WIMPLESS DARK MATTER

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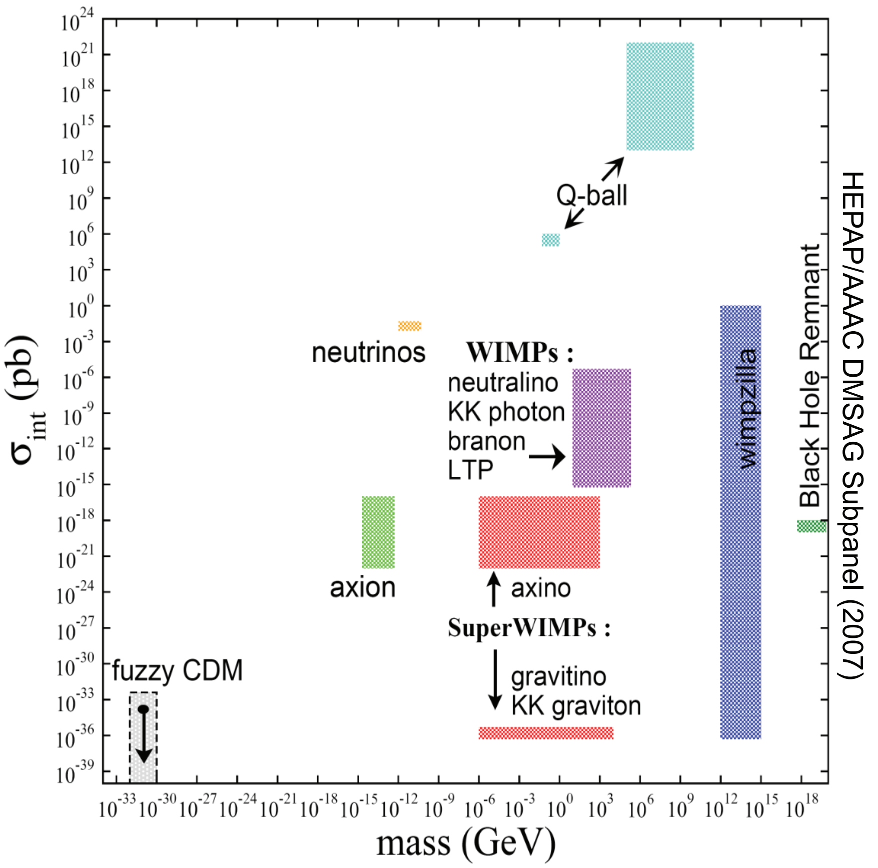
13 May 2009
UCI Joint Particle Seminar

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

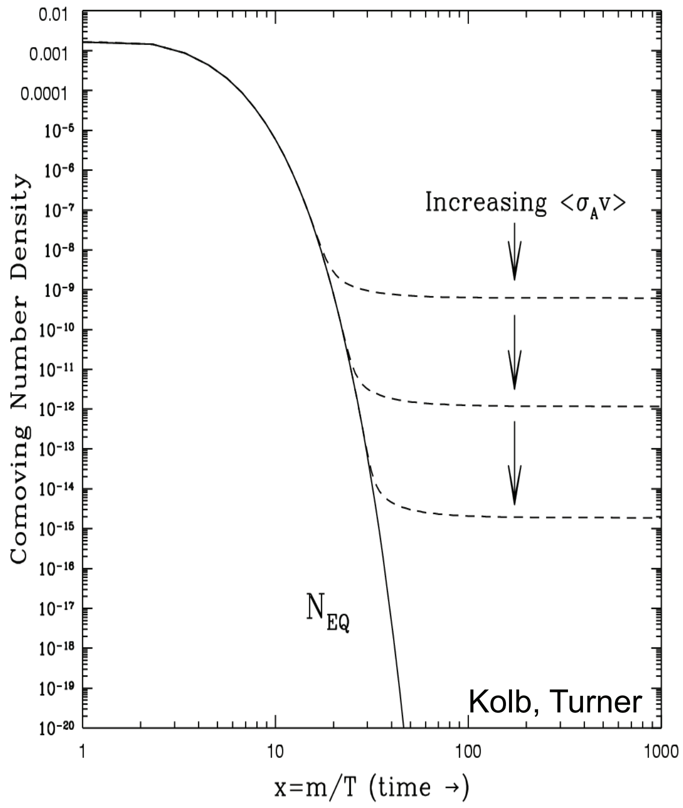


HIDDEN SECTORS

- All solid evidence for dark matter is gravitational
- Perhaps dark matter is hidden, that is, has no standard model gauge interactions

- This is not a new idea, but has traditionally suffered from drawbacks
  - Too much model-building freedom, lack of predictivity
  - Lack of experimental signals
  - Missing theoretical motivations of more popular DM candidates

