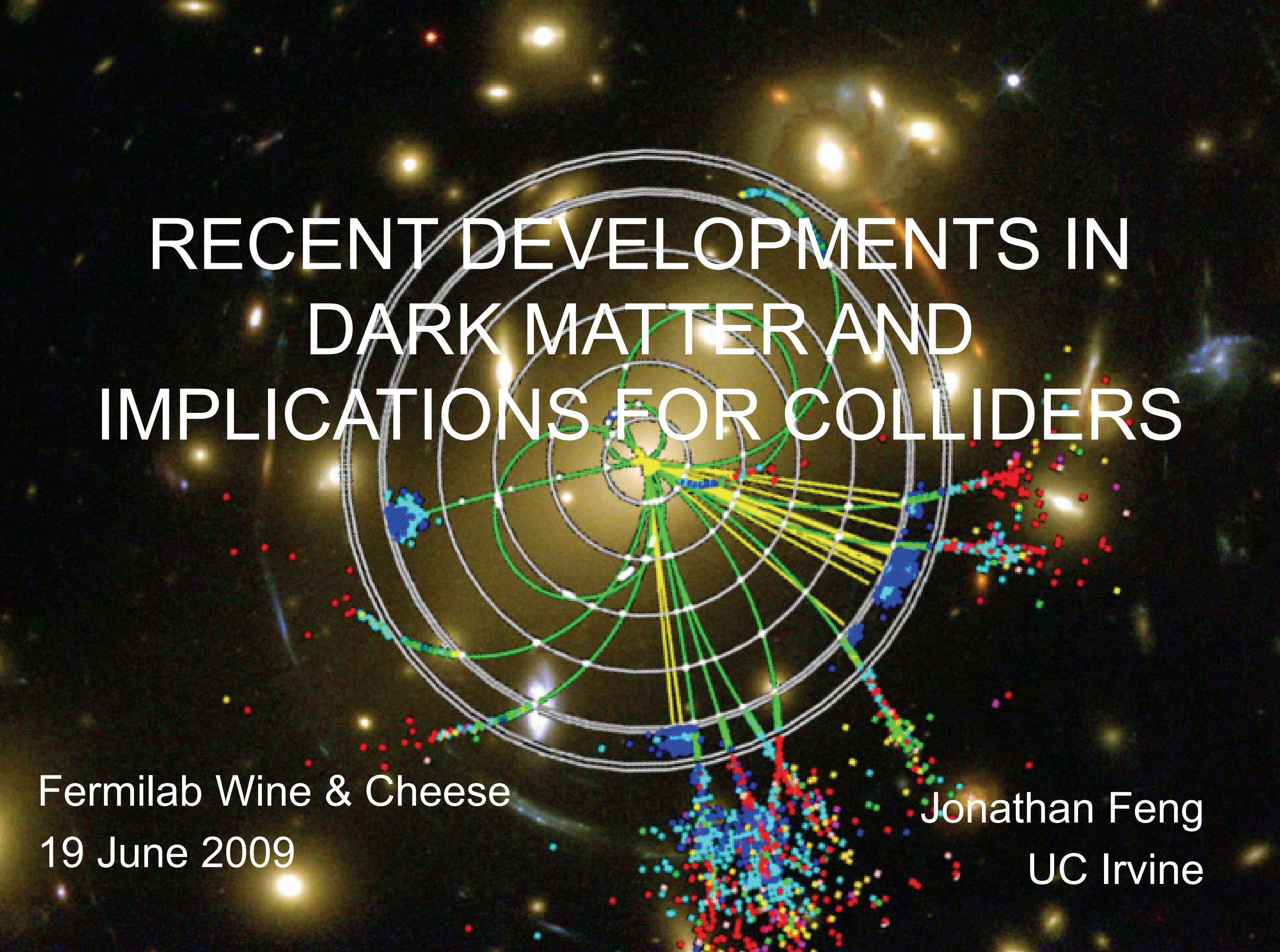
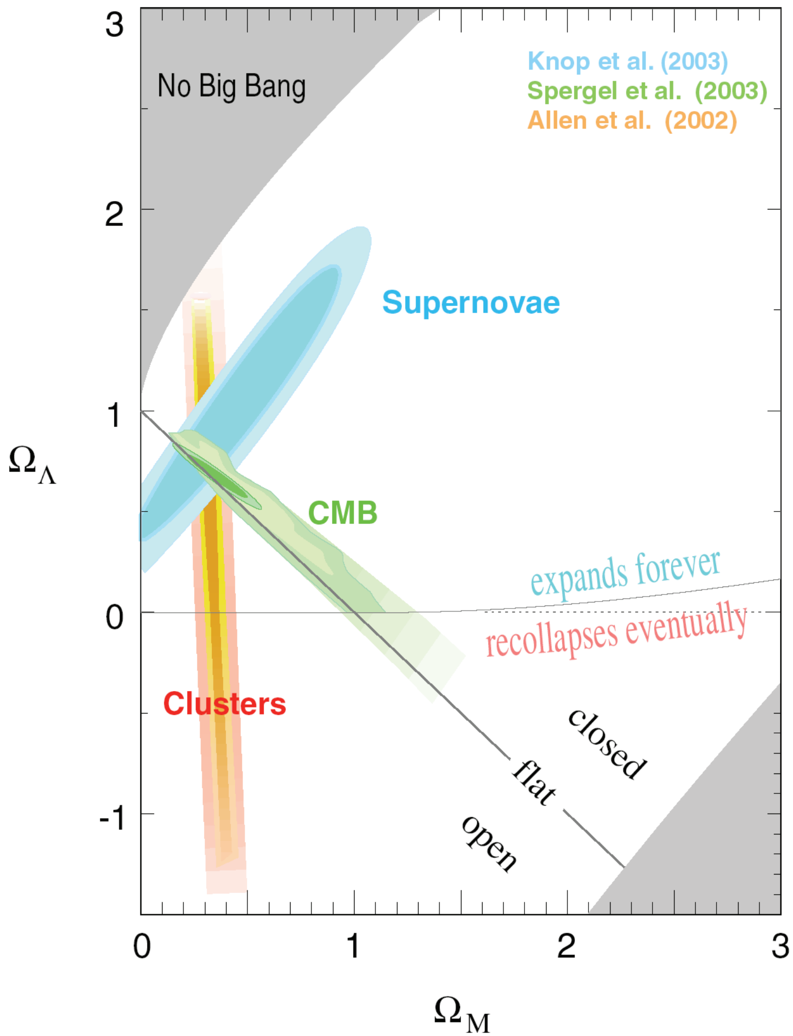


RECENT DEVELOPMENTS IN DARK MATTER AND IMPLICATIONS FOR COLLIDERS

Fermilab Wine & Cheese
19 June 2009

Jonathan Feng
UC Irvine

EVIDENCE FOR DARK MATTER



- There is now overwhelming evidence that normal (standard model) matter is not all the matter in the Universe:

  Dark Matter: 23% ± 4%

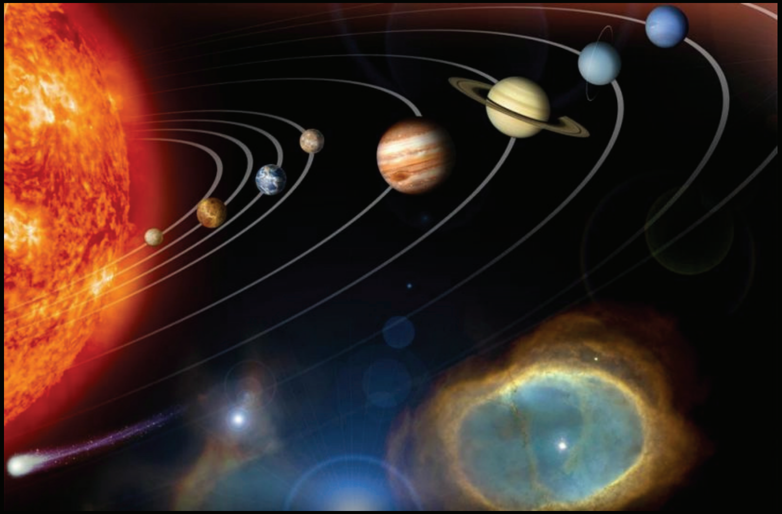
  Dark Energy: 73% ± 4%

  Normal Matter: 4% ± 0.4%

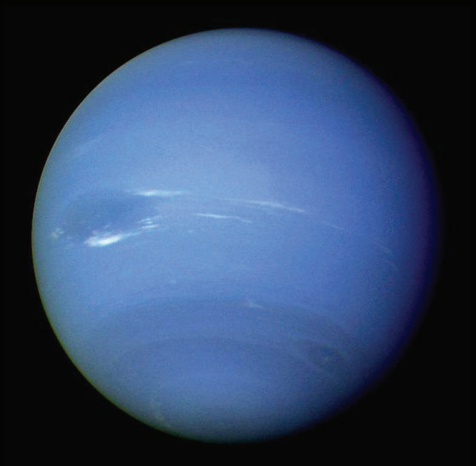
  Neutrinos: 0.2% (Σm_ν/0.1eV)

- To date, all evidence is from dark matter's gravitational effects. We would like to detect it in other ways to learn more about it.

