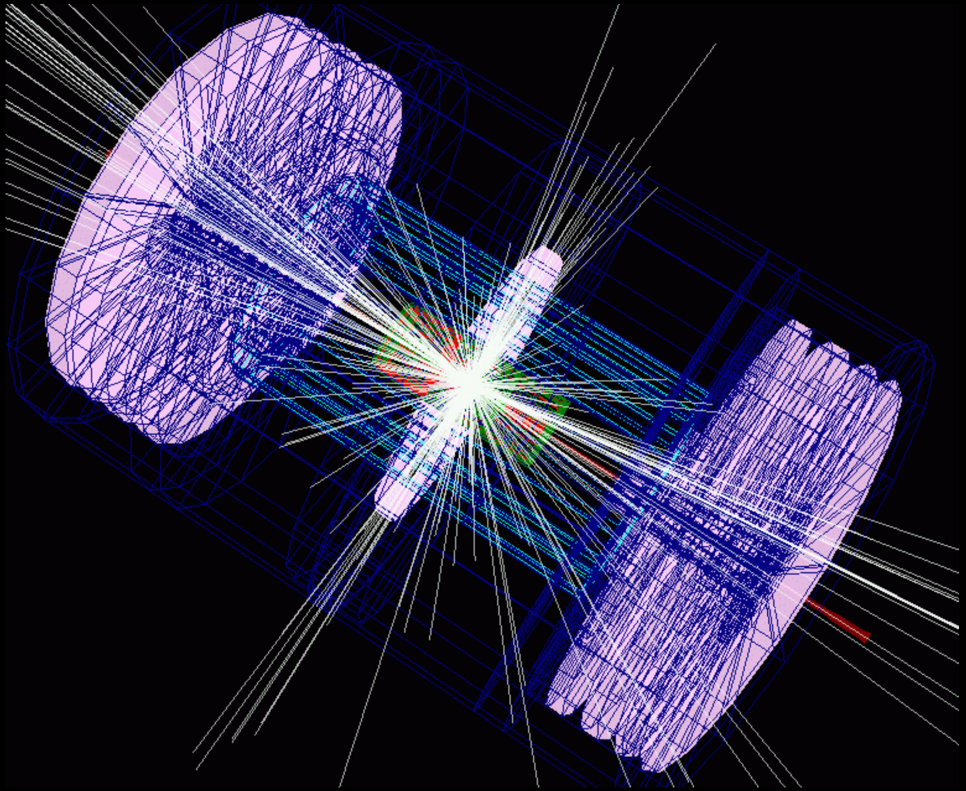
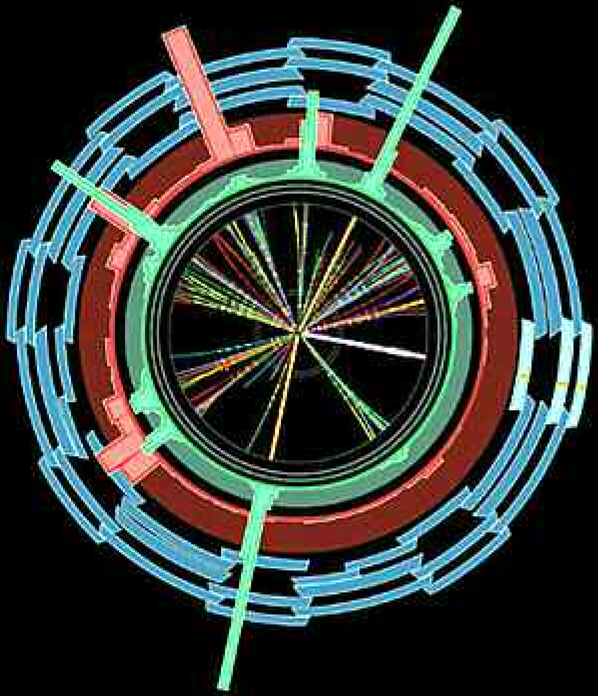
STABLE MASSIVE PARTICLES AT COLLIDERS





MALCOLM
FAIRBAIRN

Why study stable(ish) massive particles?

Nice potential collider discoveries -

✓
- Dark matter is stable
- WIMPs could be produced at LHC (if they exist)

Nasty potential collider discoveries -

✗
- Charged stable objects (not oberved today)
- long lived particles (late decay - cosmology problems)

Most exciting possibility is nasty discoveries !!!

Plan of talk

Supersymmetry :-

1. Gravity mediated SUSY breaking
2. Gauge mediated SUSY breaking
3. Split SUSY / R-hadrons

Universal Extra dimensions

Little Higgs

TeV Quantum Gravity

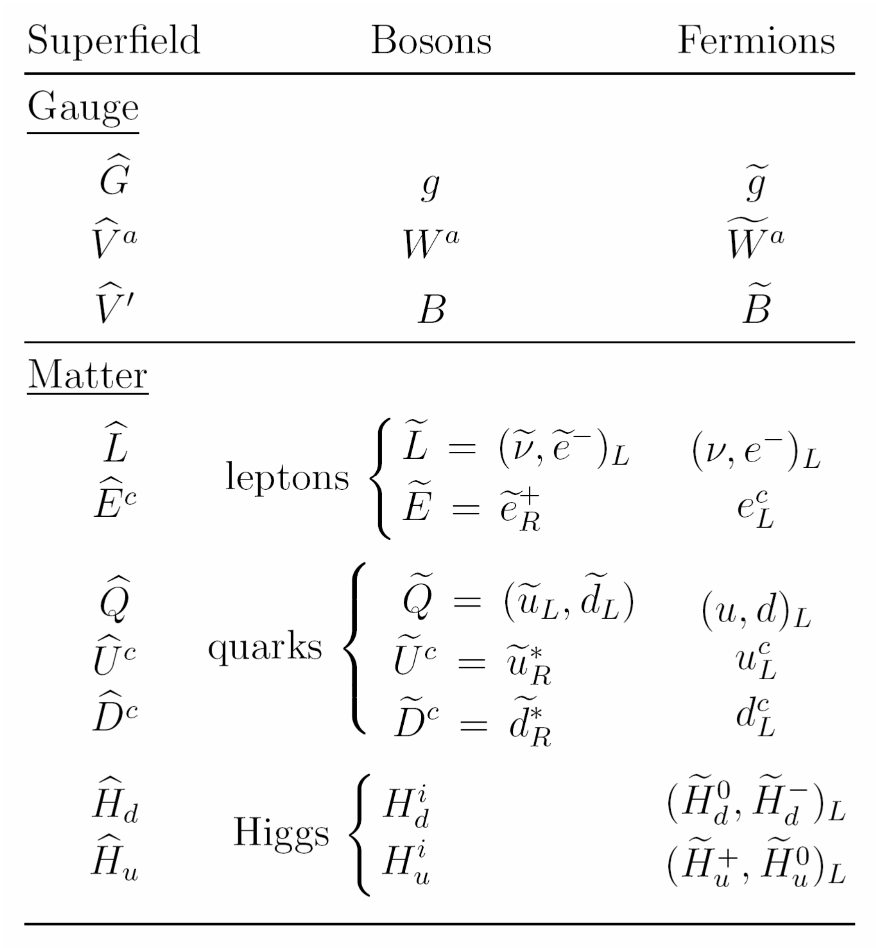
Fairbairn, Kraan, Milstead, Sjostrand, Skands and Sloan,
Phys.Rep.438,1,2007

Supersymmetry (SUSY)

The addition of superpartners to the theory

- protects Higgs mass
- aids gauge coupling unification
- provides WIMP dark matter candidate (neutralino)

Constrained Minimal supersymmetric standard model



Superfield		Bosons	Fermions
Gauge			
$\widehat{G}$		g	$\widetilde{g}$
$\widehat{V}^a$		W^a	$\widetilde{W}^a$
$\widehat{V}'$		B	$\widetilde{B}$
Matter			
$\widehat{L}$	leptons	$\widetilde{L} = (\widetilde{\nu}, \widetilde{e}^-)_L$	$(\nu, e^-)_L$
$\widehat{E}^c$		$\widetilde{E} = \widetilde{e}^+_R$	e^c_L
$\widehat{Q}$	quarks	$\widetilde{Q} = (\widetilde{u}_L, \widetilde{d}_L)$	$(u, d)_L$
$\widehat{U}^c$		$\widetilde{U}^c = \widetilde{u}^*_R$	u^c_L
$\widehat{D}^c$		$\widetilde{D}^c = \widetilde{d}^*_R$	d^c_L
$\widehat{H}_d$	Higgs	H^i_d	$(\widetilde{H}^0_d, \widetilde{H}^-_d)_L$
$\widehat{H}_u$		H^i_u	$(\widetilde{H}^+_u, \widetilde{H}^0_u)_L$

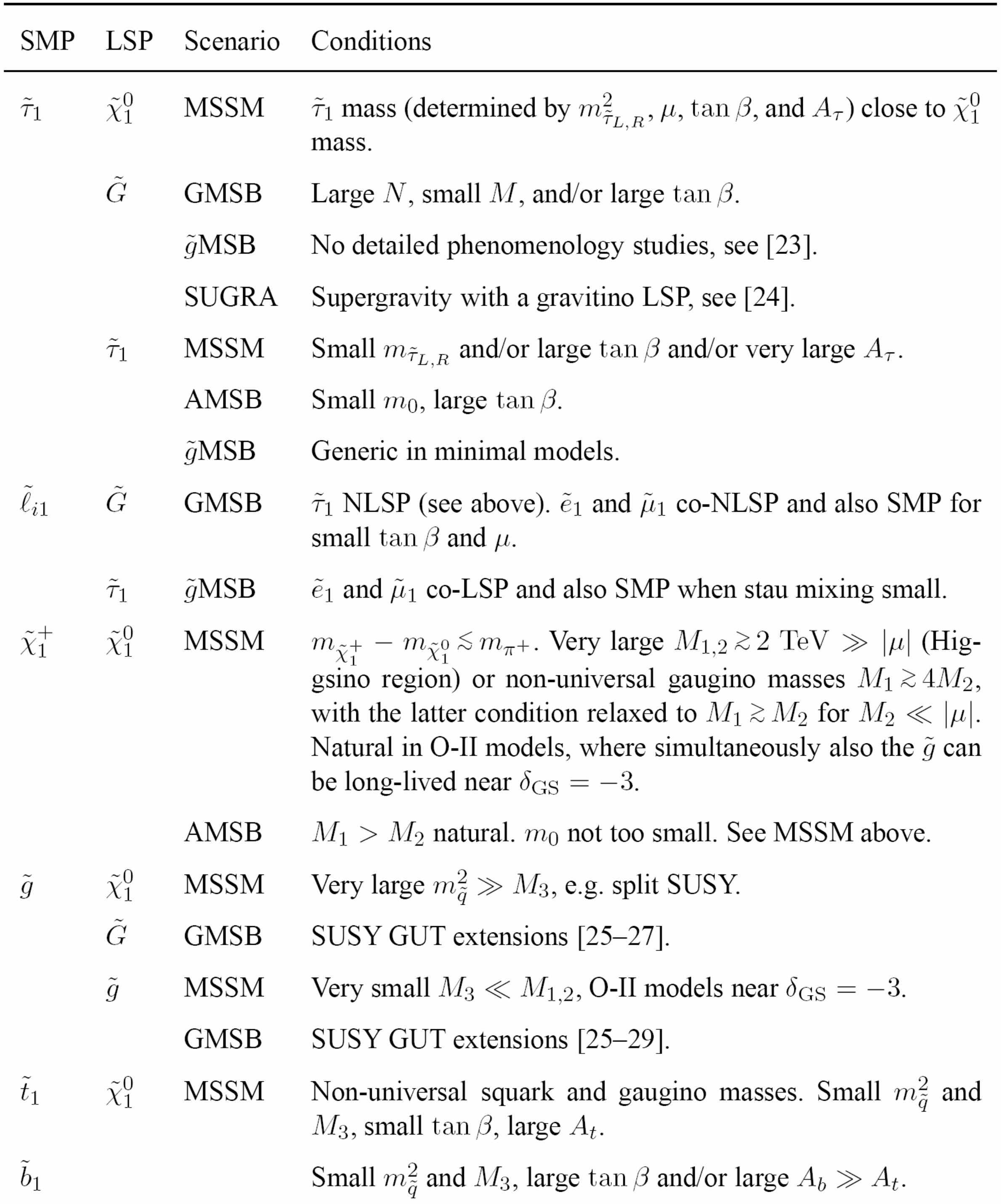
All sfermion masses equal at GUT scale

All gaugino masses equal at GUT scale

Reduced to 5 free parameters

$$\mu,\ m_0,\ m_{1/2},\ A \text{ and } B \leftrightarrow \tan\beta = \frac{v_2}{v_1}$$

Lightest superpartner LSP
and
next to lightest superpartner
NLSP
depends upon scenario

