The Cosmology of Split SUSY

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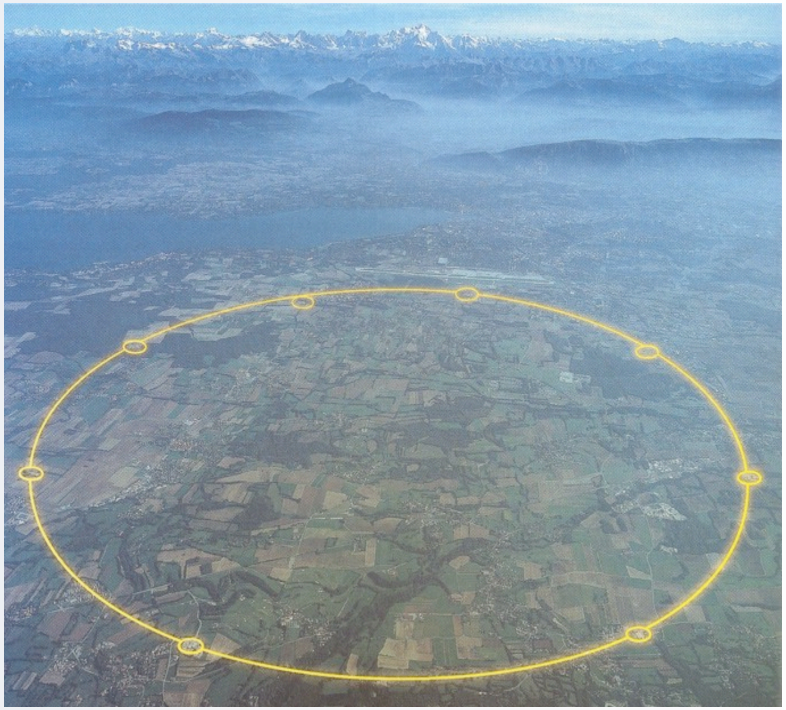
Discussions with S. Dimopoulos,
N. Arkani-Hamed, J. Wacker

The Proving Ground

- LHC Start 2007
- Should Discover source of Electroweak Symmetry Breaking—Higgs Boson
- But what Else?



Naturalness

- A full blown industry—twenty years of thinking what lies at the weak scale and beyond.
- Technicolor, Supersymmetry, Large Extra Dimensions, Warped Compactifications, Little Higgs
- None are perfect. Model Builders are busy.

TeV Scale Supersymmetry

e ® $\tilde{e}$ (selectron)

q ® $\tilde{q}$ (squark)

γ ® $\tilde{\gamma}$ (photino)

h ® $\tilde{\mathrm{h}}$ (higgsino)

Weak Scale Supersymmetry Scorecard

SUCCESSES

- Gauge Coupling Unification
- Dark Matter (χ)

FAILURES

- Where are the superpartners?
- Higgs Mass
- Flavor Changing Neutral Currents ($b \rightarrow s\ \gamma$), ($\mu \rightarrow e\ \gamma$), K-K mixing…
- Electric Dipole Moments
- Dimension 5 proton decay
- Comsological Problems (e.g. gravitino problem)

- Cosmological Constant

- Higgs Fine tune

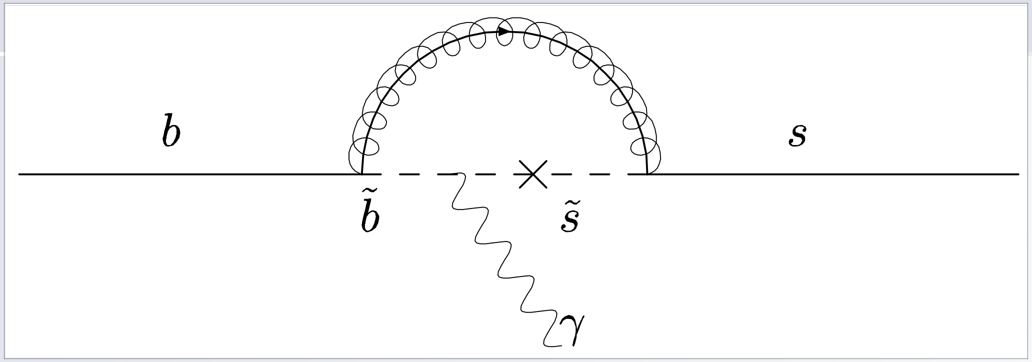
Stringy Landscape

- The existence of many vacua may liberate us from traditional ideas of naturalness.
- Weinberg C.C. Bound
- Friendly neighborhood?

(Arkani-Hamed, Dimopoulos, Kachru **hep-th/0501082**)

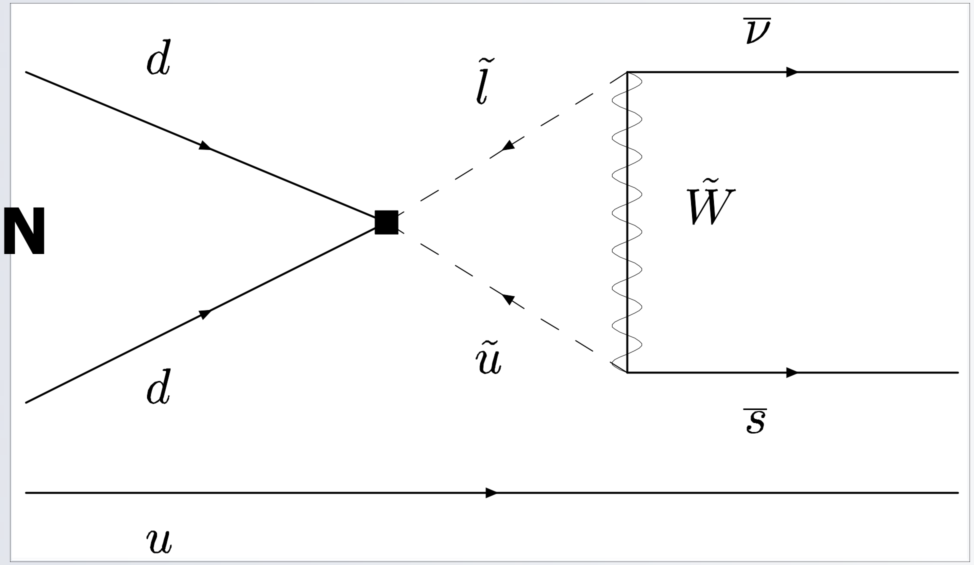
The Trouble with Scalars

FCNCs



(e.g.Gabbiani, et al. hep-ph/9604387)