THE WIMP MIRACLE



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

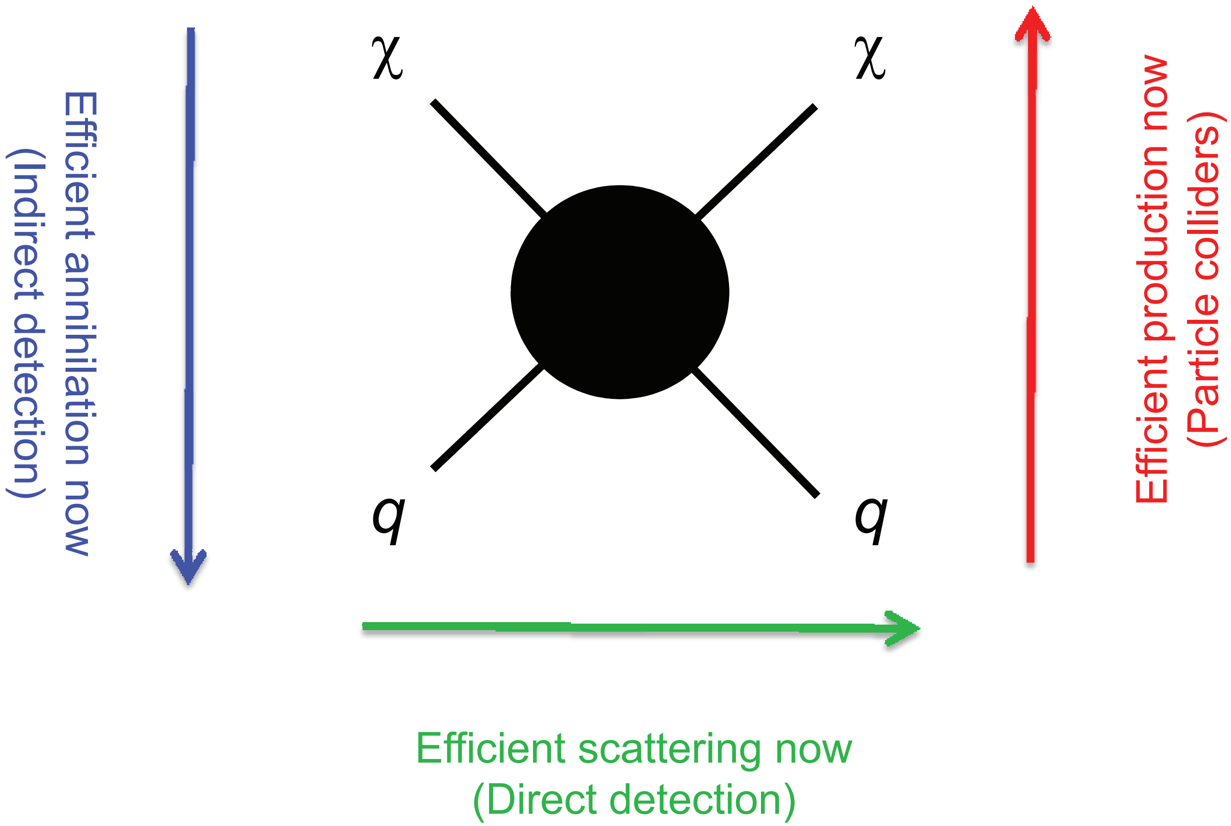
$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

- $m_X \sim m_{weak} \sim 100$ 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

WIMP IMPLICATIONS

WIMPS must interact with the SM efficiently



WIMP IMPLICATIONS

WIMPS must interact with the SM efficiently

EXCITING!

BACKGROUND CHECK: THE FLAVOR PROBLEM

- WIMP miracle → WIMPs are in theories of electroweak symmetry breaking

- EWSB theories generically suffer from the new physics flavor problem
  - new particles violate flavor bounds by many orders of magnitude
  - Δm_K, ε_K, $\mu \to e\gamma$, $\mu \to e$ conversion, electron EDM, neutron EDM

- Example: neutralino DM
  - Neutralino stable → it is the LSP, $m_{\tilde{G}} > m_\chi$
  - $m_{\tilde{G}}$ 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

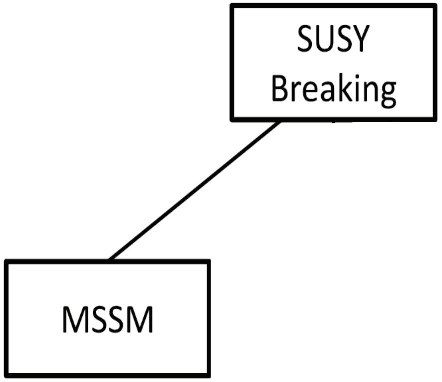
- The most elegant theories of EWSB that naturally conserve flavor are SUSY models with gauge-mediated SUSY-breaking

  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)