A PRECEDENT

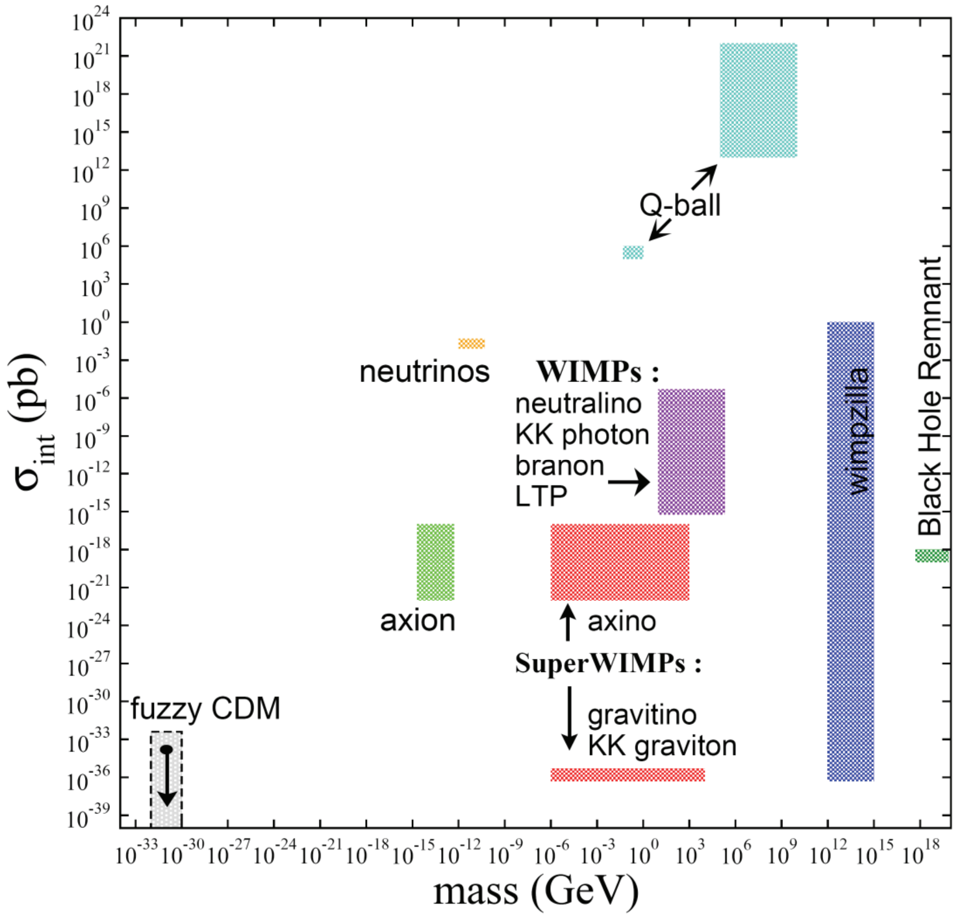


- In 1821 Alexis Bouvard found anomalies in the observed path of Uranus and suggested they could be caused by dark matter
- In 1845-46 Urbain Le Verrier determined the expected properties of the dark matter and how to find it. With this guidance, Johann Gottfried Galle discovered dark matter in 1846
- Le Verrier wanted to call it “Le Verrier,” but it is now known as Neptune, the farthest known planet (1846-1930, 1979-99, 2006-present)



DARK MATTER CANDIDATES

- There are many
- Masses and interaction strengths span many, many orders of magnitude
- Here focus on candidates with mass around m_{weak} ~ 100 GeV



HEPAP/AAAC DMSAG Subpanel (2007)

THE WIMP MIRACLE

(1) Assume a new (heavy) particle χ is initially in thermal equilibrium:

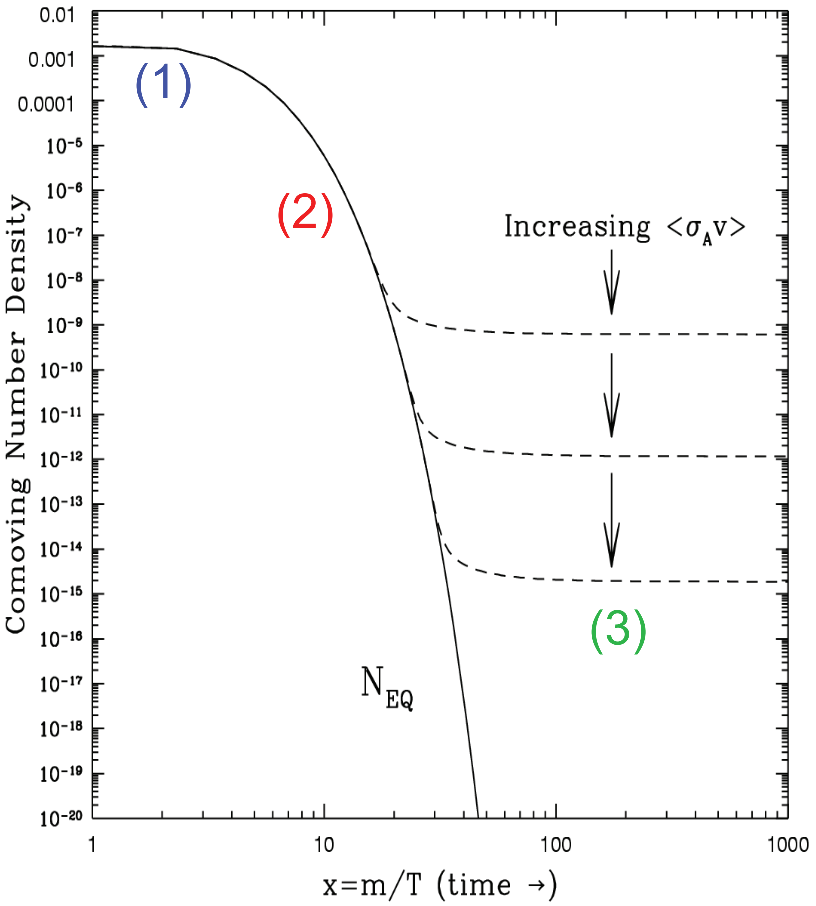
$$\chi\chi \leftrightarrow \bar{f} f$$

(2) Universe cools:

$$\chi\chi \;\substack{\rightarrow \\ \not\leftarrow}\; \bar{f} f$$

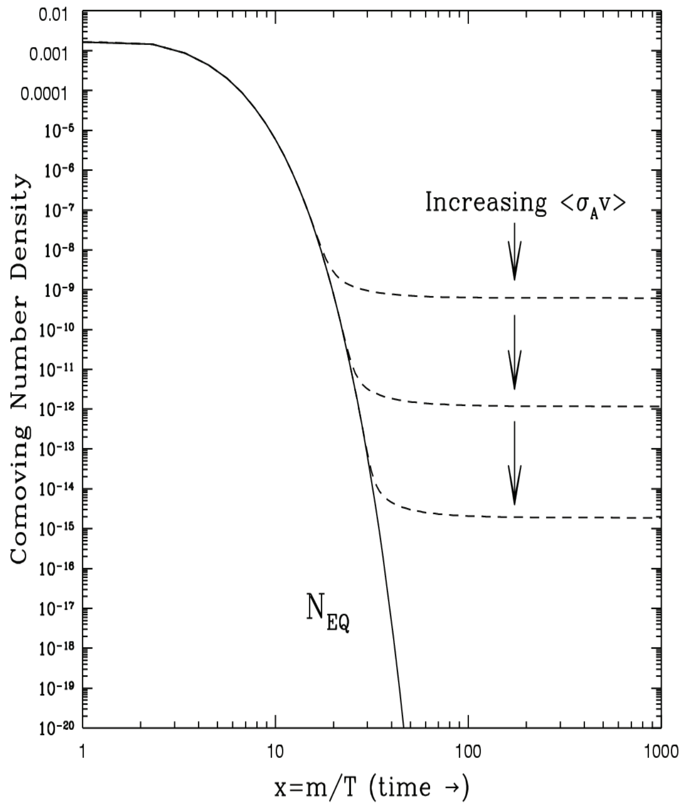
(3) χs "freeze out":

$$\chi\chi \;\substack{\not\rightarrow \\ \not\leftarrow}\; \bar{f} f$$



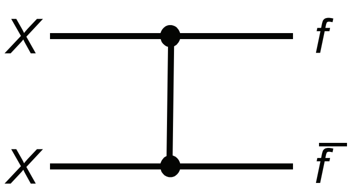
Zeldovich et al. (1960s)

