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

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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 γ rays and DAMA/CoGeNT events," (1008.1784)

Personal motivation

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

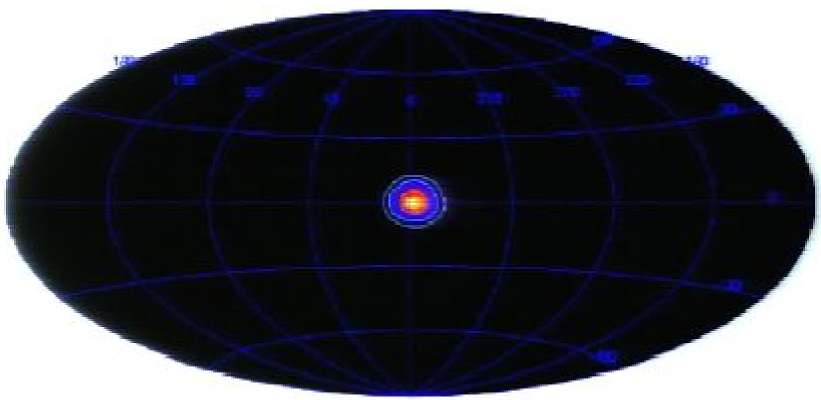

Figure 2. An MREM sky map of the 511 keV positron annihilation line emission. The contours indicate intensity levels of 10^{-2}, 10^{-3}, and 10^{-4} ph cm^{-2} s^{-1} sr^{-1}. Details are given in the text.

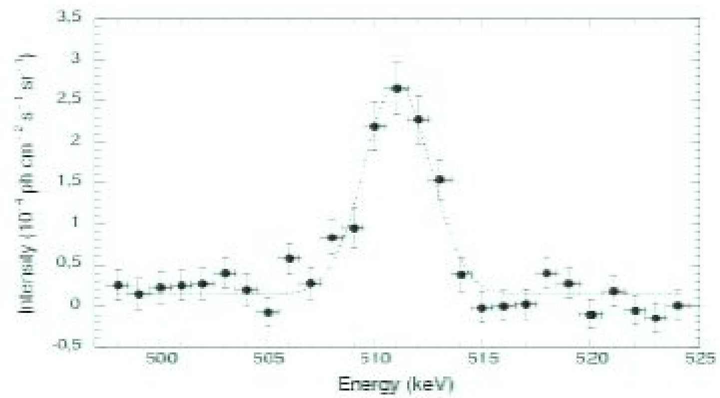

Fig. 3. 511 keV flux spectrum obtained using a gaussian centred on the GC with a FWHM of 10°.

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 ~GeV scale of breaking, this is all we need to explain several galactic cosmic ray anomalies (+ DAMA)

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

But to what extent can these anomalies really be explained?

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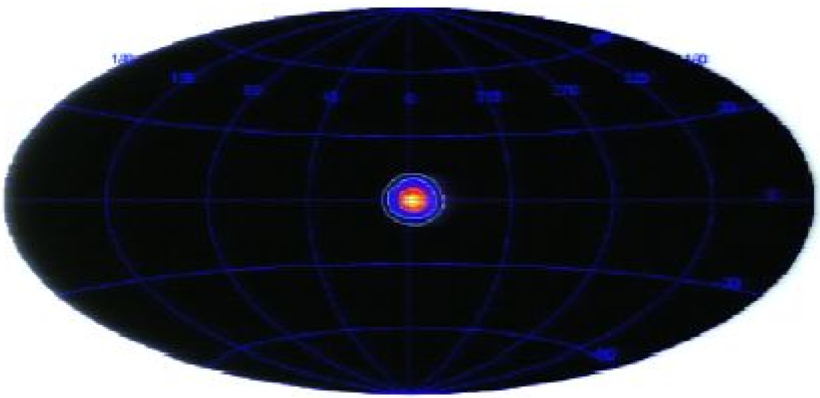

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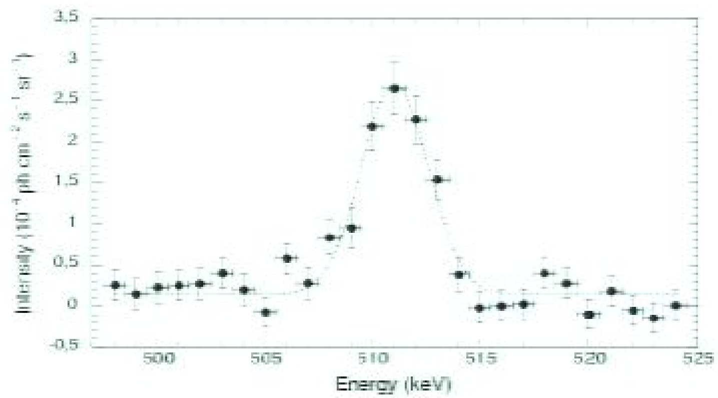

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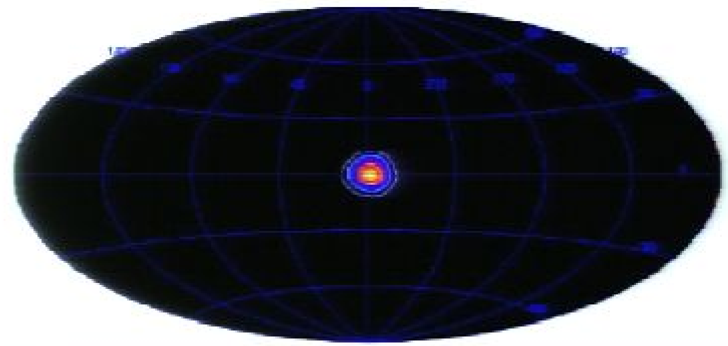
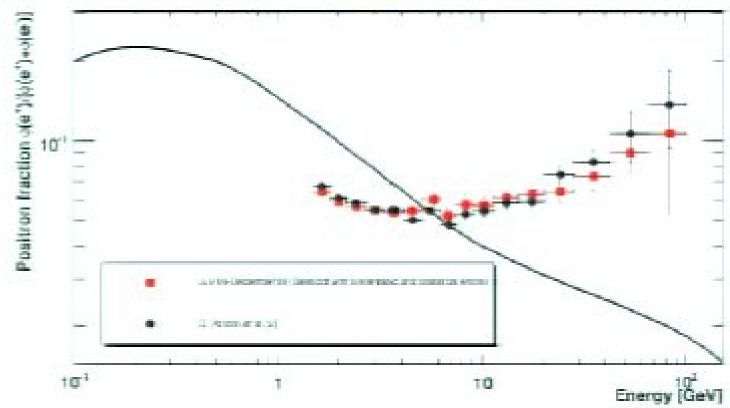
The cosmic ray anomalies

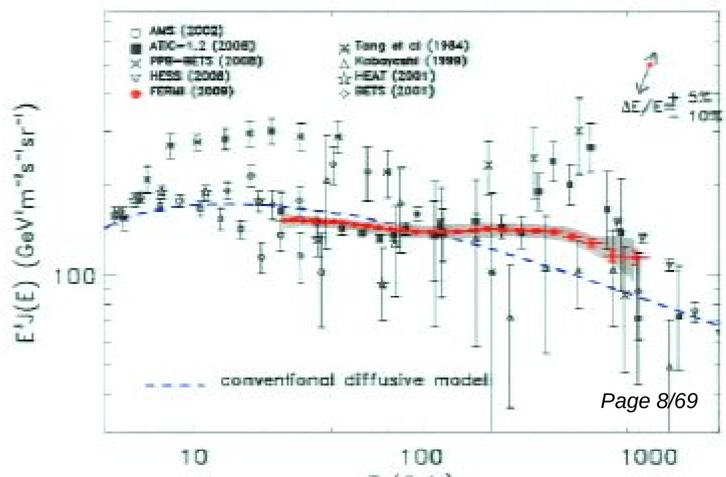
- Excess 511 keV γ's from galactic center, observed by INTEGRAL/SPI



- PAMELA positron excess at 10–100 GeV



- Fermi/LAT $e^{\pm}$ excess at 100–1000 GeV



A simple nonabelian DM model

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

$$\mathcal{L}_\chi = \tfrac{1}{2}\bar{\chi}_i(i\not{D}_{ij} - M_\chi\delta_{ij})\chi_j - \tfrac{1}{4g^2}B^a_{\mu\nu}B^{\mu\nu}_a - \tfrac{1}{\Lambda}\Delta_a B^{\mu\nu}_a Y_{\mu\nu}$$

↗ dark matter ↗ dark gauge sector ↗ mixing with SM

- Triplet VEV $\langle\Delta_2\rangle$ gives B_2-γ mixing.
- We need second triplet Δ' to fully split χ_i states:

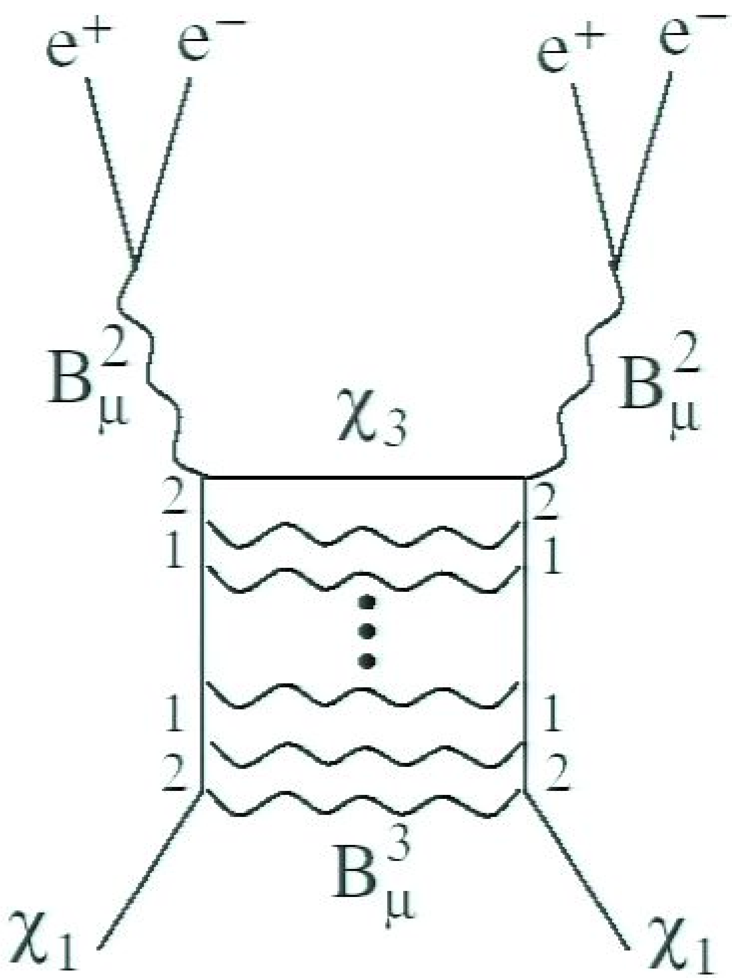
$$V_{\rm higgs} = \lambda(\Delta^2 - v^2)^2 + \lambda'(\Delta'^2 - v'^2)^2 + \lambda''(\vec{\Delta}\cdot\vec{\Delta}')^2$$

- Unbroken Z_2 symmetry can play important role:

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

χ_2, B_2, Δ_2, Δ'_2 uncharged.

Mechanism for high-energy leptons



Gauge boson mass $\mu \lesssim 2$ GeV,

explains why PAMELA sees no excess $\bar{p}$.

B's decay only into e^+e^-, $\pi^+\pi^-$, $\mu^+\mu^-$, $\bar{\nu}\nu$.

$M_\chi \sim$ TeV to explain Fermi $e^\pm$ excess.

Multiple gauge boson exchanges give rise to boost factor from Sommerfeld enhancement

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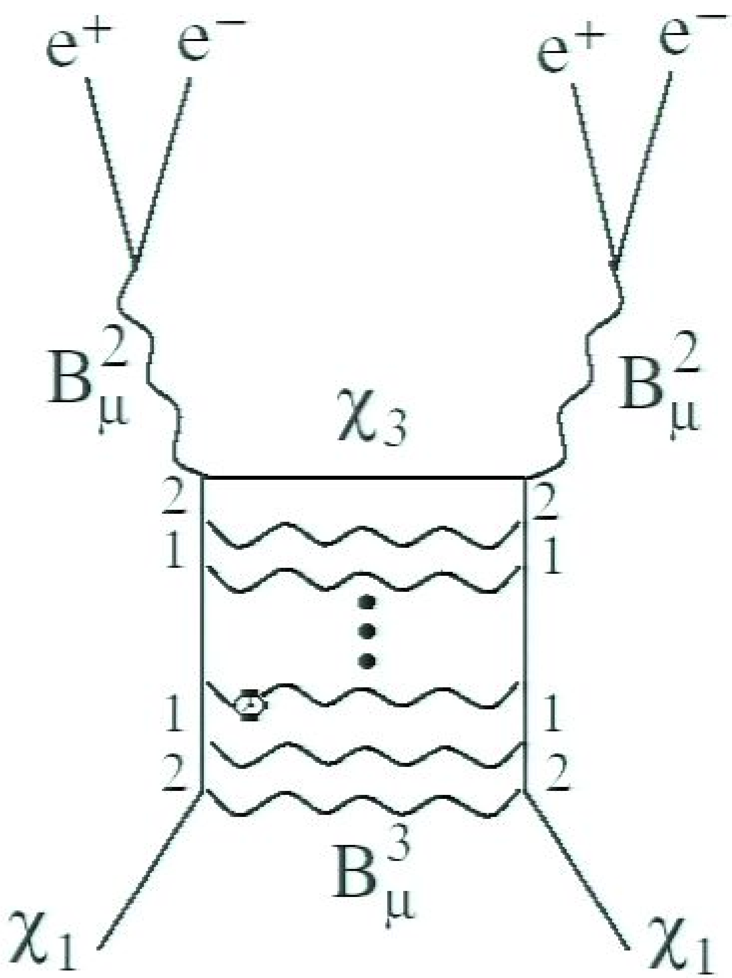

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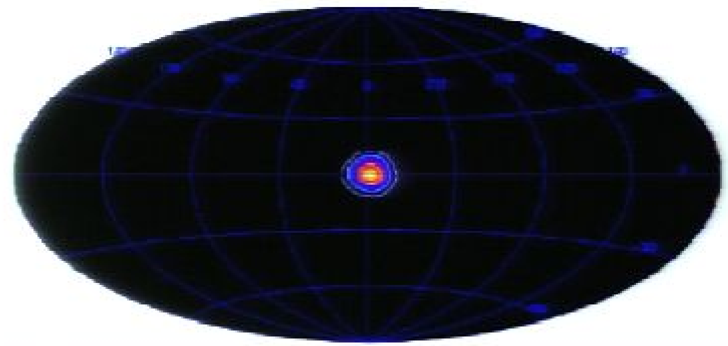

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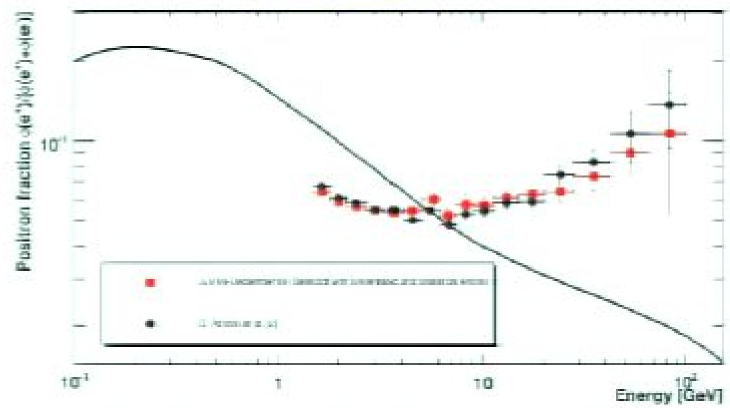

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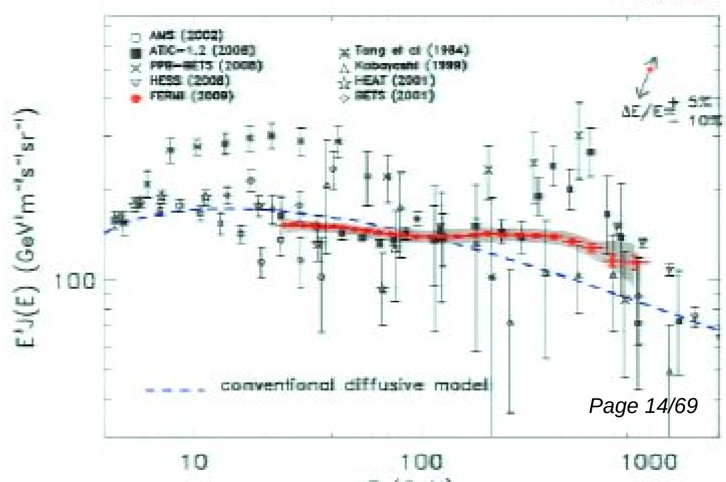

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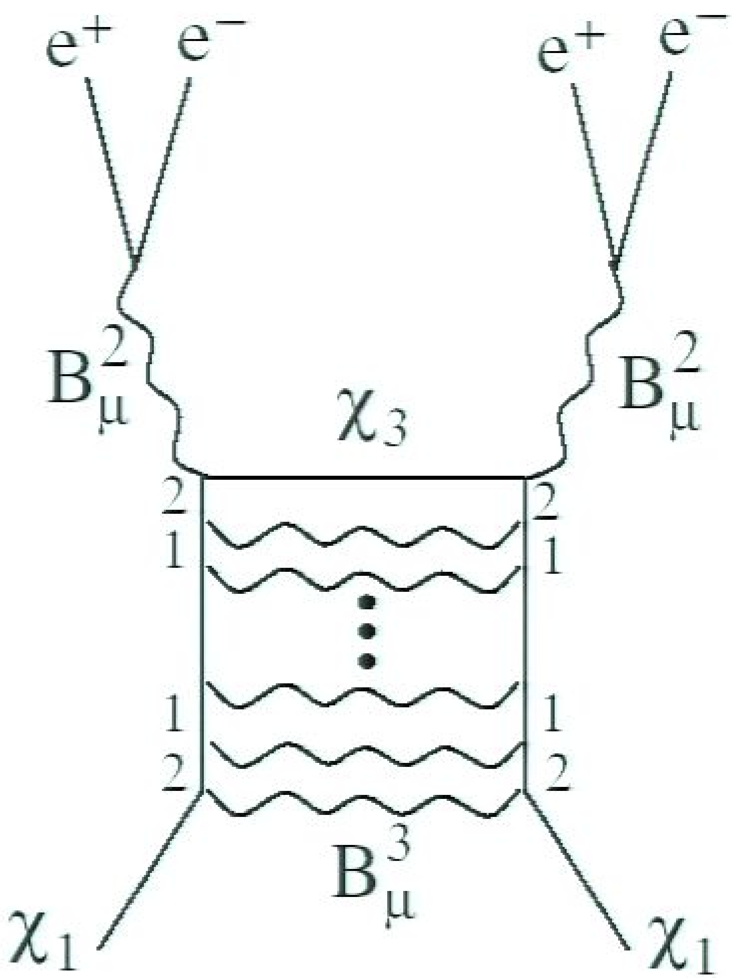

