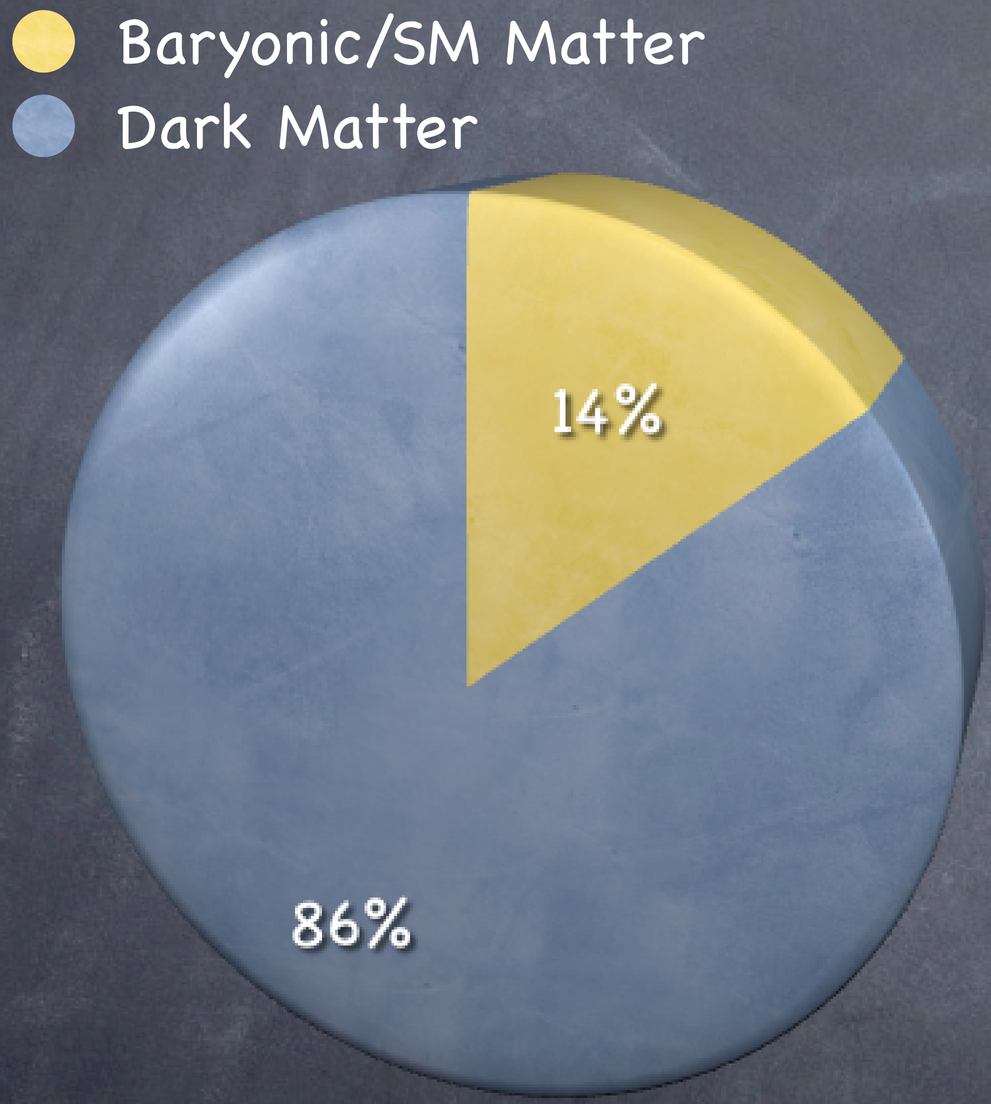
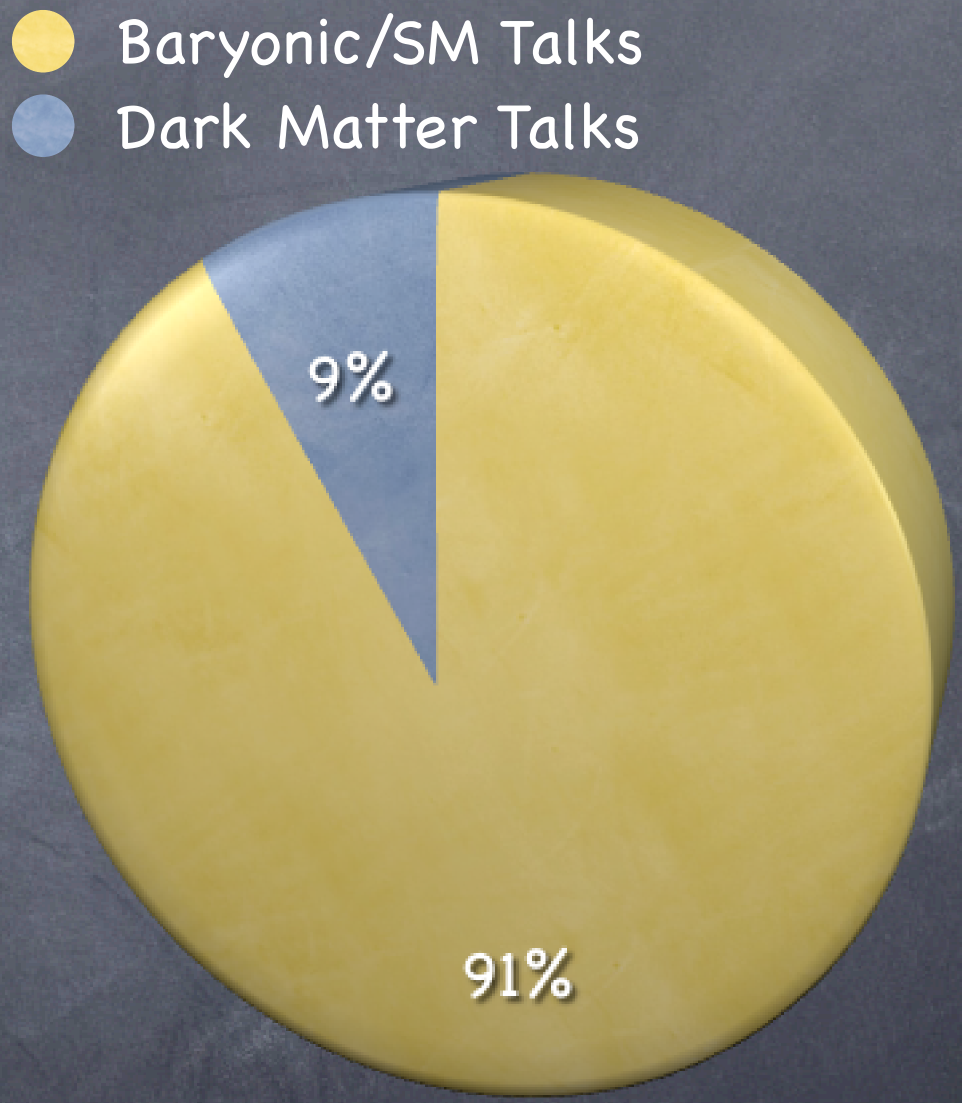
Some Theories of Dark Matter

Neal Weiner
Center for Cosmology and Particle Physics

Aspen Conference
LHC Year of the Ox

This is just one talk!





I'm going to just give one person's perspective (not all inclusive - that's what John's talk is for)

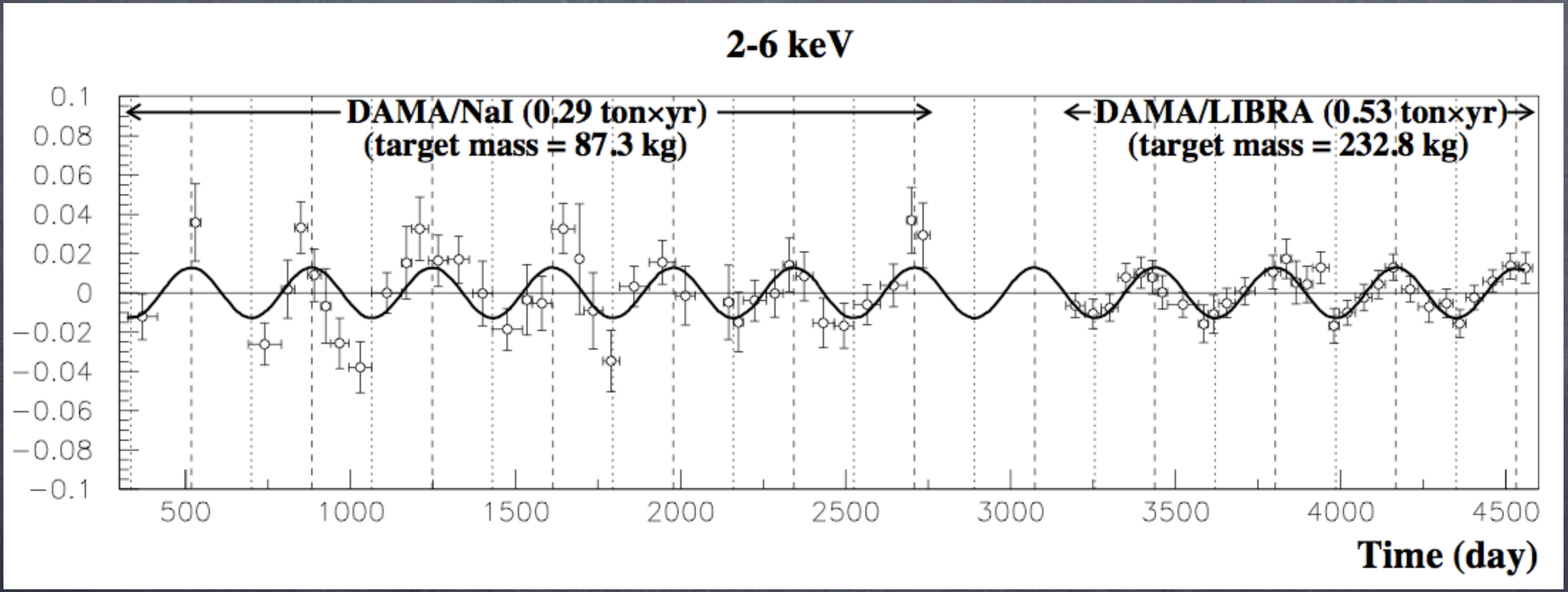
Due diligence

Motivations for dark matter theory

- Pre 2008: Theory (problem) driven
  - Hierarchy problem: SUSY + R parity, Little Higgs + T parity, etc.
  - Strong CP problem: axions
  - Both: axinos
- 2008 - present: Hint (anomaly) driven

What hints?

What hints?


2-6 keV
DAMA/NaI (0.29 ton×yr)
(target mass = 87.3 kg)
DAMA/LIBRA (0.53 ton×yr)
(target mass = 232.8 kg)
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
−0.1
500
1000
1500
2000
2500
3000
3500
4000
4500
Time (day)

What hints?

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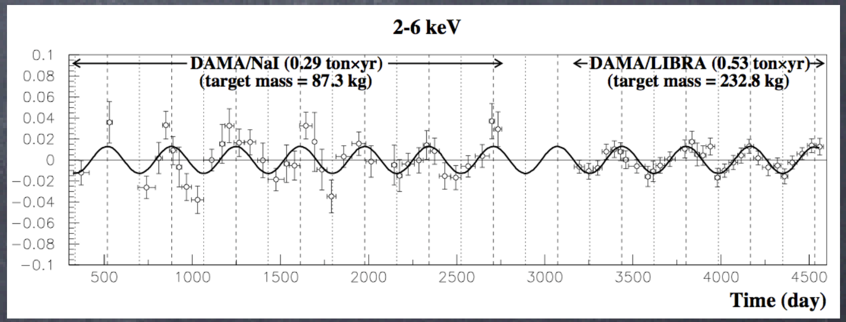
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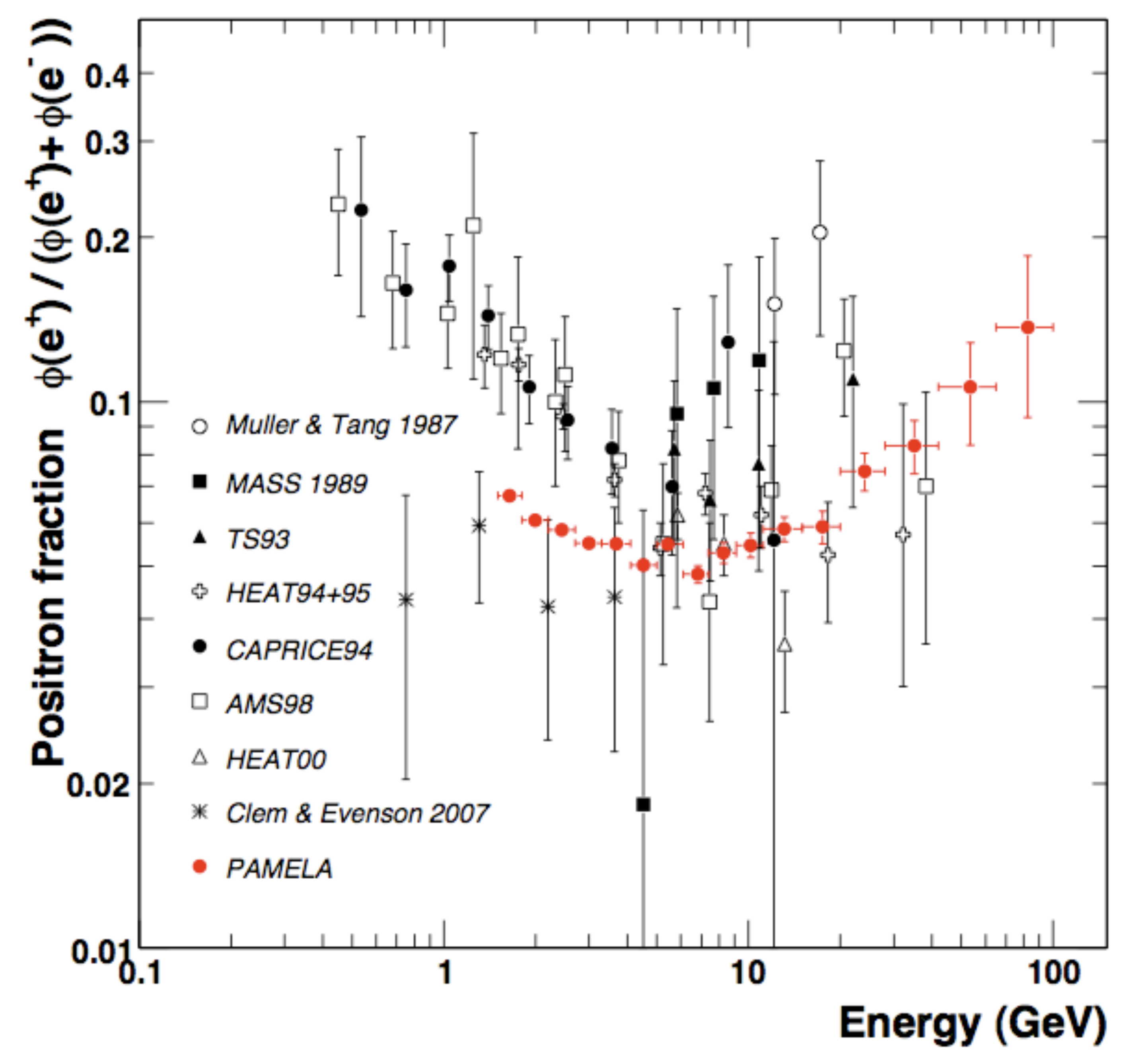
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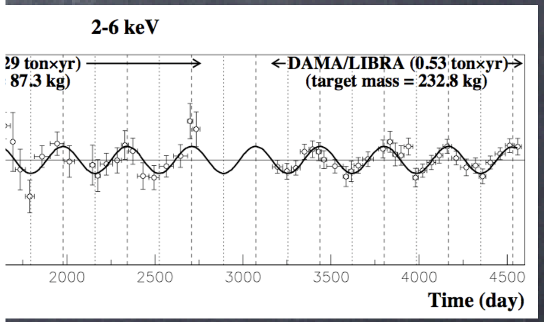
0.4
0.3
0.2
0.1
0.02
0.01
0.1
1
10
100
Energy (GeV)
Muller & Tang 1987
MASS 1989
TS93
HEAT94+95
CAPRICE94
AMS98
HEAT00
Clem & Evenson 2007
PAMELA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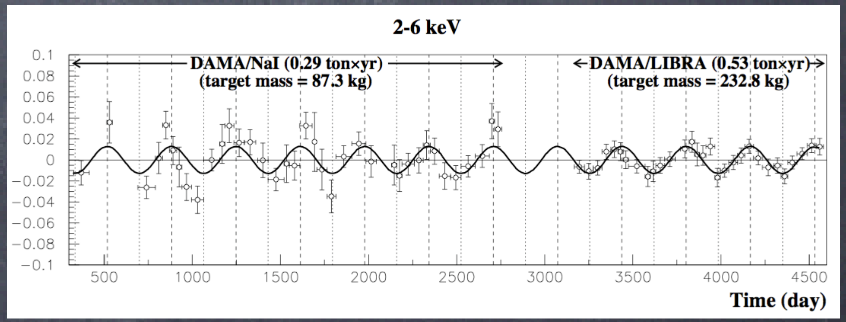
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Time (day)

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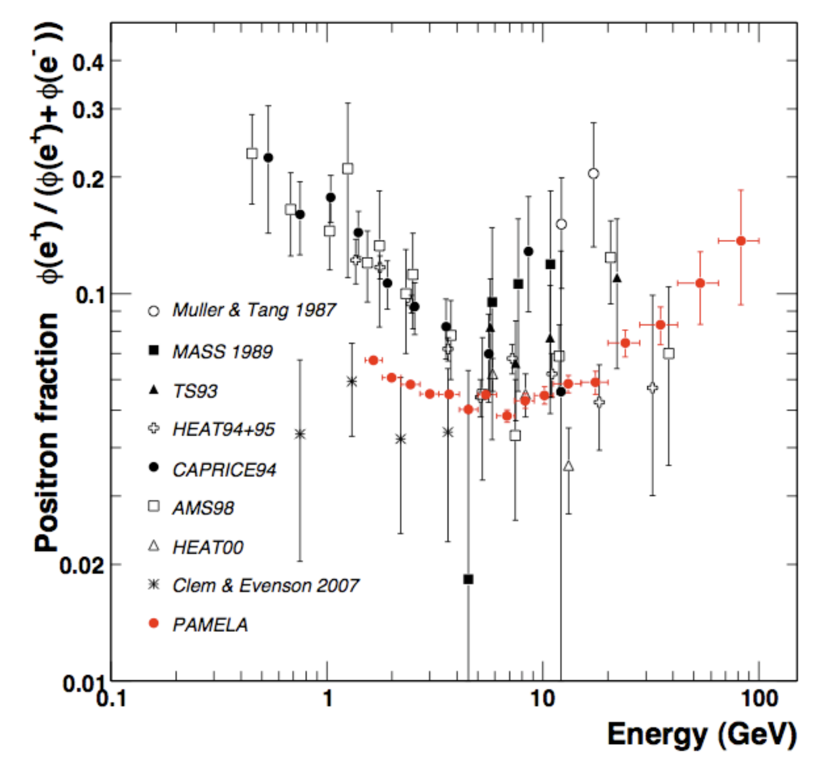
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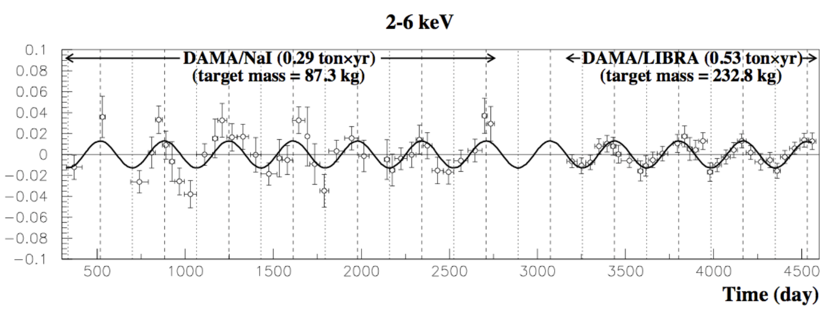
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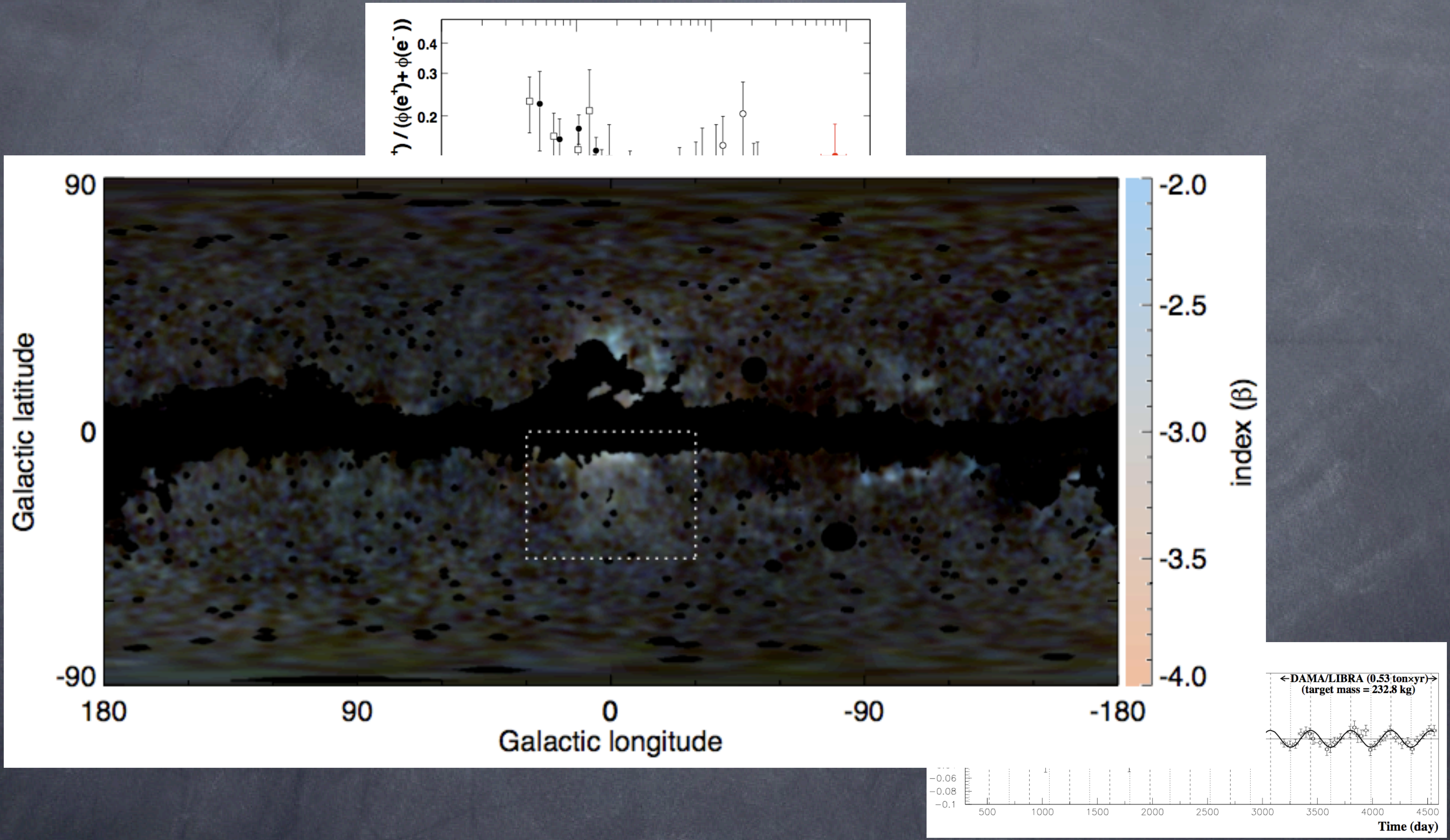

