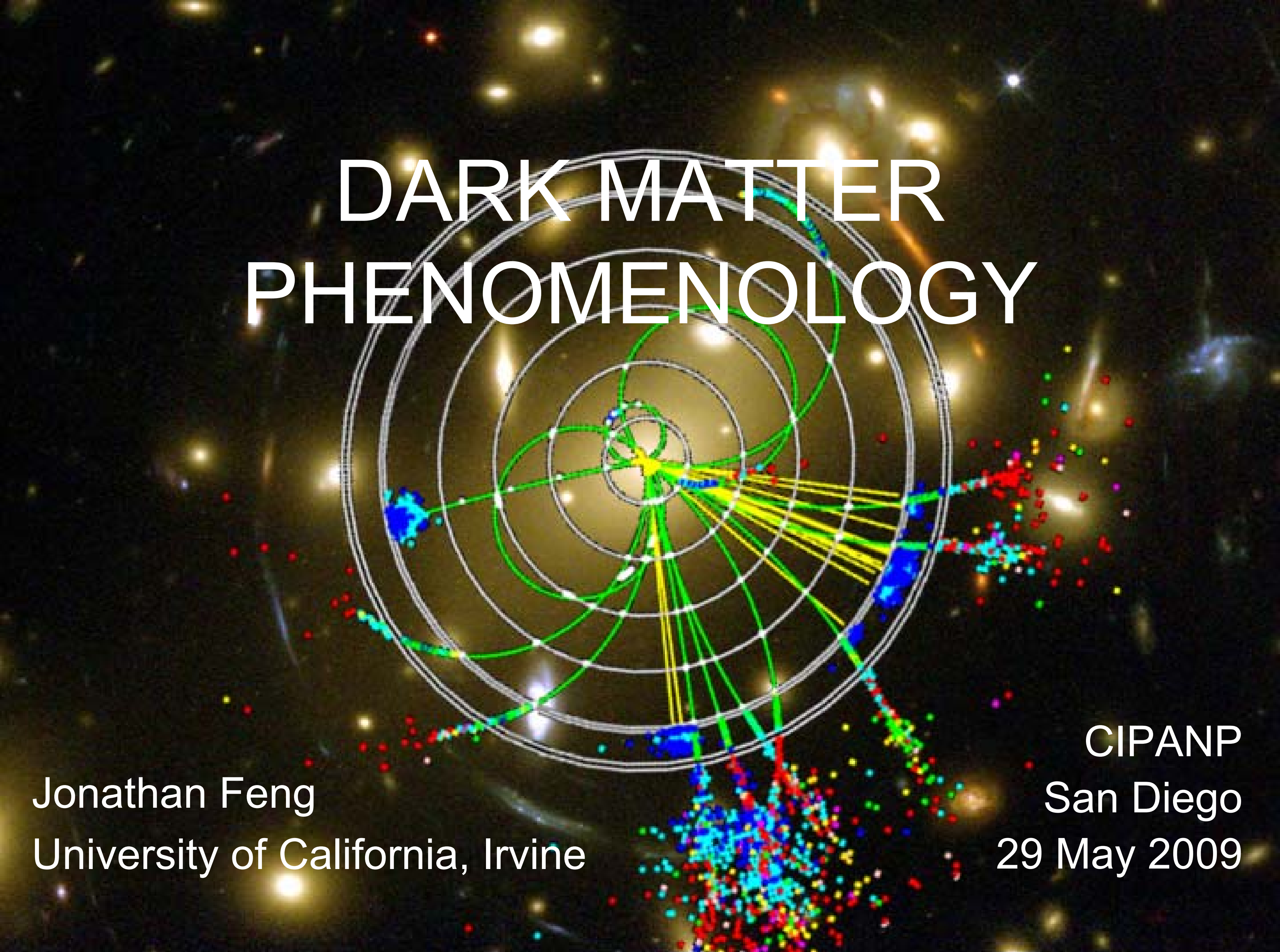

DARK MATTER PHENOMENOLOGY

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CIPANP

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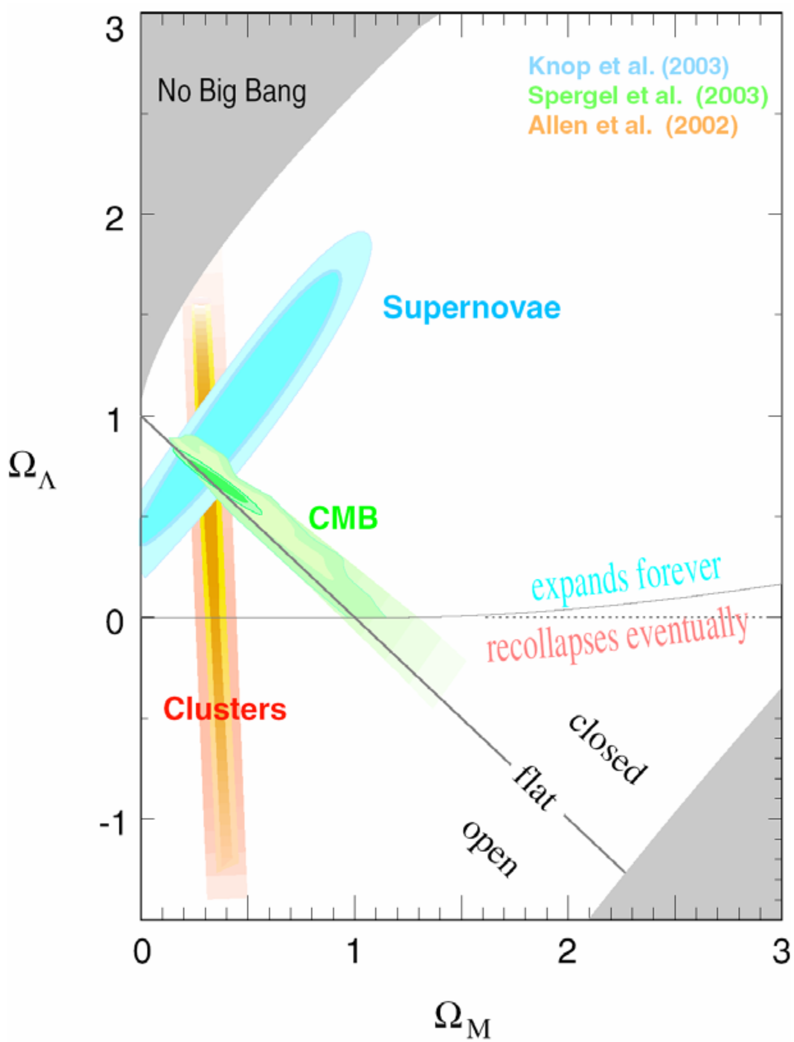
29 May 2009

