Title: Hidden Sector Dark Matter: Chasing the CoGeNT/DAMA/CRESST Ambulances

Date: Sep 24, 2011 09:00 AM

URL: http://pirsa.org/11090123

Abstract: I discuss the challenges for building models of ~10 GeV dark matter that can accommodate the numerous astrophysical constraints that threaten to exclude them, as well as direct detection constraints. A U(1)xU(1) hidden sector model with isospin violation, inelastic couplings, and annihilation into invisible products is suggested. I will also discuss similar but simpler models that could simultaneously explain excess 511 keV gamma rays from the galactic center and direct detection of light dark matter.

Definitions

World English Dictionary *Collins*

ambulance chaser

—*n*

slang (*US*) a lawyer who seeks to encourage and profit from the lawsuits of accident victims

ambulance chasing

—*n*

Implications for physics:

1) ambulance-chaser is akin to a lawyer

2) the object being chased is not quite healthy — maybe won't survive!

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ambulance-chasing

n. in science, doing research to achieve fame or to secure funding. **Subjects**: *English*, *Business*, *Science*, *Slang*

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So what's wrong with that?

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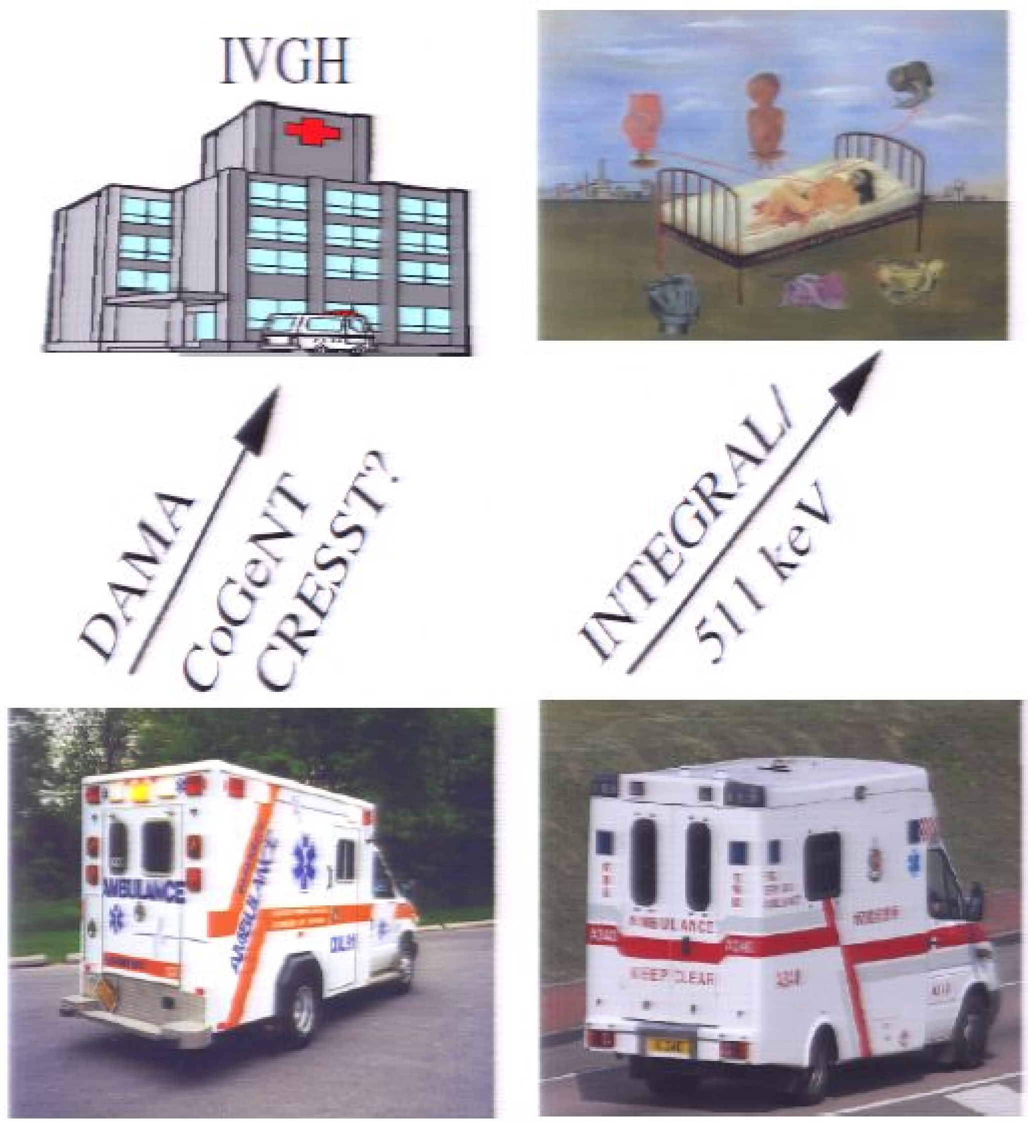
So what's wrong with that?

Moreover, what if the victim survives?

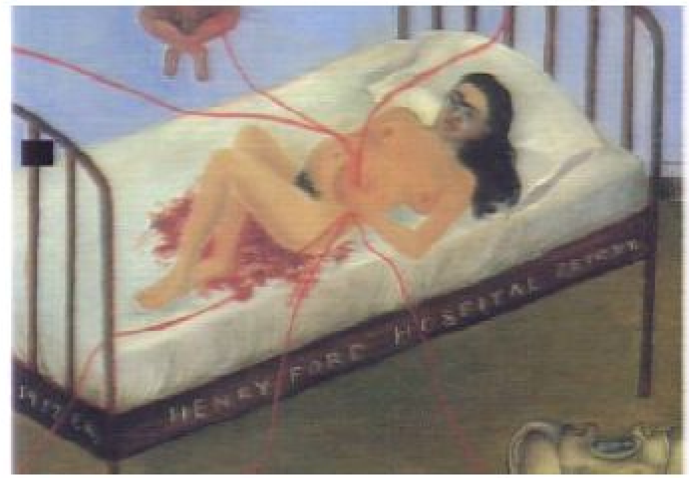
A tale of two ambulances



I will chase only one at a time in this talk.

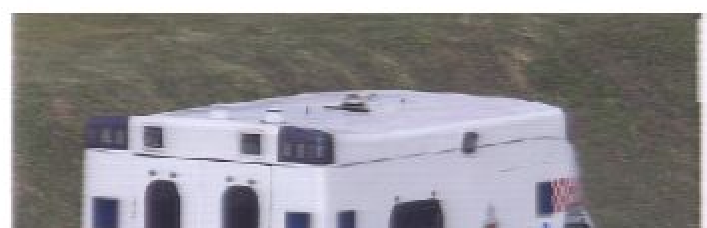
A tale of two ambulances

Isospin Violation
General Hospital

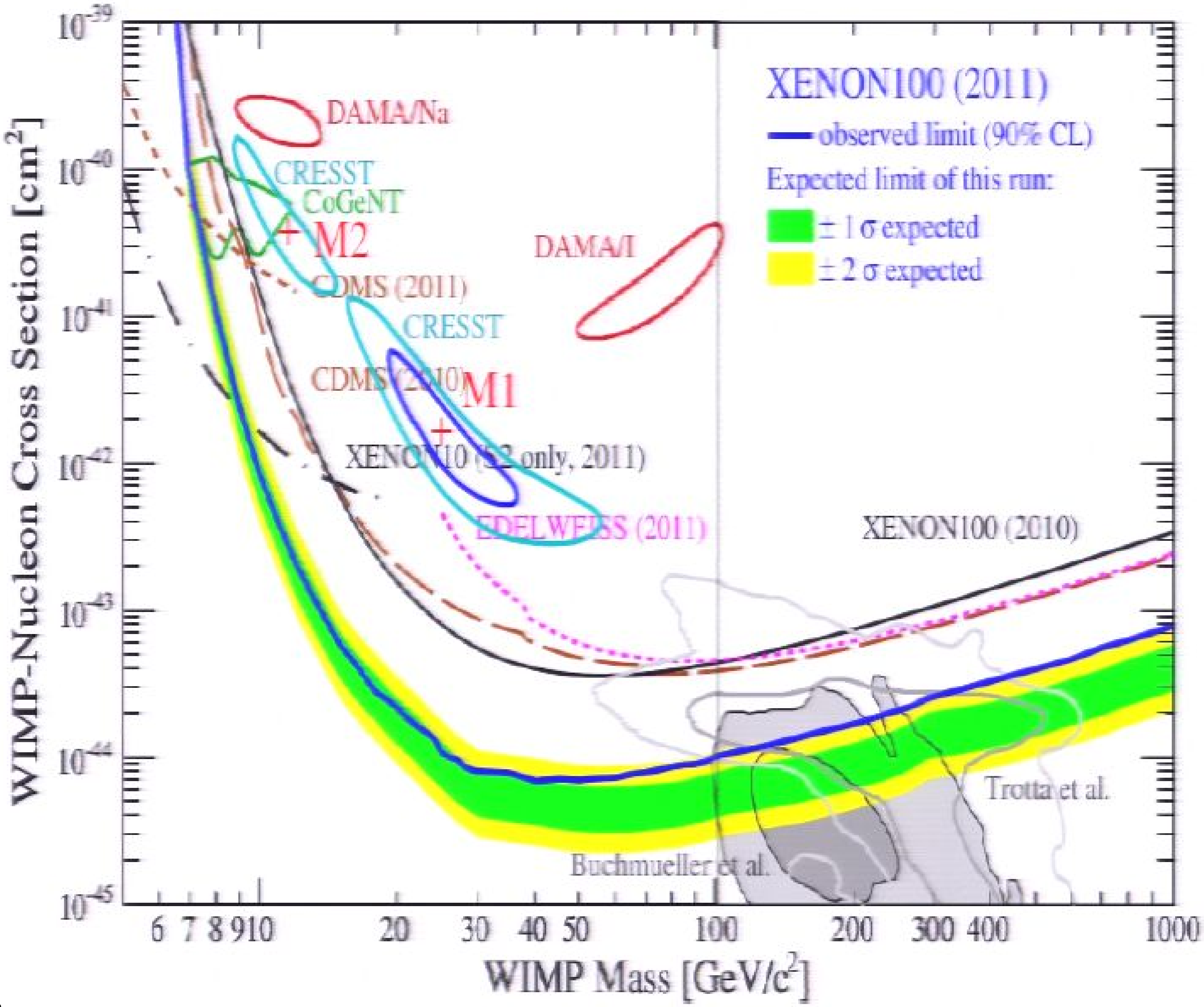


DAMA
CoGeNT
CRESST?

INTEGRAL/
511 keV

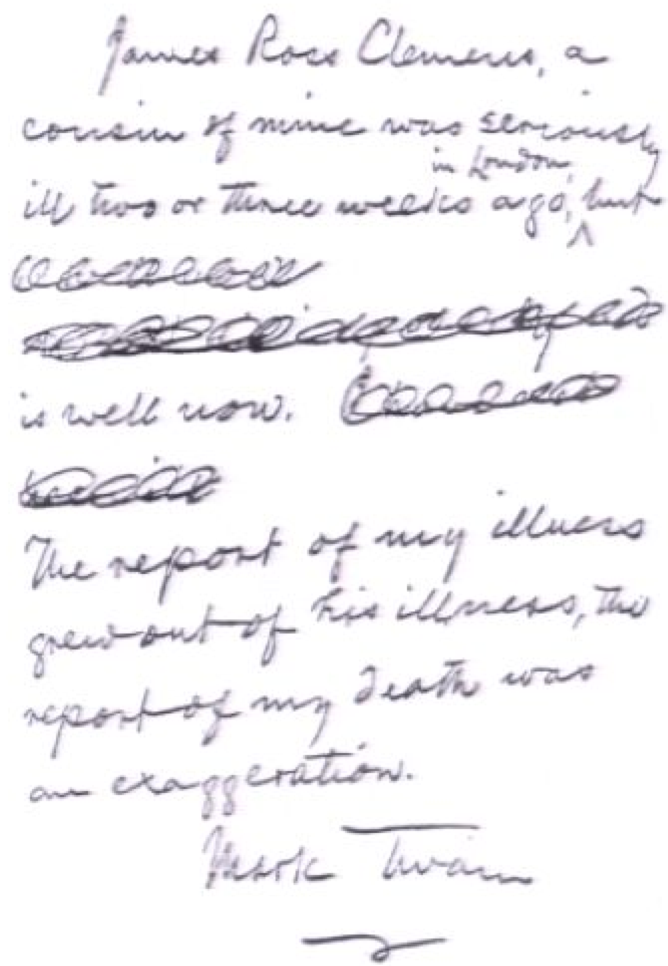


The experimental situation



Are CoGeNT and DAMA (and CRESST) dead on arrival?

Not quite


James Ross Clemens, a cousin of mine was seriously ill two or three weeks ago in London, but is well now. The report of my illness grew out of his illness, the report of my death was an exaggeration.

Mark Twain

"The report of my death was an exaggeration"

— Mark Twain

Isospin violation is the cure

—well, at least it greatly staunches the flow of blood

$$\sigma_N \sim [f_p Z + f_n(A-Z)]^2 \sigma_n, \text{ not just } A^2\sigma_n$$

If $f_p/f_n \cong -1.5$, Xenon, CoGeNT & DAMA/Na are reconciled

For Xe, $\sigma_N \to 10^{-4}\sigma_N$, CoGeNT/DAMA regions overlap!

