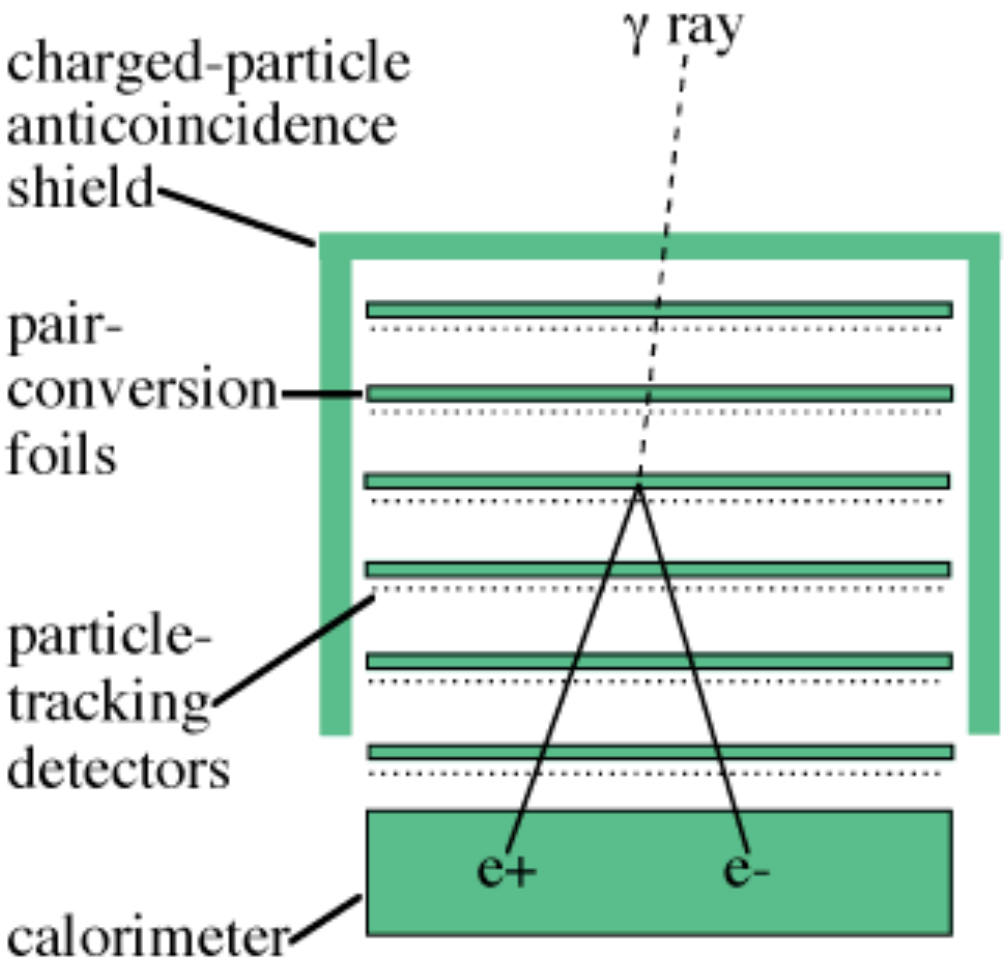
Astrofisica Nucleare e Subnucleare

GeV Astrophysics

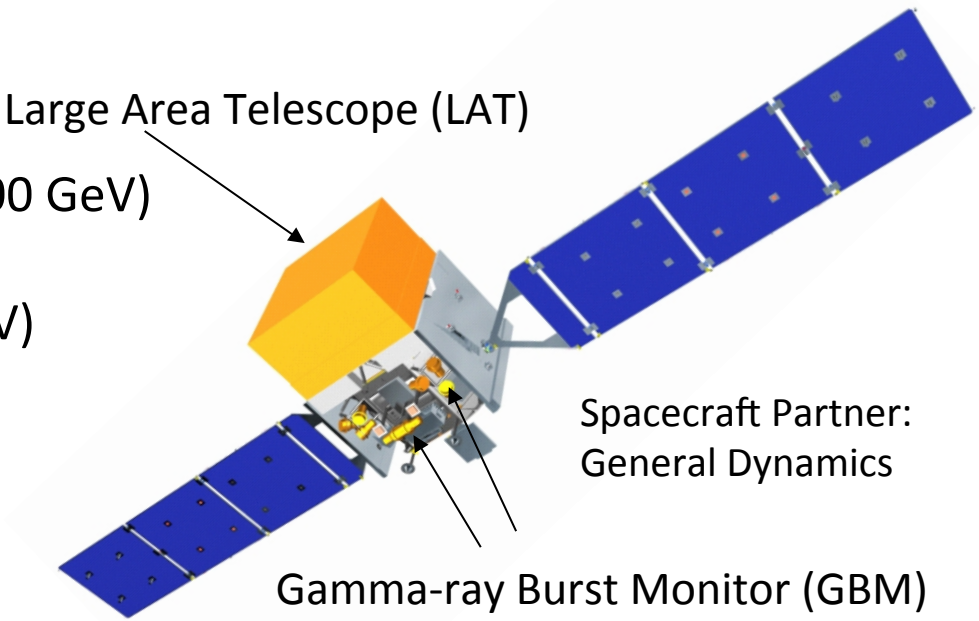
Detector Project



Fermi LAT

Key Features

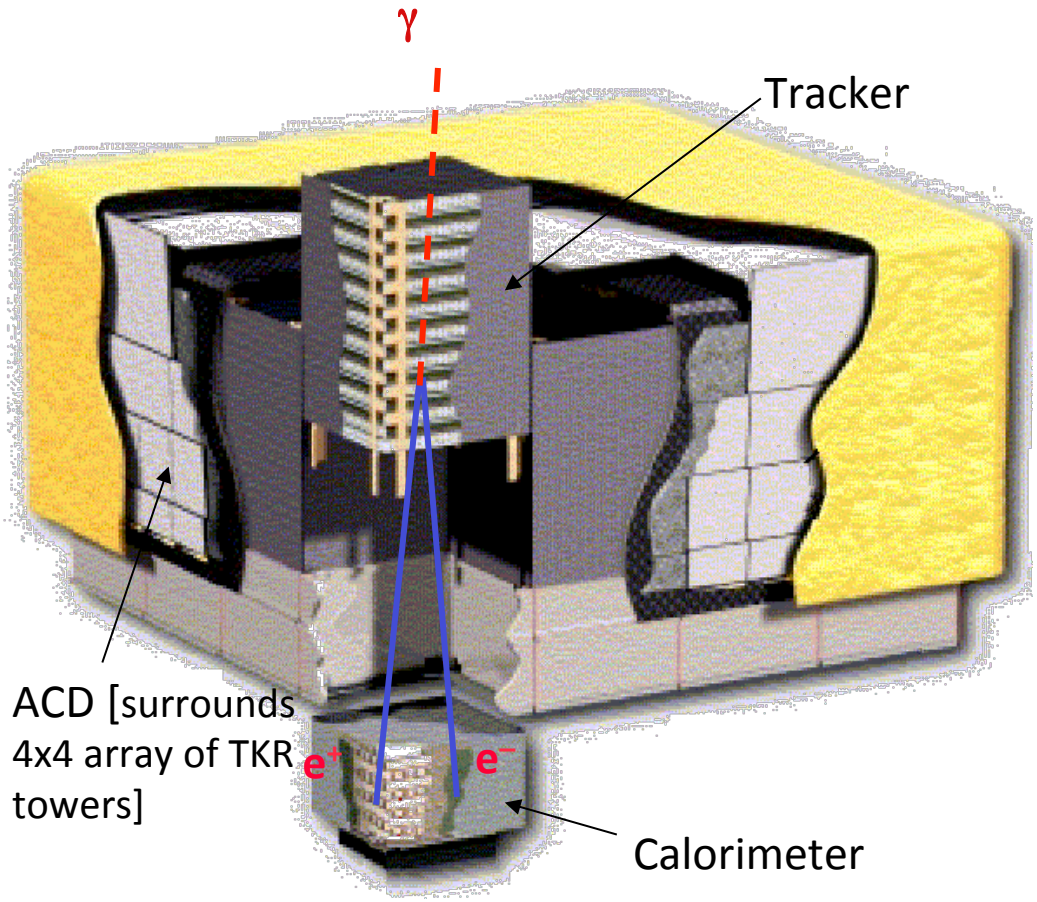
- Two instruments:
  - LAT:
    - high energy (20 MeV – >300 GeV)
  - GBM:
    - low energy (8 keV – 40 MeV)



- Huge field of view
  - LAT: 20% of the sky at any instant; in sky survey mode, expose all parts of sky for ~30 minutes every 3 hours. GBM: whole unocculted sky at any time.
- Huge energy range, including largely unexplored band 10 GeV - 100 GeV
- Large leap in all key capabilities. Great discovery potential.

Overview of LAT

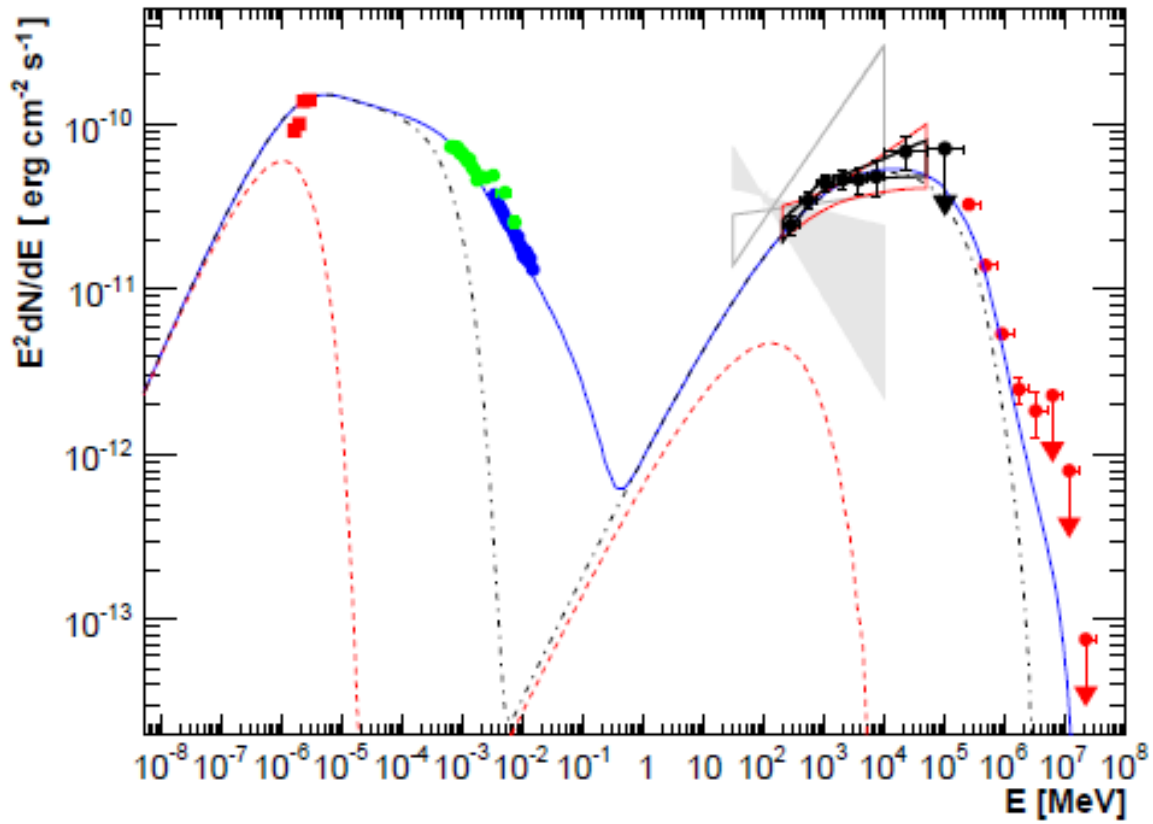
- Precision Si-strip Tracker (TKR) 18 XY tracking planes. Single-sided silicon strip detectors (228 μm pitch) Measure the photon direction; gamma ID.
- Hodoscopic CsI Calorimeter(CAL) Array of 1536 CsI(Tl) crystals in 8 layers. Measure the photon energy; image the shower.
- Segmented Anticoincidence Detector (ACD) 89 plastic scintillator tiles. Reject background of charged cosmic rays; segmentation removes self-veto effects at high energy.
- Electronics System Includes flexible, robust hardware trigger and software filters.



Systems work together to identify and measure the flux of cosmic gamma rays with energy 20 MeV - >300 GeV.

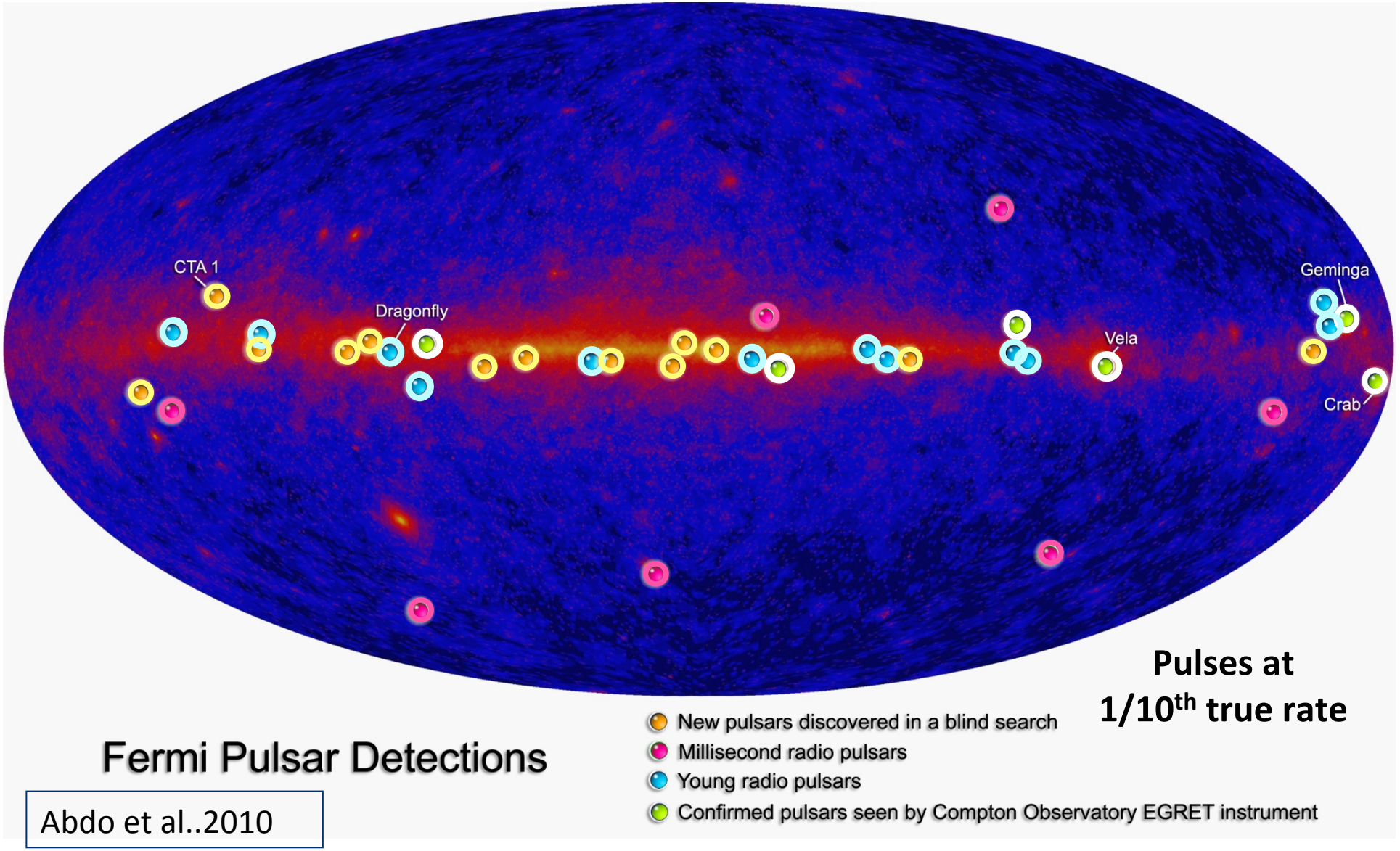
Challenge # 1 – AGN

Joint campaign on PKS 2155 with HESS



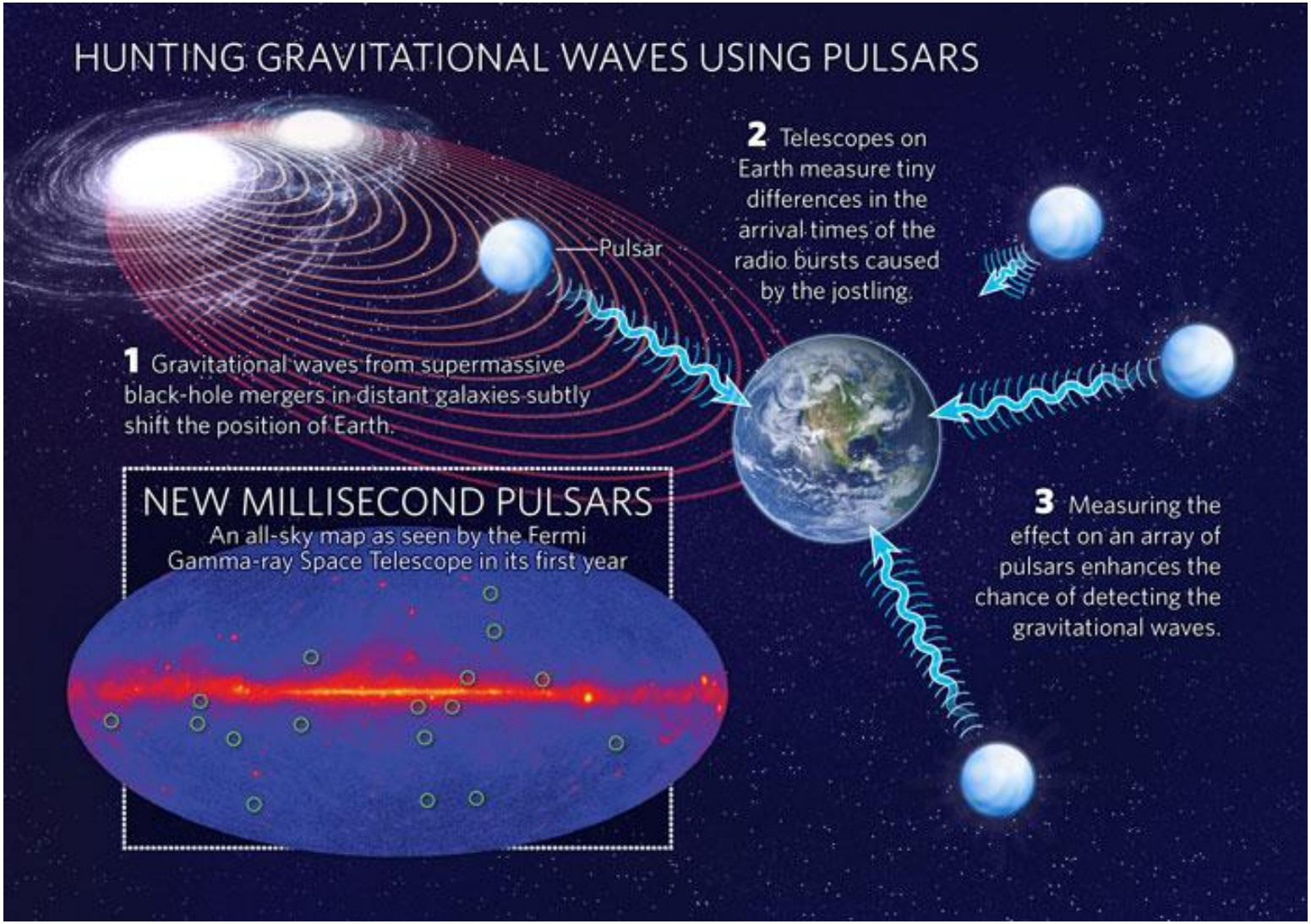
Aharonian et al. 2009

Challenge # 2 – Pulsars Blind Search

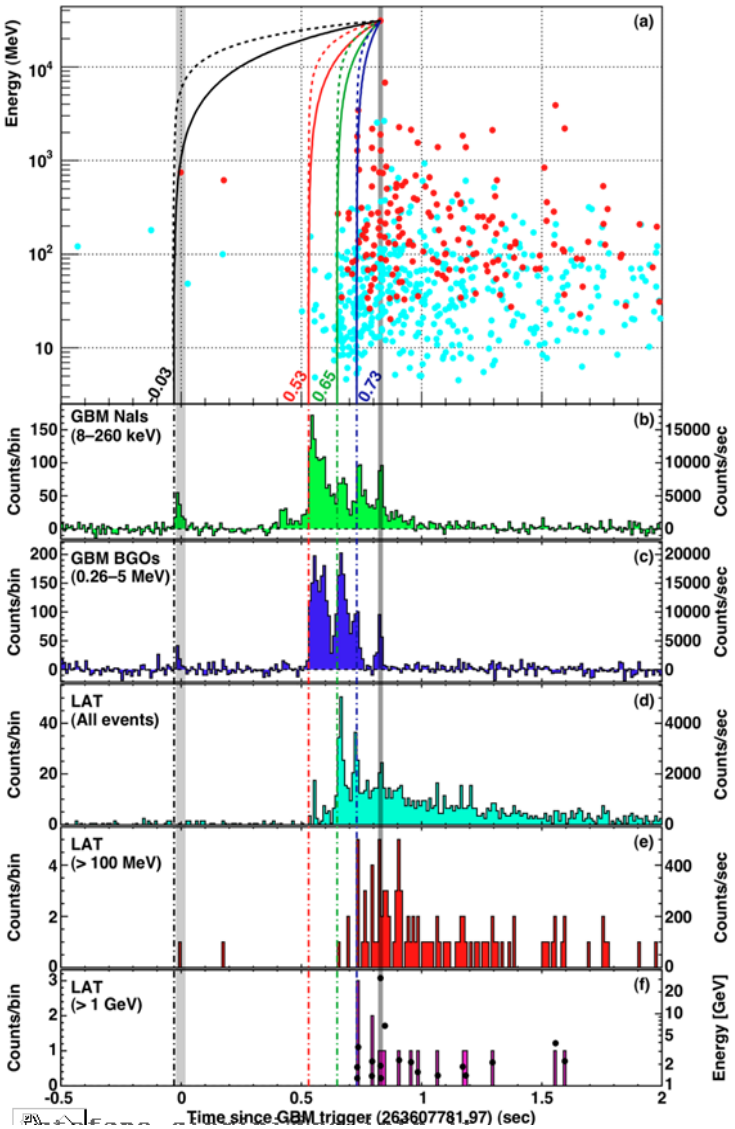


Abdo et al..2010

New MSP and GW detection



Challenge # 3 – GRB



- This GRB is a perfect case for studying Lorentz Invariance Violation
  - z = 0.9 (5.381 Gyr)
  - Emission of 31 GeV photon after 859 ms since the trigger
- Only conservative assumption!
  - the HE photon is not emitted *before* the LE photons, at different events.

