

Title: Hidden sector dark matter: direct detection and cosmic ray anomalies

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URL: <http://pirsa.org/10100056>

Abstract: If dark matter consists of a multiplet with small mass splittings, it is possible to simultaneously account for DAMA/CoGeNT hints of direct detection and the INTEGRAL 511 keV gamma ray excess from the galactic center; such dark matter must be in the 4-12 GeV mass range. I present scenarios where the DM transforms under a hidden SU(2) that can account for these observations. These models can be tested in low-energy beam dump experiments, like APEX. To explain PAMELA/Fermi excess electrons from dark matter annihilations, heavier TeV scale DM is required. I will present new more stringent constraints from Fermi gamma ray data that tend to rule out such models. However we find a loophole: DM annihilations in a nearby DM subhalo, between us and the galactic center, could provide the excess leptons while respecting gamma ray constraints.

# Hidden sector dark matter: direct detection and cosmic ray anomalies

Jim Cline, McGill U. & PI

Perimeter Institute, 5 Oct. '10

## Based on

Fang Chen, JC, Andrew Frey,

“A new twist on excited dark matter...” (0901.4327);

“Nonabelian dark matter: models and constraints” (0907.4746)

F. Chen, JC, A. Fradette, A. Frey, C. Rabideau,

“Exciting dark matter in the galactic center.” (0911.2222)

JC, Aaron Vincent, Wei Xue,

“Leptons from dark matter annihilation in milky way subhalos,”  
(1001.5399)

“Overcoming Gamma Ray Constraints with Annihilating Dark Matter  
in Milky Way Subhalos” (1009.5383)

Marco Cirelli, JC

“Can annihilating dark matter explain  
all of the cosmic ray lepton anomalies?,” (1005.1779)

JC, A. Frey, F. Chen,

“Metastable dark matter mechanisms for INTEGRAL 511 keV  
rays and DAMA/CoGeNT events.” (1008.1784)

# Personal motivation

Galactic 511 keV  $\gamma$  ray excess has been observed since 1972.

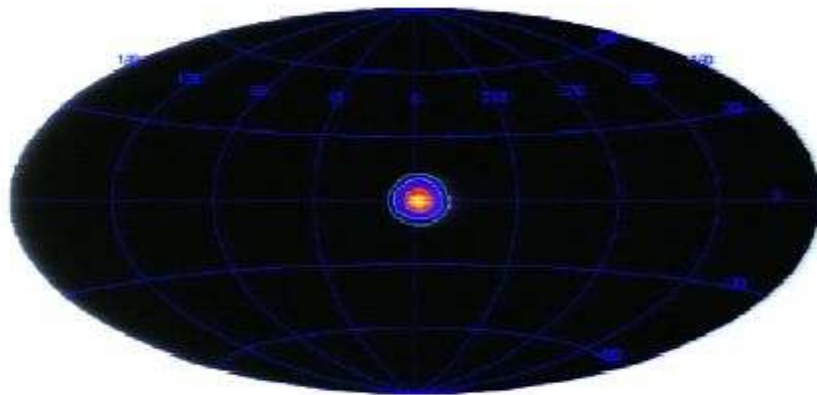


Figure 2. An MREM sky map of the 511 keV positron annihilation line emission. The contours indicate intensity levels of  $10^{-2}$ ,  $10^{-3}$ , and  $10^{-4}$   $\text{ph cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ . Details are given in the text.

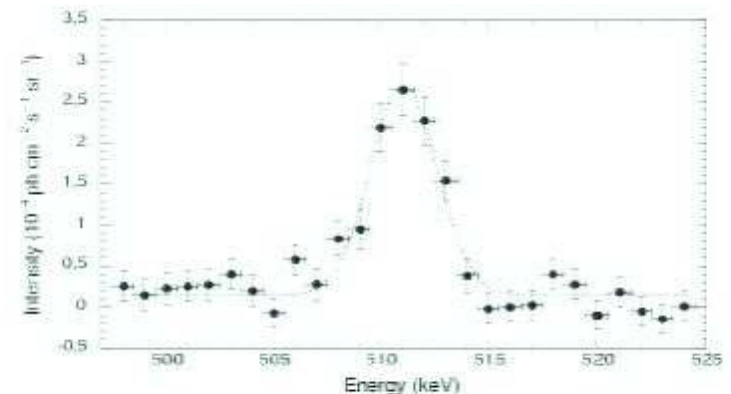


Fig. 3. 511 keV flux spectrum obtained using a gaussian centred on the GC with a FWHM of  $10^\circ$ .

So far no 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 gauge boson in beam dump experiments

# Why hidden sector DM?

- It is easy to imagine a hidden (or “dark”) sector

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{\text{hid}} + \mathcal{L}_{\text{portal}}$$

with

$$\mathcal{L}_{\text{portal}} = \lambda H_{SM}^2 H_{\text{hid}}^2 \quad \text{or} \quad \epsilon F_{SM}^{\mu\nu} F_{\text{hid},\mu\nu}$$

- Dark sector is a natural origin for dark matter.
- Dark sector gauge symmetry, like in SM, could be nonabelian and spontaneously broken

With a low  $\sim$ GeV scale of breaking, this is all we need to explain several galactic cosmic ray anomalies (+ DAMA)

(Arkani-Hamed, Finkbeiner, Slatyer, Weiner 0810.0713)

Pirsa: 10100056 But to what extent can these anomalies really be explained? Page 5/69

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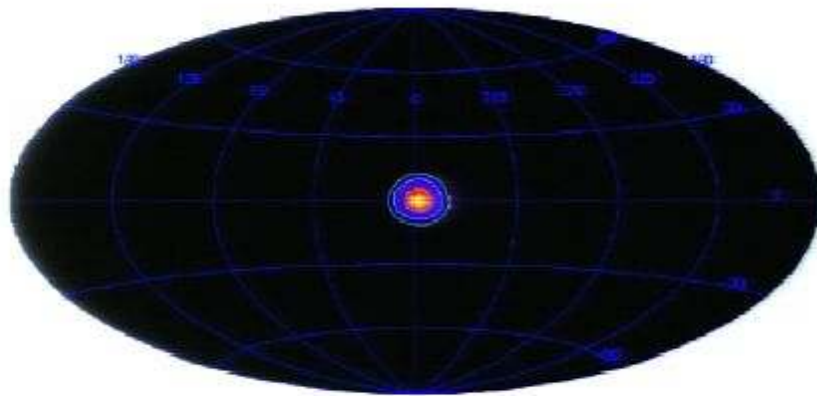


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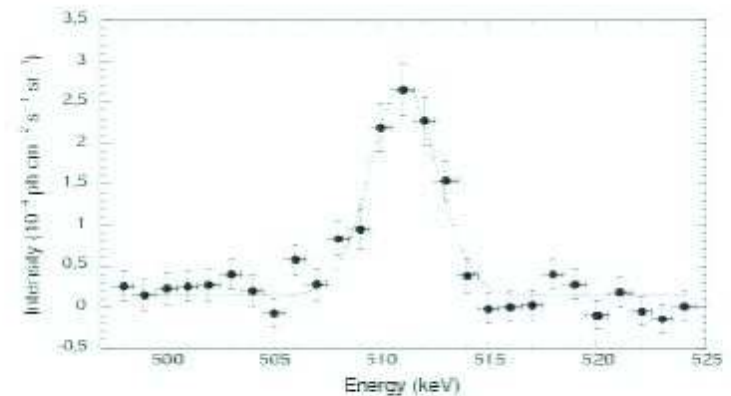


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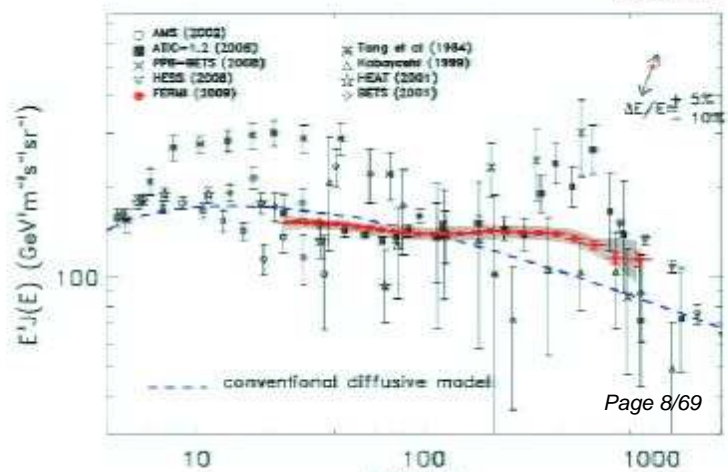
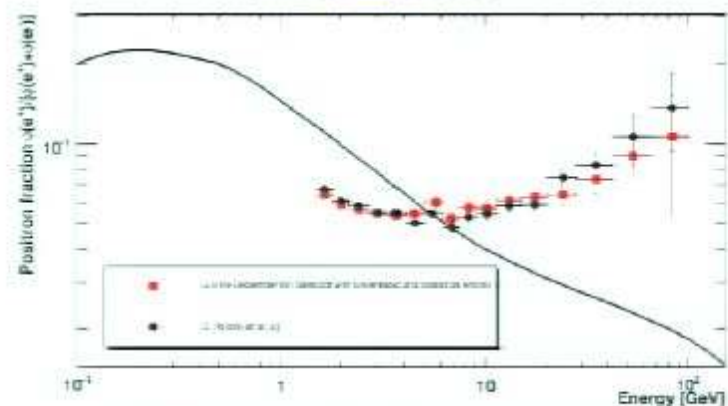
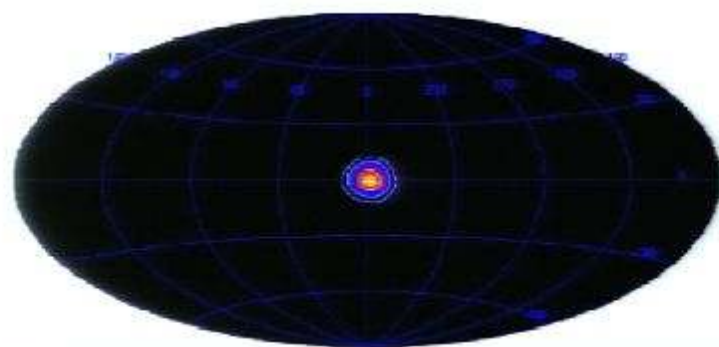
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But to what extent can these anomalies really be explained?

# The cosmic ray anomalies

- Excess 511 keV  $\gamma$ 's from galactic center, observed by INTEGRAL/SPI
- PAMELA positron excess at 10–100 GeV
- Fermi/LAT  $e^\pm$  excess at 100–1000 GeV



# A simple nonabelian DM model

- $SU(2)_{\text{dark}}$  gauge symmetry with triplet DM:

$$\mathcal{L}_\chi = \frac{1}{2} \bar{\chi}_i (i \overleftrightarrow{D}_{ij} - M_\chi \delta_{ij}) \chi_j - \frac{1}{4g^2} B_{\mu\nu}^a B_a^{\mu\nu} - \frac{1}{\Lambda} \Delta_a B_a^{\mu\nu} Y_{\mu\nu}$$

↗
↗
↗  
 dark matter                  dark gauge sector      mixing with SM

- Triplet VEV  $\langle \Delta_2 \rangle$  gives  $B_2$ - $\gamma$  mixing.
- We need second triplet  $\Delta'$  to fully split  $\chi_i$  states:

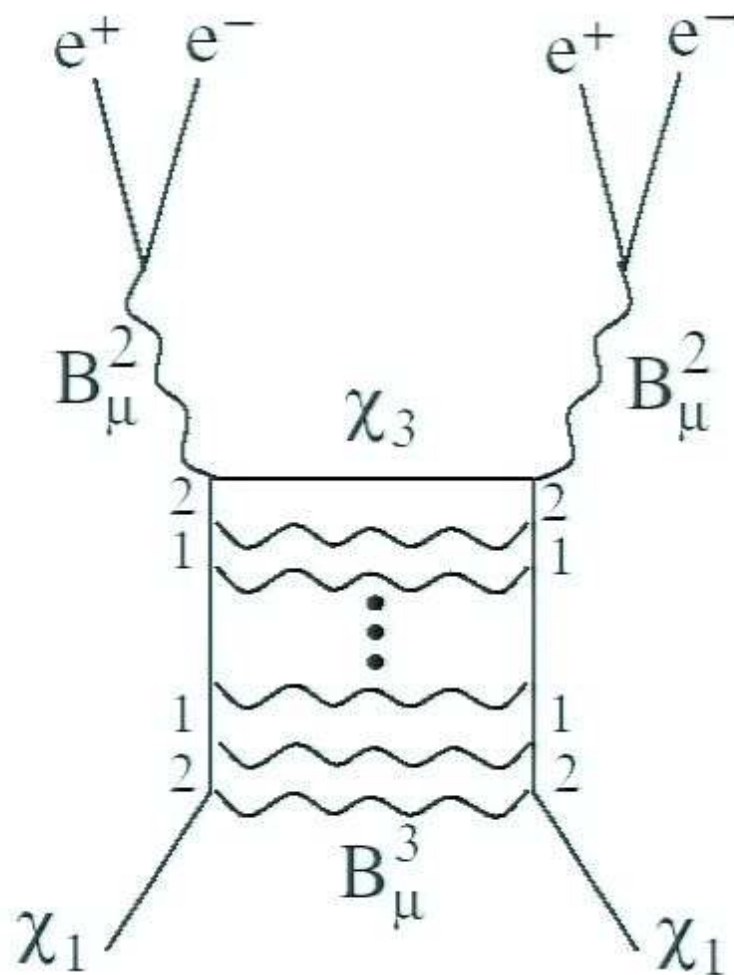
$$V_{\text{higgs}} = \lambda(\Delta^2 - v^2)^2 + \lambda'(\Delta'^2 - v'^2)^2 + \lambda''(\vec{\Delta} \cdot \vec{\Delta}')^2$$

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$\chi_2, B_2, \Delta_2, \Delta'_2$  uncharged.

# Mechanism for high-energy leptons



Gauge boson mass  $\mu \lesssim 2 \text{ GeV}$ ,  
explains why PAMELA sees no  
excess  $\bar{p}$ .

$B$ 's decay only into  $e^+e^-$ ,  $\pi^+\pi^-$ ,  
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$M_\chi \sim \text{TeV}$  to explain Fermi  $e^\pm$   
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Multiple gauge boson exchanges give rise to boost factor  
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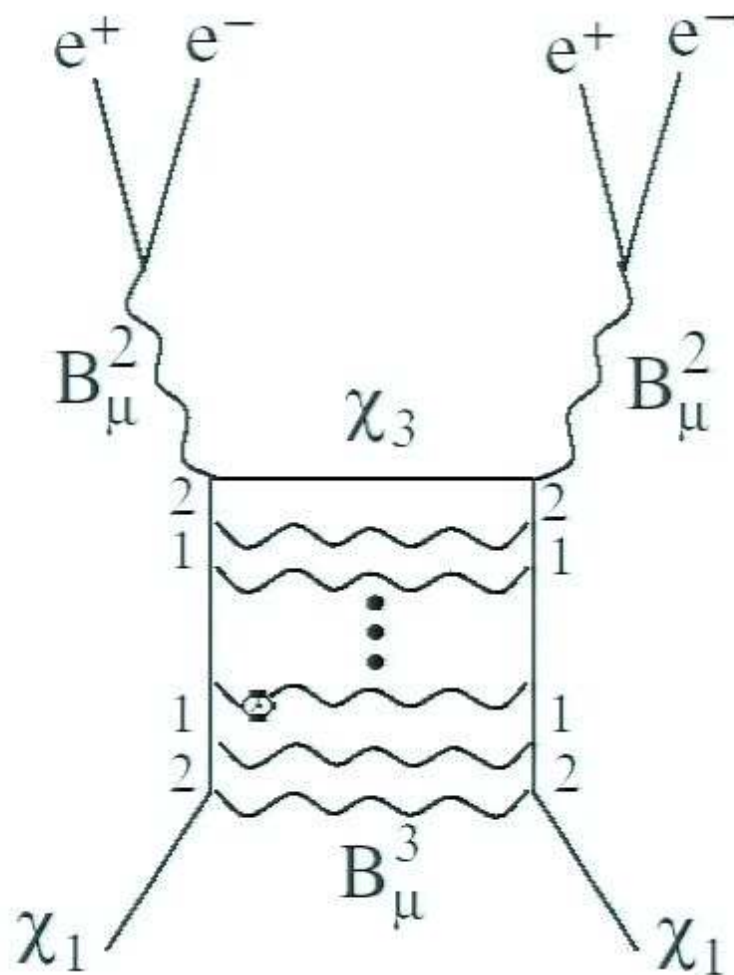
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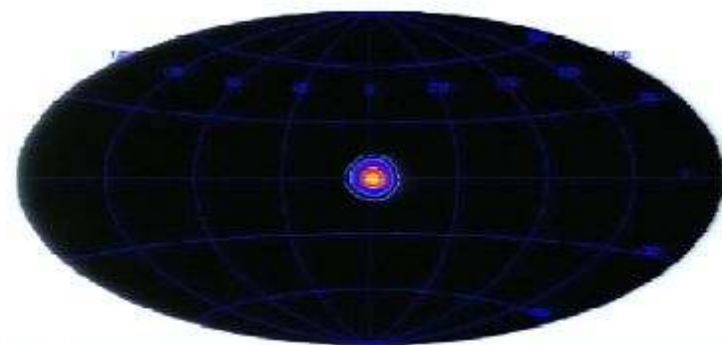
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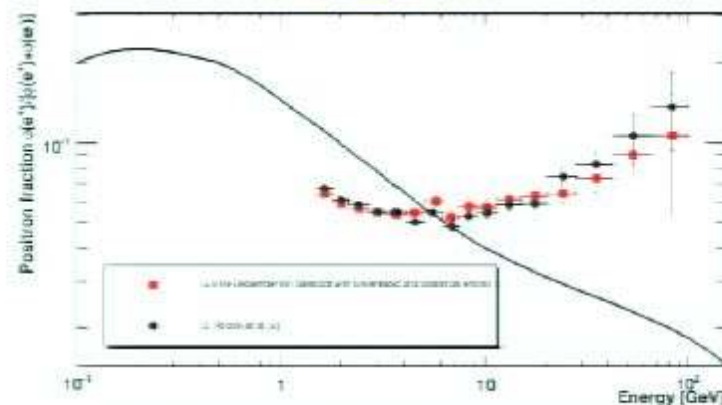
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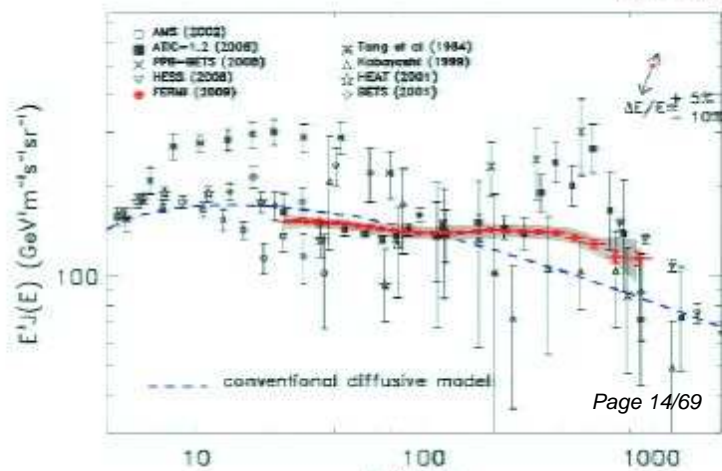
- Excess 511 keV  $\gamma$ 's from galactic center, observed by INTEGRAL/SPI