) / (φ(e⁺) + φ(e⁻))
0.4
0.3
0.2
90
0
-90
Galactic latitude
180
90
0
-90
-180
Galactic longitude
-2.0
-2.5
-3.0
-3.5
-4.0
index (β)
←DAMA/LIBRA (0.53 ton×yr)→
(target mass = 232.8 kg)
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−0.08
−0.1
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Time (day)

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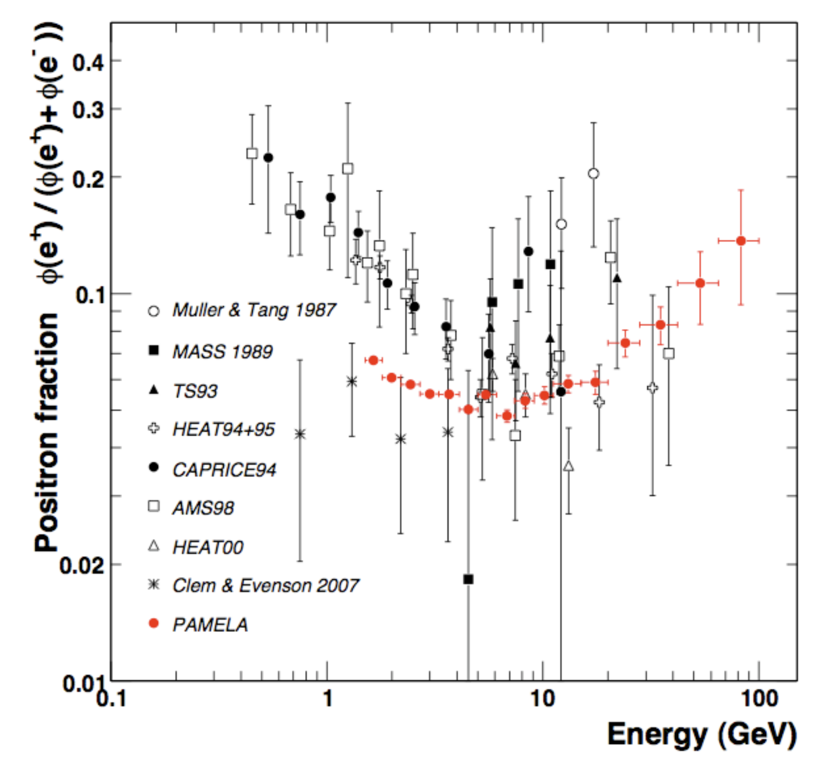
Positron fraction φ(e+) / (φ(e+)+φ(e-))
0.4
0.3
0.2
0.1
0.02
0.01
0.1
1
10
100
Energy (GeV)
○ Muller & Tang 1987
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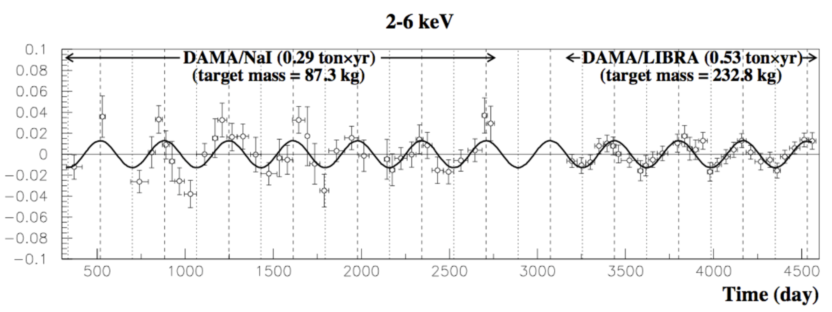
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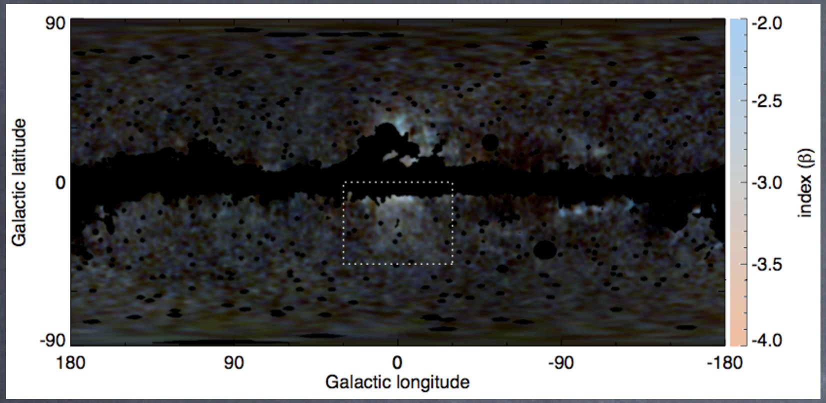
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0
-90
Galactic latitude
180
90
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-90
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Galactic longitude
-2.0
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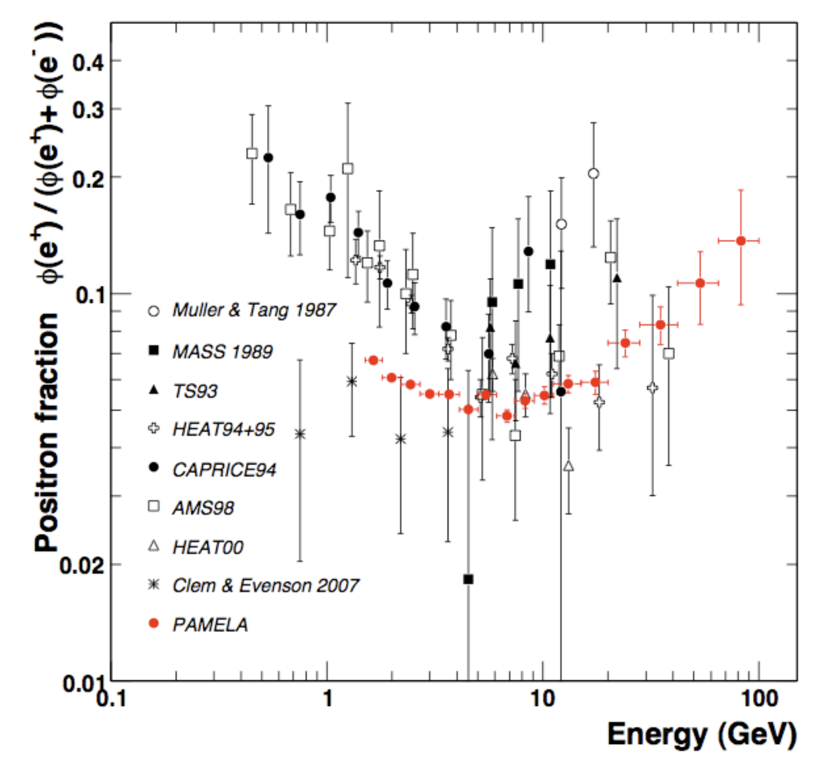
-4.0
index (β)


Positron fraction $\phi(e^+) / (\phi(e^+)+\phi(e^-))$
0.4
0.3
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0.1
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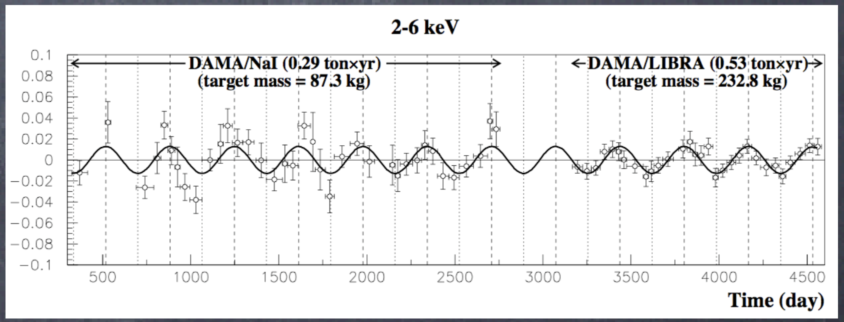
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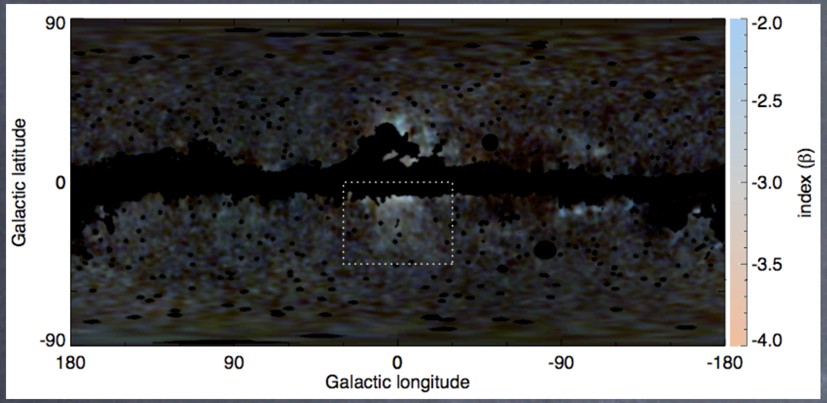
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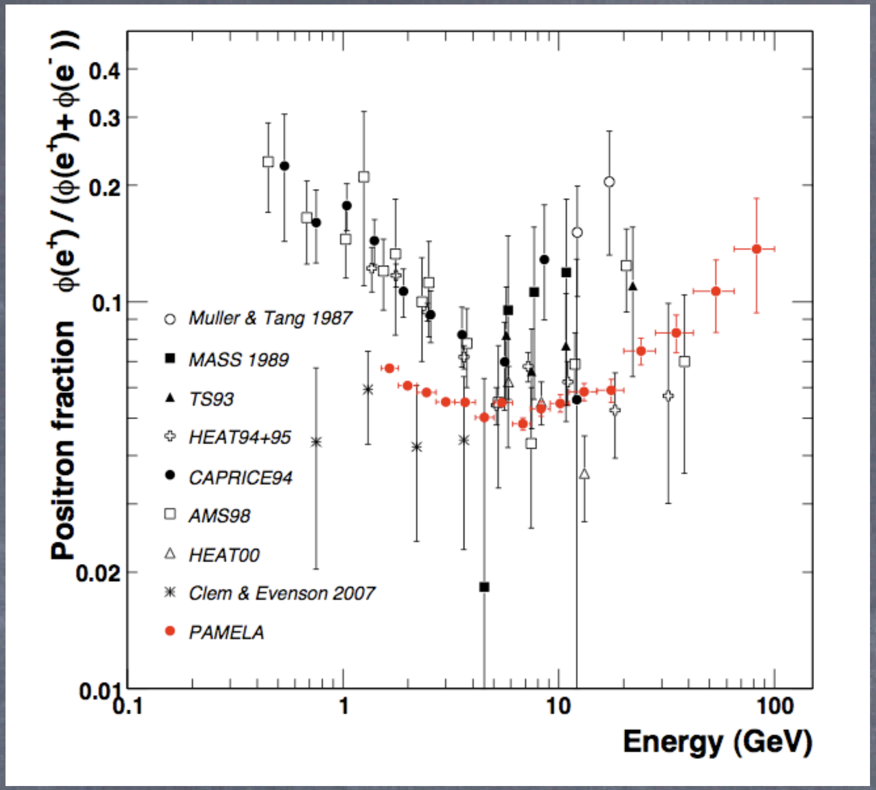
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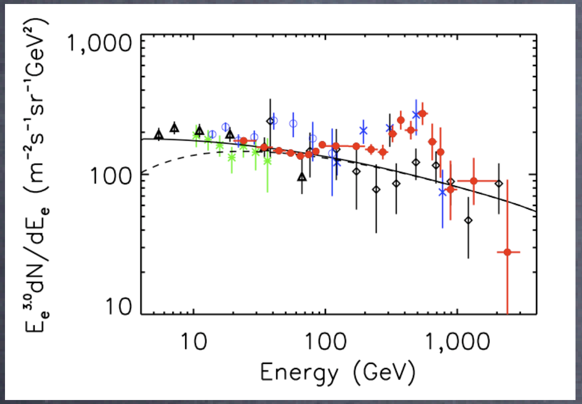
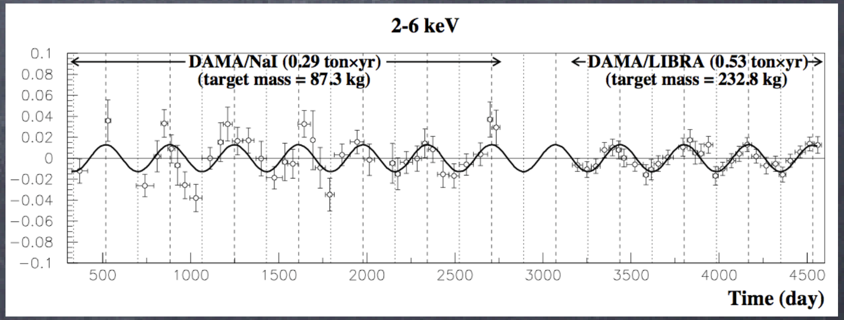

E_e^3.0 dN/dE_e (m⁻²s⁻¹sr⁻¹GeV²)
1,000
100
10
10
100
1,000
Energy (GeV)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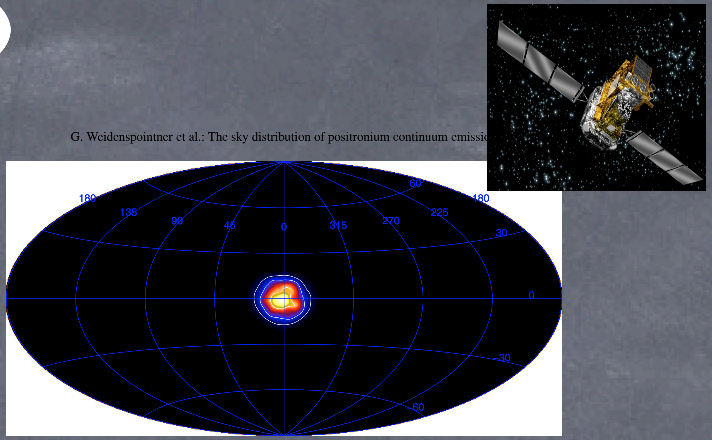
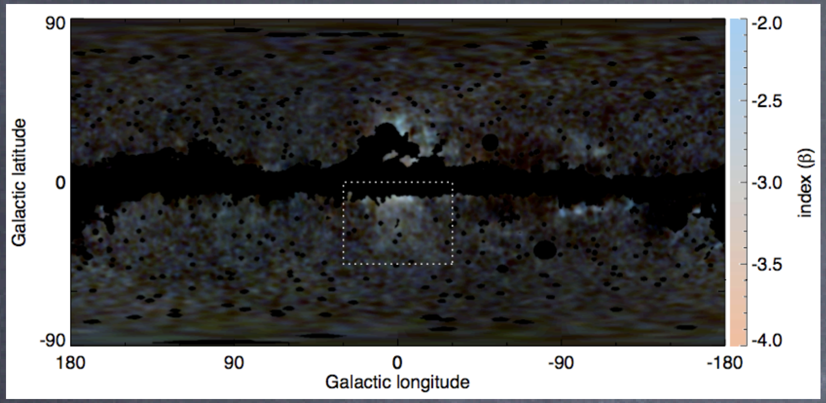
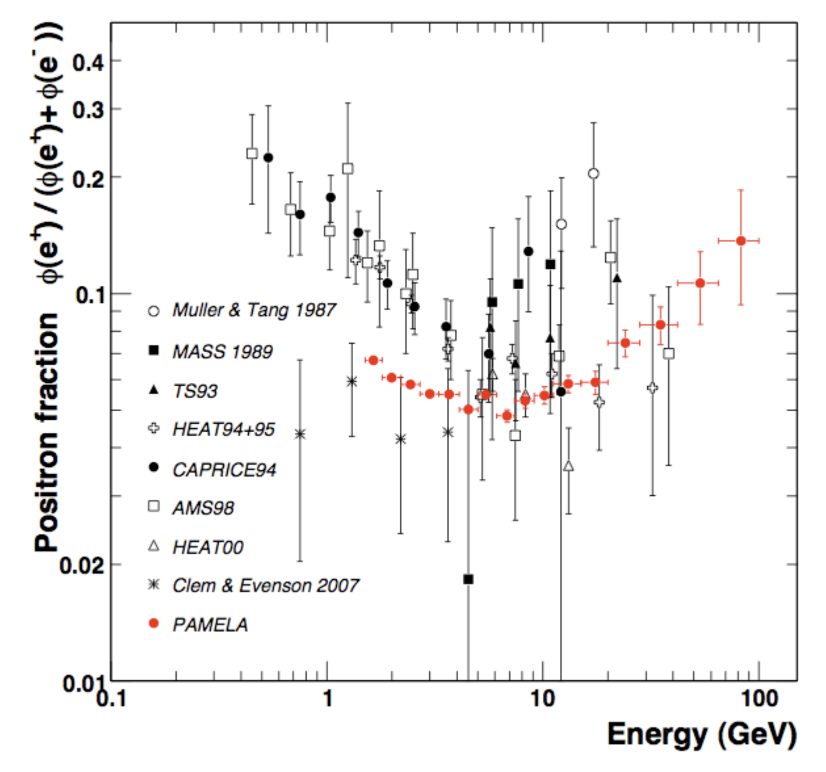
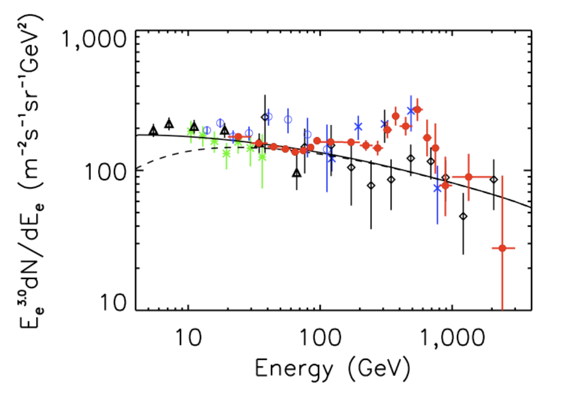
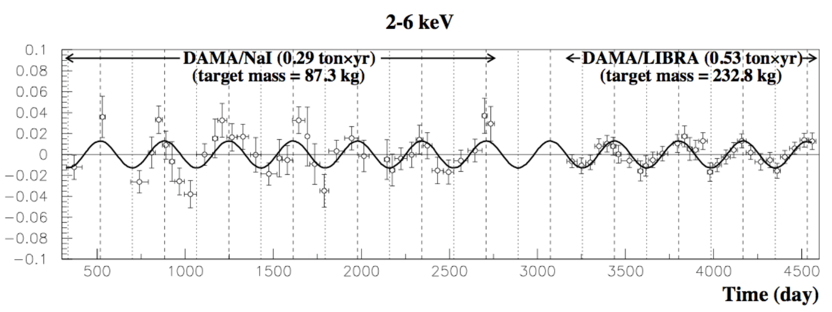

