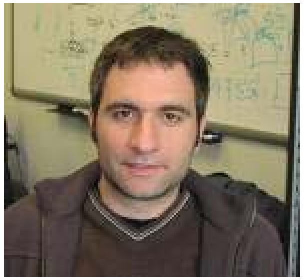
DARK MATTER MEETS THE SUSY FLAVOR PROBLEM

Work with
Manoj Kaplinghat, Jason Kumar, John Learned, Arvind Rajaraman,
Louie Strigari, Fumihiro Takayama, Huitzu Tu, Haibo Yu



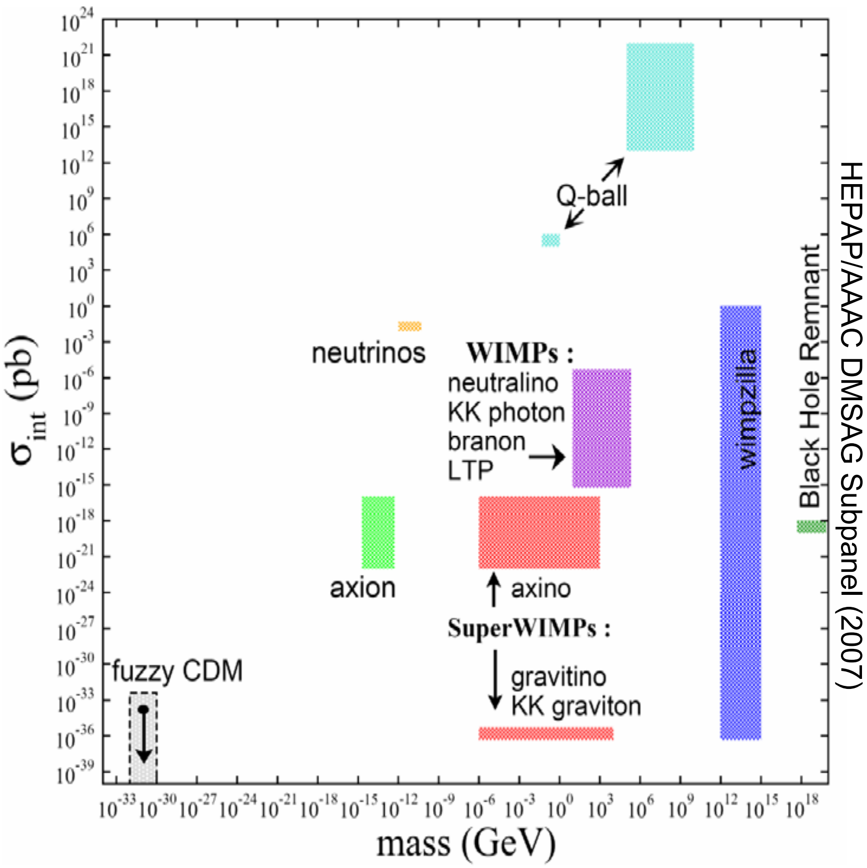

Jonathan Feng
University of California, Irvine

SLAC NAL
18 March 2009

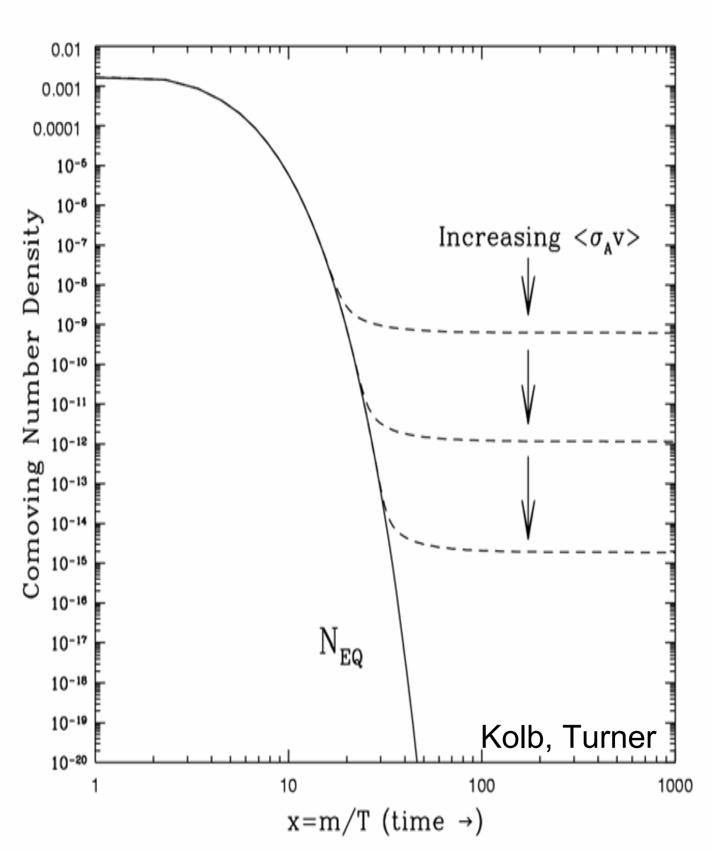
DARK MATTER

- Best evidence for new physics
  - Unambiguous
  - Intimately connected to central problems: electroweak symmetry breaking and structure formation

- Candidate masses and interactions span many orders of magnitude



THE WIMP MIRACLE



- Assume a new (heavy) particle X is initially in thermal equilibrium
- Its relic density is