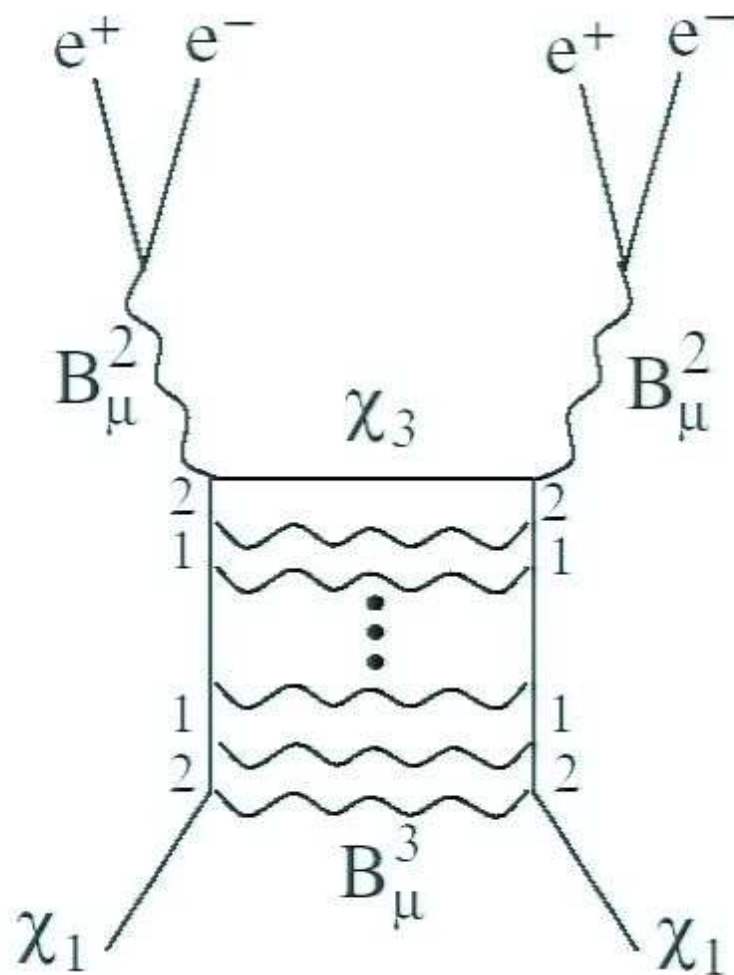
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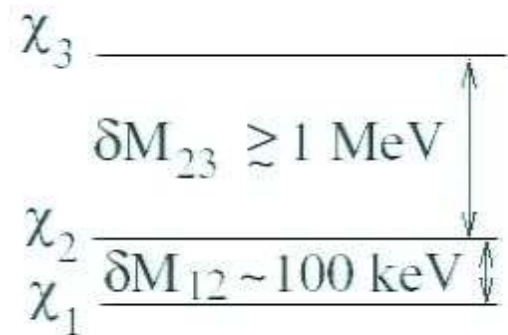
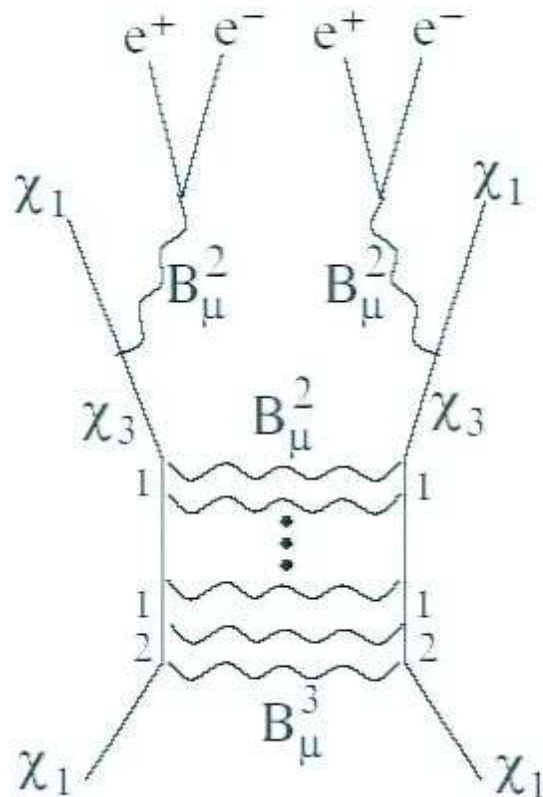
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Variation on eXcited Dark Matter (XDM) mechanism of  
**Finkbeiner, Weiner, astro-ph/0702587** :  $\chi_1\chi_1 \rightarrow \chi_3\chi_3$ ,  
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Originally proposed spectrum  
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# Origin of small mass splittings

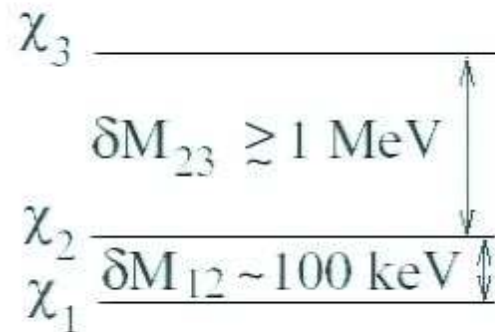
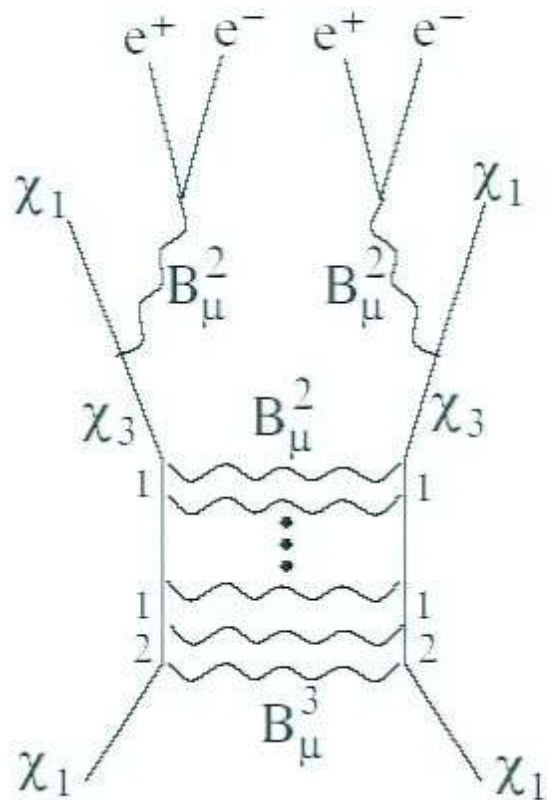
With gauge symmetry spontaneously broken, radiative mass splittings are of order  $\delta M_\chi \sim \alpha_g \delta\mu$

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For  $\delta\mu \sim 100$  MeV and  $\alpha_g \sim 0.01$ ,  $\delta M_\chi \sim$  MeV.

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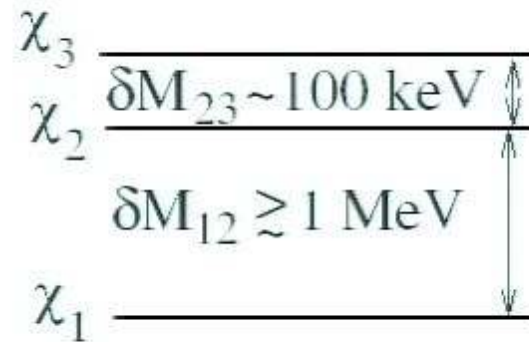
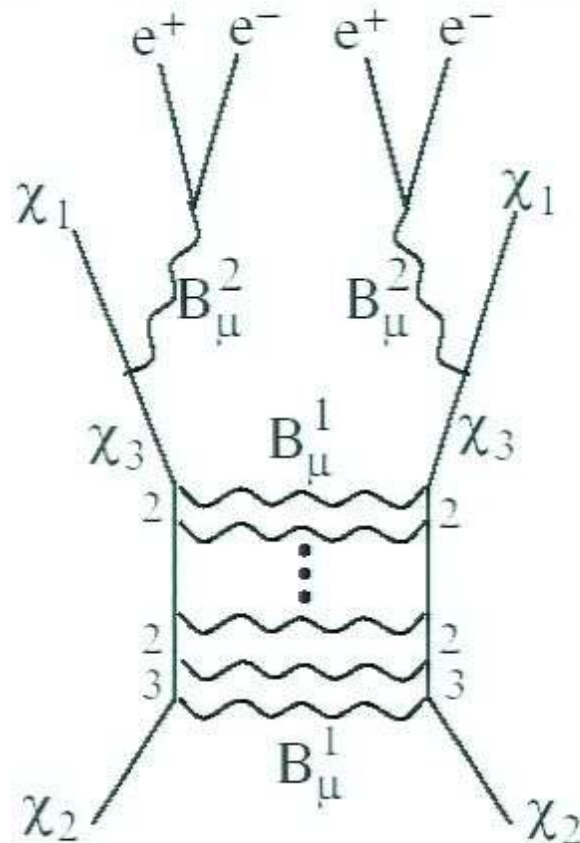
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# XDM mechanism is too slow

We showed that a different spectrum is needed to get large enough rate (Chen, JC, Fradette, Frey, Rabideau 0911.2222)

Let  $\chi_2\chi_2 \rightarrow \chi_3\chi_3$  followed by  $\chi_3 \rightarrow \chi_1 e^+ e^-$ :



Inverted hierarchy spectrum

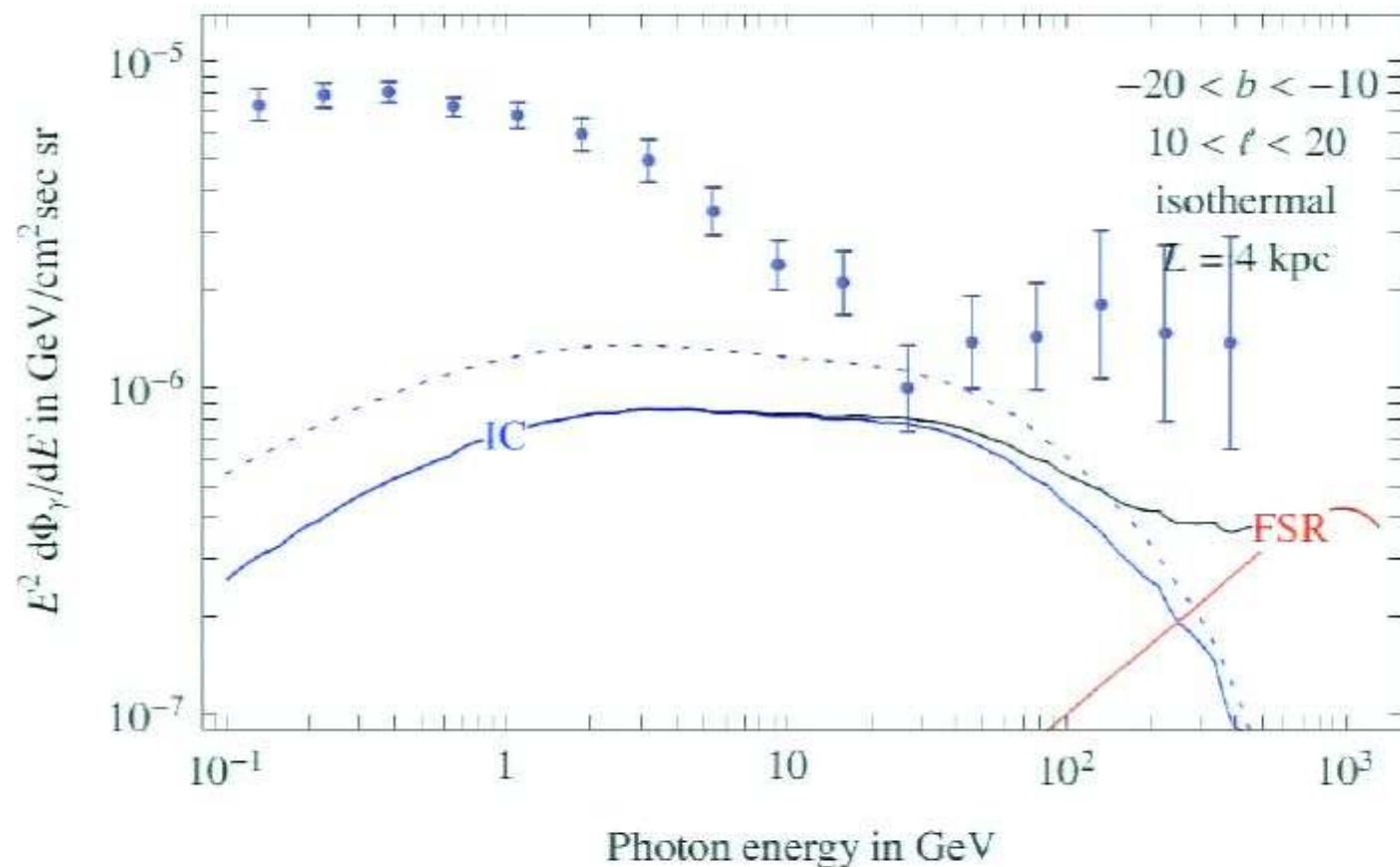
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# Fermi Inverse Compton constraint

Papucci, Strumia 0912.0742

High-energy leptons produced by  $\chi$  annihilation upscatter photons in galaxy; would contribute to  $\gamma$  ray spectrum observed by Fermi:

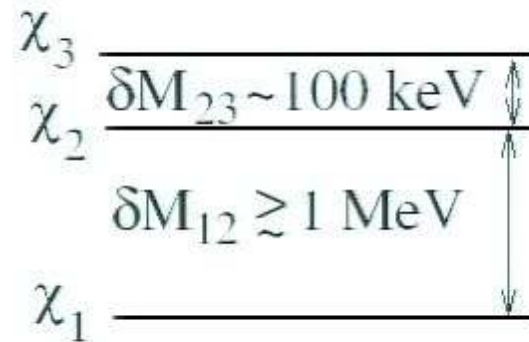
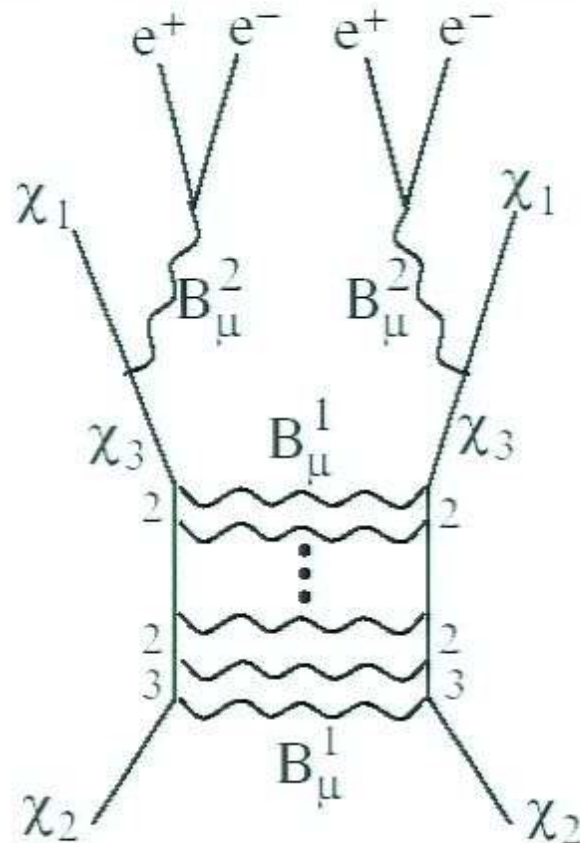
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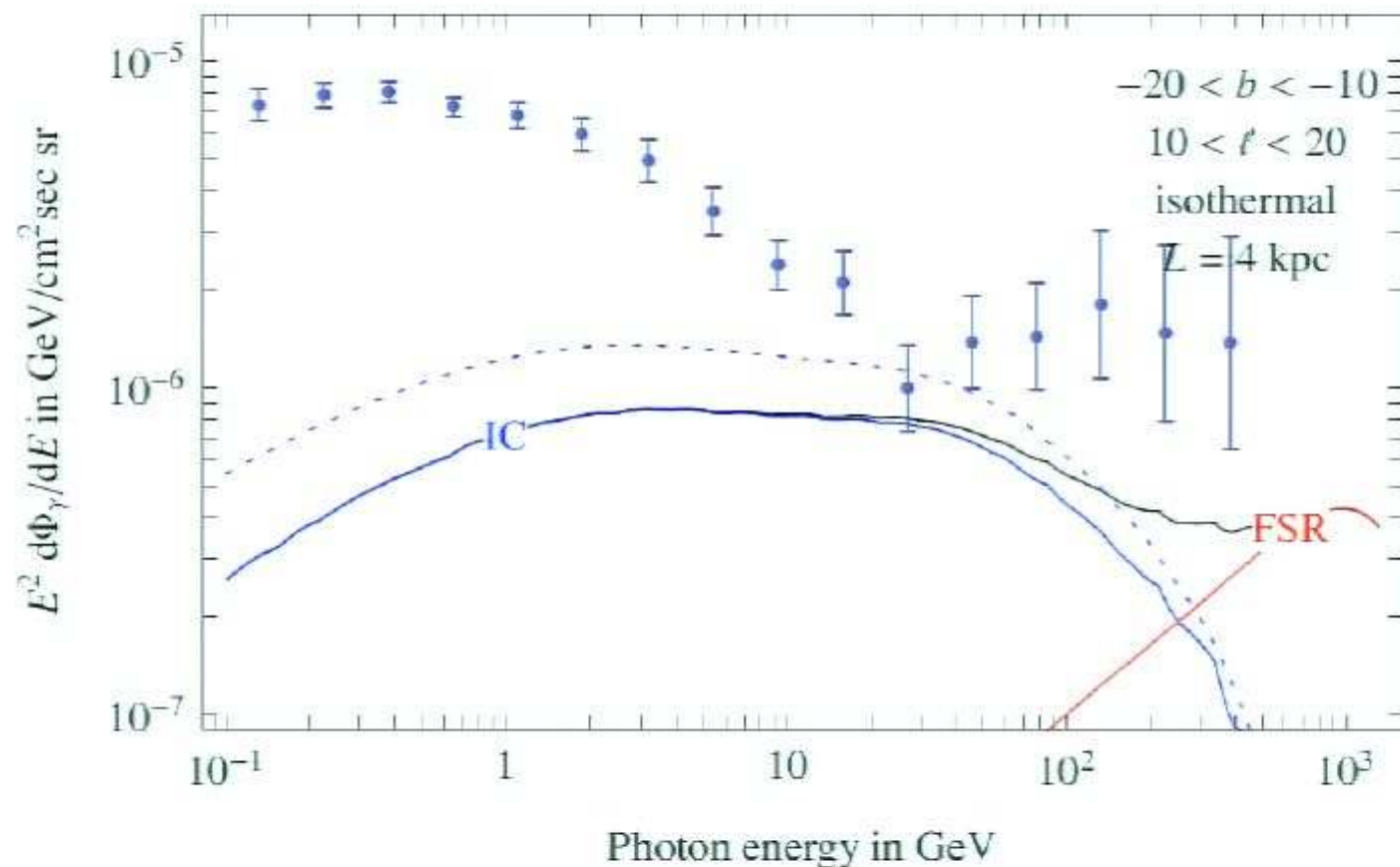
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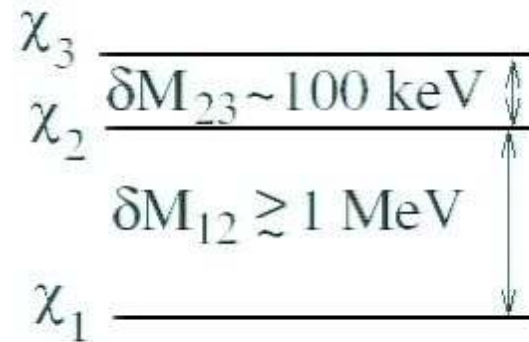
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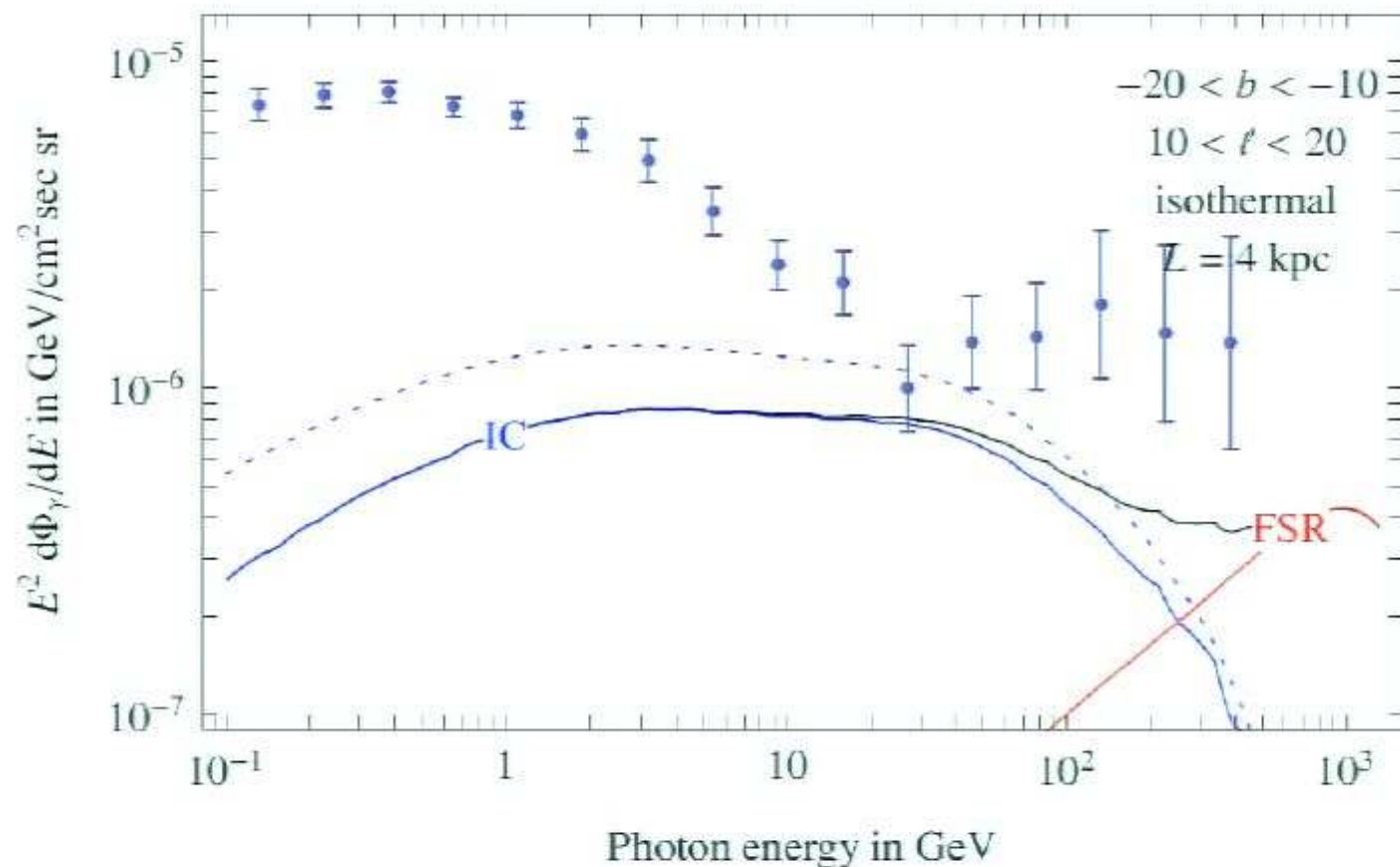
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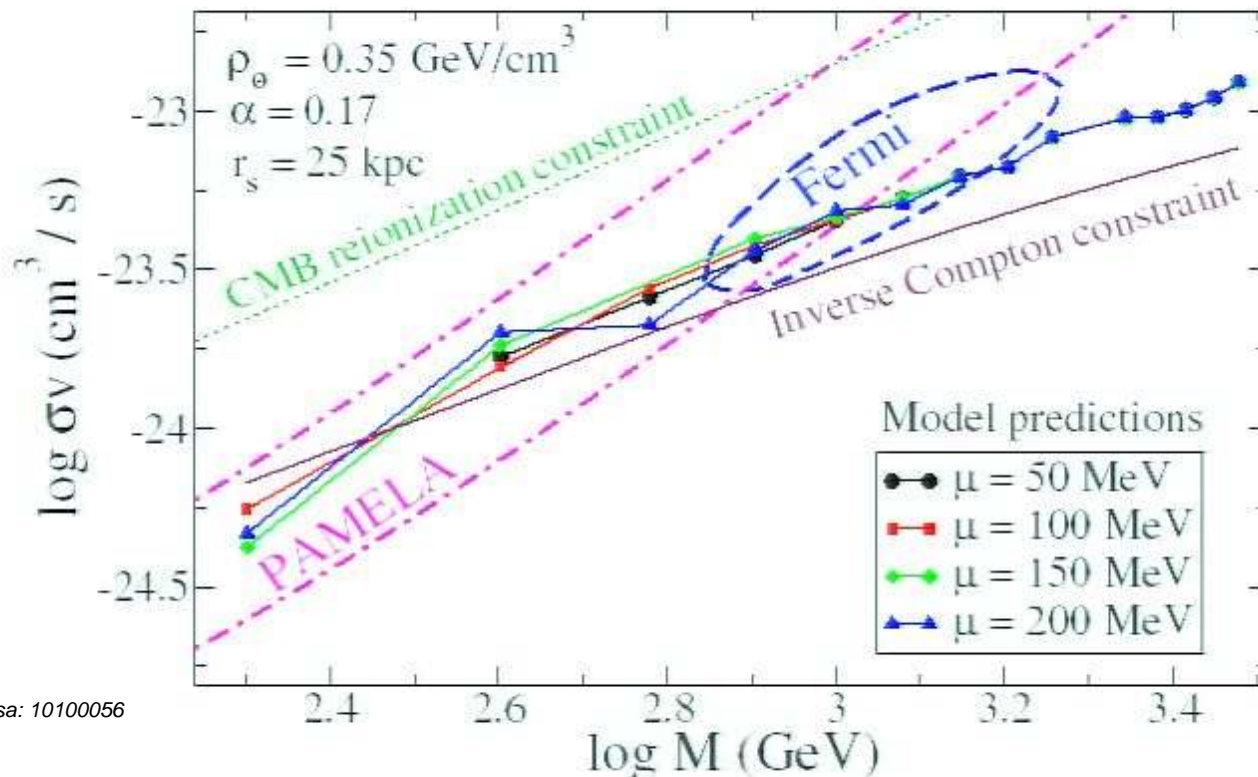
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# XDM & Fermi/PAMELA incompatible

