Astrophysical Motivations for Dark Forces

Jefferson Lab

February 19, 2010

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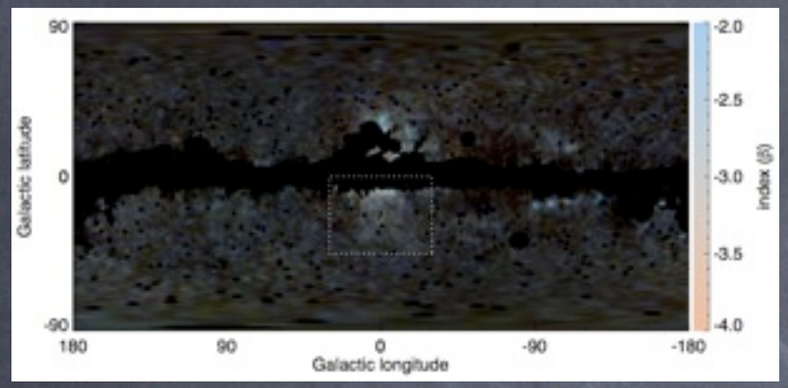
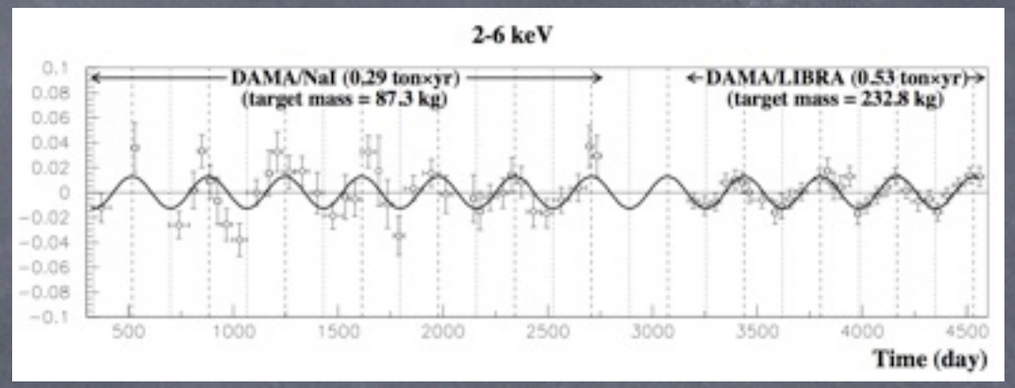
Center for Cosmology and Particle Physics
New York University

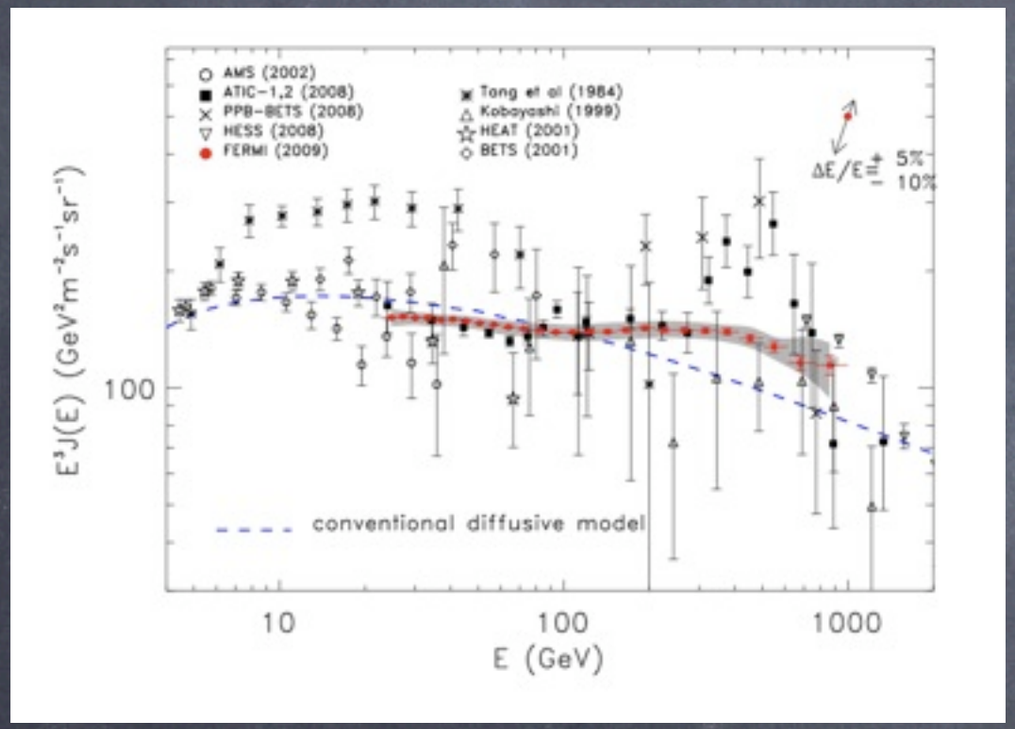
Era of data

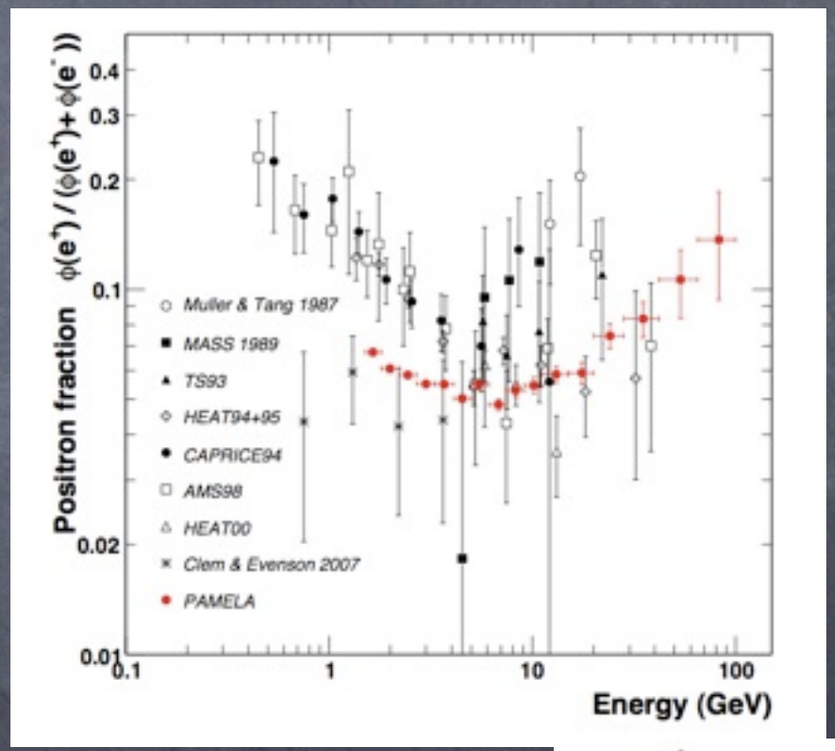
- Cosmics: PAMELA, Fermi, ATIC, HESS, AMS, ACTs, WMAP, Planck...
- Direct: CDMS, DMTPC, XENON, LUX, CRESST, COUPP, PICASSO, KIMS...
- Production: LHC/Tevatron, **Fixed Target, Beam dump**

Era of anomalies

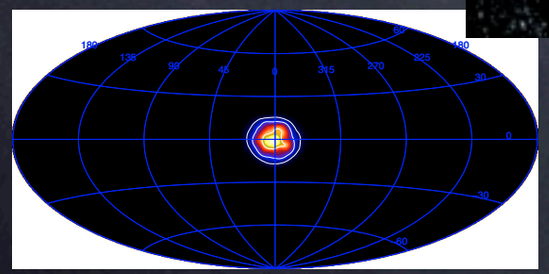


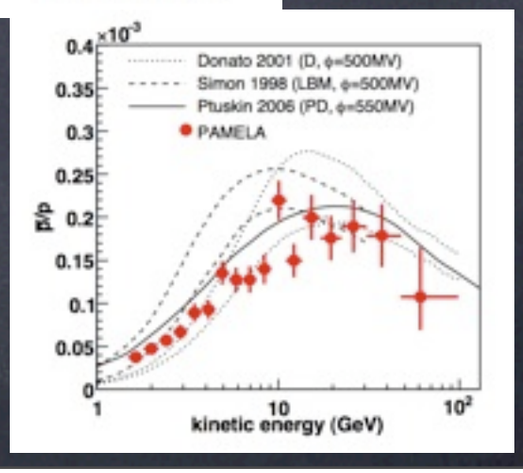






G. Weidenspointner et al.: The sky distribution of positronium continuum emissi





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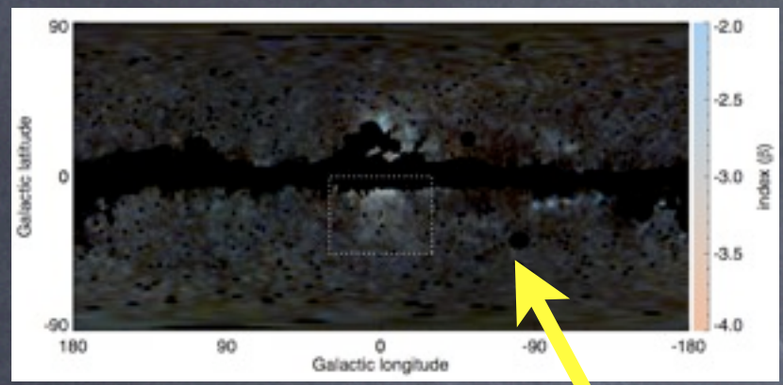
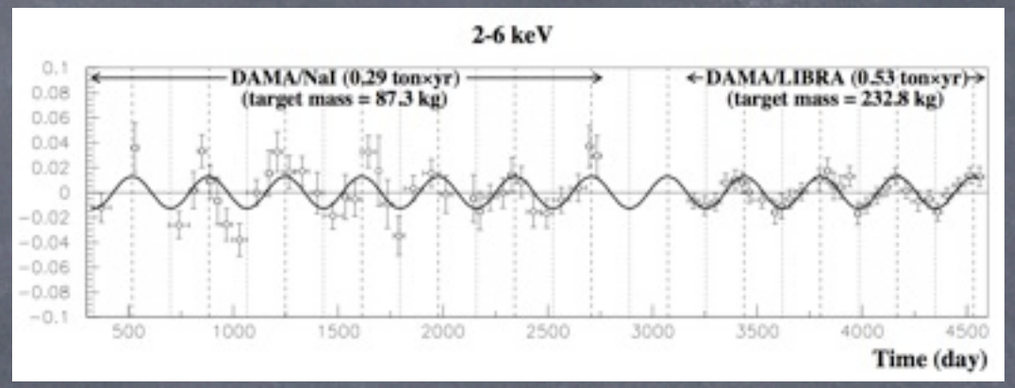
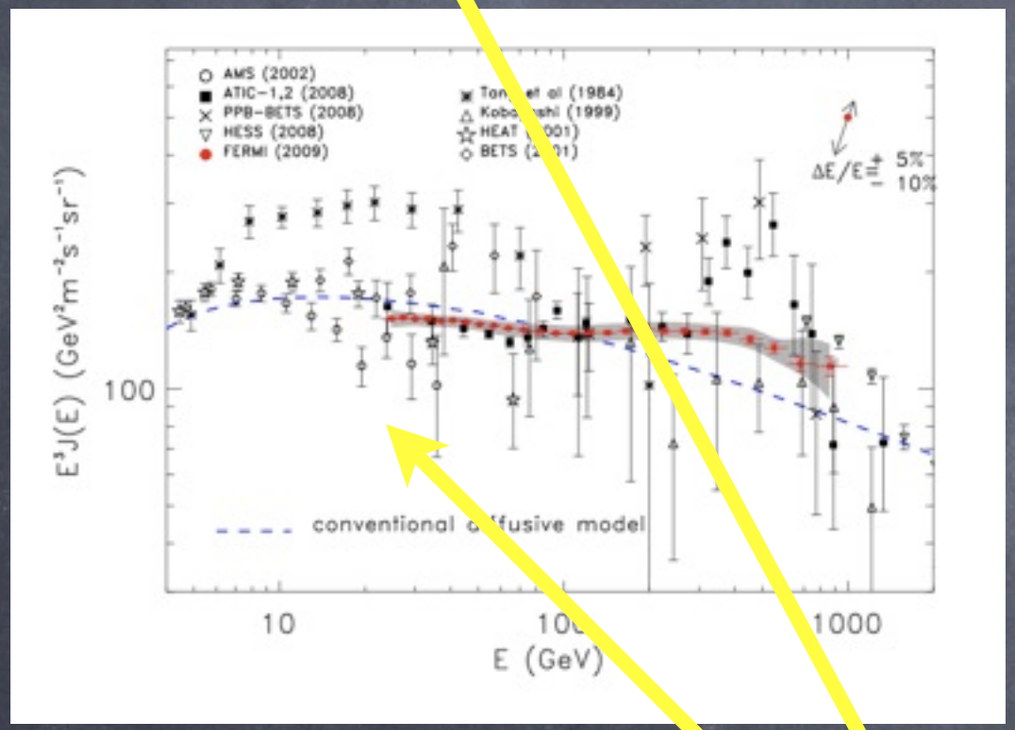
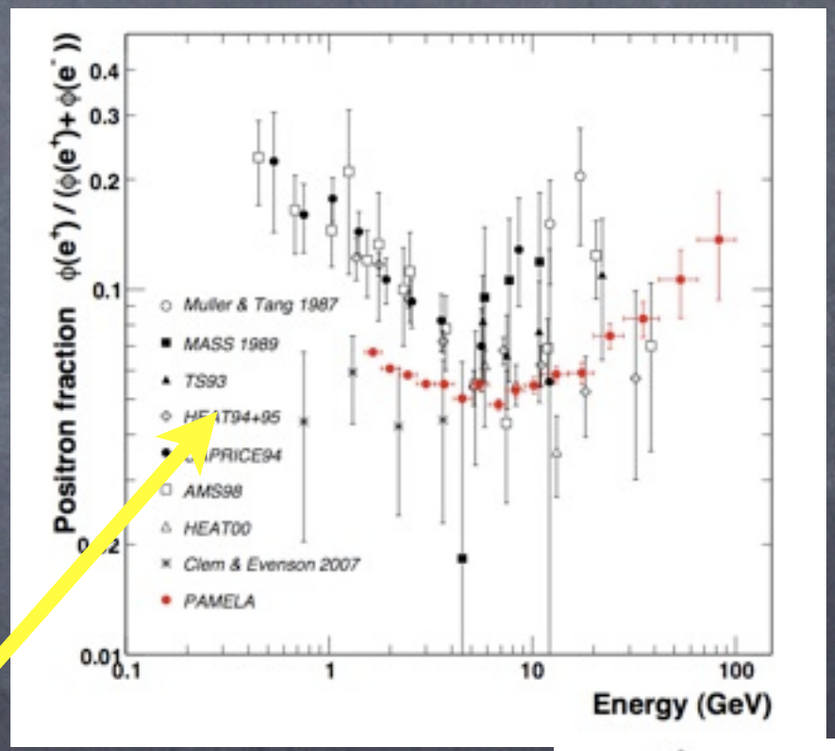


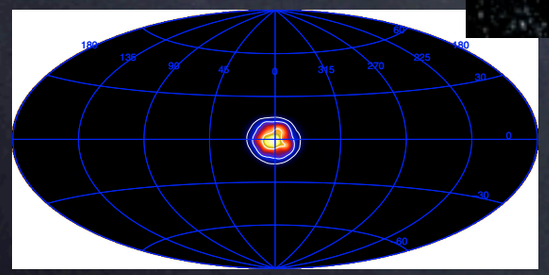


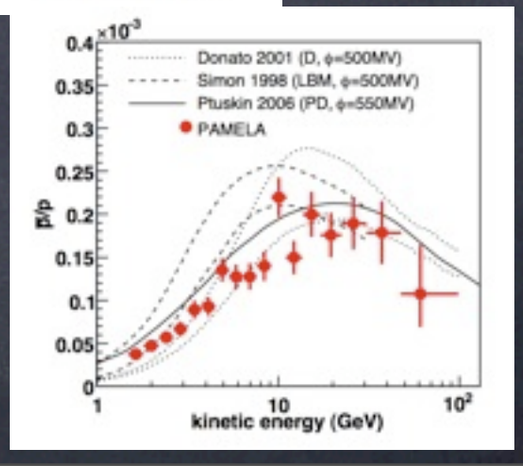




Indications of high energy electron or positron production

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





Anomalies and anomalies

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

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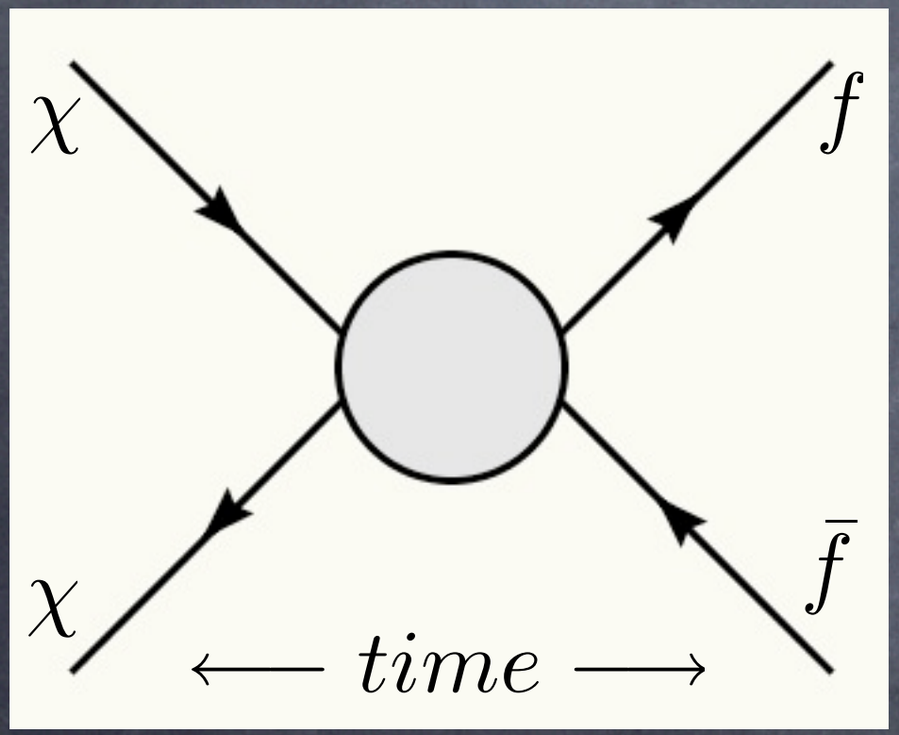
multiple indications

The framework

- Recently a new framework has emerged, where DM annihilates **not** to the SM, but to some new force carrier (A′ , ϕ, a, U)



"classic"
WIMP

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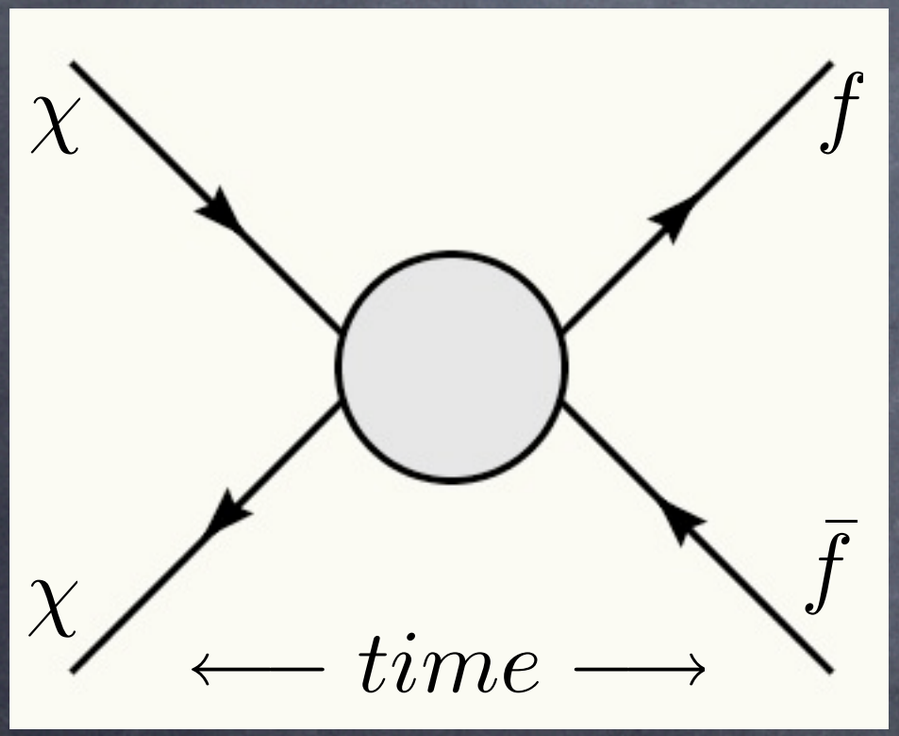

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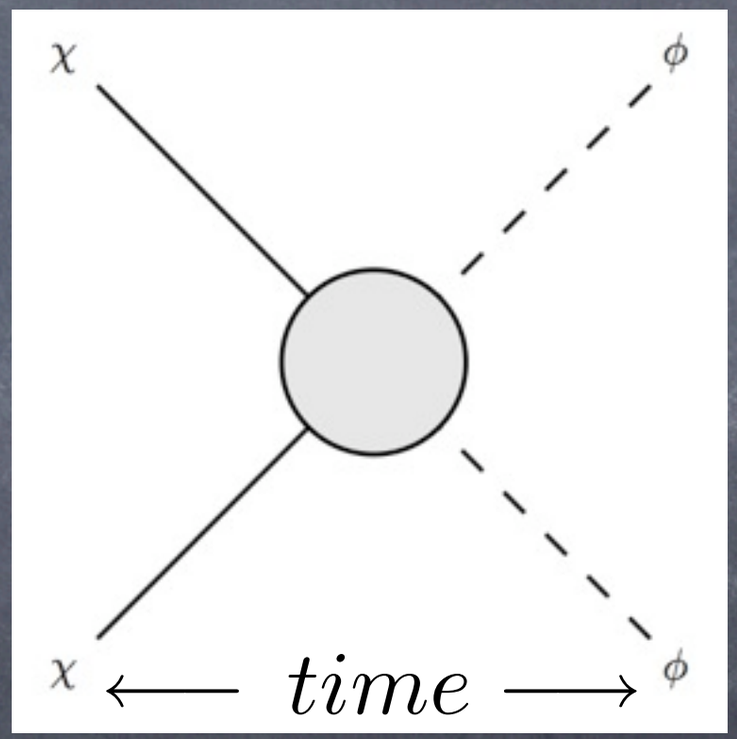
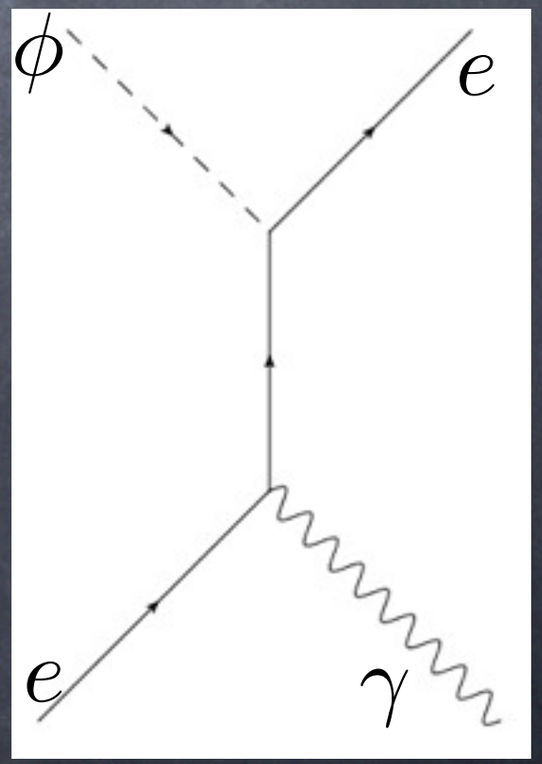


new, improved, WIMP



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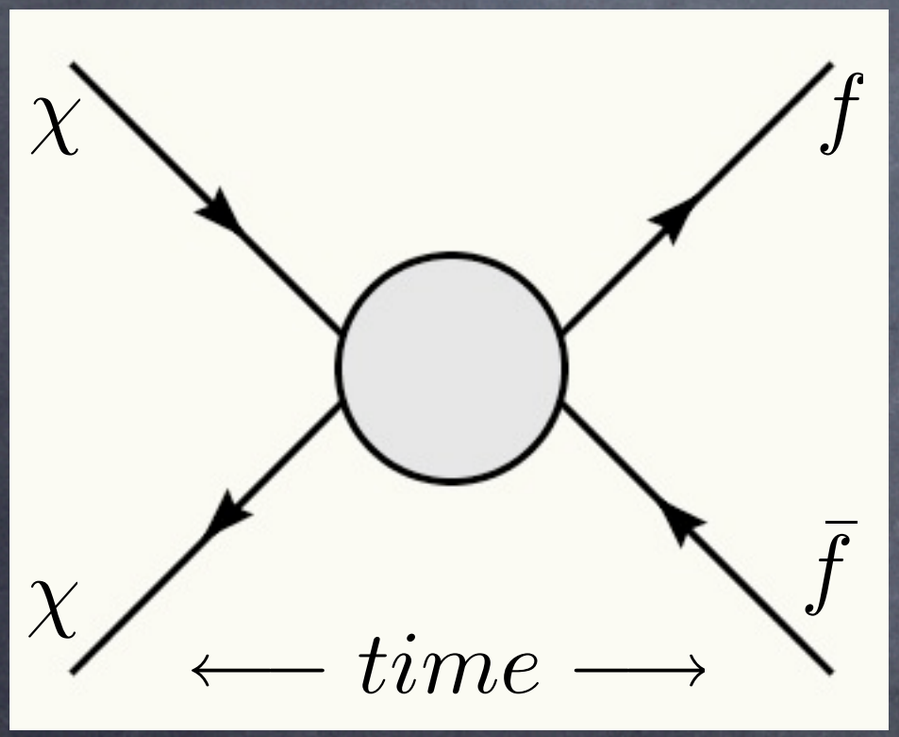

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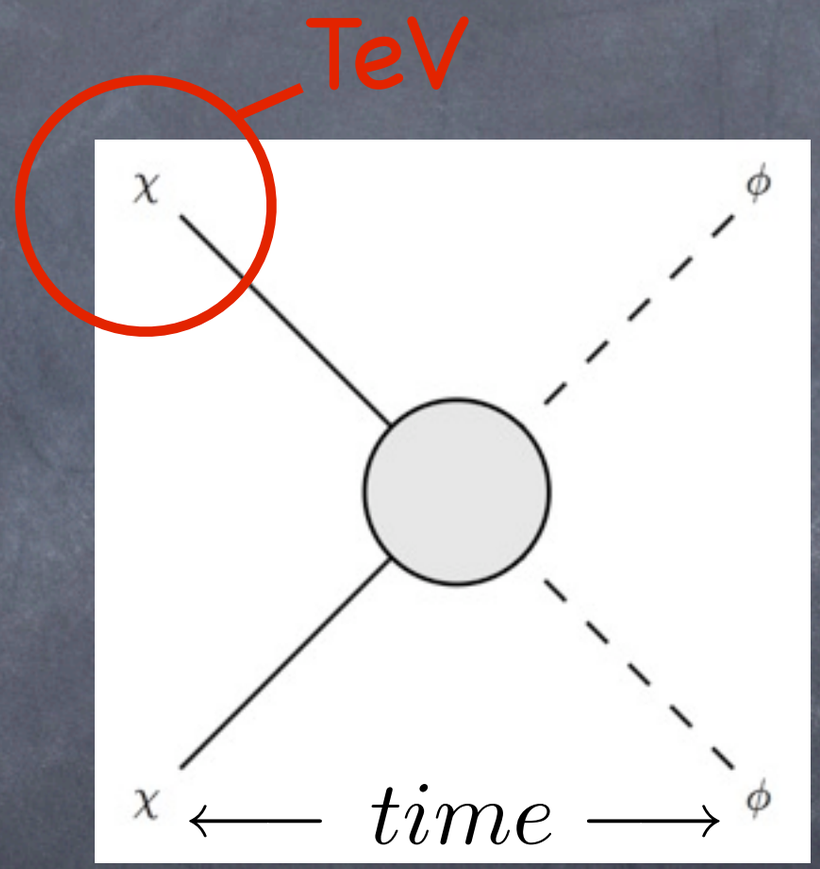

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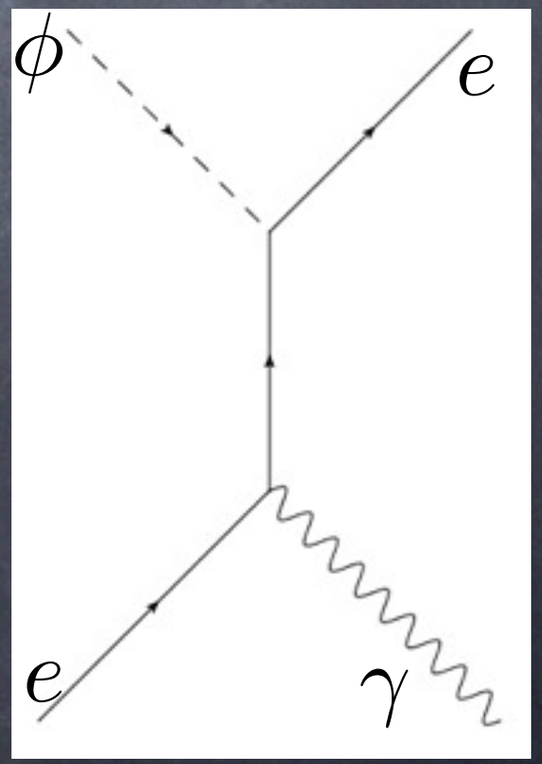

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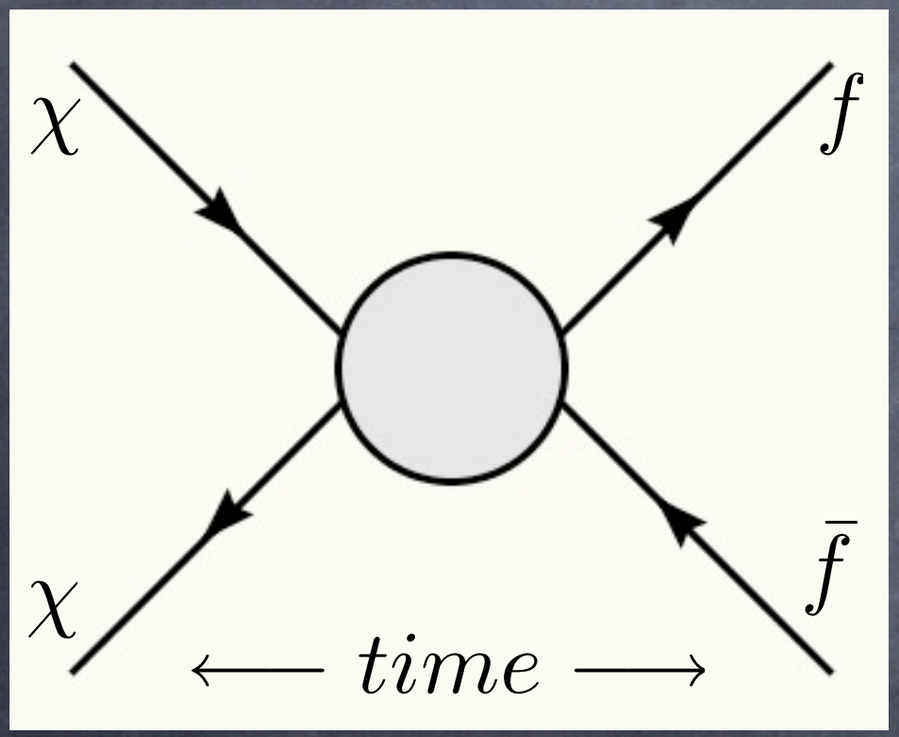

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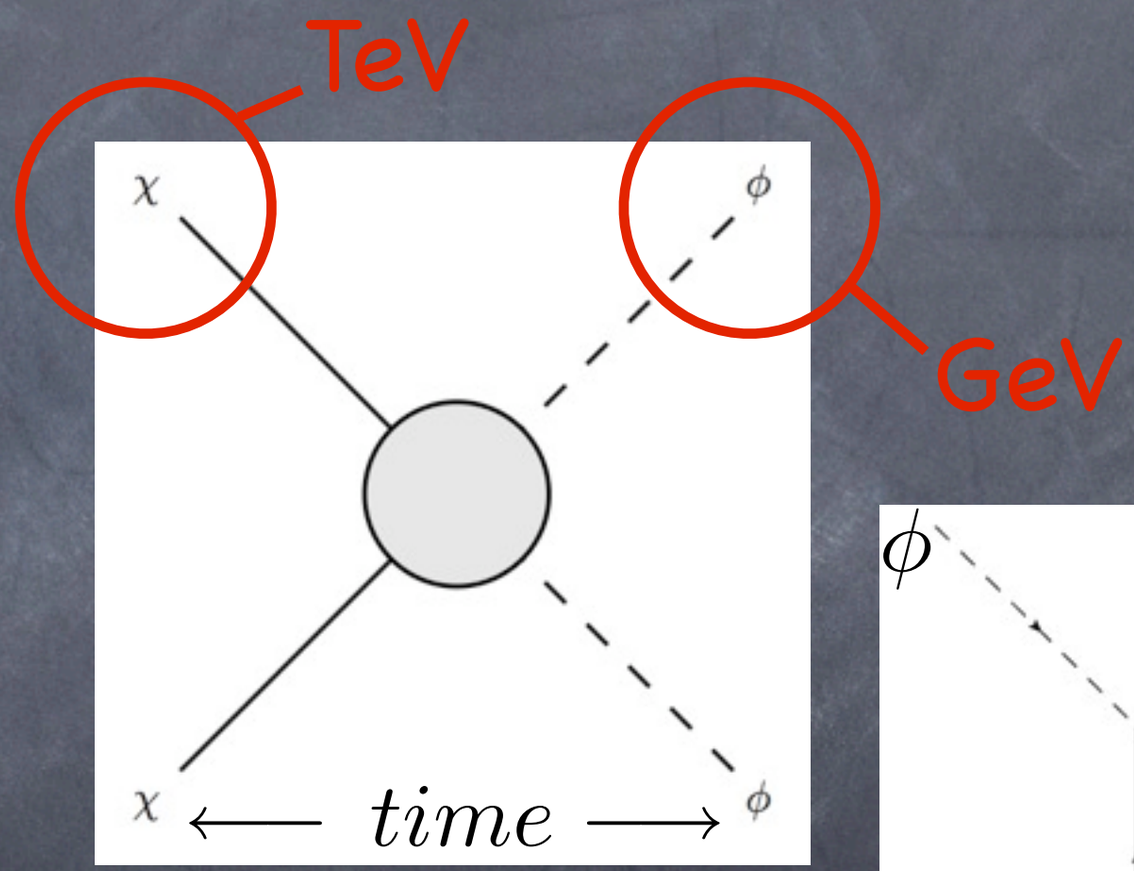

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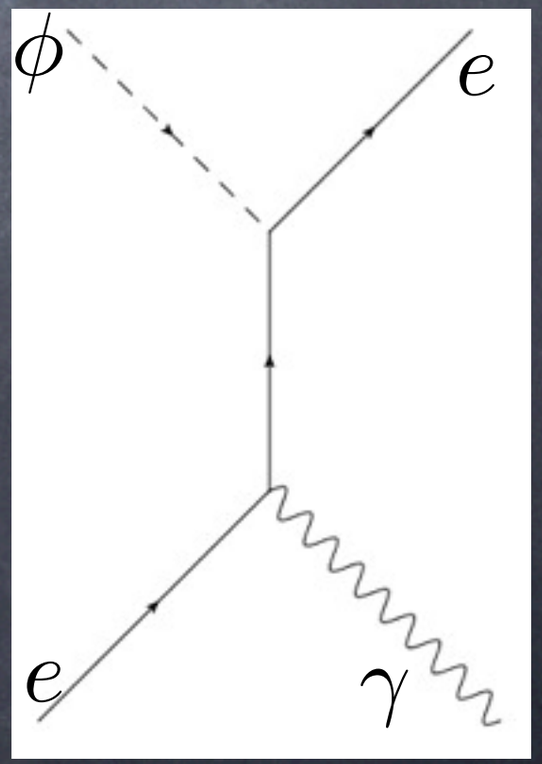
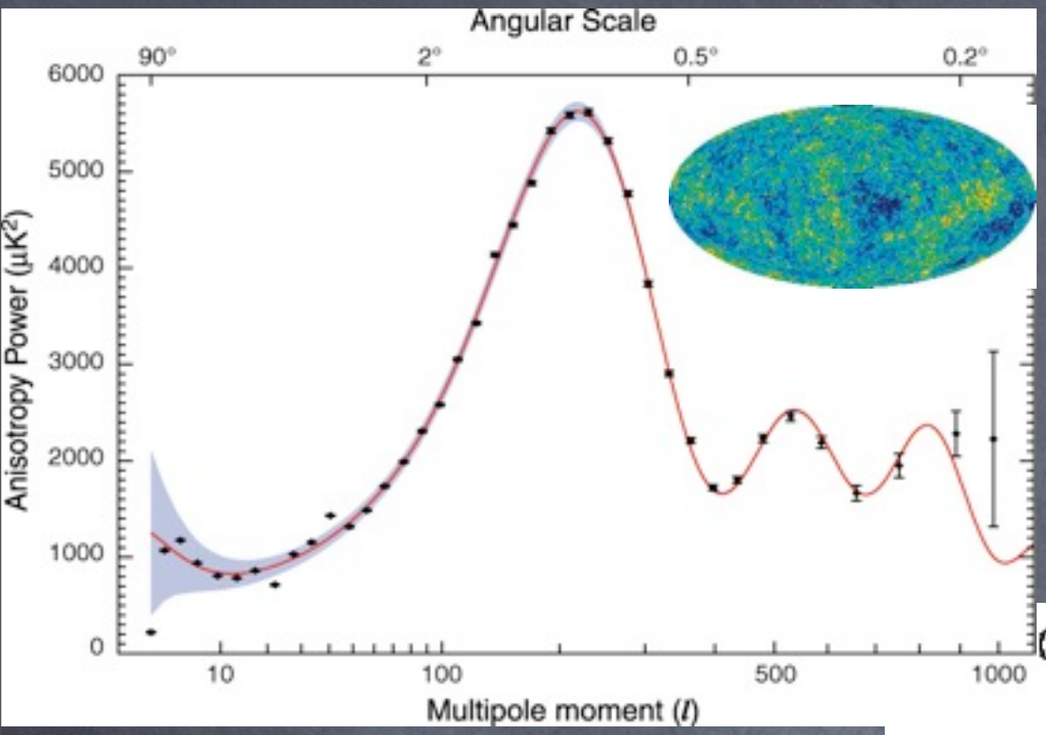
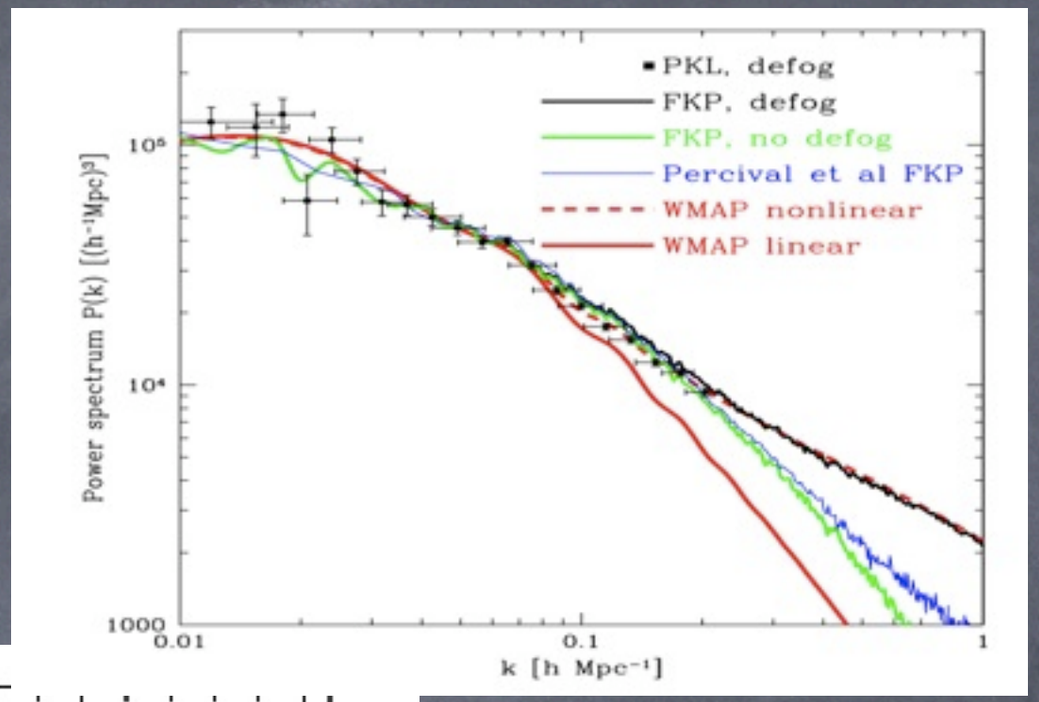
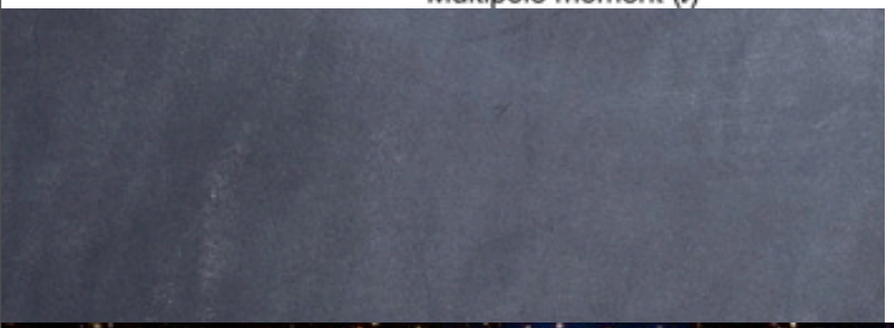
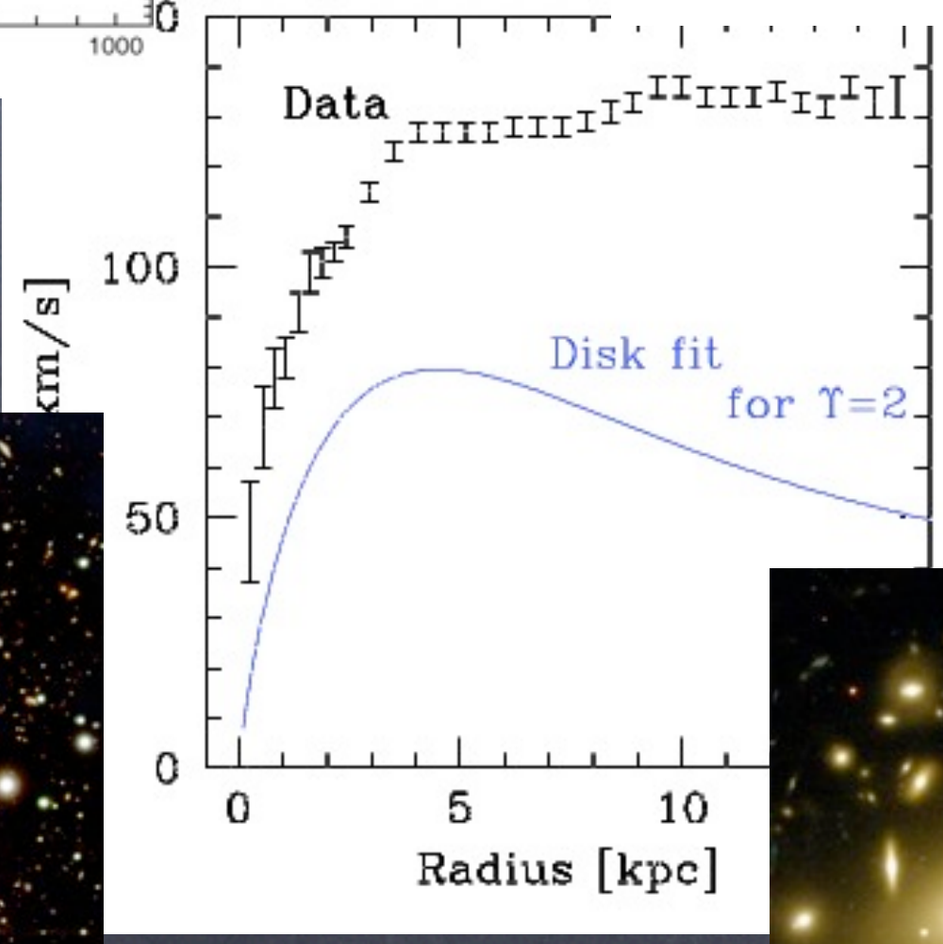


Dark Matter


Angular Scale
90°
2°
0.5°
0.2°
Anisotropy Power (μK²)
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment (l)


PKL, defog
FKP, defog
FKP, no defog
Percival et al FKP
WMAP nonlinear
WMAP linear
Power spectrum P(k) [(h⁻¹Mpc)³]
10⁵
10⁴
1000
0.01
0.1
1
k [h Mpc⁻¹]



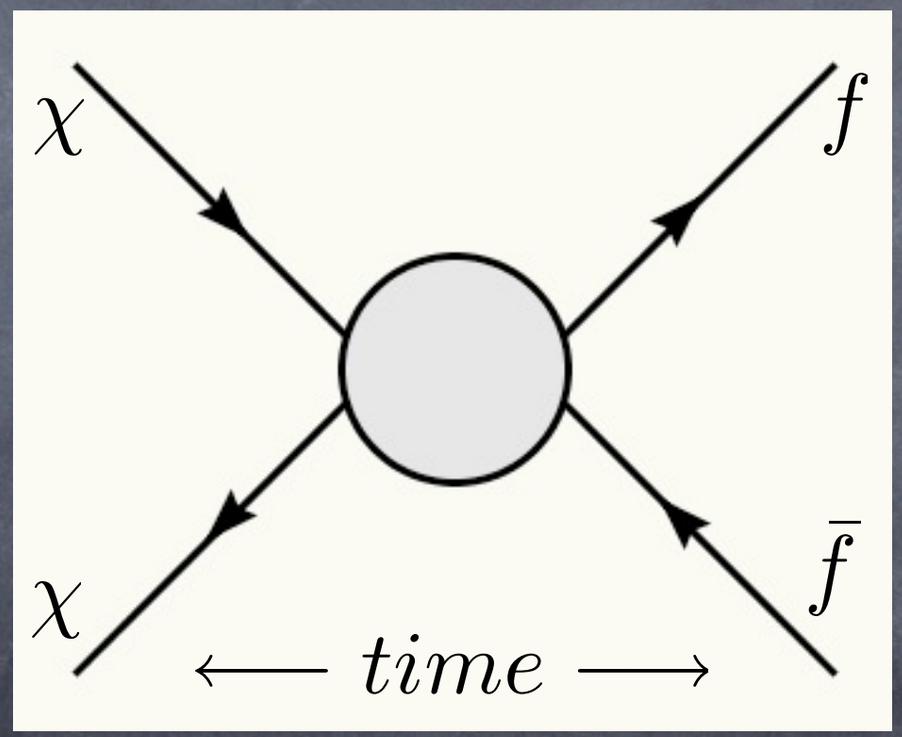

Data
Disk fit
for Υ=2
100
50
0
0
5
10
Radius [kpc]

what is it?

