# RECENT DEVELOPMENTS IN DARK MATTER: THEORY PERSPECTIVE

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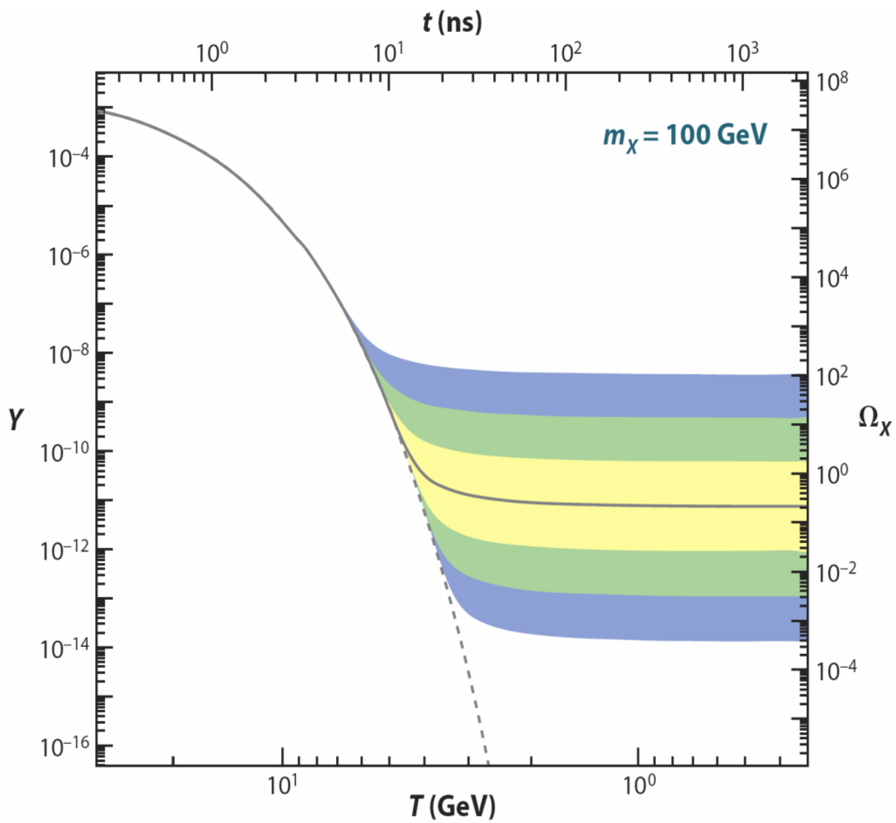
# TOPICS

- PAMELA, FERMI, … $\leftrightarrow$ BOOSTED WIMPS
- CDMS, XENON, … $\leftrightarrow$ WIMPS
- DAMA, COGENT, … $\leftrightarrow$ LIGHT WIMPS

For more, see “Dark Matter Candidates from Particle Physics and Methods of Detection,” 1003.0904, Annual Reviews of Astronomy and Astrophysics

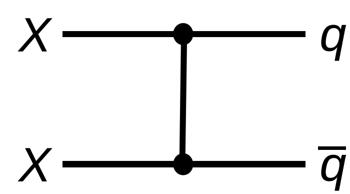
# THE WIMP MIRACLE




- Assume a new (heavy) particle *X* is initially in thermal equilibrium

- Its relic density is

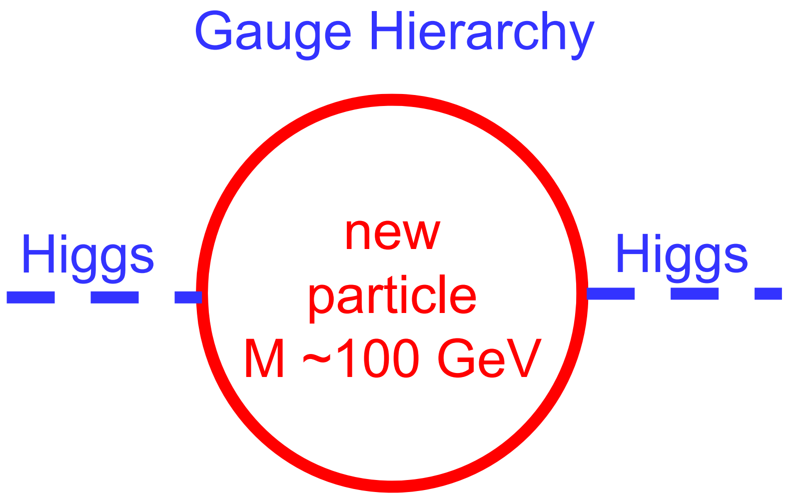
$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

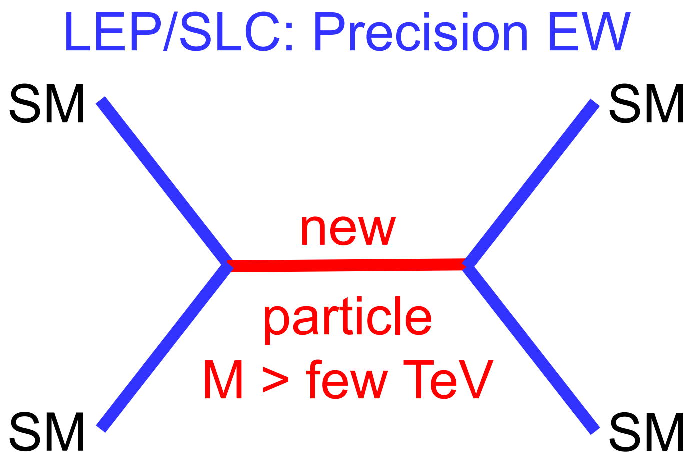



- $m_X$ ~ 100 GeV, $g_X$ ~ 0.6 → $\Omega_X$ ~ 0.1

- Remarkable coincidence: particle physics independently predicts particles with the right density to be dark matter

# WIMP STABILITY




- Simple solution: impose a discrete parity, so all interactions require pairs of new particles. This also makes the lightest new particle stable.

