Title: Nonabelian Dark Matter

Date: Nov 27, 2009 02:30 PM

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Abstract: Recent data from the PAMELA, Fermi/LAT and INTEGRAL/SPI experiments, among others, give evidence of excess electrons and positrons in the galaxy, which might be due to annihilation of dark matter. Models in which the dark matter transforms under a hidden nonabelian gauge symmetry can naturally account for the unusual features needed to fit these data. I will discuss generic features of such models, some of their distinctive consequences for cosmology, and new results for reconciling their predictions with the anomalous observations. Special attention will be given to the 511 keV gamma ray excess observed by INTEGRAL, and to the possibility that high energy lepton excesses get significant contributions from dark matter annihilation in subhalos rather than the main halo of our galaxy.

Nonabelian Dark Matter

Jim Cline, McGill University

with F. Chen, A. Frey, A. Fradette,
C. Rabideau, A. Vincent, W. Xue

PI, 27 Nov. 2009

1. Introduction

- Experimental hints of annihilating dark matter
- Theoretical framework
- How it explains the observations
- CMB and γ-ray constraints

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Experimental anomalies suggest annihilation of dark matter in the galaxy:

- PAMELA positron excess at 10-100 GeV
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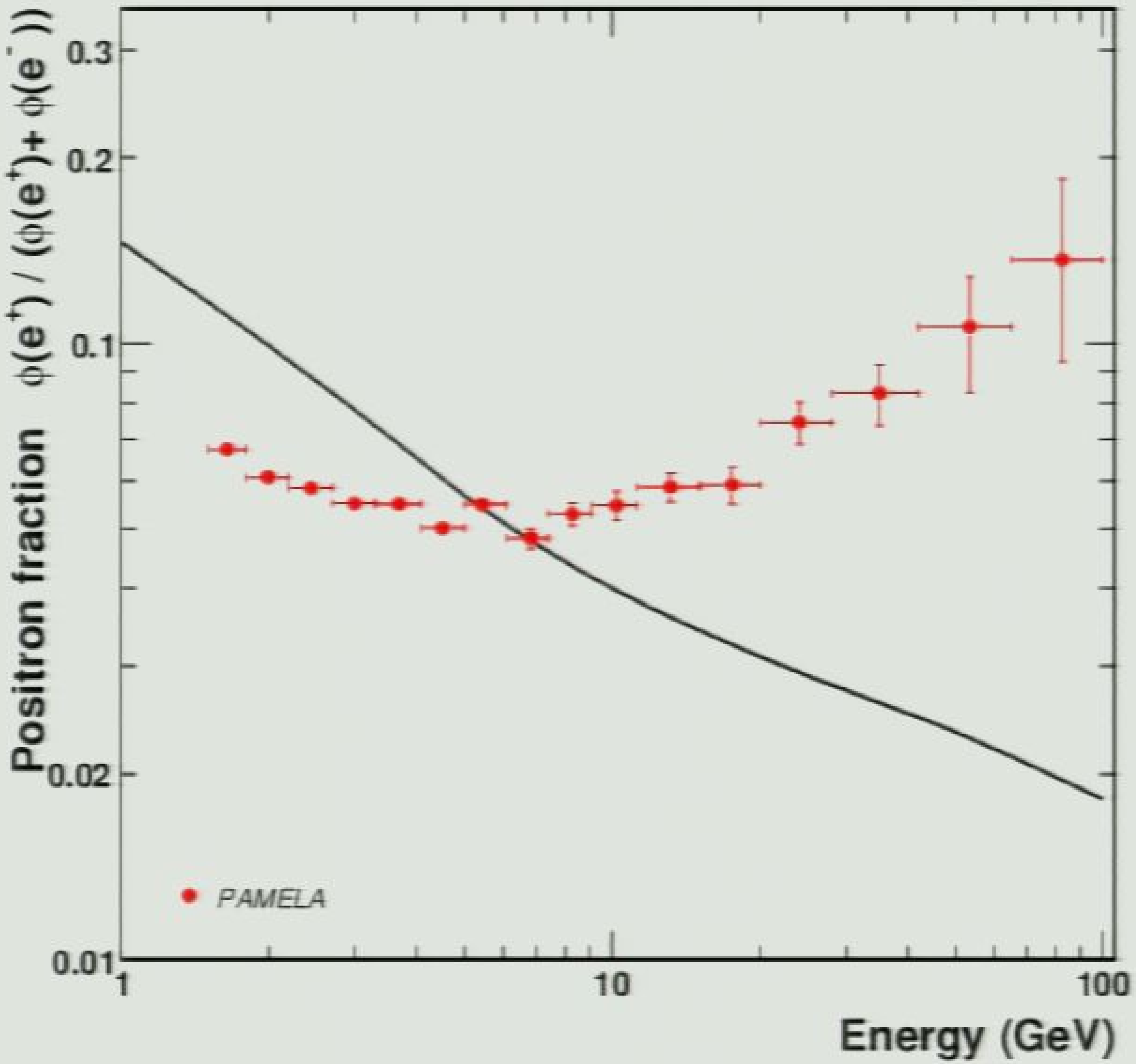
- INTEGRAL/SPI low-energy positron excess
- WMAP + Fermi "Haze"
- DAMA/LIBRA annual modulation

PAMELA (Adriani *et al.*, 0810.4995)



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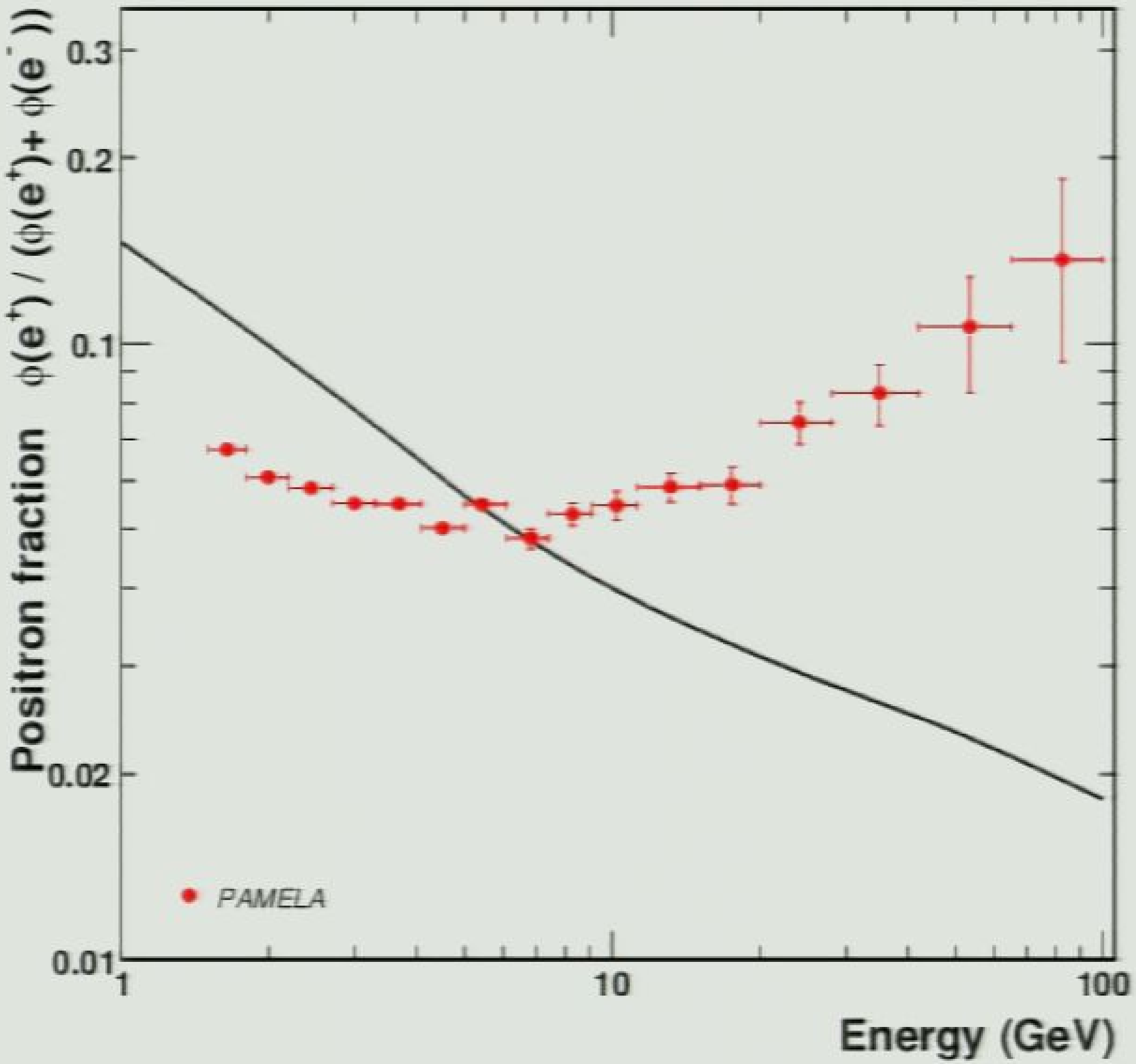

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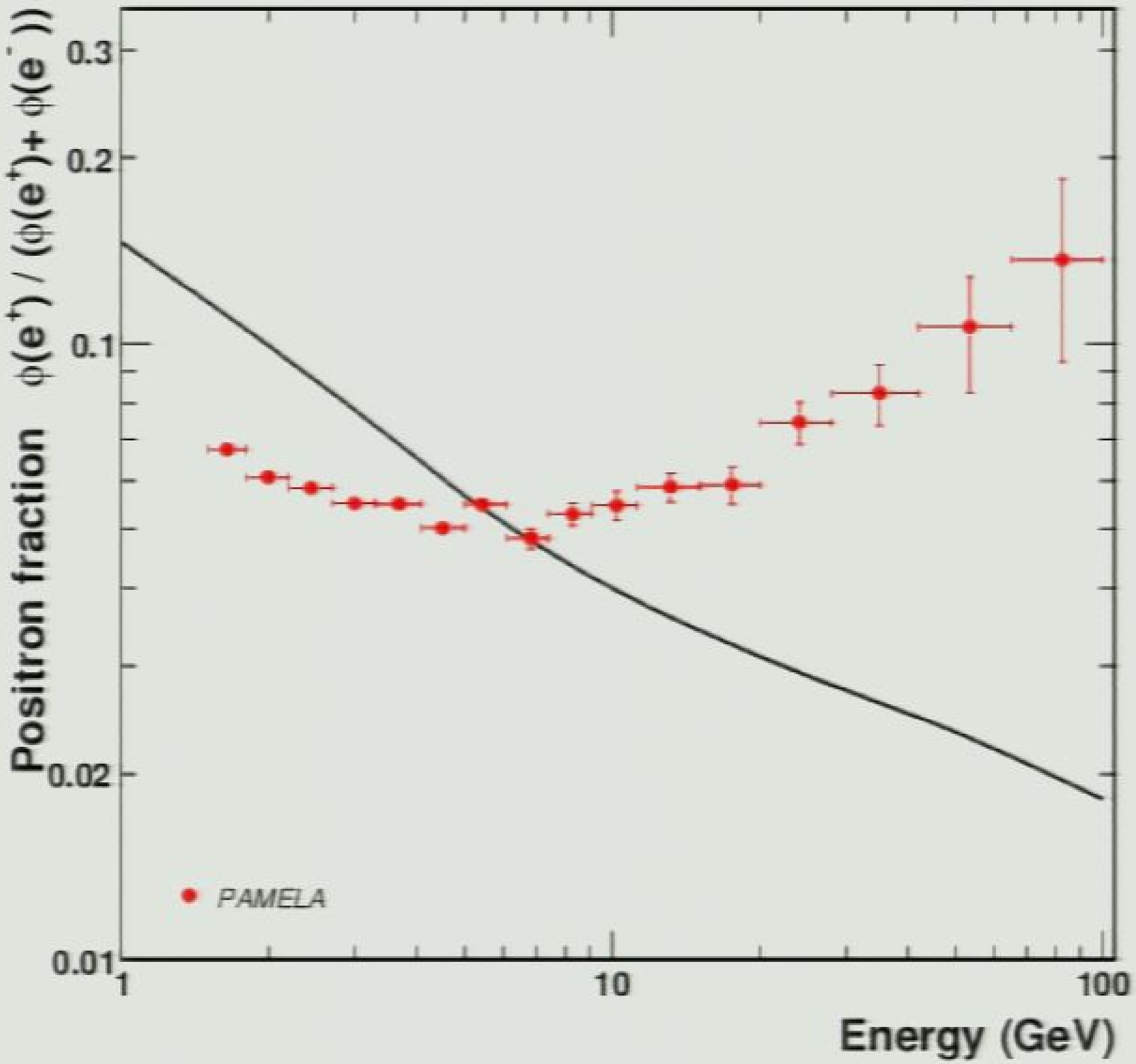

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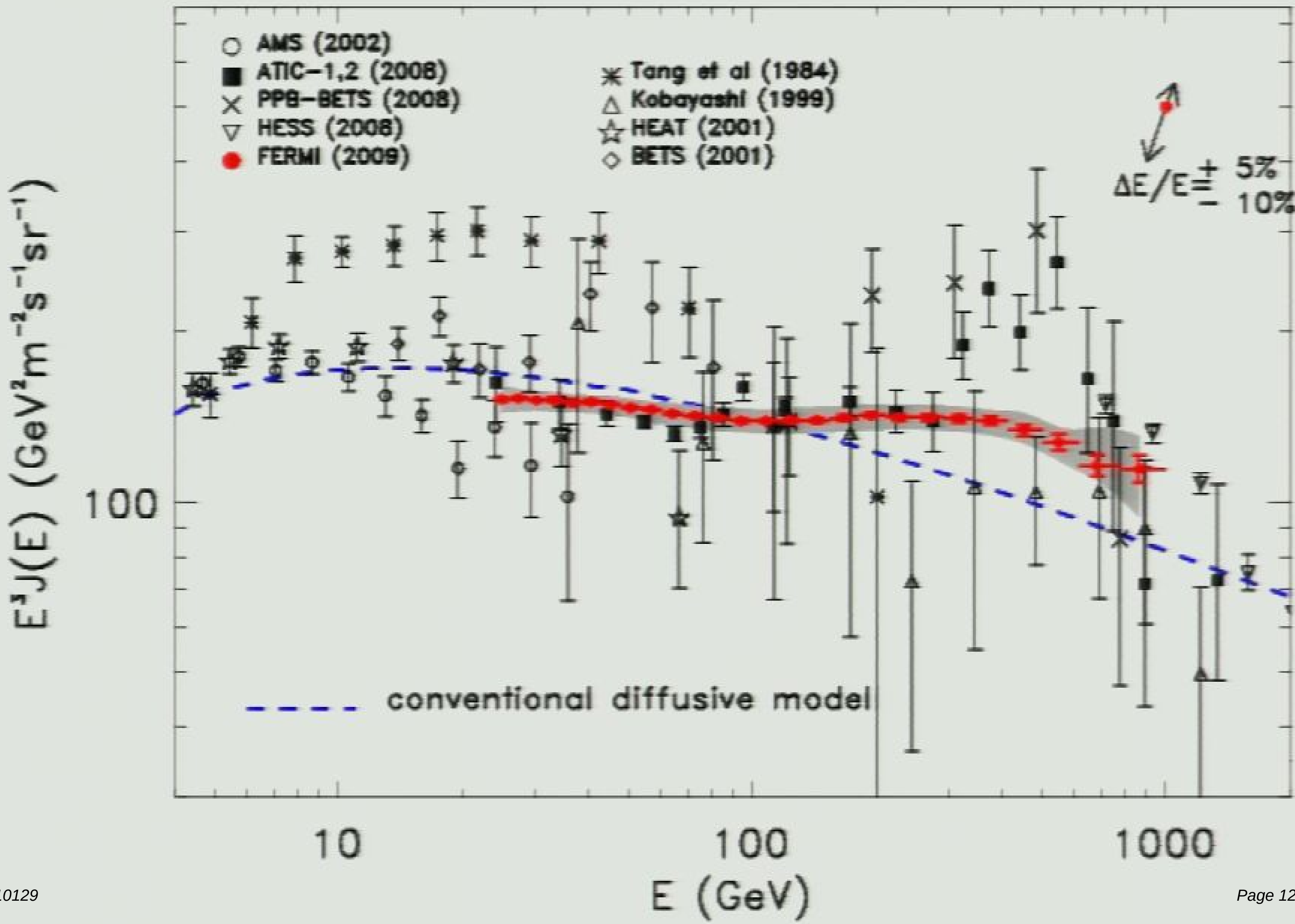

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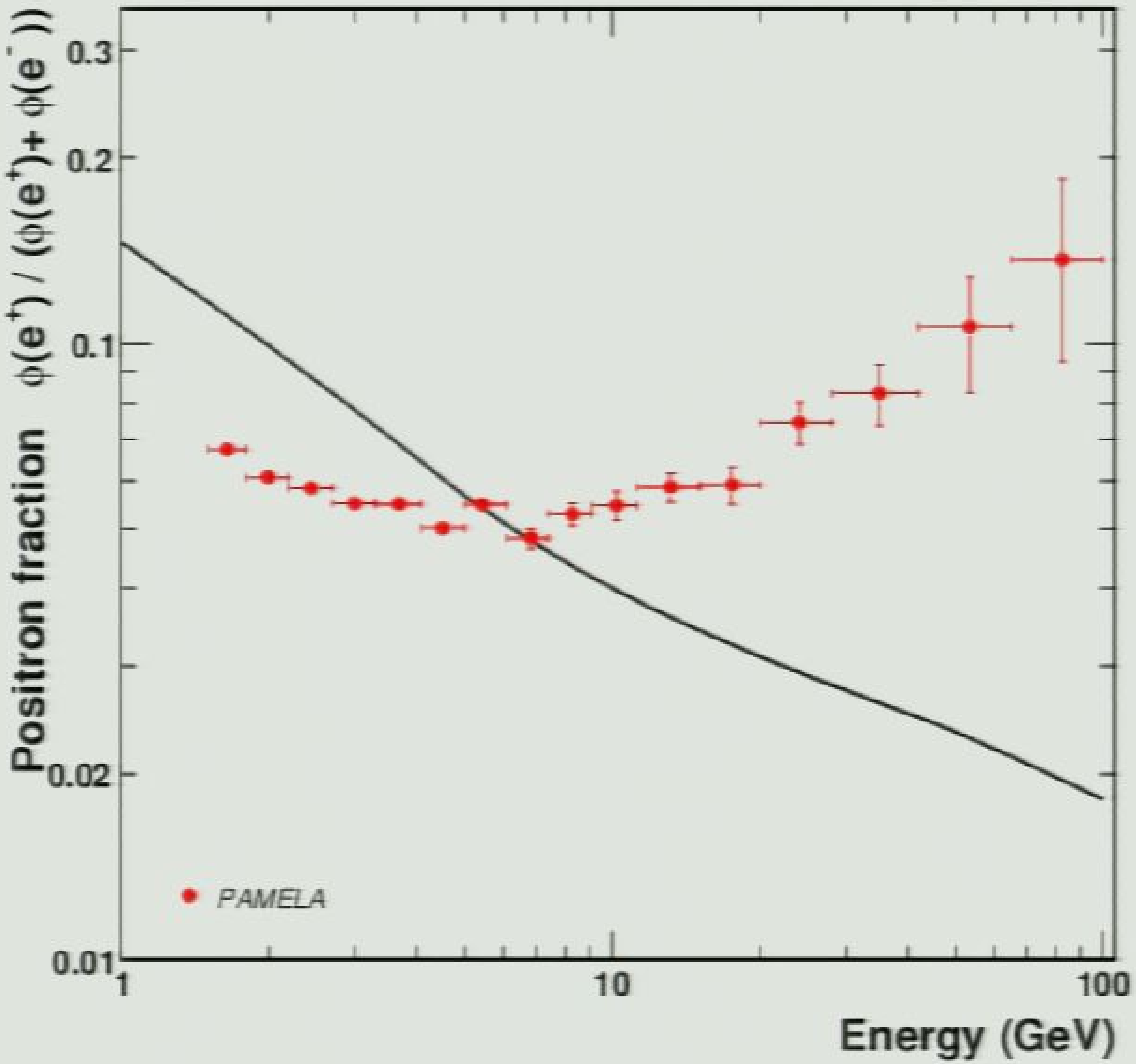

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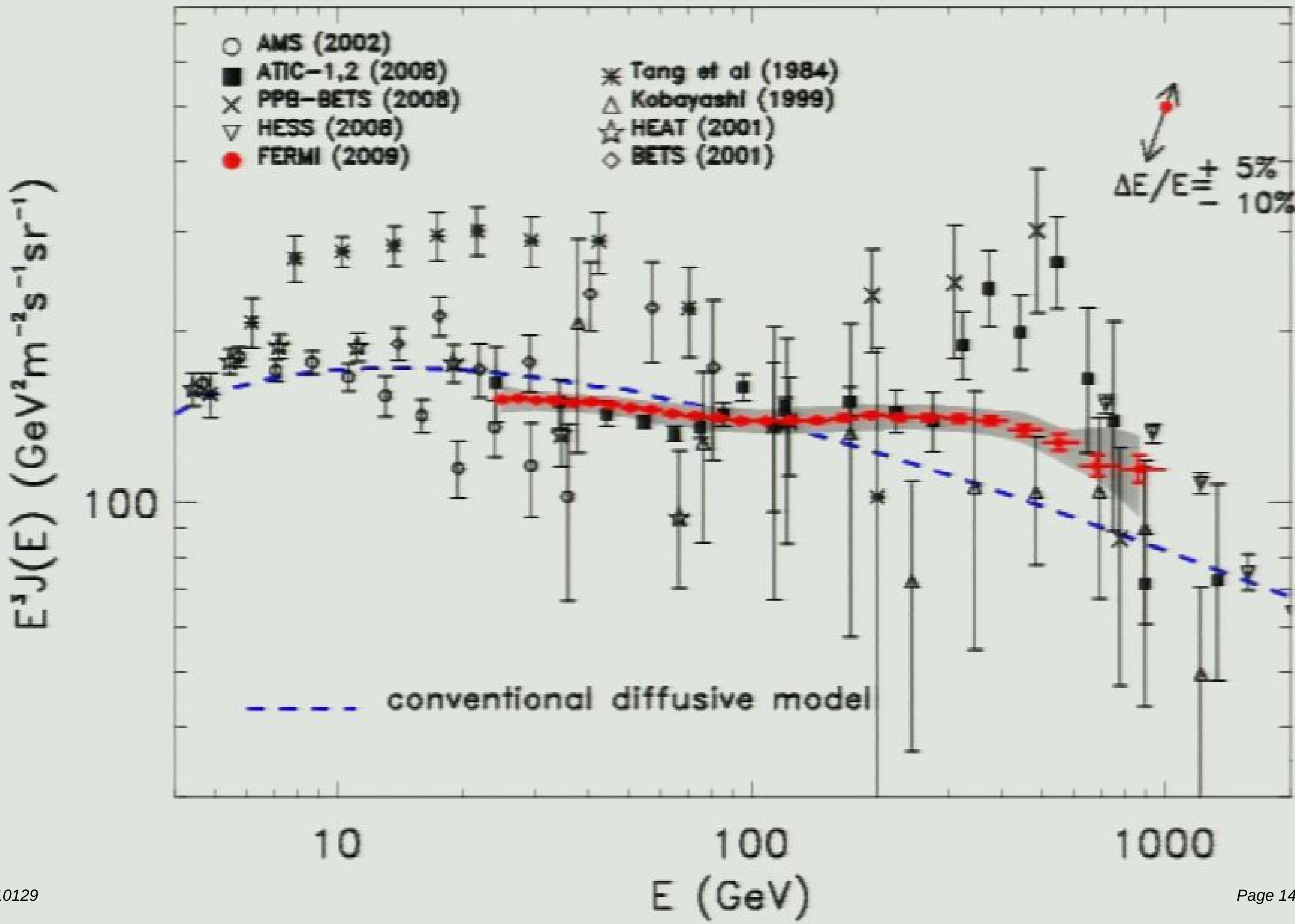

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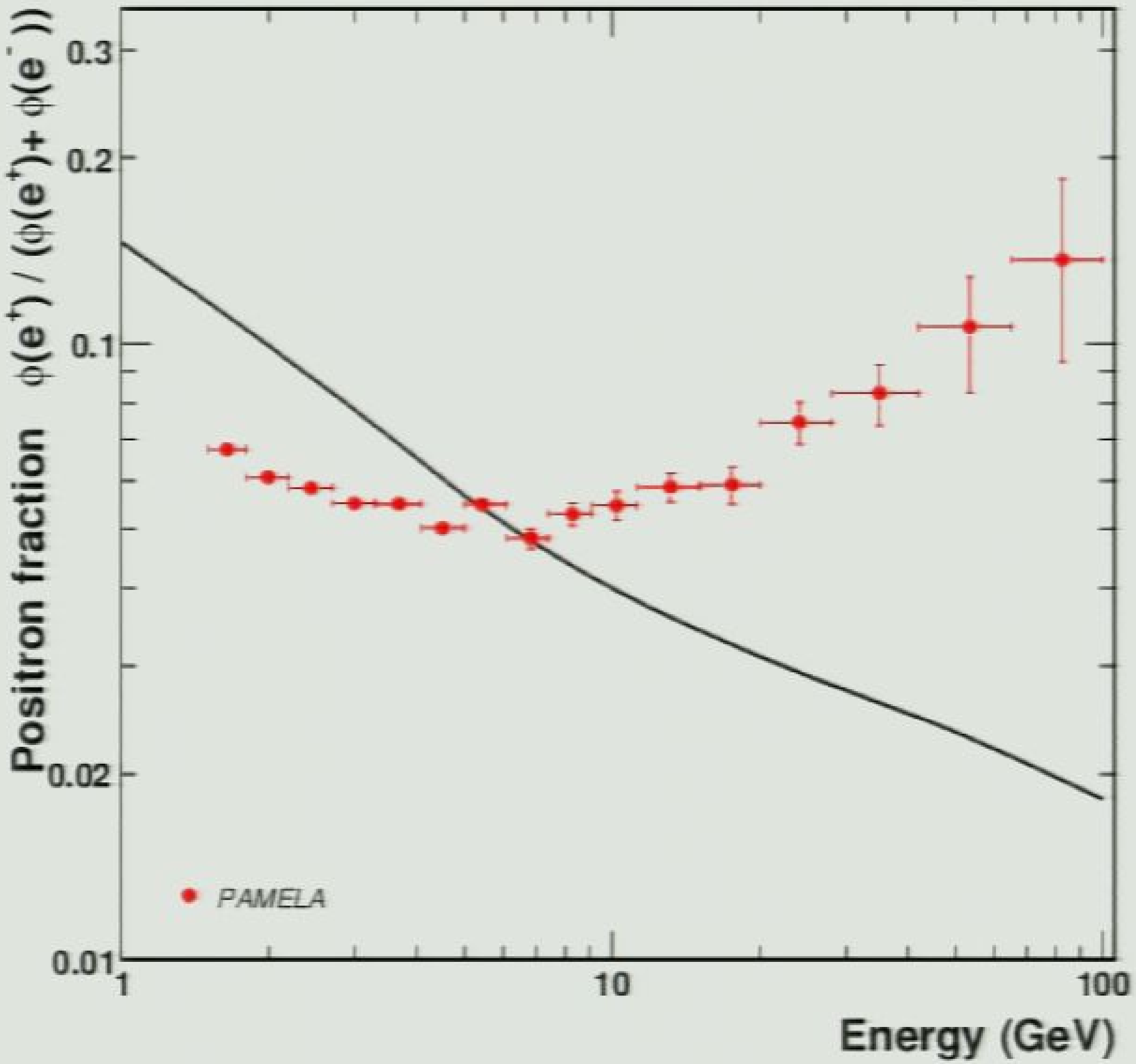