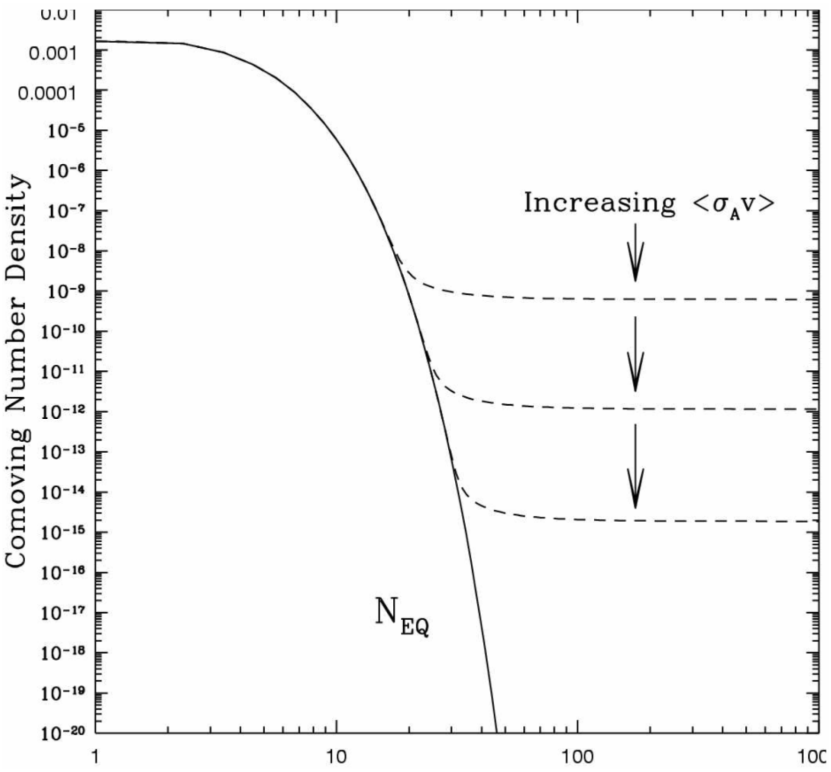


SMP	LSP	Scenario	Conditions
$\tilde{\tau}_1$	$\tilde{\chi}_1^0$	MSSM	$\tilde{\tau}_1$ mass (determined by $m^2_{\tilde{\tau}_{L,R}}$, μ, $\tan\beta$, and A_τ) close to $\tilde{\chi}_1^0$ mass.
	$\tilde{G}$	GMSB	Large N, small M, and/or large $\tan\beta$.
		$\tilde{g}$MSB	No detailed phenomenology studies, see [23].
		SUGRA	Supergravity with a gravitino LSP, see [24].
	$\tilde{\tau}_1$	MSSM	Small $m_{\tilde{\tau}_{L,R}}$ and/or large $\tan\beta$ and/or very large A_τ.
		AMSB	Small m_0, large $\tan\beta$.
		$\tilde{g}$MSB	Generic in minimal models.
$\tilde{\ell}_{i1}$	$\tilde{G}$	GMSB	$\tilde{\tau}_1$ NLSP (see above). $\tilde{e}_1$ and $\tilde{\mu}_1$ co-NLSP and also SMP for small $\tan\beta$ and μ.
	$\tilde{\tau}_1$	$\tilde{g}$MSB	$\tilde{e}_1$ and $\tilde{\mu}_1$ co-LSP and also SMP when stau mixing small.
$\tilde{\chi}_1^+$	$\tilde{\chi}_1^0$	MSSM	$m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0} \lesssim m_{\pi^+}$. Very large $M_{1,2} \gtrsim 2\ \text{TeV} \gg \lvert\mu\rvert$ (Higgsino region) or non-universal gaugino masses $M_1 \gtrsim 4M_2$, with the latter condition relaxed to $M_1 \gtrsim M_2$ for $M_2 \ll \lvert\mu\rvert$. Natural in O-II models, where simultaneously also the $\tilde{g}$ can be long-lived near $\delta_{\text{GS}} = -3$.
		AMSB	$M_1 > M_2$ natural. m_0 not too small. See MSSM above.
$\tilde{g}$	$\tilde{\chi}_1^0$	MSSM	Very large $m^2_{\tilde{q}} \gg M_3$, e.g. split SUSY.
	$\tilde{G}$	GMSB	SUSY GUT extensions [25–27].
	$\tilde{g}$	MSSM	Very small $M_3 \ll M_{1,2}$, O-II models near $\delta_{\text{GS}} = -3$.
		GMSB	SUSY GUT extensions [25–29].
$\tilde{t}_1$	$\tilde{\chi}_1^0$	MSSM	Non-universal squark and gaugino masses. Small $m^2_{\tilde{q}}$ and M_3, small $\tan\beta$, large A_t.
$\tilde{b}_1$			Small $m^2_{\tilde{q}}$ and M_3, large $\tan\beta$ and/or large $A_b \gg A_t$.

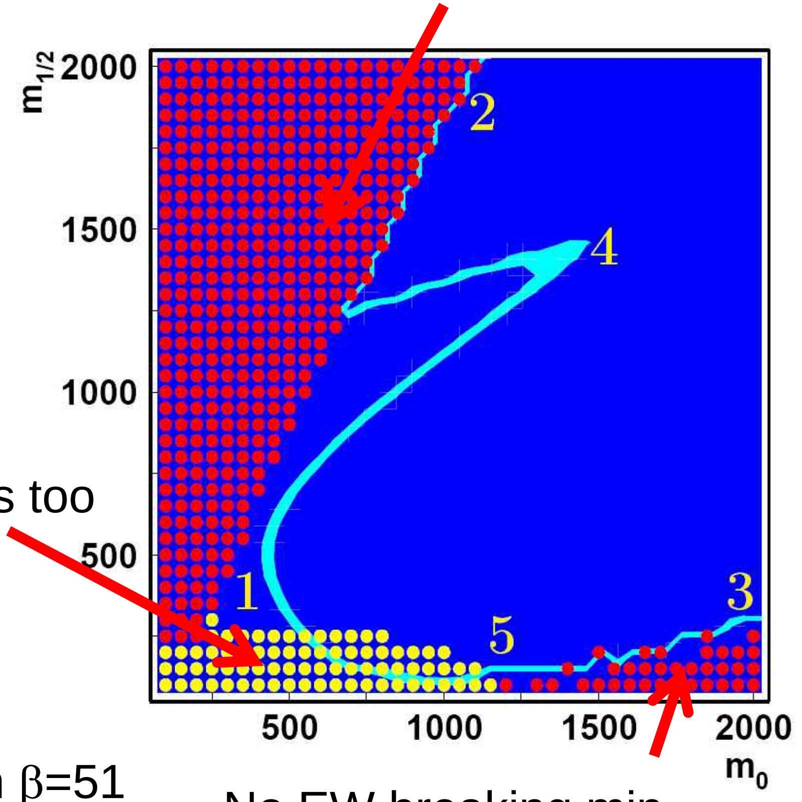
Neutralino Dark Matter

Superpartners of neutral gauge and higgs bosons mix into four majorana *neutralinos* which make good WIMP candidate

$$\chi = N_{11}\tilde{B} + N_{12}\tilde{W}_3 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0$$



Stau lighter than neutralino

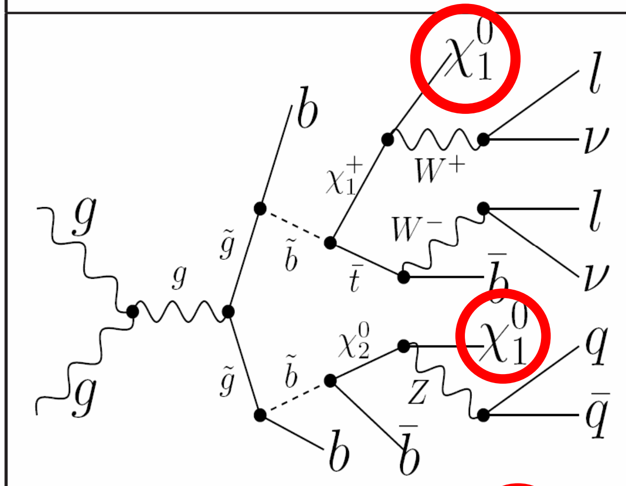
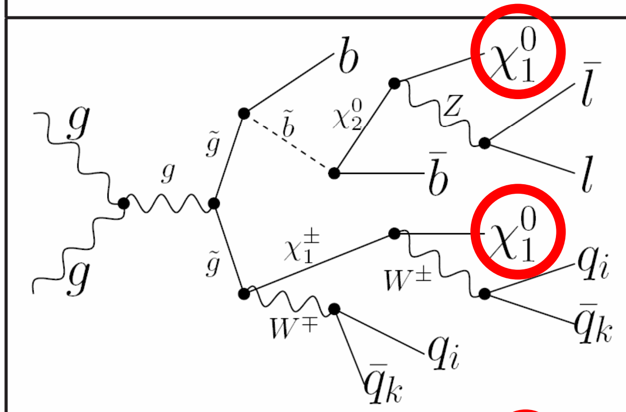
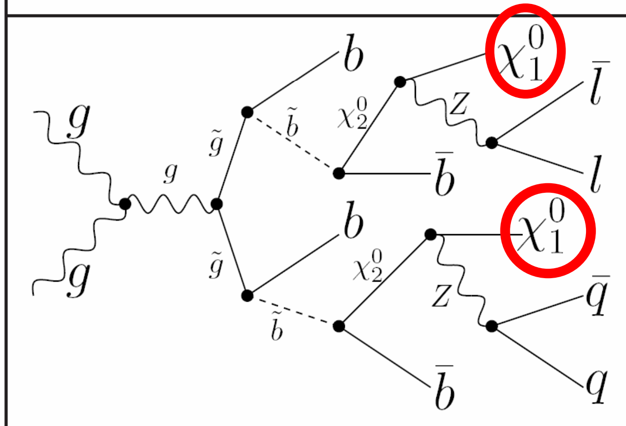


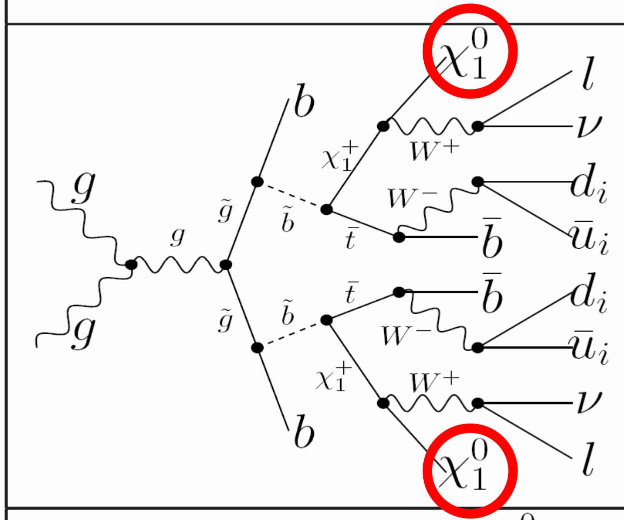
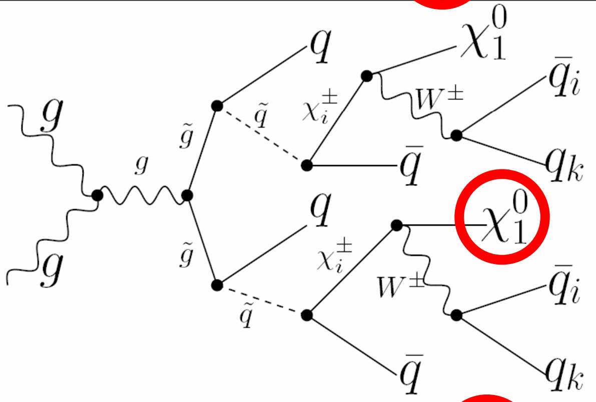
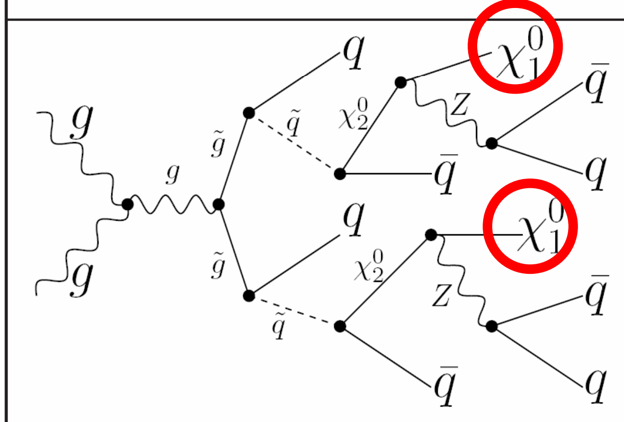
Higgs too light

tan β=51

No EW breaking min.