THE WIMP MIRACLE



- The resulting relic density is

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



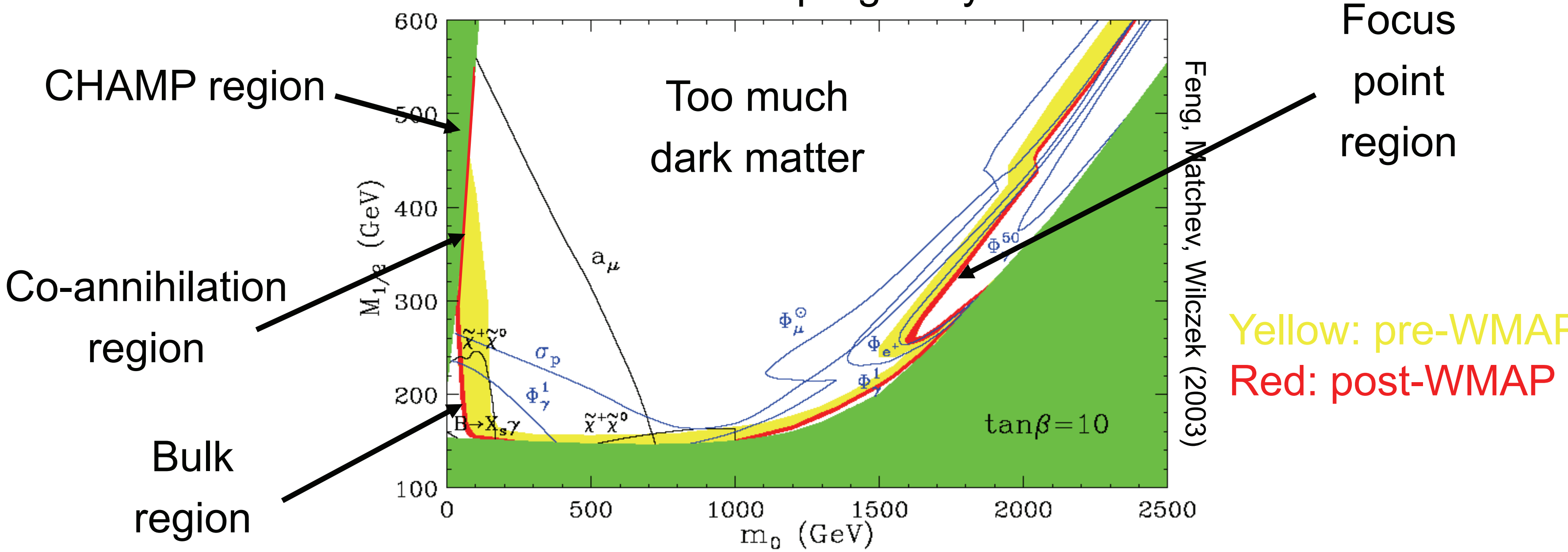
- For a WIMP, $m_X \sim 100$ GeV and $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

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

RELIC DENSITY CONSTRAINTS

Ω_{DM} = 23% ± 4% stringently constrains new physics models

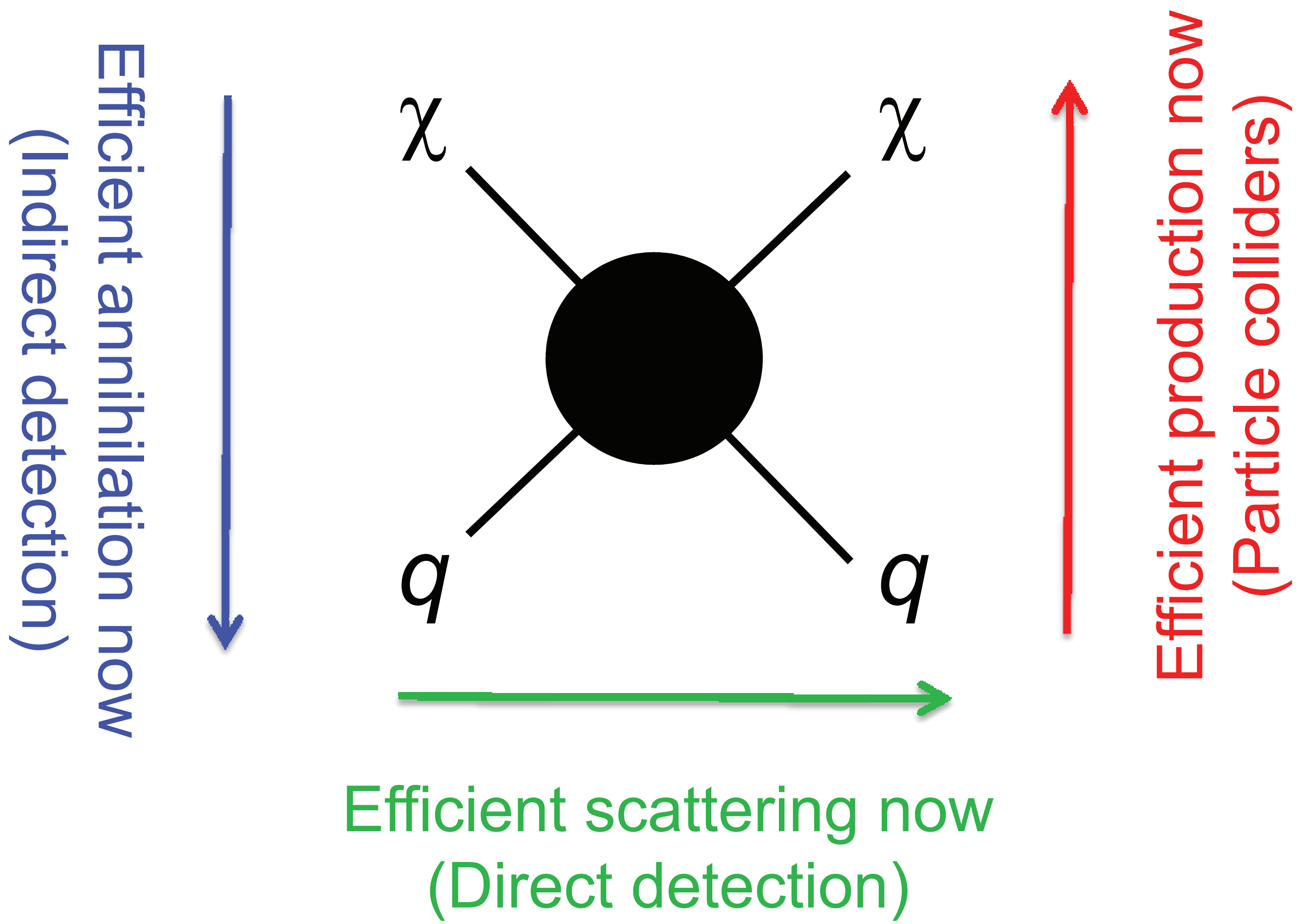
Minimal Supergravity



Cosmology excludes many possibilities, favors certain regions with distinctive collider signatures

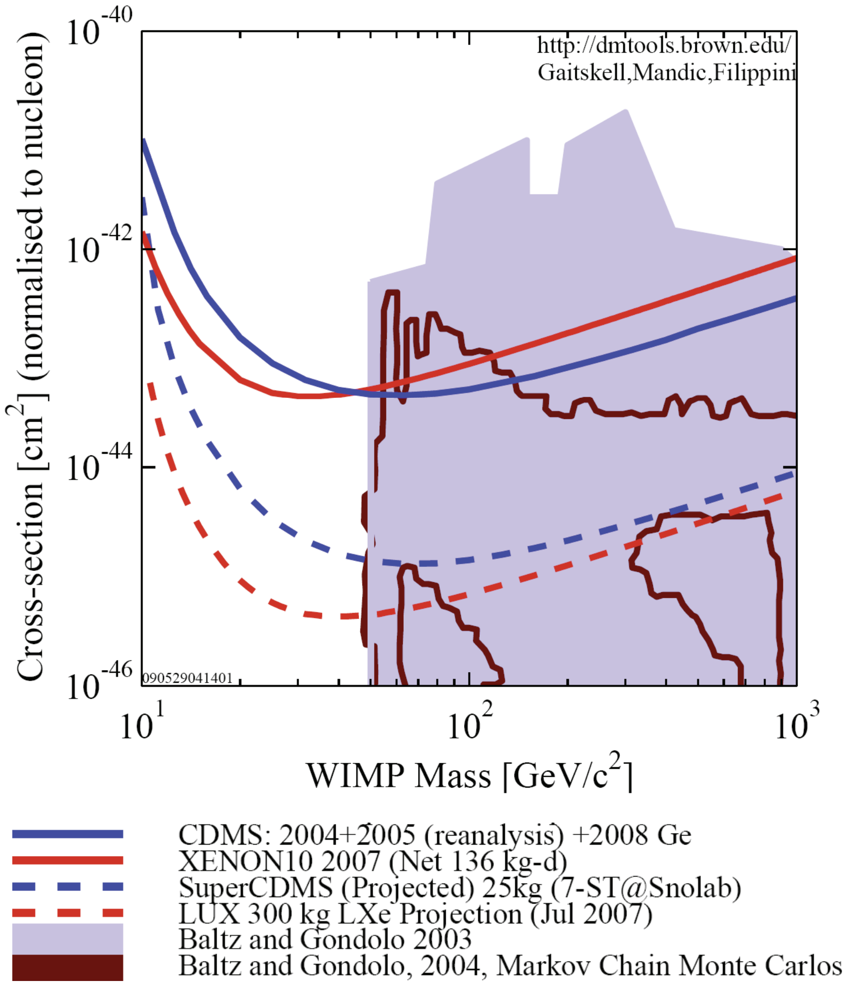
WIMP DETECTION

Correct relic density → "lower bound" on DM-SM interactions



DIRECT DETECTION

- WIMP properties
  - v ~ 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?

