Signals of Dark Forces at Fermi

Neal Weiner
Center for Cosmology and Particle Physics
New York University

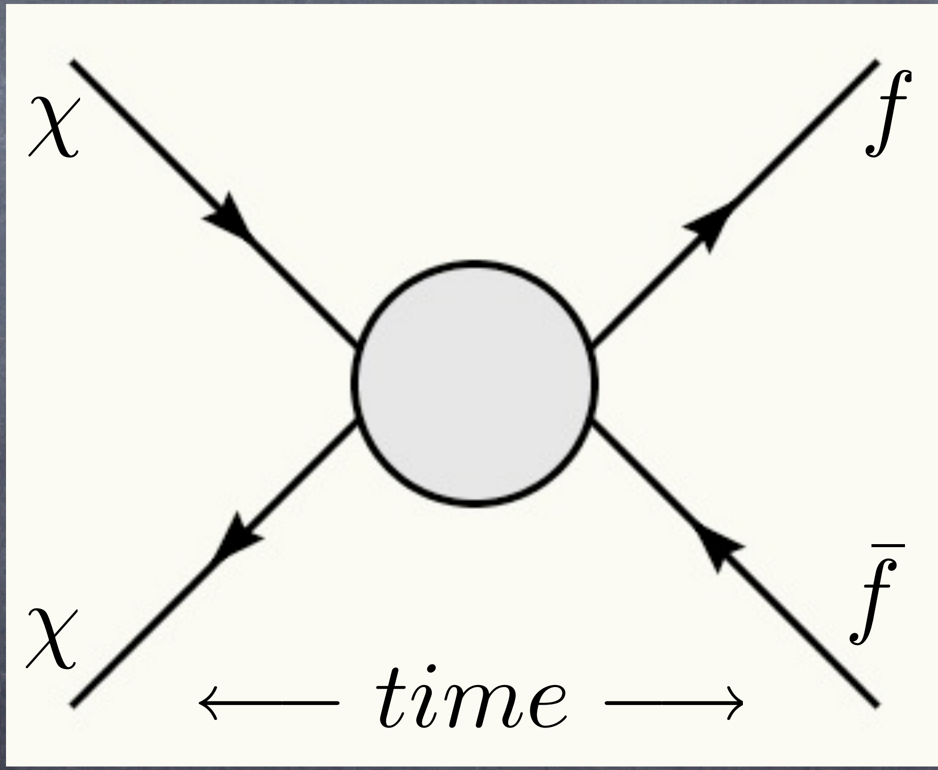
Fermi Symposium, Washington DC
November 4, 2009

DM in the Era of Data

- A wide range of experiments have seen significant signals
- These signals are hard to understand in traditional WIMP models
- A new framework has emerged with dramatic signal arising from new interactions in the dark sector

The WIMP "miracle"

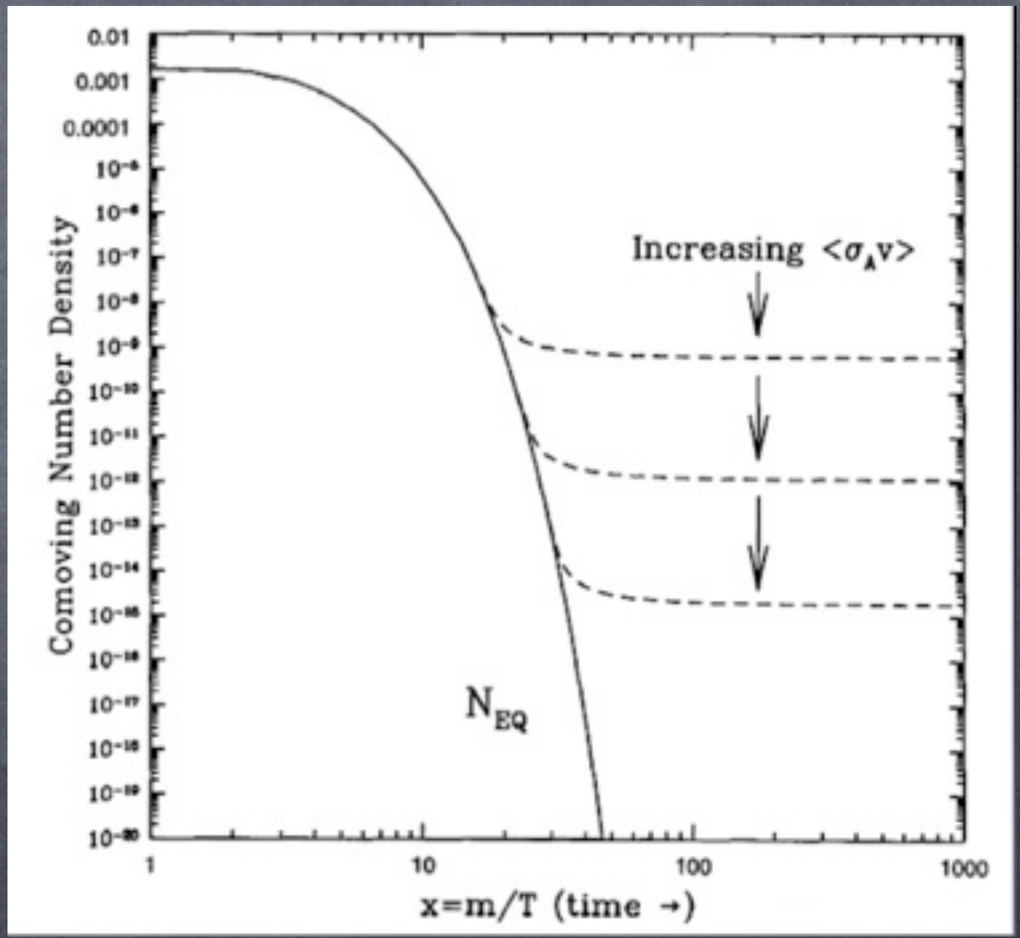
assume thermal equilibrium $\chi\chi \leftrightarrow \bar{f}f$



The WIMP "miracle"

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

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



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

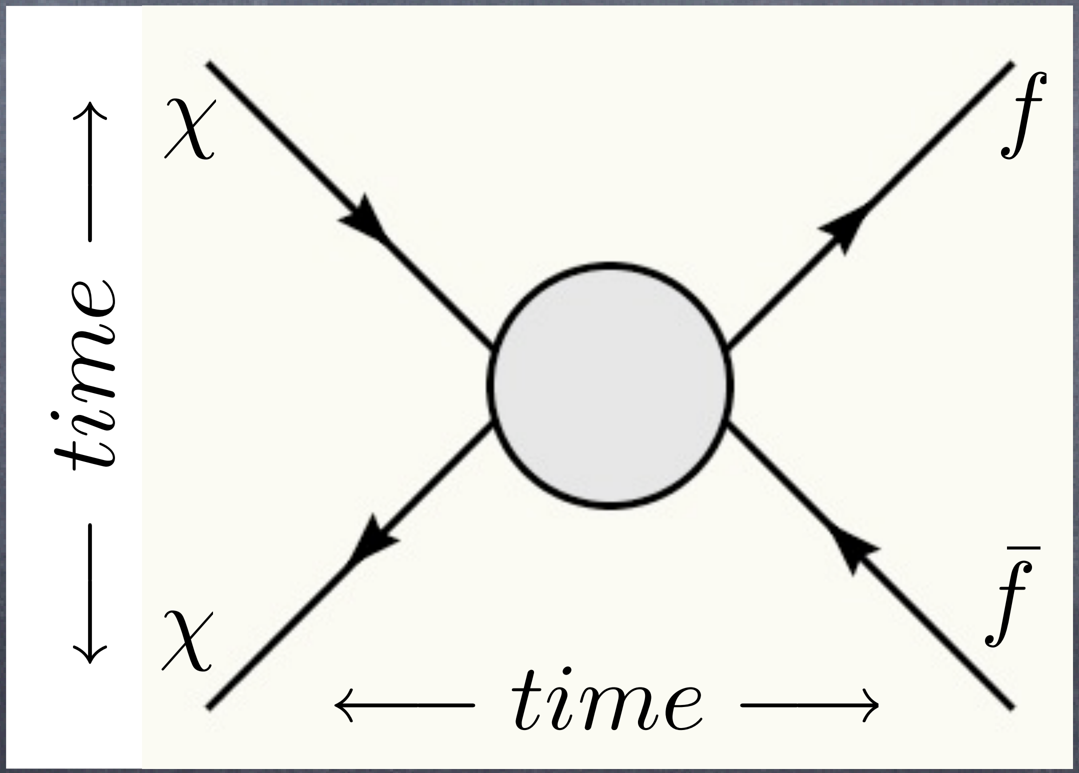
$$\approx 0.1 \times \left(\frac{\alpha^2/(100\mathrm{GeV})^2}{\langle \sigma v \rangle}\right)$$

- Signals of thermal DM

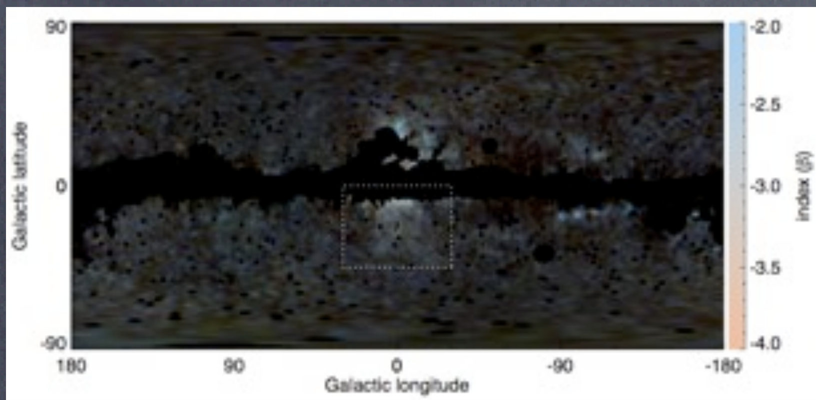
–Production (accelerators)

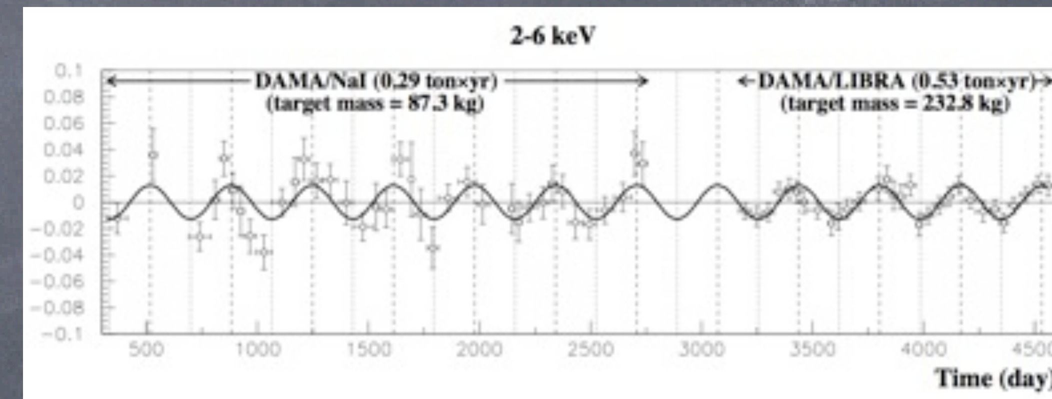
–Cosmic rays/indirect detection (PAMELA/Fermi/WMAP...)

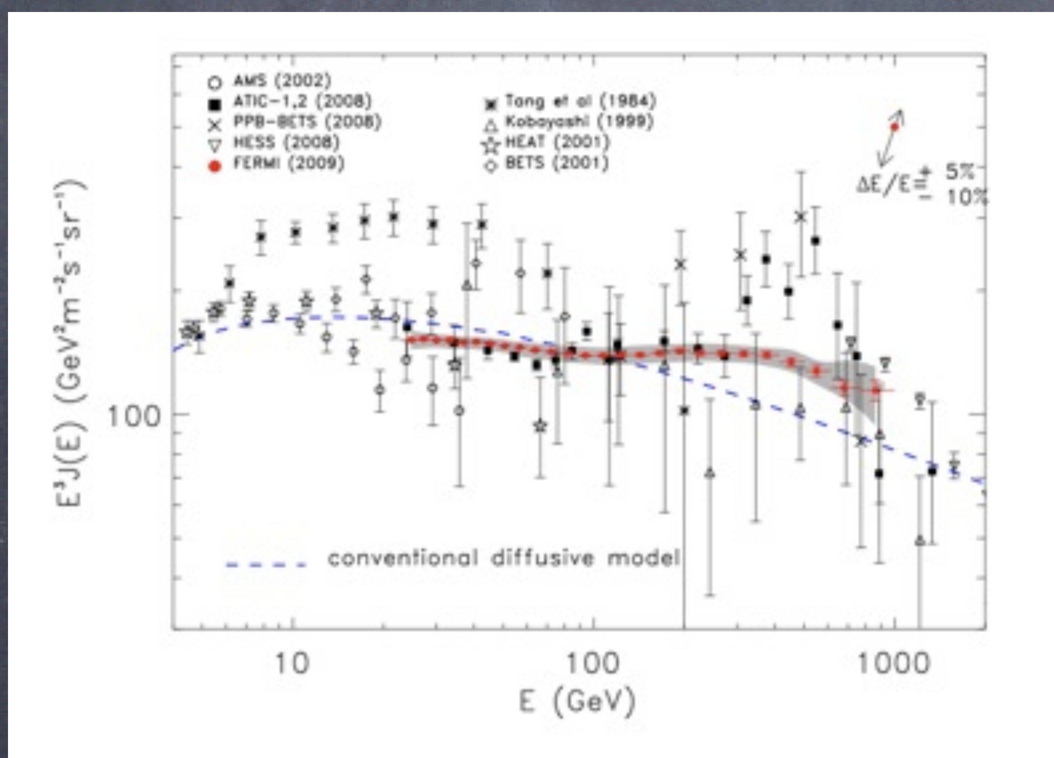
–Direct detection (DAMA/XENON/CDMS...)

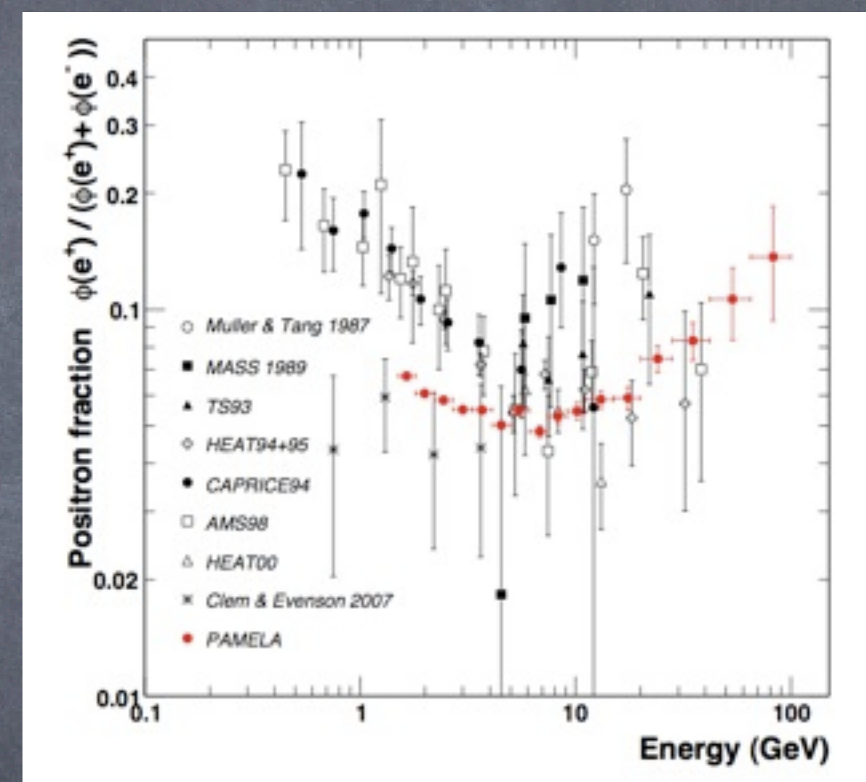


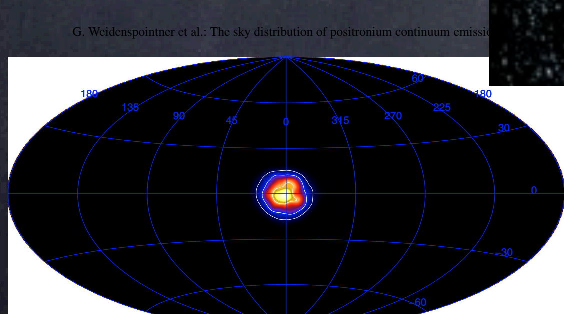
Era of anomalies

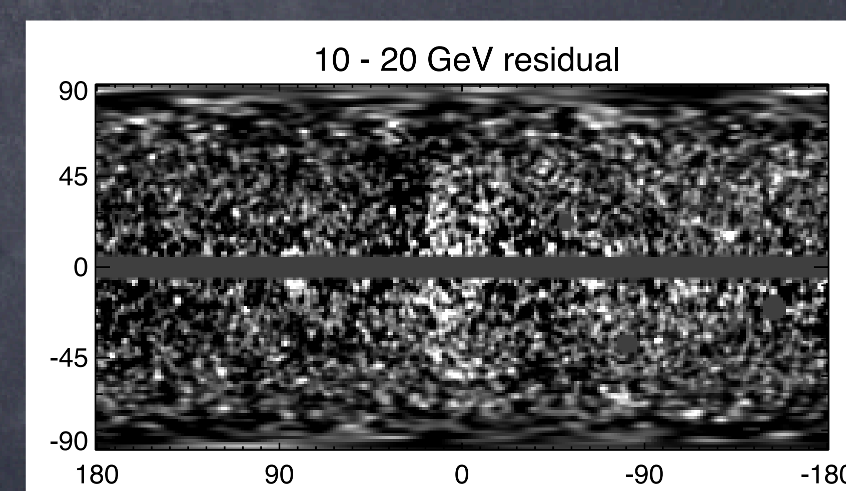




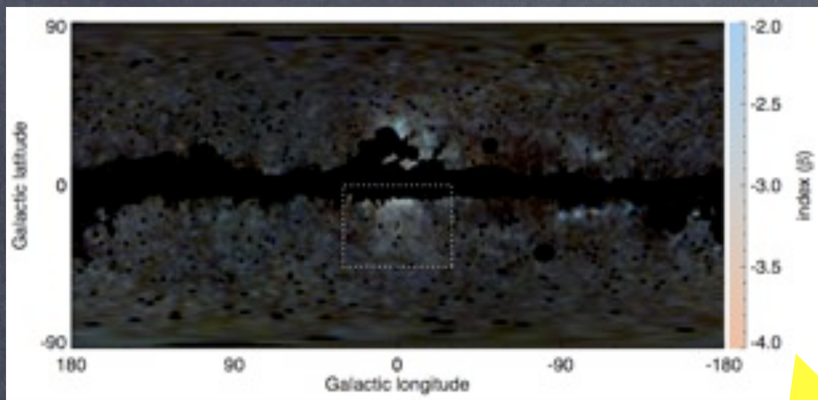


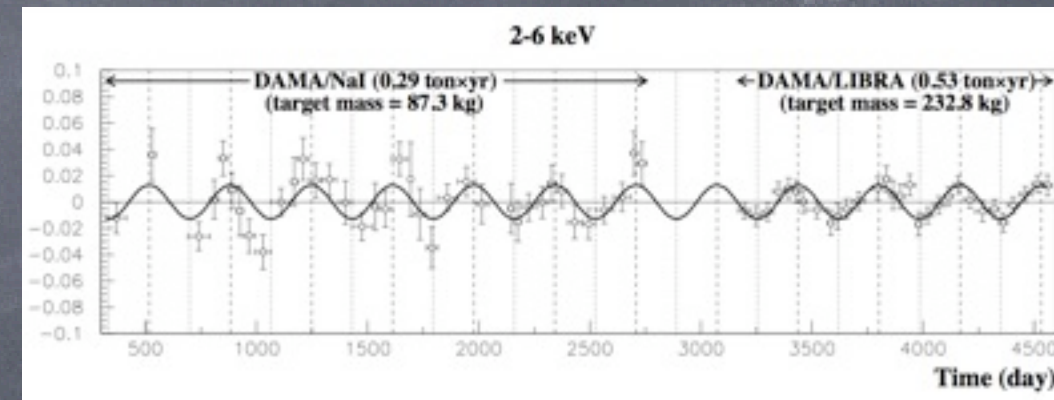


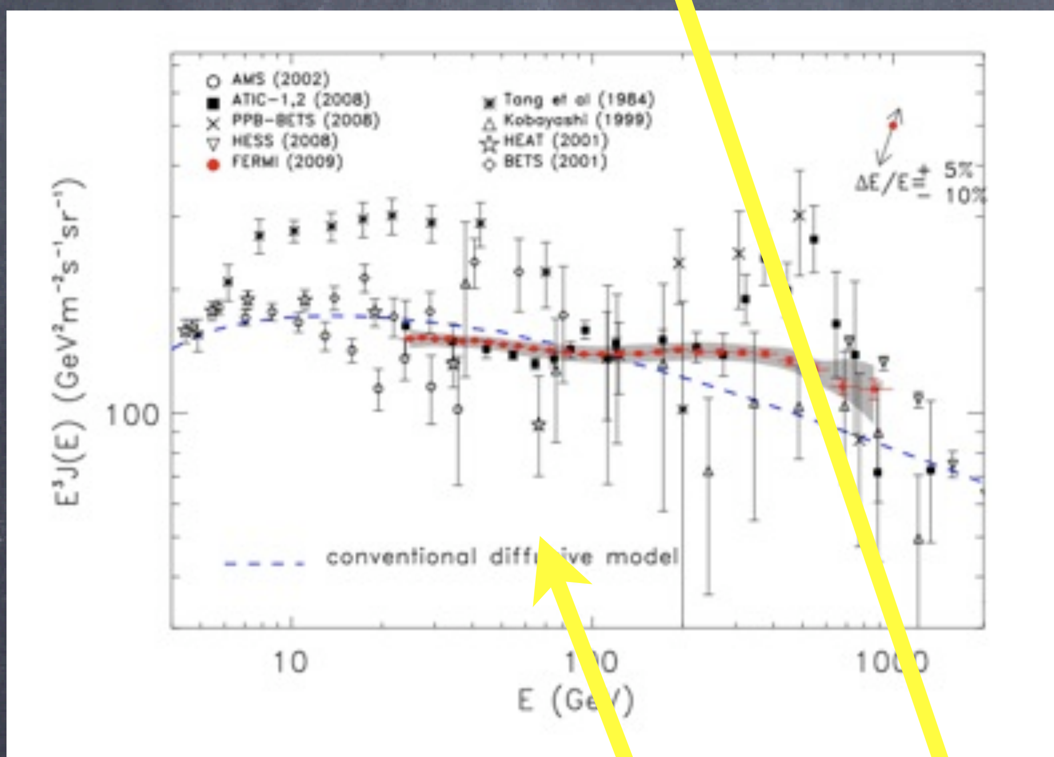


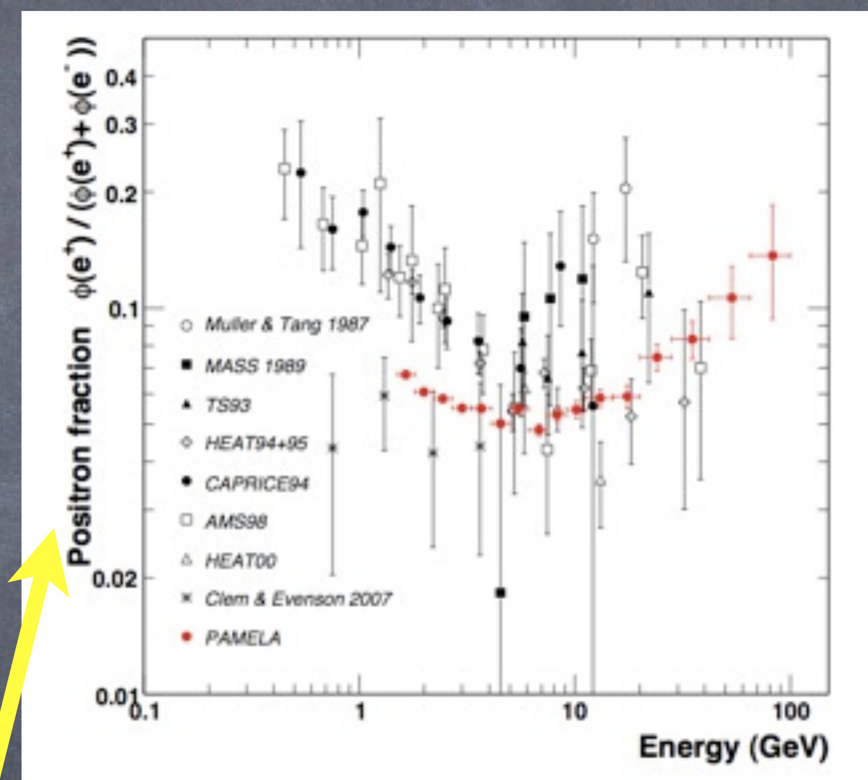


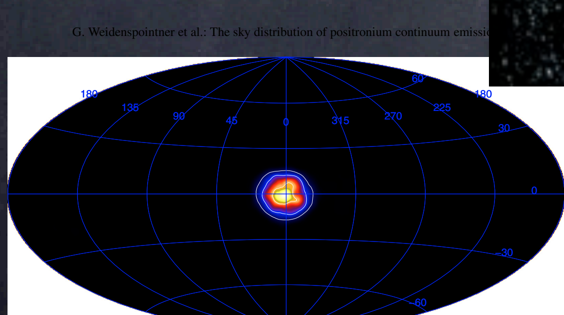
Era of anomalies



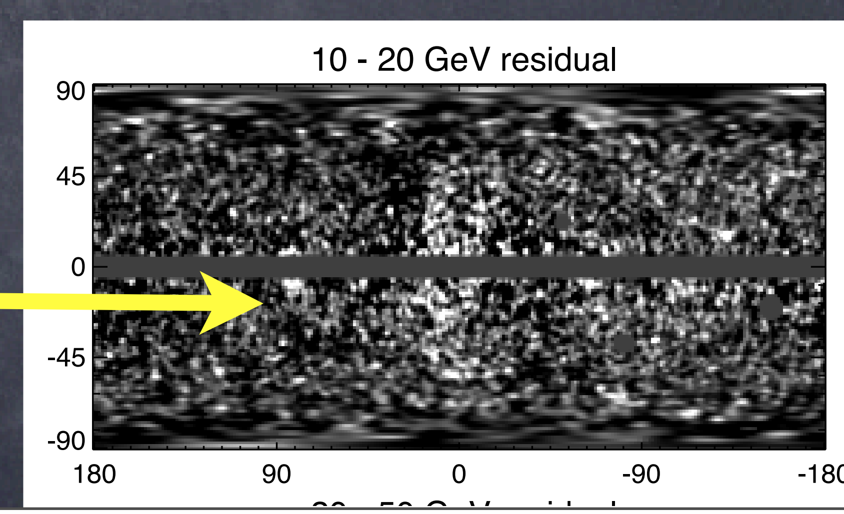








Indications of high energy electron or positron production



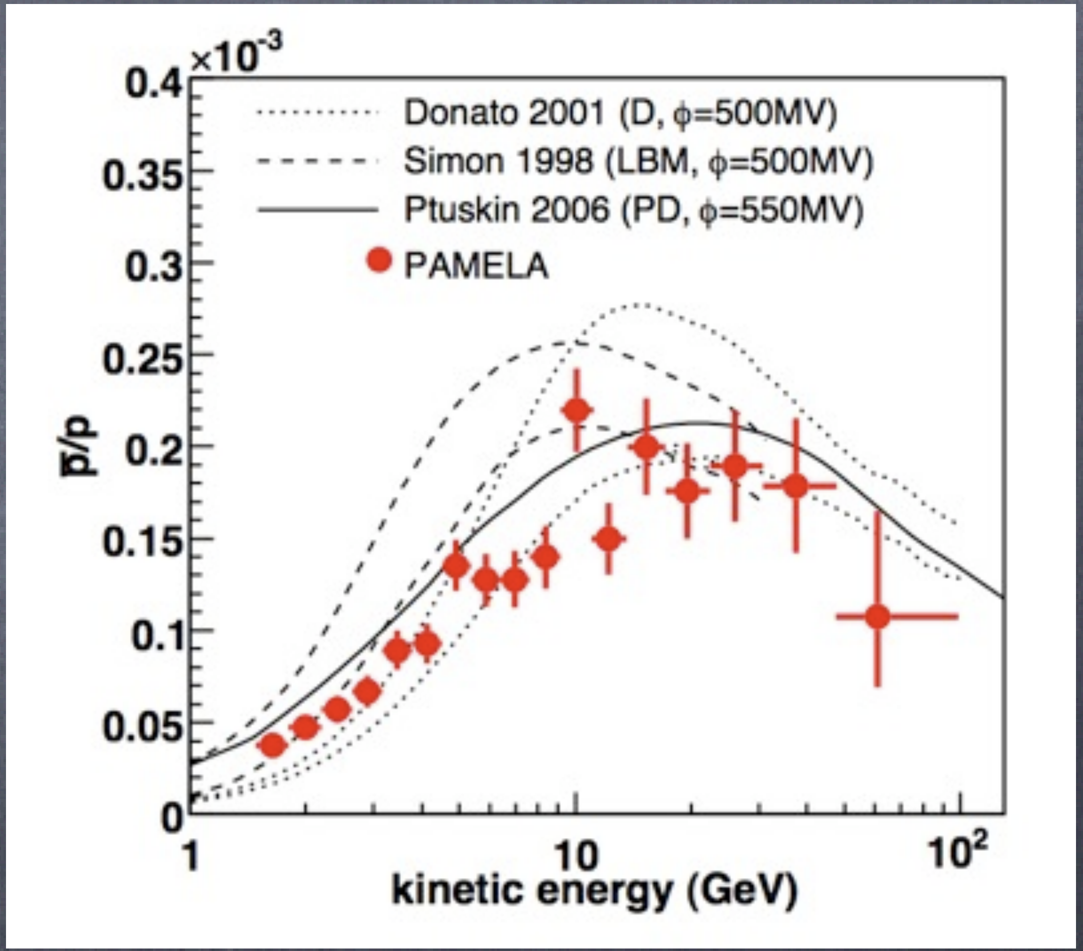
WIMP annihilations?
Not so fast

WIMP annihilations? Not so fast

- PAMELA sees no excess in antiprotons - excludes hadronic modes by order of magnitude (Cirelli et al, '08, Donato et al, '08)

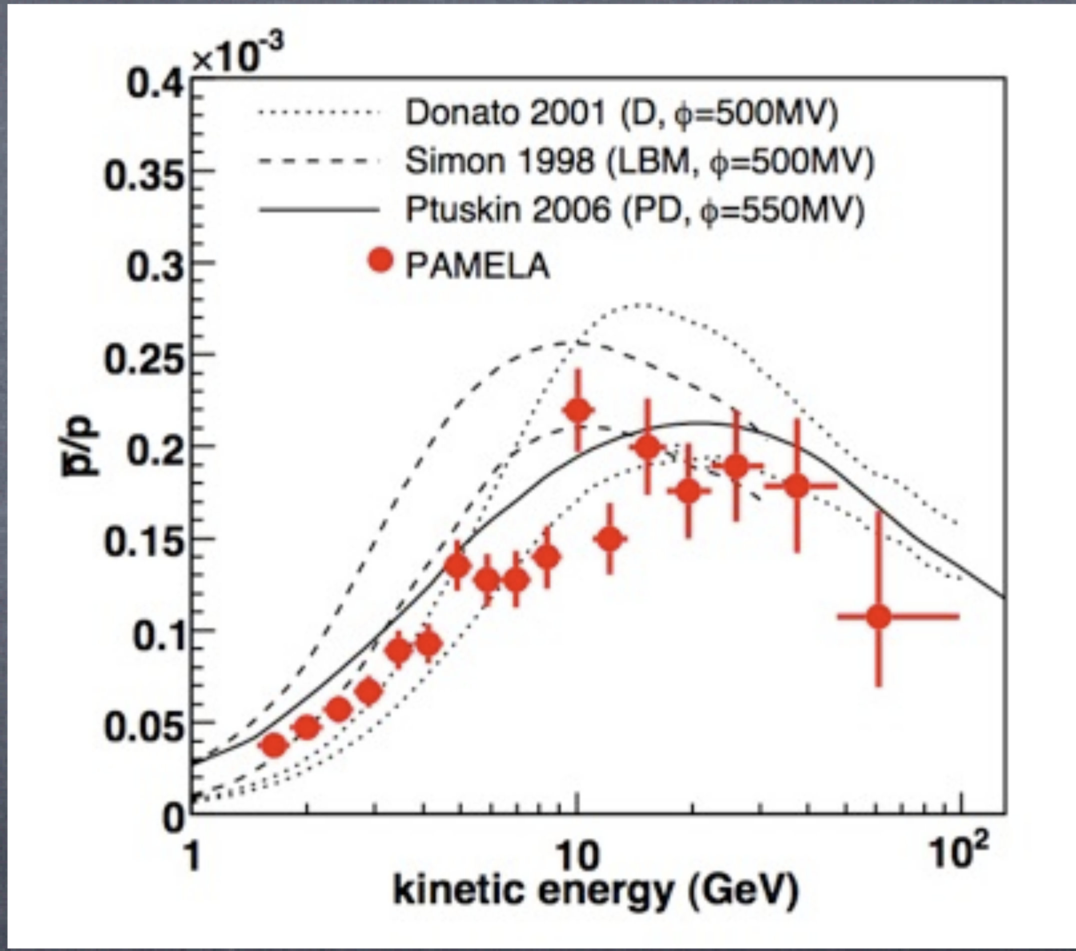
WIMP annihilations? Not so fast

- PAMELA sees no excess in antiprotons - excludes hadronic modes by order of magnitude (Cirelli et al, '08, Donato et al, '08)



