Title: Hidden Sector Dark Matter

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Abstract: TBA

Hidden Sector Dark Matter

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Summary

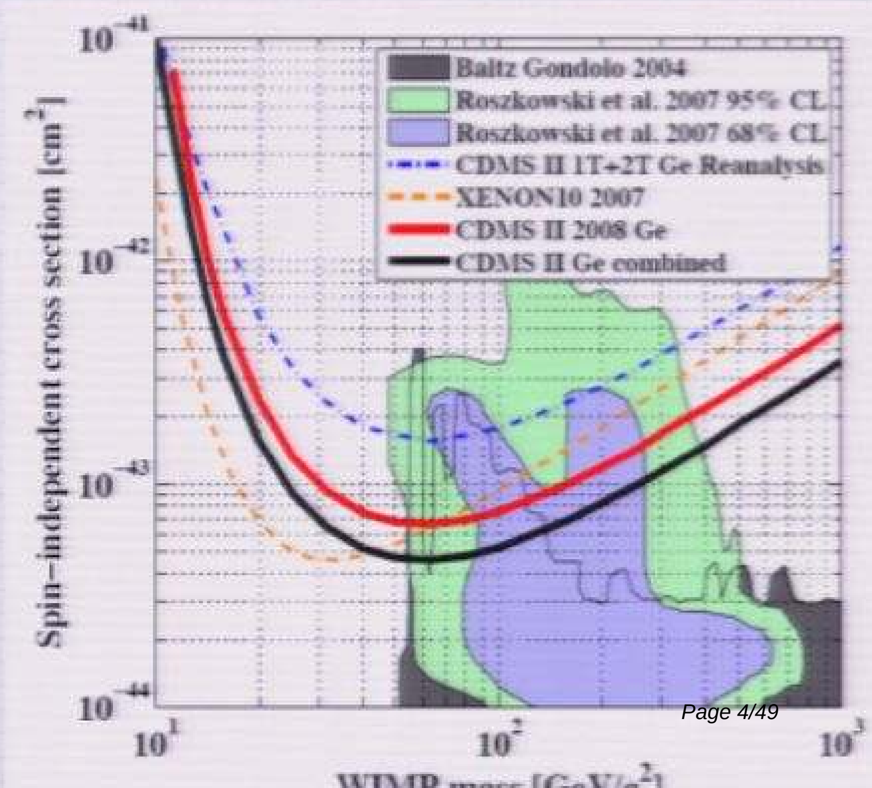
* Two Hidden Sector Dark Matter Models
    * Hidden Sector to SM via higher dim ops
        * Asymmetric Dark Matter
    * Hidden Sector to SM via kinetic mixing
* Pulsars as source of WMAP haze

WIMP DM

Standard Model ⟷ Weak scale DM

weak scale communicator

* Direct Detection
    * CDMS, XENON,...DAMA
* Indirect Detection
    * PAMELA, ATIC, Fermi



Schematic of a hidden valley

(Heavy Mediators)

Communicator

Standard Model

Dark Sector (Dark Matter)

Light
No SM charges
Often light by relation to proton mass

Baryon-DM coincidence

In standard picture, DM abundance set by thermal freezec

$$\Gamma_{ann} \lesssim H$$

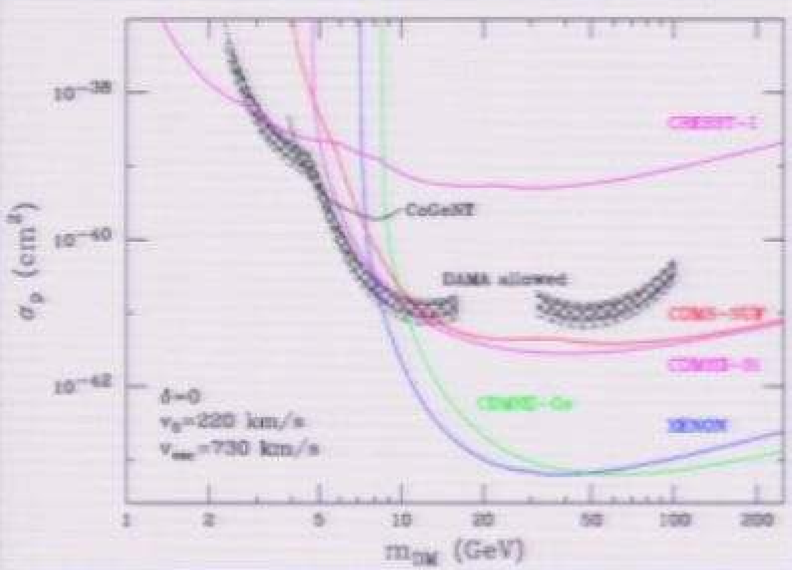
What if instead set by baryon density?

Experimentally, $\Omega_{DM} \approx 5\Omega_b$ S.M. Barr, D.B. Kaplan

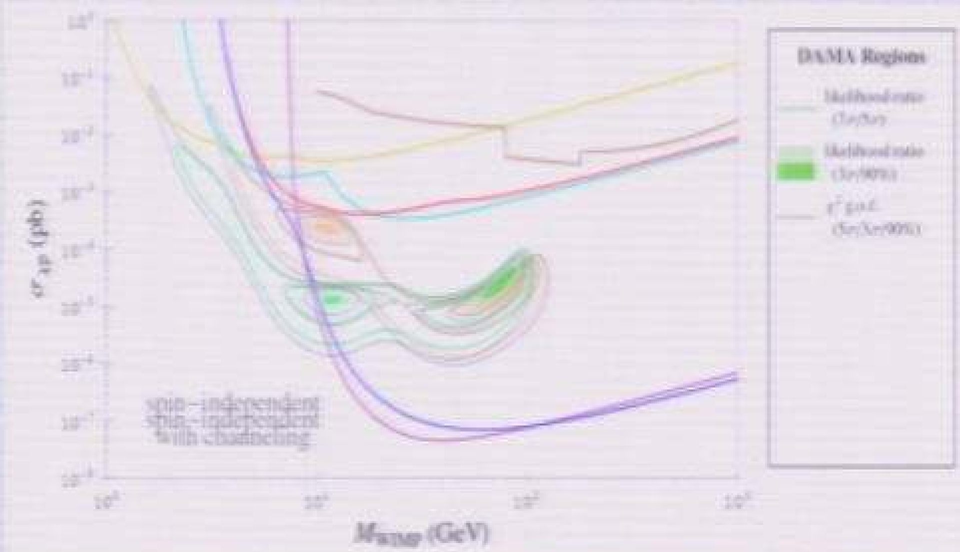
Find mechanism $n_{DM} \approx n_b$

→ $m_{DM} \approx 5m_p$

Not yet ruled out...

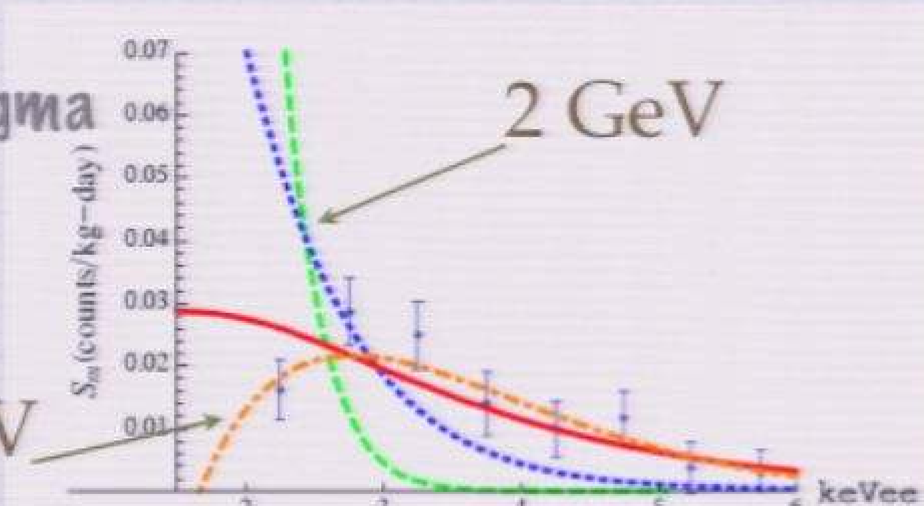


Petriello, KZ



Savage, Gelmini, Gondolo, Freese

Disfavored at 2-3 sigma



Chang et al.

