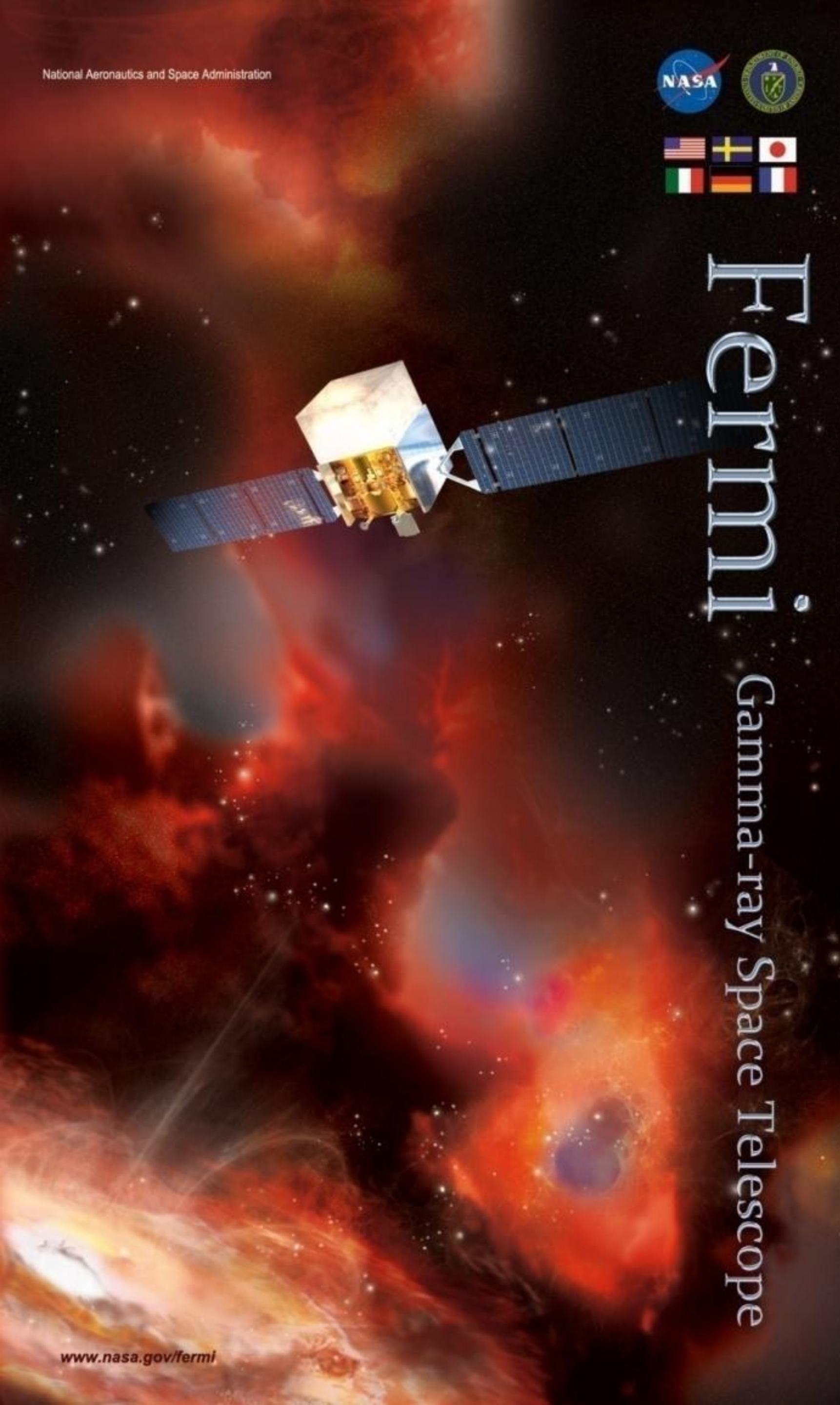


Indirect Detection Searches for Dark Matter with the *Fermi* LAT

Keith Bechtol for the ***Fermi* LAT Collaboration**

Brookhaven Forum 2011:

A First Glimpse of the Tera Scale

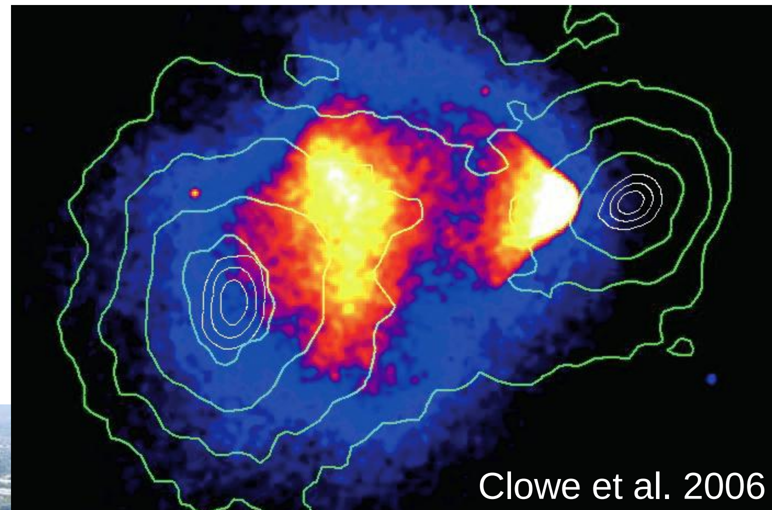
19 October 2011

NATIONAL ACCELERATOR LABORATORY

Dark Matter Search

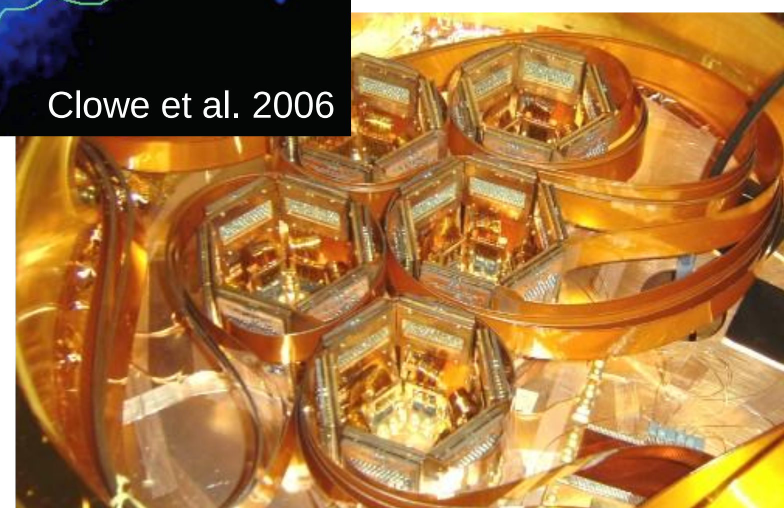
"…we suggest to view indirect searches as genuine particle physics experiments, complementing other strategies to probe so far unknown regions of parameter space…"
Bergstrom et al. 2011, Phys Rev D, 83, 045024

Three ***complementary*** search strategies



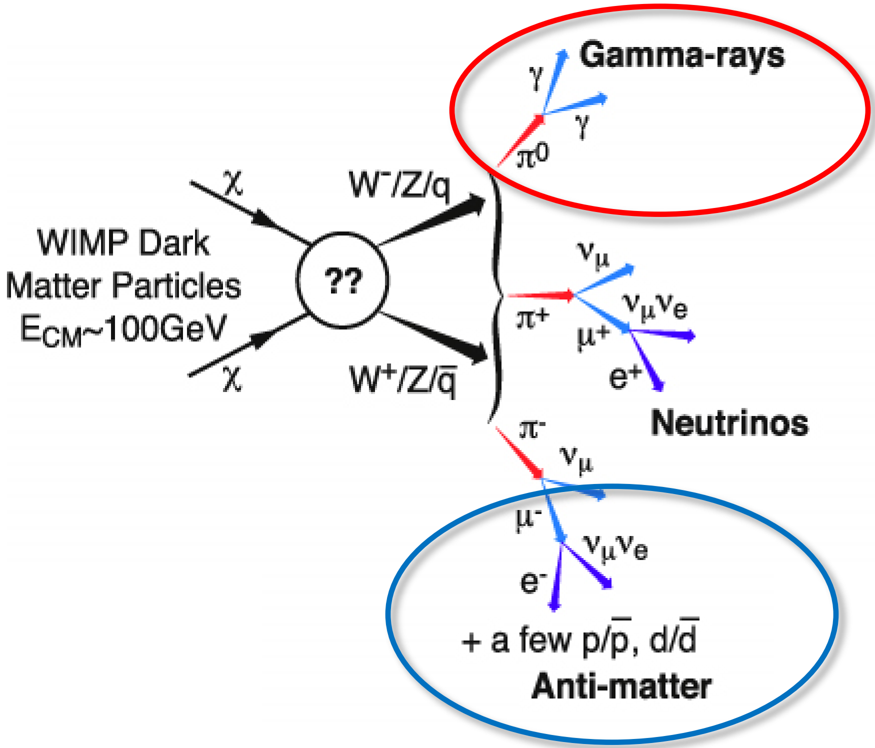
Indirect Detection

Accelerator-Based



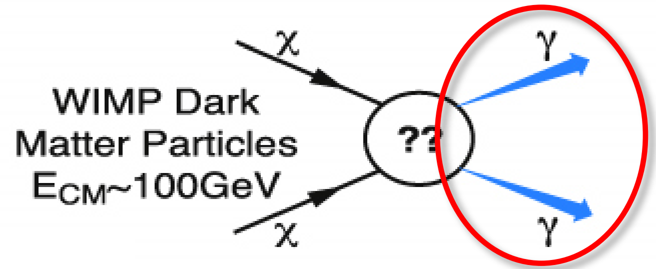
Direct Detection

Indirect Detection Channels



Search for anomalous features in cosmic rays

Search for excess gamma ray signal above astrophysical backgrounds



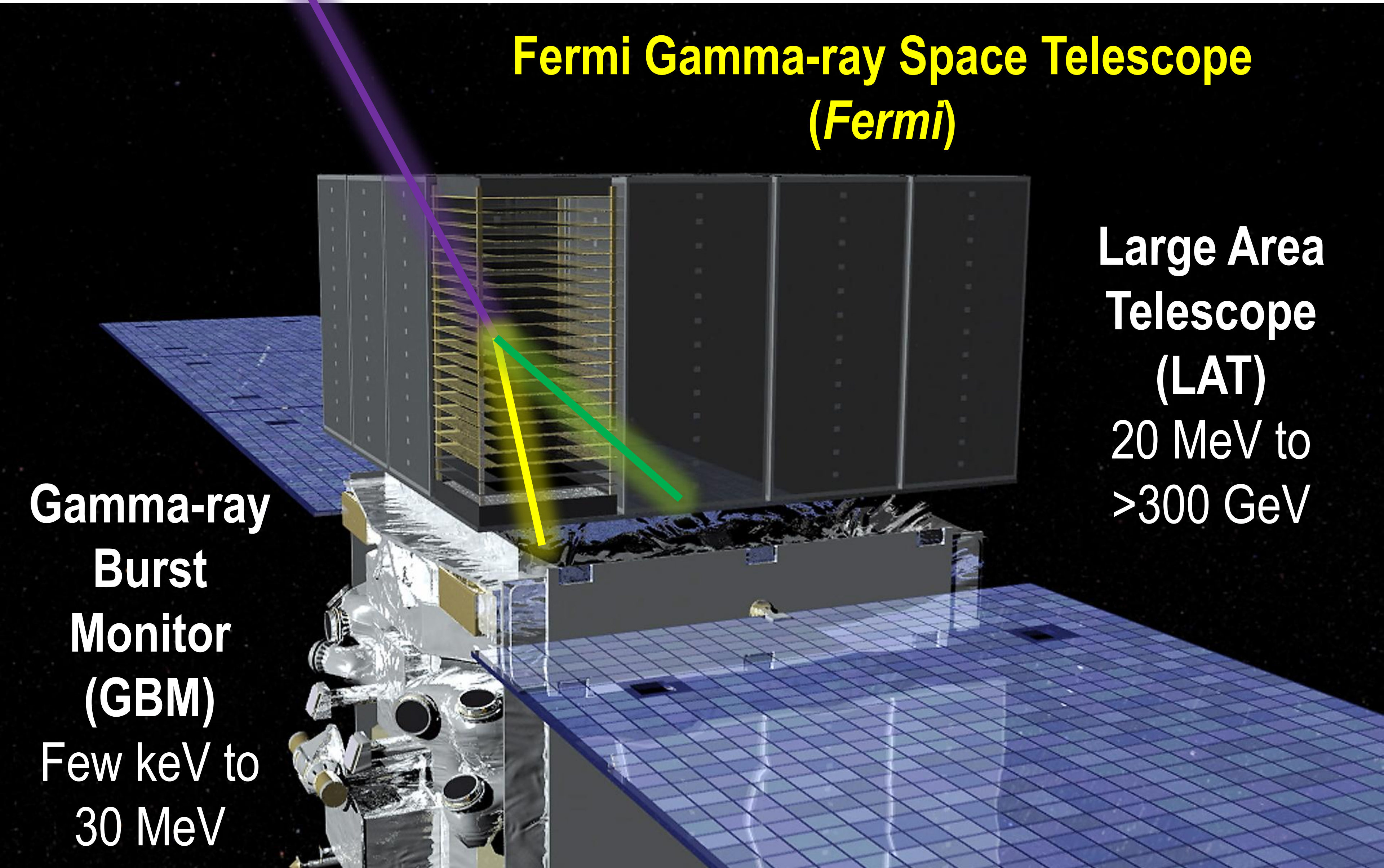
A particle detector in space is the ideal instrument for these studies

Fermi Dark Matter Search

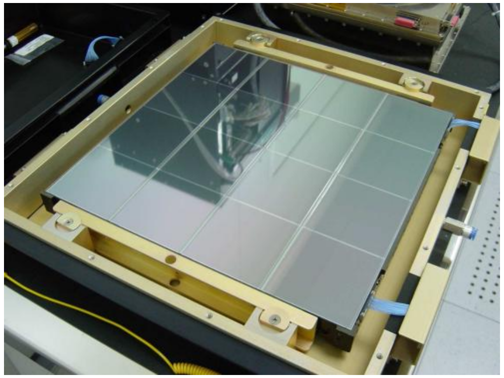
- Exploring the Extreme Universe
  - Particle Detector in Low Earth Orbit
  - Tour of the GeV Gamma-ray Sky
- Search Results (limits)
  - Strategies
  - Gamma rays
    - Galactic Center
    - Milky Way Subhalos
    - Galaxy Clusters
    - Isotropic Diffuse
  - Electrons and Positrons
- Outlook

Springel et al. 2008

Pair-Conversion Technique

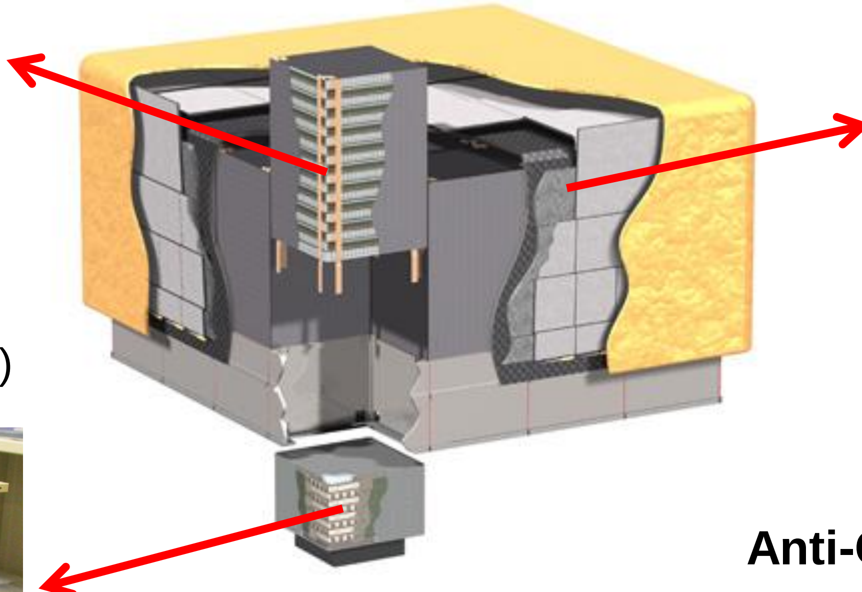


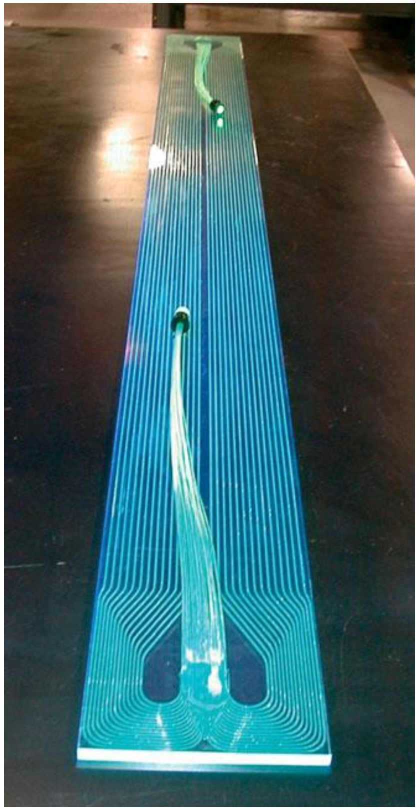
LAT Detector Subsystems



Precision Converter and Tracker

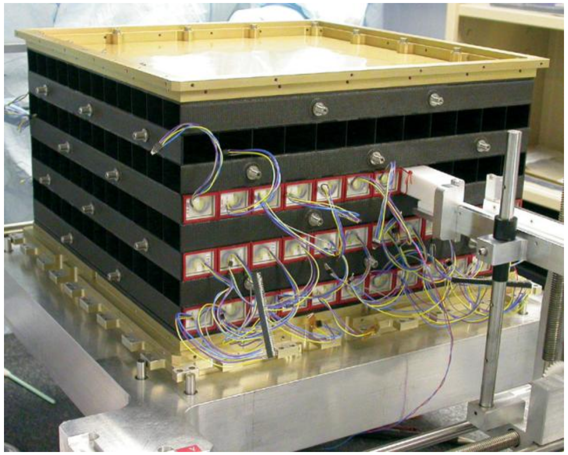
- Single sided SSD (40 cm, 228 um) ~ 80 m^2
- W foil interleaved (12x3% RL, 4x18% RL)
- 18 xy planes
- 1.5 RL





Imaging Calorimeter

- 8.6 R.L.
- 1536 CsI crystals
- Hodoscopic (12 x 8 layers)



Anti-Coincidence Detector

- 4% RL
- Segmented (89 plastic scintillator tiles, 8 ribbons)
- 0.9997 efficiency