Table 2 | Limits on Lorentz Invariance Violation

#	$t_{start} - T_0$ (ms)	Limit on $\|\Delta t\|$ (ms)	Reasoning for choice of t_{start} or limit on Δt or $\|\Delta t/\Delta E\|$	E_l † (MeV)	Valid for s_n*	Lower limit on $M_{QG,1}/M_{Planck}$
(a)❖	−30	< 859	start of any < 1 MeV emission	0.1	1	> 1.19
(b)❖	530	< 299	start of main < 1 MeV emission	0.1	1	> 3.42
(c)❖	*648*	< 181	start of main > 0.1 GeV emission	100	1	> 5.63
(d)❖	730	< 99	start of > 1 GeV emission	1000	1	> 10.0
(e)♦	—	< 10	association with < 1 MeV spike	0.1	±1	> 102
(f)♦	—	< 19	If 0.75 GeV‡ γ-ray from 1st spike	0.1	−1	> 1.33
(g)♠	$\|\Delta t/\Delta E\| < 30$ ms/GeV		lag analysis of > 1 GeV spikes	—	±1	> 1.22

nature

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nature > letters > article

Published: 01 October 1998

Tests of quantum gravity from observations of γ-ray bursts

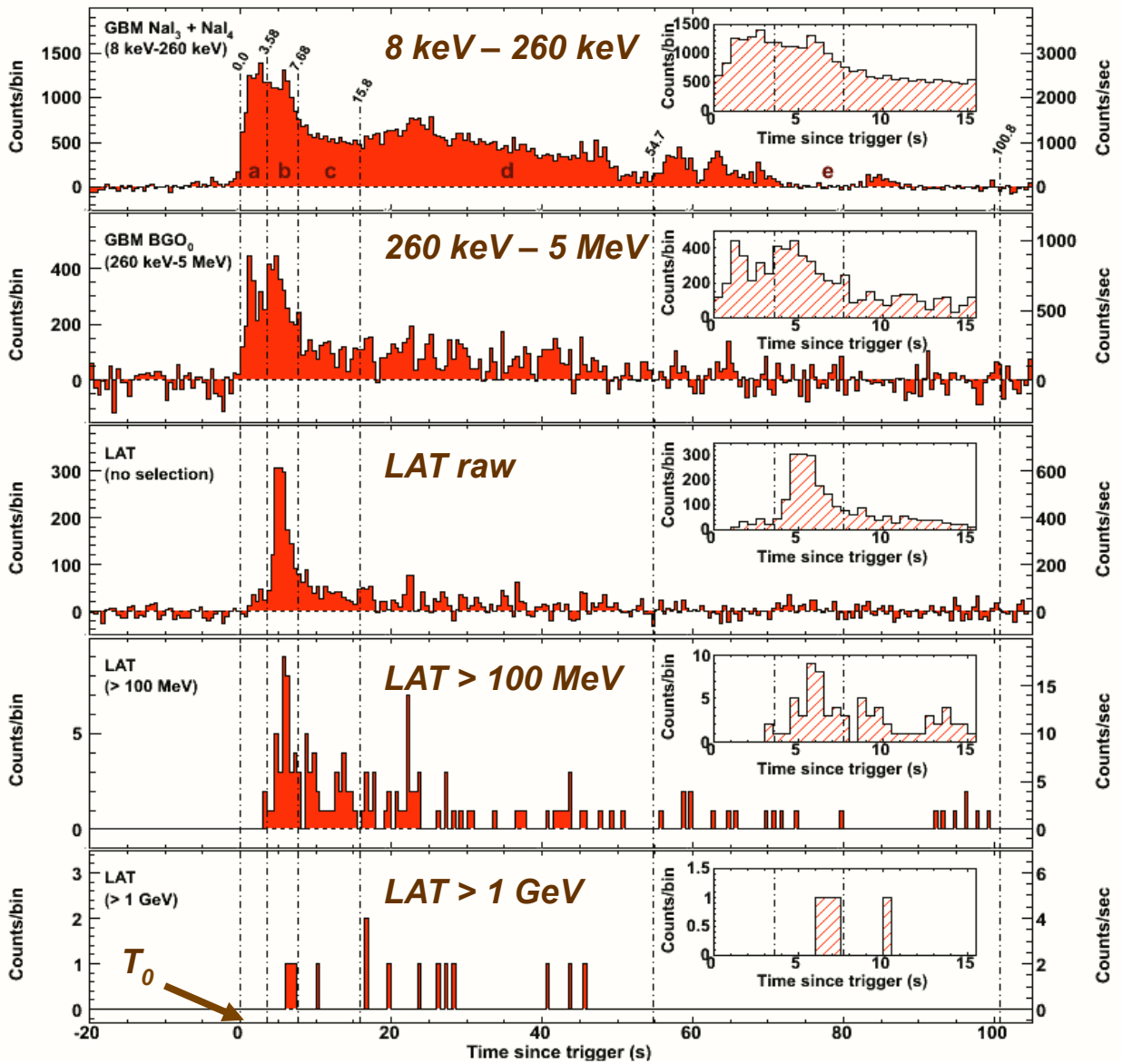
G. Amelino-Camelia, John Ellis, N. E. Mavromatos, D. V. Nanopoulos & Subir Sarkar

Nature **395**, 525 (1998) | Cite this article

The recent confirmation that at least some γ-ray bursts originate at cosmological distances[1–4] suggests that the radiation from them could be used to probe some of the fundamental laws of physics. Here we show that γ-ray bursts will be sensitive to an energy dispersion predicted by some approaches to quantum gravity. Many of the bursts have structure on relatively rapid timescales[5], which means that in principle it is possible to look for energy-dependent dispersion of the radiation, manifested in the arrival times of the photons, if several different energy bands are observed simultaneously. A simple estimate indicates that, because of their high energies and distant origin, observations of these bursts should be sensitive to a dispersion scale that is comparable to the Planck energy scale ($\sim 10^{19}$ GeV), which is sufficient to test theories of quantum gravity. Such observations are already possible using existing γ-ray burst detectors.

$$v = \frac{\partial E}{\partial p} \approx c\left(1 - \xi \frac{E}{E_{QG}}\right) \qquad \Delta t \approx \xi \frac{E}{E_{QG}} \frac{L}{c}$$

GRB080916C - Multiple detector light curve



First 3 light curves are background subtracted

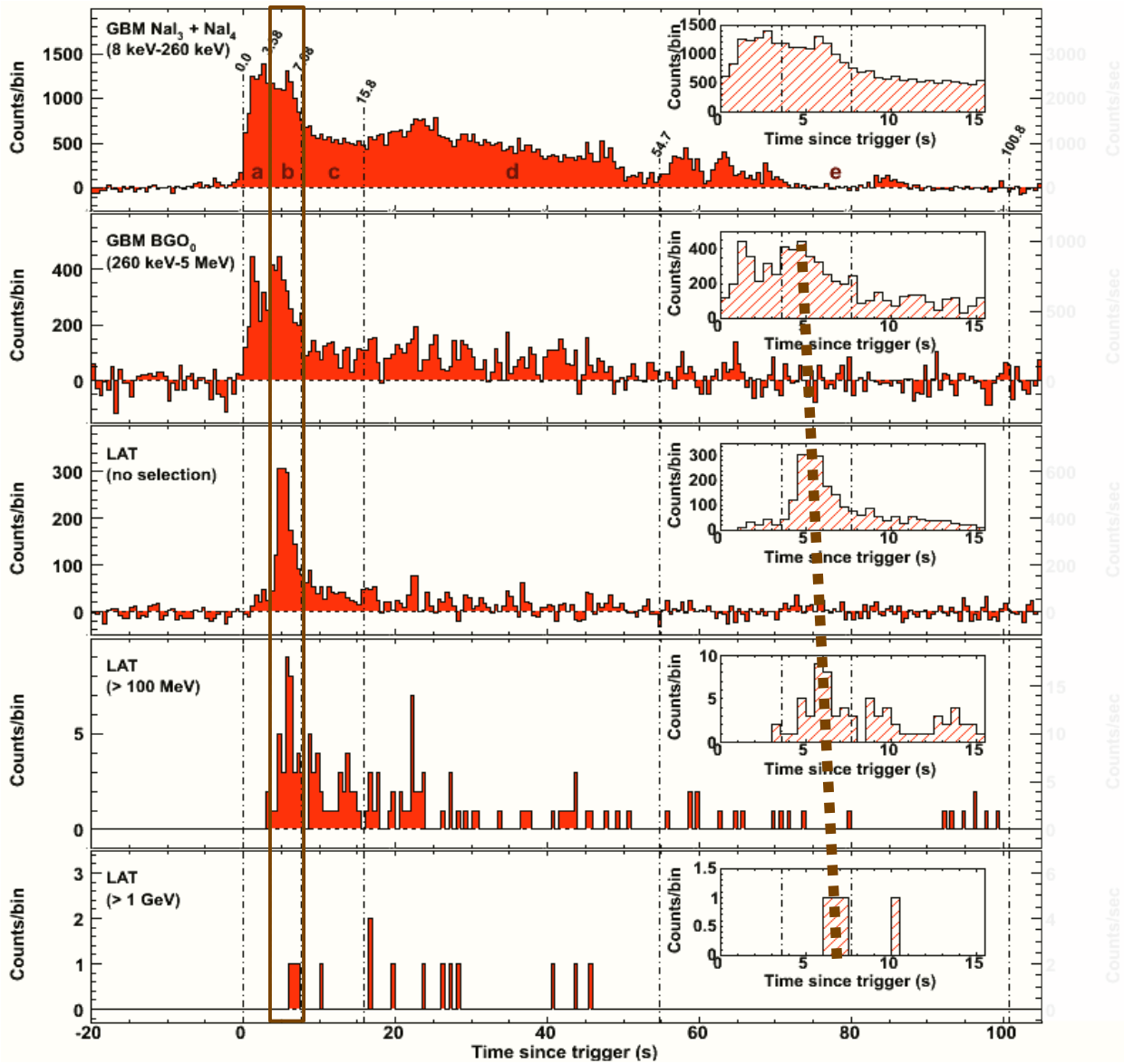
The LAT can be used as a counter to maximize the rate and to study time structures above tens of MeV

- **The first low-energy peak is not observed at LAT energies**

Spectroscopy needs LAT event selection (>100 MeV)

- **14 events above 1 GeV**

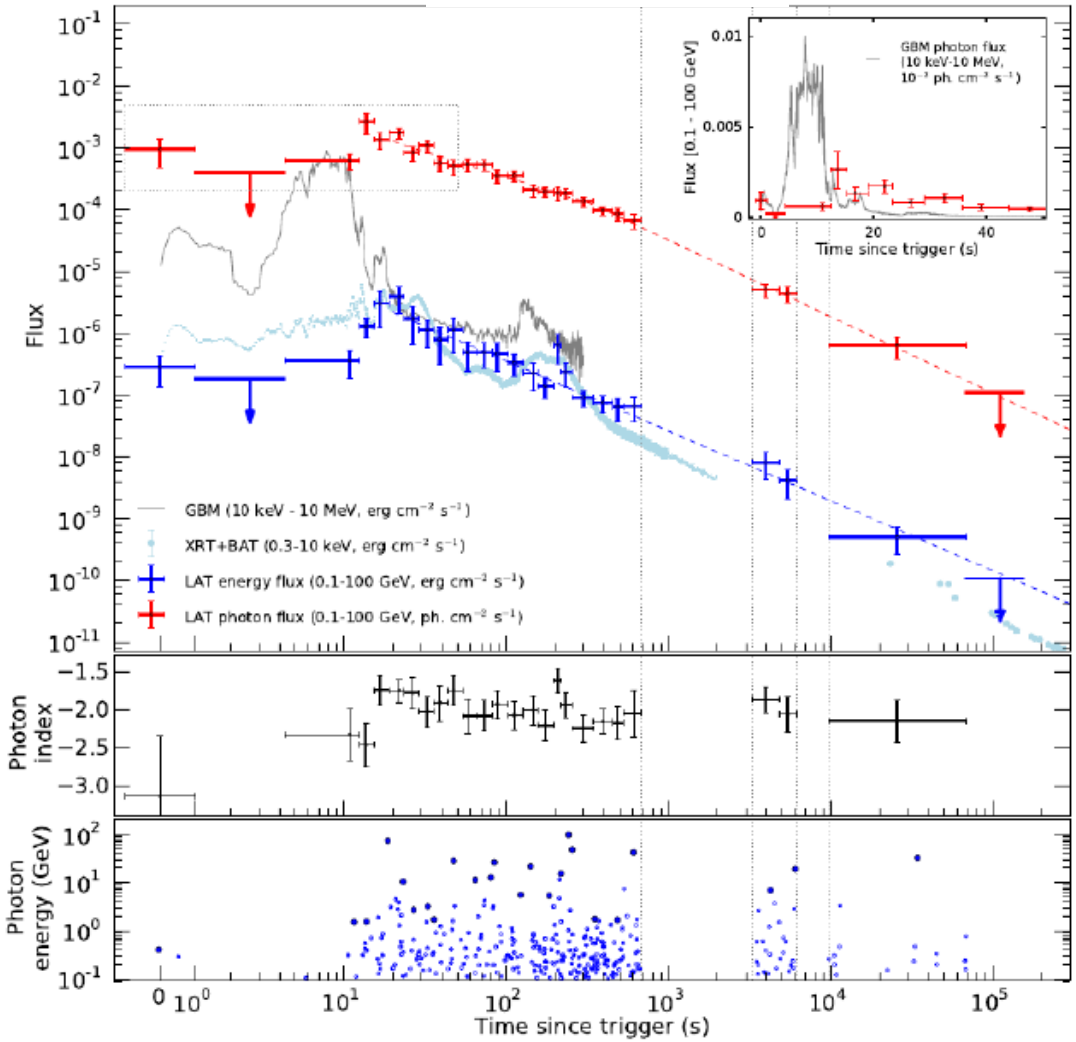
Multiple detector light curve



The bulk of the emission of the 2nd peak is moving toward later times as the energy increases

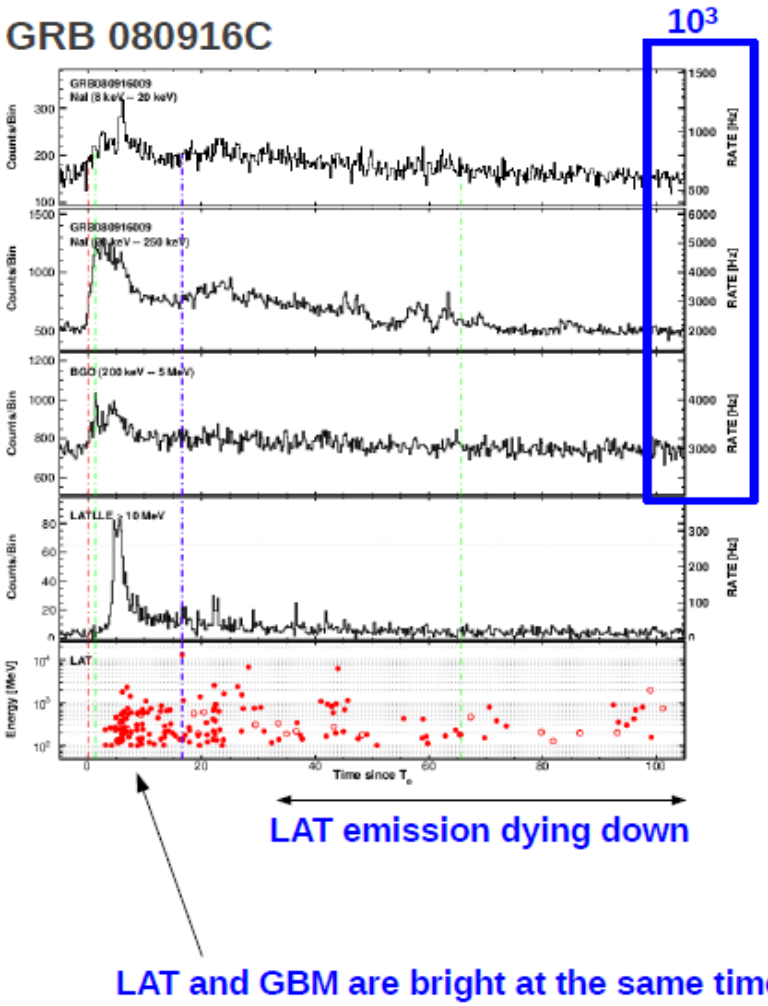
Clear signature of spectral evolution

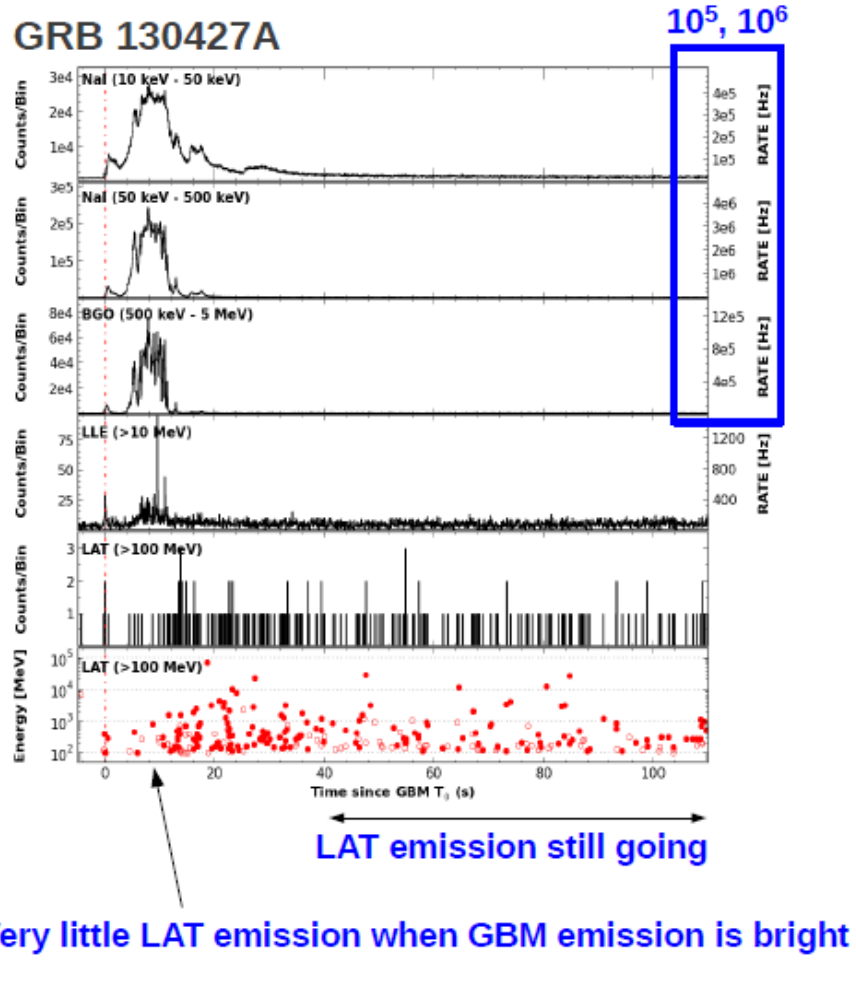
GRB 130427A



(Ackermann et al., Science, Vol. 343 no. 6166 pp. 42-47)

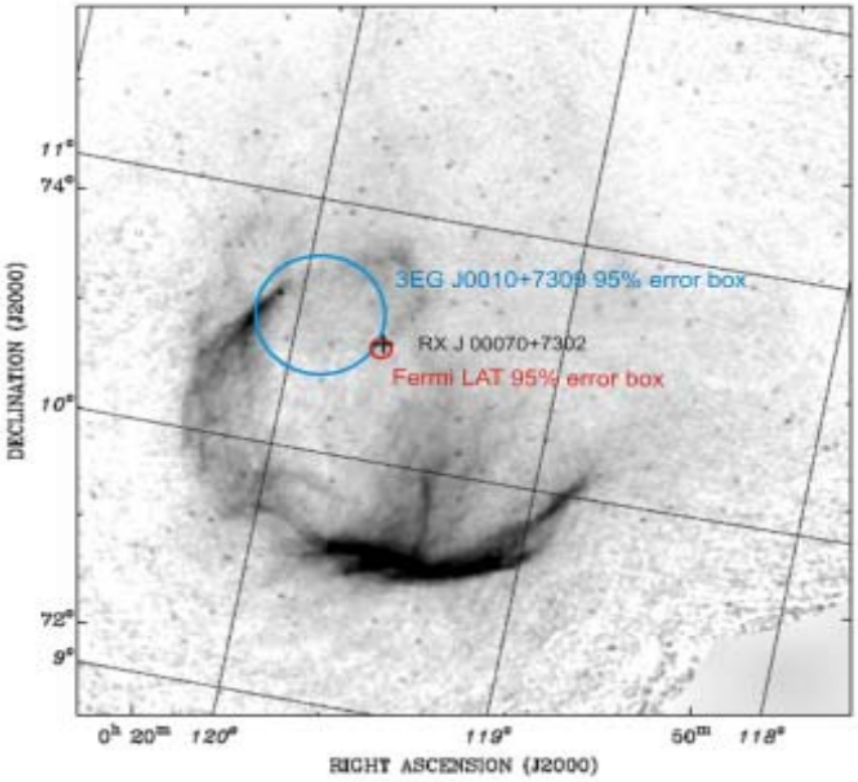
GRB 130427A

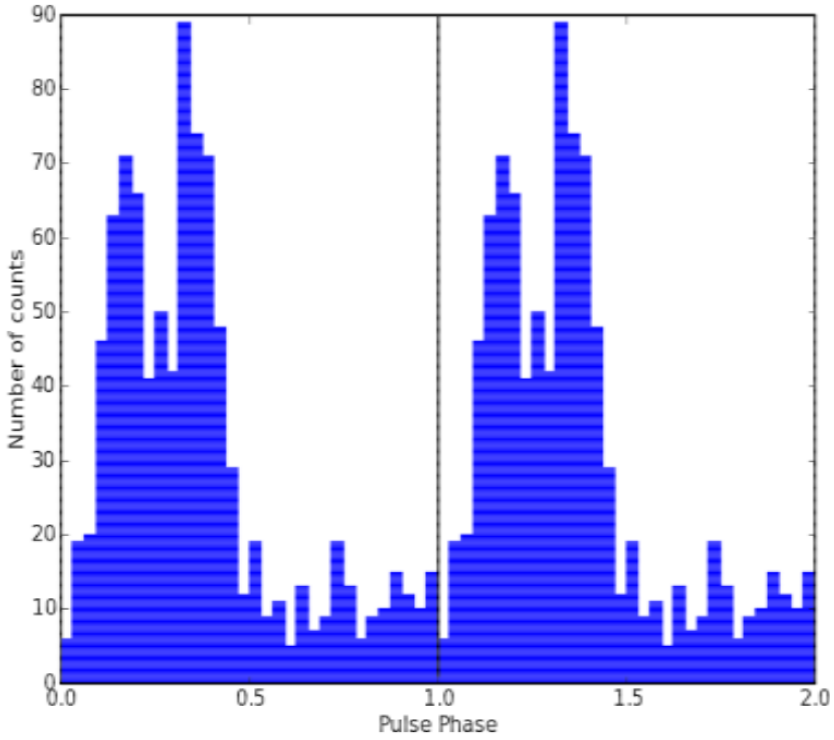

GRB 080916C
10^3
Counts/Bin
RATE [Hz]
LAT
Energy [MeV]
Time since T_0
LAT emission dying down
LAT and GBM are bright at the same time