PROTON DECAY



K+

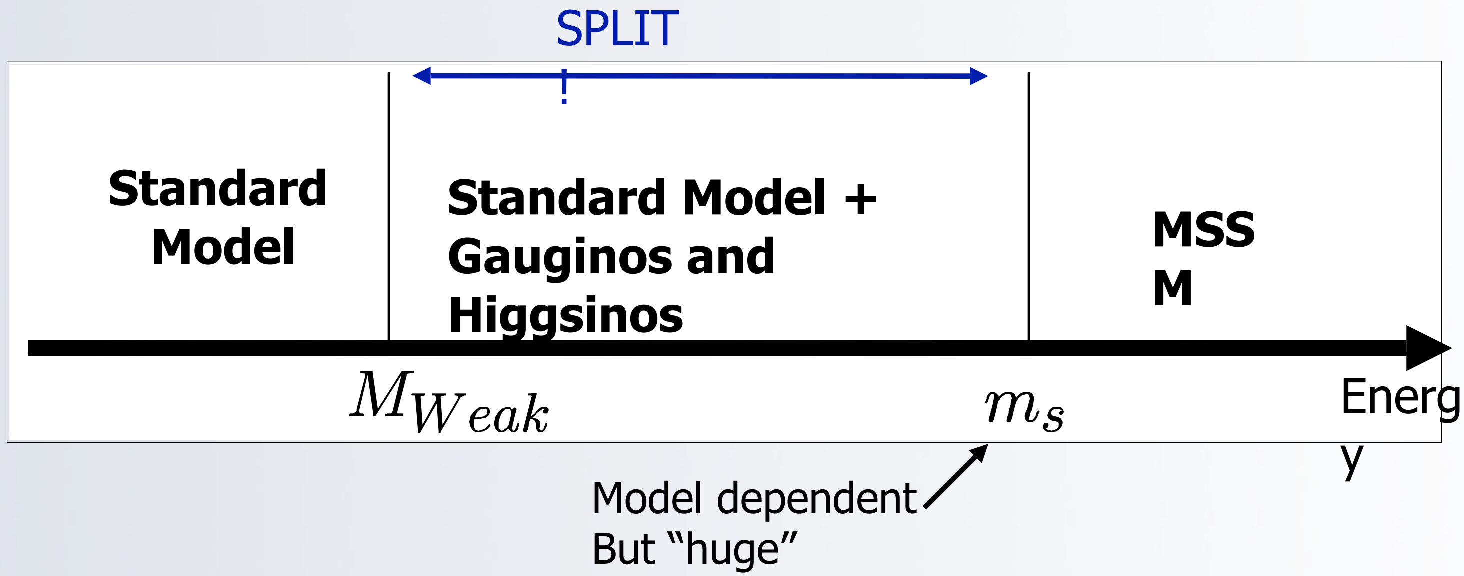
(e.g. Murayama and Pierce hep-ph/0108104)

Gauge Coupling Unification

- Scalars (and SM fermions) come in complete GUT multiplets→ don't contribute to relative running
- Higgsinos, Gauginos, Gauge Bosons, Higgs Bosons are responsible for unification.

Take Home Message

- Fermions Good, Scalars Bad
- Fermion masses can be protected by a chiral symmetry. Can be much lighter than scalars.



Why Weak Scale?

- Lost the link to the Higgs Mass… Superpartners could be anywhere?
- Existence of Dark Matter → Weak Scale. (Lee-Weinberg)

SUSY Scorecard

Split SUSY Scorecard

SUCCESSES

- Gauge Coupling Unification
- Dark Matter (χ)

PREDICTIONS

- Superpartners→Dark Matter
- Higgs Mass < 170 GeV
- Electric Dipole Moment near bound

(Arkani-Hamed, Dimopoulos, Giudice, Romanino)

[redacted]

- Higgs Fine tune

FAILURES

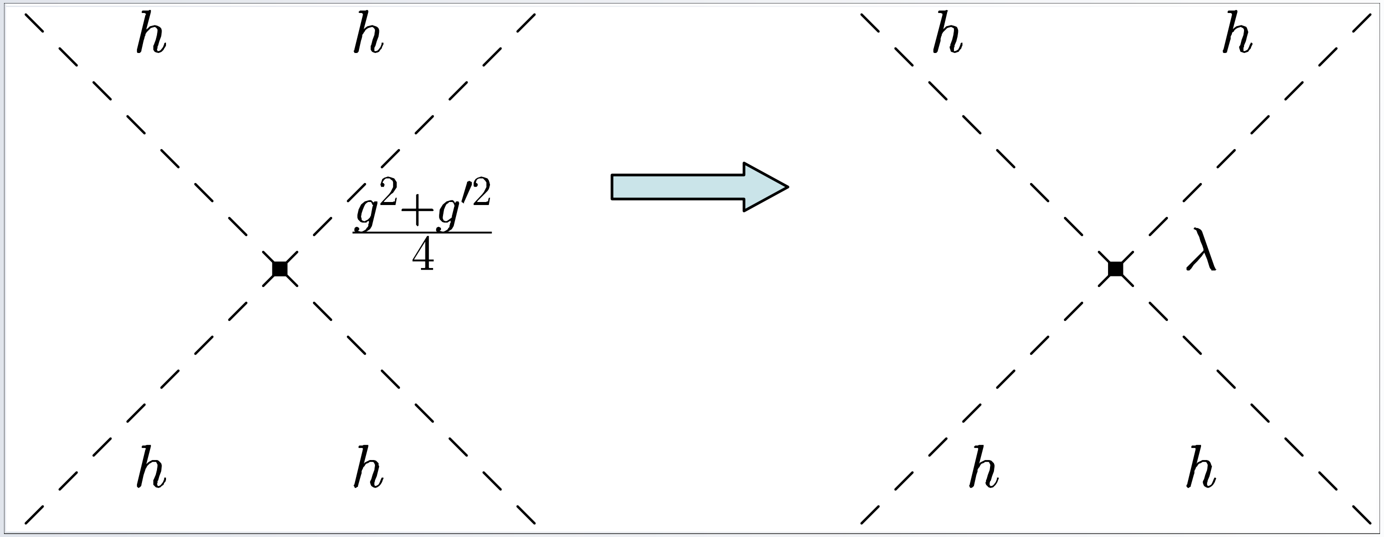
- Where are the superpartners?
- Higgs Mass
- Flavor Changing Neutral Currents ($b \to s\ \gamma$), ($\mu \to e\ \gamma$), K-K mixing…
- Electric Dipole Moments
- Dimension 5 proton decay
- Comsological Problems (e.g. gravitino problem)

The Remaining Plan

- Dark Matter and Split Supersymmetry
- Gluino Cosmology

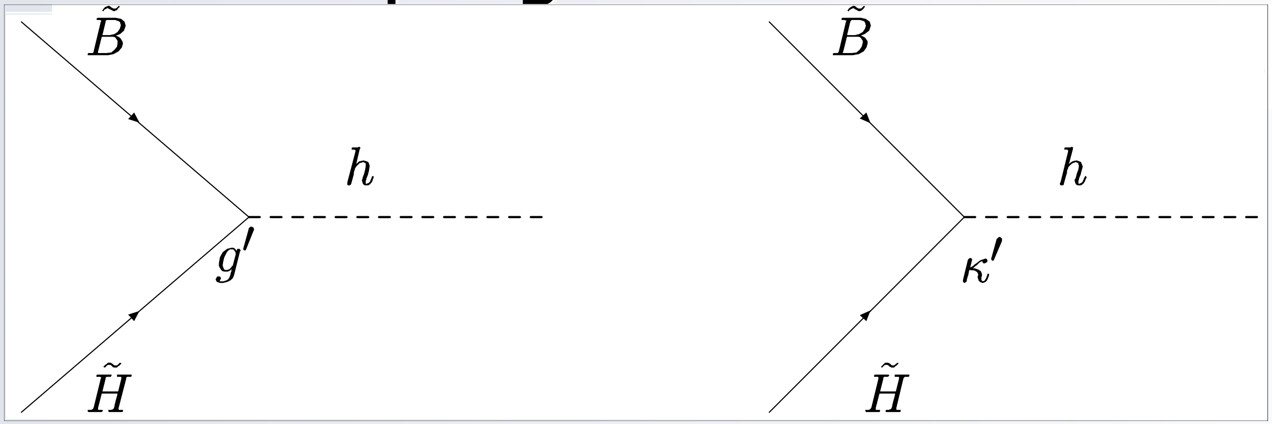
Novel Features

- Only one Higgs doublet at low energies.
- Supersymmetric boundary conditions are set at m_s



New RGEs for couplings

- Run Higgs Quartic→ Predicts the Higgs Mass.
- Gaugino Couplings are generalized Yukawa couplings.