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Variation on eXcited Dark Matter (XDM) mechanism of Finkbeiner, Weiner, astro-ph/0702587 : $\chi_1\chi_1 \rightarrow \chi_3\chi_3$,
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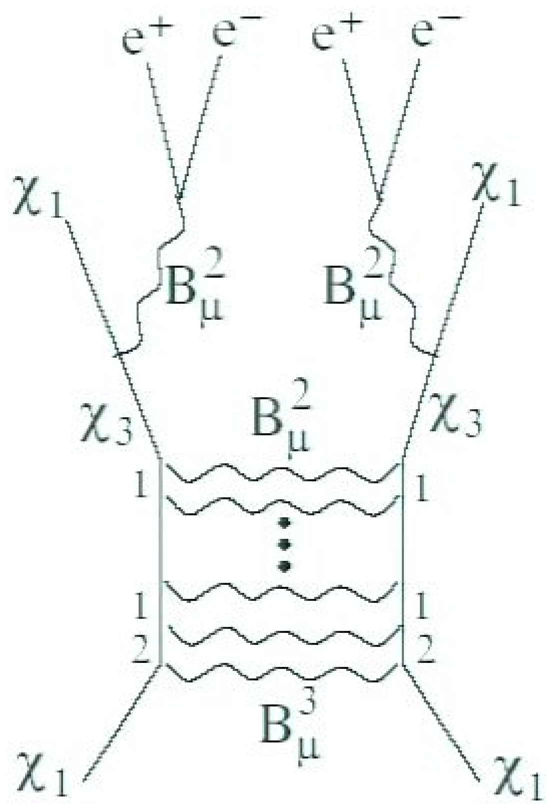
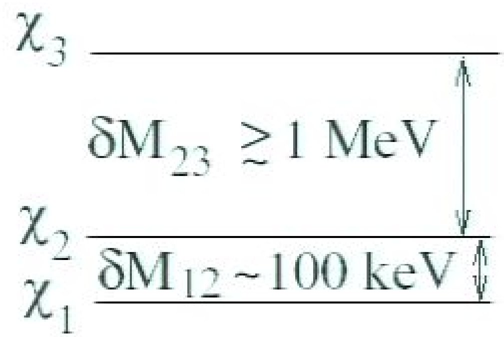




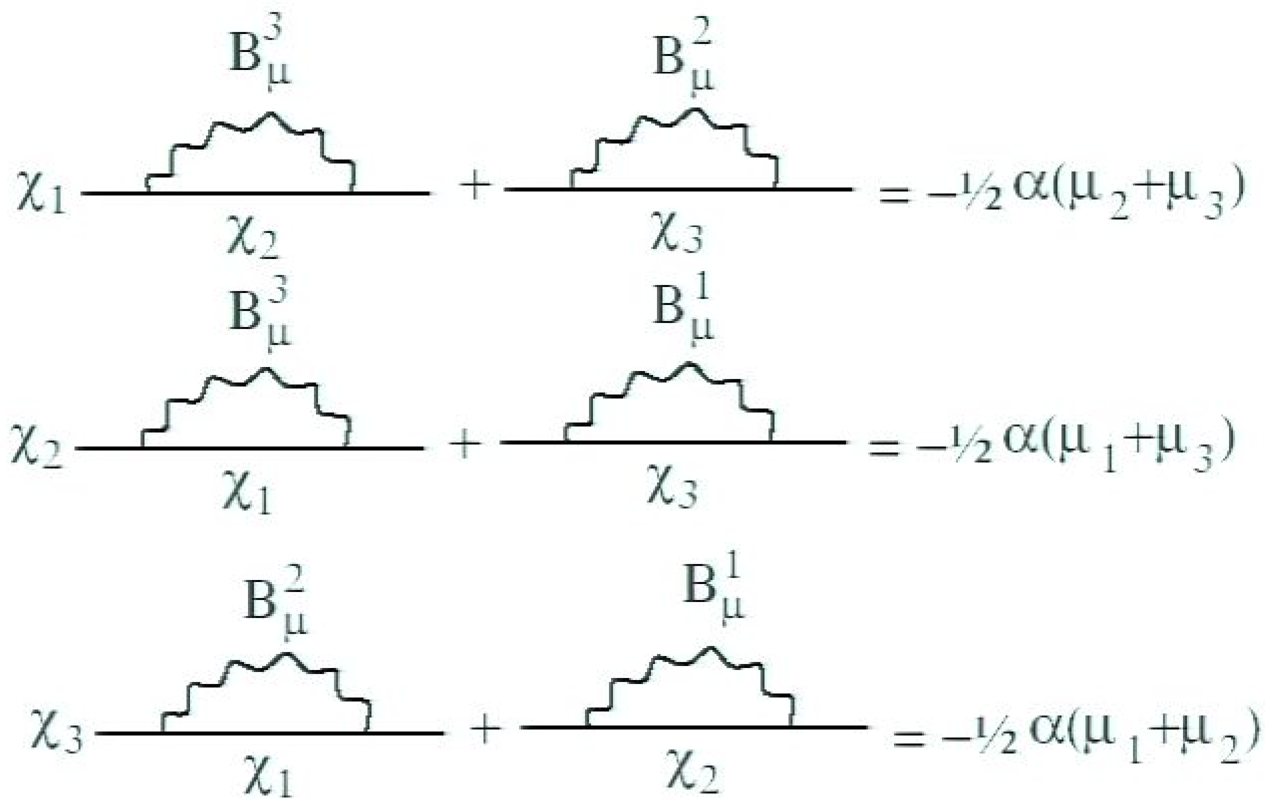
Originally proposed spectrum

(Arkani–Hamed et al., 0810.0713)

($N\chi_1 \rightarrow N'\chi_2$ excitation was proposed to explain DAMA/ LIBRA annual modulation.)

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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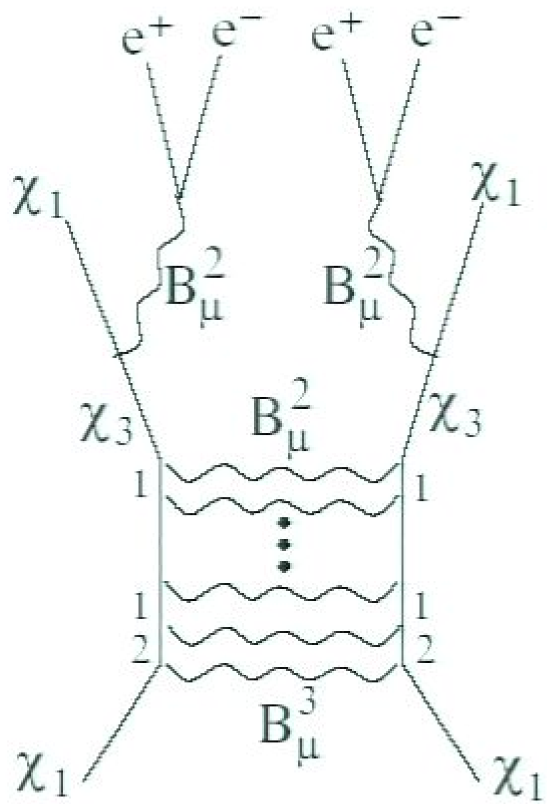

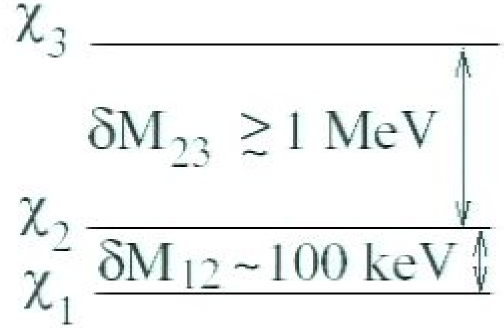

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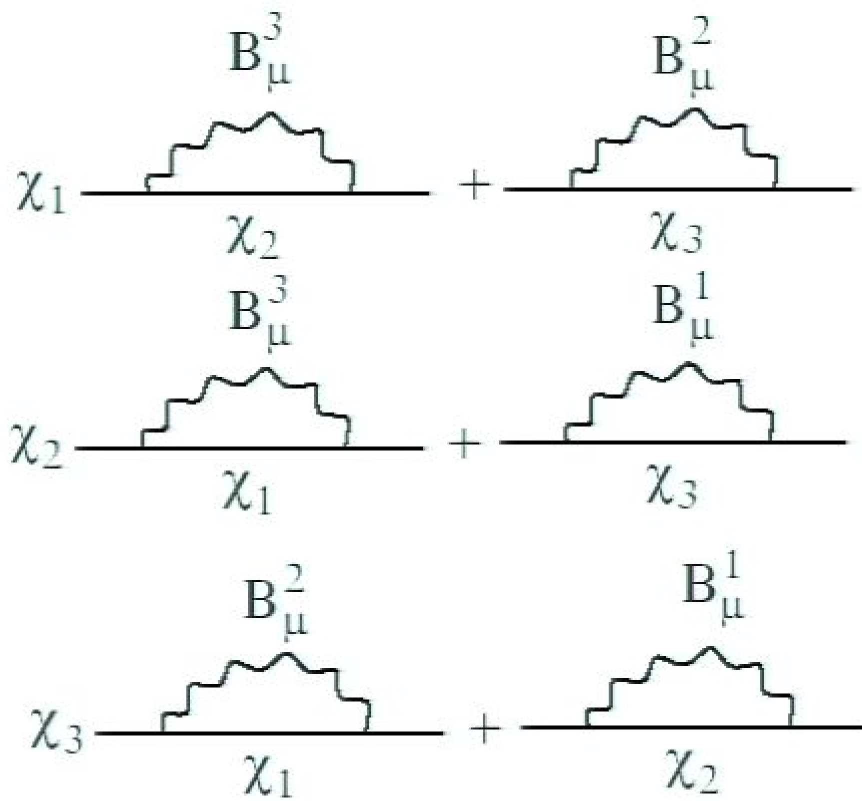

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XDM mechanism is too slow

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

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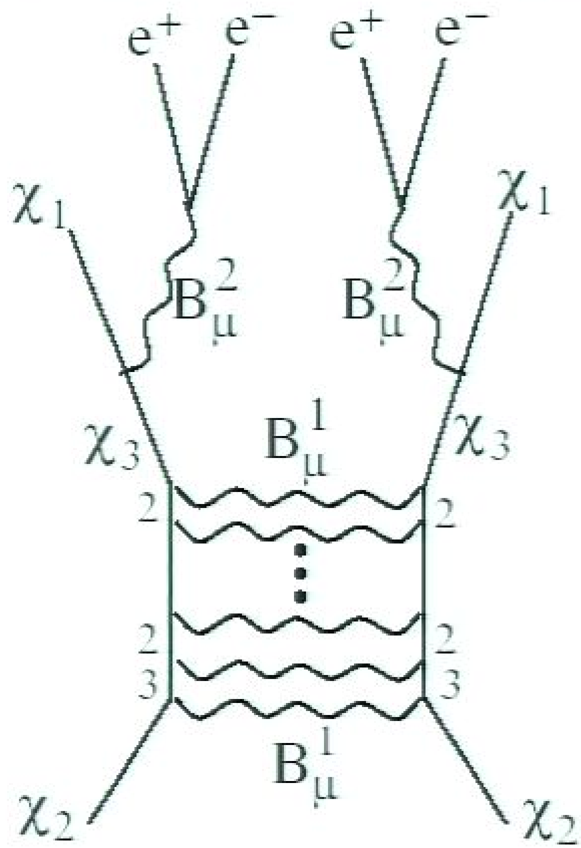

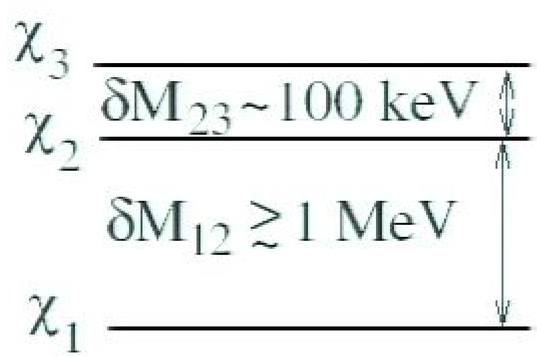

Inverted hierarchy spectrum

(Chen, JC, Frey, 0901.4327)

Need stable χ_2 population. Z_2 symmetry can prevent χ_2 decay.

Fermi Inverse Compton constraint

Papucci, Strumia 0912.0742

High-energy leptons produced by χ annihilation upscatter photons in galaxy; would contribute to γ ray spectrum observed by Fermi:

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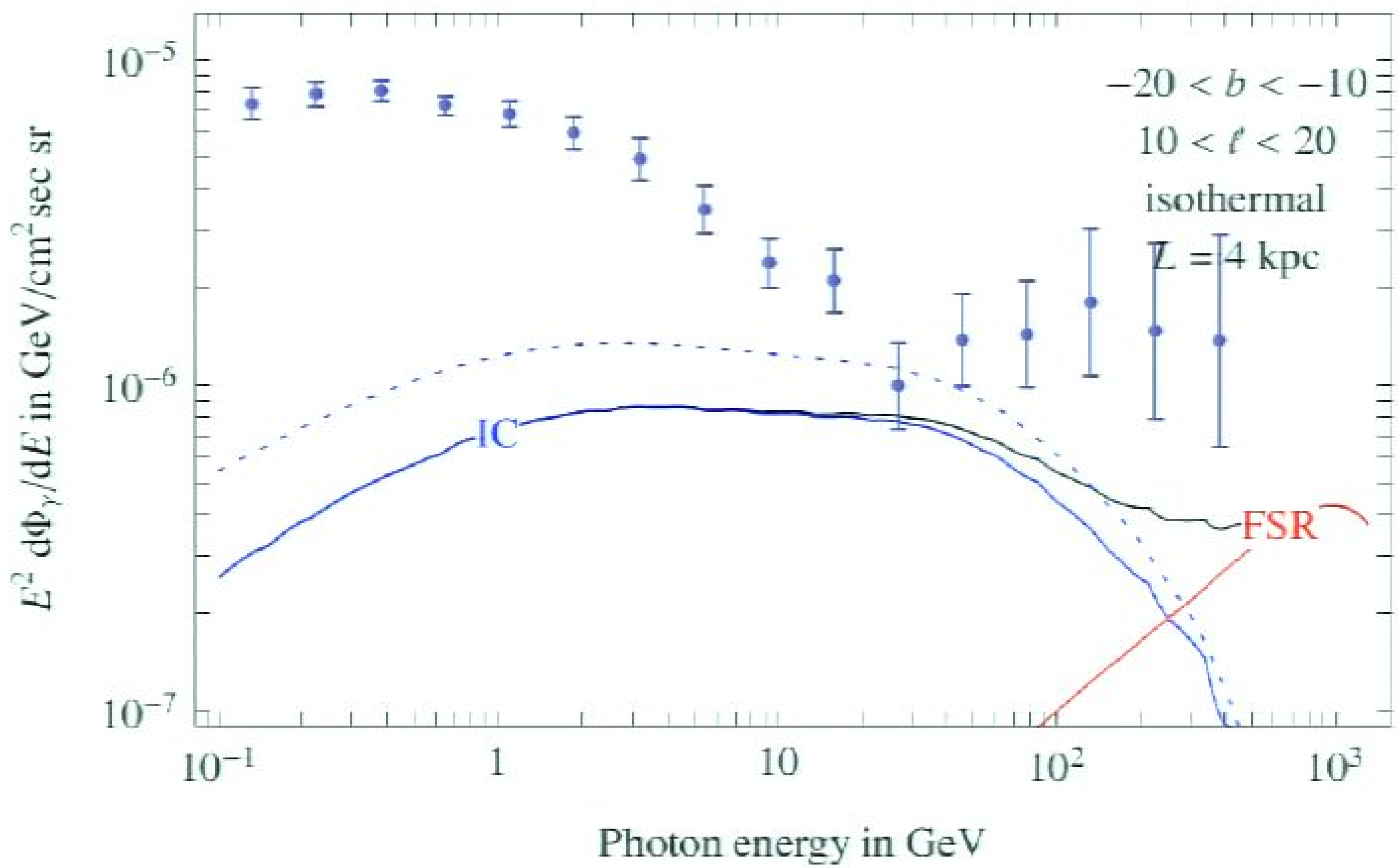

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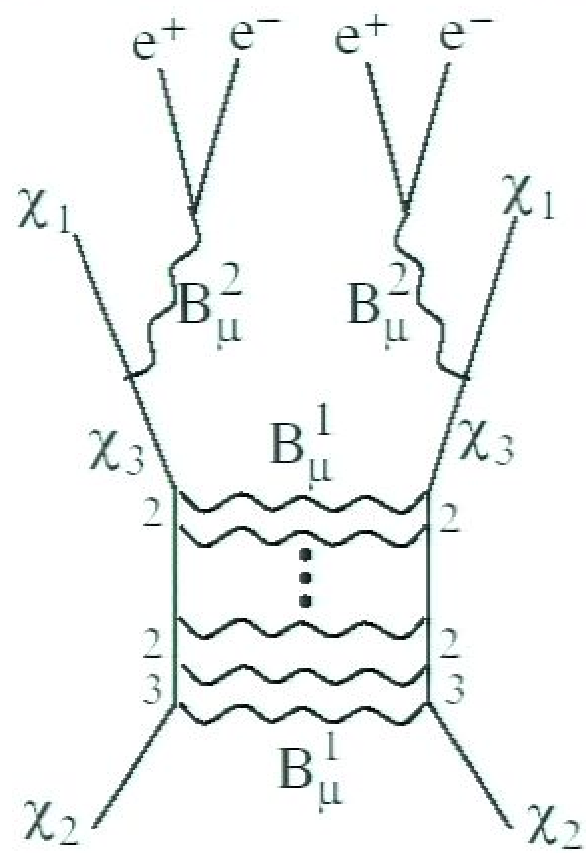

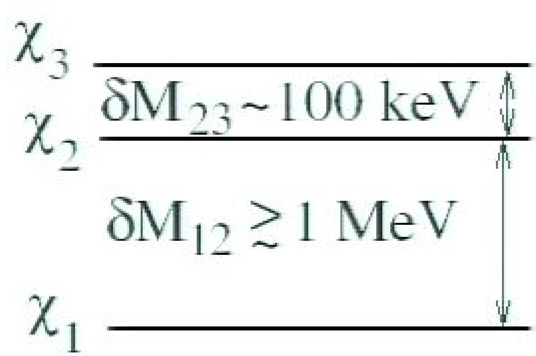

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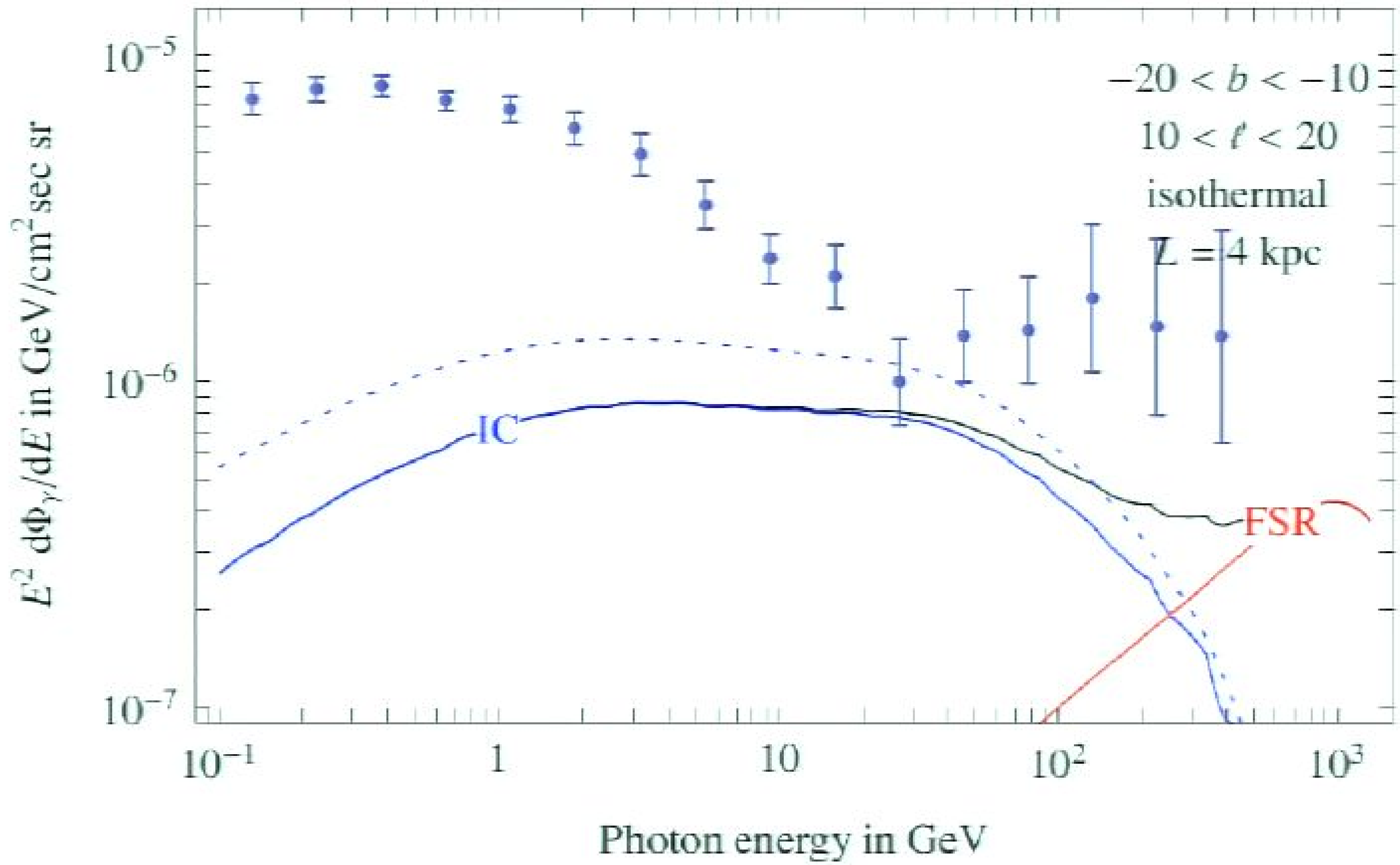

