Kaluza-Klein Theories - basic idea

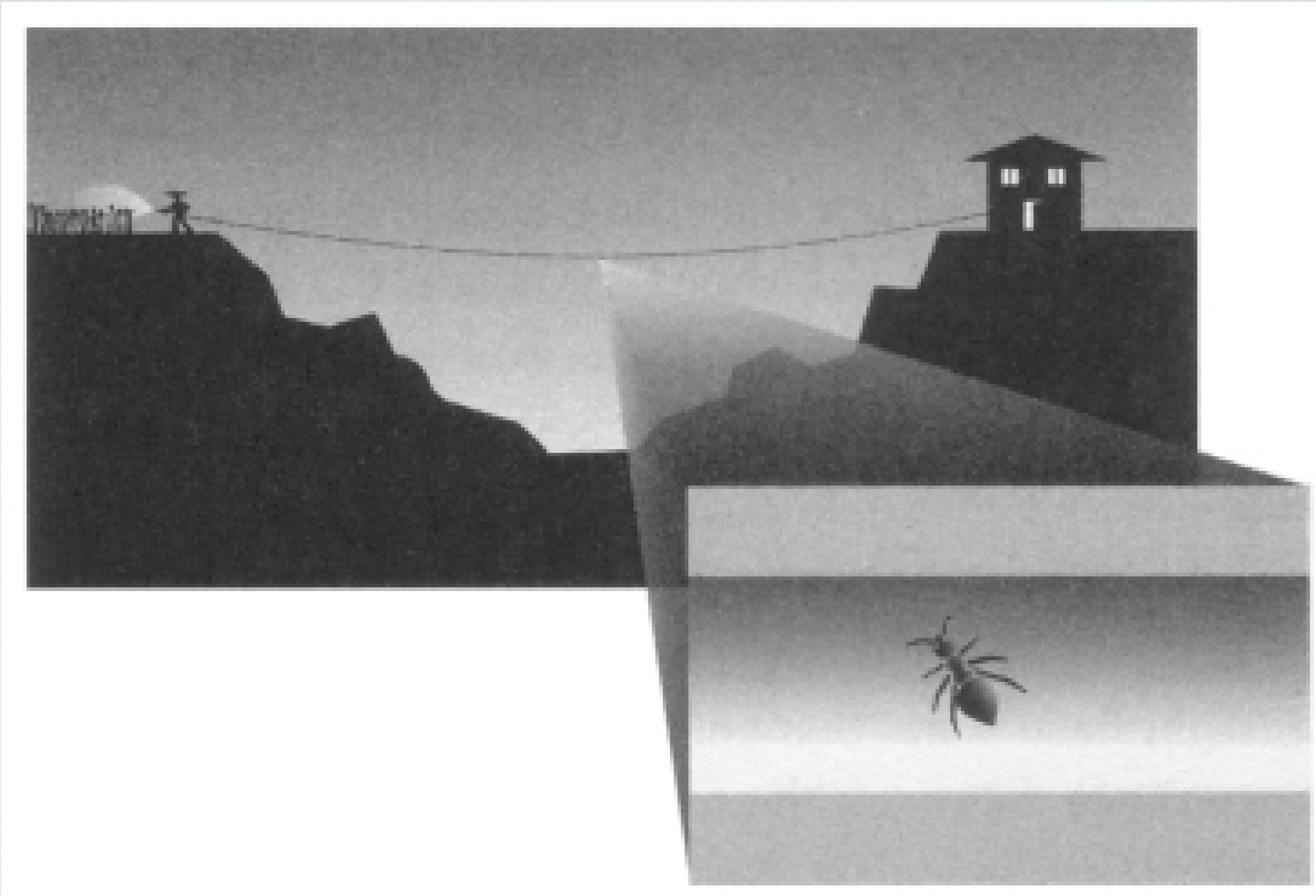
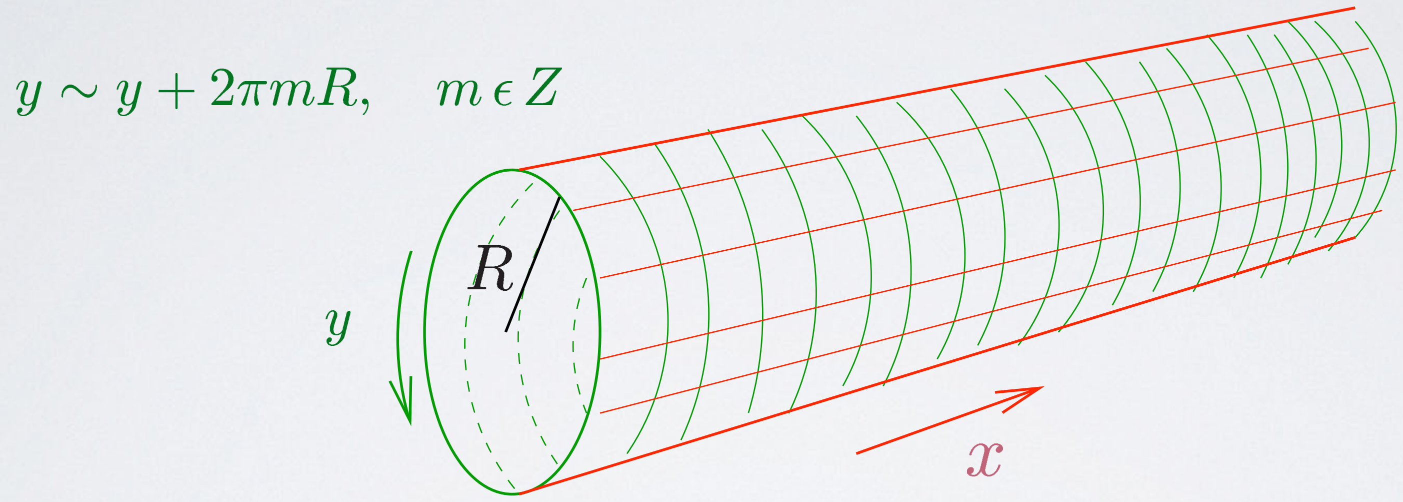


Fig. from B. Greene, '00

Kaluza-Klein Theories - basic idea

Assume extra spatial dimensions, compactified on some small scale R.