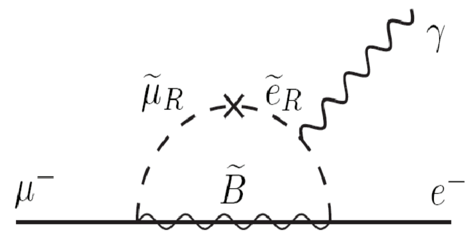


DARK MATTER VS. FLAVOR PROBLEM

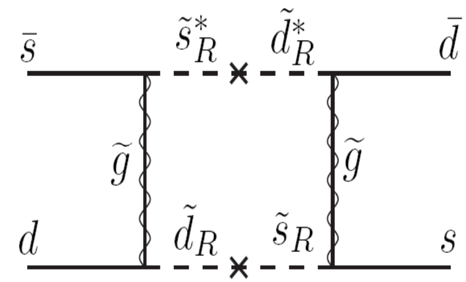
- Squark and slepton masses receive many contributions

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

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

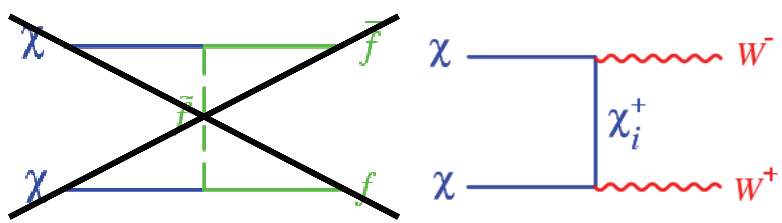


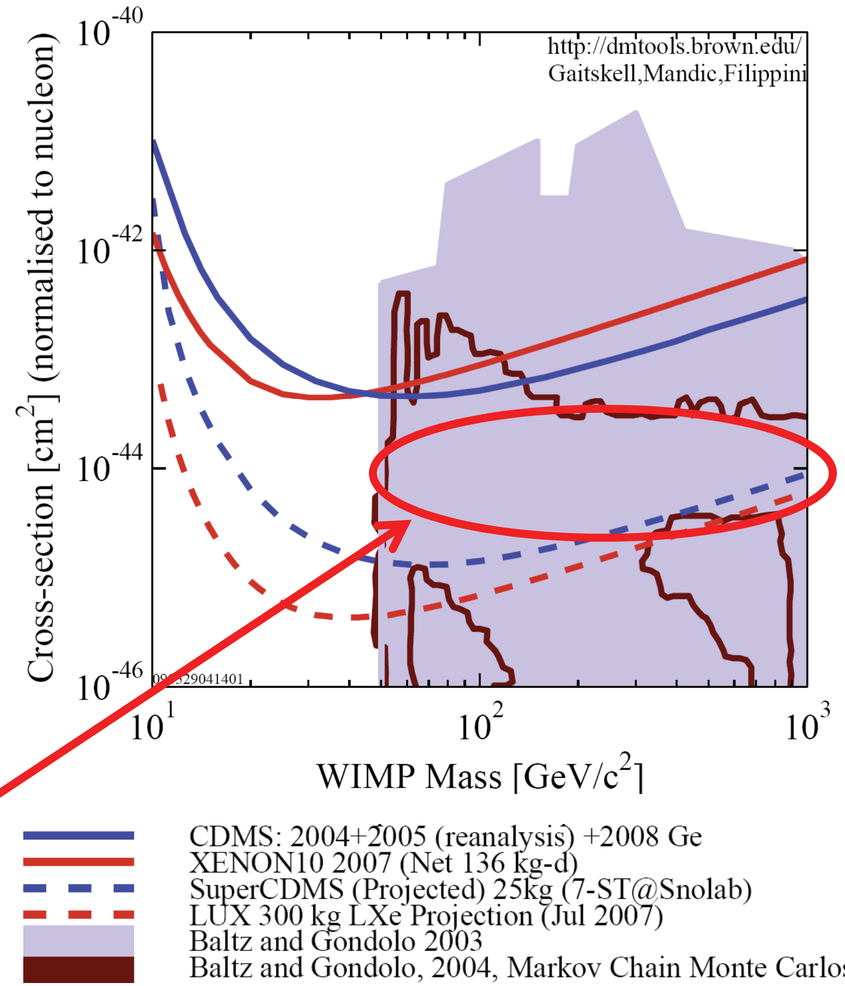
- For ~ 100 GeV sfermions, these violate low energy constraints (badly)
  - Flavor: Kaon mixing, $\mu \rightarrow e\,\gamma$
  - Flavor and CP: ε_K
  - CP: neutron EDM, electron EDM



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

- Some 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



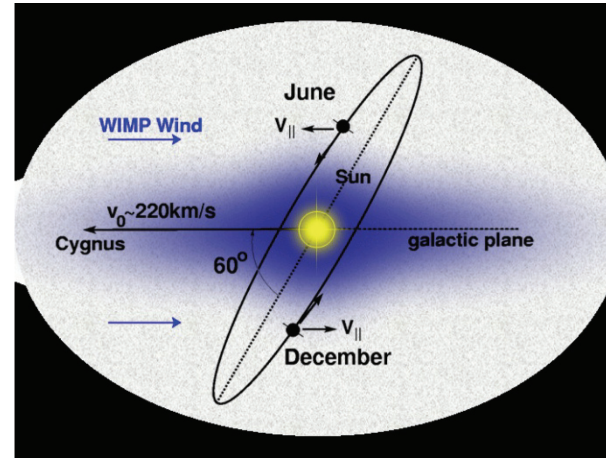


- Summary: The flavor problem → $\sigma_{SI} \sim 10^{-44}$ cm^2 (focus point SUSY, inverted hierarchy models, more minimal SUSY, 2-1 models, split SUSY,…)

