16 years of Gamma Ray Discoveries with Fermi

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on behalf of the Fermi LAT & GBM collaborations

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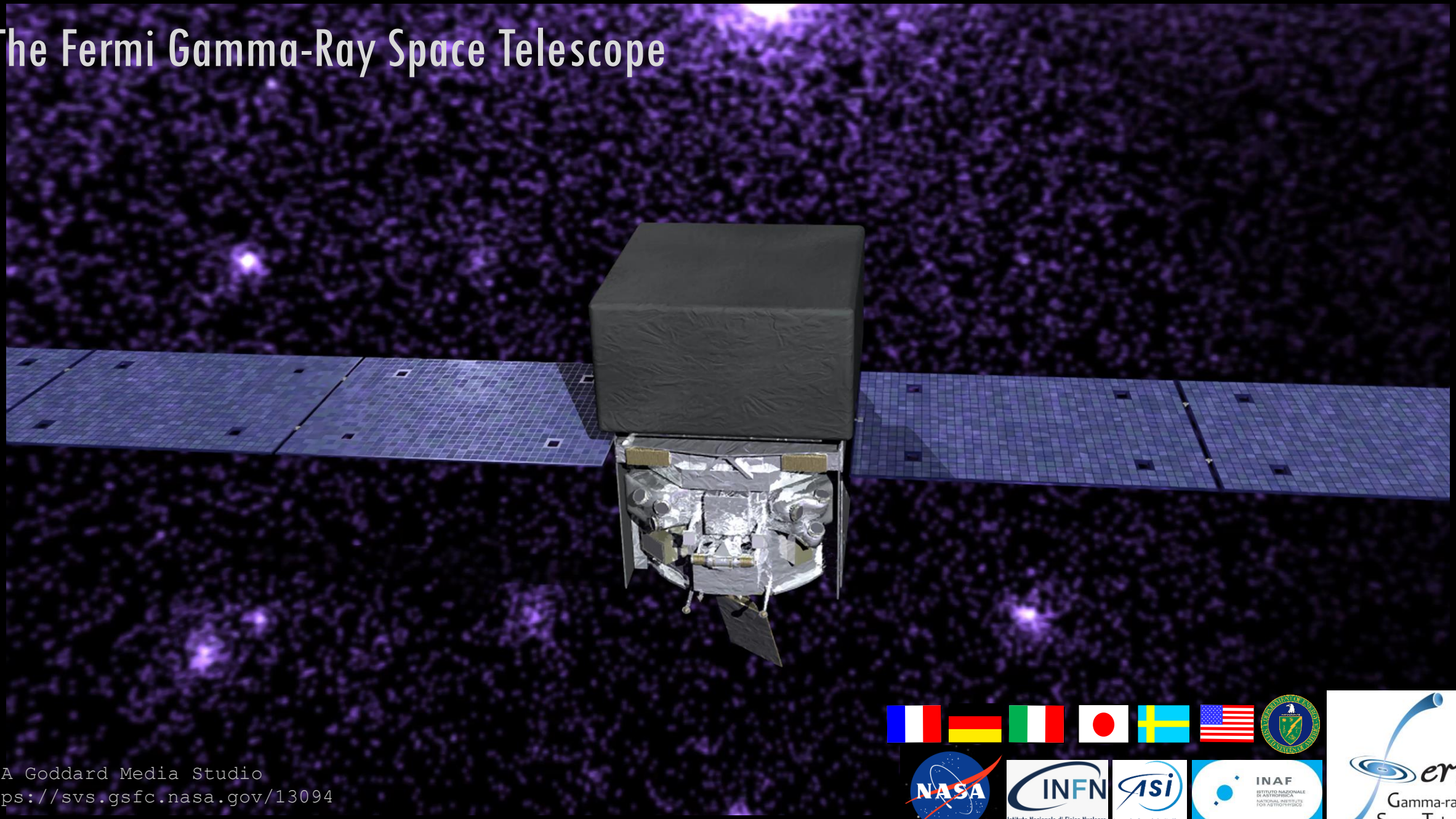
Member of the Fermi GBM and LAT Collaborations
Member of the CTAO Consortium
Affiliate member of the H.E.S.S. Collaboration

