Motivations for a New Force in the Dark Sector

Tracy Slatyer
Harvard Physics

Based on work with
Nima Arkani-Hamed, Institute for Advanced Study,
Douglas Finkbeiner, Harvard-Smithsonian Center for Astrophysics,
& Neal Weiner, NYU Center for Cosmology and Particle Physics

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WIMP searches

- Indirect detection: look for astrophysical signals of WIMP annihilation (cosmic rays, gamma rays, synchrotron, neutrinos, modifications to ionization history, etc). Many possible signatures: in past year, some hints of possible signals.

- Direct detection: measure recoils from WIMPs striking nuclei in detector volume. Many excellent experiments, strong constraints – one possible signal.

- Collider searches: explore new physics at weak scale (where we hope to find WIMPs). I will not focus on collider searches in this talk.

- Strategy: take observed signals seriously and consider implications – remembering that they may be wrong, or if right, not from dark matter.

Possible dark matter signals

Local
(near Earth)

PAMELA
positrons

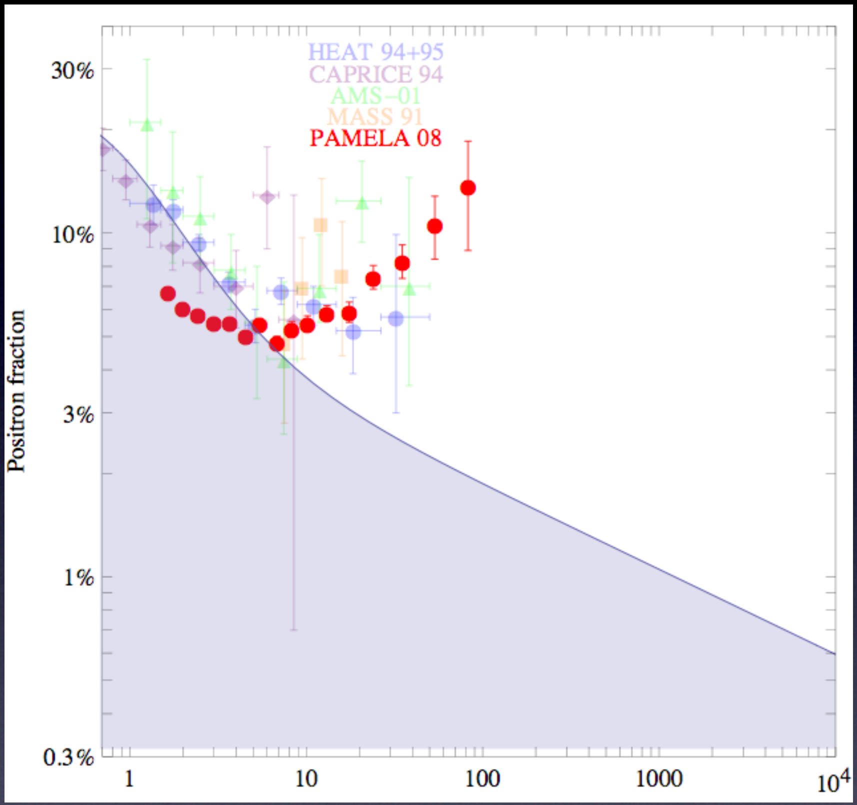
ATIC
e+ e-

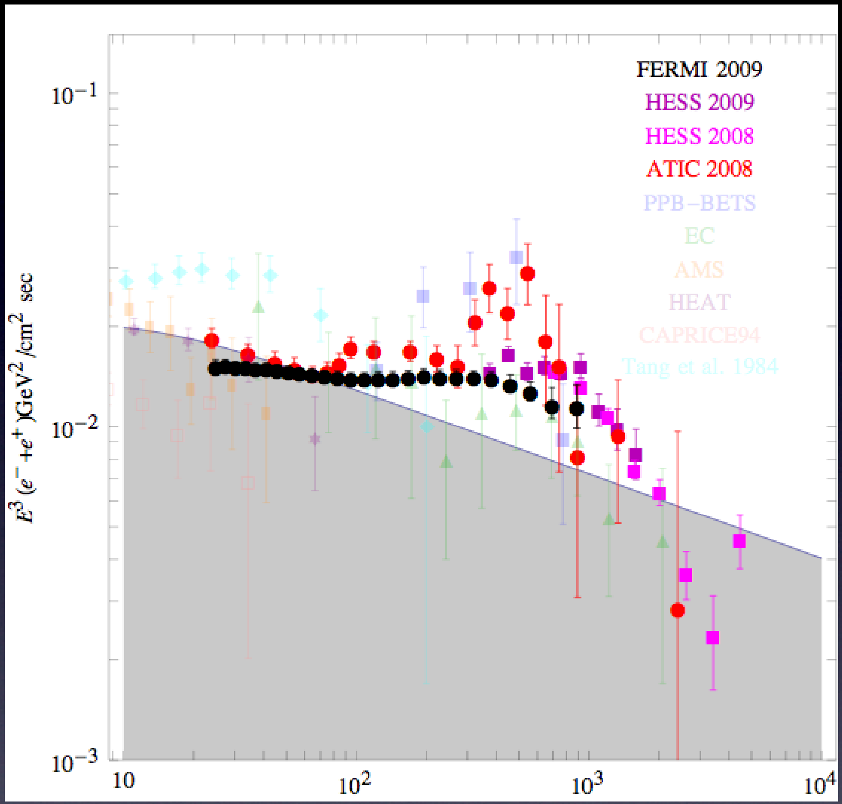
Dark
Matter?

Fermi
e+ e-

A new source of e^+e^-?

Adriani et al, 0810.4995; Chang et al, Nov 2008; Fermi/LAT Collaboration, 0905.0025





- PAMELA measures rise in positron fraction at 10-100 GeV.
- ATIC + Fermi + HESS measure $e^+ + e^-$ excess at 300-1000 GeV.
- Modified propagation? Pulsars? Dark matter annihilation?

Can excesses be fit by a thermal relic SUSY neutralino?

NO. (see e.g. Cirelli et al, 0809.2409)

- Spectrum of electrons from annihilation generally too soft.
- Antiprotons produced in annihilations, but PAMELA sees no antiproton excess.
- Cross section is 1-3+ orders of magnitude above thermal relic cross section, for 100 GeV-few TeV WIMPs.
- The first two problems (but not the third) are resolved if the WIMP annihilates only to leptons – but why?

