Exploring the Universe with Gamma-Rays: Recent Results from Fermi

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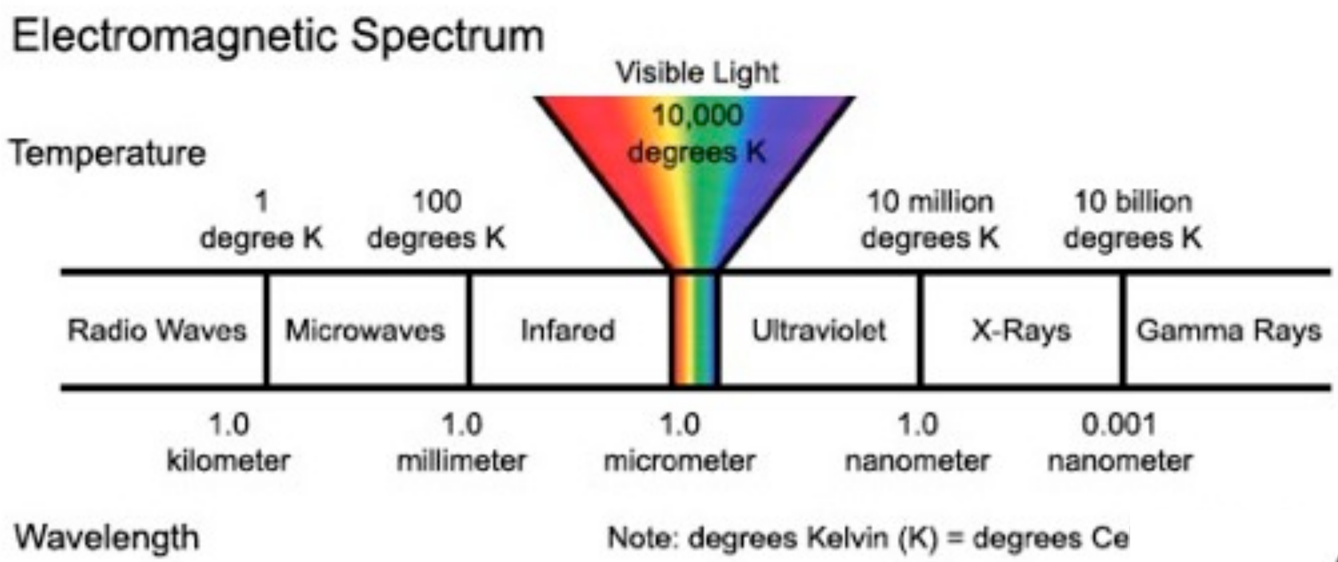
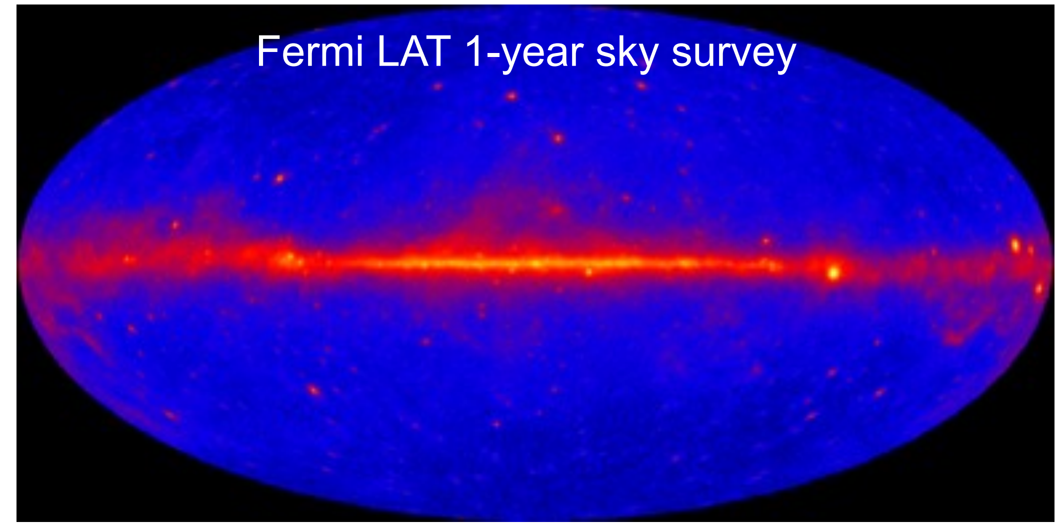
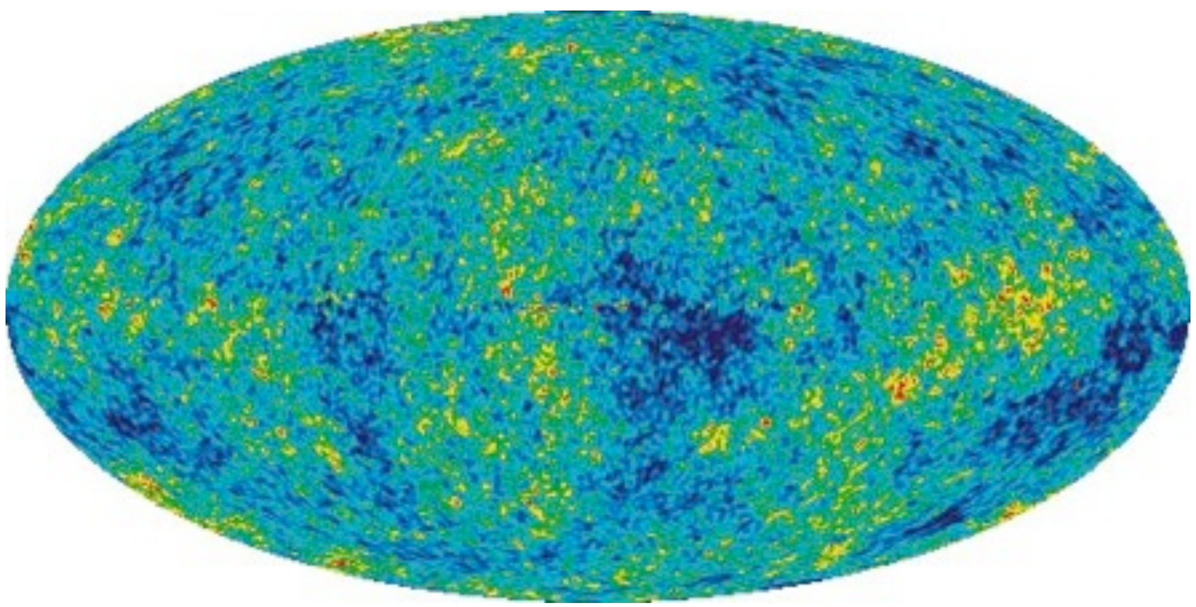
The Ohio State University

Representing the Fermi LAT Collaboration

Across the EM Spectrum

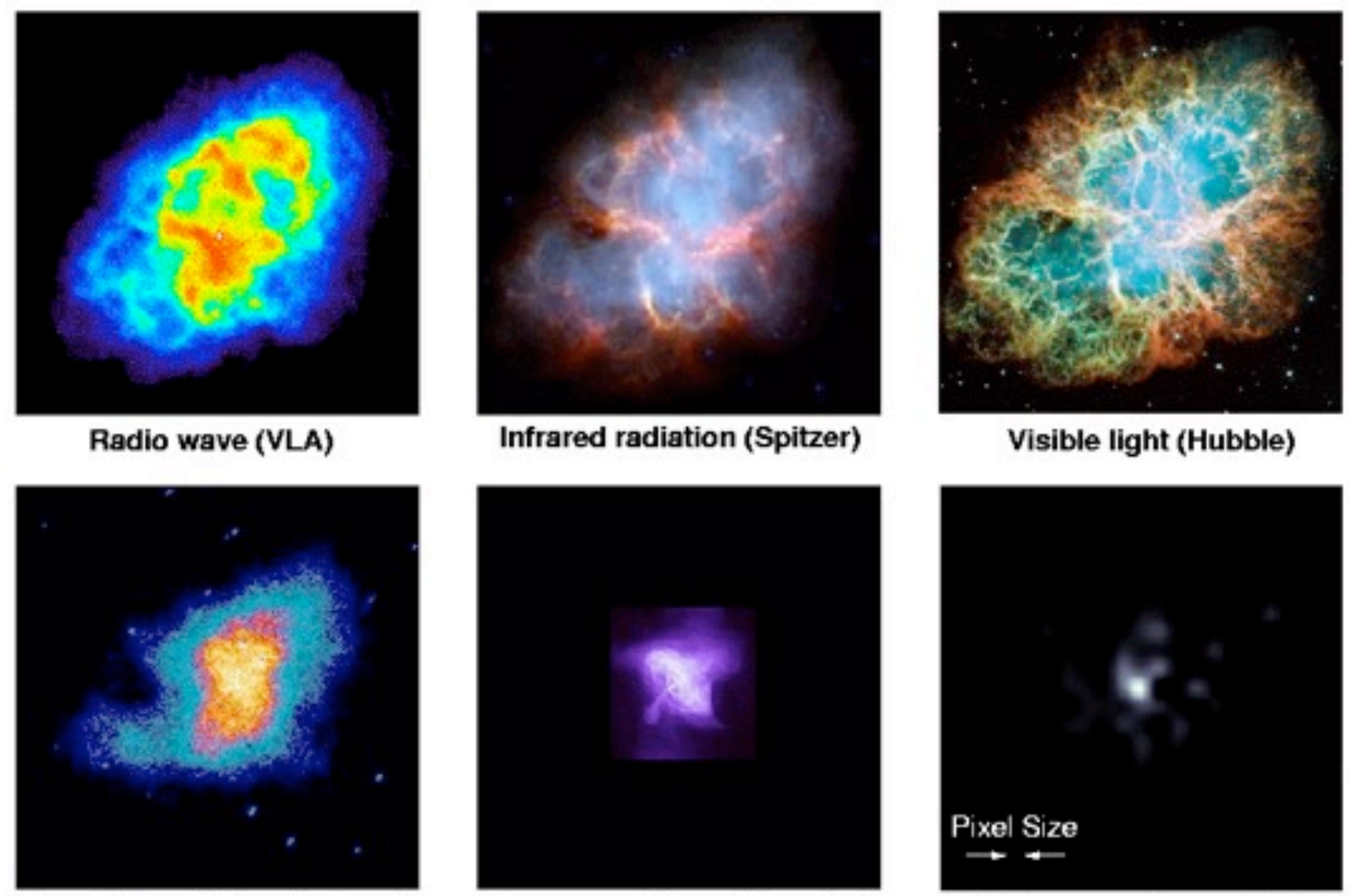






WMAP CMB - 5 year Map

Crab Nebula: Remnant of an Exploded Star (Supernova)



Radio wave (VLA) | Infrared radiation (Spitzer) | Visible light (Hubble)

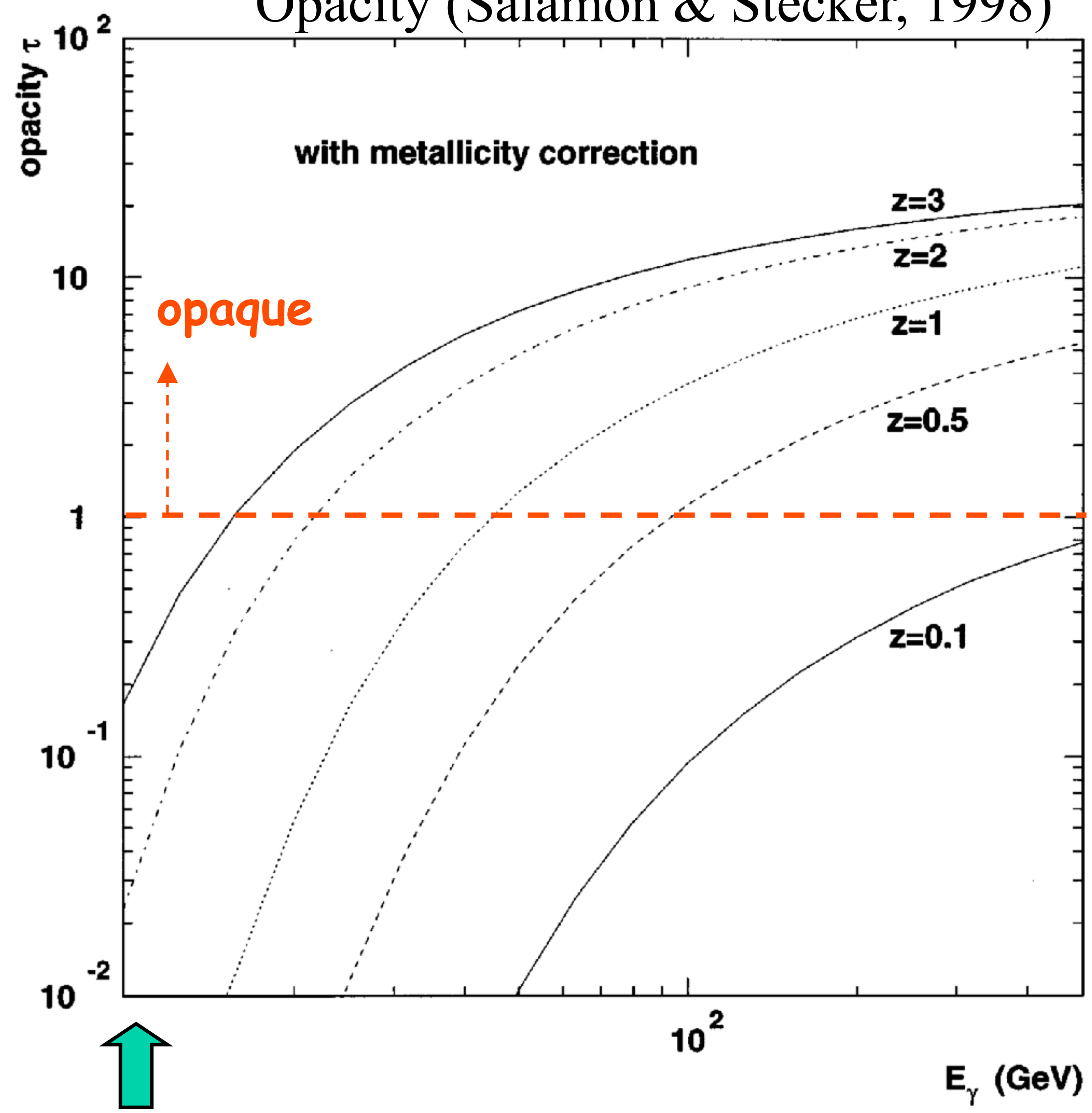
Ultraviolet radiation (Astro-1) | Low-energy X-ray (Chandra) | High-energy X-ray (HEFT) *** 15 min exposure ***

Crab Nebula: Supernova remanent with a pulsar, approximately 6,500 ly from earth. SN recorded by Chinese 1054

Gamma Rays

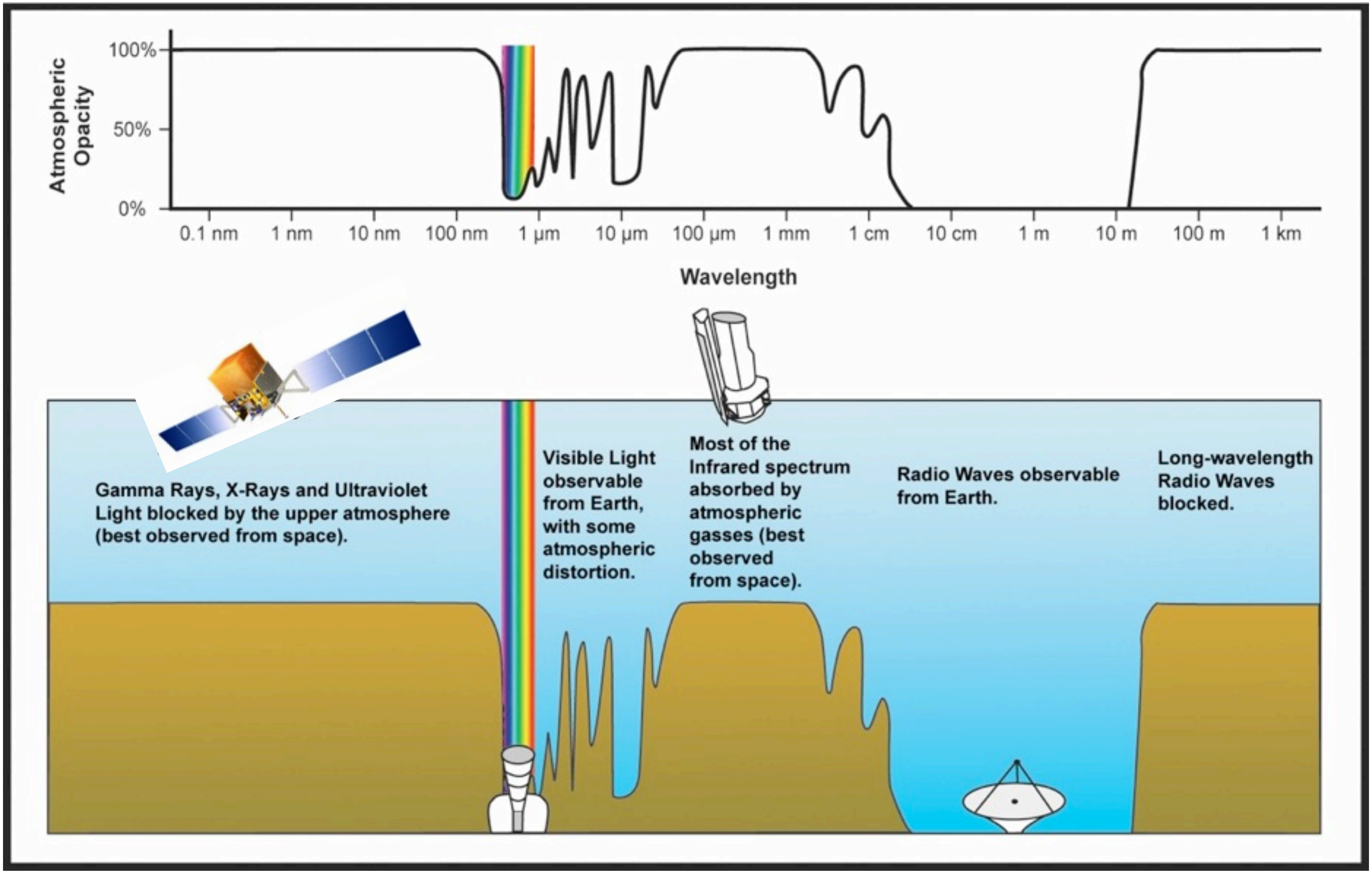
- Shortest Wavelengths in EM Spectrum ⟶ Highest Energy.
  - ★ Energies from 100's keV and higher
  - ★ Probe the most energetic phenomena:
    - ✦ Active Galactic Nuclei
    - ✦ Supernova Remnants
    - ✦ Pulsars
    - ✦ Gamma-Ray Bursts
- Point Back to source
- Detect 1 at a time.
  - ★ More "particle-like"
- Universe transparent...to a point

Opacity (Salamon & Stecker, 1998)



No significant attenuation below ~10 GeV.

Where to go?

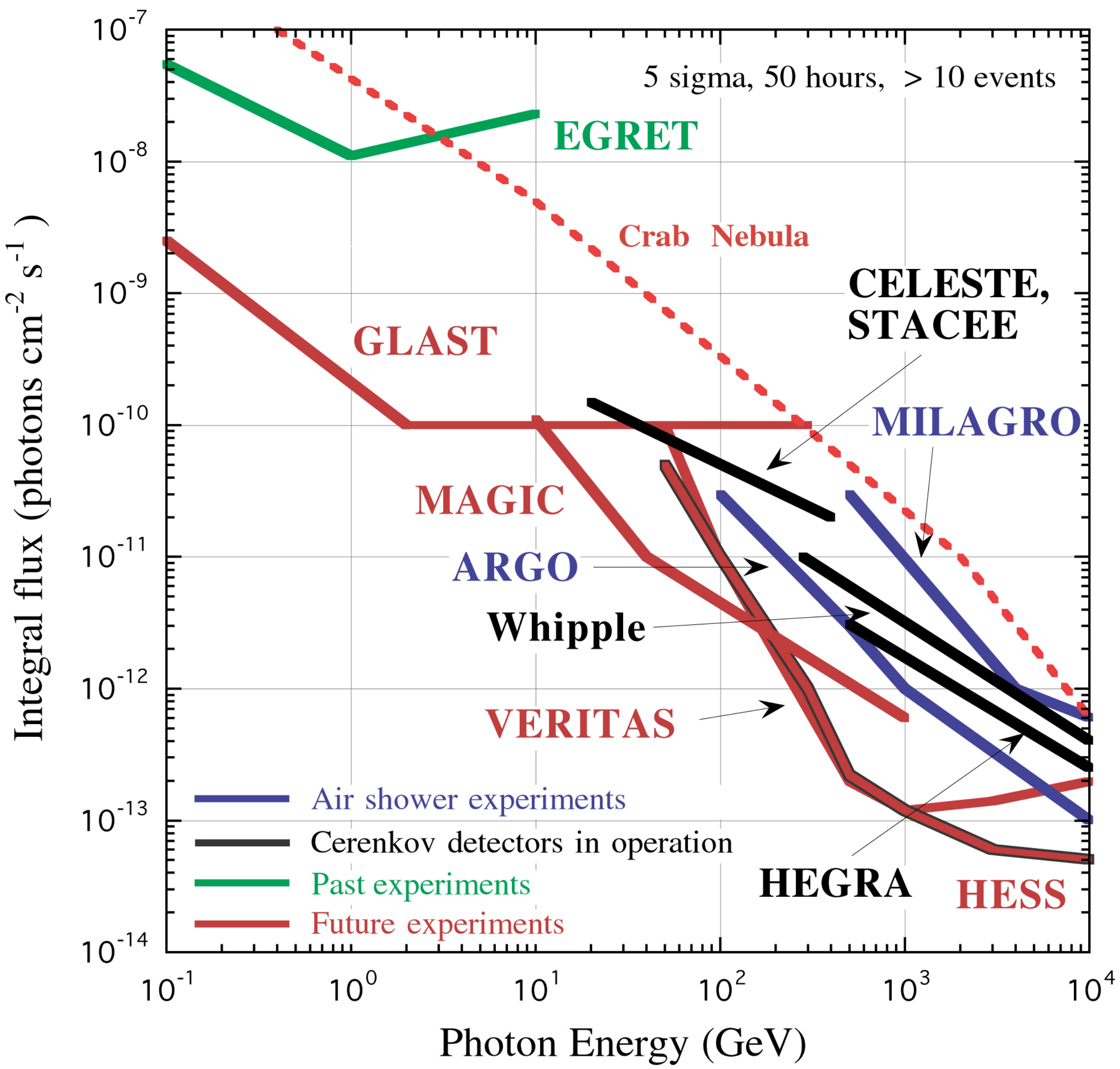


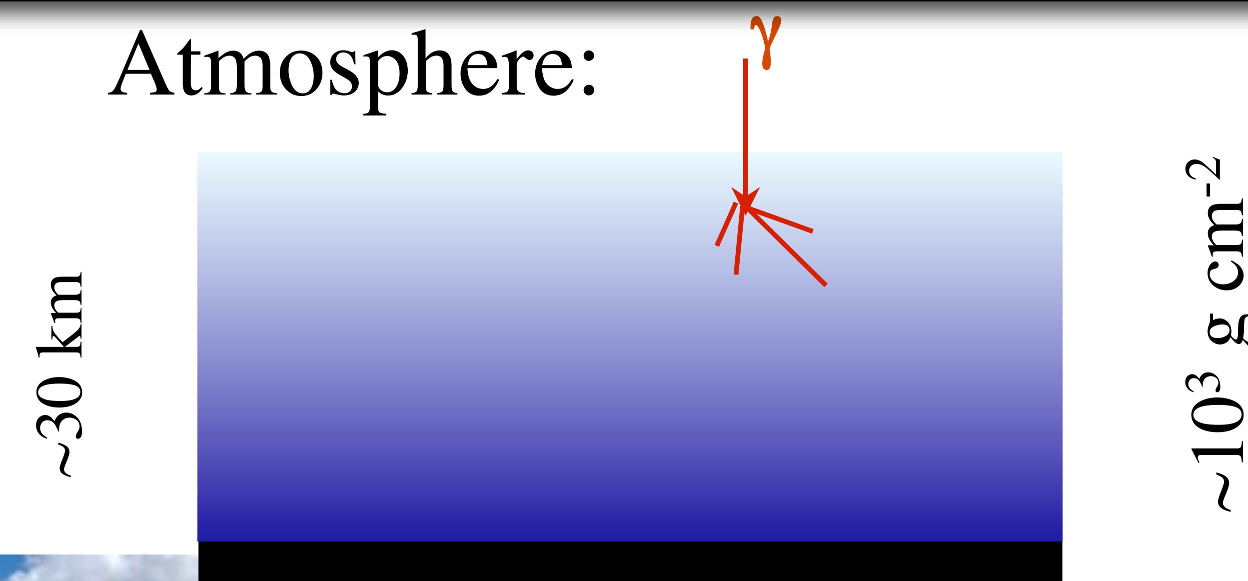
NASA Image

Space vs Ground Based

- **Space Based Observations**
  - ★ Energy: 100's keV -- 100's GeV
  - ★ Satellites.

- **Ground Based Observations**
  - ★ Energy: > 100's GeV (Esp. > 1 TeV)
  - ★ Use the Atmosphere as a detector
  - ★ Detect Čerenkov Light from shower.

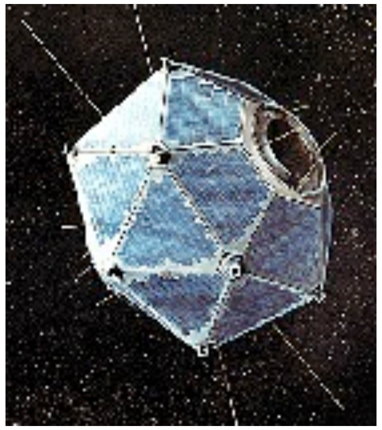




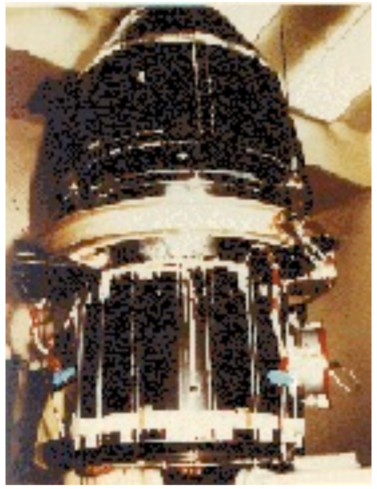
HAWC

VERITAS

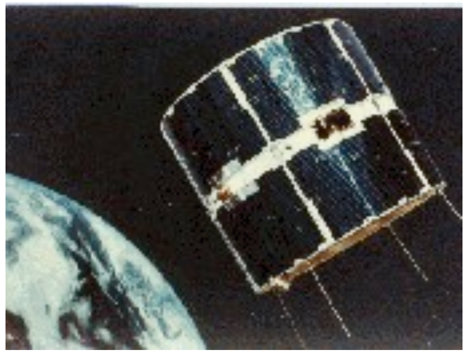
Space based observatories



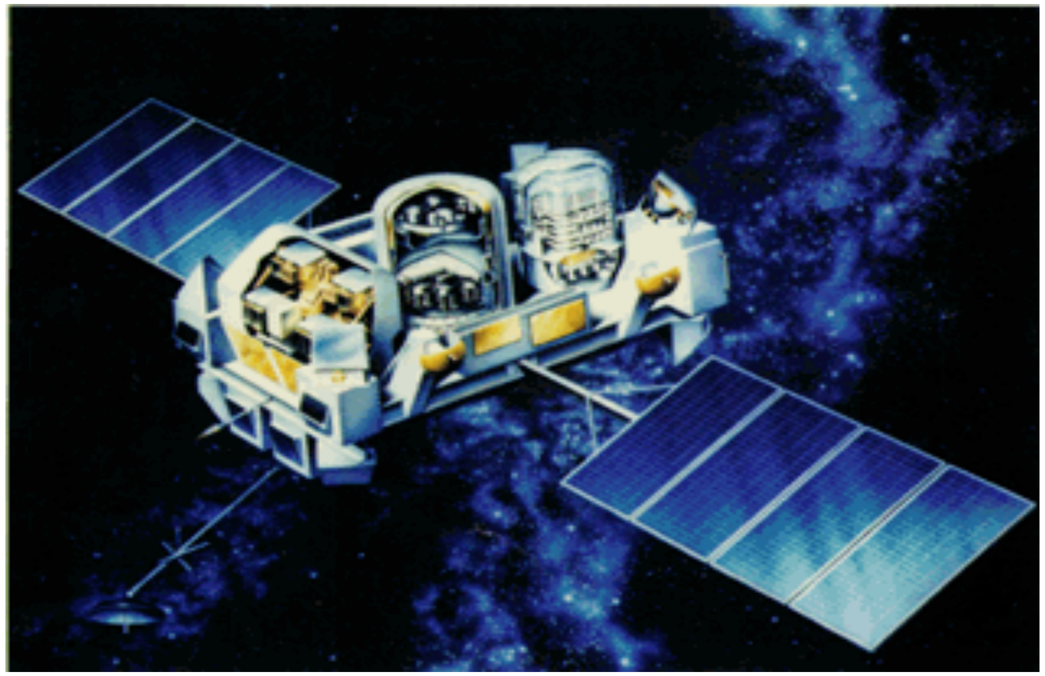
Vela Series
1960's
3 - 750 keV



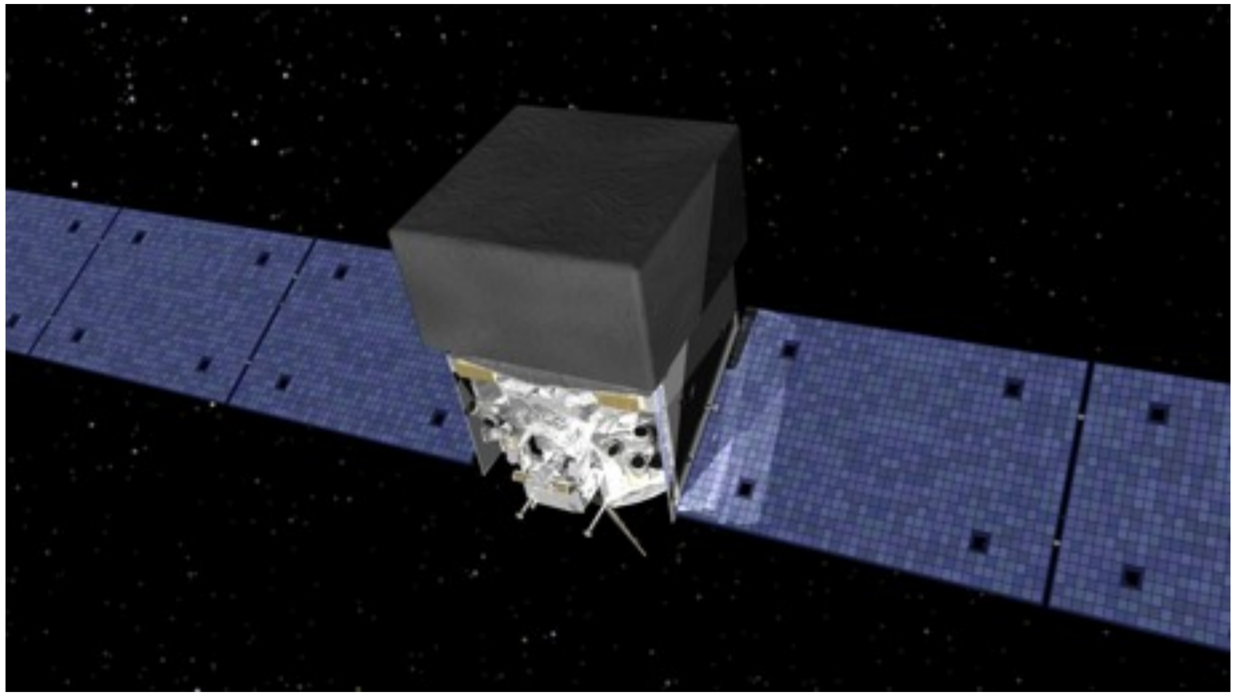
SAS-2
1975 - 1982
20 MeV - 1 GeV



COS-B
1975 - 1982
2 keV - 5 GeV



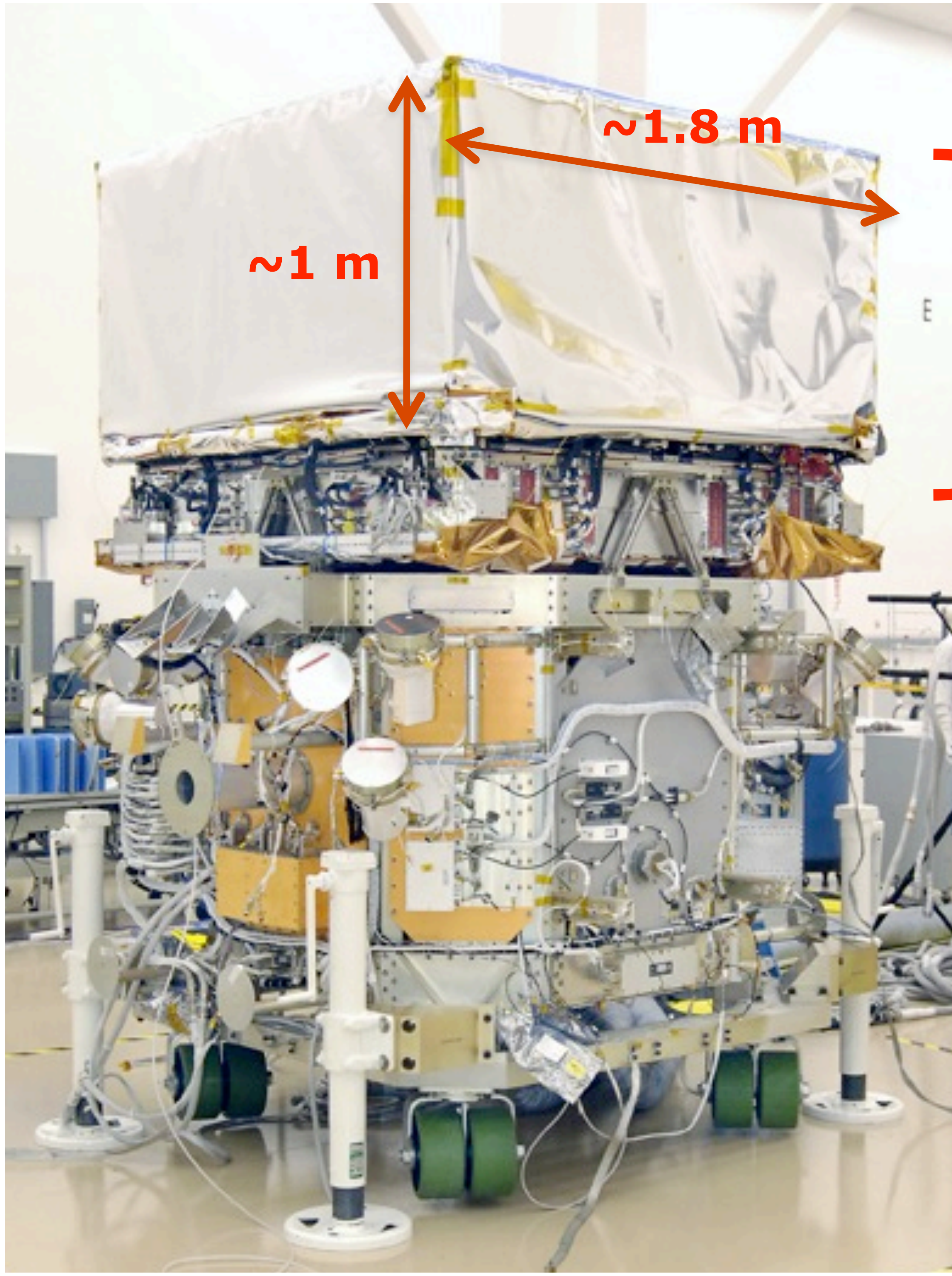
Compton Gamma-Ray Observatory
1991 - 2000



Fermi Gamma Ray Space Telescope
2008 - ?

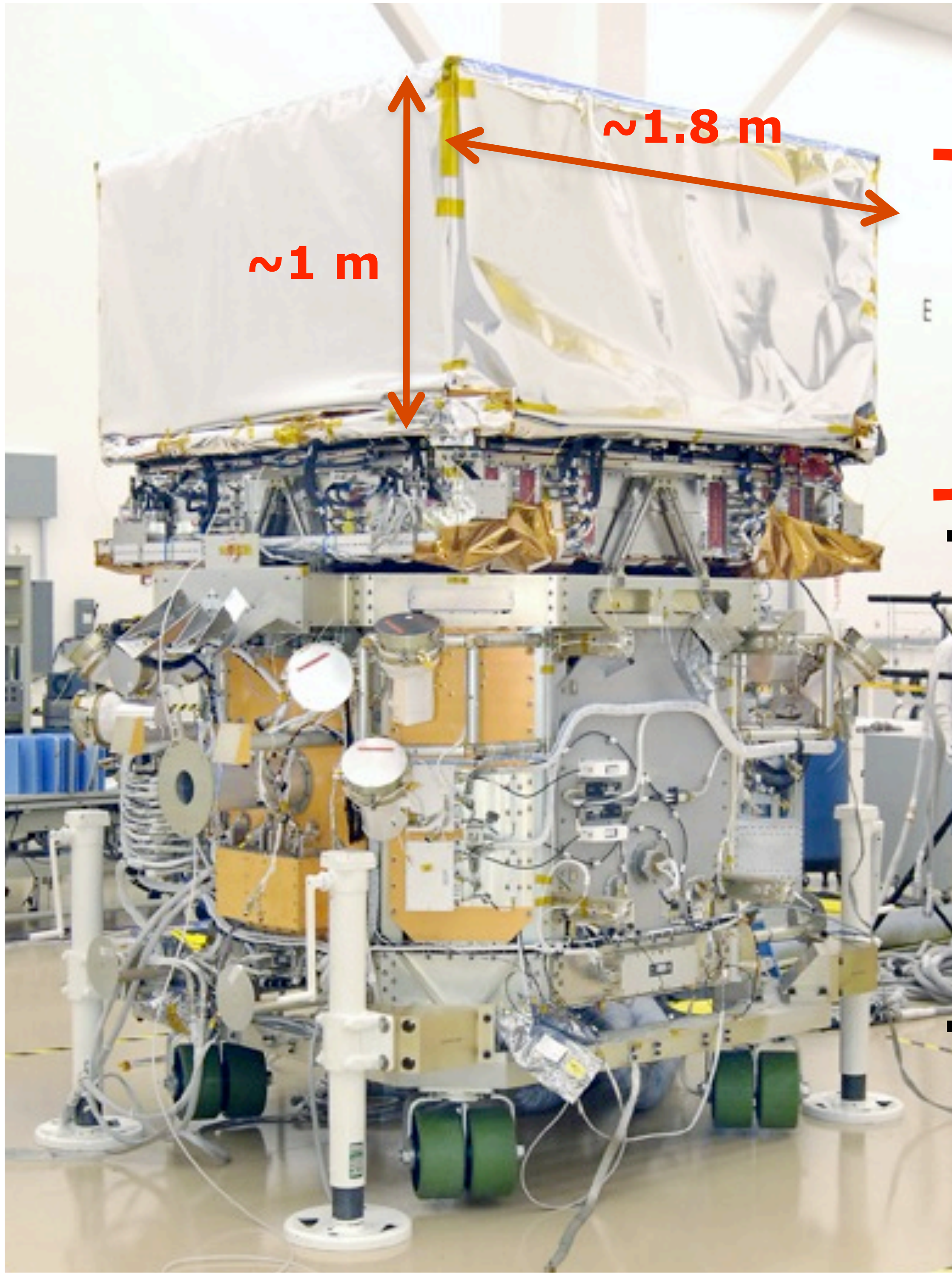
Fermi Telescope

Fermi Telescope



Large Area Telescope (LAT)
* High Energy Gamma Rays
* 20 MeV > E > ~300 GeV

Fermi Telescope



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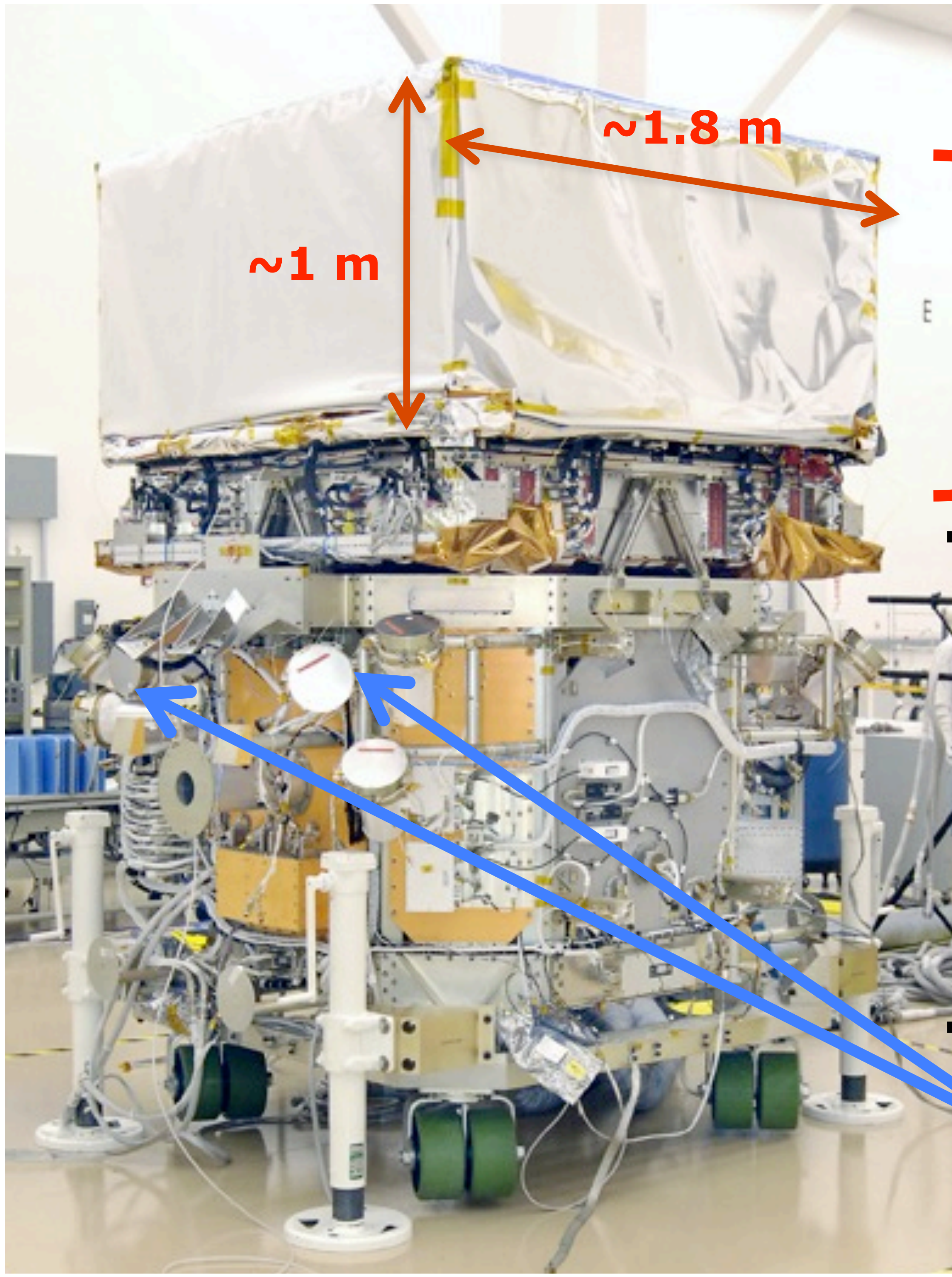
Spacecraft

Fermi Telescope



Large Area Telescope (LAT)
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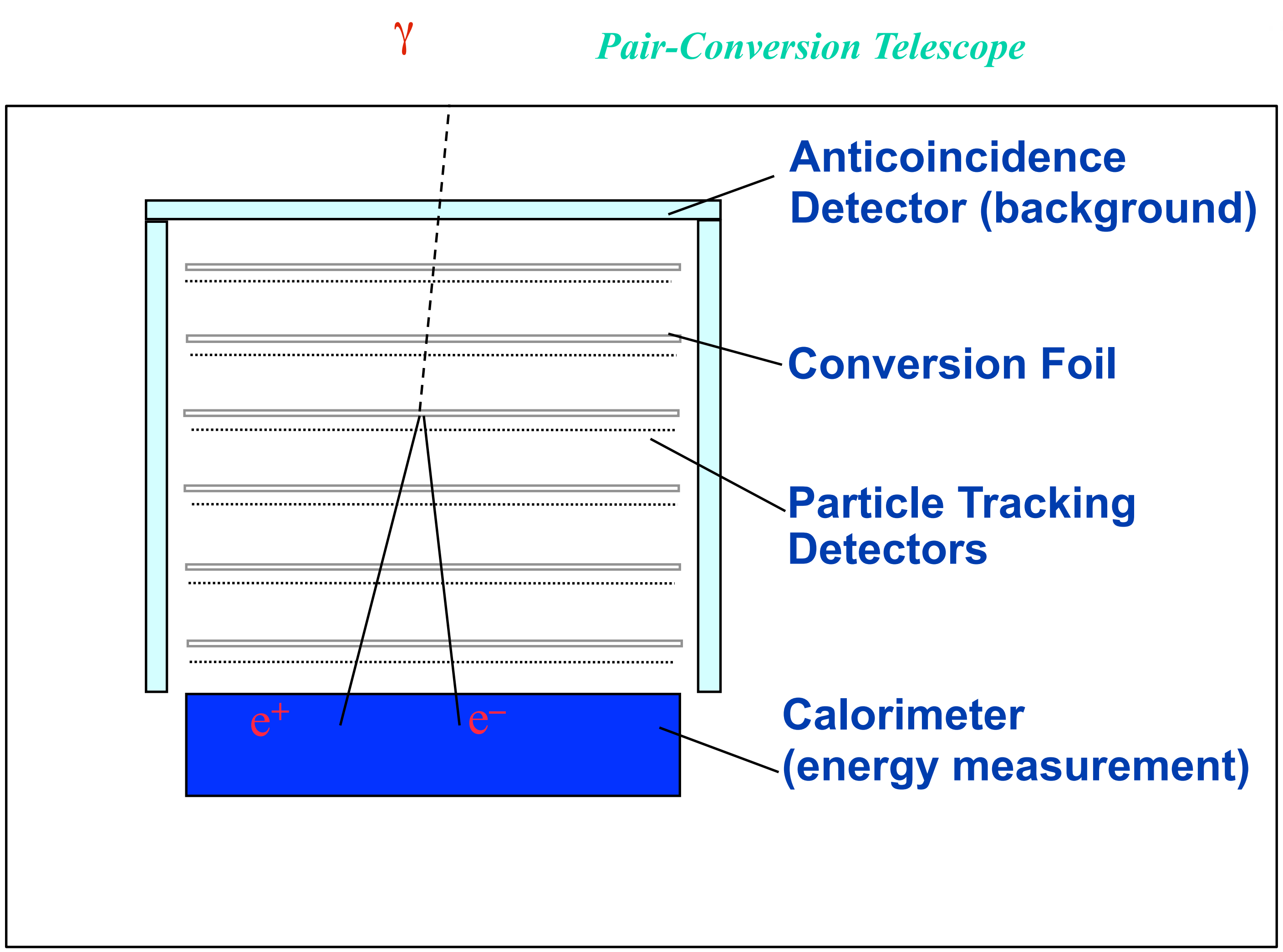
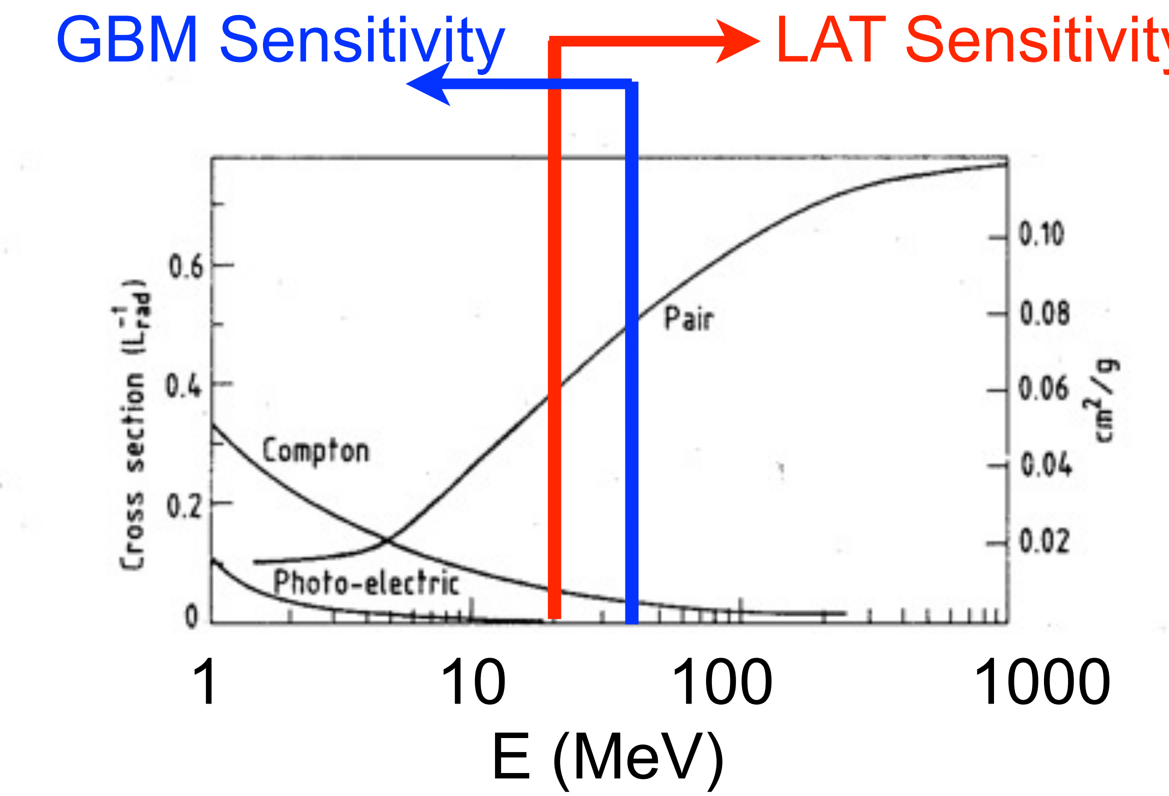
Spacecraft

Gamma-Ray Burst Monitor
* GRB Detection.
* 10 keV < E < 40 MeV

Detection Strategy

- High Energy Gamma tend to pair produce
- LAT Energy Range: 20 MeV -- ~300 GeV
- GBM: 8 keV -- 40 MeV





lengths. (Review of Particle Properties, April 1980 edition).