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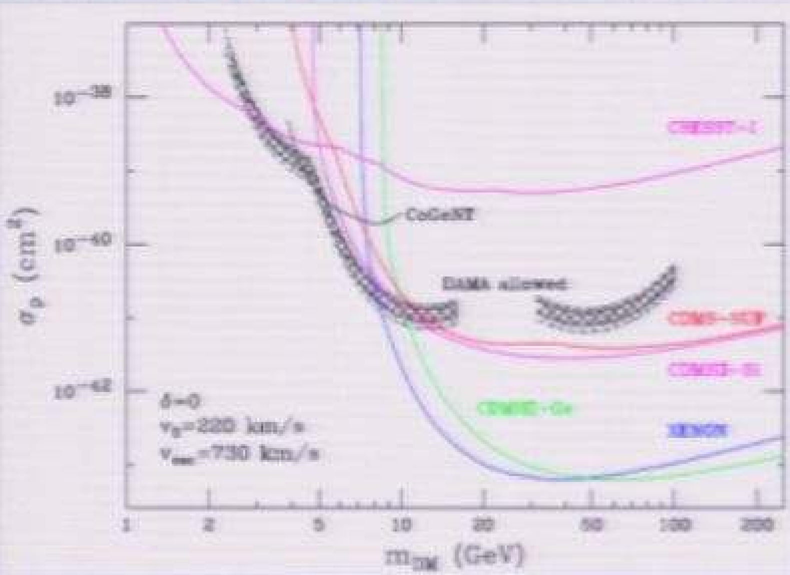

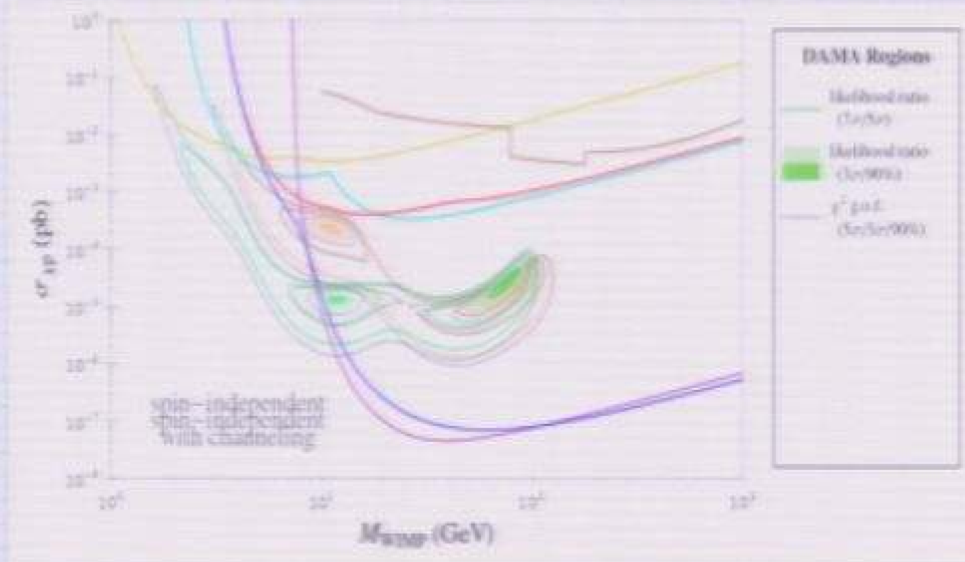

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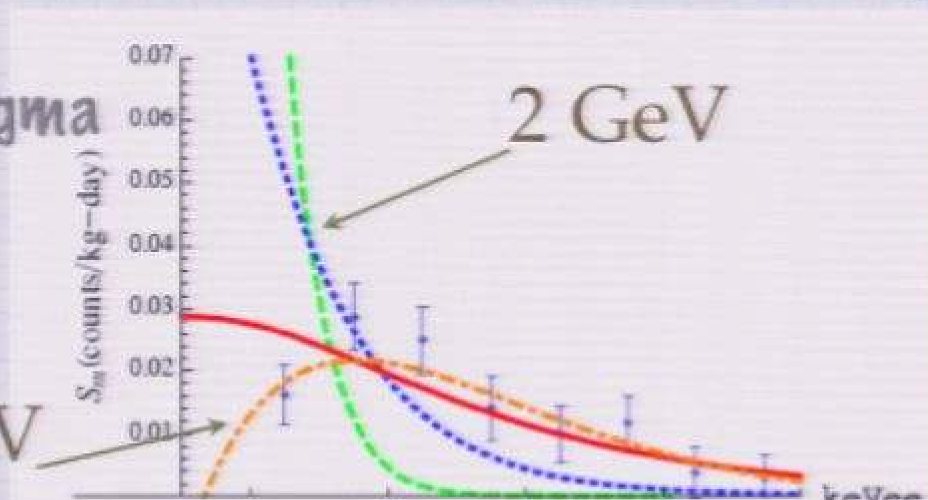

Chang et al.

A hidden valley-like solution to Baryon-DM coincidence

D. E. Kaplan, M. Luty, KZ

Integrate out heavy state
Effective operators:

$$\mathcal{L} = \frac{X^2 LHLH}{M^4}$$

$$W = \frac{X^2 udd}{M^2}$$

$$W = \frac{X^2 LH}{M}$$

X

Standard Model

Dark sterile state, fundamental or composite

Baryon-DM coincidence

A model

D. E. Kaplan, M. Luty, KZ

One example, many possibilities

DM carries lepton or baryon number

$$W = \frac{X^2 LH}{M} \quad 2(n_X - n_{\bar{X}}) \approx n_L - n_{\bar{L}}$$

DM carries lepton number L = 1/2

1. Operator transfer lepton asymmetry to DM
2. Detailed calculation

$$m_X \simeq 2.4 \text{ GeV} \frac{\Omega_{DM}}{\Omega_b} \simeq 11 \text{ GeV}$$

Baryon-DM coincidence

D. E. Kaplan, M. Luty, KZ

A model
One example, many possibilities

DM carries lepton or baryon number

$$W = \frac{X^2 LH}{M}$$

DM carries lepton number L = 1/2

3. Operator goes out of equilibrium before DM becomes non-relativistic, preventing XX -> nu nu, washing out asymmetry

4. Annihilate thermal abundance:

$$n_{DM} \sim T^3 \to 10^{-10} T^3$$

Operator drops out of equilibrium

- A. $M \gtrsim 10^9$ GeV
- B. Small temperature range where naturally happens for $M \sim 1$ TeV
  - e.g. $\tilde{\nu} \leftrightarrow XX$

$$\Gamma(\tilde{\nu} \leftrightarrow XX) \sim \frac{n_{\tilde{\nu}}}{n_X}\frac{1}{16\pi}\left(\frac{v_u}{M}\right)^2 m_{\tilde{\nu}}.$$

$$T \lesssim m_{\tilde{\nu}}/40$$

  - also $XX \leftrightarrow \tilde{\nu}\tilde{\nu}XX$

$$\Gamma \sim \frac{1}{16\pi}\left(\frac{1}{8\pi^2}\right)^2\left(\frac{v_u^2}{M^2 m_{\tilde{\nu}}^4 m_{\tilde{B}}}\right)^2 T^{11},$$

Baryon-DM coincidence

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Annihilating thermal abundance

$$n_{DM} \sim T^3 \to 10^{-10} T^3$$

- Extra relativistic states (Goldstone)

$m_X \bar{X} X e^{ia/s}$ $\quad s < 200 \text{ GeV}$ sufficient

$$\bar{X} X \to aa$$

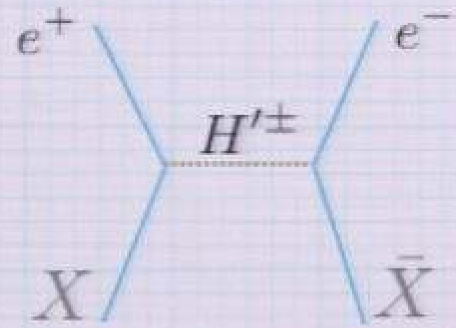
- Or, heavier Goldstones, which then decay, as in NMSSM

$$\Delta W = \lambda_X S X \bar{X} + \lambda_H S H_u H_d + \frac{\kappa}{3} S^3$$

Annihilating thermal abundance

$$n_{DM} \sim T^3 \rightarrow 10^{-10} T^3$$

* Through heavy mediators



$$m_{H'}/y' \lesssim 200 \text{ GeV}$$

* Tight constraints!