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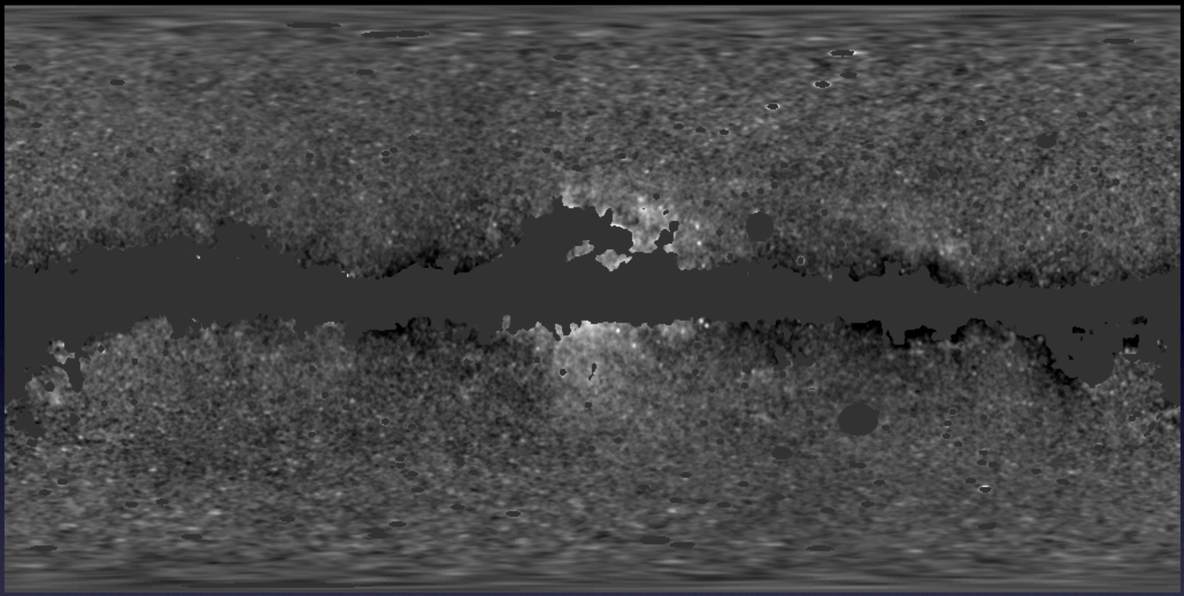
WMAP
Haze

Need WIMP to annihilate to leptons
only, with large xsec

Indirect,
Galactic center

The WMAP Haze

Hooper, Finkbeiner and Dobler, 0705.3655



- Taking WMAP maps (23-94 GHz) and subtracting all known Galactic foregrounds, we find a residual in the inner ~ 25^o.

- Looks like synchrotron, but harder spectrum than usual synchrotron emission (β~ -0.24 vs β~ -0.31) – implies harder electron spectrum.

- Difficult to explain by astrophysical mechanisms.

The Haze as WIMP annihilation?

- Electrons from WIMP annihilation give rise to synchrotron, inverse Compton scattering. ~100 GeV electrons moving through Galactic magnetic fields make synchrotron photons in the right energy range for the Haze.

- Spectrum and morphology of Haze broadly consistent with synchrotron from WIMP annihilation – WIMP annihilation injects extra high energy electrons which harden the spectrum at the required energies.

- High annihilation cross section required to fit the Haze, for TeV-scale WIMPs, even if WIMP annihilates straight to leptons.

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WIMP annihilates to leptons only

Direct

DAMA
annual mod.

Na I scintillation; exposure: 300,000 kg day.

Dark Matter?

