The Hunt For Dark Matter …Continues

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Fermilab/University of Chicago

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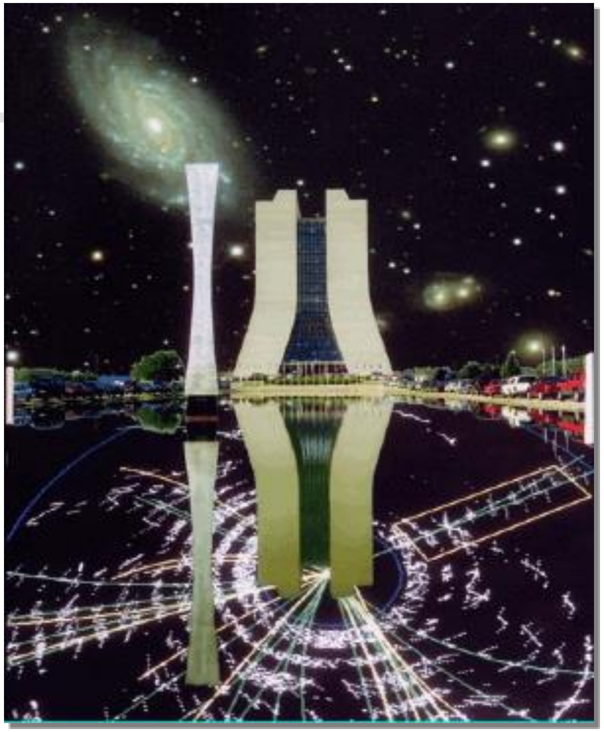
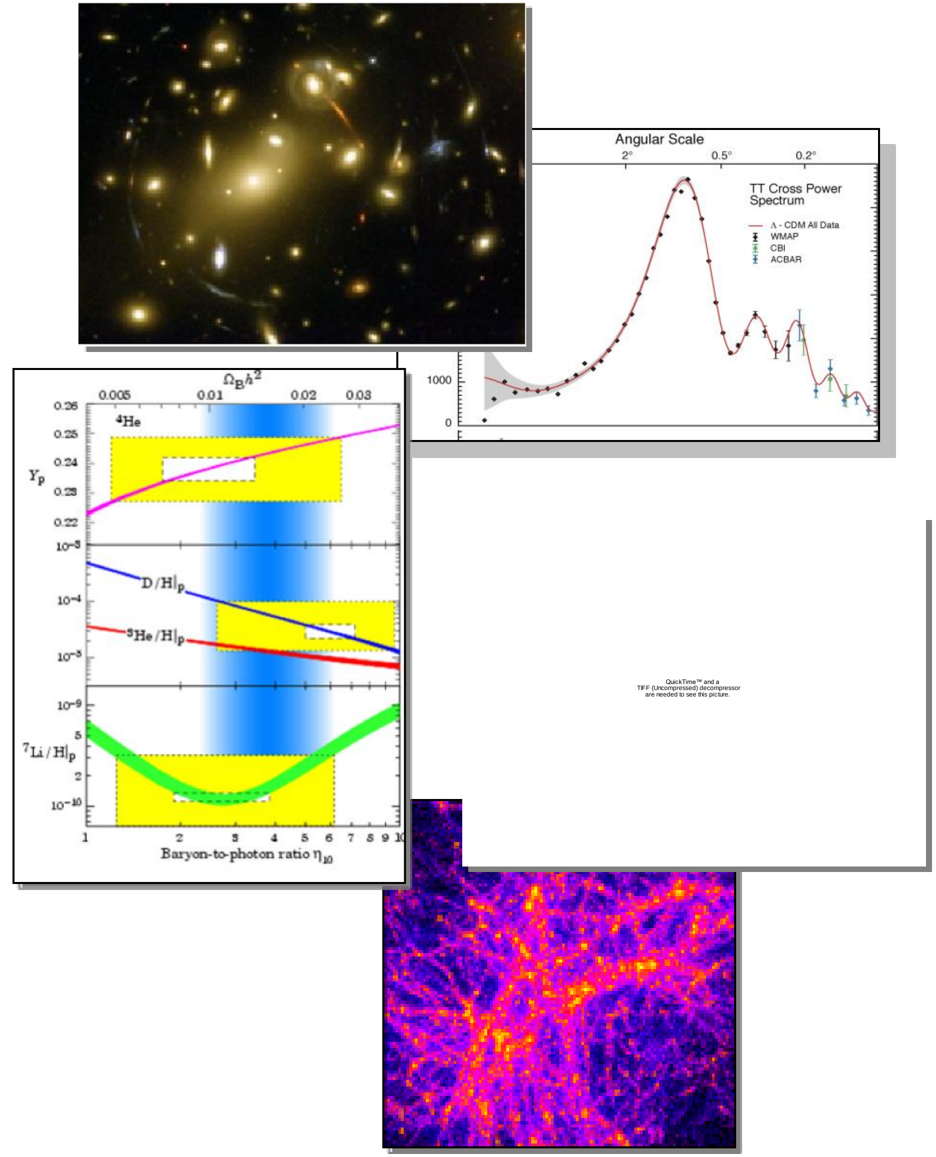
Physics Colloquium
May 6, 2010



QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

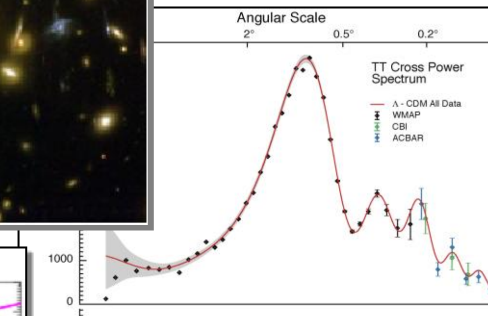
Evidence For Dark Matter

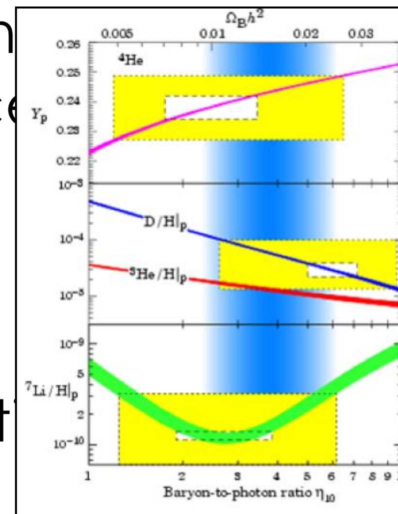
- Galactic rotation curves
- Gravitational lensing
- Light element abundances
- Cosmic microwave background anisotropies
- Large scale structure

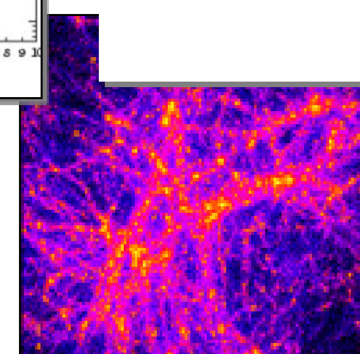


Evidence For Dark Matter

- There exists a wide variety of independent indications tha dark matter exists
- Each of these observations infer dark matter's presence th its gravitational influence
- Still no observations of dark matter's electroweak interactions (or other non-gravitational interact







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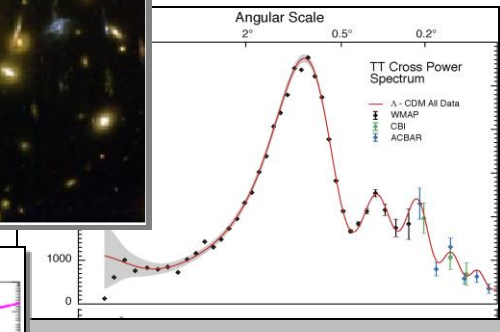
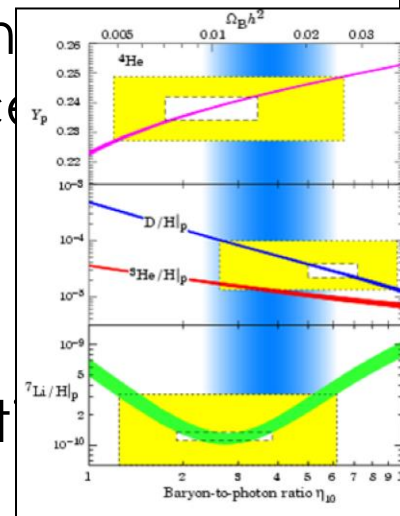
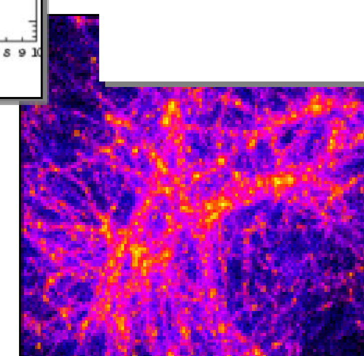
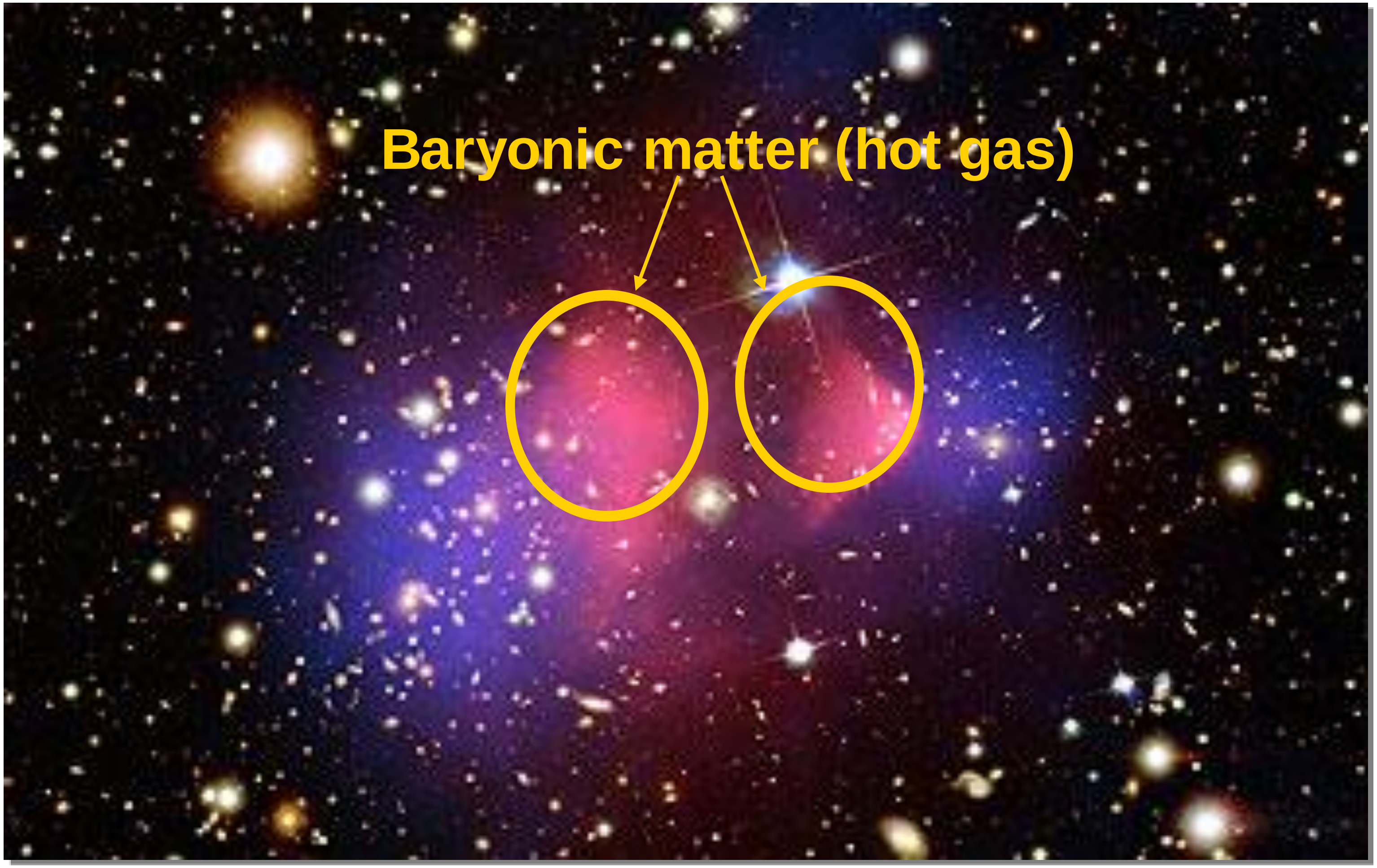






Instead of dark matter, might we not understand gravity?

NASA/Chandra Press Release,
August 21, 2006



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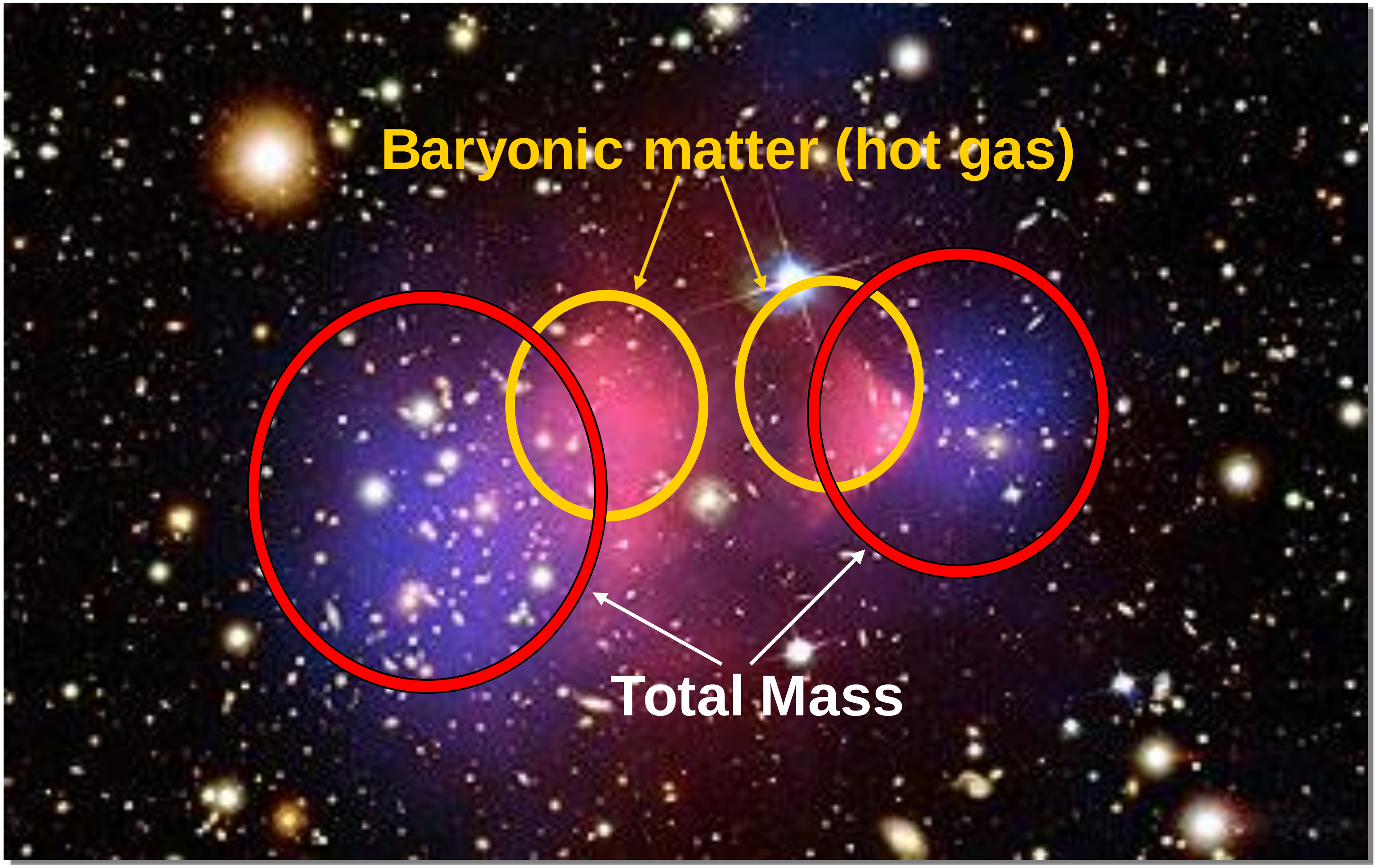


NASA/Chandra Press Release,
August 21, 2006

MOND Takes Another Bullet

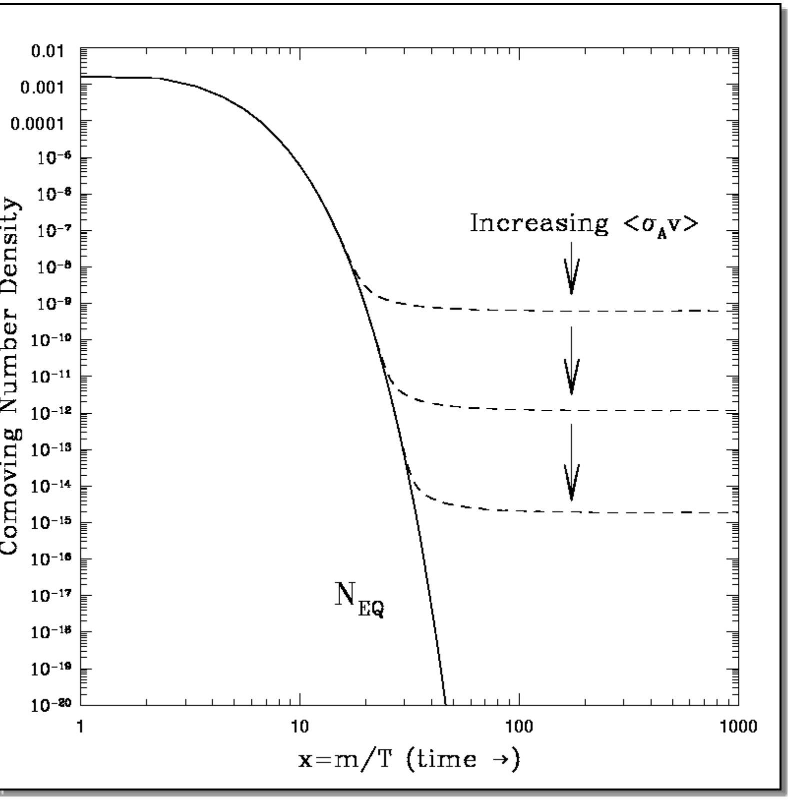
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

MACS J0025.4-1222,
R. Massey et al, August 27, 2008

Why WIMPs?

<u>The thermal abundance of a WIMP</u>

- T >> M, WIMPs in thermal equilibrium
- T < M, number density becomes Boltzmann suppressed
- T ~ M/20, Hubble expansion dominates over annihilations; freeze-out occurs
- Precise temperature at which freeze-out occurs, and the d which results, depends on the WIMP's annihilation cross sec



Why WIMPs?