WIMP annihilations? Not so fast

- PAMELA sees no excess in antiprotons - excludes hadronic modes by order of magnitude (Cirelli et al, '08, Donato et al, '08)
- The spectrum at Fermi/PAMELA is very hard - not what you would expect from e.g., W's

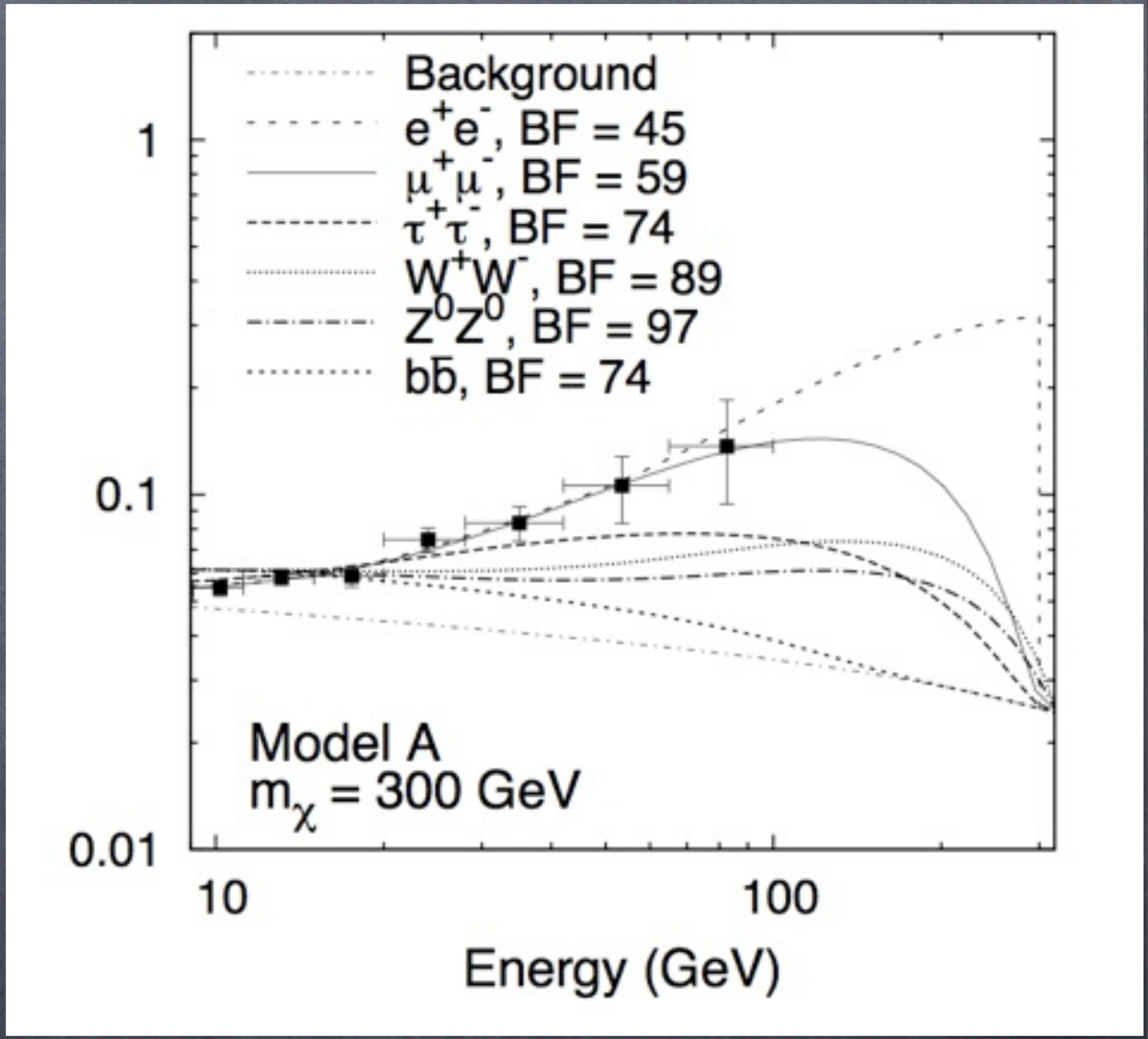


WIMP annihilations? Not so fast

- PAMELA sees no excess in antiprotons - excludes hadronic modes by order of magnitude (Cirelli et al, '08, Donato et al, '08)
- The spectrum at Fermi/ PAMELA is very hard - not what you would expect from e.g., W's

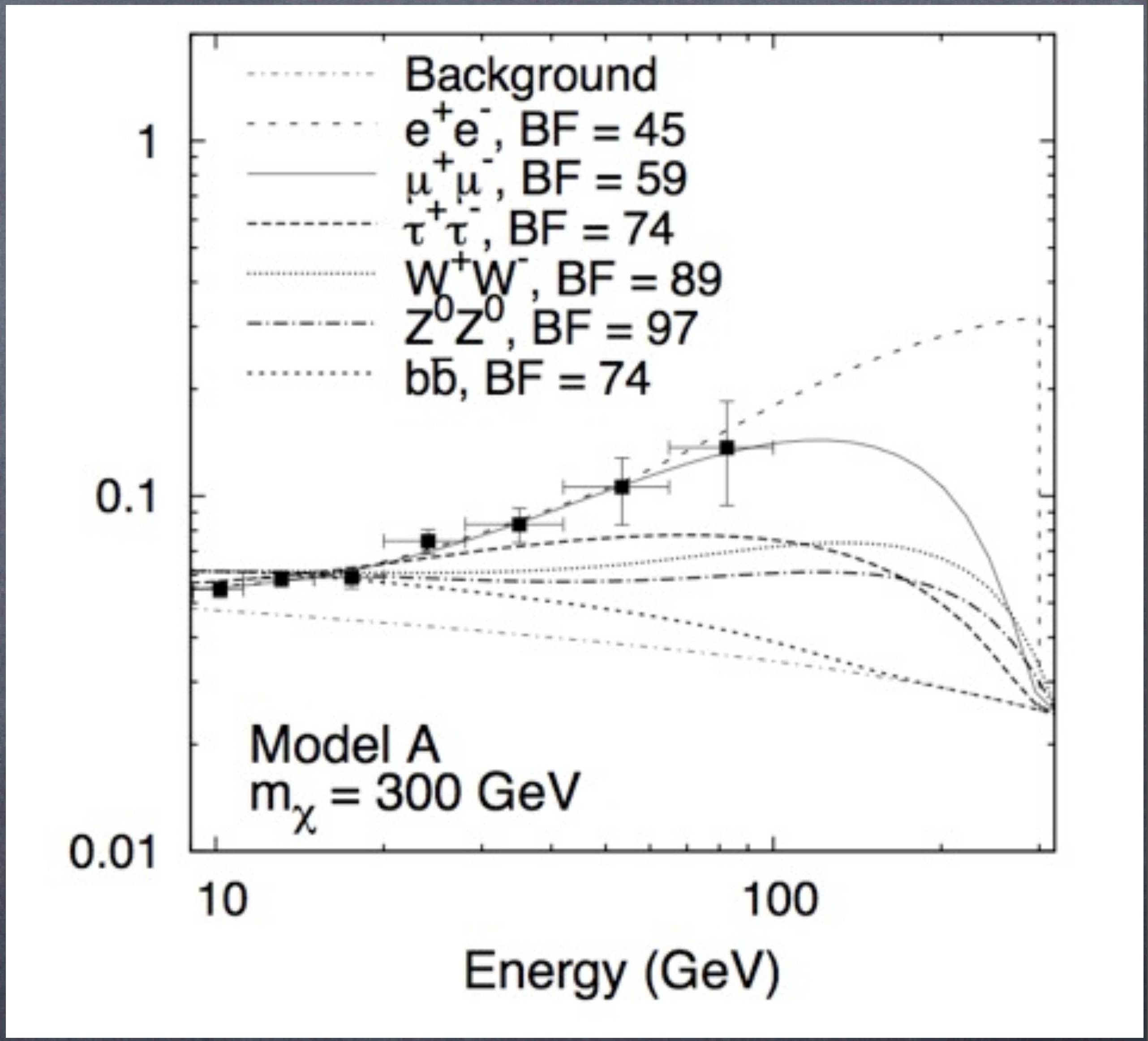
WIMP annihilations? Not so fast

- PAMELA sees no excess in antiprotons - excludes hadronic modes by order of magnitude (Cirelli et al, '08, Donato et al, '08)
- The spectrum at Fermi/PAMELA is very hard - not what you would expect from e.g., W's



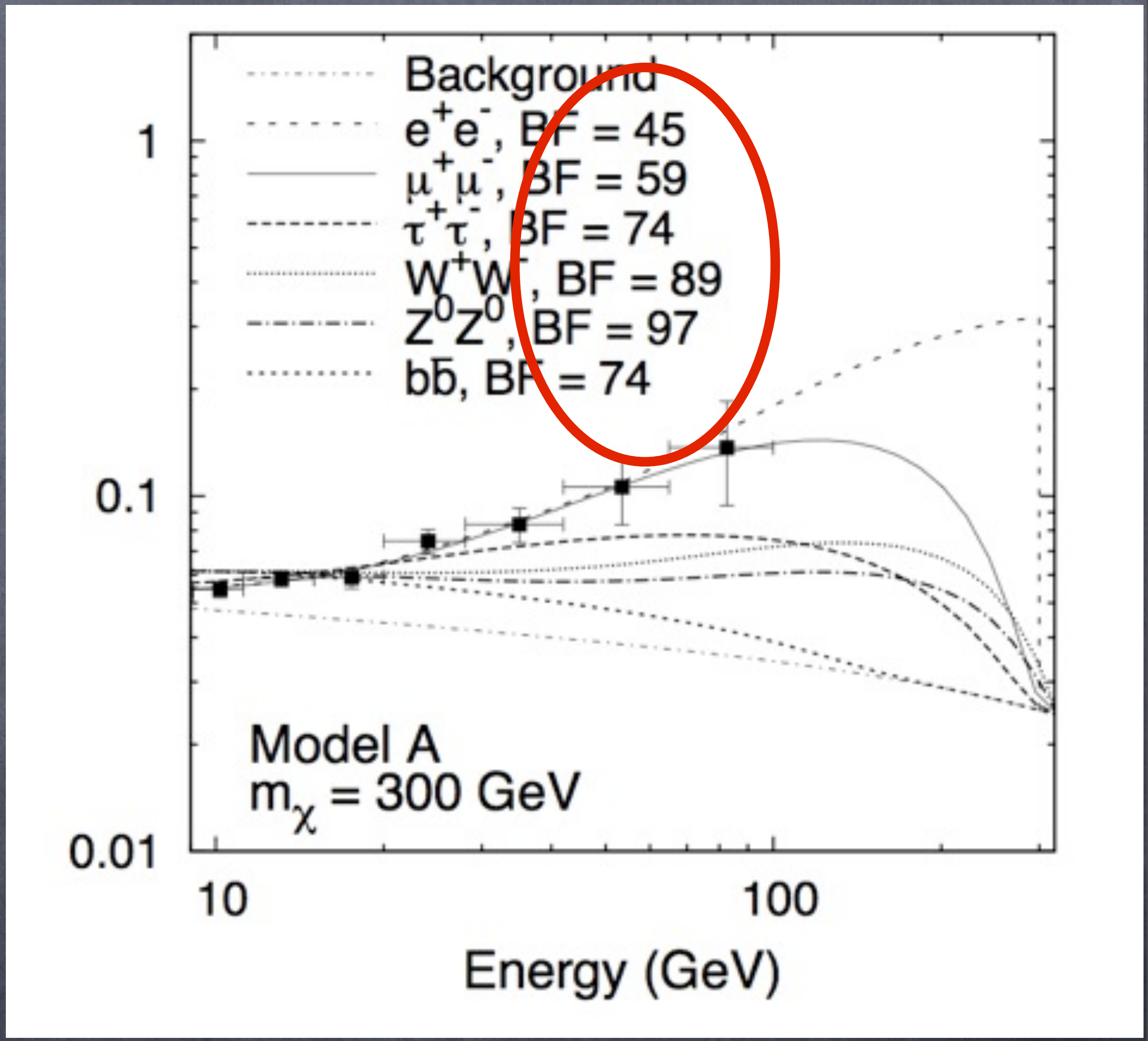
WIMP annihilations? Not so fast

- PAMELA sees no excess in antiprotons - excludes hadronic modes by order of magnitude (Cirelli et al, '08, Donato et al, '08)
- The spectrum at Fermi/ PAMELA is very hard - not what you would expect from e.g., W's
- The cross sections needed are 10-1000x the thermal



WIMP annihilations? Not so fast

- PAMELA sees no excess in antiprotons - excludes hadronic modes by order of magnitude (Cirelli et al, '08, Donato et al, '08)
- The spectrum at Fermi/PAMELA is very hard - not what you would expect from e.g., W's
- The cross sections needed are 10-1000x the thermal



The three ingredients to explain PAMELA/Fermi

The three ingredients to explain PAMELA/Fermi

- Hard lepton spectrum

The three ingredients to explain PAMELA/Fermi

- Hard lepton spectrum
- Few/no anti-protons

The three ingredients to explain PAMELA/Fermi

- Hard lepton spectrum
- Few/no anti-protons
- Large cross section (much larger than thermal - for annihilation)

The three ingredients to explain PAMELA/Fermi

- Hard lepton spectrum
- Few/no anti-protons
- Large cross section (much larger than thermal - for annihilation)
- All these can be explained by insisting that the dark matter has a new GeV scale force (Arkani-Hamed, Finkbeiner, Slatyer, NW, '08)

The XDM framework

Finkbeiner, NW astro-ph/0702587

The XDM framework

XDM:

Finkbeiner, NW astro-ph/0702587

- eXcited states
  - eXtra dark forces
    - eXtreme cosmic ray signatures

The XDM framework

XDM:

Finkbeiner, NW astro-ph/0702587

- eXcited states
  - eXtra dark forces
    - eXtreme cosmic ray signatures

cf generalizations Pospelov, Ritz, Voloshin, arxiv:0711.4866;
e^+e^- signatures Cholis, Goodenough, NW 0802.2922

The XDM framework

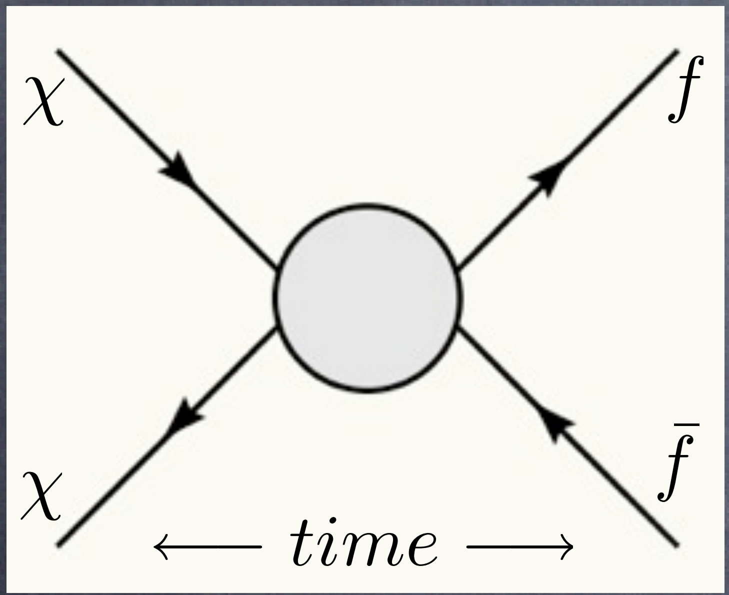
XDM:

Finkbeiner, NW astro-ph/0702587

eXcited states

eXtra dark forces

eXtreme cosmic ray signatures



"classic"
WIMP

cf generalizations Pospelov, Ritz, Voloshin, arxiv:0711.4866;
e^+e^- signatures Cholis, Goodenough, NW 0802.2922

The XDM framework

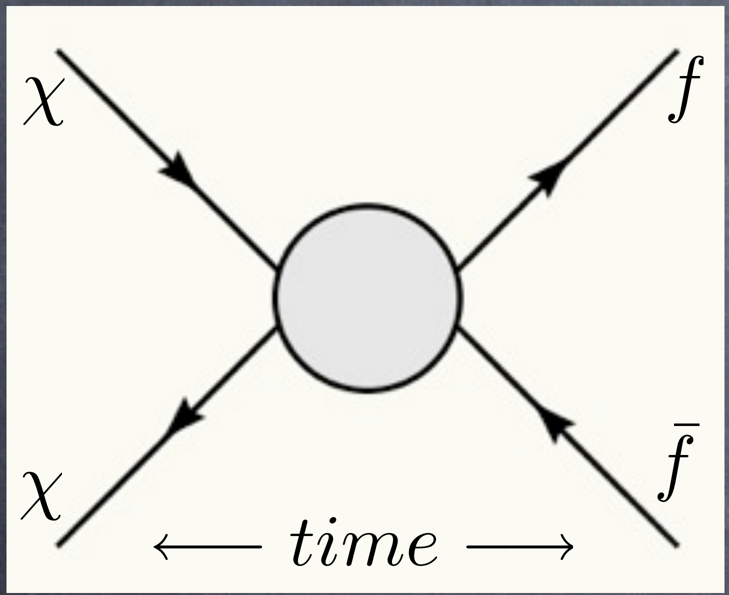
XDM:

Finkbeiner, NW astro-ph/0702587

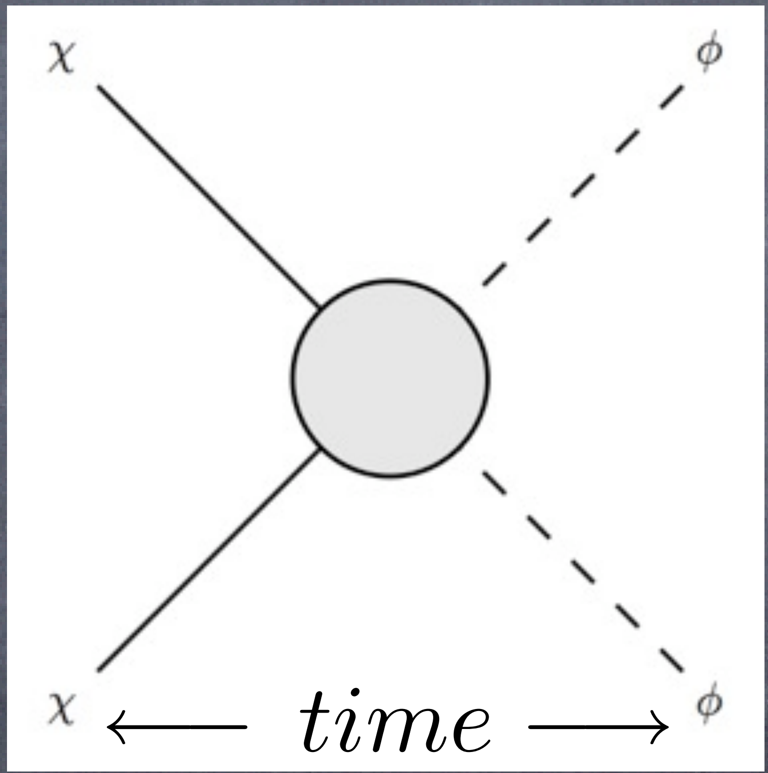
eXcited states

eXtra dark forces

eXtreme cosmic ray signatures



"classic" WIMP



XDM

cf generalizations Pospelov, Ritz, Voloshin, arxiv:0711.4866;
e^+e^- signatures Cholis, Goodenough, NW 0802.2922

The XDM framework

XDM:

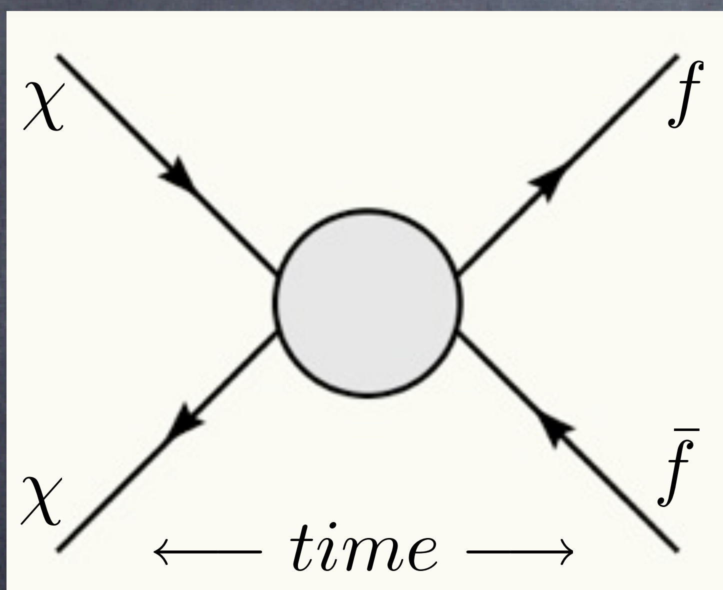
Finkbeiner, NW astro-ph/0702587

eXcited states

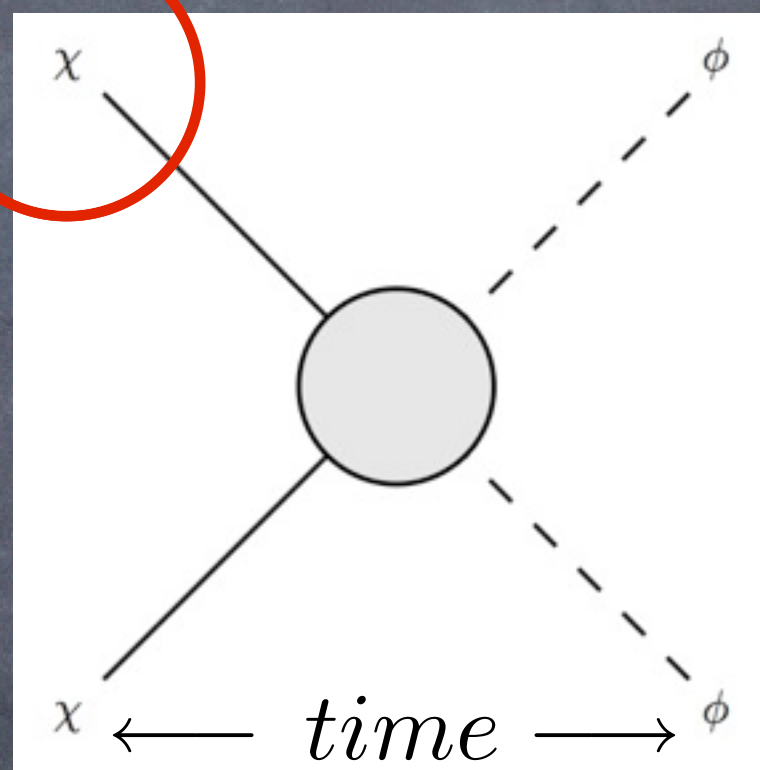
eXtra dark forces

eXtreme cosmic ray signatures

TeV



"classic" WIMP



XDM

cf generalizations Pospelov, Ritz, Voloshin, arxiv:0711.4866;

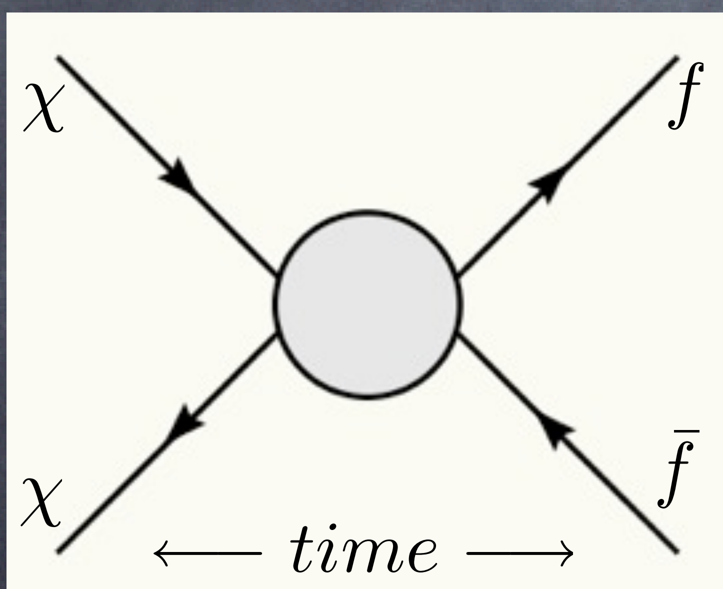
e^+e^- signatures Cholis, Goodenough, NW 0802.2922

The XDM framework

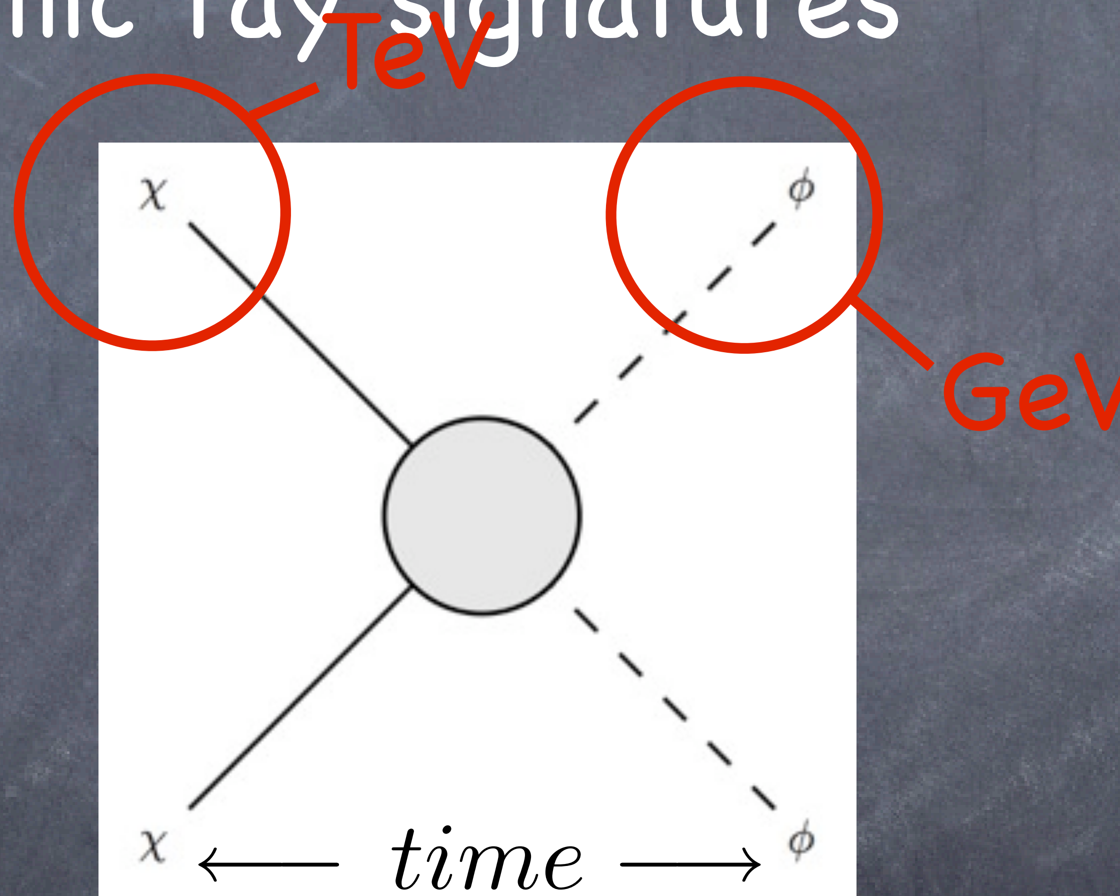
XDM:

Finkbeiner, NW astro-ph/0702587

- eXcited states
  - eXtra dark forces
    - eXtreme cosmic ray signatures



"classic"
WIMP



XDM

cf generalizations Pospelov, Ritz, Voloshin, arxiv:0711.4866;
e^+e^- signatures Cholis, Goodenough, NW 0802.2922

The XDM framework

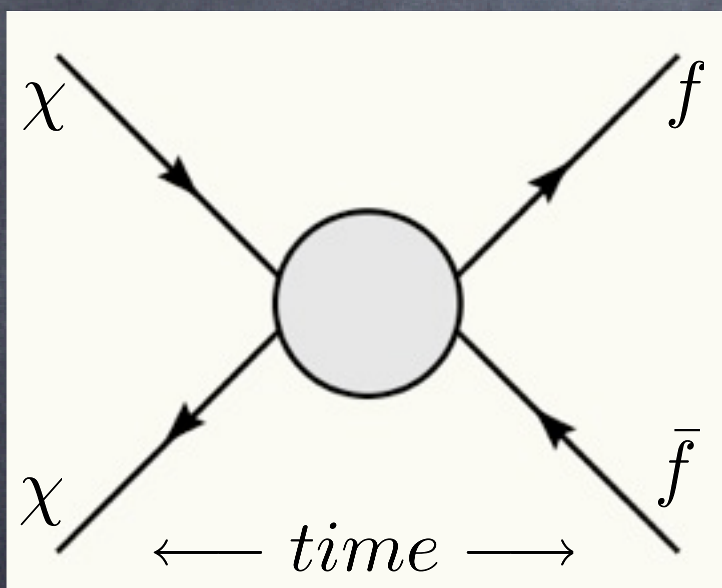
XDM:

Finkbeiner, NW astro-ph/0702587

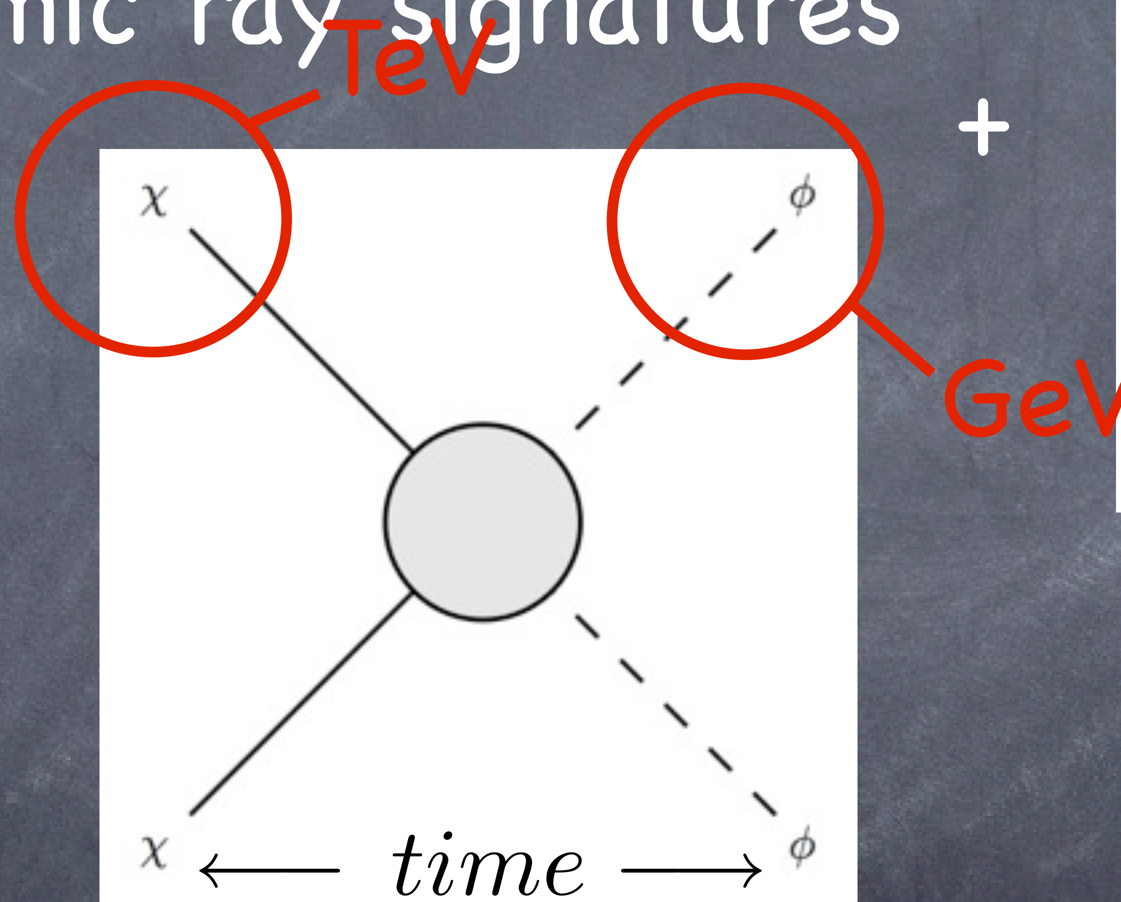
eXcited states

eXtra dark forces

eXtreme cosmic ray signatures

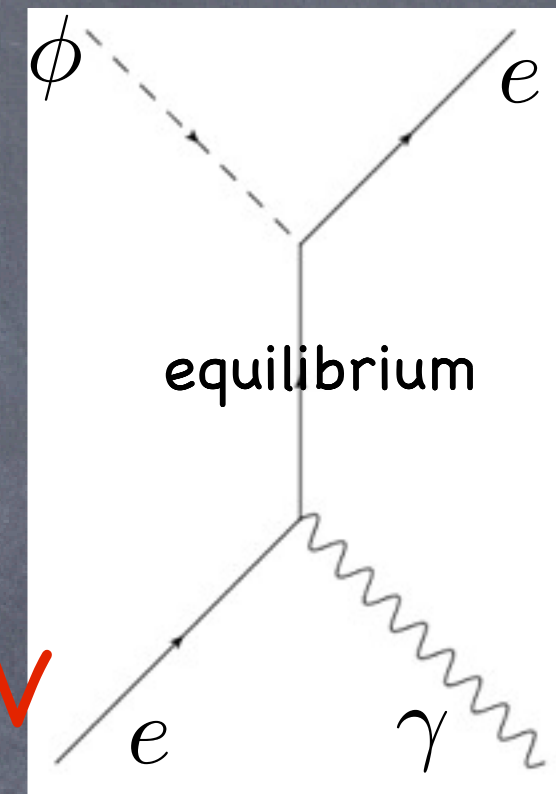


"classic"
WIMP



XDM

+



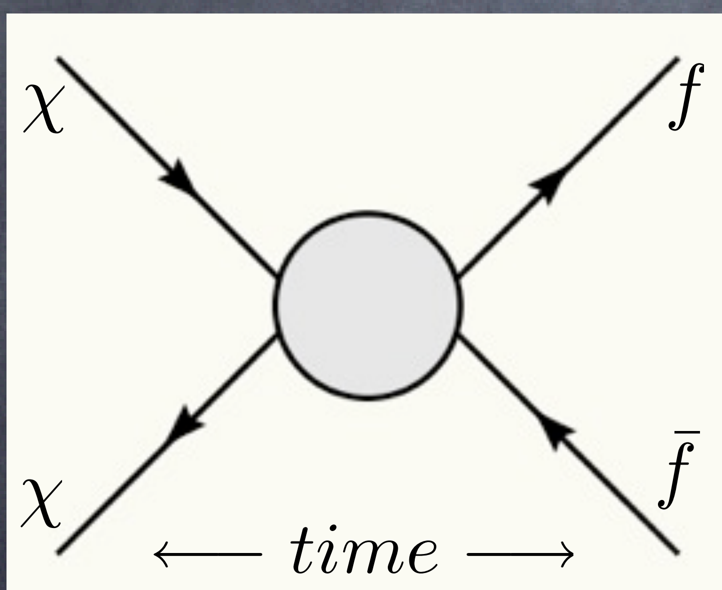
cf generalizations Pospelov, Ritz, Voloshin, arxiv:0711.4866;
e^+e^- signatures Cholis, Goodenough, NW 0802.2922