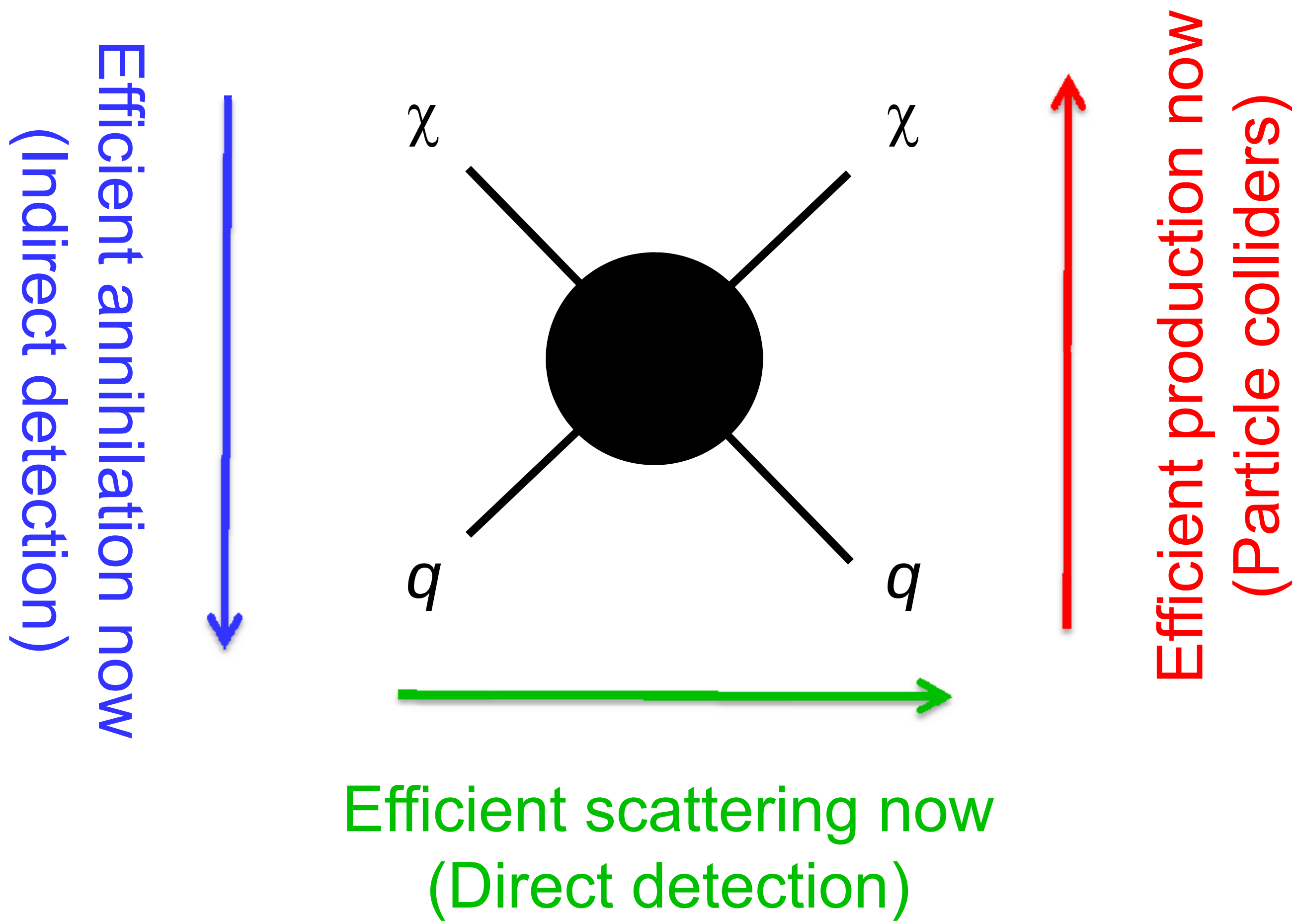
Cheng, Low (2003); Wudka (2003)

- This is a general argument for a stable weak-scale particle

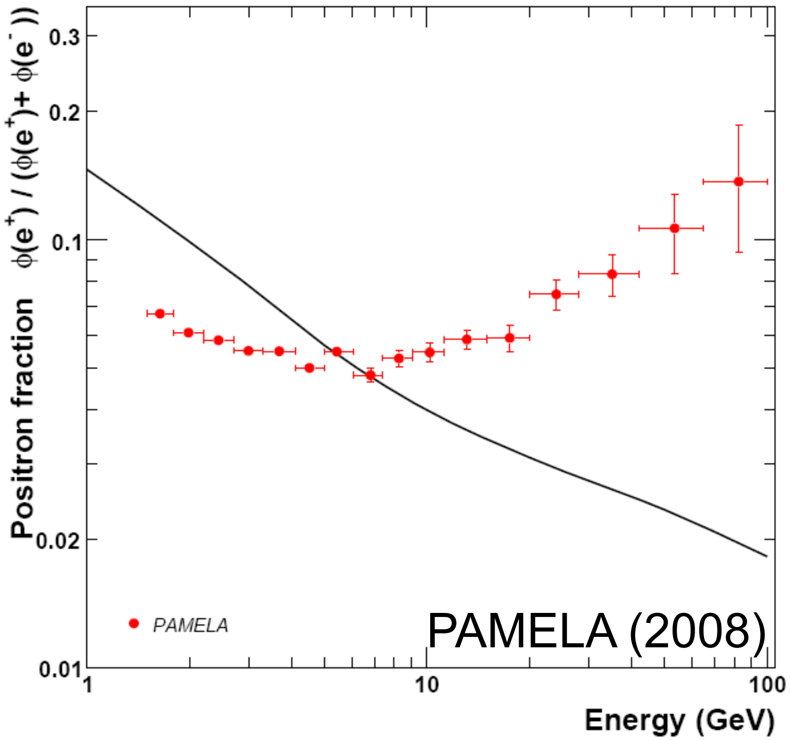
- In specific contexts, this may be augmented by additional arguments. E.g., in SUSY, proton decay → R-parity.

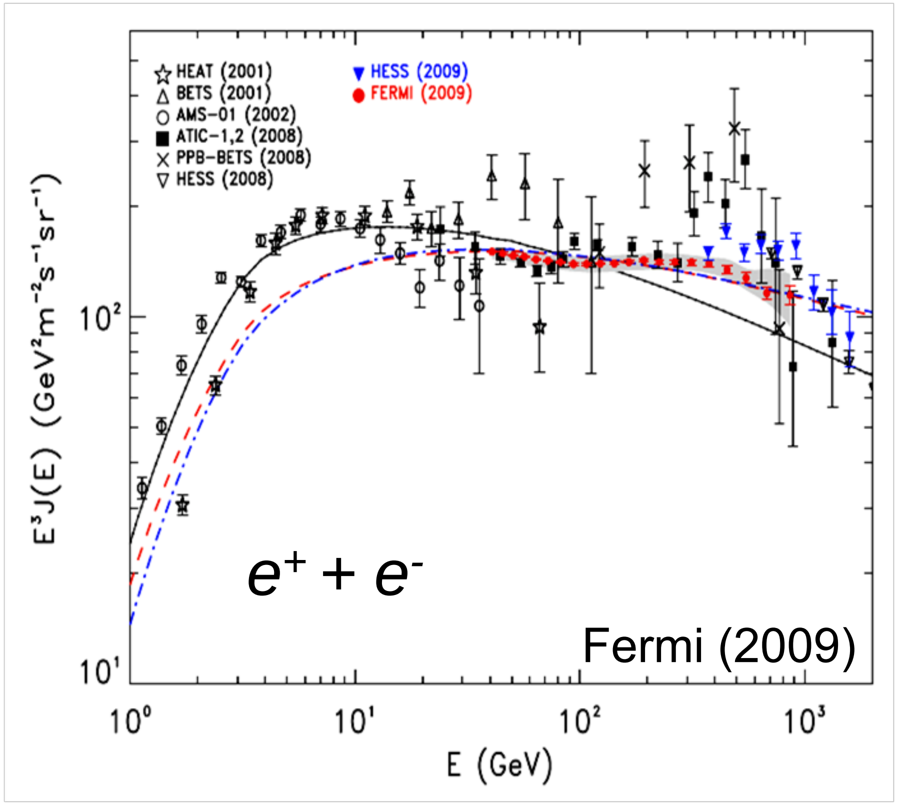
# WIMP DETECTION

Correct relic density → *Lower* bound on DM-SM interaction



# INDIRECT DETECTION



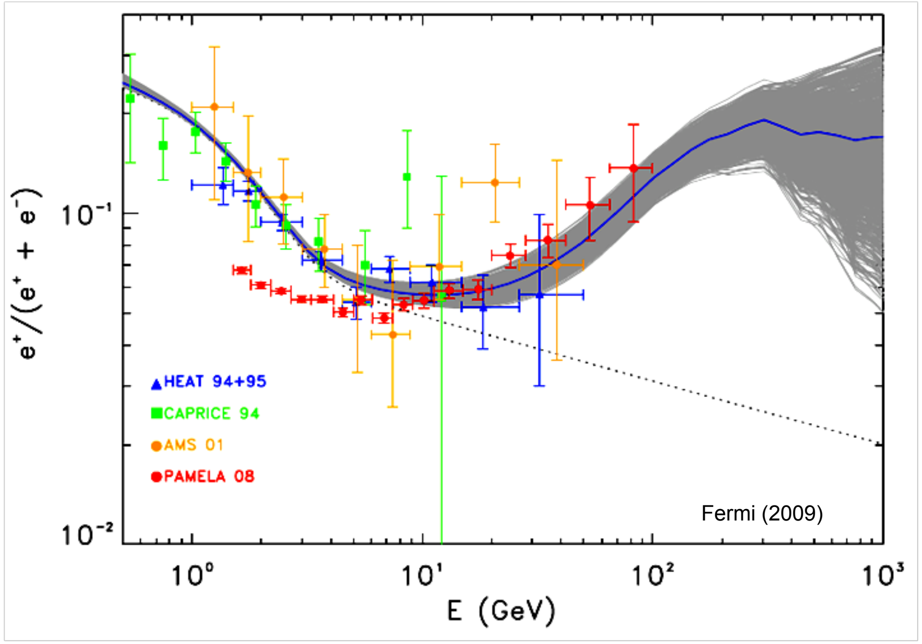




Solid lines are the predicted spectra from GALPROP (Moskalenko, Strong)