G. Weidenspointner et al.: The sky distribution of positronium continuum emissi









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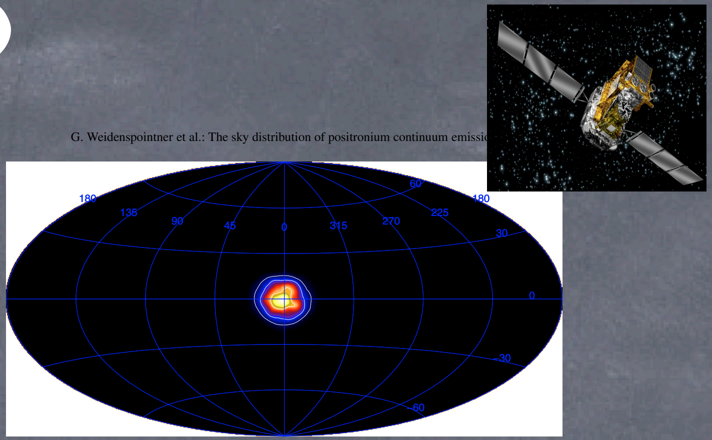
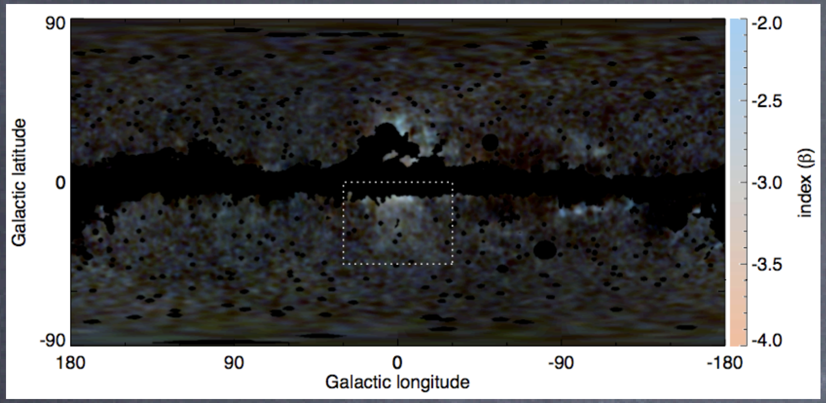

G. Weidenspointner et al.: The sky distribution of positronium continuum emissio
180
135
90
45
0
315
270
225
180
60
30
0
−30
−60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Galactic latitude
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Galactic longitude
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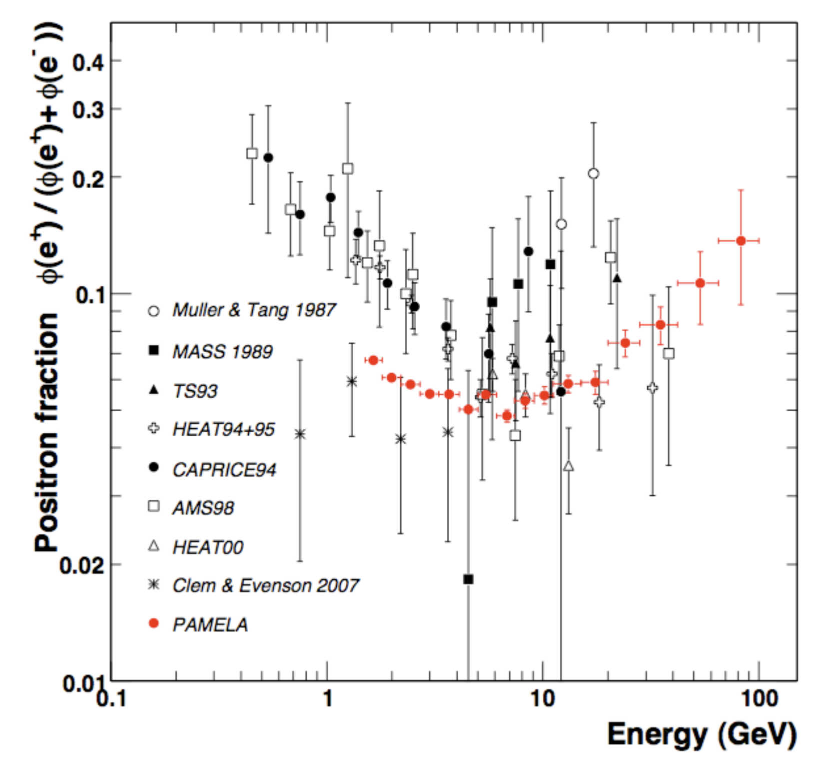
-3.5
-4.0
index (β)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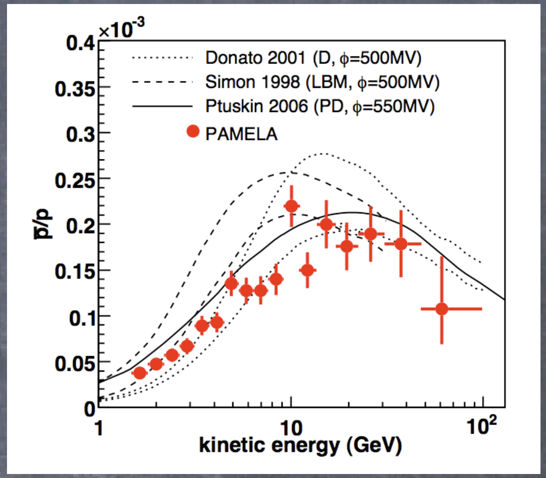
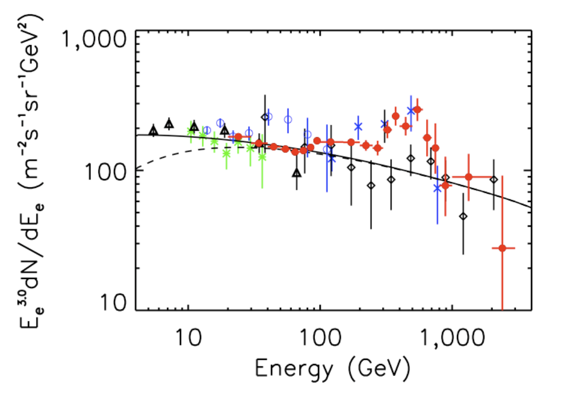

×10⁻³
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
p̄/p
1
10
10²
kinetic energy (GeV)
Donato 2001 (D, φ=500MV)
Simon 1998 (LBM, φ=500MV)
Ptuskin 2006 (PD, φ=550MV)
PAMELA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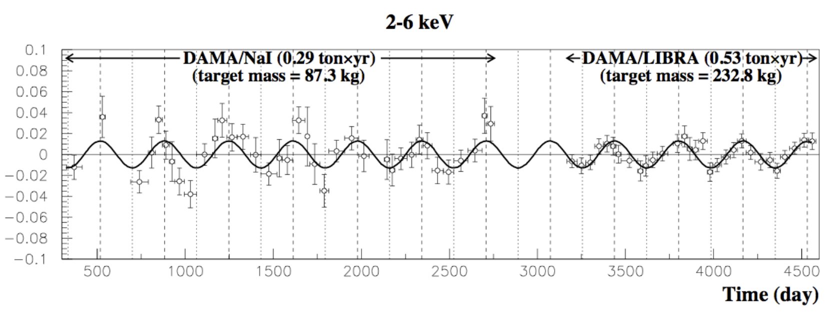
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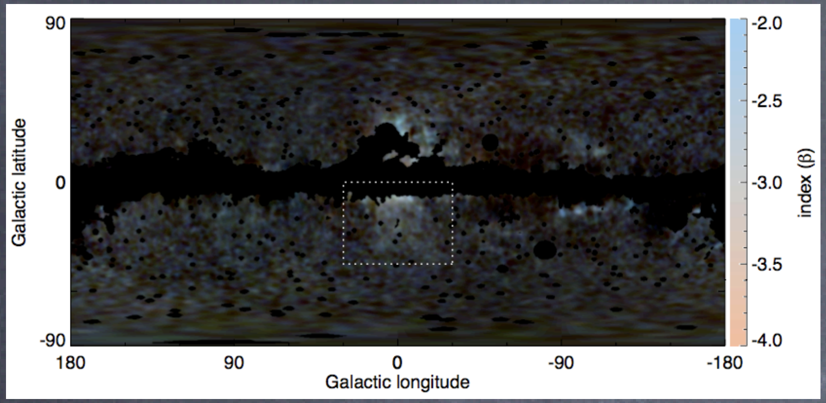

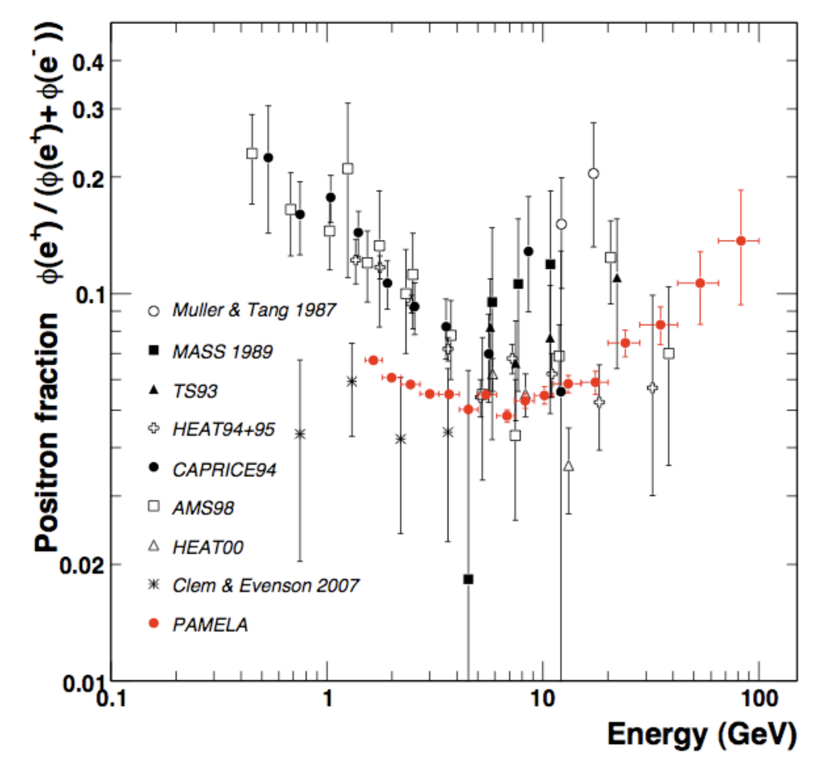

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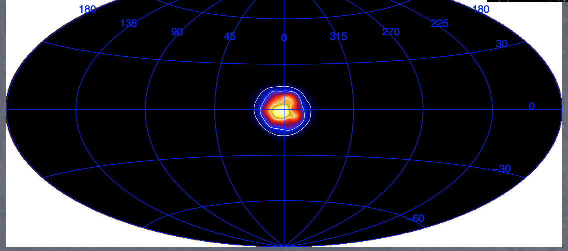

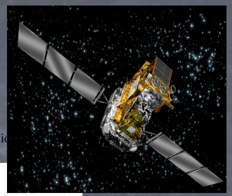

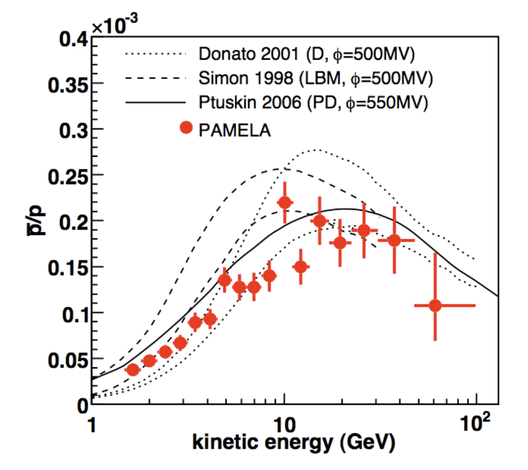

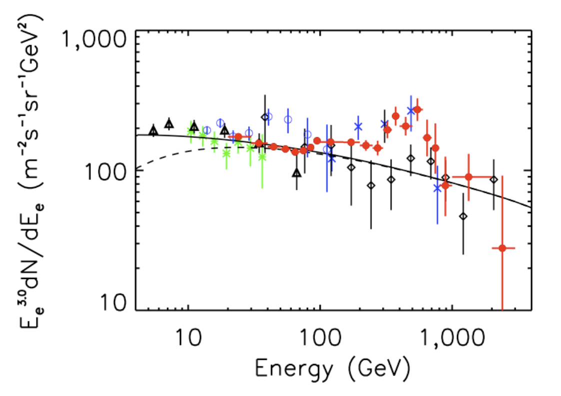

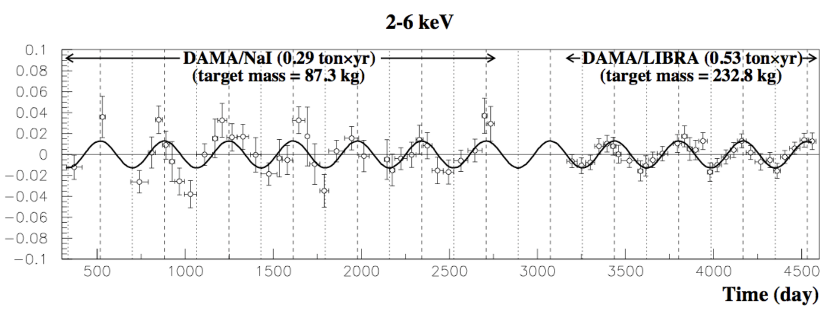

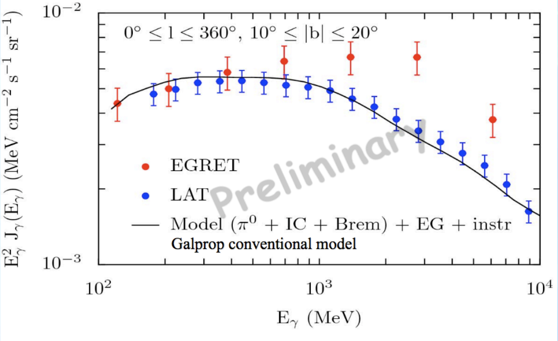

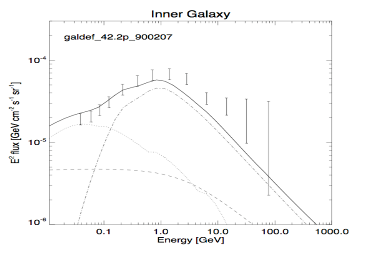

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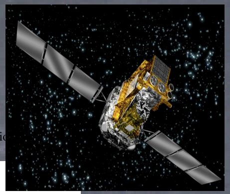
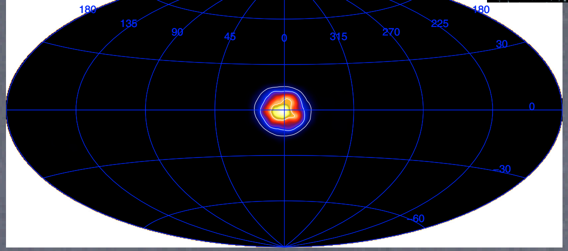
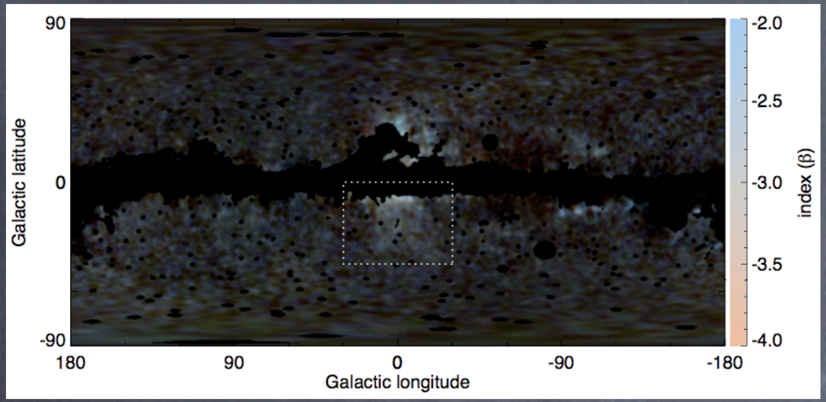
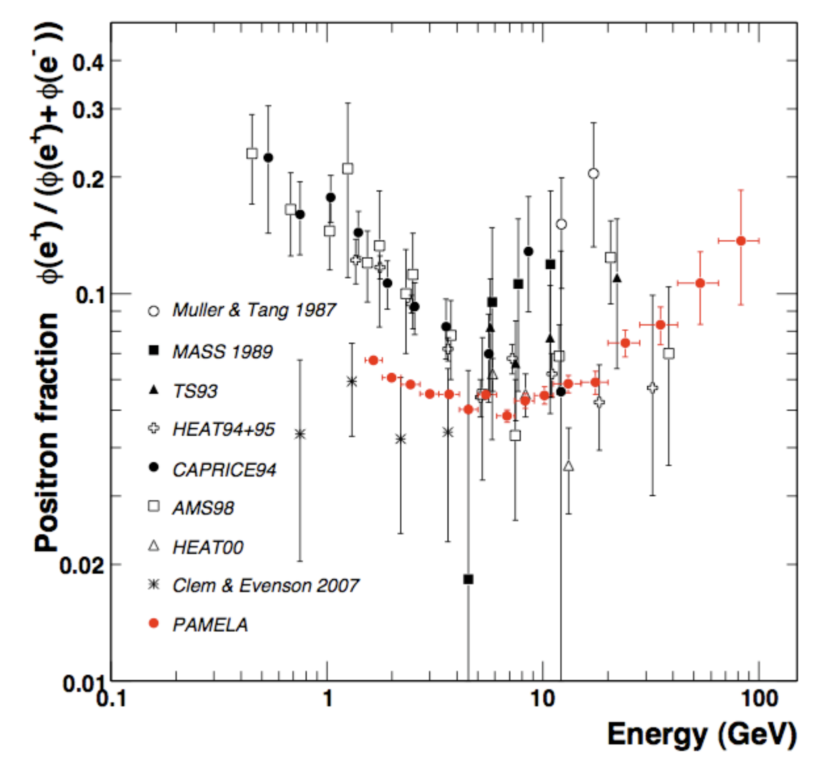
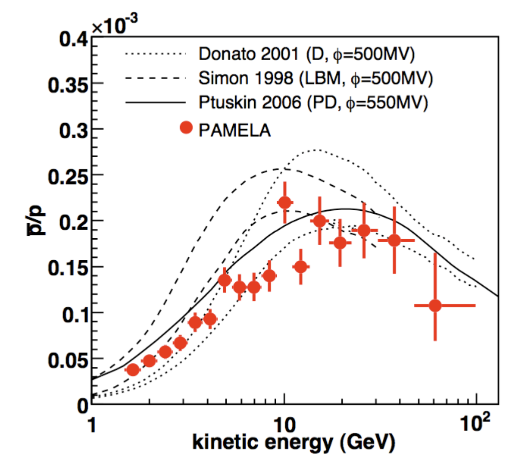
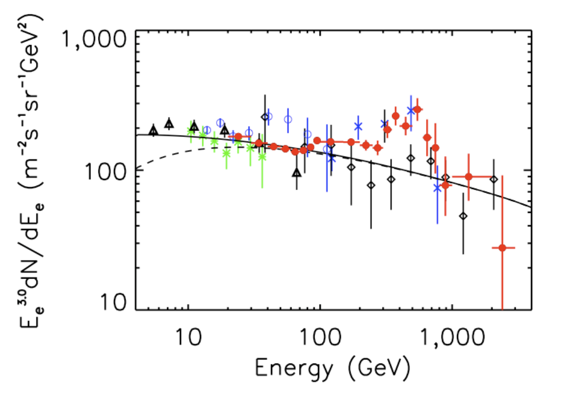




