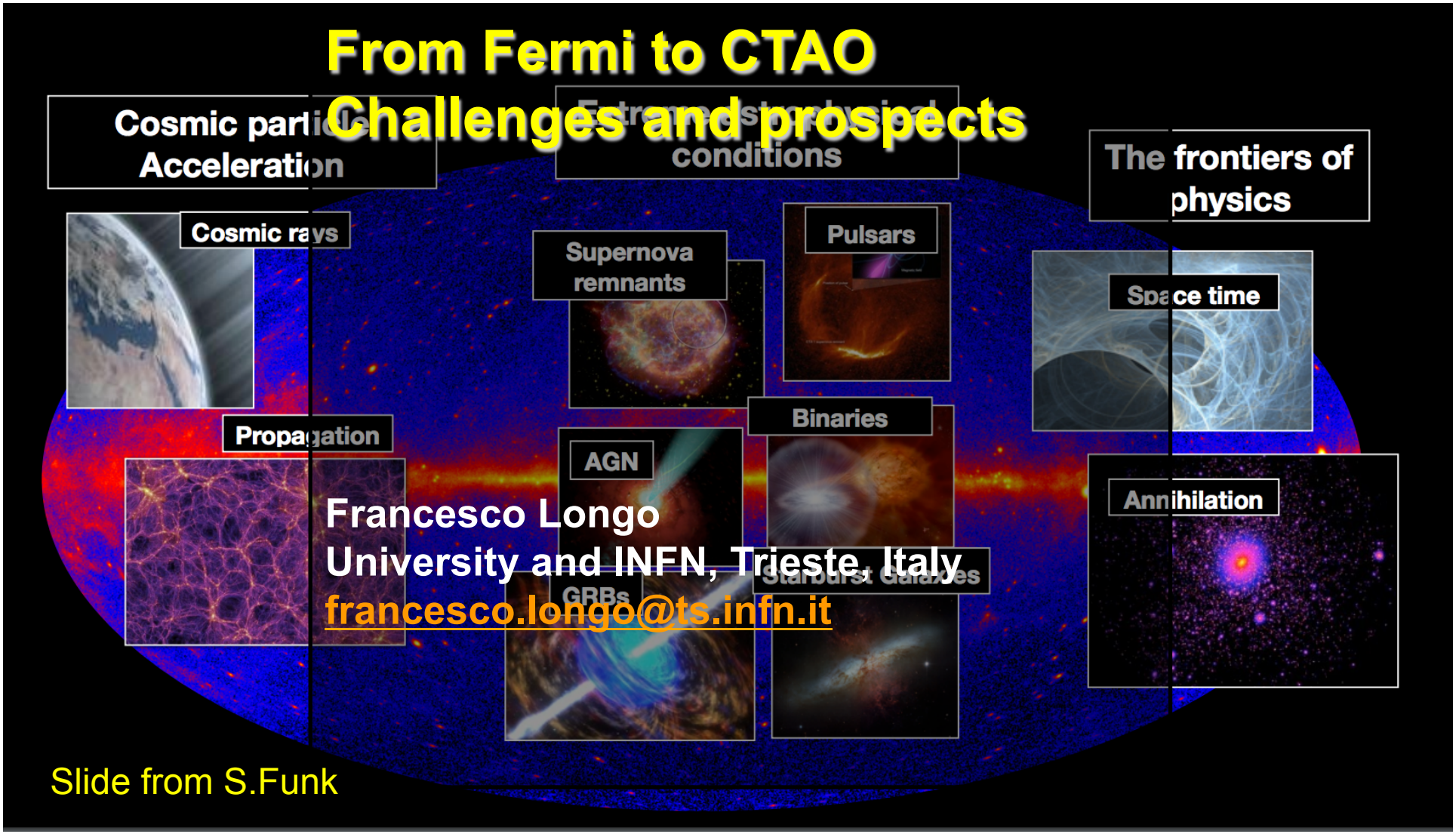
From Fermi to CTAO
Challenges and prospects



Francesco Longo
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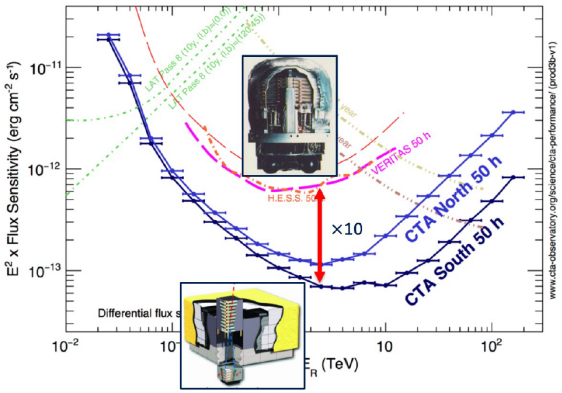
francesco.longo@ts.infn.it

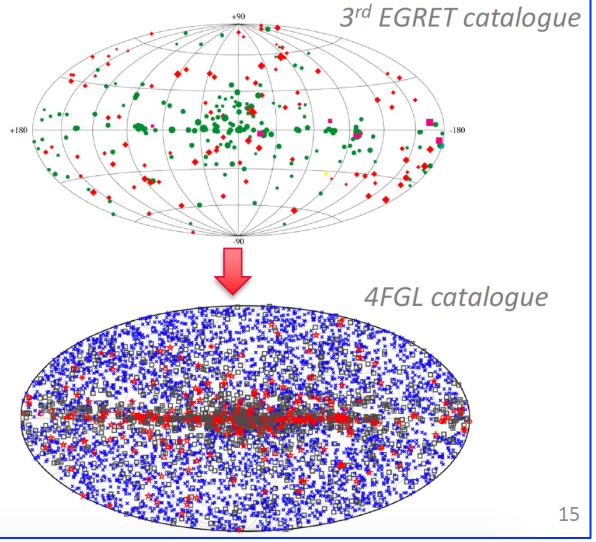
Slide from S.Funk

Take away messages …

Conclusions

- CTAO will be the first gamma-ray ground-based observatory, openly delivering data to the community
- CTAO will usher in a new era in VHE Astrophysics
  - Rich science program answering many open questions
  - Large new discovery space





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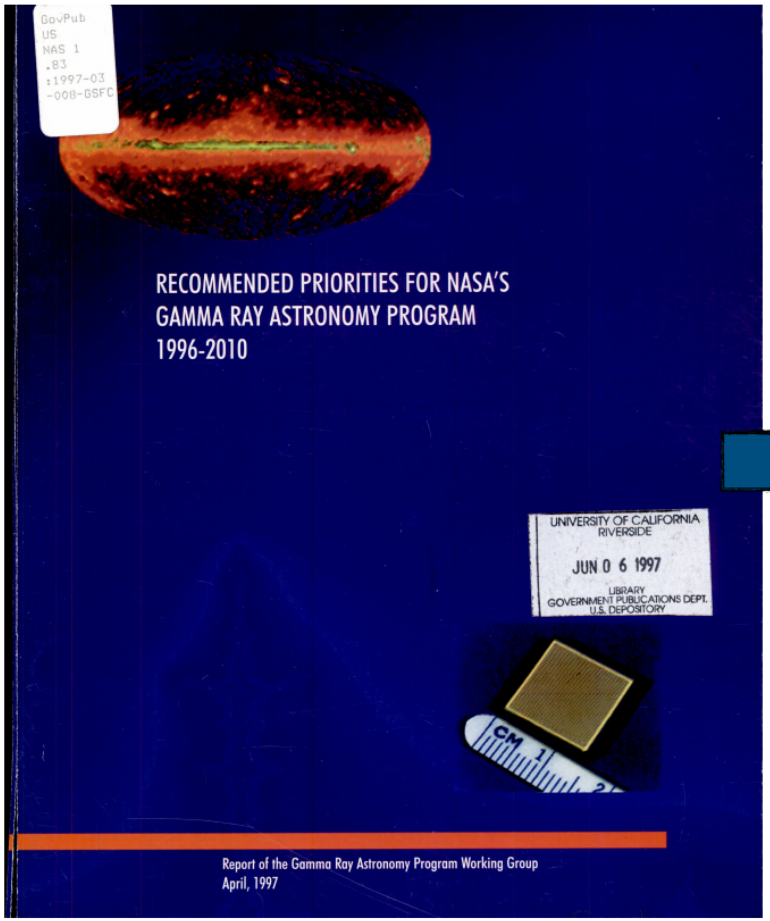
R. Zanin – EAS 2022

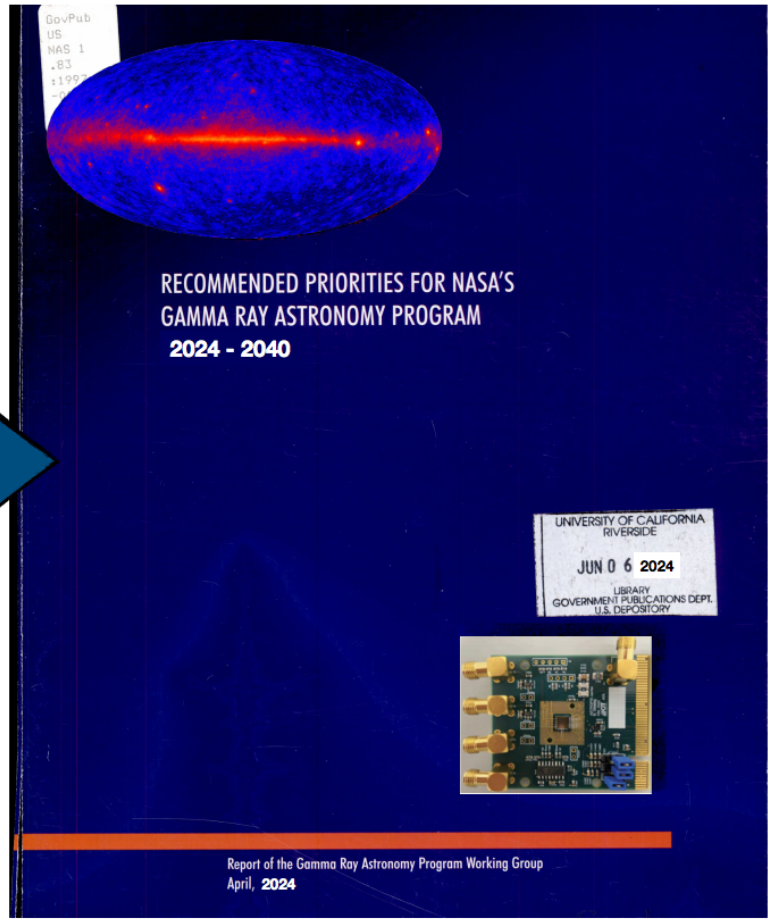
Outline

- The Fermi/LAT telescope
  - A brief history …
- A few key decisions
  - Data processing
  - Data dissemination
  - The Fermi publication policy
- VHE results by Fermi important for CTAO
  - Galactic Science
  - Extragalactic Science
  - Fundamental Physics
  - Diffuse emission
- Challenges and prospects for CTAO

A brief of history ..

R.Caputo @ 2nd CTAO symposium





A brief of history

KEY QUESTIONS IN GAMMA-RAY ASTRONOMY FROM 1997

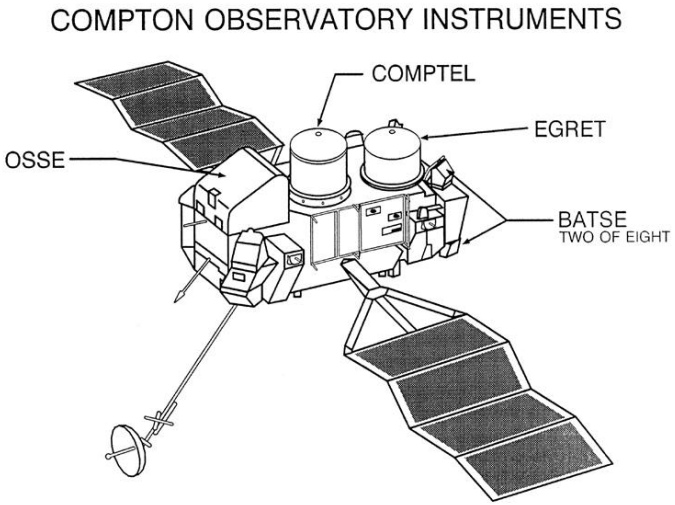
- **What is the origin and nature of gamma-ray bursts?**
- **What are the physical conditions and processes near accreting black holes and neutron stars?**
- **How does matter behave in extreme conditions like those in neutron stars, supernova expulsions and active galactic nuclei?**
- **How do astrophysical accretion processes work and what are their instabilities, periodicities and modes?**
- **What is the nature of the jets emanating from galactic black holes and AGN and how are the particles accelerated?**
- **What is the origin of the diffuse gamma-ray background?**
- **What is the nature of the unidentified high energy gamma-ray sources?**
- **What are the sites of nucleosynthesis?**
- **How do supernovae work? What are the progenitors and explosion mechanisms? What has bene the rate in the last several hundred years?**
- **What and where are the sites of cosmic ray acceleration?**

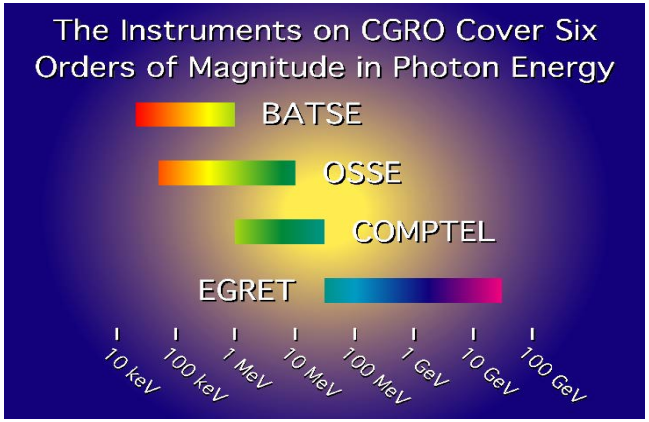
R.Caputo @ 2nd CTAO symposium

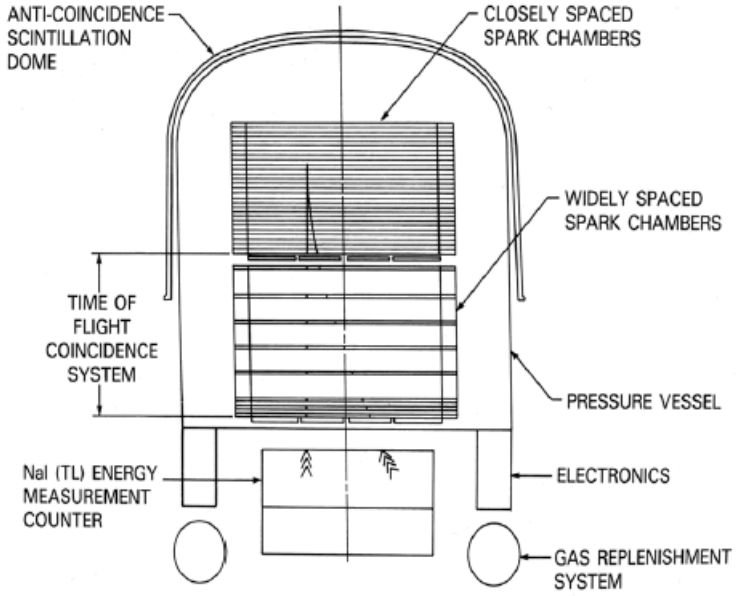
Why did they recommend these missions?

- They developed a series of **Key Science Questions** that pointed to the need for this diverse set of missions.
  - Lesson: Lead with the Science
  - Lesson: Don't shy away from the big problems
  - Lesson: Make strong/bold recommendations
- Many of these questions are still open but we have made significant progress.