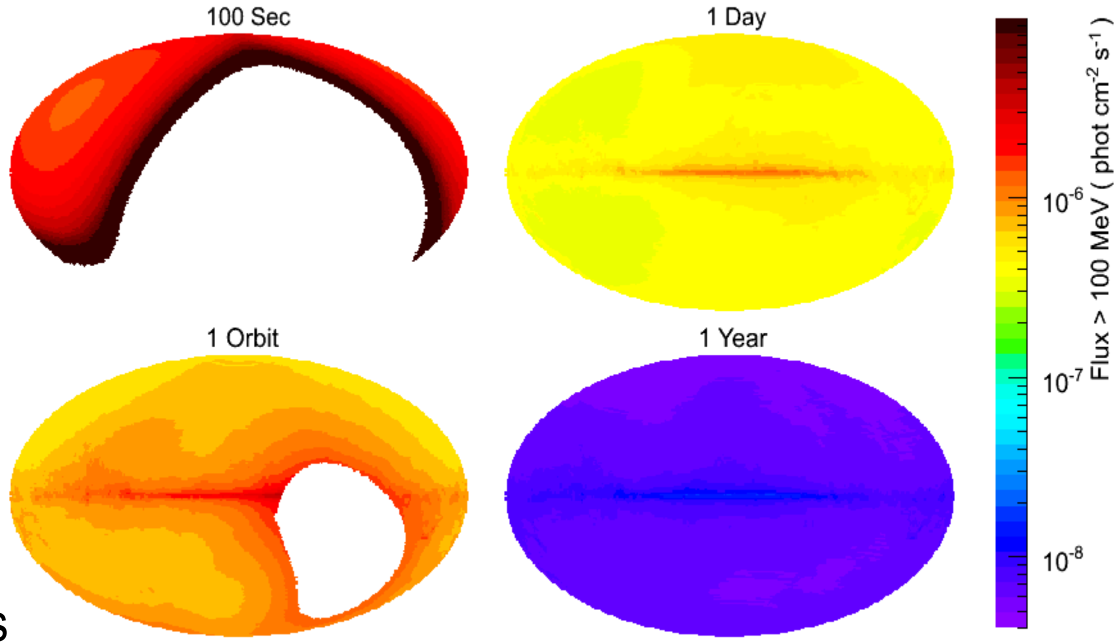
(+ Data Acquisition System)

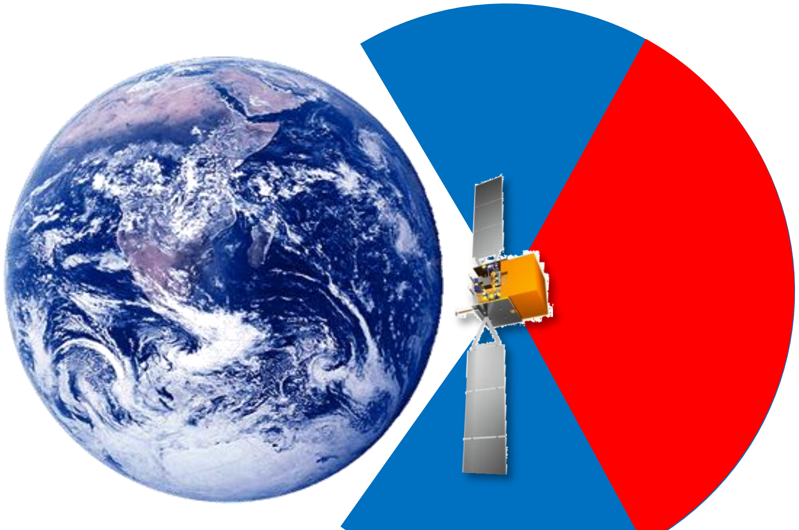
500 Hz sent to ground

- Launched 11 June 2008
- 3 years of successful operations
- Expected lifetime of 10+ years

Observation Modes

- Sky-survey mode
  - Normal operations mode
  - Full-sky every 2 orbits (~3 hrs)
- Target of Opportunity
  - Autonomous re-pointing for GRBs
  - Slew to keep target in FoV
  - Proposed pointed observations





Wide Field of View

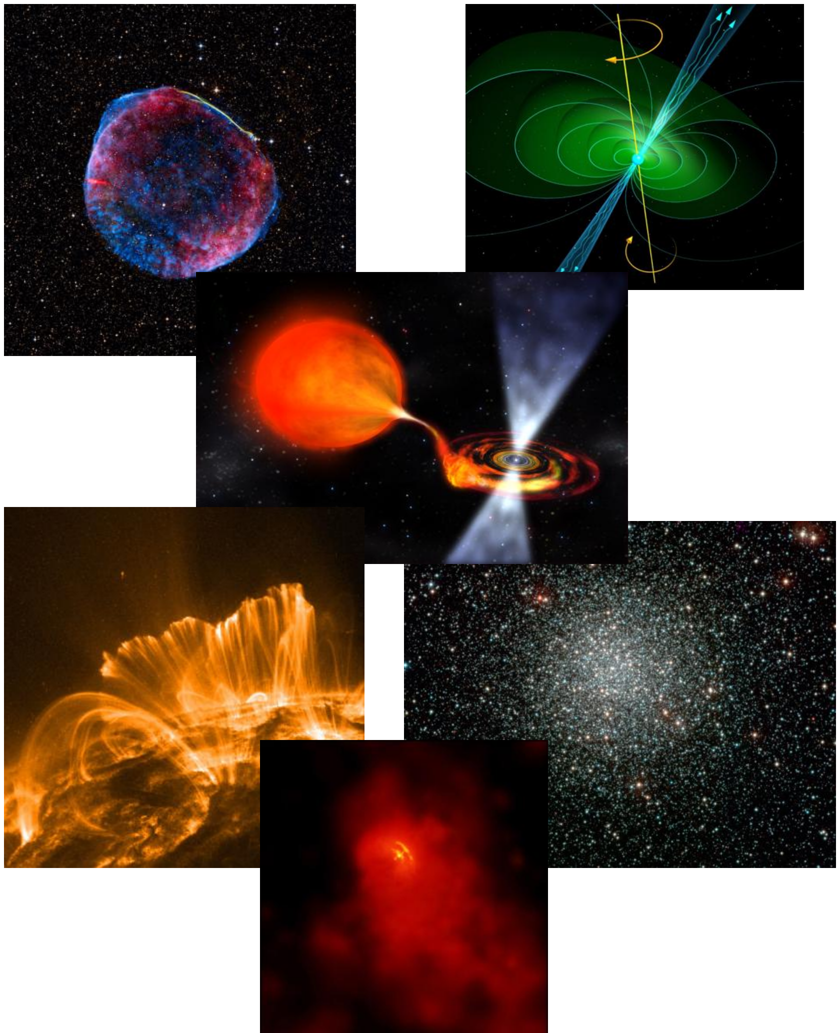
LAT : ~2.4 sr, 20% of sky

GBM: Almost entire sky not occulted by Earth

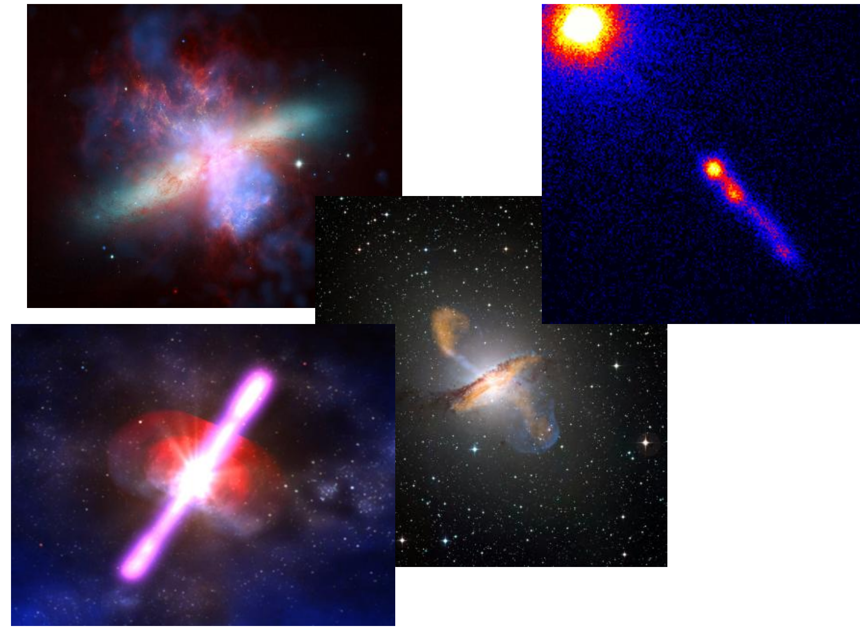
Fermi LAT Collaboration

Exploring the Extreme Universe

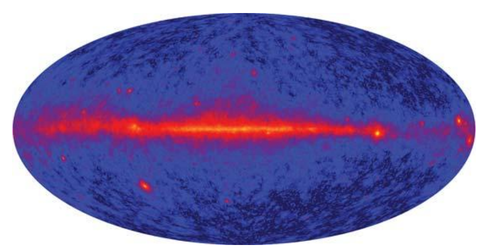
Galactic Accelerators



Extragalactic Accelerators

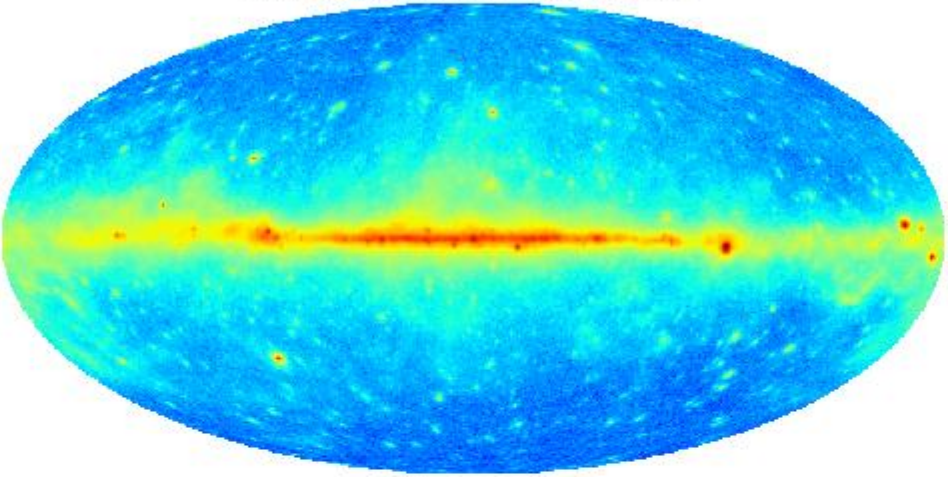


Cosmic Rays

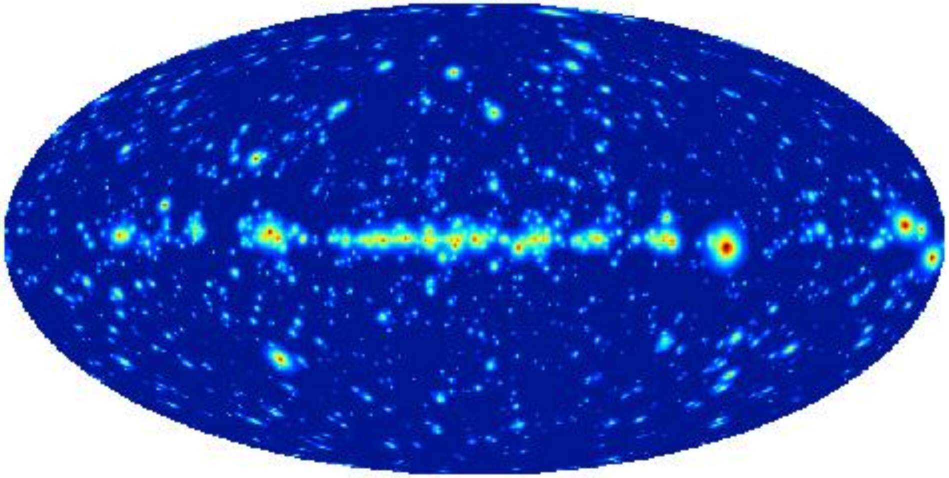


Tour of the GeV Gamma-ray Sky

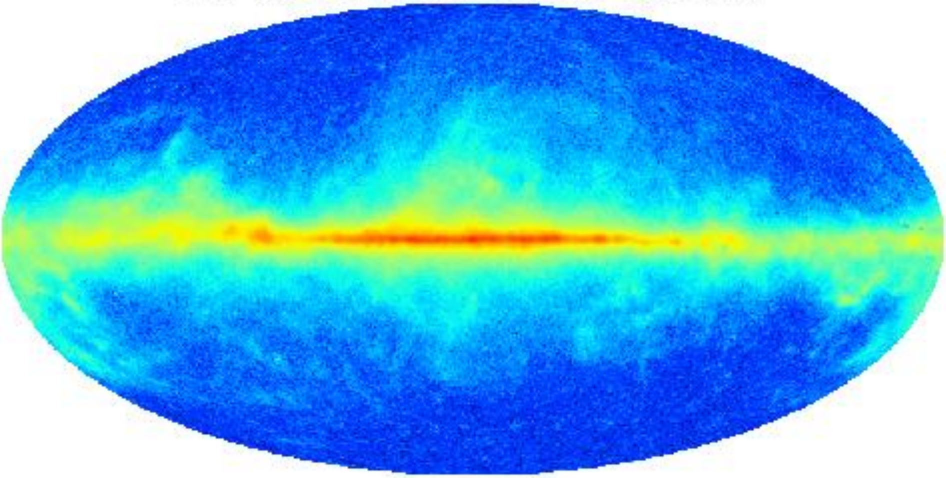
LAT photons above 300 MeV



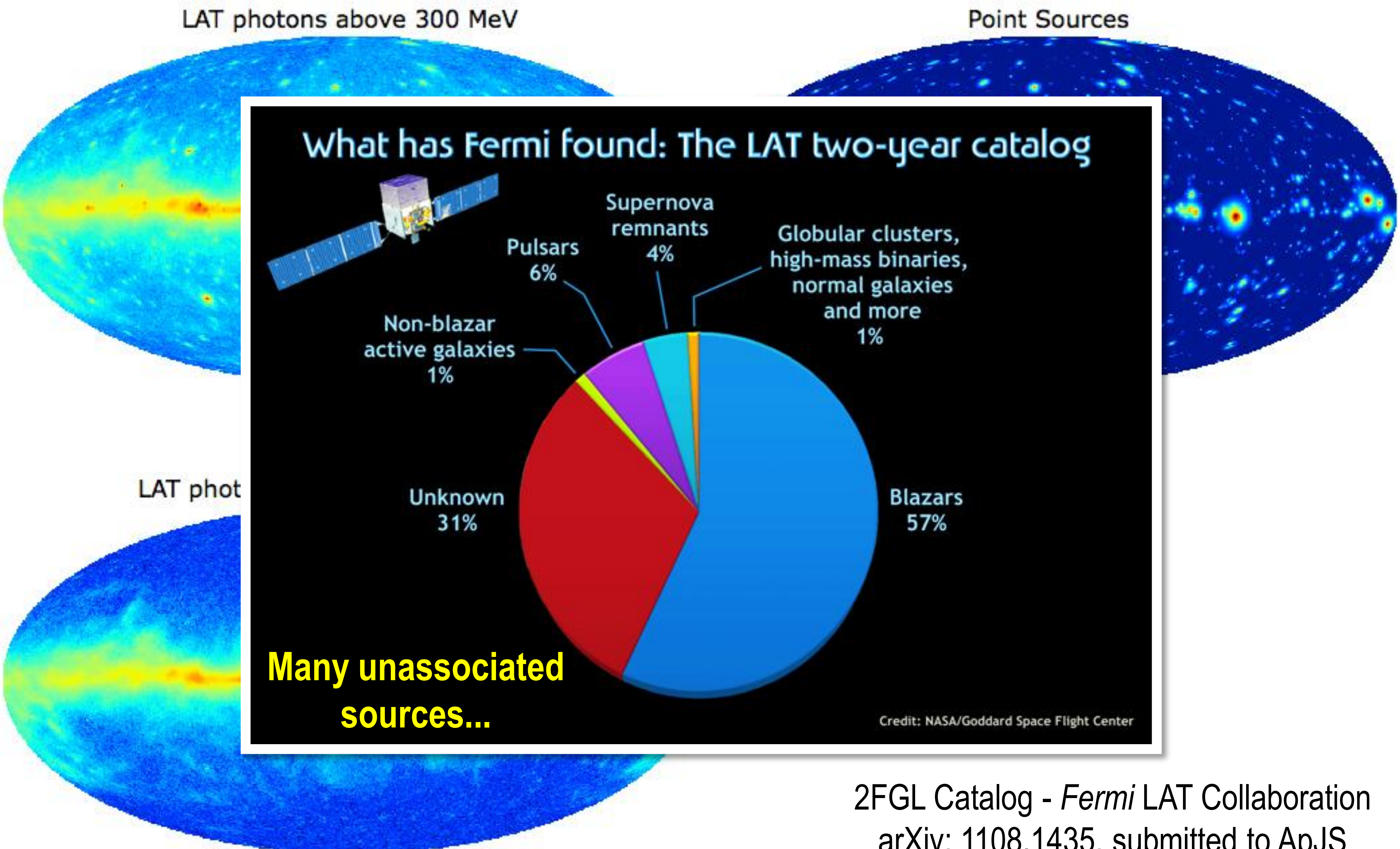
Point Sources



LAT photons from Galactic emission



Tour of the GeV Gamma-ray Sky



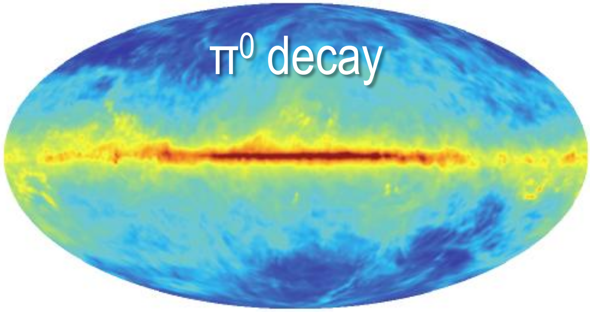
2FGL Catalog - *Fermi* LAT Collaboration
arXiv: 1108.1435, submitted to ApJS

Physics of Cosmic Rays

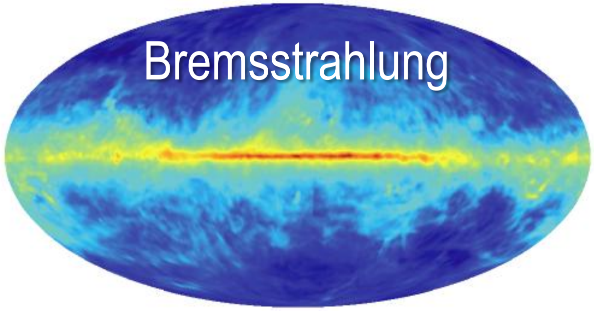
- Dominant components of interstellar energy density are *non-thermal*
  - Cosmic rays + Magnetic fields
- Complex interactions
  - **Sources:** Galactic accelerators, reacceleration, spallation, secondaries
  - **Transport:** Diffusion, convection, escape
  - **Radiative cooling:** radio synchroton, gamma-rays

Gamma-rays extend our knowledge of cosmic rays throughout the galaxy

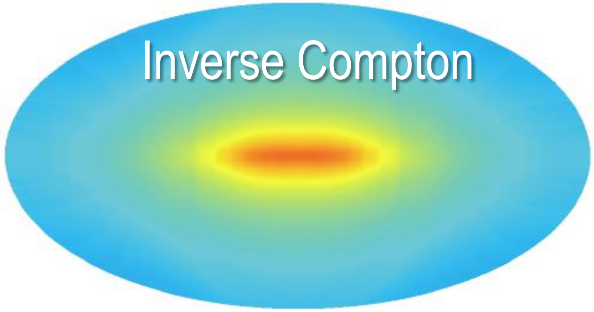
Nuclei + ambient gas



e^+e^- + ambient gas



e^+e^- + radiation fields



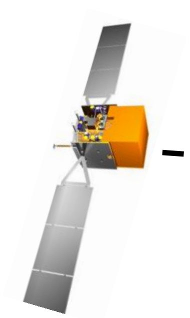
Expected Annihilation Signal

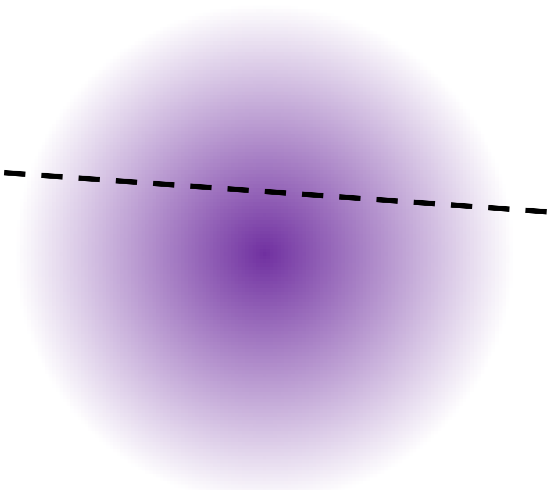
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_{ann}v\rangle}{2m_\chi^2}\sum_f \frac{dN_\gamma^f}{dE_\gamma}B_f \times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(\vec{r}(l,\theta',\phi'))dl$$

