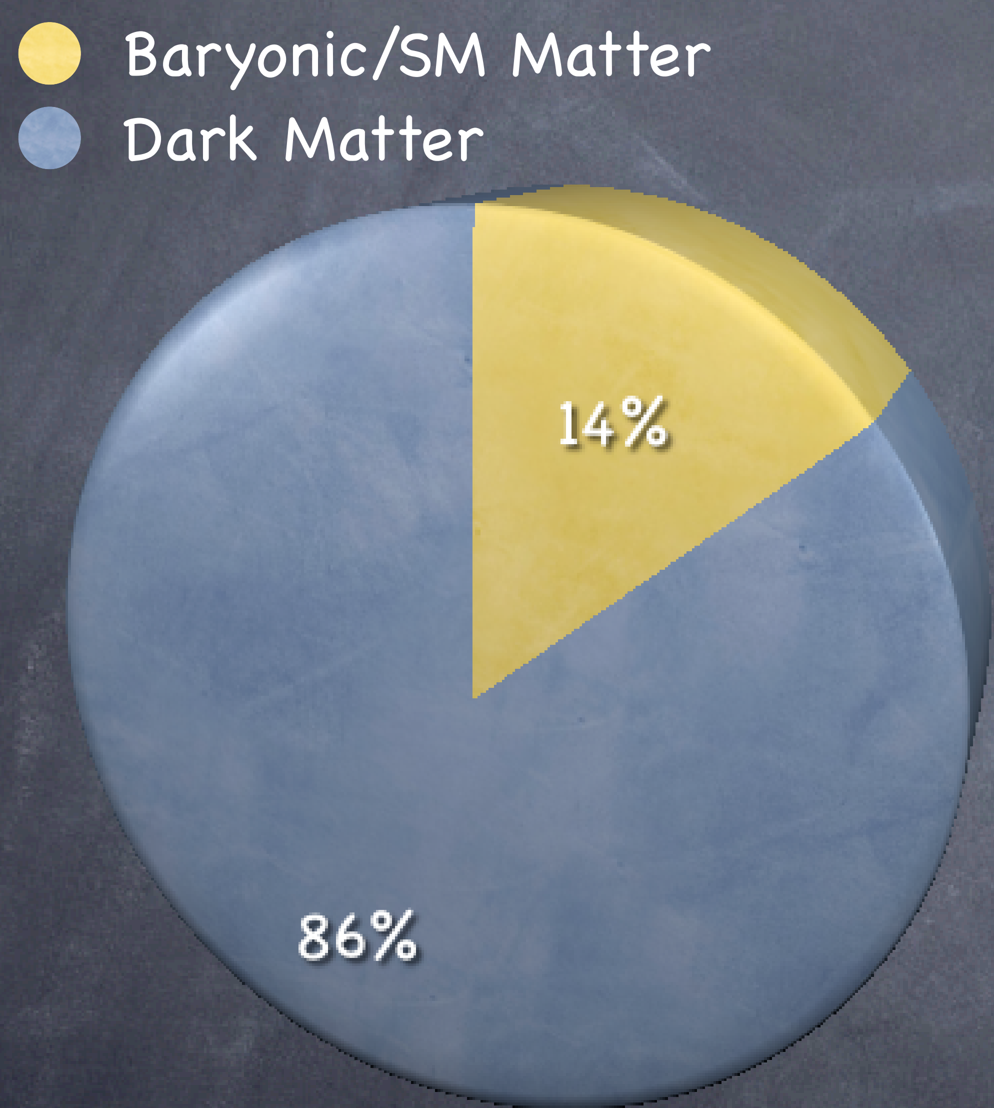
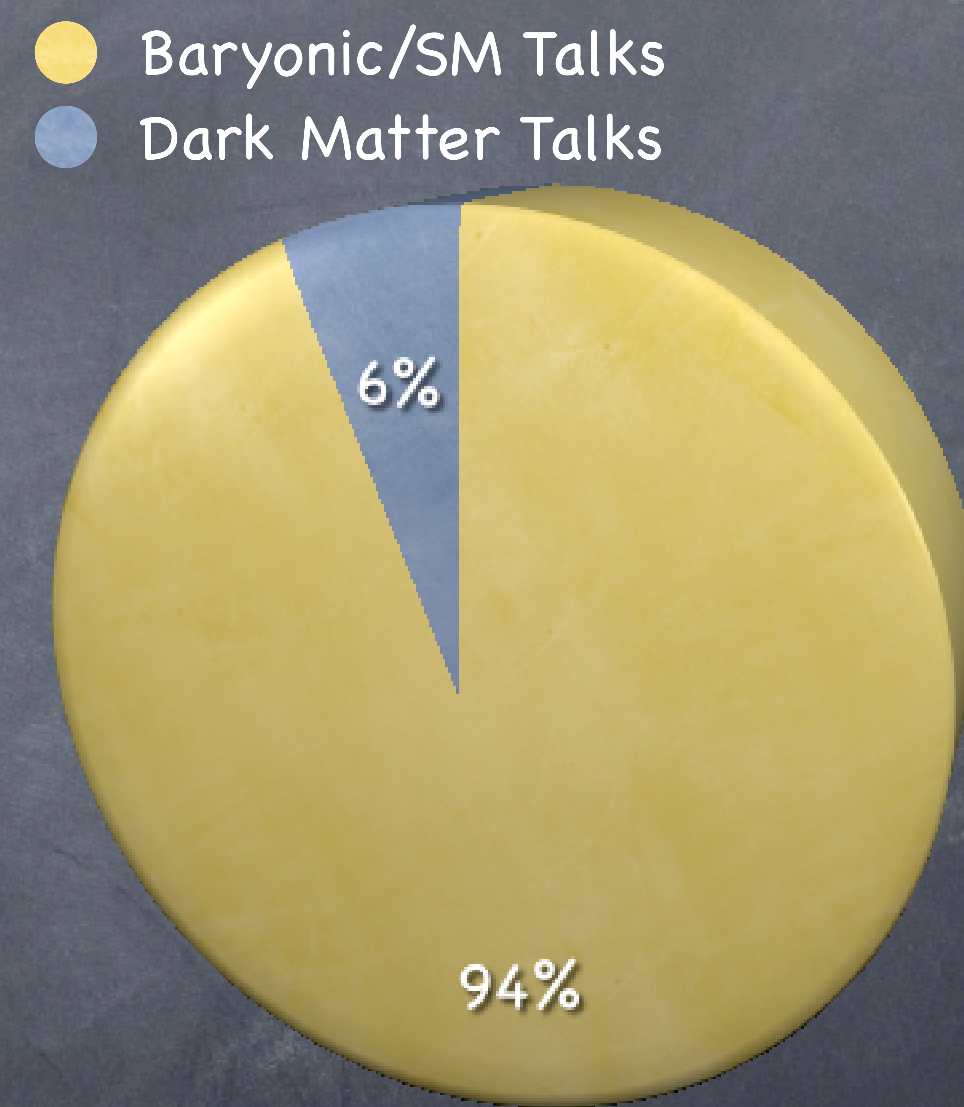
Some Theories of Dark Matter

Neal Weiner
Center for Cosmology and Particle Physics
New York University
La Thuile 2009

This is just one talk!





I'm going to just give one person's perspective (not all inclusive)

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?

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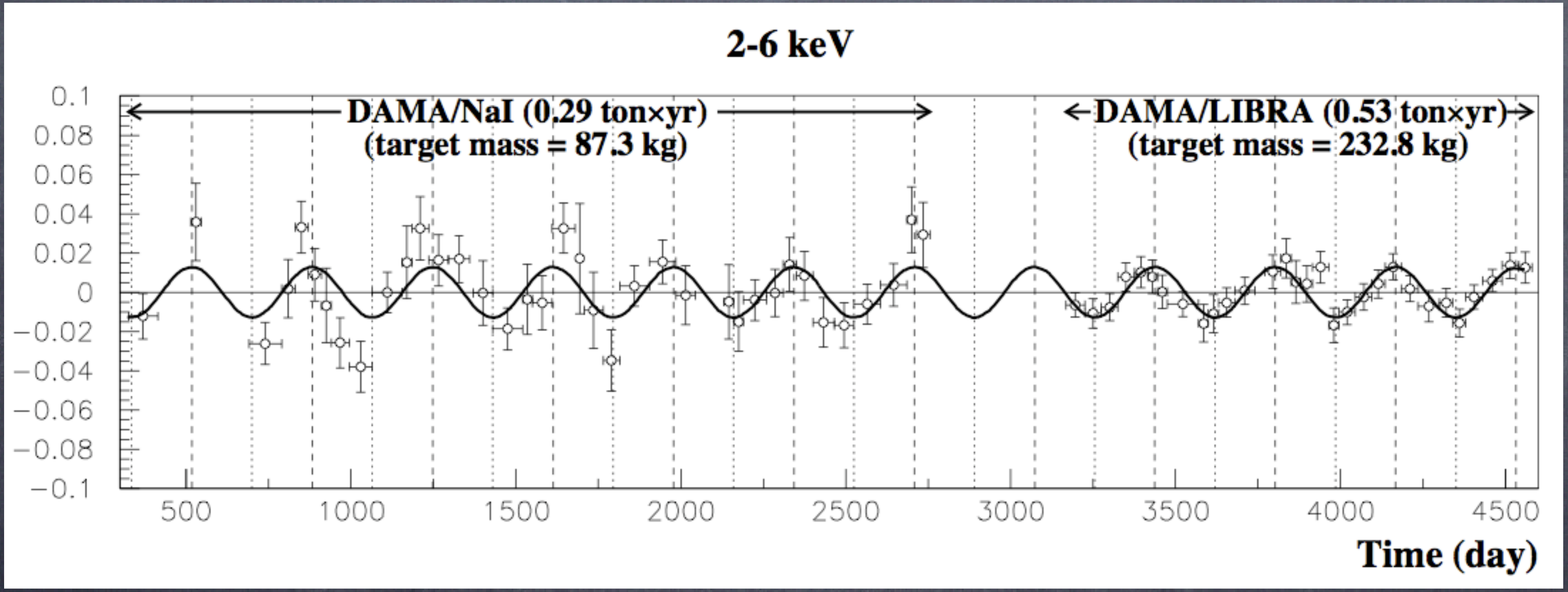
2-6 keV
DAMA/NaI (0.29 ton×yr)
(target mass = 87.3 kg)
DAMA/LIBRA (0.53 ton×yr)
(target mass = 232.8 kg)
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
−0.1
500
1000
1500
2000
2500
3000
3500
4000
4500
Time (day)

What hints?

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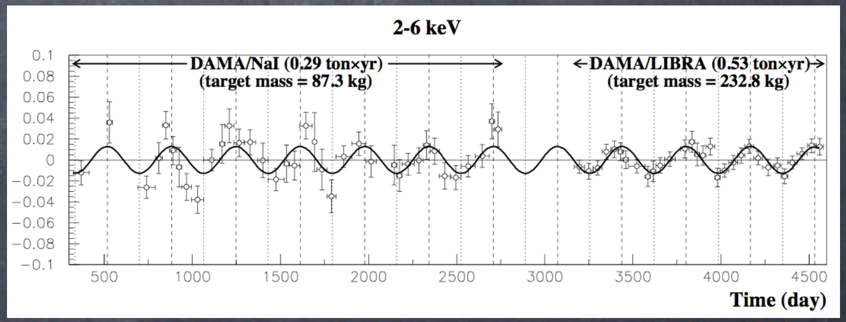
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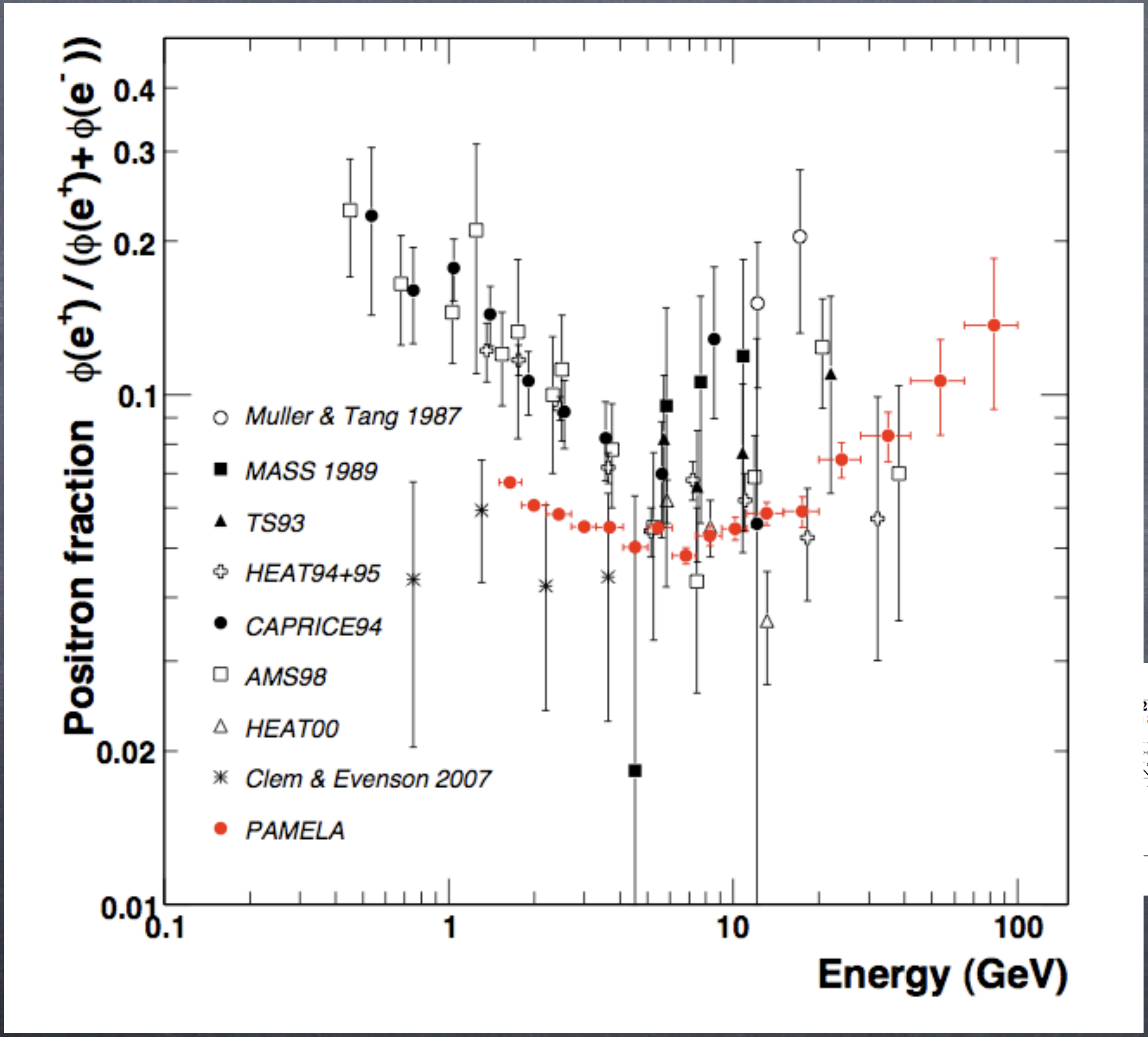
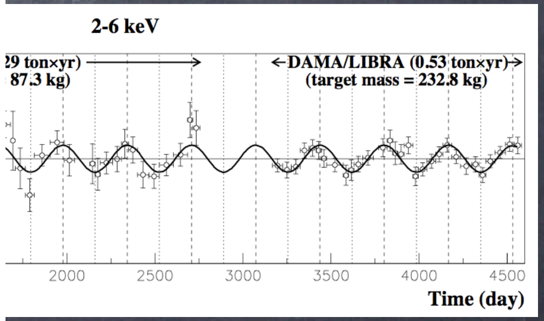


Positron fraction φ(e+) / (φ(e+)+φ(e-))
0.4
0.3
0.2
0.1
0.02
0.01
0.1
1
10
100
Energy (GeV)
Muller & Tang 1987
MASS 1989
TS93
HEAT94+95
CAPRICE94
AMS98
HEAT00
Clem & Evenson 2007
PAMELA



2-6 keV
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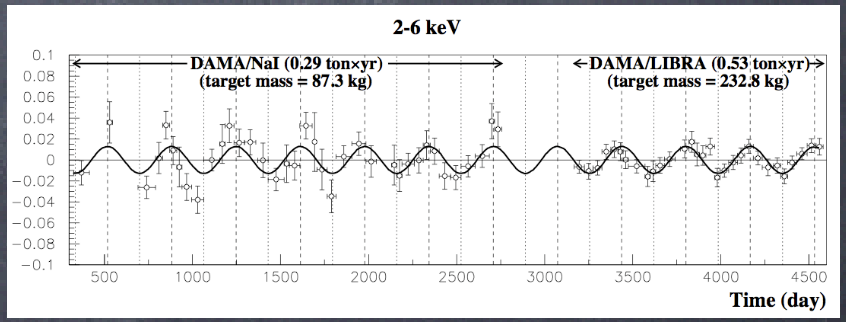
2500
3000
3500
4000
4500
Time (day)

What hints?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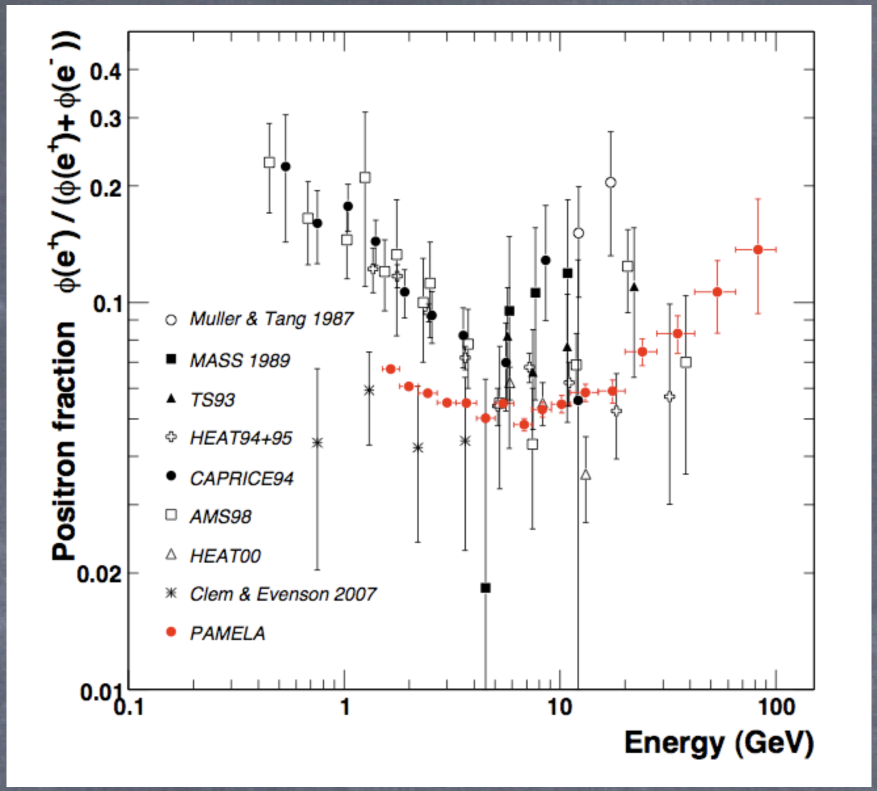

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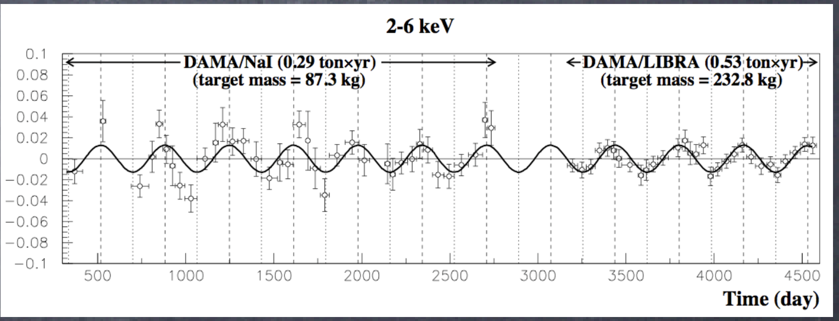

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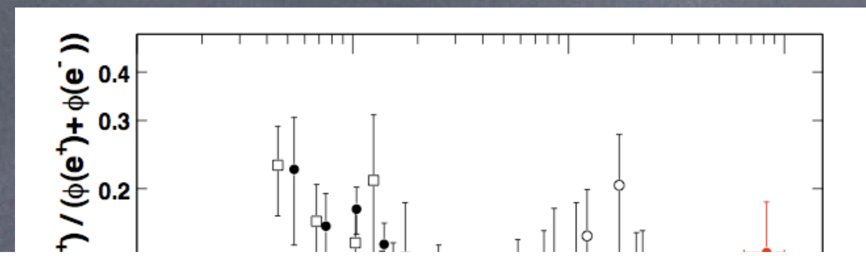
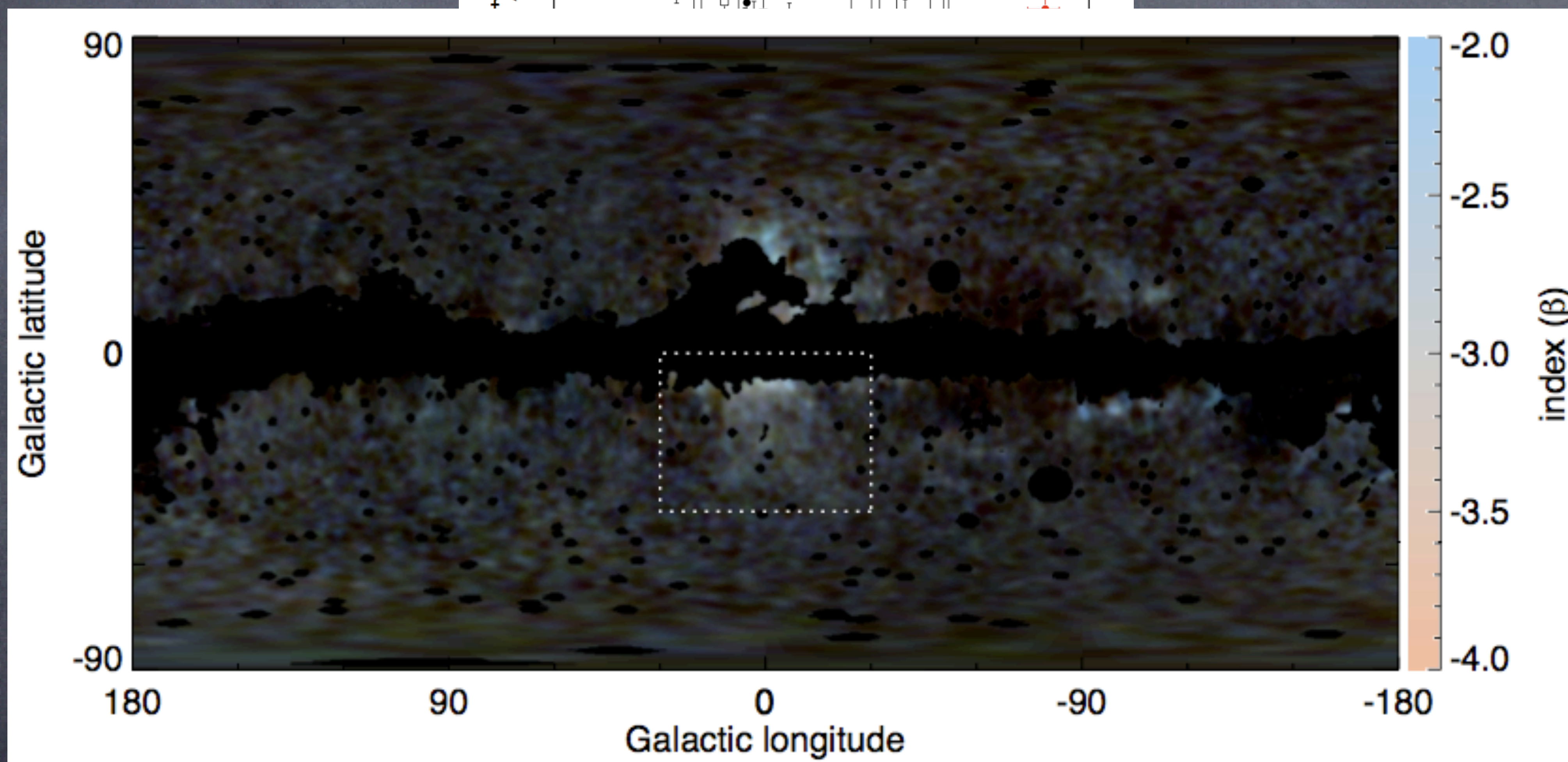
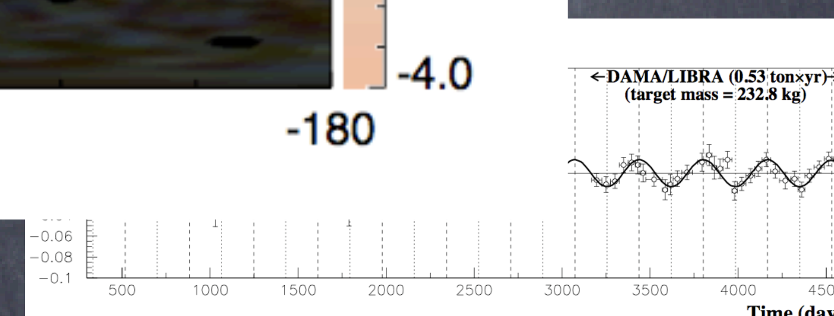