Some neutralino production channels at LHC

Process	final states
	2ℓ 2ν $6j$ $\not{E}_T$
	2ℓ $6j$ $\not{E}_T$
	2ℓ $6j$ $\not{E}_T$

Process	final states
	2ℓ 2ν $8j$ $\not{E}_T$
	$8j$ $\not{E}_T$
	$8j$ $\not{E}_T$

See e.g. Gladyshev & Kazakov 2006

Gravitinos

- Supersymmetric partner of graviton
- curved space - global SUSY is broken down to local SUGRA
- goldstino is particle associated with this breaking
- gravitino eats goldstino via Super Higgs mechanism
- gravitino mass therefore depends on SUSY breaking scale

Gravity mediated SUSY breaking

SUSY broken in hidden sector
transmitted to visible sector via gravity

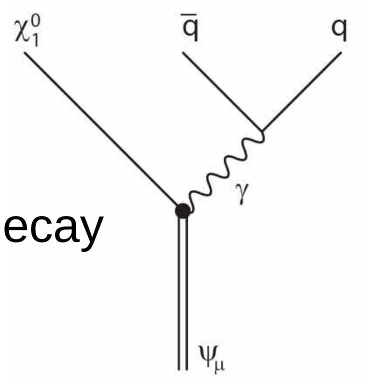
$$M_S \sim \sqrt{F} \sim 10^{11-13}\ \mathrm{GeV}$$

Masses of superpartners
in visible sector

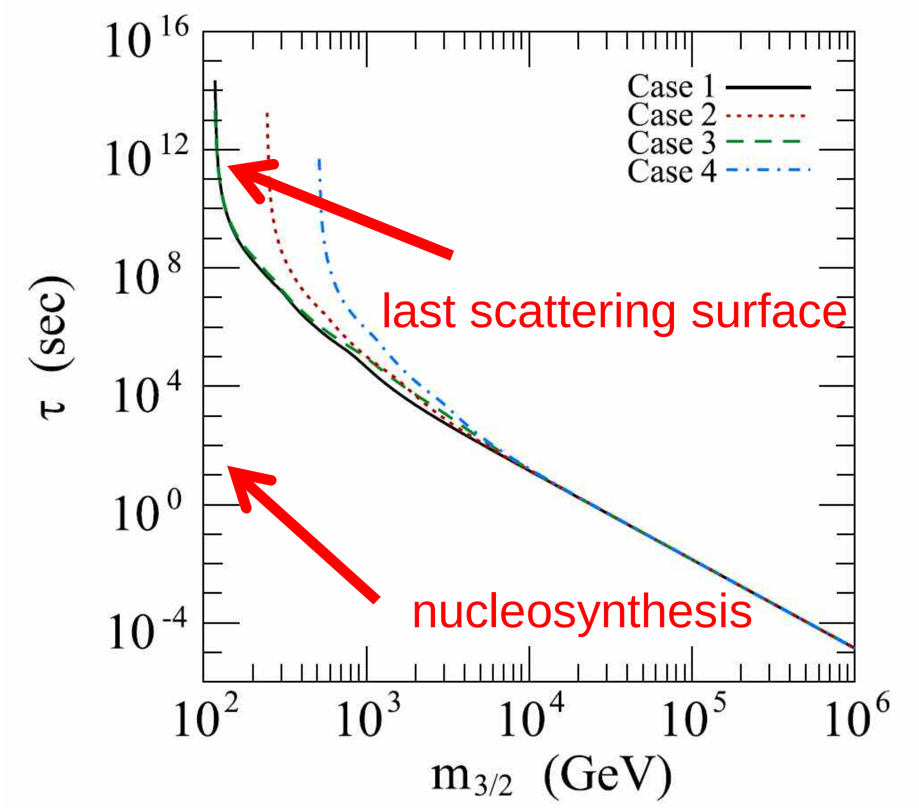
$$m \sim \frac{F}{M_{Pl}} \sim O(\mathrm{TeV})$$

Gravitino mass $m_{\widetilde{G}} \sim \dfrac{M_S^2}{M_{Pl}}$

Decaying Gravitinos

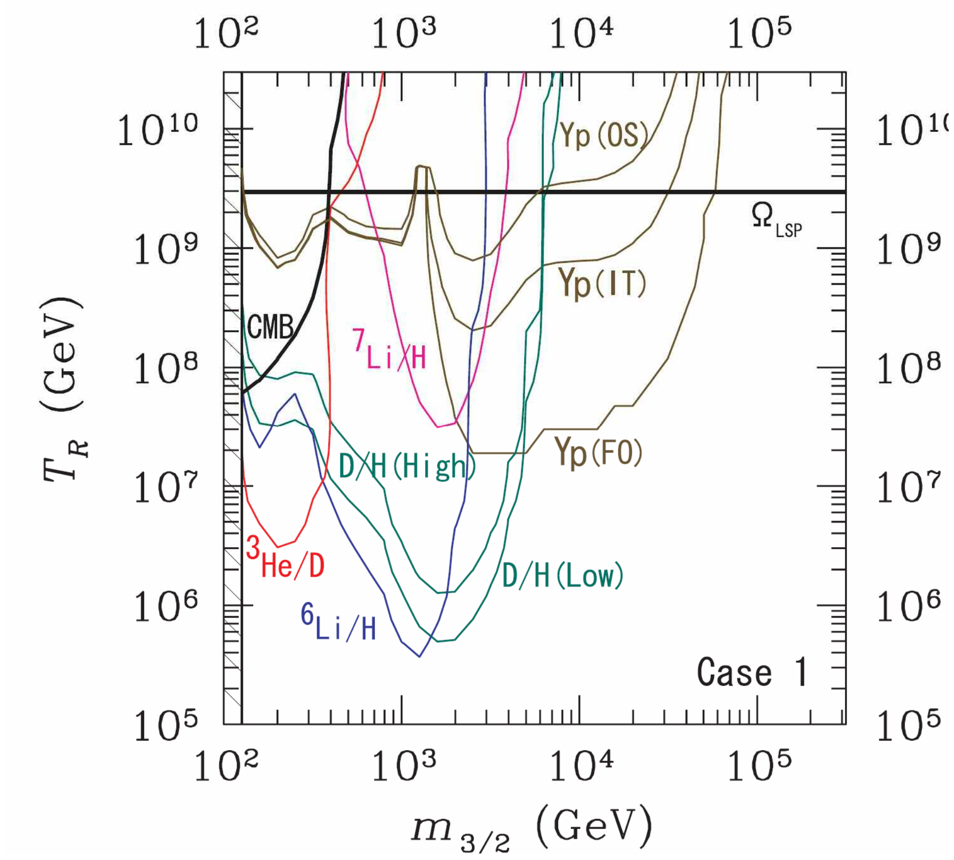


gravity mediation:- gravitino mass 100 GeV – 100 TeV, and they decay



last scattering surface

nucleosynthesis

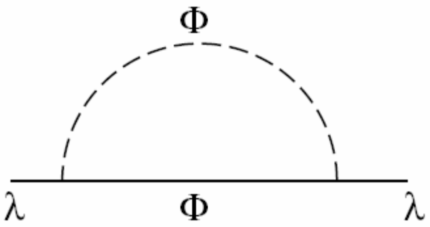


Leads to constraint on reheat temperature, e.g. Kohri et al. 2005

Gauge mediated SUSY breaking

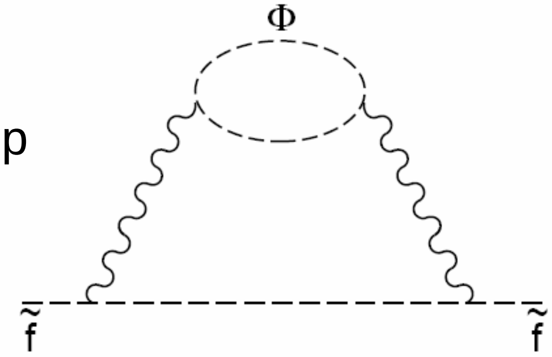
Hidden sector superfield $\langle X \rangle = M_S + \theta^2 F$ coupled at tree level to messenger fields $W = \lambda_{ij} \bar{\Phi}_i X \Phi_j$ which in turn give rise to :-

gaugino mass at 1-loop



$$m_{\tilde{\lambda}} \sim \frac{g^2}{(4\pi)^2} \frac{F}{M_S}$$

sfermion mass at 2-loop



$$m^2_{\tilde{f}} \sim \frac{g^4}{(4\pi)^4} \frac{F^2}{M_S^2}$$

$F \sim 10^{10-14} \mathrm{GeV}^2$ $\quad M_S \sim 10^{5-9} \mathrm{GeV}$ $\longrightarrow$ $m_{\tilde{G}} \ll \mathrm{TeV}$

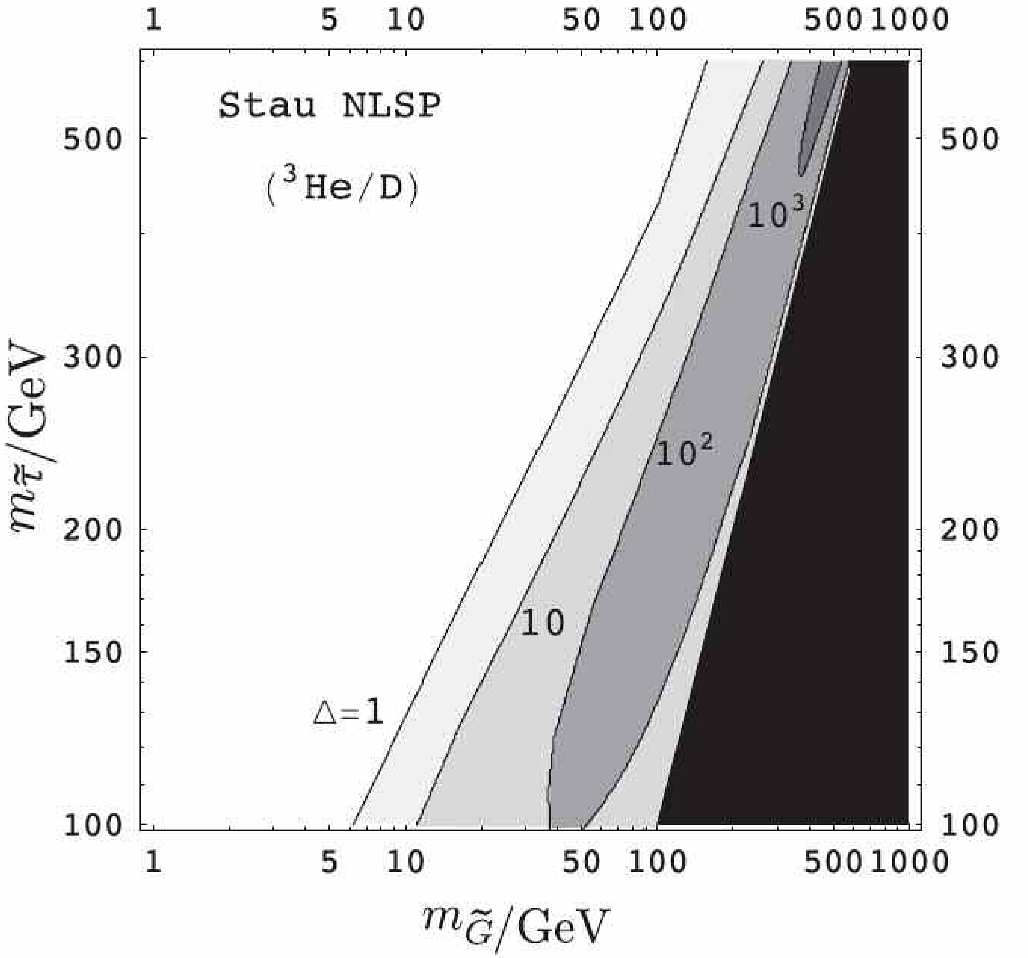
Gravitino LSP and stau NLSP is one typical scenario

Stau decay

$$\Gamma_{\widetilde{\tau}}(\widetilde{\tau} \to \widetilde{G}\tau) = \frac{m_{\widetilde{\tau}}^5}{48\pi m_{\widetilde{G}}^2 M_{\mathrm{P}}^2}\left(1 - \frac{m_{\widetilde{G}}^2 + m_\tau^2}{m_{\widetilde{\tau}}^2}\right)^4 \left[1 - \frac{4m_{\widetilde{G}}^2 m_\tau^2}{(m_{\widetilde{\tau}}^2 - m_{\widetilde{G}}^2 - m_\tau^2)^2}\right]^{3/2}$$

Buchmuller et al 2006

$$\simeq (6 \times 10^6\ \mathrm{sec})^{-1}\left(\frac{m_{\widetilde{\tau}}}{100\ \mathrm{GeV}}\right)^5 \left(\frac{10\ \mathrm{GeV}}{m_{\widetilde{G}}}\right)^2 \left(1 - \frac{m_{\widetilde{G}}^2}{m_{\widetilde{\tau}}^2}\right)^4$$



Stau decays into gravitino and tau

Photodissociates light elements created during nucleosynthesis

Need to dilute thermal abundance of staus

$$Y_{\widetilde{\tau}} = \frac{1}{\Delta} Y_{\widetilde{\tau}}^{\mathrm{thermal}}$$

Decays outside detector

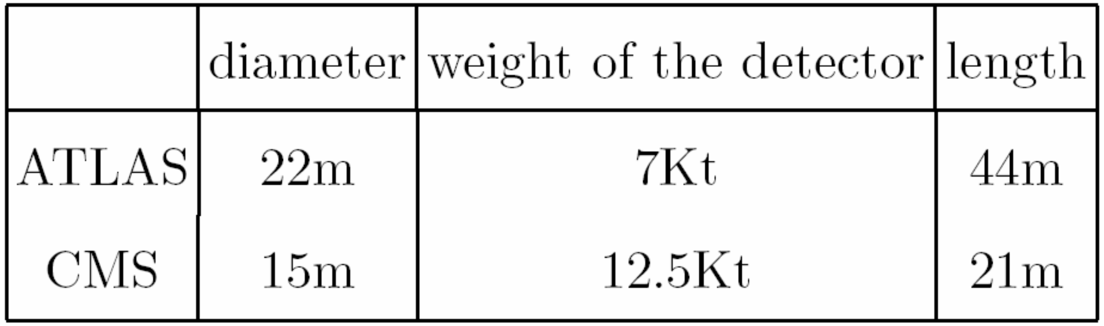
Distance travelled before decay of NLSP into gravitino

$$c\tau(\widetilde{X}\to X\widetilde{G}) \simeq 100\ \mu\text{m}\left(\frac{100\text{GeV}}{m_{\widetilde{X}}}\right)^{5}\left(\frac{\sqrt{F}}{100\text{TeV}}\right)^{4}\left(1-\frac{m_{X}^{2}}{m_{\widetilde{X}^{2}}}\right)^{-4}$$

decays here !