Pair Conversion Approach

- Veto Charge Particle Background
- Make gamma convert.
- Reconstruct directions of e+ e-
- Measure Energy e+ e-
- Reconstruct original direction and Energy of gamma.

Fermi Large Area Telescope (LAT)

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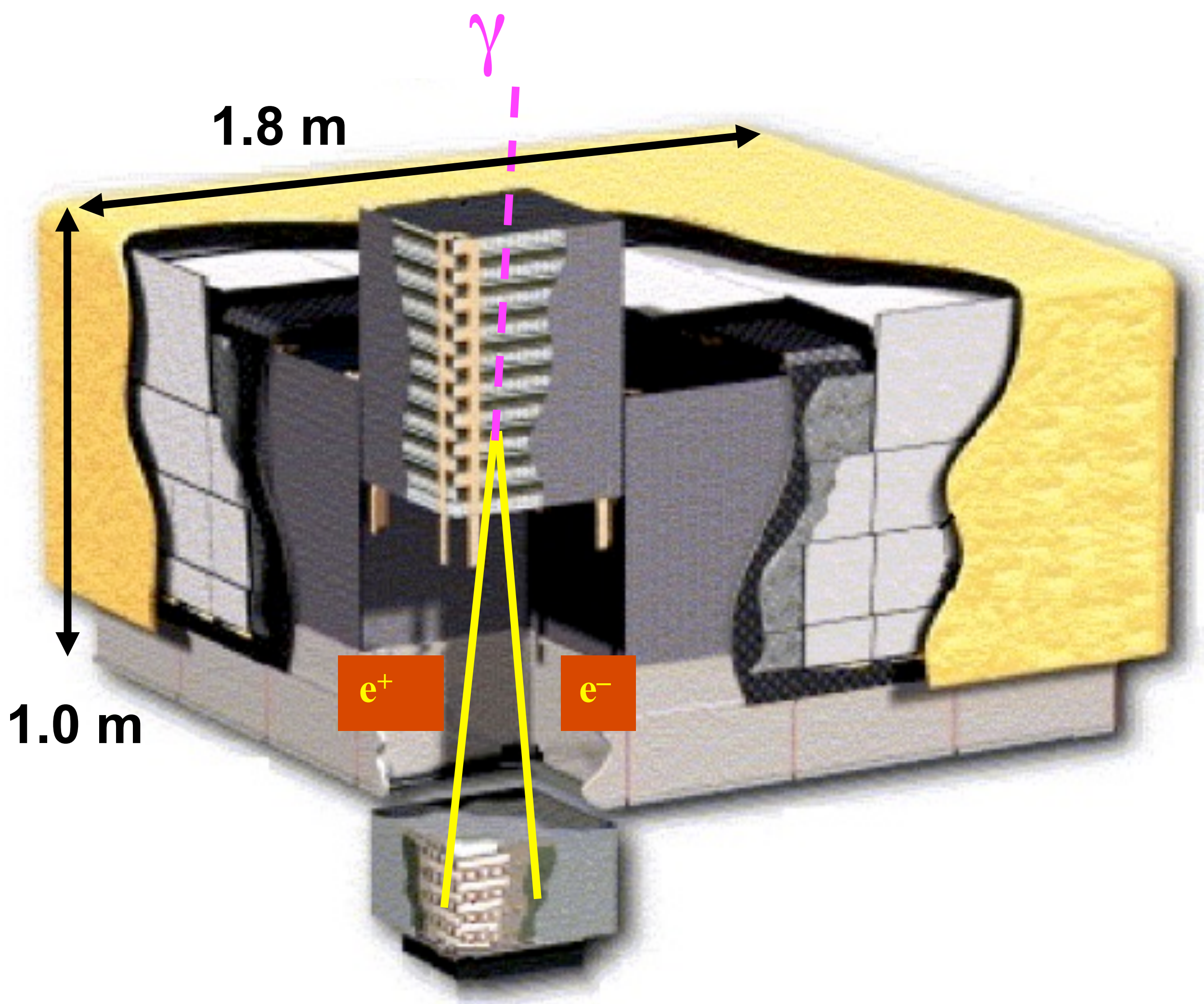

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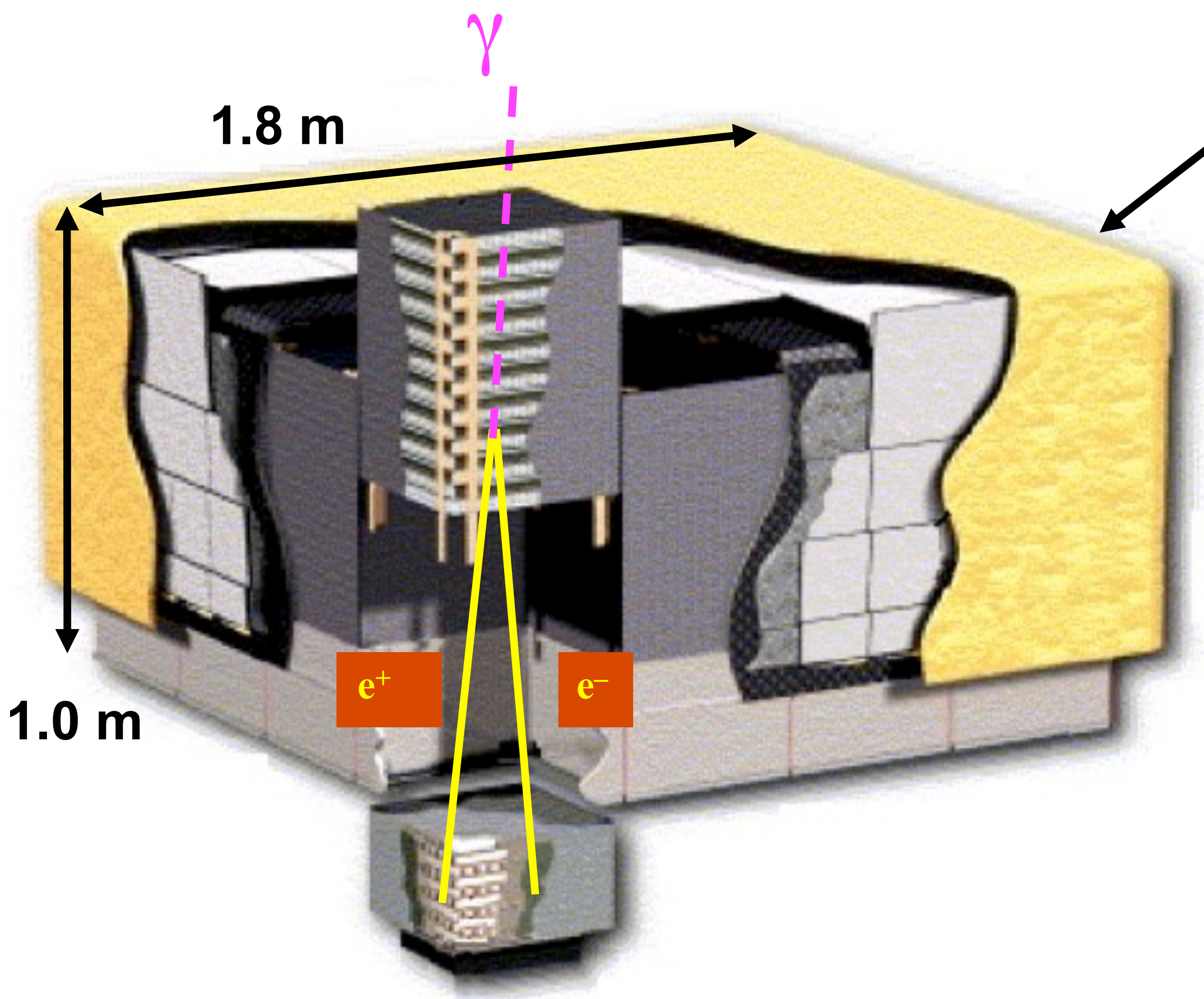

Anti-Coincidence Detector

- 4% R.L.
- 89 scintillating tiles
- efficiency (>0.9997) for MIPs

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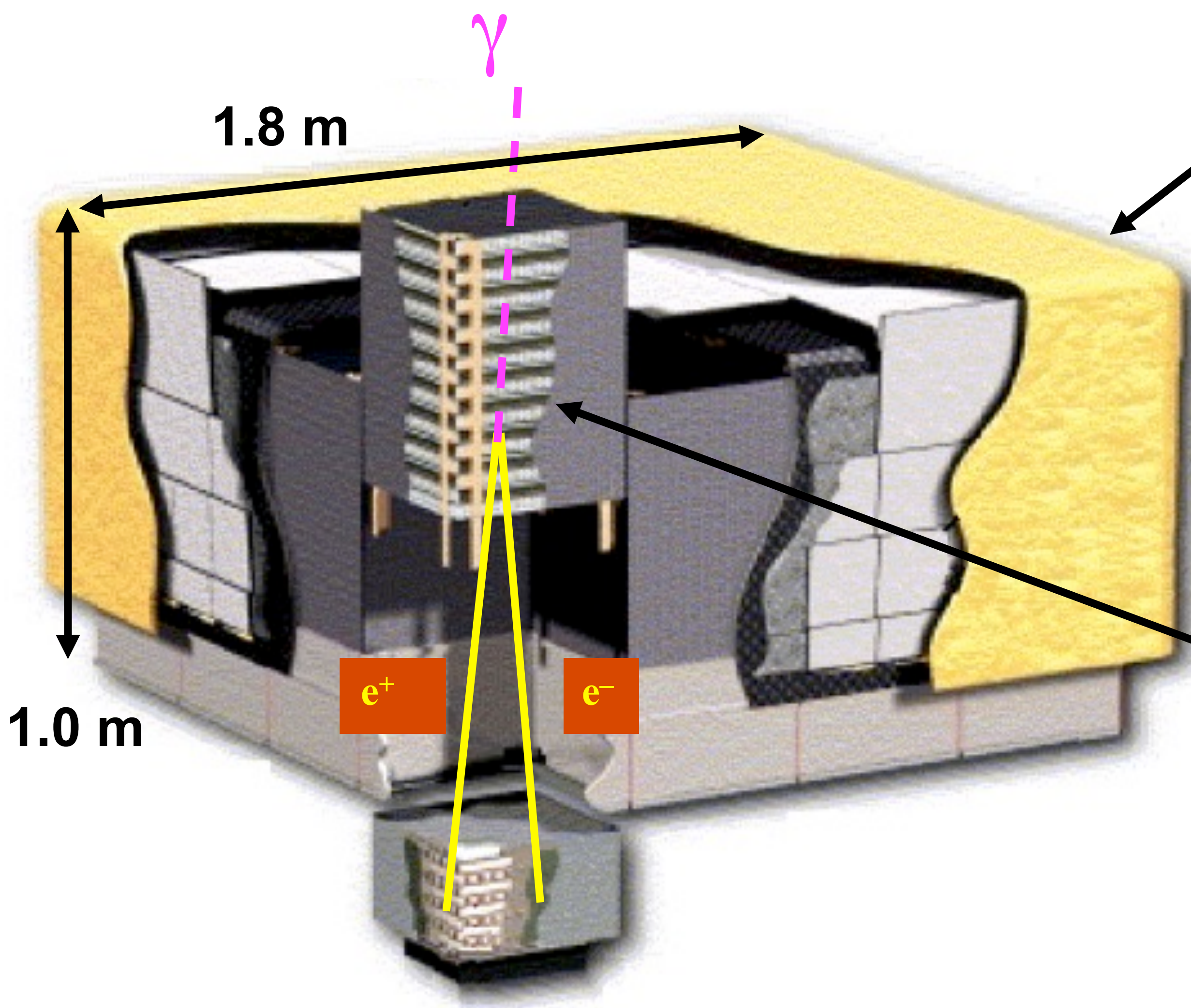

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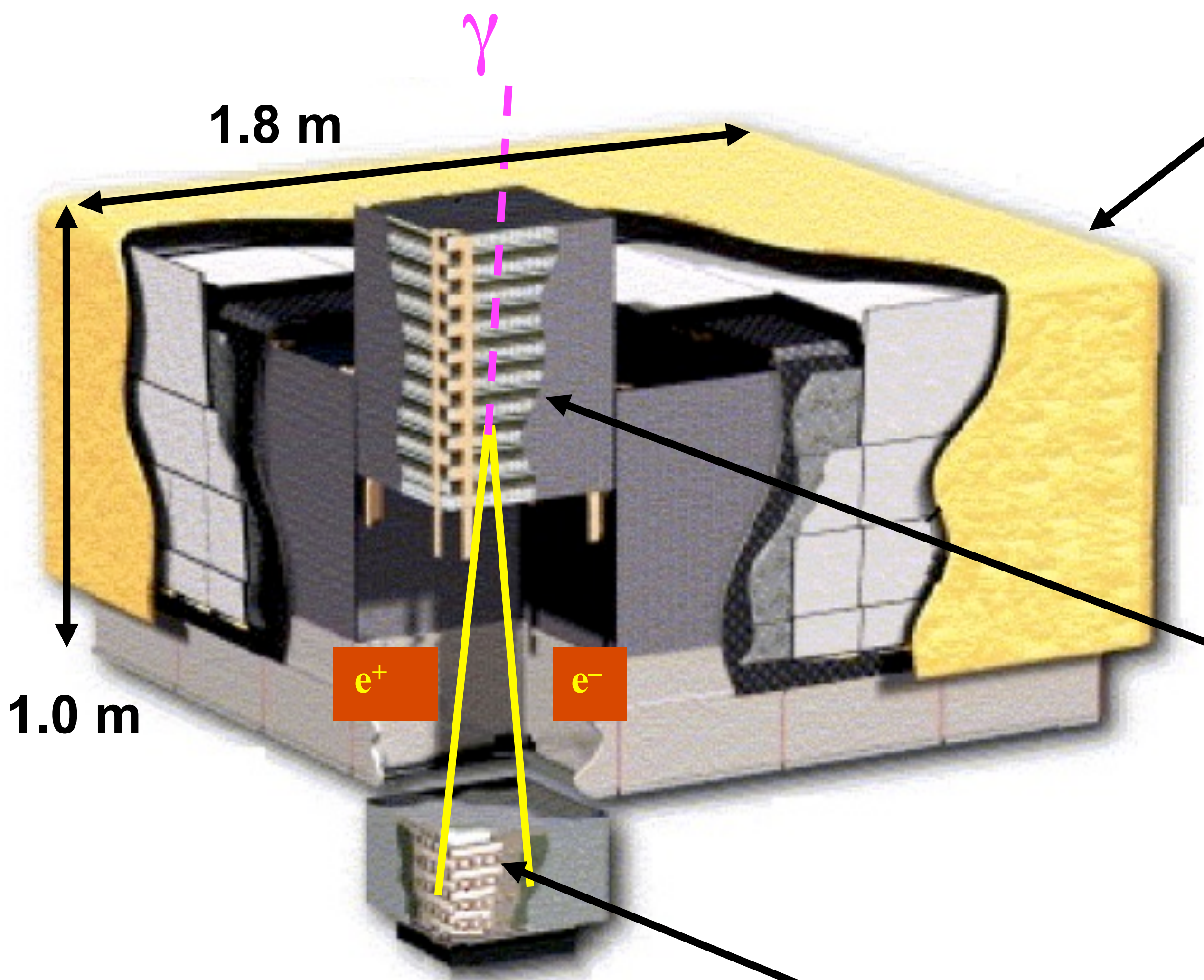
Tracking detector
- 16 tungsten foils (12x3%R.L.,4x18%R.L.)
- 18 pairs of silicon strip arrays
- 884736 strips (228 micron pitch)

Fermi Large Area Telescope (LAT)



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Calorimeter
- 8.5 radiation lengths
- 8 layers cesium iodide logs
- 1536 logs total (1200kg)

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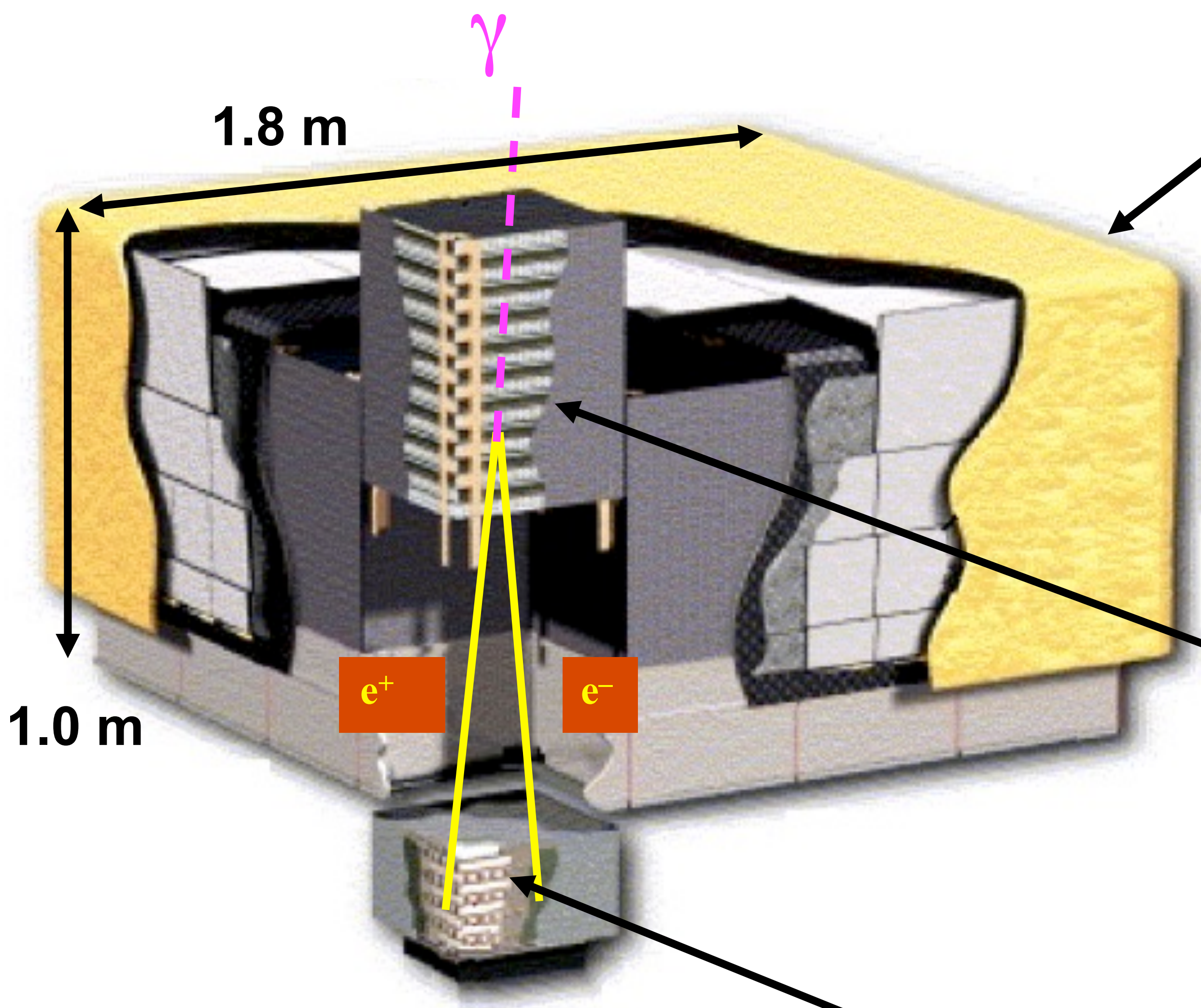

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Trigger
- Overall HW Trigger Rate ~few KHz
- Software Filters Reduce Rate
- Downlink: ~400-500 Hz
- Rate after Ground Cuts: ~few Hz

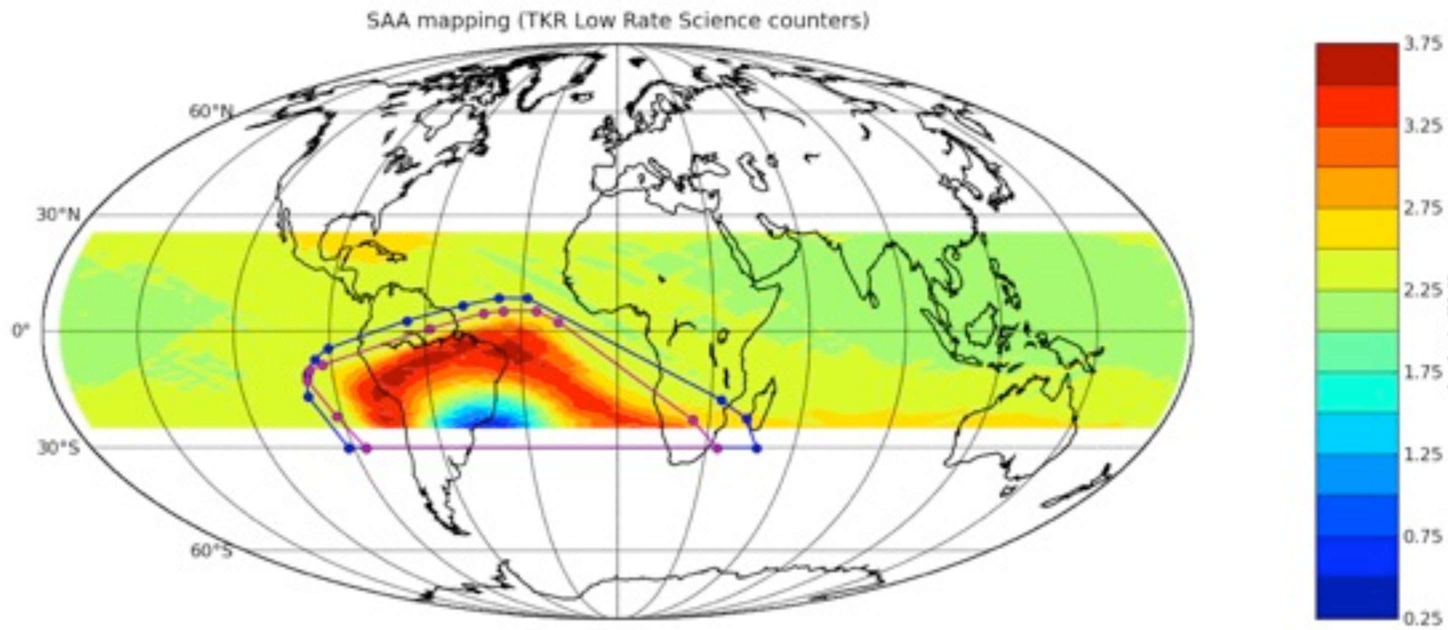

1825 LBS CAP


USAF
ULA
DELTA
GLAST

Views from the Beach

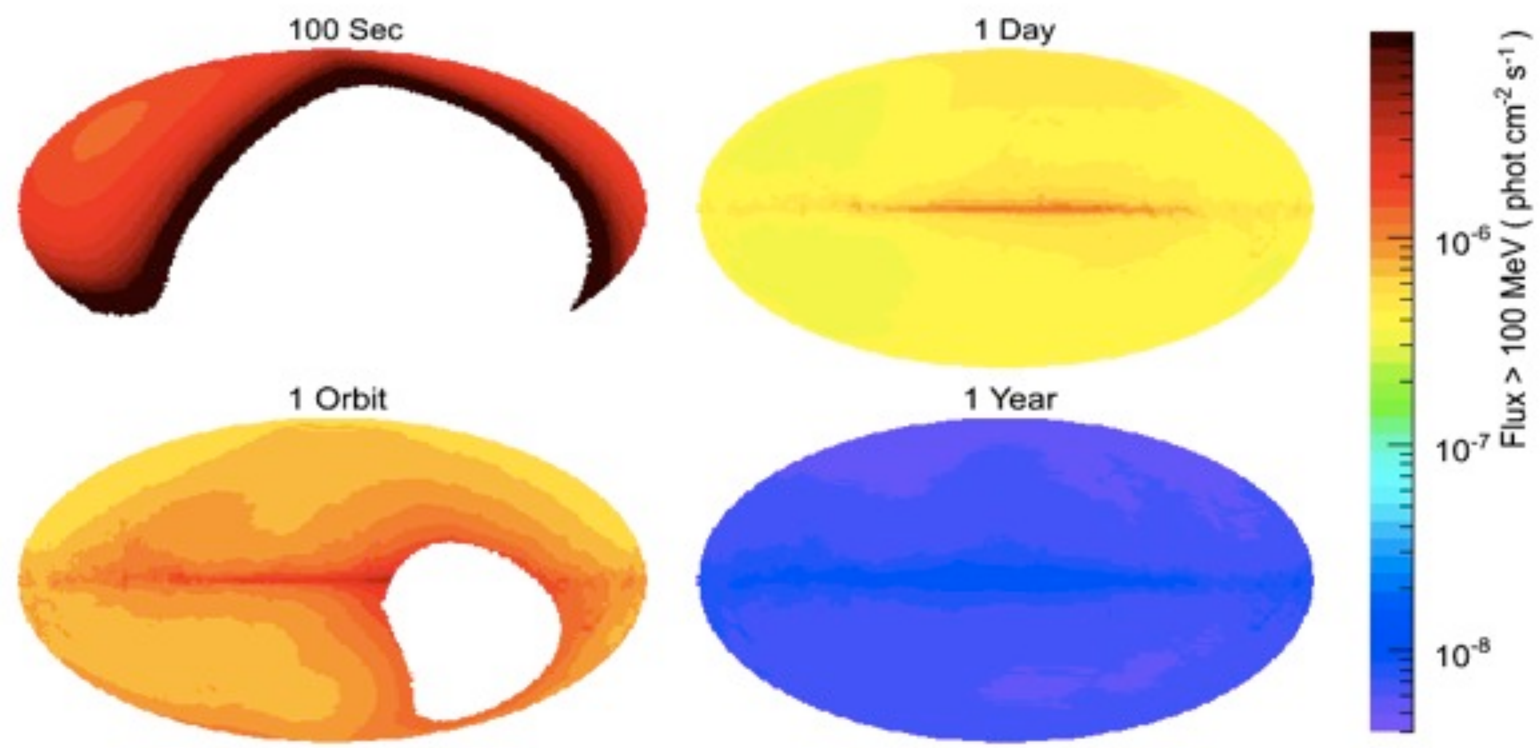
Launch of Fermi

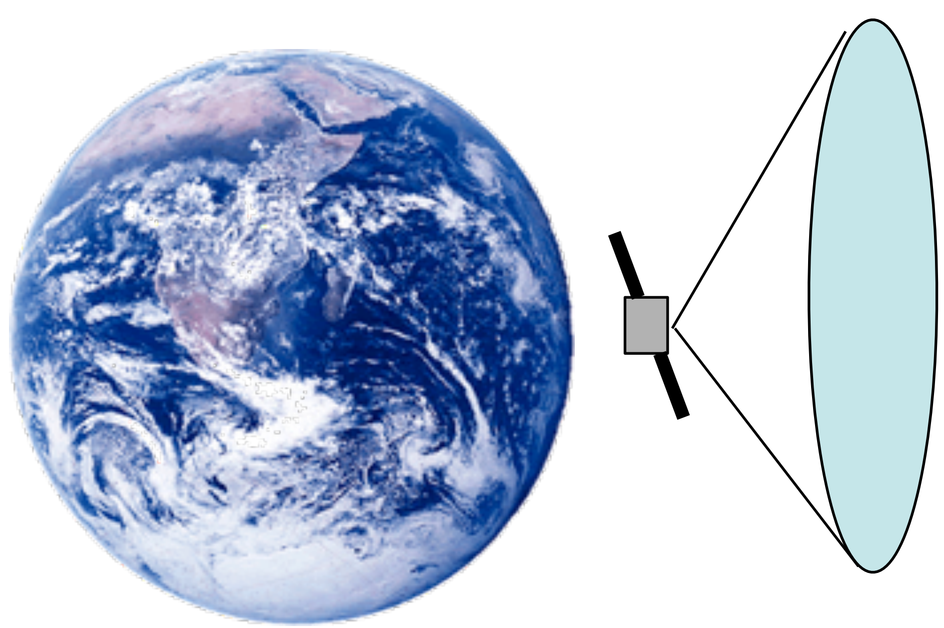
- Very Successful Launch!
- Orbit:
  - ★ Altitude: 565 km
  - ★ Inclination: 25.6 deg
  - ★ Period: ~90 min
- Turn off through SAA
- Lifetime: 5 years min.
  - ★ No expendable



Operational Modes

- Sky Survey Mode
  - ★ Typical Mode of operation
  - ★ View full sky every 2 orbits
  - ★ “Rocking” Mode (up/down)
- Targets of Opportunity
  - ★Autonomous Repoint (GRBs)
  - ★Slew to keep ToO in FOV
  - ★Later years: ToO Proposals

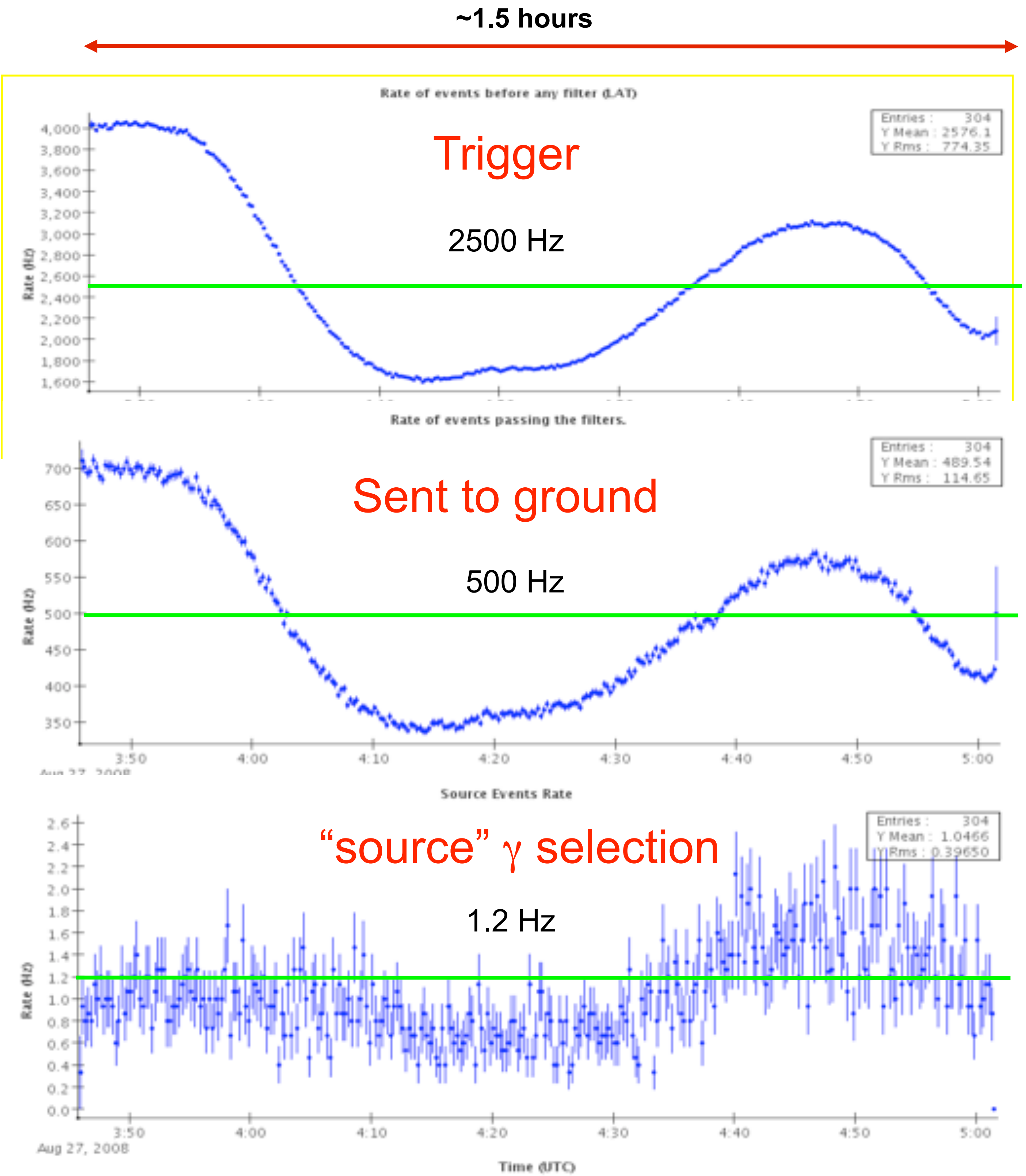




LAT: Wide Field of View ~2.4 sr

GBM: See almost all of the sky
not occulted by the earth

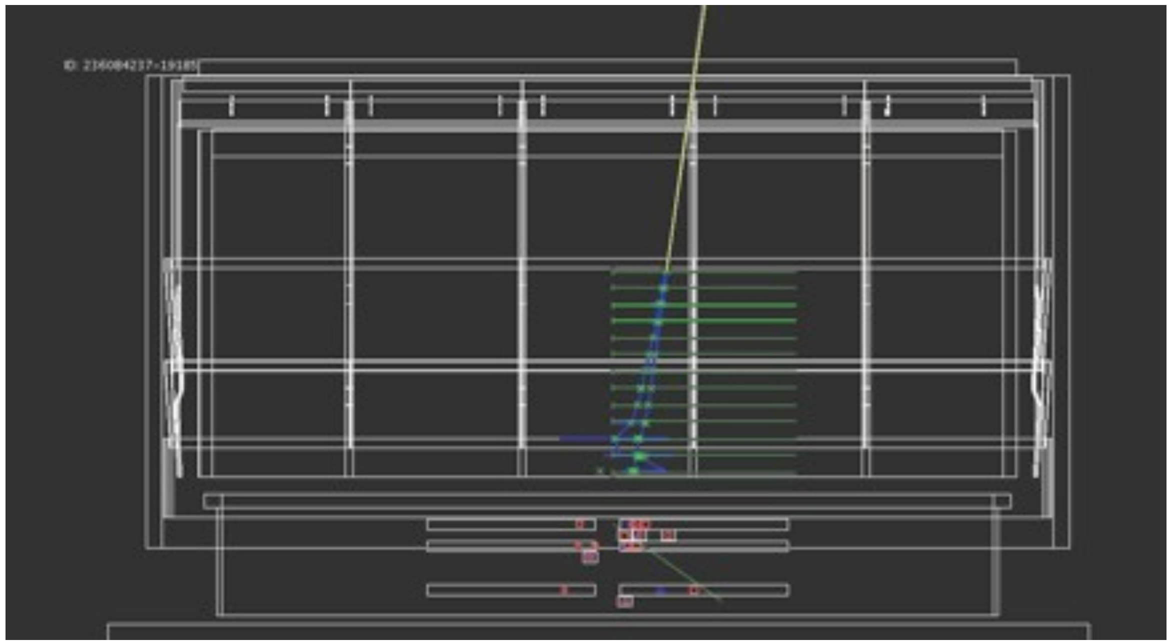
On orbit rates in nominal configuration

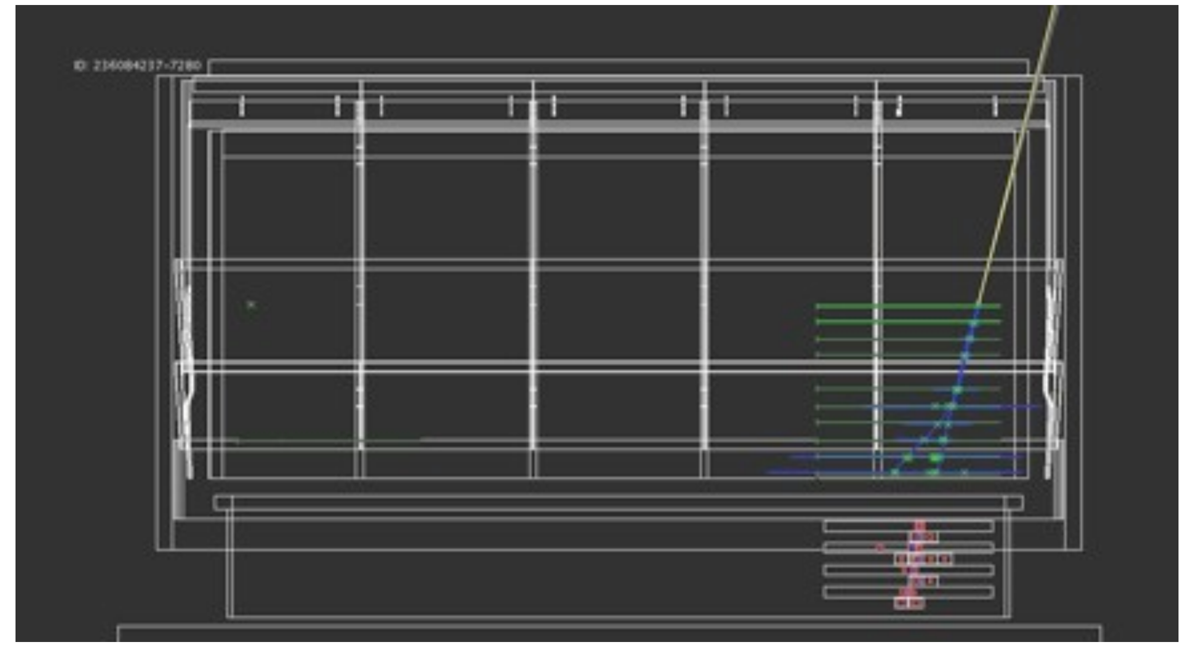


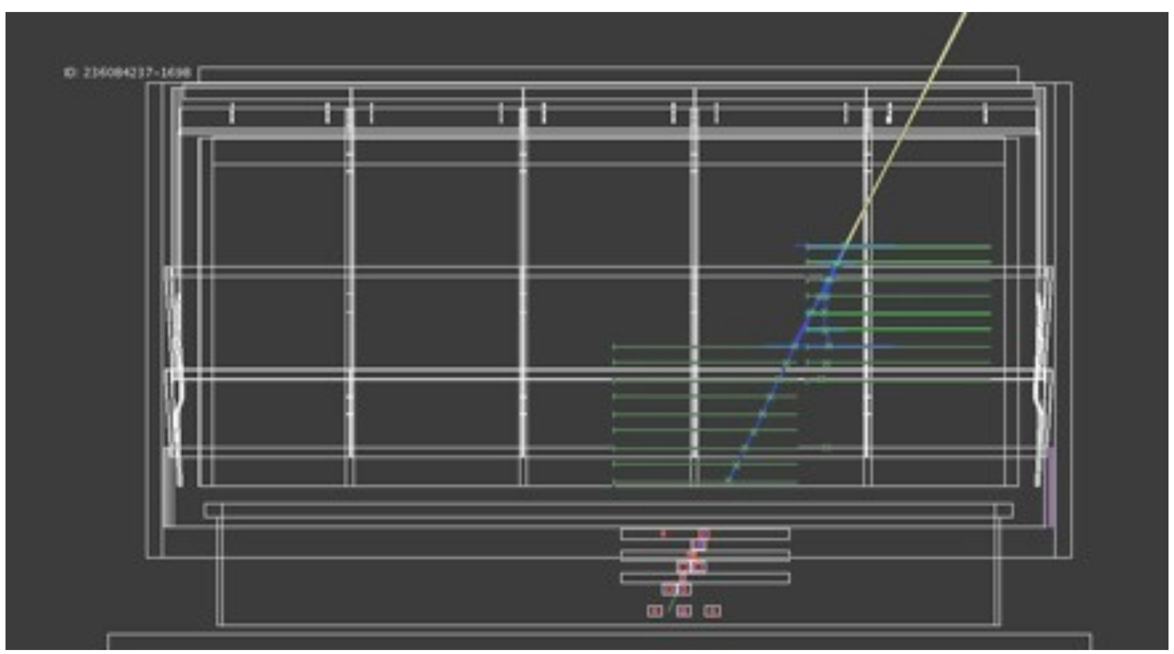
Note: Rates from Early Running

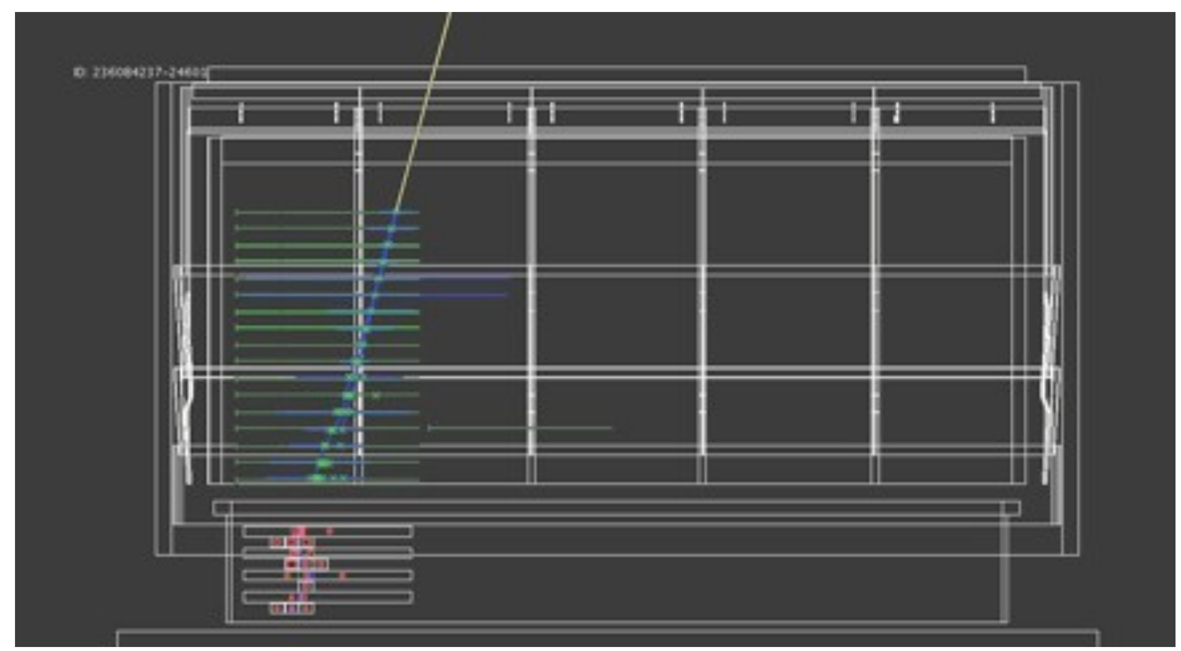
- Overall trigger rate: ~few KHz
  - ✓ Substantial variations due to orbital effects
- Downlink rate: ~400—500 Hz
  - ✓ ~90% from GAMMA filter
  - ✓ ~20—30 Hz from DGN filter
  - ✓ ~5 Hz from HIP filter
- Rate of photons after the standard background rejection cuts for source study: ~1 Hz
  - ✓ Most of the downlinked events are in fact background, final 100:1 rejection is done in ground processing.

LAT Gamma Candidate Events

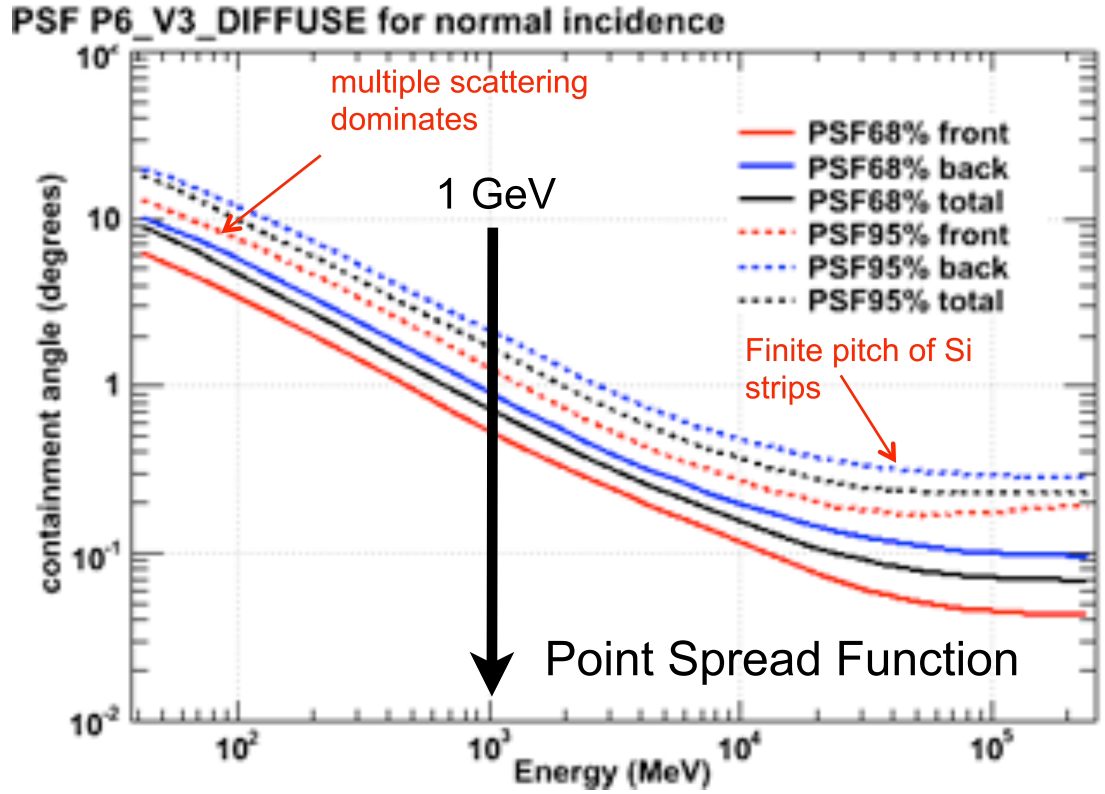


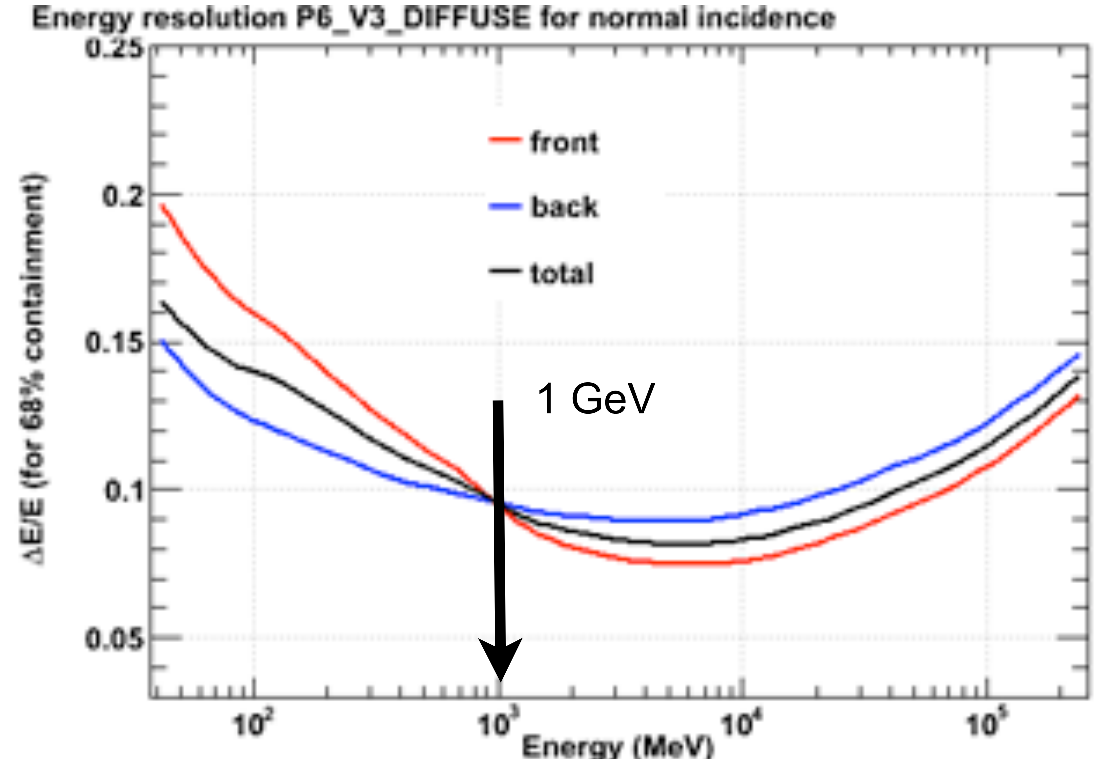


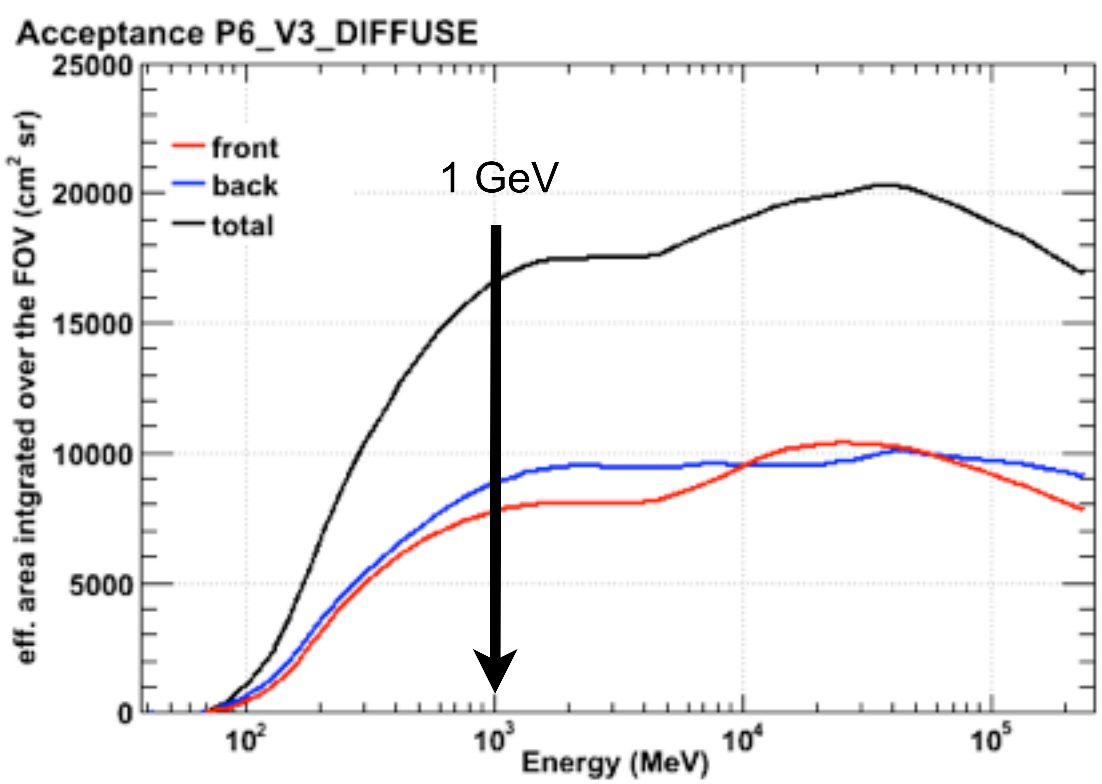


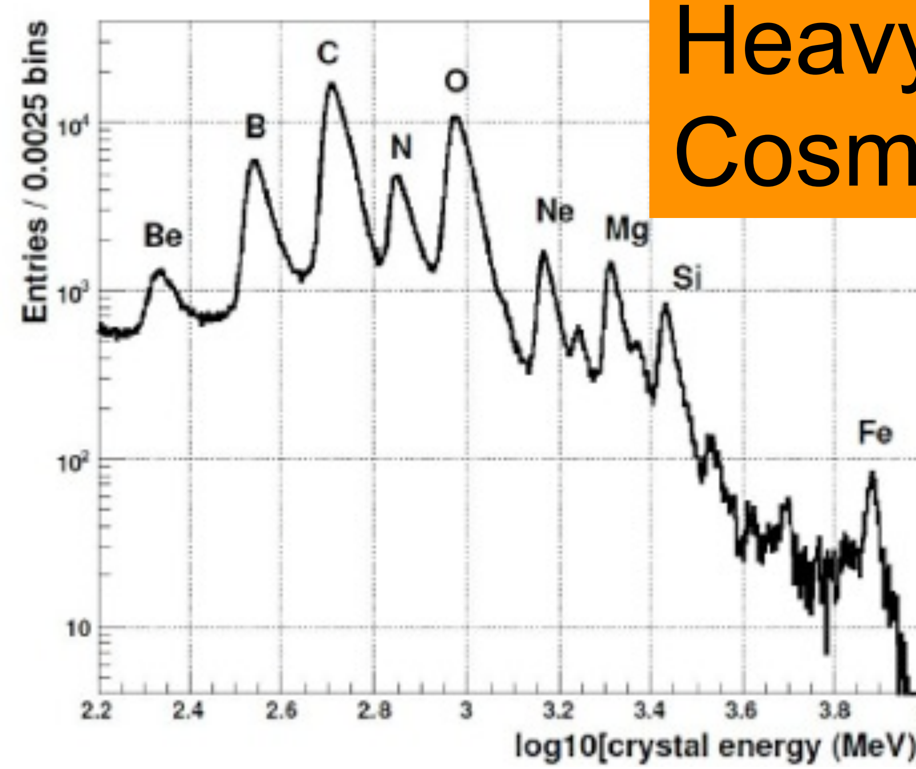


Detector Performance







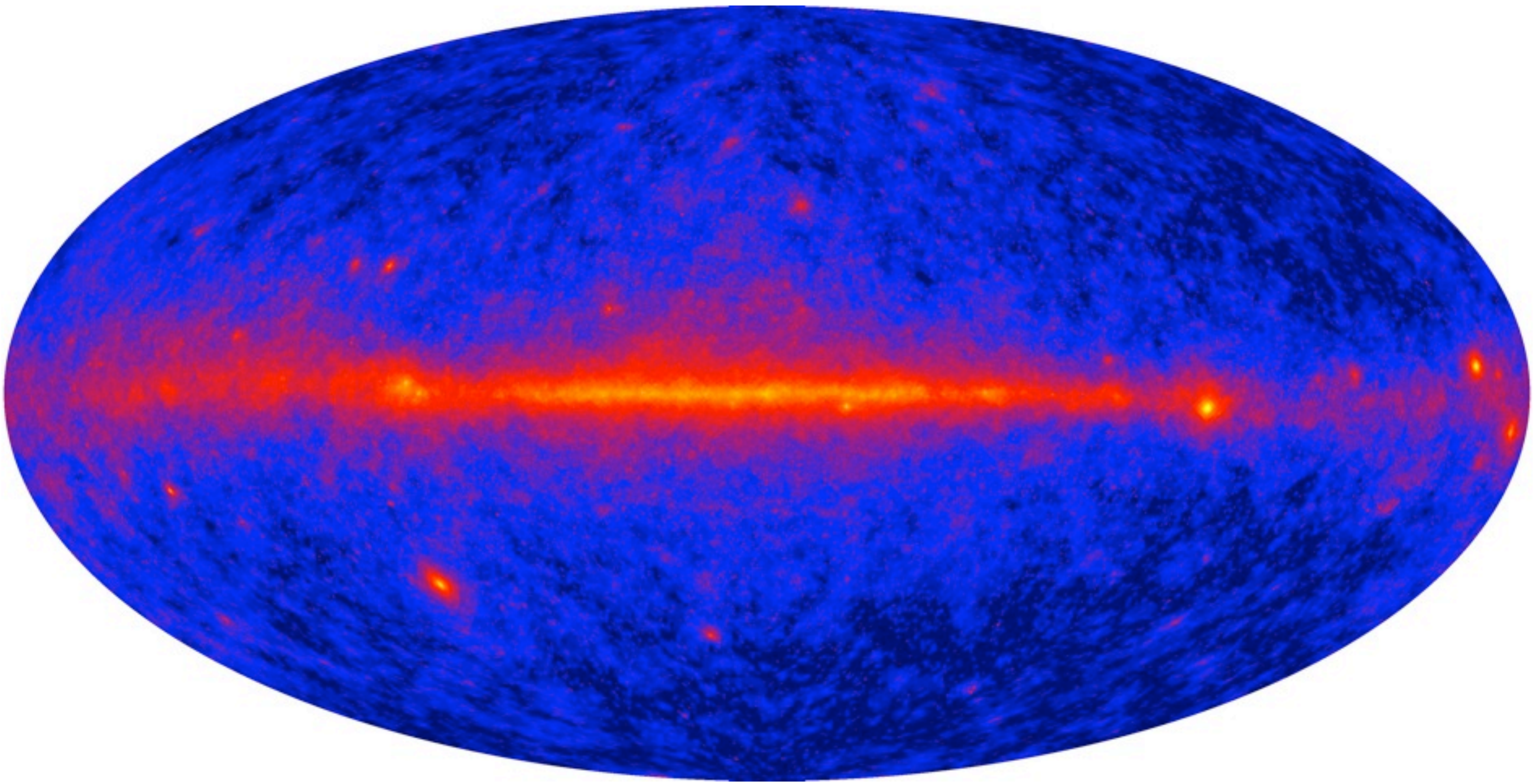


Heavy Ion Cosmic Rays!

