New Models of Dark Matter

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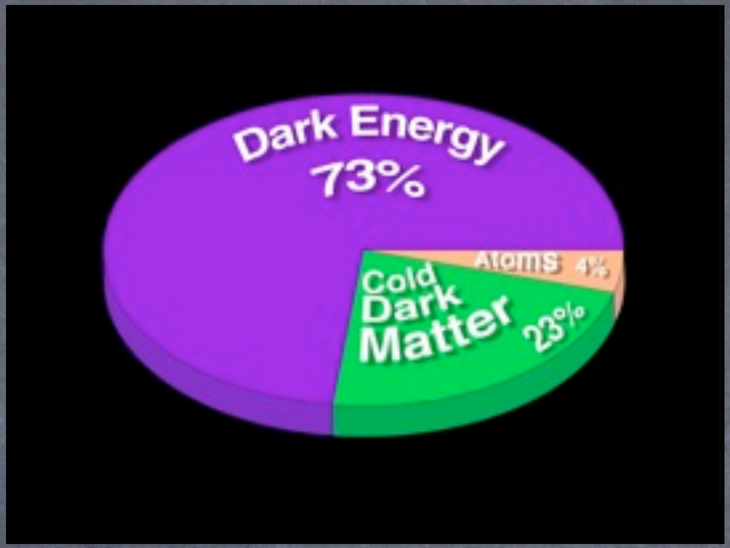
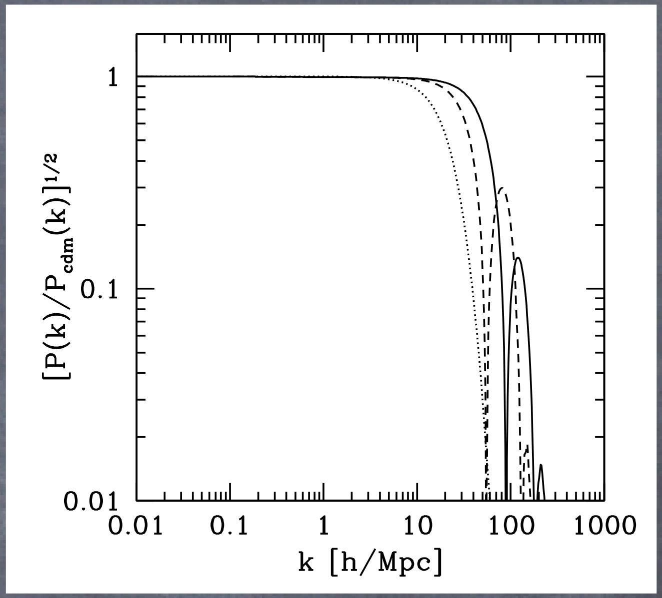
What do we know about DM?

- Its density





- It is cold
- It is weakly interacting with ordinary matter
- It has weak interactions with itself

Bullet cluster: $$\frac{\sigma}{m} \gtrsim \frac{1}{\mathrm{GeV}^3}$$

Established Paradigm of DM

- Weakly Interacting Massive Particle (WIMP) and the thermal freeze-out paradigm
- Magic thermal cross-section
- Same cross-section sets relic abundance and size of indirect detection signals

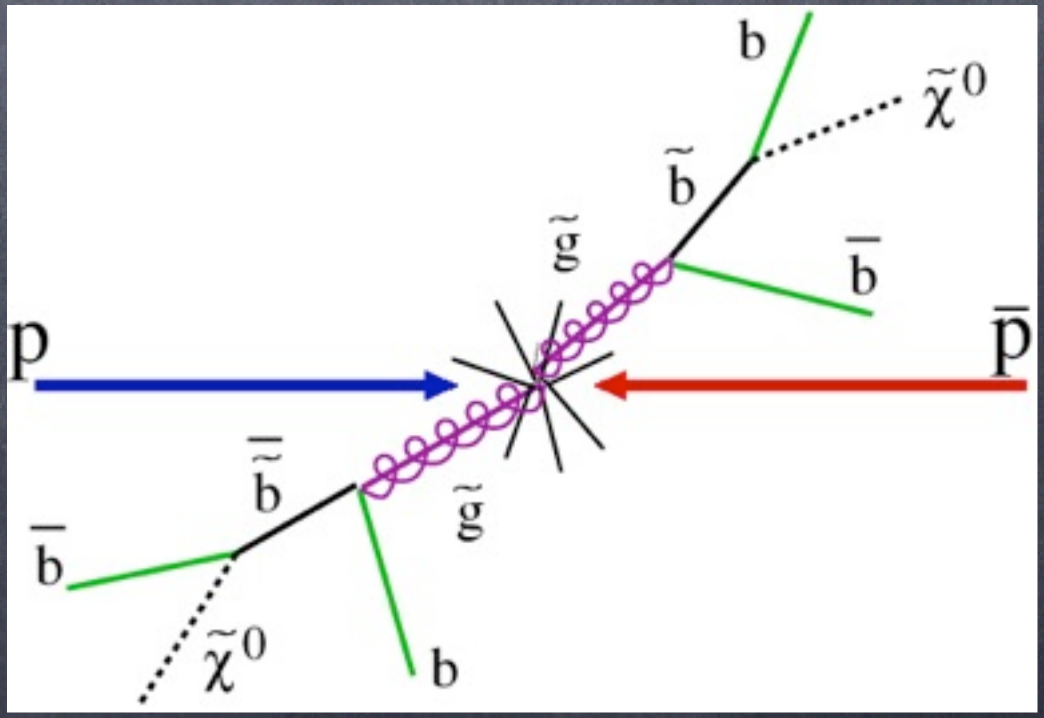
$$\Omega h^2 \approx \frac{2 \times 10^{-10}\mathrm{GeV}^{-2}}{\langle \sigma v \rangle}$$

$$\sigma v \approx \frac{g^4}{1\ \mathrm{TeV}^2} \approx 3 \times 10^{-26}\,\frac{\mathrm{cm}^3}{\mathrm{s}}$$

$$\Omega h^2 = 0.114 \pm 0.003$$

SUSY WIMP paradigm

- Further specialization of weak-scale WIMP paradigm
- Sets direct and indirect detection signal expectations, Collider experiment expectations



What do we know about DM?