GRB 130427A
10^5, 10^6
NaI (10 keV - 50 keV)
NaI (50 keV - 500 keV)
BGO (500 keV - 5 MeV)
LLE (>10 MeV)
LAT (>100 MeV)
LAT (>100 MeV)
Counts/Bin
RATE [Hz]
Energy [MeV]
Time since GBM T_0 (s)
LAT emission still going
Very little LAT emission when GBM emission is bright

Challenge # 4 – Unidentified

CTA 1 Discovery

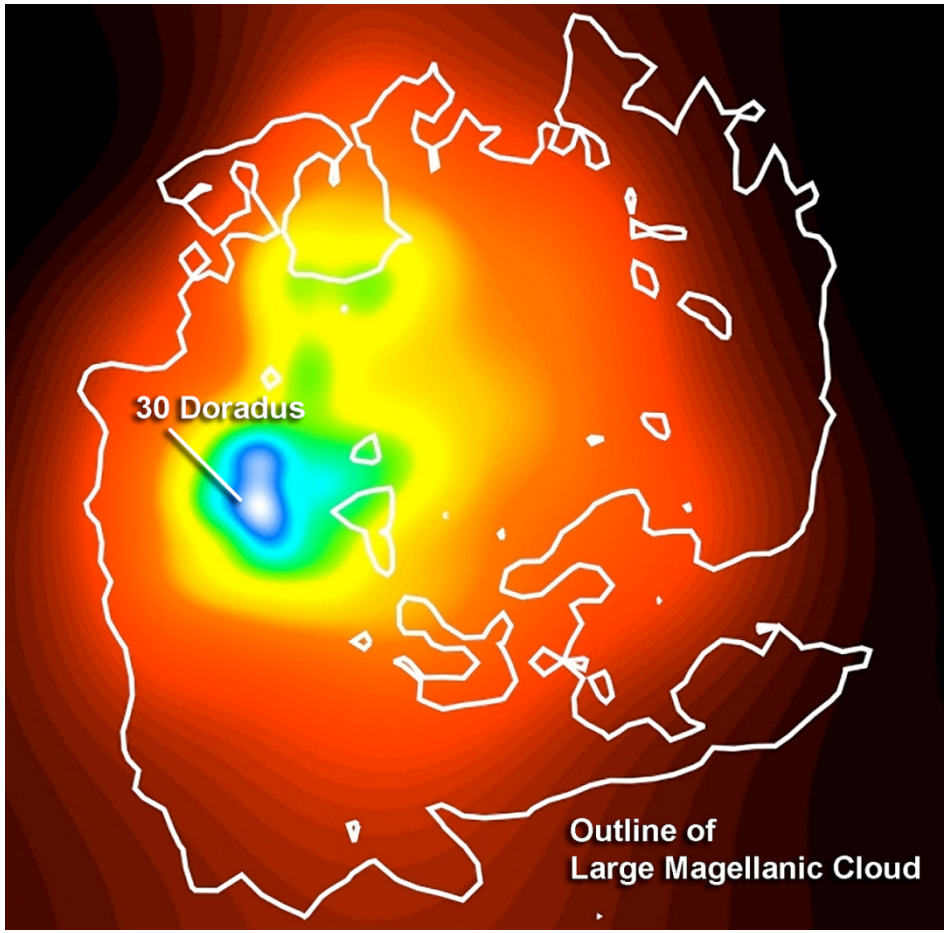




Abdo et al. 2008

Challenge # 4
Location of Gamma-ray emission

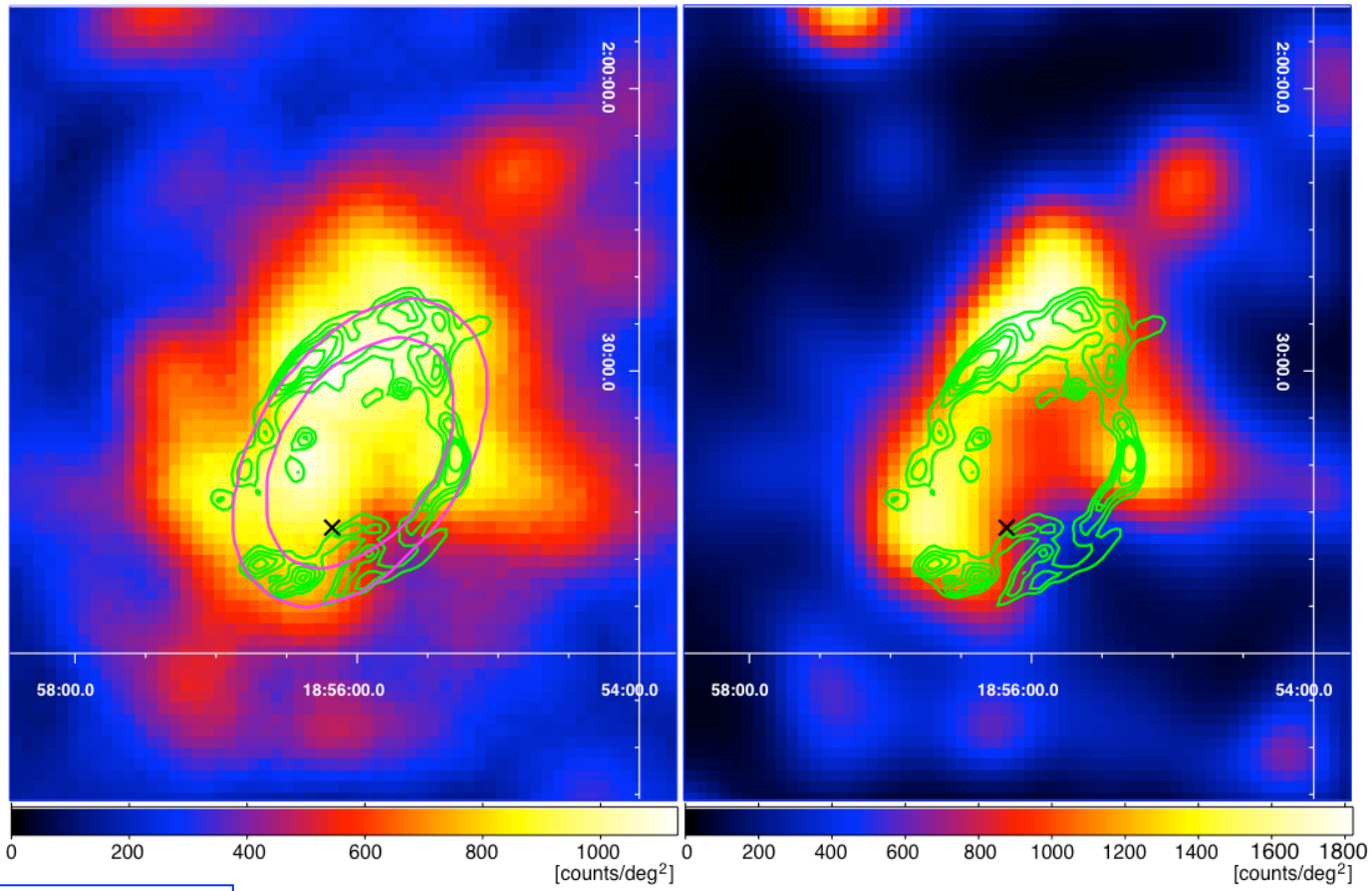
Observations of the Large Magellanic Cloud with *Fermi*



Abdo, A. A. et al. 2010

Challenge # 4
Location of Gamma-ray emission

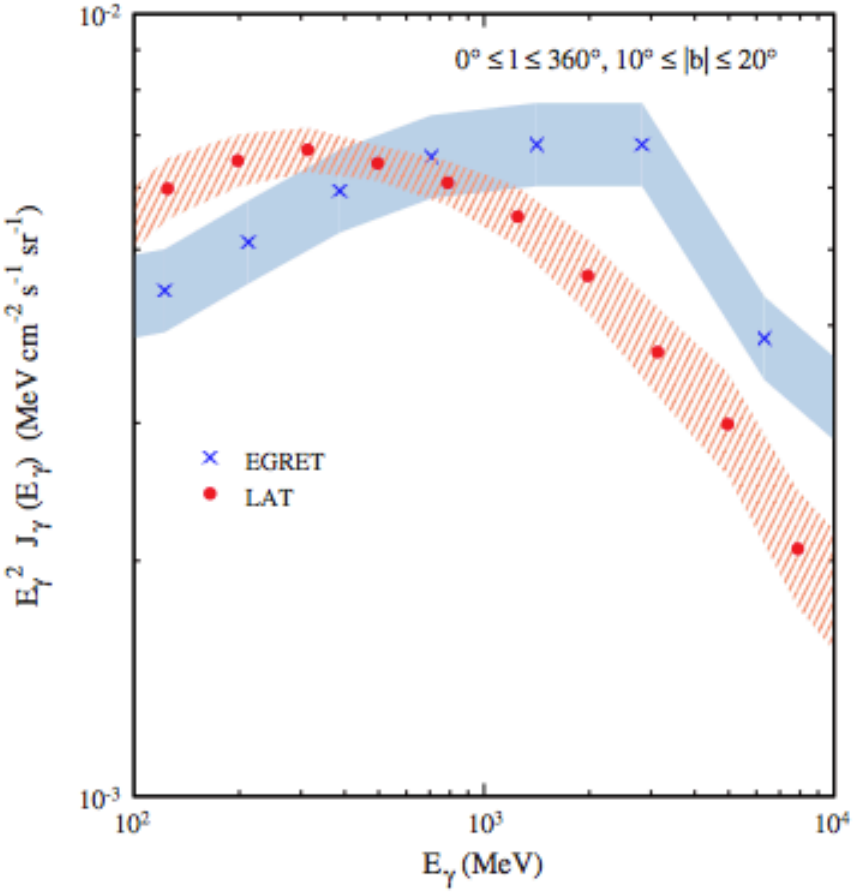
Gamma-Ray Emission from the Shell of Supernova Remnant W44 Revealed by the Fermi LAT

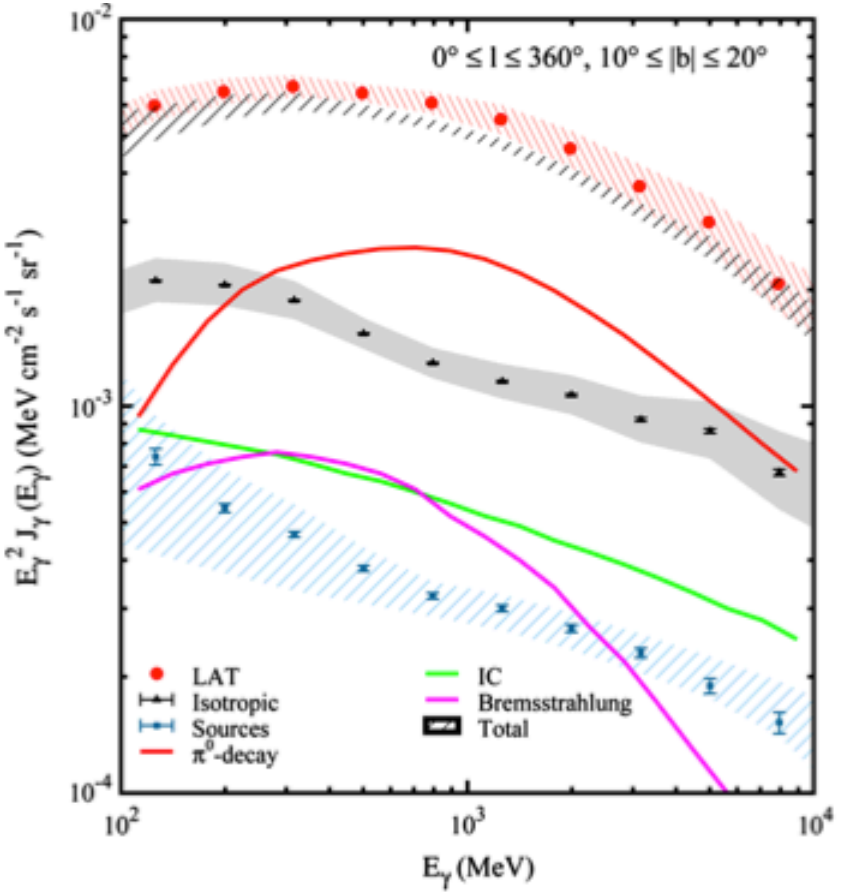


Abdo, A. A. et al. 2010

Challenge # 5 – Spectral Resolution

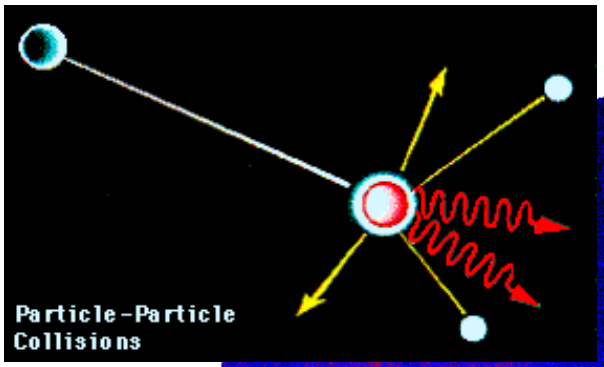
Fermi Large Area Telescope Measurements of the Diffuse Gamma-Ray Emission at Intermediate Galactic Latitudes





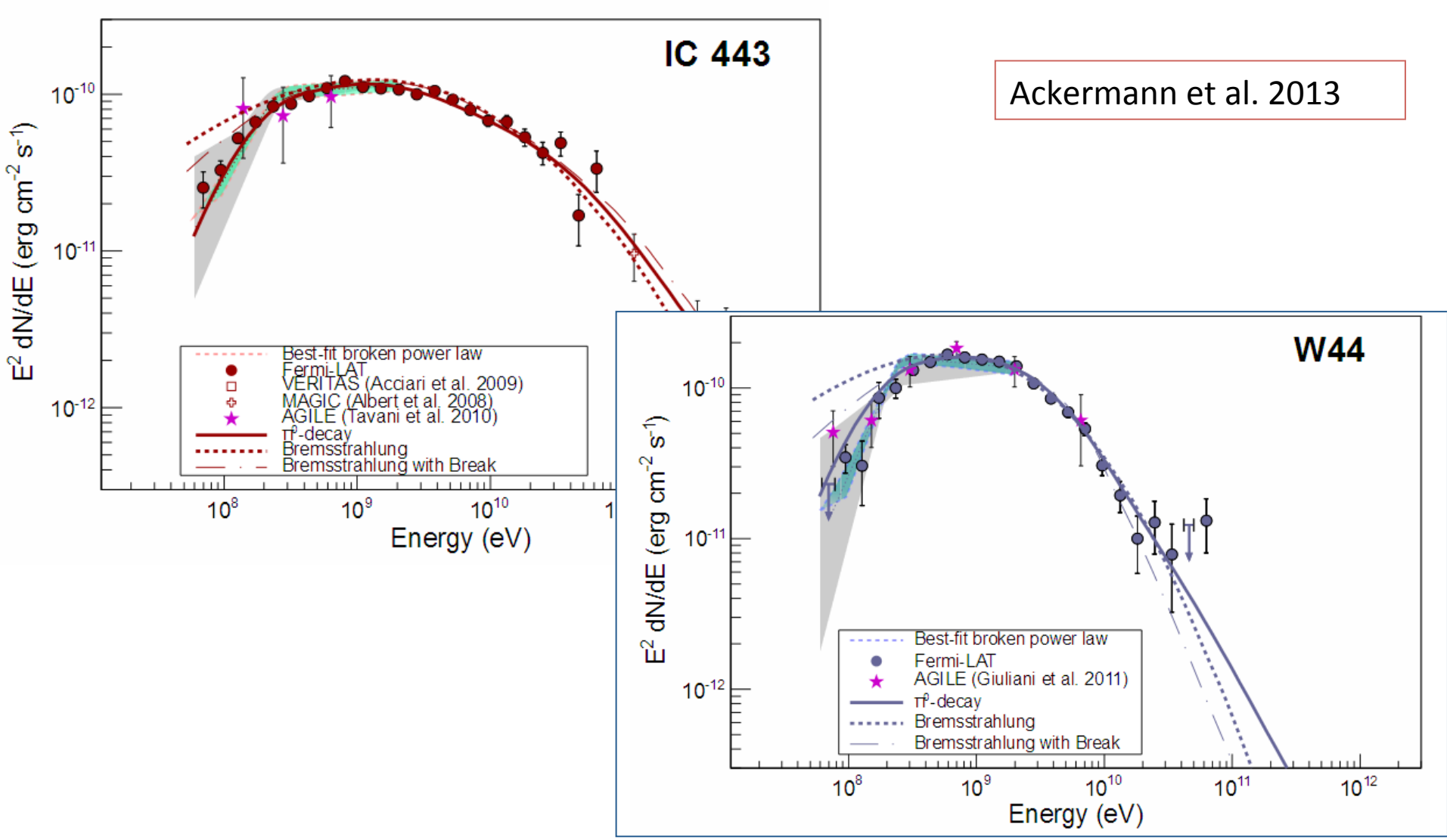
Abdo, A. A. et al. 2009

Cosmic Rays – Gamma-rays connection

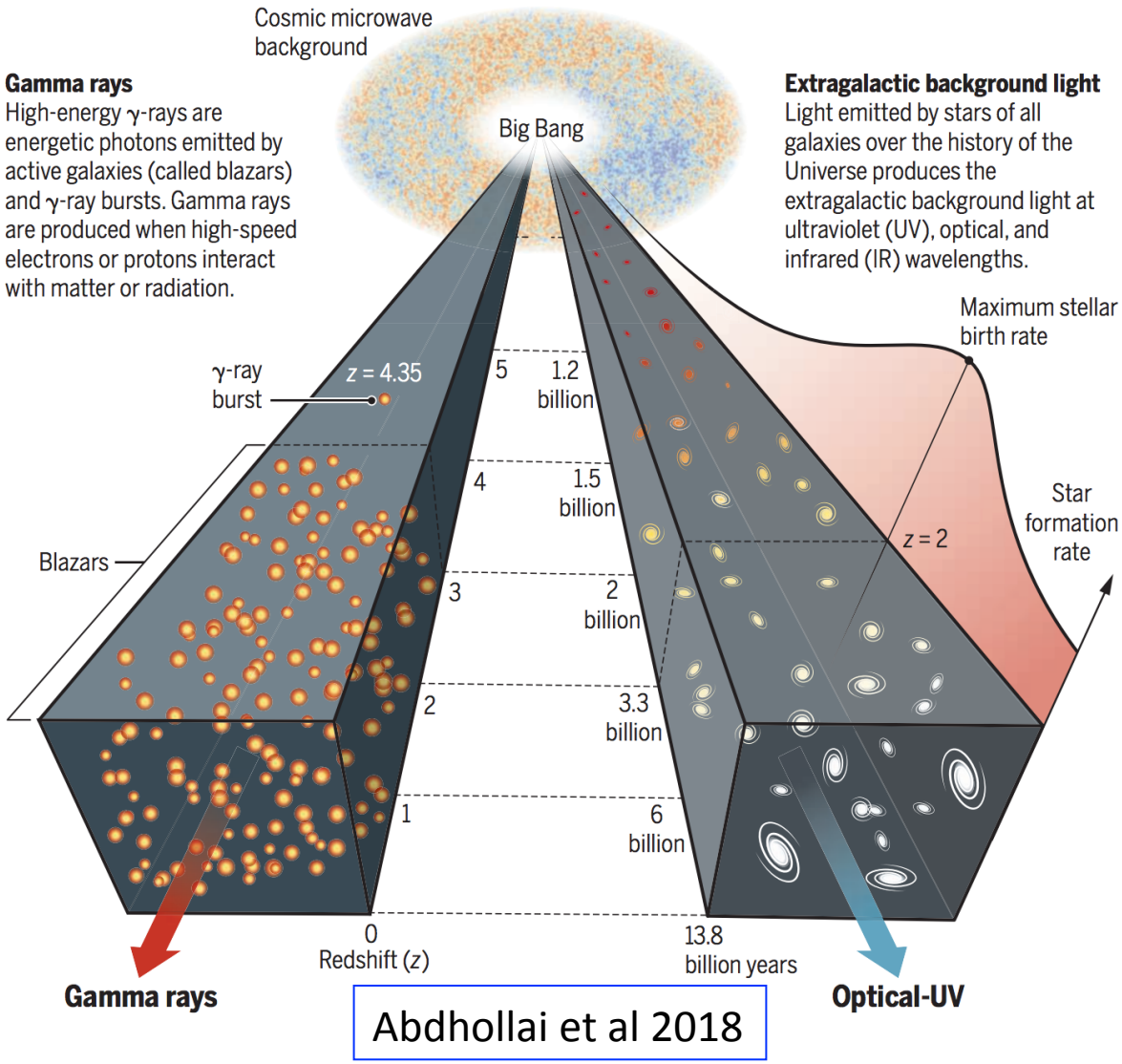


- **Galactic gamma rays trace cosmic-ray proton interactions (cosmic-ray acceleration sites & propagation)**
- **Observations of nearby galaxies provide an outside view**
- **Primary targets: galactic plane, starburst galaxies, LMC, SNR**
- **Direct CR observations**