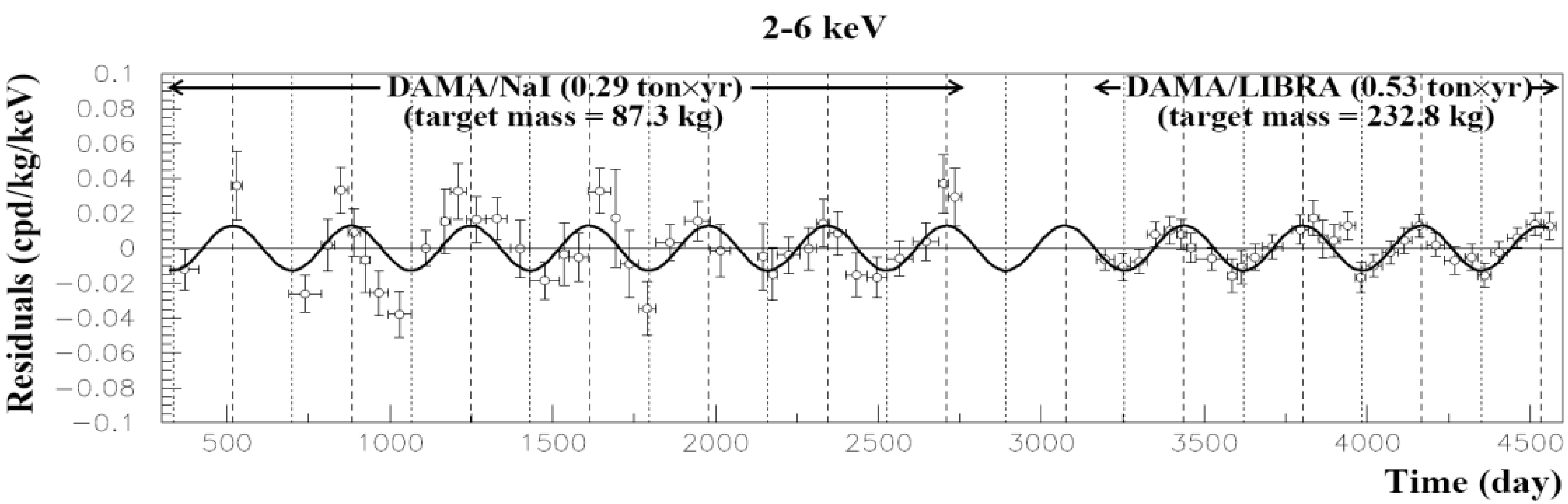
DIRECT DETECTION

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

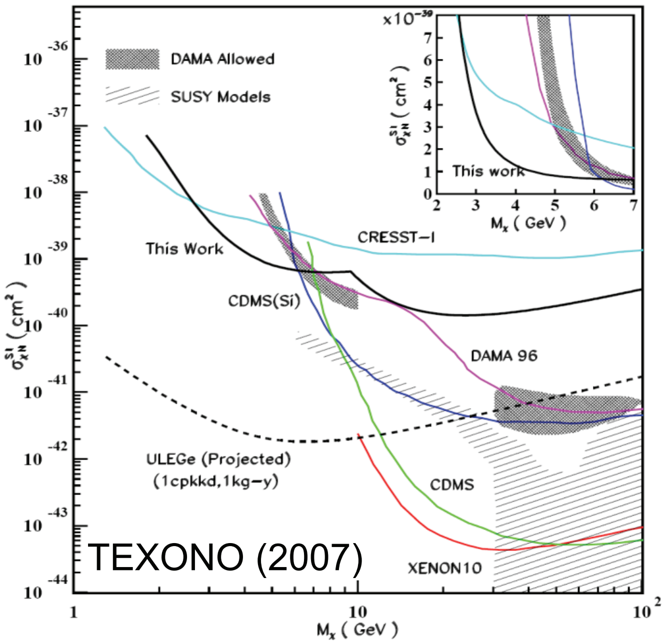
- DAMA's result is puzzling, in part because the favored region was considered excluded by others

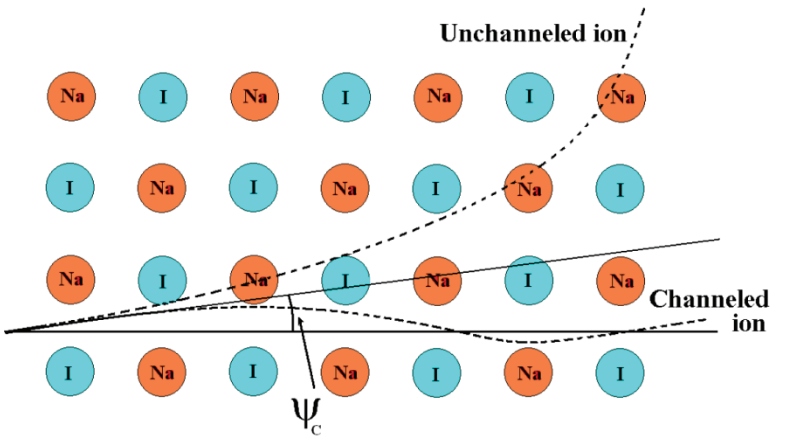
- This may be ameliorated by
  - Astrophysics
  - Channeling: in crystalline detectors, efficiency for nuclear recoil energy → electron energy depends on direction

Gondolo, Gelmini (2005)

Drobyshevski (2007), DAMA (2007)

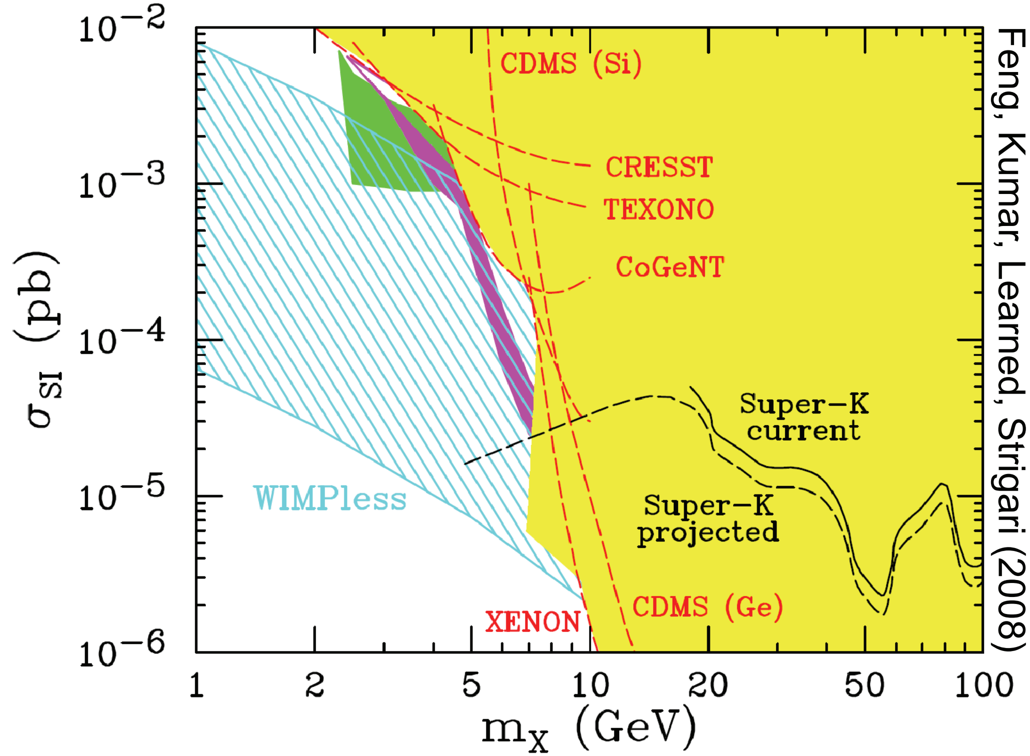
- Channeling reduces threshold, shifts allowed region to
  - Rather low WIMP masses (~GeV)
  - Very high σ_{SI} (~10^{-39} cm^2)





DAMA AND SUPER-K

- Ways forward
  - Examine channeling
  - Other low threshold direct detection experiments
- Super-K indirect detection
  - DM captured in the Sun
  - Annihilates to neutrinos
  - Neutrinos seen at Super-K



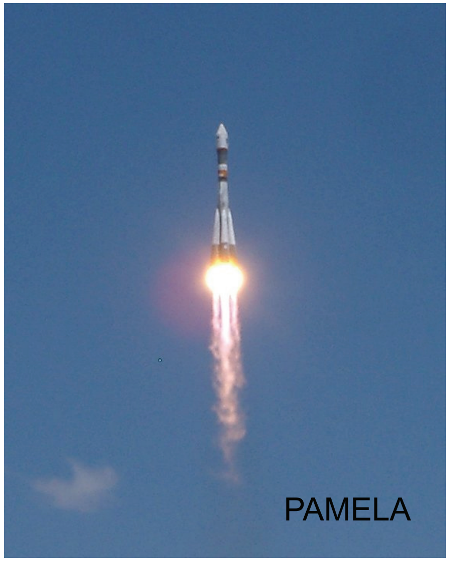
- Comparing apples to oranges? No! The Sun is full, so σ_{SI} → capture rate → annihilation rate
  - Current bound: through-going events, extends to m_X = 18 GeV
  - Ongoing analysis: fully contained events, sensitive to m_X ~ 5 GeV?

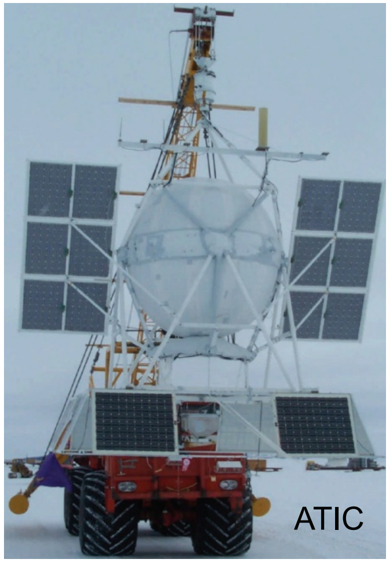
Hooper, Petriello, Zurek, Kamionkowski (2008); Feng, Kumar, Learned, Strigari (2008)