- Its density correct relic abundance ✓
- It is cold kinetically decouples above 1GeV ✓
- It is weakly interacting with ordinary matter eliminates sneutrino ✓
- It has weak interactions with itself charge neutral particles in MSSM have weak interactions ✓

Actual requirements on DM much weaker

- Its density Why are the DM and baryon densities so close to each other?
- It is cold can kinetically decouple well below 1GeV, as long as before 1 keV
- It is weakly interacting with ordinary matter will happen with any state connecting through TeV mediator
- It has weak interactions with itself no dark massless forces with O(1) gauge couplings

Looking beyond SUSY neutralinos

- ... and UED, little Higgs, etc ... WIMPs
- Dark matter is single, stable, weakly interacting massive particle, with density set by thermal freeze-out
- Two classes of models that have recently gained traction because of data

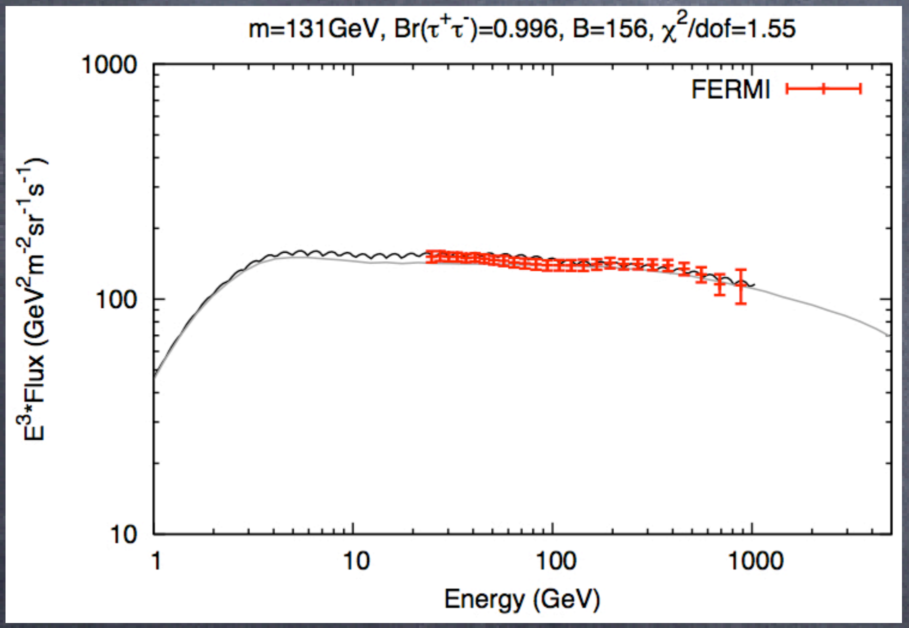
Looking Beyond SUSY Neutralino

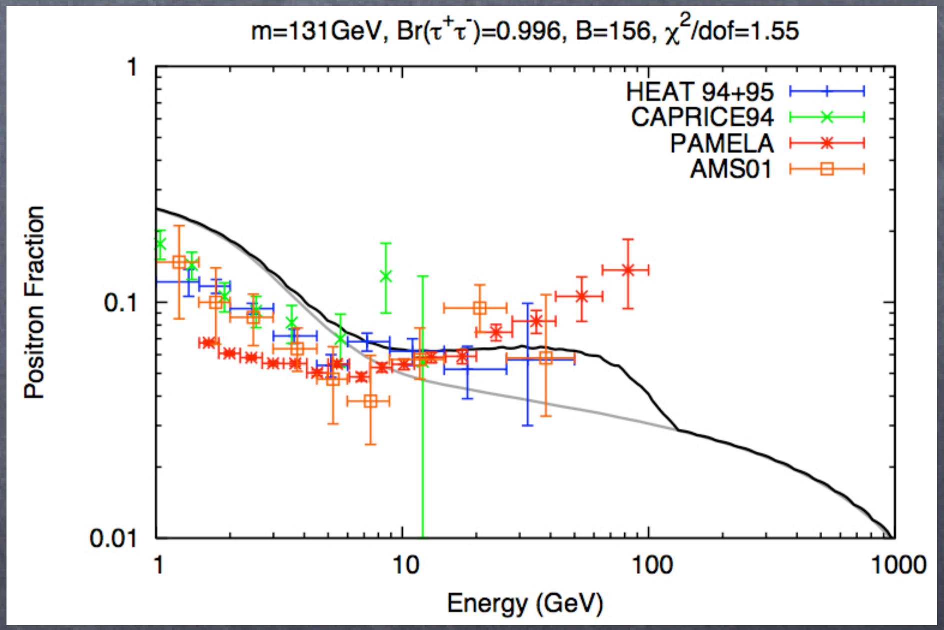
- Models with gauged dark forces, and a dark Higgs sector
- Solutions to the Baryon-DM coincidence problem