Supernova Remnants

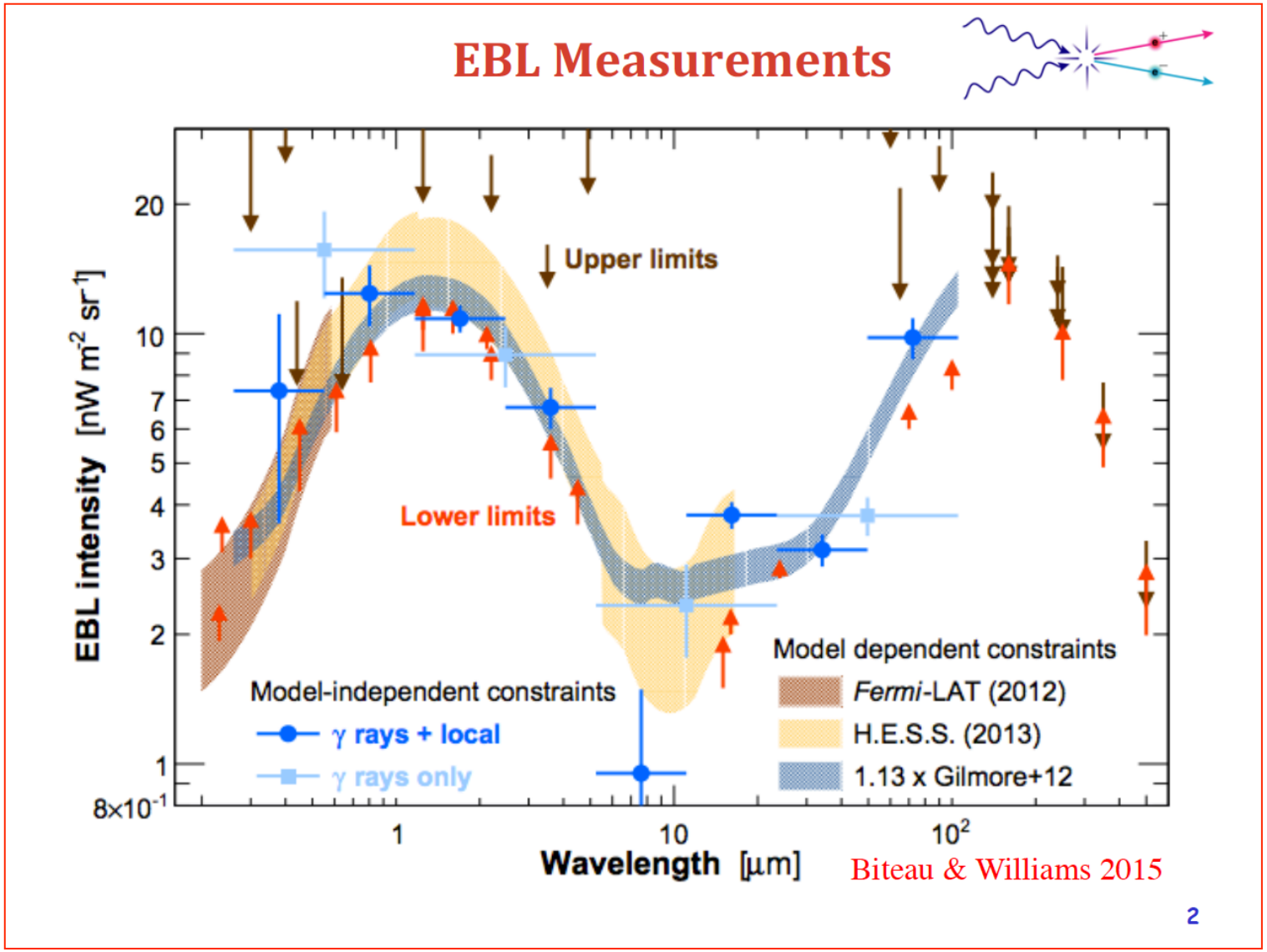


The EBL



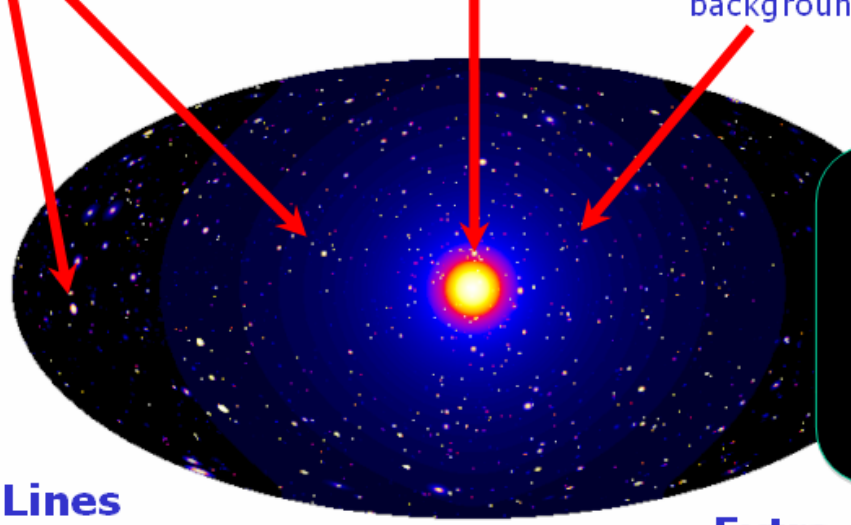
Abdhollai et al 2018

The Extragalactic Background Light



Dark Matter Searches

Gamma-ray indirect emission



All-sky map of simulated gamma ray signal from DM annihilation (Baltz 2006)

Galactic Center

Good Statistics but source confusion/diffuse background

Satellites

Low background and good source id, but low statistics, astrophysical background

Milky Way Halo

Large statistics but diffuse background

Dark Matter sources can also produce features in the local Cosmic Ray Electron spectrum

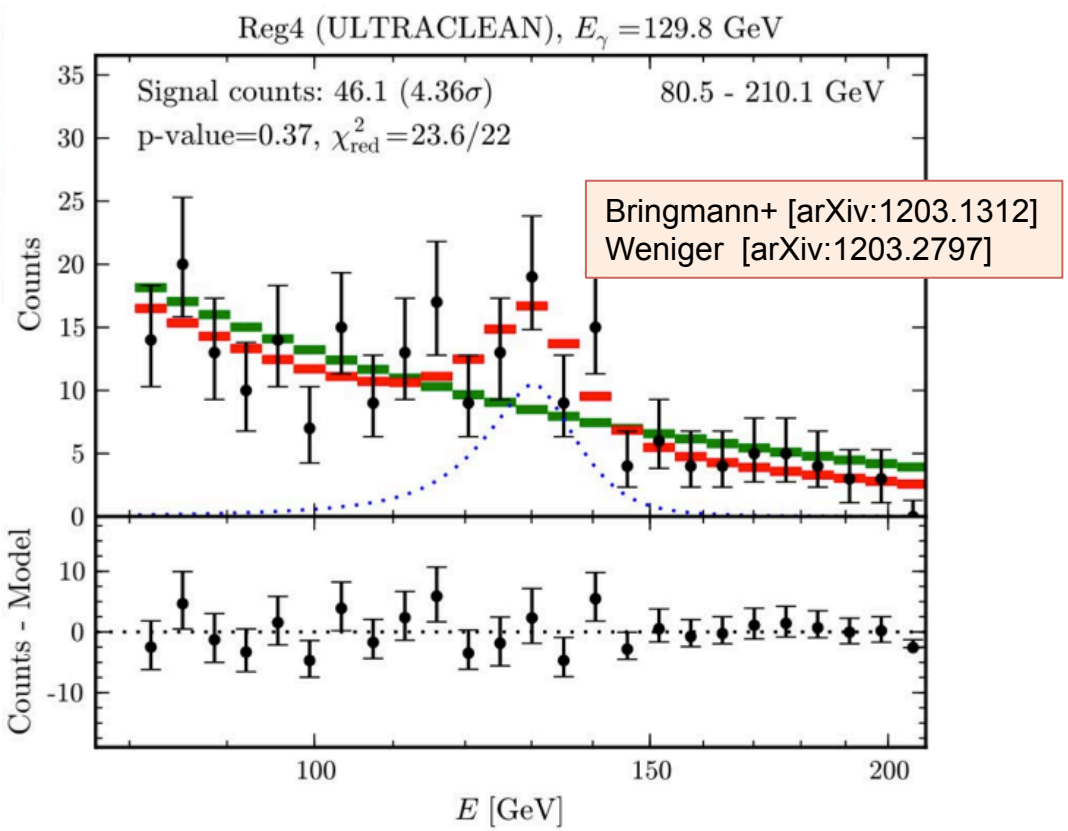
Spectral Lines

No astrophysical uncertainties, good source id, but low sensitivity because of expected small BR

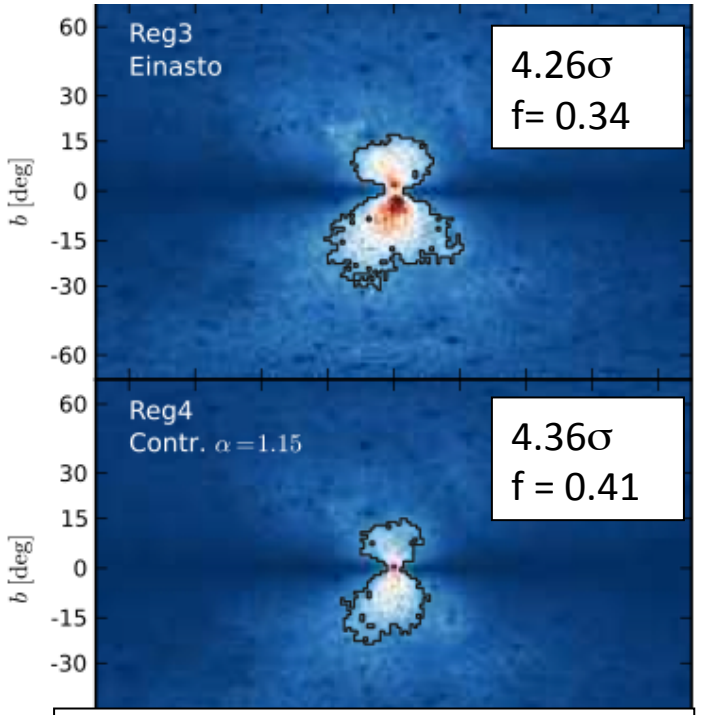
Extra-galactic

Large statistics, but astrophysics, galactic diffuse background

Narrow Spectral Feature at 130 GeV



Bringmann+ [arXiv:1203.1312]
Weniger [arXiv:1203.2797]

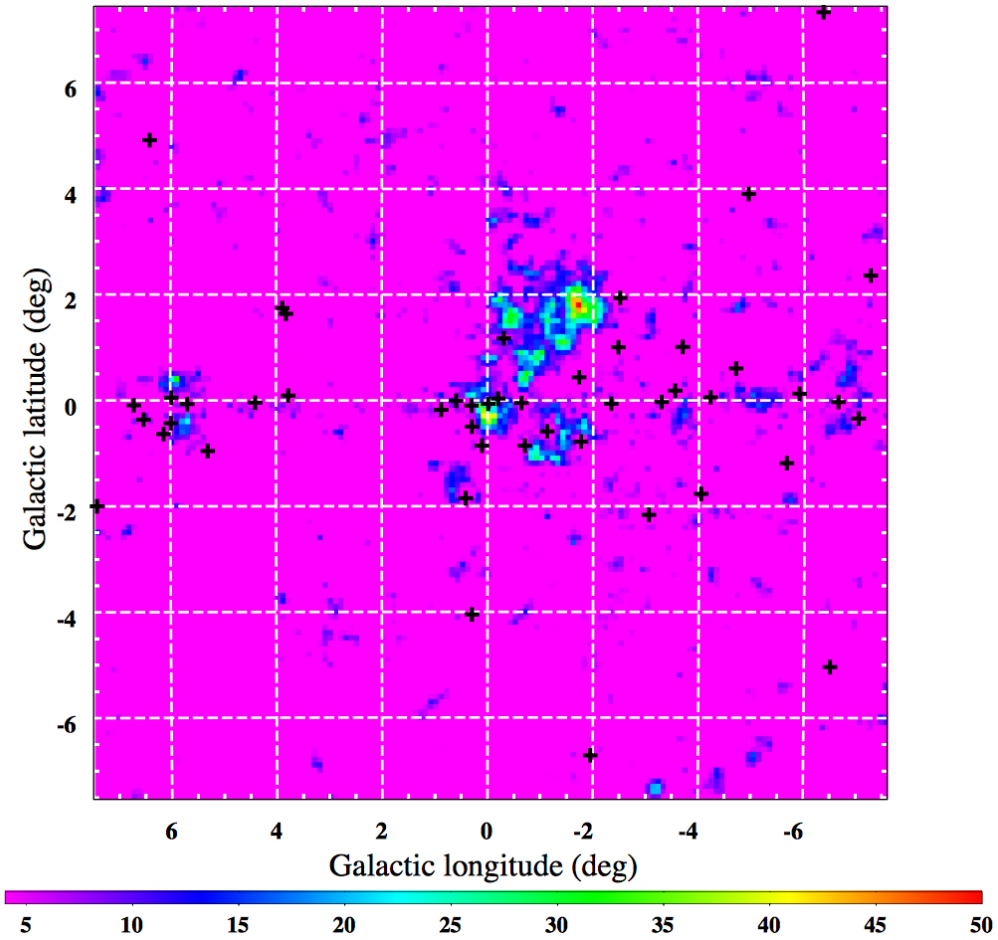


Fractional Residual (i.e., S/N):
$f = s^2 / n_s$

Bringmann et al. and Weniger showed evidence for a narrow spectral feature near 130 GeV near the Galactic center (GC) in the LAT data.

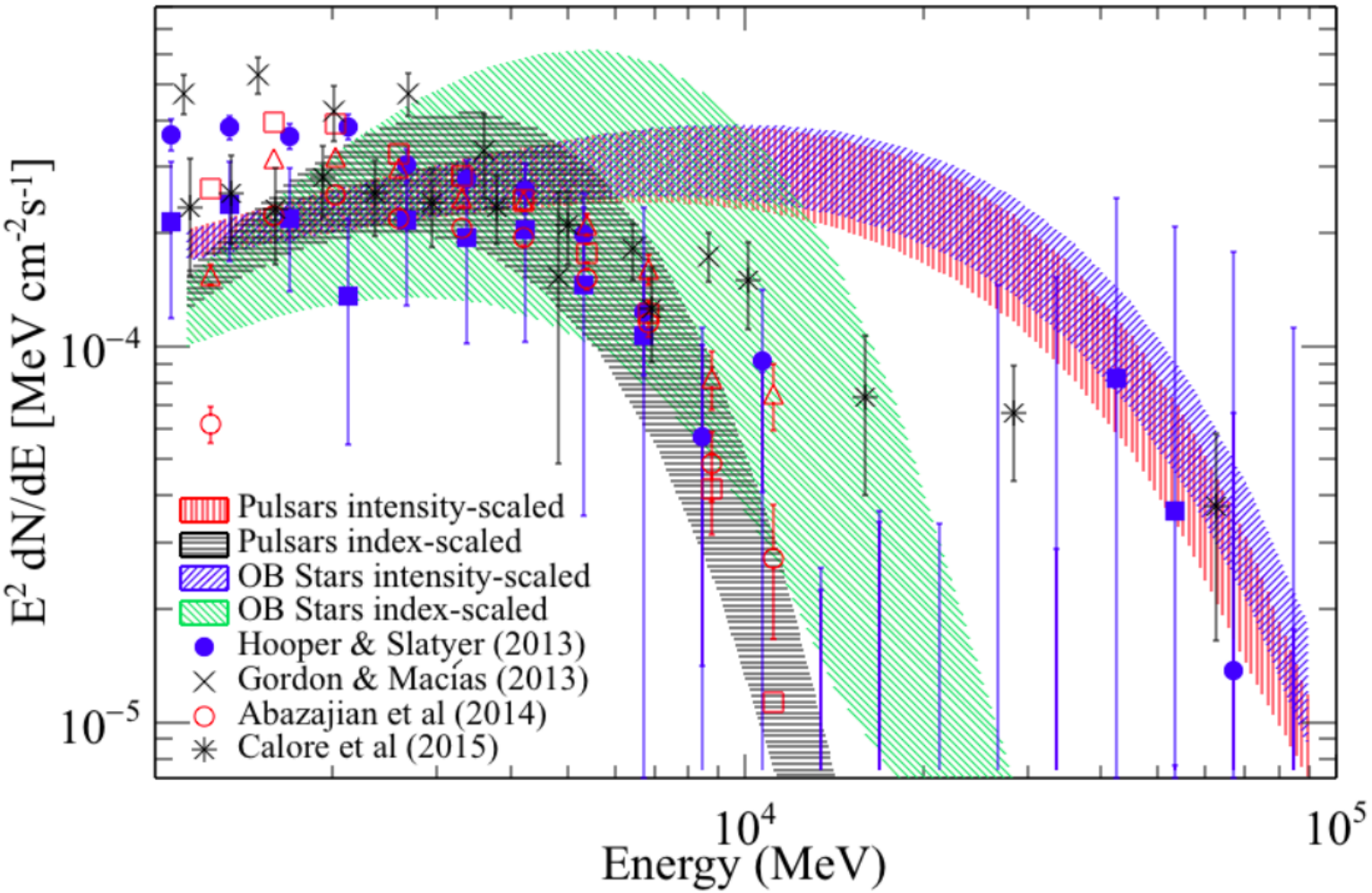
- Signal is particularly strong in 2 out of 5 test regions, shown above.
- Over 4σ local significance with S/N > 30%, up to ~60% in optimized ROI.
- Some indication of double line (111 &130 GeV).

Dark Matter searches – Galactic Center



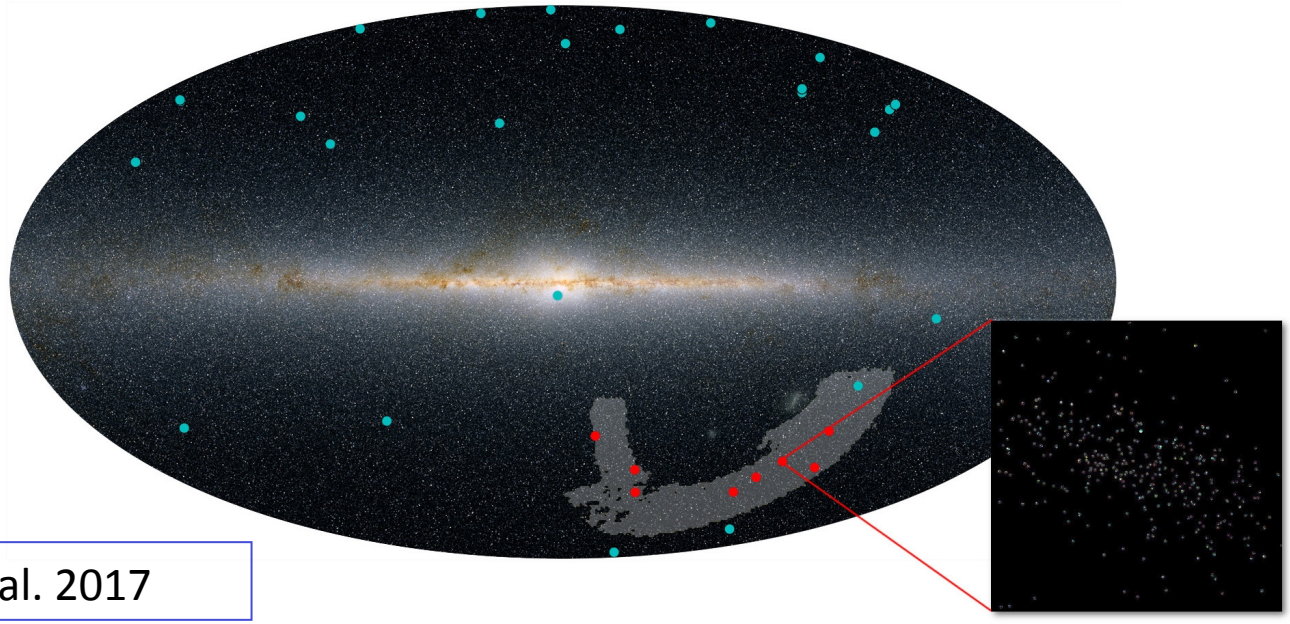
Ackermann, M. et al. 2017

Dark Matter searches – GC

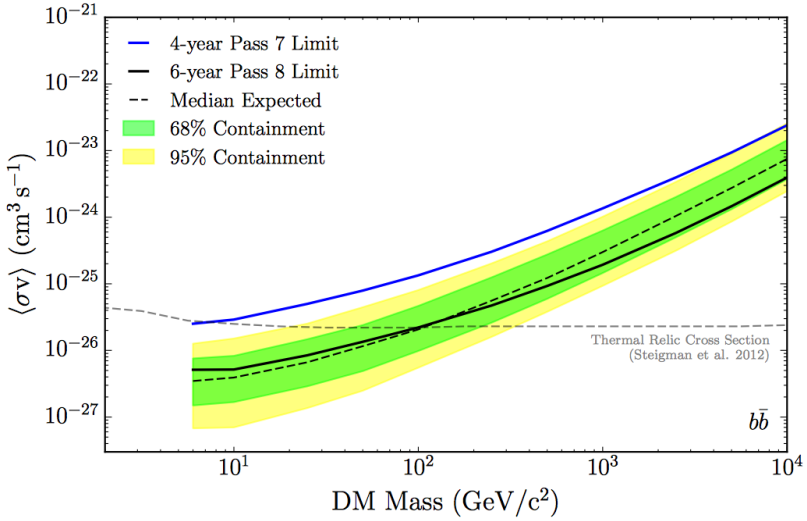


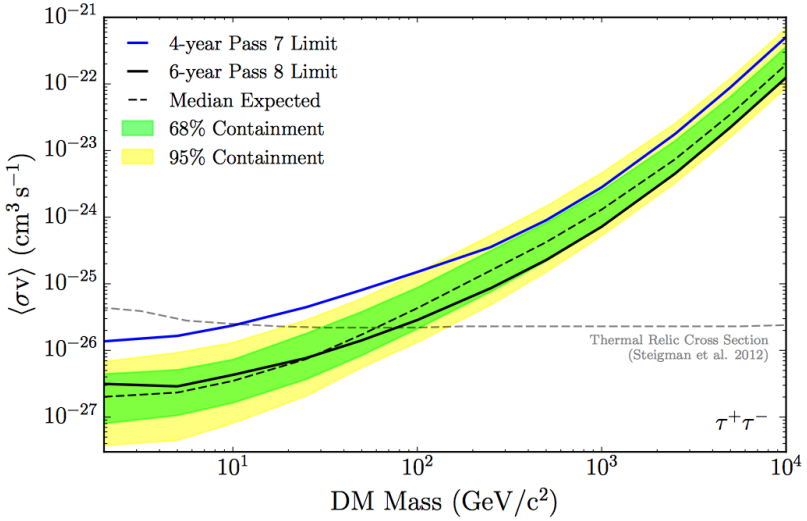
Ackermann, M. et al. 2017

Dark Matter searches – Dwarfs Galaxies



Albert, A. et al. 2017





How the LAT detects electrons

Trigger and downlink

Very versatile and configurable

- Triggering on ~ all particles that cross the LAT
  - Including electrons (8M/yr)

