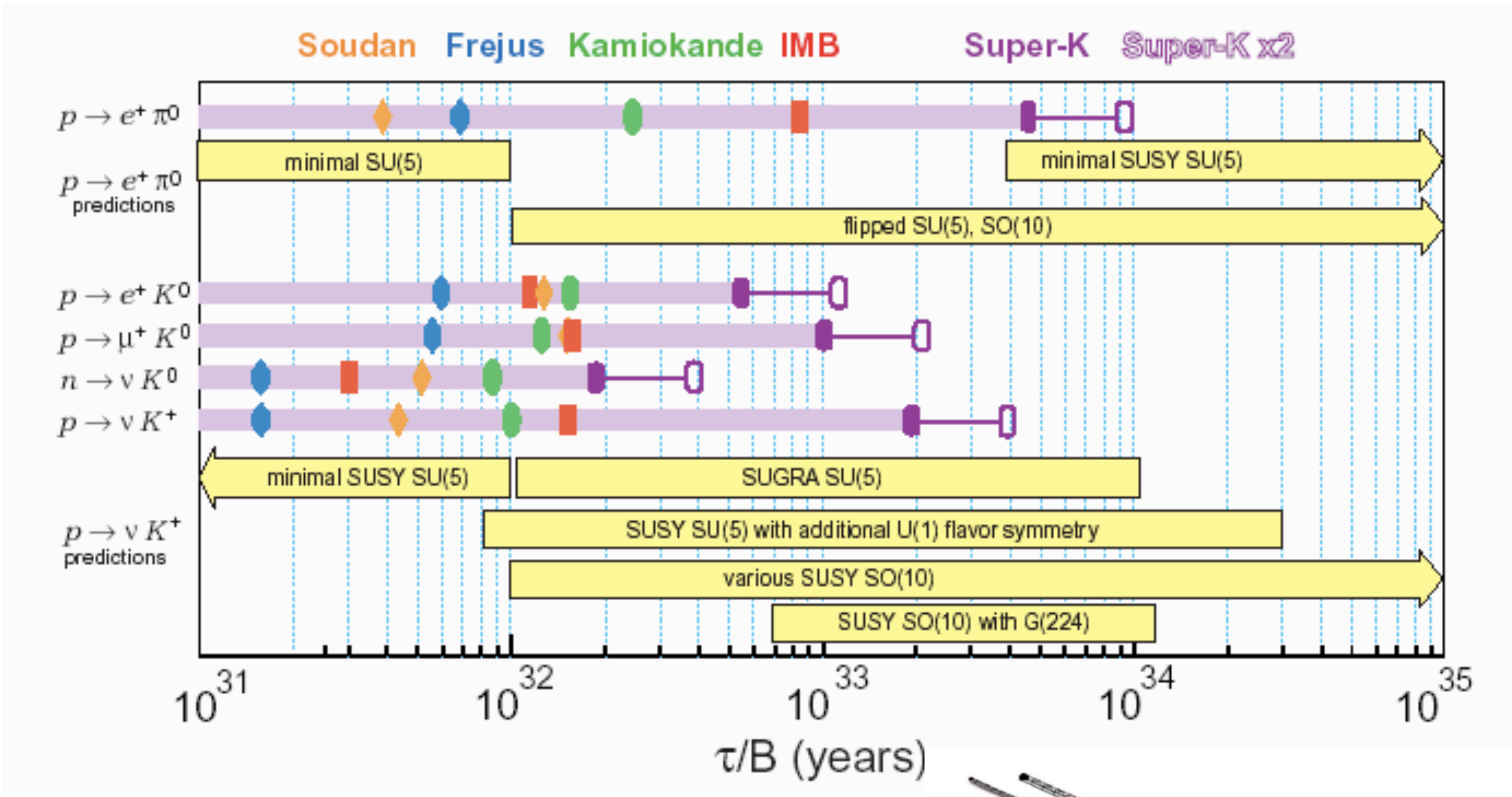




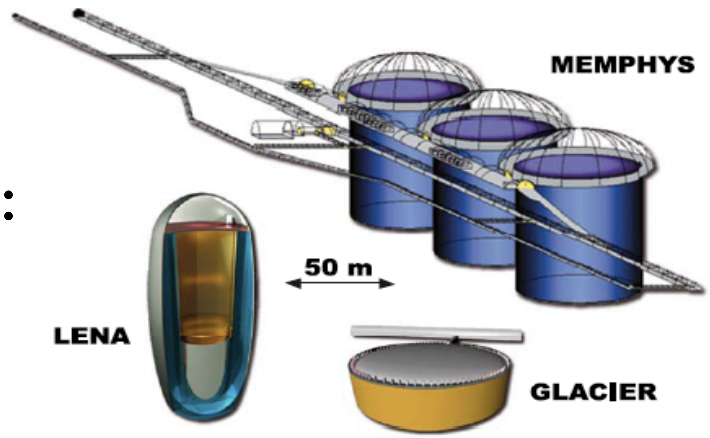
Ghilencea, Ross (12001)

The predicted strong coupling at the weak scale matches experiment to within 1%!