The WIMP "miracle"

assume thermal equilibrium

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



The WIMP "miracle"

assume thermal equilibrium

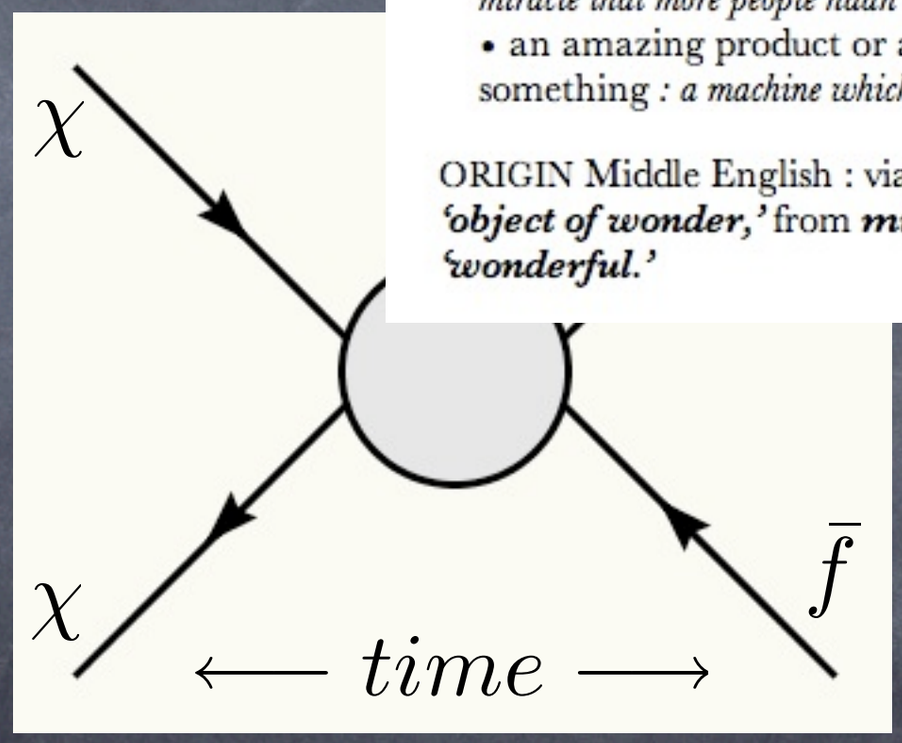
mir•a•cle |ˈmirikəl|

noun

a surprising and welcome event that is not explicable by natural or scientific laws and is therefore considered to be the work of a divine agency : *the miracle of rising from the grave.*

- a highly improbable or extraordinary event, development, or accomplishment that brings very welcome consequences : *it was a miracle that more people hadn't been killed or injured* [as adj.] : *a miracle drug.*
- an amazing product or achievement, or an outstanding example of something : *a machine which was* ***a miracle of*** *design.*

ORIGIN Middle English : via Old French from Latin ***miraculum*** ***'object of wonder,'*** from ***mirari*** ***'to wonder,'*** from ***mirus*** ***'wonderful.'***



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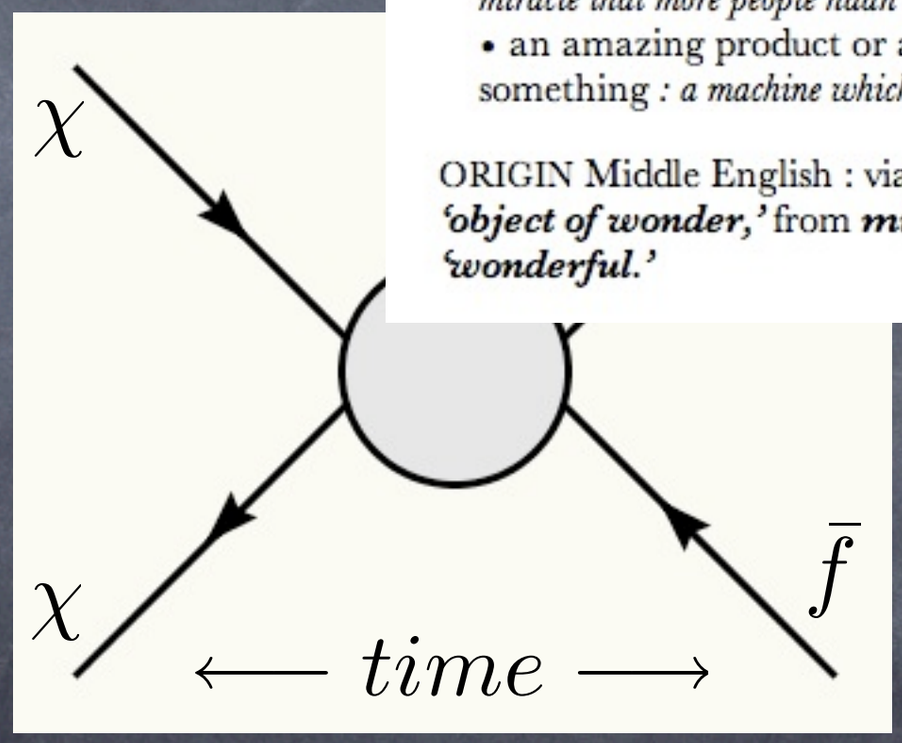

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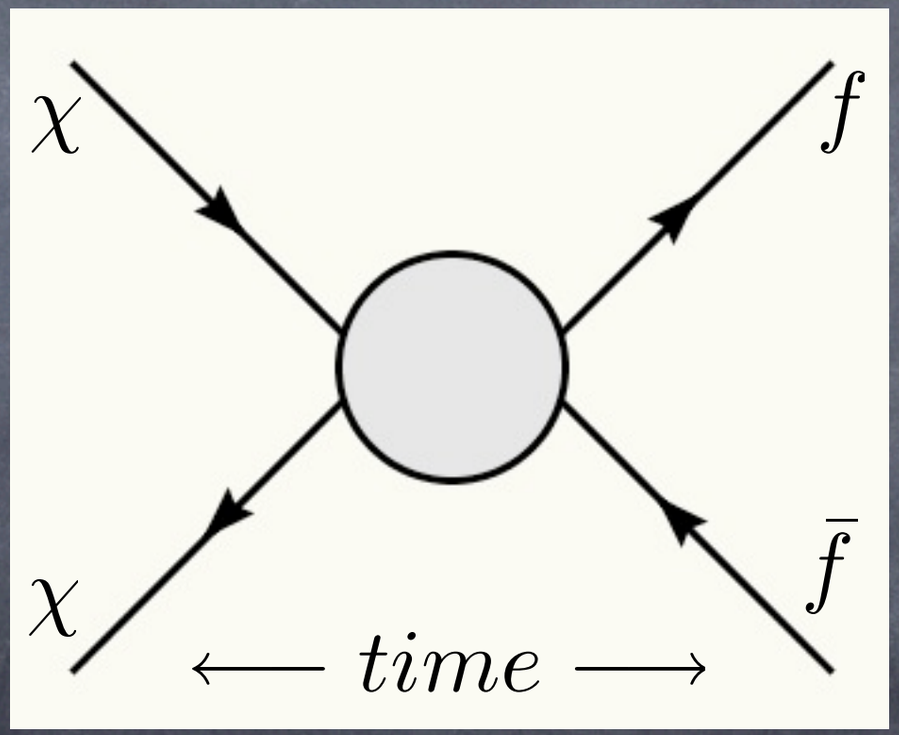
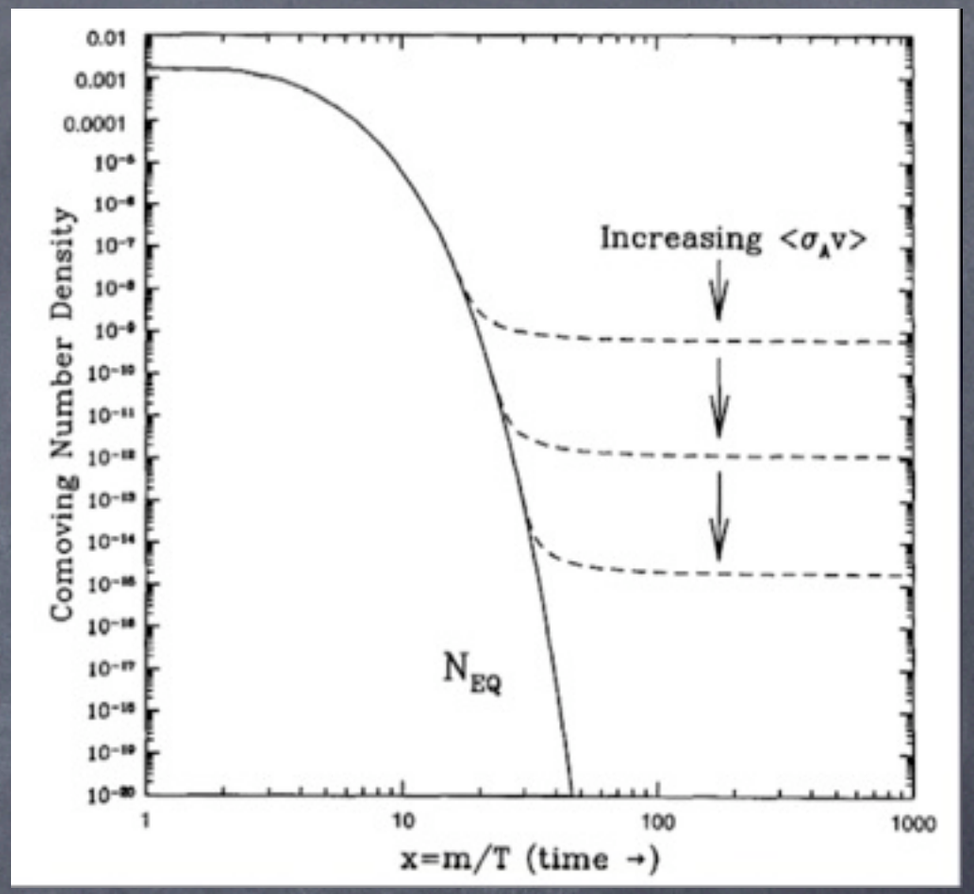


assume thermal equilibrium $\chi\chi \leftrightarrow \bar{f}f$

When T<< M_{WIMP}, number density falls as $e^{-M/T}$



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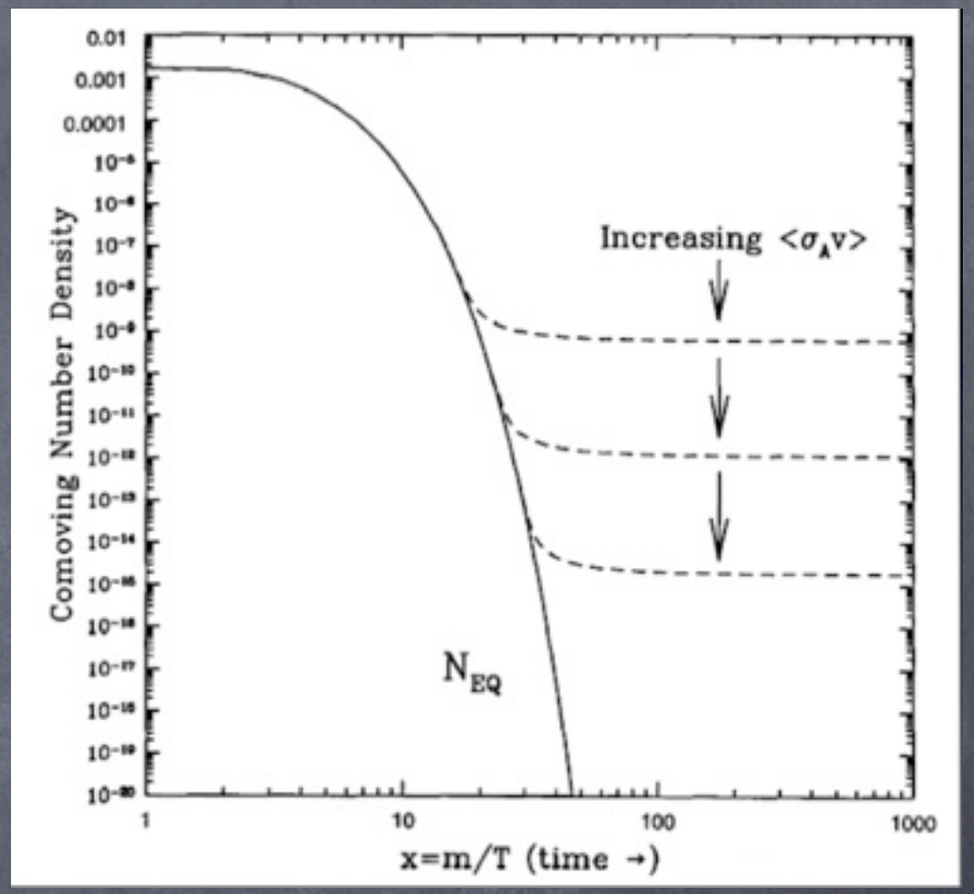

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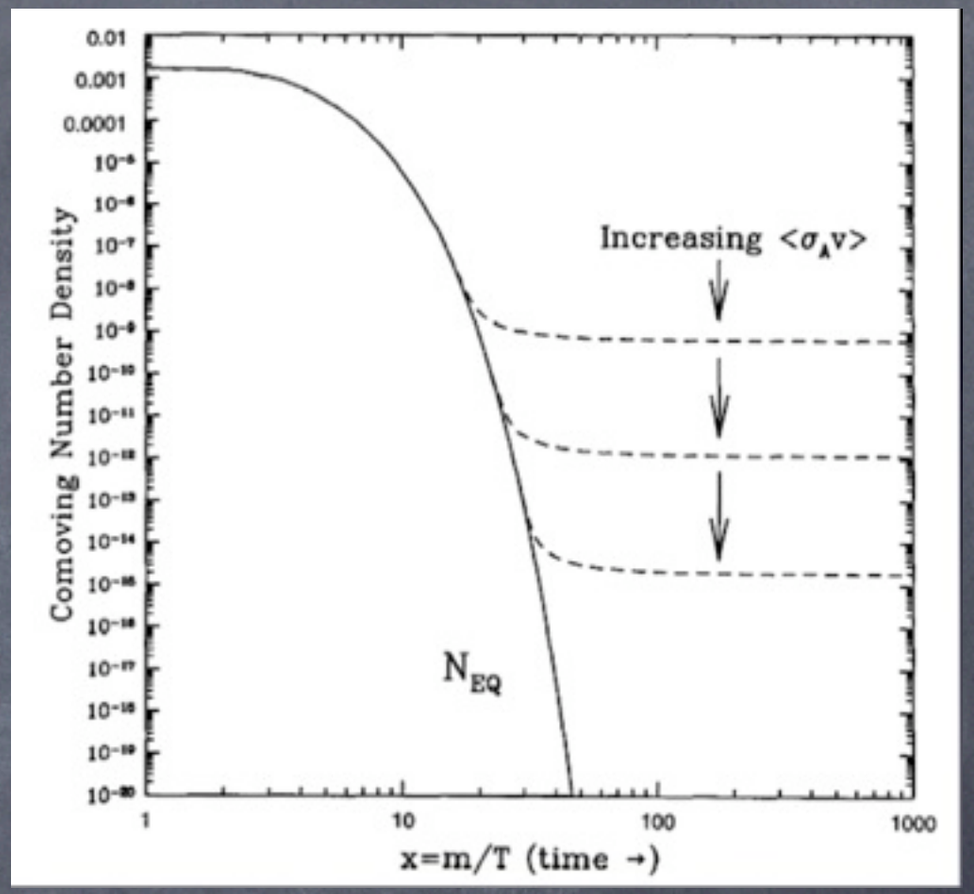

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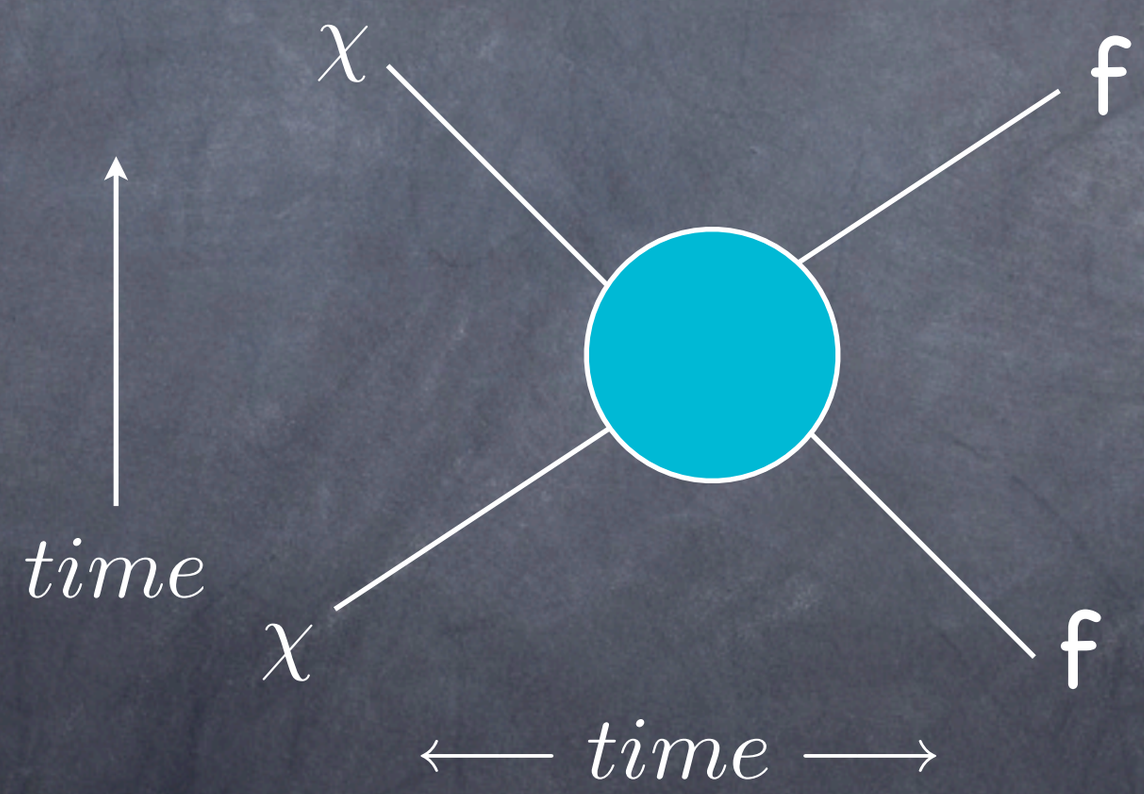
- Any weak- scale particle naturally freezes out within a few orders of magnitude of the correct cross section

- Signals of thermal DM

  - Production (accelerators)
  - Cosmic rays/indirect detection (PAMELA/Fermi/WMAP...)
  - Direct detection (DAMA/XENON/CDMS...)



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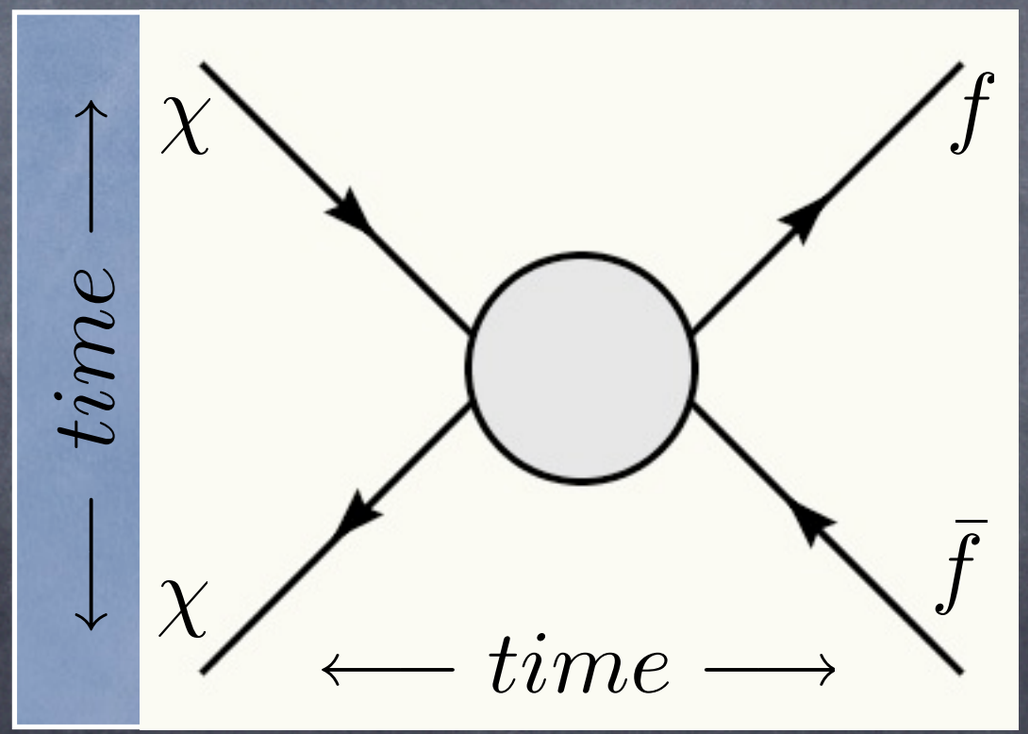
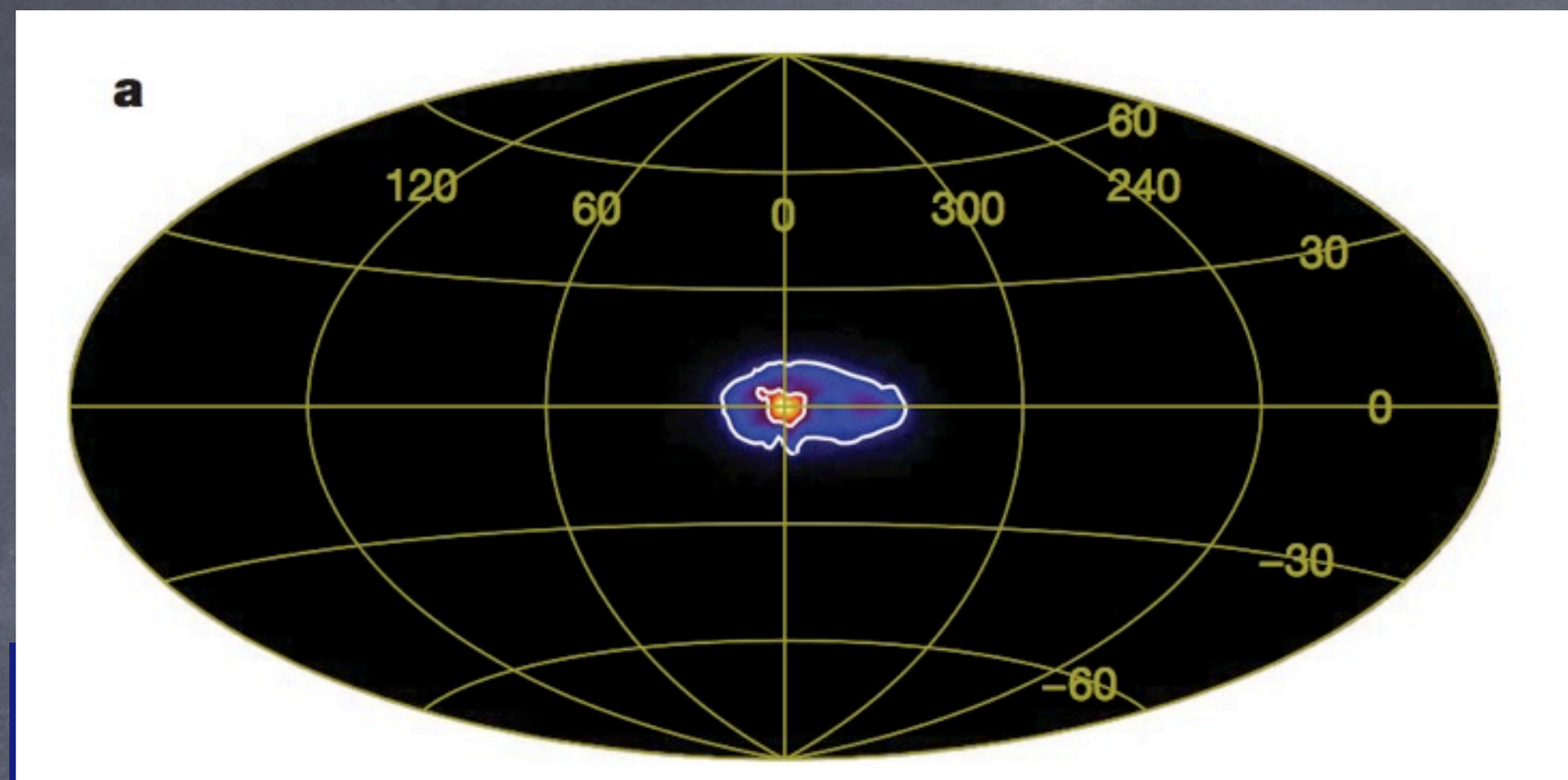
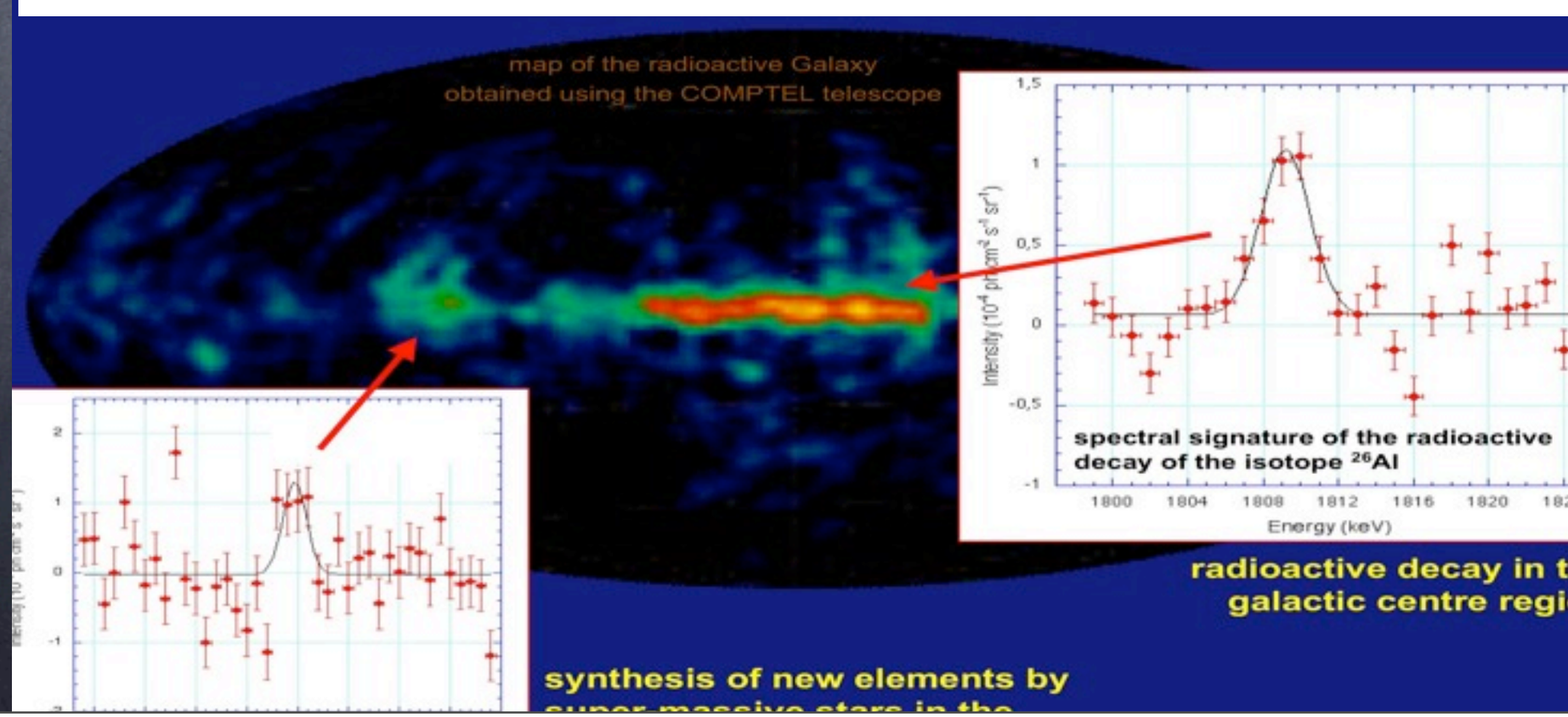


The step-child of dark matter anomalies: INTEGRAL

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...

distribution of the INTEGRAL 511 keV line





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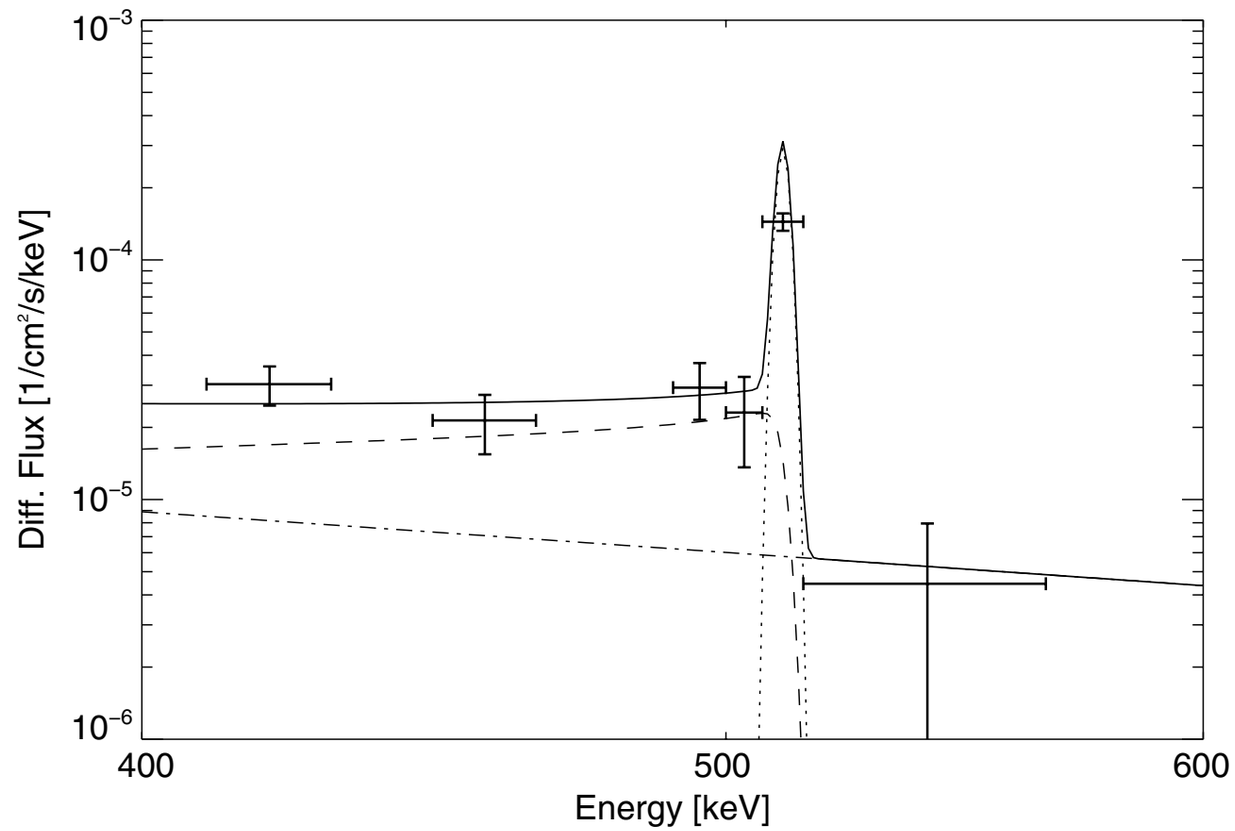


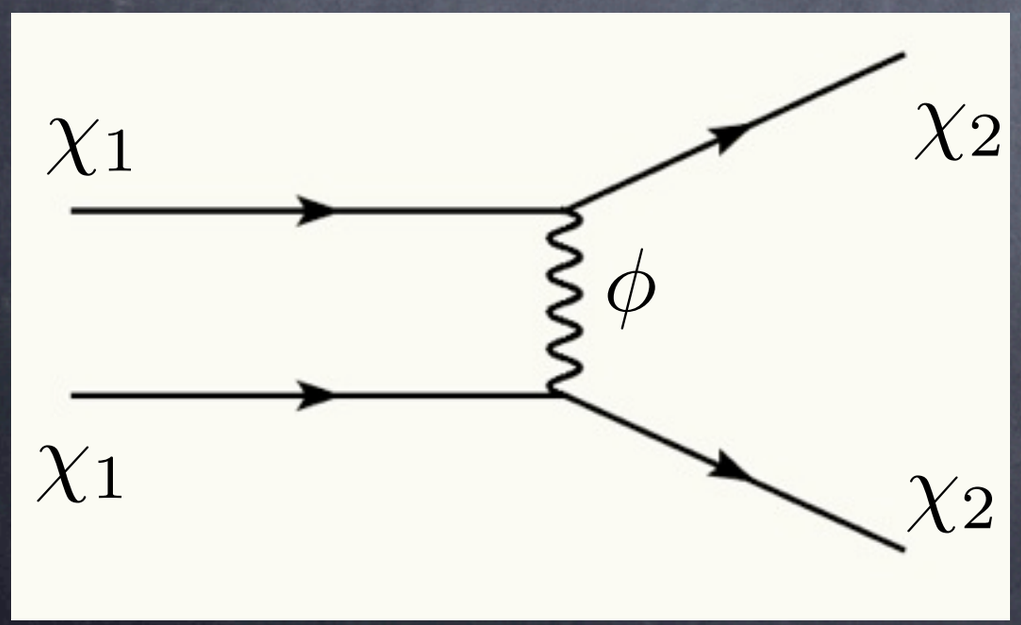
Fig. 2. A fit of the SPI result for the diffuse emission from the GC region ($|l|, |b| \leq 16°$) obtained with a spatial model consisting of an 8° *FWHM* Gaussian bulge and a CO disk. In the fit a diagonal response was assumed. The spectral components are: 511 keV line (dotted), Ps continuum (dashes), 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.