$\longrightarrow$ 'From a distance, this looks like ordinary 4D', i.e. low-energy physics should (in a certain sense) give standard 4D physics.

The UED spectrum in 5D

Including the first KK level only, one has:

- Fermions $f_{(0)}$, $f^d_{(1)}$, $f^s_{(1)}$
- Gauge Bosons $A^{r\mu}_{(0)}$, $B^{\mu}_{(0)}$, $A^{r\mu}_{(1)}$, $B^{\mu}_{(1)}$
- Mass eigenstates of the scalar spectrum:

$$
\begin{aligned}
a^0_{(k)} &= \frac{k}{RM_{Z_{(k)}}}\chi^3_{(k)} + \frac{M_Z}{M_{Z_{(k)}}} Z_{5(k)} \\
a^\pm_{(k)} &= \frac{k}{RM_{W_{(k)}}}\chi^\pm_{(k)} + \frac{W_W}{M_{W_{(k)}}} W^\pm_{5(k)}
\end{aligned}
$$

$$
\begin{aligned}
G^0_{(k)} &= \frac{M_Z}{M_{Z_{(k)}}}\chi^3_{(k)} - \frac{k}{RM_{Z_{(k)}}} Z_{5(k)} \\
G^\pm_{(k)} &= \frac{M_W}{M_{W_{(k)}}}\chi^\pm_{(k)} - \frac{k}{RM_{W_{(k)}}} W^\pm_{5(k)}
\end{aligned}
$$

$\rightsquigarrow$ Goldstones $G^0_{(0)}$, $G^\pm_{(0)}$, $G^0_{(1)}$, $G^\pm_{(1)}$, $A^5_{(1)}$

Physical scalars $H_{(0)}$, $H_{(1)}$, $a^0_{(1)}$, $a^\pm_{(1)}$

mUED mass spectrum

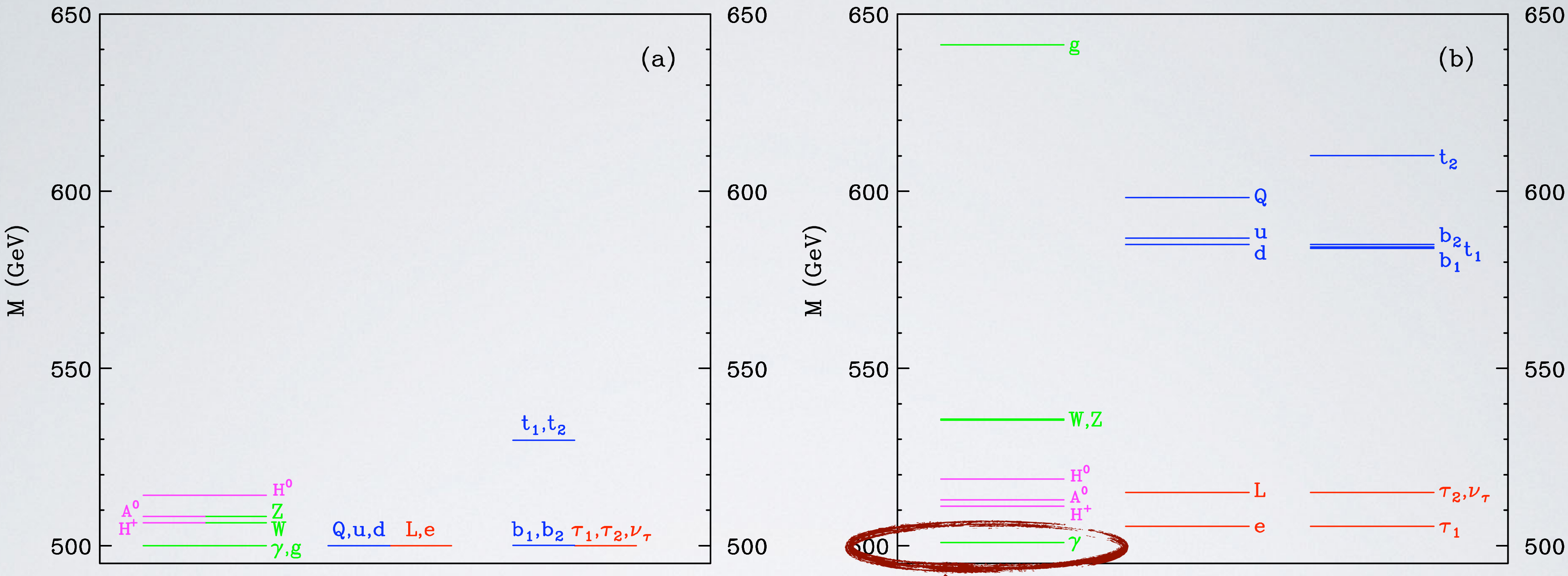
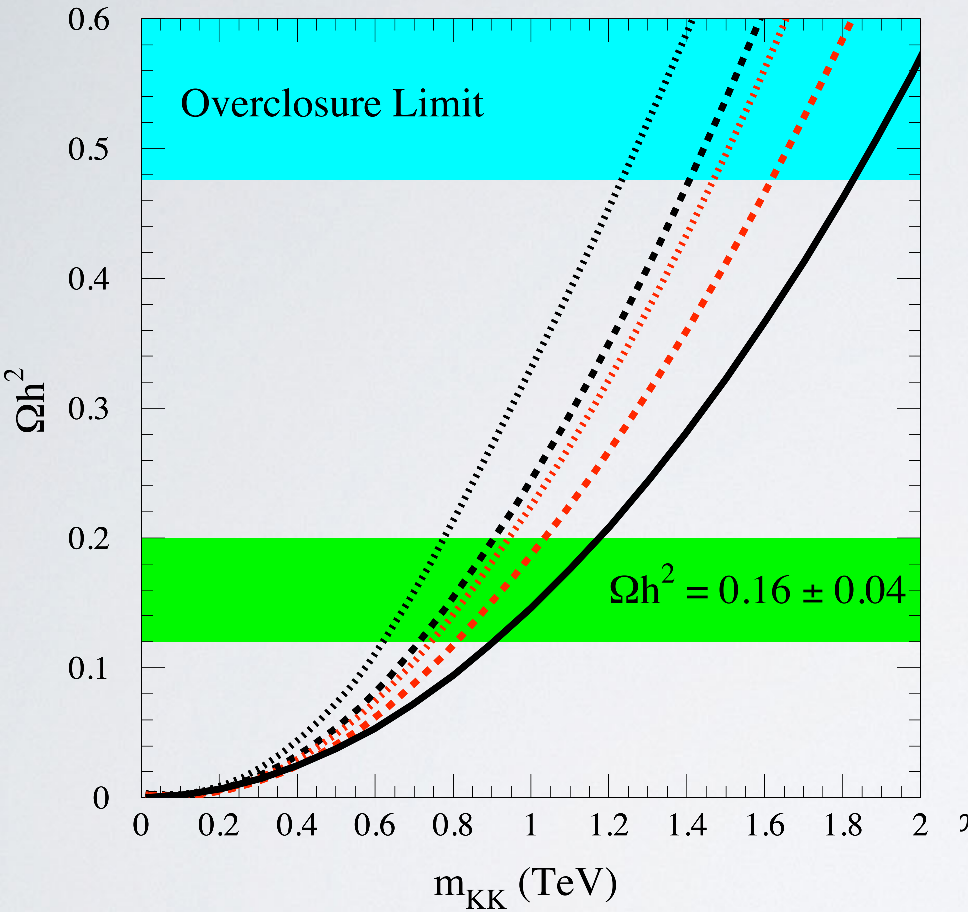