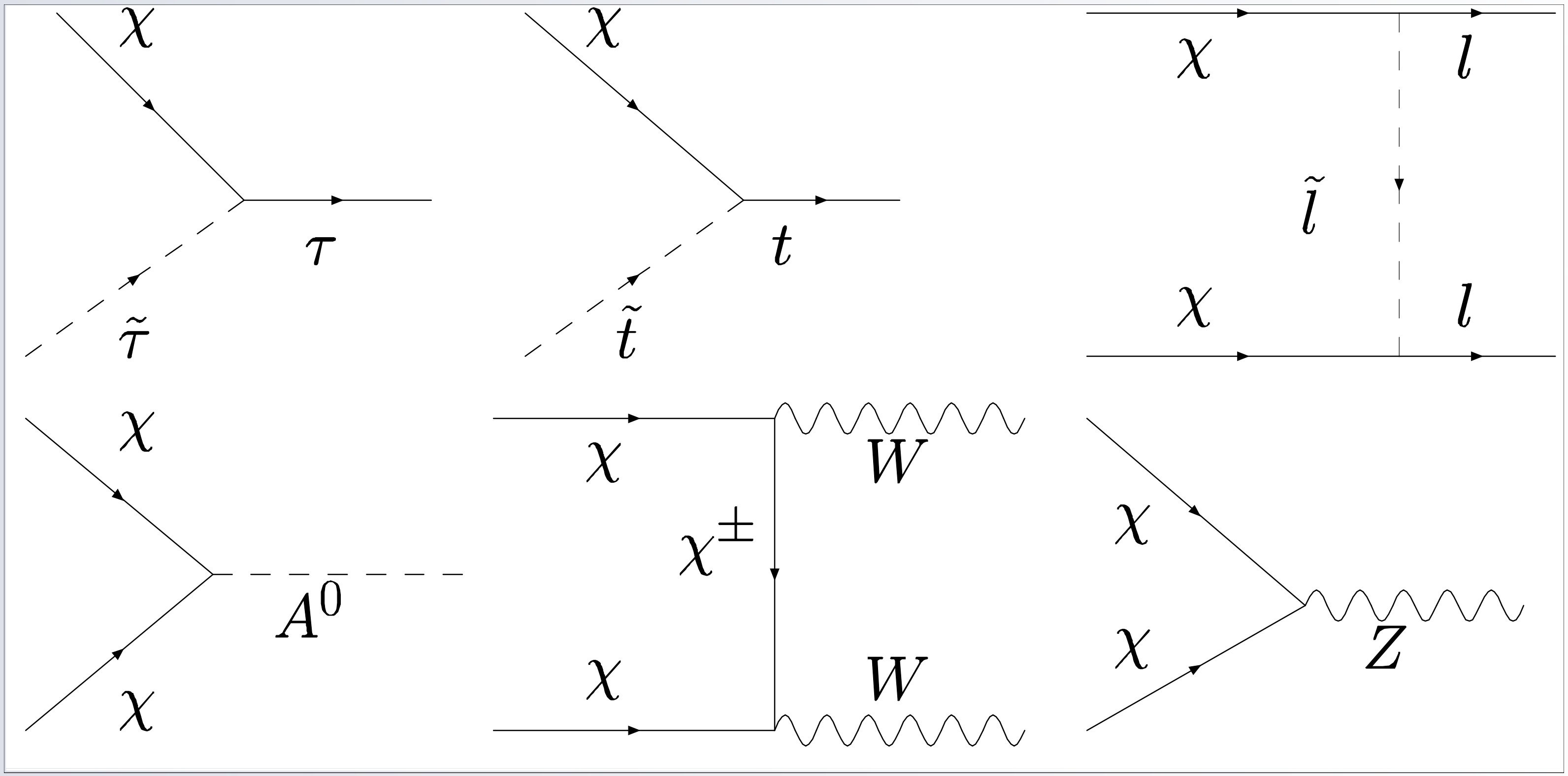
Gauge Couplings? Yukawas.

$$\kappa_1' = \sqrt{\frac{3}{10}} g_1 \sin\beta \qquad \kappa_2' = \sqrt{\frac{3}{10}} g_1 \cos\beta$$

$$\kappa_1 = \sqrt{2} g_2 \sin\beta \qquad \kappa_2 = \sqrt{2} g_2 \cos\beta.$$

$$M_{\chi^0} = \begin{pmatrix} M_1 & 0 & -\frac{\kappa_2' v}{\sqrt{2}} & \frac{\kappa_1' v}{\sqrt{2}} \\ 0 & M_2 & \frac{\kappa_2 v}{\sqrt{8}} & -\frac{\kappa_1 v}{\sqrt{8}} \\ -\frac{\kappa_2' v}{\sqrt{2}} & \frac{\kappa_2 v}{\sqrt{8}} & 0 & -\mu \\ \frac{\kappa_1' v}{\sqrt{2}} & -\frac{\kappa_1 v}{\sqrt{8}} & -\mu & 0 \end{pmatrix}, \qquad M_{\chi^\pm} = \begin{pmatrix} M_2 & \frac{v\kappa_1}{2} \\ \frac{v\kappa_2}{2} & \mu \end{pmatrix}$$

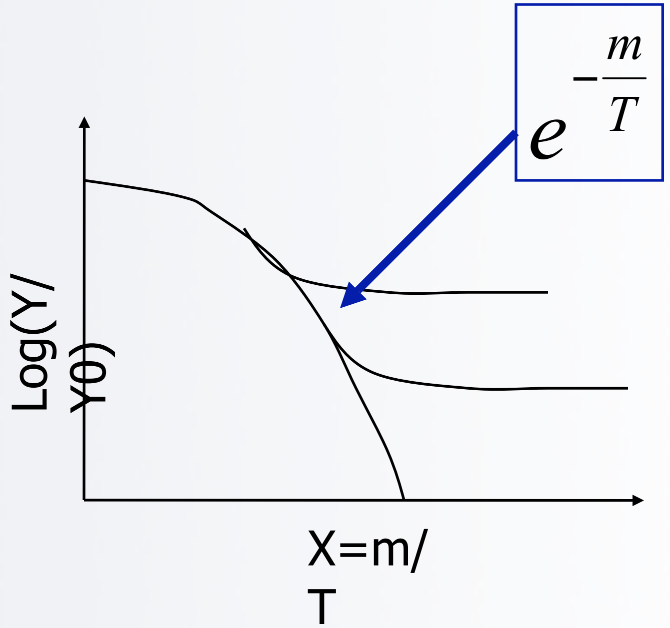
MSSM: Many Particles, Many Diagrams



Dark Matter Calculation

- Solve the Boltzman equation:

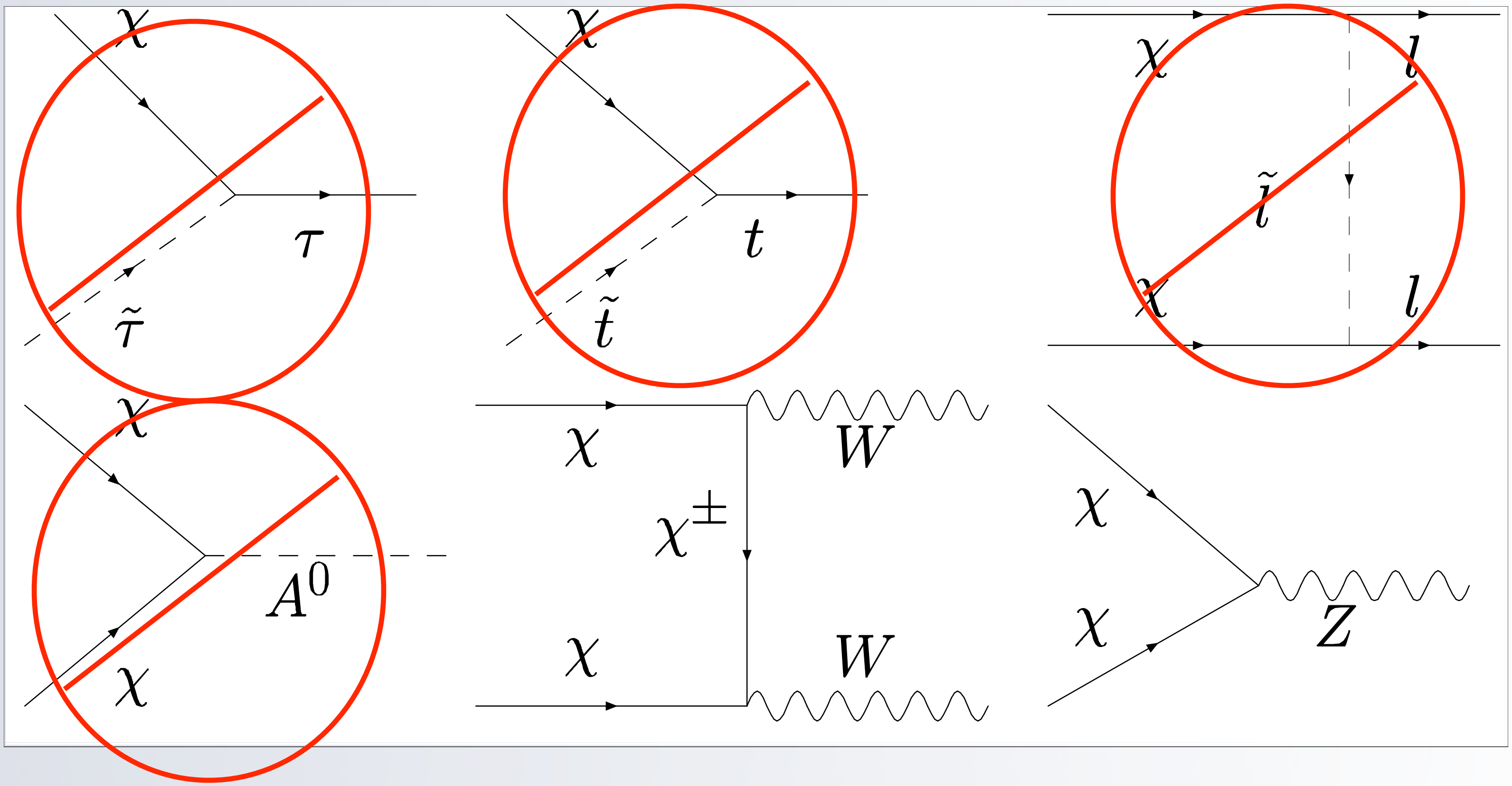
$$\frac{dn}{dt} + 3Hn = -<\sigma_A |v|> [n^2 - n_{EQ}^2]$$



Y=n/s

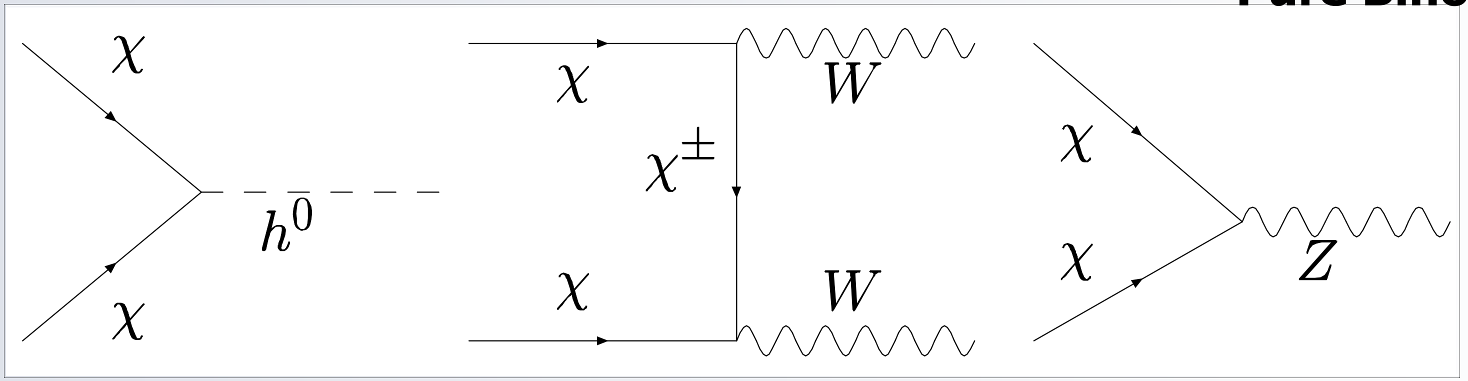
SPLIT SUSY FEWER

~~MSSM~~: ~~Many~~ Particles, FEWER ~~Many~~ Diagrams

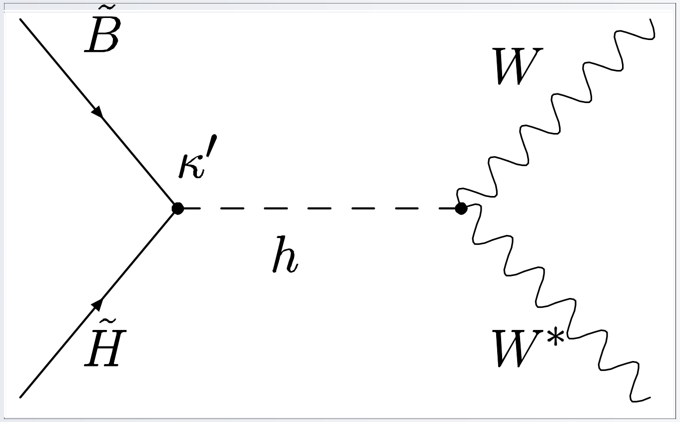


Split SUSY: Fewer Particles, Fewer Diagrams

Pure Bino Inert



- Heavier Higgs→ Wider Higgs→Easier Resonance



Split SUSY: Three regions

- Pure Wino (AMSB-like)
- "Bulk Region" (mixed Bino—Wino)
- Pure Higgsino (radiative generation of mu term)

$$16\pi^2\beta_\mu = -\mu\left(\frac{9}{10}g_1^2 + \frac{9}{2}g_2^2\right) + \frac{3}{2}\kappa_1\kappa_2 M_2 + 2\kappa_1'\kappa_2' M_1 + \frac{3}{8}\mu(\kappa_1^2 + \kappa_2^2) + \frac{1}{2}\mu(\kappa_1'^2 + \kappa_2'^2).$$

Pure Wino Case

- Naturally Arises from Anomaly Mediation.