Predictions for the proton lifetime in various unified theories



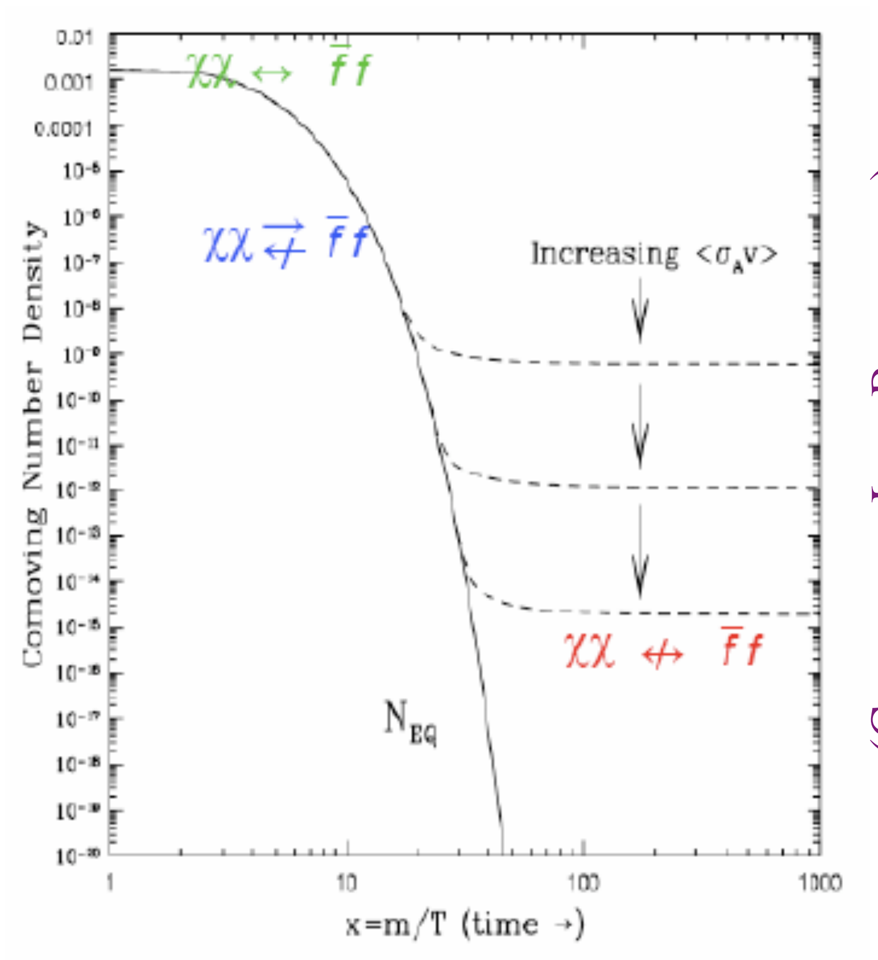
Proposed megaton scale experiments:
(will also detect supernova νs)



Ongoing R&D (FP7): LAGUNA

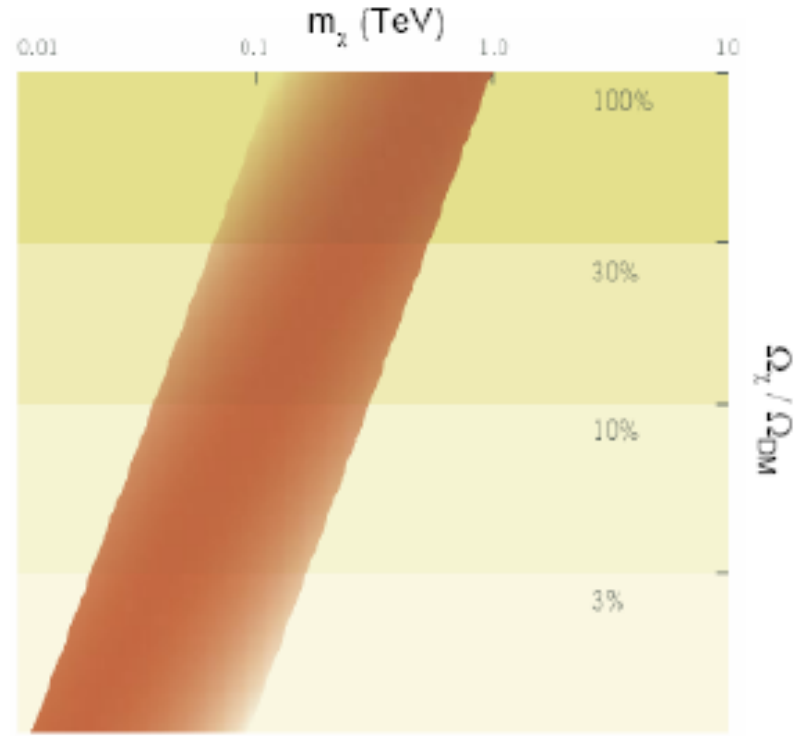
The lightest supersymmetric particle is typically neutral and stable through conservation of *R*-parity, thus a candidate for dark matter