Figure 3.2: (Taken from [46]). The full spectrum of the UED model at the first KK level, a) at tree level and b) including one loop radiative corrections, for $R^{-1} = 500$ GeV and $\Lambda R = 20$. The first column shows the gauge and Higgs bosons, where $\{H^0, H^{\pm}, A^0\}$ correspond to $\{H, a_{\pm}, a_0\}$ in the notation introduced in Section 3.3.2. In the second column, the quark doublet (Q) and singlets (u, d) as well as lepton doublet (L) and singlet (e) are shown for the first two families. In the last coloumn, finally, this is repeated for the third family to illustrate the large electroweak mass shift of the top quark.

LKP: $\gamma^{(1)} \sim B^{(1)}$ (KK graviton LKP for $R^{-1} \lesssim 800\,\mathrm{GeV}$!)

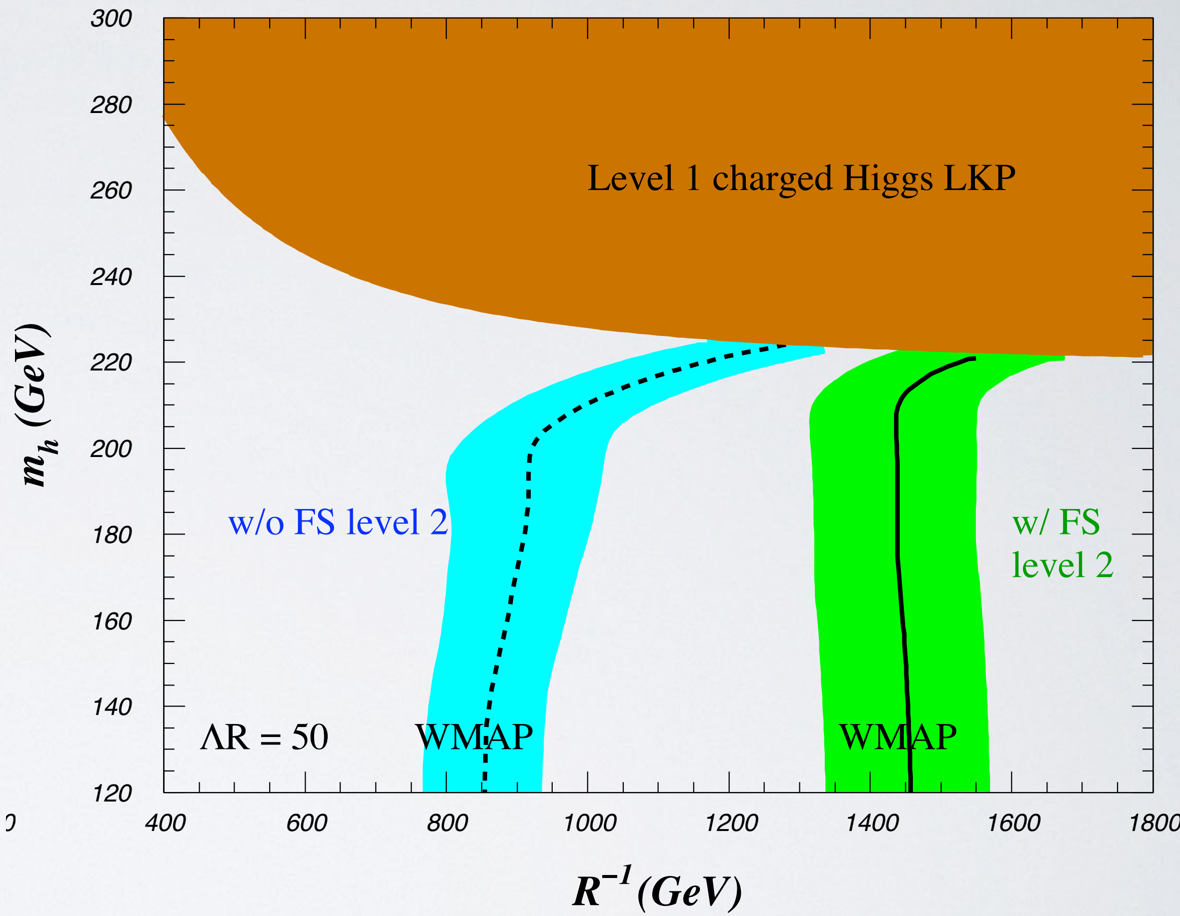
Cheng, Matchev & Schmaltz, PRD 2002

LKP relic density



First estimates, for various co-annihilation scenarios

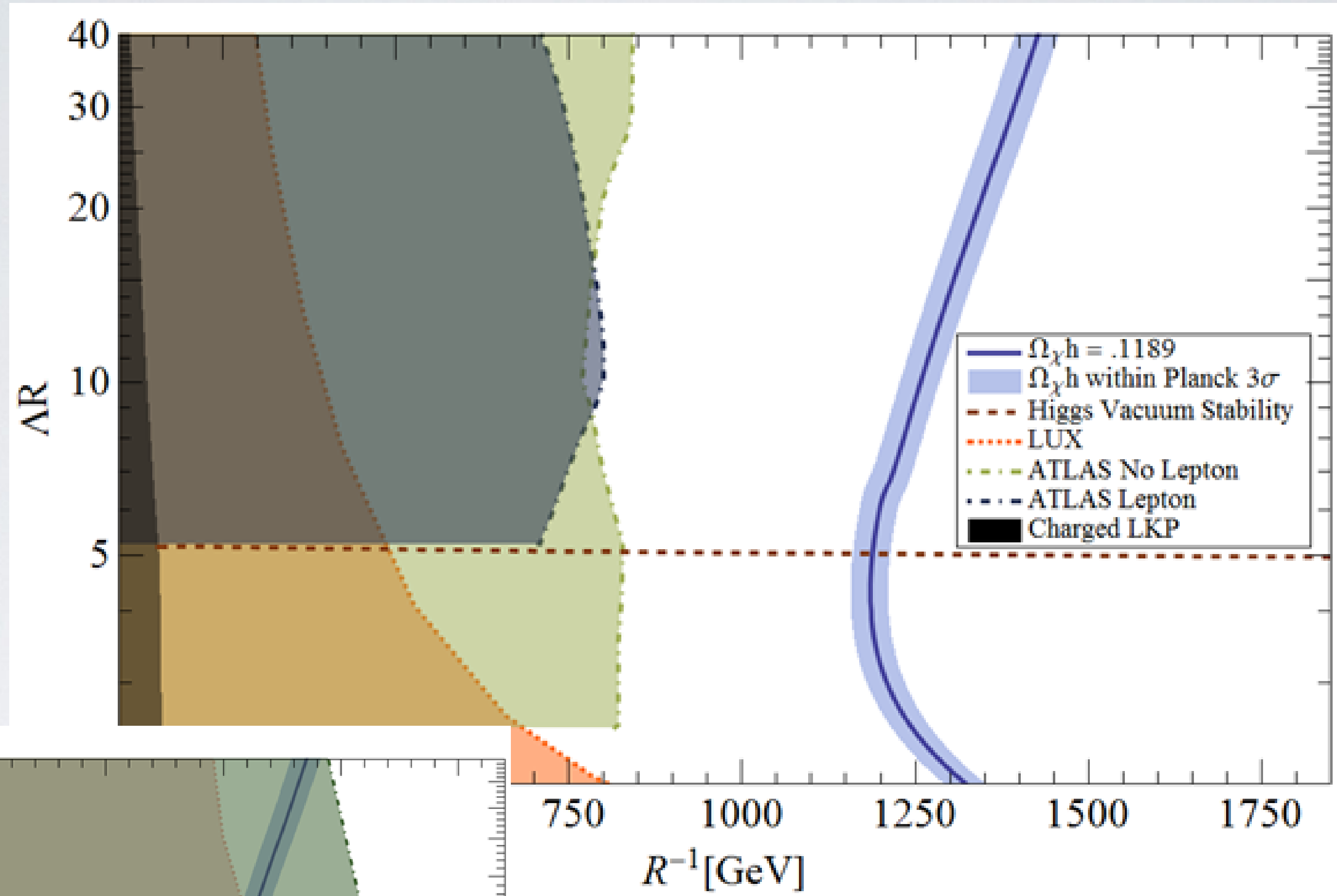
Servant & Tait, NPB '03

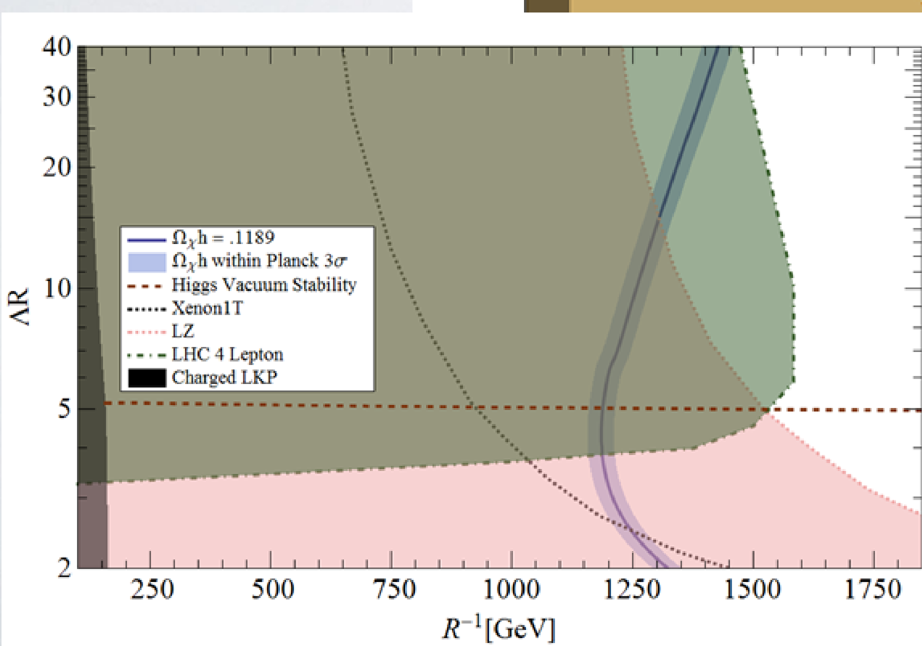


Full result in mUED, including all 2nd KK levels

Belanger, Kakizaki & Pukhov, 2010

mUED: current status



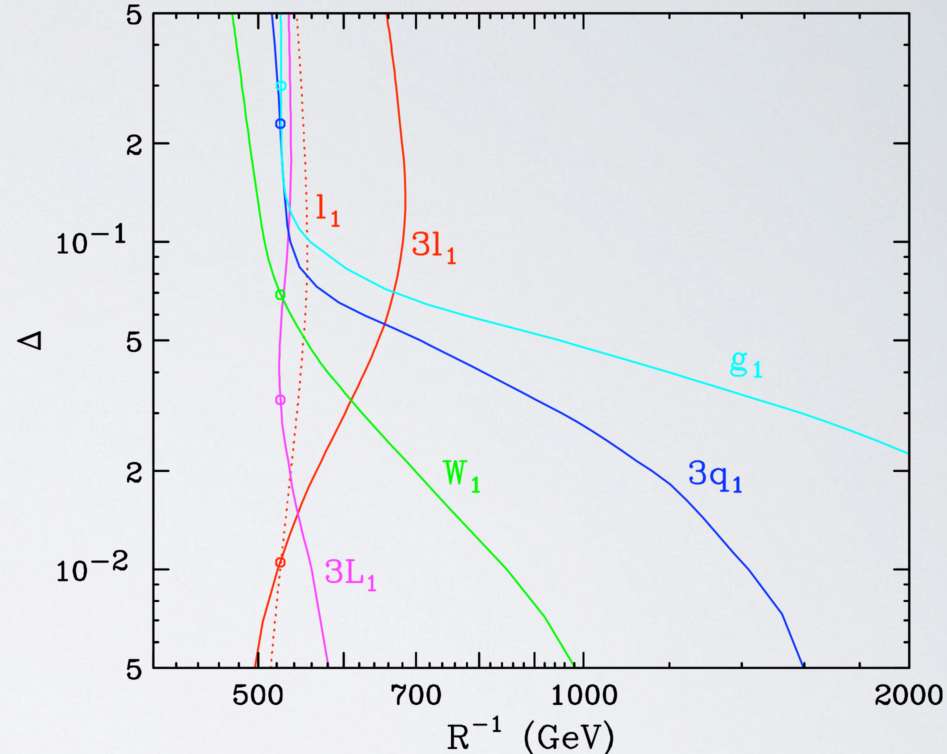


(projection)

Cornell, Profumo & Shepherd, PRD 2014

non-minimal UED

- Relic density strongly dependent on mass splittings!



Kong & Matchev, JHEP 2006

(NB: no 2nd level KK states included here!)