Observed Gamma Rays

Particle Interactions

Line of sight through dark matter distribution





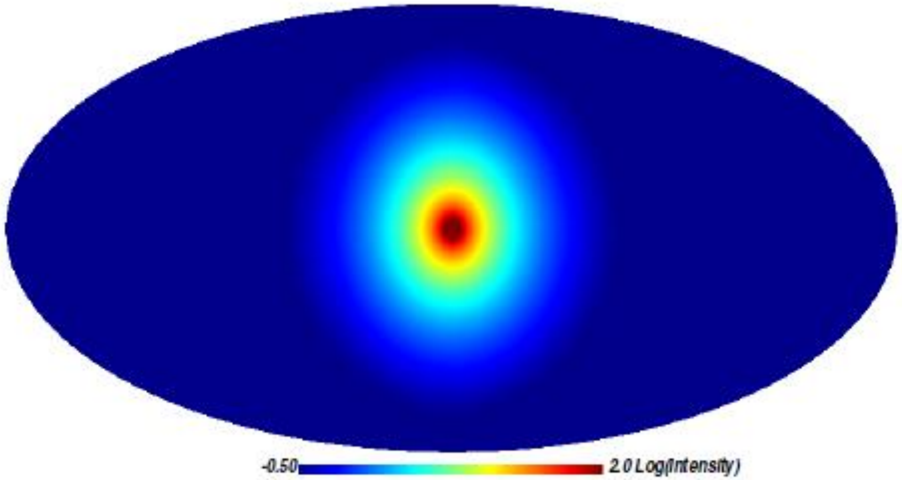
(+ final state radiation + internal bremsstrahlung)

Two-body collision rate coefficient depends on velocity distribution

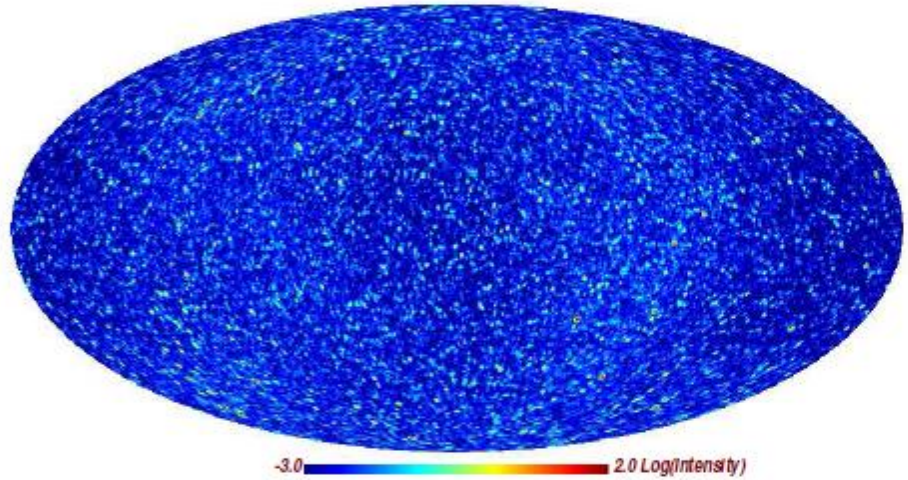
$$\langle\sigma_{ann}v\rangle = \int_0^\infty \sigma_{ann}(v)vf_v dv$$

Expected Annihilation Signal

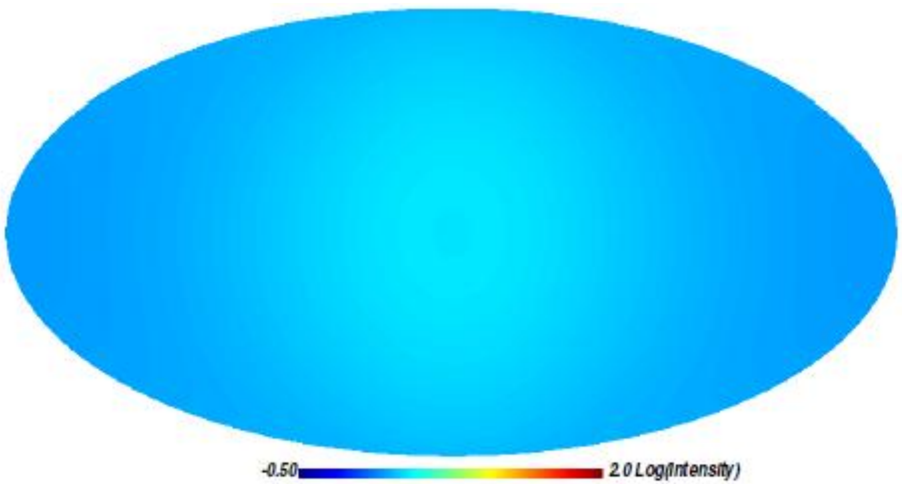
Smooth Main Halo



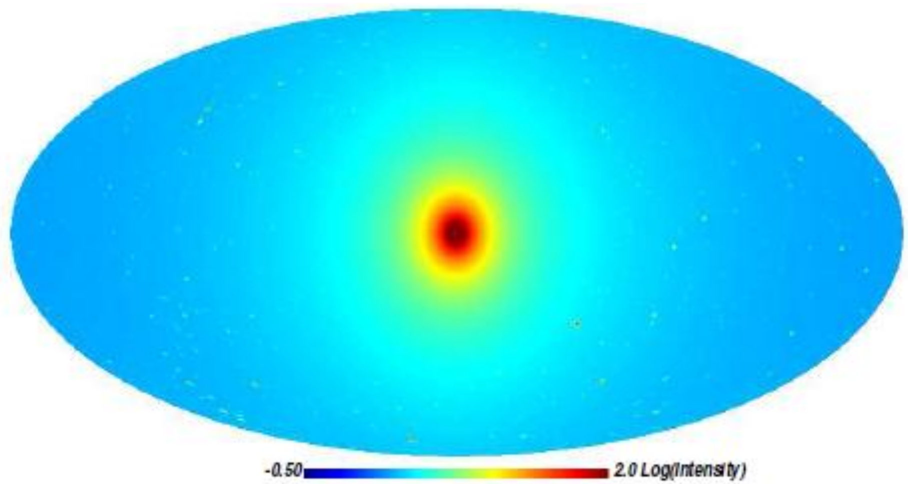
Resolved Subhalos



Unresolved Subhalos

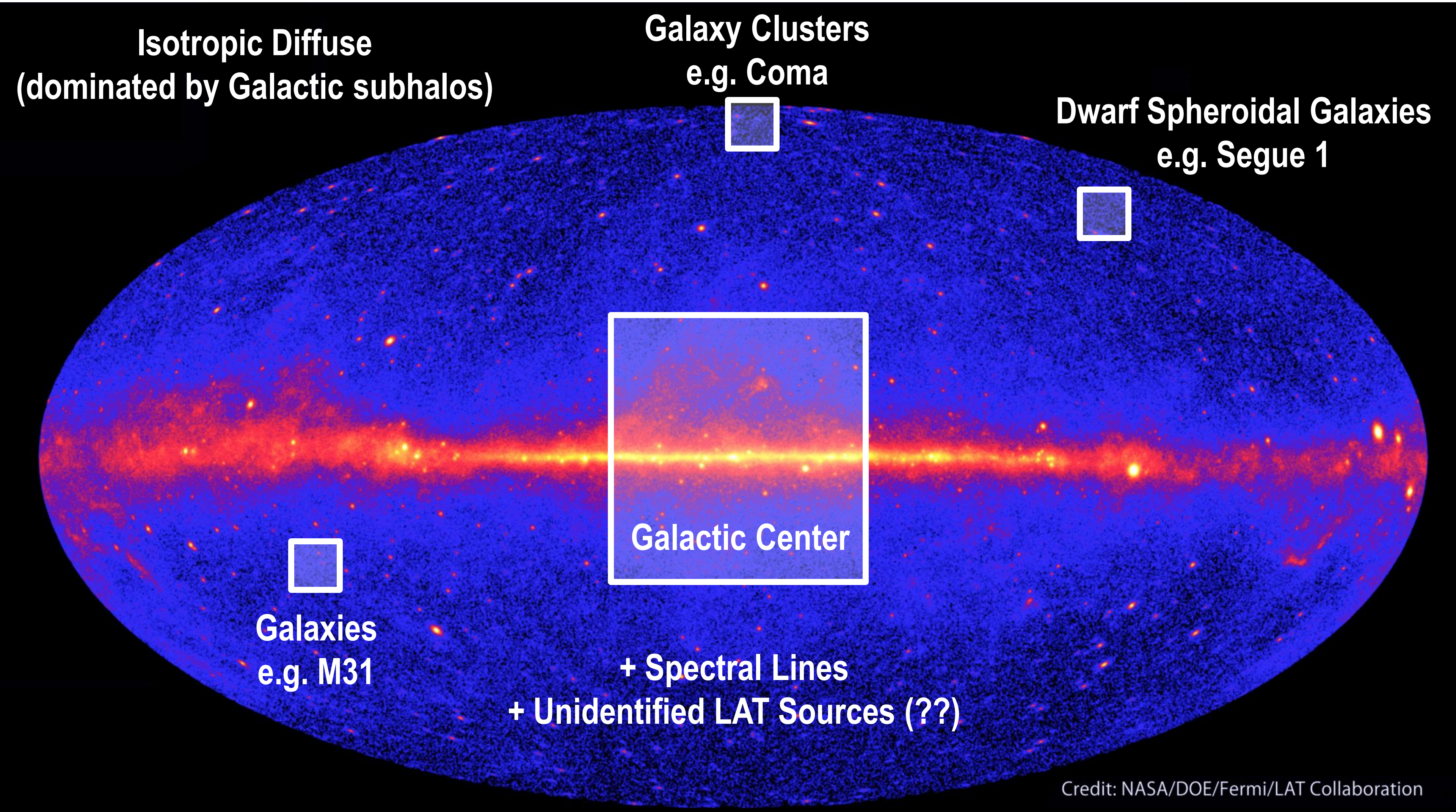


Total Emission



Springel et al. 2008

Gamma-ray Search Strategies

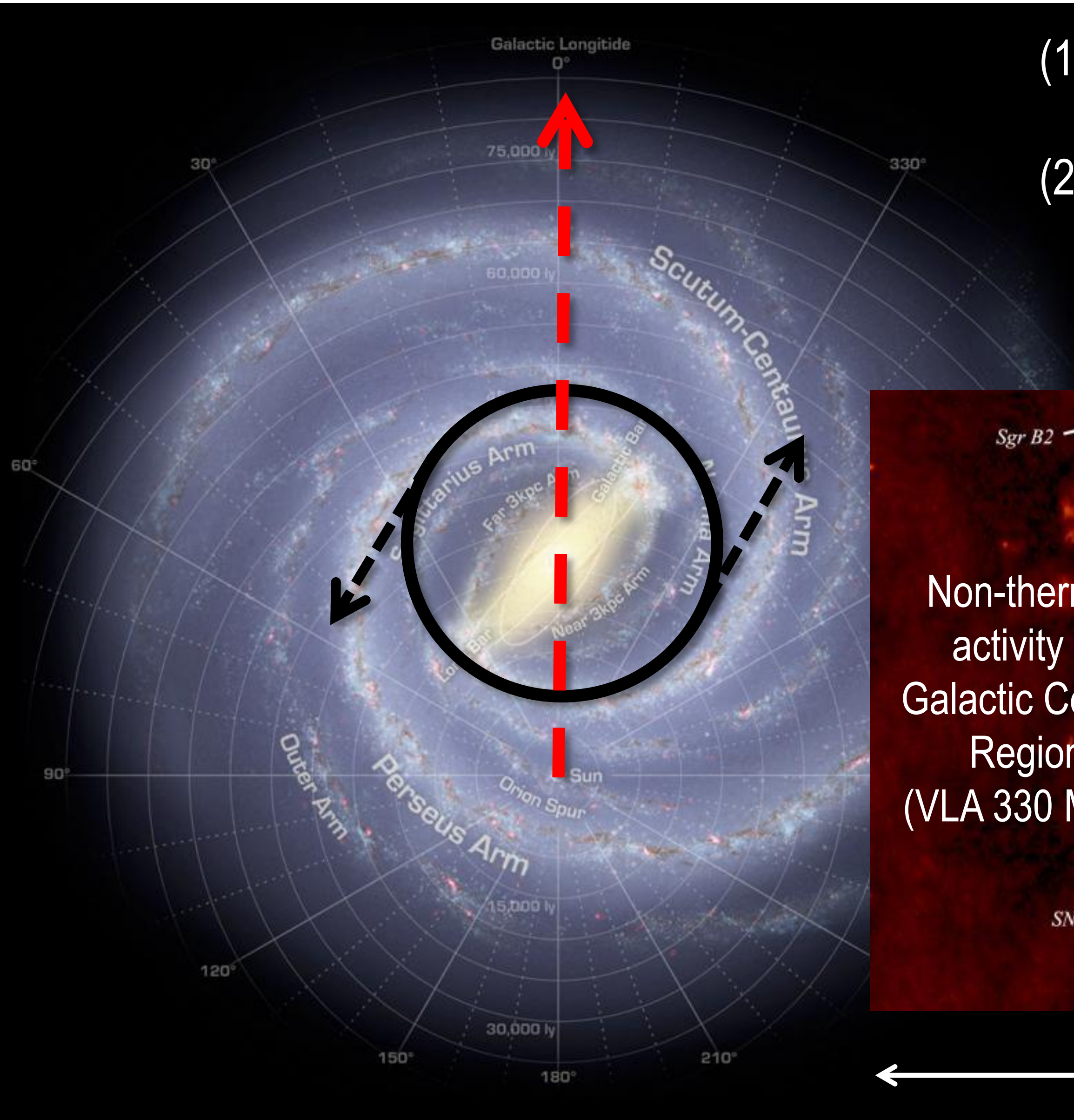


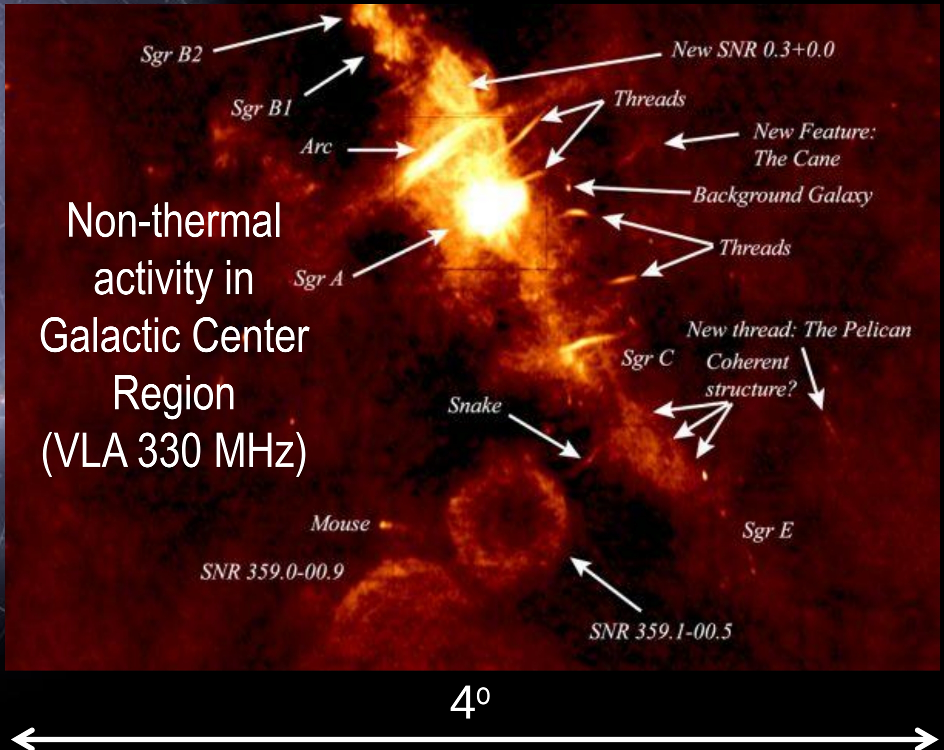
Trade-off between signal strength versus astrophysical background

Galactic Center Challenges

(1) Uncertain distances to ambient gas

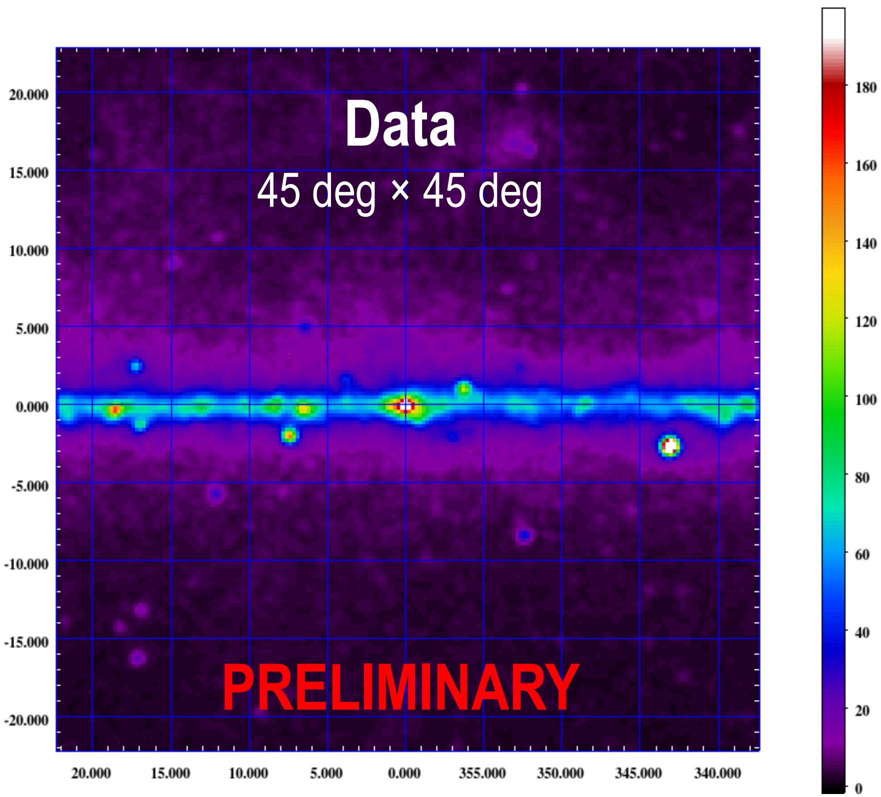
(2) Source confusion

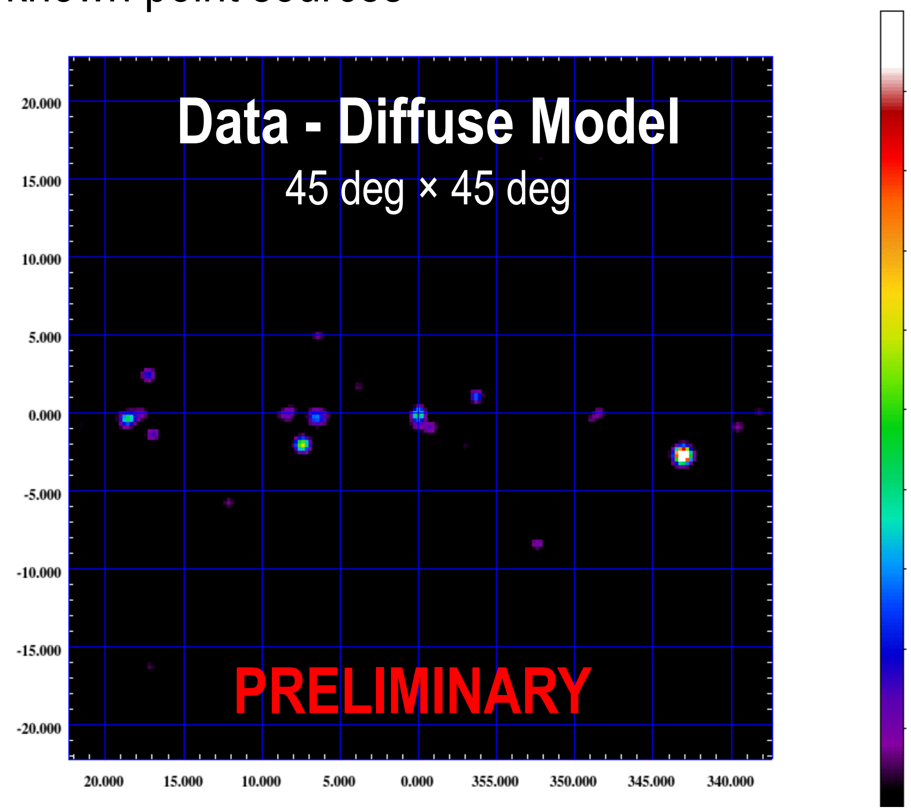




Fermi LAT View of Galactic Center

- 32 months of LAT data, energy >1 GeV
- Physically motivated numerical diffuse model (GALPROP) accounts for most of emission in region
  - Peaks in residuals consistent with known point sources