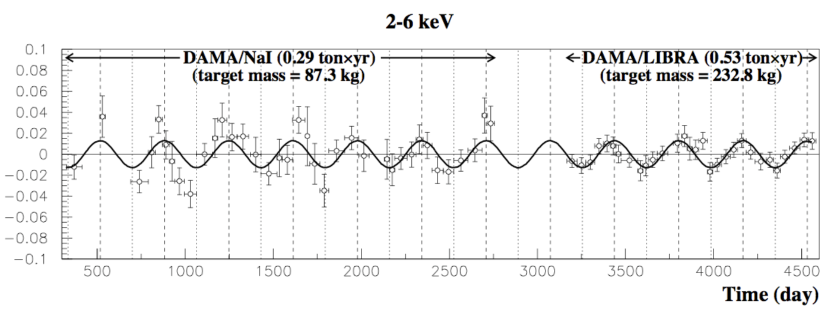


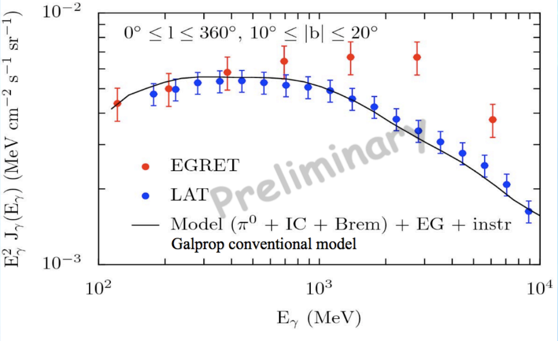


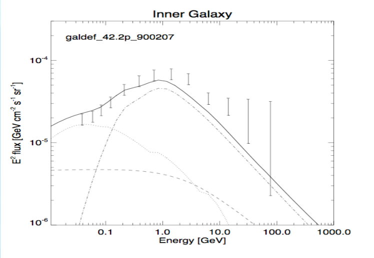




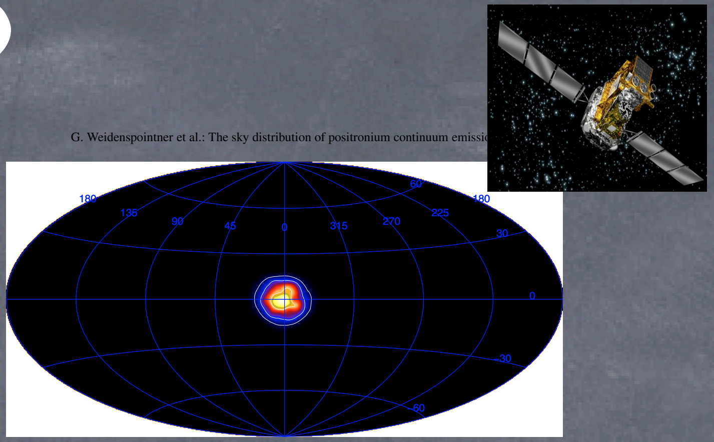
Indications of high energy electron or positron production

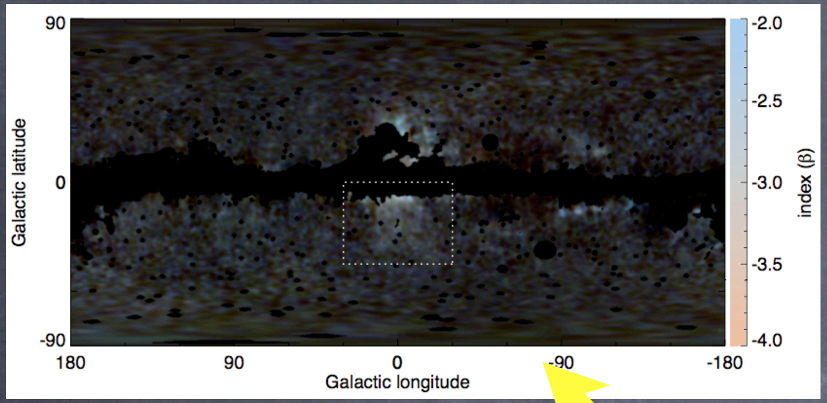


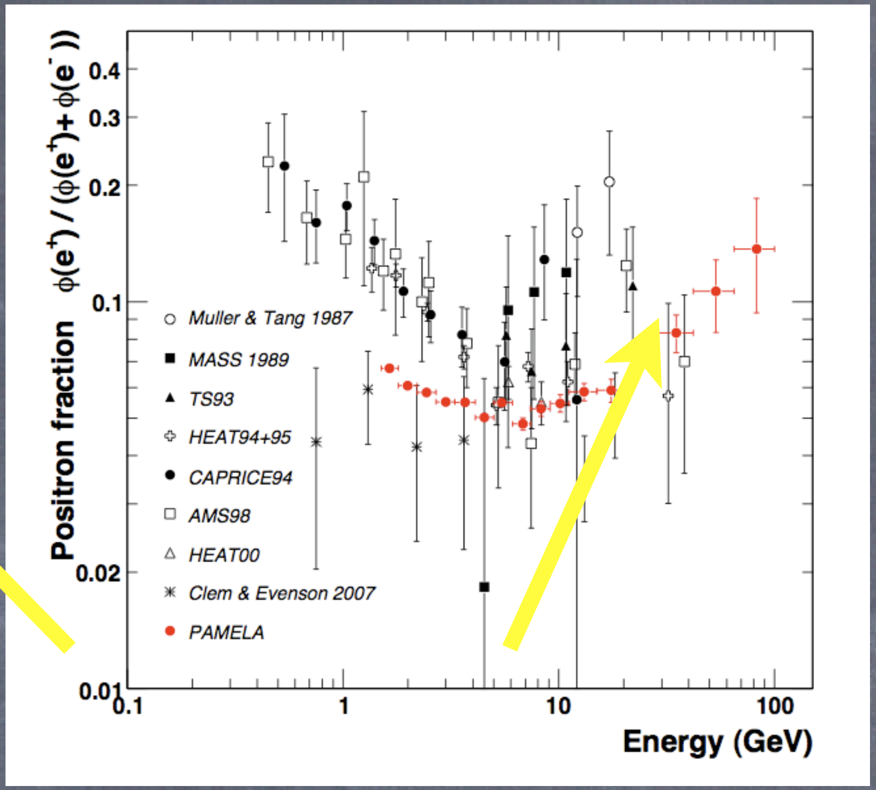


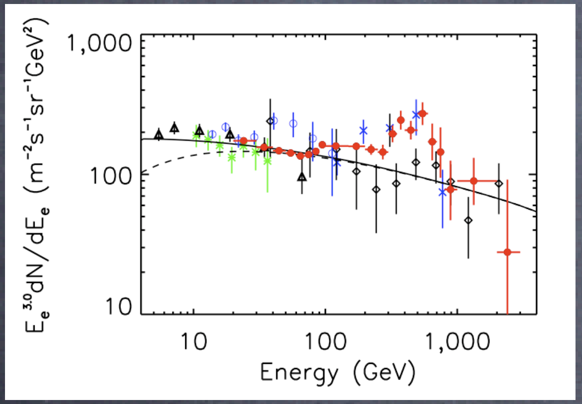


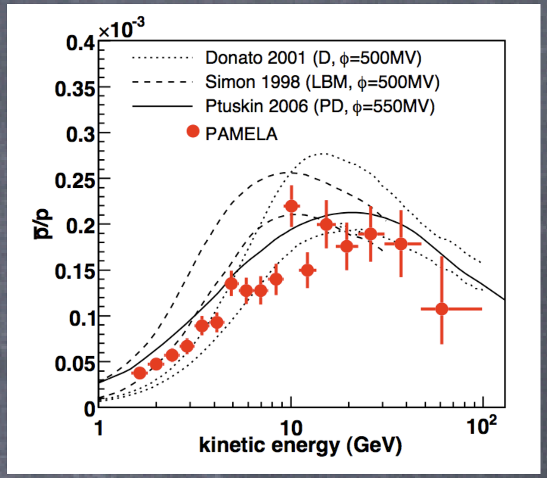
What hints?



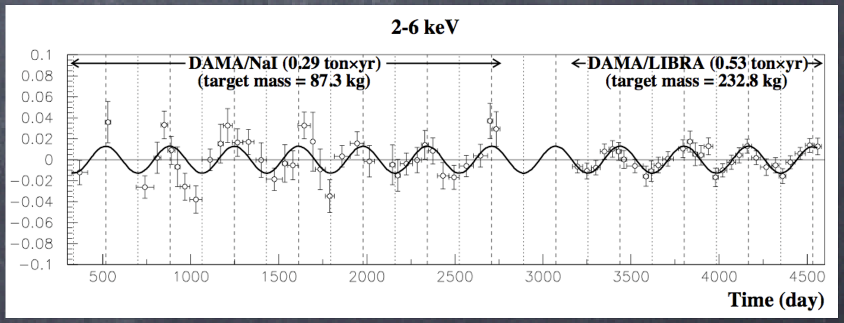


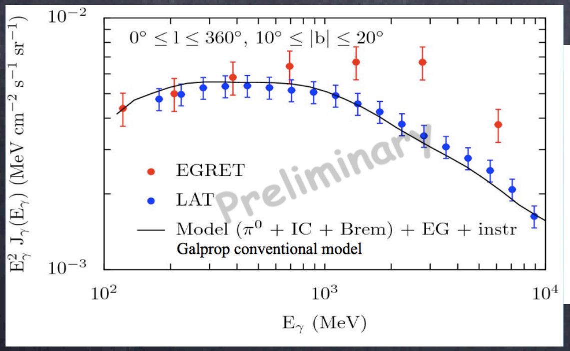


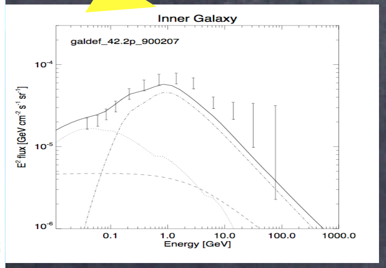




Indications of high energy electron or positron production







Hints of high energy e^+e^-

- PAMELA tells us that there is a primary source of 10-100 GeV positrons within 1kpc
- The WMAP Haze suggests us that there is a new population of 10-100 GeV positrons in the galactic center (5°-15°)
- ATIC indicates an excess of e^+e^- at 400-700GeV
- EGRET does allows for an excess of ICS photons from the galactic center

WIMP annihilations? Not so fast!

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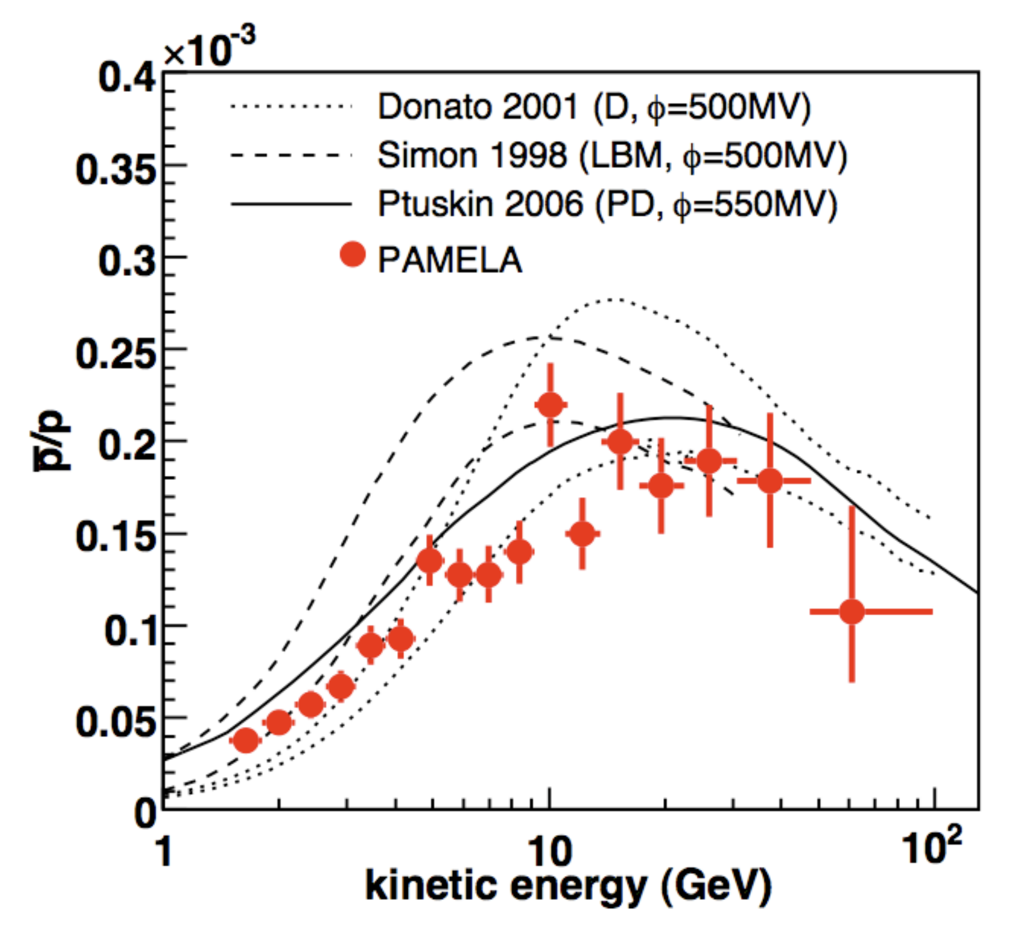

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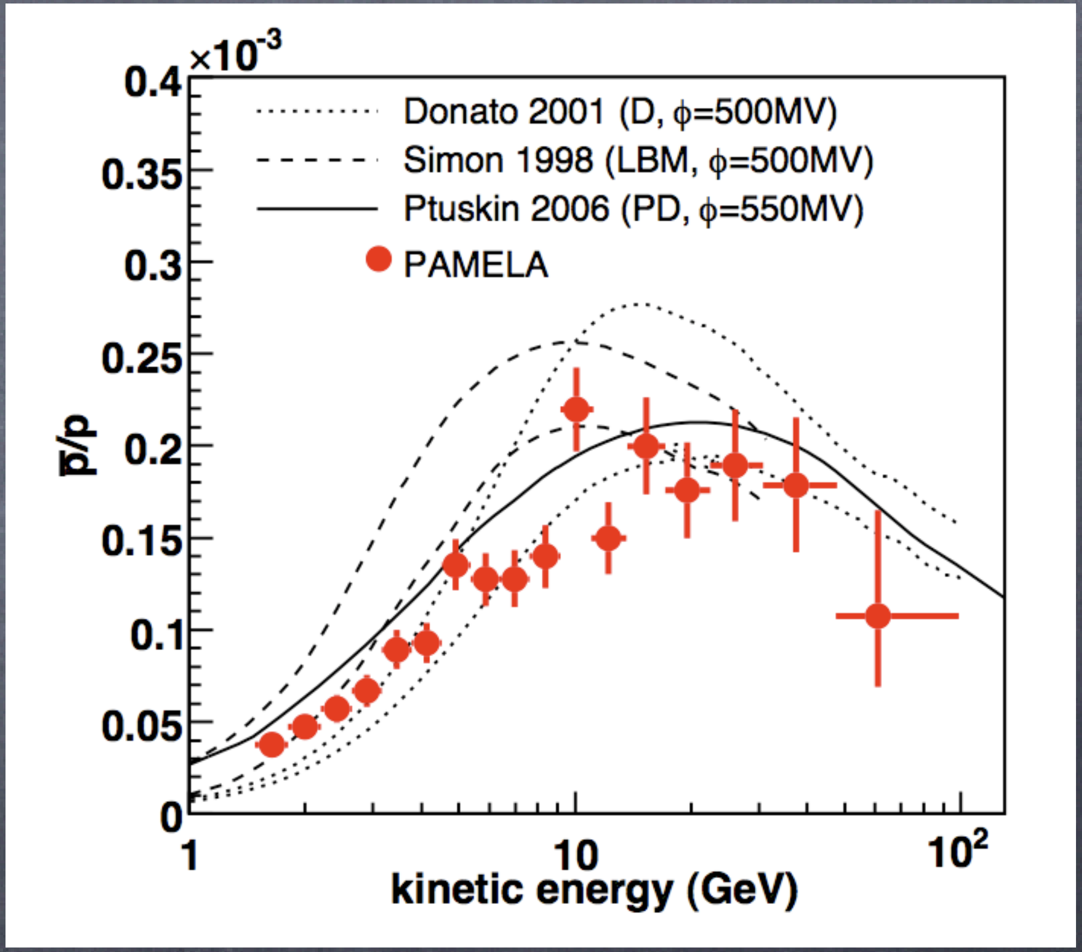

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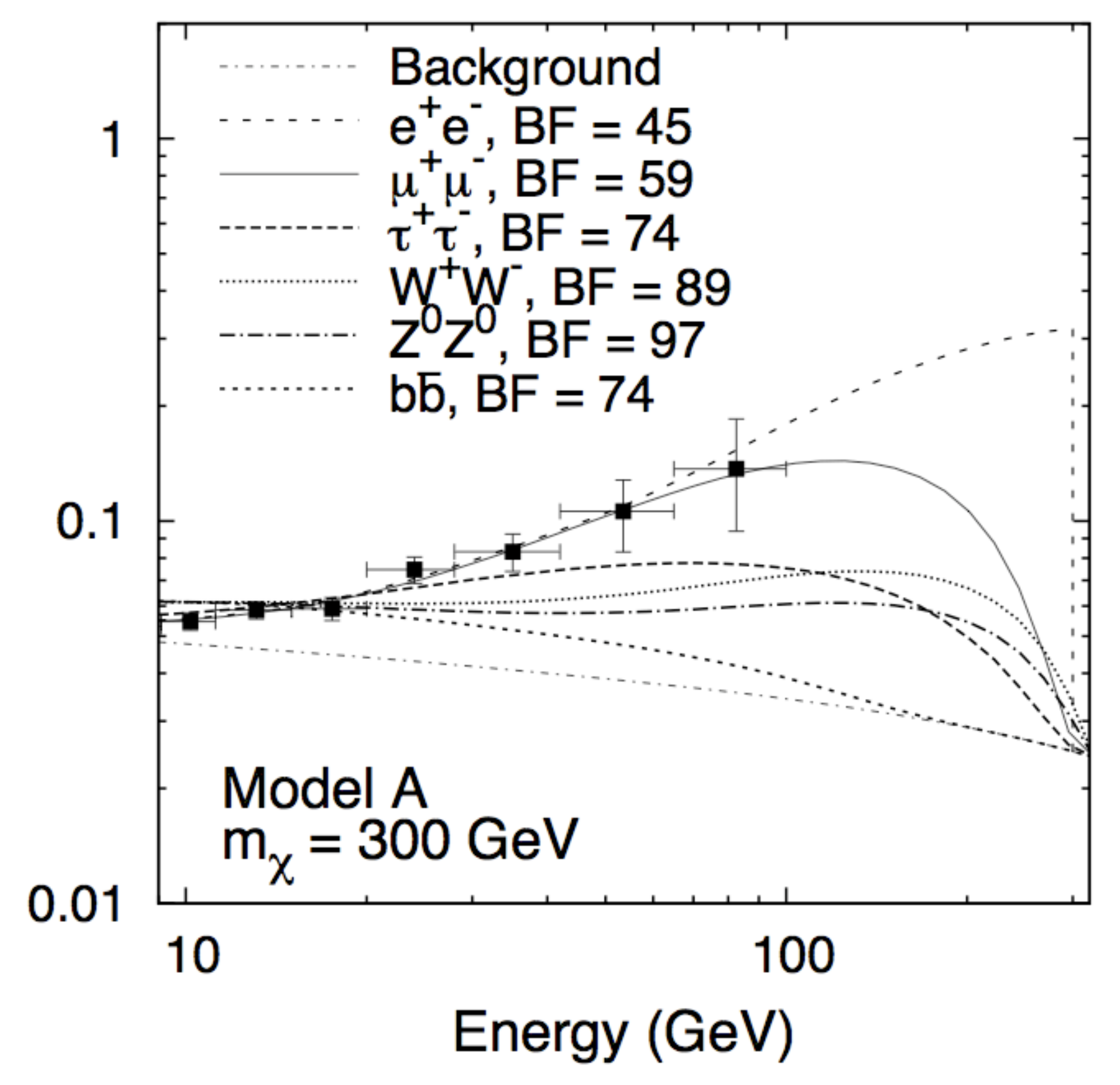

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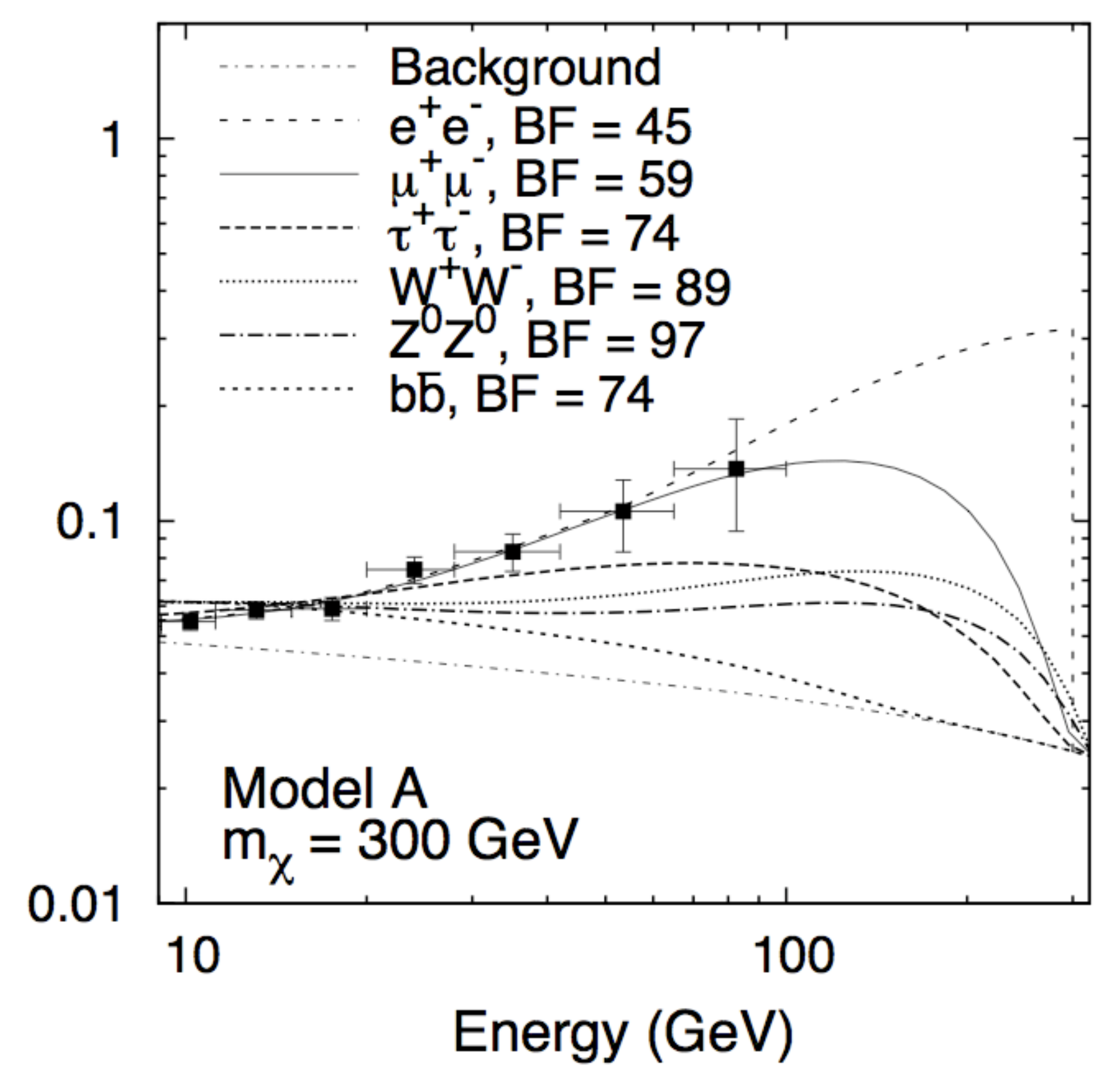

