DARK MATTER: THEORY

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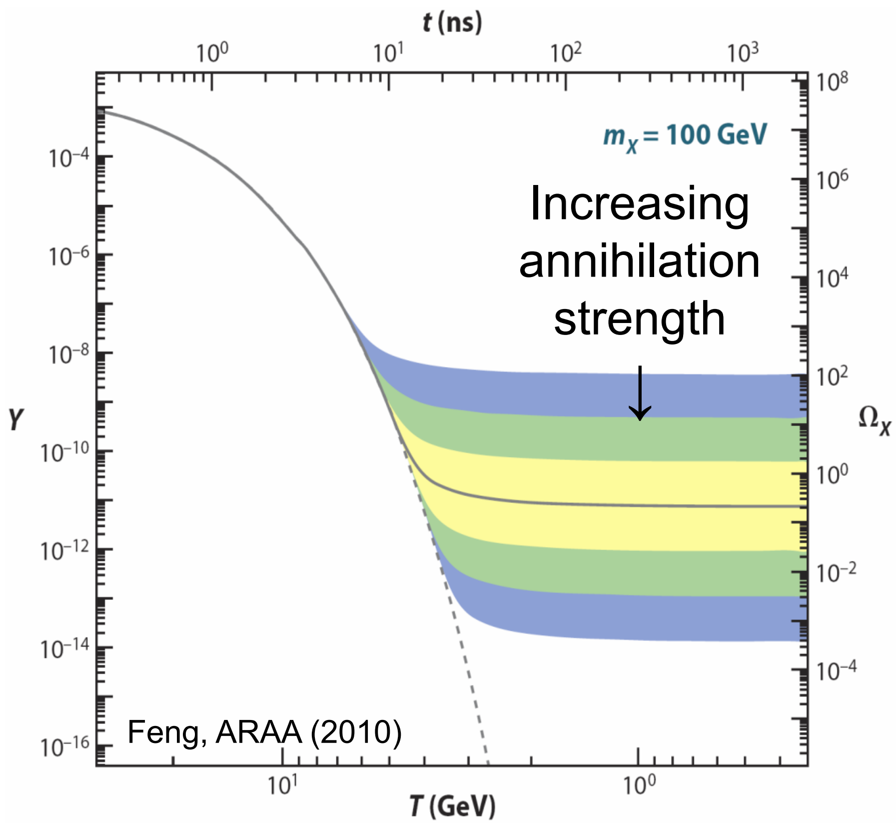
OUTLINE

- WIMPs: Current Status and the LHC
- DAMA, CoGeNT, CRESST
- WIMPless Dark Matter

Note: This is not an overview. Why?

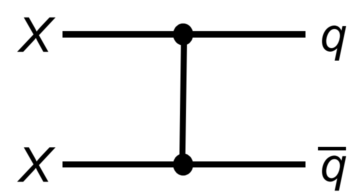
- See talks of Aaron Pierce, Dan McKinsey, Simona Murgia
- Sentimentality for when people talked about what they were excited about
- Some people seem depressed, I'd like to help

THE WIMP MIRACLE



- Thermal freeze out: the relation between Ω_X and annihilation strength is wonderfully simple:

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

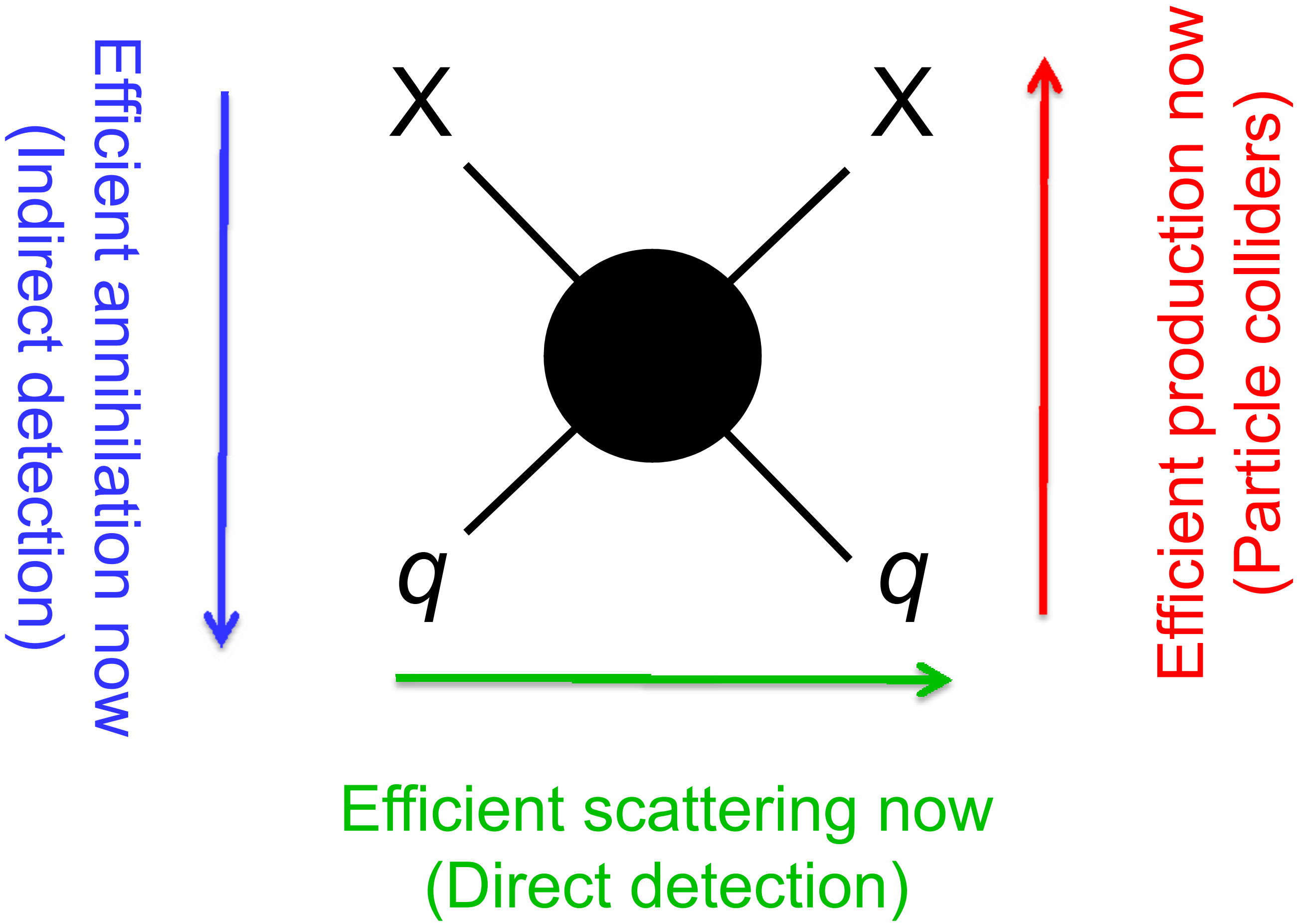


- $m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

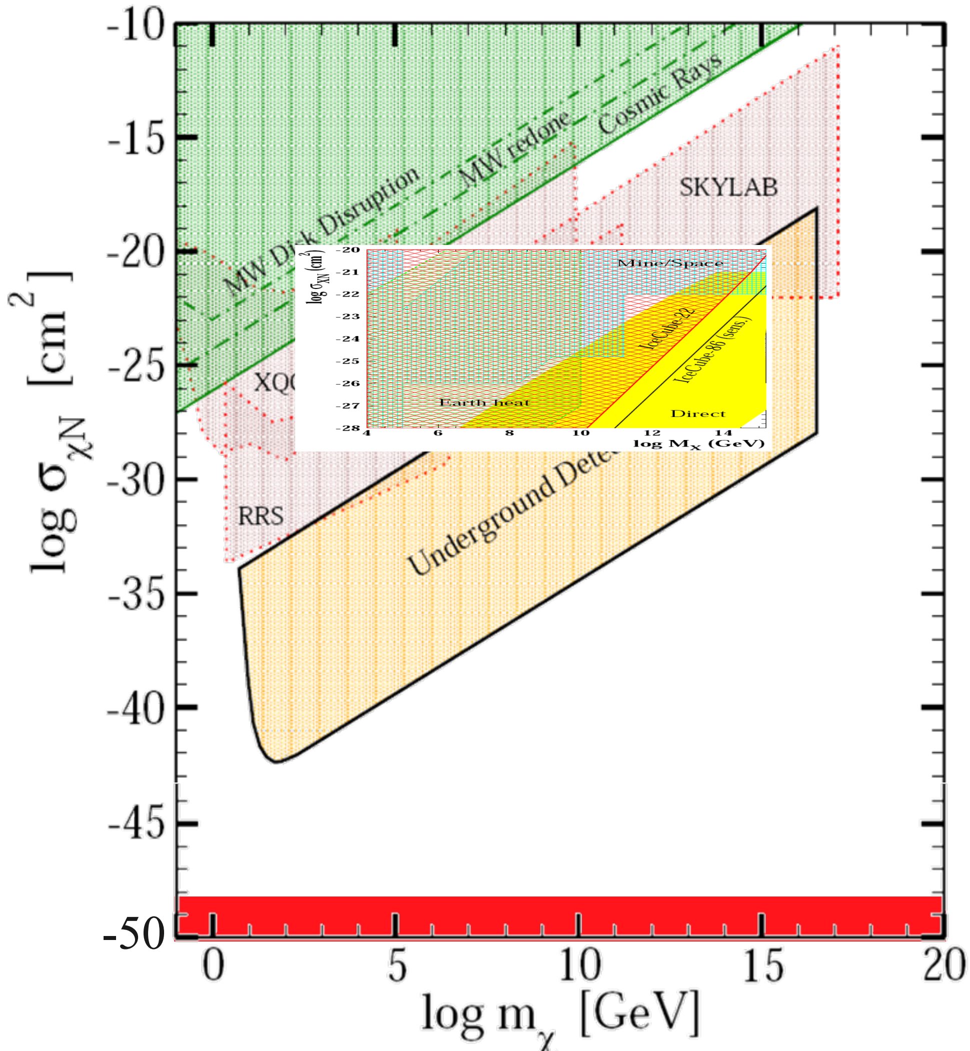
- Remarkable coincidence: both particle physics and cosmology point to weak-scale mass particles

EXPERIMENTAL PROBES

Correct relic density → Efficient annihilation then



DIRECT DETECTION: BIG PICTURE



- DM scattering off SM is probed by many experiments

  Mack, Beacom, Bertone (2007)

- Strongly-interacting window is now (almost) closed

  Albuquerque, de los Heros (2010)

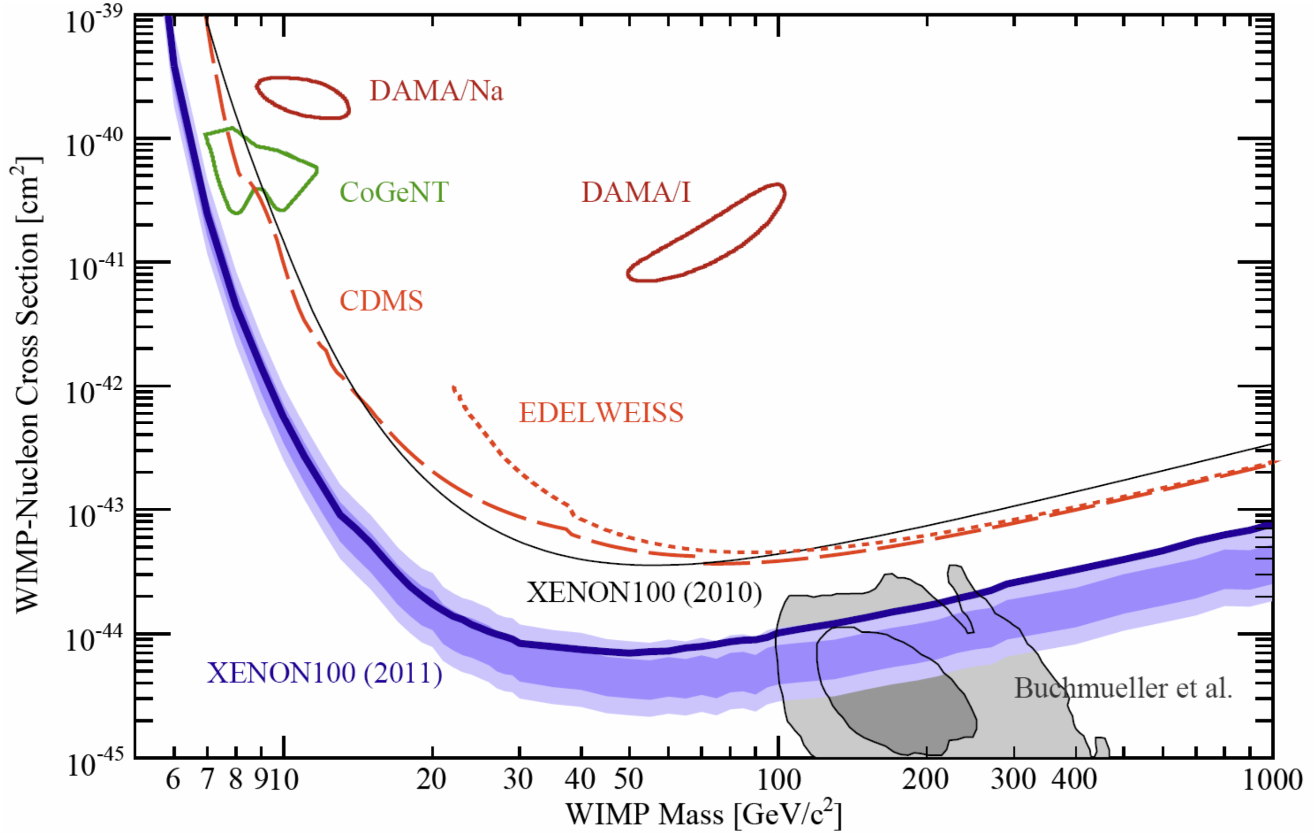
- Neutrino background provides an effective lower limit at $\sigma \sim 10^{-48}$ cm^2 ~ yb ~ 10^{-3} zb [~10 ton, non-directional]

  Strigari (2009)
  Gutlein et al. (2010)

- These considerations delimit a well-motivated, well-defined research program

CURRENT STATUS

- The excitement at low cross sections stems from the confrontation of experiment with theory
- How robust and interesting are the theoretical predictions?