DARK MATTER



Talks at CIPANP: Cushman, many others

- We know how much there is

  $\Omega_{DM}h^2 = 0.1099 \pm 0.0062$

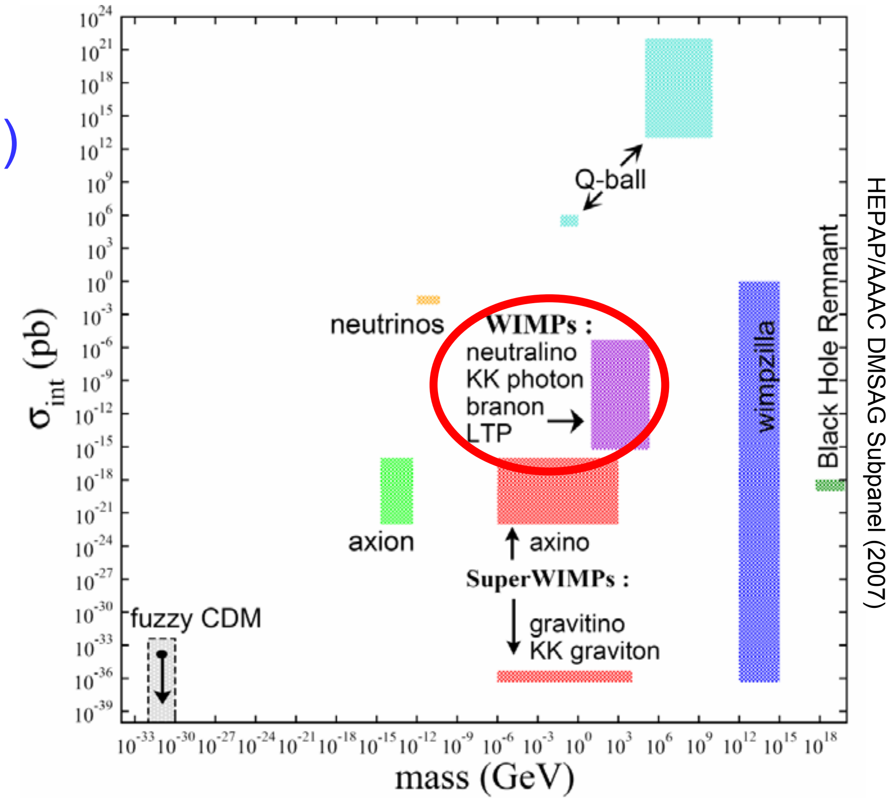
  WMAP (2008)

- But what is it?

- Intimately connected to central problems in particle physics and astrophysics
  - new particles and forces
  - structure formation

CANDIDATES

- Observational constraints
  - Not baryonic (≠ weakly-interacting)
  - Not hot (≠ cold)
  - Not short-lived (≠ stable)



- Possible masses and interaction strengths span many, many orders of magnitude

- Focus on candidates with mass around m_{weak} ~ 100 GeV

PARTICLE PHYSICS

- Fermi's constant G_F introduced in 1930s to describe beta decay

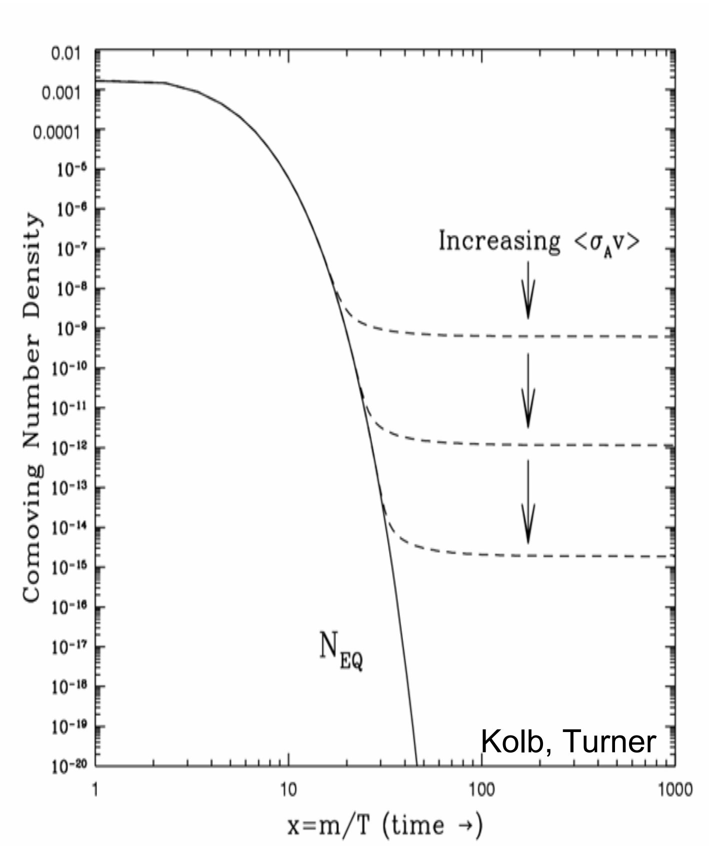
$$n \rightarrow p\, e^- \bar{\nu}$$

- $G_F \approx 1.1\ 10^5\ \mathrm{GeV}^{-2} \rightarrow$ a new mass scale in nature

$$m_{weak} \sim 100\ \mathrm{GeV}$$

- We still don't understand the origin of this mass scale, but every attempt so far introduces new particles at the weak scale