The Data

- Forcing us to look beyond an MSSM SUSY neutralino

Fermi and PAMELA





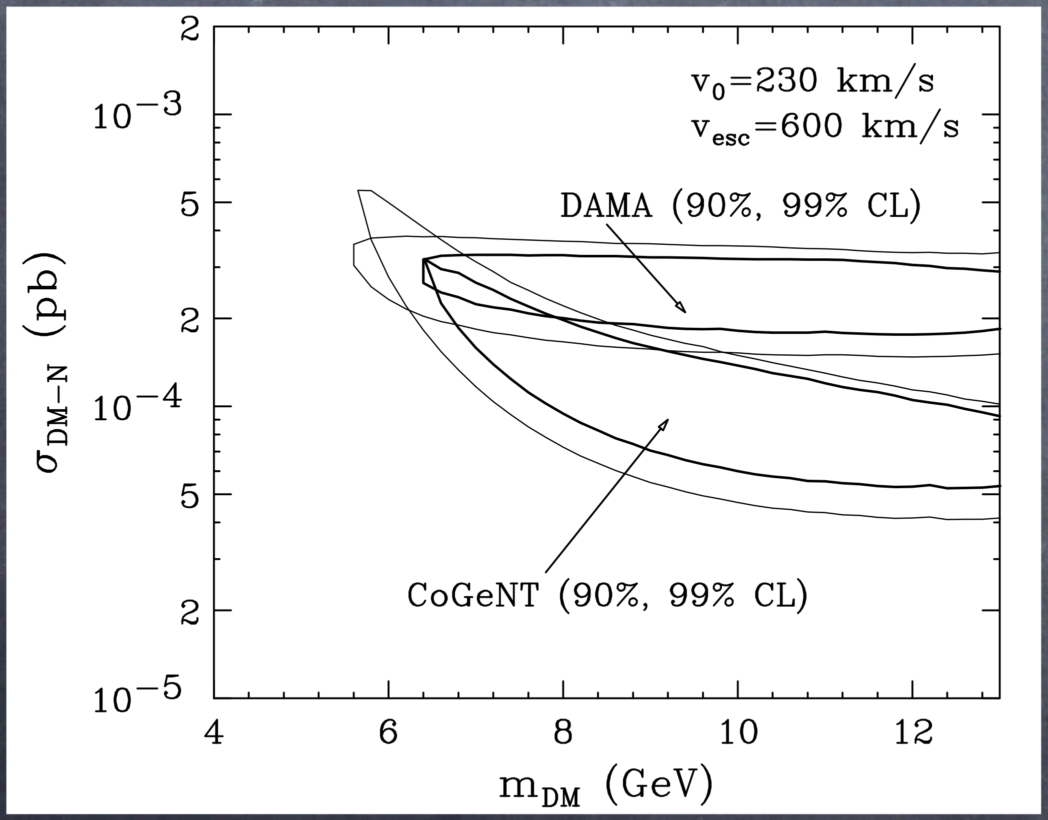
Conley, Cotta, Gainer, Hewett, Rizzo

Don't obtain hard enough spectrum from neutralino

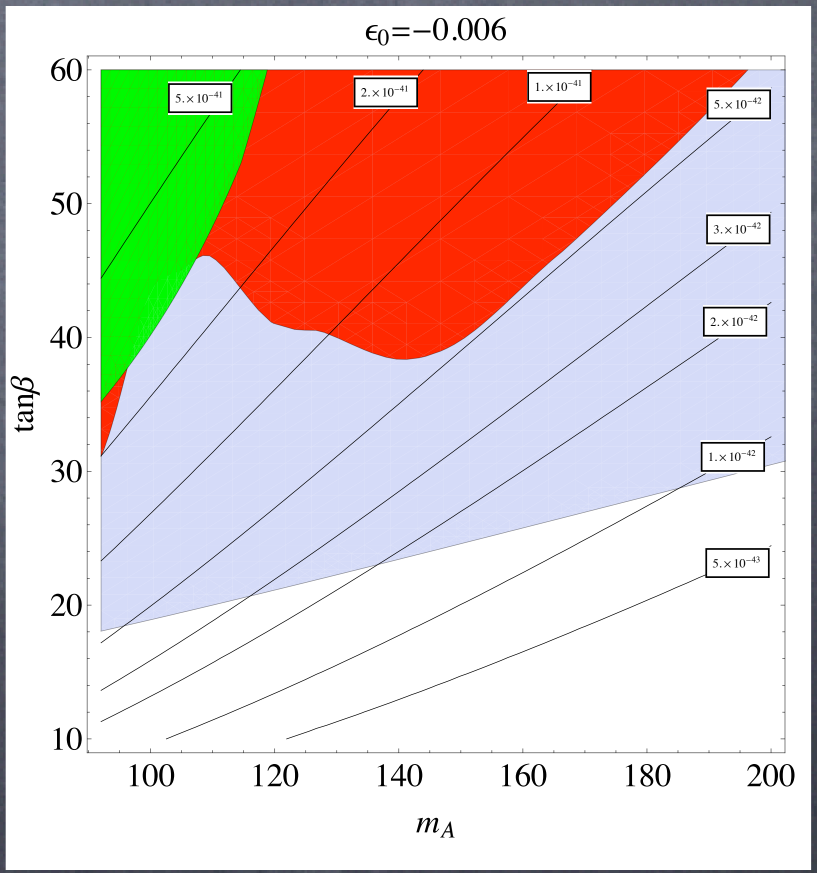
The Data

- Forcing us to look beyond a MSSM SUSY neutralino

DAMA and CoGeNT



Hooper, Collar, Hall, McKinsey



Pierce, Kuflik, KZ

Don't obtain large enough cross-section from neutralino

The Data

- Forcing us to look beyond a MSSM SUSY neutralino

PAMELA and Fermi

Dark Gauged Forces

Don't obtain hard enough spectrum from neutralino

DAMA and CoGeNT

Asymmetric Dark Matter

Don't obtain large enough cross-section from neutralino

Baryon-DM coincidence

- In standard picture, DM abundance set by thermal freeze-out

$$\Gamma_{ann} \lesssim H$$

- What if instead set by baryon density?