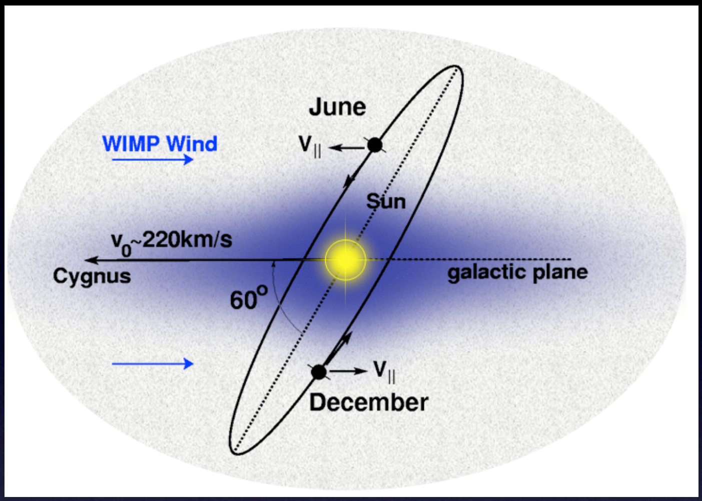
Large annihilation xsec

WMAP
Haze

Indirect, Galactic center

DAMA/LIBRA annual modulation

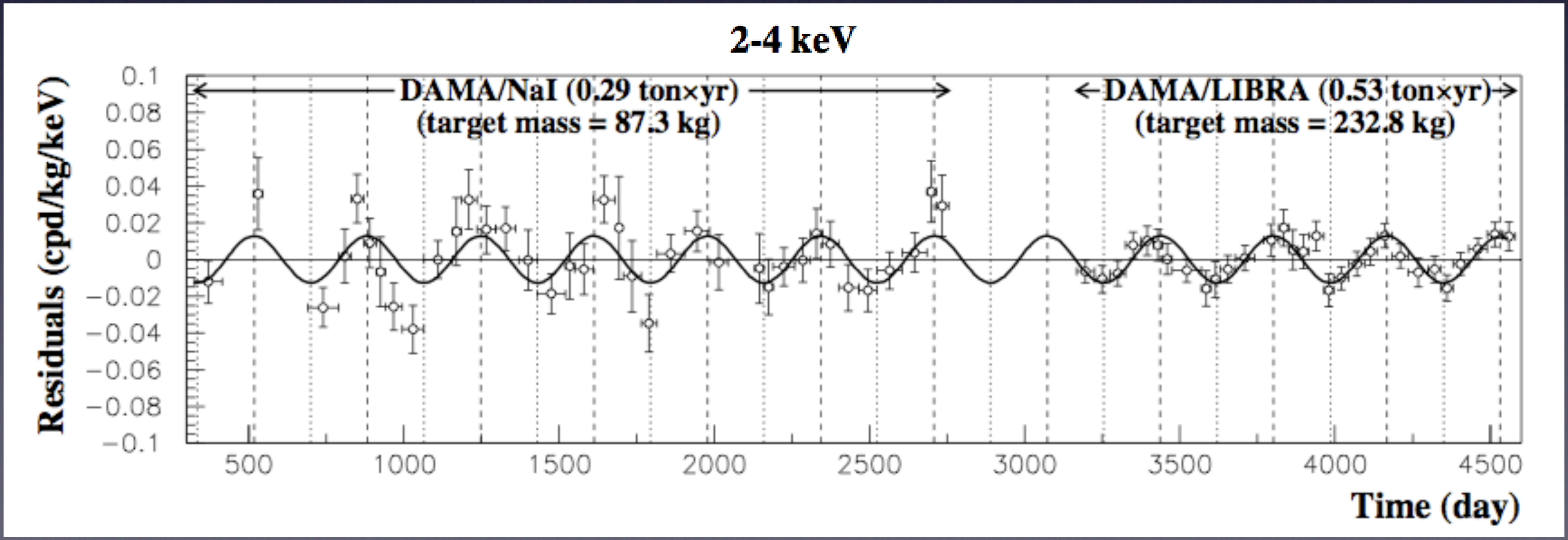
Bernabei et al., DAMA/LIBRA, 0804.2741



- As the Earth orbits the Sun, its velocity relative to the DM halo varies (period 1 year). Prediction: modulation in flux of WIMPs scattering in detector.

  Freese, Frieman and Gould (1988)

- DAMA/LIBRA detects modulation at 8.2σ with correct period and phase.

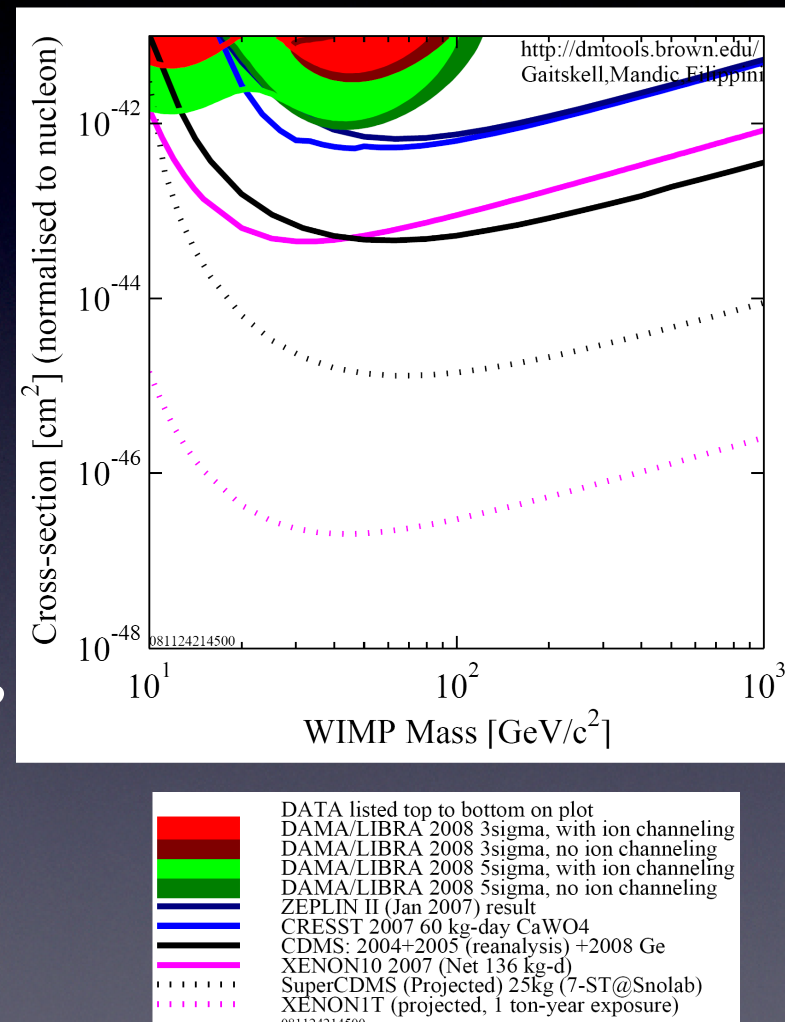


But is it WIMPs?

- DAMA/LIBRA modulation conflicts with constraints from other experiments, if interpreted as a signal of WIMP elastic scattering on nuclei.

- Maybe DAMA is wrong, or seeing physics unrelated to DM, BUT

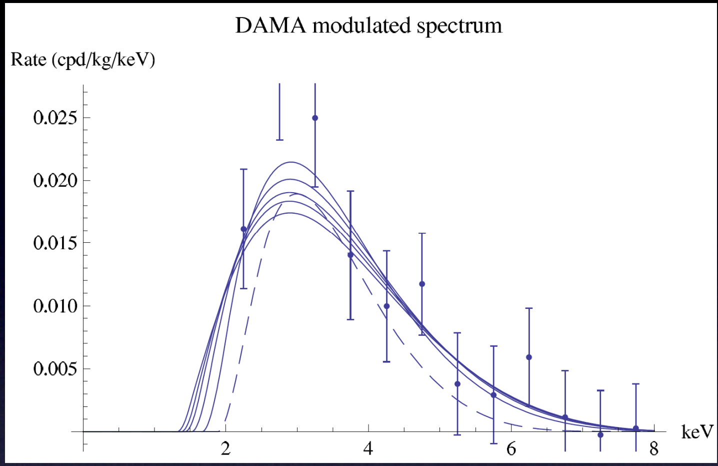
  maybe assumption of elastic scattering on nuclei is wrong.



Inelastic Dark Matter

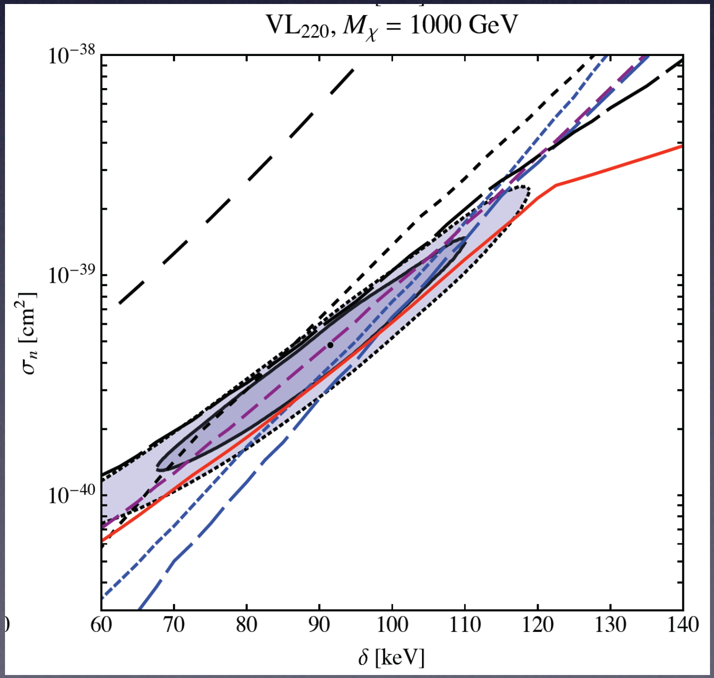
Smith & Weiner, hep-ph/0101138; Chang et al, 0807.2250; March-Russell et al, 0812.1931

Idea: dark matter scatters inelastically on nuclei. Requires DM to have excited state with small mass splitting (~100 keV). This favors DAMA in several ways:



1) Only the tail of the velocity distribution is sampled: annual modulation can be much larger than expected.