INDIRECT DETECTION

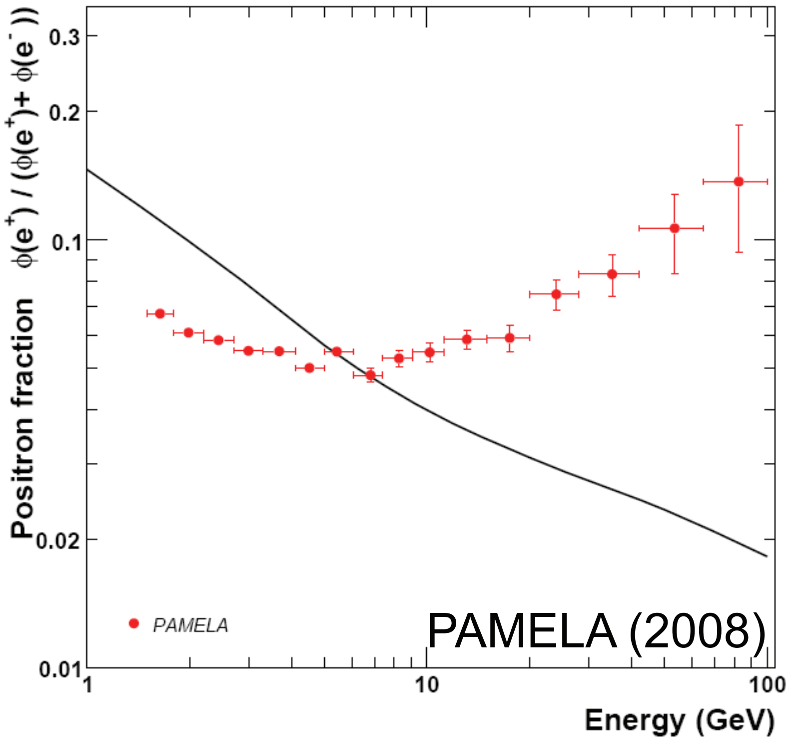
Dark Matter annihilates in ___the halo___ to
(a place)

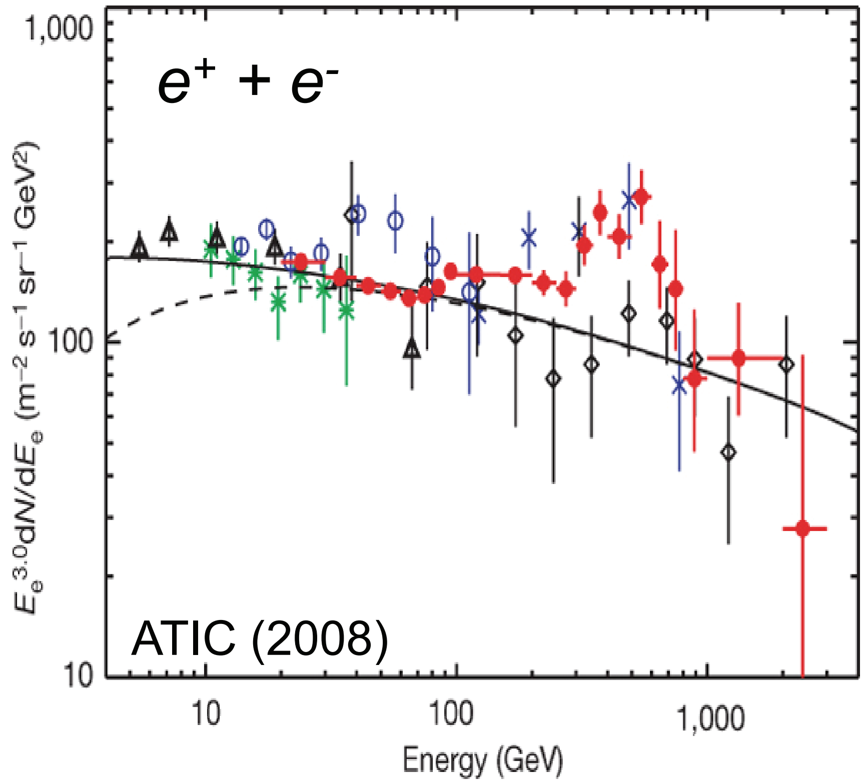
___positrons___ , which are detected by ___PAMELA/ATIC/Fermi…___.
(some particles) (an experiment)





PAMELA AND ATIC 2008

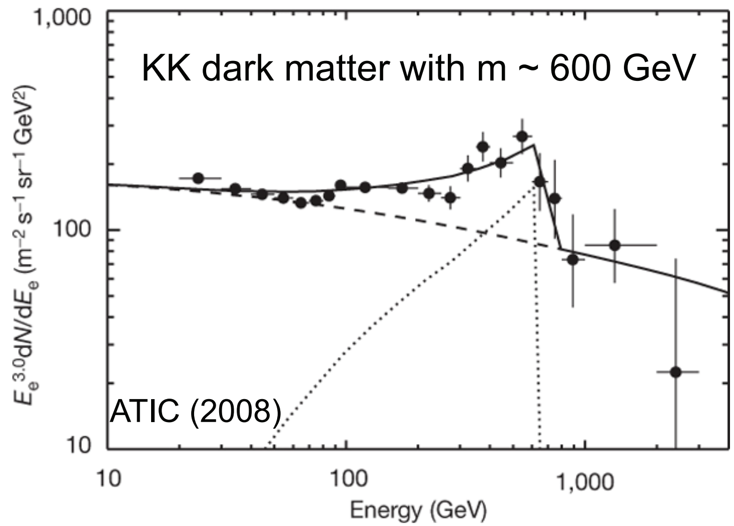




Solid lines are the predicted spectra from GALPROP (Moskalenko, Strong)

ARE THESE DARK MATTER?

- Must fit spectrum, not violate other constraints (photons, anti-protons, …)
- Neutralinos in supersymmetry
  - $\chi\chi \rightarrow e^+e^-$ suppressed by angular momentum conservation
  - $\chi\chi \rightarrow WW \rightarrow e+$ gives softer spectrum, also accompanied by large anti-proton flux

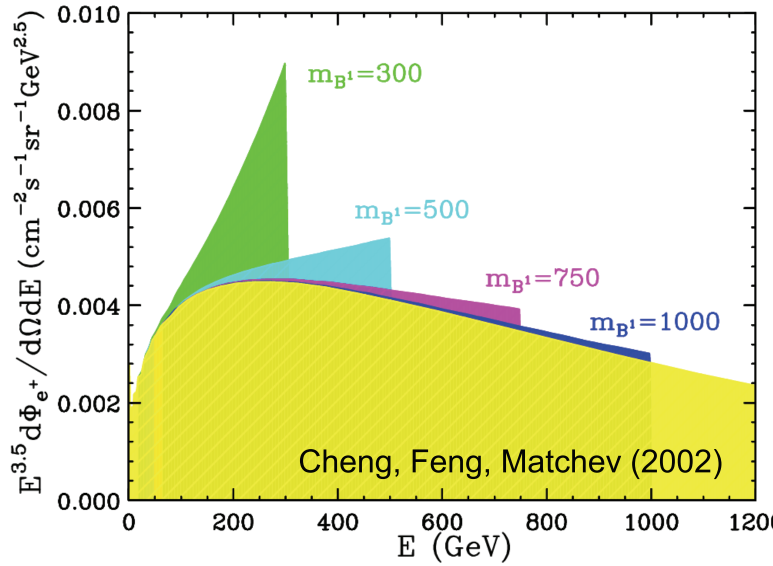


- Kaluza-Klein dark matter in UED

Appelquist, Cheng, Dobrescu (2001)

  - $B^1B^1 \rightarrow e^+e^-$ unsuppressed, hard spectrum
  - B^1 couples to hypercharge, $B(e^+e^-) = 20\%$
  - B^1 mass ~ 600-1000 GeV to get right Ω