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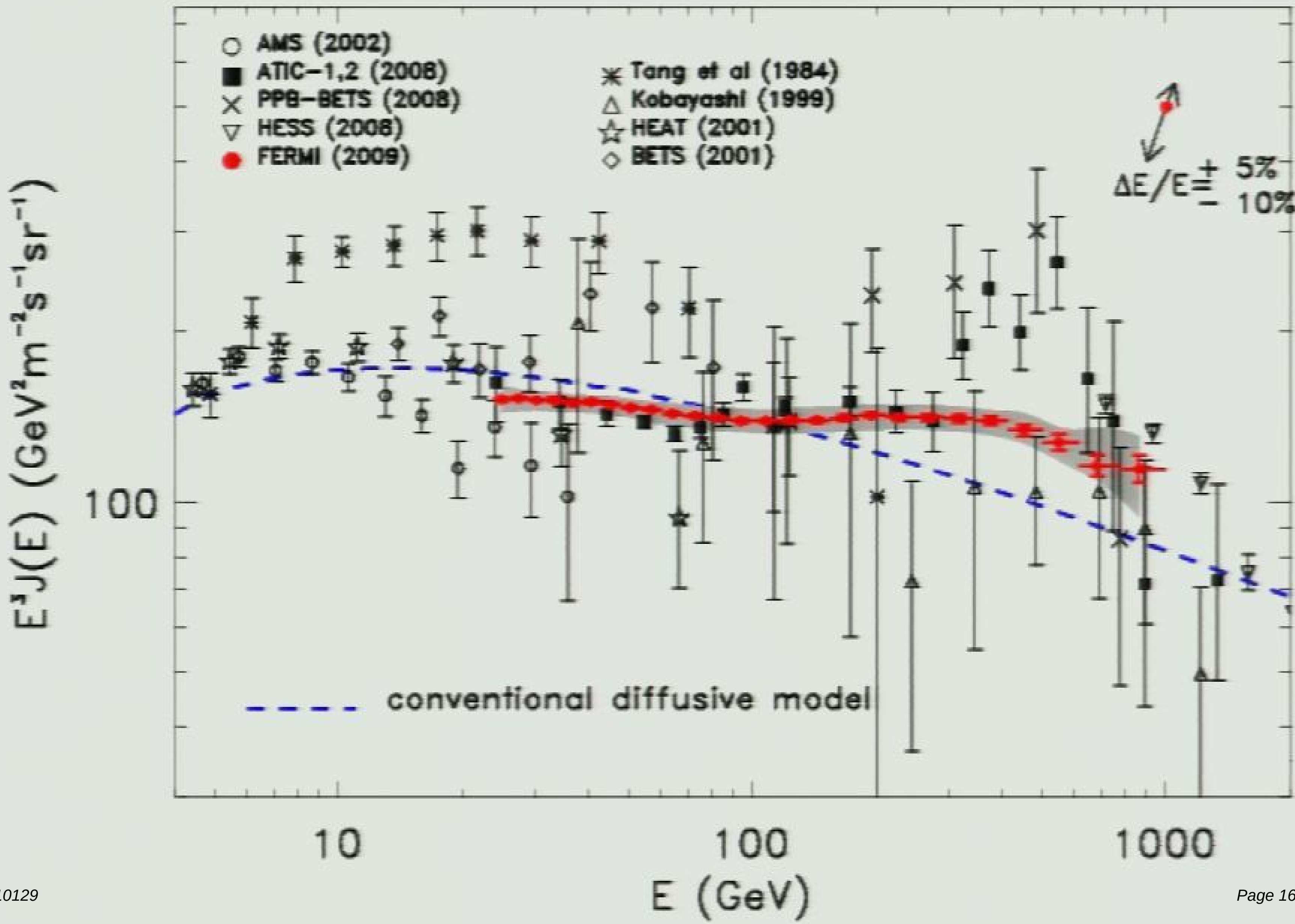
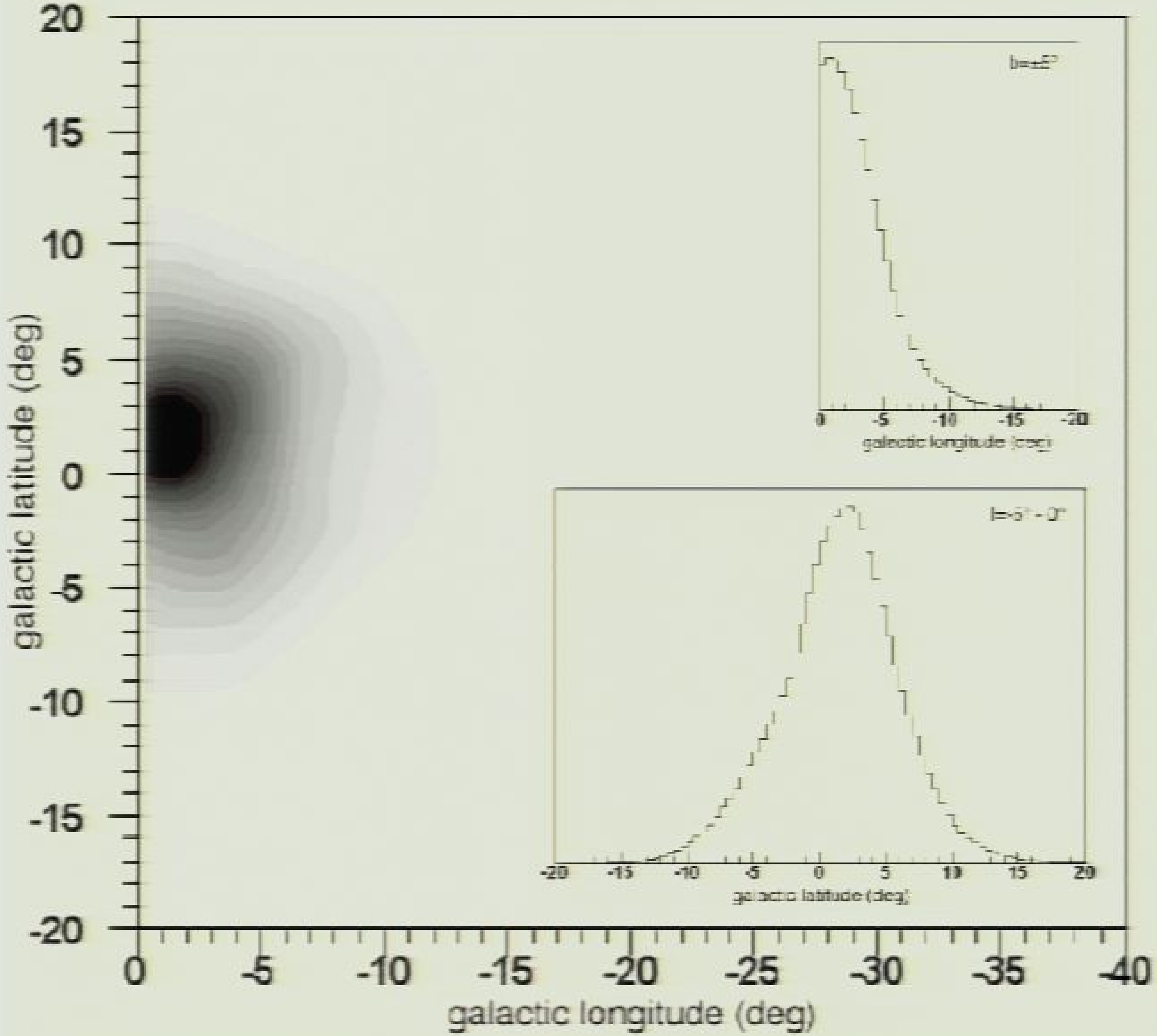


INTEGRAL/SPI 511 keV signal

Morphology (Knödlseder *et al.*, astro-ph/0309442):



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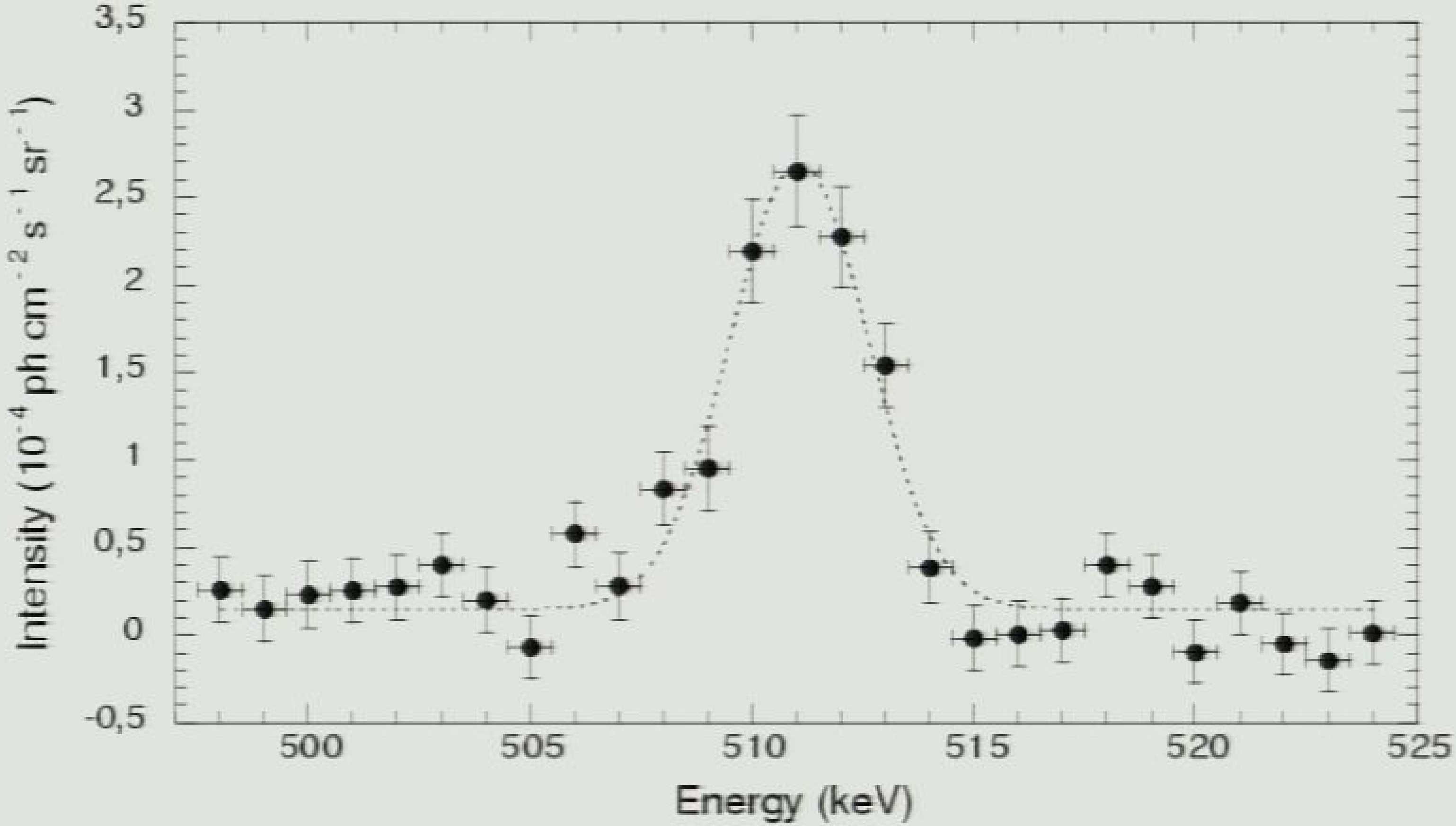

Fig. 3. 511 keV flux spectrum obtained using a gaussian centred on the GC with a FWHM of 10°.

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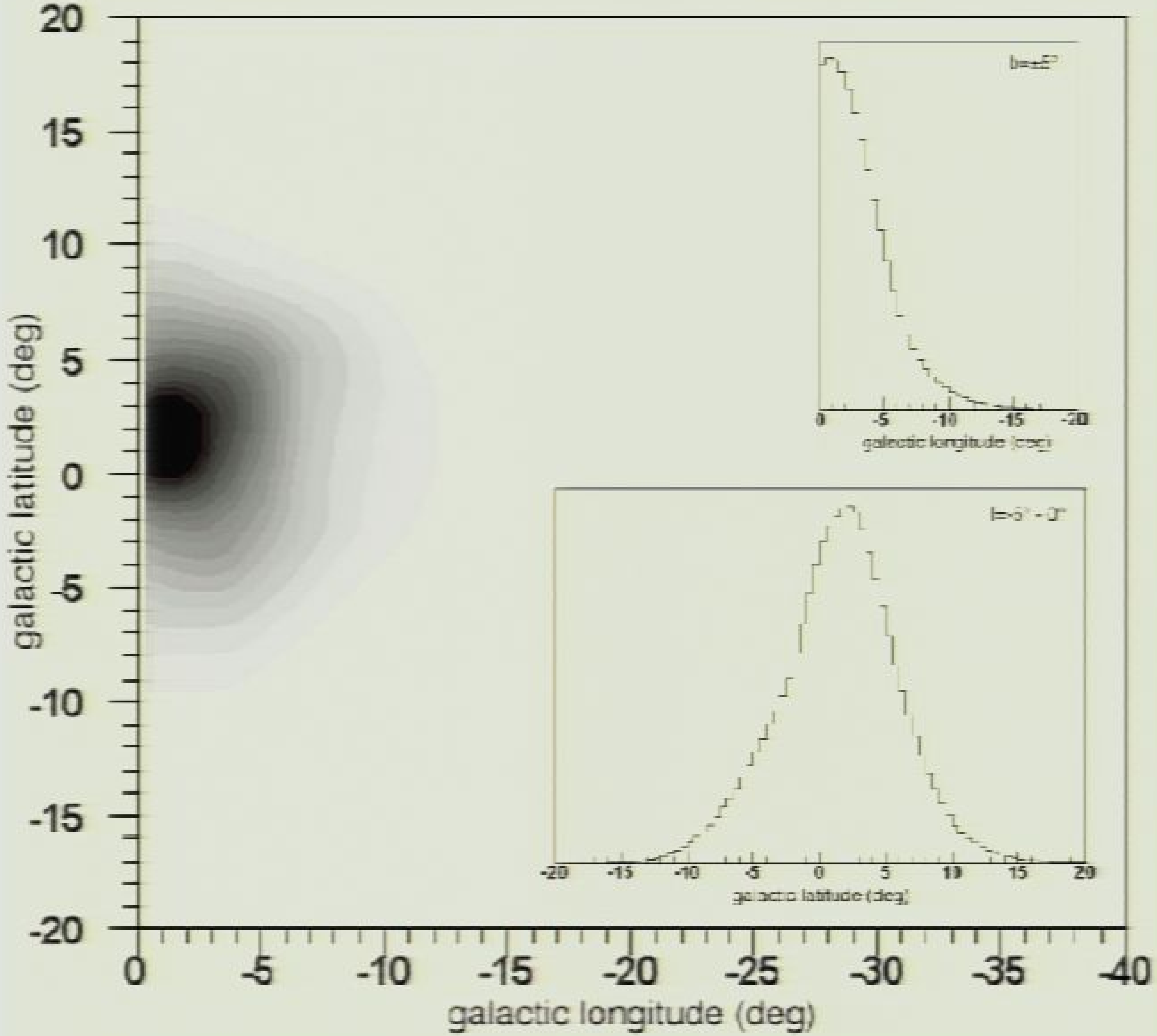

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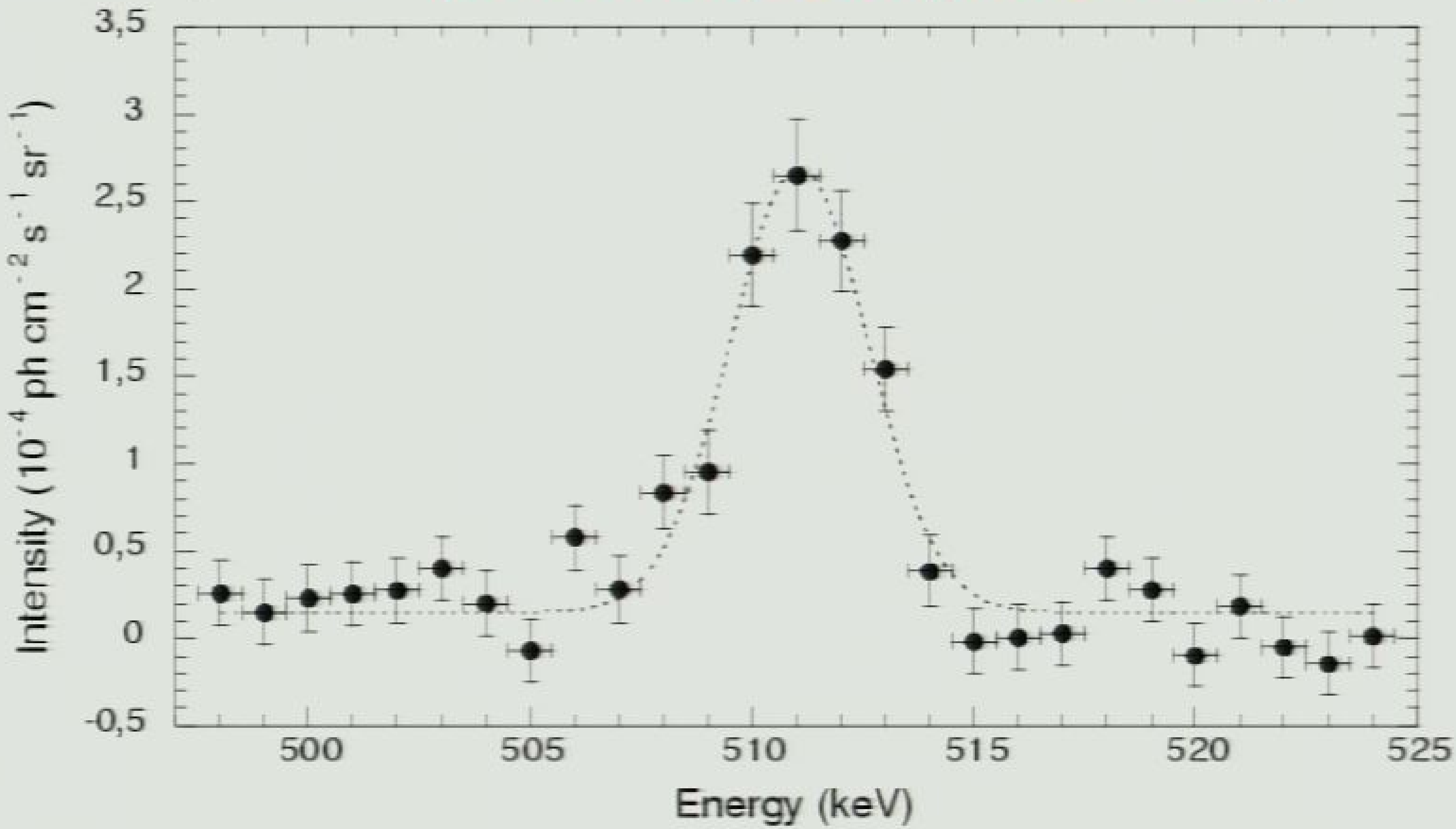

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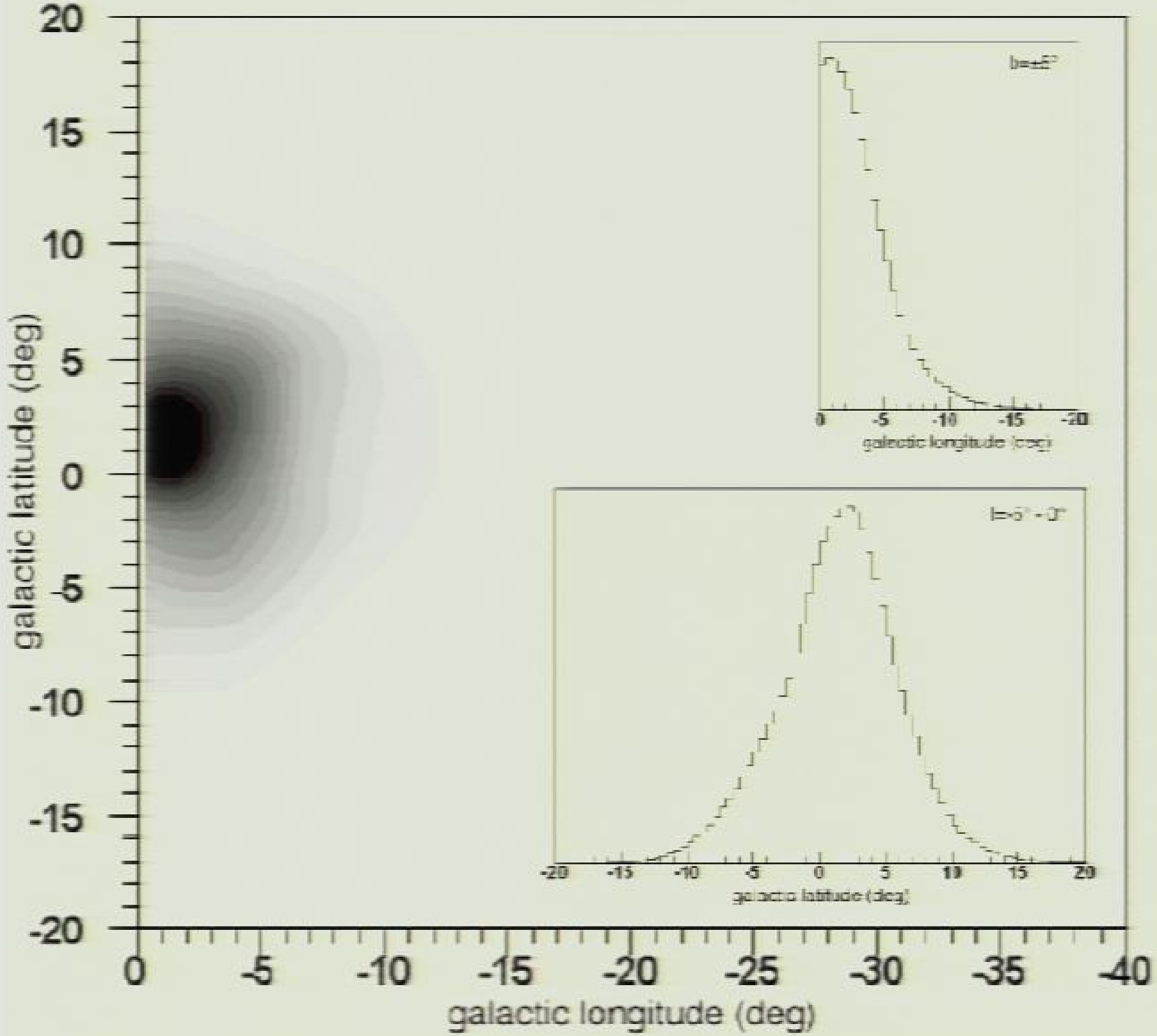

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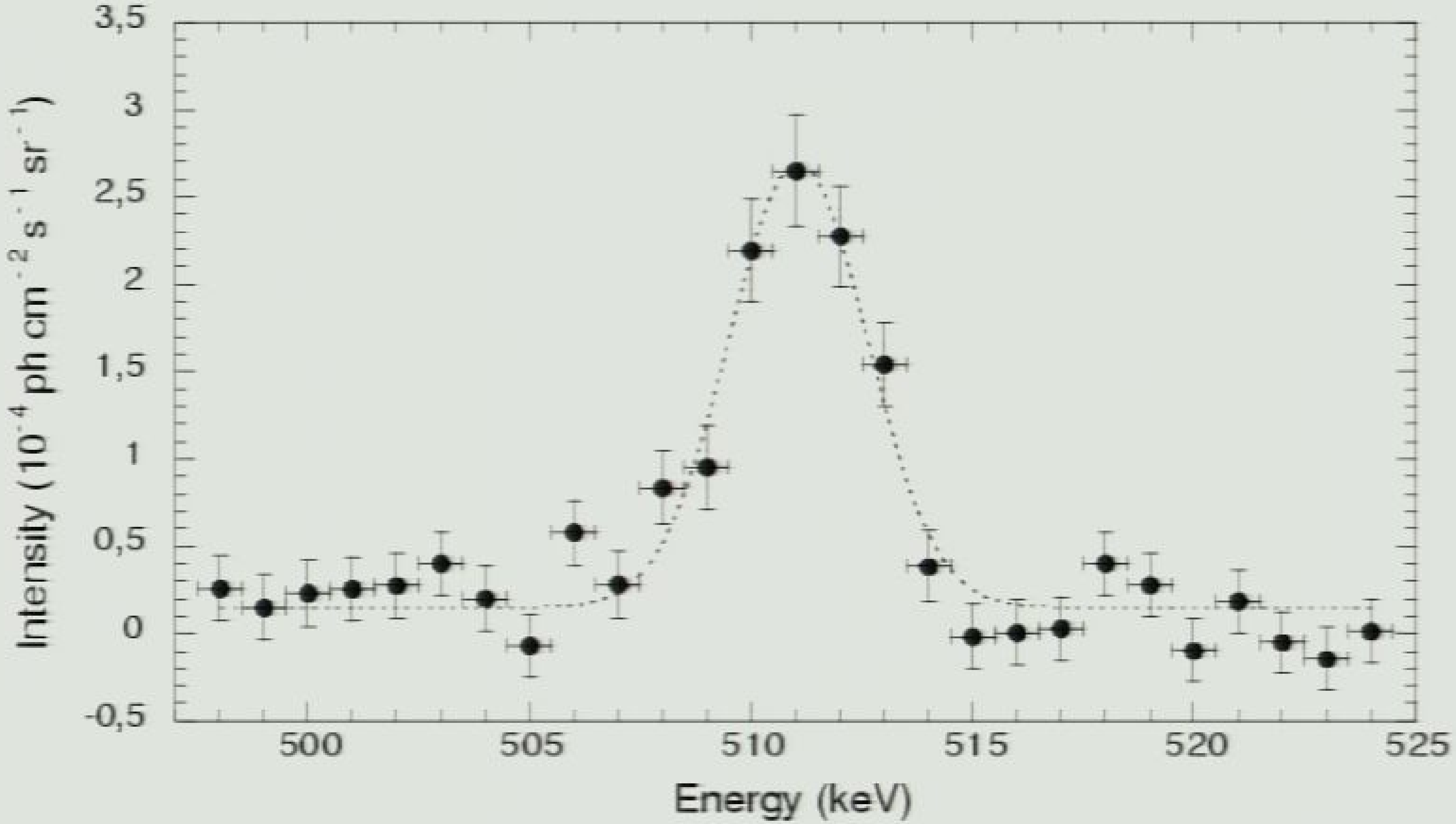

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WMAP "Haze"

(Hooper, Finkbeiner, Dobler, 0705.3655)