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

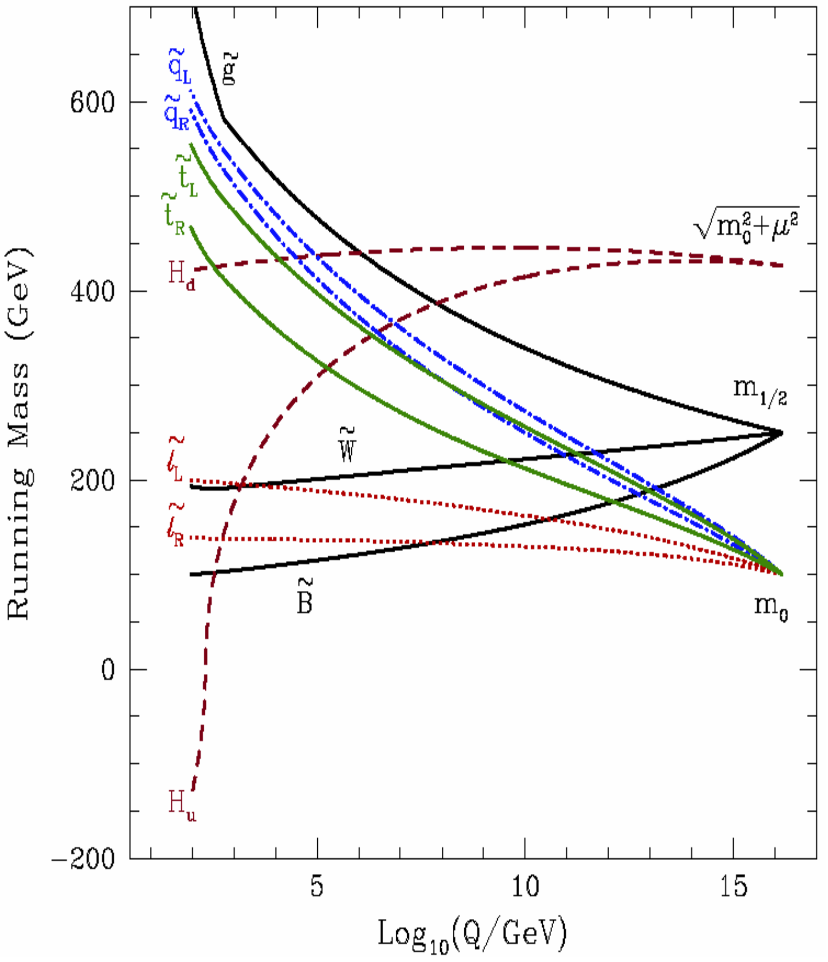
- $m_X \sim m_{weak} \sim 100$ GeV, $g_X \sim g_{weak} \sim 0.6$ } $\Omega_X \sim 0.1$

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

NEUTRALINO DARK MATTER

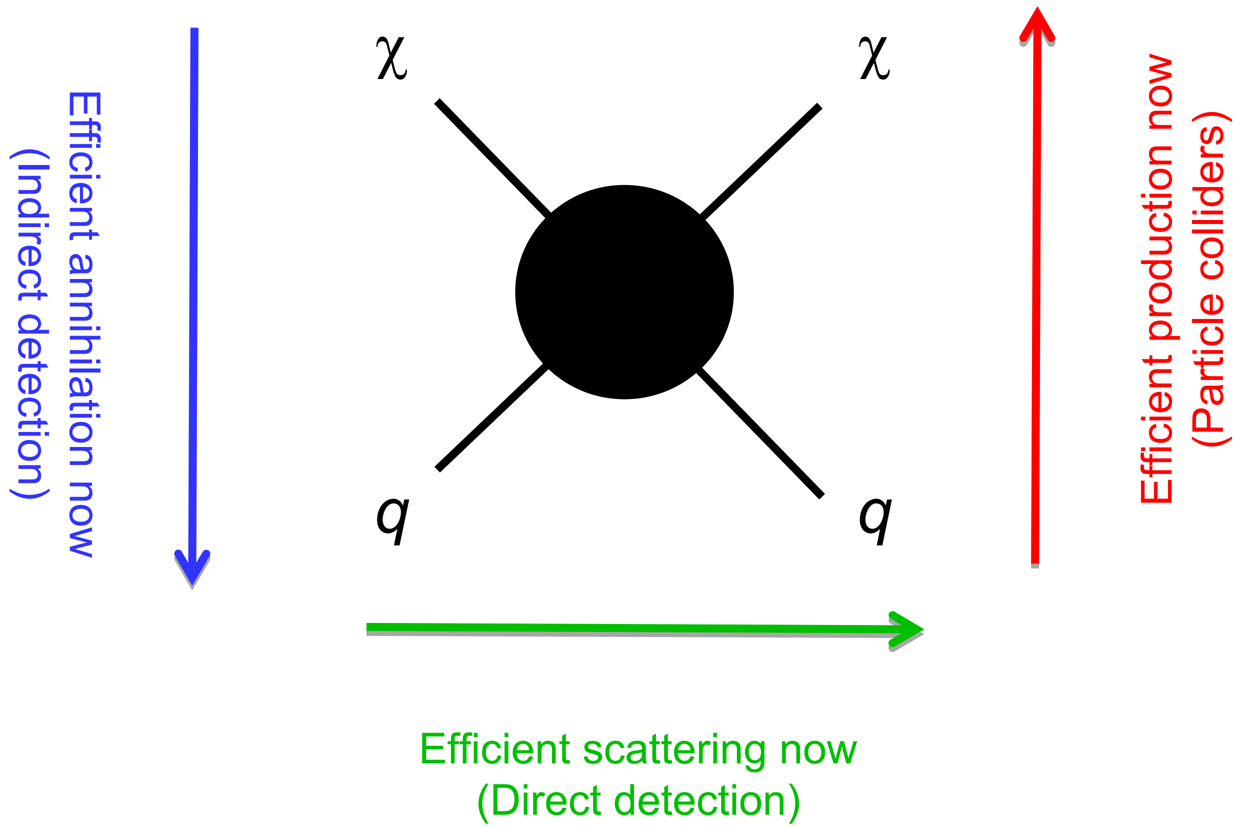
- Supersymmetry
  - Naturalness
  - force unification
  - radiative EWSB

- Neutralino naturally emerges as
  - Lightest (stable)
  - Weakly-interacting
  - ~100 GeV
  - Excellent DM candidate



NEUTRALINO IMPLICATIONS

Neutralinos must interact with the SM efficiently



NEUTRALINO IMPLICATIONS

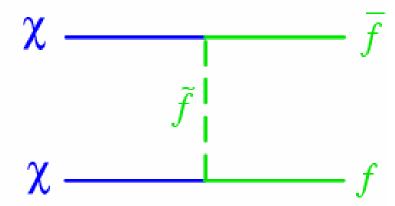
Neutralinos must interact with the SM efficiently

EXCITING!

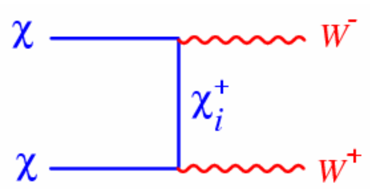
BACKGROUND CHECK: SKELETONS IN THE CLOSET