EGRET



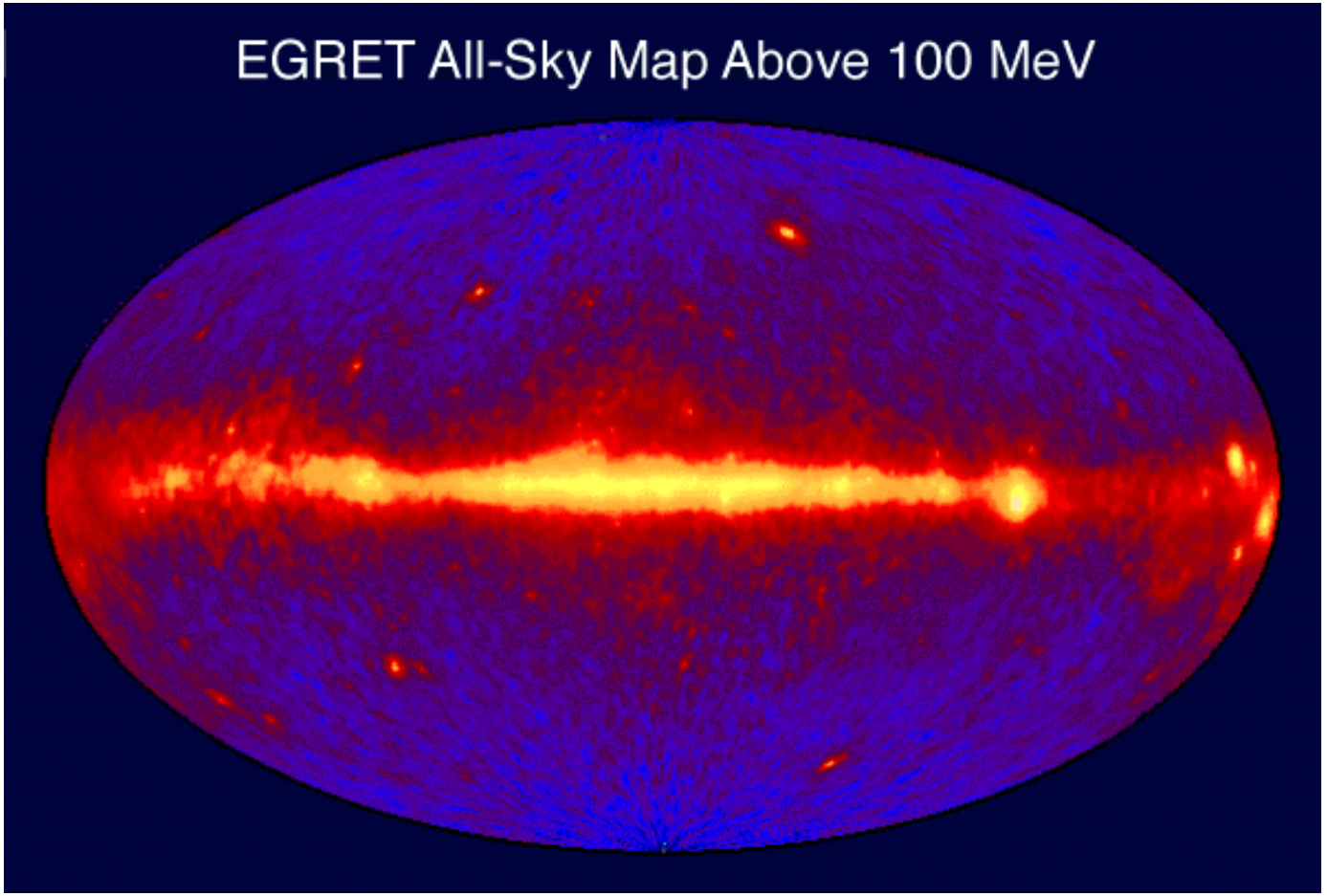




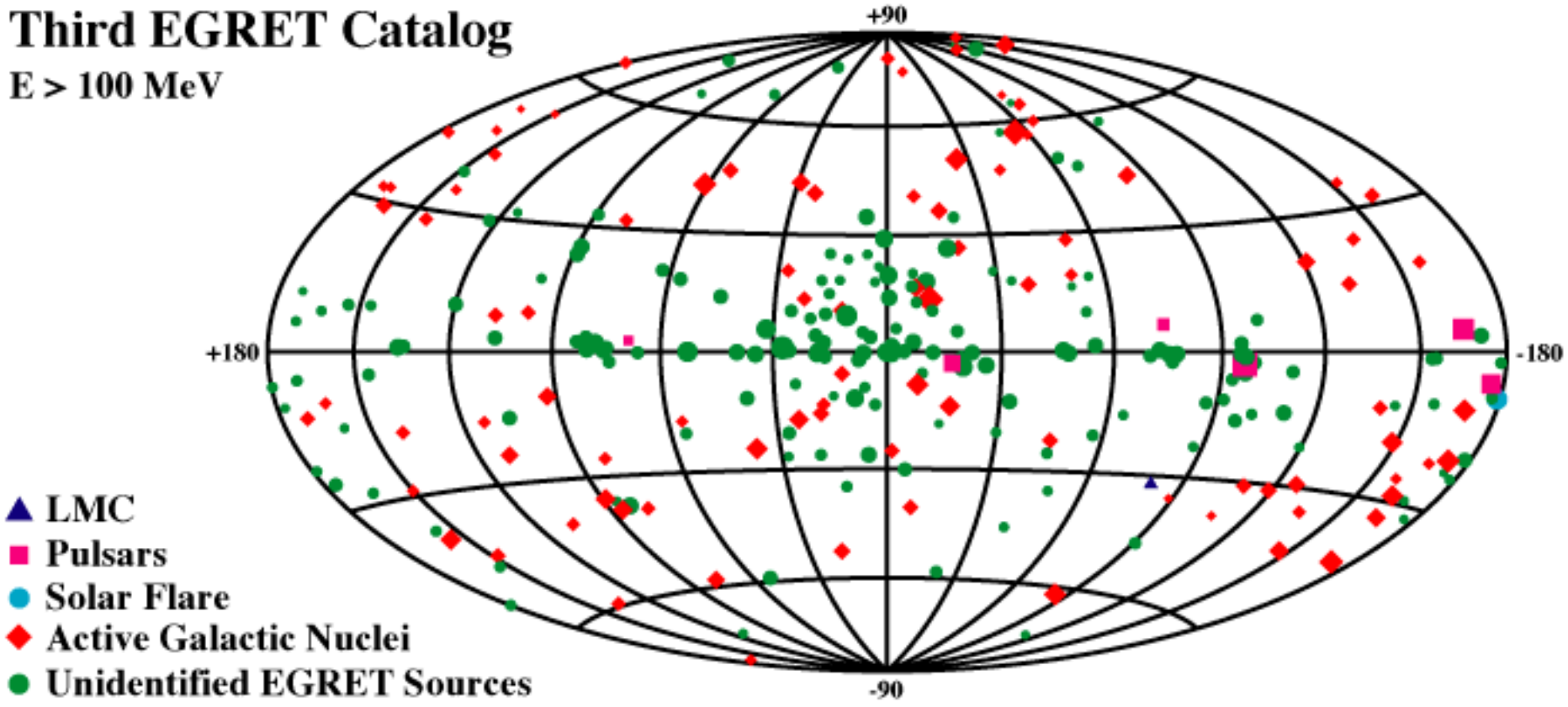
EGRET

- 1991-2000
- 30 MeV - 30 GeV
- AGN, GRB, Unidentified Sources, Diffuse Bkg

The HE sky from EGRET

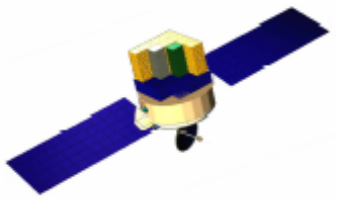


EGRET Gamma-ray Sources



Detector Project

N.Gehrels - SWG presentation ~ 2002

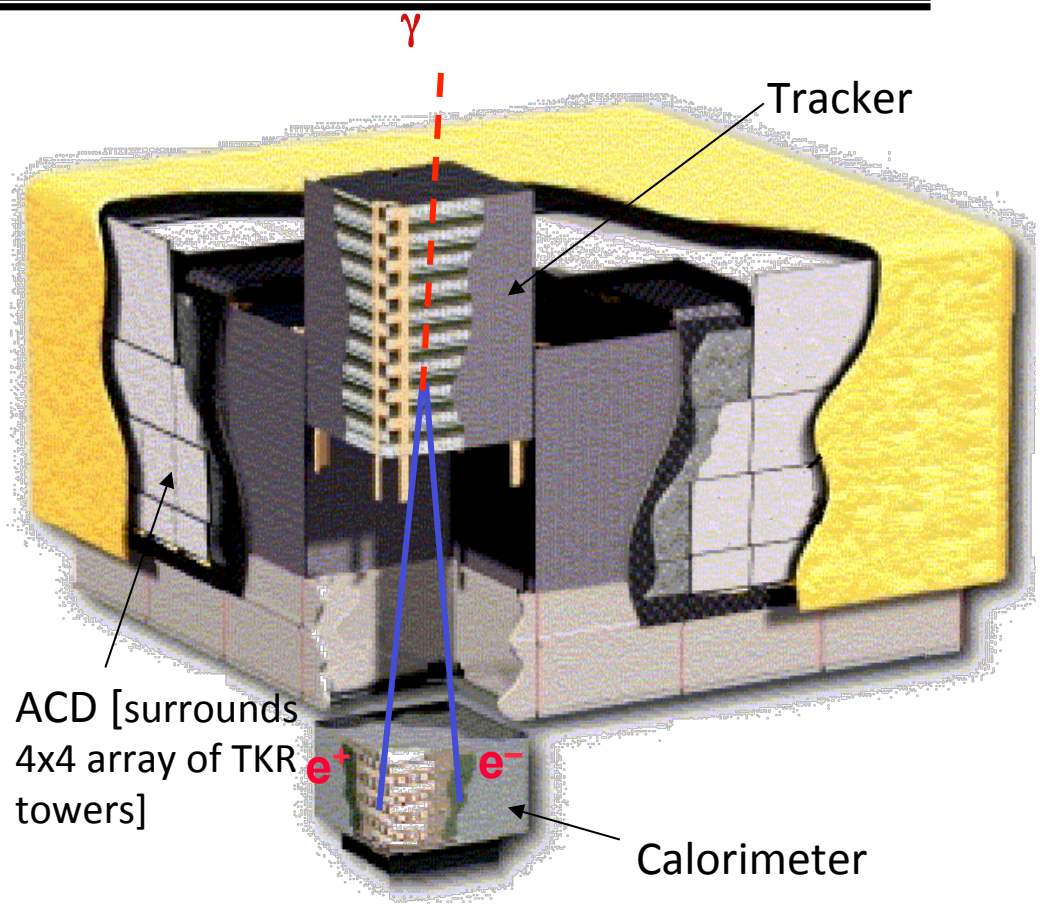


Sources Classes Predicted for GLAST

Source Class	Basis for Prediction
Active Galactic Nuclei (AGN)	EGRET quasars
Diffuse Cosmic Background	EGRET, Theory
Gamma Ray Bursts (GRBs)	EGRET, BATSE, Milagrito
Molecular Clouds, Supernova Remnants Normal Galaxies	COS-B, EGRET, Theory
Galactic Neutrons Stars (NS) & Black Holes (BHs)	COS-B, EGRET
Unidentified Gamma-ray Sources	COS-B, EGRET
Dark Matter	Theory

Overview of LAT

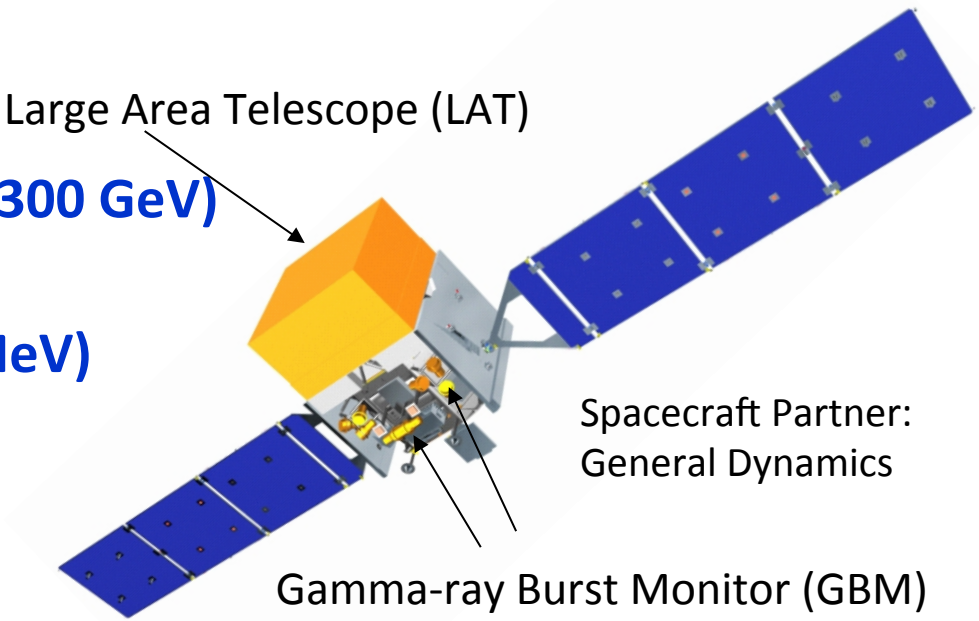
- **Precision Si-strip Tracker (TKR)** 18 XY tracking planes. Single-sided silicon strip detectors (228 μm pitch) Measure the photon direction; gamma ID.
- **Hodoscopic CsI Calorimeter(CAL)** Array of 1536 CsI(Tl) crystals in 8 layers. Measure the photon energy; image the shower.
- **Segmented Anticoincidence 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.

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.**

Fermi Gamma-ray Space Telescope

GLAST renamed *Fermi* by NASA on August 26, 2008

http://fermi.gsfc.nasa.gov/

“ Enrico Fermi (1901-1954) was an Italian physicist who immigrated to the United States. He was the first to suggest a viable mechanism for astrophysical particle acceleration. This work is the foundation for our understanding of many types of sources to be studied by NASA’s Fermi Gamma-ray Space Telescope, formerly known as GLAST. ”

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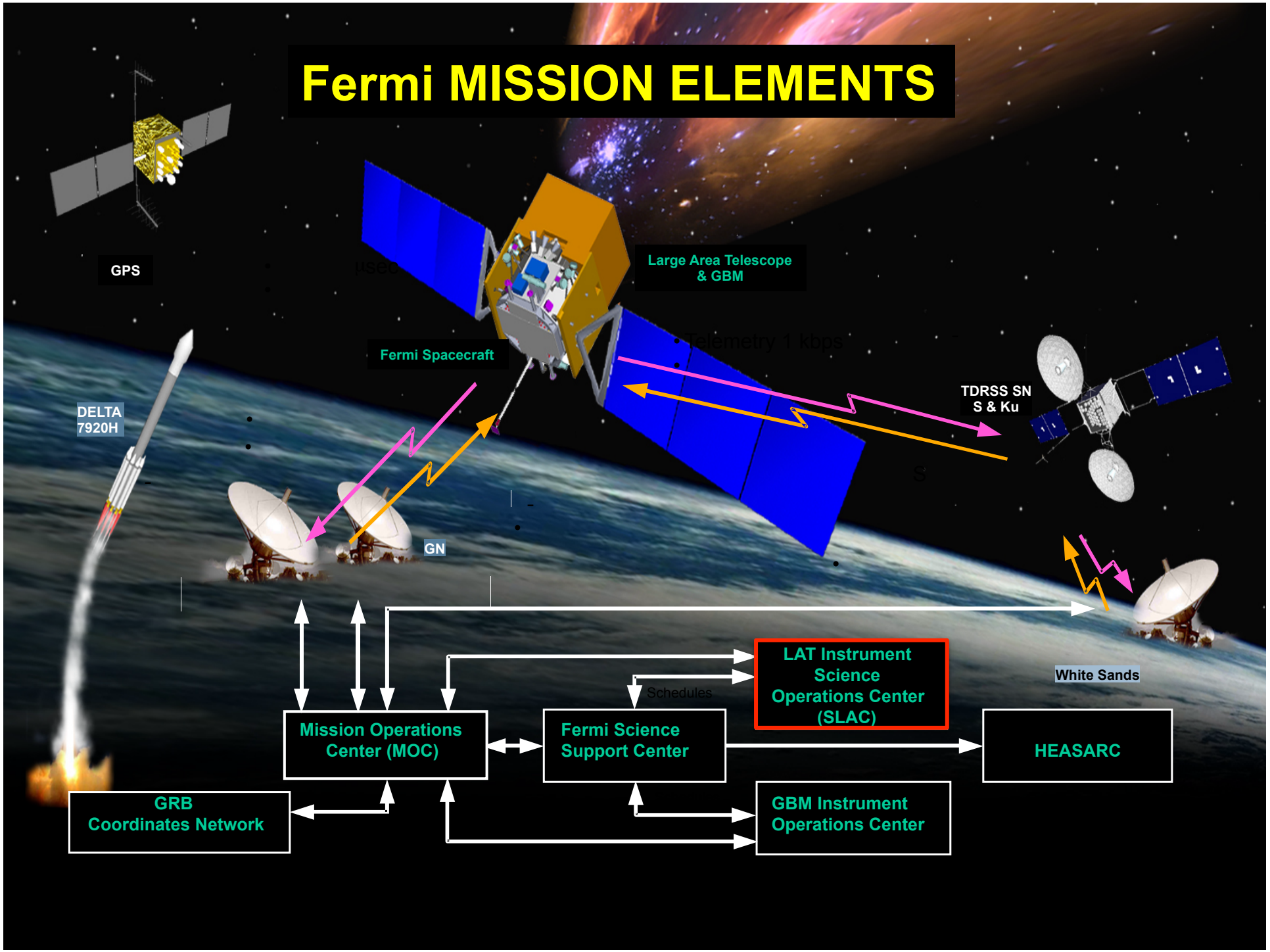

Fermi MISSION ELEMENTS
GPS
Large Area Telescope
& GBM
Fermi Spacecraft
DELTA
7920H
TDRSS SN
S & Ku
GN
White Sands
LAT Instrument
Science
Operations Center
(SLAC)
Schedules
Mission Operations
Center (MOC)
Fermi Science
Support Center
HEASARC
GRB
Coordinates Network
GBM Instrument
Operations Center

Data processing

- Low-level event reconstruction algorithms in all subsystems improving mistracking at high energy and large angles and supression of ghost events, effectively increasing the instruments Eff. Area and FoV
- New event class selections
- Improved background rejection
- Improved Monte Carlo Simulations

P8 is a **complete LAT upgrade** resulting in a large improvement in acceptance ($\sim 100\%$ below 100 MeV and $\sim 25\%$ above 1 GeV) and a significant improvement in localization and background rejection. Additional improvements are expected in energy coverage and a better understanding of the systematic uncertainty.

PASS8 new reconstruction
(e.g. Racusin et a. AAS 2014)

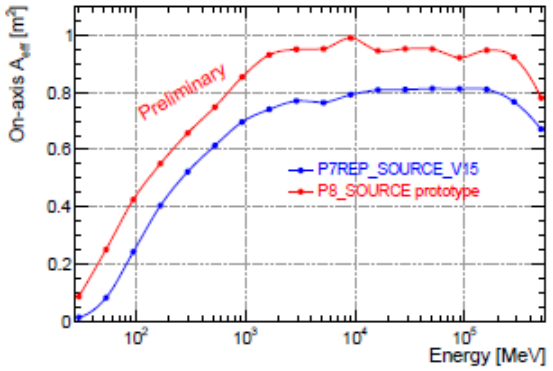


Figure 1: *Prototype P8 event class vs. P7 effective area as a function of energy.*

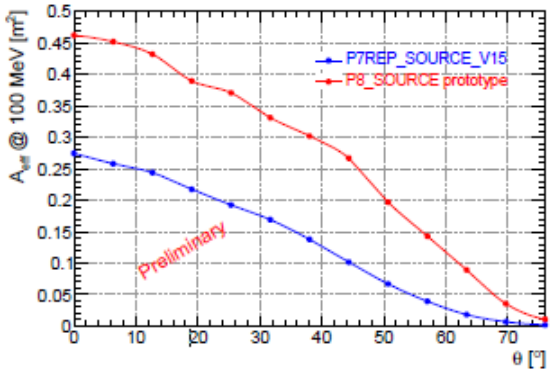
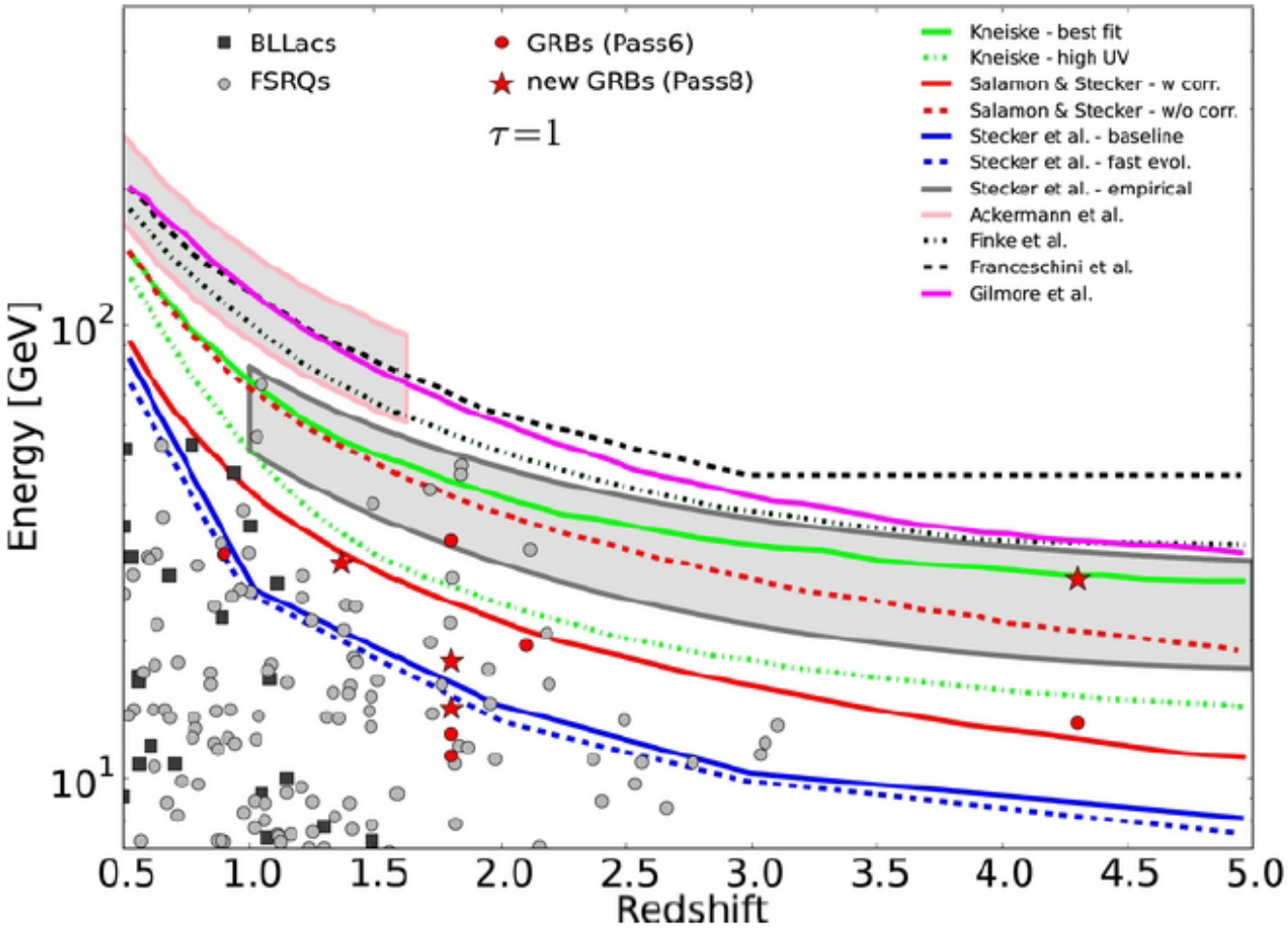


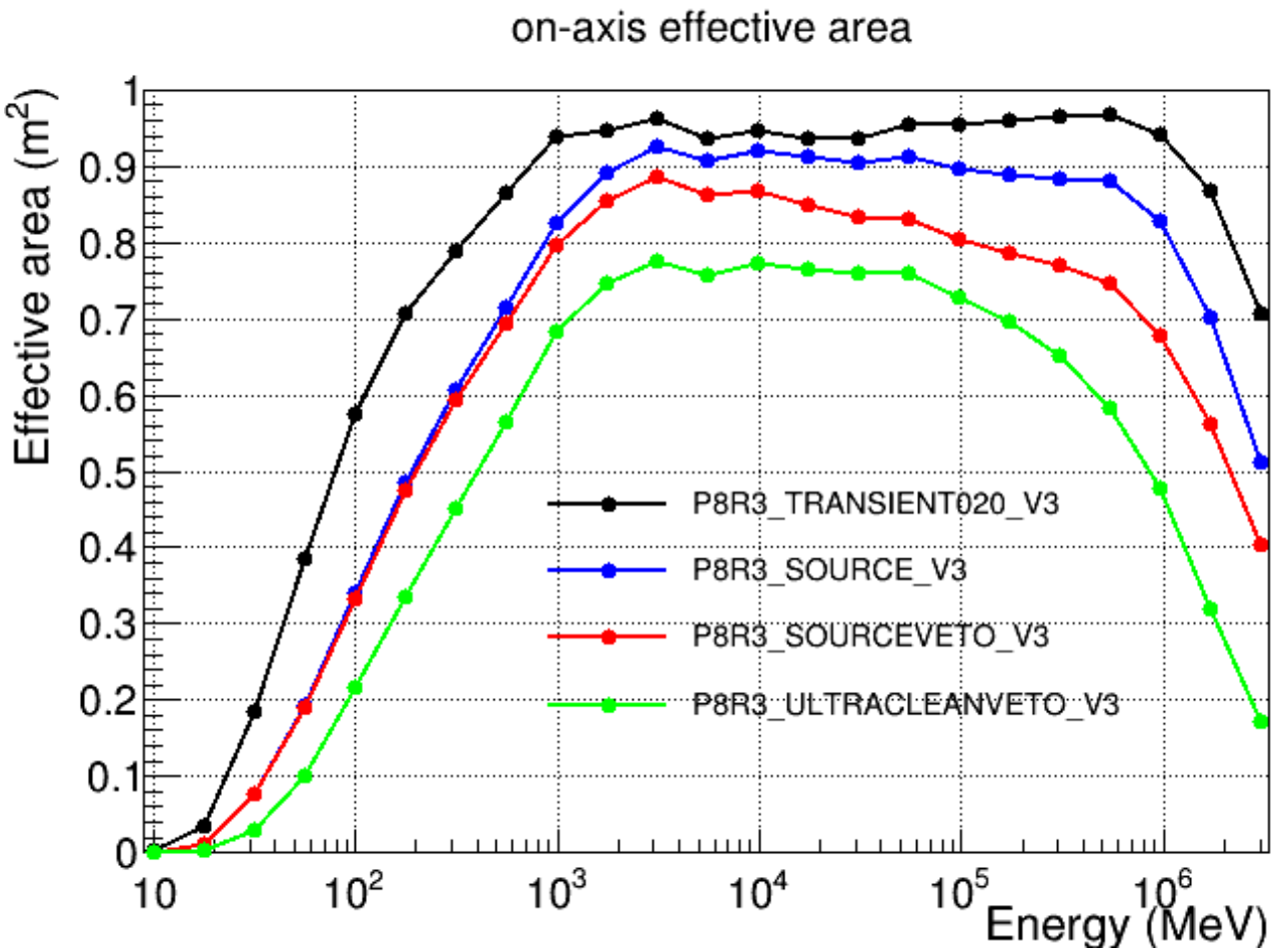
Figure 2: *Prototype P8 event class vs P7 effective area at 100 MeV as a function of the angle from the boresight.*