# ARE THESE DARK MATTER?

- Astrophysics can explain PAMELA

Zhang, Cheng (2001)
Hooper, Blasi, Serpico (2008)
Yuksel, Kistler, Stanev (2008)
Profumo (2008) ; Fermi (2009)



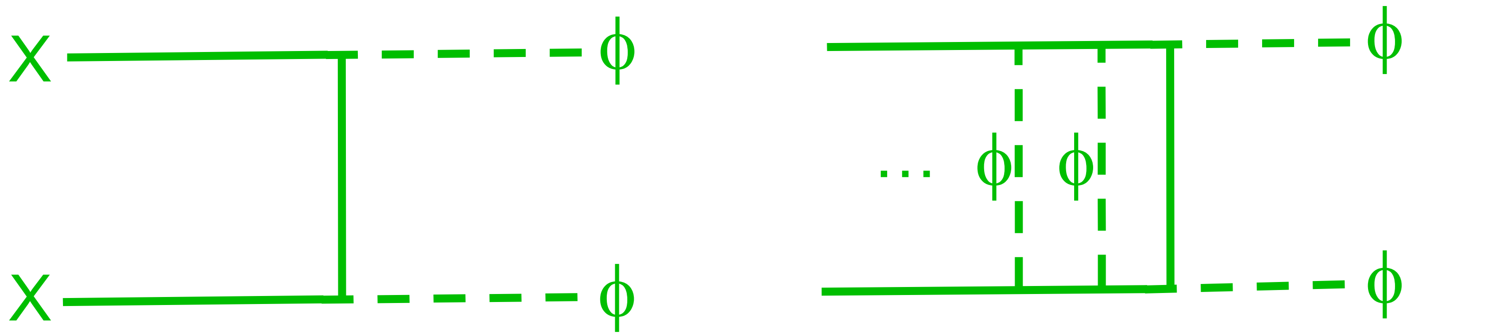

- For dark matter, there is both good and bad news

- Good: the WIMP miracle motivates excesses at ~100 GeV – TeV

- Bad: the WIMP miracle also tells us that the annihilation cross section should be a factor of 100-1000 too small to explain these excesses. Need enhancement from
  - astrophysics (very unlikely)
  - particle physics

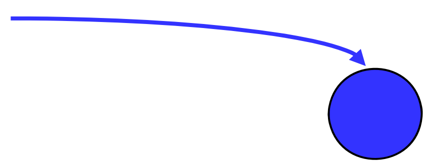
# SOMMERFELD ENHANCEMENT

- If dark matter X is coupled to a hidden force carrier $\phi$, it can then annihilate through $XX \rightarrow \phi\,\phi$




- At freezeout: $v \sim 0.3$, only 1st diagram is significant, $\sigma = \sigma^{th}$

  Now: $v \sim 10^{-3}$, all diagrams significant, $\sigma = S\sigma^{th}$, $S \sim \pi\alpha_X/v$, boosted at low velocities



Sommerfeld (1931)

Hisano, Matsumoto, Nojiri (2002)

- If $m_X \sim 2$ TeV, $S \sim 1000$, seemingly can explain excesses, get around WIMP miracle predictions

Cirelli, Kadastik, Raidal, Strumia (2008)

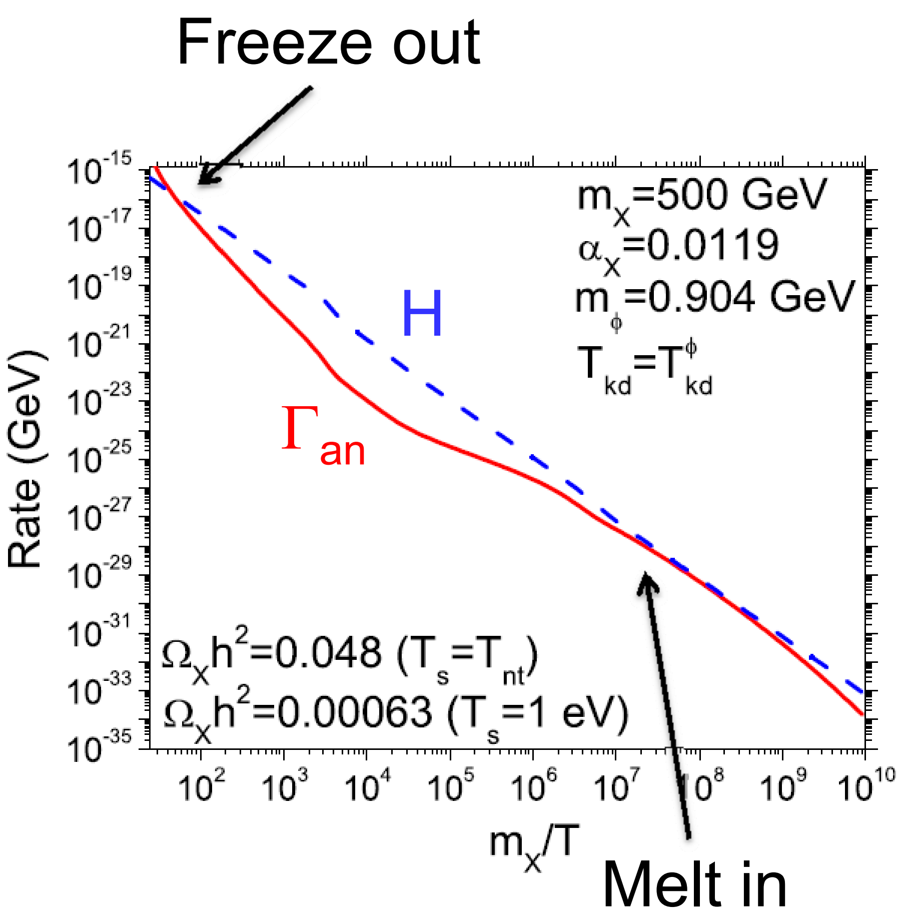
Arkani-Hamed, Finkbeiner, Slatyer, Weiner (2008)

# CONSTRAINTS ON SOMMERFELD ENHANCEMENTS

Feng, Kaplinghat, Yu (2009)

- Unfortunately, large S requires large $\alpha_X$, but strongly-interacting DM does not have the correct relic density
- More quantitatively: for $m_X$ = 2 TeV, S ~ 1000 ~ $\pi\alpha_X/v$, $v \sim 10^{-3} \rightarrow \alpha_X \sim 1 \rightarrow \Omega_X \sim 0.001$
- Alternatively, requiring $\Omega_X \sim 0.25$, what is the maximal S?
- Complete treatment requires including
  - Resonant Sommerfeld enhancement
  - Impact of Sommerfeld enhancement on freeze out