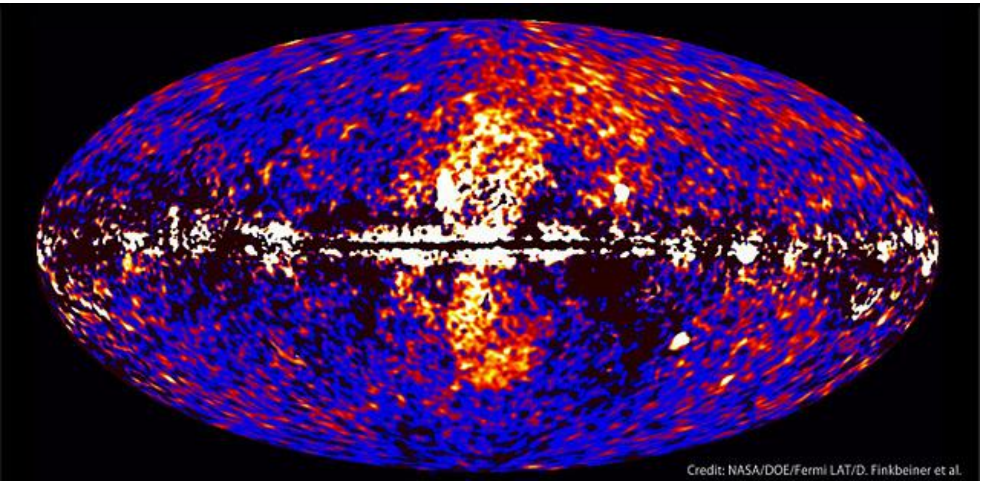


See also combined *Fermi* and H.E.S.S. analysis by Cheryakova et al. 2011

Large Scale Diffuse Residuals

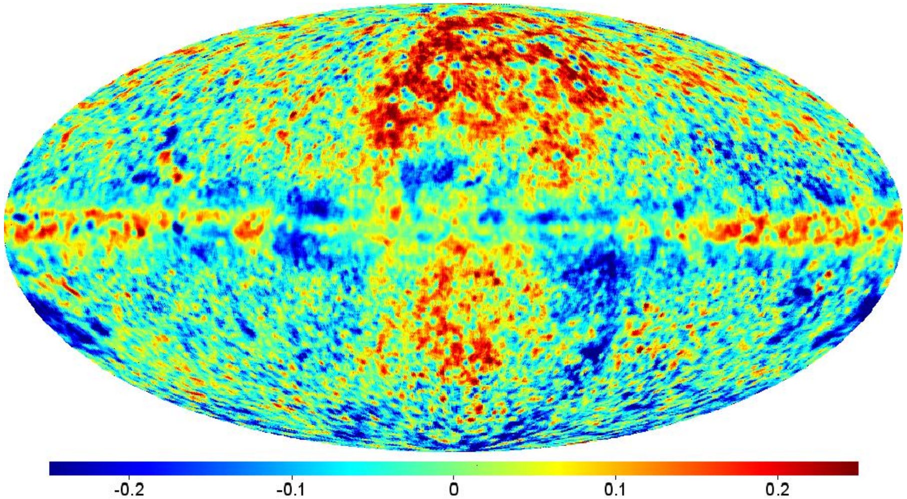
- Large scale residuals towards Galactic Center (Su et al. 2010)
  - Extended (50° above/below Galactic Center)
  - Hard spectrum relative to other diffuse components (E^{-2}, 1-100 GeV)
  - Sharp edges
  - Possible counterparts at microwave (WMAP) and X-ray (ROSAT) bands

Data – Model (1-100 GeV)



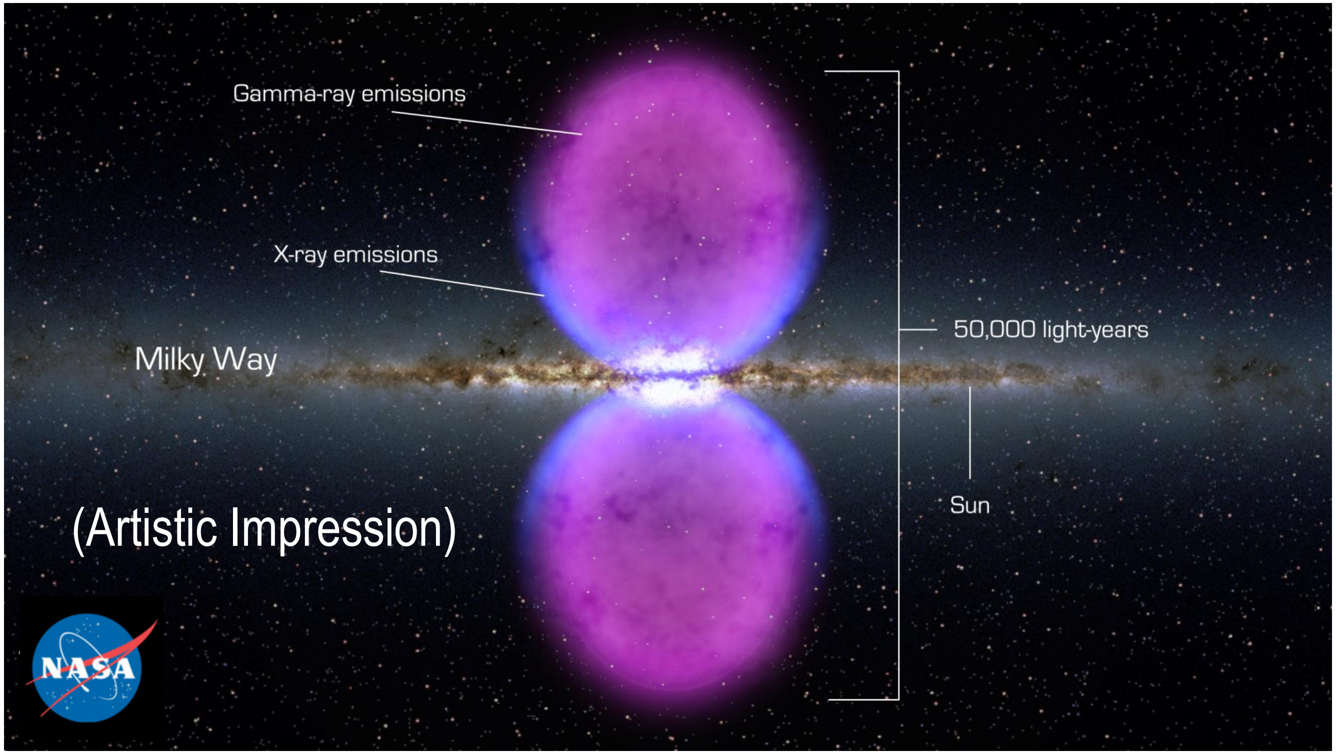
Su, Slatyer, & Finkbeiner 2010

Data - Example Model (0.2-100 GeV)



Fermi LAT Collaboration **Preliminary**

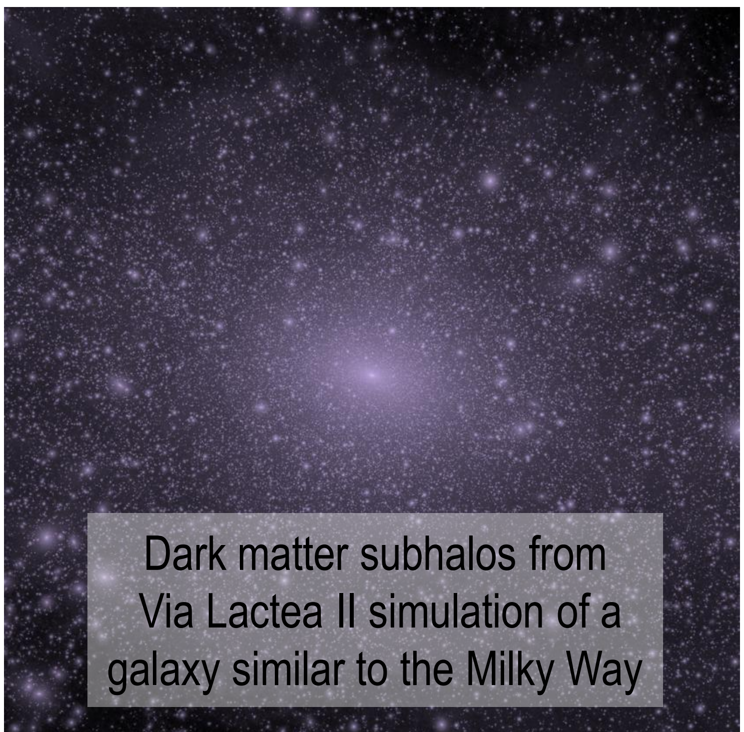
Interpretation??



- Radiation mechanism
  - Inverse Compton scattering by high energy electrons (?)
- Proposed sources
  - "Lobes" with sharp edges difficult to explain with dark matter annihilation/decay
  - Jets from the supermassive black hole during prior active phase
  - Starburst driven outflows

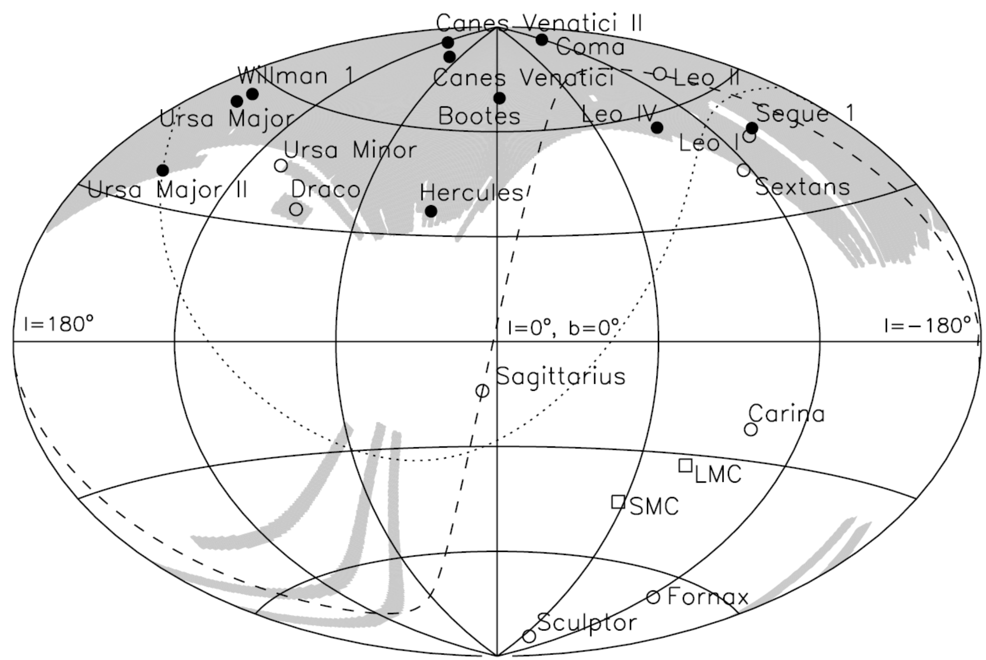
Milky Way Subhalos

- Optically detected dwarf spheriodal galaxies
  - Largest clumps of dark matter predicted by N-body simulations
  - Dark matter dominated (mass to light ratios of 10 – 1000)
  - Astrophysically "clean" – little star-formation, gas
  - ~25 discovered to far, many more predicted



Dark matter subhalos from Via Lactea II simulation of a galaxy similar to the Milky Way

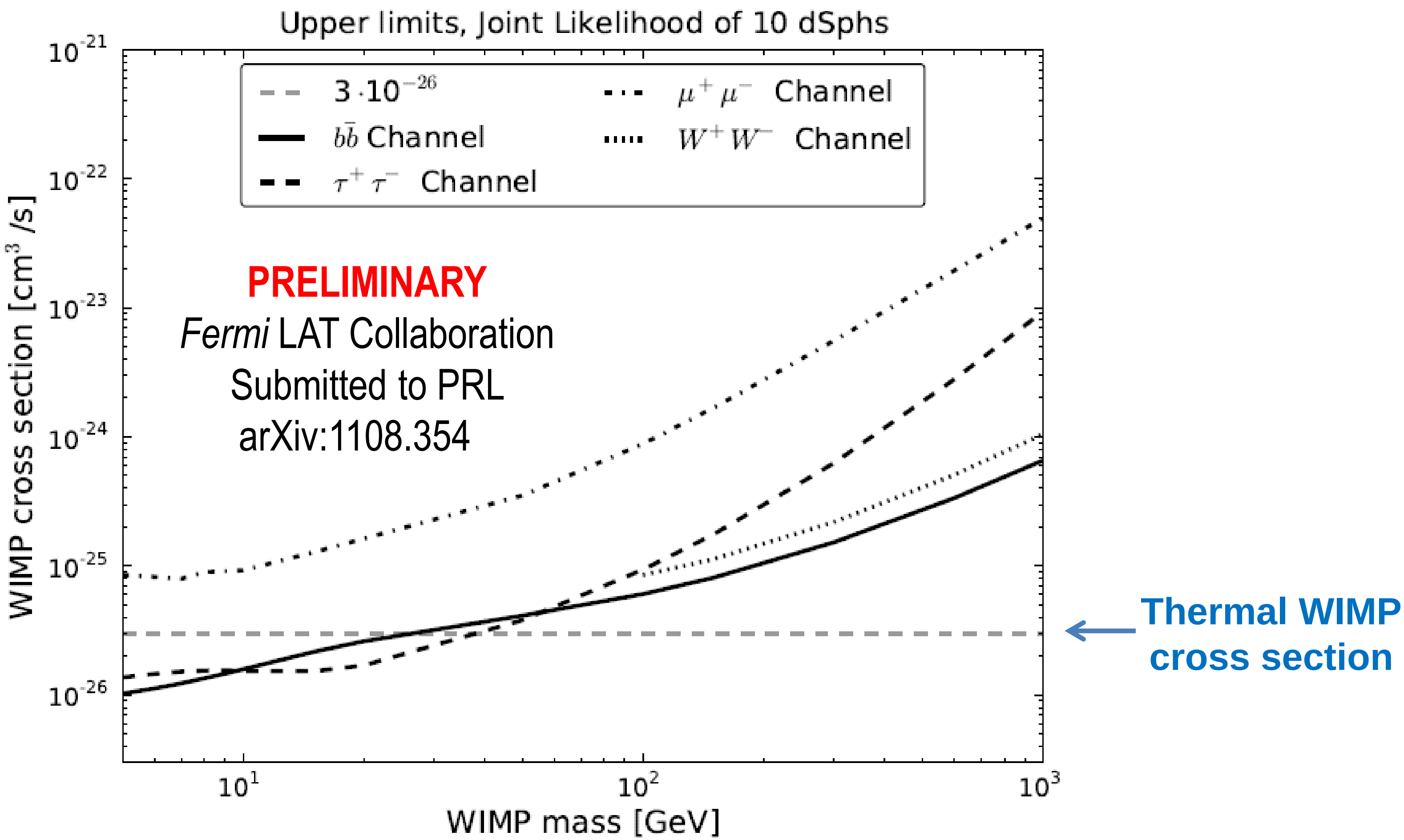
Classical (Open)
Ultra-faint (Filled)
SSDS coverage (Gray)



Belokurov et al. 2006

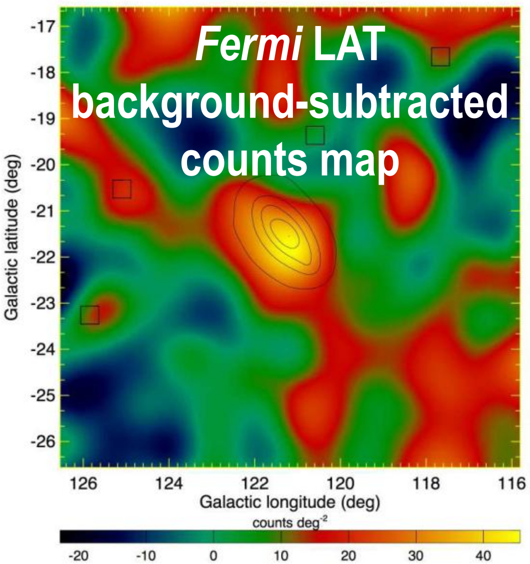
Dwarf Spheroidal Galaxies

- Composite likelihood analysis of 10 dwarf spheroidal galaxies
- Limits below thermal WIMP cross section for masses < 25 GeV