Gauge mediation:-

less than mm to more than km

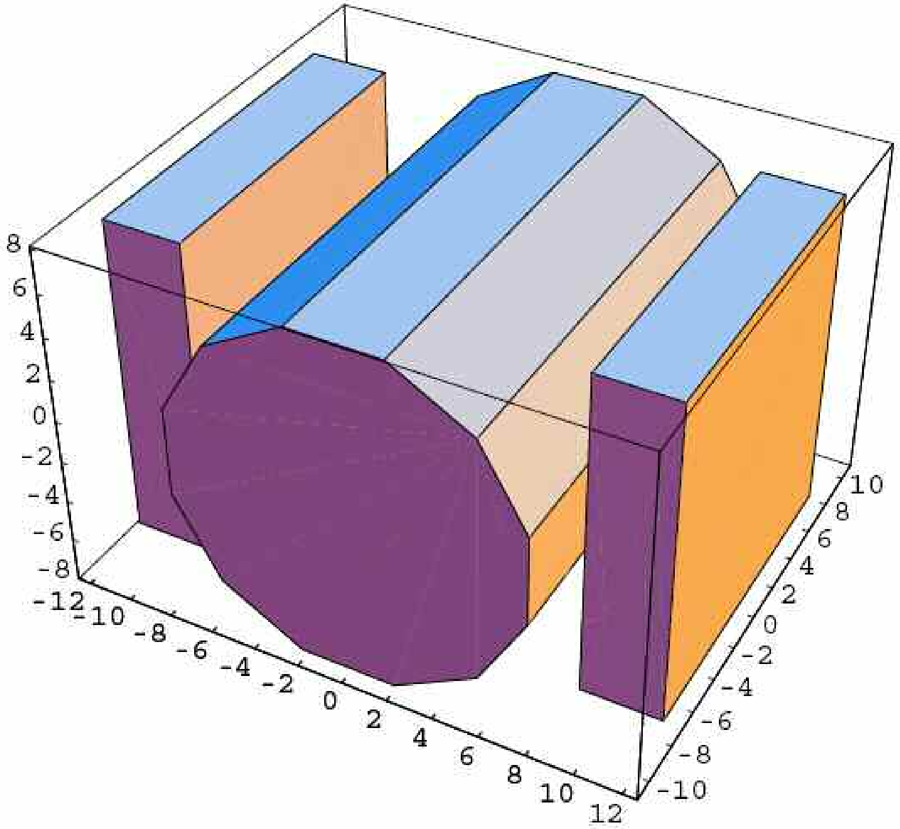


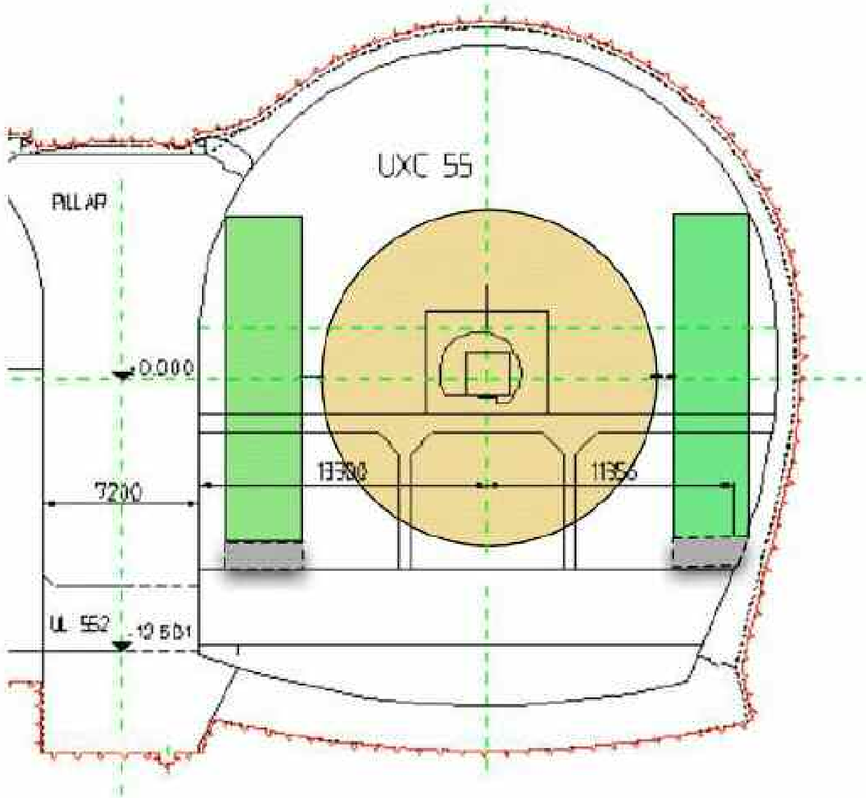
	diameter	weight of the detector	length
ATLAS	22m	7Kt	44m
CMS	15m	12.5Kt	21m

Need to slow down NLSP or may miss decay

Decays outside detector

ATLAS and CMS not really designed for this!!
Could install dense stoppers in CMS to stop charged NLSP
(no room in ATLAS cavern)





Useful for any charged particle with lifetime
10 nsec < τ < 10 years

Hamaguchi, Nojiri and de Roeck, 2006

Measuring the Planck mass

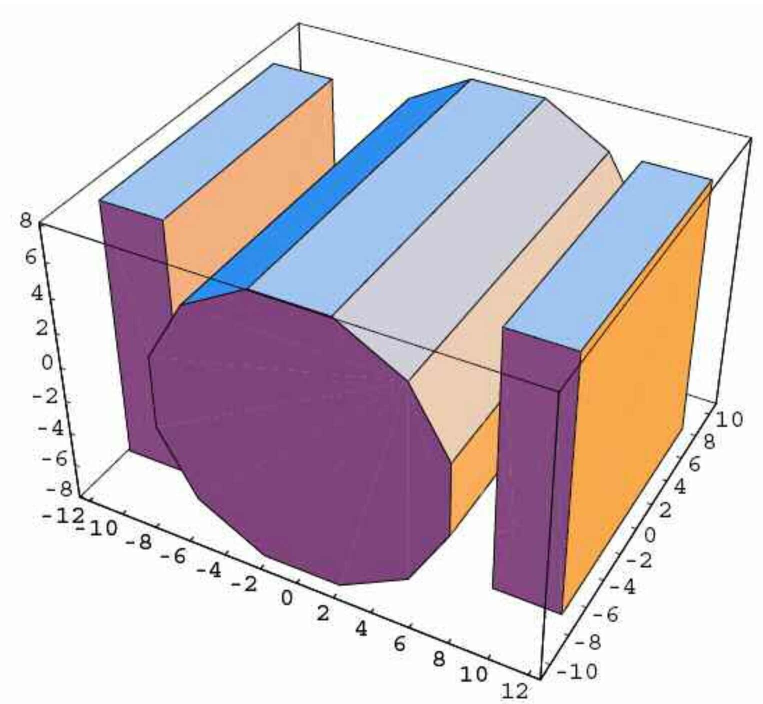
$$M_{\rm pl}^2(\text{supergravity}) \;=\; \frac{m_{\tilde\tau}^5}{48\pi m_{\tilde G}^2 \Gamma_{\tilde\tau}} \left(1-\frac{m_{\tilde G}^2+m_\tau^2}{m_{\tilde\tau}^2}\right)^4 \left[1-\frac{4m_{\tilde G}^2 m_\tau^2}{(m_{\tilde\tau}^2-m_{\tilde G}^2-m_\tau^2)^2}\right]^{3/2}$$

- kinematics lead to gravitino mass and stau mass, can therefore measure Planck mass

8 kton detector

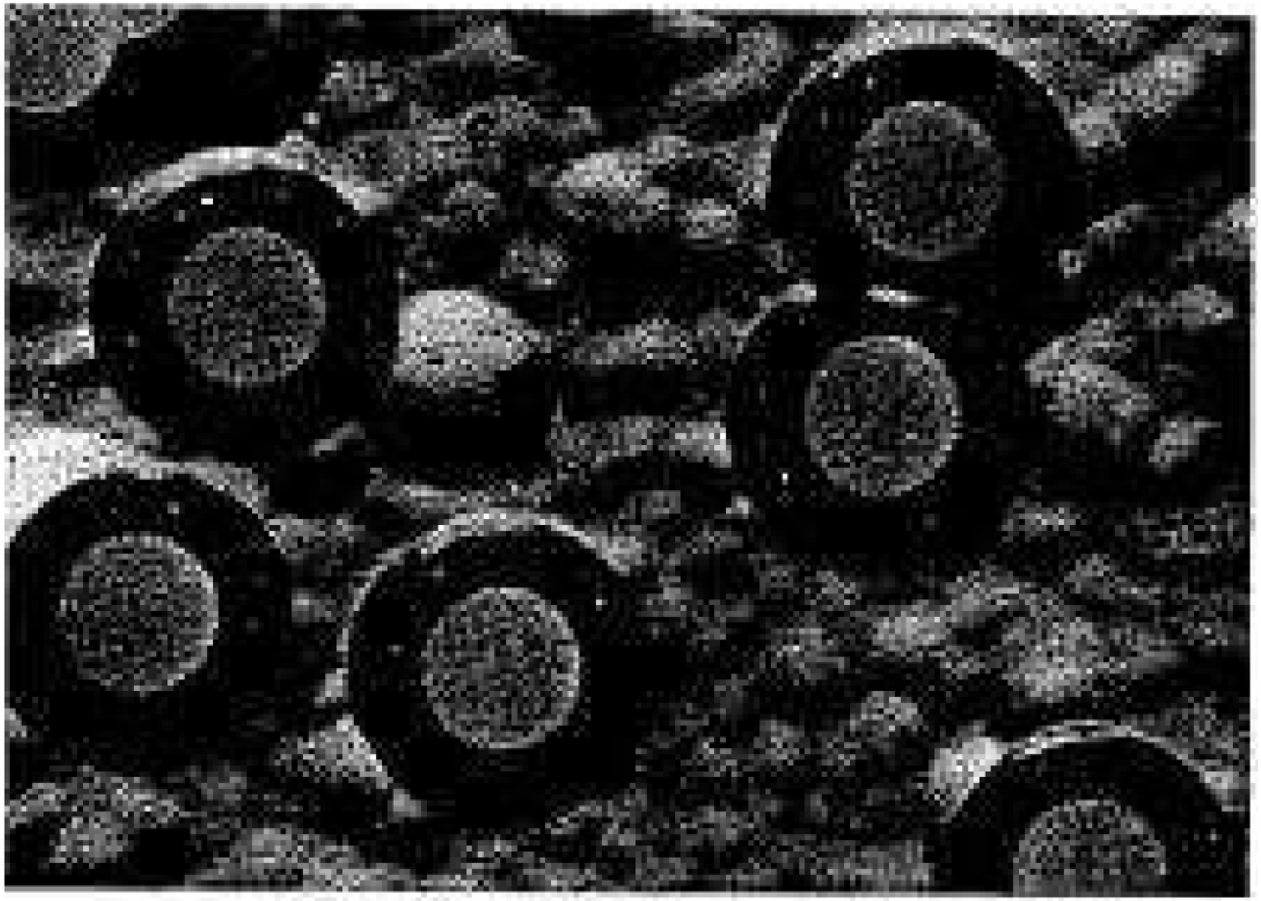
Hadronic calorimeter –
alternating layers of metal and detectors

Looks for hadronic decays of the tau,
measures energy in this way



Plastic Foils

Can put plastic foils (thin films) around collision area.
Subsequent etching with alkali reveals path of energetic charged particles



Microphotograph of heavily etched sheet which has been bombarded with 200 GeV sulphur ions
Alkali reduced sheet thickness from 1.4 mm to 0.2 mm