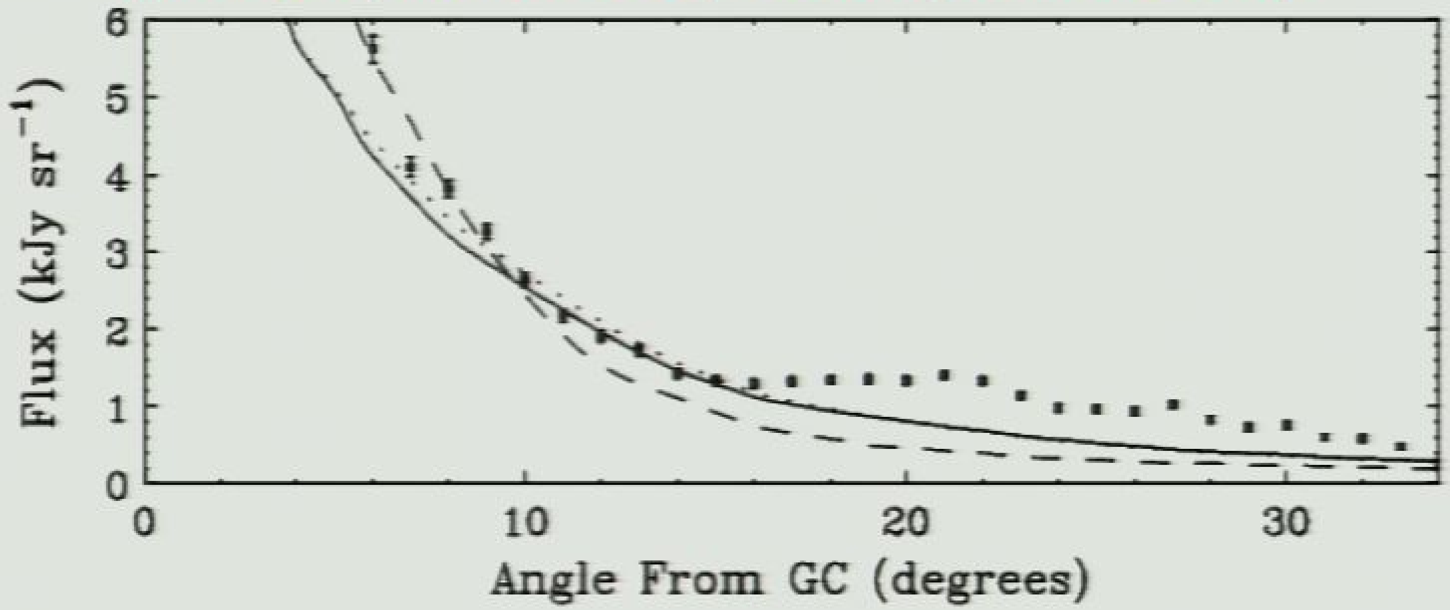

FIG. 2: The specific intensity of microwave emission in the 22 GHz WMAP channel as a function of the angle from the Galactic Center, compared to the synchrotron emission from the annihilation products of a 100 GeV WIMP annihilating to e^+e^-. In the upper frame, our default diffusion parameters

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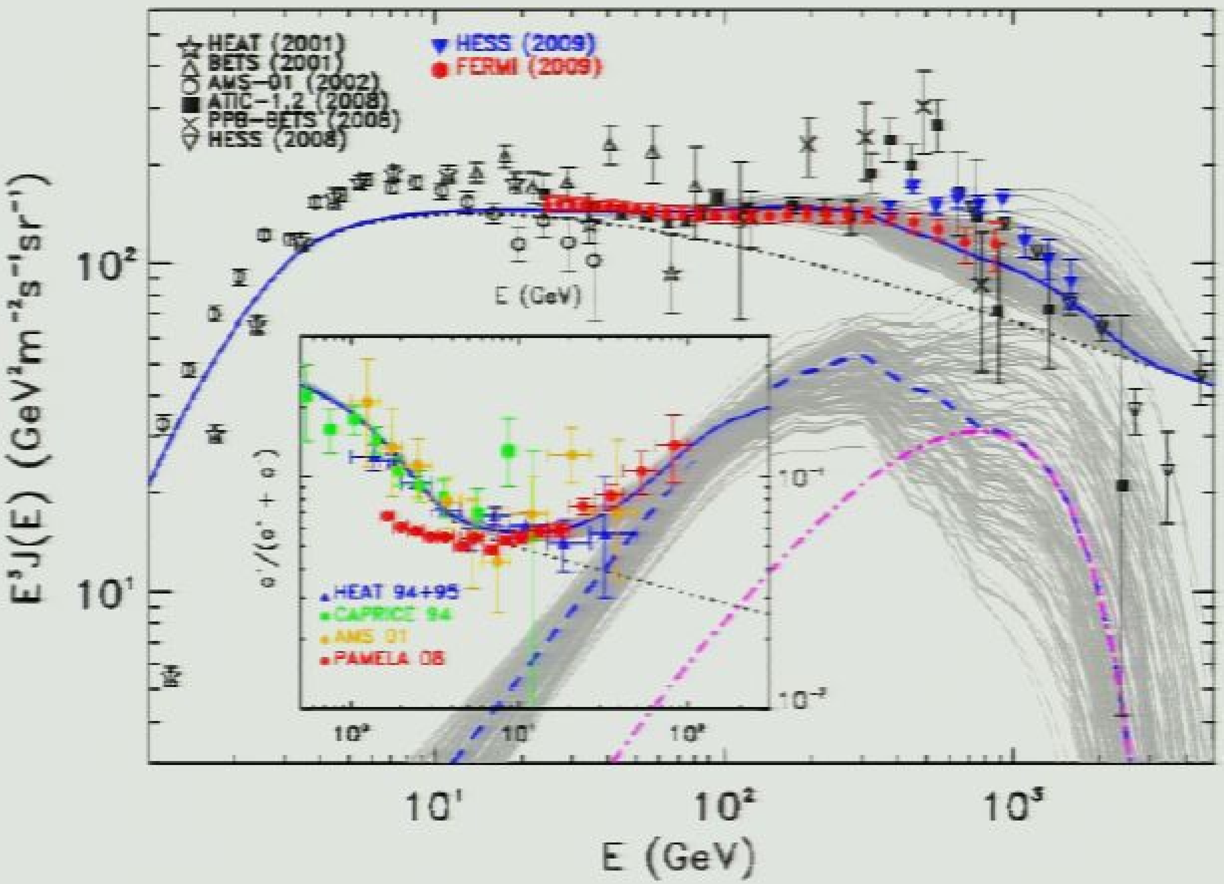

Grasso, Fermi collaboration, 0907.0373

Large astrophysical uncertainties; can get whatever we want from pulsars. Can't rule them out as explanation.

DM hypothesis still worth exploring.

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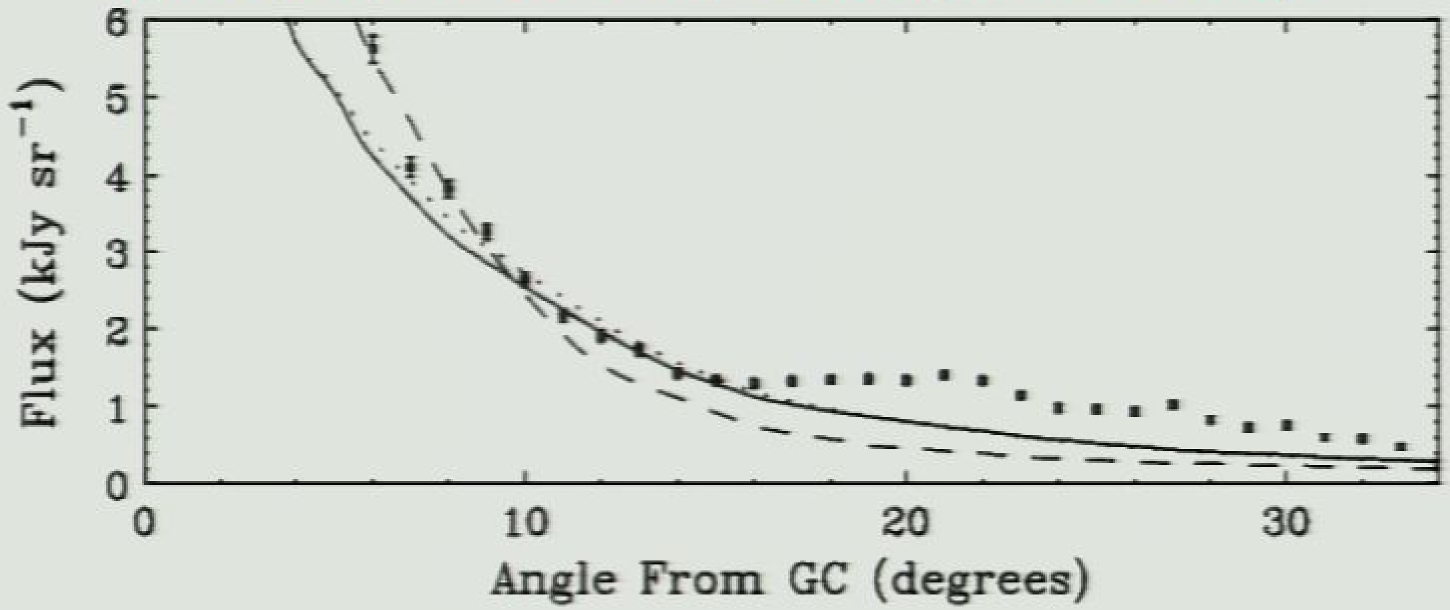

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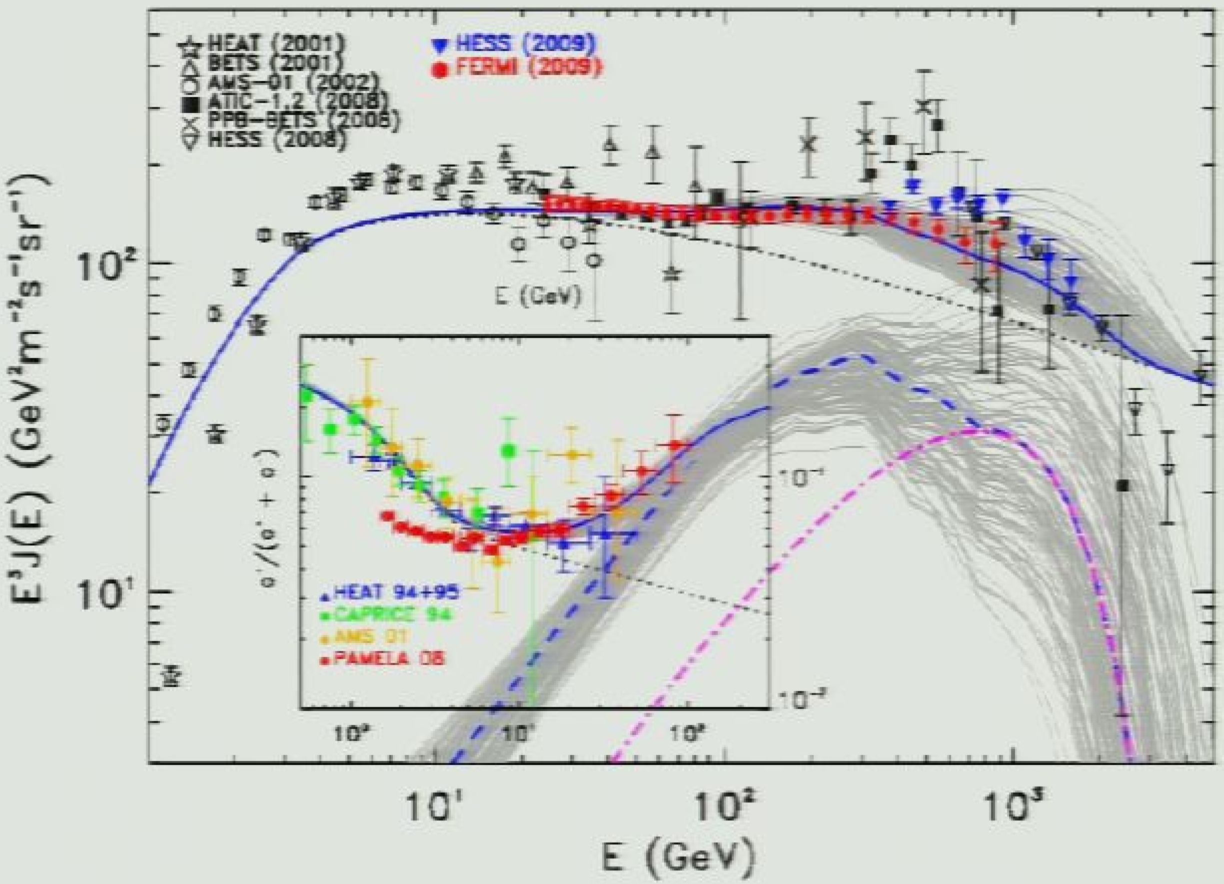

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A unified DM explanation

Arkani-Hamed, Finkbeiner, Slatyer, Weiner (0810.0713) propose that $SU(N)$ nonabelian dark matter models can explain these signals:

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

↗ dark matter ↗ dark gauge sector ↗ mixing with SM

(Mixing with SM can also arise through Higgs sector, via $\lambda\, S^2_{\rm dark}\, H^2_{SM}$ interaction)

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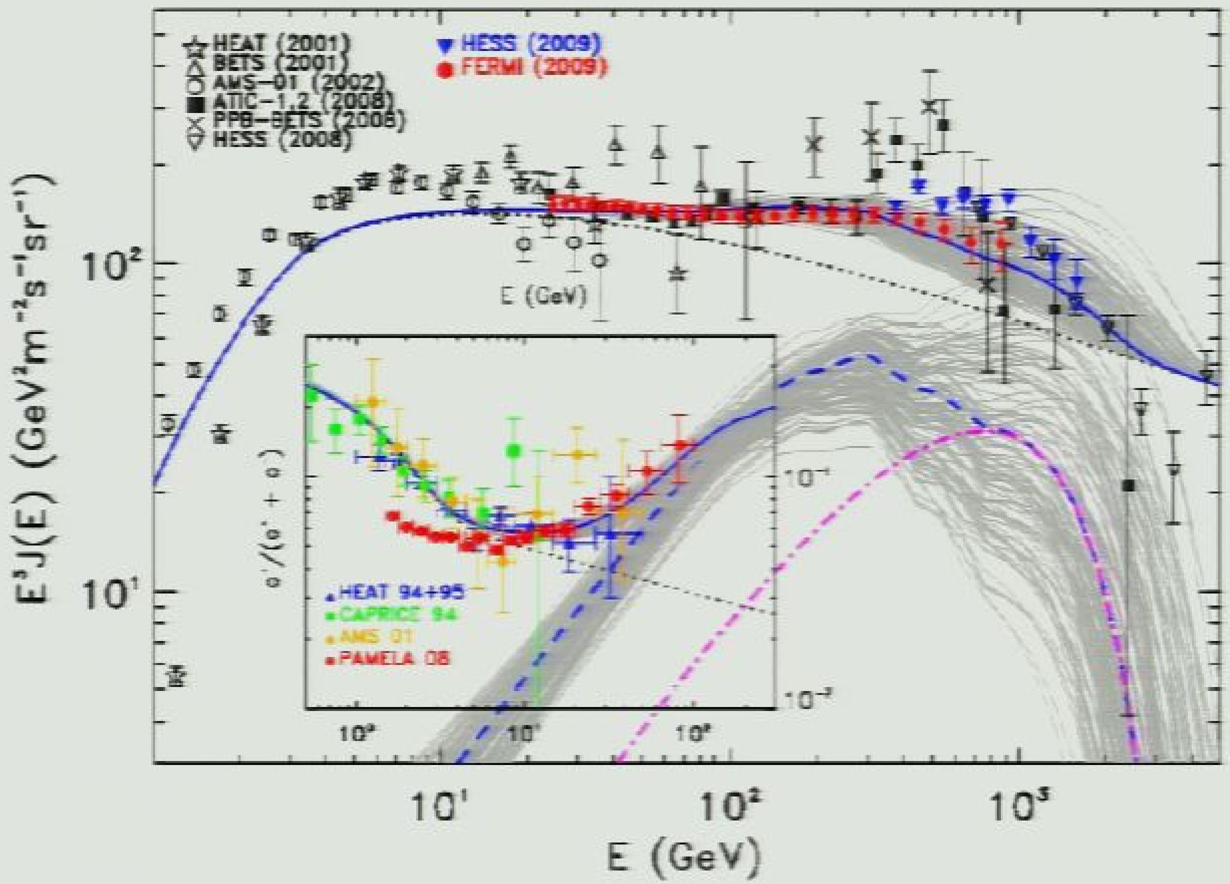

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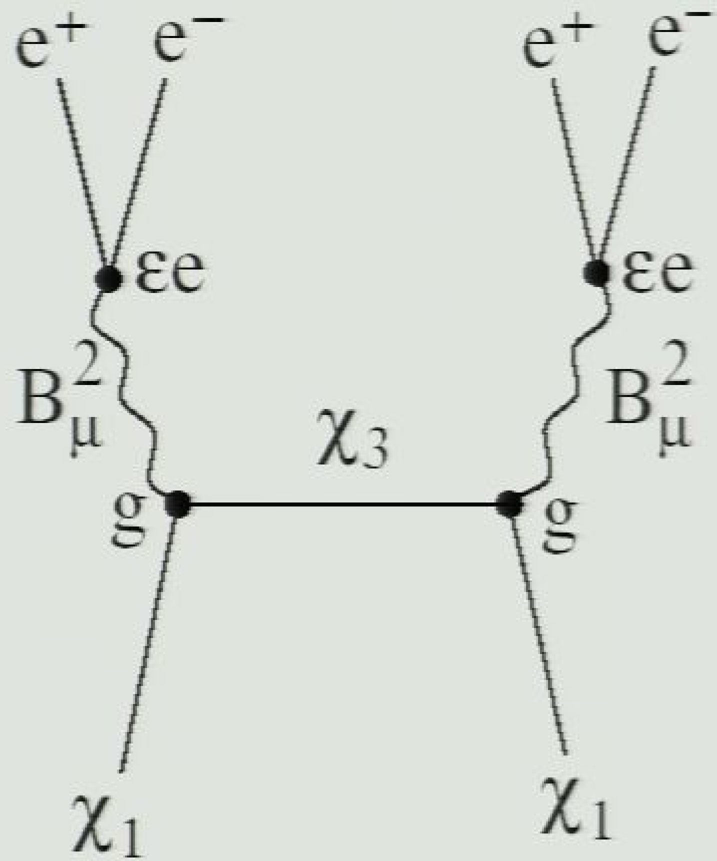

PAMELA sess no excess $\bar p$. Why are no quarks produced?

Assume mass of B is $\mu \lesssim 1$ GeV.

B's are produced on shell, decay only into e^+e^-, $\pi^+\pi^-$, $\mu^+\mu^-$, $\bar\nu\nu$.

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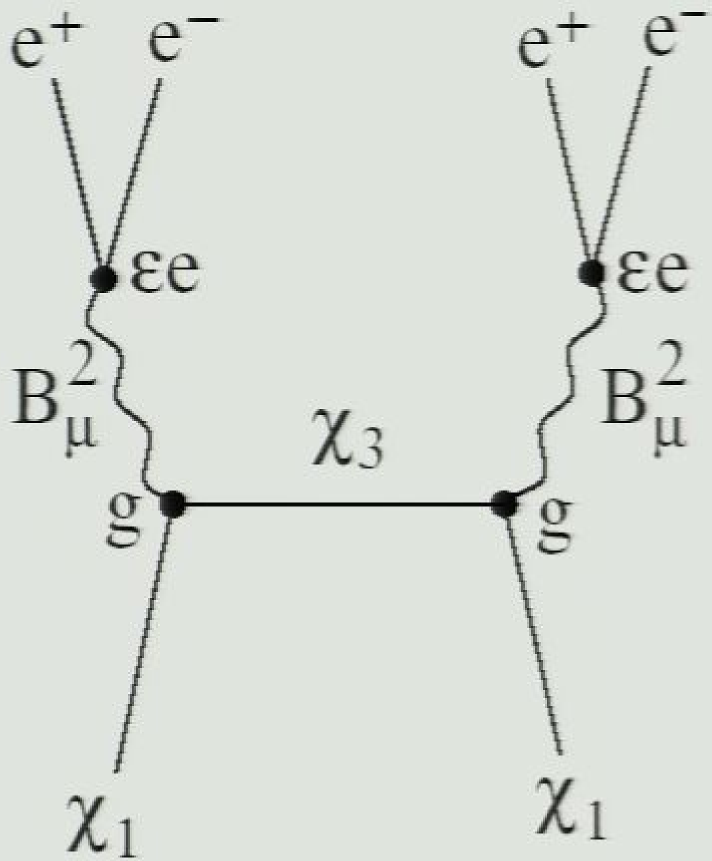

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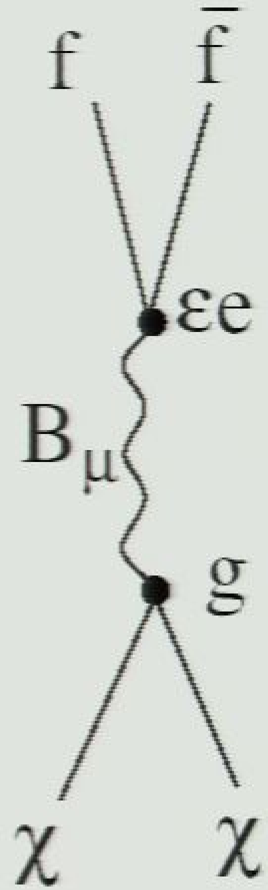
Diagonal gauge couplings allow annihilation via virtual B into any f-$\bar{f}$ pair, producing hadrons as well as leptons.



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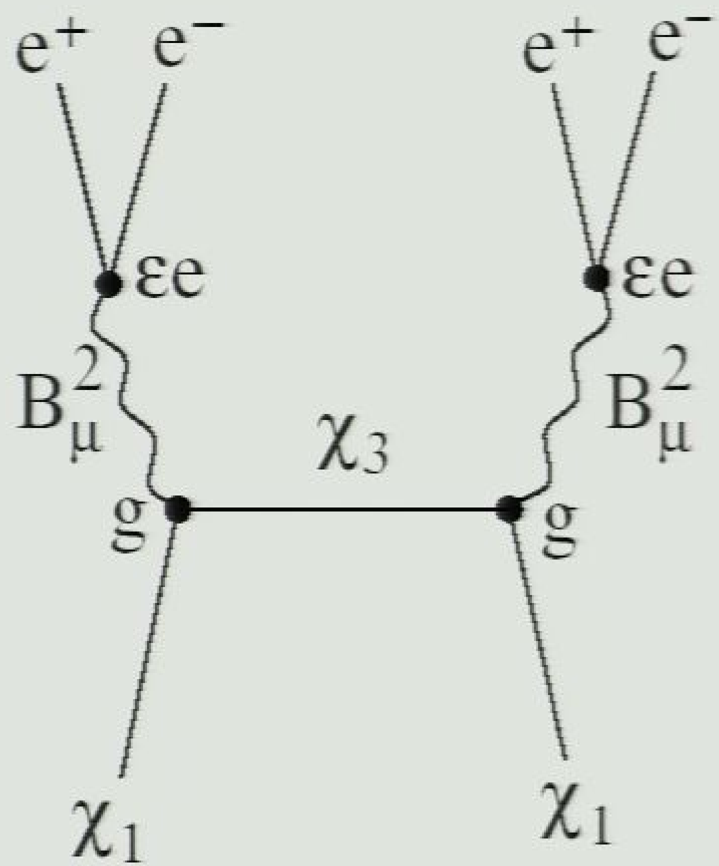

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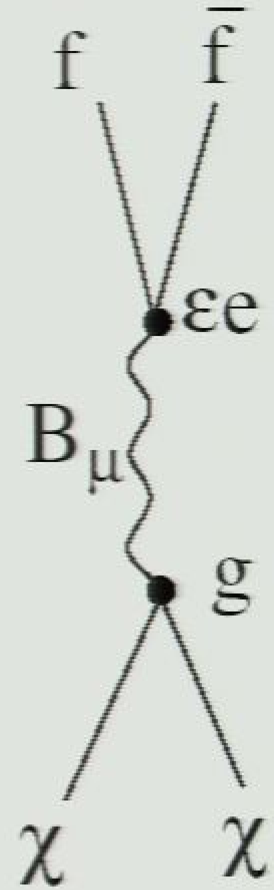

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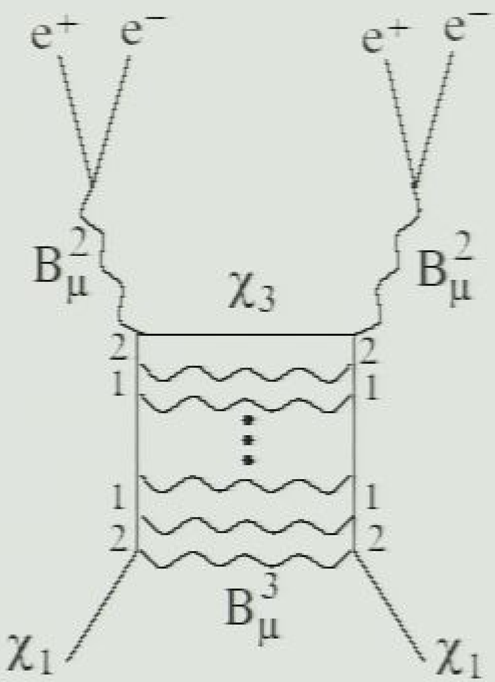
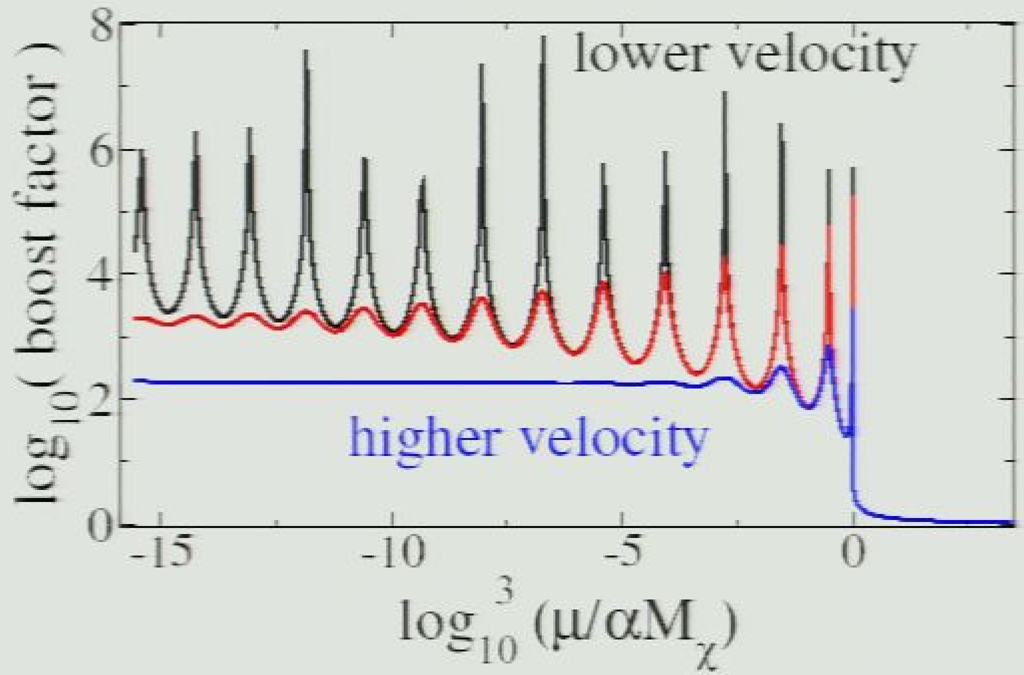
Sommerfeld Enhancement

$\sigma_{\rm ann}$ needed for PAMELA, *etc.* is too large for correct relic density. But slow DM annihilation is Sommerfeld-enhanced relative to fast DM in early universe:

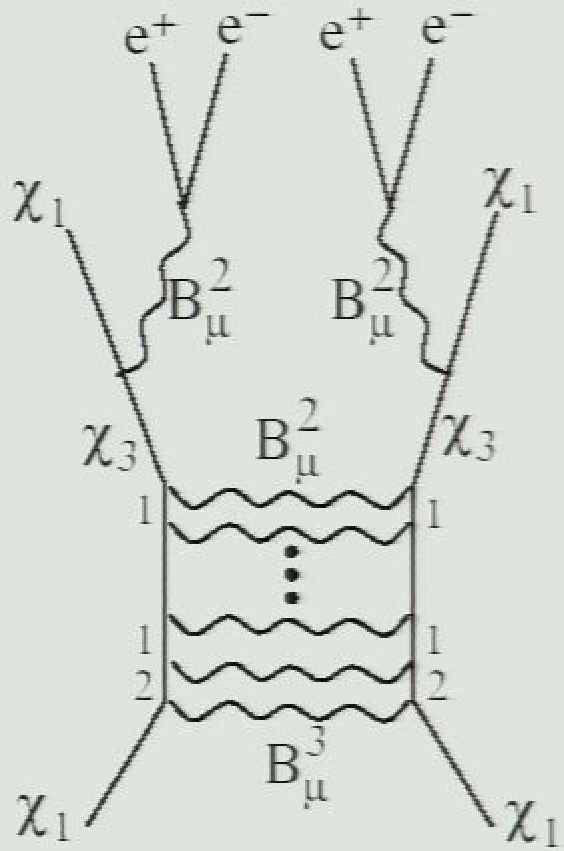


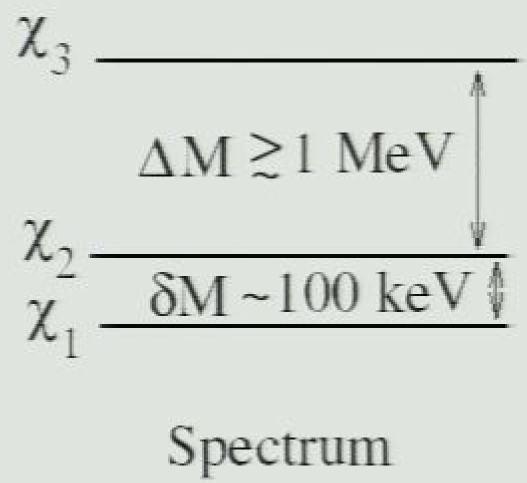


Can give "boost factors" of 1000 (or more), depending on g, μ/M_χ, and velocity of DM.