- XDM rate  $\sim \langle \sigma v \rangle \rho^2(0)$  at galactic center. Need large central density  $\rho(0)$ .
- Fermi IC constraint strongest in direction of galactic center. Need small  $\rho(0)$ !
- Einasto profile  $\rho = \rho_{\odot} \exp\left(-\frac{1}{\alpha}[(r/r_s)^{\alpha} - (r_{\odot}/r_s)^{\alpha}]\right)$  is more/less cuspy for smaller/larger values of  $\alpha$ .



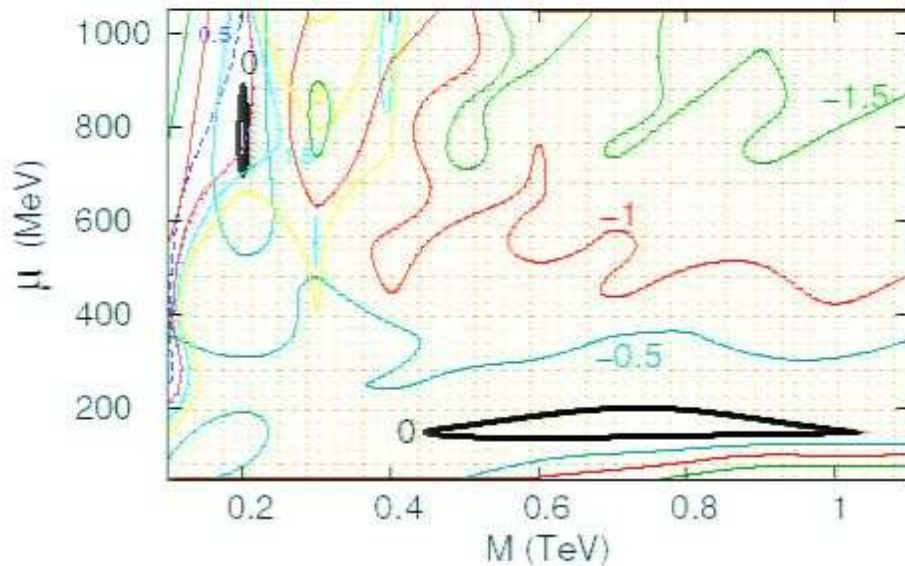
Need  $\alpha \lesssim 0.17$  for large enough XDM rate; ruled out by IC constraint.

Cirelli, JC  
1005.1779

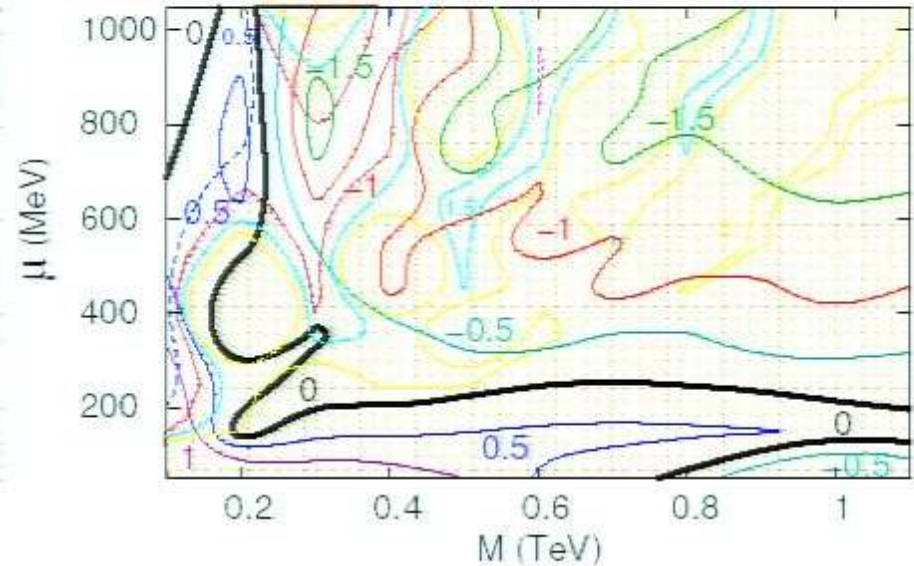
# INTEGRAL vs. PAMELA/Fermi

An illustration of the problem (JC, 1005.5001)

Contours of  $\log R_{e^+}/R_{\text{obs}}$  in DM- $B_\mu$  mass plane:



$$\alpha = 0.17, \delta M = 100 \text{ keV}$$



$$\alpha = 0.20, \delta M = 25 \text{ keV}$$

Shaded regions are ruled out by inverse Compton constraint

Need  $\alpha \gtrsim 0.20$  to satisfy (old, less-constraining version of) IC constraint

Positron rate becomes much too small for large

# Stronger Inverse Compton Constraints

Differences with previous studies:

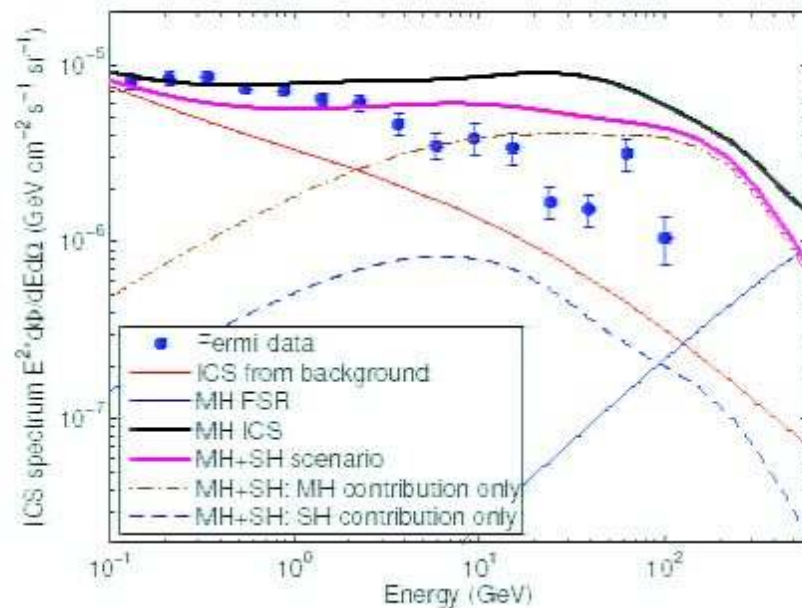
We use GALPROP to solve diffusion equation, rather than semianalytic approach (Papucci, Strumia)

We find most constraining region in sky is  $-9^\circ < b < -4.5^\circ$ ,  $0 < l < 9^\circ$ . Lin *et al.* 1004.0989 average over  $10^\circ < |b| < 30^\circ$ ,  $-15^\circ < l < 15^\circ$ .

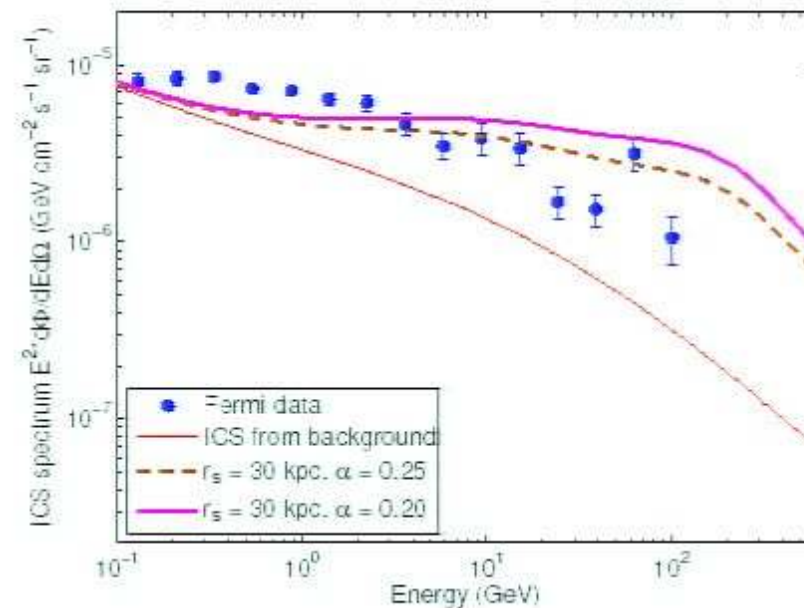
(We show constraints at  $2\sigma$  rather than  $3\sigma$ )

# Strengthening IC Constraints

A. Vincent, W. Xue, JC, (1009.5383)



$\alpha = 0.17, r_s = 25 \text{ kpc}$



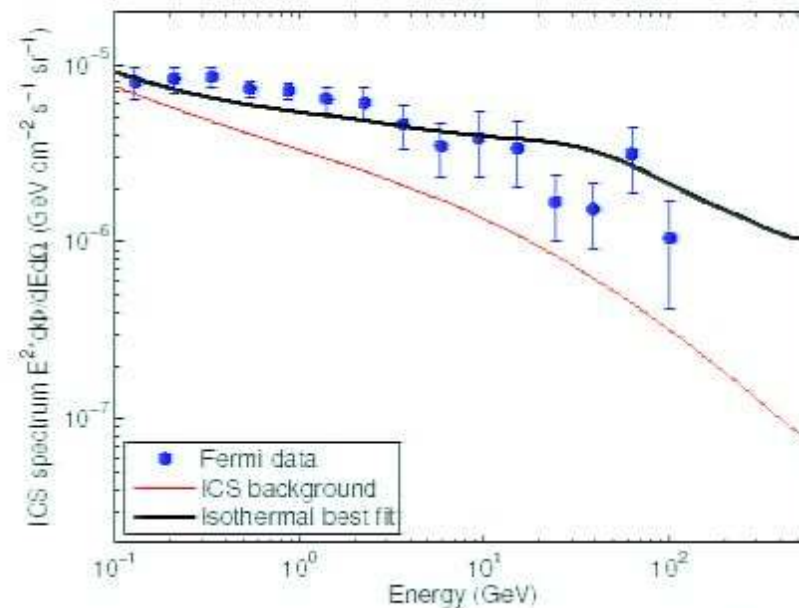
$\alpha = 0.20, 0.25, r_s = 30 \text{ kpc}$

Even less cuspy profiles violate the constraints

Using GALPROP gives more stringent constraints than semianalytic approach to solving diffusion equation

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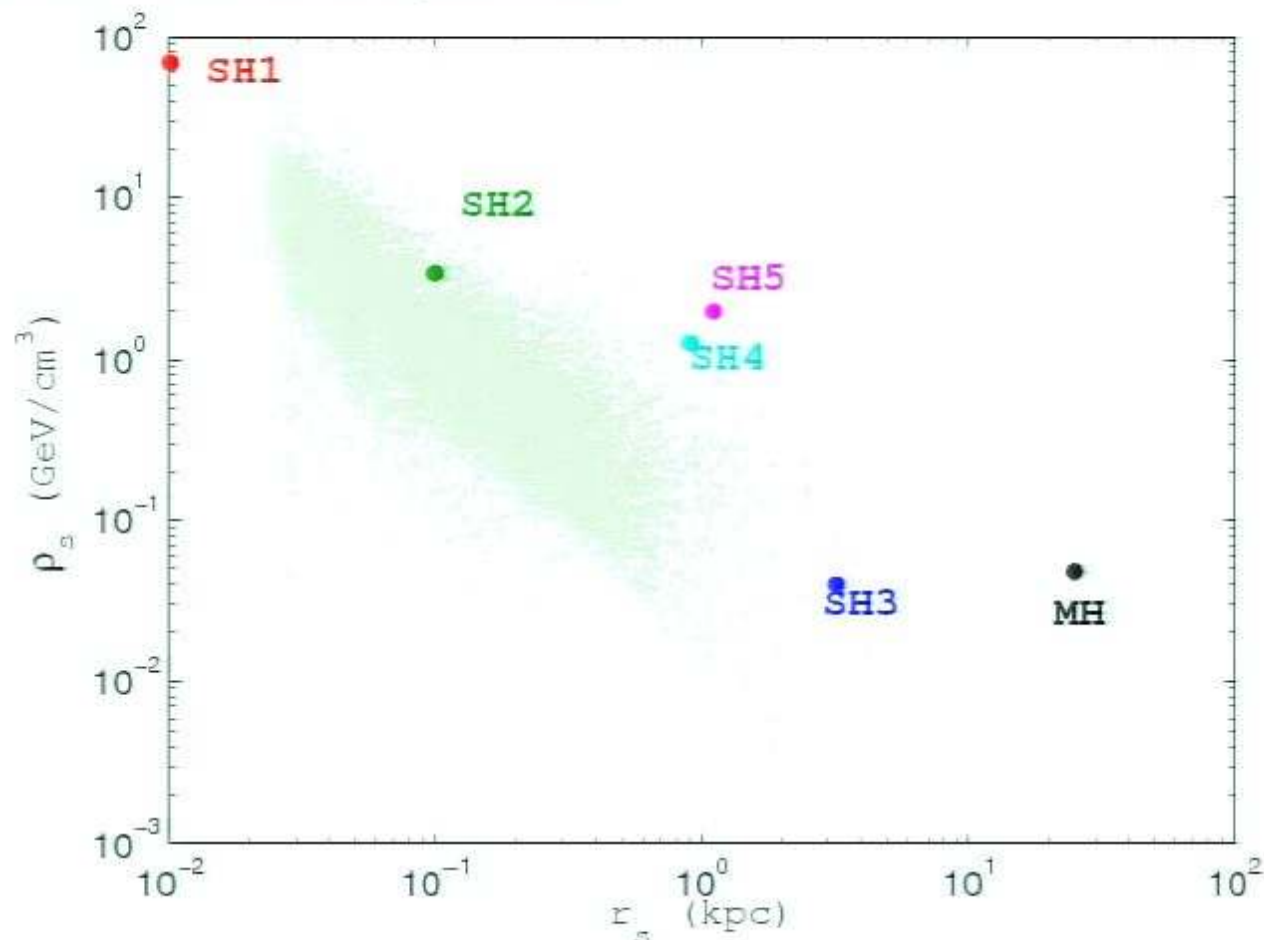


$$\text{isothermal profile, } \rho = \frac{\rho_s}{1+(r/r_s)^2}$$

Highly cored isothermal profile easily satisfied earlier constraints;  
is now ruled out (at  $2\sigma$ )

# Substructure Loophole

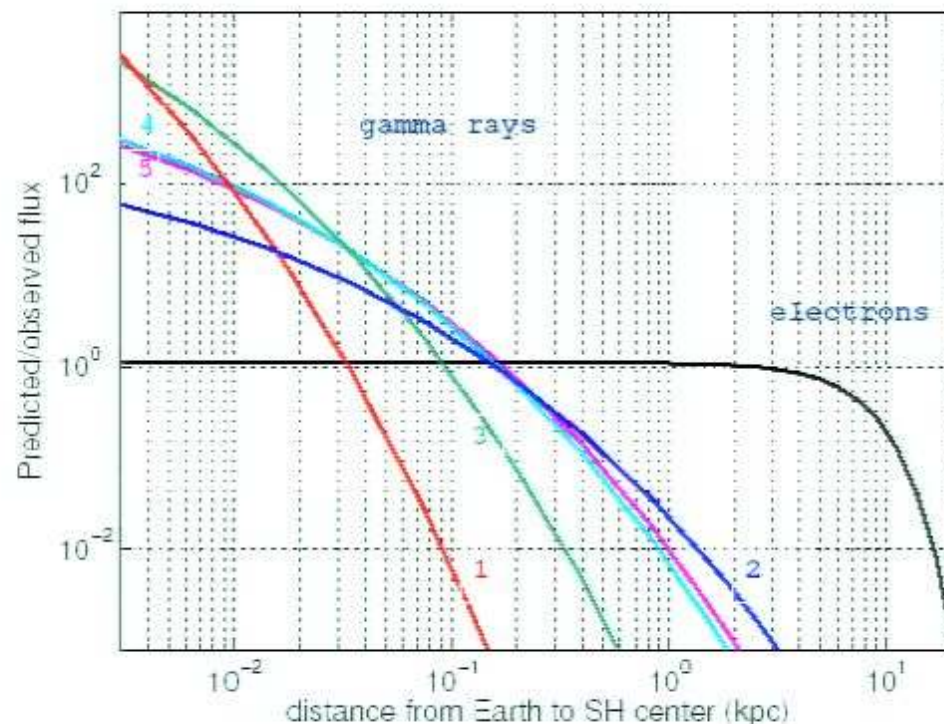
Main DM halo contains zillions of subhalos (*Via Lactea II* simulation), each with its own Einasto profile:



Outlier with high  $\rho_s$  can be source of Fermi/PAMELA  $e^\pm$  excess if it is close enough to us

# Substructure Loophole

How close? Within 3 kpc (compare to 8 kpc distance to galactic center), but farther than  $\sim 200$  pc.