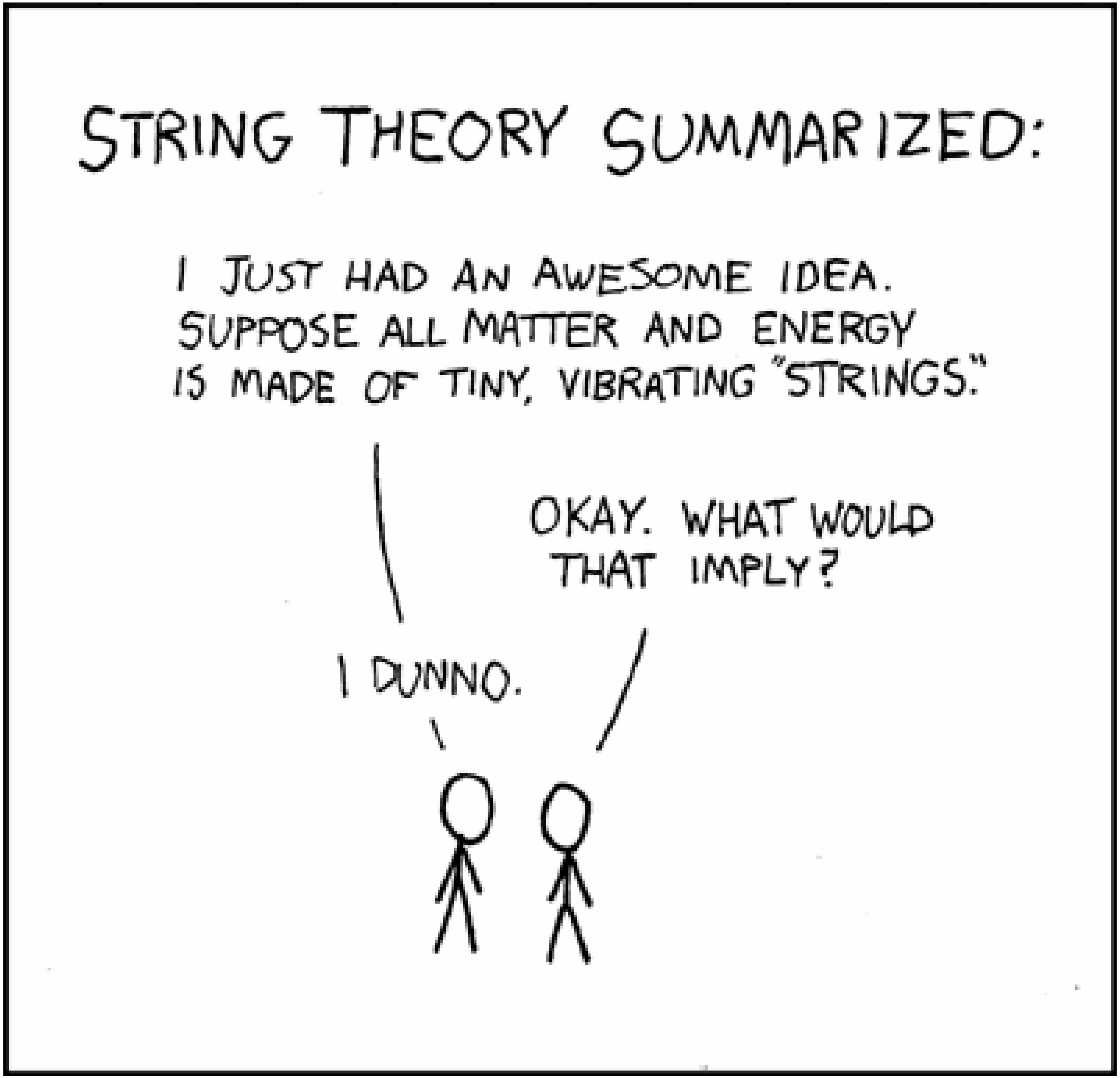
Split SUSY

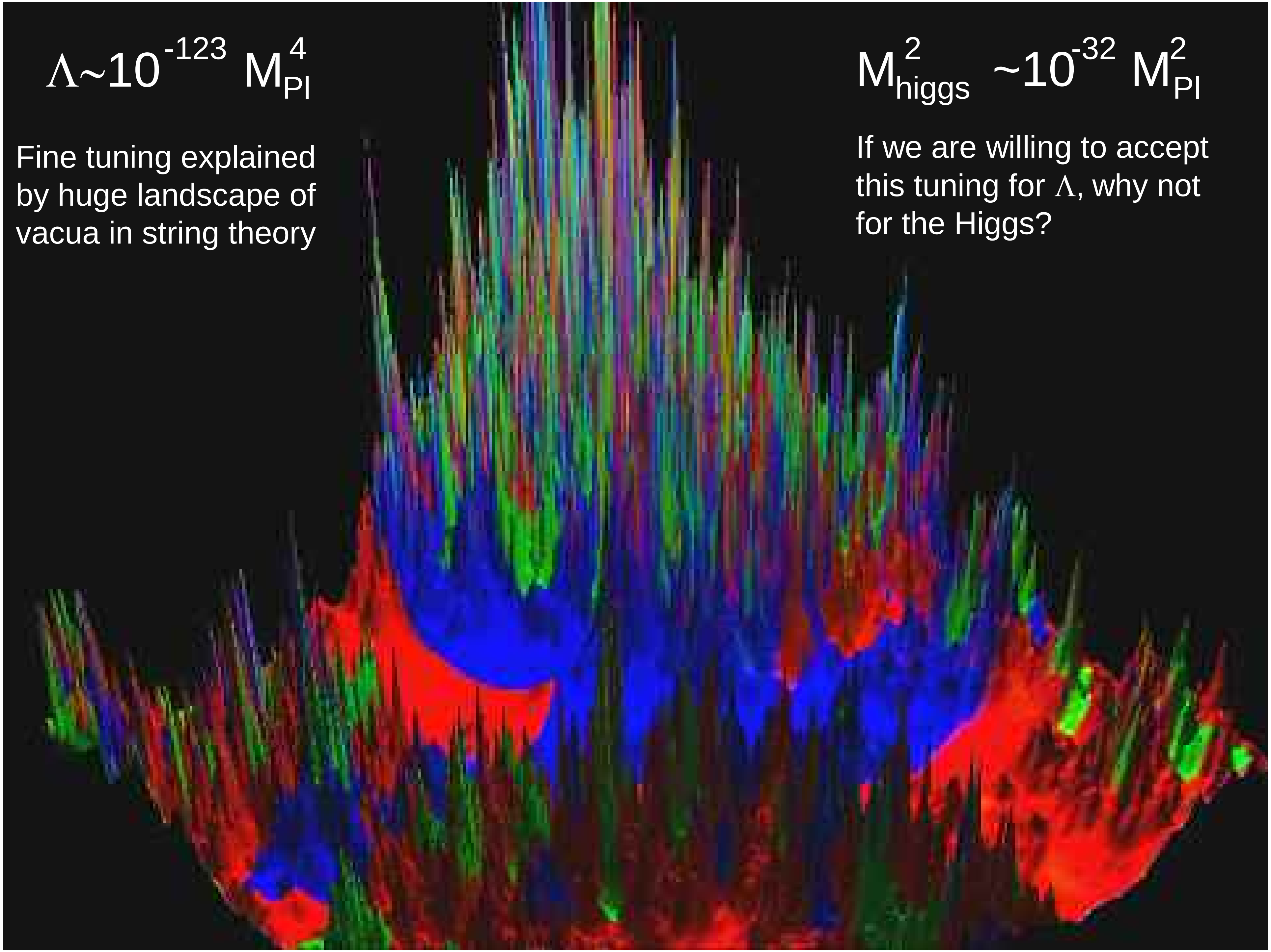
Arkani-Hamed & Dimopoulos 2004

Three successes of SUSY:-

1. Protection of Higgs mass
2. Gauge coupling unification
3. WIMP dark matter candidate

Only 1. requires sfermions at TeV


STRING THEORY SUMMARIZED:
I JUST HAD AN AWESOME IDEA. SUPPOSE ALL MATTER AND ENERGY IS MADE OF TINY, VIBRATING "STRINGS."
OKAY. WHAT WOULD THAT IMPLY?
I DUNNO.



$\Lambda \sim 10^{-123}\ M_{Pl}^4$

Fine tuning explained by huge landscape of vacua in string theory

$M_{higgs}^2 \sim 10^{-32}\ M_{Pl}^2$

If we are willing to accept this tuning for Λ, why not for the Higgs?

Split SUSY

Arkani-Hamed & Dimopoulos 2004

Three successes of SUSY:-
1. Protection of Higgs mass
2. Gauge coupling unification
3. WIMP dark matter candidate

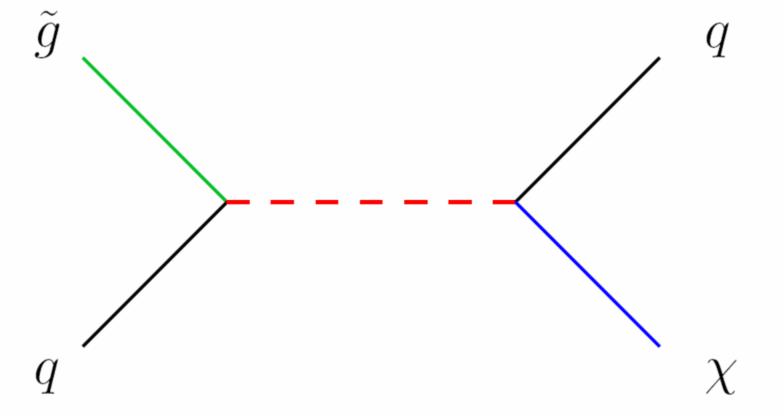
Only 1. requires sfermions at TeV

Light scalar superpartners also give rise to other problems :-

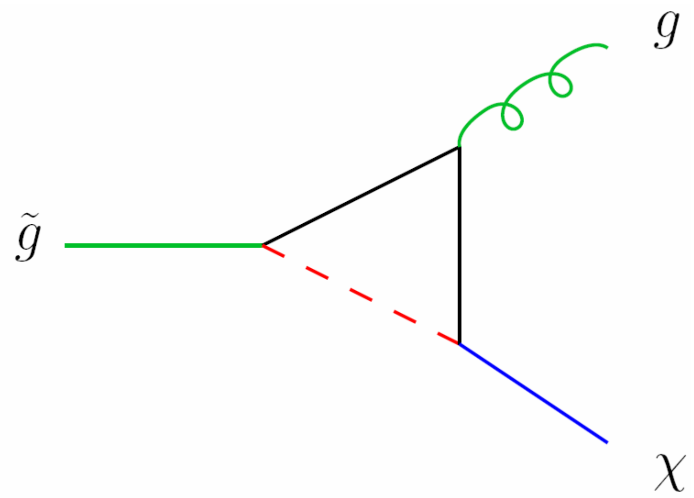
- fast proton decay
- flavour and CP violation
- relatively light Higgs

Set SUSY breaking large, fine tune higgs
higgsino and chargino mass protected by symmetry