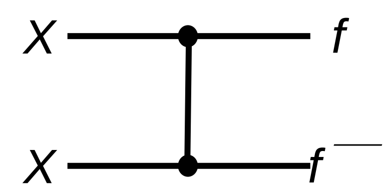
THE WIMP MIRACLE



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

- Its relic density is

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

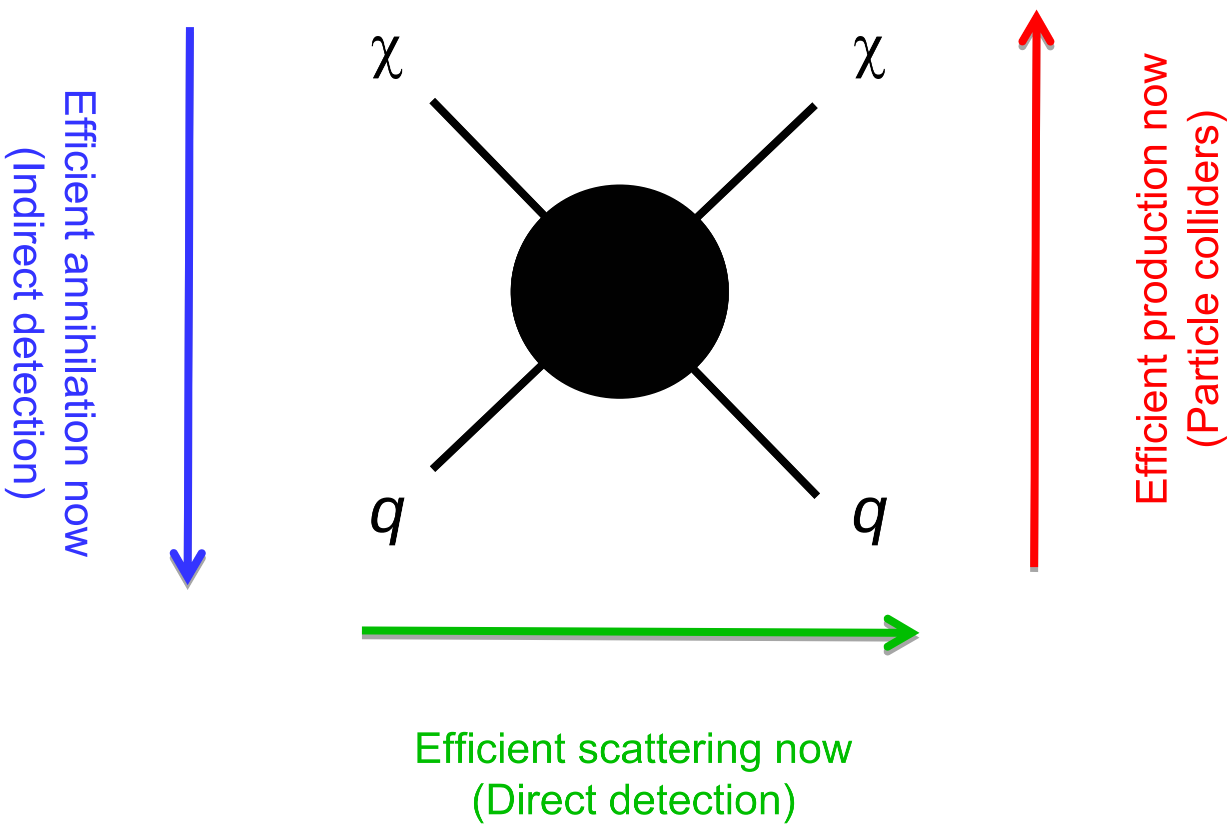


- $m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

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

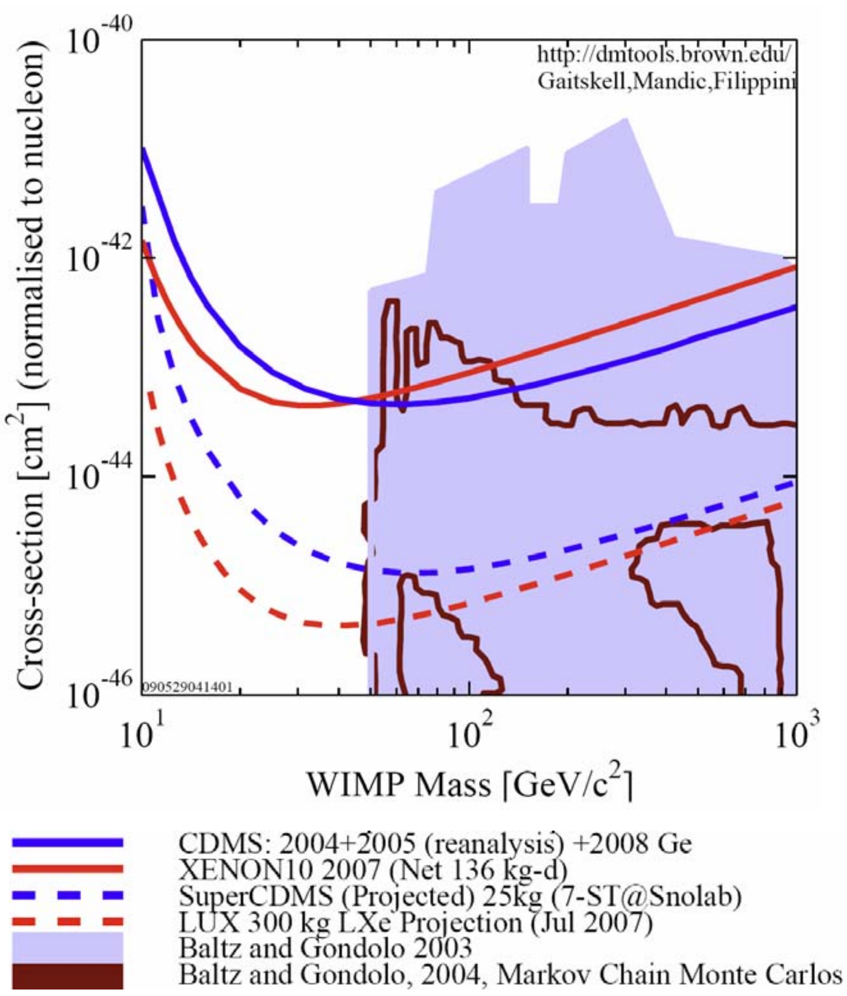
WIMP DETECTION

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



DIRECT DETECTION 1

- WIMP properties
  - $v \sim 10^{-3}$ c
  - Kinetic energy ~ 100 keV
  - Local density ~ 1 / liter
- Detected by nuclear recoil in underground detectors; two leading methods
- Background-free detection
  - Spin-independent scattering is typically the most promising
  - Theory and experiment compared in the (m_X, σ_{proton}) plane
  - Expt: CDMS, XENON, …
  - Theory: SUSY region – WHAT ARE WE TO MAKE OF THIS?