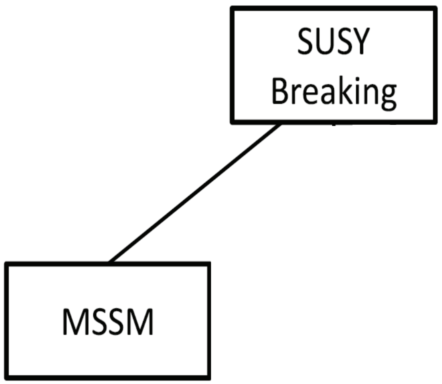
- No use of WIMP miracle

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

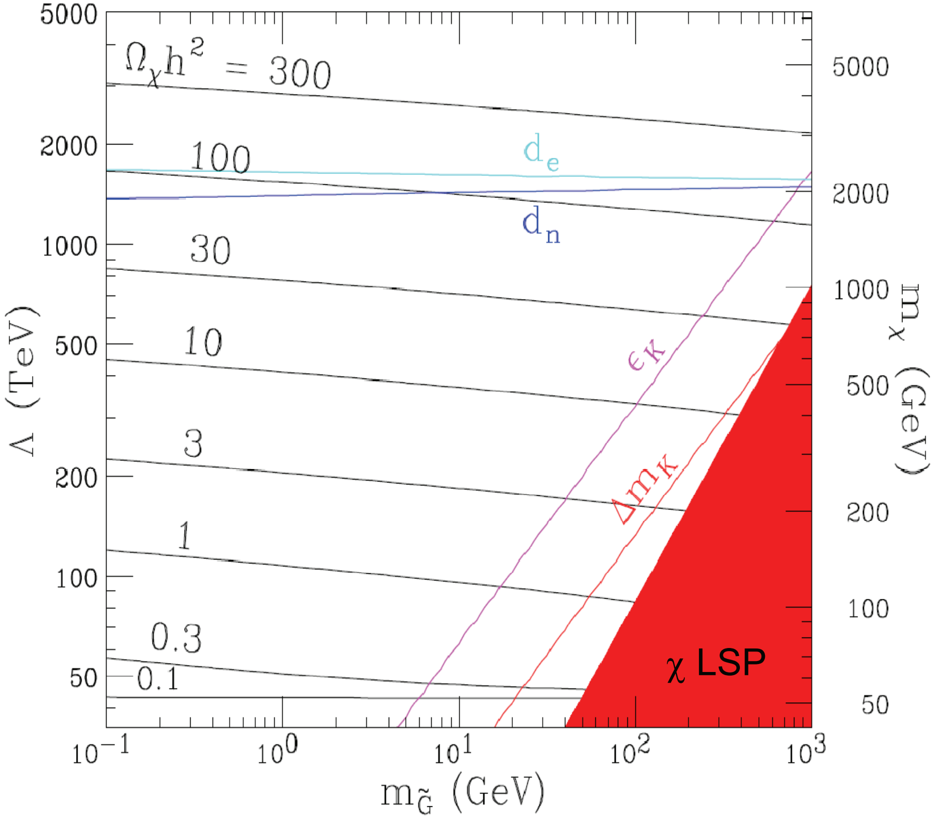
PREVIOUS SUGGESTIONS 3

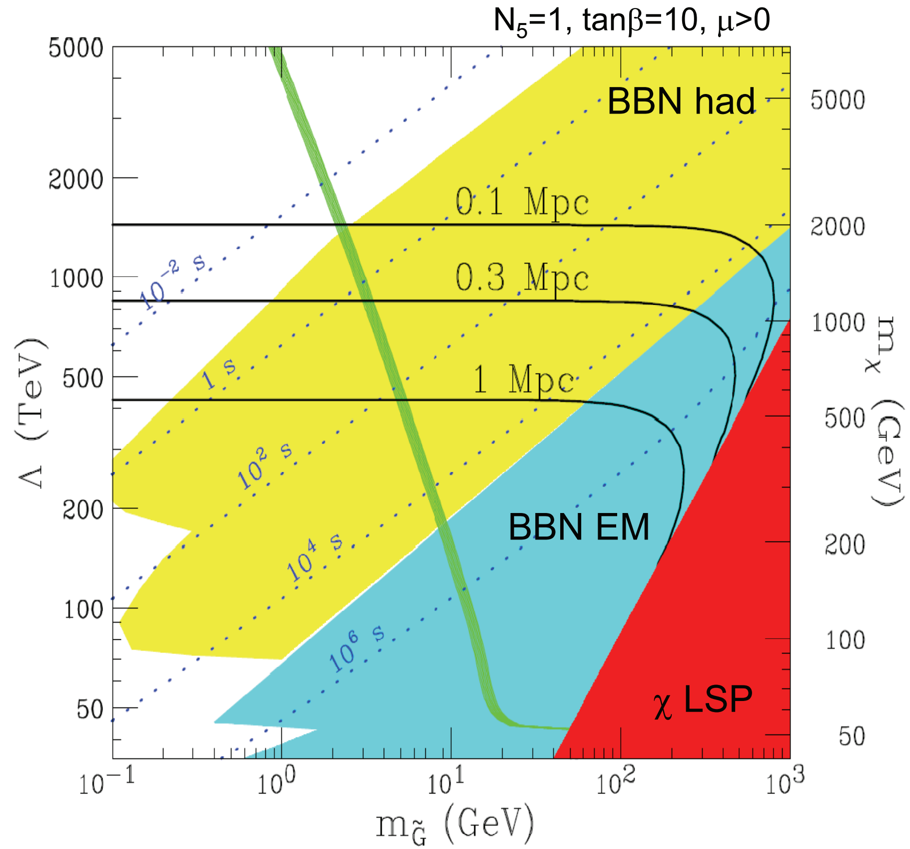
Goldilocks SUSY

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



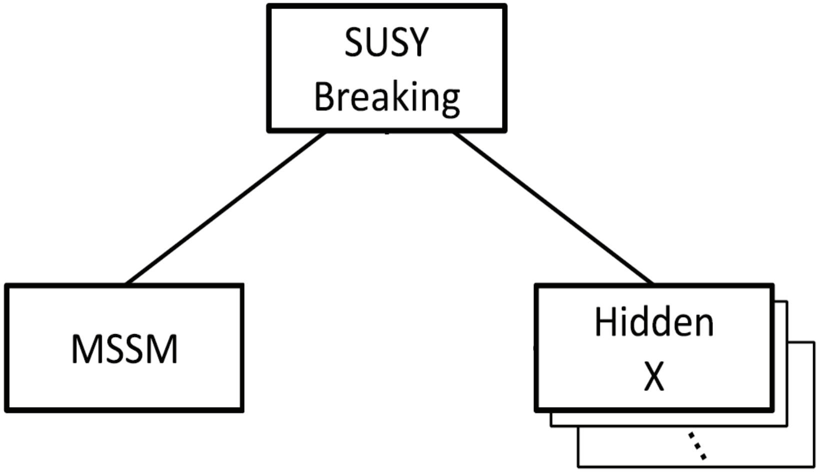


- Ω_χ ~ 100, m_χ ~ 1 TeV, $m_{\tilde{G}}$ ~ 1 GeV
- Uses the WIMP miracle
- Astrophysics constraints→ CP solved, warm $\tilde{G}$ DM