# FREEZE OUT WITH SOMMERFELD ENHANCEMENT

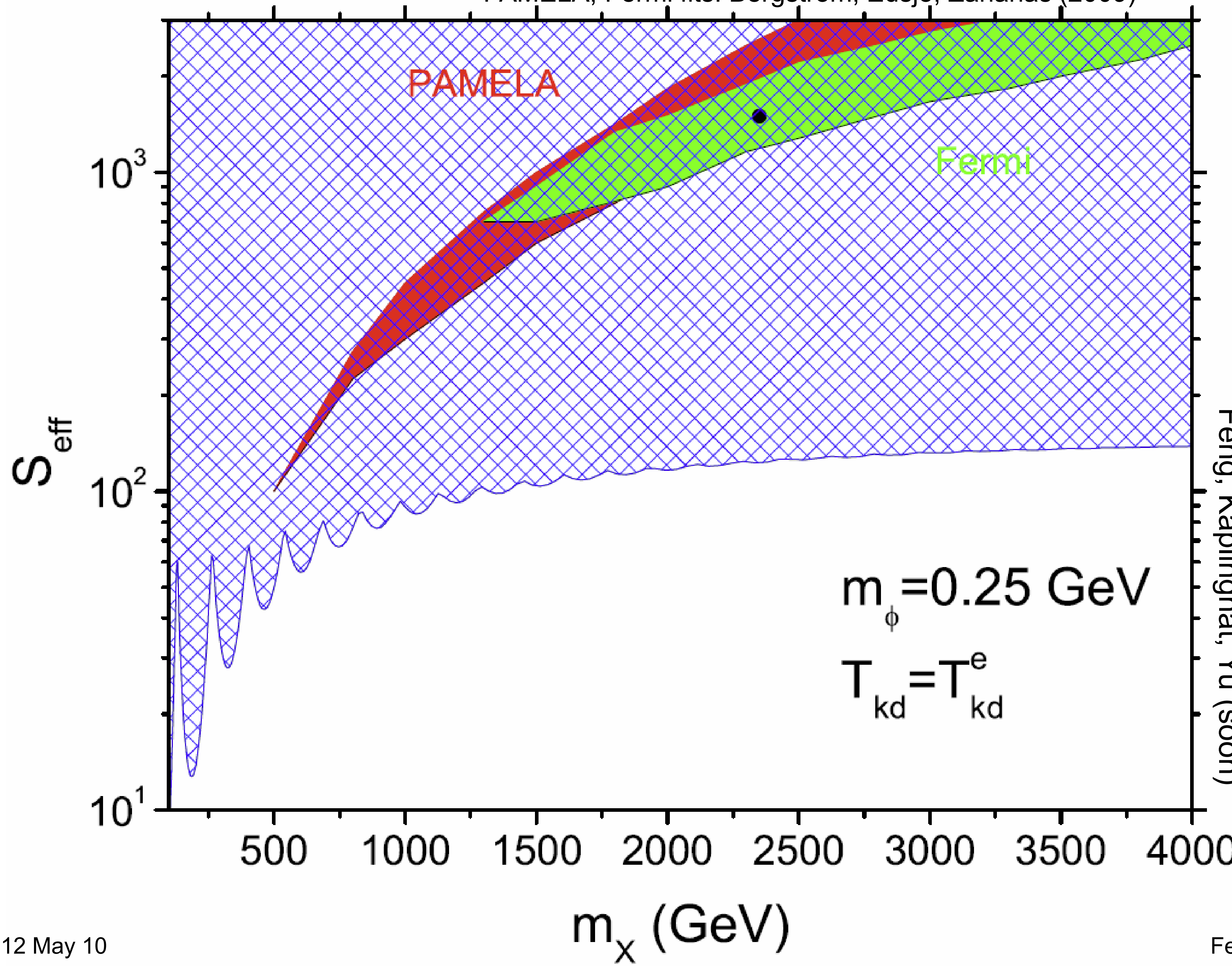



- Sommerfeld enhancement → many interesting issues

Dent, Dutta, Scherrer (2009)
Zavala, Vogelsberger, White (2009)

- To maximize S, turn knobs in the most optimistic direction
  - Assume XX → ϕϕ is the only annihilation channel
  - Delay kinetic decoupling as much as possible
  - Stop annihilations when the velocity distribution becomes non-thermal

PAMELA, Fermi fits: Bergstrom, Edsjo, Zaharias (2009)




Feng, Kaplinghat, Yu (soon)

# WAYS OUT

- Best fit region excluded by an order of magnitude
- Astrophysical uncertainties
  - Local density, small scale structure
  - Cosmic ray propagation, proton contamination in PAMELA,…
- Particle physics
  - More complicated Sommerfeld models (smaller boosts required, but generically tighter bounds)
  - Resonant annihilation

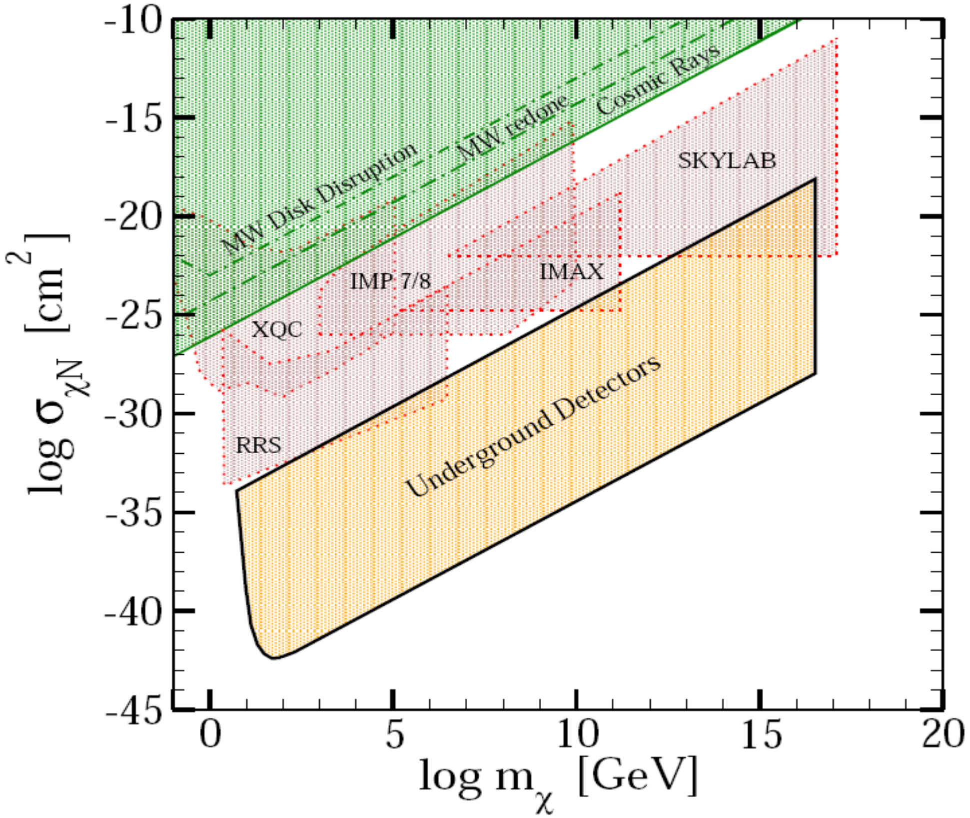
    Feldman, Liu, Nath (2008); Ibe, Murayama, Yanagida (2008); Gou, Wu (2009)
  - Non-thermal DM production (e.g., Winos)

    Grajek et al. (2008); Feldman, Kane, Lu, Nelson (2010); Cotta et al. (2010)
  - DM from decays

    Arvanitaki, Dimopoulos, Dubovsky, Graham, Harnik, Rajendran (2008)