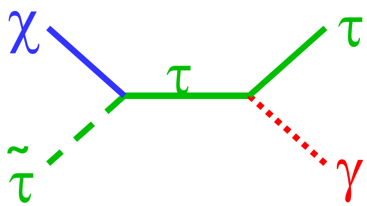


MINIMAL SUPERGRAVITY

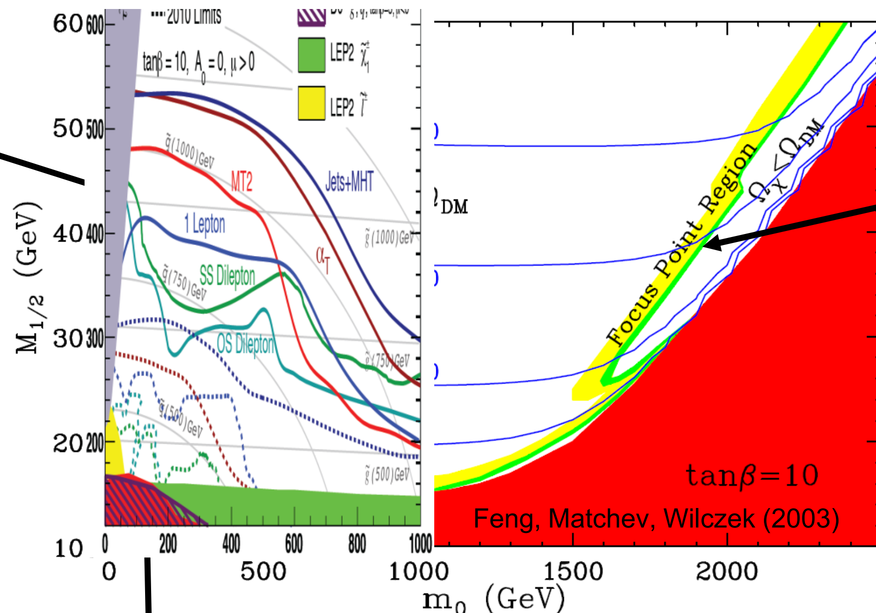
- mSUGRA/CMSSM: 4+1 parameters
- Require $\Omega_\chi = 0.23$
- LHC searches eliminate some possibilities, but not others

Ehrenfeld, Melzer-Pellmann talks

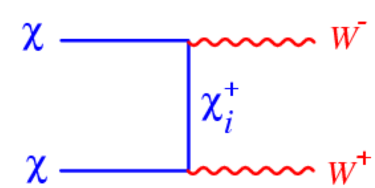
Co-annihilation region



Degenerate χ and stau

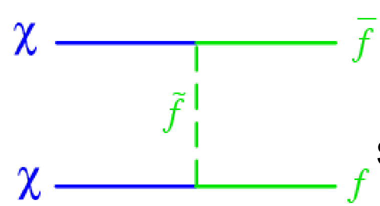


Focus point region



Mixed Higgsino-Bino Neutralinos

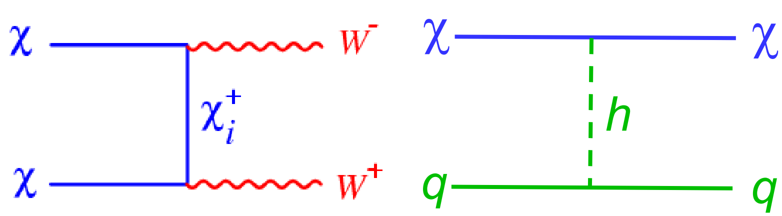
Bulk region



Light sfermions

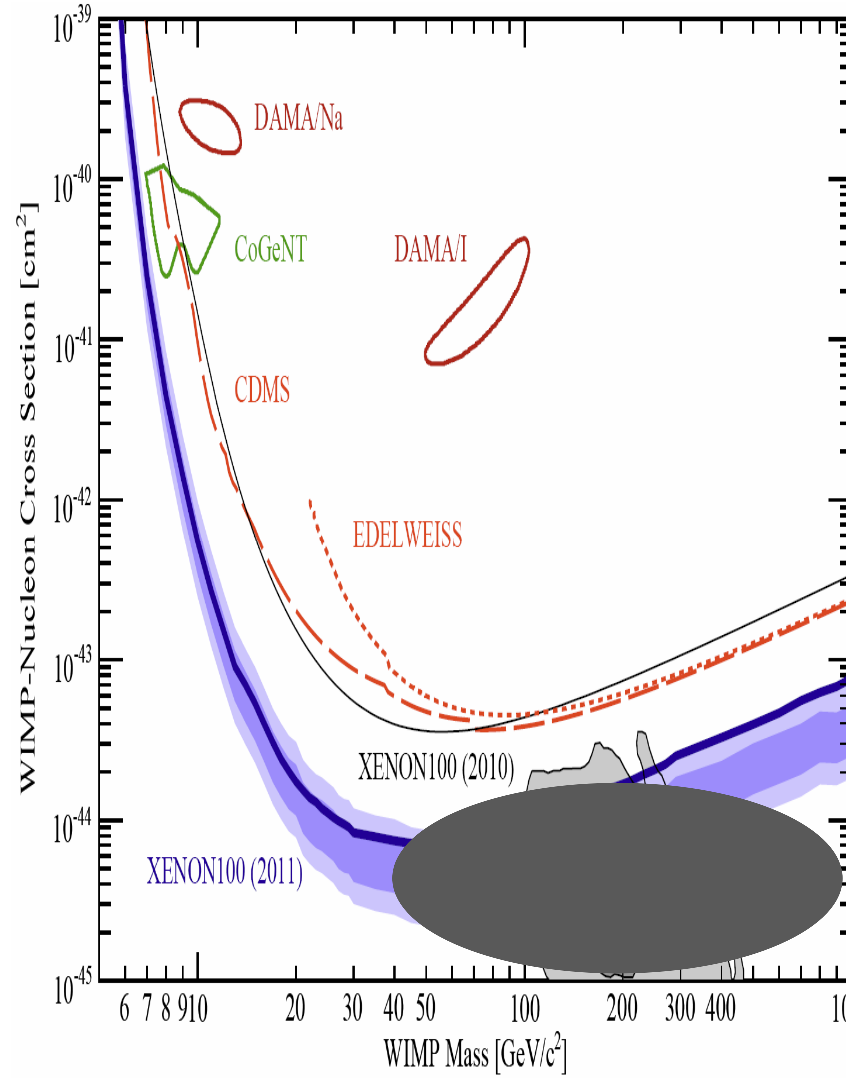
FOCUS POINT REGION

- Two main features:
  - Squarks/sleptons heavy (> 1.5 TeV)
  - Gauginos/Higgsinos lighter, $M_1 < M_{2,3}$
- Relic density determines Higgsino vs. Bino mixture, but this also fixes the scattering cross section



- Predictions collapse to a region with σ ~ 1-10 zb

- The LHC has excluded models with low cross sections, and left those with extremely bright prospects for DM detection