The thermal abundance of a WIMP

- As a result of the thermal freeze-out process, a relic density of WIMPs is left behind:

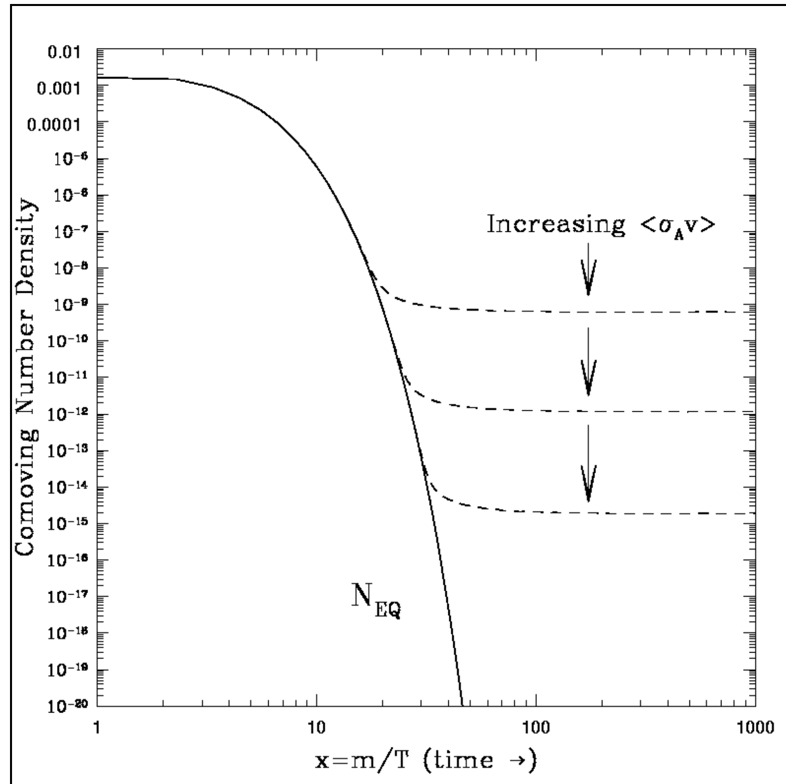
$$\Omega h^2 \sim x_F / \langle \sigma v \rangle$$

- For a GeV-TeV mass particle, to obtain a thermal abundance equal to the observed dark matter density, we need an annihilation cross section of:

$$\langle \sigma v \rangle \sim \text{pb}$$

- Generic weak interaction yields:

$$\langle \sigma v \rangle \sim \alpha^2 \, (100 \text{ GeV})^{-2} \sim \text{pb}$$



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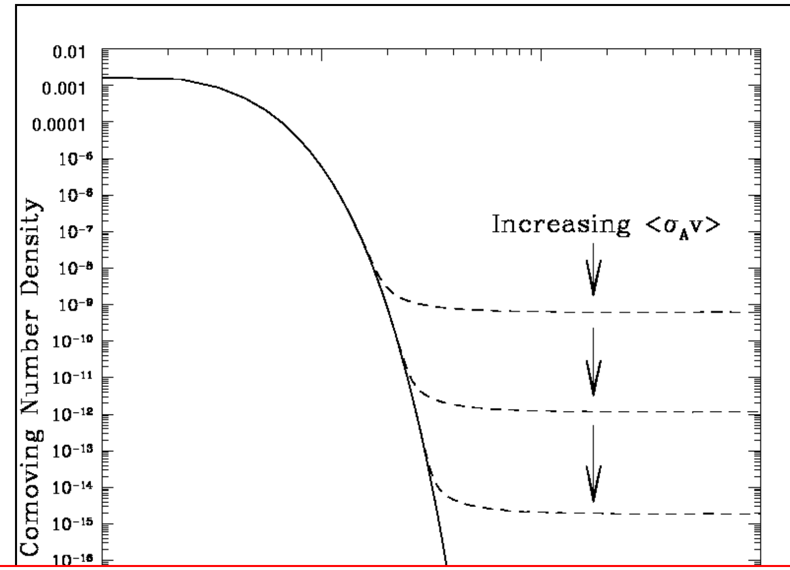
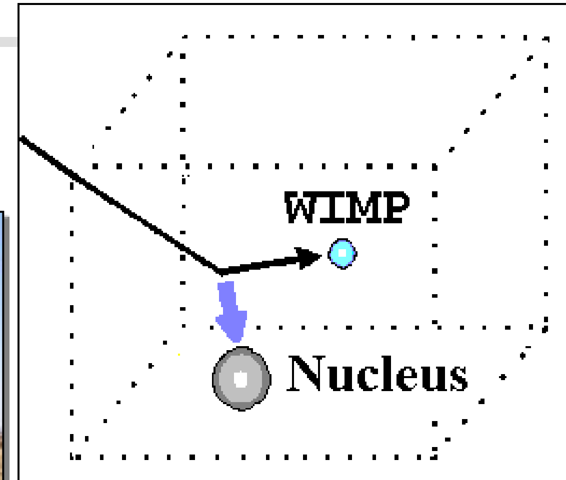


Numerical coincidence? Or an indication that dark matter originates from electroweak-scale physics?

WIMP Hunting

- Direct Detection
- Indirect Detection
- Collider Searches



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Direct Detection

- Elastic scattering between WIMPs and target nuclei

- Over the past decade, direct detection experiments have improved in sensitivity at a rate of about 1 order of magnitude every 2 years

Current Status

Direct Detection

- New results from XENON 100 have just been released
- Their limit is (slightly) more stringent than that from CDMS for WIMPs lighter than about 100 GeV
- Result is based on only 11 days of data - much stronger limits are soon to come

The Signals/Hints/Detections

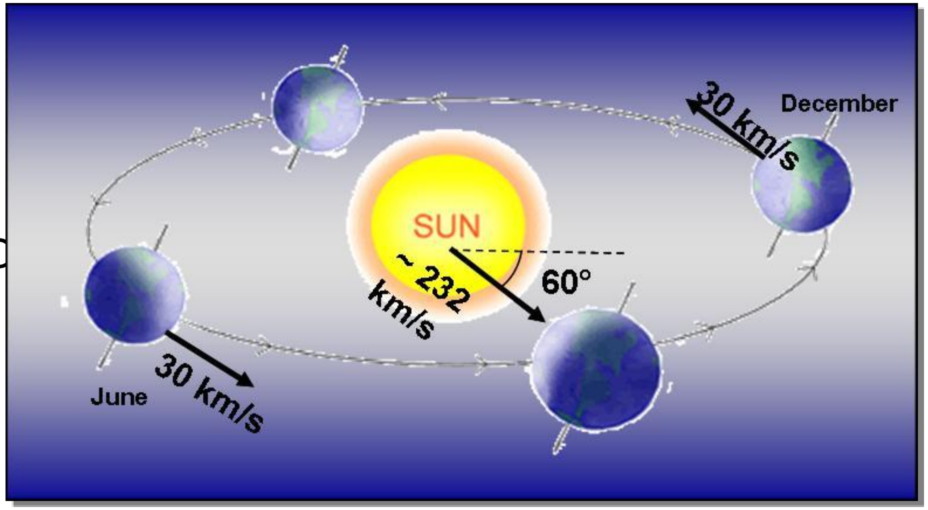
- But not all direct detection experiments have claimed null results

- For most of the past decade,
  DAMA has claimed to be observing dark matter scattering
- CoGeNT has recently reported a signal resembling dark matter
- CDMS recently reported 2 events

The Signals/Hints/Detections

DAMA/LIBRA

- Over the course of a year, the motion of the Earth around the Solar System is expected to induce a modulation in the dark matter scattering rate



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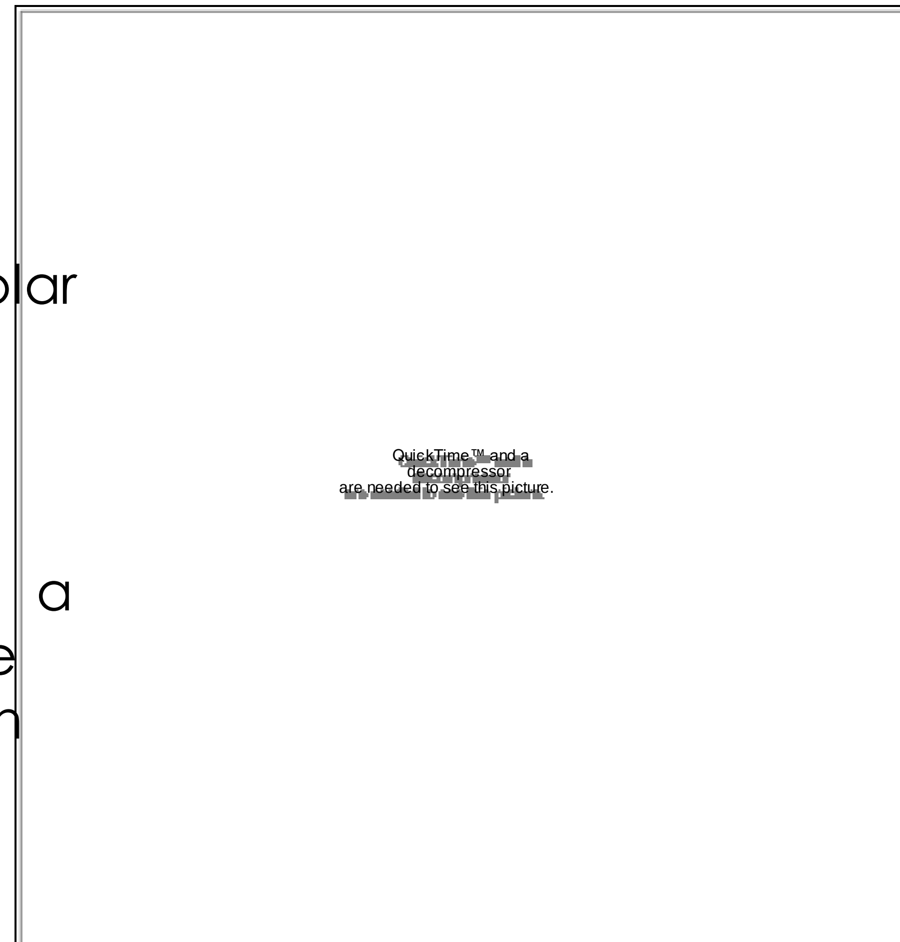
DAMA/LIBRA

- Over the course of a year, the motion of the Earth around the Solar System is expected to induce a modulation in the dark matter scattering rate

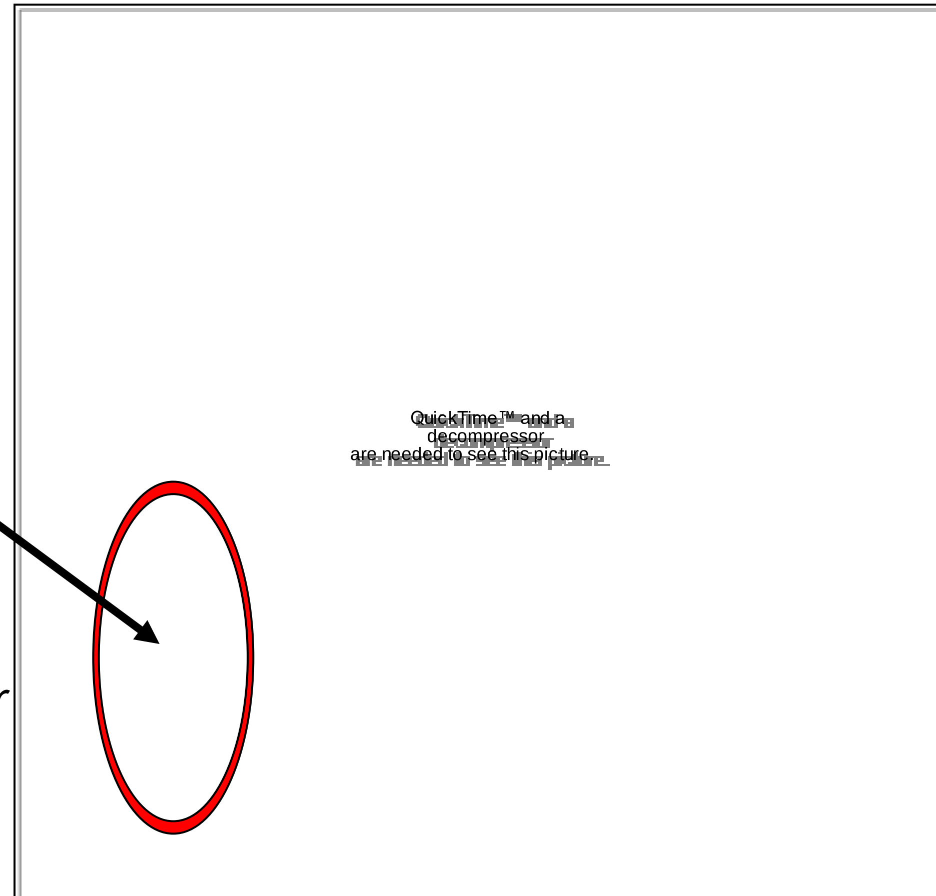
- The DAMA collaboration reports a modulation with the right phase to be dark matter, and with high statistics (8.9σ)



The Signals/Hints/Detections

CoGeNT

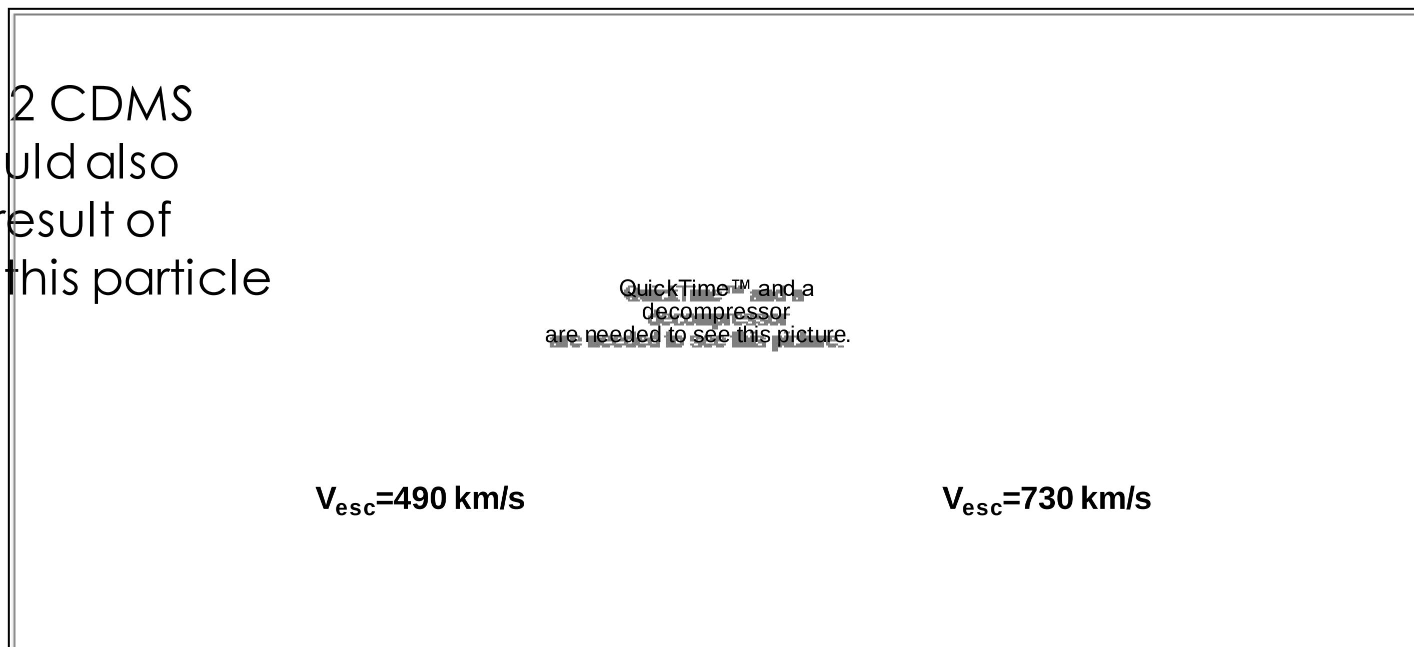
- The CoGeNT collaboration recently announced their observation of an excess of low energy events
- Although it has less exposure than other direct detection experiments, CoGeNT is particularly well suited to look for low energy events (low mass WIMPs)



CoGeNT Collaboration, arXiv:1002.4703

The Signals/Hints/Detections

- Intriguingly, the CoGeNT and DAMA signals, if interpreted as dark matter, point to a similar region of parameter space
- Depending on the velocity distribution used, and on how one treats channeling, regions can be found in which both DAMA and CoGeNT can be explained by the same ~7-10 GeV dark matter particle
- If v_{esc} is relatively large, the 2 CDMS events could also be the result of this particle



Fitzpatrick, Hooper, Zurek, arXiv:1003.0014

A CoGeNT/DAMA WIMP?

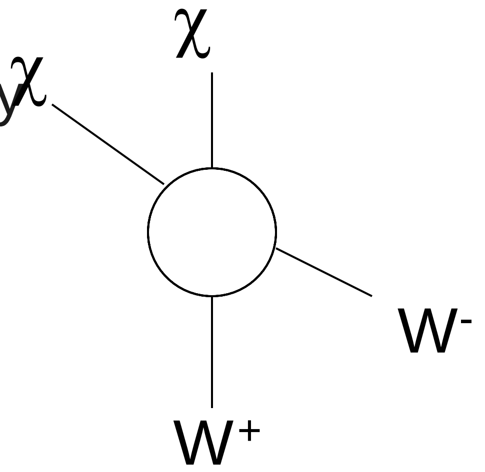
A ~10 GeV WIMP leads to many interesting implications:

- Relatively large couplings and/or light mediators are needed to avoid of the overproduction of such a particle in the early universe
- MSSM does not provide a viable dark matter candidate in this mass range (although extended supersymmetric models may)
- Simple models can accommodate these signals, but they are not the models most particle theorists are studying
- M_{DM}~10 GeV is the approximate mass range predicted in models in which the baryon asymmetry of the universe is related to the dark matter sector
- Low mass implies high annihilation rate; excellent prospects for indirect detection
- Old white dwarfs may be observably heated by such a particle

The Indirect Detection of Dark Matter

1. **WIMP Annihilation**

Typical final states include heavy fermions, gauge or Higgs bosons



The Indirect Detection of Dark Matter

1. **WIMP Annihilation**

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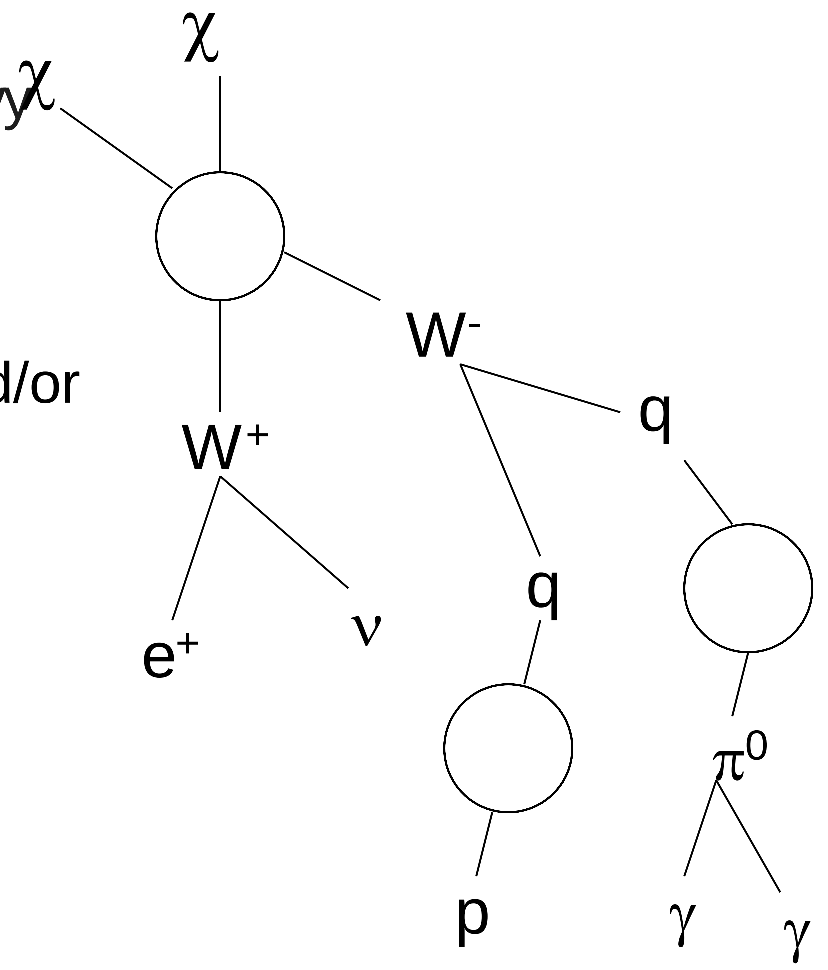
2. **Fragmentation/Decay**

   Annihilation products decay and/or fragment into combinations of electrons, protons, deuterium, neutrinos and gamma-rays