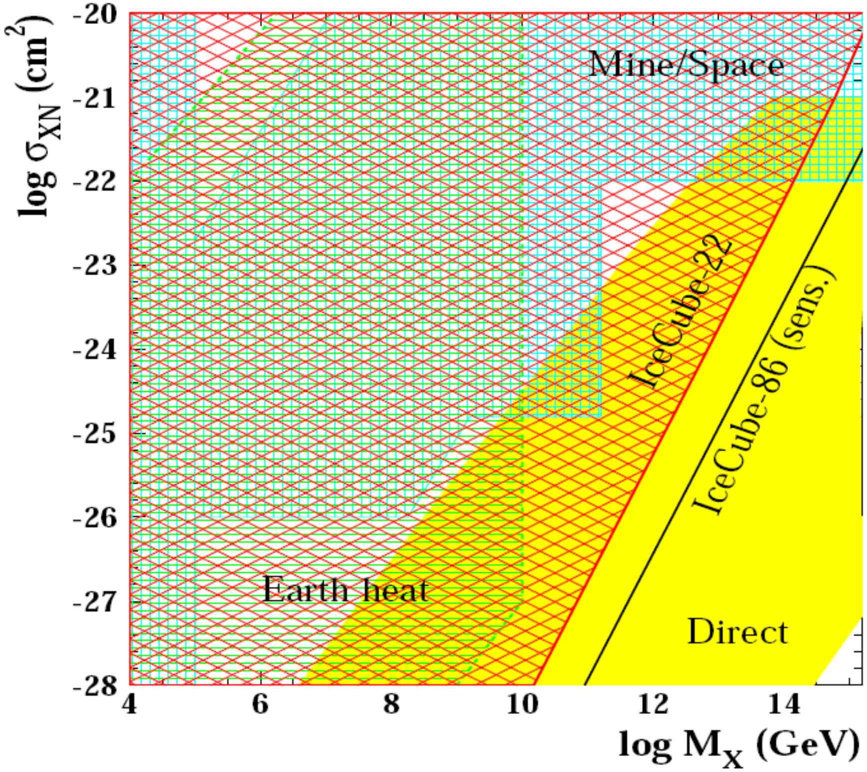
# DIRECT DETECTION

- The big picture



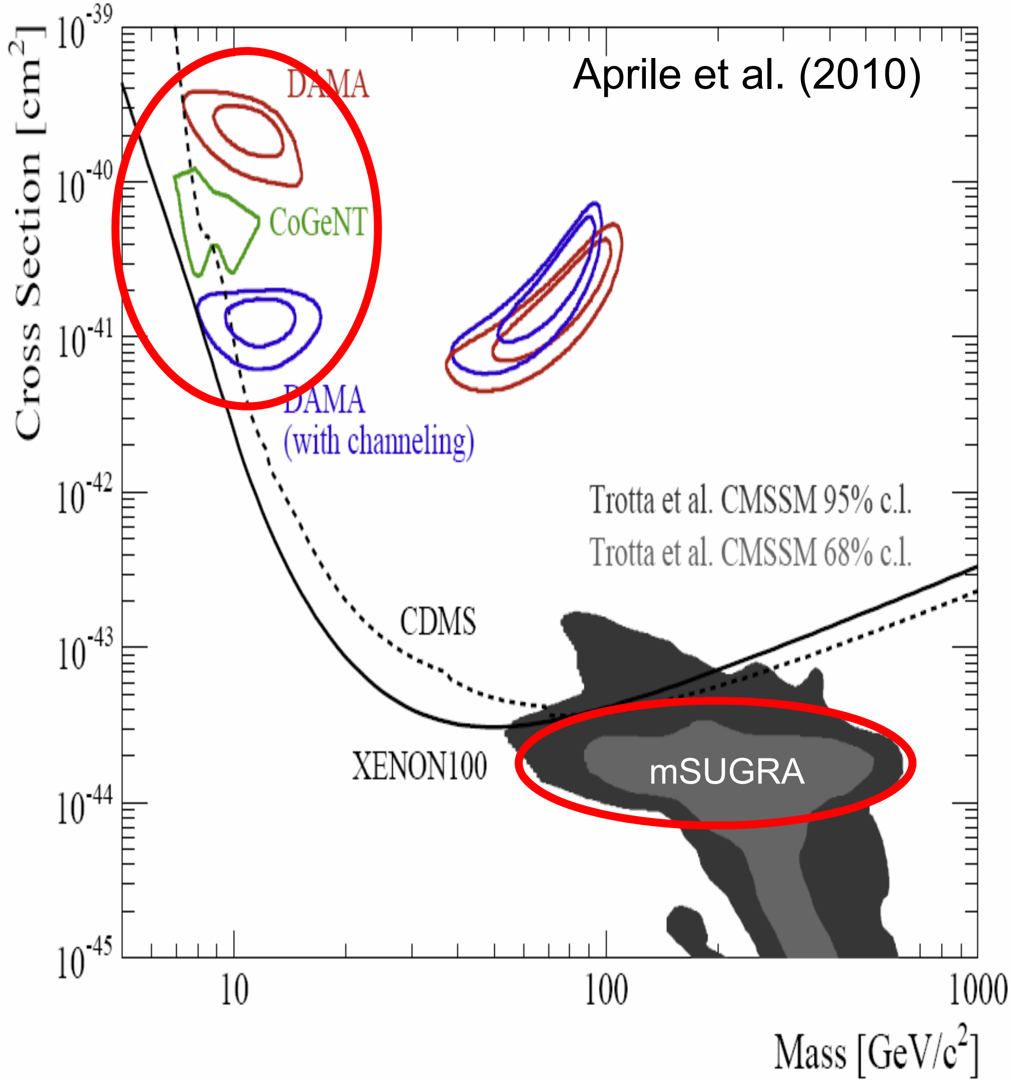

Mack, Beacom, Bertone (2007)

- Strongly-interacting window now closed




Albuquerque, de los Heros (2010)

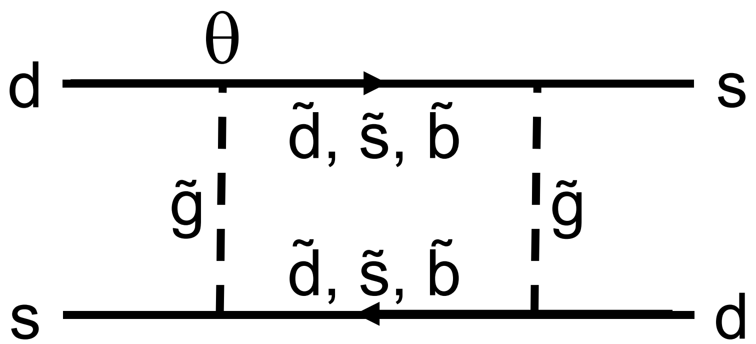
# DIRECT DETECTION



# THE SIGNIFICANCE OF $10^{-44}$ CM$^2$

- New weak scale particles generically create many problems

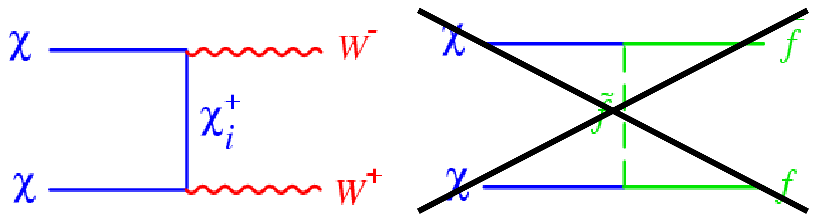
- For example: K-$\overline{\text{K}}$ mixing