10 TOP TEN

FAQs about the LHC and SUSY

10 Isn't SUSY excluded by the LHC?

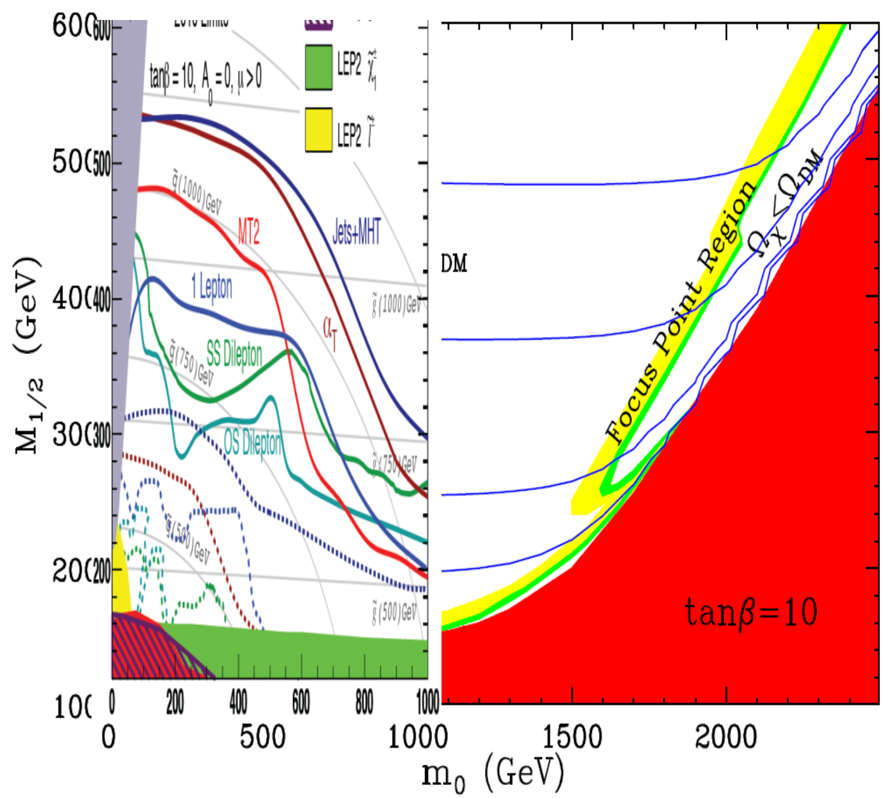
- The last time I heard so many levels of misunderstanding packed into such a short question, it was "Isn't evolution just a theory?"

9 Isn't mSUGRA/CMSSM excluded by the LHC?

- No – look at the plot! It's fantastic to think about compressed SUSY, etc. if you want, but mSUGRA is doing just fine.

8 Isn't focus point SUSY a pretty thin band of parameter space?

- So is every cosmologically preferred region. Those darn cosmologists!



7 Do people believe in mSUGRA and its ad hoc assumptions?

– No, but many theoretical ideas and models motivate heavy scalars, and they yield the same implications for dark matter as the focus point region

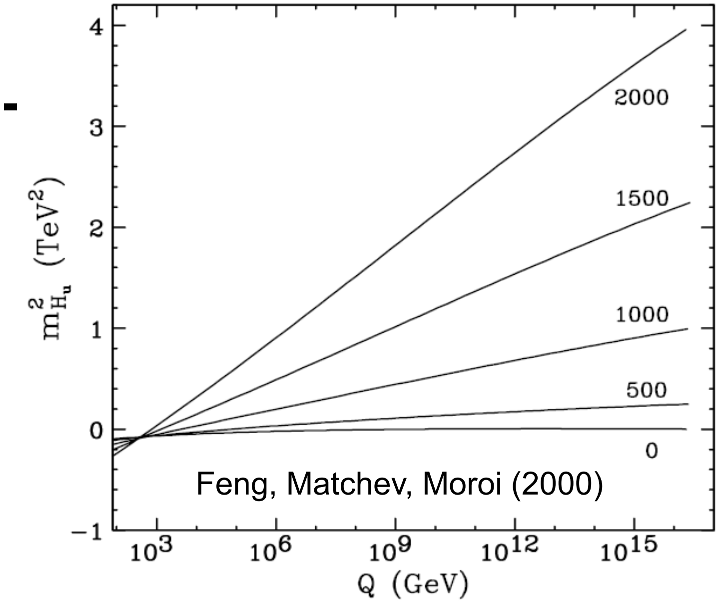
Drees (1986); Dimopoulos, Giudice (1995); Pomarol, Tommasini (1996); Cohen, Kaplan, Nelson (1996); Agashe, Graesser (1999); Dvali, Pomarol (1996); Mohapatra, Riotto (1997); Zhang (1997); Hisano, Kurosawa, Nomura (1999); Bagger, Feng, Kolda, Polonsky (1999); Arkani-Hamed, Dimopoulos (2004), Giudice, Romanino (2004); Feldman, Kane, Kuflik, Lu (2011); …

6 Aren't heavy scalars unnatural?

– Naturalness is a spectacularly brittle concept. People probably thought the neutrality of the hydrogen atom was a big problem (it's fine-tuned to 1 part in 10^{20} – quick, pull out the anthropic principle!), then along came anomaly cancelation.

5 But isn't the electroweak scale very fine-tuned?

– So 1 TeV is natural and 2 TeV isn't? What if you had 12 fingers? Anyway, focus point SUSY is not fine-tuned, in the sense of m_Z being sensitive to variations in the fundamental SUSY-breaking parameters.



4 But why should the superpartners be so heavy?

– EDMs, proton decay and coupling constant unification, and the Higgs mass all point toward multi-TeV scalars.

3 Isn't FP SUSY excluded by dark matter?

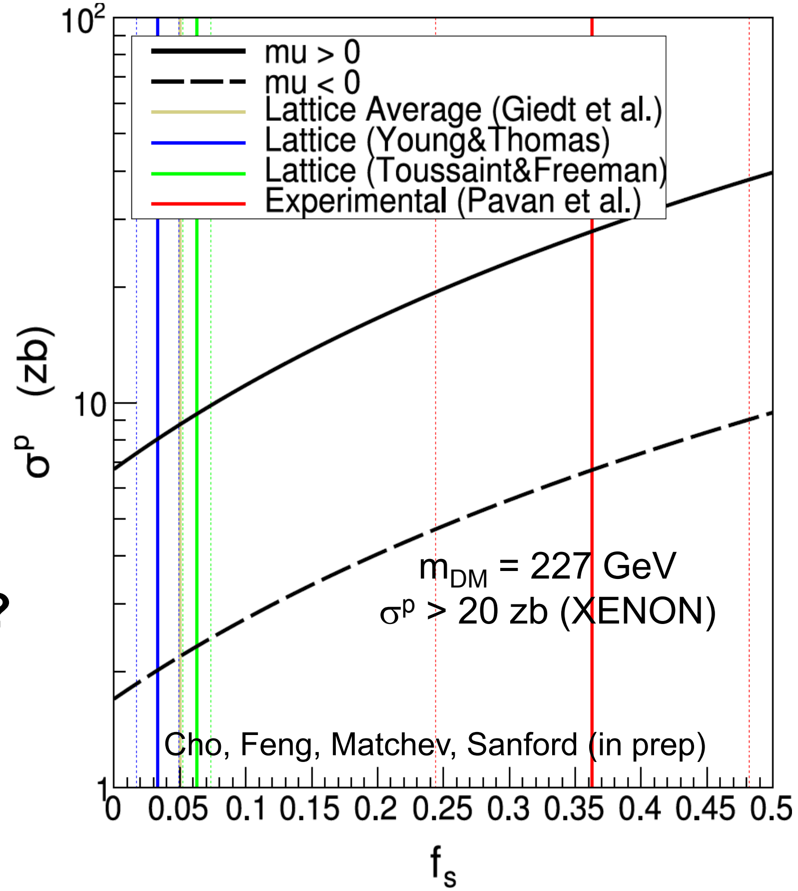
– It depends on the strange quark content and the sign of mu.