0.4
0.3
0.2


90
0
-90
Galactic latitude
180
90
0
-90
-180
Galactic longitude
-2.0
-2.5
-3.0
-3.5
-4.0
index (β)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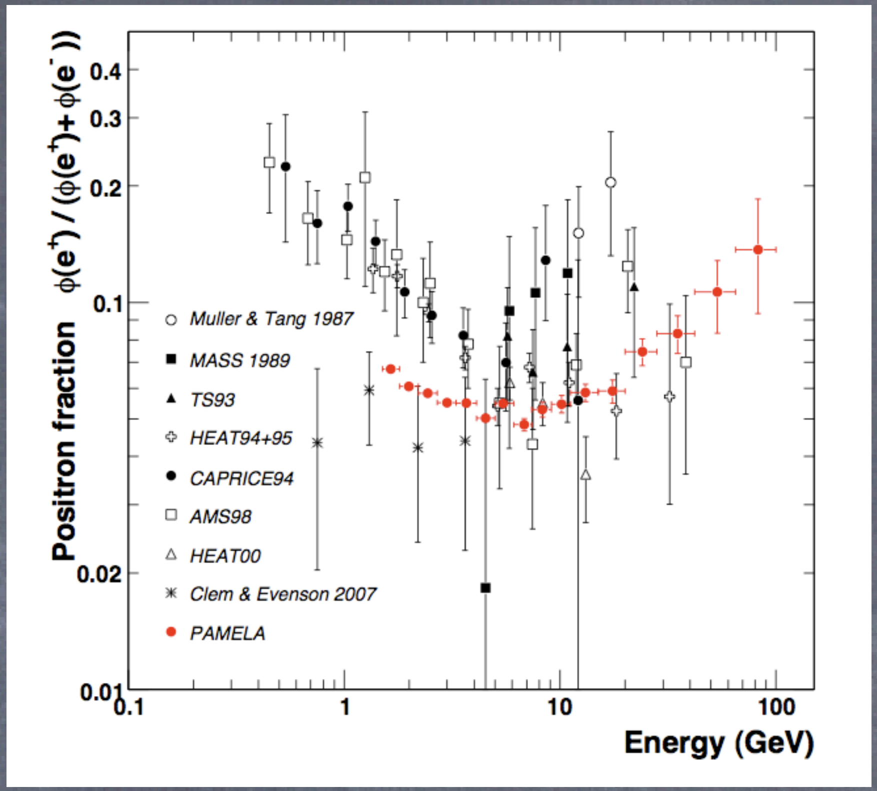

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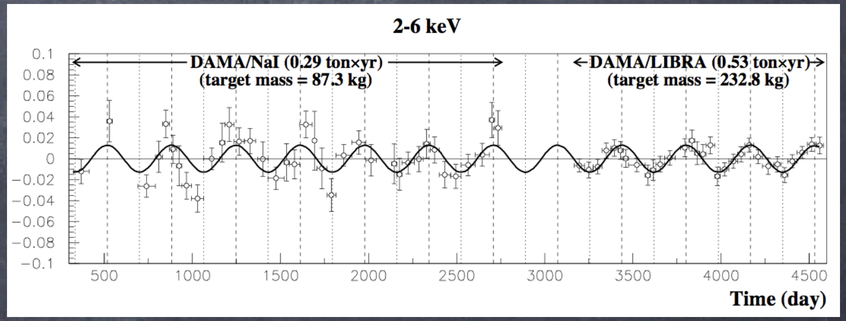

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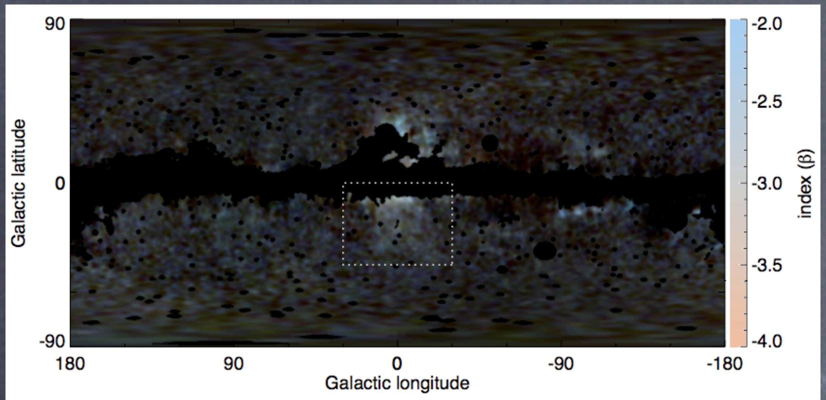
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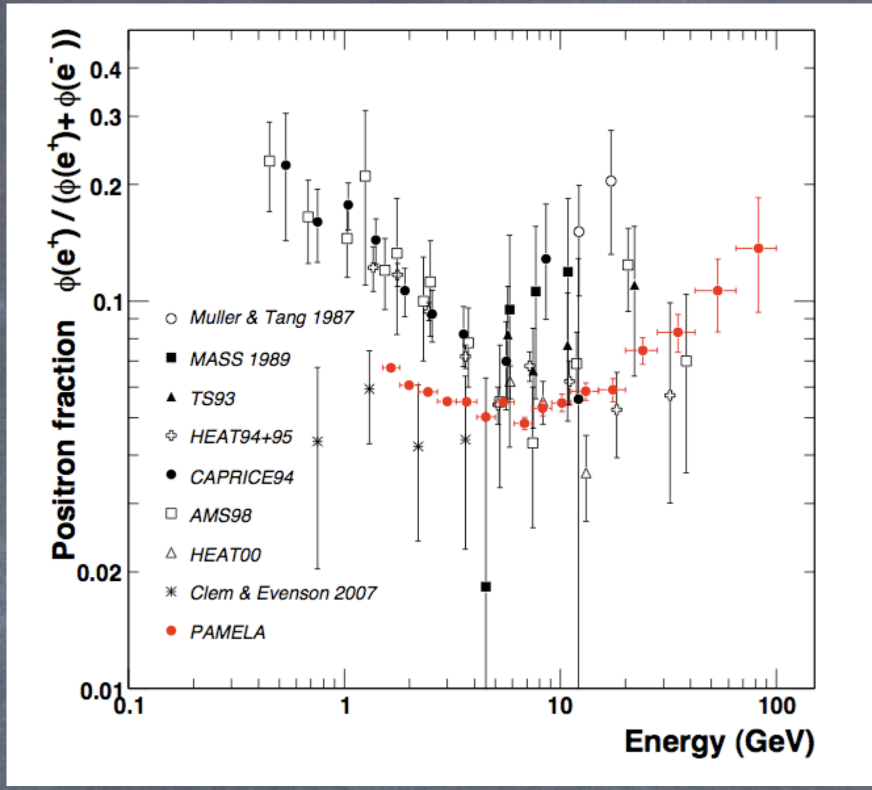
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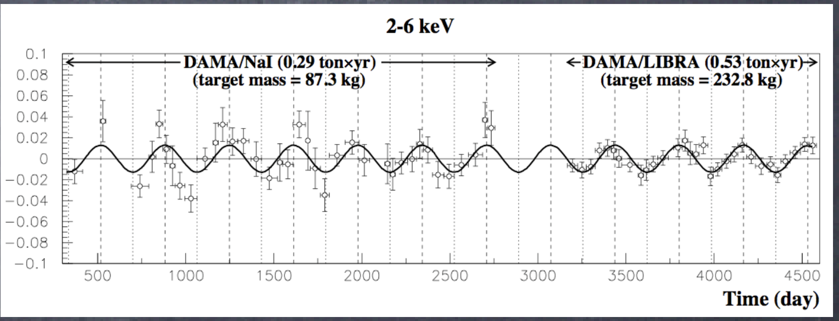
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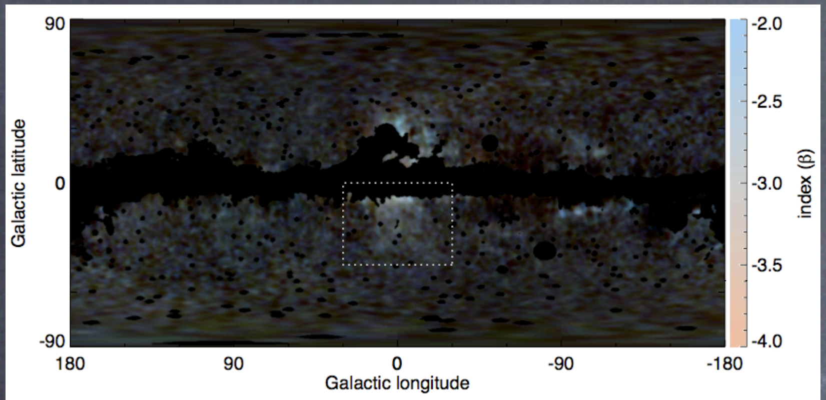

Galactic latitude
Galactic longitude
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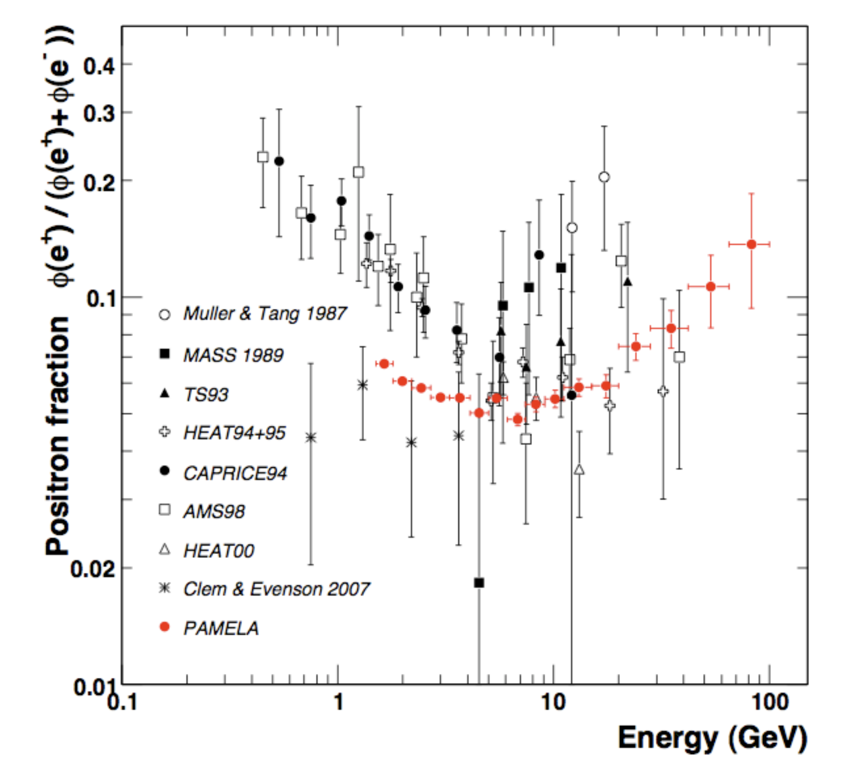

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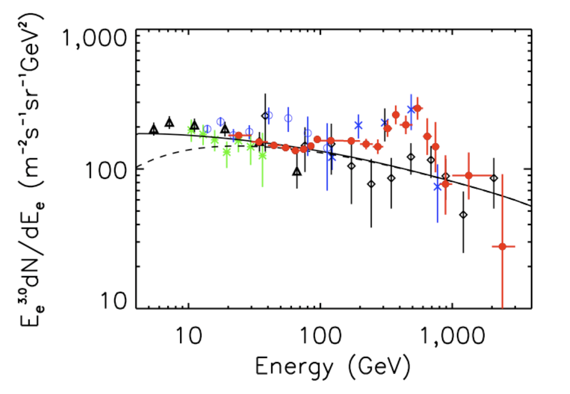
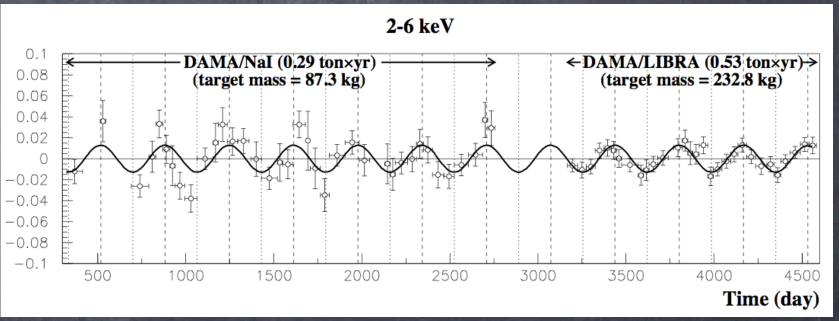


Energy (GeV)



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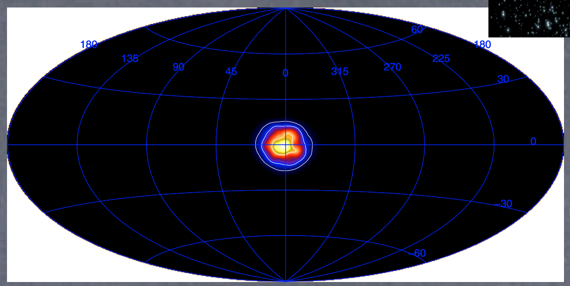
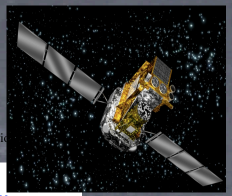
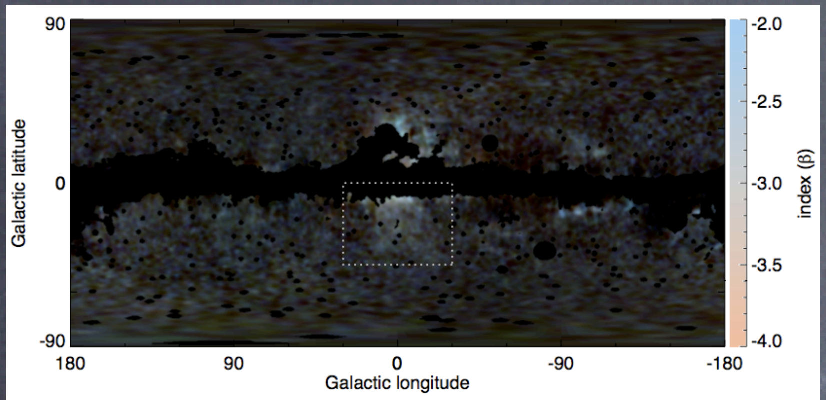

G. Weidenspointner et al.: The sky distribution of positronium continuum emission

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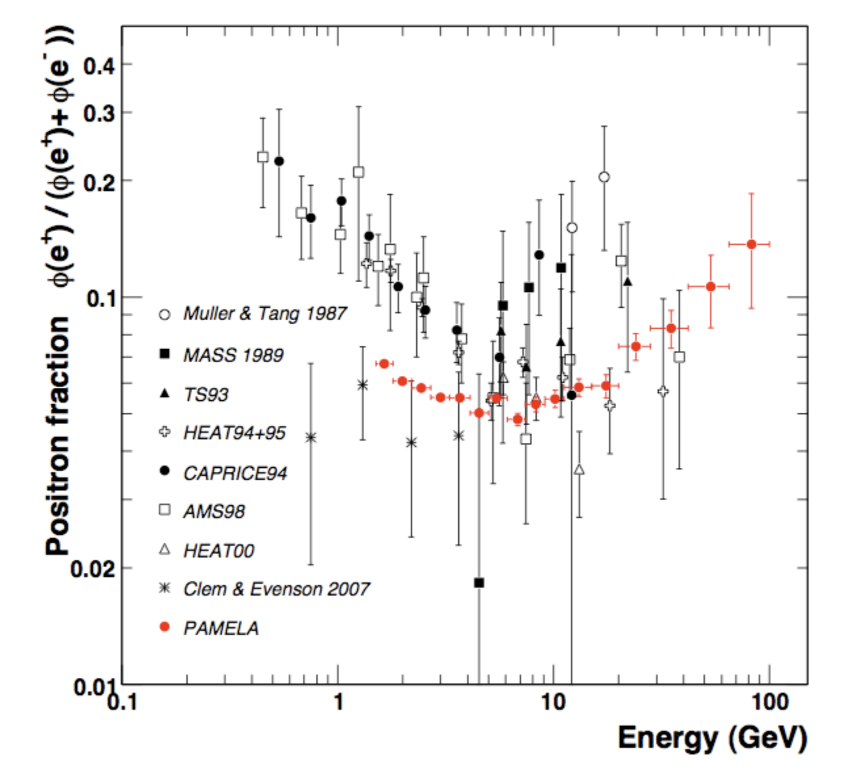
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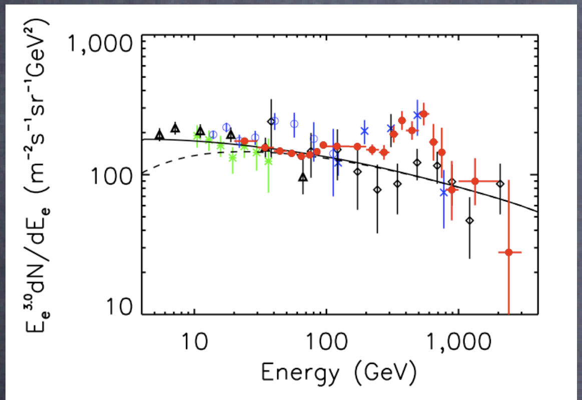
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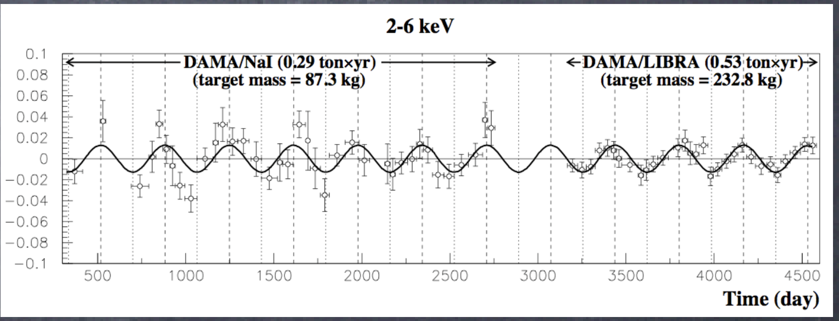
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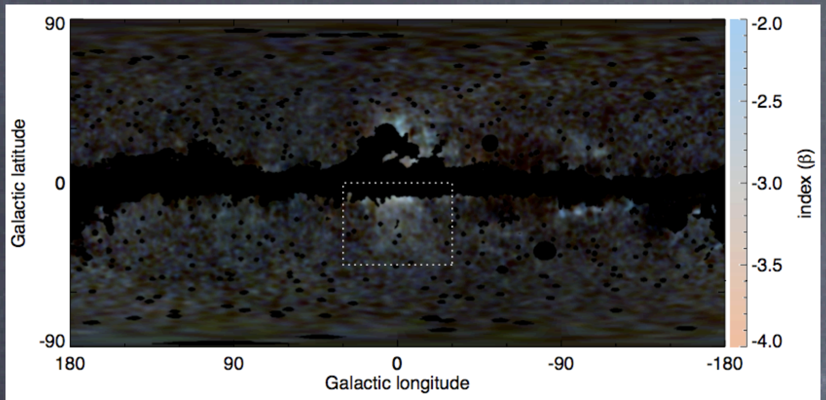
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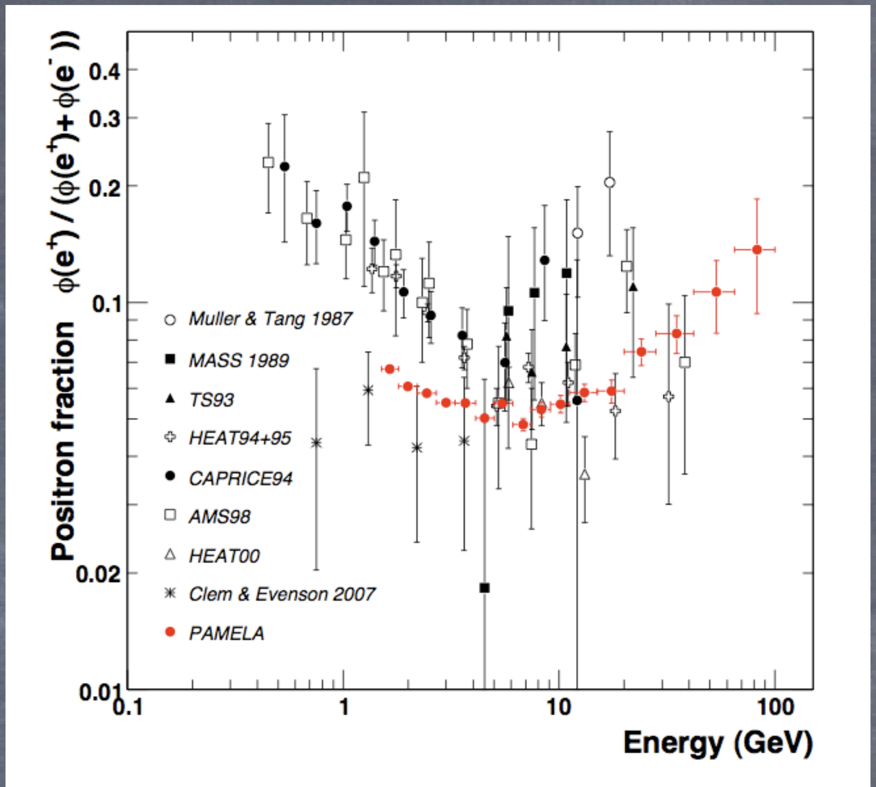
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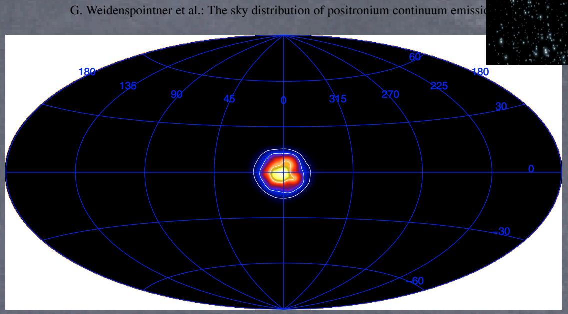
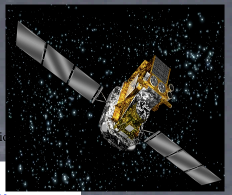
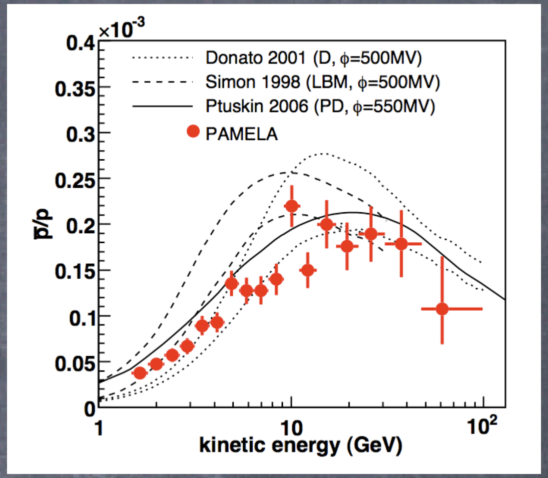
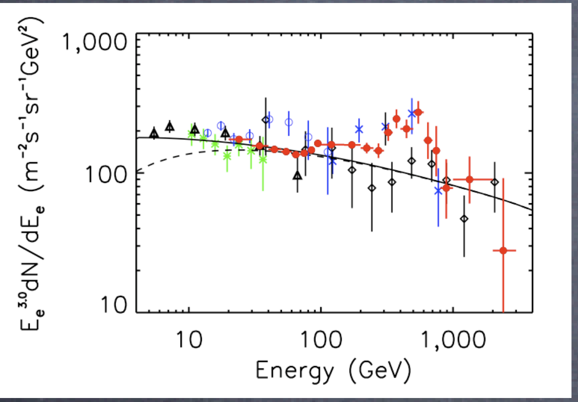
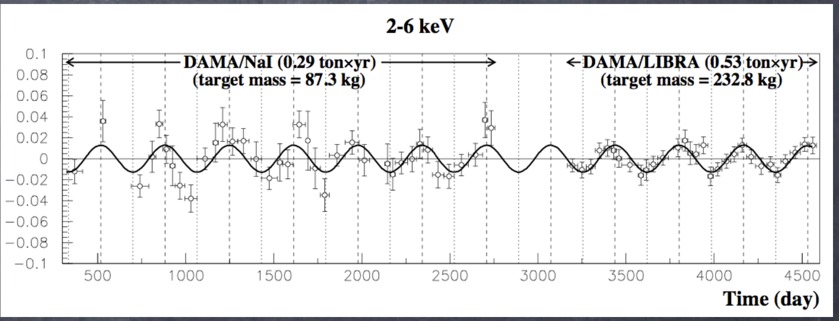

G. Weidenspointner et al.: The sky distribution of positronium continuum emissi




Donato 2001 (D, φ=500MV)
Simon 1998 (LBM, φ=500MV)
Ptuskin 2006 (PD, φ=550MV)
PAMELA
p̄/p
kinetic energy (GeV)


1,000
100
10
Energy (GeV)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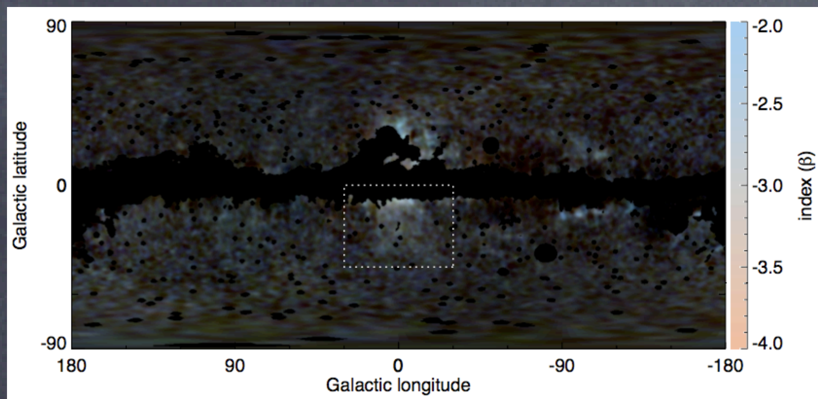