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

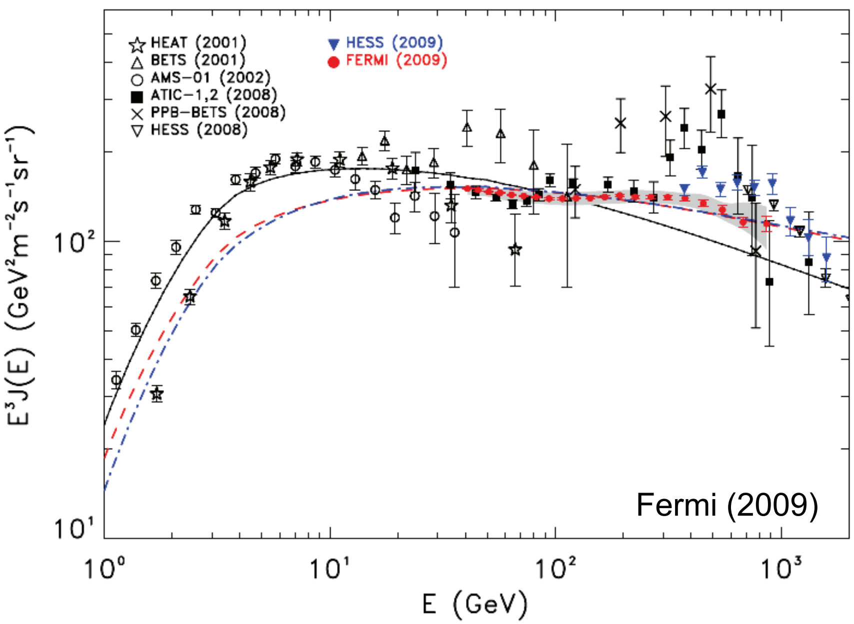


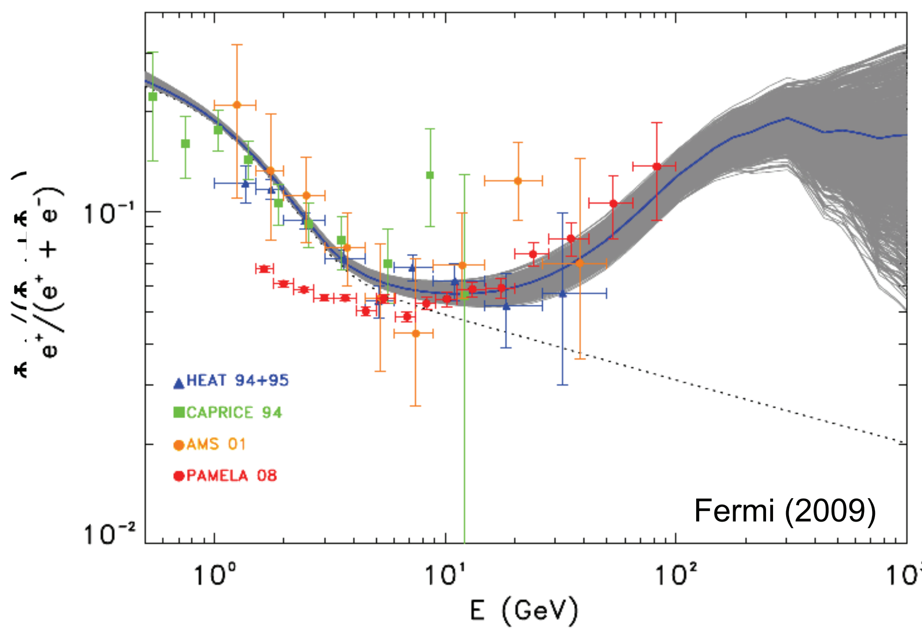
FERMI AND HESS 2009

- Fermi and HESS do not confirm ATIC: no feature, consistent with background with modified spectral index

- Pulsars can explain PAMELA

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





BEYOND WIMPS

- The anomalies (DAMA, PAMELA, …) 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*

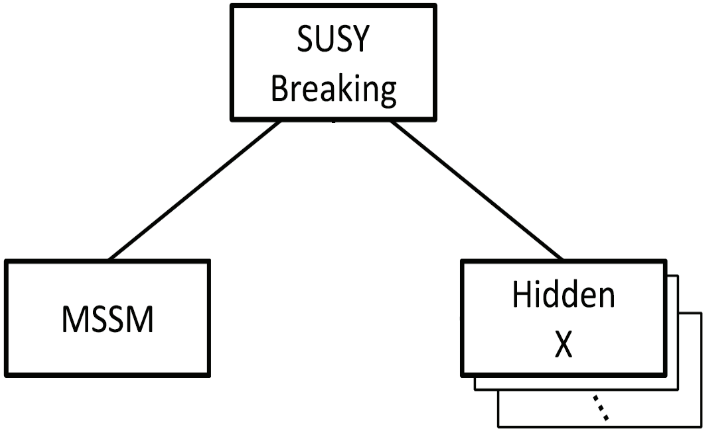
Kobsarev, Okun, Pomeranchuk (1966); many others

- What one seemingly loses
  - Connections to central problems of particle physics
  - The WIMP miracle
  - Signals

CONNECTIONS TO CENTRAL PROBLEMS IN PARTICLE PHYSICS

- We want hidden sectors

- Consider SUSY
  - Connected to the gauge hierarchy problem
  - new sectors are already required to break SUSY



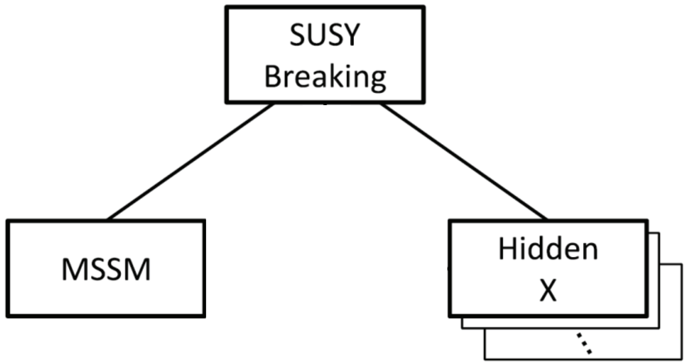
- Hidden sectors appear generically, each has its own
  - particle content
  - mass scale m_X
  - Interactions, gauge couplings g_X

- What can we say about hidden sectors in SUSY?

- Generically, nothing. But the flavor problem motivates models in which squark and slepton masses are determined by gauge couplings (and so flavor blind):

$$m_X \sim g_X^2$$

(Gauge mediation, anomaly-mediation, …)



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

- This leaves the relic density invariant!

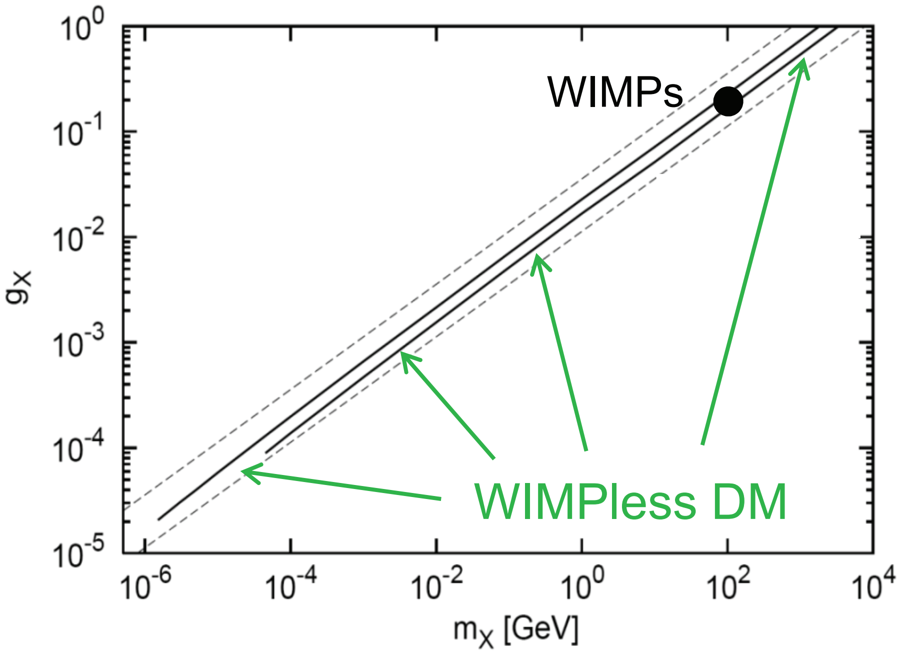
THE WIMPLESS MIRACLE

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

- 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; candidates have a range of masses and couplings, but always the right relic density
- The flavor problem becomes a virtue



- Naturally accommodates multi-component DM, all with relevant Ω

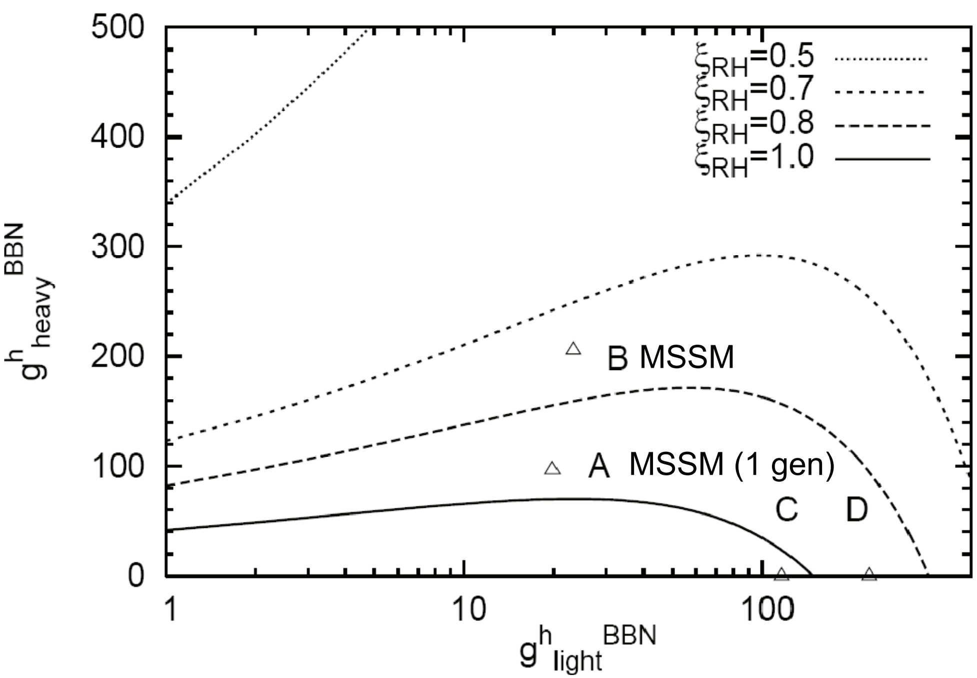
HOW LARGE CAN HIDDEN SECTORS BE?