Catch: needs to line up with galactic center to avoid much stronger gamma ray constraints

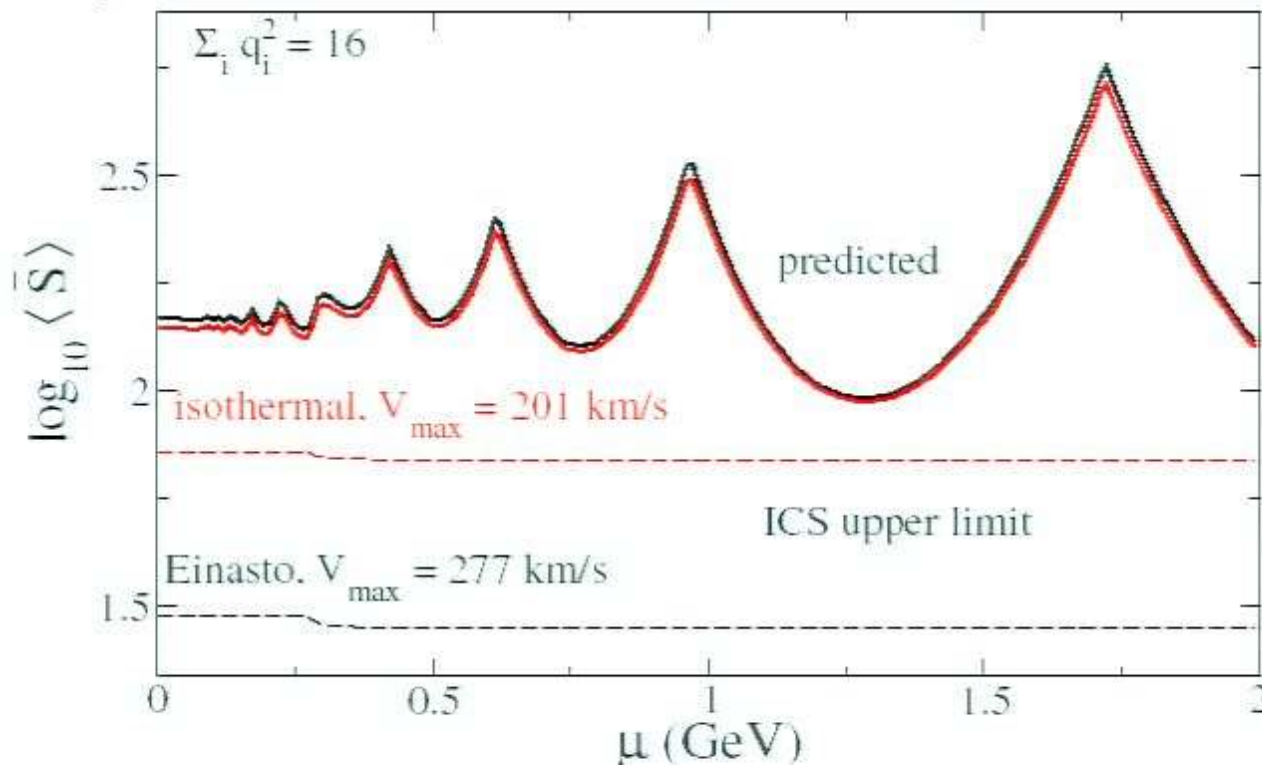
Also, need specific values of boost factors for annihilation in the subhalos, but these can be computed in a given DM model

# Constraint on main halo boost factor

Consider simplest U(1) model of DM.

Sommerfeld boost factor  $S$  is known function of gauge coupling  $\alpha_g$ , DM velocity  $v$  and mass ratio  $\mu/M$ .

$\alpha_g$  is fixed by relic density (and dark Higgs charges  $q_i$ ),  
 $M \cong 1$  TeV by fit to Fermi data.



Predicted MH boost factor is always greater than maximum allowed

# Leptophilic DM as small component

A way out: let  $\alpha_g$  exceed thermal relic value,  $\alpha_g = \sqrt{f}\alpha_{g,\text{th}}$ ,  $f > 1$

$$\langle\sigma v\rangle \rightarrow f\langle\sigma v\rangle, \quad \rho \rightarrow \frac{\rho}{f}, \quad \langle\sigma v\rangle\rho^2 \rightarrow \frac{1}{f}\langle\sigma v\rangle\rho^2$$

Predicted effective boost factor goes down by  $1/f$ .

We can satisfy main halo ICS constraint.

Subhalo boost factors for producing  $e^\pm$  also go down, but they are enhanced by small  $v$  in subhalo

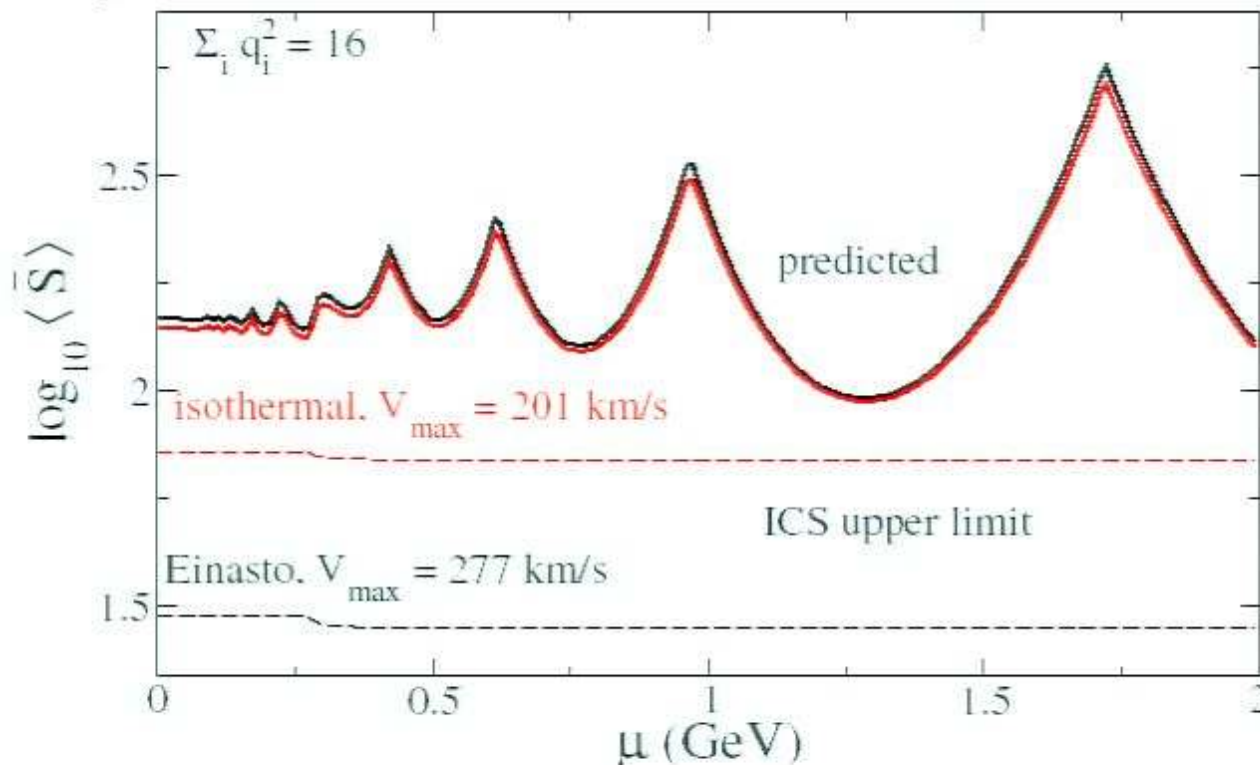
Subhalo	$r_s$ (kpc)	$\rho_s$ (GeV/cm <sup>3</sup> )	log $BF$ (needed)	$d_{\text{min}}$ (pc)	$V_{\text{max}}$ (km/s)
1	0.01	69	4.74	33.9	2.9
2	0.1	3.46	4.34	95.5	6.7
3	3.2	0.04	3.76	178	22
4	0.9	1.27	2.35	165	36
5	1.1	2.0	1.70	170	55

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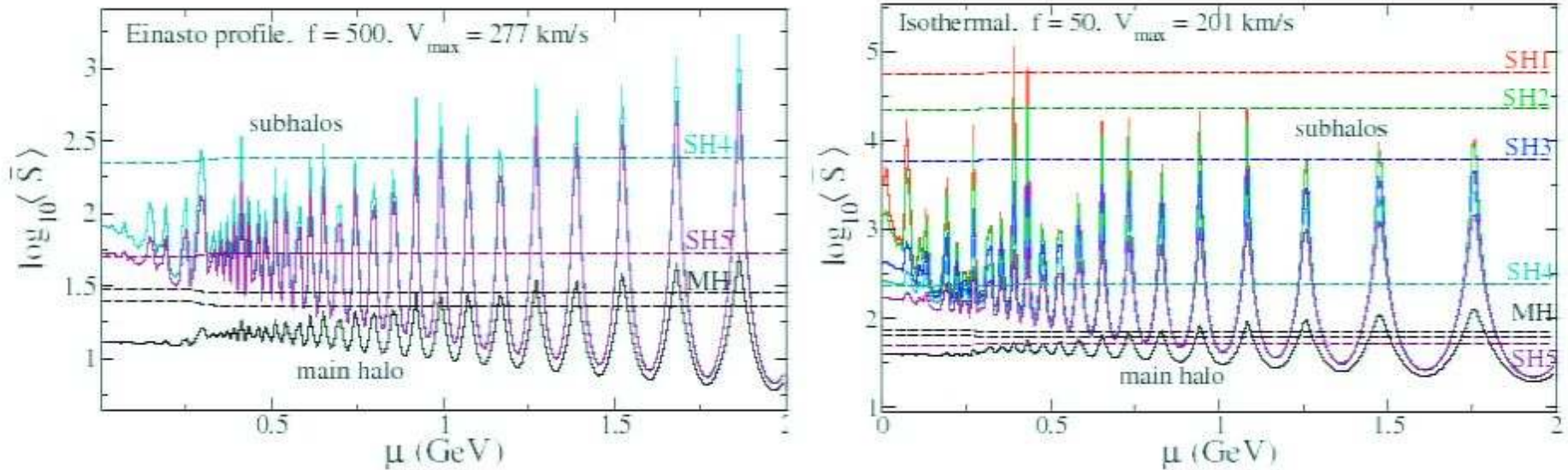
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# Specific realizations

Predicted versus desired (or upper limit) boost factors:



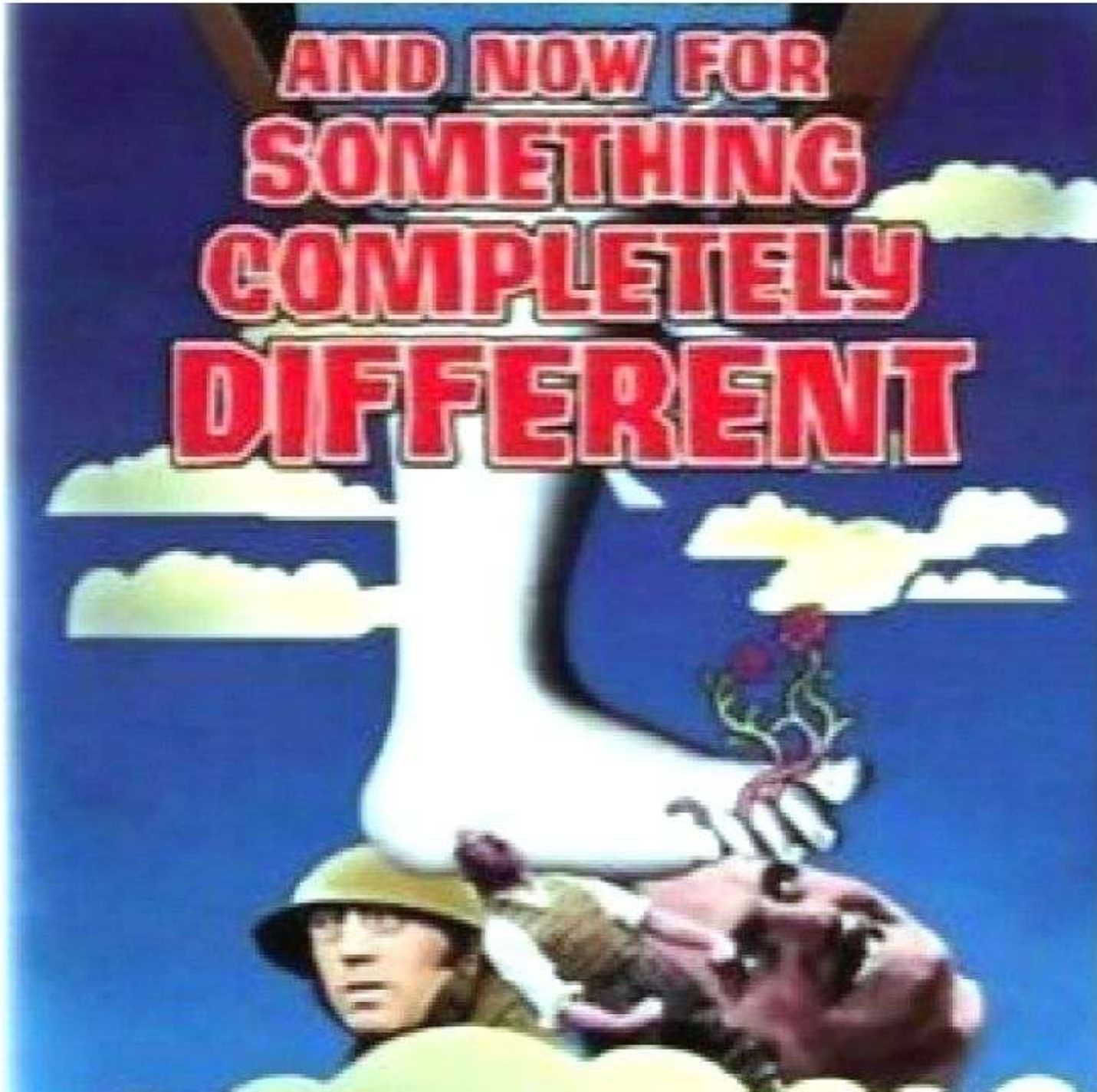
Points of intersection for subhalos are successful models