(Randall and Sundrum; **Giudice, Luty, Murayama, Rattazzi; Wells**).

$$X = m^2\theta^2$$

$$\int \frac{X^* X Q^* Q d^4\theta}{M_*^2} \Rightarrow L \ni \frac{m^4}{M_*^2} \tilde{q} \tilde{q}^*$$

$$\int \frac{XWW}{M_*} d^2\theta \Rightarrow L \ni \frac{m^2}{M_*} \bar{\lambda}\lambda$$

Anomaly Mediation

- Superconformal anomaly can communicate supersymmetry breaking.

$$m_\lambda = \frac{\beta m_{3/2}}{g}$$

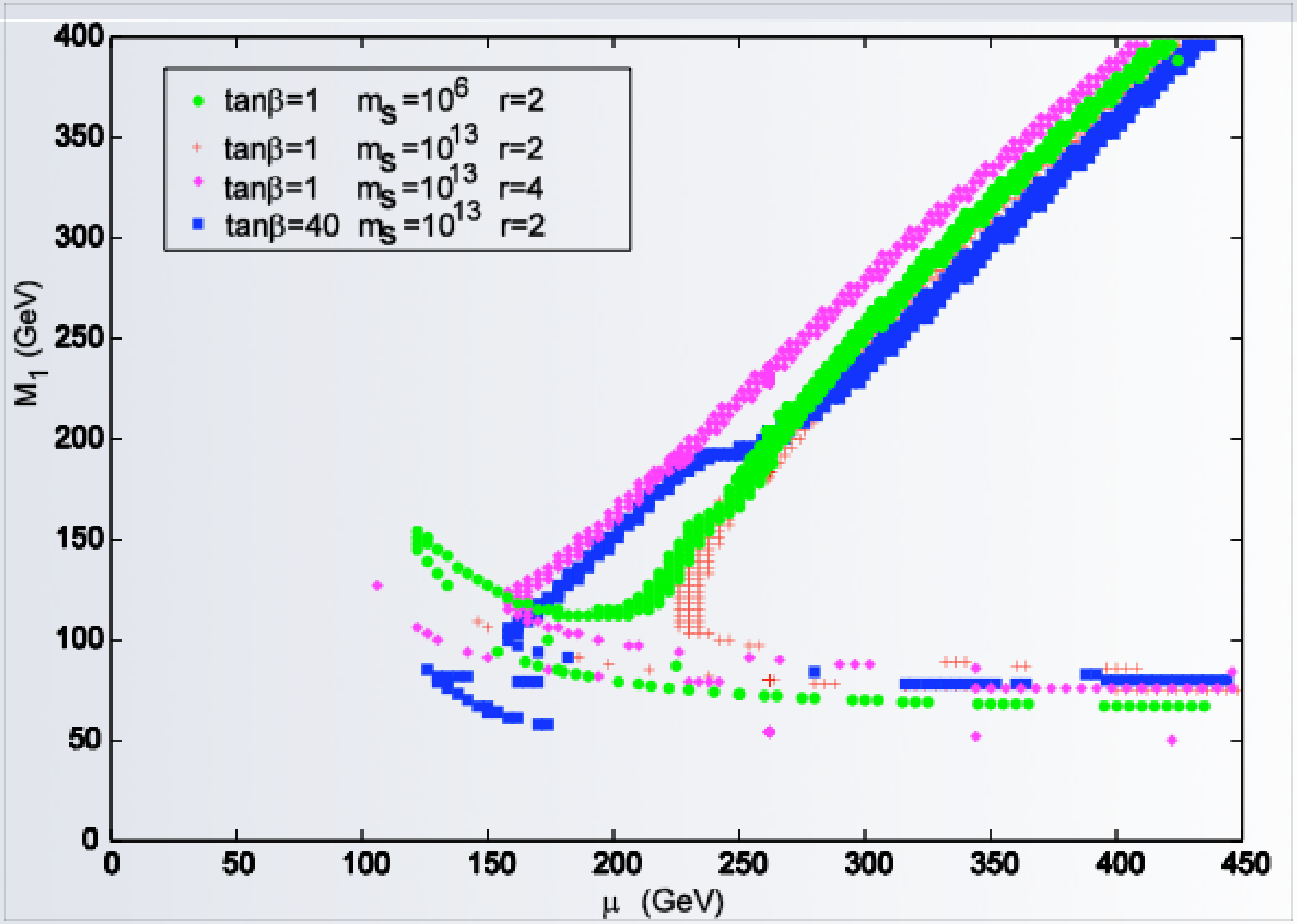
M2 : M1 : M3 = 1 : 3 : 7
M2 = 2.2 TeV

$$\int \frac{X^* X Q^* Q d^4\theta}{M_*^2} \Rightarrow$$ 100 TeV Scalar Masses

"Bulk" Allowed Region

$r = M_2 / M_1$

m_s SUSY breaking scale



AP, Phys.Rev. D70:075006,2004

Mu problem?

- Crucial that mu~M1. (NMSSM?)

$$W = \lambda X Y^2 + \kappa X H_U H_D \Rightarrow$$

$$V \supset \lambda^2 |Y|^4$$

$$m_X^2 > 0, m_Y^2 < 0 \Rightarrow$$

$$< Y > \sim m_S, < X > = 0.$$

$$L \supset A \tilde{X} \tilde{Y}^2 \Rightarrow < X > \sim A.$$

AP

Direct Detection of Dark Matter

- Look for WIMP colliding with a nucleus.