Experimentally, $\Omega_{DM} \approx 5\Omega_b$

Find mechanism $n_{DM} \approx n_b$

Gelmini, Hall, Lin, Barr, Kaplan, Kitano, Low, Farrar, Zaharijas, Fujii, Yanagida

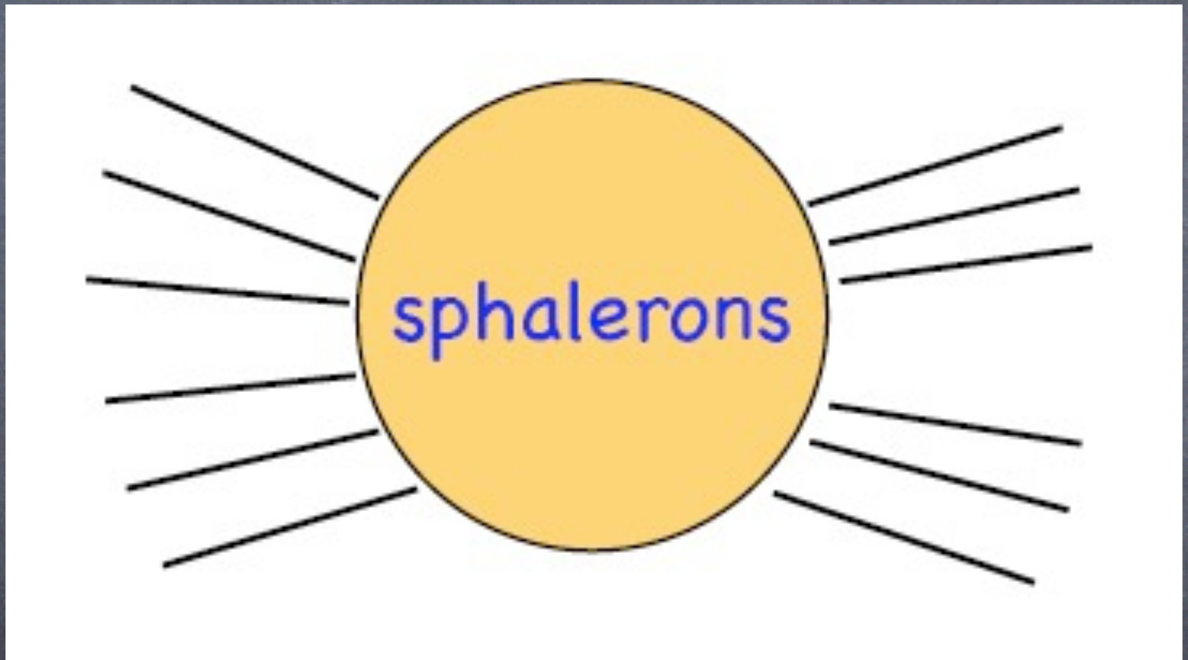
$\Rightarrow$ $m_{DM} \sim 5 \text{ GeV}$

DM-baryon coincidence

- First models used EW sphalerons to transfer the asymmetry S. Barr (1992) and D. B. Kaplan (1993) Kribs, Roy, Terning, KZ (2009)

DM carries EW quantum numbers

$$L_4 = \begin{pmatrix} \ell_4 \\ \nu_4 \end{pmatrix}$$



Visible sector

- These models no longer work because a) DM cannot be > 45 GeV b) coupling to the Z rules them out

Weak scale DM and the coincidence

- The DM can be heavier if operators relating DM and baryon densities decouple *after* DM becomes non-relativistic

Text

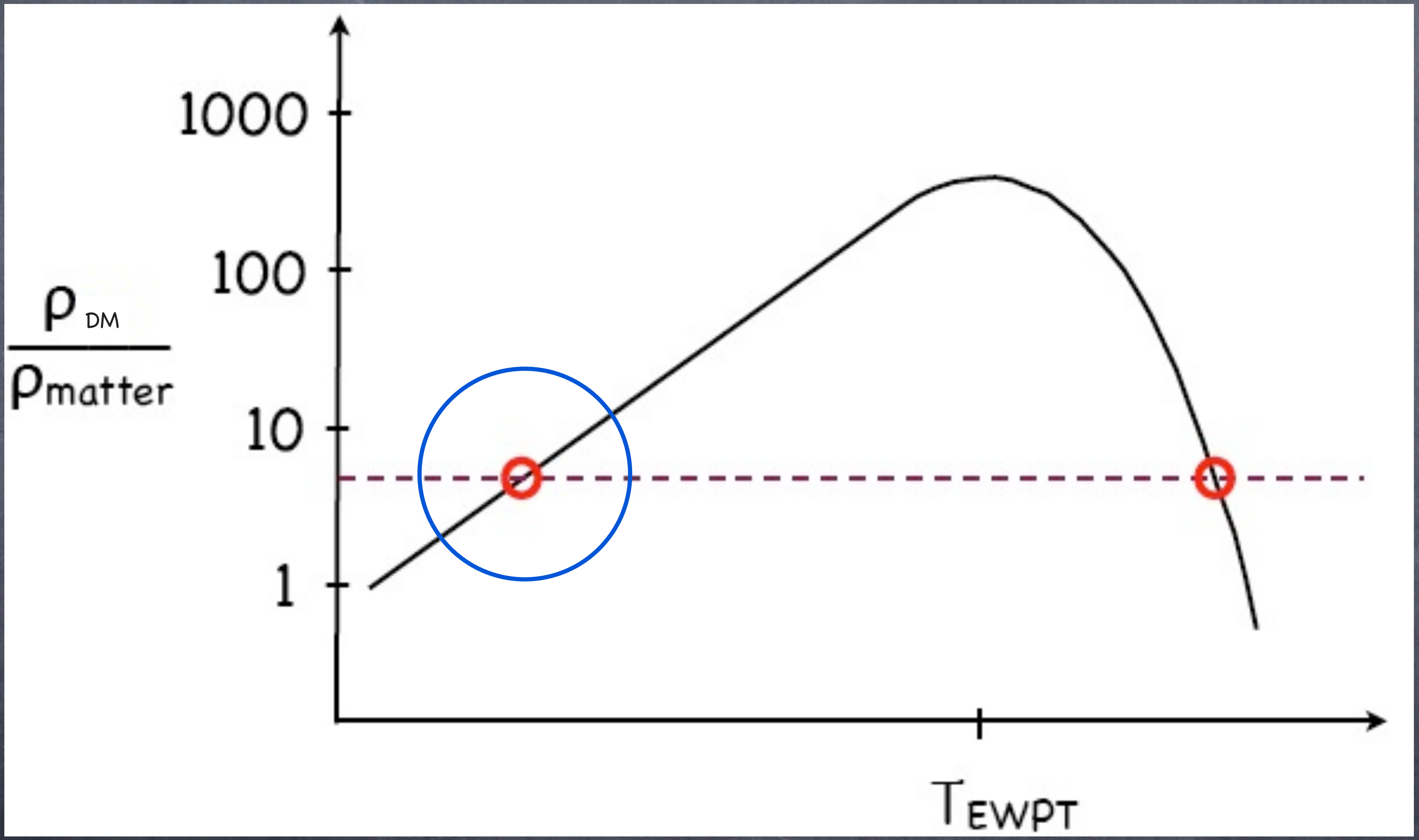
$$n_X - n_{\bar{X}} \sim (n_\ell - n_{\bar{\ell}})e^{-m_{DM}/T_d}$$

