The Abdus Salam International Centre for Theoretical Physics

1970-9

Signaling the Arrival of the LHC Era

8 - 13 December 2008

A Theory of Dark Matter

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USA

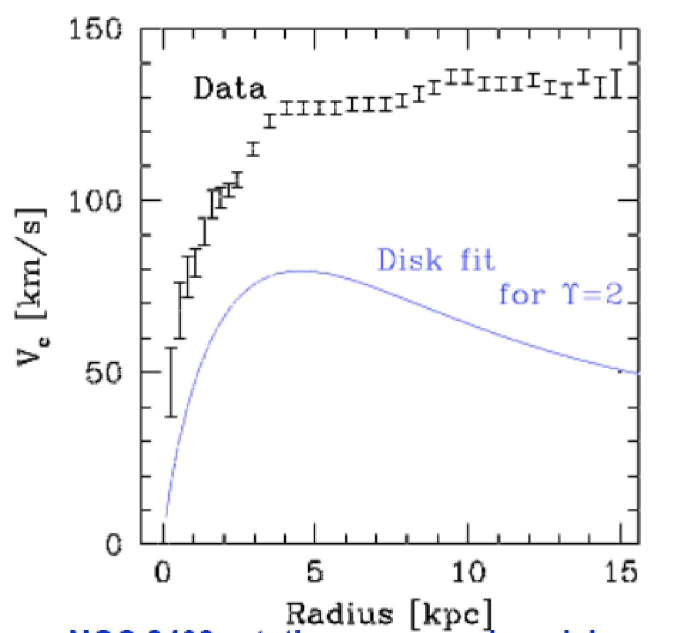
A Theory of Dark Matter

Nima Arkani-Hamed,IAS

w/ Douglas Finkbeiner,
Neal Weiner and Tracy Slatyer

Natural continuation of work pioneered by Weiner, Finkbeiner and Tucker-Smith.

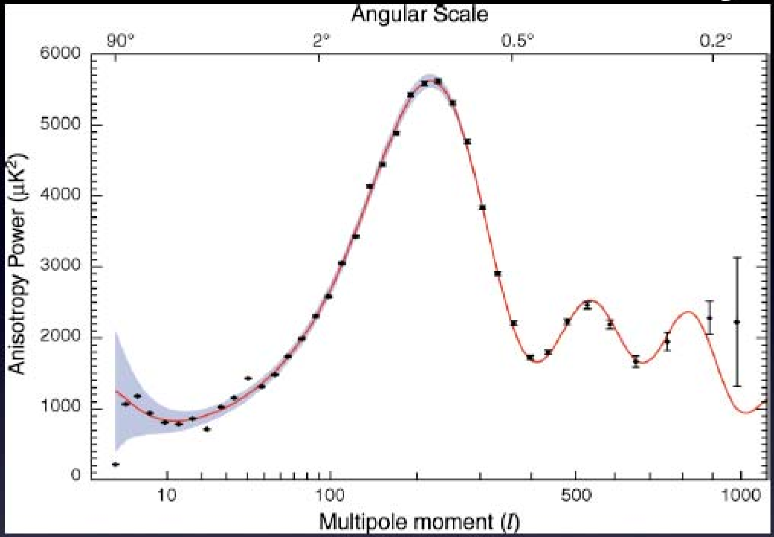
Evidence for dark matter...

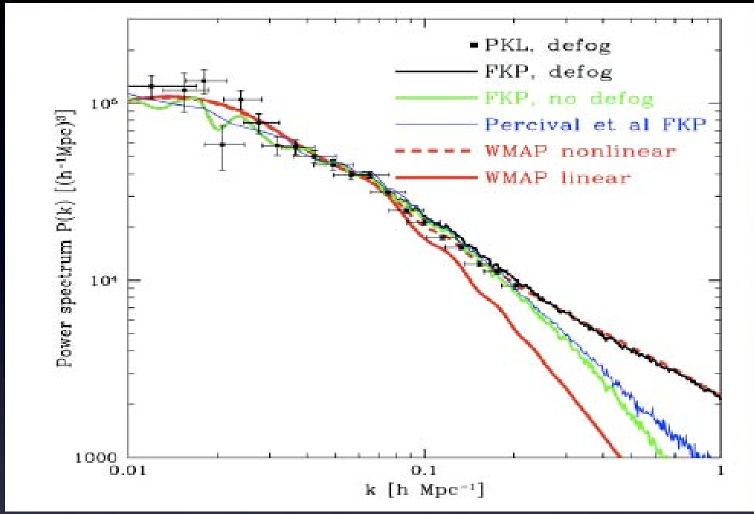


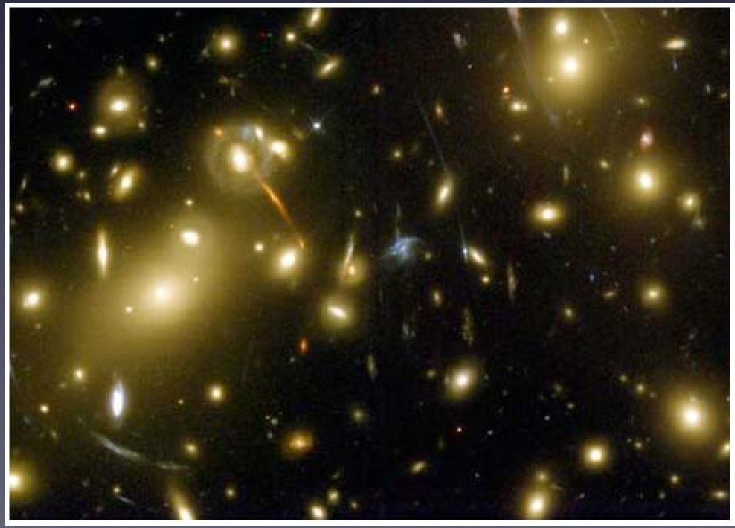
NGC 2403 rotation curve and model

Scales of dark matter

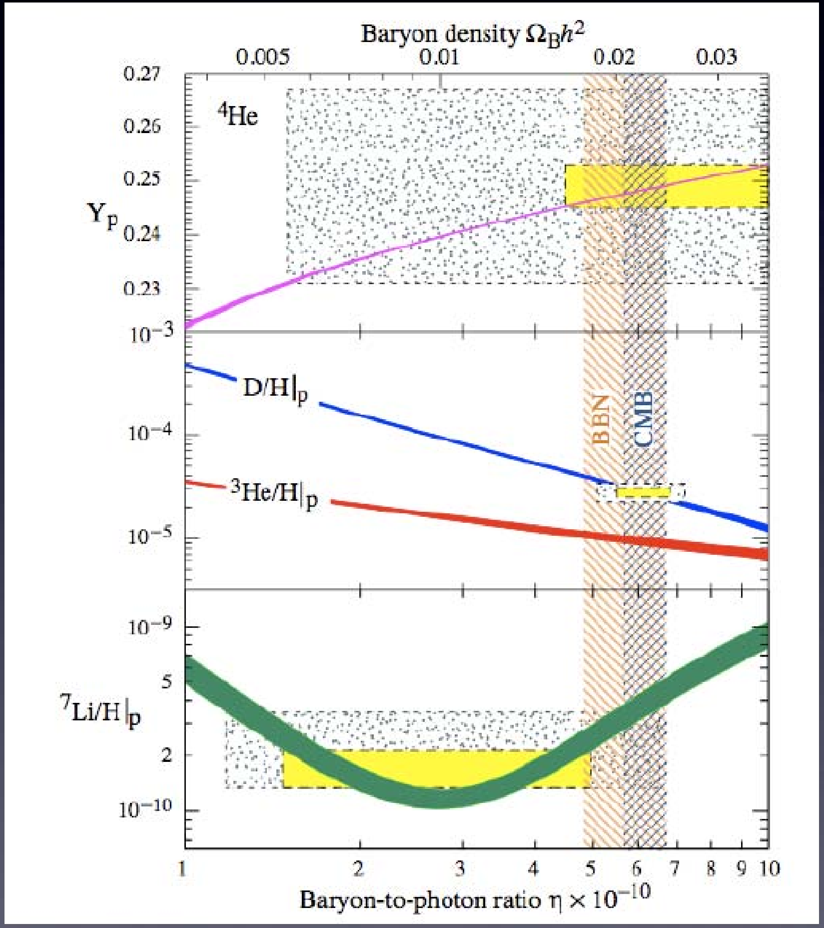
- DM tested in wide variety of arenas



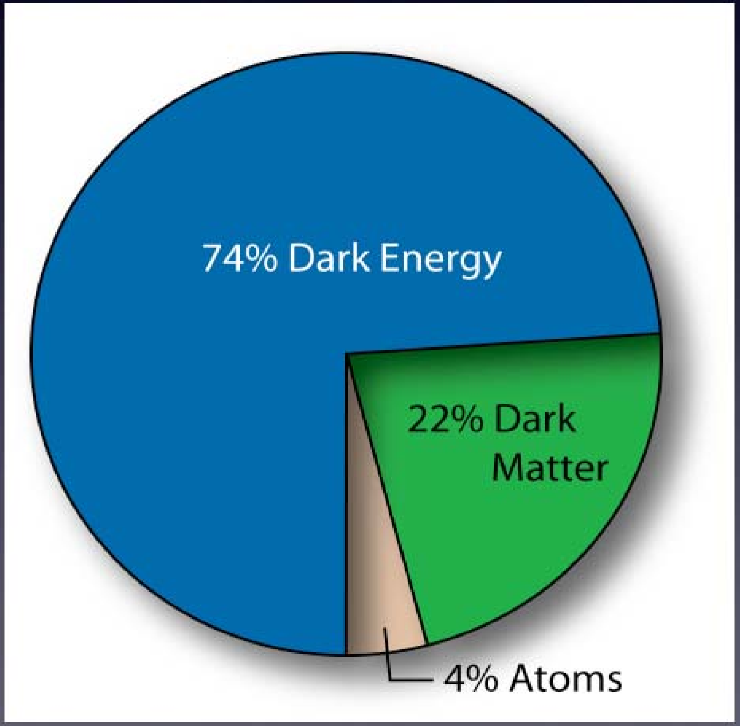




Most of the universe is beyond the standard model



- DM is collisionless, not part of the standard model



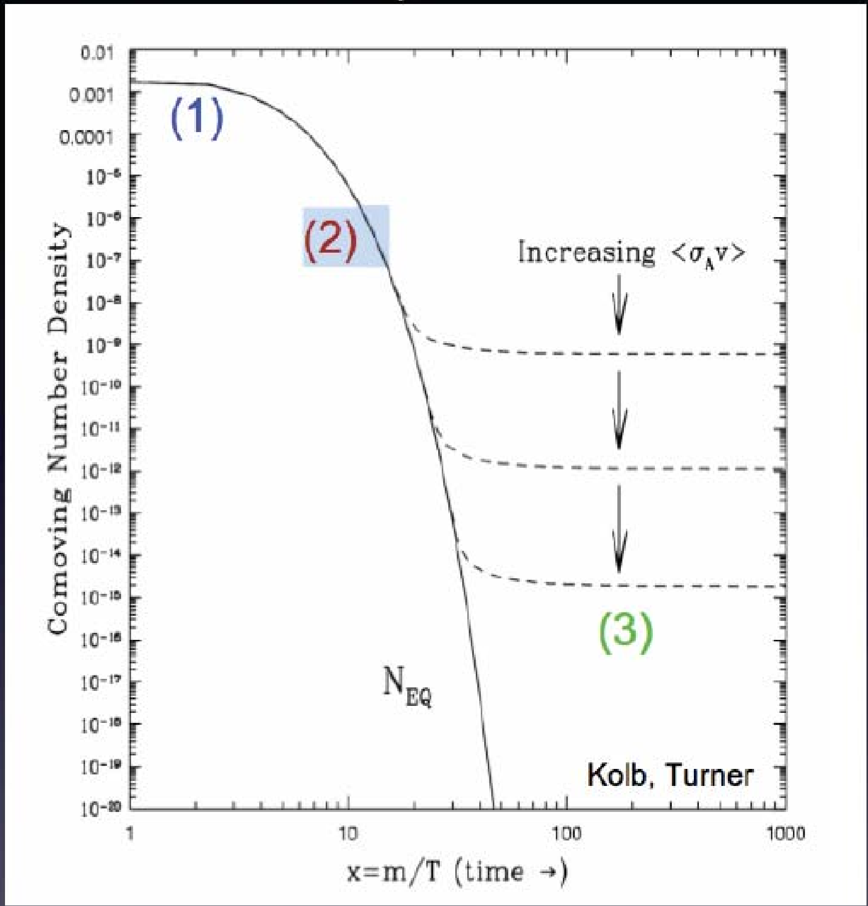
The thermal WIMP story

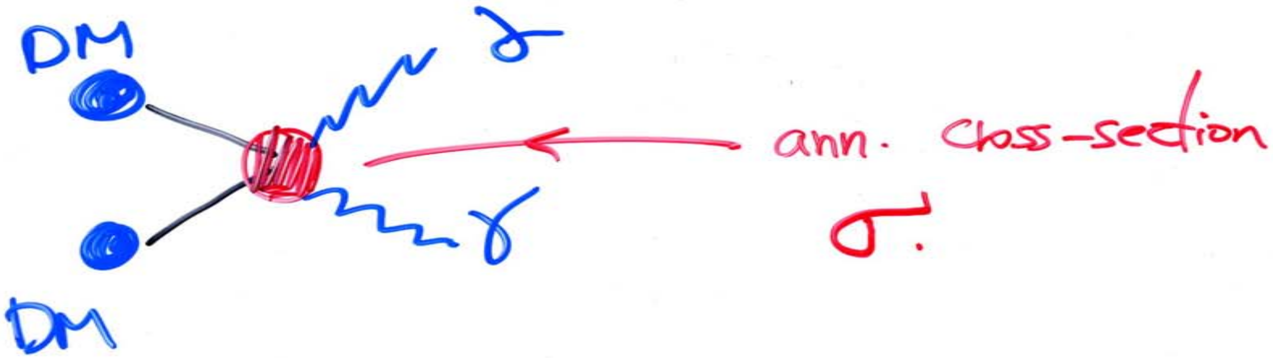
- Dark matter in thermal equilibrium early

$$\chi\chi \leftrightarrow \bar{f}f$$

- Gradually depletes until it decouples

$$\Omega h^2 \approx 0.1 \times \left(\frac{3 \times 10^{-26} cm^3 s^{-1}}{\langle \sigma v \rangle}\right)$$





Mean Free Time between collisions:

$\tau \sim (n_{DM} \sigma v)^{-1}$. Ann. stops when this is $\sim \tau_{\text{expanding universe}} \sim \frac{M_{pl}}{T^2} \sim \frac{M_{pl}}{m_{DM}^2}$.

$$\Longrightarrow \quad n_{DM} \sigma v \sim \frac{m_{DM}^2}{M_{pl}}$$

$$\Longrightarrow \left(\frac{\rho_{DM}}{T^3}\right) \sim \left(\frac{m_{DM}\, n_{DM}}{m_{DM}^3}\right) \sim \left(\frac{1}{\sigma v M_{pl}}\right)$$

$\downarrow$

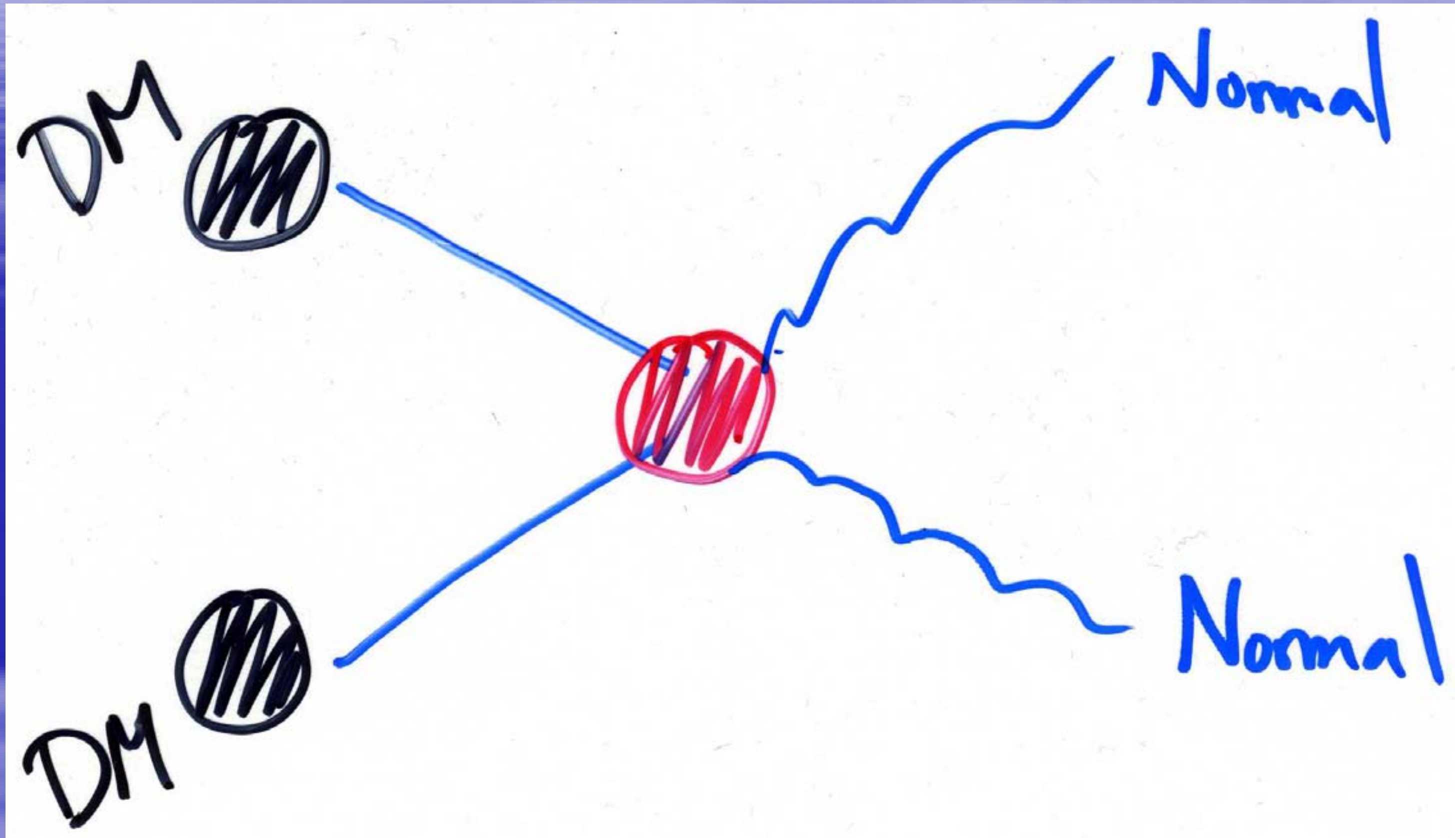
$\sim 10^{-3}$ eV

$$\Longrightarrow \sigma \sim \alpha^2 (10^{-16}\,\text{cm})^2$$

Weak Scale!

How to see dark matter

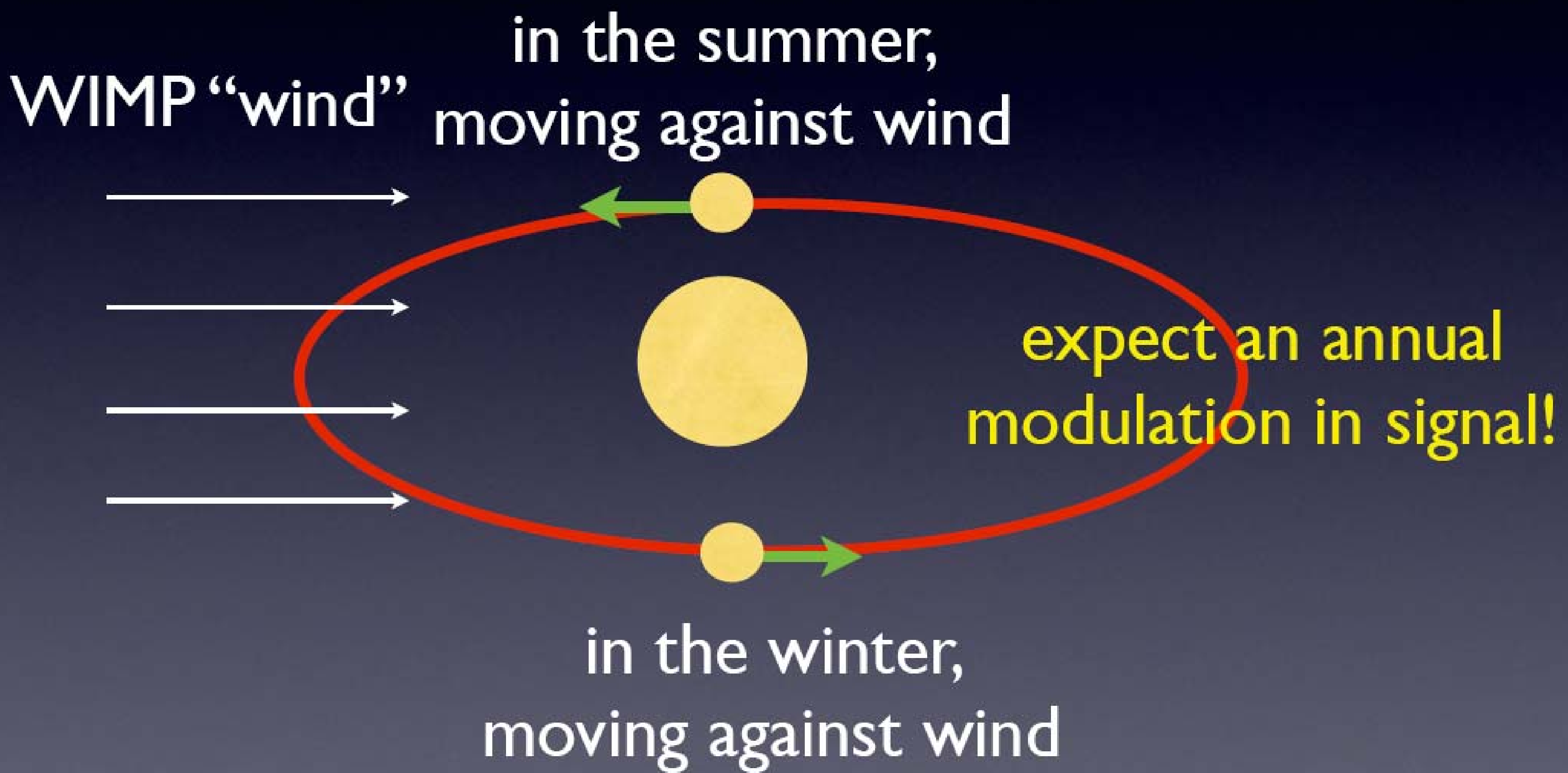
- Make it (at the LHC)
- Break it (annihilations in the halo)
- Wait for it (in direct detection experiments)