  (e.g. C

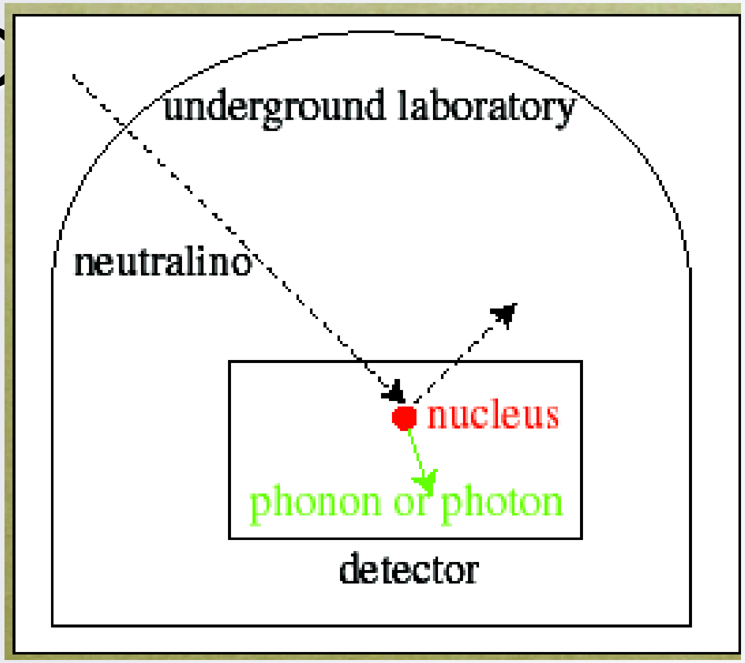
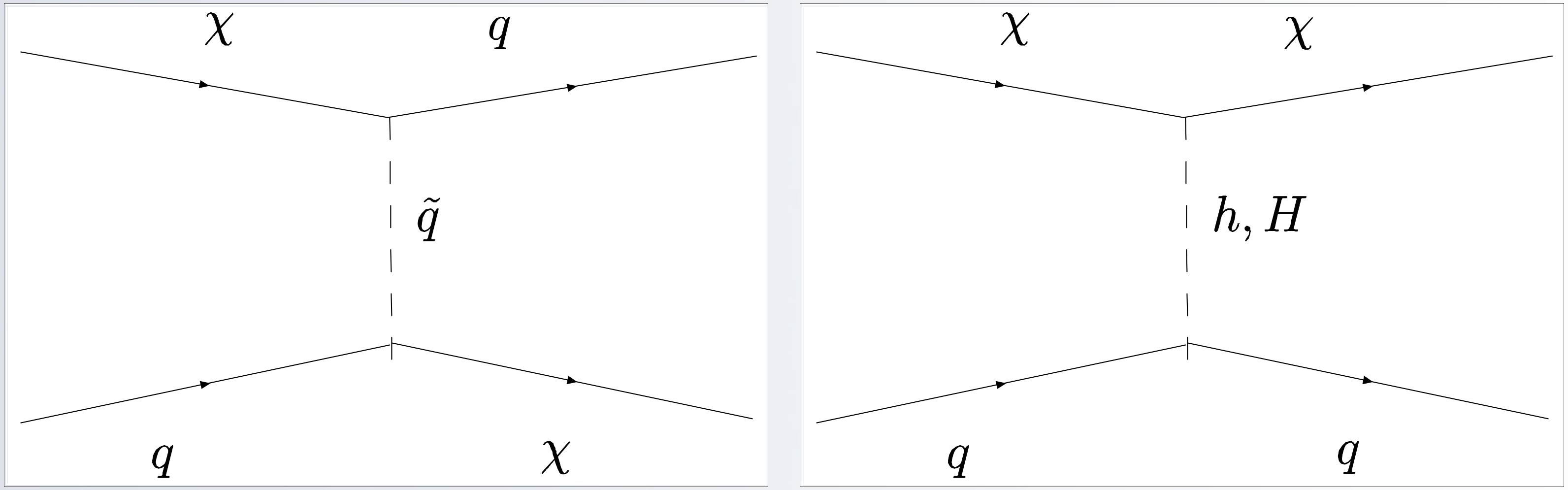
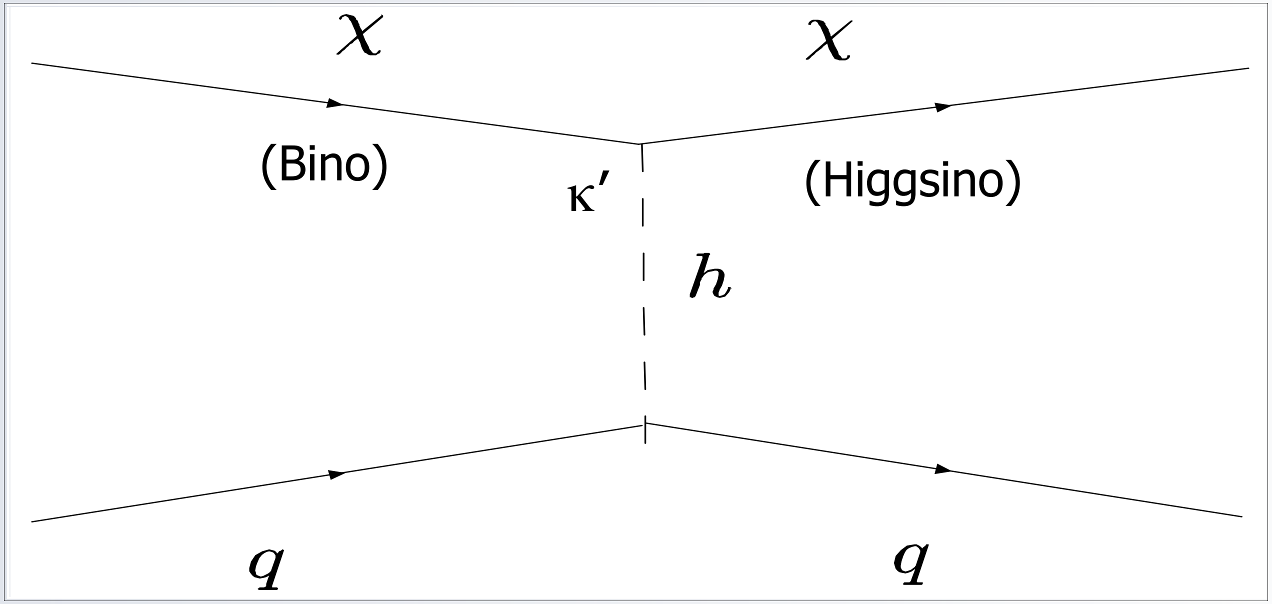


Figure from
H. Murayama

Direct Detection (MSSM)

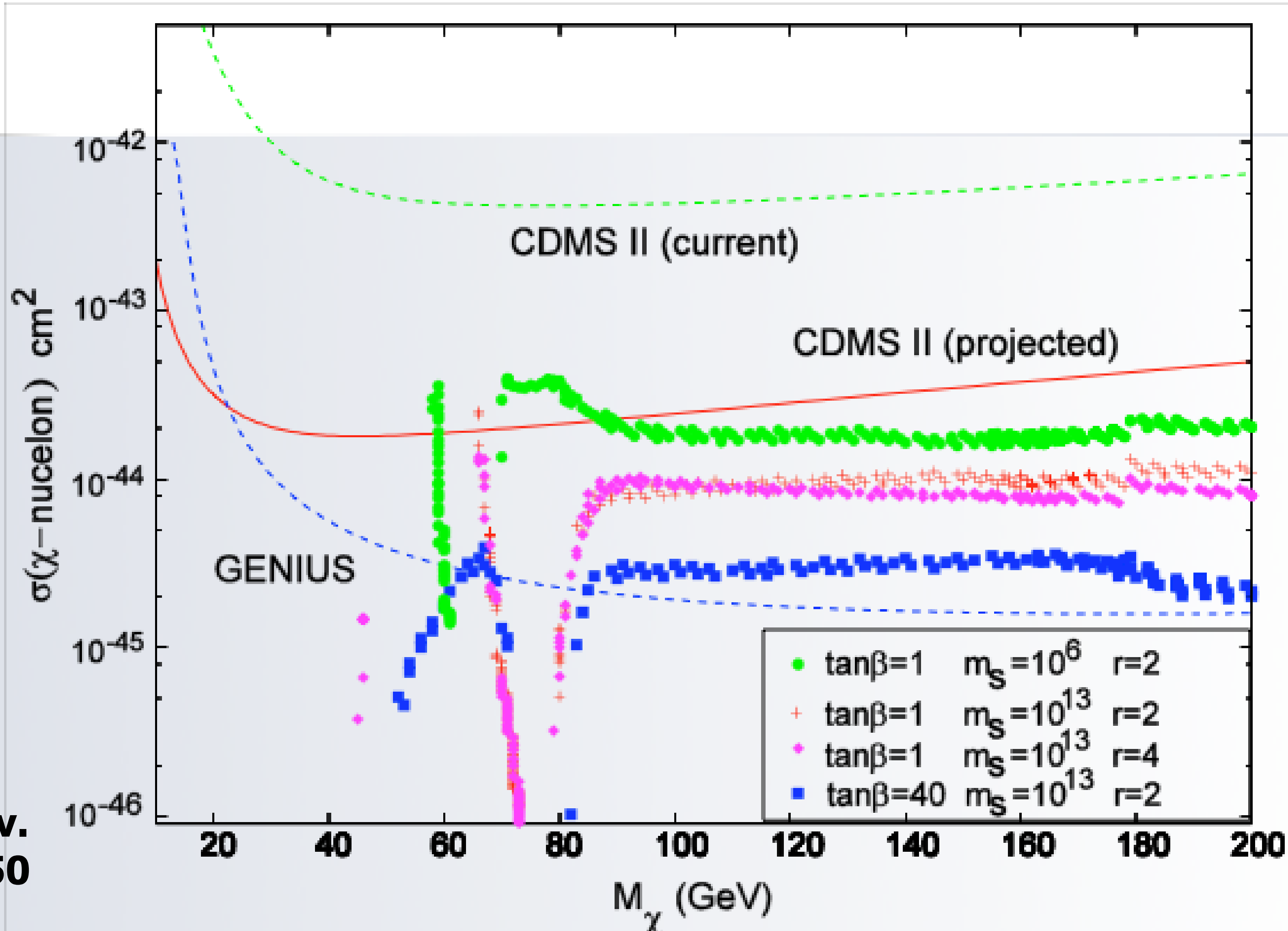


Direct Detection Split SUSY



- Mixed Dark Matter
- Higgs Boson is somewhat heavier
- Use Modified DarkSUSY

Direct Detection



AP, Phys.Rev. D70:075006,2004

Gluino Cosmology

- Heavy Squarks→ Long Lived Gluino
- A Possible Collider Signal
- A Possible constraint…
  - Exotic Isotopes (heavy hydrogen)
  - BBN
  - CMBR/Gamma Rays