Simple UV completions

* EW singlets

$$\Delta W = M\bar{N}N + \lambda' N\bar{X}^2 + y_i'\bar{N}L_i H_u.$$

* EW doublets

$$\Delta W = M\bar{D}D + \lambda'\bar{X}DH_u + y_i'L_i\bar{D}\bar{X}.$$

Baryon-DM coincidence

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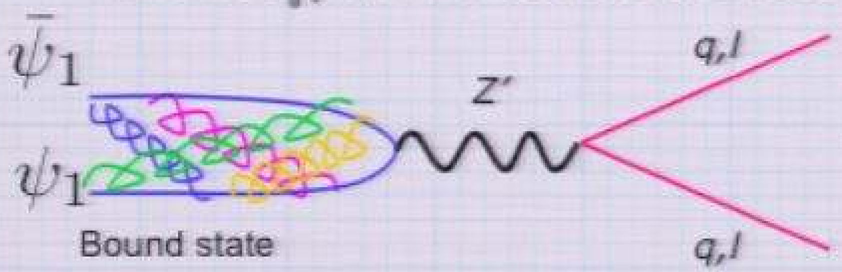
Annihilating thermal abundance

$$n_{DM} \sim T^3 \rightarrow 10^{-10} T^3$$

* Strong dynamics
  * Less stringent because only require decay, not annihilation



Symmetric part decays

$$W = \frac{\bar{\psi}_1 \psi_2 L H}{M}$$

* X states become $\bar{\psi}_1 \psi_2$ HV bound states

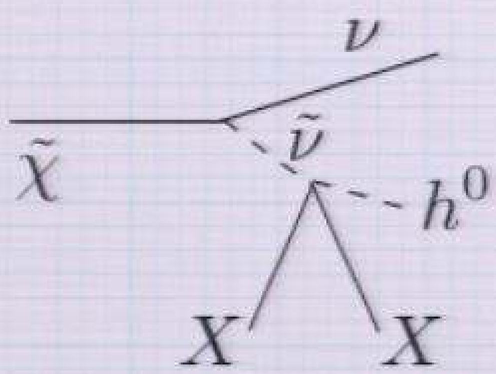
Kaplan, Luty, KZ, in progress

Implications for colliders

- MSSM LSP is not stable!

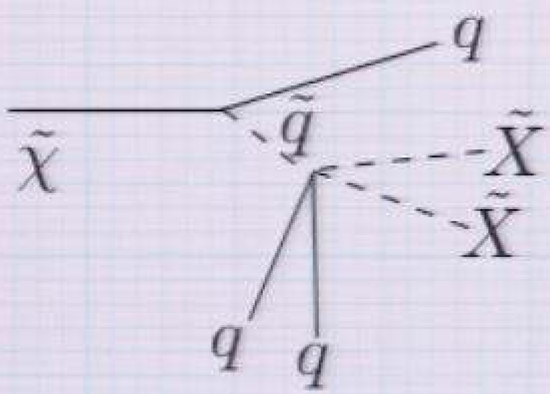
$$W = \frac{X^2 LH}{M} \qquad 2(n_X - n_{\bar{X}}) \approx n_L - n_{\bar{L}}$$

$$m_X \simeq 2.4 \text{ GeV} \frac{\Omega_{DM}}{\Omega_b} \simeq 11 \text{ GeV}$$



$$c\tau(\chi^0 \to h^0 \nu \bar{X} \bar{X}) \sim \text{mm} \left(\frac{M}{10^6 \text{ GeV}}\right)^2 \left(\frac{m_{\tilde{\nu}}}{200 \text{ GeV}}\right)^4 \left(\frac{m_{\chi^0}}{100 \text{ GeV}}\right)^{-7}$$

Collider signatures



$$W = \frac{X^2 udd}{M^2}$$

$$c\tau(\chi^0 \to qqq\tilde{X}\tilde{X}) \sim 0.3\ \text{mm} \left(\frac{M}{\text{TeV}}\right)^4 \left(\frac{m}{500\ \text{GeV}}\right)^4 \left(\frac{m_{\chi^0}}{100\ \text{GeV}}\right)^{-9}$$

$$c\tau(\tilde{X} \to Xqqq) \sim 3\ \text{mm} \left(\frac{M}{\text{TeV}}\right)^4 \left(\frac{m}{500\ \text{GeV}}\right)^2 \left(\frac{m_{\tilde{X}}}{100\ \text{GeV}}\right)^{-7}$$

Missing energy largely reduced

Schematic of a hidden sector

(kinetic mixing)

Communicator

Standard Model

Dark Sector (Dark Matter)

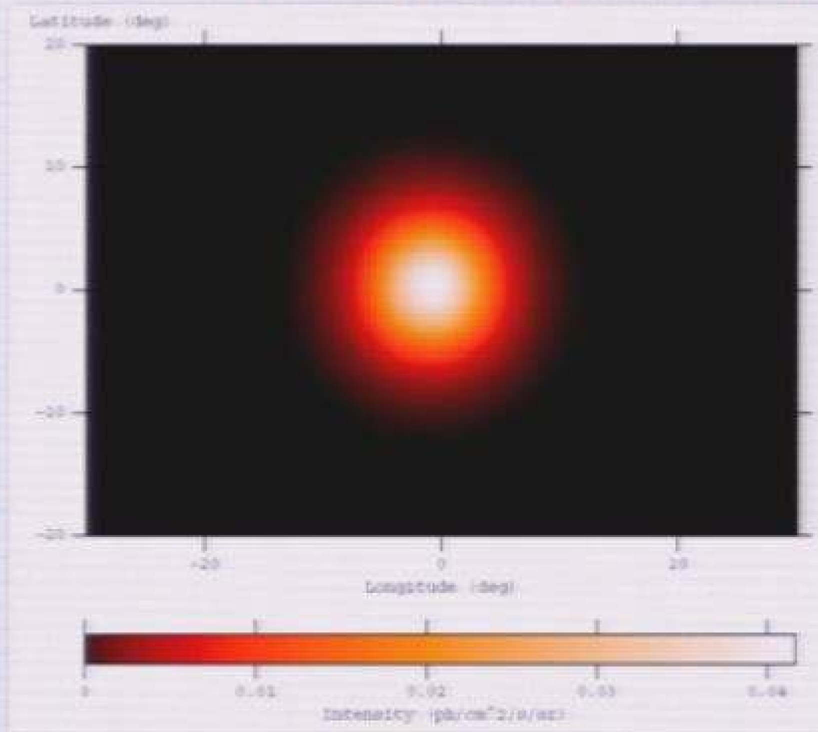
Light

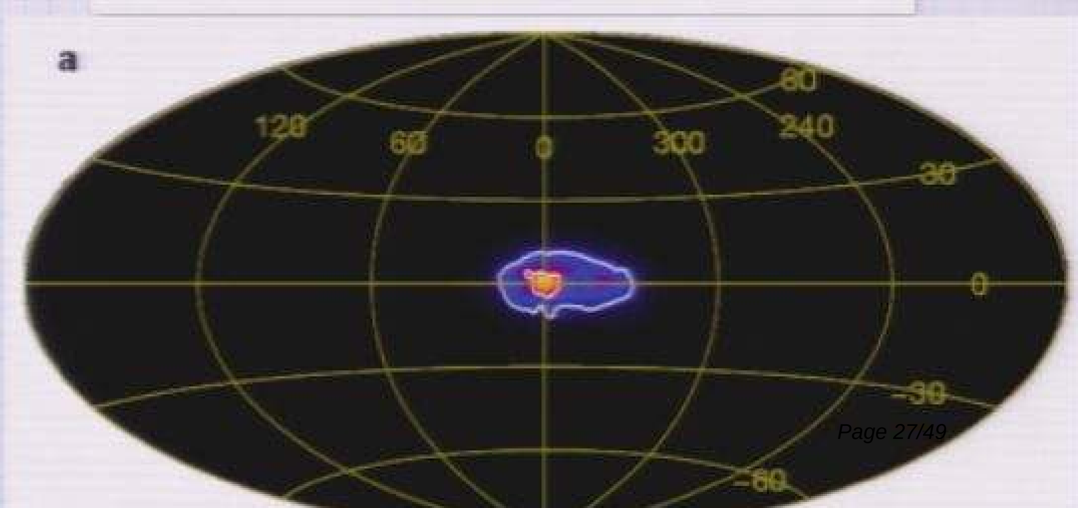
No SM charges

Naturally light by weak coupling to SUSY breaking

511 keV from kinetic mixing?