DM
DM
Normal
Normal

Anomalies and anomalies

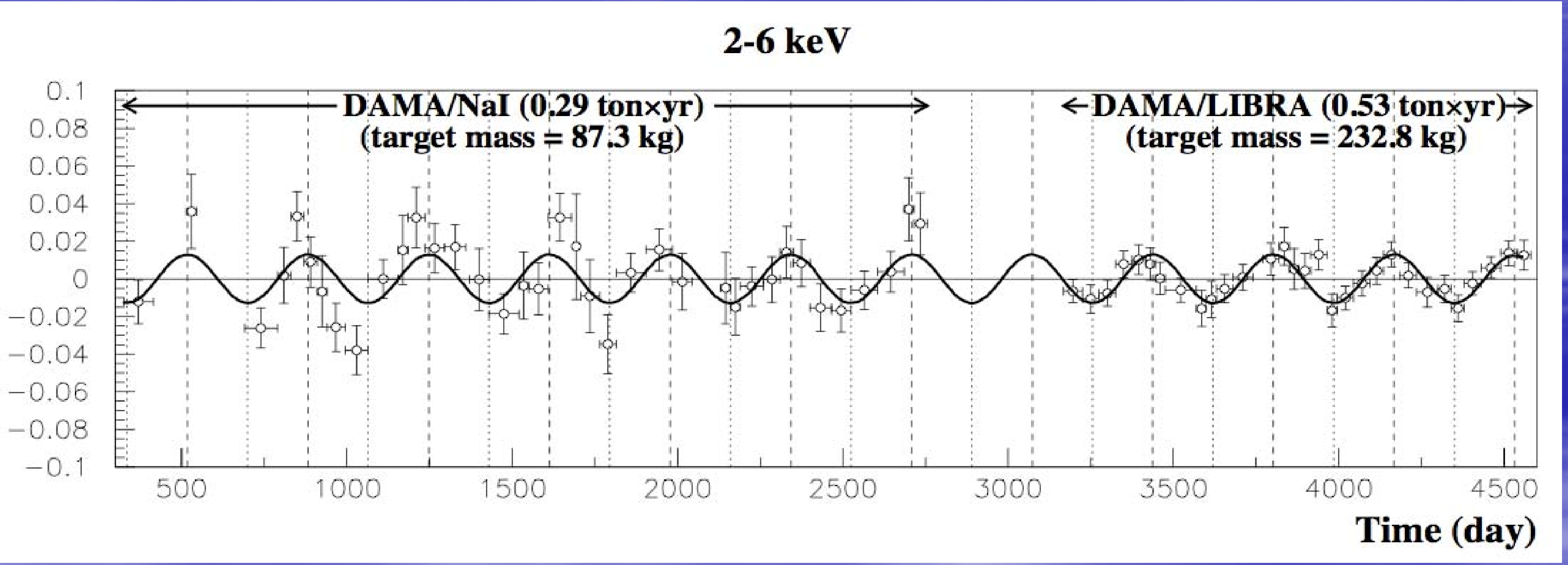
- High Energy Electrons/Positrons: PAMELA (HEAT,AMS-01), ATIC, EGRET, WMAP
- Low energy positrons: INTEGRAL
- Direct detection: DAMA/LIBRA

seasonal variation



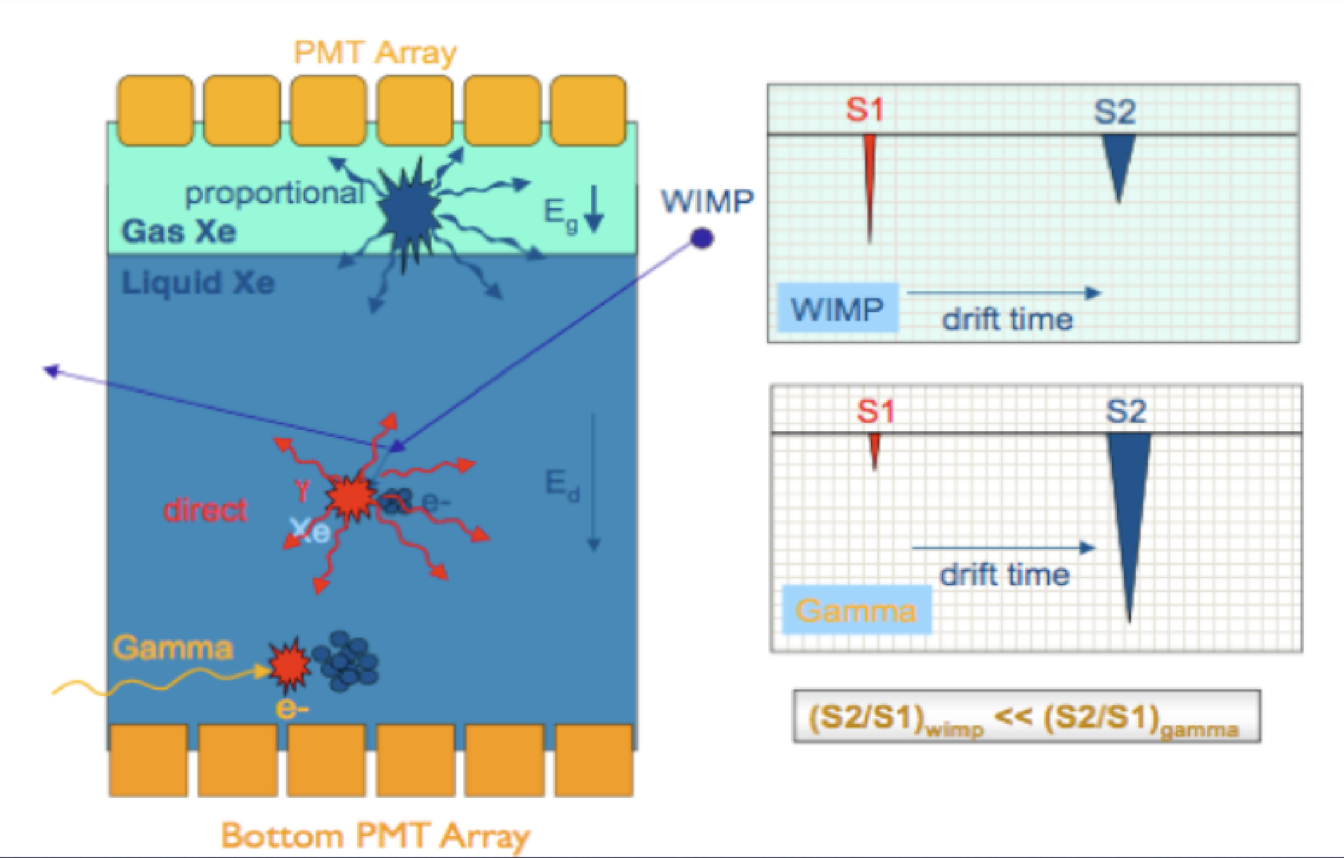
Drukier, Freese, Spergel Phys.Rev.D33:3495-3508,1986

DAMA



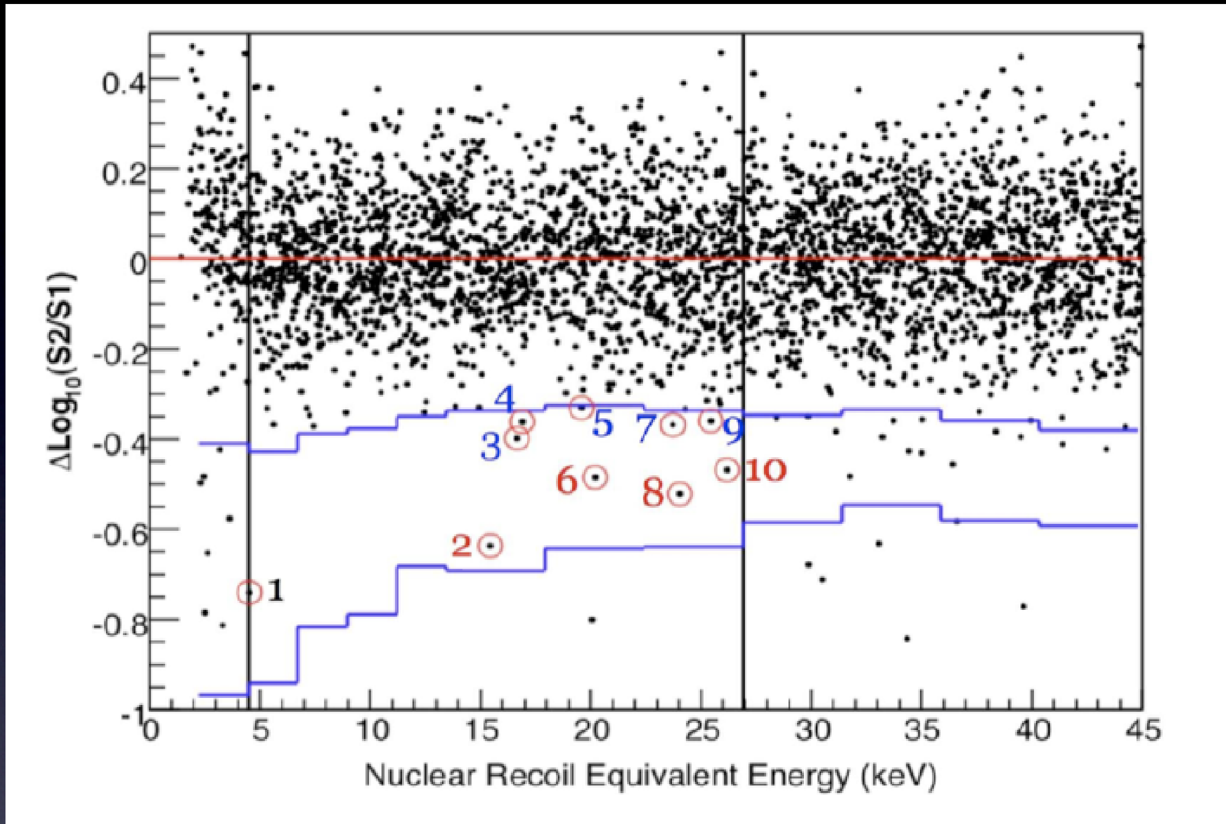
2-6 keV
DAMA/NaI (0.29 ton×yr)
(target mass = 87.3 kg)
DAMA/LIBRA (0.53 ton×yr)
(target mass = 232.8 kg)
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
−0.1
500
1000
1500
2000
2500
3000
3500
4000
4500
Time (day)

XENON



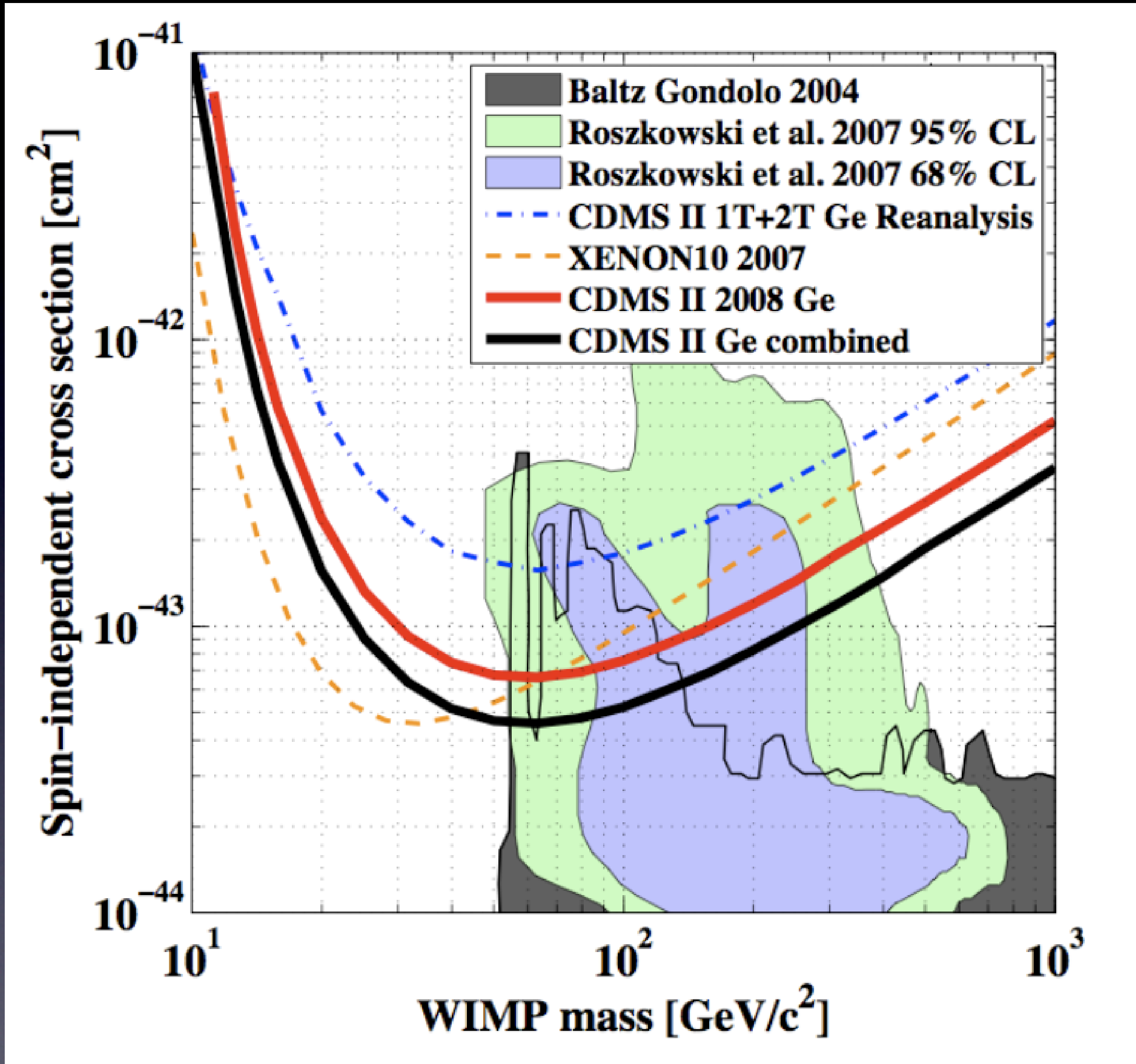
- Distinguish events by ratio of scintillation light compared with ionization

XENON



Angle et al, **Phys.Rev.Lett.100:021303,2008**

- Distinguish events by ratio of scintillation light compared with ionization



Baltz Gondolo 2004
Roszkowski et al. 2007 95% CL
Roszkowski et al. 2007 68% CL
CDMS II 1T+2T Ge Reanalysis
XENON10 2007
CDMS II 2008 Ge
CDMS II Ge combined
Spin–independent cross section [cm^2]
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^1
10^2
10^3
WIMP mass [GeV/c^2]

THE DAMA CONUNDRUM

Can the DAMA signal for WIMPs be real, while staying consistent with null results of the other experiments?


INTEGRAL/ SPI: (spectrometer)
Energy range: 20 keV - 8 MeV
Field of view: 16 deg
Angular resolution: 2.5 deg FWHM
Launched: 2002 Oct 17
Still operating...

Weidenspointner (2006)

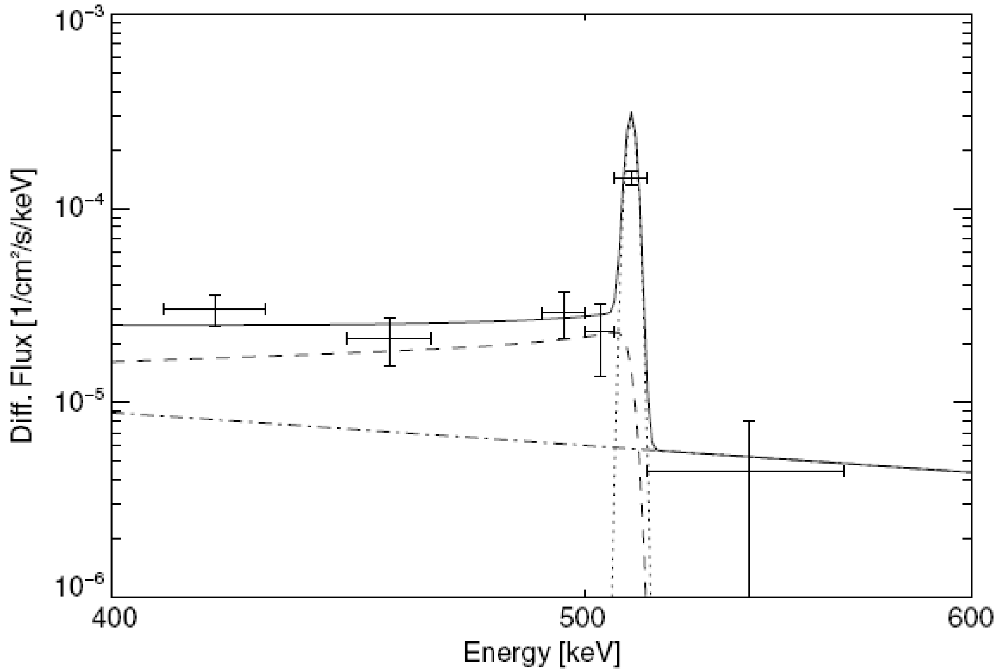
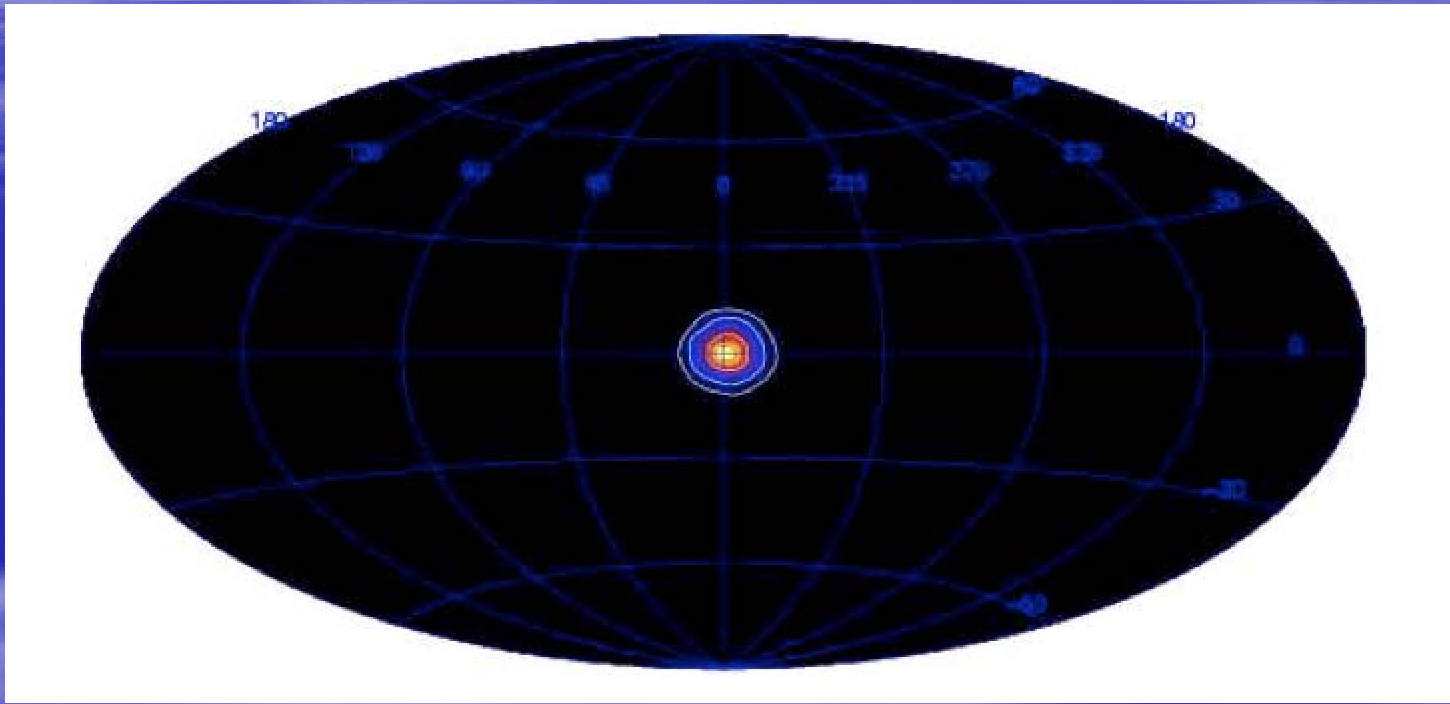


Fig. 2. A fit of the SPI result for the diffuse emission from the GC region ($|l|, |b| \leq 16°$) obtained with a spatial model consisting of an 8° *FWHM* Gaussian bulge and a CO disk. In the fit a diagonal response was assumed. The spectral components are: 511 keV line (dotted), Ps continuum (dashes), and power-law continuum (dash-dots). The summed models are indicated by the solid line. Details of the fitting procedure are given in the text.