Data processing



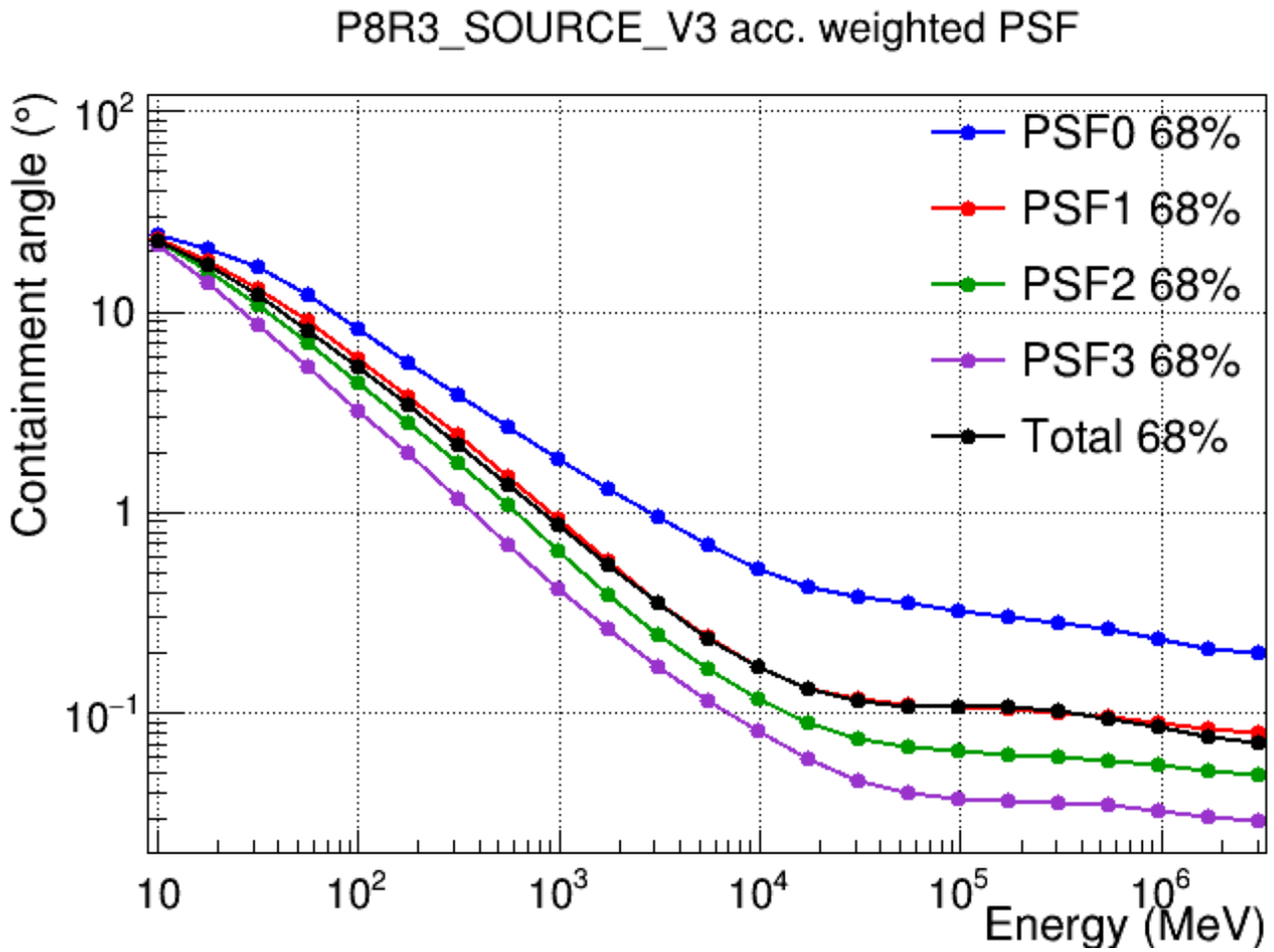
Atwood at al. 2013

Data Processing



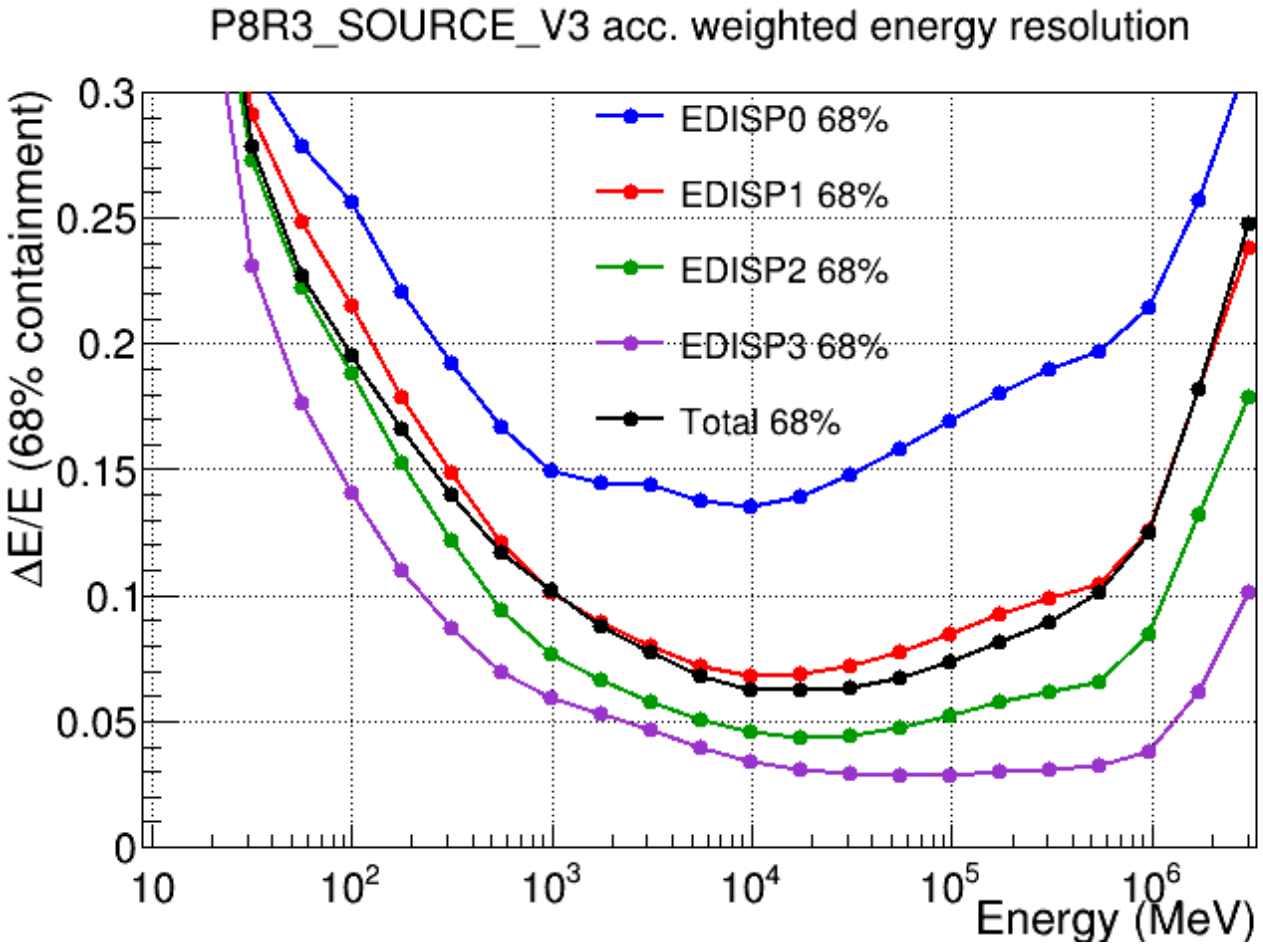
https://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

Data processing



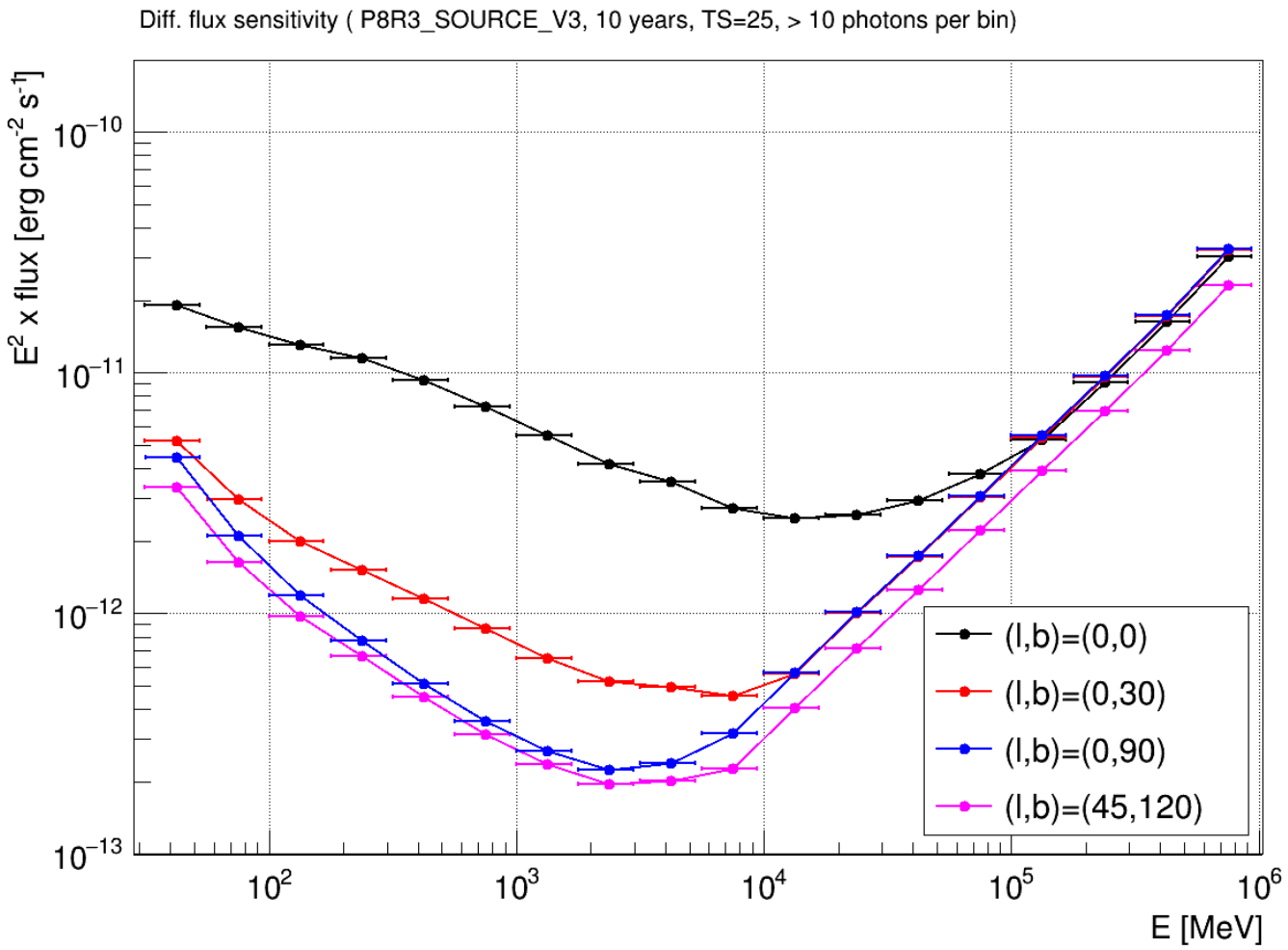
https://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

Data processing

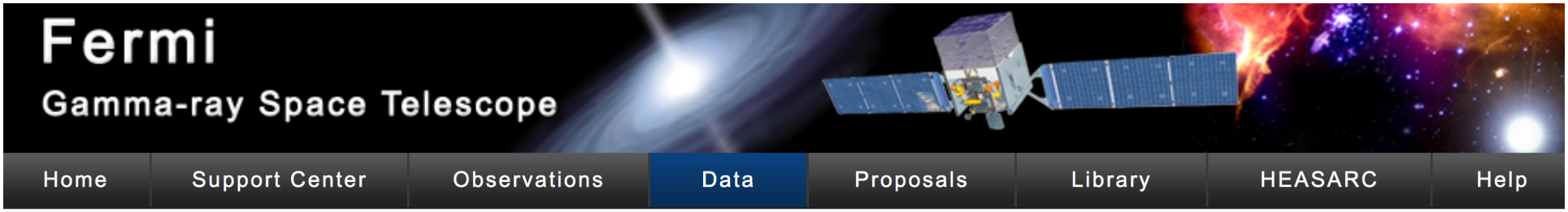


https://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

Data processing



Data Dissemination



Data

- Data Policy
- **Data Access**
  - + LAT Data
  - + LAT Catalog
  - + LAT Data Queries
  - + LAT Query Results
  - + LAT Weekly Files
  - + GBM Data
- Data Analysis
- Caveats
- Newsletters
- FAQ

Currently Available Data Products

The Fermi data released to the scientific community is governed by the data policy. The released instrument data for the GBM, along with LAT source lists, can be accessed through the Browse interface specific to Fermi. LAT photon data can be accessed through the LAT data server.

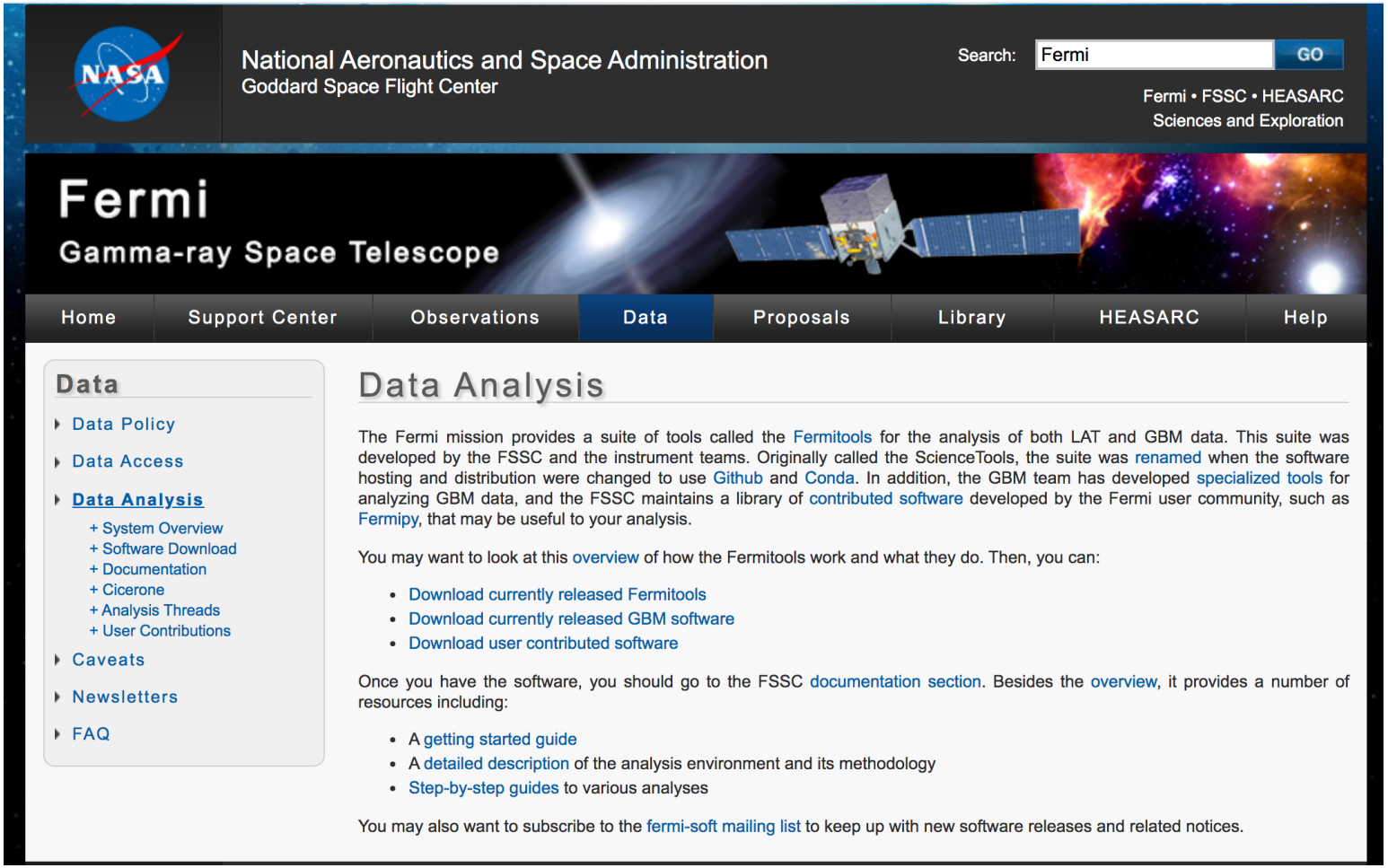
The FITS files can also be downloaded from the Fermi FTP site. The file version number is the 'xx' in the characters before the extension in each filename; you should keep track of the version numbers of files you analyze since the instrument teams may update them.

Note that the LAT and GBM data are accompanied by caveats about their use.

- LAT Photon and Extended Data
  - LAT Data Server (updated with P8R3 data 26-Nov-2018)
  - LAT Low-Energy (LLE) Data (Browse table)
  - Products available on the FTP Site (current processing version of the data).
    - Weekly Photon Files
    - Weekly Spacecraft Files

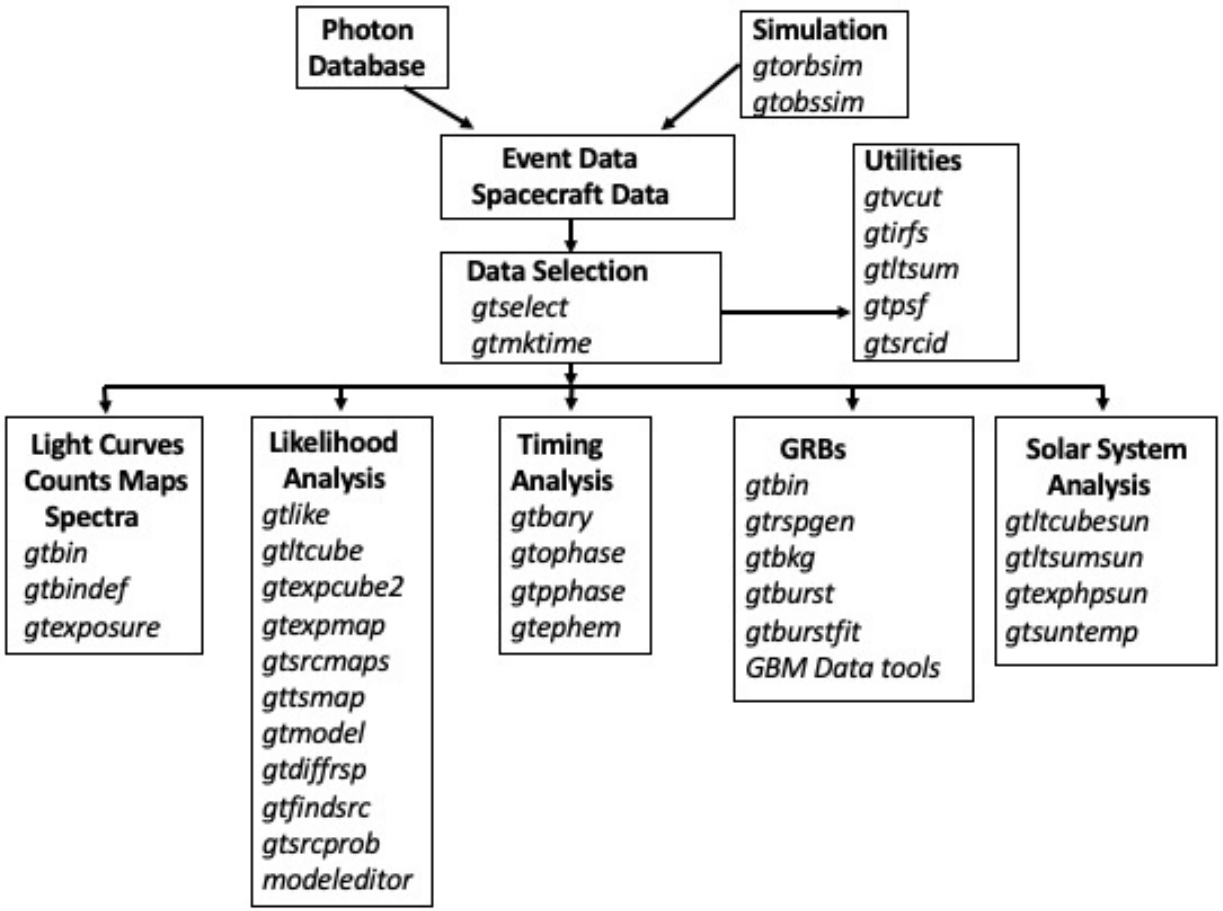
https://fermi.gsfc.nasa.gov/ssc/data/access/