- INTEGRAL/SPI has observed bright 511 keV radiation from galactic bulge
- Source of positrons remains unknown
- Evidence towards X-ray binaries?
- Consistent with annihilating dark matter with mass in 0.5-3.5 MeV range

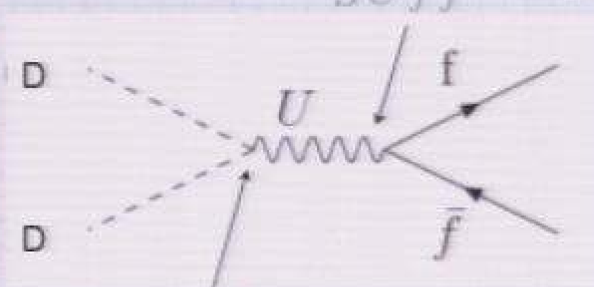




A model to explain the signal

Fayet

$g_{Uff} \sim 10^{-5}$



$g_{UDD} \sim 0.1$

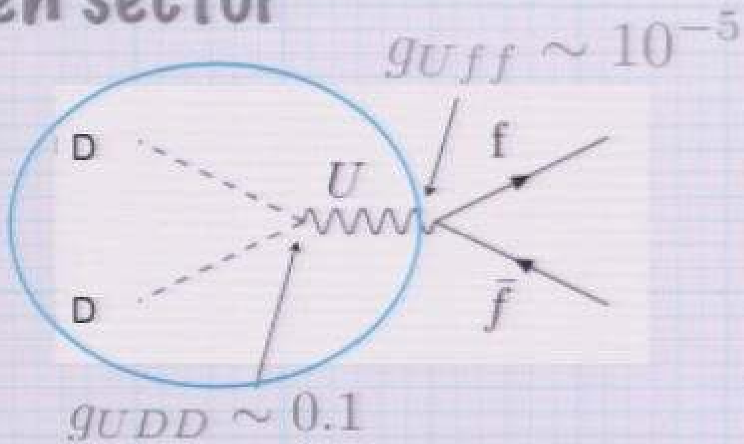
$m_U \sim 5$ MeV

- Coincident DM, mediator masses
- Small couplings
- Light (scalar) DM
- Any particle physics motivation?

A model to explain the signal

Fayet

Hidden sector



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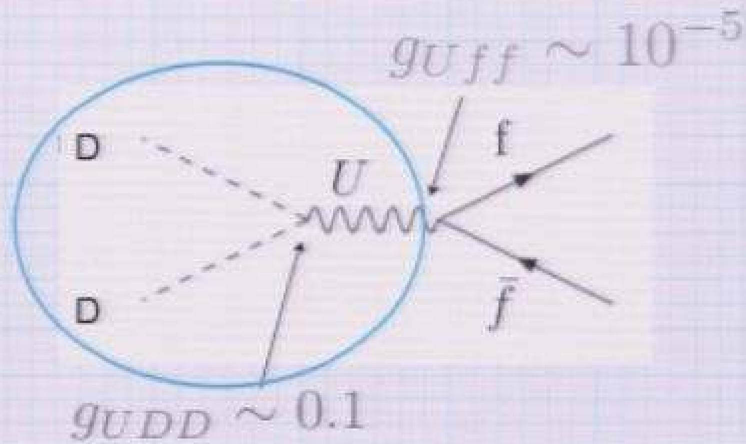
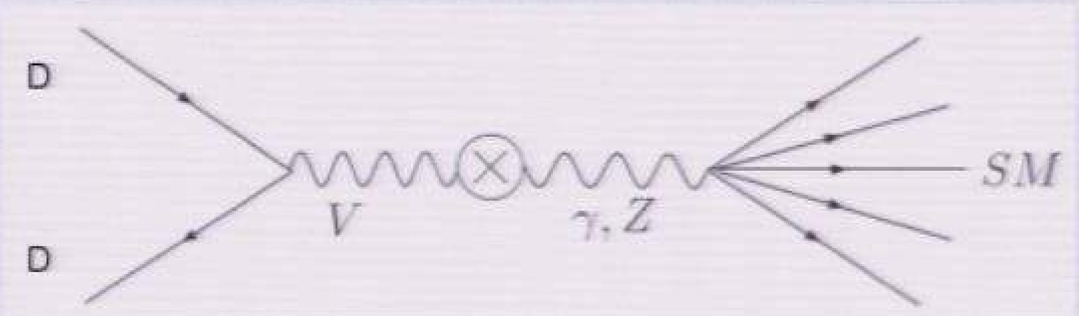
Kinetic Mixing Mediation

* Secluded DM, Pospelov, Ritz, Voloshin



* Small coupling to SM due to kinetic mixing

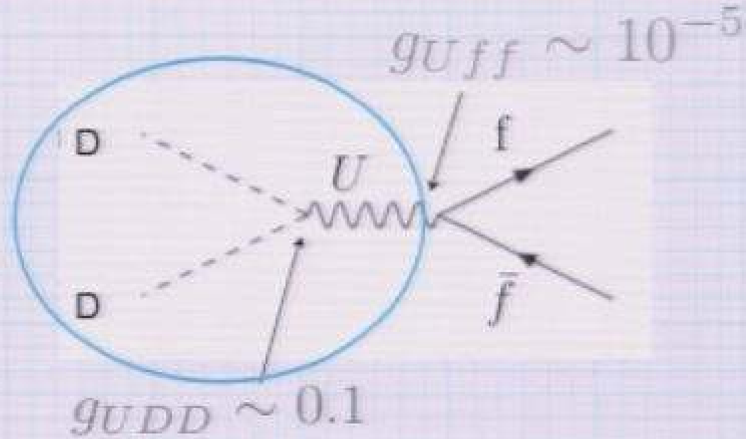


Natural Supersymmetric MeV DM

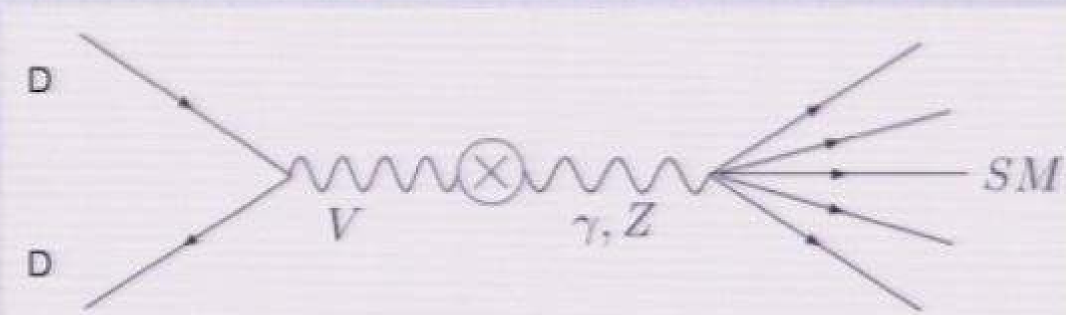
Hooper, KZ 0801.3664

$$m_{dark} \sim \chi m_{SUSY}$$

$$\chi = g_{UDD} g_{Uff}$$



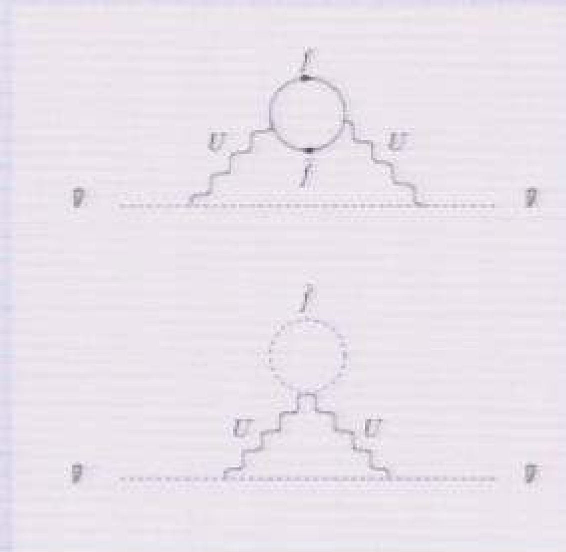
$$\chi \sim \epsilon g_{UDD} g_Y$$



"Little gauge mediation"