Main halo curve must lie below ICS bound

Can further reduce boost factors by taking larger  $f$

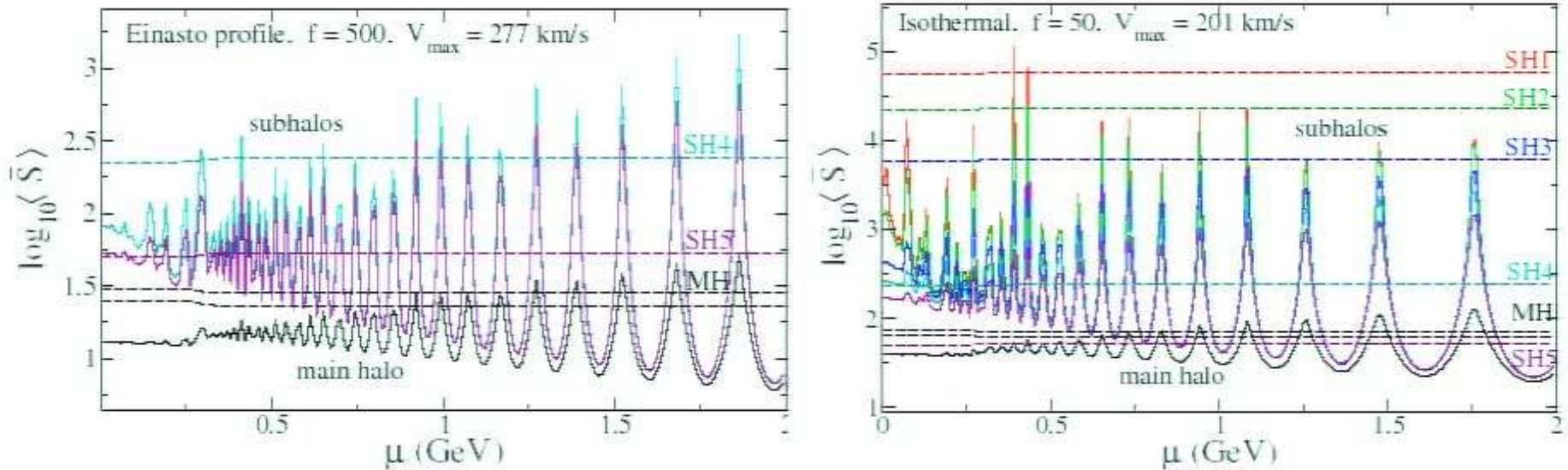
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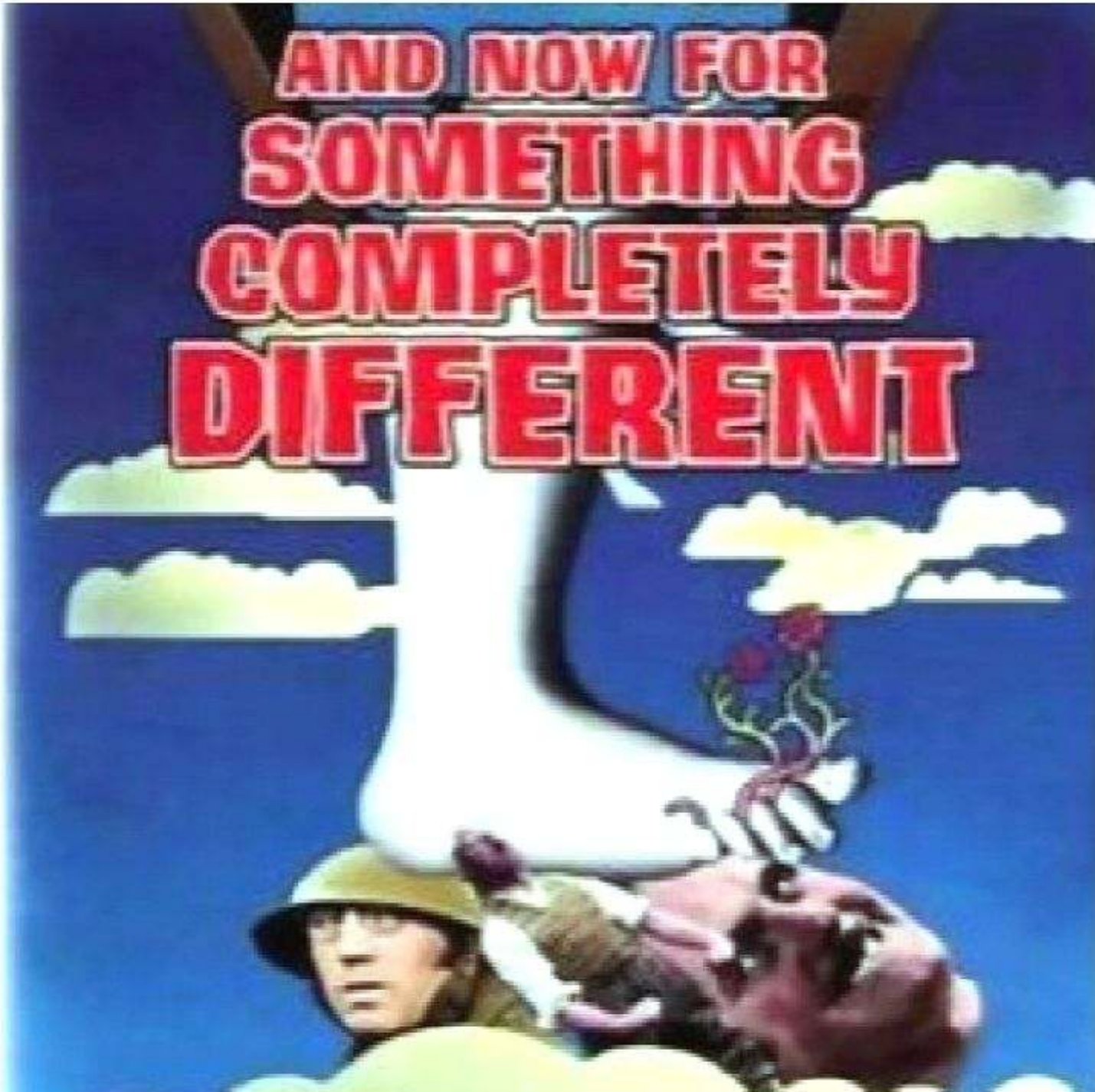
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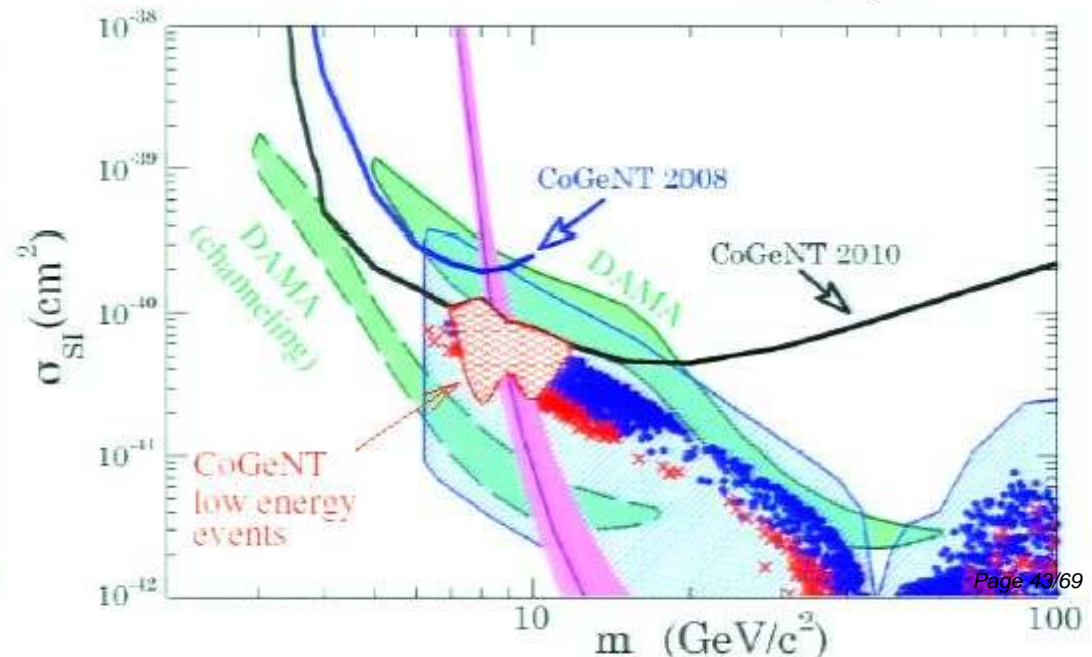
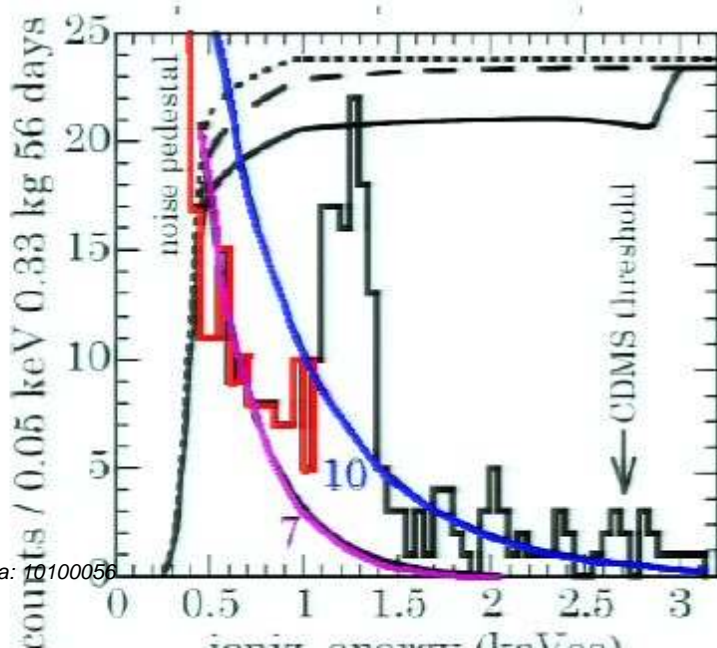
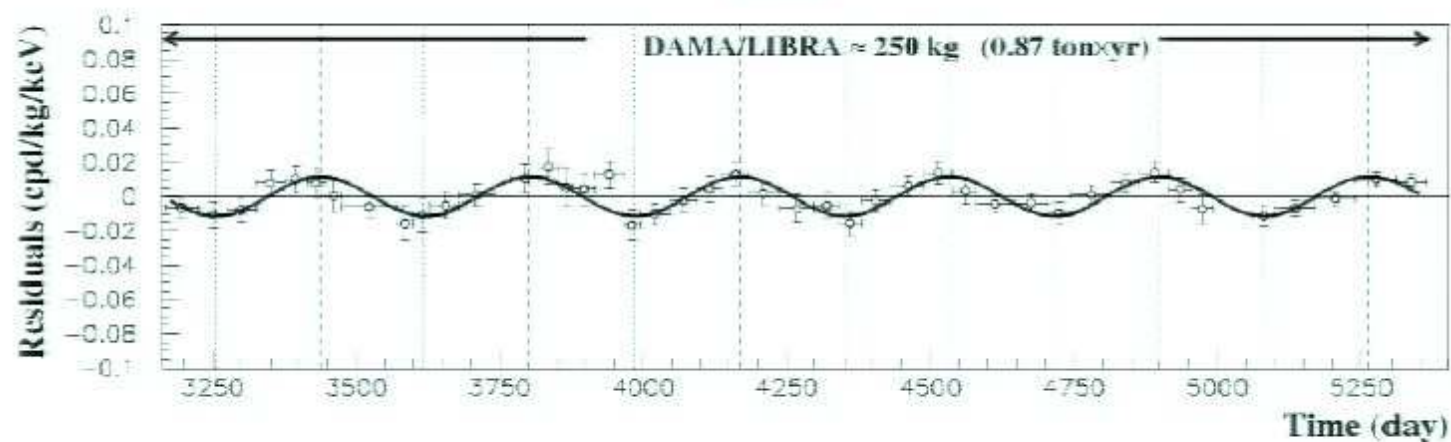
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Well, not quite...

# Light hidden sector dark matter

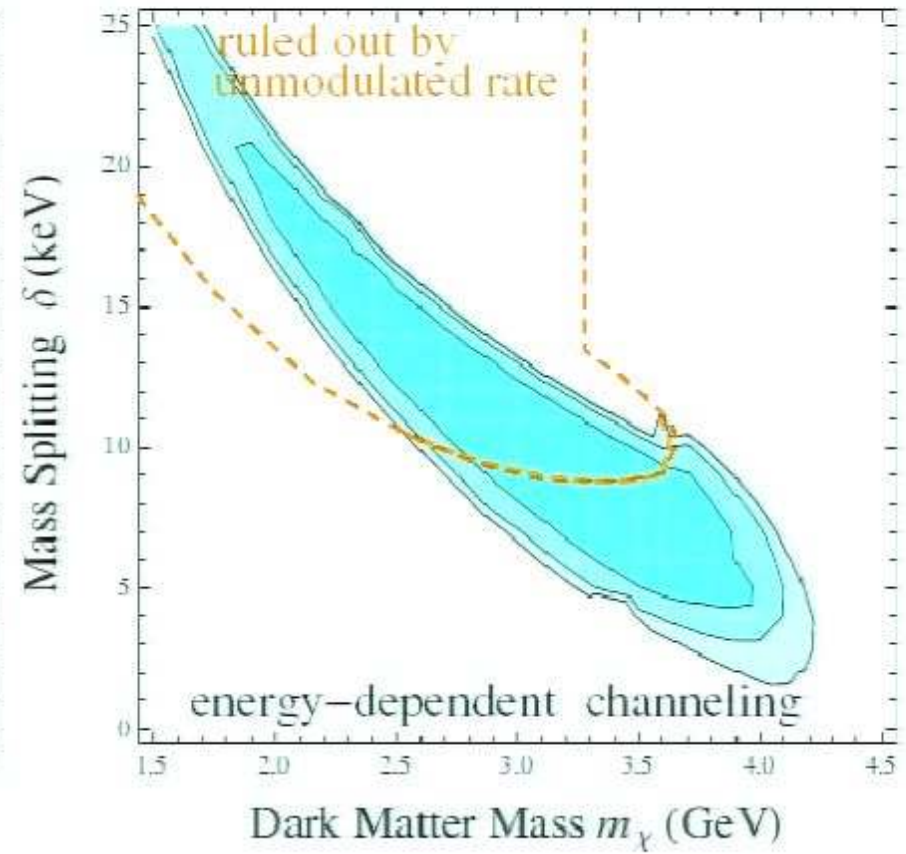
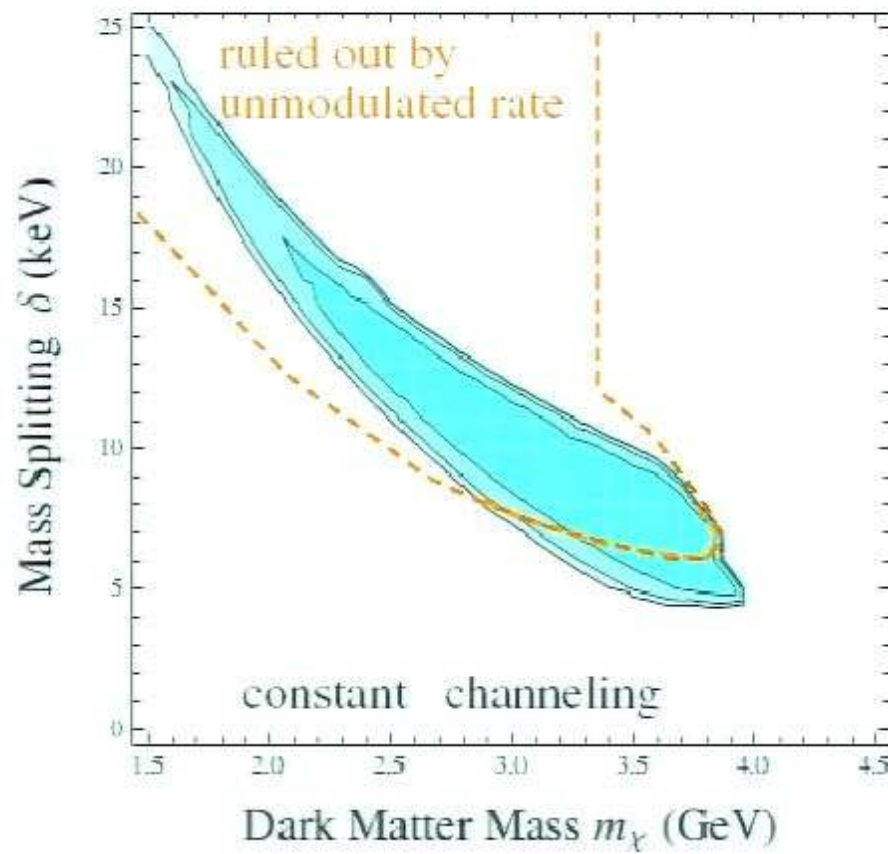
A way to recover DM explanation of 511 keV excess,  
 + DAMA annual modulation + CoGeNT excess events

2-6 keV



# Exothermic dark matter?

Graham *et al.* 1004.0937: exothermic transitions  $\chi_2 N \rightarrow \chi_1 N'$  with  $M_\chi \sim 4$  GeV,  $\delta M_\chi \sim 5$  keV can explain DAMA modulation

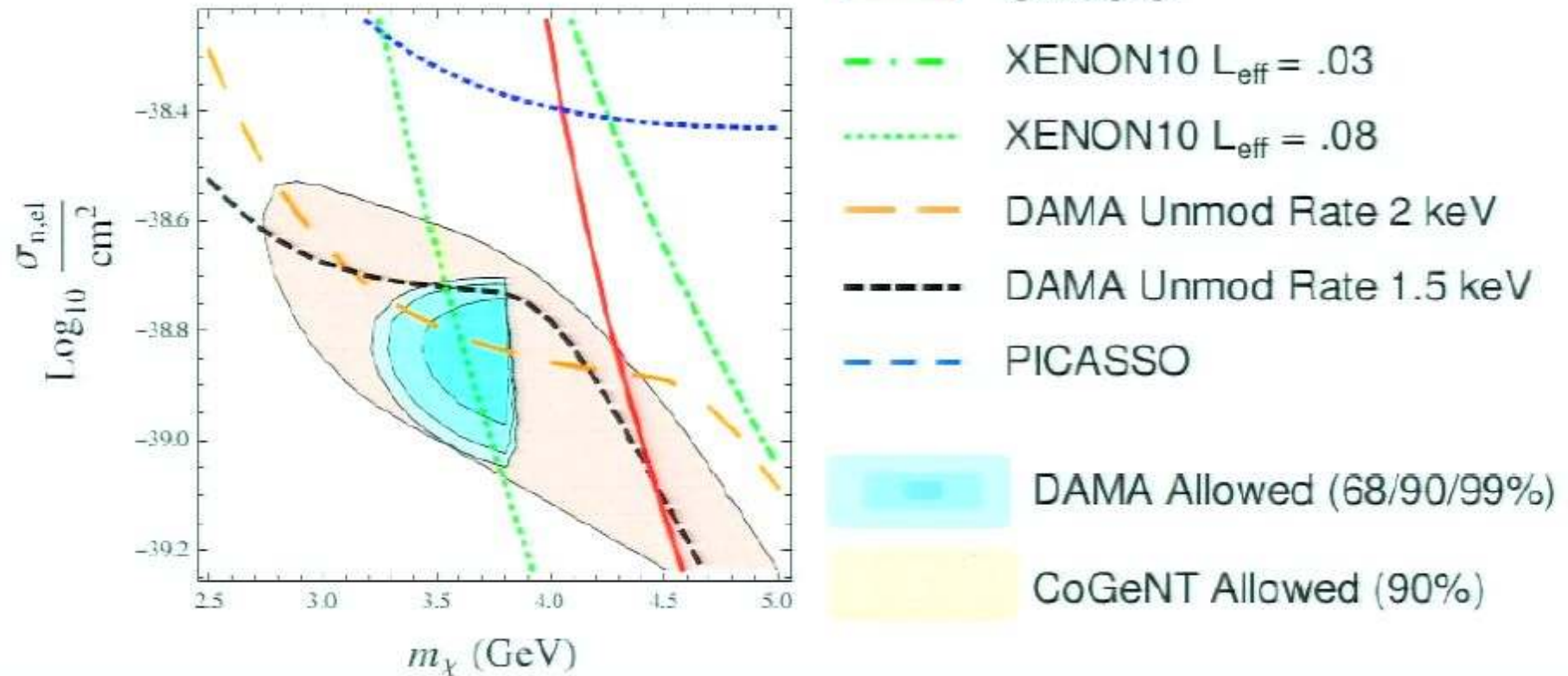


Shape of exothermic recoil energy spectrum is sensitive to DM velocity

# Exothermic dark matter?

Graham *et al.* 1004.0937: exothermic transitions can also explain CoGeNT excess events

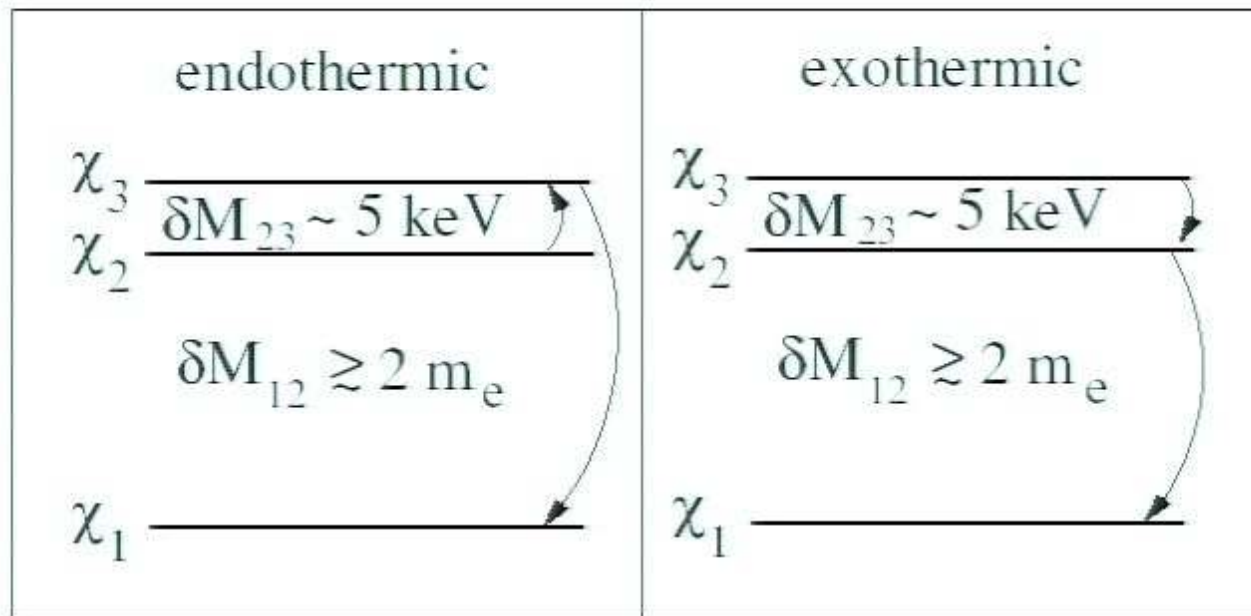
$$\delta = 6 \text{ keV}$$



# Getting the 511 keV signal in addition

JC, Frey, Chen 1008.1784: Add a third state below these two to get  $\chi_{2,3} \rightarrow \chi_1 e^+ e^-$  transitions.

We argue that either exothermic or endothermic transitions can work for DAMA/CoGeNT. (Slightly endothermic is as good as elastic.)



Just need one DM state to be metastable on 10 Gy time scale.