A NEW APPROACH

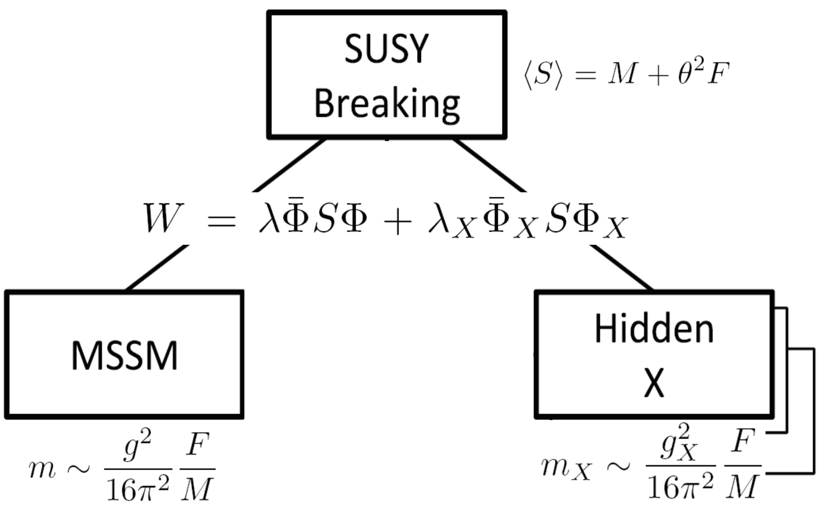
Feng, Kumar (2008)

- Consider standard GMSB with a single SUSY breaking sector and 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:

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

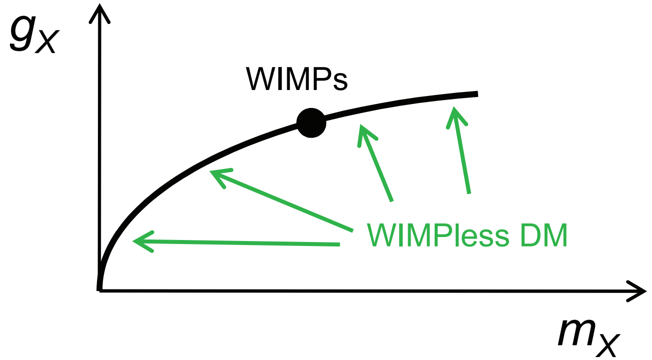
Hidden sector generically has the right relic density

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)

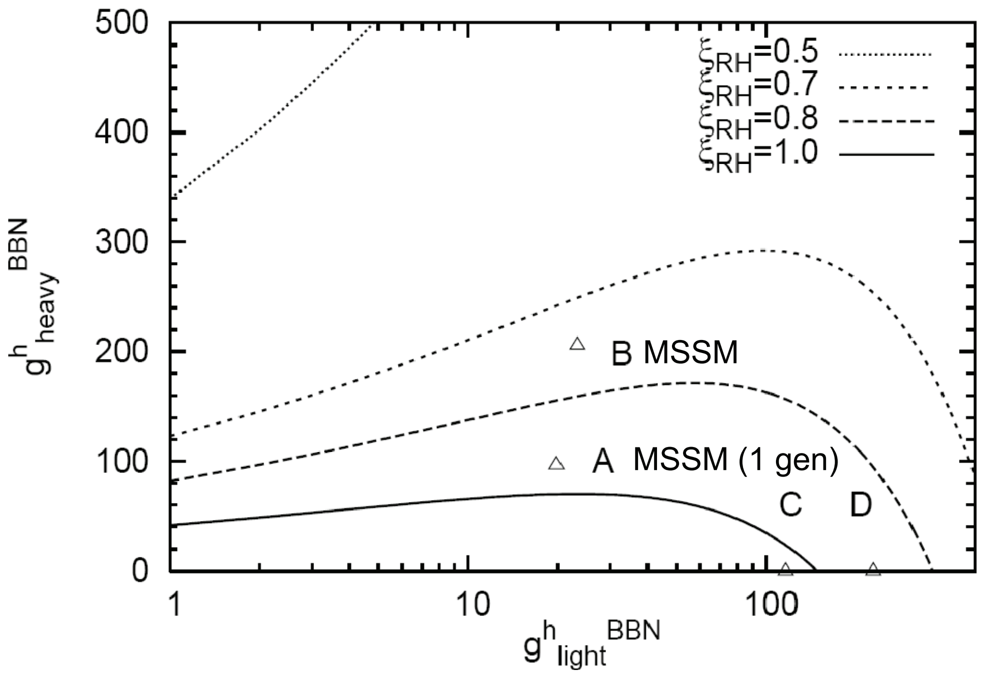
- Hidden sectors contribute to expansion rate