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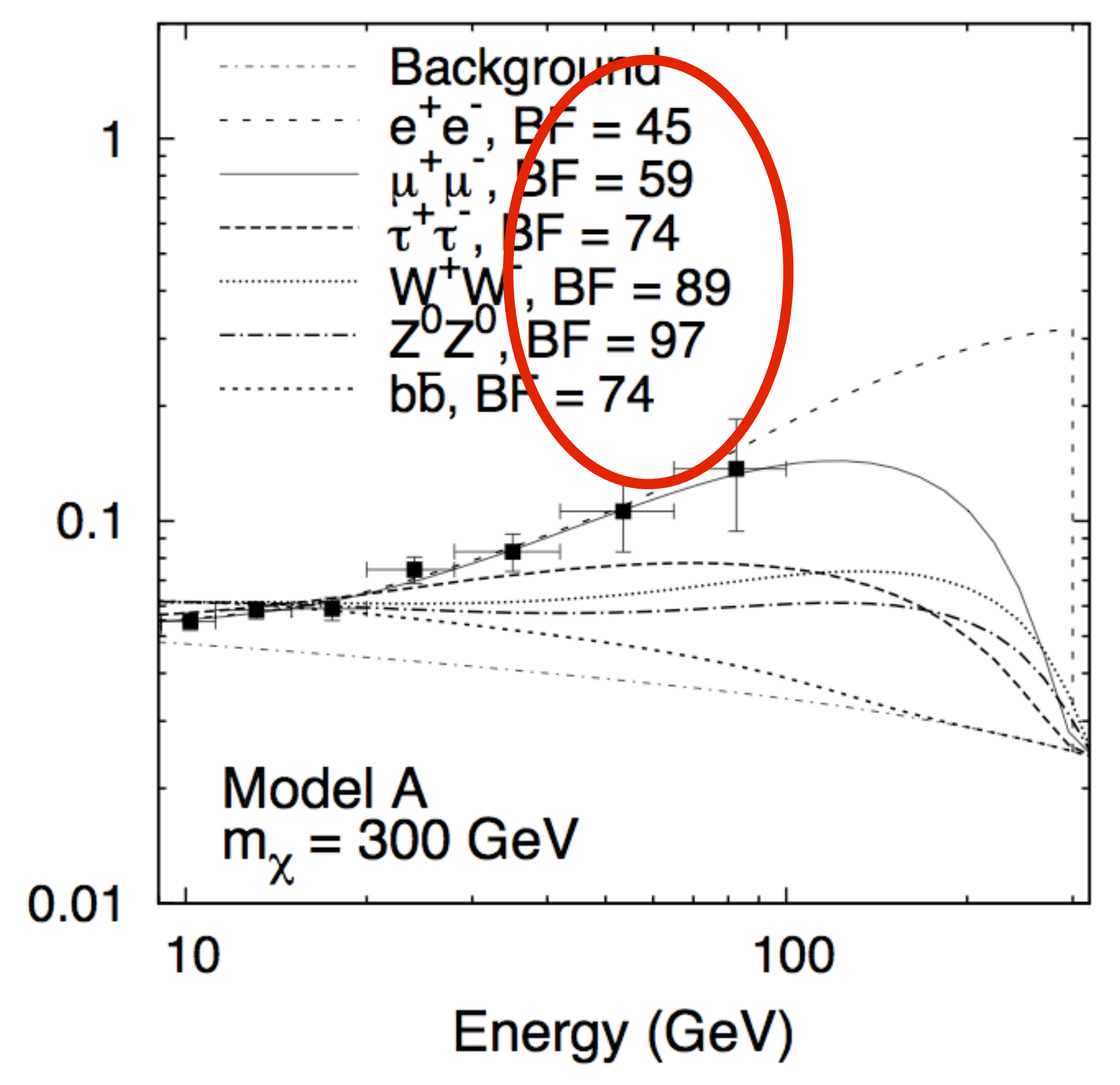

The three ingredients to explain PAMELA*

*Dark matter could also decay instead of annihilating

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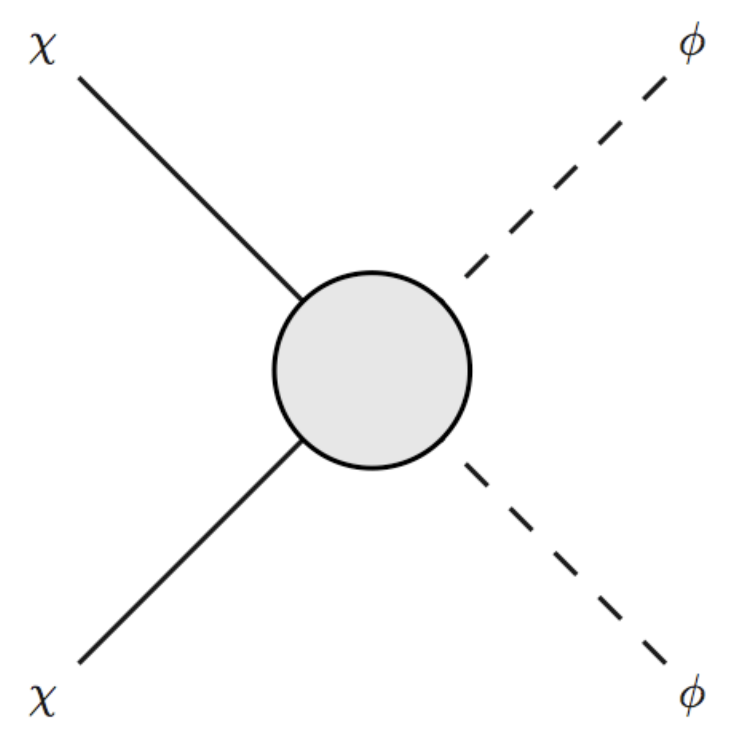
- Other possibilities with similar structure [e.g., gauge boson coupled to lepton number (Fox and Poppitz '08), axion (Nomura and Thaler '08)] have similar pheno

New forces = new annihilation modes



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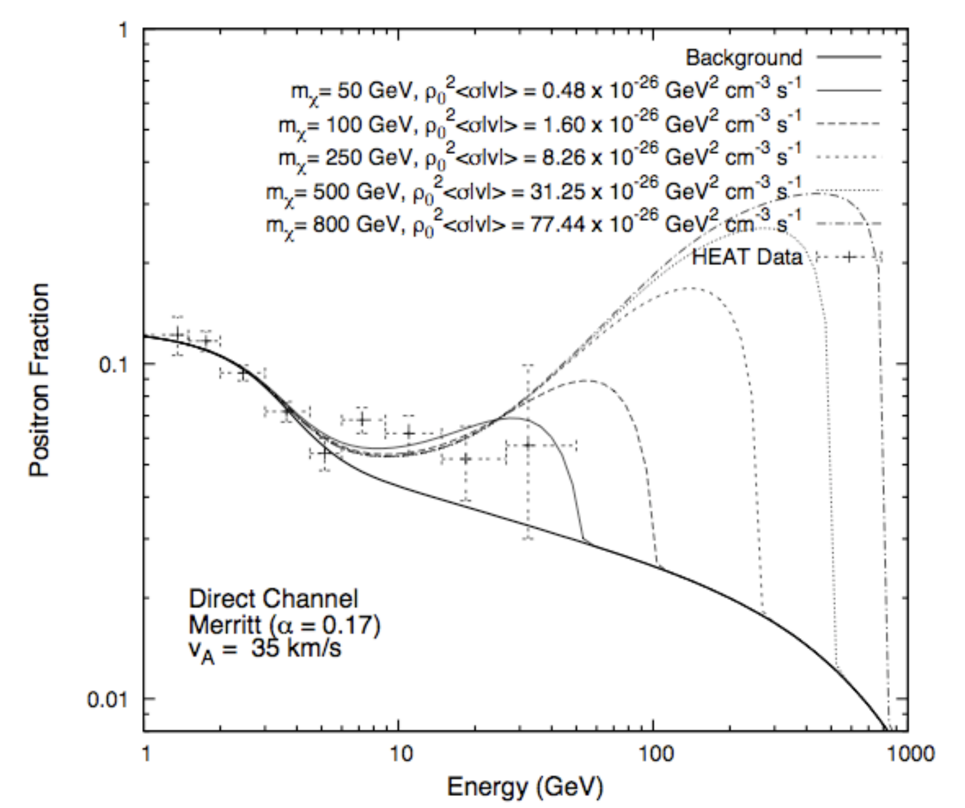

(c)Direct decay channel, v_A = 35 km/s

Cholis, Goodenough, NW, arxiv:0802.2922

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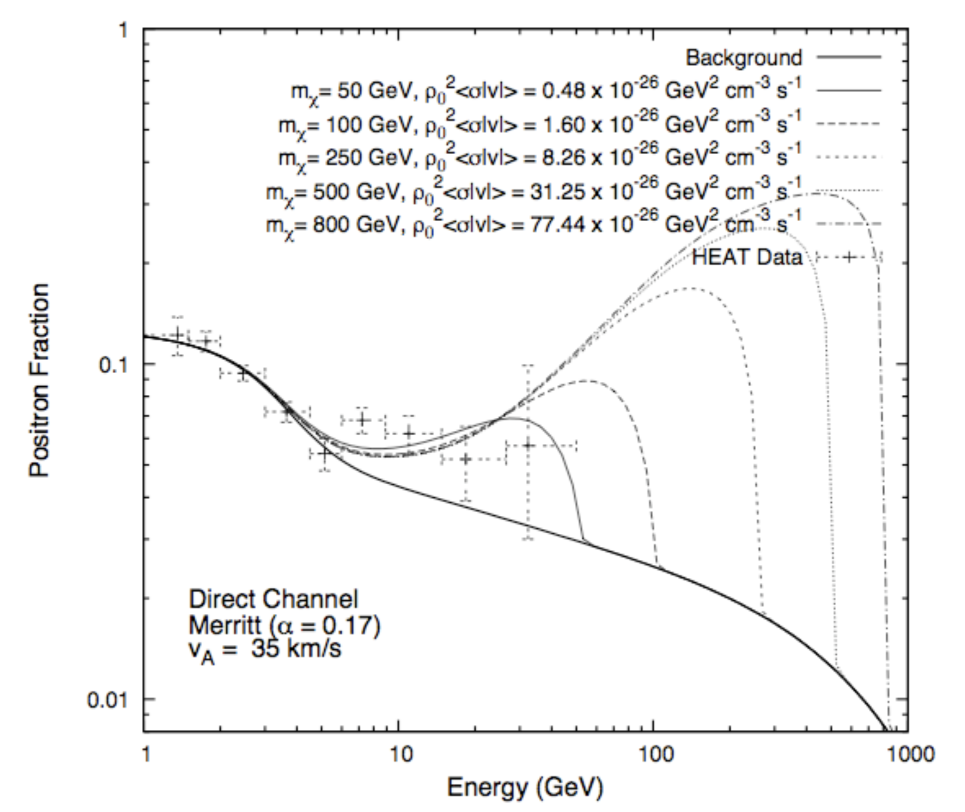

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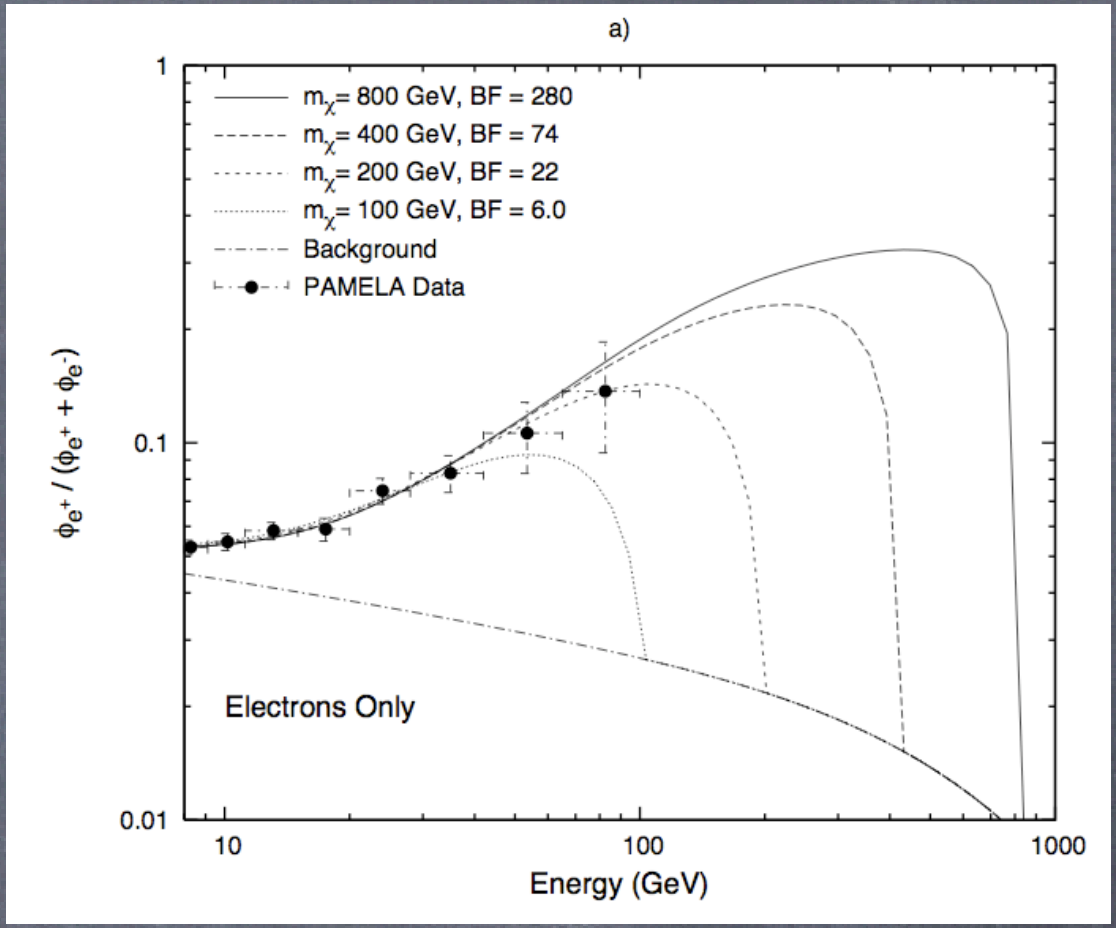

Cholis, et al, arxiv:0810.5344

Pre-PAMELA

Post-PAMELA

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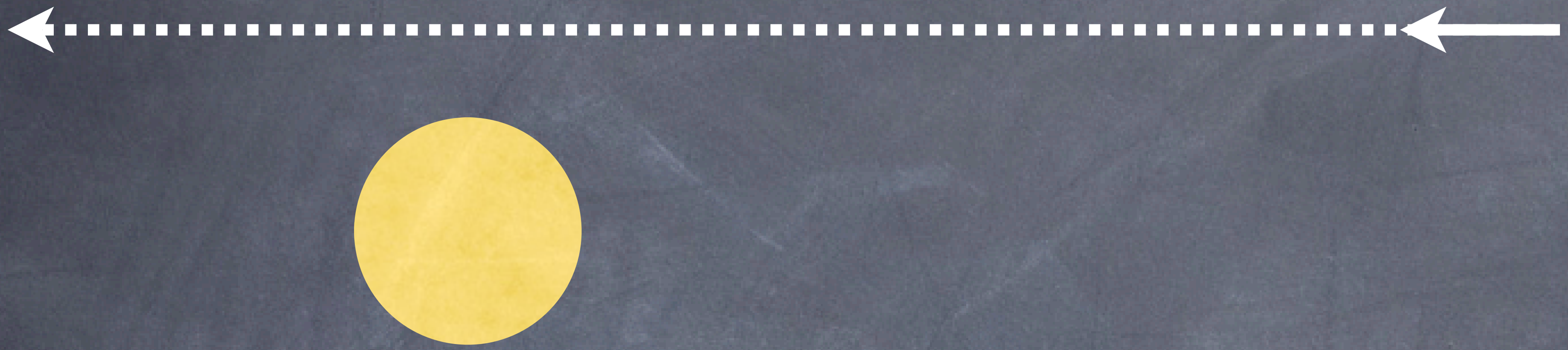
A cross section conundrum

- If the cross section were high enough to yield PAMELA/ATIC/Haze, DM would be depleted in the early universe

Sommerfeld Enhancement

High velocity



Arkani-Hamed, Finkbeiner, Slatyer, NW, '08

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$$\sigma = \sigma_0 \left(1 + \frac{v_{esc}^2}{v^2} \right)$$

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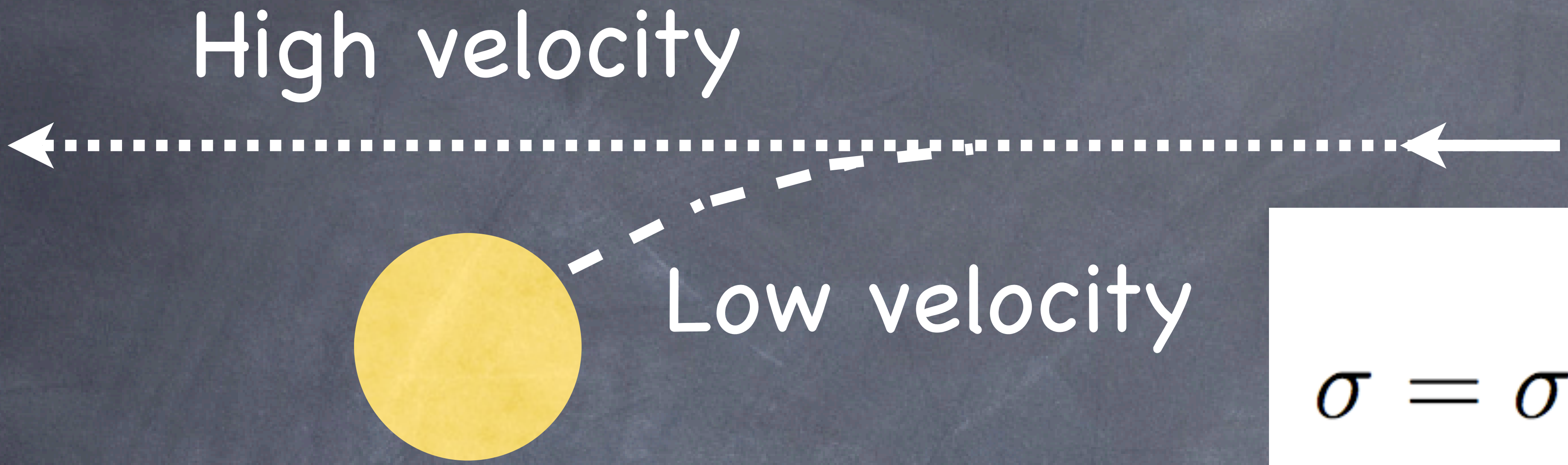

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If these signals arise from thermal dark matter, dark matter must have a long range force