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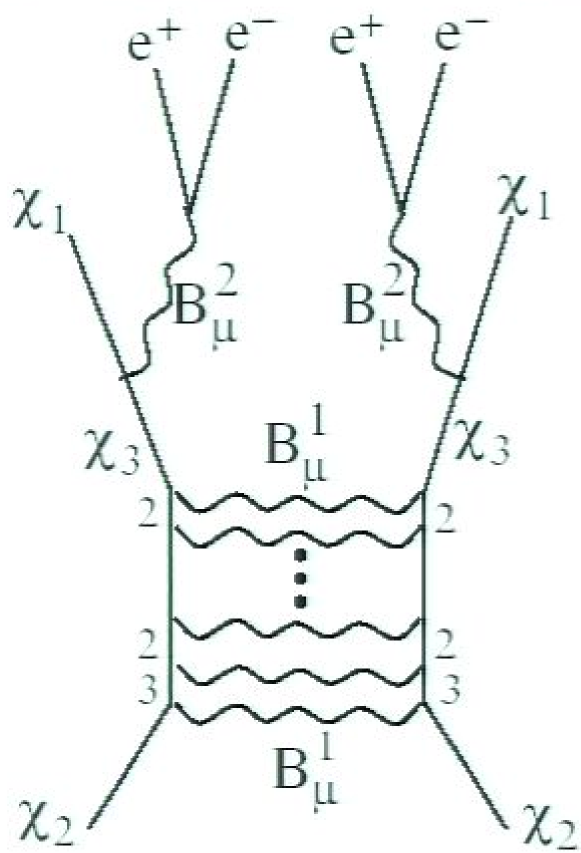

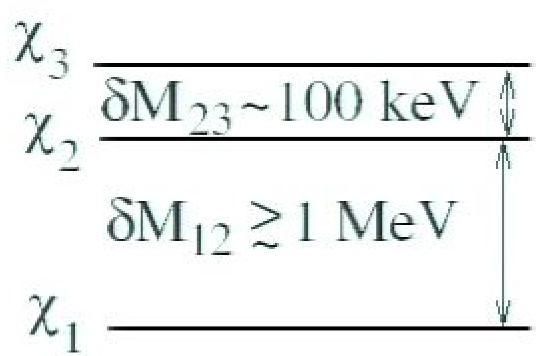

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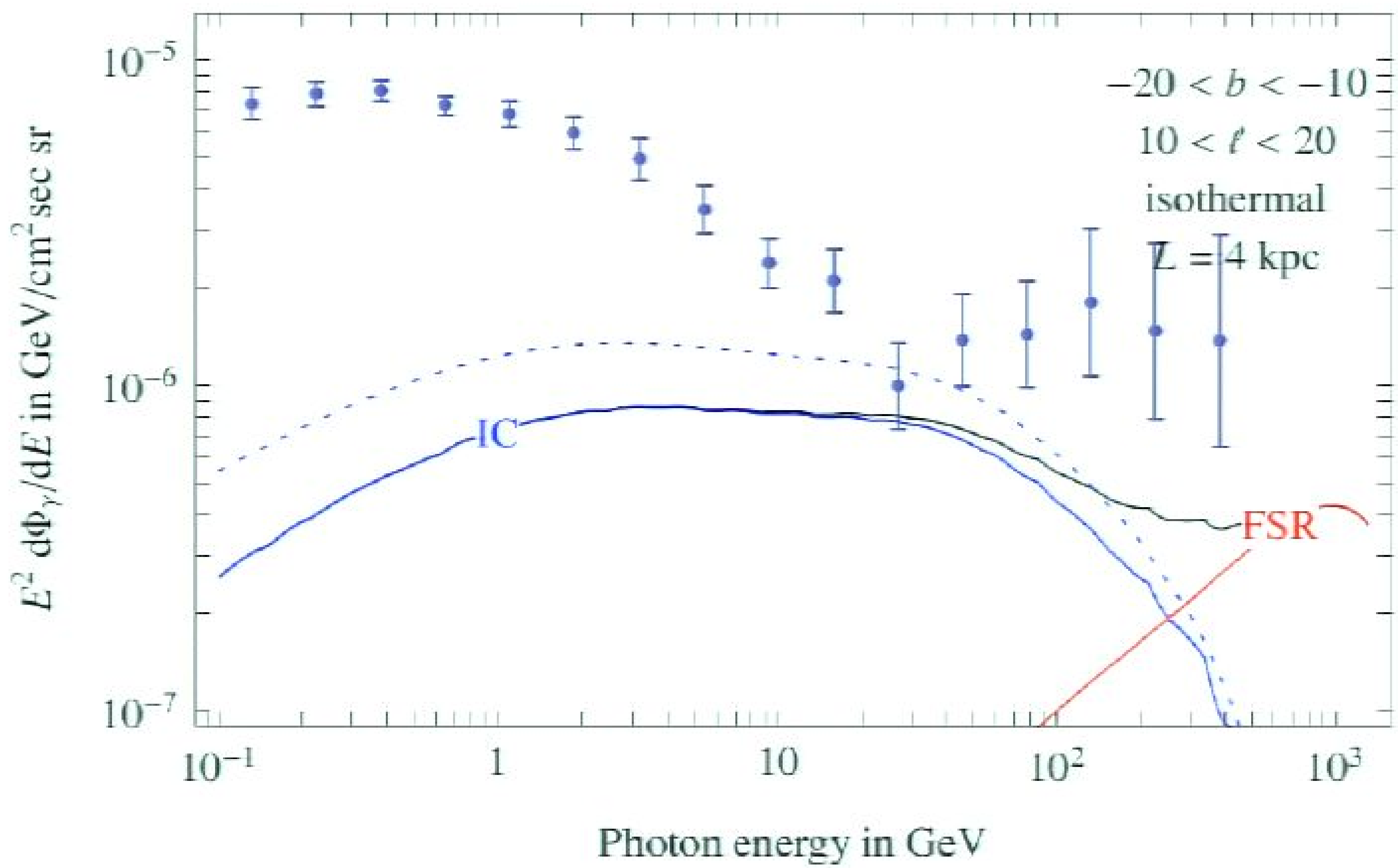
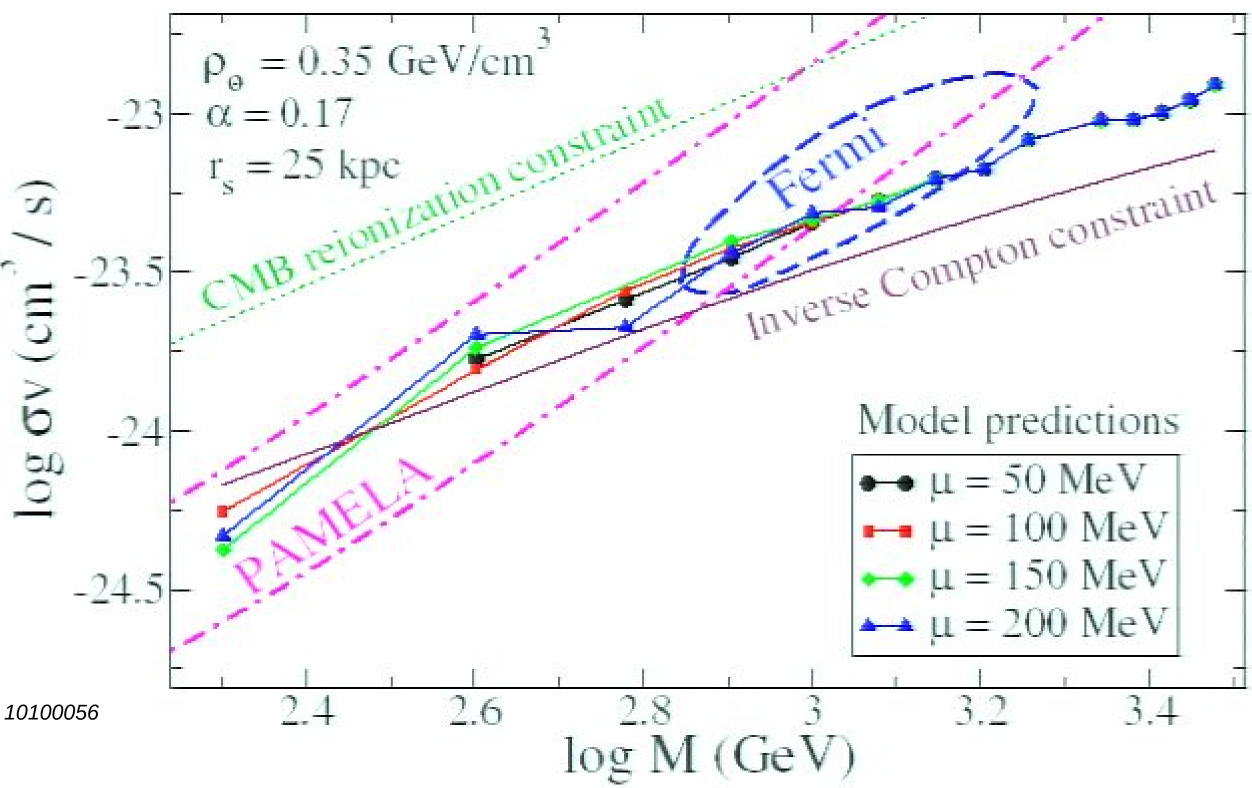


XDM & Fermi/PAMELA incompatible

- 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 α.



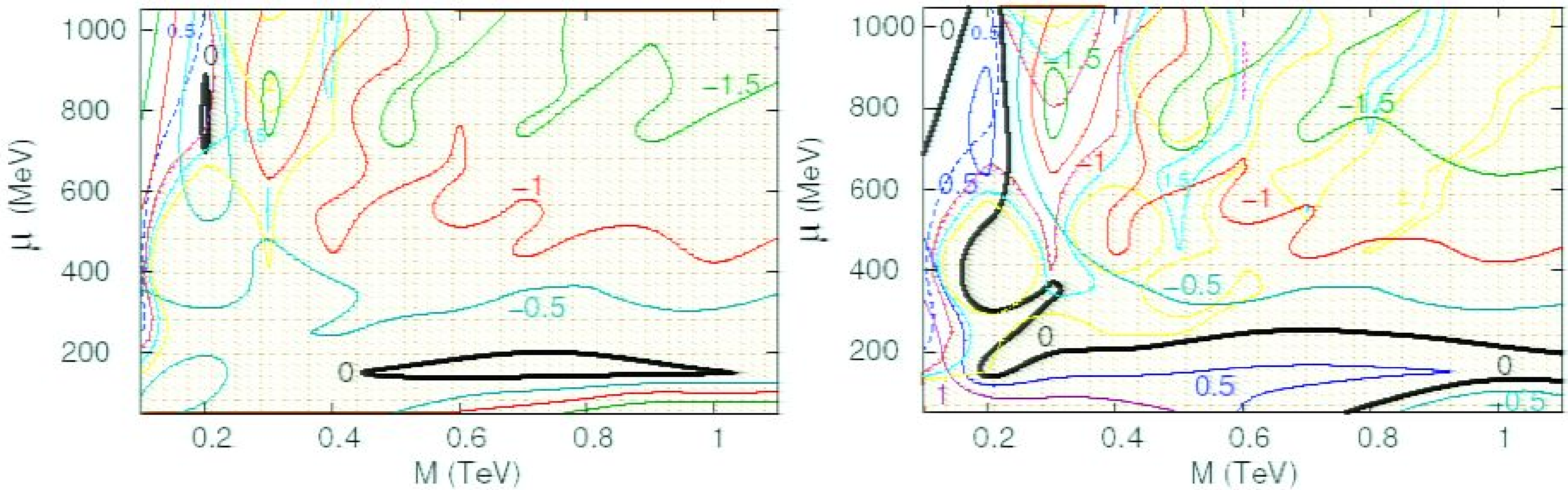
Need $\alpha \lesssim 0.17$ for large enough XDM rate; ruled out by IC constraint.

Cirelli, JC
1005.1779

INTEGRAL vs. PAMELA/Fermi

An illustration of the problem (JC, 1005.5001)

Contours of $\log R_{e^+}/R_{\rm obs}$ in DM-B_μ mass plane:



$\alpha = 0.17,\ \delta M = 100$ keV $\alpha = 0.20,\ \delta M = 25$ keV

Shaded regions are ruled out by inverse Compton constraint

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

Stronger Inverse Compton Constraints

Differences with previous studies:

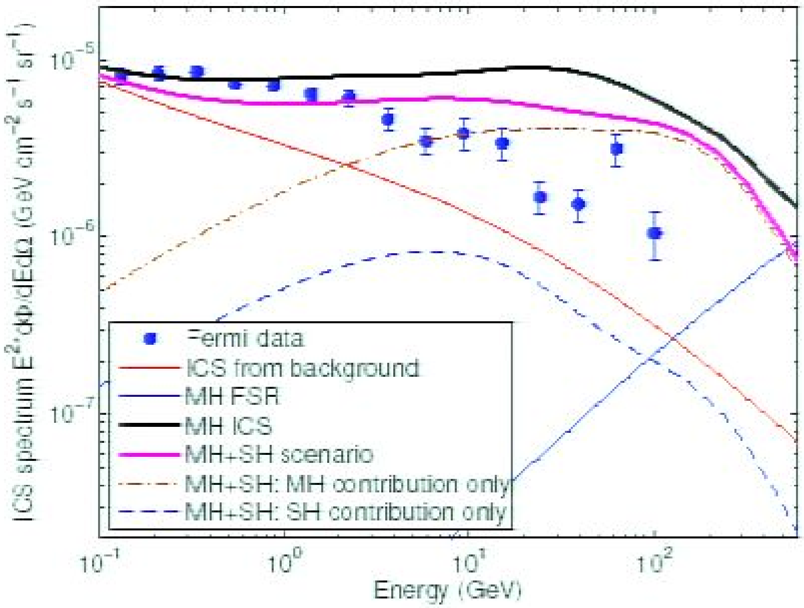
We use GALPROP to solve diffusion equation, rather than semianalytic approach (Papucci, Strumia)

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 $10^\circ < |b| < 30^\circ$, $-15^\circ < l < 15^\circ$.

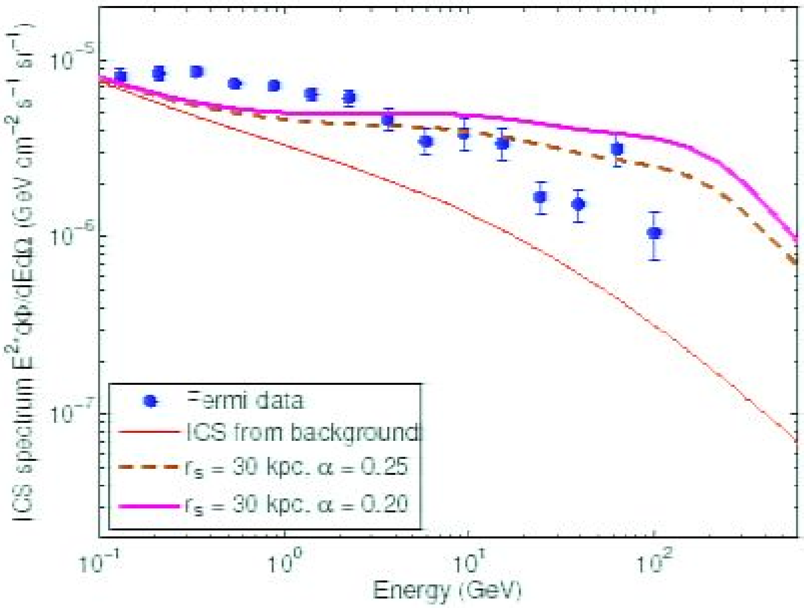
(We show constraints at 2σ rather than 3σ)