$$W_D = \lambda S \bar{D} D$$

Hooper, KZ 0801.3664



- Two loop graphs
- Introduce -m^2 for D, break U(1)_D with <D>

$$m_D^2 = -\frac{g_{UDD}^2 g_{Uff}^2}{128\pi^4} m_{\tilde{f}}^2 \log\left(\frac{\Lambda_{UV}^2}{m_{\tilde{f}^2}}\right)$$

$$= -5\ \mathrm{MeV}^2 \left(\frac{g_{UDD} g_{Uff}}{3\times 10^{-6}}\right)^2 \left(\frac{m_{\tilde{f}}}{10\ \mathrm{TeV}}\right)$$

$$m_U = g_{UDD}\langle D\rangle$$

- All superpartners obtain MeV masses (though light axion)

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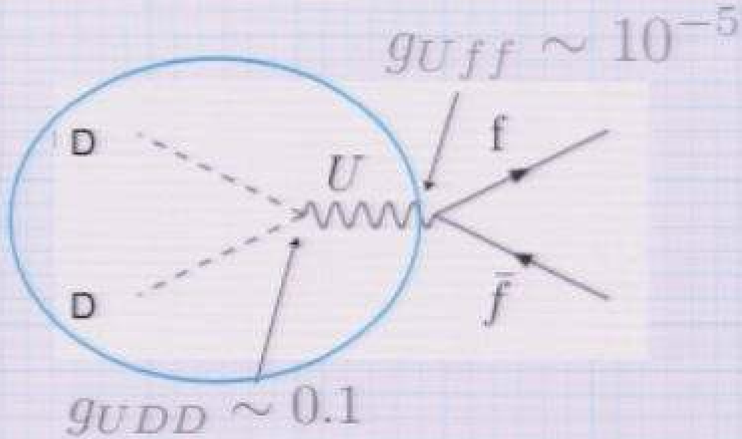

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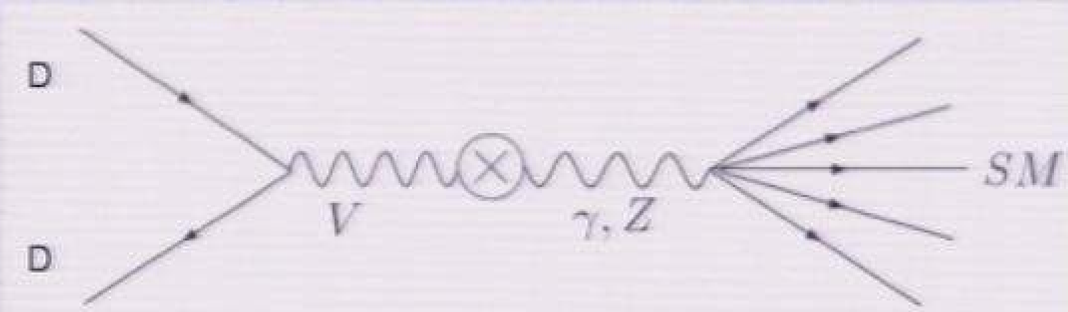

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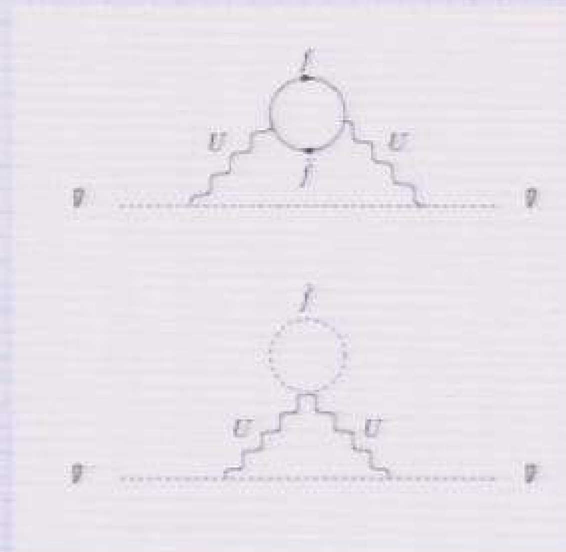

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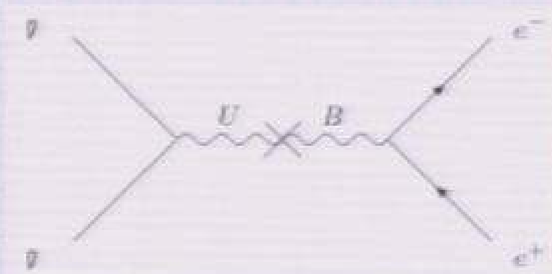
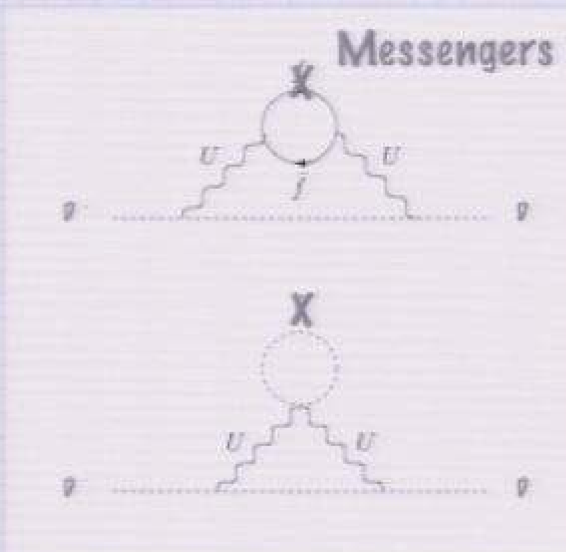
* All superpartners obtain MeV masses (though light axion)

Communicate to SM through kinetic mixing

Hooper, KZ 0801.3664



$$L_{kin} = \chi B_{\mu\nu} U^{\mu\nu}$$

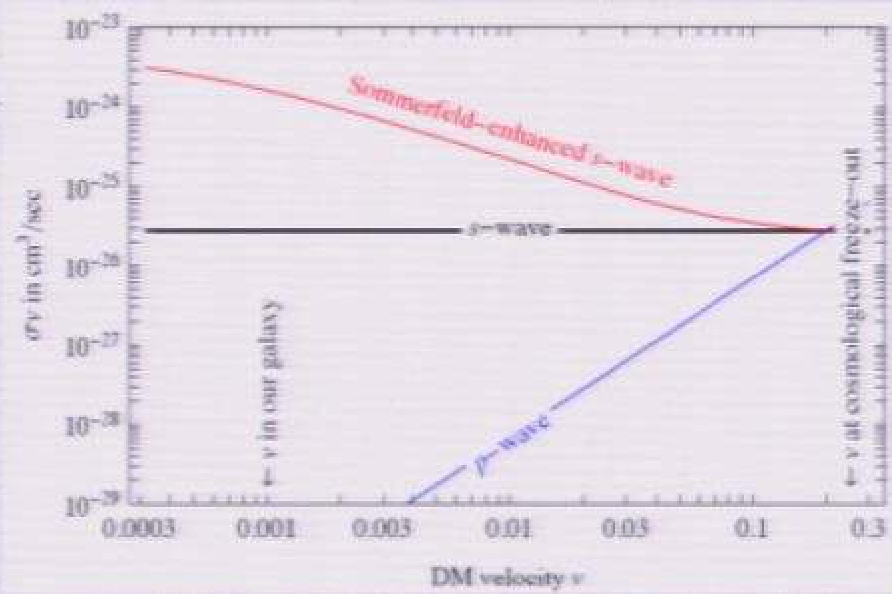


Messengers must give positive contributions!