Gluino decay in Split Susy



$$\tilde{g} \to \chi^0 q\bar{q},\ \tilde{g} \to \chi^{\pm} q\bar{q}'$$

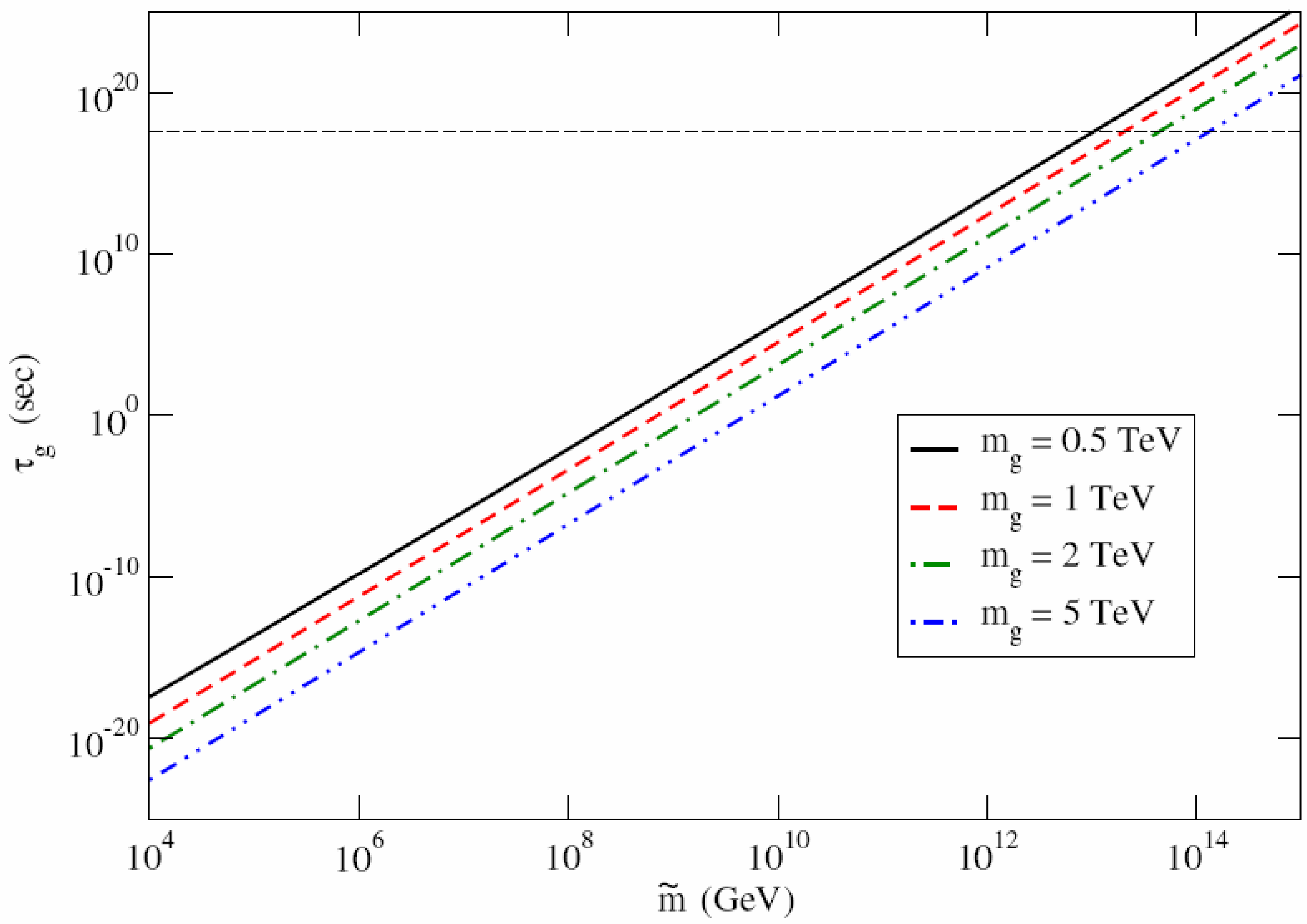


$$\tilde{g} \to \chi^0 g$$

All decay diagrams contain the heavy squarks and are therefore supressed

$$\Gamma_{\tilde{g}} \sim \frac{m_{\tilde{g}}^5}{M_S^4}$$

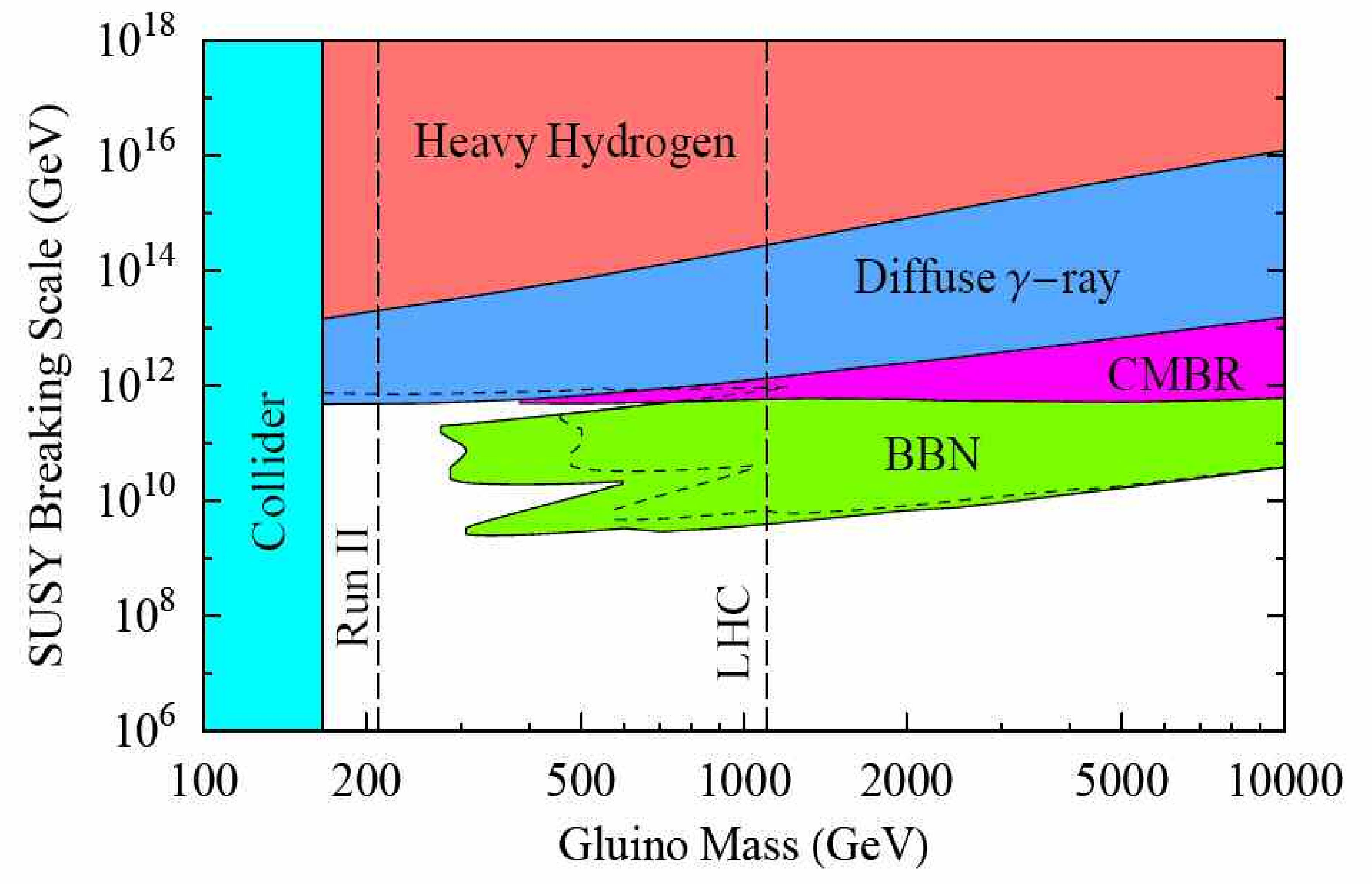
Gluino lifetime in Split SUSY



$$\Gamma_{\tilde{g}} \sim \frac{m_{\tilde{g}}^5}{M_S^4}$$

Gambino, Giudice & Slavich 2005

Cosmological constraints on Split Susy

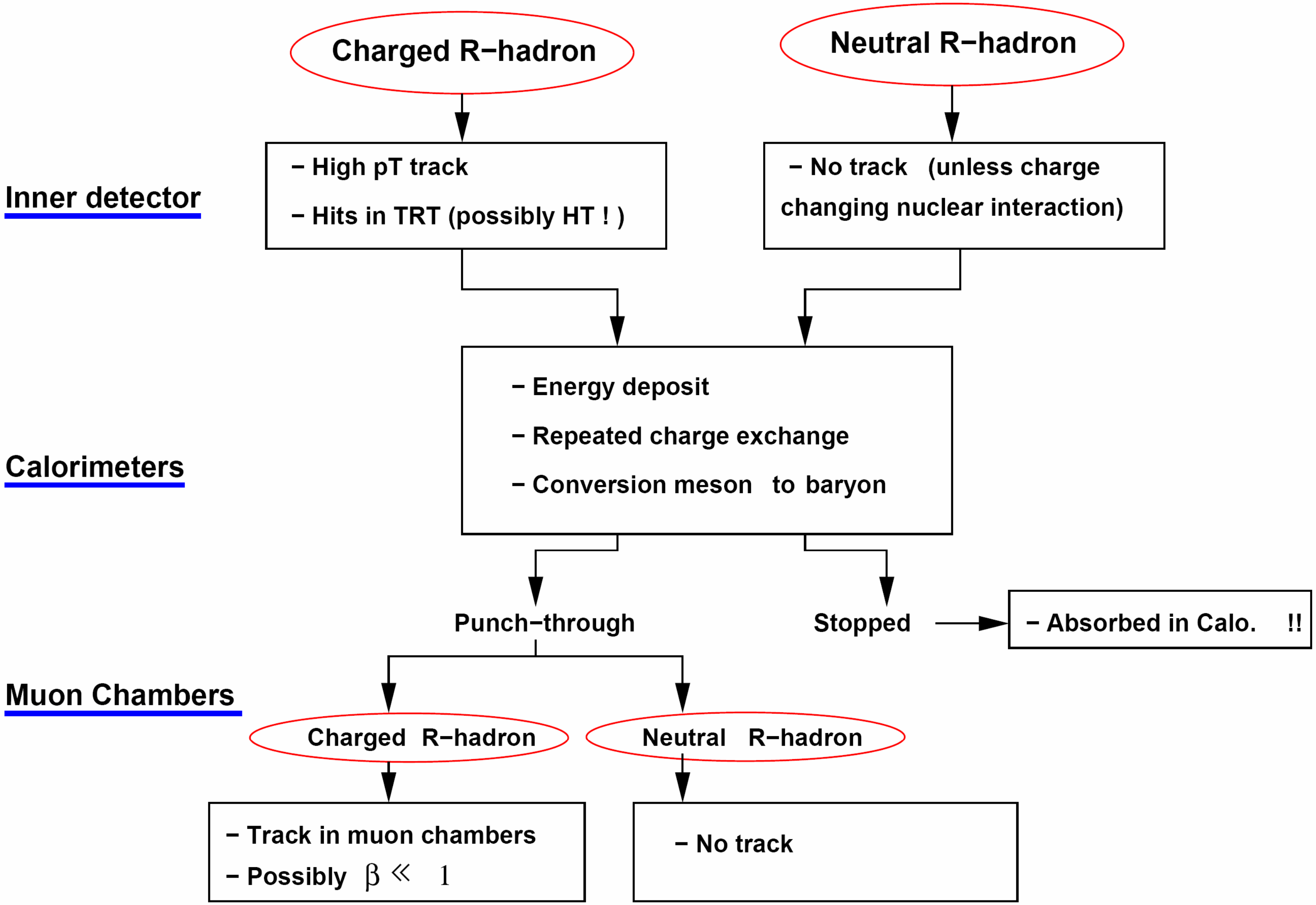


Shaded regions are ruled out

Arvanitaki et al. 2005

R-hadron detection at ATLAS

$R_g = \tilde{g}\ g,\qquad R\text{–mesons} = \tilde{g}\ q\,\bar{q},\qquad R\text{–baryons} = \tilde{g}\ q\,q\,q$



Charged R–hadron

Neutral R–hadron

Inner detector

- High pT track
- Hits in TRT (possibly HT !)

- No track (unless charge changing nuclear interaction)

Calorimeters

- Energy deposit
- Repeated charge exchange
- Conversion meson to baryon

Punch–through

Stopped

- Absorbed in Calo. !!

Muon Chambers

Charged R–hadron

Neutral R–hadron

- Track in muon chambers
- Possibly $\beta \ll 1$

- No track

Kraan et al hep-ex/0511014

Decay of R-hadrons (gluinos)

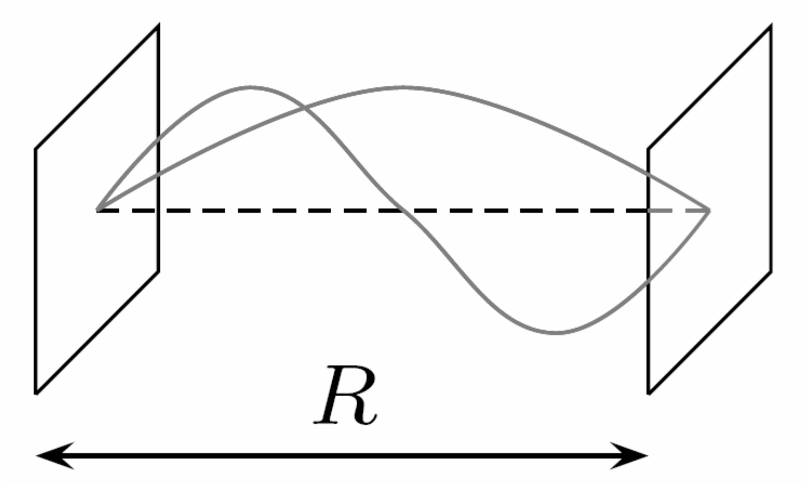
Short Lifetime - decay vertices displaced from collision centre
- event times seperated from bunch crossings

Medium Lifetime - make a note of where your two R-hadrons stopped in the calorimeter. Difference in time between decays measures lifetime.

Long Lifetime - can look for (very) heavy nuclei in calorimeter metal upon the dismantling of the LHC.

Universal extra dimensions

Appelquist et al. 2001



Extra dimensions of size
R ~ 1 / TeV into which
SM gauge fields propagate

Simplest scenario is 1 extra dimension orbifolded S^1/Z_2

Orbifolding leads to spectrum of Kaluza Klein (KK) modes such that the lightest KK mode is stable.

Potential dark matter candidate (Servant and Tait 2002)

Simplest models fully determined by $R^{-1},\ m_h,\ \Lambda$

Mass spectrum of KK particles

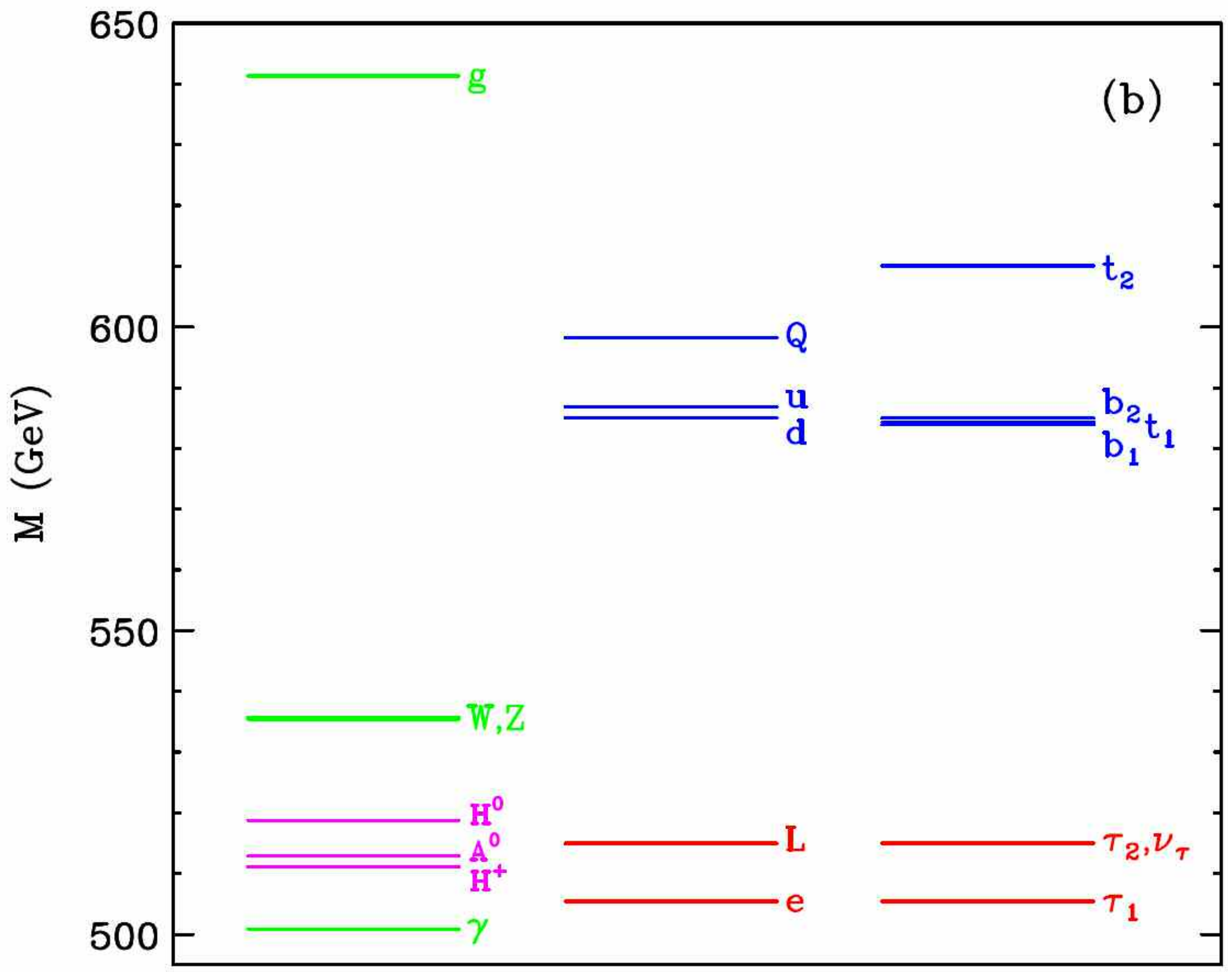
KK mass ~ 1/R + normal mass from higgs sector + radiative corrections, e.g. for higgs:-