2 Didn't many people think SUSY should have been below a TeV?

– So what? Anyway, they might be right (see 9).

1 Doesn't $(g\text{-}2)_\mu$ require light superpartners?

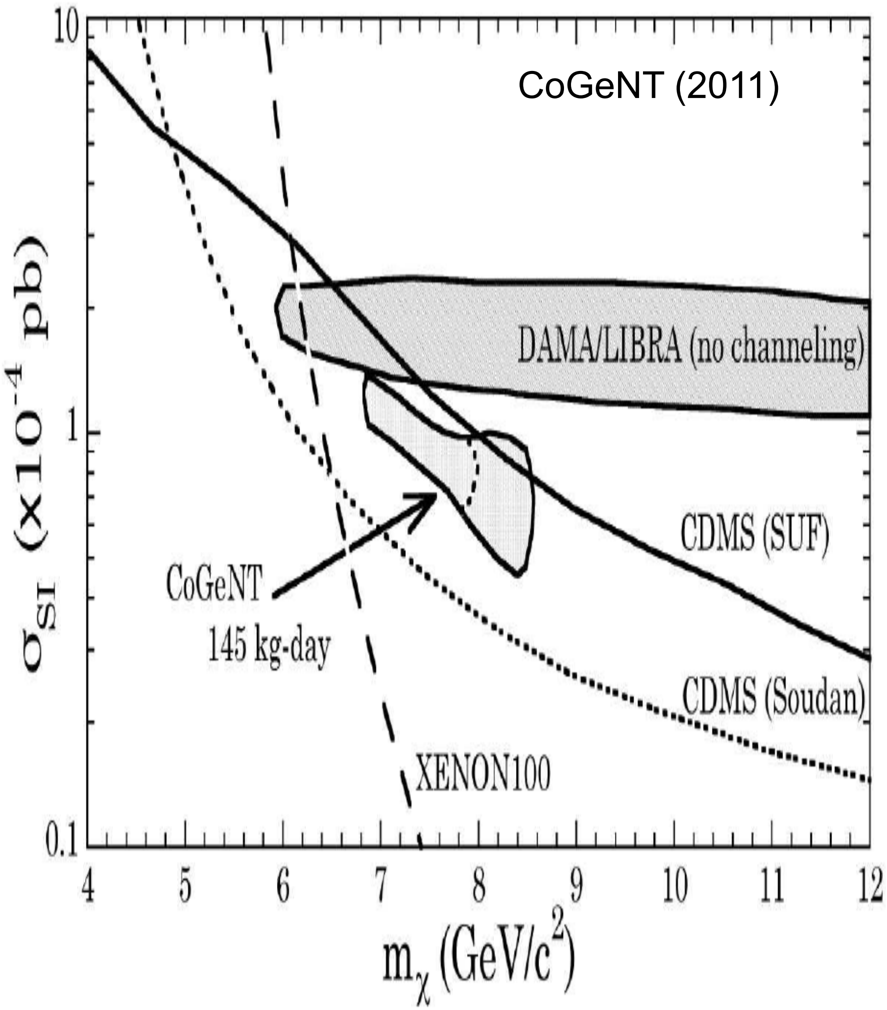
– Yes. And if you think smuons and squarks have to be degenerate, I have some beautiful ocean front property in Florida to sell you.



DAMA, COGENT, CRESST

- Direct detection signals reported
  - DAMA/LIBRA ann. modulation
  - CoGeNT
  - CoGeNT ann. modulation
  - [CRESST]
- Theoretical puzzles
  - Low mass and high σ
  - DAMA ≠ CoGeNT
  - Excluded by XENON, CDMS
- Many proposed explanations

Hooper, Collar, Hall, McKinsey (2010)
Fitzgerald, Zurek (2010)
Fox, Liu, Weiner (2010)
…



ISOSPIN-VIOLATING DARK MATTER

Giuliani (2005); Chang, Liu, Pierce, Weiner, Yavin (2010); Feng, Kumar, Marfatia, Sanford (2011)

- DM scattering off a nucleus is coherent
  - $\sigma_A \sim [\, f_p Z + f_n (A-Z)\,]^2$
- (Implicit) assumption of most of the literature: $f_n = f_p$
  - $\sigma_A \sim (f_p A)^2$
  - Can present all results for various target nuclei in the (m, σ_p) plane
  - A^2 scaling touted as "smoking gun" signature of DM
- But this is a completely unwarranted assumption – for example, consider non-degenerate up and down squarks

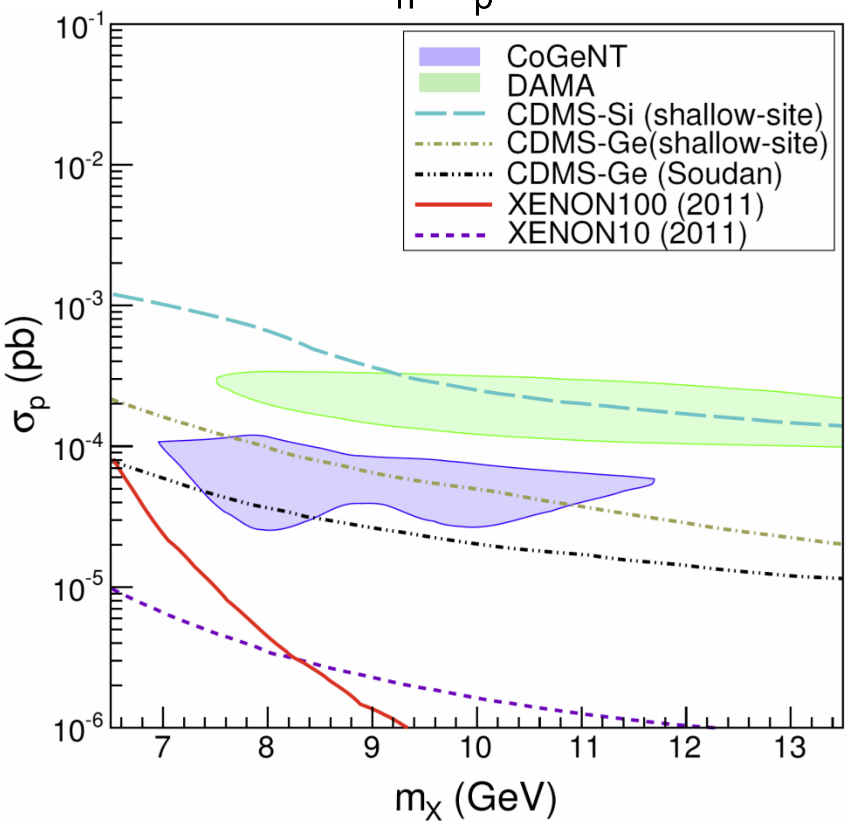
- To investigate IVDM, introduce 1 extra parameter: f_n / f_p
- Can decouple one experiment with $f_n / f_p = -Z / (A - Z)$
- Not exactly: many detectors have more than one isotope

TABLE II. A_i for isotopes and their fractional number abundances η_i in percent for all isotopes with $\eta_i > 1\%$.