Strengthening IC Constraints

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



$\alpha = 0.17,\ r_s = 25$ kpc



$\alpha = 0.20, 0.25,\ r_s = 30$ 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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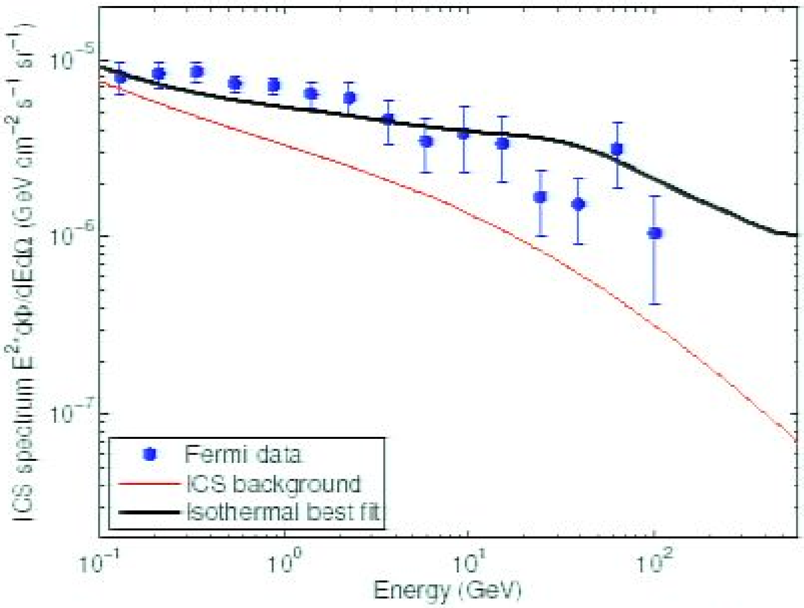
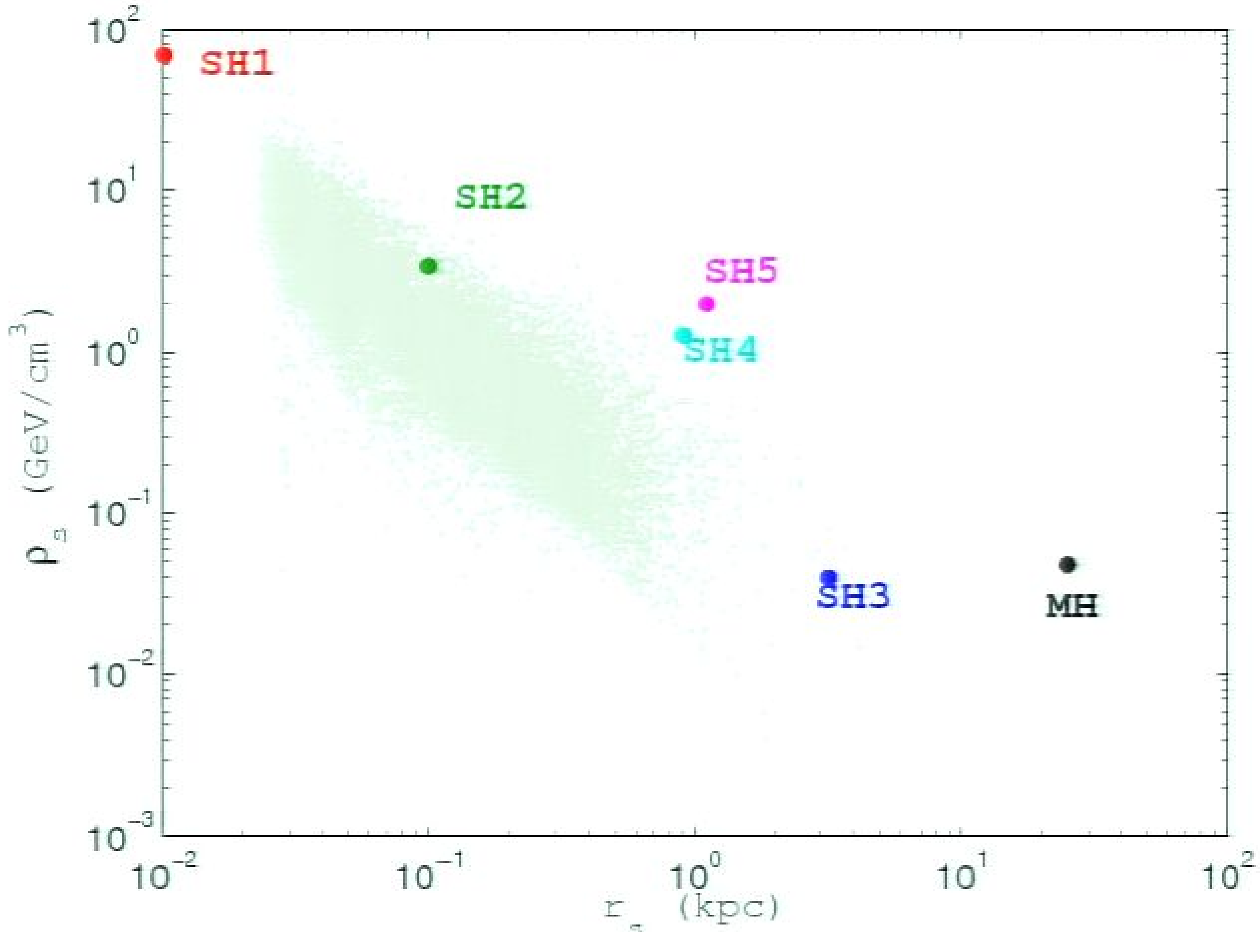


isothermal profile, $\rho = \frac{\rho_s}{1+(r/r_s)^2}$

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

Substructure Loophole

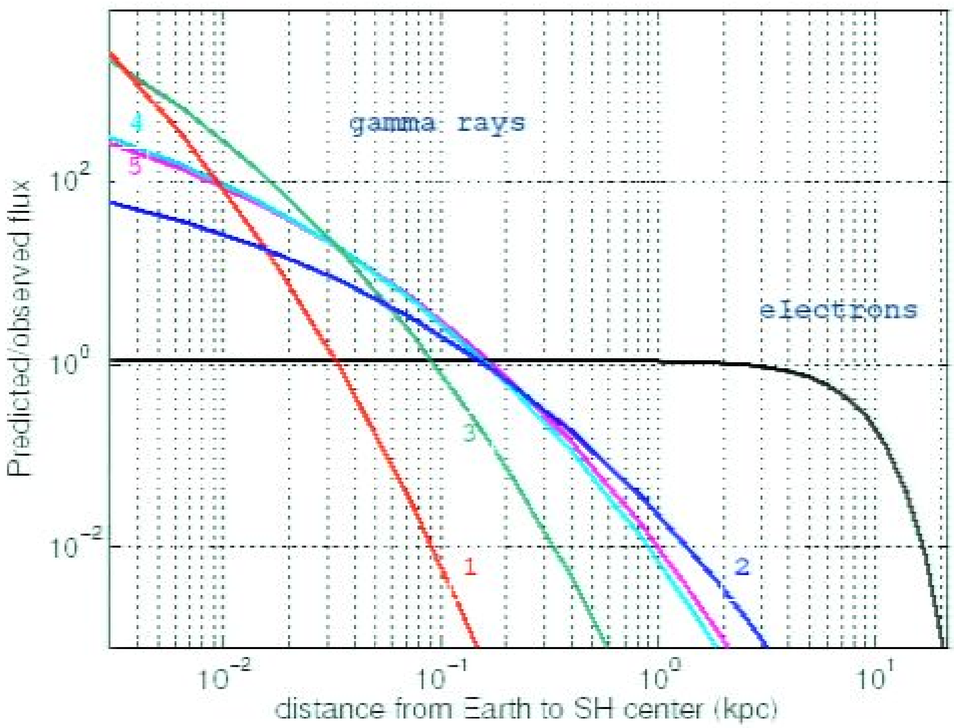
Main DM halo contains zillions of subhalos (*Via Lactea II* simulation), each with its own Einasto profile:



Outlier with high ρ_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 ~ 200 pc.



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

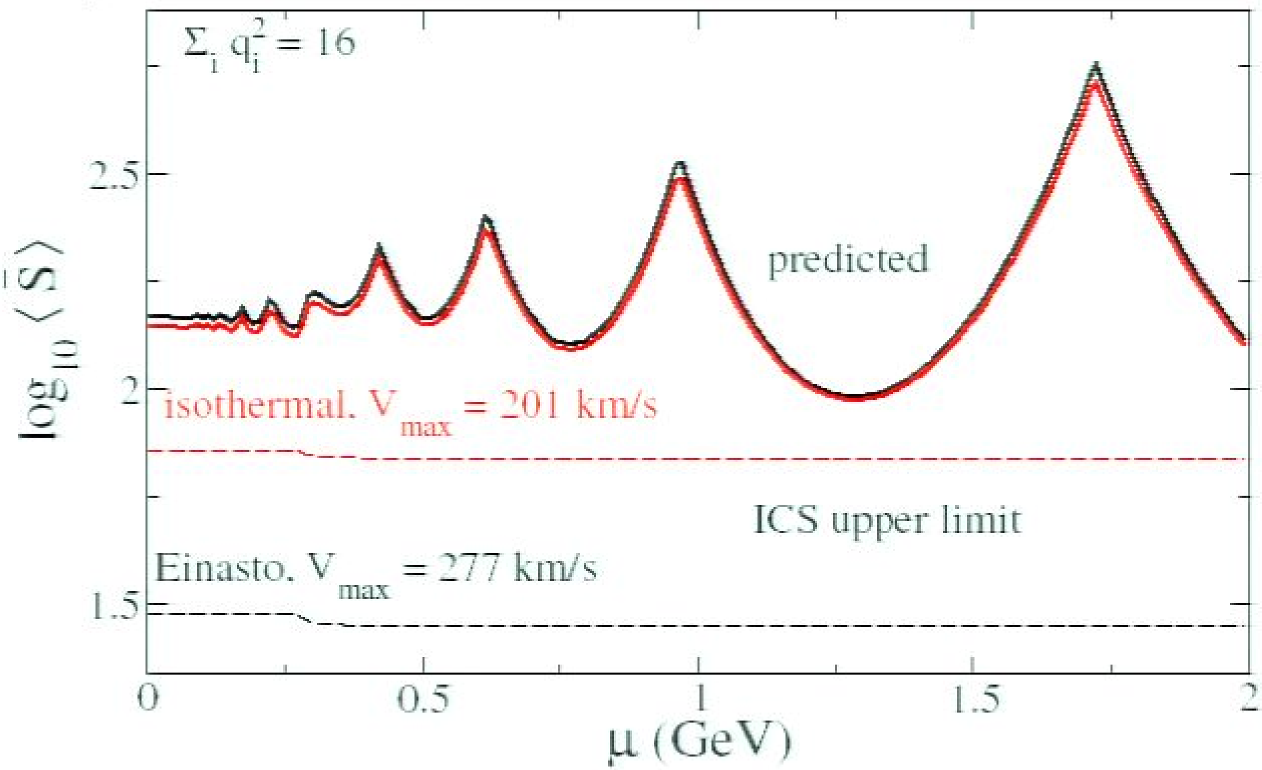
Also, need specific values of boost factors for annihilation in the subhalos, but these can be computed in a given DM model

Constraint on main halo boost factor

Consider simplest U(1) model of DM.

Sommerfeld boost factor S is known function of gauge coupling α_g, DM velocity v and mass ratio μ/M.

α_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 α_g exceed thermal relic value. $\alpha_g = \sqrt{f}\alpha_{g,\mathrm{th}}$, $f > 1$

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

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	$r_s(\mathrm{kpc})$	ρ_s $(\mathrm{GeV}/\mathrm{cm}^3)$	$\log BF$ (needed)	$d_{\min}$ (pc)	$V_{\max}$ (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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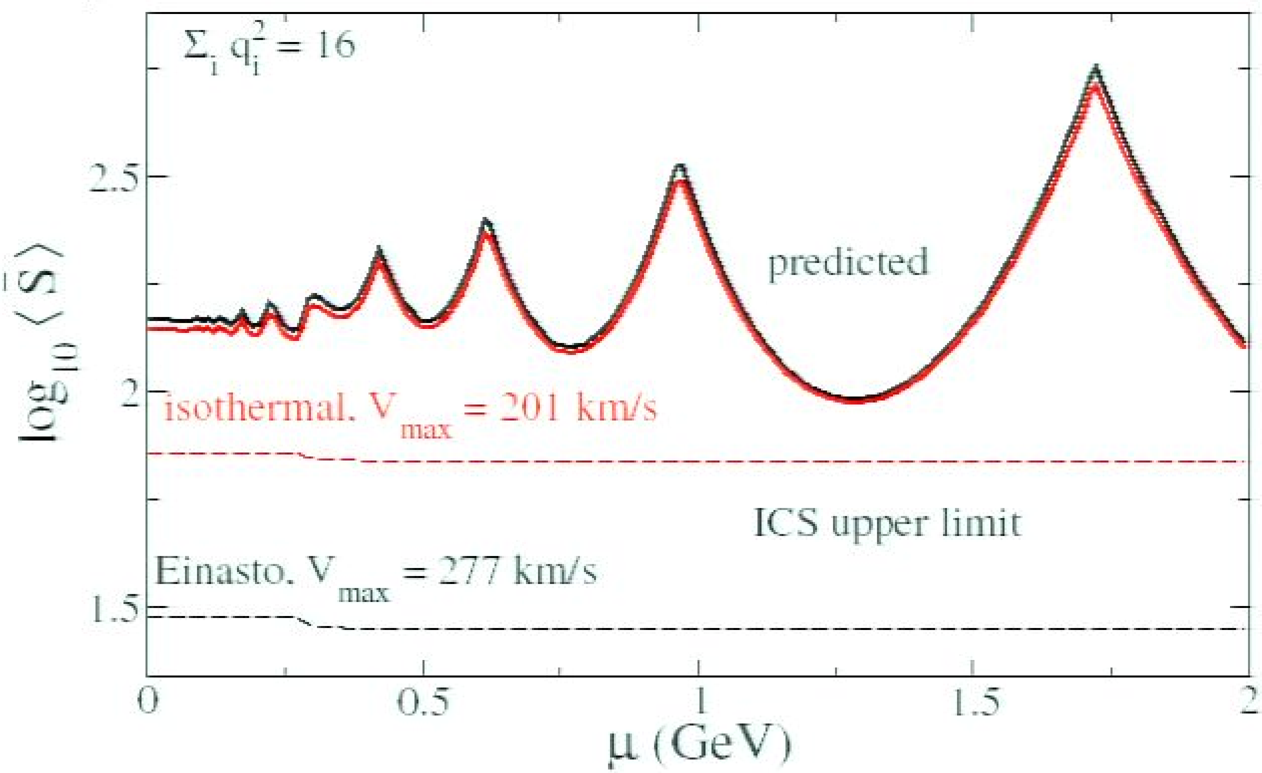

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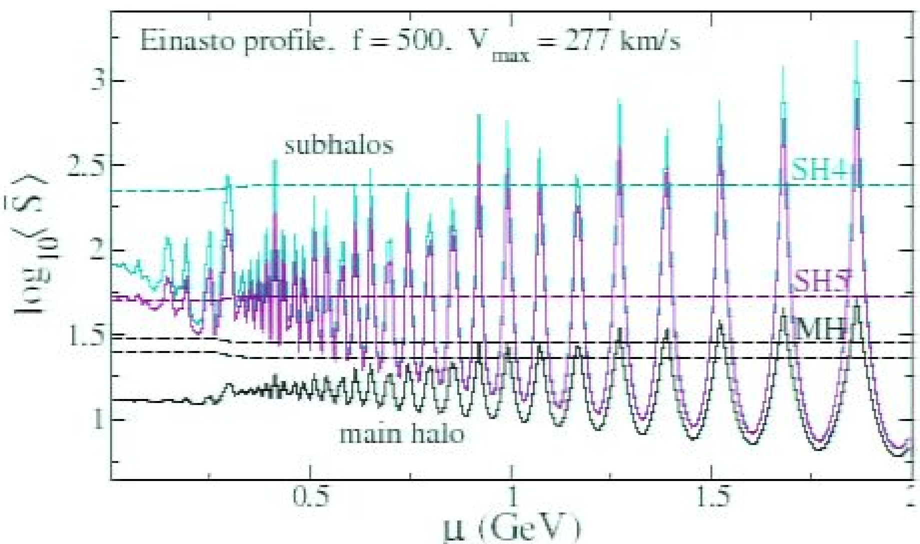
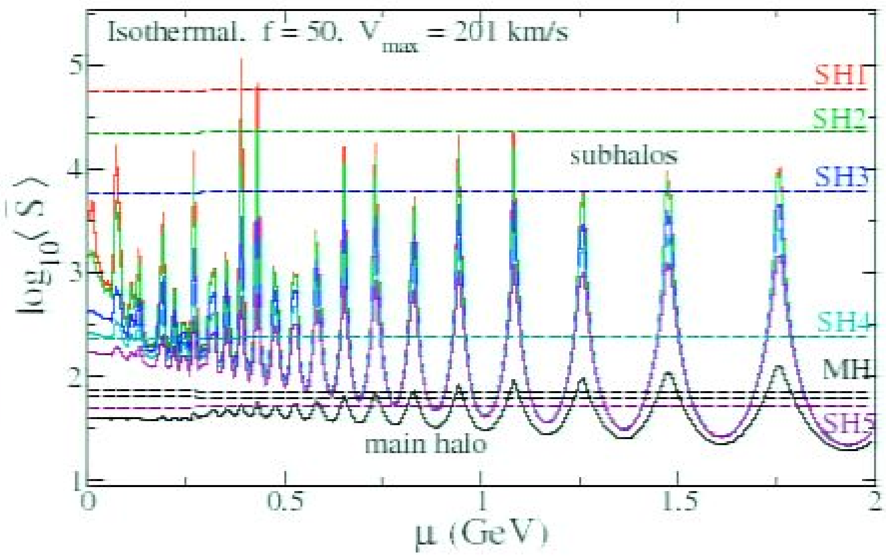
Specific realizations

Predicted versus desired (or upper limit) boost factors:



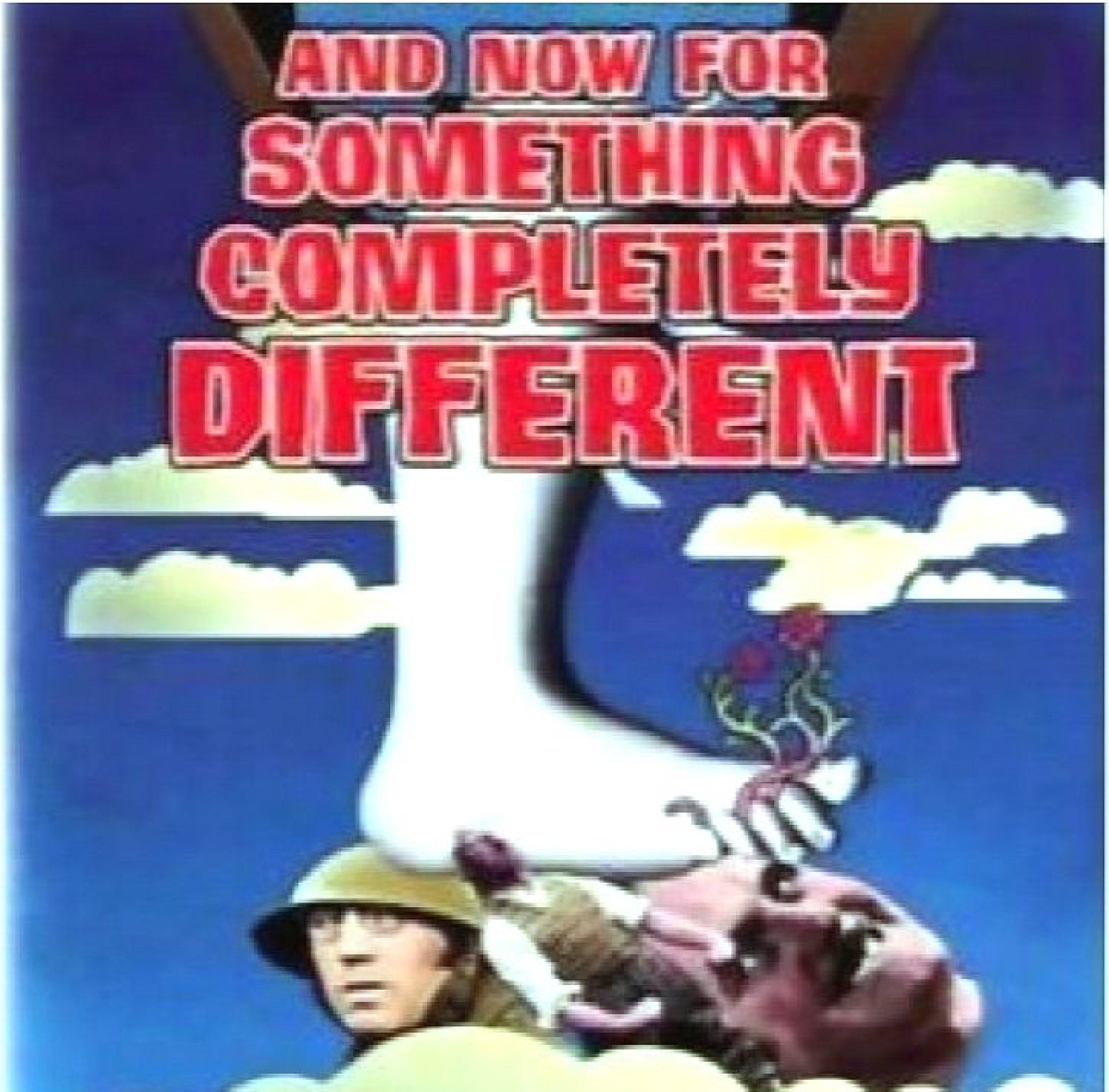


Points of intersection for subhalos are successful models

Main halo curve must lie below ICS bound

Can further reduce boost factors by taking larger f

Subhalos can rescue annihilating DM explanation of PAMELA/Fermi


AND NOW FOR
SOMETHING
COMPLETELY
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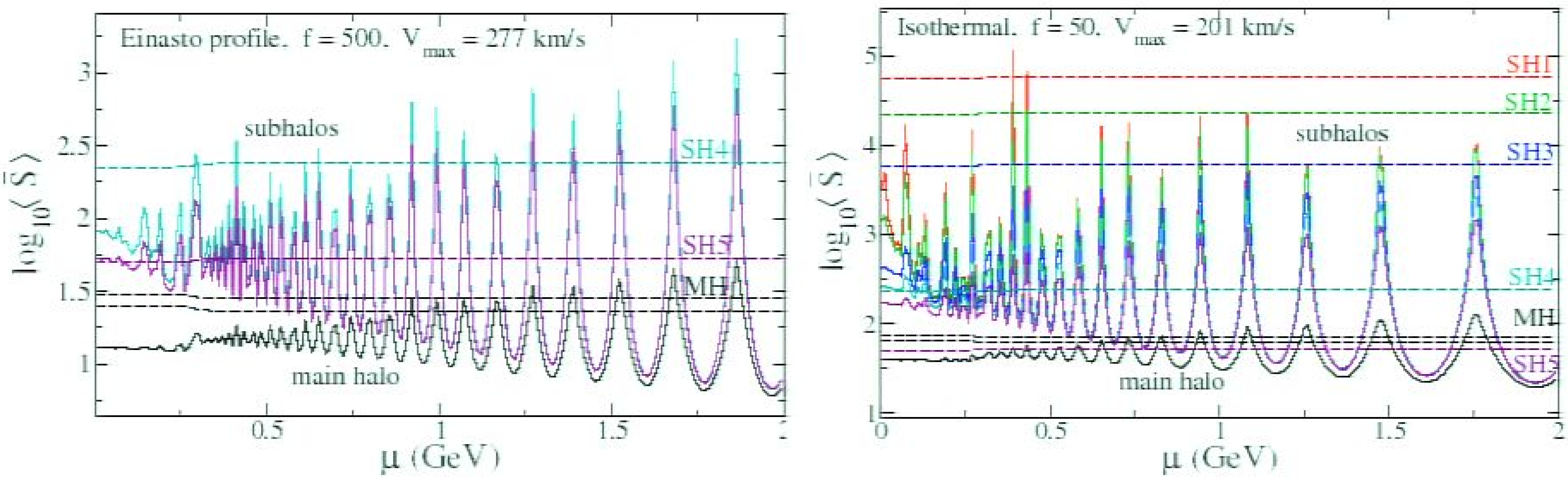