Page 46/69

( $\epsilon < 10^{-9}$  for decay of metastable state)

# Particle physics model

Same as before,

$$\mathcal{L}_\chi = \frac{1}{2} \bar{\chi}_i (i \not{D}_{ij} - M_\chi \delta_{ij}) \chi_j - \frac{1}{4g^2} B_{\mu\nu}^a B_a^{\mu\nu} - \sum_n \frac{1}{\Lambda_n} \Delta_a^{(n)} B_a^{\mu\nu} Y_{\mu\nu}$$

but need extra source of large mass splitting,

$$\frac{1}{2} y \bar{\chi}_i \Sigma_{ij} \chi_j$$

via quintuplet VEV  $\langle \Sigma_{ij} \rangle$ . Can naturally arrange

$$\delta M_{12} \sim \delta M_{13} \sim y \langle \Sigma \rangle \sim \text{MeV}$$

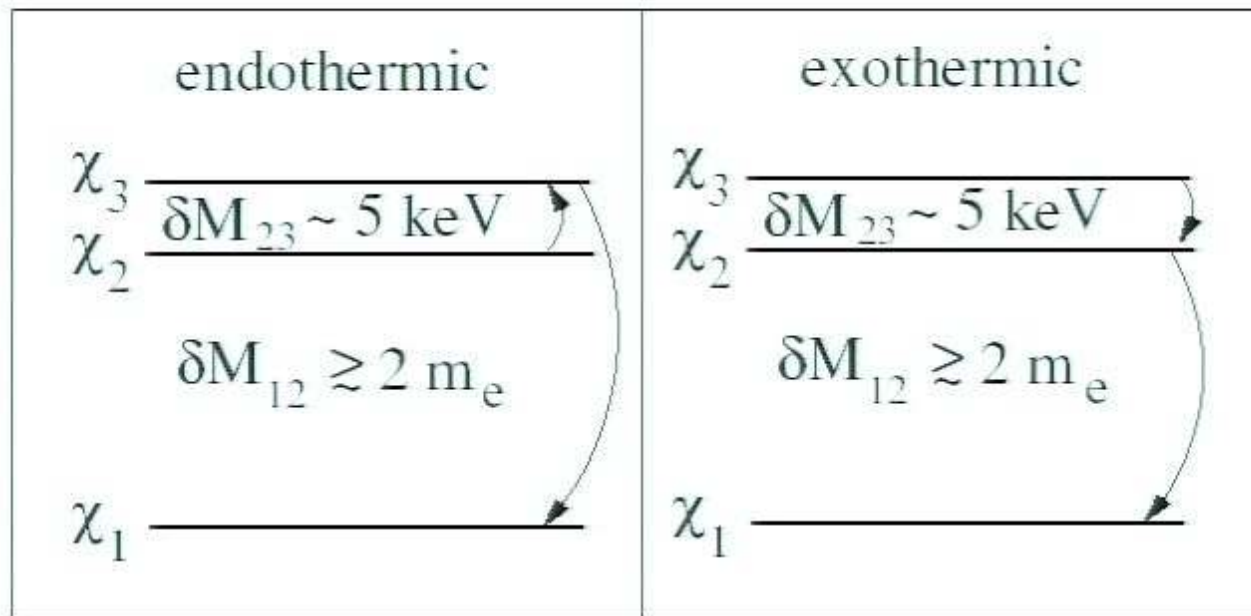
$$\delta M_{23} \sim \alpha_g (\mu_2 - \mu_3) \sim \text{keV}$$

with  $\alpha_g \sim 10^{-4}$  (relic density),  $y \sim 10^{-4}$ ,  $\langle \Delta^{(i)} \rangle \sim \langle \Sigma \rangle \sim 10 \text{ GeV}$ .

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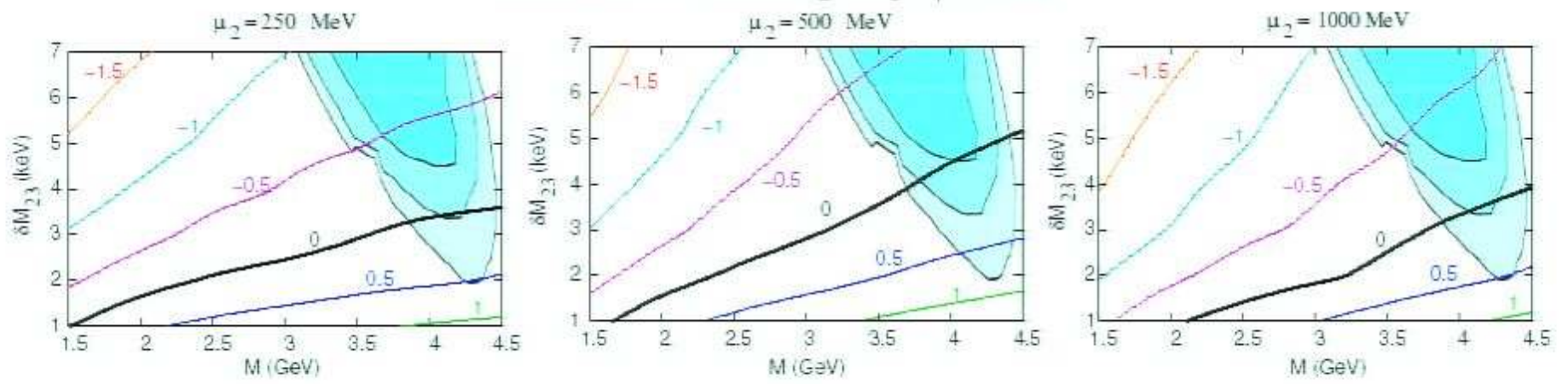
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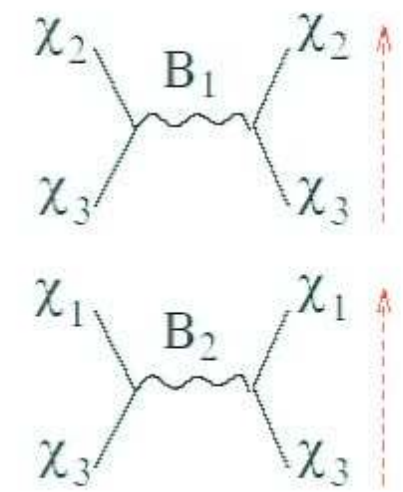
# 511 keV rate for exothermic DM

Contours of  $\log R_{e^+}/R_{obs}$



Rate of  $\chi_3\chi_3 \rightarrow \chi_2\chi_2$  at galactic center prefers smaller  $\mu_1$

Relic density of  $\chi_3$  due to  $\chi_3\chi_3 \rightarrow \chi_1\chi_1$  in early universe prefers larger  $\mu_2$



Gauge boson masses are related by symmetry breaking

mechanism (dark Higgs content):  $\mu_1 \gtrsim \sqrt{\mu_3^2 - \mu_2^2} \sim 2\sqrt{\mu_2} \delta M_{23} / \alpha_d$

# Caution: cuspy DM profile required!

We used  $\alpha = 0.065$ ,  $r_s = 5.3$  kpc Einasto profile. Much cuspier than “standard”  $\alpha = 0.17$ ,  $r_s = 20$  kpc.

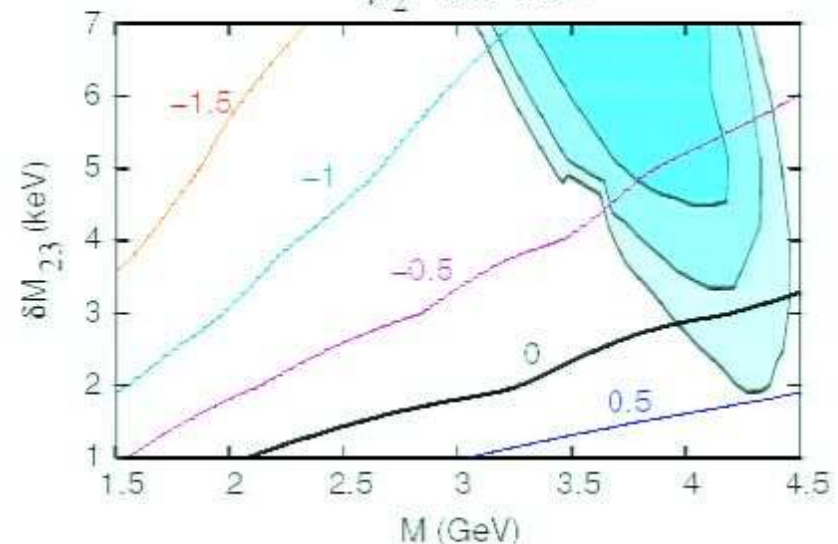
Rationale: DM simulations with baryons get cuspier profiles

Tissera *et al.* 0911.2316

Milky-way-like halos  
from Aquarius simulation

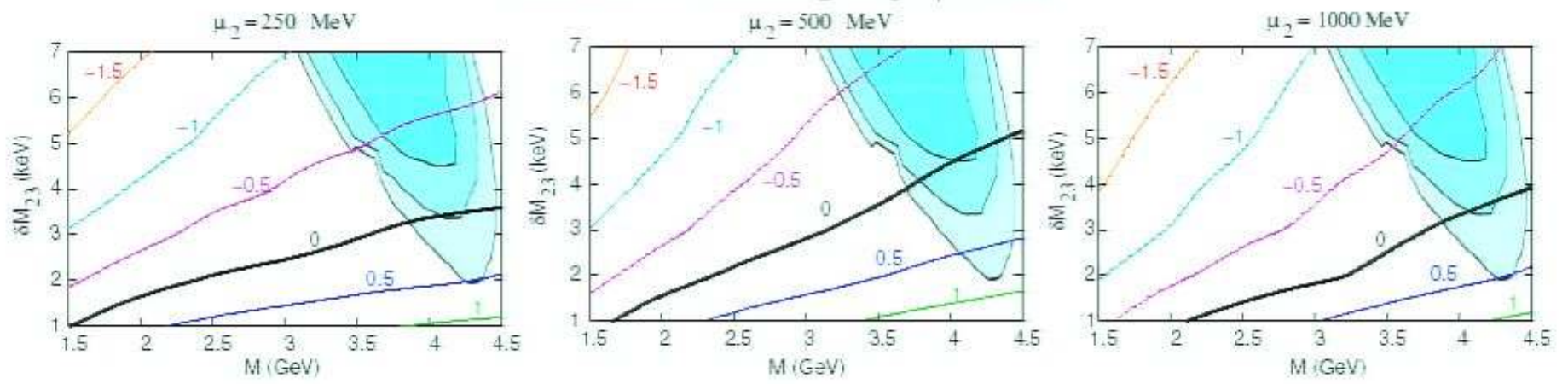
Galaxy	$\alpha$	$r_s$ (kpc)
Aq-A-5	0.065	5.3
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$\log R_{e+}/R_{\text{obs}}$  contours  
using  $\alpha = 0.08$ ,  $r_s = 7.5$  kpc:  
 $\mu_2 = 500$  MeV



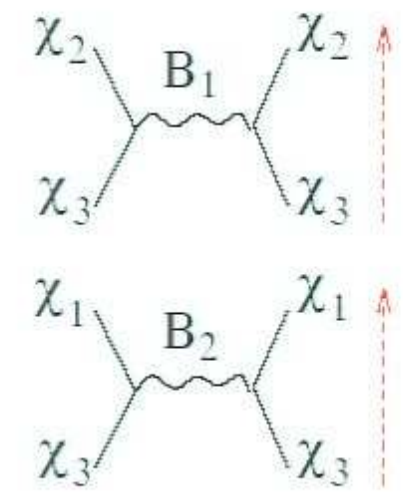
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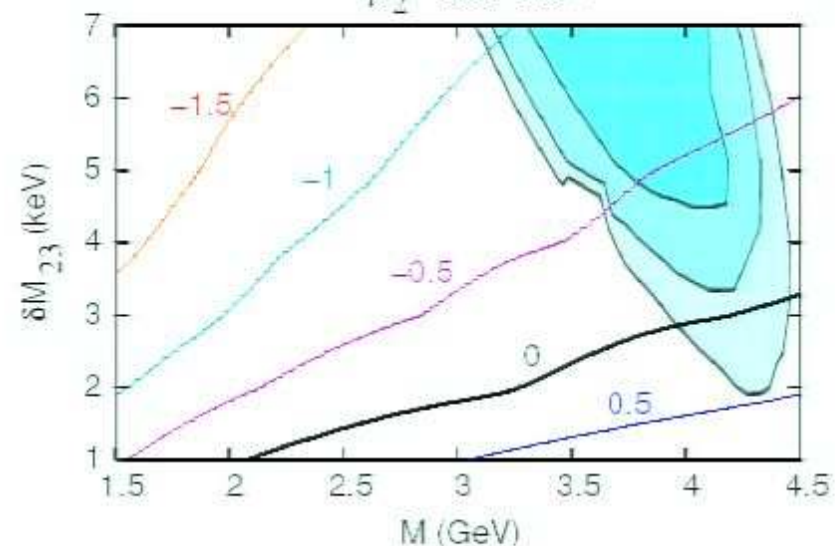
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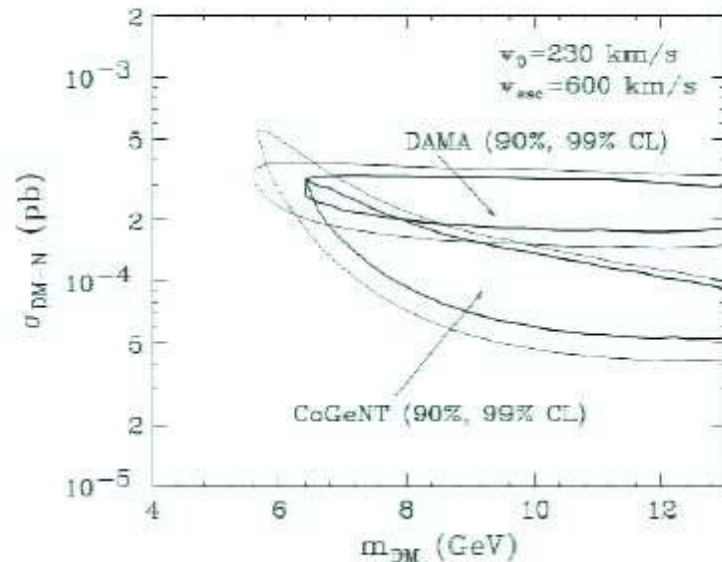
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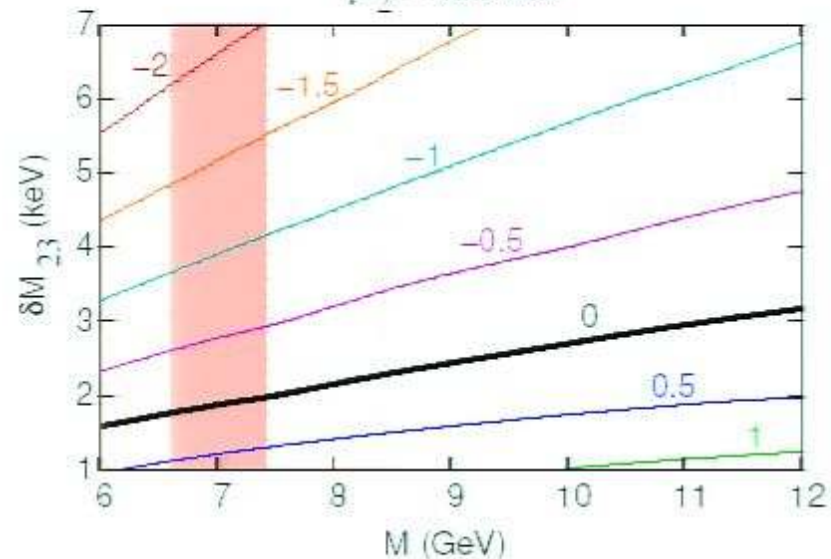
# 511 keV rate for endothermic DM

Less cuspy profiles are needed:

Hooper *et al.* 1007.1007



using  $\alpha = 0.12$ ,  $r_s = 12$  kpc:  
 $\mu_2 = 500$  MeV



Relic density of  $\chi_2$  due to  $\chi_2\chi_2 \rightarrow \chi_1\chi_1$  in early universe prefers larger  $\mu_3$ , which is heaviest of the 3 gauge bosons,

$$\mu_3 = \mu_2 + \frac{2}{\alpha_g} \delta M_{23}$$

# Decaying DM scenario

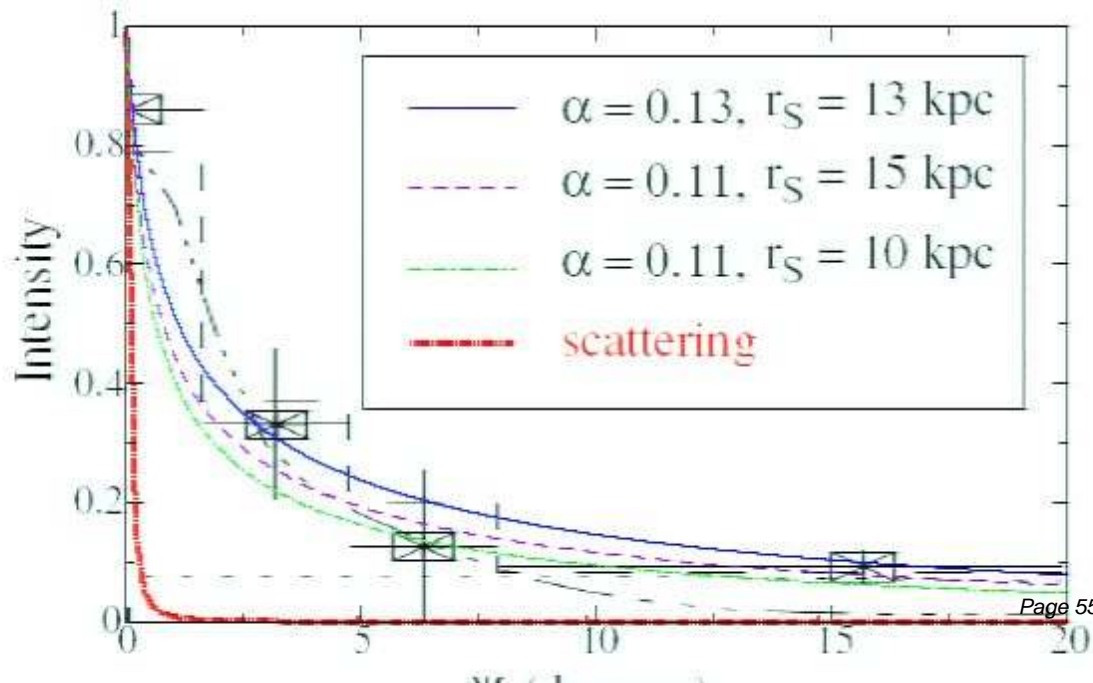
Lifetime of metastable state  $\chi_2$  or  $\chi_3$  is controlled by kinetic mixing parameter  $\epsilon_3$  or  $\epsilon_2$ ,

$$\mathcal{L}_{\text{kin}} = \sum_i \epsilon_i B_{\mu\nu}^i F^{\mu\nu}$$

where  $\epsilon_i = \langle \Delta_i \rangle / \Lambda_i$ . If  $\epsilon_{3,2} \sim 10^{-11}$  then intermediate state is already present; decays  $\chi_{2,3} \rightarrow \chi_1 e^+ e^-$  give observed rate of positrons, no need for collisions in galactic center.

Angular distribution of 511 keV signal could reflect DM halo profile; consistent with less cuspy profile

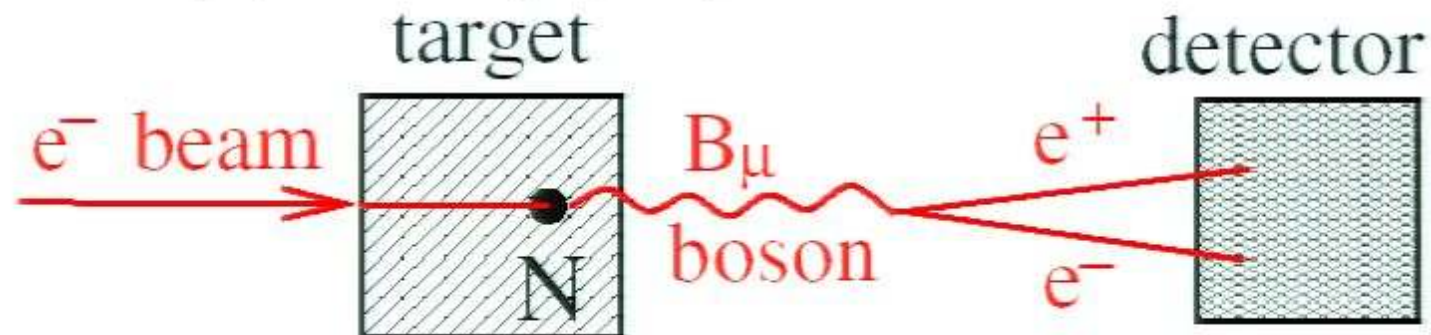
if scattering, positron transport before annihilation required



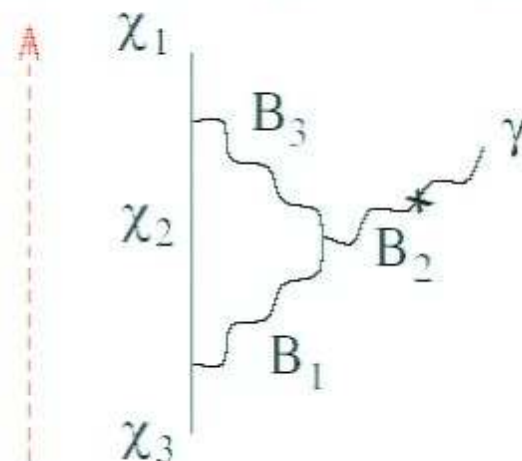
# Are there other predictions?