Ongoing discussions with S. Dimopoulos, J. Wacker, Graham, Arvanitaki, Davis

Constraints from BBN

- Radiative Decays Ellis et al. (1992)
- **Hadronic Decays** Dimopoulos et al. (1988)

Scatter off of electrons/photons or **nuclei.**

Compute the Relic Abundance

- Again, solve the Boltzman equation. Compute freeze-out temperature.

$$\ln\left\{\frac{\langle\sigma^{\rm ann}v\rangle}{4\pi^3}\sqrt{\frac{45}{2g^*(T_F)G_N}}\,m_{\tilde{g}}g_{\tilde{g}}x_F^{-1/2}\right\} = x_F$$

X=m/T

$$\langle\sigma^{\rm ann}v\rangle = \frac{1}{8m_{\tilde{g}}^4 T K_2^2(m_{\tilde{g}}/T)}\int_{4m_{\tilde{g}}^2}^{\infty}\sigma^{\rm ann}(s)s^{3/2}\beta^2 K_1(\sqrt{s}/T)ds$$

$$\frac{1}{Y_0} - \frac{1}{Y_F} = \left[\frac{45G_N}{\pi}\right]^{-1/2}\int_{x_F}^{x_0}\frac{h^*(T)}{\sqrt{g^*(T)}}\frac{m_{\tilde{g}}}{x^2}\langle\sigma^{\rm ann}v\rangle dx\ ,$$

Y=n/s

See Gondolo and Gelmini (1991)

How does annihilation proceed?

Baer, Cheung and Gunion (hep-ph/9806361)

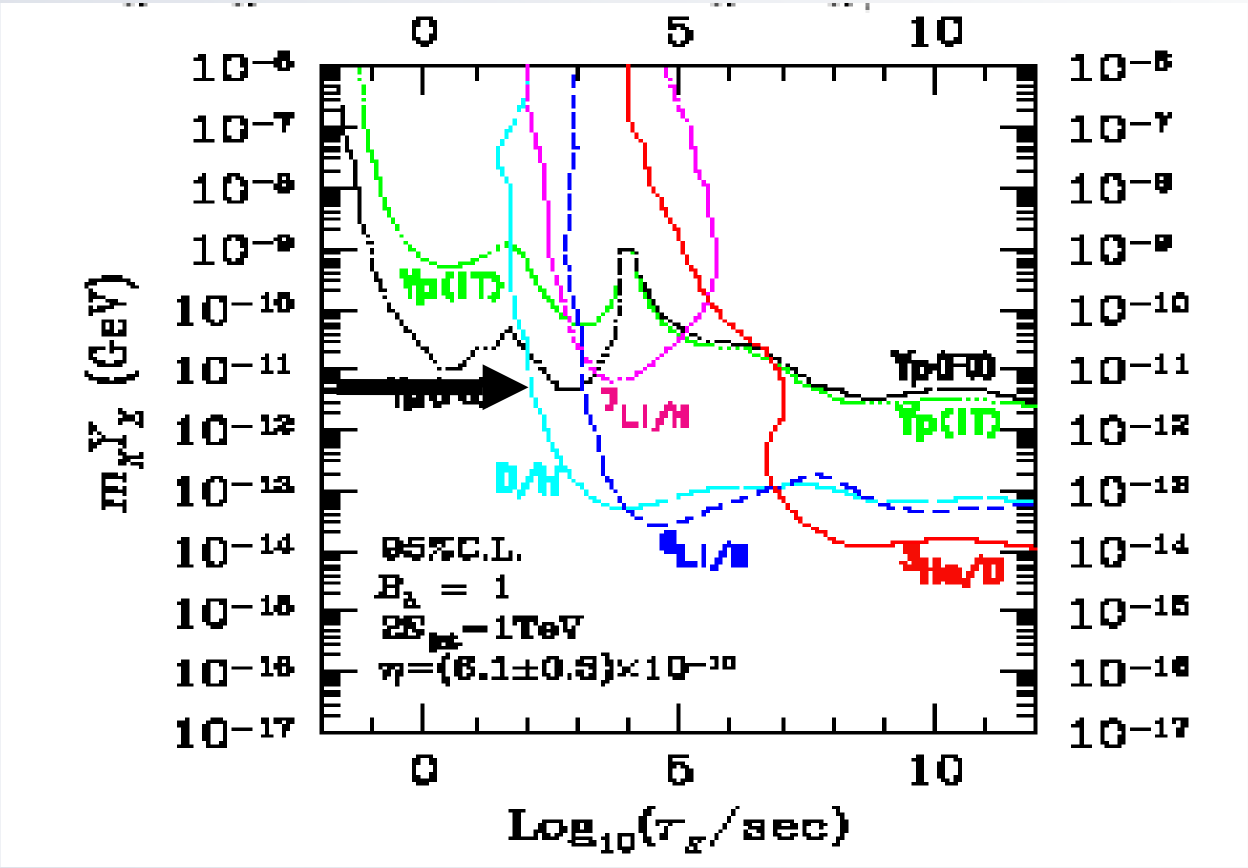
- Perturbative Annihilation

$$\sigma(\tilde{g}\tilde{g} \to gg) = \frac{3\pi\alpha_s^2}{16\beta^2 s}\left\{\log\frac{1+\beta}{1-\beta}\left[21 - 6\beta^2 - 3\beta^4\right] - 33\beta + 17\beta^3\right\}$$

$$\sigma(\tilde{g}\tilde{g} \to q\bar{q}) = \frac{\pi\alpha_s^2\overline{\beta}}{16\beta s}(3-\beta^2)(3-\overline{\beta}^2).$$

- Sommerfeld Enhancement
  - (due to low velocity)
- Gluinonia? R-Hadrons?

BBN Constraints



Kawasaki, Kahri and Moroi (hep-ph/0402490)