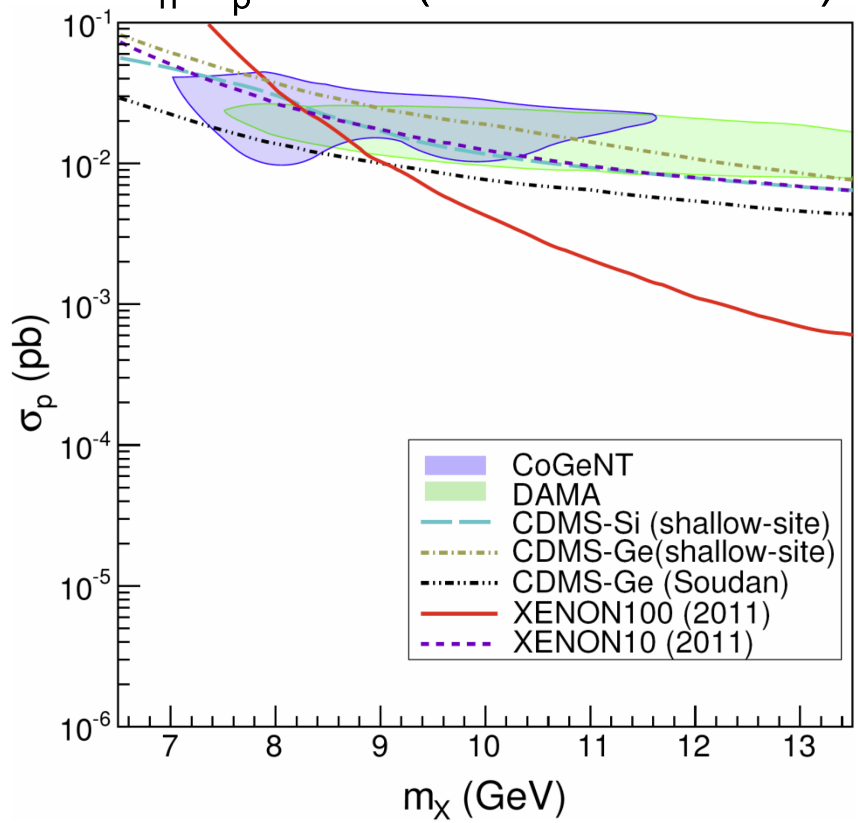
Xe	Ge	Si	Ca	W	Ne
128 (1.9)	70 (21.2)	28 (92.2)	40 (96.9)	182 (26.5)	20 (90.5)
129 (26.4)	72 (27.7)	29 (4.7)	44 (2.1)	183 (14.3)	22 (9.3)
130 (4.1)	73 (7.7)	30 (3.1)		184 (30.6)	
131 (21.2)	74 (35.9)			186 (28.4)	
132 (26.9)	76 (7.4)				
134 (10.4)					
136 (8.9)					

RECONCILING XENON/DAMA/COGENT

$f_n / f_p = 1$



$f_n / f_p = -0.7$ (-0.63 to -0.74 ok)



IMPLICATIONS OF IVDM

- Minimal IVDM is extremely predictive. Given $f_n / f_p = -0.7$ to maximally decouple XENON, predictions for all other elements are fixed.

- Success: DAMA and CoGeNT match

- Problems: CoGeNT and CDMS (marginally?) inconsistent; SIMPLE

Collar (2011); Frandsen et al. (2011); Chen, Zhang (2011); Schwetz, Zupan (2011)
Gao, Kang, Li (2011); Gao, Kumar, Marfatia (2011); An, Gao (2011); …

- Future: CRESST, XENON, COUPP, … should see signals. As conventionally plotted (assuming $f_p = f_n$),

$$\sigma_p(\text{oxygen, carbon}) \approx 8.4\ \sigma_p(\text{germanium})$$
$$\sigma_p(\text{flourine}) \approx 4.2\ \sigma_p(\text{germanium})$$

WIMPLESS DARK MATTER

Feng, Kumar (2008)
Feng, Tu, Yu (2009)

- The thermal relic density is

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

- WIMPs give the right thermal relic density, but so would lighter and more weakly interacting particles (or heavier and more strongly interacting particles)

- In the SM, dark matter cannot have significant EM or strong interactions, leaving only one possibility:
  $g_X \sim g_{weak} \sim 0.6$, that is, WIMPs

HIDDEN DARK MATTER

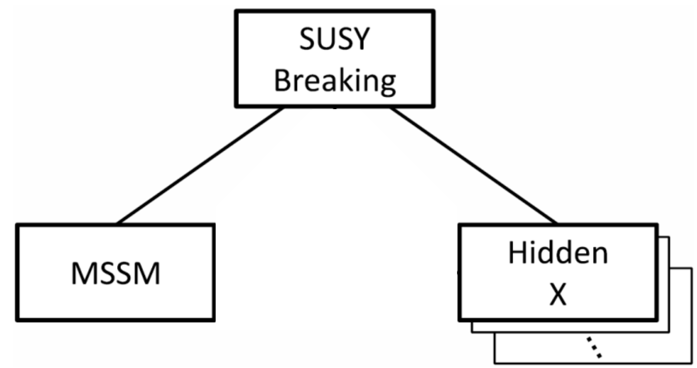
- We could conjure up a hidden sector with a particle that has the right coupling and mass

- This is not a new idea and it is viable, since all solid evidence for dark matter is gravitational

- However, it has traditionally suffered from several drawbacks
  - Too much model-building freedom, lack of predictivity
  - Lack of experimental signals
  - Missing theoretical motivations of more popular DM candidates

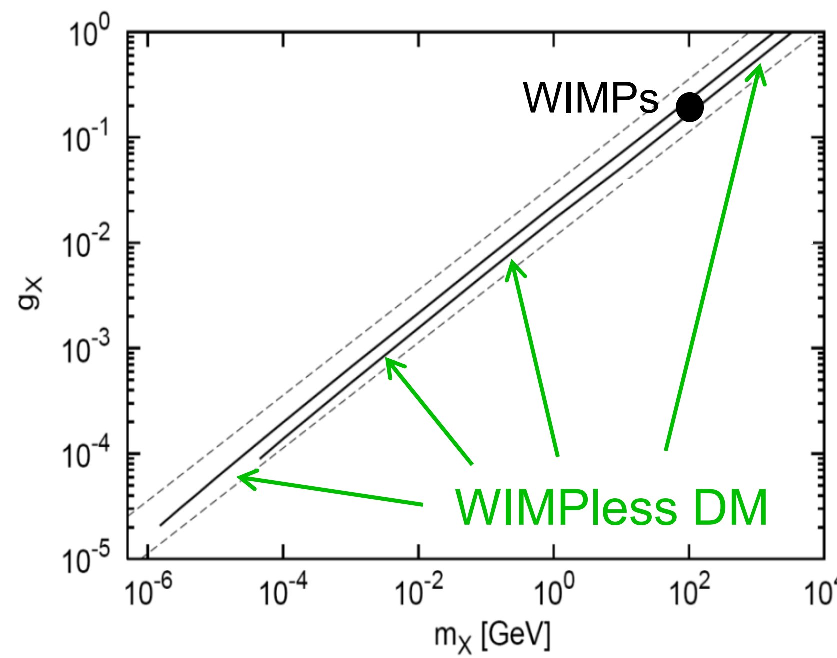
WIMPLESS MIRACLE

- Consider SUSY with a hidden sector. In SUSY models that suppress flavor violation (GMSB, AMSB, no-scale SUGRA, etc.) the masses satisfy $m_X \sim g_X^2$