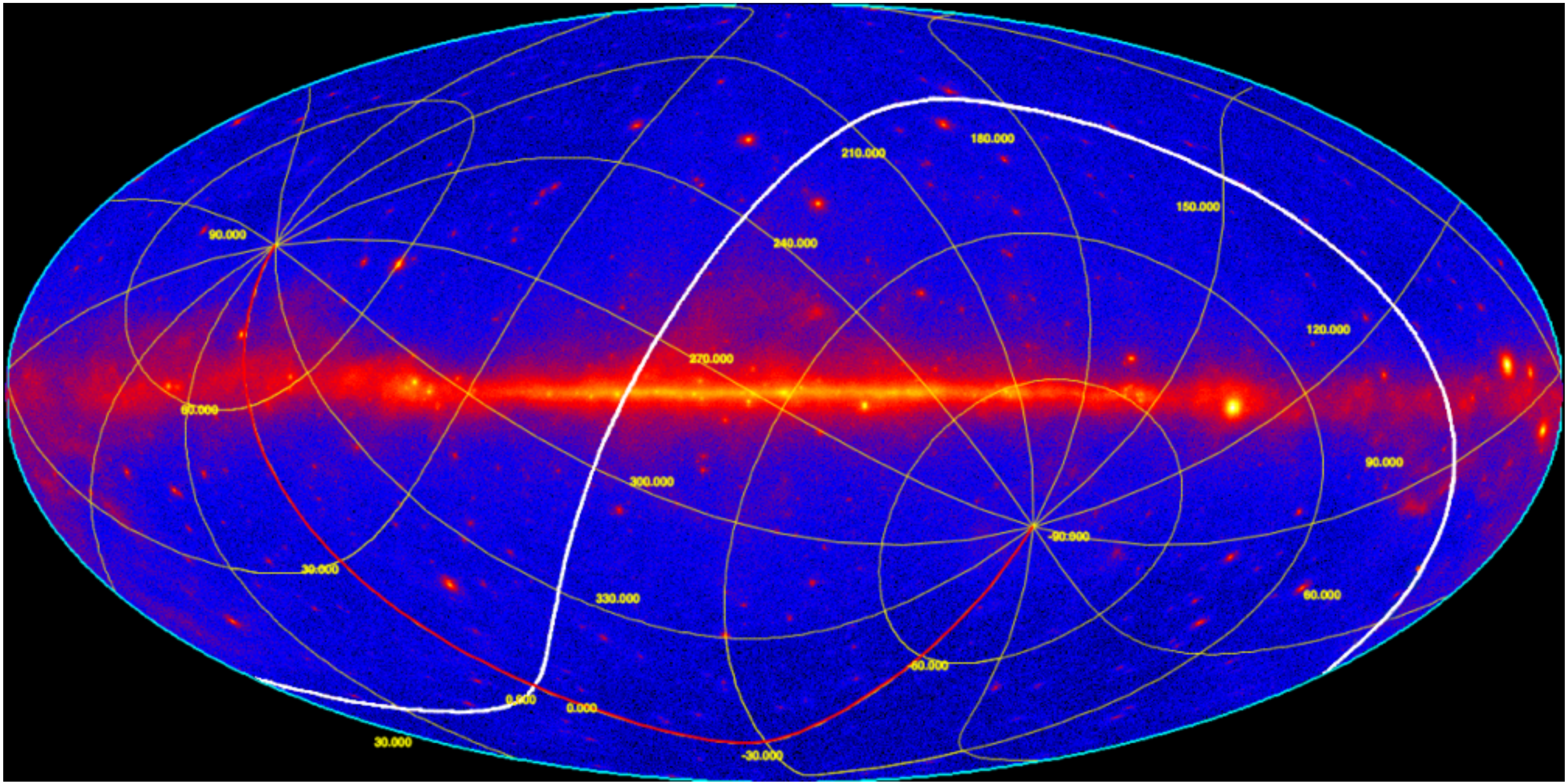
The Gamma Ray Sky

The Gamma Ray Sky

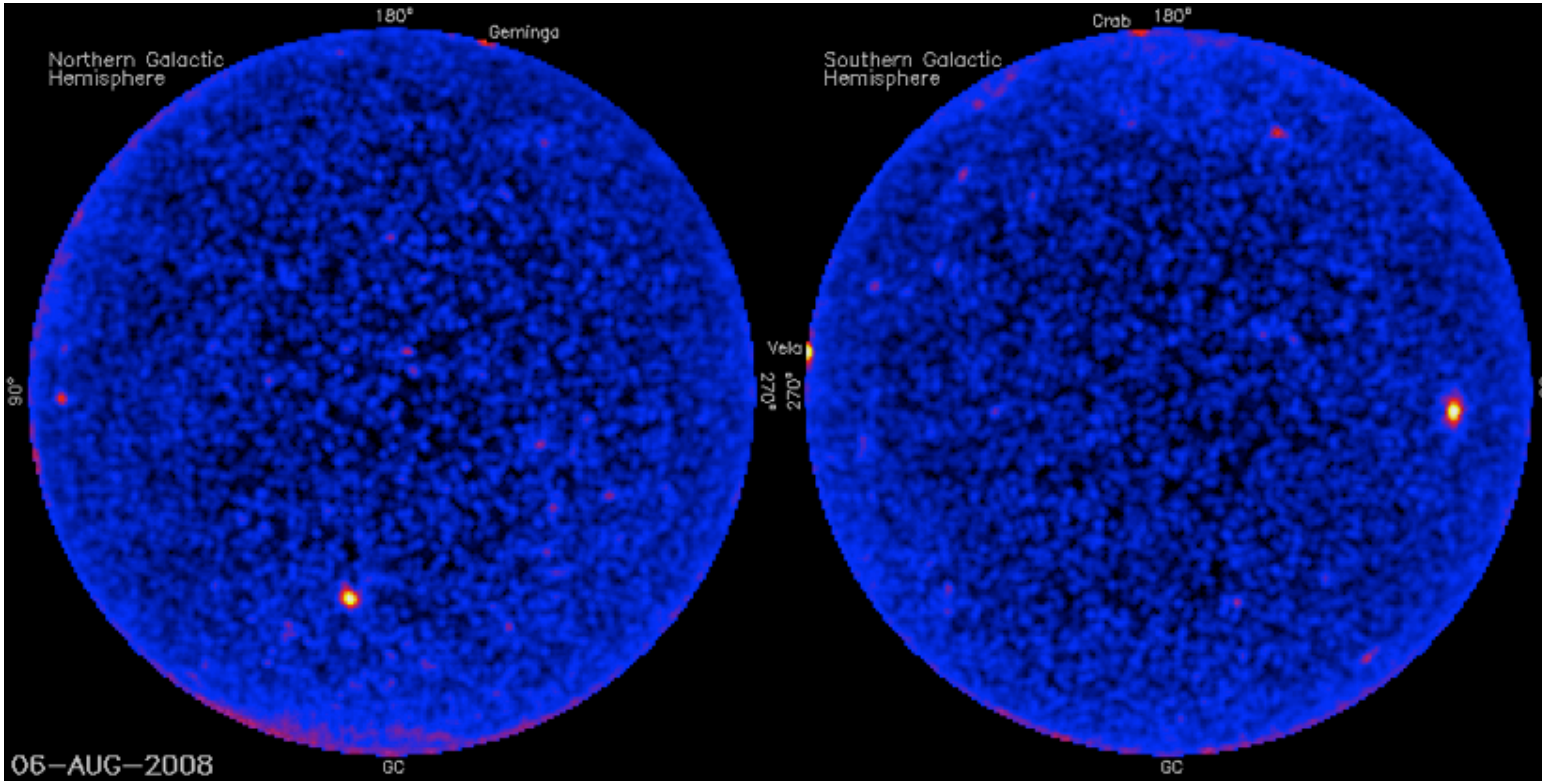
All Sky First Light Data: **Few Days of Data**

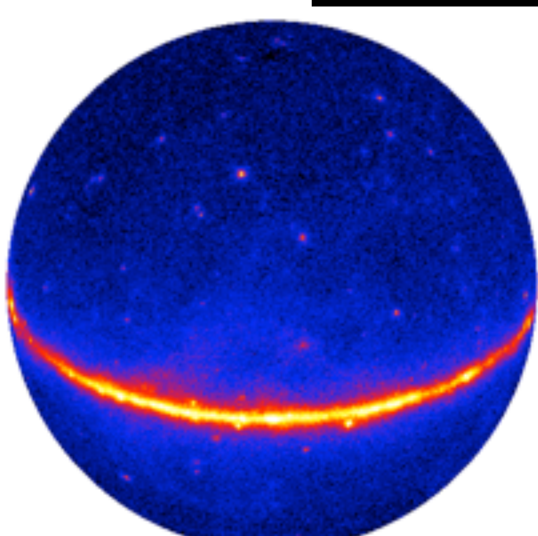


All Sky View: First Year of Data



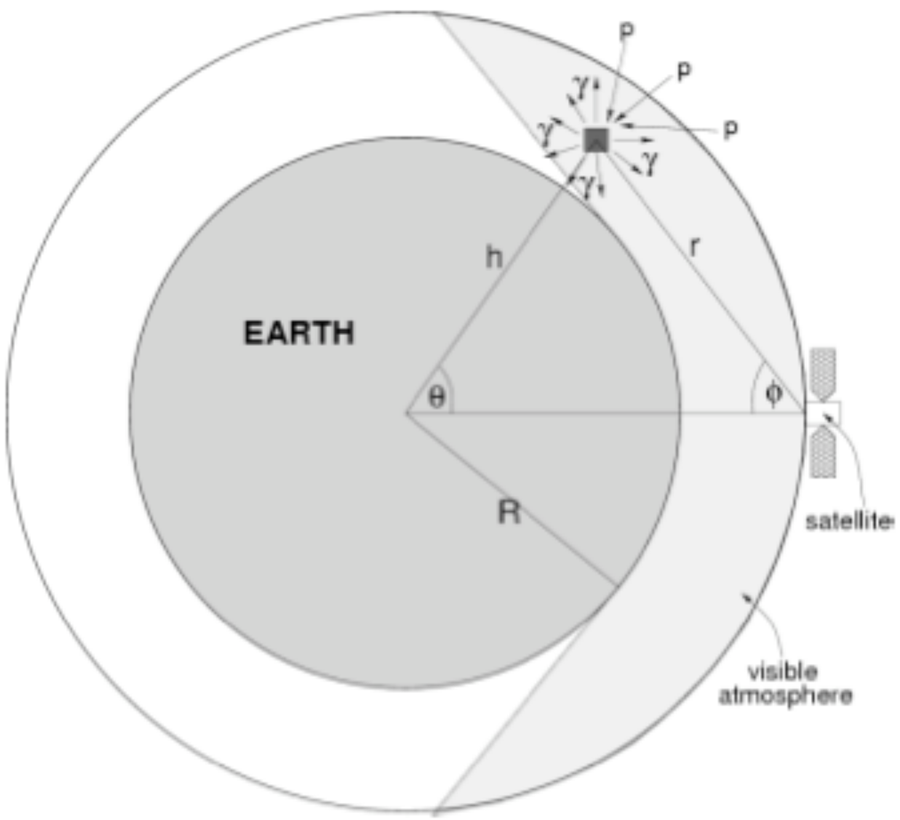
Animation of 3 month Data Set



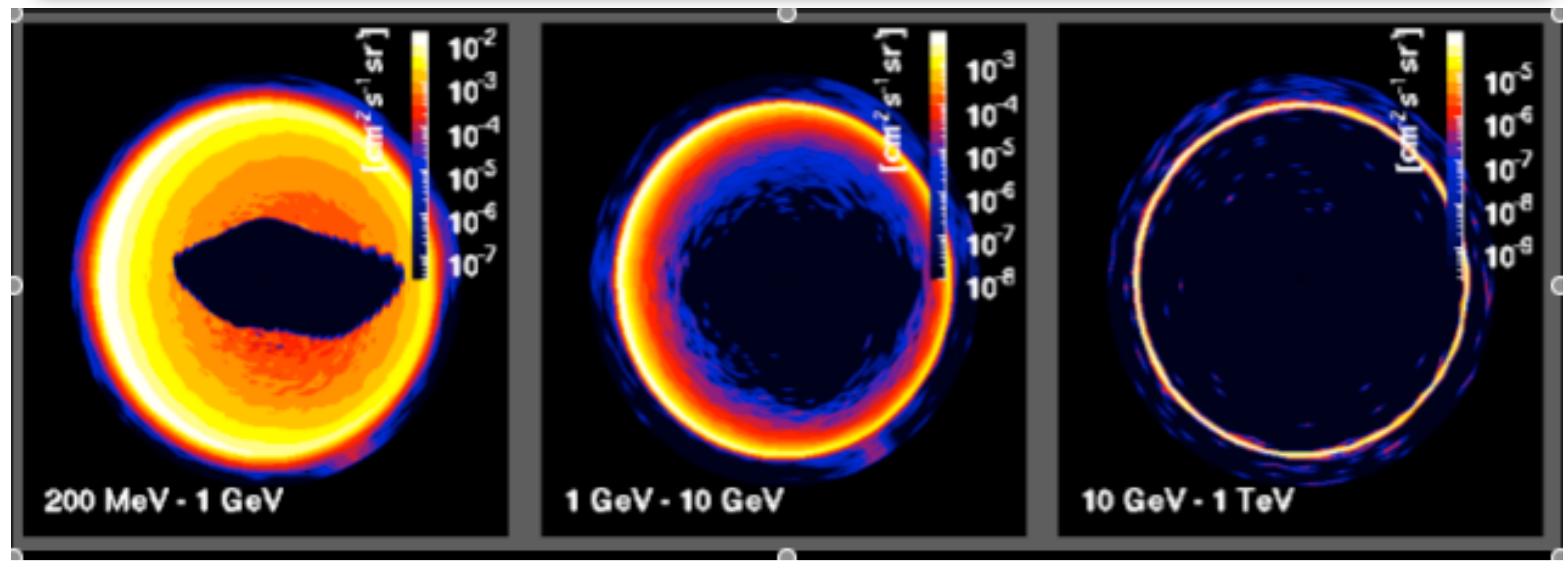


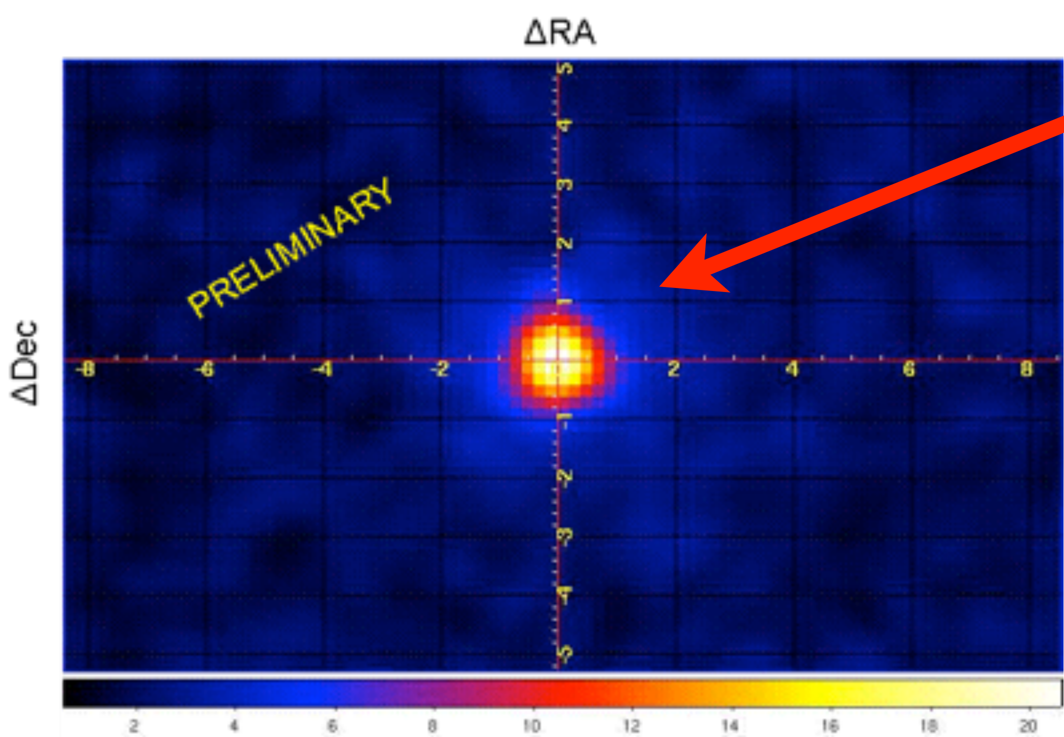
- 87 day animation, starting August 4
- pixel size 0.5 deg in center
- |b|>1.0

The Earth, the Sun, and the Moon

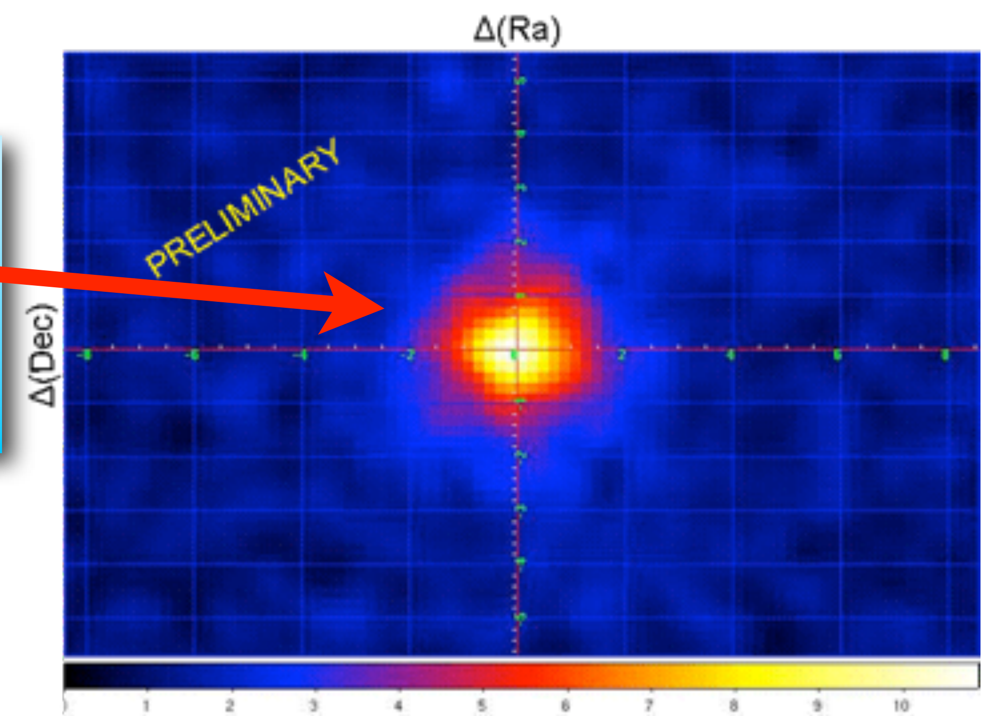


The Earth is the brightest gamma ray source in the sky.





Both the Sun and the Moon "shine" in gamma-rays.



Features of the Sky

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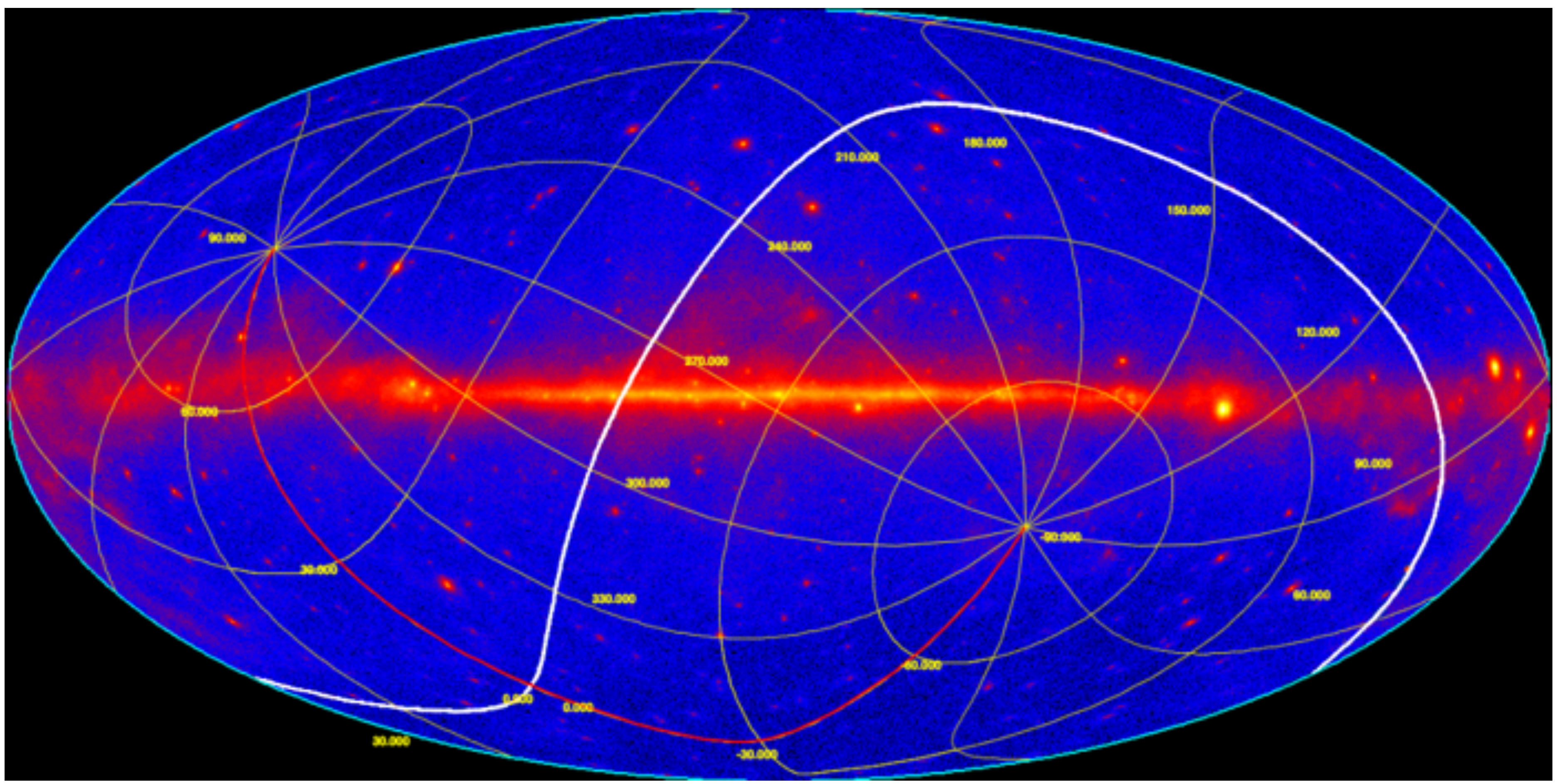
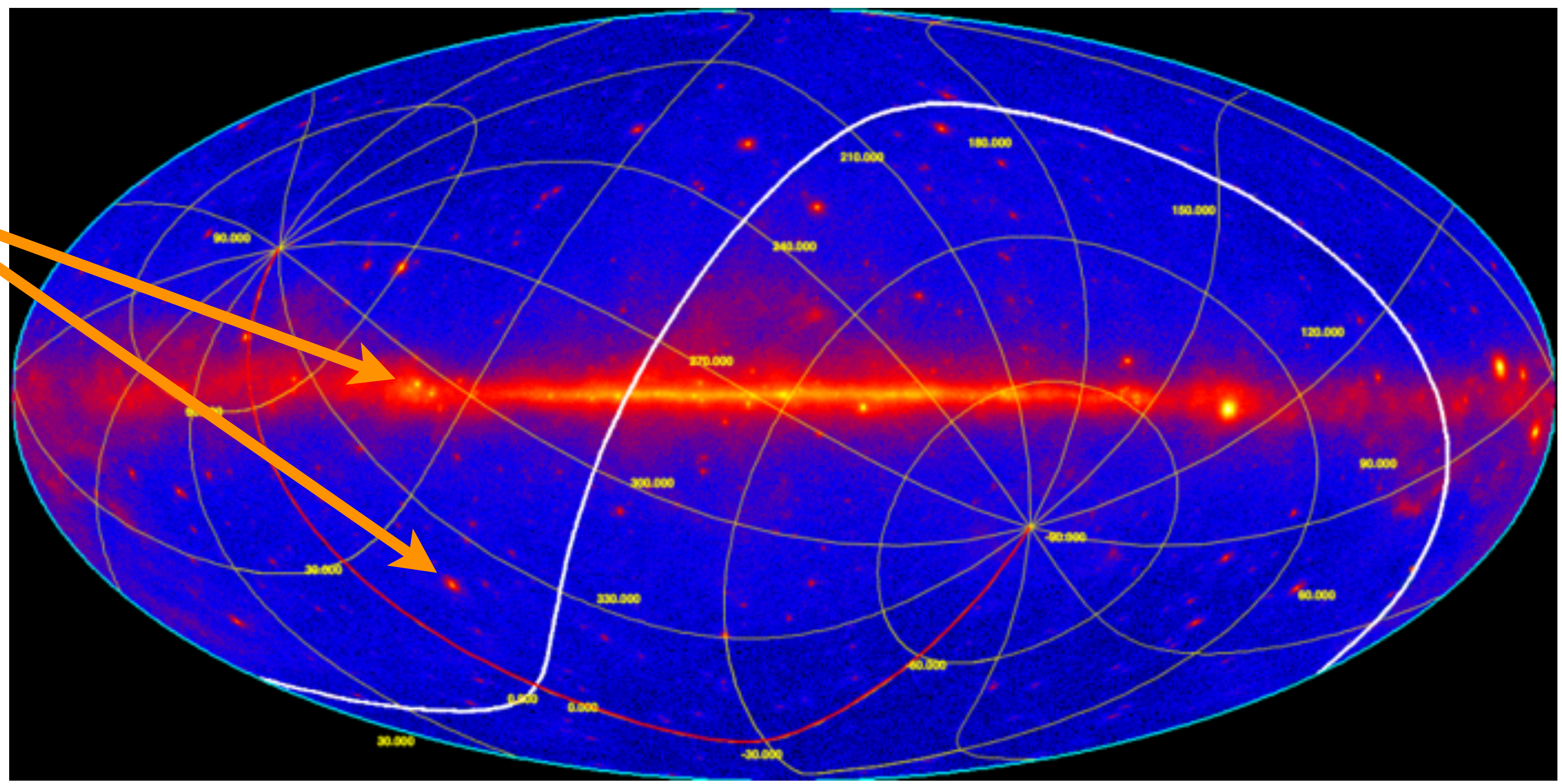


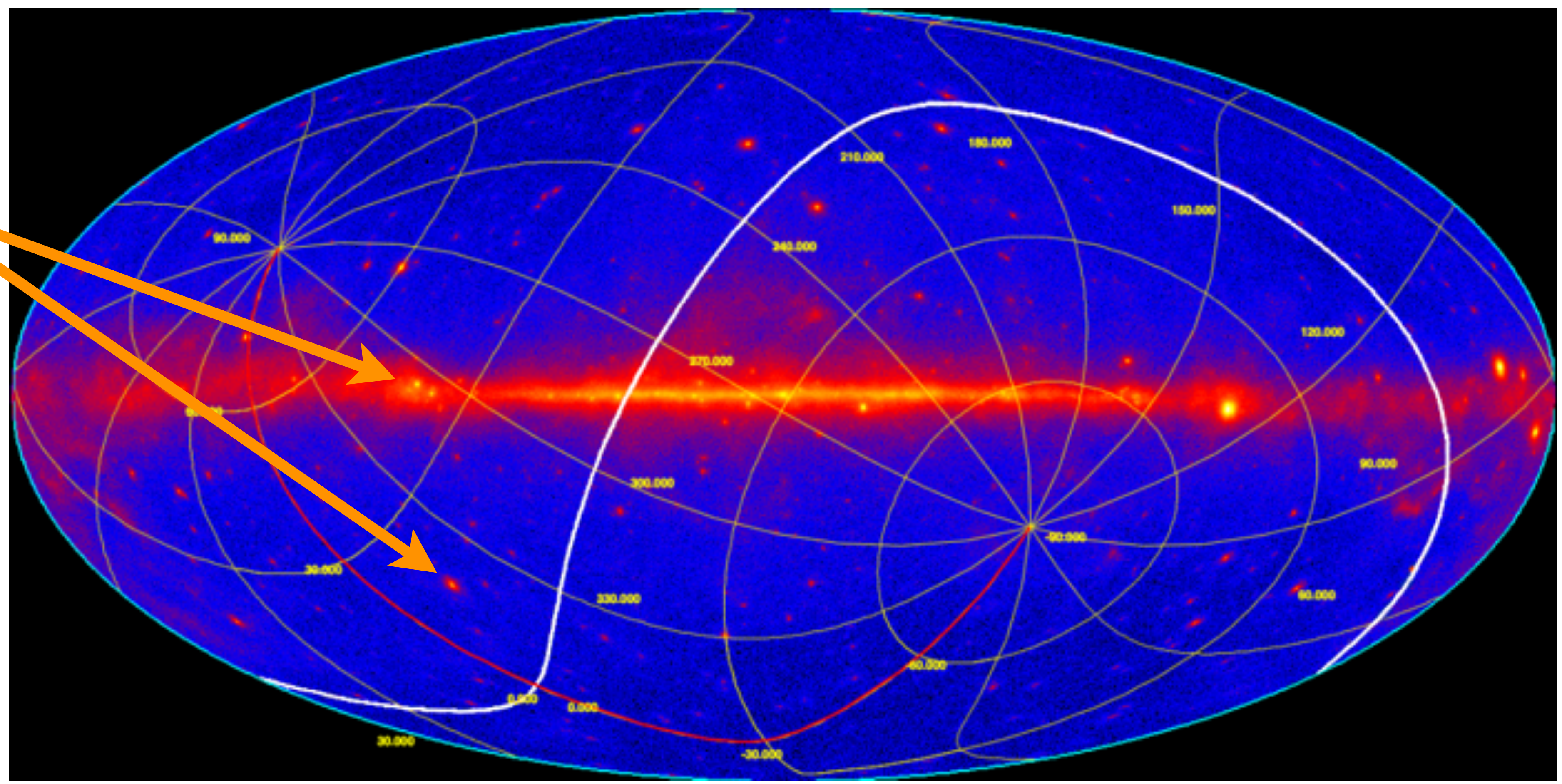
Features of the Sky

Sources:

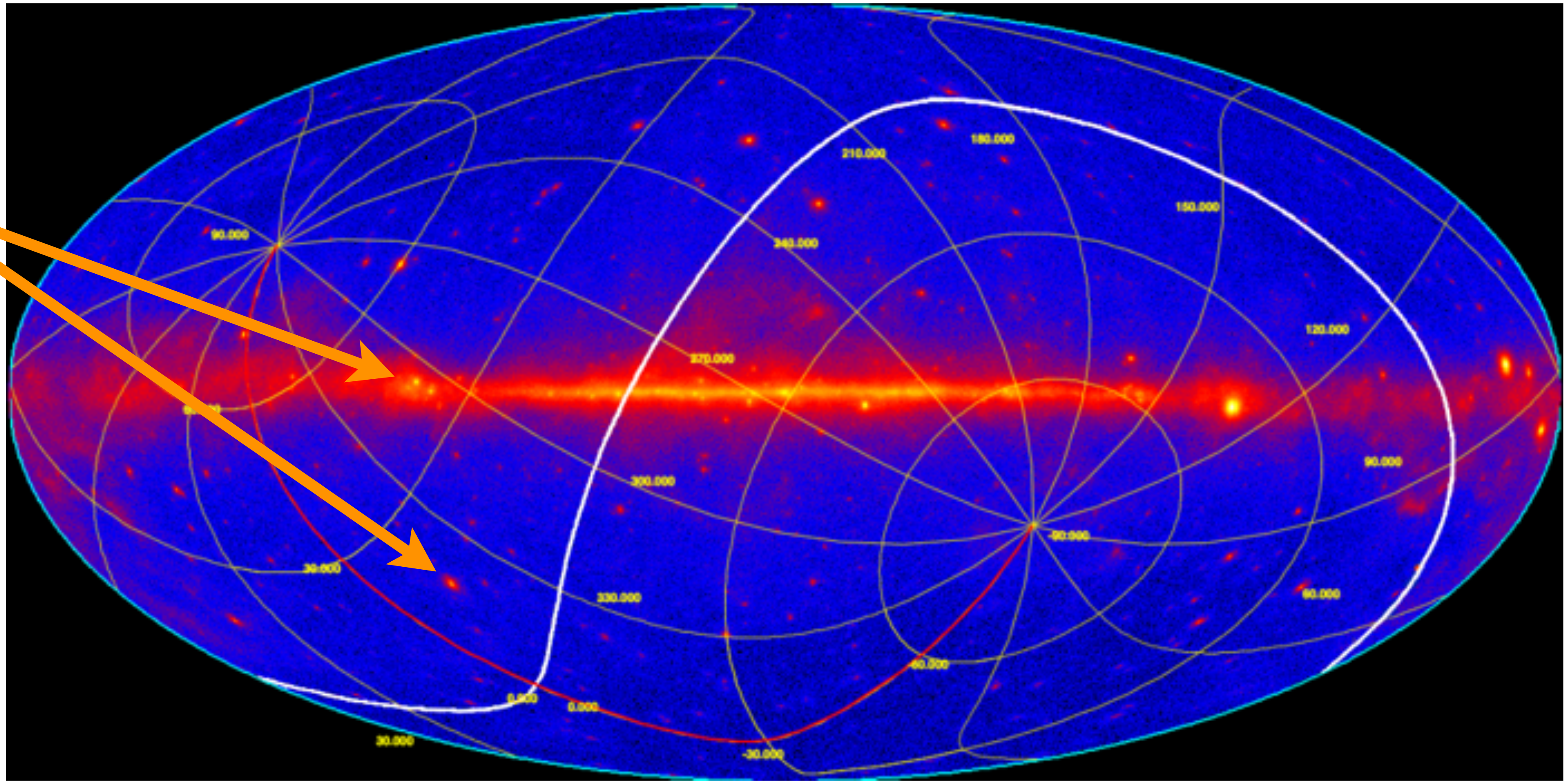


Features of the Sky

Sources:
- Galactic and Extra-Galactic



Sources:
- Galactic and Extra-Galactic
-"Constant"



Features of the Sky

<u>Sources:</u>
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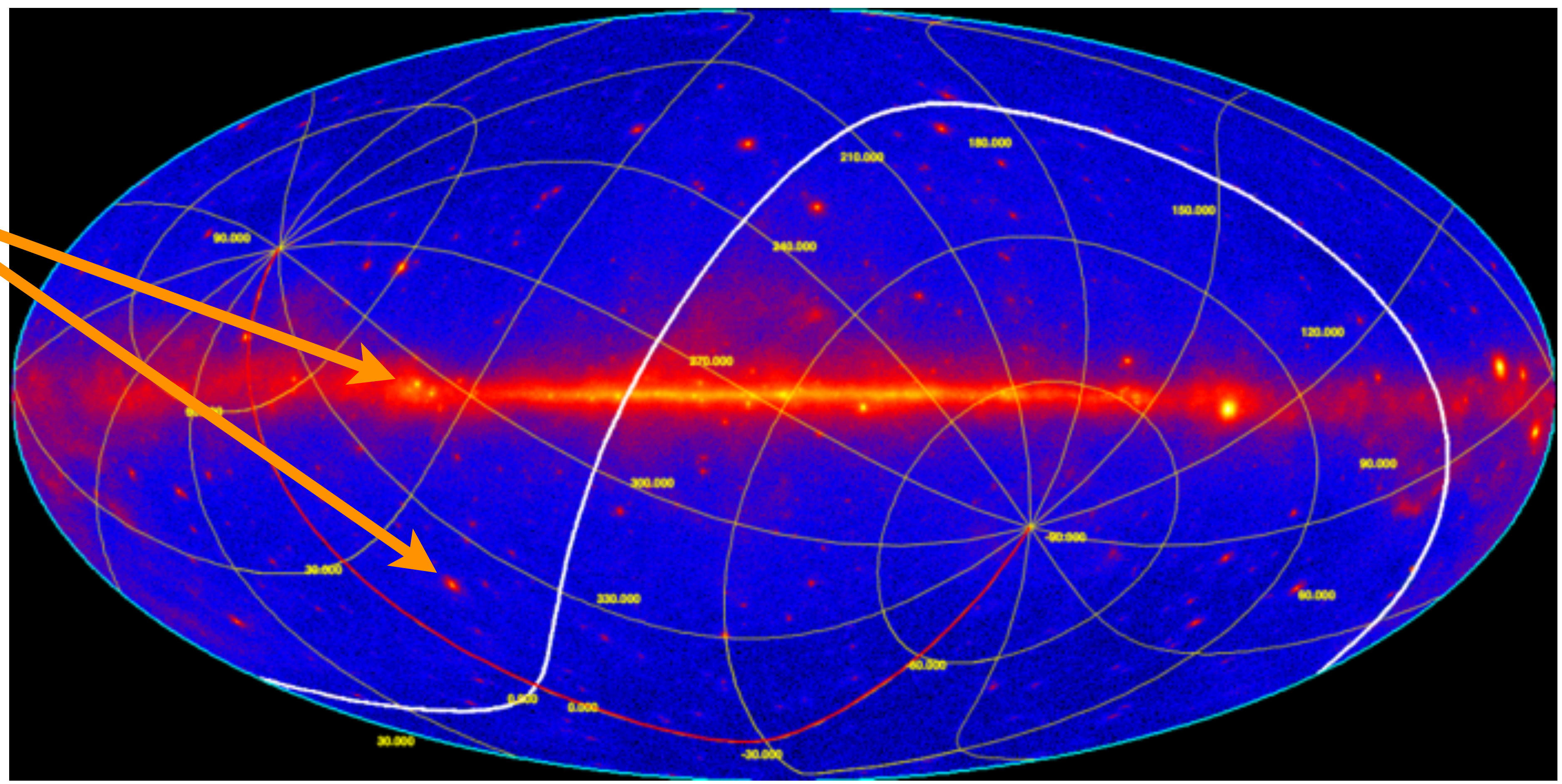
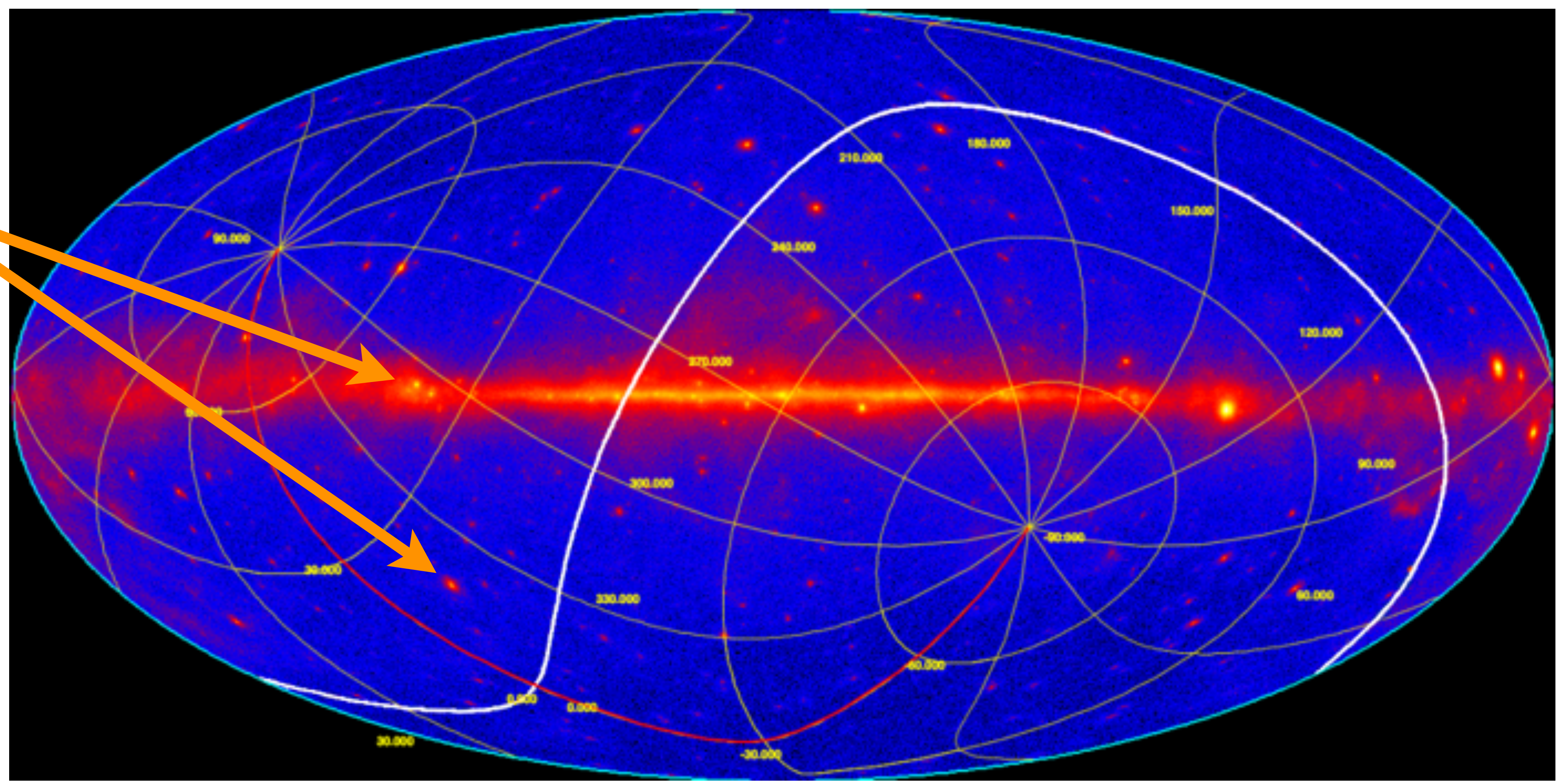
-"Constant"
-Variable



Features of the Sky

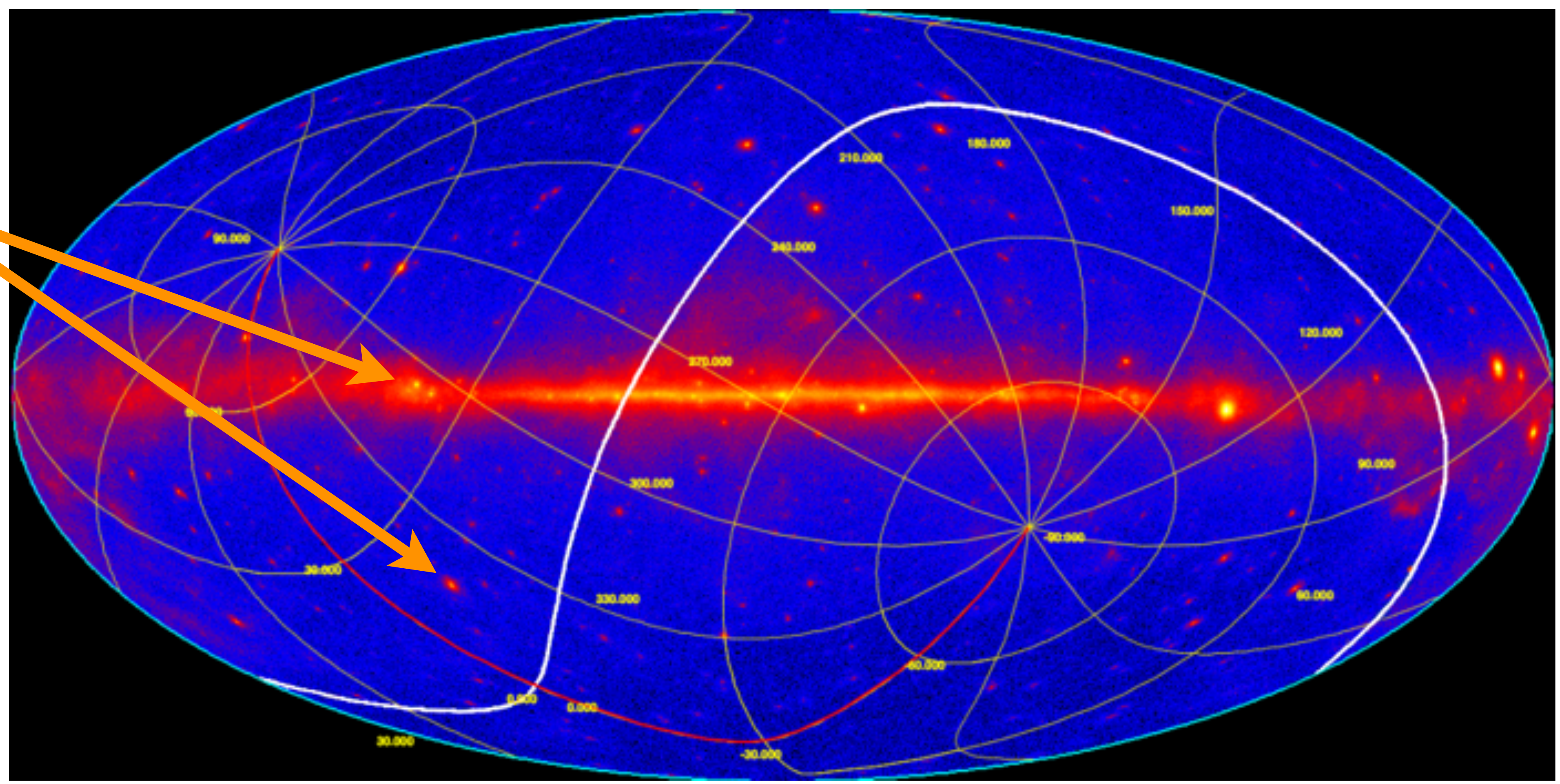
Sources:
- Galactic and Extra-Galactic
-“Constant”
-Variable
    -Regularity (Pulsars)