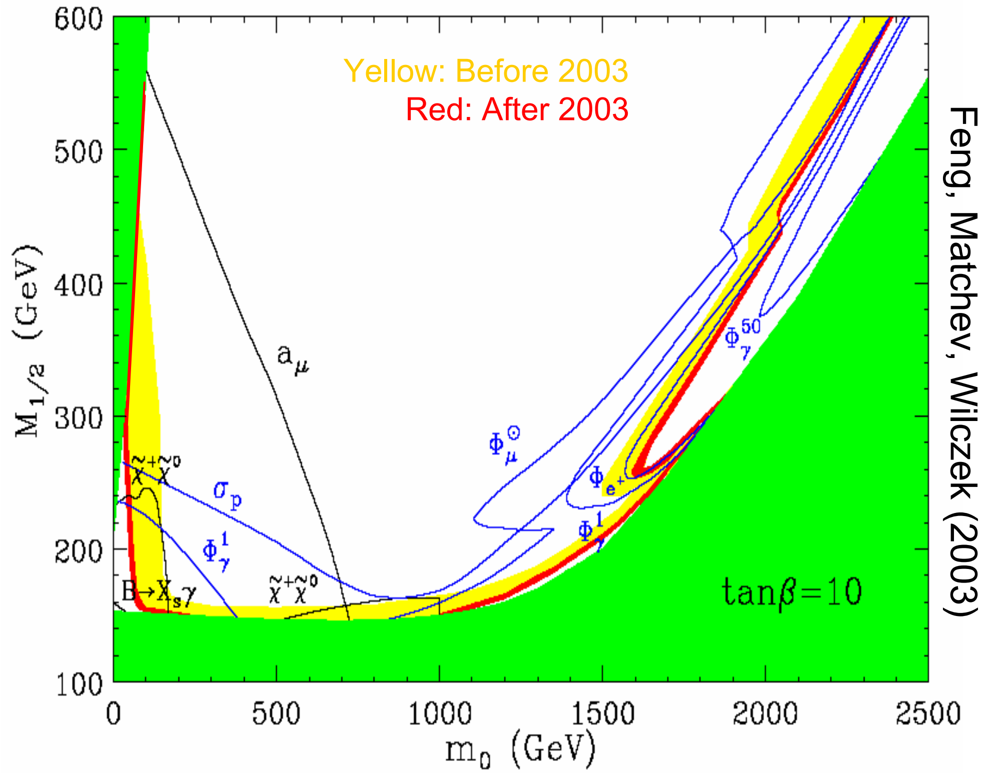
- Minor skeleton: thermal relic density

Majorana → P-wave suppressed



GUT/RGE → Bino suppressed





Feng, Matchev, Wilczek (2003)

MAJOR SKELETON: THE FLAVOR PROBLEM

- Neutralino DM → $m_{\tilde{G}} > m_\chi$
- $m_{\tilde{G}}$ characterizes the size of gravitational effects, which generically violate flavor symmetries
- Current bounds require $m_{\tilde{G}} < 0.01\ m_\chi$
- There are ways to reconcile χ DM with flavor constraints, but none is especially compelling

FLAVOR-CONSERVING MODELS

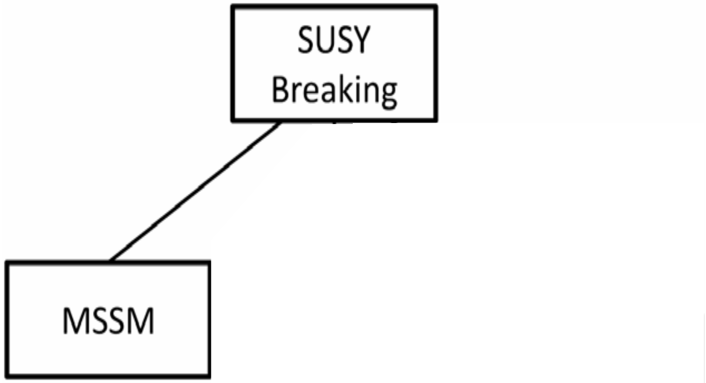
- There are well-known SUSY models that naturally conserve flavor: gauge-mediated SUSY-breaking models

  Dine, Nelson, Nir, Shirman (1995); Dimopoulos, Dine, Raby, Thomas (1996); …

- Can we find DM candidates in these models?

- 3 key features
  - $m_{\tilde{G}} << m_{\chi}$
  - Several sectors of particles
  - Superpartner masses

    $m \sim (\text{gauge couplings})^2$



PREVIOUS SUGGESTIONS 1

Thermal gravitinos: the original SUSY DM scenario

Pagels, Primack (1982)

- Universe cools from $T \sim M_{Pl}$, gravitinos decouple while relativistic, expect $n_{\tilde{G}} \sim n_{eq}$ (cf. neutrinos)
- $\Omega_{\tilde{G}} h^2 \approx 0.1 \, (m_{\tilde{G}} / 80 \text{ eV})$
- Lyman-α constraints → $m_{\tilde{G}} > 2$ keV

Viel et al. (2006); Seljak et al. (2006)

- Could be saved by late entropy production

Baltz, Murayama (2001)

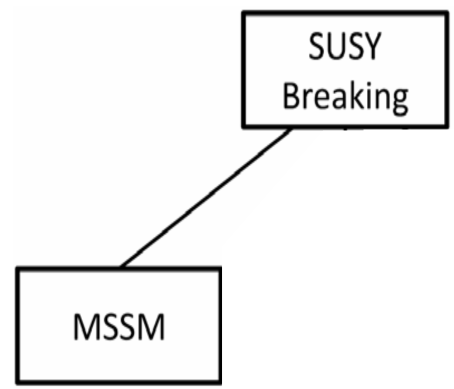
- No use of WIMP miracle

PREVIOUS SUGGESTIONS 2

Messenger sneutrino DM

Han, Hempfling (1997)