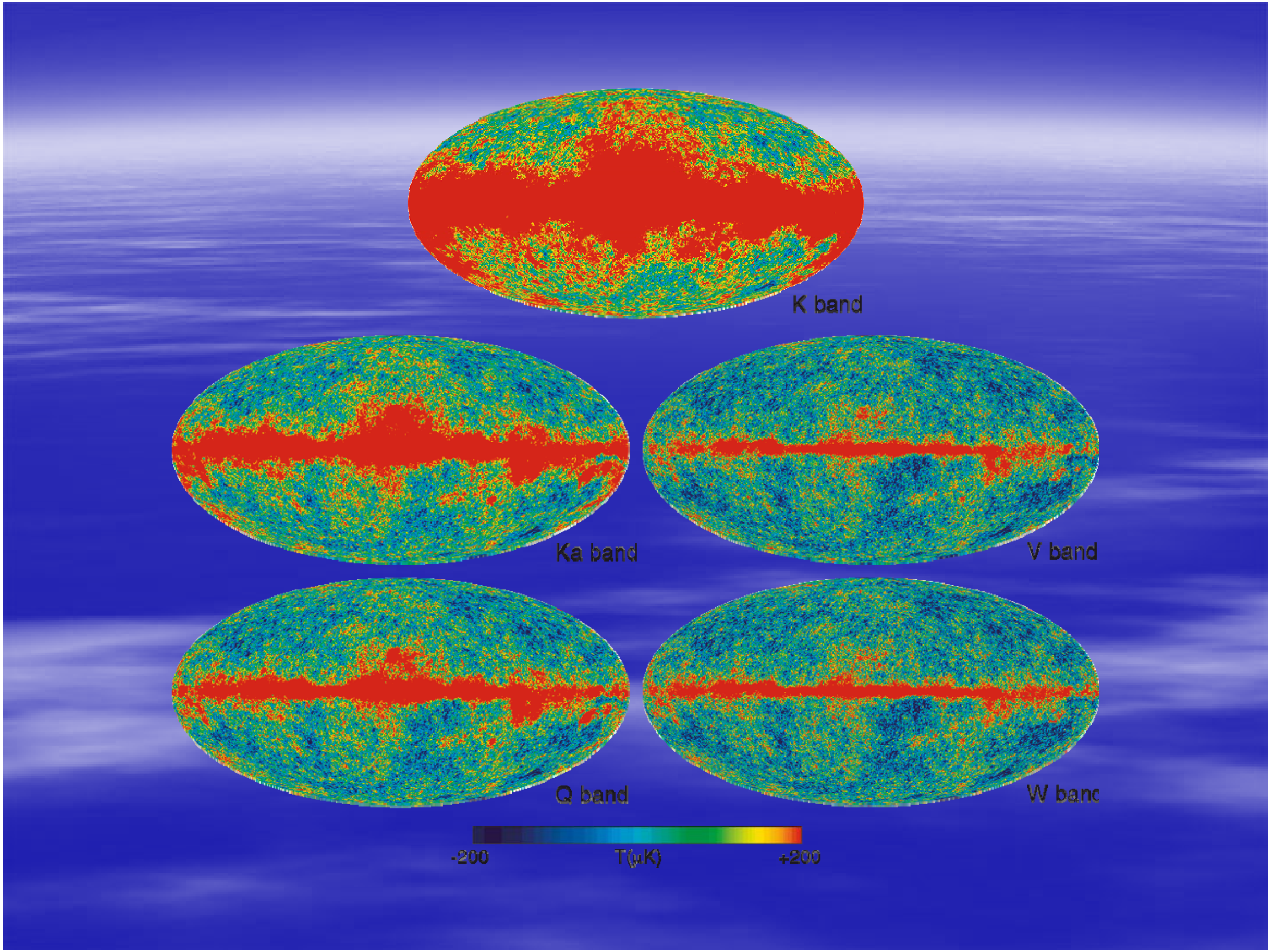
THE INTEGRAL CONUNDRUM

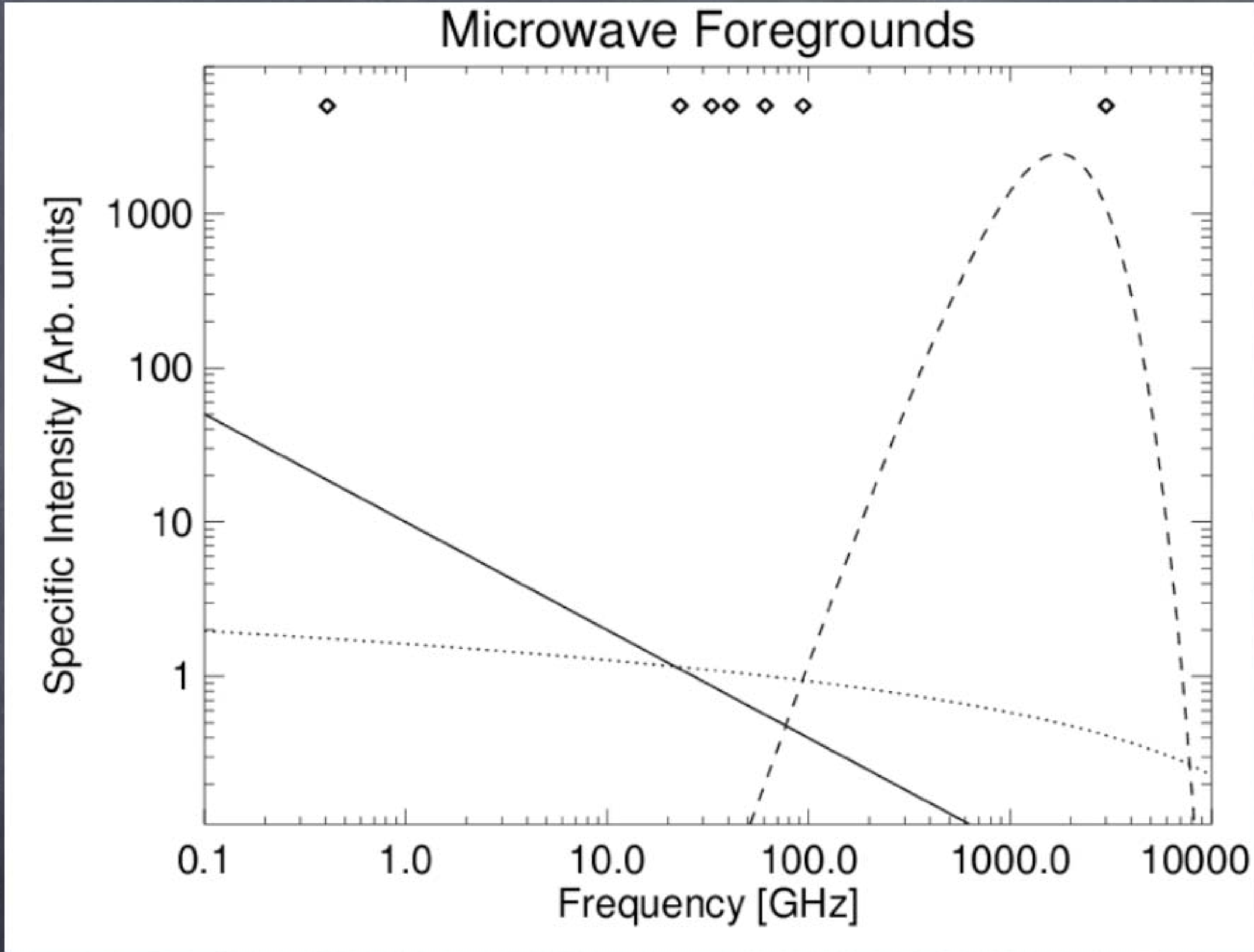
If the INTEGRAL signal has something to do with WIMPs, Where the heck is this physics at the MeV scale coming from?

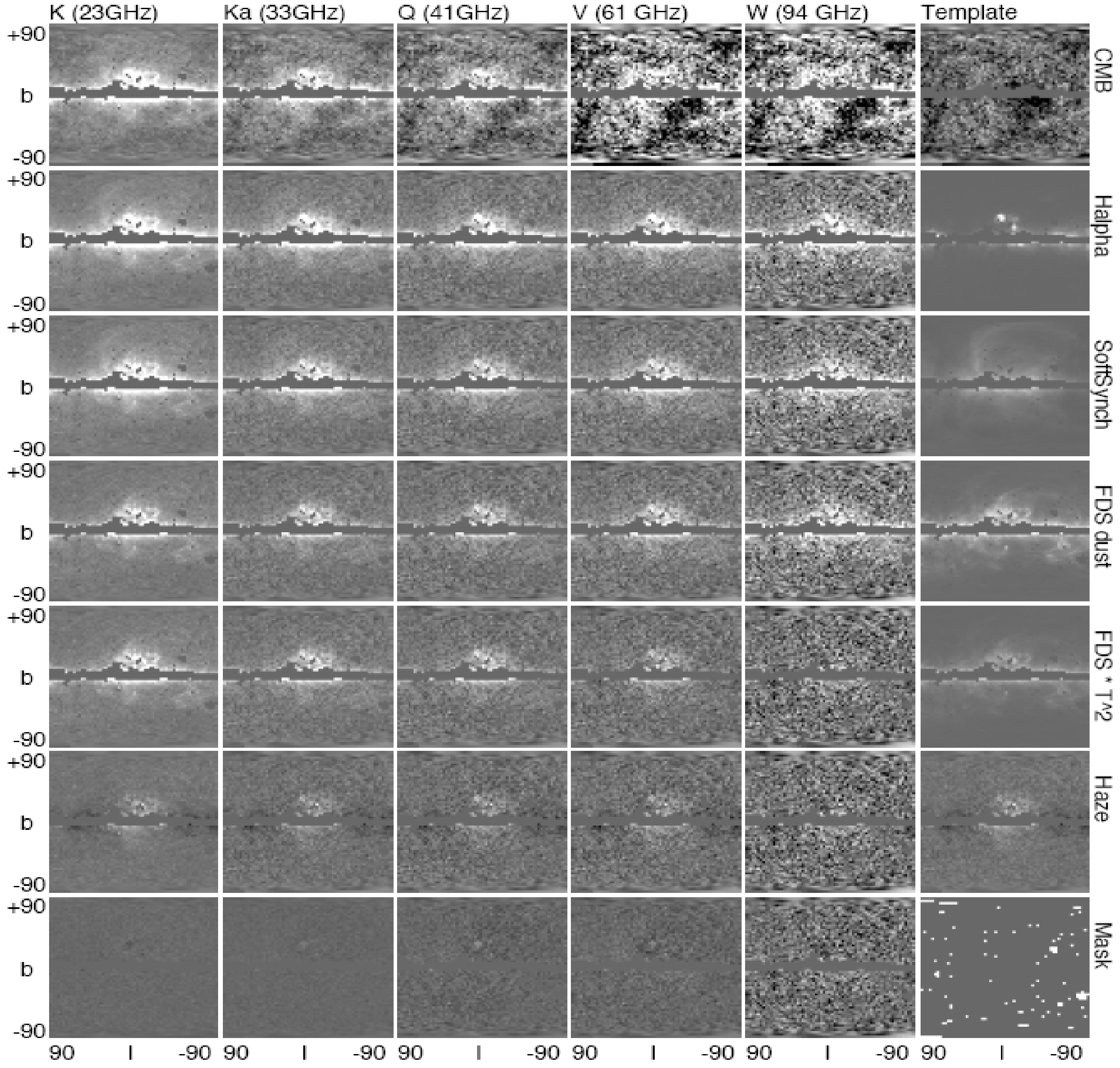
WMAP "Haze"

Finkbeiner, '99

- "Hard" spectrum of microwave radiation
- Consistent with high energy (10-100 GeV) electrons and positrons synchrotron radiating in galactic magnetic field
- PLANCK will extend the frequency range and definitively test this interpretation

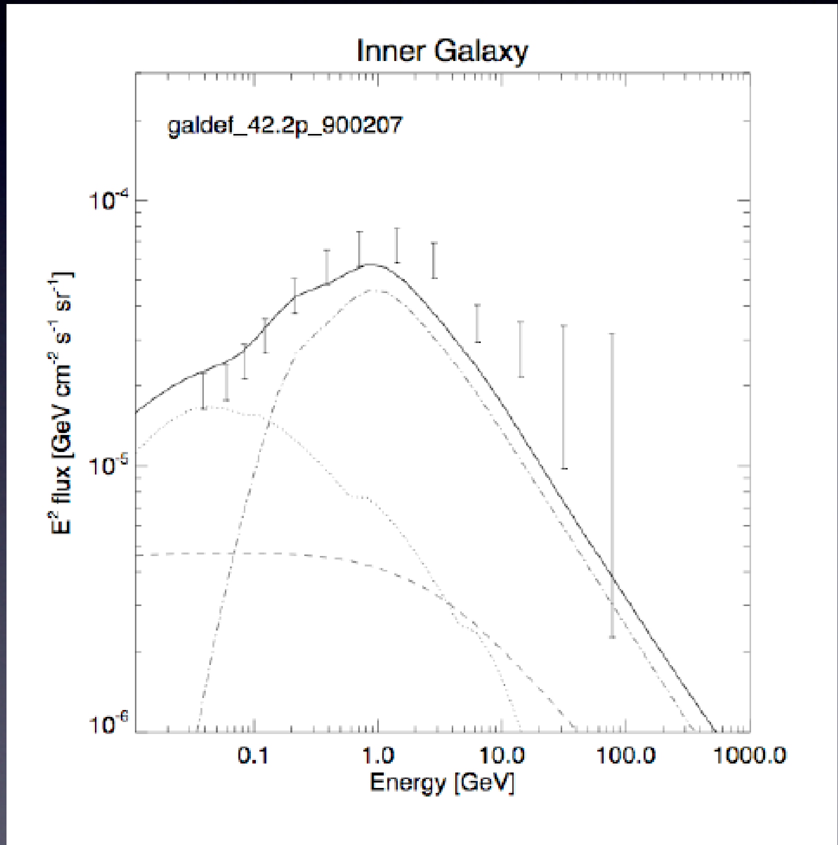

K band
Ka band
V band
Q band
W banc
-200
T(μK)
+200

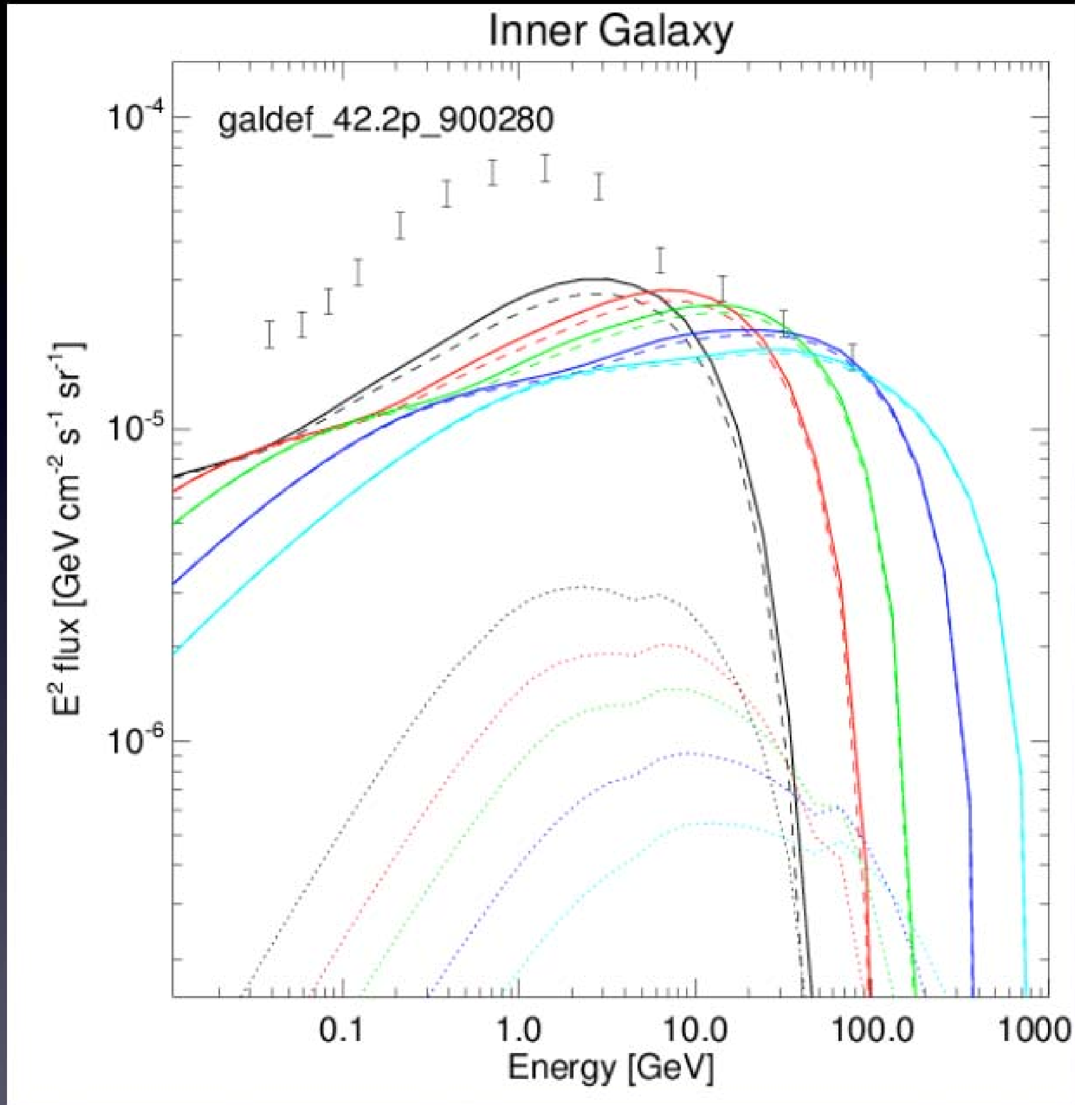

Microwave Foregrounds
Specific Intensity [Arb. units]
1000
100
10
1
0.1
1.0
10.0
100.0
1000.0
10000
Frequency [GHz]



K (23GHz)
Ka (33GHz)
Q (41GHz)
V (61 GHz)
W (94 GHz)
Template
CMB
Halpha
SoftSynch
FDS dust
FDS * T^2
Haze
Mask
+90
b
-90
90
l
-90

EGRET


Inner Galaxy
galdef_42.2p_900207
10^{-4}
10^{-5}
10^{-6}
E² flux [GeV cm⁻² s⁻¹ sr⁻¹]
0.1
1.0
10.0
100.0
1000.0
Energy [GeV]

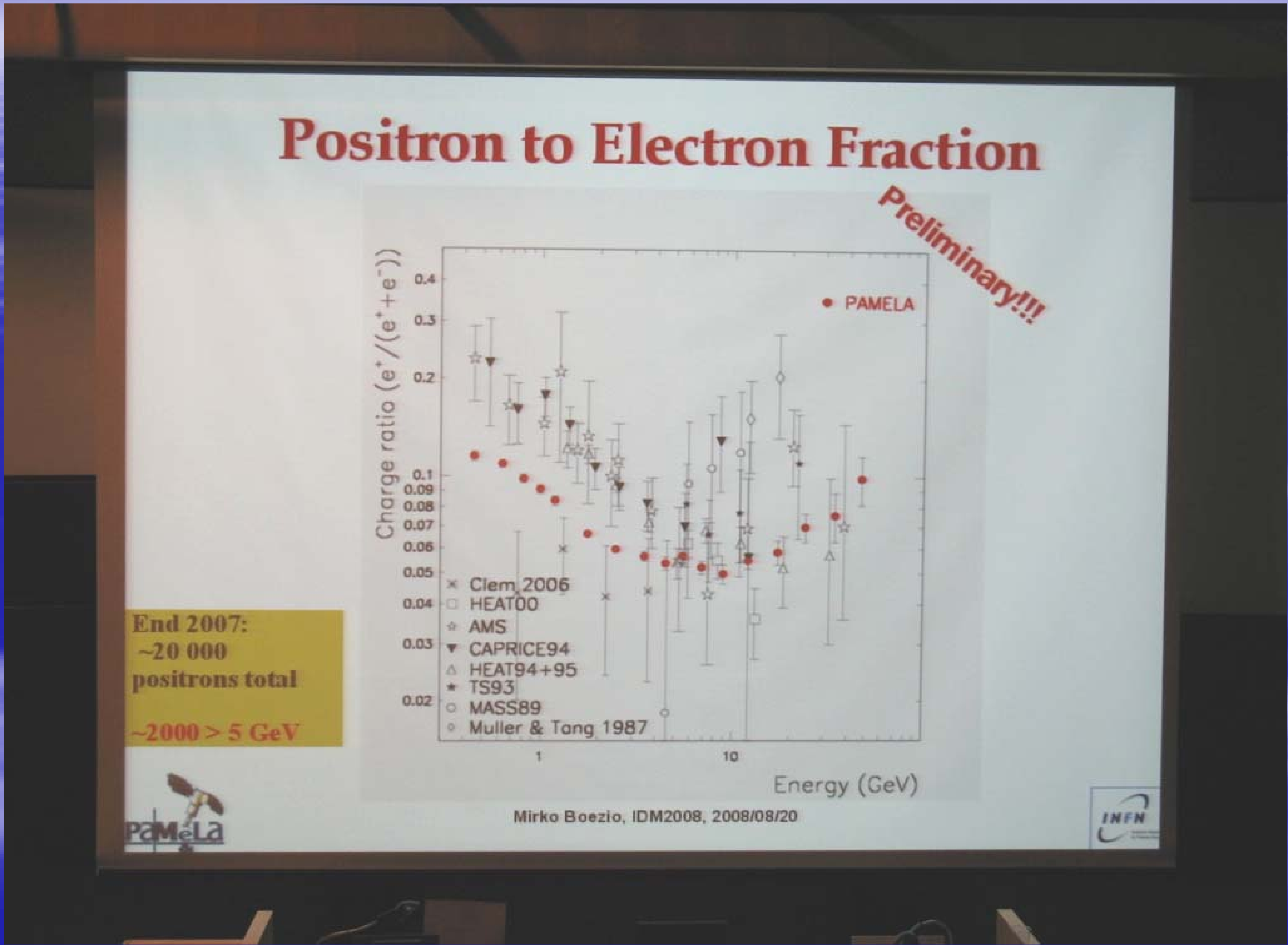


- Fermi/GLAST flying now; will report soon

To my mind there is no “Haze Conundrum”:
It is perfectly reasonably consistent with
a variety of natural WIMP candidates. Compelling!

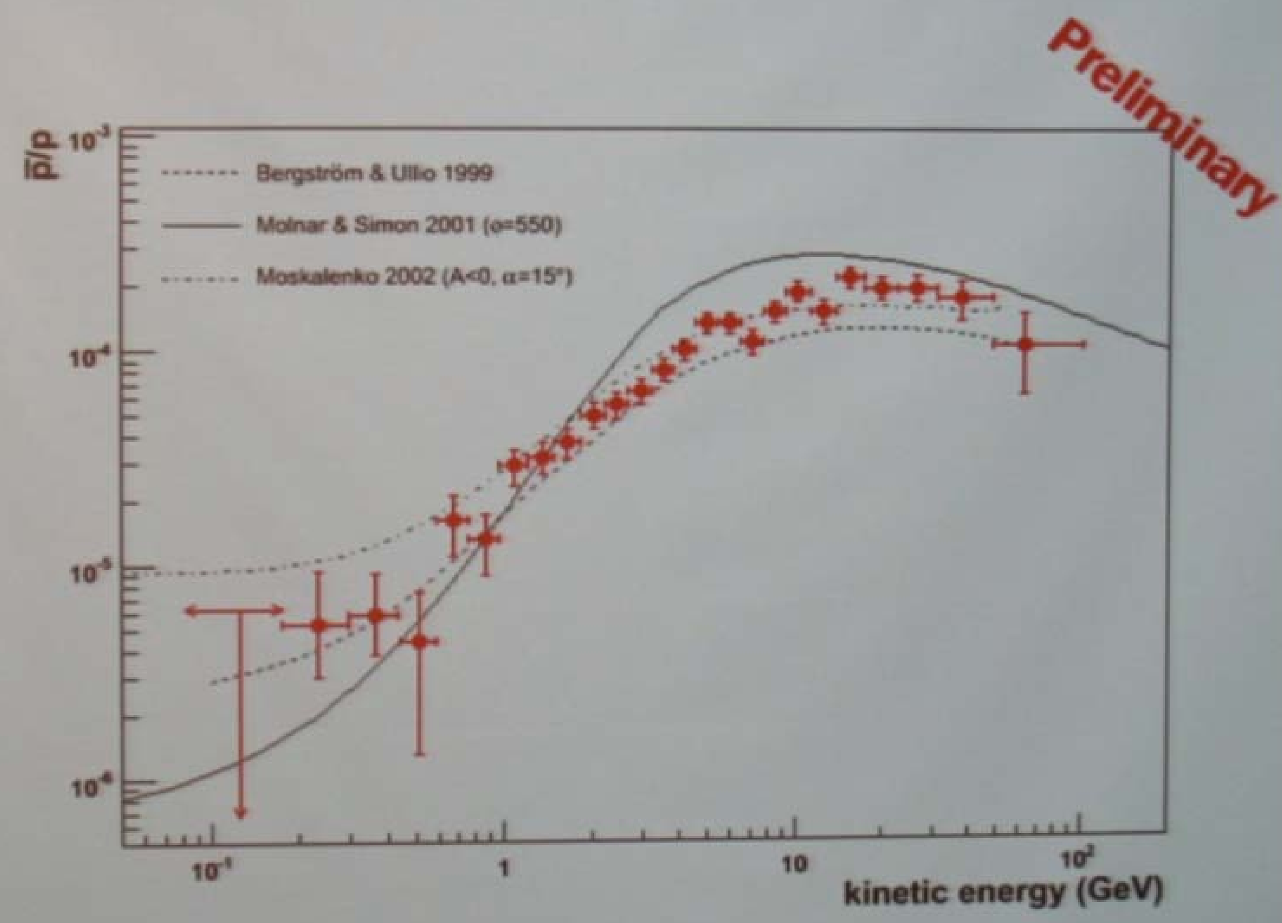
If real, should get much stronger evidence from
Planck, Fermi/GLAST.