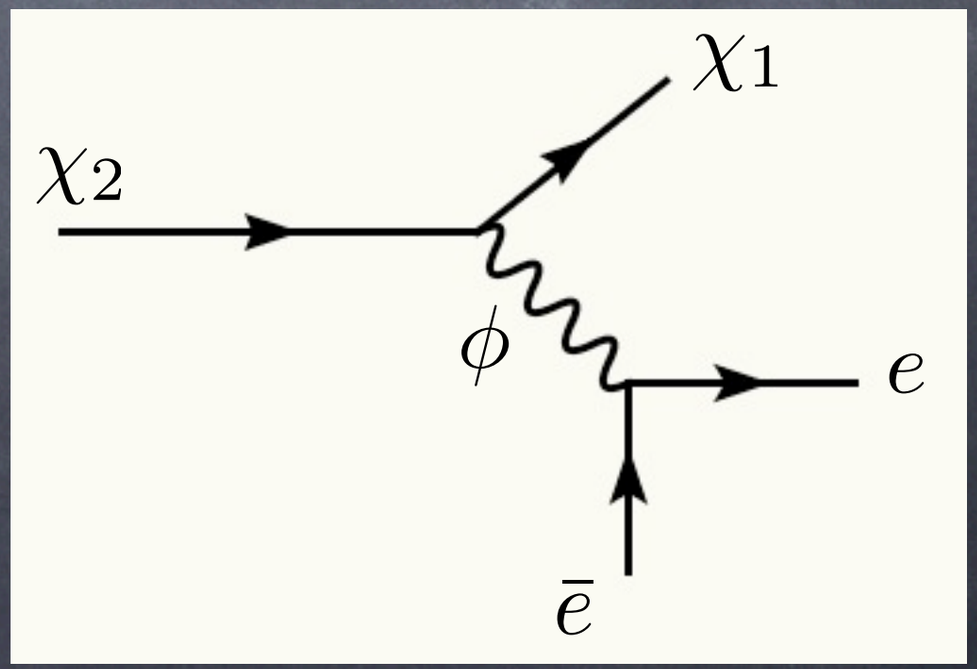
Must be injected with low energies to give narrow line shape

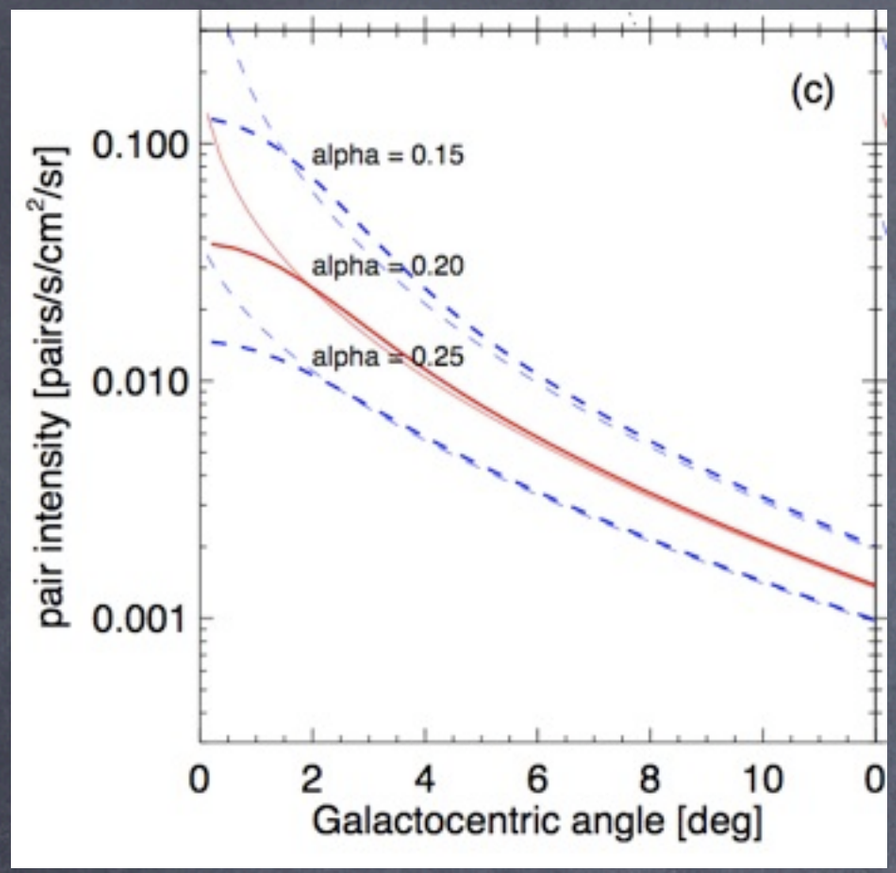
eXciting DM (XDM)

D.Finkbeiner, NW,
Phys.Rev.D76:083519,2007

- Suppose TeV mass dark matter has an excited state ~ MeV above the ground state, and a new force ϕ with mass ~ GeV through which DM can scatter into the excited state, then decay back by emitting e+e-







Need cross section near the geometric cross section, i.e.

$$\sigma \sim 1/q^2$$

Only possible if new force with mass $m_\phi < \mathrm{GeV}^2$ is in the theory

The NKOTB of dark matter anomalies: PAMELA

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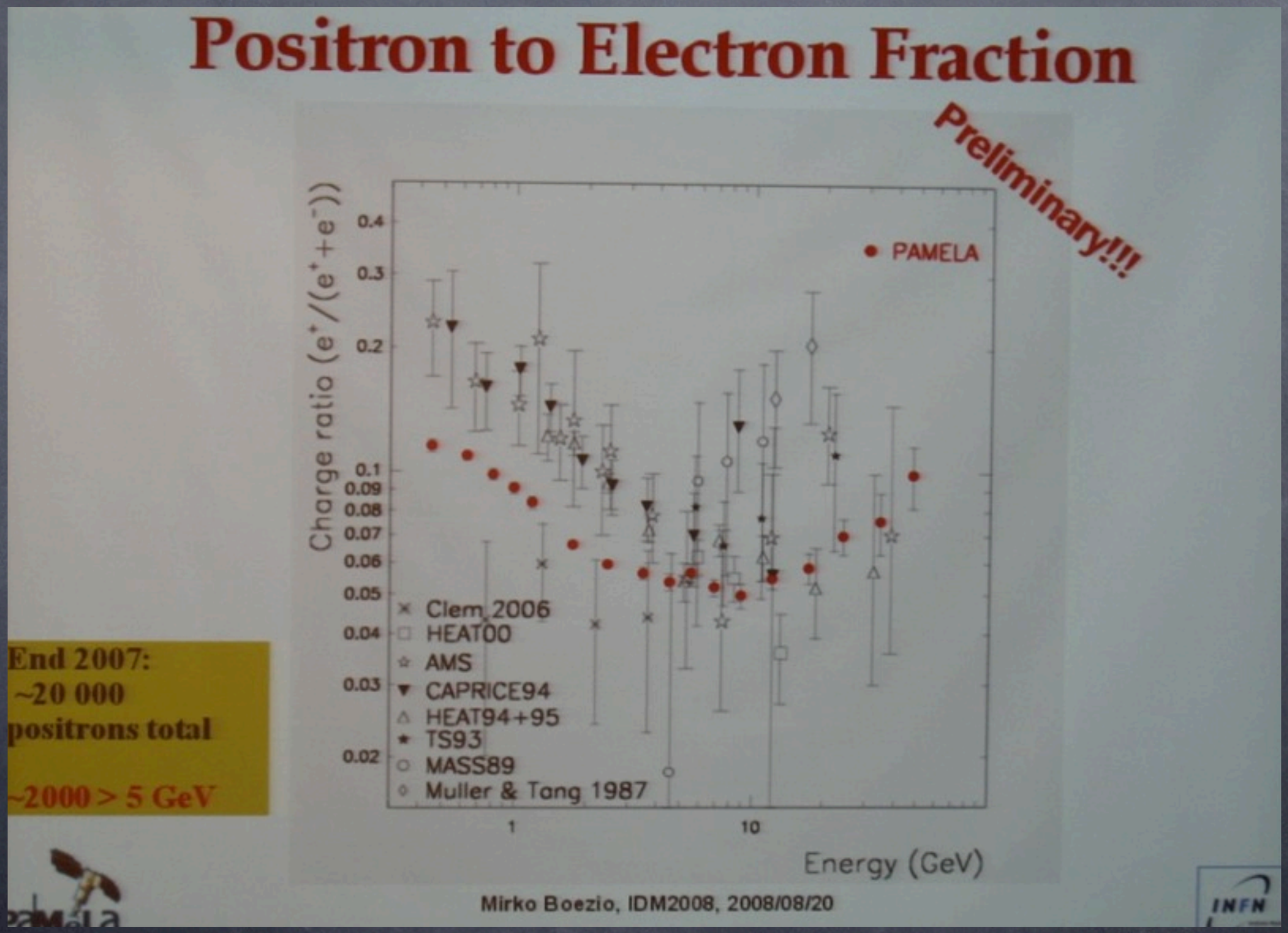
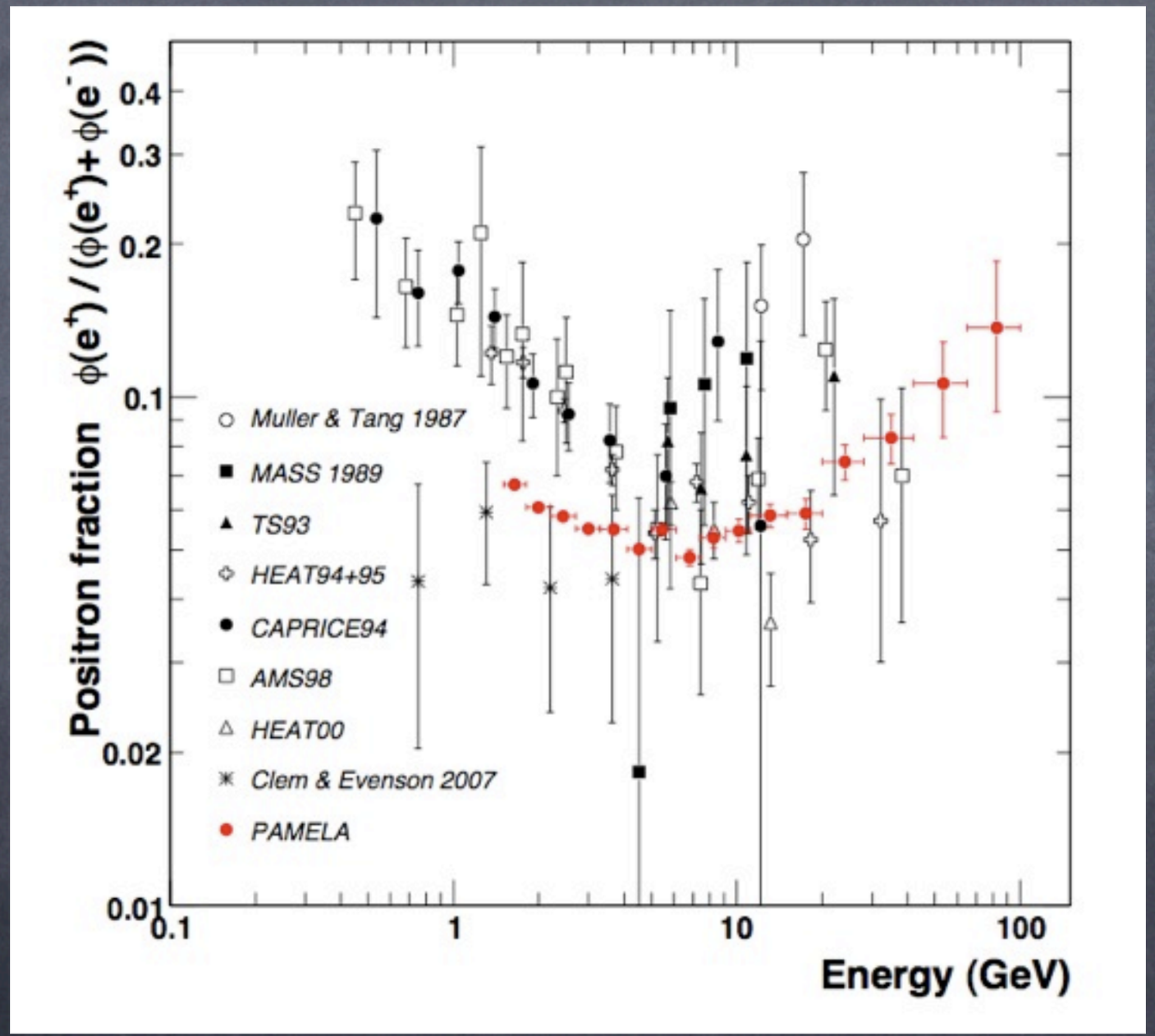
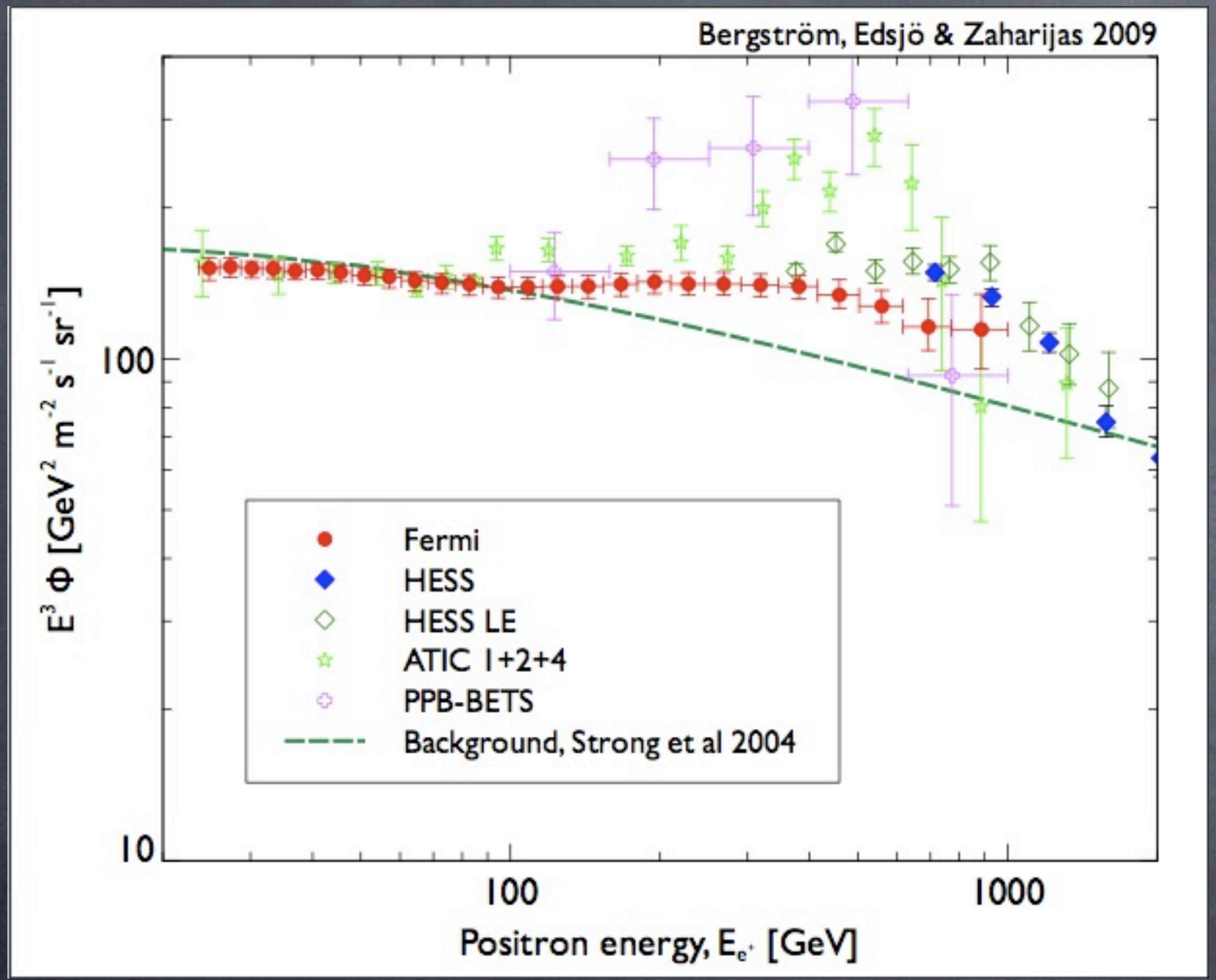
PAMELA

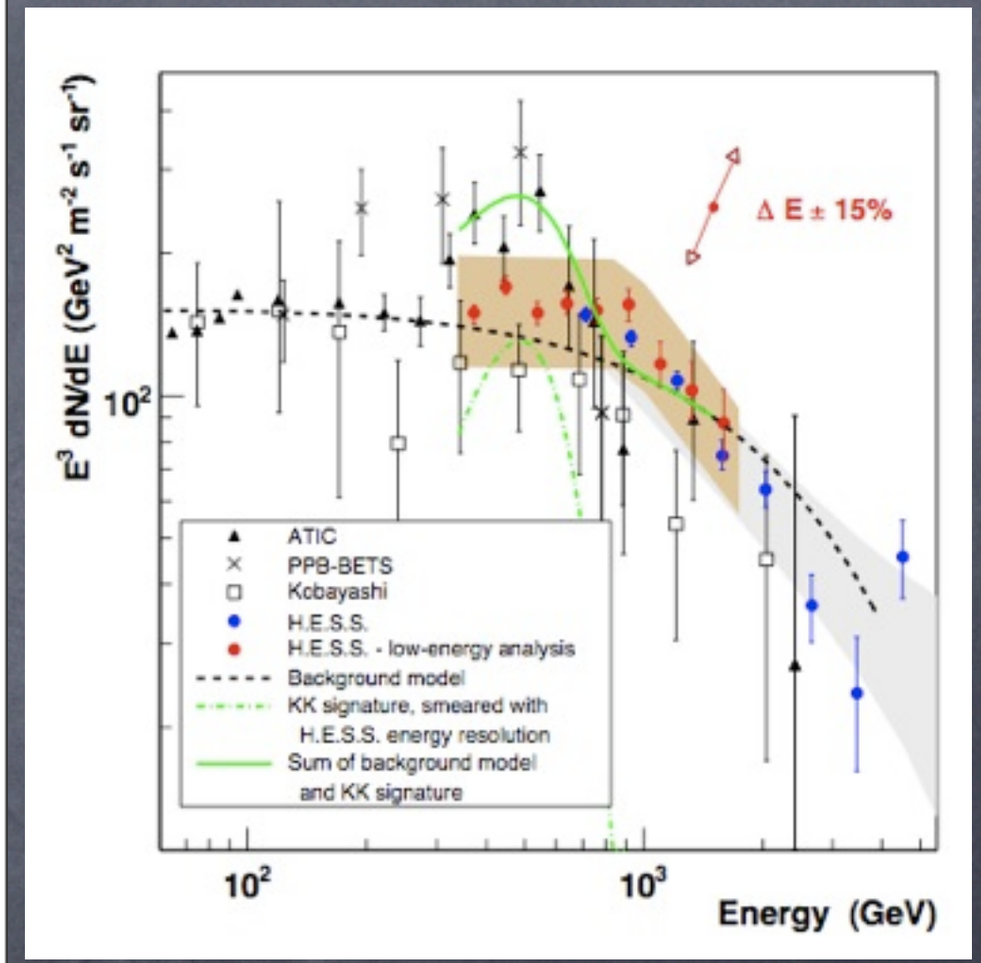

Positron to Electron Fraction
Preliminary!!!
Charge ratio ($e^+/(e^++e^-)$)
0.4
0.3
0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
1
10
Energy (GeV)
PAMELA
Clem 2006
HEAT00
AMS
CAPRICE94
HEAT94+95
TS93
MASS89
Muller & Tang 1987
End 2007:
~20 000
positrons total
~2000 > 5 GeV
Mirko Boezio, IDM2008, 2008/08/20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

PAMELA

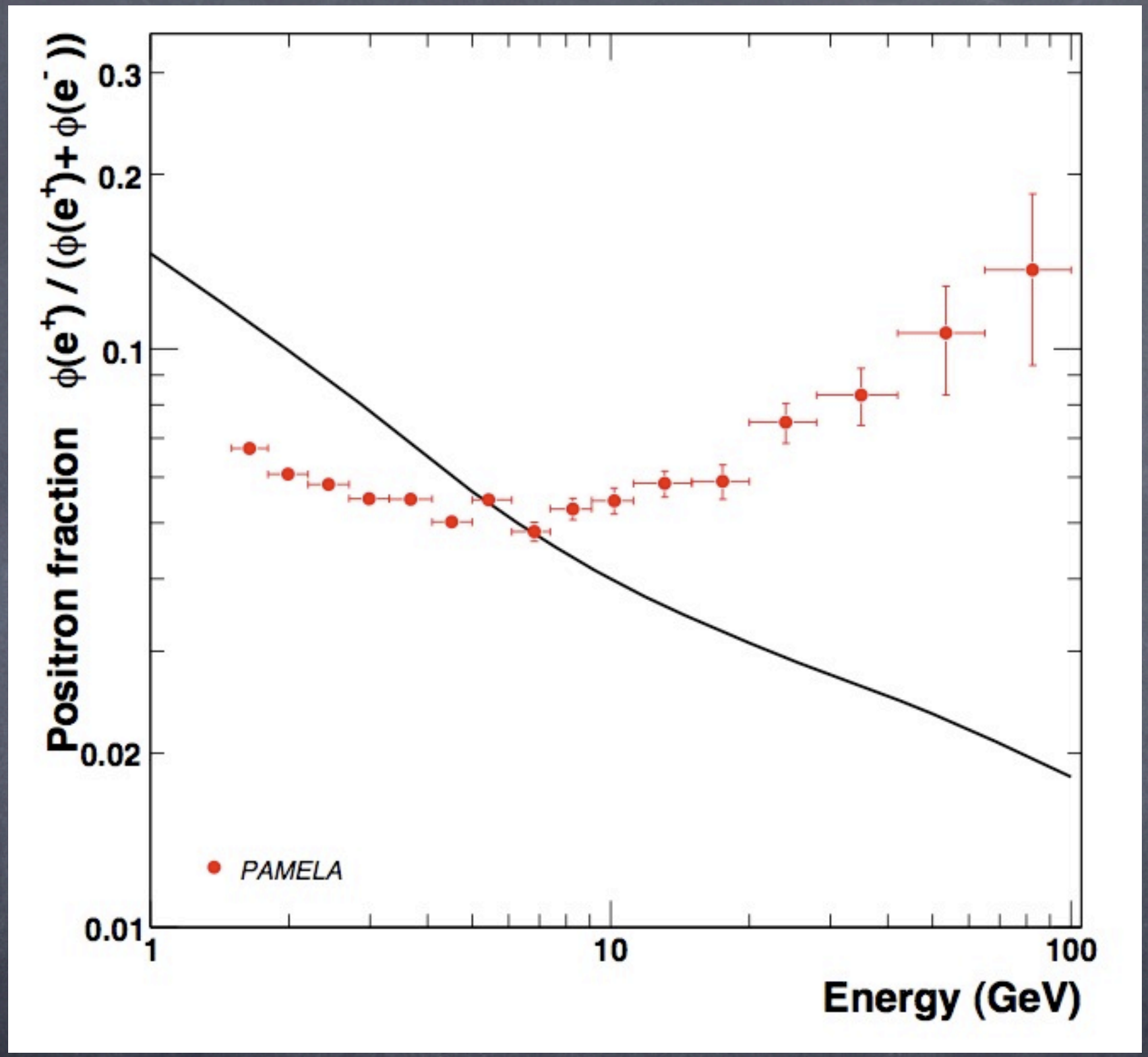

Positron fraction
φ(e+) / (φ(e+)+ φ(e-))
0.4
0.3
0.2
0.1
0.02
0.01
0.1
1
10
100
Energy (GeV)
Muller & Tang 1987
MASS 1989
TS93
HEAT94+95
CAPRICE94
AMS98
HEAT00
Clem & Evenson 2007
PAMELA

Fermi, HESS, ATIC, PPB-BETS





- **Harder** spectrum than expected - no break until ~ TeV



Positrons expected from **secondary** production

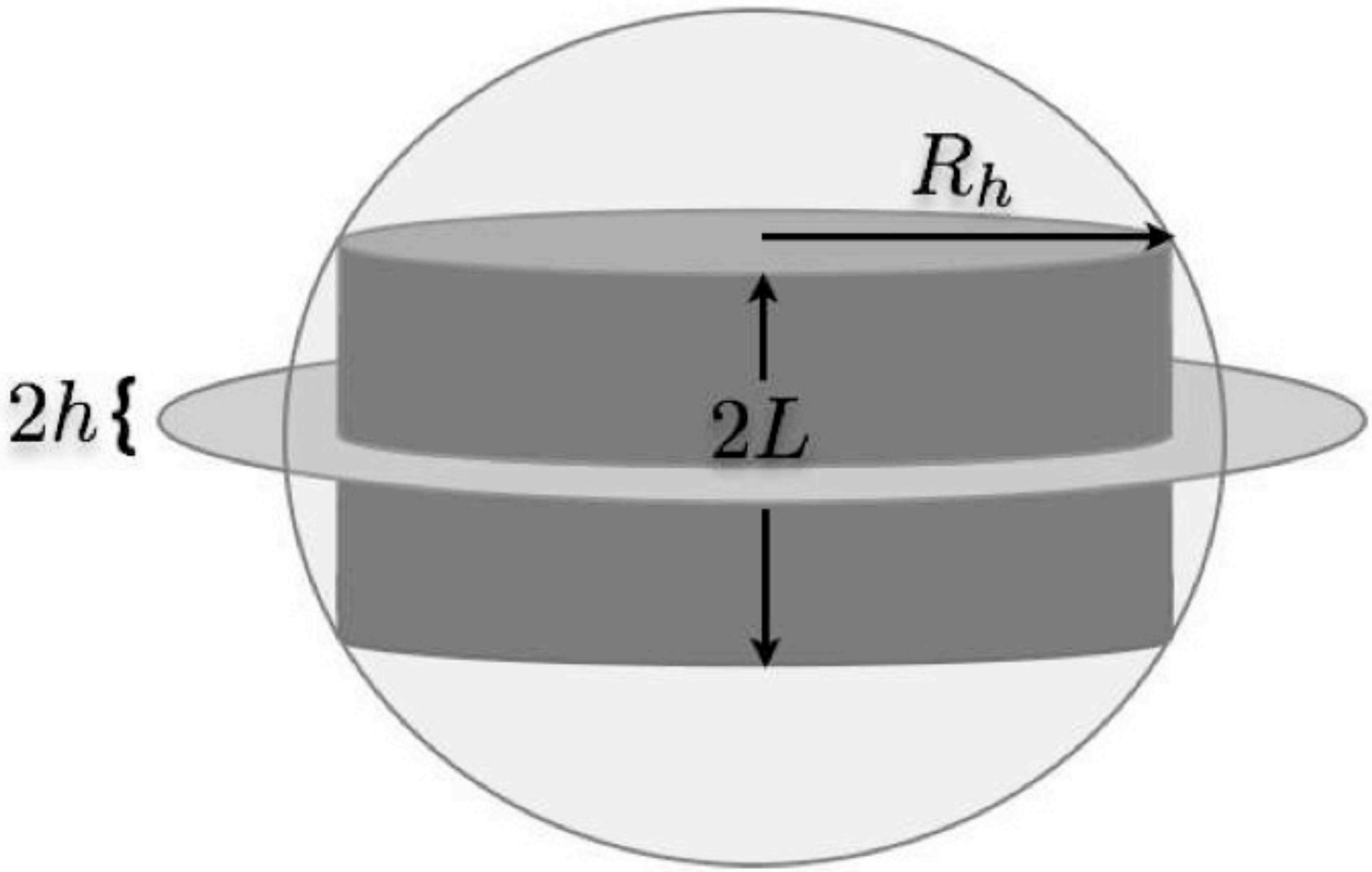
How do electrons propagate?

what we want to know

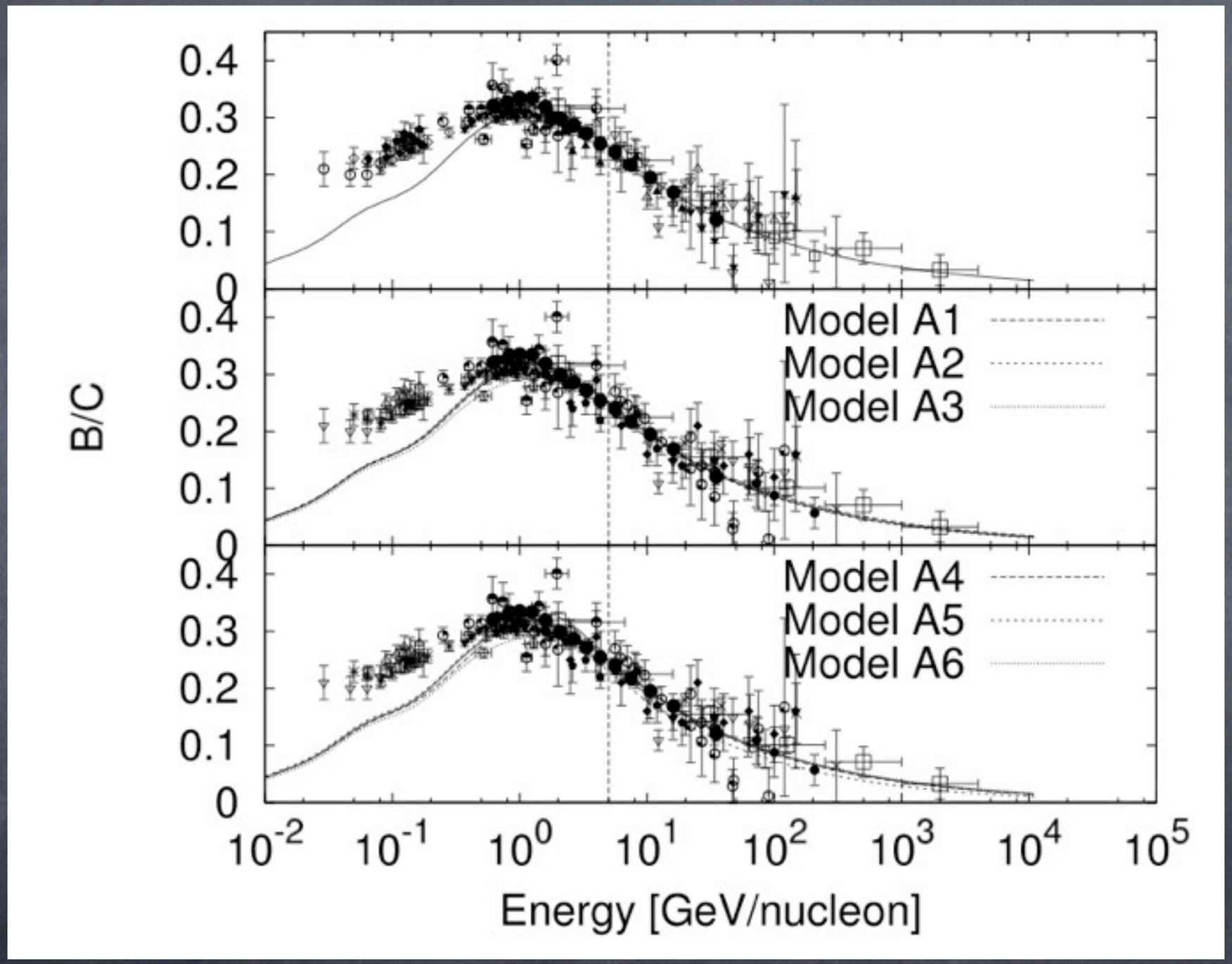
$$\frac{\partial}{\partial t}\frac{dn_e}{dE_e} = \vec{\nabla}\cdot\left[K(E_e,\vec{x})\vec{\nabla}\frac{dn_e}{dE_e}\right] + \frac{\partial}{\partial E_e}\left[b(E_e,\vec{x})\frac{dn_e}{dE_e}\right] + Q(E_e,\vec{x}),$$

diffusion (not well understood)

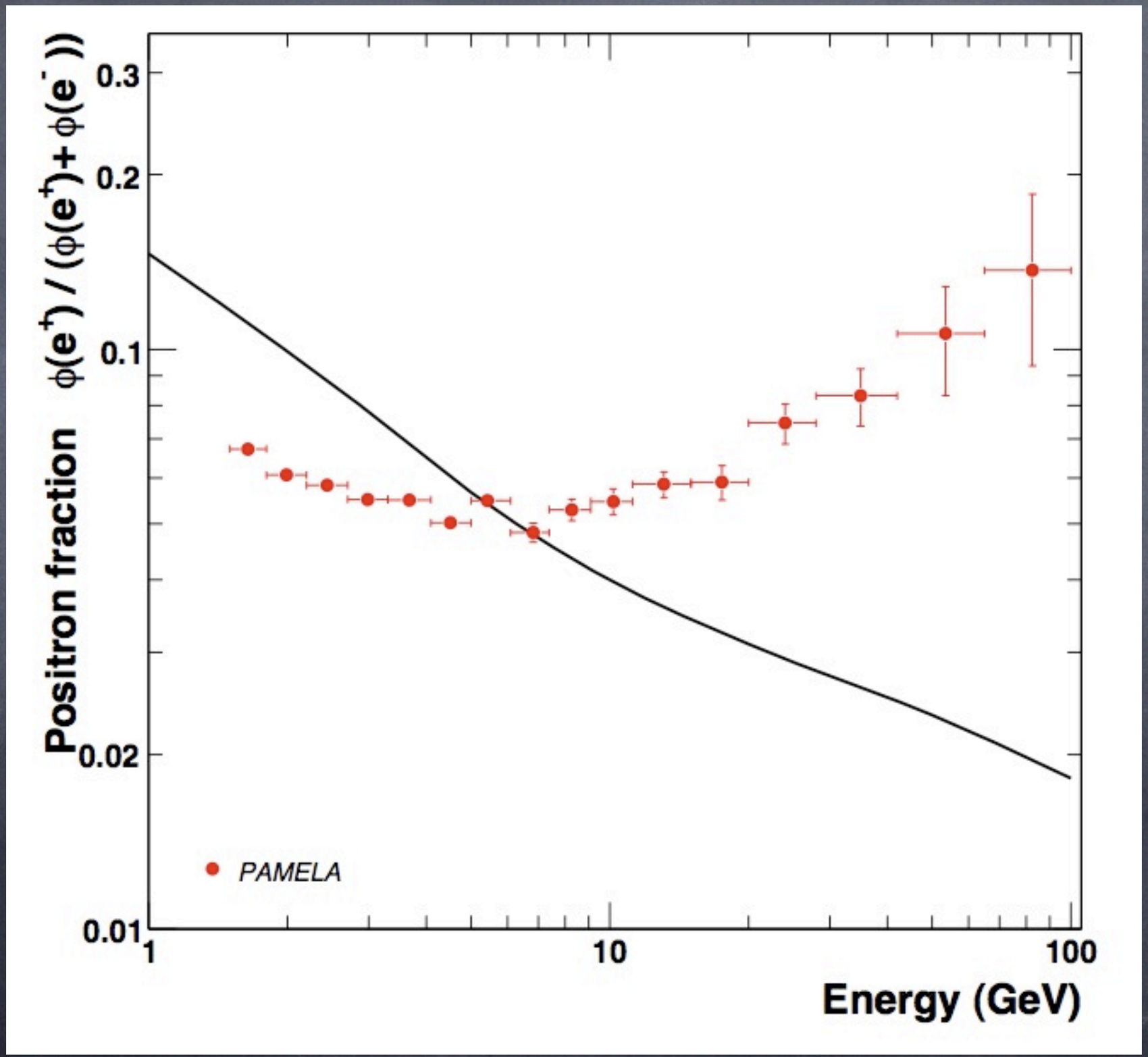
ICS and synchrotron energy losses (fairly well understood)



Grajek, Kane, Pierce, Phalen, `08

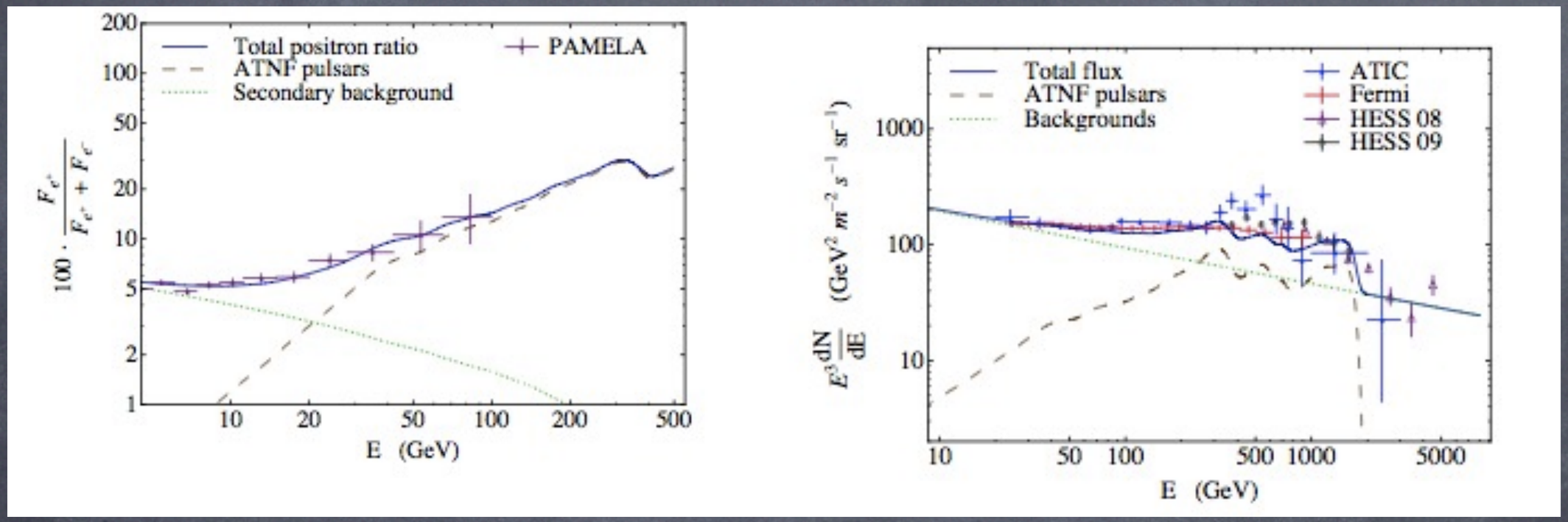


Hooper + Simet '09


Positron fraction
φ(e+) / (φ(e+)+ φ(e-))
0.3
0.2
0.1
0.02
0.01
1
10
100
Energy (GeV)
PAMELA

Astrophysics?

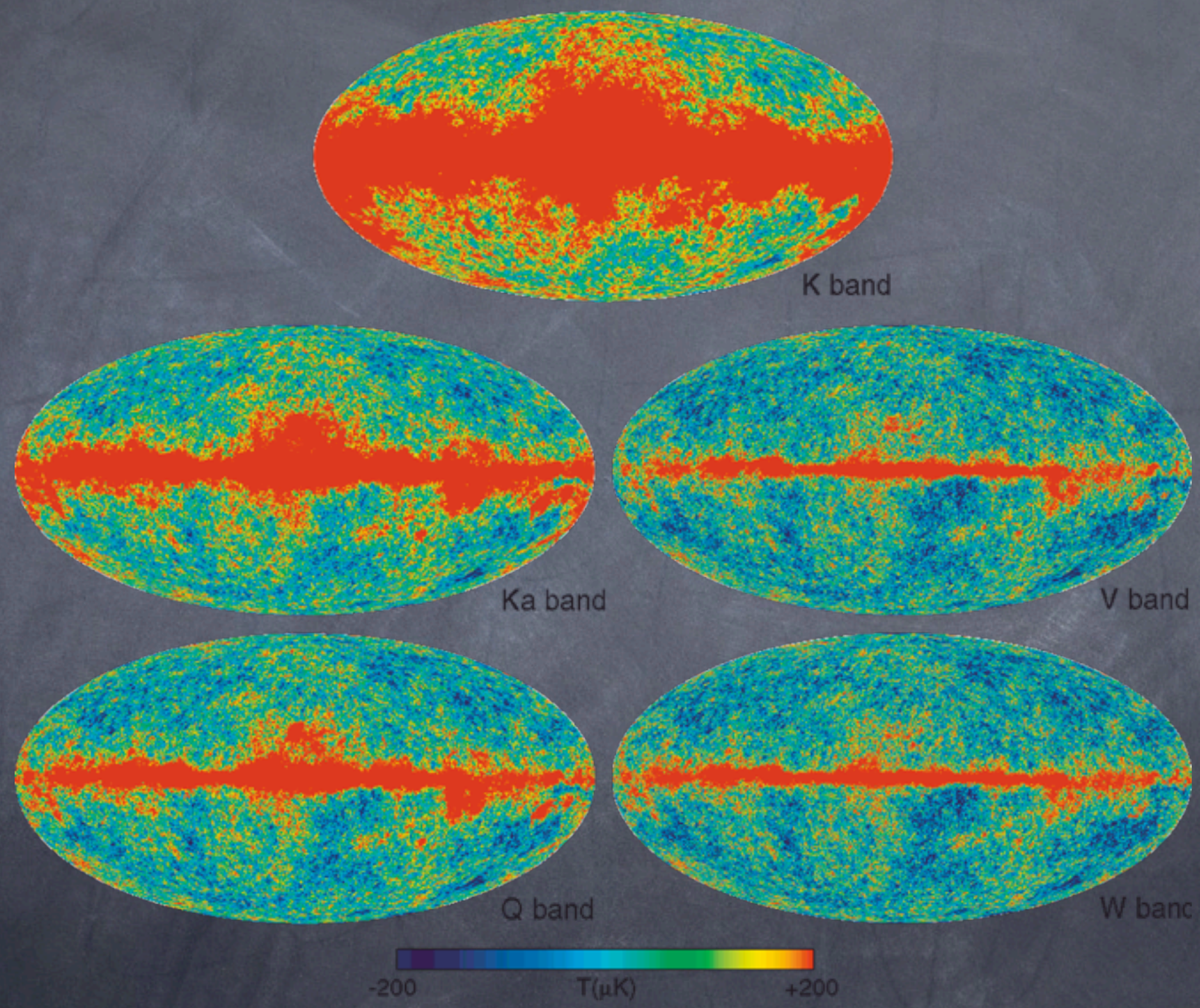
Malyshev, Cholis, Gelfand, '09

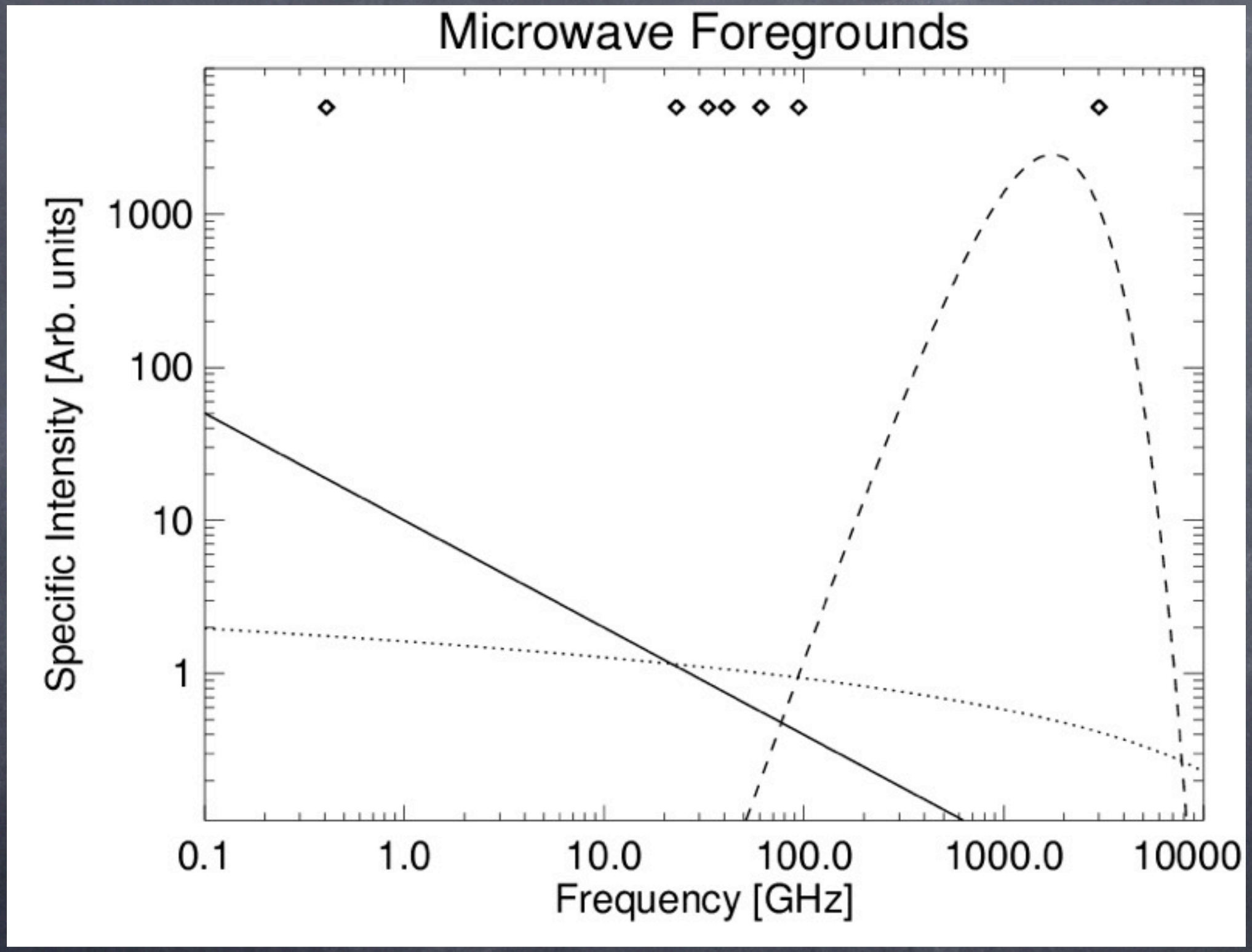


Aharonian, Atoyan, Volk '95; Hooper, Blasi, Serpico '08;Profumo '09...