The XDM framework

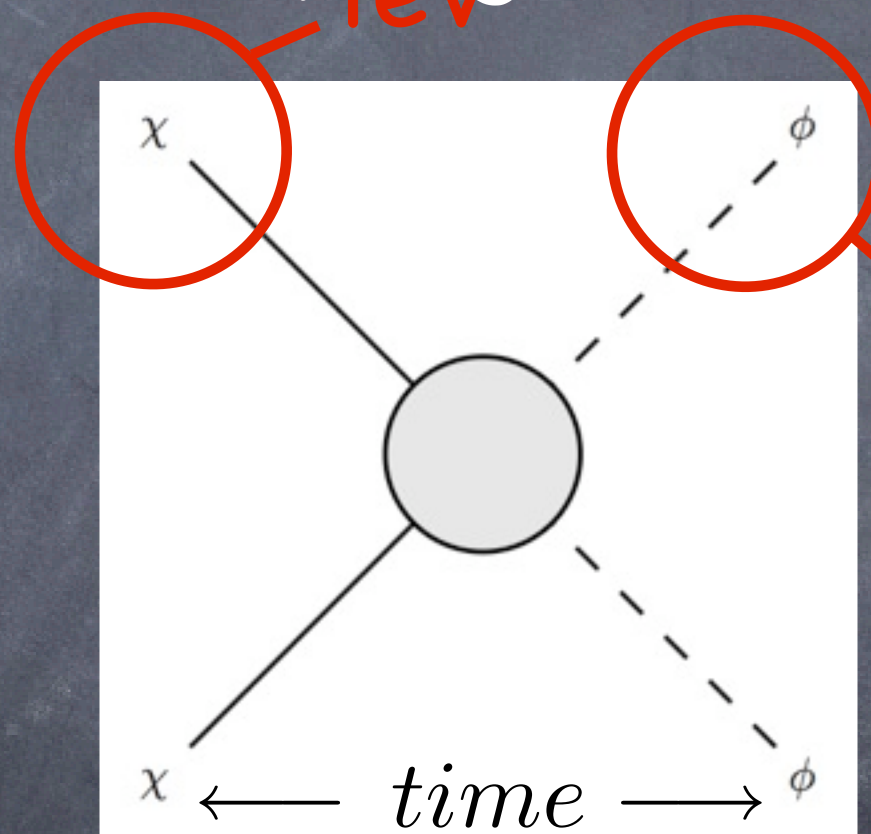
XDM:

Finkbeiner, NW astro-ph/0702587

- eXcited states
  - eXtra dark forces
    - eXtreme cosmic ray signatures

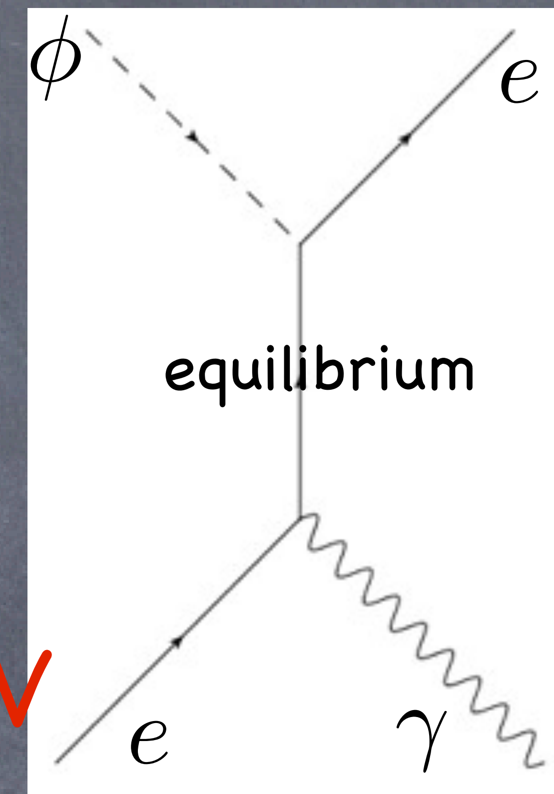


"classic"
WIMP

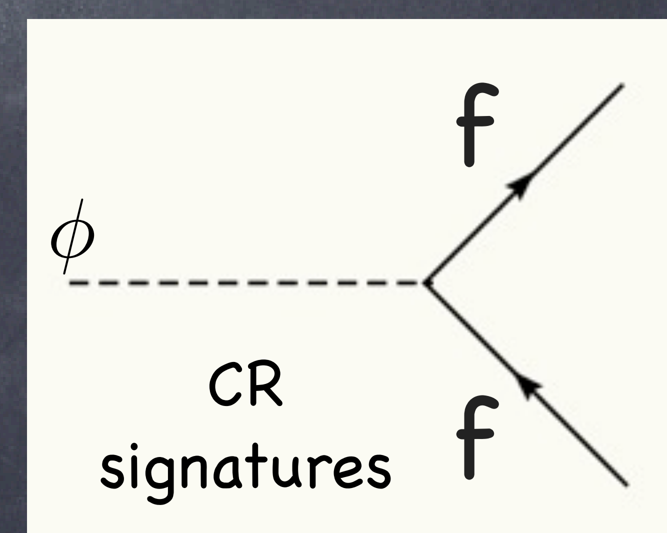


XDM

+



+



cf generalizations Pospelov, Ritz, Voloshin, arxiv:0711.4866;
e^+e^- signatures Cholis, Goodenough, NW 0802.2922

The XDM framework

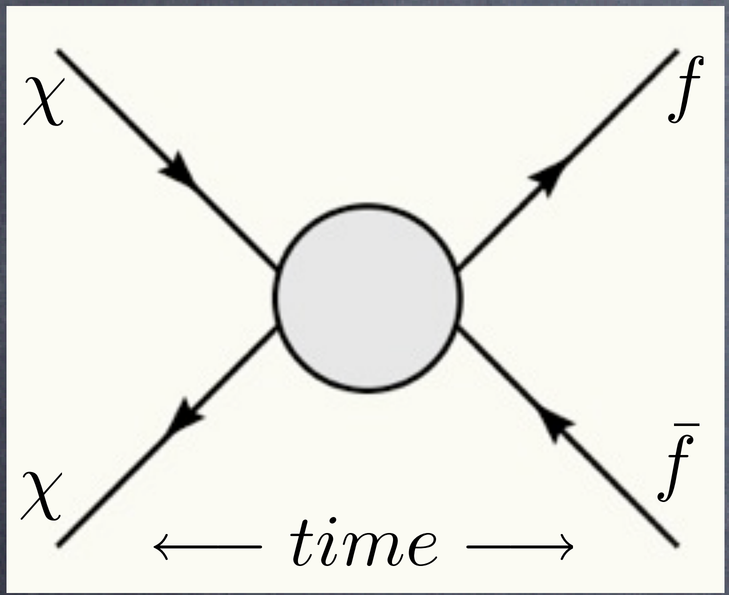
XDM:

Finkbeiner, NW astro-ph/0702587

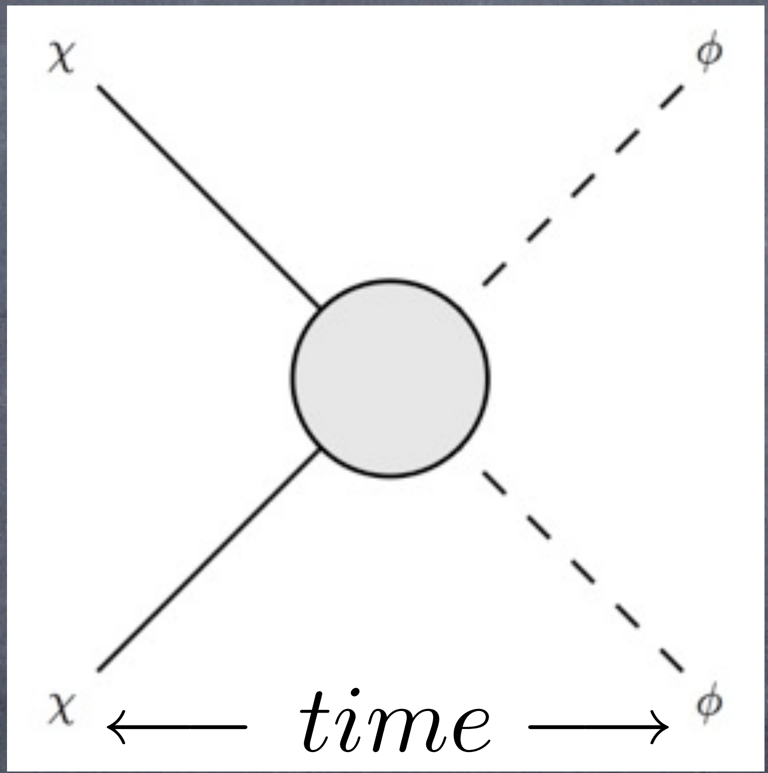
eXcited states

eXtra dark forces

eXtreme cosmic ray signatures

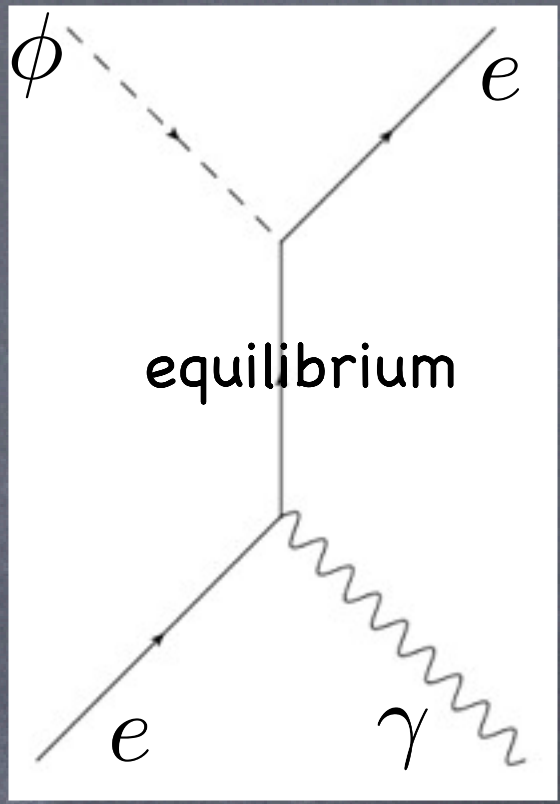


"classic"
WIMP

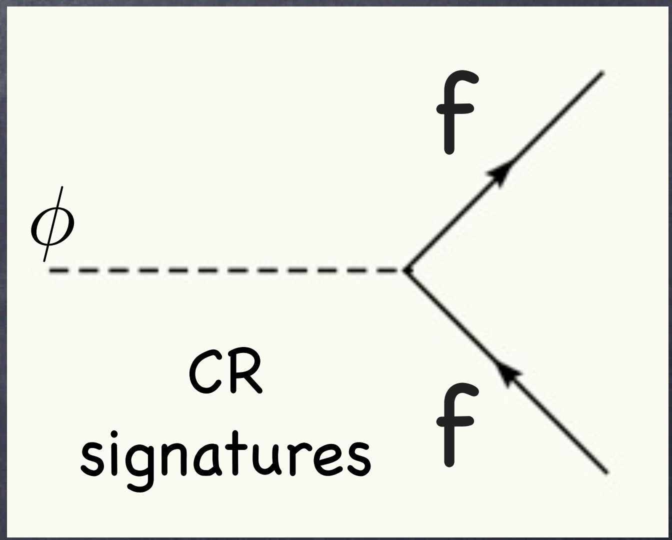


XDM

+



+



cf generalizations Pospelov, Ritz, Voloshin, arxiv:0711.4866;
e^+e^- signatures Cholis, Goodenough, NW 0802.2922

The XDM framework

XDM:

Finkbeiner, NW astro-ph/0702587

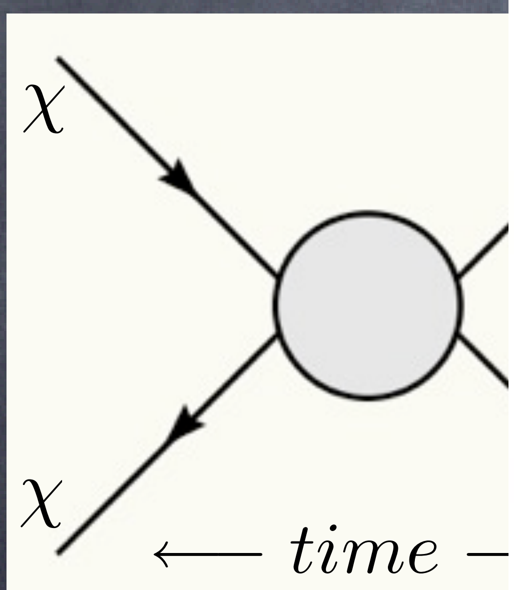
eXcited s

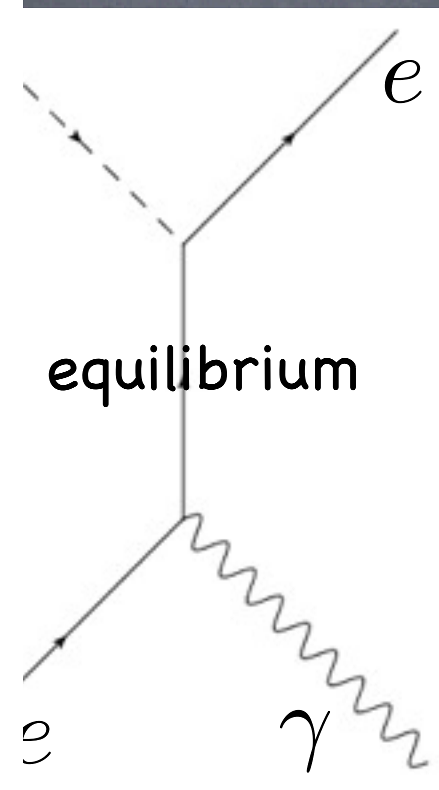
eXtra d

eXtrem

Although the freezeout process of XDM is similar to that of an ordinary WIMP, the scattering and annihilation products can clearly be different. One important feature is that the annihilation products are typically electrons and neutrinos for $m_\phi < 2m_\pi$. However, unlike, e.g., MeV dark matter, when the particles annihilate the resulting electrons and positrons are extremely energetic. This is intriguing because both the HEAT data [30] and the “haze” from the center of the galaxy [31, 32] point to new sources of multi-GeV electrons and positrons. Here, these high energy particles (from boosted on-shell ϕ particles) are related to the low energy positrons detected by INTEGRAL (from off-shell ϕ particles). Such high energy particles may create high-energy gamma rays from inverse scattering off starlight which could be observed in the future GLAST mission.

Finkbeiner + NW ’07



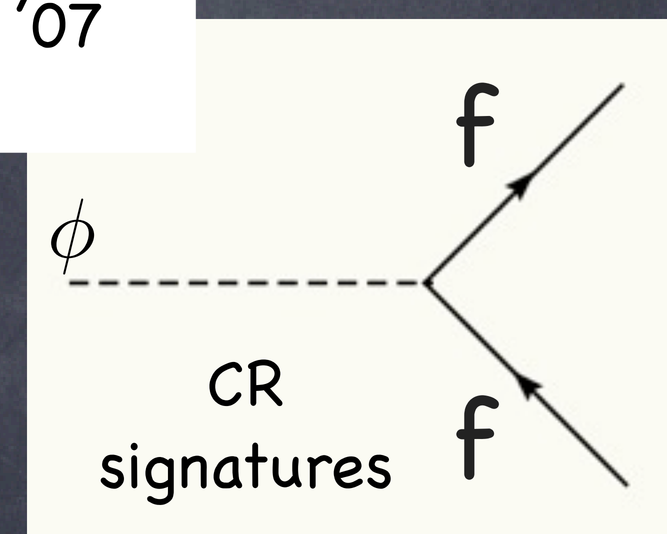


“classic

WIMP

XDM

\+



cf generalizations Pospelov, Ritz, Voloshin, arxiv:0711.4866;

e^+e^- signatures Cholis, Goodenough, NW 0802.2922

New forces = new annihilation modes

Finkbeiner, NW PRD '07

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

New forces = new annihilation modes

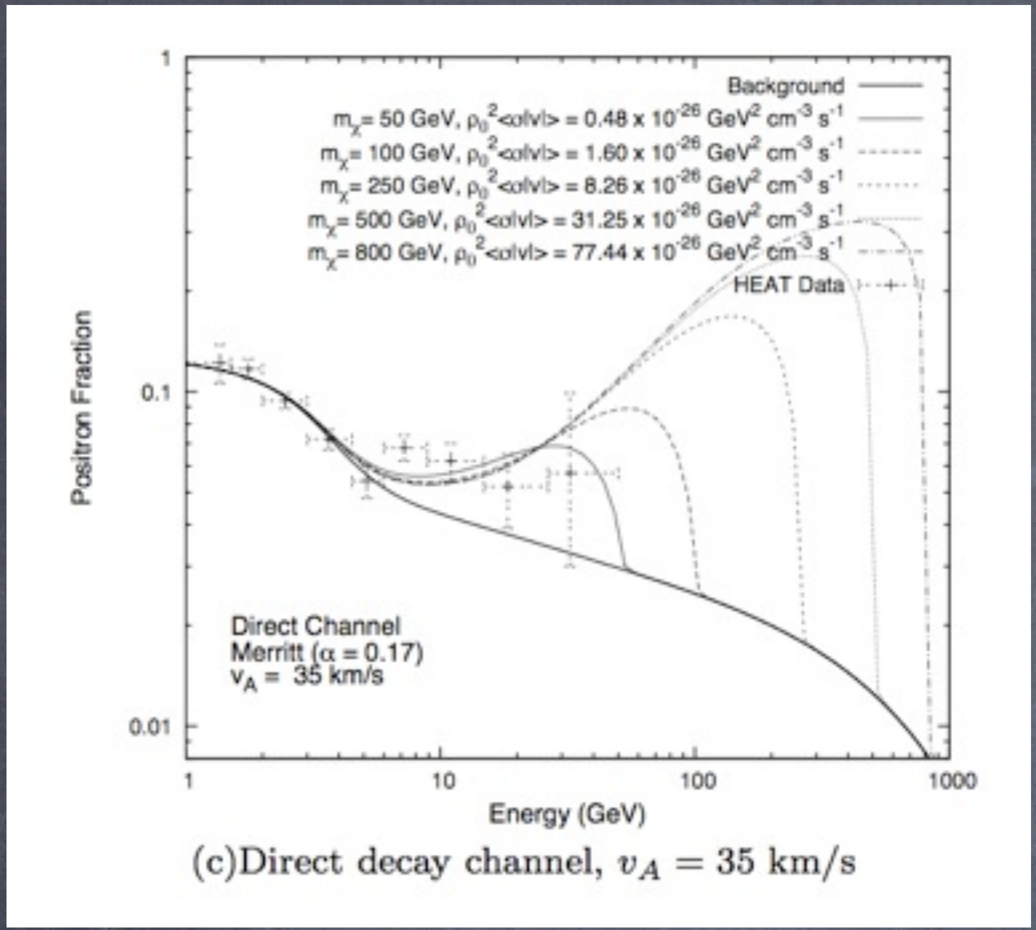
Finkbeiner, NW PRD '07

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

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

New forces = new annihilation modes

Finkbeiner, NW PRD '07



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

Cholis, Goodenough, NW, arxiv:0802.2922

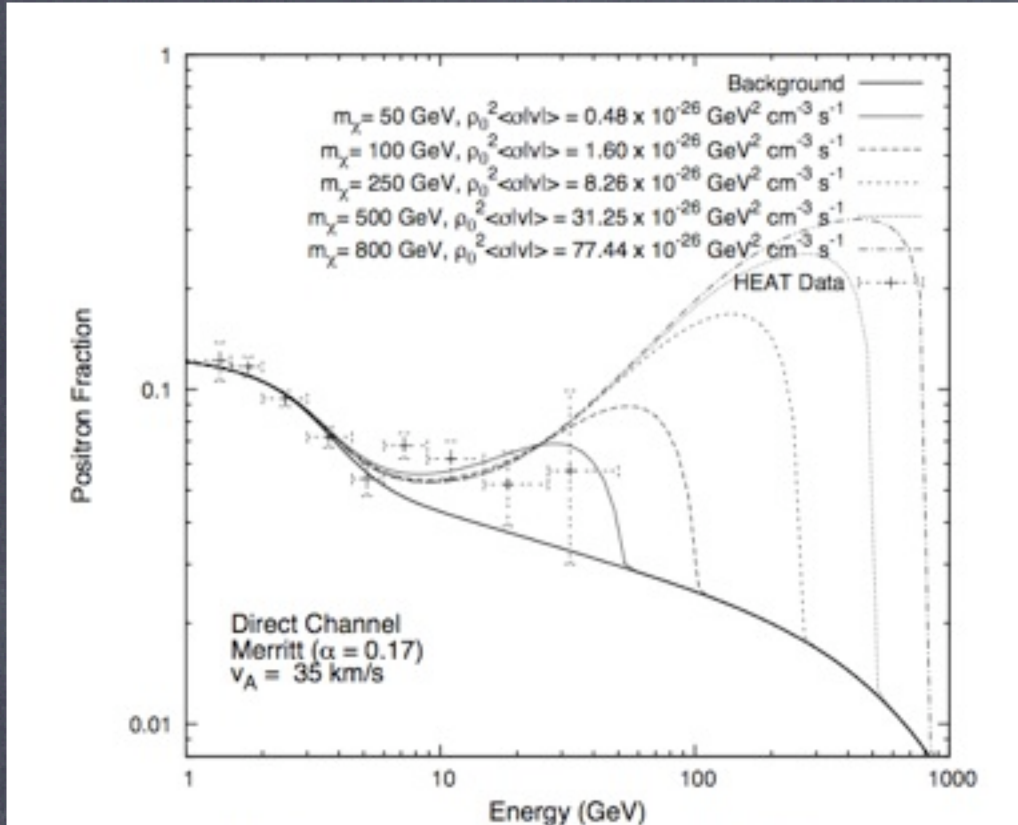
Pre-PAMELA

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

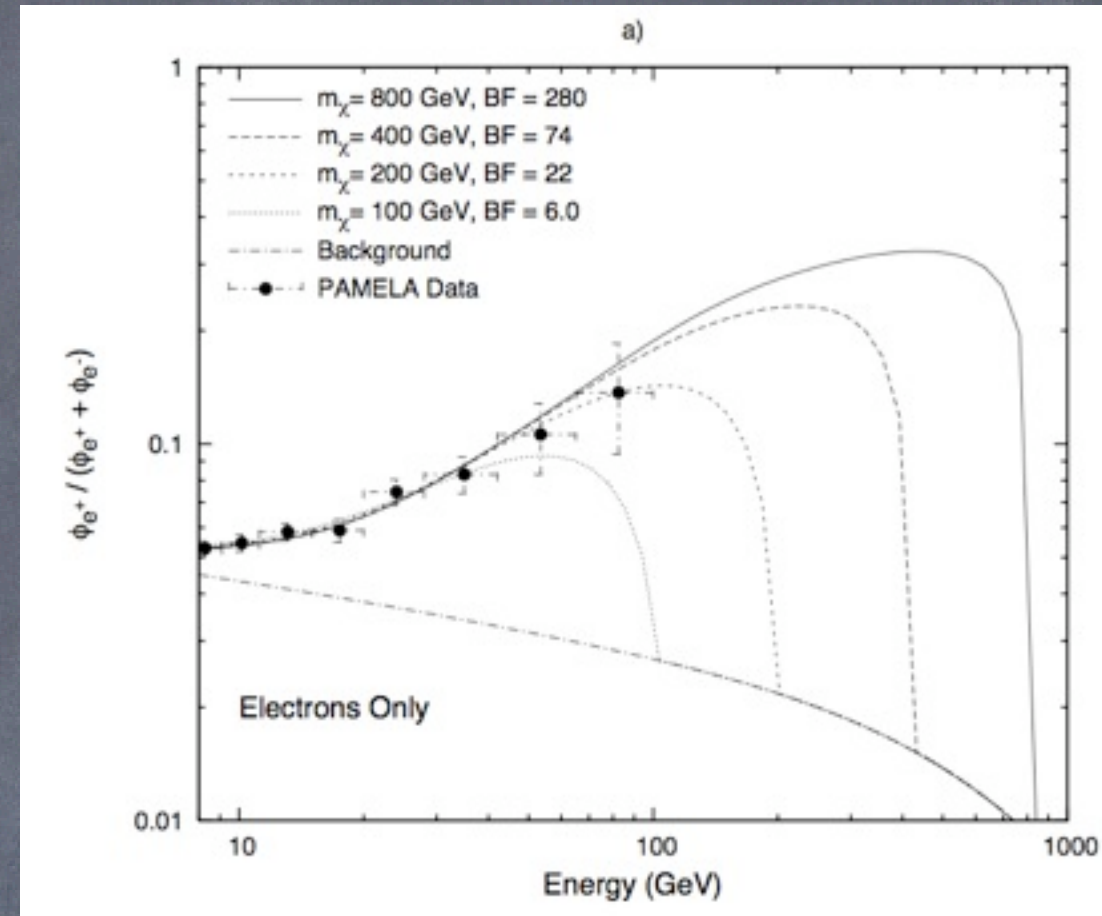
Arkani-Hamed, Finkbeiner, Slatyer, NW, '08

New forces = new annihilation modes

Finkbeiner, NW PRD '07



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



Cholis, Goodenough, NW, arxiv:0802.2922

Cholis, et al, arxiv:0810.5344

Pre-PAMELA

Post-PAMELA

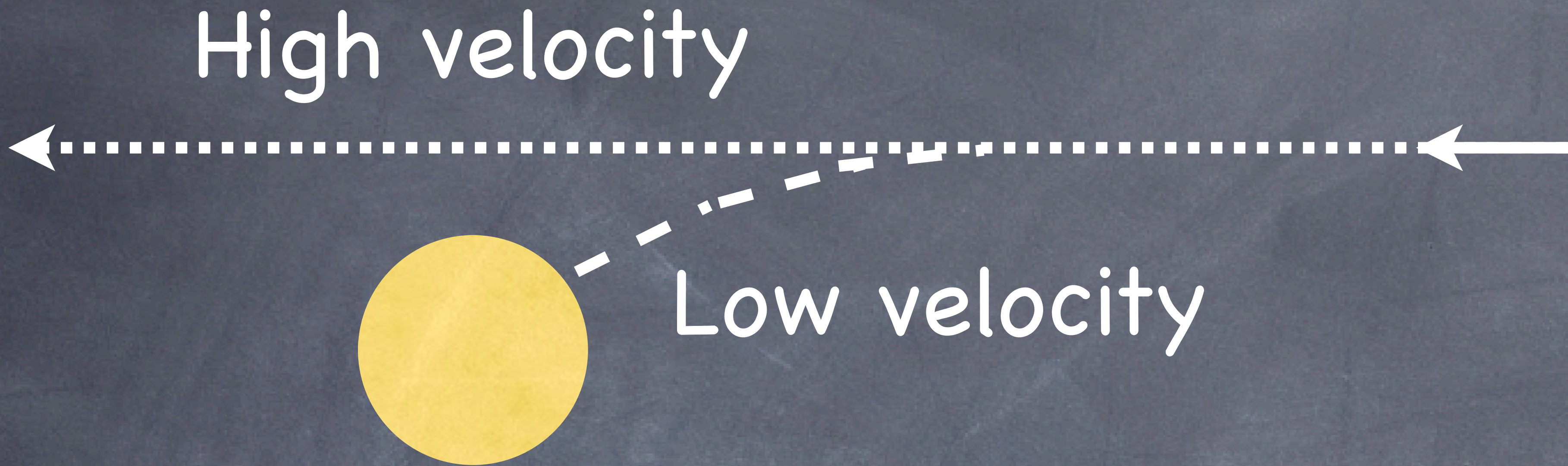
- "WIMP Miracle" works as before (sigma ~ $1/M^2$)
- No antiprotons from kinematics
- Hard positrons come from highly boosted ϕ's