INTEGRAL/SPI 511 keV excess

Same models can (possibly) explain low-energy e^+ excess from galactic center (Finkbeiner, Weiner, astro-ph/0702587)

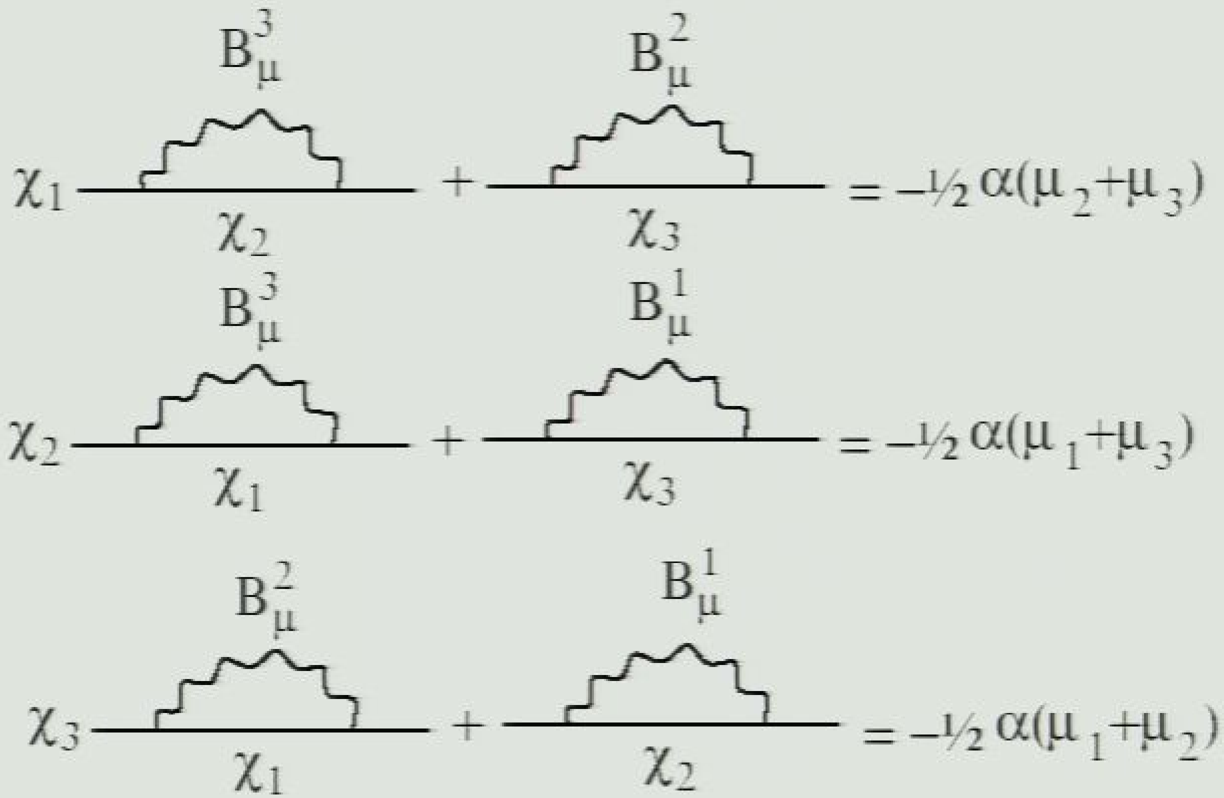




($N\chi_1 \to N'\chi_2$ excitation is proposed to explain DAMA/ LIBRA annual modulation.)

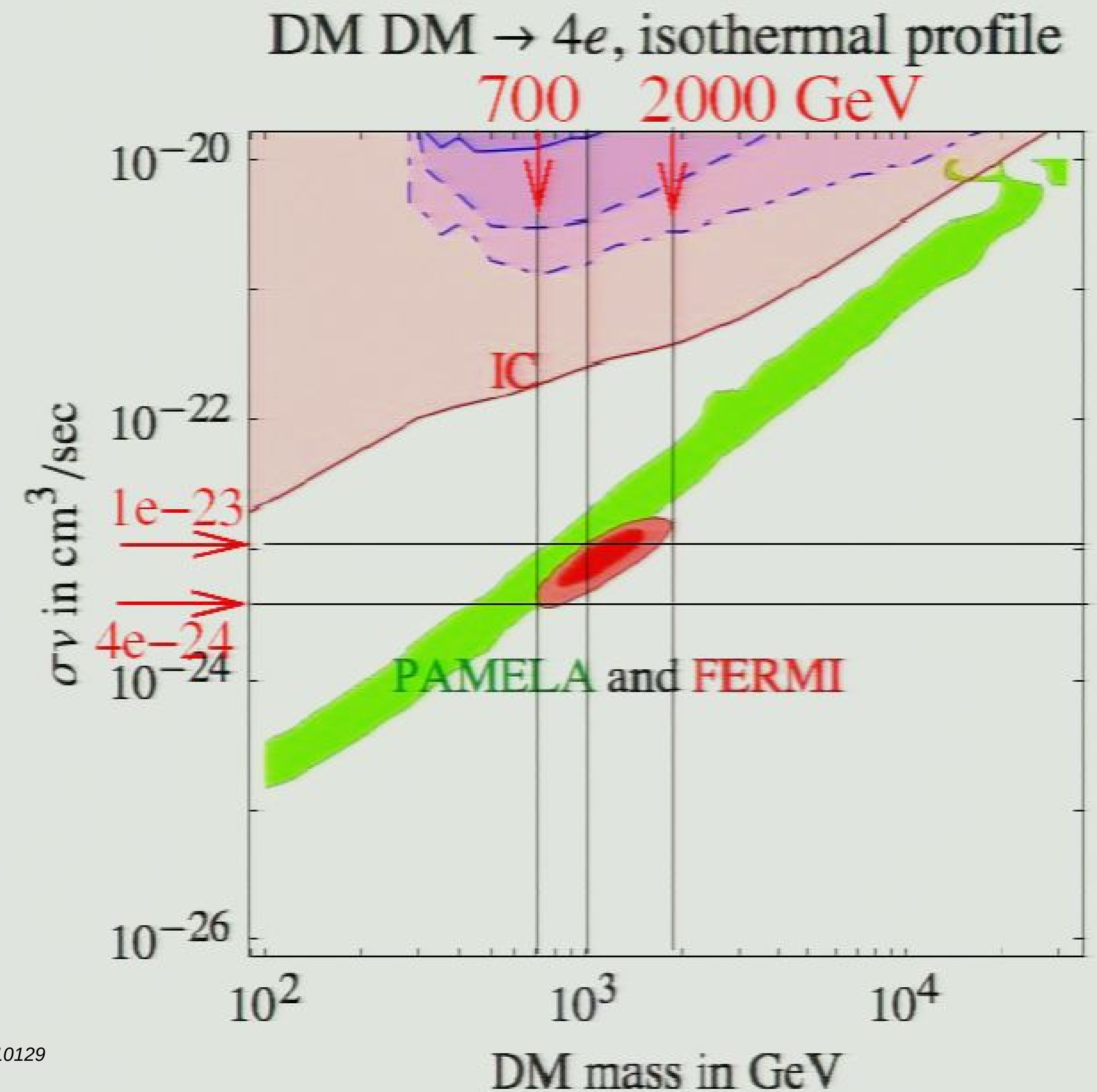
Origin of small mass splittings

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



For $\mu \sim$ GeV and $\alpha \sim 0.1$, $\delta M_\chi \sim$ MeV.

A Fit to PAMELA/Fermi Data



(Meade, Papucci, Strumia, Volansky, 0905.0480)

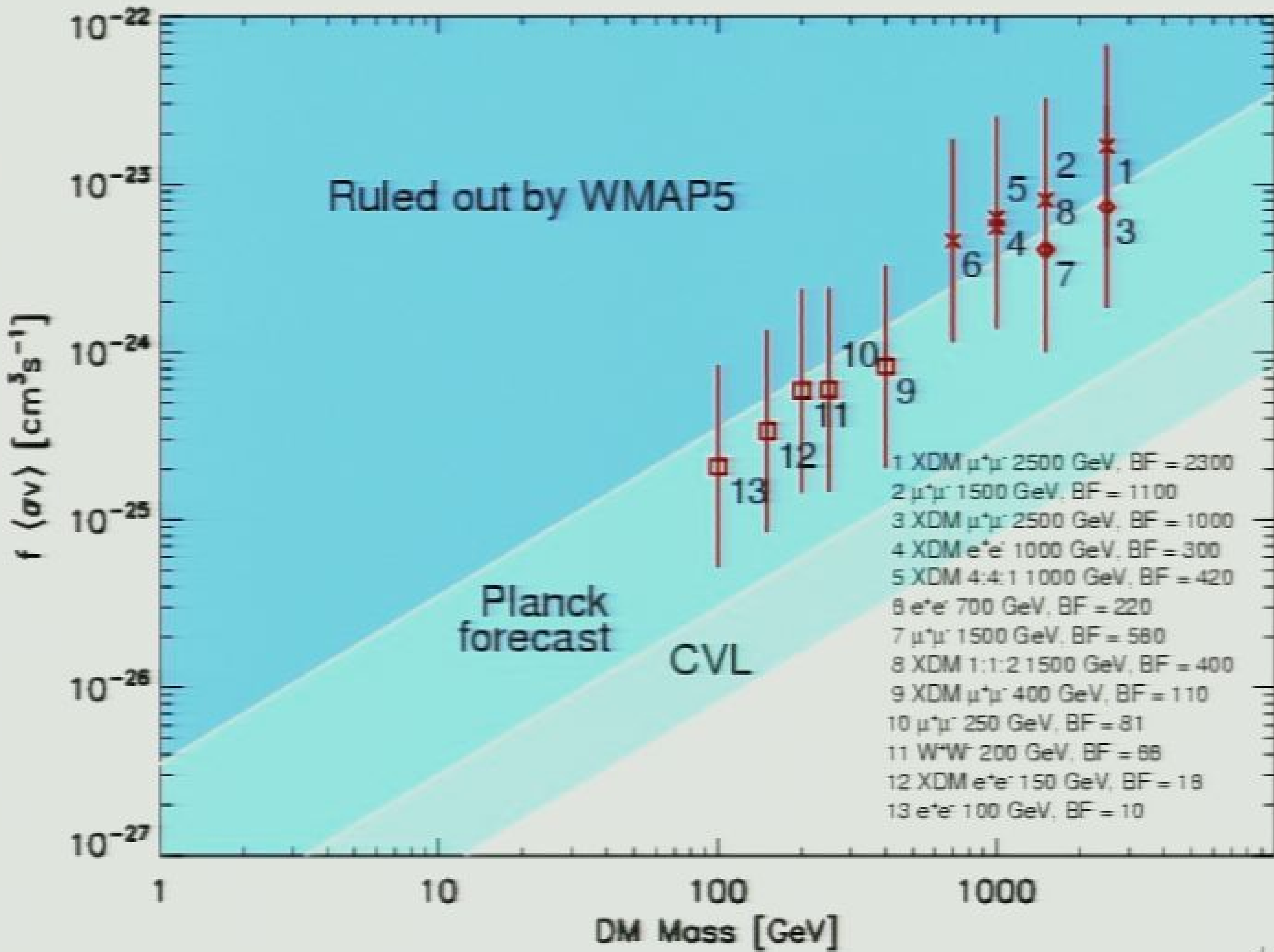
Boost factor is 330

HESS IC γ ray constraints encroach on allowed parameter space

CMB constraints are severe

Slatyer, Padmanabhan, Finkbeiner 0906.1197

Heating of photon-baryon fluid by, *e.g.*, $\chi\chi \to 4e$ changes ionization fraction after recombination.



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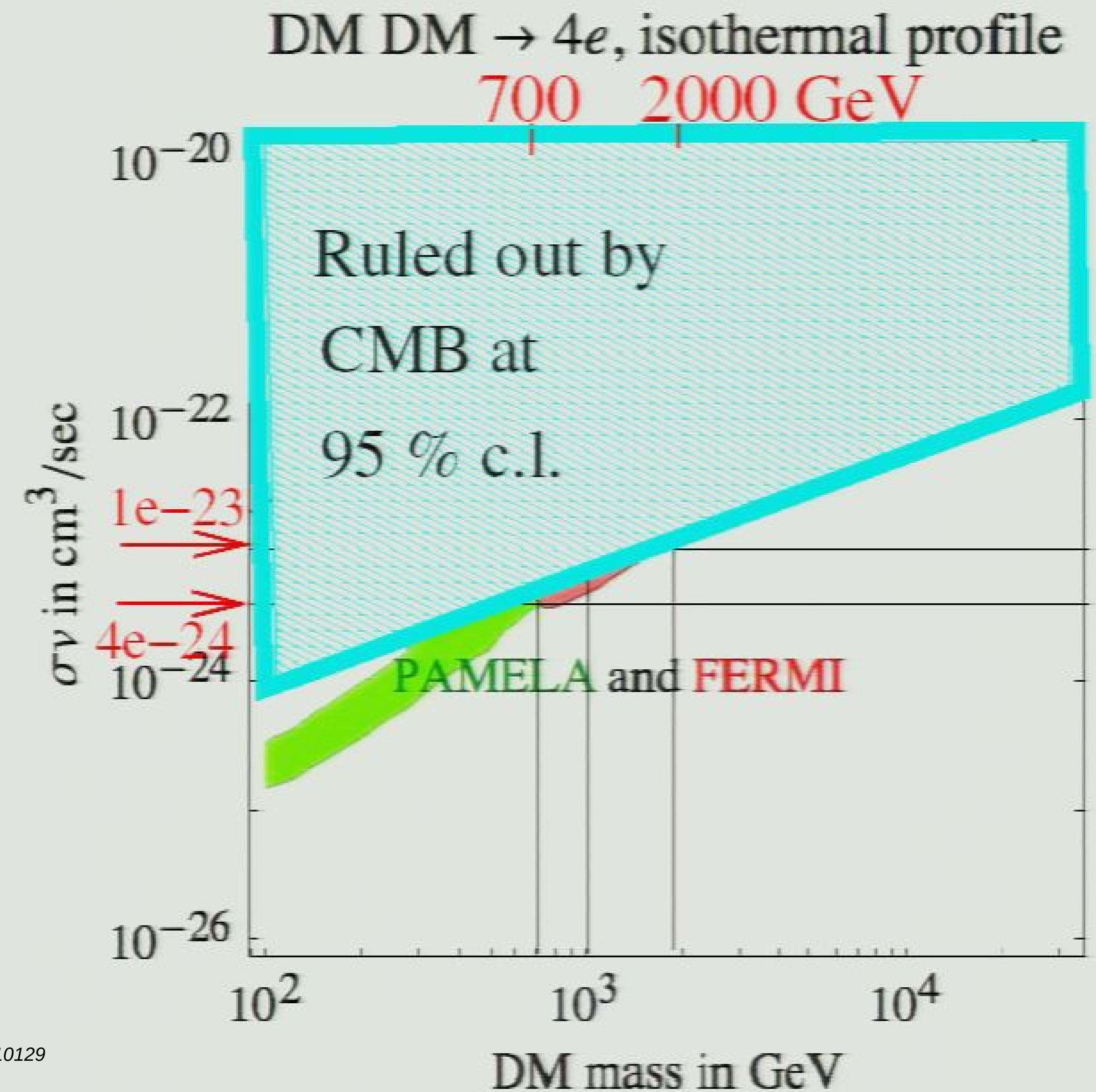

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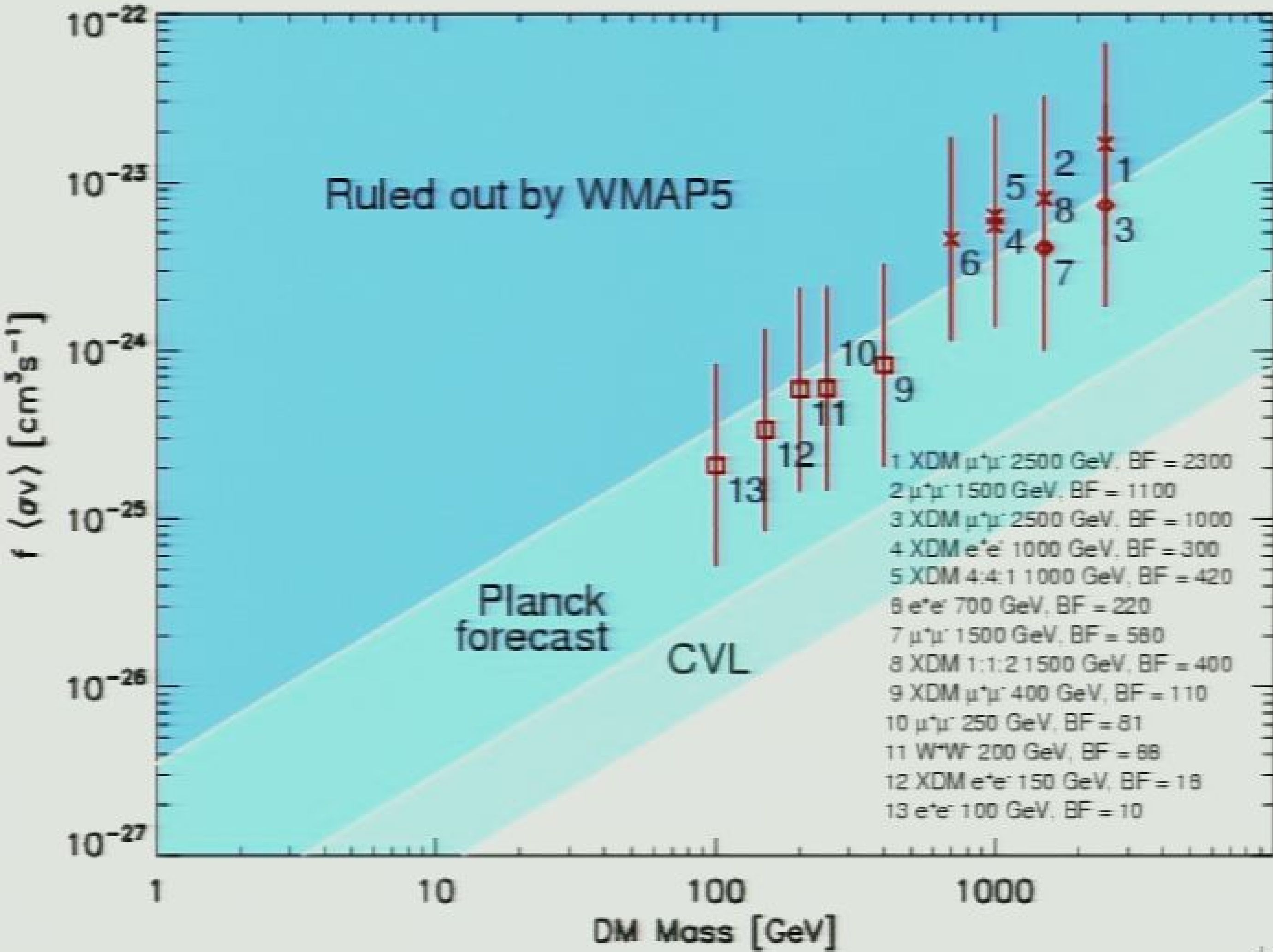

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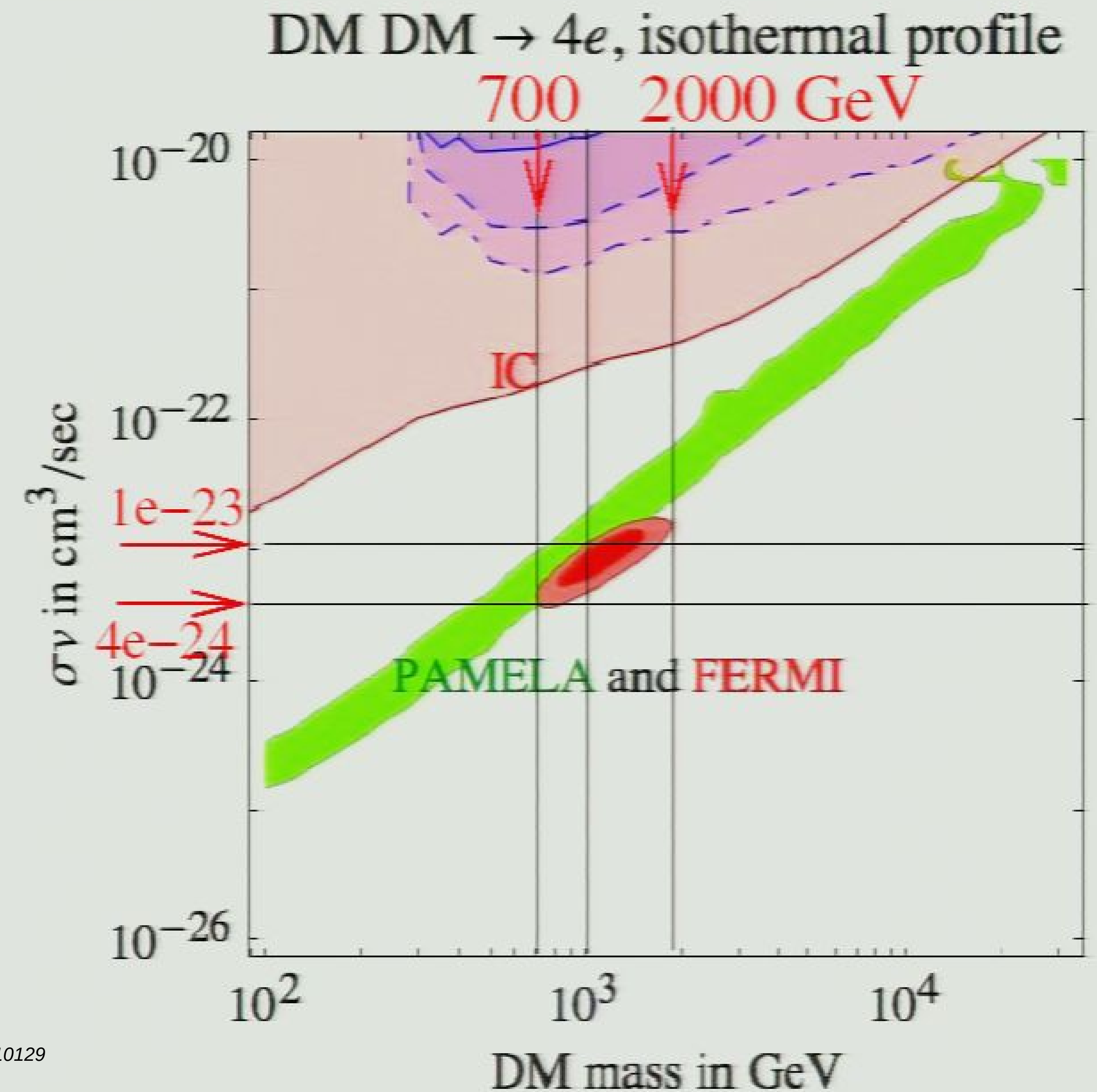

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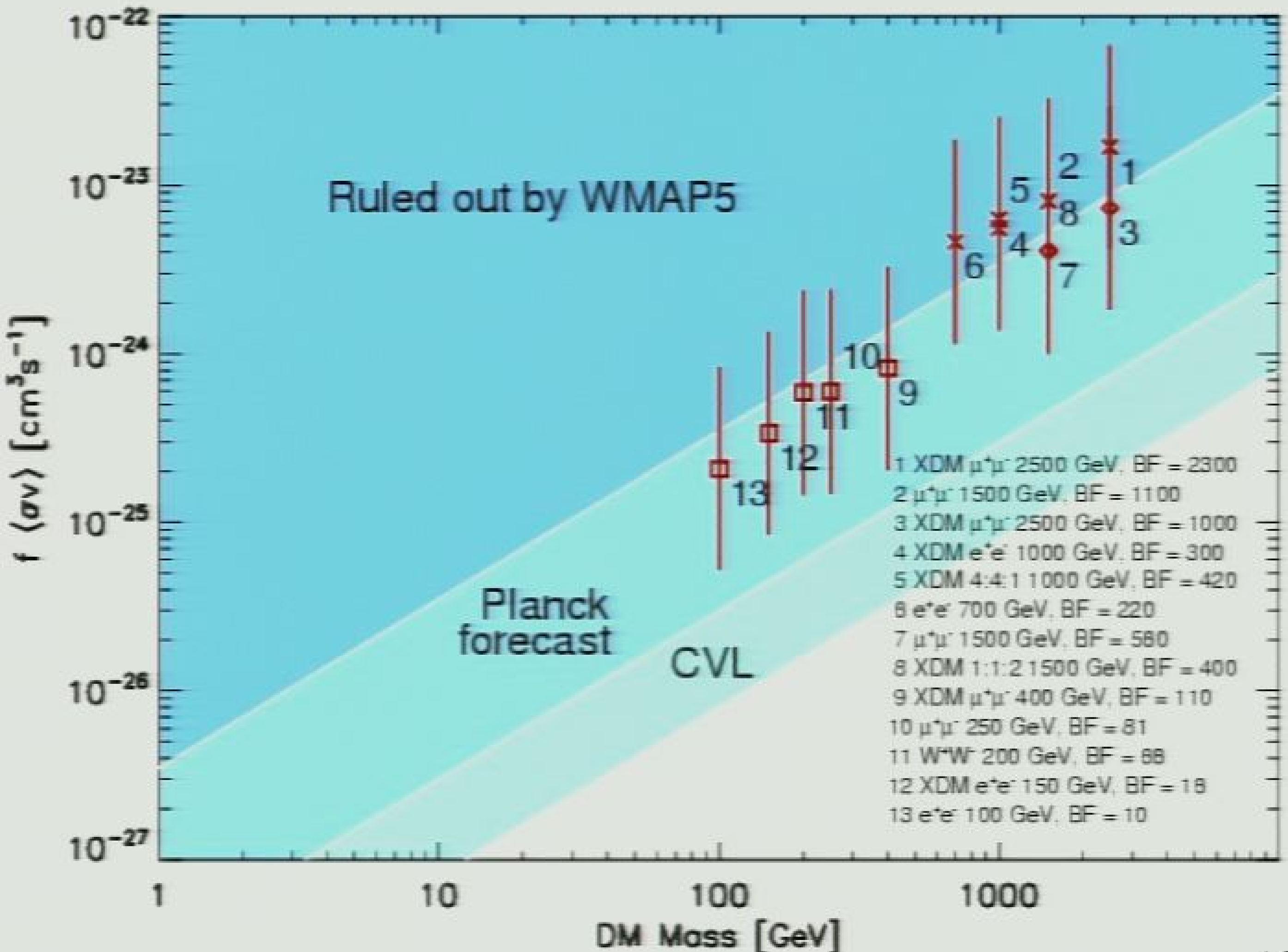

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- Building explicit models
- Studying their detailed implications
  (effect on BBN, laboratory constraints)
- Quantitative treatment of excited DM
- Contributions from subhalos of galaxy