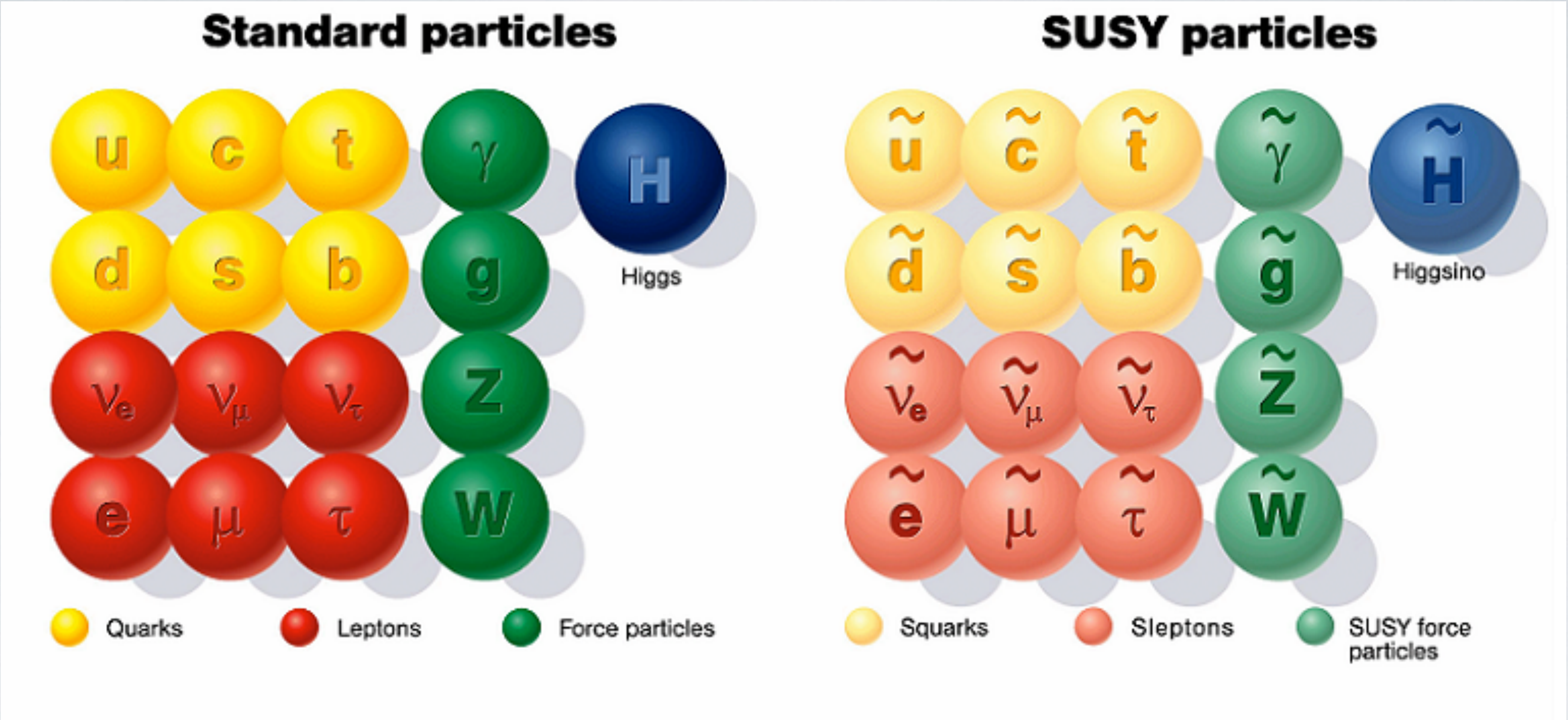
- Other LKPs possible: $Z^{(1)}, H^{(1)}$

  ($\nu^{(1)}$ ruled out just like $\tilde{\nu}$ - same workaround: Dirac masses!)

- more than one UED: yet more candidates – spinless KK photon and Z bosons

  (= linear combinations of vector components along EDs)

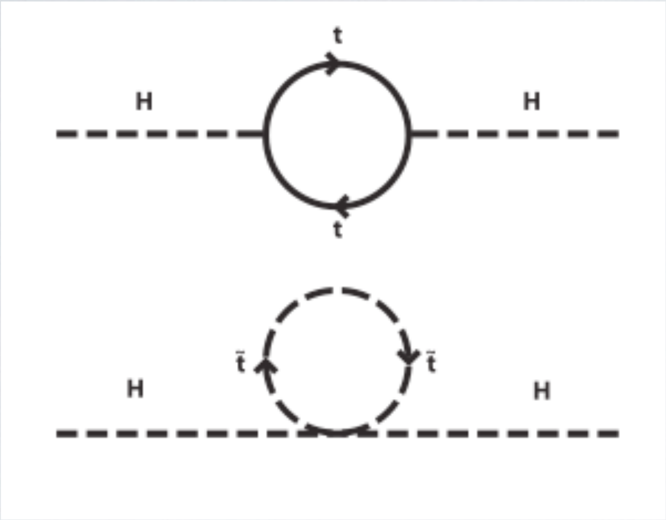
NB: Even smaller cut-off scales needed for 6D!

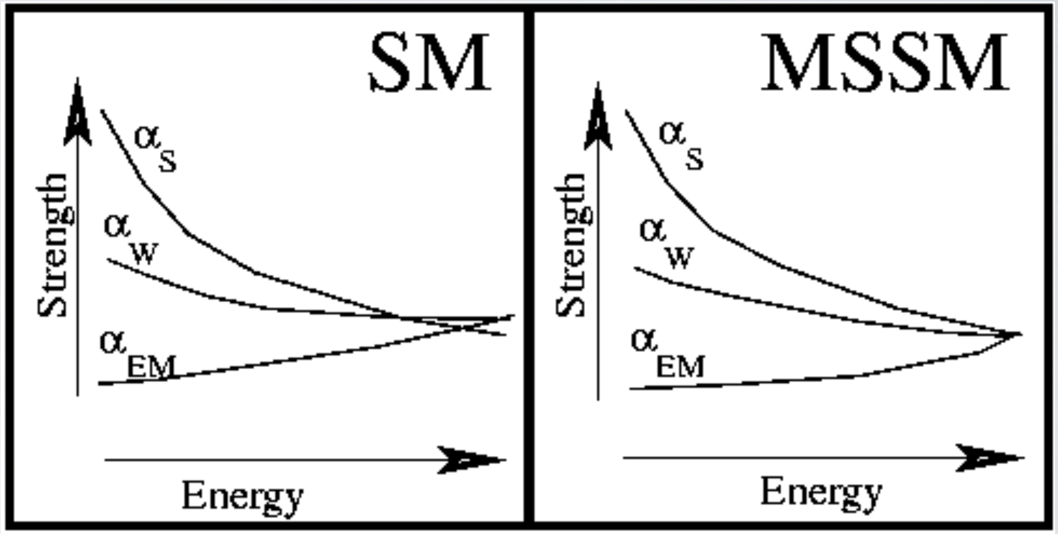


MSSM: SM + "Every particle gets a SUSY partner"

- every SM bosonic and fermionic d.o.f. gets a SUSY fermionic and bosonic d.o.f. :
  - spin 1/2 gaugino for each SM gauge boson
  - scalar partner for each SM fermion helicity state, e.g. $e \leftrightarrow \tilde{e_L}$ and $\tilde{e_R}$
- need *two* complex *Higgs doublets* to cancel triangle anomalies:
  - 3 Higgs d.o.f give masses to W and Z
  - 5 physical Higgs fields left: $h, H, A, H^{\pm}$
- add masses by including soft SUSY breaking terms: 124 free parameters!