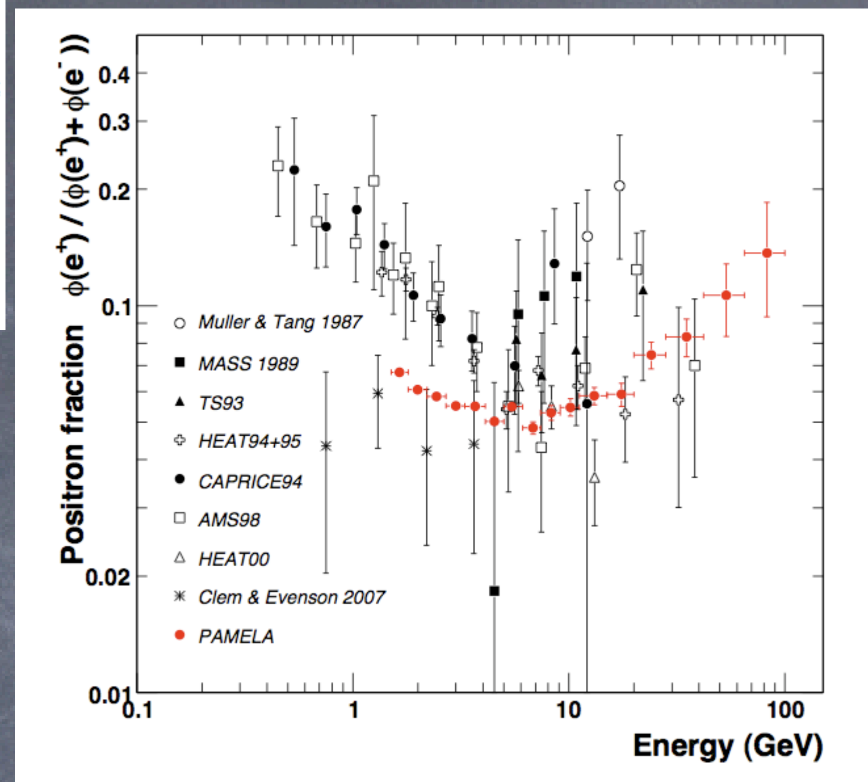

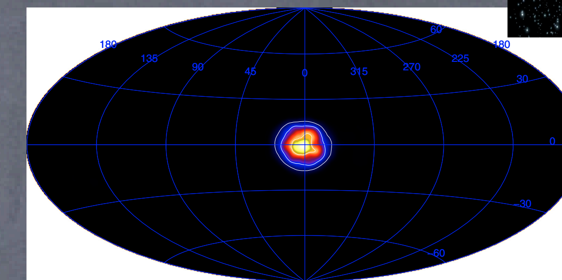

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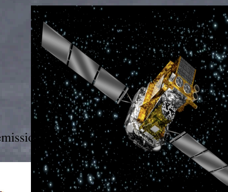

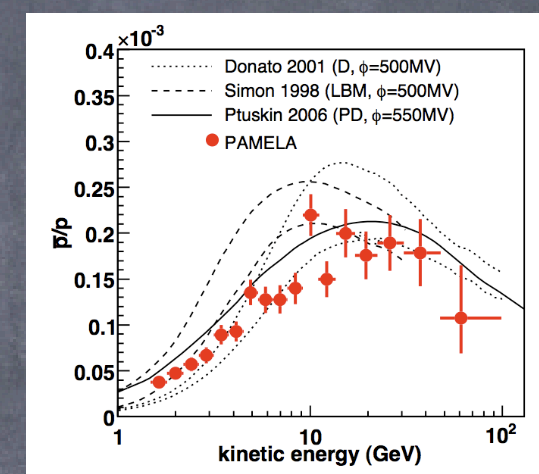

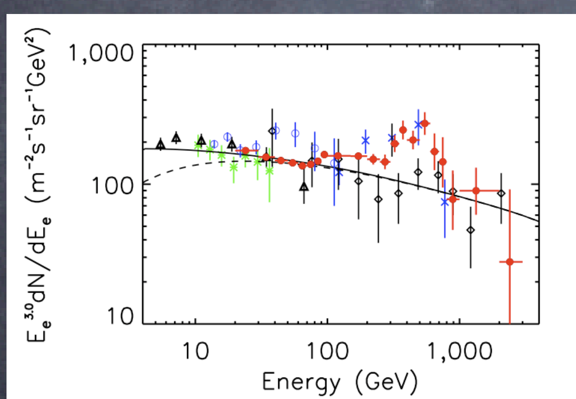

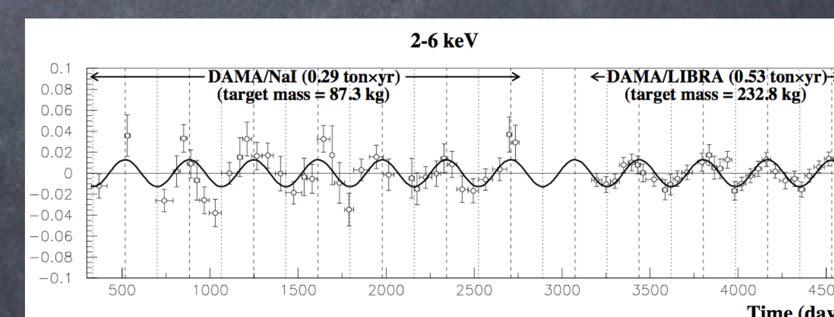

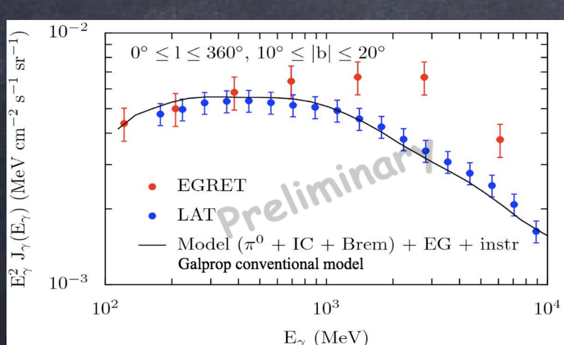

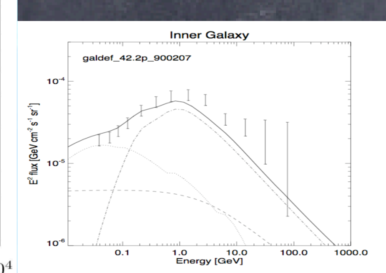

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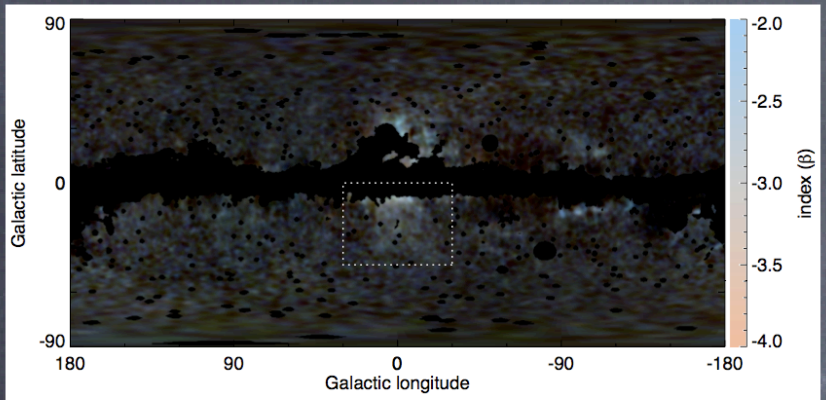
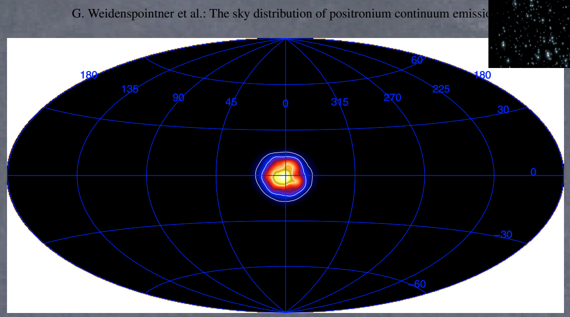
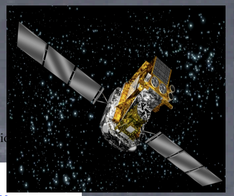
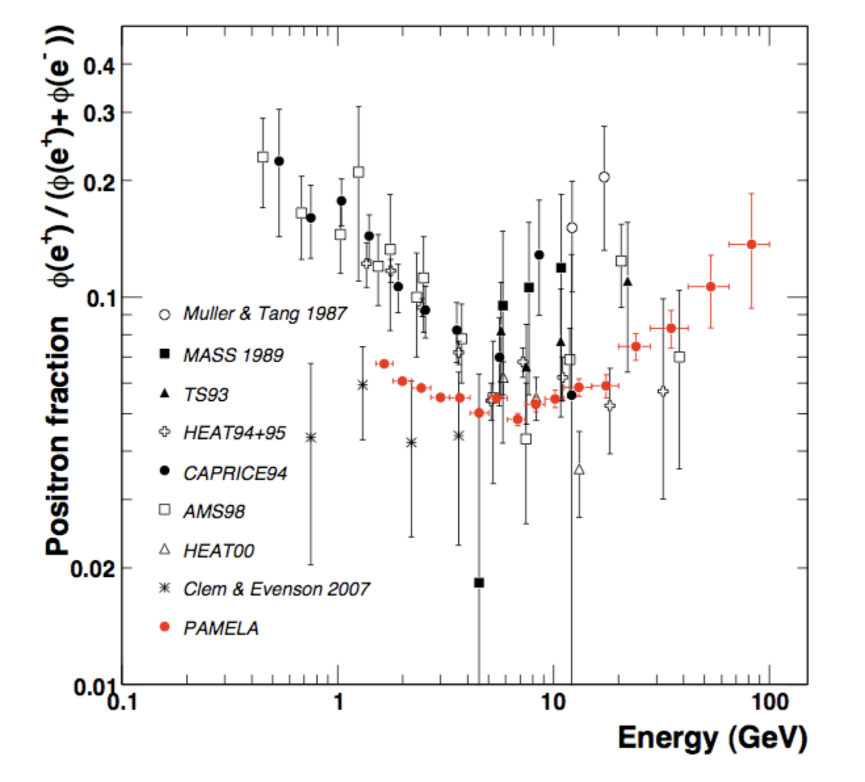
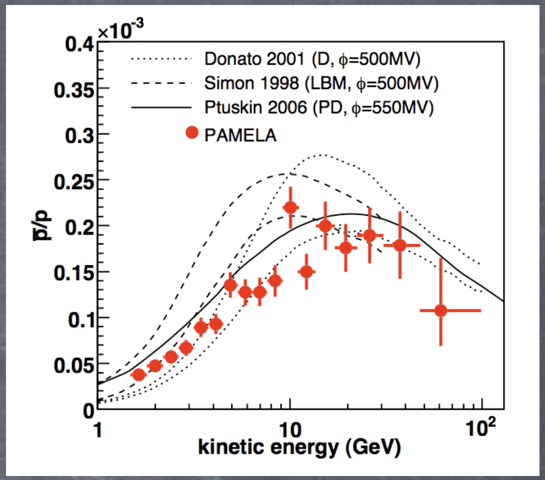
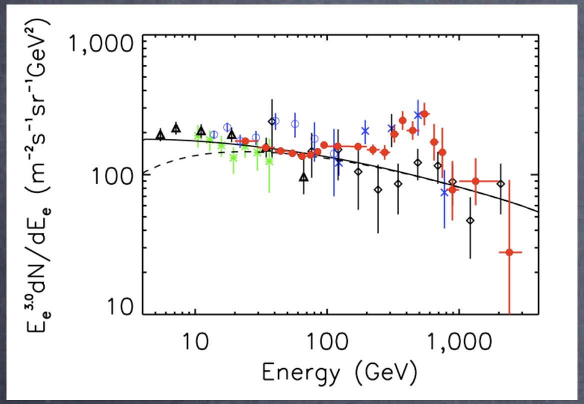




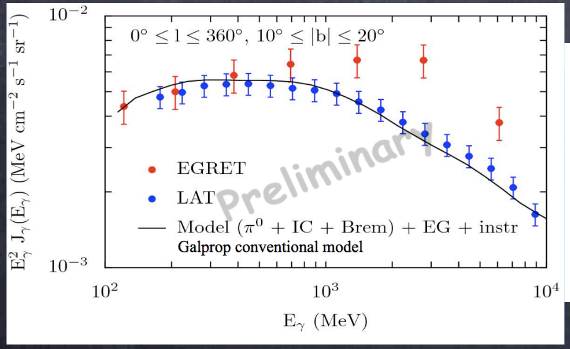


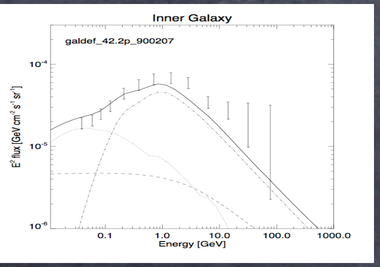


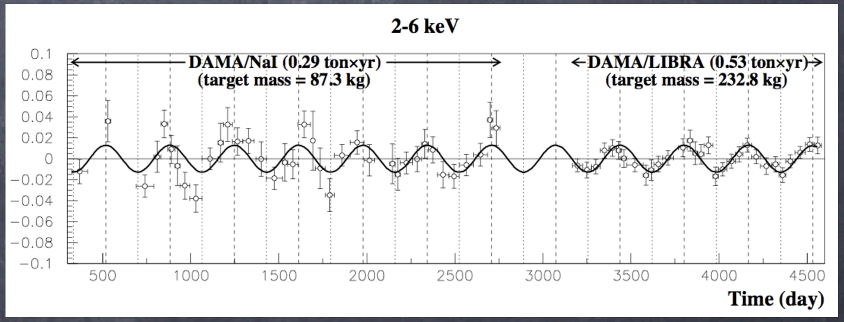




Indications of high energy electron or positron production







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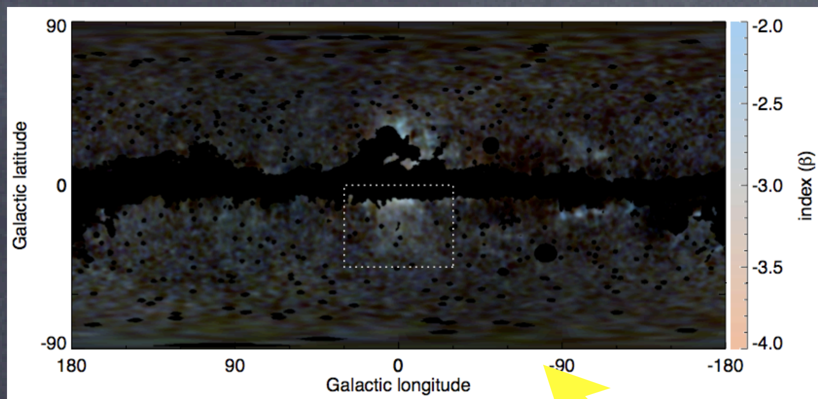

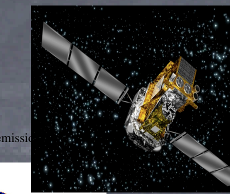

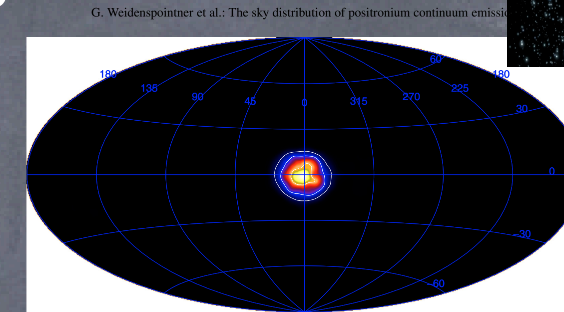

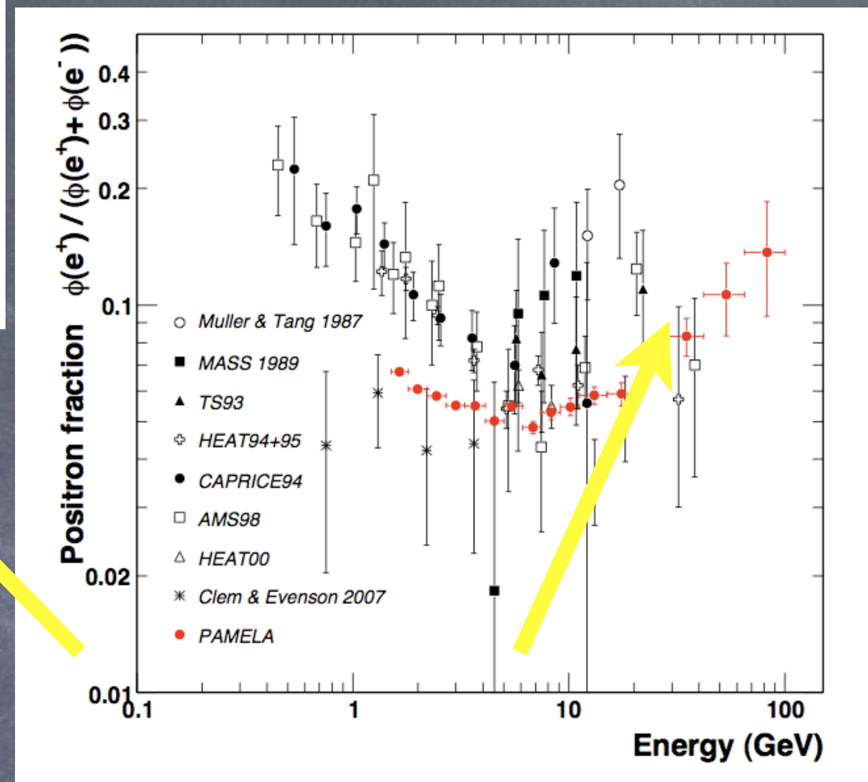

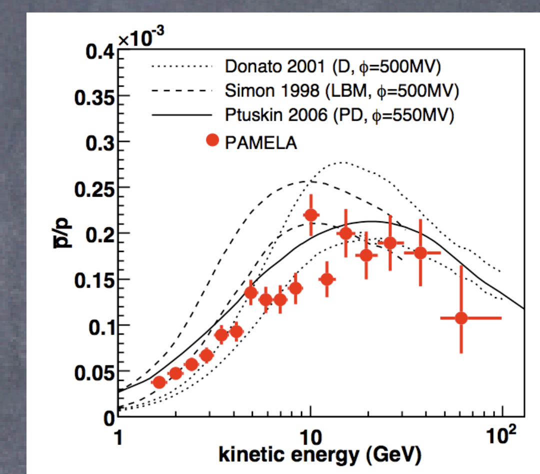

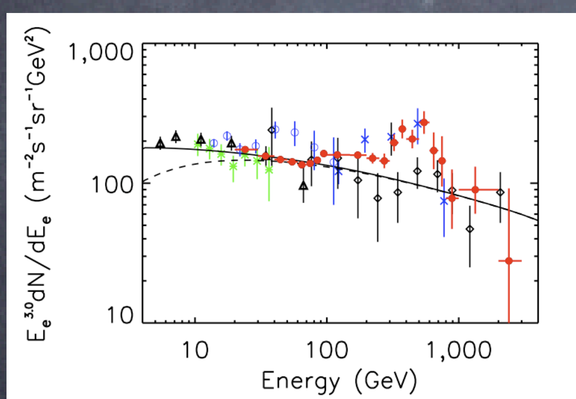

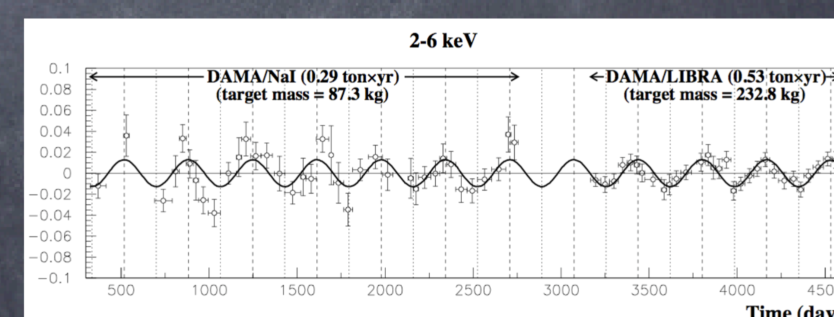

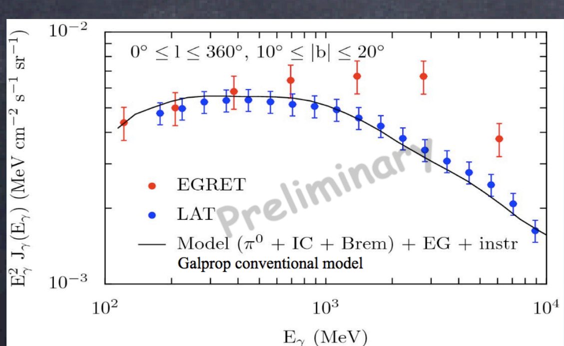

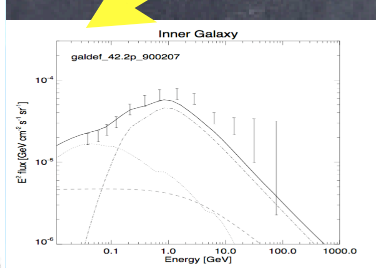

Indications of high energy electron or positron production

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 allows for an excess of ICS photons from the galactic center

WIMP annihilations? Not so fast!