We would like to test the DM annihilation hypothesis using independent observables.

- Beam dump (fixed target) experiments



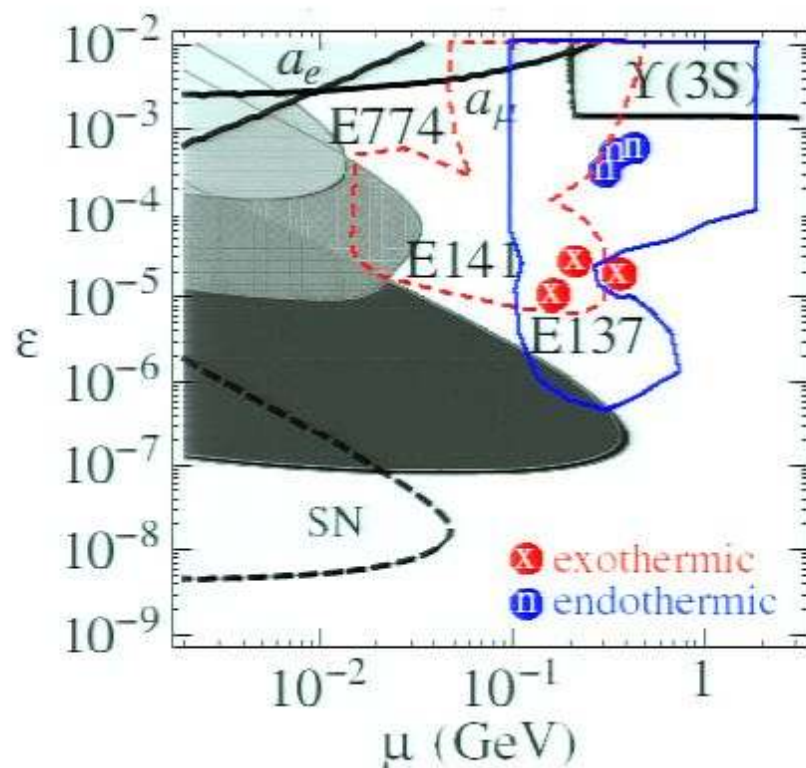
- Monoenergetic  $\gamma$  ray from  $\chi_3 \rightarrow \chi_1 \gamma$  at galactic center



transition magnetic  
moment interaction  
(Chen, JC, Frey,  
0907.0746)

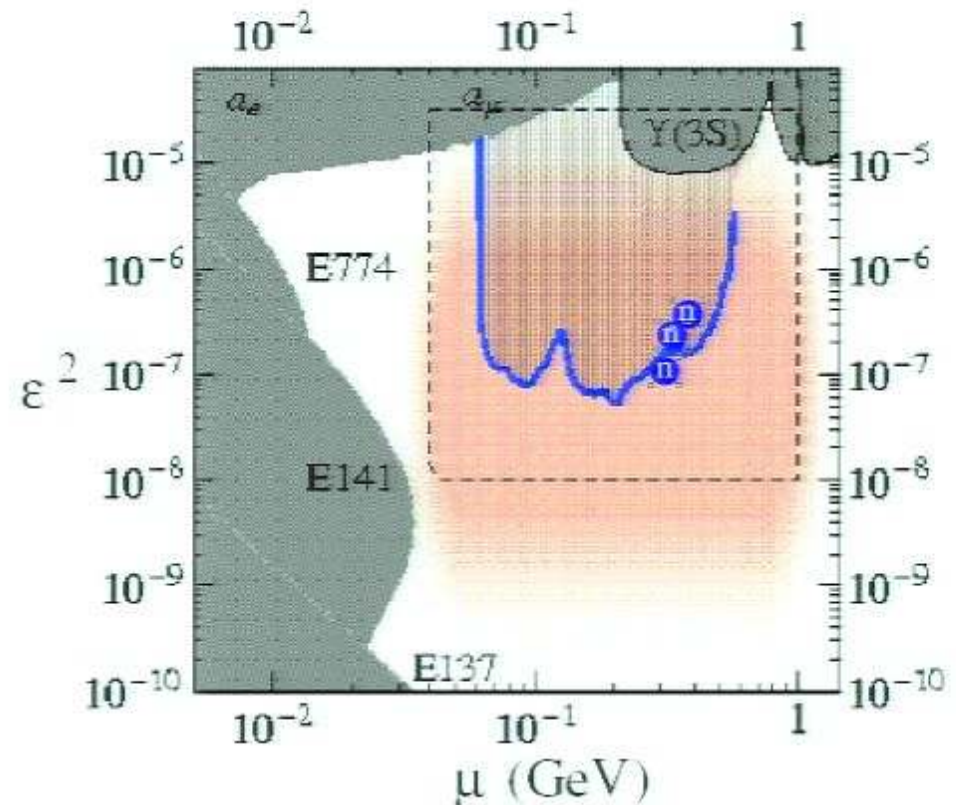
# Laboratory and other probes

Kinetic mixing  $\epsilon$  and gauge boson mass  $\mu$  parameter space is not highly constrained; provides opportunities for new fixed target searches. **Predictions of our model:**



Existing and proposed experiments

Bjorken *et al.* 0906.0580



APEX reach

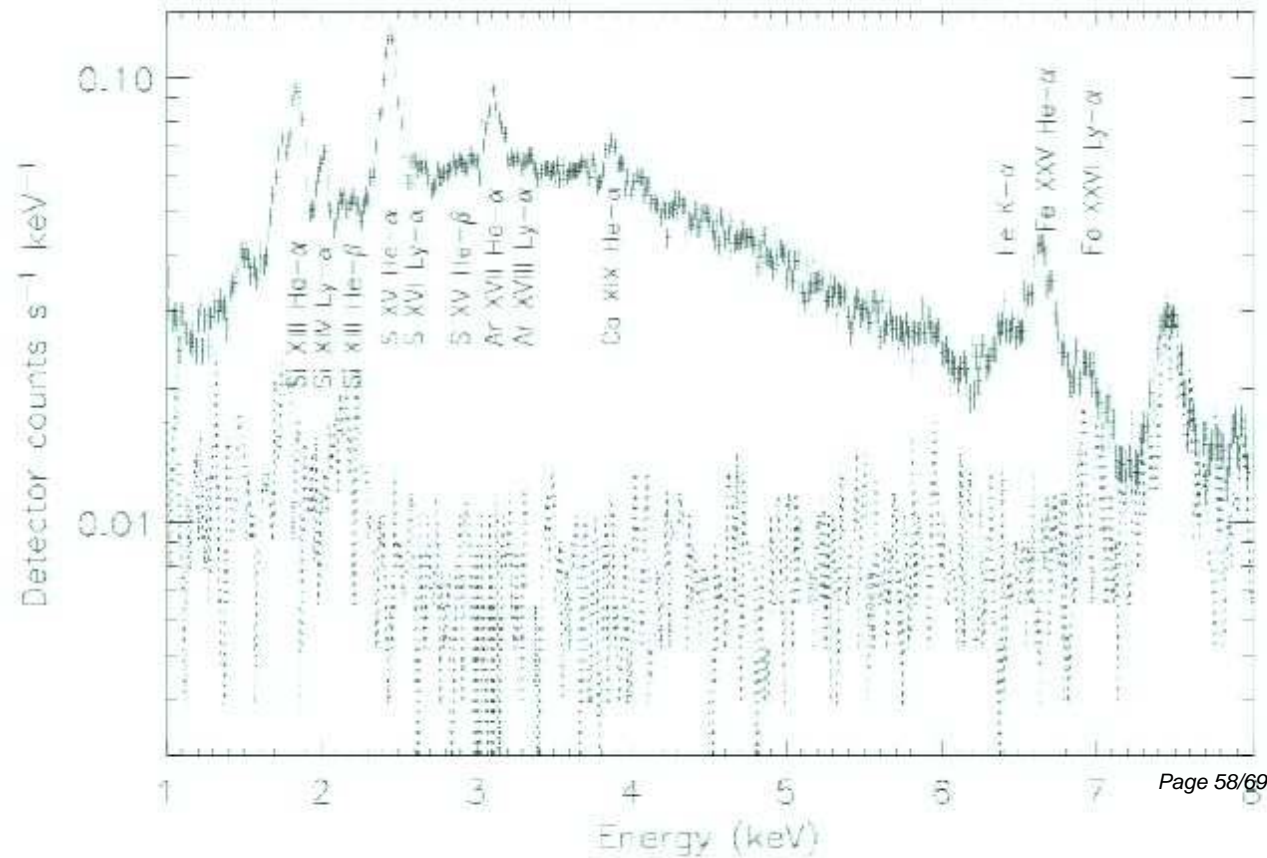
Essig *et al.* 1001.2557

# $\chi_3 \rightarrow \chi_{1,2} + \gamma$ decays in galaxy

After  $\chi_2\chi_2 \rightarrow \chi_3\chi_3$  excitation, transition magnetic moment leads to  $\chi_3 \rightarrow \chi_1\gamma$  as well as  $\chi_3 \rightarrow \chi_1e^+e^-$ .

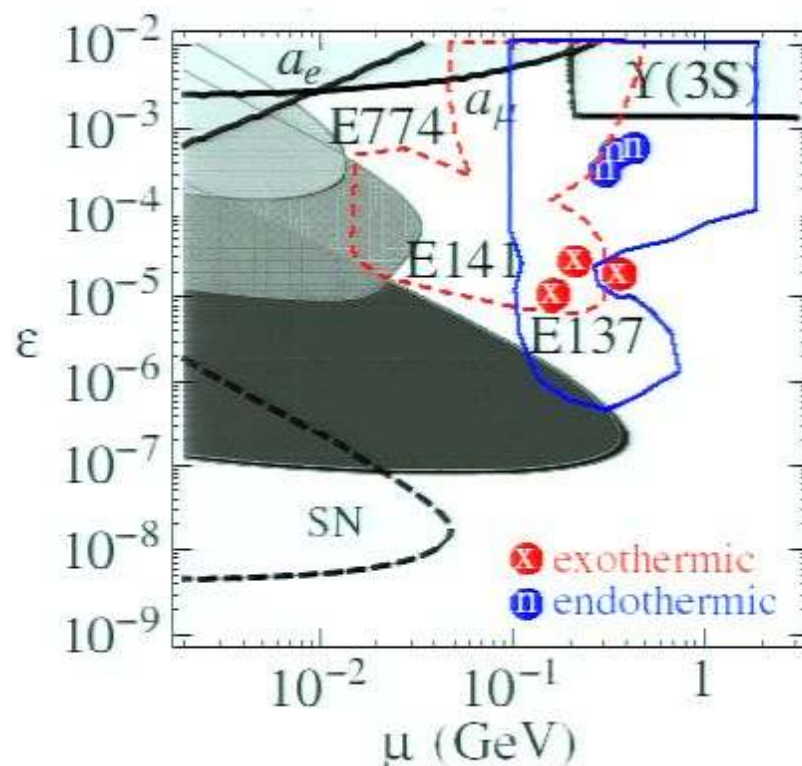
Could INTEGRAL could potentially see this  $\sim 1$  MeV  $\gamma$ ?  
We find it is too weak.

But in exothermic model, analogous decay  $\chi_3 \rightarrow \chi_2\gamma$  with  $E_\gamma \sim 5$  keV may already be ruled out by Chandra



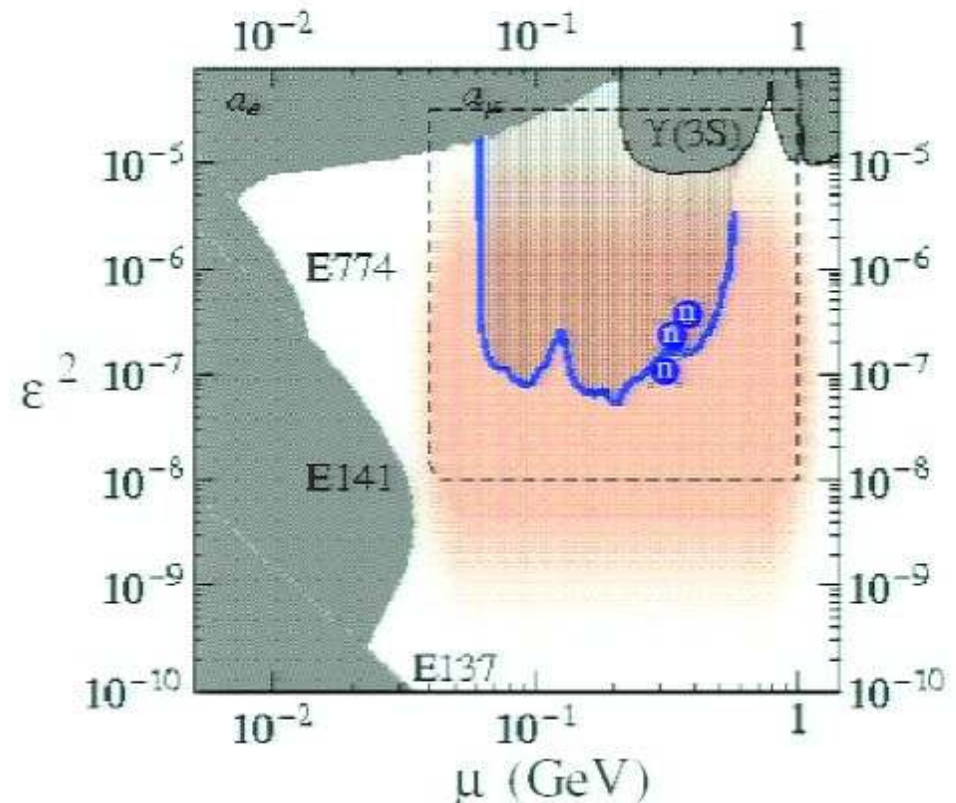
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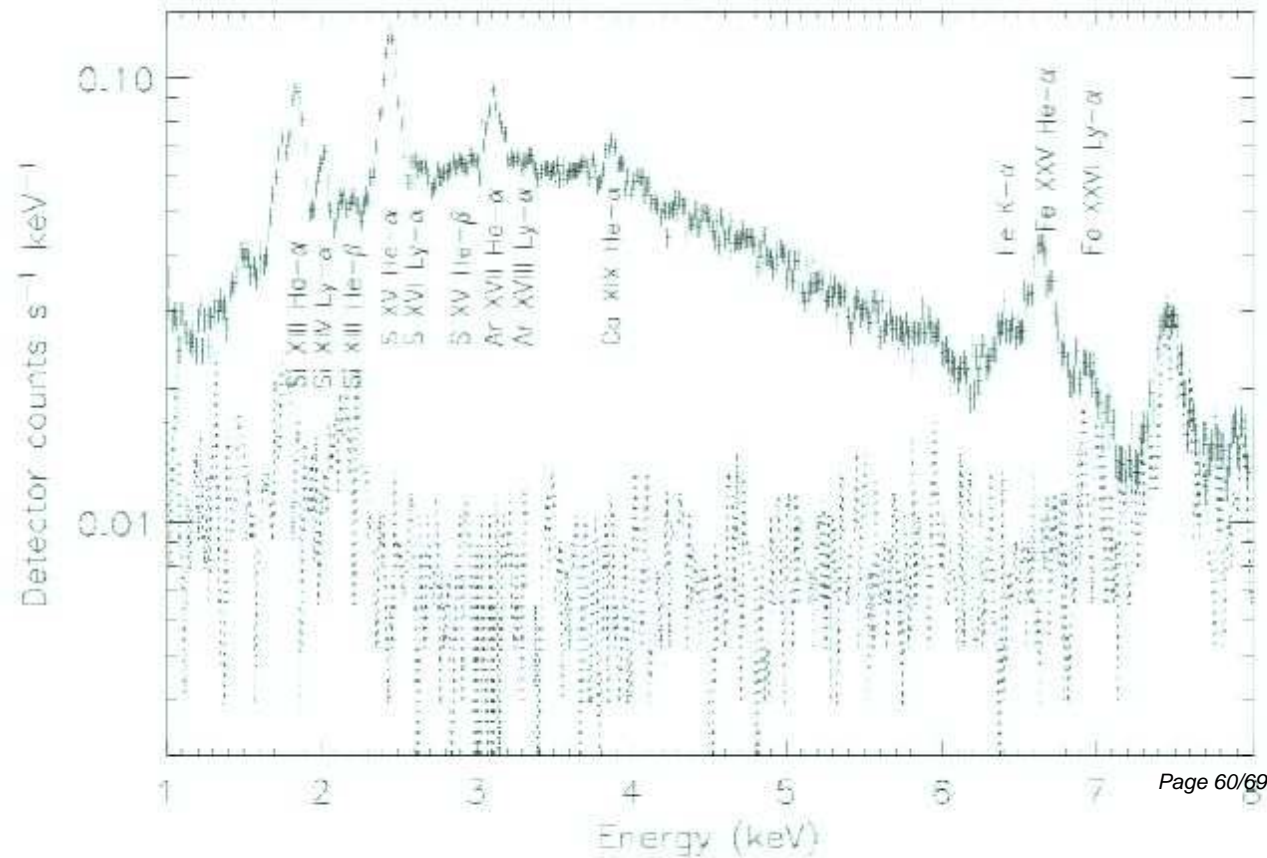
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# Conclusions

Heavy hidden sector SU(2) triplet DM can (with some tuning) explain PAMELA, Fermi/LAT cosmic ray anomalies

Light hidden sector DM can explain DAMA and CoGeNT observations, as well as INTEGRAL 511 keV excess

Other kinds of models could explain DAMA/CoGeNT, but if DM is responsible for 511 keV, multicomponent model seems like best bet

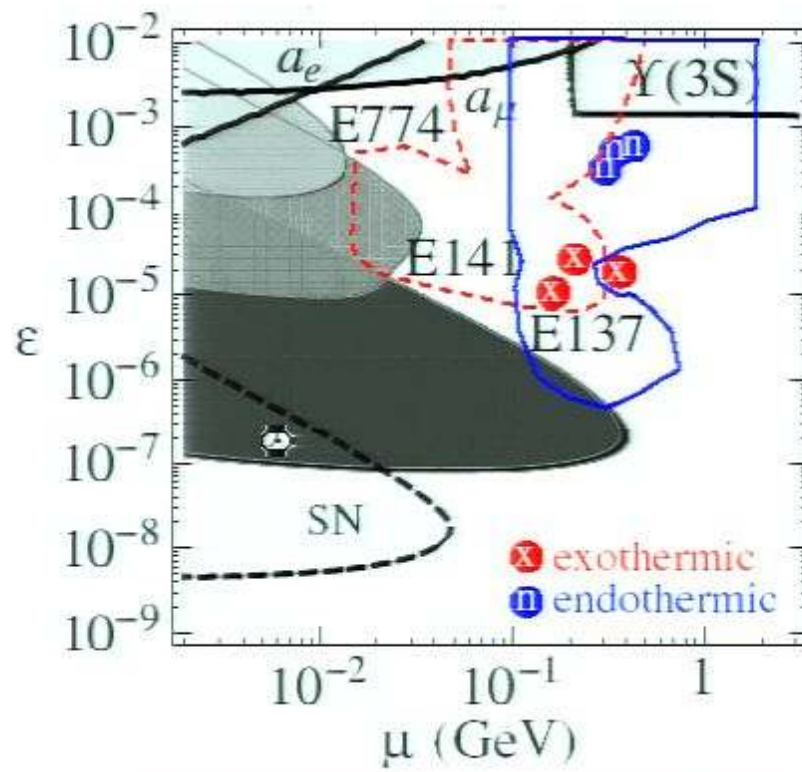
Astrophysical mechanisms for excess 511 keV remain unconvincing