Data dissemination



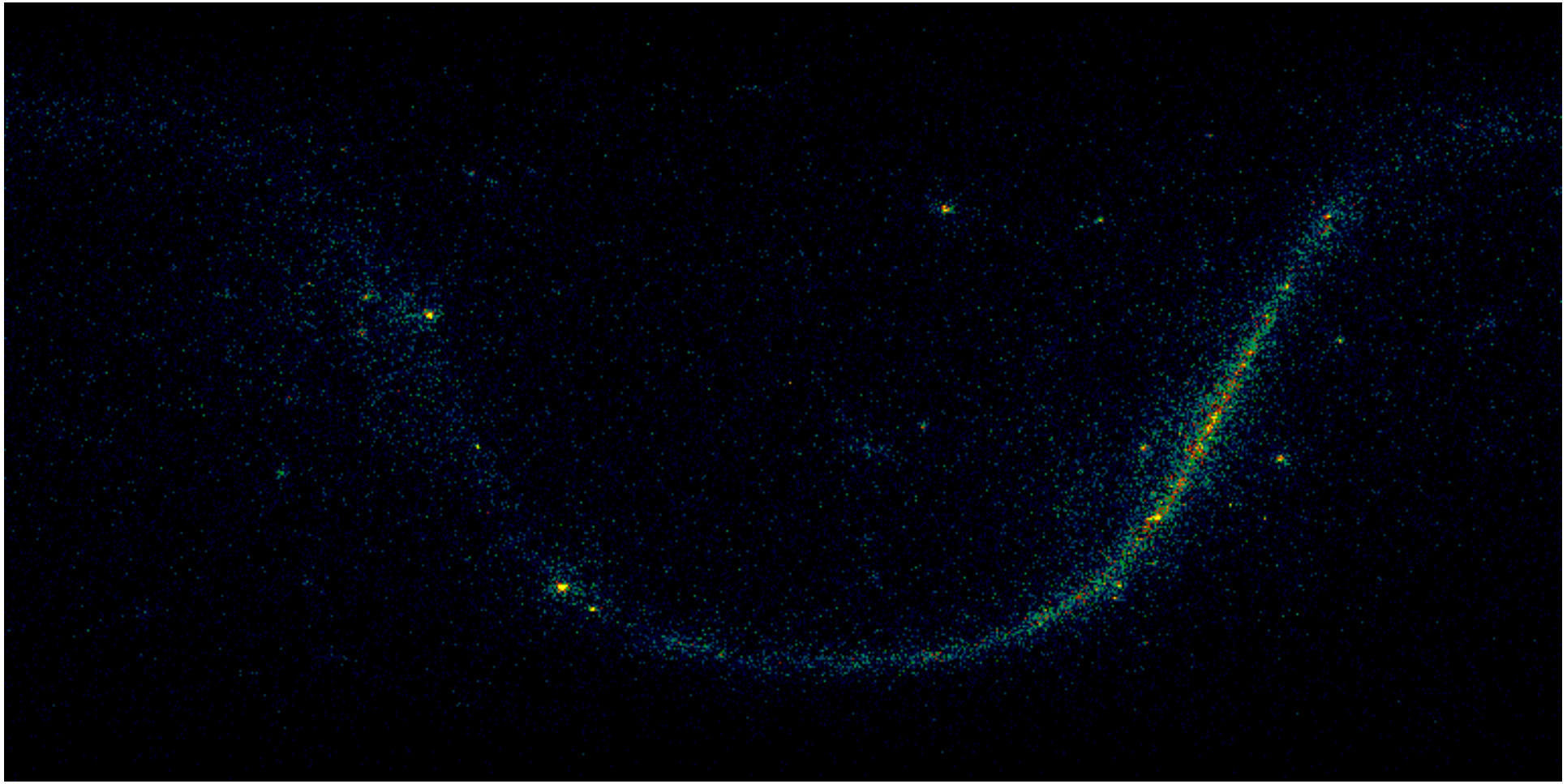
https://fermi.gsfc.nasa.gov/ssc/data/analysis/

Data dissemination



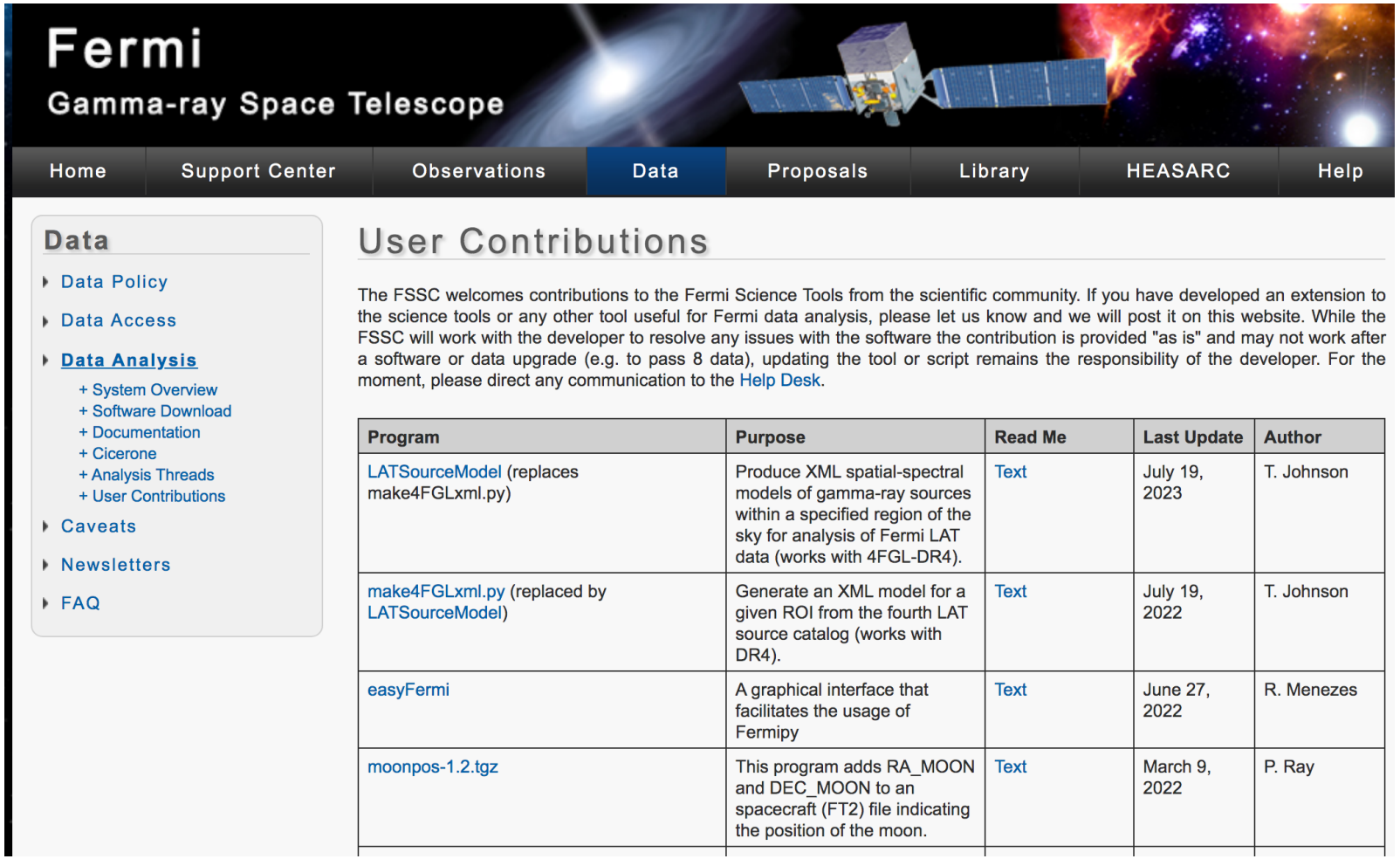
https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/overview.html

Data dissemination



https://apod.nasa.gov/apod/ap060531.html

Data dissemination



Program	Purpose	Read Me	Last Update	Author
LATSourceModel (replaces make4FGLxml.py)	Produce XML spatial-spectral models of gamma-ray sources within a specified region of the sky for analysis of Fermi LAT data (works with 4FGL-DR4).	Text	July 19, 2023	T. Johnson
make4FGLxml.py (replaced by LATSourceModel)	Generate an XML model for a given ROI from the fourth LAT source catalog (works with DR4).	Text	July 19, 2022	T. Johnson
easyFermi	A graphical interface that facilitates the usage of Fermipy	Text	June 27, 2022	R. Menezes
moonpos-1.2.tgz	This program adds RA_MOON and DEC_MOON to an spacecraft (FT2) file indicating the position of the moon.	Text	March 9, 2022	P. Ray

https://fermi.gsfc.nasa.gov/ssc/data/analysis/user/

Data dissemination

- **The Fermi Catalogs**
  - LAT catalogs and associated products (high-level products only)
    - LAT Source Catalog
      - LAT 14-year Source Catalog (4FGL-DR4)
      - LAT 12-year Source Catalog (4FGL-DR3)
      - LAT 10-year Source Catalog (4FGL-DR2)
      - LAT 8-year Source Catalog (4FGL)
      - Preliminary LAT 8-year Source List (FL8Y)
      - LAT 4-year Source Catalog (3FGL)
      - LAT 2-year Source Catalog (2FGL)
      - LAT 1-year Source Catalog (1FGL)
      - LAT 3-month Bright Source List (0FGL)
    - Light Curve Repository
    - Aperture Photometry Light Curves
      - Aperture Photometry Light Curves for LAT 10-year Catalog Sources (Updated Weekly)
      - Flaring Sources in the LAT 10-year Aperture Photometry Light Curves (Updated Weekly)
      - Aperture Photometry Light Curves for LAT 4-year Catalog Sources
      - Flaring Sources in the LAT 4-year Aperture Photometry Light Curves
      - Aperture Photometry Light Curves for the LAT 2-year Source Catalog
      - Flaring Sources in the LAT 2-year Aperture Photometry Lightcurves
    - LAT High Energy Source Catalog
      - LAT Third High Energy Source Catalog (3FHL)
      - LAT Second High-Energy Source Catalog (2FHL)
      - LAT First High-Energy Source Catalog (1FHL)

https://fermi.gsfc.nasa.gov/ssc/data/access/

Data dissemination

- **The Fermi Catalogs (4FGL – DR4)**

LAT 14-year Source Catalog (4FGL-DR4)

The Large Area Telescope (LAT) on board NASA's *Fermi* Gamma-ray Space Telescope (launched June 11, 2008) surveys the entire sky each day. This web page presents an incremental version (4FGL-DR4, for Data Release 4) of the fourth full catalog of LAT sources, based on 14 years of survey data in the 50 MeV-1 TeV energy range. For a full explanation about the catalog and its construction see the DR4 document . The DR4 data analysis is similar to 4FGL-DR3 (with a few differences explained in the text), so the reference is still the DR3 paper . Please cite both documents when you use this data release.

The source designation is the same as 4FGL, 4FGL JHHMM.m+DDMM(c,e,i,s) where the 4 refers to the fourth catalog (1FGL was released at 1 year, 2FGL at 2 years, and 3FGL at 4 years) and FGL represents Fermi Gamma-ray LAT. The "DataRelease" column set to either 1, 2, 3 or 4 tells when a source was introduced in the catalog. The optional "e", "i" and "s" designators are explained in the caveats below.

LAT Catalog Data Products

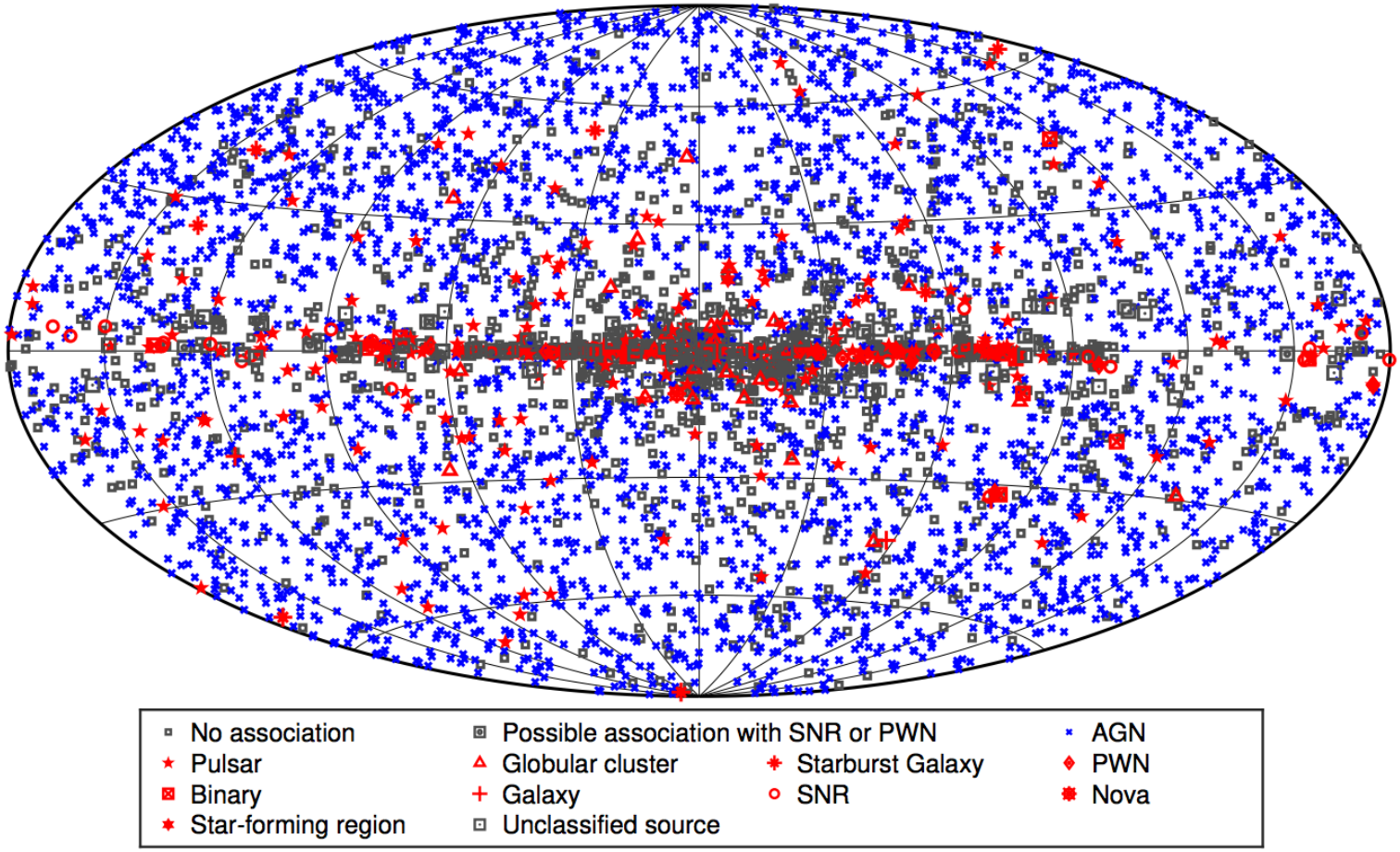
The LAT 14-year Source Catalog is currently available as a FITS file to be used for data analysis within the Fermitools. Supporting tools and documentation have been provided and are linked below.

- LAT 14-year Source Catalog (4FGL-DR4 in FITS format)
- LAT 14-year Source Catalog (BROWSE table)
- LAT 14-year Source Catalog (XML format)
- LAT 14-year Source Catalog Paper

https://fermi.gsfc.nasa.gov/ssc/data/access/lat/14yr_catalog/

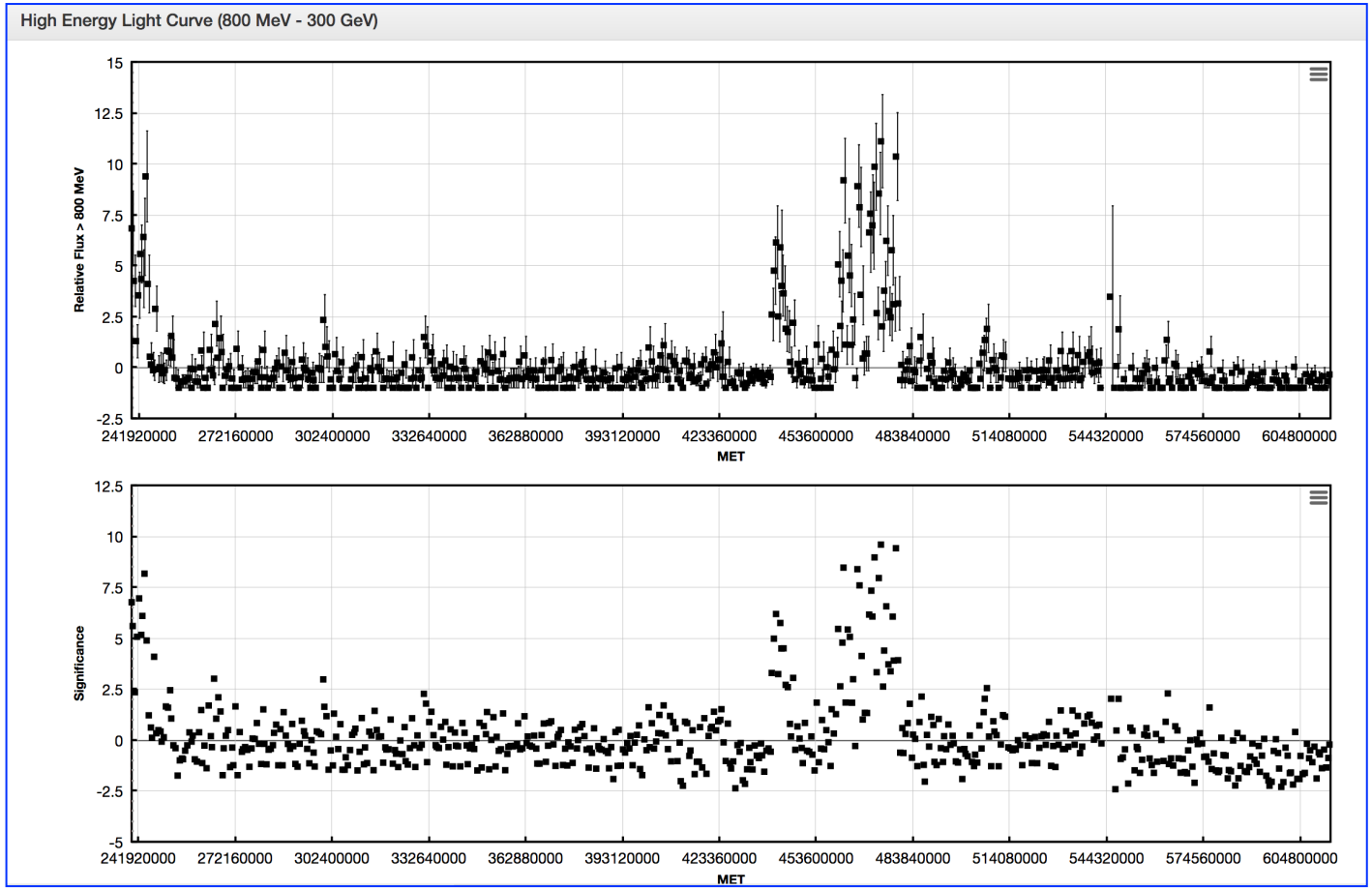
Data Dissemination

- **The Fermi Catalogs**



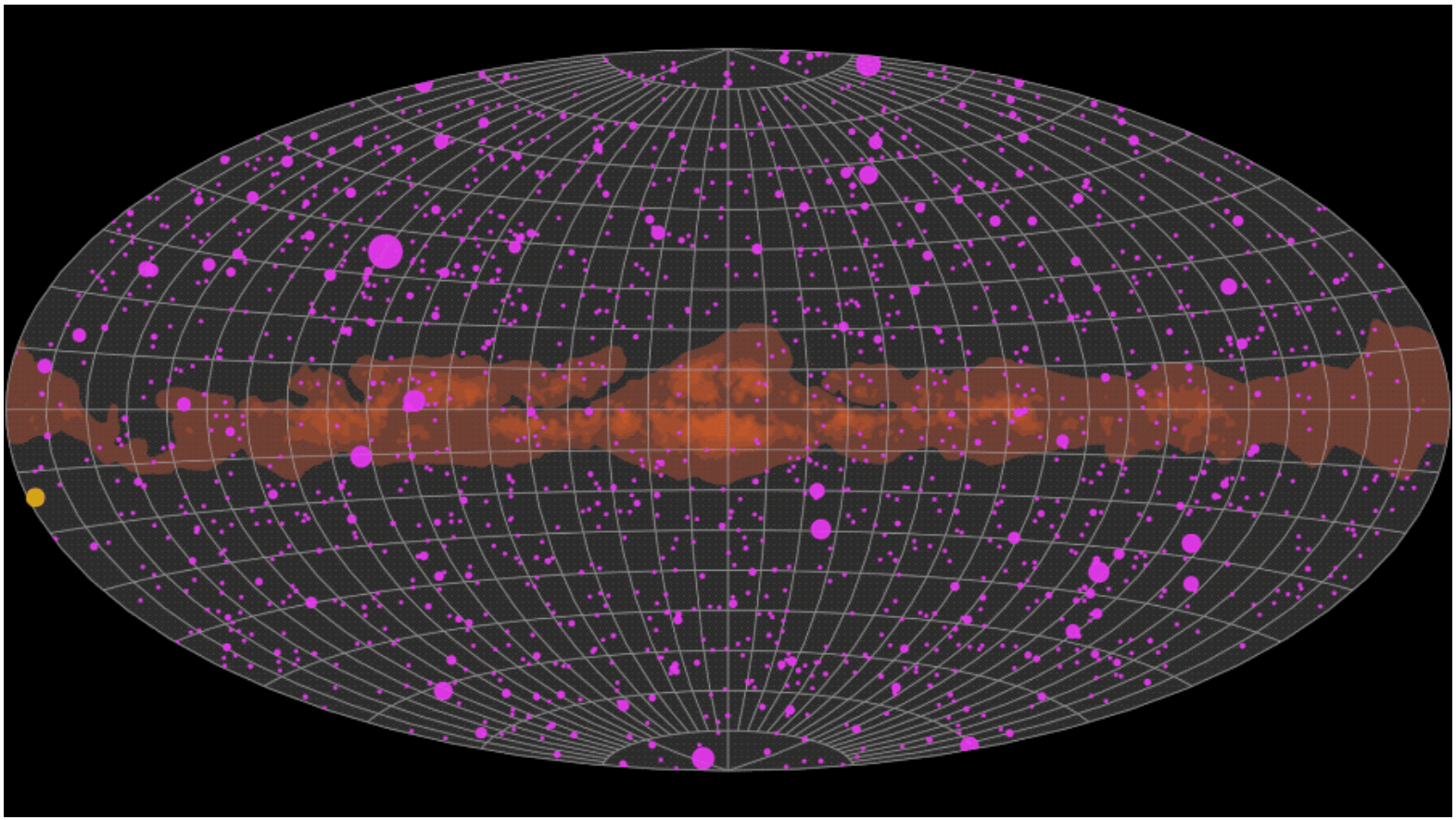
Data Dissemination

- **FAVA tool**



https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/

Data Dissemination



https://fermi.gsfc.nasa.gov/ssc/data/access/lat/LightCurveRepository/about.html

The Fermi/LAT publication policy

	Category I	Category II	Category II.5
Analysis & Scientific Papers	Papers reporting a substantially new scientific result, obtained either during the all-sky survey or from Collaboration Key Projects during subsequent phases; papers that require broad participation by collaboration (e.g., catalog)	Papers involving specialized in-depth analysis or interpretation or follow-up with details on a previously published result	Papers that are externally led if the LAT data analysis uses standard methods that have been used often and are fully tested, and the LAT data are not mandatory for the conclusions of the paper.
	Authorship: all active collaboration members are eligible; affiliated scientists and others considered on a case-by-case basis	Authorship: collaboration members (or affiliated scientists) who have substantially contributed to the scientific ideas or analysis done in paper.	Authorship: collaboration members (or affiliated scientists) who have substantially contributed to the scientific ideas or analysis done in paper.