PAMELA



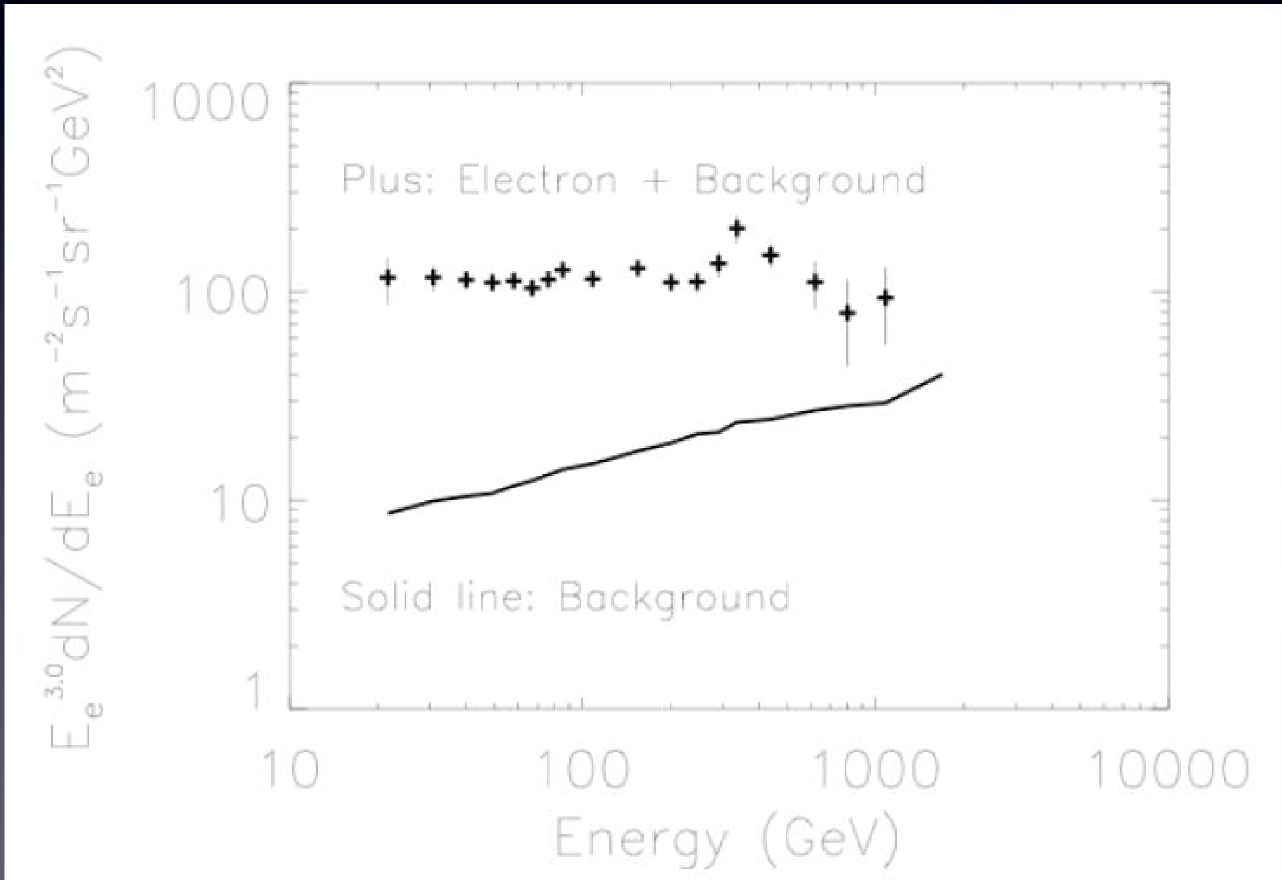
Positron to Electron Fraction
Preliminary!!!
PAMELA
Charge ratio (e+/(e+ + e-))
0.4
0.3
0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
Clem 2006
HEAT00
AMS
CAPRICE94
HEAT94+95
TS93
MASS89
Muller & Tang 1987
1
10
Energy (GeV)
End 2007:
~20 000
positrons total
~2000 > 5 GeV
Mirko Boezio, IDM2008, 2008/08/20
PaMeLa
INFN

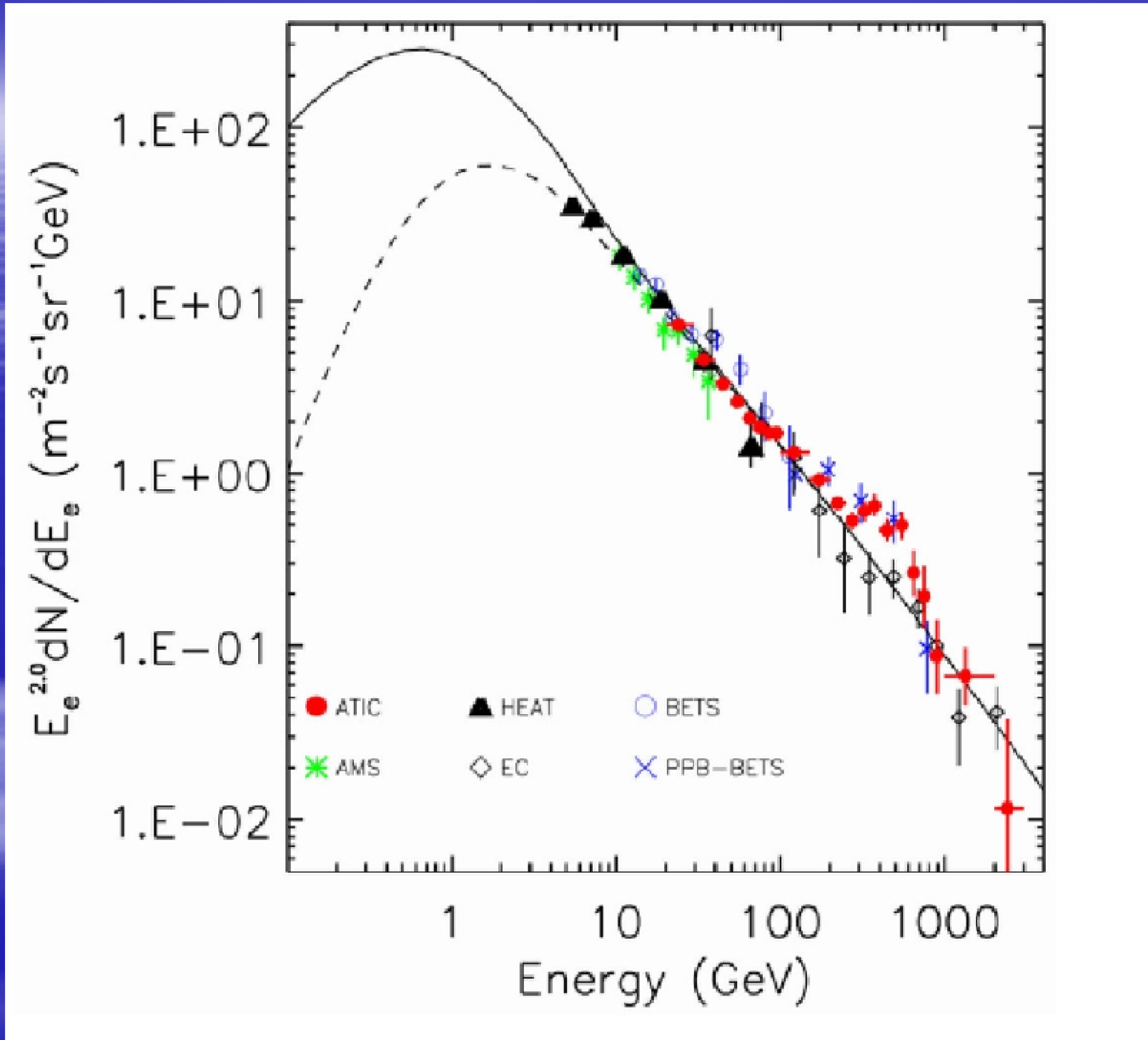
Antiproton to proton ratio



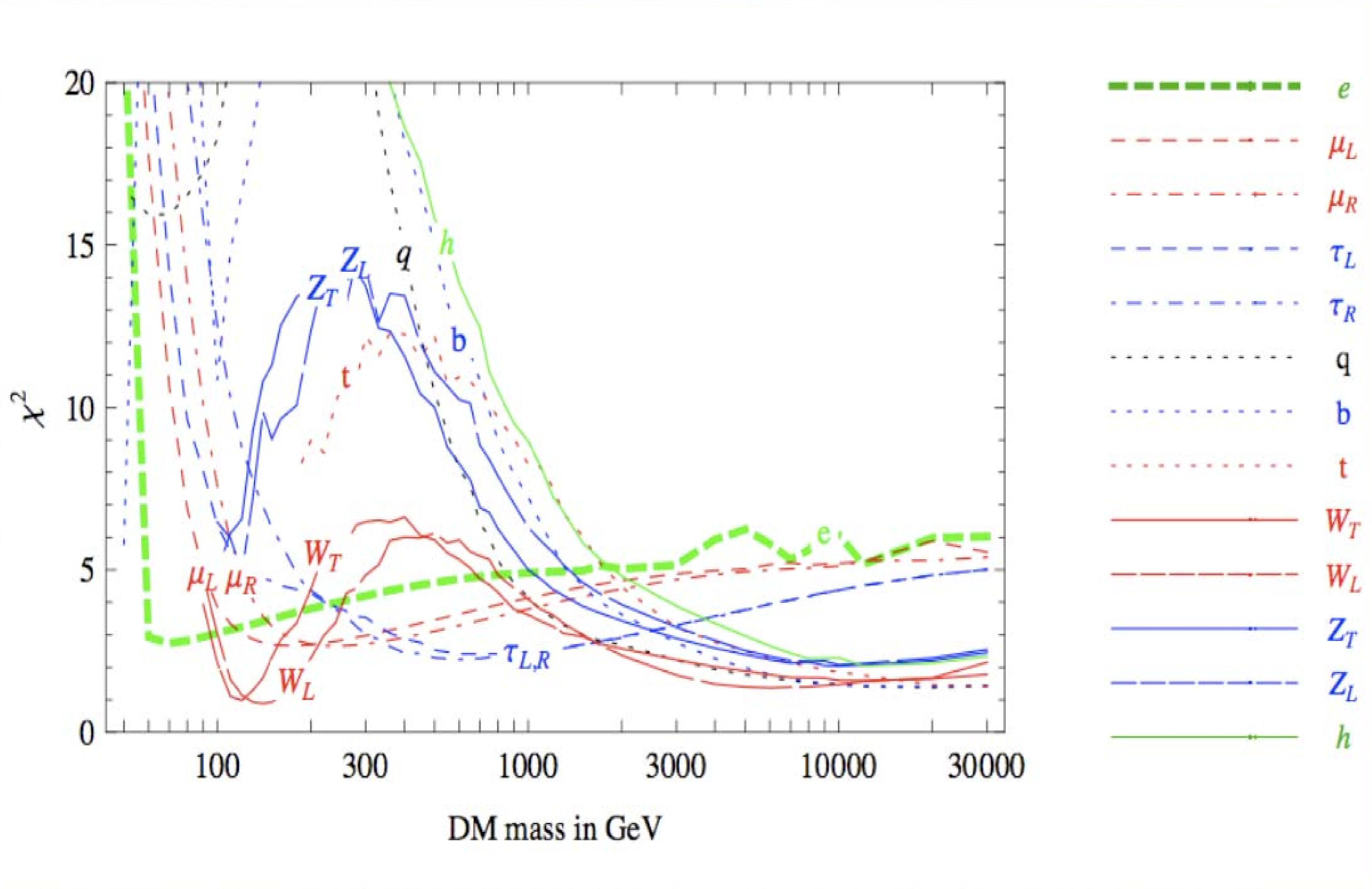
How High Does it Go?

ATIC = Advanced Thin Ionization Calorimeter
Preliminary data from 2005:

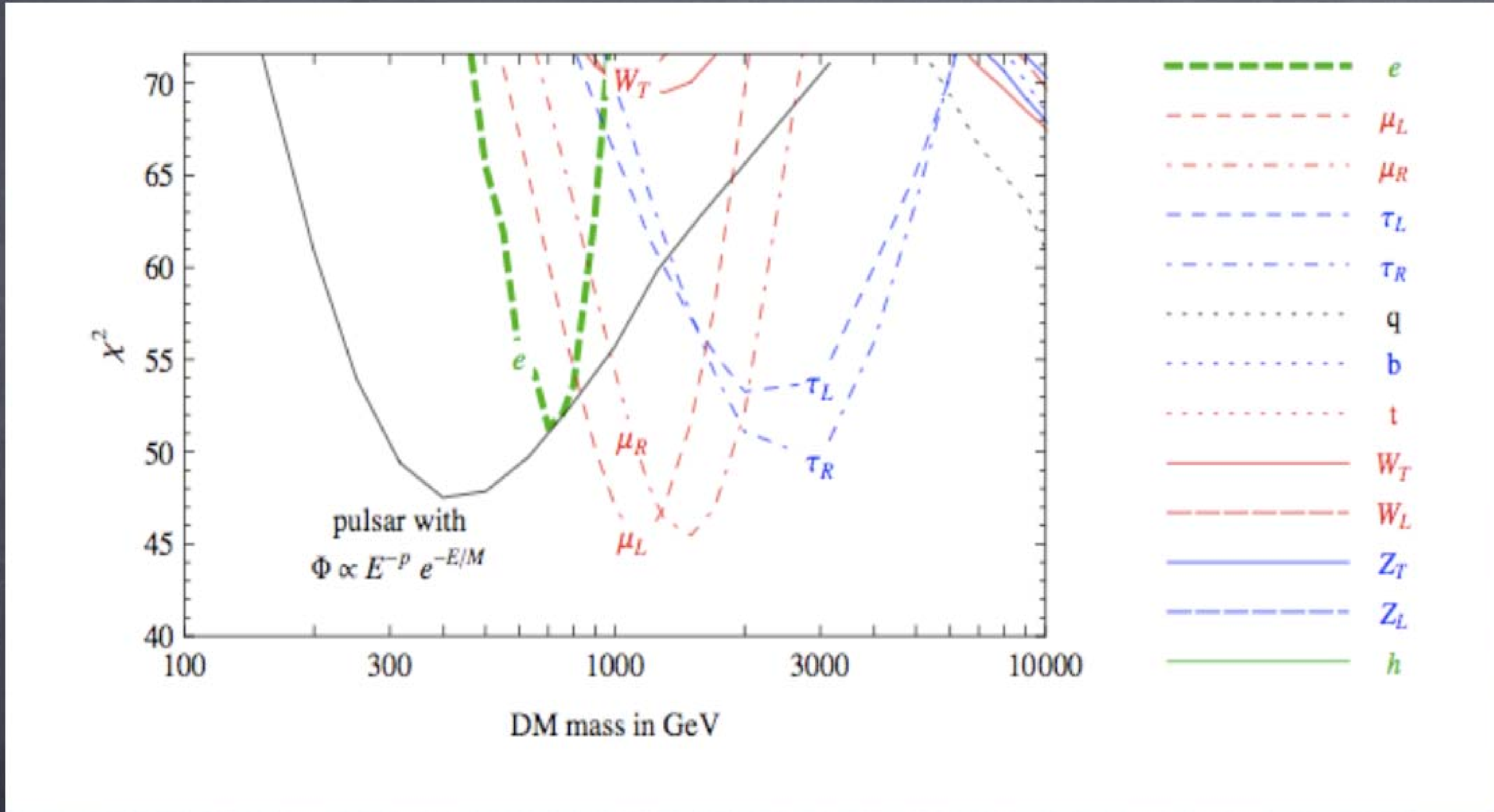




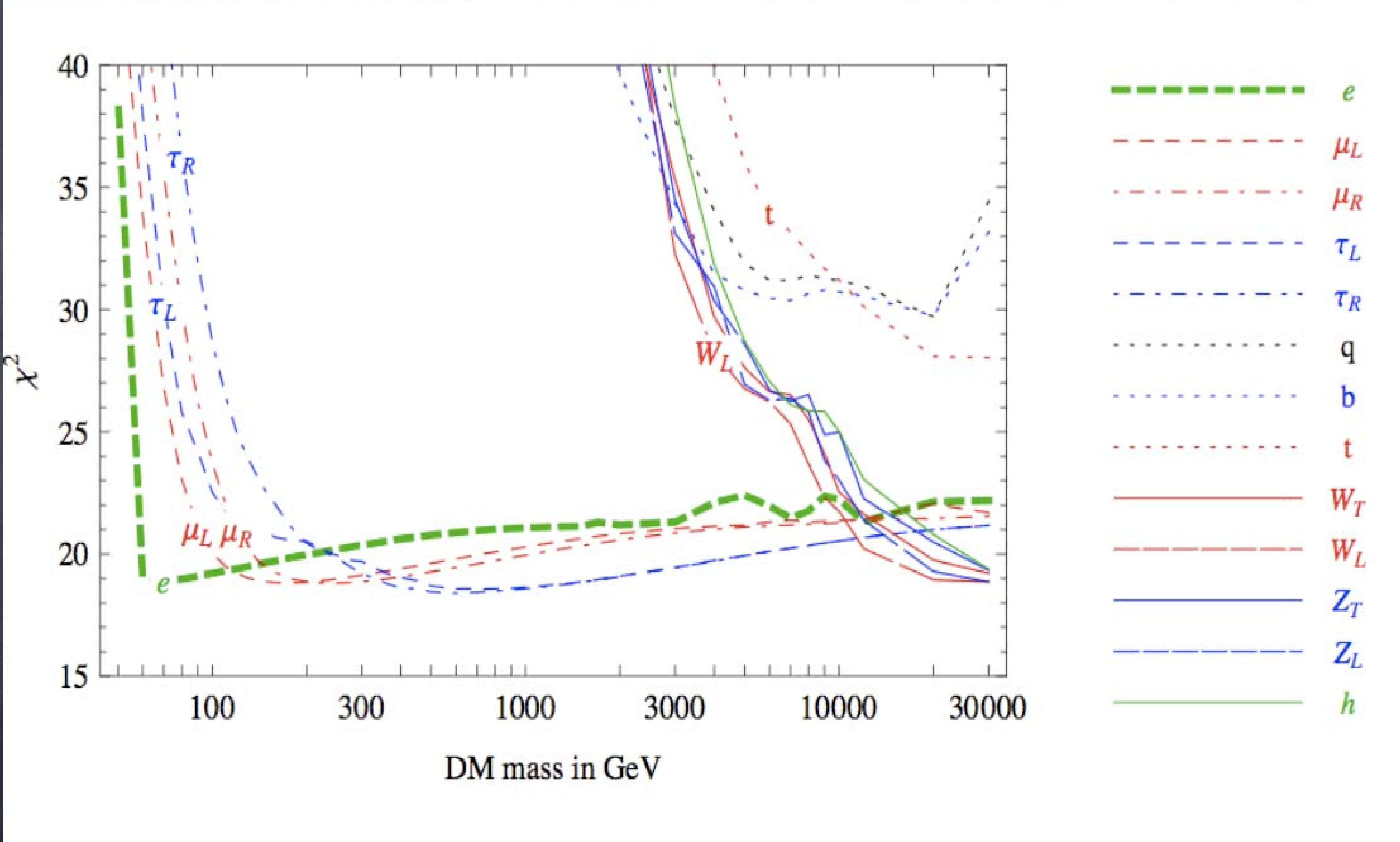
1.E+02
1.E+01
1.E+00
1.E−01
1.E−02
$E_e^{2.0} dN/dE_e$ ($m^{-2}s^{-1}sr^{-1}GeV$)
1
10
100
1000
Energy (GeV)
ATIC
HEAT
BETS
AMS
EC
PPB−BETS



PAMELA positron only: Cirelli, Strumia



PAMELA postrion +ATIC: Cirelli, Strumia



PAMELA positron + PAMELA pbar: Cirelli, Strumia

What does this say about DM

- Take ATIC seriously => 500-900 GeV WIMP
  - (Could be a lower bump from a multi-TeV WIMP)
- Take PAMELA+ATIC seriously
  - Big cross sections (boost 200-400)
  - Big cross sections **into hard leptons**
  - **Low** cross sections into hadrons

THE PAMELA/ATIC CONUNDRUMS

If the annihilation cross-section is 100-1000 times bigger than usual, why was the Dark Matter not depleted in the early universe?

Why are the annihilations dominantly into leptons?

Dark Matter is Charged under non-Abelian G_{Dark}, broken @ the GeV scale.