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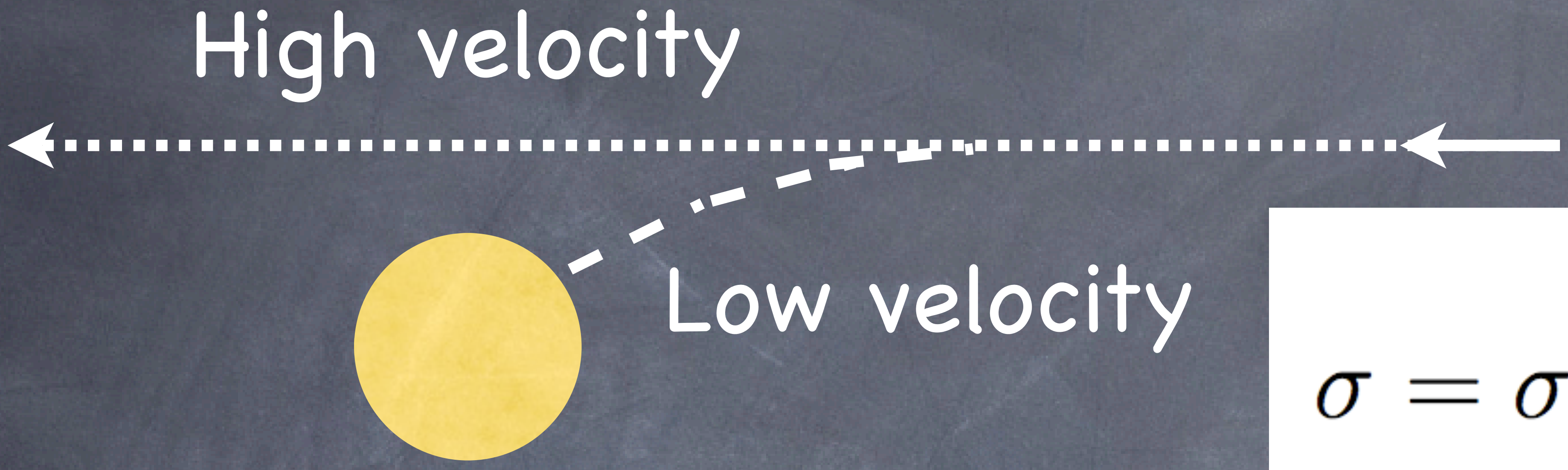

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$$m_\phi^{-1} \gtrsim (\alpha M_{DM})^{-1}$$

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PAMELA and the Haze

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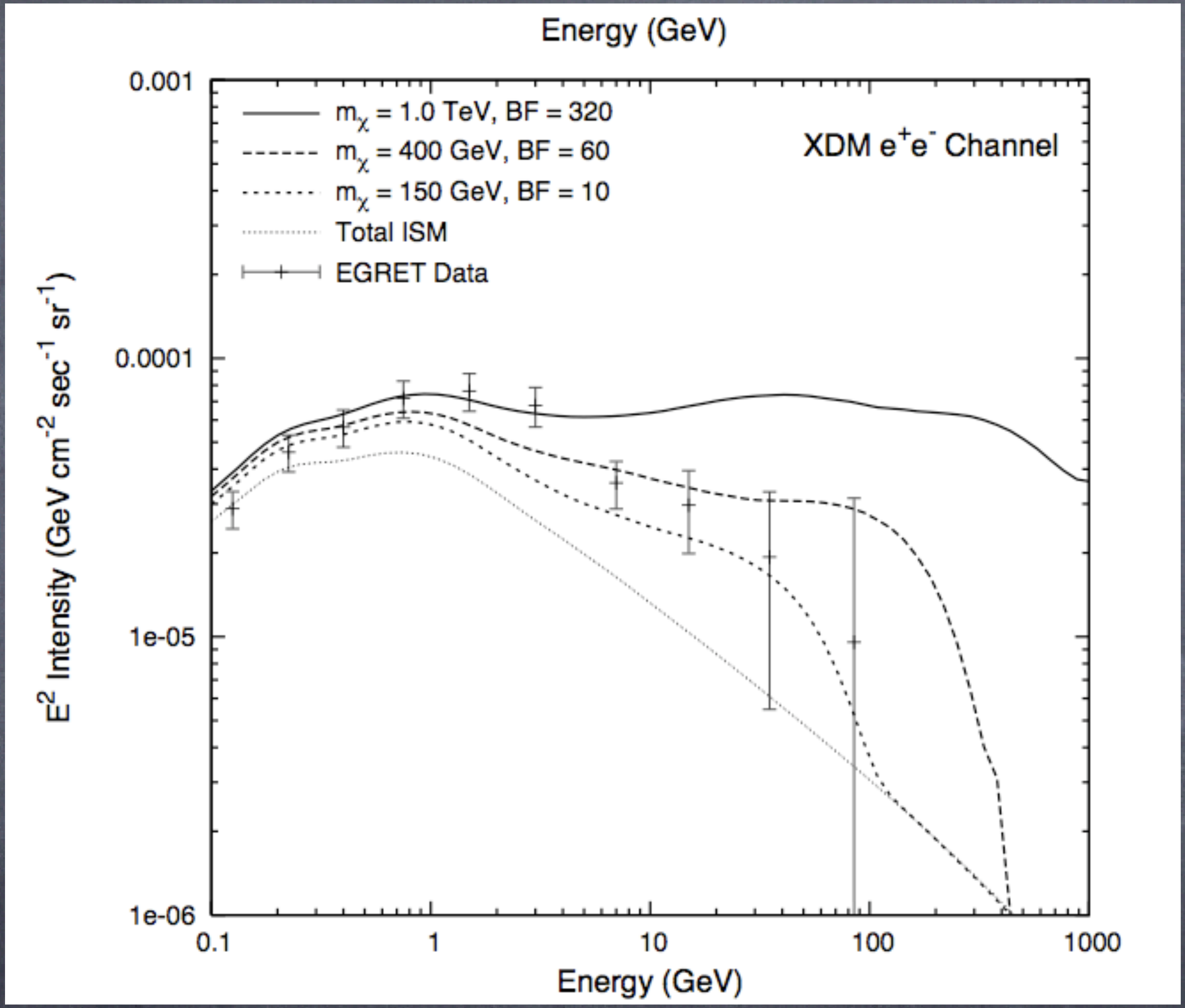
- These particles would synchrotron radiate in the 22-90 GHz range
- This is precisely the original interpretation of the Haze (Finkbeiner, astro-ph/0409027)
- Essentially any annihilating DM model that explains PAMELA will naturally explain the Haze as well

Fermi/GLAST Signals

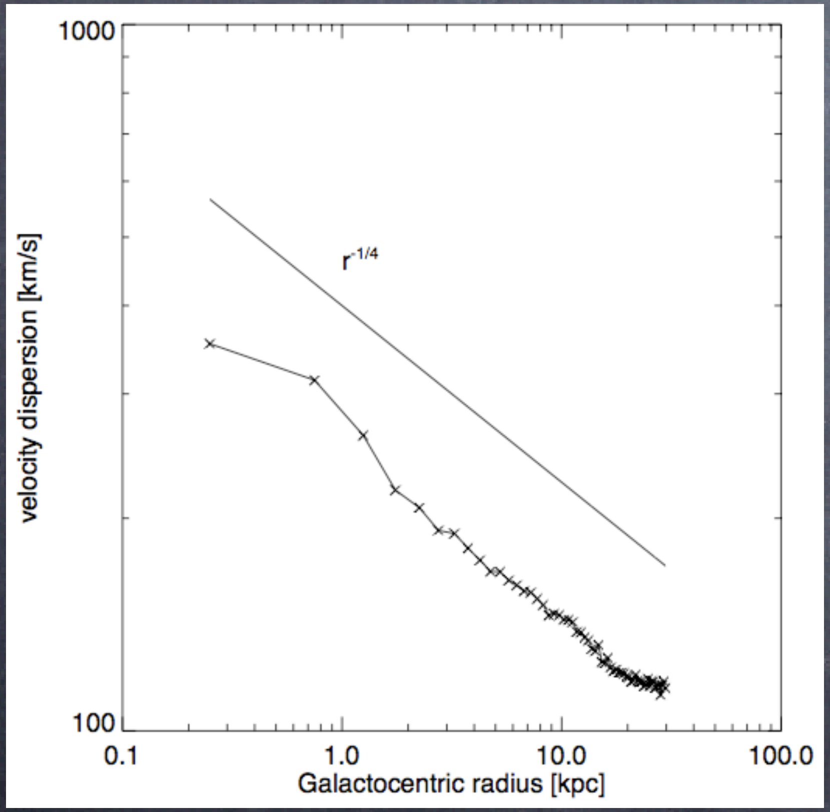


- Inverse-Compton Scatter photons in GC should be robust signature

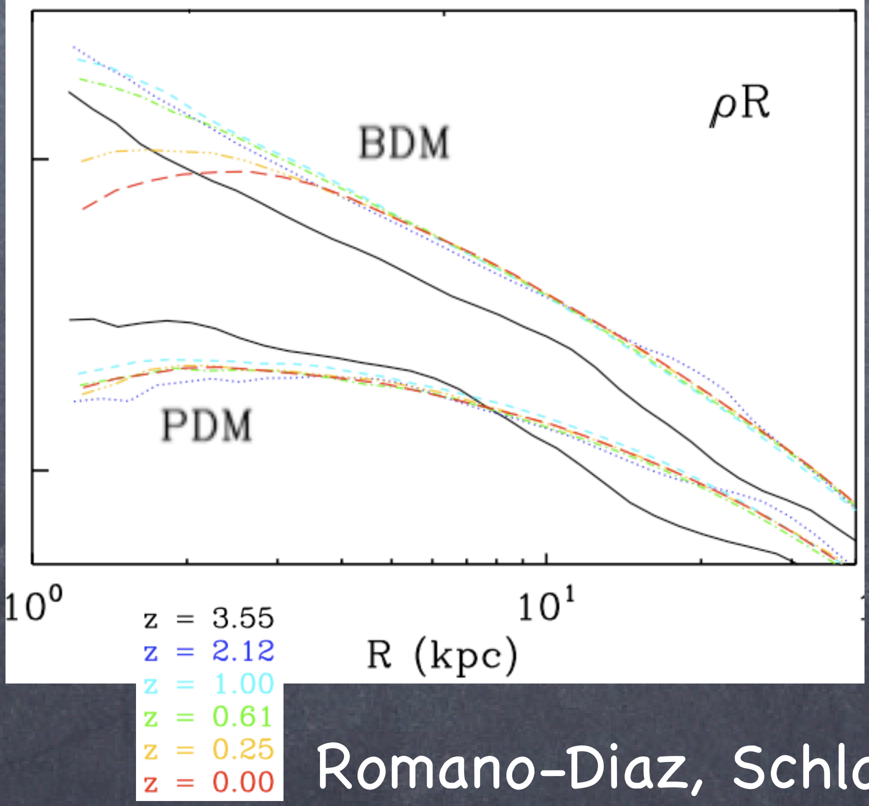
Limits from galactic center

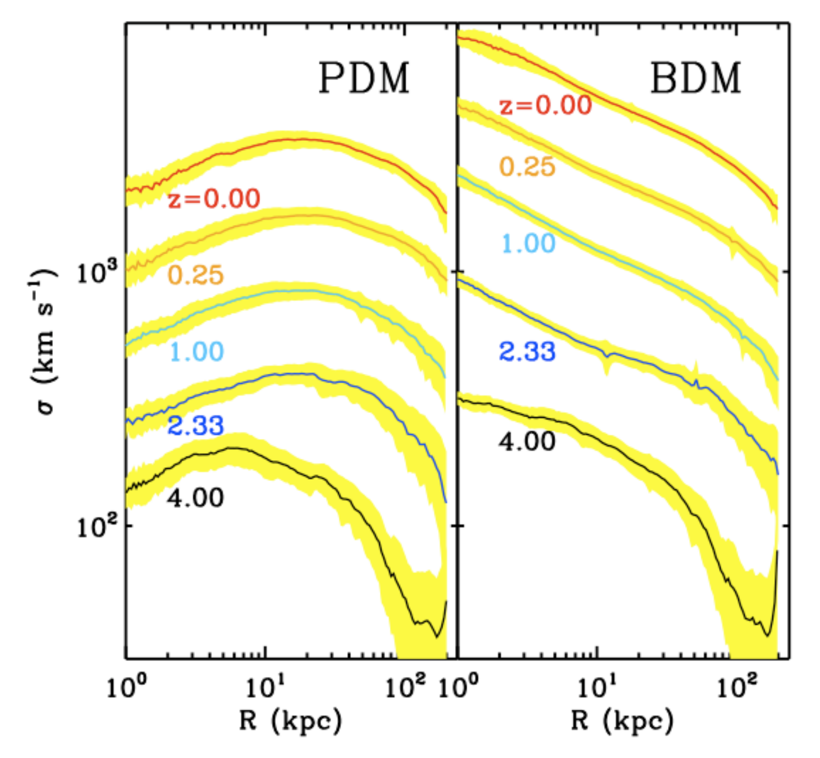
- Interesting limits from bremmed photons (Beacom, Bell, Bertone, '04; Bell & Jacques '08; Bertone, Cirelli, Strumia, Taoso, '08; Bergstrom, Bertone, Bringmann, Edsjo, Taoso, '08; Meade, Papucci, Volansky, '09; Mardon, Nomura, Stolarski, Thaler, '09)
  see talk by Tomer Volansky

- Limits rely on knowing density **and** velocity in GC - can change a lot with baryons!



Governato et al, 2006





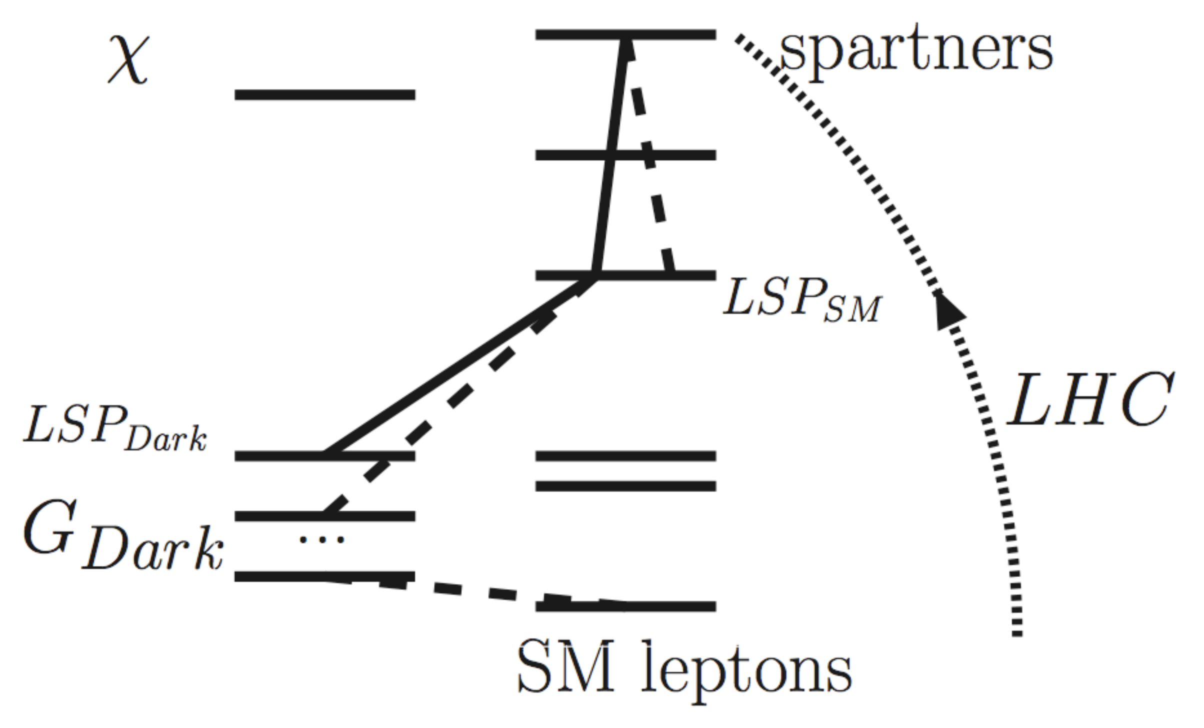
Romano-Diaz, Schlosman, Hoffman, Heller, '08

NB: **Many** simulation uncertainties (matching bulge with MW, other numerical issues involving baryons)

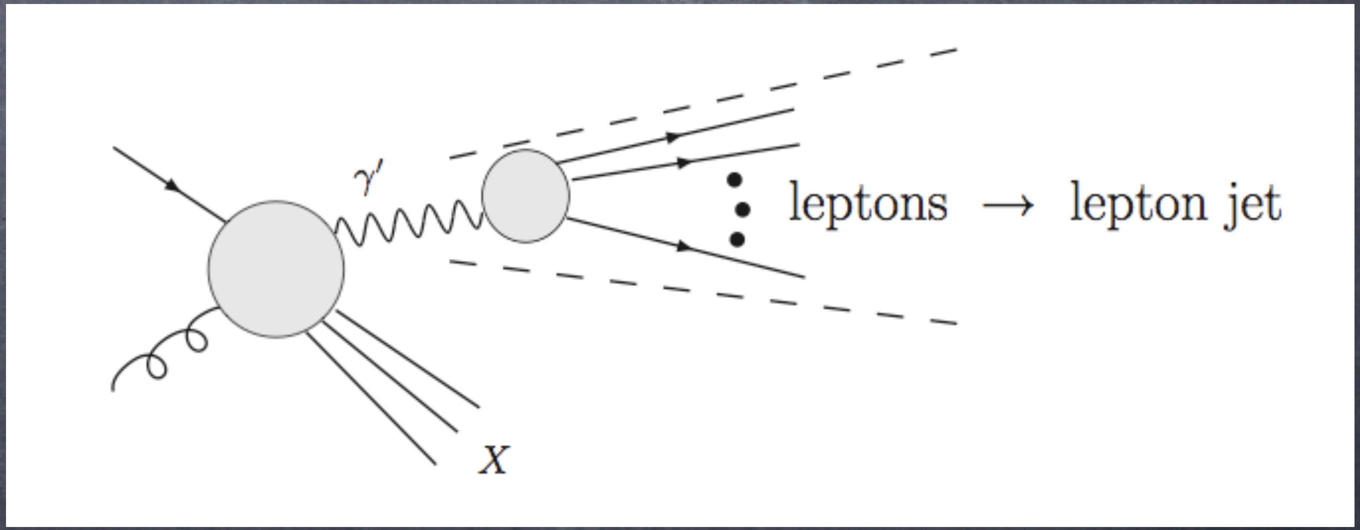
New Collider Pheno: Lepton Jets

- Production of G_{dark} states, yield boosted, highly collimated leptons

Arkani-Hamed, NW, '08; Baumgart, Cheung, Ruderman, Wang, Yavin, ` 09; Bai, Han `09



$$\tau \sim (\alpha\epsilon^2 m_{Z_{Dark}} N_{decaychannels})^{-1} \sim (\frac{10^{-7}}{\epsilon})^2 cm$$



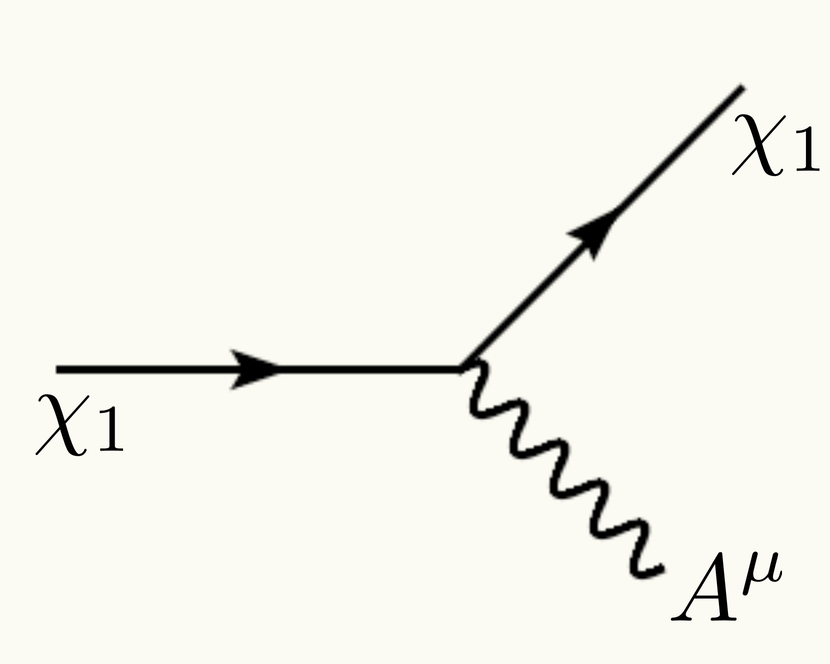
invariant mass ~GeV

See talk by Yang Bai

DAMA

Consider vector interaction

$\chi_1 \sigma_\mu \chi_1 A^\mu$



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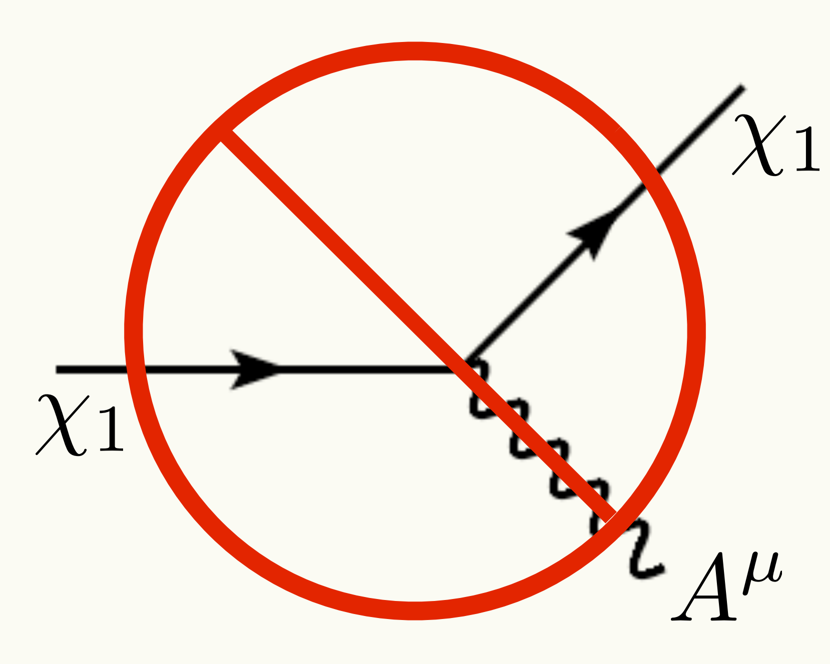