The Fermi Gamma-Ray Space Telescope



NASA Goddard Media Studio
https://svs.gsfc.nasa.gov/13094

Credit: NASA's Goddard Space Flight Center/CI Lab

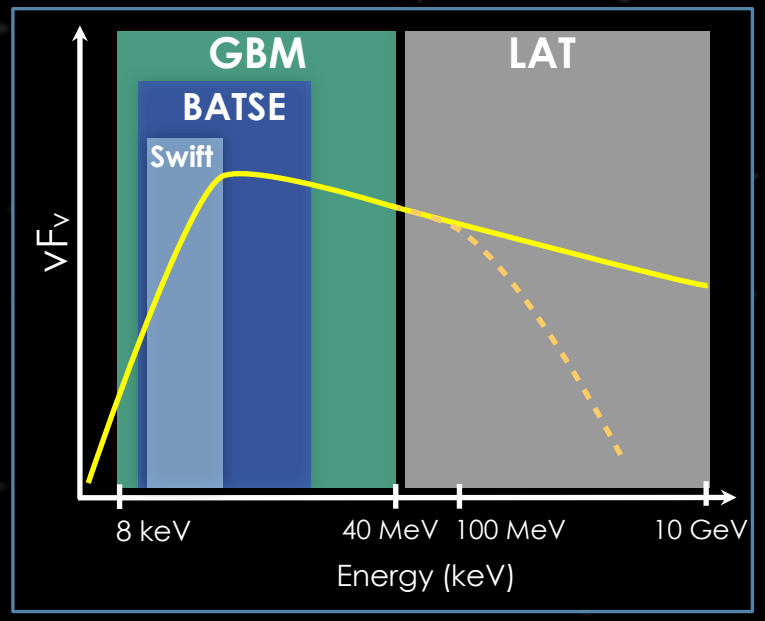
The Fermi Gamma-Ray Space Telescope

Launched on June 11, 2008

Key features
huge **FoV**
&
large **energy range**

Large Area Telescope (LAT)