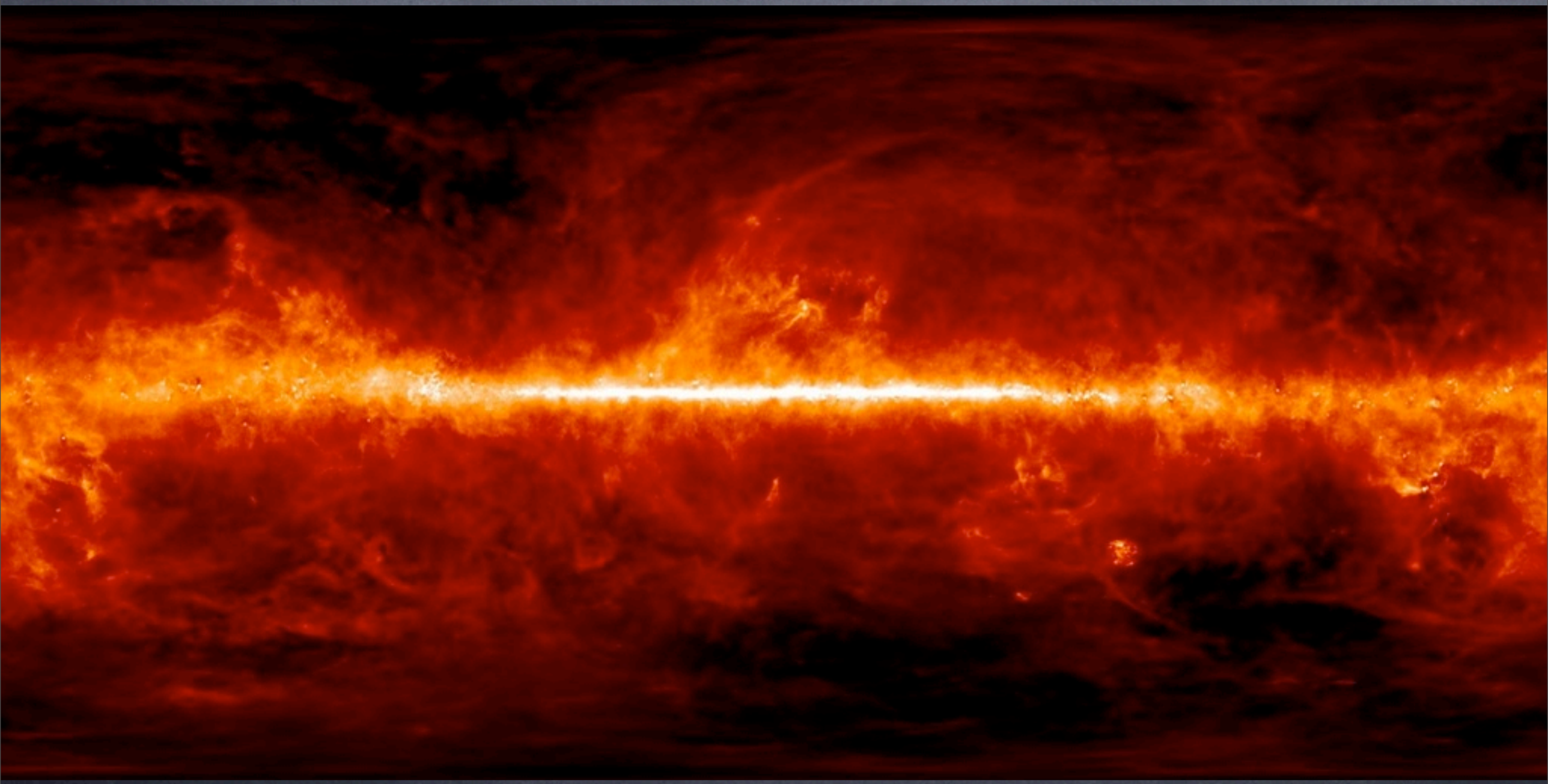
DM or Astrophysics?
(look in the inner galaxy)

WMAP

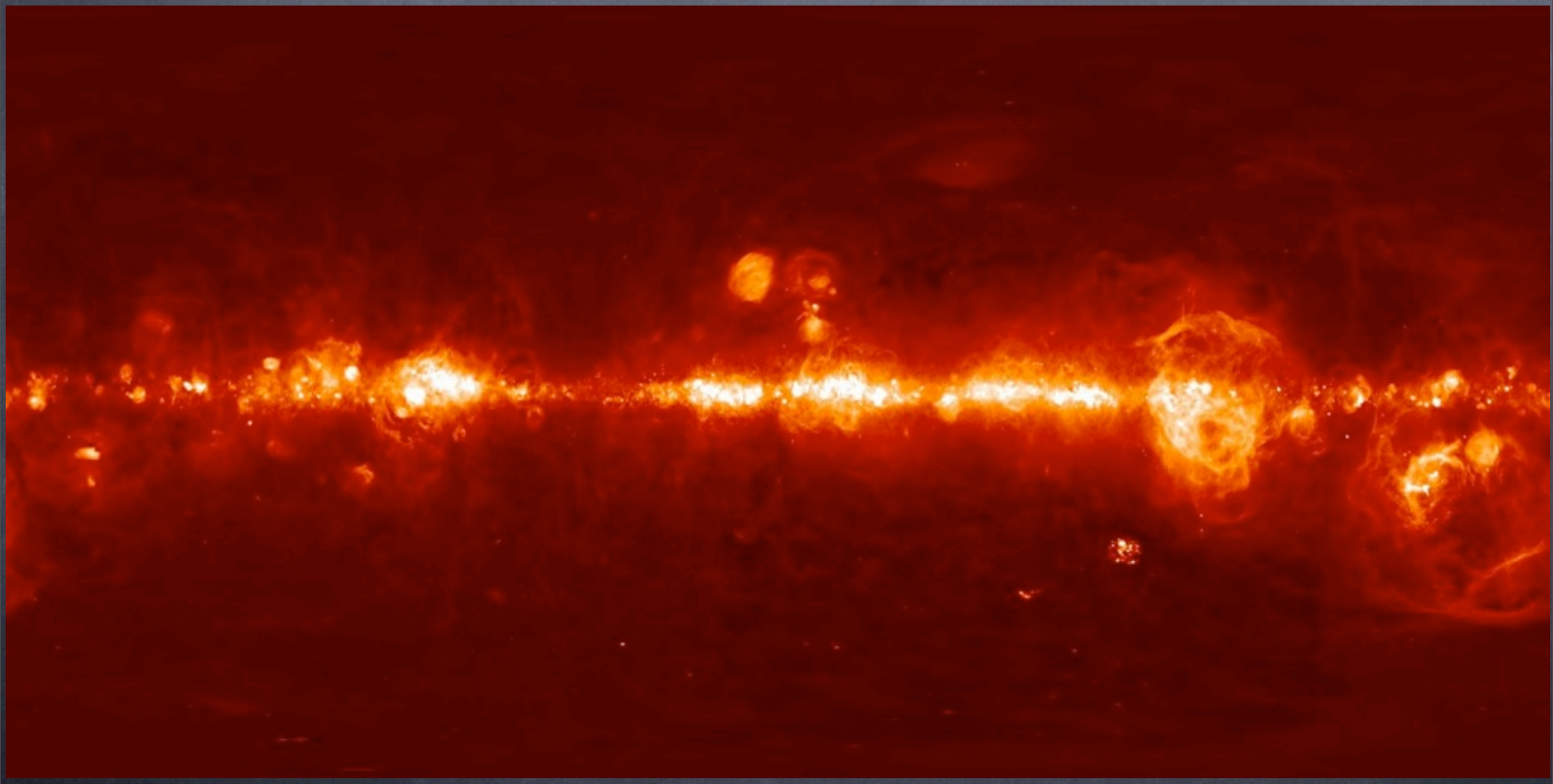



Microwave Foregrounds
Specific Intensity [Arb. units]
1000
100
10
1
0.1
1.0
10.0
100.0
1000.0
10000
Frequency [GHz]

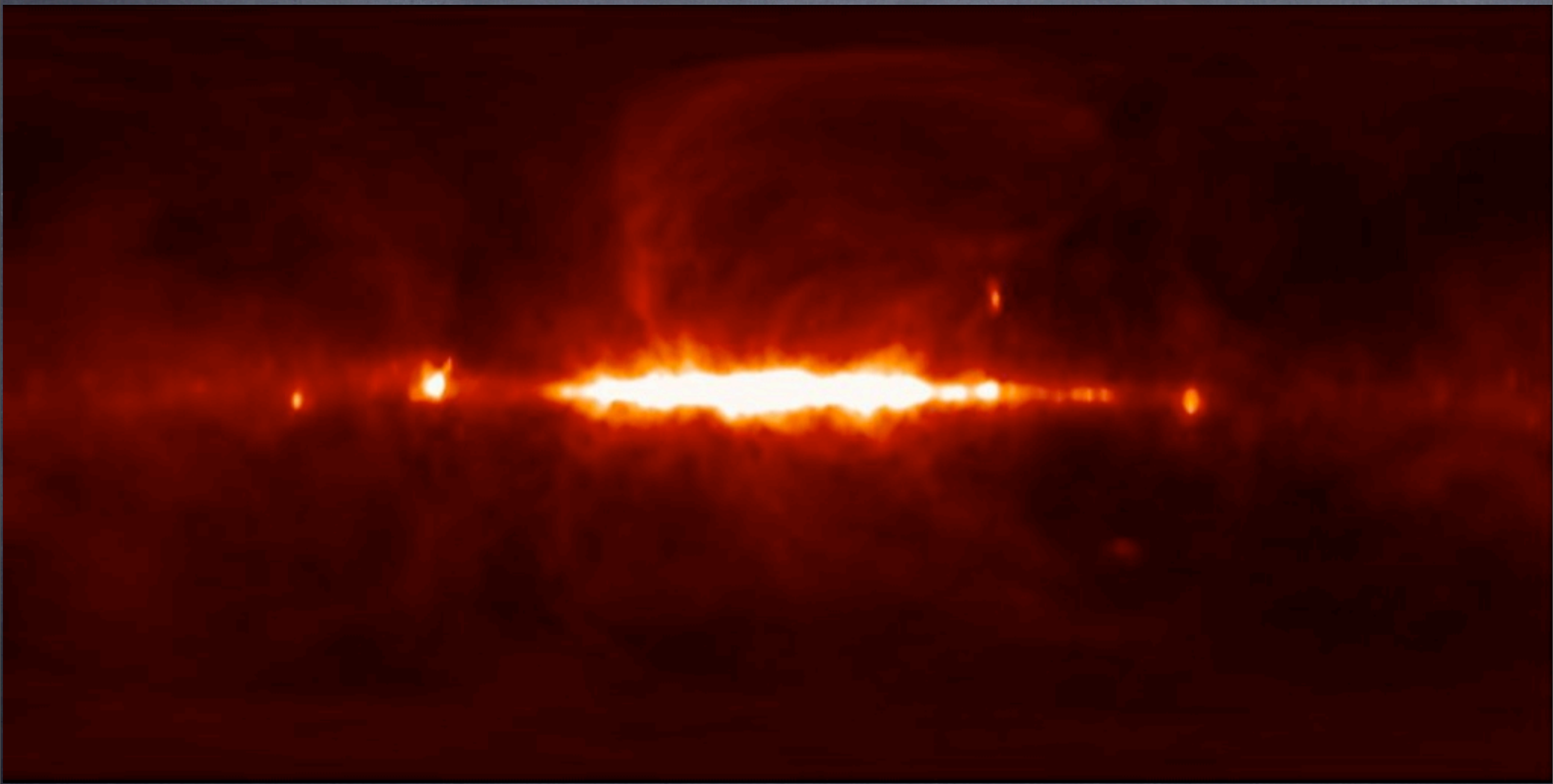
Interstellar Dust from IRAS, DIRBE (Finkbeiner et al. 1999) Map extrapolated from 3 THz (100 micron) with FIRAS.



Ionized Gas from WHAM, SHASSA, VTSS (Finkbeiner 2003)
H-alpha emission measure goes as thermal bremsstrahlung.



Synchrotron at 408 MHz (Haslam et al. 1982)



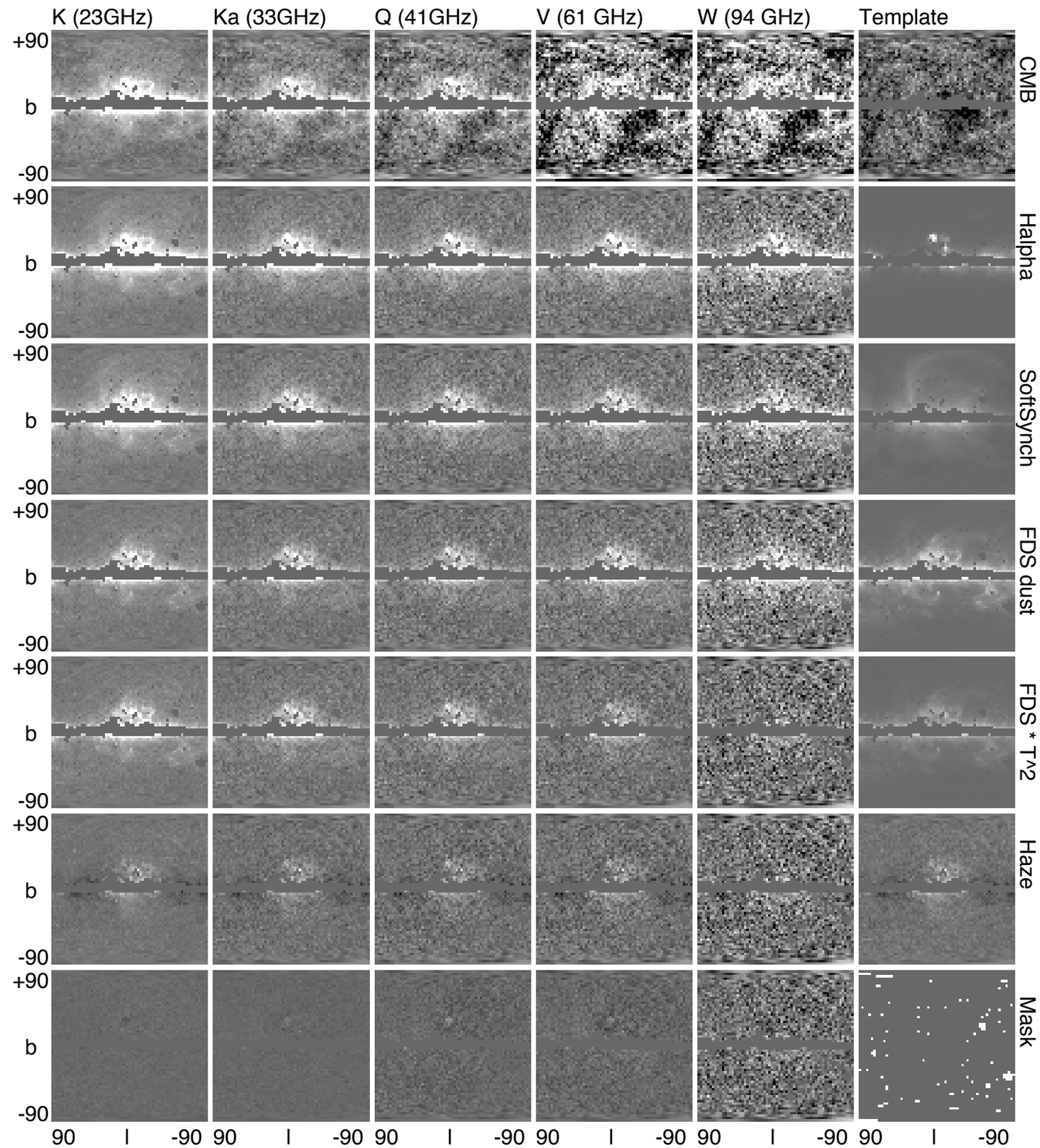
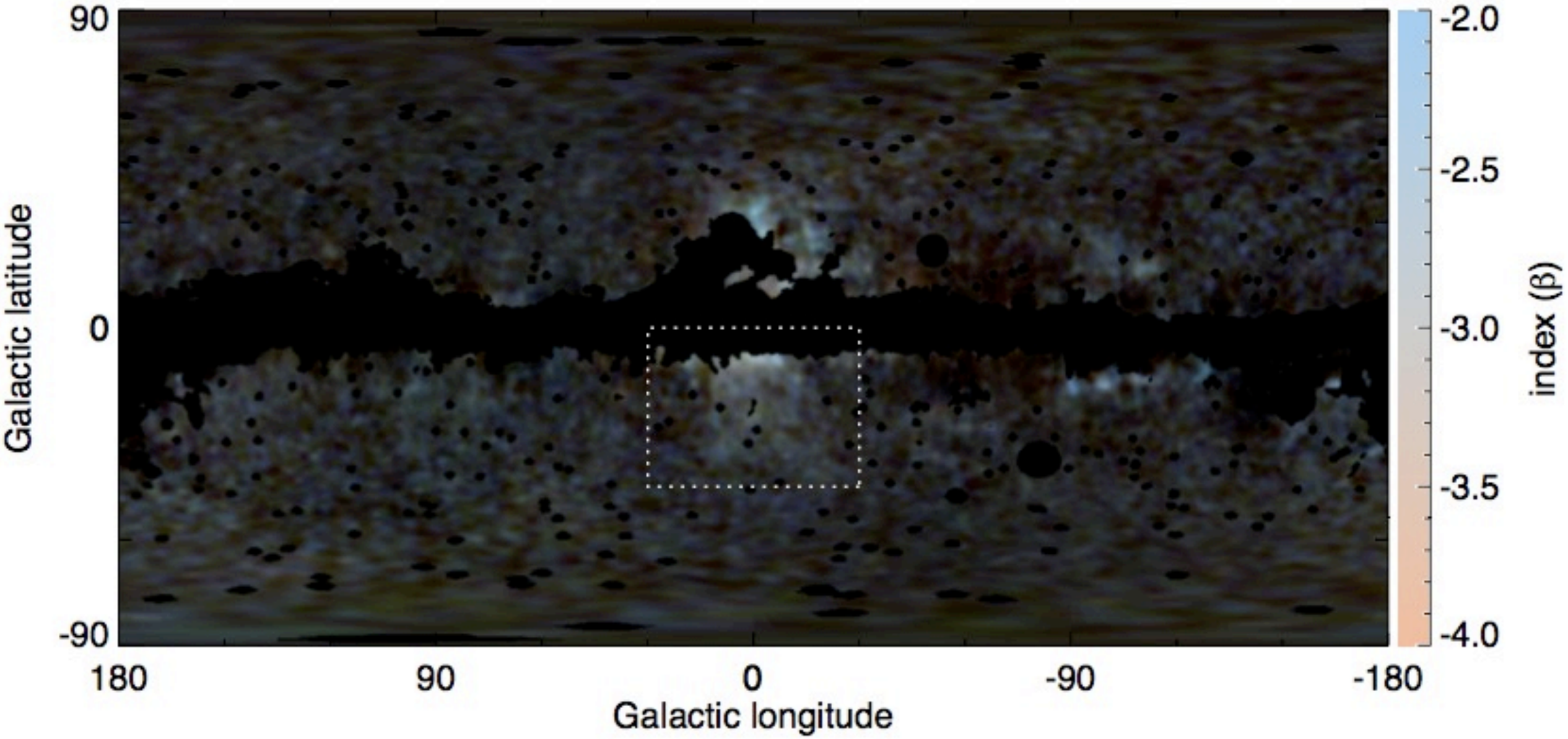


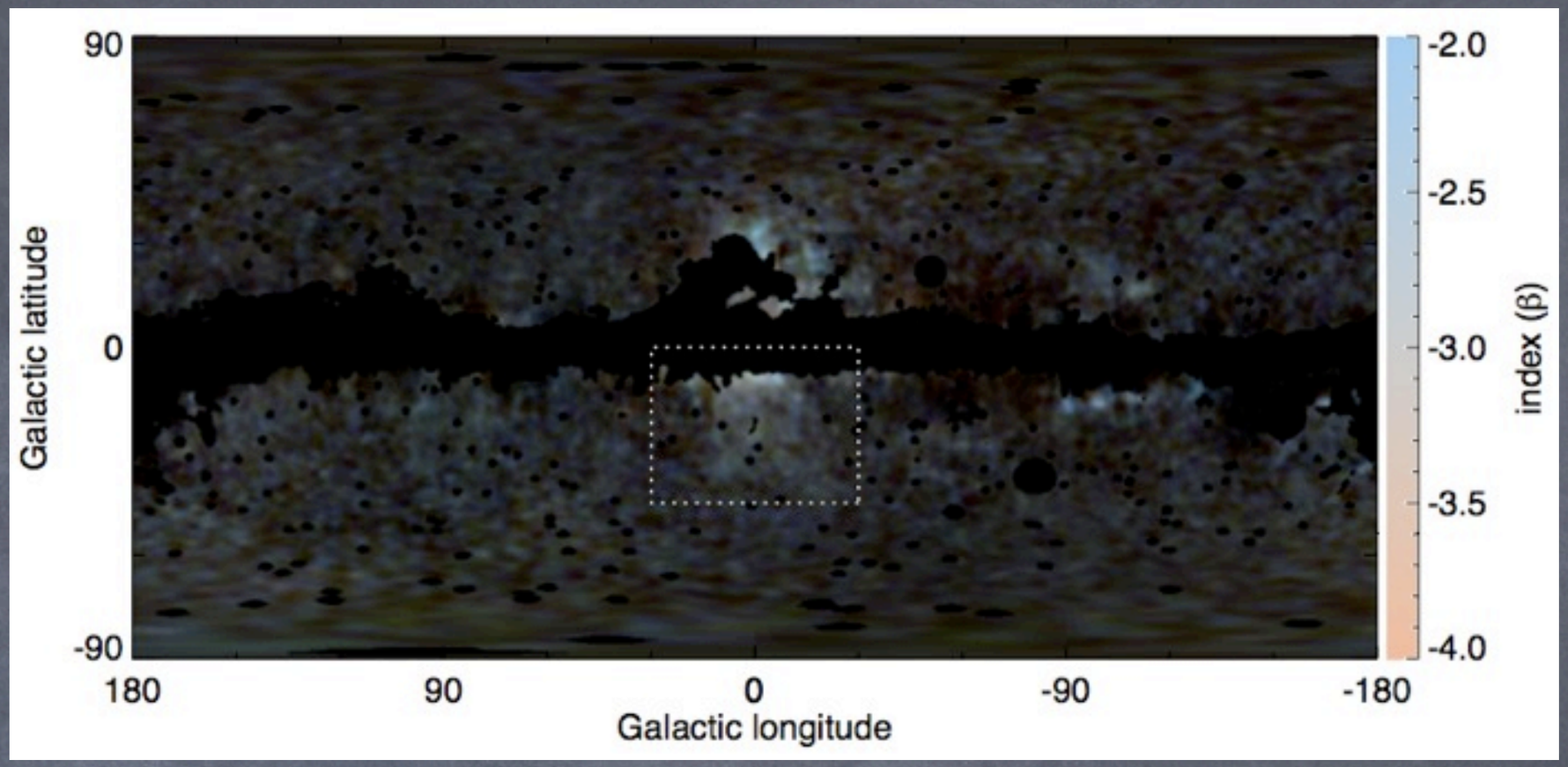
Fig. 1.— The WMAP foreground grid; see detailed discussion in §2.7.

Dobler and Finkbeiner '08



Dobler and Finkbeiner '08

A "Haze"



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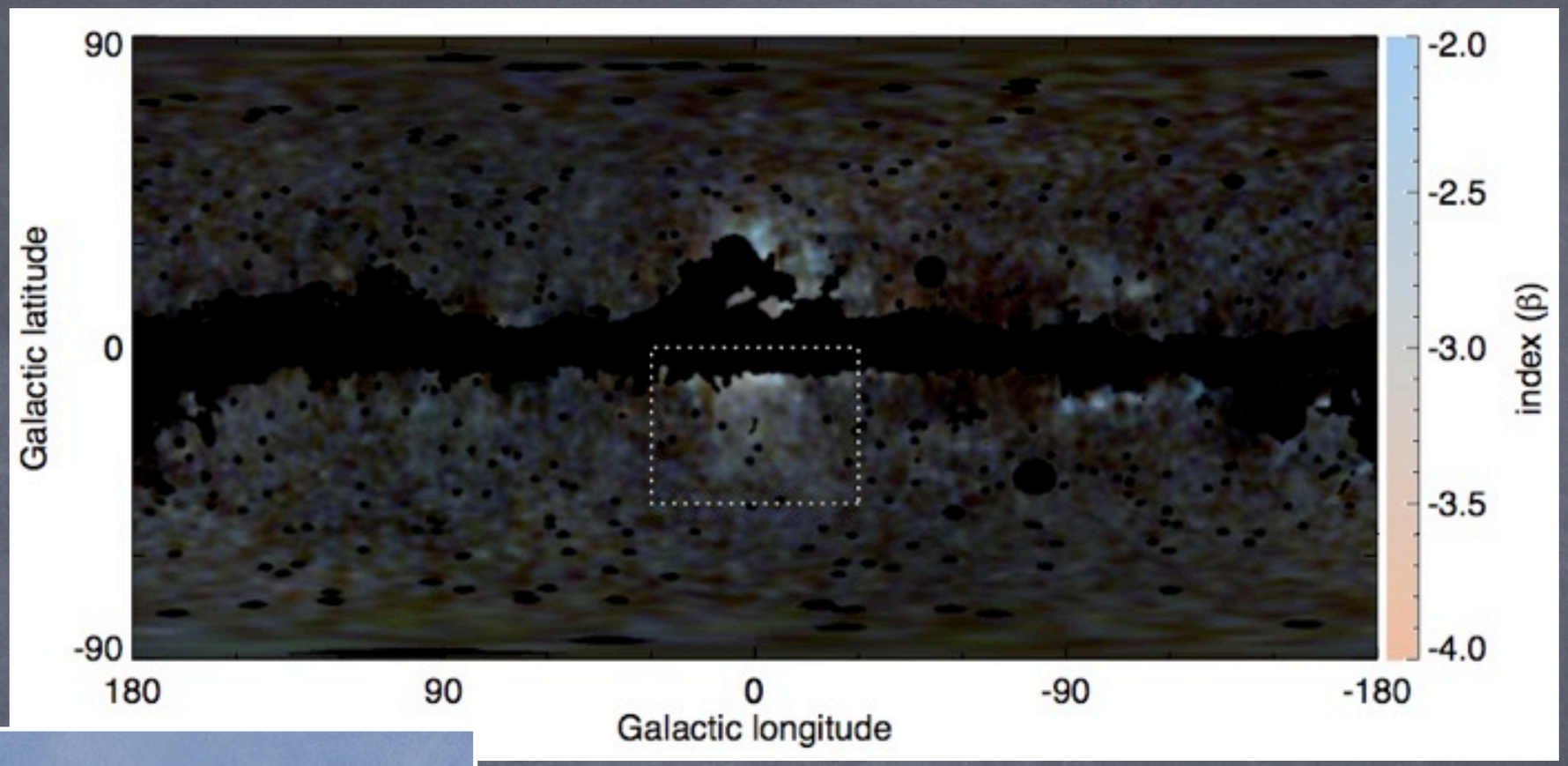
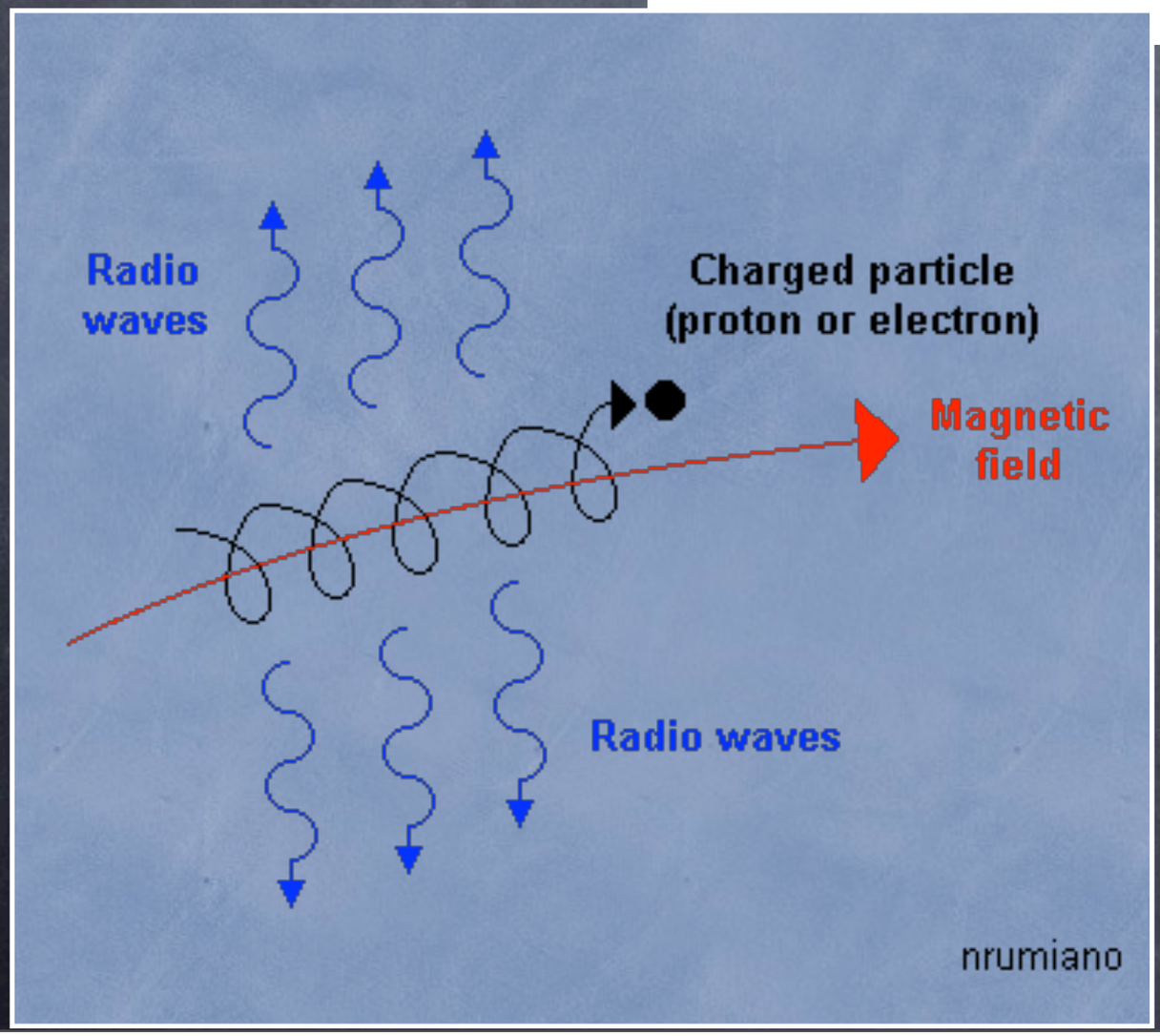
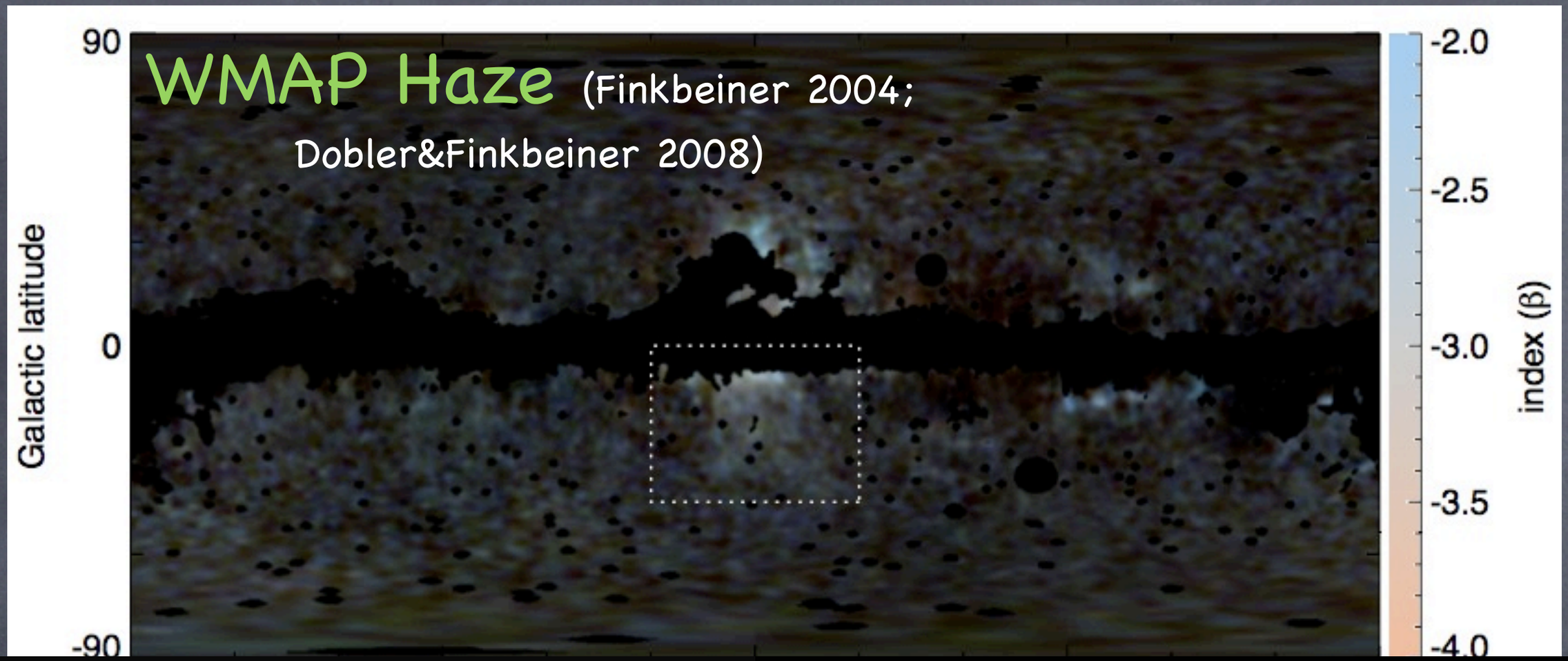


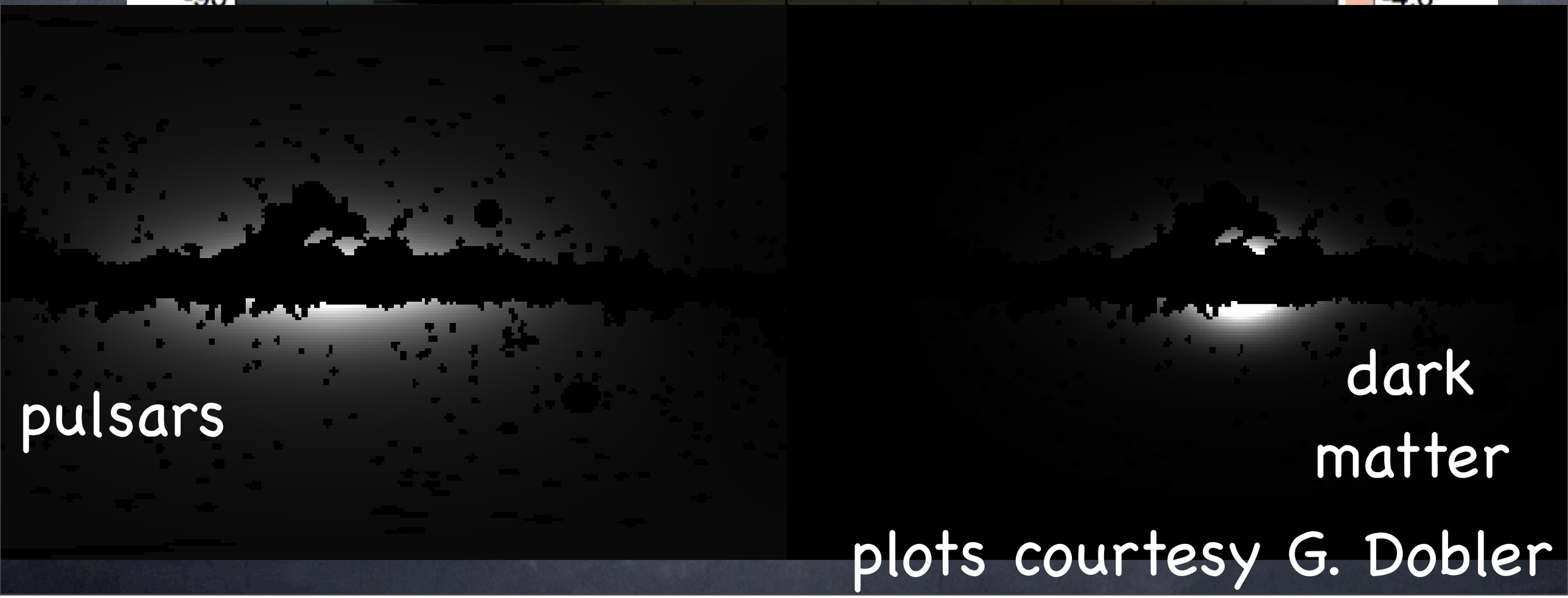


Dobler and Finkbeiner '08

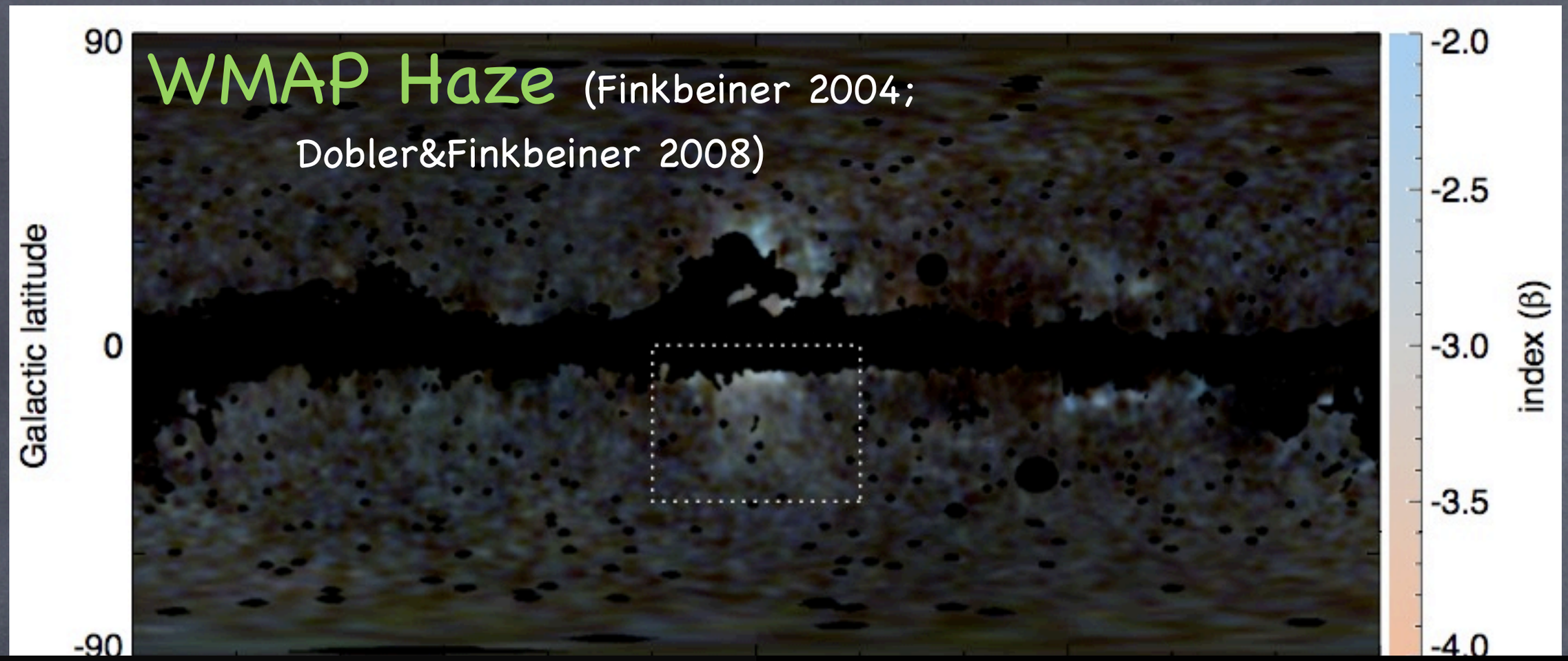
electrons spiraling in magnetic field create microwaves