DARK MATTER VS. FLAVOR PROBLEM

- Squark and slepton masses receive many contributions

- The gravitino mass $m_{\tilde{G}}$ characterizes the size of gravitational effects, which generically violate flavor and CP

$$m_{\tilde{q}}^2 = \begin{pmatrix} m_0^2 & 0 & 0 \\ 0 & m_0^2 & 0 \\ 0 & 0 & m_0^2 \end{pmatrix} + \begin{pmatrix} \sim m_{\tilde{G}}^2 & \sim m_{\tilde{G}}^2 & \sim m_{\tilde{G}}^2 \\ \sim m_{\tilde{G}}^2 & \sim m_{\tilde{G}}^2 & \sim m_{\tilde{G}}^2 \\ \sim m_{\tilde{G}}^2 & \sim m_{\tilde{G}}^2 & \sim m_{\tilde{G}}^2 \end{pmatrix}$$

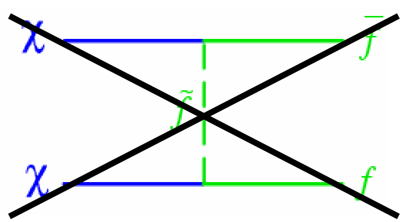
- These violate low energy constraints (badly)
  - Flavor: Kaon mixing, $\mu \to e\, \gamma$
  - Flavor and CP: ε_K
  - CP: neutron EDM, electron EDM

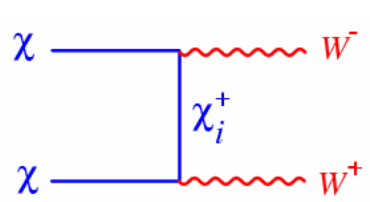
- Low energy bounds: $m_{\tilde{G}} << m_0$

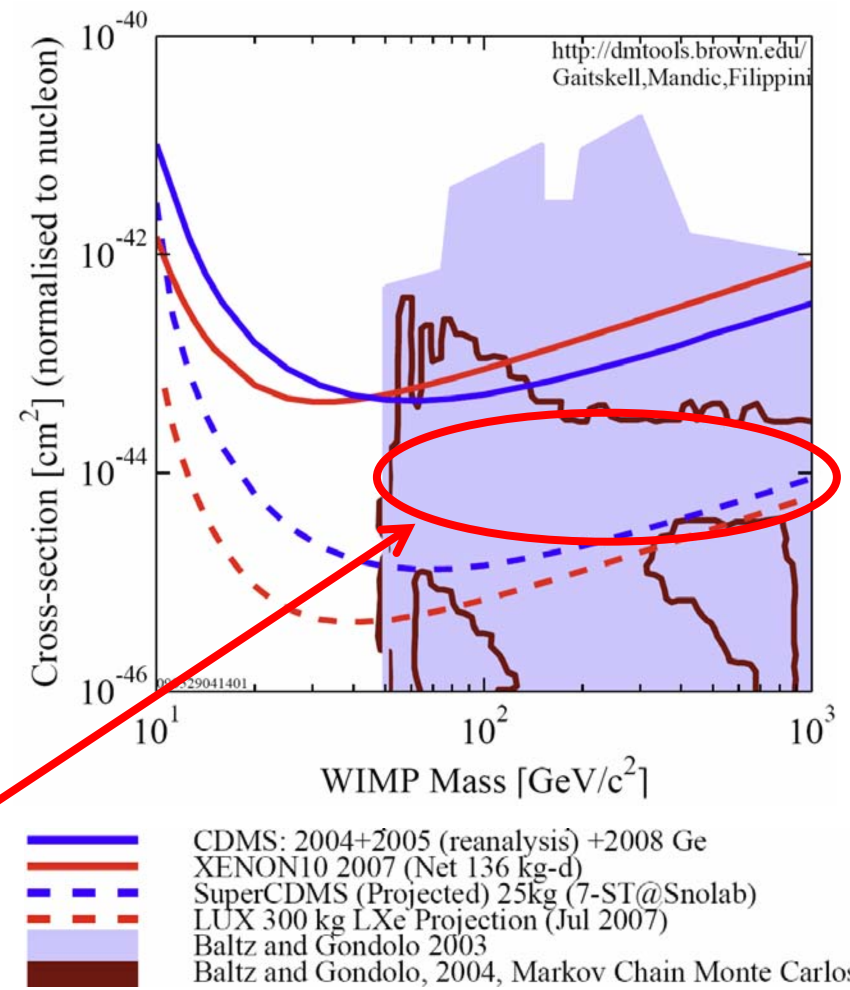
  Dark matter stability: $m_{\tilde{G}} > m_0$ Problem!

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

- Possible solutions
  - Set flavor violation to 0 by hand
  - …
  - Make sleptons and squarks heavy (few TeV or more)
- The last eliminates many annihilation diagrams, collapses predictions



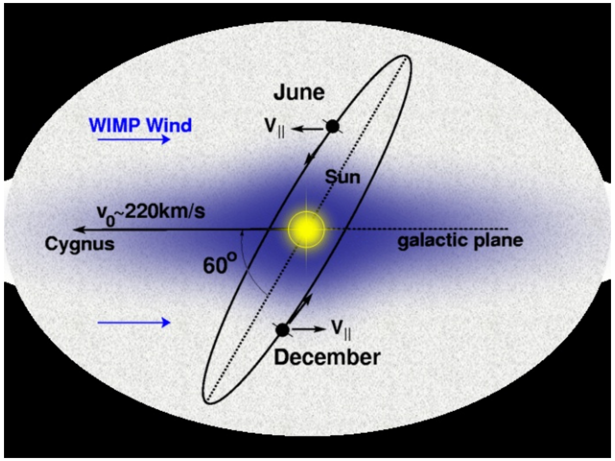




- Summary: The flavor problem → $\sigma_{SI} \sim 10^{-44}$ cm^2 (focus point SUSY, inverted hierarchy models, more minimal SUSY, 2-1 models, split SUSY,…)