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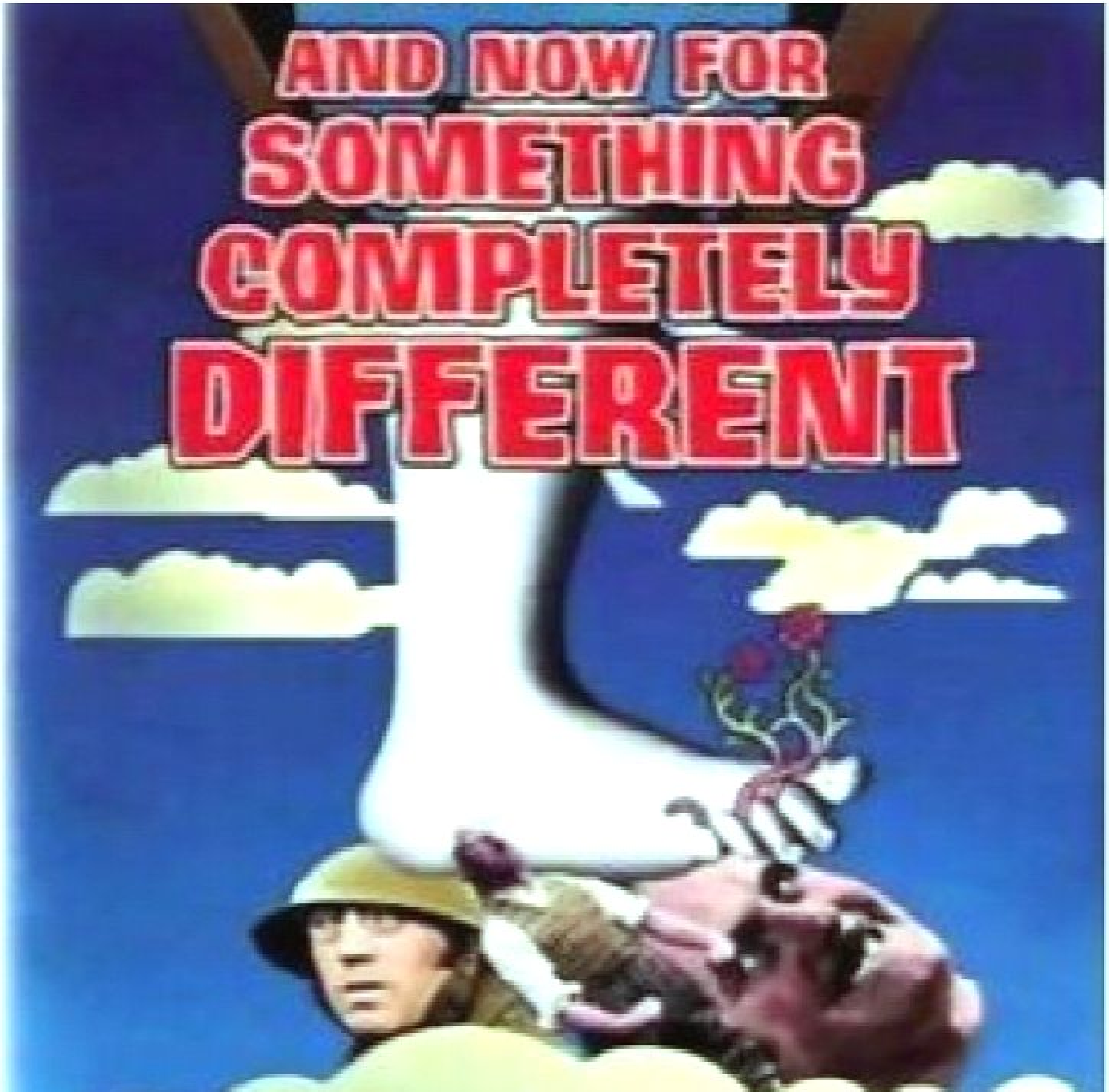
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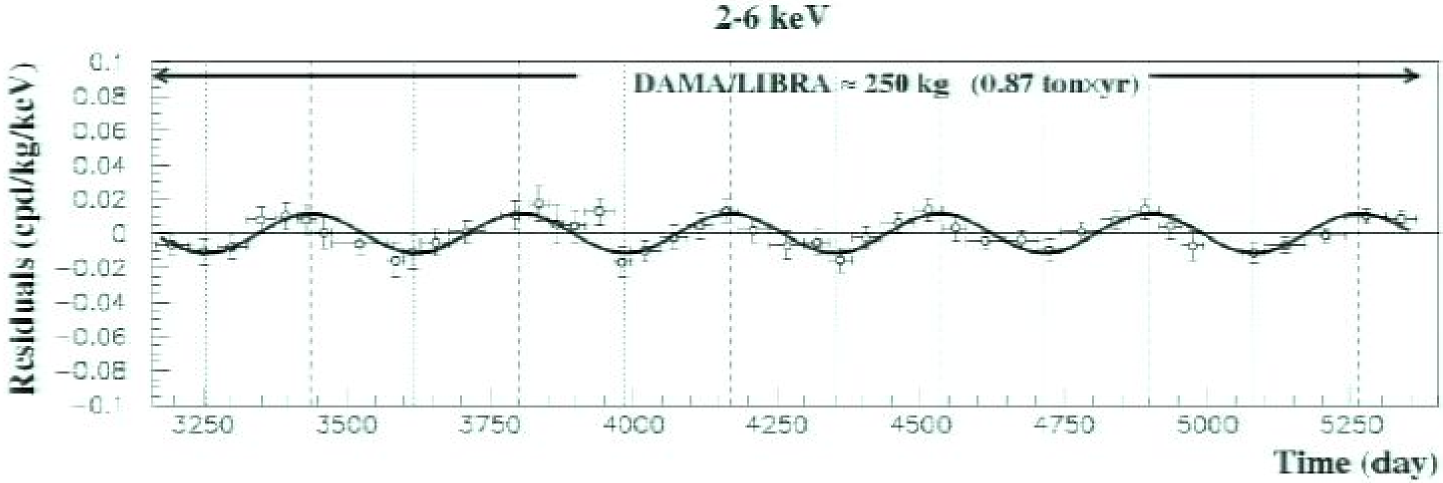
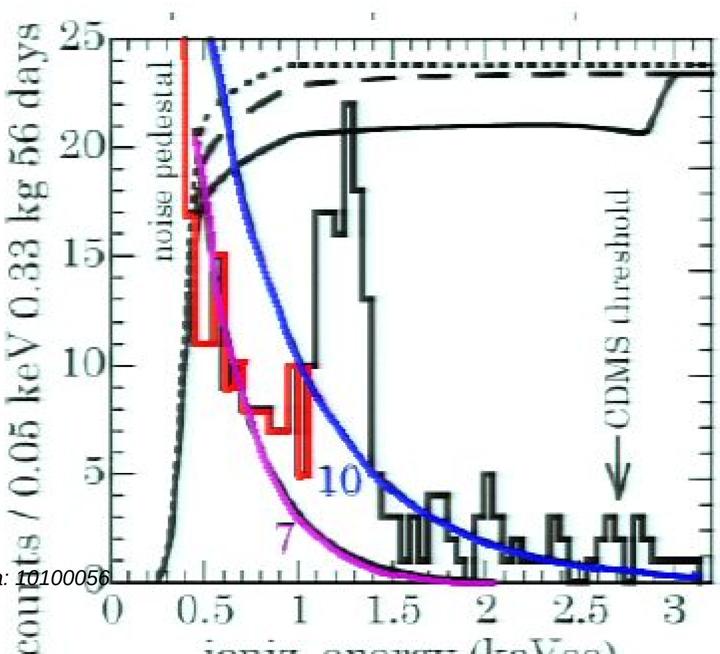
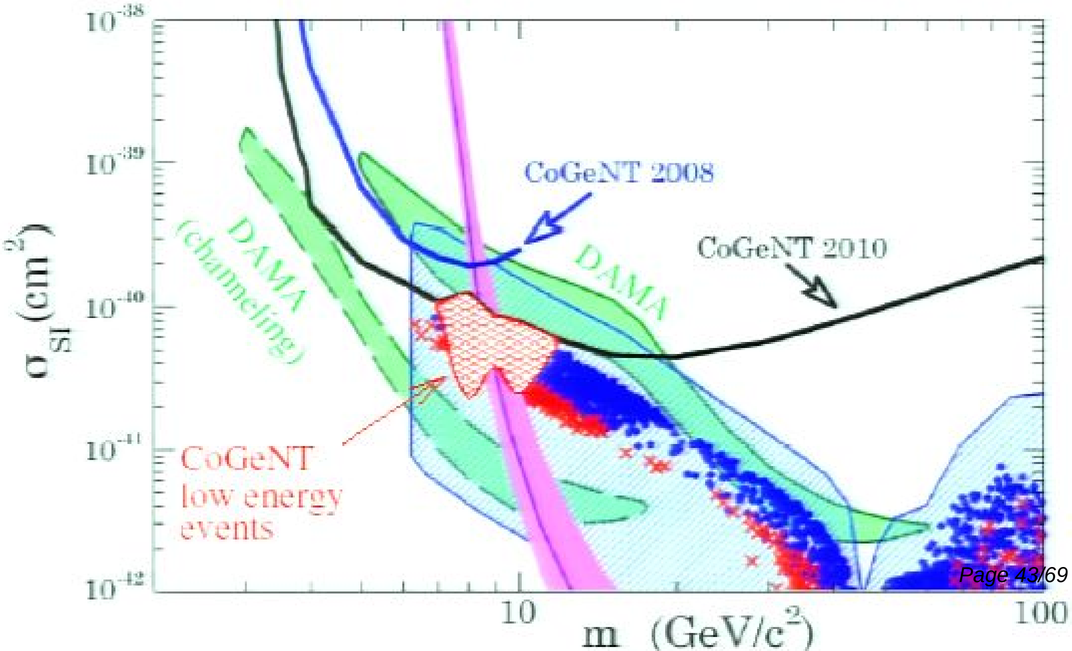
Well, not quite . . .

Light hidden sector dark matter

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

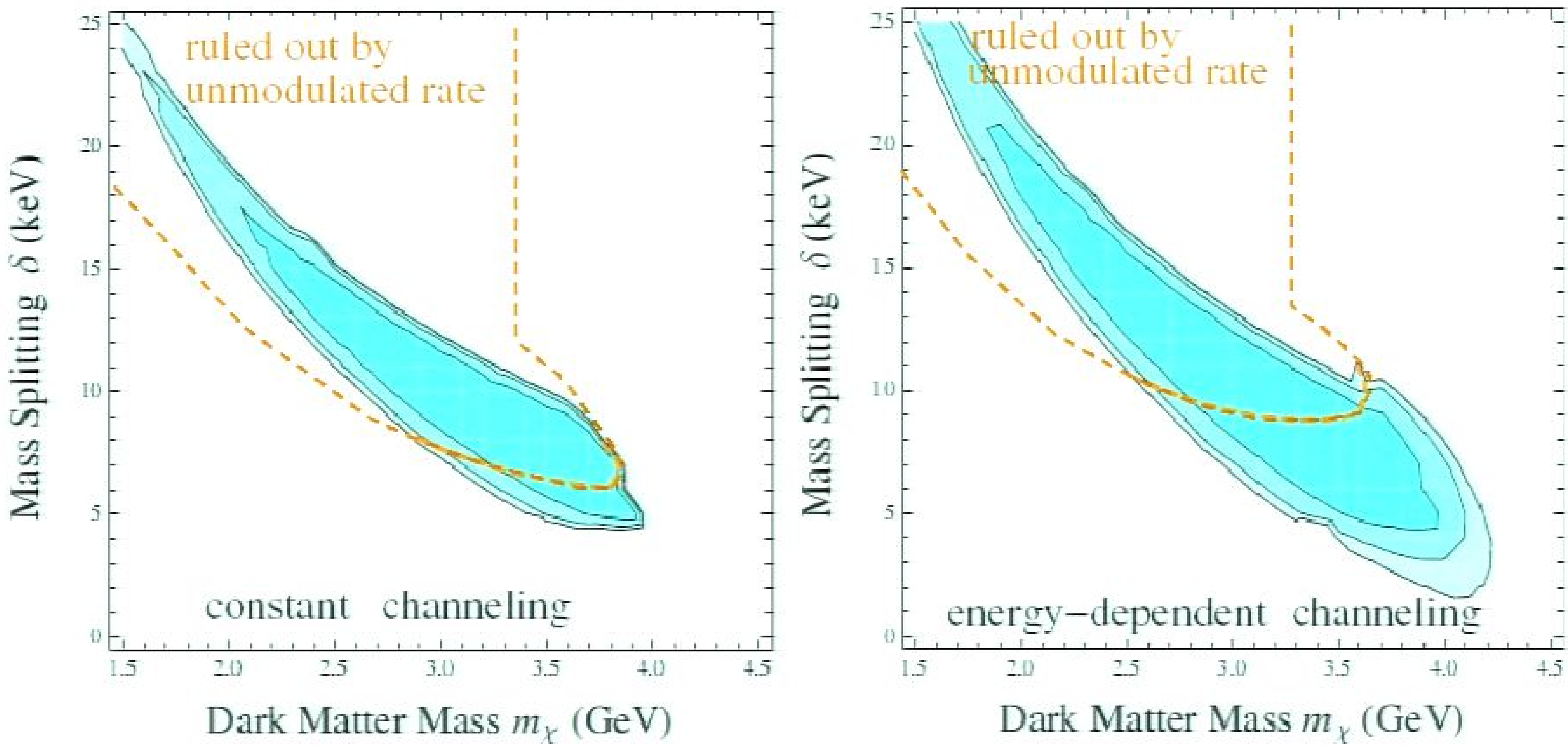






Exothermic dark matter?

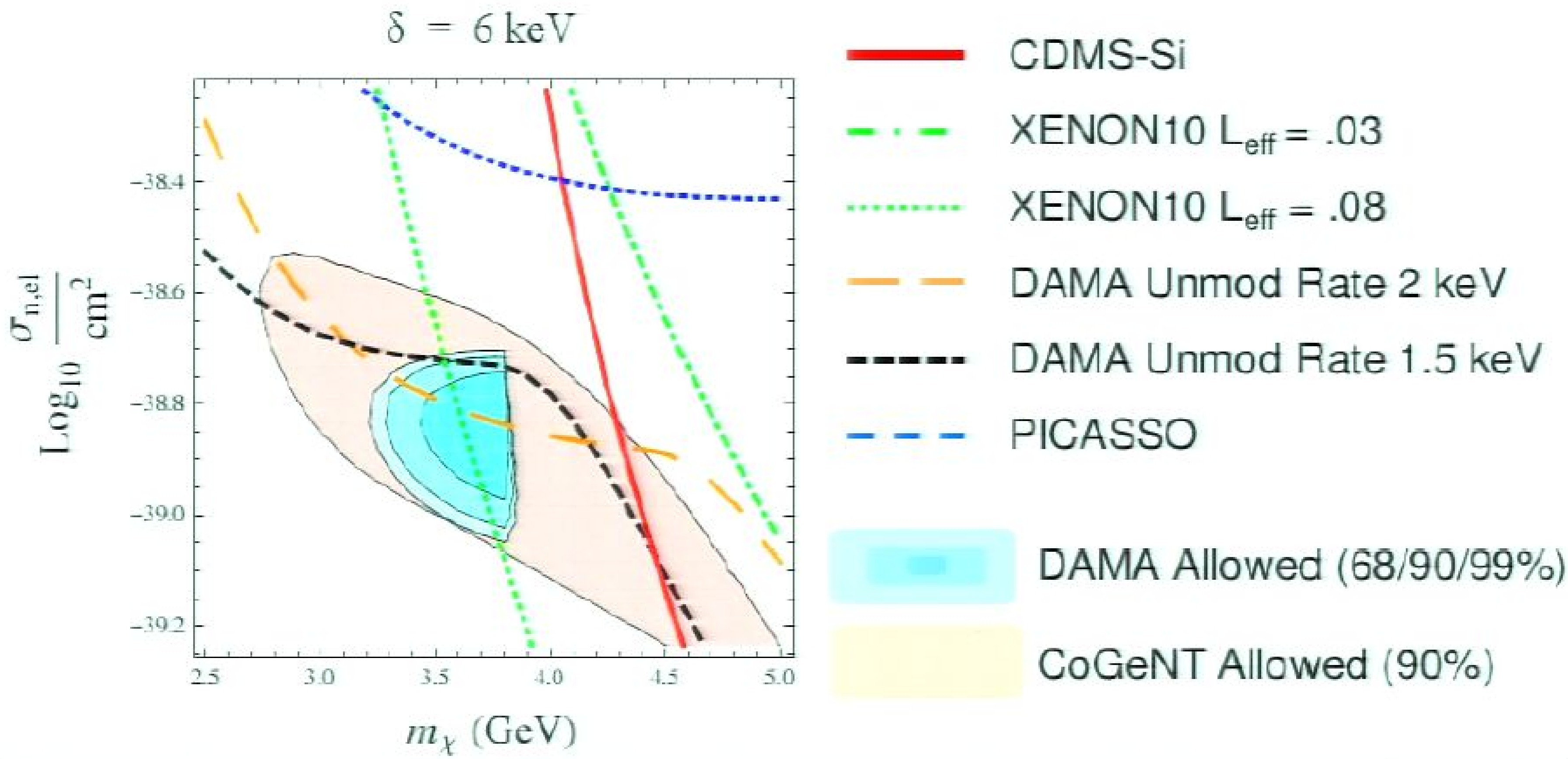
Graham *et al.* 1004.0937: exothermic transitions $\chi_2 N \to \chi_1 N'$ with $M_\chi \sim 4$ GeV, $\delta M_\chi \sim 5$ keV can explain DAMA modulation



Shape of exothermic recoil energy spectrum is sensitive to DM velocity

Exothermic dark matter?