https://www-glast.stanford.edu/ppdocuments/LAT_Pub_Policy_Rev7_02-2020.pdf

The Fermi/LAT publication policy

Publications by the Fermi LAT collaboration

Select a topi

- All
- Blazars, other AGN and Galaxy Clusters
- Calibration and Analysis Methods
- Catalogs and Source Identification
- Dark Matter and New Physics
- Diffuse, Molecular Clouds and Other Galaxies
- Galactic Sources including Pulsars
- Gamma-Ray Bursts
- Sources in the Solar System

- Fermi LA
- Independ members
- Ph. D. dis
- Public da papers
- The 2009, 2011, 2012, 2014, 2015, 2017, 2018, 2021 and 2022, Fermi Symposia
- Review of the first-year results

- nical description of the LAT instrument
- Fermi Large Area Telescope On Orbit: t Classification, Instrument Response tions, and Calibration
- 8: Toward the Full Realization of the i-LAT Scientific Potential
- Fermi-LAT improved Pass 8 event selection
- Galactic Interstellar Emission Model for the 4FGL Catalog Analysis
- Review of public talks

Jump to year: 2024 2023 2022 2021 2020 2019 2018 2017 2016 2015 2014 2013 2012 2011 2010 2009 2008 2007

2024

Insights into the broad-band emission of the TeV blazar Mrk 501 during the first X-ray polarization measurements (Accepted for publication)
Abe, S. et al. 2024, A&A Show links

First characterization of the emission behavior of Mrk 421 from radio to very high-energy gamma rays with simultaneous X-ray polarization measurements
Abe, S. et al. 2024, A&A, 684, A127 Show links

Broadband Multi-wavelength Properties of M87 during the 2018 EHT Campaign and a Very High Energy Flaring Episode (Submitted for publication)
The Event Horizon Telescope et al. 2024, A&A Show links

https://www-glast.stanford.edu/cgi-bin/pubpub

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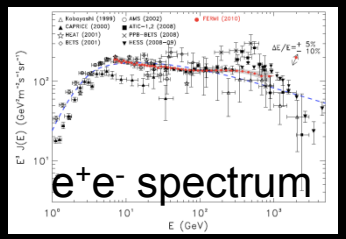
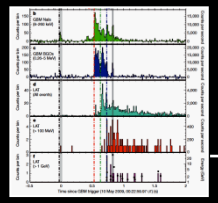
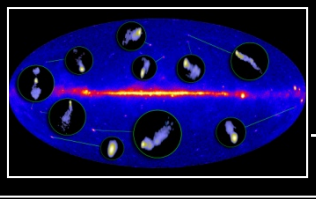
Fermi Reveals the High Energy Universe

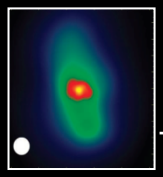




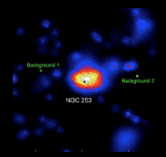
GRBs



Blazars

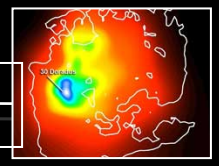


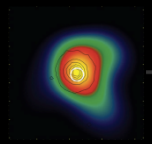
Radio Galaxies



Starburst Galaxies

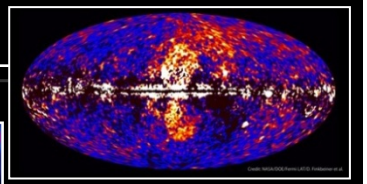
LMC SMC

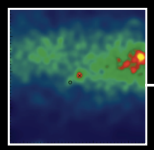




Globular Clusters

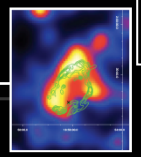
Fermi Bubbles

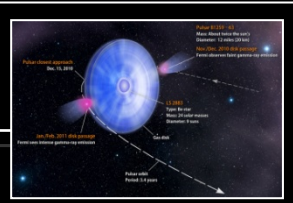




Novae

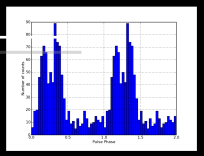
SNRs & PWN



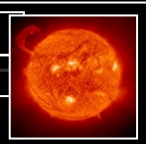


γ-ray Binaries

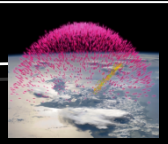
Pulsars: isolated binaries, & MSPs



Sun: flares & CR interactions



Terrestrial γ-ray Flashes



Unidentified Sources

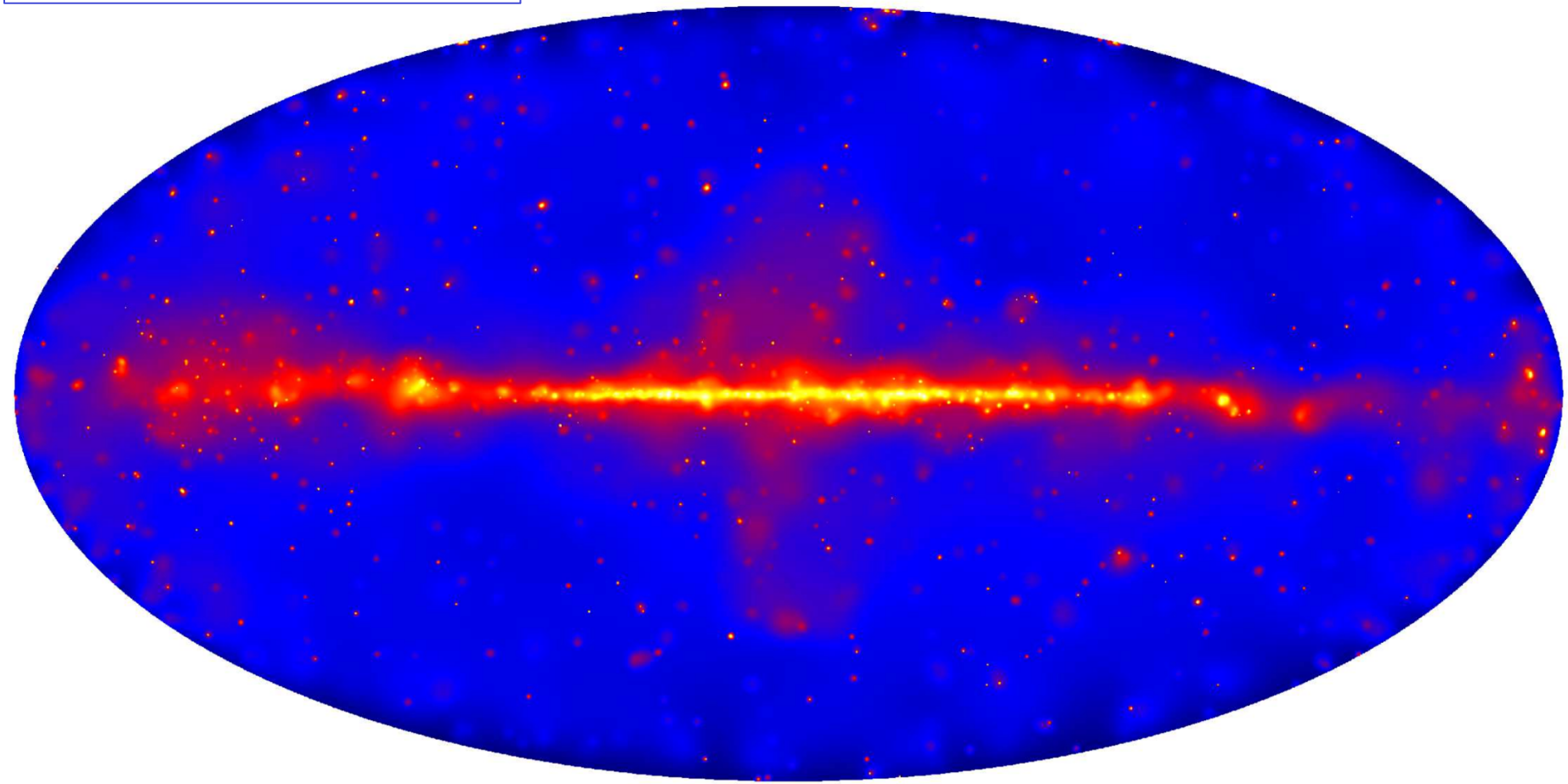
Extragalactic

Galactic

Local

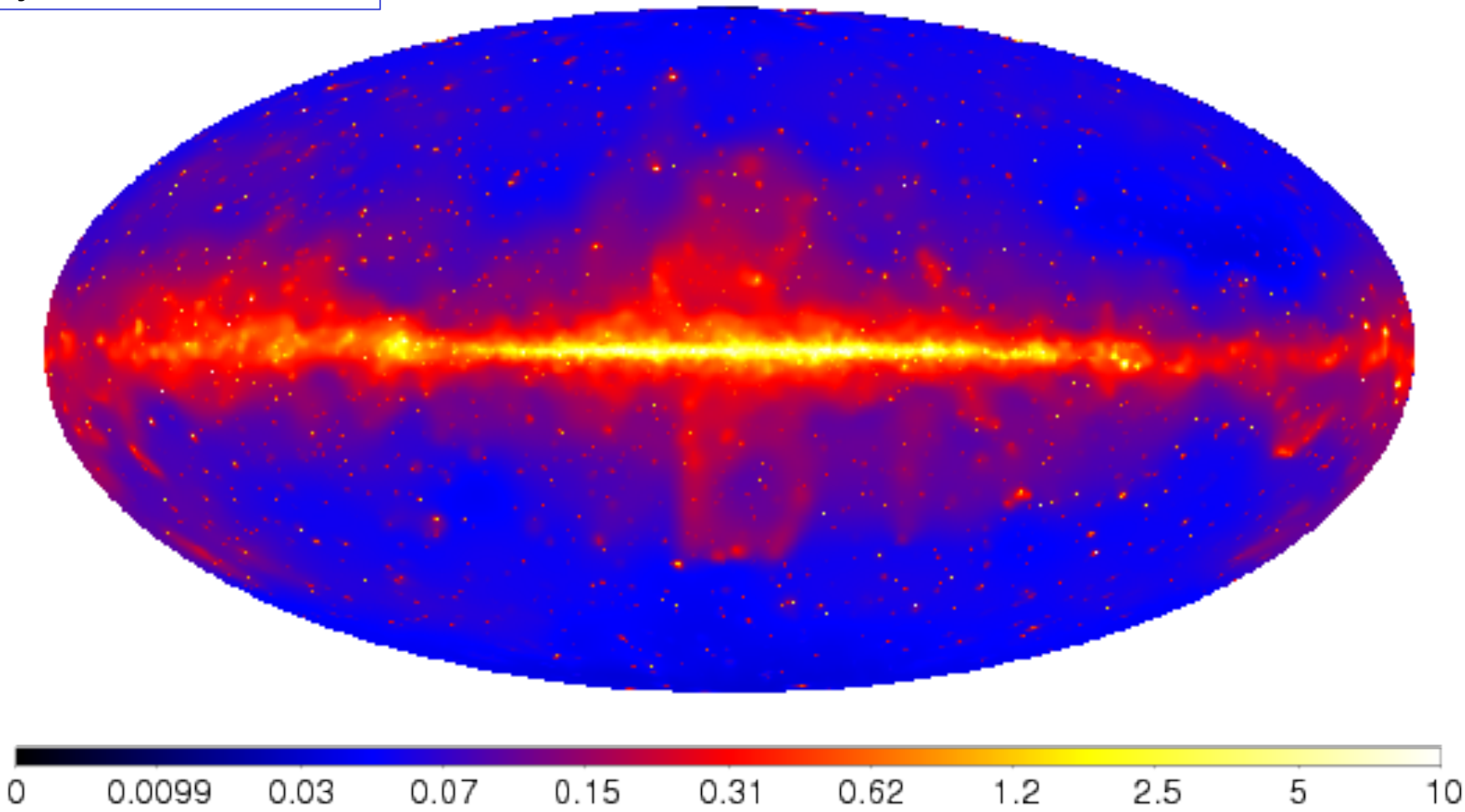
2FHL (P8 data >50 GeV) – 80 months

Ackermann, M. et al. 2016



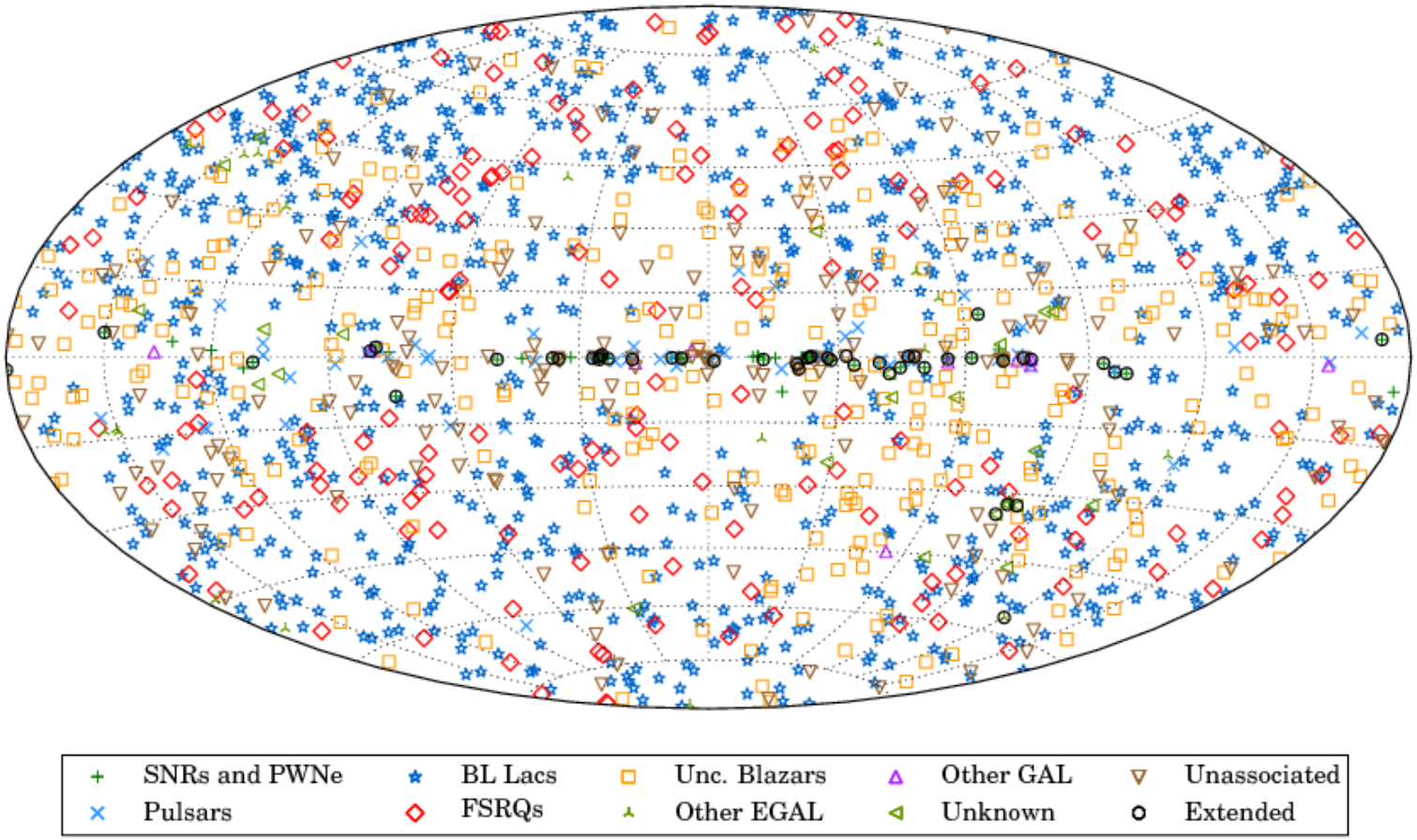
3FHL (E>10 GeV – P8)