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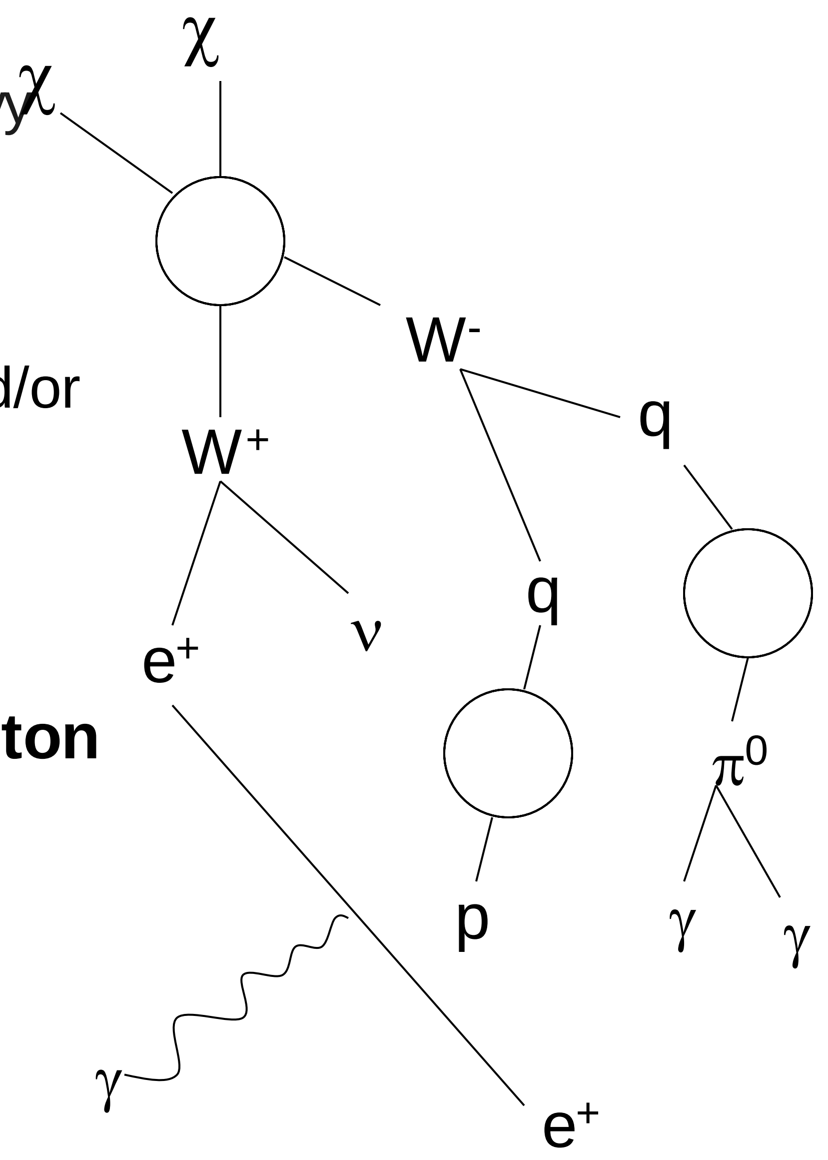
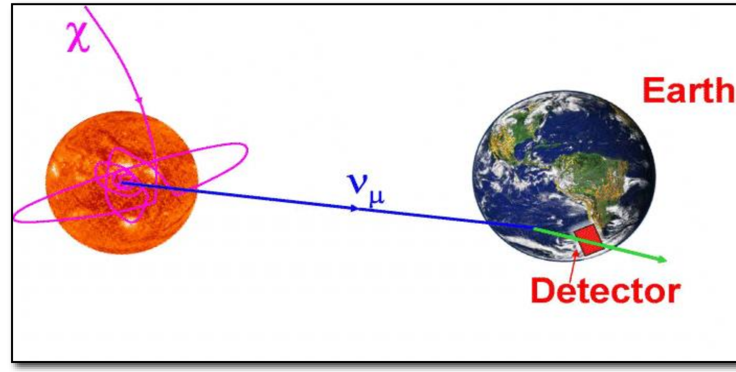
3. Synchrotron and Inverse Compton

Relativistic electrons up-scatter starlight/CMB to MeV-GeV energies, and emit synchrotron photons via interactions with magnetic fields



The Indirect Detection of Dark Matter

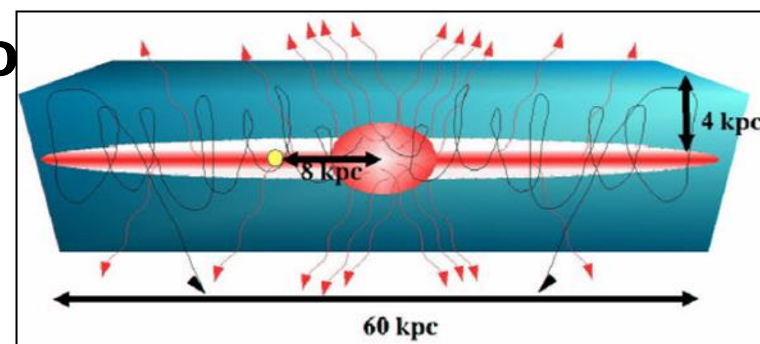
- **Neutrinos** from annihilations in the core of the Sun



- **Gamma Rays** from annihilations in the galactic halo, near the galactic center, in dwarf galaxies, etc.

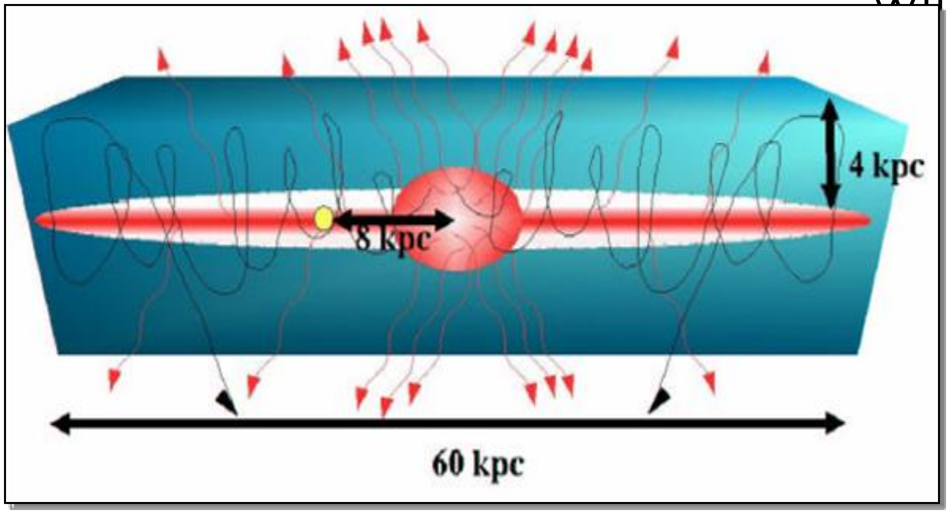
- **Positrons/Antiprotons** from annihilations throughout the galactic halo

- **Synchrotron and Inverse Compto** from electron/positron interactions with the magnetic fields and radiation fields of the galaxy



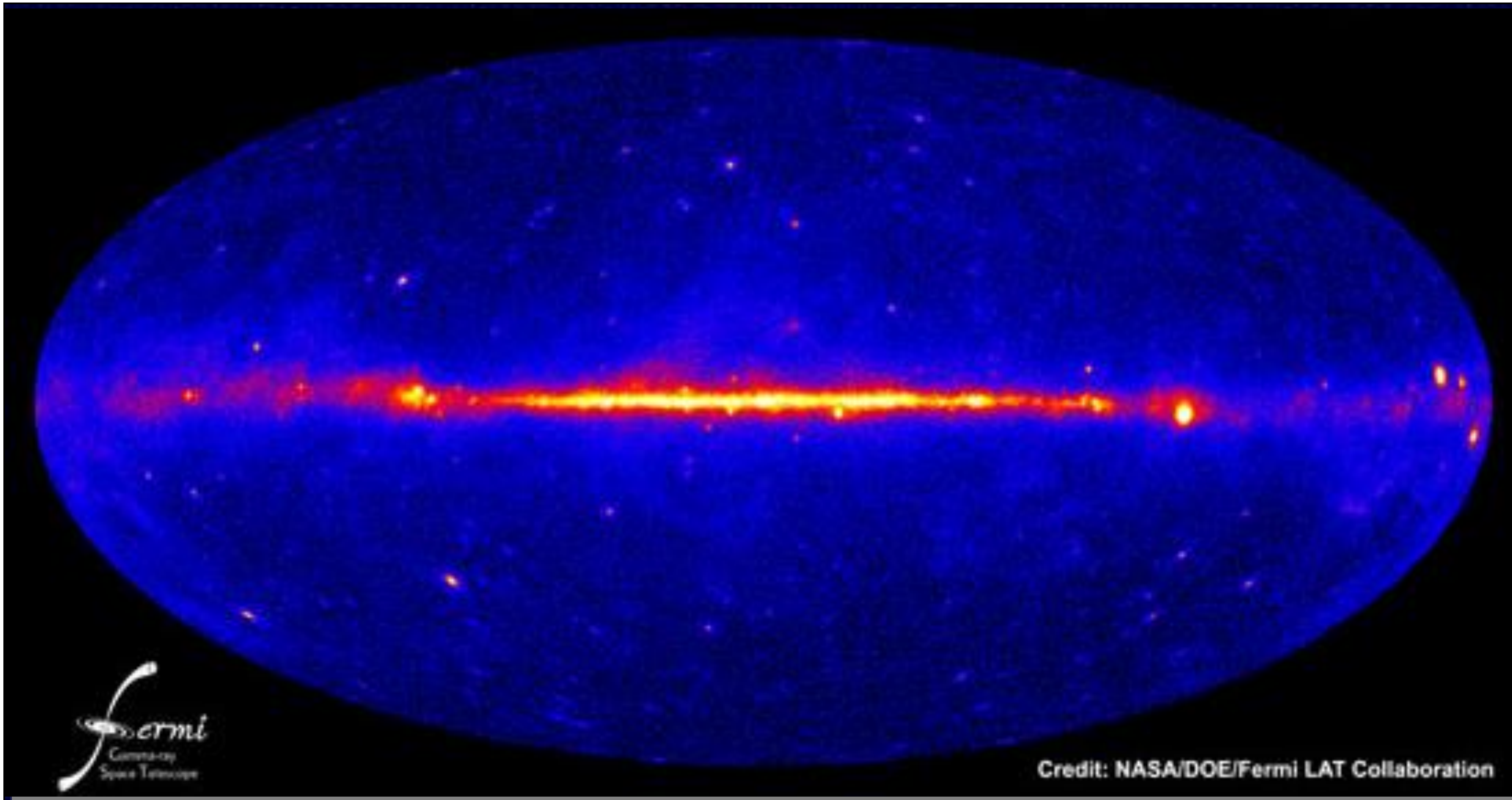
Dark Matter With Charged Cosmic Rays

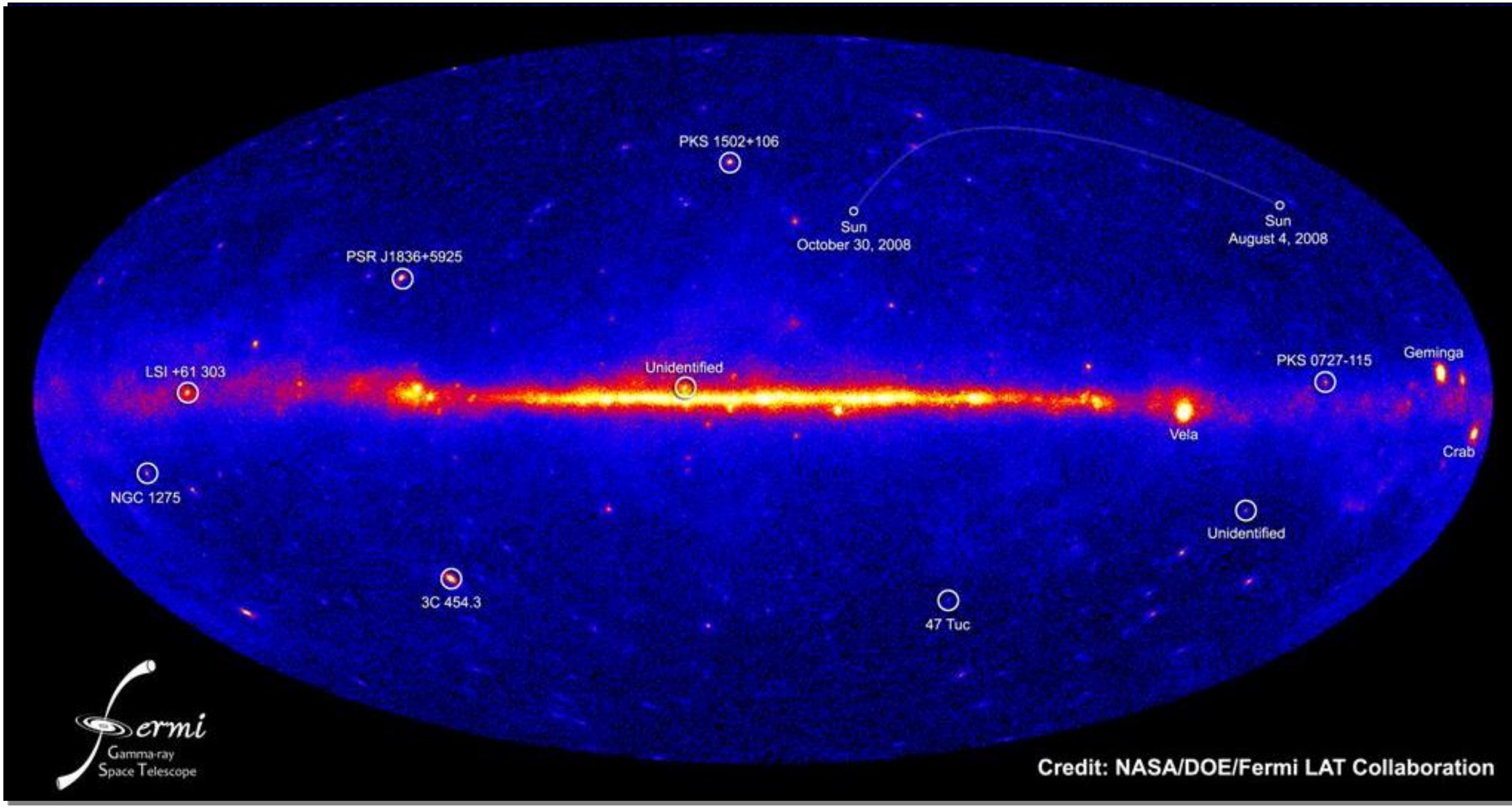
- At this point in my talk, I usually spend the next few dozen slides talking about dark matter searches with positrons, electrons, and antiprotons
- But at last count, my talk was 124 slides long
- And frankly, we have all heard that stuff a few too many times at this point (right?)
- So, onto dark matter searches with photons instead!



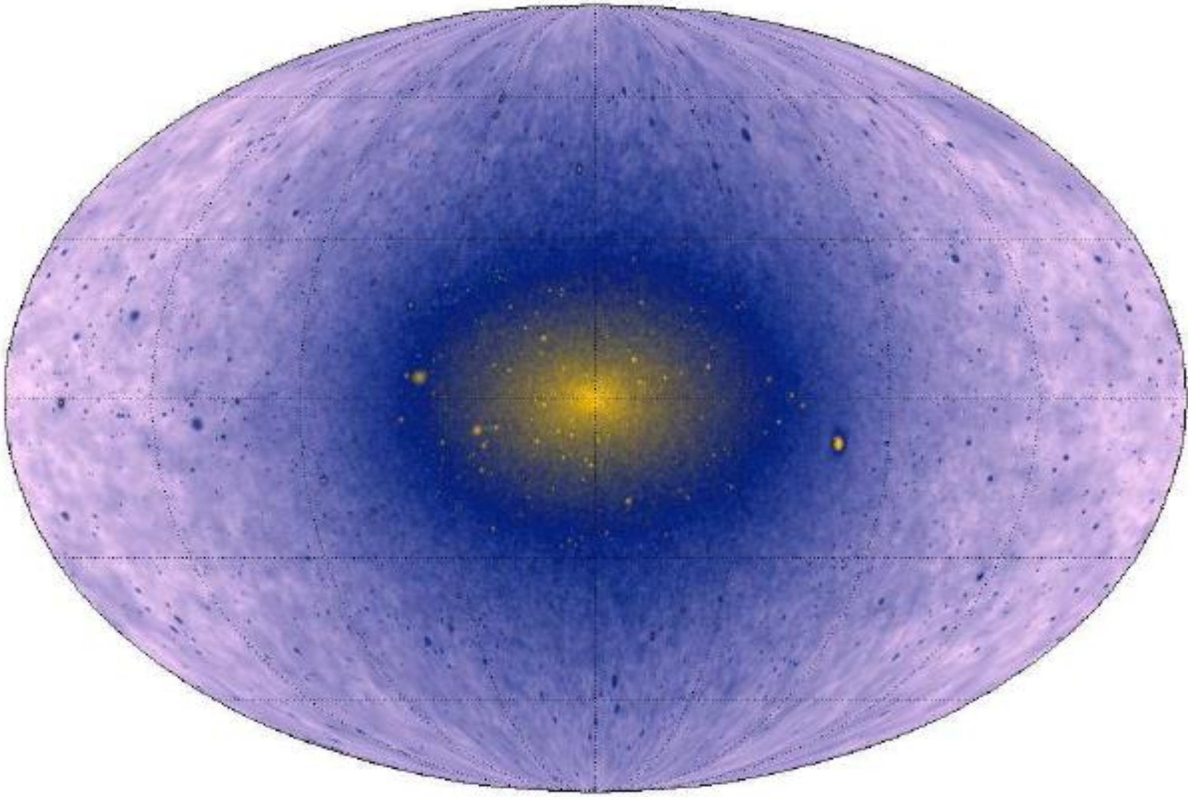
An Essential Test:
Searches For Gamma Rays From Dark Matter Annihilations With Fermi

- Last year, the FERMI collaboration announced their first results!
- In August, their first year data became publicly available
- Signatures of dark matter annihilation might appear clearly and quickly, or over years exposure, or not at all, depending on the dark matter distribution, annihilation cross section, mass, and astrophysical backgrounds


Fermi
Gamma-ray
Space Telescope
Credit: NASA/DOE/Fermi LAT Collaboration


PKS 1502+106
Sun
October 30, 2008
Sun
August 4, 2008
PSR J1836+5925
LSI +61 303
Unidentified
PKS 0727-115
Geminga
Vela
Crab
NGC 1275
Unidentified
3C 454.3
47 Tuc
Fermi
Gamma-ray
Space Telescope
Credit: NASA/DOE/Fermi LAT Collaboration

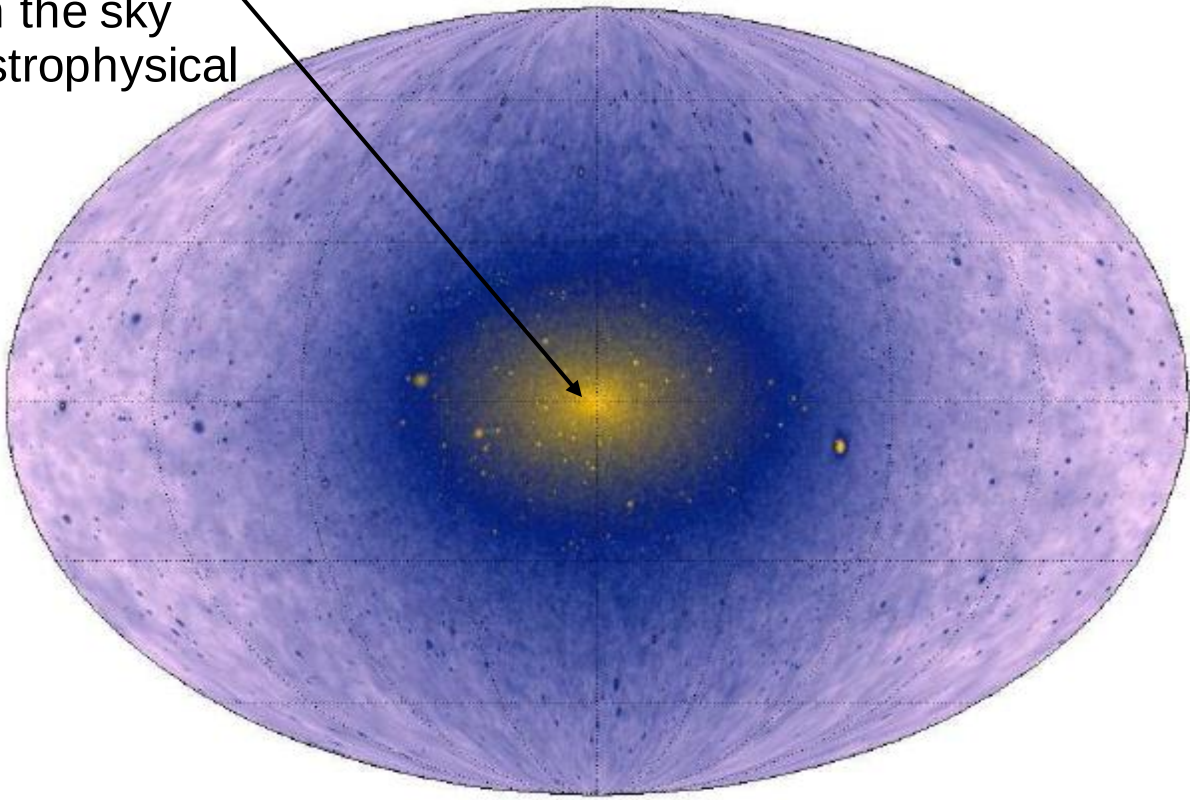
Where To Look For Dark Matter With Fermi?



Where To Look For Dark Matter With Fermi?