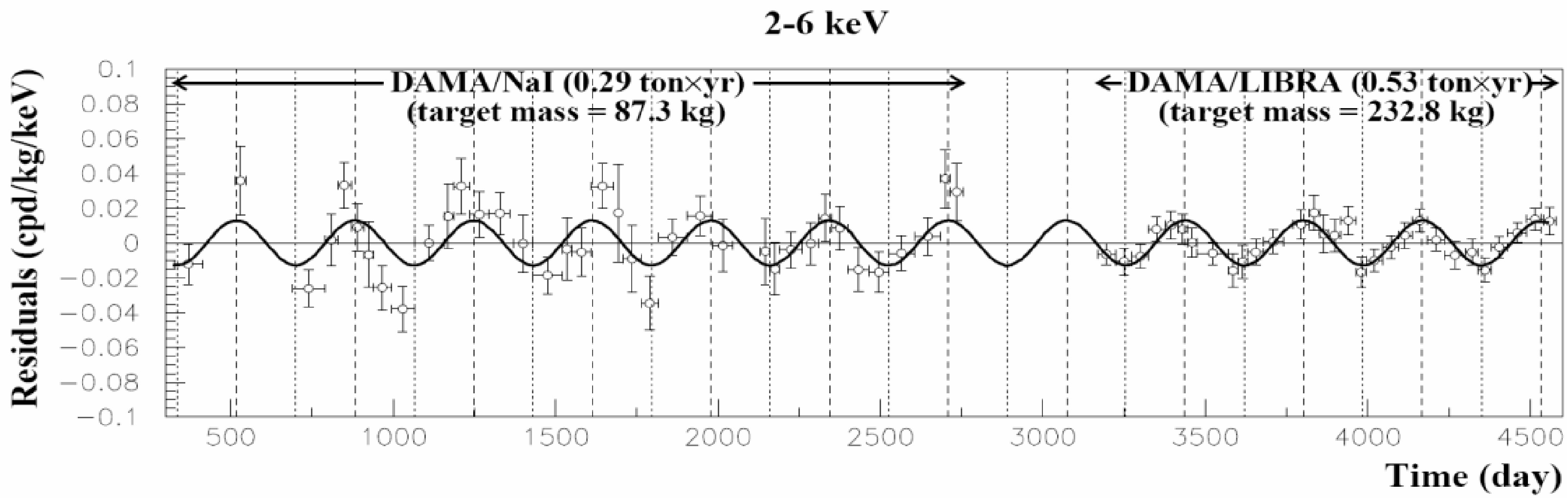
DIRECT DETECTION 2

Annual modulation: Collision rate should change as Earth's velocity adds constructively/destructively with the Sun's.



Drukier, Freese, Spergel (1986)

DAMA: 8σ signal with T ~ 1 year, max ~ June 2



DAMA (2008)

CHANNELING

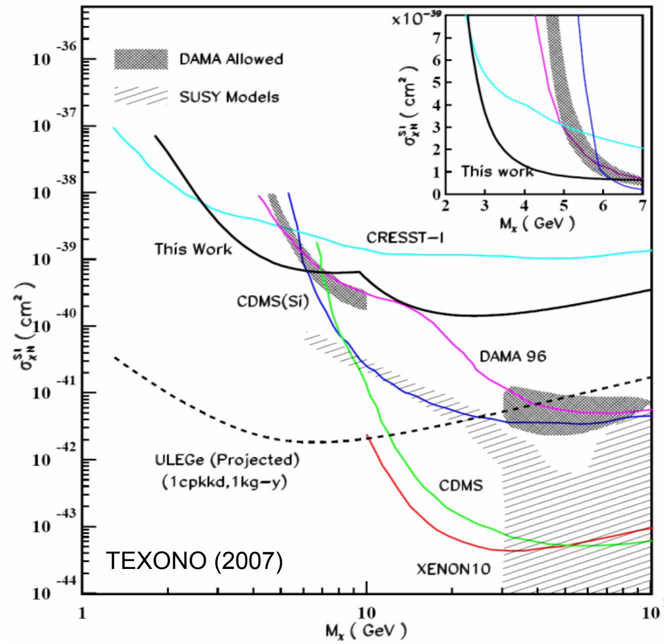
- DAMA's result is puzzling, in part because the favored region was considered excluded by others

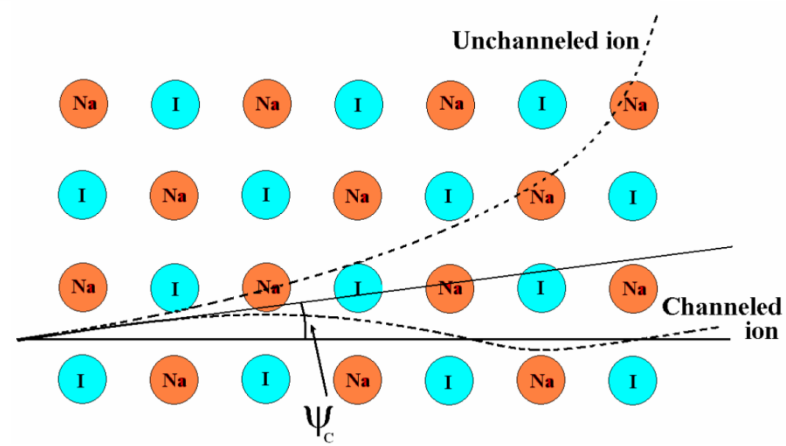
- This may be ameliorated by
  - Astrophysics
  - Channeling: in crystalline detectors, efficiency for nuclear recoil energy → electron energy depends on direction

Gondolo, Gelmini (2005)

Drobyshevski (2007), DAMA (2007)

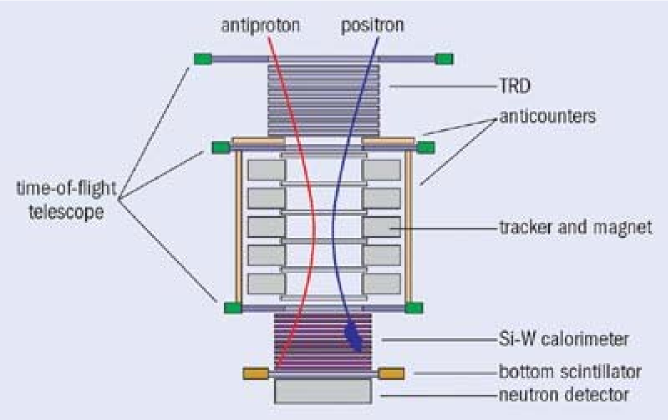
- Channeling reduces threshold, shifts allowed region to
  - Rather low WIMP masses (~GeV)
  - Very high σ_{SI} (~10^{-39} cm^2)