2) Bigger nuclei kinematically better (I better than Ge, worse than W).



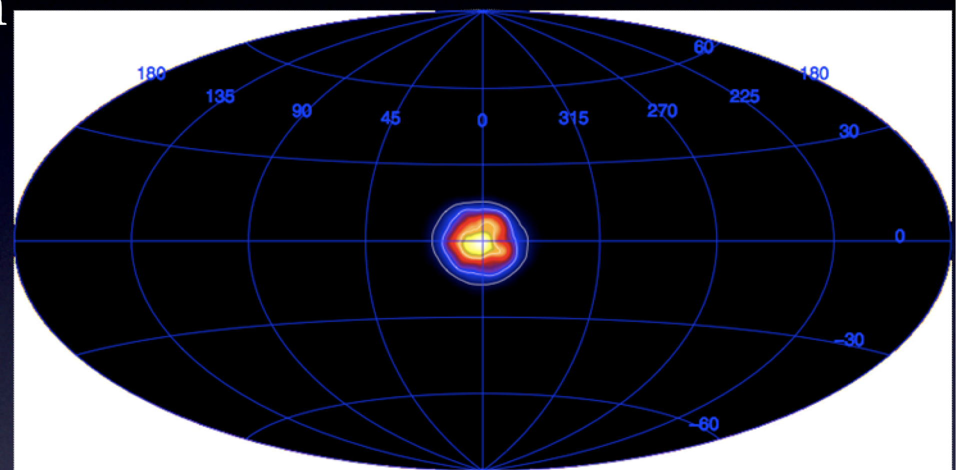
3) Higher energies are better (because of built-in energy scale). DAMA has huge exposure time but little sensitivity to low energy events. Experiments focusing on low-energy events (where conventional spectrum rises exponentially) may miss signal entirely.

Related idea: eXciting Dark Matter?

Finkbeiner and Weiner, astro-ph/0702587

- INTEGRAL spectrometer observes excess 511 keV emission from Galactic center.
- Total power + spatial distribution can be explained if dark matter possesses a ~1 MeV excited state.
- When this state is collisionally excited, decay back to ground state produces a pair.
- Introduce new particle (~1 GeV) to mediate the excitation.

Weidenspointner et al 06



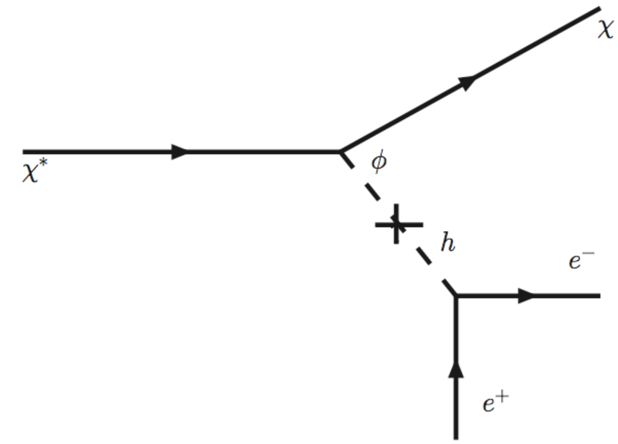


FIG. 5: Decay of the excited state into the ground state.

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WIMP annihilates to leptons only

Dark Matter?

Large annihilation xsec

Direct

DAMA
annual mod.

Na I scintillation; exposure: 200,000 kg day.

Small mass splitting(s) (100 keV – 1 MeV)

WMAP
Haze

INTEGRAL
511 keV

Indirect, Galactic center

The connection: a new force in the dark sector

Arkani-Hamed et al, 0810.0713; Pospelov and Ritz, 0810.1502

- Mass splittings ~100 keV – 1 MeV can be naturally (radiatively) generated if the dark matter is a charged multiplet under some new dark gauge group. Gauge bosons with mass ~1 GeV give correct scale for splittings.

- But then the WIMP naturally annihilates into these gauge bosons (which subsequently decay to SM particles), and we have:

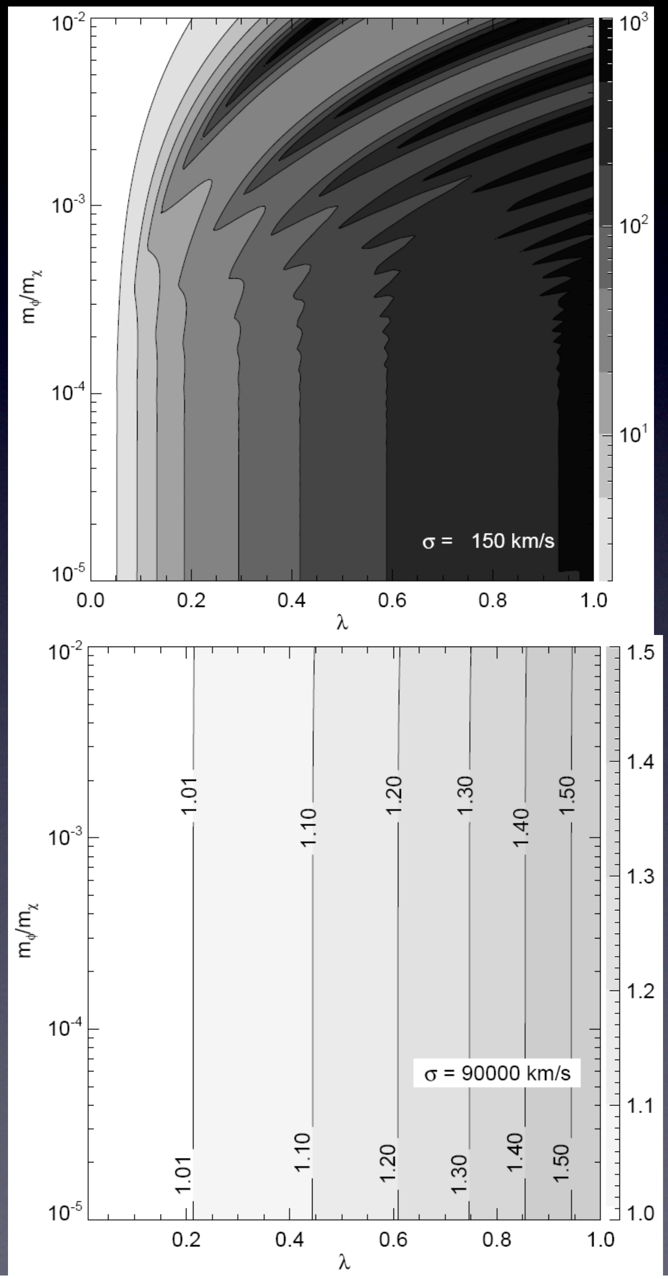
1) No production of antiprotons (or other hadrons) due to the small mass of the gauge bosons.