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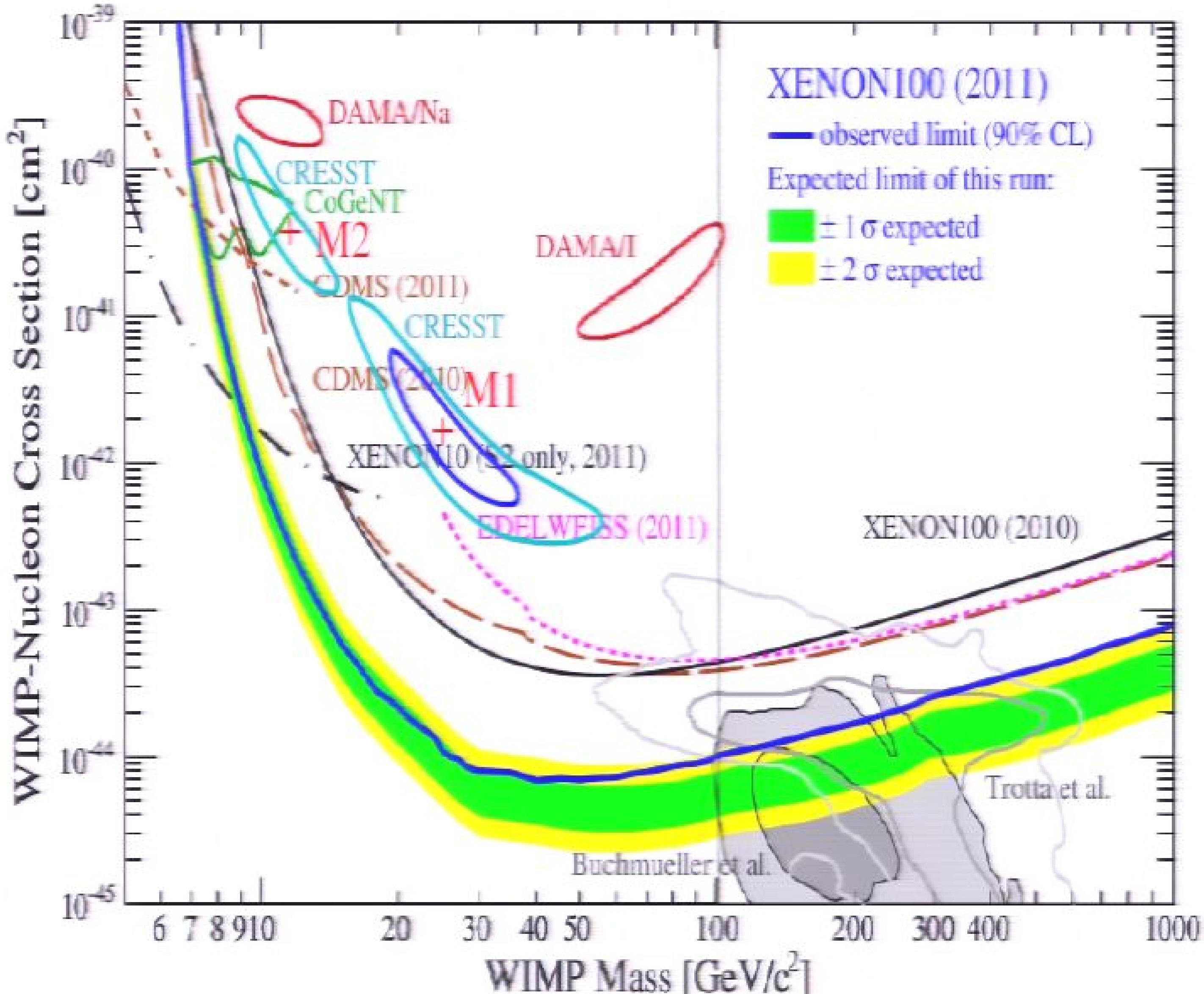

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CRESST M2 region is factor of > 2 below CoGeNT/DAMA in isospin-violating model. I will not pursue CRESST here.

But new CoGeNT reanalysis might change this linear combination in the future

Isospin violation is the cure

The doctors who exploited this treatment:

Drs. Chang, Liu, Pierce, Weiner, Yavin, 1004.0697

Drs. Feng, Kumar, Marfatia, Sanford, 1102.4331

Drs. Frandsen, Kahlhoefer, March-Russell, McCabe, McCullough, Schmidt-Hoberg, 1105.3734

Drs. Schwetz, Zupan, 1106.6241

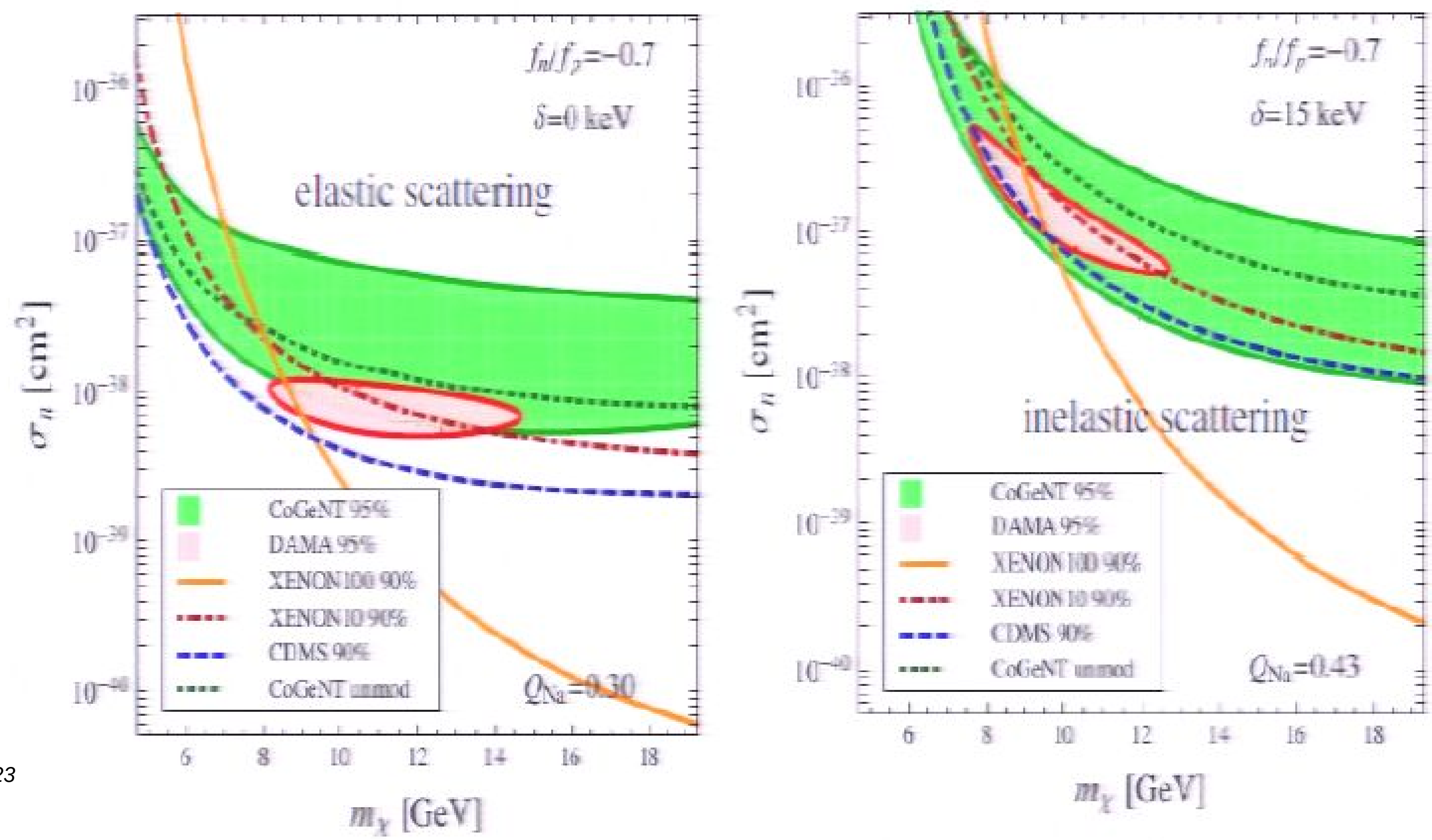
Drs. Farina, Pappadopulo, Strumia, Volansky, 1107.0715

Inelastic couplings may also help

CDMS also has germanium but sees no signal.

CoGeNT result based largely upon annual modulation.

Inelastic scattering enhances modulation relative to unmodulated rate, reduces tension between the two.



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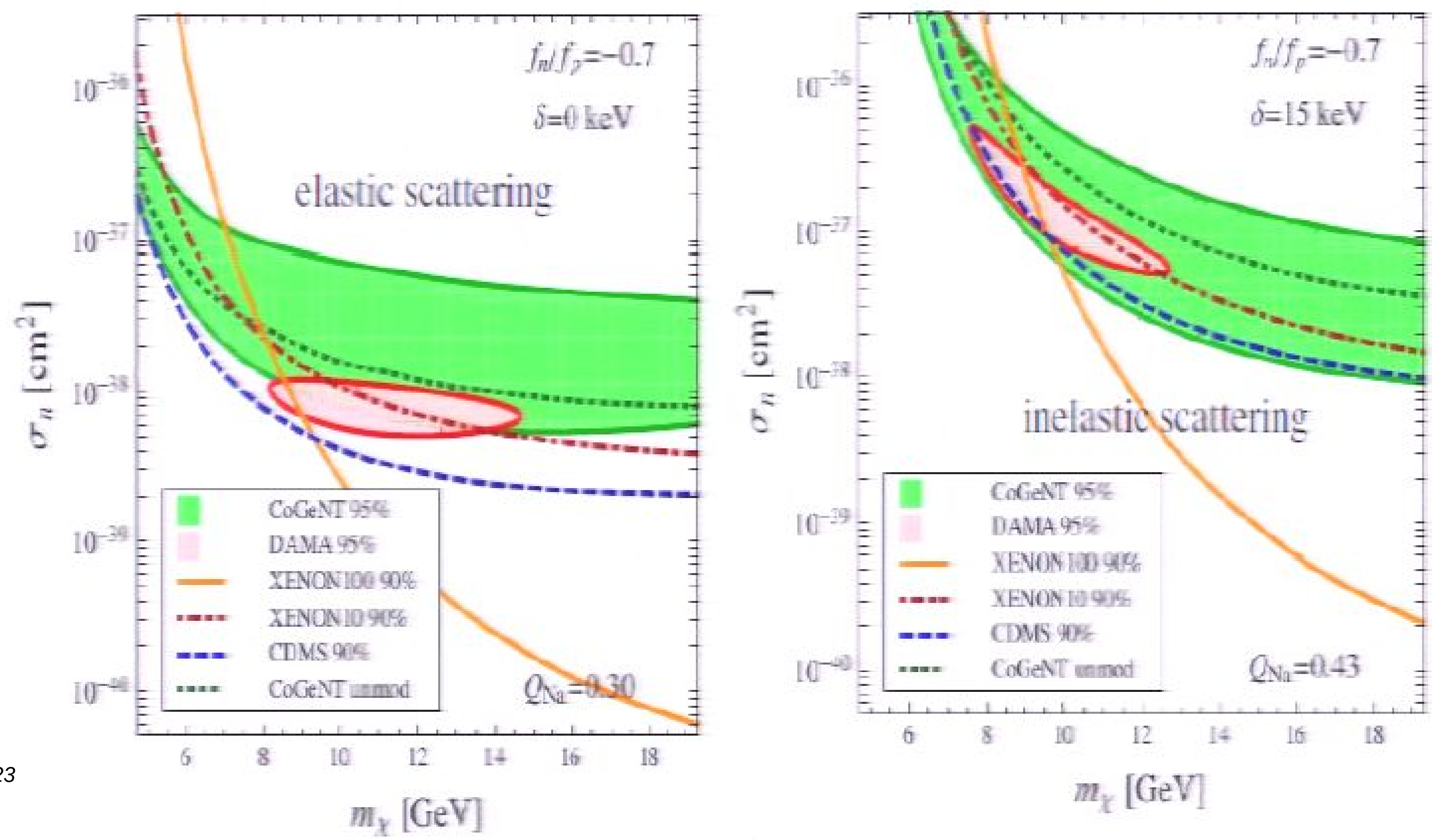
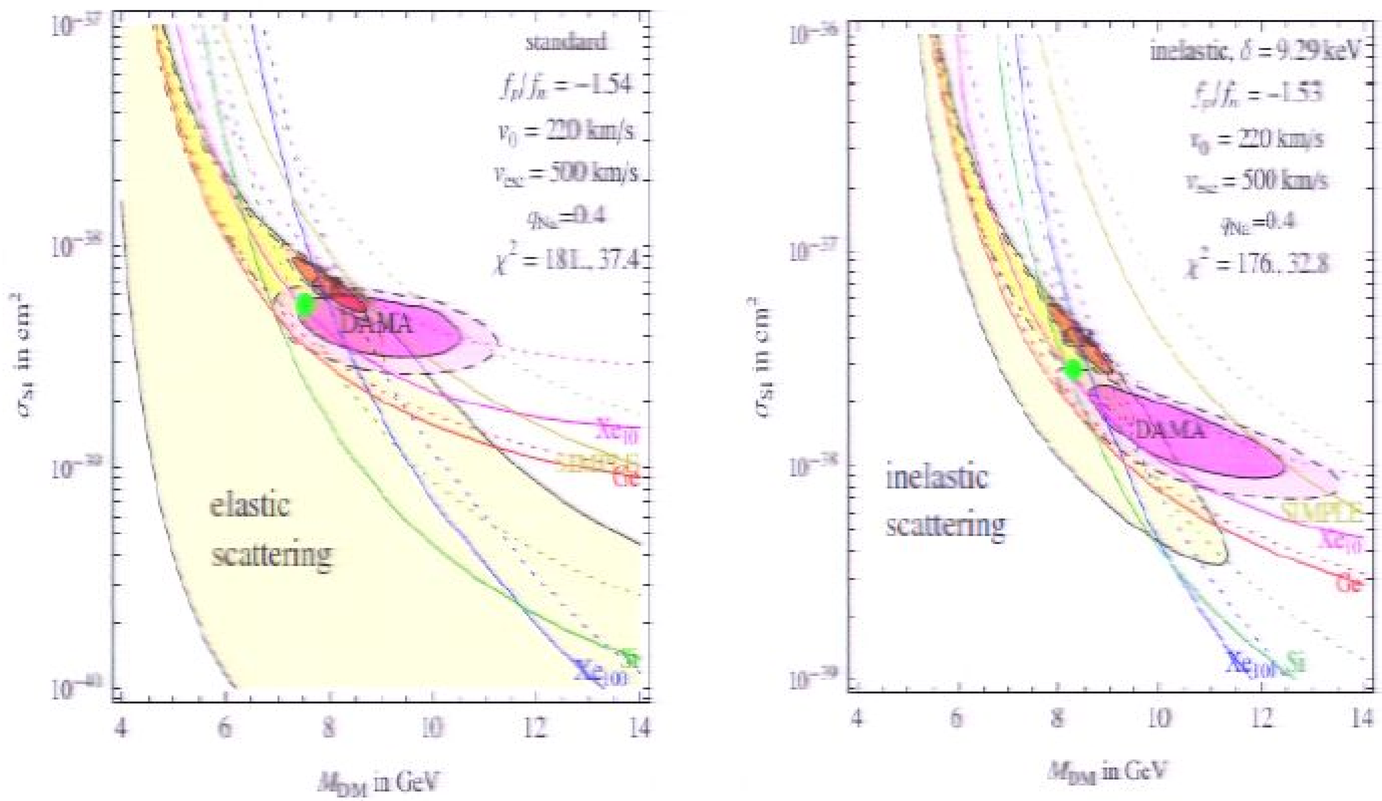


But improvement to global fit is small

Farina *et al.*, 1107.0715



Moreover global fit is not very good:

$\chi^2 = 181$ (w/ CoGeNT rate), 37.4 (CoGeNT Modulation only)

Good fit would be $\chi^2 = 43,\ 8$.