$$\rho_{DM} = m_{DM}(n_X - n_{\bar{X}})$$

- Partial DM asymmetry wash-out
- Used in techni-baryon DM models
  - DM mass from source other than EWSB

Chivukula, Barr, Farhi (1992)
Gudnason, Kouvaris, Sannino (2006)

Two mass windows



Asymmetric Dark Matter

D. E. Kaplan, Luty, KZ (2009)

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2. Have asymmetry transferring operator decouple before DM becomes non-relativistic (otherwise DM asymmetry washes out)

Asymmetric Dark Matter

D. E. Kaplan, Luty, KZ (2009)

- Cosmological history:

1. Transfer lepton or baryon asymmetry to DM through higher dimension operator
2. Have asymmetry transferring operator decouple before DM becomes non-relativistic (otherwise DM asymmetry washes out)
3. Annihilate away symmetric abundance

Asymmetric Dark Matter

An example of Asymmetric Dark Matter

DM carries lepton number L=1/2

$$W = \frac{\bar{X}^2 L H}{M}$$

- Operator transfers lepton asymmetry to DM

$$2(n_X - n_{\bar{X}}) \approx n_L - n_{\bar{L}}$$

$$m_X \simeq 2.4\ \mathrm{GeV}\frac{\Omega_X}{\Omega_b} \simeq 11\ \mathrm{GeV}$$

- Operator goes out of equilibrium

Asymmetric Dark Matter

An example of Asymmetric Dark Matter

DM carries lepton number L=1/2

$$W = \frac{\bar{X}^2 LH}{M}$$

- Prevents wash-out of asymmetry
- Symmetric abundance annihilated away

Many Examples of ADM

Integrate out heavy state
Effective operators:

$$W = \frac{\bar{X}^2 LH}{M}$$

$$W = \frac{\bar{X}^2 udd}{M^2}$$

$$\mathcal{L} = \frac{\bar{X}^2 LHLH}{M^4}$$

Standard Model

Dark sterile state,
fundamental or composite

Many Examples of ADM

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Standard Model

Visible

Dark sterile state,
fundamental or composite

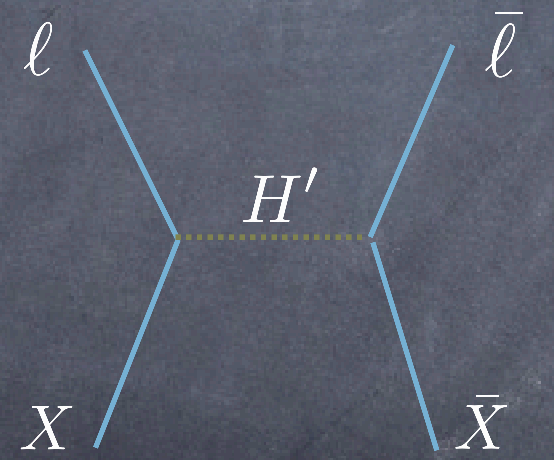
Hidden

Annihilating Symmetric Abundance

- The asymmetry is very small relative to the symmetric part $n_X - n_{\bar{X}} \approx 10^{-10}(n_X + n_{\bar{X}})$