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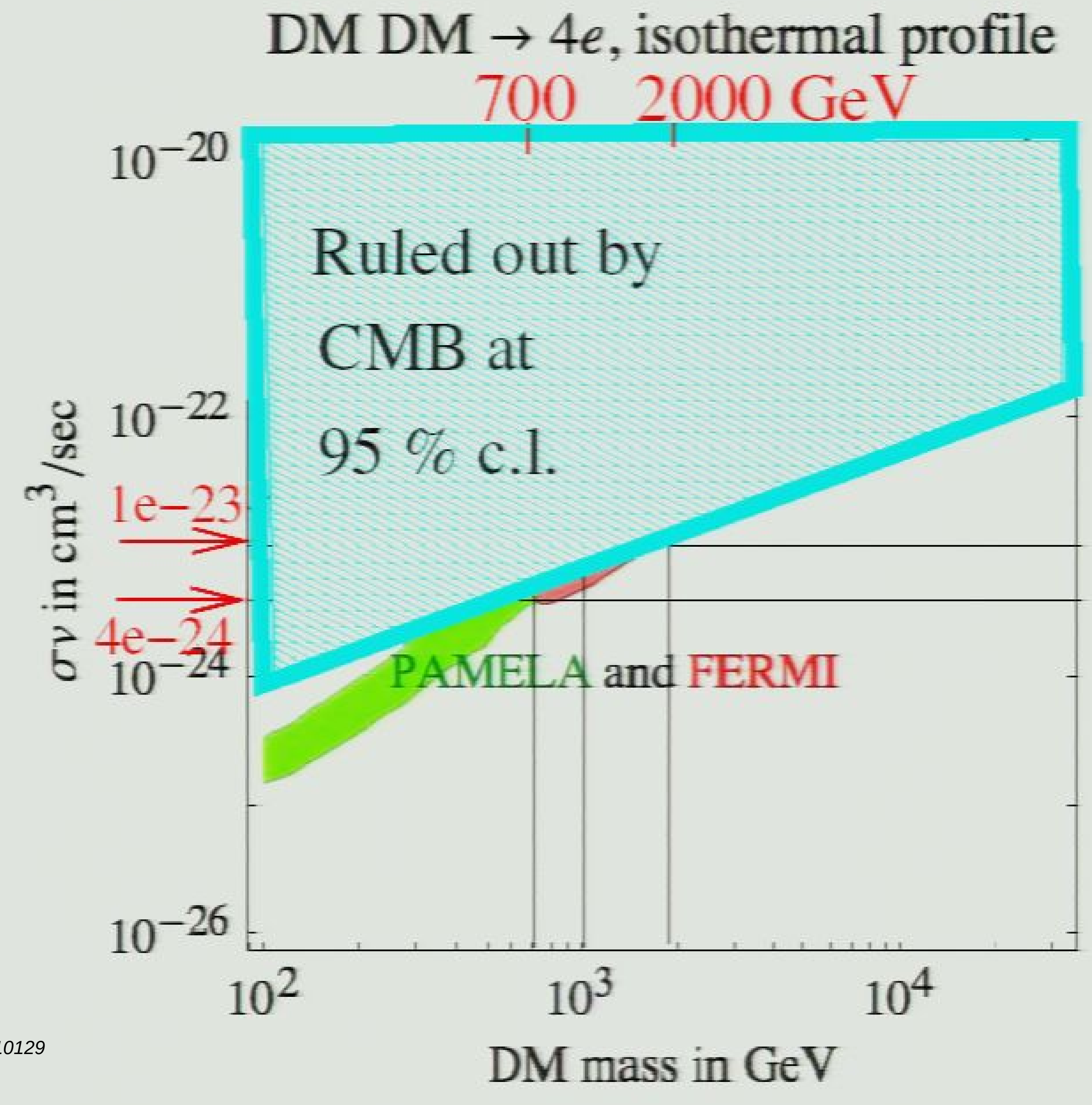

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Model building

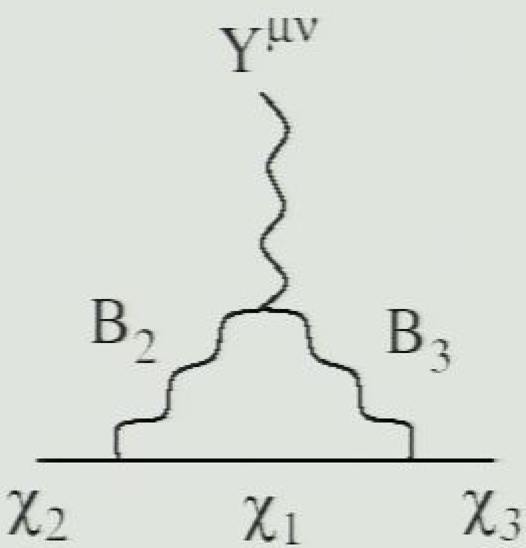
Must choose:

- Dark gauge group; $SU(2)$ is simplest
  (others considered $SU(2) \times U(1)$)
- Rep. of $SU(2)$ for DM
  we consider 2, 3, 5
- Dark Higgs VEV's to break $SU(2)$ and DM degeneracy
  e.g., doublet + triplet, two triplets, 5-plet
- Gauge boson or Higgs portal to Standard Model
  $\frac{1}{\Lambda}\Delta_a B_a^{\mu\nu} Y_{\mu\nu} \to \epsilon B_1^{\mu\nu} Y_{\mu\nu}$ or $\lambda S^2 H^2$

Compute: relic density, DM and gauge boson mass spectra

New: DM transition magnetic moment!

Direct coupling of DM to γ is forbidden at tree-level, but not at one loop, from nonabelian term in $\epsilon B^1_{\mu\nu} Y^{\mu\nu}$:



$$\mu_{23} \cong \frac{\epsilon g^3}{128\pi^2 M_\chi}\left(\ln\frac{M_\chi}{\mu} - 1\right)$$

($\epsilon =$ gauge kinetic mixing strength)

New signature: monoenergetic γ

Branching ratio $B = \Gamma(\chi_3 \to \chi_2\gamma)/\Gamma(\chi_3 \to \chi_1 e^+e^-)$ can be significant; not yet seen by INTEGRAL, leads to constraint

$$\alpha_g \lesssim 0.08\left(\frac{200\text{ MeV}}{\mu}\right)^2\left(\frac{M_\chi}{1\text{ TeV}}\right)\left(\frac{\delta M_{23} - 2m_e}{100\text{ keV}}\right)^{3/2}$$

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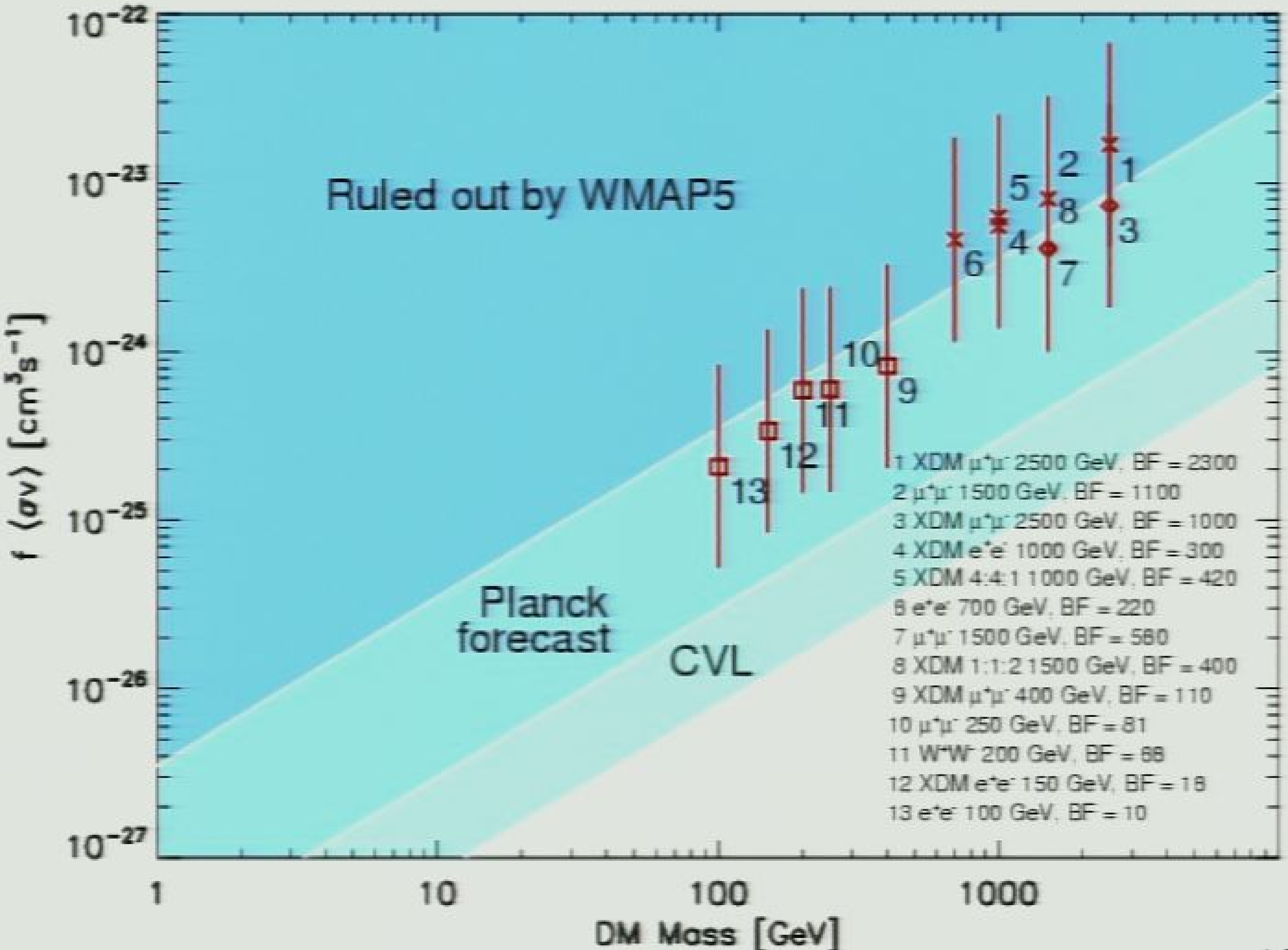
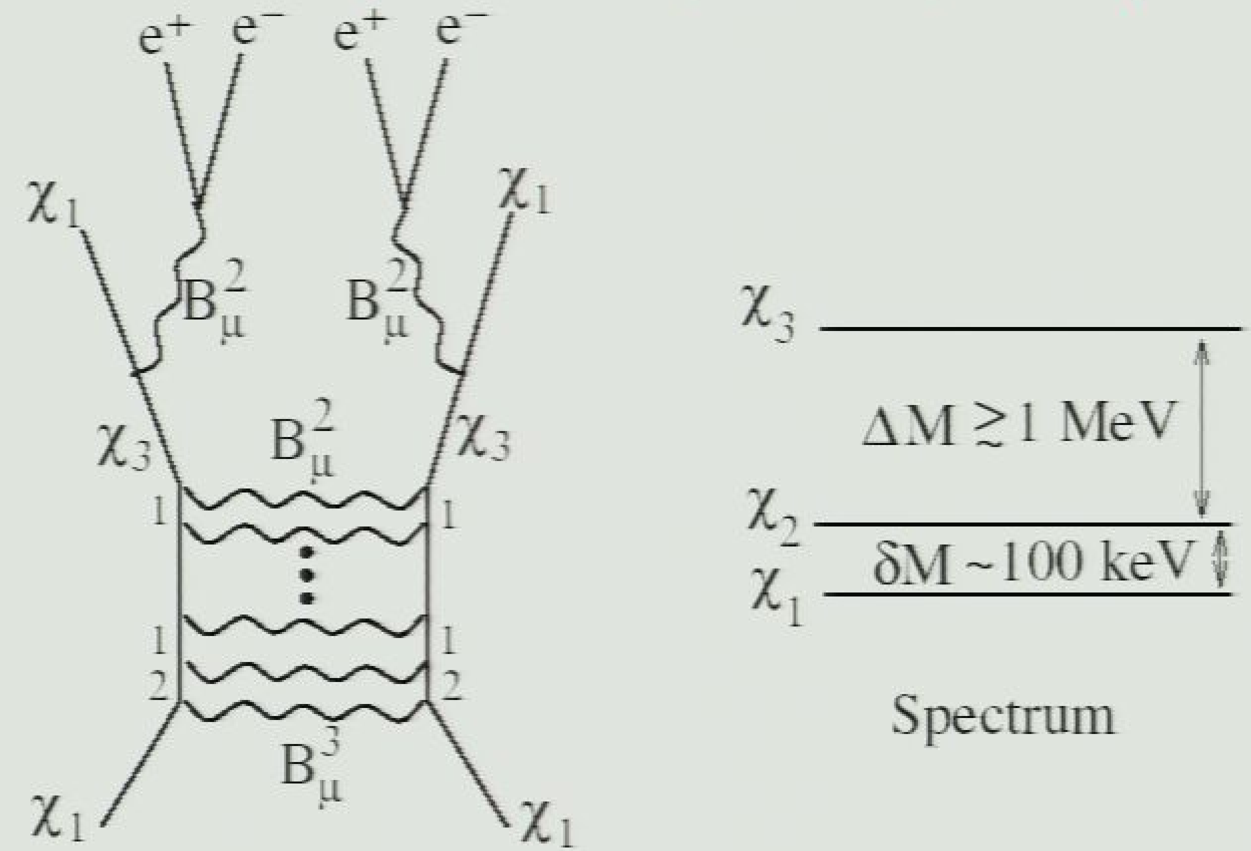
Slatyer, Padmanabhan, Finkbeiner 0906.1197

Heating of photon-baryon fluid by, *e.g.*, $\chi\chi \to 4e$ changes ionization fraction after recombination.



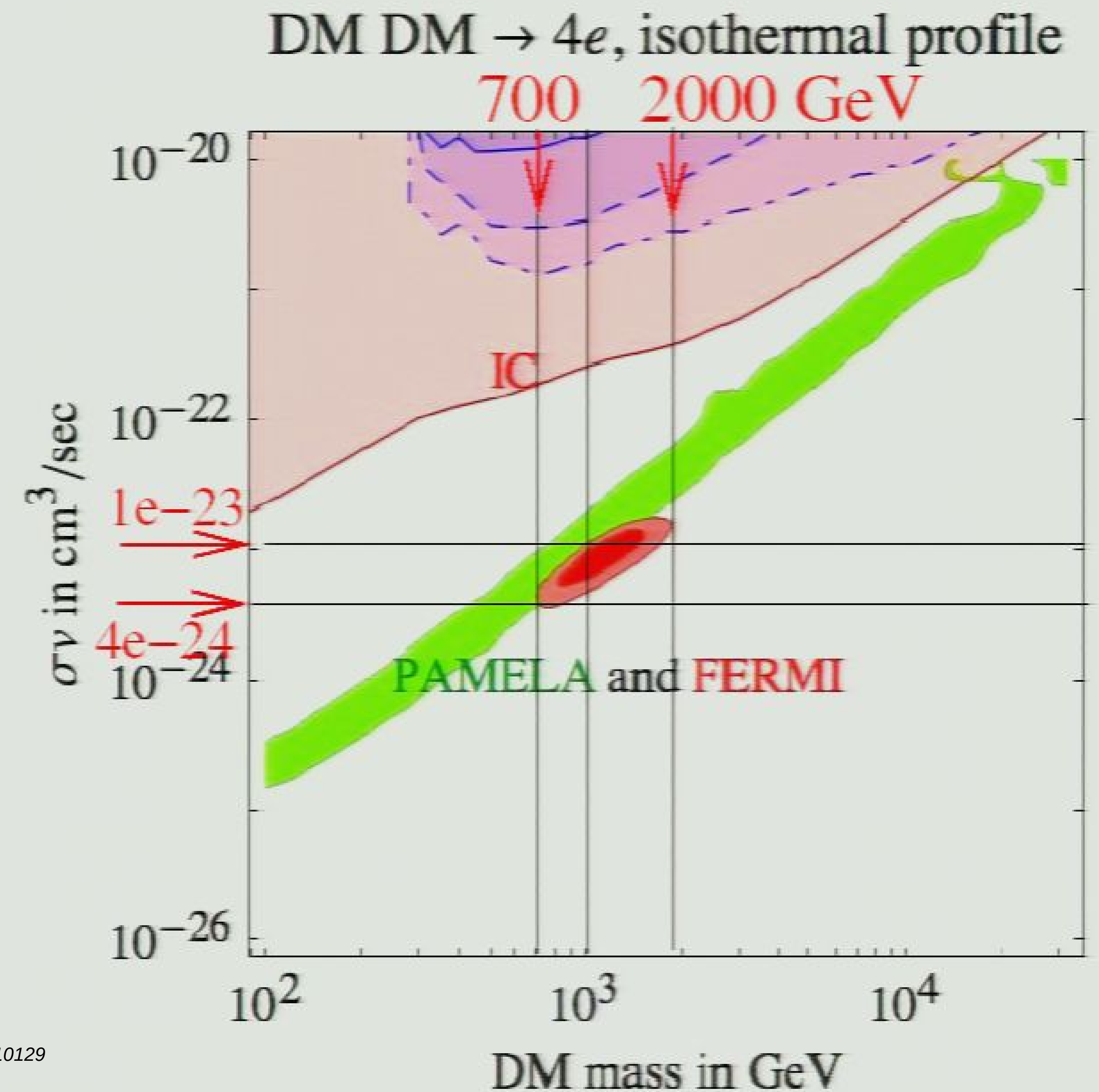
INTEGRAL/SPI 511 keV excess

Same models can (possibly) explain low-energy e^+ excess from galactic center (Finkbeiner, Weiner, astro-ph/0702587)



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

A Fit to PAMELA/Fermi Data



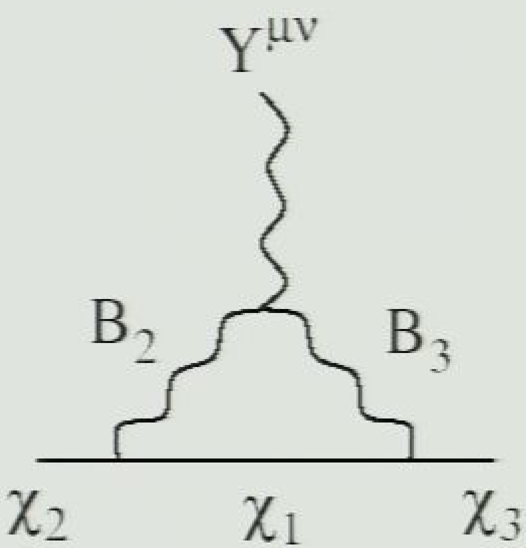
(Meade, Papucci, Strumia, Volansky, 0905.0480)

Boost factor is 330

HESS IC γ ray constraints encroach on allowed parameter space

New: DM transition magnetic moment!

Direct coupling of DM to γ is forbidden at tree-level, but not at one loop, from nonabelian term in $\epsilon B^1_{\mu\nu} Y^{\mu\nu}$:



$$\mu_{23} \cong \frac{\epsilon g^3}{128\pi^2 M_\chi}\left(\ln\frac{M_\chi}{\mu} - 1\right)$$

($\epsilon =$ gauge kinetic mixing strength)

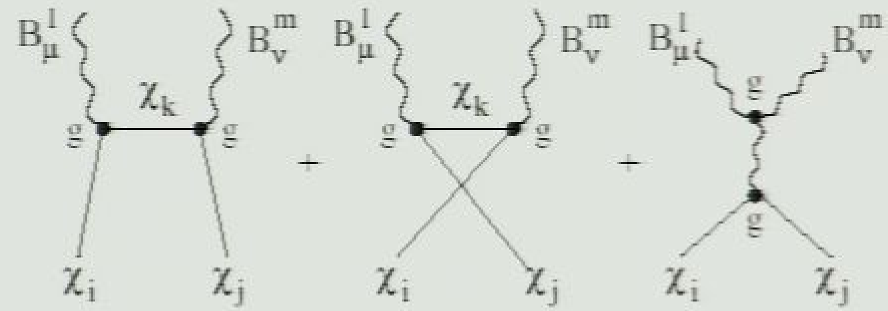
New signature: monoenergetic γ

Branching ratio $B = \Gamma(\chi_3 \to \chi_2\gamma)/\Gamma(\chi_3 \to \chi_1 e^+ e^-)$ can be significant; not yet seen by INTEGRAL, leads to constraint

$$\alpha_g \lesssim 0.08 \left(\frac{200\ \mathrm{MeV}}{\mu}\right)^2 \left(\frac{M_\chi}{1\ \mathrm{TeV}}\right)\left(\frac{\delta M_{23} - 2m_e}{100\ \mathrm{keV}}\right)^{3/2}$$

Relic density

Must compute $\sigma(\chi\chi \to BB)$:



$$\langle \sigma_{\rm ann} v_{\rm rel} \rangle \cong \frac{\pi \alpha_g^2}{M_\chi^2} \times \left\{ \begin{array}{ll} 0.14, & \text{doublet DM} \\ 0.88, & \text{triplet DM} \\ 5.18, & \text{quintuplet DM} \end{array} \right\}$$

For correct relic density need

$$\alpha_g = \left\{ \begin{array}{ll} 0.077, & \text{doublet} \\ 0.031, & \text{triplet} \\ 0.013, & \text{quintuplet} \end{array} \right\} \times \left(\frac{M_\chi}{1\ \rm TeV} \right)$$

$\Rightarrow$ Close to transition magnetic moment bound

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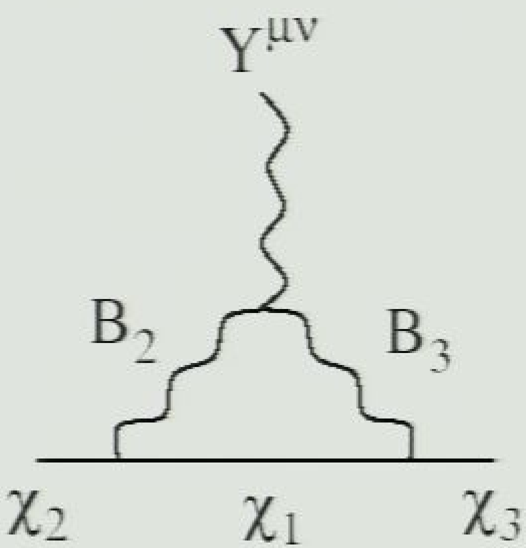

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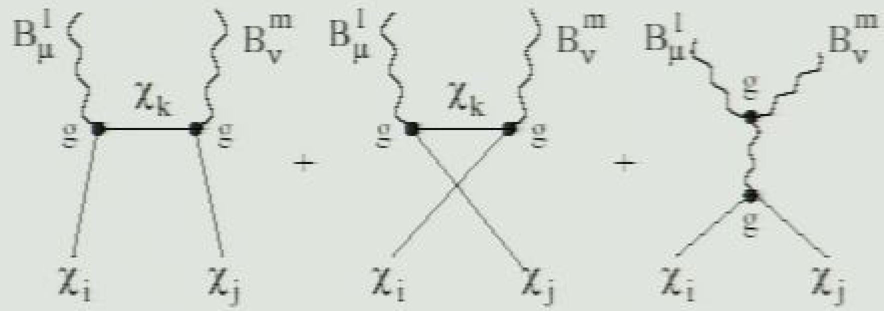

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$\Rightarrow$ Close to transition magnetic moment bound

New BBN constraint

Rothstein, Schwetz, Zupan 0903.3116 suggest long-lived intermediate gauge bosons so $B_1 \to e^+e^-$ occurs far from galactic center; weakens γ ray constraints.

We show that such B_1's would dominate universe at BBN: ruled out!

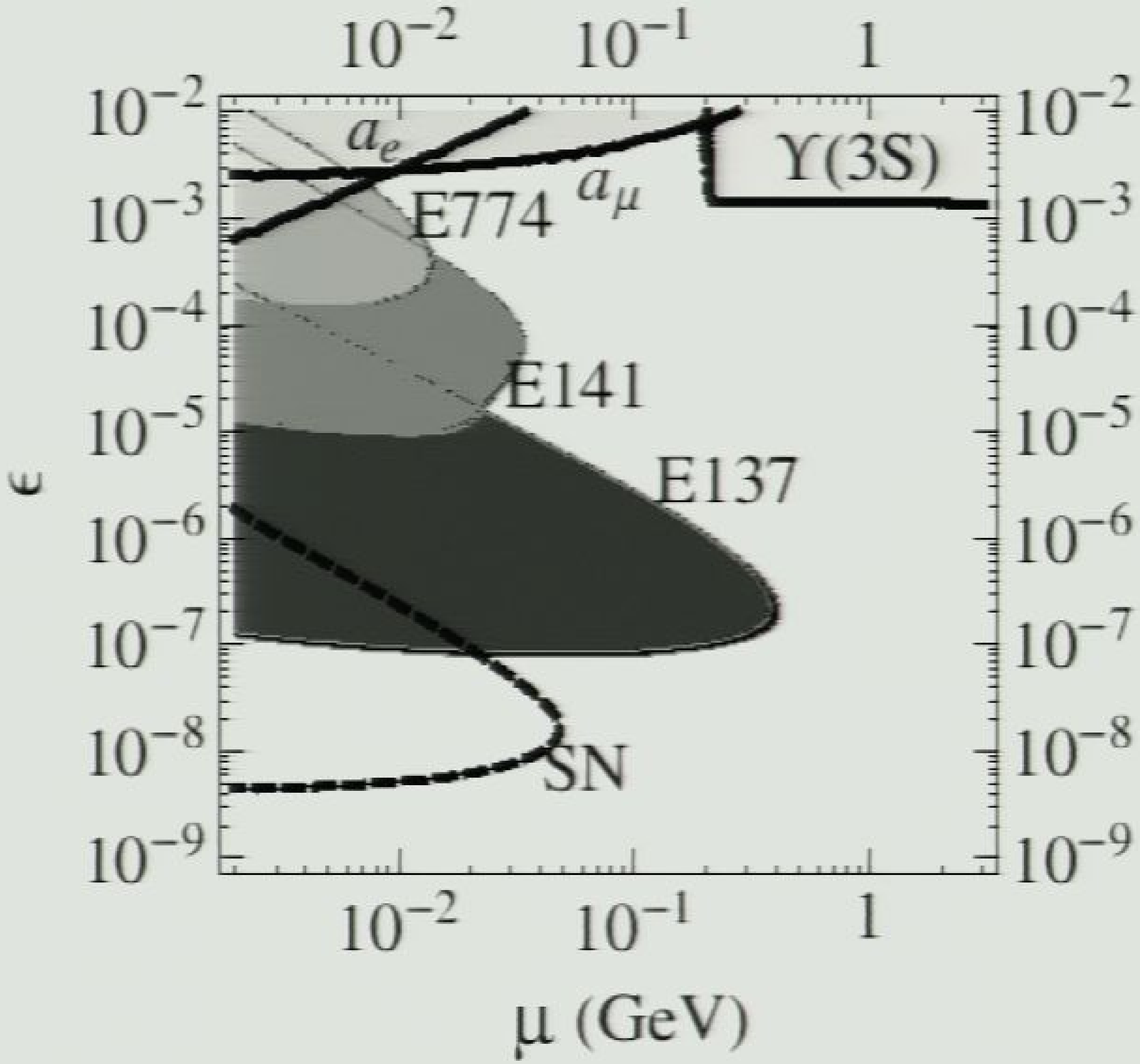
Lower bound on gauge mixing parameter from BBN:

$$\epsilon > 4 \times 10^{-11} \left(\frac{100 \text{ MeV}}{\mu} \right)^{1/2}$$

Compare to value needed for long-lived intermediate states:

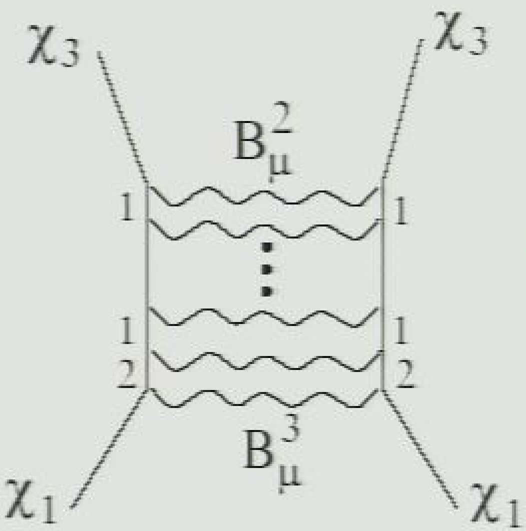
$$\epsilon \sim 10^{-16}$$

Laboratory constraints on gauge mixing



Bjorken, Essig, Schuster, Toro, 0906.0580

Excited DM mechanism (Finkbeiner, Weiner 2007)



Ladder diagrams can enhance $\sigma_{\chi_1\chi_1 - \chi_3\chi_3}$, but is it enough?