- Hidden sectors contribute to expansion rate
- BBN: N_ν = 3.24 ± 1.2, excludes an identical copy of the MSSM

Cyburt et al. (2004)

- But this is sensitive to temperature differences; even a factor of 2 makes a hidden MSSM viable

ξ_{RH} = ratio of reheat temperatures

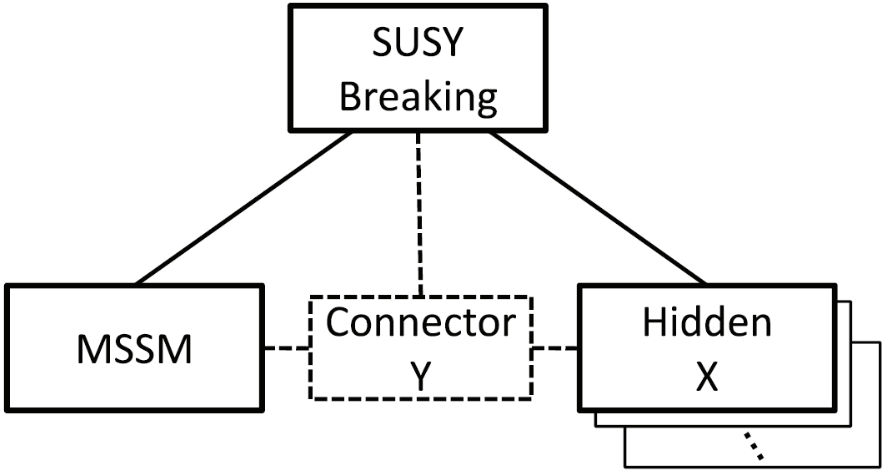


$$g_*^h(T^h_{\rm BBN})\left(\frac{T^h_{\rm BBN}}{T_{\rm BBN}}\right)^4 = \frac{7}{8}\cdot 2\cdot (N_{\rm eff}-3) \leq 2.52\ (95\%\ {\rm CL})$$

SIGNALS

- Hidden DM has no SM gauge interactions, but may interact through non-gauge couplings

- For example, introduce connectors Y with both MSSM and hidden charge



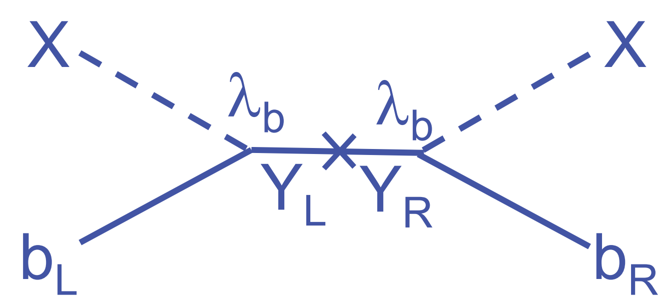
- Y particles mediate both annihilation to and scattering off SM particles

EXAMPLE

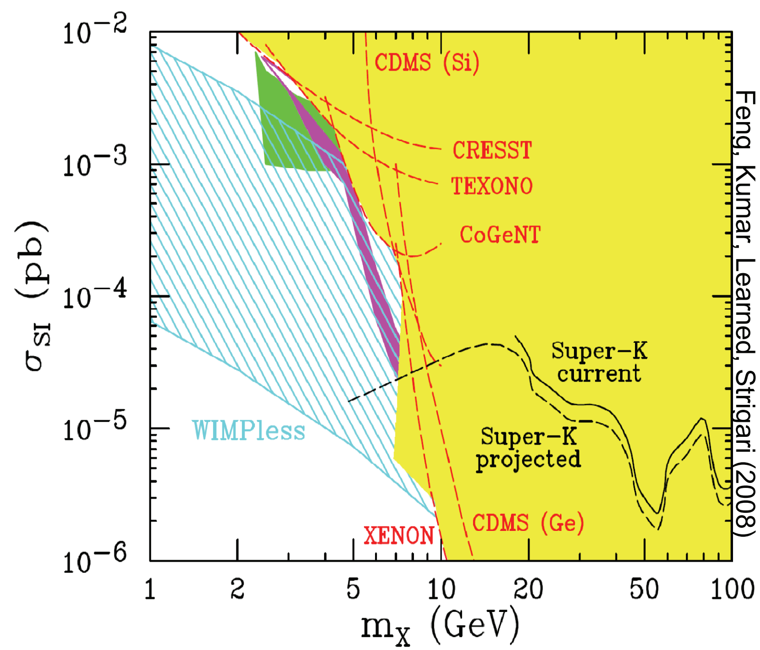
- Assume WIMPless DM X is a scalar, add fermion connectors *Y*, interacting through

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

For f=b, Y's are b', t' with hidden charge Kribs, Plehn, Spannowsky, Tait (2007)



- Explains DAMA easily
  - $\lambda_b \sim 0.3\text{-}1$
  - $m_X \sim 5$ GeV (WIMPless miracle)
  - $m_Y \sim 400$ GeV (large σ_{SI})



- Any such DAMA explanation → exotic b', t' at Tevatron, LHC

HIDDEN CHARGED DM

How is dark matter stabilized? Conventional answer is by a parity conservation, but there are no such SM examples

MSSM	
m_W	sparticles, W, Z, t
~GeV	q, l
0	p, e, γ, ν, $\tilde{G}$

Hidden, flavor-free MSSM	
m_X	sparticles, W, Z, q, l, $\tilde{\tau}$ (or τ)
0	g, γ, ν, $\tilde{G}$

- If the hidden sector is a flavor-free MSSM, natural DM candidate is any hidden charged particle, stabilized by exact $U(1)_{EM}$ symmetry, just like the SM electron

HIDDEN CHARGED DM

Feng, Kaplinghat, Tu, Yu (2009)

DM with hidden charge requires a re-thinking of the standard cold DM picture:

- Bound states form (and annihilate) in the early Universe → relic density
- Sommerfeld enhanced annihilation → decays in protohalo
- Compton scattering $X \gamma^h \to X \gamma^h$ delays kinetic decoupling → small scale structure
- Rutherford scattering $XX \to XX$: self-interacting, collisional dark matter

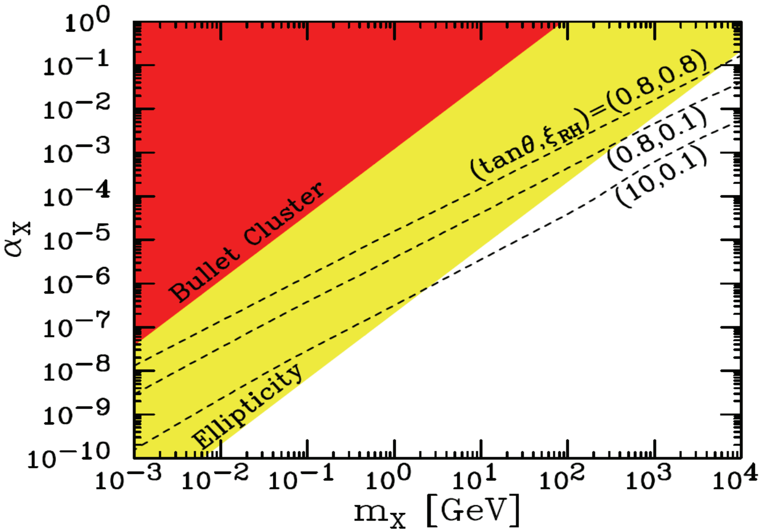
BOUNDS ON COLLISIONAL DM

- Hidden charged particles exchange energy through Rutherford scattering
- Constraints on collisions
  - Bullet cluster
  - Non-spherical halos → DM can't be too collisional
- Consistent with WIMPless miracle for 1 GeV < m_{DM} < 10 TeV
- Interesting astrophysics
- Many interesting, related ideas

Pospelov, Ritz (2007); Hooper, Zurek (2008)

Ackerman, Buckley, Carroll, Kamionkowski (2008)

Kamionkowski, Profumo (2008), …



CONCLUSIONS

- Rapid experimental progress
  - Direct detection
  - Indirect detection
  - Colliders (LHC)
- Proliferation of new classes of candidates with widely varying properties and implications for particle physics and astrophysics
- 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