$\Rightarrow$ Something(s) not properly understood.

10 GeV DM vs. astrophysical constraints

The patient risks dying from complications:

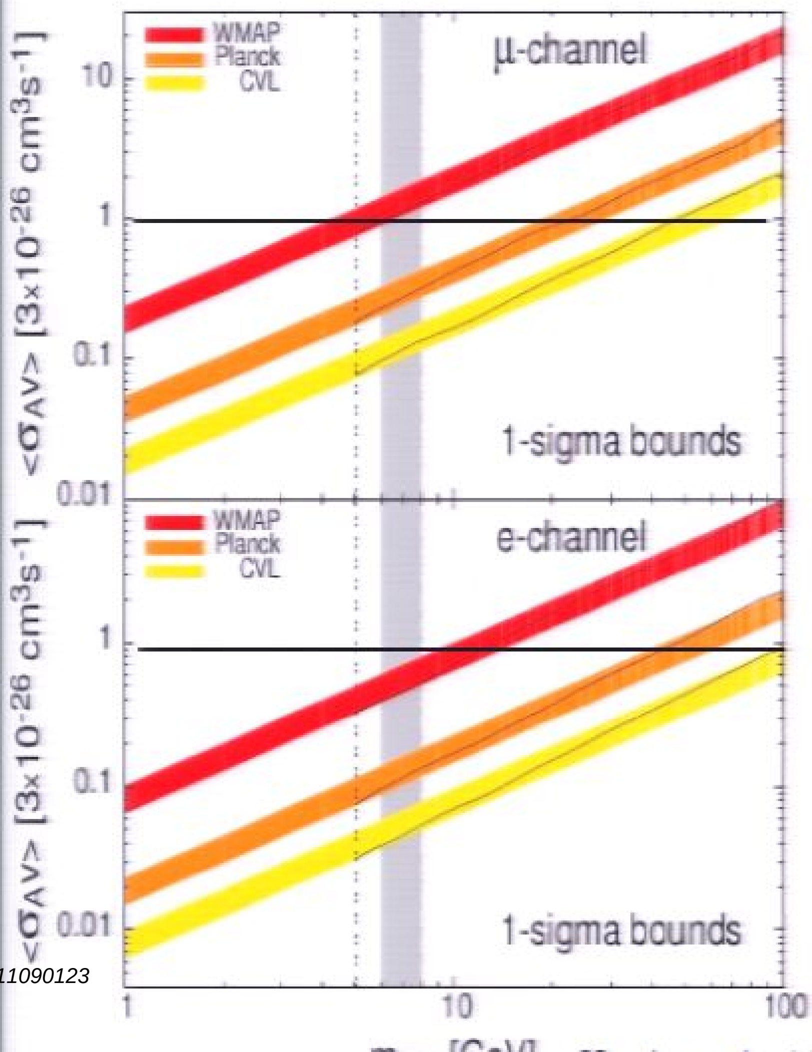
- CMB constraints
- SuperK constraints
- Fermi constraints
- Pamela constraints

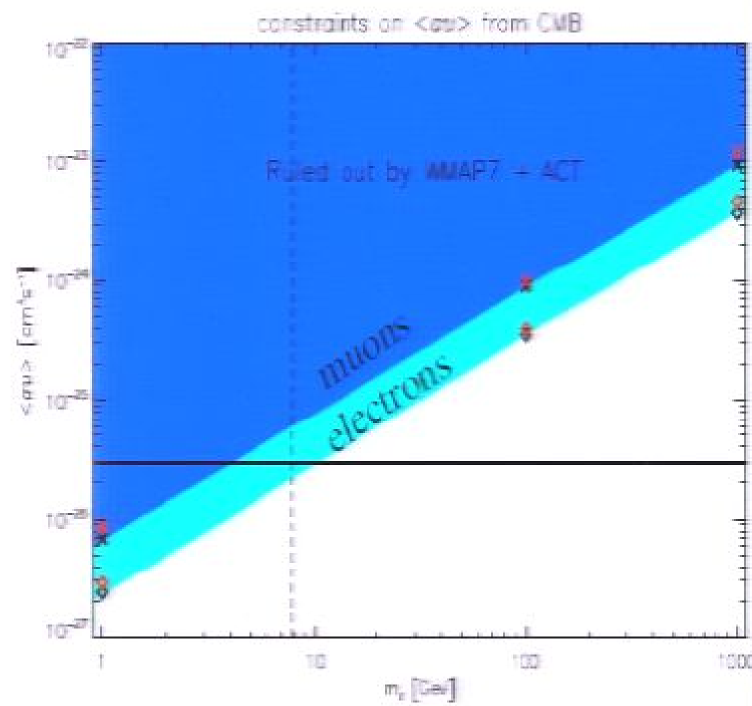
If $\chi\chi \to$ SM particles with $\langle\sigma_{\rm ann}\rangle = 3 \times 10^{-26}$ cm^3/s, almost no annihilation channel is safe.

Only $\chi\chi \to \mu^+\mu^-$ or light quarks with $E < 2m_p$ are allowed.

CMB constraint

Reionization limits amount of e.m. energy deposited by annihilation products; favors ν-rich decays





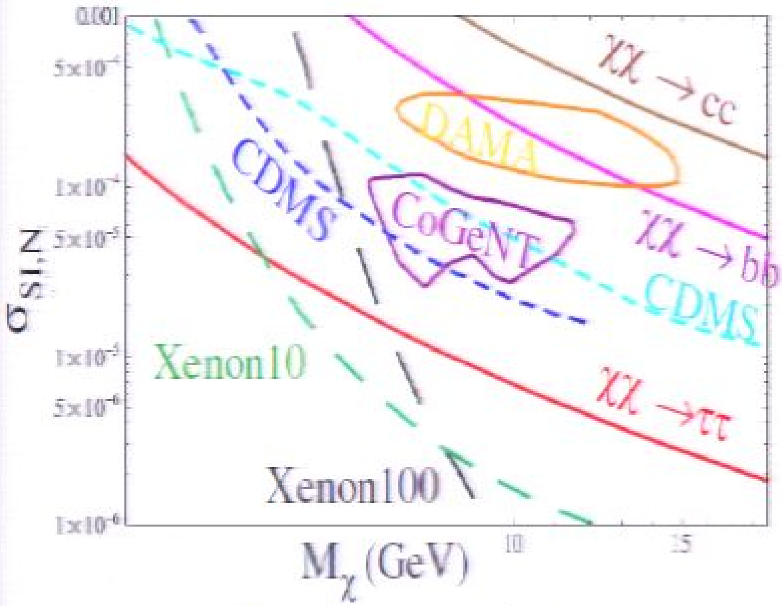
Galli *et al.*, 1106.1528

All other SM particles are intermediate between electrons and muons

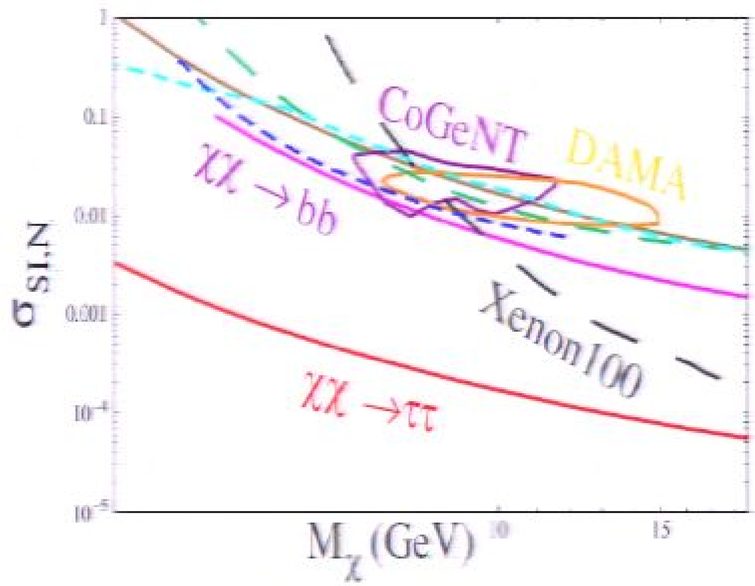
$\chi\chi \to X + \nu$ in the sun

Isospin violation reduces capture of DM in sun by limited amount: factor of 0.04

Chen, Zhang, 1106.4044



Isospin conserving



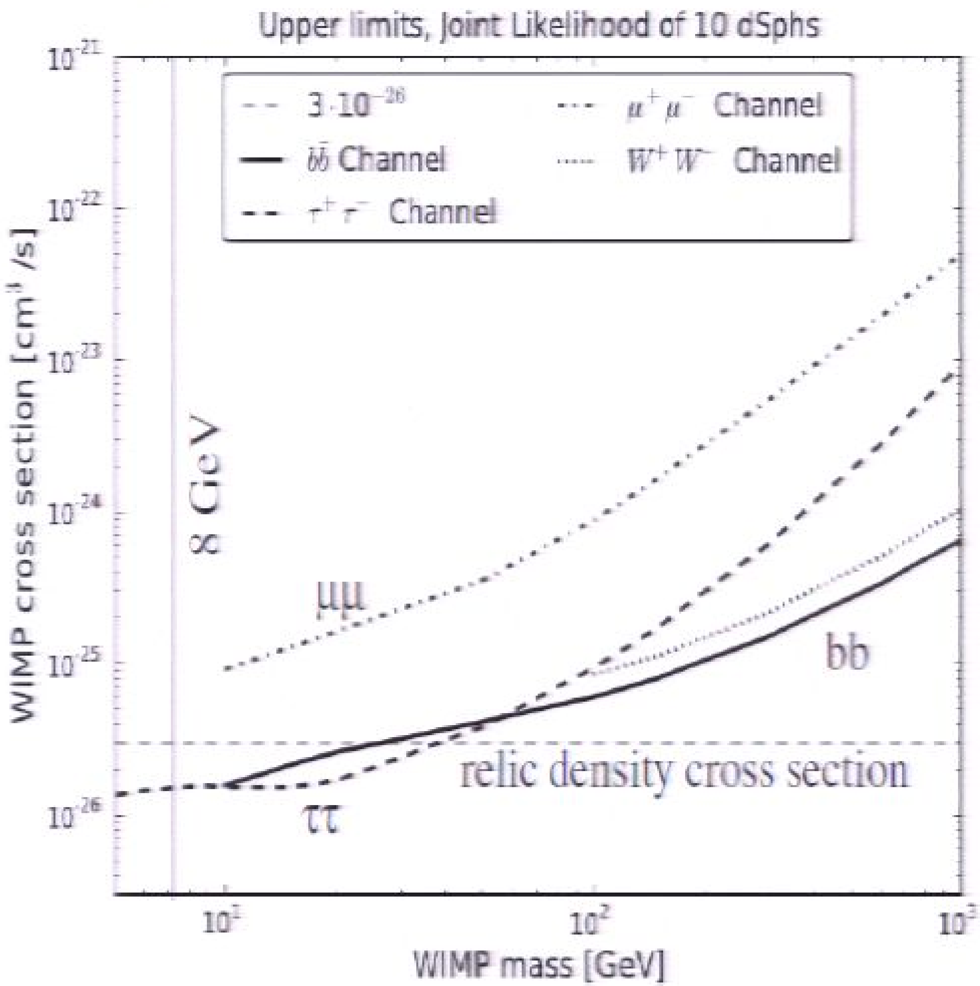
Isospin violating

$\chi\chi \to cc$ marginally allowed with isospin violation
lighter quarks and muons ok

Fermi dwarf galaxy constraint

Fermi/LAT collaboration, 1108.3546

Dwarf galaxies are DM-rich, baryon-poor;
good source of gamma rays from DM annihilation.