2) Light force carriers cause a nonperturbative Sommerfeld enhancement to annihilation at low velocity (can be 2-3 orders of magnitude).

The Sommerfeld enhancement

- Exchange of light force carriers gives nonperturbative enhancement factor S to annihilation xsec.
- In non-resonant case, S scales as 1/v for $v/c < \alpha$, until saturation when m_ϕ / M ~ v/c.
- In resonant regions (dependent on α, m_ϕ / M), S can scale as $1/v^2$.
- S ~ 1 at DM freeze-out ($\beta \sim 0.3$), but can be 2-3 orders of magnitude in local halo ($\beta \sim 10^{-4}$-10^{-3}).

(see e.g. Hisano et al, hep-ph/0412403)



The kinetic mixing mechanism

- Dark U(1) mixes with SM hypercharge via kinetic mixing term, $\delta L = \varepsilon F^{\mu\nu} F'_{\mu\nu}$. Can arise from GUT or Planck scale quantum corrections, 

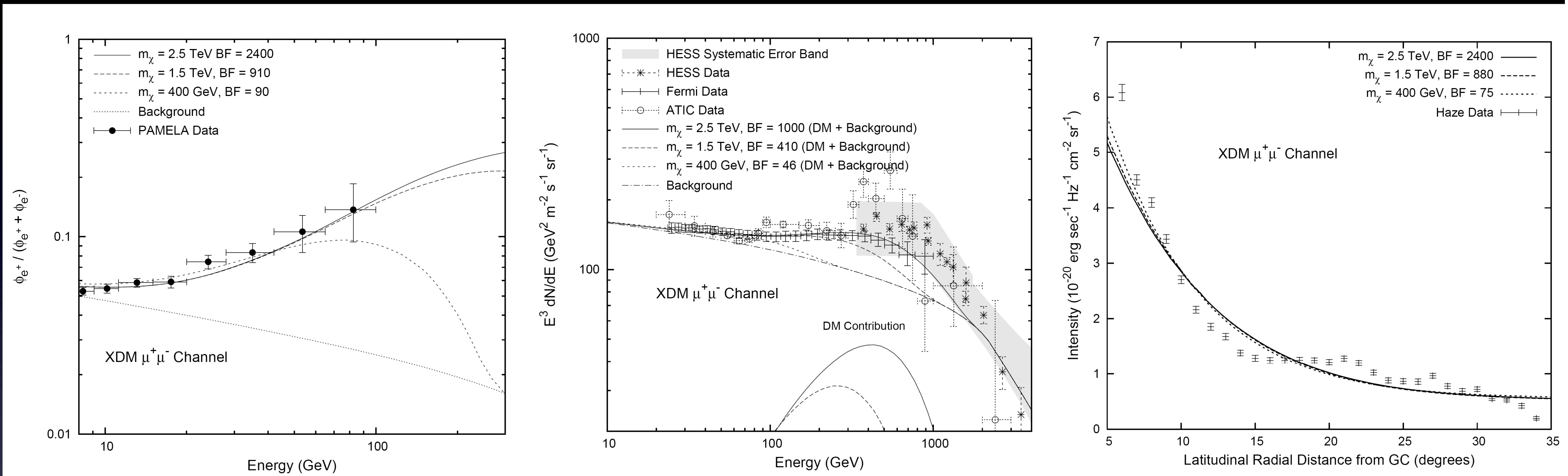
with $\epsilon \lesssim \frac{e g_D}{16\pi^2} \sim 10^{-4} - 10^{-3}$. (Holdom ’86)

- In supersymmetric theories, this term leads to D-term mixing, inducing the required GeV scale automatically: $m_\phi^2 \sim \varepsilon\, m_W^2$

- Gauge boson couples to electroweak charge, may be detectable at fixed target and B factory experiments (current experimental results only constrain $\varepsilon < 10^{-3}$).

- This is a general framework, specific implementations have been developed (e.g. Arkani-Hamed & Weiner 08; Baumgart et al 09; Cheung et al 09; Katz and Sundrum 09; Morrissey, Poland & Zurek 09).

Fits to observed excesses



Cholis et al. 08

These annihilation channels fit the observed cosmic ray spectra well (requiring significant boost factors, provided by Sommerfeld enhancement); also generate the WMAP Haze via synchrotron, with similar boost factors.

Summary

- If PAMELA/Fermi/ATIC excesses, are WIMP physics:
  => high cross section ~ Sommerfeld enhancement
  => goes to leptons ~ annihilate through light state

(see also Nomura & Thaler 0810.5397 – related “axion portal” scenario)

- If WMAP Haze is WIMP physics:
  => high cross section (if ~TeV WIMP) ~ Sommerfeld enhancement
  => hard spectrum ~ annihilate through light state

- If DAMA or the INTEGRAL excess is WIMP physics:
  => inelastic scattering ~ mass splittings generated radiatively by new particle (to explain DAMA + INTEGRAL, non-Abelian group required)

(see also e.g. Alves et al 0903.3945 – “composite IDM” scenario, splittings are hyperfine transitions, again requires new force at GeV scale)

if *any* part of this story is true, it suggests a new ~ GeV scale force in the dark sector.

Upcoming tests

- 2009: Fermi LAT will probe gamma rays from various regions of Galaxy– if inverse Compton scattering signal is observed, indicates population of high energy electrons. Signals from different sky areas can help constrain the source. DM annihilation may also directly produce hard gamma rays (from FSR, possibly pion decay).