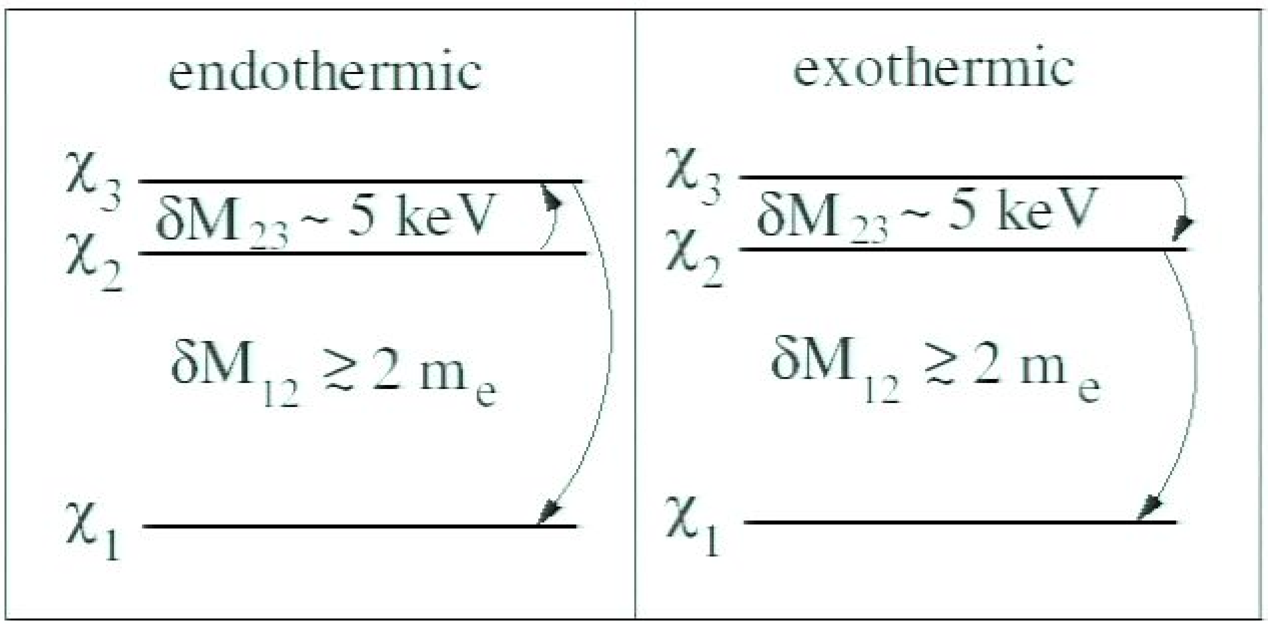
Graham *et al.* 1004.0937: exothermic transitions can also explain CoGeNT excess events



Getting the 511 keV signal in addition

JC, Frey, Chen 1008.1784: Add a third state below these two to get $\chi_{2,3} \to \chi_1 e^+ e^-$ 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.
($\epsilon < 10^{-9}$ for decay of metastable state)

Particle physics model

Same as before,

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

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

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

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

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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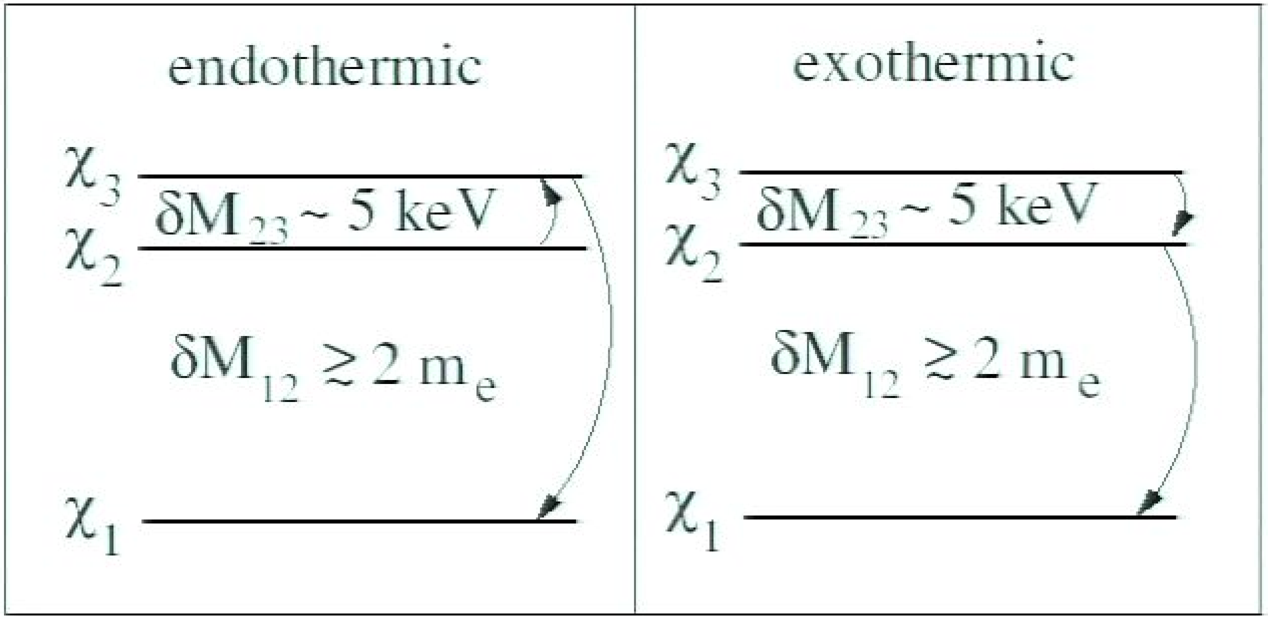

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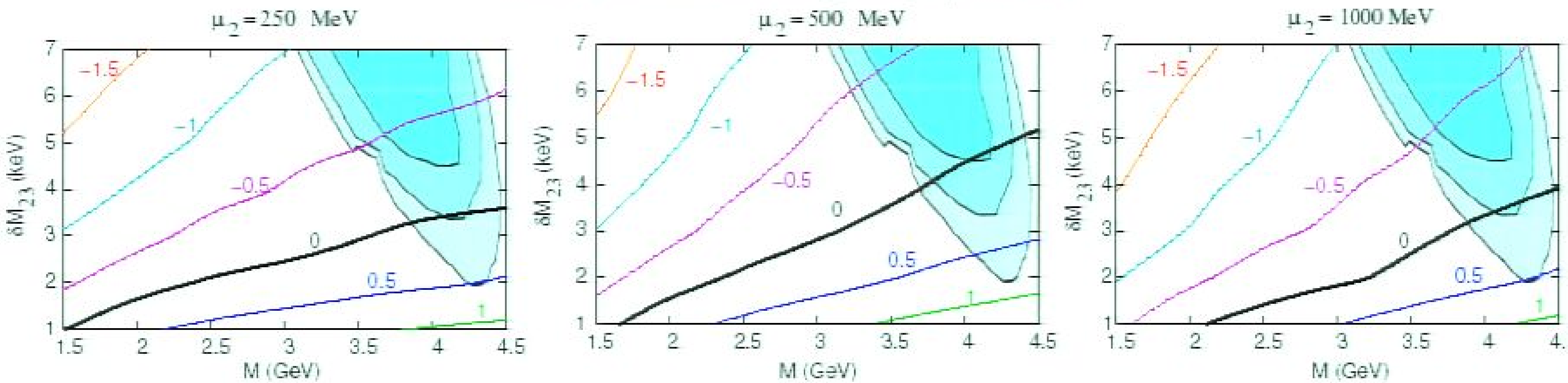
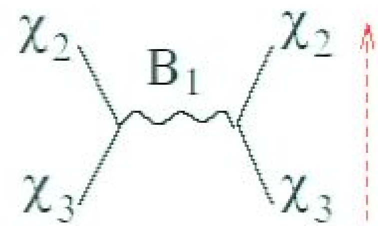
511 keV rate for exothermic DM

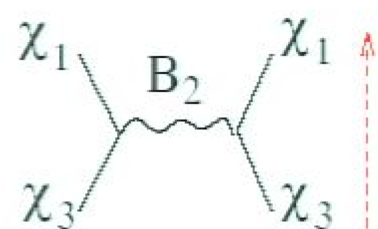
Contours of $\log R_{e^+}/R_{\rm obs}$



Rate of $\chi_3\chi_3 \to \chi_2\chi_2$ at galactic center prefers smaller μ_1



Relic density of χ_3 due to $\chi_3\chi_3 \to \chi_1\chi_1$ in early universe prefers larger μ_2



Gauge boson masses are related by symmetry breaking mechanism (dark Higgs content): $\mu_1 \gtrsim \sqrt{\mu_3^2 - \mu_2^2} \sim 2\sqrt{\mu_2\,\delta M_{23}/\alpha_g}$

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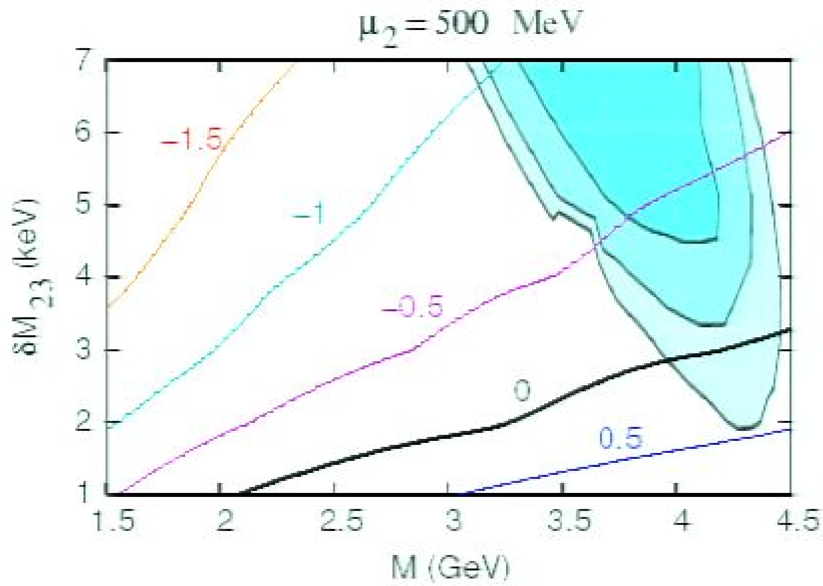
$\log R_{e+}/R_{\rm obs}$ contours
using $\alpha = 0.08$, $r_s = 7.5$ kpc:



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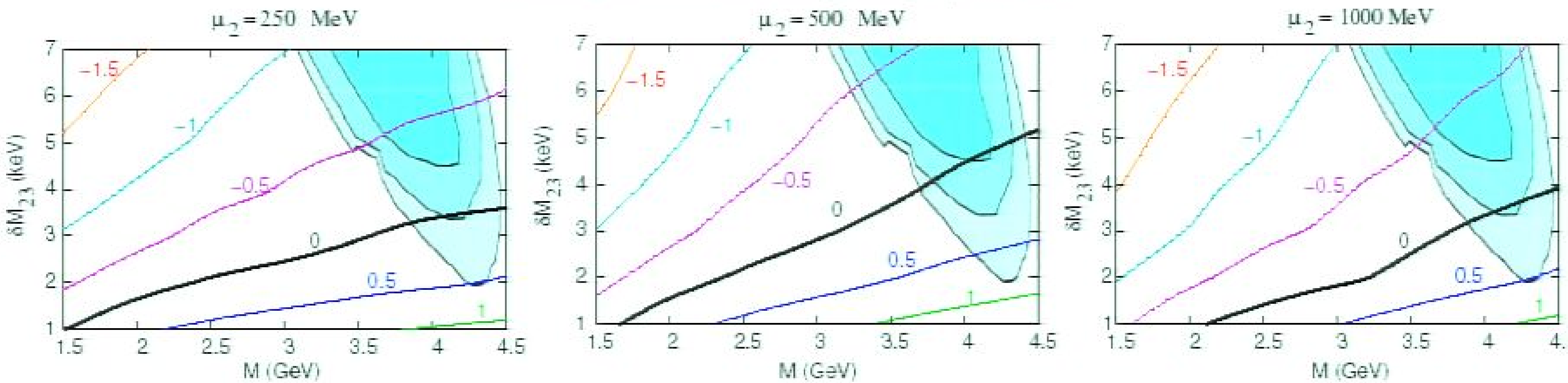

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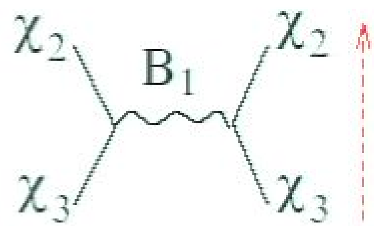

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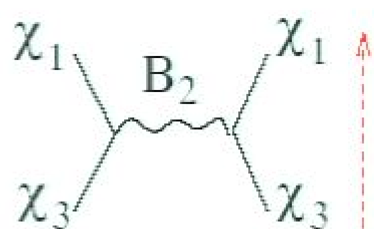

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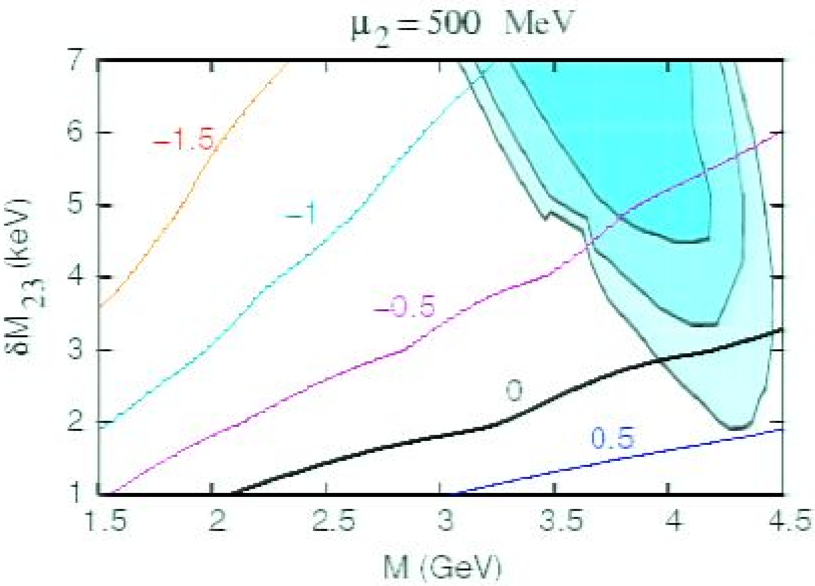
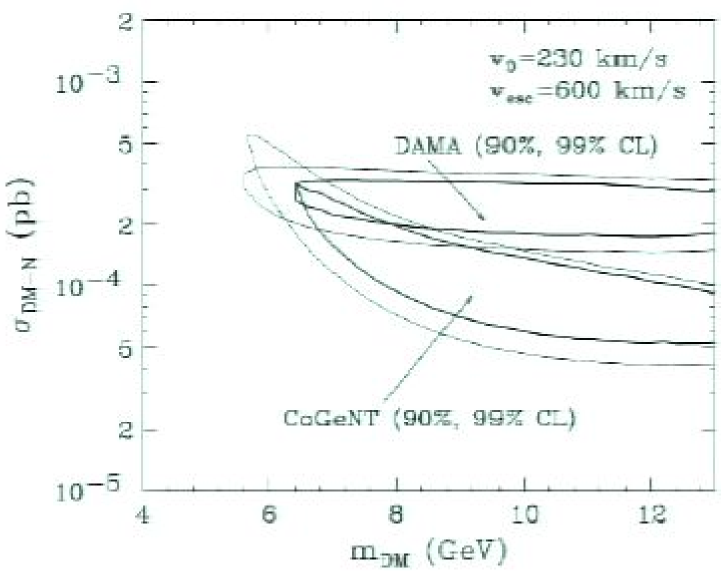


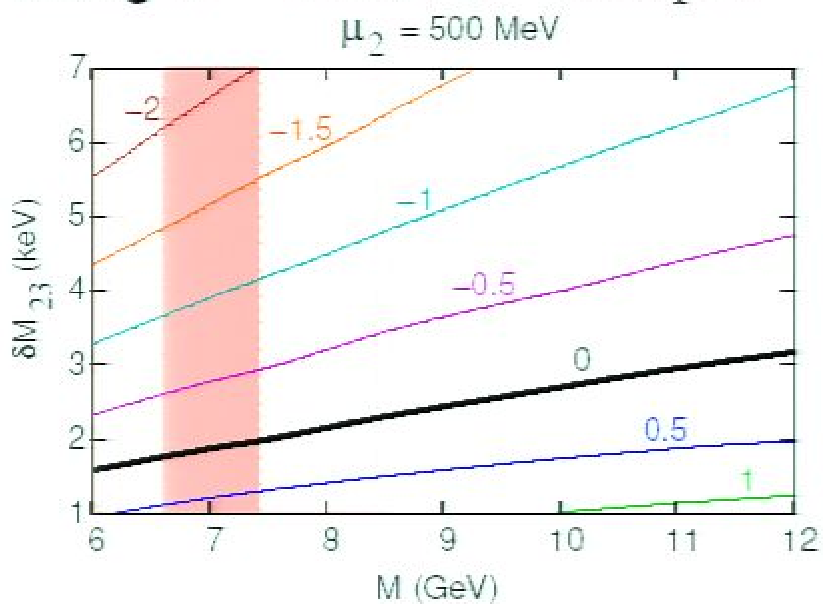
511 keV rate for endothermic DM

Less cuspy profiles are needed:

Hooper *et al.* 1007.1007



using $\alpha = 0.12$, $r_s = 12$ kpc:



Relic density of χ_2 due to $\chi_2\chi_2 \to \chi_1\chi_1$ in early universe prefers larger μ_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 χ_2 or χ_3 is controlled by kinetic mixing parameter ϵ_3 or ϵ_2.