Only the $\chi\chi \to \mu^+\mu^-$ channel is allowed at $M_\chi \sim 10$ GeV

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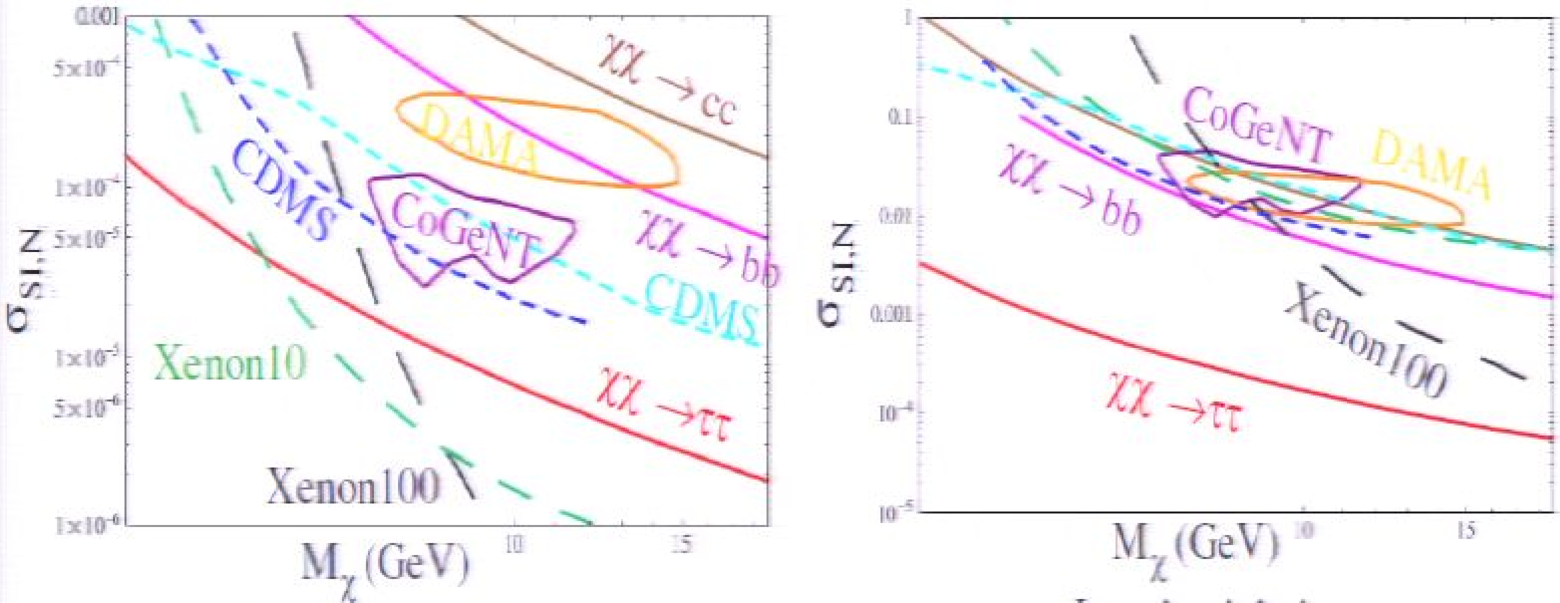

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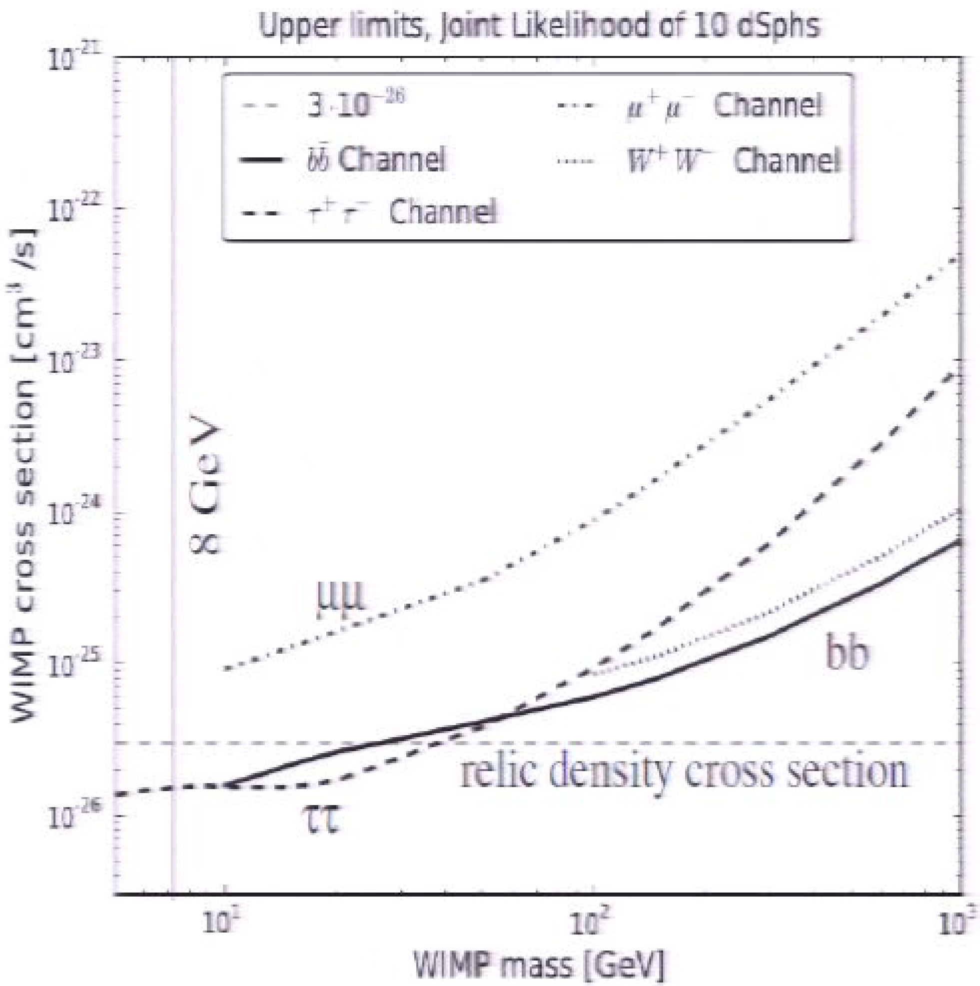

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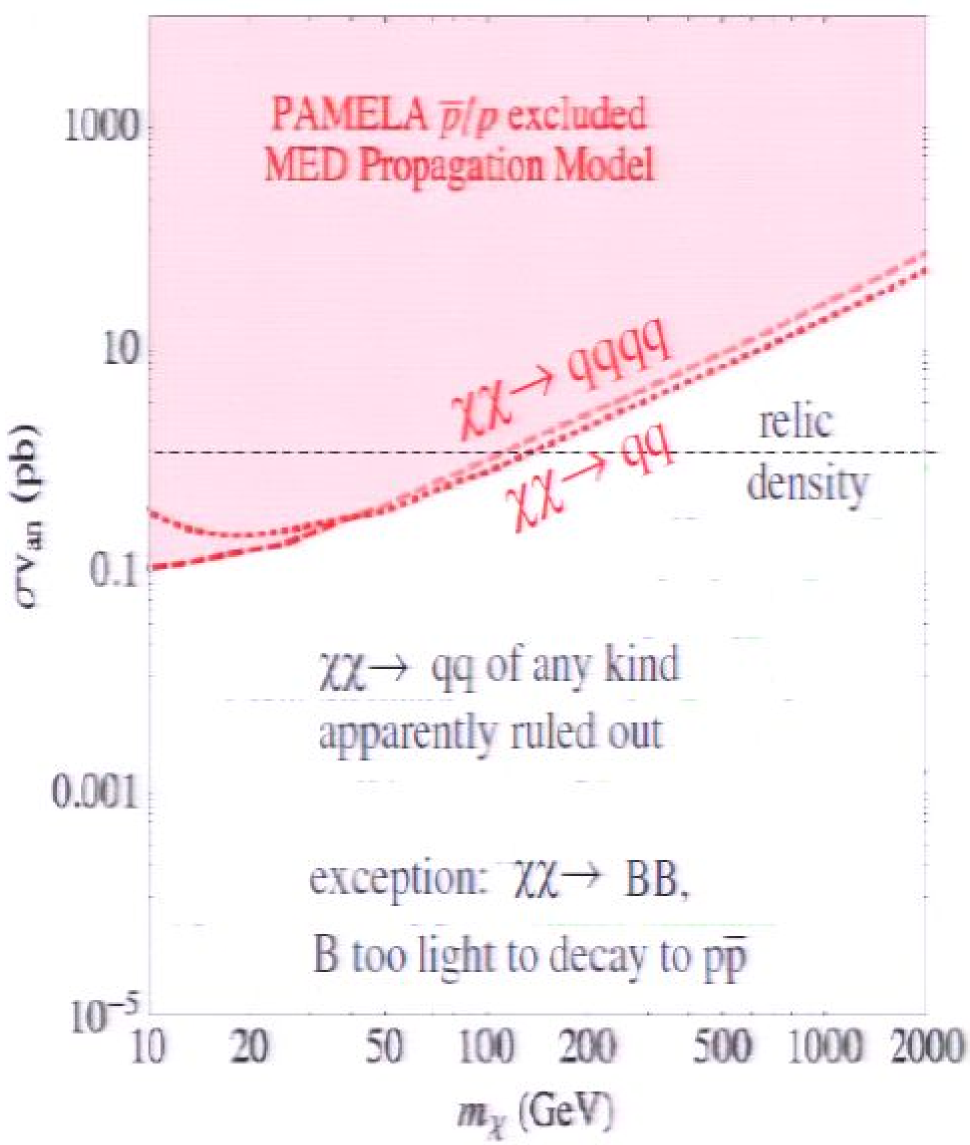
PAMELA $\bar{p}$ constraint

Cao, Low, Shaughnessy, 0912.4510



A way out: invisible annihilation from hidden sector dark matter

Hidden sector models could naturally have annihilation products invisible to the standard model: "dark neutrinos"

These escape all the above constraints

Are subject to others, like BBN and SN cooling

Hidden sector models can also meet the other challenges of light dark matter

We need rich physics from the hidden sector, but why not?

DM provides 85% of the mass of the universe;
Why should the dark sector be less complex than the standard model?

A model

Quasi-Dirac DM coupling to Z'_μ and gauged baryon number vector boson B_μ (JC, A. Frey, 1108.1391, 1109.4639)

$$
\begin{aligned}
V &= (g_B B_\mu + g_{Z'} Z'_\mu)(\chi_1^\dagger \sigma^\mu \chi_1 - \chi_2^\dagger \sigma^\mu \chi_2) + g_B \bar{N} \not{B} N + \epsilon e \bar{p} \not{Z}' p \\
&+ y_\chi \Phi \chi_1 \chi_2 + y_\nu \Phi \nu_1 \nu_2 + M_\nu \nu_2 \nu_2 + \tilde{g}_B^2 |\tilde{\phi}|^2 B^2 + g_{Z'}'^2 |\phi'|^2 Z'^2 \\
&+ \left\{ 4(g_B B_\mu + g_{Z'} Z'_\mu)^2 |\phi|^2 + \tfrac{1}{2} y_\phi (\phi \chi_1 \chi_1 + \phi^* \chi_2 \chi_2), \quad \begin{matrix}\text{inelastic} \\ \text{model}\end{matrix} \right\}
\end{aligned}
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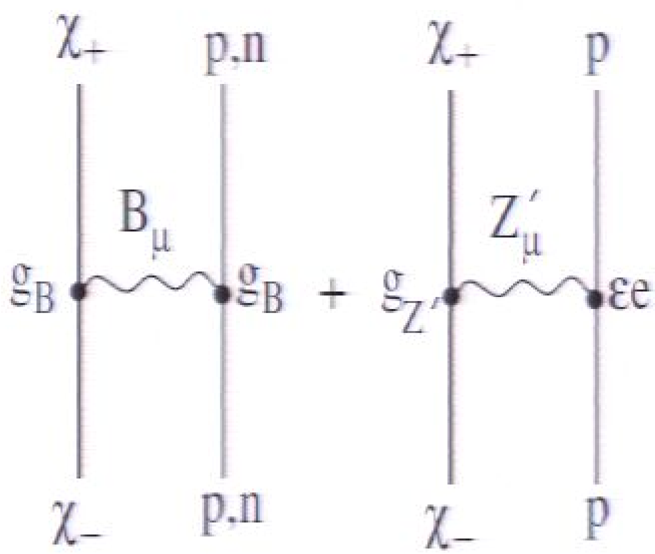

Isospin violation from interference of B and Z' exchange

B interacts with p and n

Z' interacts with charged particles only, by kinetic mixing with photon

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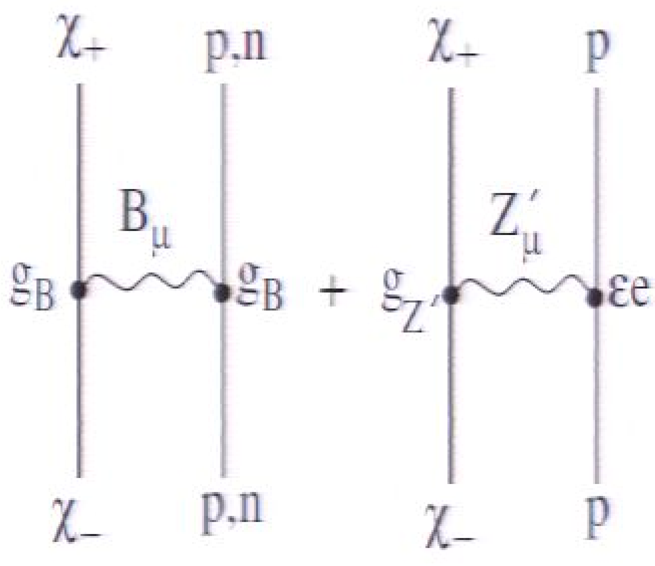

For optimal isospin violation, tune

$$\frac{f_p}{f_n} = 1 + \frac{g_{Z'} \epsilon e}{g_B^2} \frac{m_B^2}{m_{Z'}^2} \cong -1.5$$

For observed σ_n (CoGeNT/DAMA)

$$\frac{m_B}{g_B} = 232 \text{ GeV}, \quad \frac{m_{Z'}^2}{(g_{Z'} \epsilon)} = -(80 \text{ GeV})^2$$

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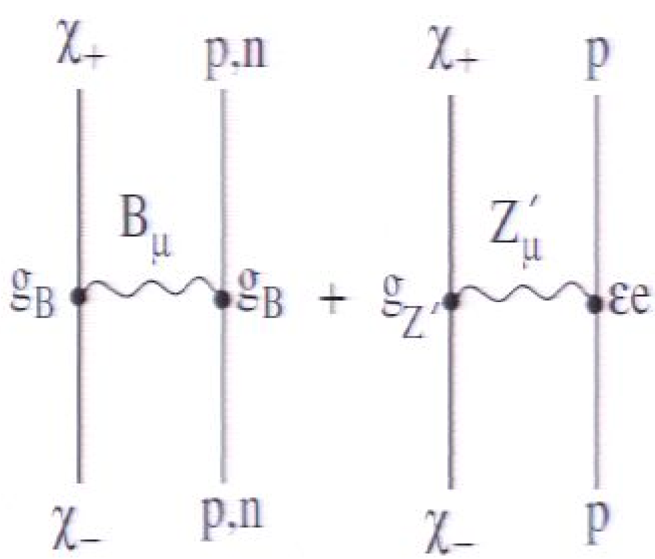

Scattering is inelastic:

Large Dirac mass $M_\chi = y_\chi \langle \Phi \rangle$

Small Majorana mass $\mu = y_\phi \langle \phi \rangle$

Mass matrix $\begin{pmatrix} \mu & M_\chi \\ M_\chi & \mu \end{pmatrix}$

Eigenvalues $M_\chi \pm \mu$

Eigenstates $\chi_\pm = \frac{1}{\sqrt{2}}(\chi_1 \pm \chi_2)$

Gauge couplings are off-diagonal

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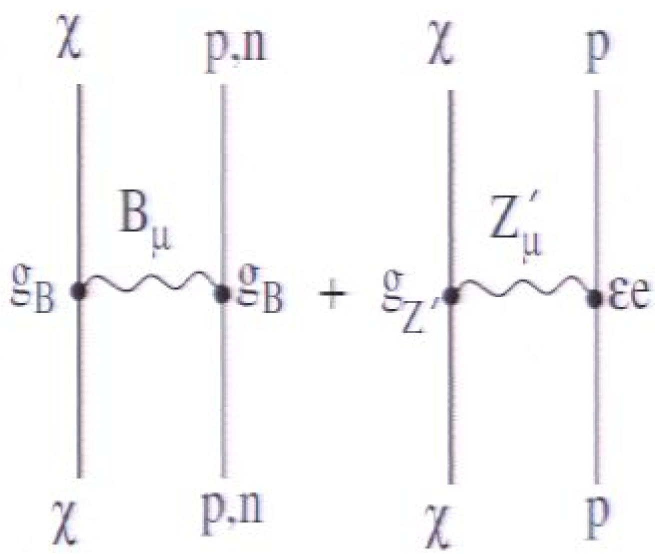

Model is simplified if we don't demand inelastic scattering;

remove the Higgs field ϕ

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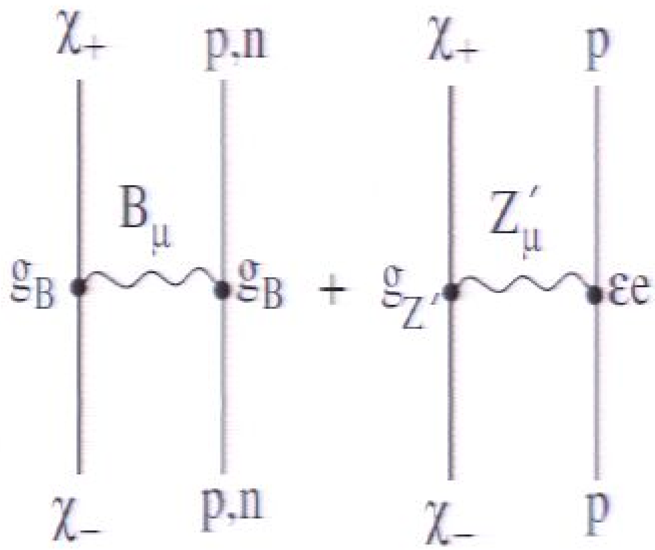

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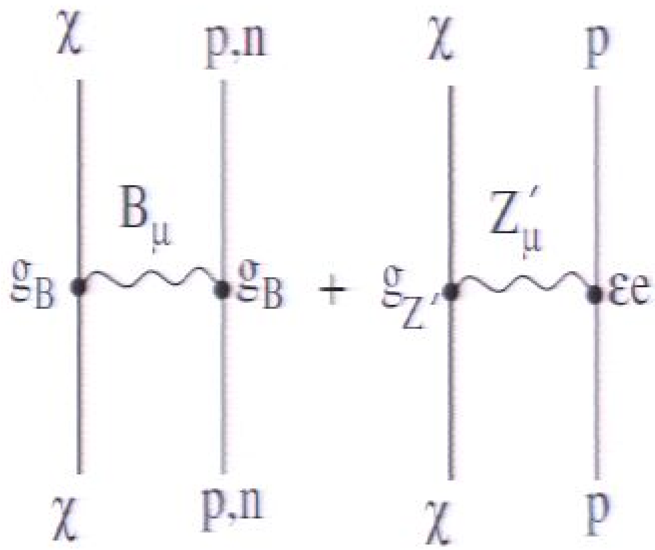

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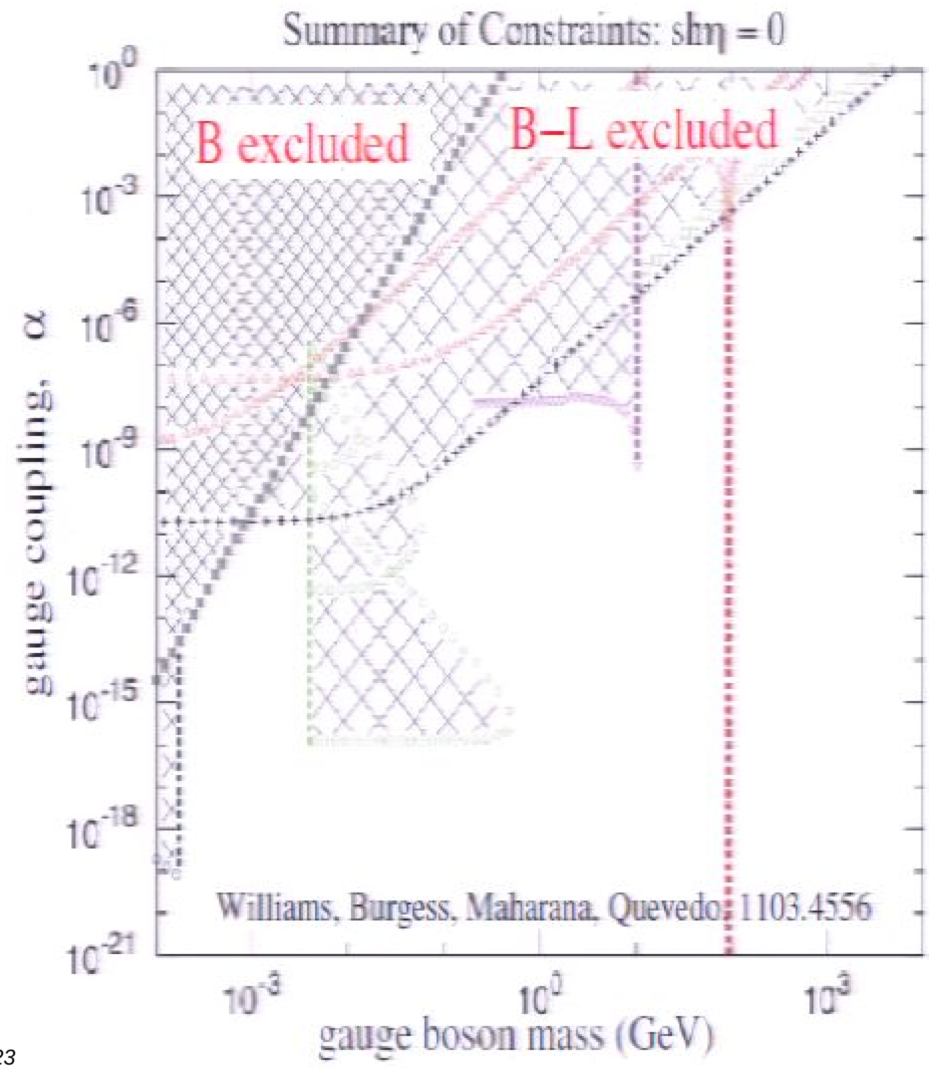
Why couple to baryon number?

Light vectors coupling to both B and L are highly constrained by many experiments



Coupling to B only is relatively unconstrained

B is anomalous

To cancel anomalies, need 4th generation of exotic quarks with $B = \pm 1$

$\langle \tilde{\phi} \rangle$ breaks B, can give mass to vector-like 4th generation quarks

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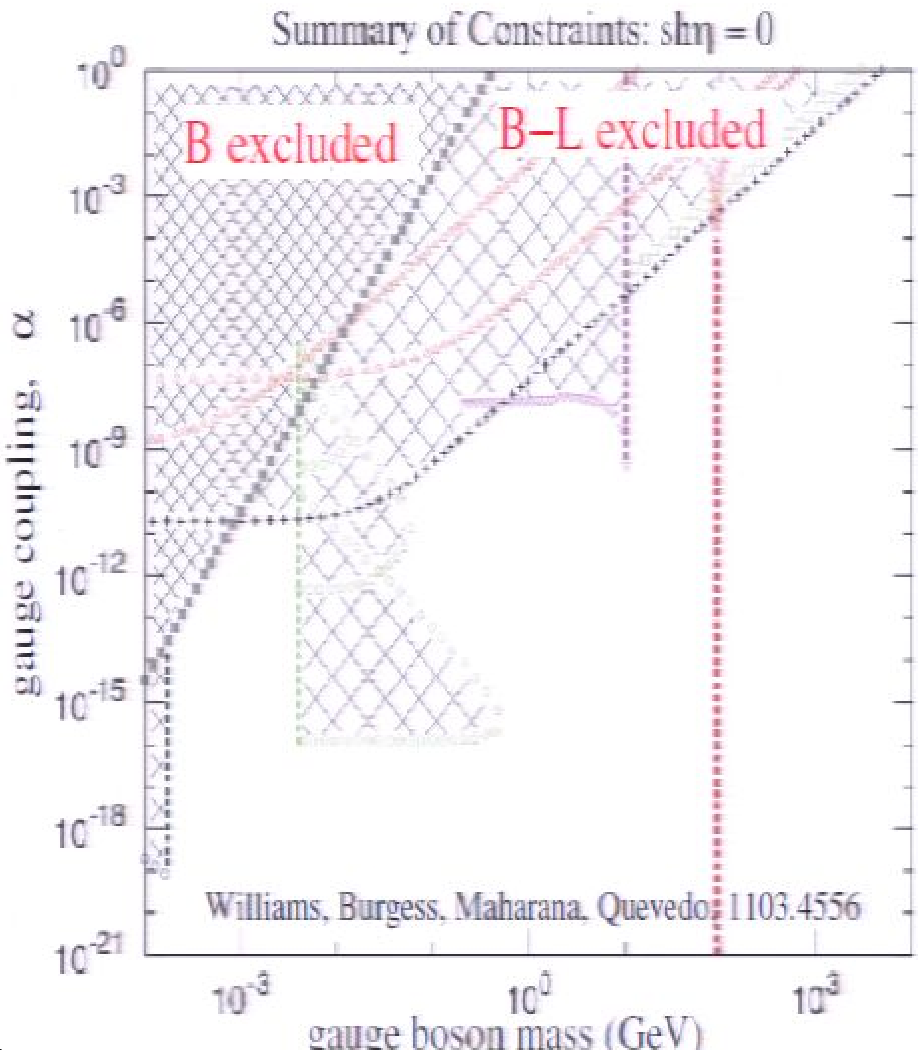

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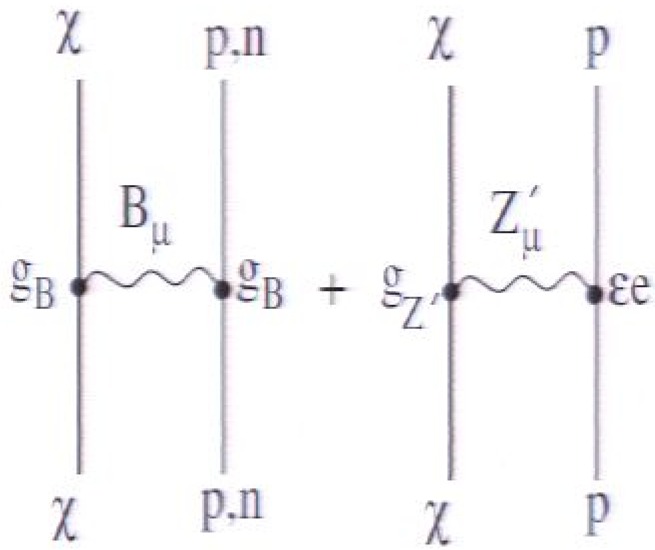

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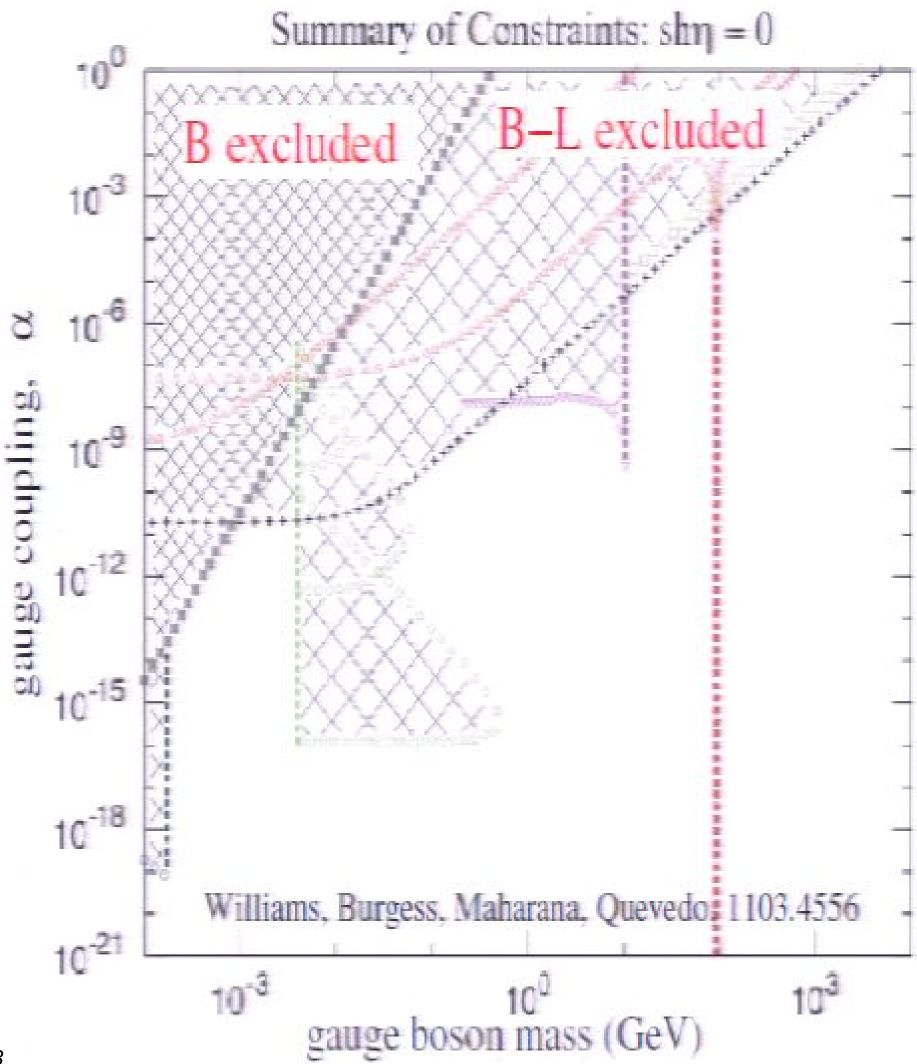