$$\delta m_H^2 = \left(\frac{3}{2}g^2 + \frac{3}{4}g'^2 - \frac{m_h^2}{v^2}\right)\frac{\ln(\Lambda^2 R^2)}{16\pi^2}\,R^{-2}$$

$$R^{-1} = 500\ \text{GeV},$$

$$\Lambda R = 20,$$

$$m_h = 120\ \text{GeV}$$

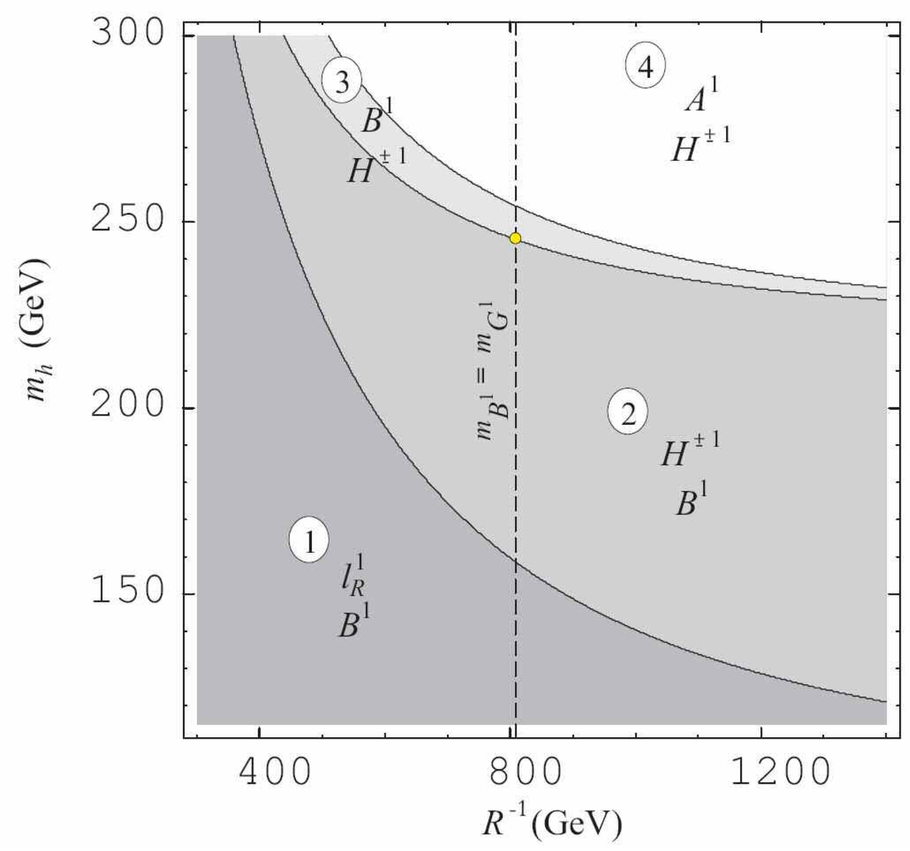


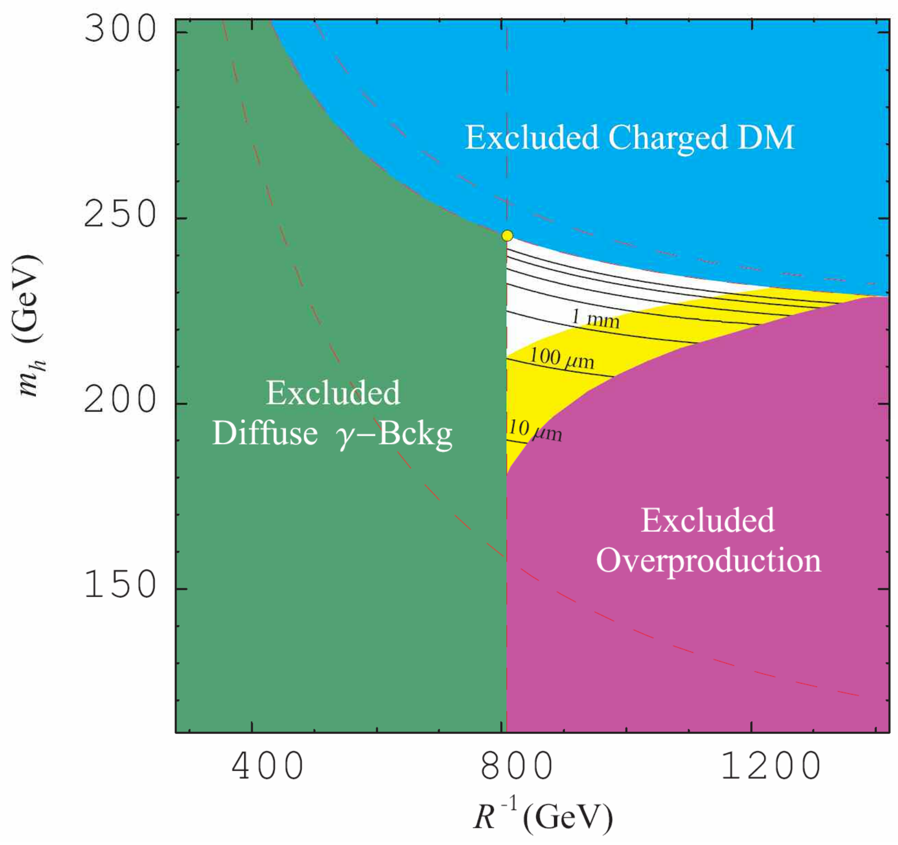
Cheng et al. 2006

Decay of next to lightest KK mode can be interesting

MINIMAL universal extra dimensions

Decay of KK mode to graviton supressed, occurs late, creates diffuse background





Small area of parameter space remains for UED – (assuming no late inflation)

Cembranos et al. 2006

Little Higgs and T-parity

Composite Higgs attractive –
dimensional tranmutation explains hierarchy between GUT and EW scales

However LEP tells us no strongly coupled physics below 10 TeV

Higgs mass less than 245 GeV favoured by experiment – Little Hierarchy

Solution - assume Higgs is goldstone boson of broken symmetry group at 10 TeV

In order to get successful EW symmetry breaking we then require extra gauge particles around TeV which mess up electroweak precision variable unless they have a parity. **T-parity**

Little Higgs and T-parity

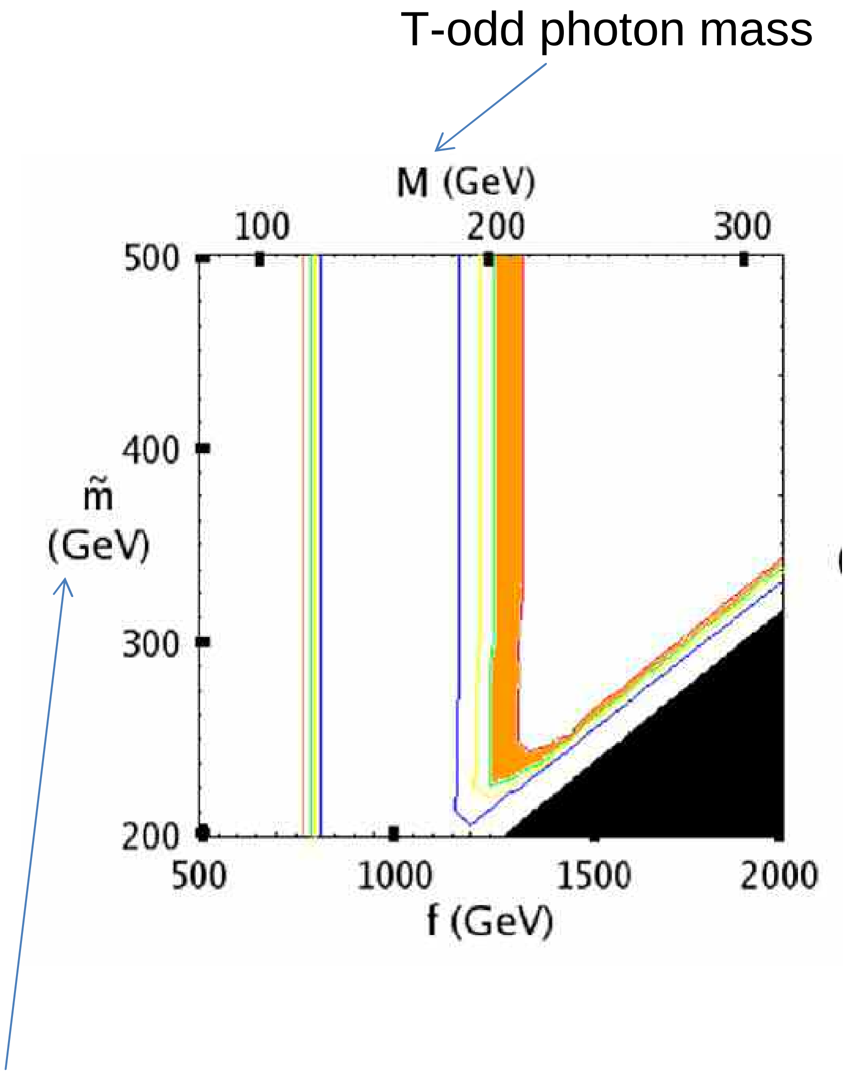
Standard model particles T-even
extra particles around TeV T-odd

Lightest T-odd particle typically photon

Good dark matter candidate –

orange band is favoured by WMAP

Related collider phenomenonolgy to UED

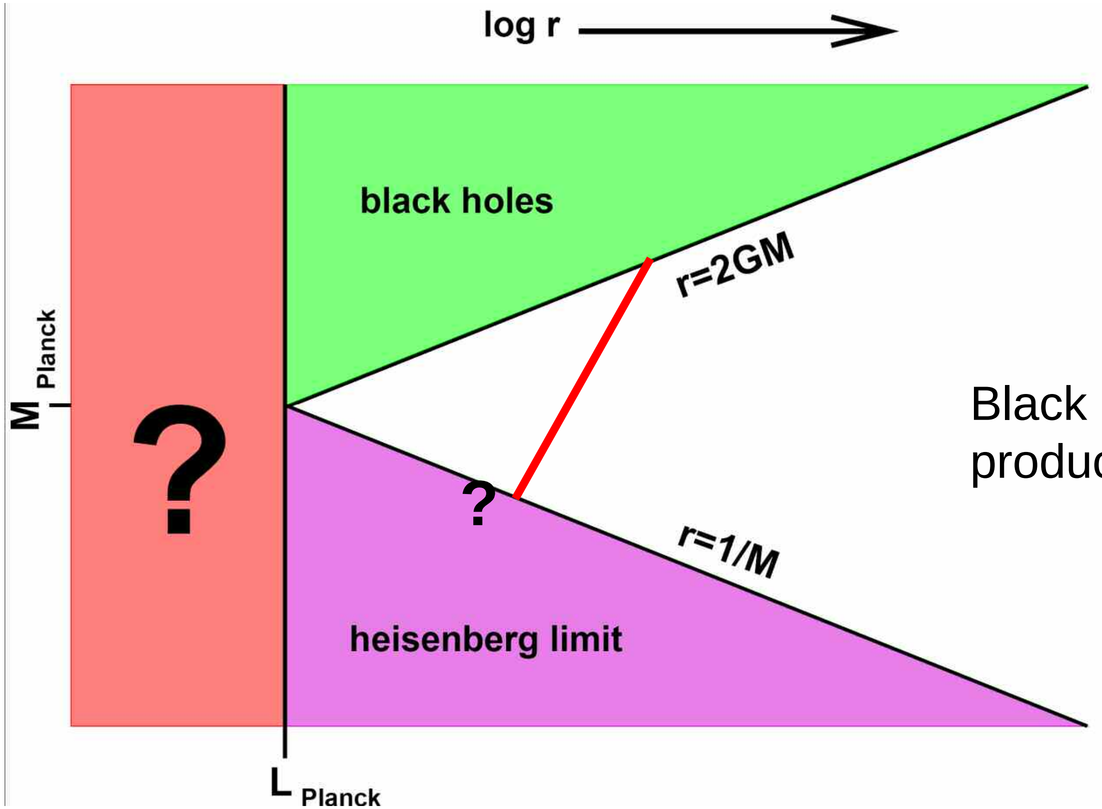


T-odd quark and leptons partner masses

TeV Quantum Gravity

d extra dimensions into which only gravity can propogate

$$4\pi G = \frac{4\pi}{M_P^2} = \left(\frac{1}{RM_F}\right)^d \frac{1}{M_F^2}$$



Black holes may be produced at LHC energies.