Features of the Sky

Sources:

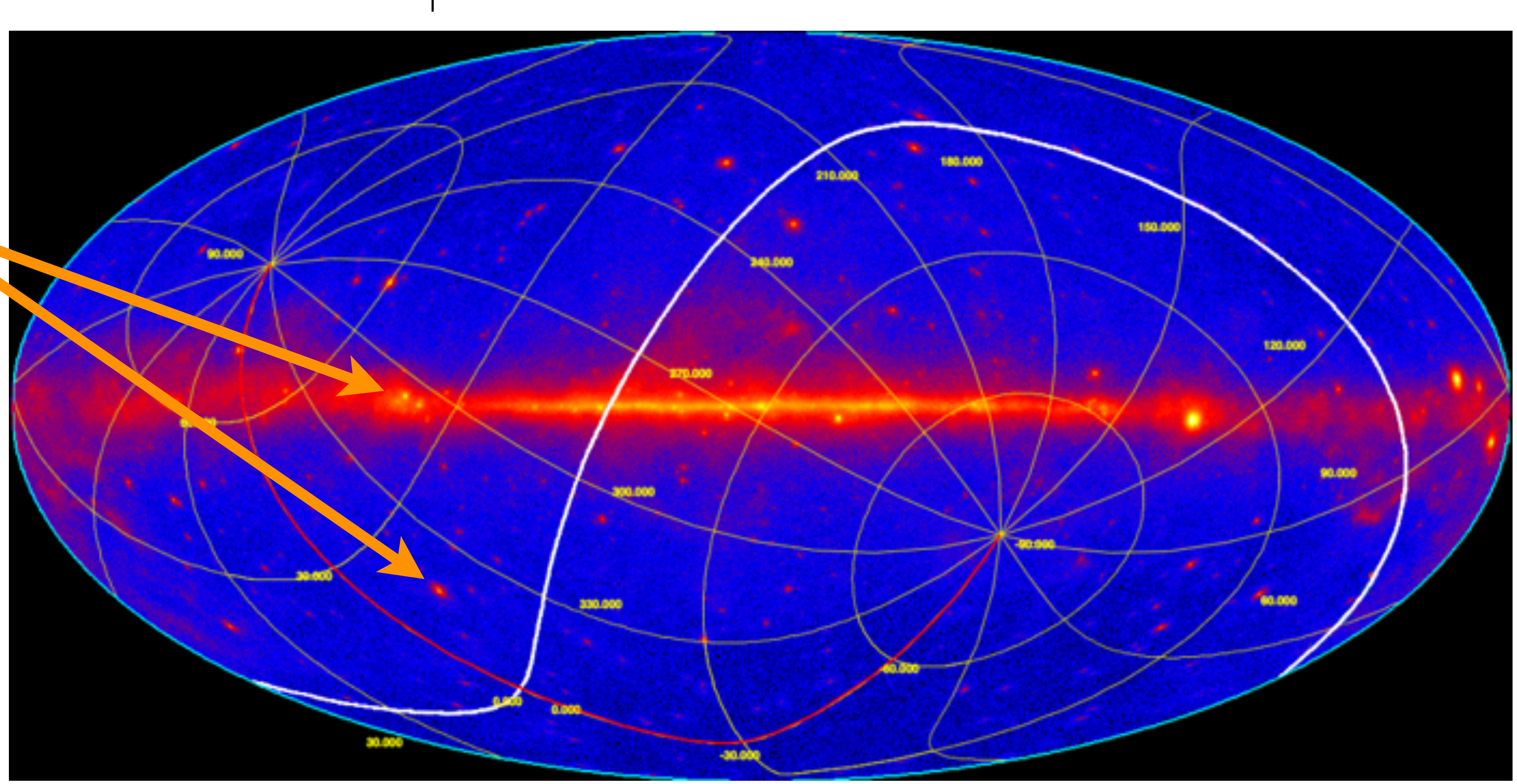
- Galactic and Extra-Galactic
- "Constant"
- Variable
    - Regularity (Pulsars)
    - Flaring (AGN)



Features of the Sky

Sources:

- Galactic and Extra-Galactic
-“Constant”
-Variable
    -Regularity (Pulsars)
    -Flaring (AGN)
-Transient:



Features of the Sky

Sources:
- Galactic and Extra-Galactic
- "Constant"
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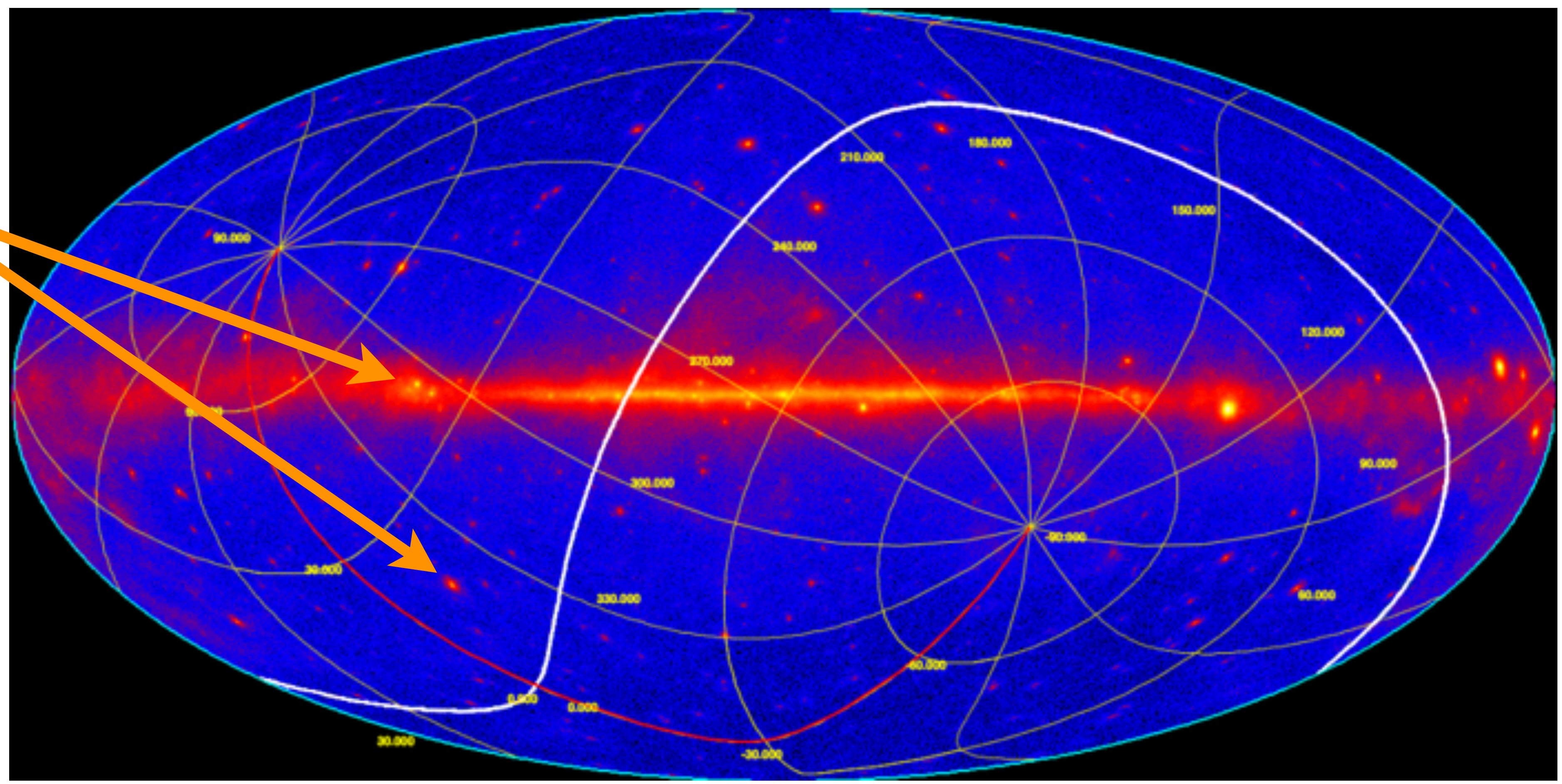
  - Flaring (AGN)
- Transient:
  - One time events (GRBs)



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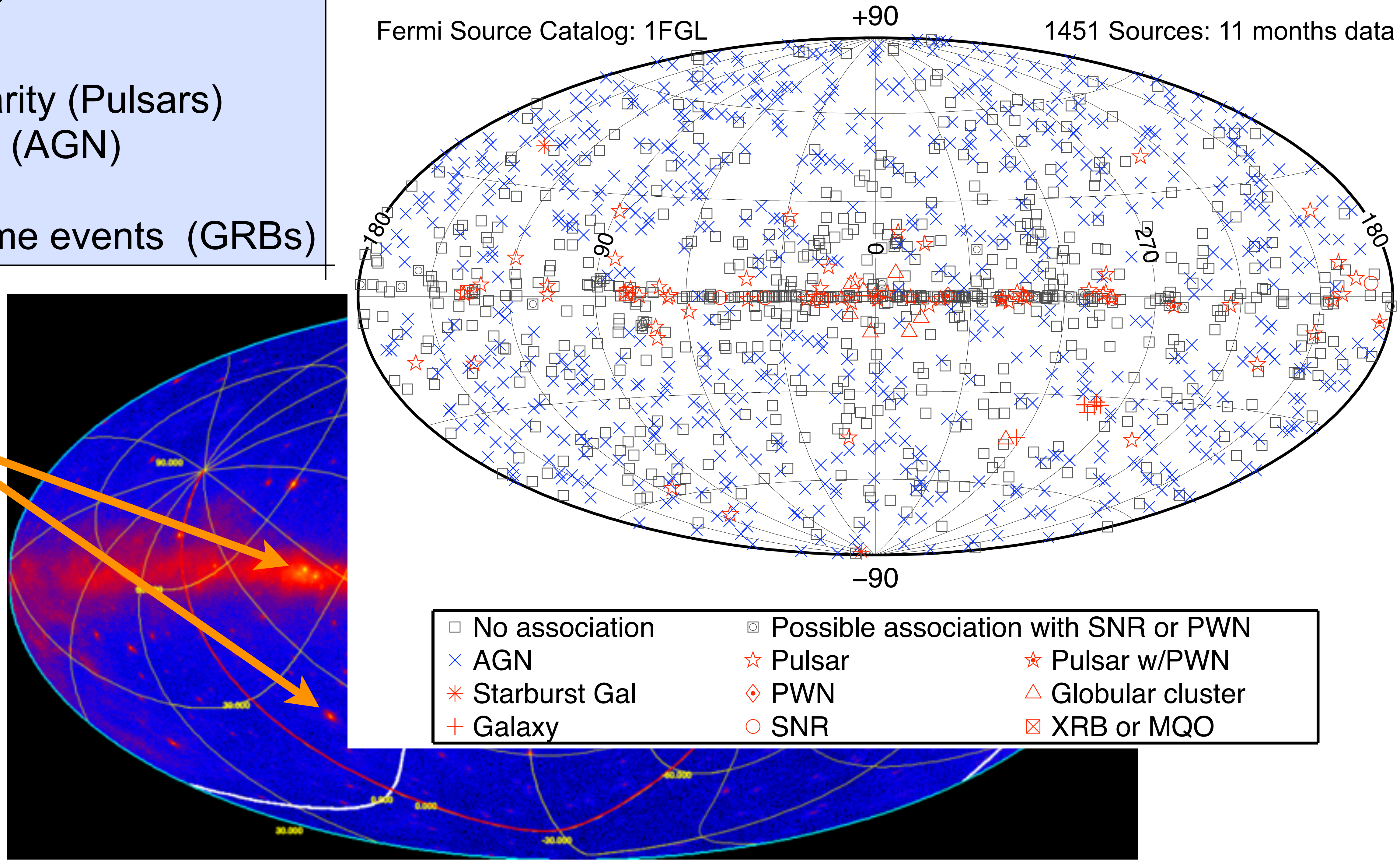

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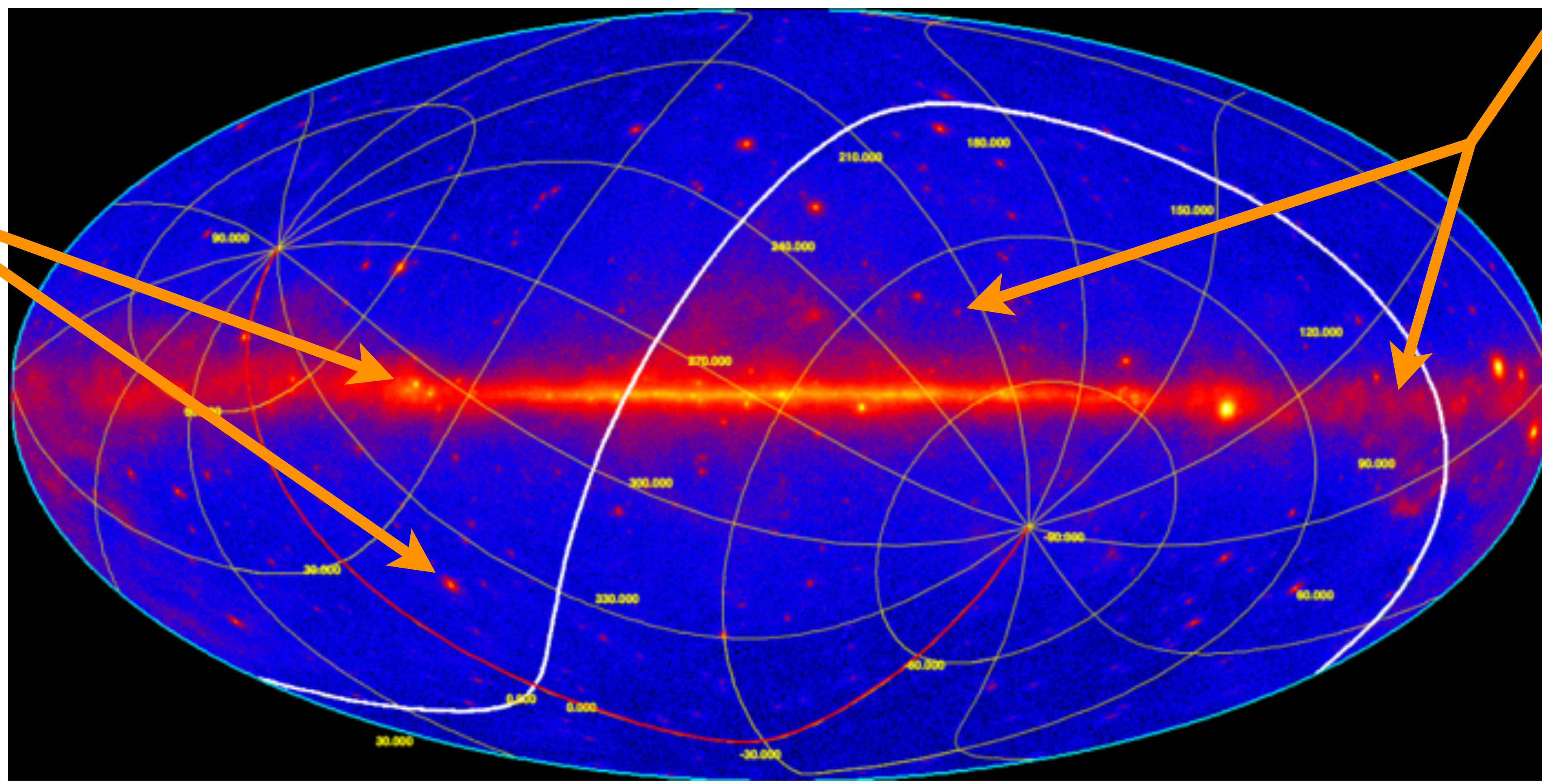
Diffuse Emission:



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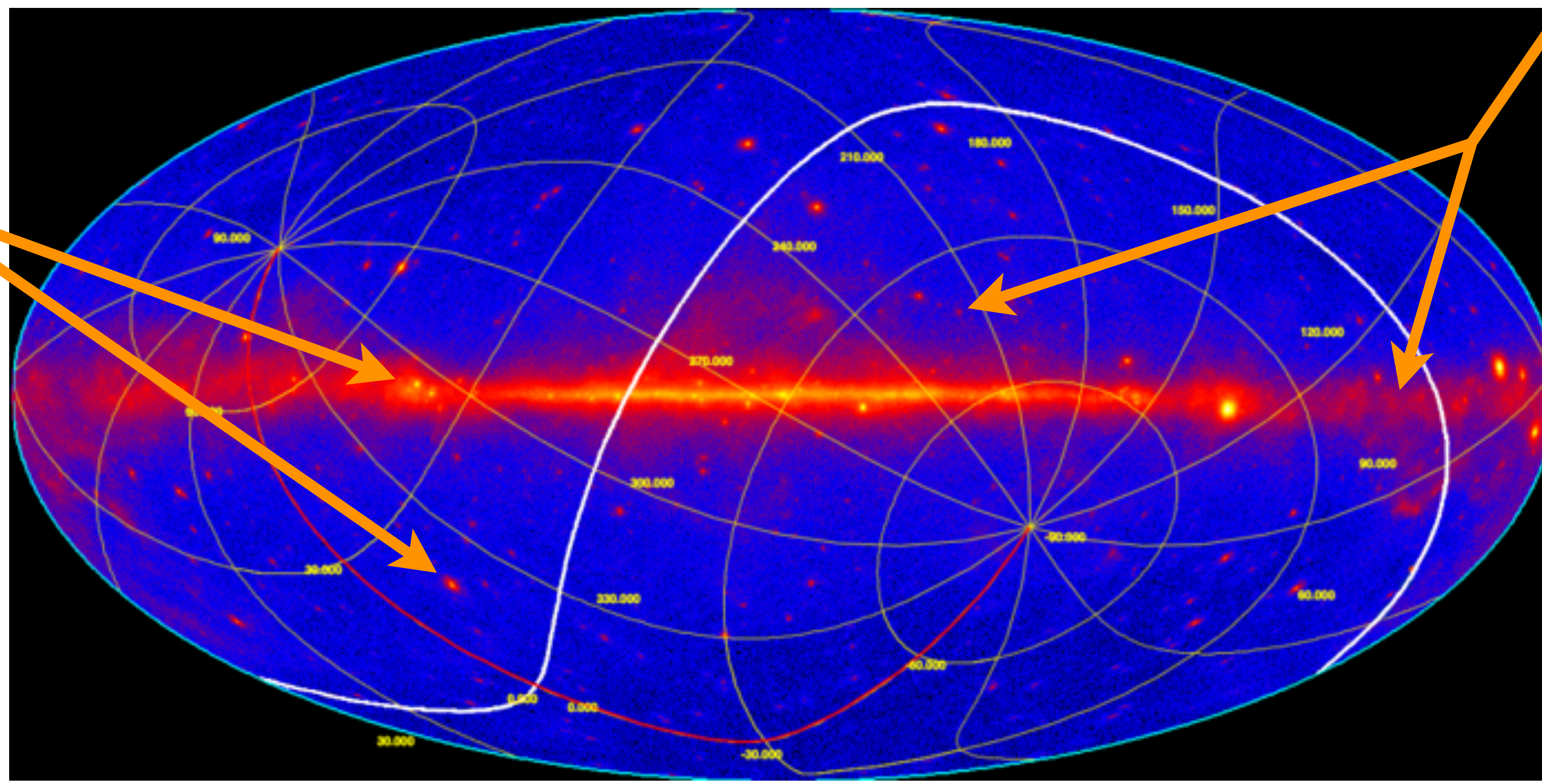
Diffuse Emission:
- Galactic and Extra-Galactic



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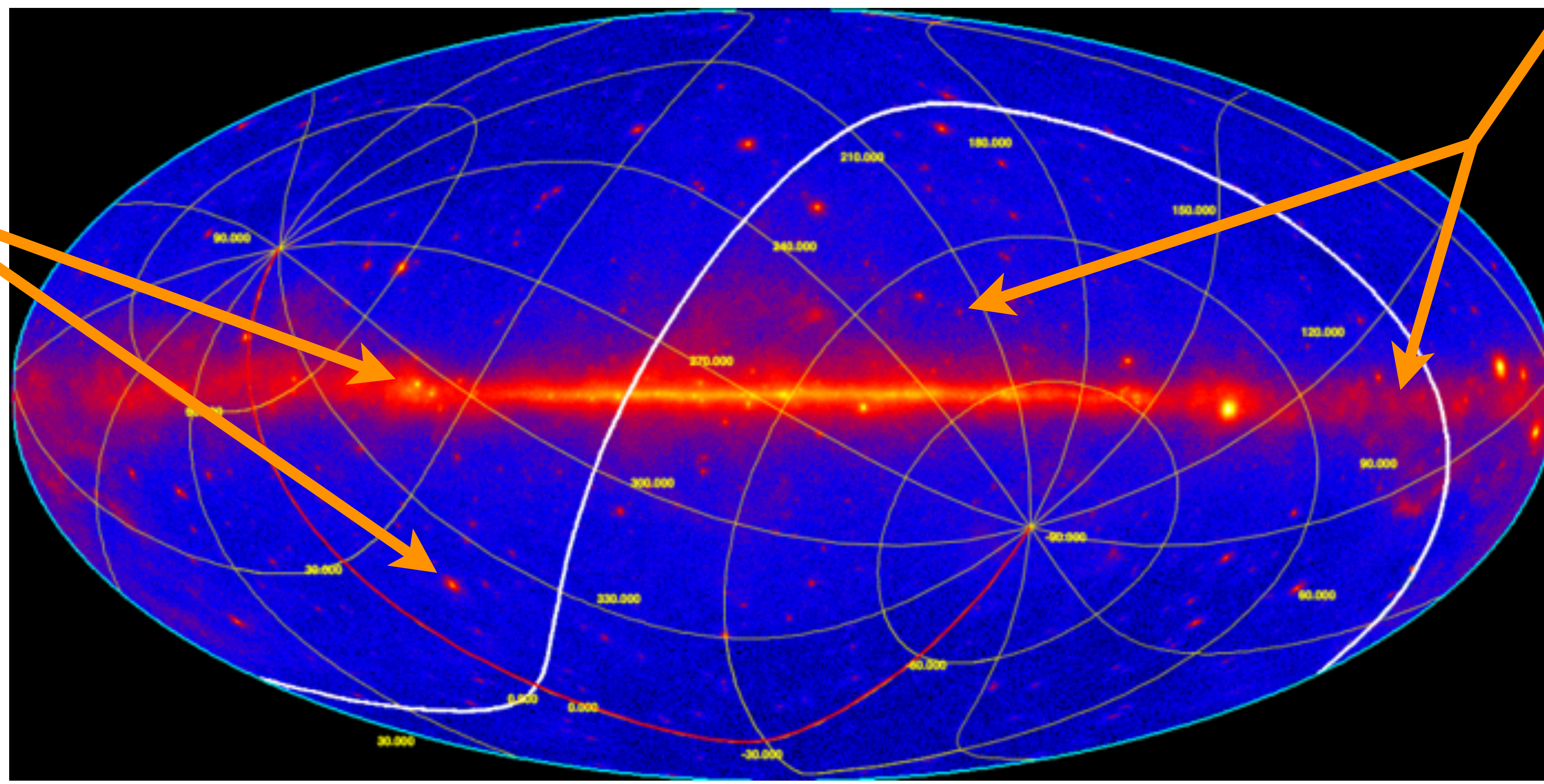
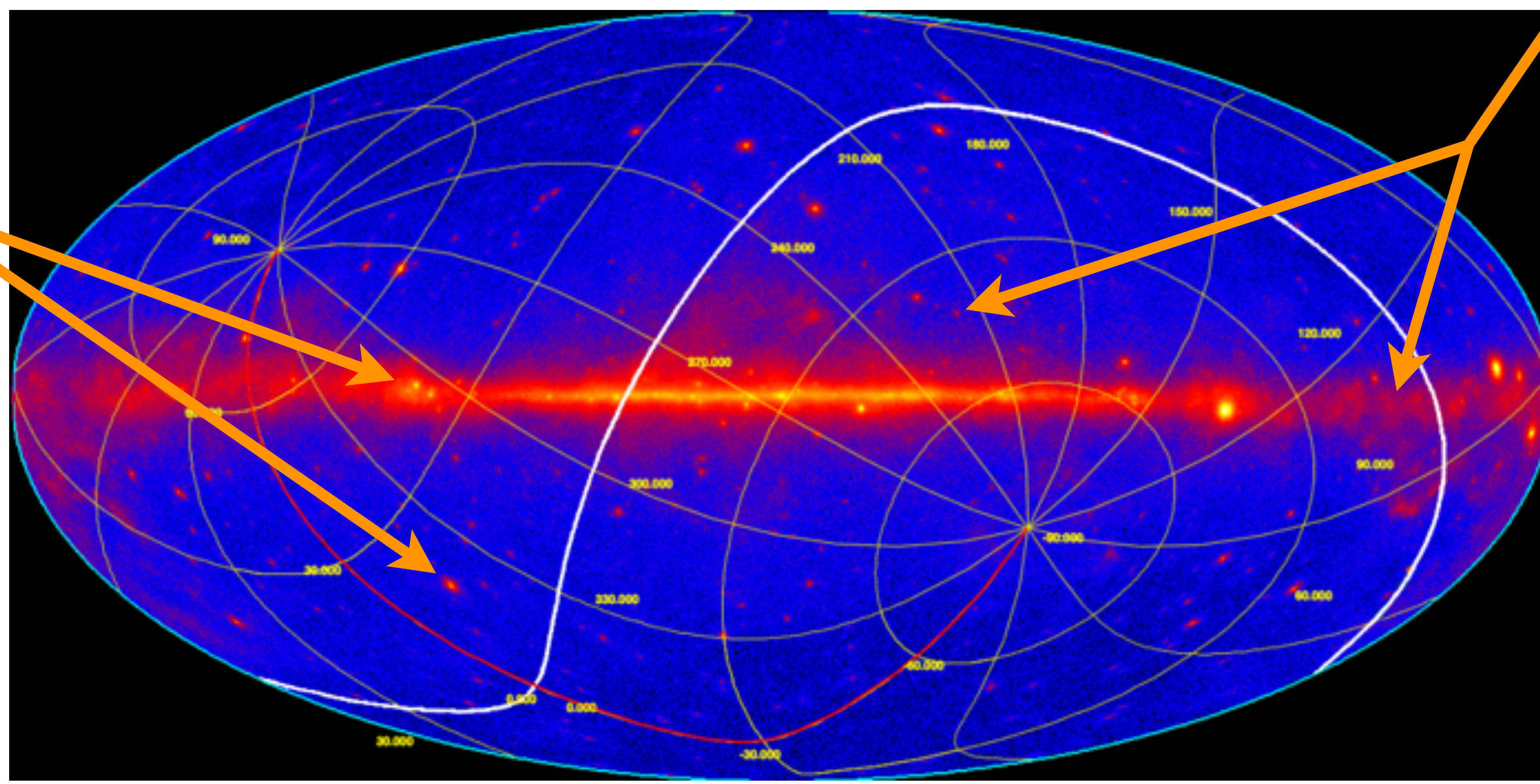
Diffuse Emission:
- Galactic and Extra-Galactic
- Cosmic-ray Interaction with



Features of the Sky

Sources:
- Galactic and Extra-Galactic
-“Constant”
-Variable
    -Regularity (Pulsars)
    -Flaring (AGN)
-Transient:
    -One time events (GRBs)

Diffuse Emission:
- Galactic and Extra-Galactic
- Cosmic-ray Interaction with
    - material (dust, gas)



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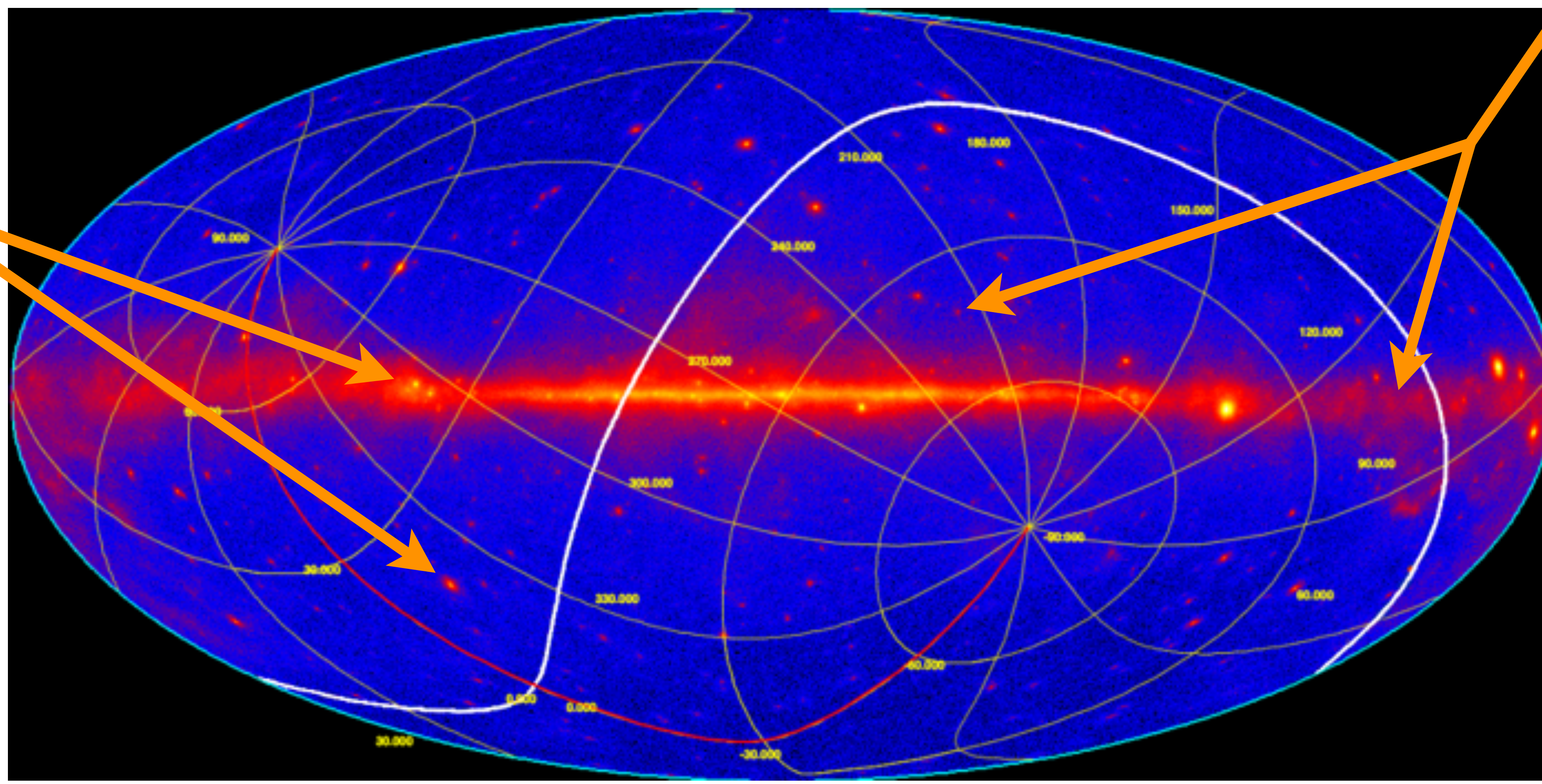

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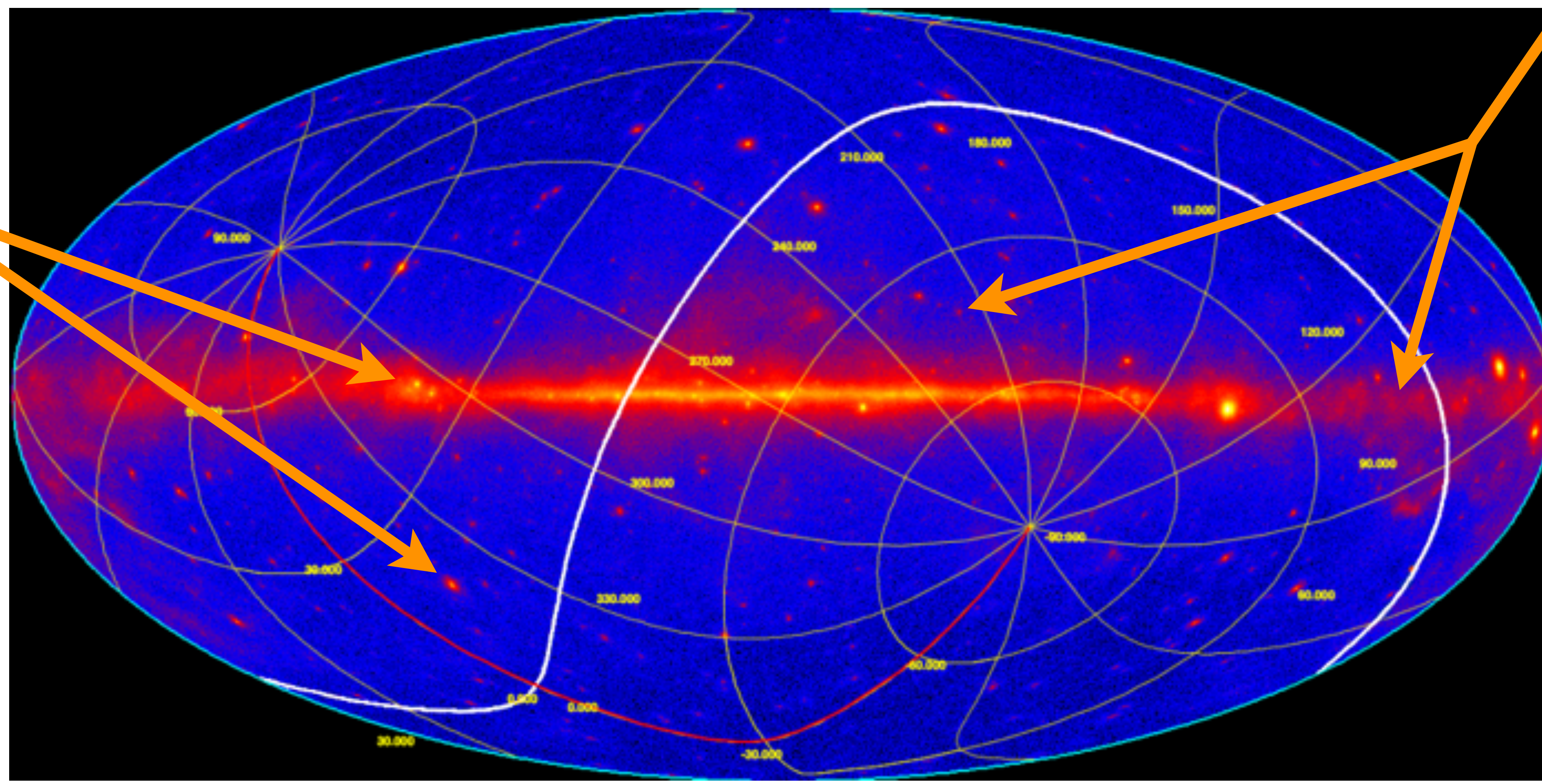
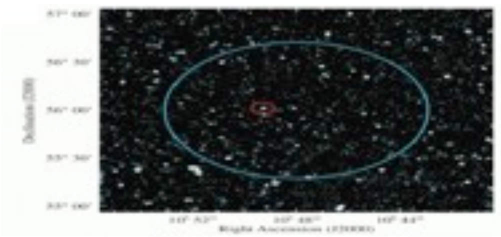
- Dark Matter Annihilation or decay???

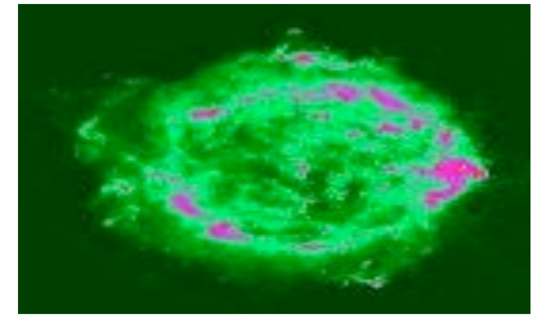


Fermi Science

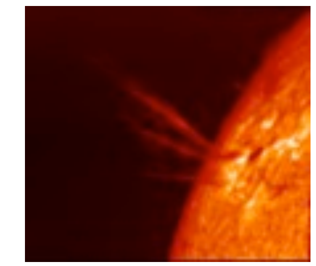


Unidentified sources

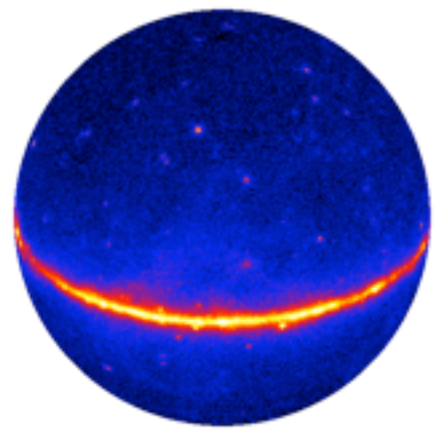
Active Galactic Nuclei

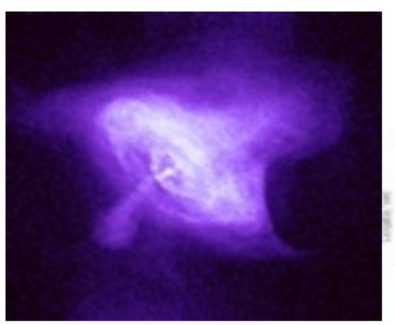


Cosmic ray acceleration

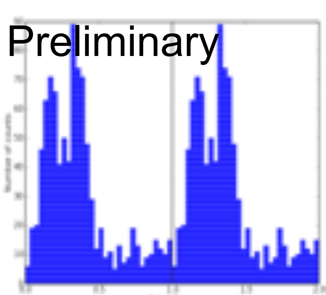


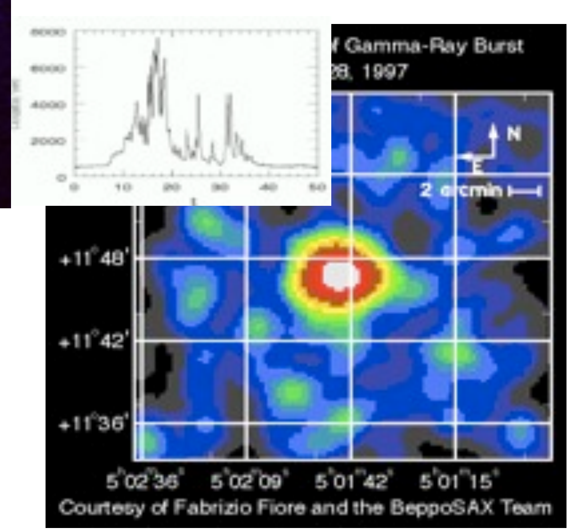
Solar flares



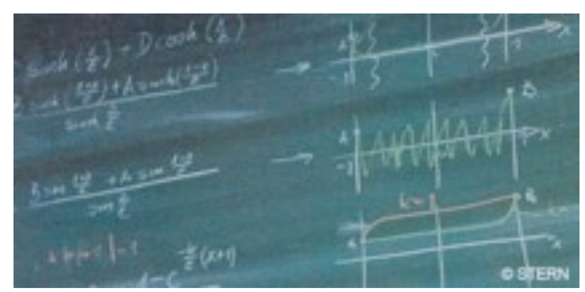


Pulsars





Gamma Ray Bursts

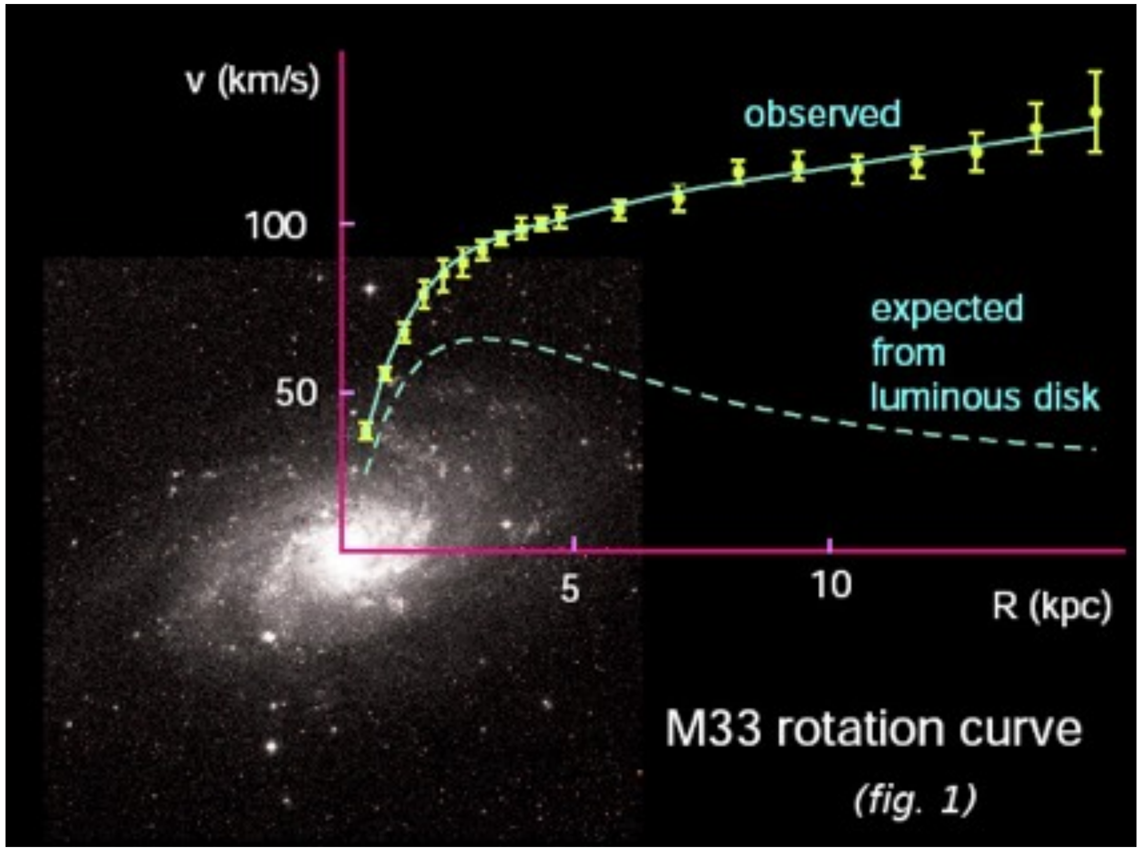


Quantum Gravity?

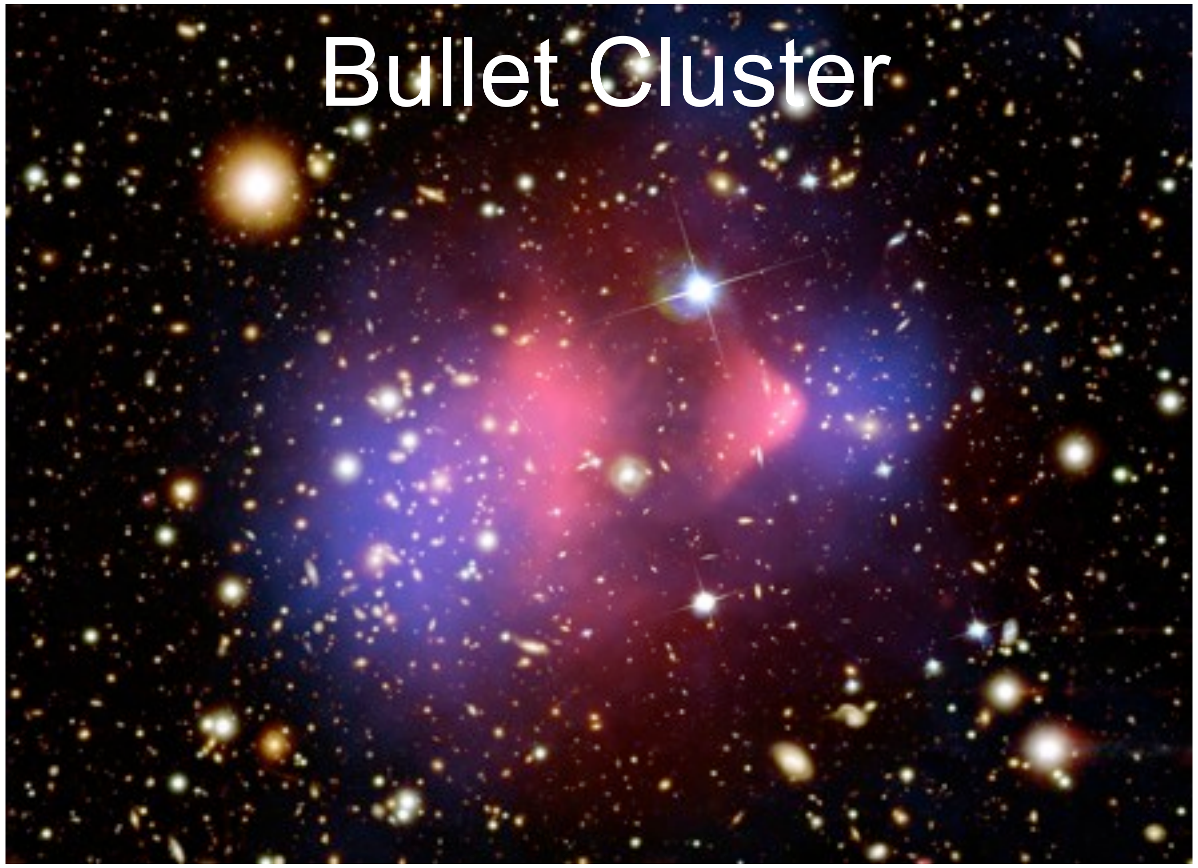
Dark matter

The Dark Side...

- The universe seems to be composed of ~23% dark matter.
- Candidate:
  Weakly Interacting Massive Particle
- WIMP might decay or self-annihilate
- Could lead to gamma-rays.