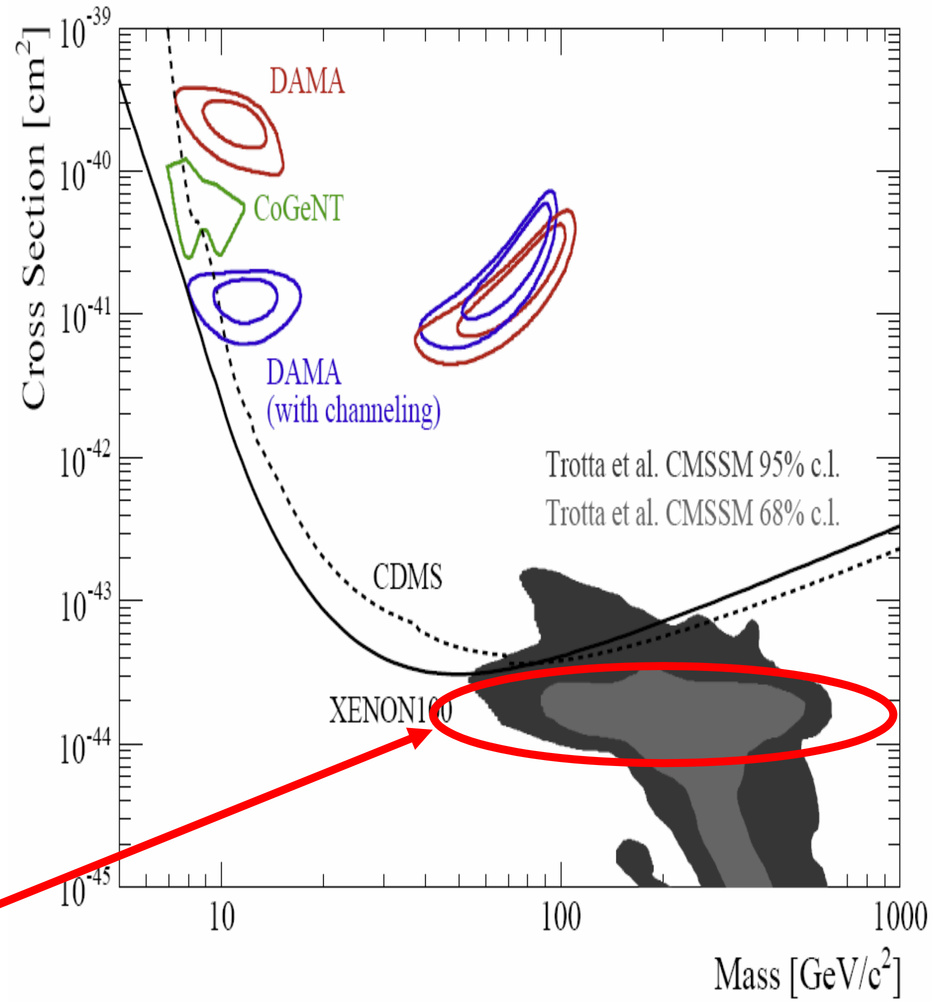

- Three possible solutions
  - Alignment: θ small
  - Degeneracy (e.g. gauge mediation): typically not compatible with neutralino DM, because neutralinos decay to gravitinos
  - Decoupling: m > few TeV

# THE SIGNIFICANCE OF $10^{-44}$ CM$^2$

- Consider decoupling




- Remaining diagram depends on 3 parameters: $M_1$, $M_2$, $\mu$ ($\tan\beta$)
- Impose gaugino mass unification, $\Omega h^2 = 0.11$
- One parameter left: $m_\chi$
- Predictions collapse to a line



# STATUS OF SUSY

$10^{-43}$ cm$^2$

$10^{-44}$ cm$^2$

No DM

DM

# LIGHT WIMPS

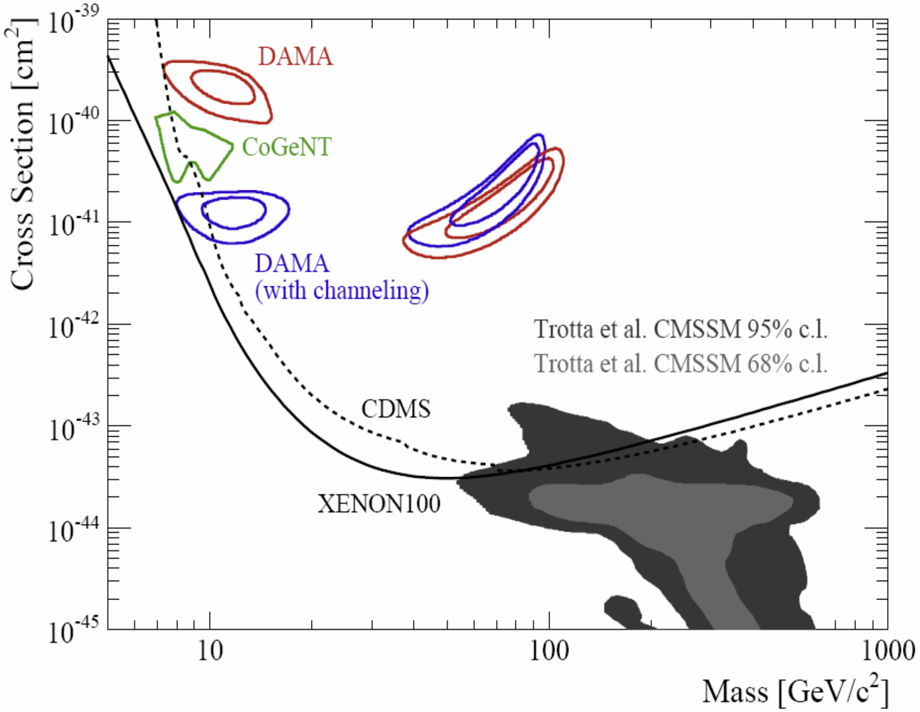
- ~10 GeV DM may explain DAMA
- This region is now tentatively supported by CoGeNT (2010), disfavored by XENON100 (2010)
- Conventional WIMPs?
  - Low masses: unusual, but not so difficult (e.g., neutralinos w/o gaugino mass unification)

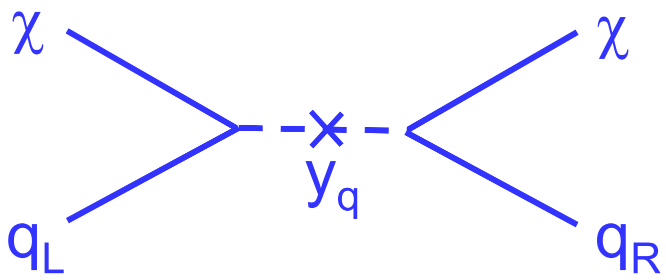
Dreiner et al. (2009)

  - High cross sections: very difficult (chirality flip implies large suppression)

Bottino et al. (2006)

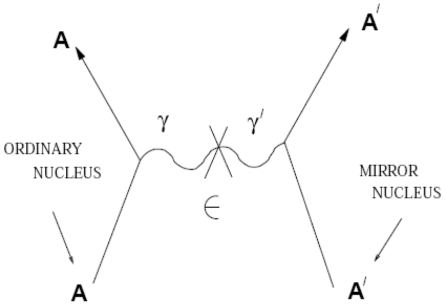
Kuflik, Pierce, Zurek (2010)



# LIGHT WIMP MODELS

- Mirror matter




Foot (2008)

- Asymmetric DM: relate DM number asymmetry to baryon number asymmetry, so $m_X / m_p \sim \rho_X / \rho_p \sim 5$