  because $n_b/n_\gamma \approx 10^{-10}$

- Remove via annihilation through heavy states

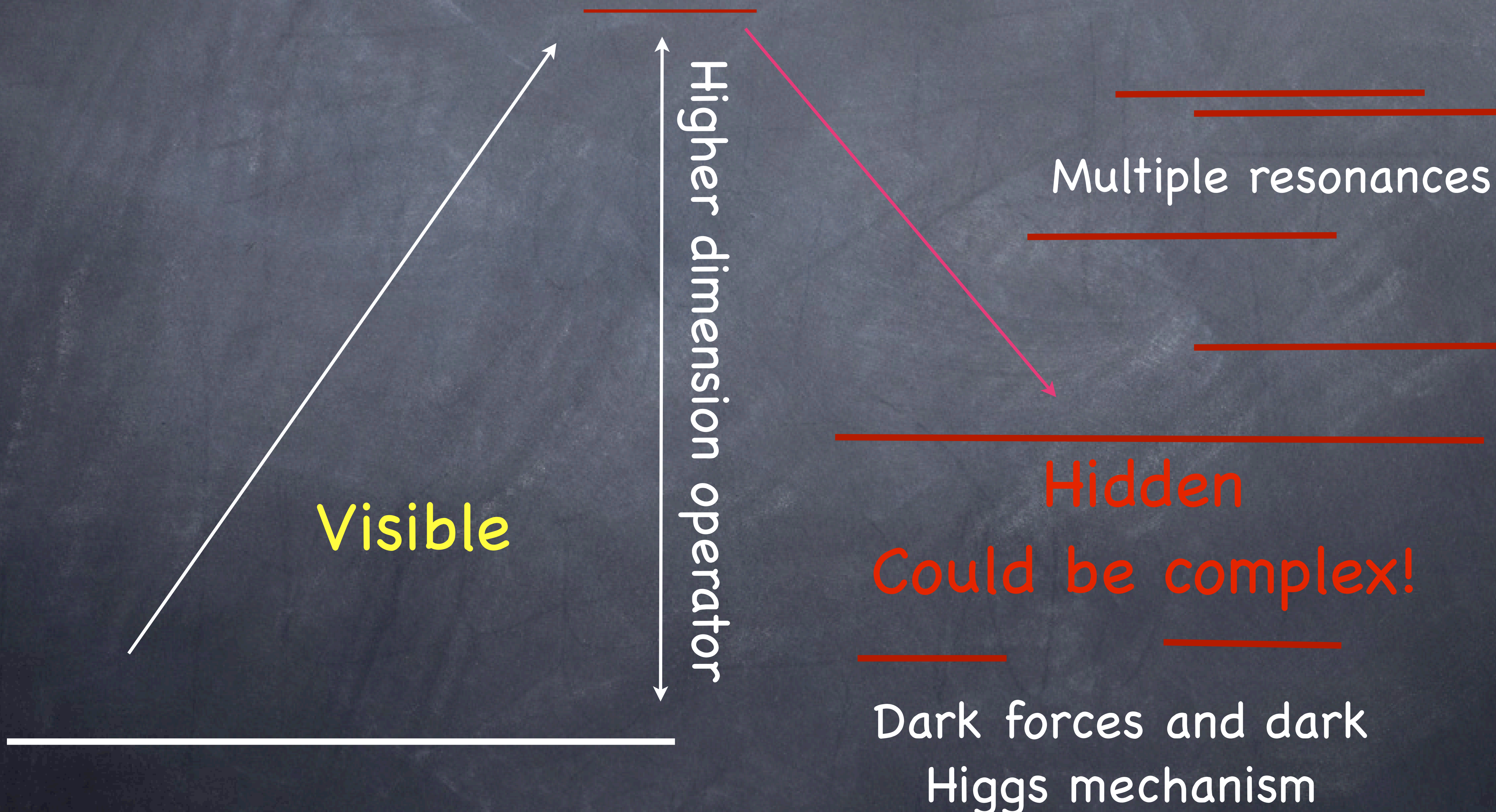


$$m_{H'}/y \lesssim 200 \text{ GeV}$$

- Or, add new light states $\bar{X}X \to aa$

- The new states could be part of mechanism for DM mass generation $e^{ia/f} m_X \bar{X}X$

ADM: Gateway to a Hidden World



Looking Beyond SUSY Neutralino

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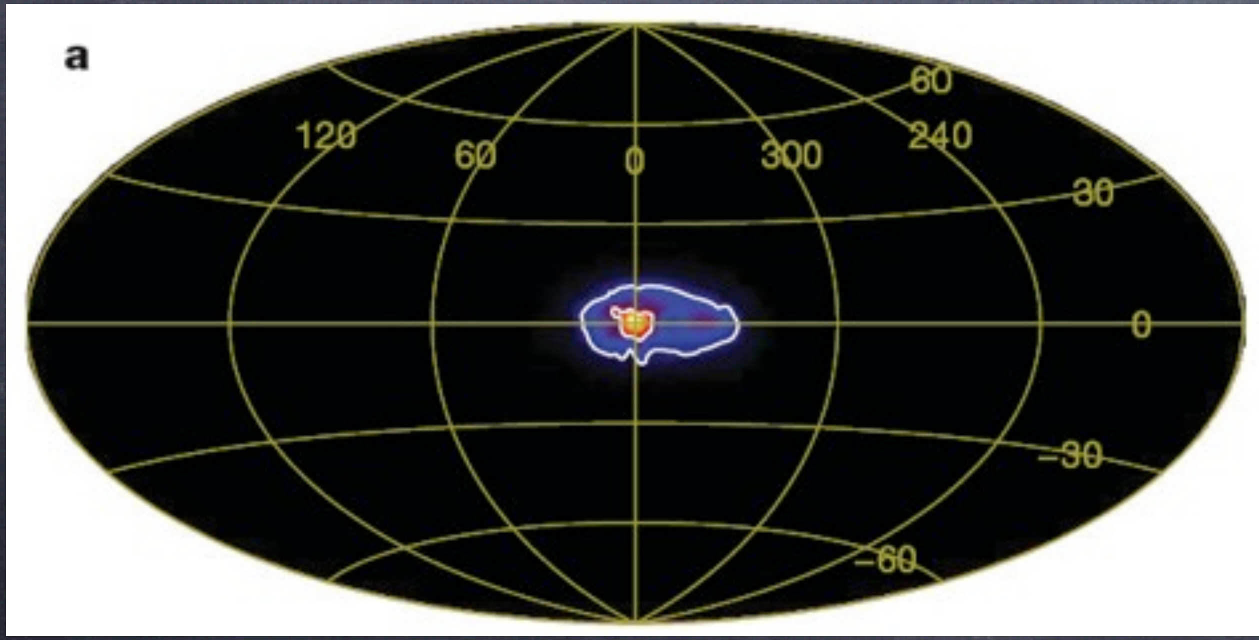
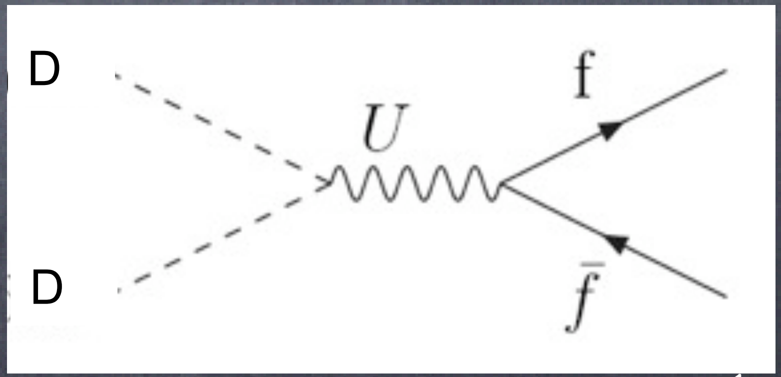
Dark Forces in Dark Sectors