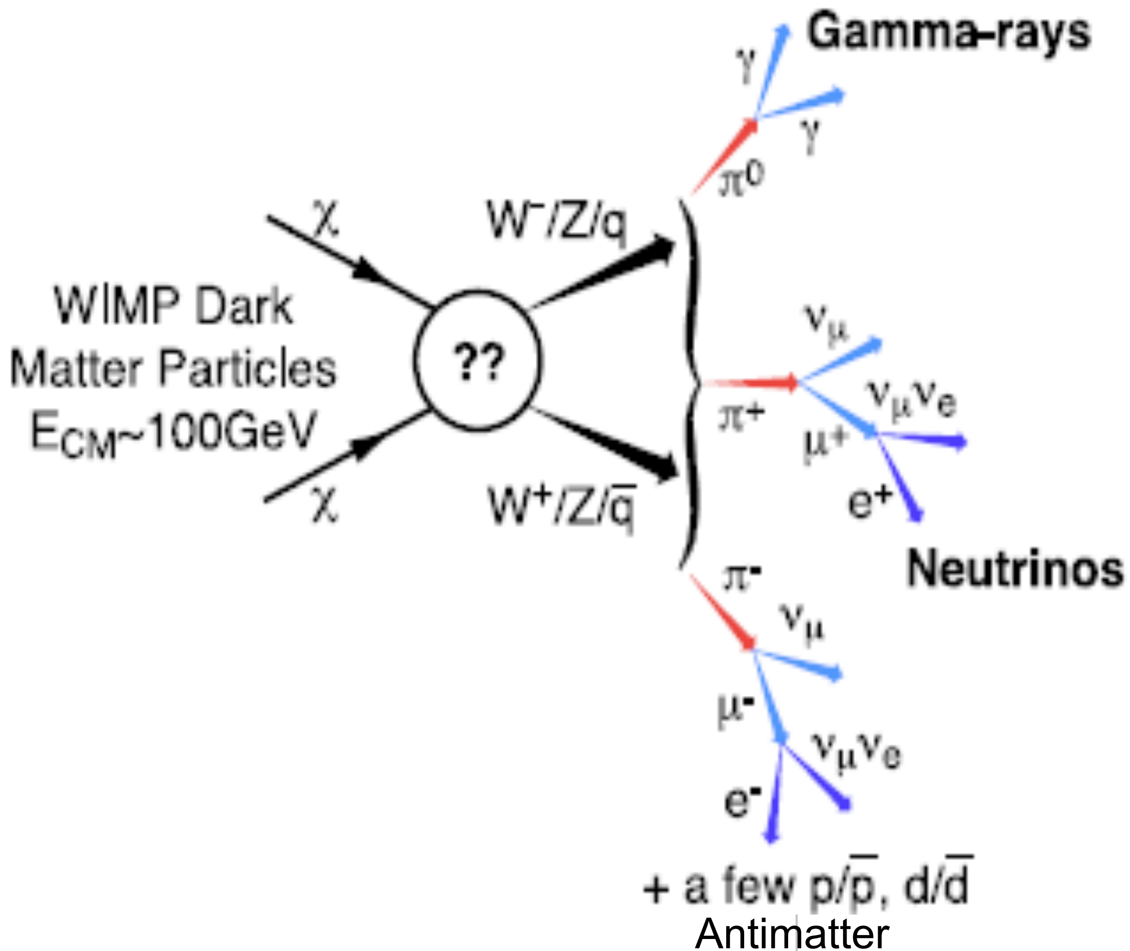


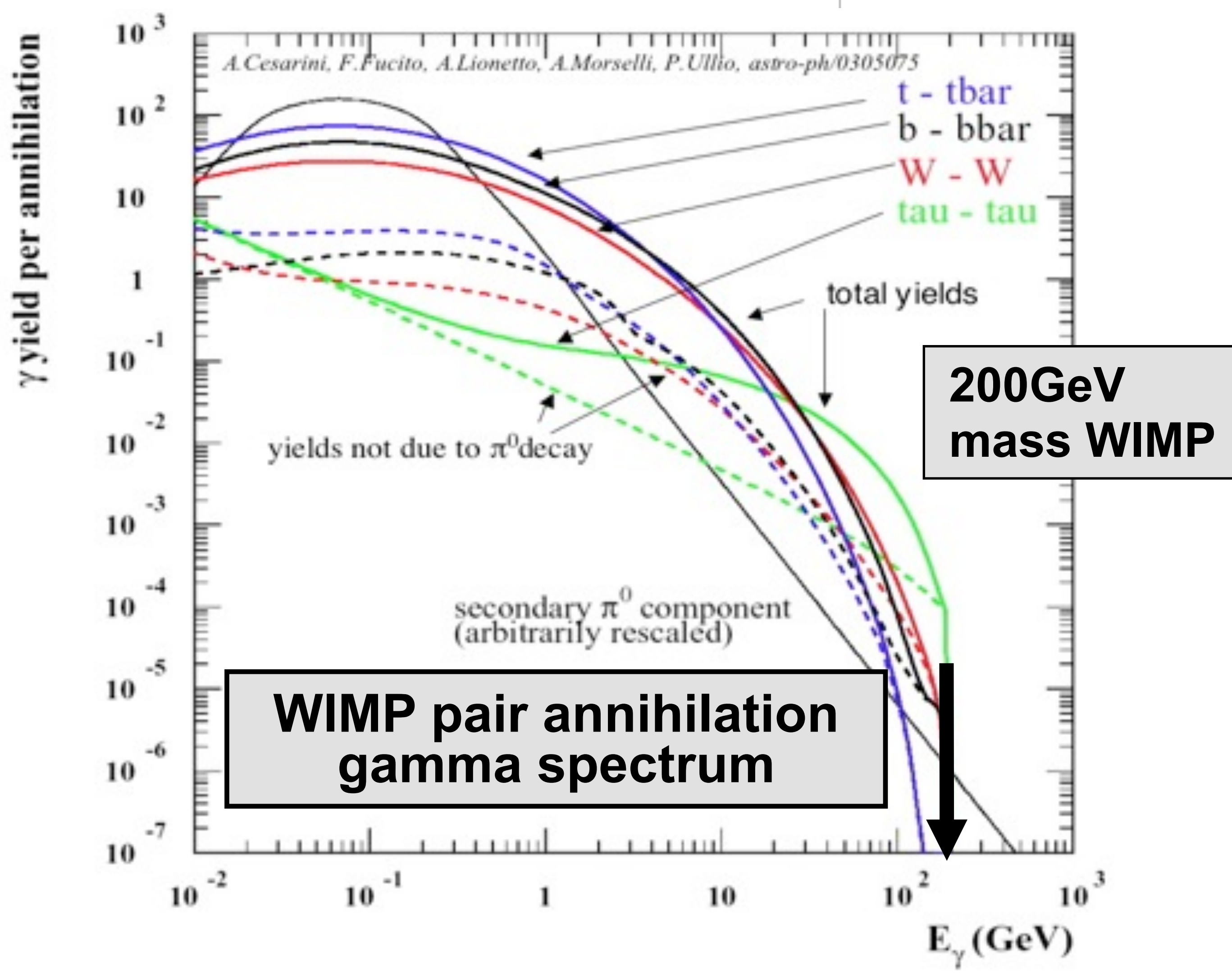
www4.nau.edu/

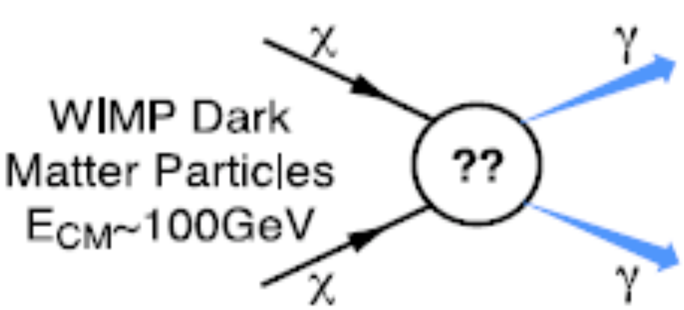


Chandra/Hubble

WIMP Annihilation







Gamma ray yield per final state $b\bar{b}$

M_{WIMP}	Total# γ	>100MeV	>1GeV	>10GeV
10 GeV	17.3	12.6	1.0	0
100GeV	24.5	22.5	12.4	1.0
1TeV	31.0	29.3	22.4	12.3

Spectral shape & flux magnitude

γ-ray flux factors

$\int(\sum_i dN/dE\ B_i)dE$
x
$4\pi \int\rho^2(r)r^2dr / M^2_{WIMP}$
x
$<\sigma v> / 2$
x
$1/4\pi d^2$

Energy spectrum
(depends upon particle mass, branching fractions)

x

number density²
(depends upon dark matter clustering)

x

annihilation cross-section
(depends upon underlying particle physics, inflation…)

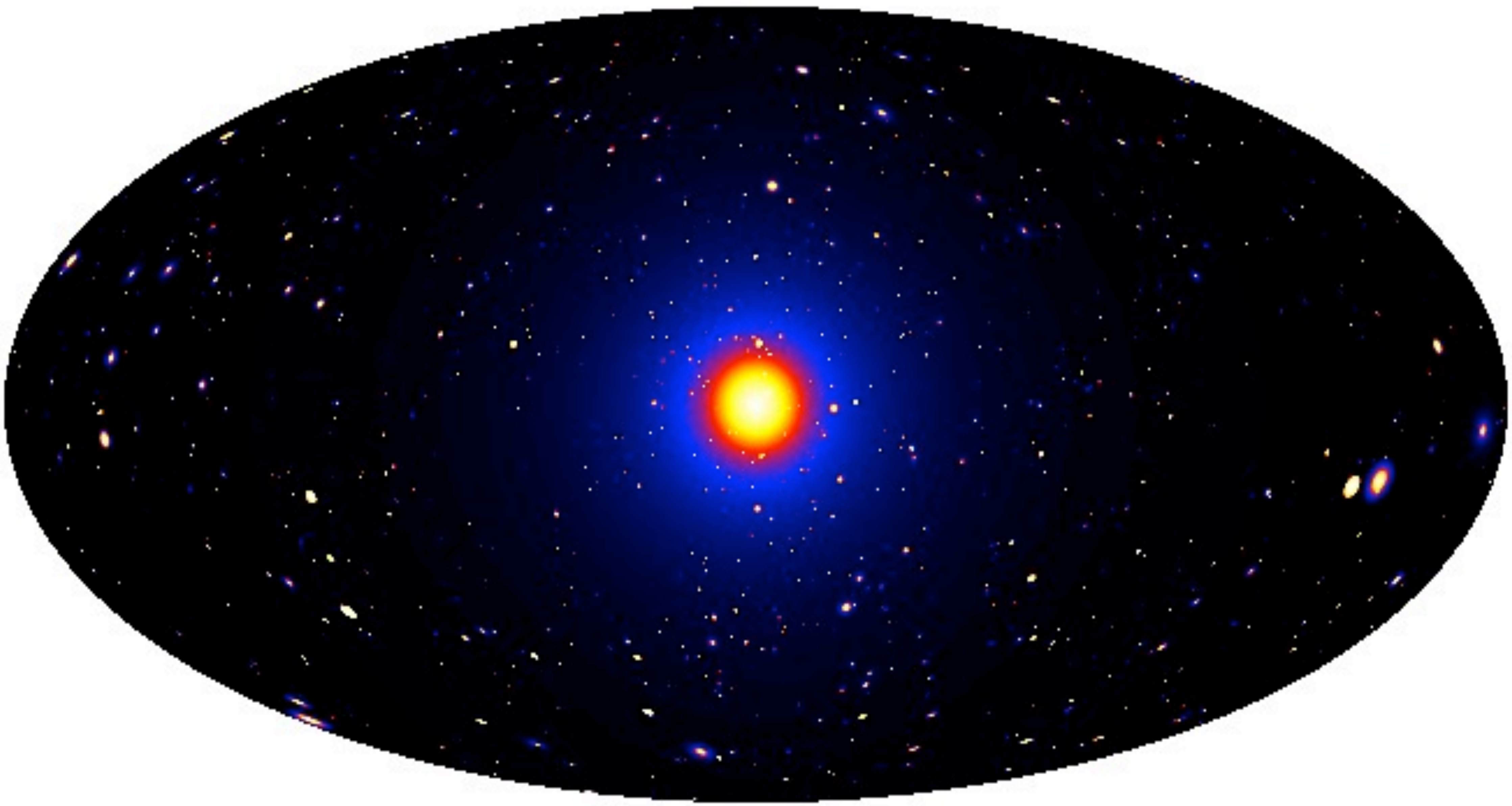
x

distance⁻²
(depends upon dark matter clustering)

Spectral shape: Universal

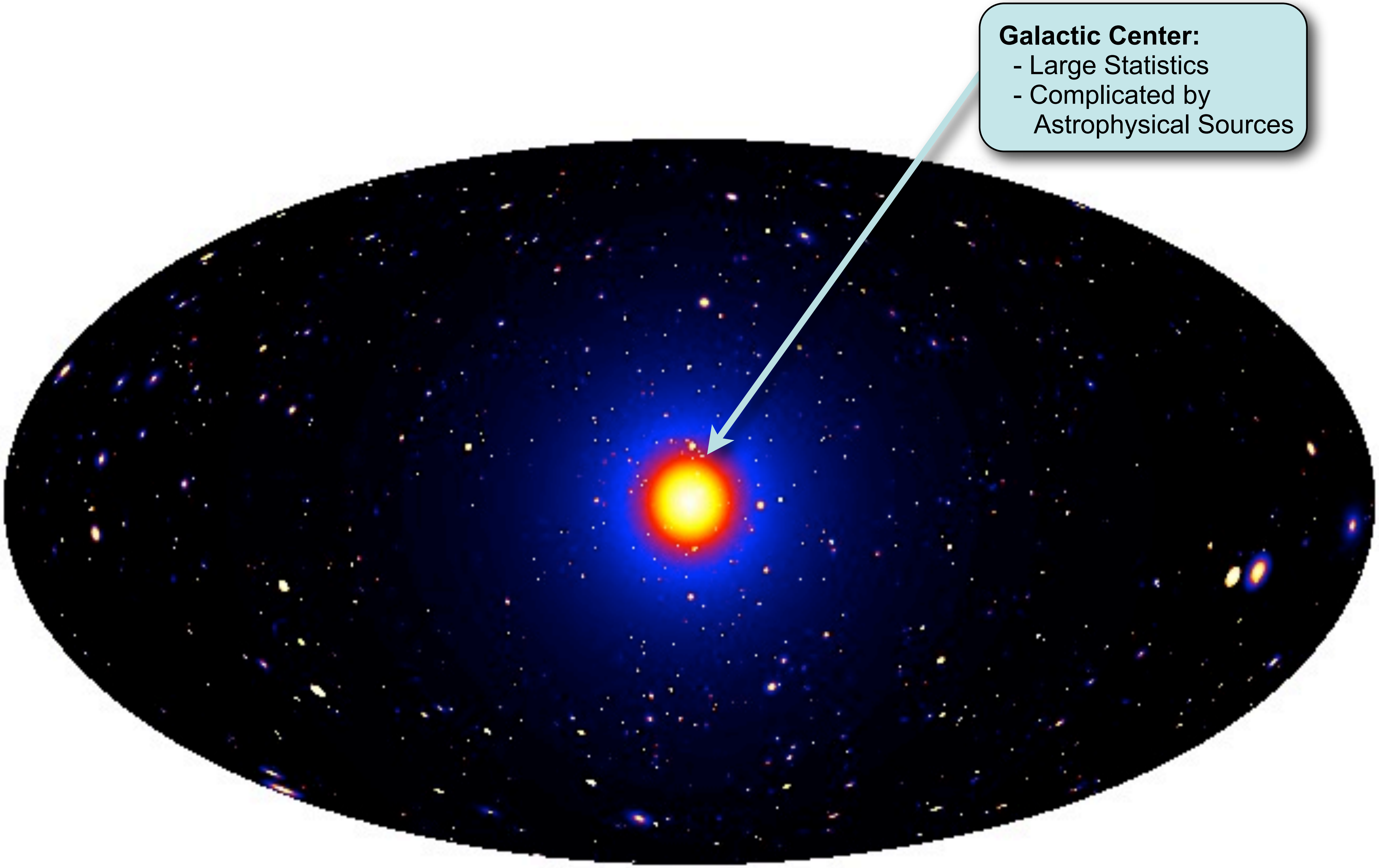
Flux magnitude: *Factors difficult to disentangle for single point source*

Targets in the DM Sky



Milky Way Halo simulated by Taylor & Babul (2005)

All-sky map of DM gamma ray emission (Baltz 2006)



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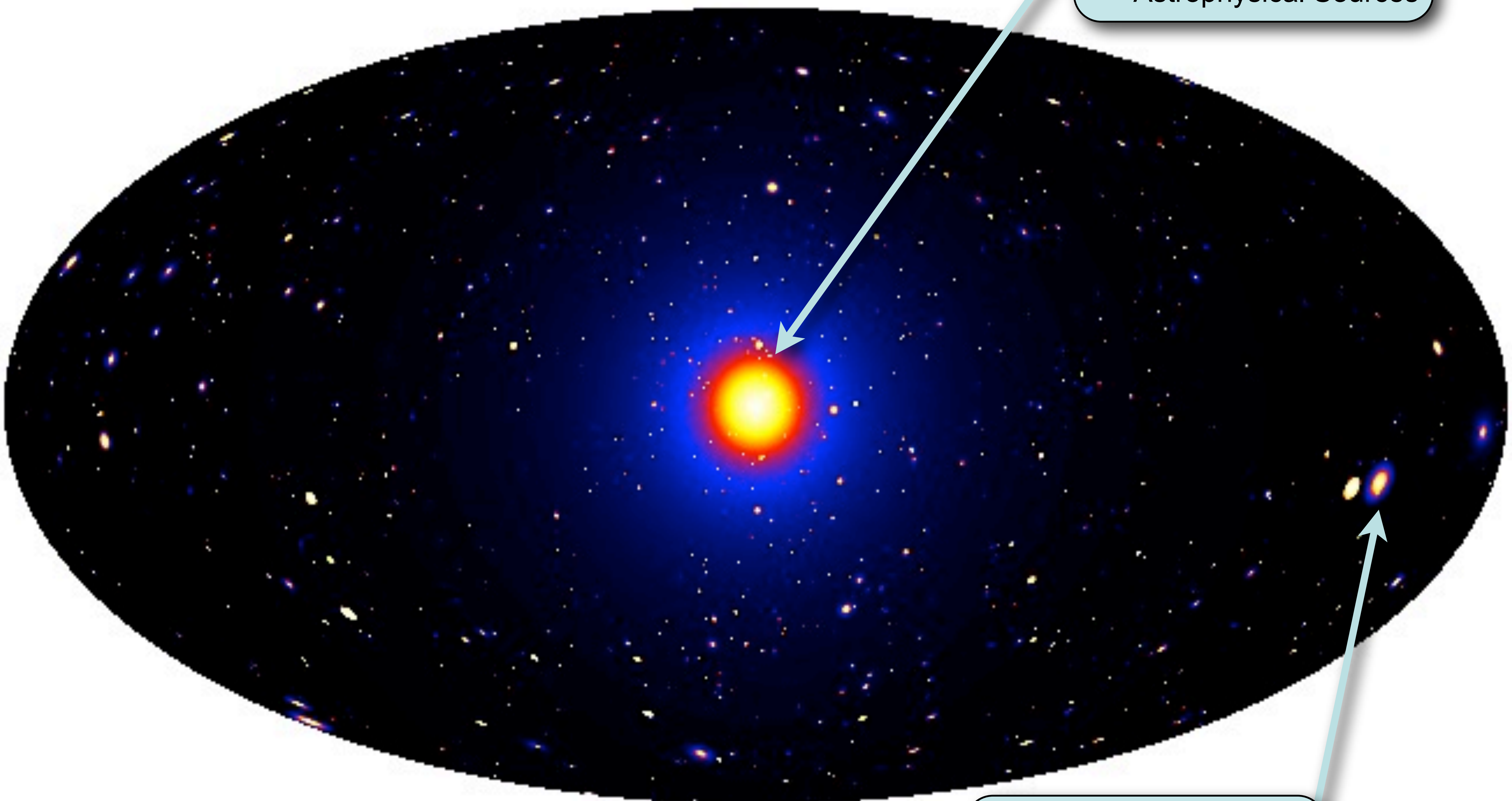

Galactic Center:
- Large Statistics
- Complicated by Astrophysical Sources

Nearby Galaxies:
- dSph DM Enriched
- Known location
- Lower Statistics

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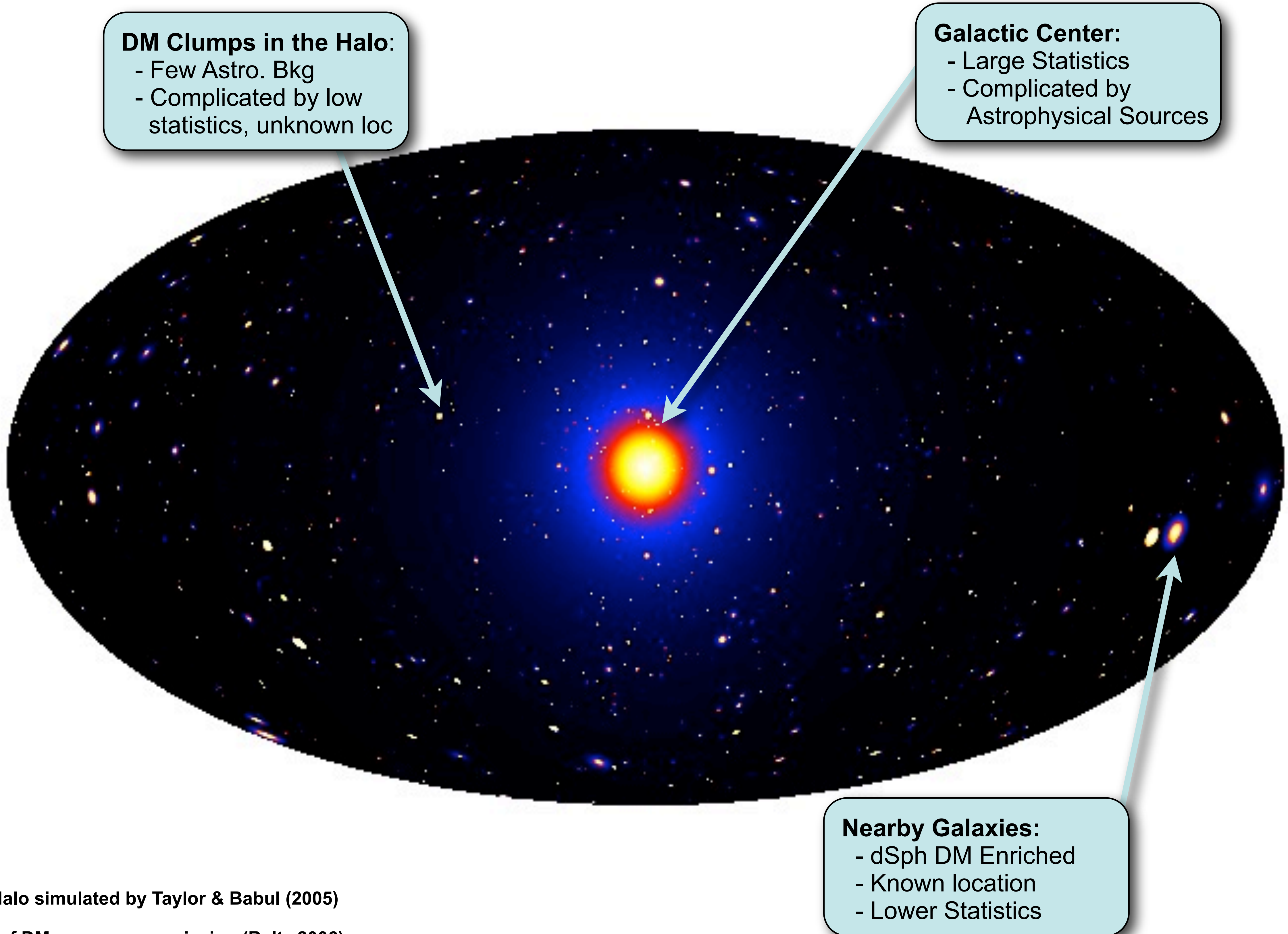

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DM Clumps in the Halo:
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- Complicated by low statistics, unknown loc

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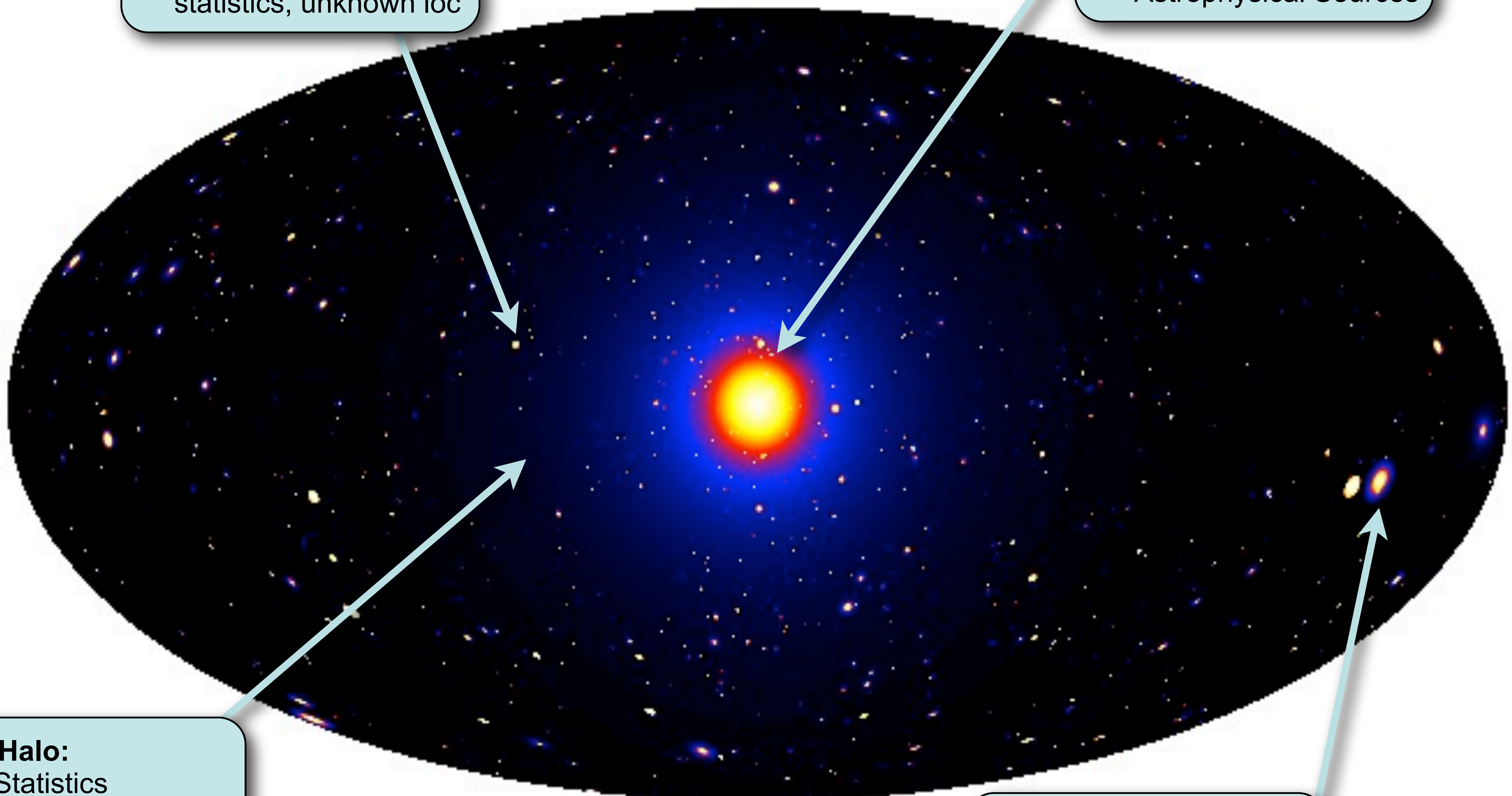

Galactic Halo:
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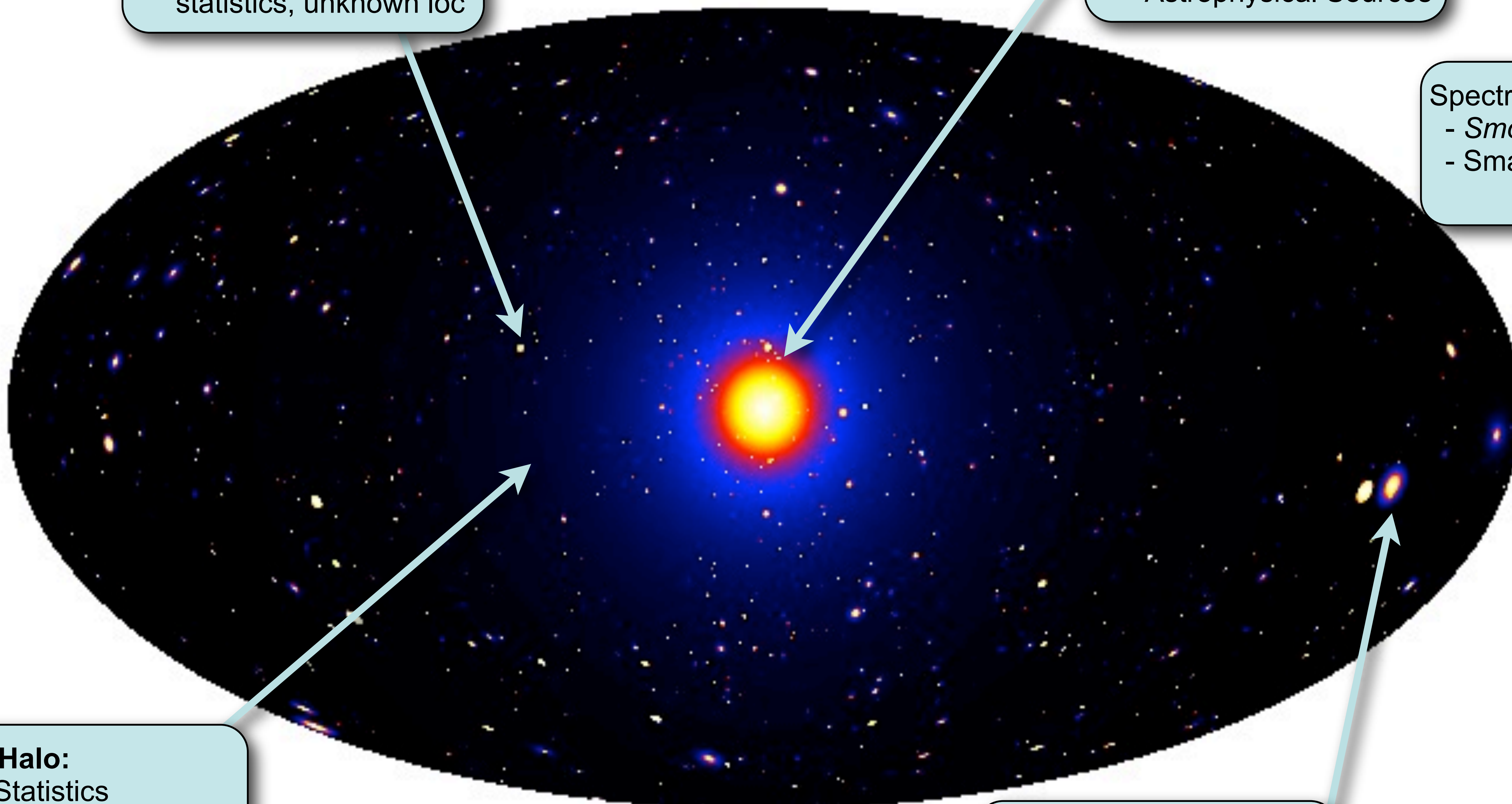
Spectral Lines:
- *Smoking Gun*
- Small Stat.



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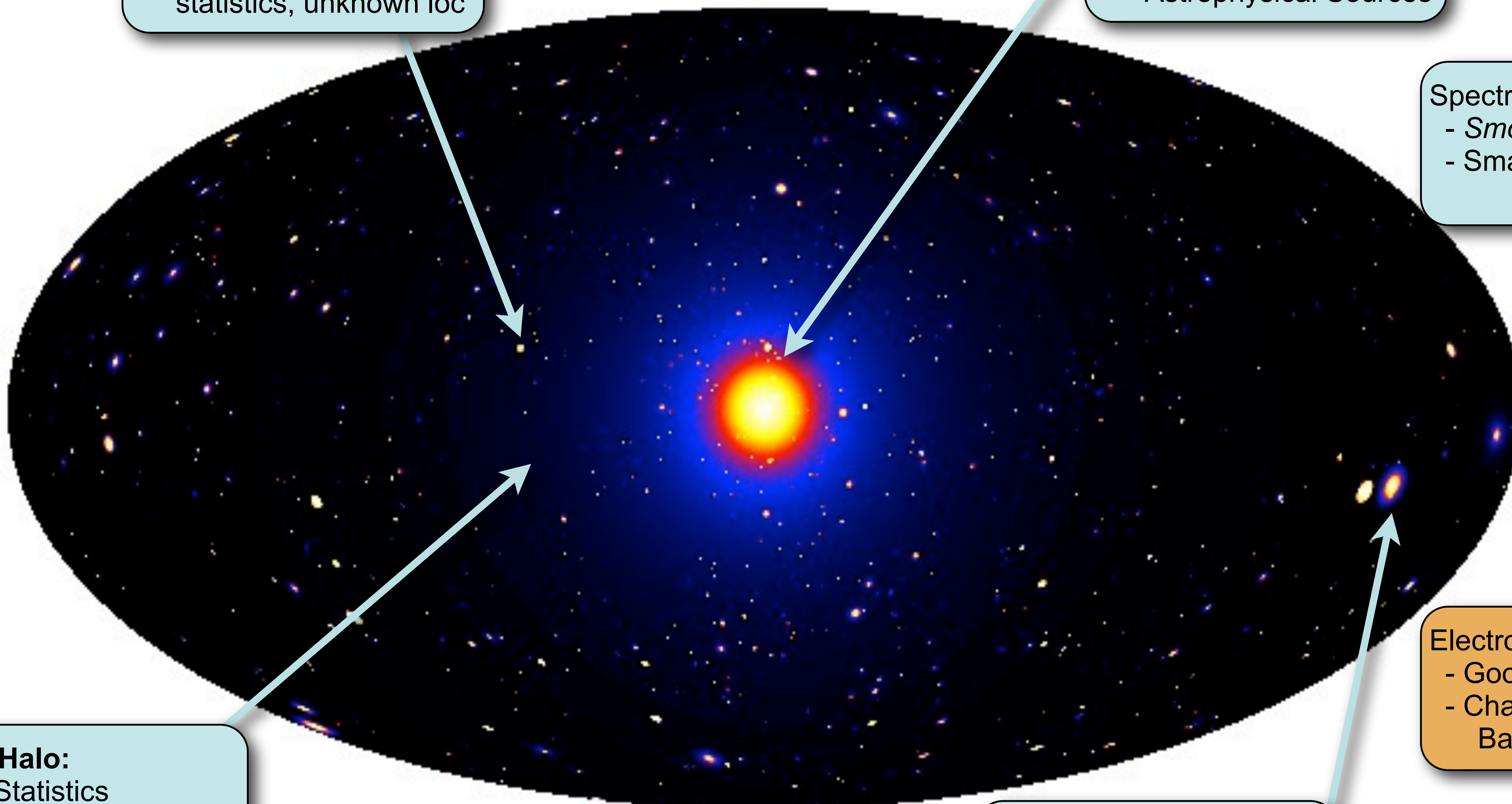


Electrons:
- Good Stats.
- Challenge: Backgrounds

Galactic Halo:
- Large Statistics
- Complicated by diffuse Y-rays from Cosmic Rays

Nearby Galaxies:
- dSph DM Enriched
- Known location
- Lower Statistics

Milky Way Halo simulated by Taylor & Babul (2005)

All-sky map of DM gamma ray emission (Baltz 2006)

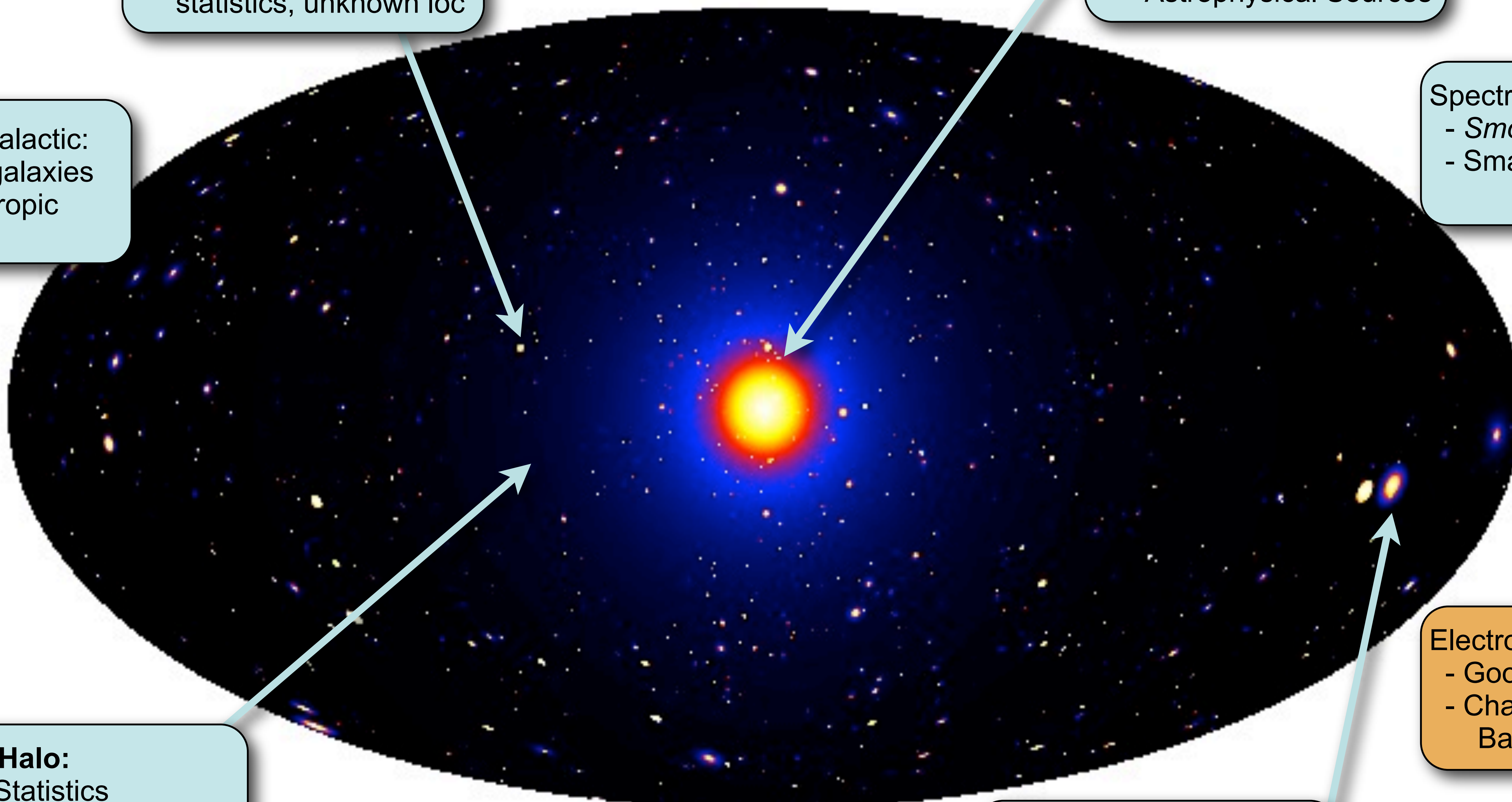
Targets in the DM Sky

DM Clumps in the Halo:
- Few Astro. Bkg
- Complicated by low statistics, unknown loc

Galactic Center:
- Large Statistics
- Complicated by Astrophysical Sources

Extragalactic:
- All galaxies
- Isotropic

Spectral Lines:
- *Smoking Gun*
- Small Stat.



Electrons:
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Galactic Halo:
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Nearby Galaxies:
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- Lower Statistics

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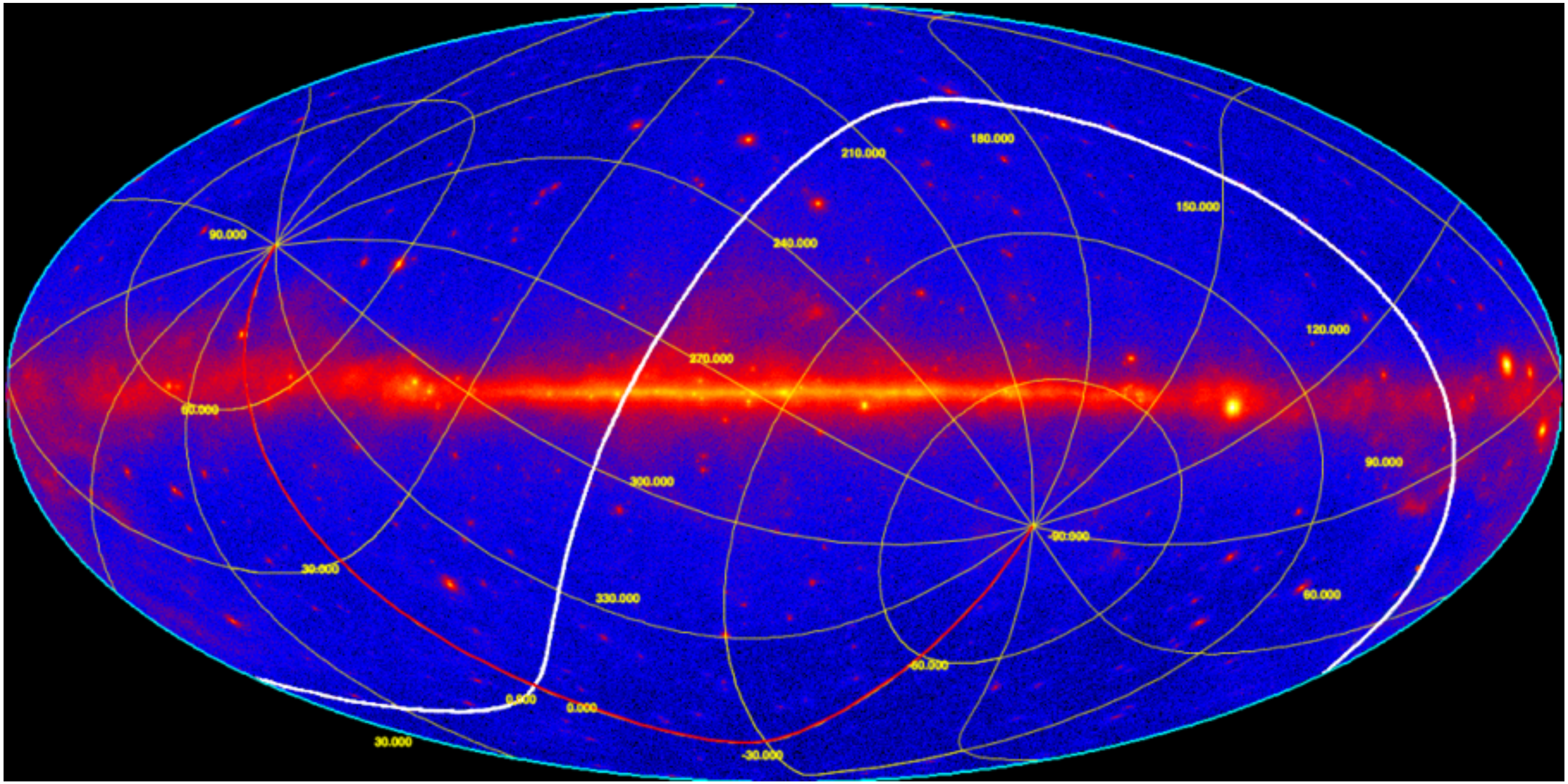
All-sky map of DM gamma ray emission (Baltz 2006)

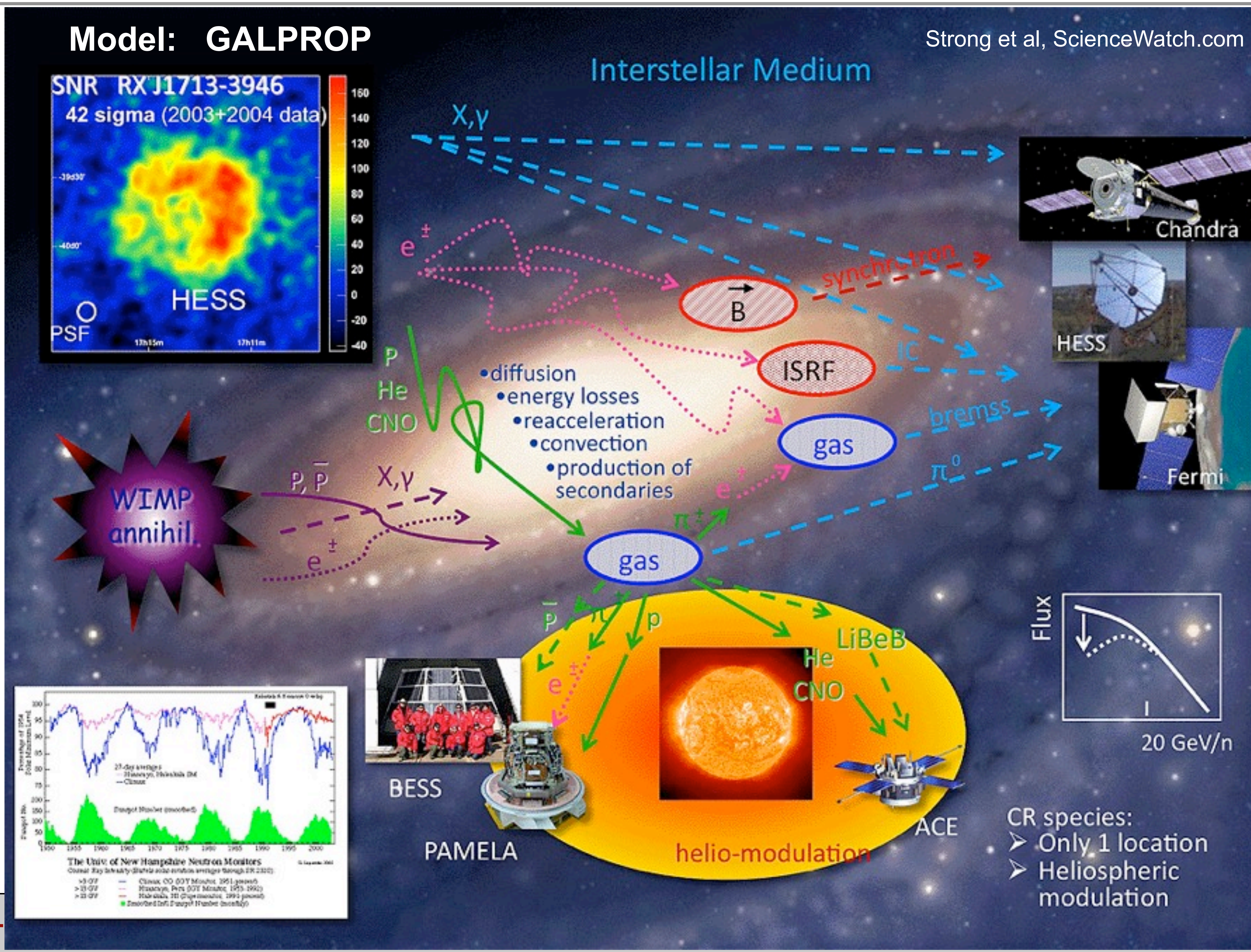
The Full Gamma-Ray Sky

All Sky View: First Year Data



Challenge: Need to account for all the gamma-rays from non-DM sources

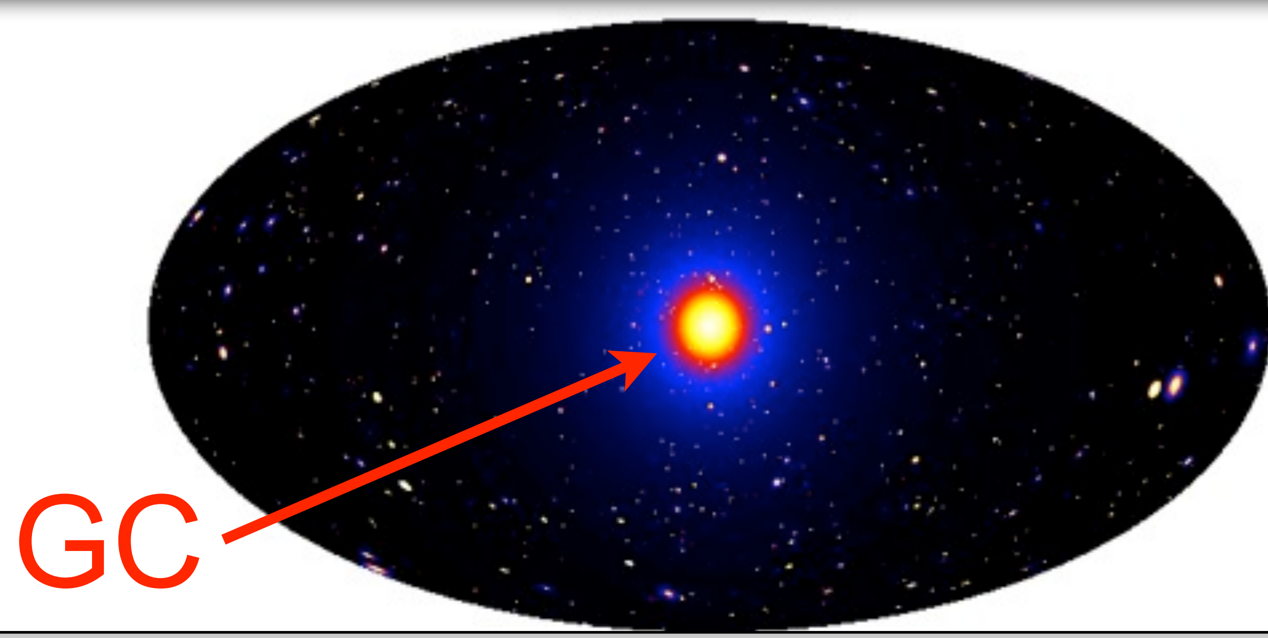
Diffuse Gamma-Ray Background

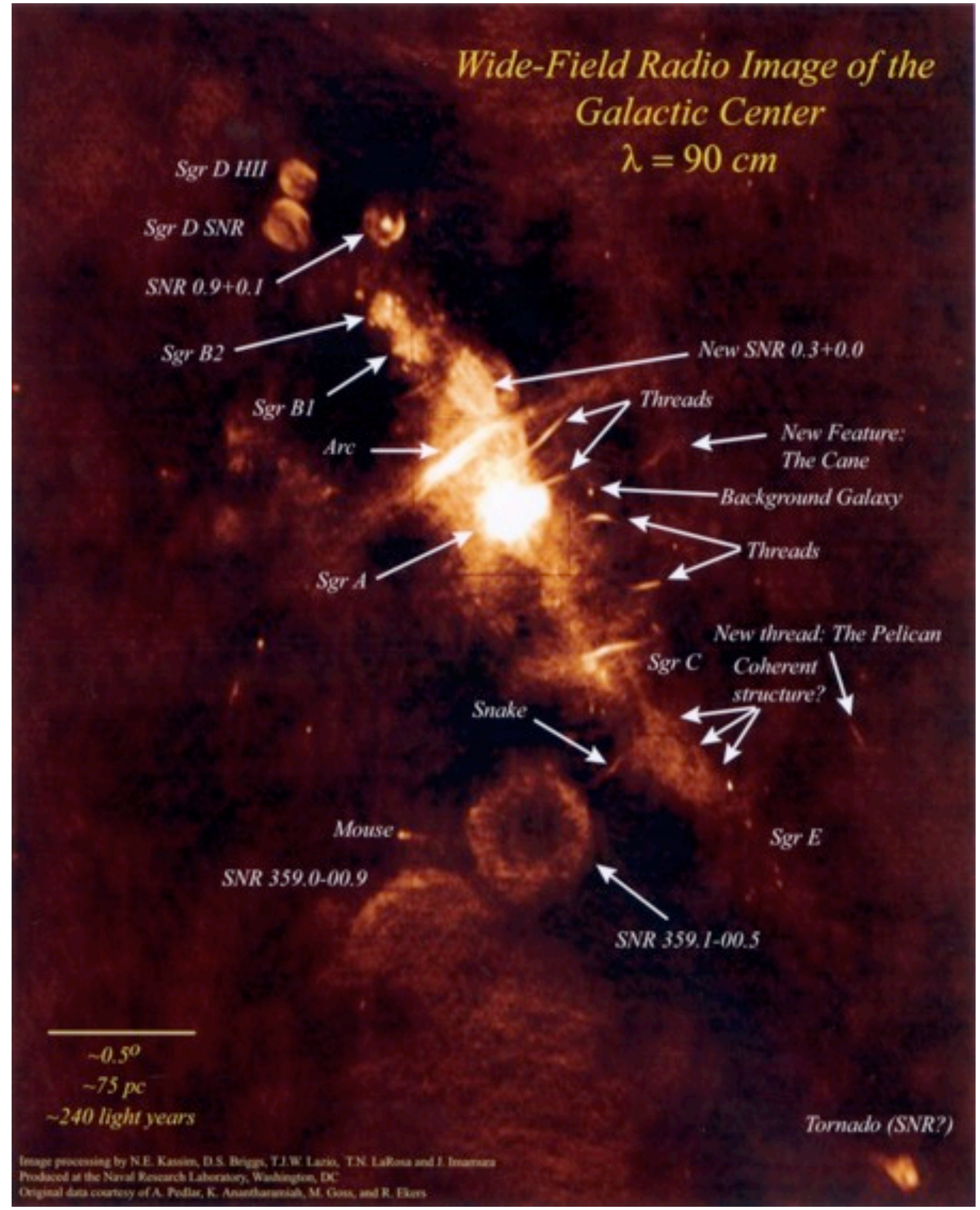


Tuesday, April 26, 2011

Galactic Center

- Highest Flux of γ-rays from DM
- Challenge: Understand Astrophysical Bkgs
  - ⋆ Source confusion
  - ⋆ Energetic Sources
  - ⋆ Diffuse Emission along line of sight.
- Analysis Approach: (arXiv 0912.3828)
  - ⋆ 7 x 7 region around GC
  - ⋆ 11 months of data (front converting)
  - ⋆ E>400 MeV