Talk of An

- WIMPless DM

Talks of Kumar, Badin, Yeghiyan, Fan, Sessolo

- Other candidates, related issues

Talks of Ibe, McCaskey, Ralston

# WIMPLESS DM

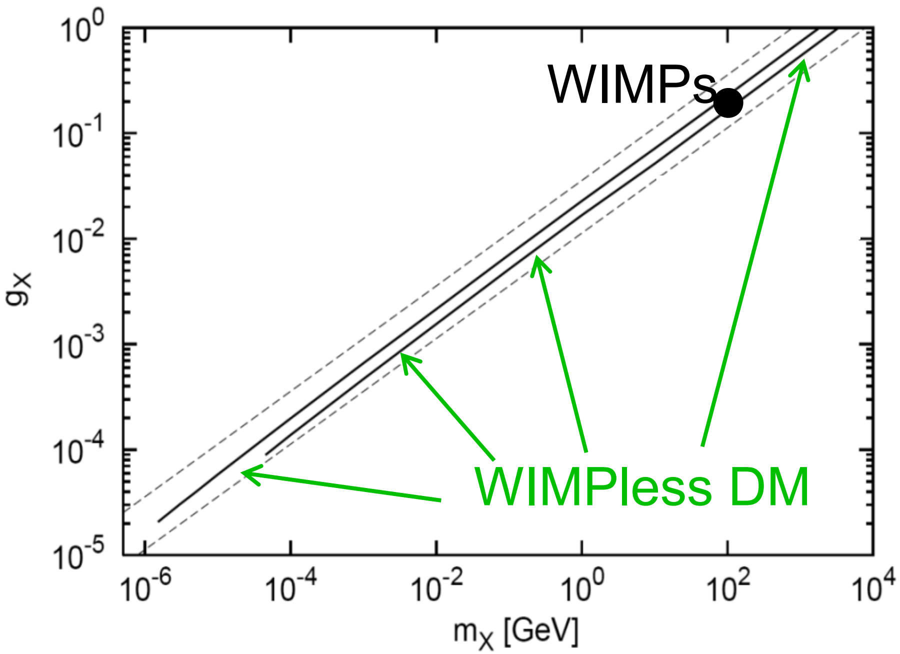
Feng, Kumar (2008); Feng, Tu, Yu (2008)

- Thermal relics in a hidden sector with mass $m_X$ and gauge coupling $g_X$

  The thermal relic density constrains only one combination of $g_X$ and $m_X$ :

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

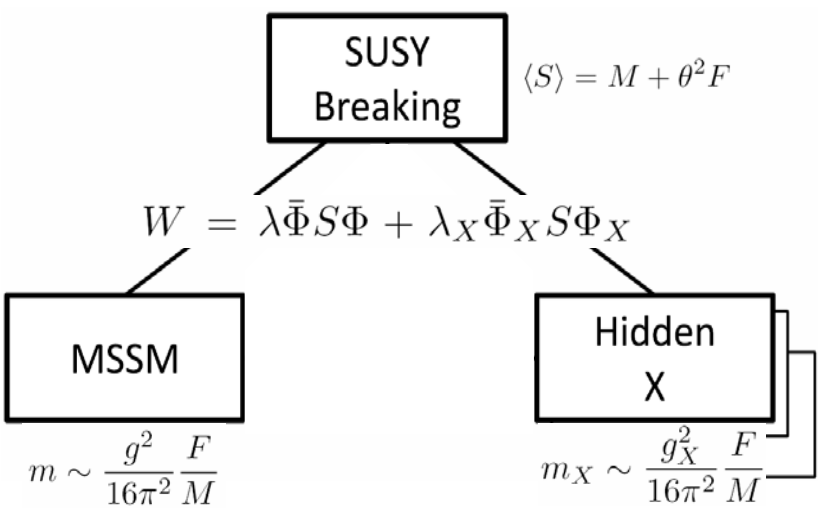
  These models map out the remaining degree of freedom




- This decouples the WIMP miracle from WIMPs

# THE WIMPLESS MIRACLE

- Can this be arranged? Consider GMSB




Superpartner masses ~ gauge couplings squared

- Cosmology

$$\frac{m_X}{g_X^2} \sim \frac{m}{g^2} \sim \frac{F}{16\pi^2 M}$$

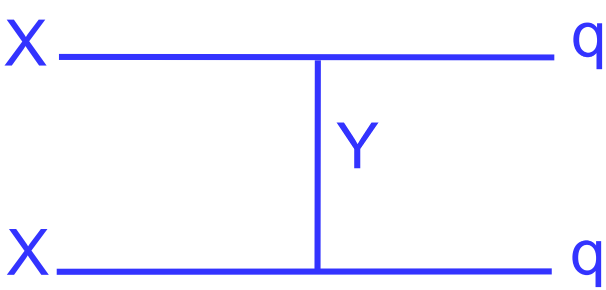
$\Omega$ depends only on the SUSY Breaking sector:

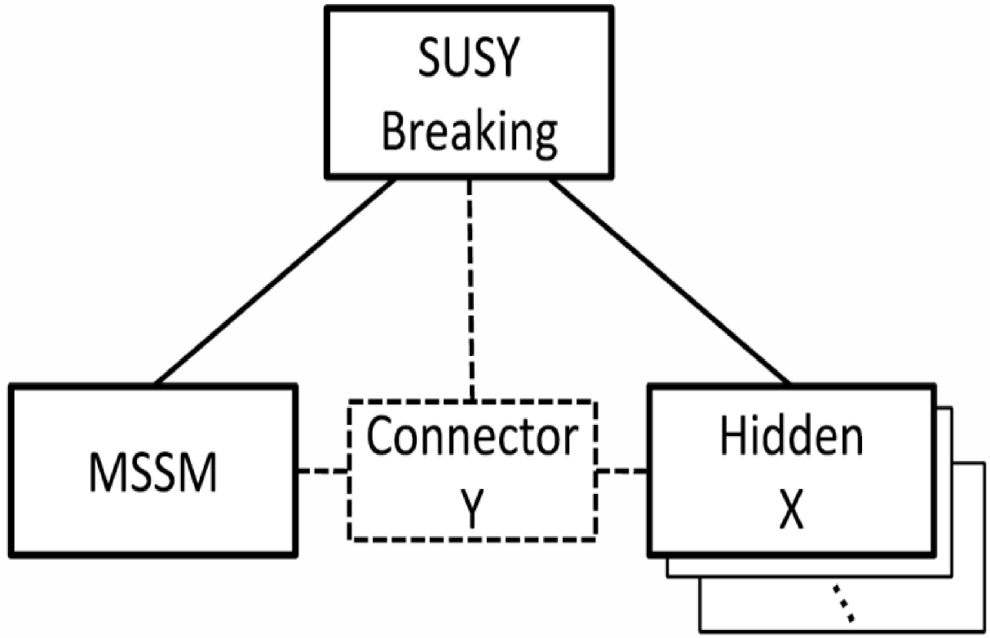
$$\Omega_X \sim \Omega_{WIMP} \sim \Omega_{DM}$$

- This is generic in SUSY (AMSB, gMSB, no-scale SUGRA,…): is this what the flavor problem is telling us?

# WIMPLESS SIGNALS

- Hidden DM may interact with normal matter through non-gauge interactions



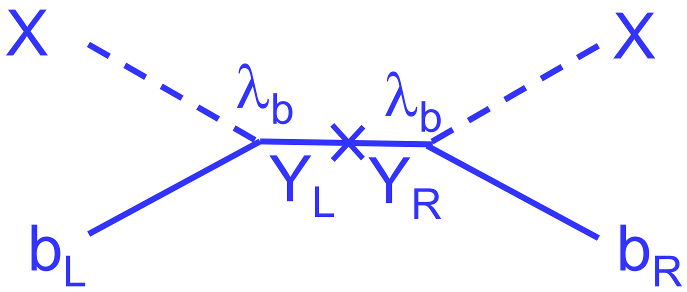



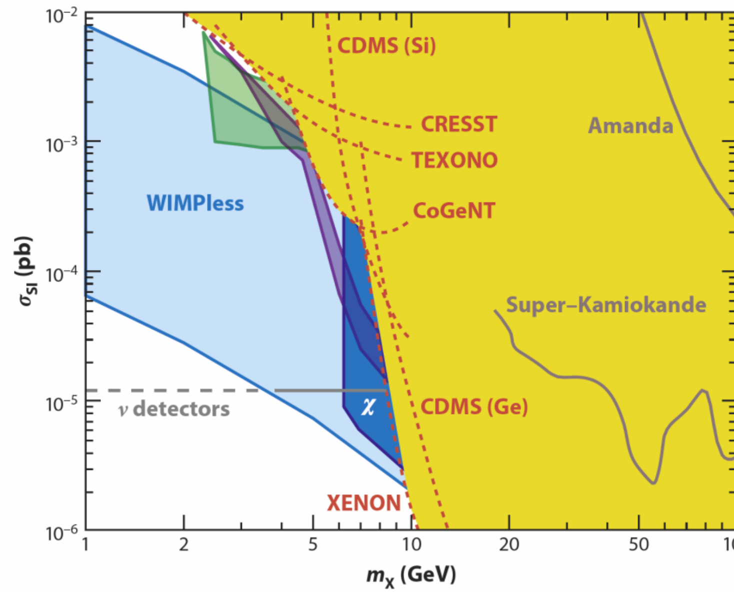
# WIMPLESS DIRECT DETECTION

- The DAMA/CoGeNT region is easy to reach with WIMPless DM
- E.g., assume WIMPless DM X is a scalar, Y is a fermion, interact with b quarks through