Ajello, M. et al. 2017

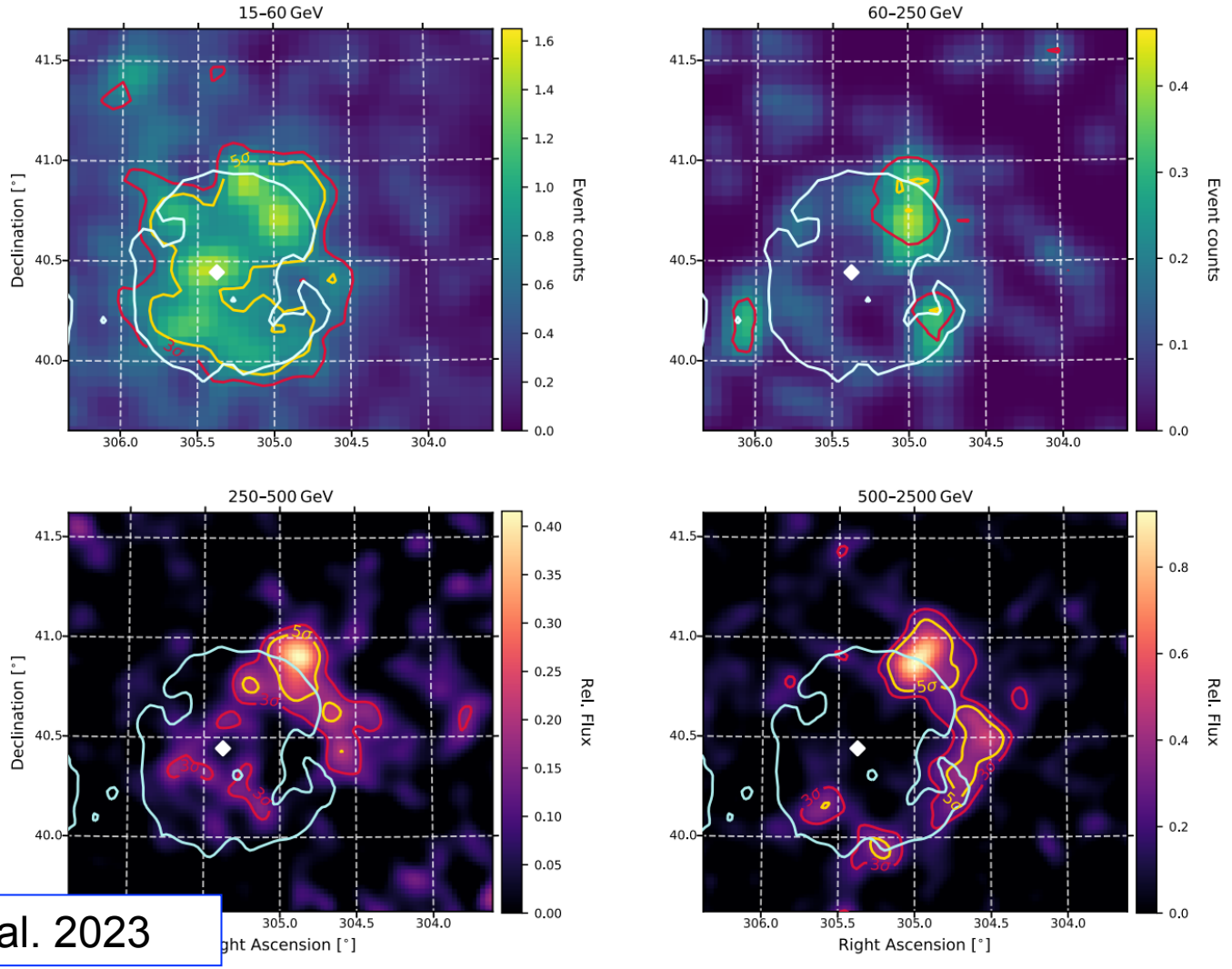


3 FHL

Ajello, M. et al. 2017

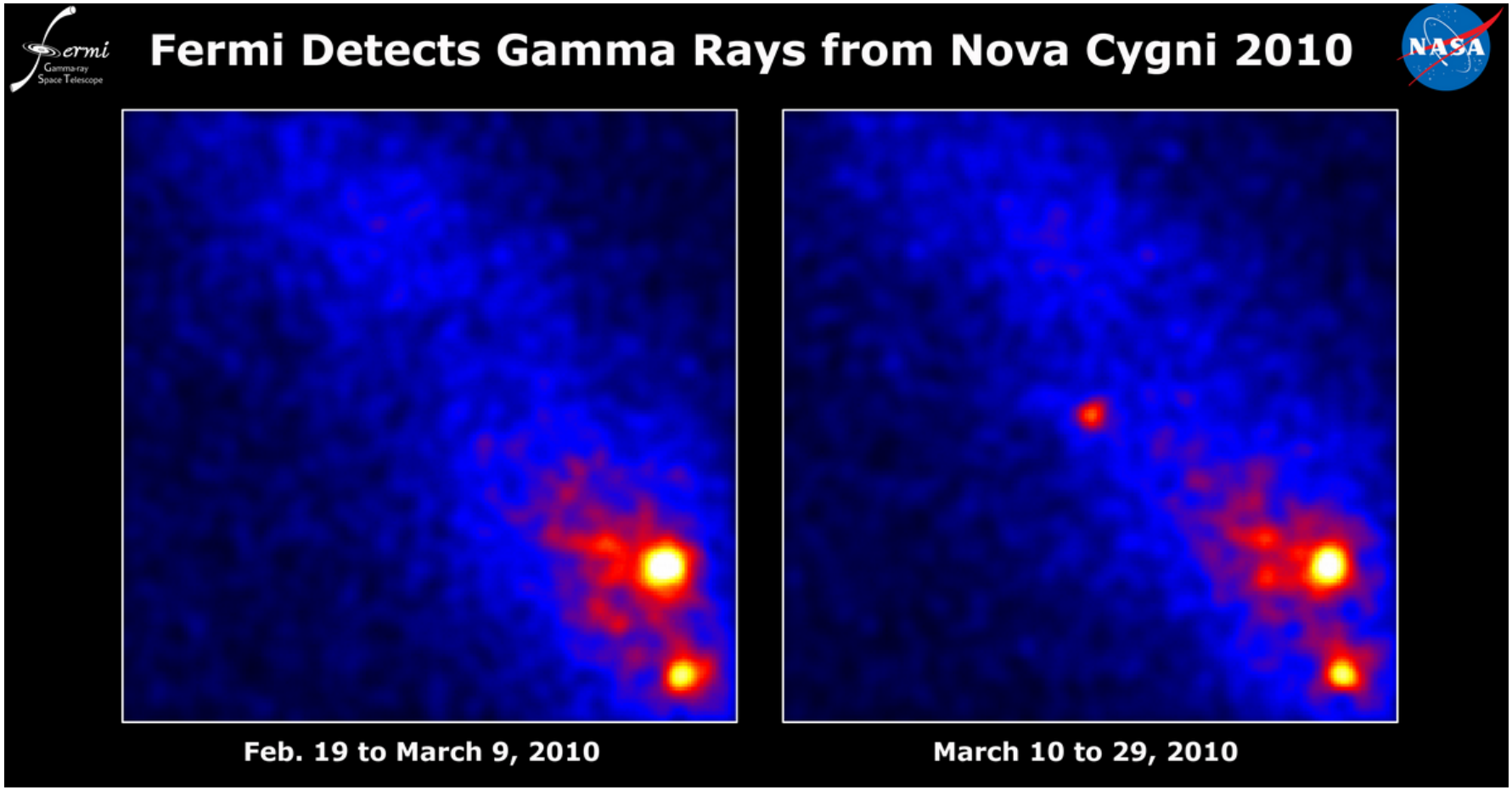


HE Gamma Ray from SNR



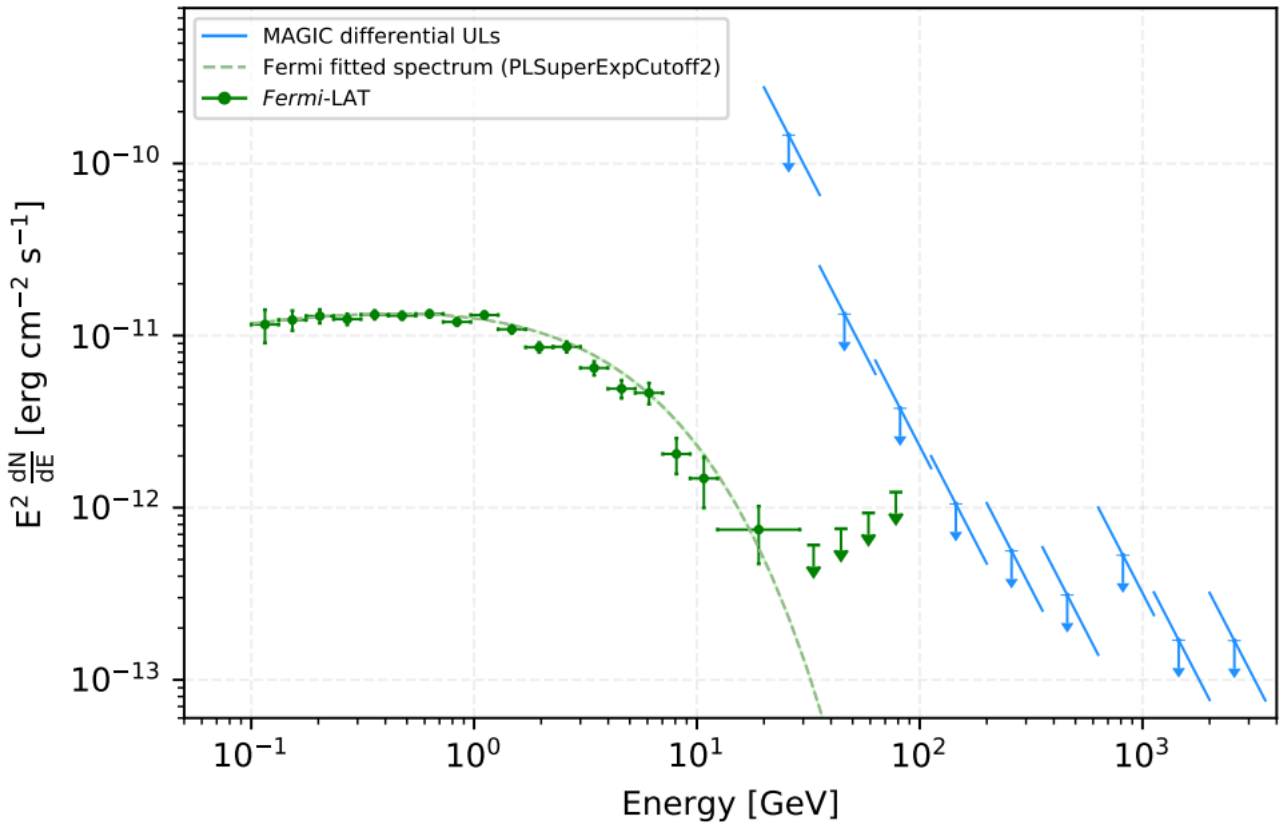
Acciari, V. et al. 2023

Nova emitting in Gamma Rays



Abdo, A. A. et al. 2010

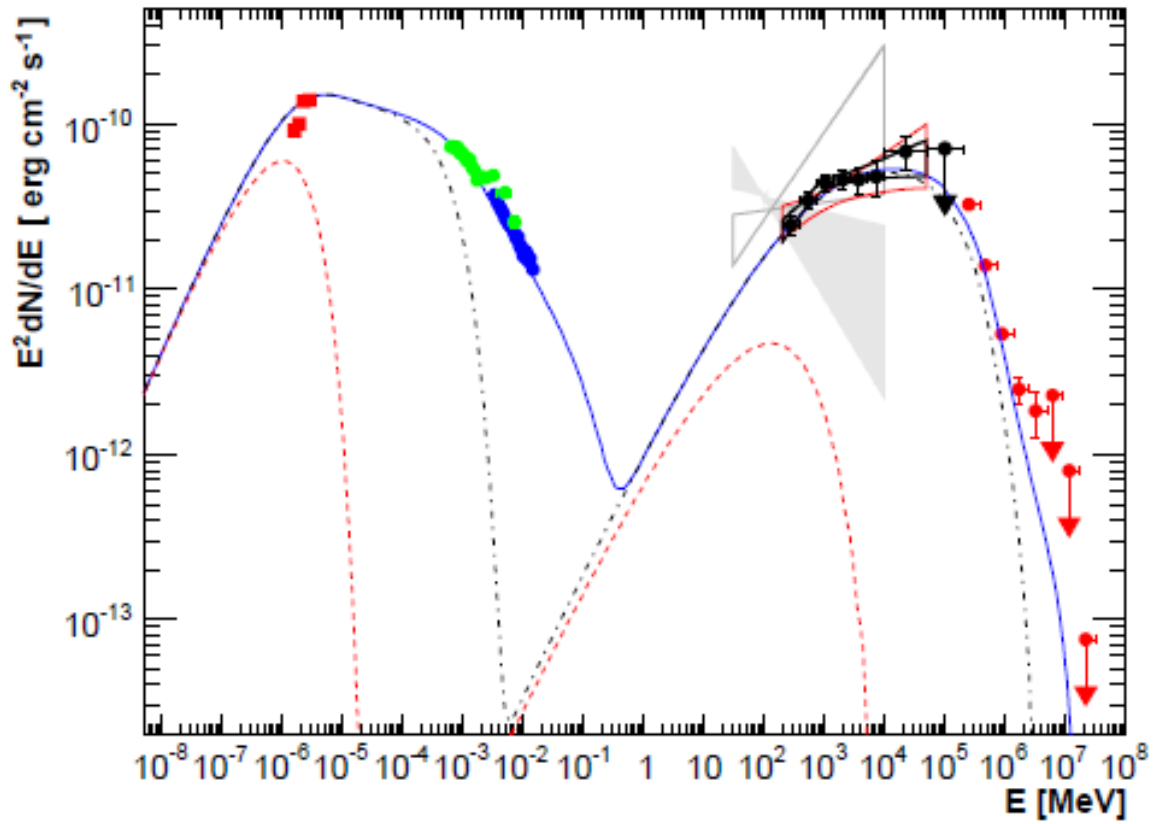
PSR at high energies



Acciari et al.2021

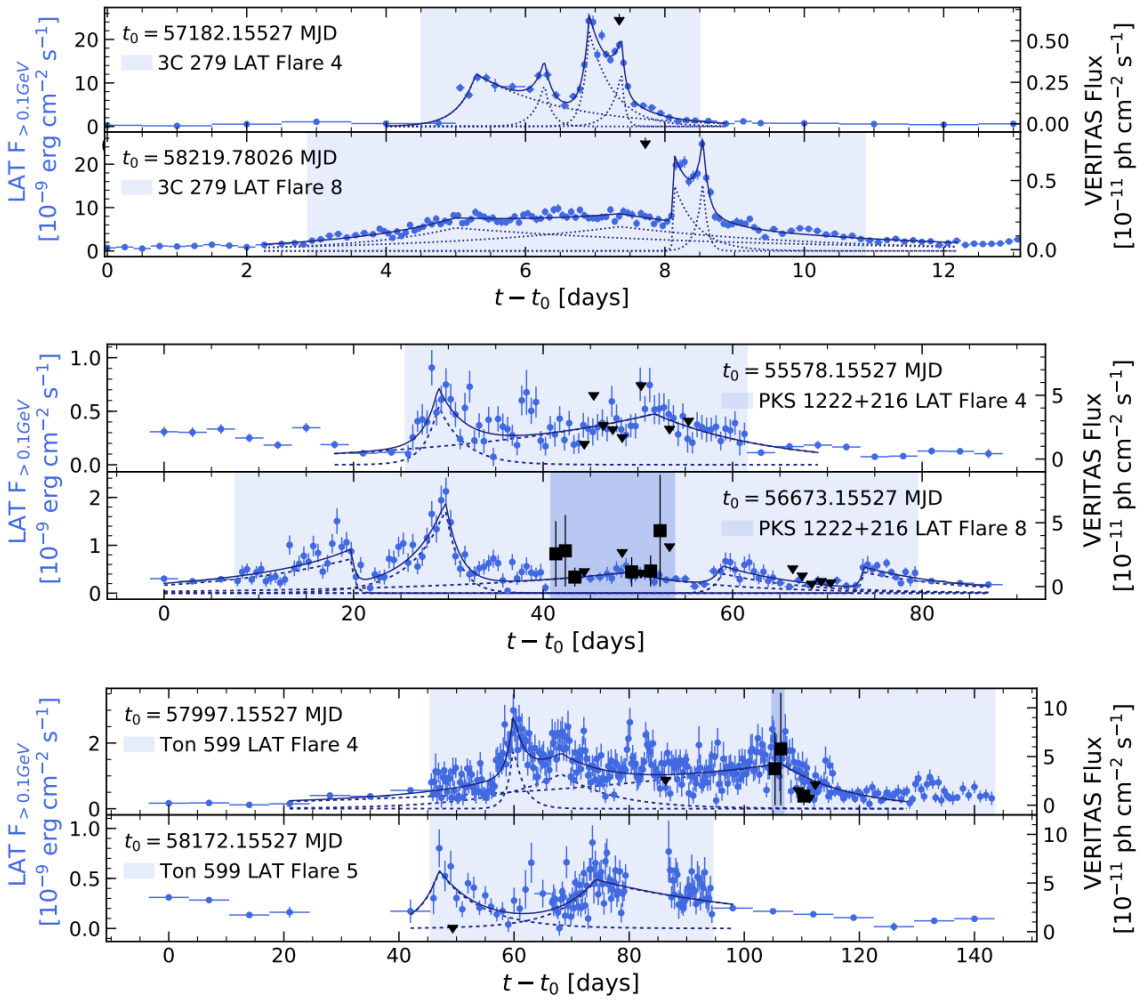
Active Galactic Nuclei SED

Joint campaign on PKS 2155 with HESS



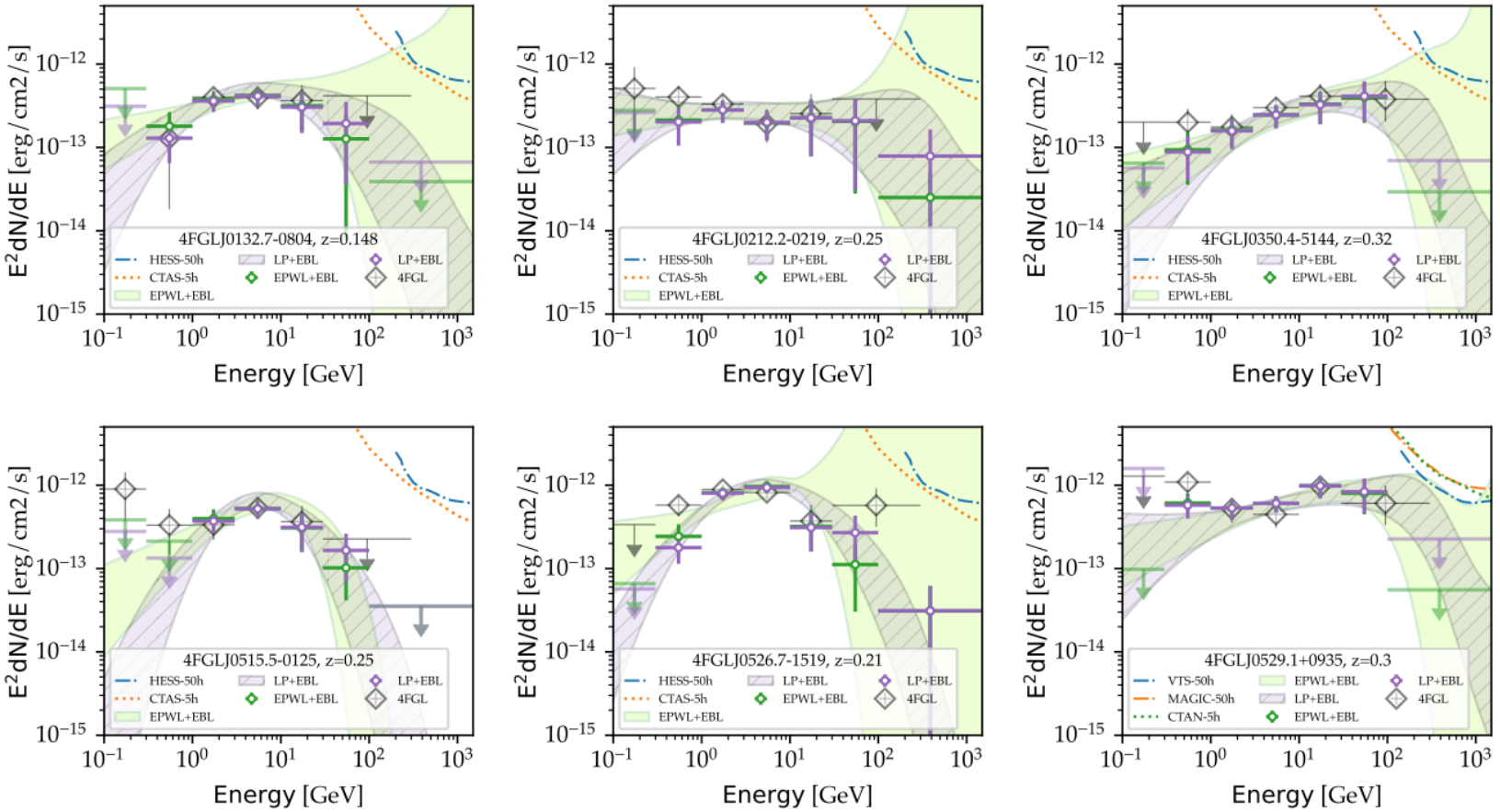
Aharonian et al. 2009

Blazars variability



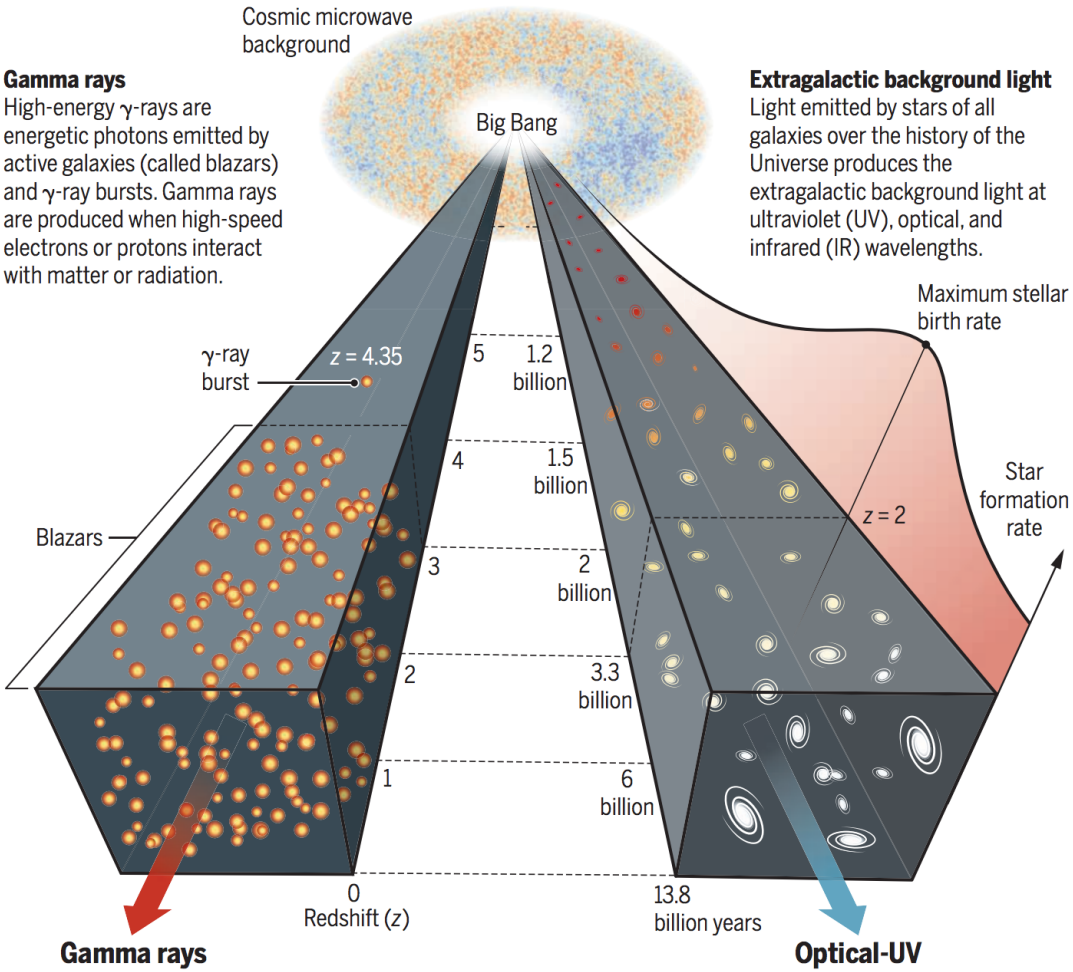
Adams et al 2022

EHBL blazars



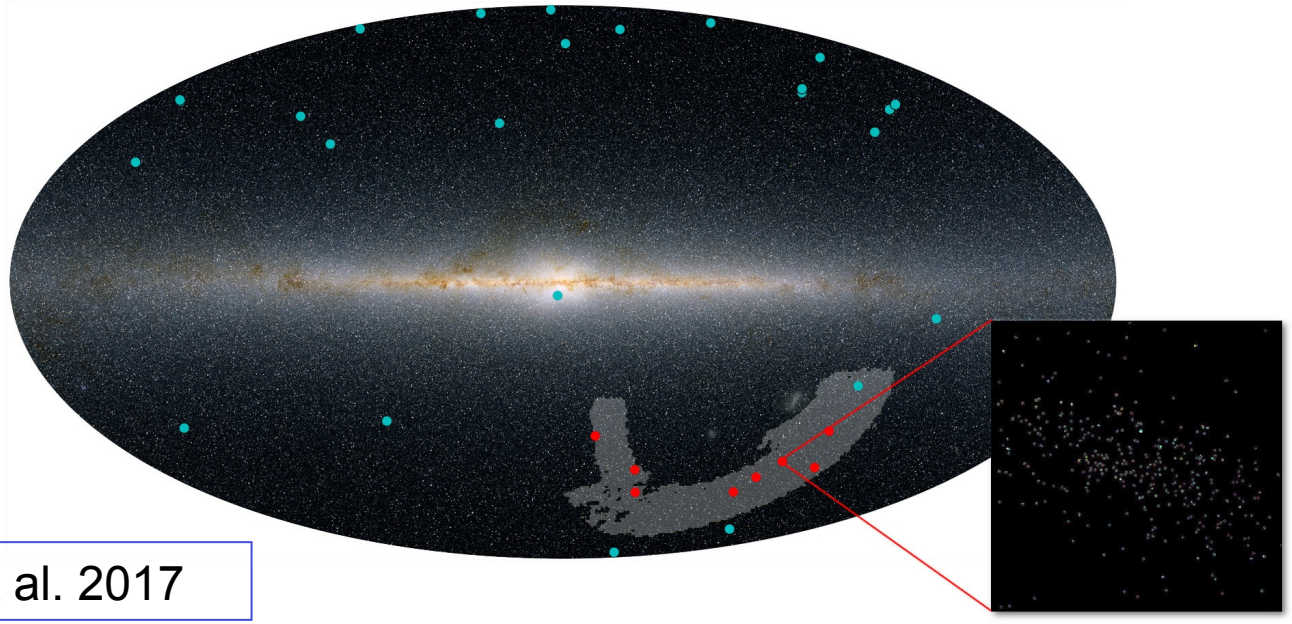
Nievas Rosillo, M. et al. 2022

The EBL

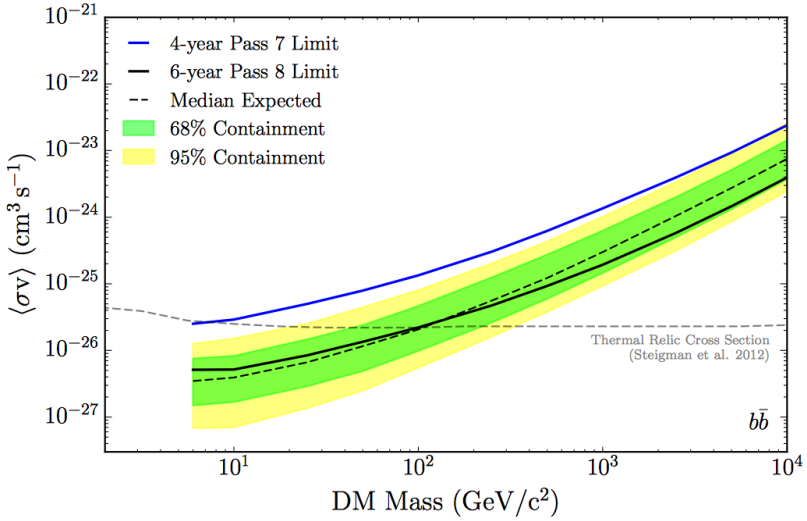


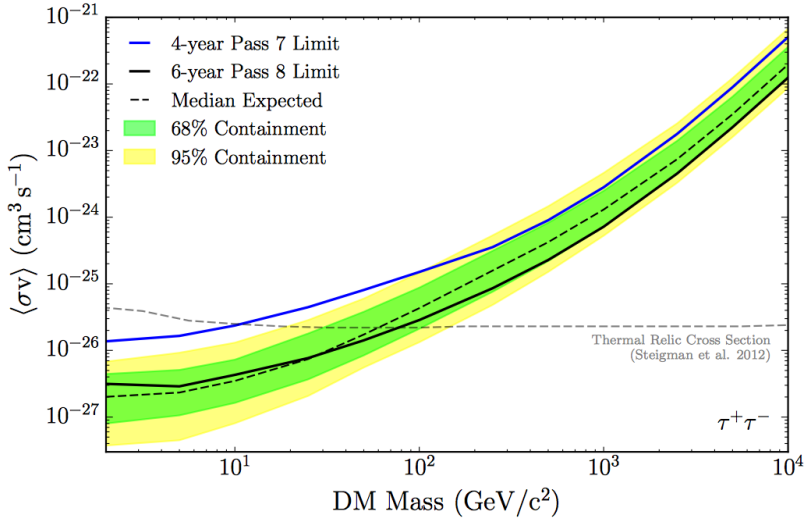
Abdhollai et al 2018

Dwarfs Galaxies – DM



Albert, A. et al. 2017



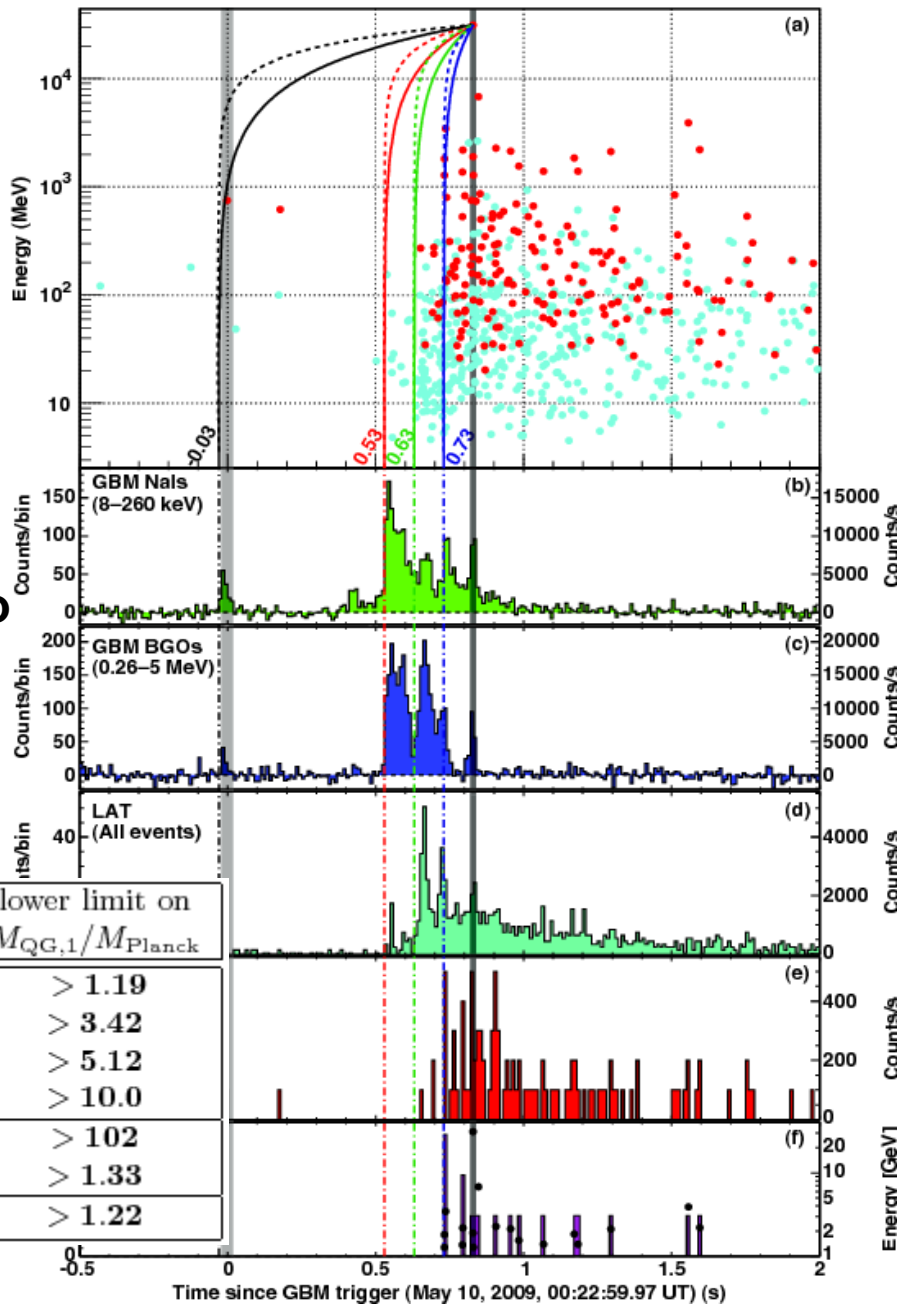


LIV with GRBs

- A short bright burst with
  - A 31 GeV photon associated
  - redshift determination (z~0.9)
- allows to set stringent lower limits on LIV effect in photon time arrival.

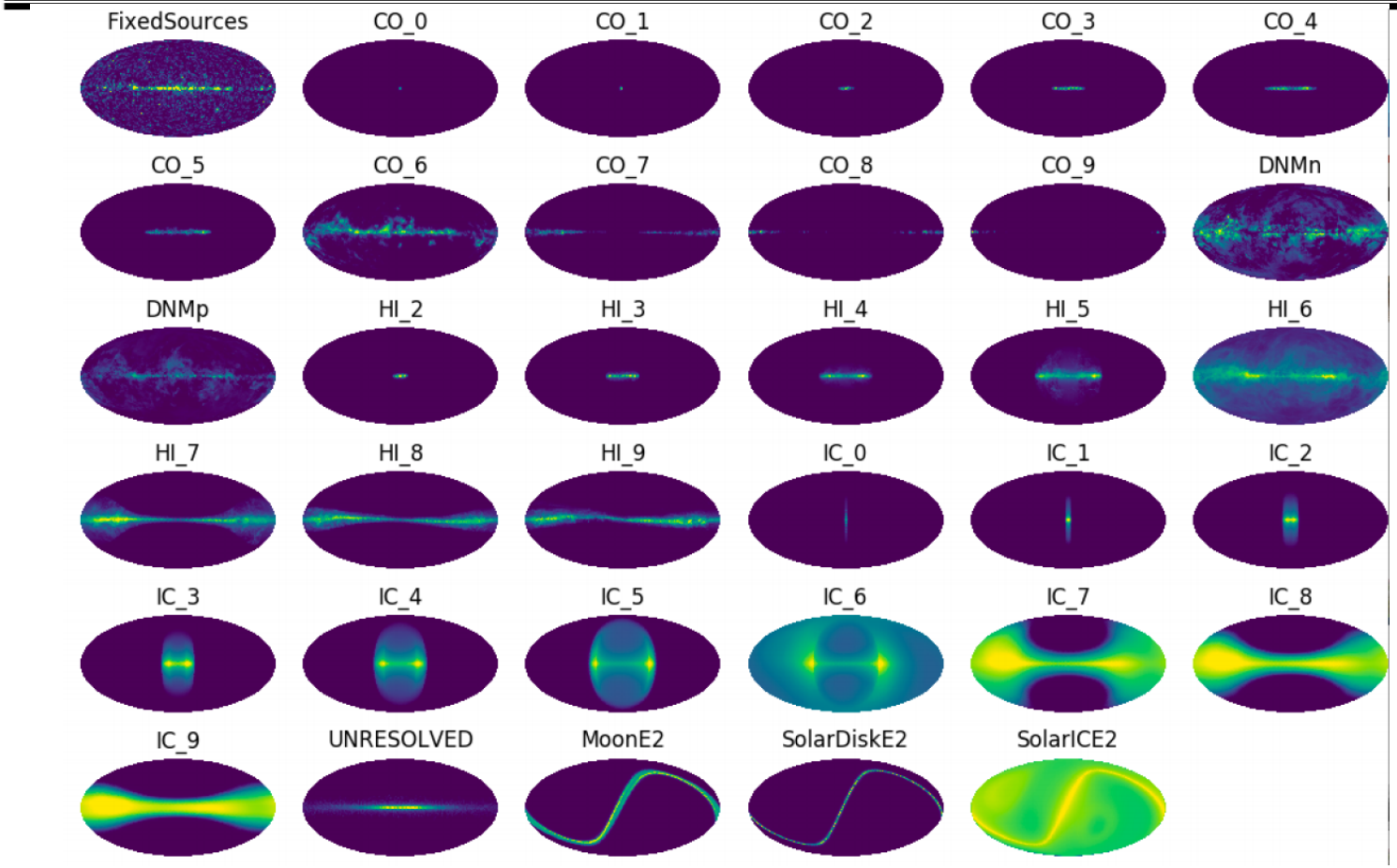
$$M_{QG} > 1.19 \times M_{Plank}$$

- If $M_{QG} \sim M_{Planck}$ is expected, *Fermi* starts to disfavor linear effect