Additional Annihilation

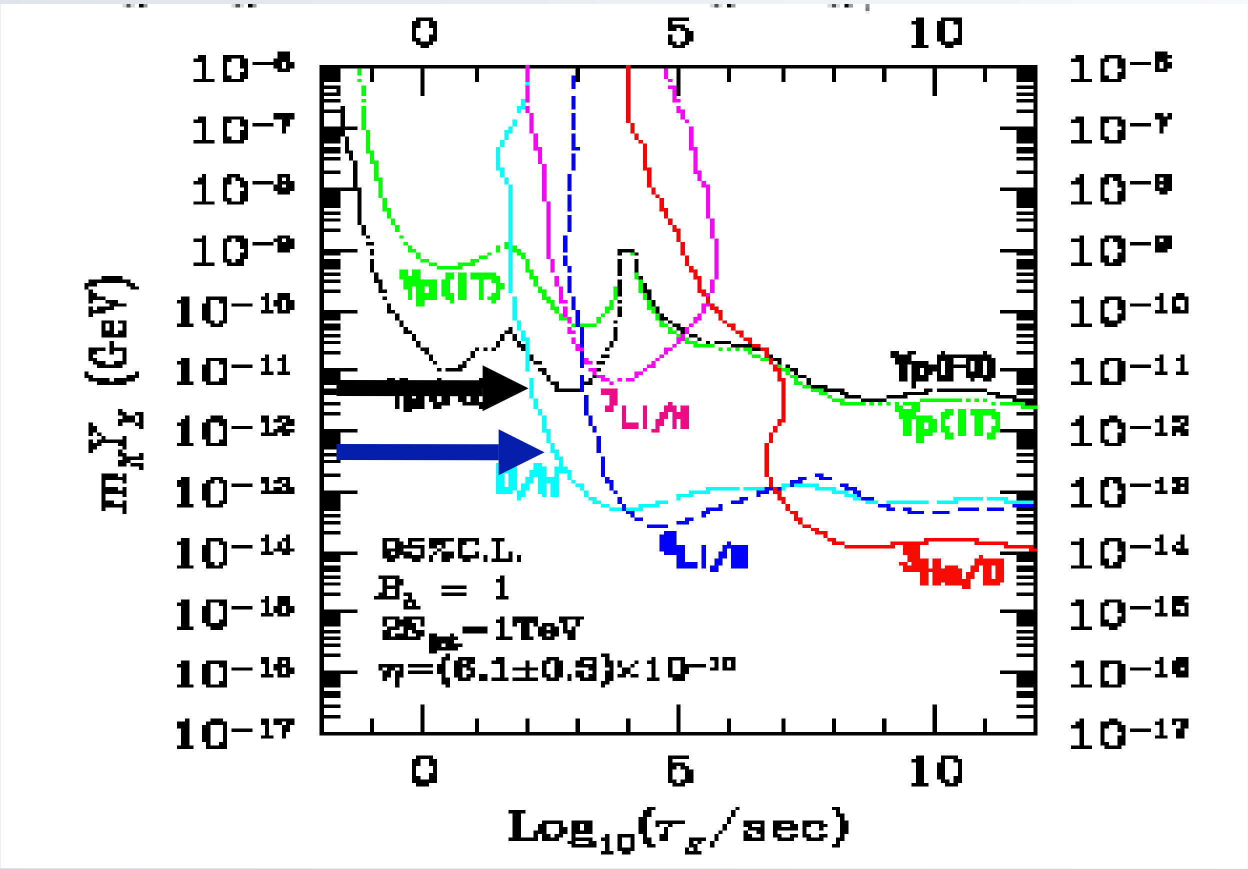
- Extreme possibility→ gluinos annihilate with

$$\sigma \approx 1/\Lambda_{QCD}^2$$

- This evades all BBN constrains by ~factor 30.
- More likely: use "heavy gluino effective theory". Assume saturates s-wave unitarity.

$$\sigma \approx 4\pi/k^2 \approx 4\pi/(m_g^2\beta^2)$$

BBN Constraints



Kawasaki, Kahri and Moroi (hep-ph/0402490)

Conclusions

- Dark Matter provides the link to the weak scale in the split story.
- Split SUSY Dark Matter is simpler
- Mixed case accessible at Direct Detection and LHC→ confirm DM!
- Tells us something about MSSM without resonances and co-annihilations.

Gluino Lifetime

$$\tau \approx 8\left(\frac{m_S}{10^9\ \mathrm{GeV}}\right)^4\left(\frac{1\ \mathrm{TeV}}{m_{\tilde{g}}}\right)^5 \text{seconds}$$

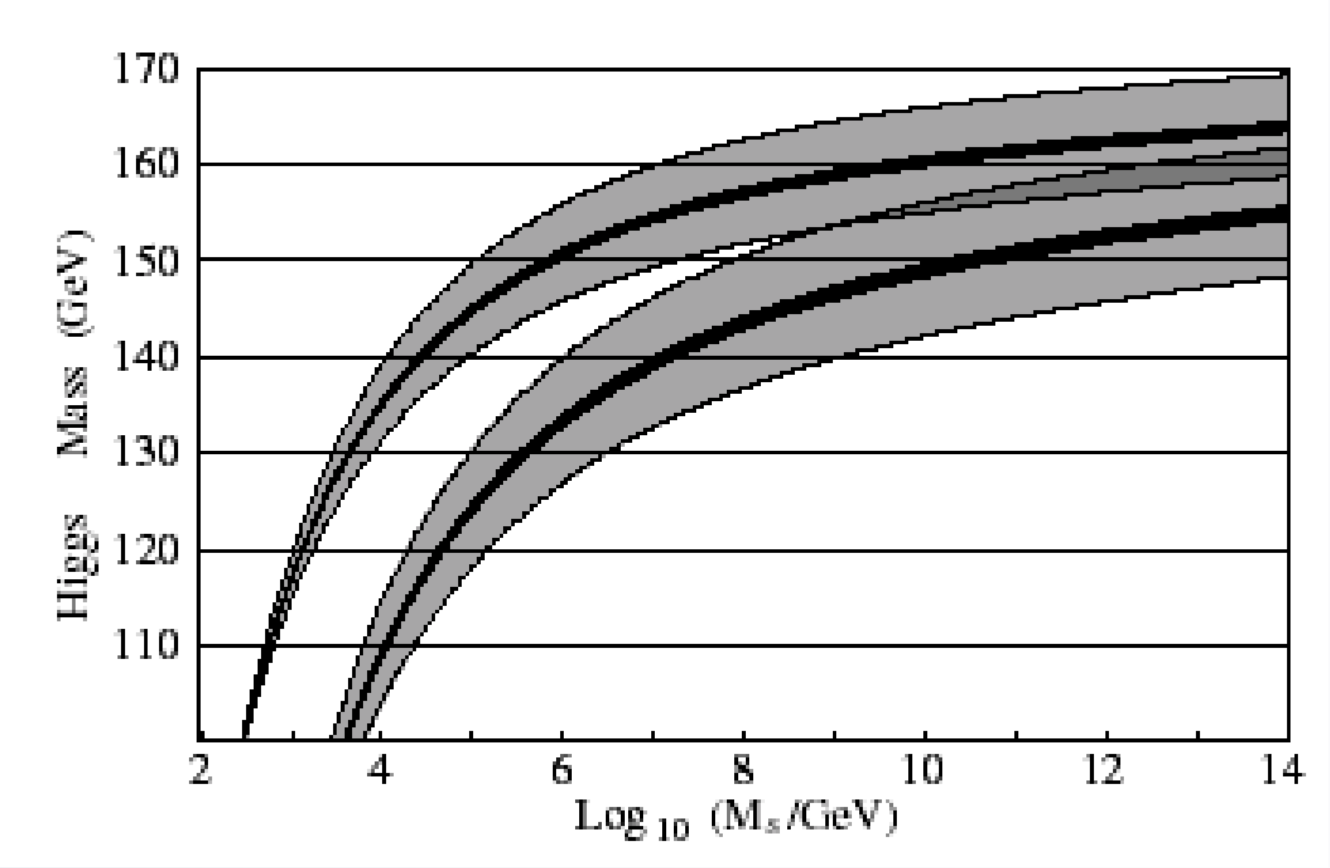
Dawon, Eichten, Quigg (1985)

Indirect Detection

Dependent on model of galactic halo.
  Can see gamma annihilation?
  Some optimism for pure wino region.

Arvanitaki and Graham hep-ph/0411376
Masiero et al. hep-ph/0412058

Higgs Mass



Wacker, et al. (2004)

Other Possibilities for Dark Matter

- Gravitino Decay could provide additional source of Dark Matter.

→lighter DM (all other things equal)

- Depends on reheat temp, and mass of gravitino. (Arkani-Hamed, Dimopoulos, Giudice, Romanino)