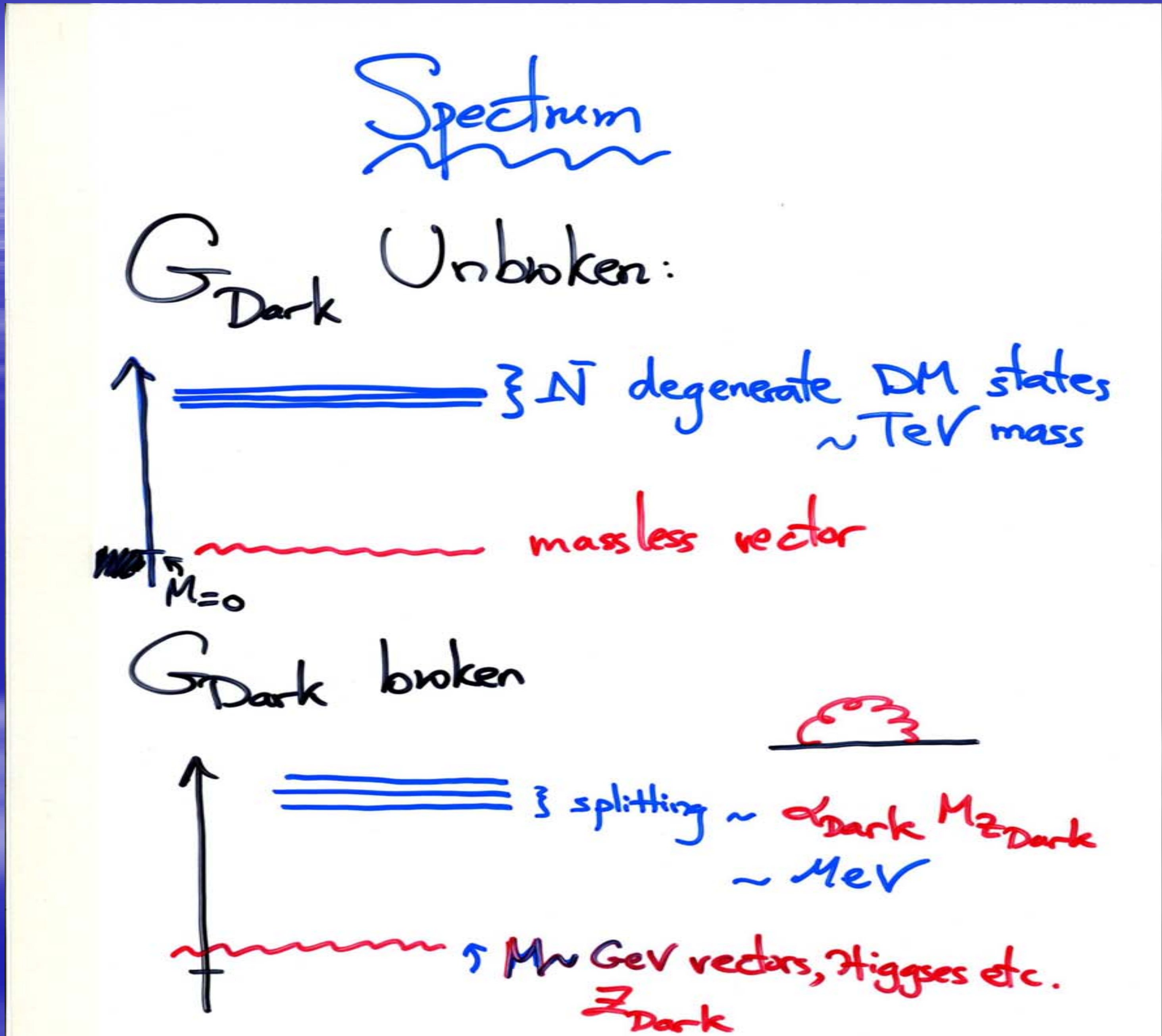
This Unifies previous ideas:

★ "Exciting" DM for INTEGRAL

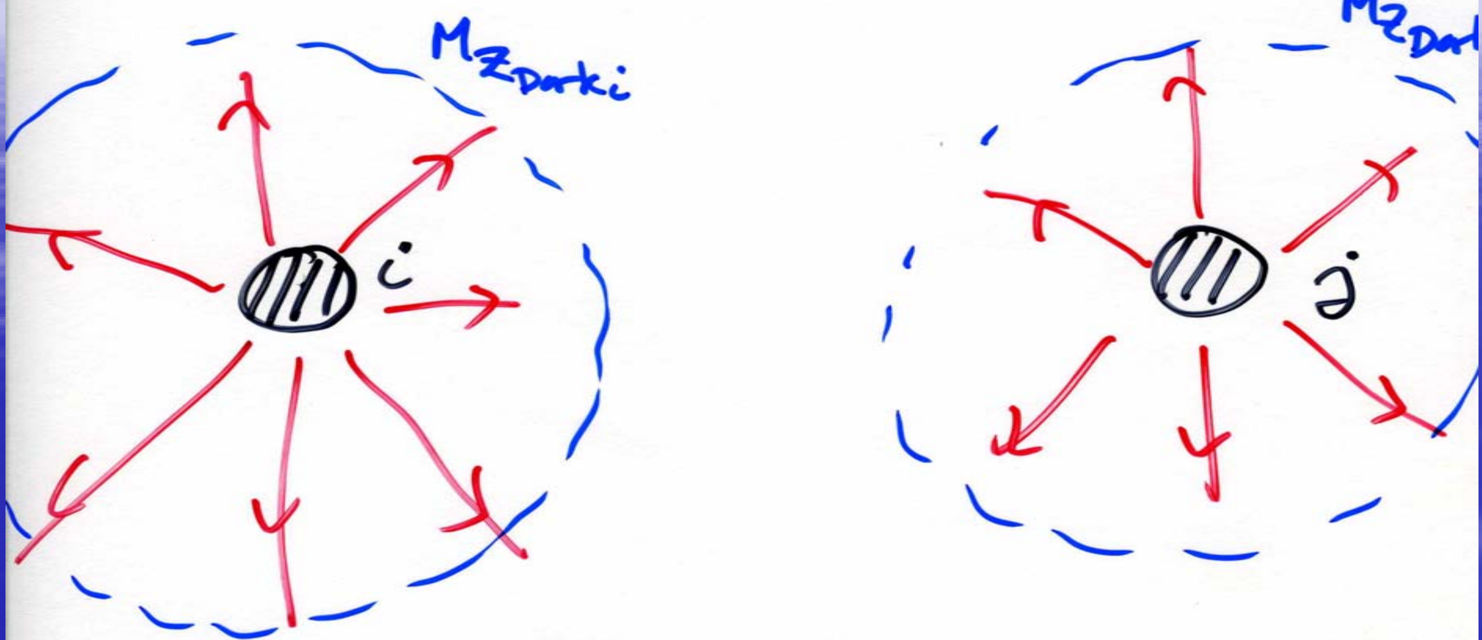
Weiner, Finkbeiner, ..

★ "Inelastic" DM for DAMA

Weiner, Tucker-Smith, ..



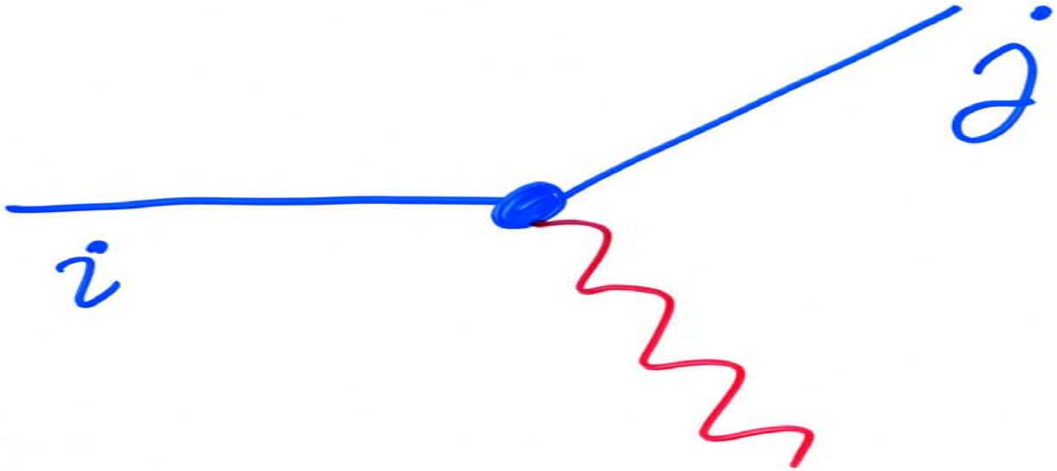
Spectrum
G Dark Unbroken:
} N degenerate DM states
~ TeV mass
massless vector
M=0
G Dark broken
} splitting ~ α Dark M Z Dark
~ MeV
M ~ GeV vectors, Higgses etc.
Z Dark



$$E = \int d^3r \, \frac{1}{2} \mathcal{E}^2 \sim \int \frac{dr}{r} \, \alpha_{Dark} e^{-M_{Dark} r}$$

$$\Delta M_{ij} \sim \alpha_{Dark} \left(M_{Z_{Dark\,i}} - M_{Z_{Dark\,j}} \right)$$

Vector Couplings



$i \neq j$;

Very Important!

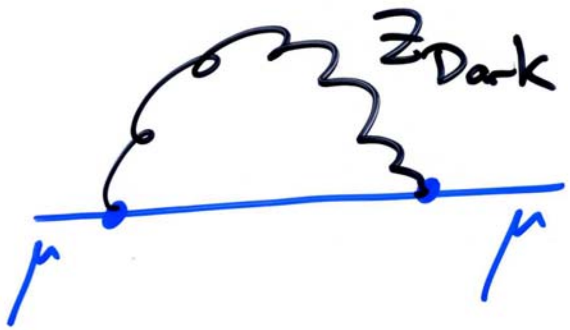
Coupling to the Standard Model

kinetic mixing w/ photon:

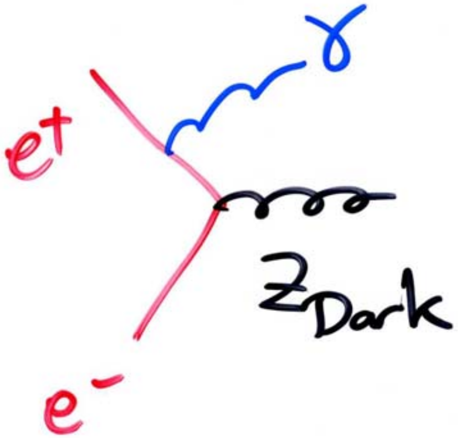
$$\varepsilon \; \vec{E}_{\gamma} \cdot \vec{B}_{Dark}$$

Naturally $\sim 10^{-3 \to -4}$

Expt'l limits



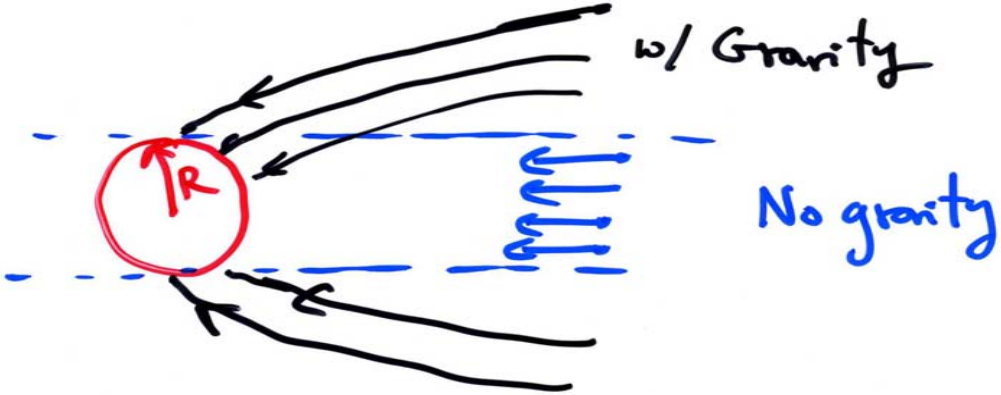
muon (g-2)



Direct searches @ low-E e^+e^- machines [not yet done?]

$$\epsilon \sim 10^{-3} \text{ is ok.}$$

DM annihilation + "Sommerfeld Enhancement"



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

- Sommerfeld Effect is quantum counterpart of this classical phenomenon e.g. Coulomb $V(r) = -\frac{\alpha}{r}$

$\sigma = \sigma_0 \left(\frac{\pi\alpha}{v}\right)$ for $v \lesssim \alpha$

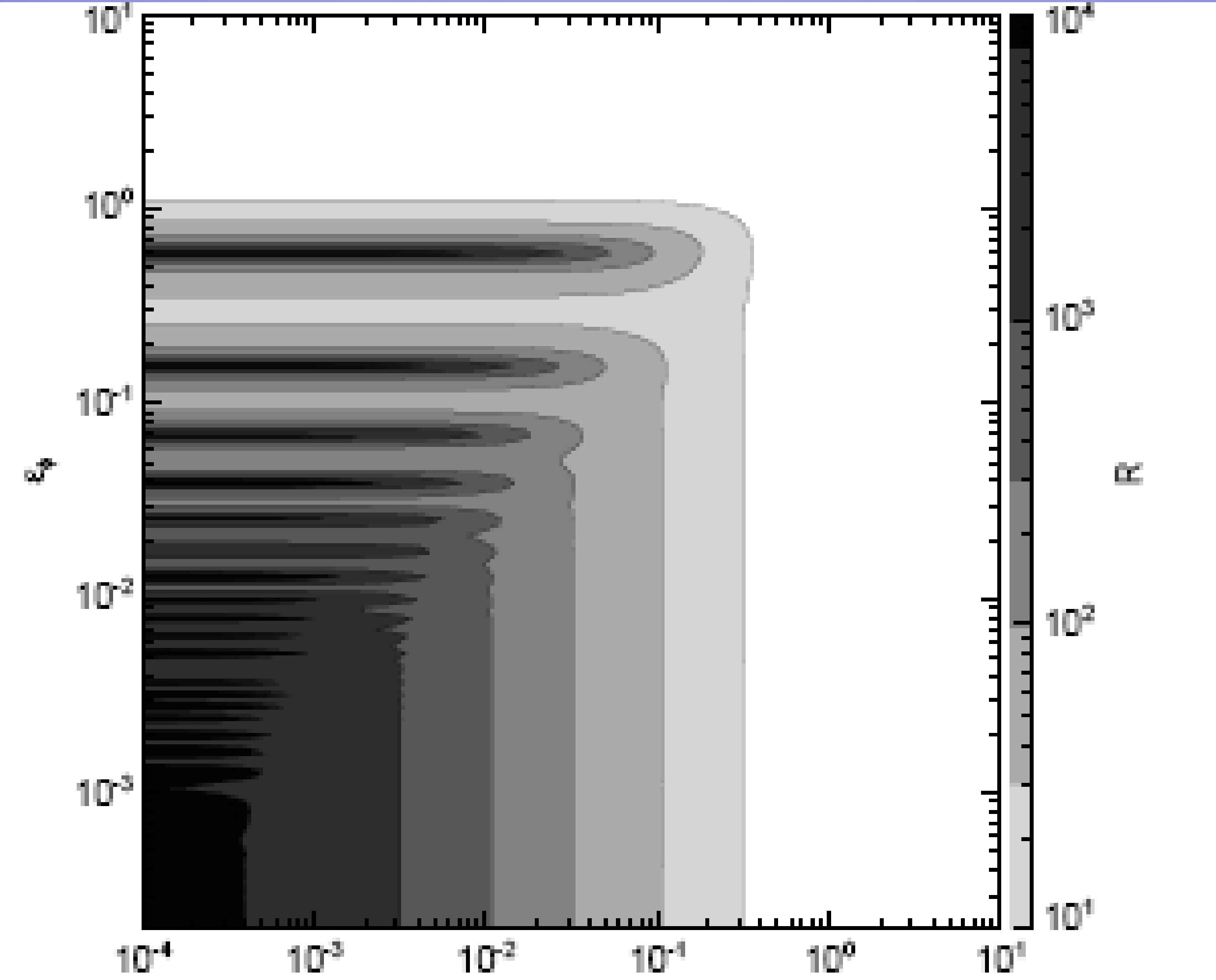
For Yukawa $V(r) = -\frac{\alpha}{r} e^{-M_\phi r}$,

$\sigma = \sigma_0 \left(\frac{\pi\alpha}{v}\right)$ till $Mv \sim M_\phi$,

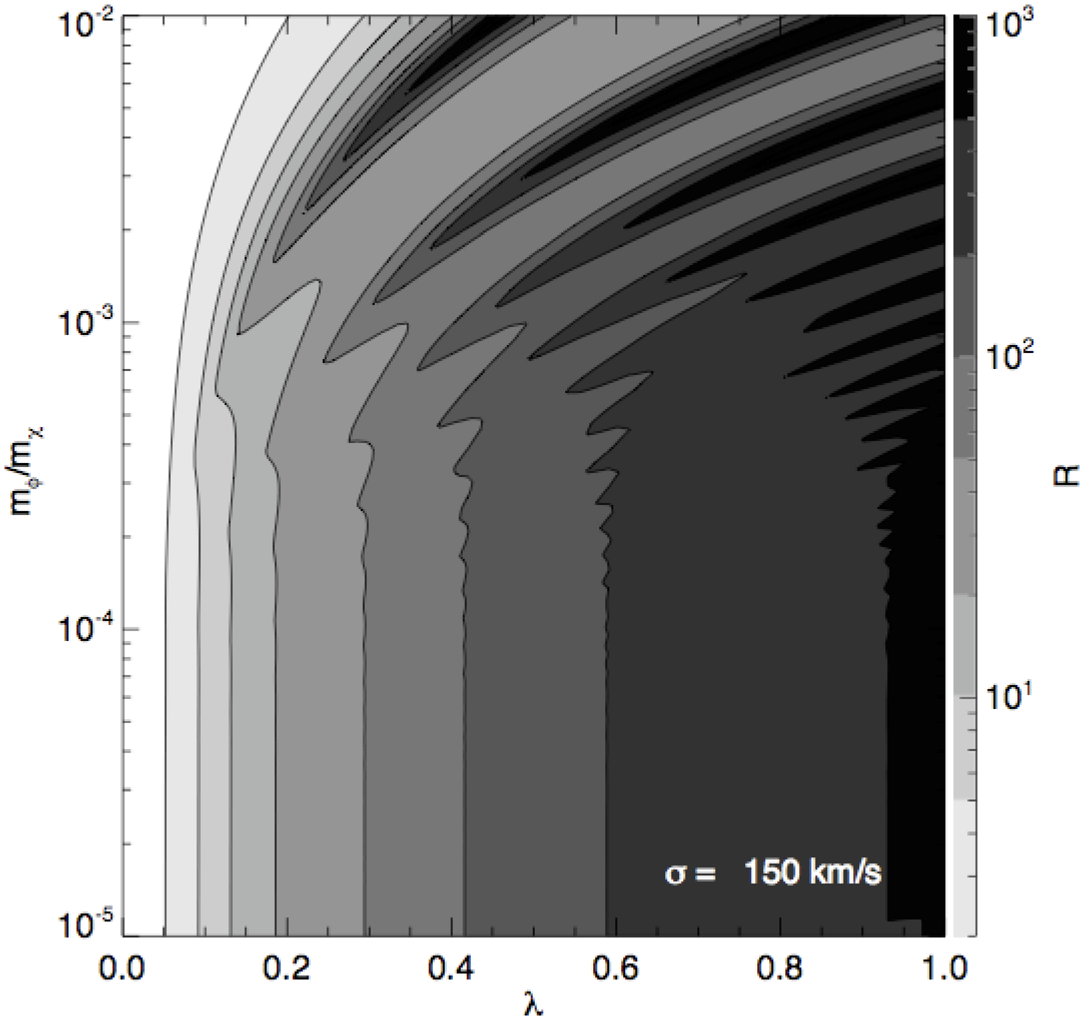
Saturates @ $\sigma = \sigma_0 \left(\frac{\alpha M}{M_\phi}\right)$.

~ 100 increase for $M_{DM} \sim \text{TeV}$,

$M_\phi \sim \text{GeV}$

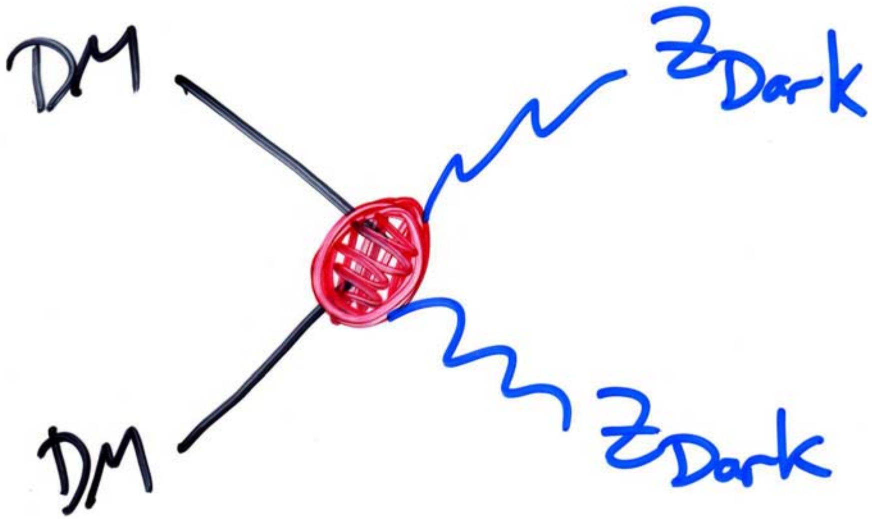


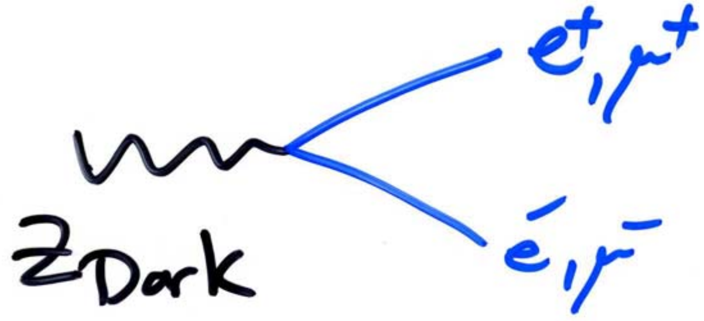
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-3
10^-2
10^-1
10^0
10^1
10^4
10^3
10^2
10^1