- 2010: XENON100, LUX experiments have excellent sensitivity to inelastic scattering (due to high mass of xenon) – can rule out IDM.

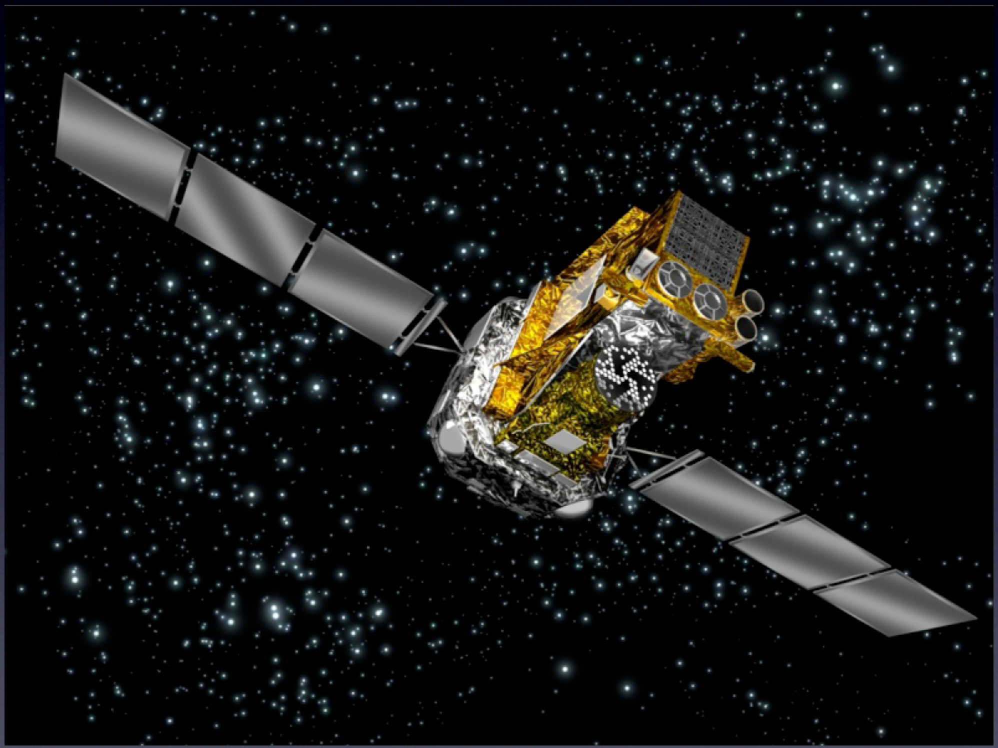
- Collider tests? Possible signatures in LHC, B factories, fixed target experiments (see e.g. Arkani-Hamed & Weiner 08, Baumgart et al 09, Essig, Schuster & Toro 09, Bjorken et al 09, Batell, Pospelov & Ritz 09, Reece & Wang 09).

- Other constraints: neutrinos, CMB, ionization history… (e.g. Spolyar et al 09, Nussinov, Wang & Yavin 09, Menon et al 09; Galli et al 09, TRS, Padmanabhan & Finkbeiner 09; Belikov & Hooper 09, Cirelli, Iocco & Panci 09, Huetsi, Hektor & Raidal 09).

BONUS SLIDES

INTEGRAL

- Energy range: 20 keV - 8 MeV
- Detector area: 500 cm^2
- Field of view: 16 deg (fully coded)
- Angular resolution: 2.5 deg FWHM
- Satellite launched Oct 17 2002, still operating



XDM fits to INTEGRAL signal

This plot shows some fits to the spatial distribution of the INTEGRAL signal using the XDM toy model proposed in astro-ph/0702587, for varying DM masses and halo profiles.