Its cosmological (thermal) relic abundance is *naturally* of the required order



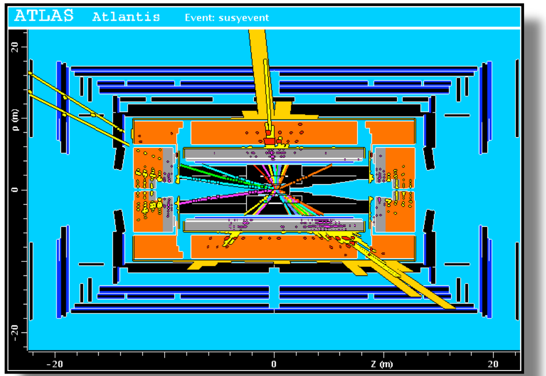
(Courtesey: Lars Bergstorm)

$$\Omega_\chi \sim <\sigma_A v>^{-1} \sim m_\chi^2/(k\alpha^2)$$



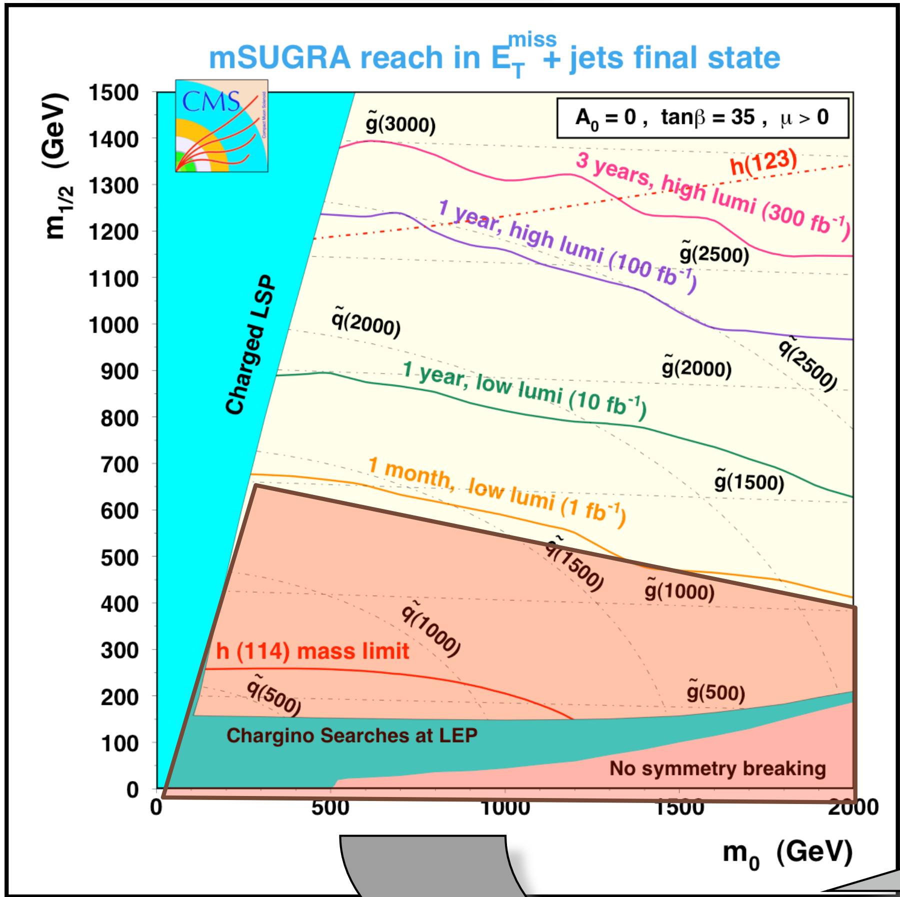
But is *R*-parity really conserved? (matter-parity suffices to prevent nucleon decay!)