Pospelov, Ritz hep-ph/0703128 claim unitarity limit on σ makes effect too weak to explain INTEGRAL/SPI 511 keV signal.

$$\sigma(v) = \sum_l \frac{\pi(2l+1)}{M_0^2 v^2} f_l(v)$$

Unitarity $\Rightarrow f_l \leq 1$. But how many partial waves might contribute? Must actually compute σ.

Compute ladder diagrams? Easier: solve Schrödinger eq.!

Schrödinger eq. for XDM

Since $v/c \ll 1$, use NR QM (Arkani-Hamed *et al.*, (0810.0713)

$$-\Phi_l'' + \left(\frac{l(l+1)}{x^2} + \Gamma(\hat{V} - \Delta)\right)\Phi_l = 0. \qquad \hat{V} = \begin{pmatrix} 0 & -\frac{e^{-\eta x}}{x} \\ -\frac{e^{-\eta x}}{x} & 1 \end{pmatrix}$$

where $x = 2\frac{\delta M}{\alpha_g} r$ and

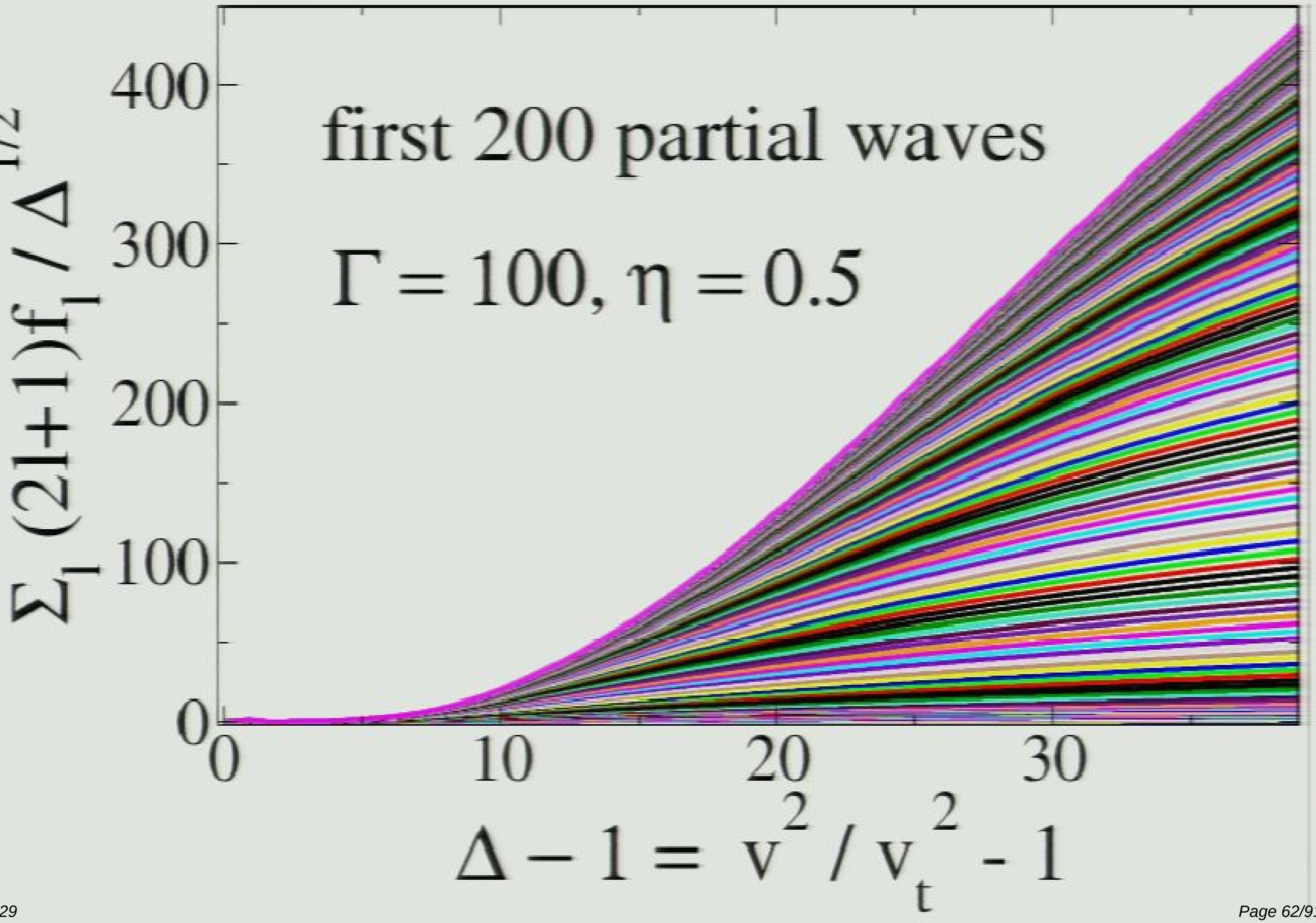
$$\Phi_l = \begin{pmatrix} \chi_1 \\ \chi_3 \end{pmatrix}_l, \quad \Gamma = \frac{\alpha_g^2 M_\chi}{2\delta M}, \quad \Delta = \frac{k^2}{2M_\chi \delta M} = \frac{v^2}{v_t^2}, \quad \eta = \frac{\alpha_g \mu}{2\delta M}$$

(v_t = threshold velocity for producing χ_3)

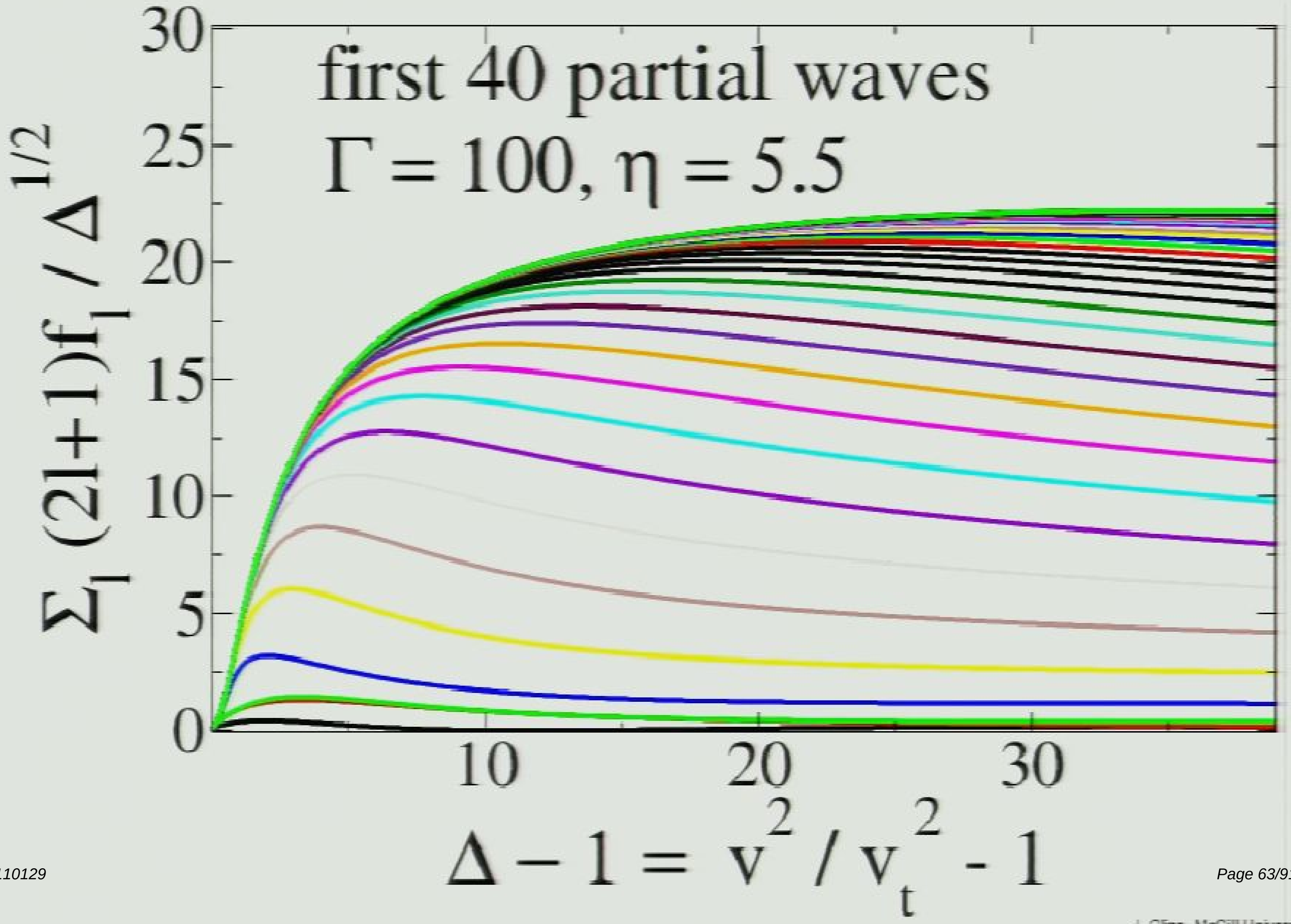
Must solve numerically for $f_l(v)$. For small μ ($\eta < 1$), hundreds of partial waves can (in principle) contribute.

Numerically challenging!

Partial wave contributions: low μ



Partial wave contributions: larger μ



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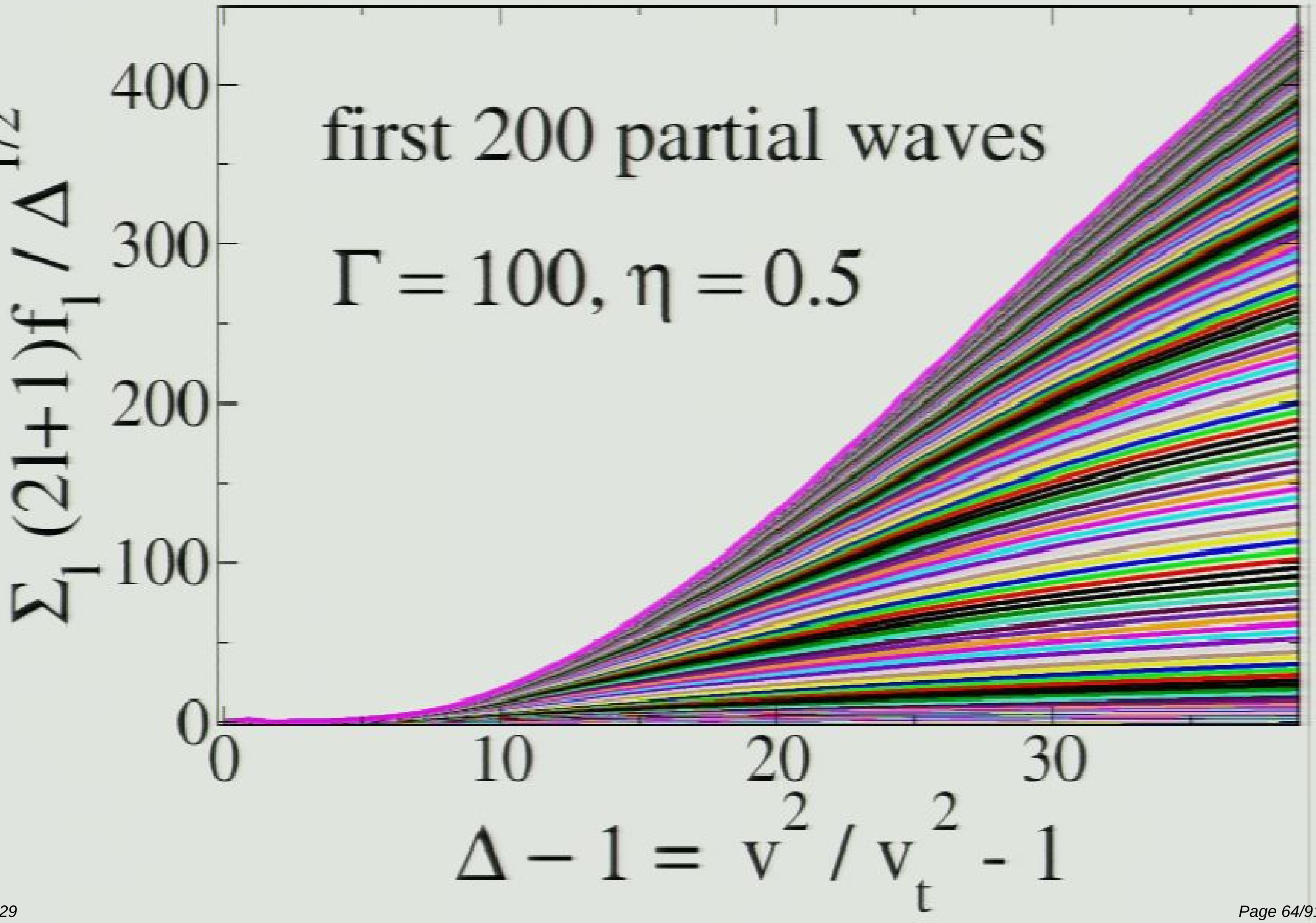

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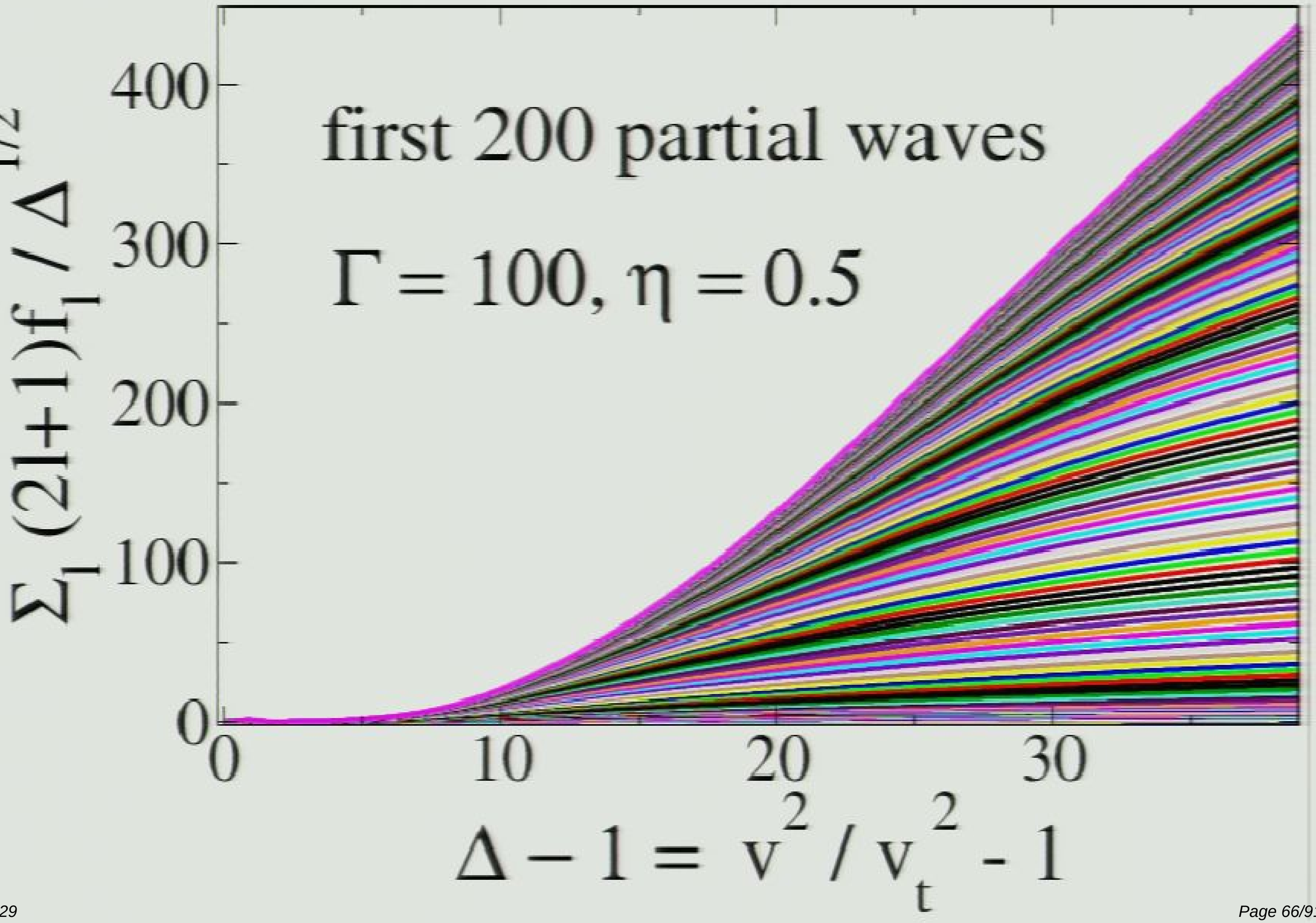

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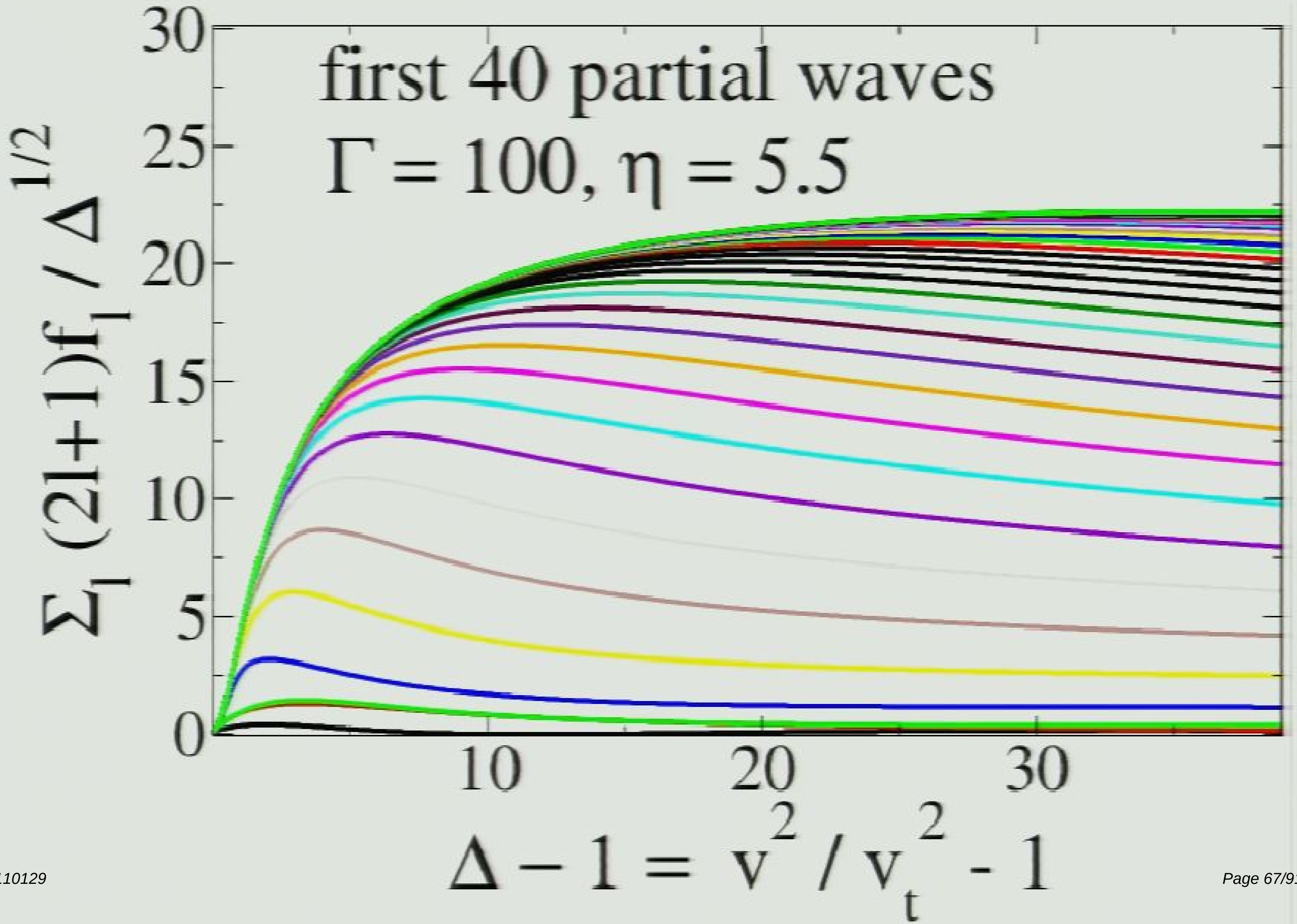
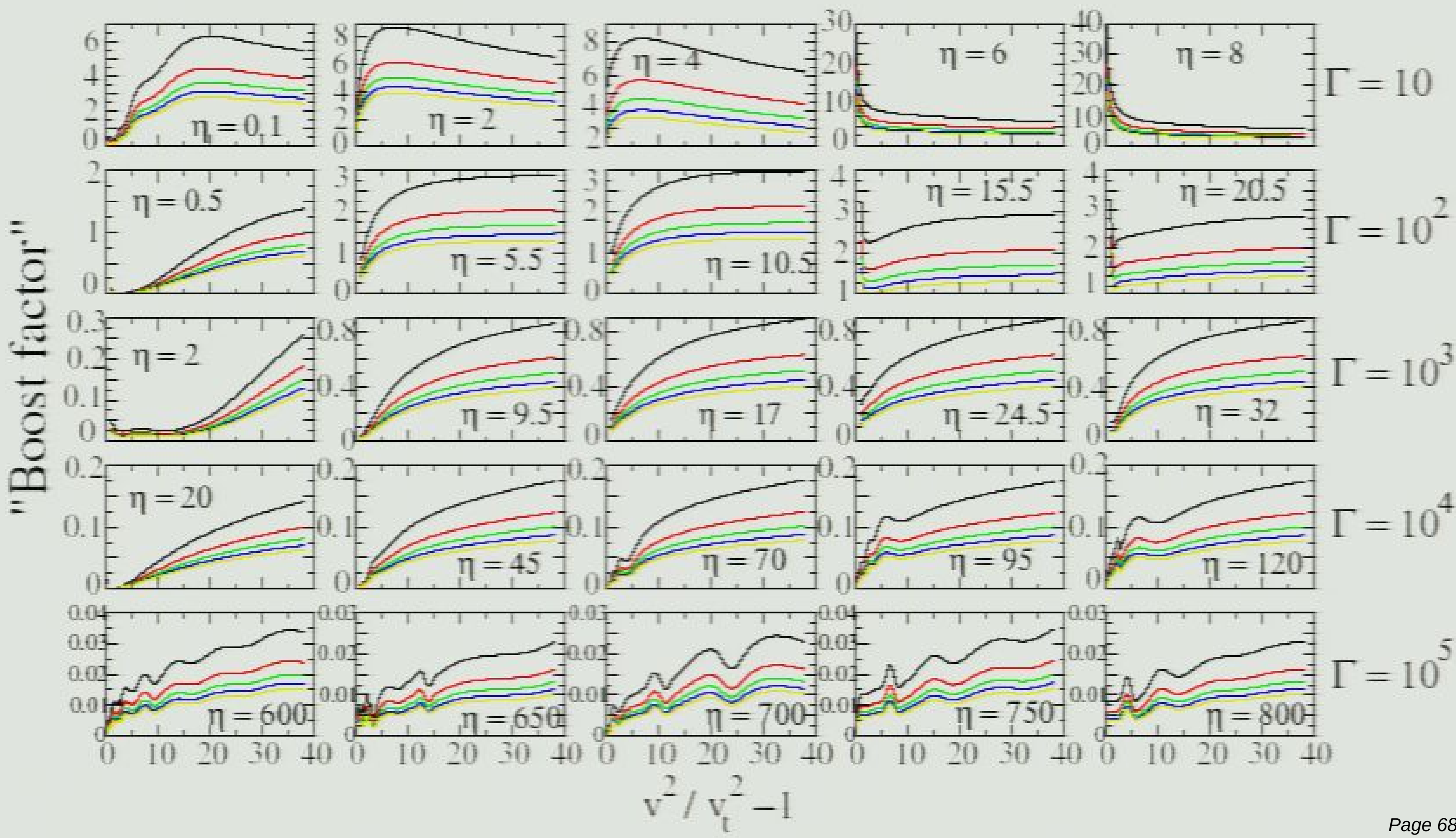


"Boost factors" not always > 1!

$\frac{\sigma_{\rm true}}{\sigma_{\rm Born}} < 1$ if gauge coupling $\alpha_g > 10\sqrt{\delta M / M_\chi}$



XDM: rate of e^+ production

Rate of e^+ production in galaxy center is

$$R_{e^+} = 4\pi \int_0^{r_c} \mathrm{d}r\, r^2 \frac{\langle \sigma v \rangle}{2} \left(\frac{\rho(r)}{M_\chi} \right)^2$$

where $\rho(r) =$ DM density profile (Einasto or NFW) and

$$\langle \sigma v \rangle (r) = \int \mathrm{d}^3 v_1 \int \mathrm{d}^3 v_2\, f(v_1, r) f(v_2, r)\, \sigma(v_{\rm rel})\, v_{\rm rel}$$

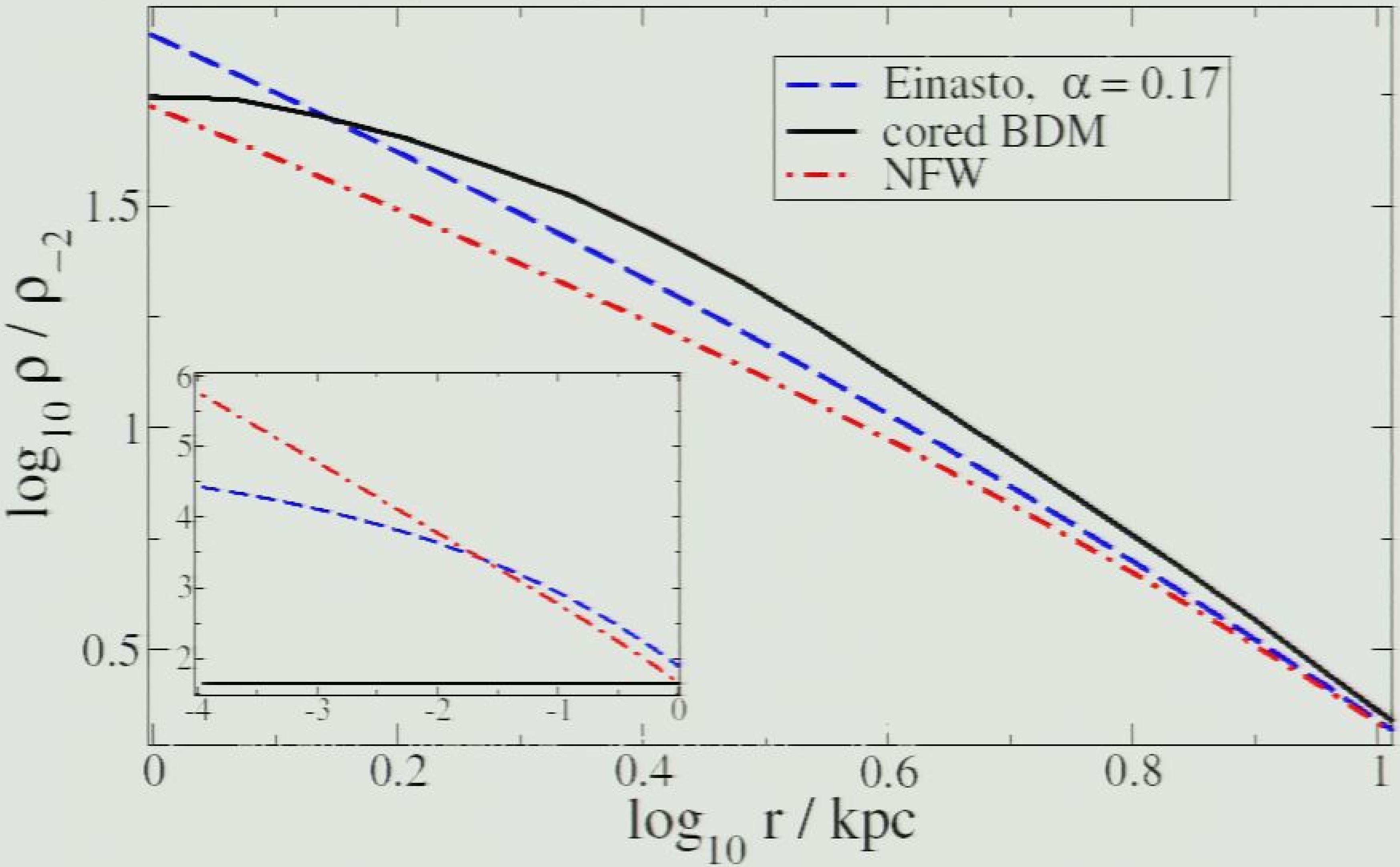
Distribution function is Maxwell-Boltzmann,

$$f(v, r) = N \exp\left(-\frac{v^2}{2 v_s^2(r)} \right) \quad \text{for} \quad v \le v_{\rm esc}.$$

Velocity dispersion is $v_s(r)$ known from N-body simulations.