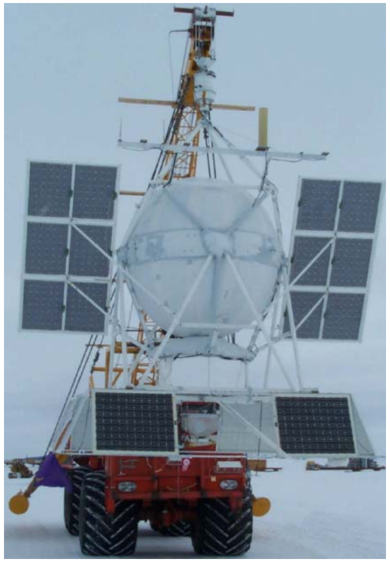




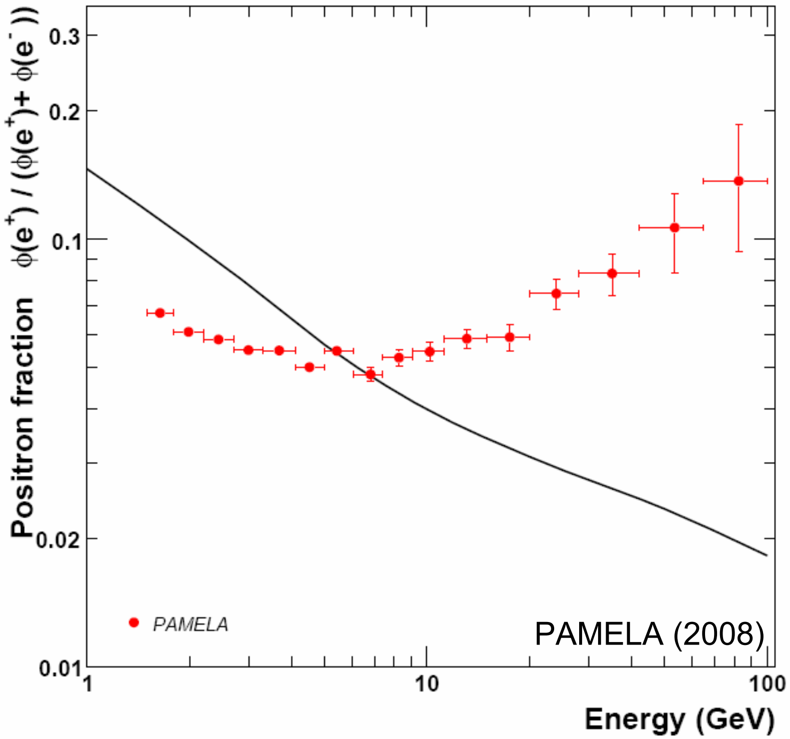
INDIRECT DETECTION

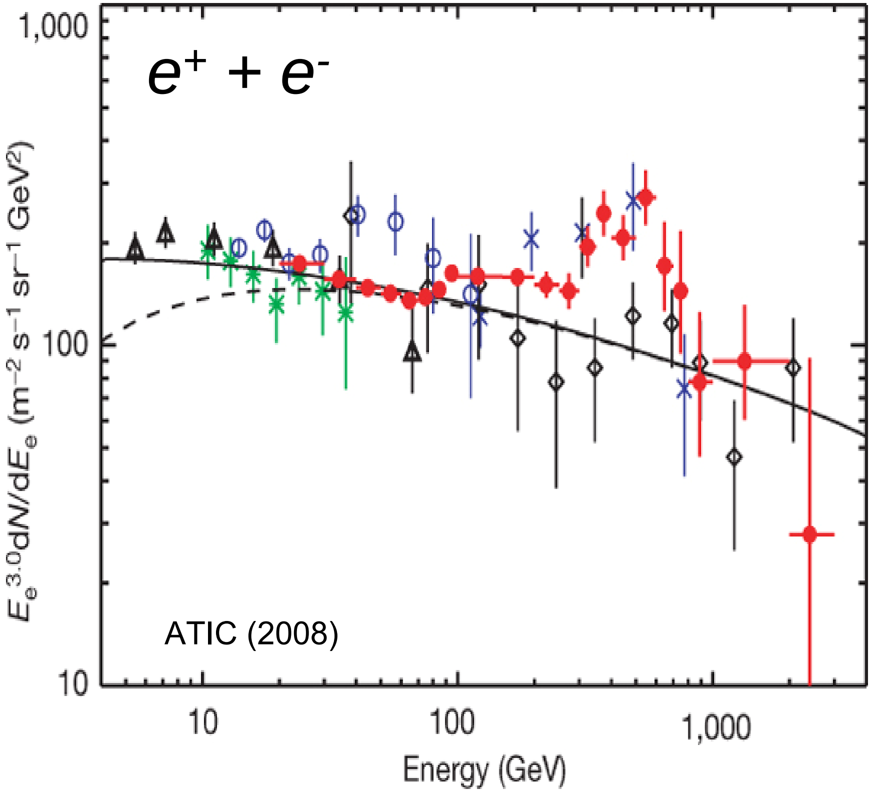
Dark Matter annihilates in ___the halo___ (a place) to ___positrons___ (some particles), which are detected by ___PAMELA/ATIC/…___ (an experiment).





PAMELA AND ATIC RESULTS





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

ARE THESE DARK MATTER?

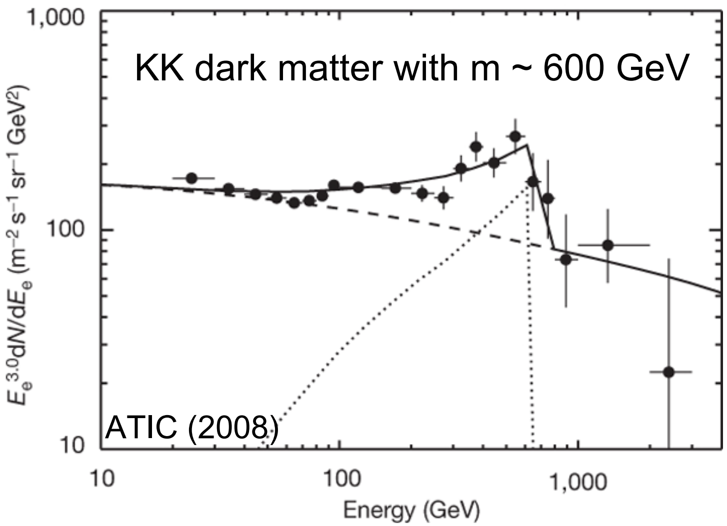
- Shape consistent with some dark matter candidates