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

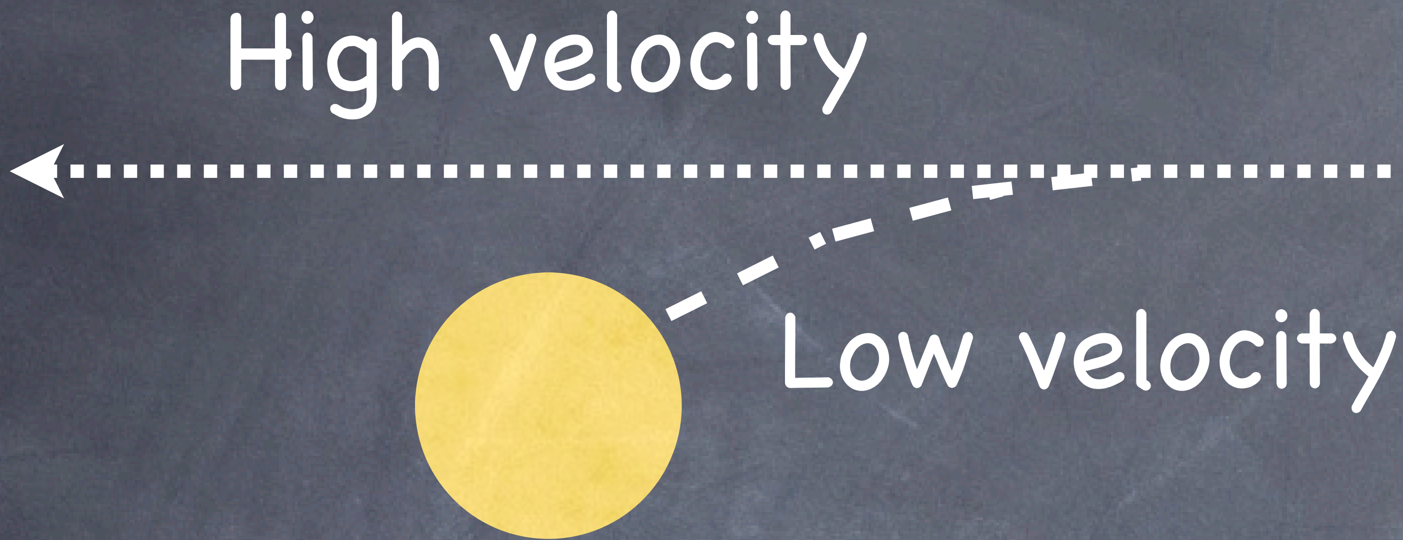
Sommerfeld Enhancement

High velocity

Sommerfeld Enhancement

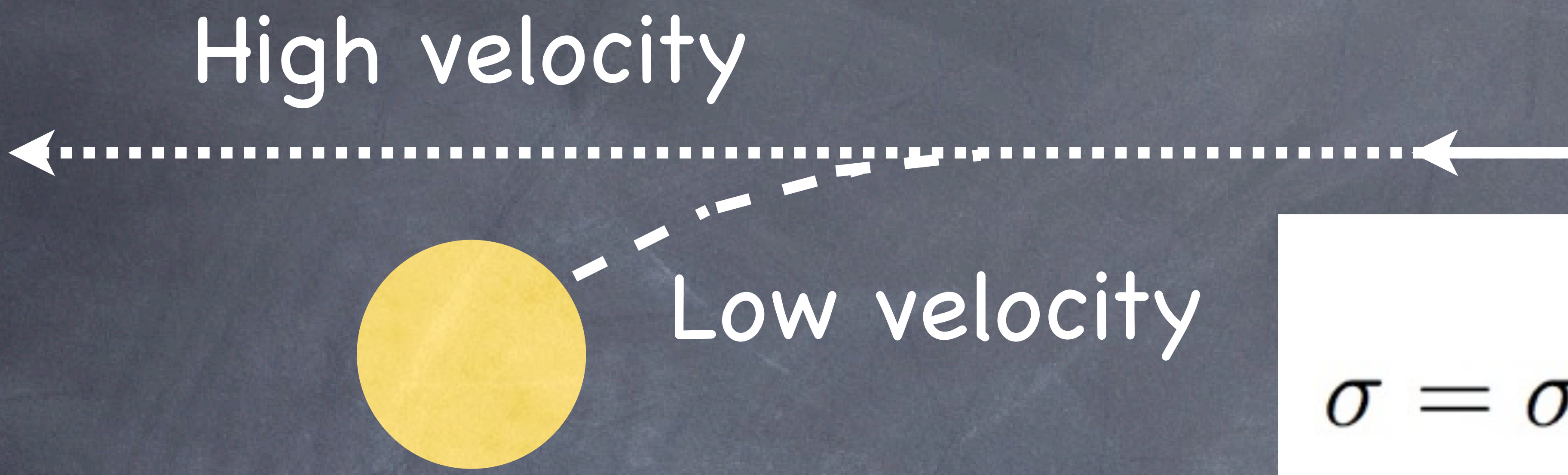


Sommerfeld Enhancement



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

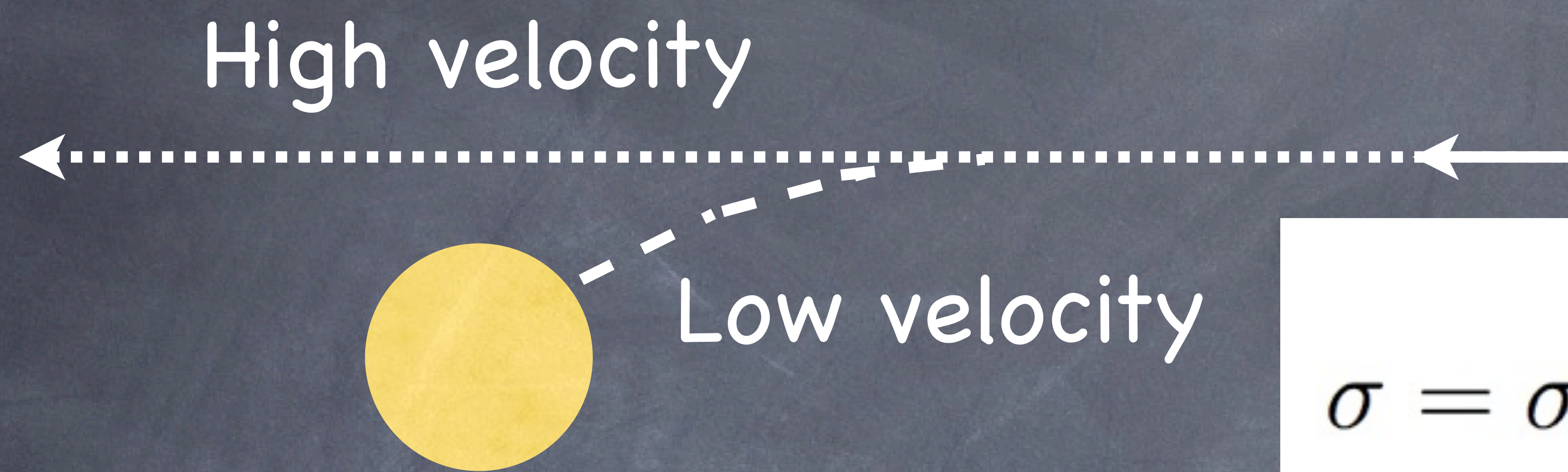
Sommerfeld Enhancement



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

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

Sommerfeld Enhancement

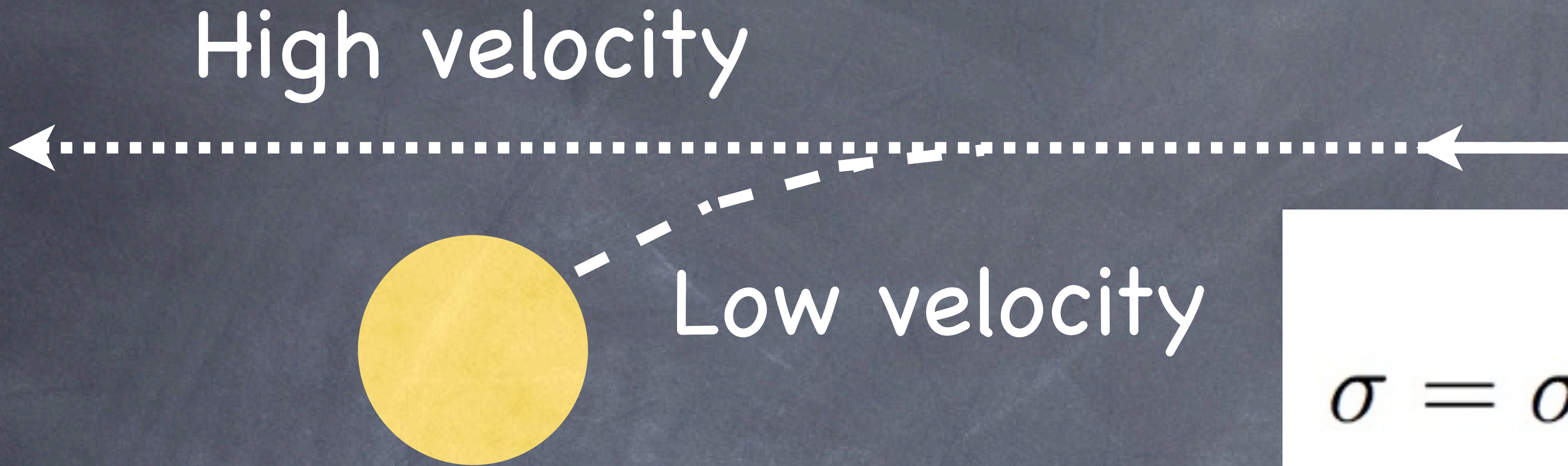


$$\sigma = \sigma_0 \left(1 + \frac{v_{esc}^2}{v^2} \right)$$

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

Sommerfeld Enhancement

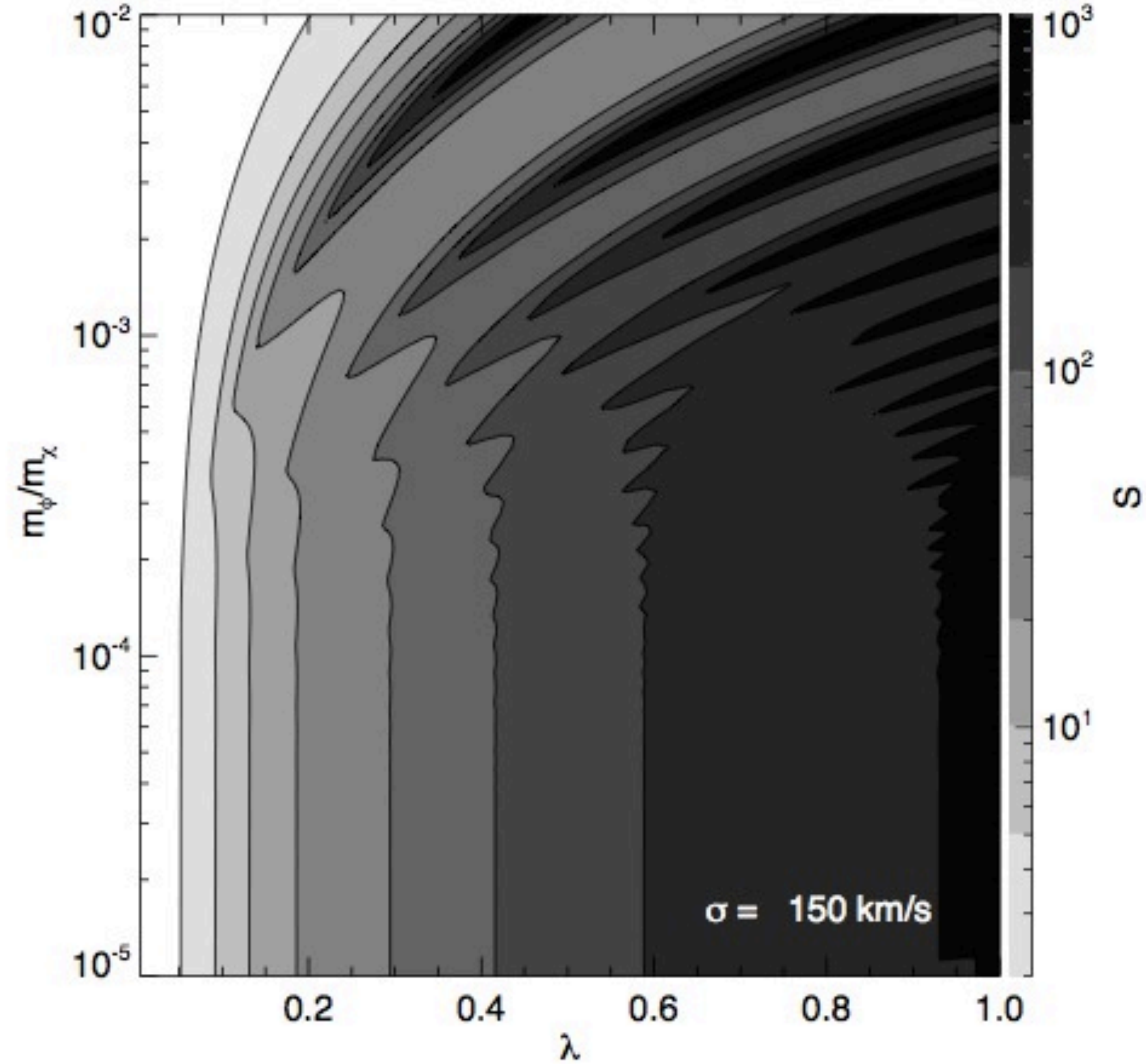


$$\sigma = \sigma_0 \left(1 + \frac{v_{esc}^2}{v^2} \right)$$

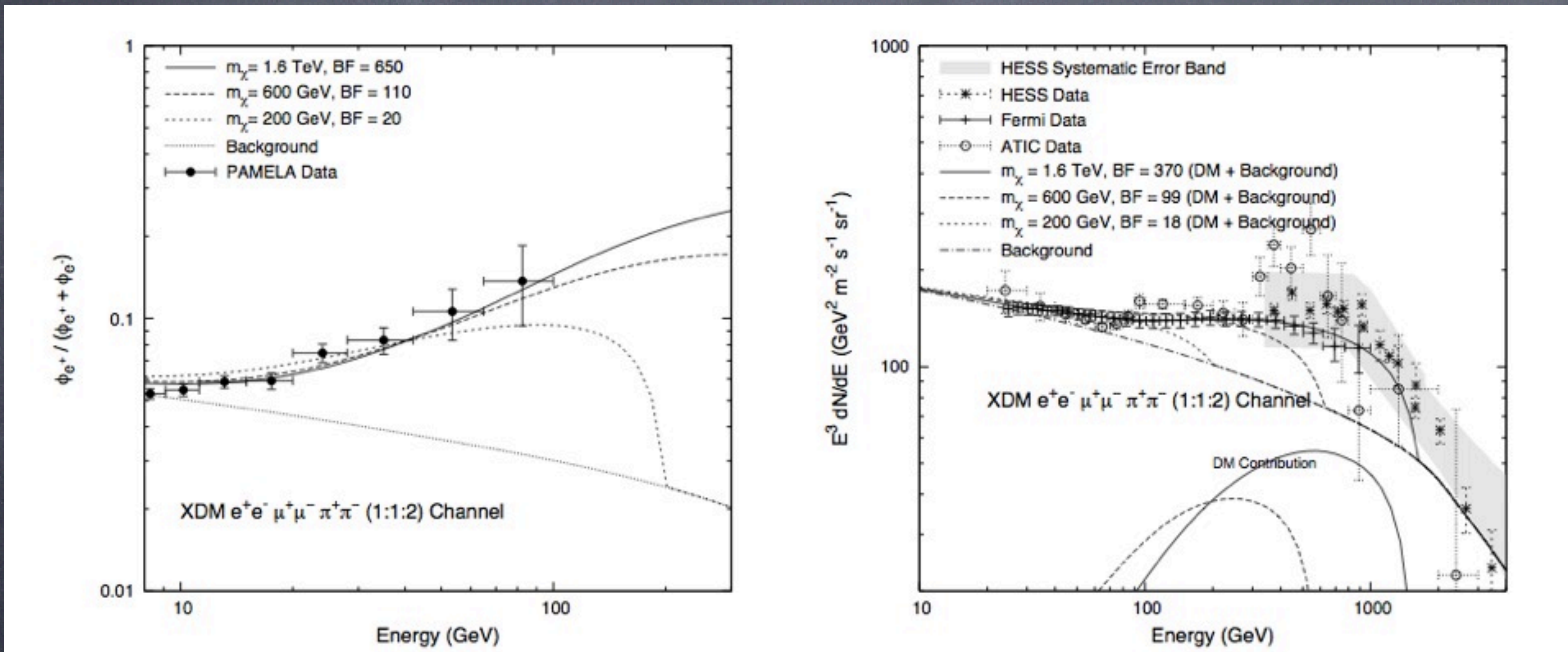
If particles interact via a "long range" force, cross sections can be much larger than the perturbative cross section

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

long ~ fm



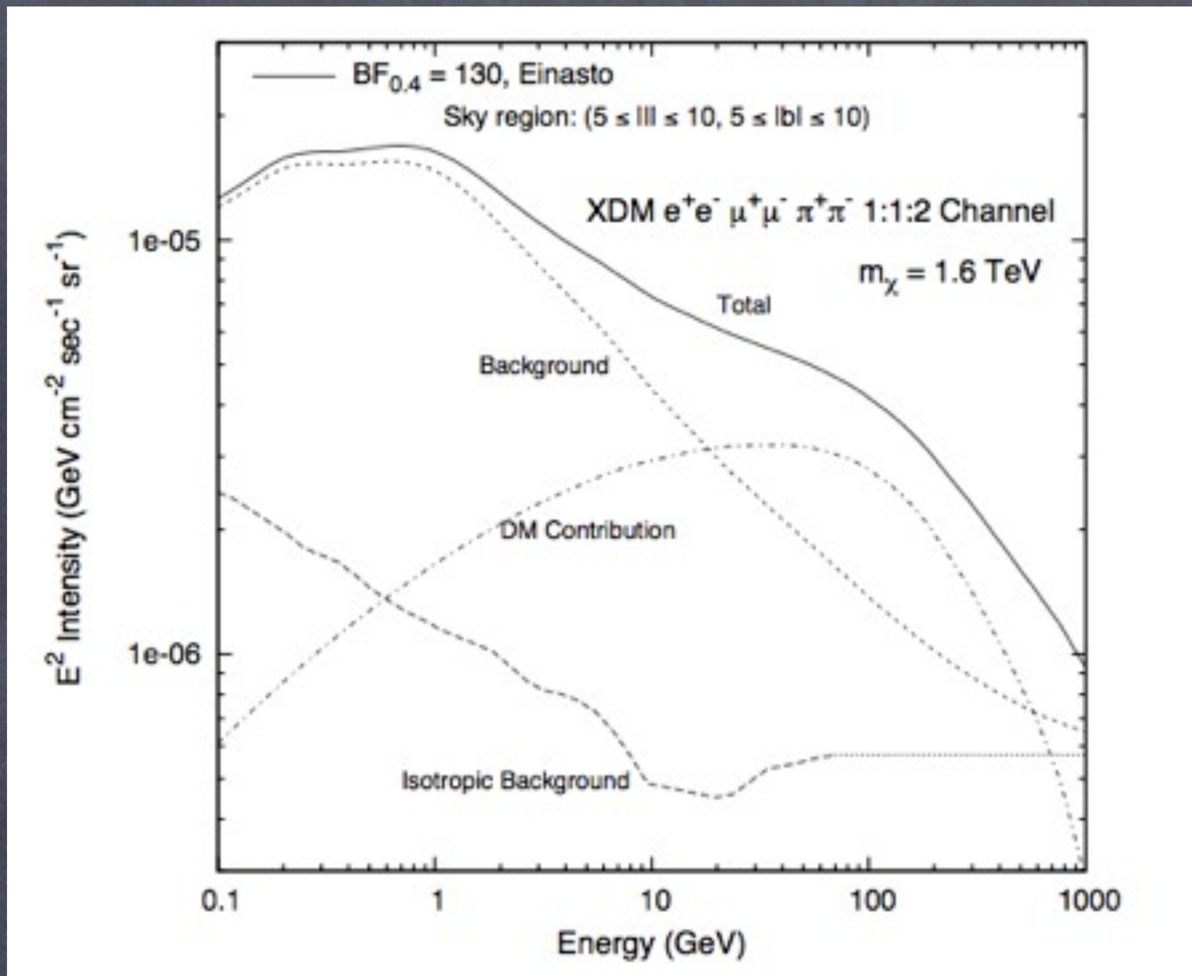
10^{-2}
10^{-3}
10^{-4}
10^{-5}
m_ϕ/m_χ
0.2
0.4
0.6
0.8
1.0
λ
$\sigma = 150$ km/s
10^3
10^2
10^1
S



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
$\phi_{e^+} / (\phi_{e^+} + \phi_{e^-})$
Energy (GeV)
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)

A new force carrier

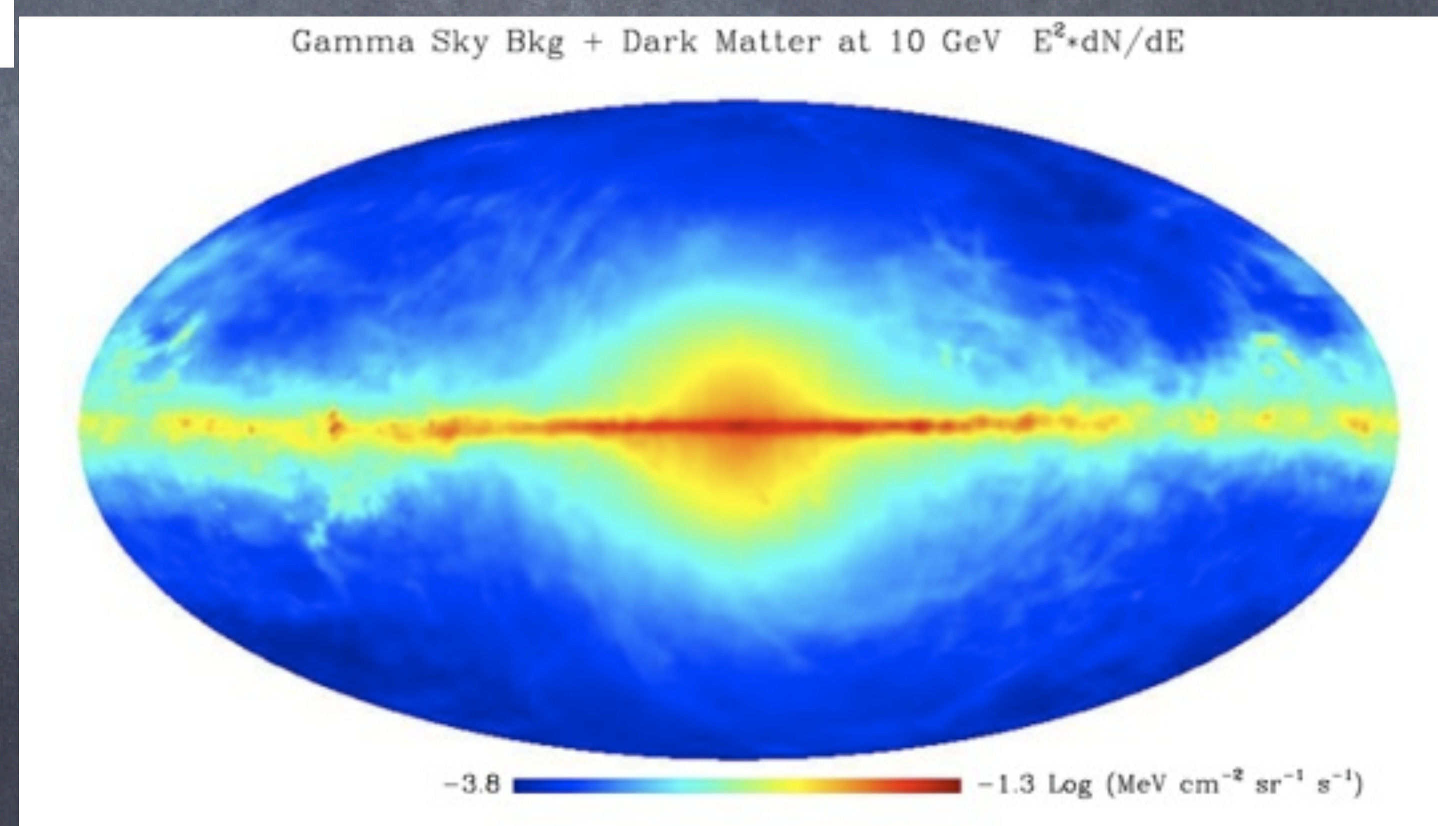
- Dark matter interacting with a new force naturally explains the cosmic ray signatures
  - Large cross section (Sommerfeld)
  - Lots of leptons (too light to go into much else)
  - No anti-protons (too light to make them)



ICS gamma rays should show change in index at high energies

Inner galaxy

(ISRF) Porter et al, ApJ 682 08;
(Connections to PAMELA) Cholis et al, 0811.3641; Zhang et al, arXiv:0812.0522; Borriello, Cuoco, Miele, arXiv: 0903.1852; Regis, Ulio arXiv:0904.4645 ; Cirelli, Panci arXiv:0904.3830; Meade, Papucci, Strumia, Volansky, arxiv: 0905.0480; Cholis et al arxiv:0907.3953

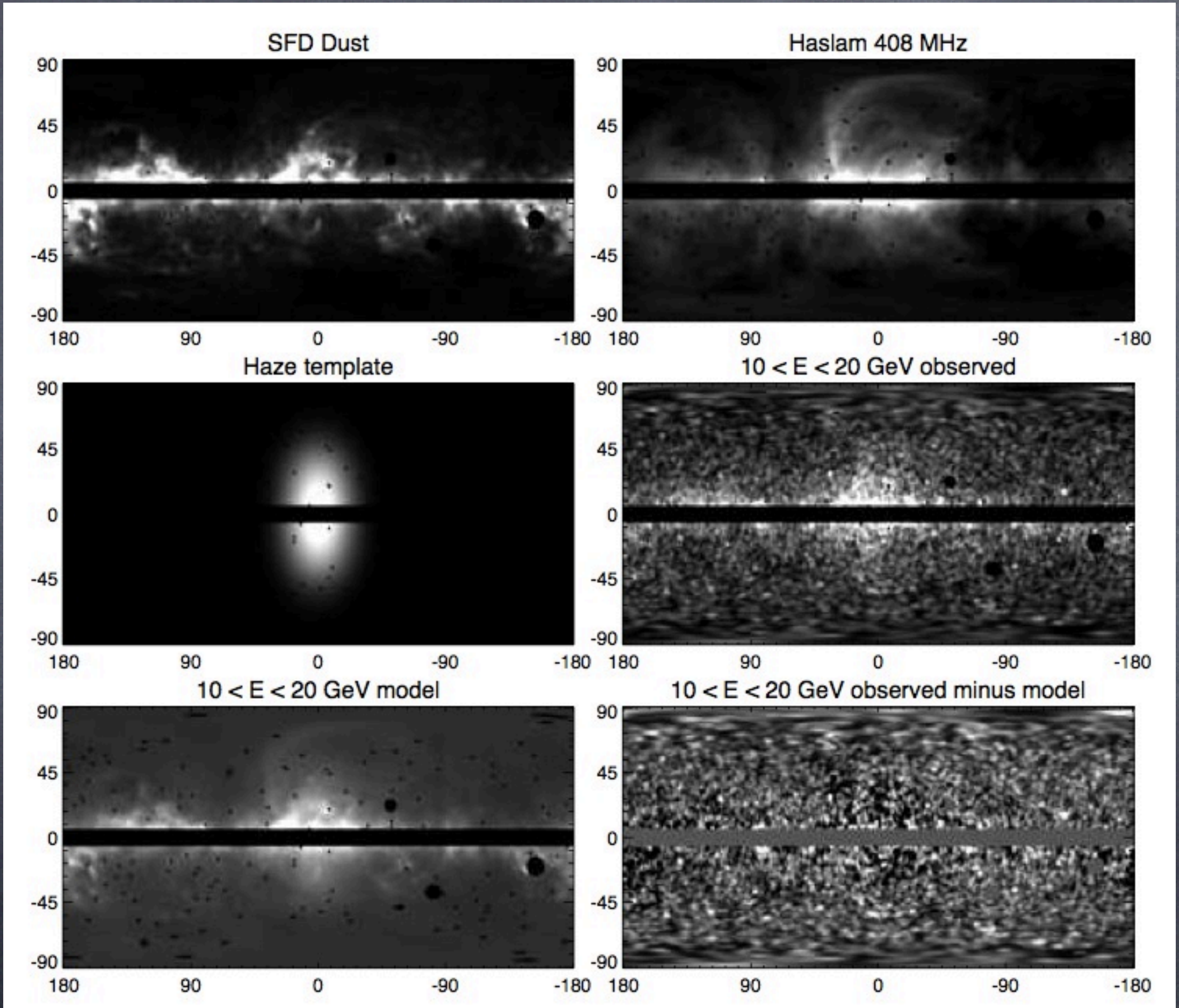


Borriello, Cuoco, Miele, arXiv:0903.1852

A Regression Analysis

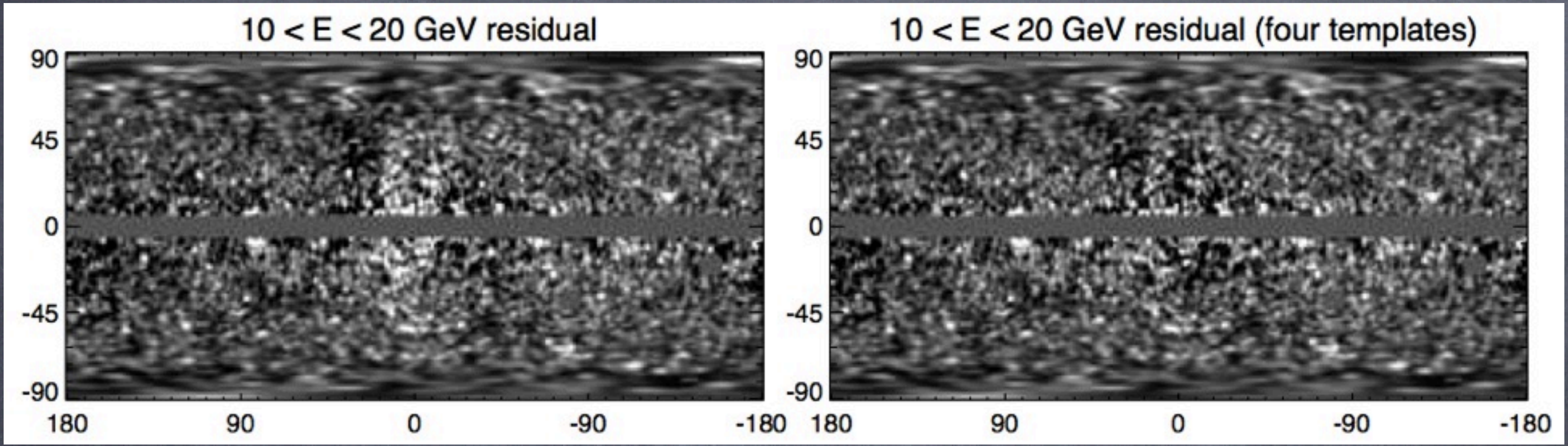
Dobler et al, '09

- Can approach the inner galaxy with simple (but physical) approach
- Use **spatial** morphology to address backgrounds
- SFD dust map as tracer of of pions, Haslam as tracer of (soft) ICS



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

The Fermi Haze



- Template analysis indicates hardening of electron spectrum in IG
- A long way from knowing the origin, but could have been a strong constraint

DM in the era of anomalies

DM in the era of anomalies

- A wide range of anomalies have forced us to reconsider our assumptions about DM

DM in the era of anomalies

- A wide range of anomalies have forced us to reconsider our assumptions about DM
- Large electronic excesses at Fermi/PAMELA require large rates of lepton production

DM in the era of anomalies

- A wide range of anomalies have forced us to reconsider our assumptions about DM
- Large electronic excesses at Fermi/PAMELA require large rates of lepton production
- New GeV mass force can give boost without appealing to substructure and e+e- through kinematics

DM in the era of anomalies

- A wide range of anomalies have forced us to reconsider our assumptions about DM
- Large electronic excesses at Fermi/PAMELA require large rates of lepton production
- New GeV mass force can give boost without appealing to substructure and e+e- through kinematics
- Diffuse emission may hold hints of DM, but too early to say

Thanks to the Fermi Collaboration!

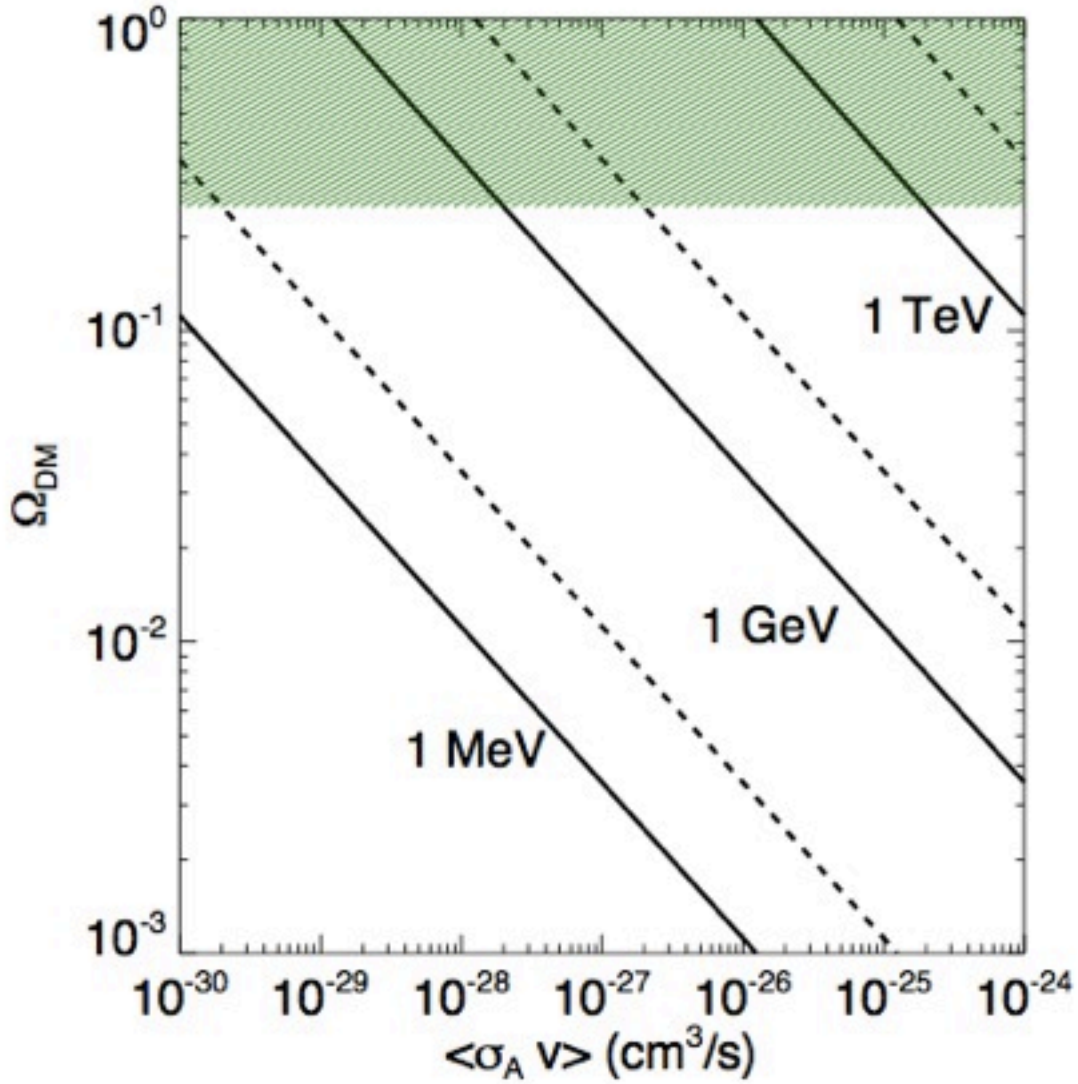


FIG. 8: Contours in the Ω_{DM}-$\langle\sigma_A v\rangle$ plane with $\epsilon_{dm,0} = 10^{-24}$ eV/s, for $M_{DM}/f = 1$ TeV, 1 GeV, and 1 MeV (solid), and 10 TeV, 10 GeV, and 10 MeV (dashed). Regions above these contours are accessible to an experiment with the sensitivity to measure $\epsilon_{dm,0} = 10^{-24}$ eV/s. The shaded region shows the region excluded by our fiducial model.

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.

Slatyer, Finkbeiner, Padmanabhan '09

Finkbeiner and Padmanabhan '05

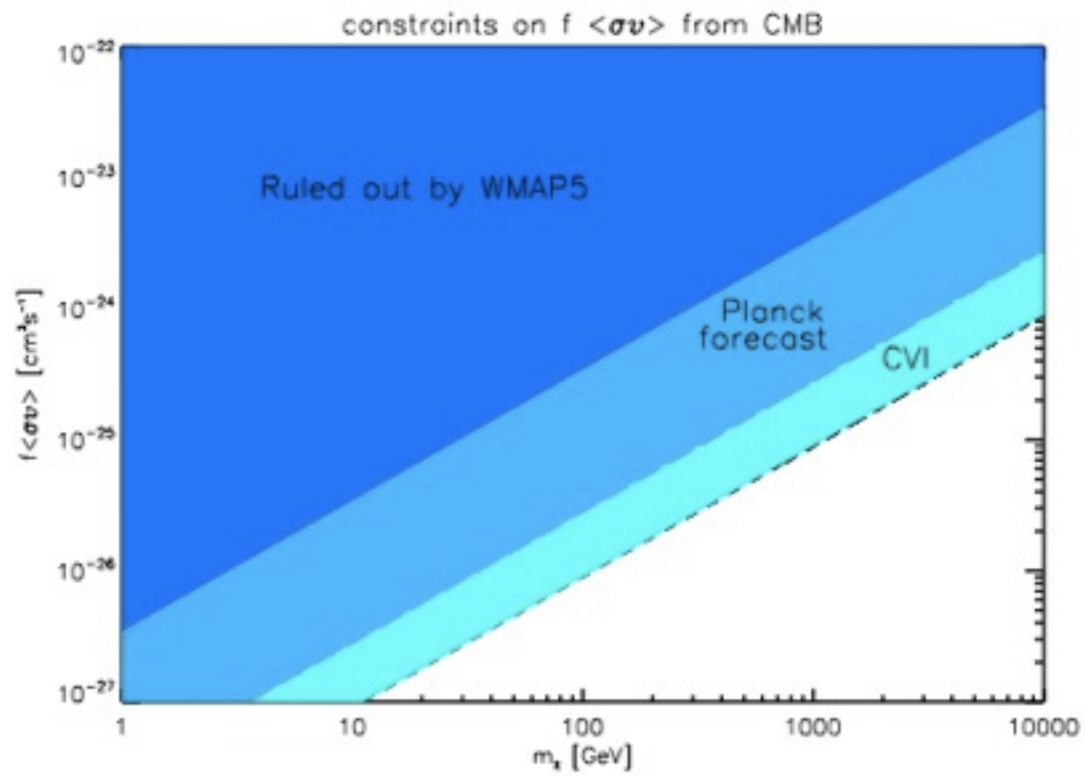


FIG. 4: Constraints on the self-annihilation cross-section at recombination $(\sigma v)_{z_r}$ times the gas–shower coupling parameter f. The dark blue area is already excluded by WMAP5 data, whereas the more stringent limit (dashed area) refers to the constraints which will be possible to apply with Planck. The light blue area is the zone ultimately allowed to probe by a cosmic variance limited experiment with angular resolution comparable to Planck.