- Messenger sneutrino has right relic density for m ~ 1-3 TeV



- No use of WIMP miracle

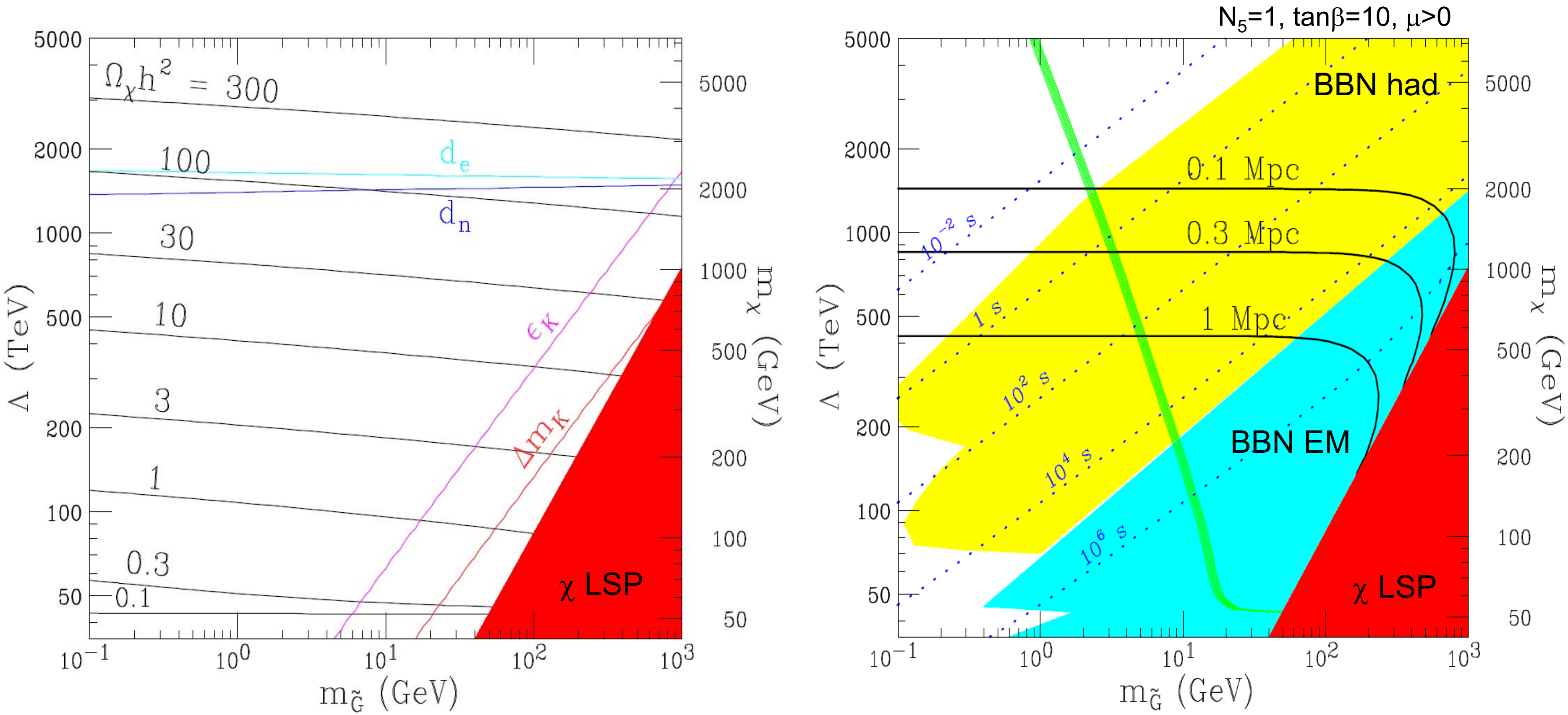
PREVIOUS SUGGESTIONS 3

Goldilocks SUSY

Feng,, Smith, Takayama, (2007)

- Eliminate both skeletons simultaneously: χ overproduced, decays to gravitino that is light enough to solve the flavor problem, but heavy enough to be all of DM
- $\Omega_\chi \sim m_\chi^2$, $\Omega_{\tilde{G}} \sim m_\chi\, m_{\tilde{G}}$; flavor → $m_{\tilde{G}} / m_\chi < 0.01$
- Solution guaranteed for sufficiently large m_χ , $m_{\tilde{G}}$
- But is it natural? Consider mGMSB

GOLDILOCKS SUSY

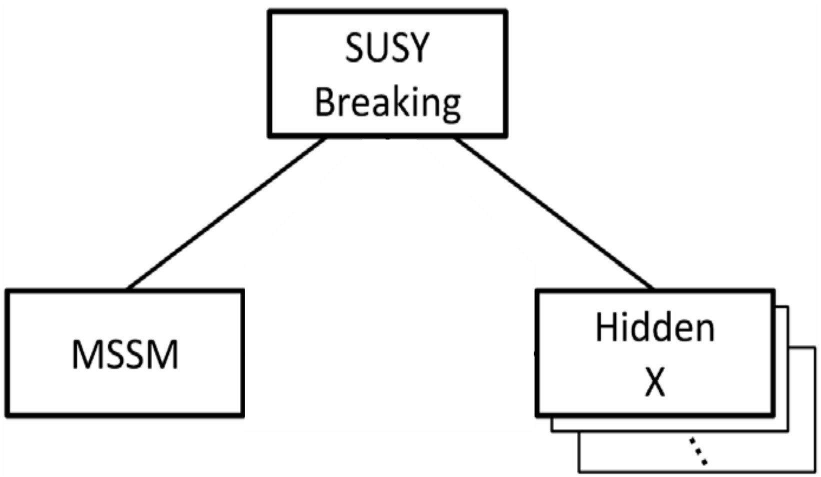


- Ω_χ ~ 100, m_χ ~ 1 TeV, $m_{\tilde{G}}$ ~ 1 GeV
- Uses the WIMP miracle
- Astrophysics constraints→ CP solved, warm $\tilde{G}$ DM

A NEW APPROACH

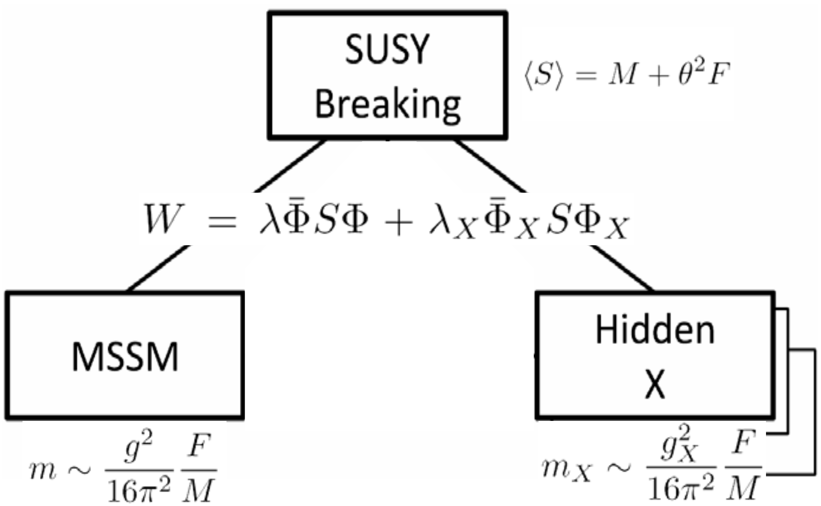
Feng, Kumar (2008)

- Consider standard GMSB with one or more hidden sectors
- Each hidden sector has its own matter content, gauge groups, couplings



THE WIMPLESS MIRACLE

- Particle Physics



Superpartner masses depend on gauge couplings

- Cosmology

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

Ω depends only on the SUSY Breaking sector:

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

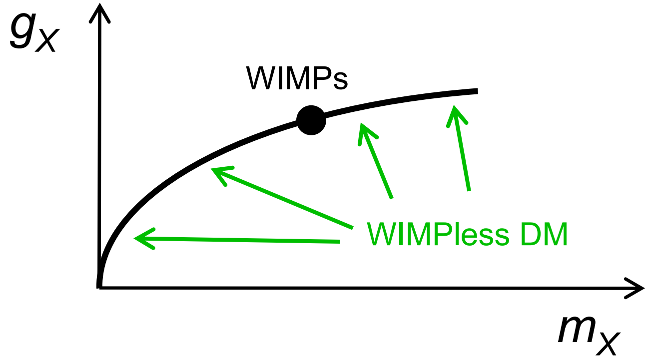
Hidden sector generically has the right relic density

THE WIMPLESS MIRACLE

- 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, candidates have a range of masses/couplings, but always the right relic density
- The flavor problem becomes a virtue
- Naturally accommodates multi-component DM, all with relevant Ω

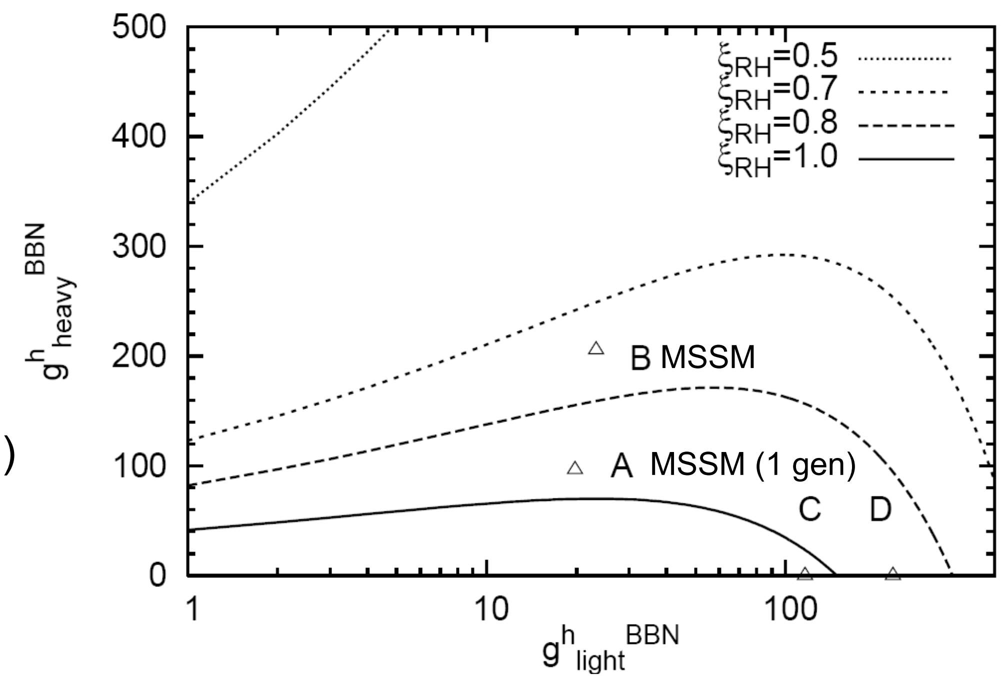
HOW LARGE CAN HIDDEN SECTORS BE?

Feng, Tu, Yu (2008)

- 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

ξ_{RH} = ratio of reheat temperatures

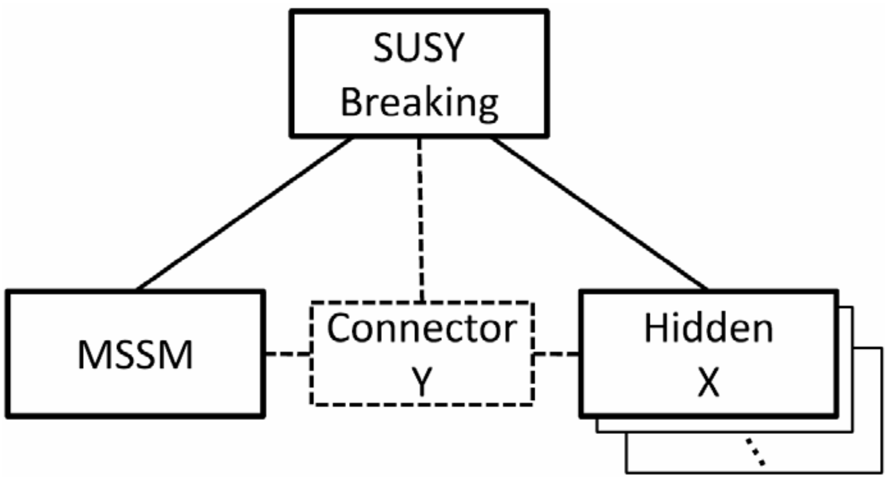


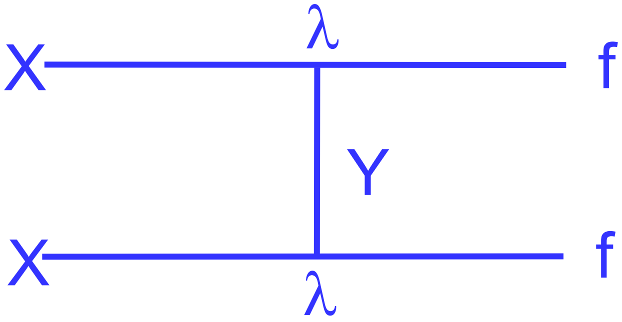
$$g_*^h(T_{\rm BBN}^h)\left(\frac{T_{\rm BBN}^h}{T_{\rm BBN}}\right)^4 = \frac{7}{8}\cdot 2\cdot (N_{\rm eff}-3) \leq 2.52 \ (95\% \ {\rm CL})$$

WIMPLESS DETECTION

Feng, Kumar, Strigari (2008); Feng, Kumar, Learned, Strigari (2008)

- WIMPless DM has no SM gauge interactions, but may interact through Yukawa couplings
- For example, introduce connectors Y with both MSSM and hidden charge
- Y particles mediate both annihilation to and scattering with MSSM particles





EXAMPLE

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

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

- XX → ff preserves WIMPless miracle, as long as $\lambda_f < 1$

- For f = b, Y's are "4th generation mirror quarks," constrained by collider direct searches, precision electroweak, Yukawa perturbativity:

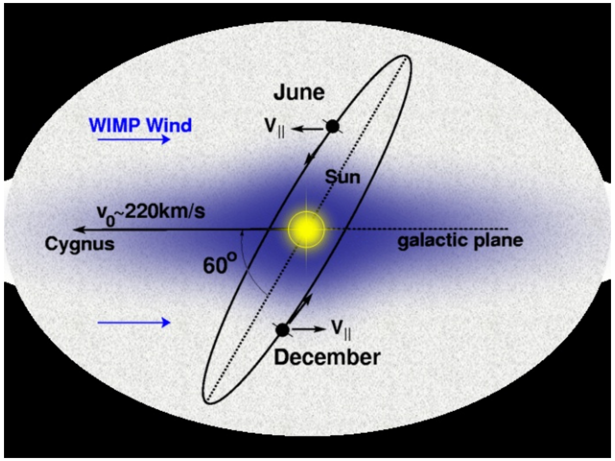
  $250 \text{ GeV} < m_Y < 500 \text{ GeV}$