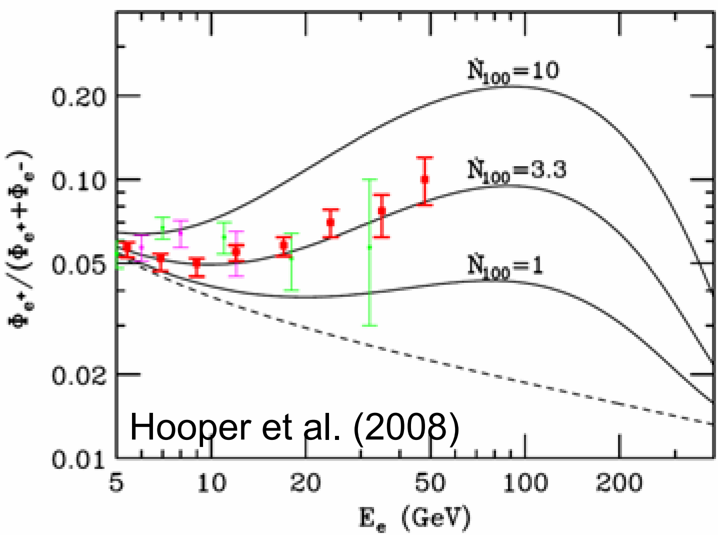
- Flux is a factor of 100-1000 too big for a thermal relic; requires enhancement
  - astrophysics (very unlikely)
  - particle physics

- No enhancement seen in anti-protons

- Pulsars can explain PAMELA

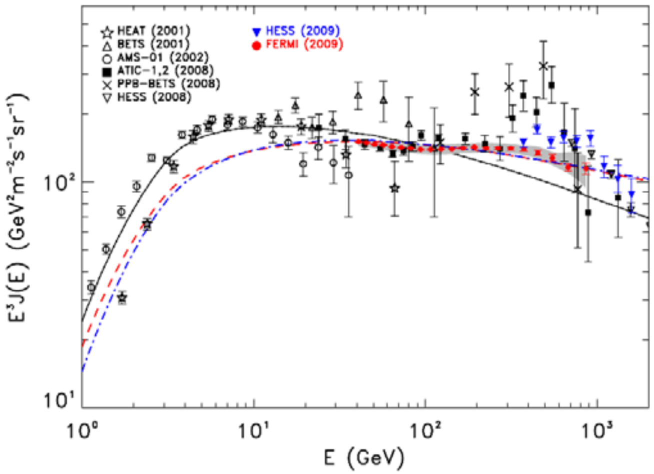
Zhang, Cheng (2001); Hooper, Blasi, Serpico (2008)
Yuksel, Kistler, Stanev (2008); Profumo (2008)
Fermi LAT Collaboration (2009)

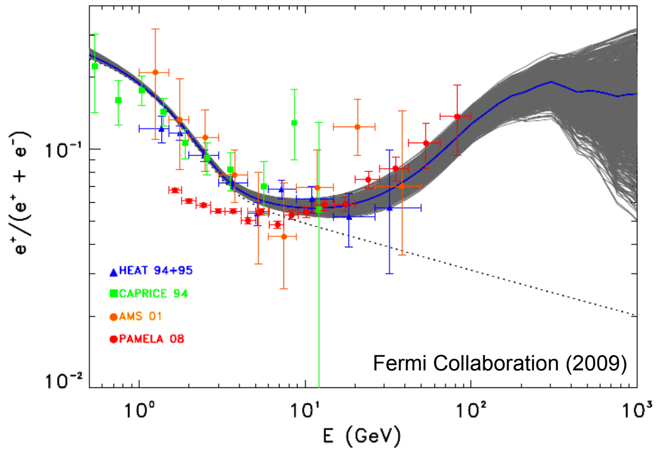


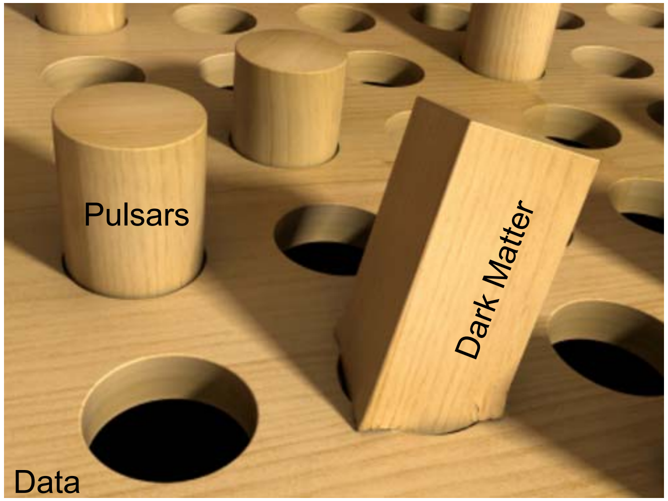


FERMI AND HESS

- Fermi and HESS do not confirm ATIC: no feature, consistent with background
- Pulsars can explain PAMELA







HIDDEN DARK MATTER

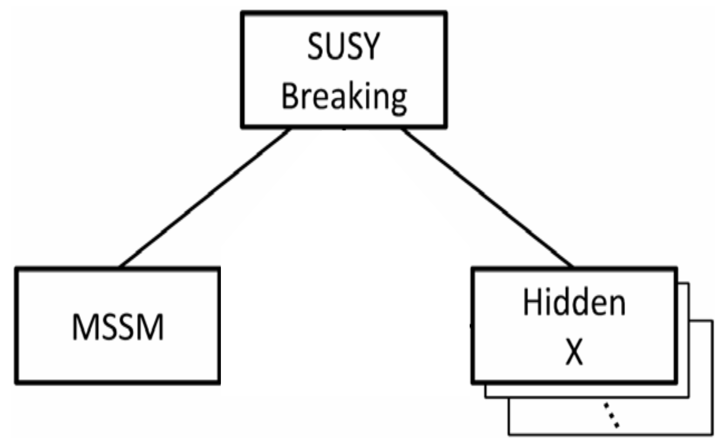
- The anomalies (DAMA, PAMELA, ATIC, …) are not easily explained by canonical WIMPs
- Start over: What do we really know about dark matter?
  - All solid evidence is gravitational
  - Also solid evidence *against* strong and EM interactions
- A reasonable 1st guess: dark matter has no SM gauge interactions, i.e., it is *hidden*

Kobsarev, Okun, Pomeranchuk (1966); many others

- What one seemingly loses
  - Connection to central problems of particle physics
  - The WIMP miracle
  - Non-gravitaitonal signals

WIMP MIRACLE REVISITED

- Consider SUSY: Hidden sectors appear generically. Each has its own
  - mass scale m_X
  - gauge couplings g_X



- But the flavor problem motivates models with squark/slepton masses determined by gauge couplings (and so flavor-blind):

$$m_X \sim g_X^2$$

(e.g., gauge mediation,anomaly-mediation)

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

- This implies that Ω_X is constant in all sectors!