- 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

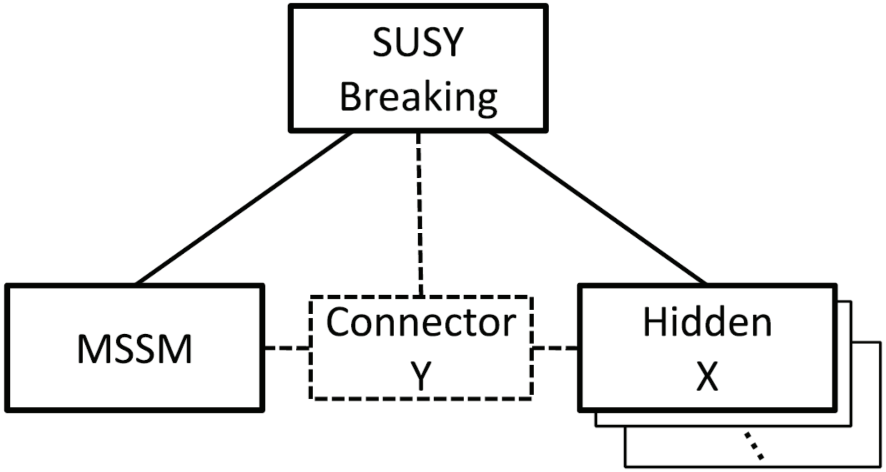


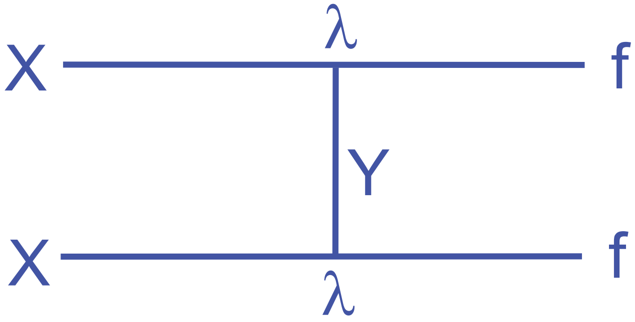
$$g_*^h(T_{\rm BBN}^h)\left(\frac{T_{\rm BBN}^h}{T_{\rm BBN}}\right)^4 = \frac{7}{8}\cdot 2\cdot (N_{\rm eff}-3) \le 2.52\ (95\%\ {\rm CL})$$

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:

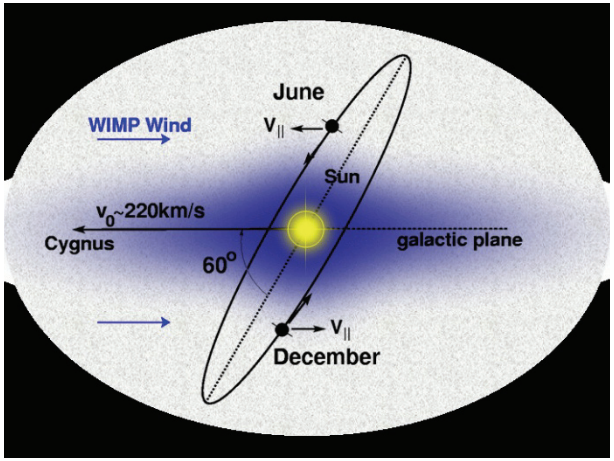
$$250 \text{ GeV} < m_Y < 500 \text{ GeV}$$