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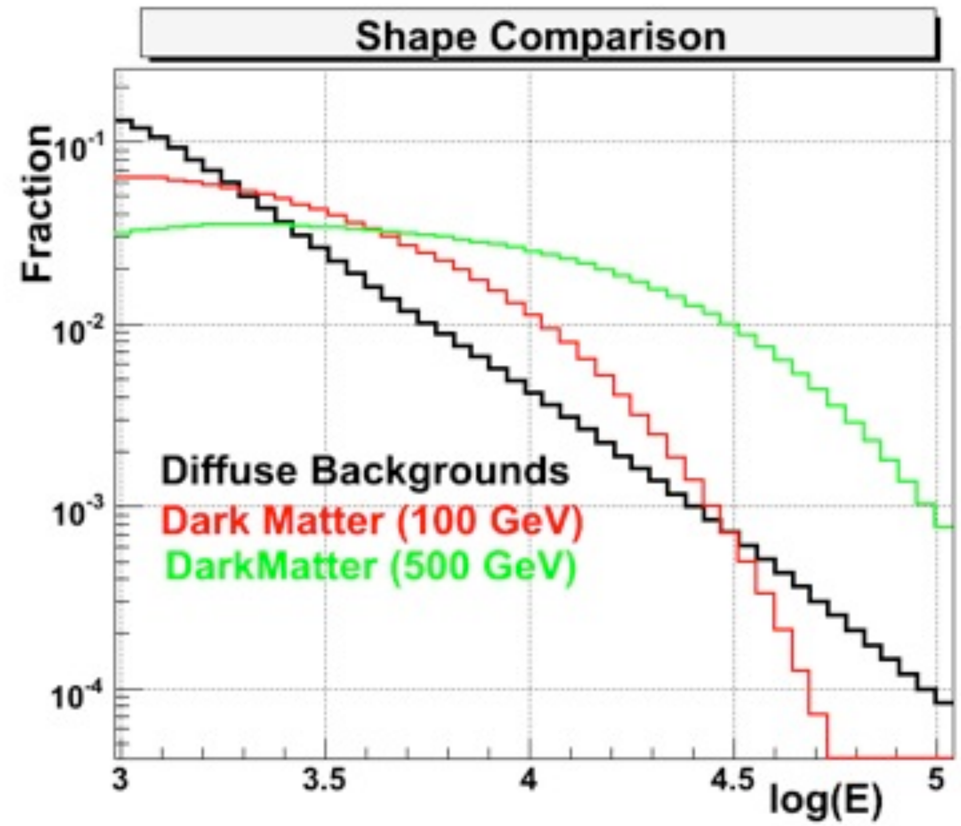

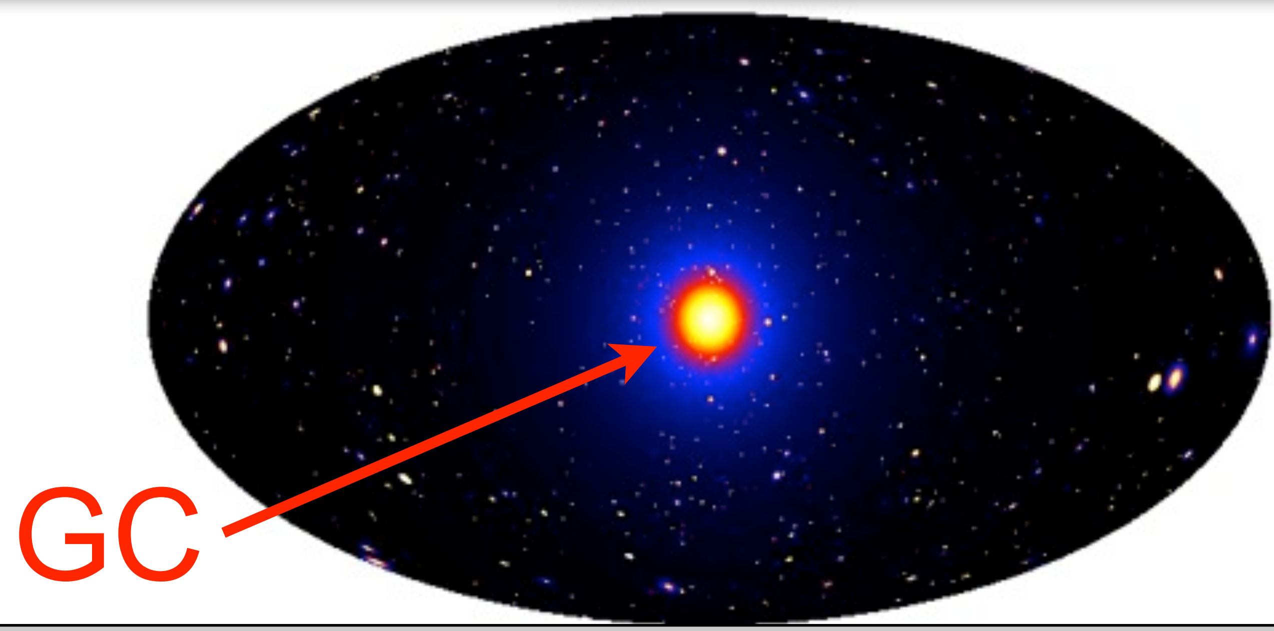

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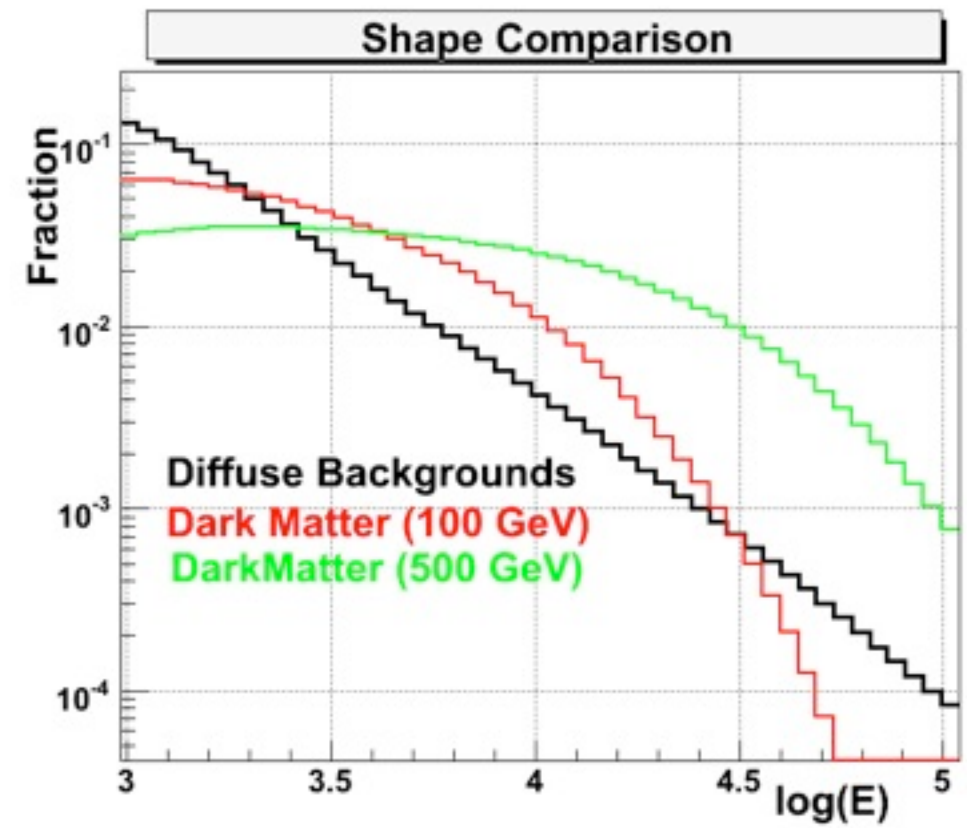

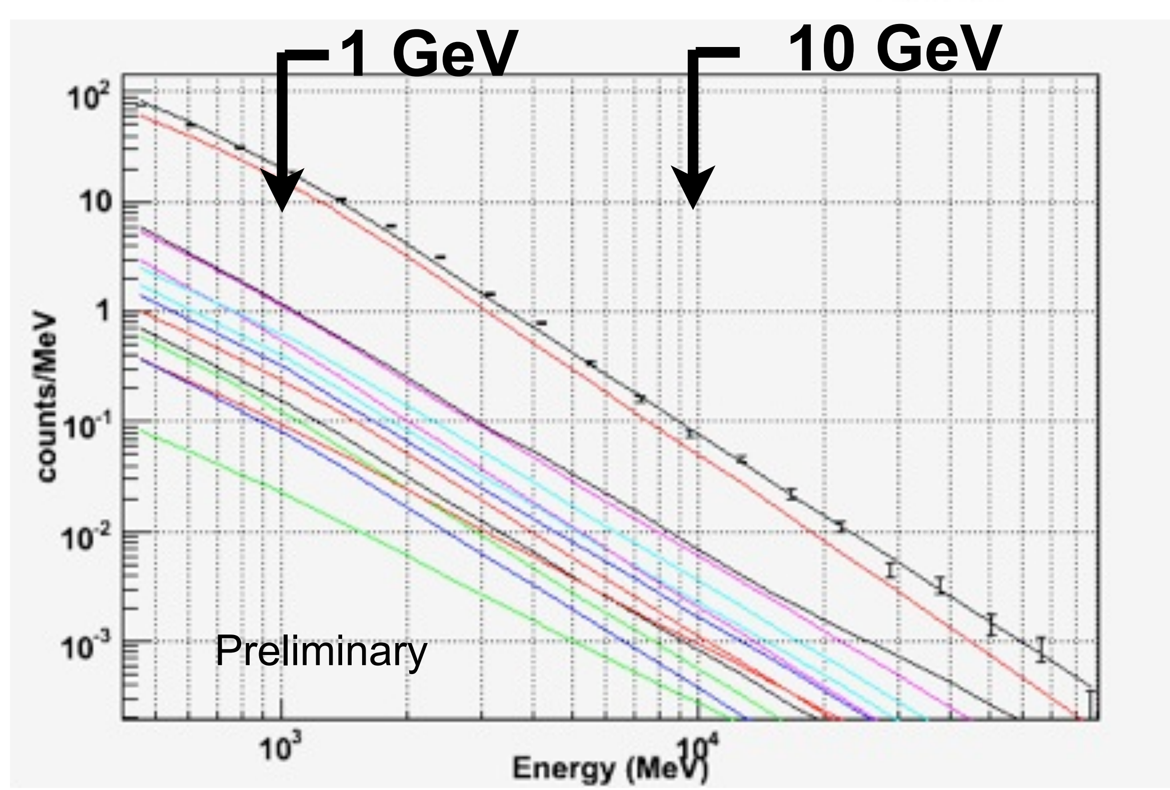

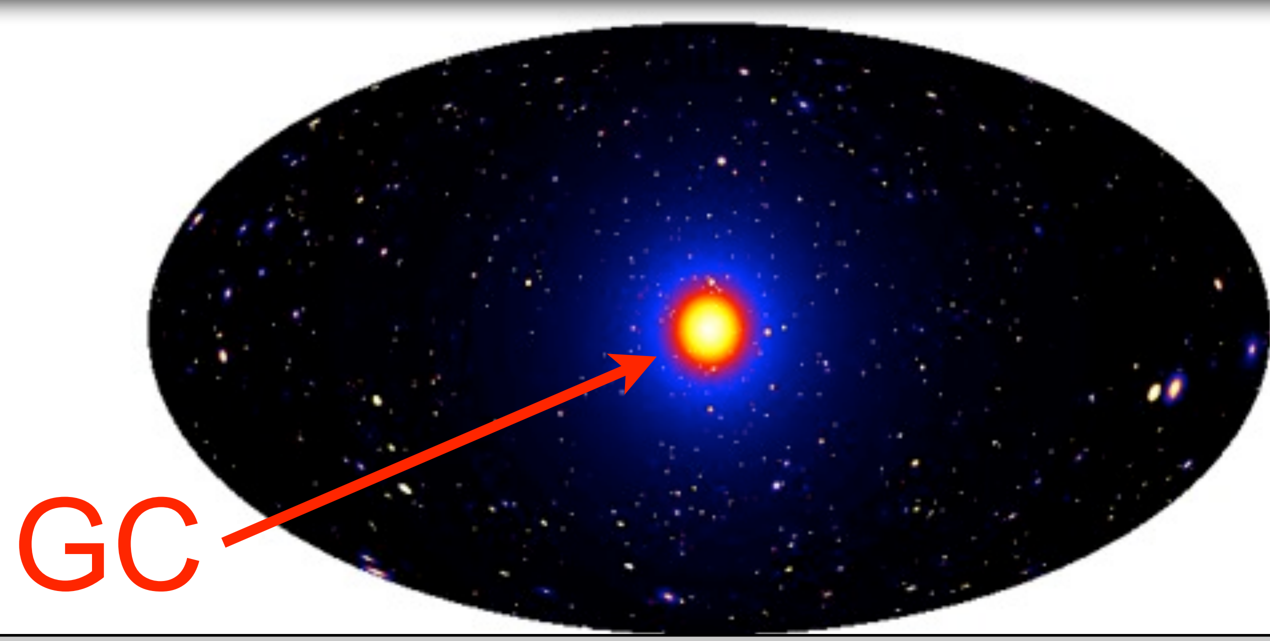

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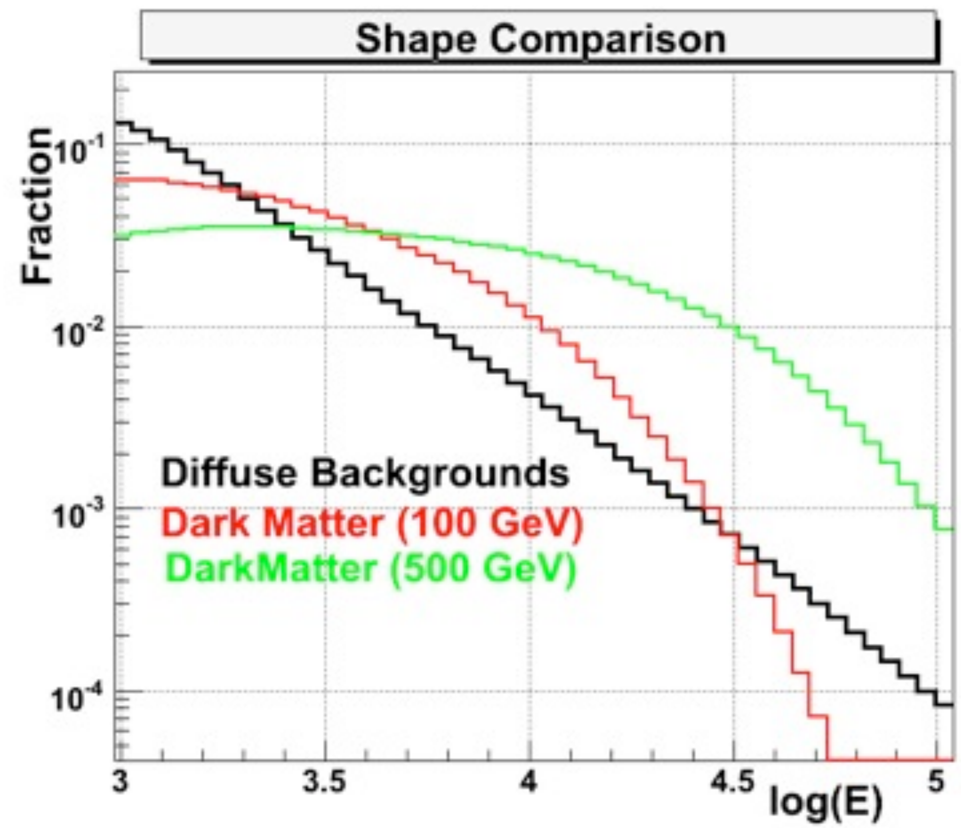

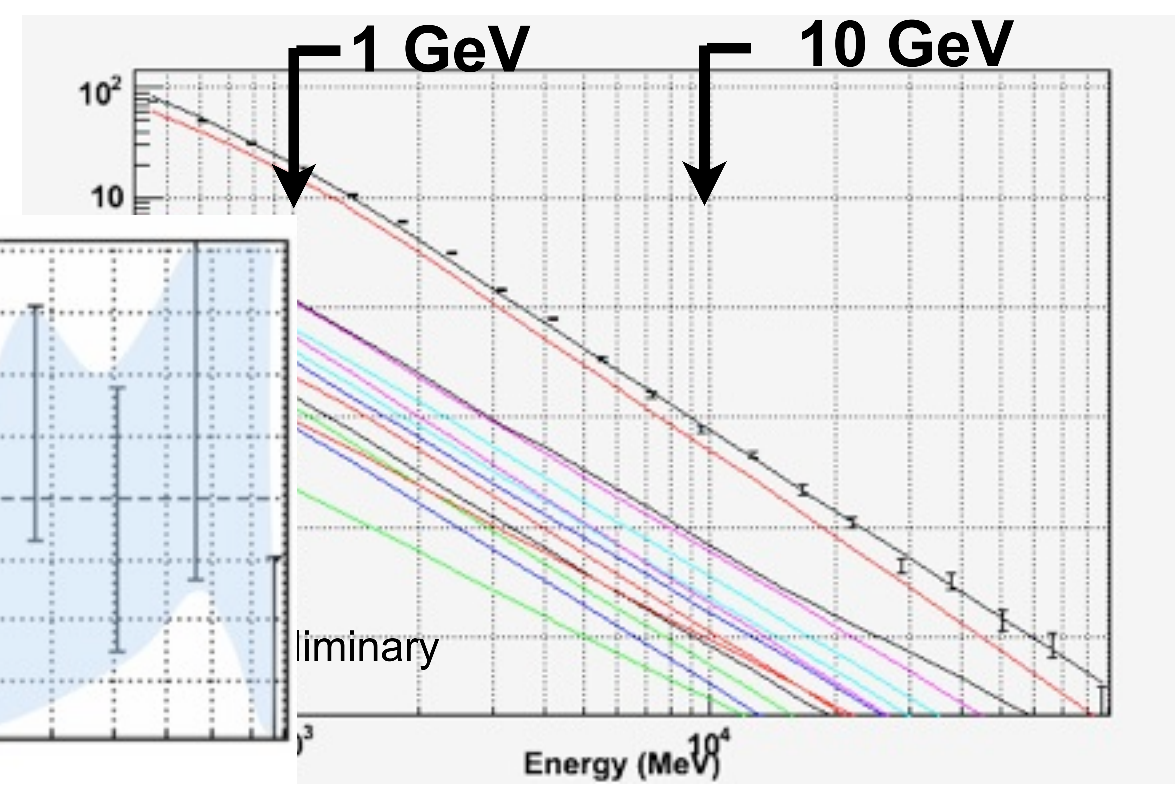

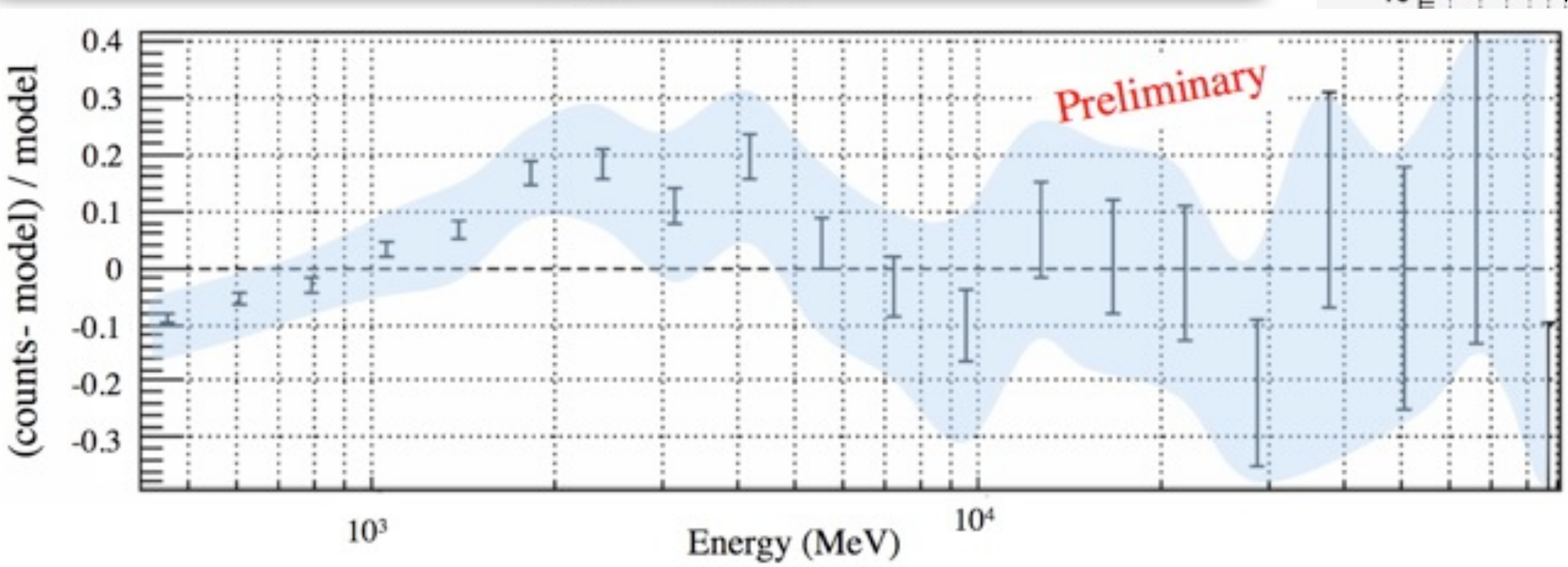

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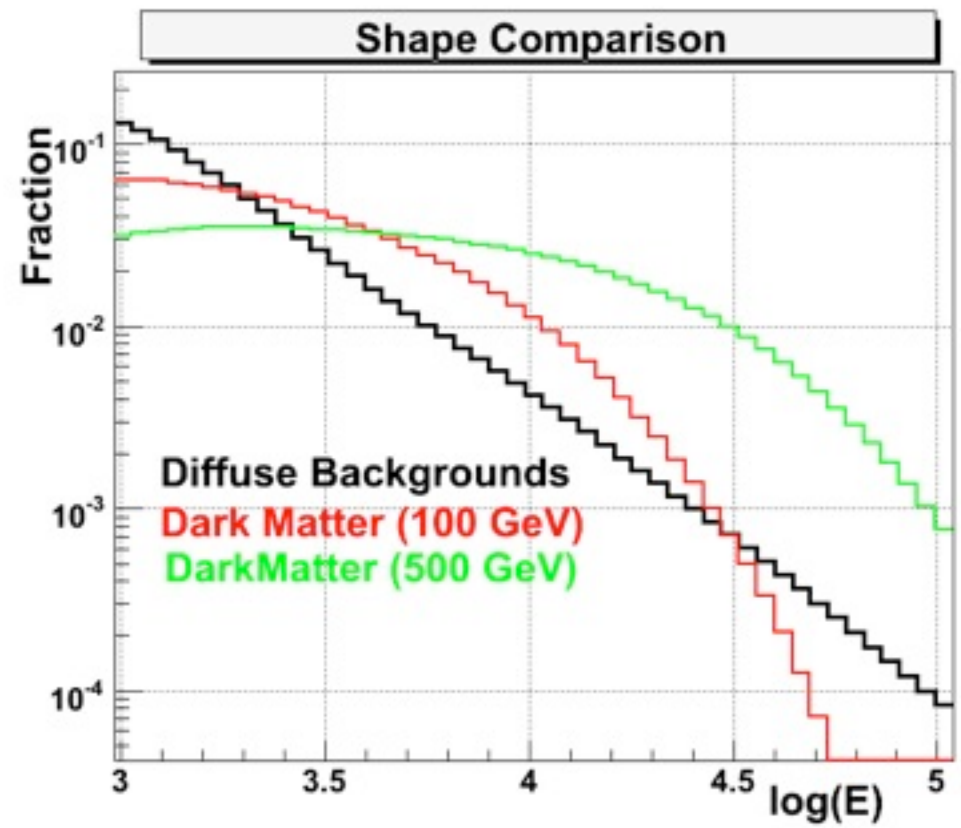
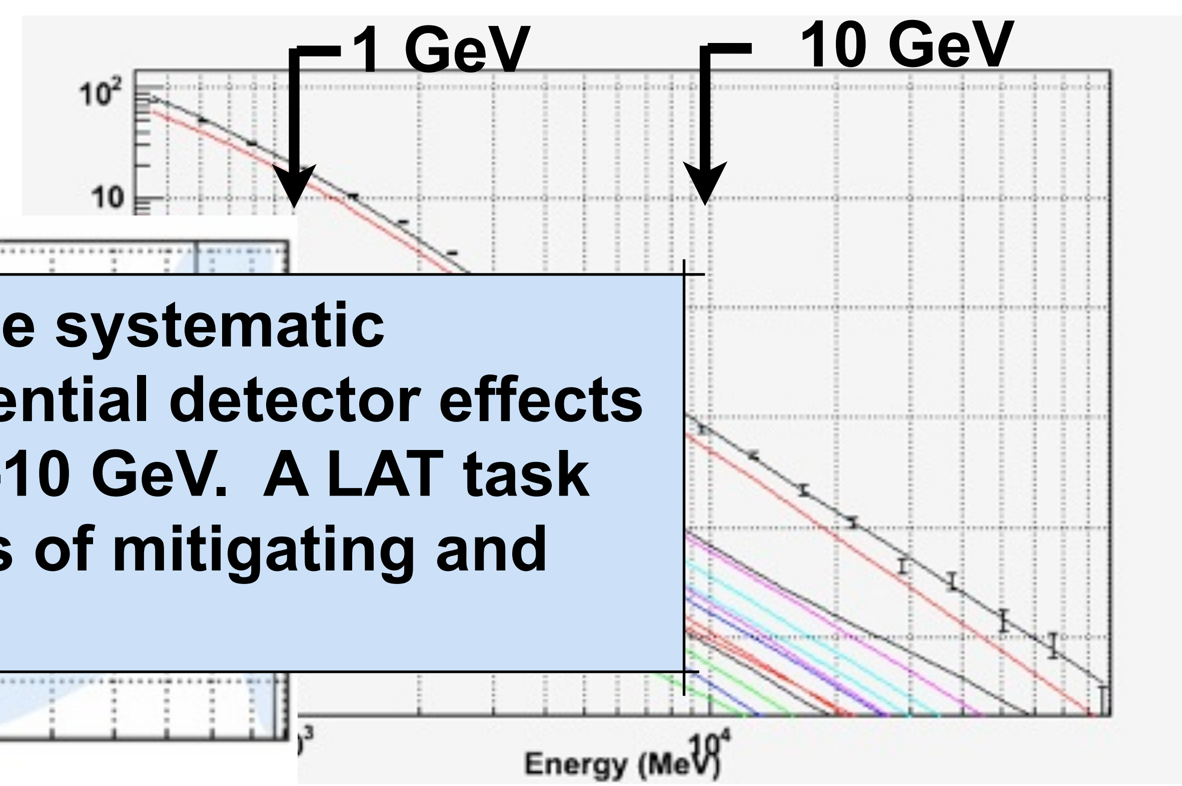
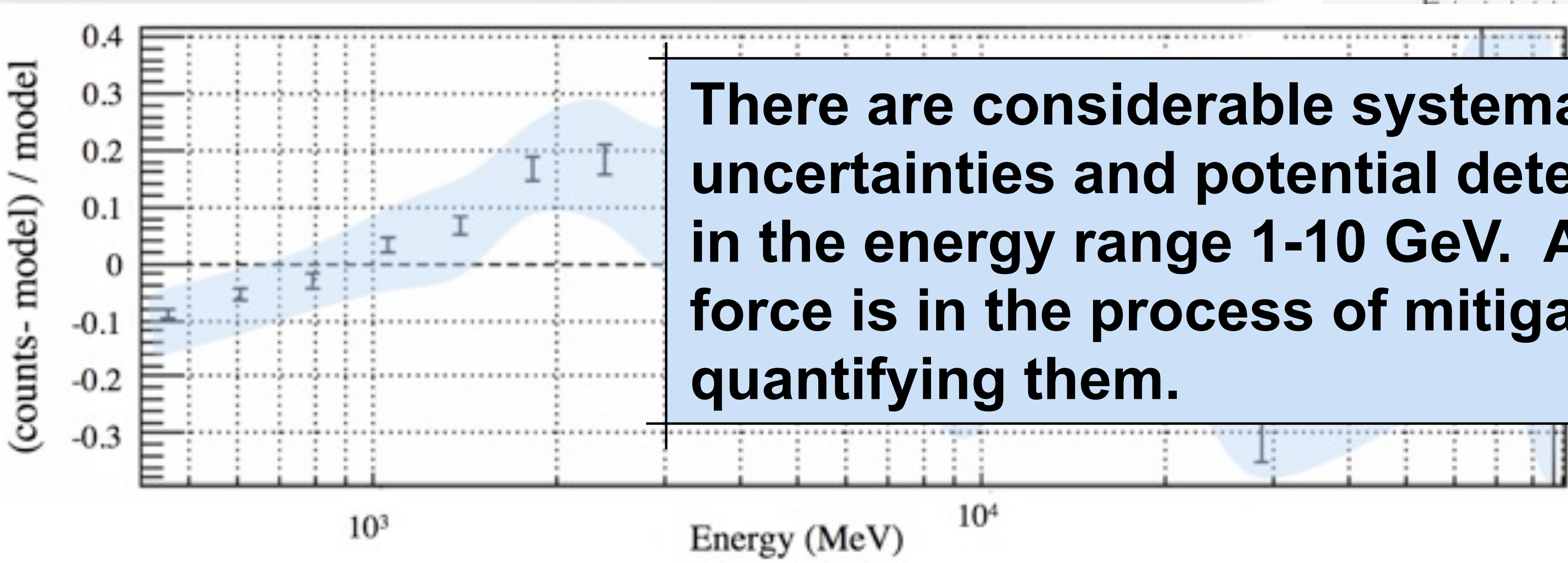






There are considerable systematic uncertainties and potential detector effects in the energy range 1-10 GeV. A LAT task force is in the process of mitigating and quantifying them.

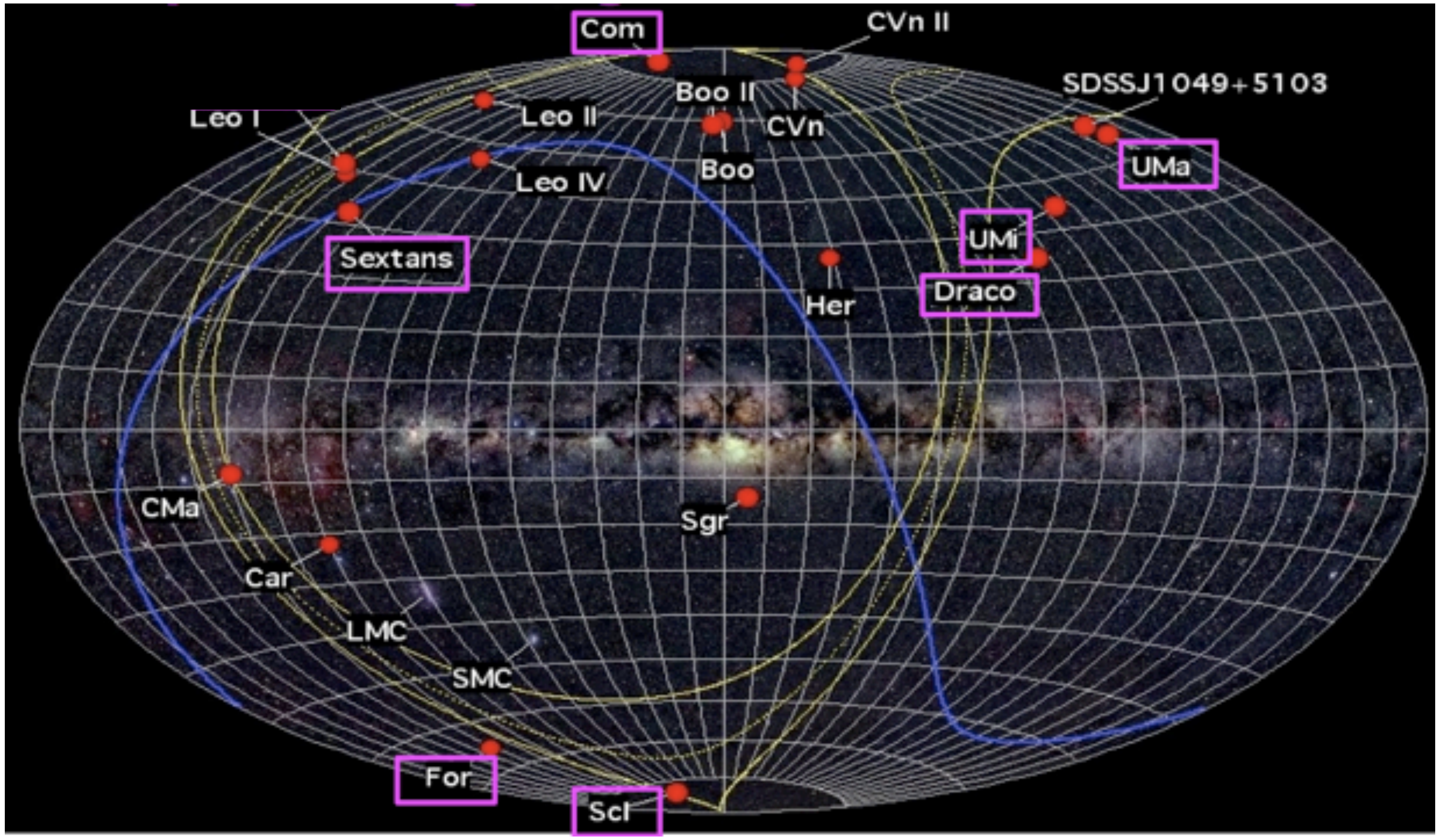
Dwarf Spheroidal (dSph) Galaxies

- dSphs are excellent DM targets of opportunity.
  - ★ N-Body DM Simulation predicts large clumps that support star formation.
  - ★ Very high Mass/Light Ratio (Dark Matter dominated)
  - ★ Low content of gas and dust (low astrophysical gamma-ray sources)
  - ★ Many close by (<100 kpc)
- Consider the 14 targets for Fermi (e.g. high gal. lat.)

Astrophys. J. **712**, 147 (2010)

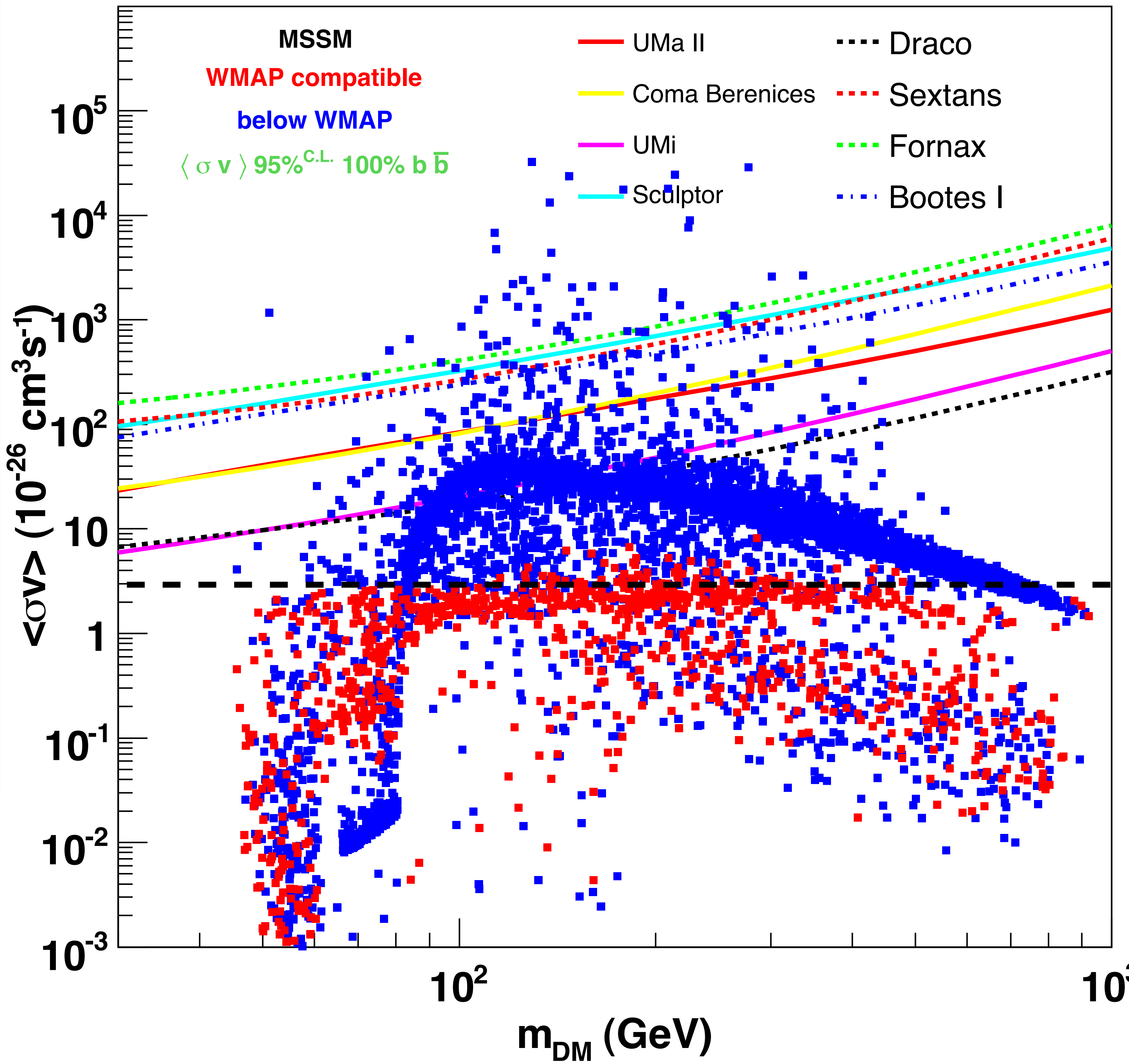
arXiv preprint: 1001.4531

- 11 month data set
- 100 MeV < E < 50 GeV
- dSph will be point-like.
- Backgrounds
  - ★ Existing point-like sources
  - ★ Galactic Diffuse



Limits from dSph Galaxies

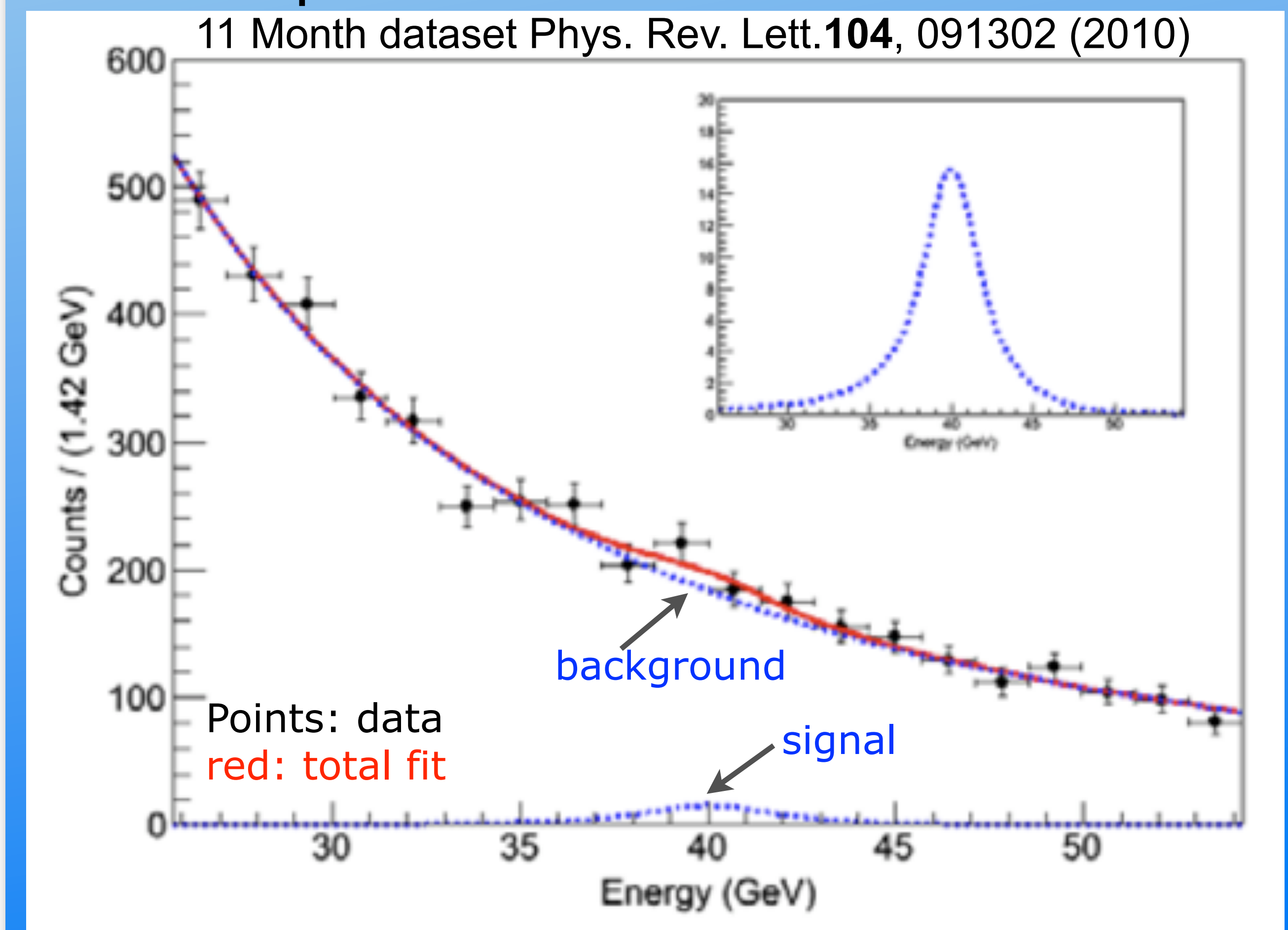
- No excess of events was detected for any of the dSph.
- Set 95% CL upper limits on flux from the sample.
- For 8 of the 14, the flux limits are combined with DM density inferred from stellar data(*) to constrain dark matter models.
- Beginning to constrain some models.
- Current work is focused on “stacking” the dSph galaxies to make use of their combined statistical power.

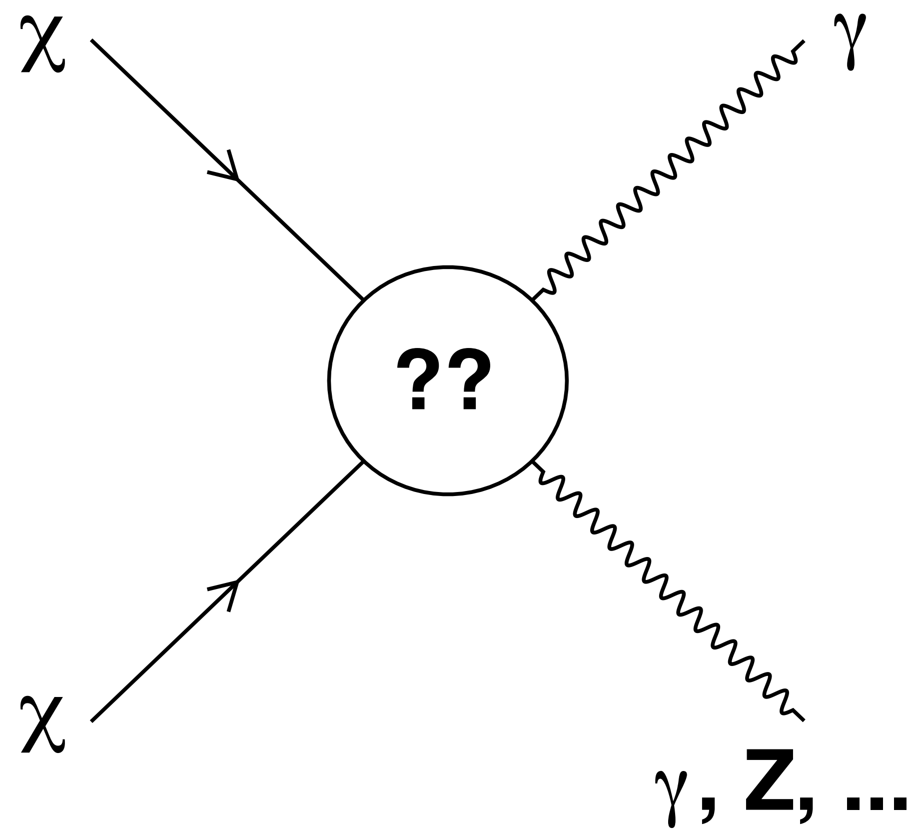


(*) stellar data from the Keck observatory (by Martinez, Bullock, Kaplinghat)

- ***"Smoking Gun" Signal***
- Expected Branching fraction Small
  - Typically 10^{-1} to 10^{-4}
- Energy Resolution is key!
- Instrument resolution ~10% at 100 GeV
- Scan energy (7-200 GeV) looking for a bump.

Example fit for a 40 GeV line





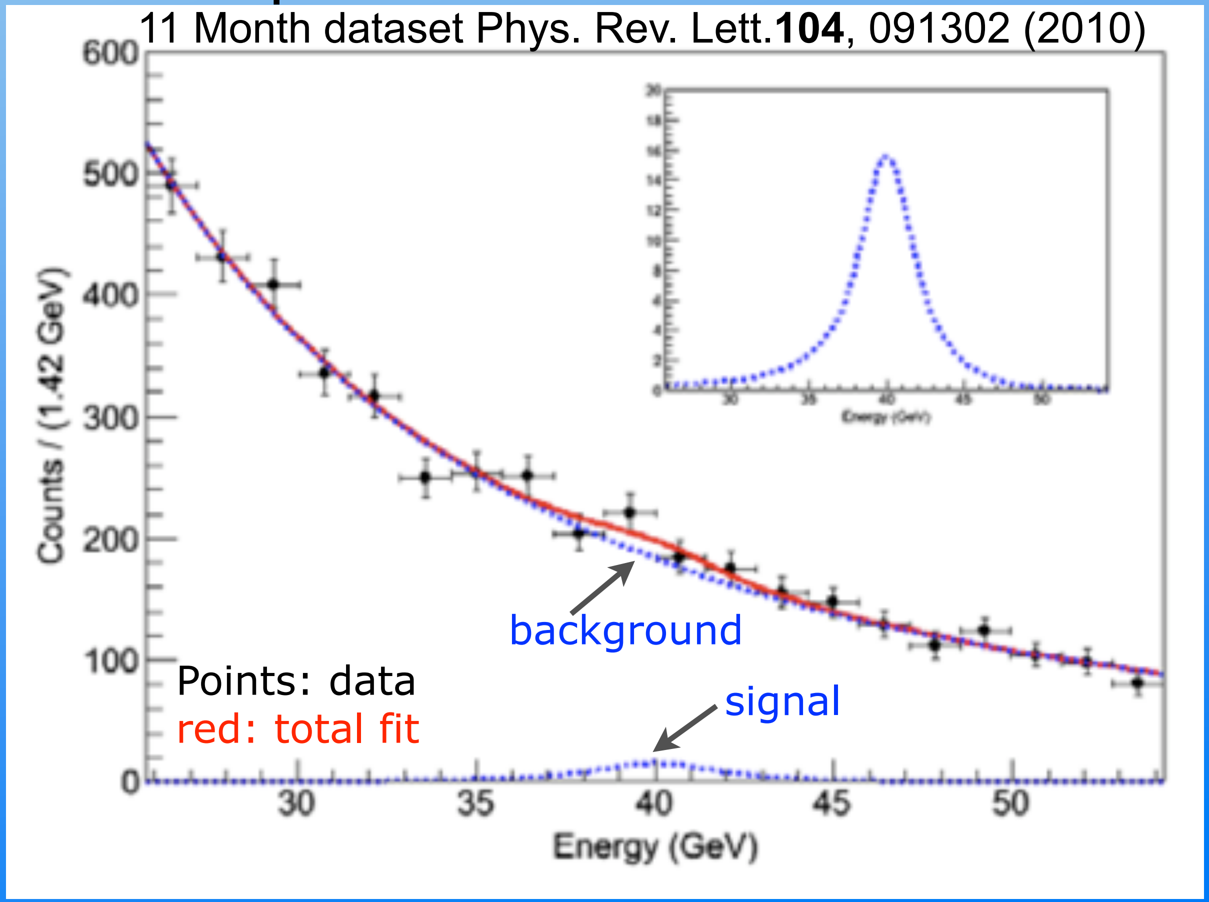
Final State $\gamma\gamma \rightarrow E_\gamma = M_{DM}$

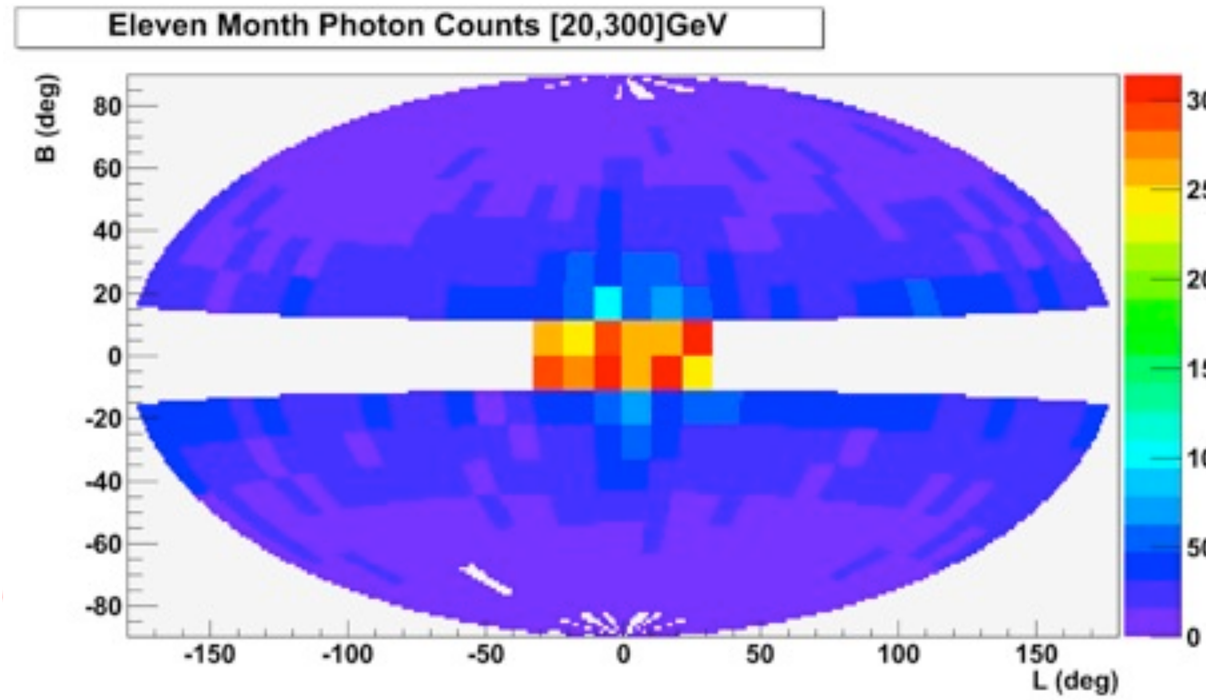
Final State $\gamma Z \rightarrow E_\gamma = M_{DM} - \frac{M_Z^2}{4M_{DM}}$

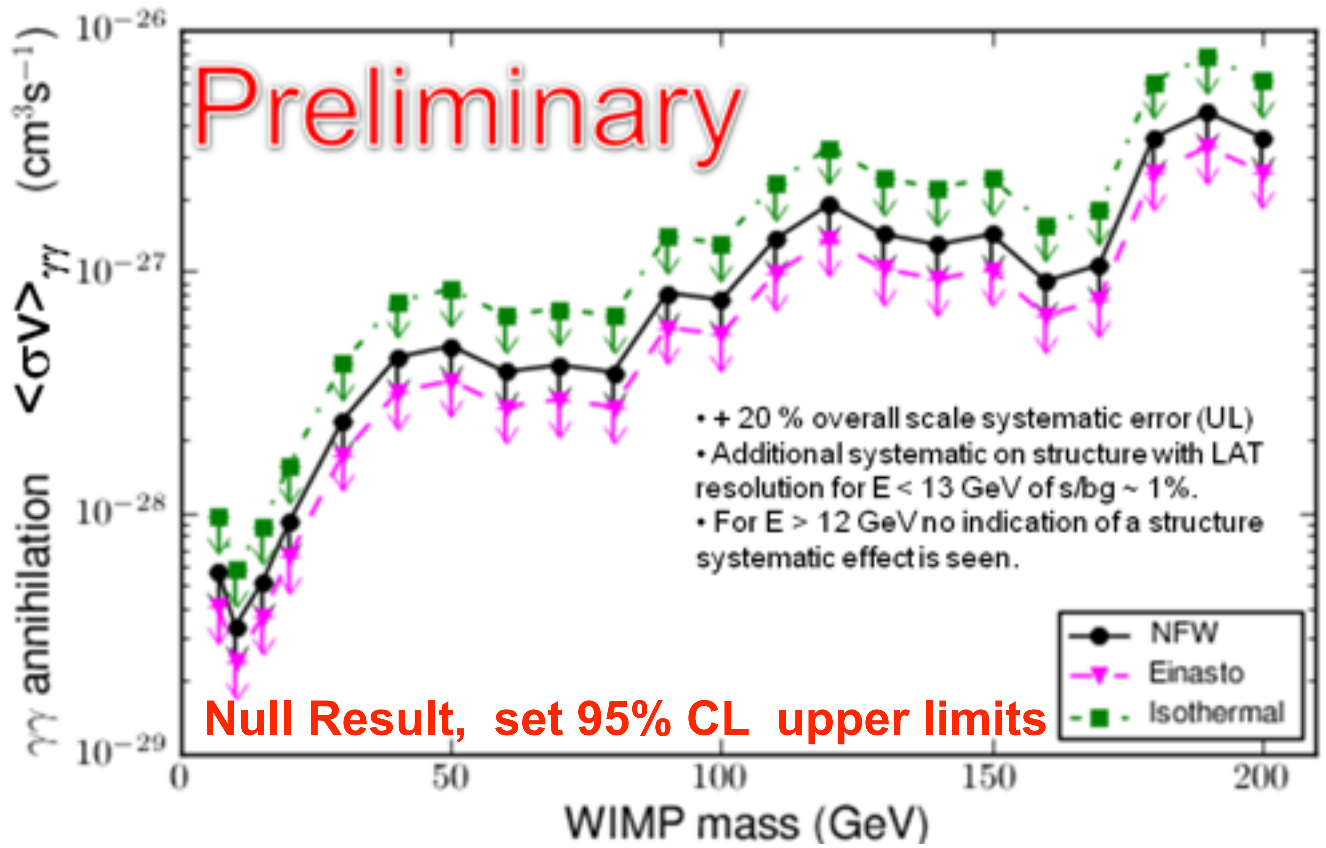
Searching for Dark Matter Gamma Ray Lines

- 23 month data sample
- Signal Model is line smeared by LAT response function.
- Background is power-law fit to side-bands
- Search Region:
  - |b|>10º and 20º x 20º around GC
- Remove sources (|b|>1º).