Arkani-Hamed et al ‘98, Antoniadis et al ‘98

Modified Uncertainty Principle at Planck Scale ?

$$\Delta x \geq \frac{\hbar}{\Delta p} + L_p^2 \frac{\Delta p}{\hbar}$$

Heuristic argument then suggests
modified Hawking temperature :-

$$T_{GUP} = \frac{Mc^2}{4\pi}\left[1 \mp \sqrt{1 - M_P^2 / M^2}\right]$$

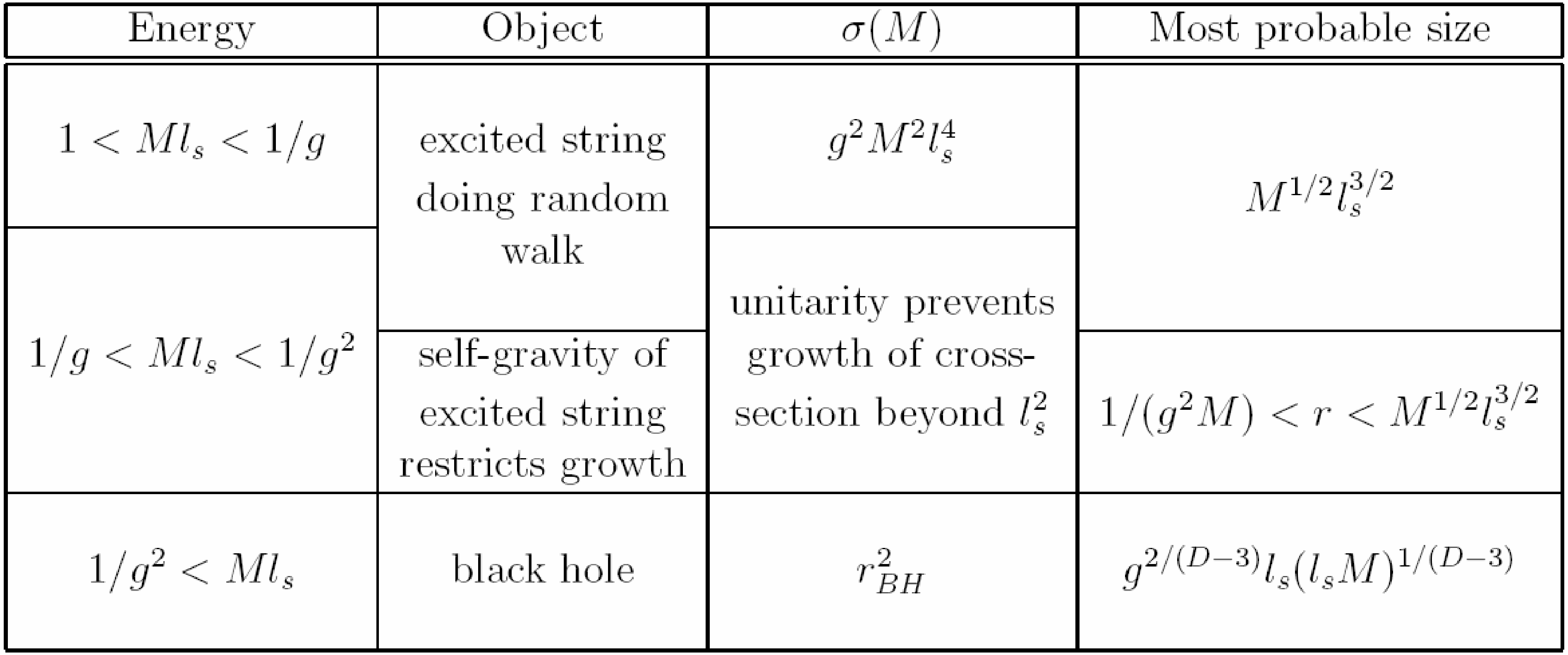
Temperature goes to zero close to the Planck scale.

Stable remnants at end point of black hole evaporation? Dark matter candidate?
(Pisin Chen)

N.B. This is not what string theory predicts…

Endpoint of black hole decay in string theory

Black hole undergoes phase transition to string ball



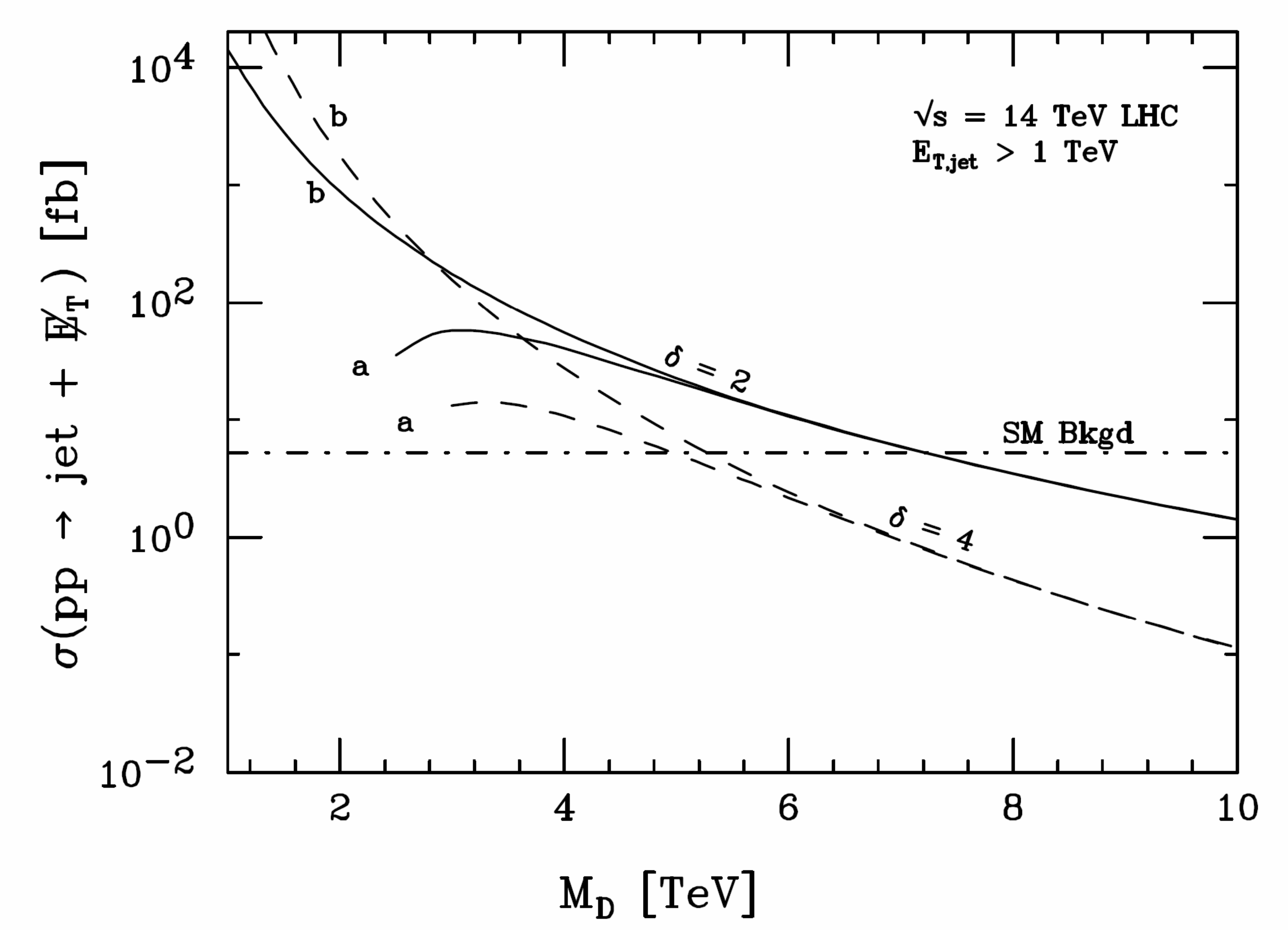
Energy	Object	$\sigma(M)$	Most probable size
$1 < Ml_s < 1/g$	excited string doing random walk	$g^2 M^2 l_s^4$	$M^{1/2} l_s^{3/2}$
$1/g < Ml_s < 1/g^2$		unitarity prevents growth of cross-section beyond l_s^2	
	self-gravity of excited string restricts growth		$1/(g^2 M) < r < M^{1/2} l_s^{3/2}$
$1/g^2 < Ml_s$	black hole	r_{BH}^2	$g^{2/(D-3)} l_s (l_s M)^{1/(D-3)}$

Bowick et al ’86, Amati et al ’89, Damour and Veneziao ‘99

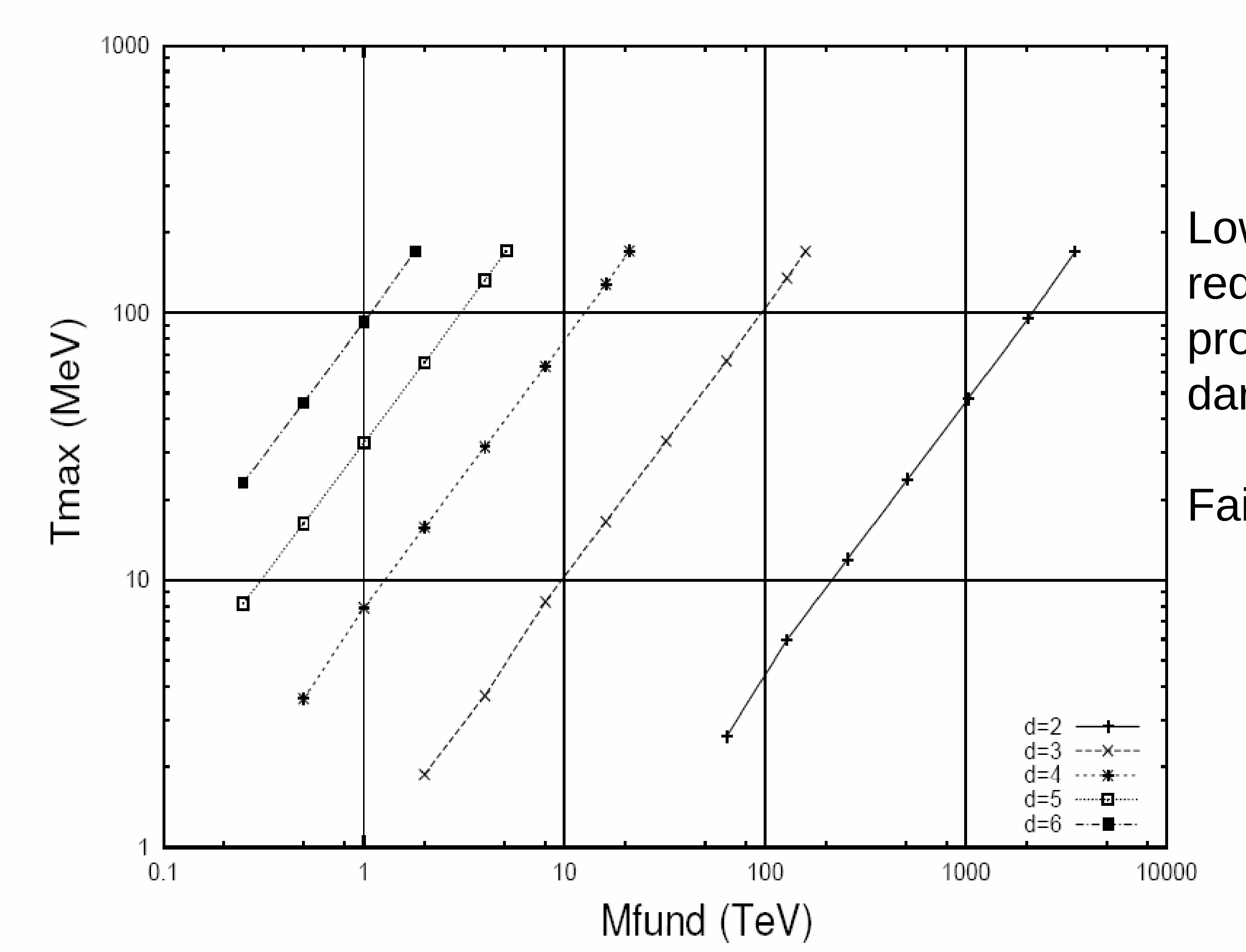
KK graviton production in TeV quantum gravity

$$pp \longrightarrow \text{jet} + \not{E}_T$$

Giudice, Rattazzi and Wells ‘98



Discovery of TeV gravity would create big questions in cosmology



Low reheat temperature required to avoid over-production of decaying KK dark matter

Fairbairn and Griffiths 2001

Conclusions

Creation of long lived particles
At colliders creates new
challenges and possibilities for
cosmology and particle physics

Lets hope for unexpected surprises !