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

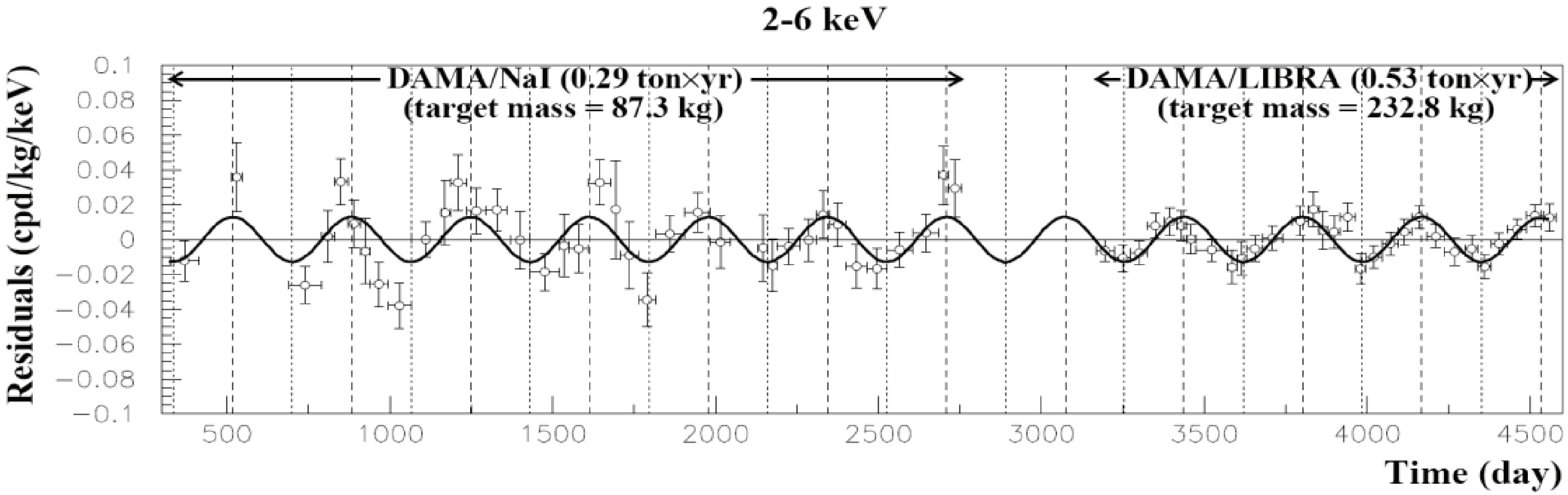
DIRECT DETECTION: DAMA

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



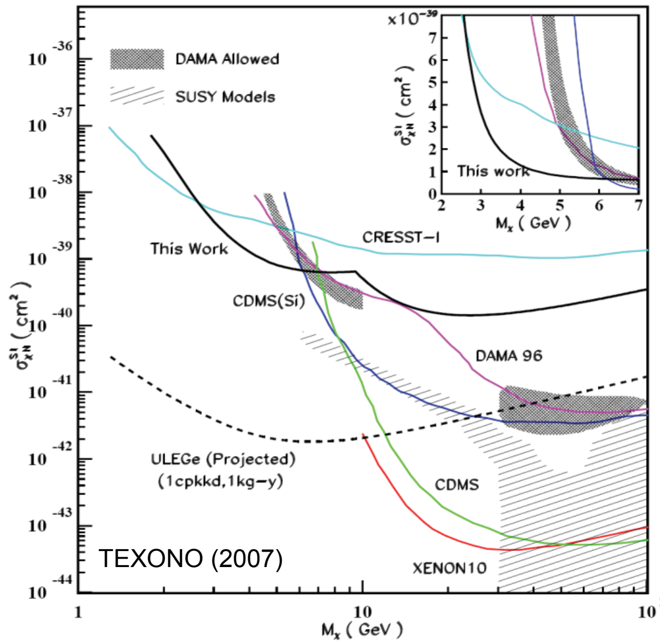
DAMA (2008)

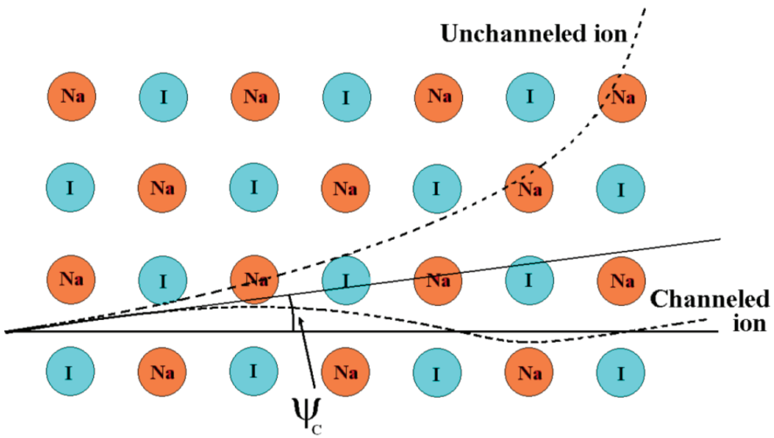
CHANNELING

- 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)

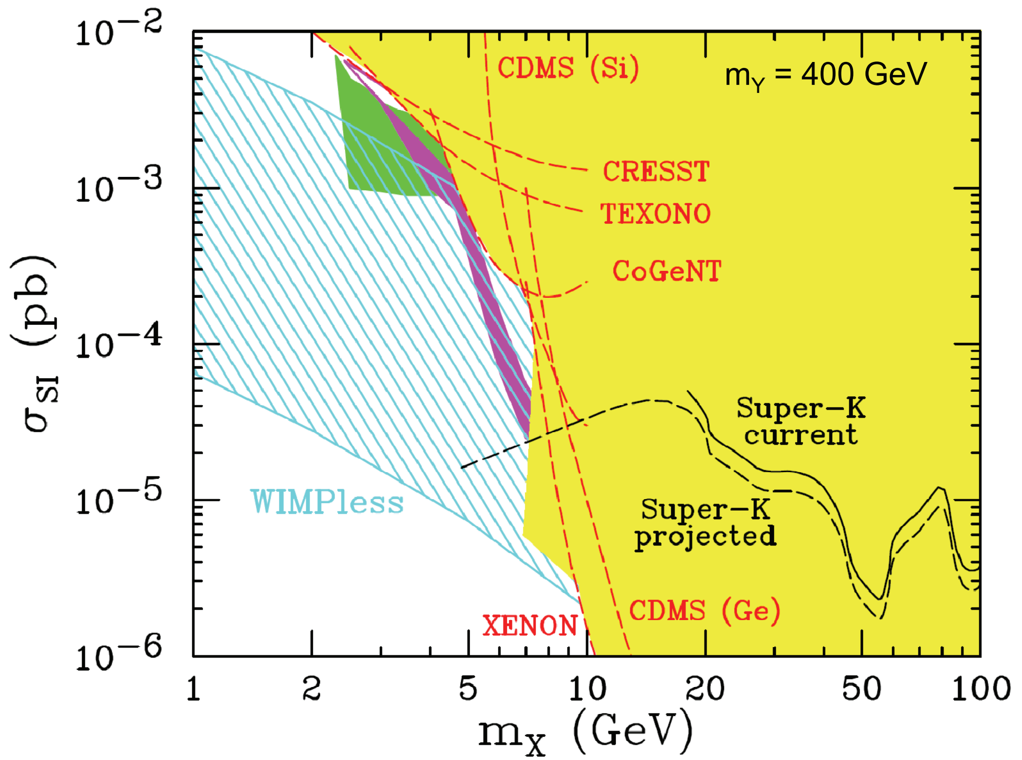




Gondolo, Gelmini (2005)
Drobyshevski (2007), DAMA (2007)