- This leaves the relic density invariant

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$



- "WIMPless Miracle": hidden sectors of these theories automatically have DM with the right Ω for a large range of masses

- Is this what the new physics flavor problem is telling us?

WIMPLESS SIGNALS

- Direct Detection: easy to obtain DAMA, CoGeNT masses, cross sections

  Feng, Kumar, Strigari (2009)

- SuperK, IceCube

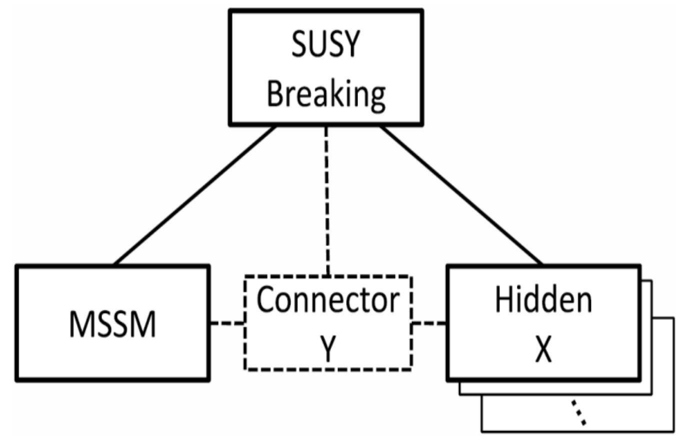
  Hooper, Petriello, Zurek, Kamionkowski (2009)
  Feng, Kumar, Strigari, Learned (2009)
  Kumar, Learned, Smith (2009)
  Barger, Kumar, Marfatia, Sessolo (2010)

- Meson decays

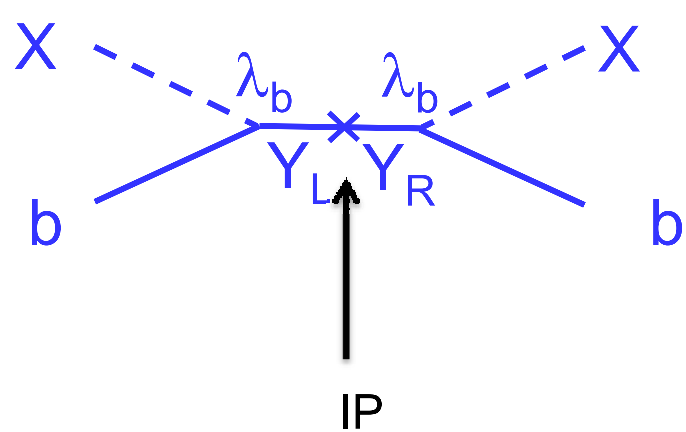
  McKeen (2008)
  Yeghiyan (2009)
  Badin, Petrov (2010)

- Colliders: connectors are non-sequential 4th generation quarks

  Alwall, Feng, Kumar, Su (2010, 2011)
  Warburton talk



$$\mathcal{L} = \lambda_f X \bar{Y}_L f_L + \lambda_f X \bar{Y}_R f_R$$



WIMPLESS AMSB

Feng, Shadmi (2011); Feng, Rentala, Surujon (2011)

- AMSB is a particularly attractive framework for WIMPless dark matter

Randall, Sundrum (1999); Giudice, Luty, Murayama, Rattazzi (1999)

- Masses are $\tilde{m} \sim \frac{g^2}{16\pi^2} M_{3/2}$, where the gravitino mass is ~ 100 TeV, so

$$\frac{m_X}{g_X^2} \sim \frac{1}{16\pi^2} M_{3/2} \sim \frac{m_{\text{weak}}}{g_{\text{weak}}^2}$$

- Extremely predictive: all soft SUSY-breaking masses determined by dimensionless couplings

$$\dot{g} = \frac{1}{16\pi^2} b g^3$$

$$\gamma_i^j = \frac{1}{16\pi^2}\left[\frac{1}{2} y_{imn} y^{jmn} - 2\delta_i^j g^2 C(i)\right]$$

$$M_\lambda = \frac{1}{16\pi^2} b g^2 m_{3/2}$$

$$(m^2)_i^j = \frac{1}{2} \dot{\gamma}_i^j m_{3/2}^2$$

$$A^{ijk} = -(y^{pjk}\gamma_p^i + y^{ipk}\gamma_p^j + y^{ijp}\gamma_p^k) m_{3/2}$$

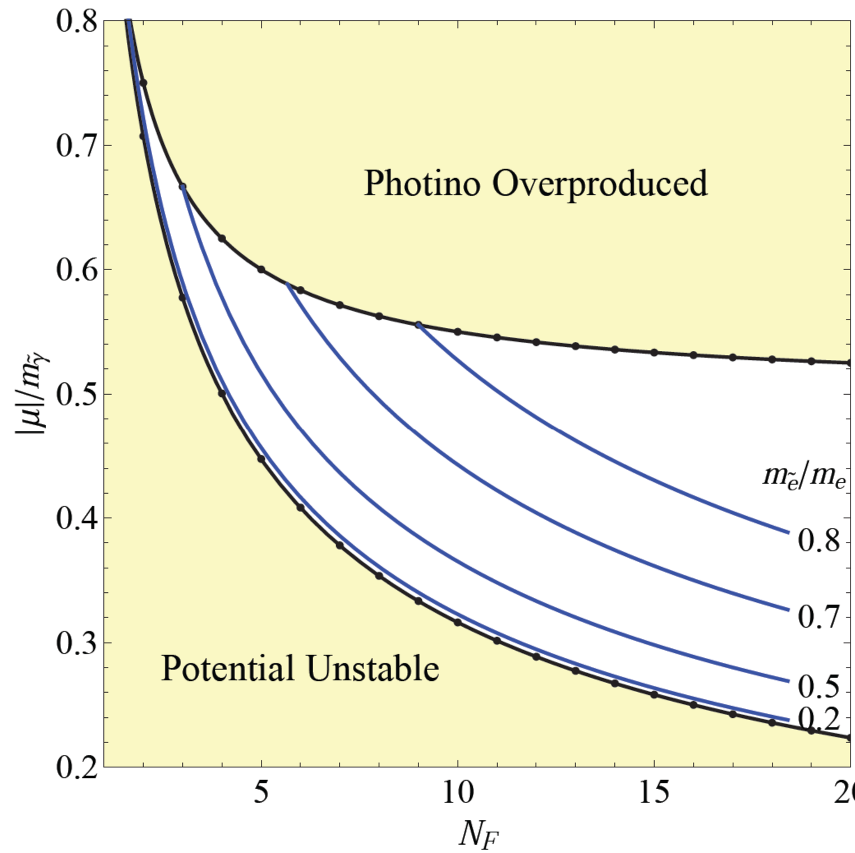
- No good MSSM thermal relic: Ω = 0.23 → Wino mass ~ 2.5 TeV
  (In the MSSM, SU(2) is “accidentally” near-conformal)