WMAP Haze (Finkbeiner 2004; Dobler&Finkbeiner 2008)





plots courtesy G. Dobler



Natural interpretation is of new source of 10+ GeV e+e- in galactic center, but with larger amplitude than locally

pulsars

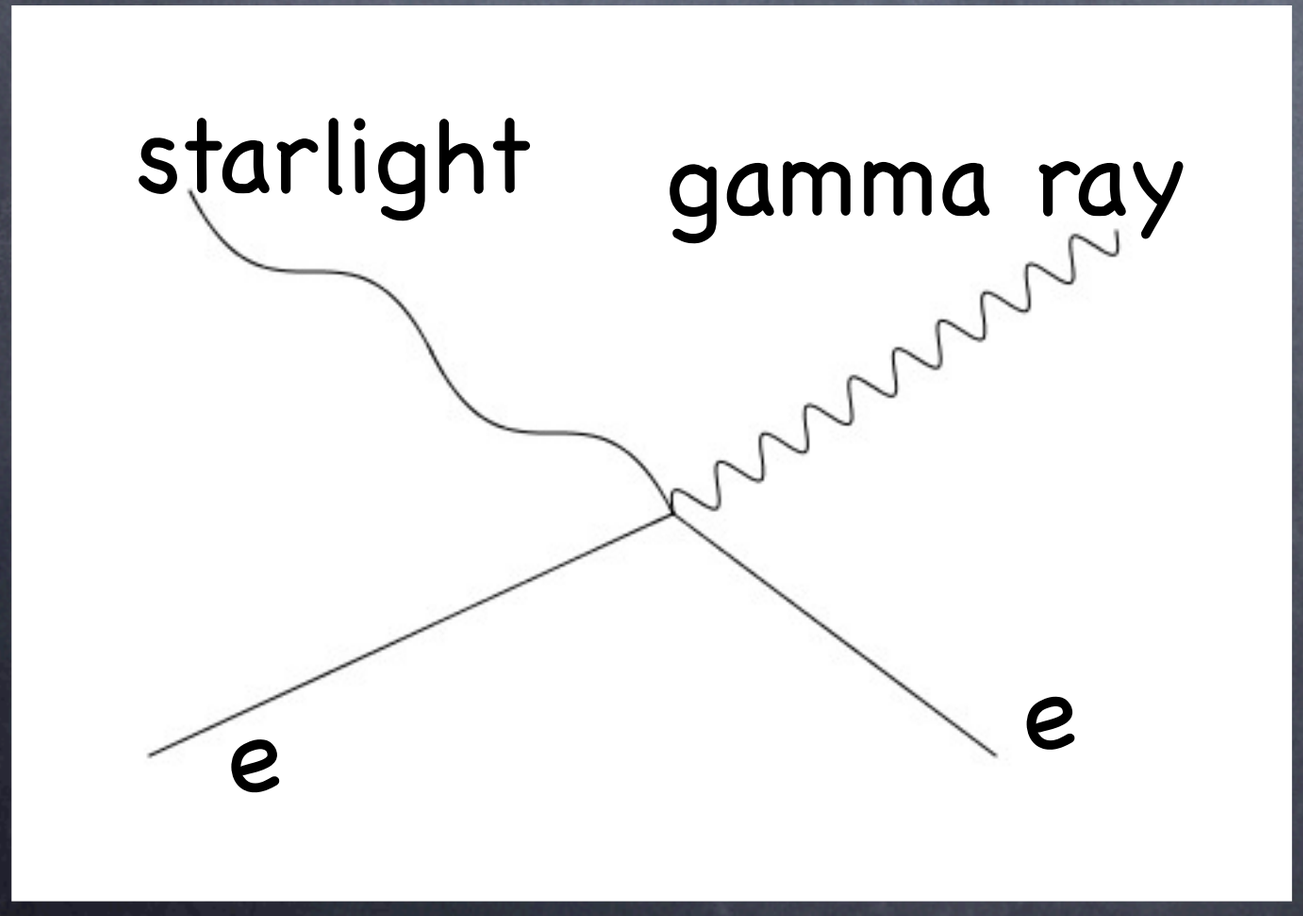
dark matter

good fit for DM explanation

plots courtesy G. Dobler

Fermi ICS

In the inner galaxy, high energy e+e- convert energy to synchrotron radiation (WMAP haze) **and inverse-compton scattered photons**



Same electrons should upscatter starlight into gamma rays

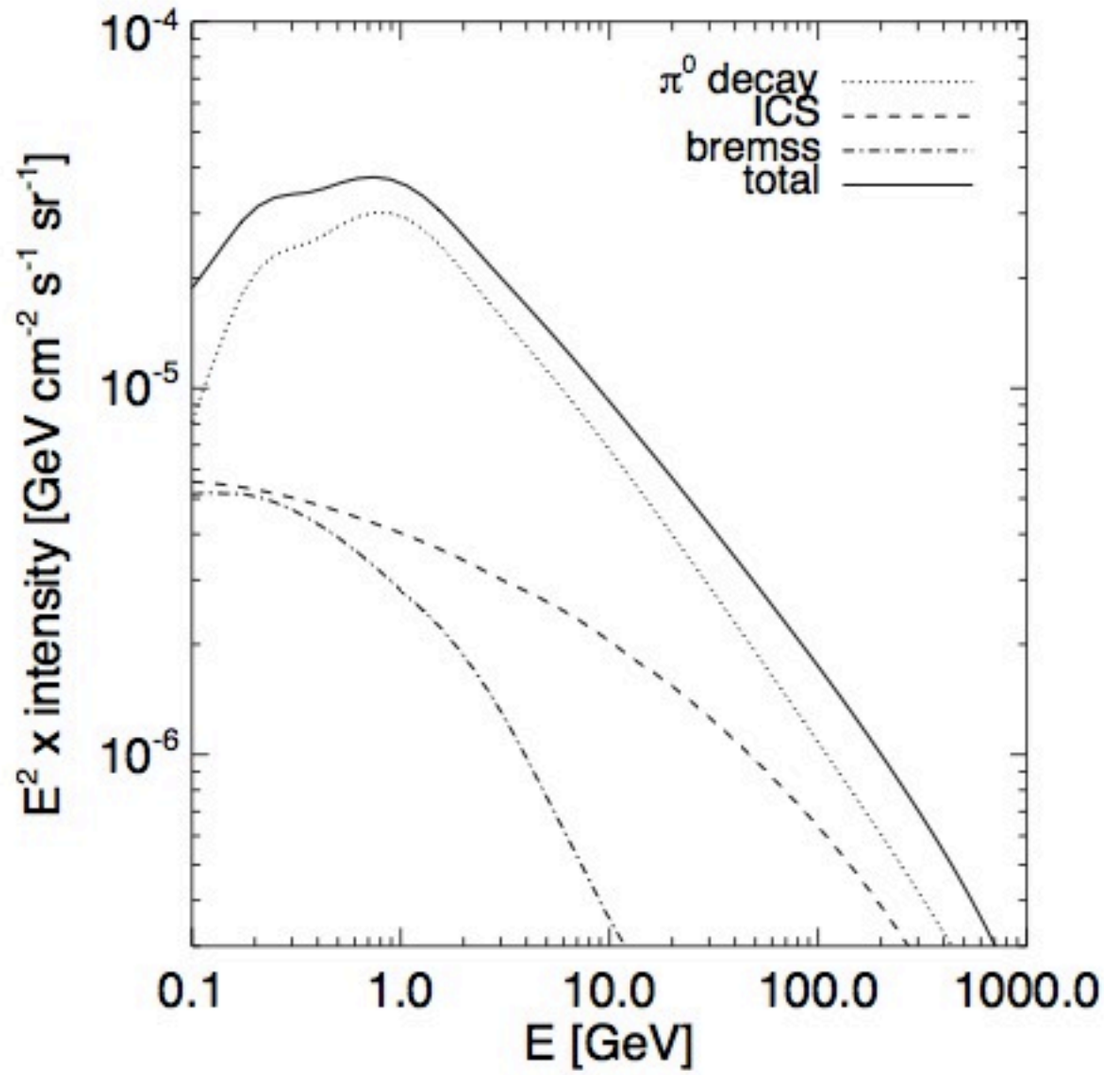
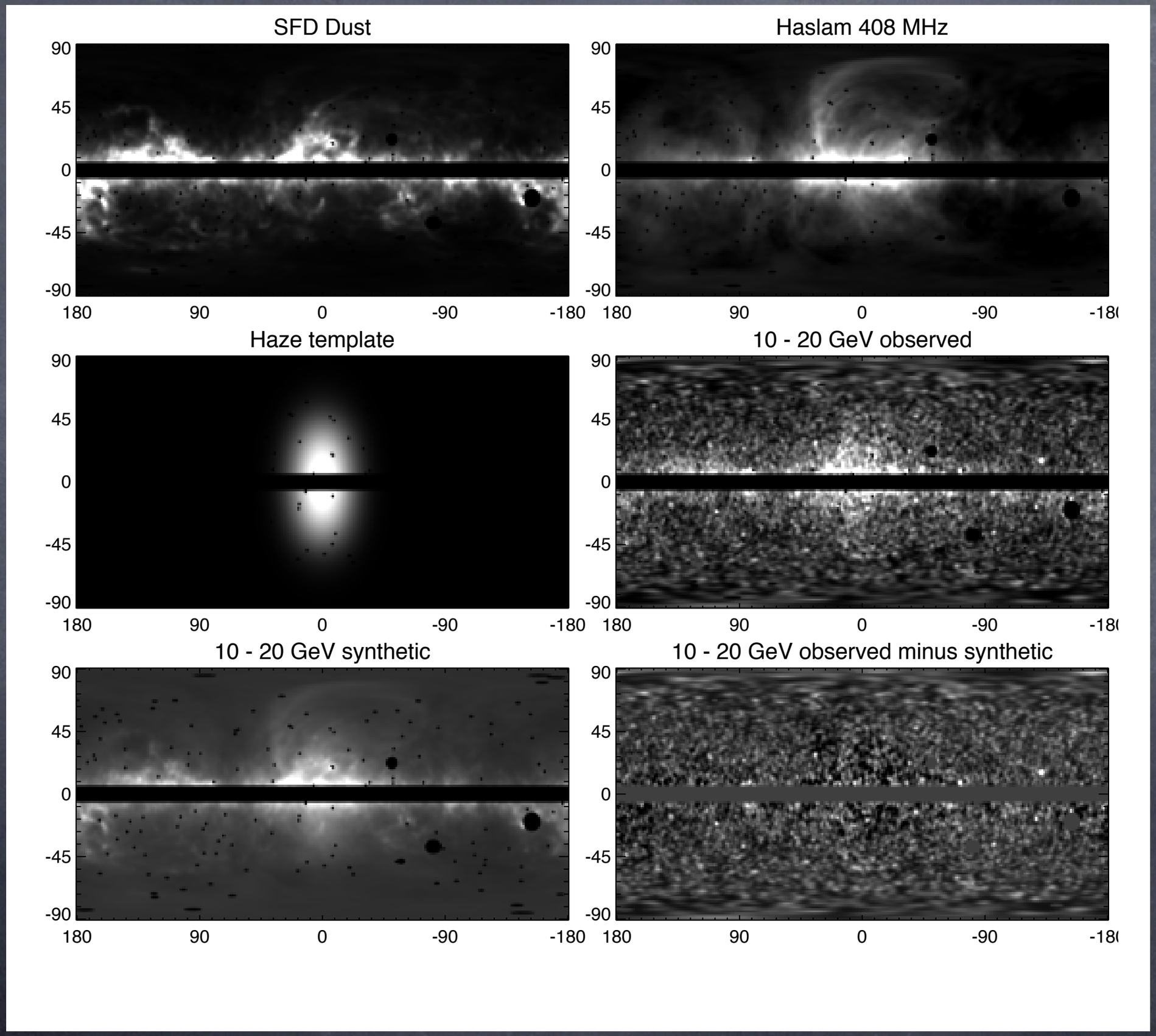
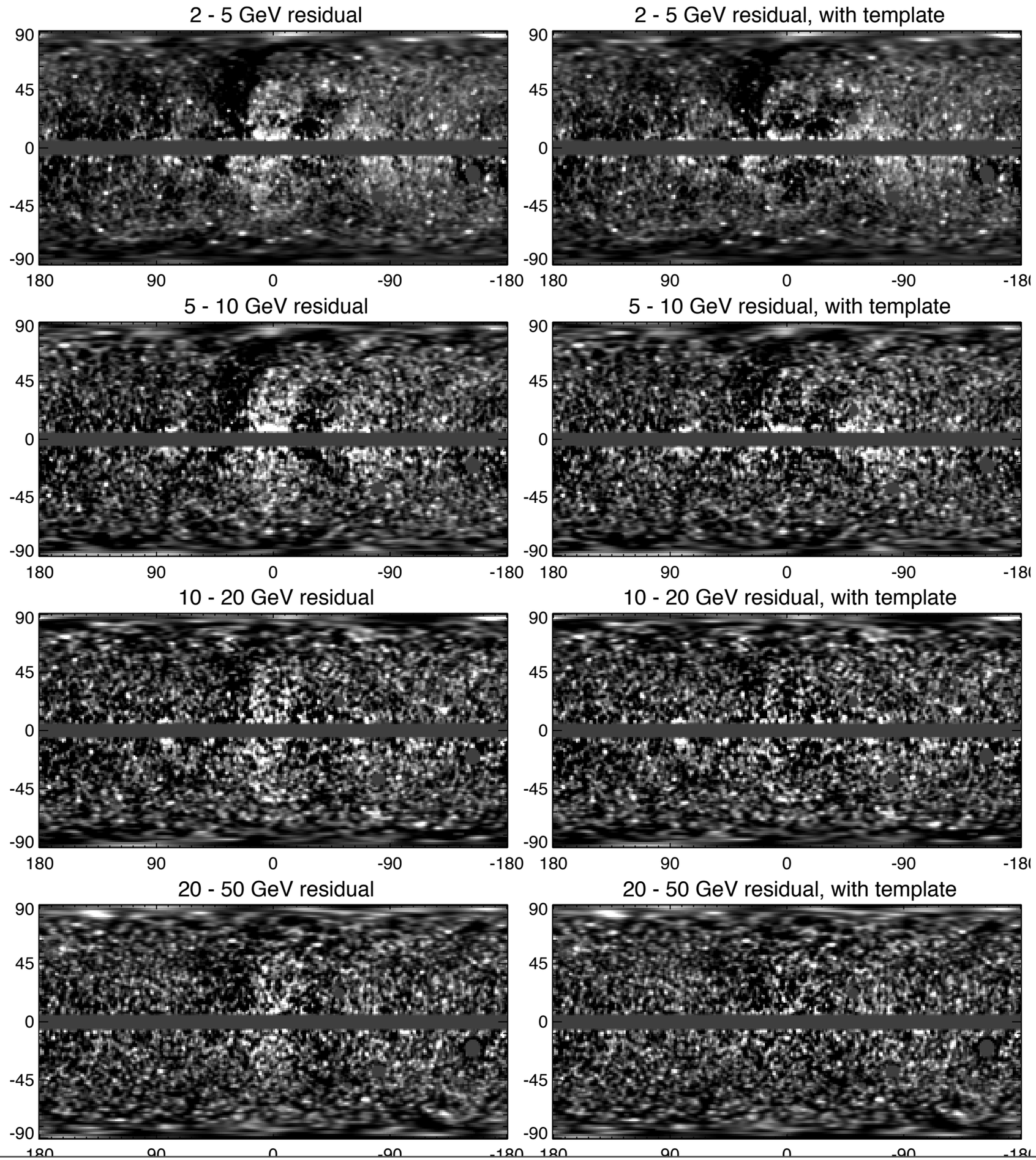


FIG. 2.— GALPROP model illustrating the three primary gamma-ray emission mechanisms (see §3) and their relative amplitudes in the Galactic plane ($|\ell| \leq 30$, $|b| \leq 5$).

Fermi ICS


SFD Dust
Haslam 408 MHz
Haze template
10 - 20 GeV observed
10 - 20 GeV synthetic
10 - 20 GeV observed minus synthetic
90
45
0
-45
-90
180
90
0
-90
-180


2 - 5 GeV residual
2 - 5 GeV residual, with template
5 - 10 GeV residual
5 - 10 GeV residual, with template
10 - 20 GeV residual
10 - 20 GeV residual, with template
20 - 50 GeV residual
20 - 50 GeV residual, with template
90
45
0
-45
-90
180
90
0
-90
-180

Hints of high energy e^+e^-

- PAMELA tells us that there is a primary source of 10-100 GeV positrons within 1kpc
- Fermi indicates an excess of e^+e^- up to ~ 1 TeV (ATIC as well)
- The WMAP Haze suggests us that there is a new population of 10-100 GeV positrons in the galactic center (5°-15°)
- Fermi gamma rays seem also to indicate high energy electron production in galactic center
- NB: Hard analyses!

WIMP annihilations? Not so fast!

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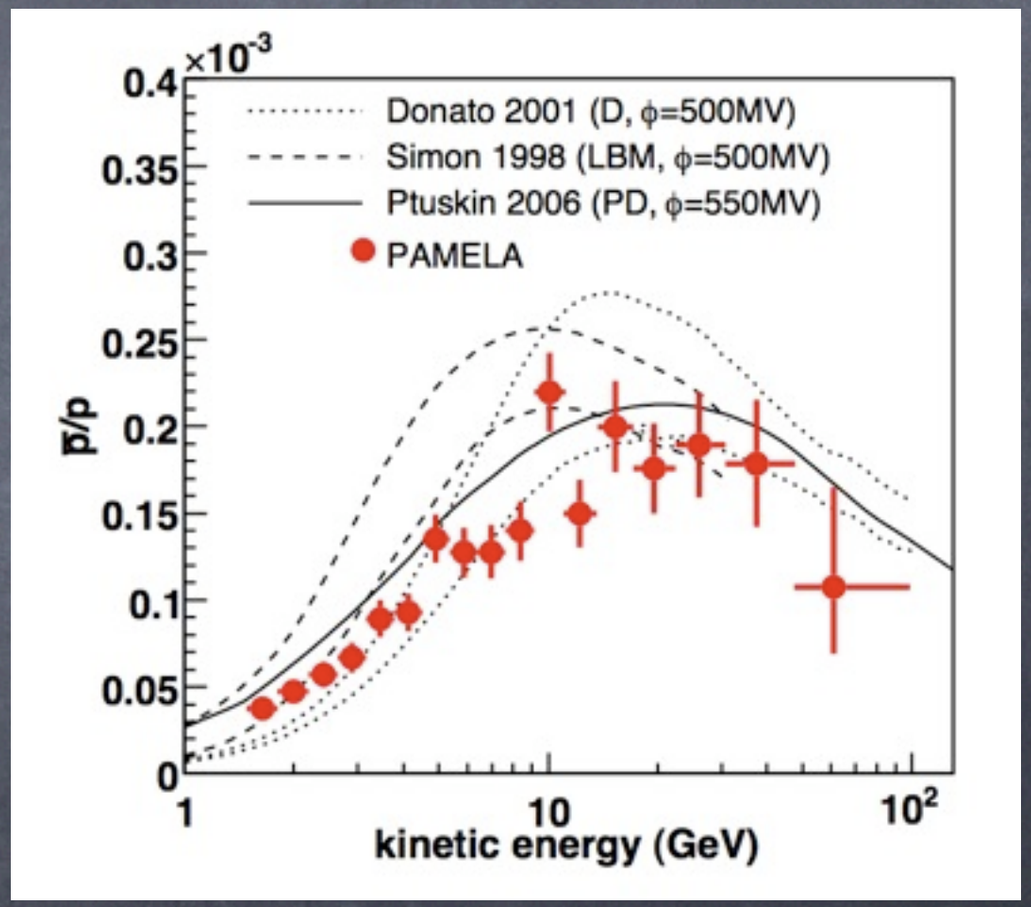

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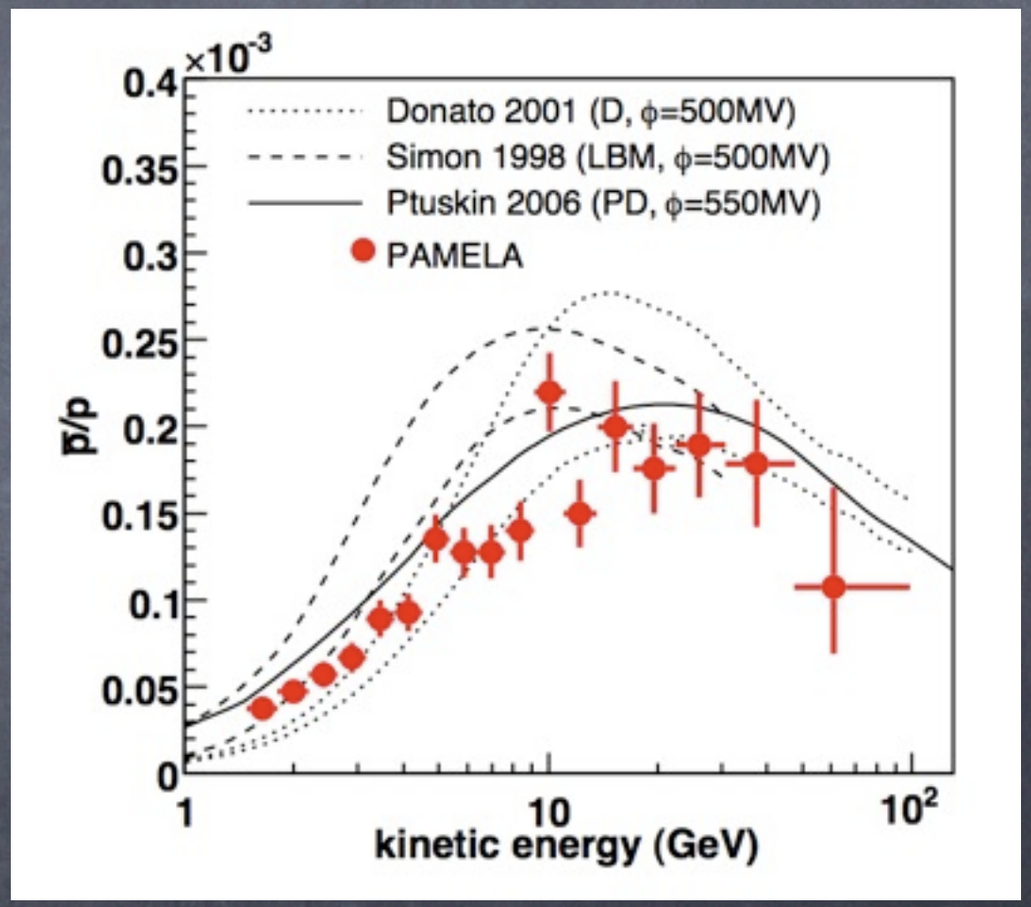

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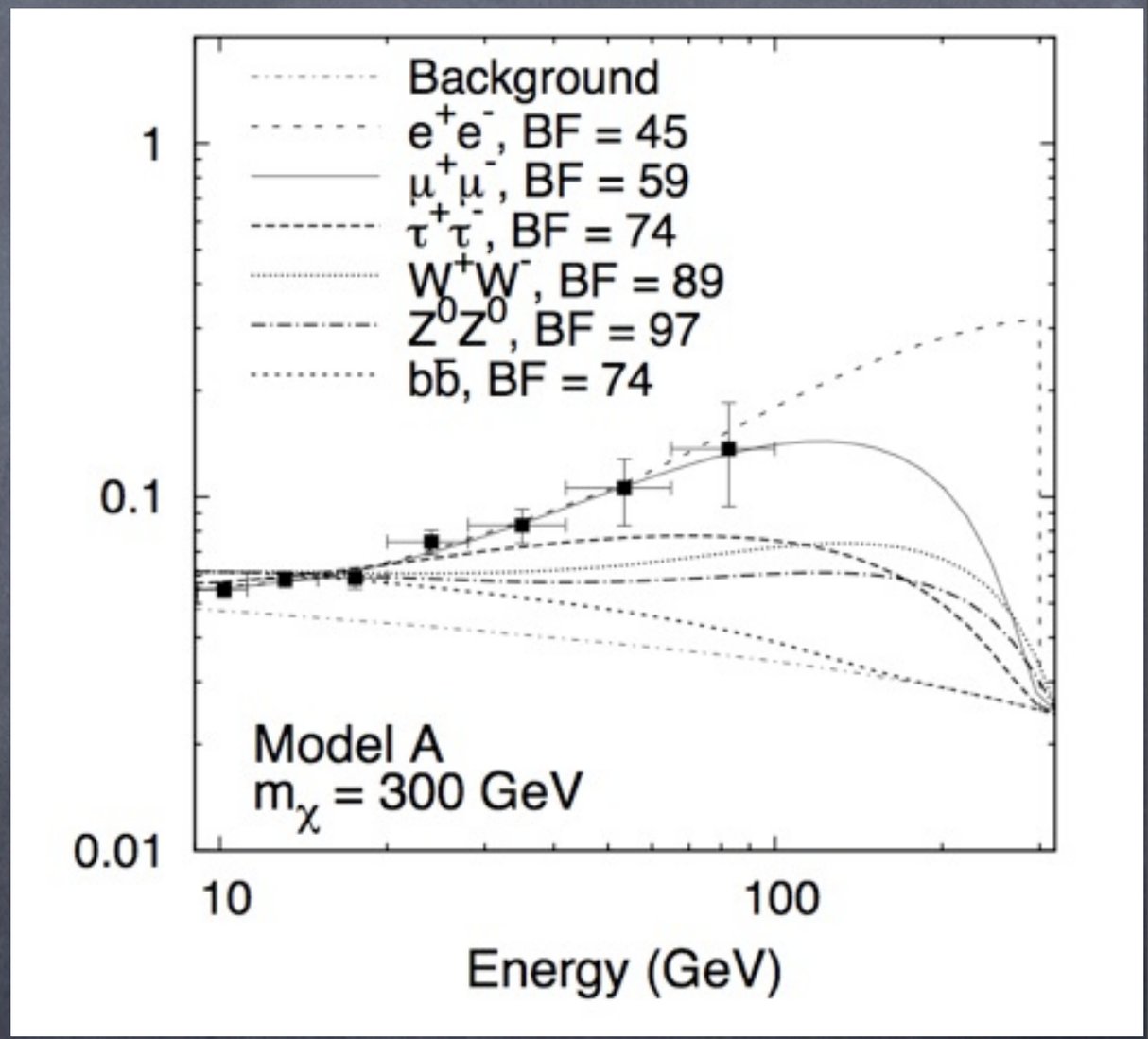

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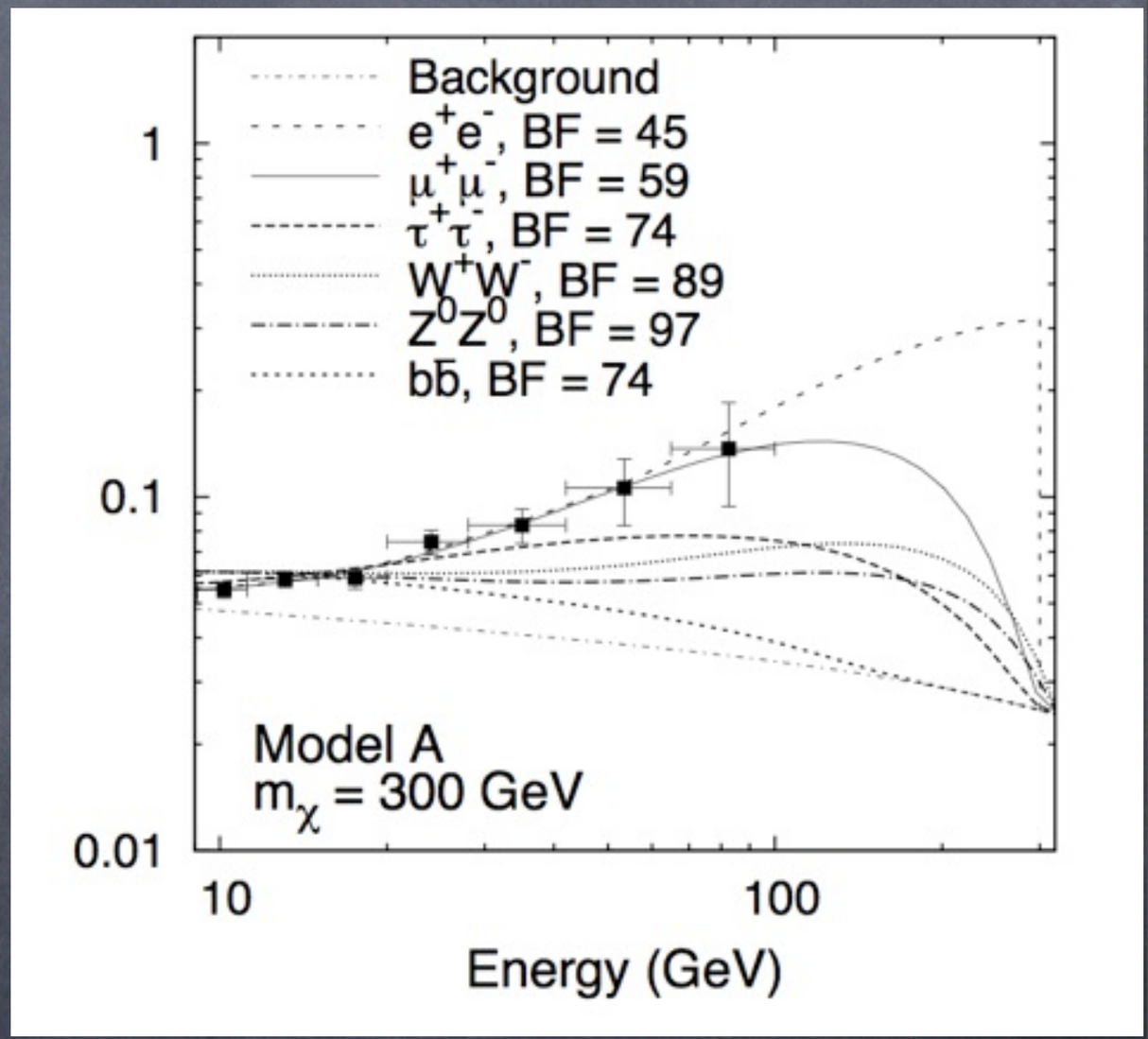
- The cross sections needed are 10-1000x the thermal



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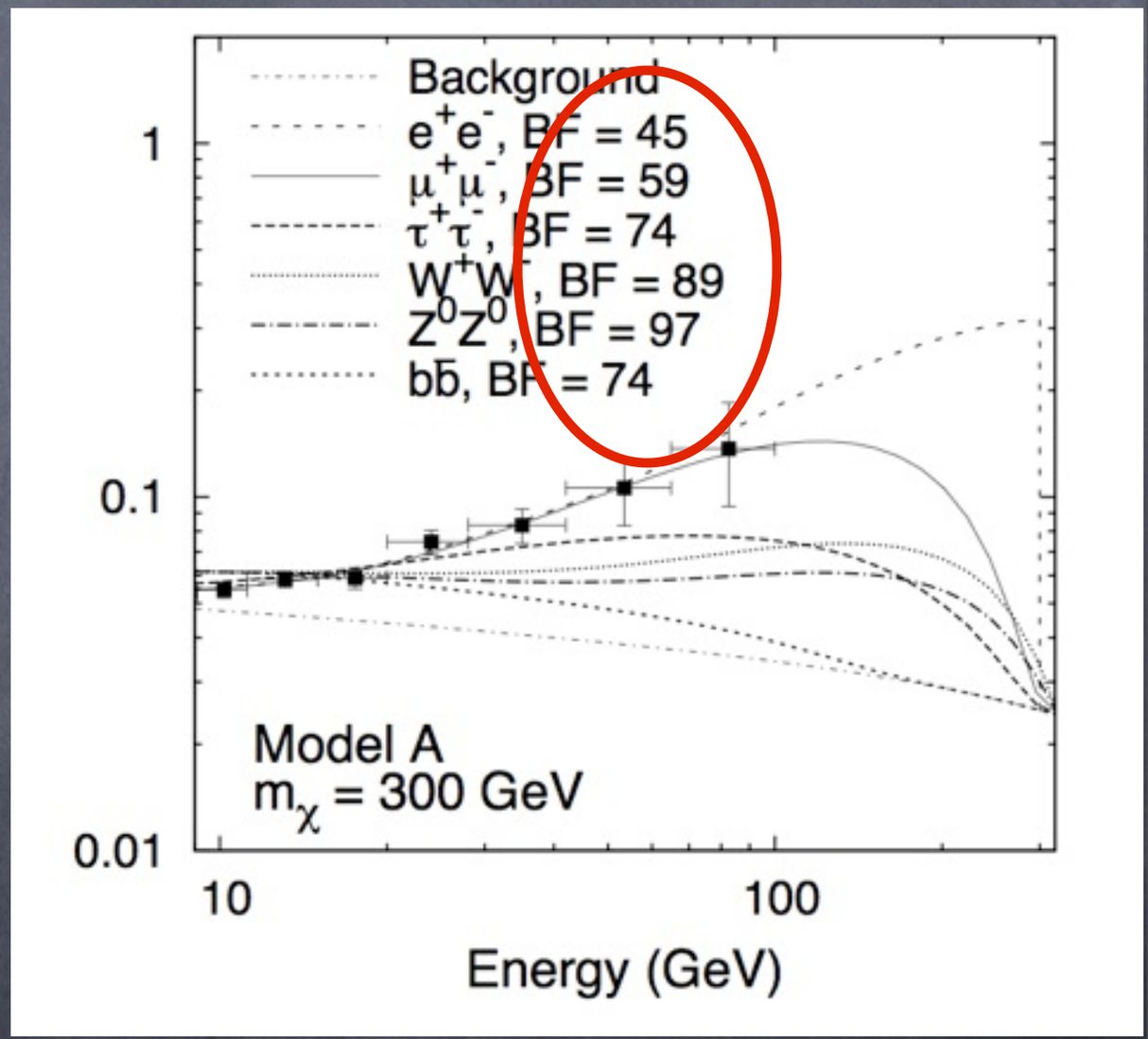

The three ingredients to explain PAMELA/Fermi

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- Hard lepton spectrum

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- **Wide** range of models all share similar structure (Pospelov and Ritz, '08; Fox and Poppitz '08; Nomura and Thaler '08; Nelson and Spitzer '08; Katz and Sundrum '08...)

New forces = new annihilation modes

Finkbeiner, NW PRD '07; Pospelov, Ritz, Voloshin PLB '08

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

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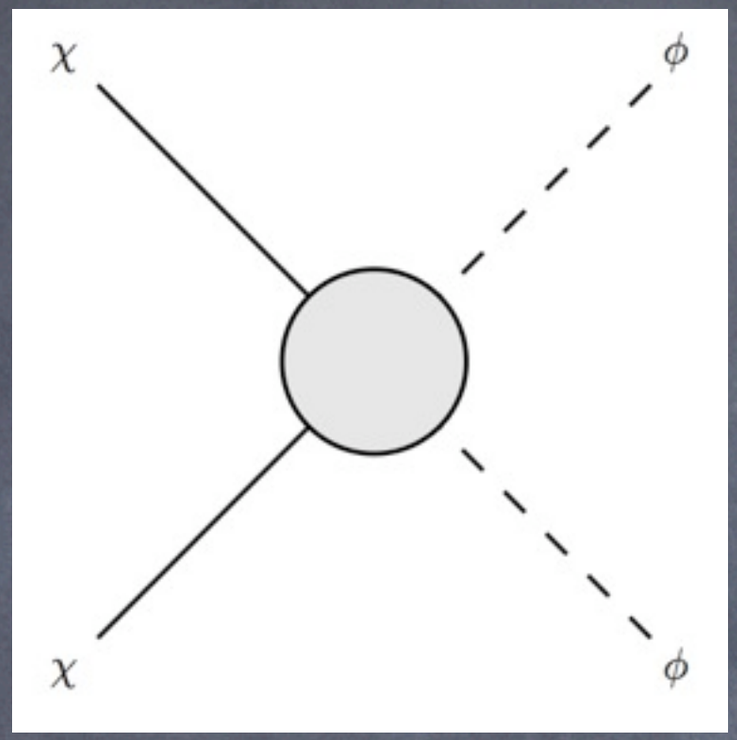

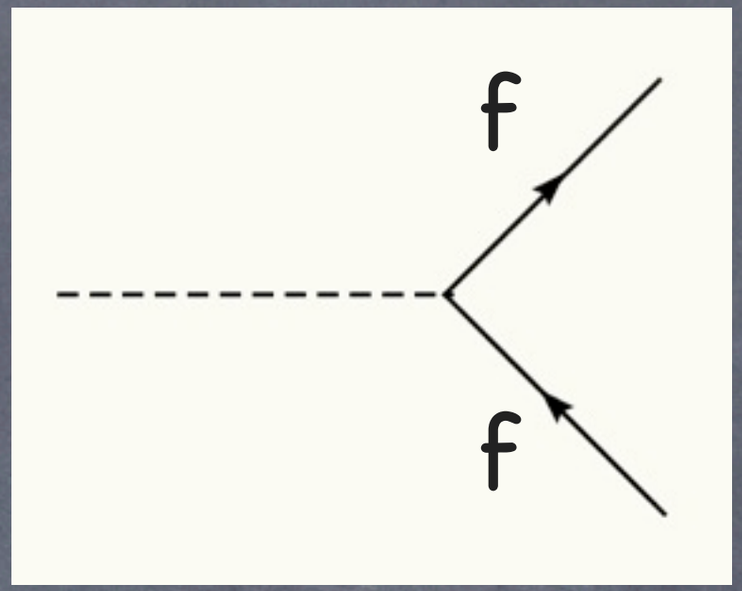

Arkani-Hamed, Finkbeiner, Slatyer, NW, '08

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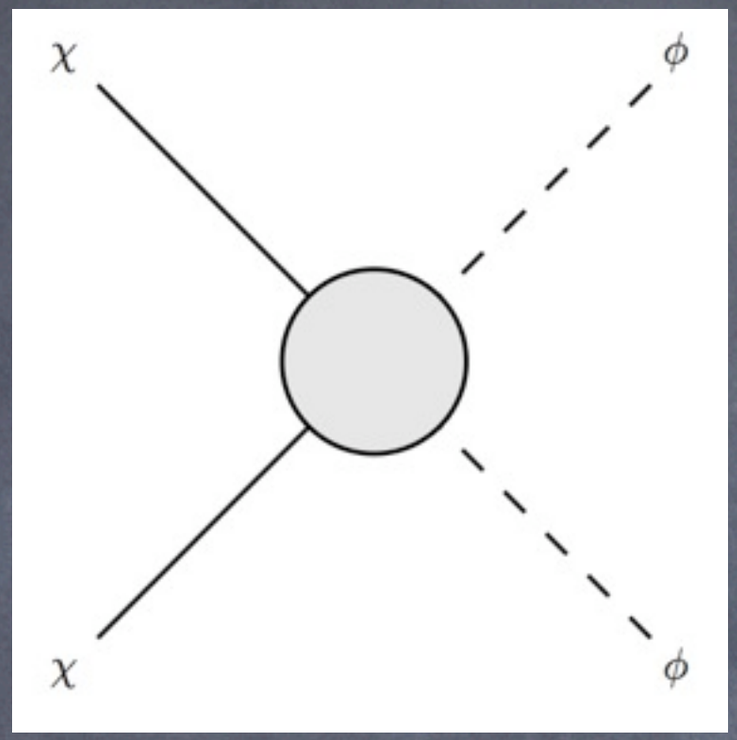

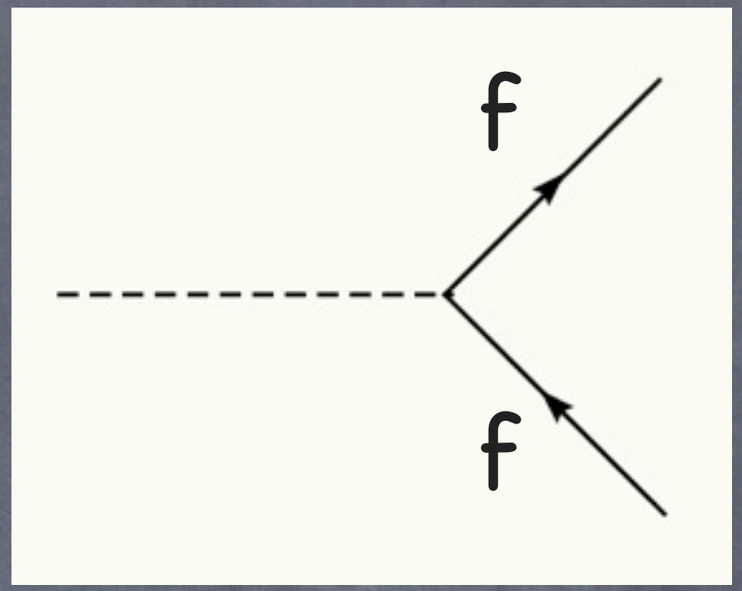

- "WIMP Miracle" works as before (sigma ~ $1/M^2$)
- No antiprotons comes from kinematics
- Hard positrons come from highly boosted ϕ's/A's