MSSM: some achievements





Conservation of R-parity

$$R \equiv (-1)^{3B+L+2s}$$

(introduced to suppress proton decay)

Lightest SUSY particle
(*LSP*) is *stable*!

Potential DM candidates in the MSSM

Standard Model particles and fields		Supersymmetric partners			
		Interaction eigenstates		Mass eigenstates	
Symbol	Name	Symbol	Name	Symbol	Name
$q = d, c, b, u, s, t$	quark	$\tilde{q}_L, \tilde{q}_R$	squark	$\tilde{q}_1, \tilde{q}_2$	squark
$l = e, \mu, \tau$	lepton	$\tilde{l}_L, \tilde{l}_R$	slepton	$\tilde{l}_1, \tilde{l}_2$	slepton
$\nu = \nu_e, \nu_\mu, \nu_\tau$	neutrino	$\tilde{\nu}$	sneutrino	$\tilde{\nu}$	sneutrino
g	gluon	$\tilde{g}$	gluino	$\tilde{g}$	gluino
$W^\pm$	W-boson	$\tilde{W}^\pm$	wino		
H^-	Higgs boson	$\tilde{H}_1^-$	higgsino	$\tilde{\chi}^\pm_{1,2}$	chargino
H^+	Higgs boson	$\tilde{H}_2^+$	higgsino		
B	B-field	$\tilde{B}$	bino		
W^3	W^3-field	$\tilde{W}^3$	wino		
H_1^0	Higgs boson	$\tilde{H}_1^0$	higgsino	$\tilde{\chi}^0_{1,2,3,4}$	neutralino
H_2^0	Higgs boson	$\tilde{H}_2^0$	higgsino		
H_3^0	Higgs boson				

(color) charged

Table from Bertone-review

Sneutrinos:

Generally too large direct detection cross sections

Lightest Neutralino:

Prototype WIMP candidate!

also

Gravitino:

Planck-scale suppressed interactions ⇝ no WIMP candidate!