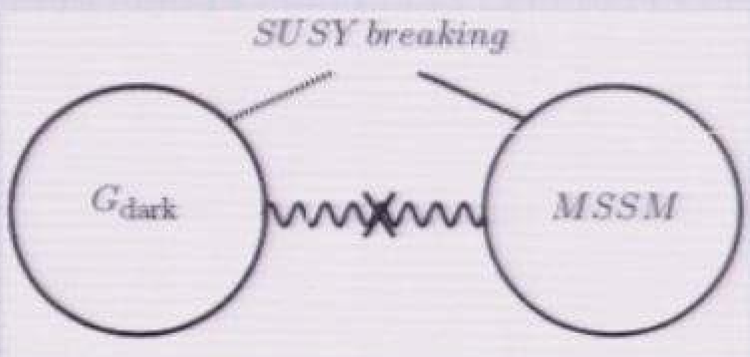
Sommerfeld enhancement and dark forces

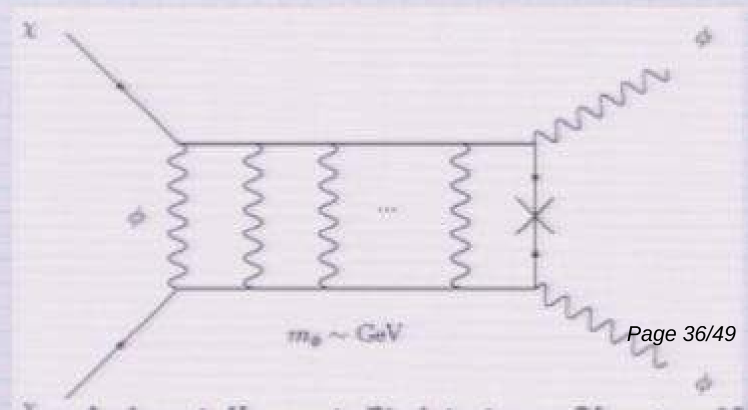
$$\alpha m_{DM} \gtrsim m_\phi \sim 1 - 10 \text{ GeV}$$

* Light mediators are natural in hidden supersymmetric models!



Cirelli and Strumia





D-term mediated

Baumgart, Cheung, Ruderman, Wang, Yavin, '09

* Not through two loop graphs "F-term" mediated
* From hypercharge D-term induced from Higgs vev

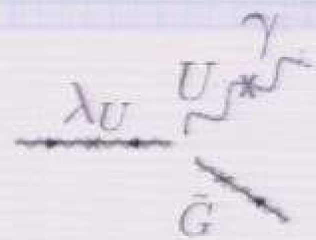
$$V_{\text{gauge}} = \frac{1}{2}D_Y^2 + \frac{1}{2}D_y^2 - \epsilon D_Y D_y + g_Y D_Y \sum_i Q_i |H_i|^2 + g_y D_y \sum_i q_i |h_i|^2$$

$$V_{\text{gauge}} \supset \epsilon D_y \langle D_Y \rangle = \xi D_y$$
$$\xi = \epsilon \langle D_Y \rangle = \epsilon \frac{g_Y}{2} \cos 2\beta \, v^2$$

D-term mediated

- Problem with late decays to gravitino

$$\tau = \frac{16\pi \langle F \rangle^2}{m_x^5 |P_\gamma|^2}$$
$$\simeq (3 \times 10^3\, s) \left(\frac{\sqrt{\langle F \rangle}}{100\ \mathrm{TeV}}\right)^4 \left(\frac{1\ \mathrm{GeV}}{m_x}\right)^5 \left(\frac{\epsilon}{|P_\gamma|}\right)^2 \left(\frac{10^{-3}}{\epsilon}\right)^2$$



- Generically, lightest state in hidden sector should be heavier than gravitino, otherwise problematic

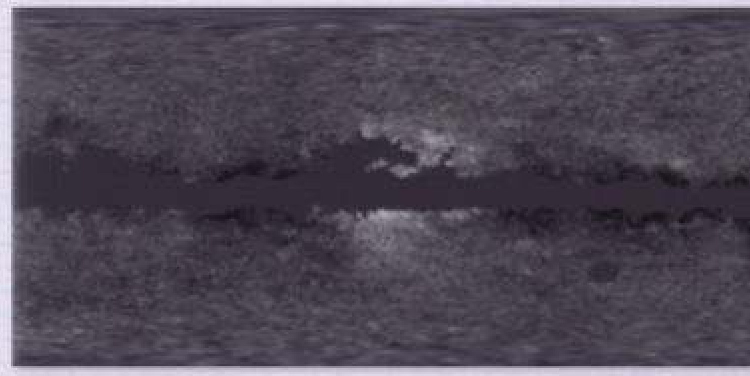
- Probably need some sequestering

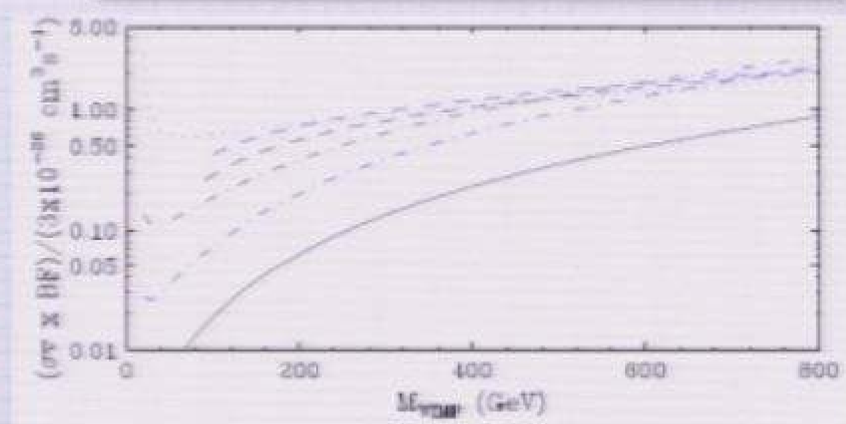
Katz, Sundrum '09

The WMAP Haze

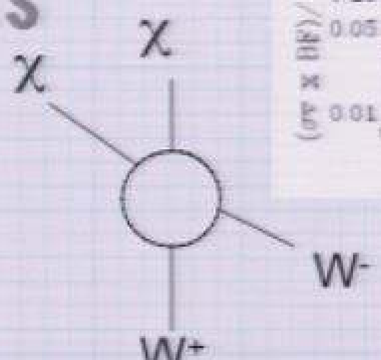
- Is it there?
  - Lots of background synchrotron radiation, from dust
- What causes it?
  - DM annihilation to charged byproducts which radiate in magnetic field?

Finkbeiner
Finkbeiner and Dobler 2007





Hooper, Dobler, Finkbeiner 2007



The WMAP Haze from DM

* Magic thermal annihilation cross-section
    * Gets right relic density
* But annihilation cross-section quite dialable

$$\Omega_c h^2 = 0.114 \pm 0.003$$

$$\Omega h^2 \approx \frac{2 \times 10^{-10} \mathrm{GeV}^{-2}}{\langle \sigma v \rangle}$$

$$\sigma v \approx \frac{g^4}{1\ \mathrm{TeV}^2} \approx 3 \times 10^{-26} \frac{\mathrm{cm}^3}{\mathrm{s}}$$

* Density profile, Magnetic field profile, ratio of energy lost by inverse Compton to synchrotron
* Several orders of magnitude in cross-section

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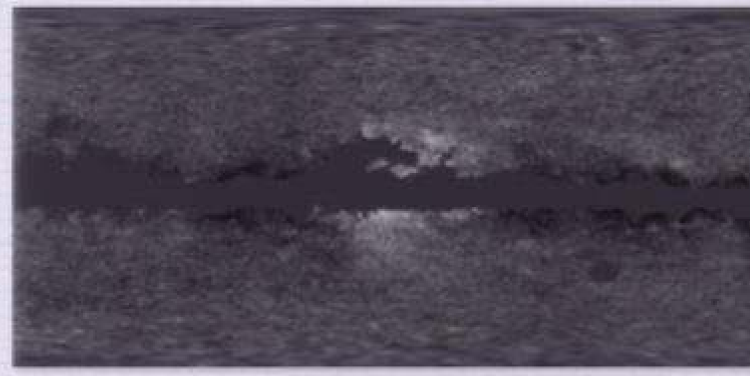