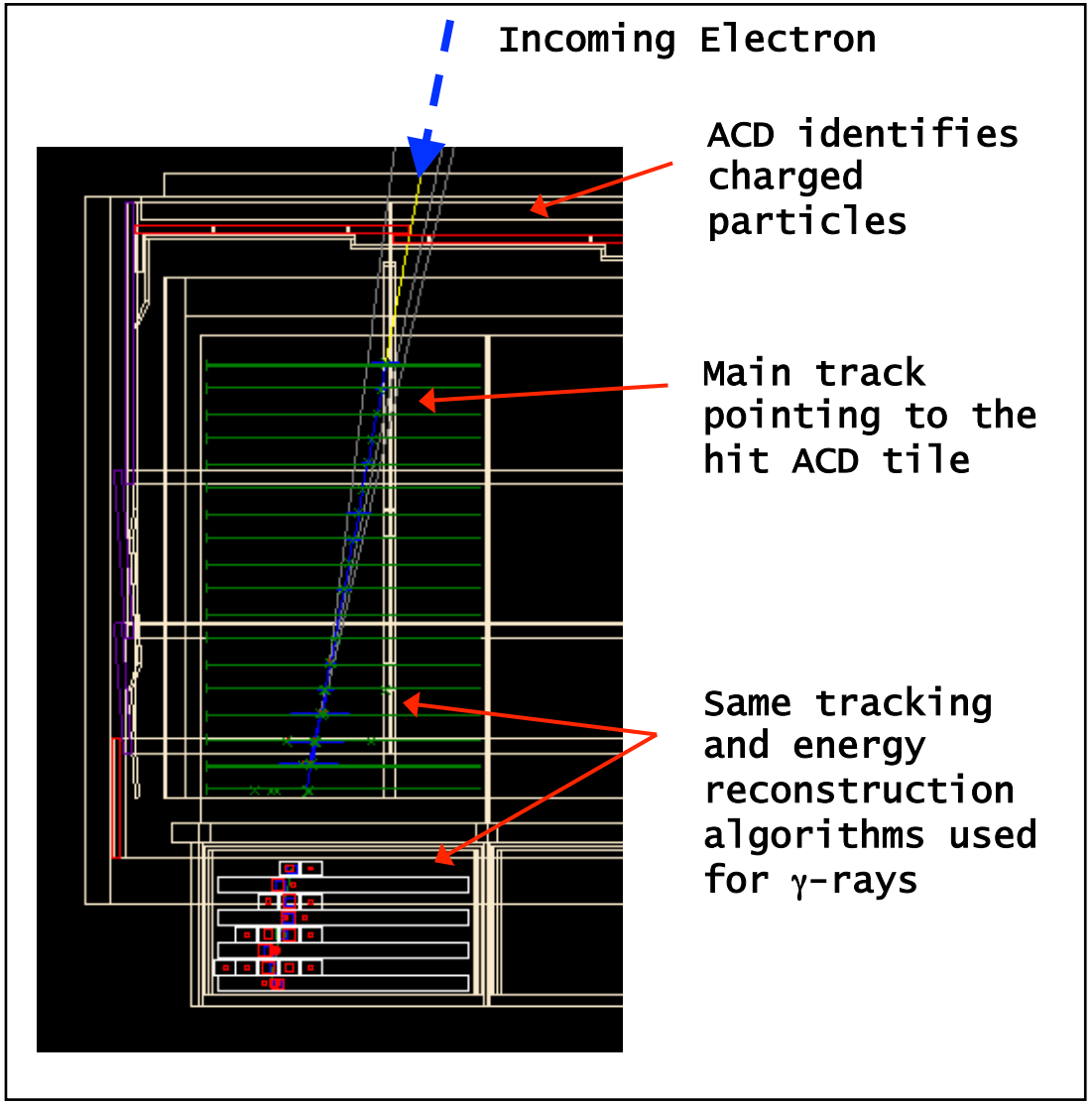
On board filtering to fit bandwidth

- Remove many charged particles
- Keeps all events with more than 20 GeV in the CAL (HE)
- Prescaled (1:250) sample of unfiltered triggers (LE)

Electron identification

The challenge is identifying the good electrons among the proton background

- Rejection power of $10^3 - 10^4$ required
- Can not separate electrons from positrons
- → Dedicated high energy electron event selection



Importance of a direct CRE measurement

- Probe CR models
  - Sources (including DM), interactions, propagation, diffusion
- Probe CR targets (ISM, ISRF)
  - Propagation and diffusion
  - Strong connection with diffuse gamma-ray radiation
- Probe possible nearby sources
  - limited electron lifetime within Galaxy
- Answers to long-standing questions and vast literature

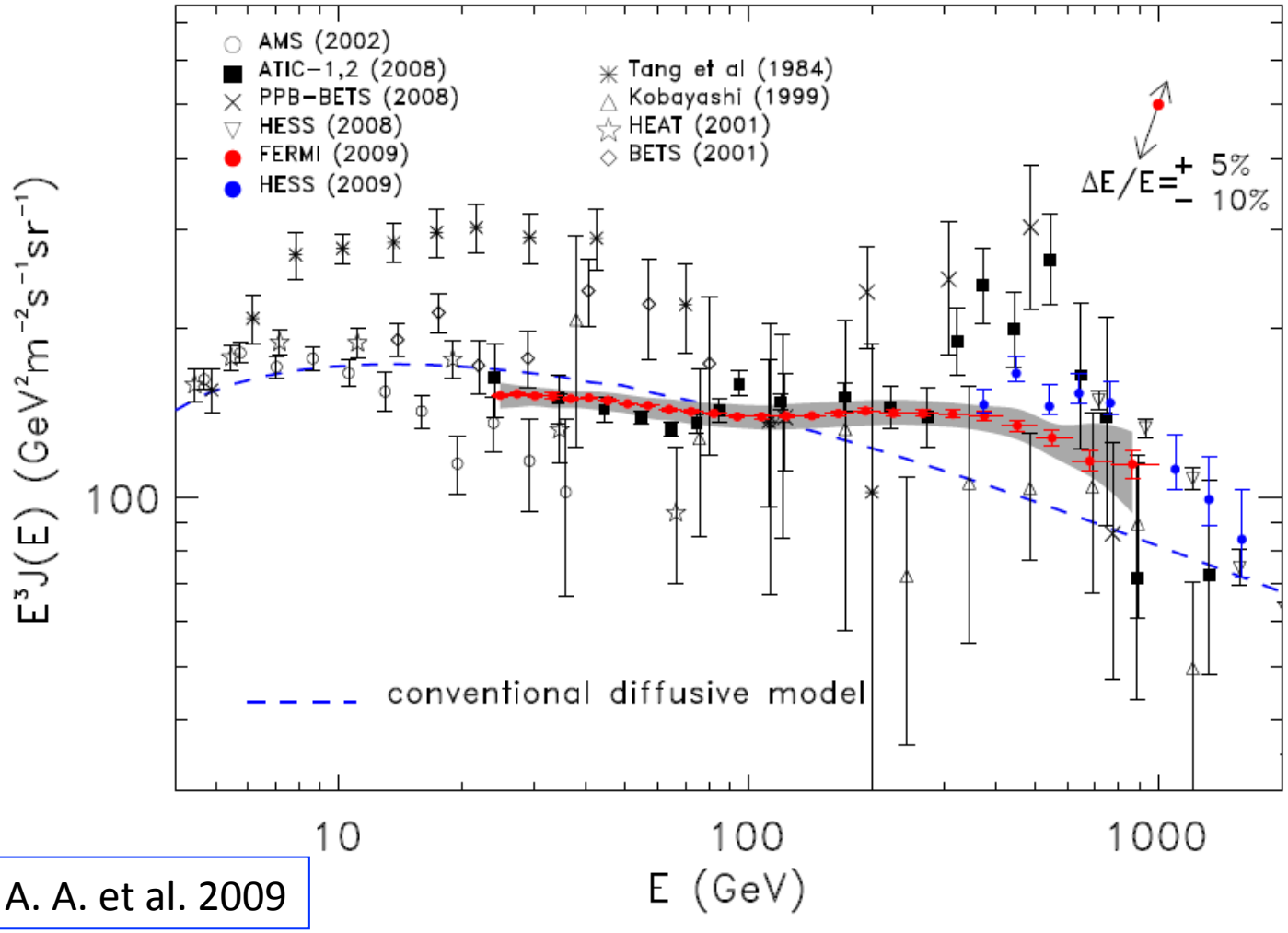
THE ASTROPHYSICAL JOURNAL, 162:L181–L186, December 1970

PULSARS AND VERY HIGH-ENERGY COSMIC-RAY ELECTRONS

C. S. SHEN*
Department of Physics, Purdue University, Lafayette, Indiana 47907
Received 1970 June 8; revised 1970 September 19

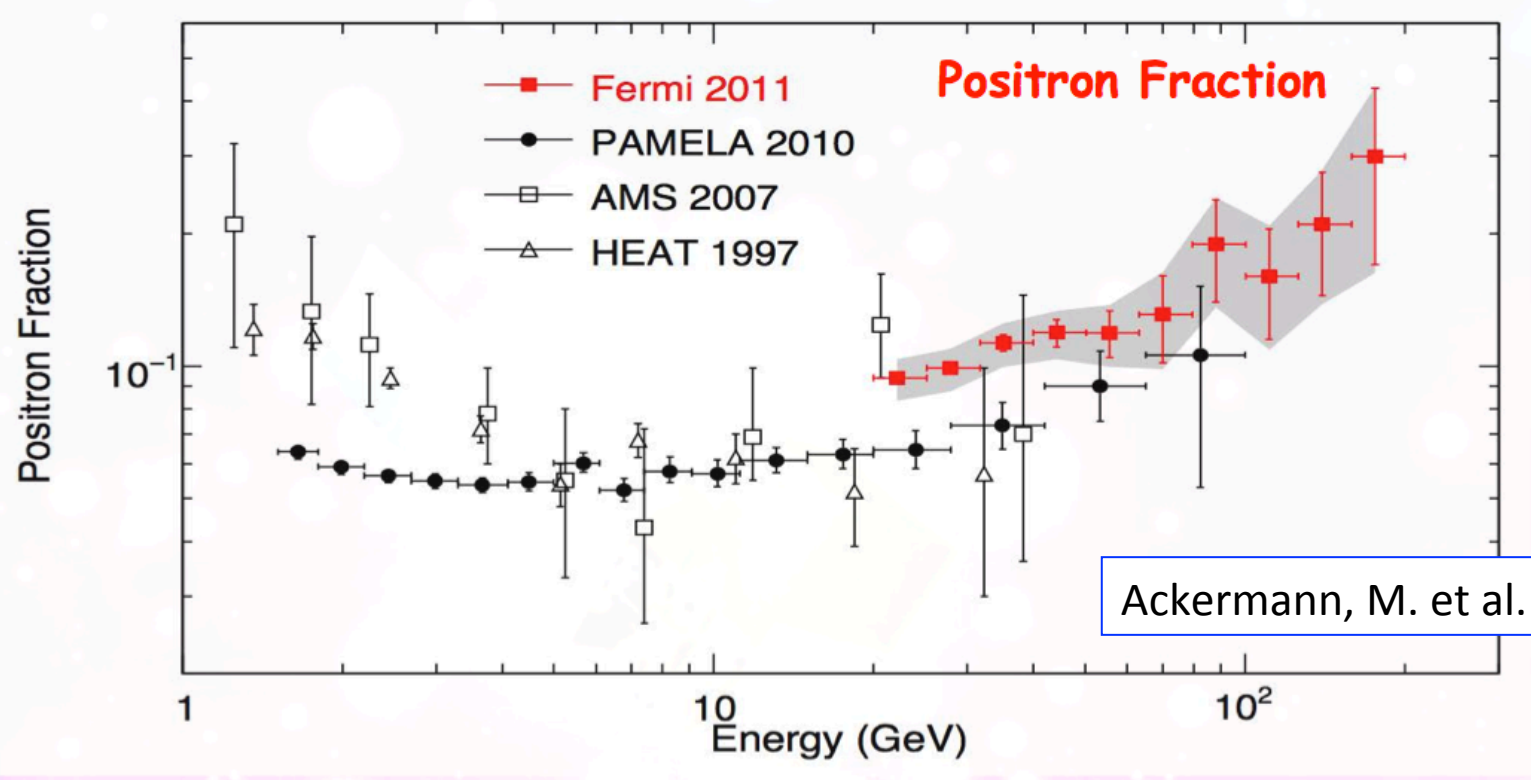
PRL 102, 181101 (2009) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 8 MAY 2009

Measurement of the Cosmic Ray $e^+ + e^-$ Spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope



Abdo, A. A. et al. 2009

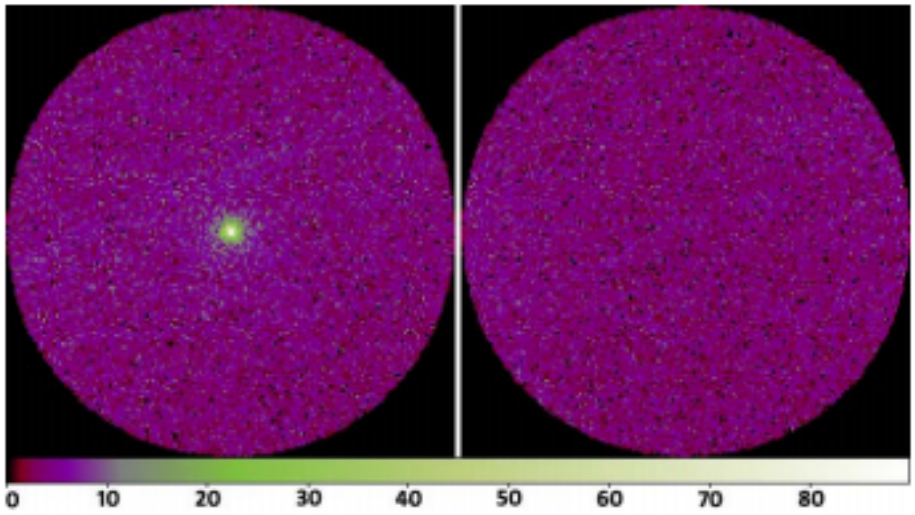
Positron Fraction Measurements

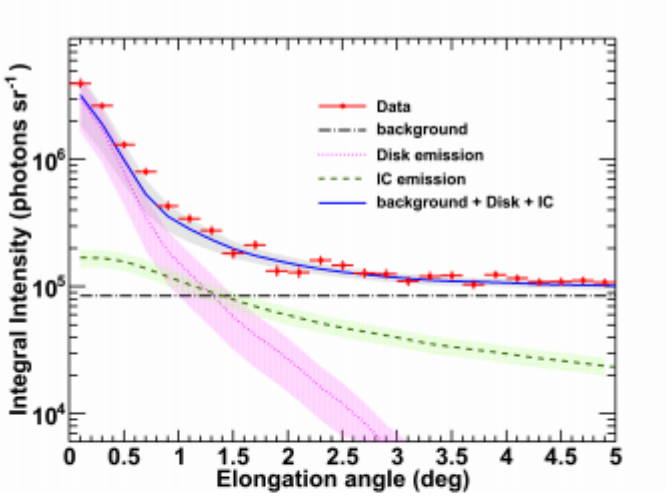


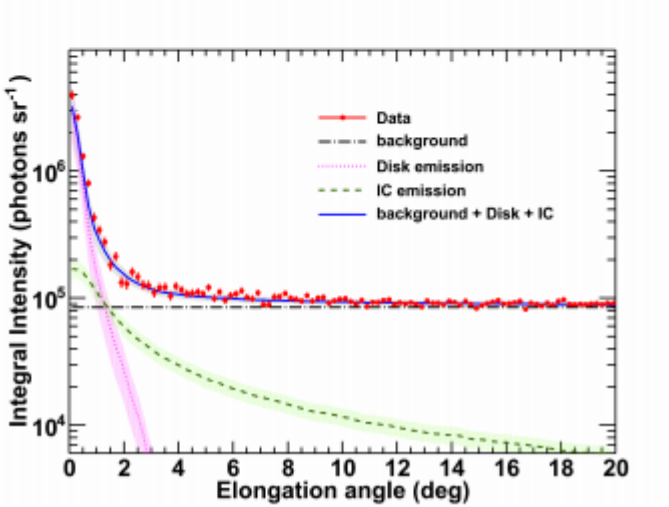
Ackermann, M. et al. 2012

- **PAMELA and Fermi-LAT observe a rise in local e^+ fraction above ~10 GeV**
- **This disagrees with conventional models (e.g., GALPROP) for cosmic rays (secondary e^+ production only)**
- **No similar rise is seen in anti-proton fraction**