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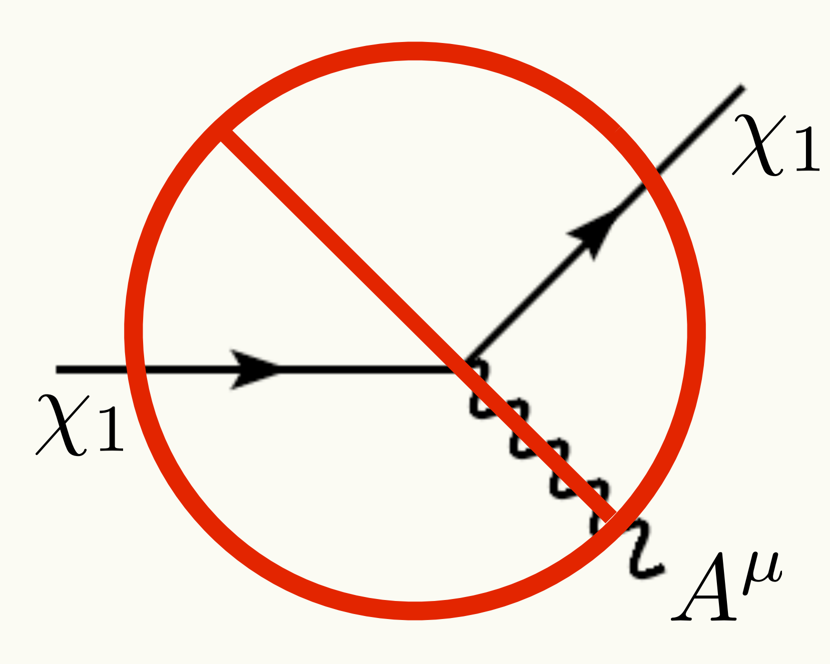

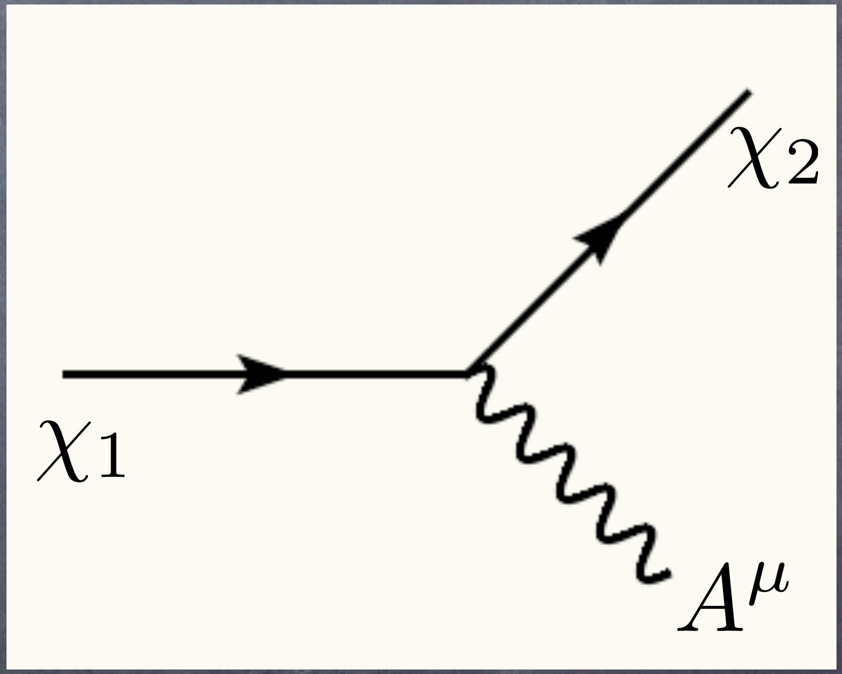

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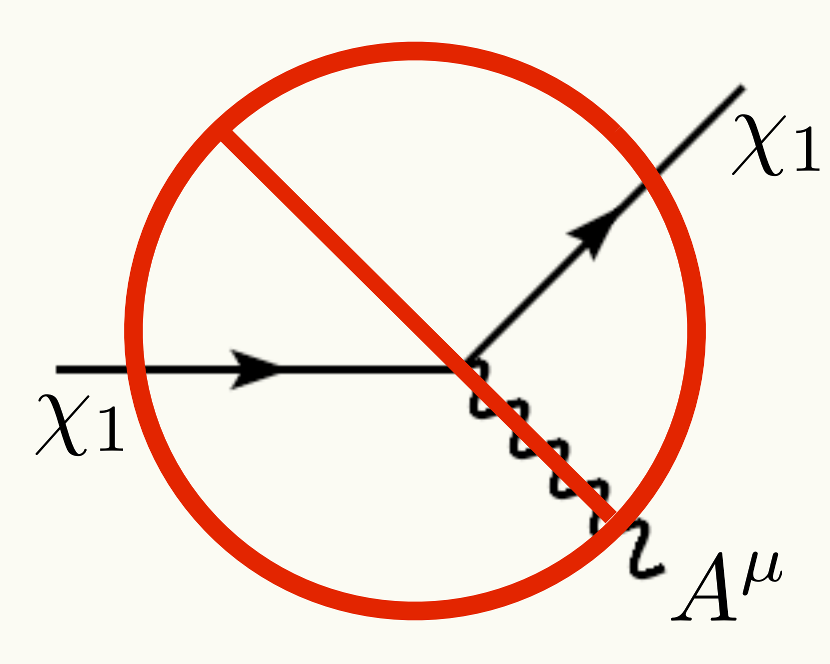
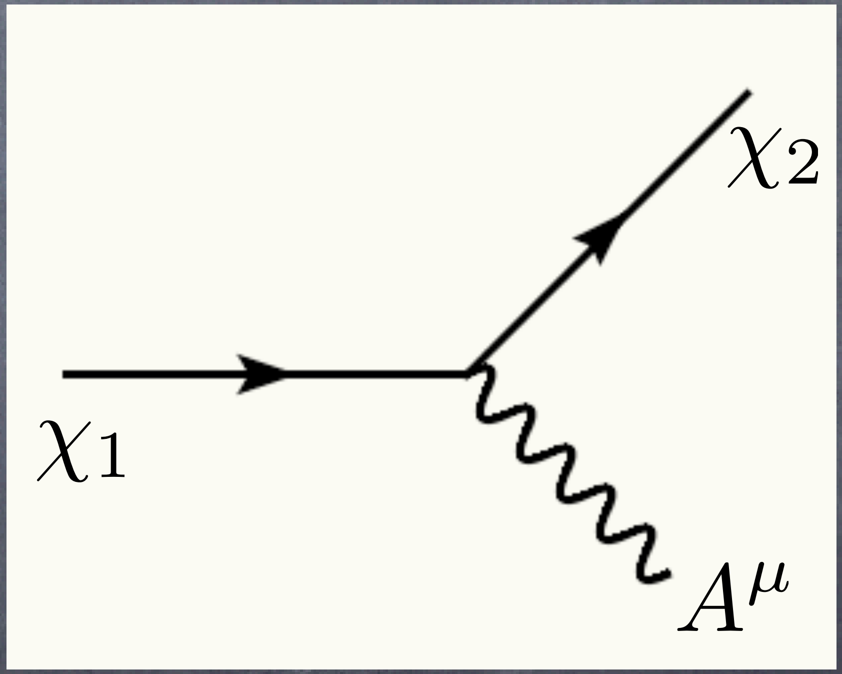
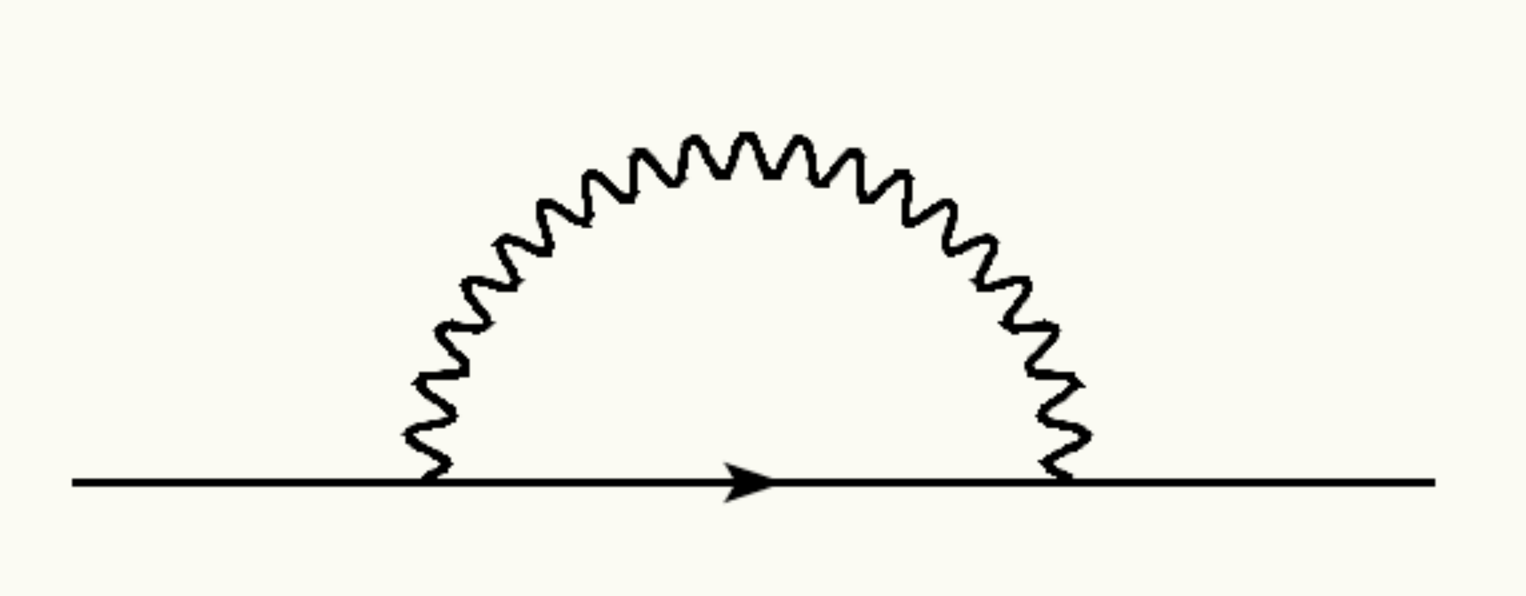




Vector interaction => multiple DM states; for Sommerfeld, these states must be kinematically accessible

$$m_\chi \frac{v^2}{2} \lesssim \delta$$

Natural scales of splittings



- If the force is a non-Abelian gauge symmetry, different dark matter states are split from one another

$$\delta \approx \alpha m_A \sim \mathrm{MeV}$$

For SE **require** $\delta \overset{\sim}{<} M_\chi v^2$

“Inelastic” dark matter

D.Tucker-Smith, NW, **Phys.Rev.D64:043502,2001;Phys.Rev.D72:063509,2005**

- DM-nucleus scattering must be inelastic
- If dark matter can only scatter off of a nucleus by transitioning to an excited state (100 keV), the kinematics are changed dramatically

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$$\frac{v^2 \mu_{\chi N}}{2} > \delta$$

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  - Favors heavy targets (Iodine) over light ones (Germanium)
  - Enhances modulation (typically 30%, but up to 100%)
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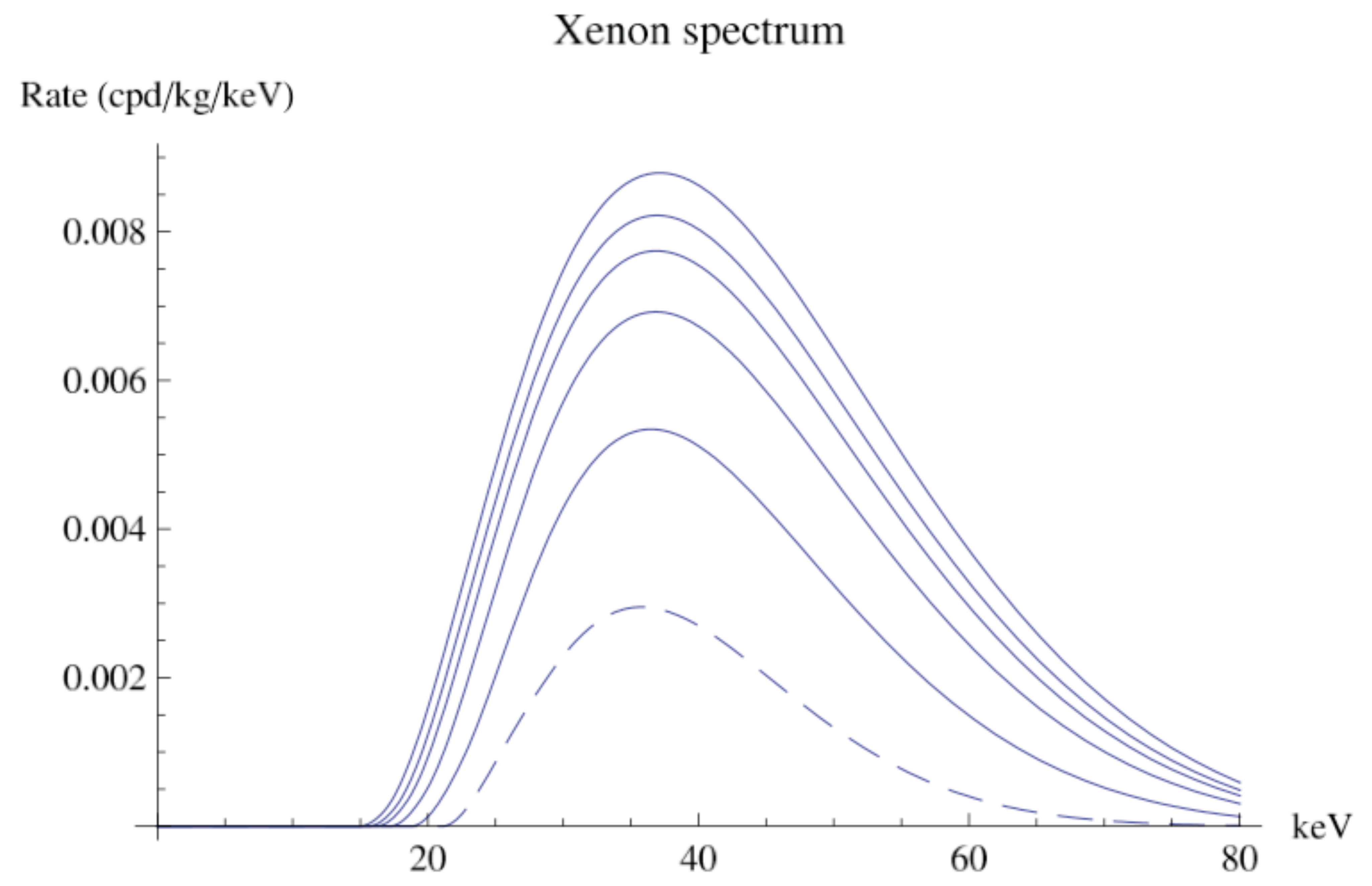
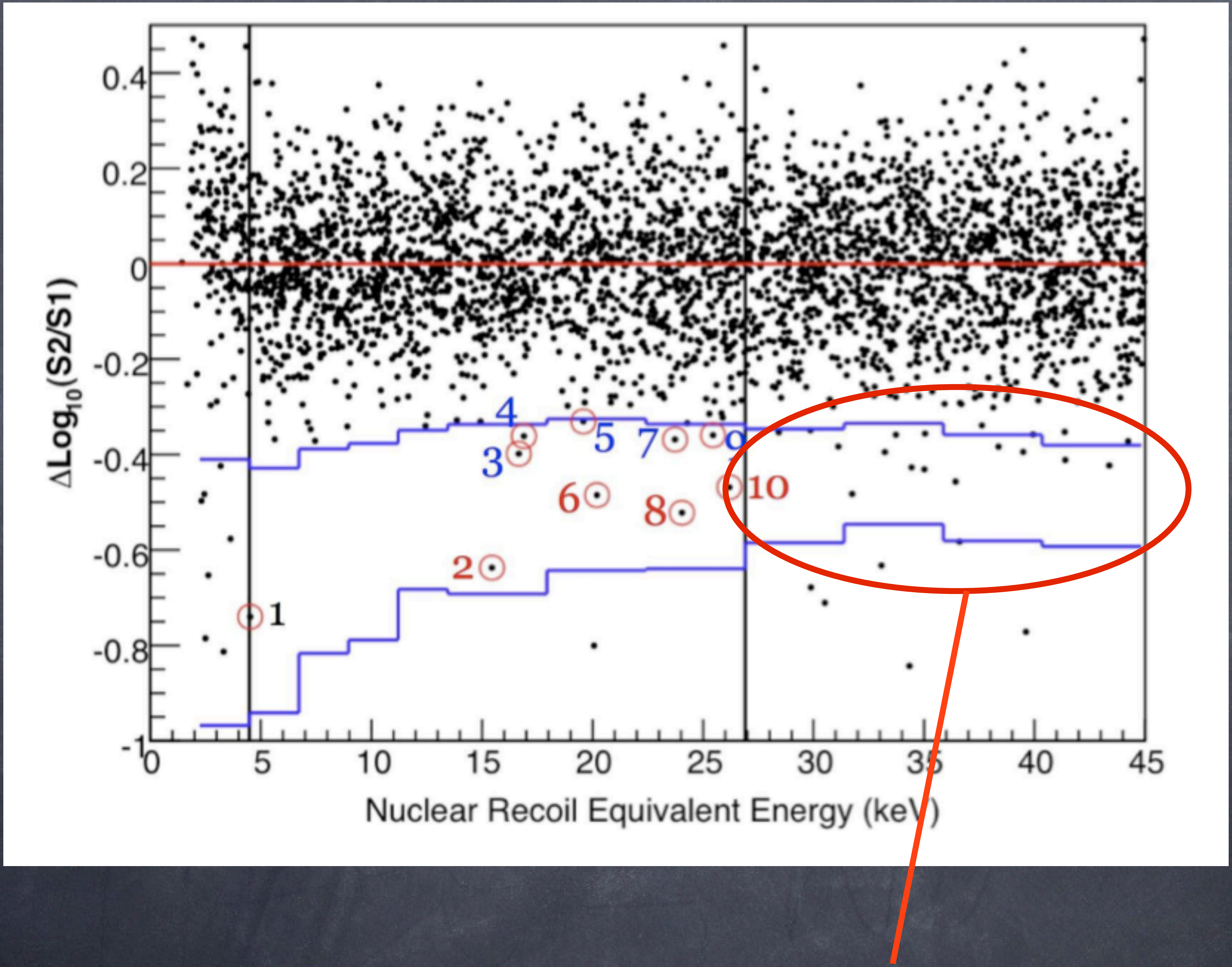
  - Enhances modulation (typically 30%, but up to 100%)
  - Depletes low energy events
- Together these effects allow a positive DAMA signal consistent with other results (CDMS, XENON10, ZEPLIN, CRESST, KIMS)

Focus on the spectrum





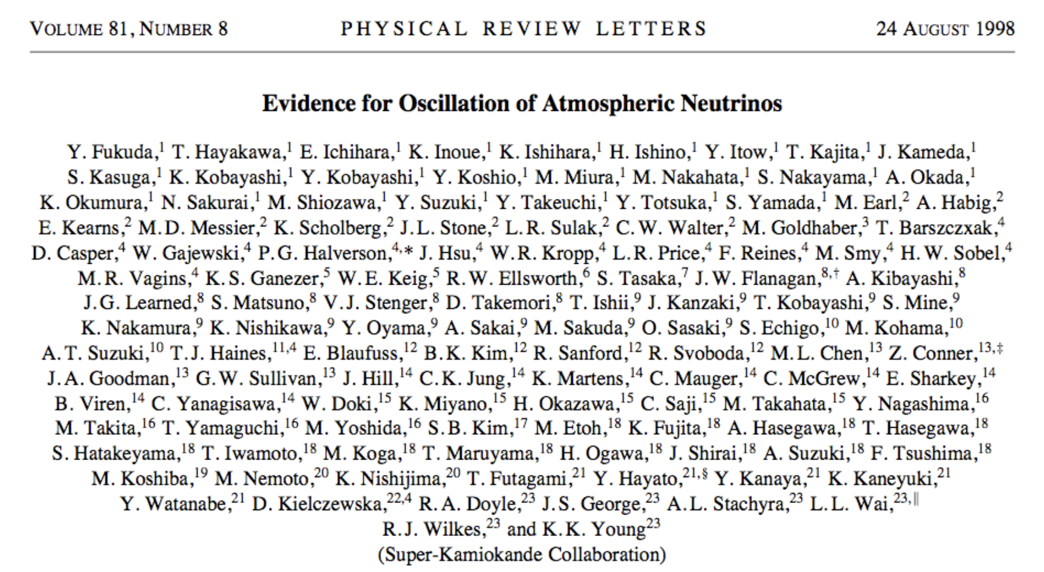
What about these events?