DAMA AND SUPER-K

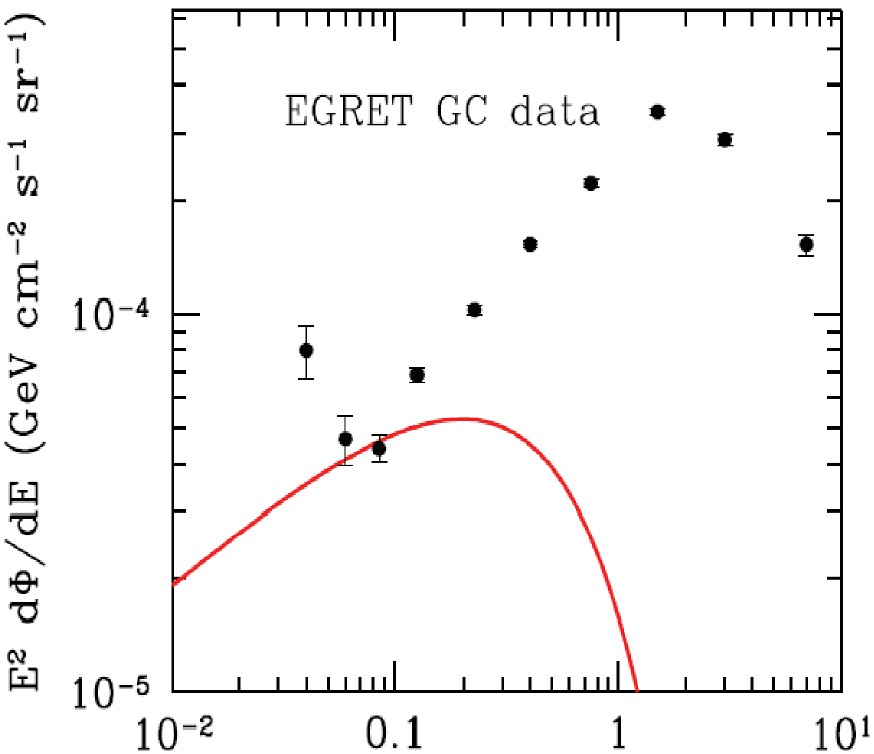
- WIMPless DM naturally explains DAMA with λ_b ~ 0.3-1 (cf. typical neutralino: m ~ 100 GeV, σ_{SI} ~10^{-8} pb)
- DAMA may be corroborated if Super-K extends its through-going analysis to fully contained analysis sensitive to E_ν ~ few GeV



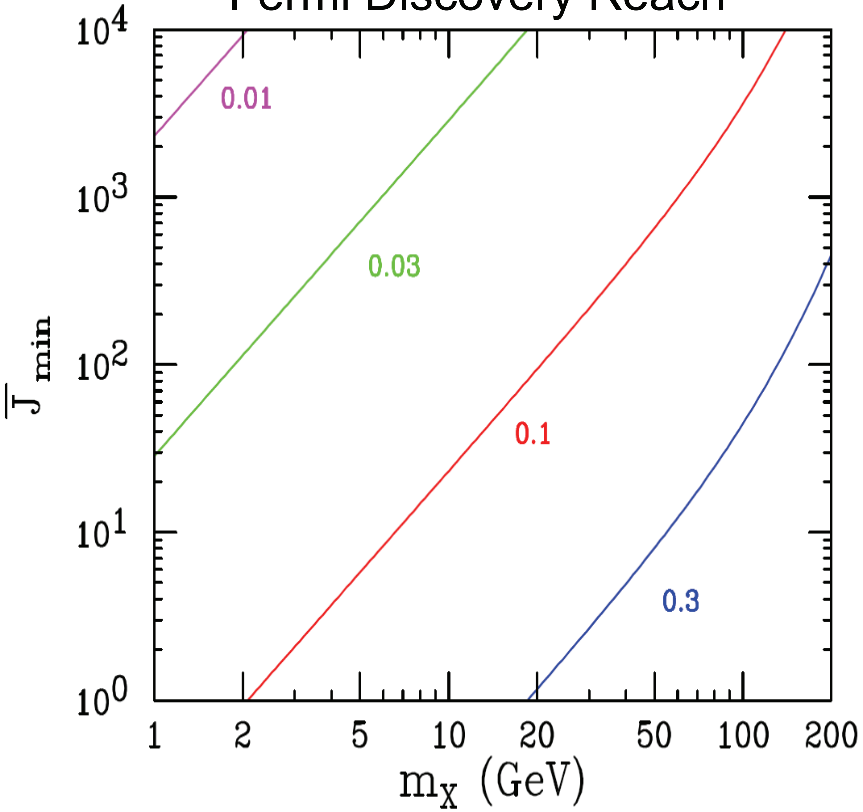
INDIRECT DETECTION

- 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, $\tilde{\tau}$ (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; natural choice is X = hidden stau

HIDDEN CHARGED DM

Feng, Kaplinghat, Tu, Yu (2009)

- Can DM have hidden charge? Many modifications to the standard CDM picture
  - Bound states form (and annihilate) in the early Universe
  - Annihilation is Sommerfeld enhanced at low velocities
  - Compton scattering $X \gamma^h \rightarrow X \gamma^h$: DM stays in kinetic contact with the thermal bath to lower temperatures
  - Rutherford scattering $XX \rightarrow XX$: self-interacting, collisional dark matter