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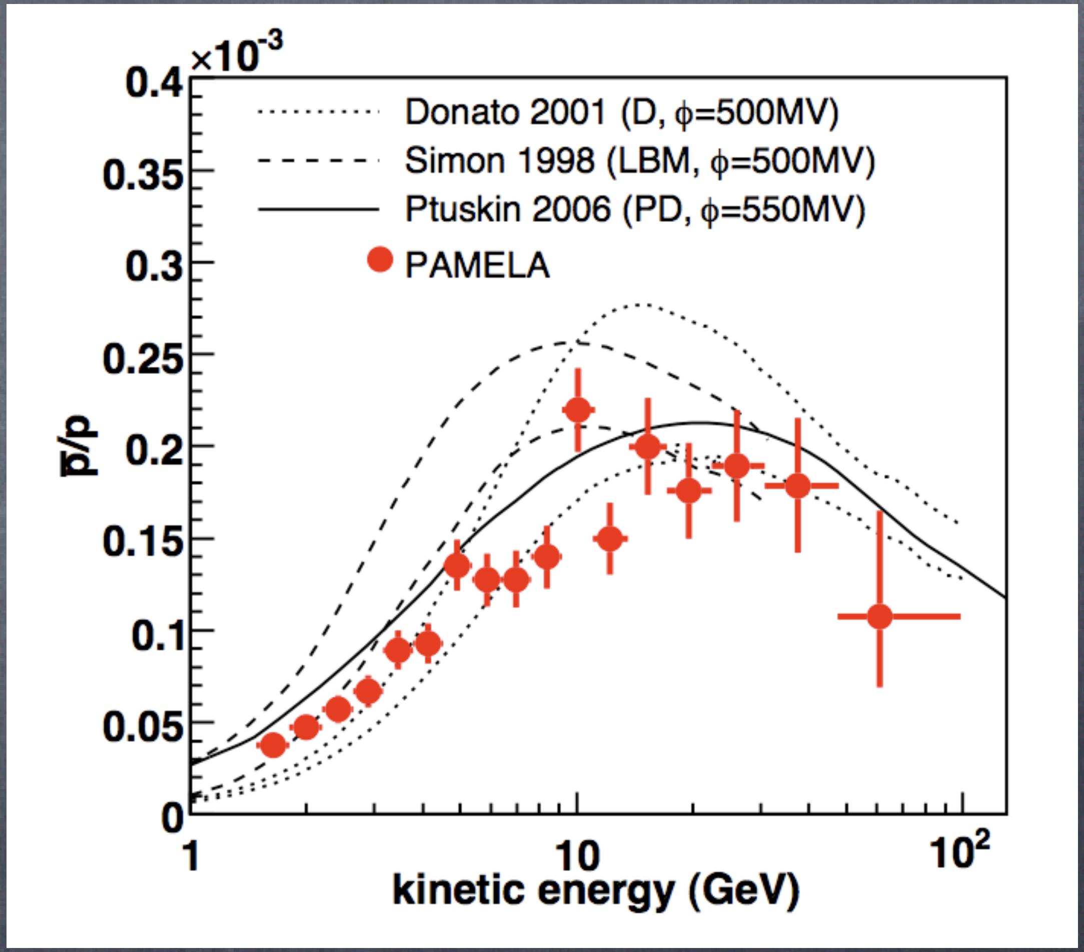

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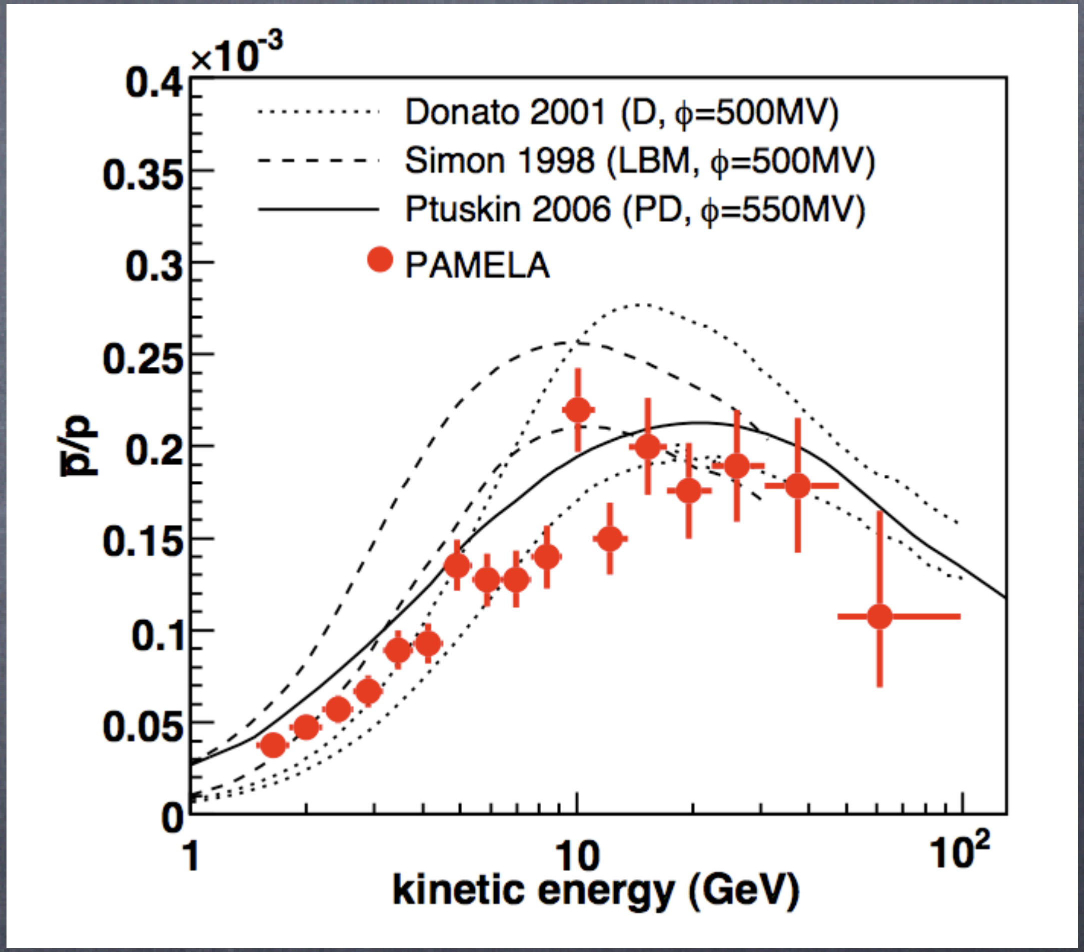

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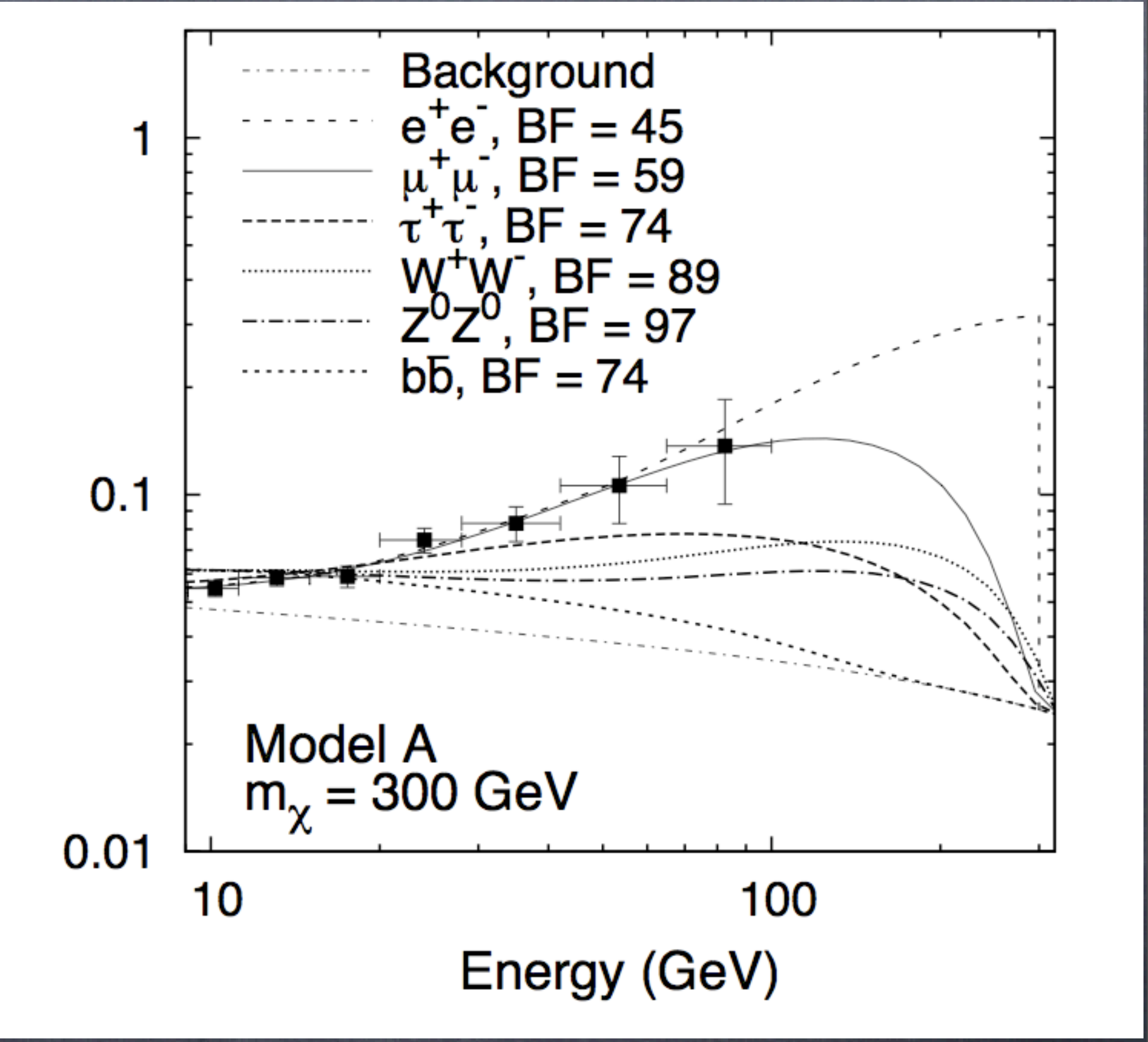

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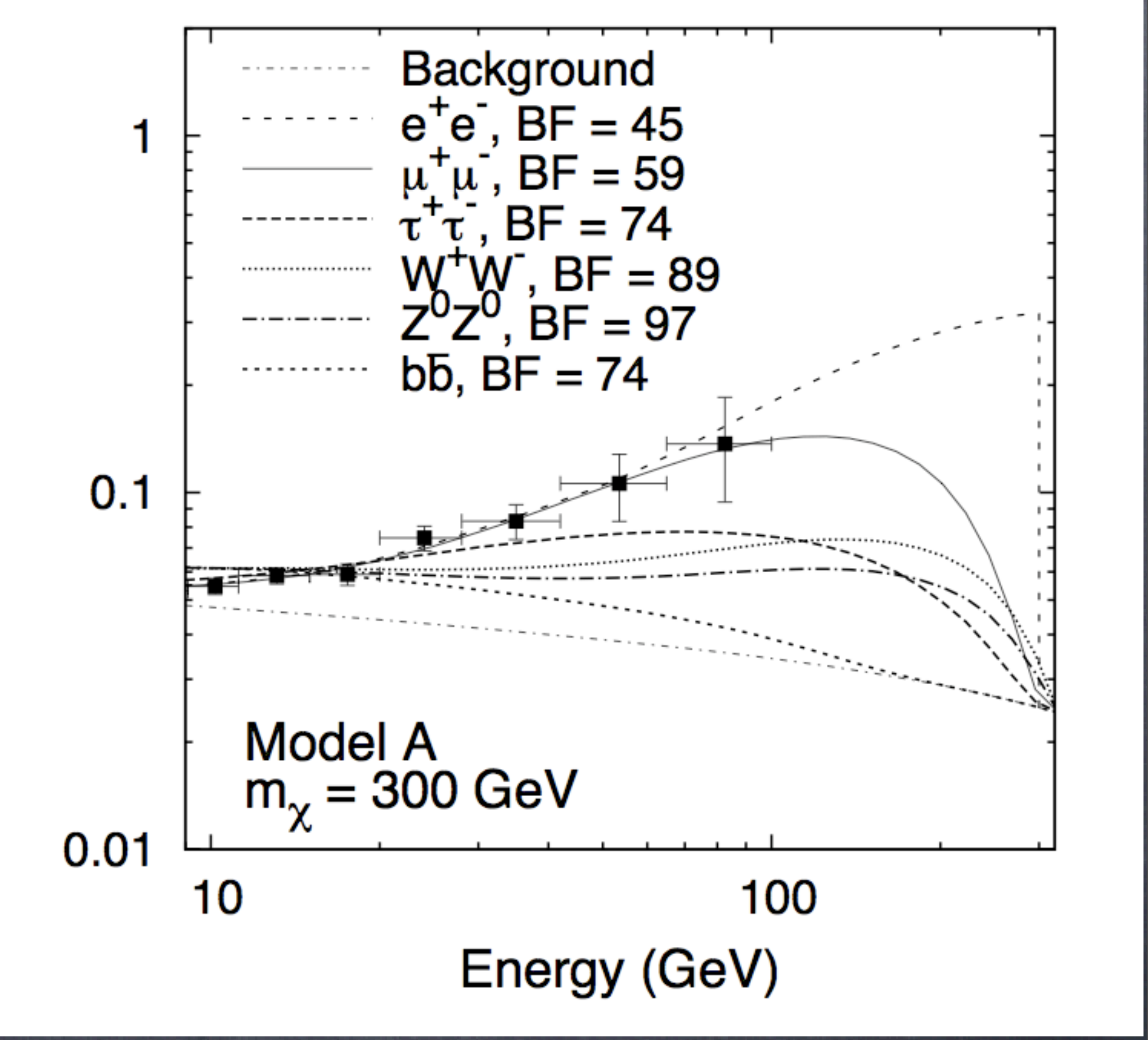

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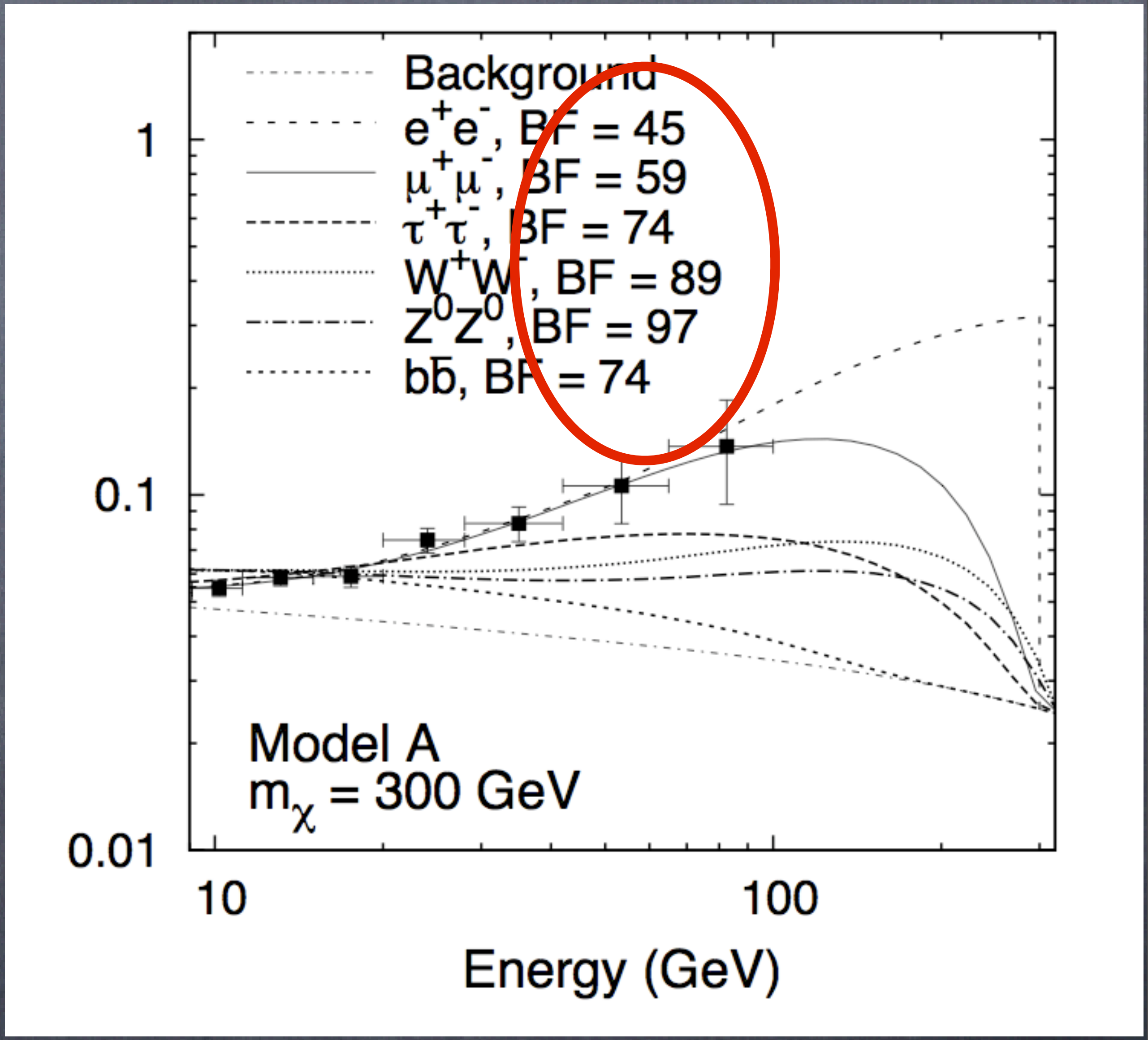

The three ingredients to explain PAMELA*

*Dark matter could also decay instead of annihilating

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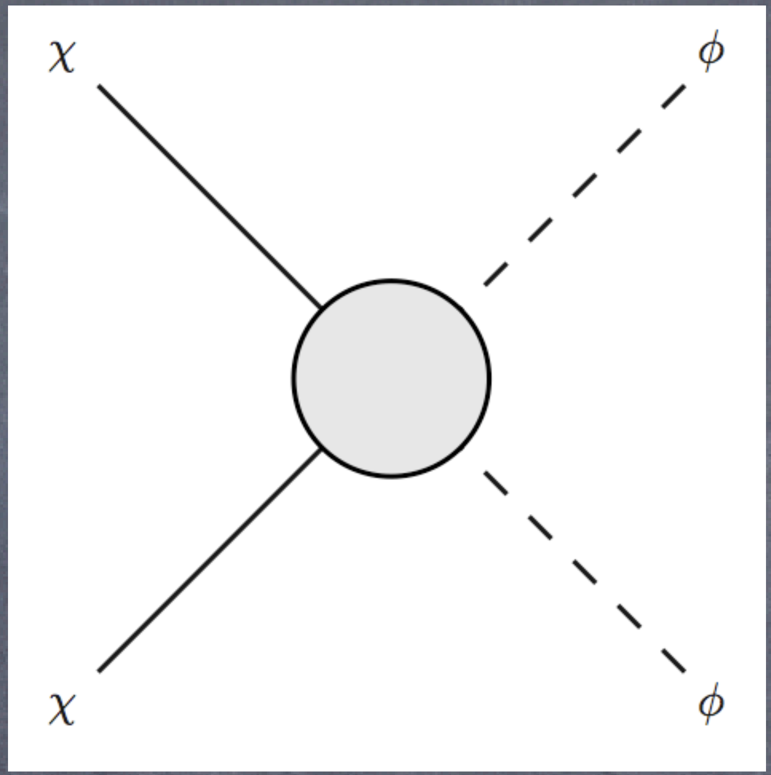
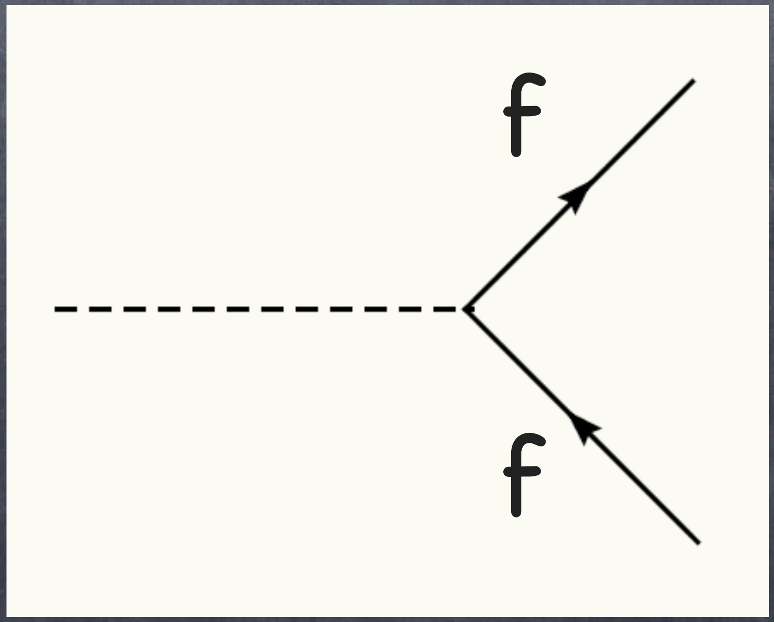
- All these can be explained by insisting that the dark matter is charged under G_{dark} which is broken at the GeV scale, weakly mixed with the SM
- Other possibilities with similar structure [e.g., gauge boson coupled to lepton number (Fox and Poppitz '08), axion (Nomura and Thaler '08)] have similar pheno

New forces = new annihilation modes





ϕ

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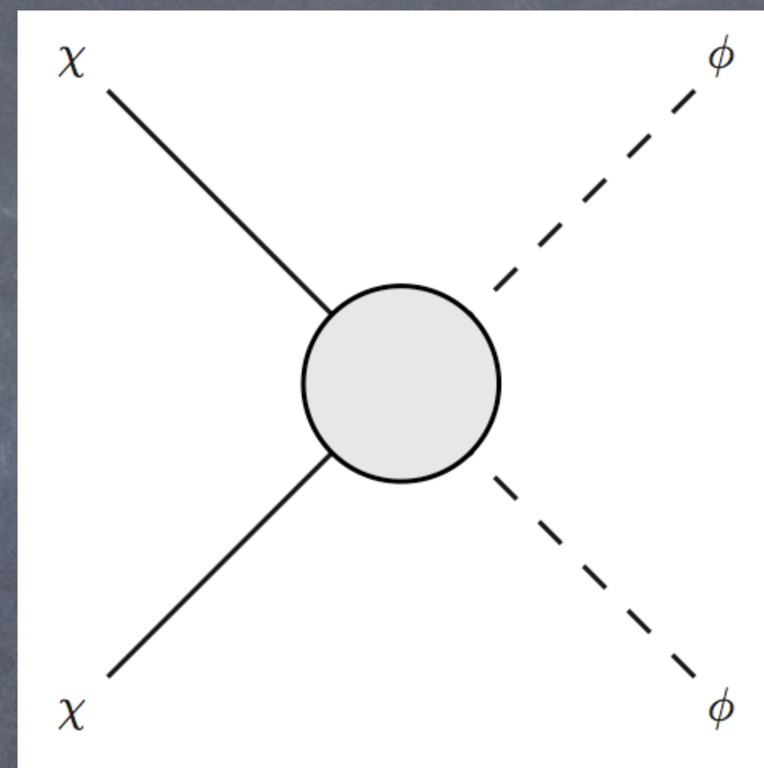

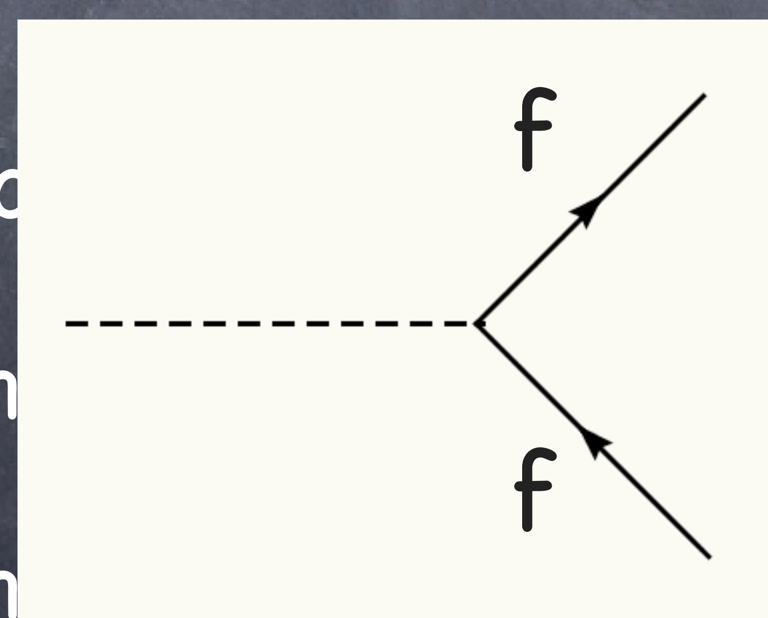

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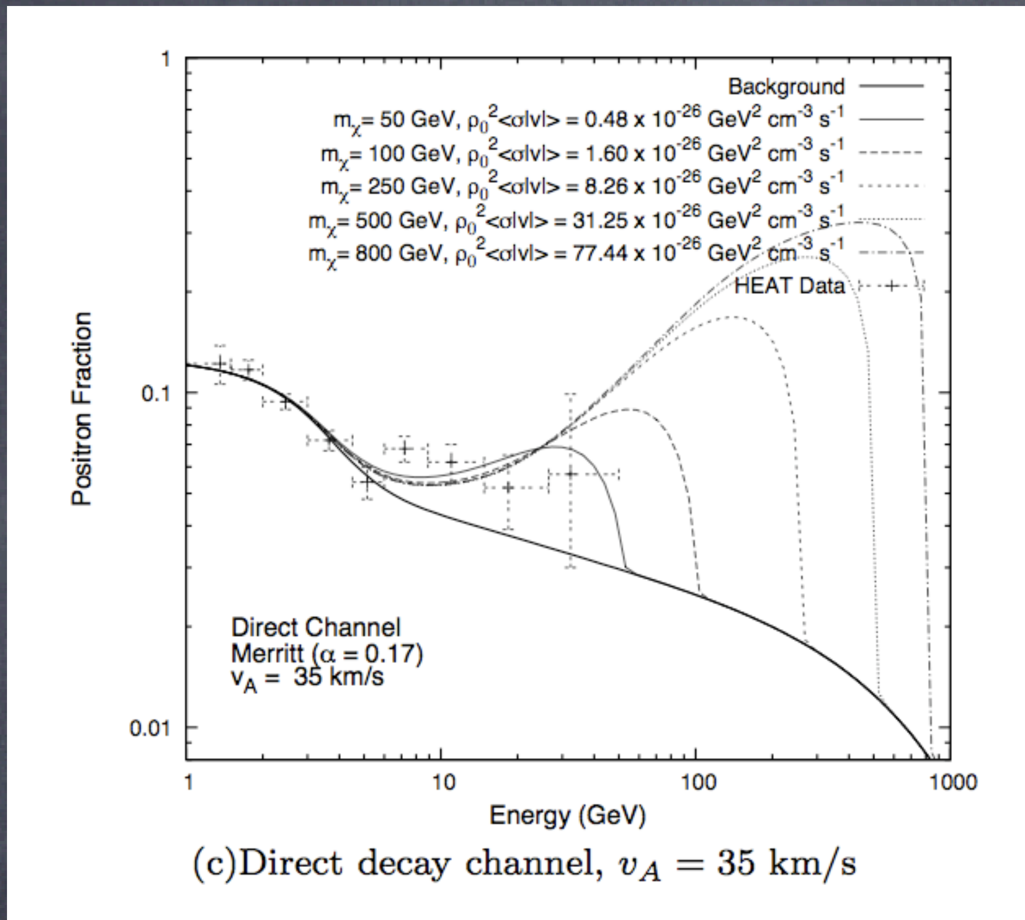