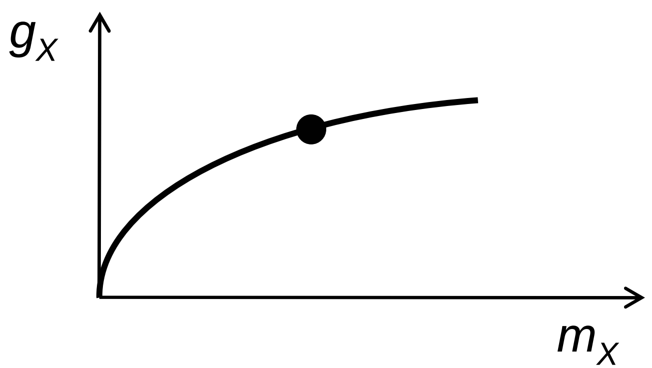
WIMPLESS MIRACLE

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

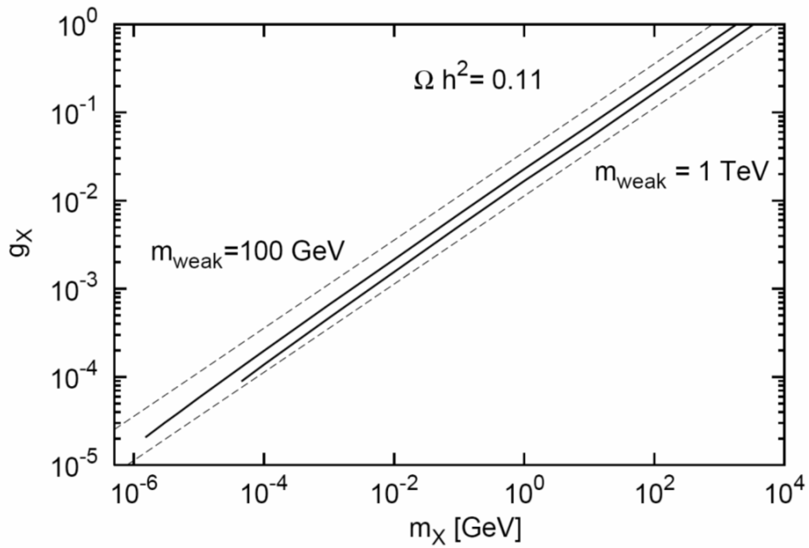
- The thermal relic density constrains only one combination of g_X and m_X

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

- These models map out the remaining degree of freedom



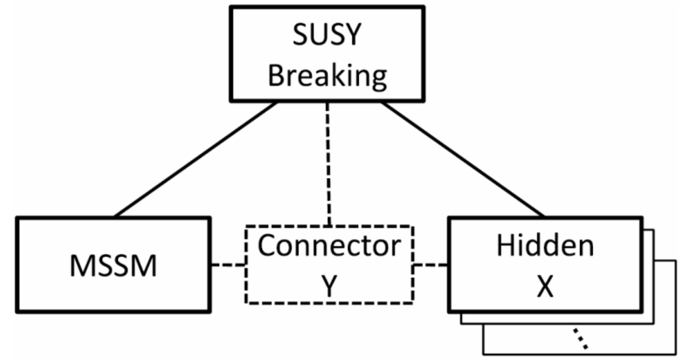
- This framework decouples the WIMP miracle from WIMPs, motivates candidates with a range of masses/couplings



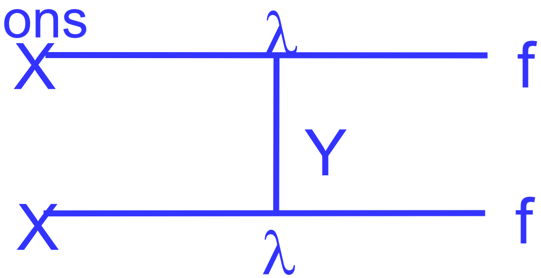
HIDDEN DM SIGNALS

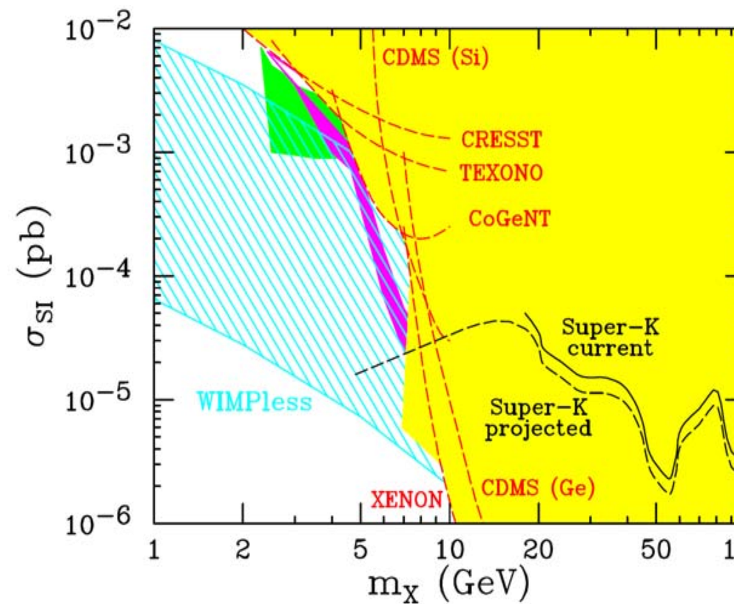
- Hidden DM may have only gravitational effects, but still interesting: e.g., it may have hidden charge, Rutherford scattering → self-interacting DM

Feng, Kaplinghat, Tu, Yu (2009)



- Alternatively, hidden DM may interact with normal matter through non-gauge interactions





Feng, Kumar, Learned, Strigari (2008)

- Many new, related ideas

Pospelov, Ritz (2007); Hooper, Zurek (2008)
Arkani-Hamed, Finkbeiner, Slatyer, Weiner (2008)
Ackerman, Buckley, Carroll, Kamionkowski (2008)

CONCLUSIONS

- Rapid experimental progress
  - Direct detection
  - Indirect detection
  - Colliders (LHC)

- Proliferation of new classes of candidates
  - WIMP dark matter
  - Hidden dark matter
  - …

- In the next few years, many DM models will be stringently tested; we will either see something or be forced to rethink some of our most cherished prejudices