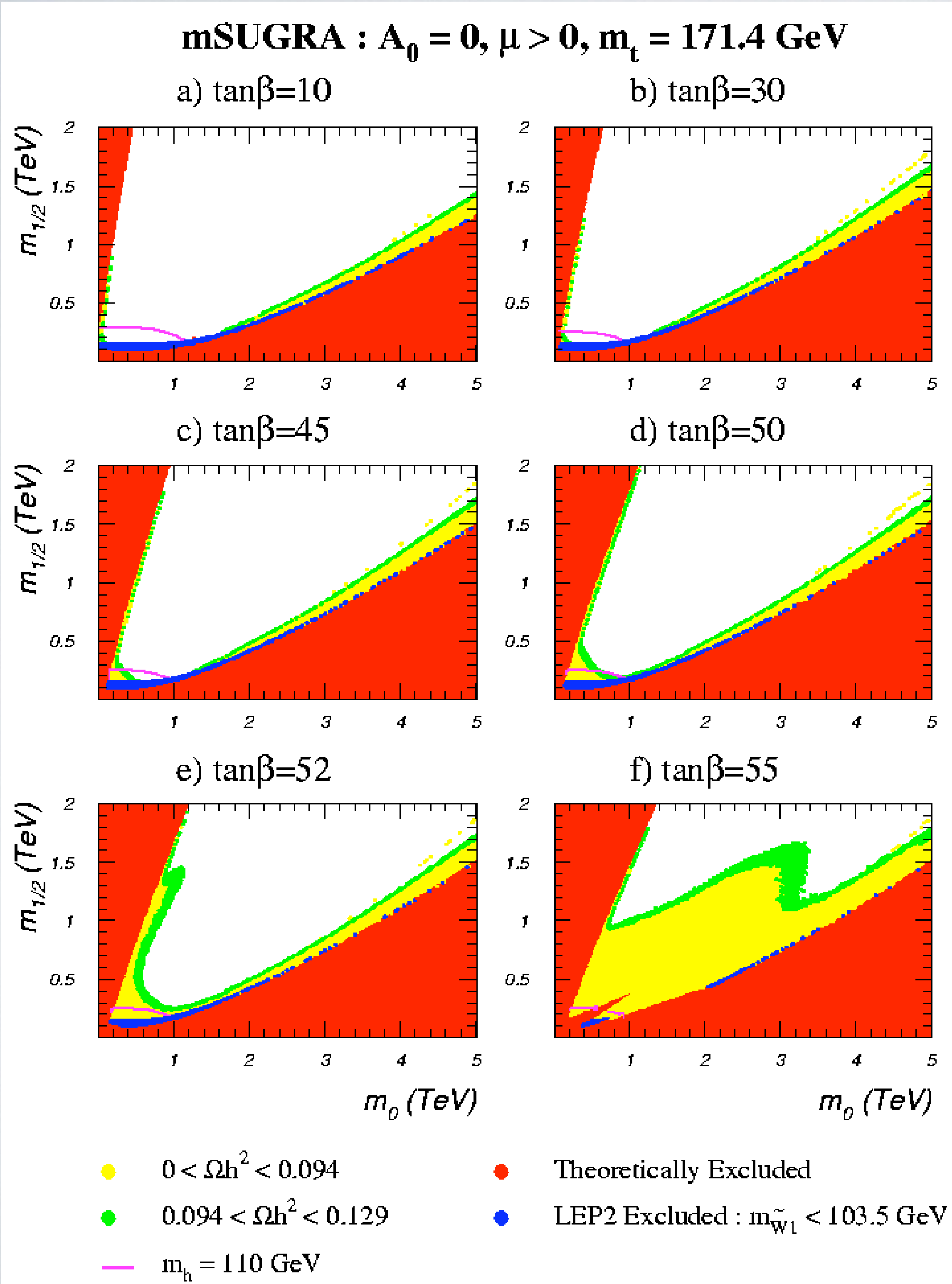


Figure 2. *The m_0 vs. $m_{1/2}$ plane in mSUGRA for $A_0 = 0$ and various values of $\tan\beta$, with $\mu > 0$ and $m_t = 171.4$ GeV. The red-shaded regions are excluded because electroweak symmetry is not correctly broken, or because the LSP is charged. Blue regions are excluded by direct SUSY searches at LEP2. Yellow and green shaded regions are WMAP-allowed, while white regions are excluded owing to $\Omega_{\widetilde{Z}_1}h^2 > 0.129$. Below the magenta contour in each frame, $m_h < 110$ GeV.*

Baer, Park & Tata, NJP 11 (2009)

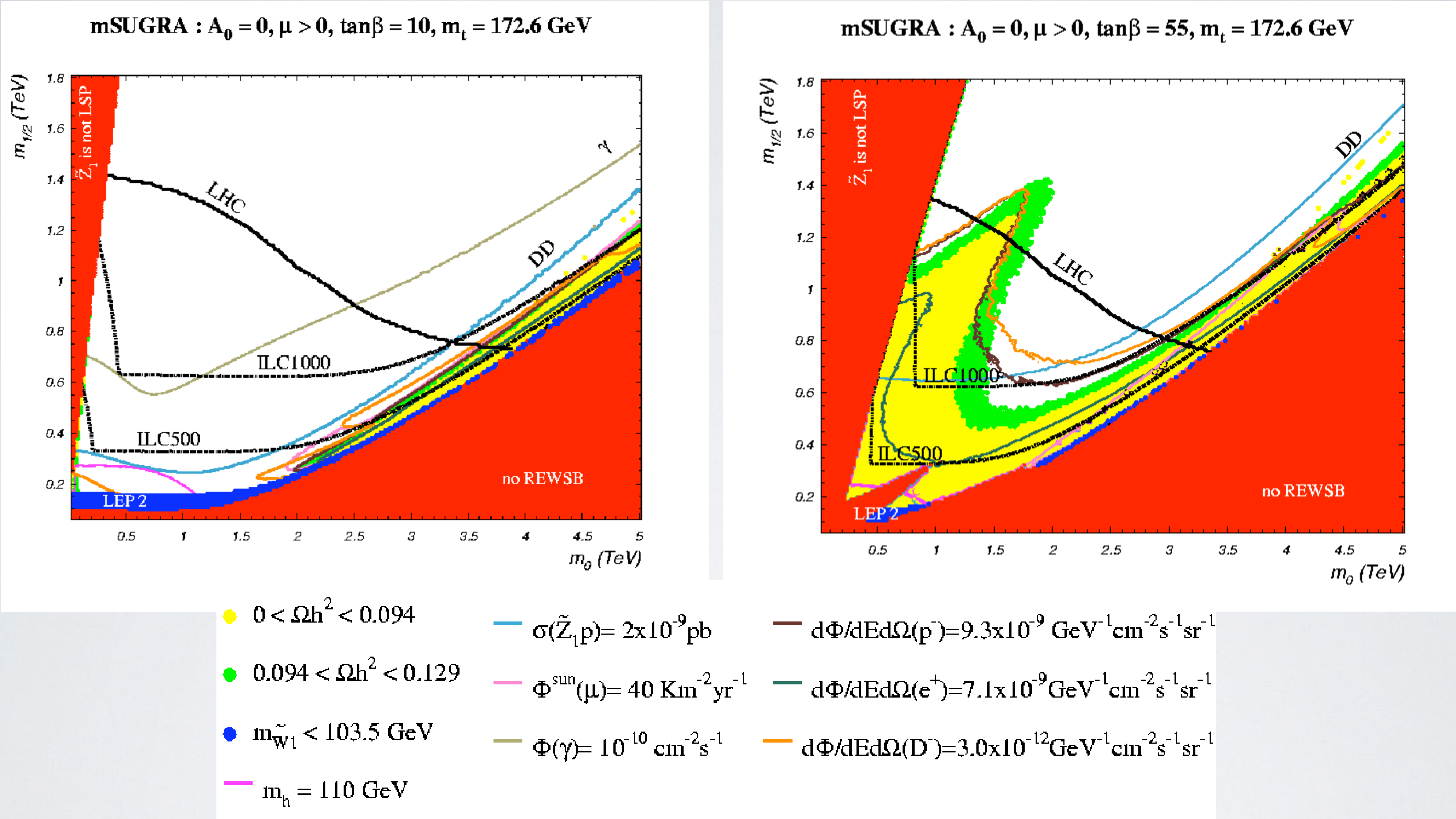


Figure 5. *The projected reach of various colliders, direct and indirect dark matter search experiments in the* m_0 *vs.* $m_{1/2}$ *plane of the mSUGRA model for* $A_0 = 0$, $\mu > 0$, $m_t = 172.6$ *GeV for* $\tan\beta = 10$ *(left frame) and* $\tan\beta = 55$

Baer, Park & Tata, NJP 11 (2009)