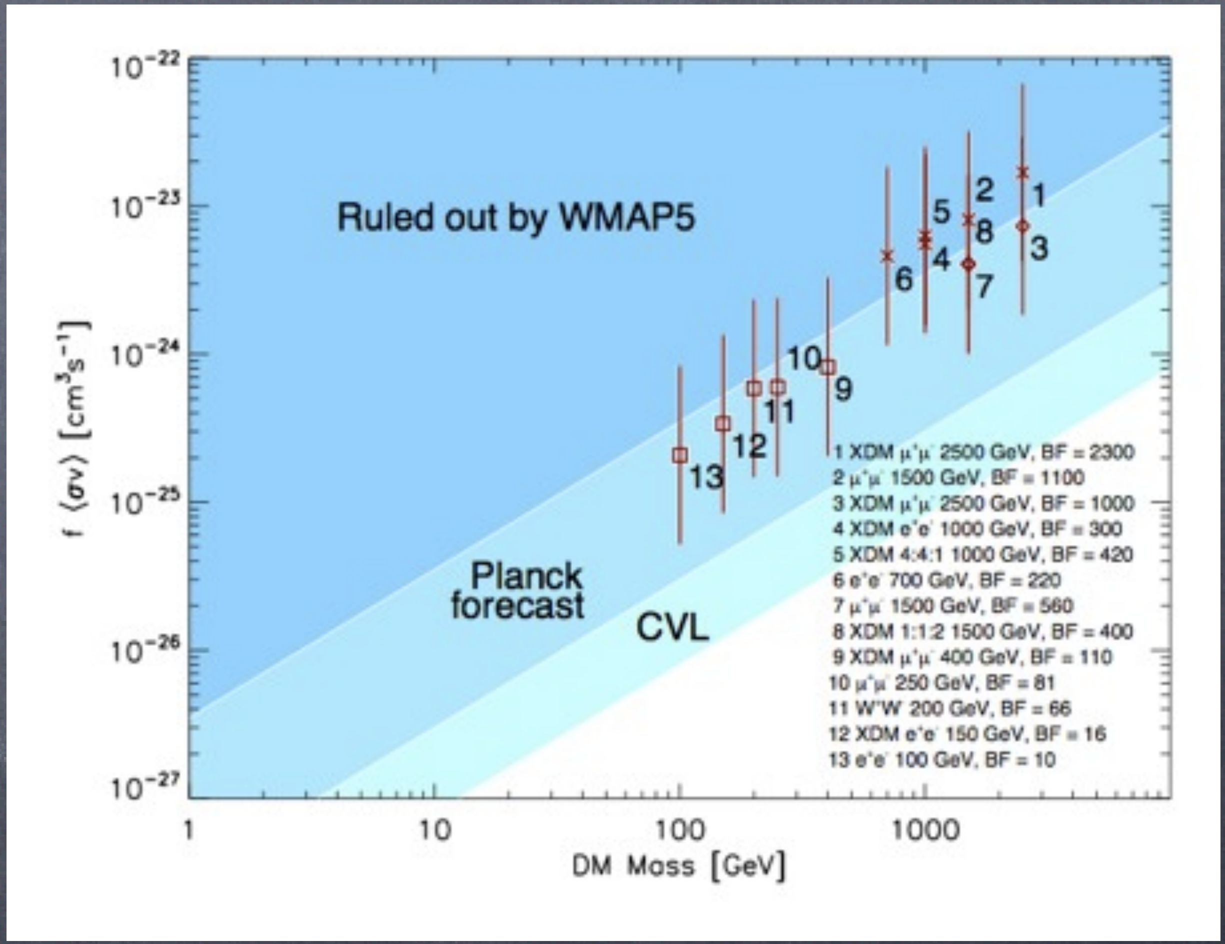
Galli, Iocco, Bertone, Melchiorri '09

Going Forward

Planck

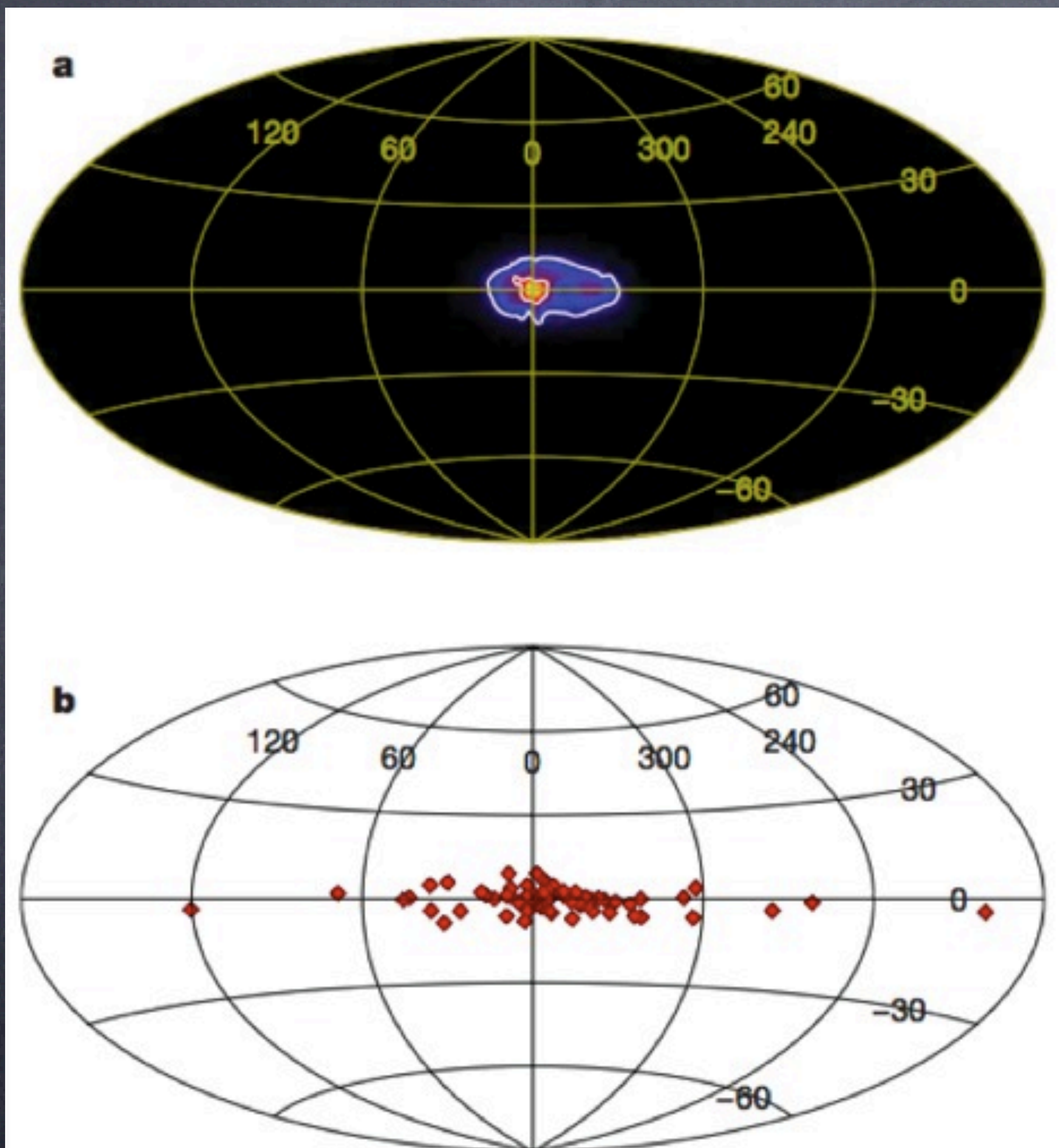
Slatyer, Finkbeiner, Padmanabhan '09

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

INTEGRAL



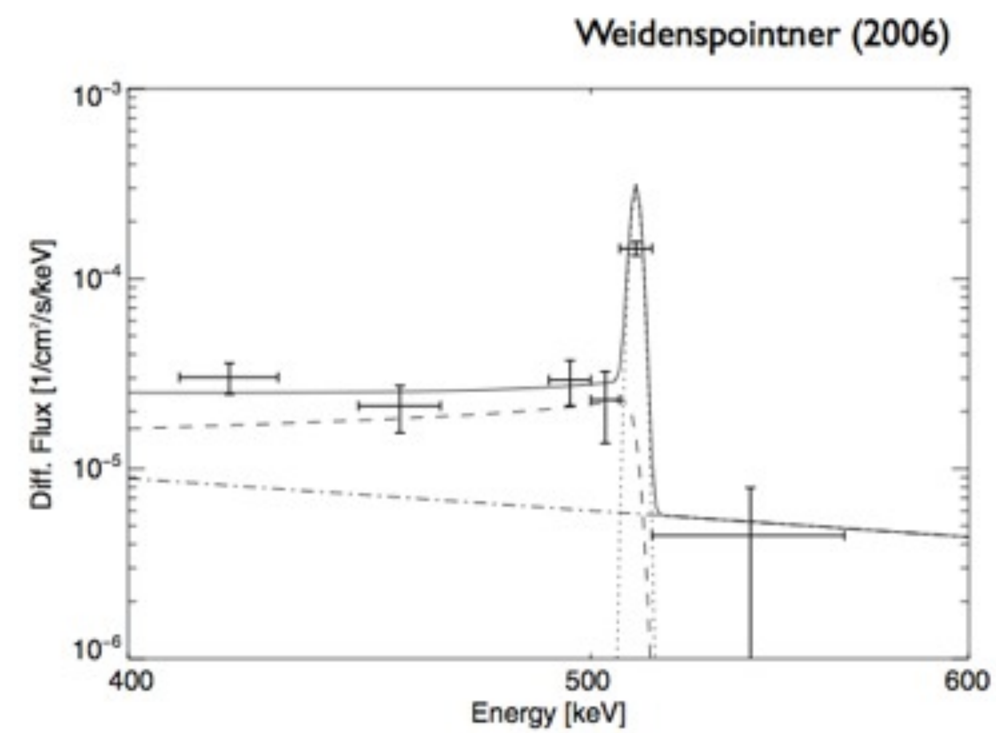
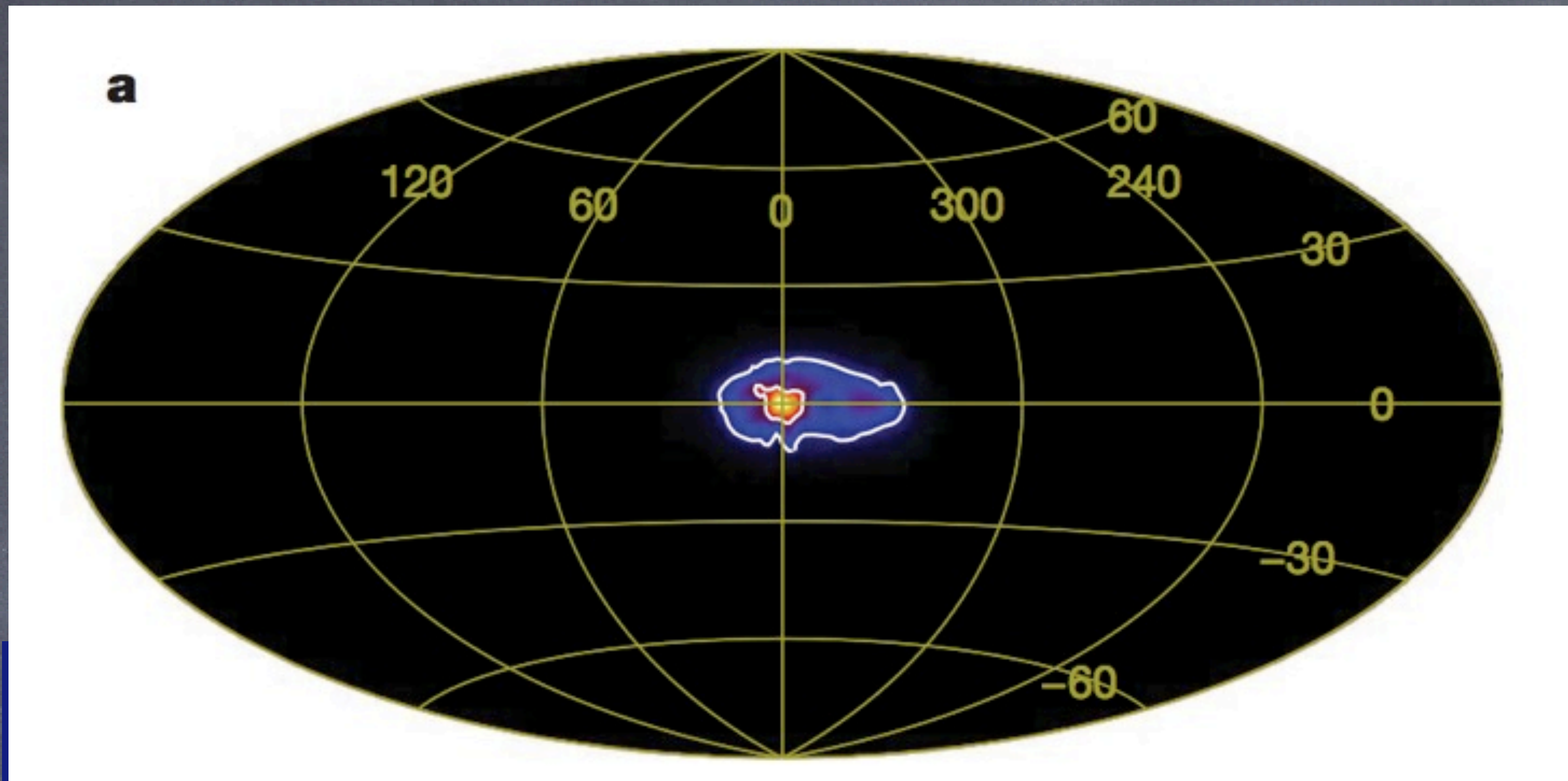
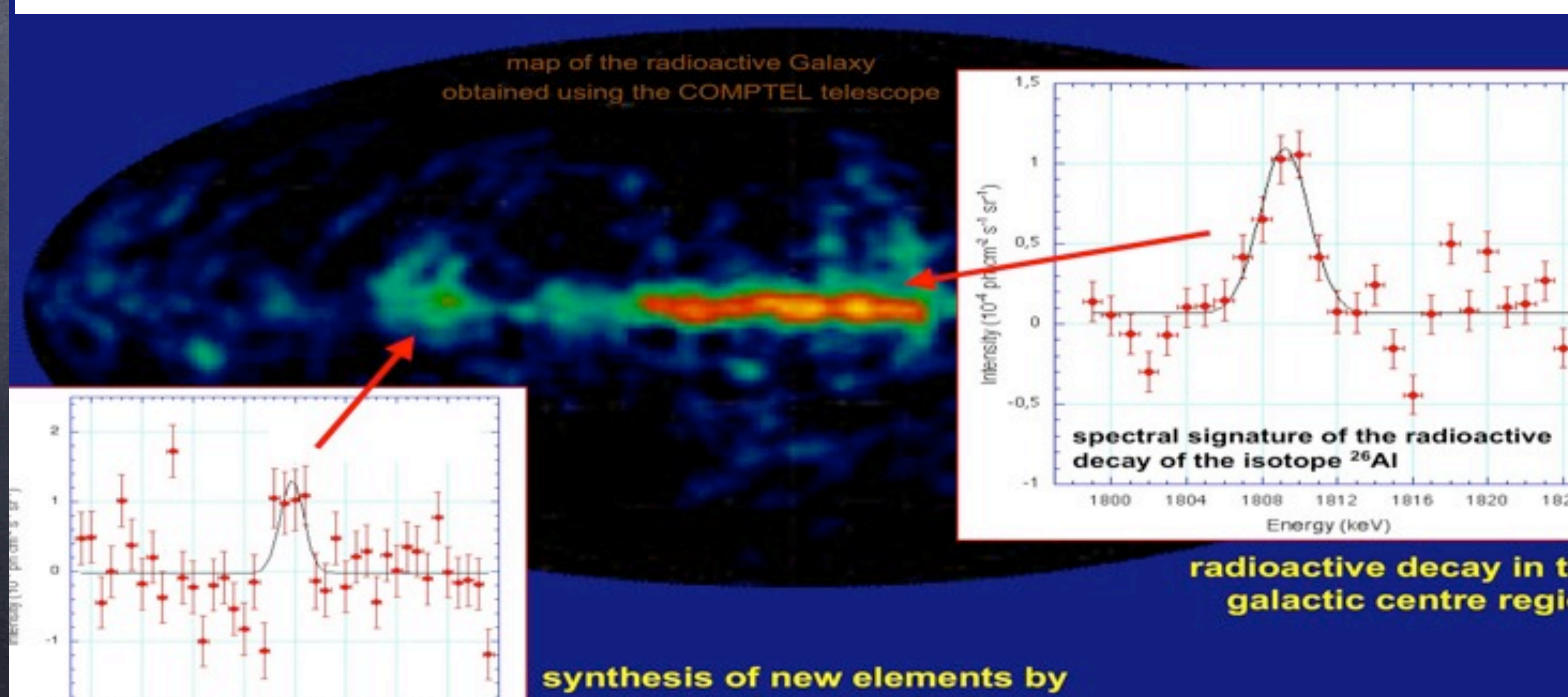


Fig. 2. A fit of the SPI result for the diffuse emission from the GC region ($|l|, |b| \leq 16°$) obtained with a spatial model consisting of an 8° *FWHM* Gaussian bulge and a CO disk. In the fit a diagonal response was assumed. The spectral components are: 511 keV line (dotted), Ps continuum (dashes),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

LMXB's having some trouble: Private communcation: P. Ubertini

distribution of the INTEGRAL 511 keV line

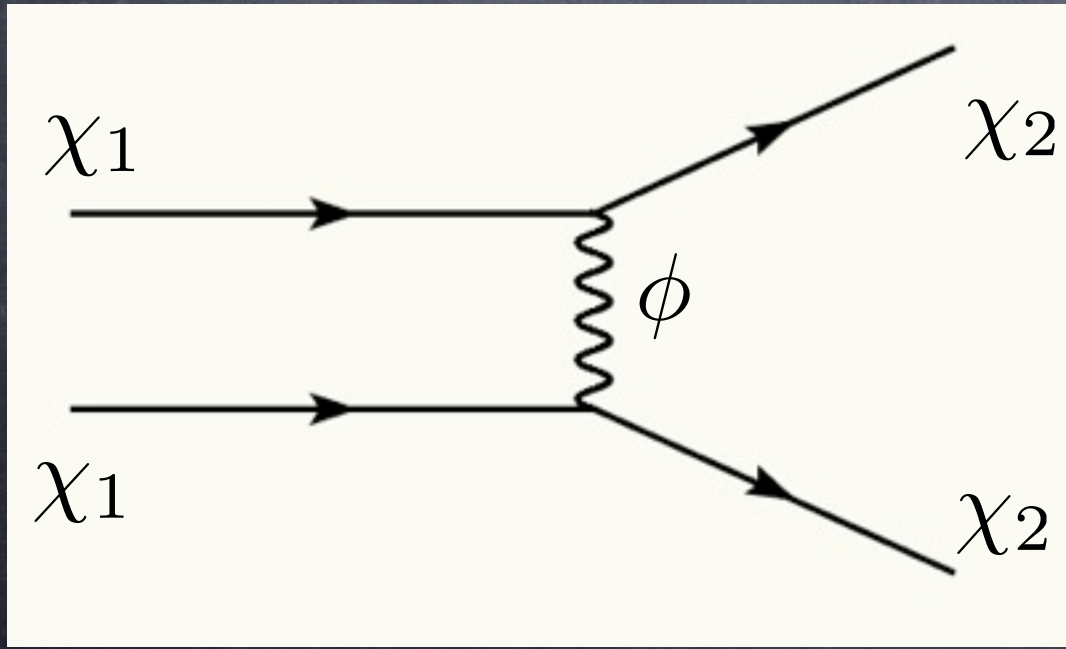


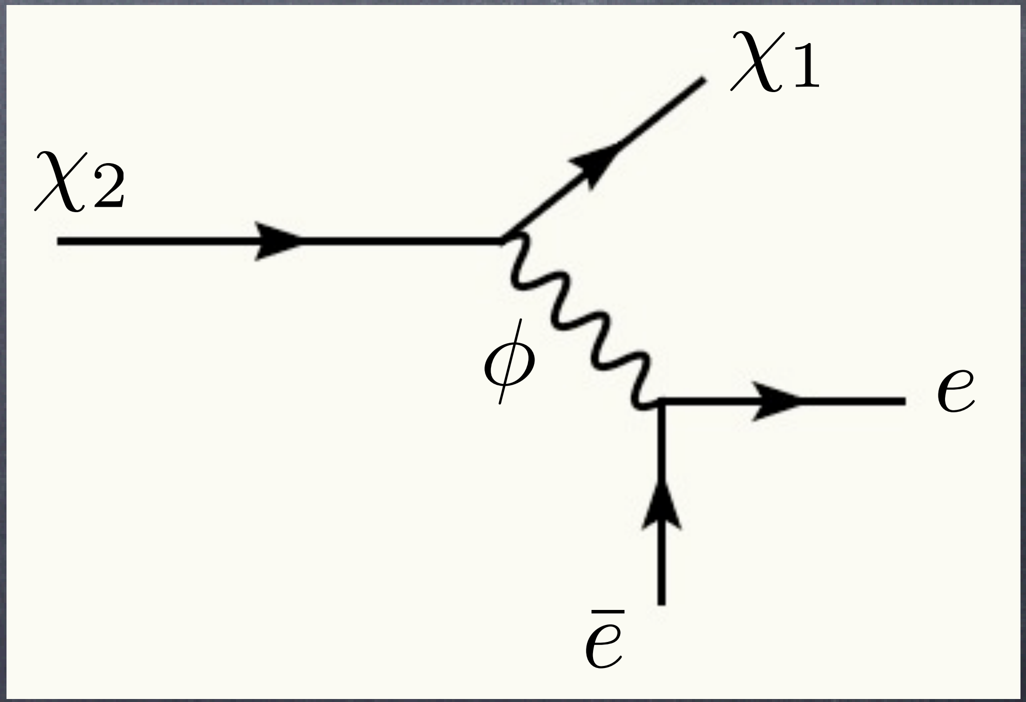


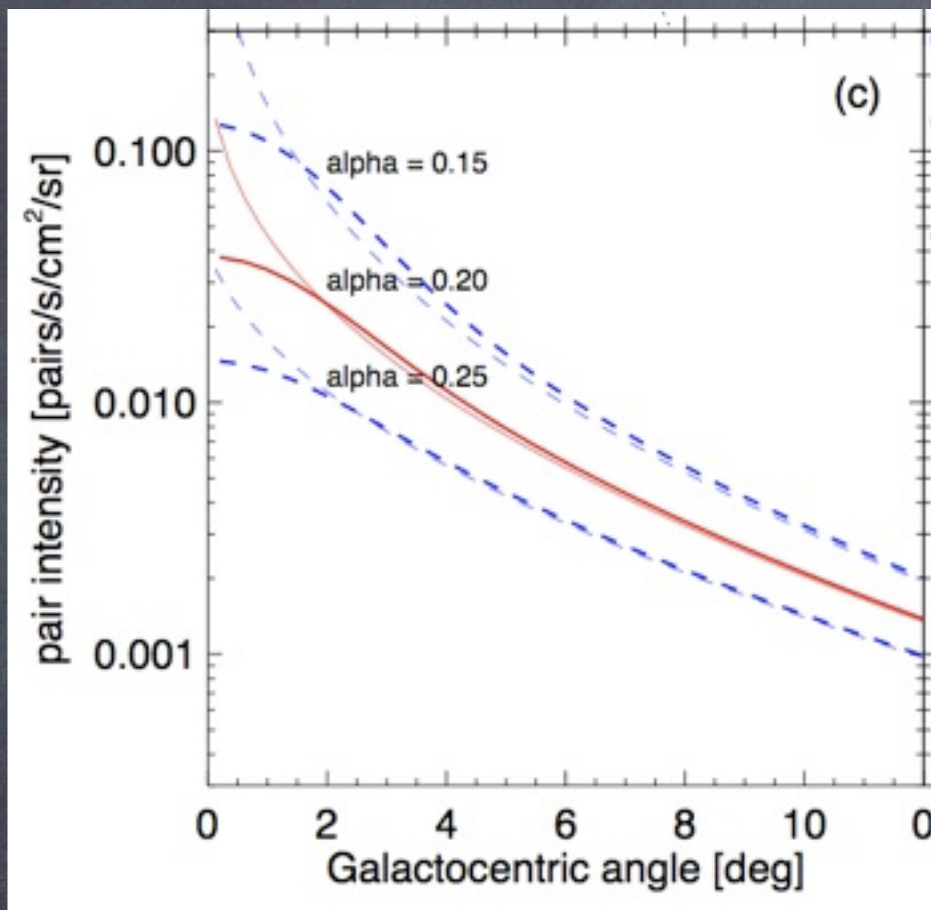
eXciting DM (XDM)

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-





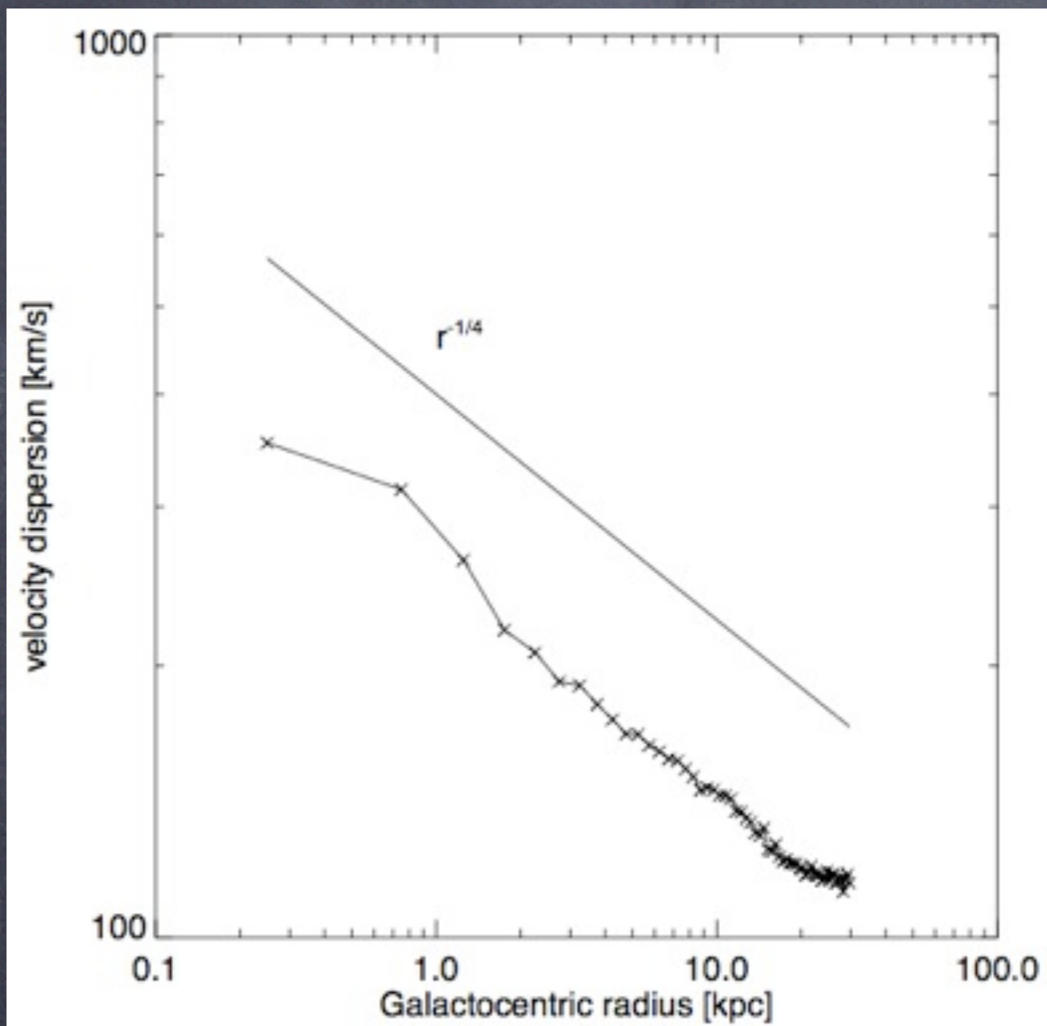


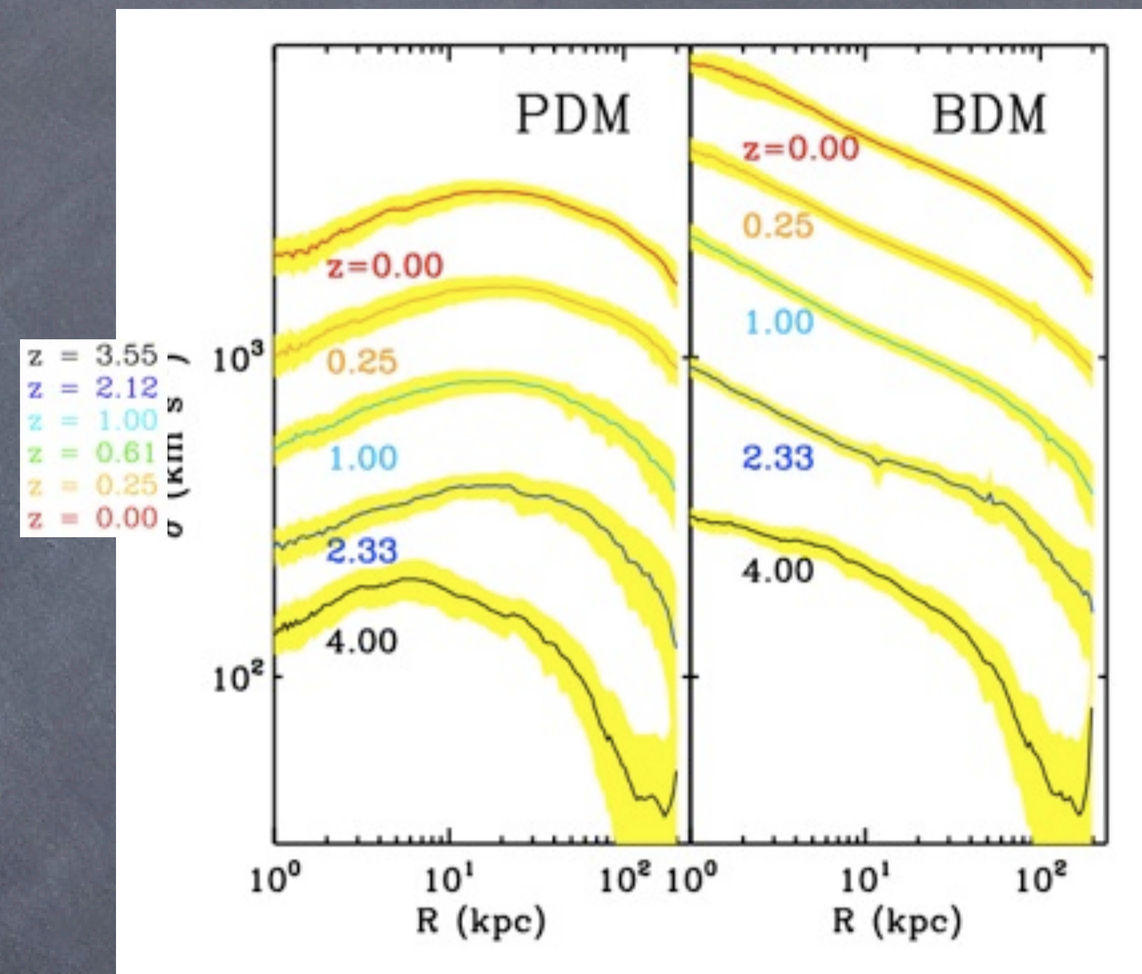
Need cross section near the geometric cross section, i.e.