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

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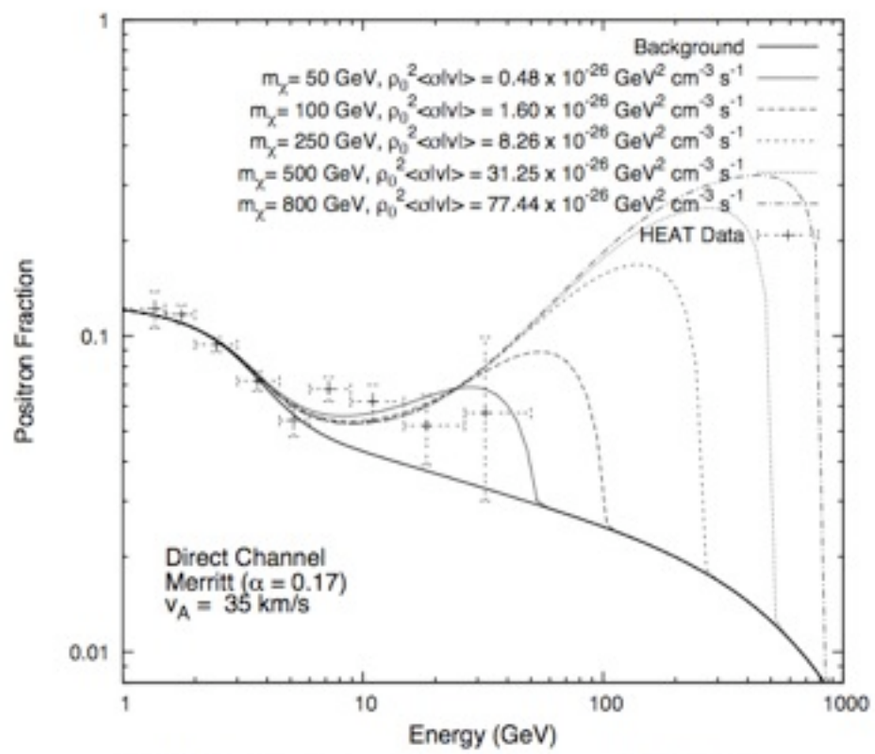

(c)Direct decay channel, $v_A = 35$ km/s

Cholis, Goodenough, NW, arxiv:0802.2922

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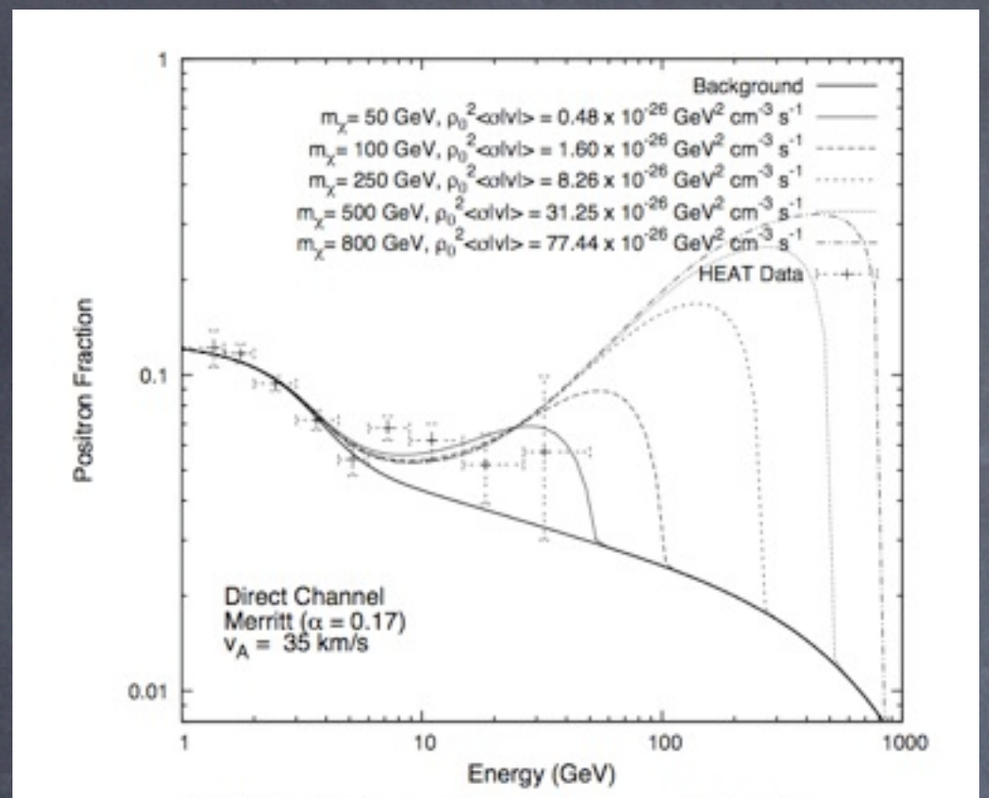

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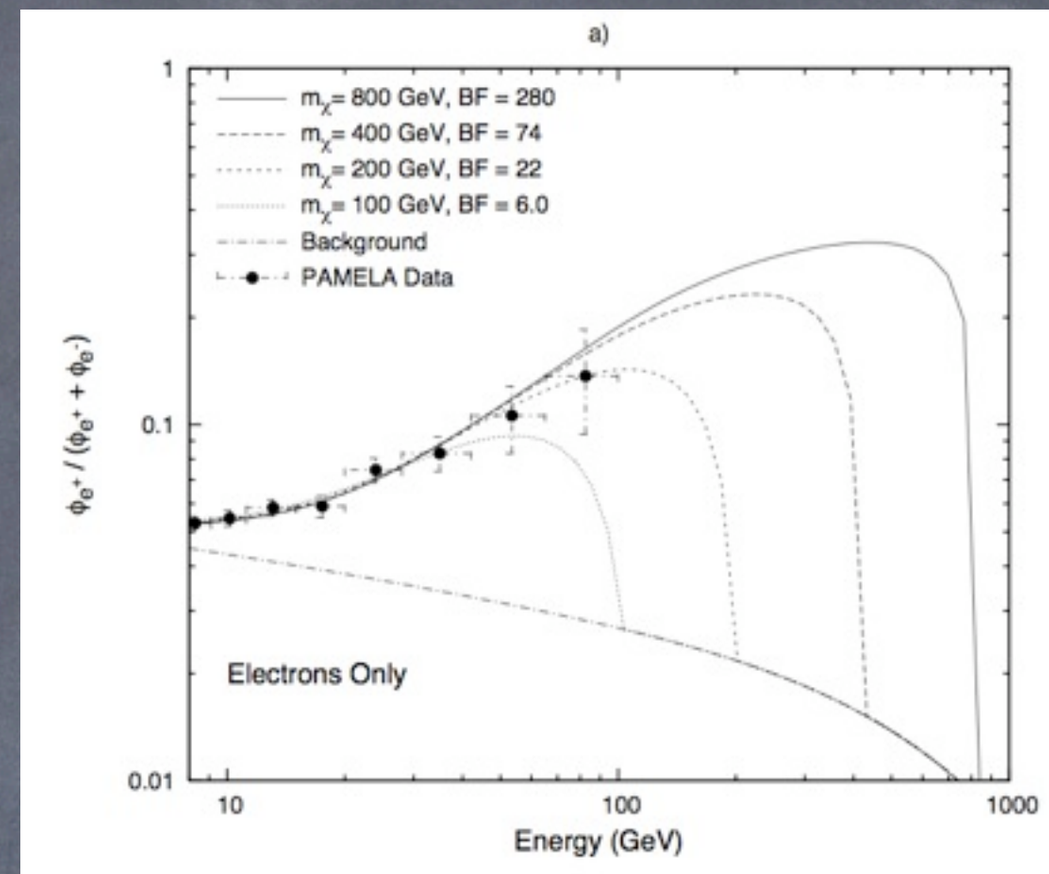

Cholis, et al, arxiv:0810.5344

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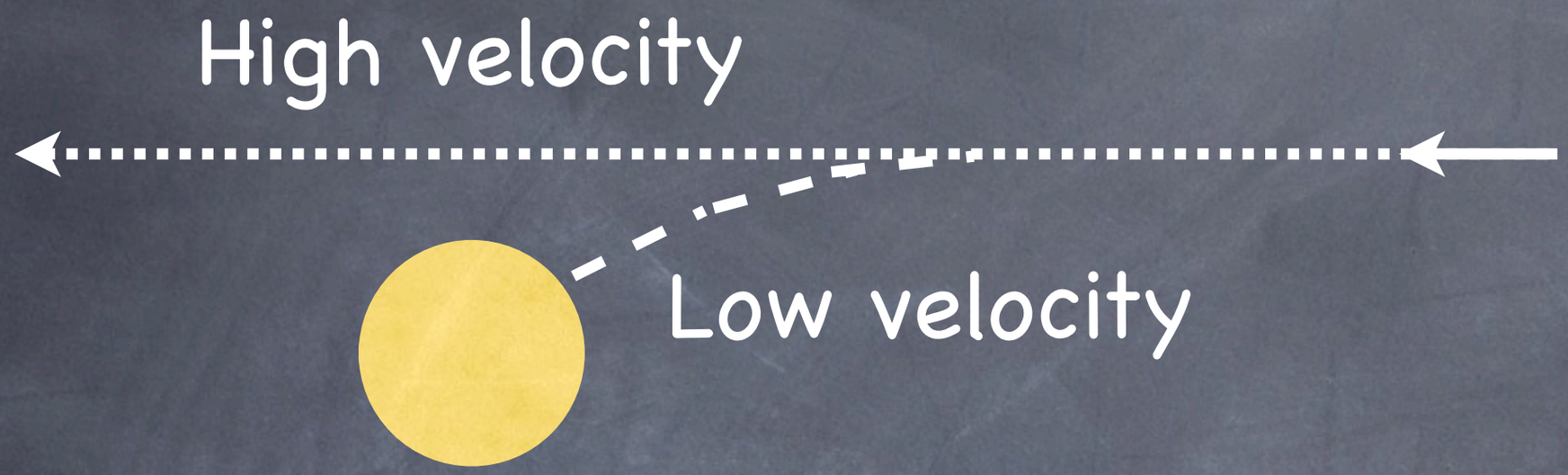
Sommerfeld Enhancement

High velocity

Hisano, Nojiri, Matsumoto '04; Cirelli & Strumia '07; Arkani-Hamed, Finkbeiner, Slatyer, NW, '08

Sommerfeld Enhancement



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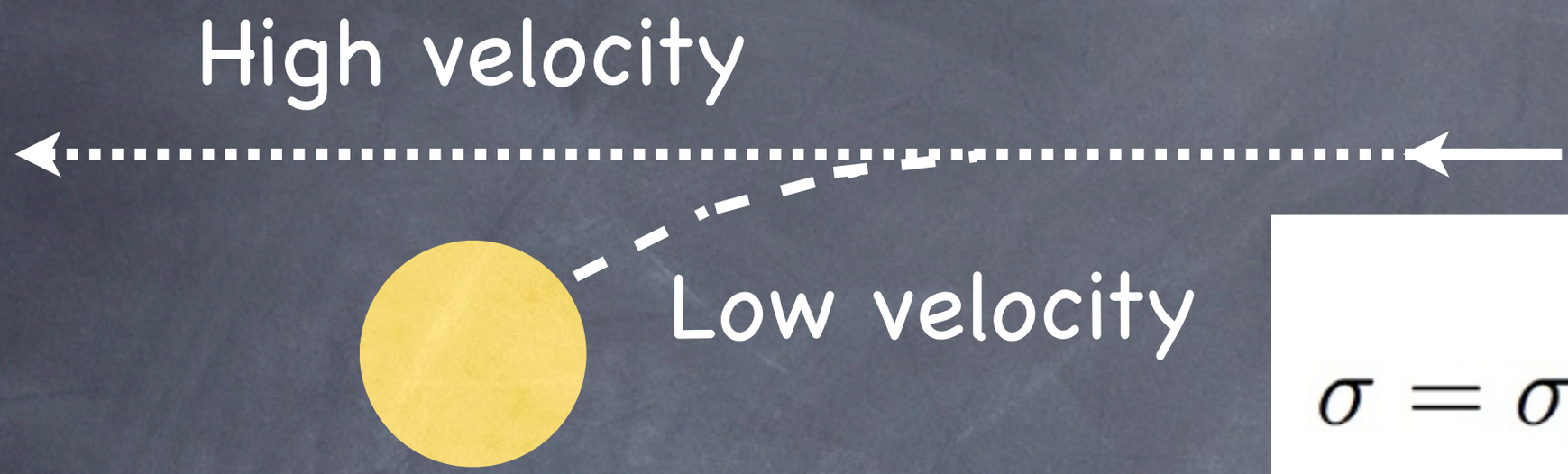

$$\sigma = \sigma_0 \left(1 + \frac{v_{esc}^2}{v^2} \right)$$

Hisano, Nojiri, Matsumoto '04; Cirelli & Strumia '07; Arkani-Hamed, Finkbeiner, Slatyer, NW, '08

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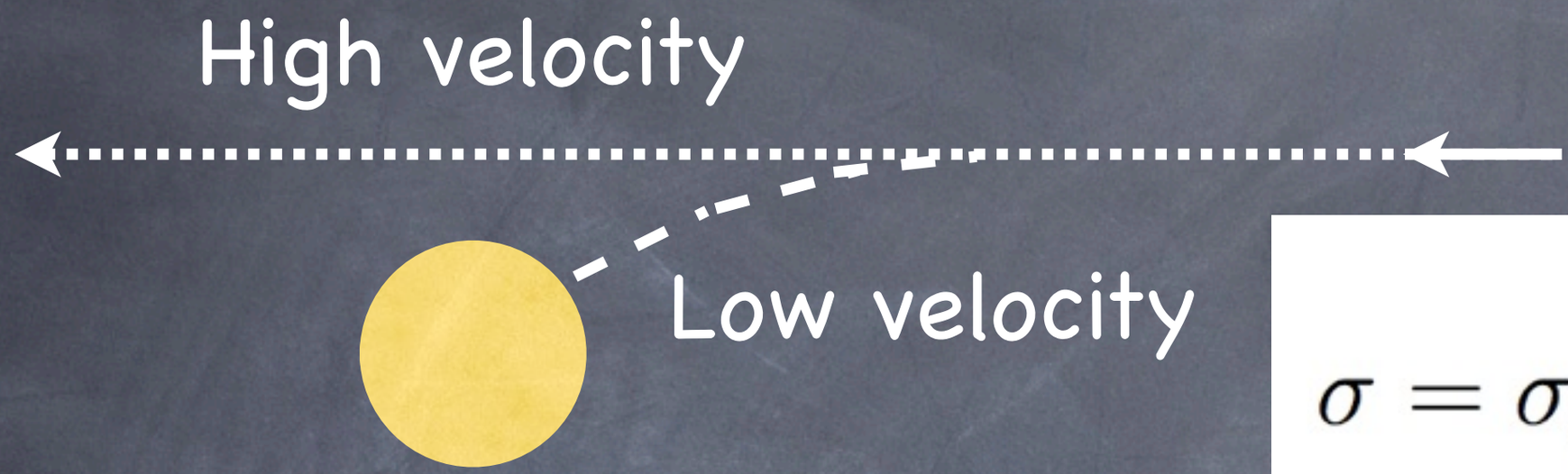

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If particles interact via a "long range" force, cross sections can be much larger than the perturbative cross section

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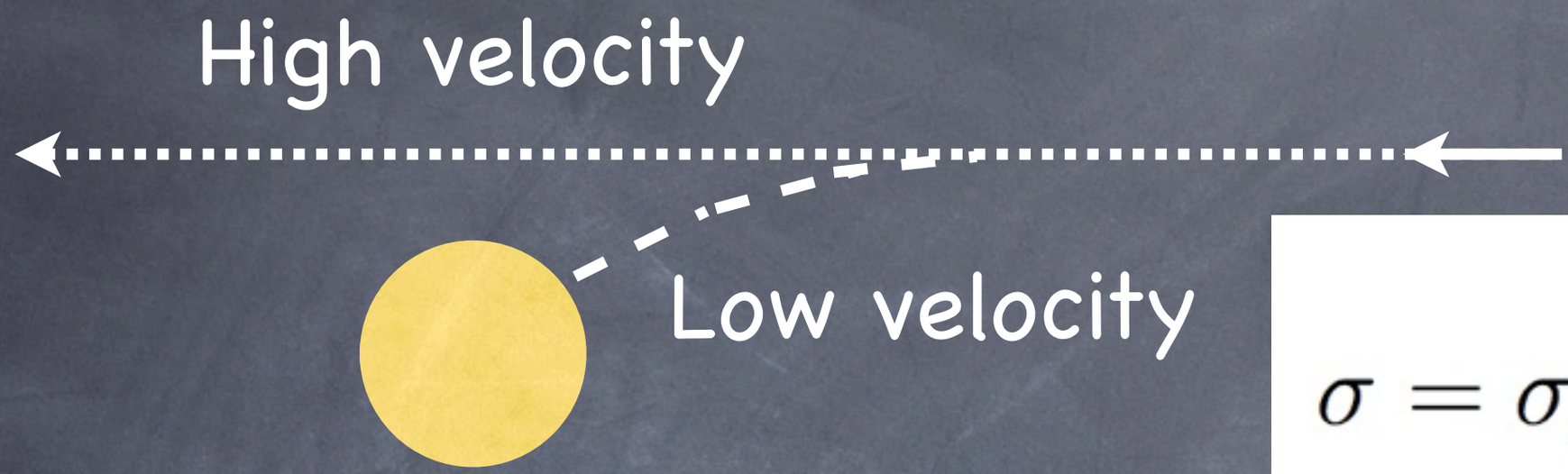

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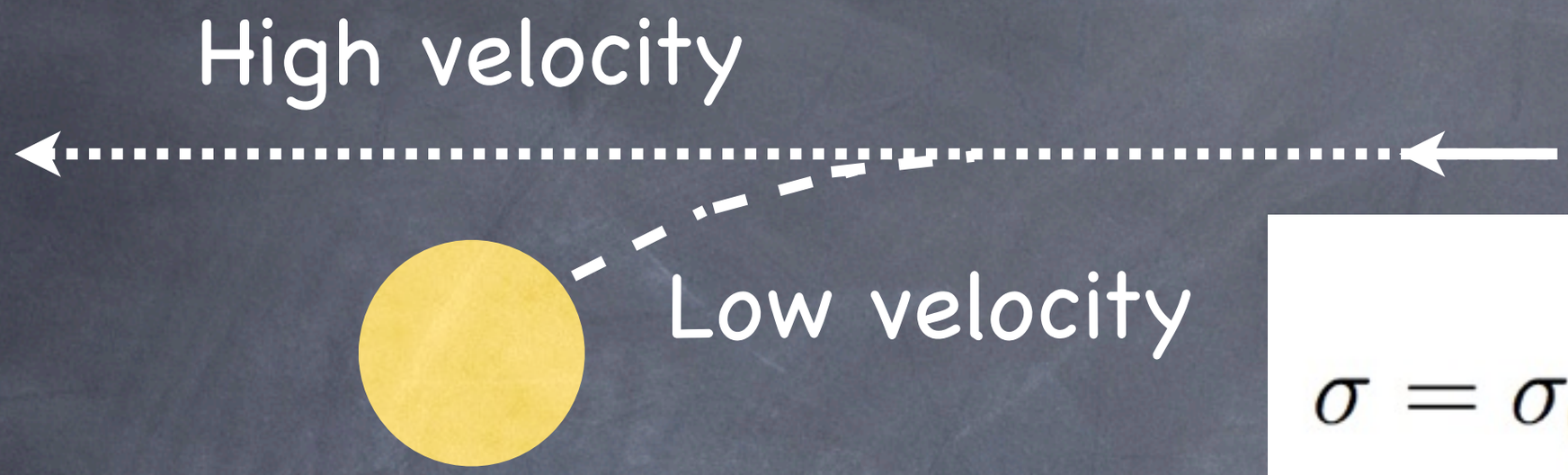
If particles interact via a "long range" force, cross sections can be much larger than the perturbative cross section

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

Hisano, Nojiri, Matsumoto '04; Cirelli & Strumia '07; Arkani-Hamed, Finkbeiner, Slatyer, NW, '08

Sommerfeld Enhancement



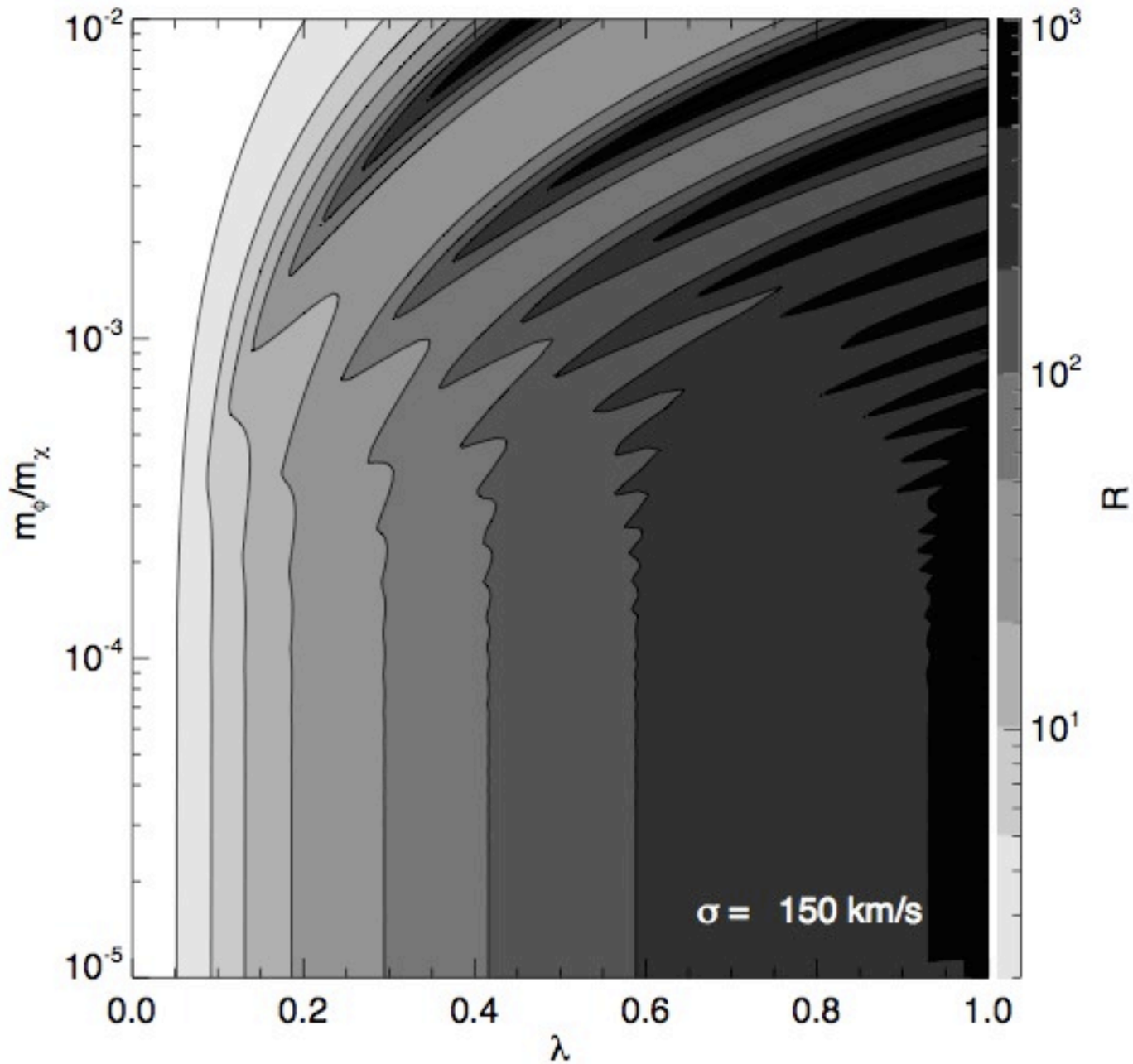
$$\sigma = \sigma_0 \left(1 + \frac{v_{esc}^2}{v^2}\right)$$

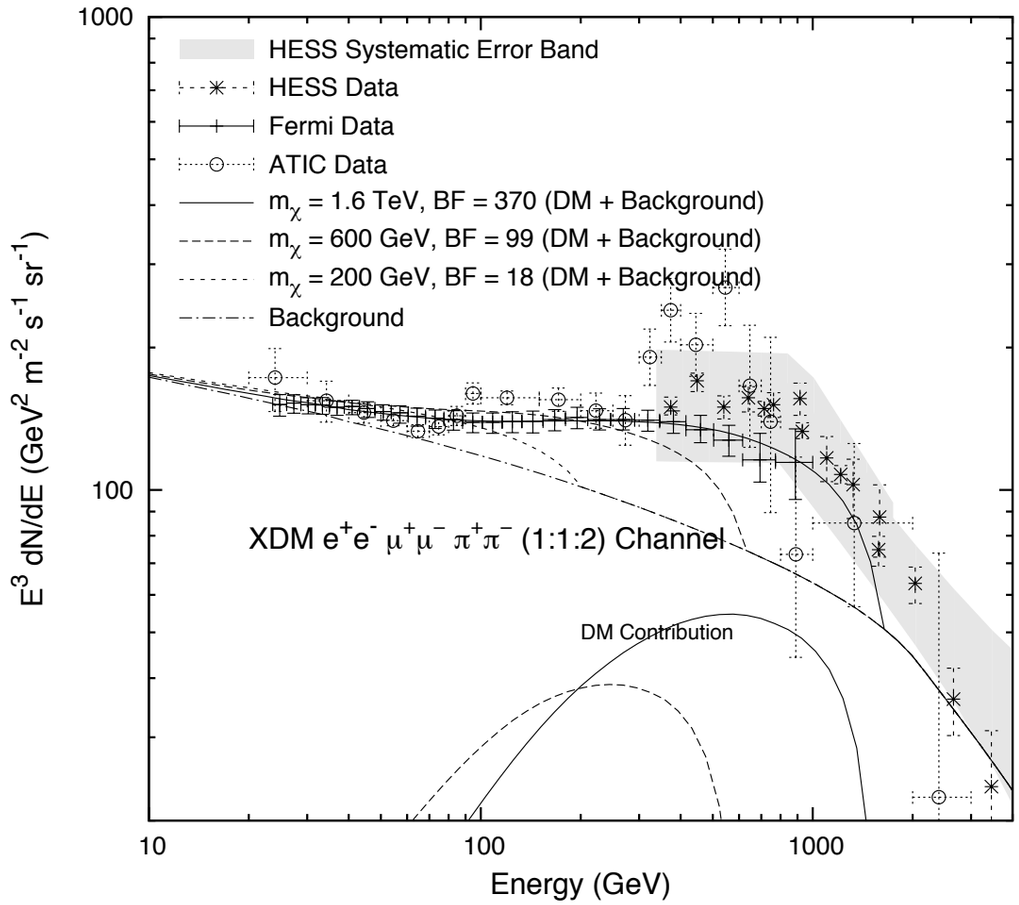
If particles interact via a "long range" force, cross sections can be much larger than the perturbative cross section

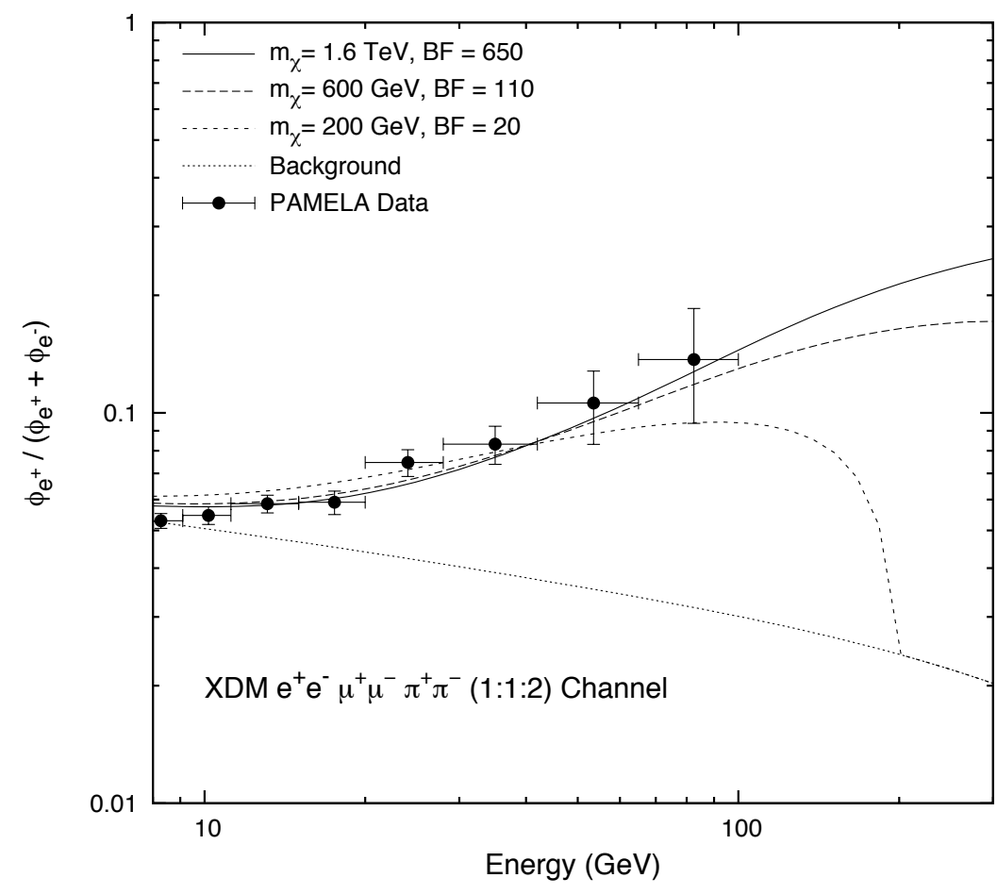
If these signals arise from thermal dark matter, dark matter must have a long range force

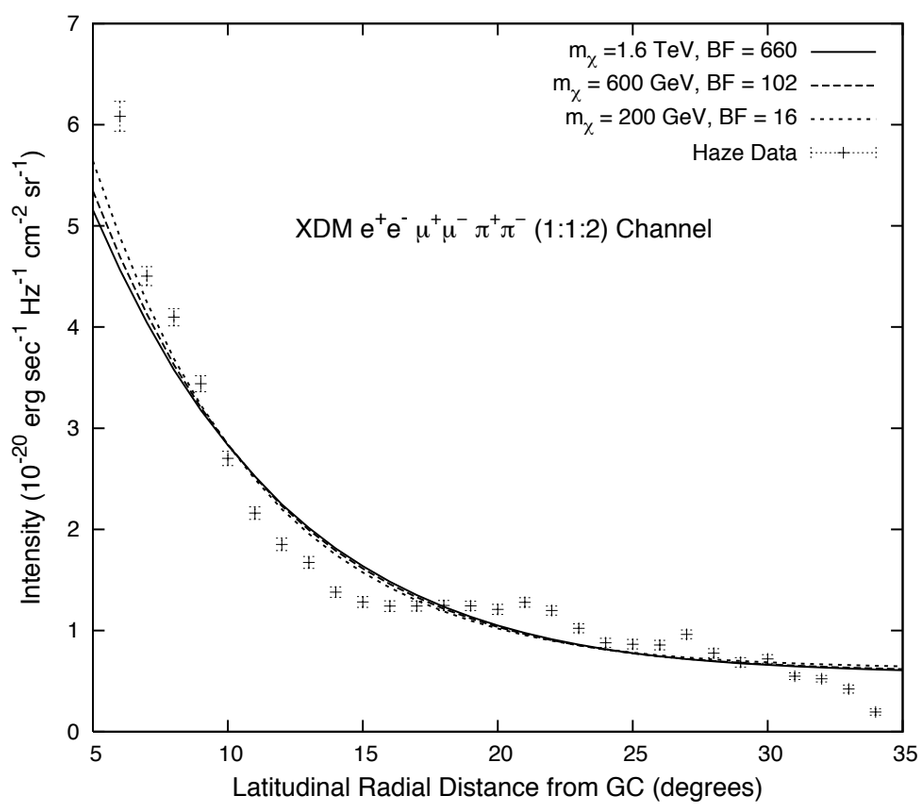
$$m_\phi^{-1} \gtrsim (\alpha M_{DM})^{-1} \text{ (fm)}$$

Hisano, Nojiri, Matsumoto '04; Cirelli & Strumia '07; Arkani-Hamed, Finkbeiner, Slatyer, NW, '08


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
10^3
10^2
10^1
R
σ = 150 km/s

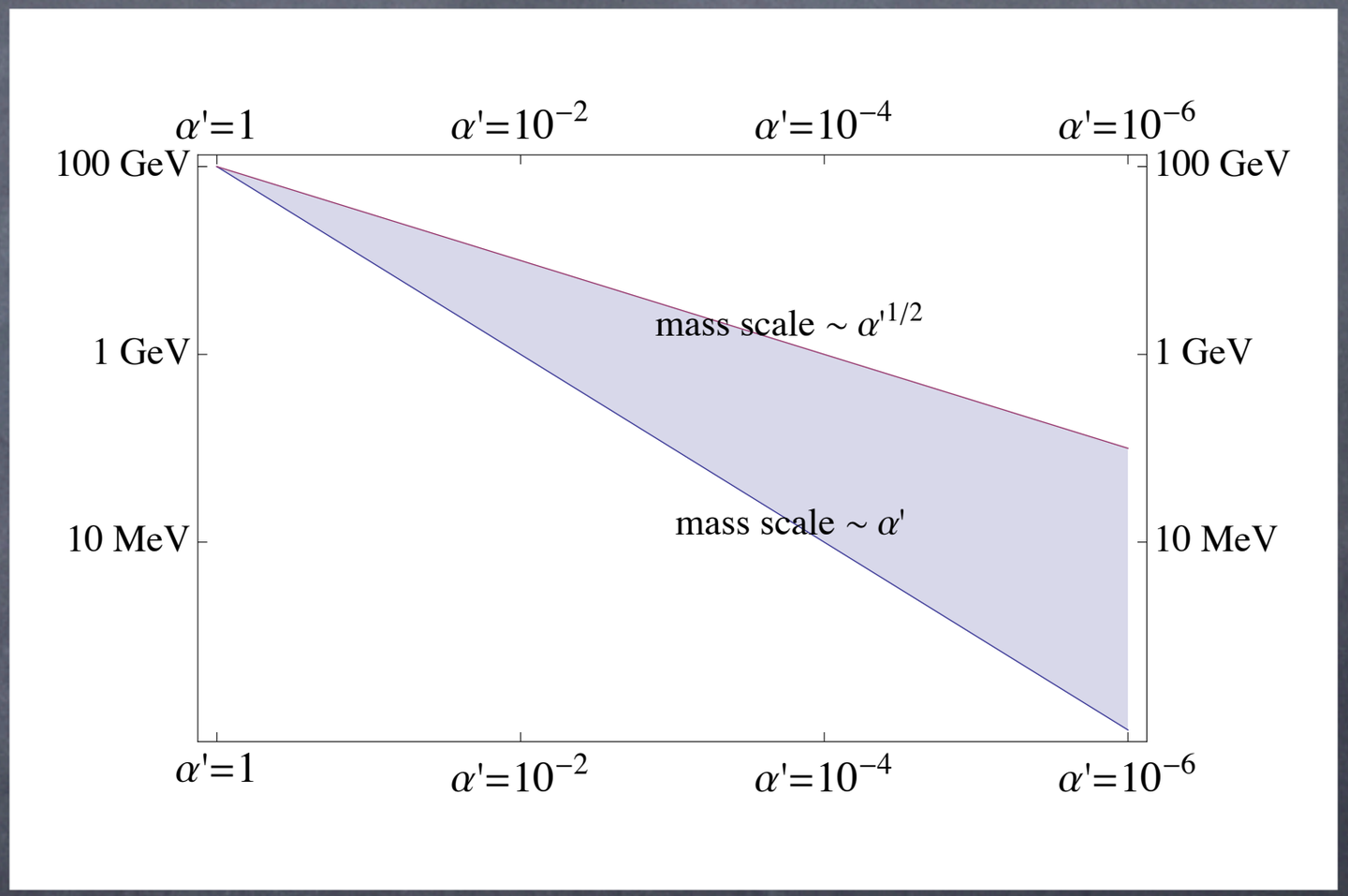

HESS Systematic Error Band
HESS Data
Fermi Data
ATIC Data
m_χ = 1.6 TeV, BF = 370 (DM + Background)
m_χ = 600 GeV, BF = 99 (DM + Background)
m_χ = 200 GeV, BF = 18 (DM + Background)
Background
XDM e^+e^- $\mu^+\mu^-$ $\pi^+\pi^-$ (1:1:2) Channel
DM Contribution
E^3 dN/dE (GeV^2 m^{-2} s^{-1} sr^{-1})
Energy (GeV)


m_χ= 1.6 TeV, BF = 650
m_χ= 600 GeV, BF = 110
m_χ= 200 GeV, BF = 20
Background
PAMELA Data
XDM e^+e^- $\mu^+\mu^-$ $\pi^+\pi^-$ (1:1:2) Channel
ϕ_{e^+} / (ϕ_{e^+} + ϕ_{e^-})
Energy (GeV)


m_χ =1.6 TeV, BF = 660
m_χ = 600 GeV, BF = 102
m_χ = 200 GeV, BF = 16
Haze Data
XDM e^+e^- $\mu^+\mu^-$ $\pi^+\pi^-$ (1:1:2) Channel
Intensity (10^{-20} erg sec^{-1} Hz^{-1} cm^{-2} sr^{-1})
Latitudinal Radial Distance from GC (degrees)

How natural the GeV scale?

Interactions with standard model generate scales



Works most naturally with new physics models (SUSY, Randall-Sundrum, etc)

Searching for WIMPs

Searching for WIMPs

- How to detect a WIMP?