Example fit for a 40 GeV line







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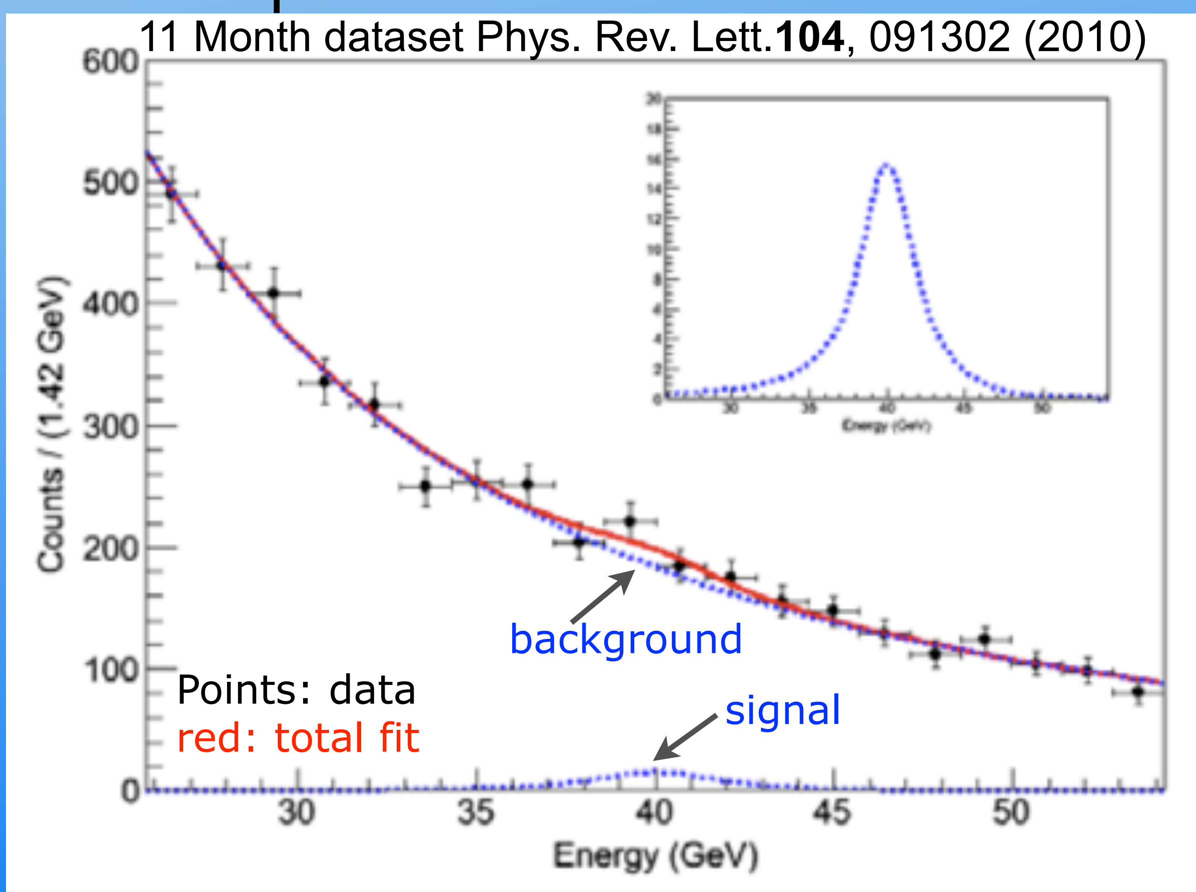
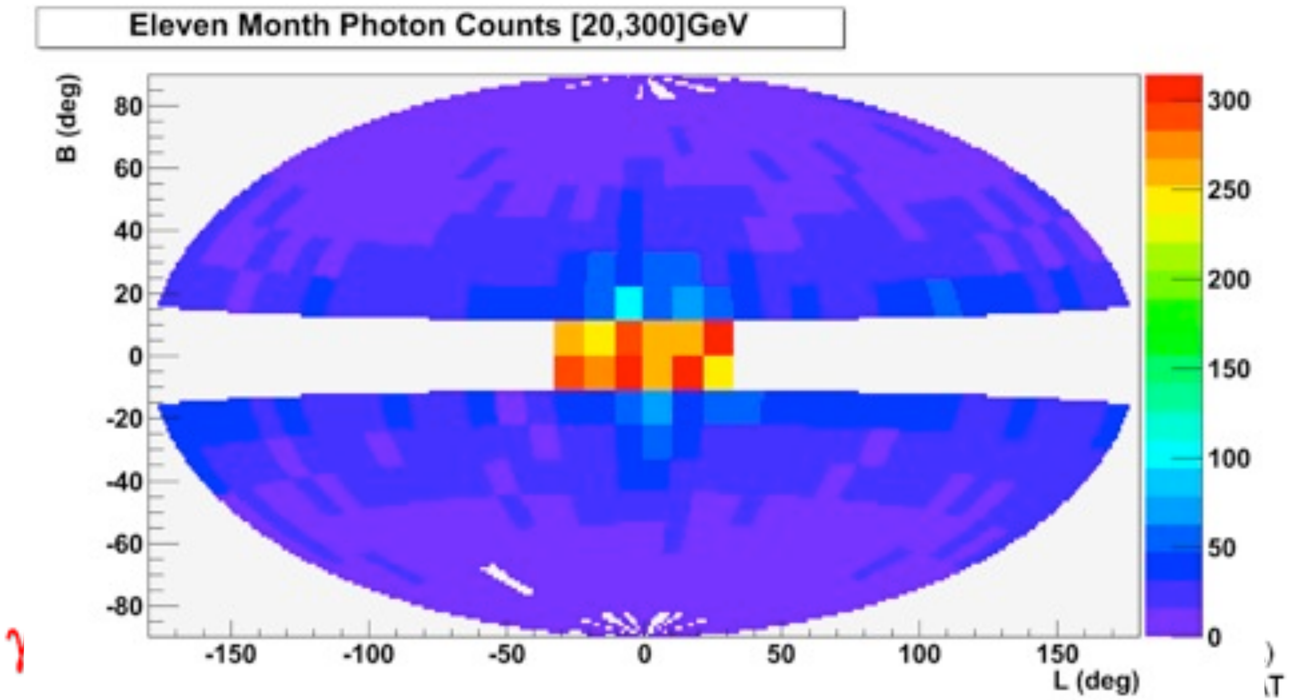
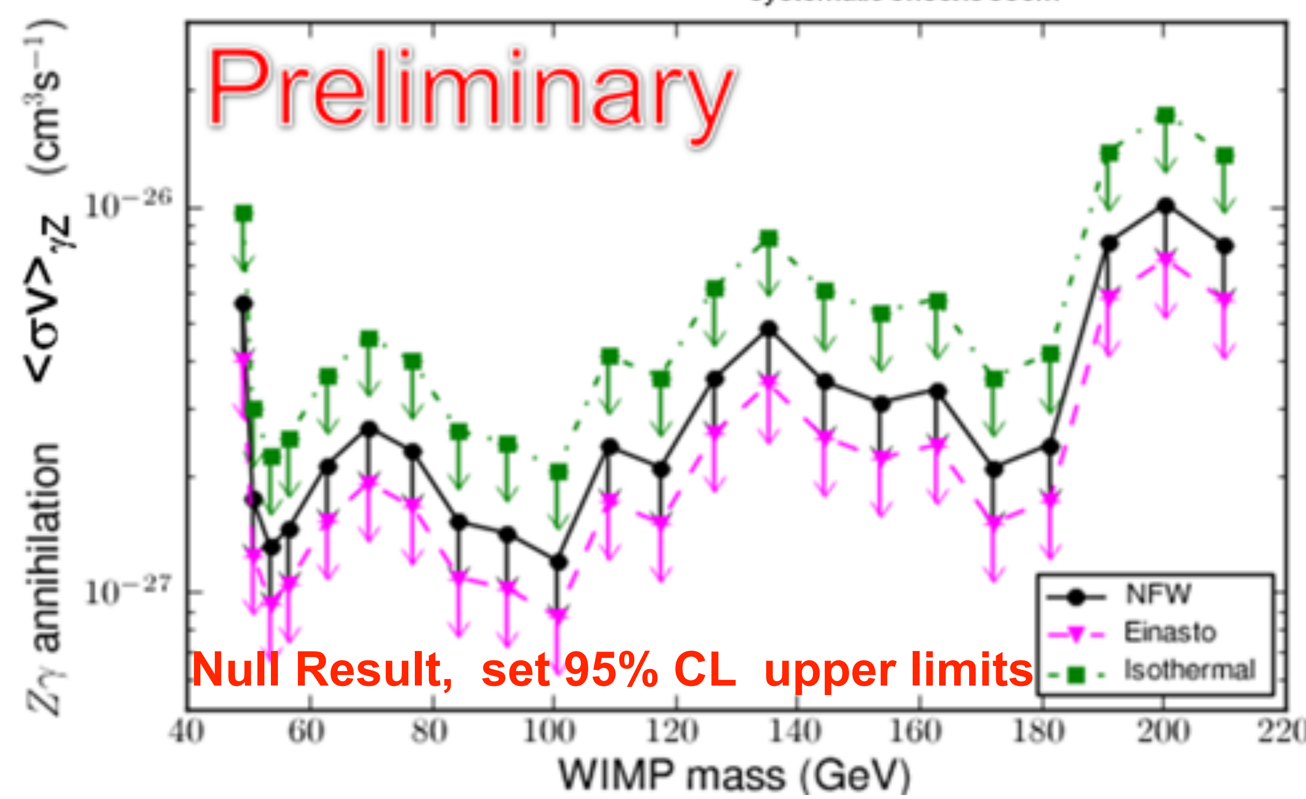




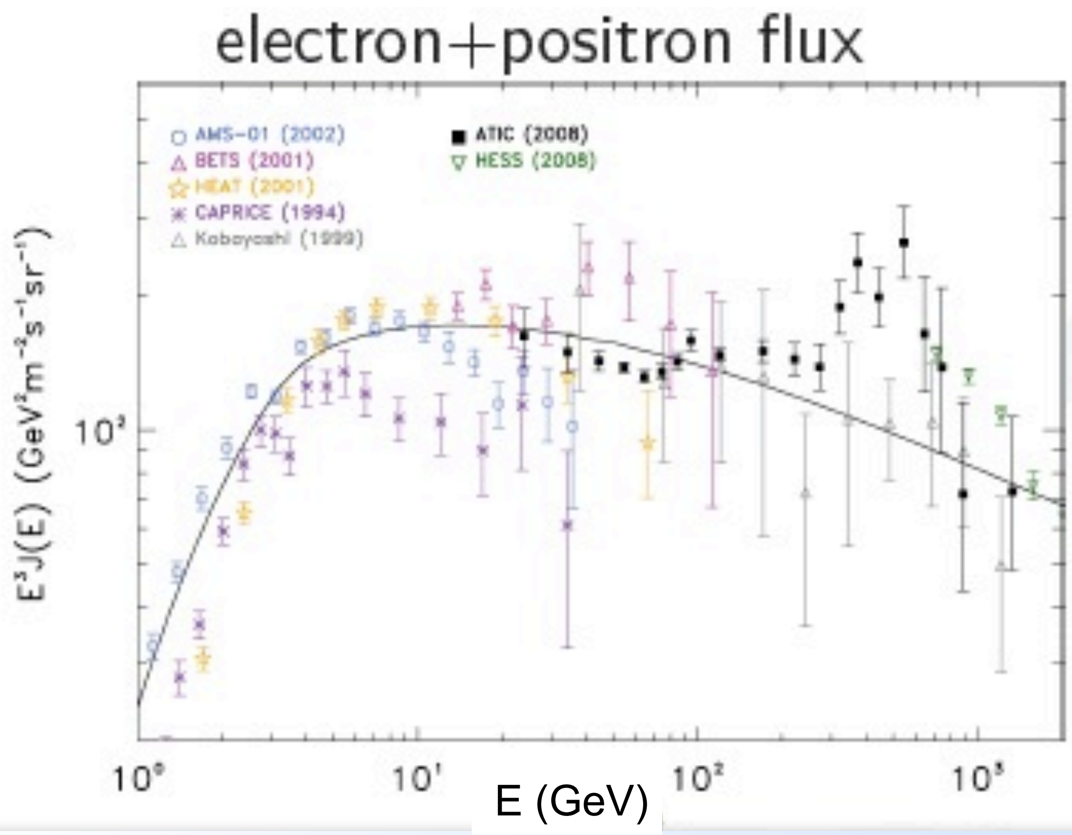
resolution for E < 13 GeV of s/bg ~ 1%.
• For E > 12 GeV no indication of a structure
systematic effect is seen.

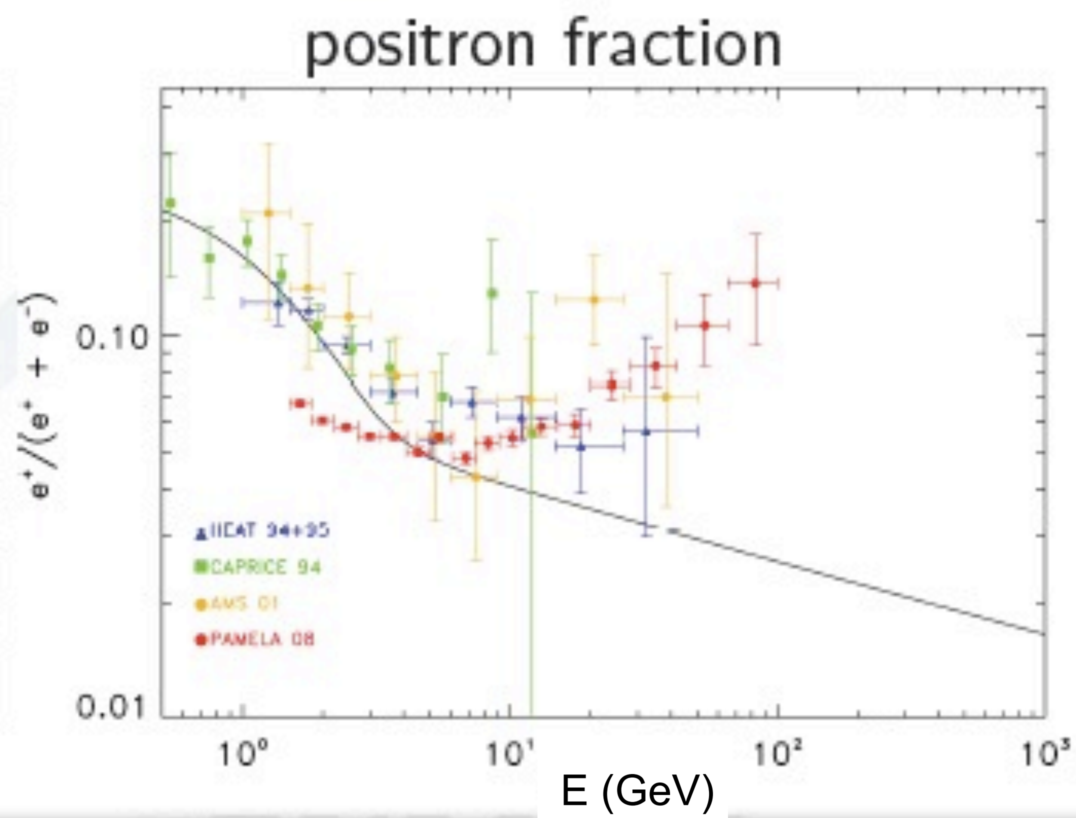


Fermi detects more than just gamma-rays.

One of the best cosmic ray electron observatories

Interesting Features of Cosmic Ray Electrons



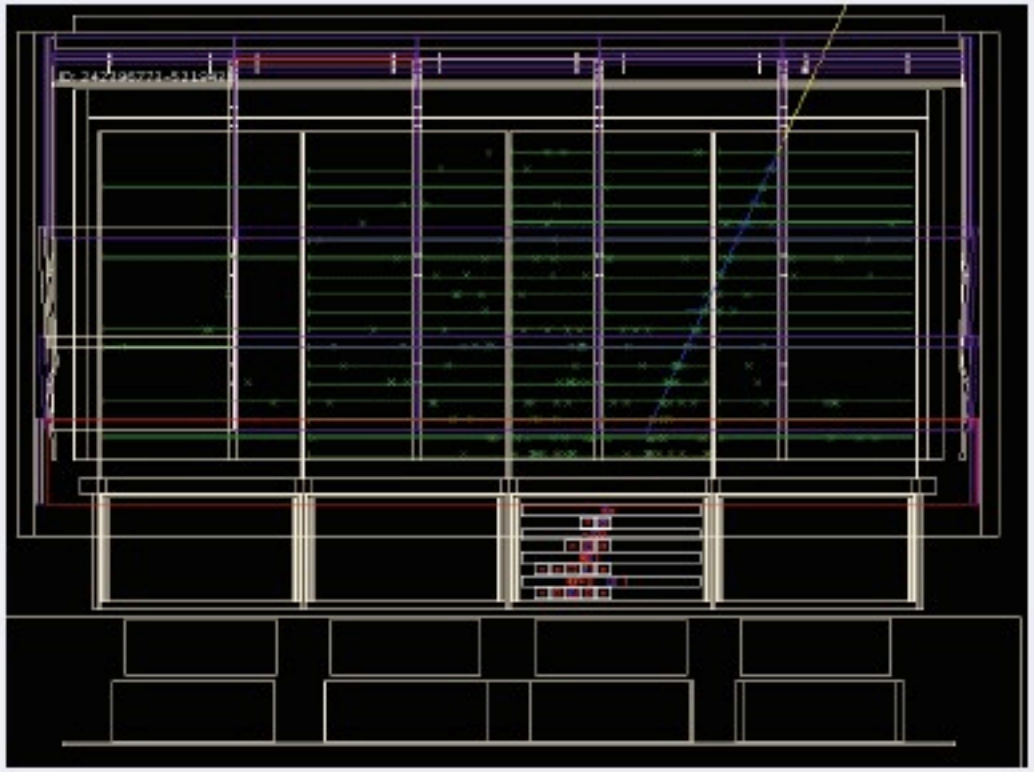


- Spectral Features:
  - ★ ATIC excess around 600 GeV
  - ★ H.E.S.S possible cutoff around 1 TeV
- Pamela shows excess in positron fraction
- Lots of interest soon after launch.
- Fermi LAT is an excellent electron/positron detector.

⇒ Nearby sources expected ? astrophysical or exotic origin ?

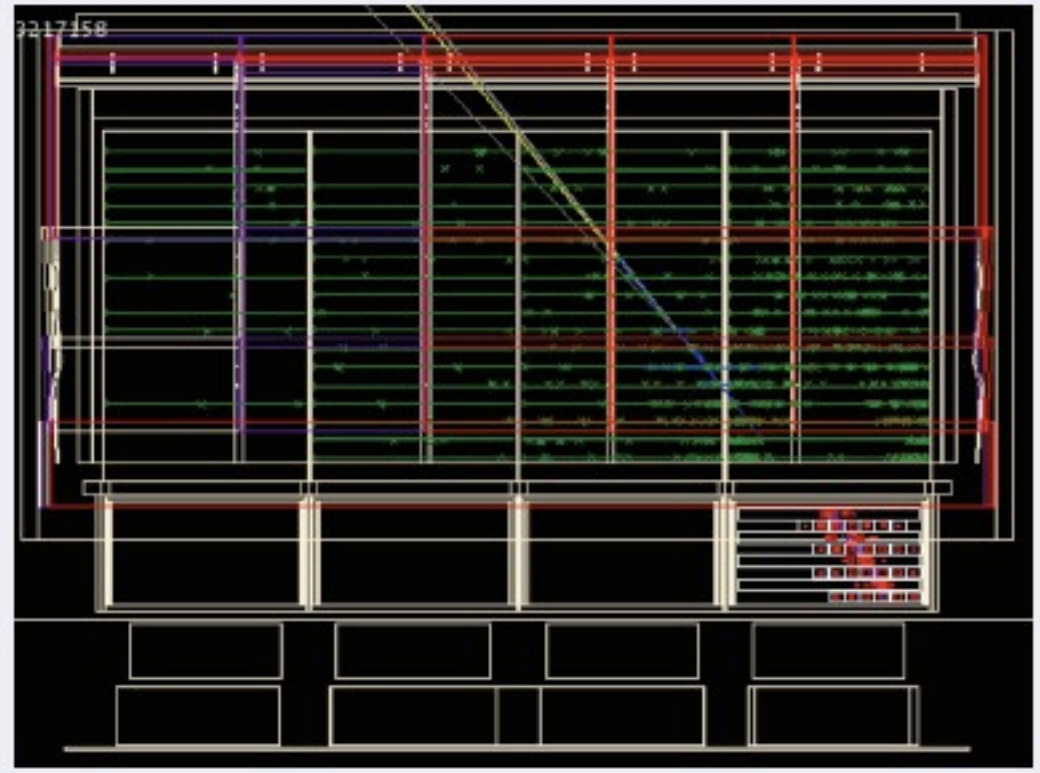
Electrons and Hadrons With Fermi

Electron candidate



- few ACD tile hits in conjunction with the track
- clean main track with extra-clusters very close to the track - note backsplash from the calorimeter
- well defined symmetric shower in the calorimeter, not fully contained

Hadron candidate



- large energy deposit per ACD tile
- small number of extra clusters around main track, large number of clusters away from the track
- large and asymmetric shower profile in the calorimeter

- LAT does not distinguish electrons from positrons
  - ★ For what follows: “electrons” means both
- All events with E > 20 GeV are sent to the ground.

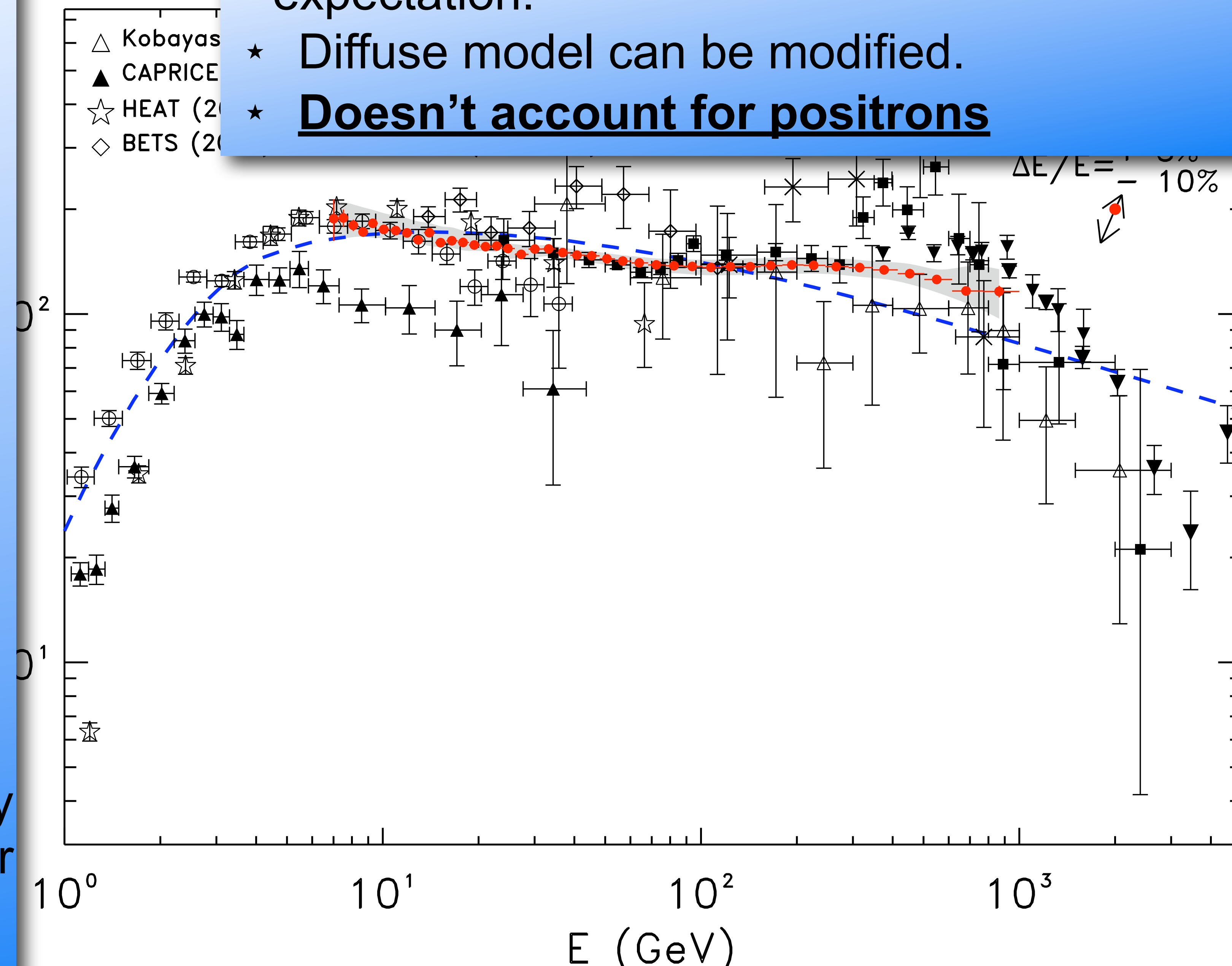
⇒ hereafter, electrons will mean *electrons+positrons*

Resulting Fermi Electron Spectrum

- Excellent Statistics:
  - ~7.8M evts HE
  - ~124,000 evts LE
- No Evidence of prominent spectral feature seen by ATIC.
- Excess above 200 GeV
- Can explain this with an additional leptonic component with a hard spectrum.
- The data can accommodate a contribution from nearby sources (e.g. pulsars) or possible DM annihilations.

Phy Rev D82, 092004 (2010)

- Fermi Data not compatible with prelaunch expectation.
  - Diffuse model can be modified.
  - **<u>Doesn't account for positrons</u>**

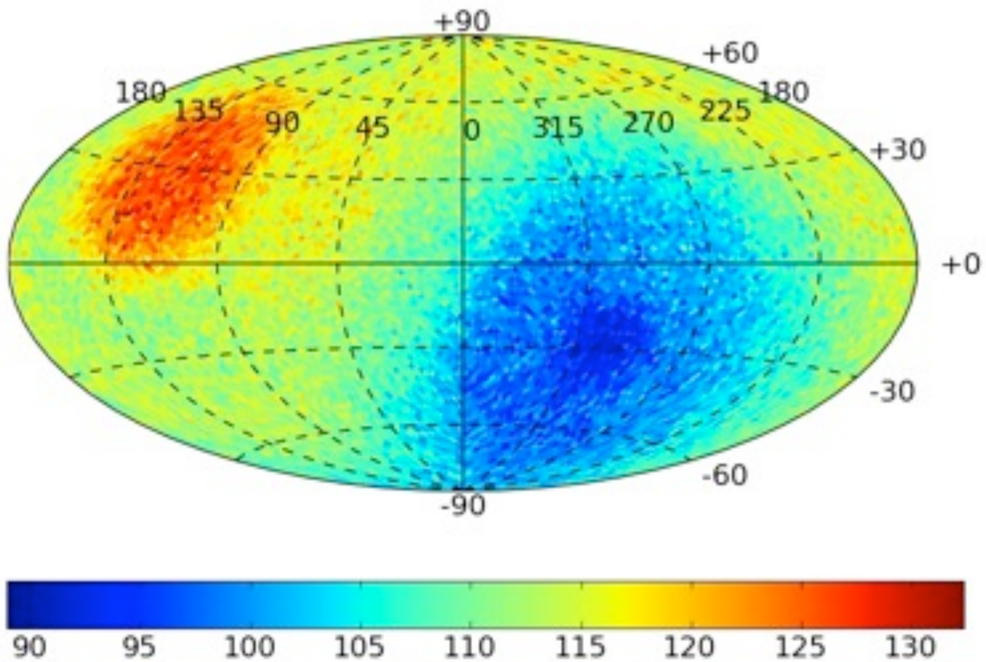


Search for Anisotropies of CRE

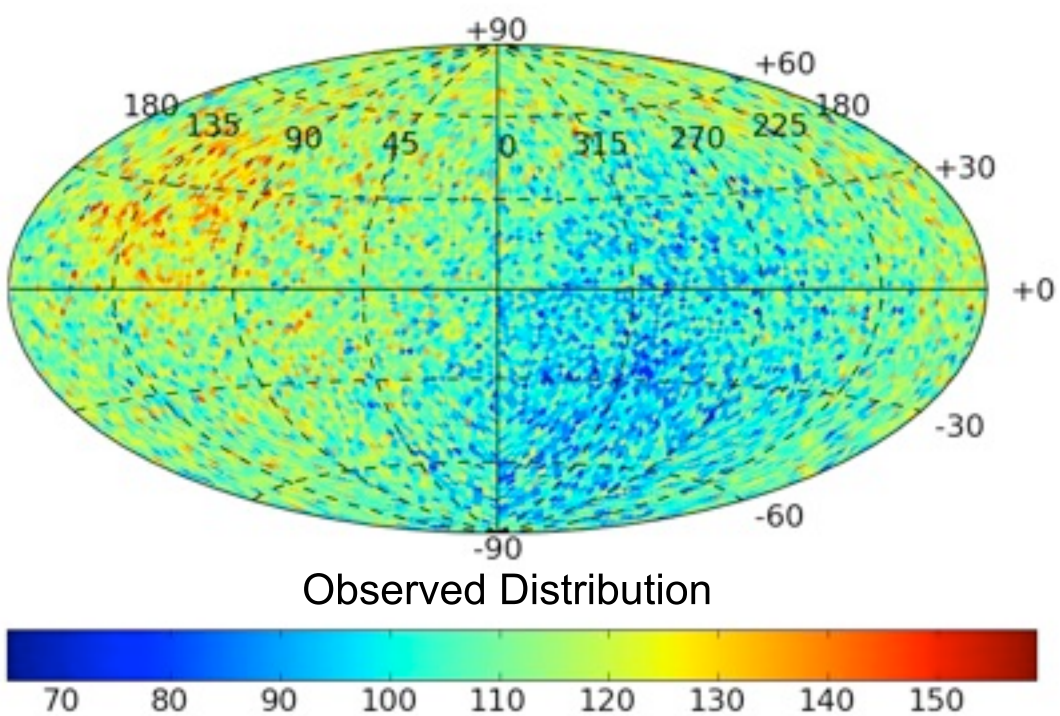
Phy Rev D82, 092003 (2010)

- Expect CRE to be isotropic due to GMF.
- Perform search for Anisotropies for CRE
  - E>60, 120, 240, 480 GeV
- Performed a power spectrum analysis
- No Anisotropies are observed.

Expected Distribution for Isotropic Distribution



Number of Events



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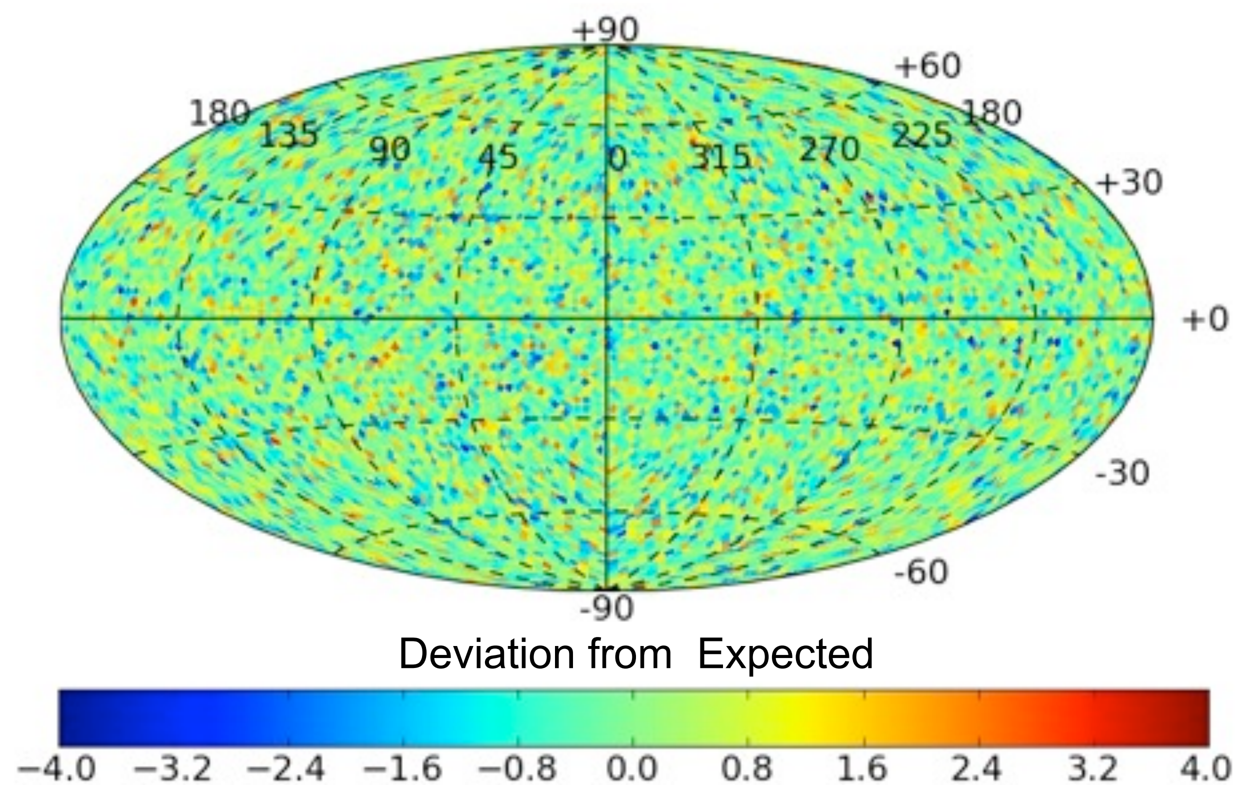

Significance (σ)

Search for Anisotropies of CRE

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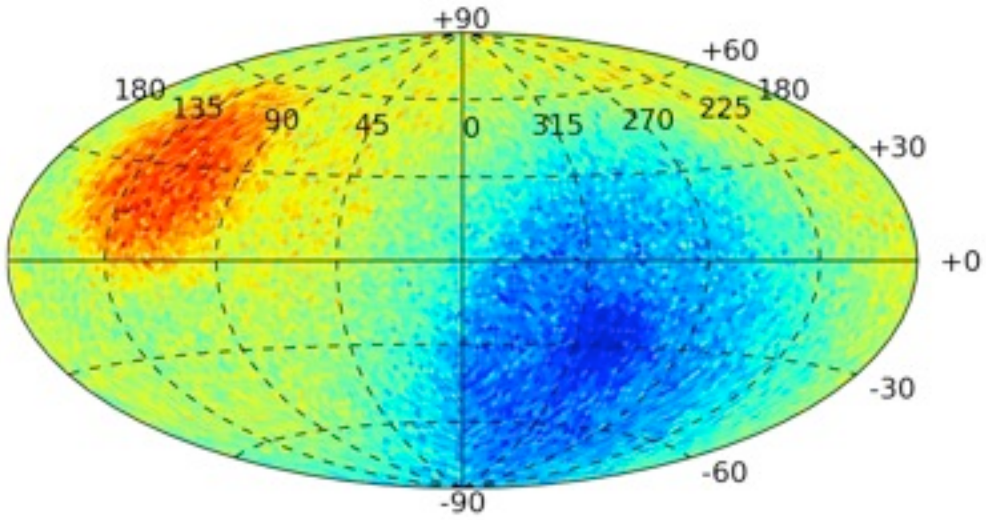
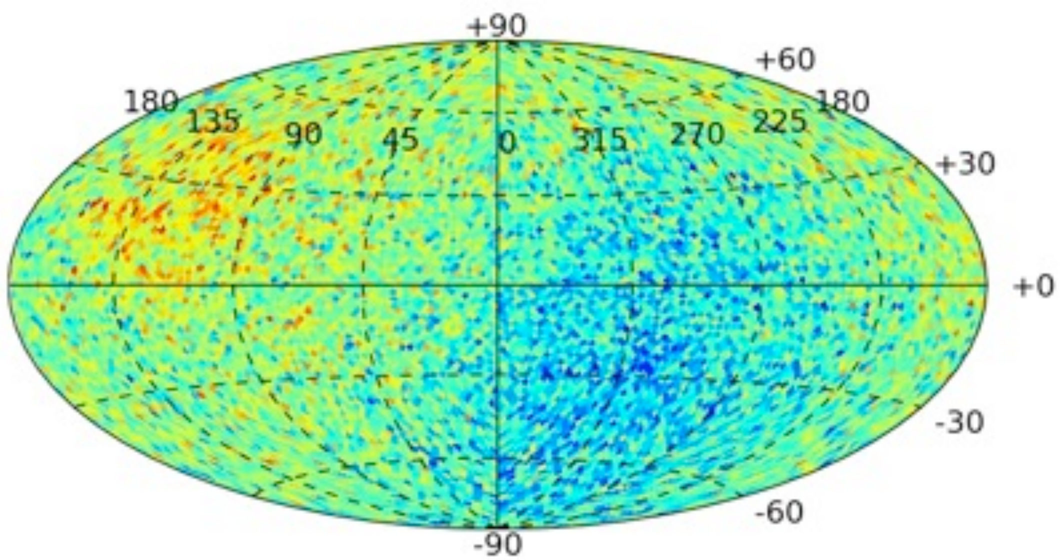
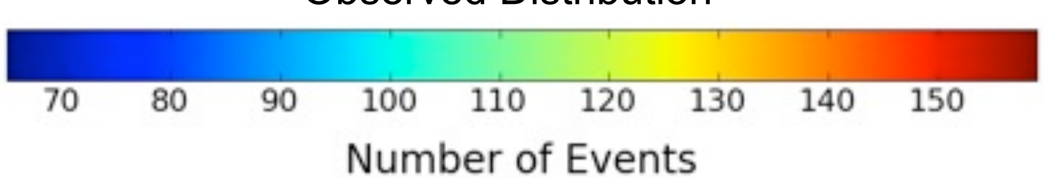




Observed Distribution



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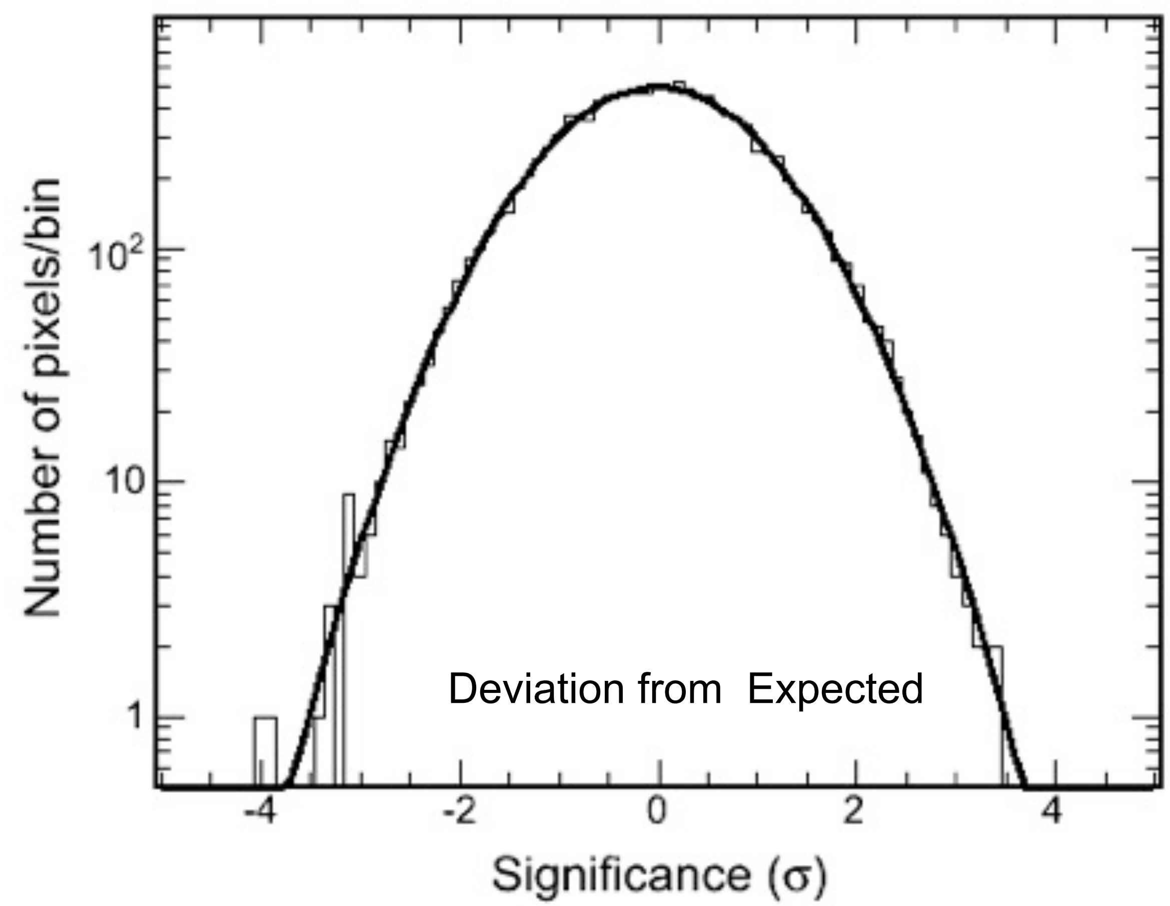
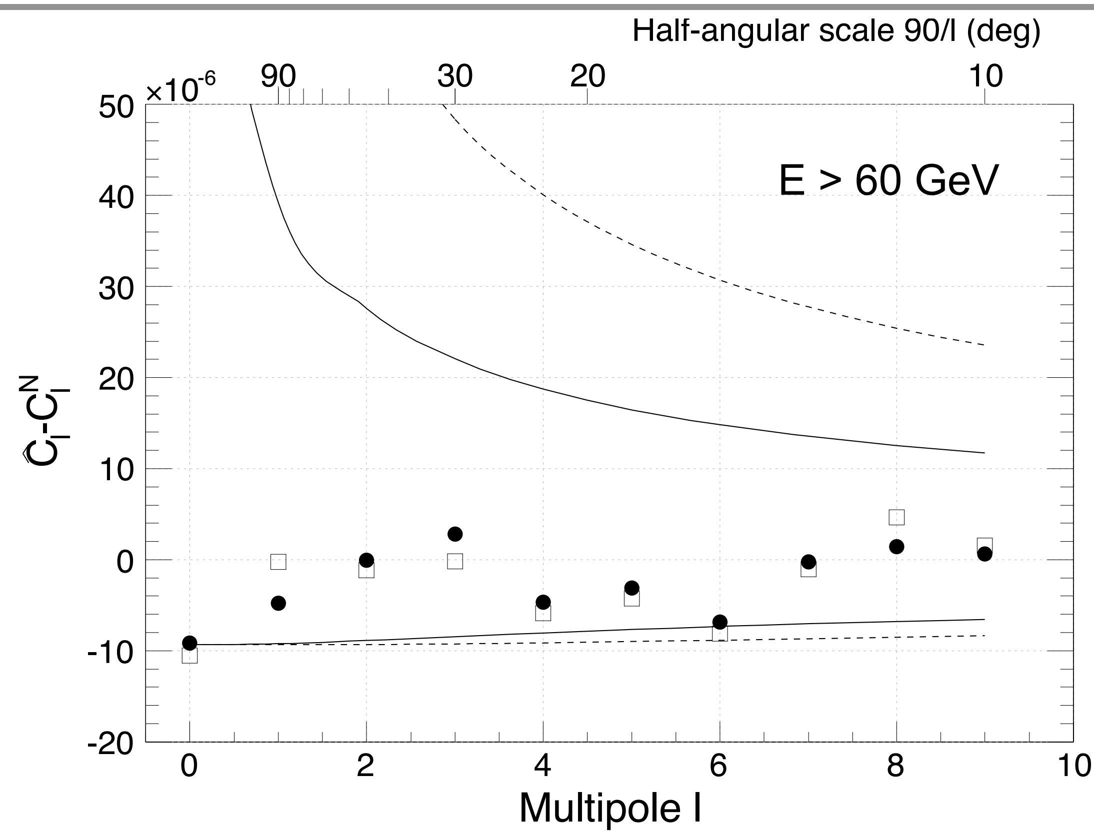
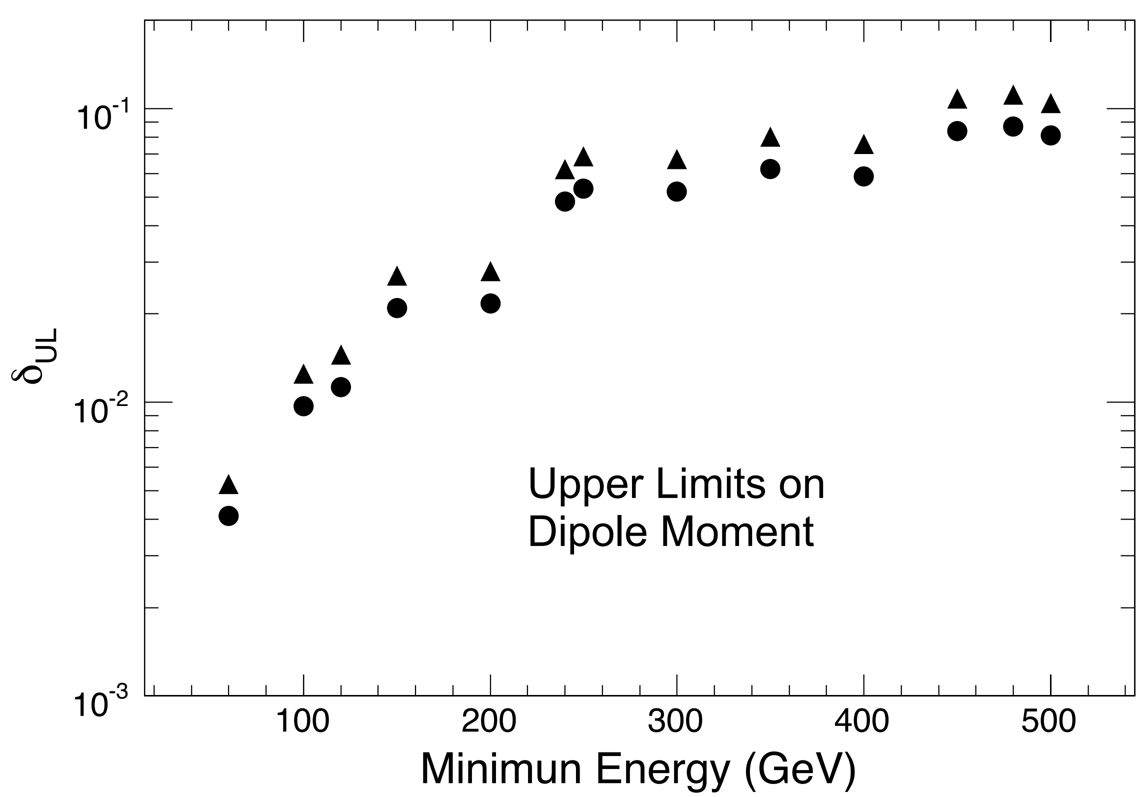
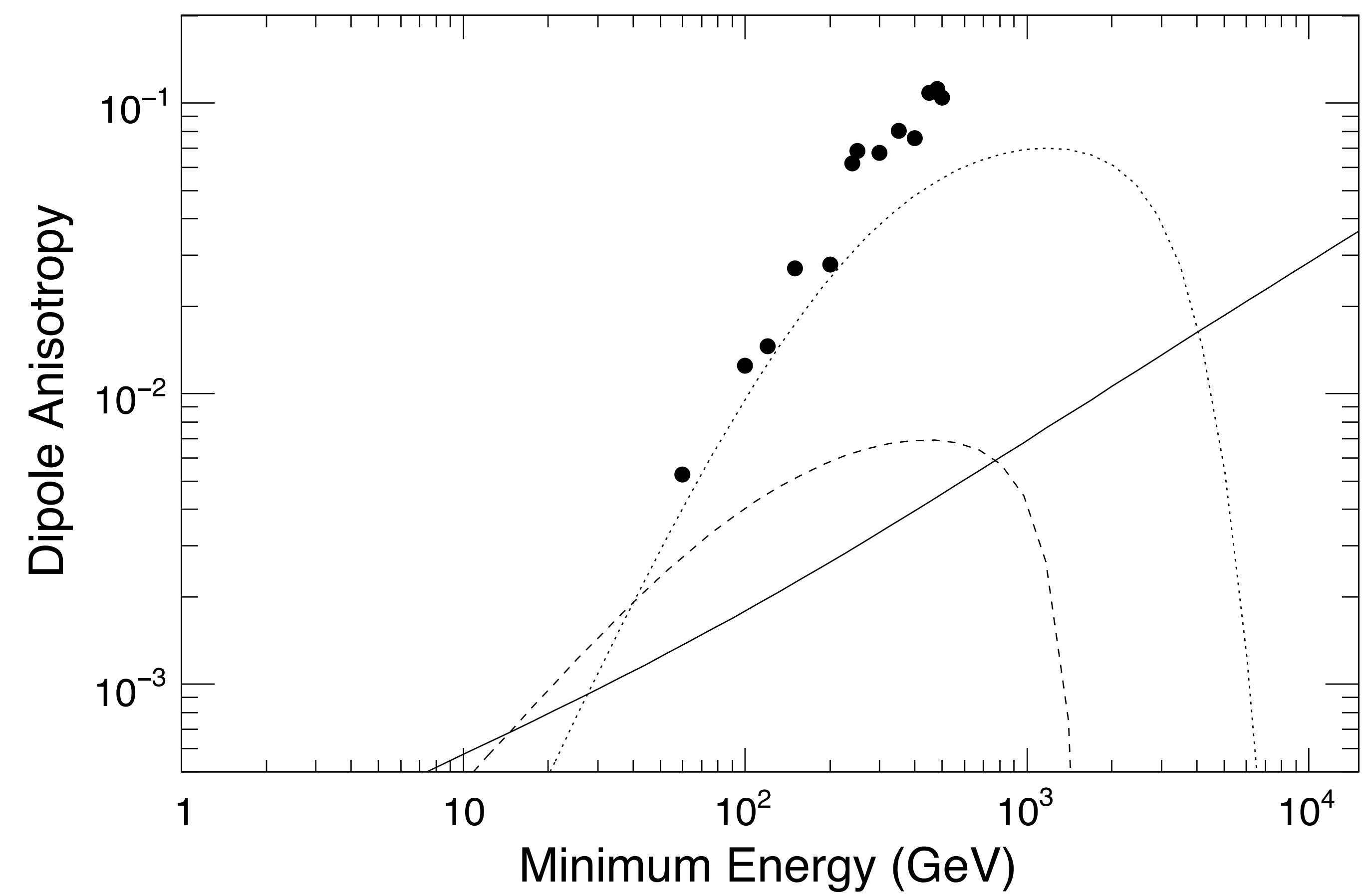


Limits on Anisotropies of CRE



- Perform a power spectrum analysis
- multipole moments consistent with white noise from isotropic distribution.
- Focus on dipole moment and place limits as a function of lower energy bound.
- Compare with possible sources.