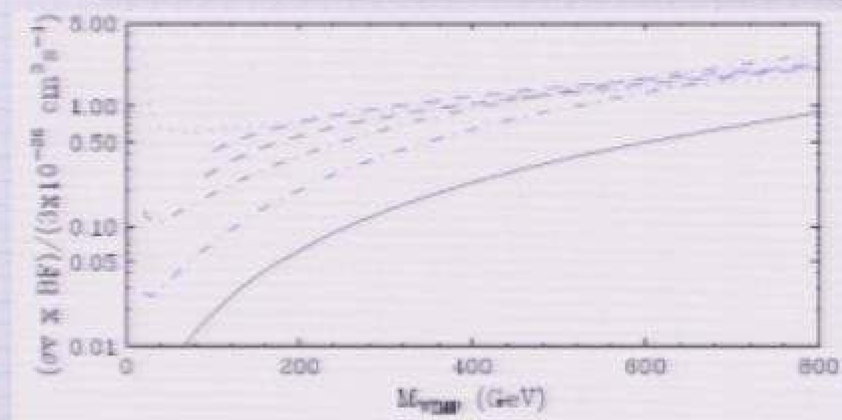

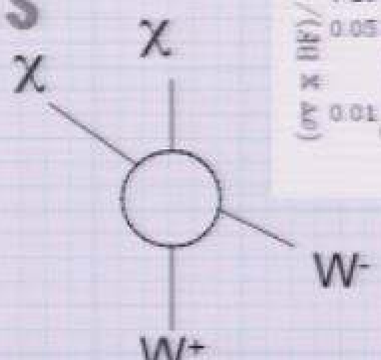

Hooper, Dobler, Finkbeiner 2007

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* Magic thermal annihilation cross-section

$$\Omega_c h^2 = 0.114 \pm 0.003$$

$$\Omega h^2 \approx \frac{2 \times 10^{-10} \mathrm{GeV}^{-2}}{\langle \sigma v \rangle}$$

  * Gets right relic density

$$\sigma v \approx \frac{g^4}{1\ \mathrm{TeV}^2} \approx 3 \times 10^{-26} \frac{\mathrm{cm}^3}{\mathrm{s}}$$

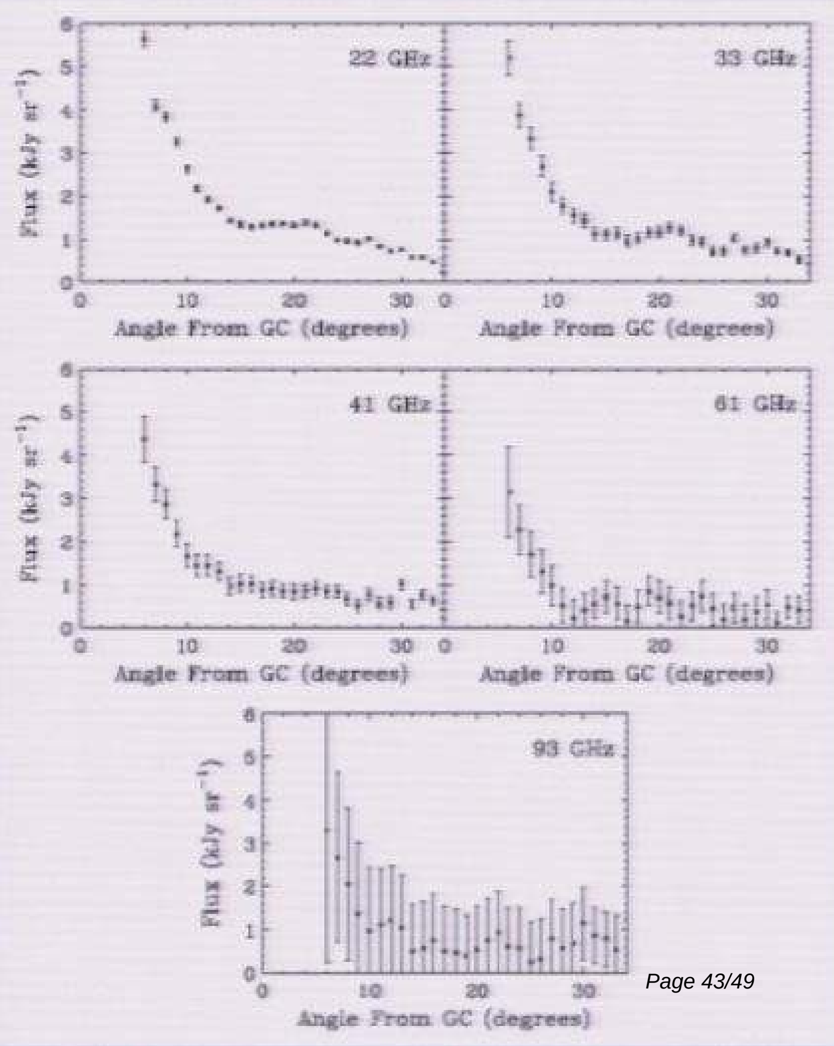
* But annihilation cross-section quite dialable

* Density profile, Magnetic field profile, ratio of energy lost by inverse Compton to synchrotron

* Several orders of magnitude in cross-section

WMAP Haze from Astrophysical Electrons?

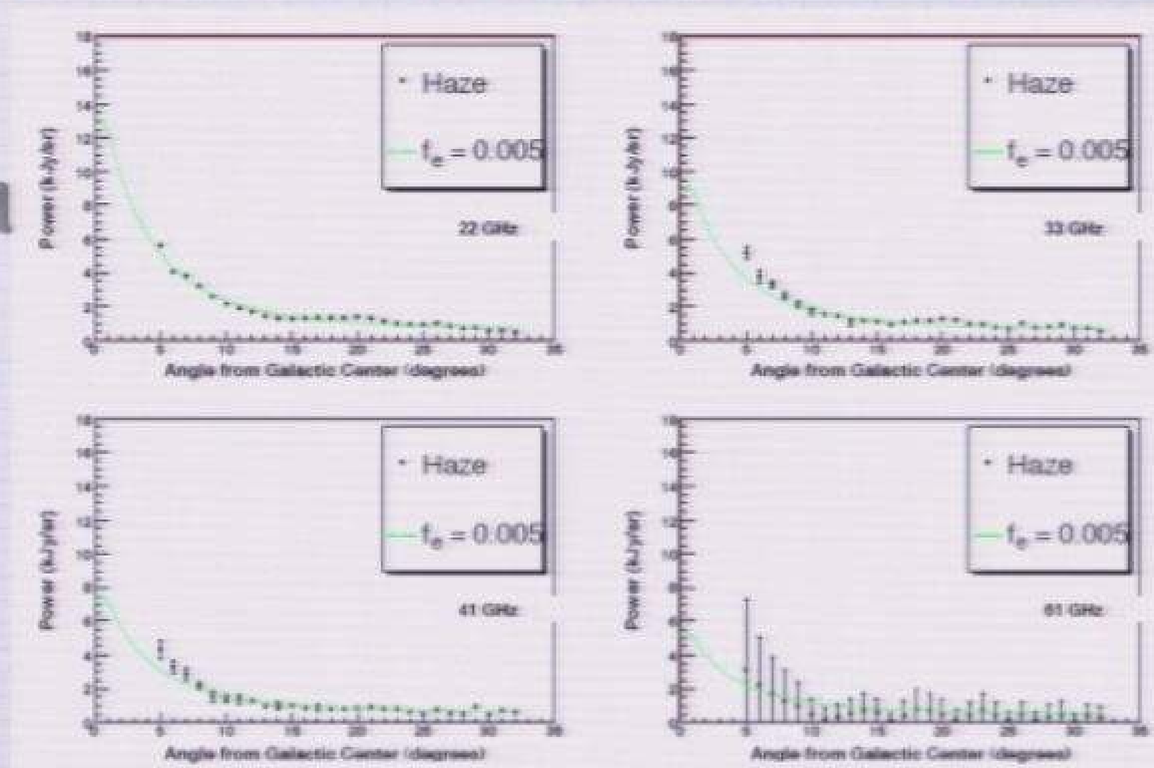
- Total flux of synchrotron
- Angular profile from galactic center
- Frequency band dependence $\frac{dn_e}{dE_e} \propto E_e^{-\alpha}$
- Morphology -- approximately spherical



WMAP Haze from Astrophysical Electrons?