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

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

Velocities in the GC





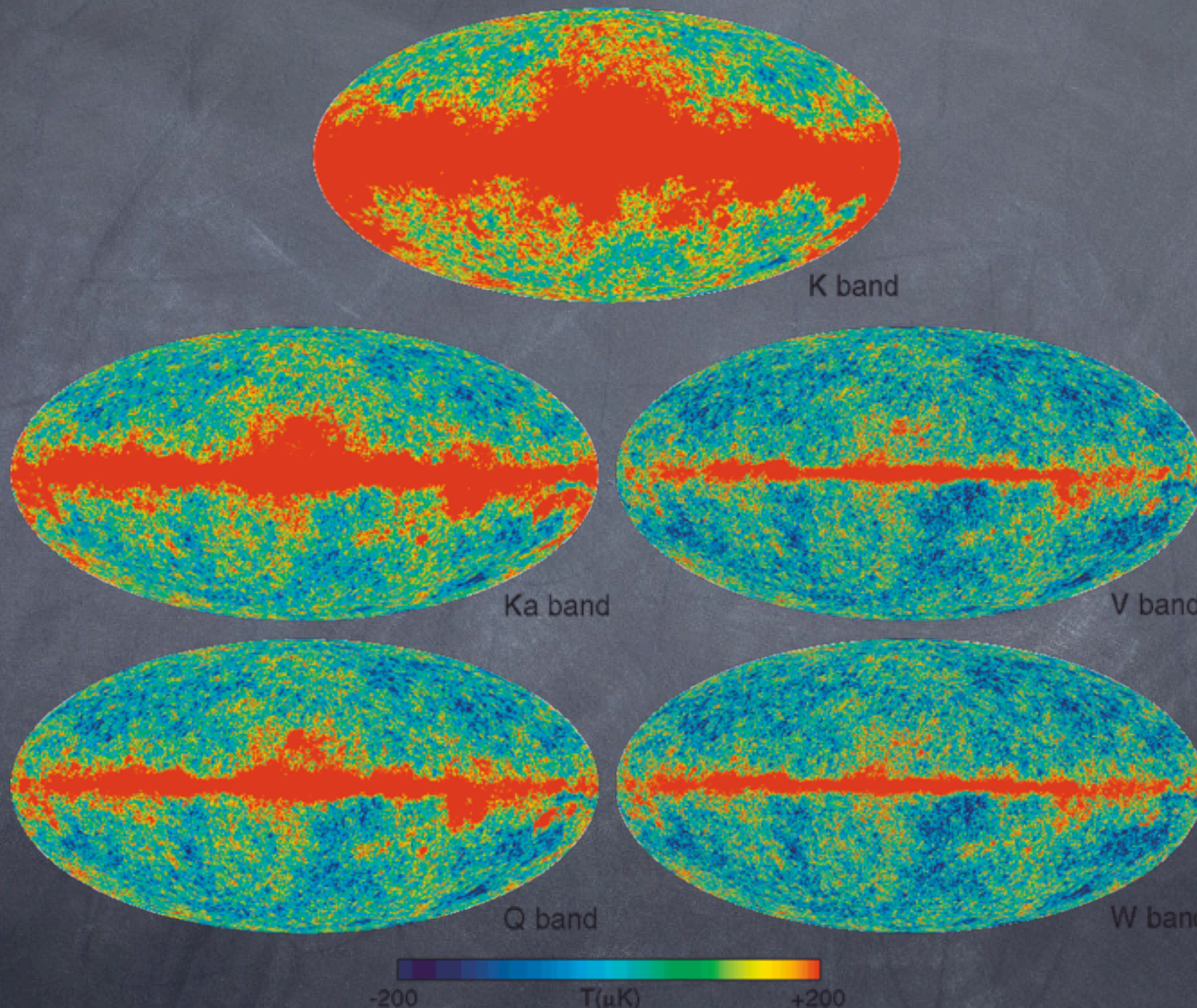
Governato et al, 2006

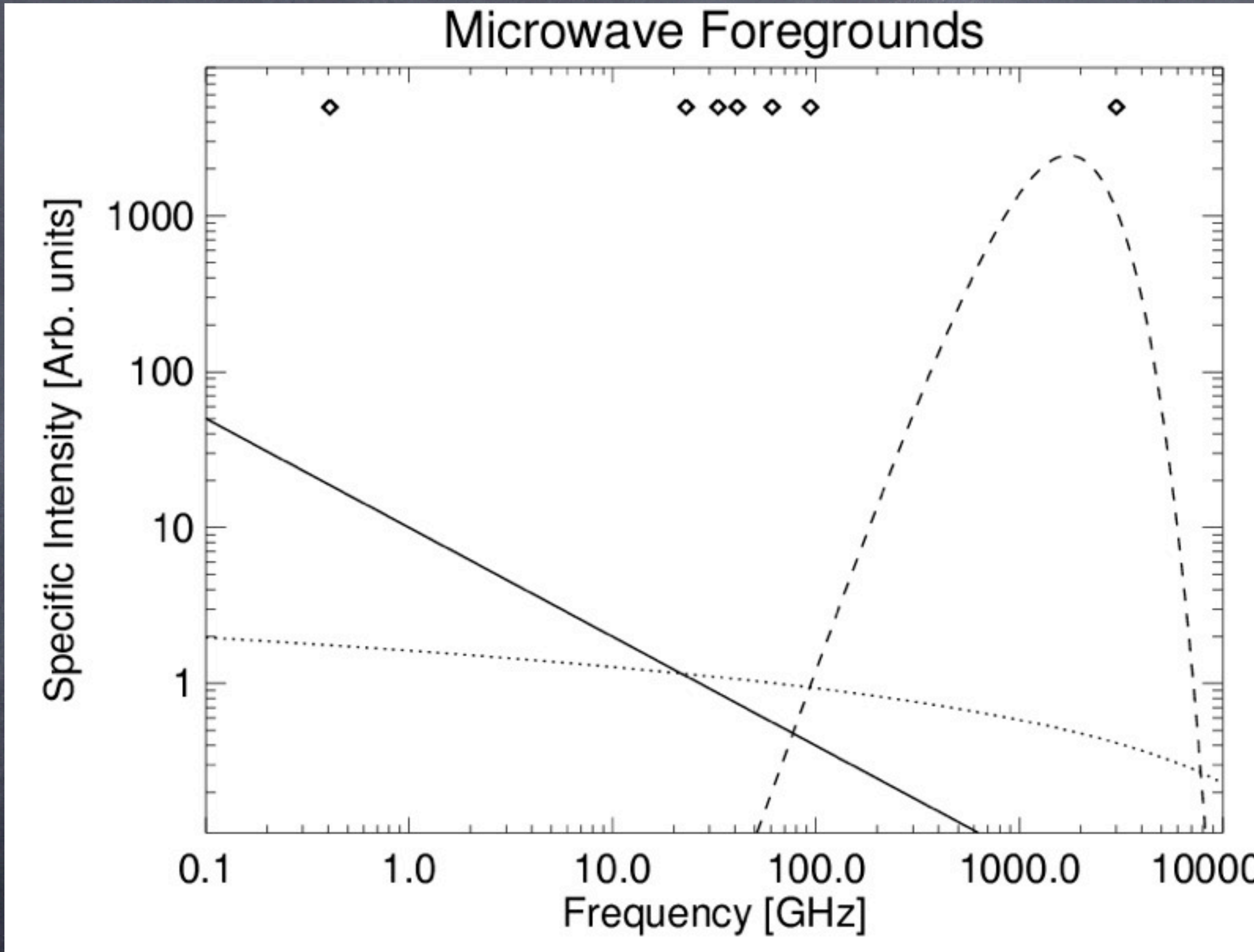
Romano-Diaz, Schlosman, Hoffman, Heller, '08

Also Navarro et al ('09, private communication)

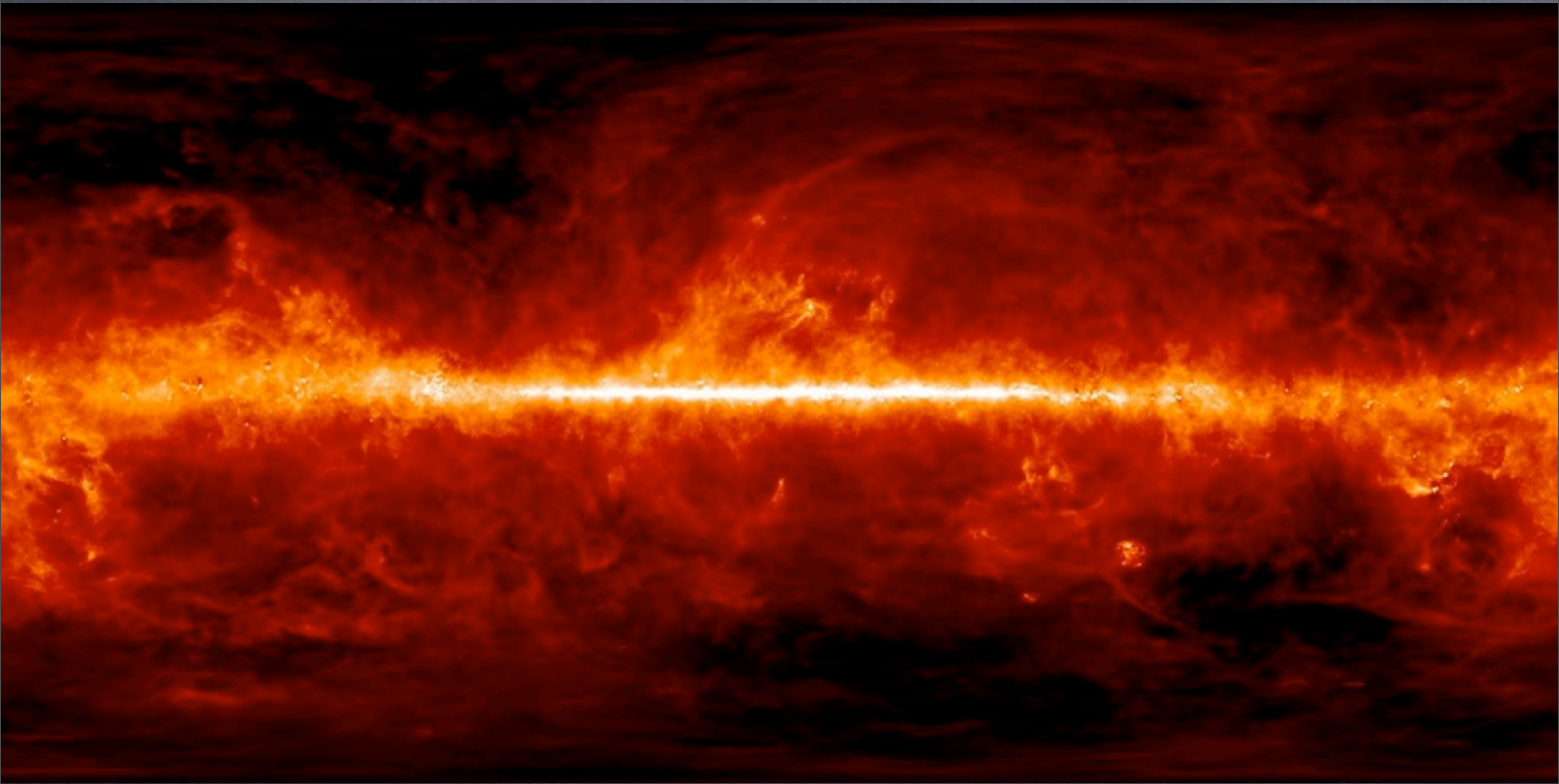
Increased velocities make XDM explanations work over broader range of parameters

WMAP

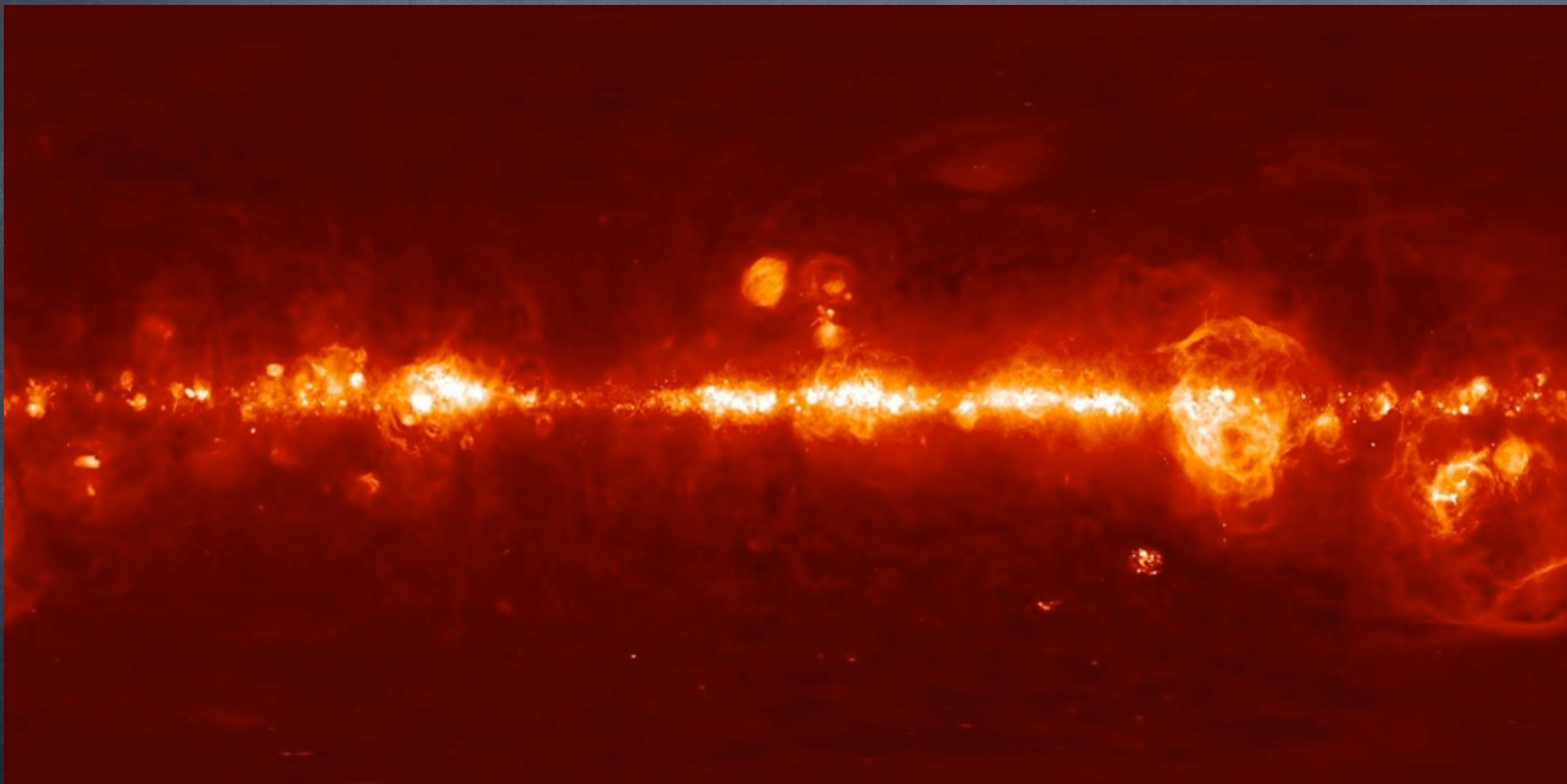



Microwave Foregrounds
Specific Intensity [Arb. units]
1000
100
10
1
0.1
1.0
10.0
100.0
1000.0
10000
Frequency [GHz]

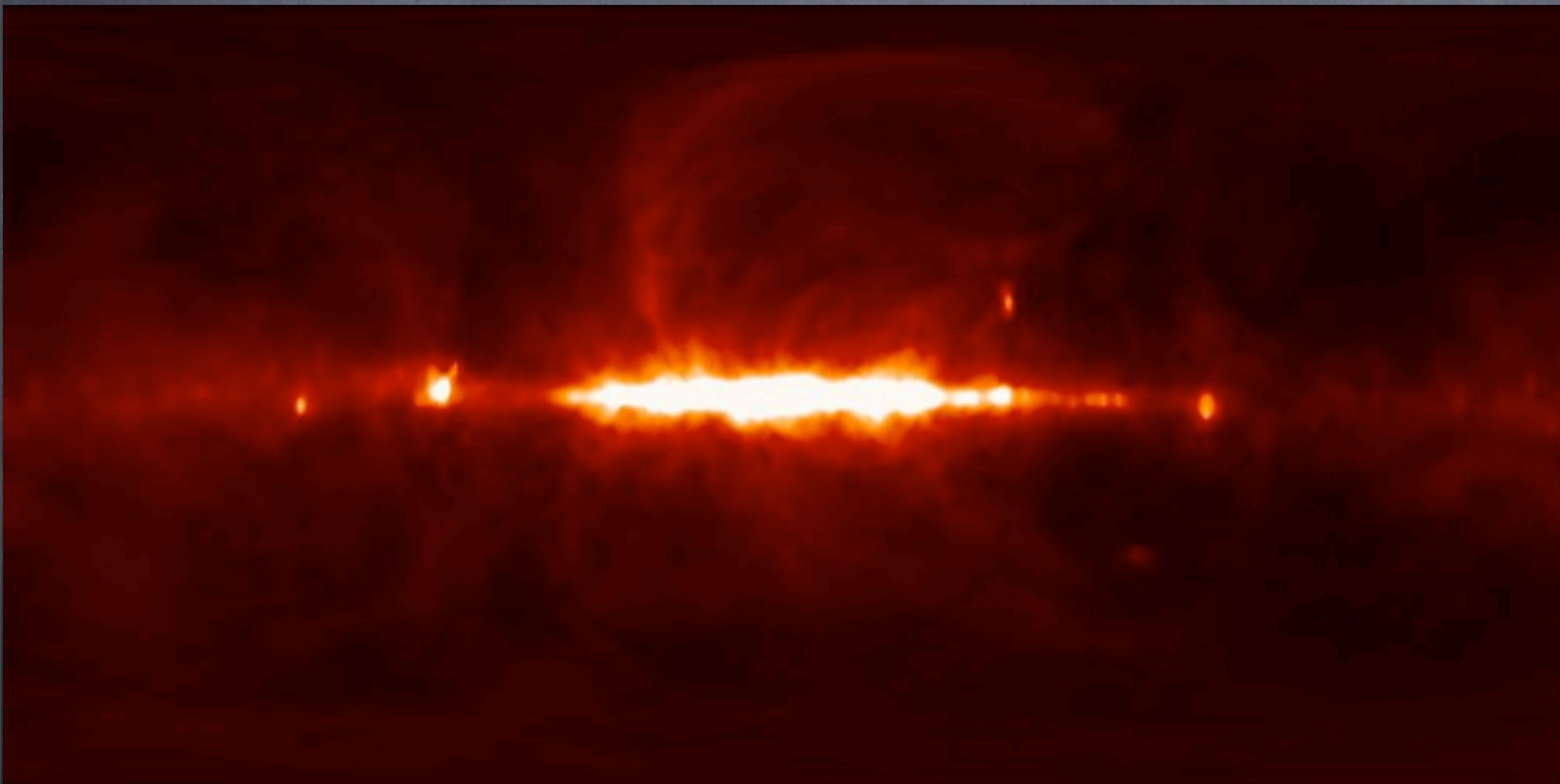
Interstellar Dust from IRAS, DIRBE (Finkbeiner et al. 1999) Map extrapolated from 3 THz (100 micron) with FIRAS.



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



Synchrotron at 408 MHz (Haslam et al. 1982)



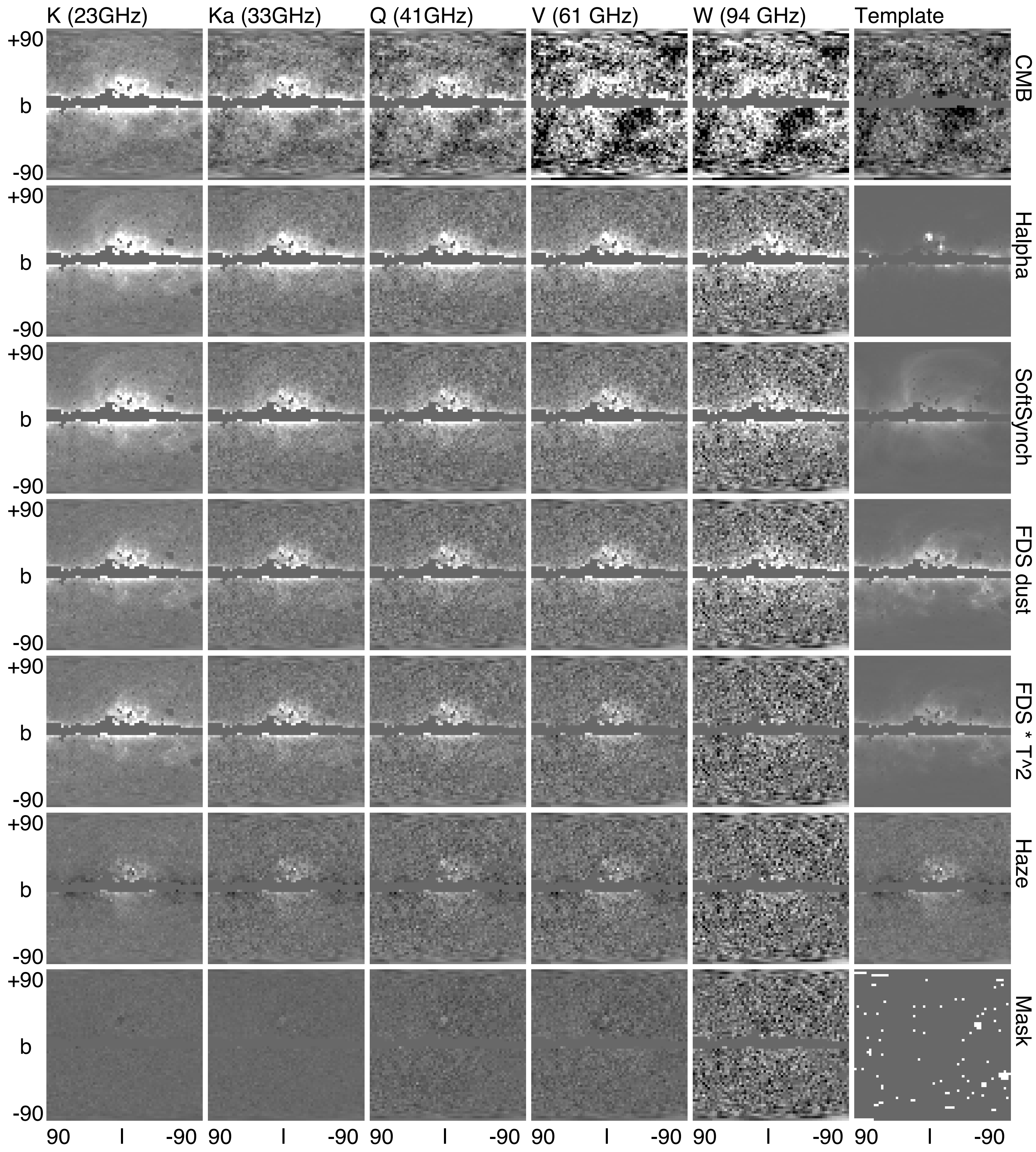
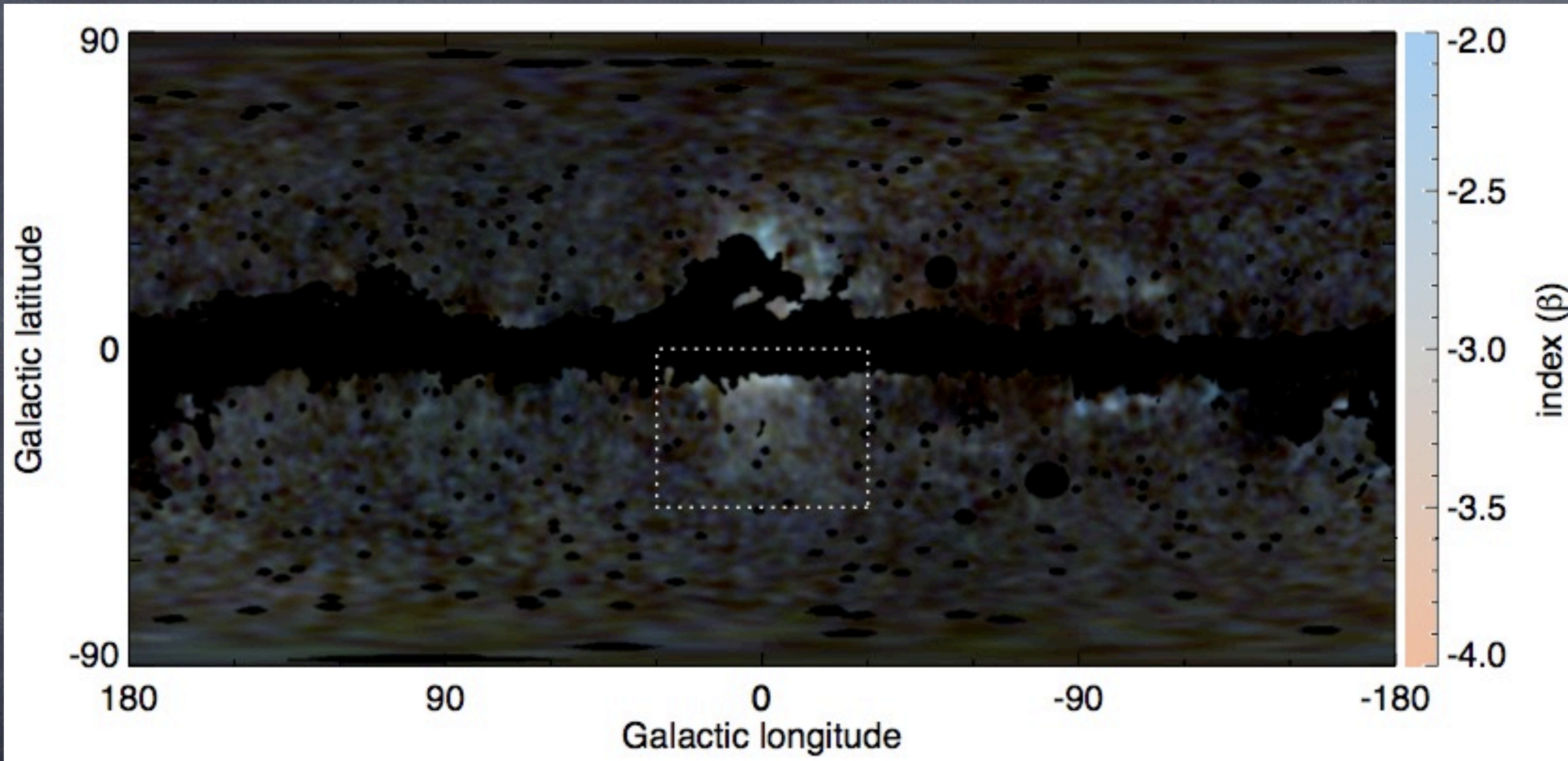
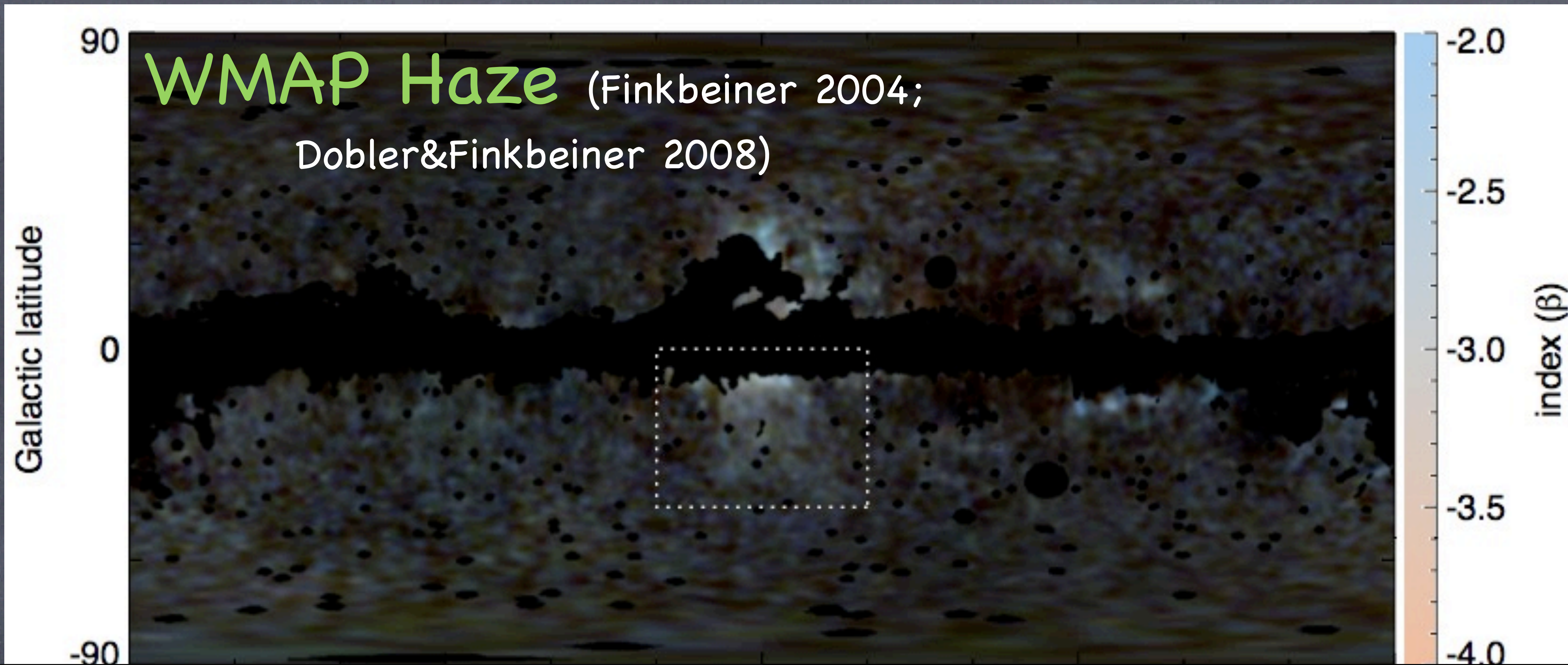


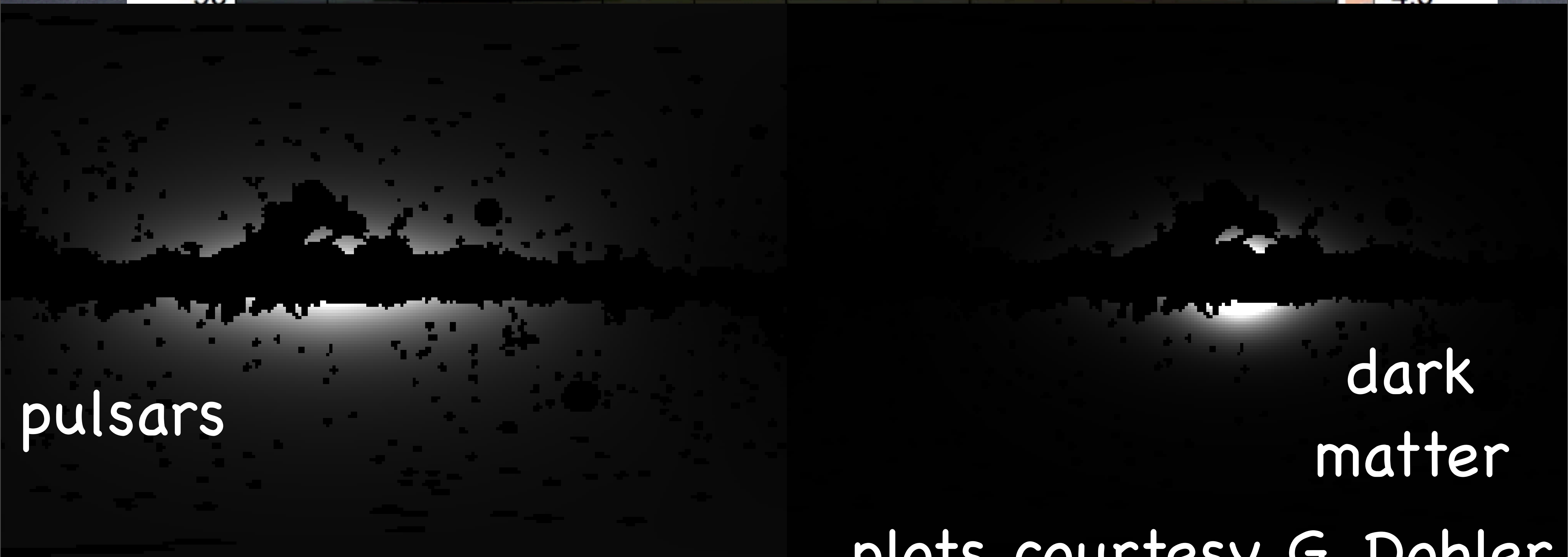
Fig. 1.— The WMAP foreground grid; see detailed discussion in §2.7.