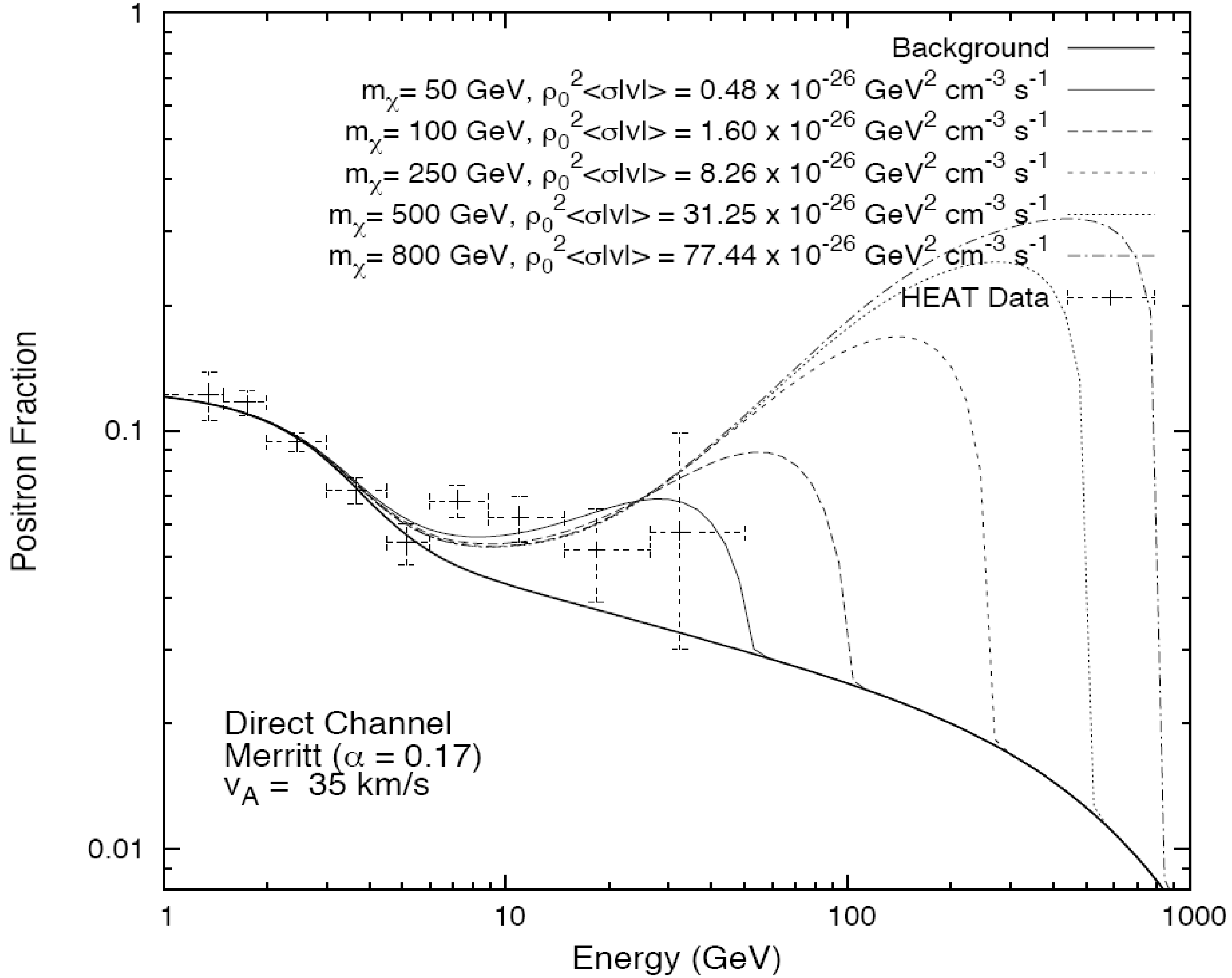
10^{-2}
10^{-3}
10^{-4}
10^{-5}
m_ϕ/m_χ
0.0
0.2
0.4
0.6
0.8
1.0
λ
$\sigma =$ 150 km/s
10^3
10^2
10^1
R

New Annihilation Modes

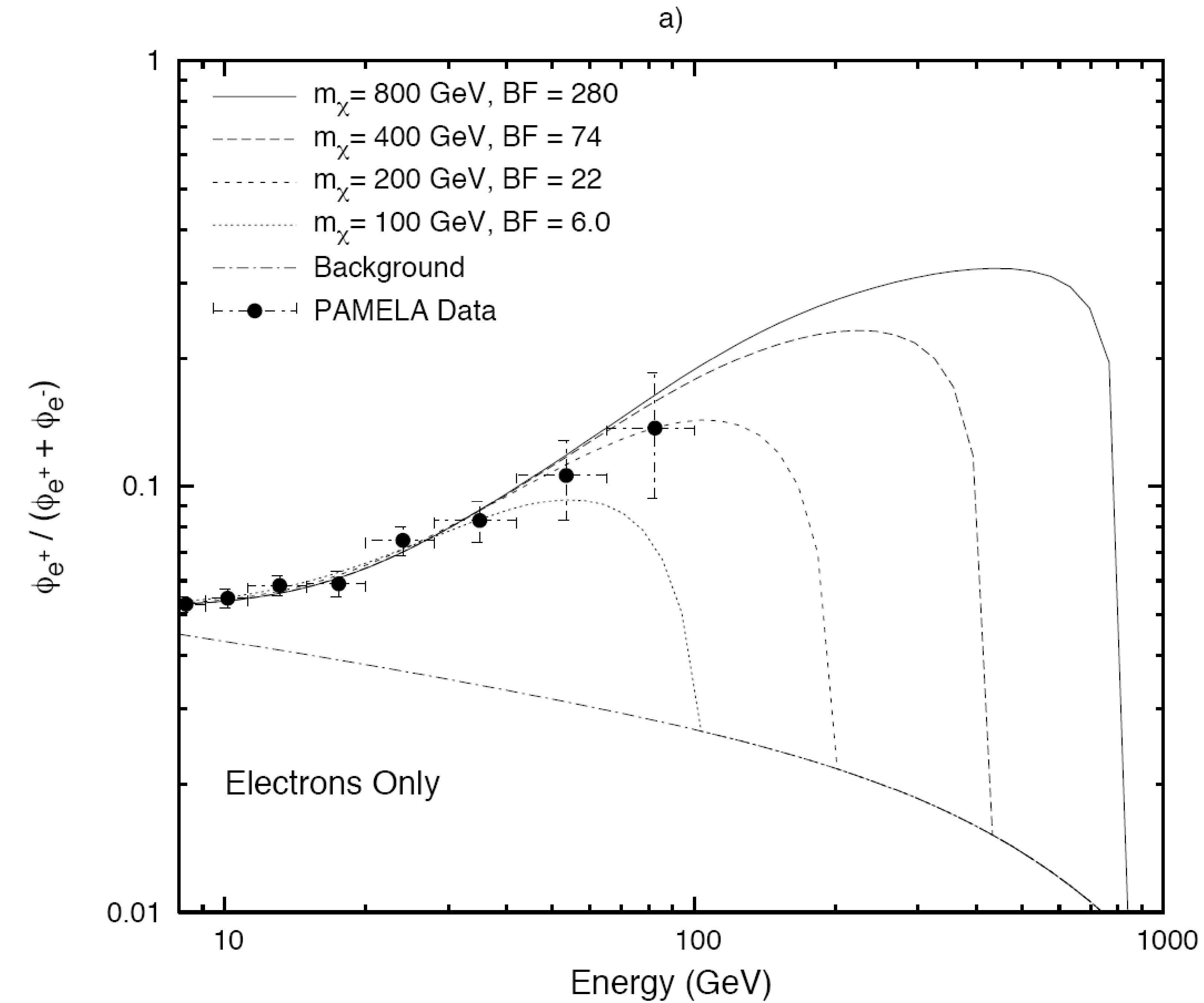


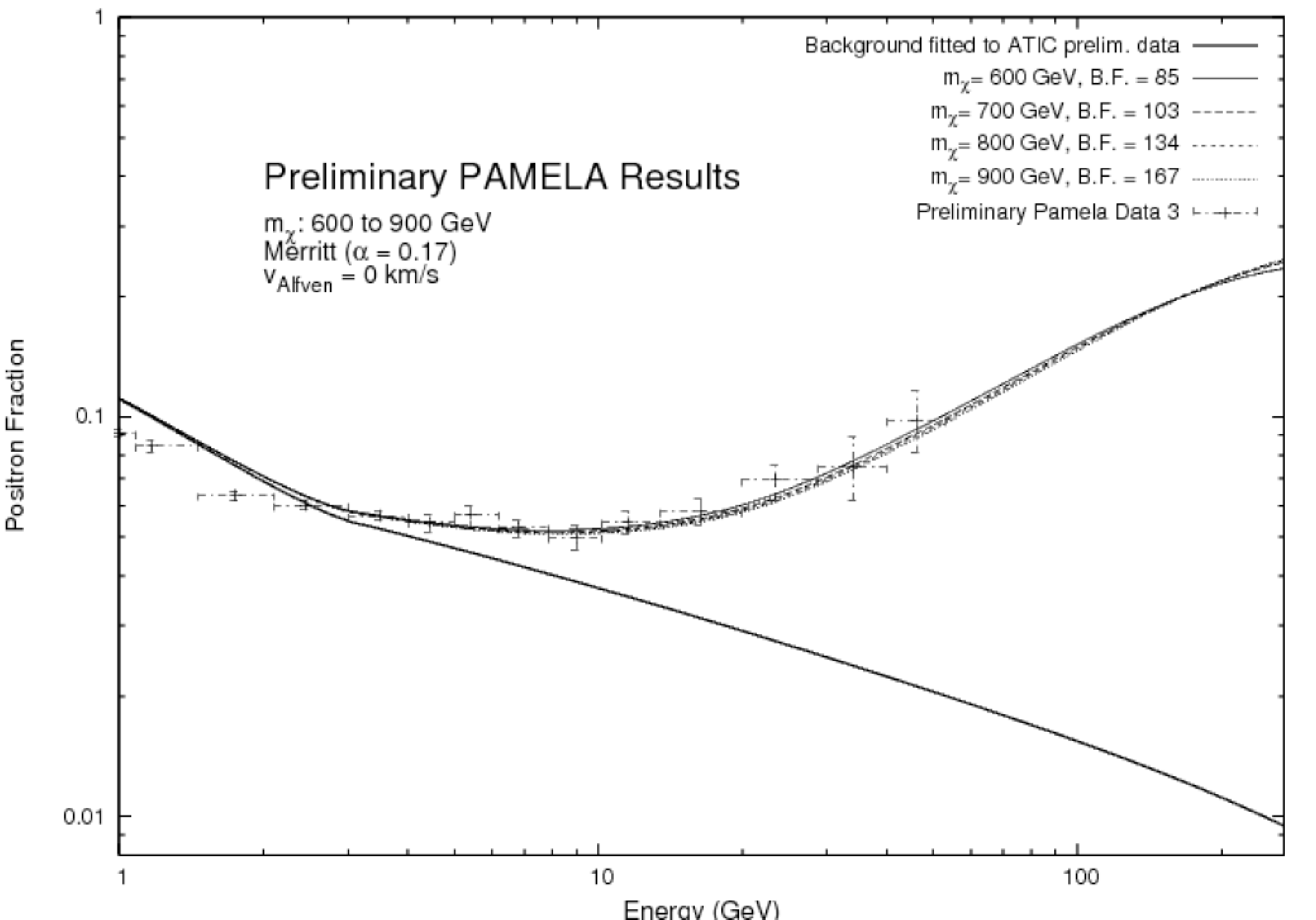


too light to decay to antiprotons.

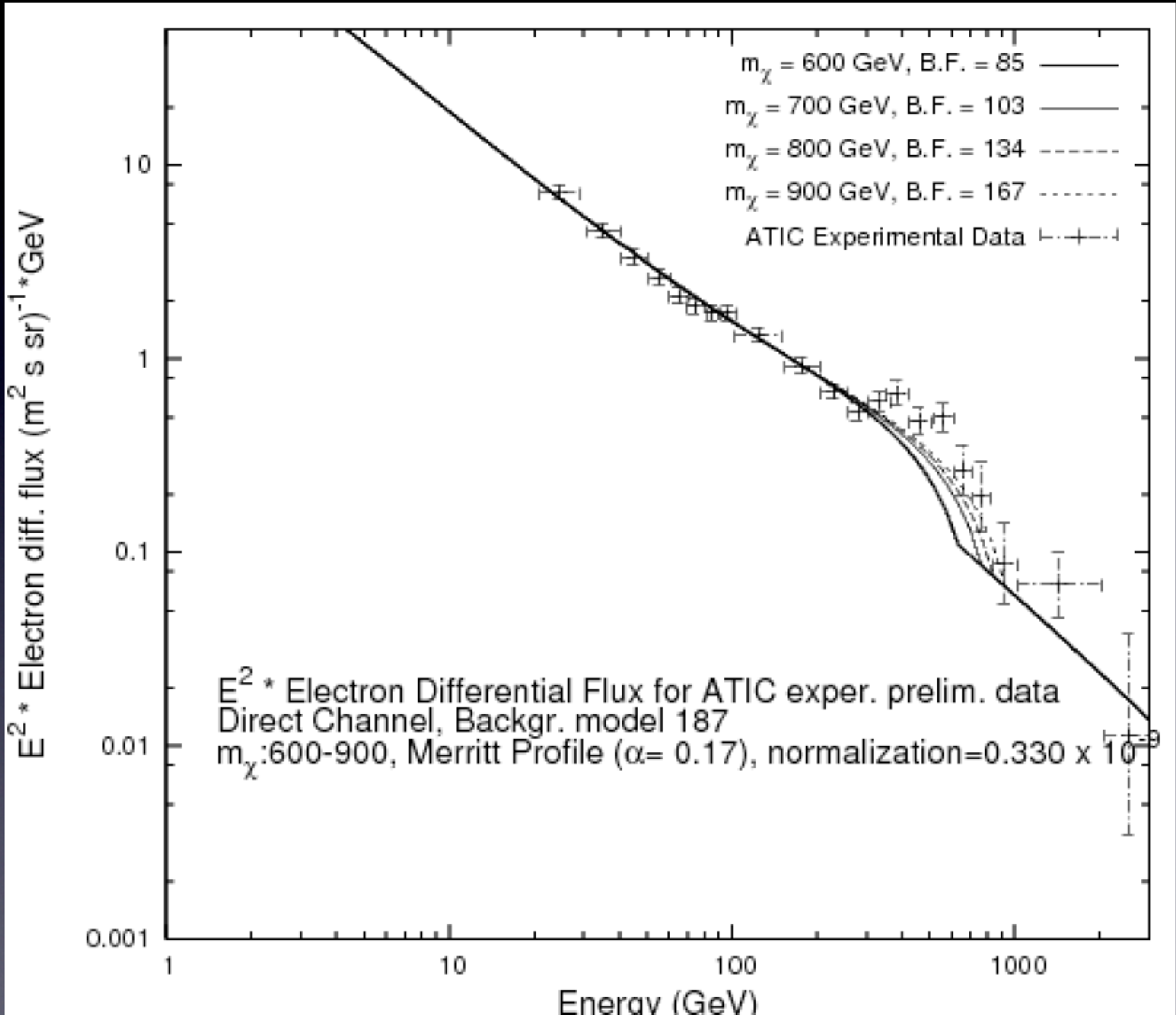


(c)Direct decay channel, $v_A = 35$ km/s

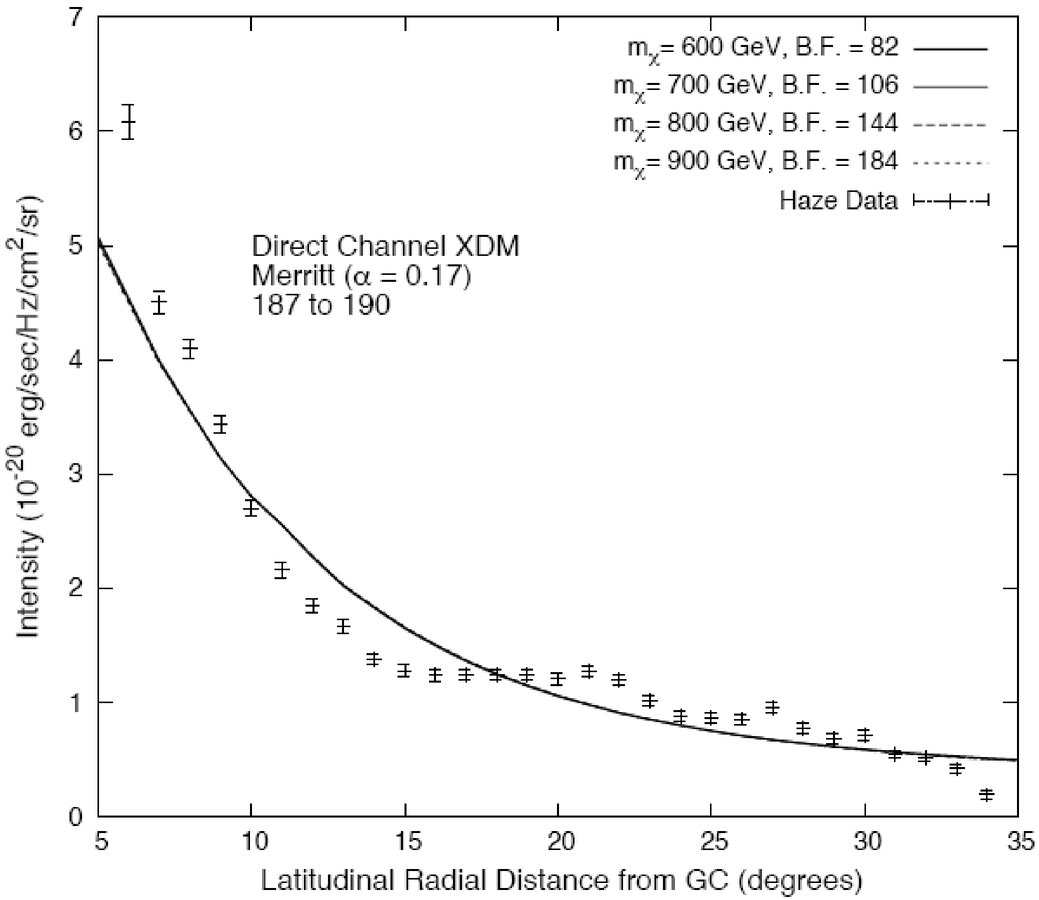

a)
m_χ= 800 GeV, BF = 280
m_χ= 400 GeV, BF = 74
m_χ= 200 GeV, BF = 22
m_χ= 100 GeV, BF = 6.0
Background
PAMELA Data
Electrons Only
$\phi_{e^+} / (\phi_{e^+} + \phi_{e^-})$
Energy (GeV)
1
0.1
0.01
10
100
1000



Preliminary PAMELA Results
m_χ: 600 to 900 GeV
Merritt (α = 0.17)
v_{Alfven} = 0 km/s
Background fitted to ATIC prelim. data
m_χ= 600 GeV, B.F. = 85
m_χ= 700 GeV, B.F. = 103
m_χ= 800 GeV, B.F. = 134
m_χ= 900 GeV, B.F. = 167
Preliminary Pamela Data 3
Positron Fraction
Energy (GeV)
1
0.1
0.01
1
10
100

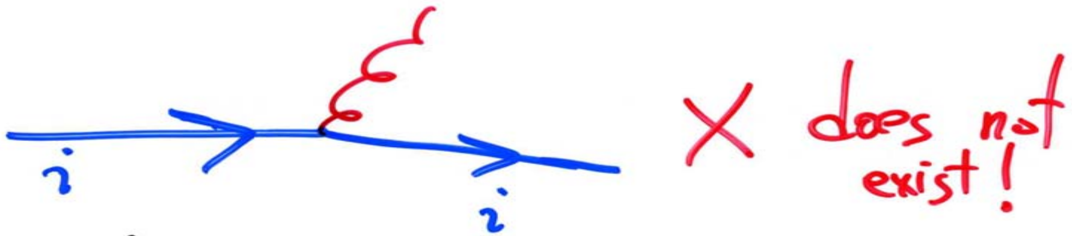


mχ = 600 GeV, B.F. = 85
mχ = 700 GeV, B.F. = 103
mχ = 800 GeV, B.F. = 134
mχ = 900 GeV, B.F. = 167
ATIC Experimental Data
E² * Electron Differential Flux for ATIC exper. prelim. data
Direct Channel, Backgr. model 187
mχ:600-900, Merritt Profile (α= 0.17), normalization=0.330 x 10⁻⁹
E² * Electron diff. flux (m² s sr)⁻¹ * GeV
Energy (GeV)
10
1
0.1
0.01
0.001
1
10
100
1000

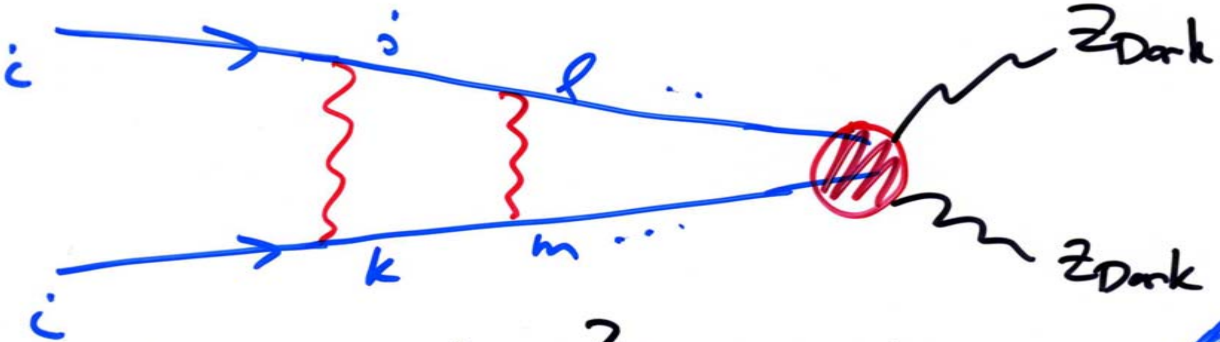


m_χ= 600 GeV, B.F. = 82
m_χ= 700 GeV, B.F. = 106
m_χ= 800 GeV, B.F. = 144
m_χ= 900 GeV, B.F. = 184
Haze Data
Direct Channel XDM
Merritt (α = 0.17)
187 to 190
Intensity (10^-20 erg/sec/Hz/cm^2/sr)
Latitudinal Radial Distance from GC (degrees)

Actually, Sommerfeld effect is even more interesting w/ vectors...



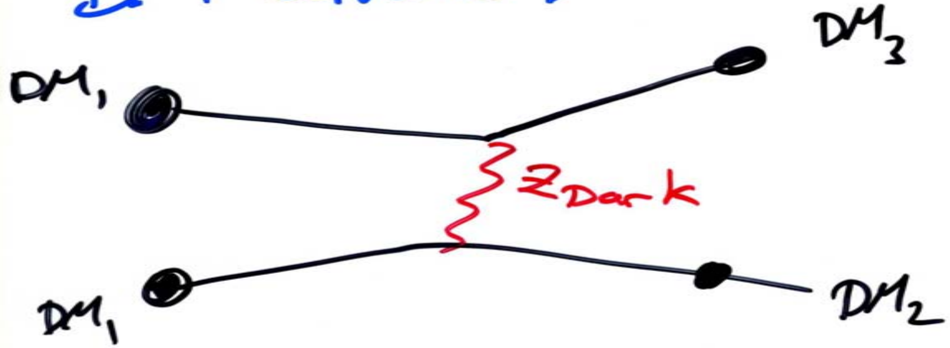
Quantum oscillation phenomenon!



Need $M v^2 \sim \Delta M_{DM}$ ✓

$\sim$ MeV $\quad\quad \sim$ MeV

But this means, parametrically, there must be enough energy to make excited states in DM collisions!