The Galactic Center

-Brightest spot in the sky
-Considerable astrophysical backgrounds



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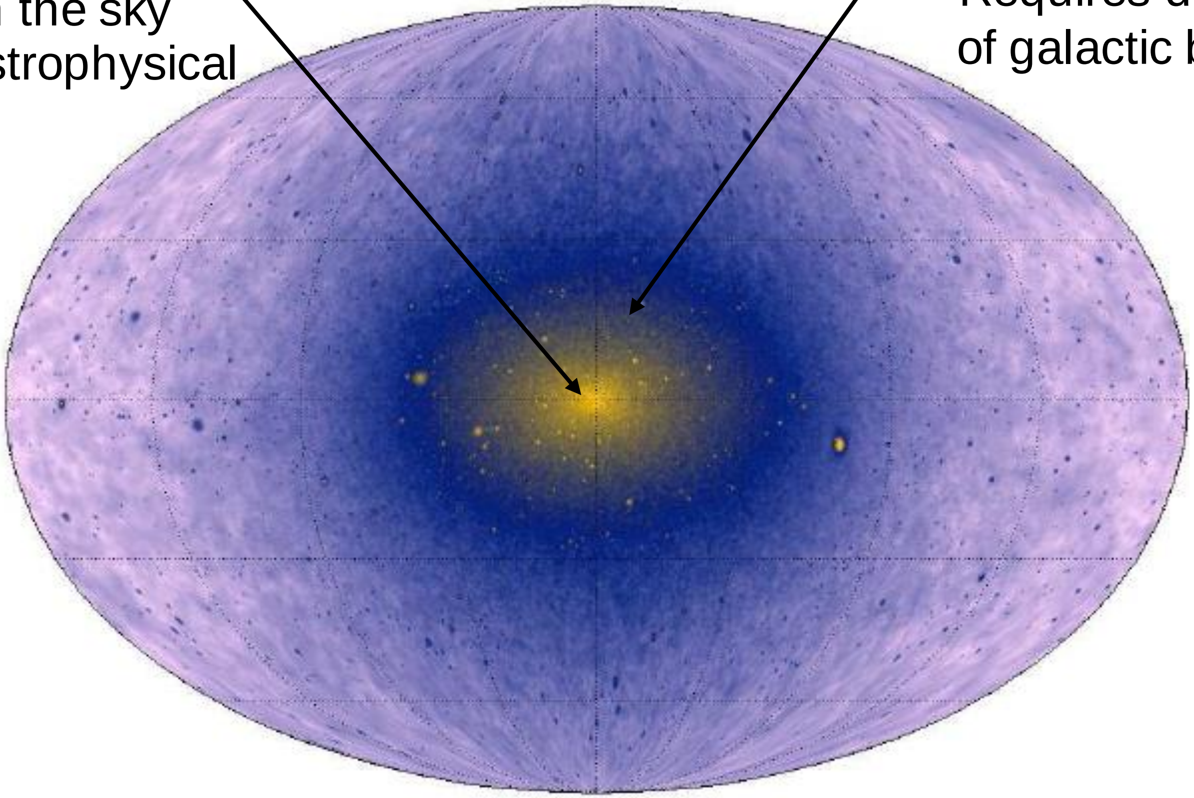
The Galactic Halo

-High statistics
-Requires detailed model of galactic backgrounds



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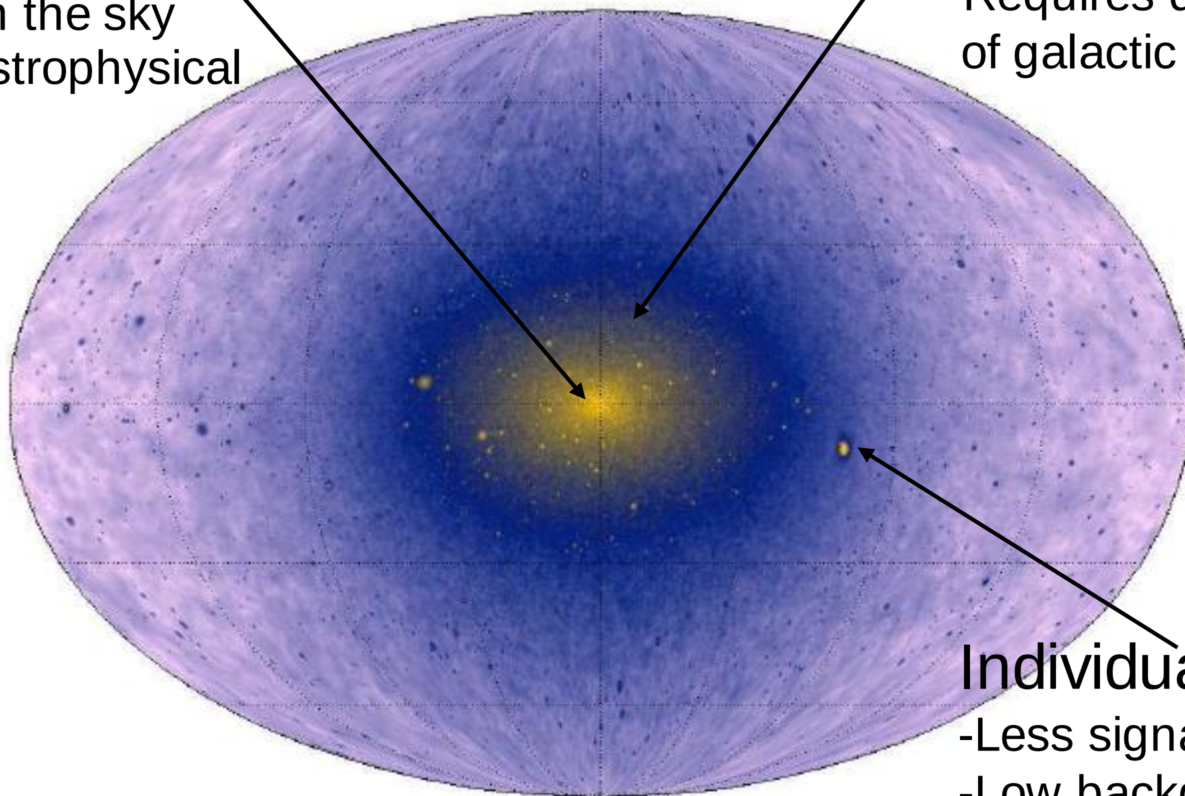

Individual Subhalos
-Less signal
-Low backgrounds

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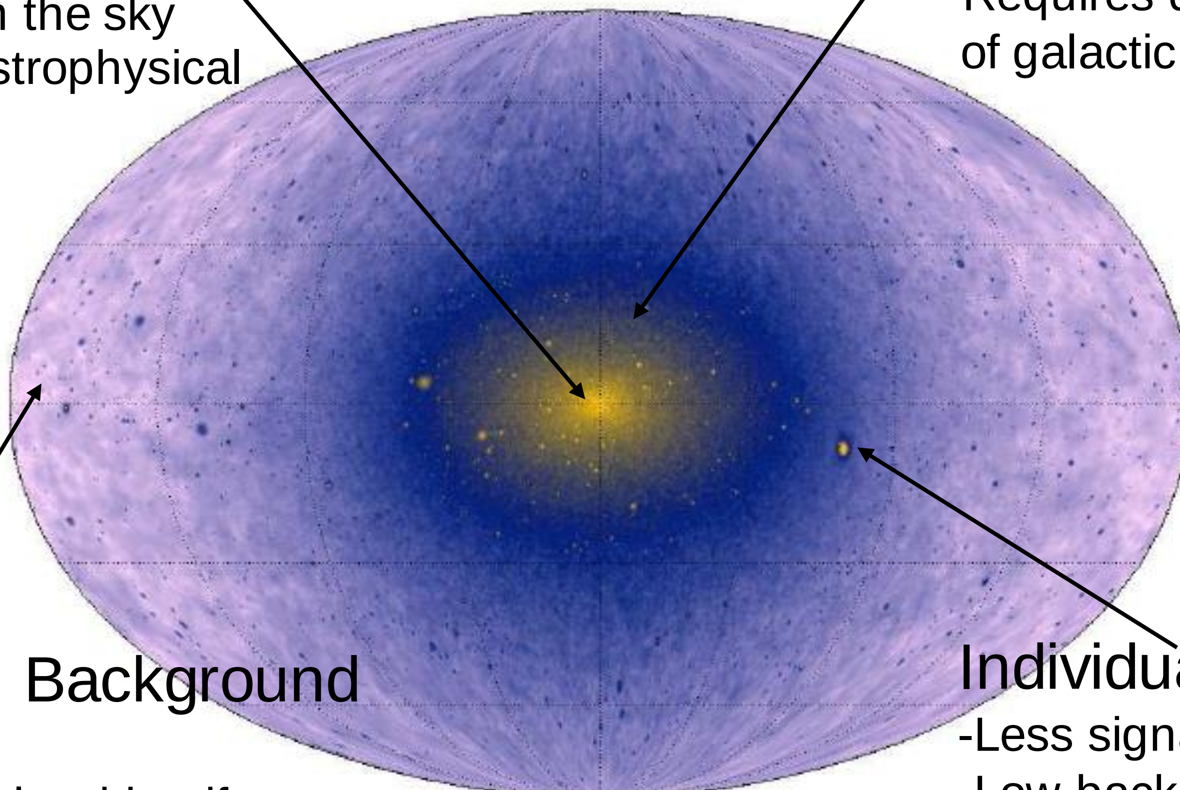

Extragalactic Background
-High statistics
-potentially difficult to identify

Individual Subhalos
-Less signal
-Low backgrounds

QuickTime™ and a
decompressor
are needed to see this picture.

8) Isotropic Diffuse

Dwarf Spheroidal Galaxies

- The FGST collaboration has recently placed some relatively stringent limits on dark matter from observations of a number of satellite galaxies (dwarf spheroidals) of the Milky Way
- The most stringent limits come from those dwarfs which are 1) dense, 2) nearby, and 3) in low background regions of the sky

QuickTime™ and a
decompressor
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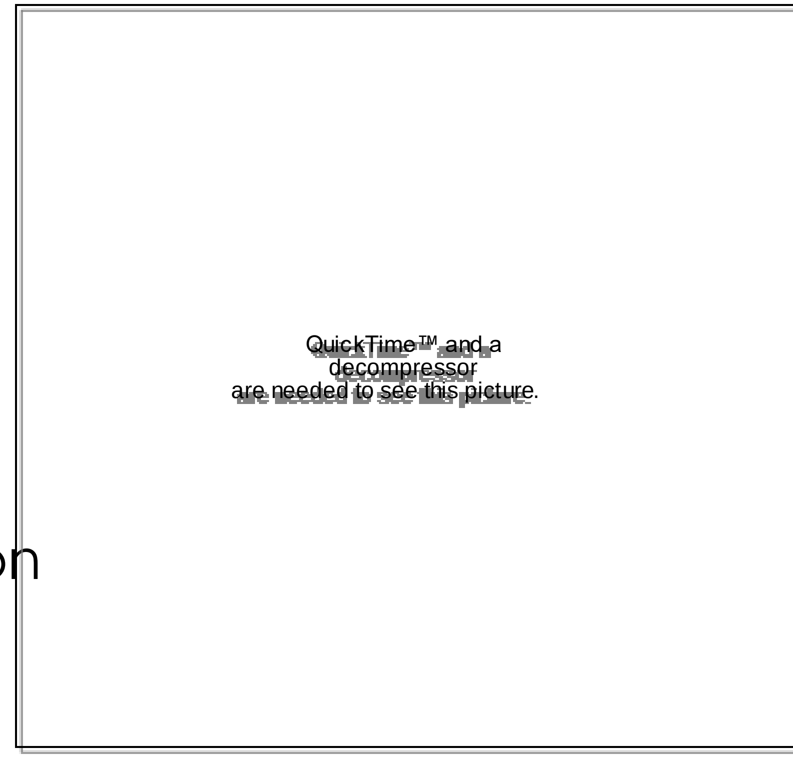
See also the analysis of Segue 1 by P. Scott *et al.*, arXiv:0909.3300

Isotropic Diffuse Emission

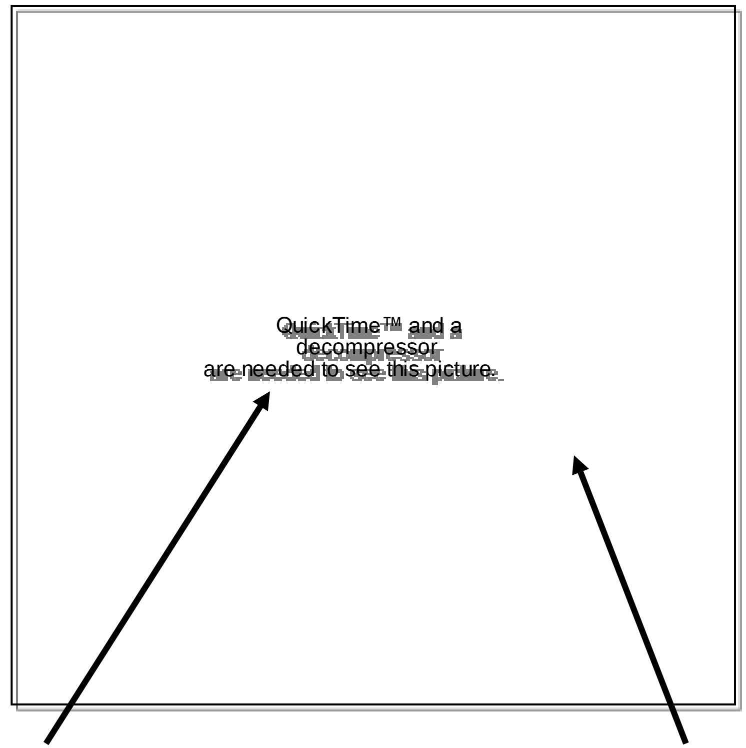
- In typical models, the diffuse background from extragalactic dark matter annihilation produces about 0.1% to 1% of the flux observed by EGRET
- As Fermi resolves more sources (blazars, etc.), the background will decrease, leading to stronger limits on the dark matter annihilation rate



Belikov and Hooper, PRD, arXiv:0906.2251; Profu
and Jeltema, JCAP, arXiv:0906.0001;
Ullio, Bergstrom, Edsjo, Lacey, PRD, astro-ph/0207125

Isotropic Diffuse Emission

- Annihilations to charged leptons also lead to gamma-rays through inverse Compton scattering with the CMB (Pamela motivated models may produce an observable flux of IC photons)



Belikov and Hooper, PRD, arXiv:0906.2251;
Profumo and Jeltema, JCAP, arXiv:0906.0001

Fermi and the Extragalactic Gamma-Ray Background

- Fermi's ability to identify signatures of dark matter annihilation in the extragalactic background depends critically on how much of the background can be resolved into individuals sources (blazars, etc.)
- If we are a bit lucky (large flux, resolvable background), Fermi should be able to resolve a large fraction of the isotropic background observed by EGRET

Blazar Simulation

QuickTime™ and a
decompressor
are needed to see this picture.

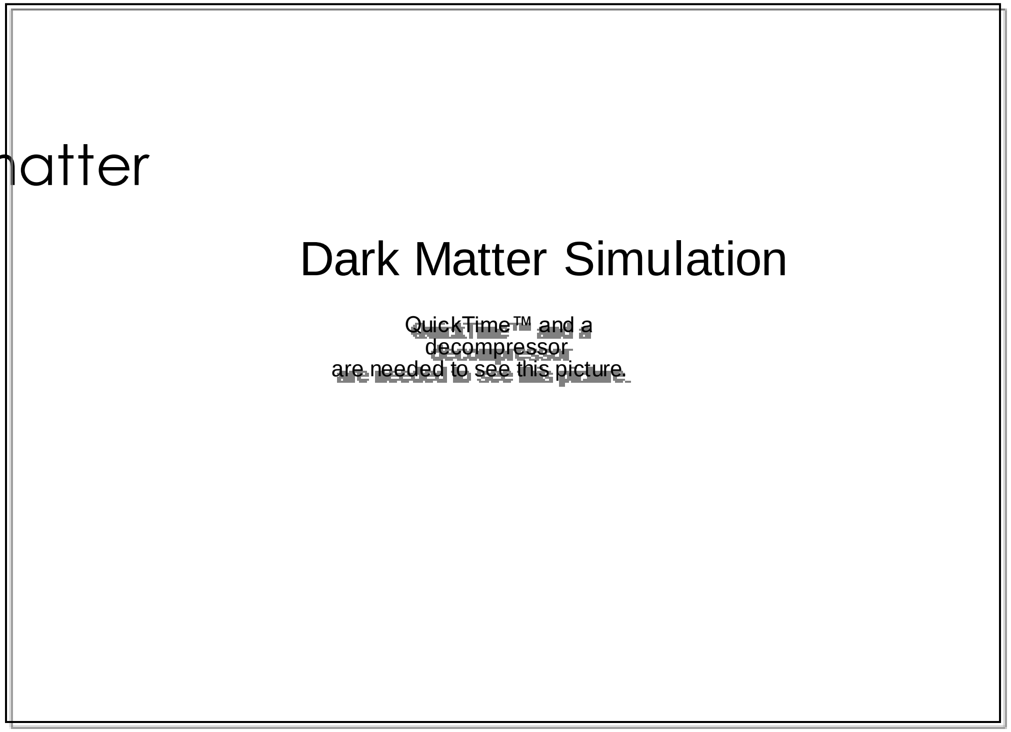
Dark Matter Simulation

QuickTime™ and a
decompressor
are needed to see this picture.

Dodelson, Belikov, Hooper, Serpico, PRD, arXiv:0903.2829

Fermi and the Extragalactic Gamma-Ray Background

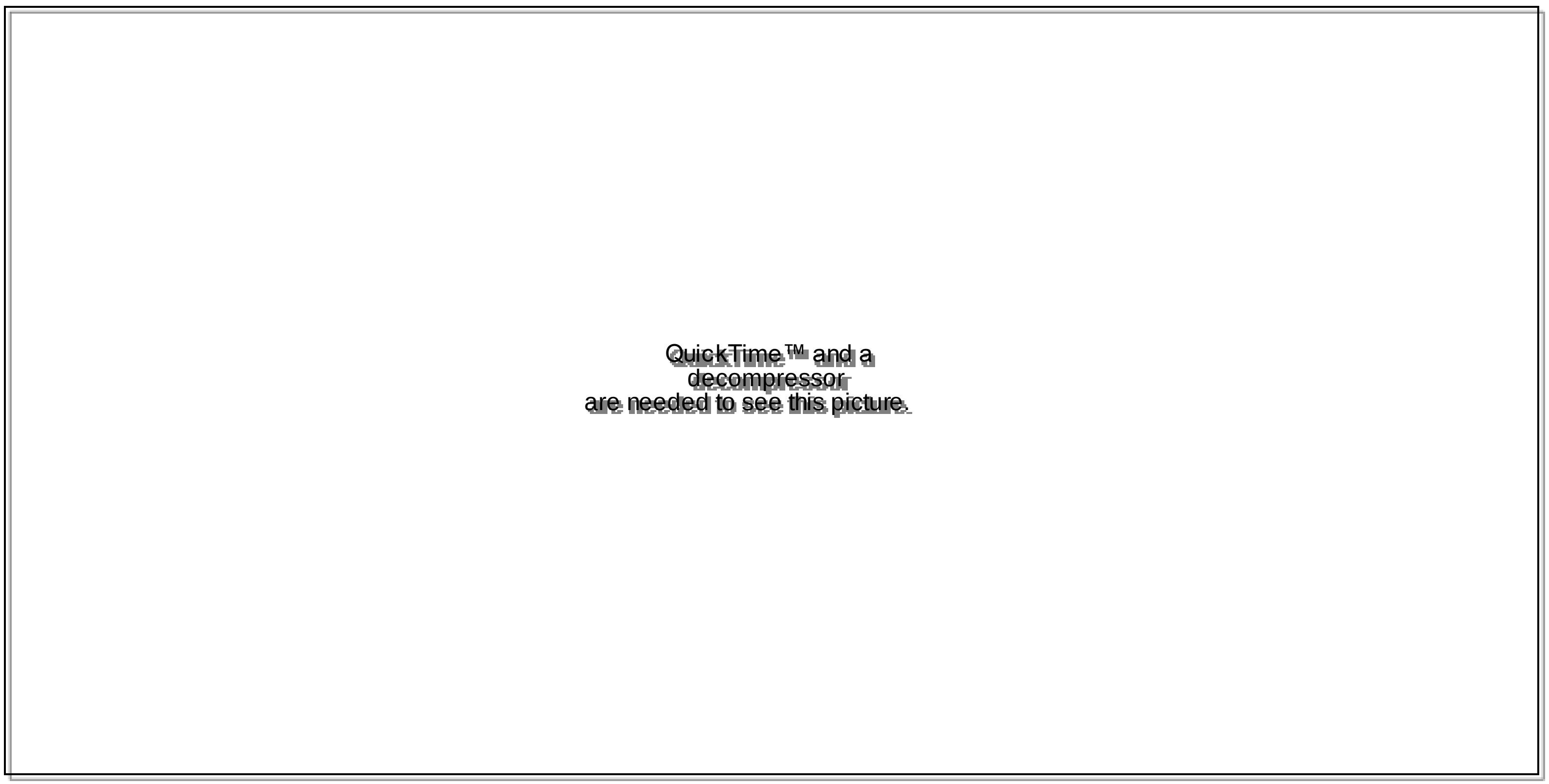
- The Fermi collaboration has recently released its measurements of the isotropic gamma ray background - factor of several improvement from EGRET’s measurement at >10 GeV
- This new background is low enough to place fairly stringent limits on dark matter annihilation