Sensitivity to DM profiles

Cuspier Einasto* profile gives larger rate than does NFW†



$^{*}\ \rho \sim \exp\left(-\frac{2}{\alpha}\left(\left(\frac{r}{r_{-2}}\right)^{\alpha} - 1\right)\right)$ $\quad$ $^{\dagger}\ \rho \sim \left(\frac{r}{r_{-2}}\right)^{-1}\left(1 + \frac{r}{r_{-2}}\right)^{-2}$

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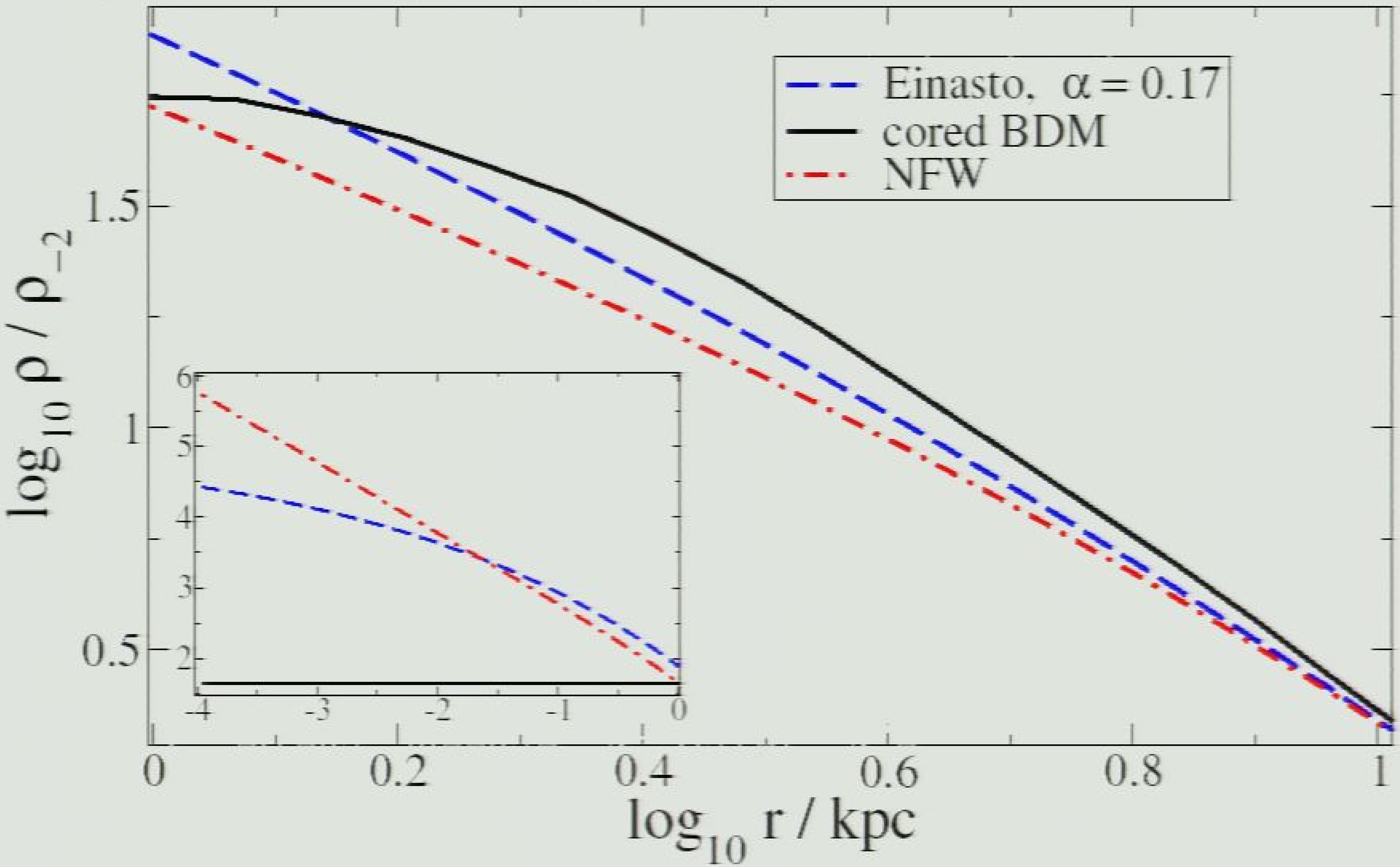
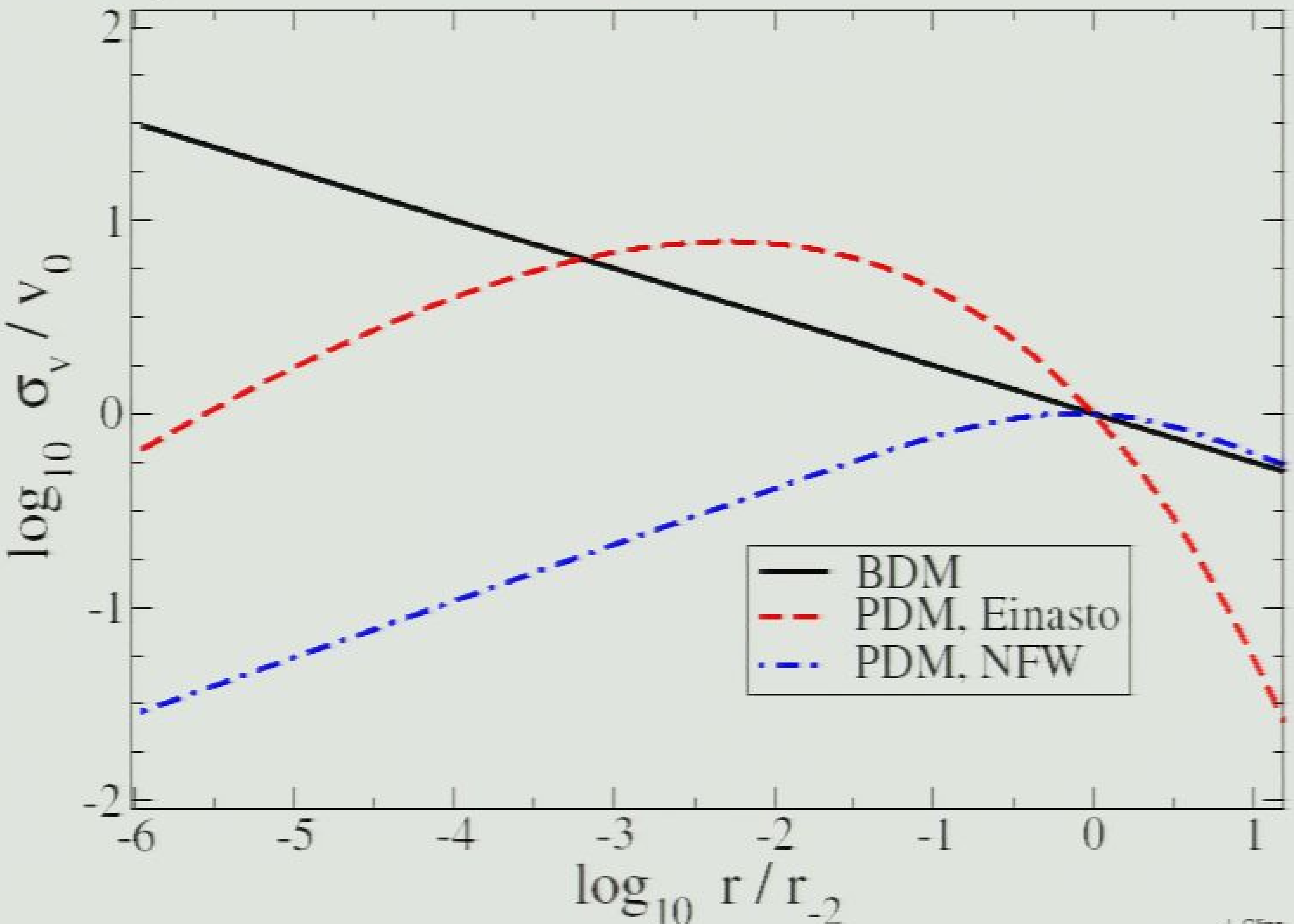


* $\rho \sim \exp\left(-\frac{2}{\alpha}\left(\left(\frac{r}{r_{-2}}\right)^{\alpha} - 1\right)\right)$ † $\rho \sim \left(\frac{r}{r_{-2}}\right)^{-1}\left(1 + \frac{r}{r_{-2}}\right)^{-2}$

Sensitivity to DM velocity dispersion

N-body simulations with baryons have $\sigma_v \sim r^{-1/4}$ in galactic center (Romano-Diaz *et al.*, 0808.0195), increases rate relative to pure DM simulations.



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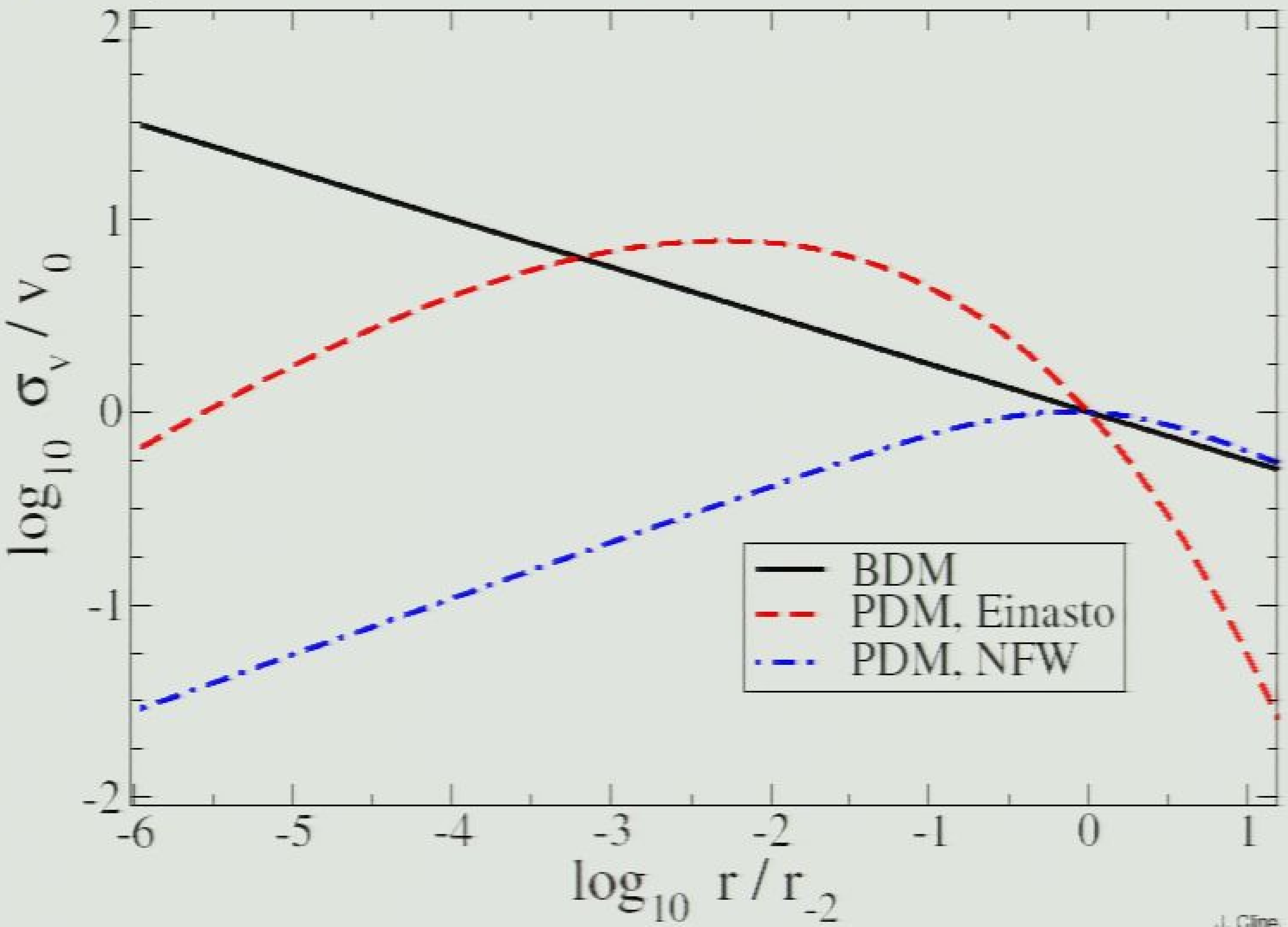
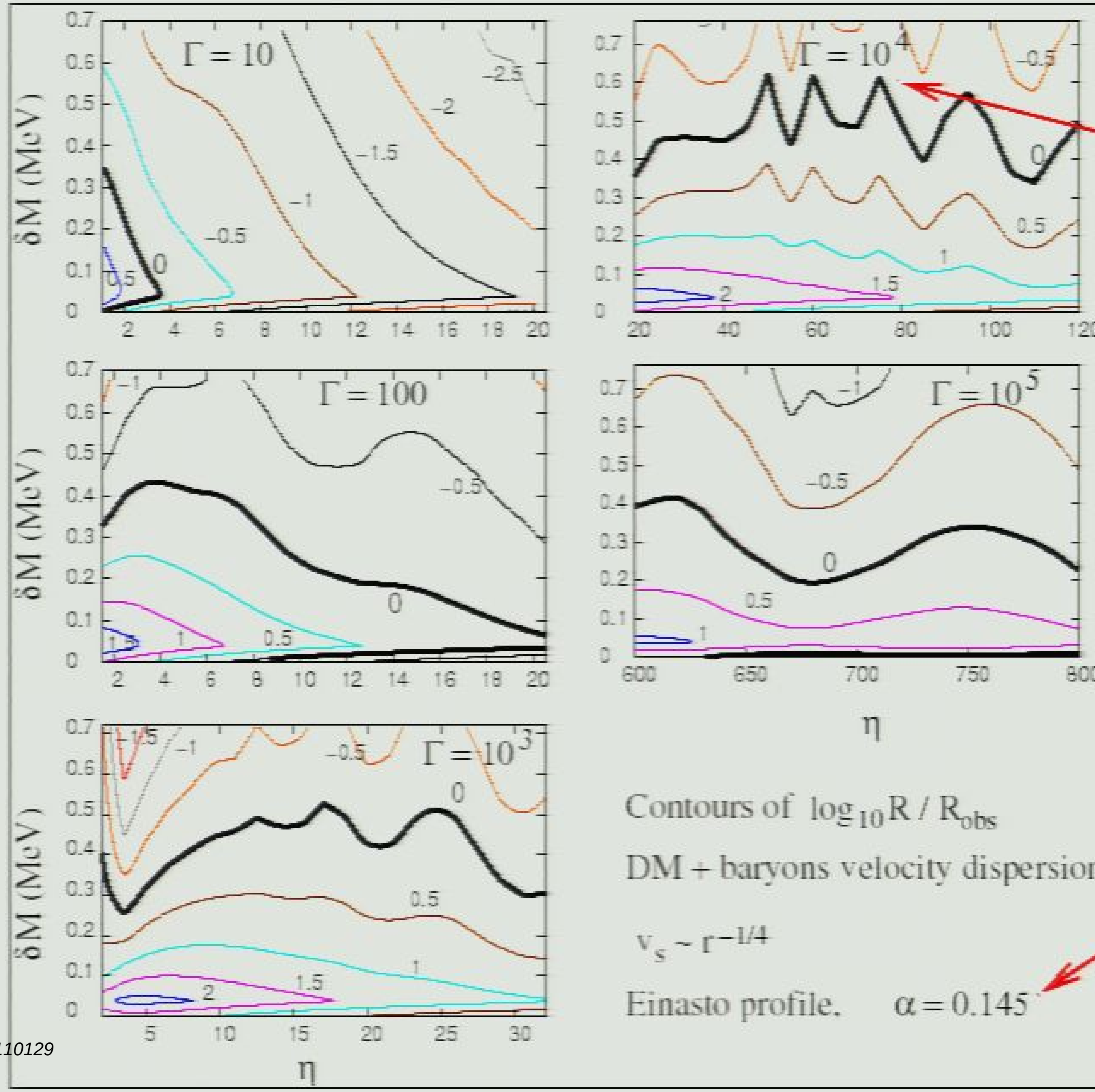


XDM: results (with A. Fradette and C. Rabideau)



largest value of δM ~ 600 keV

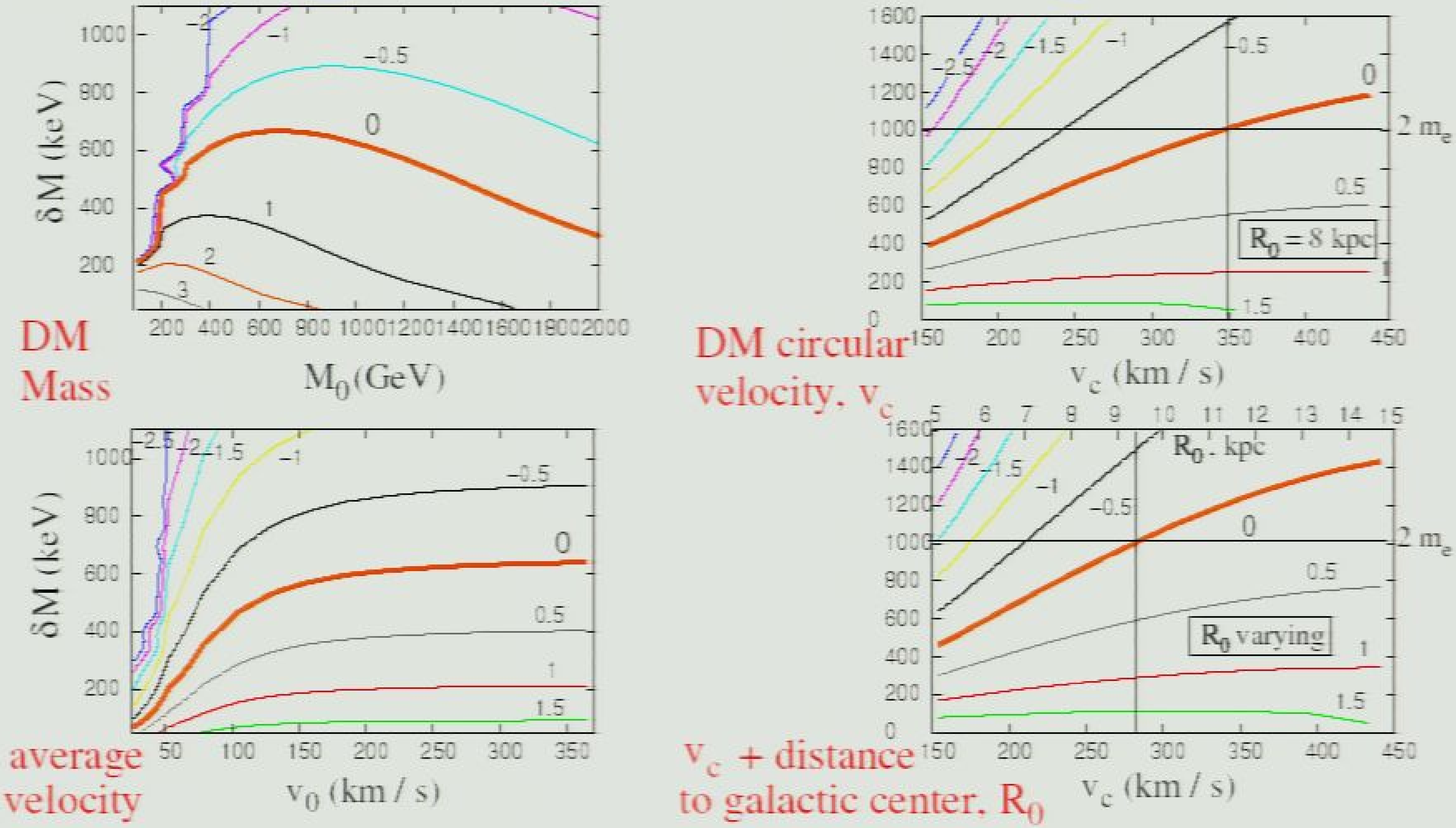
assume

$M_\chi = 1$ TeV

Einasto parameter (Pedrosa et al., 0910.4380)

J. Cline, McGill University – p. 33

XDM: dependence on other parameters

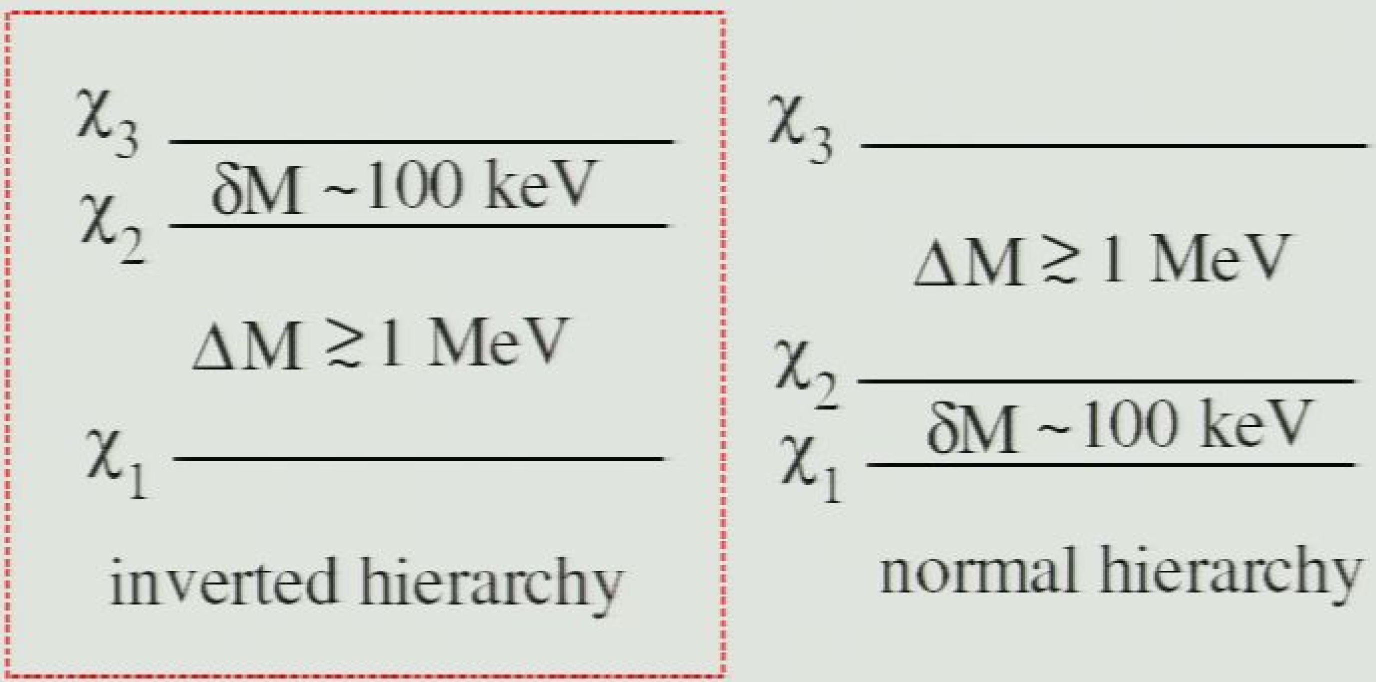


Cannot achieve $\delta M \geq 2m_e$ for reasonable values of galactic parameters.

Insufficient phase space for $\chi_3 \rightarrow \chi_1 e^+ e^-$

Inverted mass hierarchy for XDM

Chen, JC, Frey, 0901.4327 suggested a solution—inverted mass hierarchy:



Requires relic population of χ_2, stable against $\chi_2 \to \chi_1 + \ldots$

Z_2 symmetry can insure this.

Nonthermal DM origin required

Problem: intermediate state can be depopulated in same way,

$$\chi_2\chi_2 \to \chi_3\chi_3 \to \chi_1\chi_1 + 2e^+ + 2e^-$$

in early universe. Need to increase DM velocity to avoid Sommerfeld enhancement.

Nonthermal DM production: late decay of DM predecessor $S \to \chi\chi$ leads to faster-than-thermal χ's.

E.g., long-lived scalar S decays, $S \to \chi\chi$, via dimension-6 operator

$$\frac{g_X^2}{m_X}|S|^2\,\bar{\chi}\chi$$

after phase transition where S gets VEV $\langle S \rangle \sim$ TeV.

Nonthermal DM origin required

Sommerfeld-enhanced cross-section goes like $\langle \sigma v \rangle \sim 1/v$.

Suppose $v \sim 1$ and $T = T_d$ when χ is produced by $S \to \chi\chi$.

Velocity redshifts as $v \sim T/T_d$ at lower T. Find that

$$\frac{n\langle \sigma v \rangle}{H} = \frac{2 \times 10^5\, T_d}{\sqrt{g_*} M_\chi}$$

Excitations stay out of equilibrium for $M_\chi \sim 1$ TeV if decay occurs at $T_d \sim 5$ MeV.