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- How to detect a WIMP?
- Step 1: Build big detector

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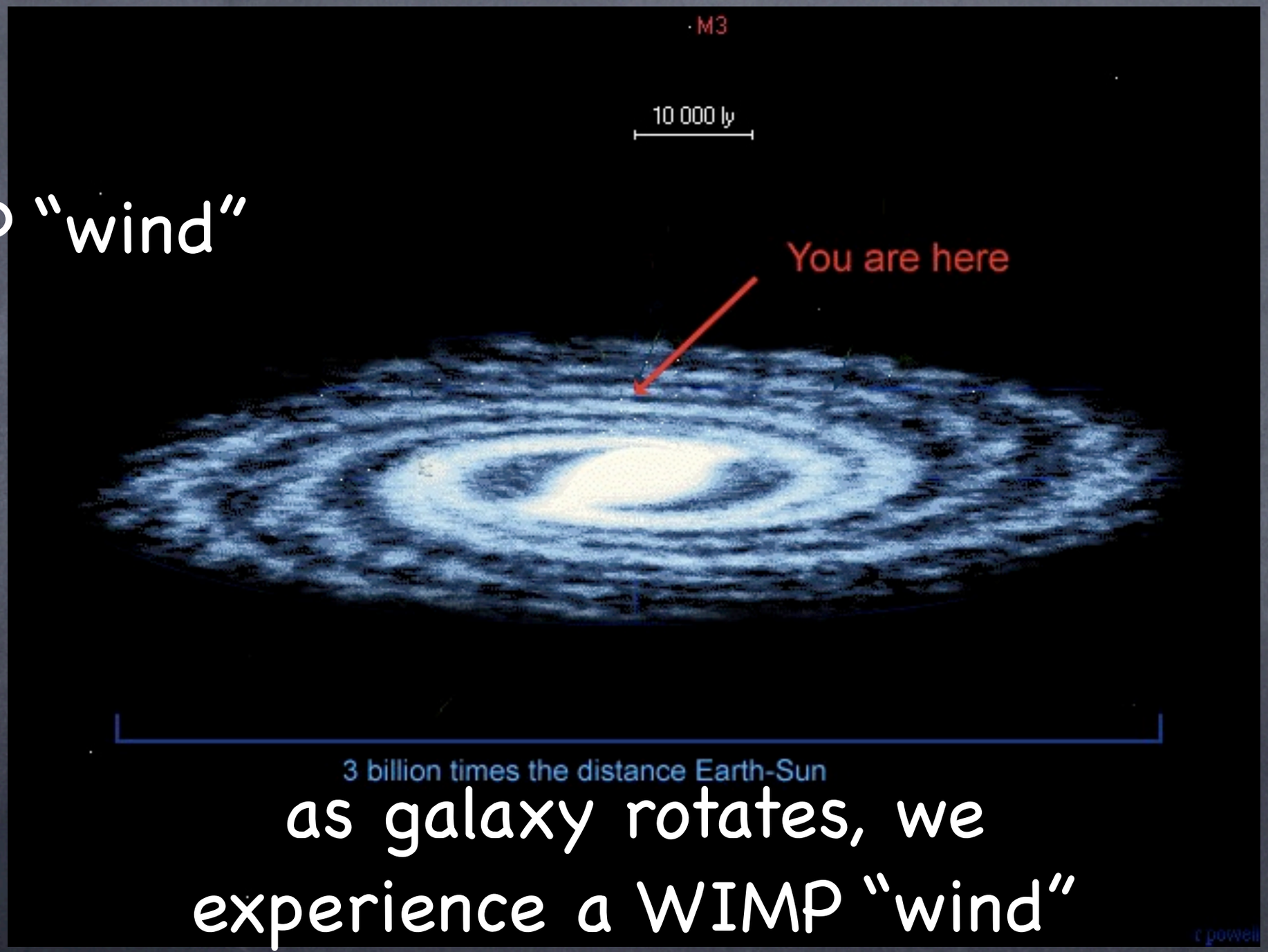
- Step II: Go deep underground to shield from cosmic rays
- Step III: Have no other background

seasonal variation

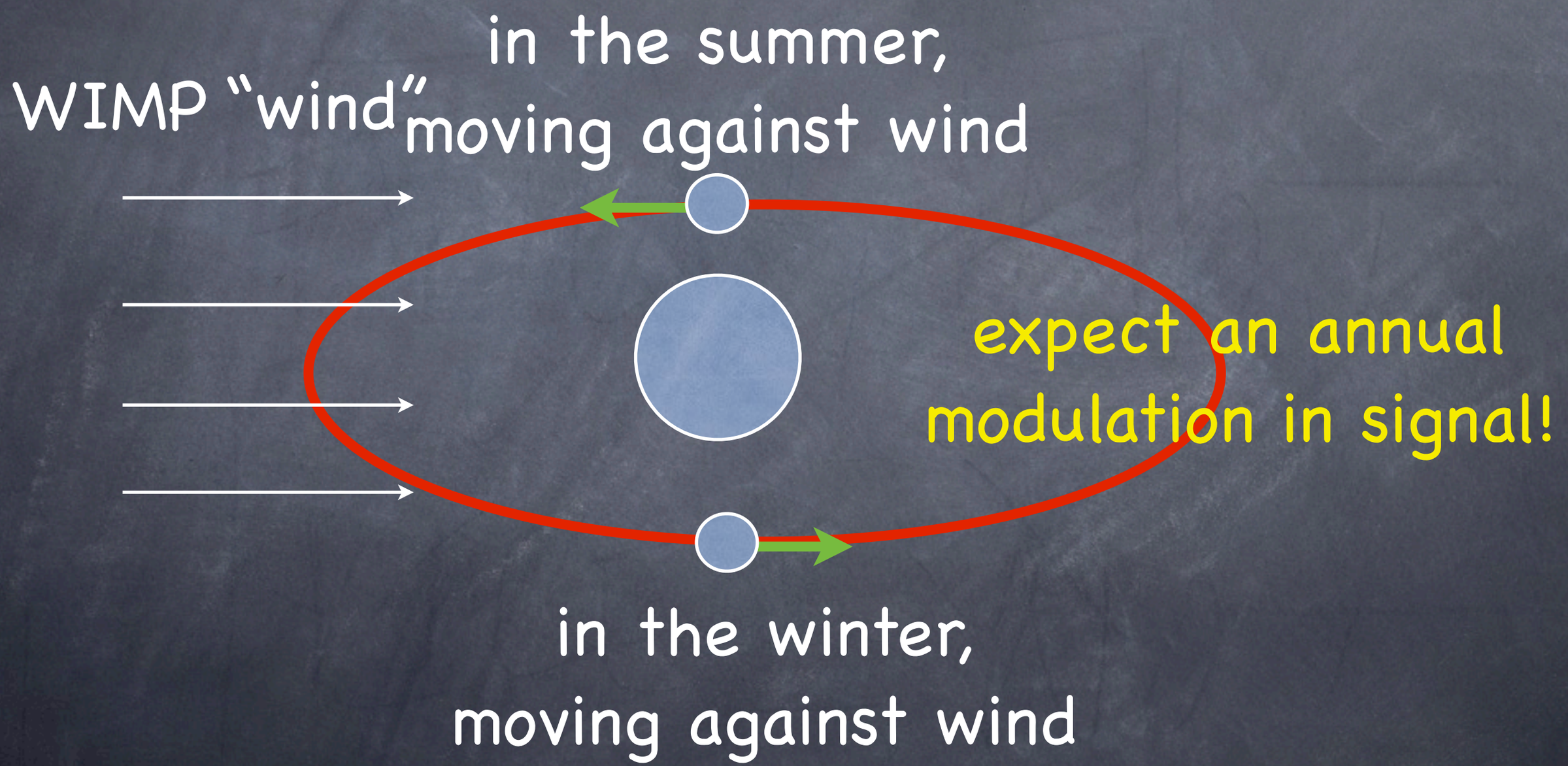
WIMP "wind"



as galaxy rotates, we experience a WIMP "wind"

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

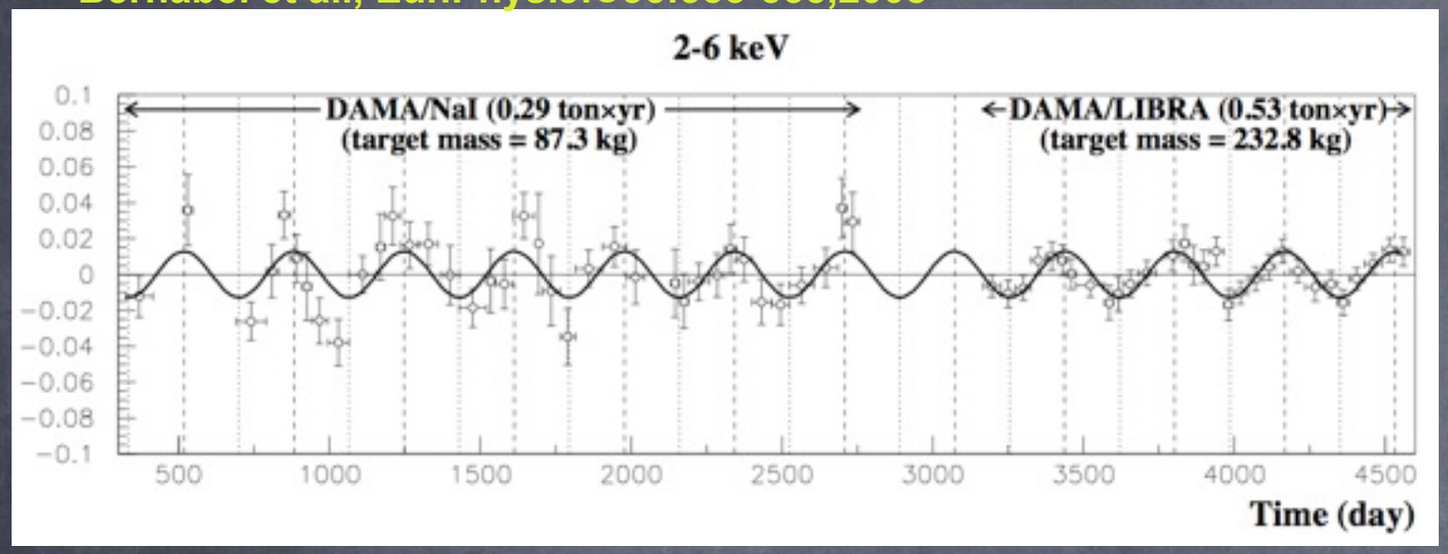
seasonal variation



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

DAMA experiment

Bernabei et al., Eur.Phys.J.C56:333-355,2008

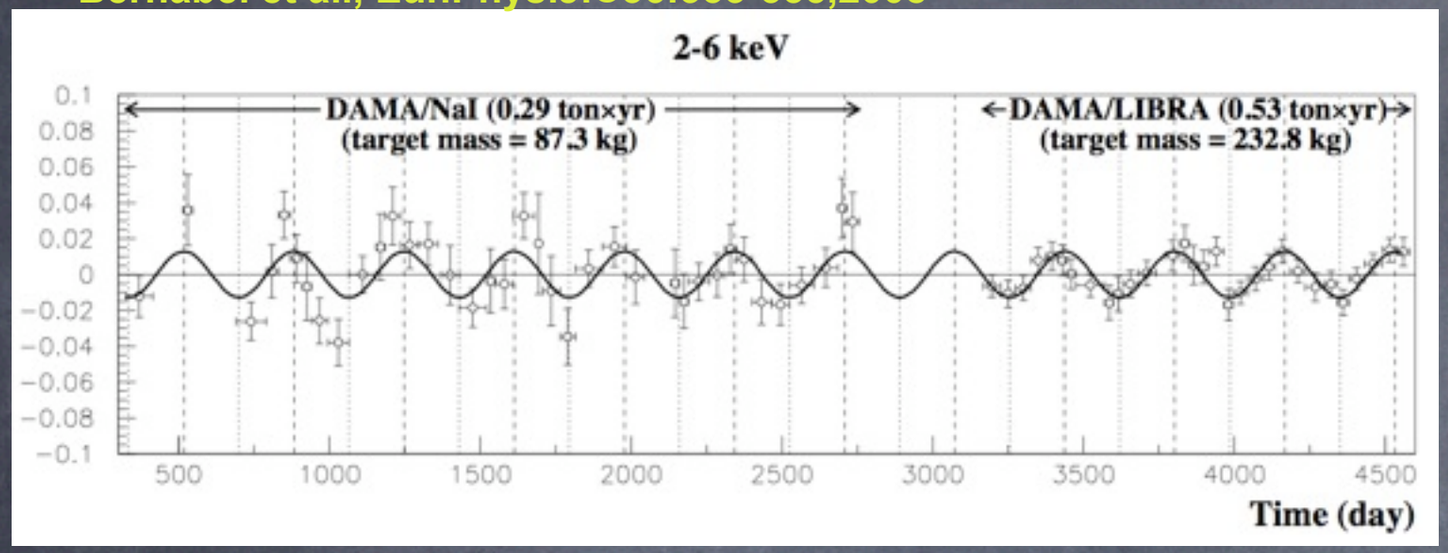


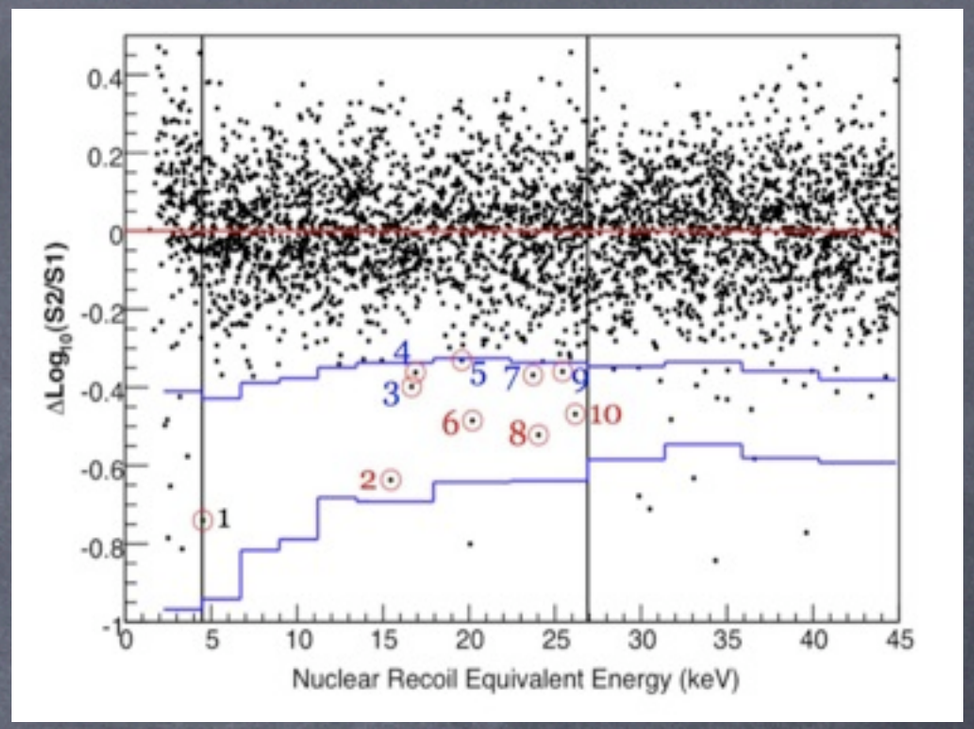
- 8.3 sigma signal for modulation
- only in "single hit" events
- proper phase

Dark matter?

DAMA experiment

Bernabei et al., Eur.Phys.J.C56:333-355,2008





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

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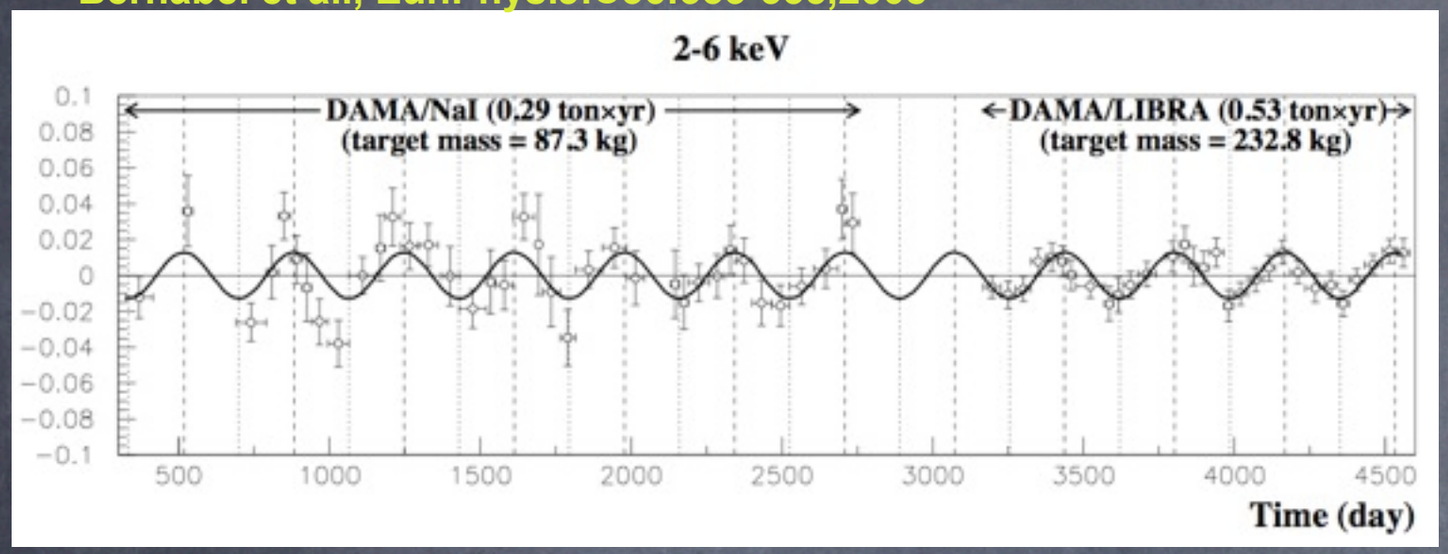

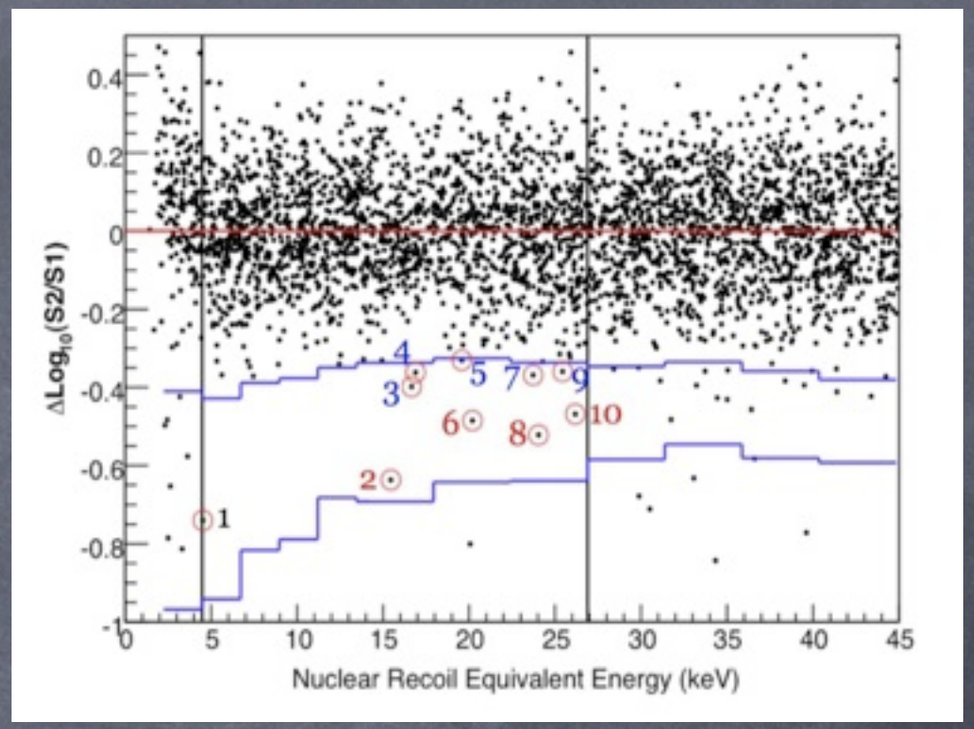

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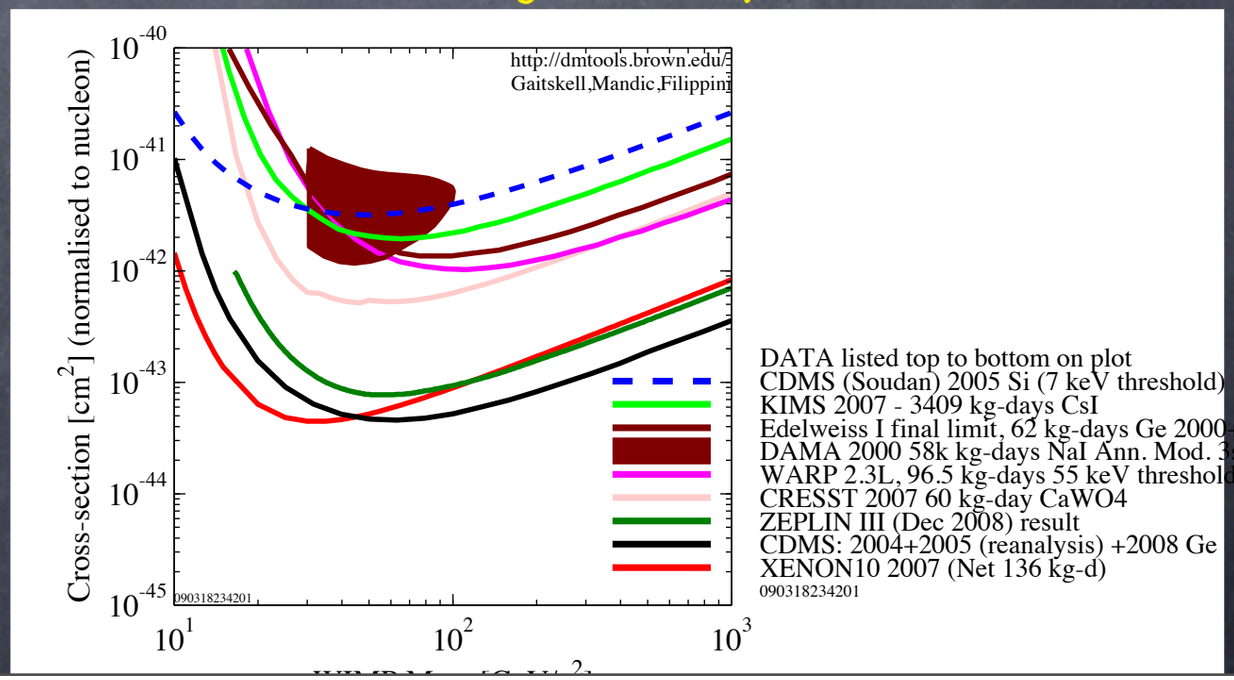
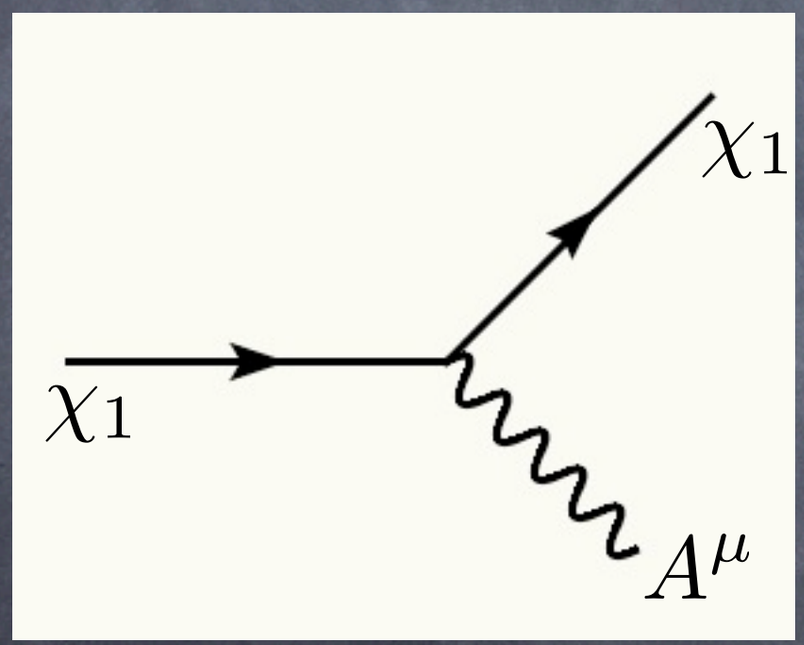


Consider vector interaction

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



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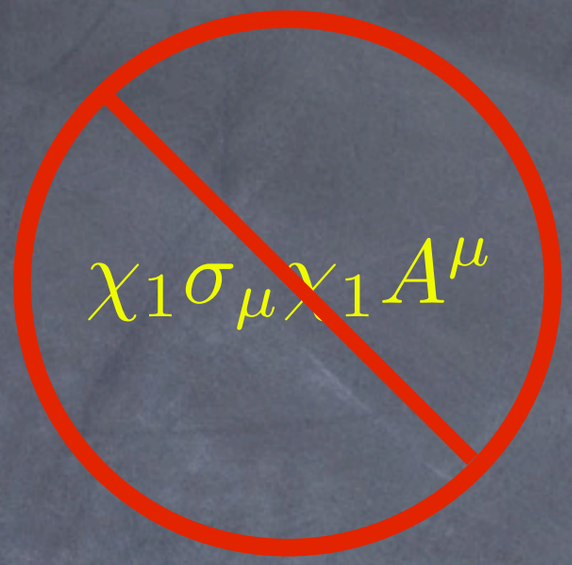

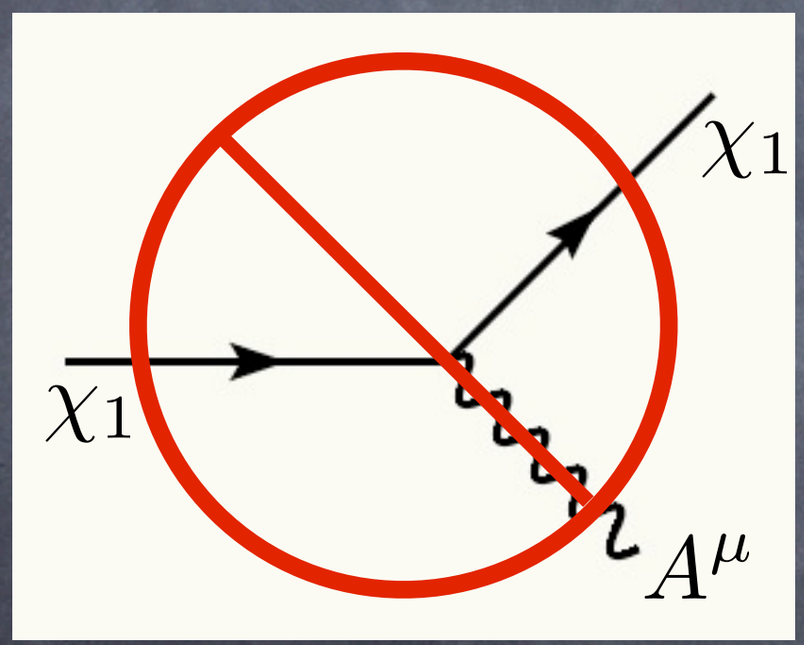

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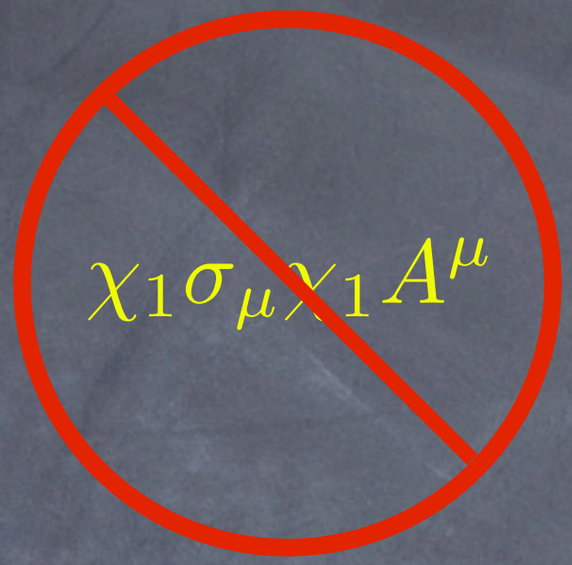
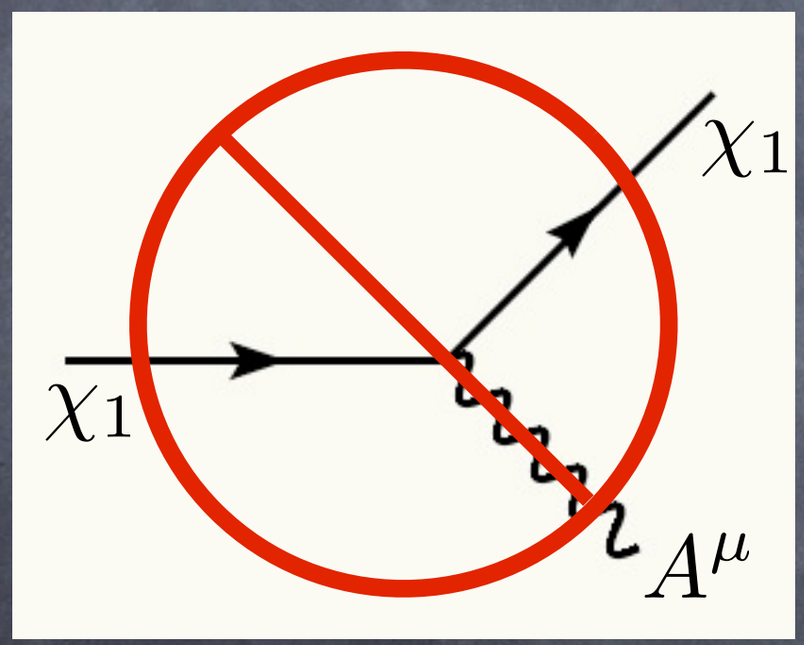
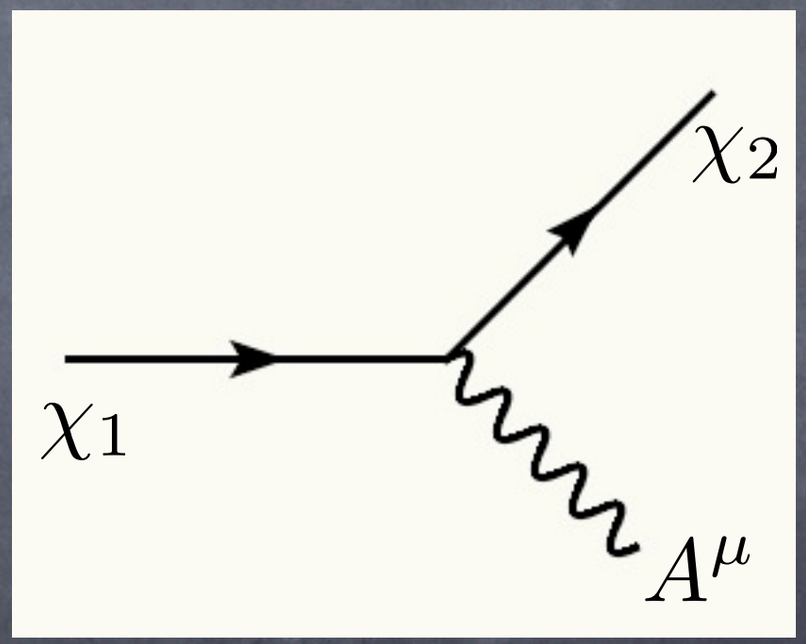


$\chi_1 \sigma_\mu \chi_2 A^\mu$





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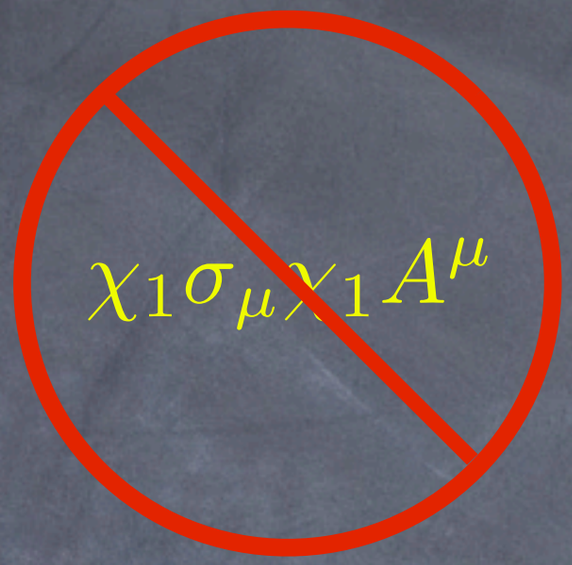

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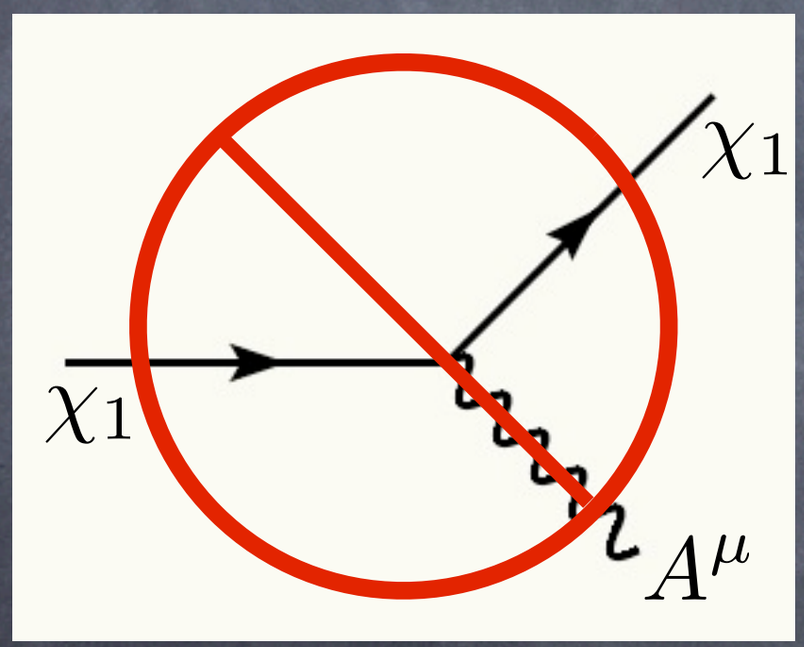

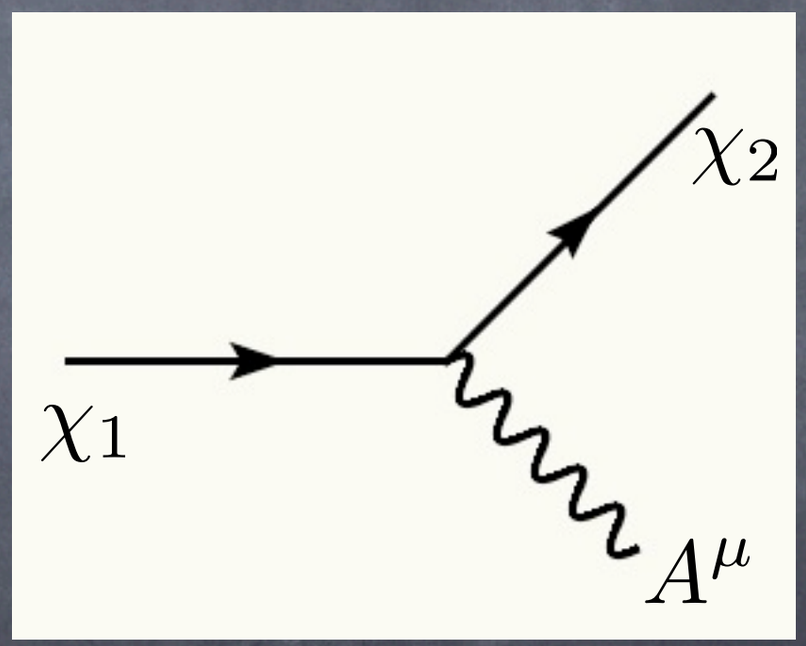

Vector interactions for massive WIMPs (M_{DM}>M_{force}) **always** require multiple states

interaction is off-diagonal

Question:

δ

Question:

- What is the splitting between those states? δ

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$$\frac{\delta}{M} \lesssim \frac{\alpha^2}{4}$$

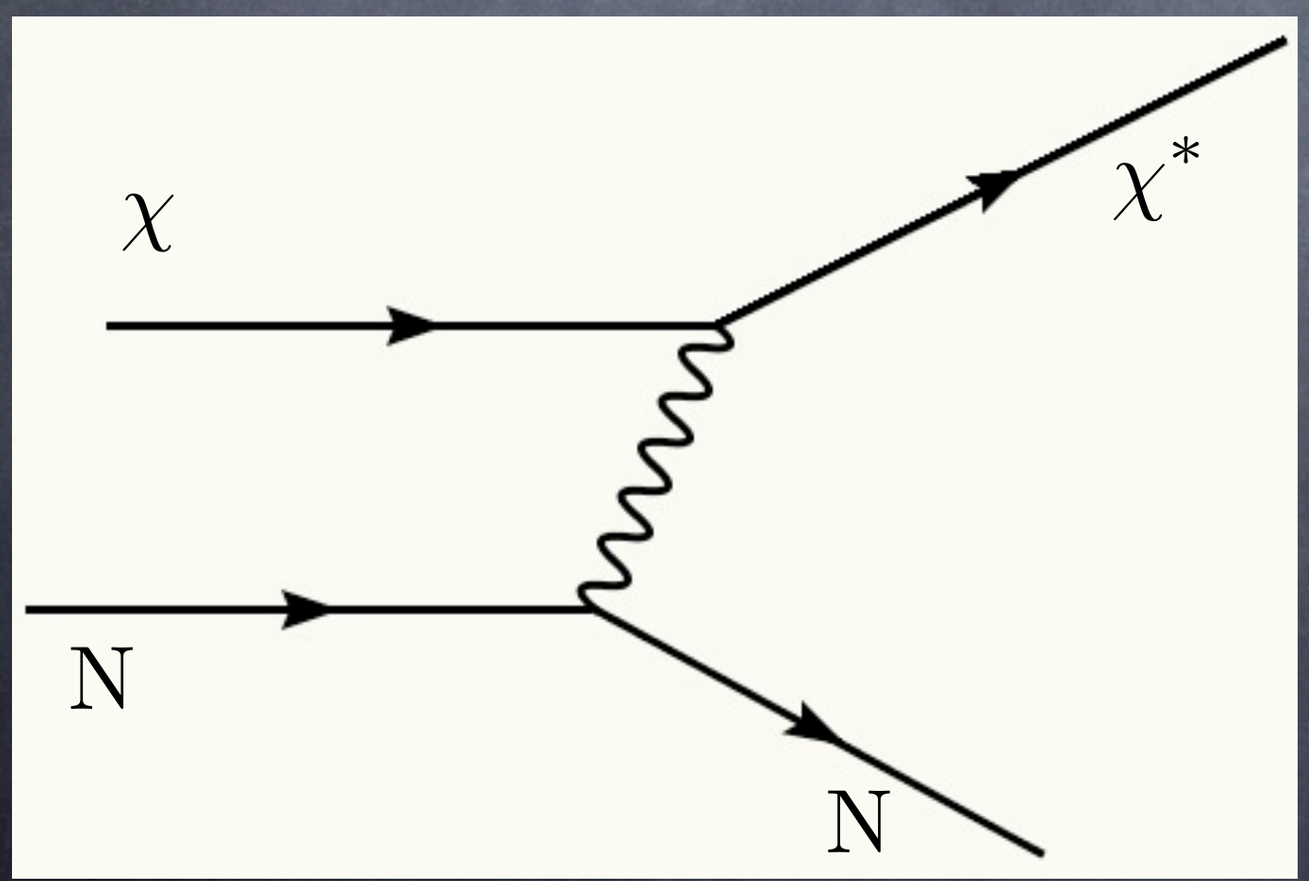
For $\alpha \sim 10^{-2}$ $M \sim TeV$

$$\delta \sim 100\text{MeV} \sim \text{kinetic energy of a WIMP}$$

"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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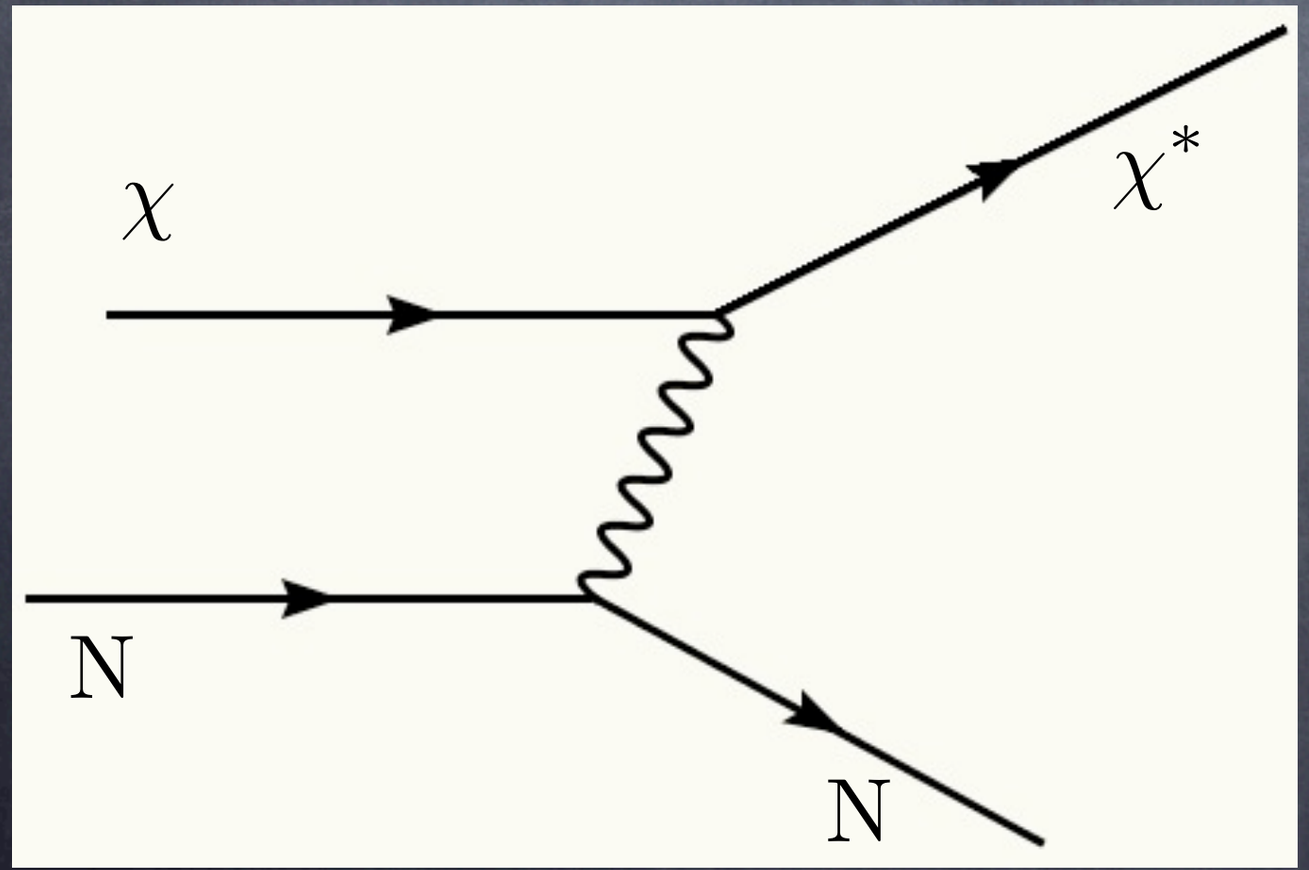
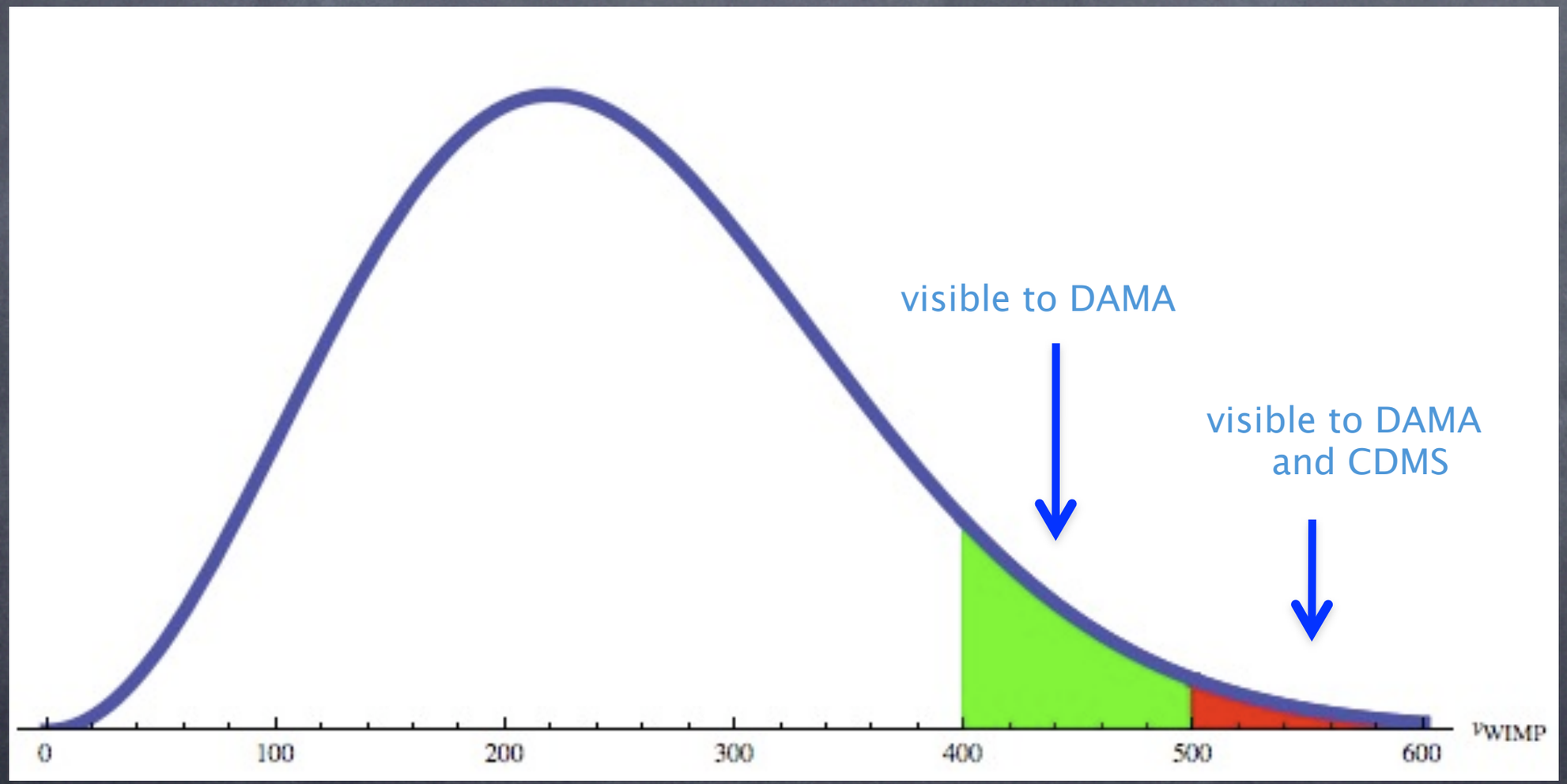