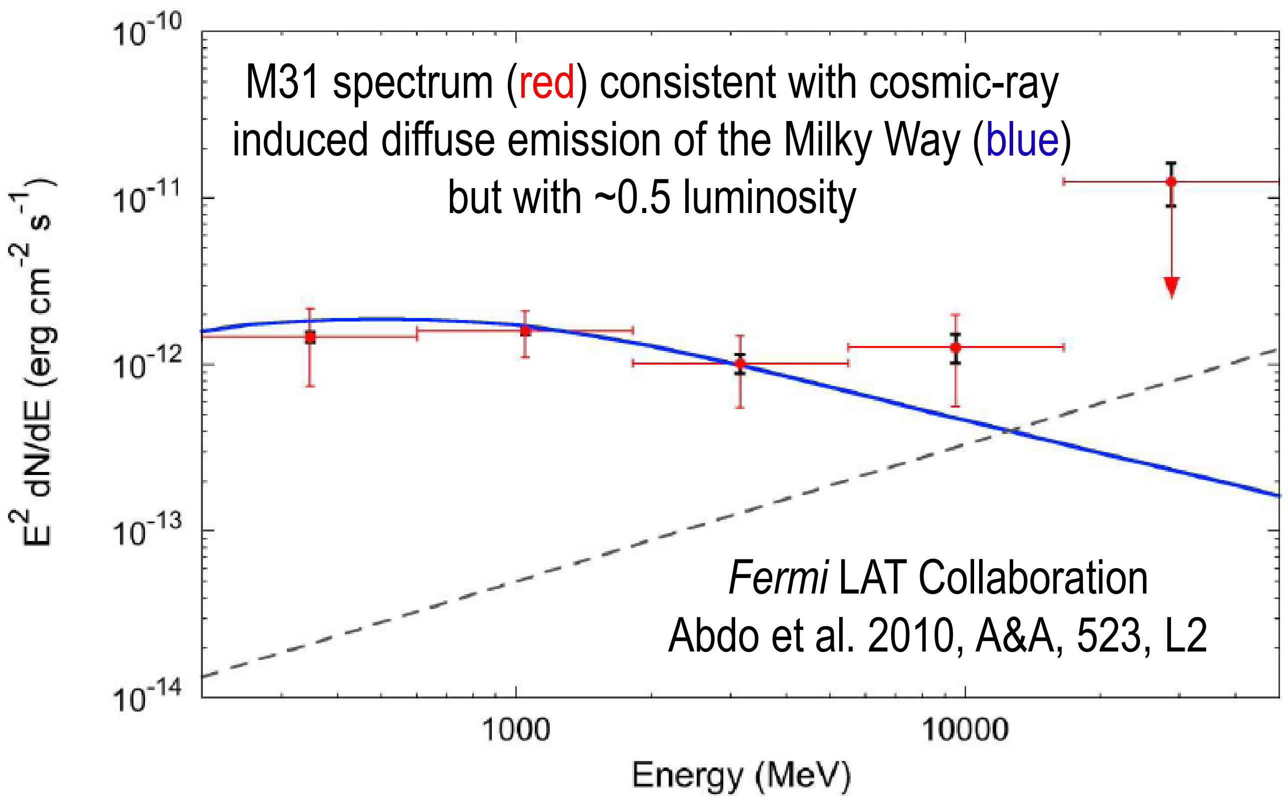


Nearby Galaxies (e.g. M31)

- Massive dark matter halos
  - Substructures could provide significant "boost" relative to smooth halo
  - N-body simulations suggest spatially extended emission
- Must consider cosmic-ray induced emission first



Sister galaxy to the Milky Way, M31 (Andromeda), now detected by *Fermi* LAT



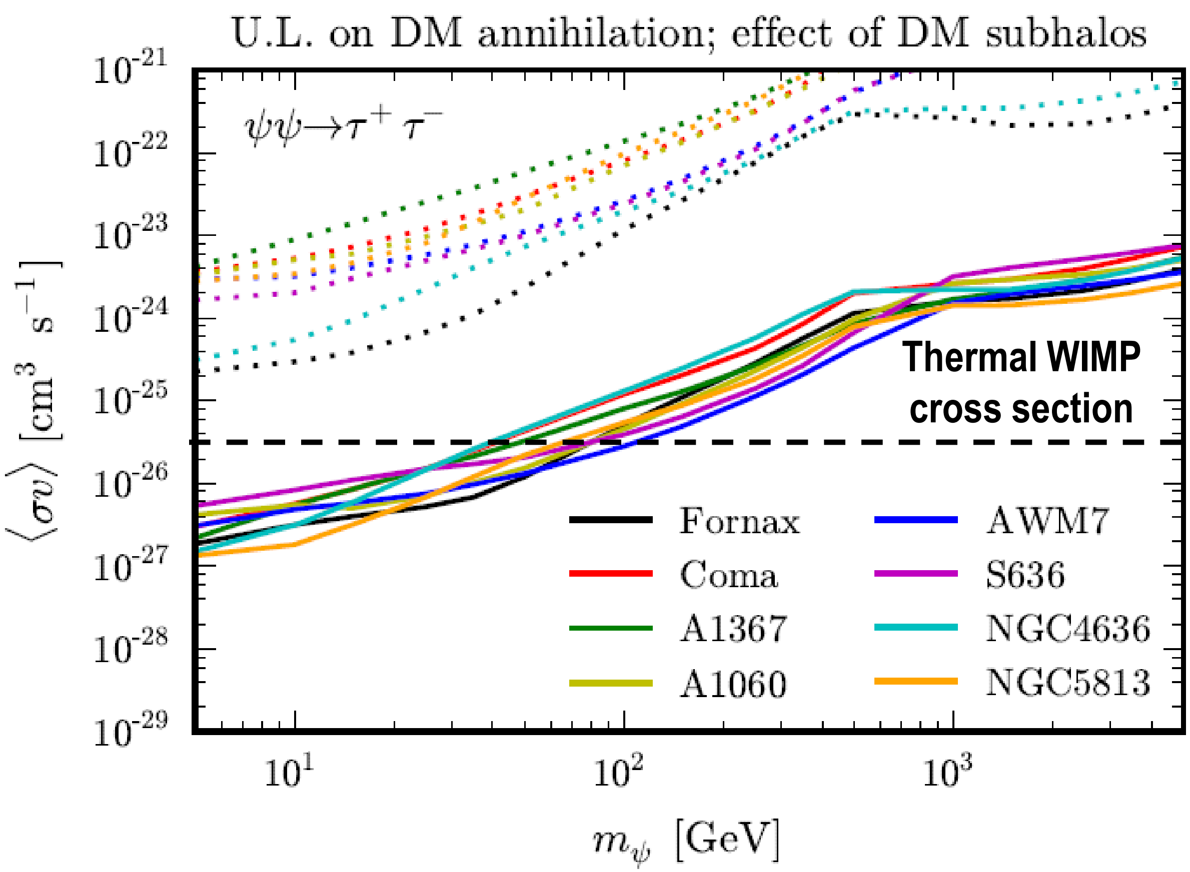
Galaxy Clusters

- Coma cluster proposed as a high signal to noise target
  - Extrapolations from N-body simulations (Gao et al. 2011, arXix:1107.1916)
- Highlights importance of understanding dark matter substructures

Dotted = smooth halo

Solid = including substructures down to 10^{-6} solar masses

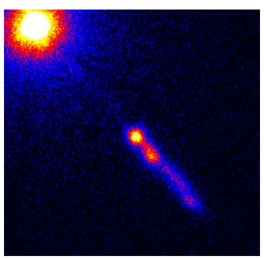
Huang et al. 2011, arXiv:1110.1529

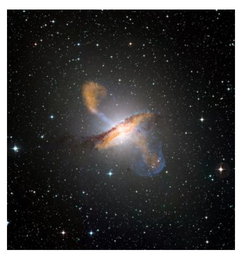
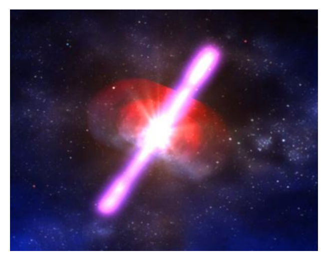


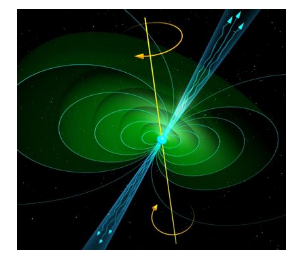
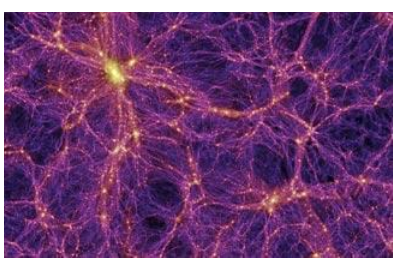
Isotropic Diffuse Component (IGRB)

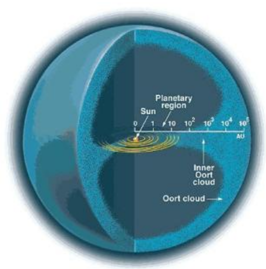
- Universe mostly transparent to gamma rays with energy < 100 GeV

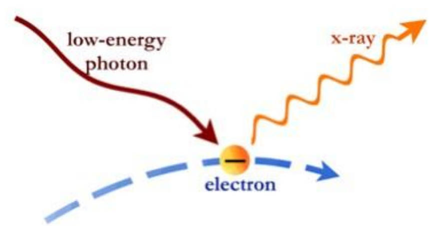
- Isotropic diffuse gamma-ray background (IGRB) component includes
  - Unresolved extragalactic sources,
  - Unresolved Galactic sources mimicking an isotropic population
  - Possible truly diffuse processes

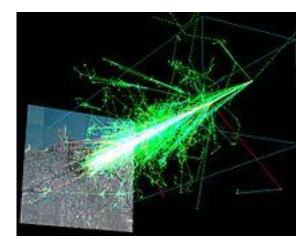


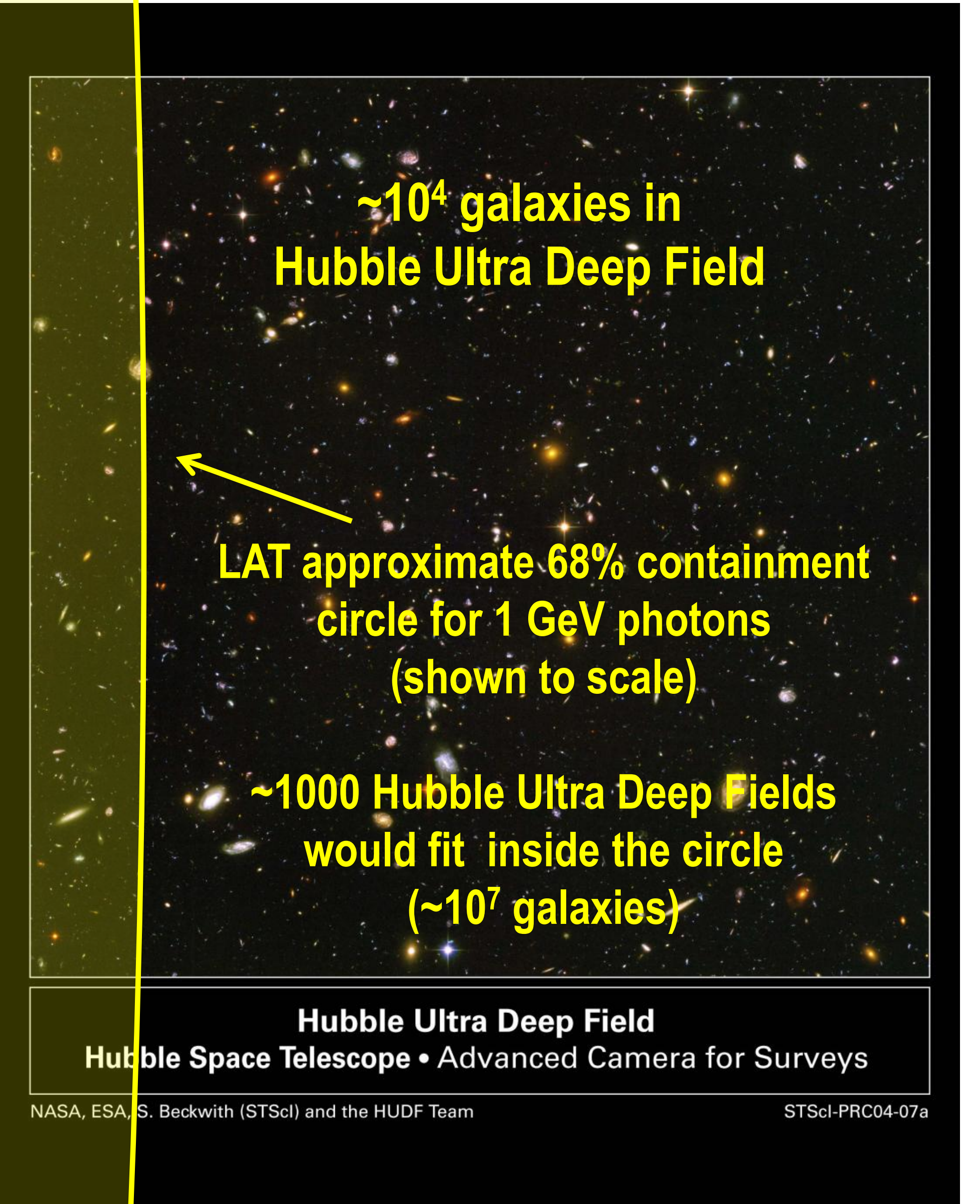









IGRB

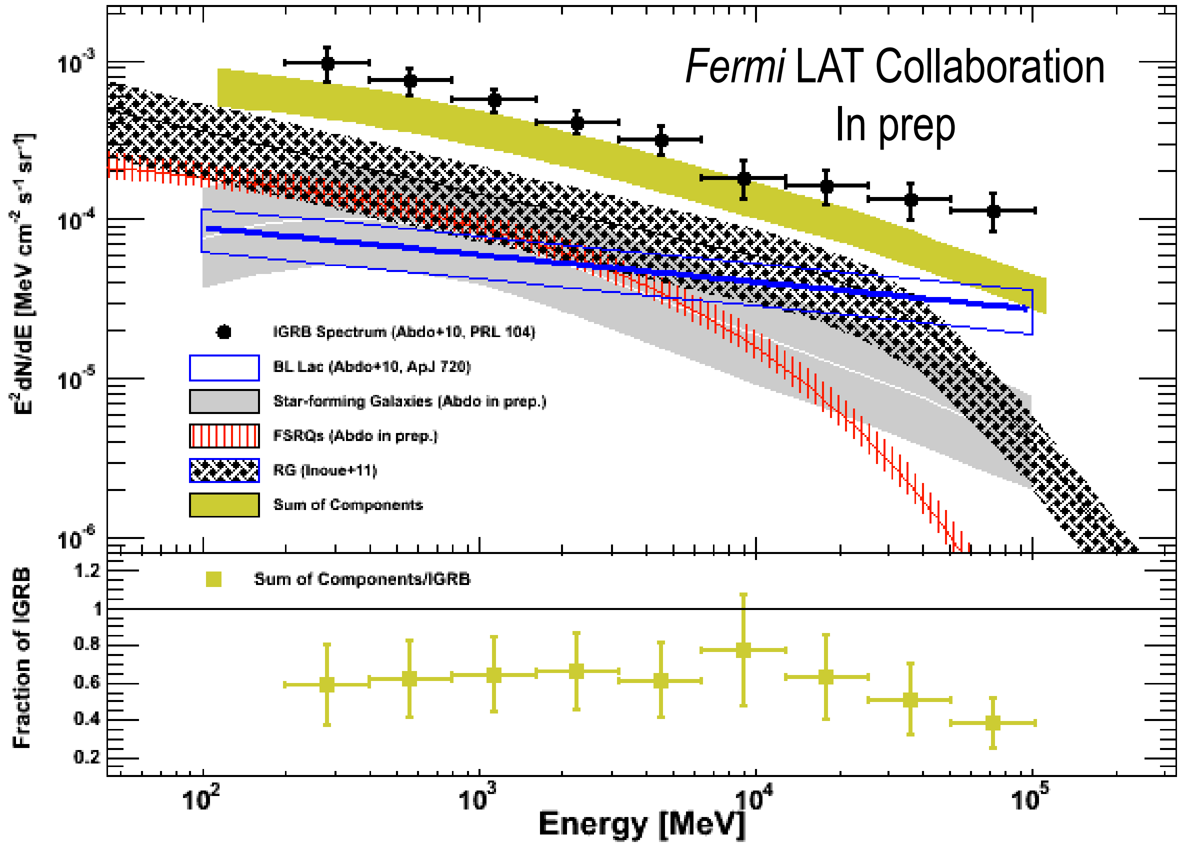


A Sunday Afternoon on the Island of La Grande Jatte
Georges Seurat

IGRB Contributions

- Established sources
  - Blazars
  - Non-blazar active galaxies
  - Star-forming galaxies
  - Gamma-ray Bursts (<1%)
  - Millisecond pulsars

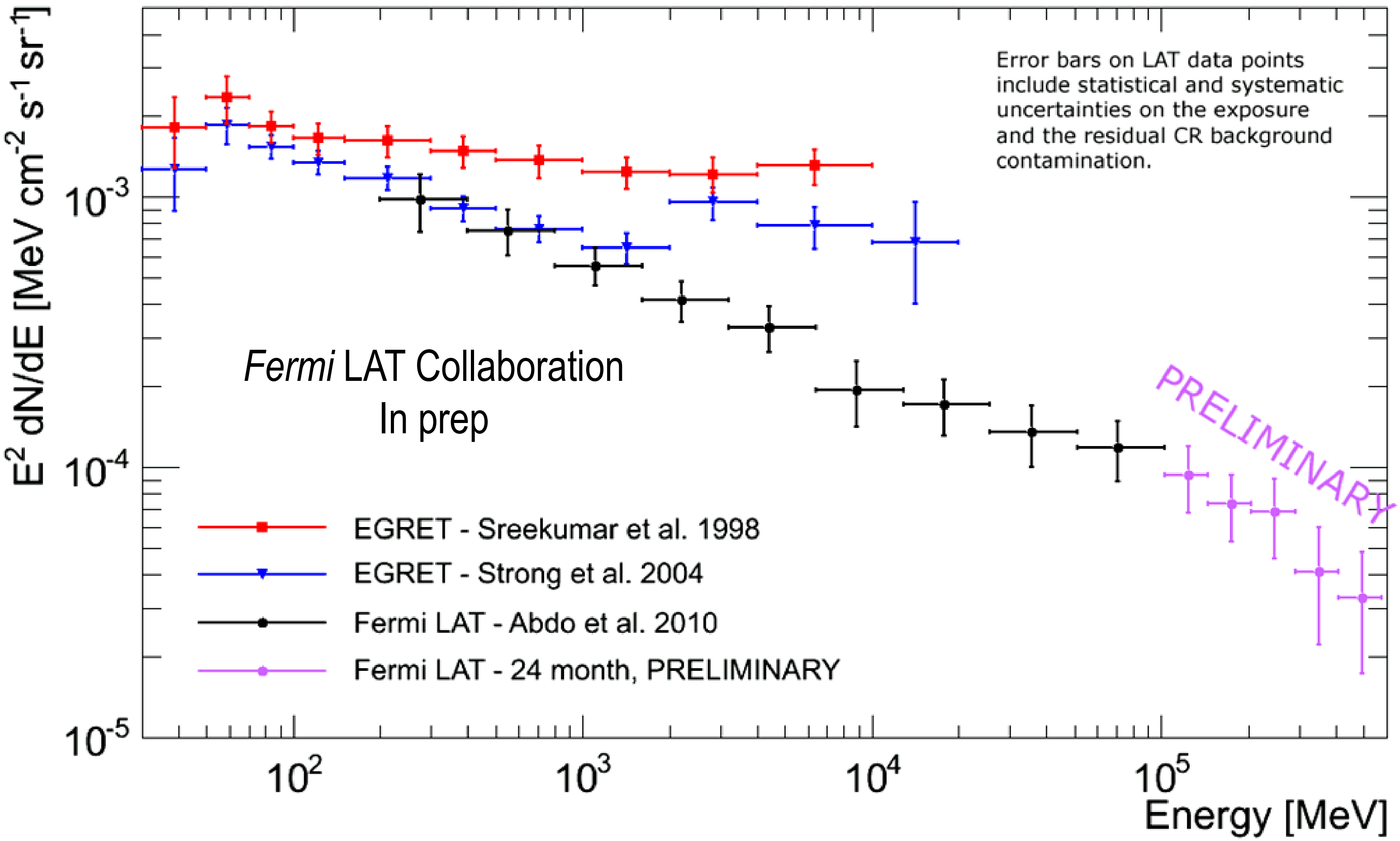
- Proposed contributors
  - Electromagnetic cascades
  - Galaxy clusters
  - Giant Galactic electron halo
  - Small solar system bodies
  - Dark matter halo (?)