Kribs, Plehn, Spannowsky, Tait (2007); Fok, Kribs (2008)

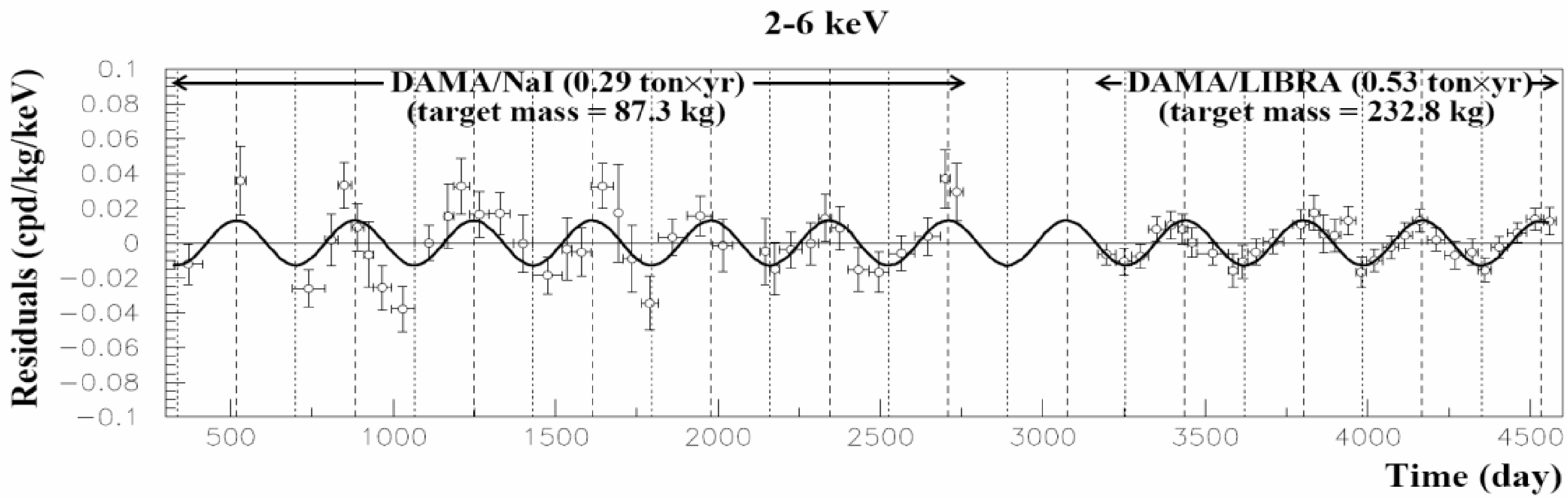
DIRECT DETECTION: DAMA

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

Drukier, Freese, Spergel (1986)



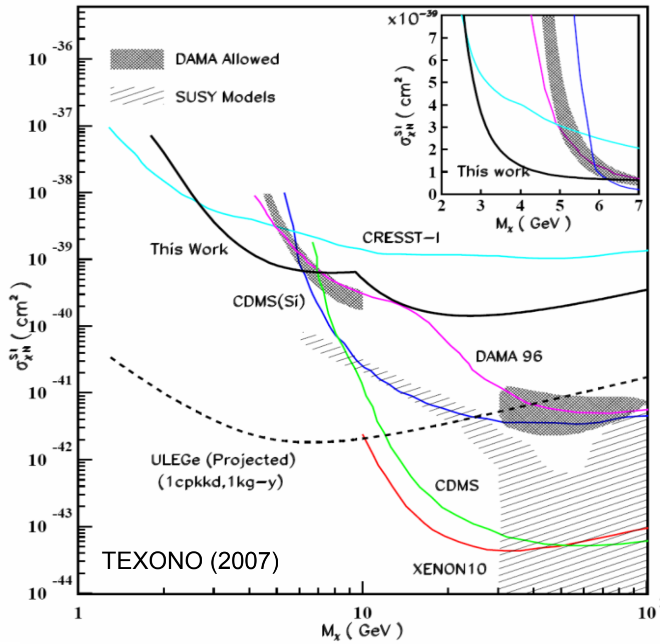
DAMA: 8σ signal with T ~ 1 year, max ~ June 2

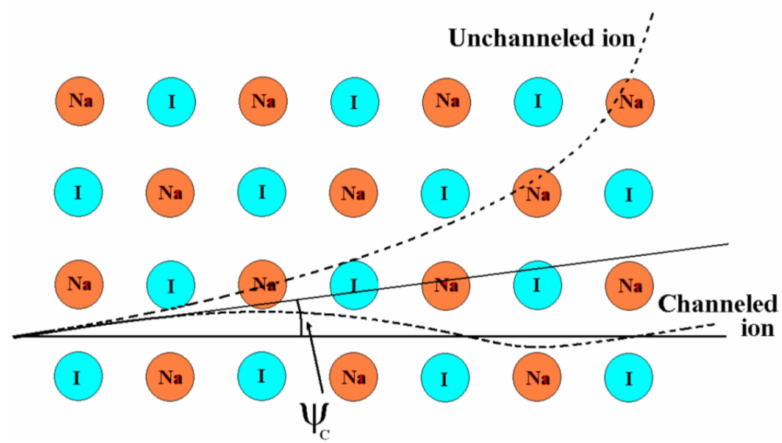


DAMA (2008)

CHANNELING

- DAMA's result is puzzling, in part because the favored region was considered excluded by others
- This may be ameliorated by astrophysics and channeling: in crystalline detectors, efficiency for nuclear recoil energy → photons depends on direction
- Channeling reduces threshold, shifts allowed region to lower masses. Consistency possible, but requires uncomfortably low WIMP masses (~ GeV)