The Quiet Sun

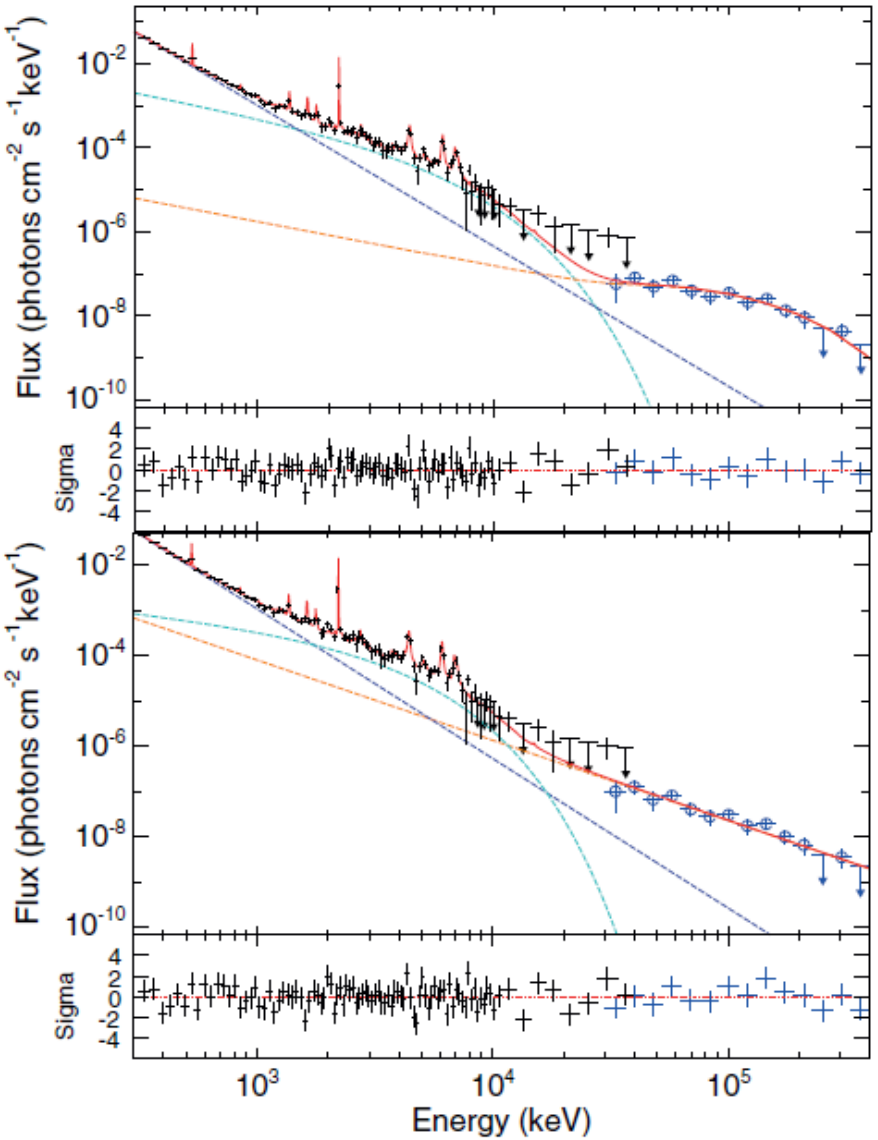






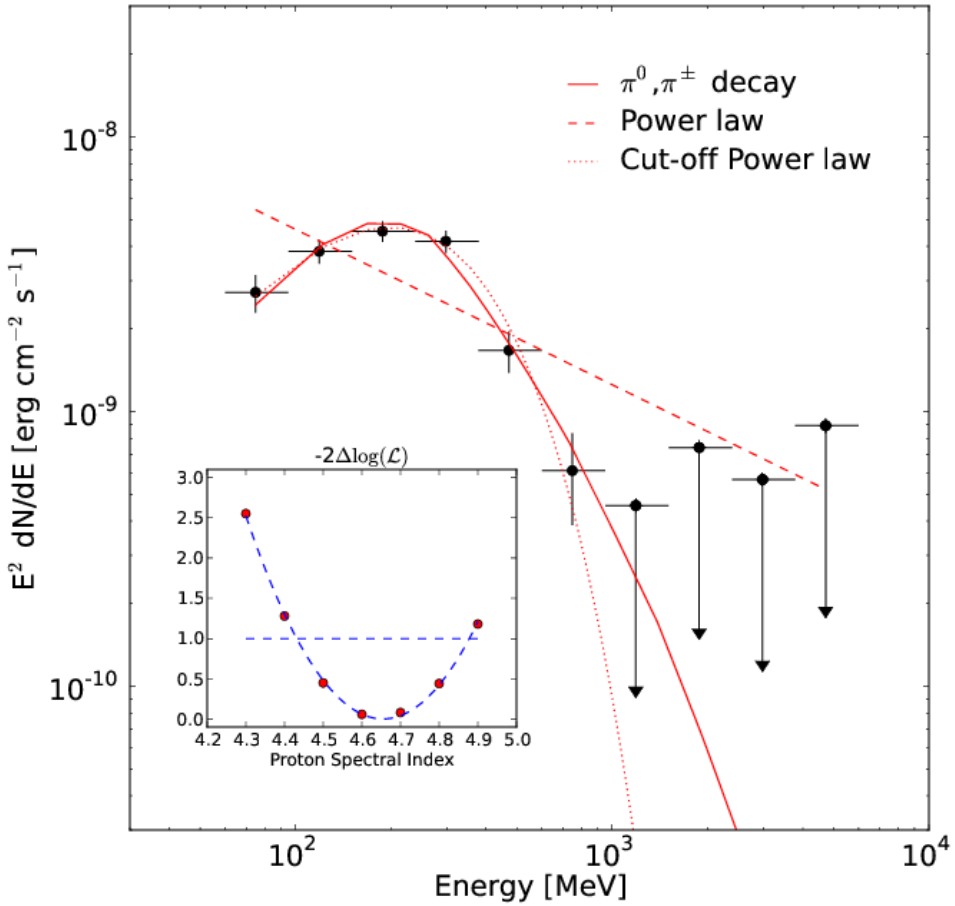
Abdo, A. A. et al. 2011

Challenge #5: Flaring Sun

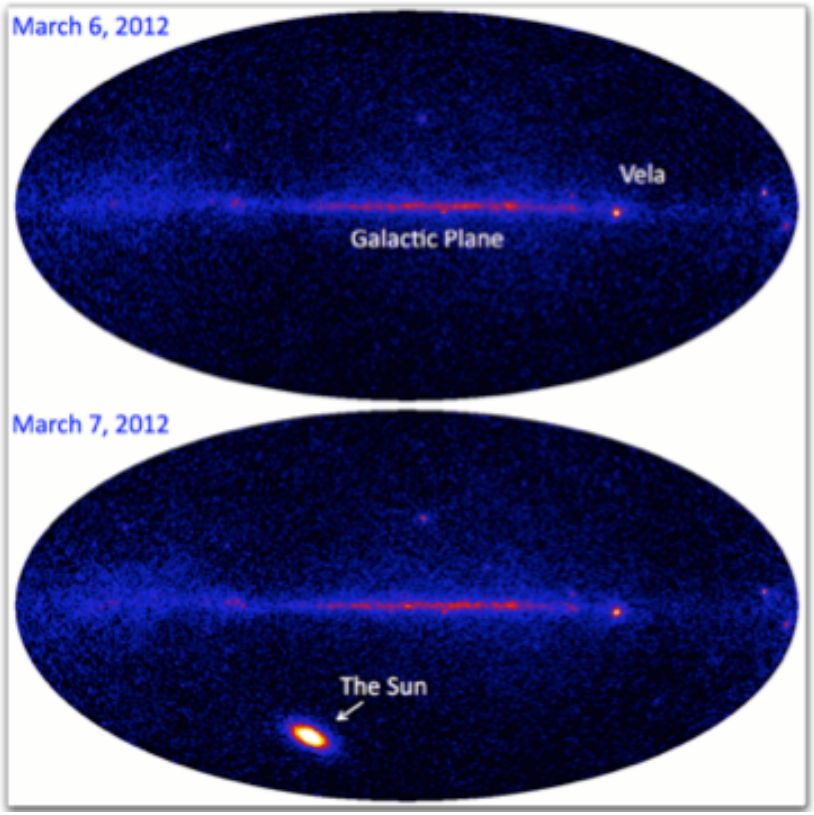


Ackermann, M. et al 2012

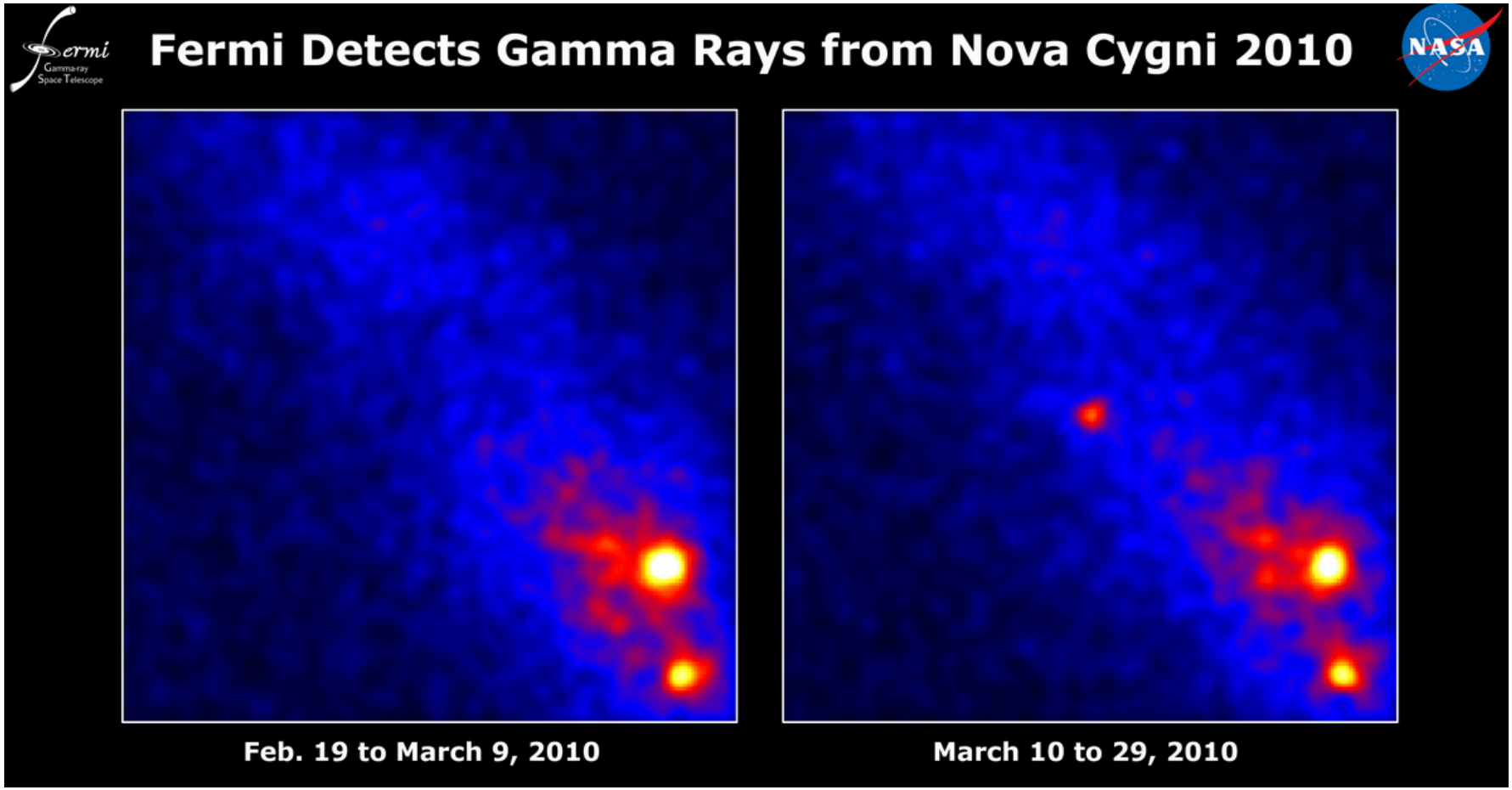
Solar Flares



Ajello, M. et al. 2014



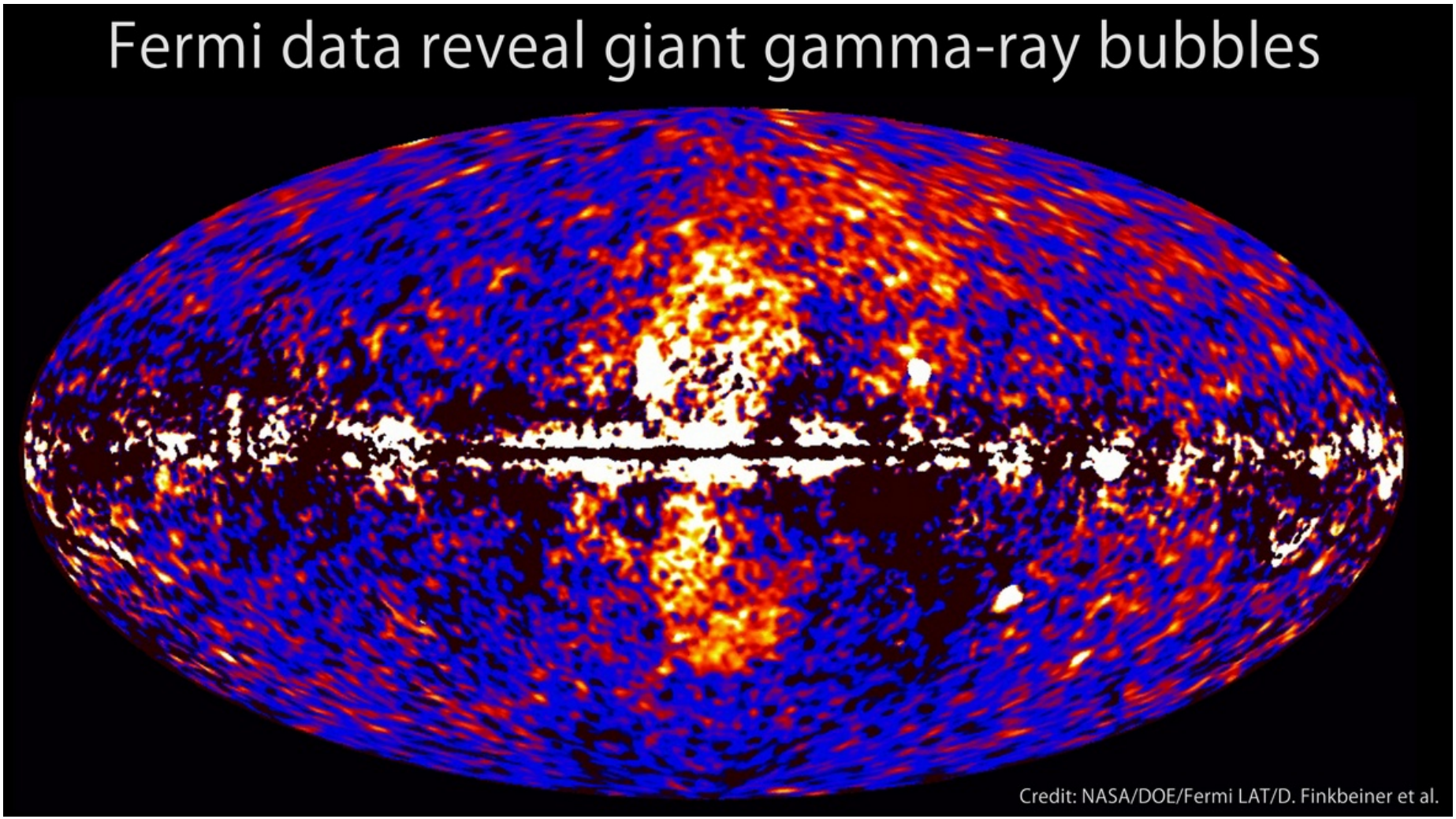
Surprise! Nova emitting in Gamma Rays!



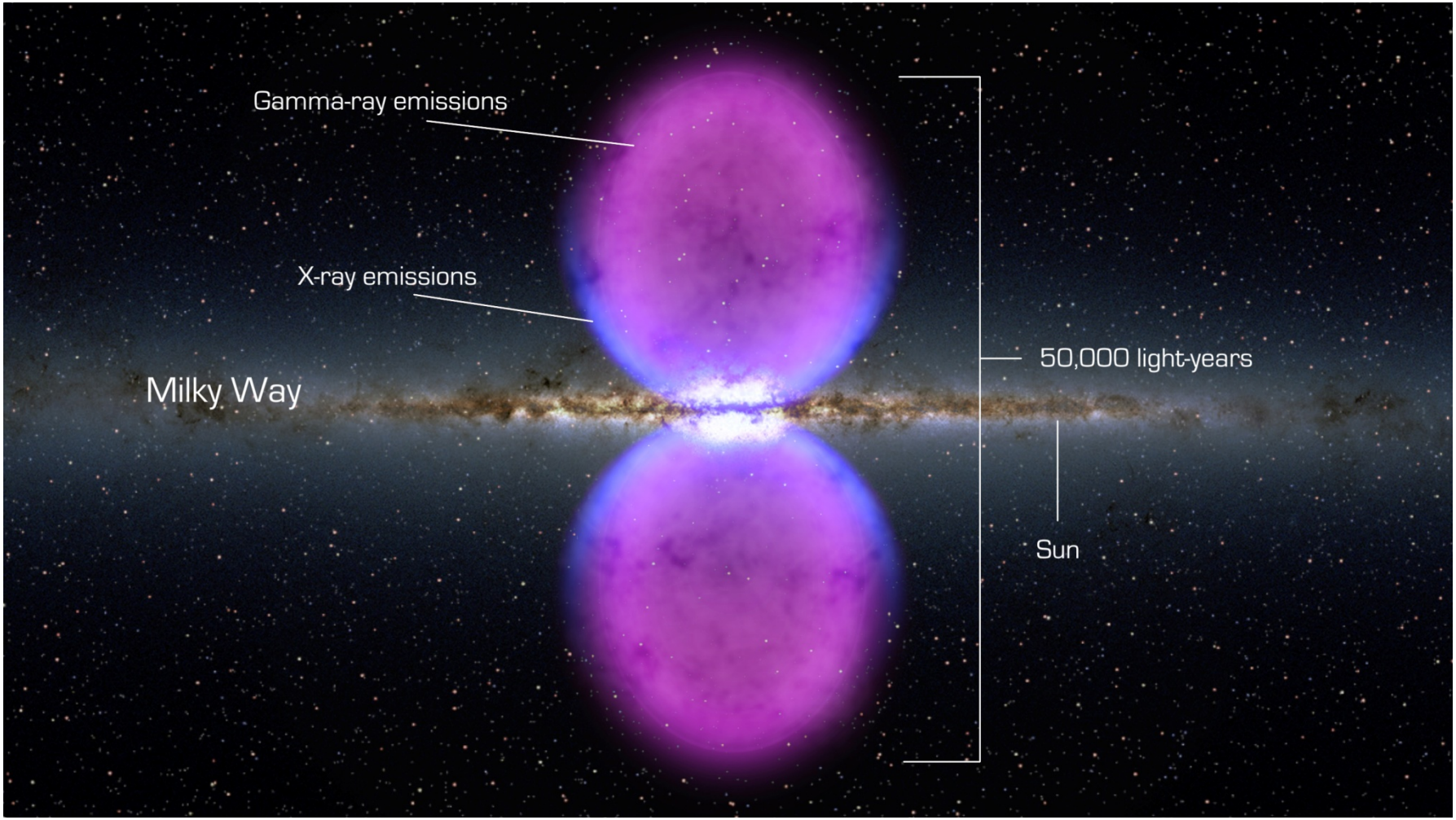
Abdo, A. A. et al. 2010

Gamma Ray Novae

Surprise! The Fermi Bubbles



Fermi bubbles



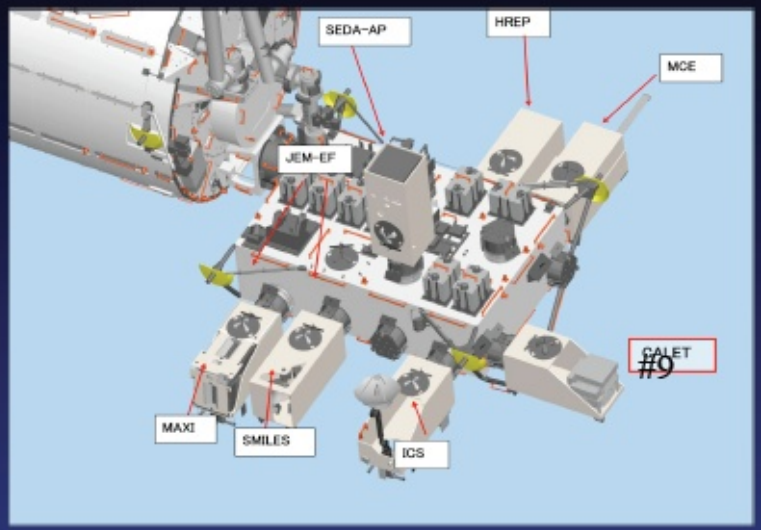
LAT team analysis: Ackermann, M. et al. 2017

CALET?

CALorimetric Electron Telescope (CALET)

P. S. Marrocchesi for the CALET Collaboration – RICAP11 – 2011 May 26

- **Instrument:**
  High Energy Electron and Gamma-Ray Telescope
- **Carrier:**
  HTV: H-IIA Transfer Vehicle
- **Attach Point on the JEM-EF:** #9
  for heavy (< 2000 kg) payloads
- **Nominal Orbit:**
  407 km, 51.6° inclination
- **Launch plan:**
  FY 2013
- **Life Time:**
  ≥ 5 years



1 GeV ~ 20 TeV for electrons

20 MeV ~ TeV for gamma-rays

Weight: 500 kg

GF (fiducial volume): ~ 0.12 m^2sr

Power Consumption: 640 W

Data Rate: 300 kbps

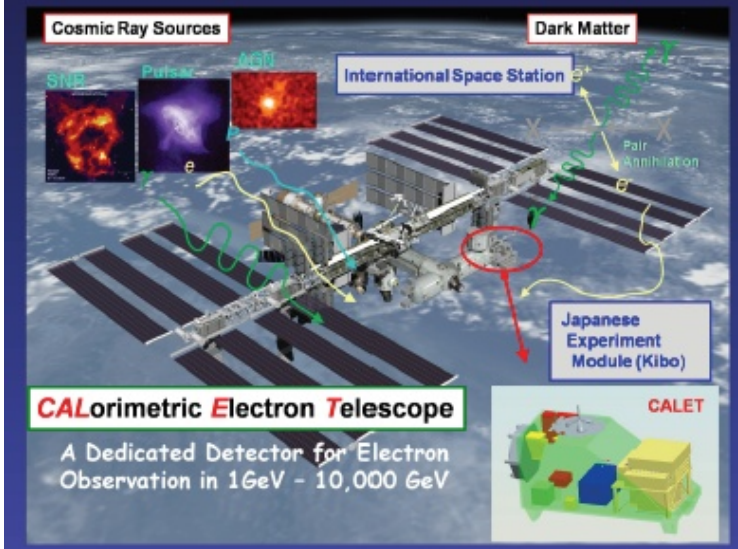
Firenze
Pisa
Siena
Roma Tor Vergata

CALET?