* Total flux of synchrotron
* Angular profile from galactic center
* Frequency band dependence
* Morphology -- approximately spherical

* Pulsar contribution



WMAP Haze from Astrophysical Electrons?

* Total flux of synchrotron ✓
* Angular profile from galactic center ✓
* Frequency band dependence ✓
* Morphology -- approximately spherical

* Pulsar contribution

$$\int Q_0 \left(\frac{E_e}{GeV}\right)^{-\alpha} e^{-E_e/E_{cut}} E_e dE_e = W_0.$$

$$B(r,z) = B_0 e^{-r/r_0 - |z|/z_0}$$

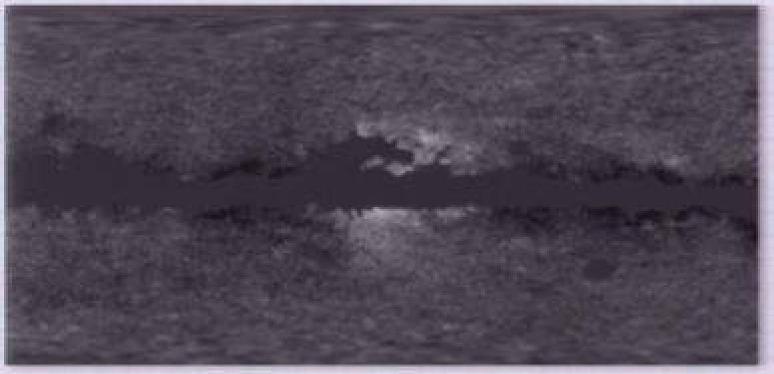
$$Q(E_e) = Q_0 f_e \left(\frac{E_e}{GeV}\right)^{-\alpha} e^{-E_e/E_{cut}}$$

WMAP Haze from Astrophysical Electrons?

* Total flux of synchrotron ✓
* Angular profile from galactic center ✓
* Frequency band dependence ✓
* Morphology -- approximately spherical

* Pulsar contribution

$$B(r,z) = B_0 e^{-r/r_0 - |z|/z_0}$$



Not published for fits

Courtesy of G. Dobler

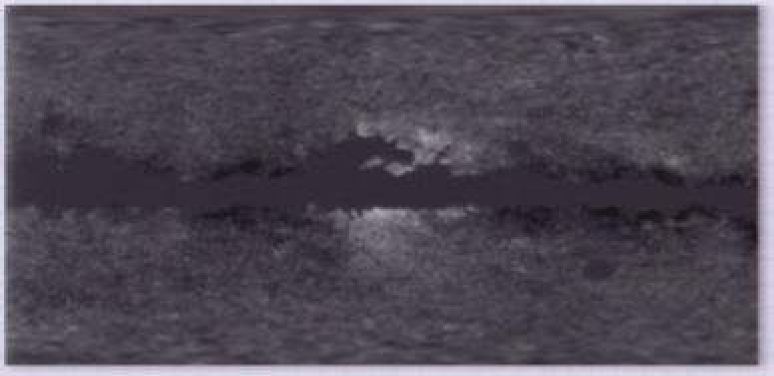
WMAP Haze from Astrophysical Electrons?

* Total flux of synchrotron ✓
* Angular profile from galactic center ✓
* Frequency band dependence ✓
* Morphology -- approximately spherical

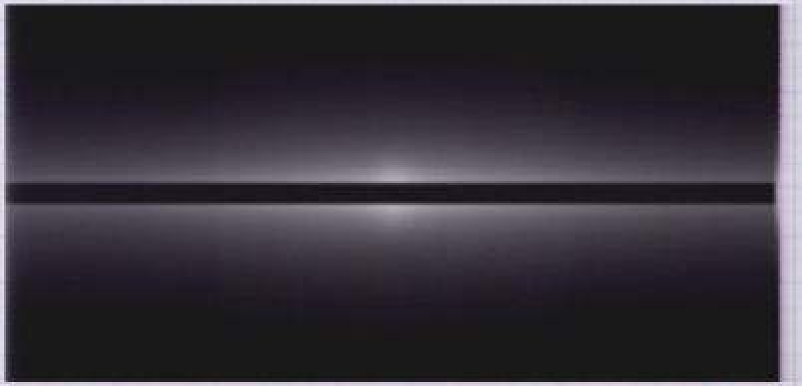
* Pulsar contribution

$$B(r,z) = B_0 e^{-r/r_0 - |z|/z_0} \rightarrow B(r,z) = B_0 e^{-r/r_0' - |z|/z_0} + B_1$$

$$r_0' << r_0$$



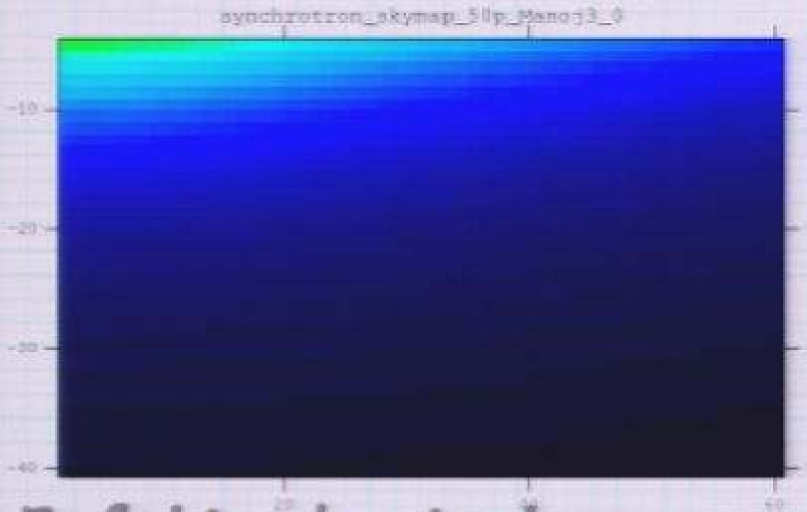
Not published for fits



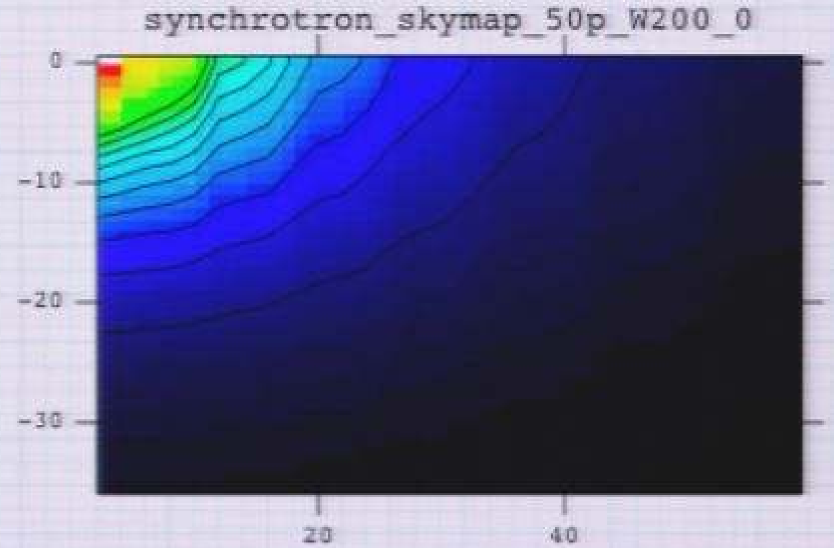
Roughly spherical?

Morphology of B-field and the Haze

B-field cylindrical geometry



$B(R, z) = 10\mu\text{G}\ e^{-|r|/7\text{kpc}-|z|/z_0}$



B-field spherical geometry

Summary: models

* Solutions to baryon-DM coincidence problem can offer compelling models of DM
    * DM states may reside in low mass hidden sectors
    * Or, states can be much heavier and have a Boltzmann suppression
    * Low mass DM states and higgses can also be quite natural with weak coupling to SUSY breaking sector
* Pulsars may be a significant contributor to the WMAP haze
    * Morphology issue still remains to be analyzed further