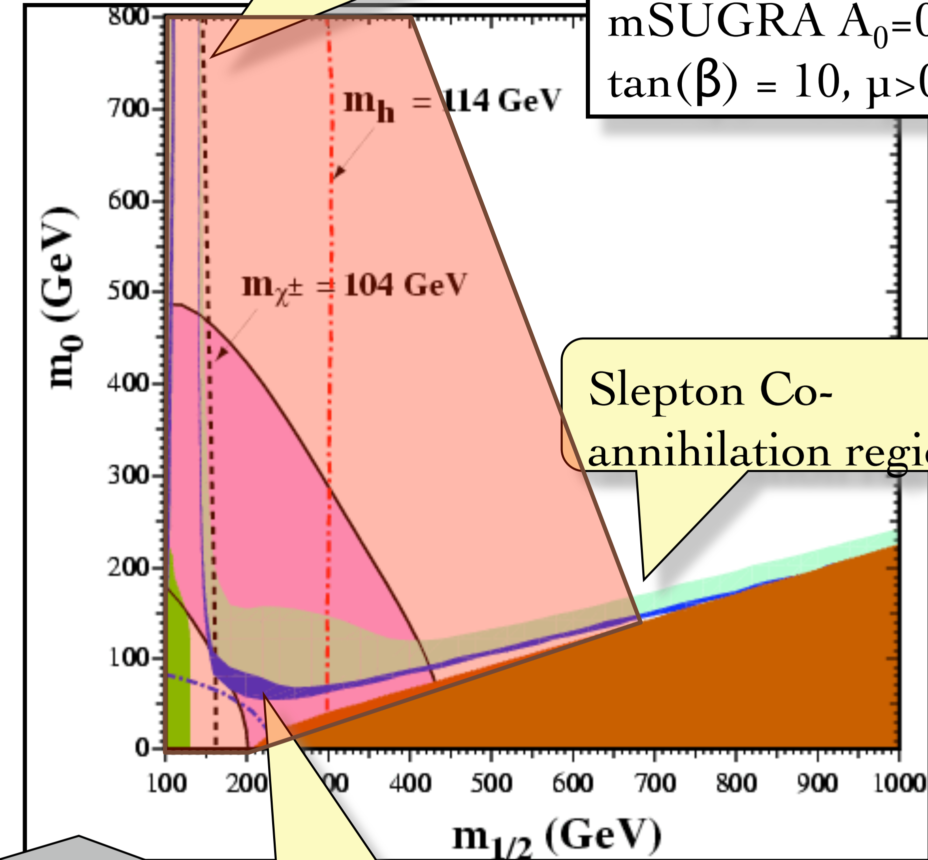
This possibility will be tested at the LHC



Region probed with 1 fb^{-1}

'Focus point' region: annihilation to gauge bosons





mSUGRA A_0=0, $\tan(\beta)$ = 10, μ>0

Slepton Co-annihilation region

'Bulk' region: t-channel slepton exchange

WMAP constraints

(Courtesey: Alan Barr)

However LSPs are *not* the only candidate for dark matter

Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
Λ_{QCD}	**Nucleons**	Baryon number	$\tau > 10^{33}$ yr (dim-6 OK)	'freeze-out' from thermal equilibrium	$\Omega_B \sim 10^{-10}$ *cf.* observed $\Omega_B \sim 0.05$
$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino? Technibaryon?	R-parity? (walking) Technicolour	violated? $\tau \sim 10^{18}$ yr e+ excess?!	'freeze-out' from thermal equilibrium Asymmetric (like the *observed* baryons)	$\Omega_{LSP} \sim 0.3$ $\Omega_{TB} \sim 0.3$
$\Lambda_{\text{hidden sector}} \sim (\Lambda_F M_P)^{1/2}$ $\Lambda_{\text{see-saw}} \sim \Lambda_{Fermi}^2/\Lambda_{B-L}$	Crypton? (hidden valley, sequestered) **Neutrinos**	Discrete (*very* model-dependent) Lepton number	$\tau > 10^{18}$ yr Stable	Varying gravitational field during inflation Thermal (like CMB)	$\Omega_X \sim 0.3$? $\Omega_\nu > 0.003$
M_{string} M_{Planck}	Kaluza-Klein states? Axions	? Peccei-Quinn	? stable	? Field oscillations	? Ω_a » 1!

No definite indication from theory … must decide by experiment!

Summary

Non-accelerator particle physics is *exciting* science … probing *fundamental* conservation laws (*B*, *L*) and the nature of the dark matter in the universe

The theory is necessarily speculative, being beyond the Standard Model, but there are reasonable expectations for discoveries with the ambitious experiments being planned

The UK has expertise in key areas – both in experiment (*CRESST*, *DRIFT*, *NaIAD*, *ZEPLIN*) and in underground infrastructure (Boulby), and is set to play a *lead role* in the next-generation dark matter experiments (e.g. *EURECA*)

Possible involvement in megaton detectors for proton decay and SN neutrinos (also LBL expts?) needs to be discussed