(c)Direct decay channel, $v_A = 35$ km/s

Cholis, Goodenough, NW, arxiv:0802.2922

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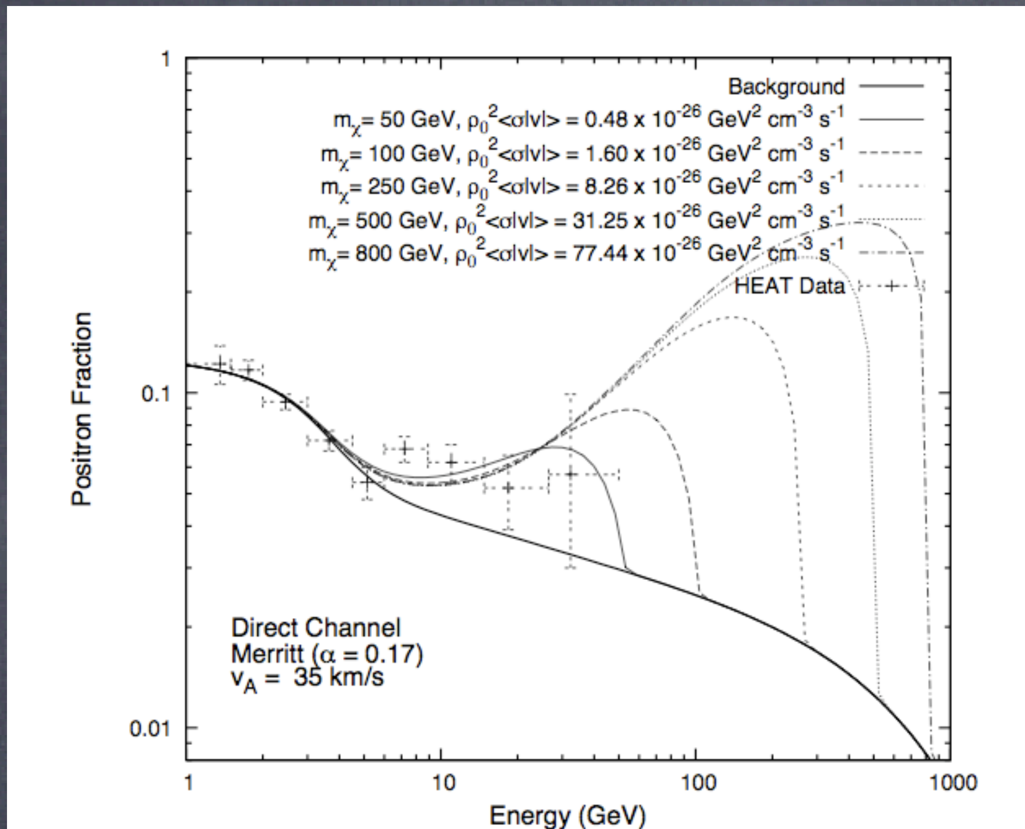

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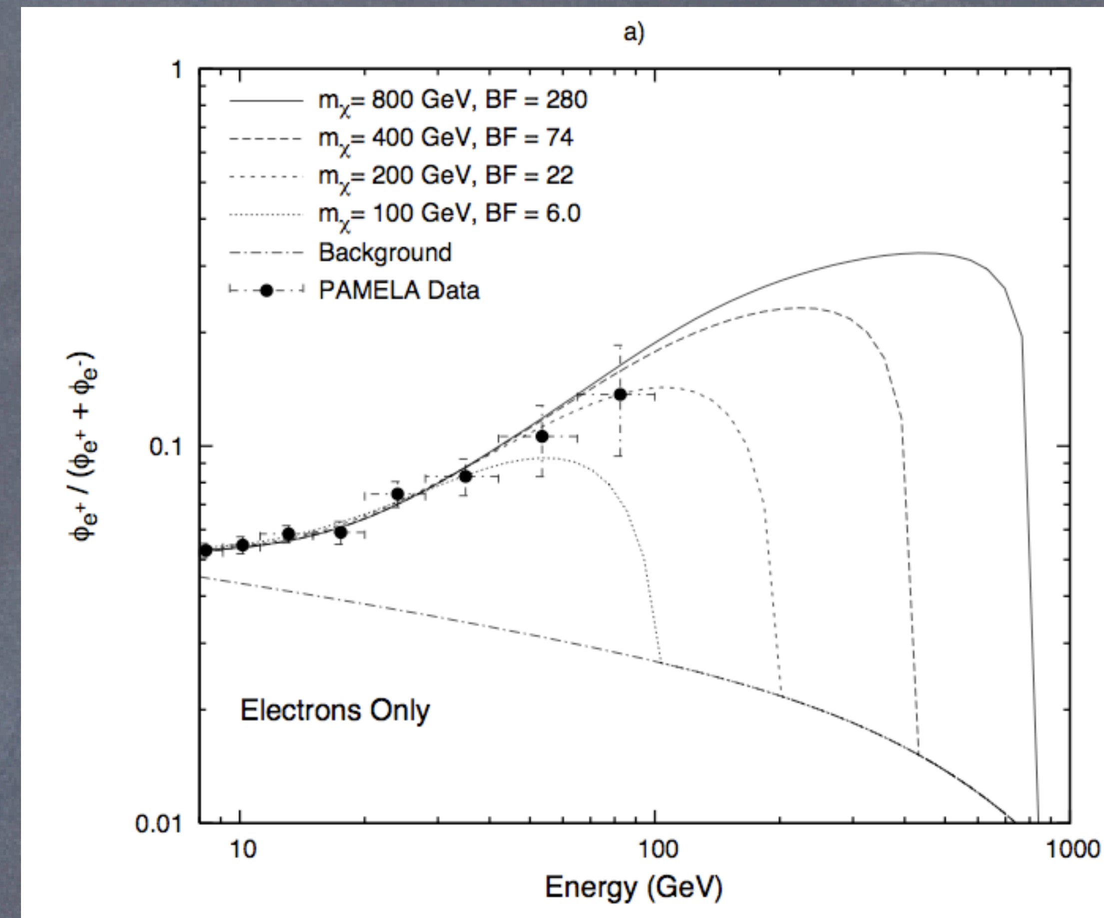

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A cross section conundrum

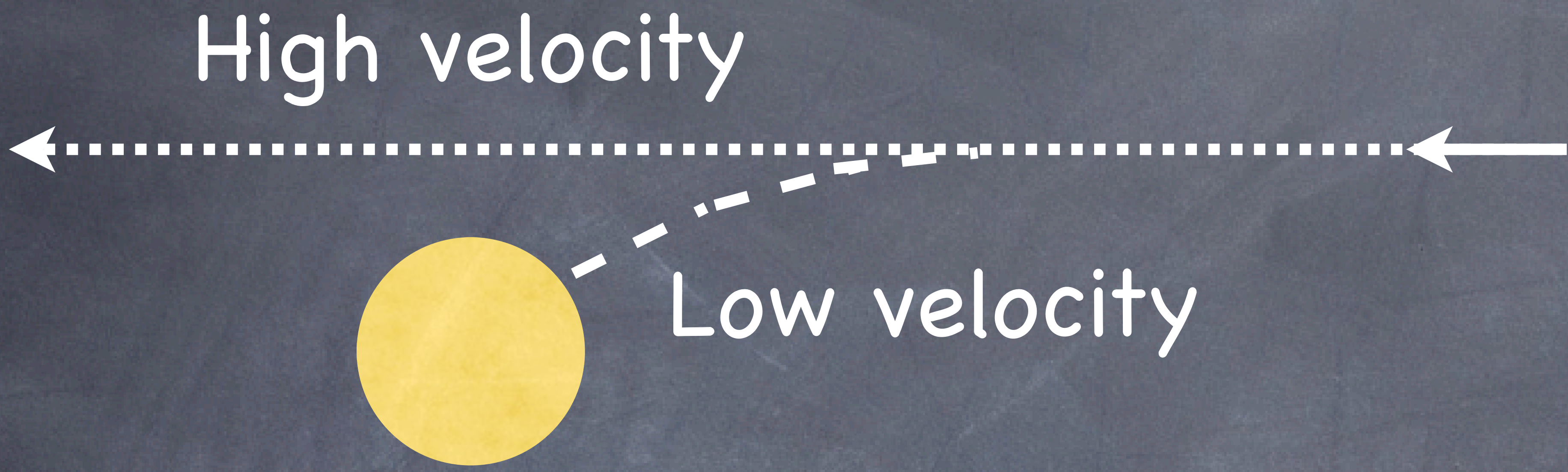
- If the cross section were high enough to yield PAMELA/ATIC/Haze, DM would be depleted in the early universe

Sommerfeld Enhancement

High velocity

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

Sommerfeld Enhancement



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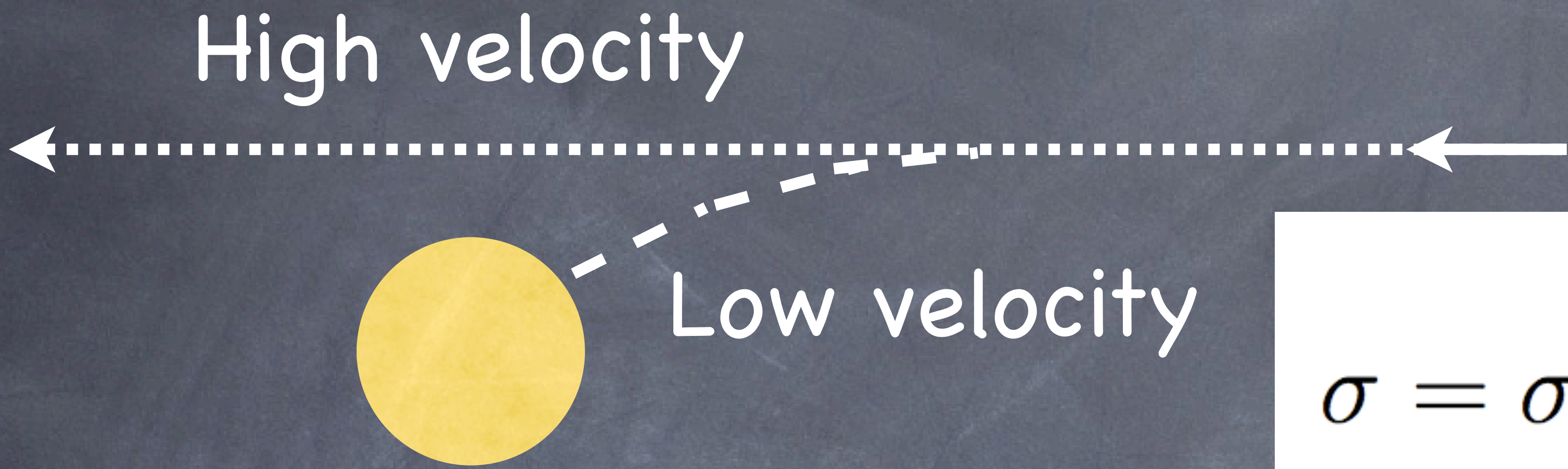

$$\sigma = \sigma_0 \left(1 + \frac{v_{esc}^2}{v^2} \right)$$

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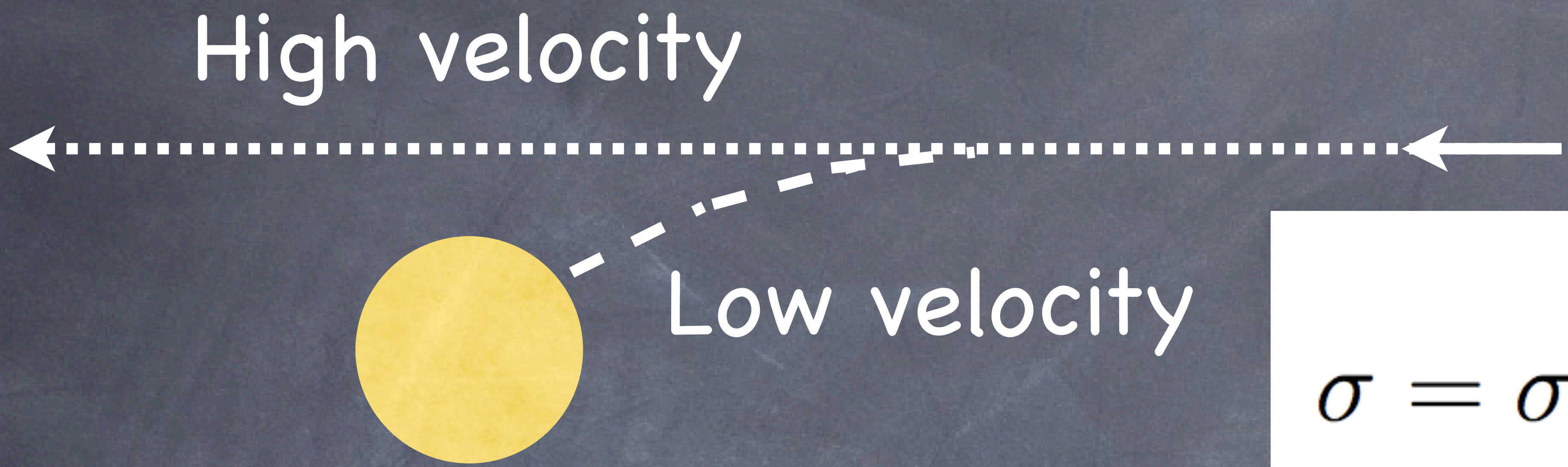

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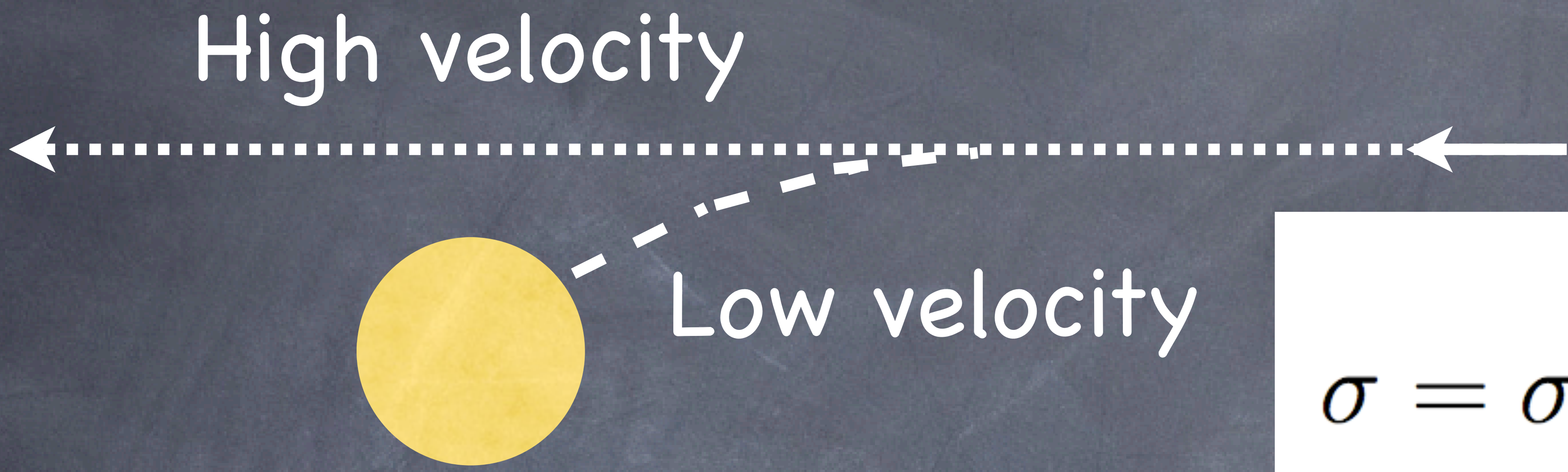

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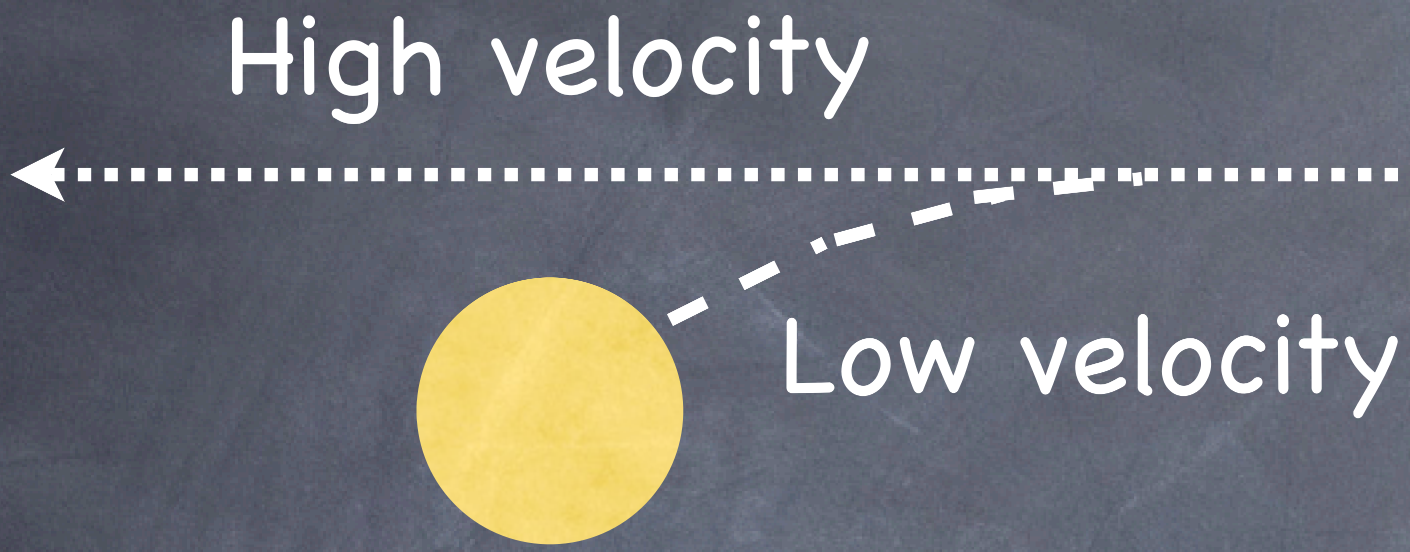

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$$m_\phi^{-1} \gtrsim (\alpha M_{DM})^{-1}$$

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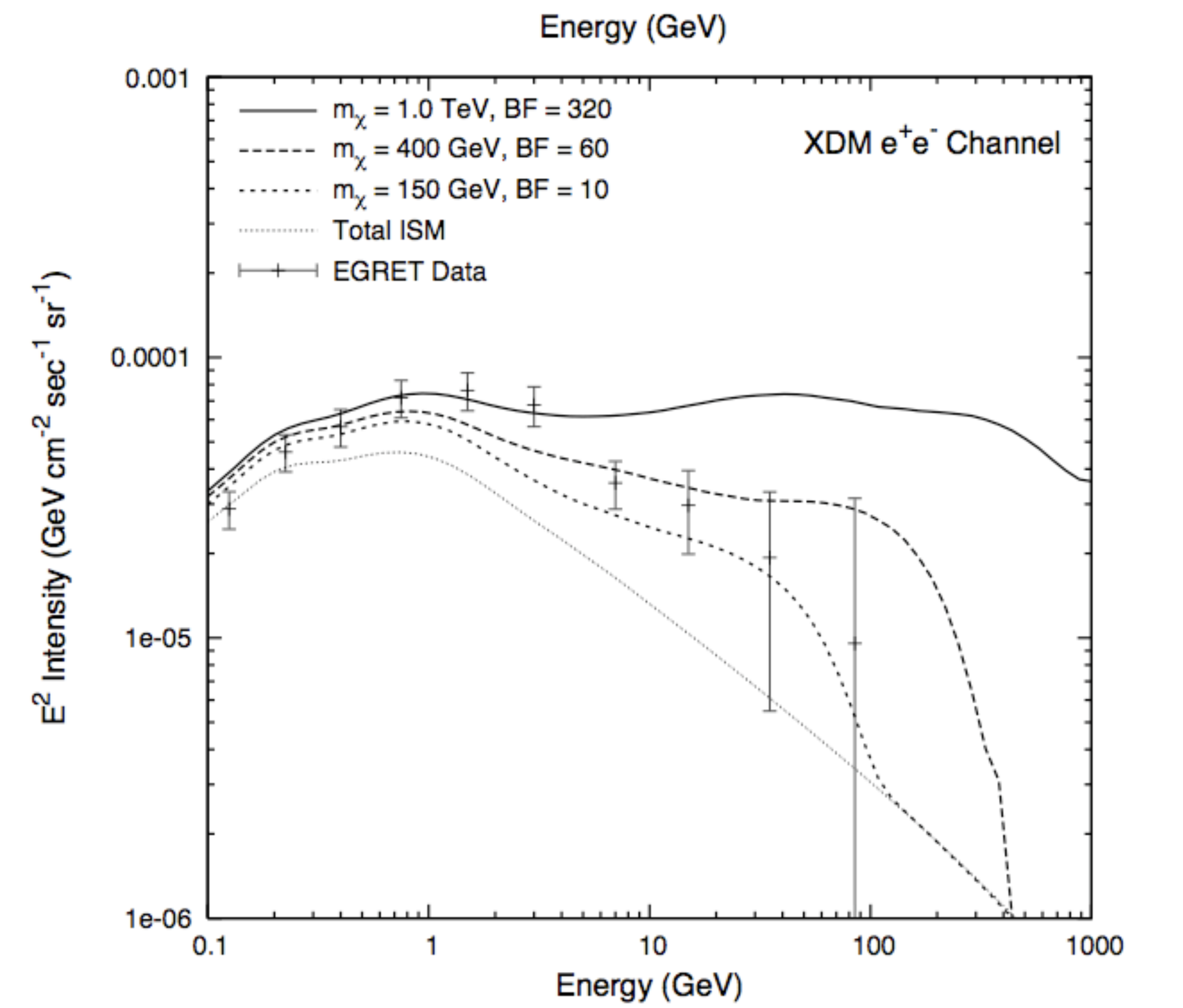
- These particles would synchrotron radiate in the 22-90 GHz range
- This is precisely the original interpretation of the Haze (Finkbeiner, astro-ph/0409027)
- Essentially any annihilating DM model that explains PAMELA will naturally explain the Haze as well

Fermi/GLAST Signals



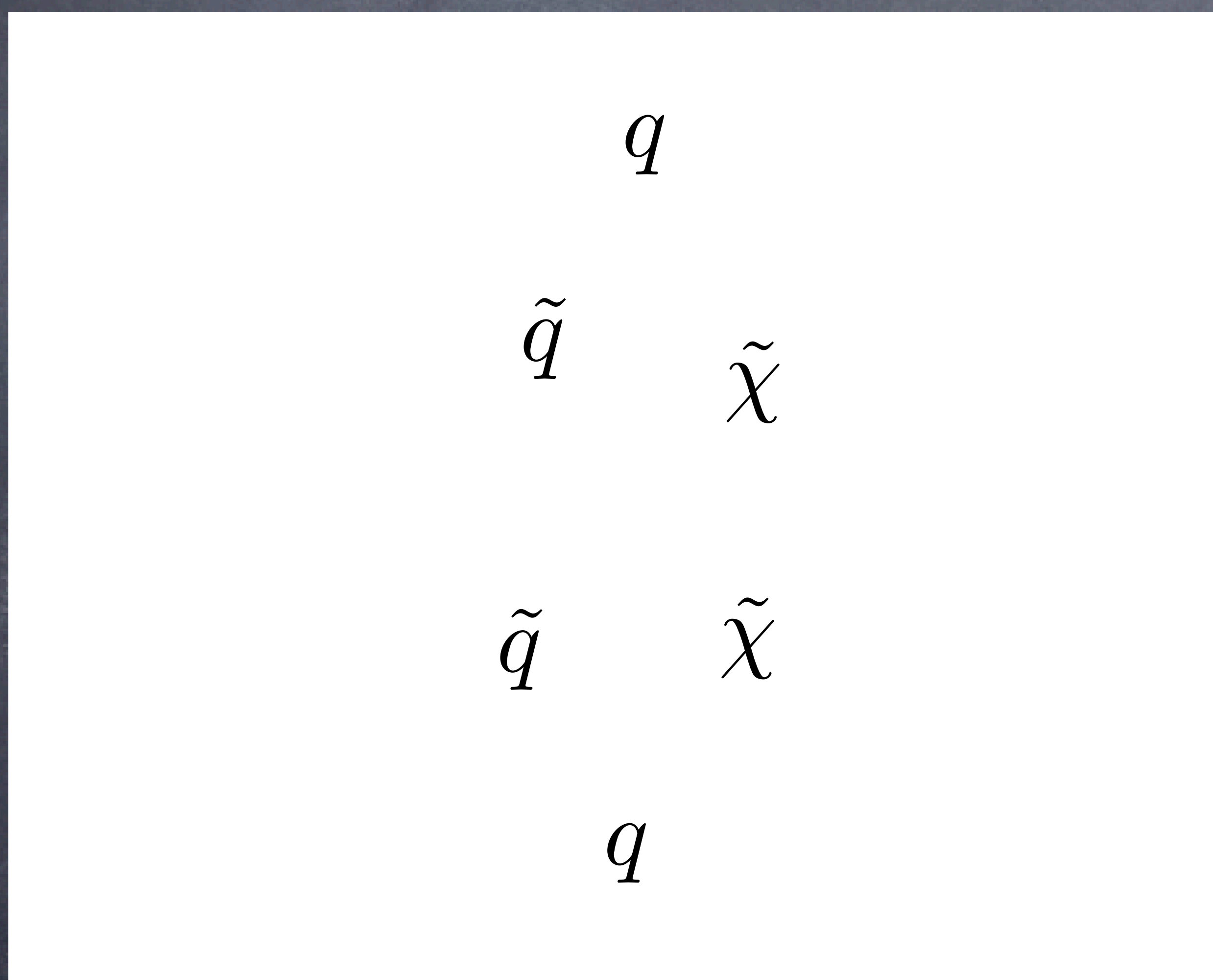
- Inverse-Compton Scatter photons in GC should be robust signature

Also many opportunities for ACTs from final state radiation from dwarfs (in progress)

New Collider Pheno: Lepton Jets

- Production of G_{dark} states, yield boosted, highly collimated leptons ("lepton jets")