Dobler and Finkbeiner ’08

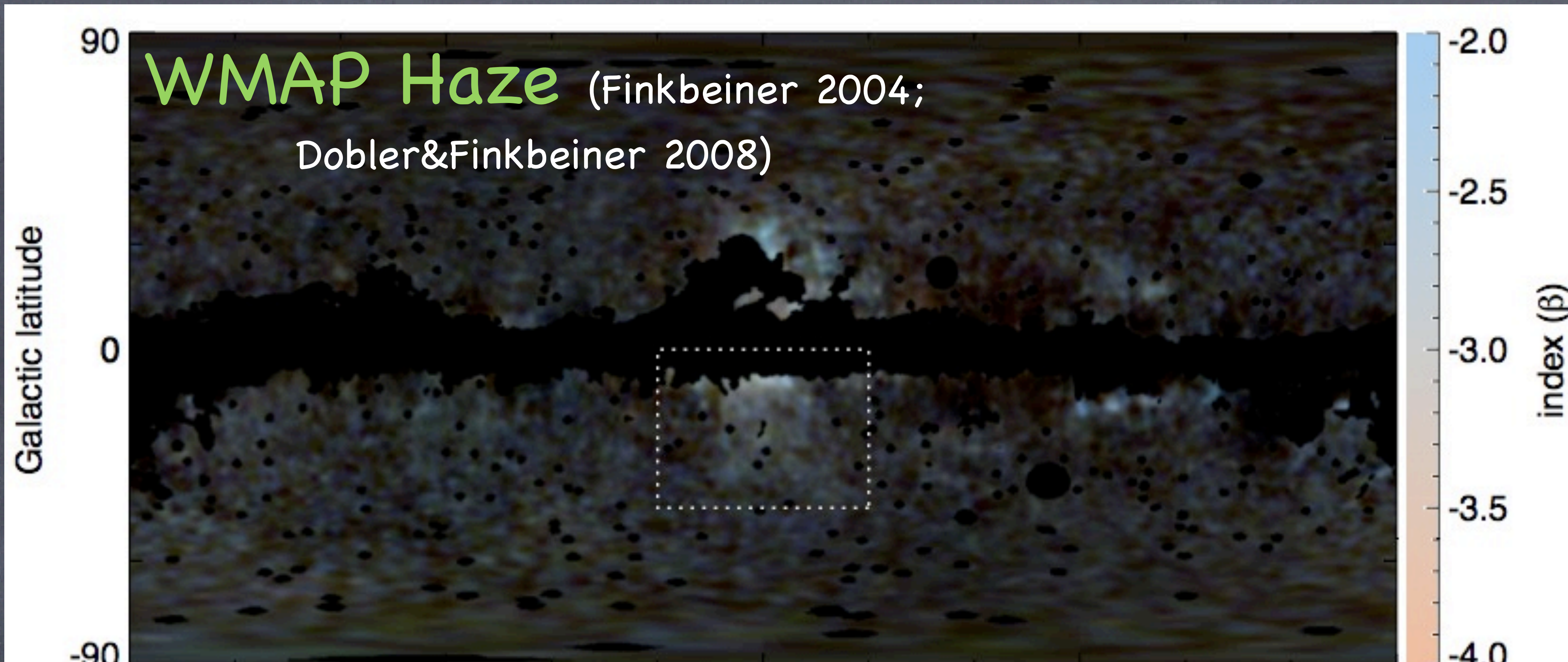


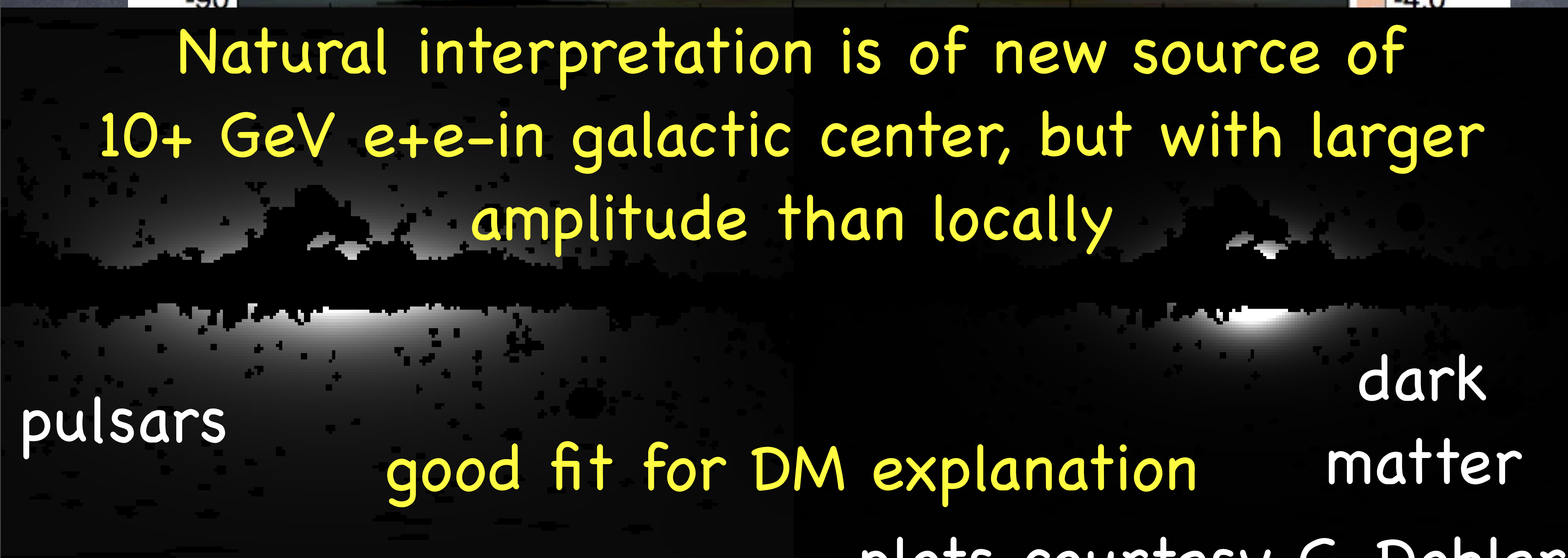
Dobler and Finkbeiner '08





plots courtesy G. Dobler





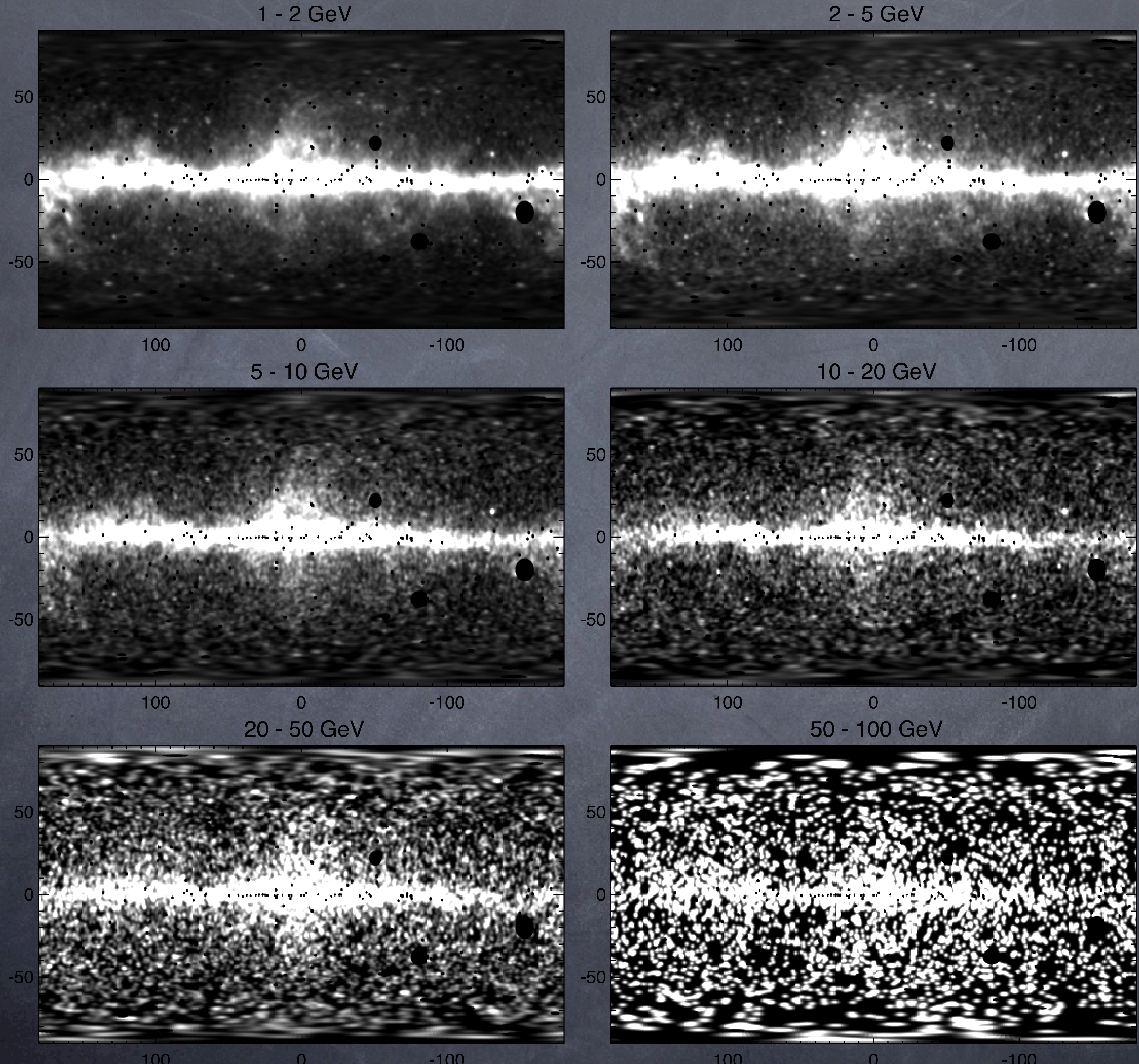
Natural interpretation is of new source of 10+ GeV e+e-in galactic center, but with larger amplitude than locally

pulsars

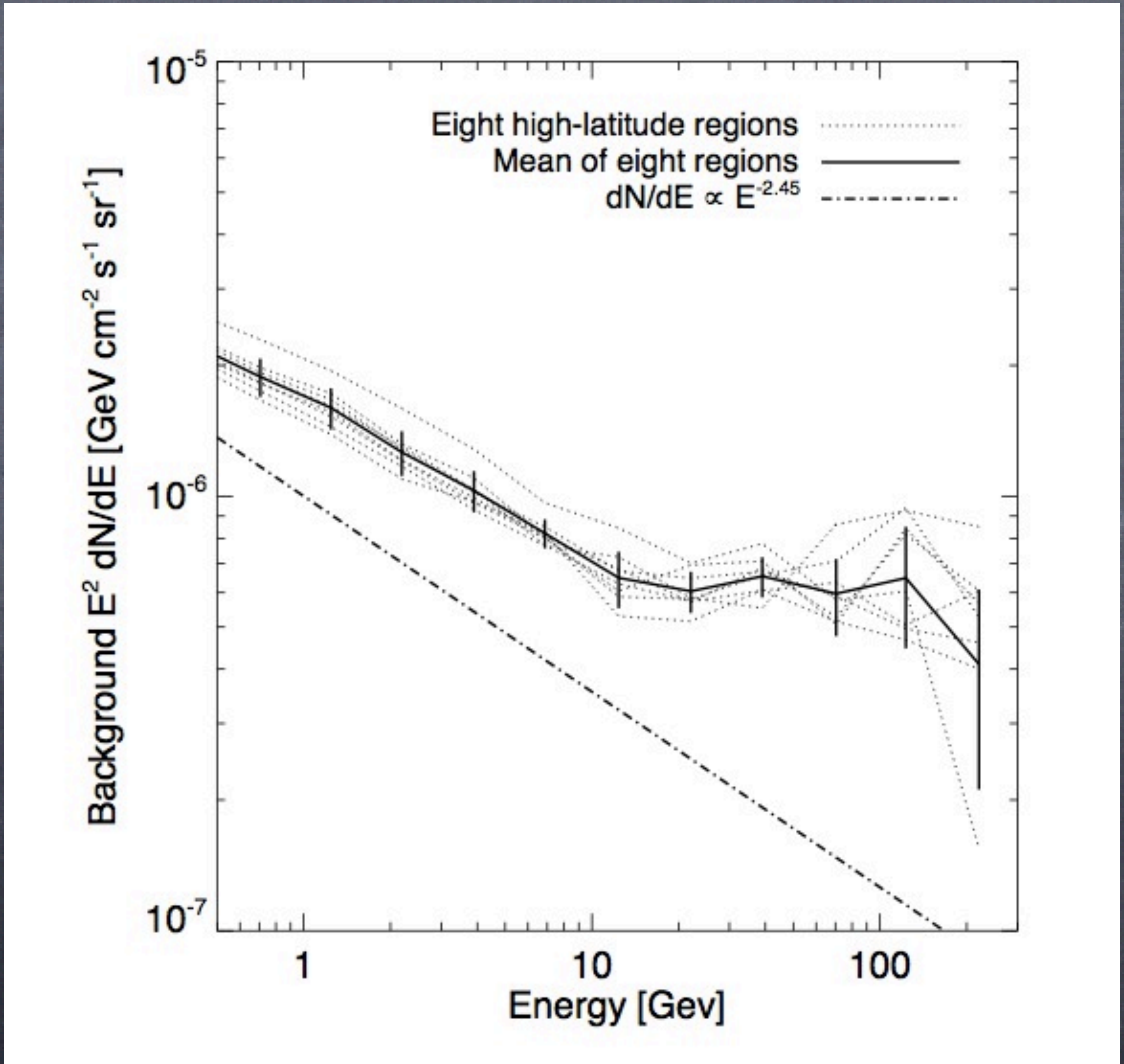
dark matter

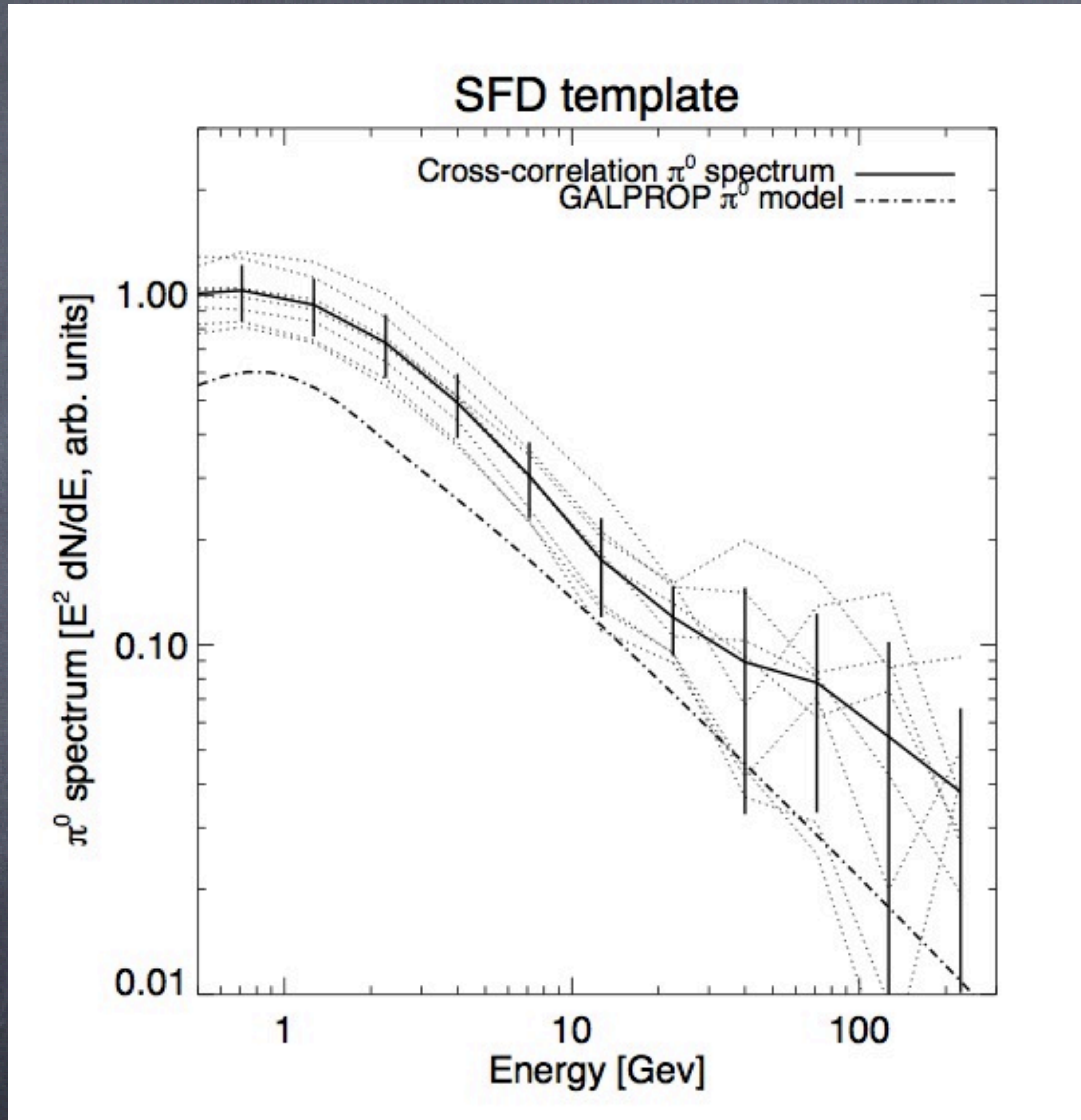
good fit for DM explanation

plots courtesy G. Dobler


1 - 2 GeV
2 - 5 GeV
5 - 10 GeV
10 - 20 GeV
20 - 50 GeV
50 - 100 GeV
50
0
-50
100
0
-100

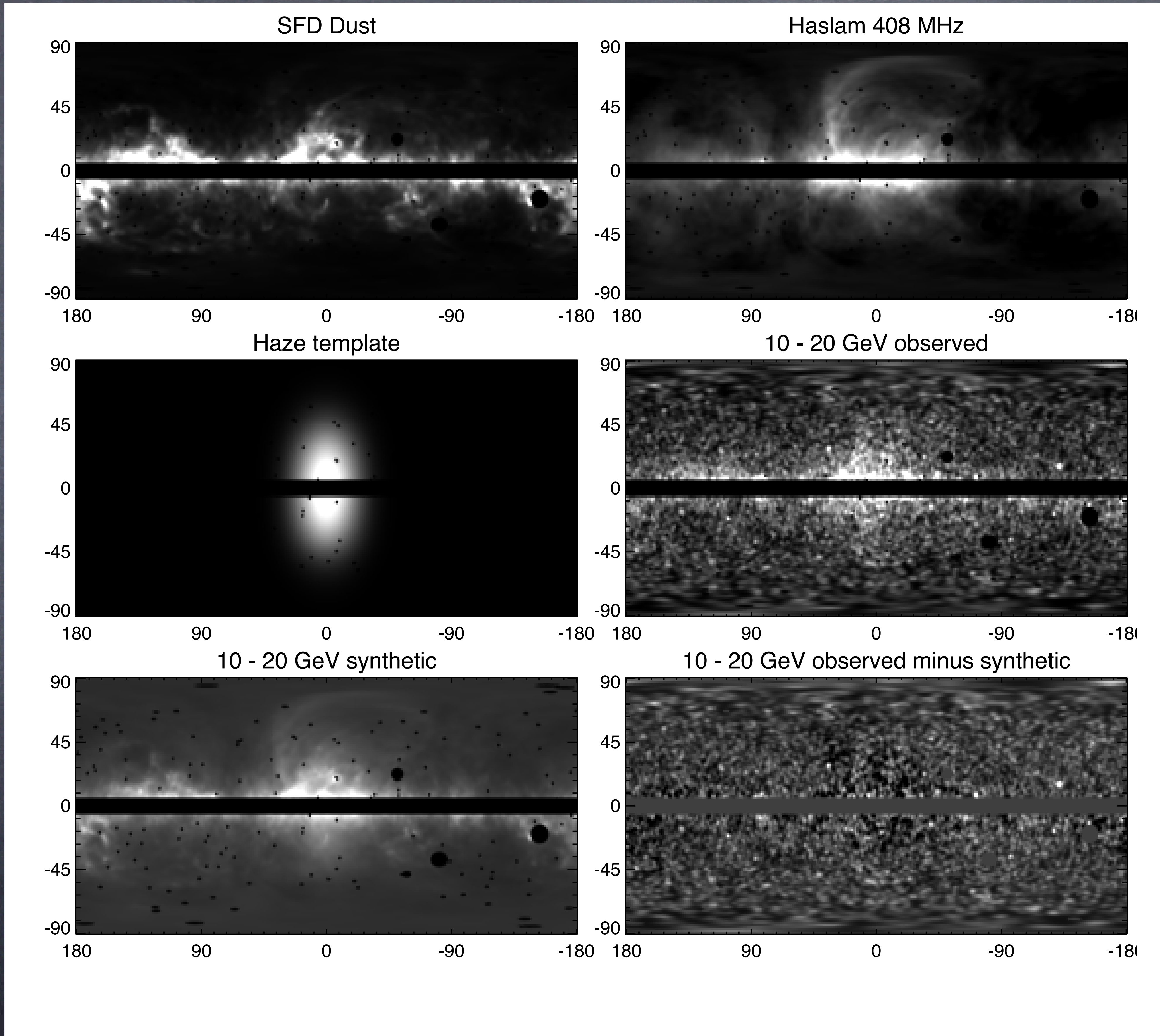
Backgrounds



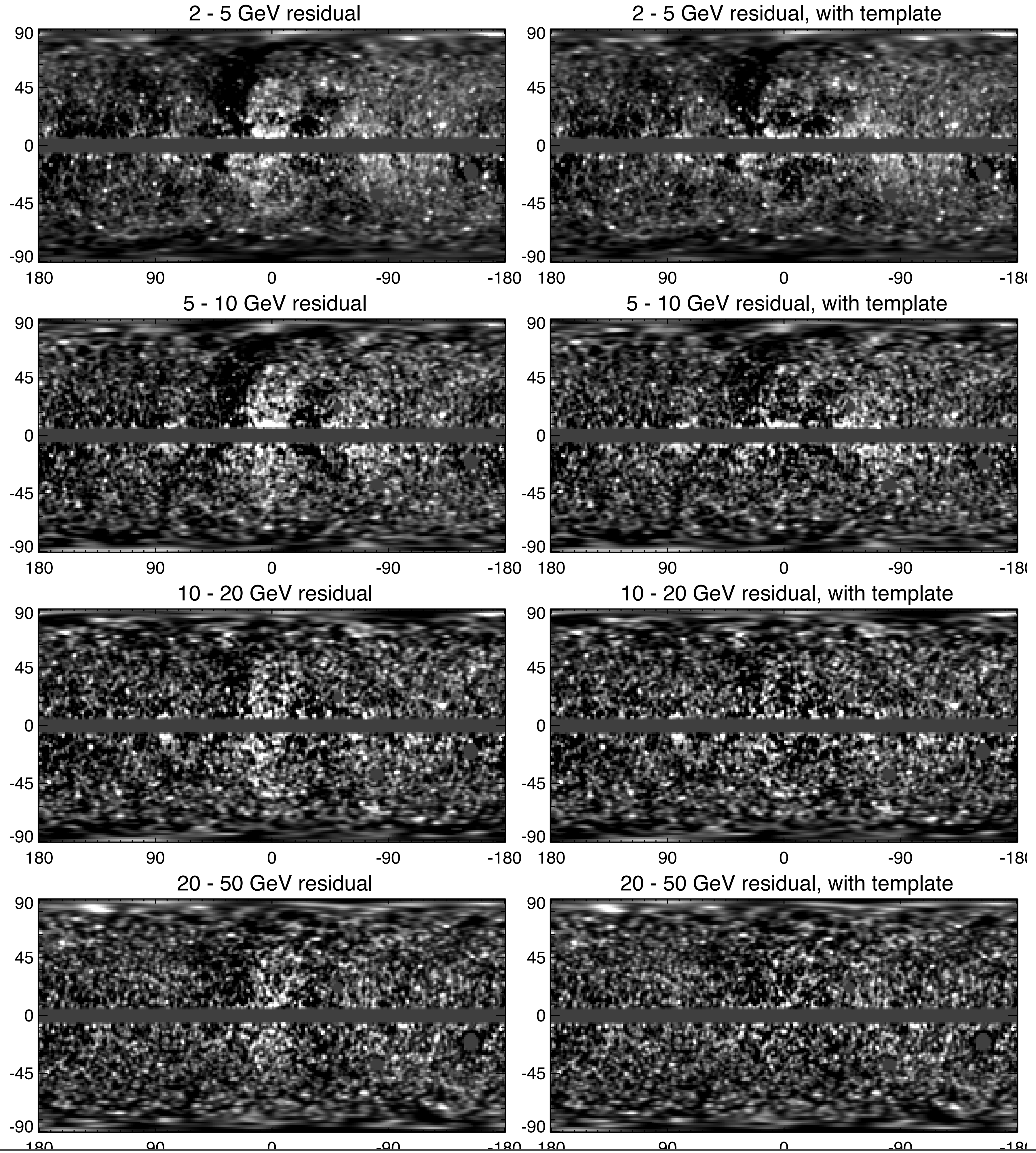


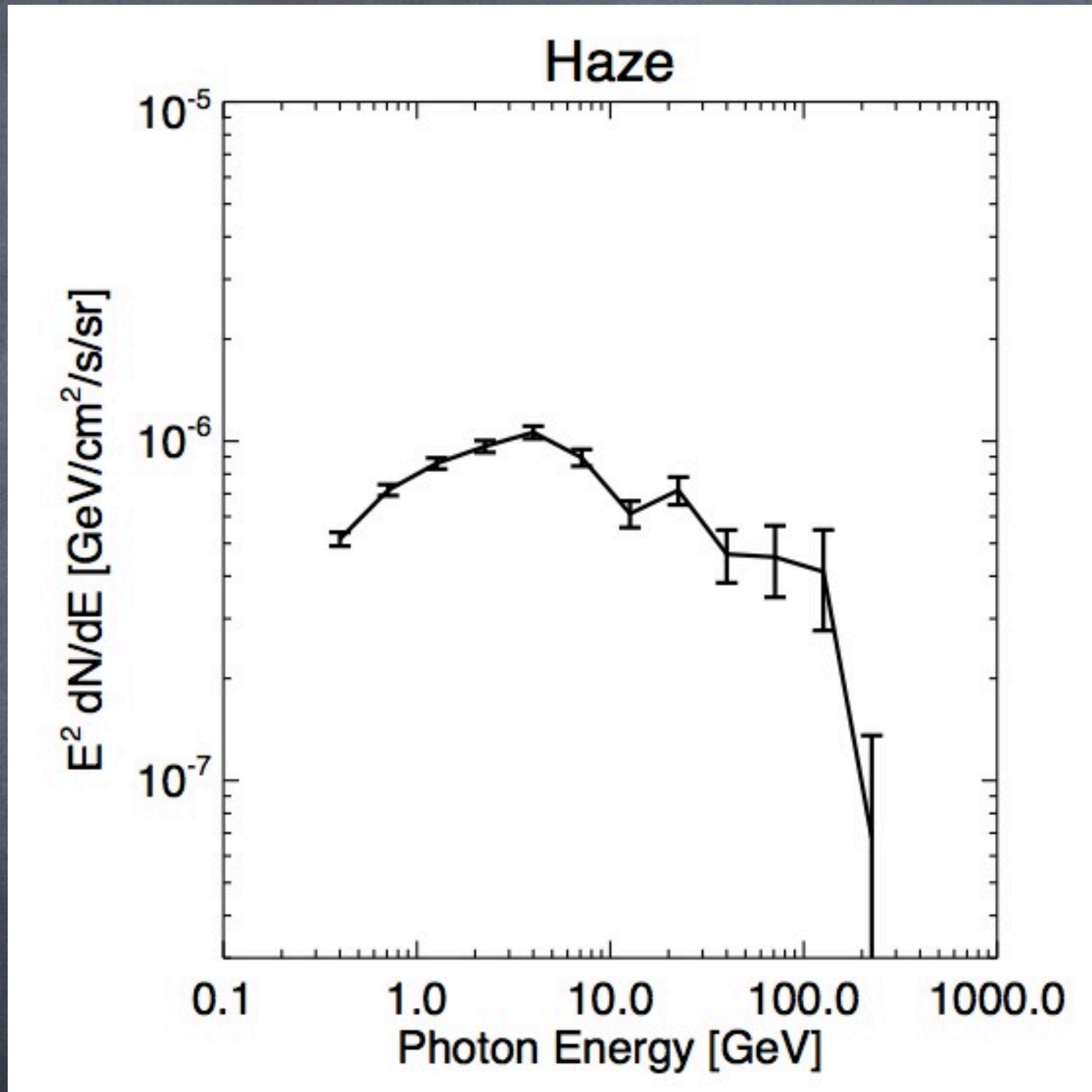
SFD template
Cross-correlation π^0 spectrum
GALPROP π^0 model
1.00
0.10
0.01
1
10
100
Energy [Gev]
π^0 spectrum [E^2 dN/dE, arb. units]

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

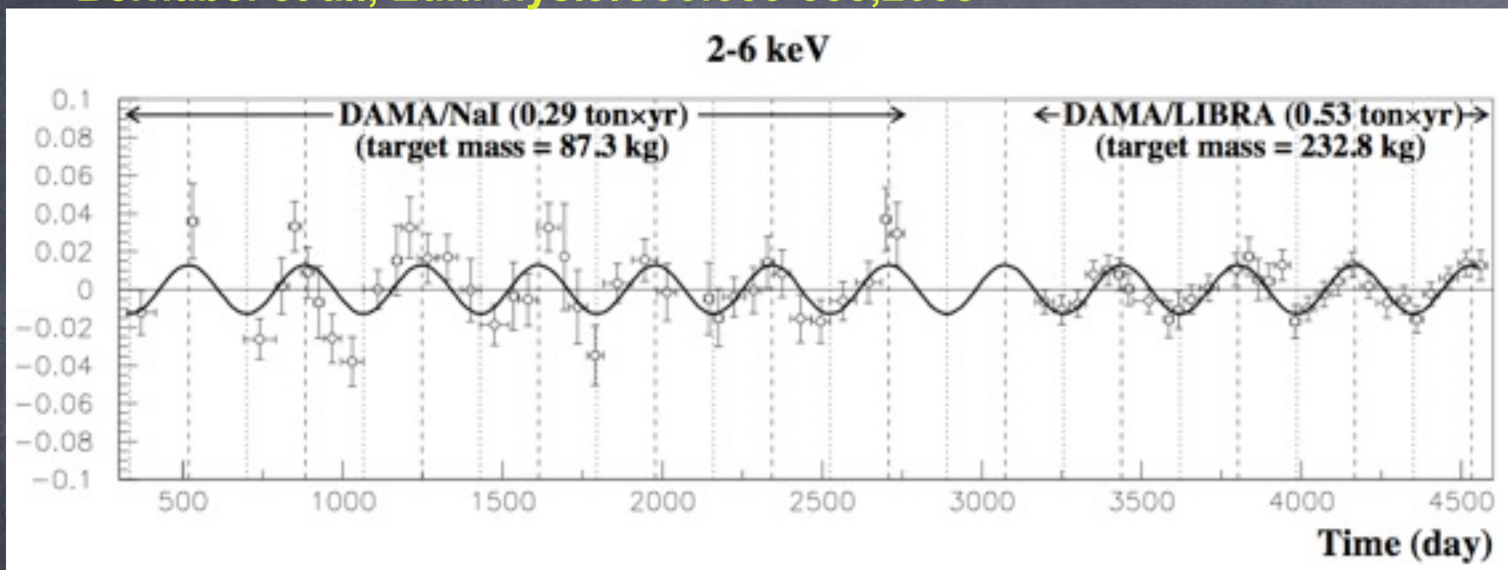

2 - 5 GeV residual
2 - 5 GeV residual, with template
5 - 10 GeV residual
5 - 10 GeV residual, with template
10 - 20 GeV residual
10 - 20 GeV residual, with template
20 - 50 GeV residual
20 - 50 GeV residual, with template
90
45
0
-45
-90
180
90
0
-90
-180

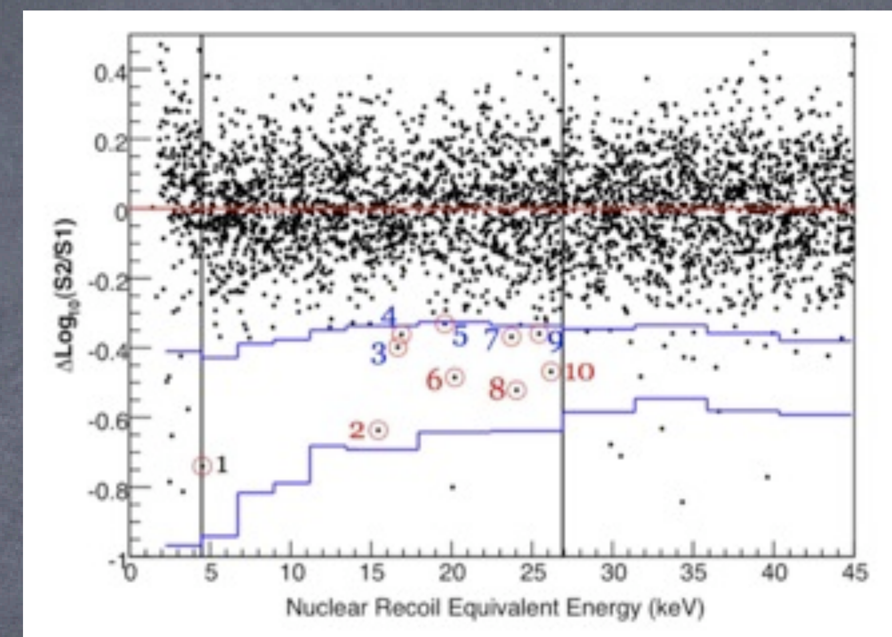


Haze
10^{-5}
10^{-6}
10^{-7}
E^2 dN/dE [GeV/cm^2/s/sr]
0.1
1.0
10.0
100.0
1000.0
Photon Energy [GeV]

DAMA experiment

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

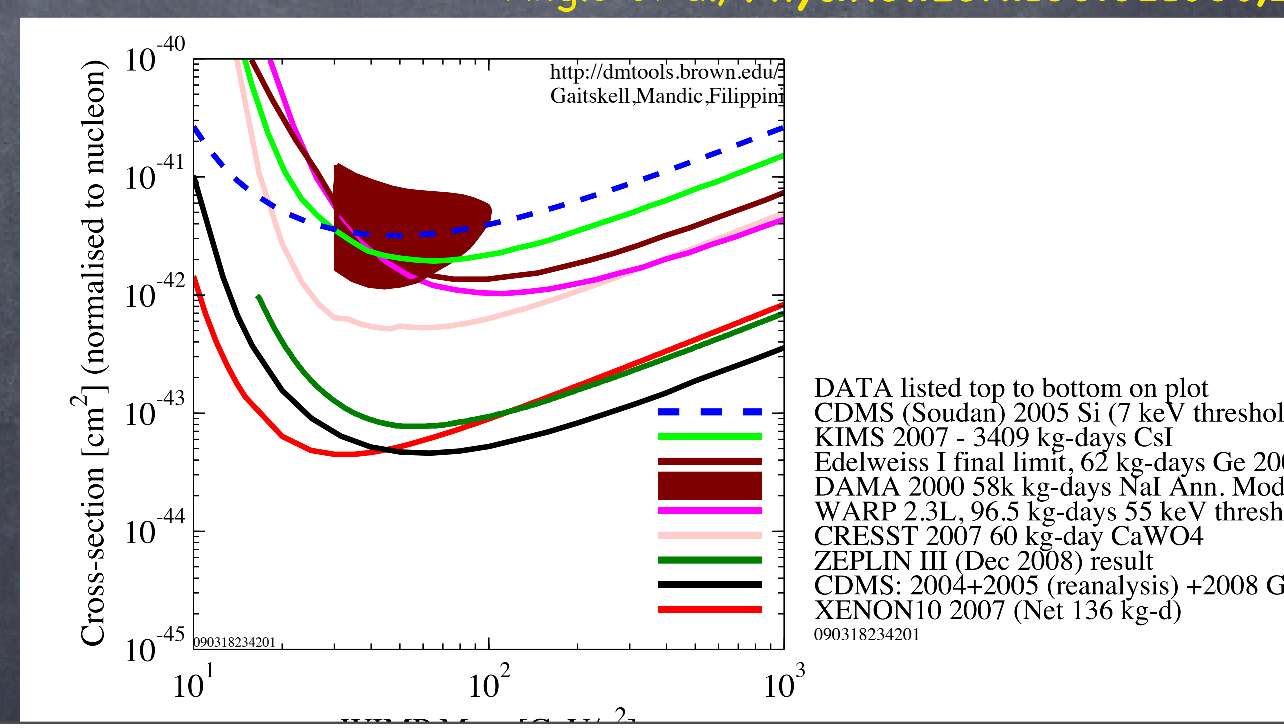




Angle et al, **Phys.Rev.Lett.100:021303,2008**

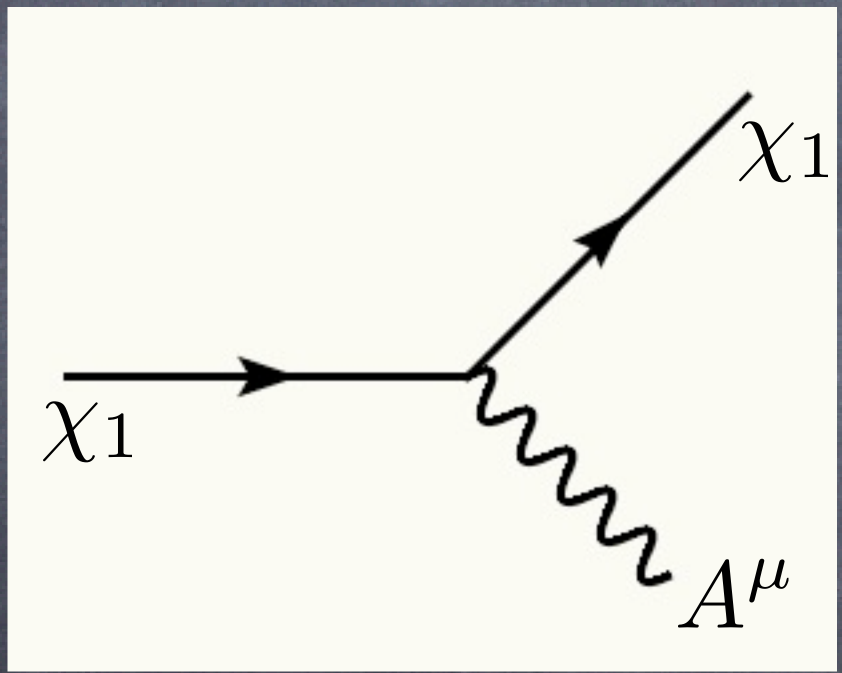
- 8.3 sigma signal for modulation
- only in "single hit" events
- proper phase

Dark matter?