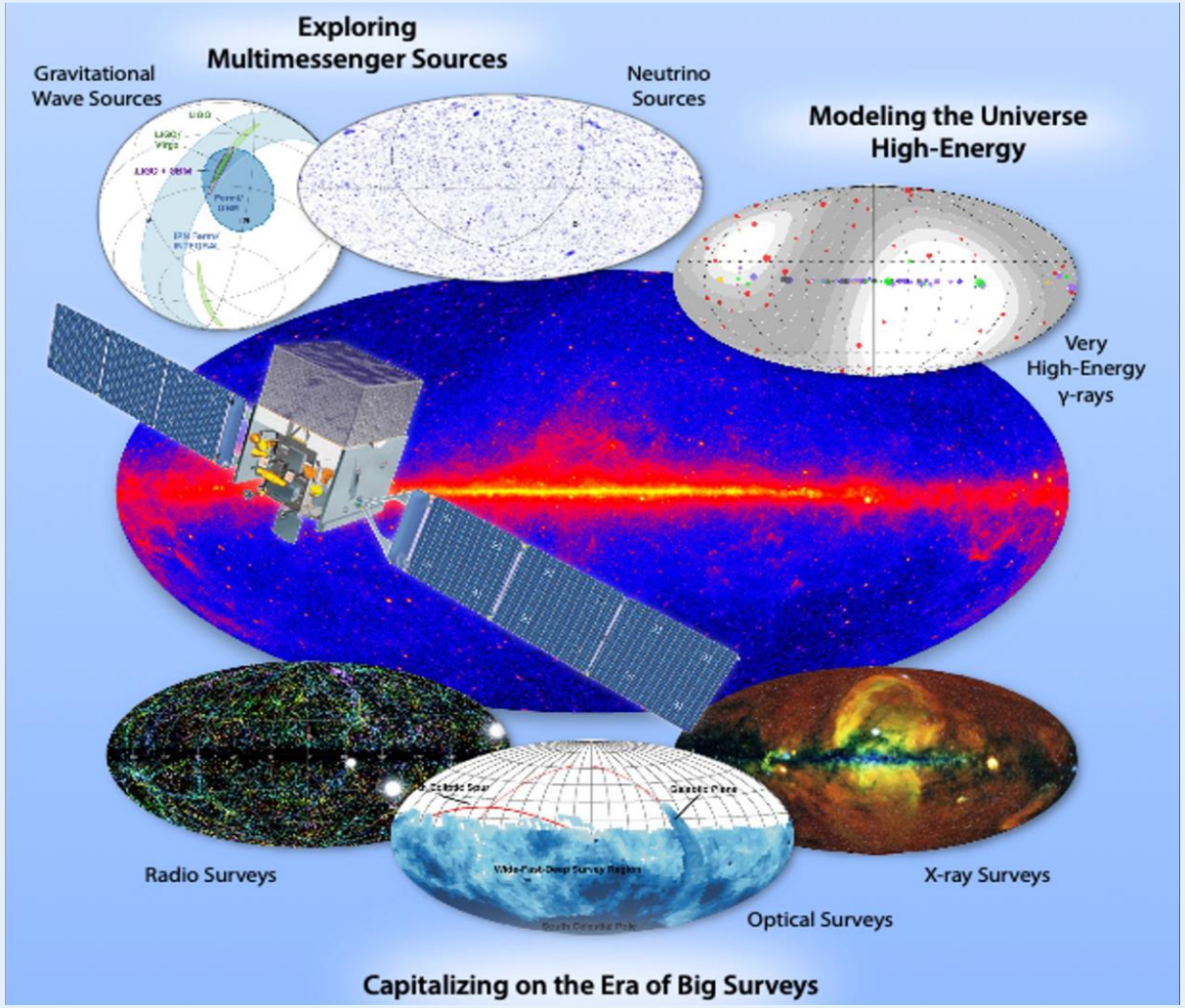
Pair conversion telescope
20 MeV → 300 GeV



Gamma-ray Burst Monitor (GBM)

14 Scintillator detectors (12 NaIs, 2 BGOs)
8 keV – 40 MeV

Fermi mission status and prospects



- *Spacecraft and instrument performance is excellent at 16 years*
  - *2 maneuvers (2013 and 2024) to avoid close approaches to other spacecrafts*
- Last NASA Senior Review (SR) in 2022
  - Fermi recommended for continuation for 3 years until next SR in 2025
    - *"Fermi provides unique access to the gamma-ray portion of the electromagnetic spectrum and the largest simultaneous field-of-view of any space telescope.*
      Its data give us a time-domain view of the entire gamma-ray sky and are a crucial asset for gravitational-wave and multi-messenger astrophysics."
- *Lifetime of orbit extends into the mid-2030s*

National Aeronautics and Space Administration

FERMI'S GAMMA-RAY COSMOS

Fermi Six-year Sky Map

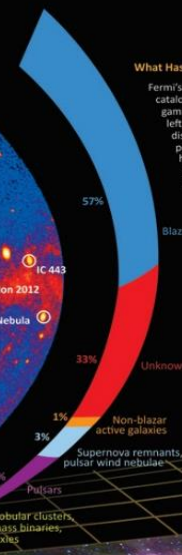
This all-sky view, centered on our Milky Way Galaxy, is the deepest and best-resolved portrait of the gamma-ray sky to date. It incorporates observations by NASA's Fermi Gamma-ray Space Telescope from August 2008 to August 2014 at energies greater than 1 billion electron volts (GeV). For comparison, the energy of visible light falls between 2 and 3 electron volts. Lighter shades indicate stronger emission.
NASA/DOE/Fermi LAT Collaboration

The gamma-ray sky isn't dark even far away from bright sources. Some of this radiation arises close to home, when high-velocity protons (cosmic rays) interact with interstellar gas and starlight. Much of the emission originates far beyond our galaxy and is thought to be the collective glow of sources too faint to detect directly.