Fermi Collaboration, arXiv:1002.4415

Fermi and the Extragalactic Gamma-Ray Background

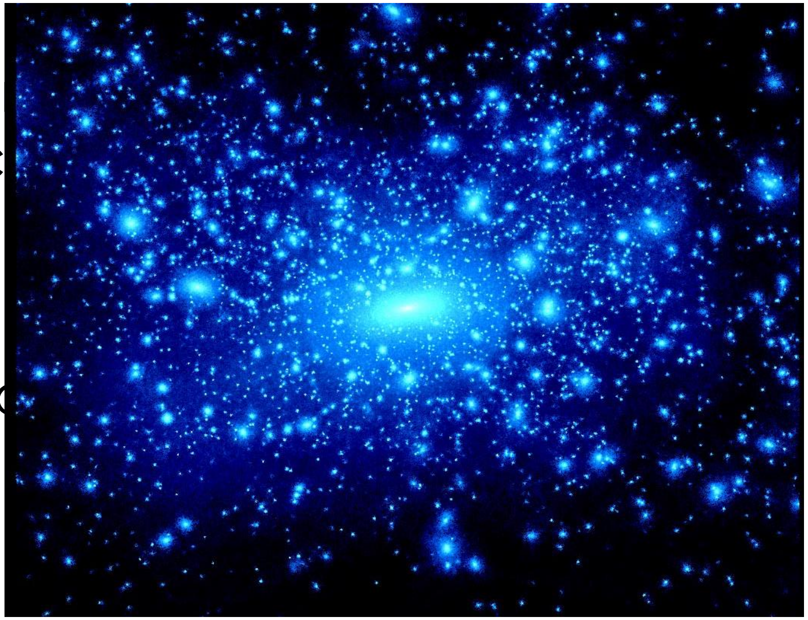
- Combining galactic diffuse and isotropic diffuse contributions, limits of $\sim 10^{-25}$ cm^3/s are found (m~100 GeV), although results depend on substructure assumptions (similar to dwarf limits)



Fermi Collaboration, arXiv:1002.4415

Nearby Dark Matter Subhalos

- In the standard picture of hierarchical structure formation, dark matter formed the smallest halos first, which larger merged to eventually form galaxies and clusters
- The Milky Way is expected to contain ~5x10^{16} subhalos of Ea mass or greater (~30-40 per pc our local neighborhood)
- Simulations find ~10% of the Milky Way halo's mass is expected to 10^7-10^{10} solar mass subhalos
- Potentially detectable gamma ray point sources



Nearby Dark Matter Subhalos

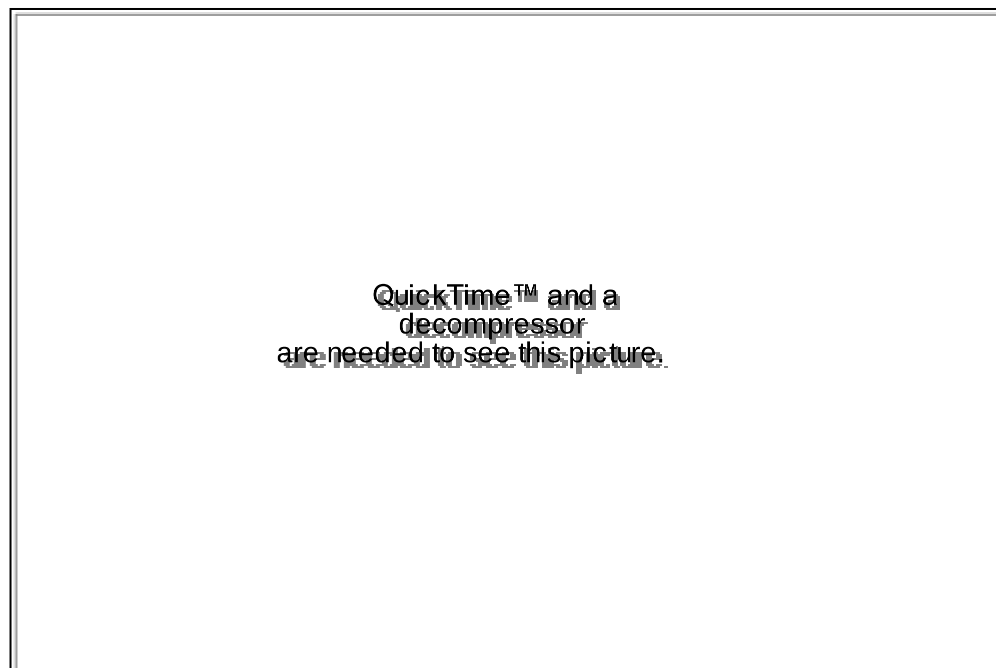
- The Fermi Collaboration has recently published a catalog of point sources, 368 of which are more than 10° away from the galactic plane and not associated with any known source in other wavelengths
- Might some number of these unidentified sources be dark matter subhalos?

Fermi Collaboration, arXiv:1002.2280

Nearby Dark Matter Subhalos

- To be detectable by FGST, a 10^{-3} solar mass halo would have to be within ~0.1 pc; at this distance, the subhalo would likely be extended (not point-like)
- A 10^{3} solar mass halo could be as far away as ~100 pc, and appear as point-like to FGST

$\Rightarrow$ *Focus on large subhalos*



M. Buckley and D. Hooper, arXiv:1004.1633

Nearby Dark Matter Subhalos

- The number of subhalos detectable by FGST depends on the WIMP's mass, annihilation cross section, and annihilation channel
- A 50 GeV WIMP with a simple thermal cross section is expected to yield a few subhalos that are detectable by FGST
- If sub-substructure is significant the number can be larger
- Variations in halo profile shape and mass losses assumed can alter the number of subhalos by a factor of a few in either direction

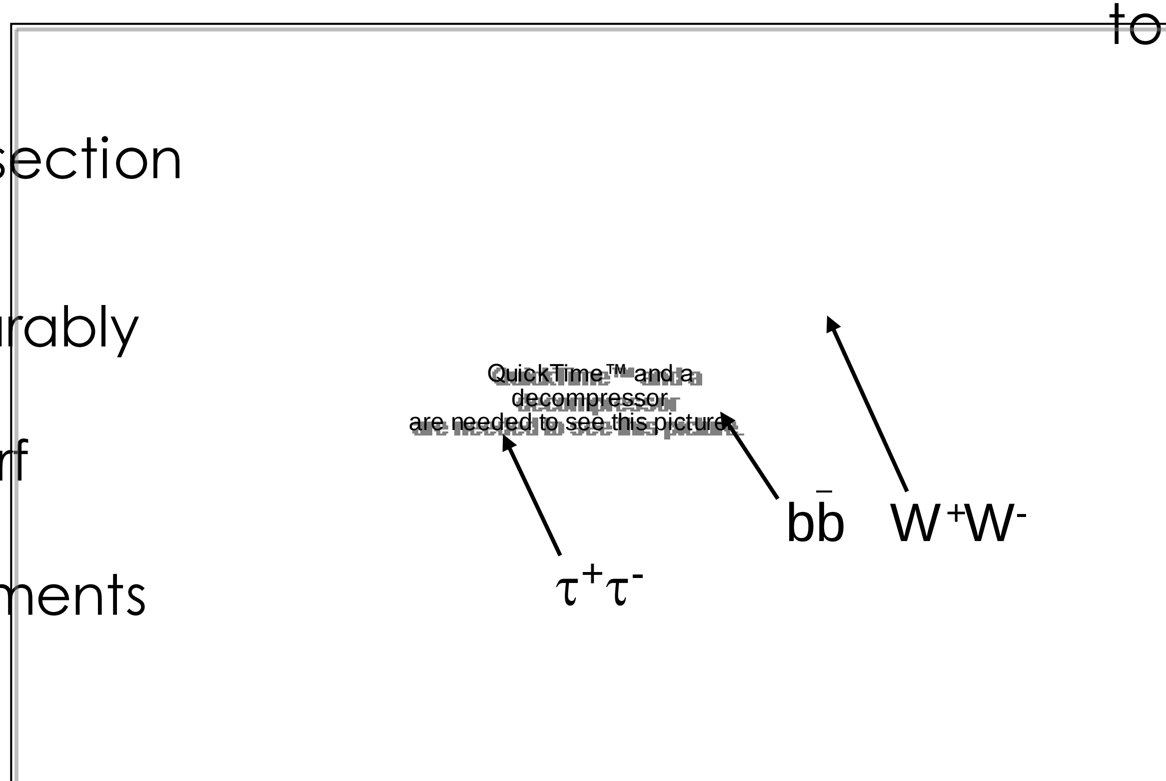
M. Buckley and D. Hooper, arXiv:1004.1633

Nearby Dark Matter Subhalos

- Comparing the spectrum of unidentified sources in the FGST catalog to that predicted from annihilating dark matter, we calculate the maximum number subhalos contained within the catalog (typically ~20-60).

- We then translate this to a limit on the WIMP’s annihilation cross section

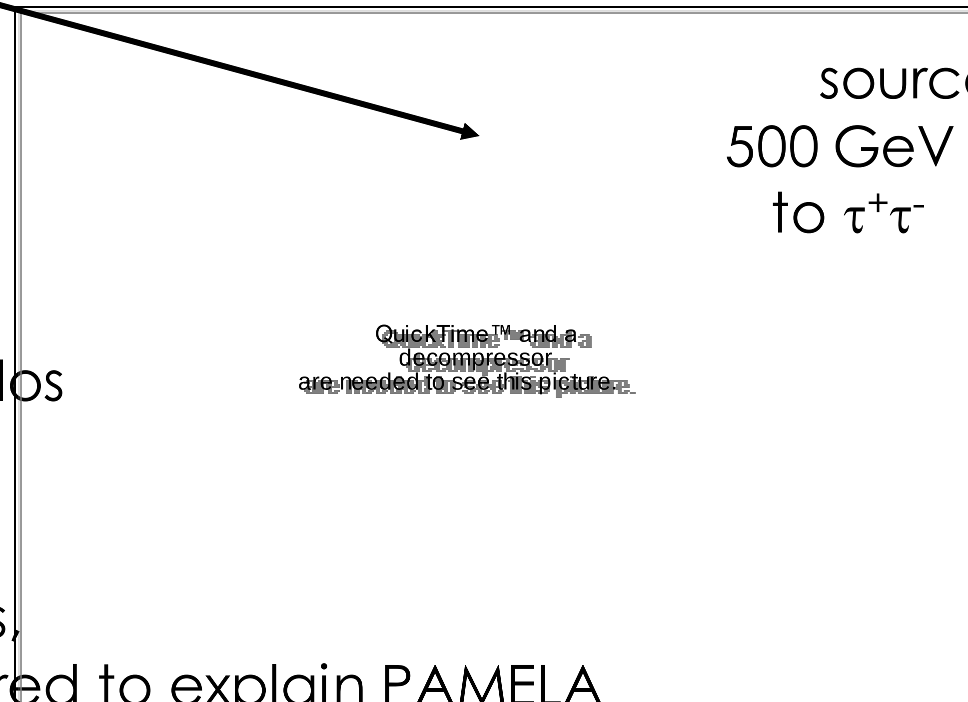
- For masses below ~200 GeV, comparably stringent to those derived from dwarf spheroidal and diffuse emission measurements



M. Buckley and D. Hooper, arXiv:1004.1633

Nearby Dark Matter Subhalos

- But what would a subhalo population within the FGST look like?
- Perhaps something like this?
- A surprising number of FGST sources can be well fit by a 500 GeV WIMP annihilating to $\tau^+\tau^-$
- Bump-like feature could be explained by ~30 subhalos within the FGST catalog
- Corresponds to a cross section of ~6×10^{-23} cm^3/s, not far from that required to explain PAMELA



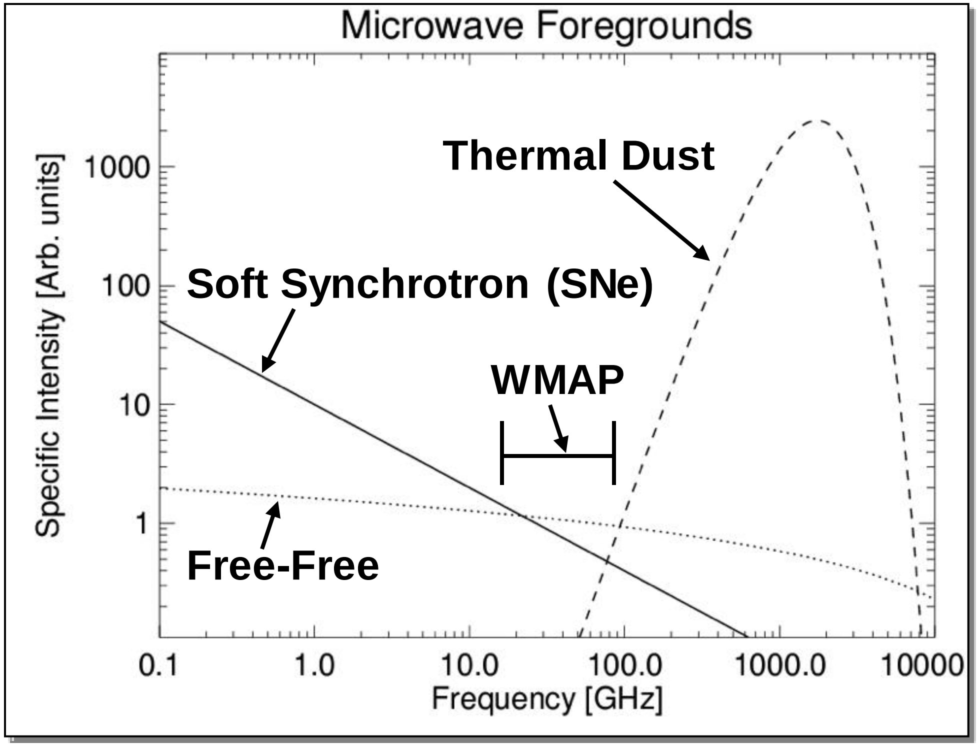
- Or it could just be a feature of the astrophysical source population

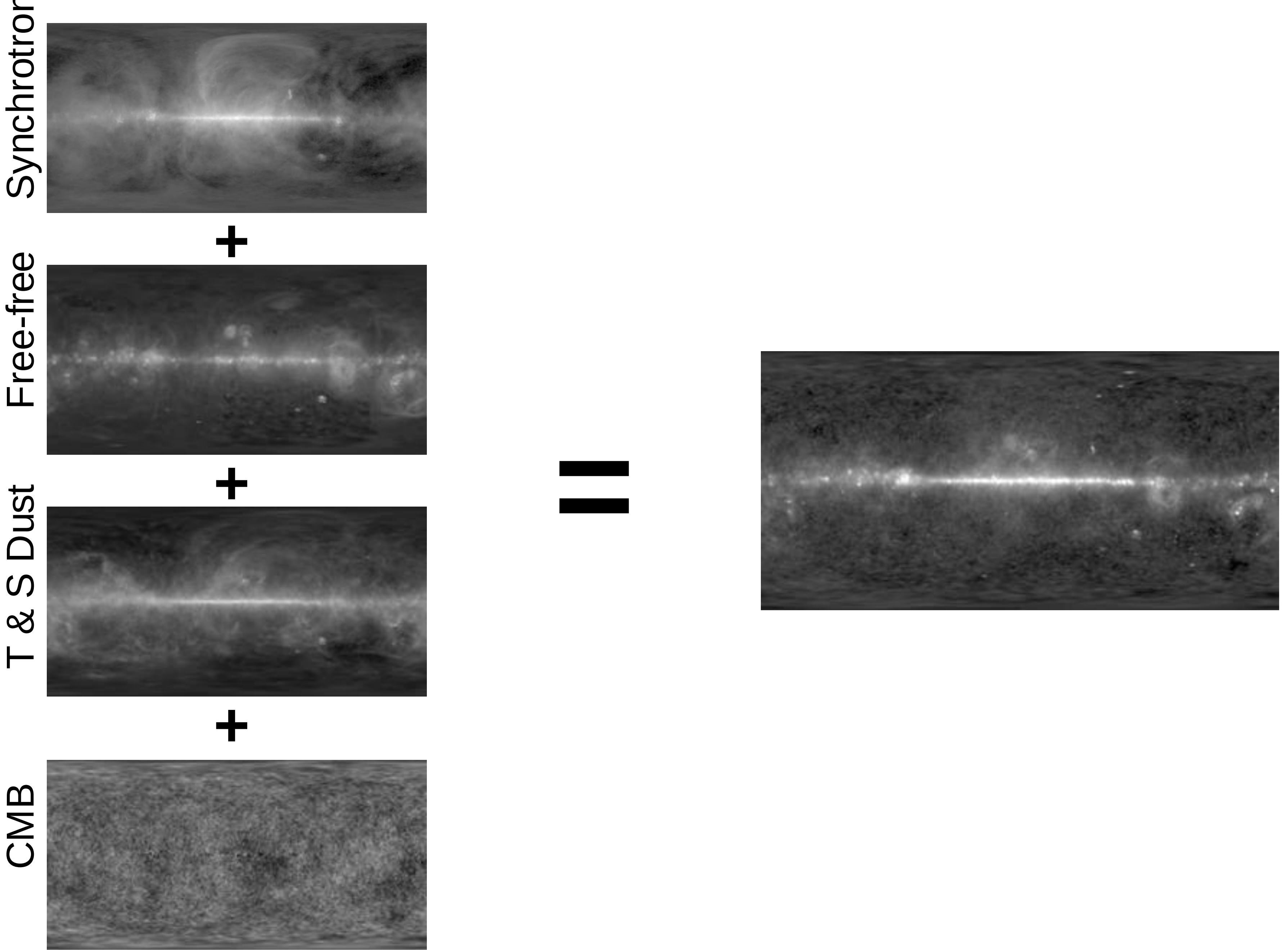
M. Buckley and D. Hooper, arXiv:1004.1633