CALET Overview

Observation

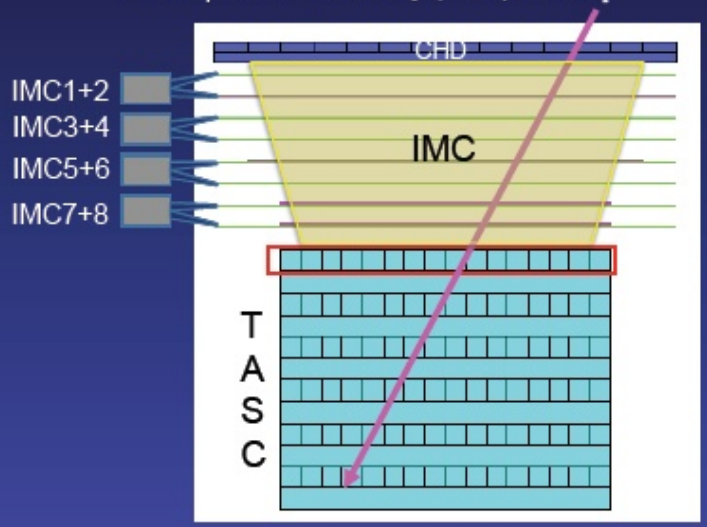
- **Electrons** : 1 GeV - 10 TeV
- **Gamma-rays** : 10 GeV-10 TeV (GRB > 1 GeV)
  + Gamma-ray Bursts : 7 keV-20 MeV
- **Protons, Heavy Nuclei**:
  several 10 GeV- 1000 TeV (per particle)
- **Solar Particles and Modulated Particles in Solar System**: 1 GeV-10 GeV (Electrons)



Instrument

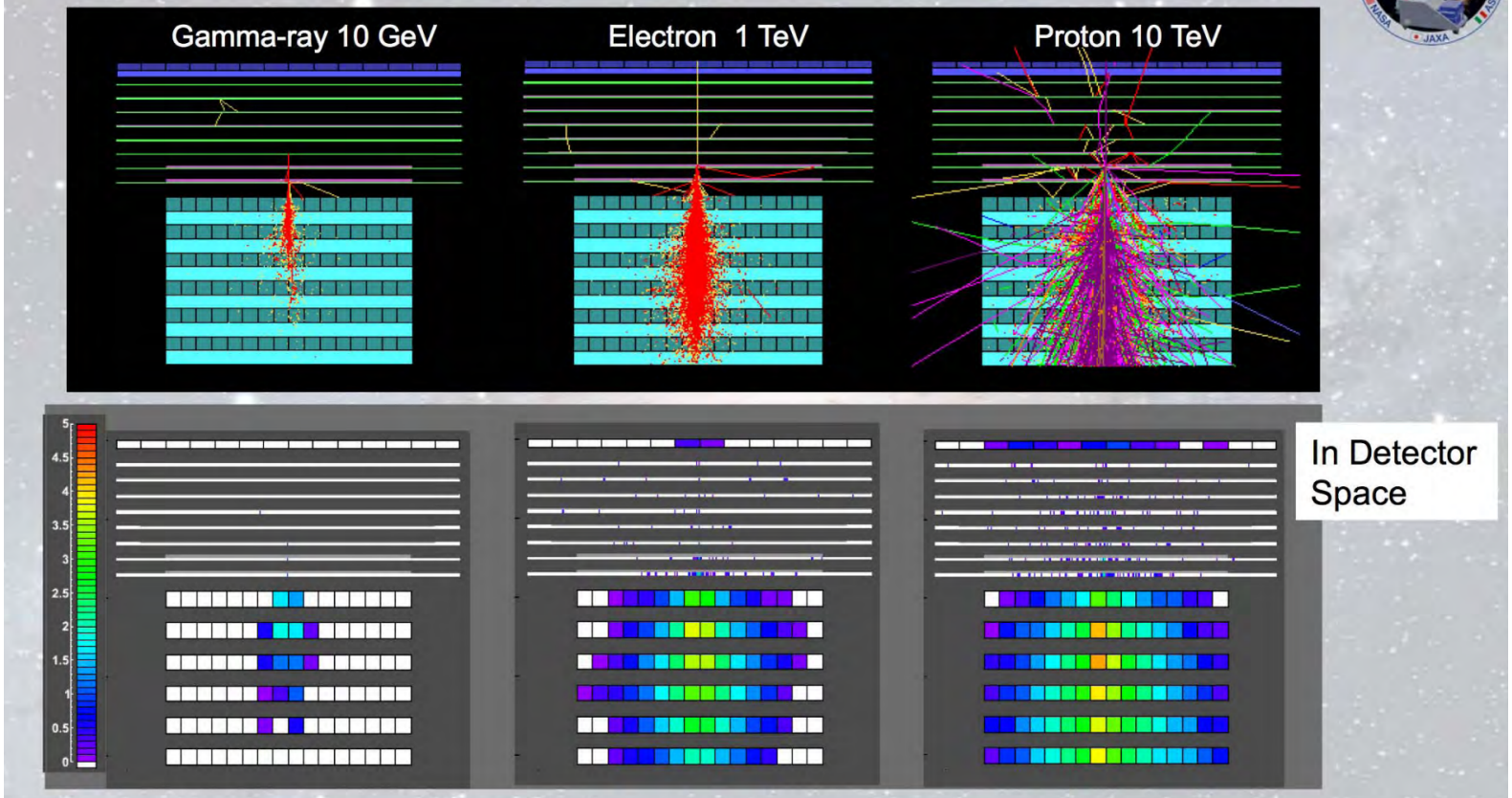
High Energy Electron and Gamma-Ray Telescope:

- CHarge Detector (CHD)
  (Charge Measurement in Z=1-40)
- Imaging Calorimeter (IMC)
  (Particle ID, Direction)
  Total Thickness of Tungsten (W): 3 X_0 0.11 λ_I
  Layer Number of Scifi Belts: 8 Layers × 2(X,Y)
- Total Absorption Calorimeter (TASC)
  (Energy Measurement, Particle ID)
  PWO 20mm x 20mm x 320mm
  Total Depth of PWO: 27 X_0 (24cm) , 1.35 λ_I



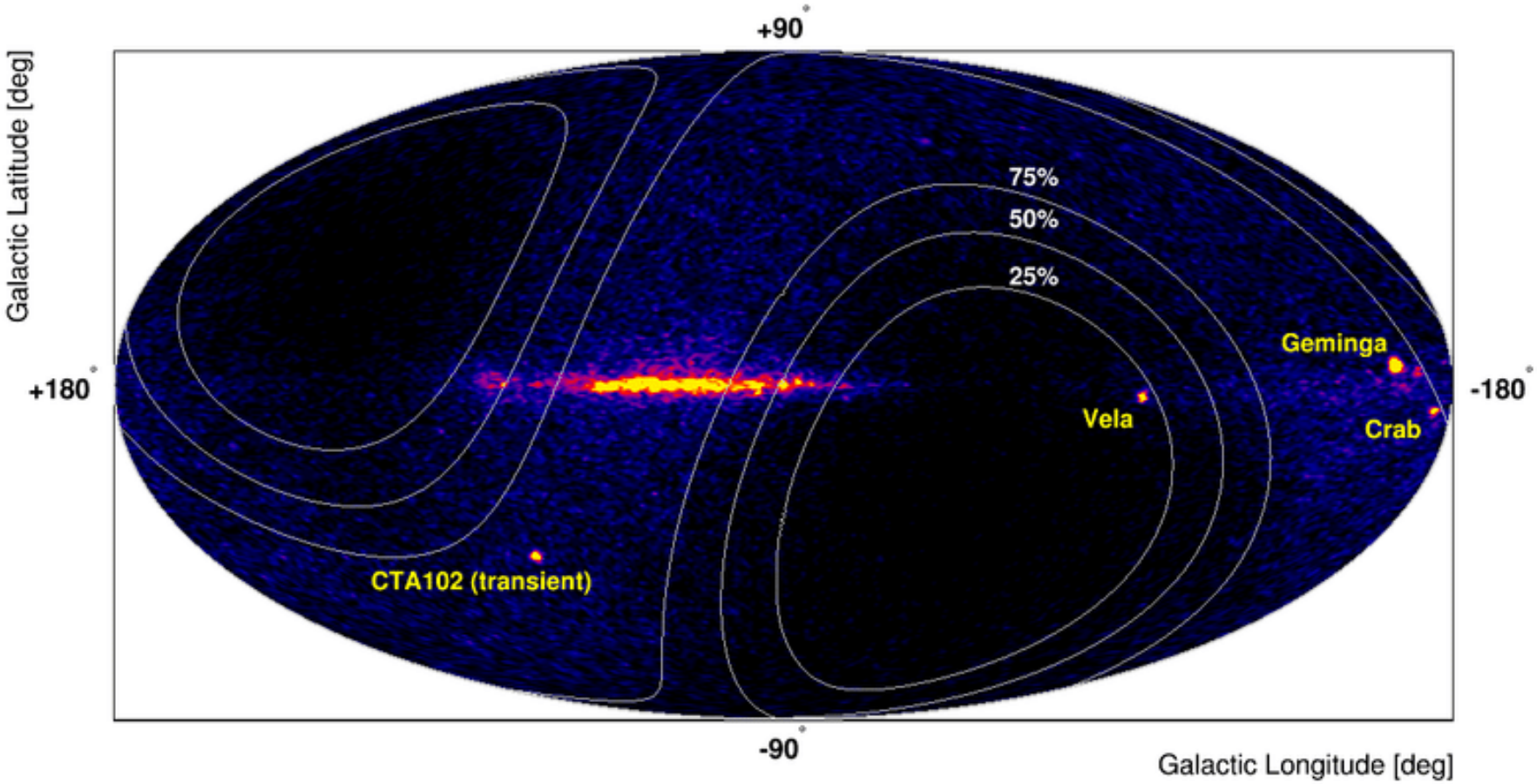
CALET

CALET/CAL Shower Imaging Capability (Simulation)



- Proton rejection power > 10^5 can be achieved with the IMC and TASC shower imaging capability.
- Charge of incident particle is determined to $\Delta Z = 0.15 - 0.3$ with the CHD.

CALET gamma-sky



Gamma-400?

AC - anticoincidence detectors

C - multilayer converter

C1- C6 6 x 0,14Xo W

CD1 - CD6 6 x Si (x,y) strip detectors (pitch 0.1 mm)

CD7 - CD8 Si (x,y) strip detectors (pitch 0.1 mm)

S1, S2 - TOF detectors

TRD - transition radiation detectors

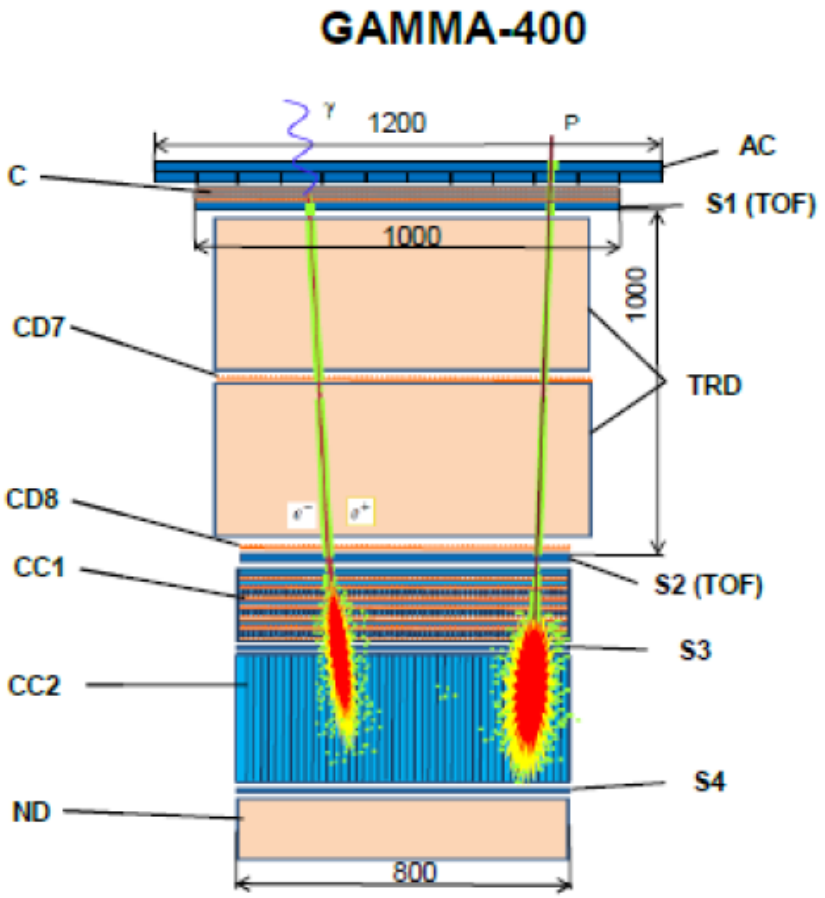
CC1 - imaging calorimeter (9Xo)

10 layers BGO + Si (x, y) strip detectors (pitch 0.5 mm)

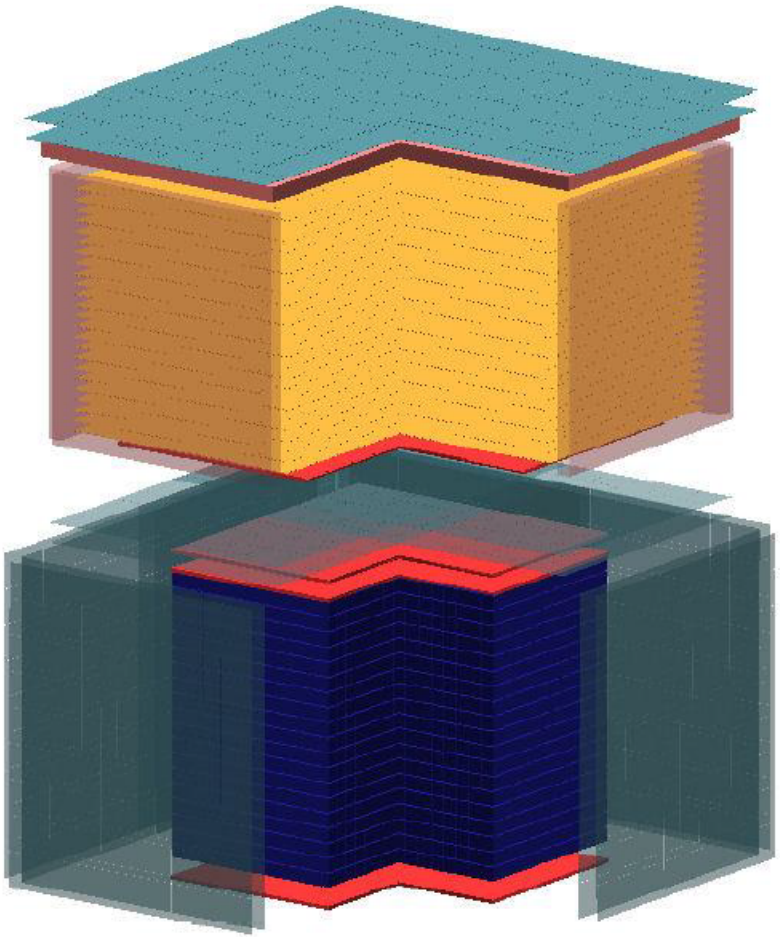
CC2 - BGO imaging calorimeter (21.5Xo)

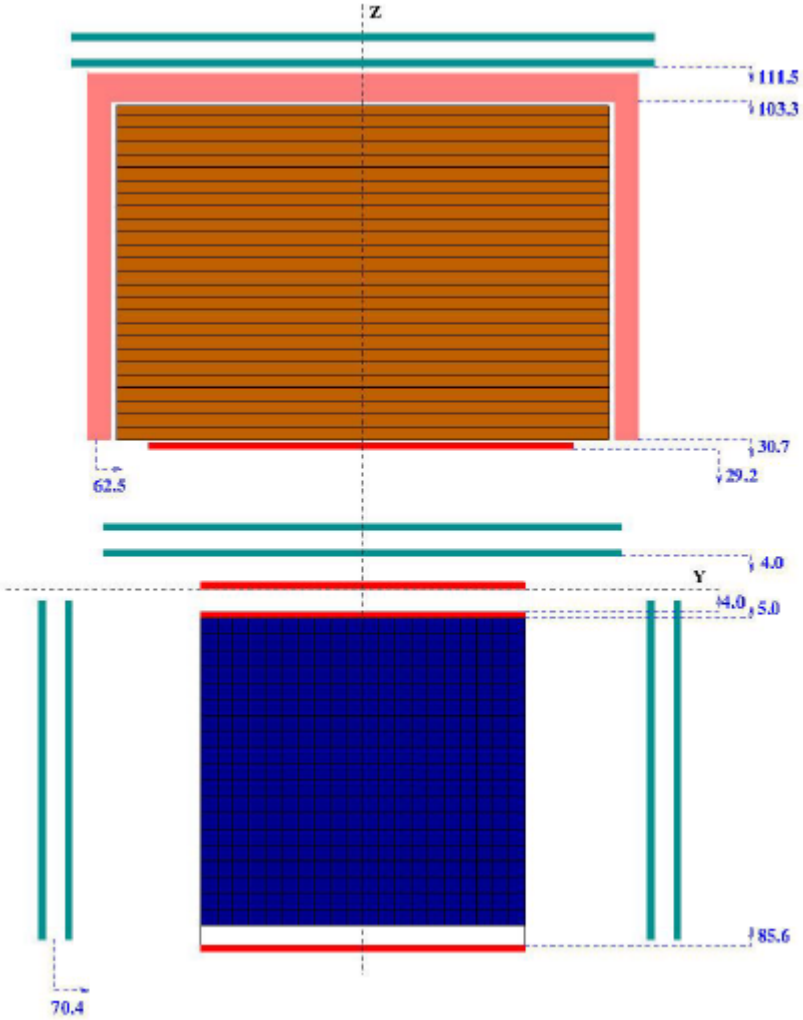
S3, S4 - scintillator detectors

ND - neutron detectors

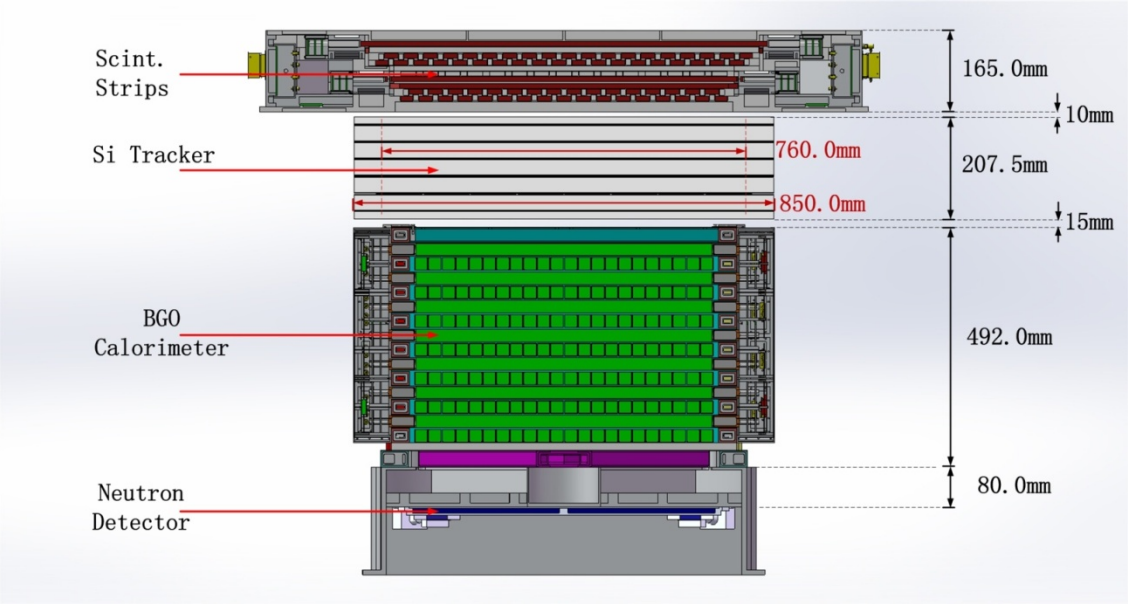


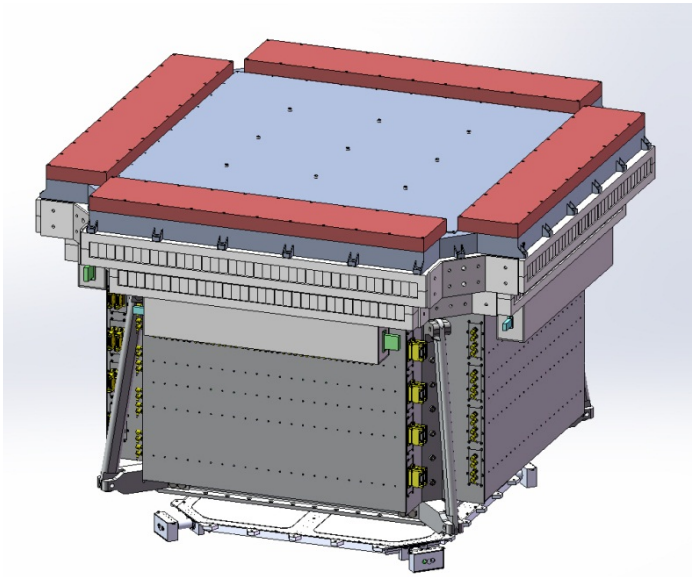
Gamma400





DAMPE

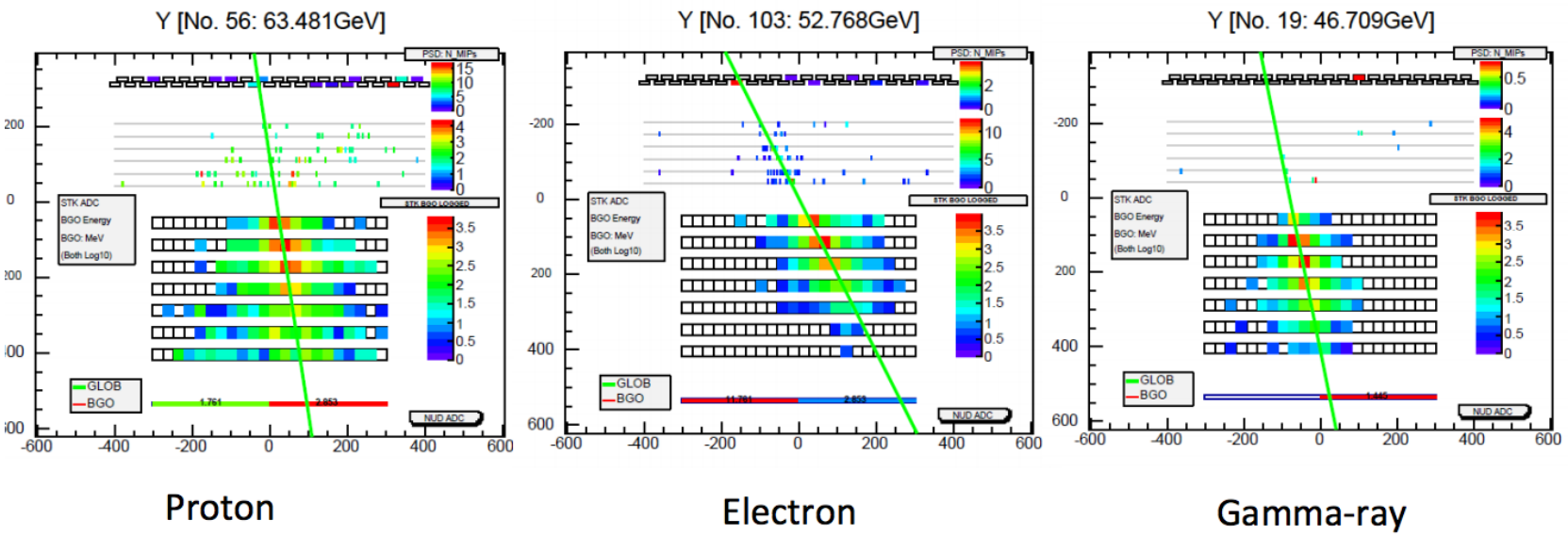




The detector is consisted of 4 parts:
Top scintillators (charge measurement)
Si tracker (5 layers)
BGO calorimeter
Neutron detector