GRB 130427A
PSR J1311–3430
Cygnus X
IC 443
Nova Mon 2012
NGC 6624
Crab Nebula
B0218+357
LMC
3C454.3

What Has Fermi Found?

Fermi's Large Area Telescope (LAT) has cataloged more than 3,000 discrete gamma-ray sources. The graph at left shows a breakdown of these discoveries. Blazars – active galaxies powered by supermassive black holes – constitute the single largest class. Nearly a third of sources are unassociated with objects seen at any other wavelength, and their natures remain unknown.



B0218+357

The gravity of a faint foreground galaxy causes light from the distant blazar B0218+357 to take different paths and form dual images (bright spots in this Hubble photo). The paths have different lengths, so when one image has a flare, it will appear in the other after a delay. Fermi detected delays of nearly 12 days in B0218, providing the first gamma-ray measurements of a gravitational lens.
NASA/ESA and the Hubble Legacy Archive

Cygnus X

Monster stars in a region called Cygnus X carve out cavities in the interstellar gas. The stars' powerful outflows collide, forming shock waves that can accelerate protons to high energies. These particles eventually strike gas or starlight, producing gamma rays. *NASA/DOE/Fermi LAT Collaboration and NASA/IPAC/MSX*

Ursa Major
Leo

GRB 130427A

On April 27, 2013, a blast of light from a dying star in a distant galaxy became the focus of astronomers around the world. The explosion, known as a gamma-ray burst and designated GRB 130427A, was detected by Fermi for about 20 hours. The burst included a 95 GeV gamma ray, the most energetic light yet detected from a GRB.
NASA/DOE/Fermi LAT Collaboration

NGC 6624

Fermi found the youngest millisecond pulsar yet known, in the globular star cluster NGC 6624. Spinning 11,000 times a minute, pulsar J1823–3021A is 25 million years old, less than 3 percent the typical age.
NASA/DOE/Fermi LAT Collaboration

Pulsar off
Pulsar on

PSR J1311-3430

Gamma-ray pulsar J1311-3430 heats the facing side of its companion star and is slowly evaporating it, as shown in this artist's rendering. The material often blocks the pulsar's radio beam.
NASA's Goddard Space Flight Center/Cruz deWilde

Nova Mon 2012

Fermi observations prove that stellar outbursts called novae emit gamma rays. Novae typically occur when a white dwarf in a binary system with a sun-like star erupts as shown in this artist's rendering of Nova Monocerotis in 2012. Gamma rays likely arise from colliding shock waves in the rapidly expanding debris.
NASA's Goddard Space Flight Center/S. Wiessinger

IC443, the Jellyfish Nebula

The shock waves of supernova remnants like the Jellyfish Nebula can accelerate protons to near the speed of light. When they slam into nearby gas clouds, gamma rays are produced. Fermi detects this emission, confirming that supernova remnants accelerate high-energy cosmic rays. *NASA/DOE/Fermi LAT Collaboration; NOAO/AURA/NSF; JPL-Caltech/UCLA*

3C 454.3

In December 2009, 3C 454.3 was briefly the brightest object in the gamma-ray sky. The gamma rays come from a jet powered by matter falling toward the galaxy's supermassive black hole. In this case, we're looking almost right down the barrel of the jet, which means the blazar can be especially bright despite lying 7 billion light-years away. *NASA/DOE/Fermi LAT Collaboration*

3C 454.3

30 Doradus
LMC outline

LMC

Fermi sees gamma rays from star-forming regions like 30 Doradus in the Large Magellanic Cloud (LMC). More stars are forming in this "star factory" than in any similar location in the Milky Way, leading to intense gamma-ray emission.
NASA/DOE/Fermi LAT Collaboration