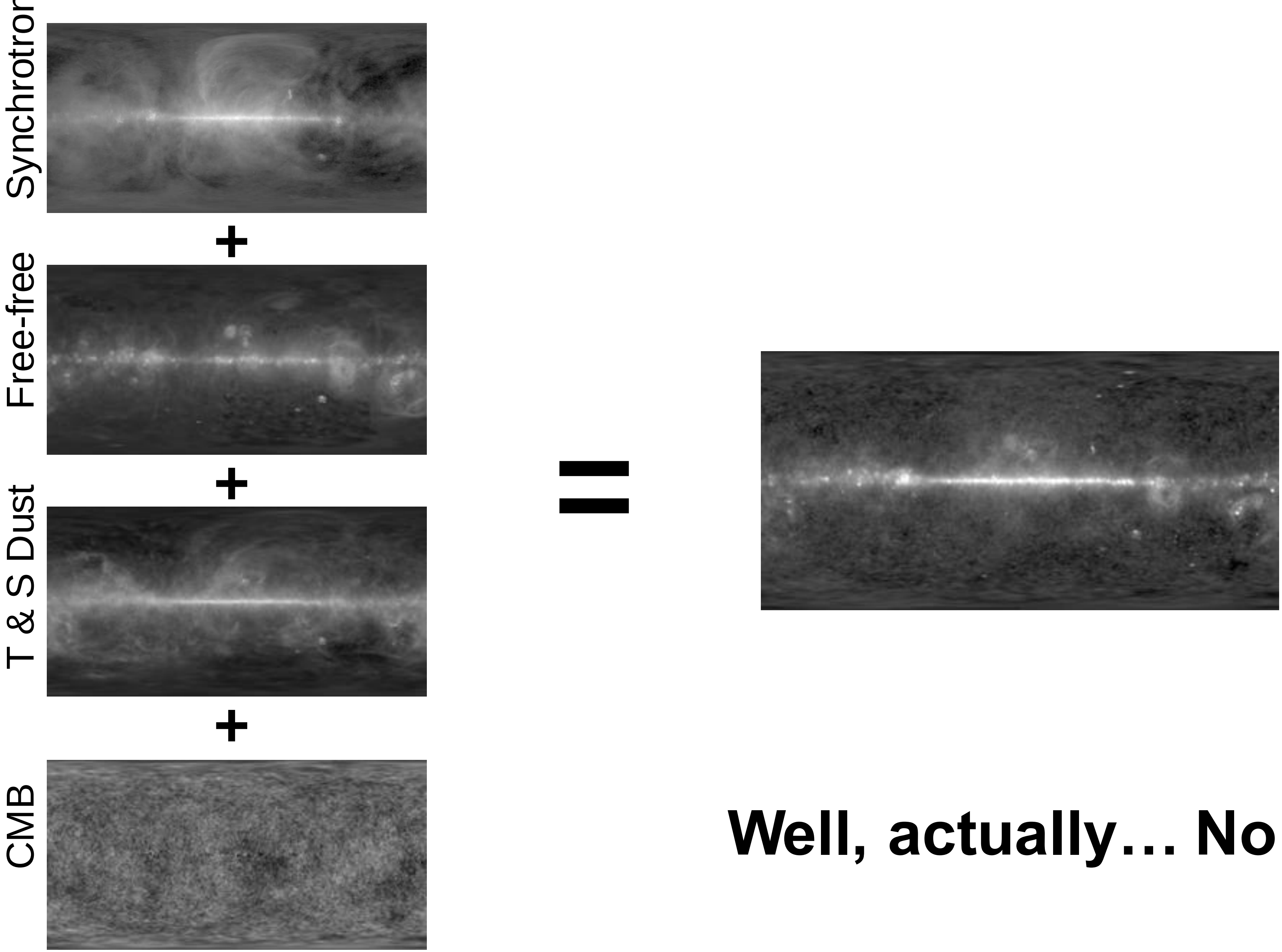
WMAP and Dark Matter

- WMAP does not only detect CMB photons, but also a number of galactic foregrounds

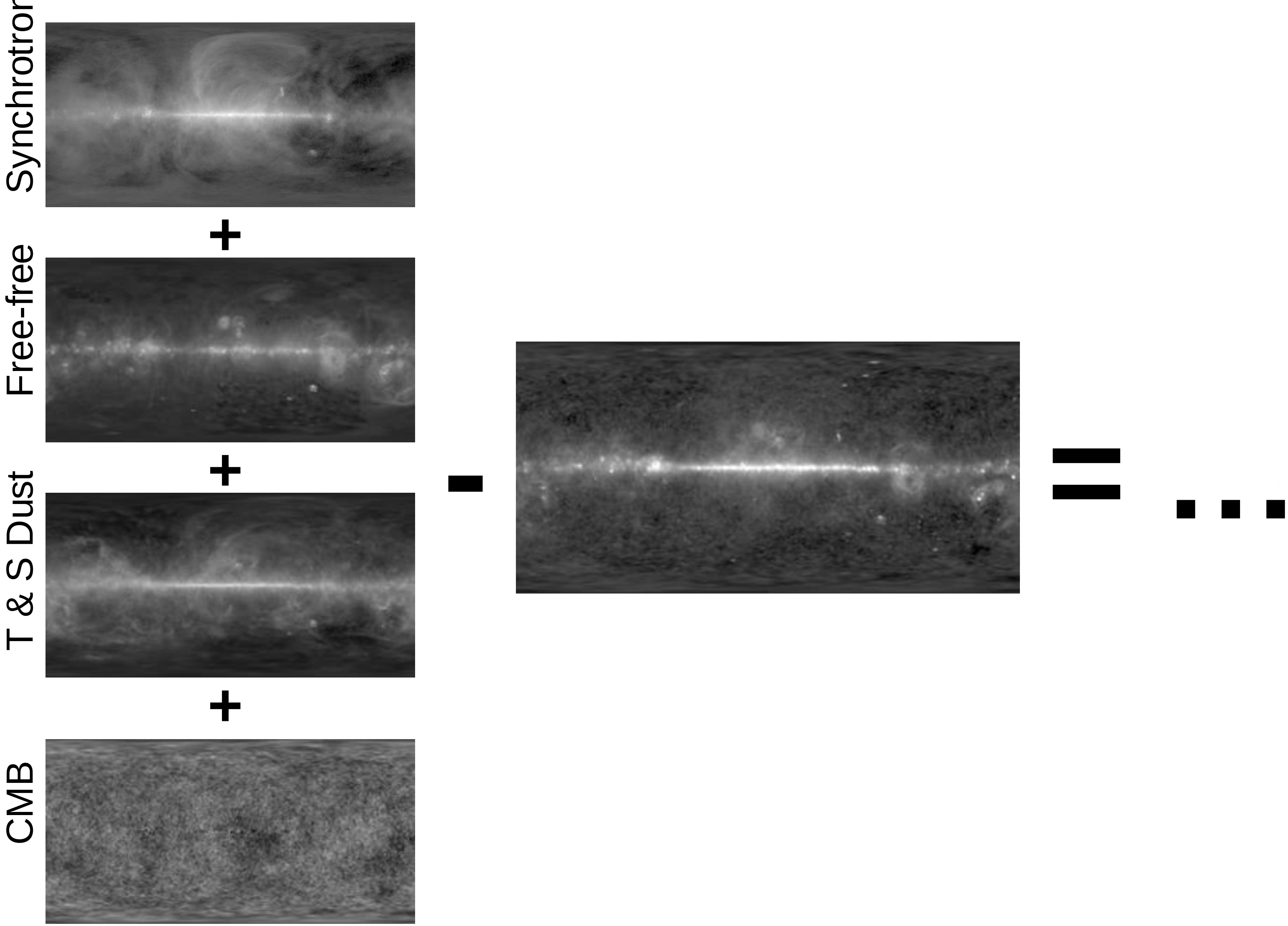
- GeV-TeV electrons emit synchrotron in the range of WMAP



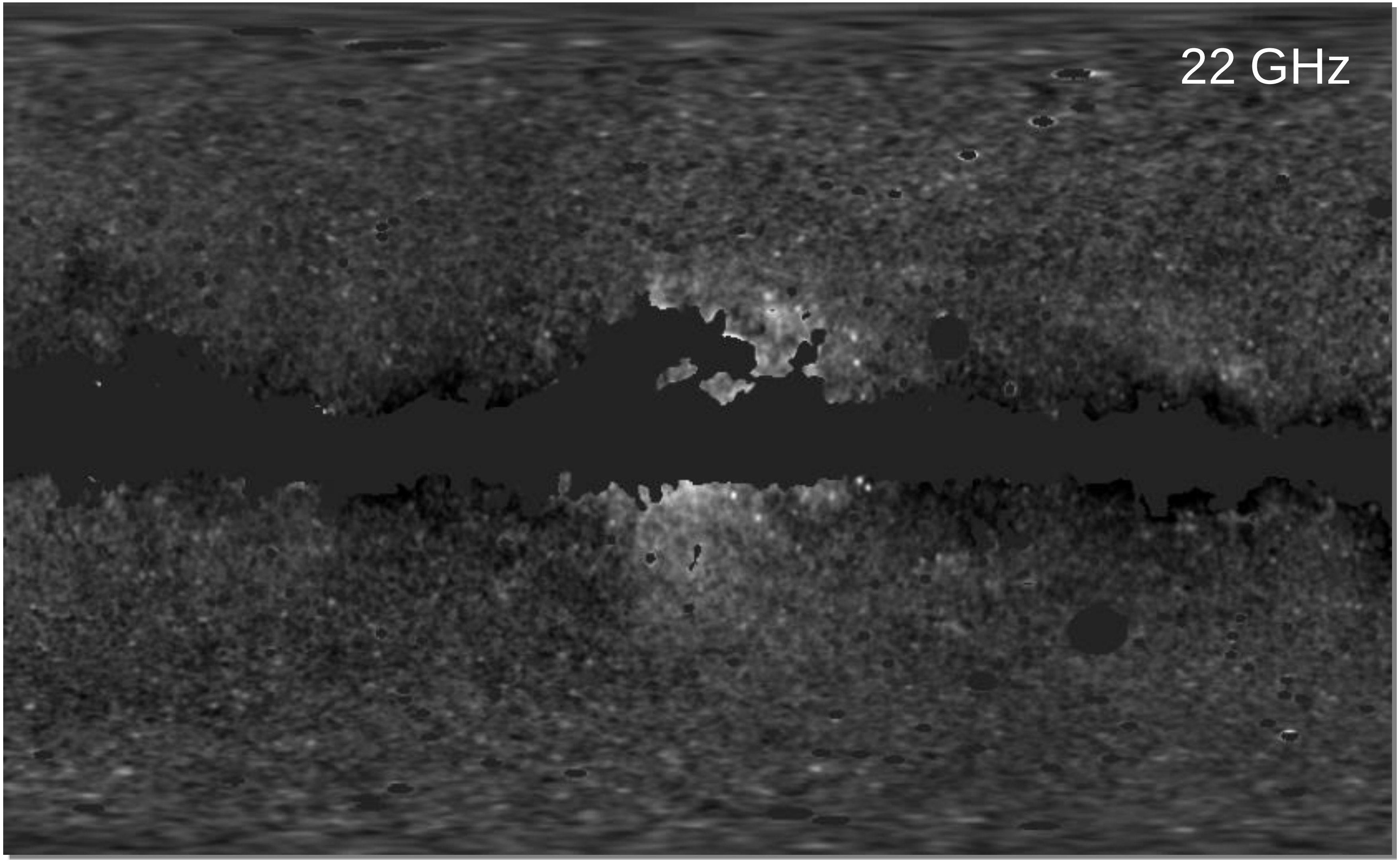

Synchrotron
+
Free-free
+
T & S Dust
+
CMB
=



Well, actually… No


Synchrotron
Free-free
T & S Dust
CMB

“The WMAP Haze”



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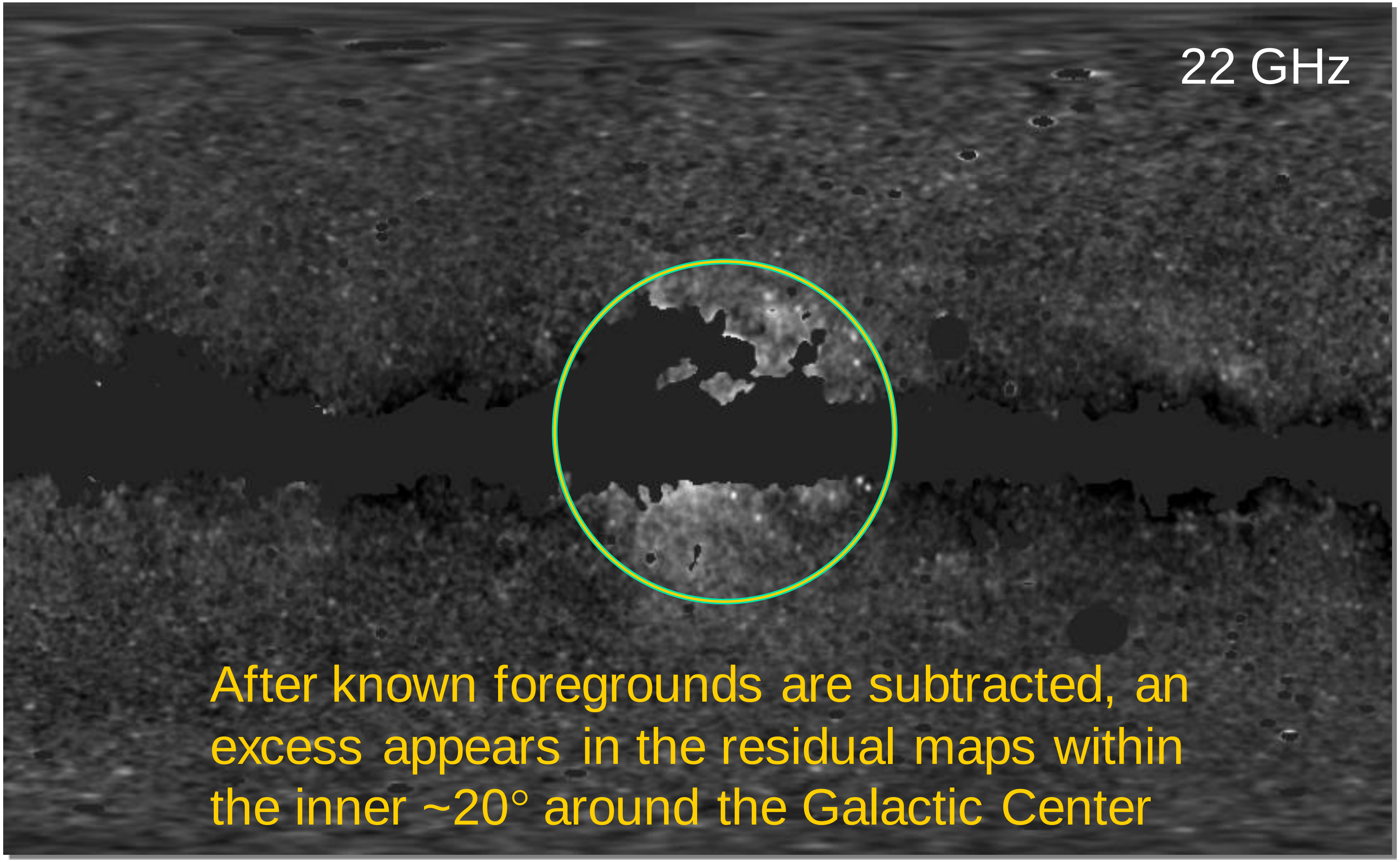
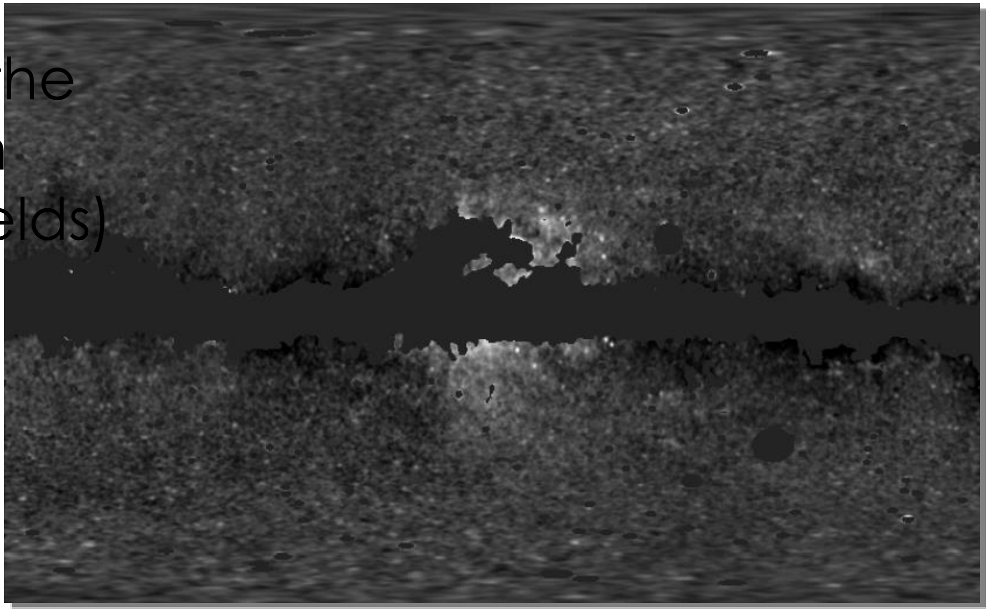


WMAP and Dark Matter

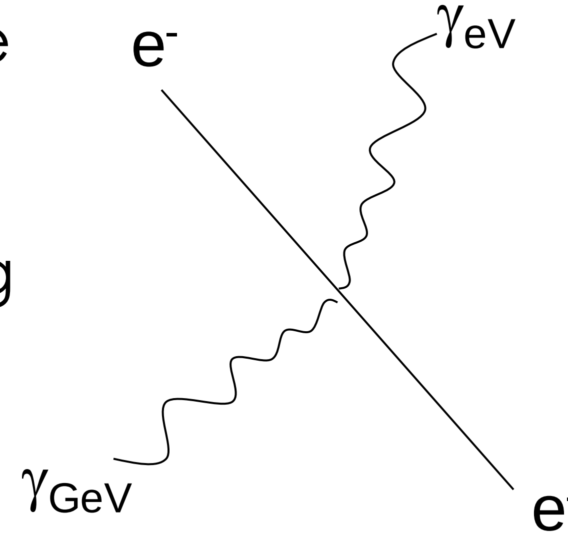
- The WMAP haze is consistent with being synchrotron emission from a population of energetic electrons/positrons
- In simple dark matter scenarios (cusped profile, weak-scale mass, thermal cross section), annihilations can generate the electrons/positrons responsible for the observed haze
(see Hooper, Dobler, Finkbeiner, PRD, 2007)
- Details depend on poorly understood details of the galactic center region (diffusion, magnetic fields)
- Difficult to explain with astrophysical sources



Inverse Compton Gamma-Rays As A Test of the WMAP Haze

- If relativistic electrons/positrons are the source of the WMAP Haze, then those particles should also interact with starlight via Inverse Compton scattering

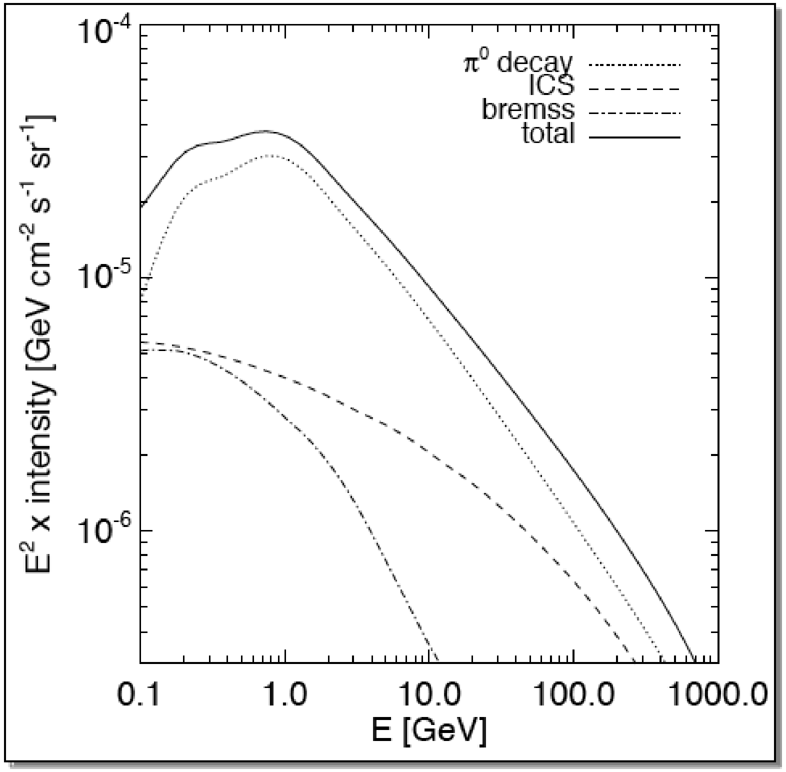
- Predicted to produce a gamma-ray spectrum within the energy range of FGST, and with a likely observable intensity (assuming $\rho_B \sim \rho_{SL}$)



Inverse Compton Gamma-Rays As A Test of the WMAP Haze

- Recently, Dobler et al. have claimed to have definitively identified the Inverse Compton counterpart to the WMAP Haze in the FGST data

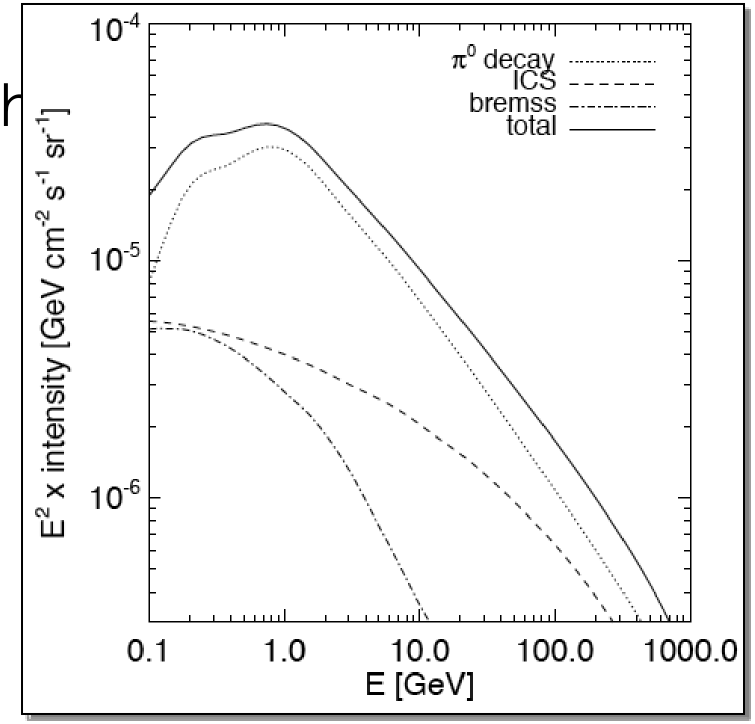
- Challenge is in separating Inverse Compton flux from other components