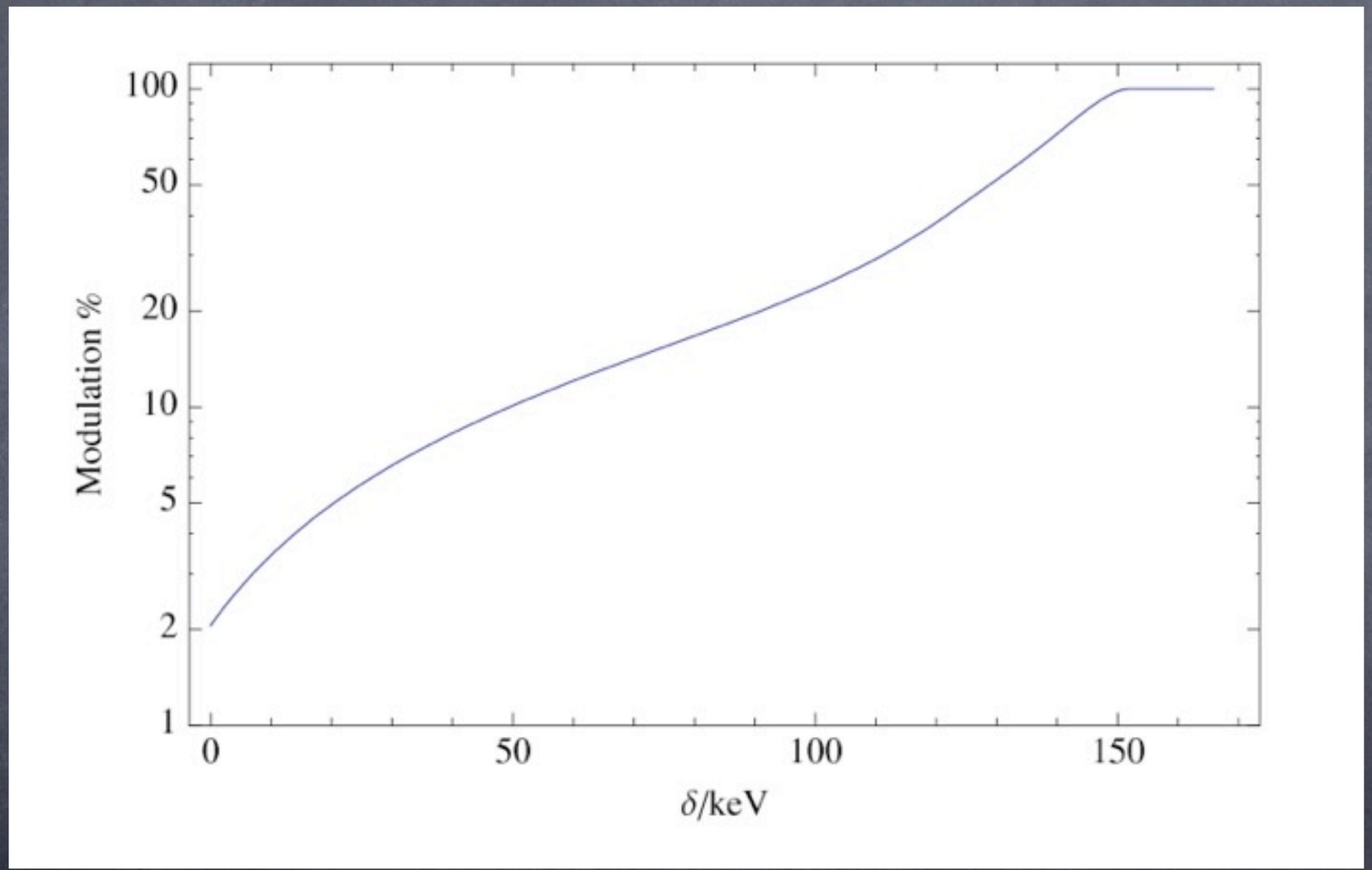
$$\frac{v^2 \mu_{\chi N}}{2} > \delta$$

Favors heavier targets



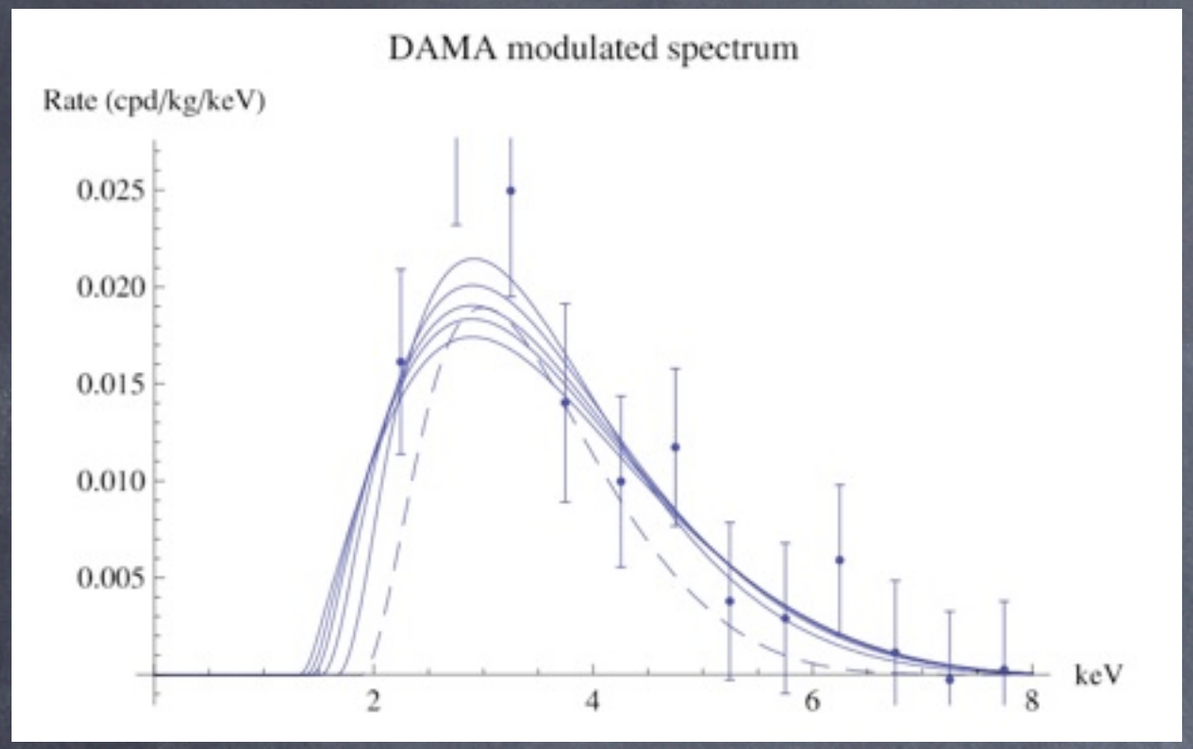
Disfavors CDMS

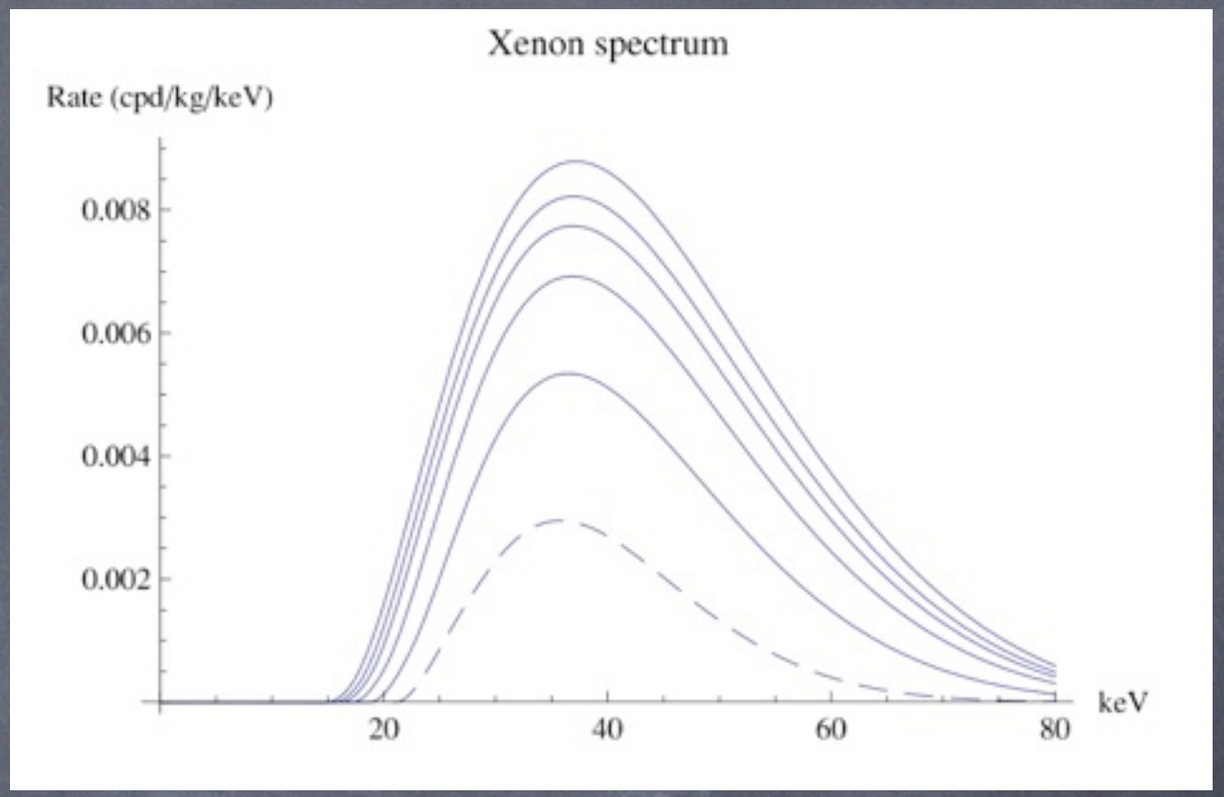
Enhanced modulation



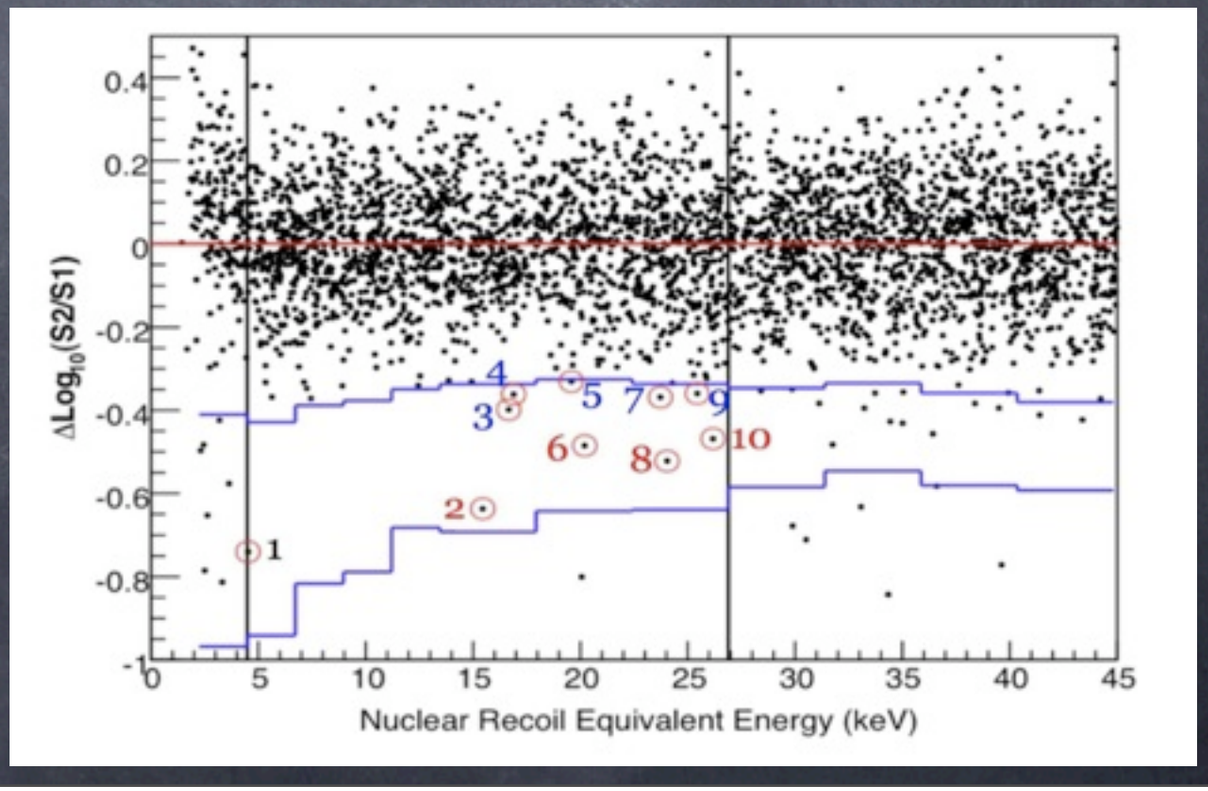
Favors modulation experiments

Modified spectrum





Together, these three effects allow a positive DAMA signal consistent with XENON/CDMS/CRESST/KIMS...



A new force in the dark sector

- Outputs > Inputs
  - GeV mediator gives all aspects of the anomalies (size, leptons, no antiprotons)
- Non-Abelian or multi-state models give natural explanation for **all** anomalies (INTEGRAL, DAMA, and e+e-)

Perspective

Nuclear Physics B347 (1990) 1–11
North-Holland

NEUTRINO MOMENTS, MASSES AND CUSTODIAL SU(2) SYMMETRY *

Howard GEORGI and Michael LUKE

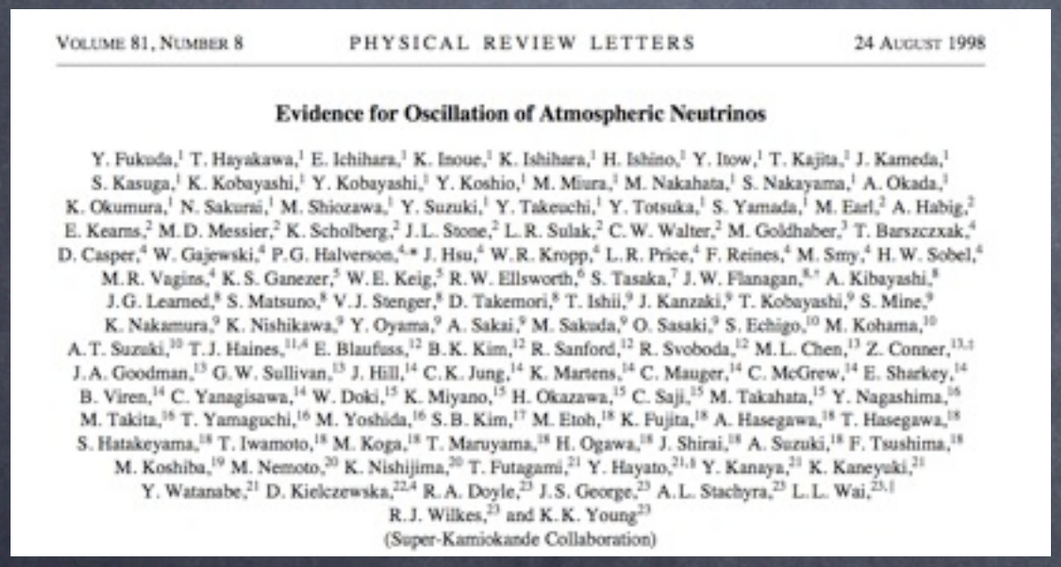
Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

Received 17 April 1990

We identify and exemplify a new mechanism which leads to a nonzero magnetic moment for a neutrino, while suppressing the neutrino's mass. The mechanism requires that the contribution to the neutrino mass of the new particles that are responsible for its magnetic moment is approximately canceled by a contribution from neutral particles, related by a custodial SU(2) symmetry.

1. The problem

Most likely, the solar neutrino problem [1] has nothing whatever to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of B^8 neutrinos coming from the sun as well as they do, to within a factor of 2 or 3 [2]. However, one aspect of the solar neutrino data, the apparent modulation of the flux of solar neutrinos with the sun-spot cycle, is certainly intriguing [3]. It is, of course, possible that this is an astrophysical problem rather than a particle physics problem. But that would require a synchronization of cycles of the interior of the sun with those of the convective layer, both in frequency and in *phase*. Thus it seems particularly interesting that there may be a particle physics explanation of this effect [4], involving a magnetic moment of the electron neutrino



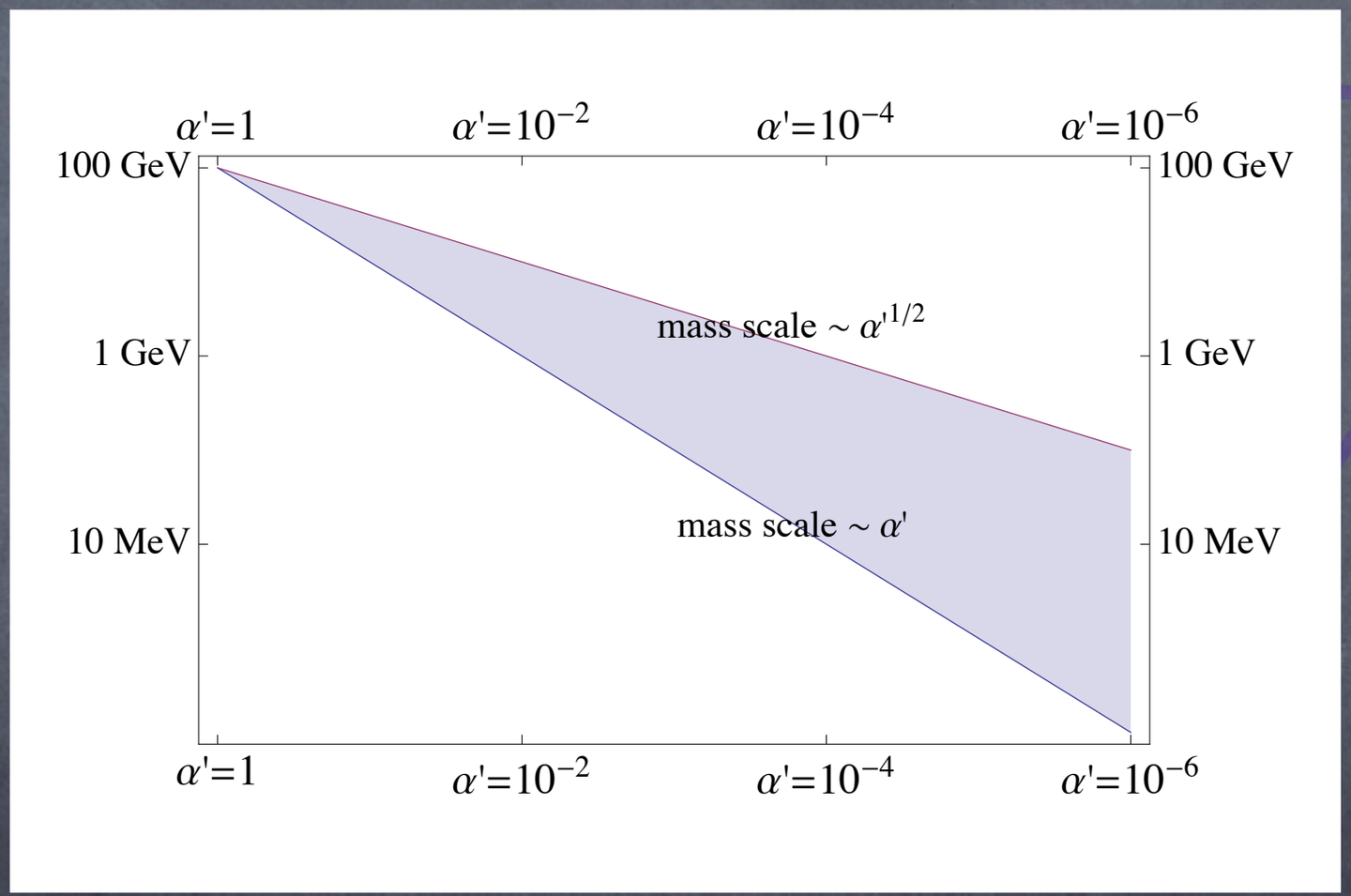
VOLUME 81, NUMBER 8 PHYSICAL REVIEW LETTERS 24 AUGUST 1998

Evidence for Oscillation of Atmospheric Neutrinos

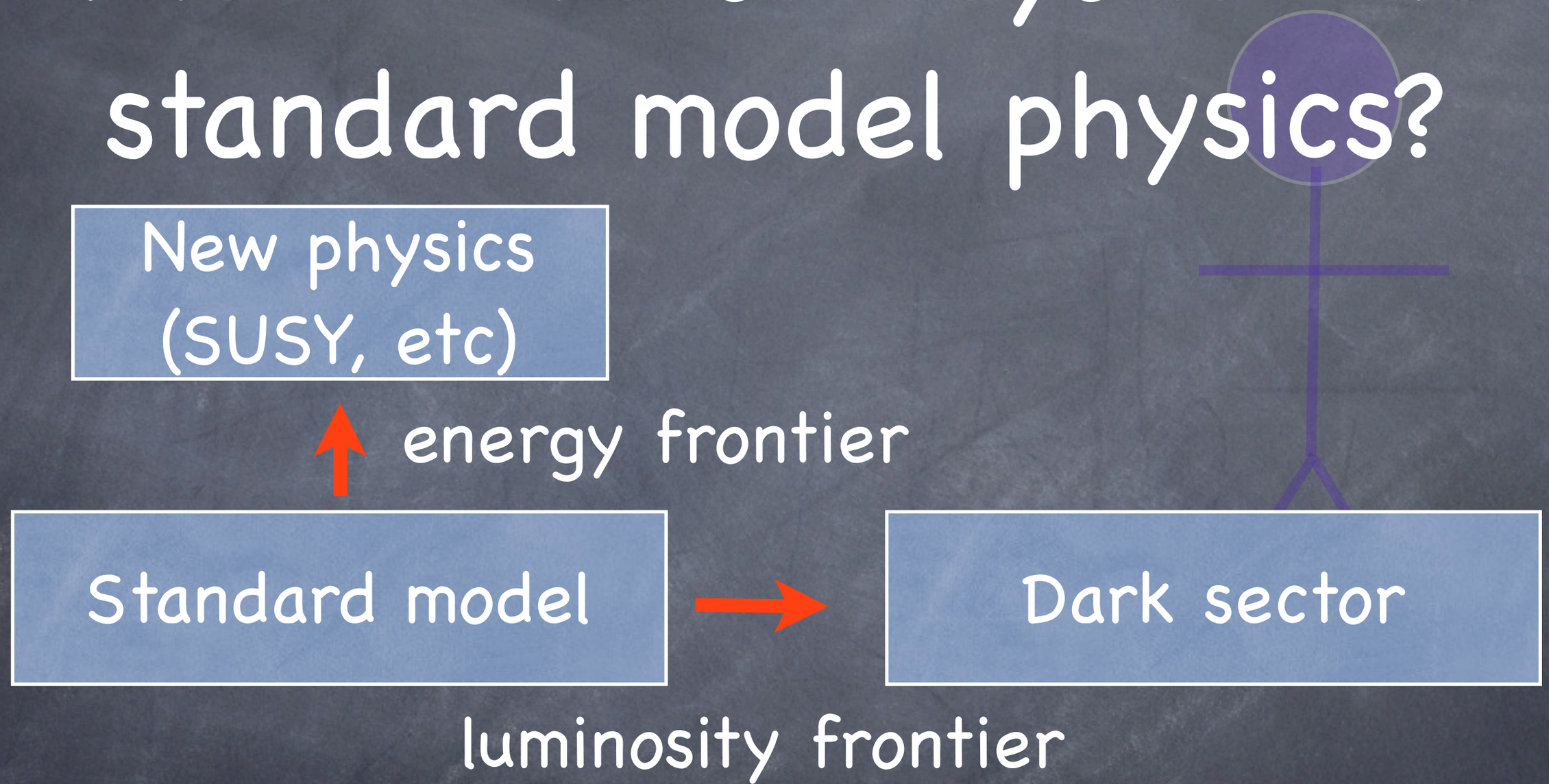
Y. Fukuda,[1] T. Hayakawa,[1] E. Ichihara,[1] K. Inoue,[1] K. Ishihara,[1] H. Ishino,[1] Y. Itow,[1] T. Kajita,[1] J. Kameda,[1] S. Kasuga,[1] K. Kobayashi,[1] Y. Kobayashi,[1] Y. Koshio,[1] M. Miura,[1] M. Nakahata,[1] S. Nakayama,[1] A. Okada,[1] K. Okumura,[1] N. Sakurai,[1] M. Shiozawa,[1] Y. Suzuki,[1] 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)

"Unreliable" astrophysical signals can be the first sign of new physics

The future of beyond the standard model physics?



The future of beyond the standard model physics?



Motivating dark forces

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- Single ingredient: new dark force at ~ GeV addresses key issues
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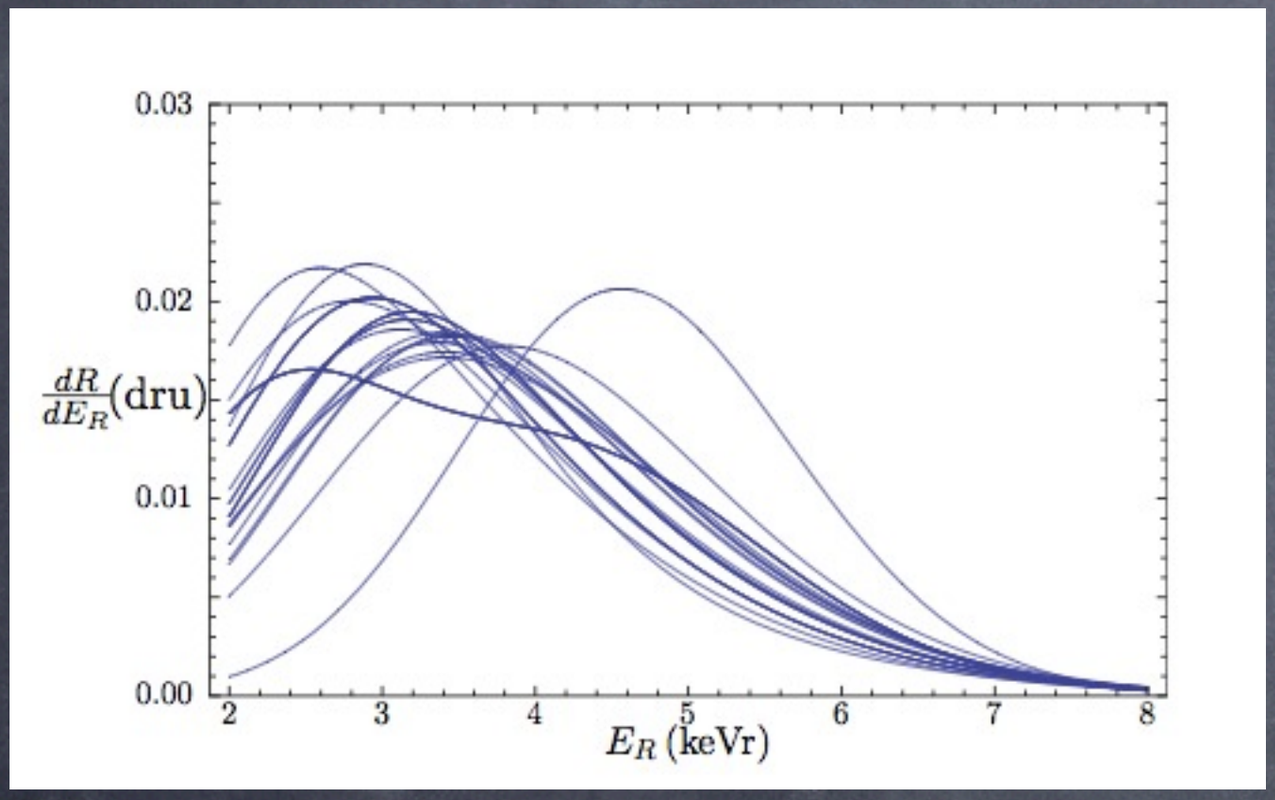
  - Excited states for DAMA/INTEGRAL
- Testable

- Thank you very much!

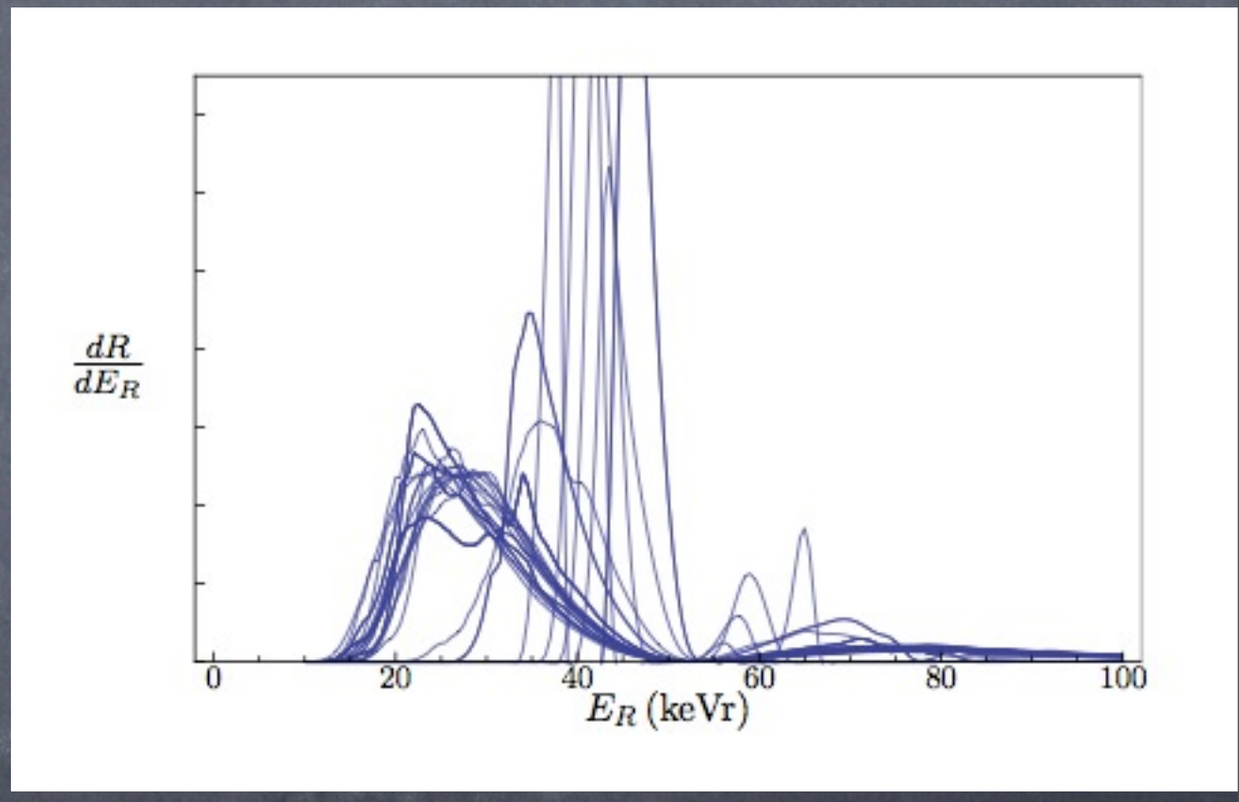
Supplemental Slides

Spectra in "realistic" halos

Kuhlen & NW, in prep



DAMA, 100 GeV, 130 keV

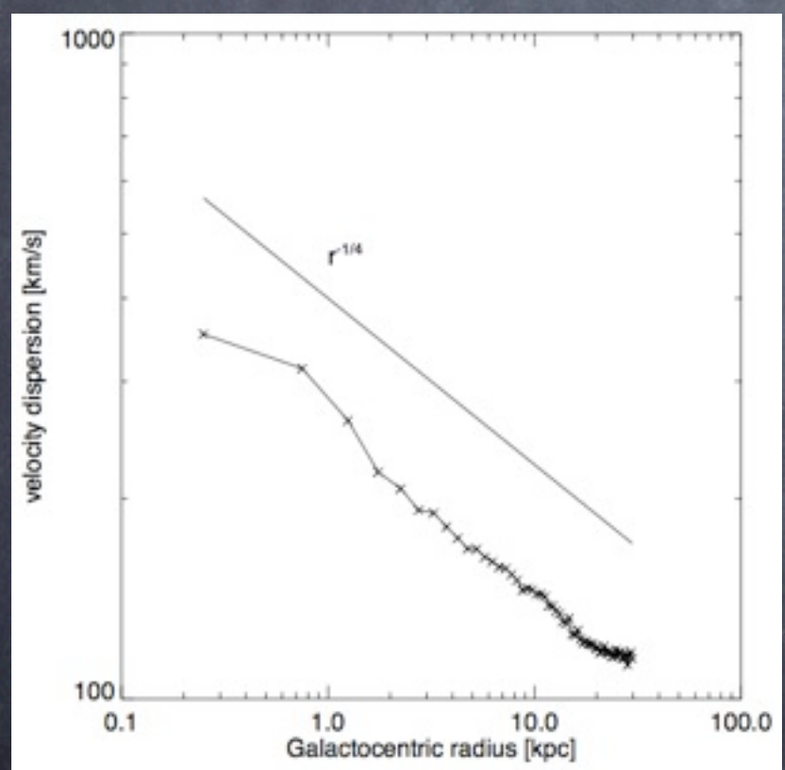


CRESST (norm to 1), 100 GeV, 130 keV

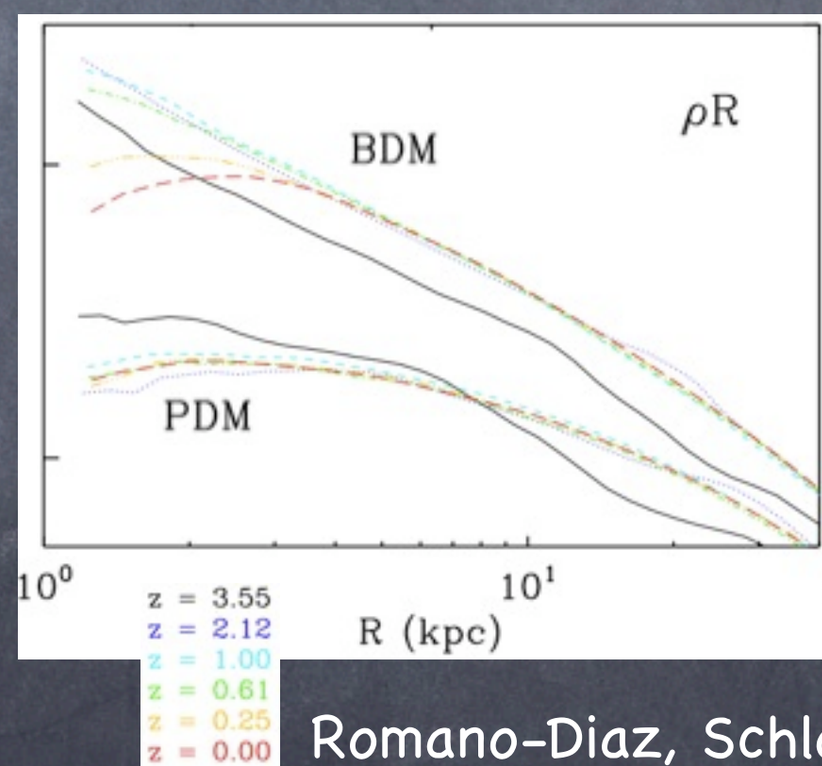
Yellin techniques (optimum interval, maximum gap, pmax) unreliable for inelastic models in experiments with good energy resolution

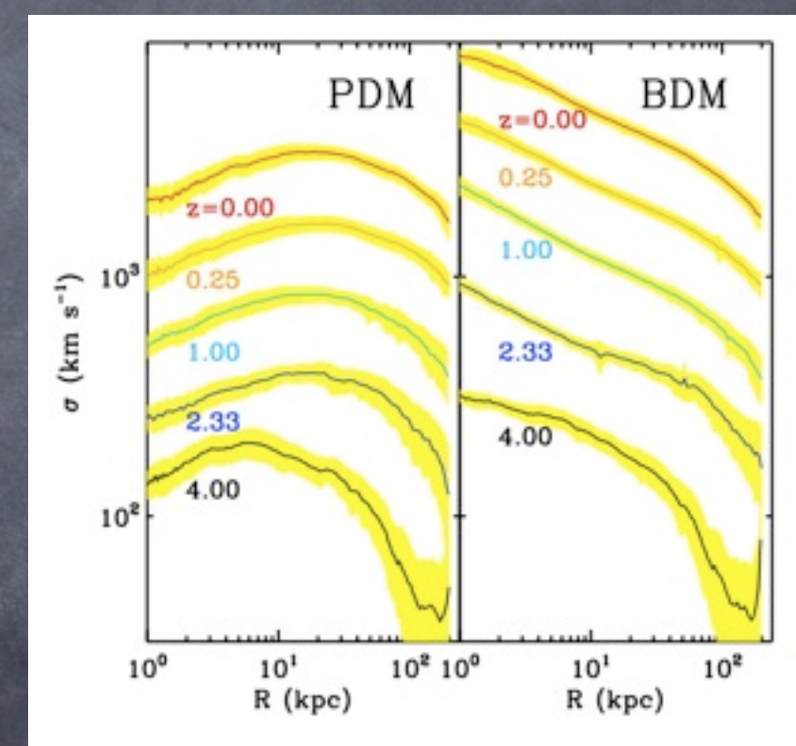
Limits from galactic center

- 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

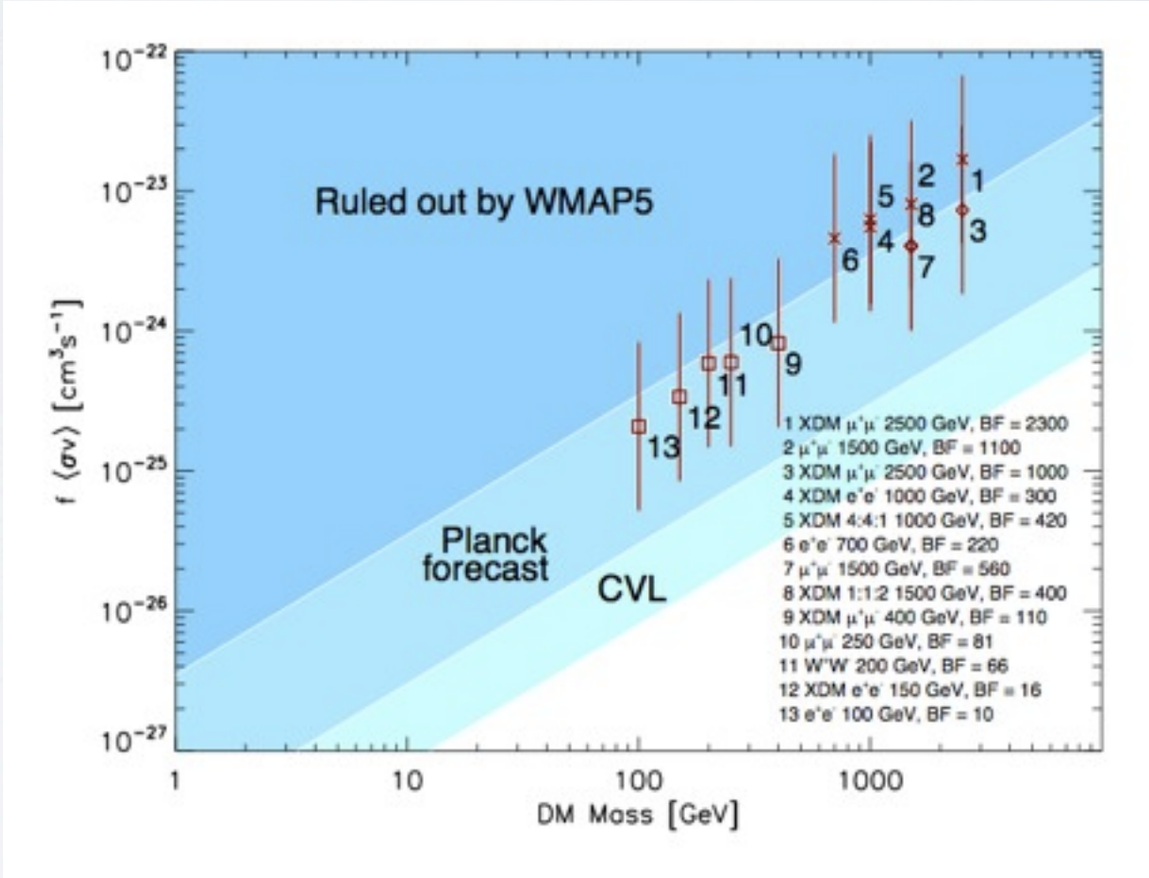
NB: **Many** simulation uncertainties (matching bulge with MW, other numerical issues involving baryons)

GOING FORWARD

Planck

Padmanabhan&Finkbeiner '04; Bertone, Galli, Iocco, Melchiorri, '09;Slatyer, Finkbeiner, Padmanabhan '09

DM annihilation injects high-energy particles into the IGM [71], which heat and ionize neutral hydrogen as they cool. This ionizing energy does not generally change the redshift of recombination, but does alter the residual ionization after recombination. The increased ionization fraction leads to a broadening of the last scattering surface, attenuating correlations between temperature fluctuations. The low-ℓ correlations between polarization fluctuations, on the other hand, are enhanced by the thicker scattering surface.



Should definitively test DM electronic production