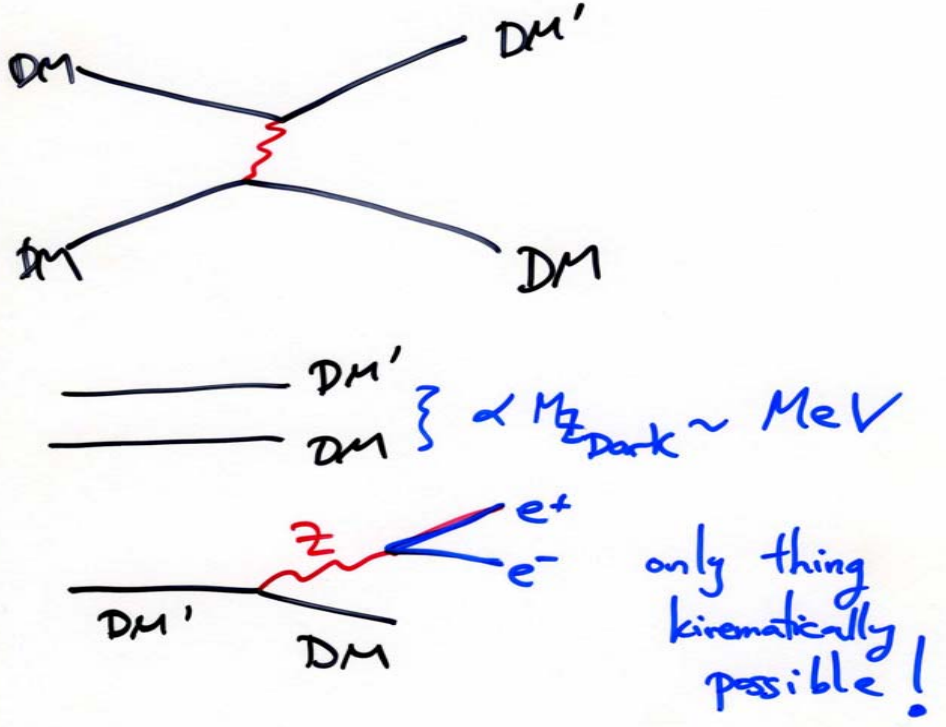


since we needed (+ have)

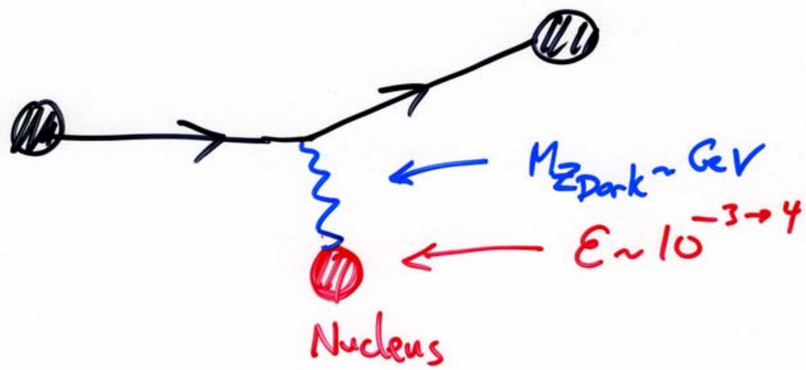
$M_{Z_{Dark}} \lesssim M_{DM} v$ anyway,

Geometric cross-section!

... This explains INTEGRAL!



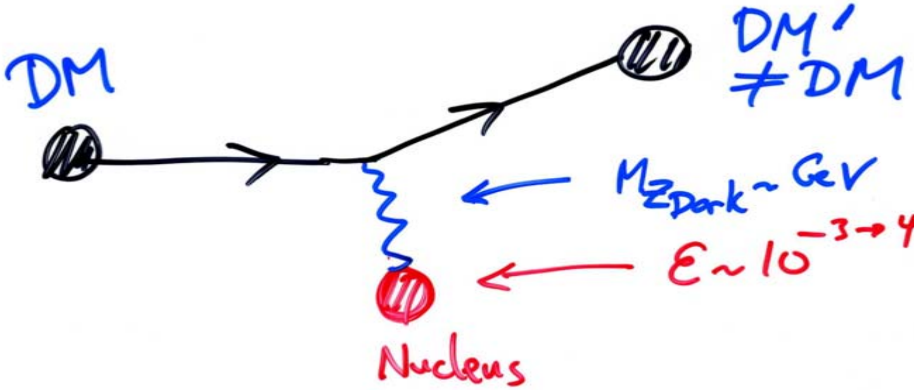
What about Direct Detection?



$$\sigma \sim \frac{\epsilon}{M_{Z_{Dark}}^2} \sim \frac{1}{M_Z^2}$$

~ the same as usual WIMPS

What about Direct Detection ?



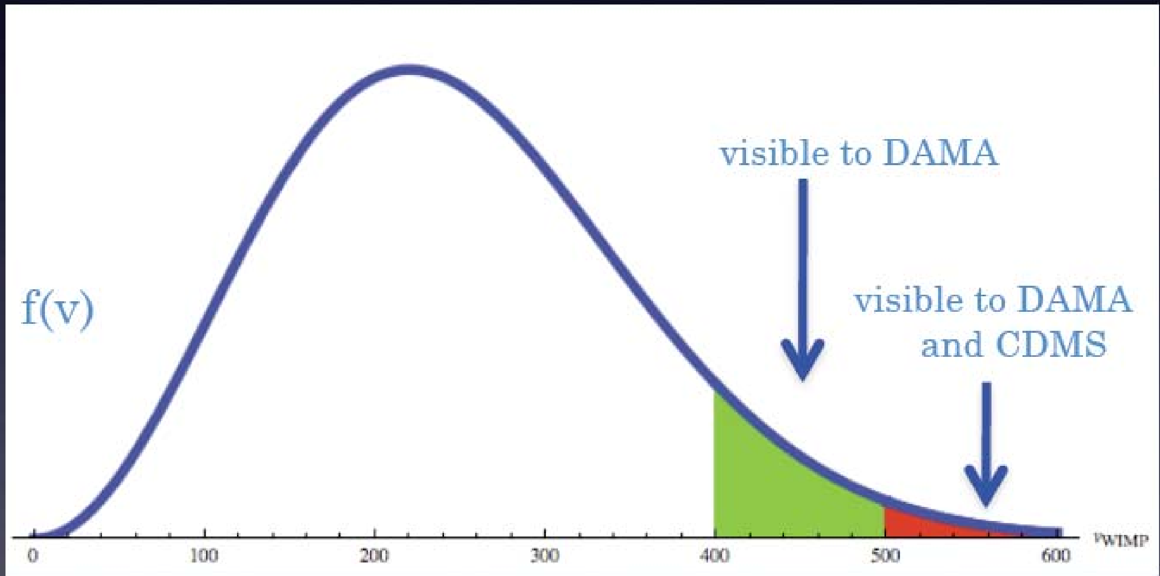
$$\sigma \sim \frac{\epsilon}{M_{Z_{Dark}}^2} \sim \frac{1}{M_Z^2}$$

~ the same as usual WIMPS

BUT INELASTIC COLLISION!

must have enough kinetic energy to scatter

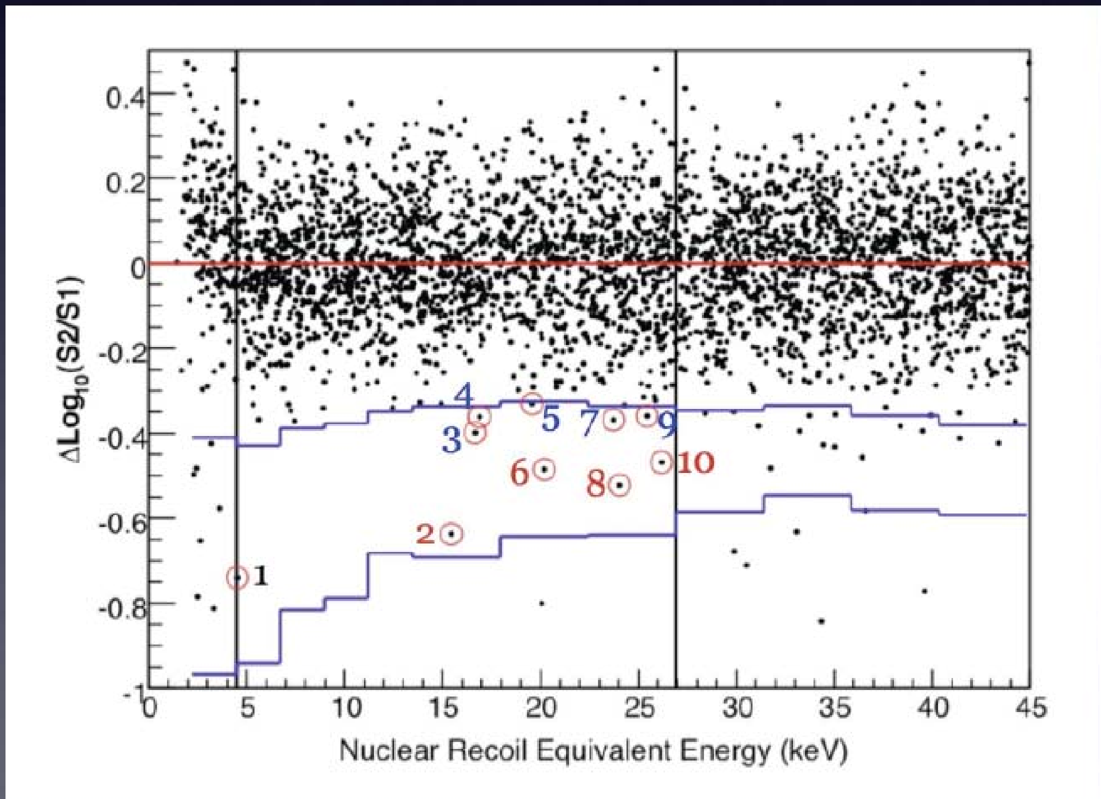
favors heavier targets of light targets



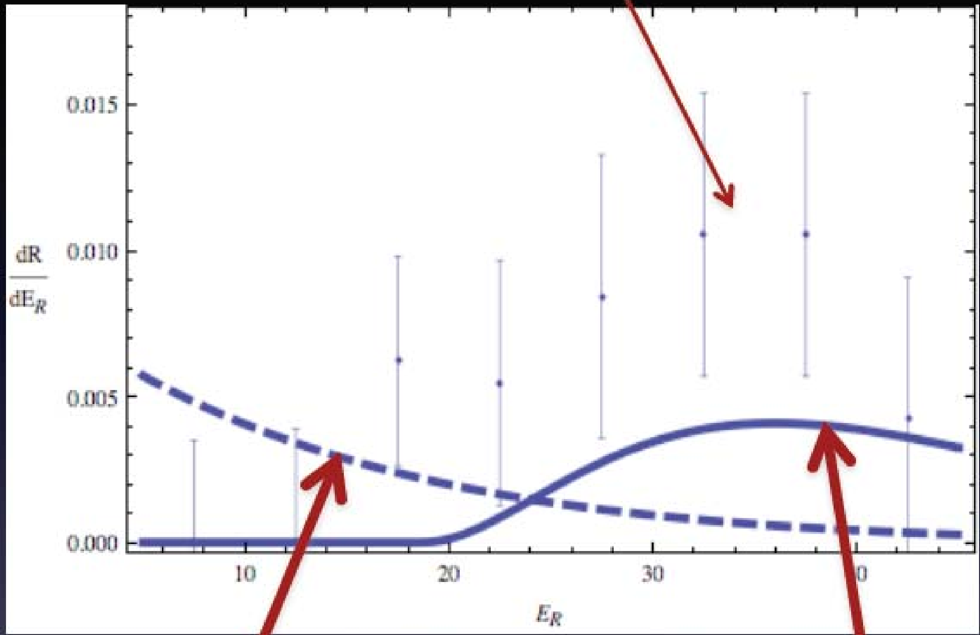
Modulation is also significantly enhanced

Spectrum is dramatically modified

- Standard WIMPs have a spectrum that peaks at low energies



XENON10 data adjusted for efficiencies (taking unpublished acceptance x efficiency = 0.3, error bars estimated)



M_χ=100 GeV, δ = 0 keV, normalized to inelastic XENON10 signal

M_χ=100 GeV, δ = 120 keV, normalized to DAMA 2-6 keV

Consequences for direct detection

- Three factors
  - Heavy targets favored
  - Enhanced Modulation
  - Modified spectrum
- Allows DAMA positive result with other negative results

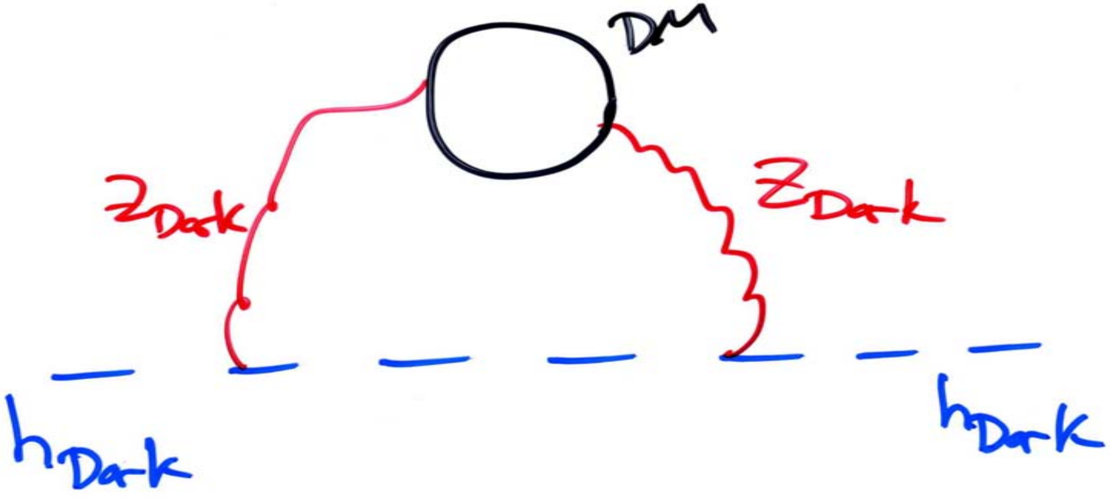
So, we have seen a multitude of phenomena, ranging over 6 decades of energy from ~ MeV → ~ TeV, follow from

"Dark Matter is charged under non-Abelian G_{Dark} broken @ the GeV scale".

The GeV scale is fixed by and plays a role in several overlapping phenomena:

- ★ Provides Sommerfeld Enhancement to explain PAMELA/ATIC σ.
- ★ Provides new annihilation channel that goes dominantly into leptons, again for PAMELA/ATIC
- ★ Radiatively splits DM states @ ~ MeV scale – predicts INTEGRAL signal + inelastic interpretation of DAMA.

SUSY explains the GeV scale



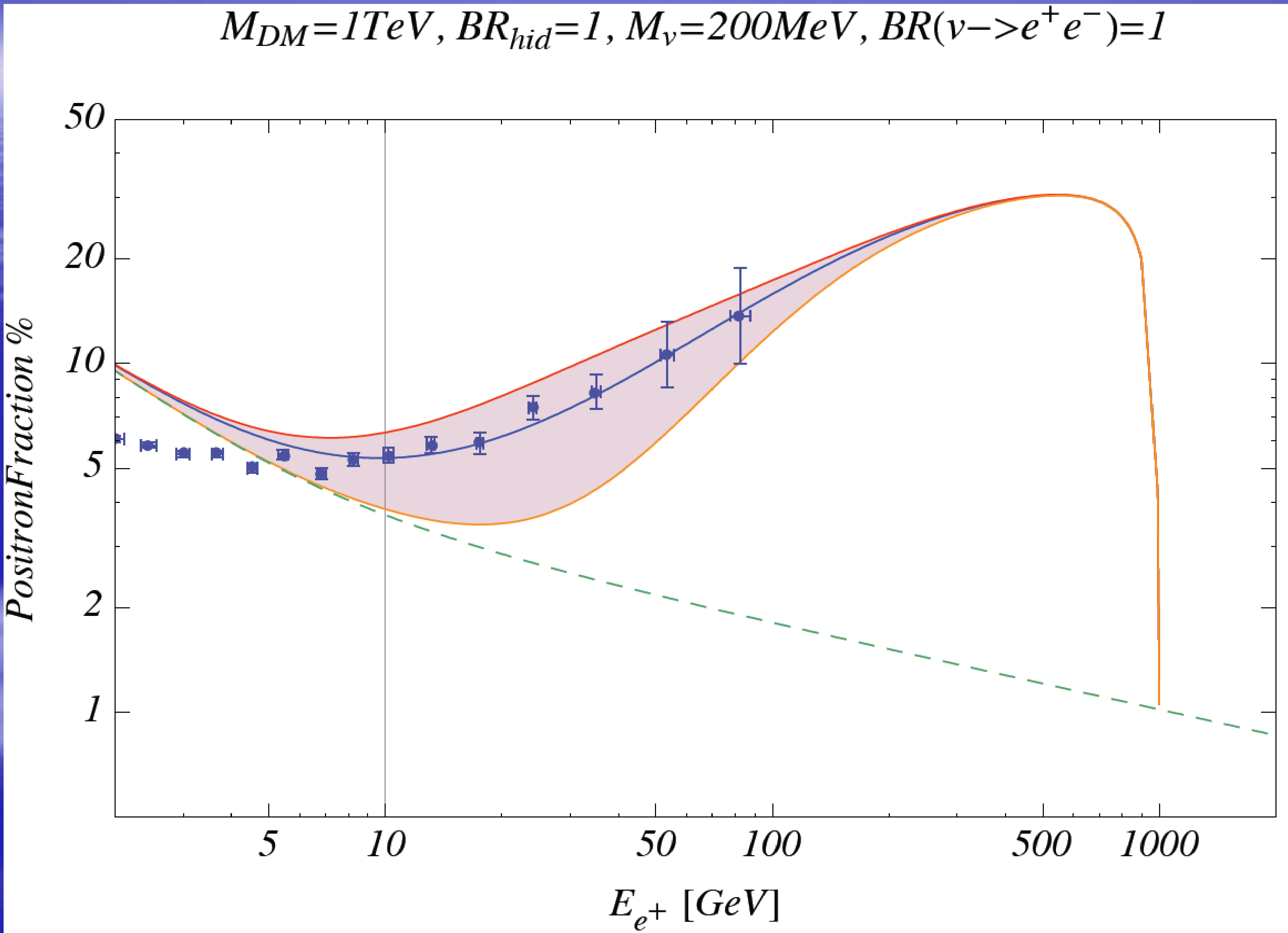
$$m^2_{h_{Dark}} \sim \left(\frac{\alpha}{4\pi}\right)^2 M_{DM}^2$$

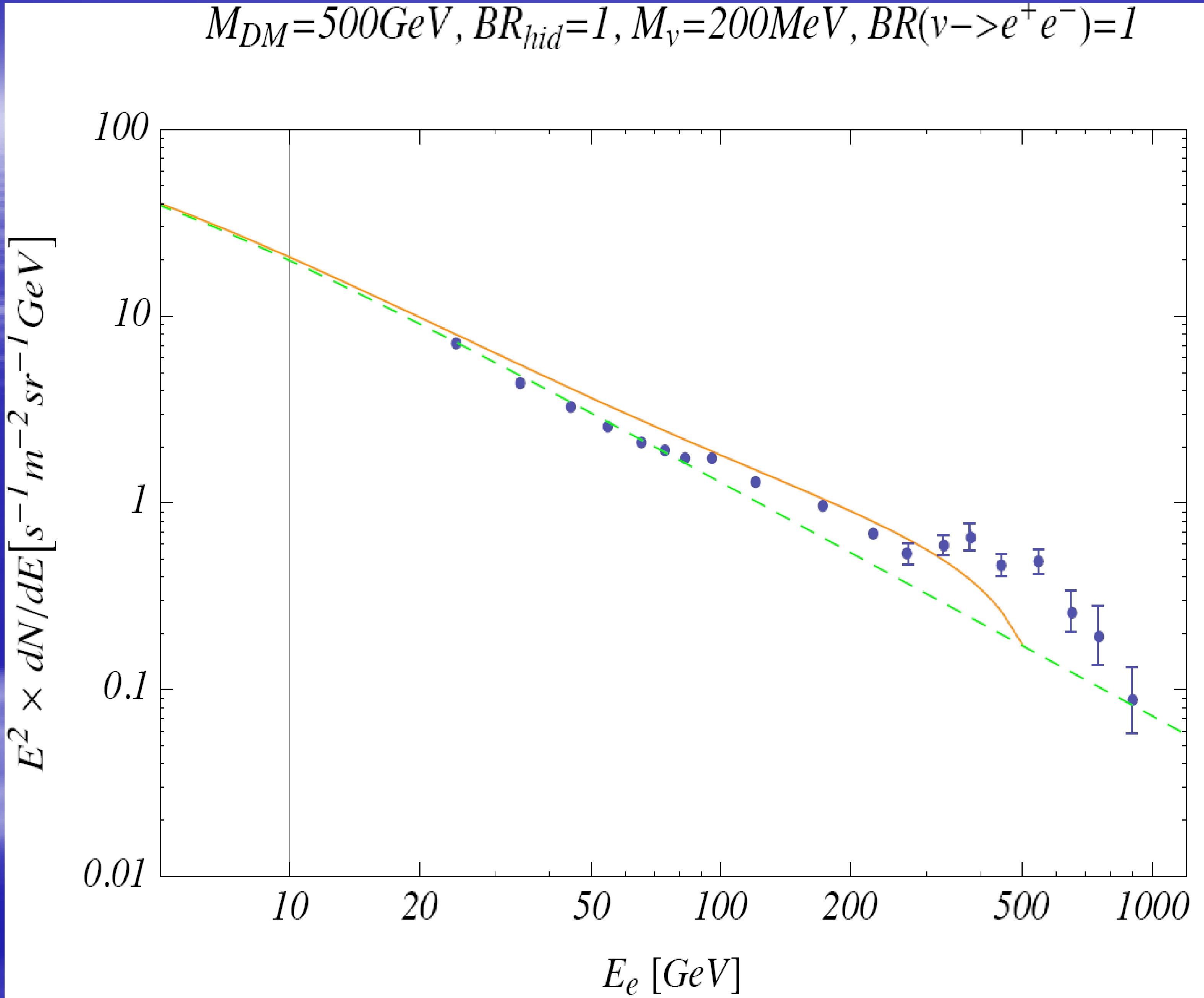
$$\sim (\text{GeV})^2 \;!$$

How will we Decide?