Dobler, Finkbeiner, Cholis, Slayter, Weiner arXiv:0910.4583

Inverse Compton Gamma-Rays As A Test of the WMAP Haze

- Dobler et al. use three techniques to study the FGST data:
  1) Cross correlate FGST maps with the FGST 1-2 GeV map



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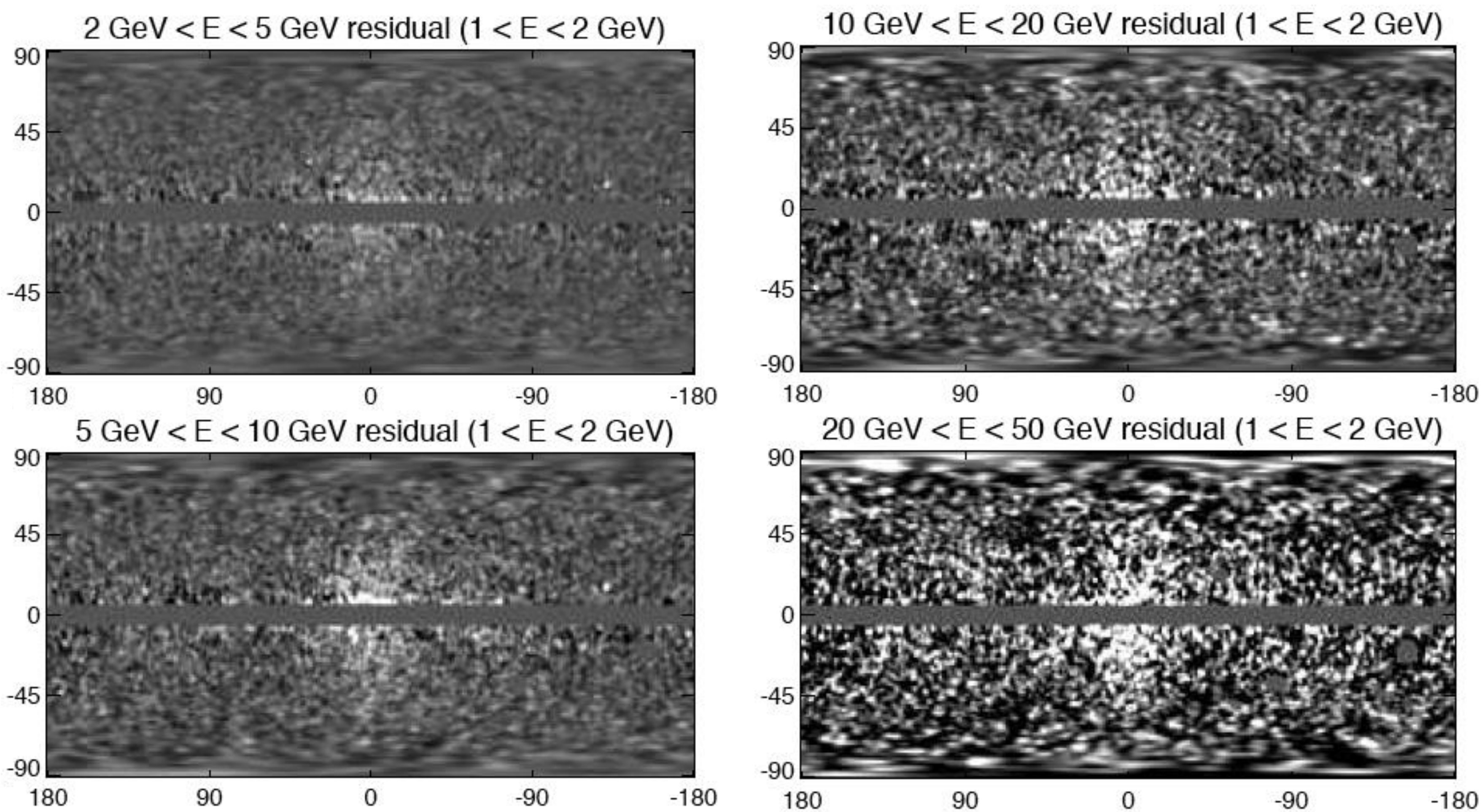
Inverse Compton Gamma-Rays As A Test of the WMAP Haze



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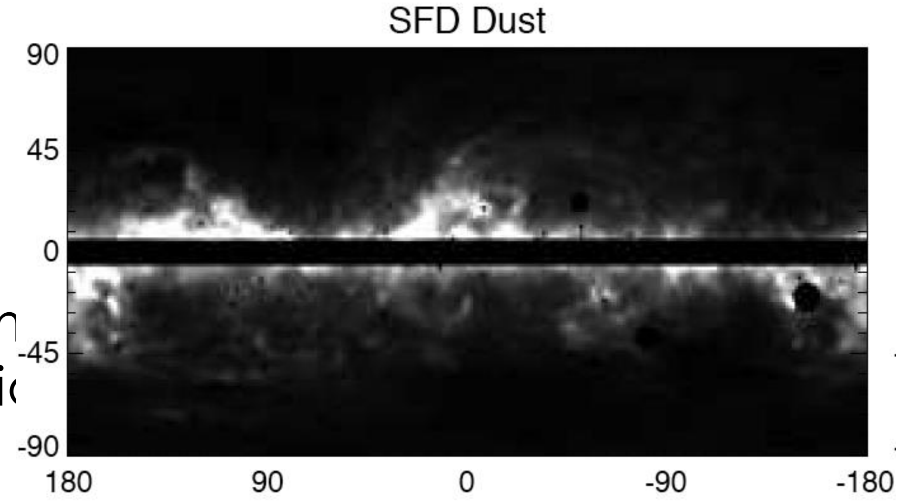
Inverse Compton Gamma-Rays As A Test of the WMAP Haze

- Dobler et al. use three techniques to study the FGST data:

  1) Cross correlate FGST maps with the FGST 1-2 GeV map

  2) Cross correlate FGST maps with dust maps (assum dust traces gas, and thus pi gamma rays)



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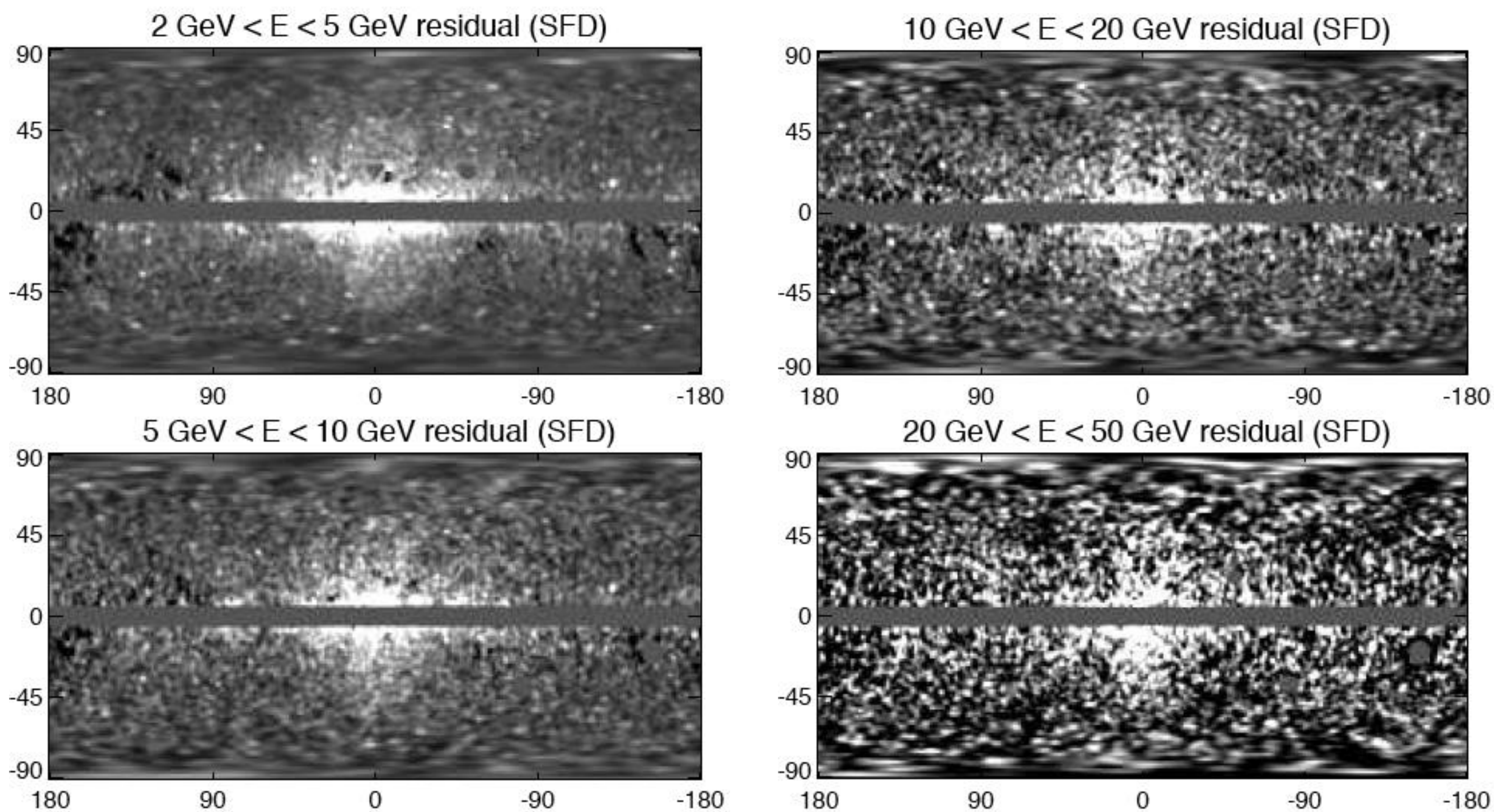
Inverse Compton Gamma-Rays As A Test of the WMAP Haze



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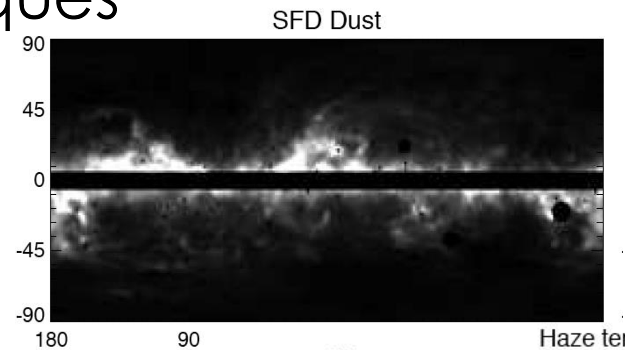
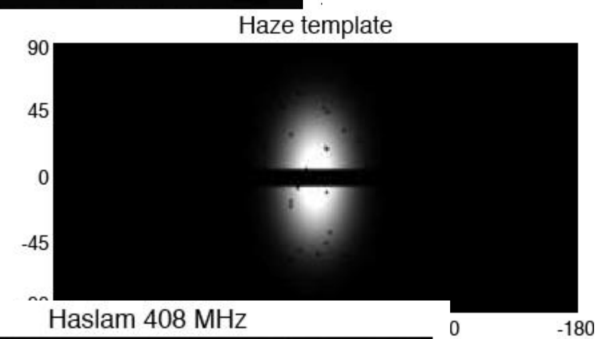
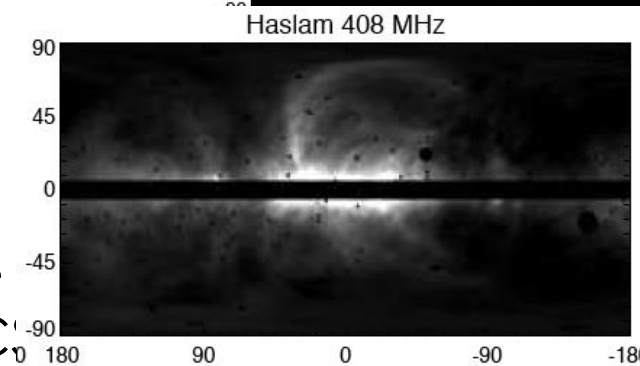
Inverse Compton Gamma-Rays As A Test of the WMAP Haze

- Dobler et al. use three techniques to study the FGST data:
  1) Cross correlate FGST maps with the FGST 1-2 GeV map
  2) Cross correlate FGST maps with dust maps (assumption: dust traces gas, and thus pion gamma rays)
  3) Cross correlate FGST maps with dust maps, Haslam map, and a haze-like template (additional assumption: e- interacting with magnetic fields trace e- scattering with starlight, and thus IC traces synchrotron)



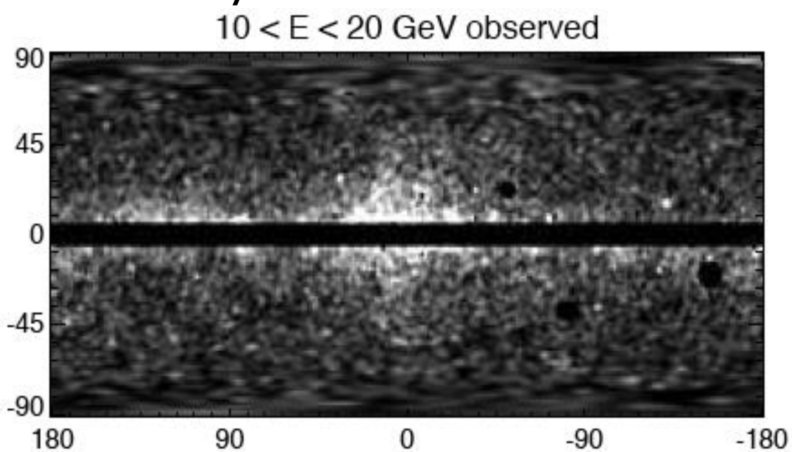




Dobler, Finkbeiner, Cholis, Slayter, Weiner arXiv:0910.4583

Inverse Compton Gamma-Rays As A Test of the WMAP Haze

- Full dust+haslem+haze-like model very successfully matches FGST data:



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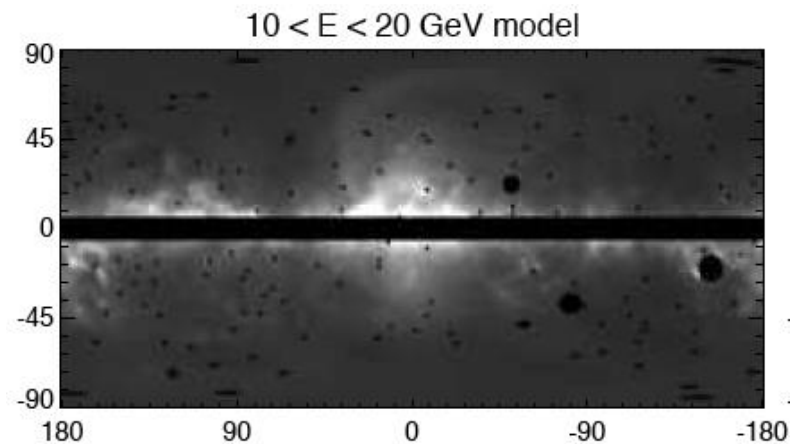

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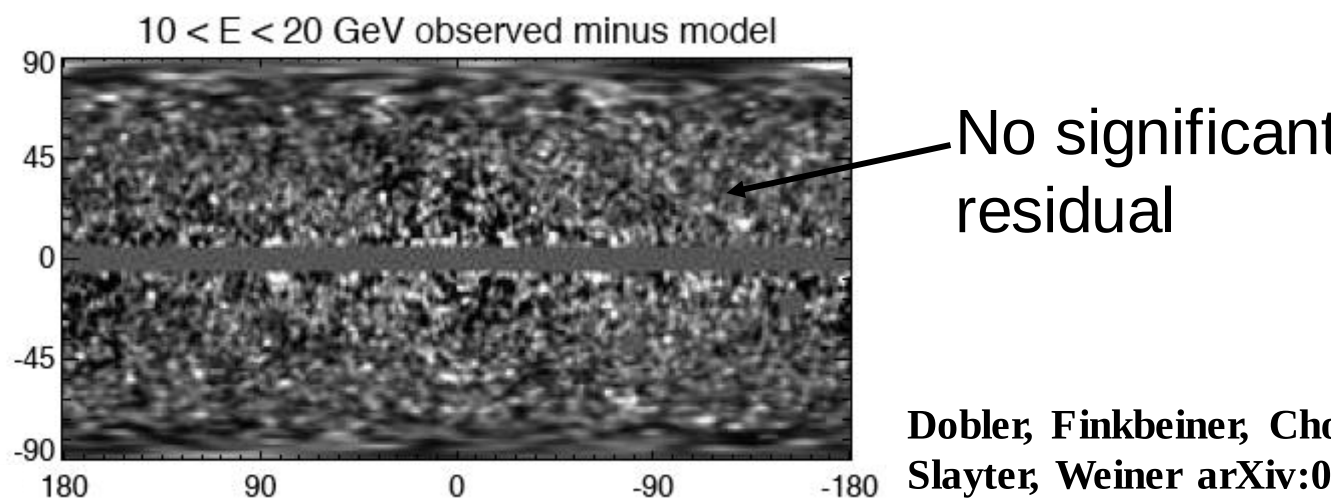
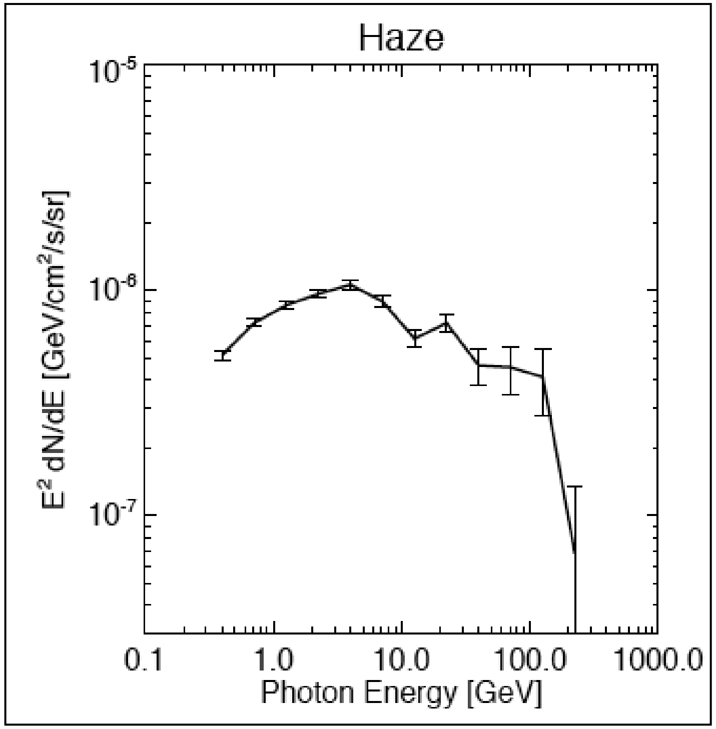


Dobler, Finkbeiner, Cholis, Slayter, Weiner arXiv:0910.4583

Inverse Compton Gamma-Rays As A Test of the WMAP Haze

- Dobler et al. even claim to be able to extract the spectrum of the Inverse Compton Haze
- If taken at face value, the reported spectrum requires the responsible *electron* spectrum to extend to ~TeV energies (Observations of the WMAP Haze require electrons of at least ~50 GeV, above which is not constrained)
- The ICS spectrum measurement appears to be tractable only using template method 3, which involves the greatest number of assumptions and greatest possible systematic errors (my advice: take the spectrum measurement with a grain of salt)