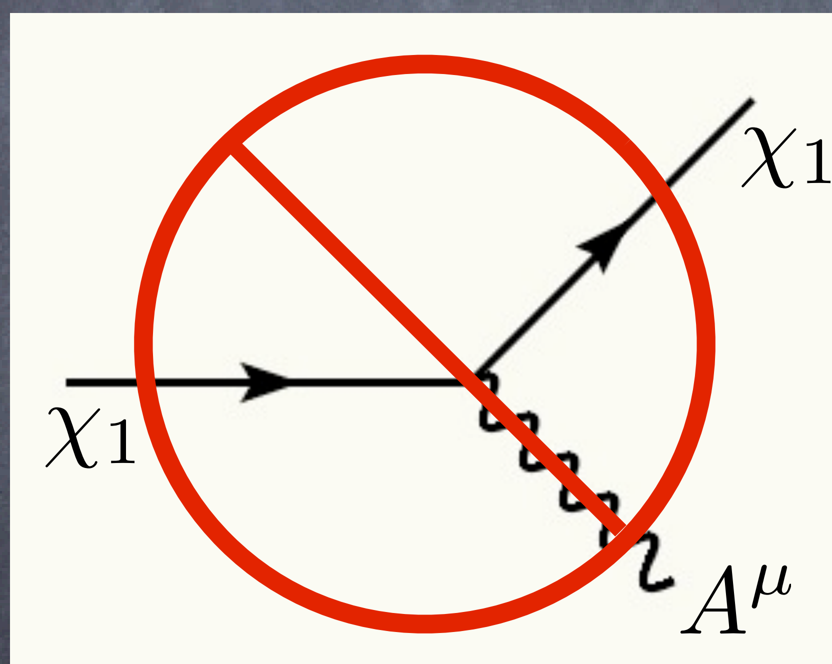
Consider vector interaction

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



Consider vector interaction

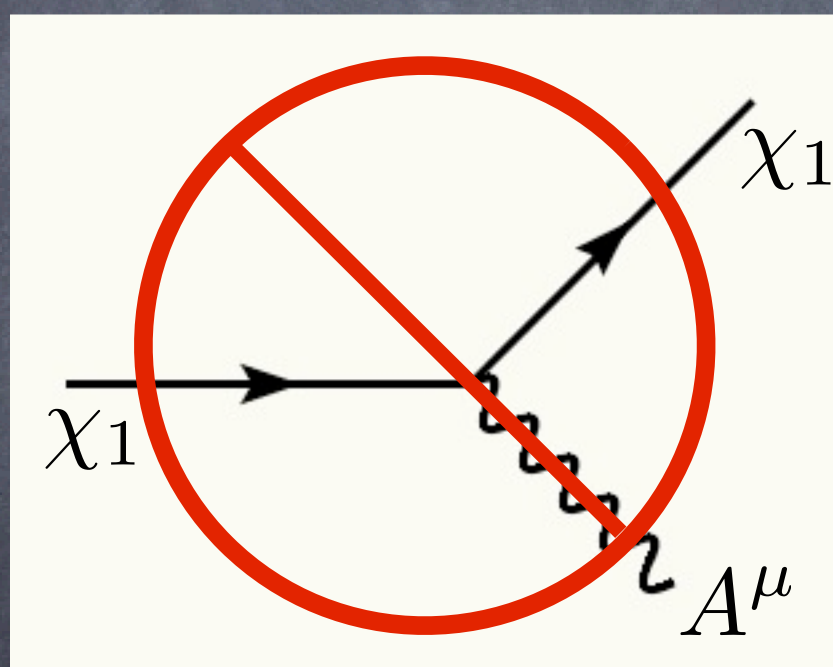
$$\cancel{\chi_1 \sigma_\mu \chi_1 A^\mu}$$

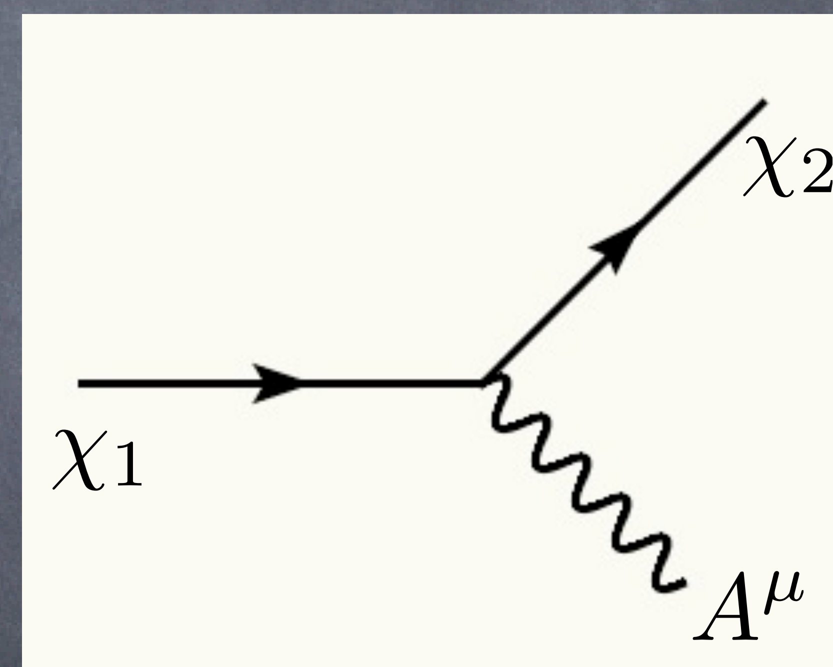


Consider vector interaction

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

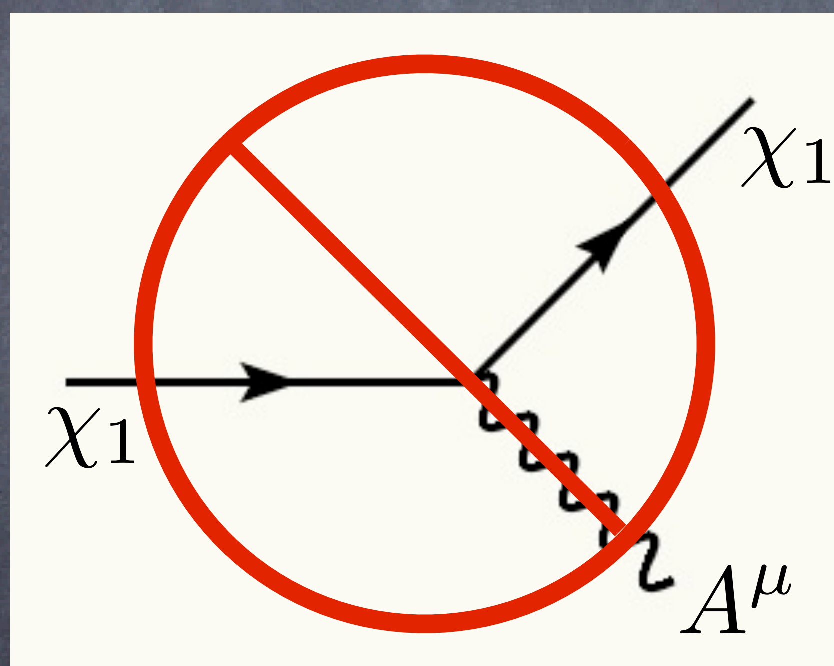
$\chi_1 \sigma_\mu \chi_2 A^\mu$

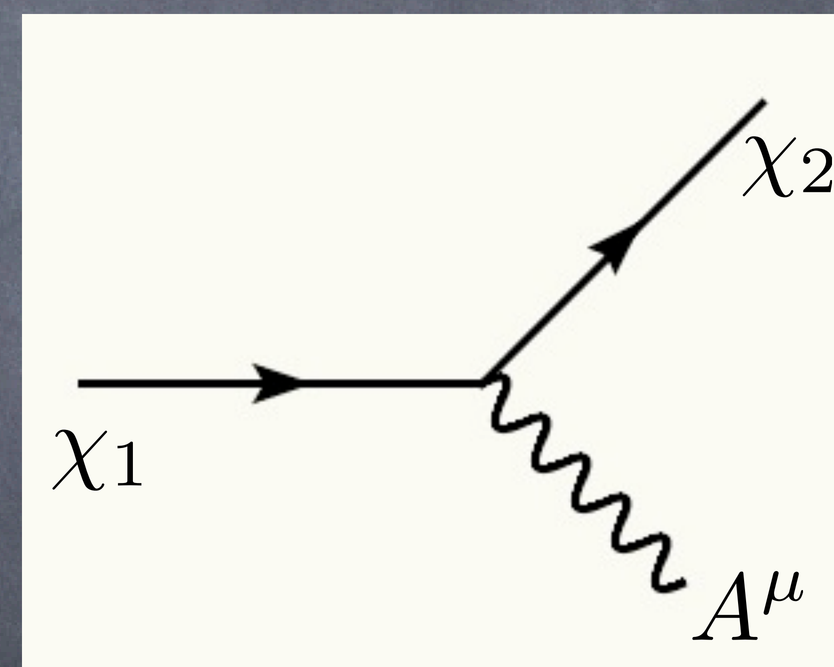




Consider vector interaction

$\cancel{\chi_1 \sigma_\mu \chi_1 A^\mu}$ $\chi_1 \sigma_\mu \chi_2 A^\mu$





Vector interactions for massive WIMPs (M_{DM}>M_{force}) **always** require multiple states interaction is off-diagonal

Question:

- What is the splitting between those states? δ
- Tiny?
- Comparable to WIMP kinetic energy?
- Huge?
- For Sommerfeld Enhancement (i.e., PAMELA), states must be small

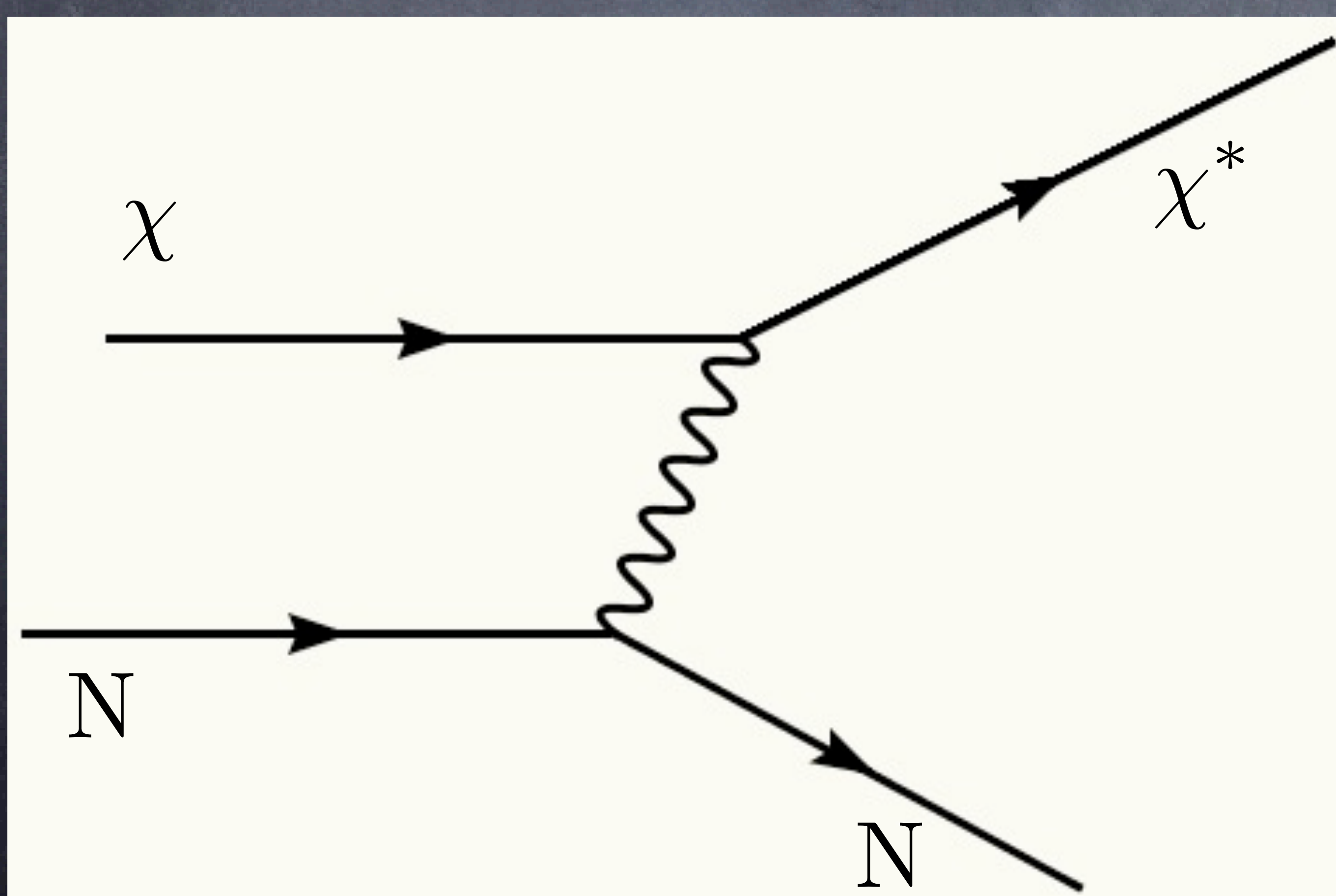
$$\frac{\delta}{M} \lesssim \frac{\alpha^2}{4}$$ For $\alpha \sim 10^{-2}$ $M \sim TeV$

$$\delta \sim 10\,\mathrm{MeV} \sim \text{kinetic energy of a WIMP}$$

"Inelastic" dark matter

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

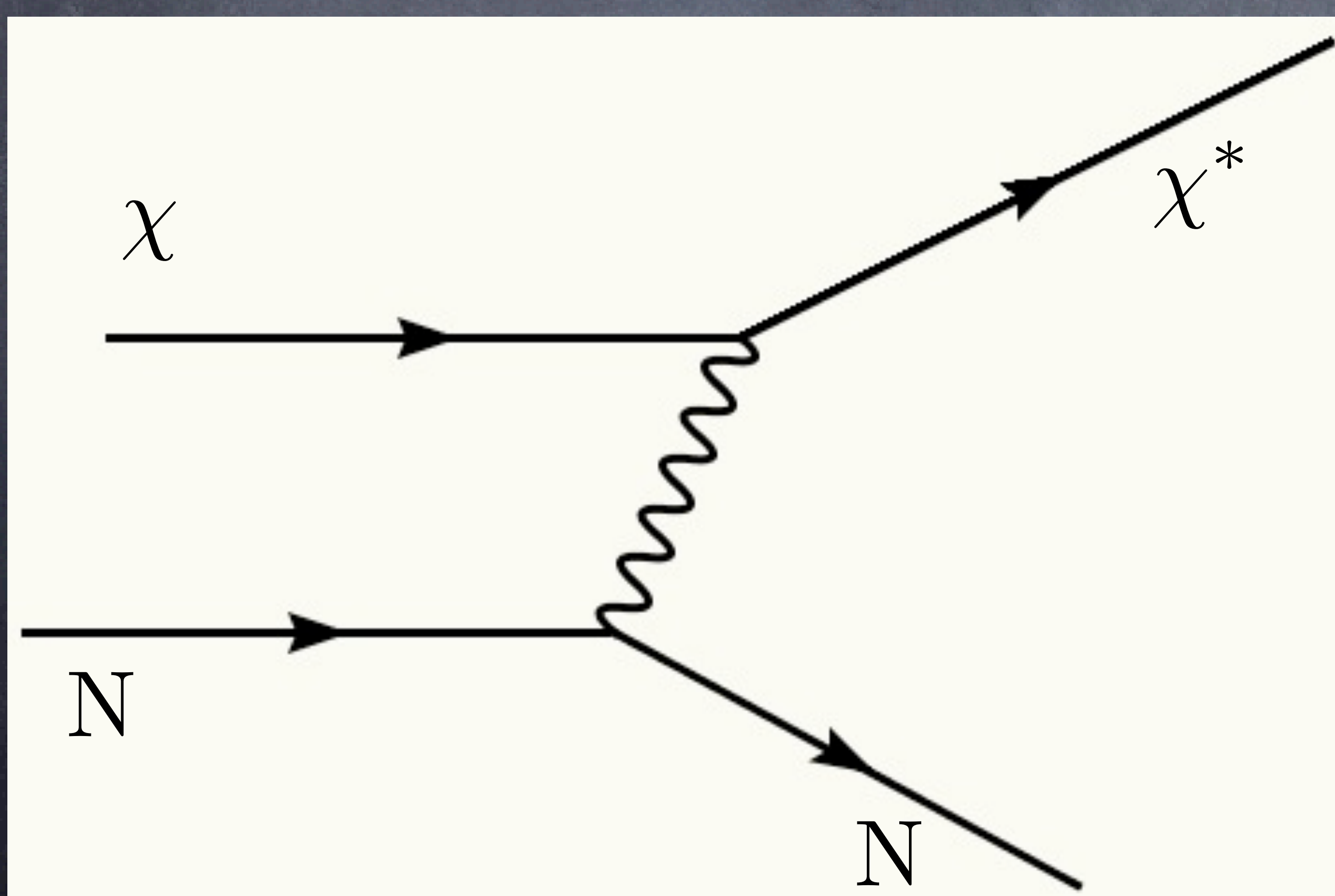
- DM-nucleus scattering must be inelastic
- If dark matter can only scatter off of a nucleus by transitioning to an excited state (100 keV), the kinematics are changed dramatically



“Inelastic” dark matter

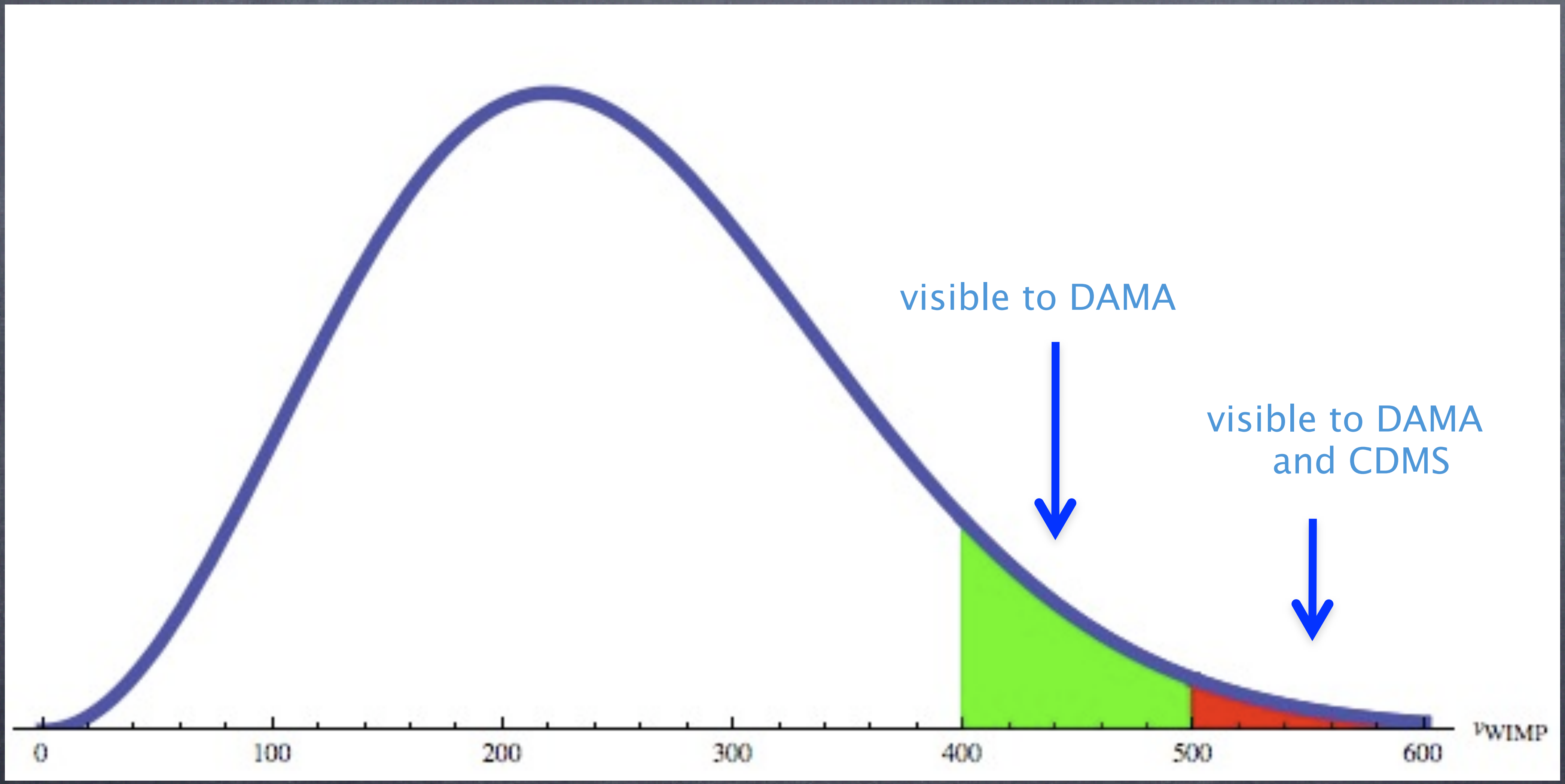
D.Tucker-Smith, NW, **Phys.Rev.D64:043502,2001;Phys.Rev.D72:063509,2005**

- 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



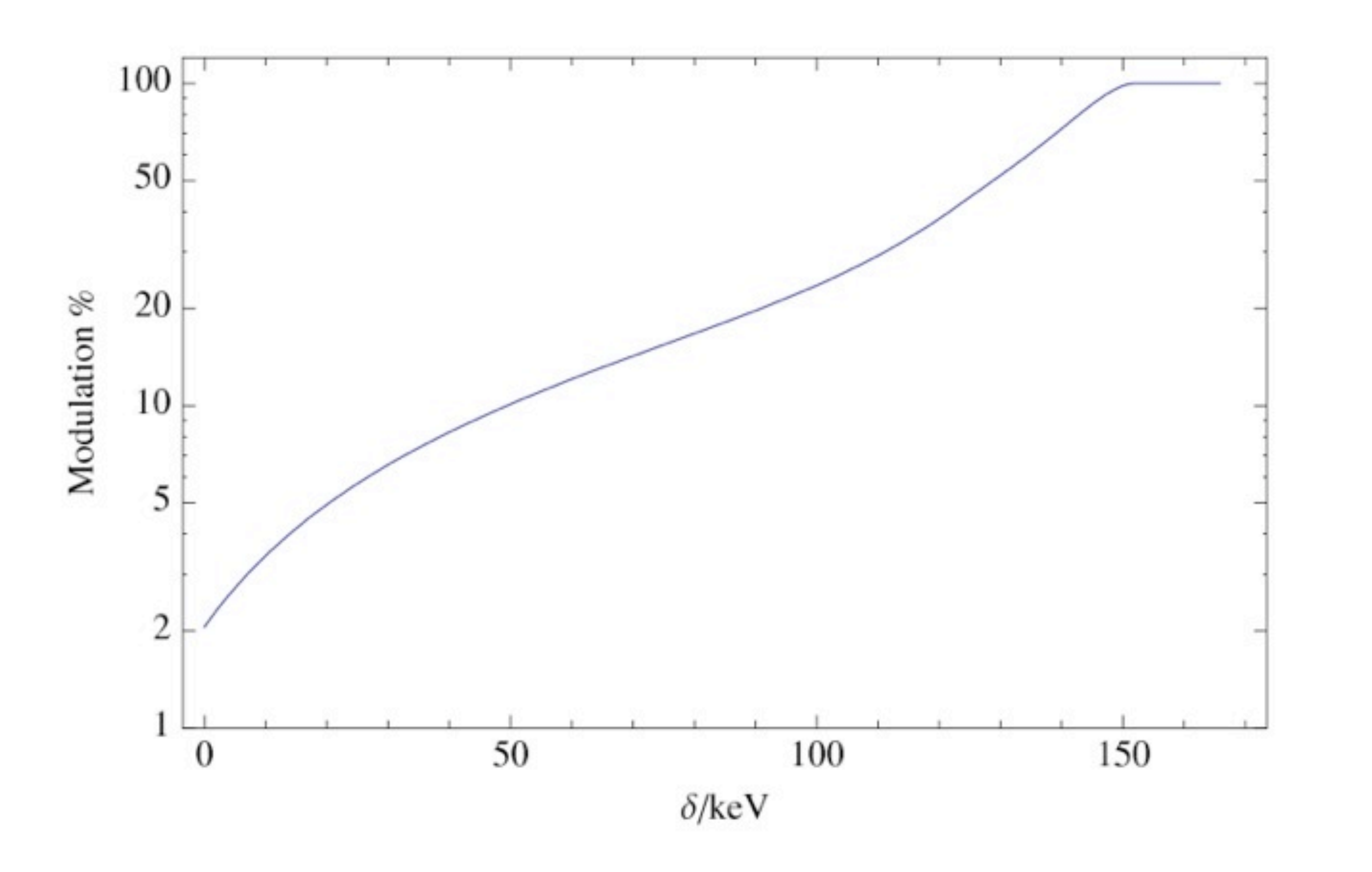
$$\frac{v^2 \mu_{\chi N}}{2} > \delta$$

Favors heavier targets



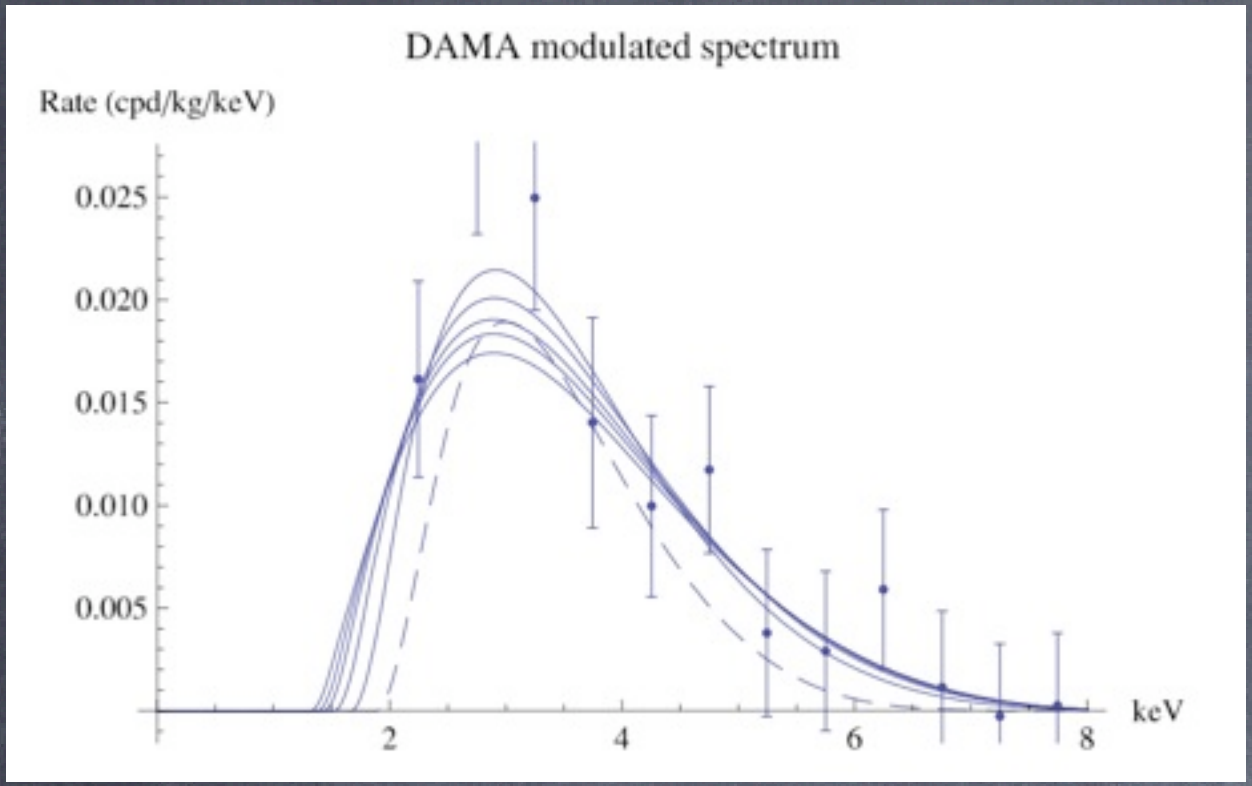
Disfavors CDMS

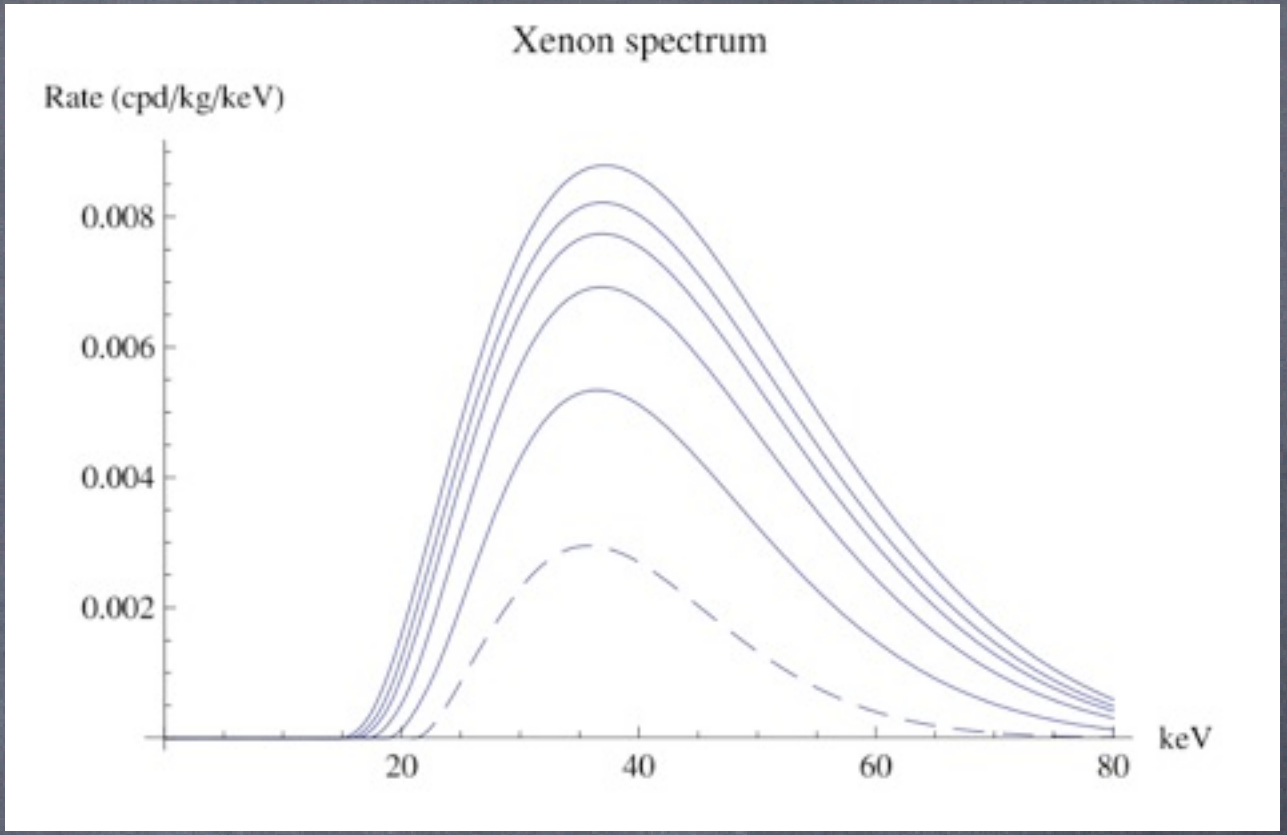
Enhanced modulation



Favors modulation experiments

Modified spectrum





How robust are these effects?