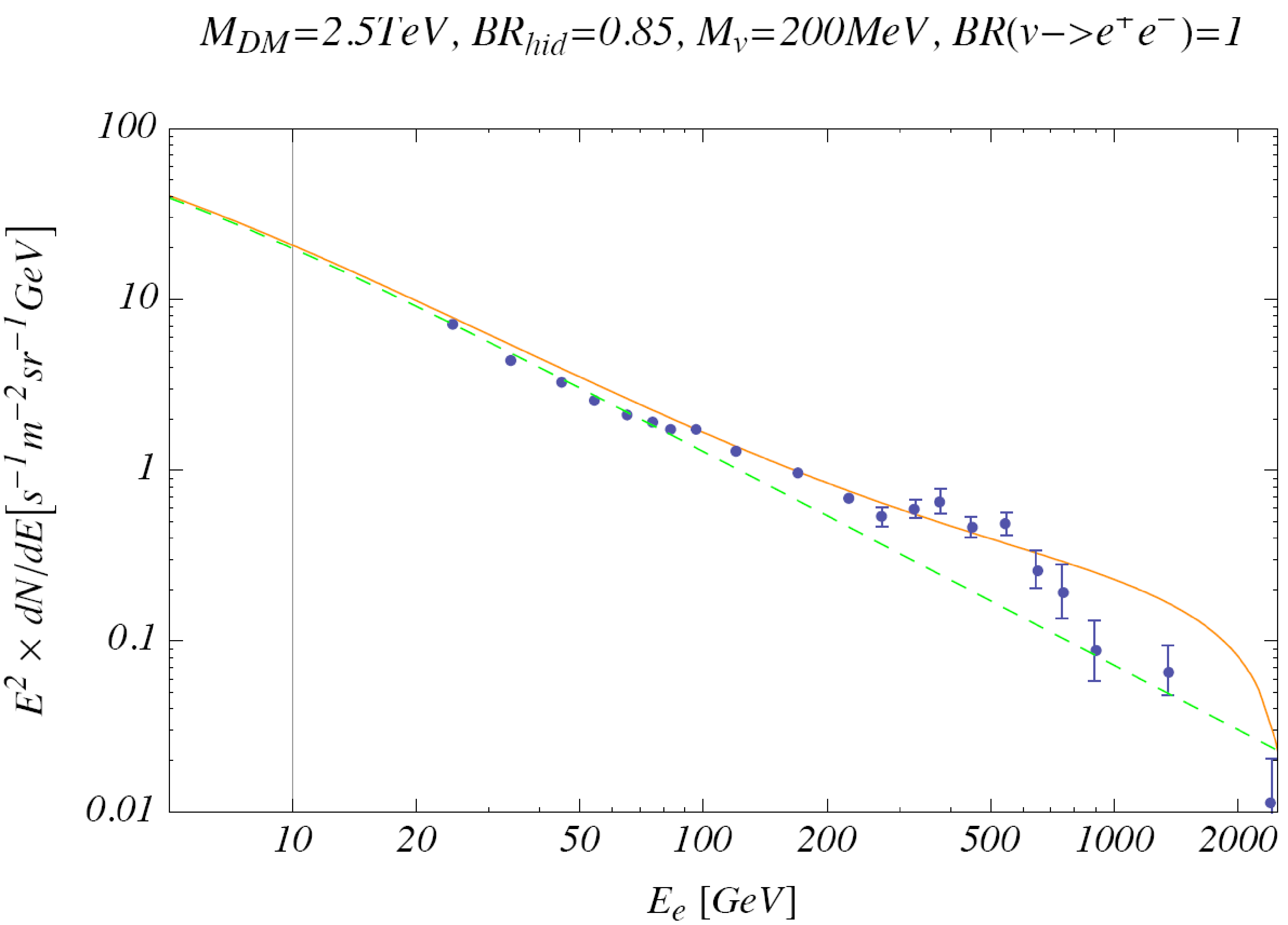
- ☆ Next generation direct detection experiments. ⟵ Inelasticity
- ☆ Fermi/GLAST, HESS, Planck ⟵ Photons.
- ☆ L.H.C + "Lepton Jets".

Meade, Papucci and Volansky, in Progress

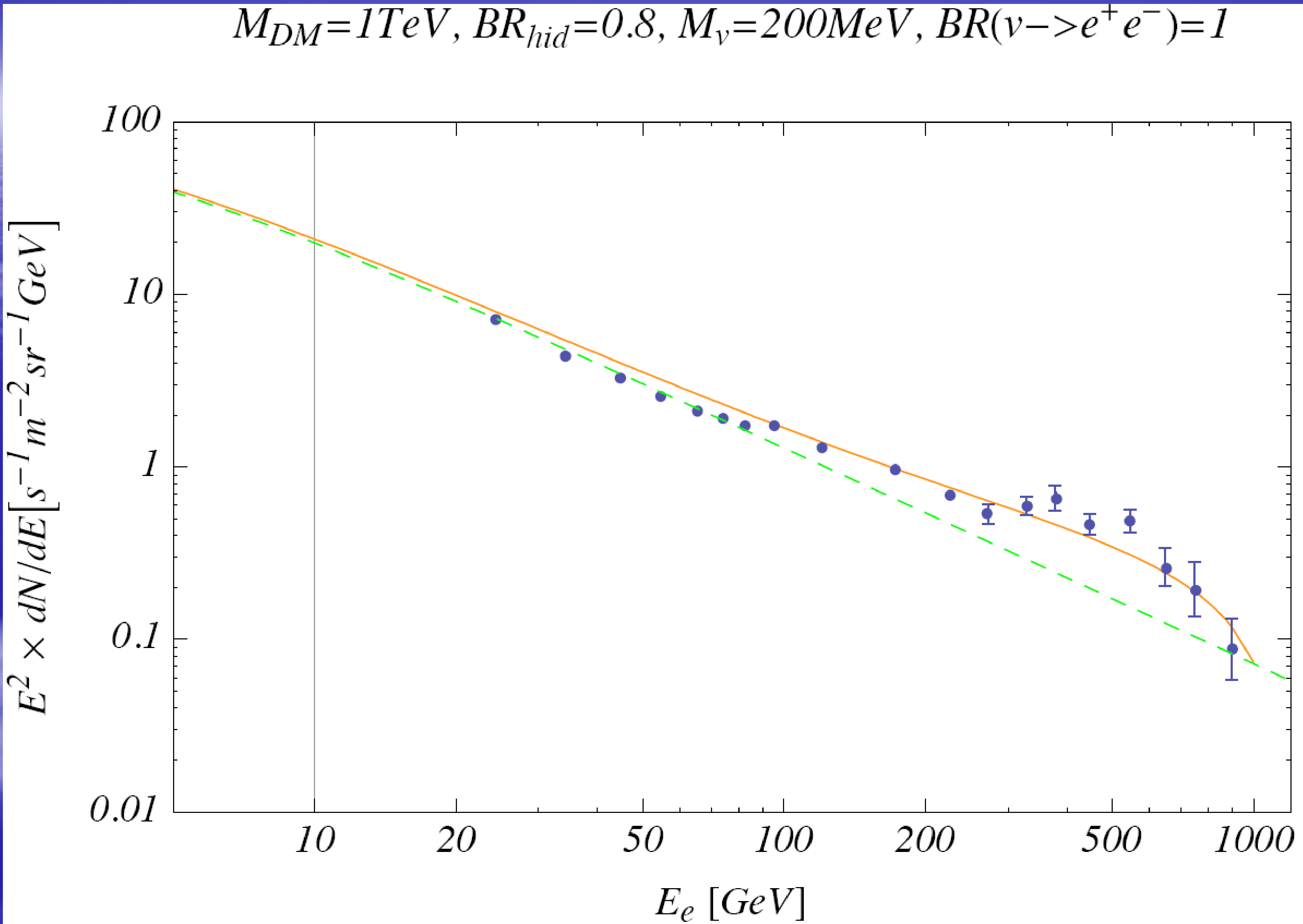




M_{DM}=500GeV, BR_{hid}=1, M_v=200MeV, BR(v->e^+e^-)=1
100
10
1
0.1
0.01
$E^2 \times dN/dE\,[s^{-1}m^{-2}sr^{-1}GeV]$
10
20
50
100
200
500
1000
E_e [GeV]



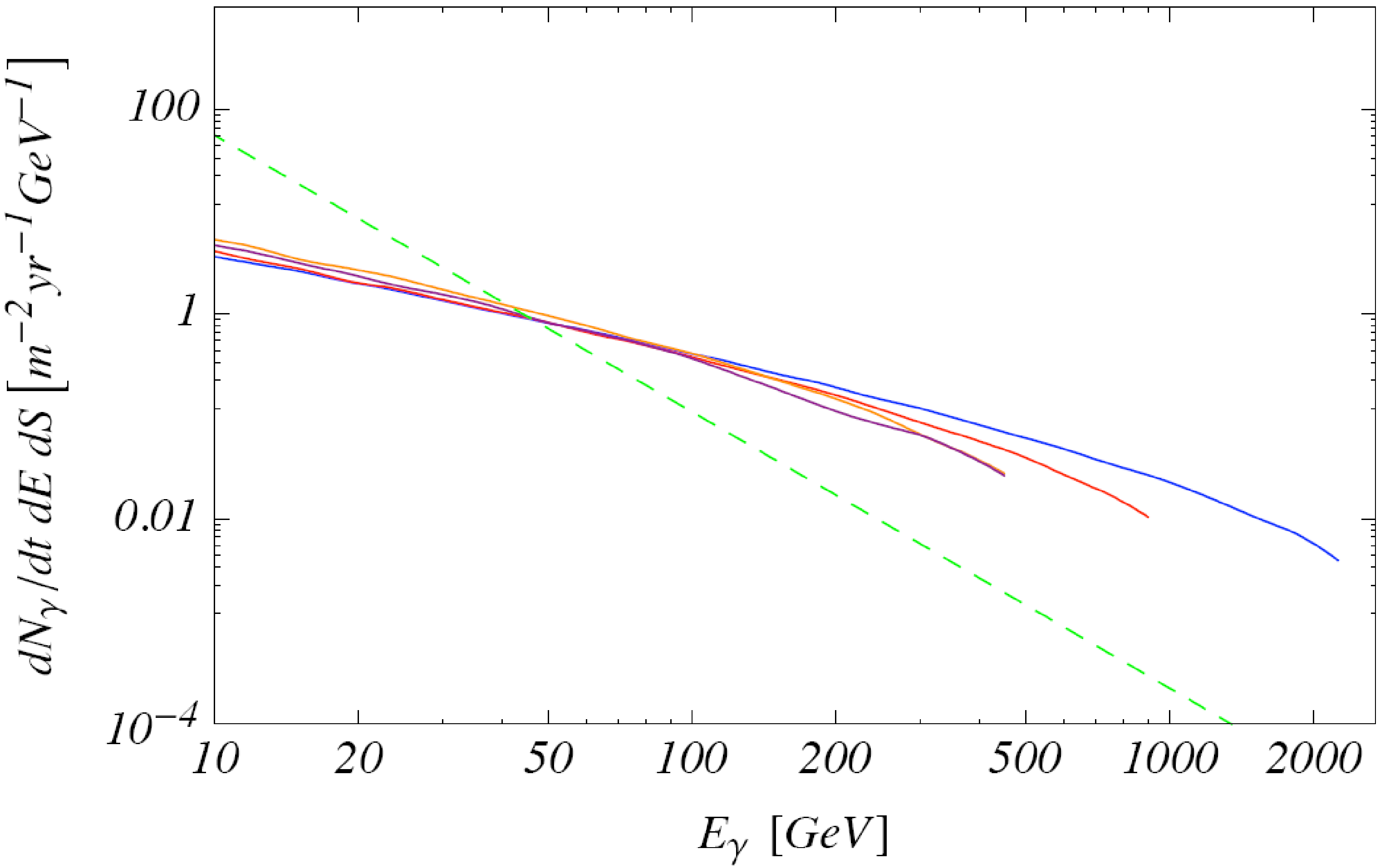
M_{DM}=2.5TeV, BR_{hid}=0.85, M_v=200MeV, BR(v−>e^+e^-)=1
100
10
1
0.1
0.01
10
20
50
100
200
500
1000
2000
$E^2 \times dN/dE[s^{-1}m^{-2}sr^{-1}GeV]$
E_e [GeV]



M_{DM}=1TeV, BR_{hid}=0.8, M_v=200MeV, BR(v->e^+e^-)=1
100
10
1
0.1
0.01
$E^2 \times dN/dE[s^{-1}m^{-2}sr^{-1}GeV]$
10
20
50
100
200
500
1000
E_e [GeV]

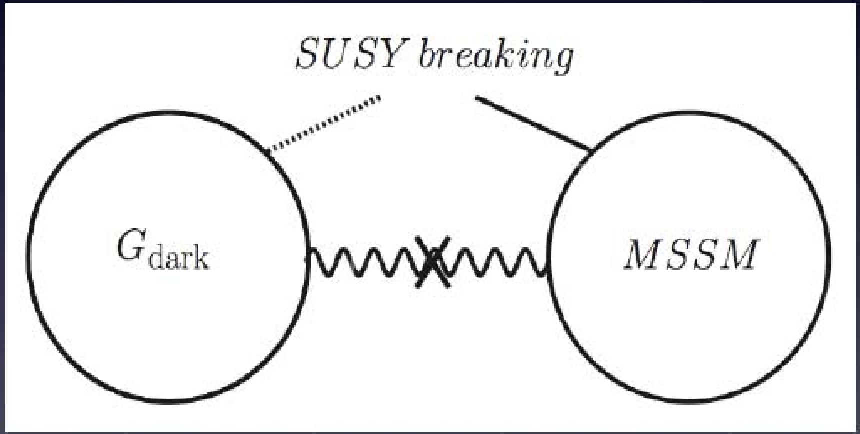
Photon Flux in $\Omega=10^{-3}$sr.

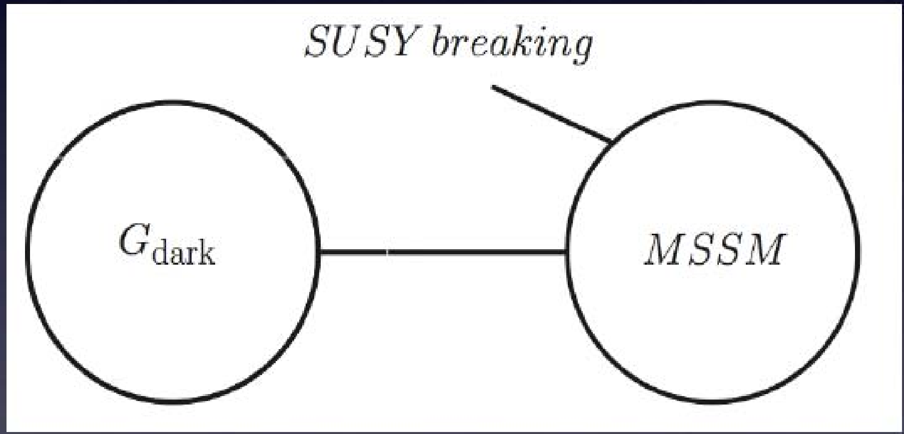
NFW, M_{DM}=0.5,1,2.5TeV, BR_{hid}=1,0.14, M_v=200MeV, BR(v->e^+e^-)=1



LHC?

- How can we see these states at the LHC?





Cf "Hidden Valley" Models; Strassler, Zurek et. al.

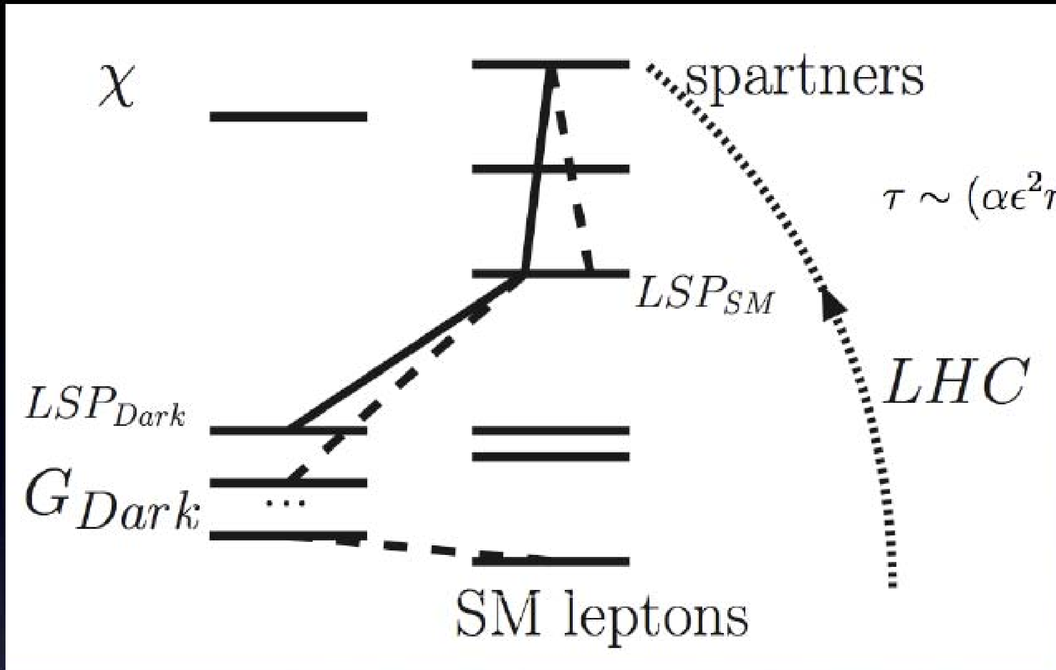
LHC!

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{Dark} + \mathcal{L}_{mix}$$

$$\mathcal{L}_{mix} = -\frac{1}{2}\epsilon f^{\mu\nu}_{Dark} F^{\mu\nu}$$

$$\epsilon' \bar{\eta} \bar{\sigma}^{\mu} \partial_{\mu} \chi_0$$

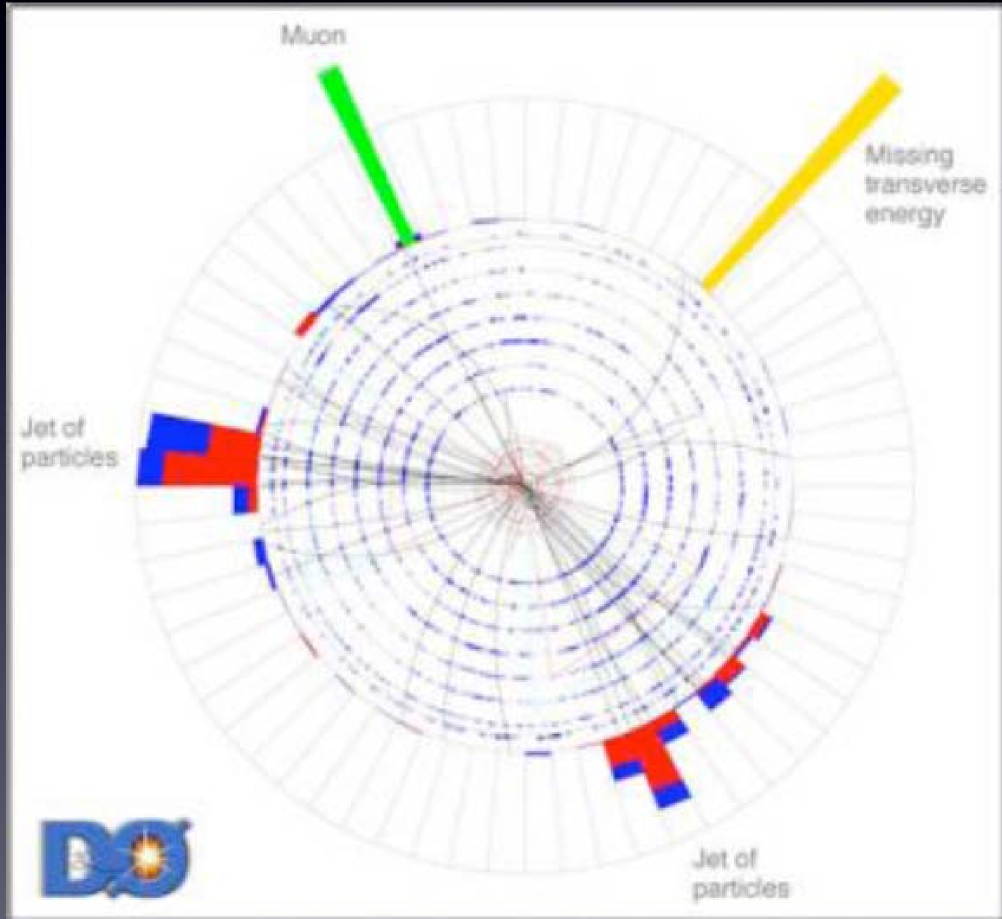
LSP_{SM} is weakly mixed with LSP_{dark}



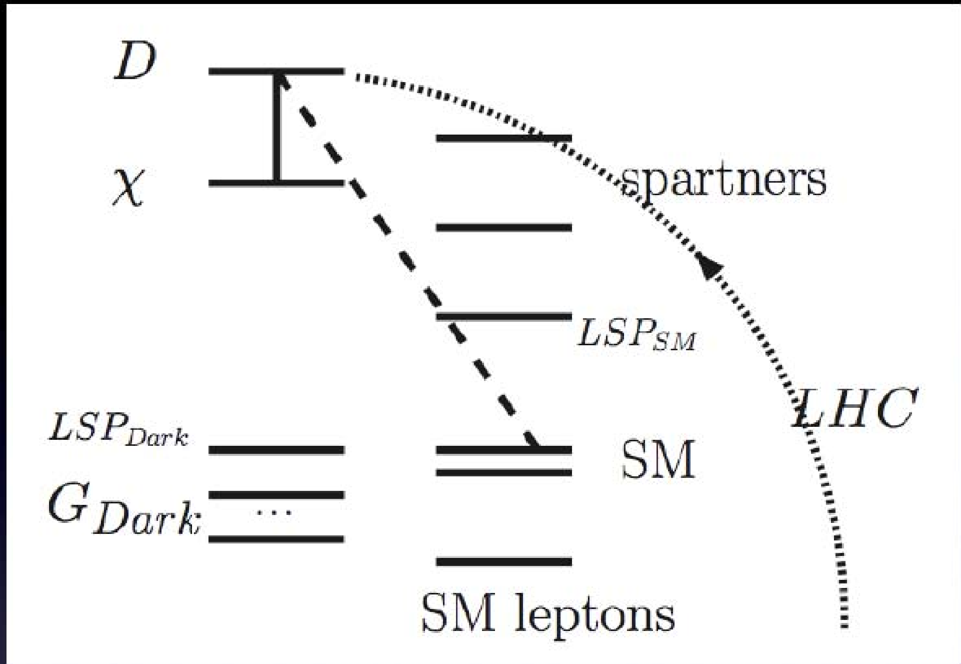
$$\tau \sim (\alpha \epsilon^2 m_{Z_{Dark}} N_{decaychannels})^{-1} \sim (\frac{10^{-7}}{\epsilon})^2 cm$$

- Vectors will decay in detector; scalars decaying off-shell may or may not
- Displaced vertices possible
- Expect jets (from e.g., squark decay), MET (from LSP_{dark} or gravitino), and *lepton jets* (collections of leptons with invariant mass ~ 1 GeV)

- Lepton jets striking
- Fail lepton isolation cuts
- MET often aligned



If there are also link fields: new colored particles, likely long-lived!



$$\frac{1}{M}(DL^c)(d^c e^c)$$

$$qLD^c$$

Long lived state

Promptly decaying state

Superpartner diagram gives lepton jets as well

STAY TUNED!

Whether or not these anomalies are real, we are getting a taste of how exciting fundamental physics is becoming as we enter a new epoch dominated by fresh data from new experiments in High-Energy Physics, Astrophysics and Cosmology.