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



invariant mass ~GeV

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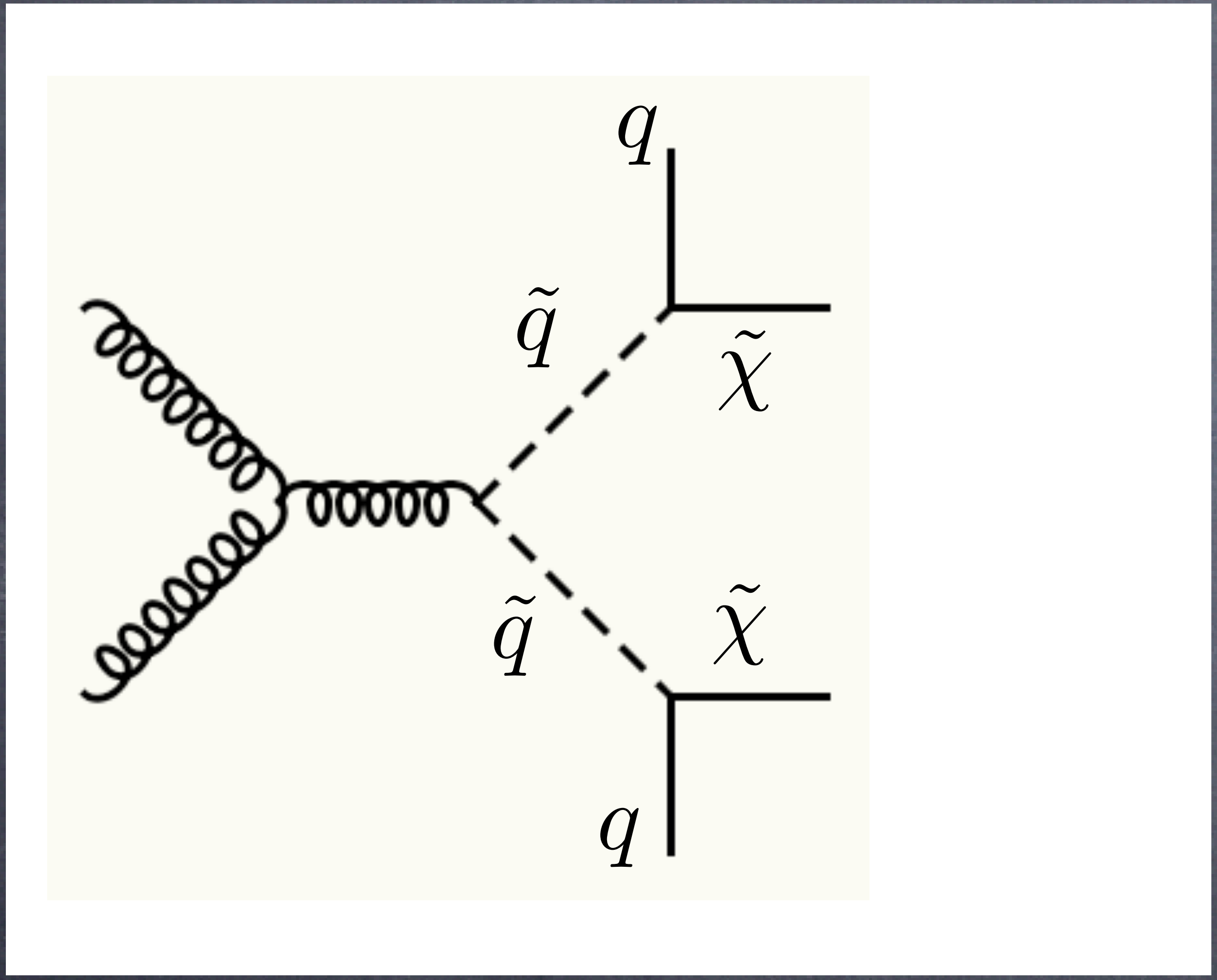

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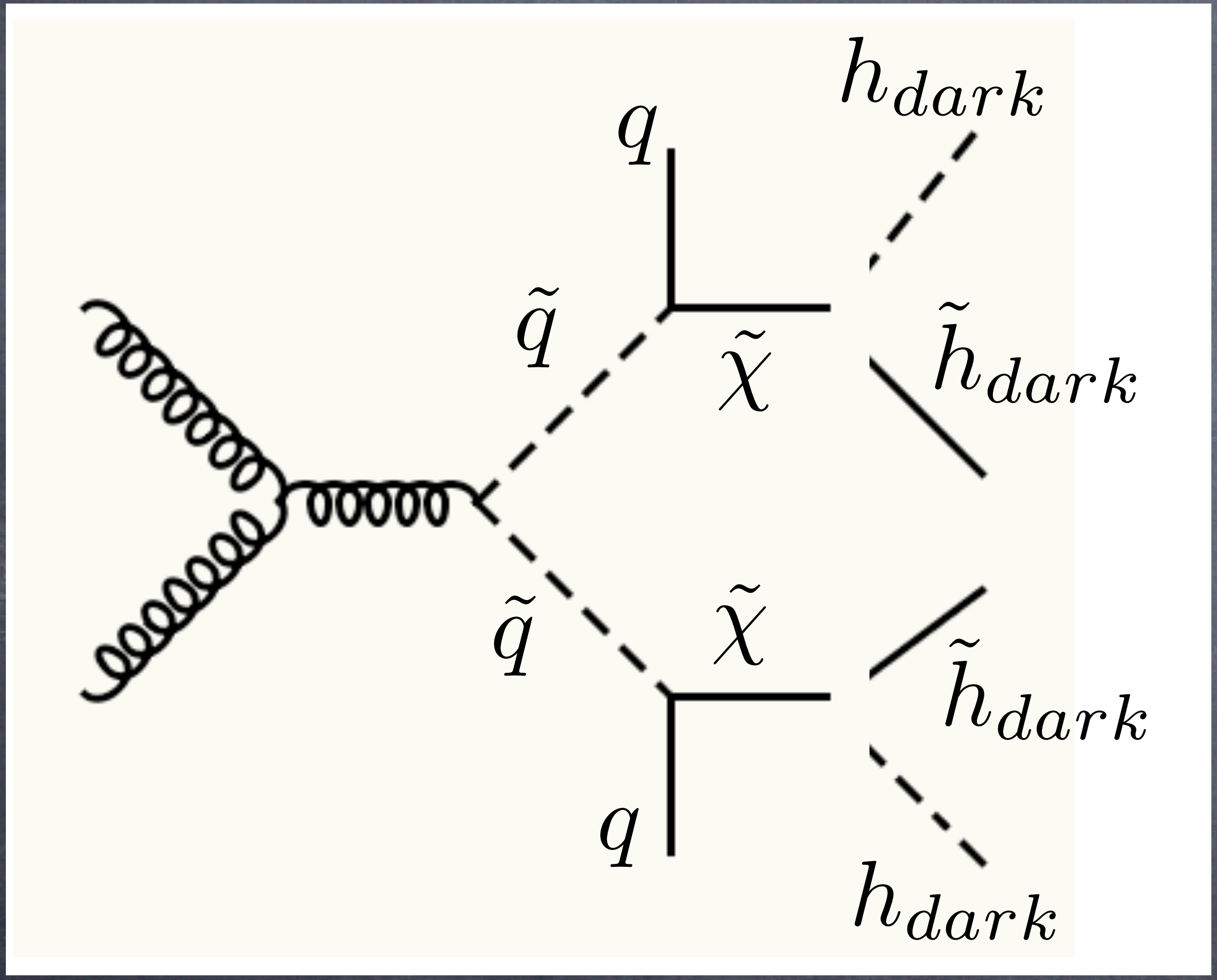

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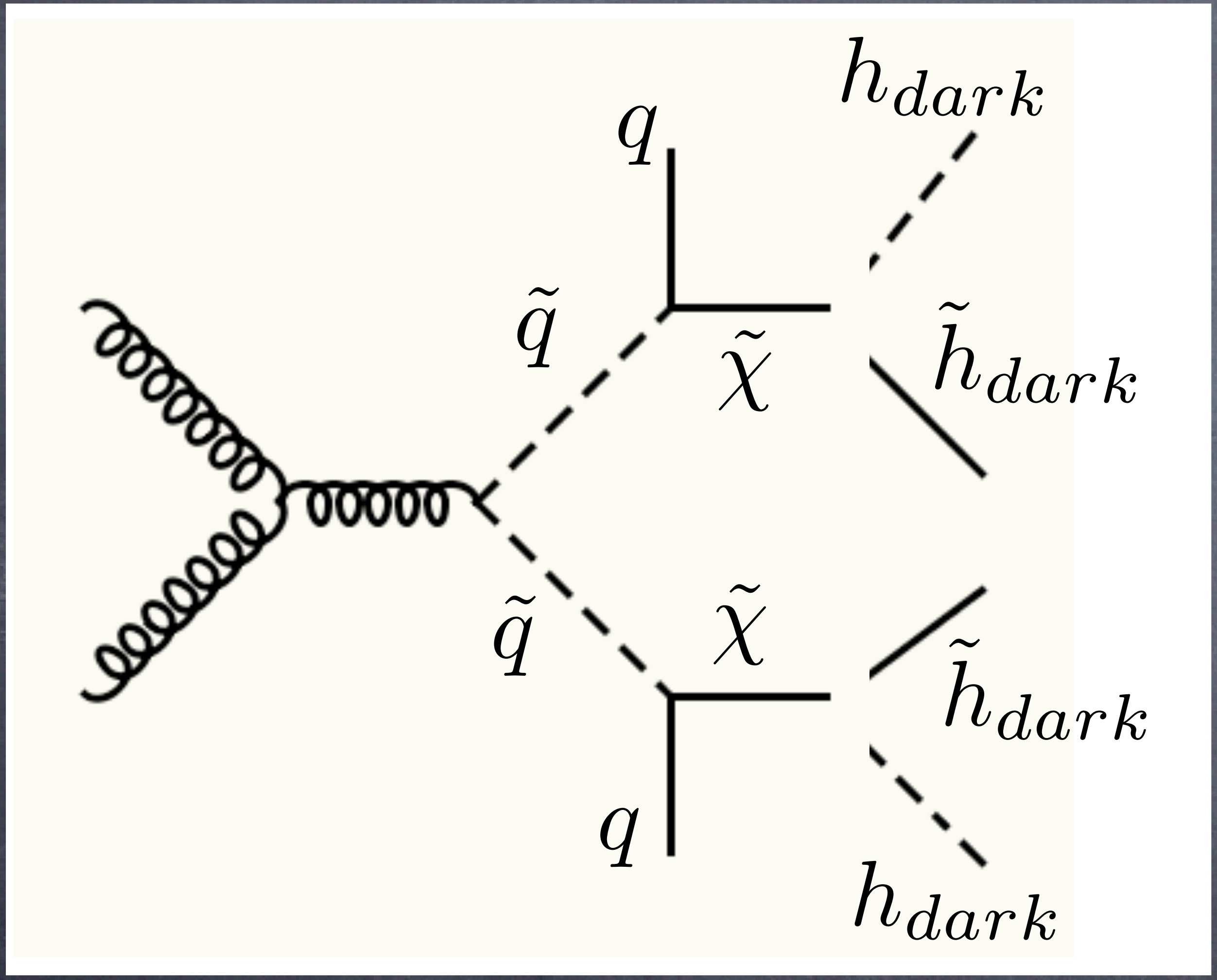

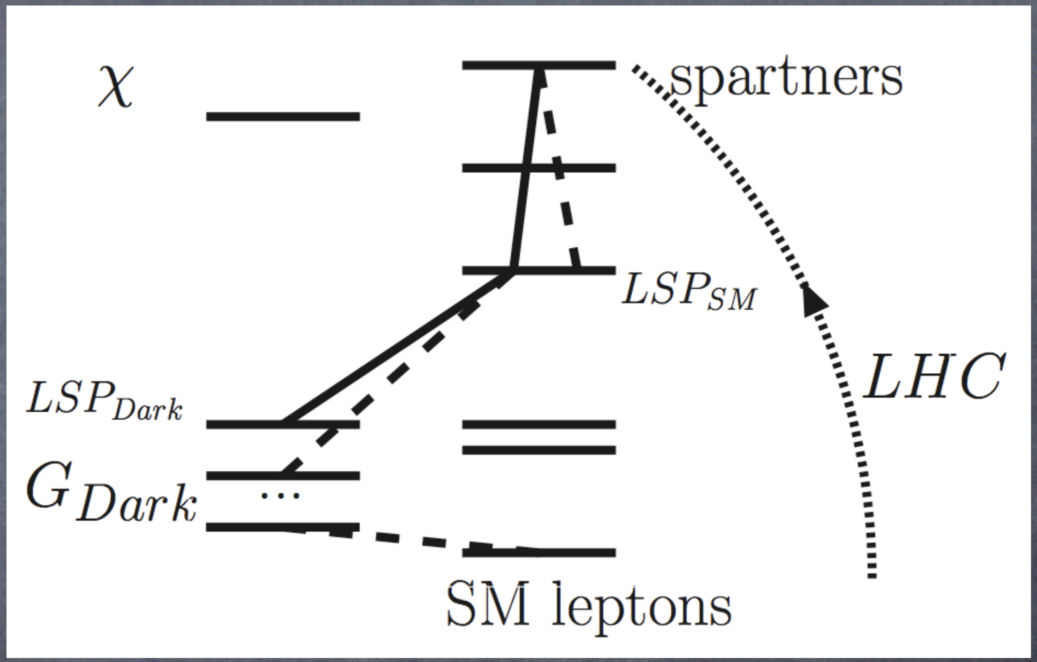

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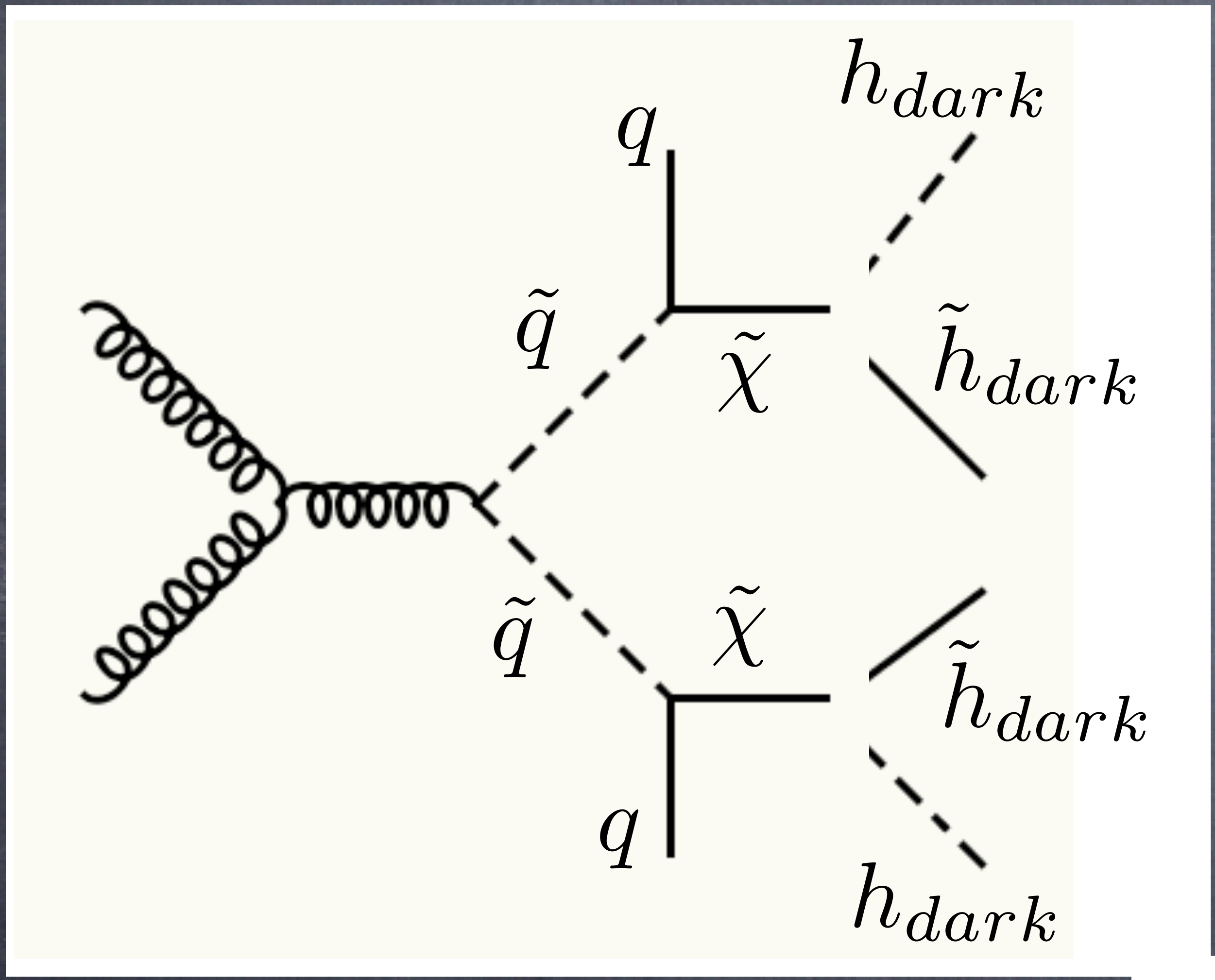

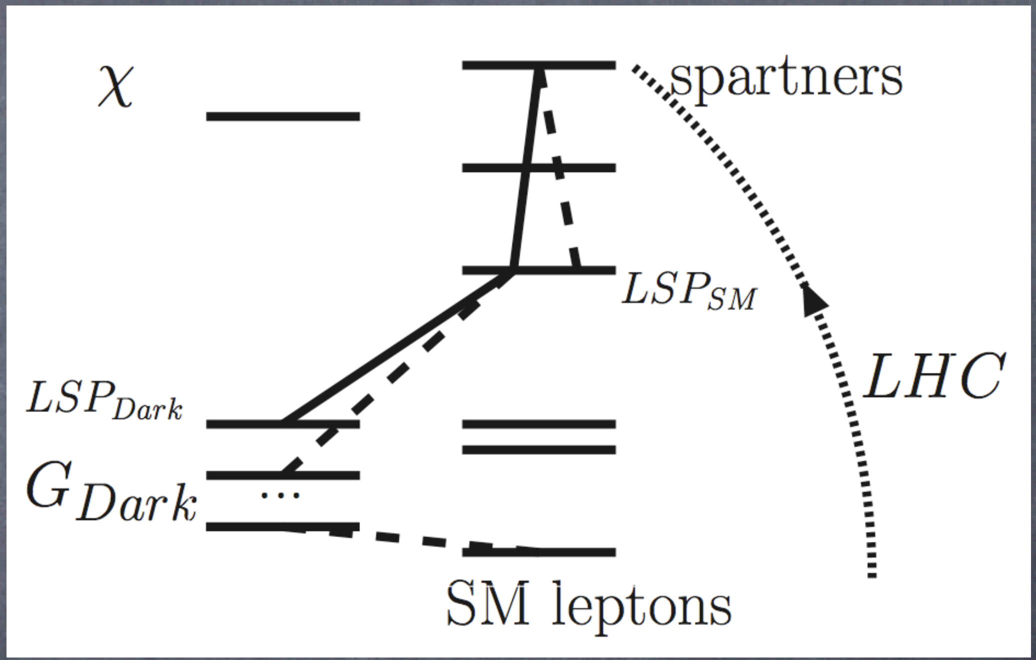

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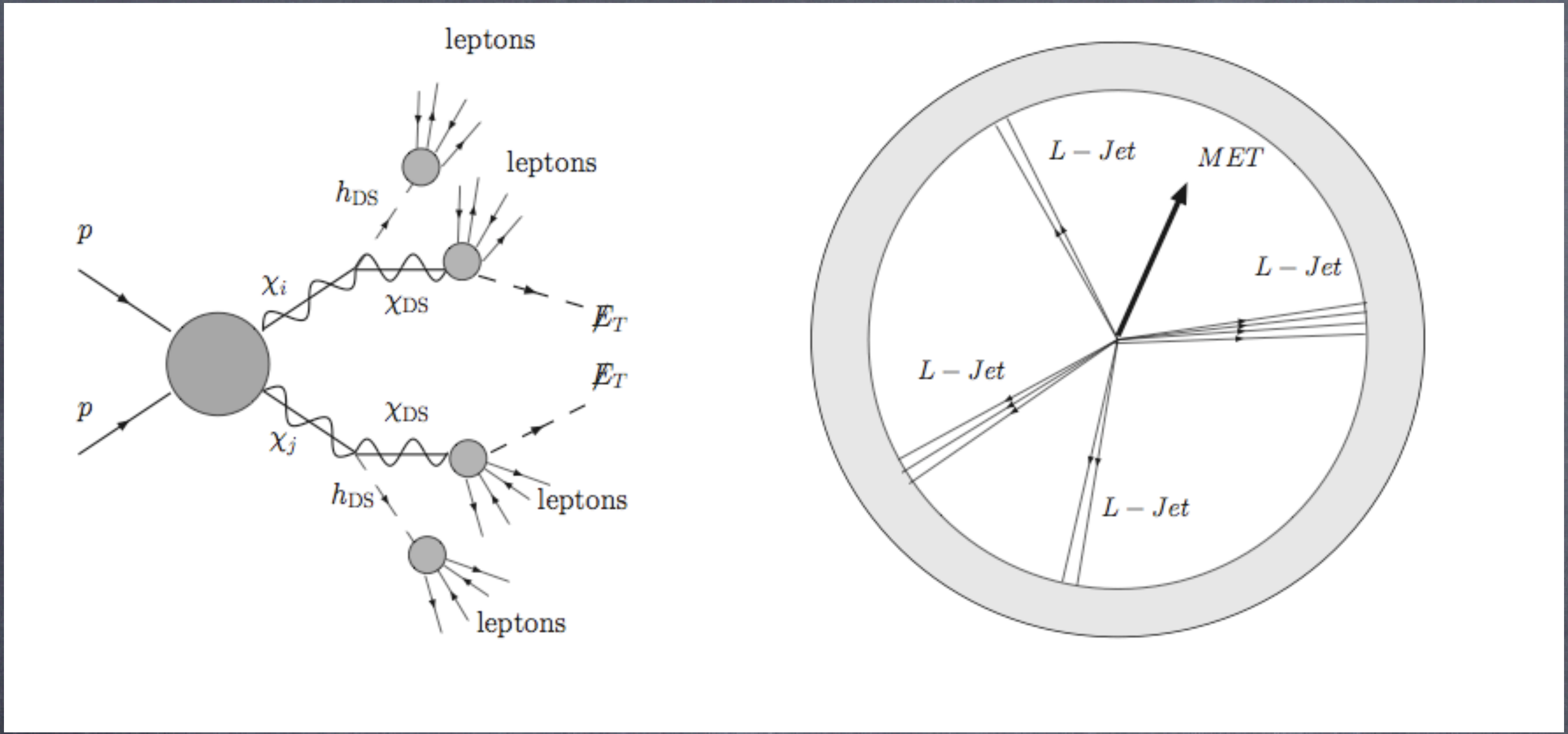
$$\tau \sim (\alpha\epsilon^2 m_{Z_{Dark}} N_{decaychannels})^{-1} \sim (\frac{10^{-7}}{\epsilon})^2 cm$$



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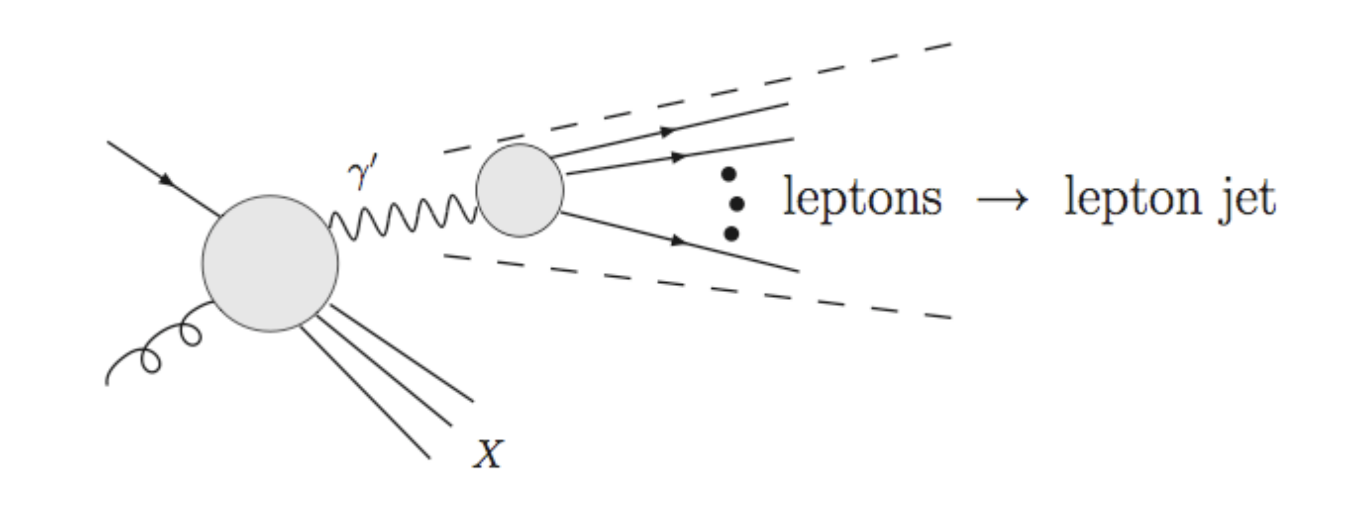
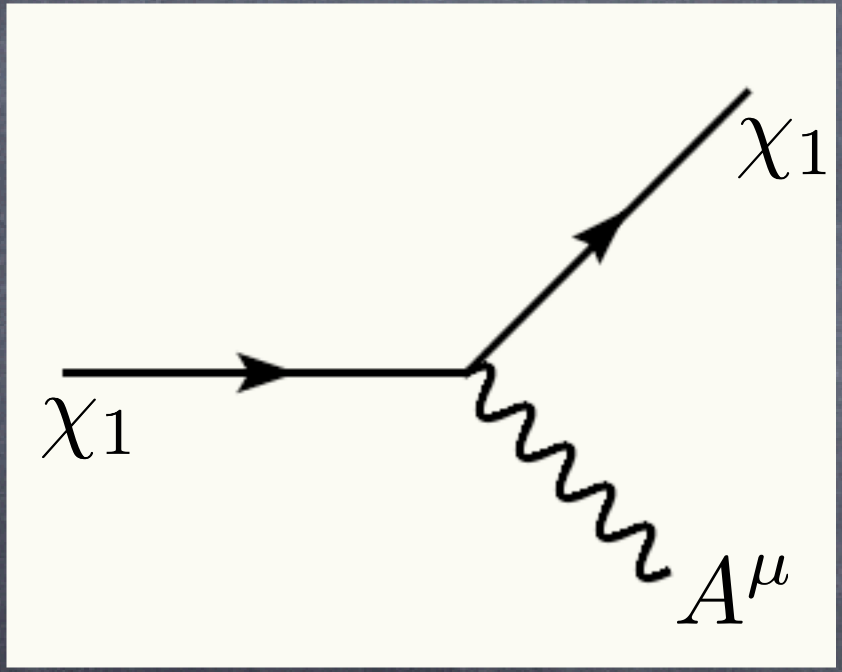