50,000 light-years
Galactic plane emission removed for clarity

Fermi Bubbles

Fermi data revealed vast gamma-ray bubbles extending tens of thousands of light-years from the Milky Way's plane. The Fermi Bubbles may be related to past activity of the supermassive black hole at our galaxy's heart. *NASA/DOE/Fermi LAT Collaboration*

Crab Nebula

The Crab Nebula, a young supernova remnant containing a pulsar, surprised Fermi astronomers with gamma-ray flares set off by the most energetic particles ever traced to a specific astronomical object. To account for the flares, scientists say electrons near the pulsar must be accelerated to energies a thousand trillion (10^{15}) times greater than visible light.
NASA/CXC/SAO/J. Hester et al.

Credit: NASA/Fermi/Sonoma State University/A. Simonnet

Fermi Gamma-ray Space Telescope

Transients Timescale Pipelines

Pipeline
Method
Timescale
Distribution
Status

LAT Transient Factory (LTF)
Likelihood Around GBM/BAT triggers
seconds to orbits
LAT Team - Results in GCNs
Triggered + Blind Search

***Fermi* All-sky Variability Analysis (FAVA)**
Aperture Photometry, 1 week
ATels, FAV catalogs

***Fermi* LAT Light Curve Repository**
Likelihood LAT Catalog Sources
3 days, Weekly

LAT Burst Advocate Tool
Likelihood Around GBM/BAT triggers
100 s, 1000 s
LAT Team - Results in GCNs

***Fermi* LAT Monitored Sources**
Daily, Weekly above 10^{-6} cm^{-2}s^{-1}

GBM Targeted Search
ground search
ms - s
Temporal/Spatial Input

GBM Onboard Triggers
rate triggers
16 ms - minutes
GCN Notices

LAT Automated Science Processing (ASP) + Flare Advocates
Likelihood
6 & 24 hour
ATels, GCN notices (on AGN)

LAT Catalogs
Likelihood, associations
FGL, FHL, LAC, FLE, PSR

GBM Untargeted Search
ground search
ms - s
GCN Notices

μs ***ms*** ***s*** ***minutes*** ***hours*** ***days*** ***months*** ***years***