- Dark Forces in the Dark Sector are not new
- An example: MeV Dark Matter   Fayet



511 keV line observed by integral toward galactic center

$g' = 1$ $g = 10^{-6}$

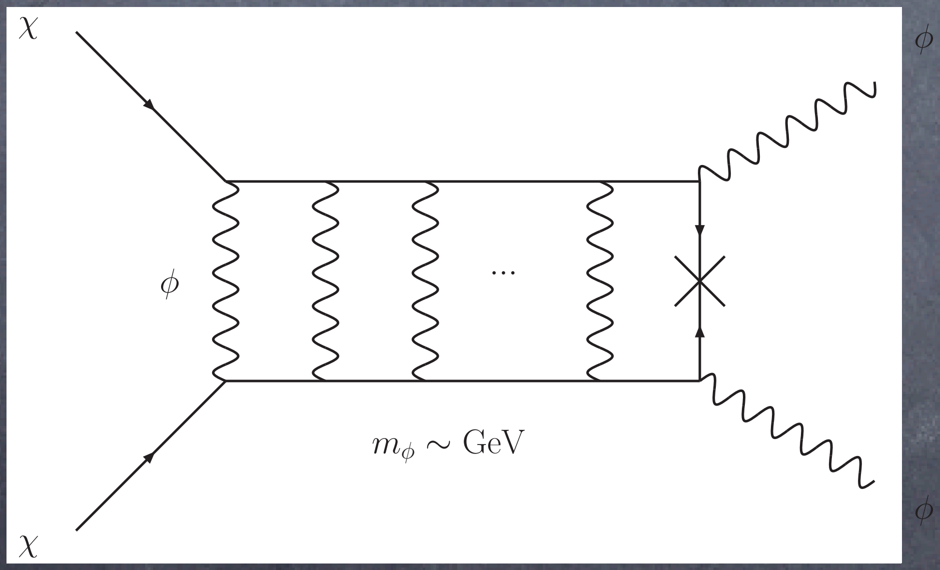


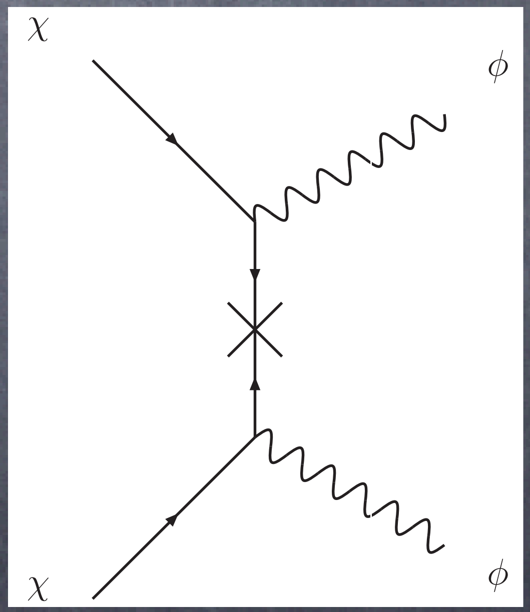
$m_{DM} = 1 \text{ MeV}$ $m_U = 1 \text{ MeV}$

A recent example of dark forces

Arkani-Hamed, Finkbeiner, Slatyer, Weiner   Pospelov and Ritz

- PAMELA and Fermi positron excesses
- How to obtain annihilation to *leptons*?





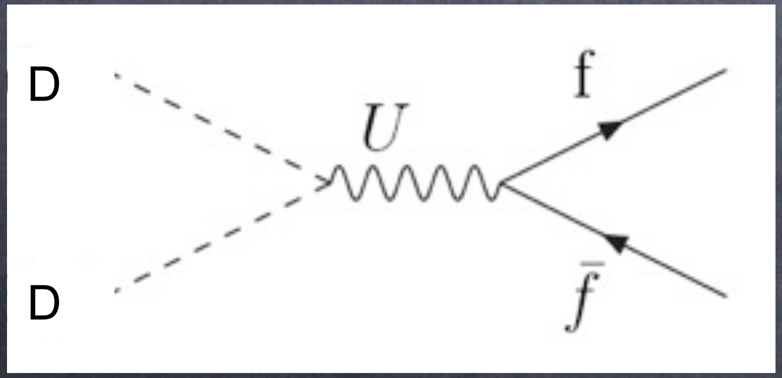
Requires light hidden gauge boson, light hidden Higgses

How does SUSY enter?

- It can stabilize the Higgses in the hidden sector, even when they are much lighter than the weak scale!

- An example: MeV Dark Matter

$g' = 1$ $\qquad g = 10^{-6}$



$m_{DM} = 1\ \mathrm{MeV} \qquad m_U = 1\ \mathrm{MeV}$

Weak coupling to SUSY breaking

$$m_D \sim g g' m_{SUSY}$$

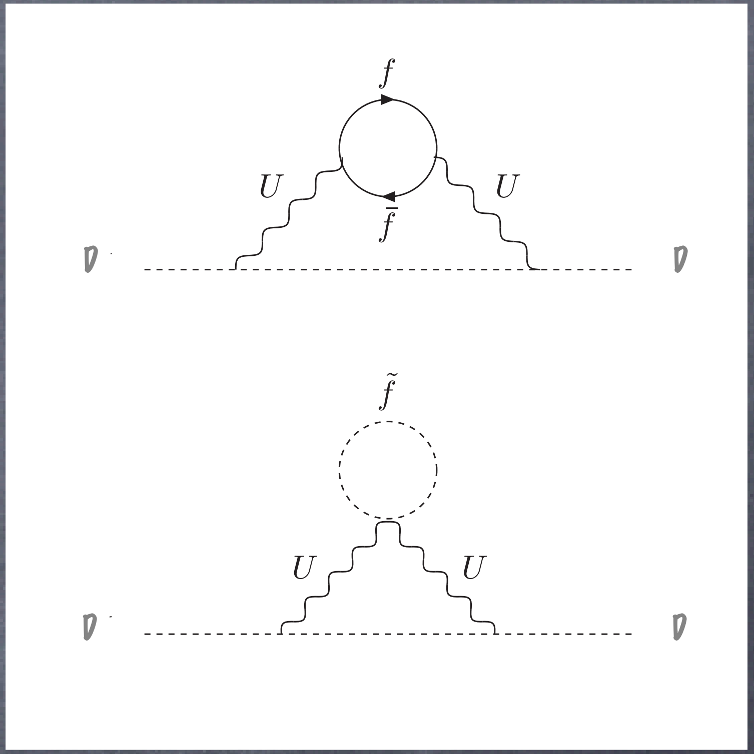
Small hidden SUSY masses!