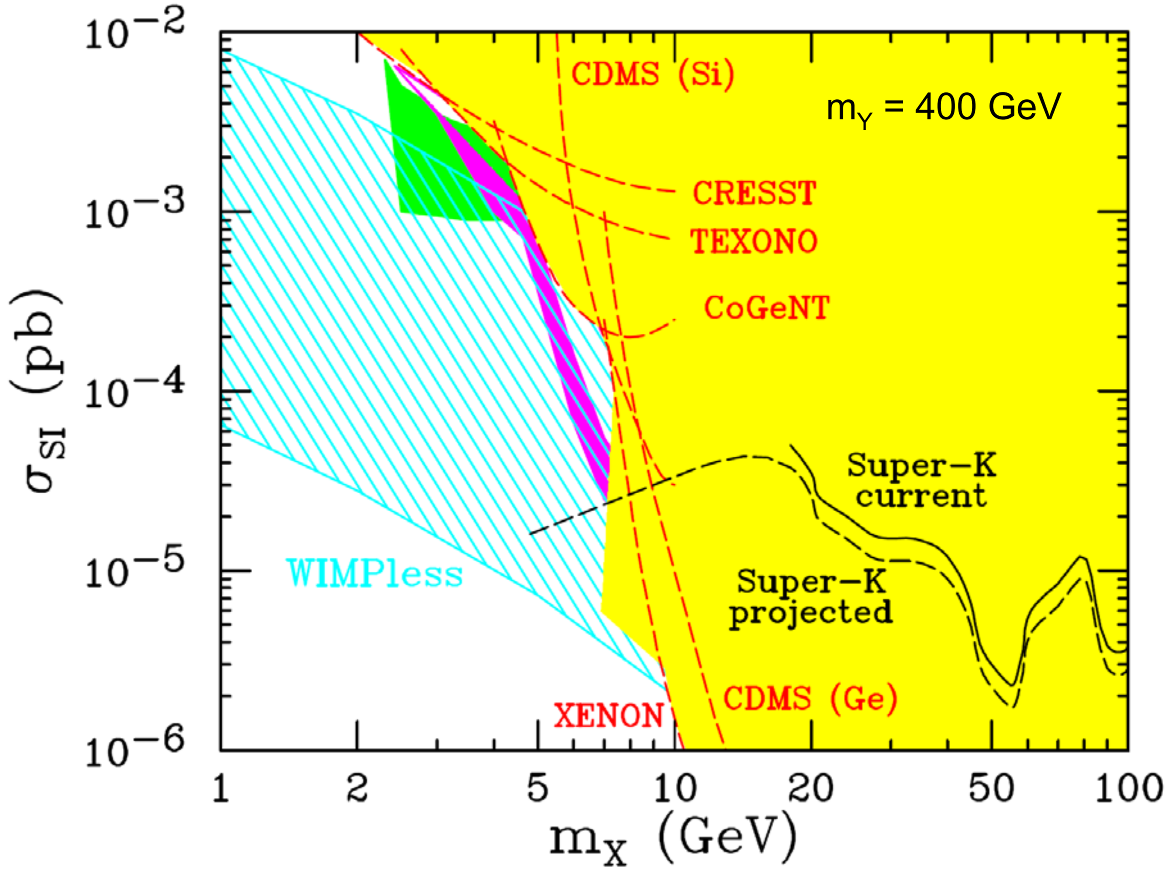




Gondolo, Gelmini (2005)
Drobyshevski (2007), DAMA (2007)

DAMA AND WIMPLESS DM

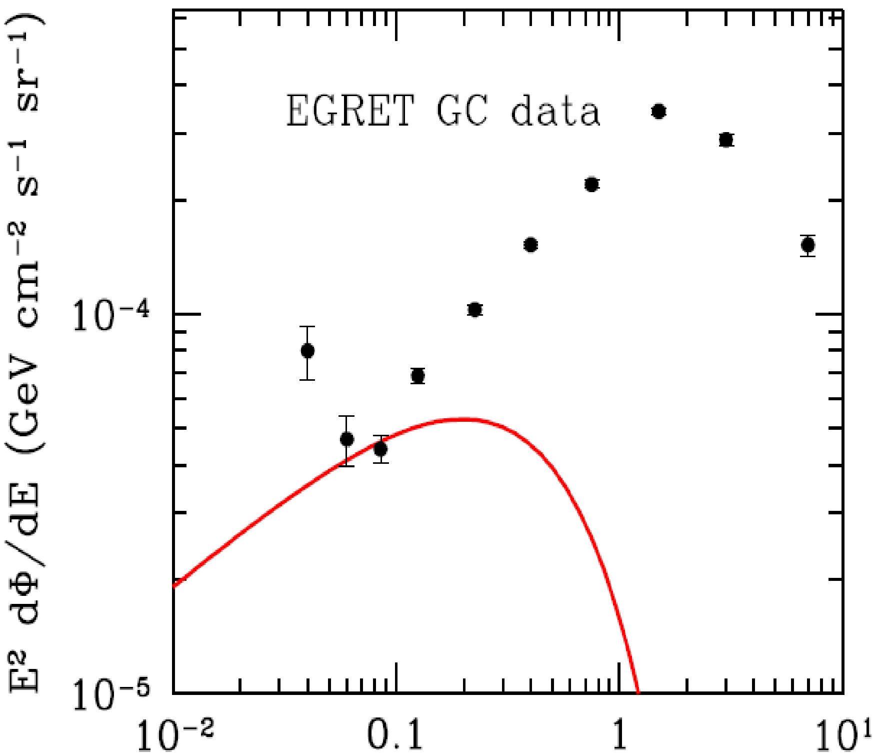
- WIMPless DM naturally explains DAMA with λ_b ~ 0.3-1 (cf. typical neutralino: m ~ 100 GeV, σ_{SI} ~10^{-8} pb)