A substantial fraction of IGRB emission can be accounted for by established extragalactic sources

Many different estimates in literature for different components,
Could still be room for other source classes/processes

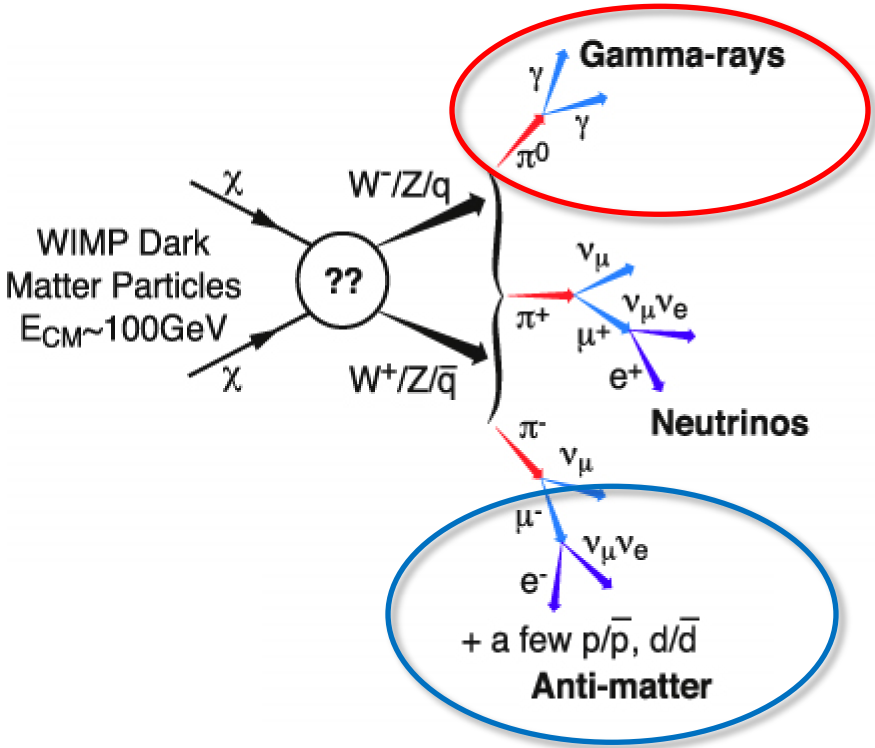
IGRB Spectrum



Gamma rays above ~100 GeV can interact with extragalactic background light (IR, optical)

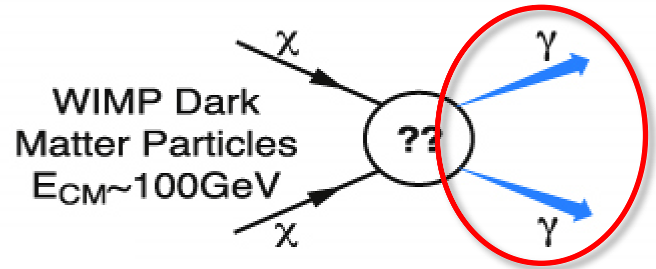
Exact spectral cutoff shape expected for cosmological populations varies by population and depends on extragalactic background light model

Indirect Detection Channels



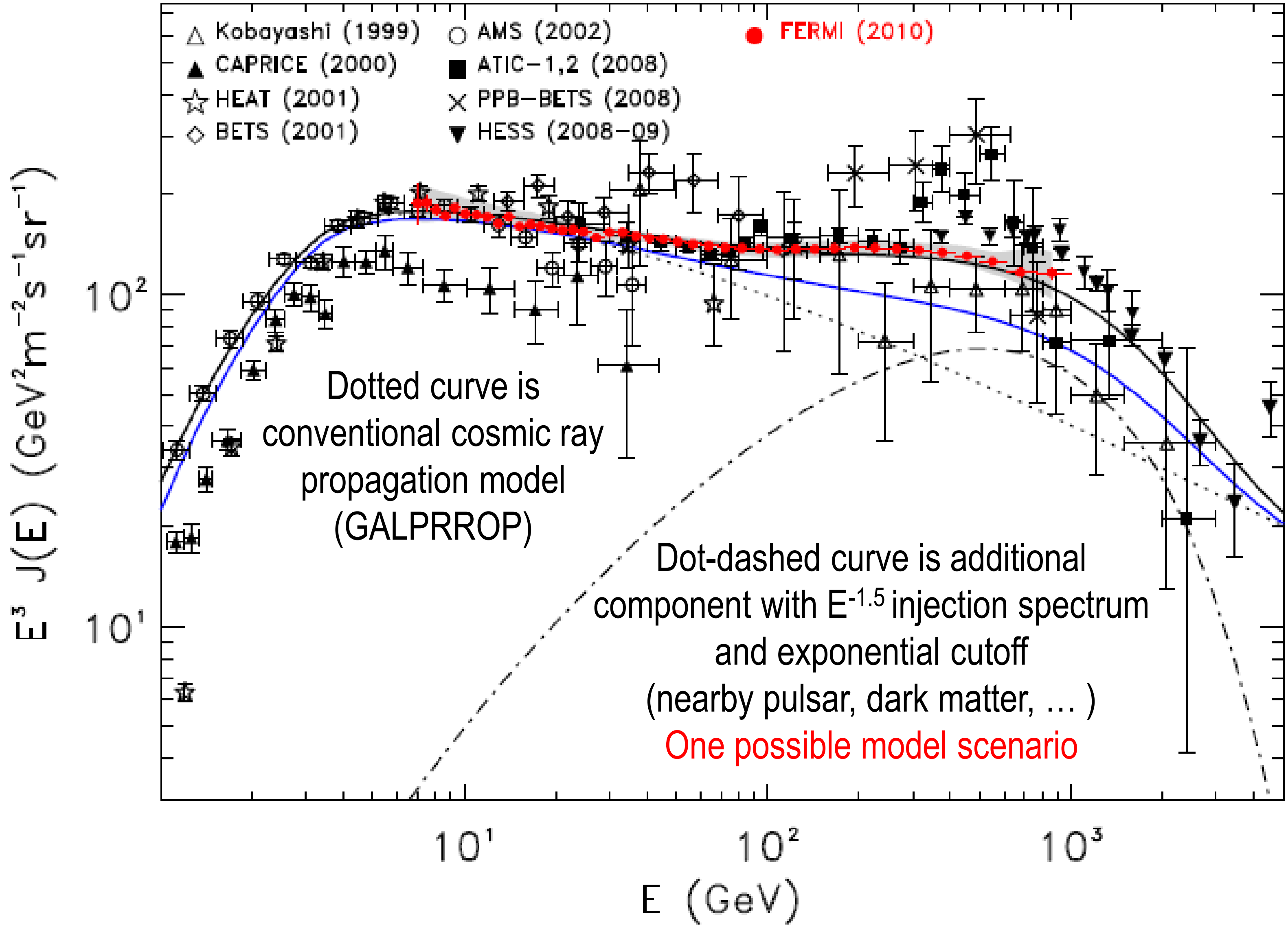
Search for anomalous features in cosmic rays

Search for excess gamma ray signal above astrophysical backgrounds



A particle detector in space is the ideal instrument for these studies

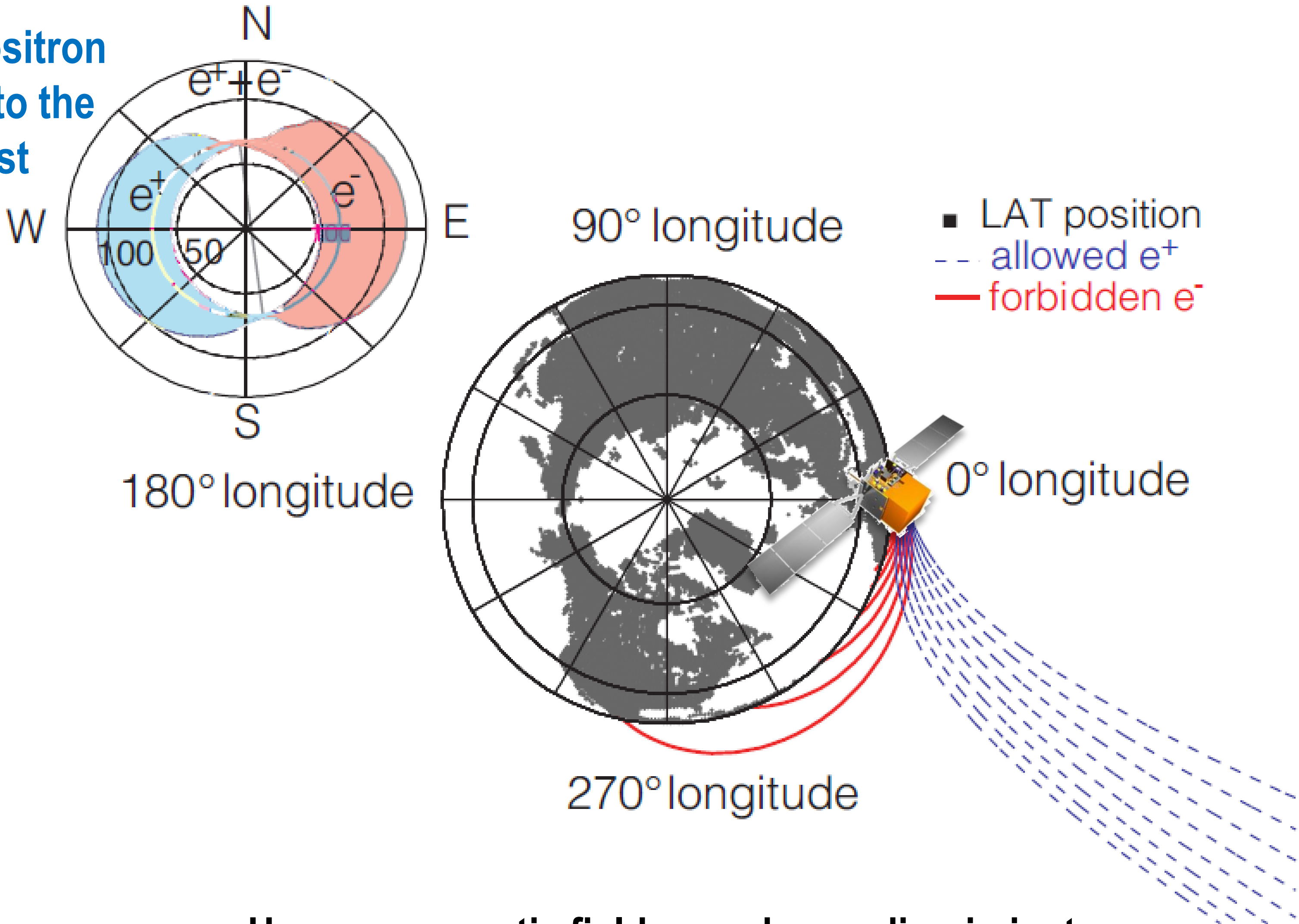
Total e⁺ e⁻ Spectrum



Fermi LAT Collaboration, Ackermann et al. 2010, Phys. Rev. D, 82, 092004

Separate e^+ e^- Spectrum

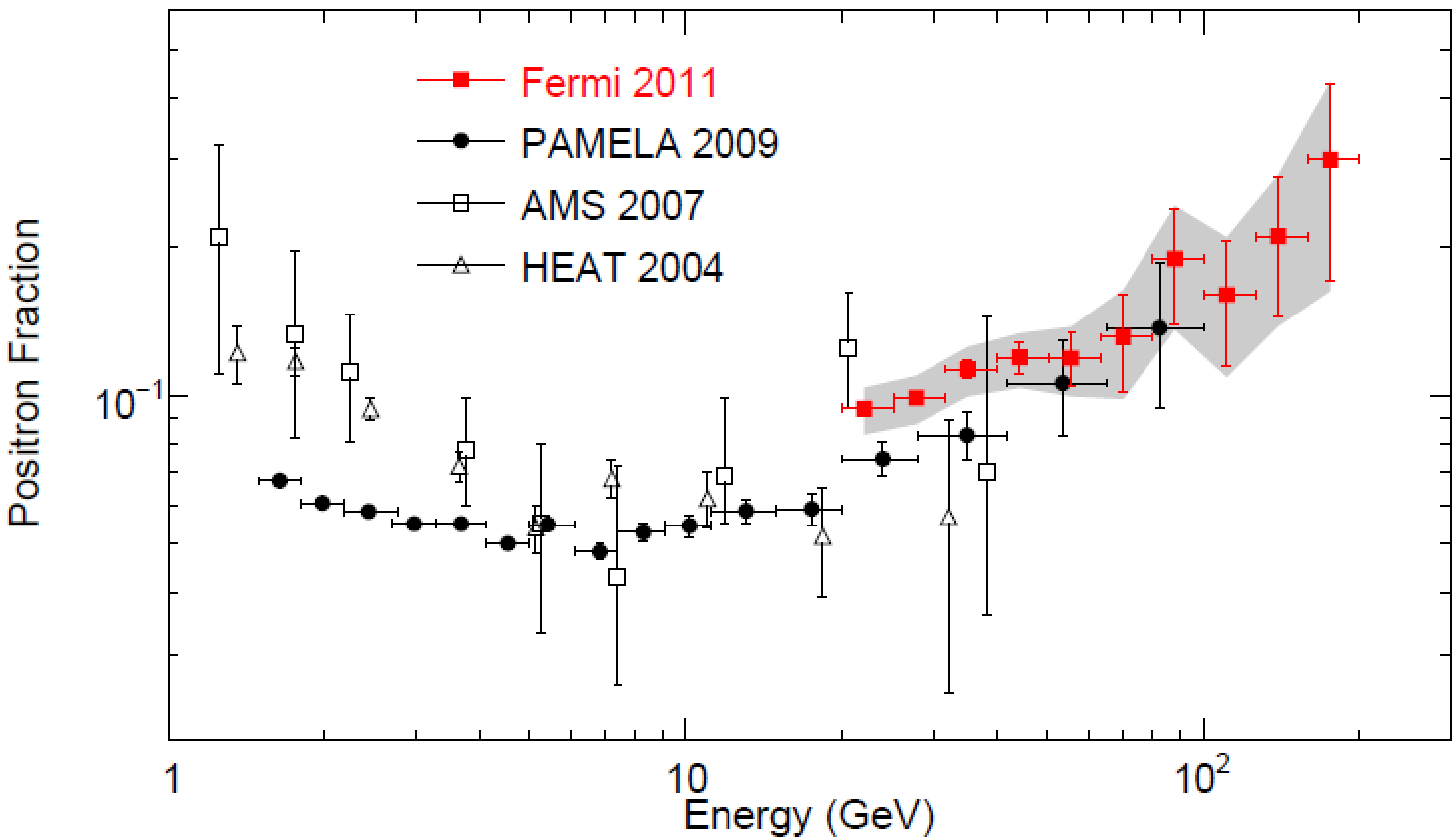
Pure positron signal to the West



Use geomagnetic field as a charge discriminator

Separate e^+ e^- Spectrum

- Positron fraction increases with energy between 20 – 200 GeV
  - Consistent with PAMELA results, will soon be tested by AMS-02



Fermi LAT Collaboration, Ackermann et al. 2011, arXiv:1109.0521, submitted to PRL

Fermi Gamma-ray Space Telescope

Indirect Detection Outlook

No conclusive indirect detection signal of dark matter

Time to be concerned? Or should we remain hopeful?

KIPAC KAVLI INSTITUTE FOR PARTICLE ASTROPHYSICS AND COSMOLOGY

- Home
- Accommodations
- Agenda
- Committee
- Contact
- Participants
- Reception
- Travel & Directions

Detecting Dark Matter with Gamma Rays

October 13-14, 2011

SLAC National Accelerator Laboratory

Meno Park, CA

Workshop last week at SLAC to discuss these questions

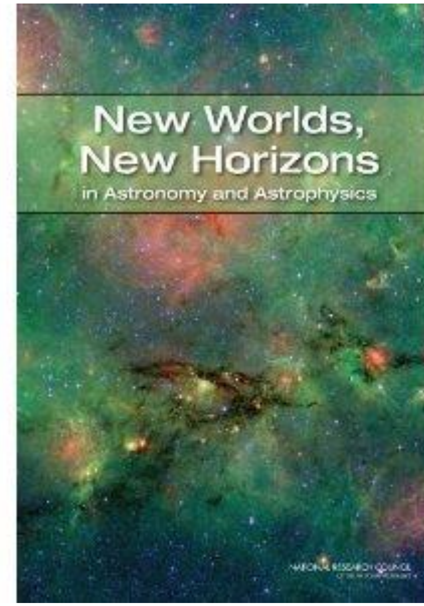
http://kipac.stanford.edu/kipac/events/detecting_dark_matter

Reasons for Optimism

- Only 1/5 of the sky surveyed to sufficient depth to find ultra-faint dwarf galaxies
  - Large optical surveys (e.g. DES, LSST) will find many more
- *Fermi* LAT not yet background-limited at high energies
  - Sensitivity will improve faster than square root of time
- Understanding of halo inner profiles and boost factors from substructure is work in progress
  - Source of astrophysical uncertainty when interpreting gamma-ray flux limits
- Discovery potential at colliders and direct detection experiments

Future of Gamma-ray Searches

- Proposed Cherenkov Telescope Array (CTA)
  - Proven technology on a larger scale
  - 3 different telescope sizes
  - Energy Range: tens of GeV to multi-TeV
  - Field of view: 5 – 10 deg



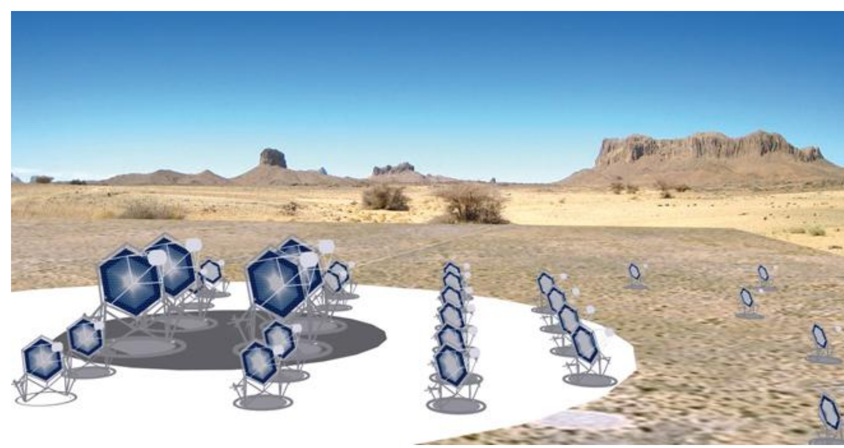
- Highly ranked by astrophysics prioritization panels in US and Europe