Implications

- (Preliminary) dedicated re-analysis does not rule out iDM explanation of DAMA
- Unexpected population of events at intermediate energies needs to be investigated

Conclusions

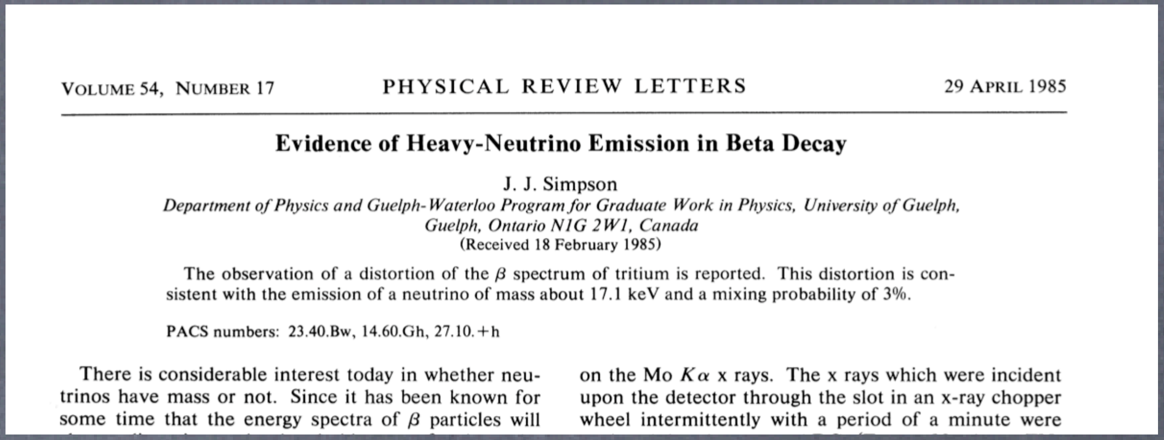
Historical Perspective



VOLUME 81, NUMBER 8 PHYSICAL REVIEW LETTERS 24 AUGUST 1998

Evidence for Oscillation of Atmospheric Neutrinos

Y. Fukuda,[1] T. Hayakawa,[1] E. Ichihara,[1] K. Inoue,[1] K. Ishihara,[1] H. Ishino,[1] Y. Itow,[1] T. Kajita,[1] J. Kameda,[1] S. Kasuga,[1] K. Kobayashi,[1] Y. Kobayashi,[1] Y. Koshio,[1] M. Miura,[1] M. Nakahata,[1] S. Nakayama,[1] A. Okada,[1] K. Okumura,[1] N. Sakurai,[1] M. Shiozawa,[1] Y. Suzuki,[1] Y. Takeuchi,[1] Y. Totsuka,[1] S. Yamada,[1] M. Earl,[2] A. Habig,[2] E. Kearns,[2] M.D. Messier,[2] K. Scholberg,[2] J.L. Stone,[2] L.R. Sulak,[2] C.W. Walter,[2] M. Goldhaber,[3] T. Barszczxak,[4] D. Casper,[4] W. Gajewski,[4] P.G. Halverson,[4,*] J. Hsu,[4] W.R. Kropp,[4] L.R. Price,[4] F. Reines,[4] M. Smy,[4] H.W. Sobel,[4] M.R. Vagins,[4] K.S. Ganezer,[5] W.E. Keig,[5] R.W. Ellsworth,[6] S. Tasaka,[7] J.W. Flanagan,[8,†] A. Kibayashi,[8] J.G. Learned,[8] S. Matsuno,[8] V.J. Stenger,[8] D. Takemori,[8] T. Ishii,[9] J. Kanzaki,[9] T. Kobayashi,[9] S. Mine,[9] K. Nakamura,[9] K. Nishikawa,[9] Y. Oyama,[9] A. Sakai,[9] M. Sakuda,[9] O. Sasaki,[9] S. Echigo,[10] M. Kohama,[10] A.T. Suzuki,[10] T.J. Haines,[11,4] E. Blaufuss,[12] B.K. Kim,[12] R. Sanford,[12] R. Svoboda,[12] M.L. Chen,[13] Z. Conner,[13,‡] J.A. Goodman,[13] G.W. Sullivan,[13] J. Hill,[14] C.K. Jung,[14] K. Martens,[14] C. Mauger,[14] C. McGrew,[14] E. Sharkey,[14] B. Viren,[14] C. Yanagisawa,[14] W. Doki,[15] K. Miyano,[15] H. Okazawa,[15] C. Saji,[15] M. Takahata,[15] Y. Nagashima,[16] M. Takita,[16] T. Yamaguchi,[16] M. Yoshida,[16] S.B. Kim,[17] M. Etoh,[18] K. Fujita,[18] A. Hasegawa,[18] T. Hasegawa,[18] S. Hatakeyama,[18] T. Iwamoto,[18] M. Koga,[18] T. Maruyama,[18] H. Ogawa,[18] J. Shirai,[18] A. Suzuki,[18] F. Tsushima,[18] M. Koshiba,[19] M. Nemoto,[20] K. Nishijima,[20] T. Futagami,[21] Y. Hayato,[21,§] Y. Kanaya,[21] K. Kaneyuki,[21] Y. Watanabe,[21] D. Kielczewska,[22,4] R.A. Doyle,[23] J.S. George,[23] A.L. Stachyra,[23] L.L. Wai,[23,‖] R.J. Wilkes,[23] and K.K. Young[23]
(Super-Kamiokande Collaboration)



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Evidence of Heavy-Neutrino Emission in Beta Decay

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The observation of a distortion of the β spectrum of tritium is reported. This distortion is consistent with the emission of a neutrino of mass about 17.1 keV and a mixing probability of 3%.

PACS numbers: 23.40.Bw, 14.60.Gh, 27.10.+h

There is considerable interest today in whether neutrinos have mass or not. Since it has been known for some time that the energy spectra of β particles will

on the Mo $K\alpha$ x rays. The x rays which were incident upon the detector through the slot in an x-ray chopper wheel intermittently with a period of a minute were

- Dark Matter is as neutrino physics was (maybe)
  - Suggestions and hints of new physics
  - Will become clearer with time
- Remember: it was the “unreliable” astrophysical hints that ended up being right!

Conclusions

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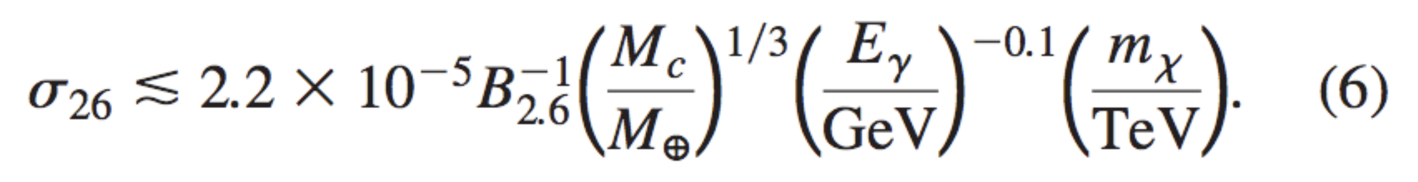
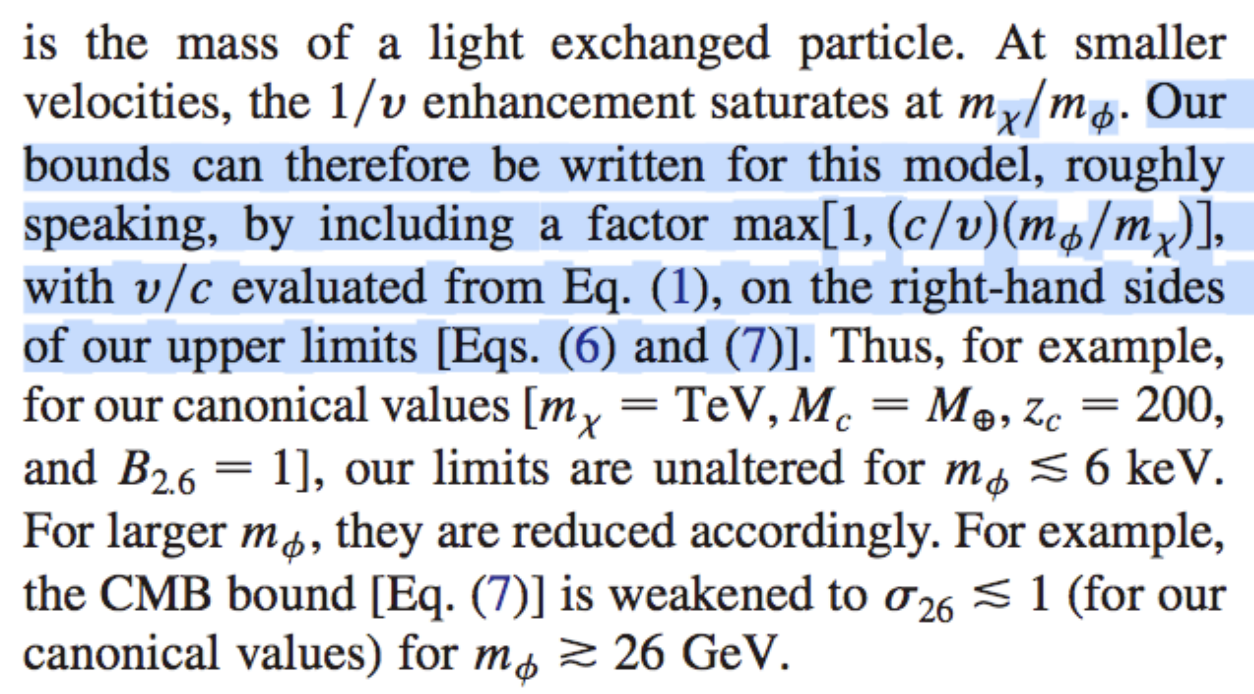
- Such a model has dramatic collider signals (“lepton jets”), gamma ray signals, and dark matter direct detection signals
- Data driven - will know more soon!

Backup slides

Kamionkowski + Profumo

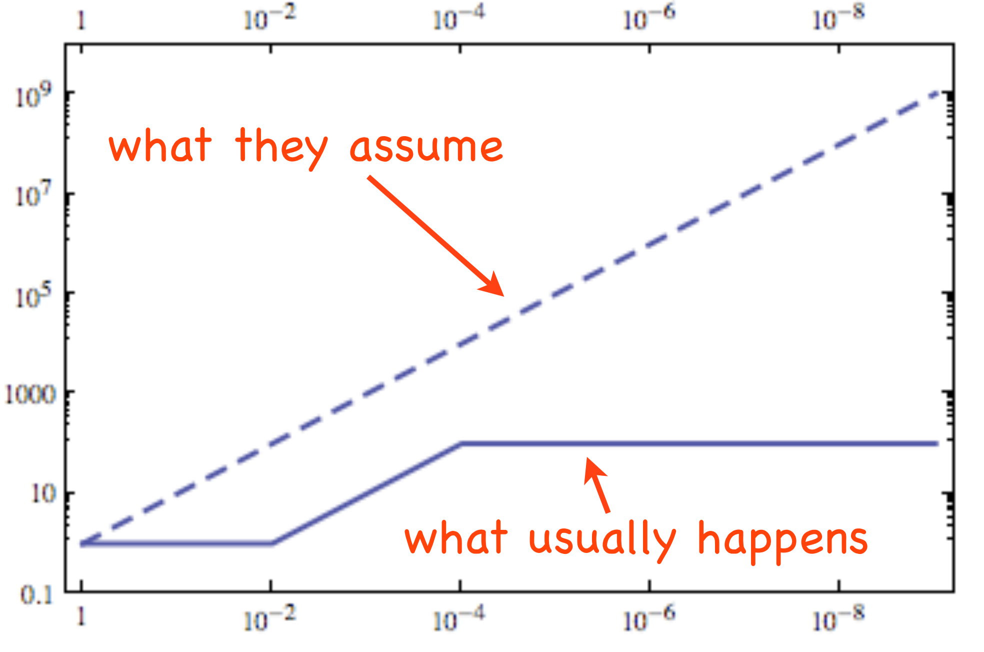


$$\sigma_{26} \lesssim 2.2 \times 10^{-5} B_{2.6}^{-1} \left(\frac{M_c}{M_\oplus}\right)^{1/3} \left(\frac{E_\gamma}{\mathrm{GeV}}\right)^{-0.1} \left(\frac{m_\chi}{\mathrm{TeV}}\right). \qquad (6)$$



is the mass of a light exchanged particle. At smaller velocities, the $1/v$ enhancement saturates at m_χ/m_ϕ. Our bounds can therefore be written for this model, roughly speaking, by including a factor $\max[1, (c/v)(m_\phi/m_\chi)]$, with v/c evaluated from Eq. (1), on the right-hand sides of our upper limits [Eqs. (6) and (7)]. Thus, for example, for our canonical values [$m_\chi = \mathrm{TeV}, M_c = M_\oplus, z_c = 200$, and $B_{2.6} = 1$], our limits are unaltered for $m_\phi \lesssim 6$ keV. For larger m_ϕ, they are reduced accordingly. For example, the CMB bound [Eq. (7)] is weakened to $\sigma_{26} \lesssim 1$ (for our canonical values) for $m_\phi \gtrsim 26$ GeV.

boost

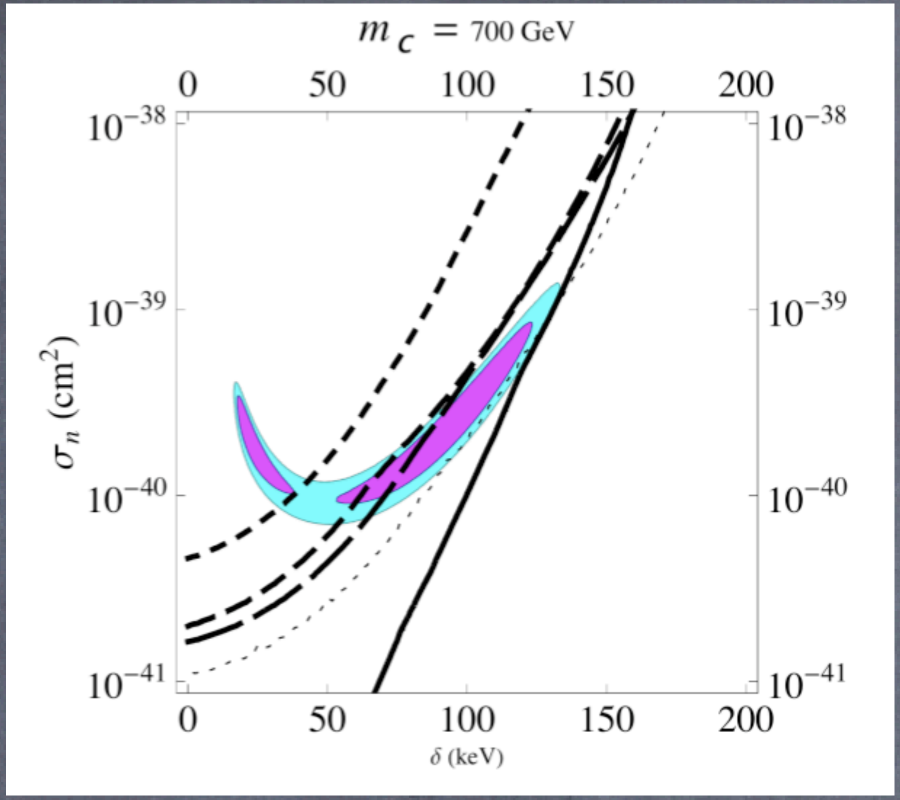


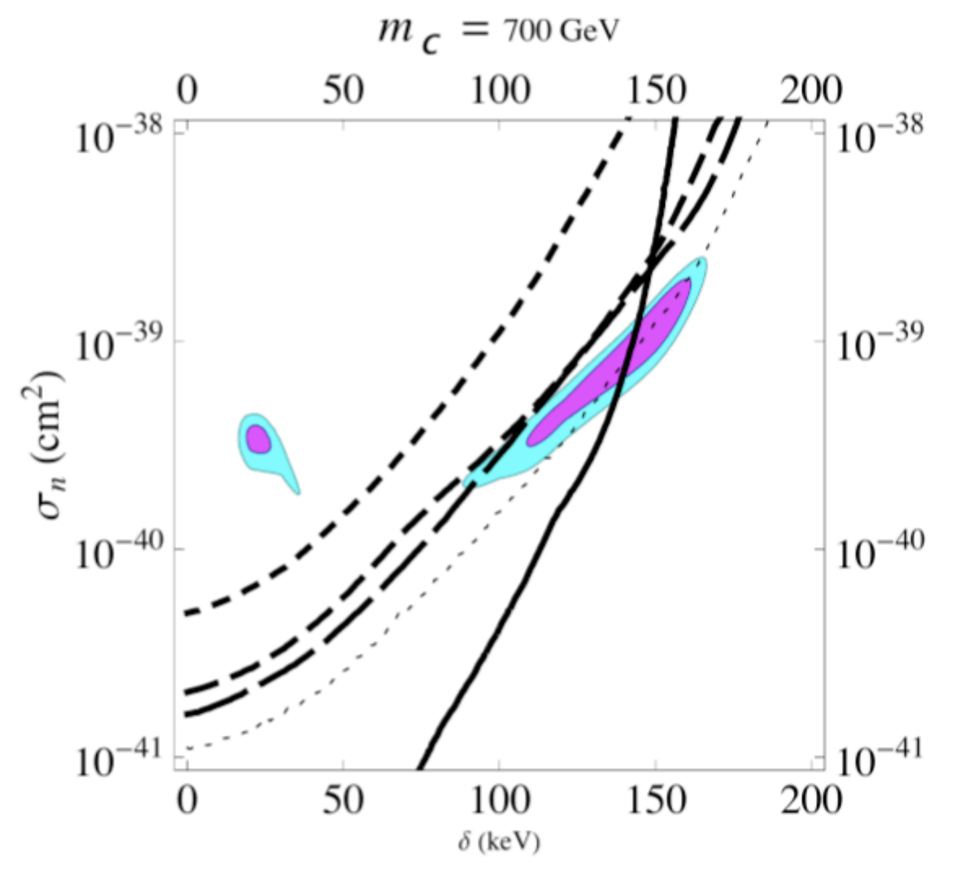
velocity

More simply phrased as maximum boost. I find (using their numbers) at 1 TeV $\mathrm{BF}_{\max}$ ~ 4000

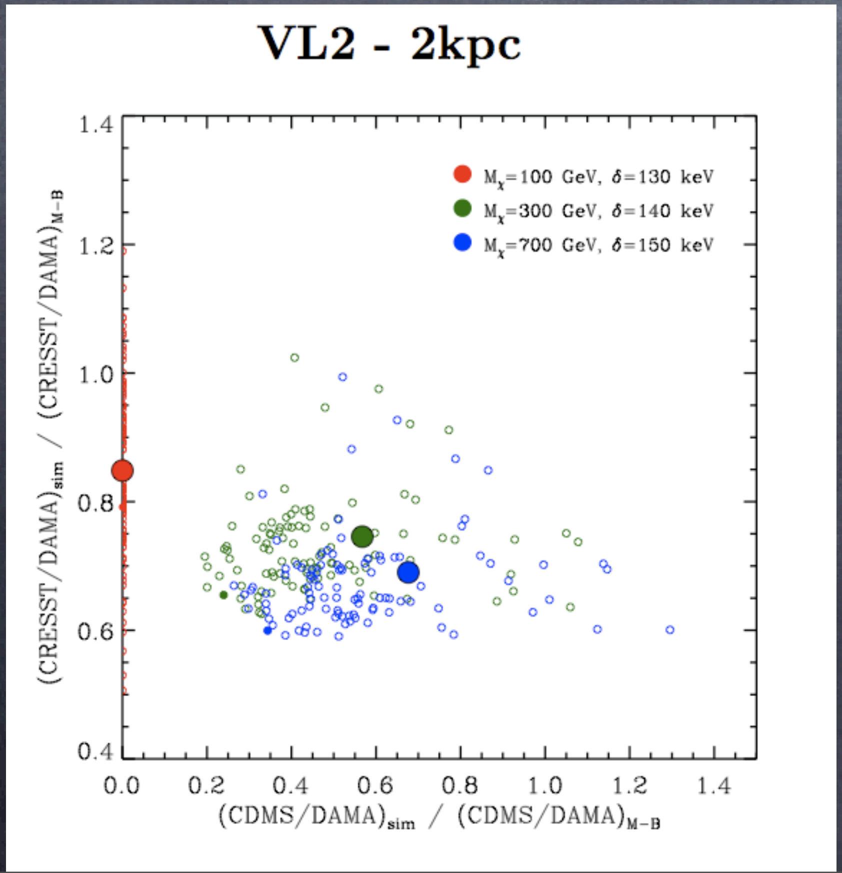
Explaining DAMA with High Masses

Maxwellian





particular 1kpc sphere in VLII



Michael Kuhlen, NW in progress