Dobler, Finkbeiner, Cholis, Slayter, Weiner arXiv:0910.4583

Inverse Compton Gamma-Rays As A Test of the WMAP Haze

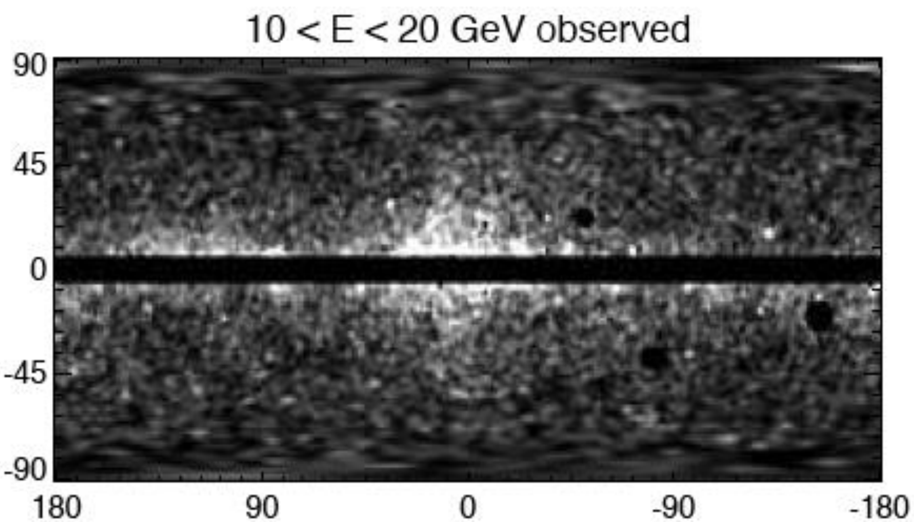
- To summarize, in the words of the authors:

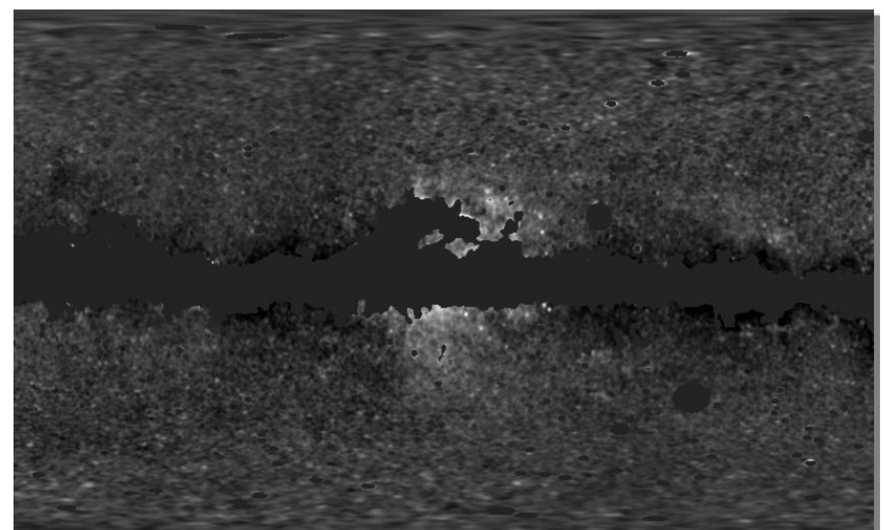
> "Although our template fitting technique is subject to significant uncertainties due to uncertain line of sight gas and CR distributions, a robust positive residual has been identified. …
>
> …This settles a long-standing question about the origin of the WMAP haze. Until recently, it has been argued that the WMAP haze had alternative explanations, such as free–free emission from hot gas or spinning dipole emission from rapidly rotating dust grains. However, the existence of this ICS signal proves that the microwave haze is indeed synchrotron emission from a hard electron spectrum."

Dobler, Finkbeiner, Cholis, Slayter, Weiner arXiv:0910.4583

WMAP and Dark Matter

- Highly energetic electrons and positrons are surprisingly common within the central kiloparsecs of the Milky Way
- Not the product of any plausible propagation mechanism or other such effect
- Constitutes the discovery of bright source(s) of e^+e^- pairs with a very hard spectral index





Dan Hooper - *The Hunt For Dark Matter*

Some of the most interesting early dark matter results from Fermi

1) Galactic Diffuse Emission Measurement

2) The Galactic Center Region

-Many sources of background

-Current analysis did not attempt to remove backgrounds

-Fairly weak limit of $\sigma v \sim 3 \times 10^{-25}$ cm^3/s (ten times thermal WIMP estimate)

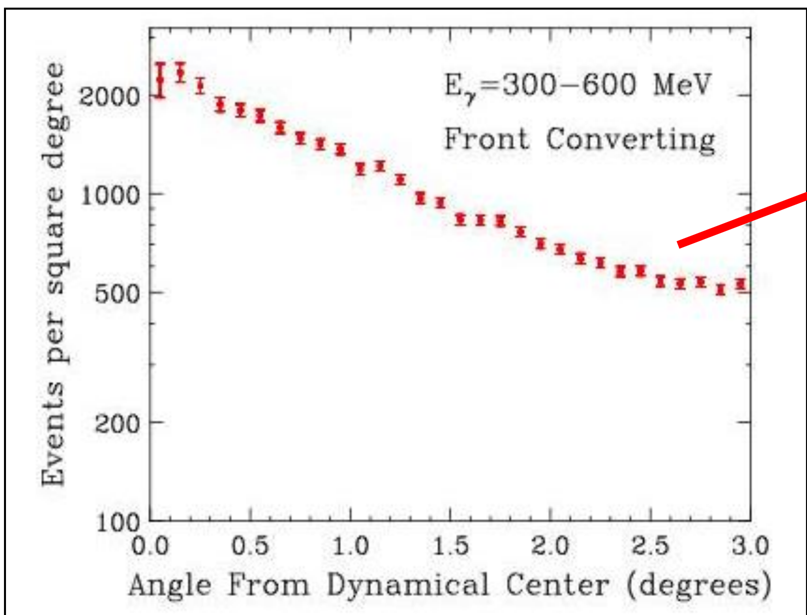
Dark Matter In The Galactic Center Region

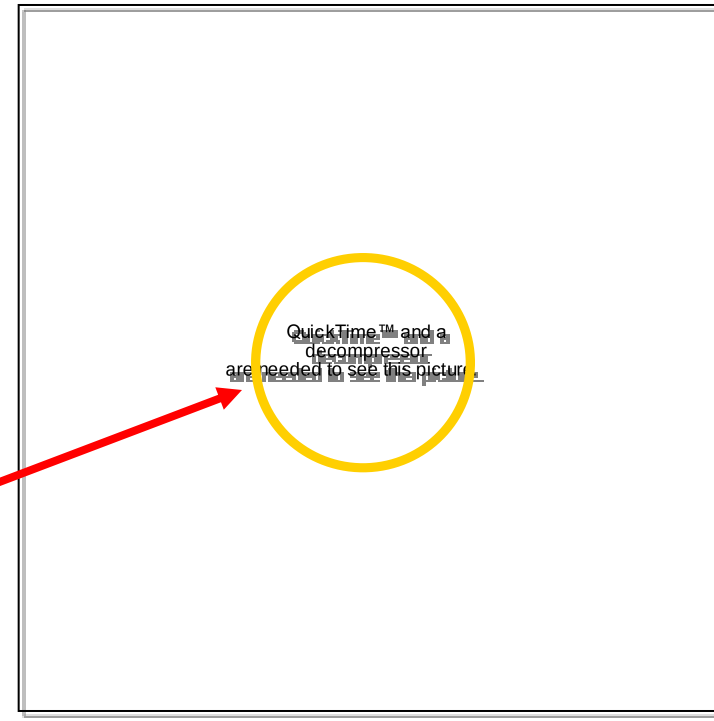
- The region surrounding the Galactic Center is complex; backgrounds are poorly understood

- This does not necessarily make searches for dark matter in this region intractable, however

Dark Matter In The Galactic Center Region

- Within the inner few degrees around the Galactic Cetner, the emission observed by FGST steeply increases with angle



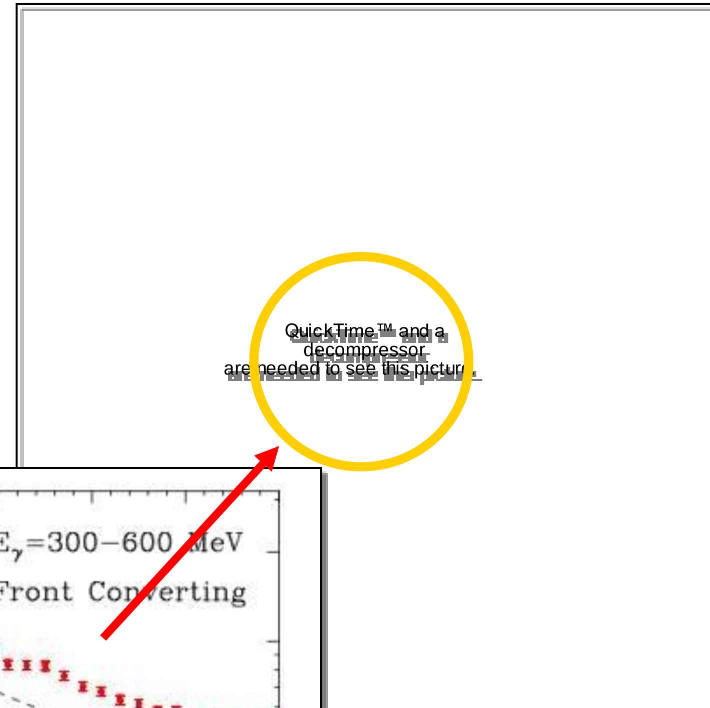


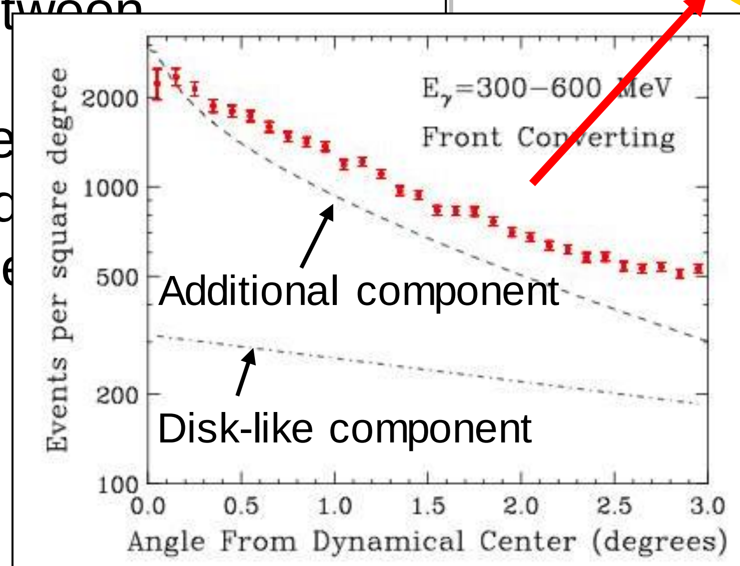
L. Goodenough, D. Hooper, arXiv:0910.2998

Dark Matter In The Galactic Center Region

- Within the inner few degrees around the Galactic Cetner, the emission observed by FGST steeply increases with angle

- If the diffuse background is modeled with the shape of the disk emission between 3° and 6°, another component is required ... is more concentrated ... symmetric around the ... center





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Dark Matter In The Galactic Center Region

- We sum three components to the angular profile of events observed by FGST:
  1) Disk-like emission
  2) Emission from the known TeV HESS source
  3) Dark matter-like emission (γ=1.1)

- Below ~1 GeV, relatively little disk-like emission; no evidence for HESS source emission

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Dark Matter In The Galactic Center Region

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are needed to see this picture.

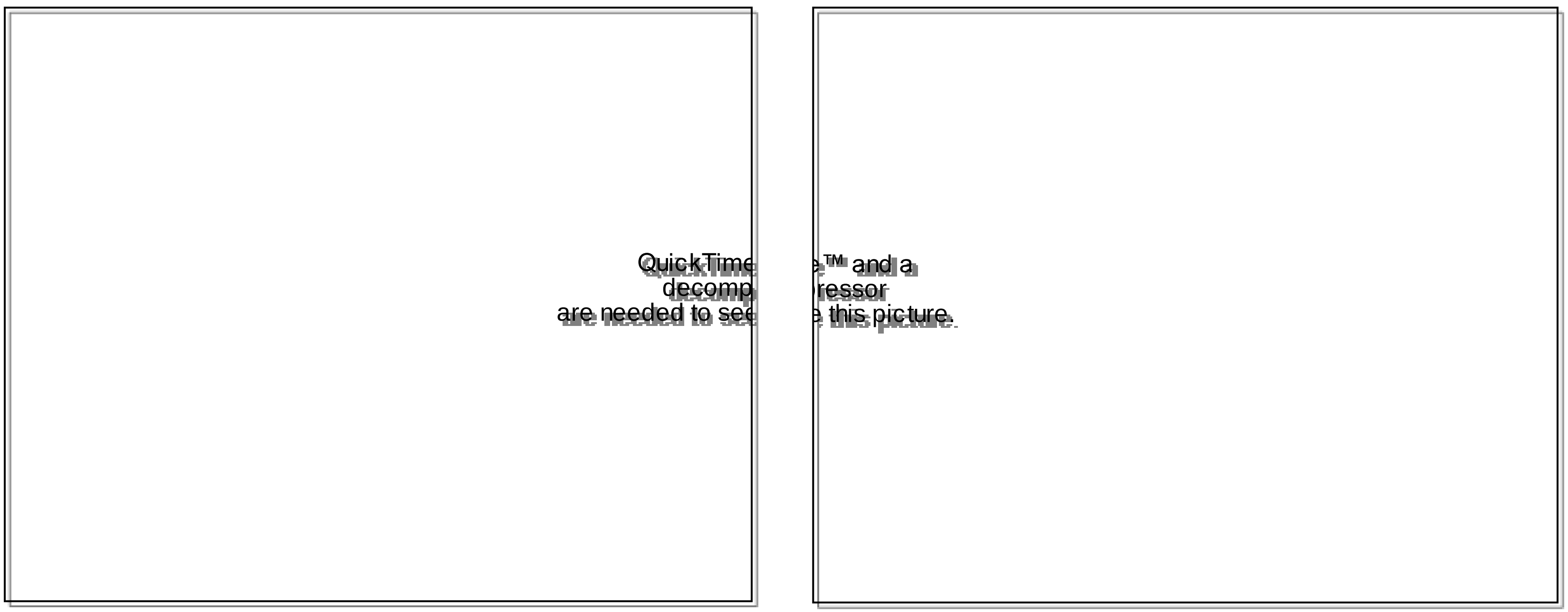
- Below ~1 GeV, relatively little disk-like emission; no evidence for HESS source emission

- Above ~1 GeV, HESS source and disk-like emission become increasingly significant

L. Goodenough, D. Hooper, arXiv:0910.2998

Dark Matter In The Galactic Center Region

- The spectrum contains a “bump-like” feature at ~1-5 GeV
- Can be fit quite well by a simple 25-30 GeV dark matter particle, in a cusped distribution (γ~1.1), annihilating to bb with σv ~ 9 x 10^{-26} cm^3/s



L. Goodenough, D. Hooper, arXiv:0910.2998

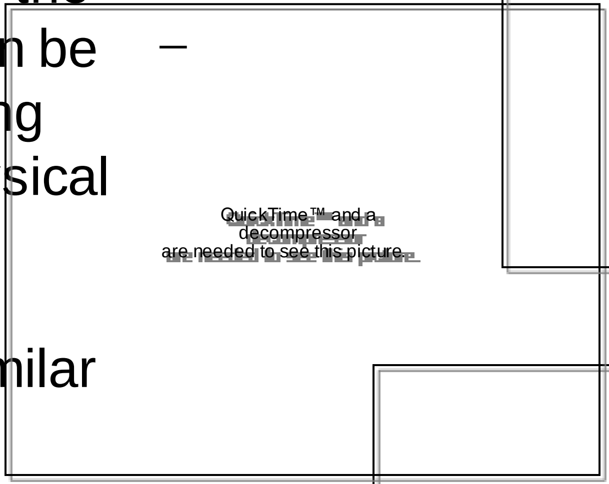
Dark Matter In The Galactic Center Region

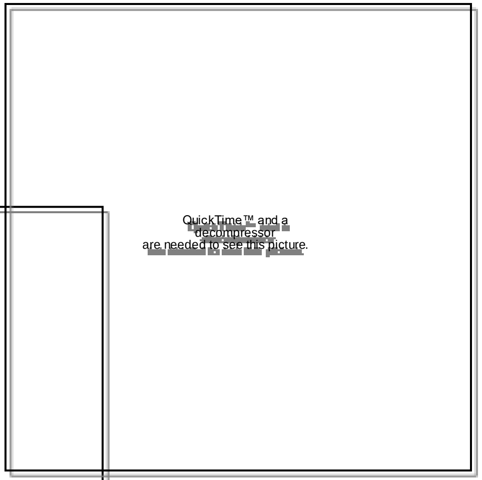
Some words of caution:

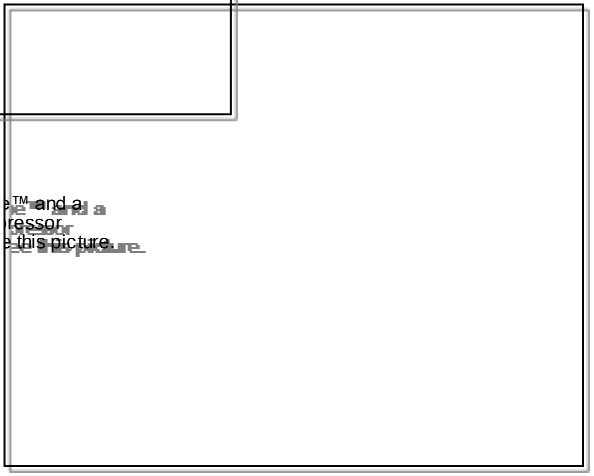
- Although the angular distribution and spectrum observed from the inner Milky Way by FGST can be well fit by a simple annihilating dark matter scenario, an astrophysical background with a similar angular distribution and spectrum cannot be ruled out (π^0 decays have similar spectral shape, for example)

- The inner galaxy is a complex region, which must be scrutinized before any confident claims can be made

- Searches in other regions of the sky will be important to confirm or refute this interpretation





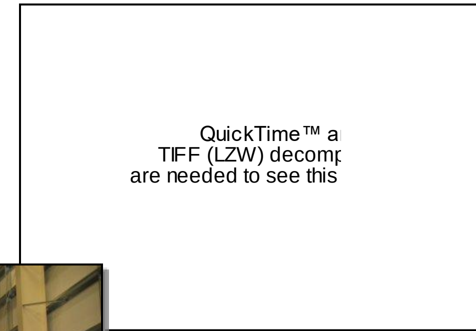


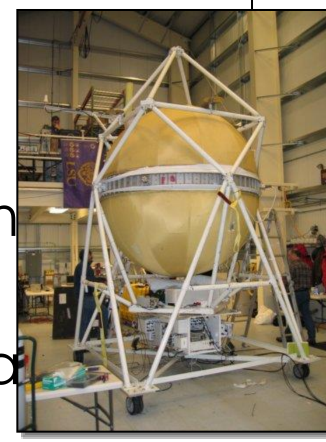
L. Goodenough, D. Hooper, arXiv:0910.2998

Summary

- Observations from DAMA, CoGeNT, CDMS, Pamela, FGST, and WMAP have each been interpreted as possible signals of dark matter particles

- Although the origin of these signals cann be said for certain, they each appear consistent with being the result of da matter

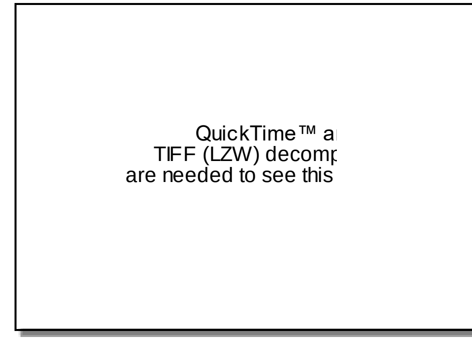




Summary

<u>One Year From Now</u>

- Low threshold CDMS analysis; further results from XENON 100; modulation search from CoGeNT?
- Pamela positron fraction up to 200 GeV?
- More data from Fermi, and more analysis of Fermi data
- First data AMS-02?
- Further input from ground based gamma ray telescopes, and observations at other wavelengths



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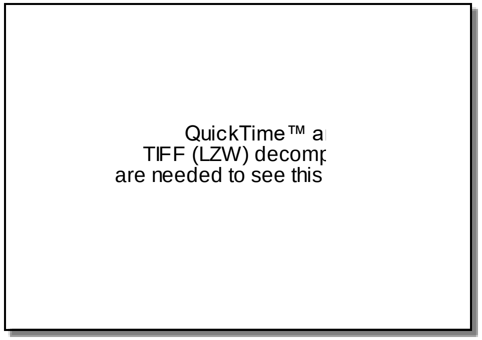

-Currently, we are facing a puzzling, ambiguous and incomplete picture

-With the wide range of observational tools available, we may soon be able to move from puzzle to discovery