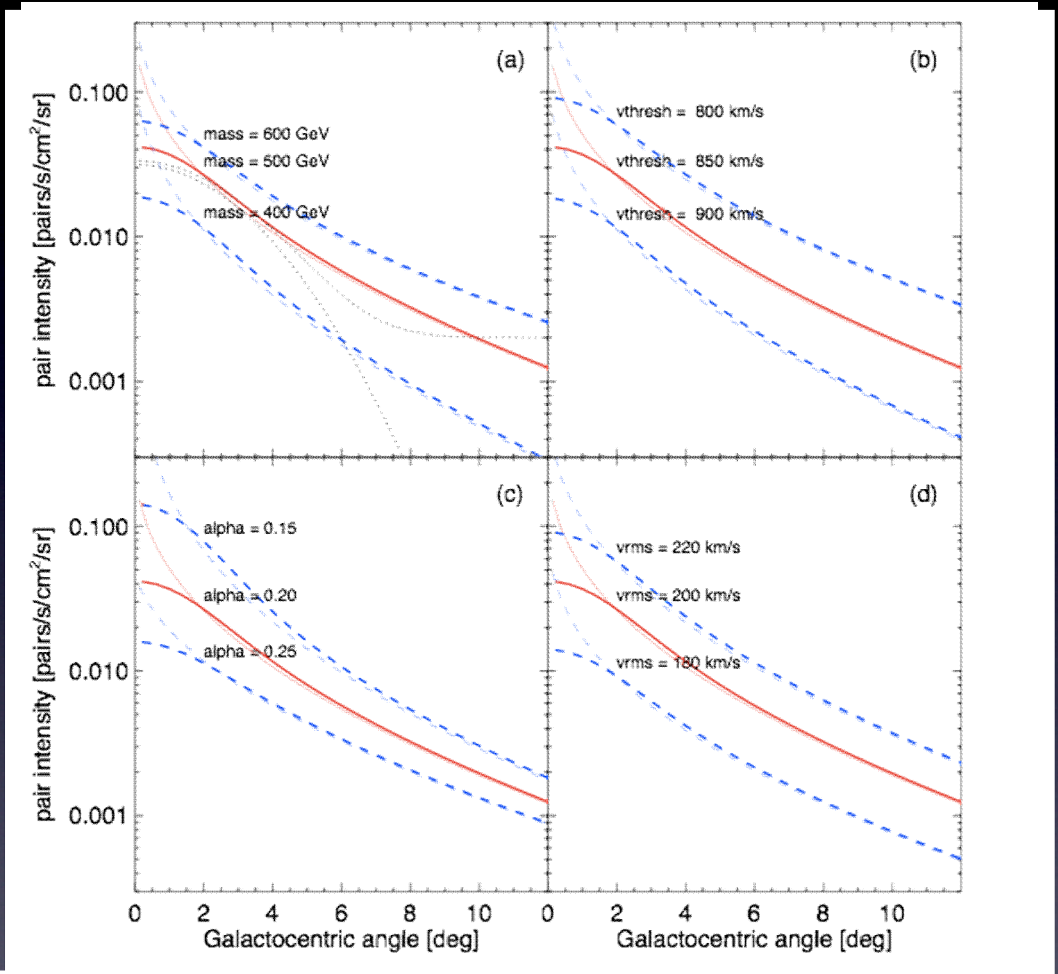


FIG. 2: Model curves for the constant sigma model in Eq (2), taking $\sigma_{mr} = 1.3 \times 10^{-26}$ cm$^2 \left(\frac{0.3 \text{ GeV}/cm^3}{\rho_0}\right)^2 = 2.4 \times 10^{-27} - 1.2 \times 10^{-25}$ cm^2, both unsmoothed (*thin*) and smoothed by a 3° FWHM beam (*thick*) to approximate the spatial response of SPI. In all cases the solid red lines represent our fiducial model ($M = 500$ GeV, $v_{thresh} = 850$ km/s, and halo parameters $v_{rms} = 200$ km/s, and Merritt index $\alpha = 0.2$), and dashed blue lines represent variations of one parameter. (a) $M = 400, 500, 600$ GeV with δ held fixed at 1 MeV so that $v_{thresh} = 950, 850, 776$ km/s, respectively. (b) $v_{thresh} = 800, 850, 900$ km/s, keeping $M = 500$ GeV while δ now varies above and below 1 MeV. (c) The Merritt profile index α is varied (see Eq 6). (d) The RMS velocity in the inner Milky Way is varied. This is assumed to be constant with radius. The observed 6° FWHM signal (*lower dotted line*) and that signal plus an arbitrary baseline of 0.002 (*upper dotted line*) are shown in (a). The SPI zero is set by measurements 10° off the Galactic plane to correct for instrumental background.

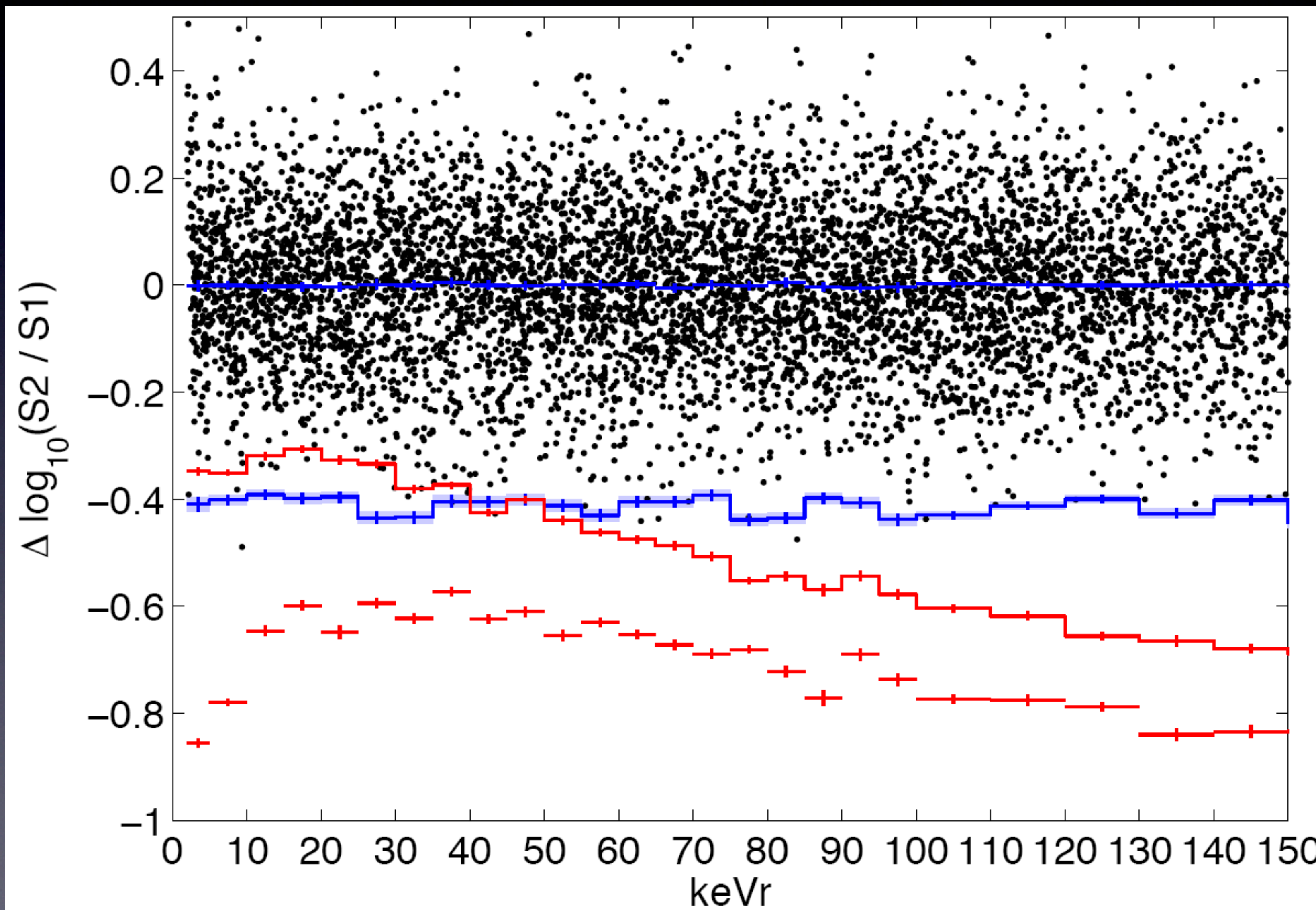
XENON10 reanalysis

(Note: these are only VERY preliminary results)