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Invisible annihilation

"Dark neutrinos" ν' with small seesaw mass are annihilation products of $\chi\chi \to \Phi\Phi \to 4\nu'$

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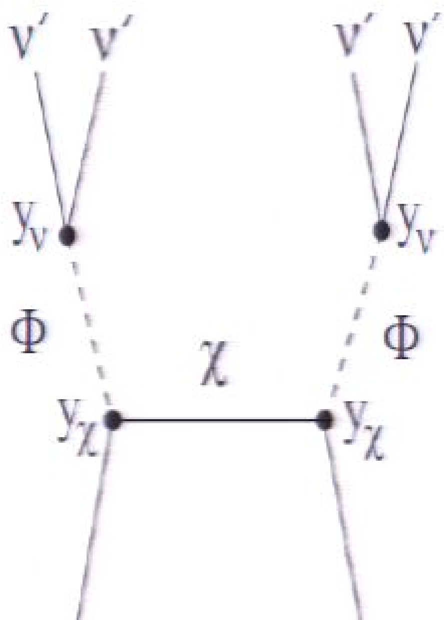

If $m_\Phi \sim 1$ GeV, ν' decouples before QCD phase transition: BBN okay

CMB constraint: $m_{\nu'} = \frac{y_\nu^2 \langle\Phi\rangle^2}{M_\nu} < 6.5$ eV

$\Rightarrow y_\nu \lesssim 10^{-5} \left(\frac{M_\nu}{1\ \text{TeV}}\right)^{1/2}$

Supernova cooling from $NN \to NN\nu'\nu'$ requires small mixing

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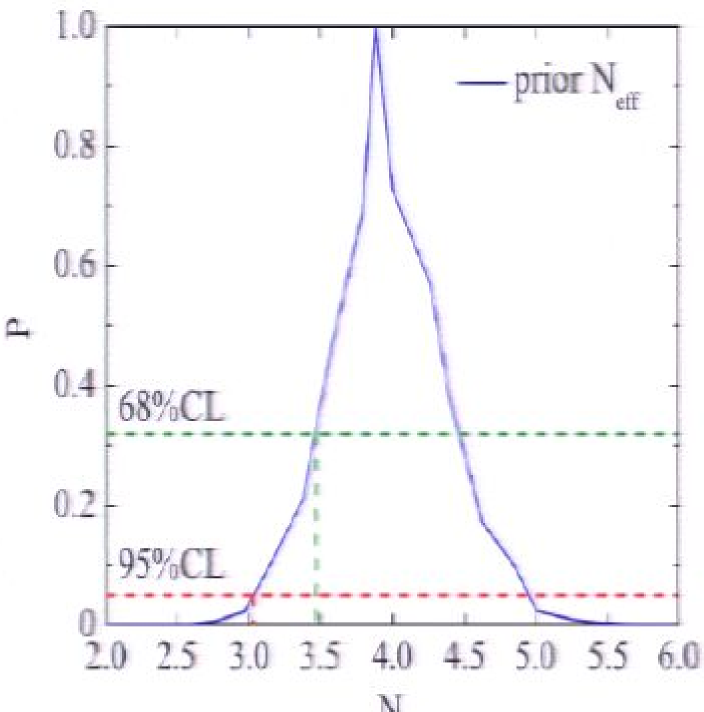
V \;=\;& (g_B B_\mu + g_{Z'} Z'_\mu)(\chi_1^\dagger \sigma^\mu \chi_1 - \chi_2^\dagger \sigma^\mu \chi_2) + g_B \bar{N} \not{B} N + \epsilon e \bar{p} \not{Z}' p \\
+\;& y_\chi \Phi \chi_1 \chi_2 + y_\nu \Phi \nu_1 \nu_2 + M_\nu \nu_2 \nu_2 + \tilde{g}_B^2 |\tilde{\phi}|^2 B^2 + g'^2_{Z'} |\phi'|^2 Z'^2 \\
+\;& \left\{ 4(g_B B_\mu + g_{Z'} Z'_\mu)^2 |\phi|^2 + \tfrac{1}{2} y_\phi (\phi \chi_1 \chi_1 + \phi^* \chi_2 \chi_2), \quad \text{inelastic model} \right\}
\end{aligned}
$$



Several papers find that new CMB data indicate extra species of dark ν's:

Hamann *et al.* 1006.5276

Riess *et al.* 1103.2976

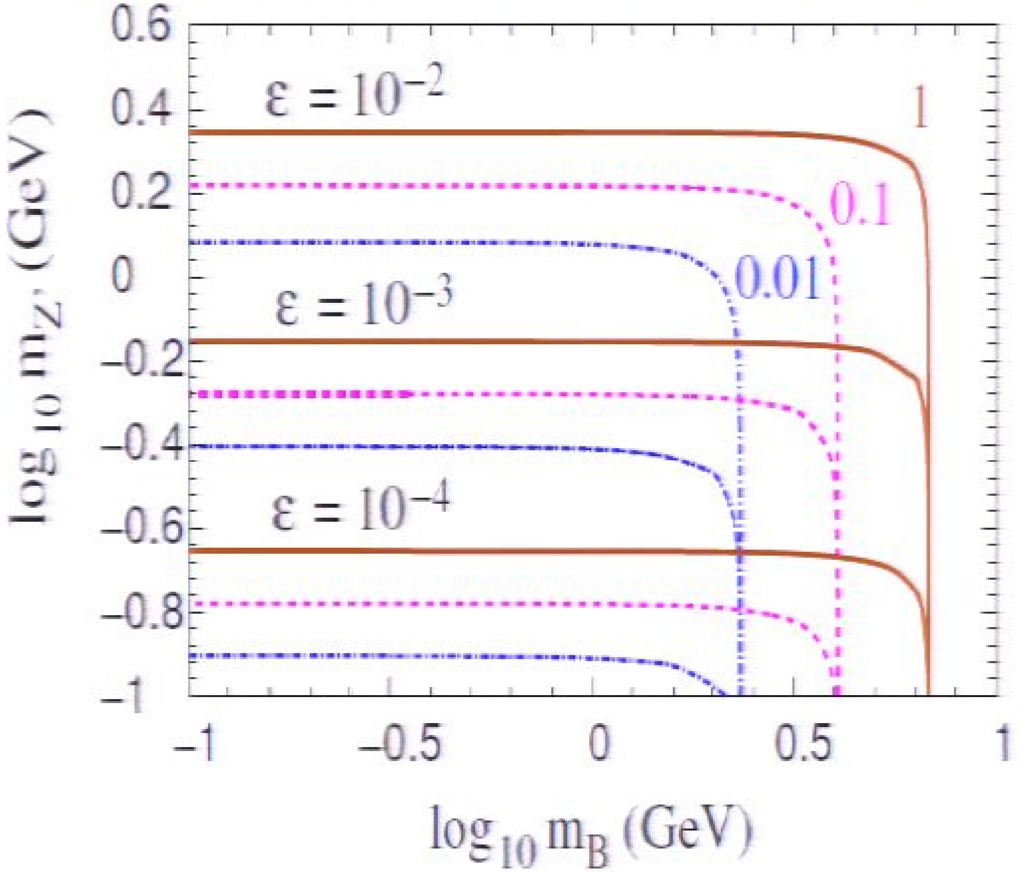
Hou *et al.* 1104.2333

Smith *et al.* 1105.3246

← Archidiacono *et al.* 1109.2767

Relic density constraint

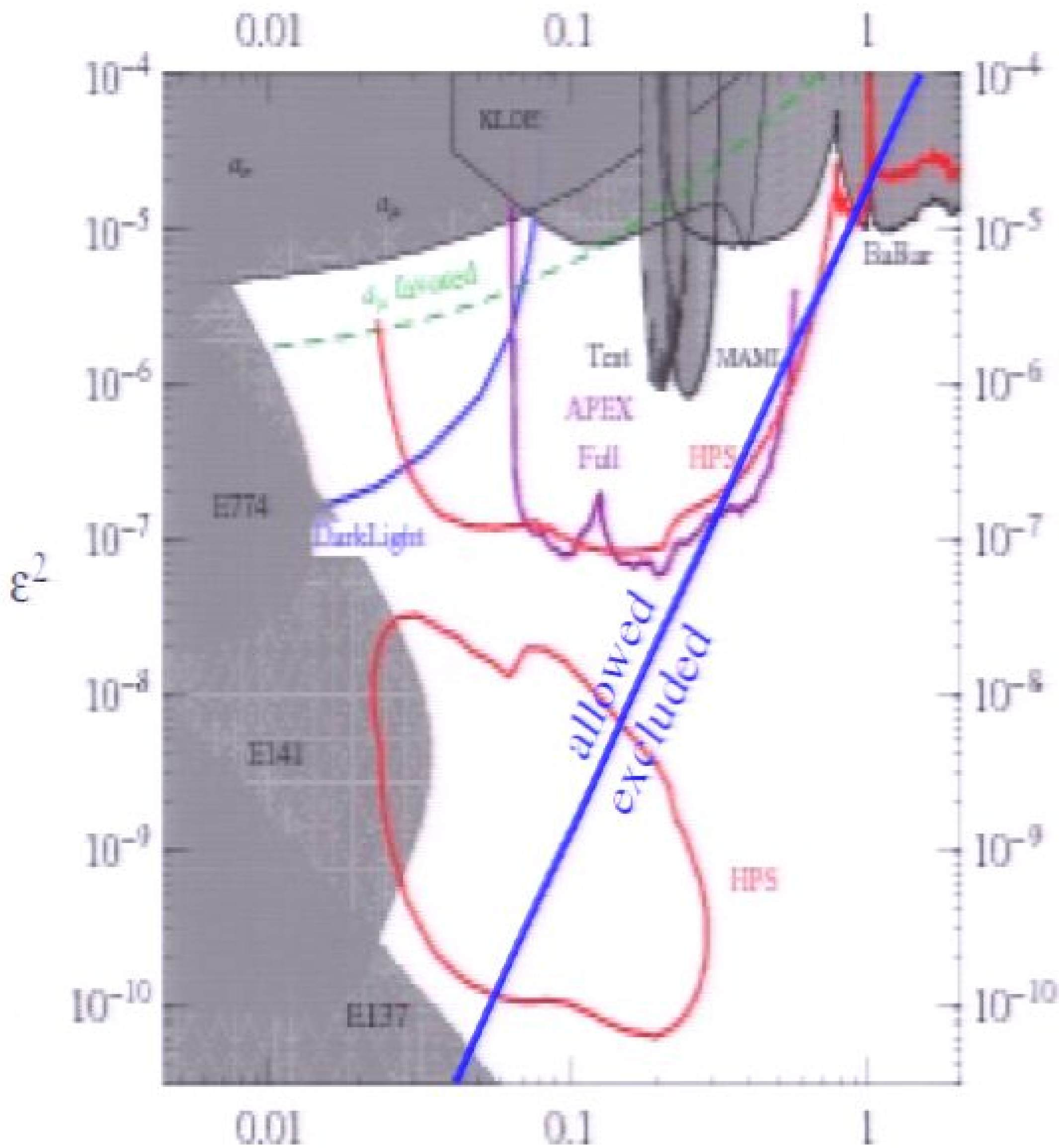
Annihilation to SM particles must be subdominant to $\chi\chi \to 4\nu'$ to evade astrophysical bounds. Puts upper limit on gauge boson masses (proxy for couplings).



Maximum $m_{Z'}$ depends on gauge kinetic mixing parameter ϵ,

Predictions for low-energy searches

Several current and proposed searches for light kinetically mixed Z''s



APEX, KLOE, MAMI currently running

DarkLight, HPS proposed at JLab

Our model should be discoverable

Part 2: the 511 keV ambulance

Galactic 511 keV γ ray excess has been observed since 1972.

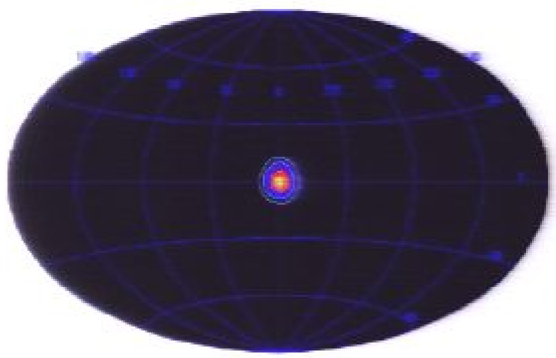


Figure 2. An MREM sky map of the 511 keV positron annihilation line emission. The contours indicate intensity levels of 10^{-2}, 10^{-3}, and 10^{-4} ph cm^{-2} s^{-1} sr^{-1}. Details are given in the text.

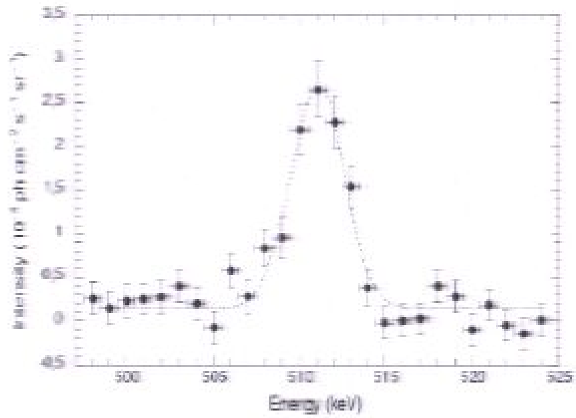


Fig. 3. 511 keV flux spectrum obtained using a gaussian centred on the GC with a FWHM of 10°.

$\sim 10^{43} e^+/\mathrm{s}$ from inner kpc of Milky Way.

So far no strongly convincing astrophysical explanation.