DAMPE Gamma results

DAMPE γ-ray Selection: Different Events



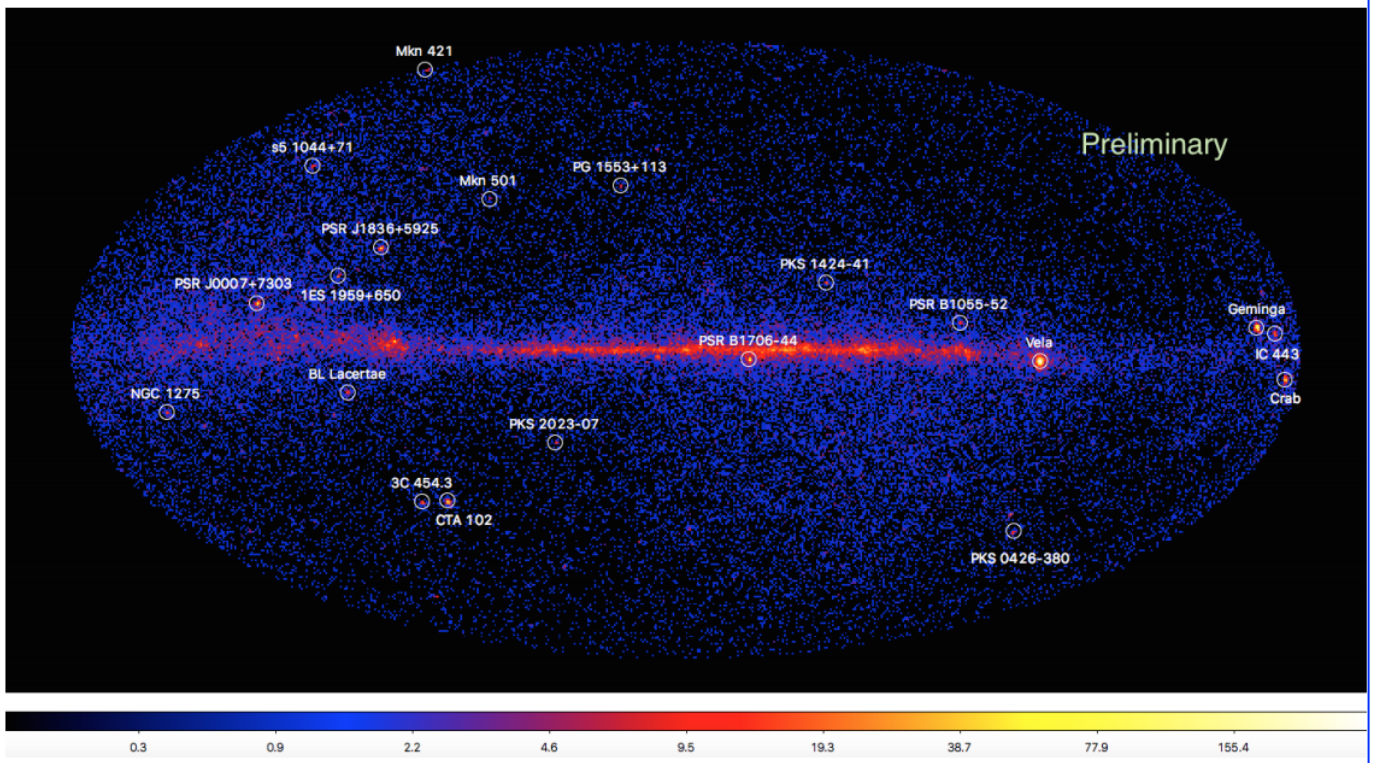
Proton Electron Gamma-ray

- e(γ)/p separation: BGO shower pattern
- e/γ separation: PSD and STK charge measurement

DAMPE Gamma results

DAMPE γ-ray Sky Map (Counts)

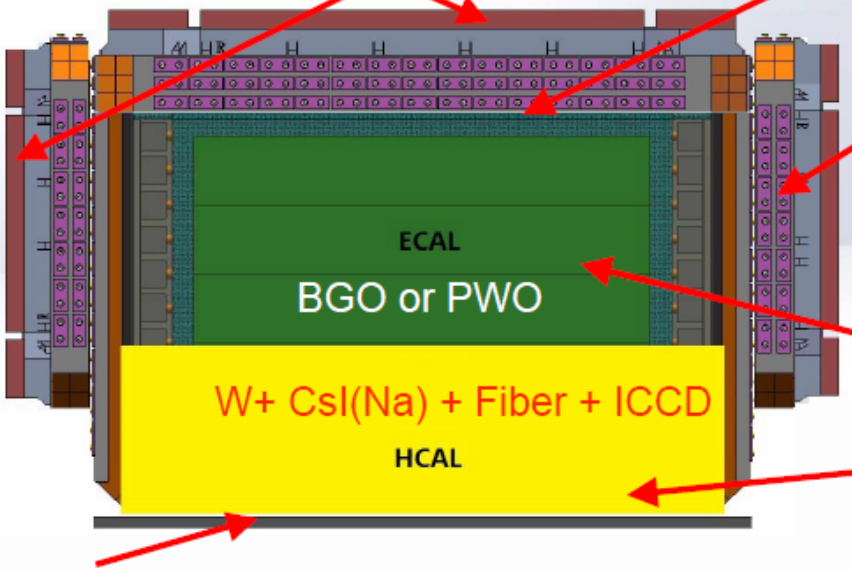
- 510 days
- E>2 GeV
- 90,000 events
- 0.5°×0.5° pexel
- Mollweide projection



HERD

Baseline Design: ~2 T, ~2 KW

Charge detector: Si+PIN.
Top: 2x(70x70x(1cm×1cm×500um));
Sides: 4x(2x(70x40x (1cm×1cm×500um)))



Shower Tracker:
W: $4X_0$; 10x3.5mm +
2x17.5mm + 2x35mm
Scin. Fibers:
14x(2x(700x(1x1x700mm^3)))

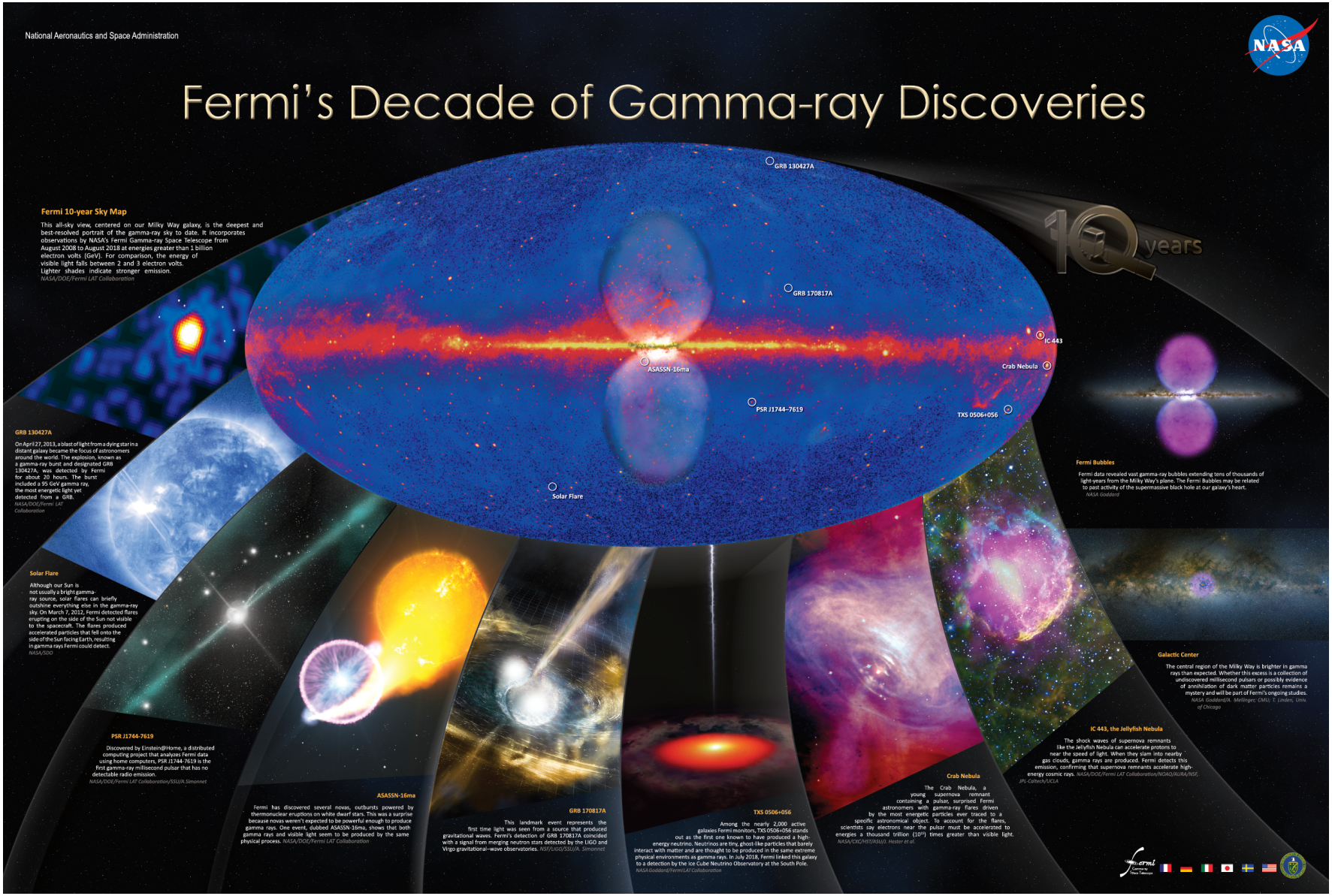
Nucleon Tracker: scin. fibers
400x(1x1x700mm^3)+
700x(1x1x400mm^3)

ECAL: $16X_0$=$0.7X_{NIL}$
3x(2x(25x25x700mm^3))

HCAL: W: 20x3.5mm ($0.8X_{NIL}$)
CsI: 20x(2.5cmx2.5cmx0.2cm)

Neutron detector: B-doped plastic scintillator for delayed signals. Enhanced e/p discrimination. (TBD)

Scientific Highlights of the LAT



Future Gamma-ray Experiments?

Scientific Motivations and Technical Design Considerations for Future High-Energy γ-ray Telescopes in Light of Lessons Learned from the Fermi Large Area Telescope.

Eric Charles[a]
on behalf of the *Fermi* Large Area Telescope Collaboration

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ABSTRACT

Five years into the *Fermi Gamma-ray Space Telescope* (*Fermi*) mission we have learned a great deal about the γ-ray sky, yet many open questions remain, and many new puzzles have arisen. In this contribution we will consider the science drivers for a variety of topics in high-energy gamma-ray astronomy, and how these drivers map into design considerations for future gamma-ray instruments in the energy range above 5 MeV. Specifically, we take the performance parameters and data set of the Large Area Telescope on the *Fermi* observatory (*Fermi*-LAT) as a baseline, and consider the scientific questions that could be probed by improving those parameters. We will also discuss the current state of detector technologies used in space-based γ-ray telescopes and discuss the magnitude of advances that would be required to make a future *Fermi*-like mission transformational enough to warrant the cost and effort. These summaries are intended to be useful for selecting technologies and making basic design decisions for future γ-ray telescopes.

Table 1. Summary of the importance of instrument performance parameters for science topics in high-energy γ-ray astronomy. Key performance parameter are marked as "1", other important parameters as "2", marginally relevant parameters as "3" and irrelevant parameters are unmarked. The performance parameters are background rejection ("Bkg"), point-source sensitivity ("Source"), on-axis $A_{\rm eff}$ ("$A_{\rm eff}$"), field-of-view (FOV), point-source localization ("PSF Loc."), extension detection/ associating a given γ ray with a particular source ("PSF Ext."), energy bandpass ("Band"), energy resolution ("Energy Res."), spectral resolution ("Energy spec."), relative timing and deadtime between readouts ("Timing Rel.") and absolute timing ("Timing Abs.").

			Acceptance		PSF		Energy			Timing	
Topic	Bkg.	Source	$A_{\rm eff}$	FOV	Loc.	Ext.	Band	Res.	Spec.	Rel.	Abs.
GRB Detection	2	1	1	1	3	-	2	-	-	-	-
GRB Localization	2	2	2	2	1	-	-	-	-	-	-
GRB Modeling	2	2	1	1	-	2	1	2	1	2	3
GRB EBL Studies	2	3	1	1	-	2	2	2	-	-	3
GRB LIV Studies	3	-	1	1	-	2	2	2	-	1	2
AGN Pop. Studies	3	1	1	2	1	-	1	3	2	-	-
AGN Variability	3	1	1	1	-	-	2	3	2	-	-
AGN EBL Studies	3	1	1	2	-	1	2	3	3	-	-
Nearby Galaxies	3	1	1	2	3	1	1	3	2	-	-
Galactic Diffuse	1	2	2	2	-	1	3	3	2	-	-
Extra-Galactic Diffuse	1	2	2	2	-	2	1	3	2	-	-
Radio Timed Pulsars	3	1	1	1	-	2	2	3	2	3	1
Blind Search Pulsars	2	2	1	1	1	2	2	3	2	3	1
Pulsar Radio Targets	3	1	1	2	1	-	3	3	3	-	-
Pulsar Modeling	3	2	1	2	-	2	2	2	1	3	1
SNR / PWN	2	2	1	2	3	1	1	2	1	-	-
X-ray Binaries	2	1	1	2	2	3	1	3	2	-	-
Galactic Novae	2	1	1	2	1	3	1	3	2	-	-
Earth	-	-	3	2	-	3	1	3	1	-	-
Sun / Moon	2	1	1	2	3	1	1	3	2	-	-
Solar Flares	2	1	1	1	1	3	1	3	2	2	-
TGFs	-	-	2	2	-	-	3	-	-	1	2
DM dSph	2	1	1	2	-	2	2	3	2	-	-
DM Galaxy Clusters	2	1	1	2	-	1	2	3	2	-	-
DM Inner Galaxy	3	2	2	2	1	1	1	3	1	-	-
DM Lines	1	-	2	2	-	3	1	1	1	-	-

Design considerations

- Summary of interaction processes
  - Radiation Length
  - Pair conversion and Compton scatter
  - Energy Losses of Electrons and Positrons
  - Electromagnetic Shower Propagation
  - Multiple Coulomb Scattering
  - Plane thickness and Hit spacing

Implication for Instrument Performance

- Background rejection versus FOV.
- Aeff versus PSF.
- Sky-survey versus Pointed Observations
- PSF, Timing Resolution versus Power Budget.
- Energy Resolution versus Aeff and FOV.
- Size versus Complexity of Event Readout, Triggering and Filtering.
- Optimal Orbit.

Implication for Instrument Performance

Semiconductor-based solid state trackers. These include both strip and pixel detectors made from semiconductors such as silicon, germanium or diamond. All of these can achieve very precise positional accuracy, generally better than 30% of the channel pitch and as good as half that for detectors that use pulse height information to place hits between channels. Semiconductor detectors can also provide good measurements of the ionization energy deposited.

The limitation of these technologies are primarily geometrical. First, they they are generally built with thin flat planes, providing one measurement per plane (or two for double-sided detectors). The thickness of the planes is $> 200\mu m$, corresponding to $> 0.002X_0$ for particles at normal incidence, and increasing as the $\cos^{-1}$ of the incidence angle. Furthermore, the semiconductor wafers require support structures, increasing the X_0 per measurement. Second, they achieve high precision by having extreme segmentation, and the number of readout channels can grow very large and present challenges for the power and thermal budget and the available data transmission bandwidth (see Sec. 4.2). The 18 bi-layer LAT has 884k channels. Building an instrument with 200 layers of $0.005X_0$ each for a total of $1X_0$ of conversion target would increase that 100-fold. Furthermore, with the LAT's spatial resolution of $\sim 70\mu m$ the layers would need to be placed at least 2 cm apart to avoid degrading the PSF at 100 MeV. This would result in a 4 m tall instrument.

Implication for Instrument Performance

Time Projection Chambers. TPCs work by using a near uniform electric field to drift charge carries produced by ionization to the sides of the detector, where they are read out by sensor pads, which provide positional information in both direction transverse to the drift direction. Positional information in the longitudinal direction comes from measuring the drift time of the charge carriers.

Advances in solid-state sensor technology have made it possible to build very small individual channels on the amplification and sensor pads, allowing for excellent ($50\mu m$ or better) resolution in the transverse directions. However, the diffusion of the charge carriers limits the positional resolution in the longitudinal direction, particularly for large gas TPCs. With careful tuning of the drift gas longitudinal resolutions of $< 200\mu m$ for 1 m scale TPCs have been achieved.

TPCs can also quantify the ionization, which is useful for particle identification and quantifying the energy lost by charge particles in the TPC. The latter is particularly important for reconstructing Compton-scattering events.

One advantage of gas TPCs is that the density of the gas is low enough that several position measurement can contribute to the direction measurement, giving an excellent PSF. Furthermore, the density can be tuned to optimize the X_0 per-measurement. However, even the densest gases would require extreme pressures to provide enough target material for pair-conversion to reach LAT-like level; e.g., using Xe would require 50 bar of pressure at 300 K to reach $1X_0$/m. This suggests either segmented TPC cells with converter material between them, or placing converter material in the TPC.

Gas TPCs have other potential disadvantages. 1) The lower resolution in the longitudinal direction. 2) The difficulties in keeping the gas tuned for optimal performance. 3) The degradation of the gas and the readout sensor from chemical interaction between the two. 4) The difficulties in operating high-pressure gas systems in orbit. These last two suggest that the drift gas is potentially a mission-limiting consumable. On the other hand, it is worth noting that gas-based detection systems have been used successfully in several mission.

Solid-state (i.e., drift-detectors) or liquid TPCs offer less flexibility in tuning the X_0 per-measurement, but are also somewhat less difficult to operate in orbit. However, it is worth nothing that liquid Ar (as in LArGO) requires substantial cooling, potentially creating a mission-limiting consumable or increasing the heat load on the spacecraft radiators.

Implication for Instrument Performance

Hodoscopic Crystal Calorimeters Calorimeters for pair-conversion γ-ray mission have been homogeneous high-Z scintillating crystals. For ground-based calorimeters where the shower is largely contained, the energy resolution is usually parametrized as:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}, \tag{12}$$

where the first term represents stochastic and sample fluctuations, the second term comes from the calibration uncertainties, and the third term from the electronics noise in the channels contributing to the shower. Typical ground-based electromagnetic have 15 to 20 X_0, and can achieve resolutions as good as $2\%/\sqrt{E/1\mathrm{GeV}}$. Mass constraints for space missions coupled with the generally smooth spectra of astrophysical sources in the GeV range suggest using somewhat thinner calorimeters. The LAT, for example, is only $8.6X_0$ at normal incidence, and achieves energy resolution of better than 10% from 1 GeV to 100 GeV. Once the shower-maximum (Eq. (8)) is beyond the calorimeter depth, Eq. (12) breaks down with increasing energy.

Plastic Scintillators. Plastic scintillators are efficient, low-cost detectors. They have been used successfully as anti-coincidence charged particle vetoes in several γ-ray telescopes, and can provide particle background rejection factors better than to 10^4. Furthermore, the LAT has shown that segmenting the veto system can avoid "self-veto" from backsplash particles in high-energy γ-ray events.

As mentioned in Sec. 3.5, very high rates of X-rays are observed in the LAT ACD during bright solar flares. This raises the possibility of designing the readout system of any veto system so that it can double as a bright transient detector and spectrograph.

Discussion

Optimizing the PSF. The largest potential gains in many science areas come from improving the PSF, particularly at the lower energies in the MCS dominated regime (< 1 GeV). Furthermore, no space-based instrument can feasibly compete with CTA above ~ 50 GeV in terms of $A_{\rm eff}$ and detection sensitivity, which limits the need to extend the energy bandpass to the highest energies where almost all analyses would be signal-limited. This in turn suggests that for future instruments, the balance between improving the PSF or the $A_{\rm eff}$ should be pushed in favor of the PSF relative to the LAT. For a practical figure of comparison when considering instrument designs it would make sense to try and obtaining the best possible PSF while keeping the on-axis $A_{\rm eff}$ with a factor of two of the LAT over the energy bandpass of the instrument.

Interestingly, improving the PSF requires decreasing the MCS, which will also increase the sensitivity to polarization.

Increasing the Low-Energy $A_{\rm eff}$. The low-energy $A_{\rm eff}$ (i.e, below 100 MeV) of the LAT is limited primarily be three factors. 1) The falling cross section for pair-conversion. 2) The need to pass through 3-layer of high-density converter to leave enough hits to reconstruct a track. 3) The dearth of information about the event deposited in the detector, which makes background rejection much more difficult. Fortunately, these issues can be mitigated by including the measurement of Compton-scattering events in the instrument design and by reducing the MCS scattering in the tracking volume.

Discussion

Choosing the FOV and the Instrument Geometry. The large FOV of the LAT and the all-sky survey mode it allowed has enabled many breakthroughs and is well-suited to the highly variable nature of many γ-ray emitting sources. It is worth recalling that the FOV of the LAT is 2.5 sr as compared to the un-occulted sky in low Earth orbit of 8.4 sr or 12.6 sr for the whole sky. Thus, the maximum potential gain in the FOV is somewhere between a factor of 3.5 to 5, depending on the orbit. Although not huge, this could be combined with a factor of 2 to 3 increase in the average effective area to obtain a factor of 10 increase in the acceptance without hugely increasing the size of the instrument, an important limitation in space missions.

On the other hand, the best ways to improve the PSF are to decreases the density of the material in the tracker and to space the tracking element further apart. Given the space limitations, both of these could result in a FOV that is somewhat smaller than the LAT's. These considerations present two alternate instrument geometries as opposite extremes to consider.

The first, designed to have an excellent PSF and a limited FOV, would be tall and relatively narrow, and maximize the lever-arm in the direction of travel of the incoming γ rays. Such an instrument would be suited to an observing strategy of scanning the Galactic plane with occasional pointings and limited surveys of high-Galactic latitude sources and regions.

The second, designed to maximize the FOV while retaining a very good PSF, would be as compact as possible for a given surface area, i.e., cubic or spherical. In this geometry, one of the challenges it so avoid building an intrinsic directionality into the instrument, e.g., a design with a tracker above a calorimeter is only sensitive to γ rays going "down", can not exceed a FOV 6.3 sr, and is unlikely to do better than about FOV 3 sr unless the tracker is extremely squat. So, in this case it is worth considering novel geometries, such a calorimeter sandwiched between two trackers.

An interesting alternative is the possibility of a "monolithic" instrument, i.e., one with a single sub-system that measures both the direction and energy of the incoming γ rays. In practice, this likely would be done in one of three ways, each of which would present substantial design challenges. 1) Adding a magnet to measure the momenta of the charged particles in the tracking volume. 2) Building a particle tracker that is several radiation lengths thick. 3) Increasing the readout granularity of a hodoscopic calorimeter to extent that it does not limit the PSF.

Conclusion

Summary We have presented a series of summaries of information that may be useful in the design of future high-energy γ-ray telescopes. Specifically, we have summarized the instrument performance factors critical for scientific goals, the physical mechanisms influencing the detector design, and the most popular detector technologies. We have also laid out the key trade-offs that must be considered.

Almost all of this information is available in greater detail elsewhere. However, we hope that this contribution will prove useful by consolidating the material in a single source.