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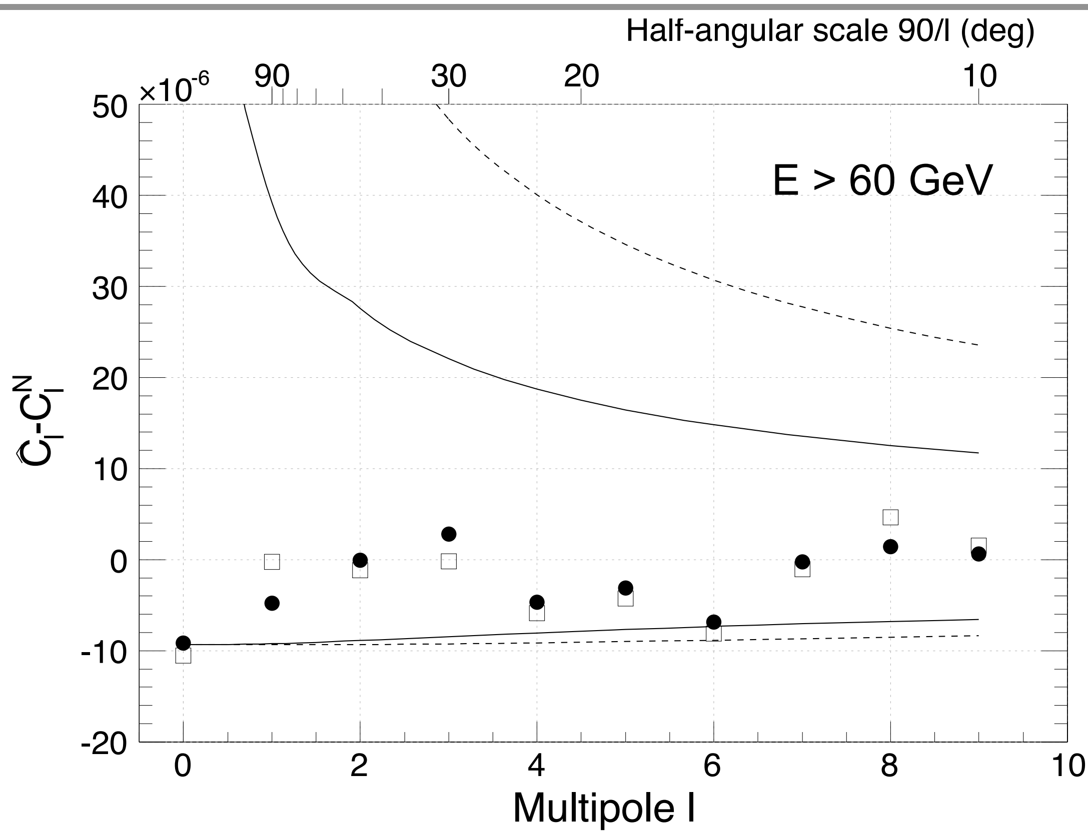

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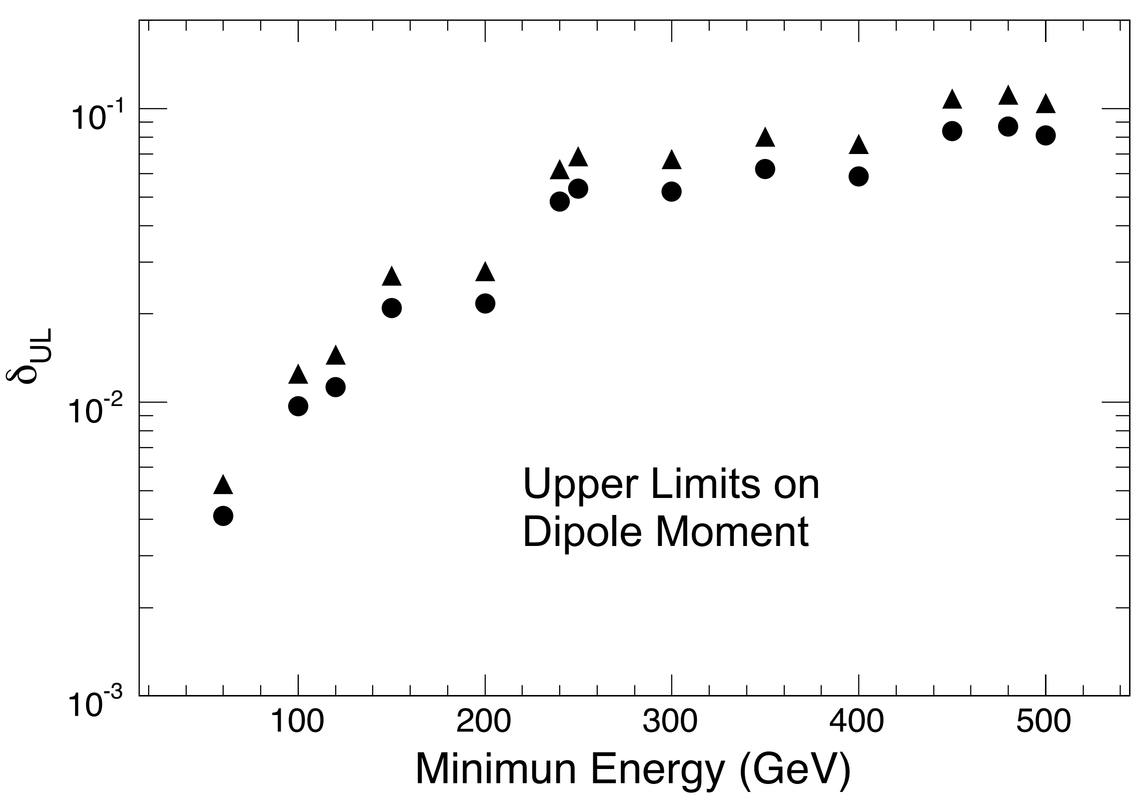
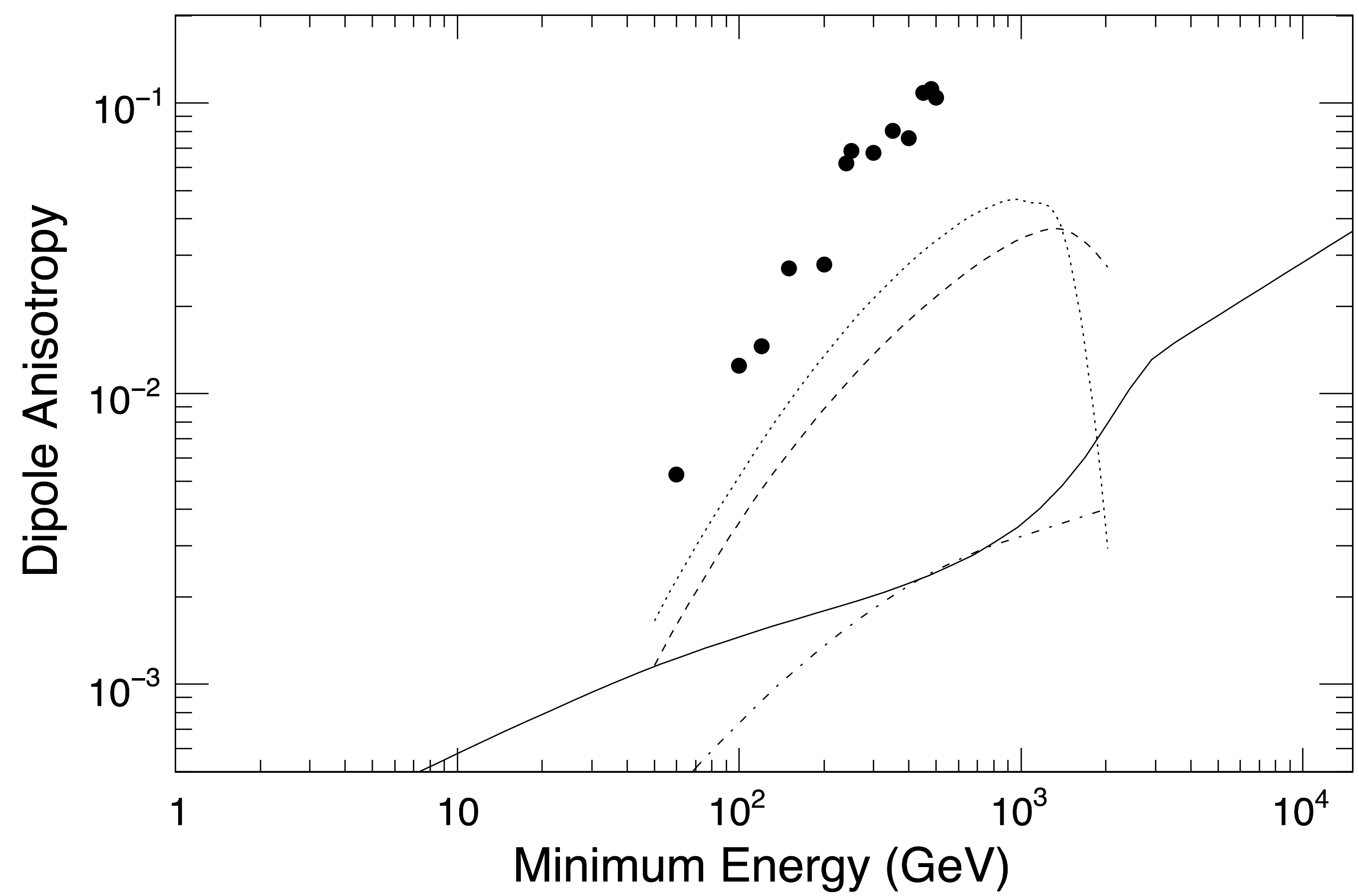
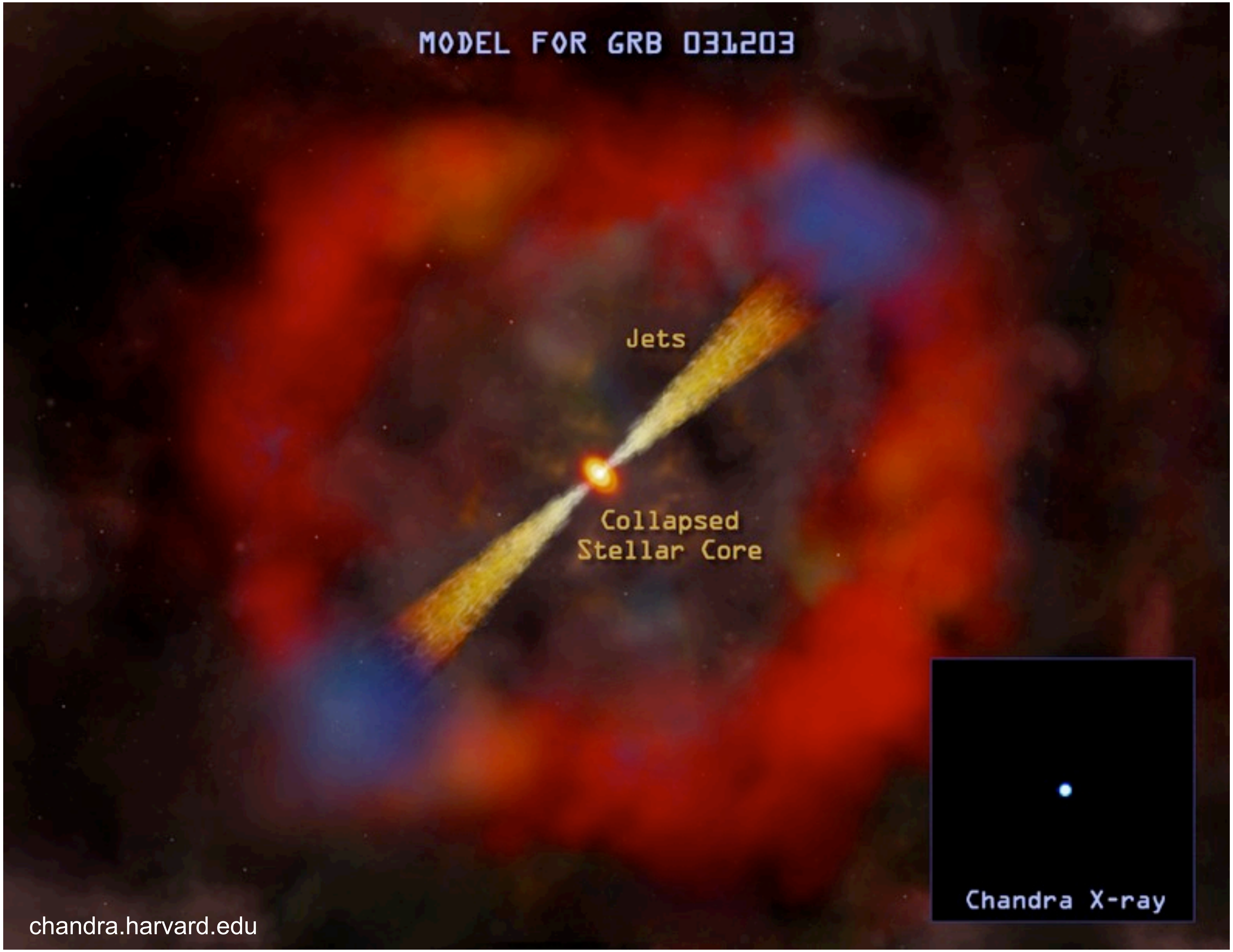
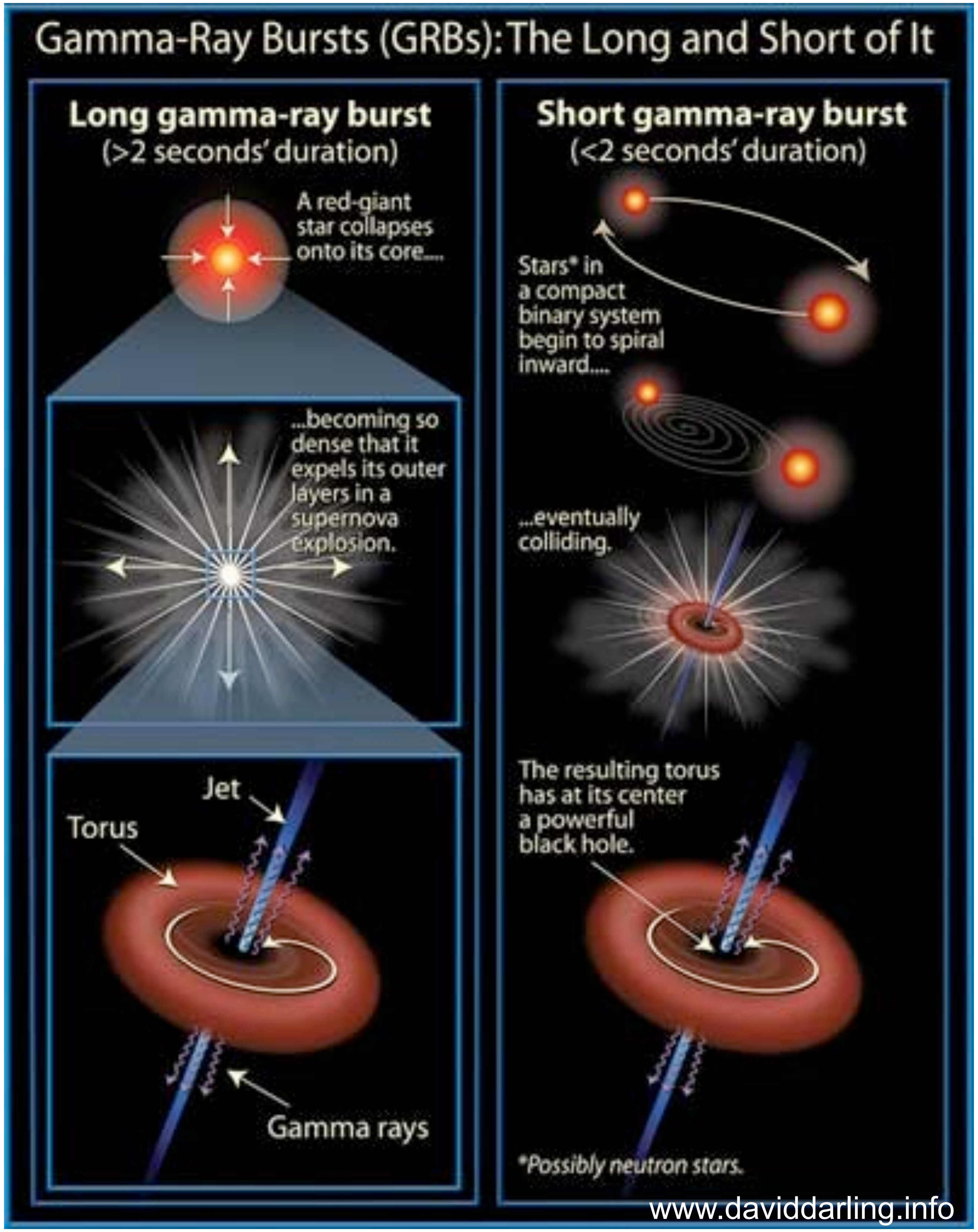





MODEL FOR GRB 031203
Jets
Collapsed
Stellar Core
Chandra X-ray
chandra.harvard.edu

Gamma Ray Bursts

- Gamma Ray Bursts were seen with the earliest satellites.
- CGRO studies in detail.
  - Isotropic --> Extragalactic
- redshift measurement 1997
- Very Energetic
  - Beamed: E ~ 10^{44} J
- Seem to be of two types
  - Long/Short Duration.



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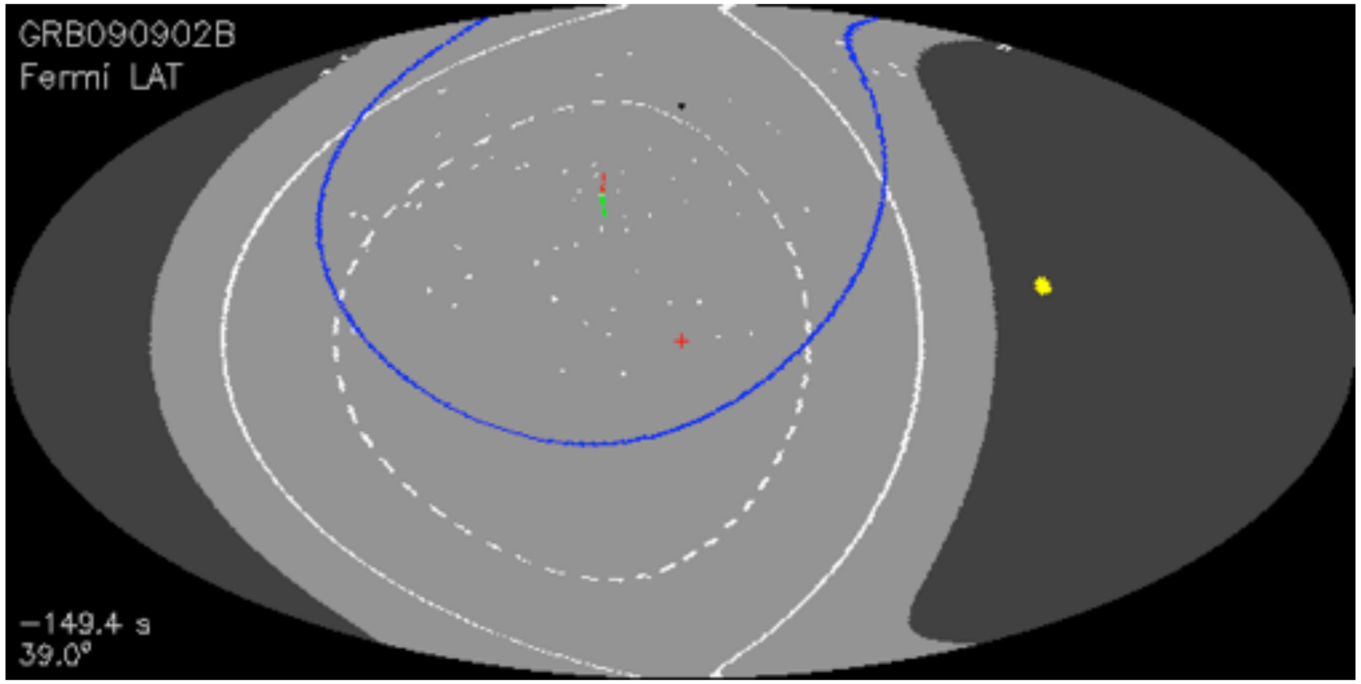

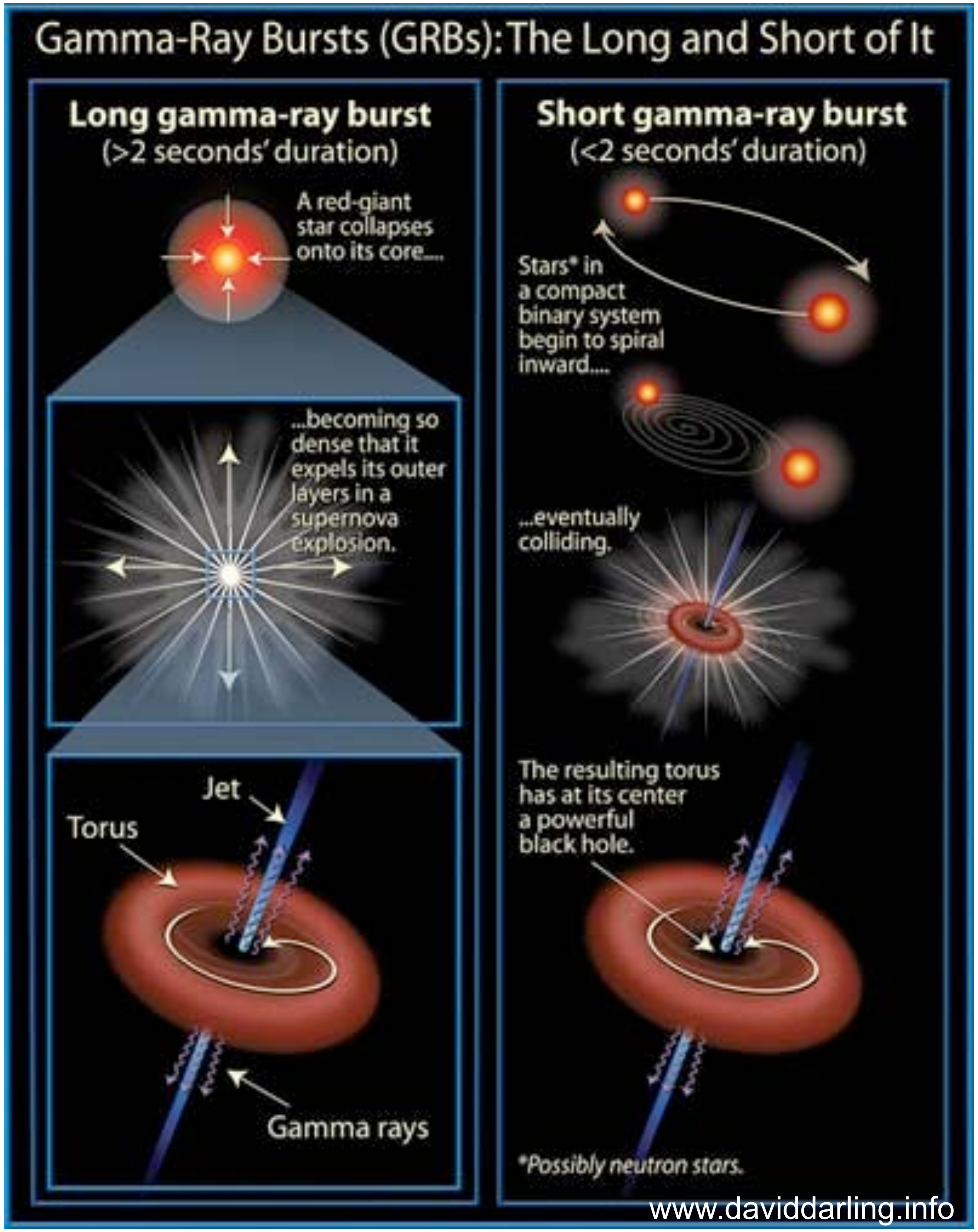

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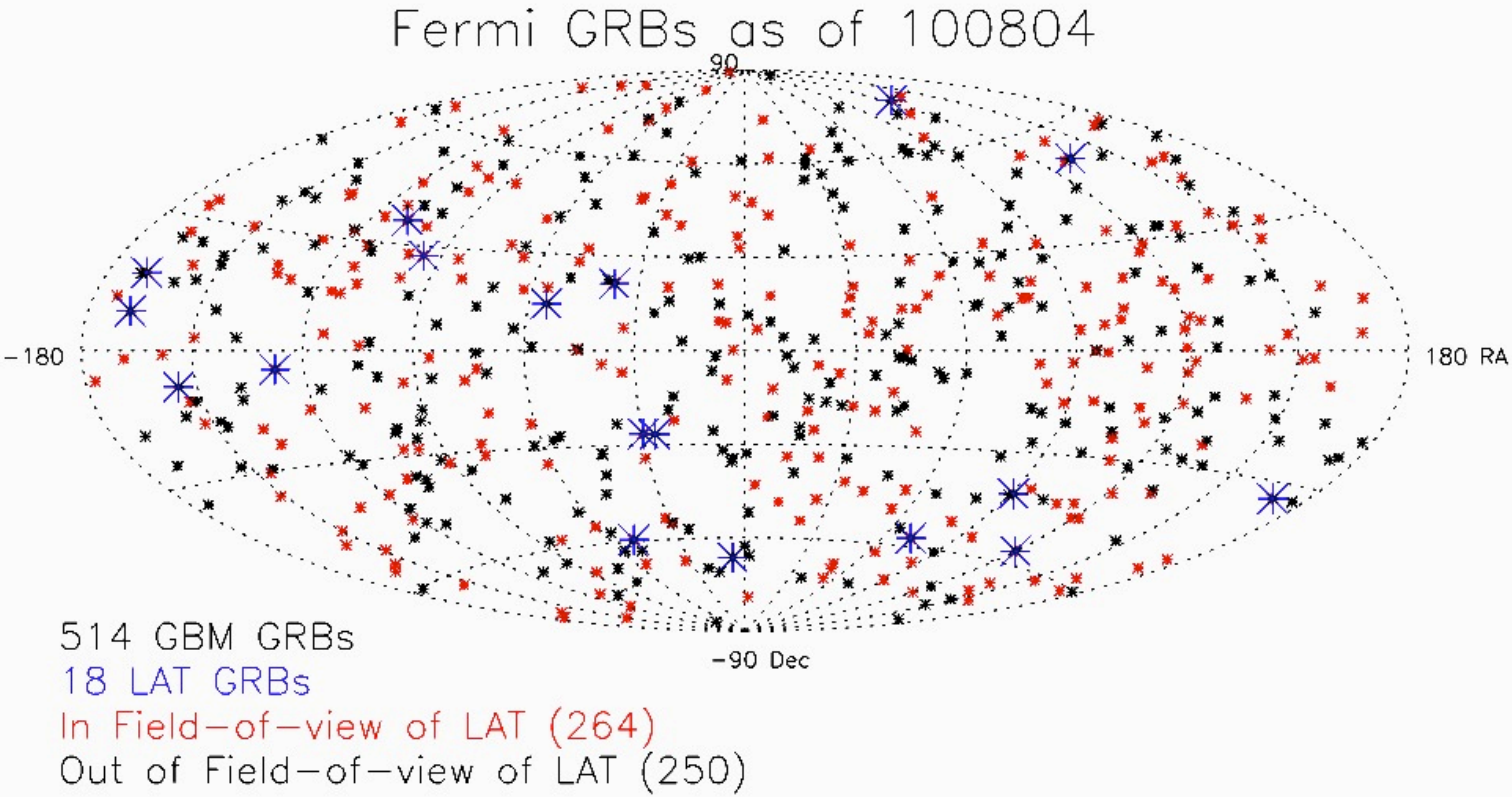
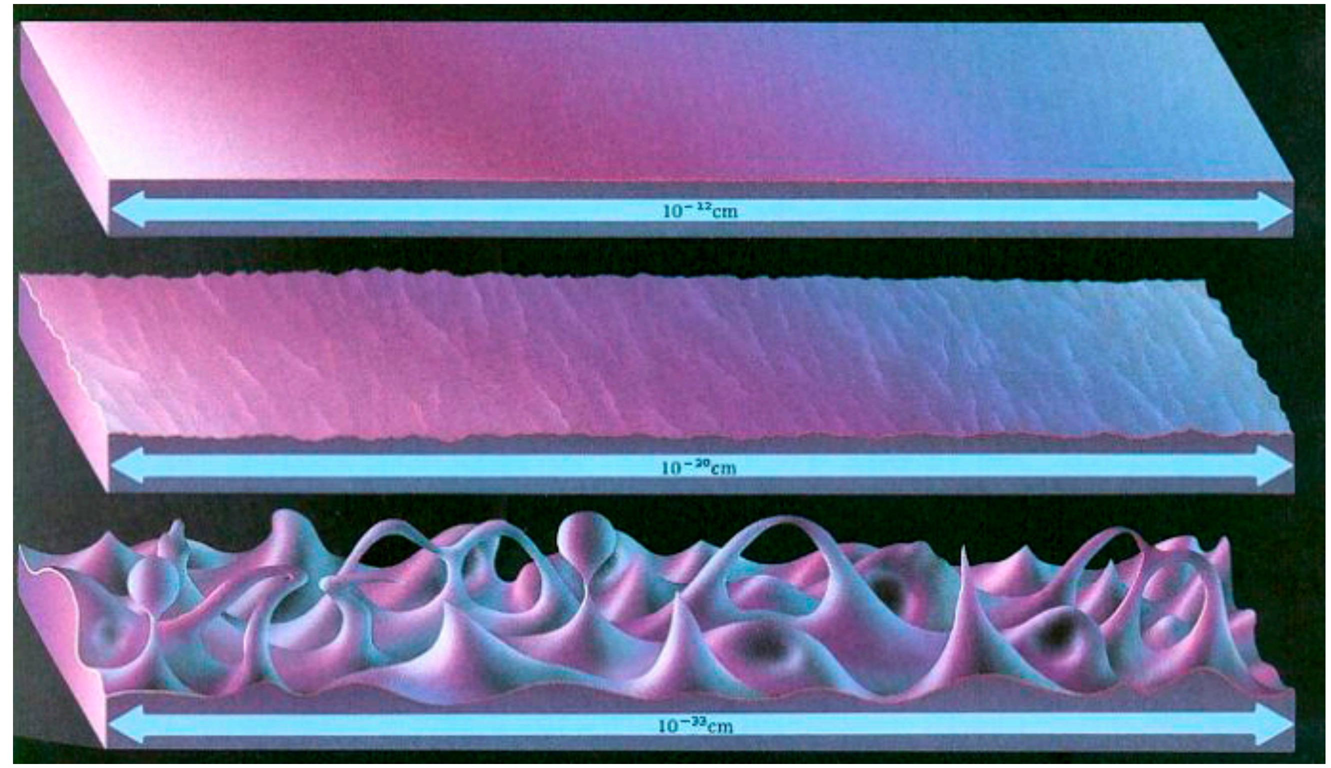


Observable Rate: ~ 1/day by satellites
Estimate: 1/galaxy/million years

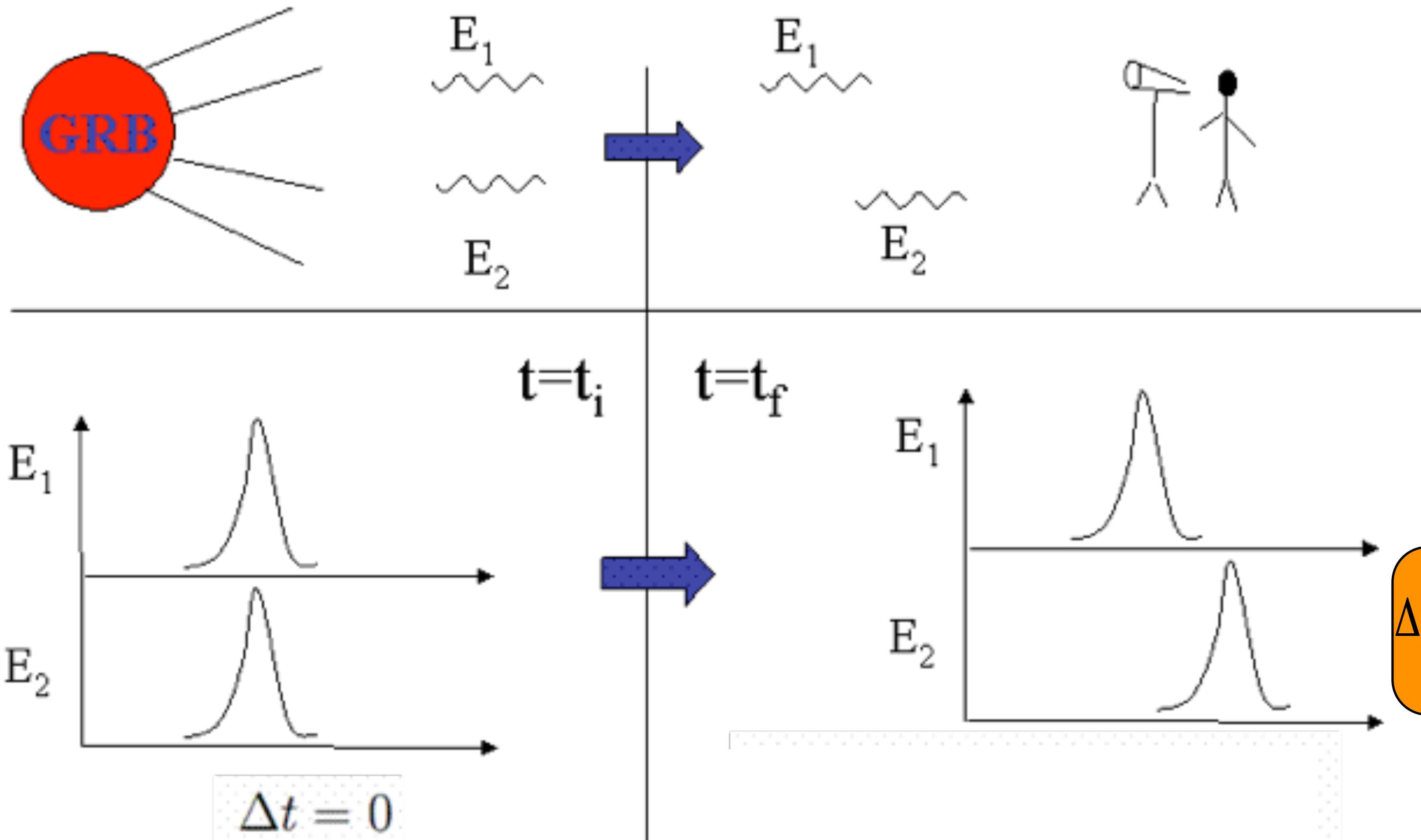
Test of Fundamental Physics

- Quantum Gravity could distort space at very small scales.
- Some Quantum Gravity Models predict that this distortion of space could lead to:
  - ⋆ Lorentz Invariance Violation (LIV)
  - ⋆ a.k.a: speed of light that is not constant.
  - ⋆ a.k.a: Speed that depends on wavelength (energy) of the light
- **<u>Very Small Effect</u>**...need:
  - ⋆ Source with a short pulse
  - ⋆ Emits light over a wide range of high energies
  - ⋆ Very Far Away.



A Gamma Ray Burst with:
*A short emission time
*High and Low Energy Gamma Rays
*A measured Redshift (i.e. Distance)

Basic Idea



For Distant GRBs the delays can be sizable and easily measurable.
Rough Numbers:

$$\Delta t \approx 10\,\mathrm{ms} \times \left[\frac{E_\gamma}{1\,\mathrm{GeV}}\right] \times \left[\frac{d_{CM}}{1\,\mathrm{Gpc}}\right] \quad \text{using } E_{QG} = E_{Plank}$$

$$\frac{p_{ph}^2 c^2}{E_{ph}^2} - 1 = \sum_{k=1}^{\infty} s_k \left(\frac{E_{ph}}{M_{QG,k}c^2}\right)^2 = \sum_{k=1}^{\infty} s_k \left(\frac{E_{ph}}{\xi_k M_{Planck} c^2}\right)^2$$

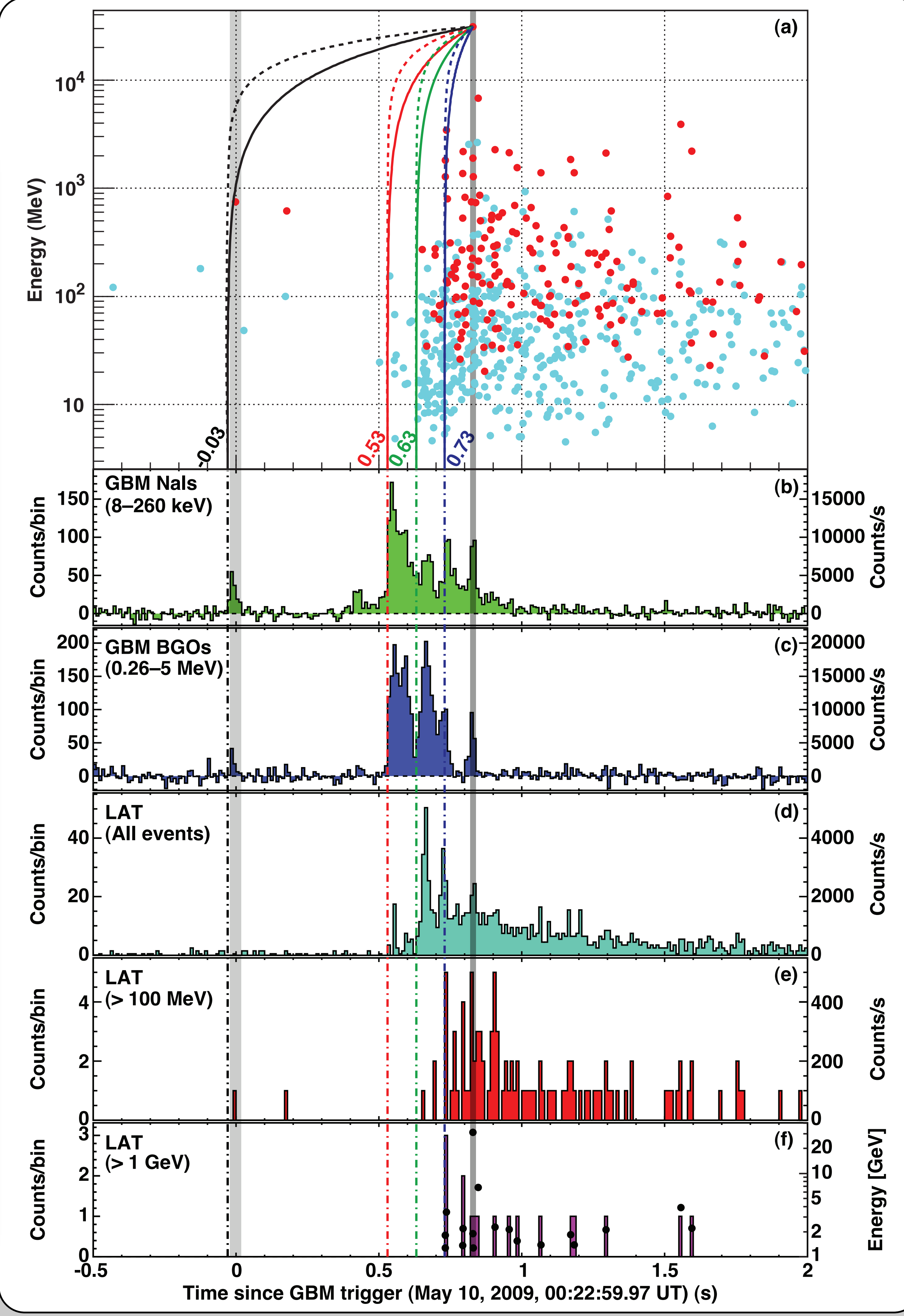
$$M_{QG,k} = \xi_k M_{Planck} \qquad s_k \in \{-1, 0, 1\}$$

$$v_{ph} = \frac{\partial E_{ph}}{\partial p_{ph}} \approx c\left[1 - s_n \frac{n+1}{2}\left(\frac{E_{ph}}{M_{QG,n}c^2}\right)^n\right] \qquad n = \min\{k | s_k \neq 0\}$$

$$\Delta t = s_n \frac{(1+n)}{2H_o} \frac{(E_h^n - E_l^n)}{(M_{QG,n}c^2)^n} \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}} dz'$$

GRB090510

- GRB090510: Short GRB w/ HE Photons
  - ⋆ After glow measured
  - ⋆ z = 0.903 +/- 0.003
- Short Pulses
  - ⋆ Observed in the GBM and LAT
- High Energy Gamma 31 GeV
  - ⋆ 1σ Range: 27.97 - 36.32 GeV
  - ⋆ Associated with GRB at 5σ
- **<u>Limits on QG:</u>**
  - ⋆ Assume 1st Pulse: $\xi_1 > 1.19$
  - ⋆ Analyze all HE: $\xi_1 > 1.2$
  - ⋆ Later Pulses: $\xi_1^{530ms} > 3.42$
    $\xi_1^{630ms} > 5.12$
    $\xi_1^{730ms} > 10.0$



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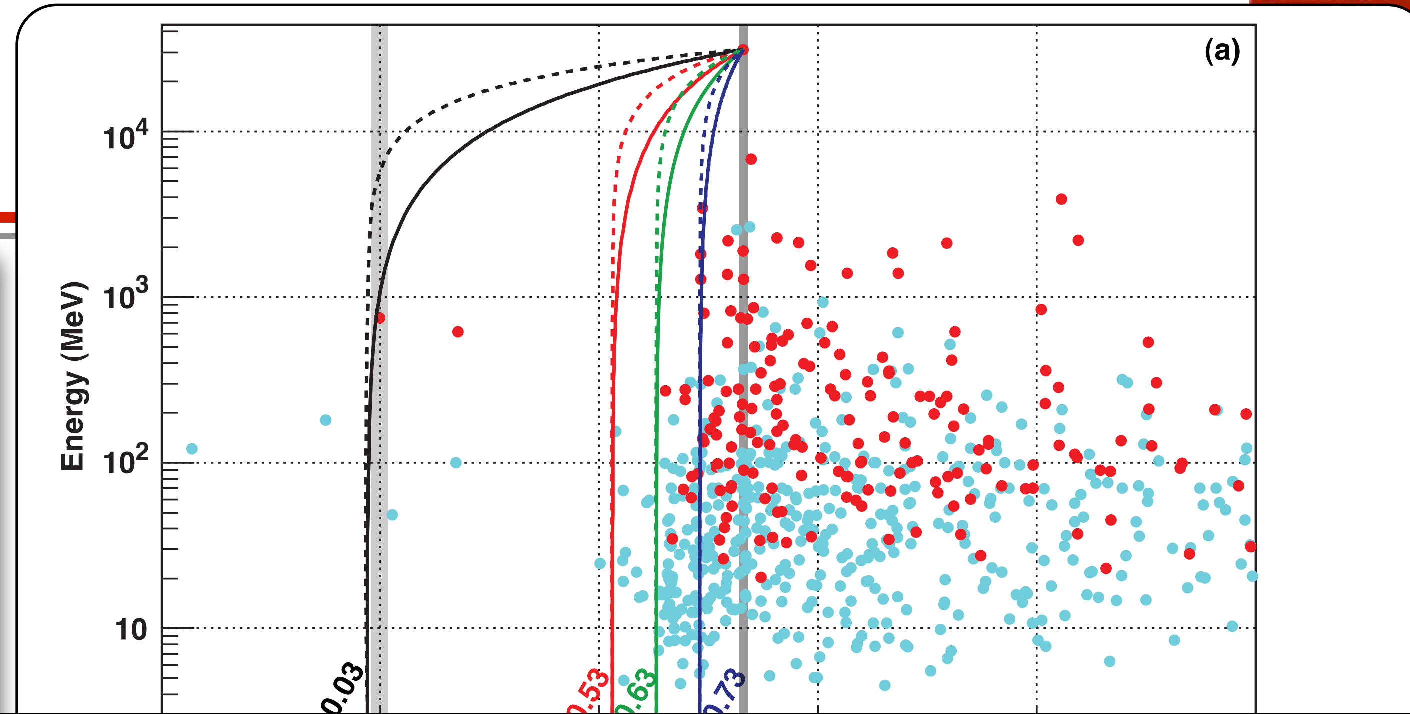

Conclusions:

* Strictest limits (n=1) ever placed on LIV by an order of magnitude

* Most QG Models have have $M_{QG,n} < M_{Planck} \quad (\xi_n < 1.0)$. Most conservative limits give limits above the Planck Energy

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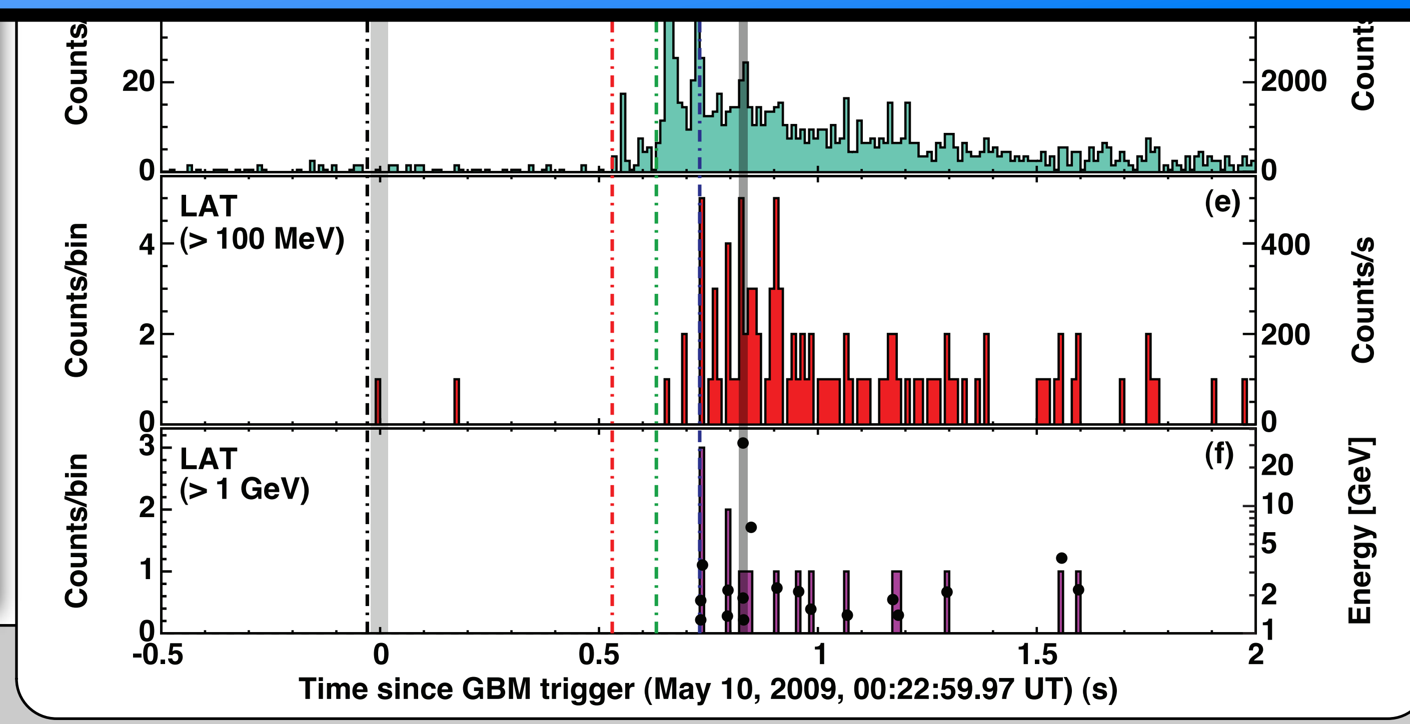

Summary

- Fermi has been working very well and carrying out a wide variety of astrophysical measurements.
- Multi-pronged Searches for Dark Matter WIMPs
  - Number of challenging topics still under study.
- Tests of fundamental physics (LIV)
- Fermi is a great detector of cosmic ray electrons/positrons.
- **We are ~2-3 years into a 5-10 year mission.**

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Hopefully most exciting results still to come!