- Missing Energy Signatures no longer key signal of DM sector
- Direct production of new dark forces - reexamination of low energy e+e- data (being done)

Direct Detection and DAMA

Consider vector interaction

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



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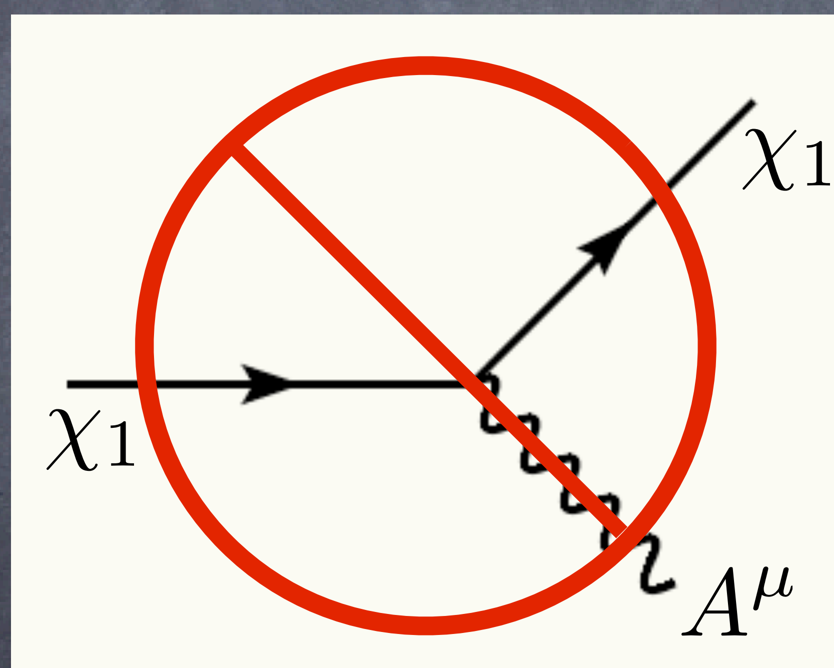
$$\cancel{\chi_1 \sigma_\mu \chi_1 A^\mu}$$



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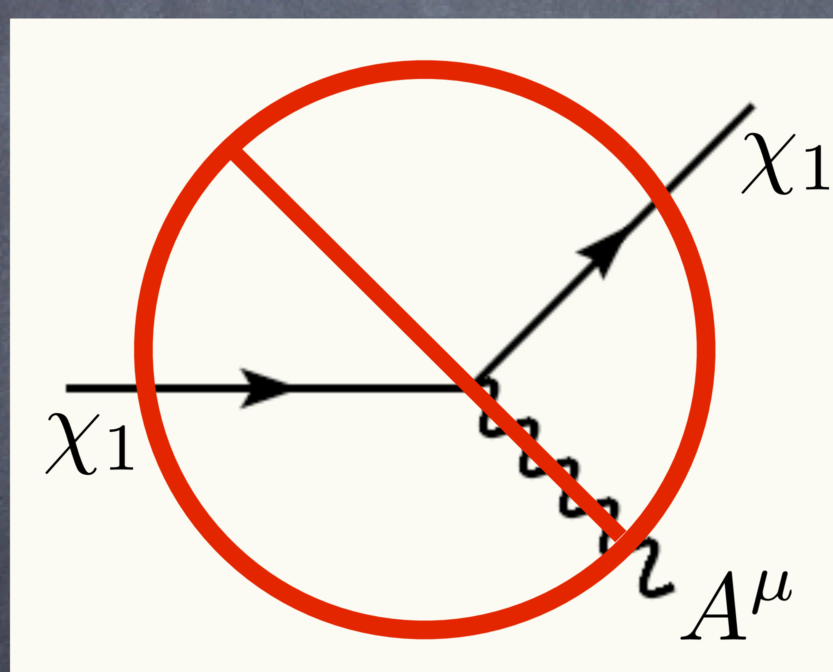

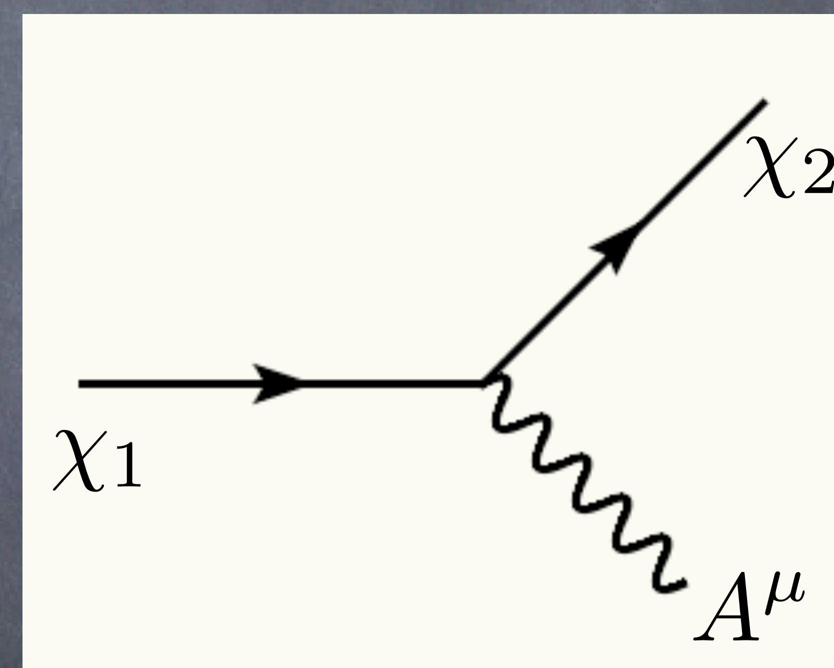

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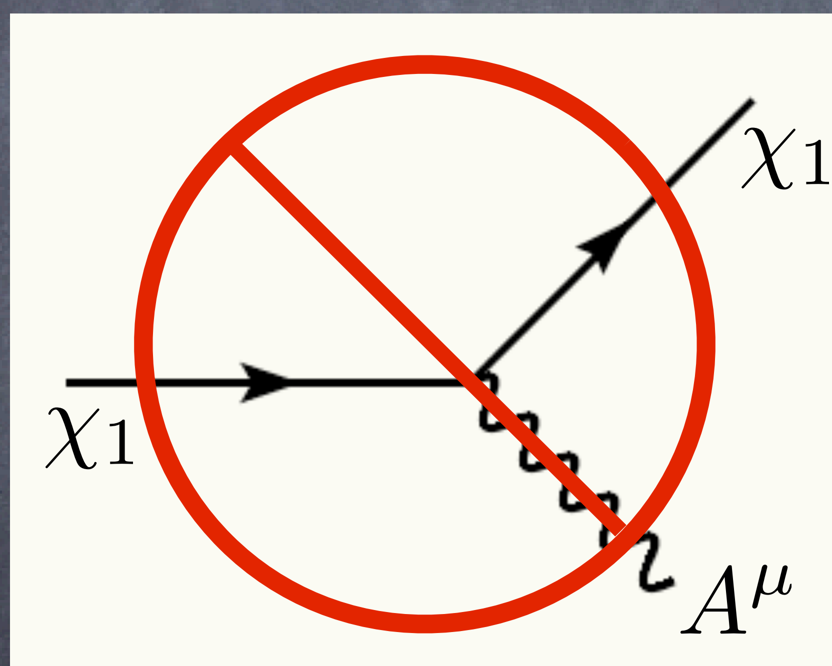
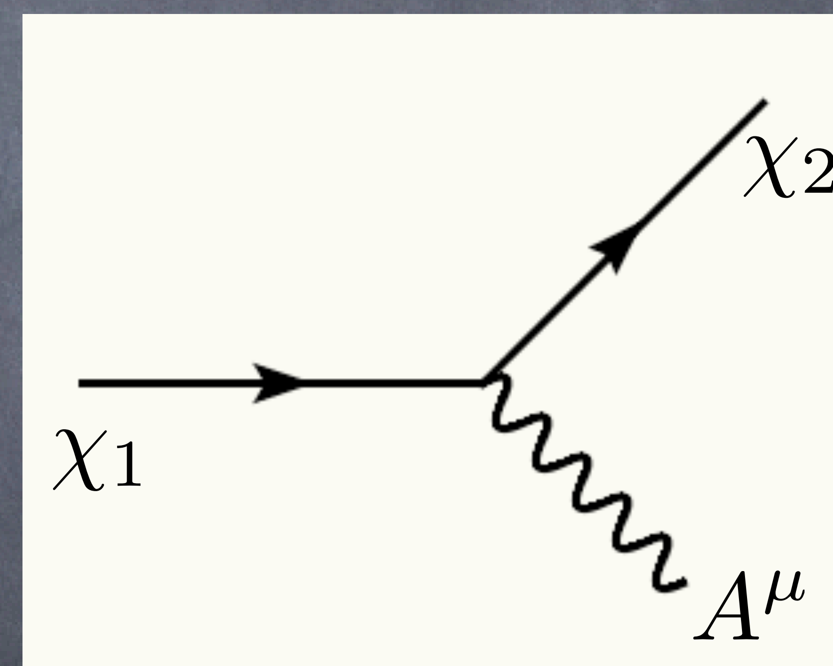
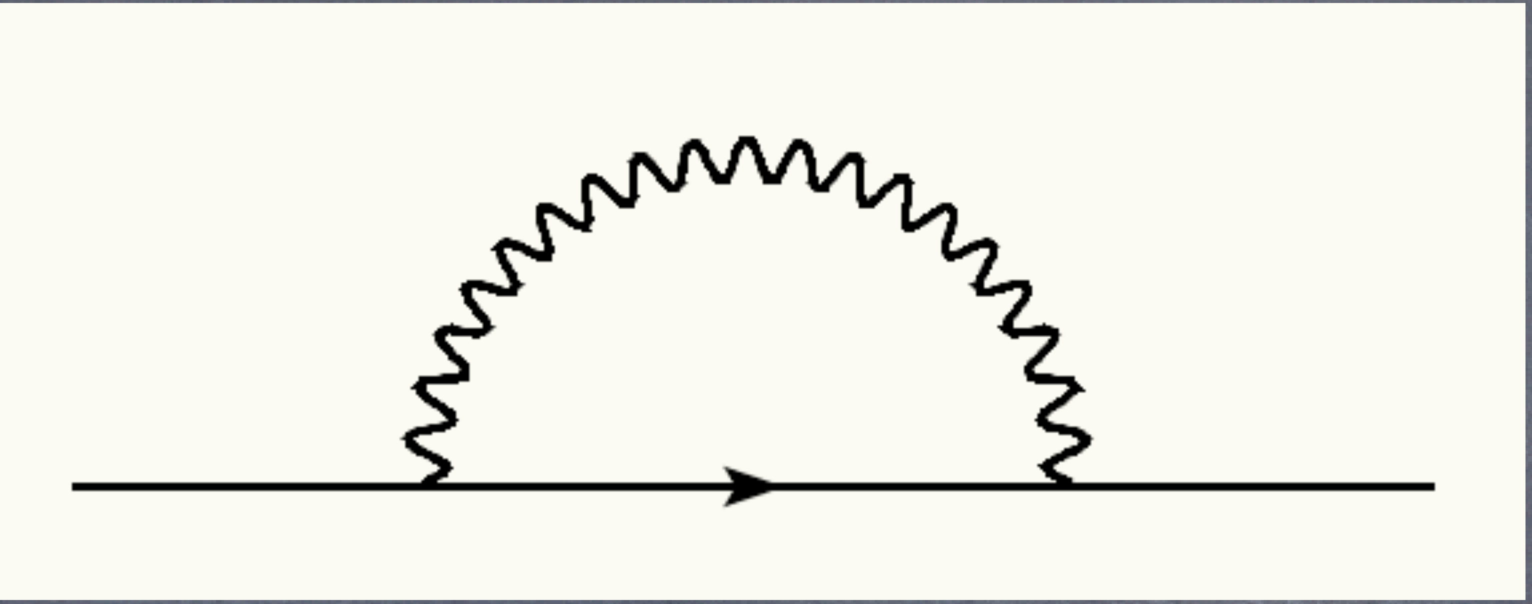




Vector interaction => multiple DM states; for Sommerfeld, these states must be kinematically accessible

$$\delta \lesssim M_\chi v^2$$

Natural scales of splittings



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

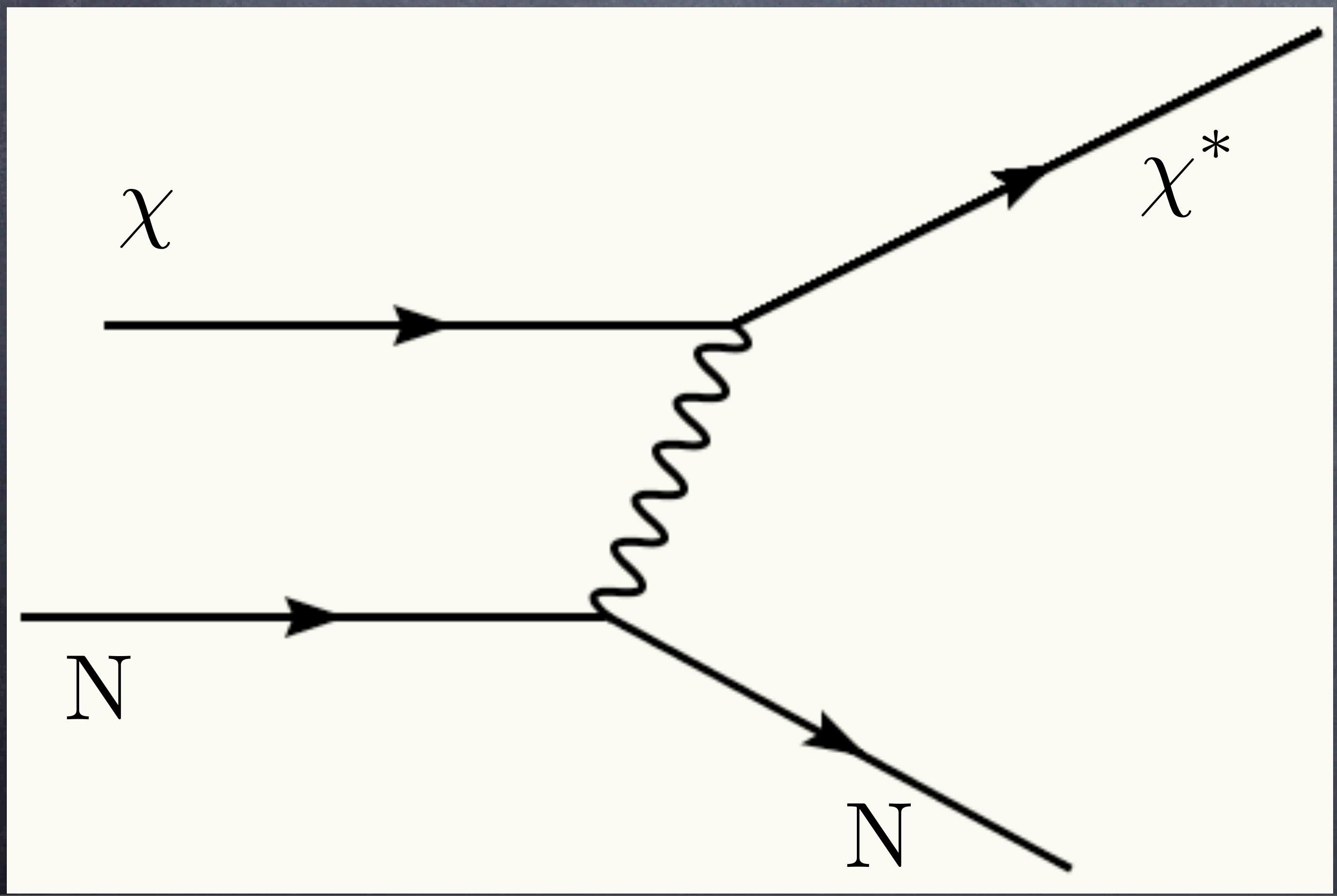
$$\delta \approx \alpha m_A \sim \text{MeV}$$

For SE **require** $\delta \lesssim M_\chi v^2$

“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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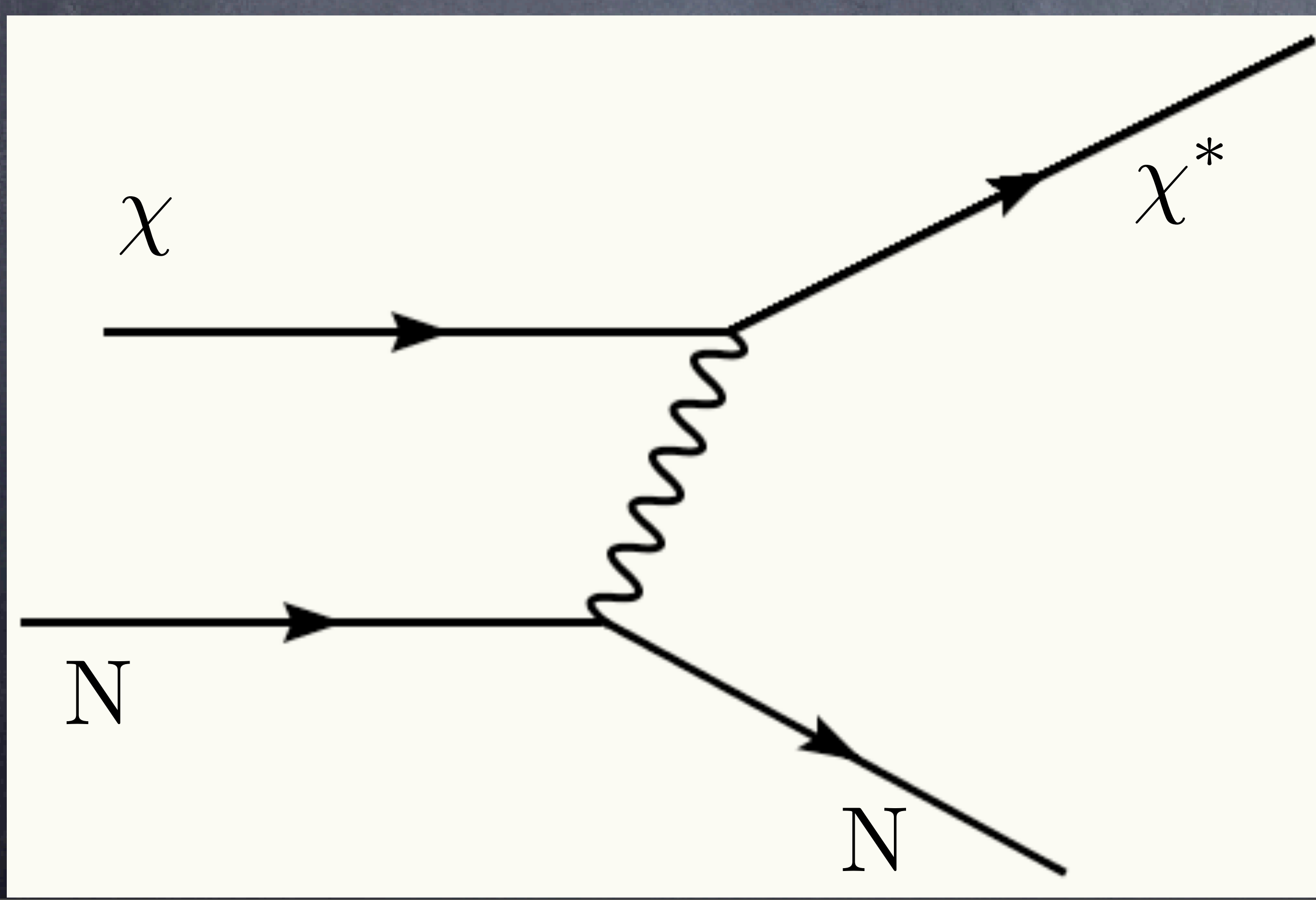

$$\frac{v^2 \mu_{\chi N}}{2} > \delta$$

- Such a scenario
  - Favors heavy targets (Iodine) over light ones (Germanium)
  - Enhances modulation (typically 30%, but up to 100%)
  - Depletes low energy events

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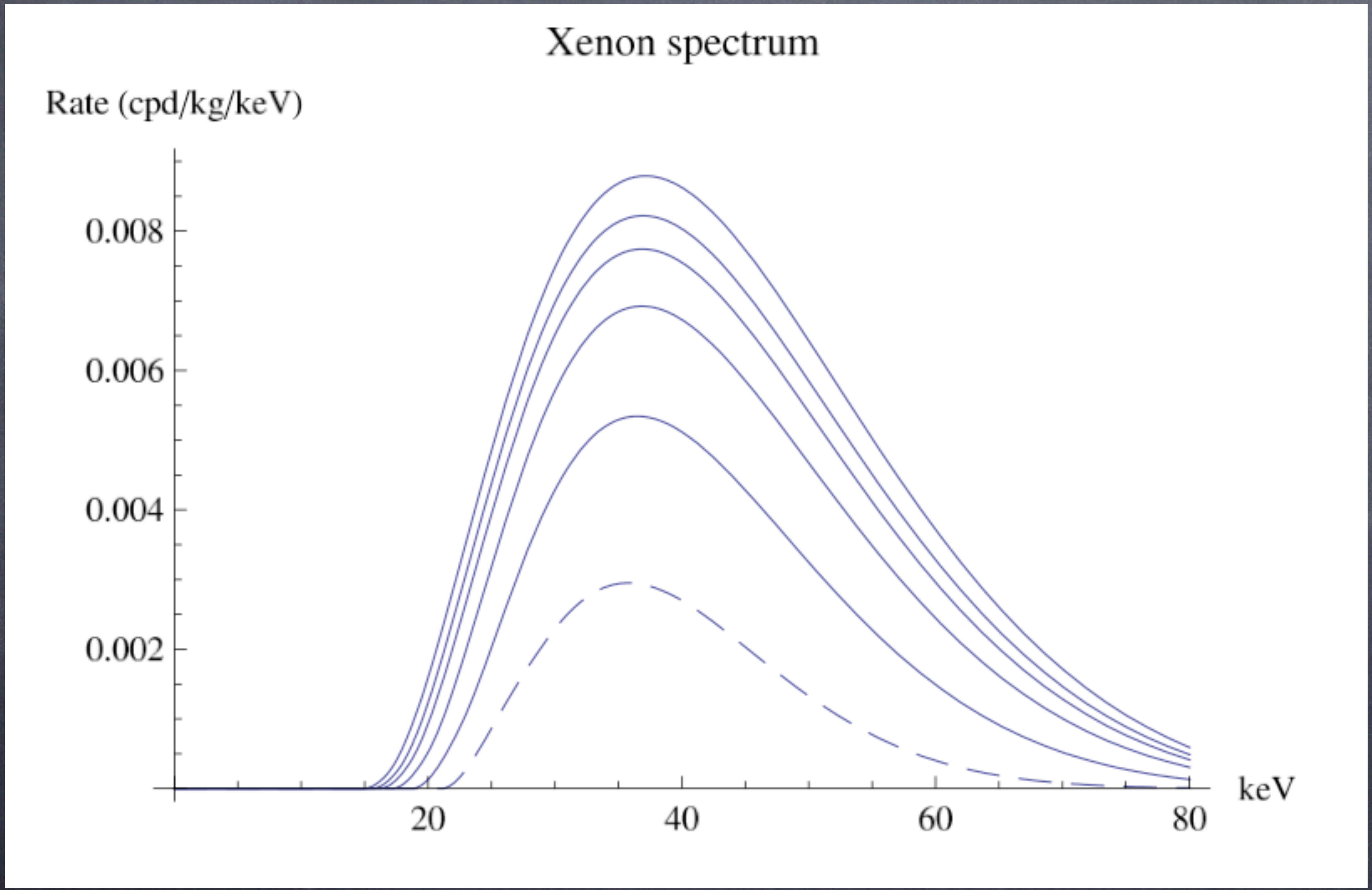
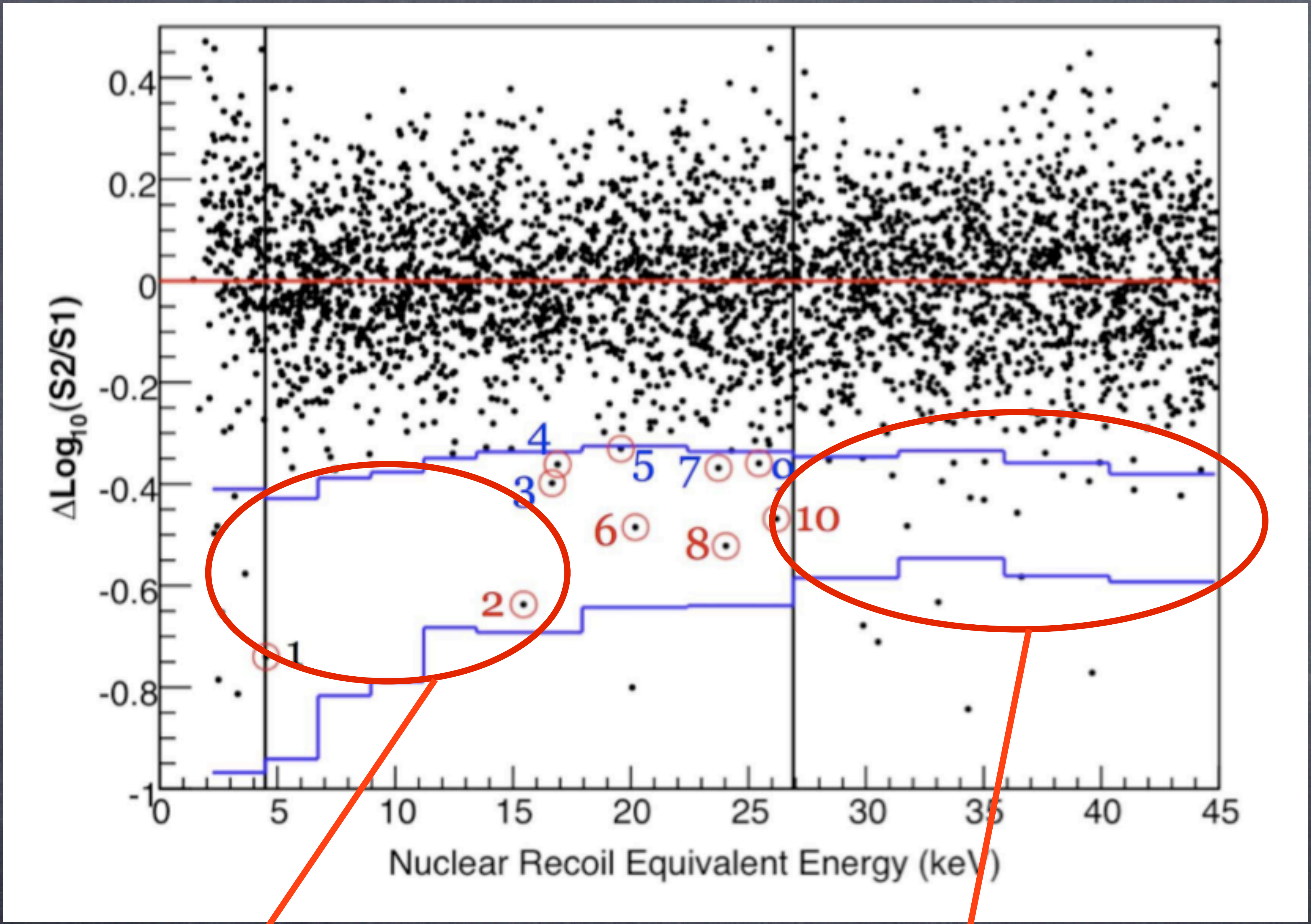
  - Favors heavy targets (Iodine) over light ones (Germanium)
  - Enhances modulation (typically 30%, but up to 100%)
  - Depletes low energy events
- Together these effects allow a positive DAMA signal consistent with other results (CDMS, XENON10, ZEPLIN, CRESST, KIMS)