Dim. 6 operator gives right lifetime if

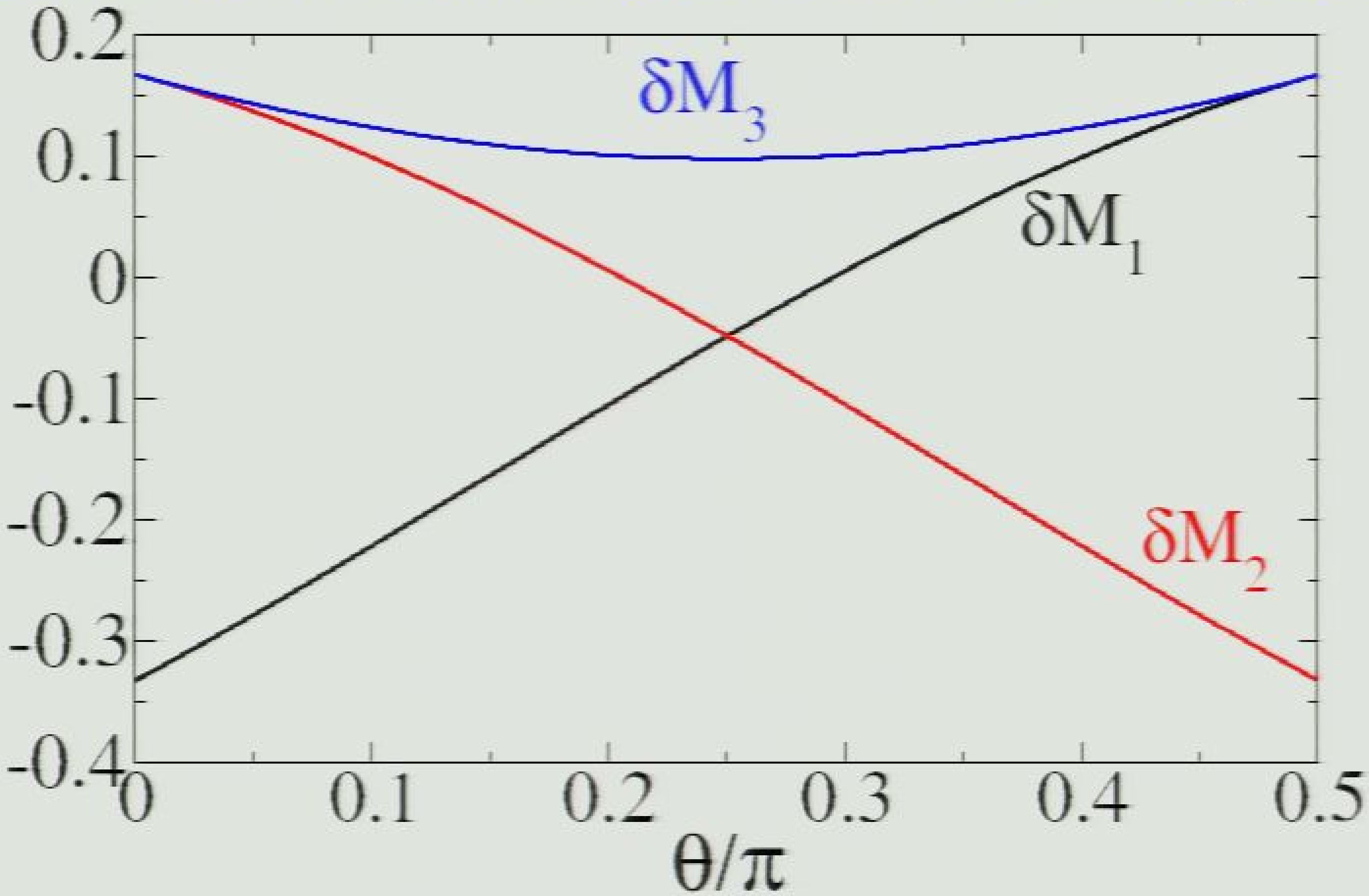
$$\frac{m_X}{g_X^2} \sim 10^{16}\ \text{GeV},$$

the GUT scale. Intriguing possibility?

Mass spectrum of triplet DM

Chen, JC, Frey, 0907.4746 computes spectra for various DM reps. and Higgs VEV's.

2 orthogonal triplet Higgses with $\tan\theta = \Delta_2/\Delta_1$:



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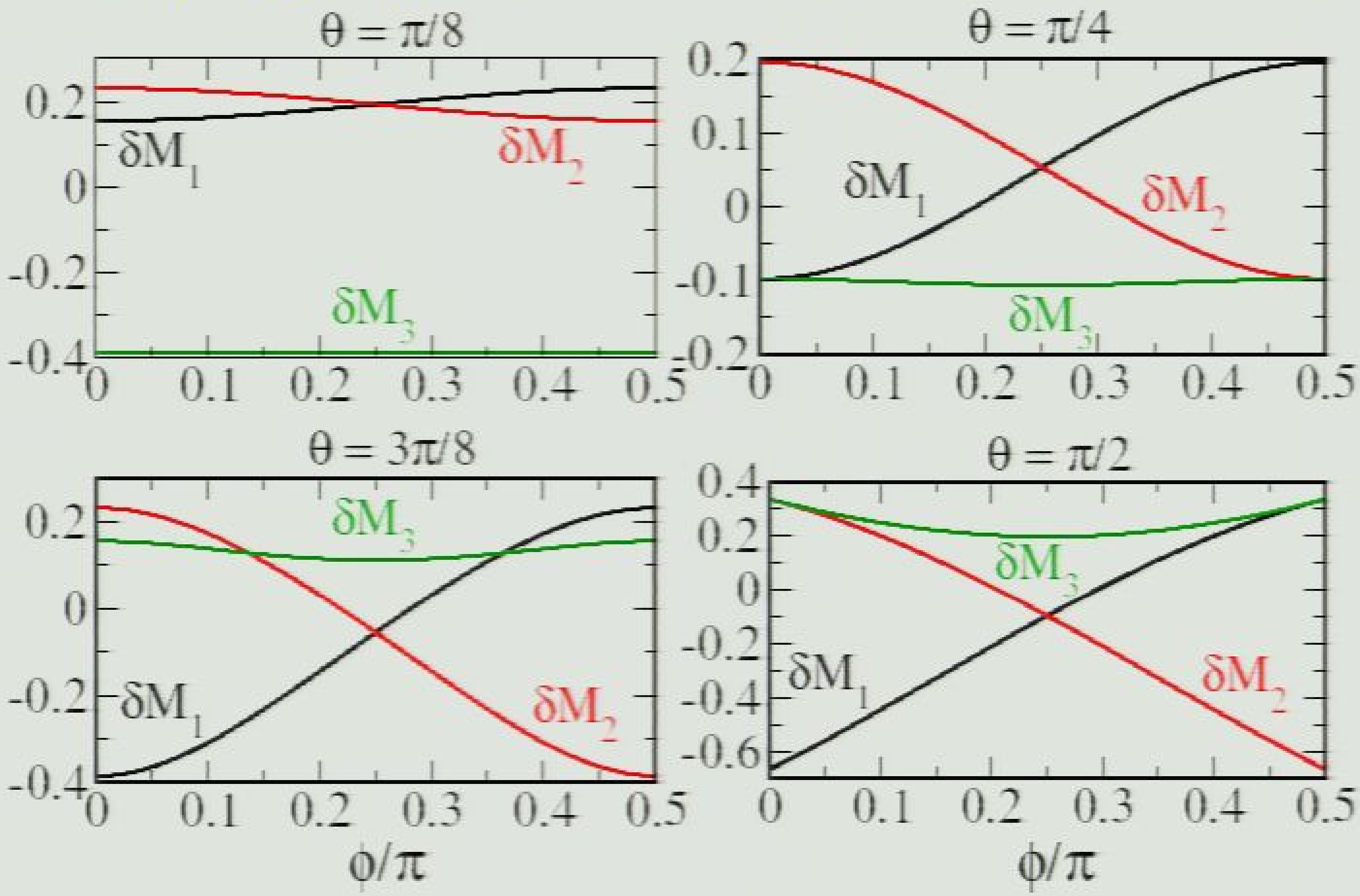
3 orthogonal triplet Higgses with
$(\Delta_1, \Delta_2, \Delta_3) = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$:



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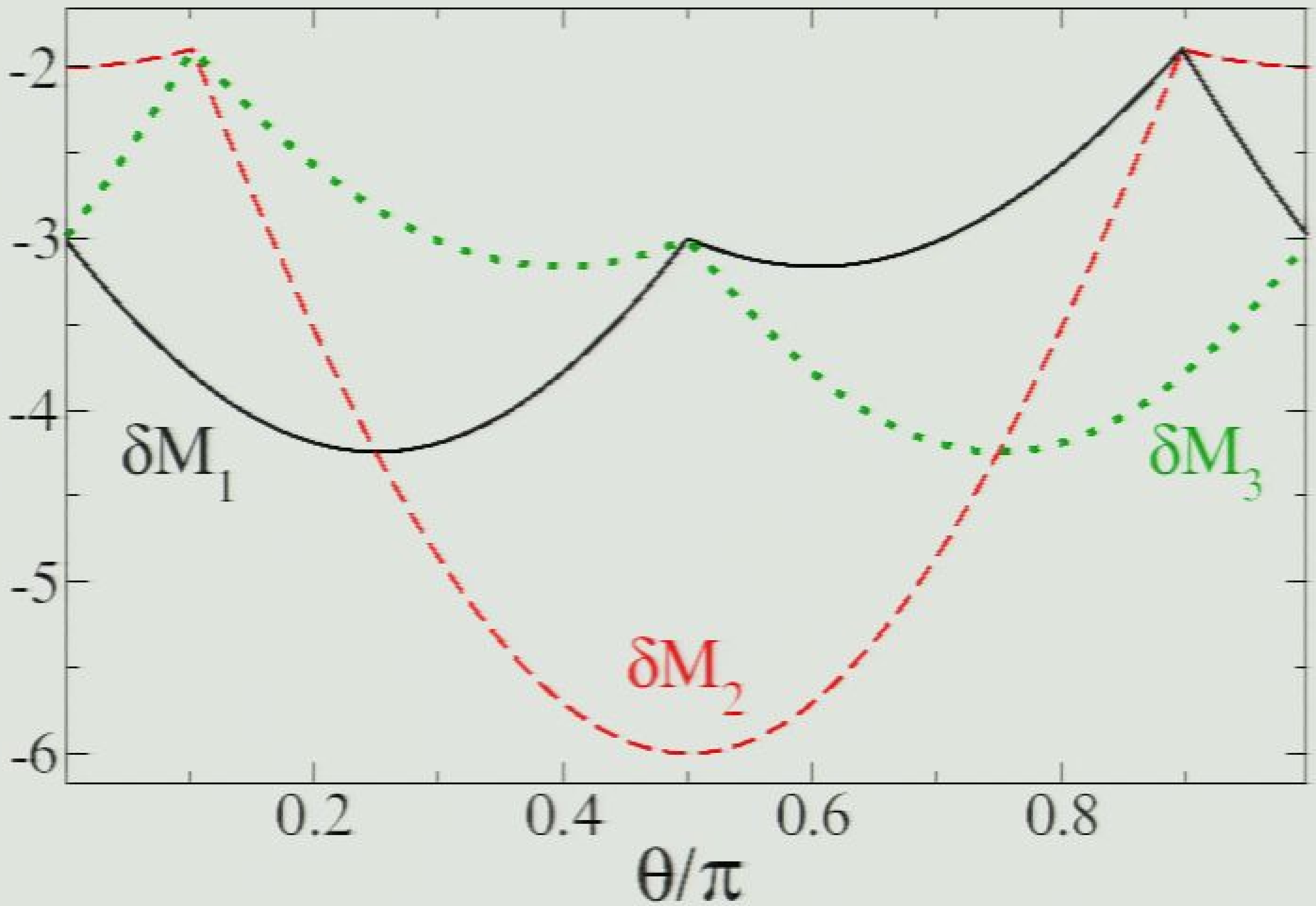
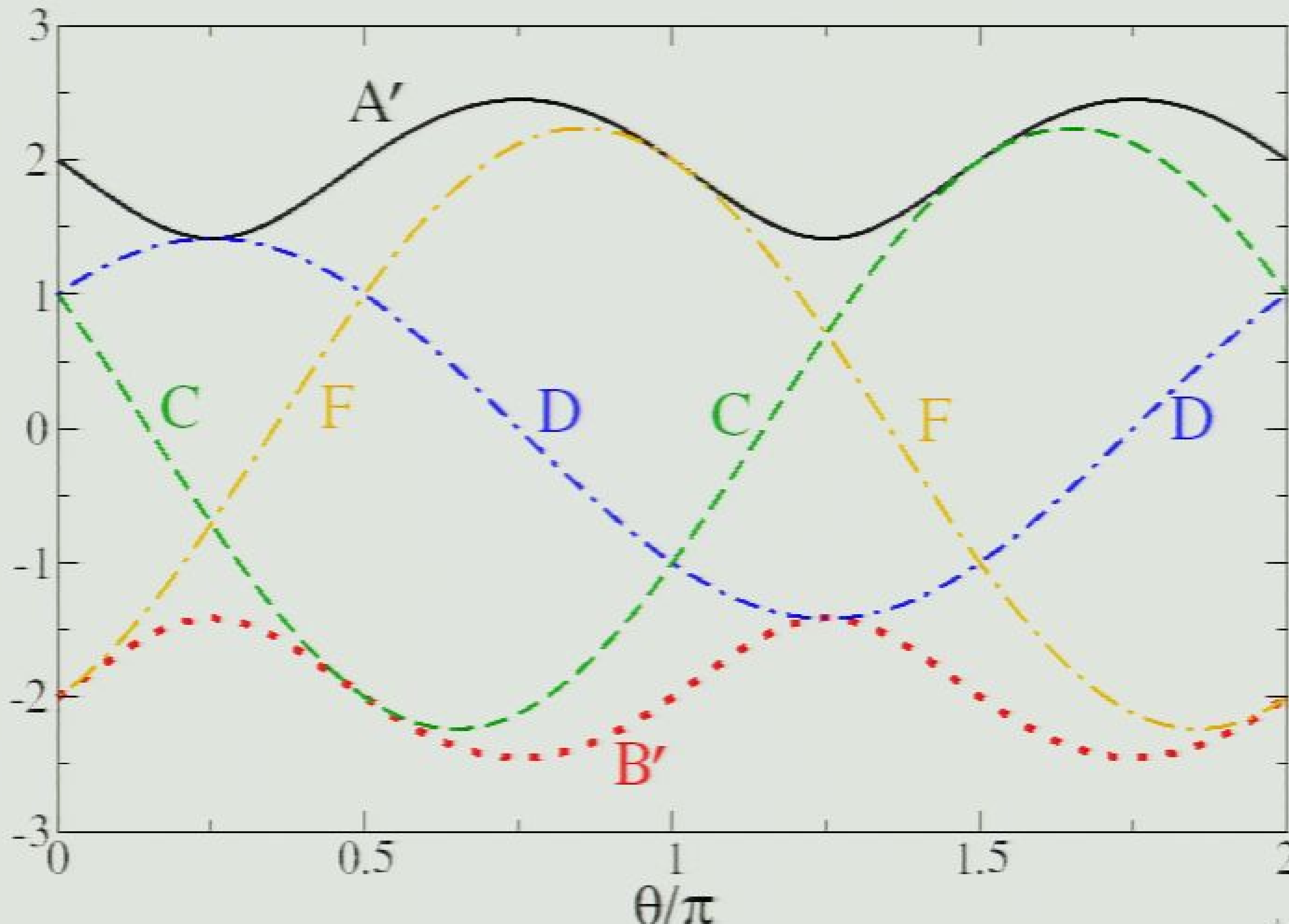
quintuplet Higgs Σ_{ij} with $\tan\theta = \frac{\Sigma_{22}-\Sigma_{11}-\Sigma_{33}}{2(\Sigma_{11}-\Sigma_{33})}$



Mass spectrum of quintuplet DM

Chen, JC, Frey, 0907.4746 computes spectra for various DM reps. and Higgs VEV's.

arbitrary Higgses such that $\tan\theta = \frac{\mu_3-\mu_2}{\mu_1-\mu_2}$:



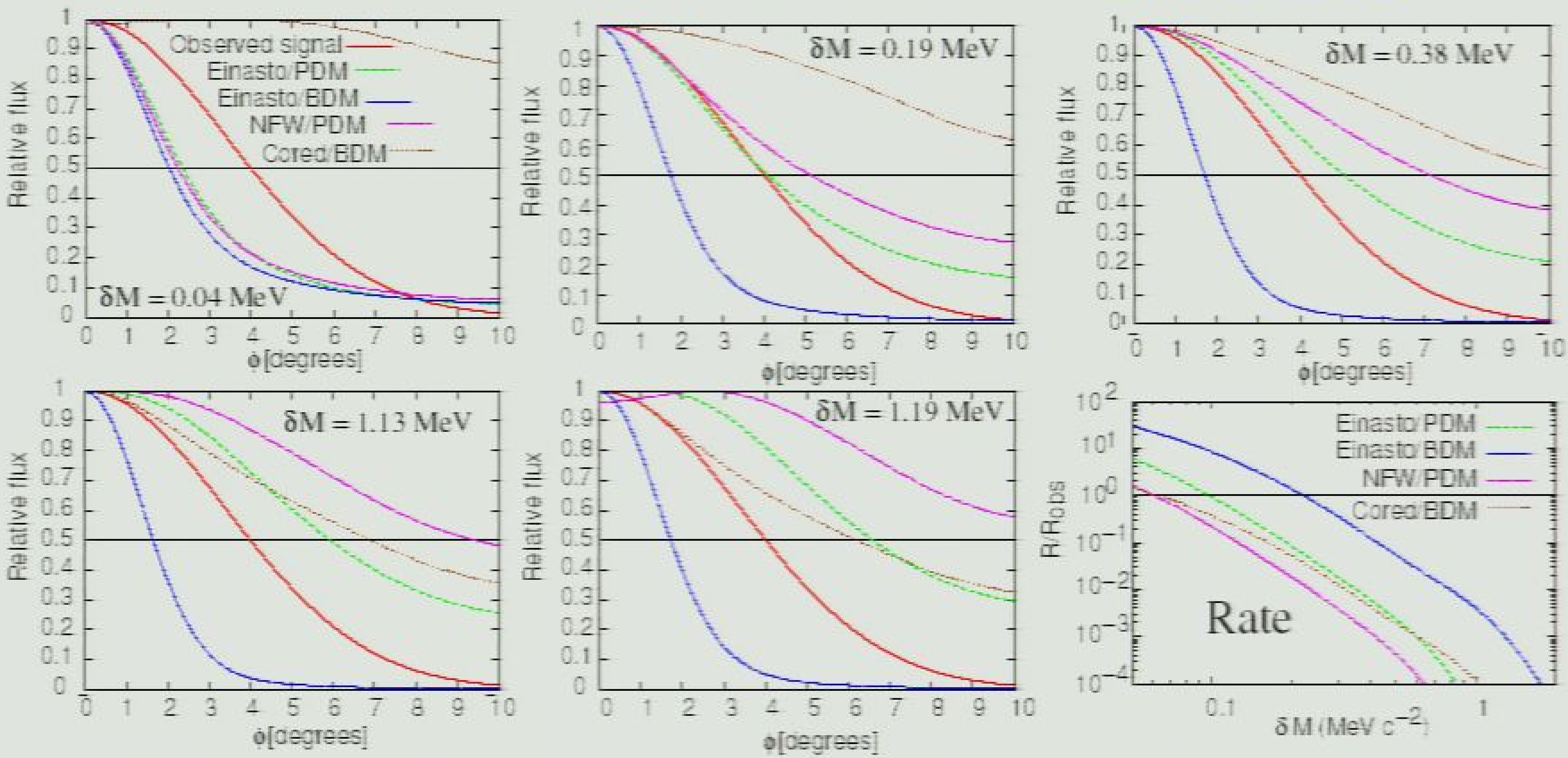
Many examples with
inverted mass hierarchy

(and Z_2 symmetry to keep
intermediate state stable)

Angular distribution of 511 keV signal

Same DM profiles which are good for rate are good for angular distribution:

Einasto with baryonic velocity dispersion (blue curves)



Propagation of e^+ before decay can widen the angular distribution

Subhalo contribution to positrons

in progress with A. Vincent, W. Xue

- Galaxy contains $> 10,000$ DM subhalos
- Velocity dispersions $v_s \sim 0.1\frac{\text{km}}{\text{s}}$ much smaller than in halo
- Sommerfeld enhancement much larger than in halo, $\sim 10^5$
- HESS γ ray constraints are weakened for annihilations outside galactic center

Can subhalos be dominant source of e^+e^-? Other papers considered only γ ray signal from subhalo annihilations:

Bovy, 0903.0413;

Kuhlen, Madau, Silk, 0907.0005;

Kistler, Siegal-Gaskins, 0909.0519

Subhalo contribution: methodology

Use Via Lactea simulation data. Annihilation rate is sum over subhalos (out to 100's of kpc),

$$R \sim \sum_i \int d^3x\, \rho_i^2(x)\, \langle \sigma v \rangle_i$$

where

$$\langle \sigma v \rangle_i = \int d^3v\, \langle \sigma v \rangle_0\, S(v)\, f_i(v, r)$$

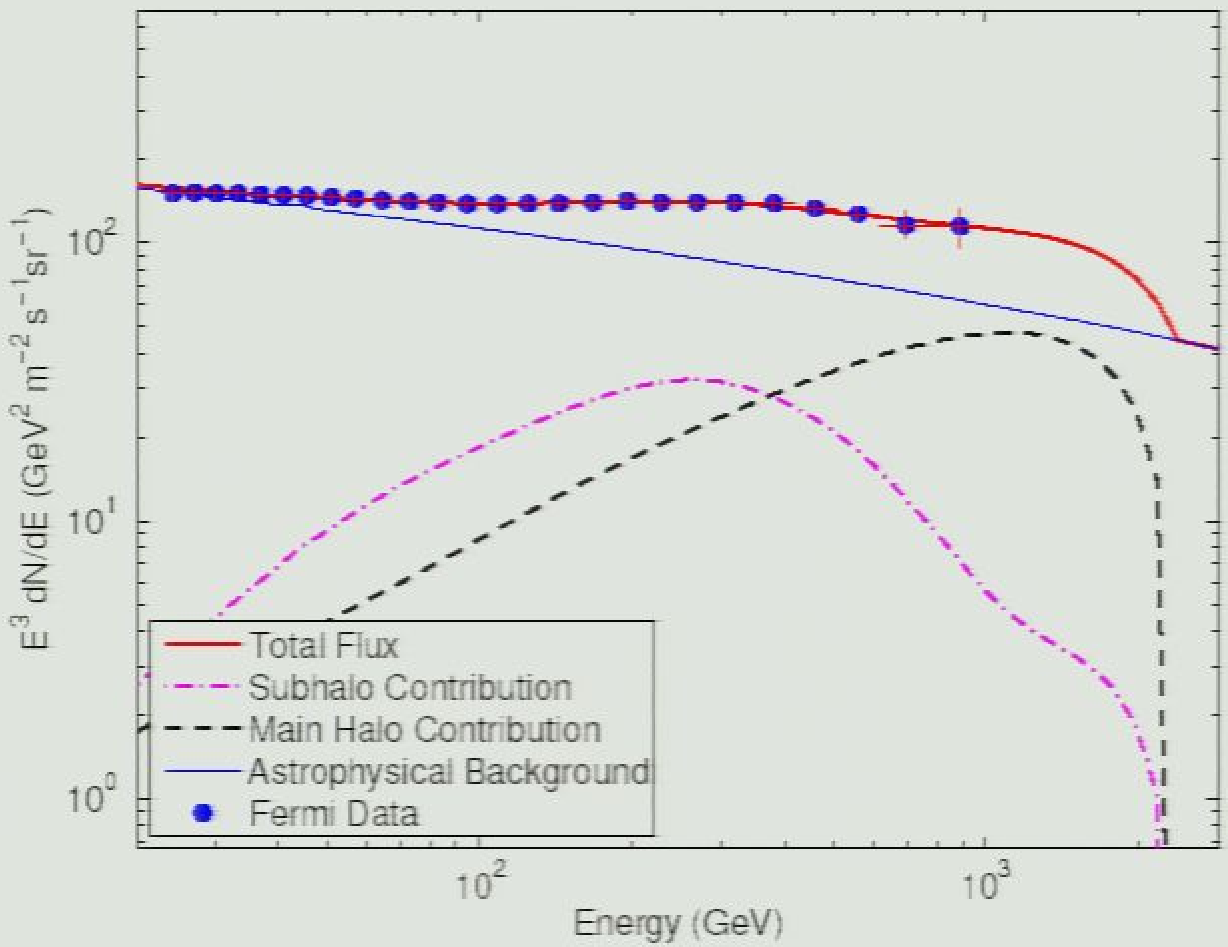
and $S(v) =$ Sommerfeld boost factor.

Contributions outside visible galaxy provide new source term for modified GALPROP code.

Subhalos: preliminary results

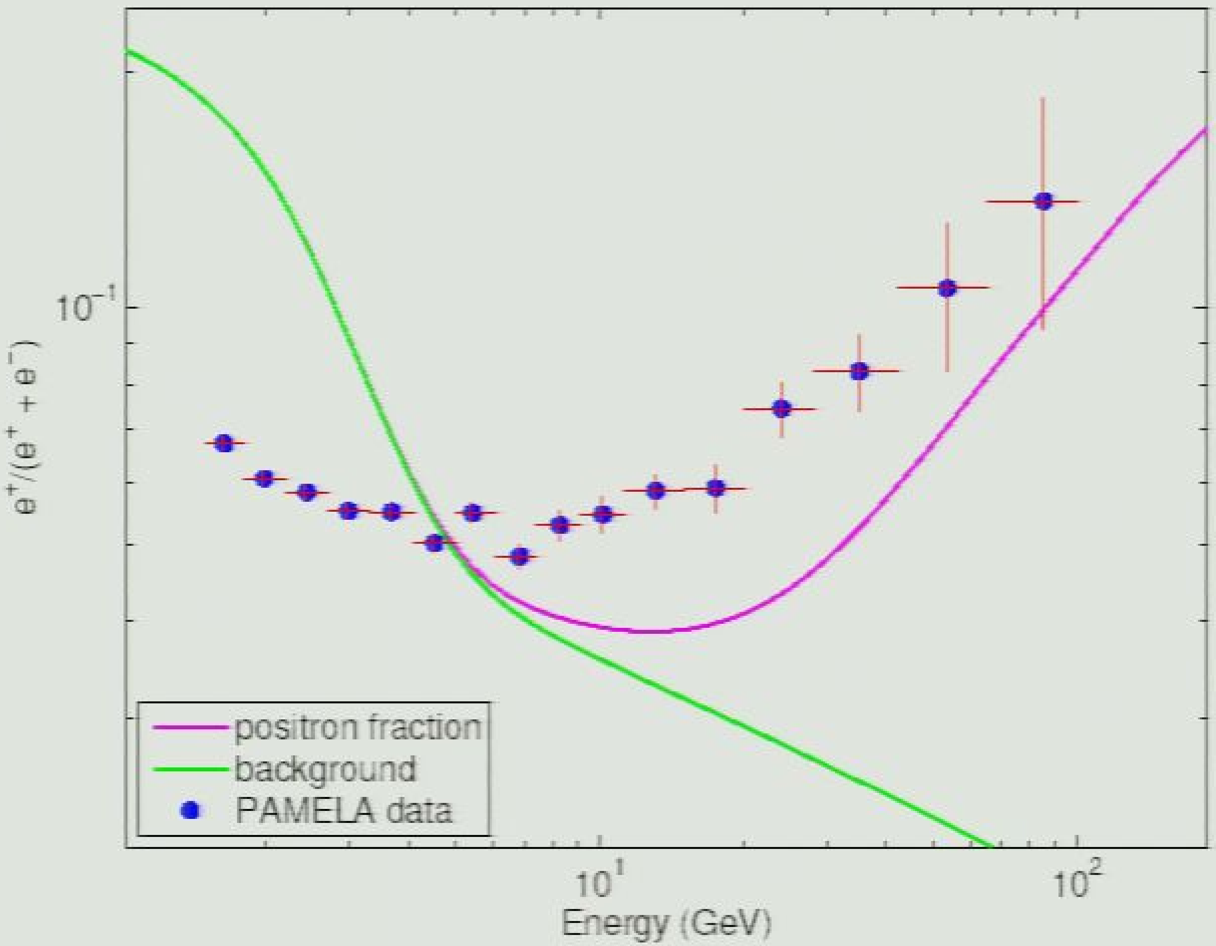
Fit to Fermi is improved with 30% contribution from subhalos

Need $M_\chi = 2.2$ TeV, $S_{\rm eff} = 145(4825)$ for main (sub)halo(s)



Subhalos: preliminary results

Fit to PAMELA is not so good:



$\chi^2 \sim 100$; compare to Fermi fit, $\chi^2 = 2$.

Conclusions

Pulsars may be the source of observed e^+e^-, but astrophysical uncertainties too great to ever prove it

Still room for DM interpretation, though CMB constraints are tight

New γ ray data to come from Fermi may tell us if DM explanation is correct

XDM interpretation of 511 keV excess may still be right even if PAMELA/Fermi is not due to DM

Subhalo e^+ production and nonthermal DM history are intriguing possibilities