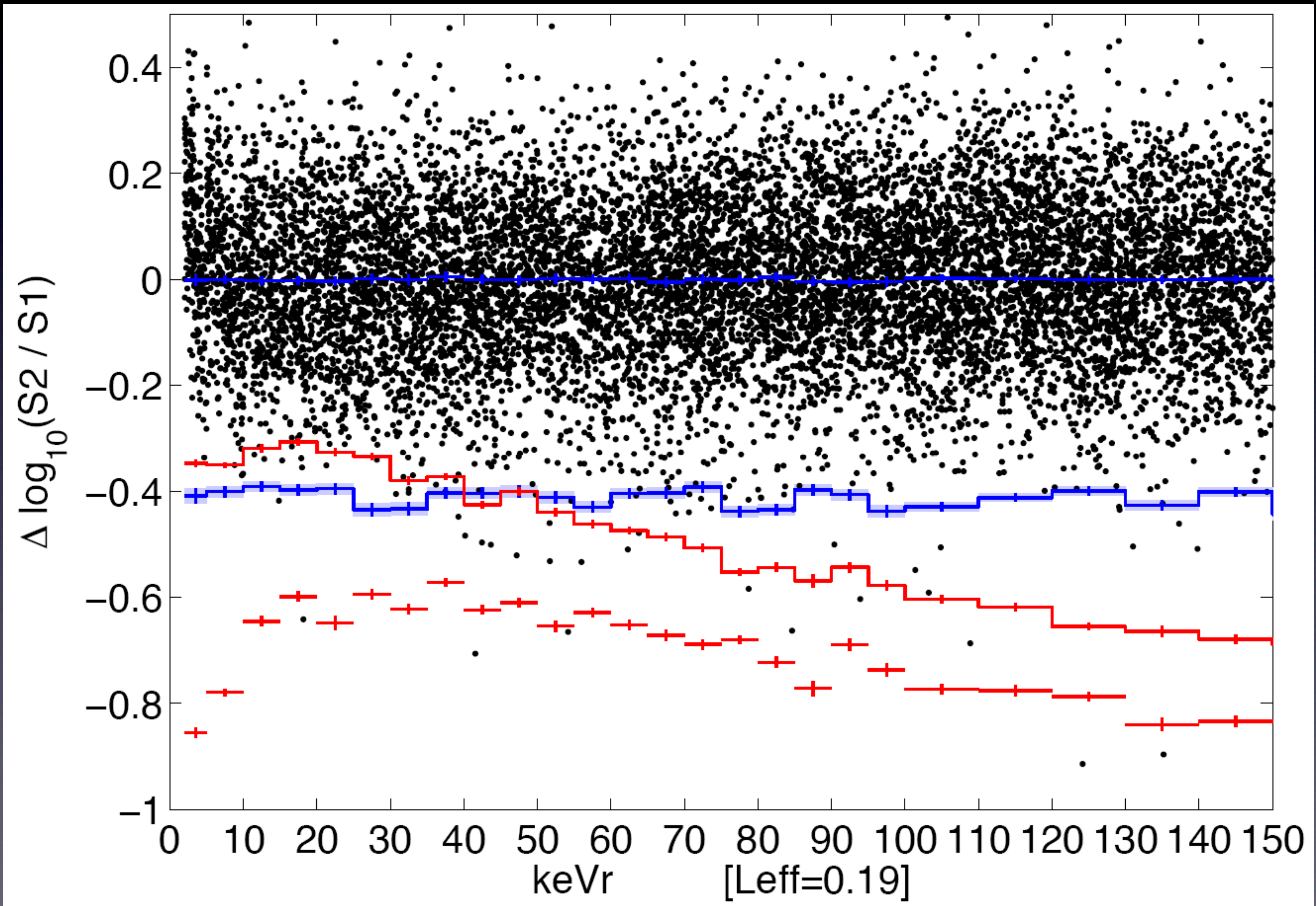
- Detector uses liquid xenon (A=131), high nuclear mass favorable for detecting inelastic dark matter.

- Preliminary, unpublished reanalysis by Sorensen, presented at SnowPAC 2009 (February).
  - Electron recoils distinguished from nuclear recoils by amount of scintillation light relative to ionization (nuclear recoils have more scintillation per ionization).
  - Background from electron double scatterings, where one scattering occurs outside drift field – ionization only measured for one scatter, scintillation light for two.
  - Can use distribution of scintillation light on PMTs to identify and exclude events where one scattering occurs very close to edge of detector.

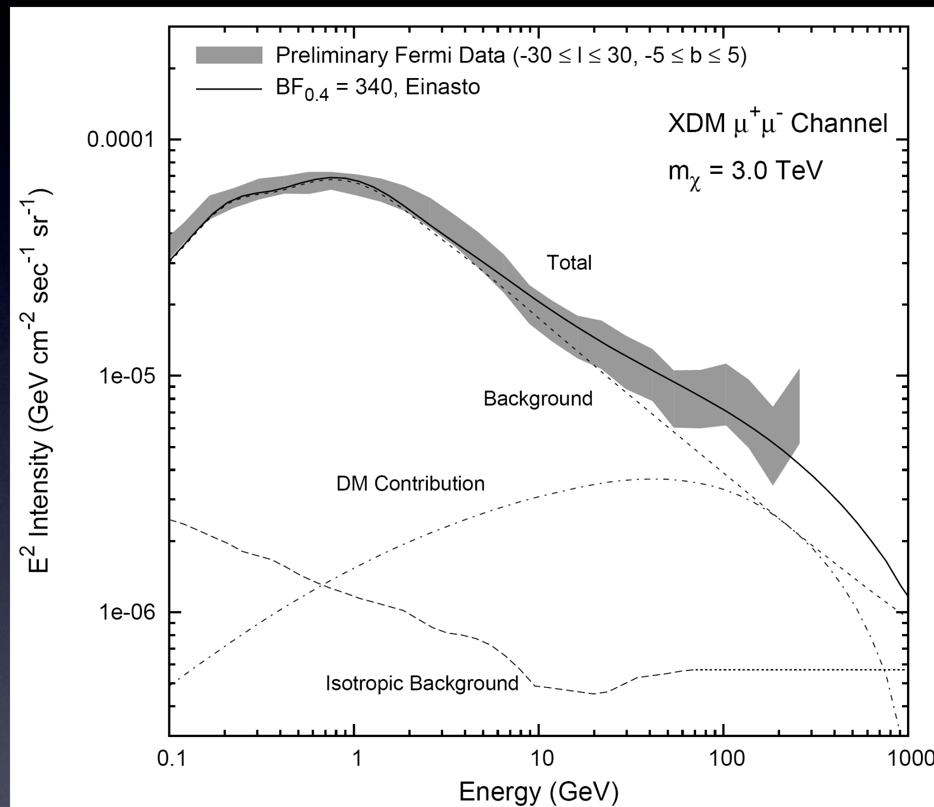
XENON10: Calibration Run PRELIMINARY



XENON10: Data Run
PRELIMINARY



Inner Galaxy Gamma Rays from Fermi LAT – PRELIMINARY



Note: the Fermi LAT team has indicated that at energies around and above 100 GeV there may be significant contamination by (non-photon) cosmic rays, causing a false rise in the measured spectrum.