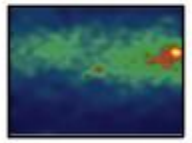
Photon Timing

All Sky Cadence

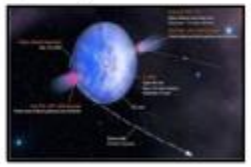
Pulsars

Solar Flares

Novae

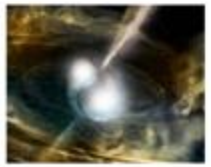


γ-ray Binaries



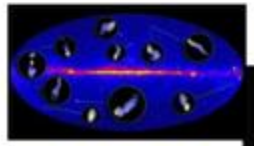
Terrestrial γ-ray Flashes

GRBs



Magnetar Flares

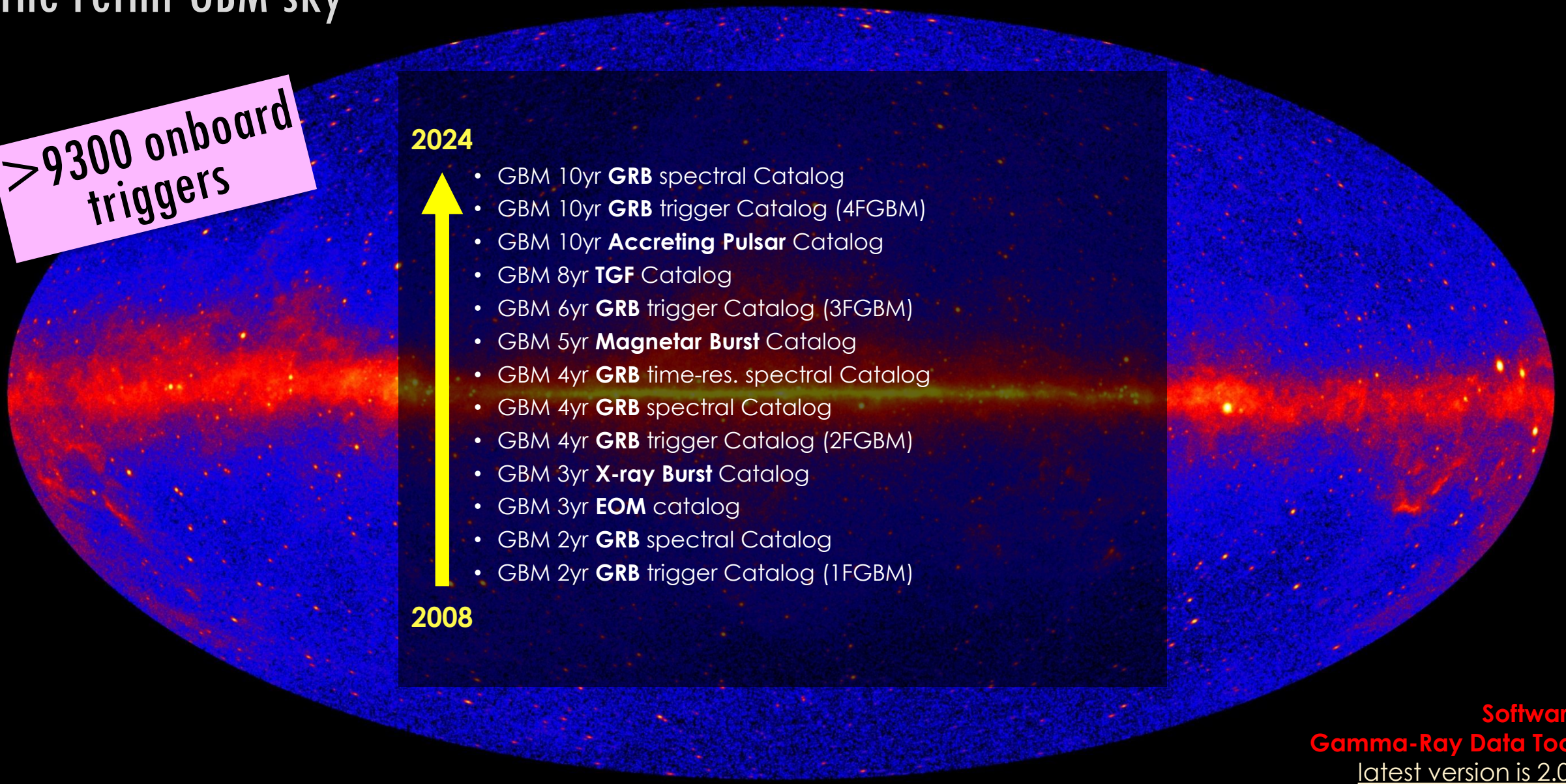
Blazar Flares



Crab Flares

Not to scale

The Fermi-GBM sky



>9300 onboard triggers

2024

- GBM 10yr **GRB** spectral Catalog
- GBM 10yr **GRB** trigger Catalog (4FGBM)
- GBM 10yr **Accreting Pulsar** Catalog
- GBM 8yr **TGF** Catalog
- GBM 6yr **GRB** trigger Catalog (3FGBM)
- GBM 5yr **Magnetar Burst** Catalog
- GBM 4yr **GRB** time-res. spectral Catalog
- GBM 4yr **GRB** spectral Catalog
- GBM 4yr **GRB** trigger Catalog (2FGBM)
- GBM 3yr **X-ray Burst** Catalog
- GBM 3yr **EOM** catalog
- GBM 2yr **GRB** spectral Catalog
- GBM 2yr **GRB** trigger Catalog (1FGBM)