←

Current Generation
e.g. VERITAS
4 telescopes

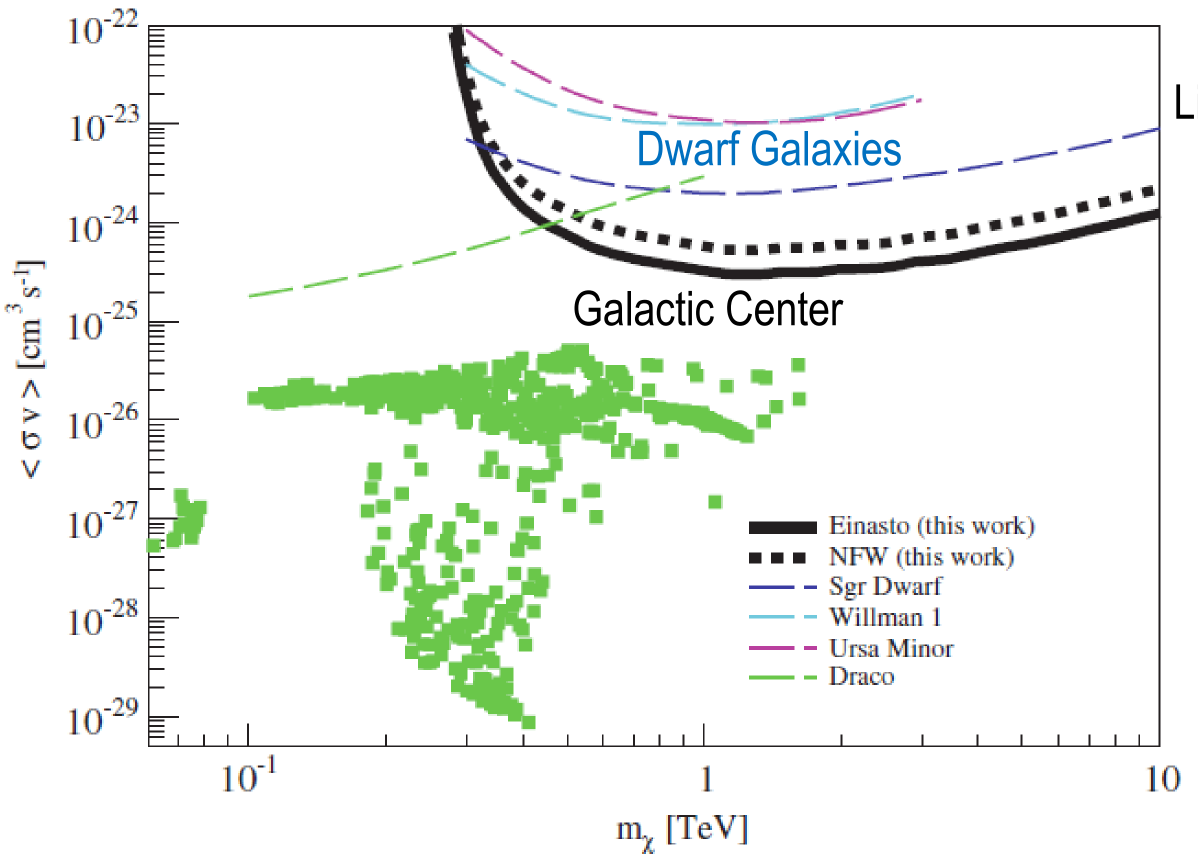
Next Generation
CTA
~50+ telescopes

→



TeV View of the Galactic Center

- 112 hrs of observation with H.E.S.S.
  - Max usable time ~1000 hrs / yr, systematics limited after ~100 hrs for single target
- Galactic Center is a promising target for TeV observatories



Limits from Sagittarius Dwarf based on 11 hrs of H.E.S.S. observations

H.E.S.S. Collaboration, Abramowski et al. 2011, PRL, 106, 161301

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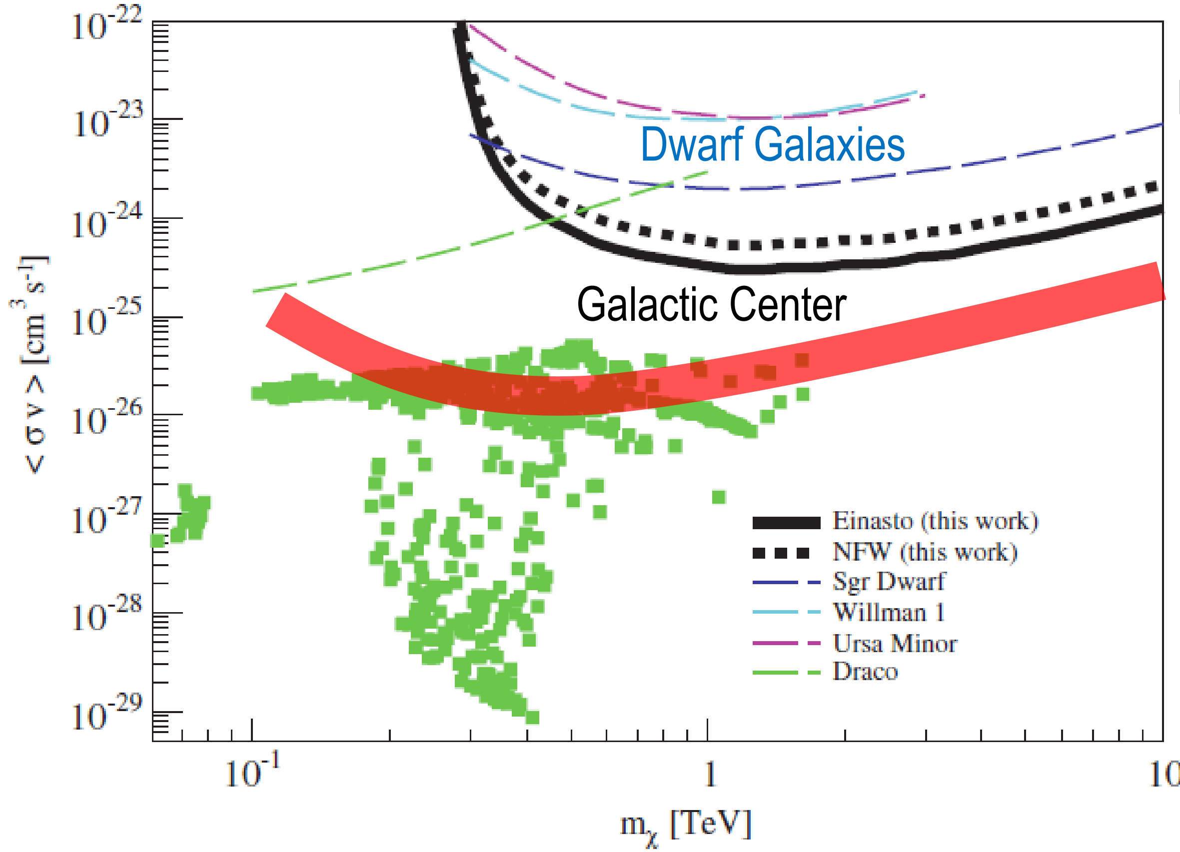


Limits from Sagittarius Dwarf based on 11 hrs of H.E.S.S. observations

CTA will be ~10x more sensitive than current instruments and extend lower energy threshold

H.E.S.S. Collaboration, Abramowski et al. 2011, PRL, 106, 161301

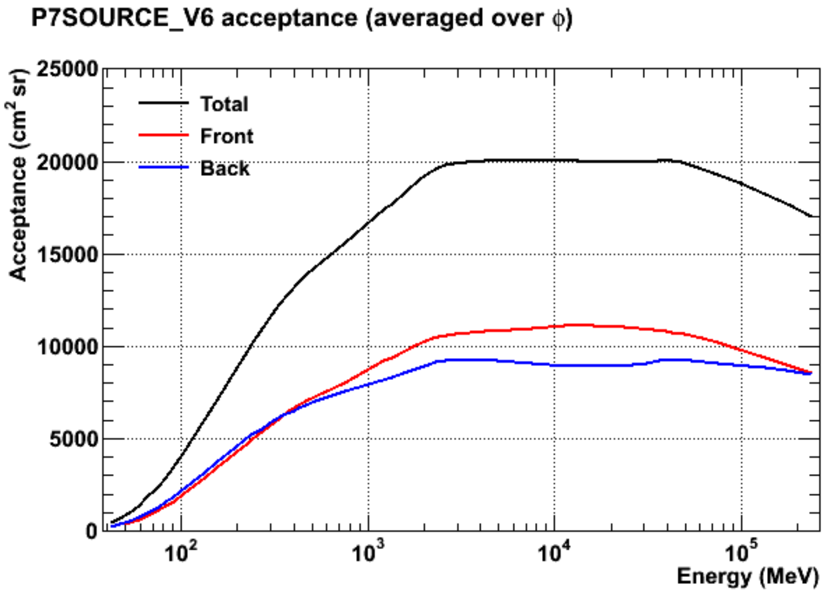
Fermi Gamma-ray Space Telescope

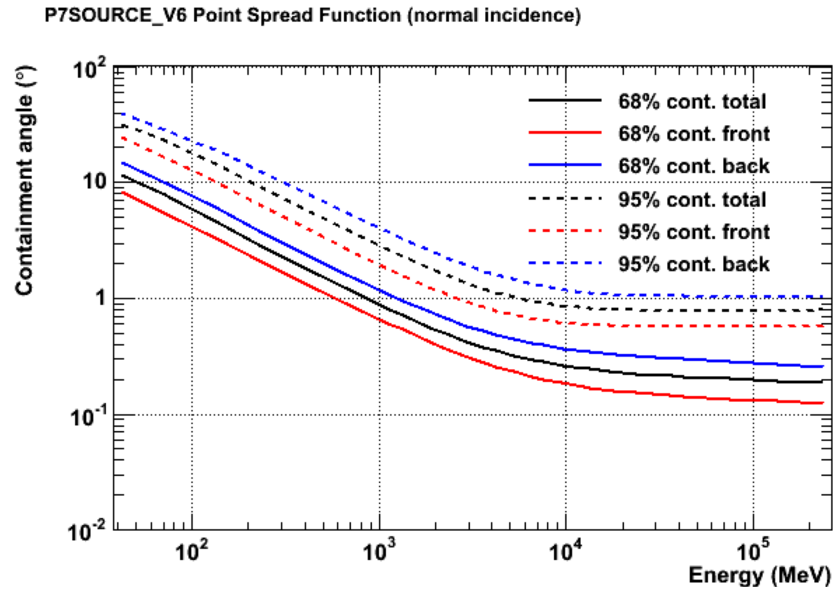
Summary

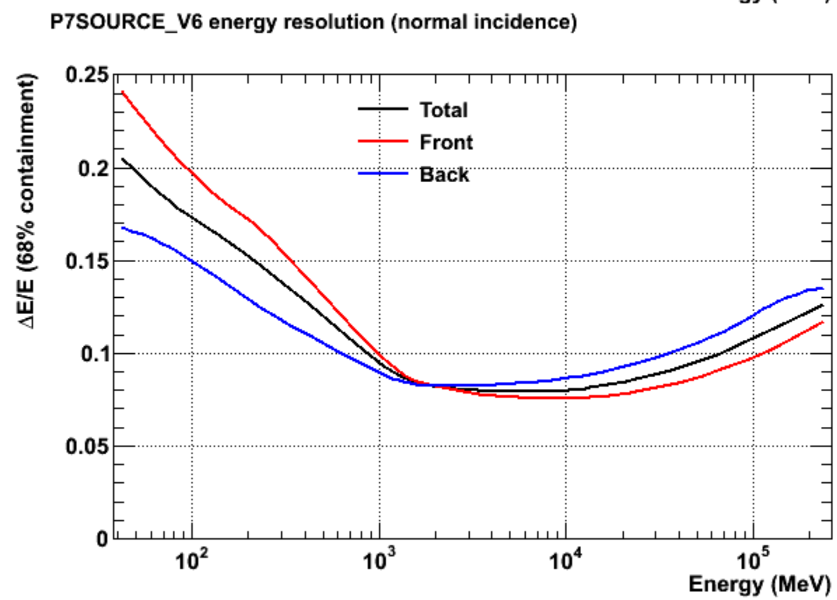
- Indirect detection methods connect dark matter in the cosmos with dark matter in the lab
- *Fermi* LAT operating smoothly for 3 years
  - Broad science mission, many astrophysical + fundamental physics results
- No indirect detection of dark matter signal
  - **Limits start to explore WIMP thermal relic parameter space**
- Opportunities for progress exist on many fronts
  - Theory (e.g. inner profile, substructure boost factors)
  - Discovery potential of accelerator-based and direct detection searches
  - Multiwavelength (e.g. optical surveys finding more dwarfs)
  - Continued gamma-ray observations with *Fermi* (and hopefully CTA)

Extras / Back-ups

Instrument Performance





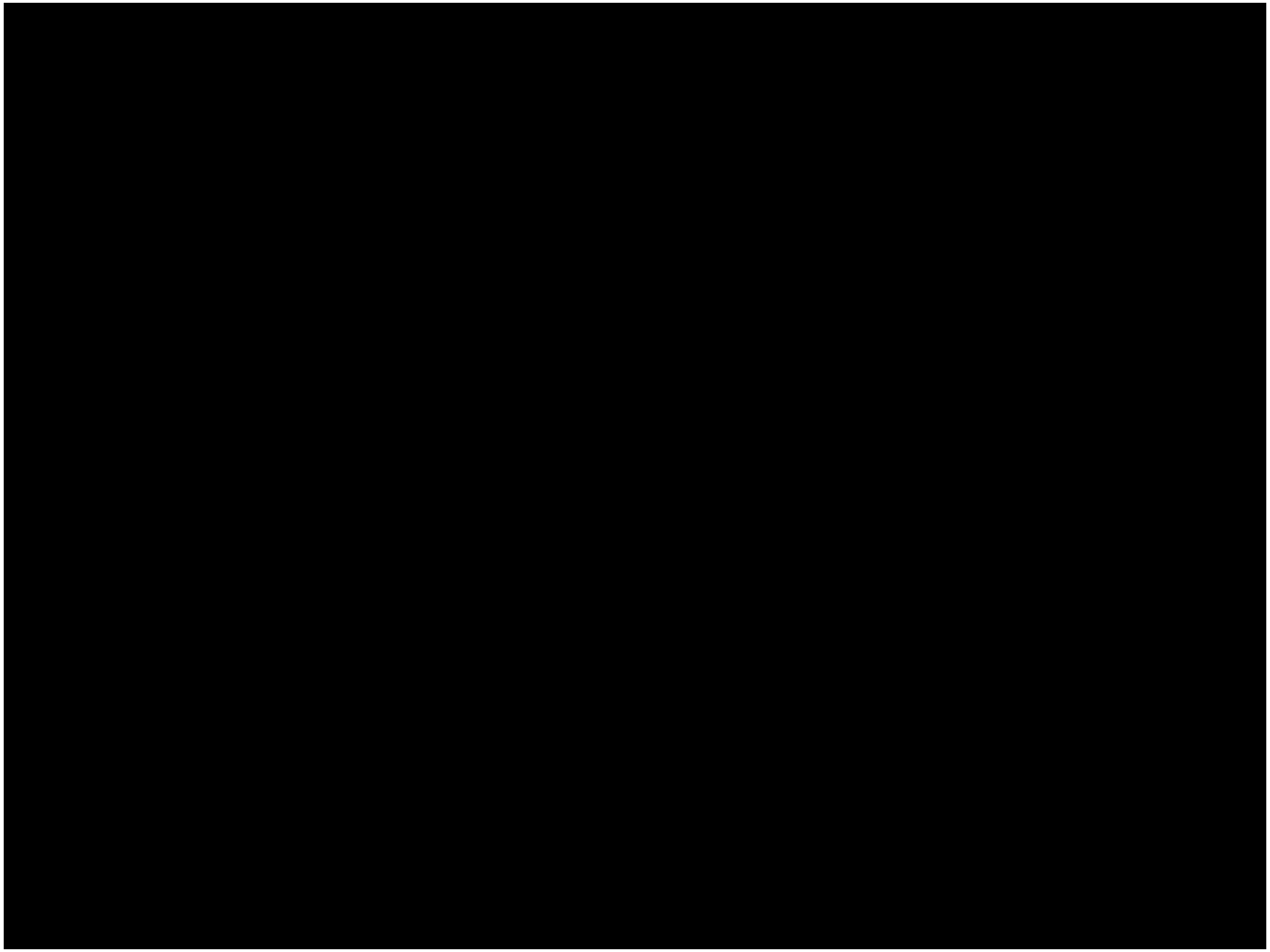


Effective Area = geometric area
× trigger efficiency
× selection efficiency

Low Earth Orbit

Cosmic ray flux >10^3 gamma ray flux

Tour of the GeV Gamma-ray Sky

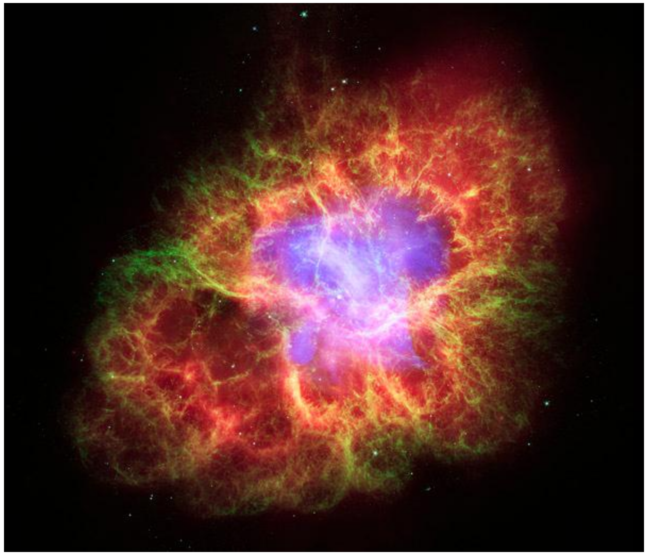


3 month “movie” of GeV gamma-ray sky

Flares of the Crab Nebula

- Historical supernova (1054)
  - Pulsar
  - Pulsar wind nebula
- Often used as calibration source
  - Bright across electromagnetic spectrum
  - The “Crab” is a commonly used flux unit

Slow-motion pulsations at 800 nm
Actual period is 33 ms
Cambridge University Lucky Imaging Camera

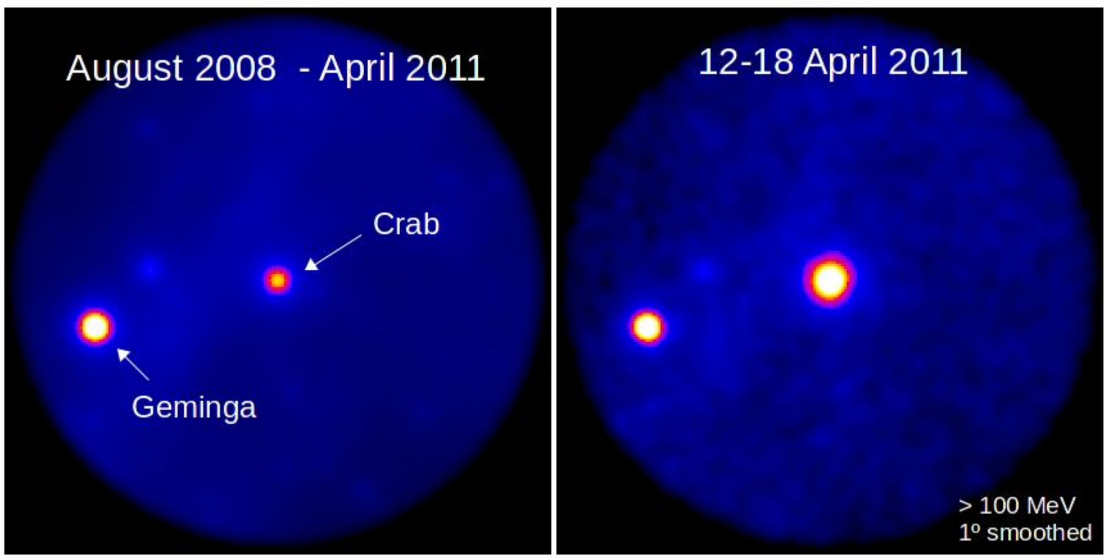


IR (Spitzer)
Optical (Hubble)
X-ray (*Chandra*)

Flares of the Crab Nebula

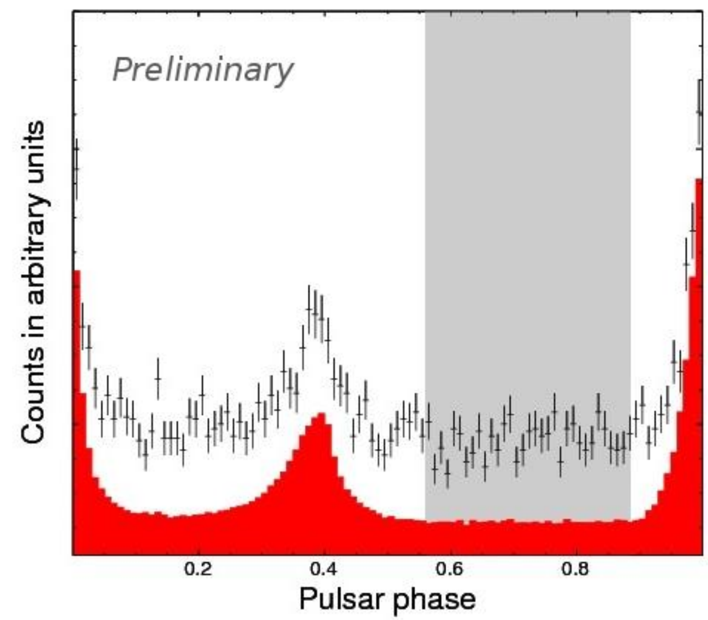
- 3 unexpected flares detected by *Fermi* LAT
  - Brightest yet occurred in April 2011
  - Closer look reveals low-level variability at all times