Little Gauge Mediation

- Two loop graphs
- Introduce negative m^2 for D, break dark gauge group
- MeV example:

$$m_D^2 = -\frac{g^2 g'^2}{128\pi^4} m_{\tilde{f}}^2 \log\left(\frac{\Lambda_{UV}^2}{m_{\tilde{f}}^2}\right)$$
$$\simeq -5\ \mathrm{MeV}^2 \left(\frac{gg'}{3\times 10{-}6}\right)^2$$

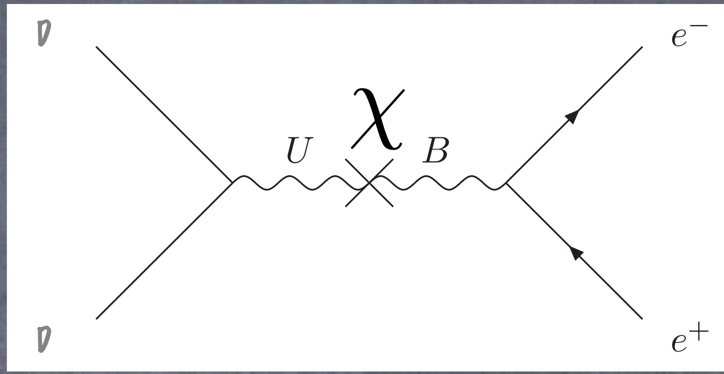
- How to obtain small couplings?



Hooper, KZ (2008)

Kinetic Mixing

Arkani-Hamed, Finkbeiner, Slatyer, Weiner
Pospelov and Ritz
Cheung, Ruderman, Wang, Yavin



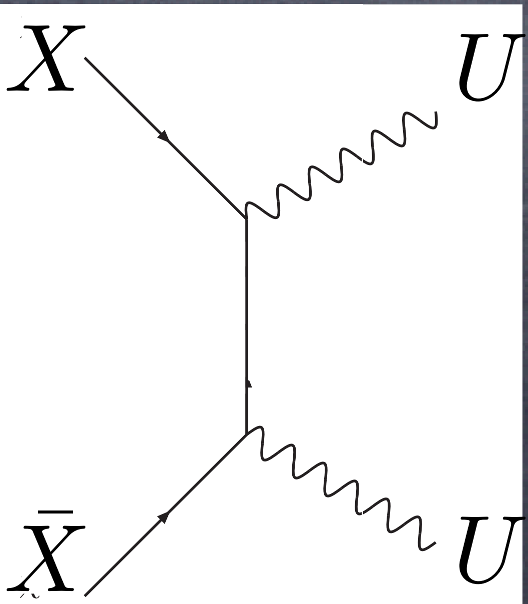
- A mechanism for naturally generating GeV scale

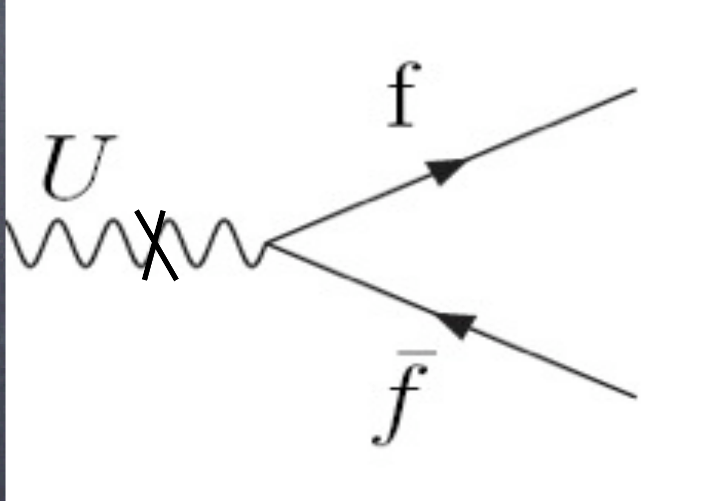
$$
\begin{aligned}
m_D^2 &= -\frac{g^2 g'^2 \chi^2}{128\pi^4} m_{\tilde{f}}^2 \log\left(\frac{\Lambda_{UV}^2}{m_{\tilde{f}}^2}\right) \\
&\simeq -5\ \mathrm{GeV}^2 \left(\frac{g g' \chi}{3\times 10^{-3}}\right)^2
\end{aligned}
$$

$$m_D^2 \sim g' \chi v^2 \cos 2\beta$$

Asymmetric Dark Matter, recap

- Use this mechanism both to generate the DM mass scale and to provide an efficient annihilation mechanism for symmetric abundance
- ADM is charged under dark gauge group





Cohen, Phalen, Pierce, KZ

Outlook

- Not seeking to over-emphasize the specifics of any single model.
- However, as data arrives, we may continue to be pushed to look at New Models of DM
- The SUSY neutralino is a well motivated DM candidate ...
- BUT there is a broad world of models

Outlook

- Considered specifically

  Asymmetric Dark Matter

  GeV Hidden Sectors

- Found both classes of models have qualitatively different cosmology than SUSY neutralinos

- There is a broad world of DM models to explore!