Focus on the spectrum





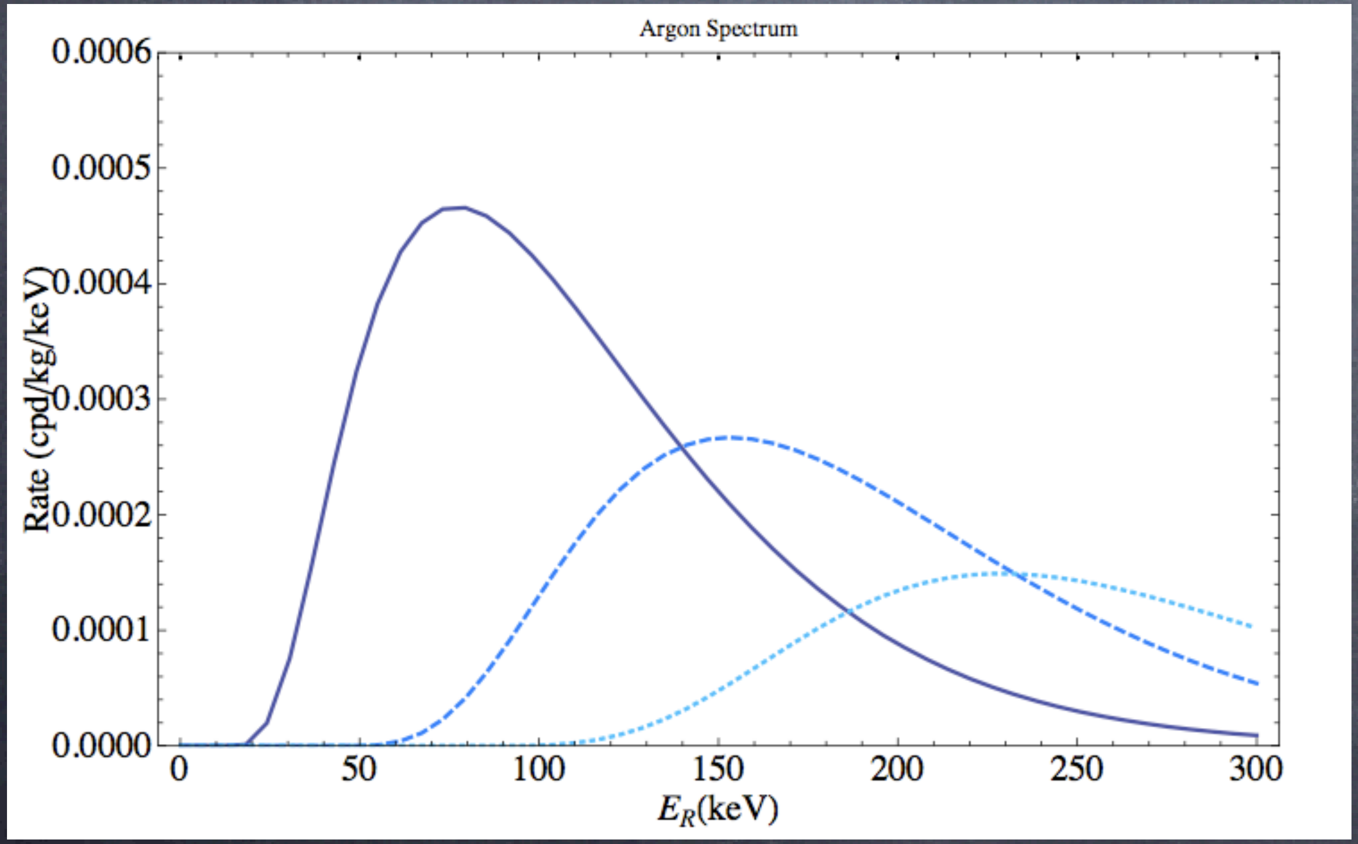
Strong limits from low energies

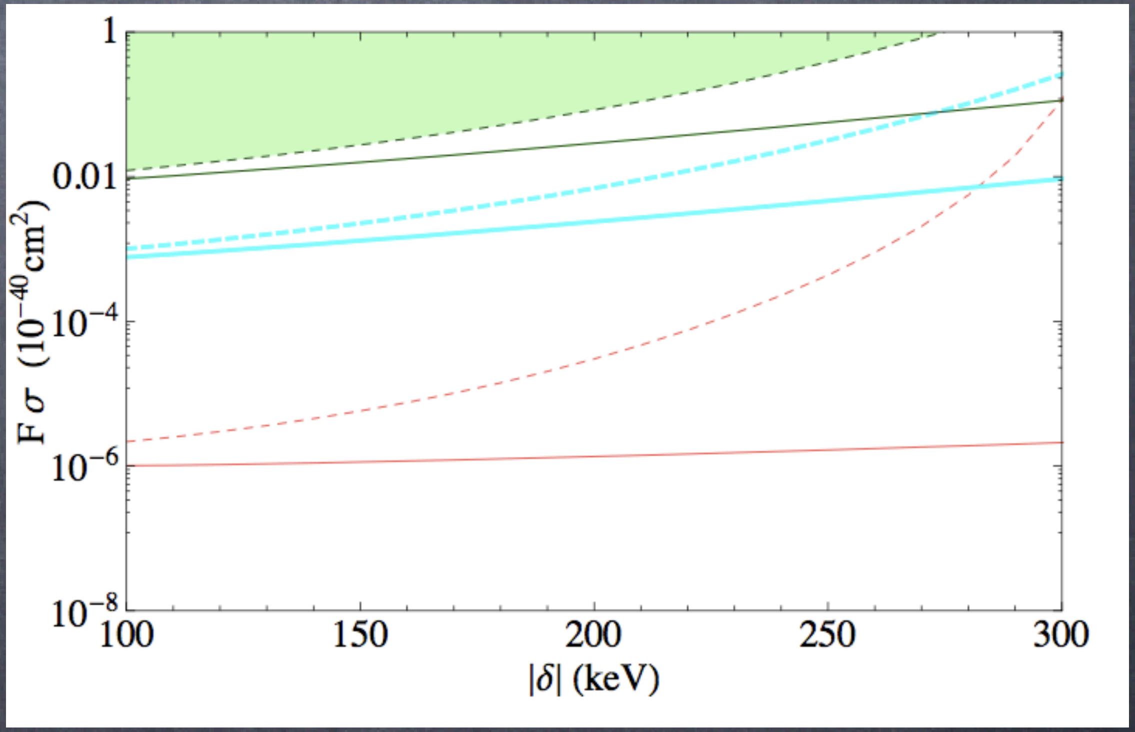
Excess events at higher energies

Down-scattering possible

- Relic populations of excited states are possible

- Can be long-lived - see down-scattering





Conclusions

Historical Perspective

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Evidence for Oscillation of Atmospheric Neutrinos

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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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- Data driven - will know more soon!

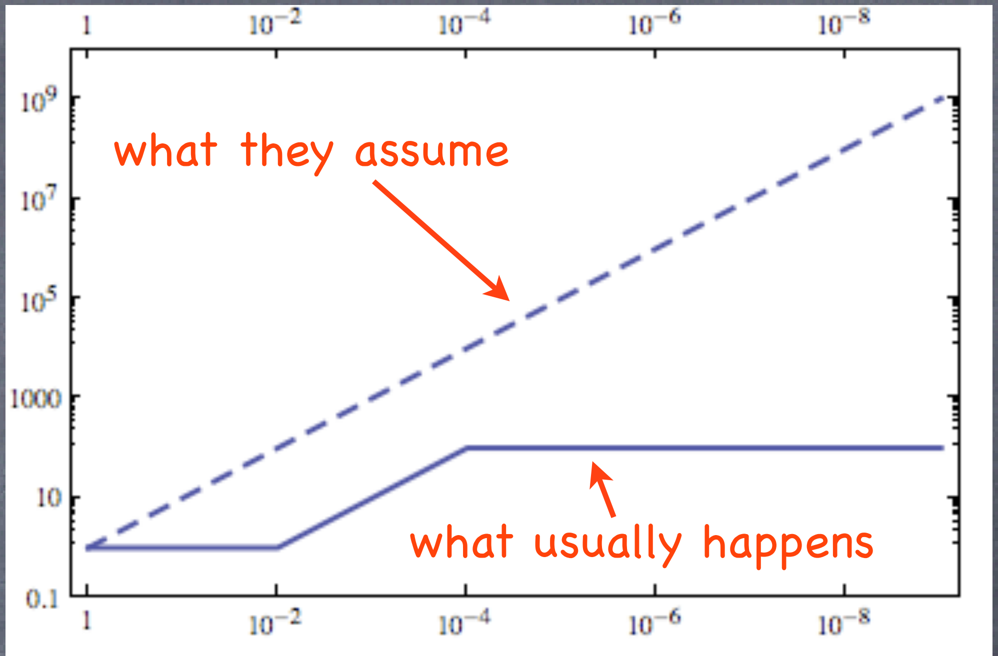
Backup slides

Kamionkowski + Profumo

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

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 [$m_\chi = \text{TeV}, M_c = M_\oplus, z_c = 200$, 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

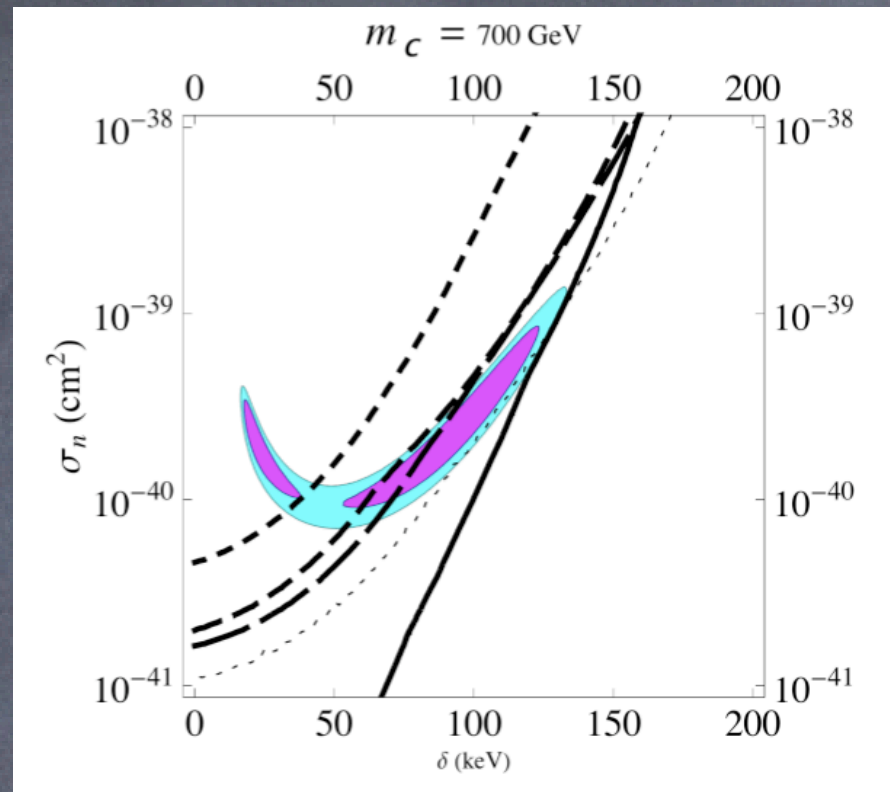


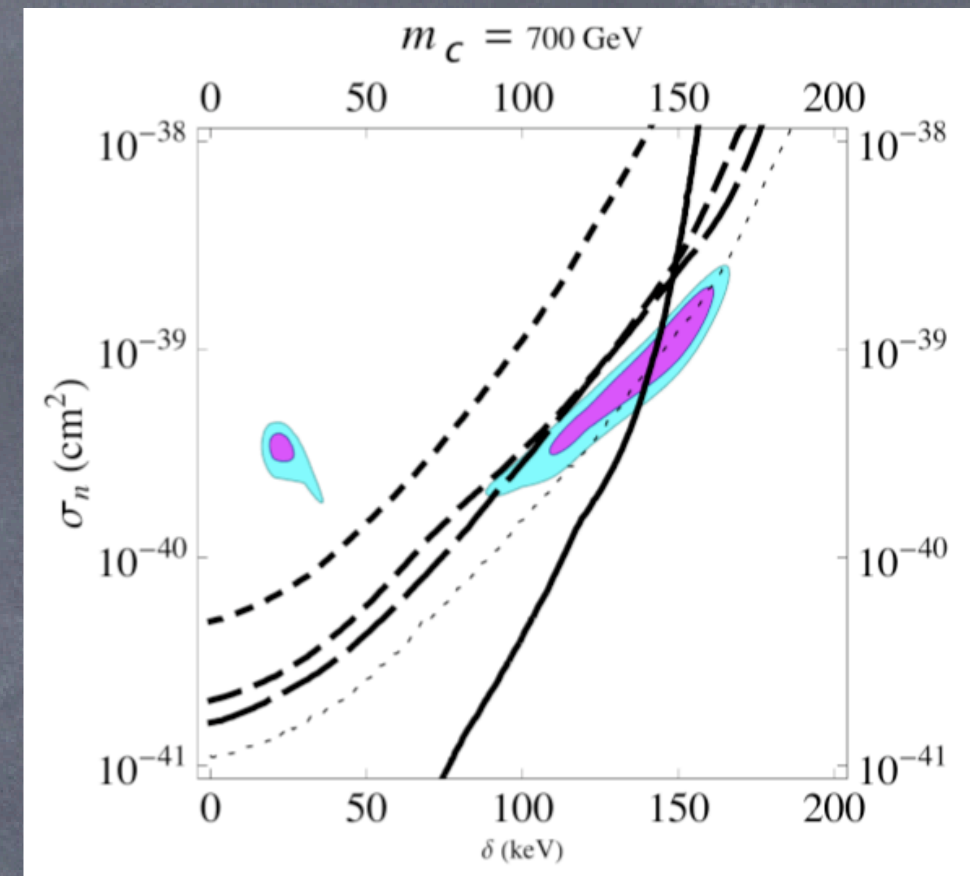
velocity

More simply phrased as maximum boost. I find (using their numbers) at 1 TeV BF_{max} ~ 4000

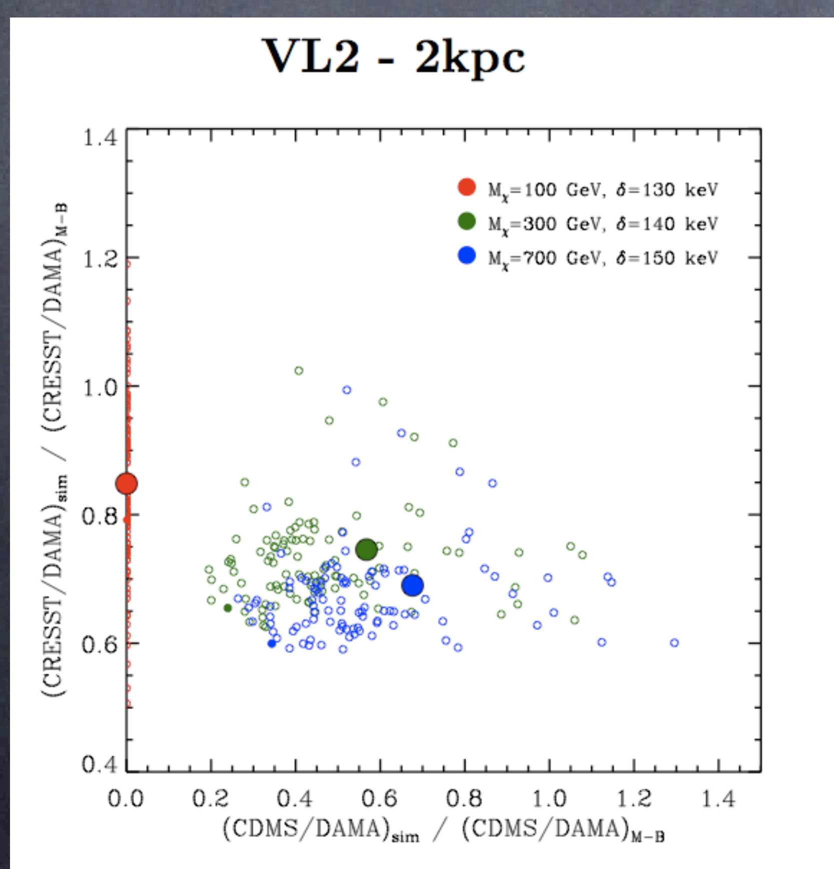
Explaining DAMA with High Masses

Maxwellian





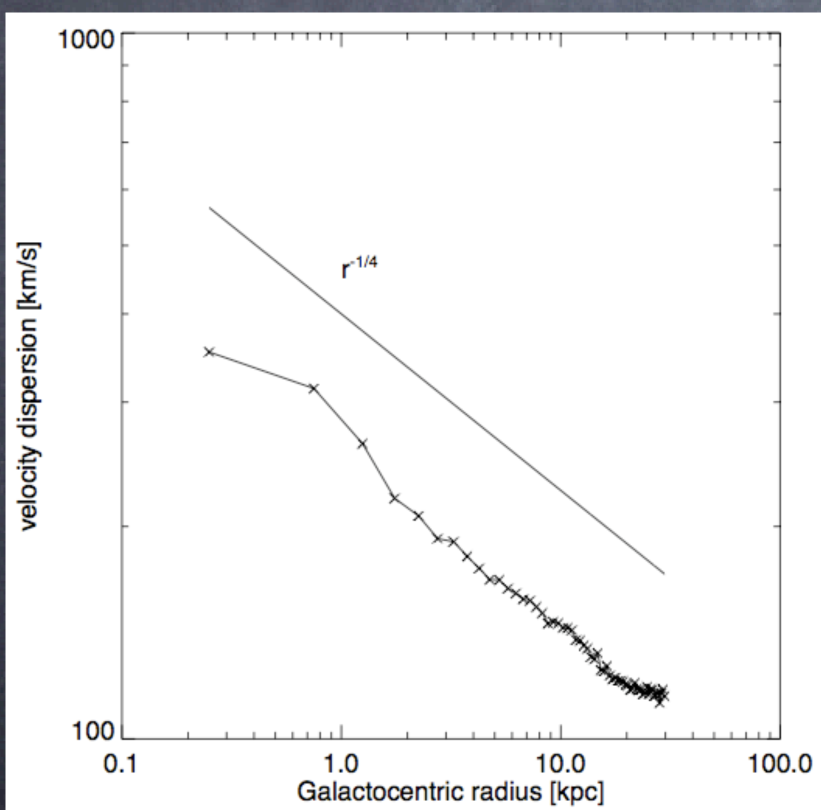
particular 1kpc sphere in VLII



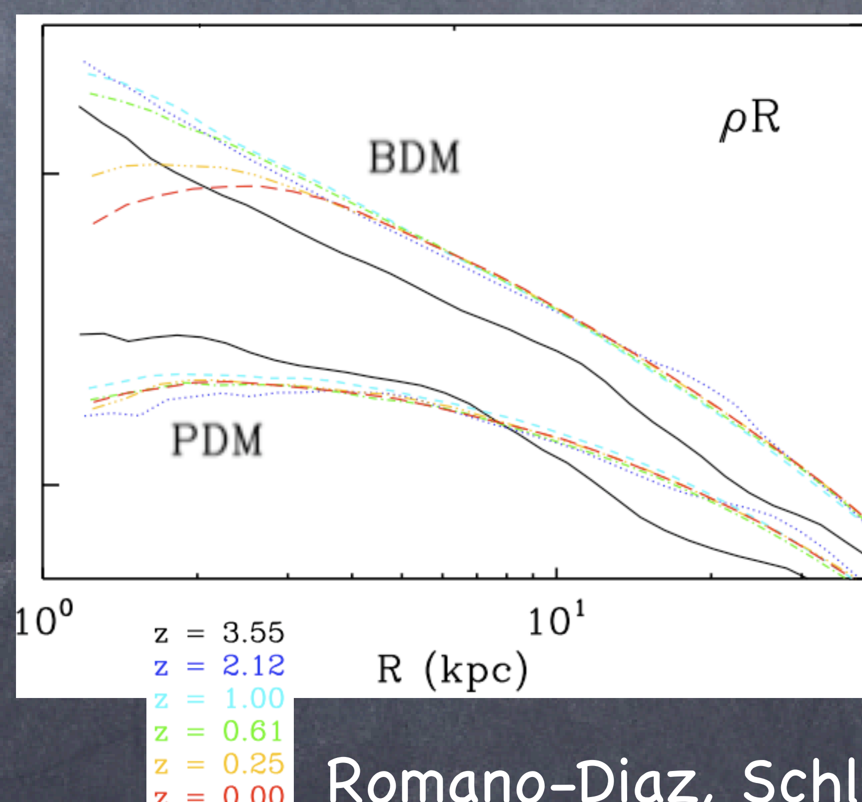
Michael Kuhlen, NW in progress

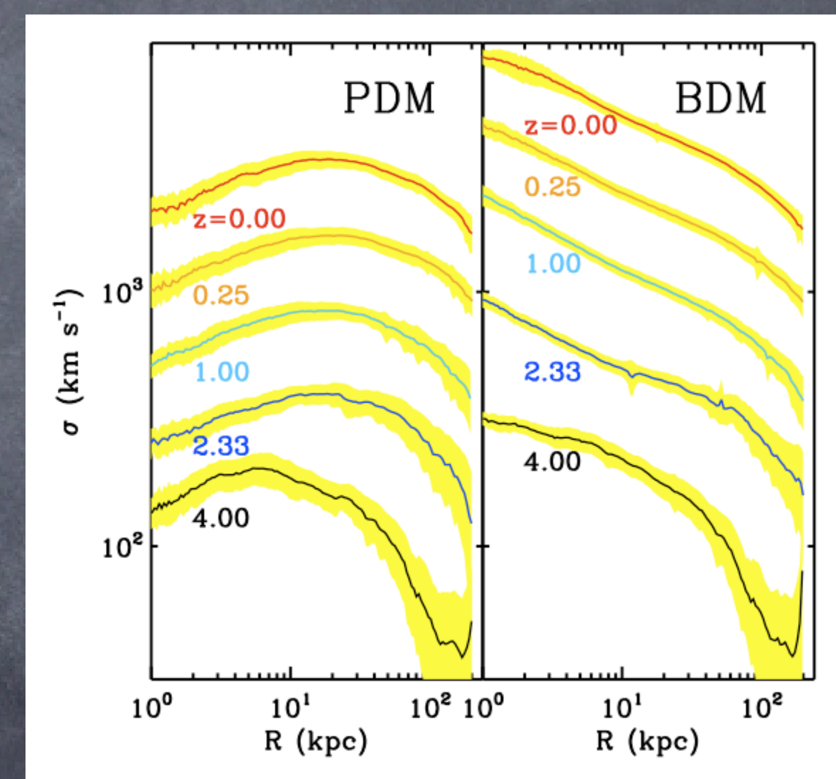
Limits from galactic center

- 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)
- 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)