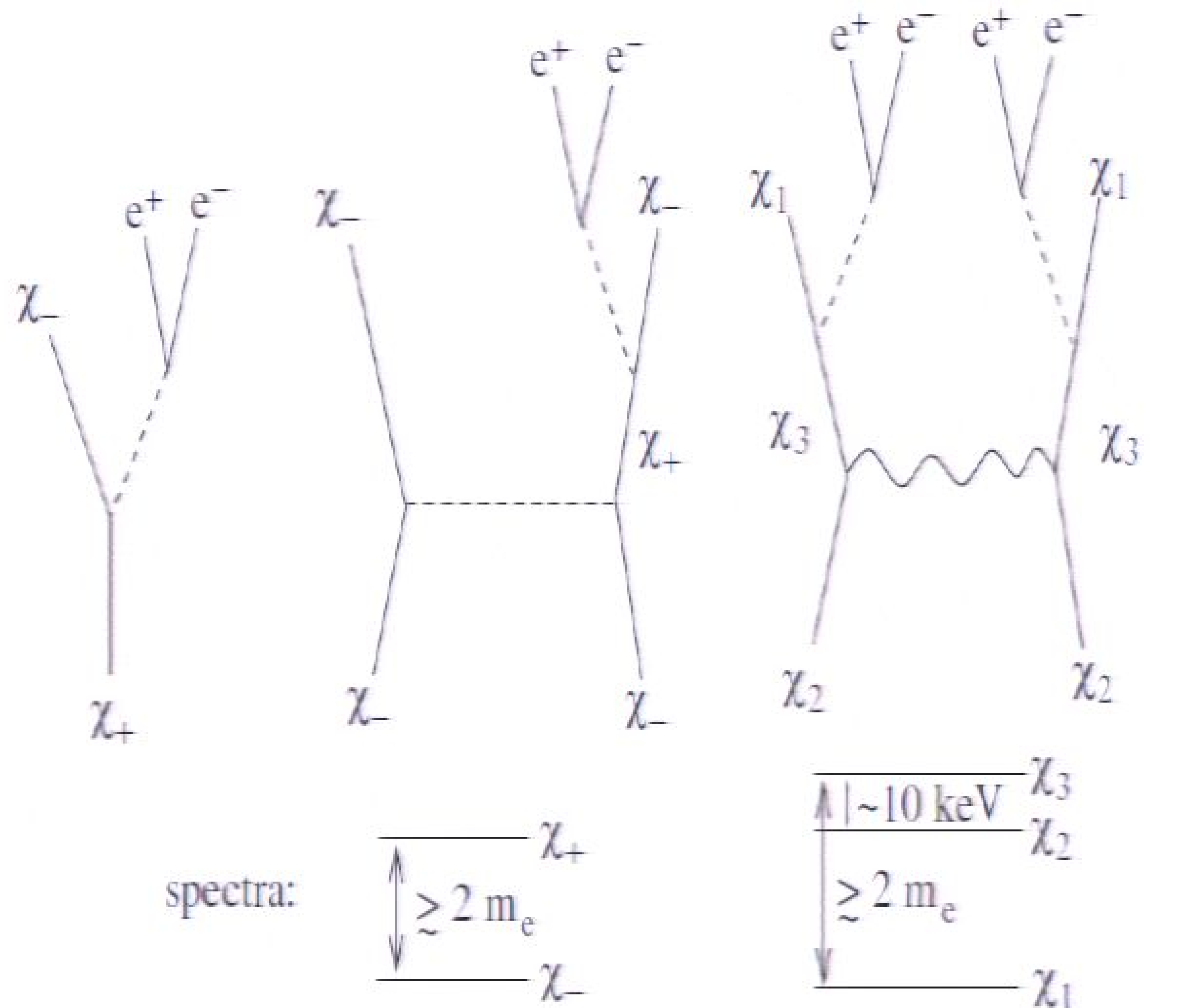
Dark matter models with small ($\sim$ MeV) mass splitting can naturally explain the signal.

How to prove it? Need some complementary signals:

e.g., direct detection of DM, detection of light mediator particles

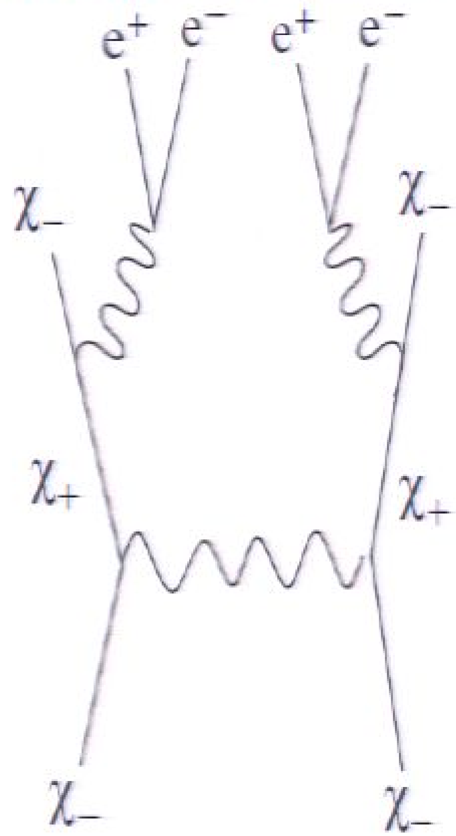
DM mechanisms

Three possiblities: decay (Pospelov, Ritz,hep-ph/0703128), scattering of ground states (Finkbeiner, Weiner astro-ph/0702587) or of long-lived metastable states (Chen, JC, Frey, 0901.4327, 1008.1784)



Symmetric XDM mechanism too slow

Version involving double excitation (Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 0810.0713), incorporated into nonabelian DM proposals



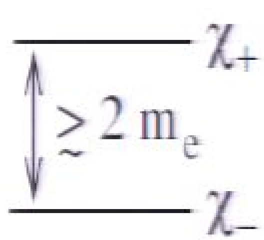
Chen, JC, Fradette, Frey, Rabideau 0911.2222:

rate is too small to match observation,

due to large mass gap and limited cross section

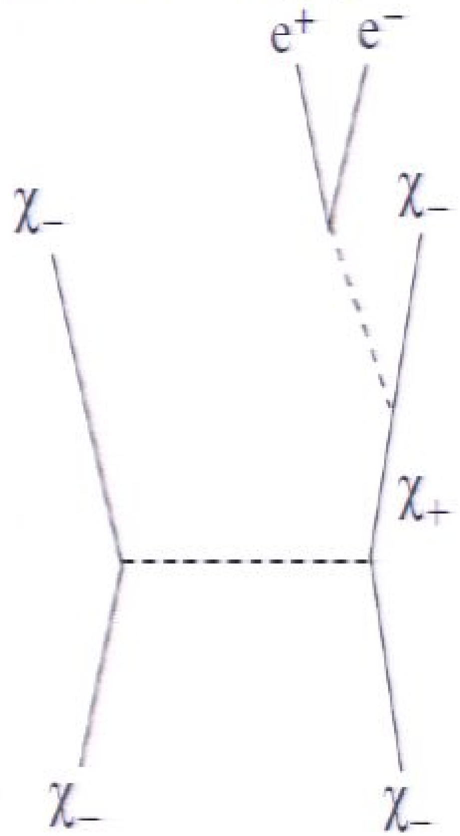
Fermi γ ray constraints also present obstacle for heavy DM (JC, 1005.5001)

spectrum:



Simplest version can still work

Finkbeiner and Weiner, astro-ph/0702587 original version has smaller mass gap

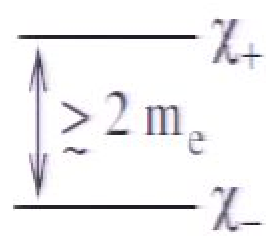


Morris, Weiner 1109.3747:

Smaller energy requirement compatible with large enough rate

Sensitive to high-v tail of Maxwellian velocity distribution

spectrum:



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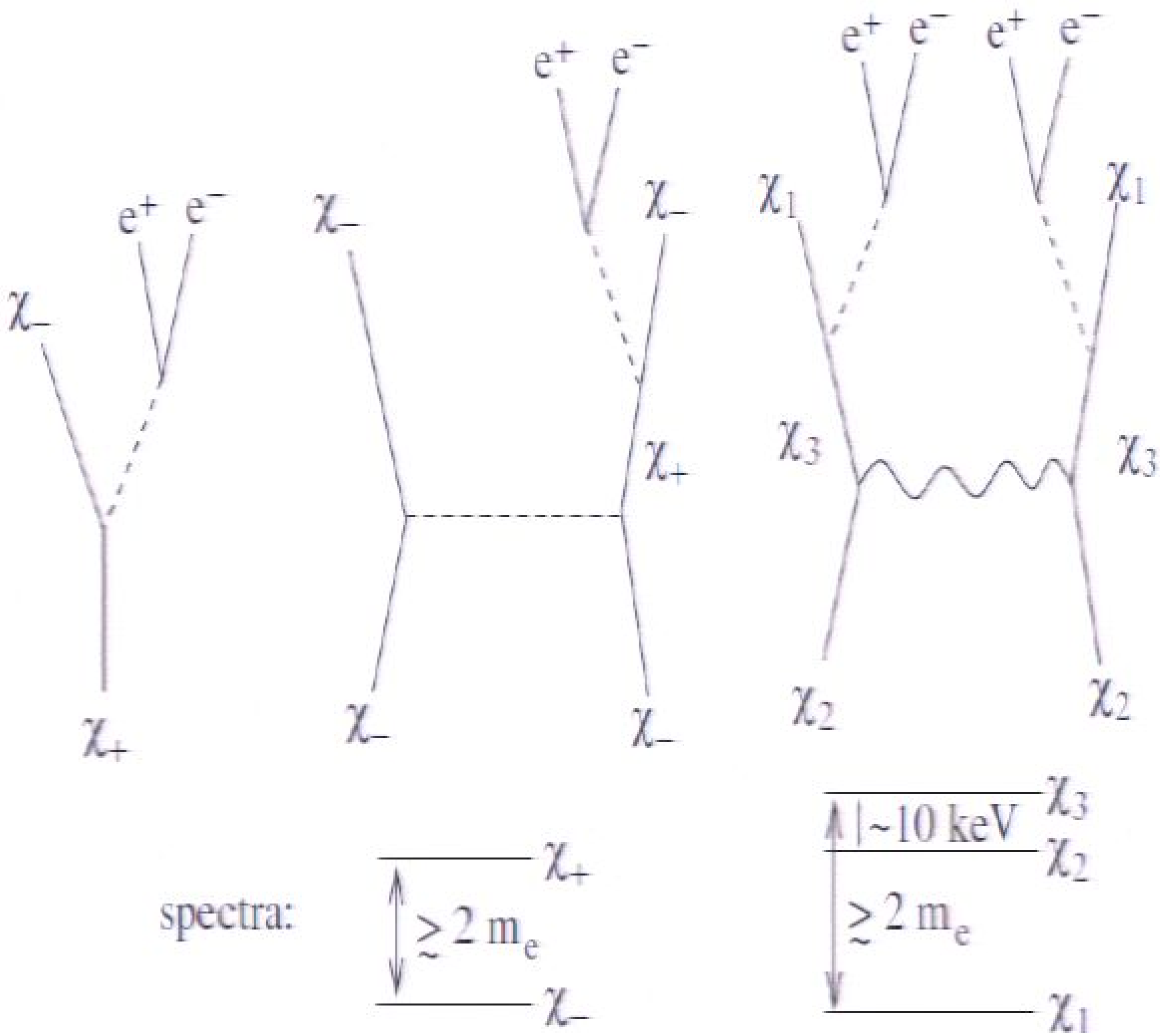

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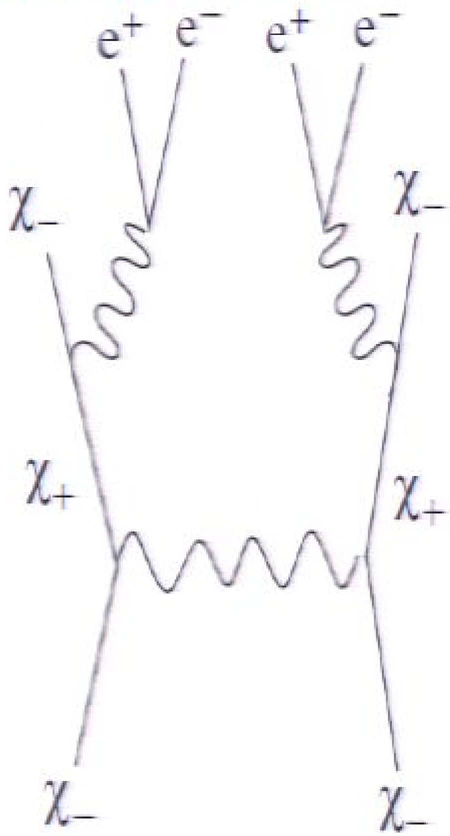

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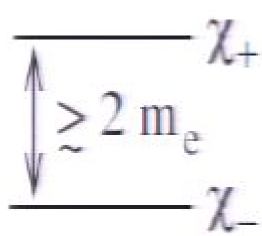

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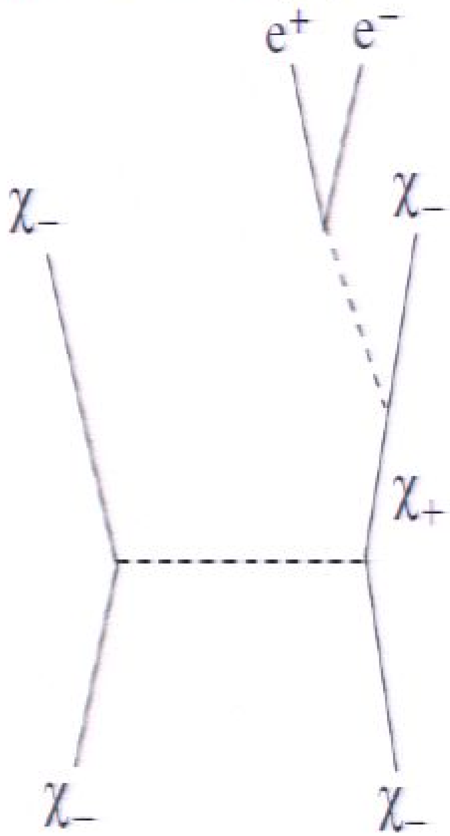