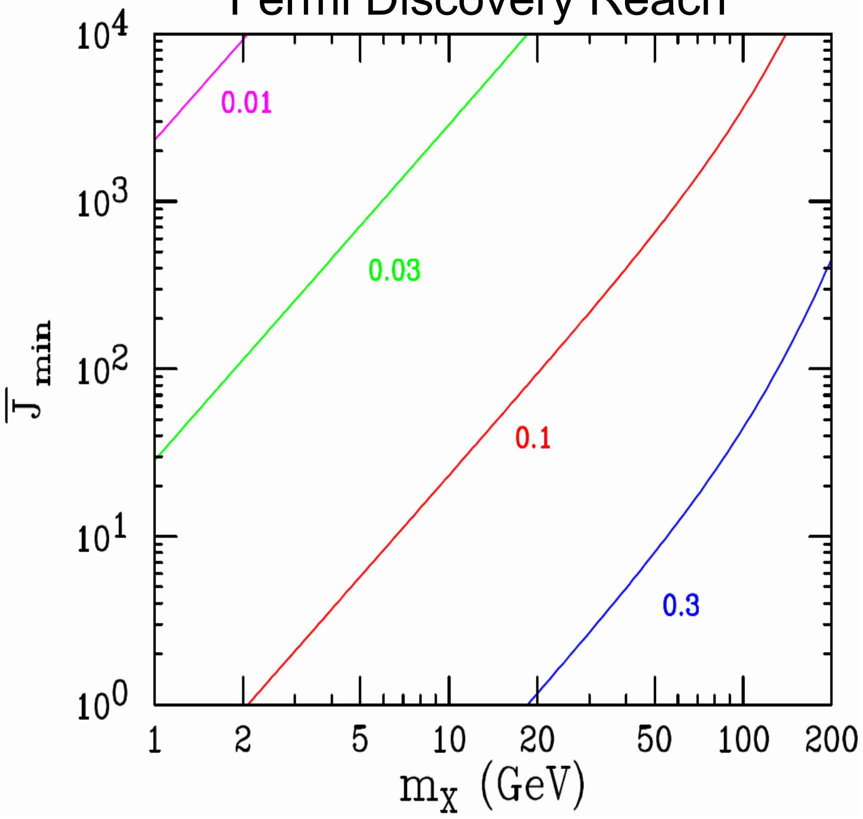
INDIRECT DETECTION

- Indirect searches also promising for low masses, even for smooth halos

DAMA parameters, NFW, J ~ 4



Fermi Discovery Reach



HIDDEN CHARGED DM

- This requires that an m_X particle be stable. Is this natural?

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

Flavor-free MSSM O(1) Yukawas	
m_X	sparticles, W, Z, q, l, $\tilde{t}$ (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

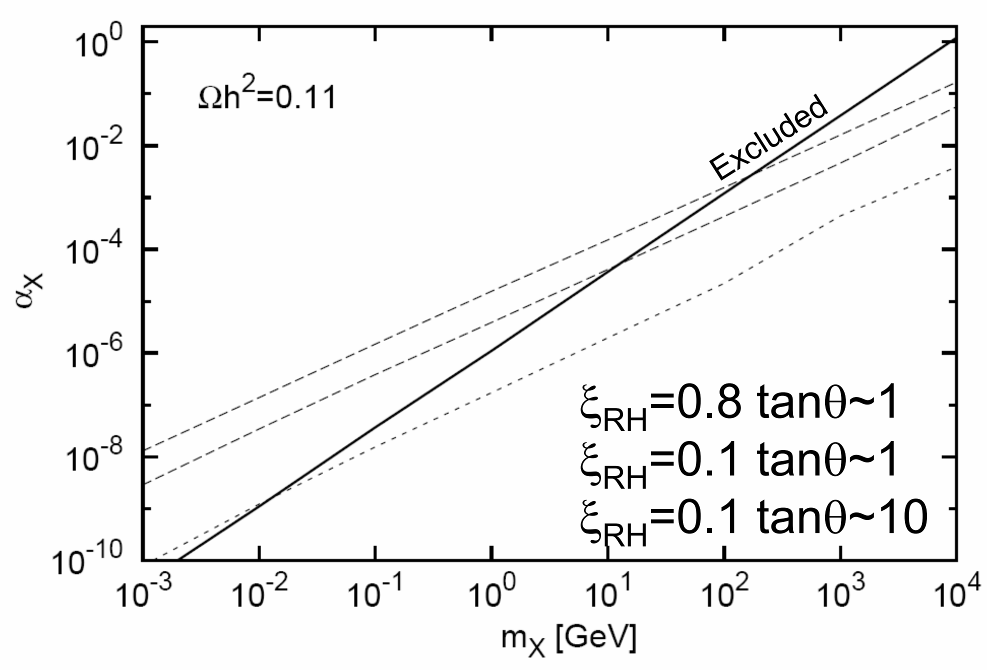
HIDDEN CHARGED DM

Feng, Kaplinghat, Tu, Yu (2009)

- Hidden charged particles exchange energy through Rutherford scattering

- Non-spherical galaxy cores → DM can't be too collisional, require

  $E/(dE/dt) > 10^{10}$ years



- Annihilates through weak (to neutrinos) and EM (to photons)
- m_X ~ 10 GeV (100 MeV) allowed for $\tan\theta = 1$ (10)

See also Ackerman, Buckley, Carroll, Kamionkowski (2008)

ANNIHILATION

- Annihilation is Sommerfeld enhanced by α/v

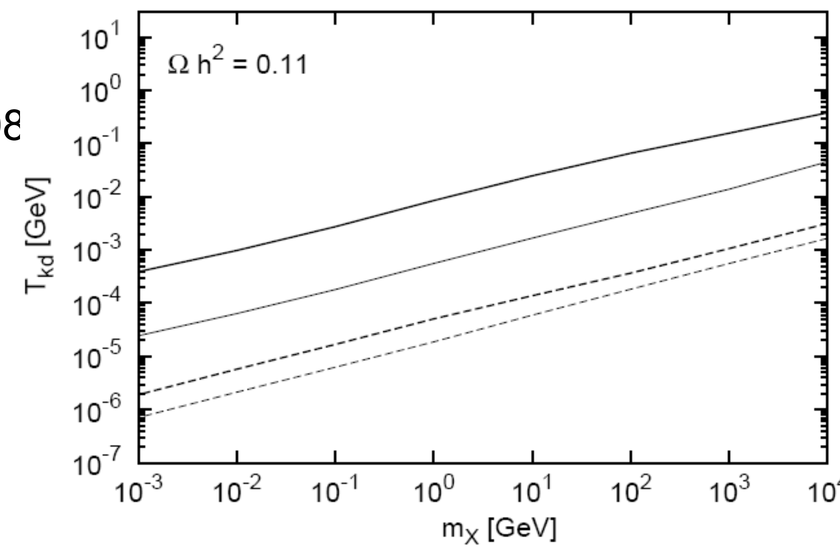
$$M_c \simeq 33\,(T_{\rm kd}/10\,{\rm MeV})^{-3}\,M_\oplus$$

$$(v/c) \sim 6.0 \times 10^{-9}\,(M_c/M_\oplus)^{1/3}(z_c/200)^{1/2}$$

- Strong constraint from protohaloes, formed at z ~ 200 with low velocity dispersion

Kamionkowski, Profumo (2008

- Can $m_\gamma = 0$? Yes!
  - T_{kd} is lower than for WIMPs
  - $\alpha \sim 10^{-6}$ for $m_X \sim$ GeV



Feng, Kaplinghat, Tu, Yu (2009)

CONCLUSIONS

- Neutralino DM has a flavor problem
- Reconciliation → qualitatively new DM candidates
- WIMPless dark matter
  - No flavor problem (GMSB)
  - Preserves WIMP miracle
  - Large direct, indirect signals
  - Explains DAMA, with testable implications
  - Motivates hidden charged DM with exact hidden $U(1)_{EM}$
  - Collisional, implications for structure formation