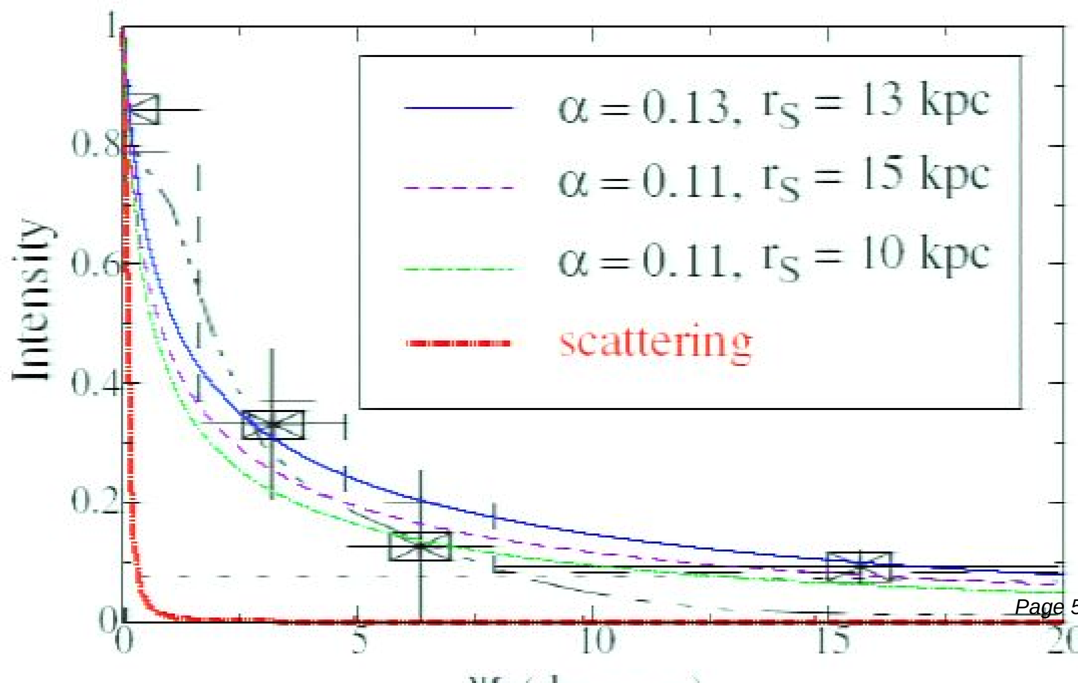
$$\mathcal{L}_{\rm kin} = \sum_i \epsilon_i B^i_{\mu\nu} F^{\mu\nu}$$

where $\epsilon_i = \langle \Delta_i \rangle / \Lambda_i$. If $\epsilon_{3,2} \sim 10^{-11}$ then intermediate state is already present; decays $\chi_{2,3} \to \chi_1 e^+ e^-$ 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

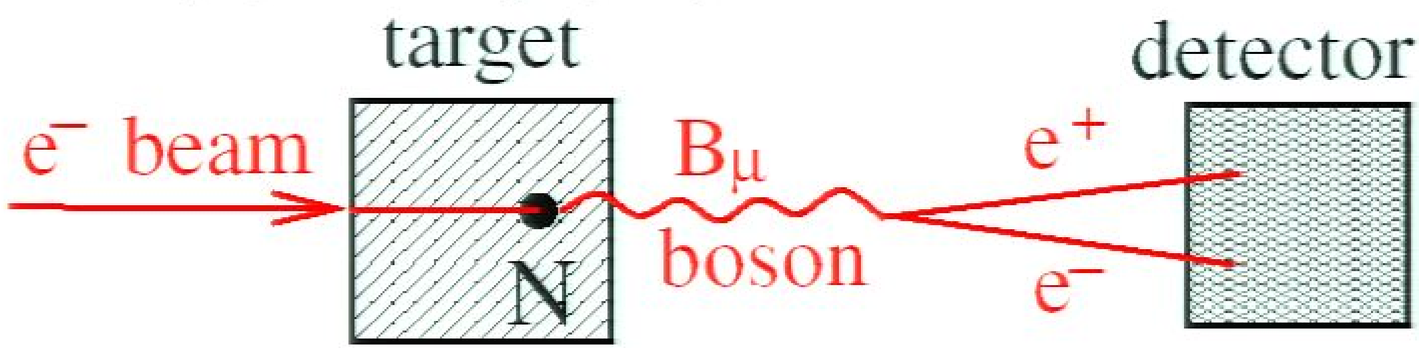
if scattering, positron transport before annihilation required



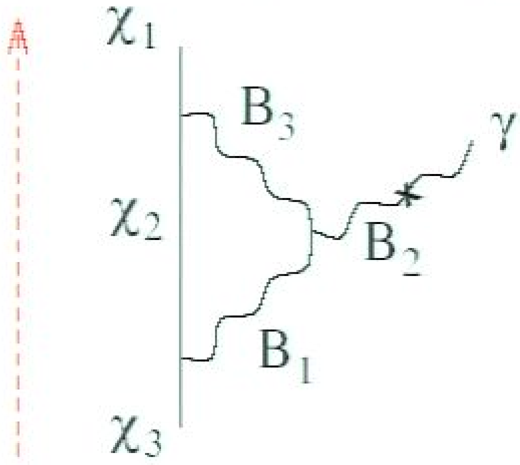
Are there other predictions?

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

- Beam dump (fixed target) experiments



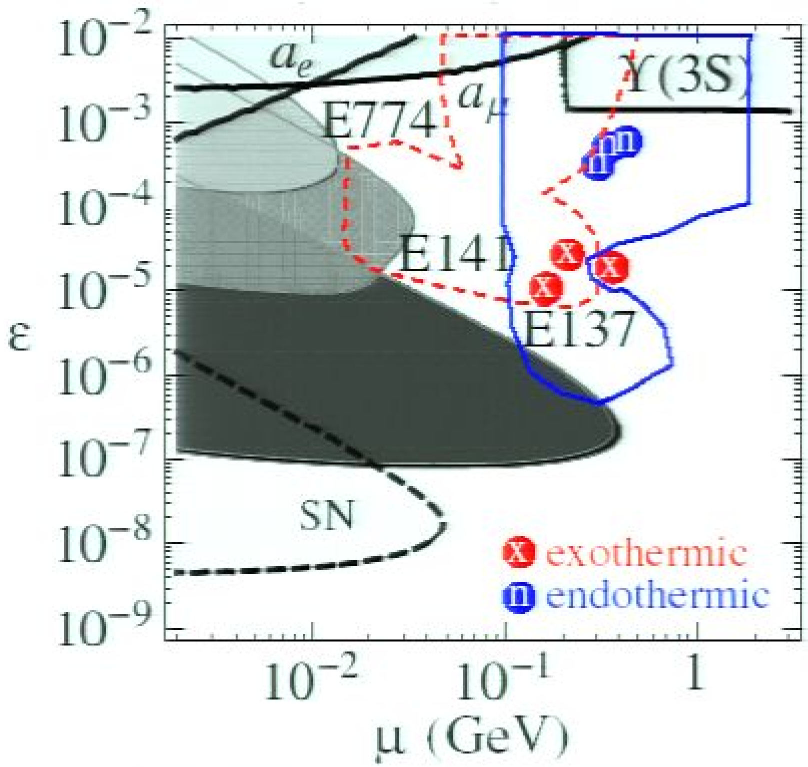
- Monoenergetic γ ray from $\chi_3 \to \chi_1\gamma$ at galactic center



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

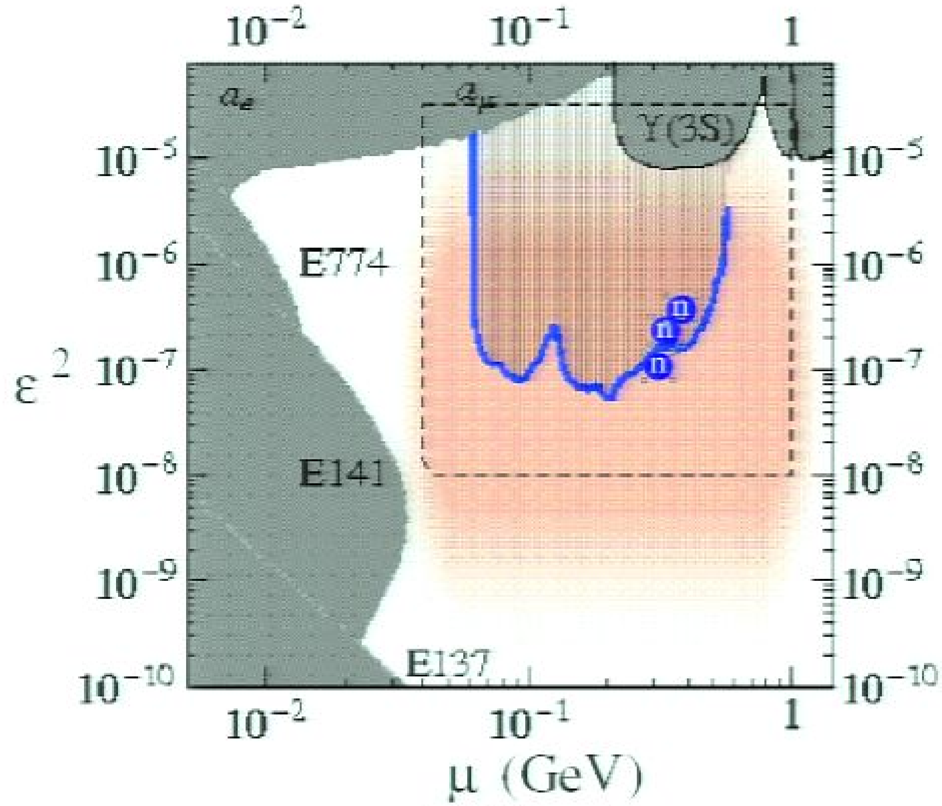
Laboratory and other probes

Kinetic mixing ϵ and gauge boson mass μ parameter space is not highly constrained; provides oppportunities for new fixed target searches. Predictions of our model:



Existing and proposed experiments

Bjorken *et al.* 0906.0580



APEX reach

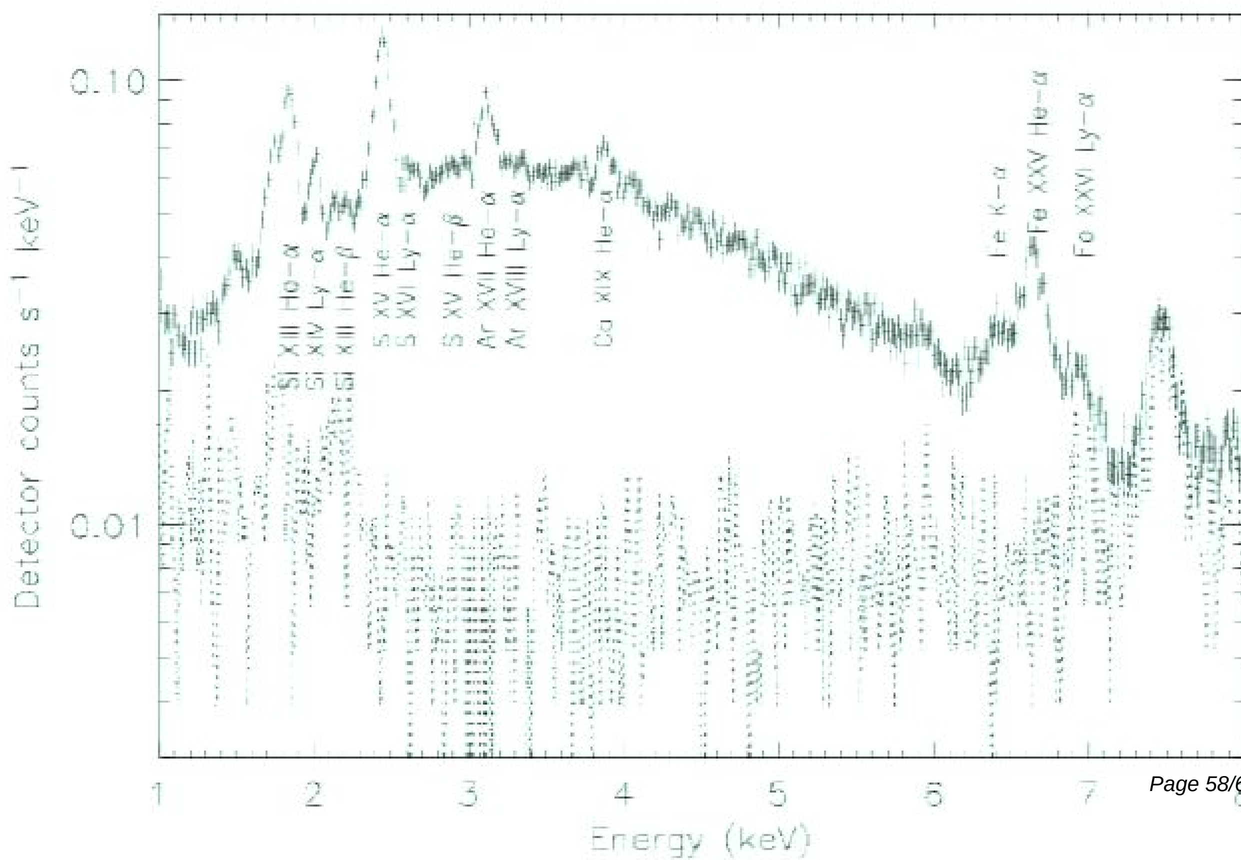
Essig *et al.* 1001.2557

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

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

Could INTEGRAL could potentially see this ~ 1 MeV γ?
We find it is too weak.

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



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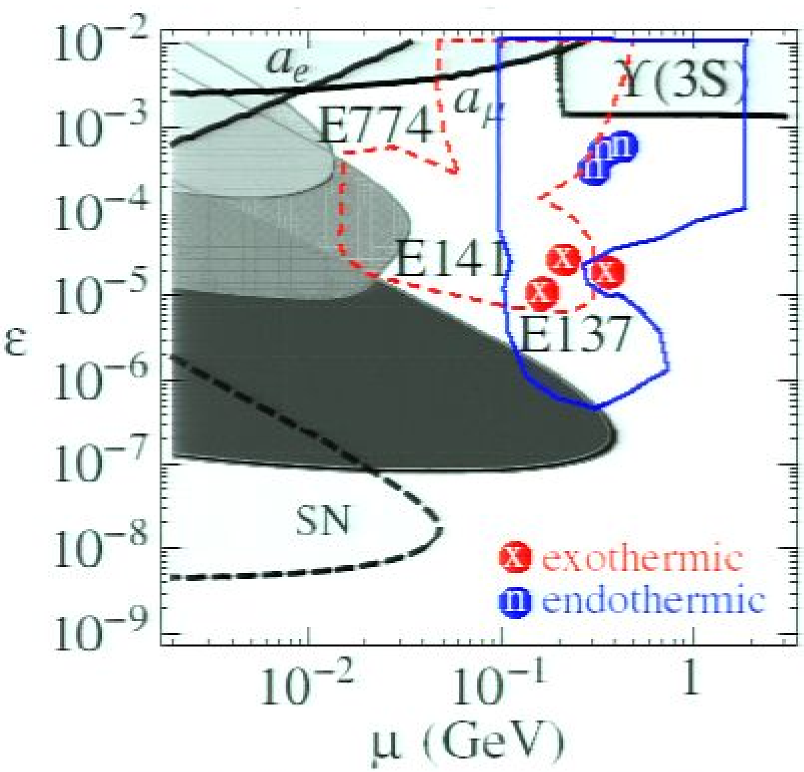

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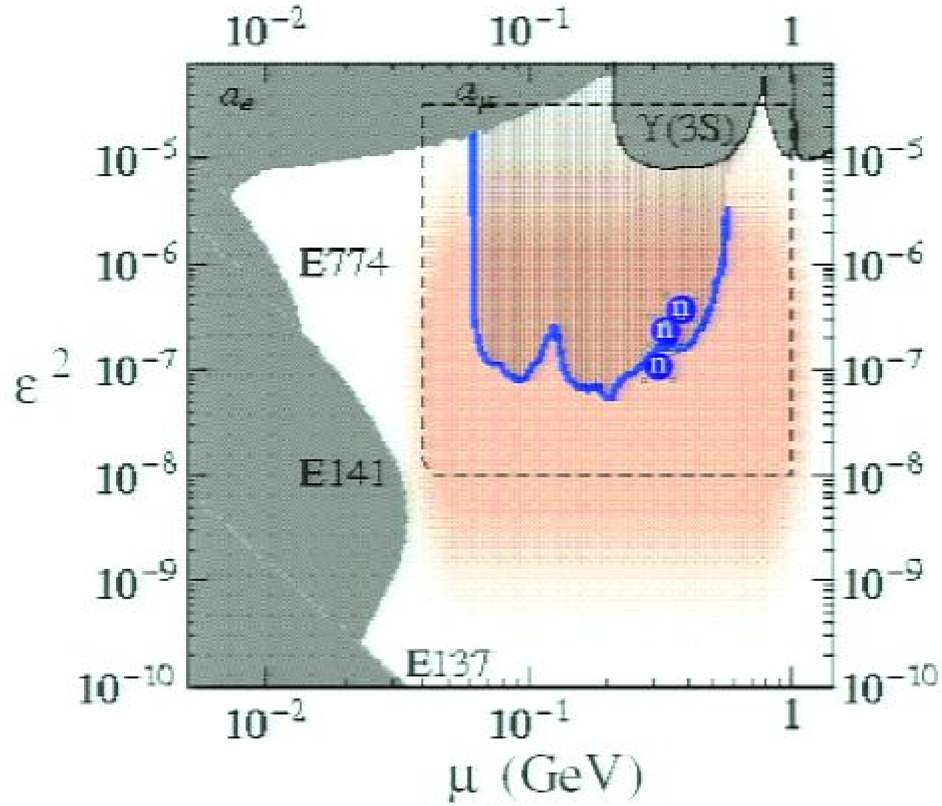

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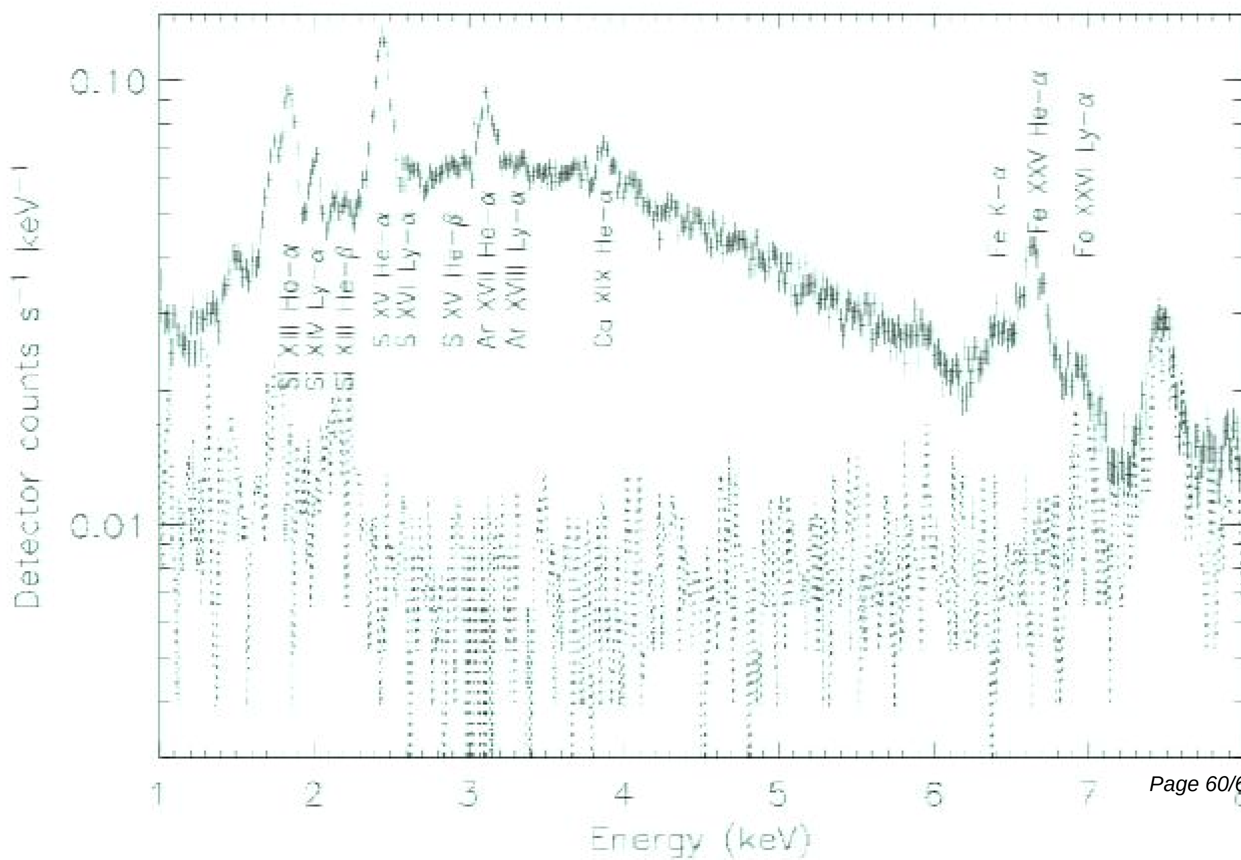

Conclusions

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 γ, direct detection, could be complementary probes