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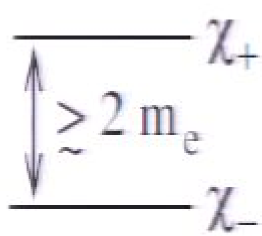
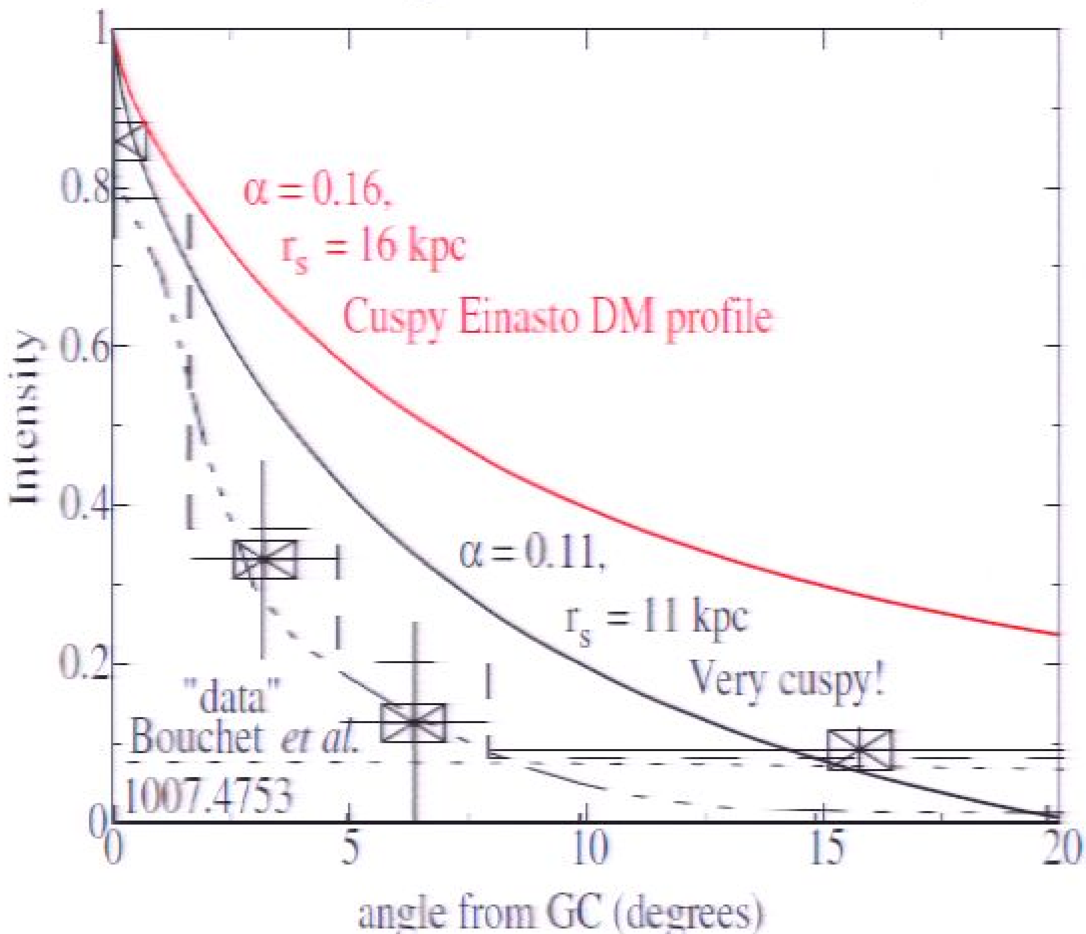


Decaying DM models don't work!

JC, P. Martin, E. McDonough, A. Vincent, in progress

Angular shape of decay signal $I(\theta) \sim \frac{1}{\tau}\int dl\,\rho$
(line-of-sight integral of DM density profile)
Too broad to agree with observed shape:



Simplest Excited Dark Matter Model

JC, A. Frey, E. McDonough, in progress

Original model of Finkbeiner, Weiner, astro-ph/0702587:

$$M_\chi \chi_1 \chi_2 + y_1 \phi \chi_1 \chi_1 + y_2 \phi \chi_2 \chi_2 + \frac{1}{2} m_\phi^2 \phi^2 + \lambda \phi^2 h^2$$

Can we get 511 keV, correct relic density, and any other prediction?

$y_i \sim 0.35$, $m_\phi \sim 1$ GeV, $M_\chi \sim 100$ GeV gives ~ right positron rate and relic density.

Direct detection constrains h-ϕ mixing angle: $\theta \lesssim 10^{-5}$

θ too small to allow for ϕ discovery in beam dump experiments

Sommerfeld enhancement too small (~ 10) for indirect detection

Seemingly no further testable predictions

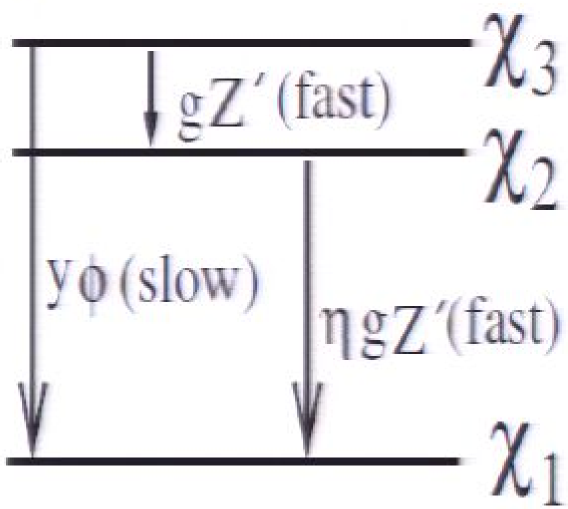
Metastable Excited Dark Matter Model

JC, A. Frey, E. McDonough, in progress

Need 3 DM states: quasi-Dirac ψ_1, ψ_2 and Majorana s,

$$M_\chi \psi_1 \psi_2 + \tfrac{1}{2} m s s + y(\phi \psi_1 - \phi^* \psi_2) s + \text{h.c.} + \tfrac{1}{2} g\, Z'_\mu (\psi_1^\dagger \sigma^\mu \psi_1 - \psi_2^\dagger \sigma^\mu \psi_2)$$

$\frac{\sqrt{2} y \langle \phi \rangle}{M_\chi + m} \equiv \eta \sim 10^{-3} \Rightarrow$ see-saw mass splitting, $\delta M_{23} = \eta^2 (M_\chi + m)$.



Relation to mass eigenstates:

$$\psi_1 \cong \tfrac{1}{\sqrt{2}}(\chi_2 + \chi_3 + \eta \chi_1)$$

$$\psi_2 \cong \tfrac{1}{\sqrt{2}}(\chi_2 - \chi_3 - \eta \chi_1)$$

$$s \cong \chi_1 - \eta \chi_3$$

χ_3 is cosmologically long-lived due to weak $y \phi \chi_3 \chi_1$ interaction.

Z' kinetically mixes with photon, mediates $\chi_3 \chi_3 \to \chi_2 \chi_2$ in galaxy and $\chi_2 \to \chi_1 e^+ e^-$

Highly constrained

Correct rate of $\chi_3\chi_3 \to \chi_2\chi_2 \to \chi_1\chi_1 + 2(e^+e^-)$ in GC

$$\Rightarrow g \sim m_{Z'}/(5\ \mathrm{GeV})$$

$\chi_3\chi_3 \to \chi_2\chi_2$ freezes out early enough to preserve χ_3 abundance

$$\Rightarrow \epsilon > 10^{-3}\, g$$

$\chi_3 \to \chi_1 e^+ e^-$ lifetime much longer than age of universe

$$\frac{\sqrt{y\alpha}}{m_\phi} < \frac{1}{19\ \mathrm{TeV}} \left(\frac{M_\chi}{10\ \mathrm{GeV}}\right)^{1/4}$$ ($\alpha = h$-ϕ mixing angle)

$\chi_3\chi_3 \to Z'Z'$ gives correct relic abundance

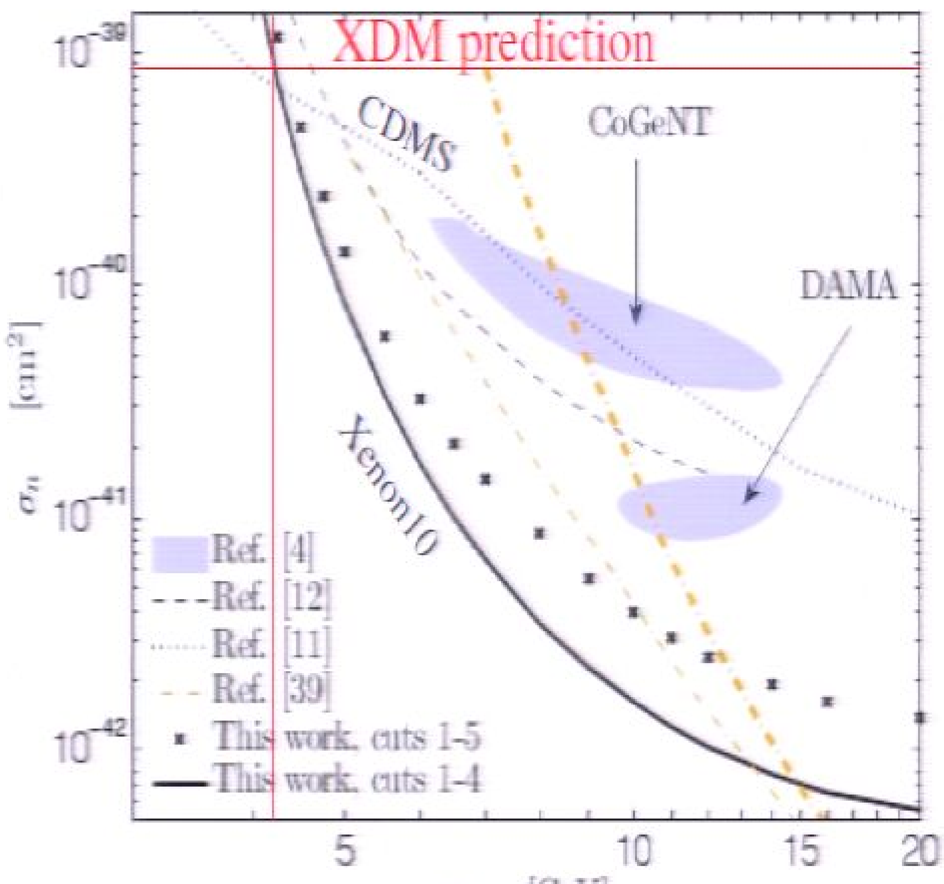
$$m_{Z'} = 166\ \mathrm{MeV} \left(\frac{M_\chi}{\mathrm{GeV}}\right)^{1/2}$$

Direct detection

Previous constraints give lower limit for cross section on protons:

$$\sigma_p = \frac{(g\epsilon e \mu_p)^2}{\pi m_{Z'}^4} \gtrsim 10^{-38}\ \mathrm{cm}^2$$

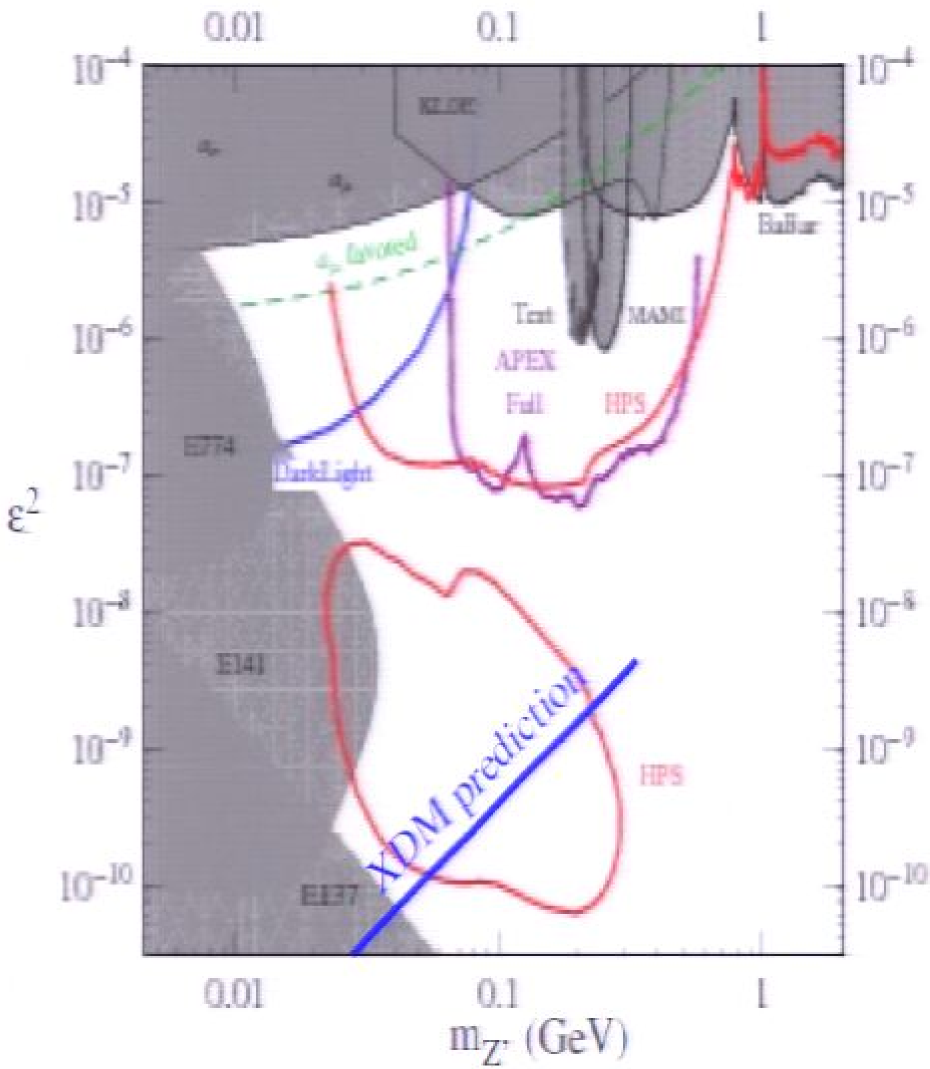
no coupling to neutrons—weakens sensitivity by ~ 0.2.



Our DM candidate must have $M_\chi \lesssim 4$ GeV

Discovery potential for Z'

Previous constraints give relation between Z' kinetic mixing and mass,



$$\epsilon \cong 10^{-3} \frac{m_{Z'}}{5\ \text{GeV}}$$

Prediction falls within HPS sensitivity

Conclusions

Hidden sector dark matter models can be economical without being simplistic.

Can give reasonable account of isospin-violating light DM interactions via interference of two vector exchanges.

Invisible annihilation products could be extra dark radiation recently suggested

Can explain excess 511 keV γ rays via excited DM mechanism; decay mechanism now excluded

Both predict ϵ-$m_{Z'}$ in the range for discovery by JLab experiments