- Constraints
  - Enhanced annihilation shouldn't destroy the WIMPless miracle
  - Enhanced annihilation in protohalos shouldn't violate bounds
  - Delayed kinetic decoupling shouldn't erase too much small scale structure
  - Enhanced self-interactions shouldn't violate bounds on collisional DM

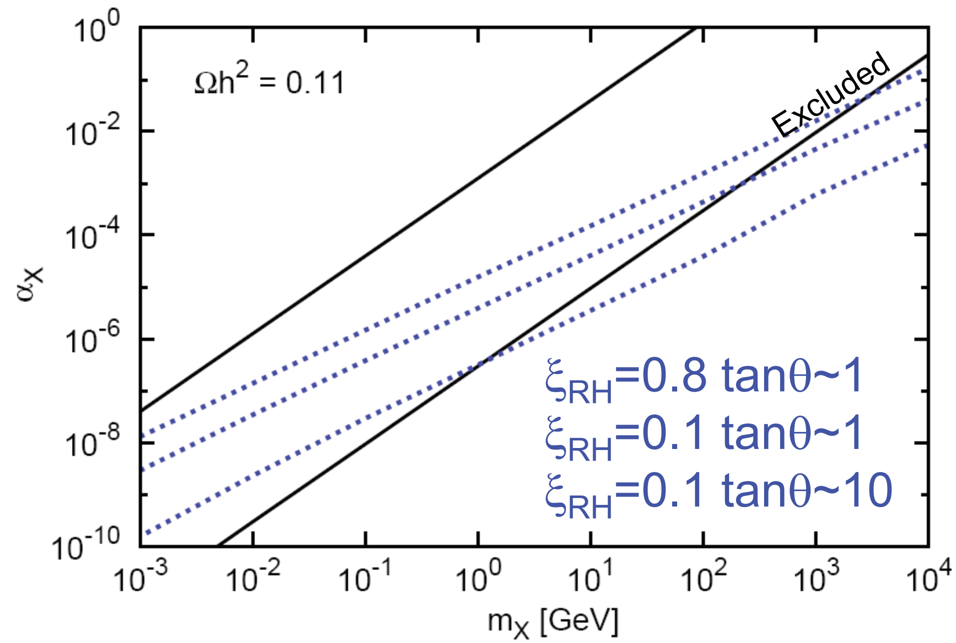
BOUNDS ON SELF-INTERACTIONS

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 ~ 1 GeV (100 GeV) allowed for tanθ ~ 10 (1)
  - Qualitatively different conclusions from U(1)-only case

Ackerman, Buckley, Carroll, Kamionkowski (2008)

BOUNDS ON ANNIHILATIONS

- At low v, annihilation is Sommerfeld enhanced by α/v

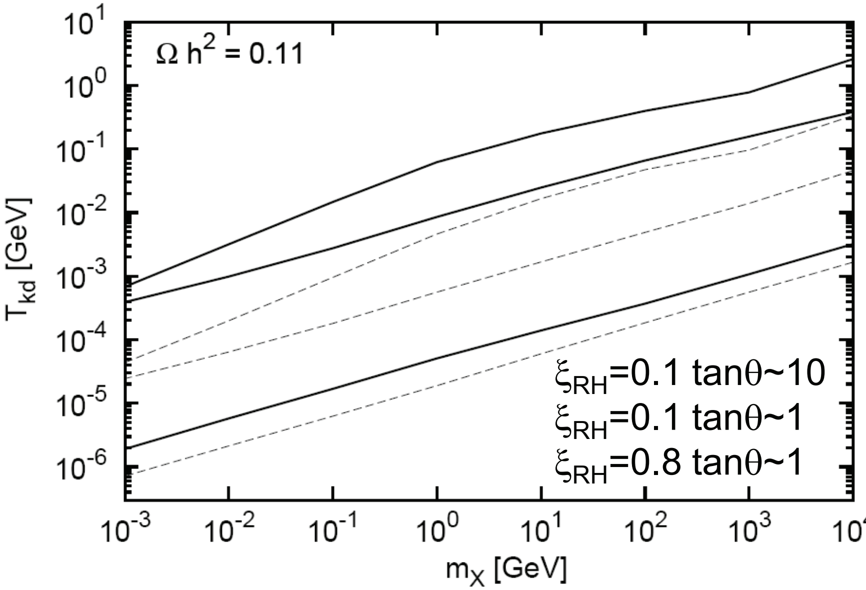
$$M_c \simeq 33\,(T_{\rm kd}/10\,{\rm MeV})^{-3}\,M_\oplus$$

$$(v/c) \sim 6.0\times10^{-9}\,(M_c/M_\oplus)^{1/3}(z_c/200)^{1/2}$$

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

Kamionkowski, Profumo (2008)

- Bottom line
  - With connectors: annihilation to visible particles → $m_X < 10$ GeV
  - Without connectors: annihilation to hidden particles, no constraints



Feng, Kaplinghat, Tu, Yu (2009)

CONCLUSIONS

- Dark matter may be in a hidden sector

- WIMPless dark matter
  - Present in standard particle physics models (SUSY)
  - Generalizes WIMP miracle to MeV < m_X < 10 TeV, $10^{-8} < \alpha_X < 0.1$
  - In contrast to WIMPs, is naturally consistent with (and motivated by) the new physics flavor problem

- Signals
  - With connectors: DAMA, SuperK, Fermi, …
  - With hidden charge: collisional dark matter