Exposure Corrected Counts Map > 100 MeV



Geminga constant, Flare stands out

Pulsar Phasogram

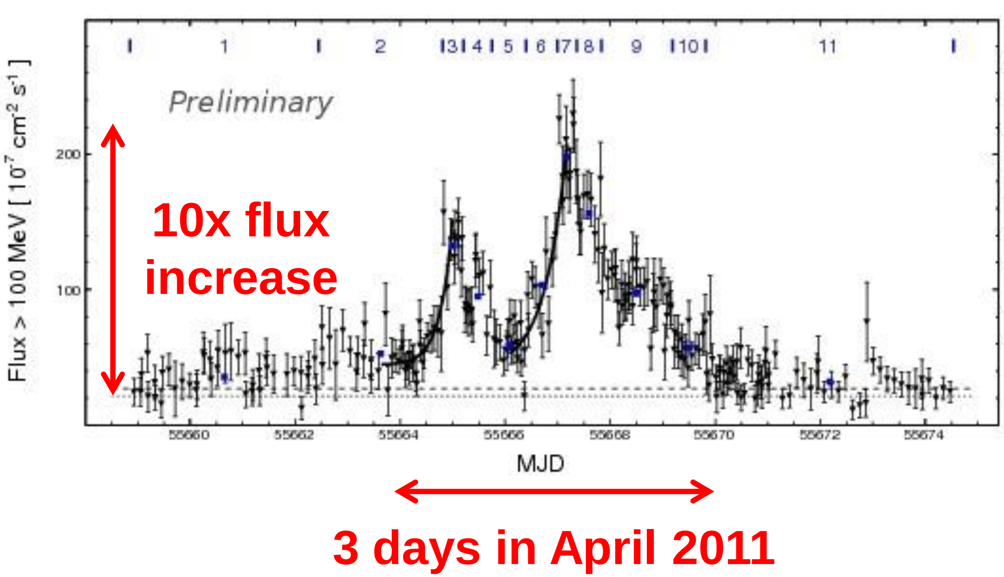


Flares first reported by the *Fermi* LAT Collaboration, Abdo et al. 2010, Science, 331,739

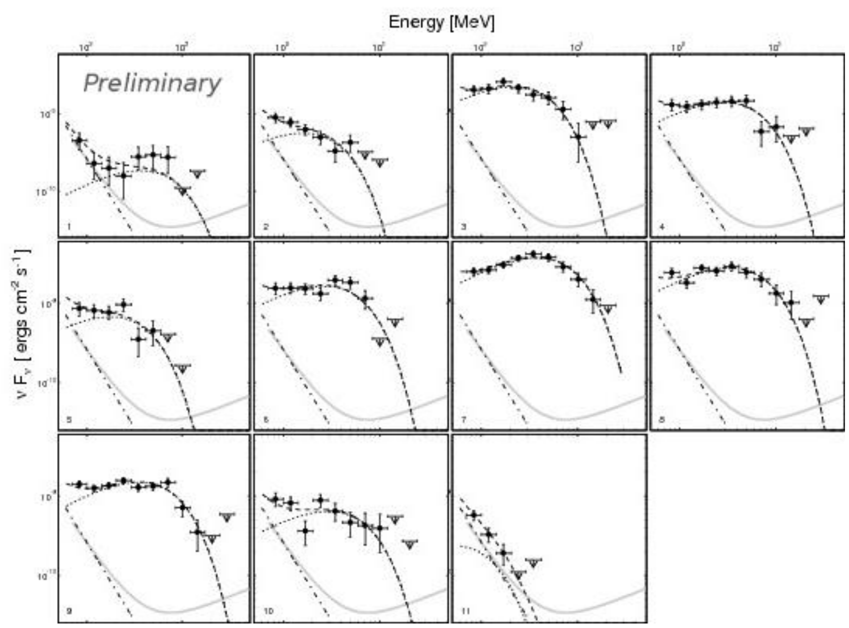
Flares of the Crab Nebula

- **Flux doubling time < 8 hours**
- **Synchrotron emission**
- ***PeV electrons!***
  - Highest energy particles ever associated with a particular object

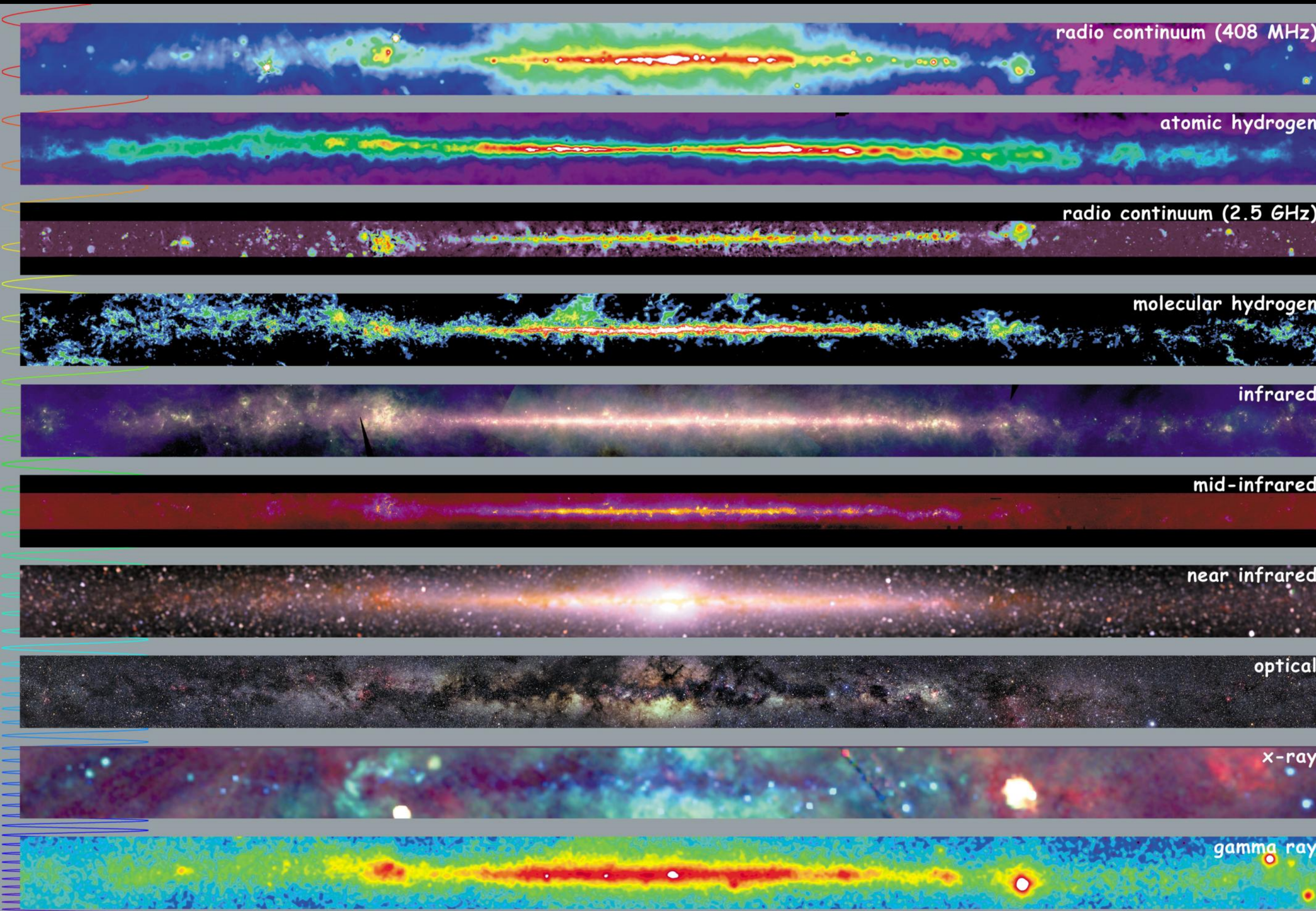
Light Curve



Spectral Evolution



Grey curve is 35 month average nebula spectrum

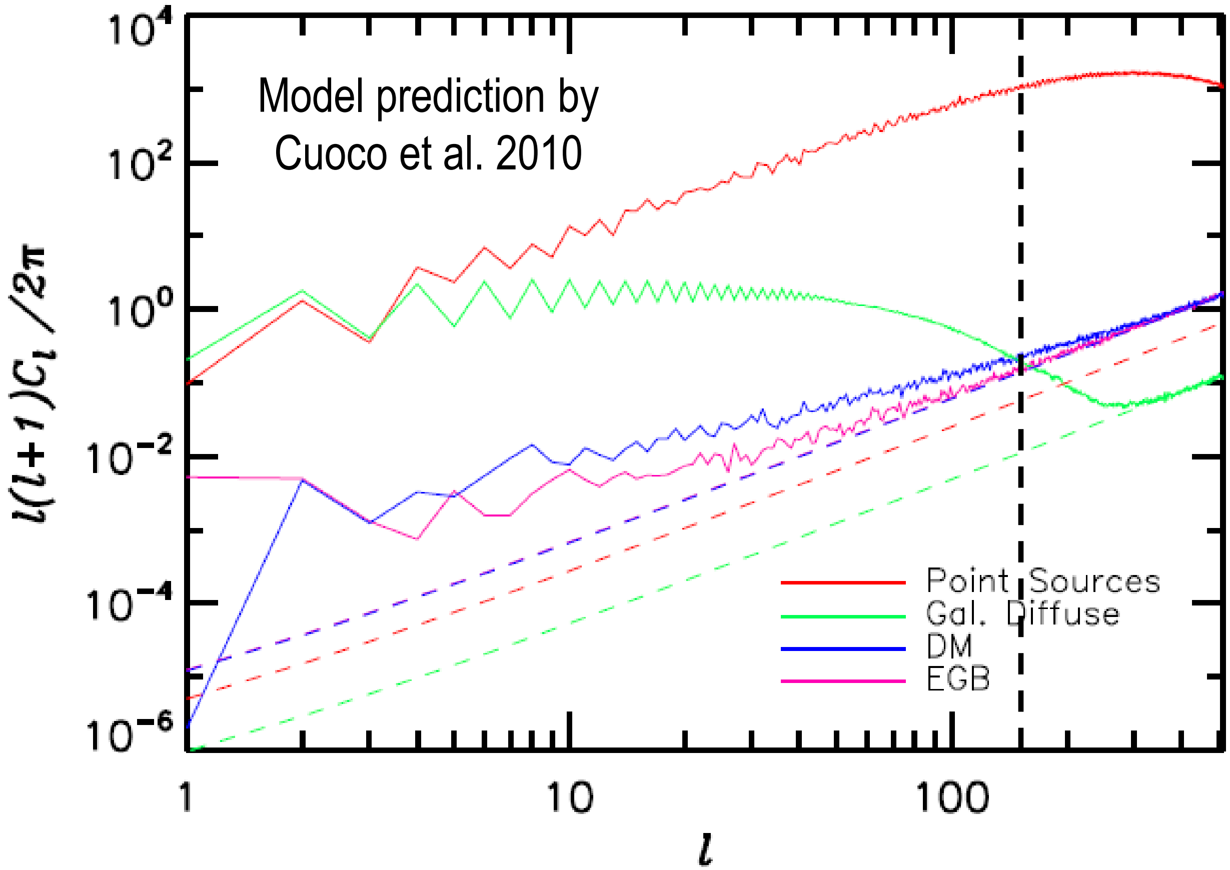


http://adc.gsfc.nasa.gov/mw

Multiwavelength Milky Way

IGRB Anisotropy Analysis

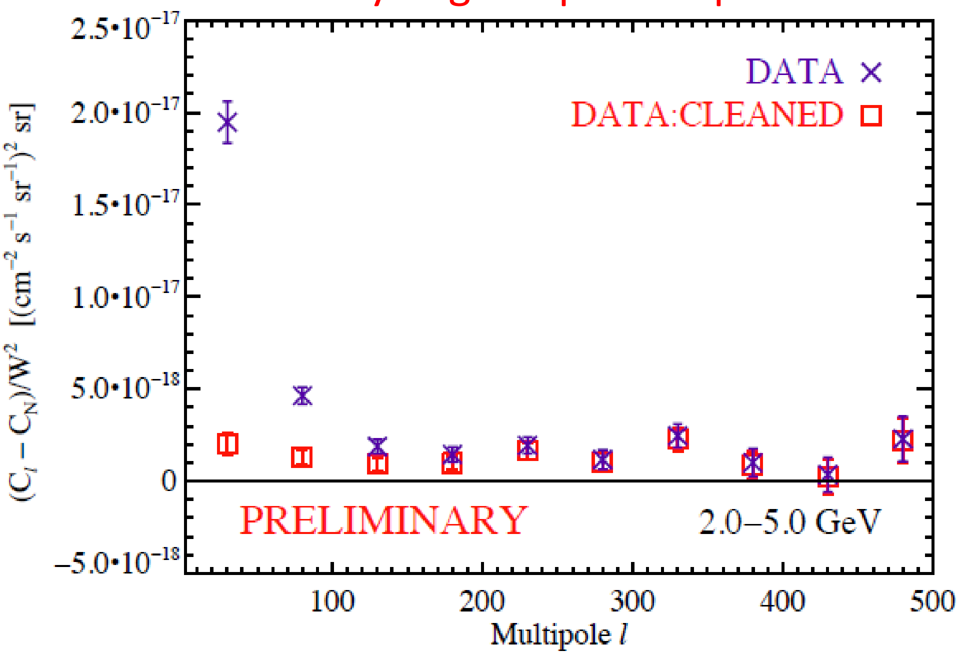
- IGRB anisotropies provides another handle for dark matter searches
  - Dark matter annihilation could be significant for multipoles $\ell > 150$



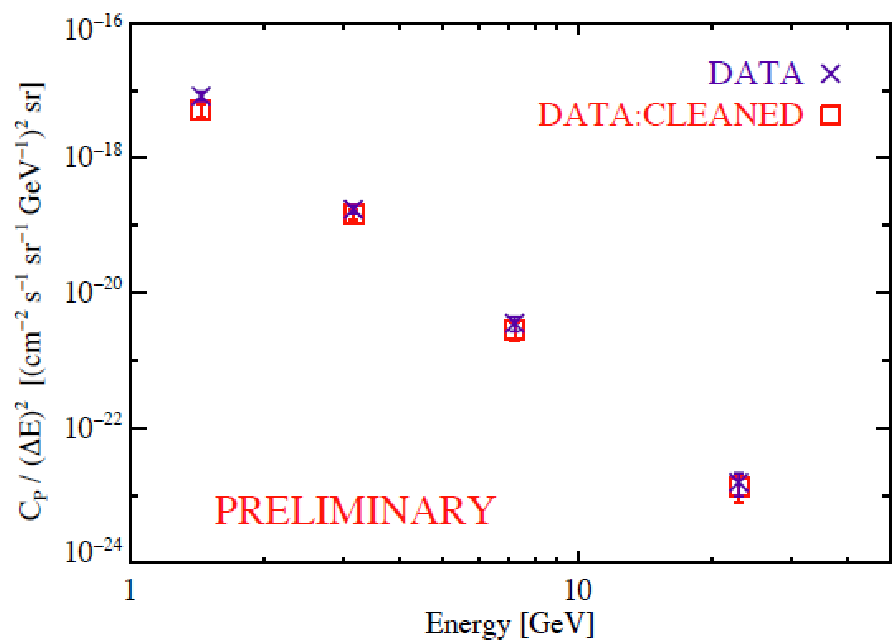
IGRB Anisotropy Analysis

- Significant (>5σ) detection of anisotropies found in 1-5 GeV range
  - Less significant detection (>2.5σ) up to 50 GeV
- Consistent with arising from a source class with power law energy spectrum $E^{-2.4}$
  - Matches mean spectral index of LAT-detected blazars

Intensity angular power spectrum



Intensity anisotropy energy spectrum



DATA:CLEANED = DATA - Galactic diffuse model

IGRB Anisotropy Analysis

- Anisotropy analysis and population studies point to blazars contributing ~30% of IRGB intensity and ~100% of IGRB anisotropy
- Implies components making up remaining ~70% of IGRB intensity have a very low level of anisotropy
  - Consistent with e.g. star-forming galaxies as major contributor
  - Inconsistent with e.g. millisecond pulsars as major contributor
  - Suggests dark matter annihilation/decay contributes less than ~45% of IGRB intensity (model dependent, large uncertainties)

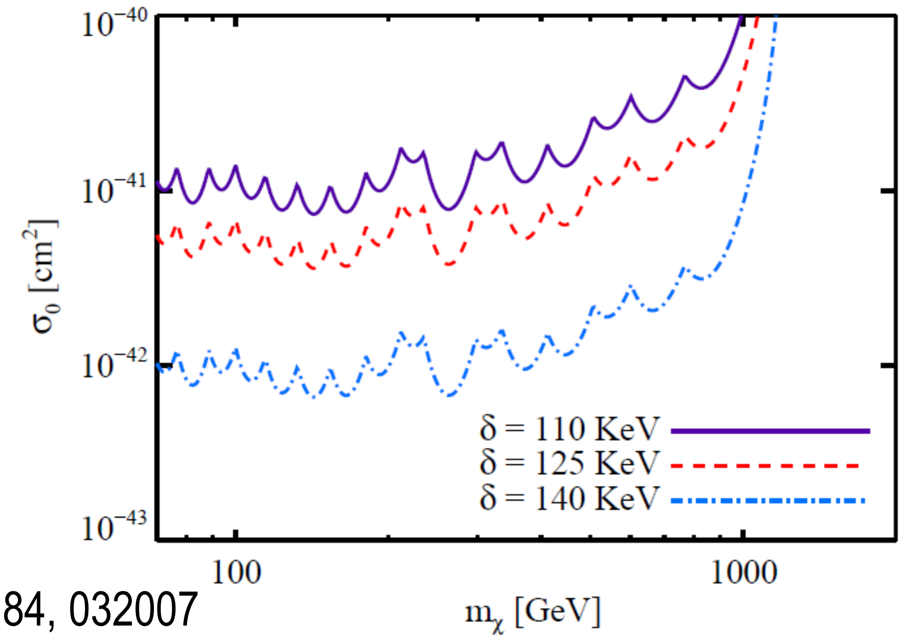
Results from Cuoco, Komatsu, & Siegal Gaskins, in prep

Search for $e^+ e^-$ from the Sun

- Two classes of dark matter models
  - Annihilation through light intermediate states proposed to satisfy PAMELA, ATIC, and *Fermi* $e^+ e^-$ results
  - Inelastic dark matter models proposed to reconcile inconsistencies between DAMA/LIBRA and CDMS results
- Both predict high energy $e^+ e^-$ from the Sun
  - No known astrophysical background of $e^+ e^-$ with energy >100 GeV

Most stringent limits on intermediate state dark matter models using gamma rays

Limits exclude inelastic dark matter models that reconcile DAMA/LIBRA and CDMS for masses > 70 GeV and assuming annihilitation into $e^+ e^-$



Fermi LAT Collaboration, Ajello et al. 2011,Phys Rev D., 84, 032007