- Abdo et al., Nature, 462, 331



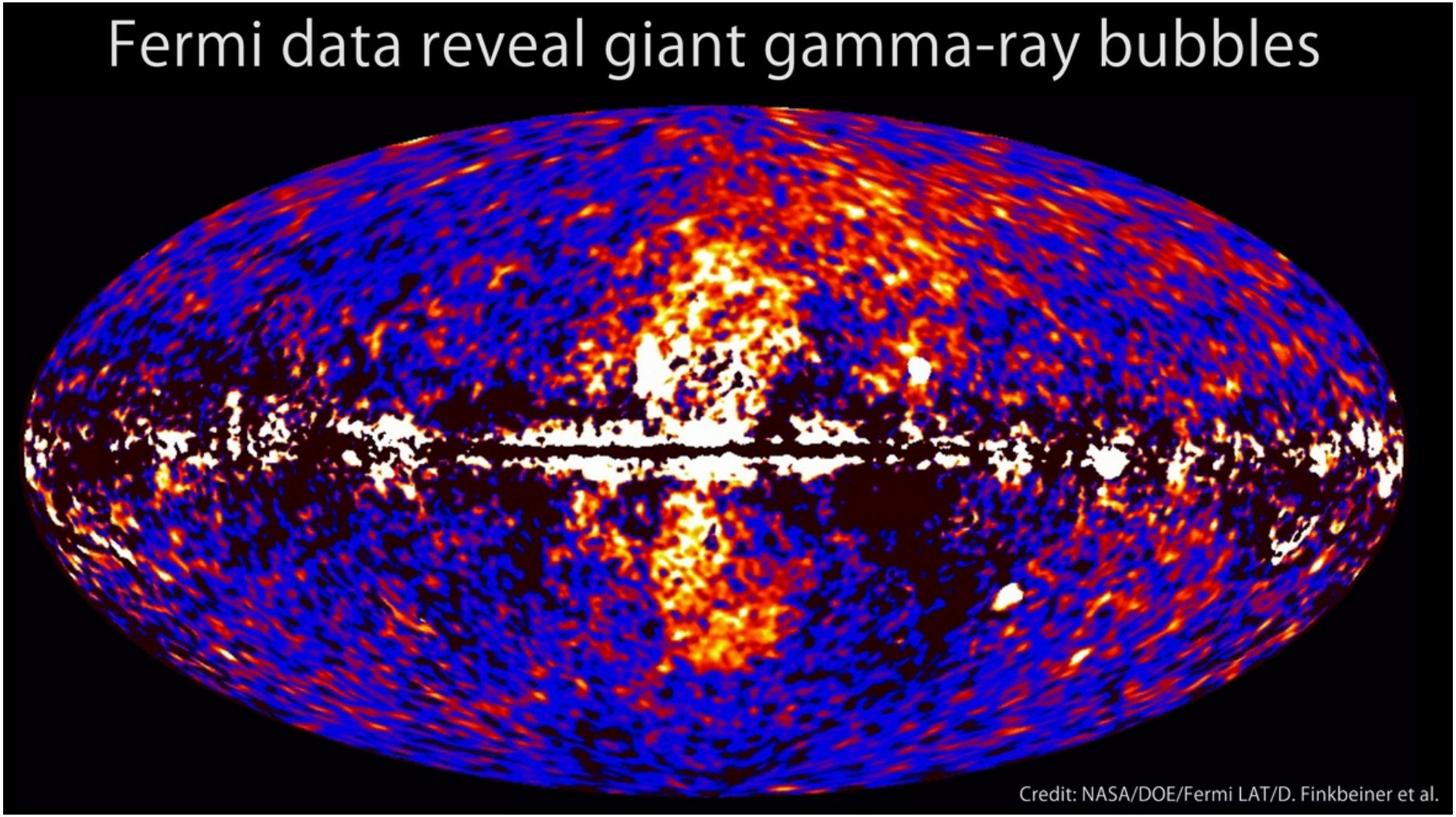
t_{start} (ms)	limit on $\lvert\Delta t\rvert$ (ms)	Reason for choice of t_{start} or limit on Δt	E_l (MeV)	valid for s_n	lower limit on $M_{QG,1}/M_{Planck}$
-30	< 859	start of any observed emission	0.1	1	> 1.19
530	< 299	start of main < 1 MeV emission	0.1	1	> 3.42
630	< 199	start of > 100 MeV emission	100	1	> 5.12
730	< 99	start of > 1 GeV emission	1000	1	> 10.0
—	< 10	association with < 1 MeV spike	0.1	± 1	> 102
—	< 19	if 0.75 GeV γ is from 1st spike	0.1	± 1	> 1.33
$\lvert\frac{\Delta t}{\Delta E}\rvert < 30$ $\frac{ms}{GeV}$		lag analysis of all LAT events	—	± 1	> 1.22

Diffuse emission modeling



https://fermi.gsfc.nasa.gov/ssc/data/analysis/software/aux/4fgl/Galactic_Diffuse_Emission_Model_for_the_4FGL_Catalog_Analysis.pdf

The Fermi Bubbles

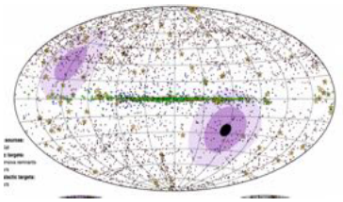


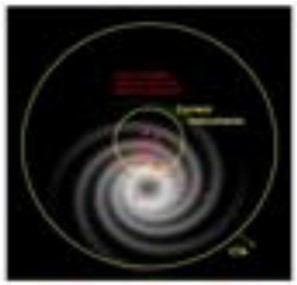
Su, M. et al. 2010

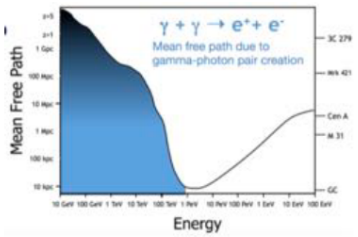
Outline

- The Fermi/LAT telescope
  - A brief history …
- A few key decisions
  - Data processing
  - Data dissemination
  - The Fermi publication policy
- VHE results by Fermi important for CTAO
  - Galactic Science
  - Extragalactic Science
  - Fundamental Physics
  - Diffuse emission
- Challenges and prospects for CTAO