  $\lambda_b ( XY_L b_L + XY_R b_R ) + m_Y Y_L Y_R$

- Naturally correct mass, cross section
  - $m_X$ ~ 5-10 GeV (WIMPless miracle)
  - large $\sigma_{SI}$ for $\lambda_b$ ~ 0.3 – 1 (flip chirality on heavy Y propagator)



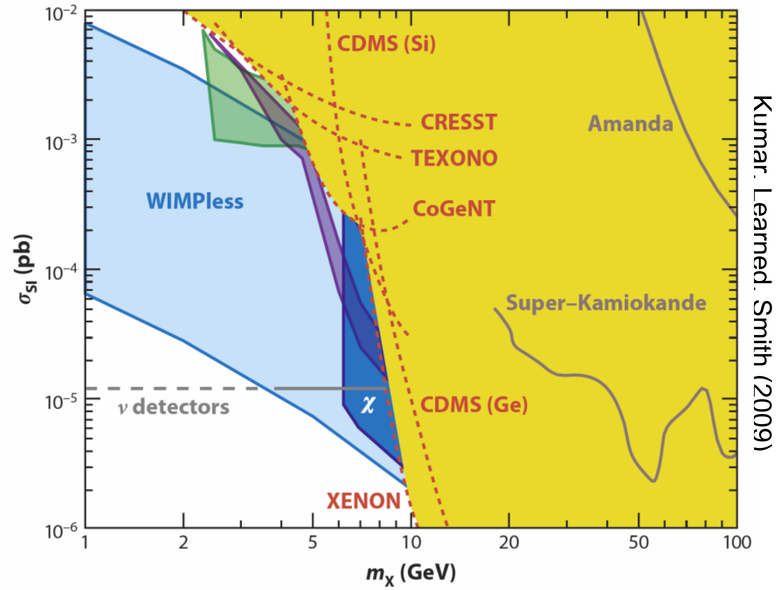

Kumar, Learned, Smith (2009)

# FUTURE PROSPECTS

- More direct detection, of course, but also

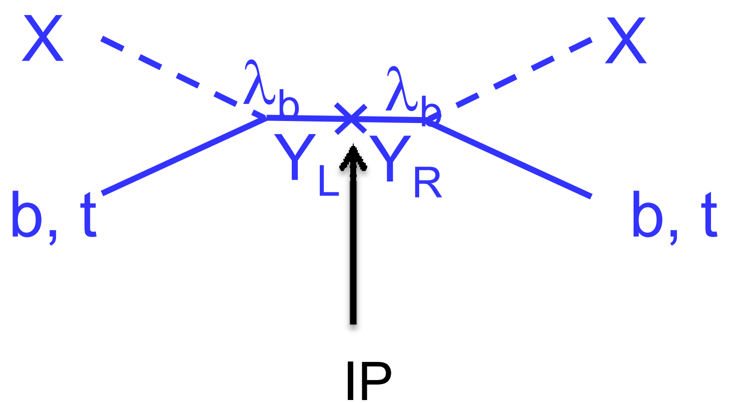
- SuperK, IceCube

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




- Light DM in Upsilon decays

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

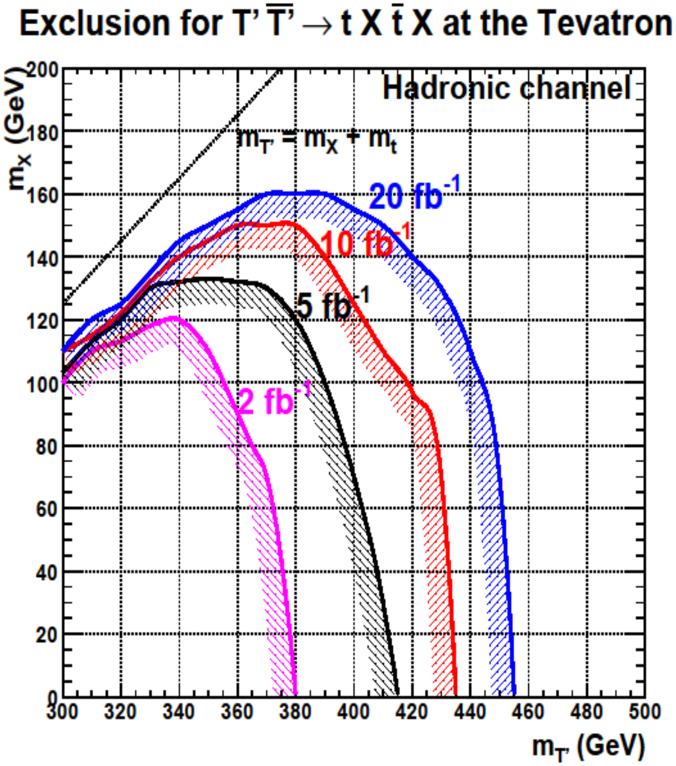


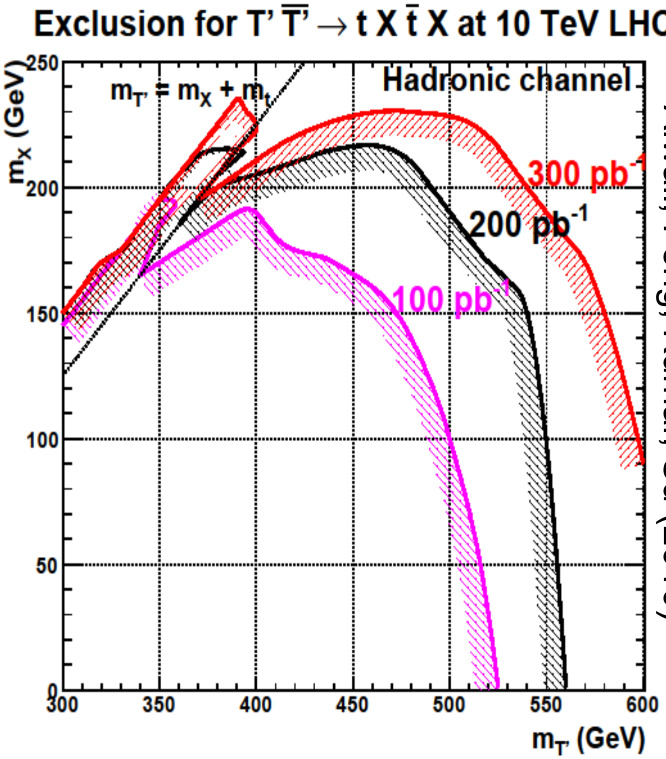

- Tevatron and LHC can find connector particles: colored, similar to 4th generation quarks

# EXOTIC 4TH QUARKS AT LHC

Direct searches, perturbativity → 300 GeV < $m_Y$ < 600 GeV

The entire region can be excluded by 10 TeV LHC with 300 $pb^{-1}$ (~7 TeV LHC with 1 $fb^{-1}$); significant discovery prospects




Alwall, Feng, Kumar, Su (2010)

# CONCLUSIONS

- DM searches are progressing rapidly on all fronts
  - Direct detection
  - Indirect detection
  - LHC

- Proliferation of DM candidates, but many are tied to the weak scale

- In the next few years, these DM models will be stringently tested