AMSB WITH HIDDEN QED

- Consider the simplest possibility: hidden QED with N_F degenerate flavors of leptons and sleptons

$$
\begin{aligned}
m_{\tilde{\gamma}} &= 2N_F \frac{g^2}{16\pi^2} M_{3/2} \\
m_{e_i} &= |\mu| \\
m^2_{\tilde{e}_{i\pm}} &= \sqrt{|\mu|^2 - \frac{m^2_{\tilde{\gamma}}}{N_F}} \\
m_{\gamma} &= 0 \ .
\end{aligned}
$$

- Require vacuum stability, photinos decay to sleptons



Feng, Rentala, Surujon (2011)

MULTI-COMPONENT DM

- Symmetries: U(1) charge, lepton flavor, R-parity

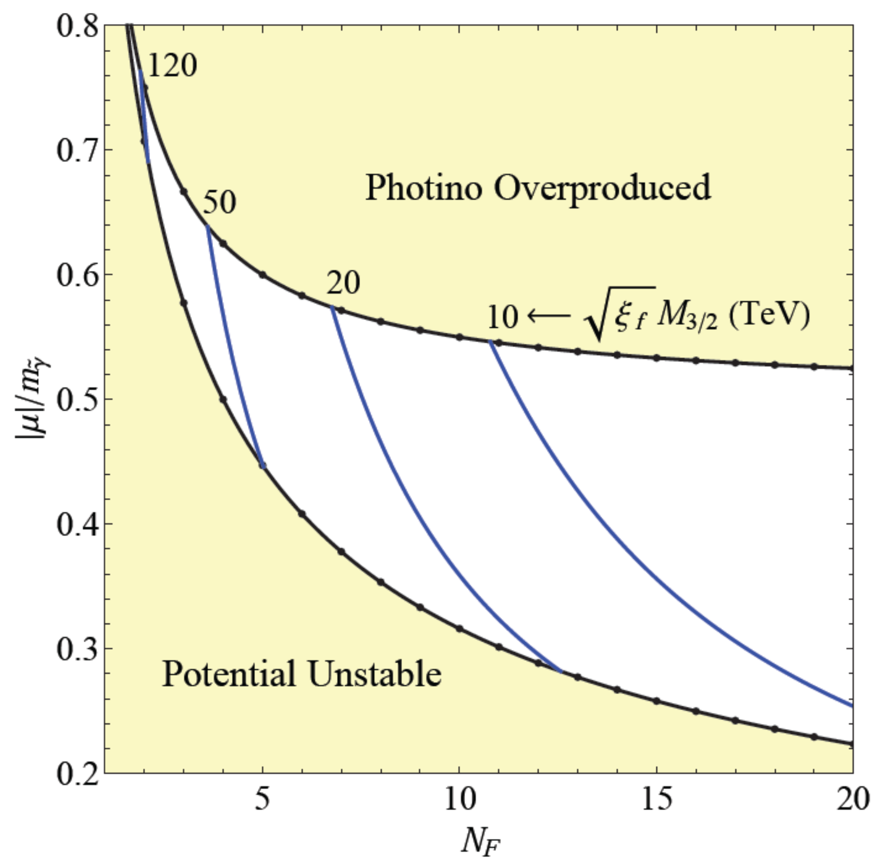
- N_F leptons, N_F sleptons are all stable, all contribute significantly to relic density

- Annihilate to massless hidden photons

- Correct relic density for

  $\xi = T^h / T^v \sim 1$

  $M_{3/2} \sim 100$ TeV



SIGNALS

- The hidden photons are massless and the DM is hidden (s)leptons
- Dark matter self-interacts through Coulomb interactions, with a wealth of interesting implications (halo shapes)
- Photons contribute $\Delta N_{\rm eff} \sim 0 - 2$ and is 0.2-0.4 in the simplest models

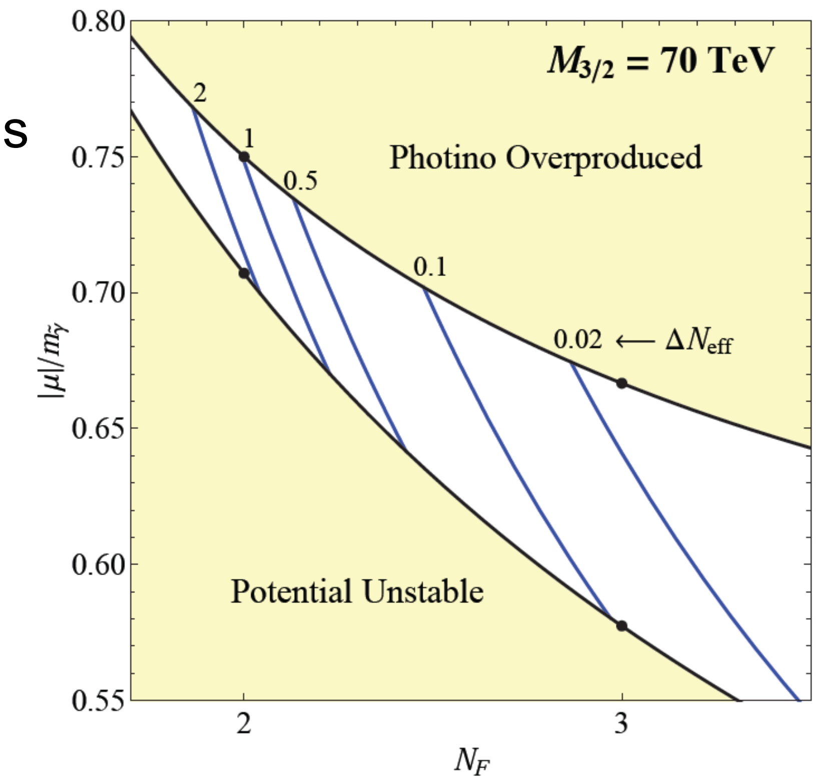
  Current bounds:

$$\Delta N_{\rm eff} = 0.19 \pm 1.2 \text{ (95\% CL) BBN}$$
$$\Delta N_{\rm eff} = 1.29^{+0.86}_{-0.88} \text{ (68\% CL) CMB}$$

  Planck data currently available:

$$\sigma(N_{\rm eff}) \approx 0.3$$

- See Vikram Rentala's talk Thursday 3:50pm



CONCLUSIONS

- Both cosmology and particle physics → new particles at the weak scale
- Ignore the nattering nabobs of negativism; these are early days and there is much work to be done
- "This is often the way it is in physics – our mistake is not that we take our theories too seriously, but that we do not take them seriously enough. It is always hard to realize that these numbers and equations we play with at our desks have something to do with the real world."

  – Steven Weinberg, *The First Three Minutes*