Fixed target experiments, monochromatic galactic MeV  $\gamma$ , direct detection, could be complementary probes

A higher resolution instrument than INTEGRAL could help us solve the 511 keV mystery

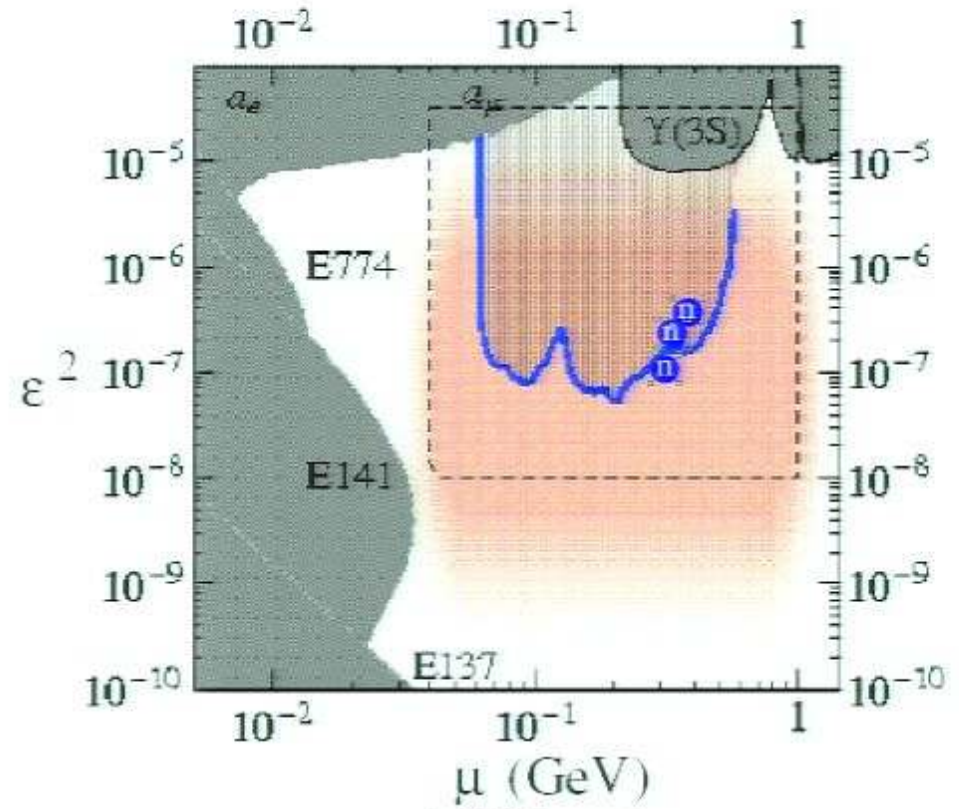
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*Essig et al. 1001.2557*

# Hidden sector dark matter: direct detection and cosmic ray anomalies

Jim Cline, McGill U. & PI

Perimeter Institute, 5 Oct. '10

# A simple nonabelian DM model

- $SU(2)_{\text{dark}}$  gauge symmetry with triplet DM:

$$\mathcal{L}_\chi = \frac{1}{2} \bar{\chi}_i (i \overleftrightarrow{D}_{ij} - M_\chi \delta_{ij}) \chi_j - \frac{1}{4g^2} B_{\mu\nu}^a B_a^{\mu\nu} - \frac{1}{\Lambda} \Delta_a B_a^{\mu\nu} Y_{\mu\nu}$$

↗
↗
↗  
 dark matter                  dark gauge sector      mixing with SM

- Triplet VEV  $\langle \Delta_2 \rangle$  gives  $B_2$ - $\gamma$  mixing.
- We need second triplet  $\Delta'$  to fully split  $\chi_i$  states:

$$V_{\text{Higgs}} = \lambda(\Delta^2 - v^2)^2 + \lambda'(\Delta'^2 - v'^2)^2 + \lambda''(\vec{\Delta} \cdot \vec{\Delta}')^2$$

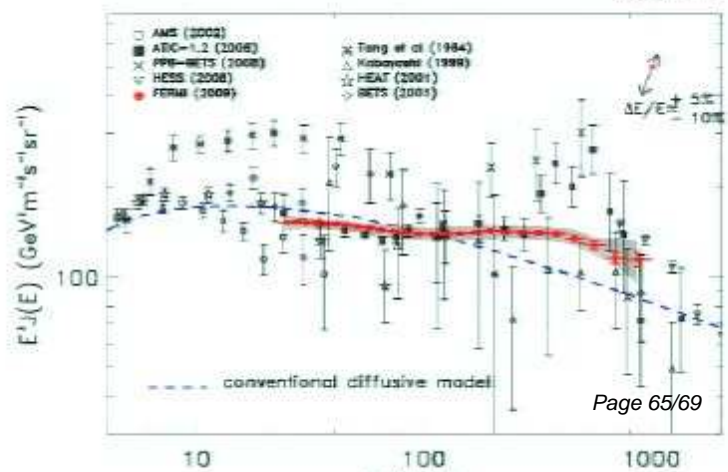
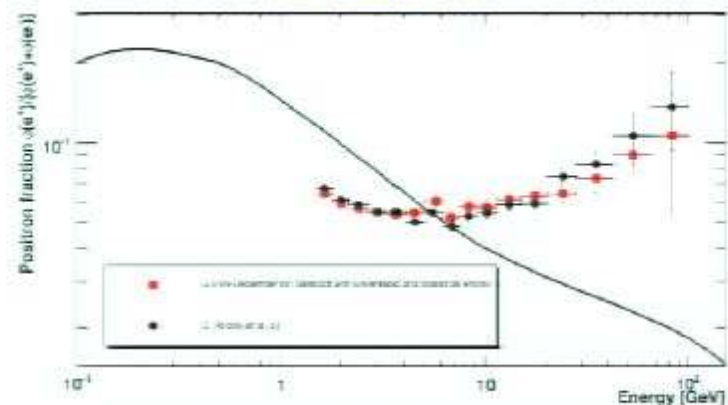
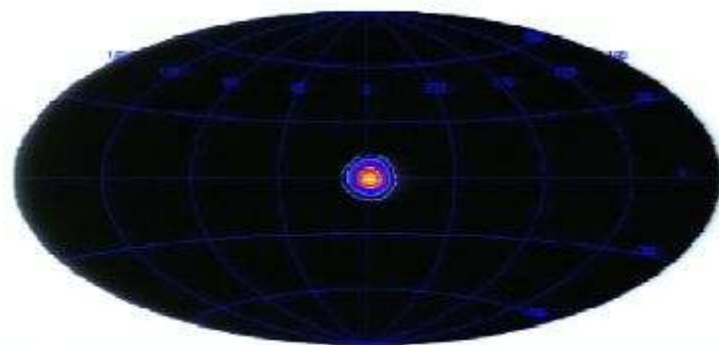
- Unbroken  $Z_2$  symmetry can play important role:

$$\chi_{1,3} \rightarrow -\chi_{1,3}, \quad B_{1,3} \rightarrow -B_{1,3}, \quad \Delta_{1,3} \rightarrow -\Delta_{1,3}, \quad \Delta'_{1,3} \rightarrow -\Delta'_{1,3}$$

$\chi_2, B_2, \Delta_2, \Delta'_2$  uncharged.

# The cosmic ray anomalies

- Excess 511 keV  $\gamma$ 's from galactic center, observed by INTEGRAL/SPI
- PAMELA positron excess at 10–100 GeV
- Fermi/LAT  $e^\pm$  excess at 100–1000 GeV



# Personal motivation

Galactic 511 keV  $\gamma$  ray excess has been observed since 1972.

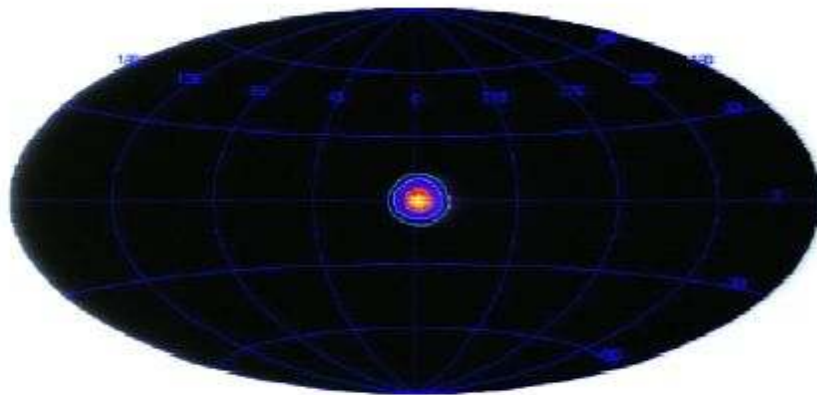


Figure 2. An MREM sky map of the 511 keV positron annihilation line emission. The contours indicate intensity levels of  $10^{-2}$ ,  $10^{-3}$ , and  $10^{-4}$   $\text{ph cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ . Details are given in the text.

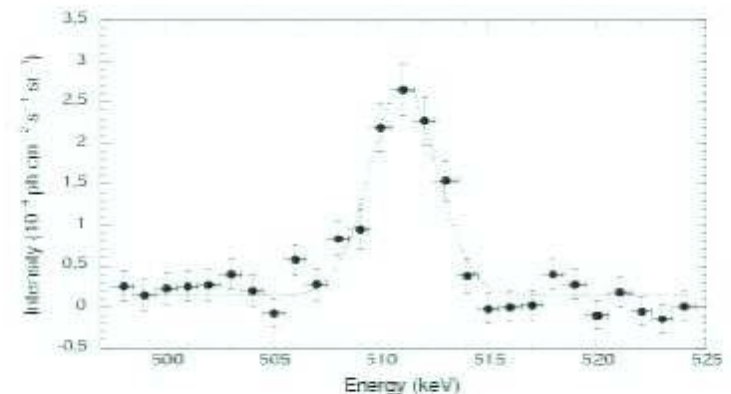


Fig. 3. 511 keV flux spectrum obtained using a gaussian centred on the GC with a FWHM of  $10^\circ$ .

So far no 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 gauge boson in beam dump experiments

# Conclusions

Heavy hidden sector SU(2) triplet DM can (with some tuning) explain PAMELA, Fermi/LAT cosmic ray anomalies

Light hidden sector DM can explain DAMA and CoGeNT observations, as well as INTEGRAL 511 keV excess

Other kinds of models could explain DAMA/CoGeNT, but if DM is responsible for 511 keV, multicomponent model seems like best bet

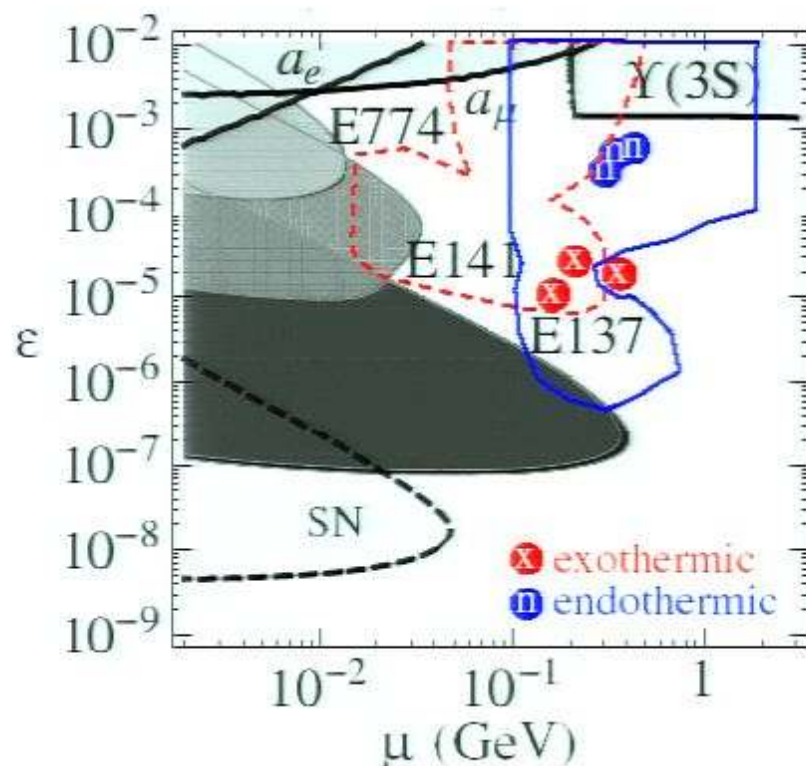
Astrophysical mechanisms for excess 511 keV remain unconvincing

Fixed target experiments, monochromatic galactic MeV  $\gamma$ , direct detection, could be complementary probes

A higher resolution instrument than INTEGRAL could help us solve the 511 keV mystery

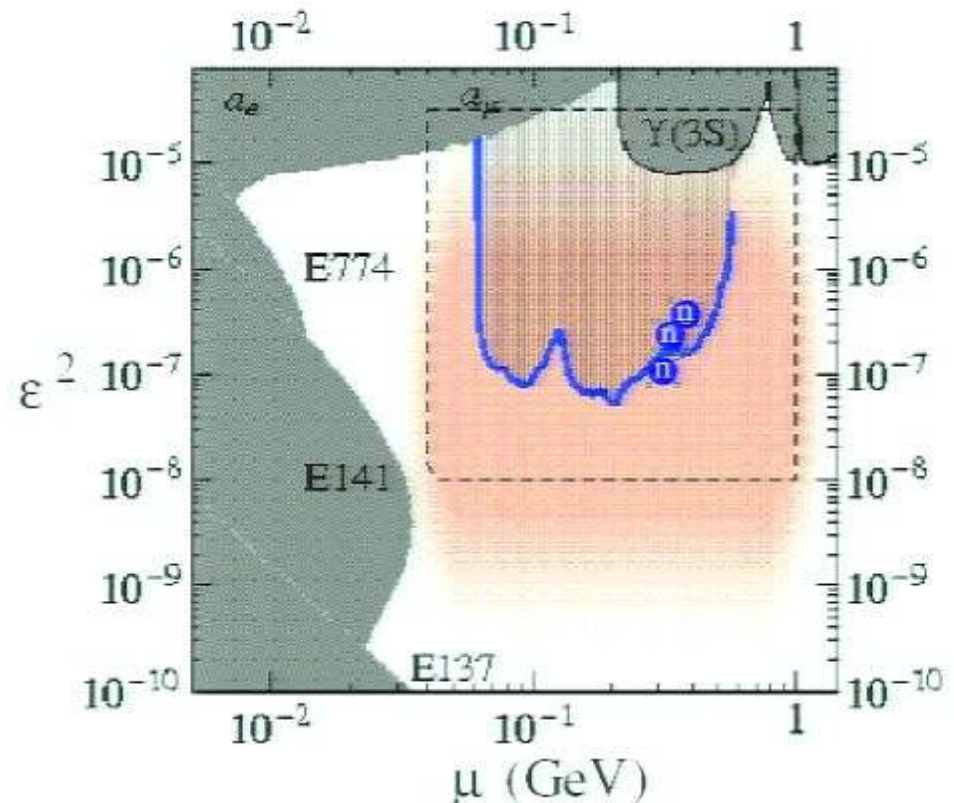
# Laboratory and other probes

Kinetic mixing  $\epsilon$  and gauge boson mass  $\mu$  parameter space is not highly constrained; provides opportunities for new fixed target searches. **Predictions of our model:**



Existing and proposed experiments

*Bjorken et al. 0906.0580*

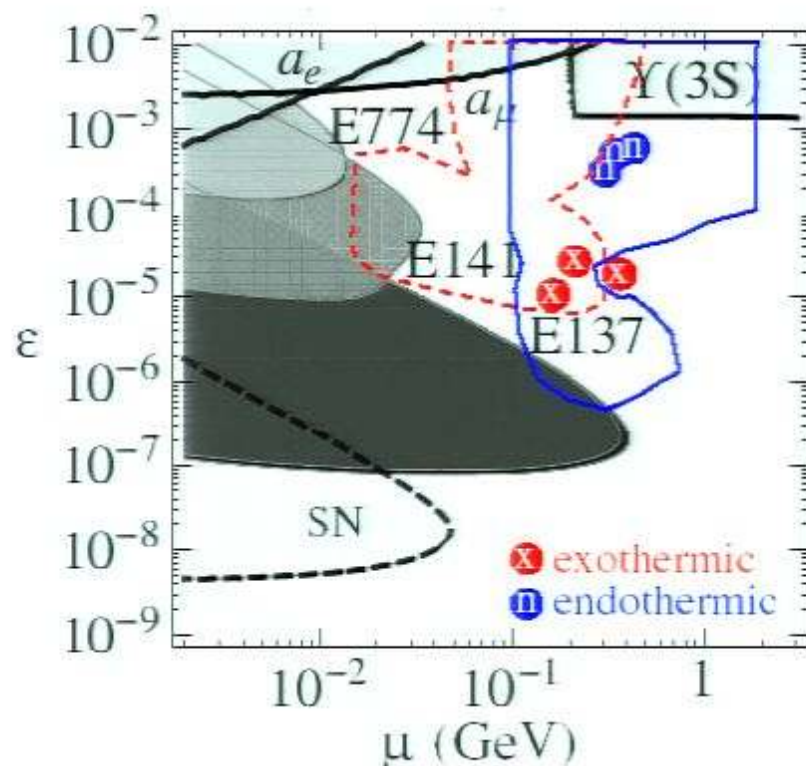


APEX reach

*Essig et al. 1001.2557*

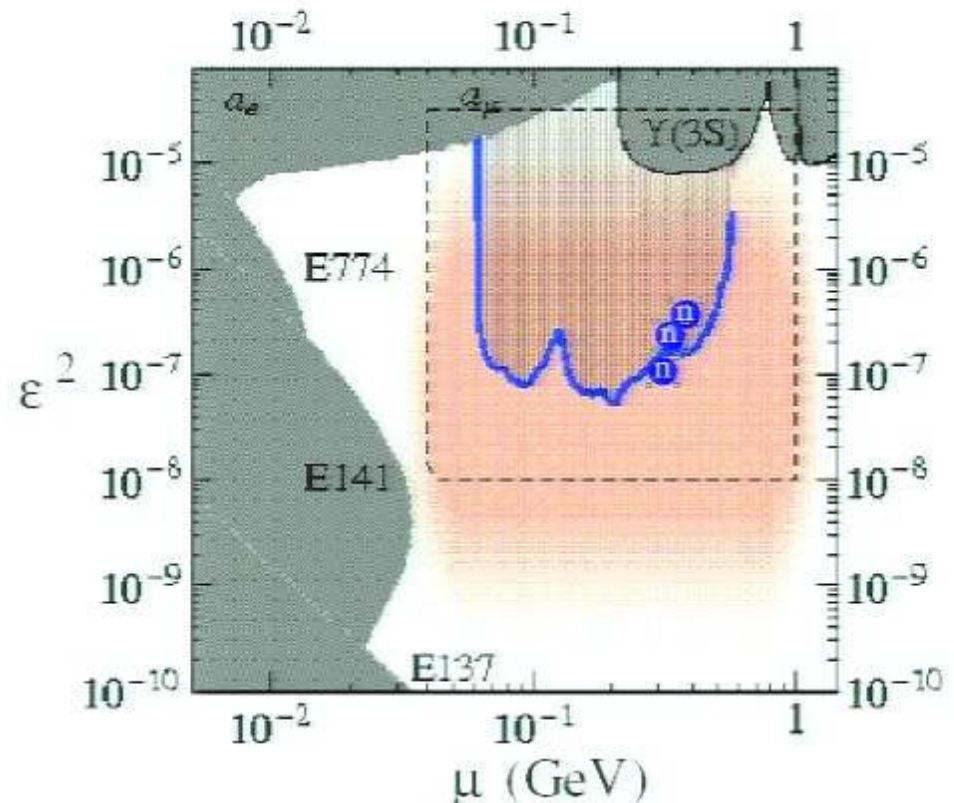
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