Design drivers

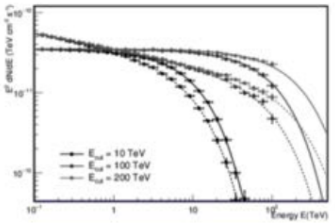






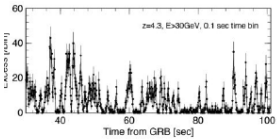
Full sky coverage

10 x sensitivity



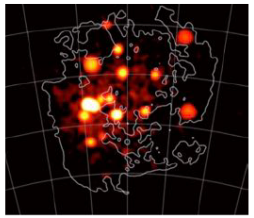
Energies down to 20 GeV

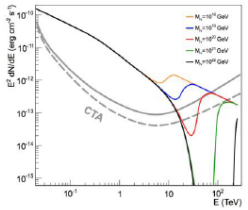
Energies up to 300 TeV



Rapid slewing 20 sec

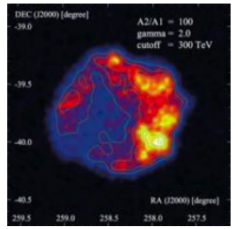
~ 10◦ FoV





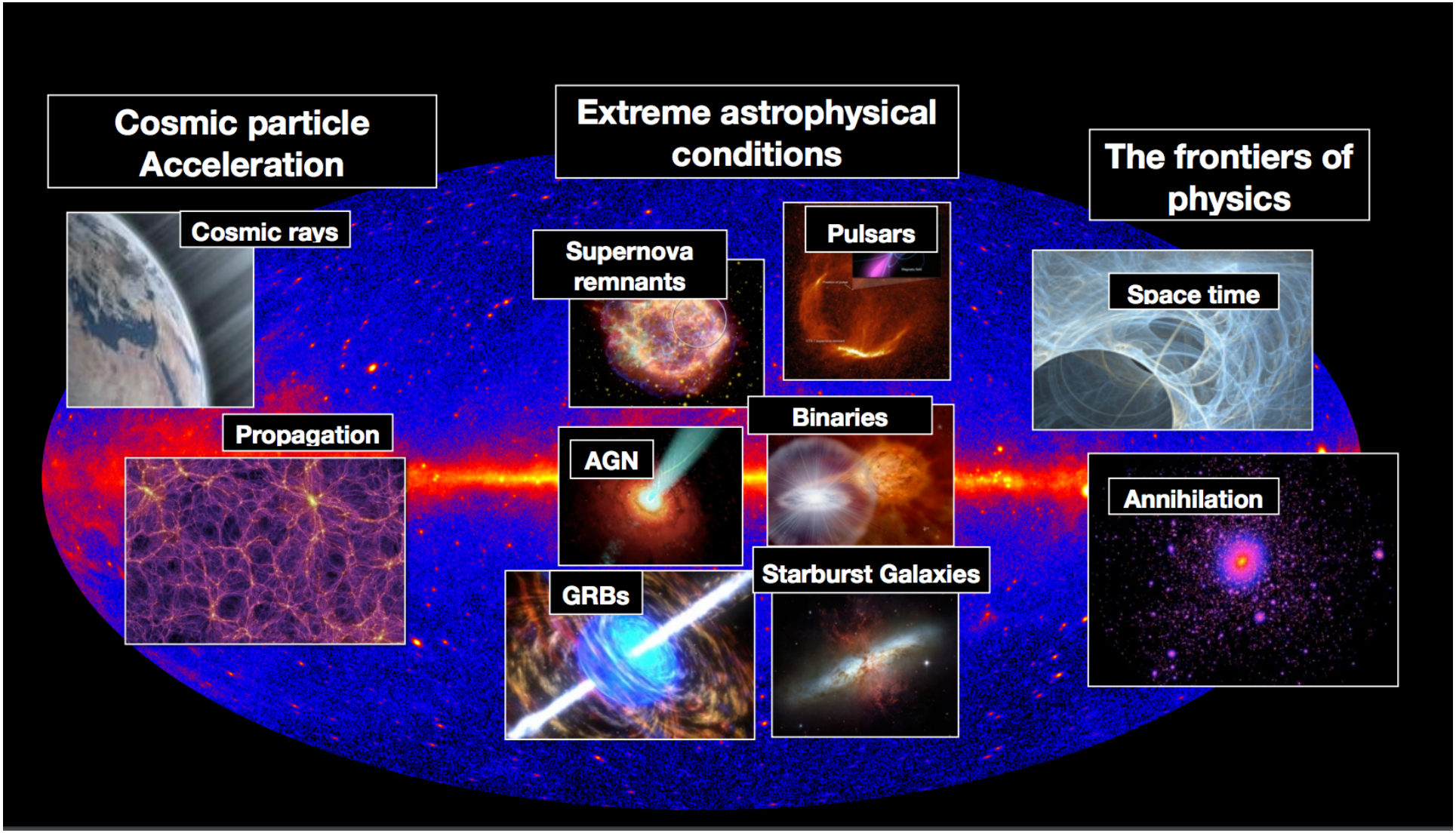
10% energy resolution

arcmin angular resolution

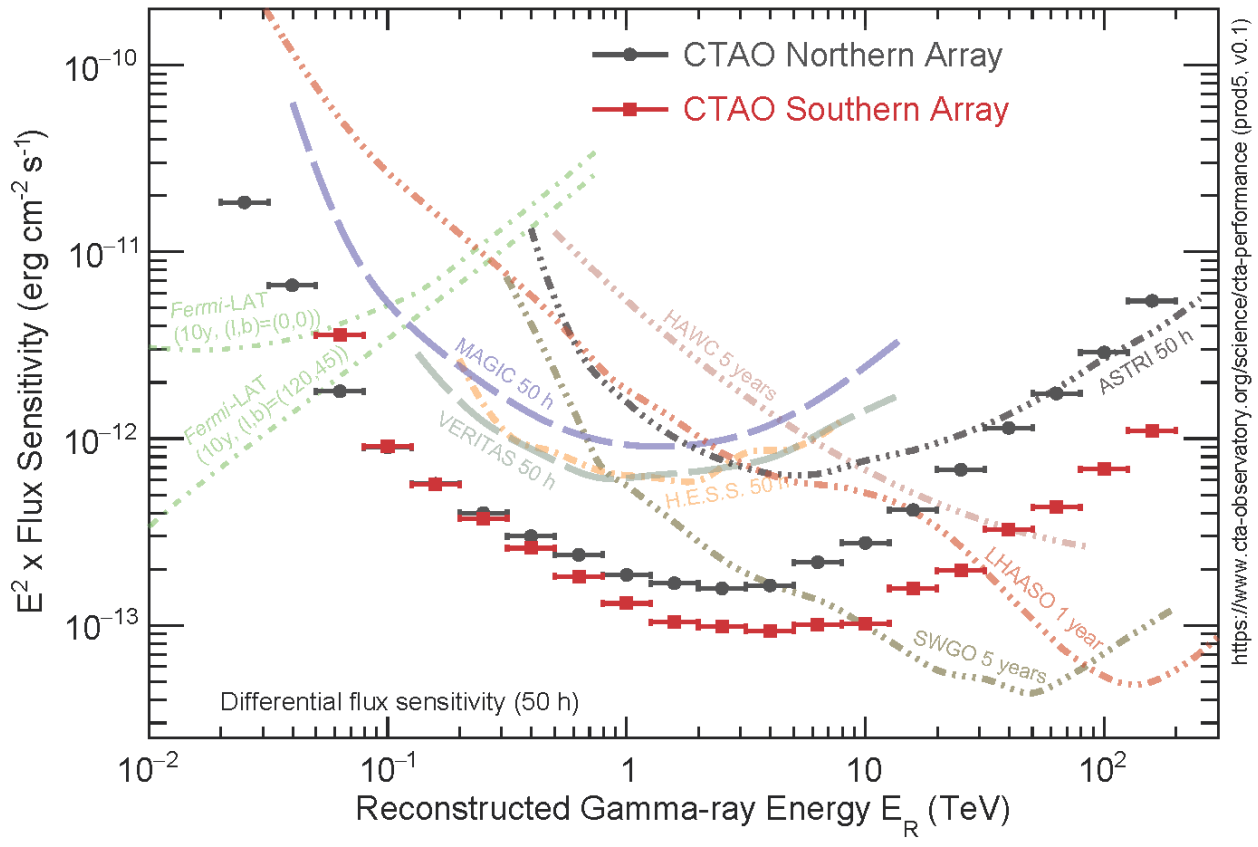


R.Zanin – TeVPa 2019

Astrophysics with CTAO



CTAO performance



https://www.ctao.org/for-scientists/performance/

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Science with CTA

CTA will have important synergies with many of the new generation of major astronomical and astroparticle observatories. Multi-wavelength and multi-messenger approaches combining CTA data with those from other instruments will lead to a deeper understanding of the broad-band non-thermal properties of target sources, elucidating the nature, environment, and distance of gamma-ray emitters. Details of synergies in each waveband are presented.

https://arxiv.org/abs/1709.07997

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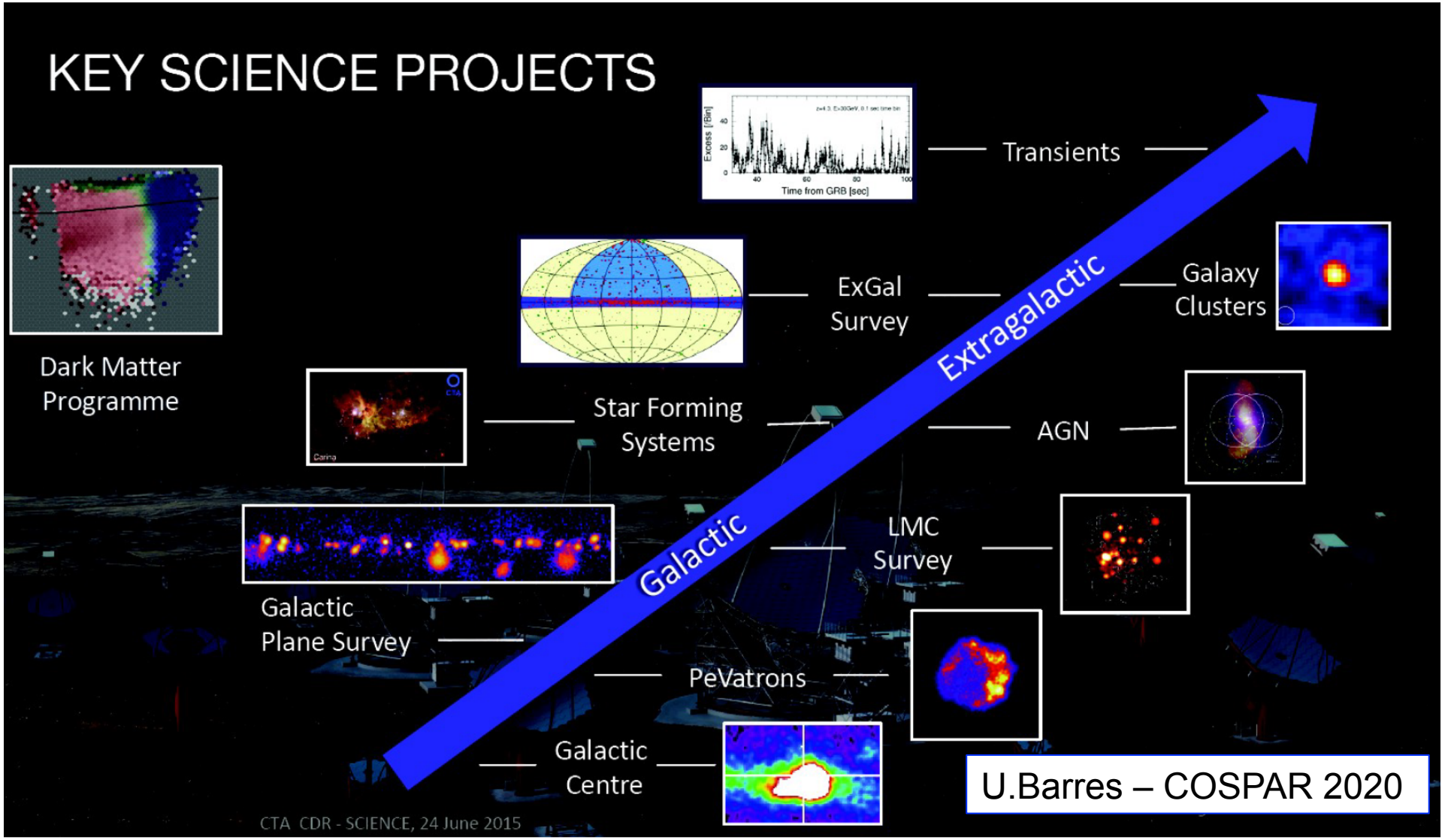
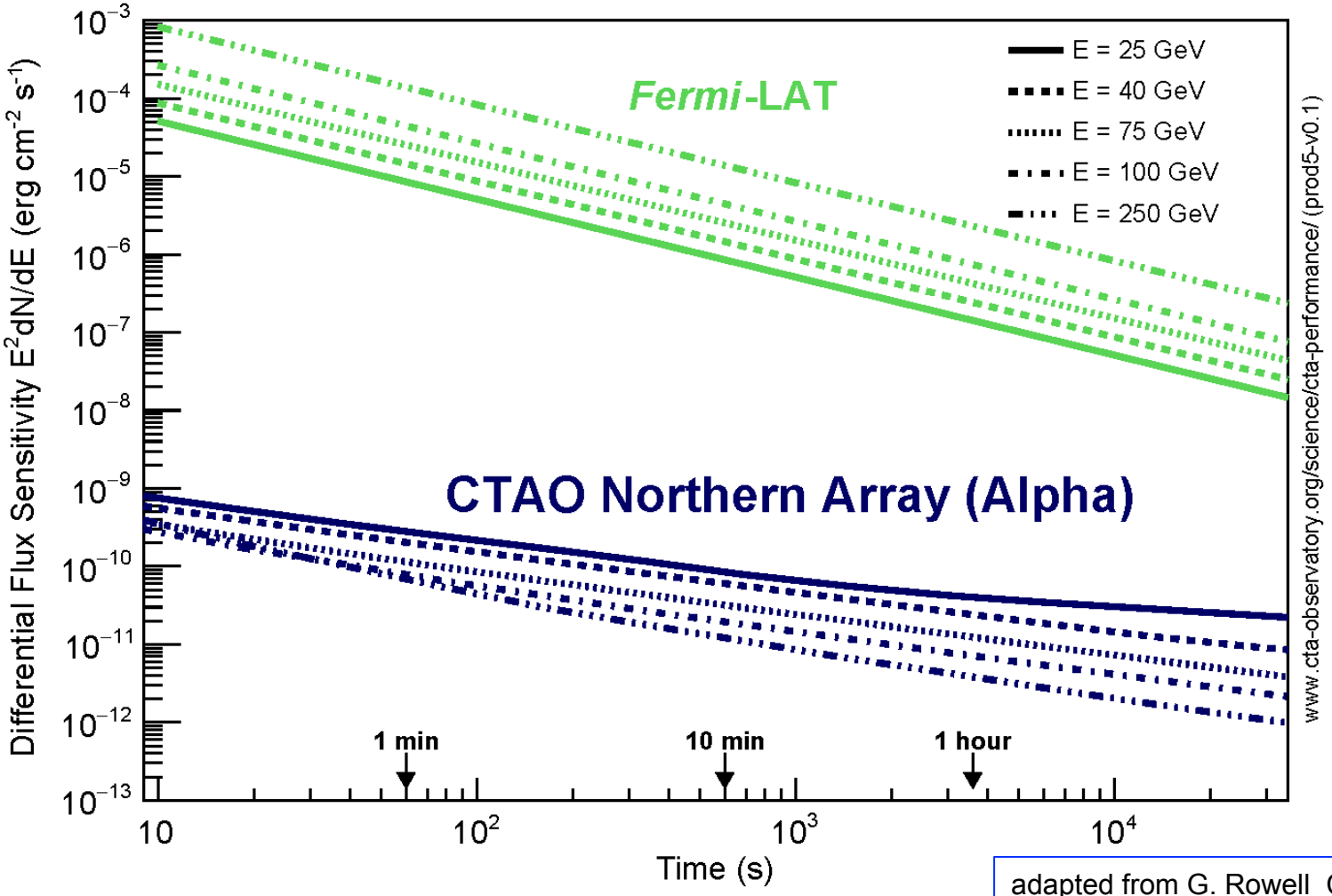
A Census of particle accelerators across all cosmic scales



Transients & Variable Sources: CTA Sensitivity vs. Time

(CTA Collab 2019)

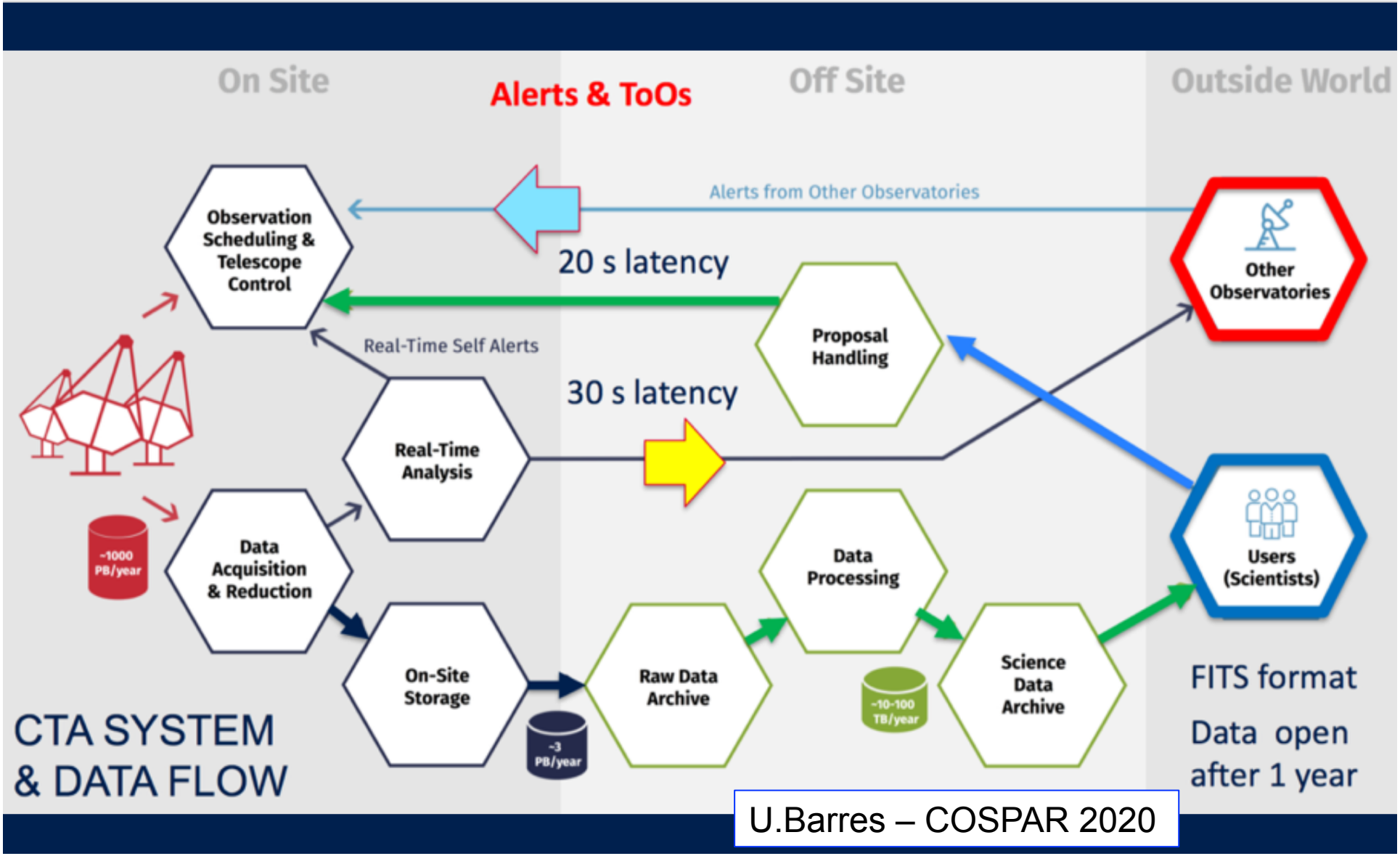


adapted from G. Rowell COSPAR2020

CTA >10,000 times more sensitive than Fermi-LAT in multi-GeV range

→ GRBs, AGN, giant pulses, FRBs, GW, SGR bursts.....

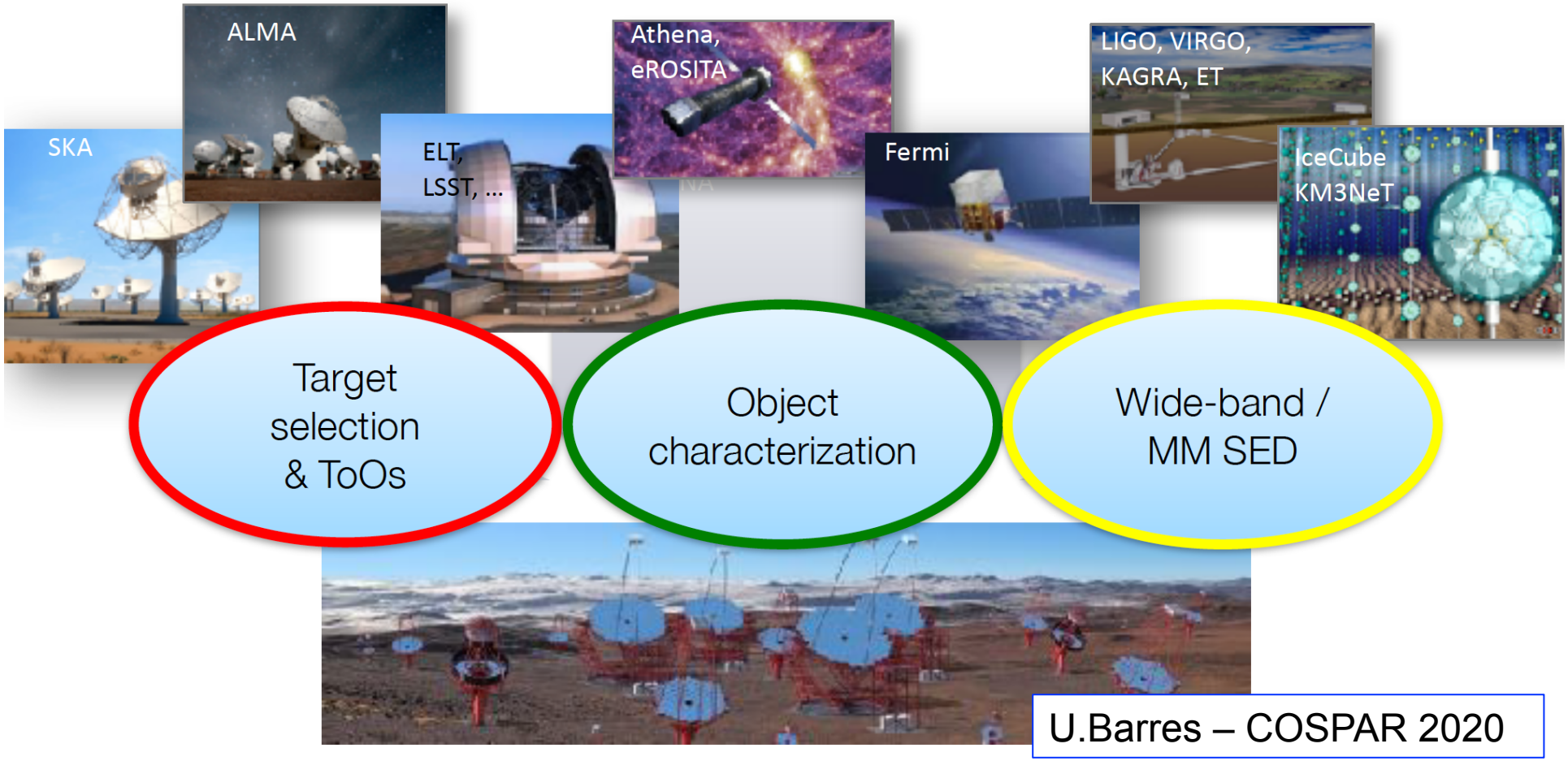
CTA Transients Science



U.Barres – COSPAR 2020

MWL and Multi-Messenger Perspectives

Synergies with astrophysical facilities…



U.Barres – COSPAR 2020

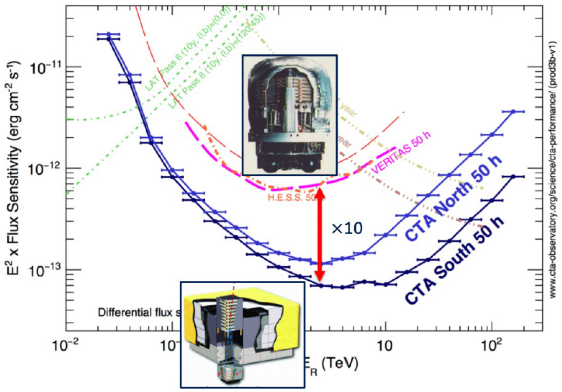
Toward CTAO

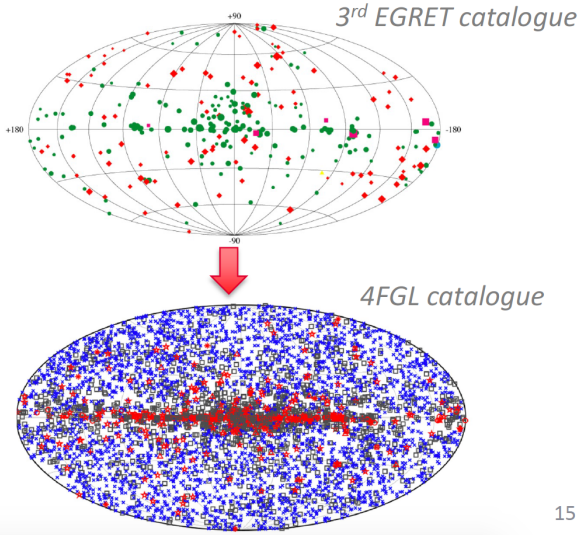
https://www.ctao.org

Take away messages …

Conclusions

- CTAO will be the first gamma-ray ground-based observatory, openly delivering data to the community
- CTAO will usher in a new era in VHE Astrophysics
  - Rich science program answering many open questions
  - Large new discovery space





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adapted from R. Zanin – EAS 2022

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