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

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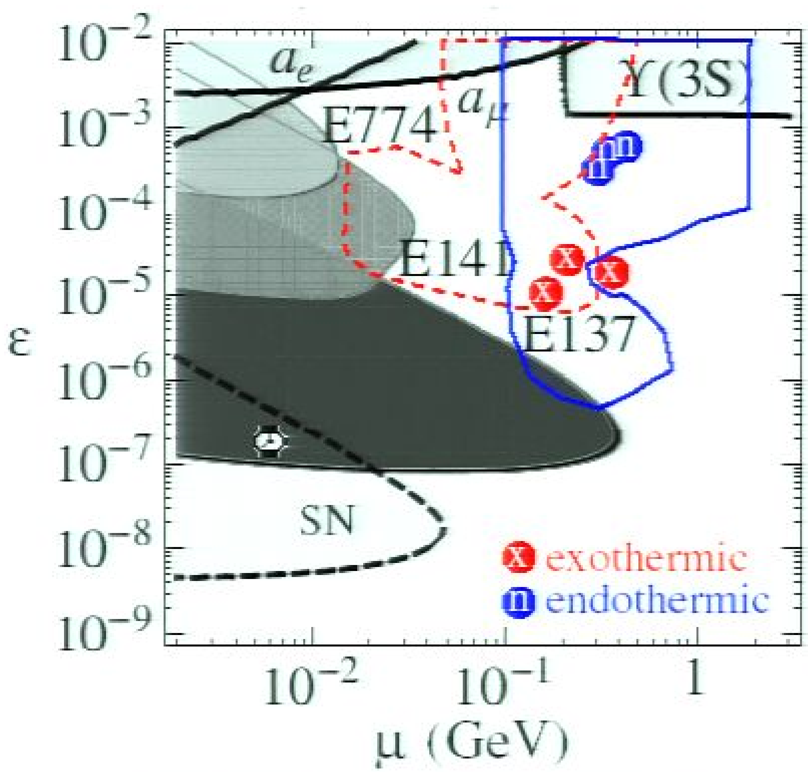

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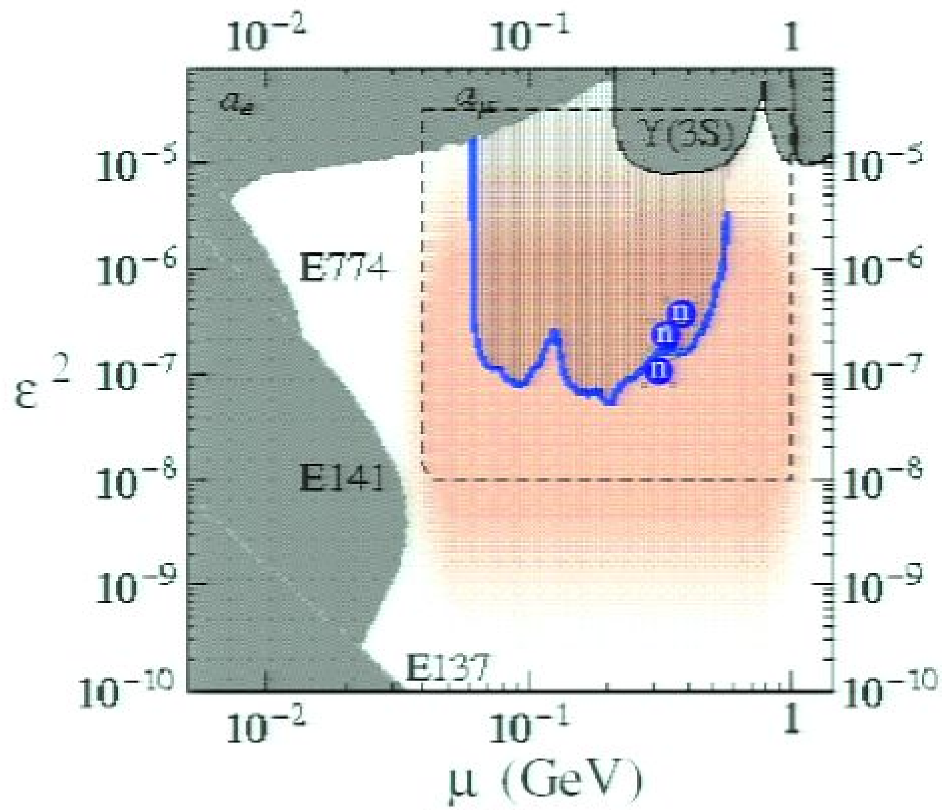

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Hidden sector dark matter: direct detection and cosmic ray anomalies

Jim Cline, McGill U. & PI

Perimeter Institute, 5 Oct. ‘10

A simple nonabelian DM model

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

$$\mathcal{L}_\chi = \tfrac{1}{2}\bar{\chi}_i(i\not{D}_{ij} - M_\chi\delta_{ij})\chi_j - \tfrac{1}{4g^2}B^a_{\mu\nu}B_a^{\mu\nu} - \tfrac{1}{\Lambda}\Delta_a B_a^{\mu\nu}Y_{\mu\nu}$$

↗ dark matter ↗ dark gauge sector ↗ mixing with SM

- Triplet VEV $\langle\Delta_2\rangle$ gives B_2-γ mixing.
- We need second triplet Δ' to fully split χ_i states:

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

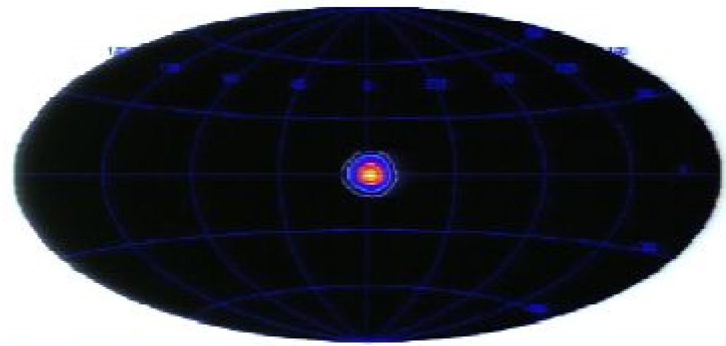
- Unbroken Z_2 symmetry can play important role:

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

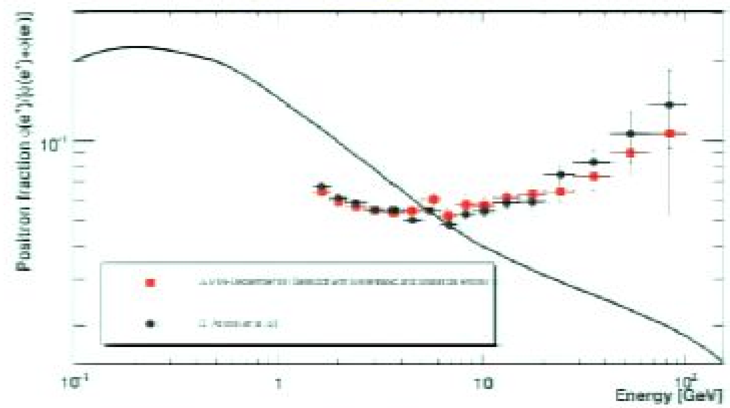
χ_2, B_2, Δ_2, Δ'_2 uncharged.

The cosmic ray anomalies

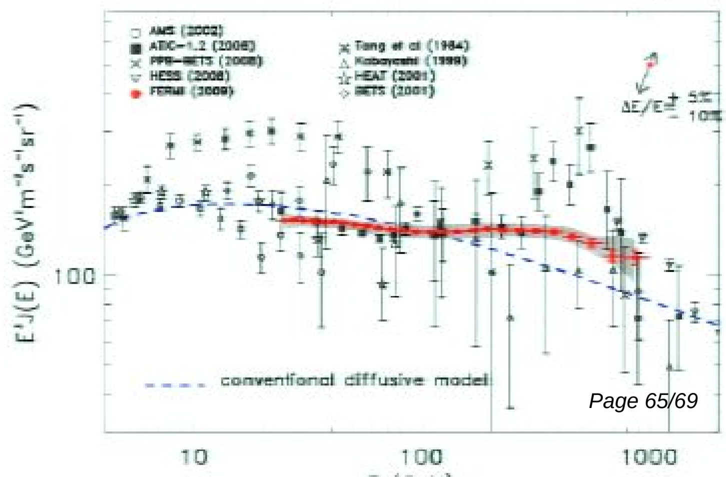
- Excess 511 keV γ's from galactic center, observed by INTEGRAL/SPI



- PAMELA positron excess at 10−100 GeV



- Fermi/LAT $e^{\pm}$ excess at 100−1000 GeV



Personal motivation

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

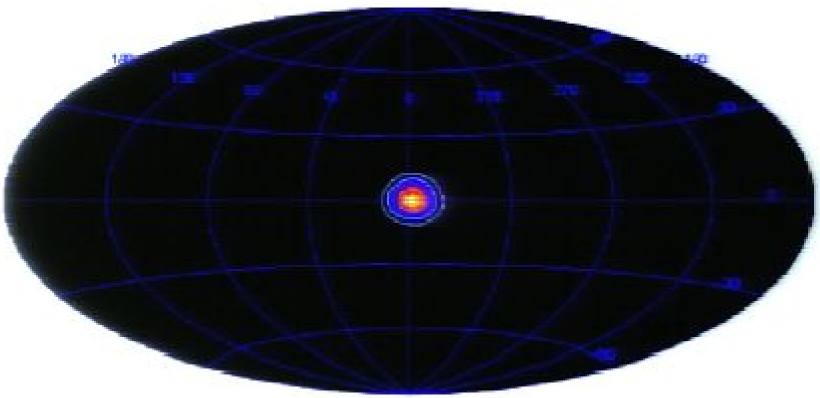


Figure 2. An MREM sky map of the 511 keV positron annihilation line emission. The contours indicate intensity levels of 10^{-2}, 10^{-3}, and 10^{-4} ph cm^{-2} s^{-1} sr^{-1}. Details are given in the text.

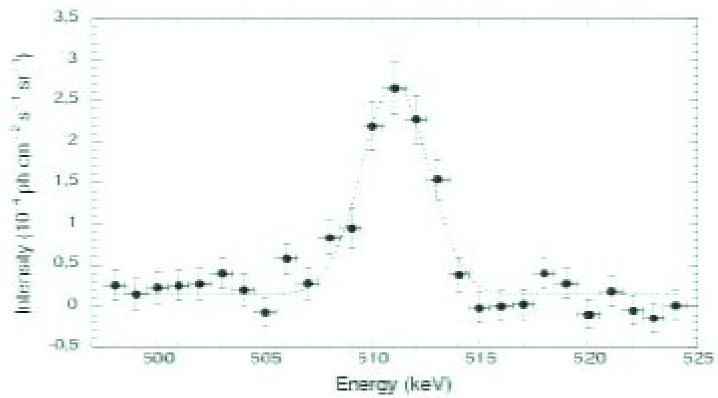


Fig. 3. 511 keV flux spectrum obtained using a gaussian centred on the GC with a FWHM of 10°.

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

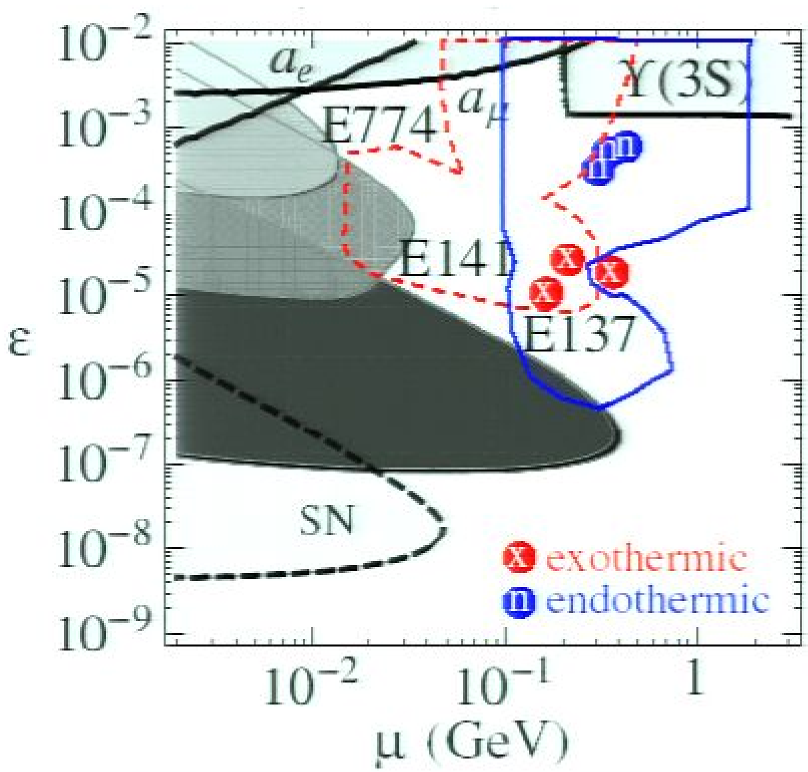
Astrophysical mechanisms for excess 511 keV remain unconvincing

Fixed target experiments, monochromatic galactic MeV γ, direct detection, could be complementary probes

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

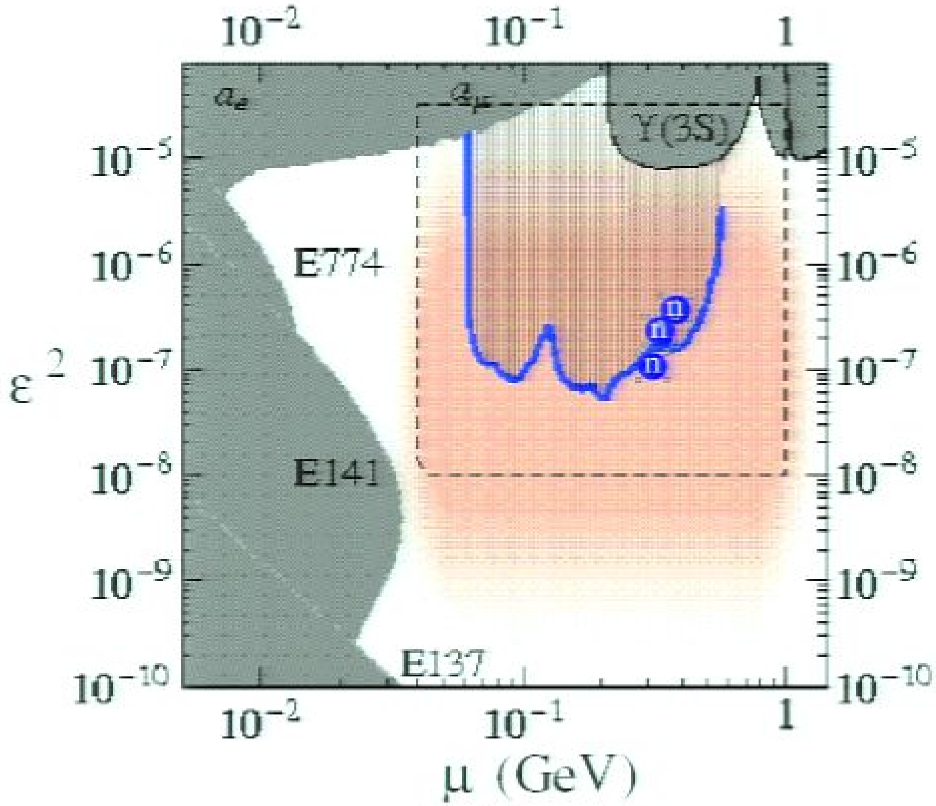
Laboratory and other probes

Kinetic mixing ϵ and gauge boson mass μ parameter space is not highly constrained; provides oppportunities for new fixed target searches. Predictions of our model:



Existing and proposed experiments

Bjorken *et al.* 0906.0580



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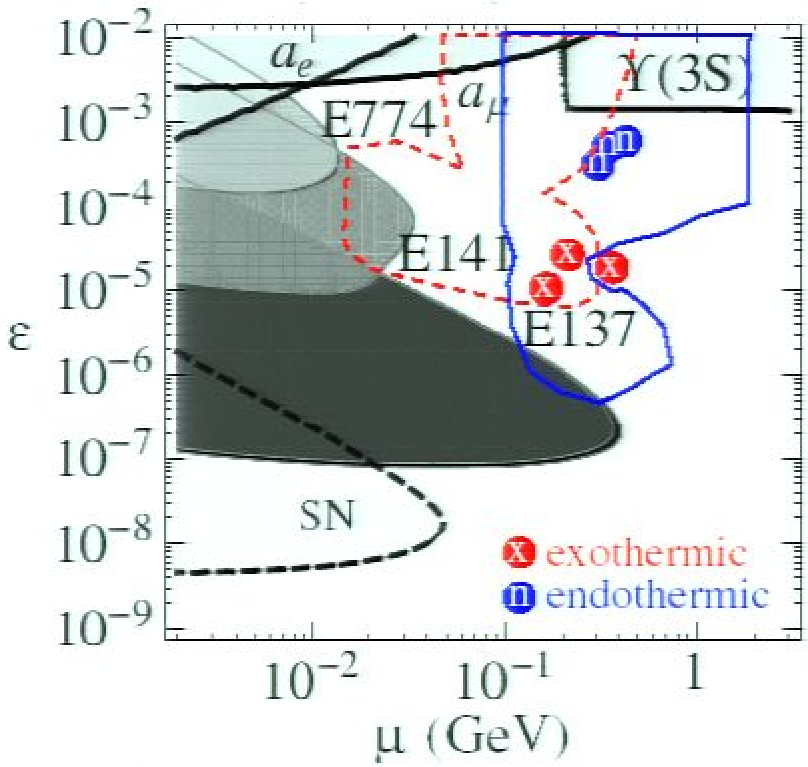

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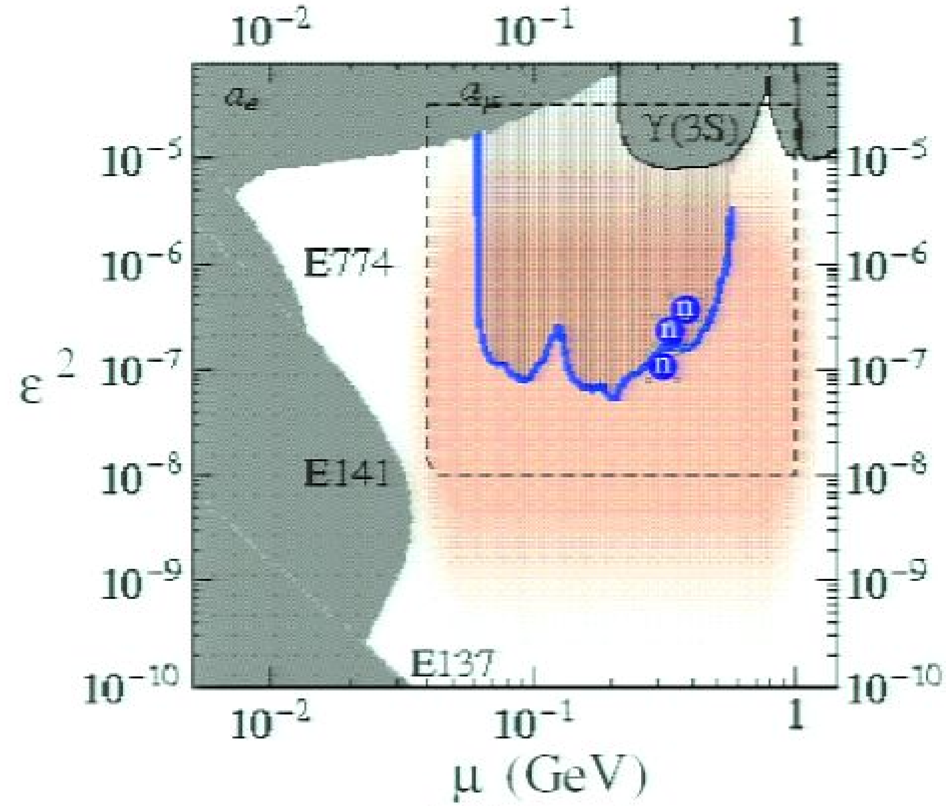

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