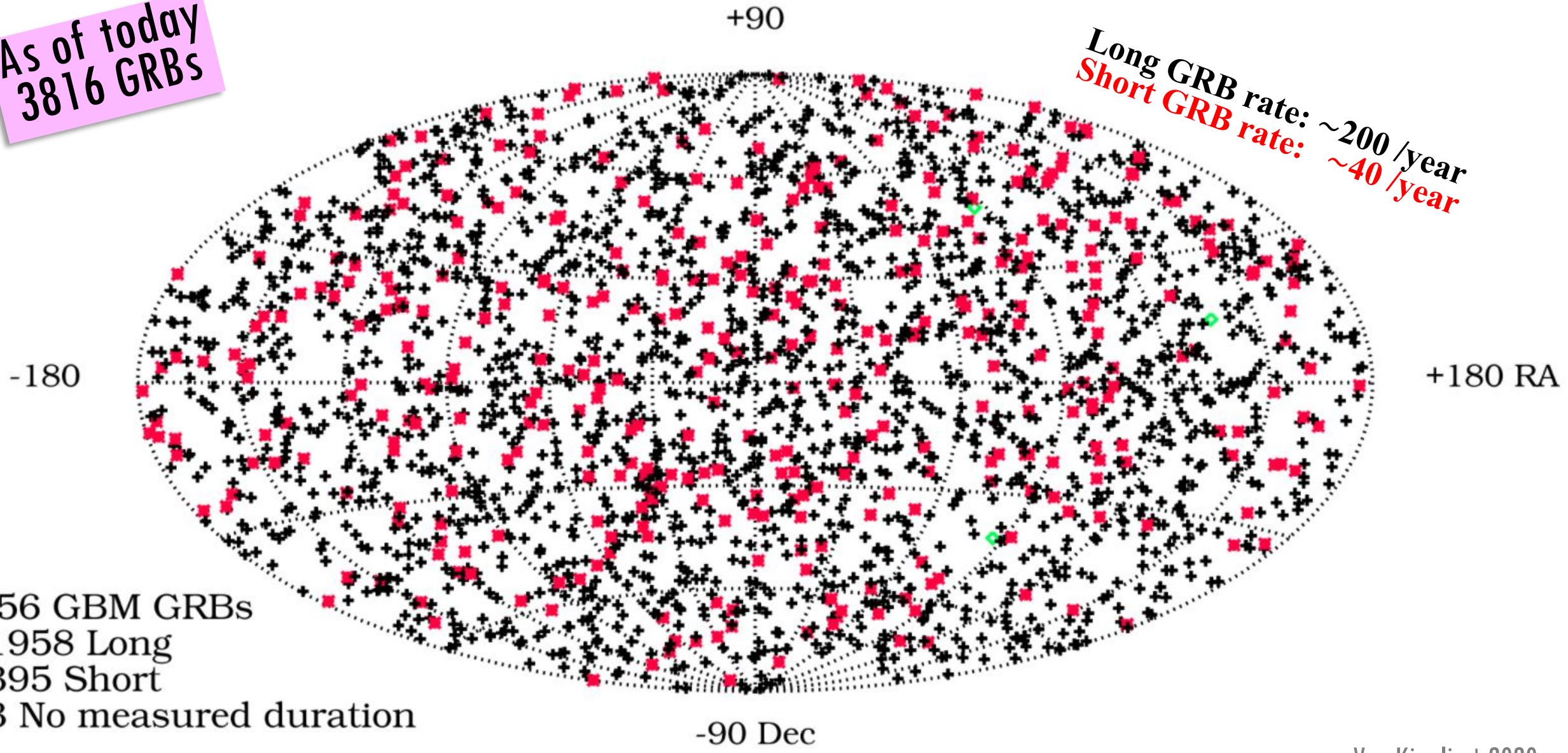
2008

Software:
Gamma-Ray Data Tools
latest version is 2.0.4

Credit: NASA/Fermi LAT Collaboration

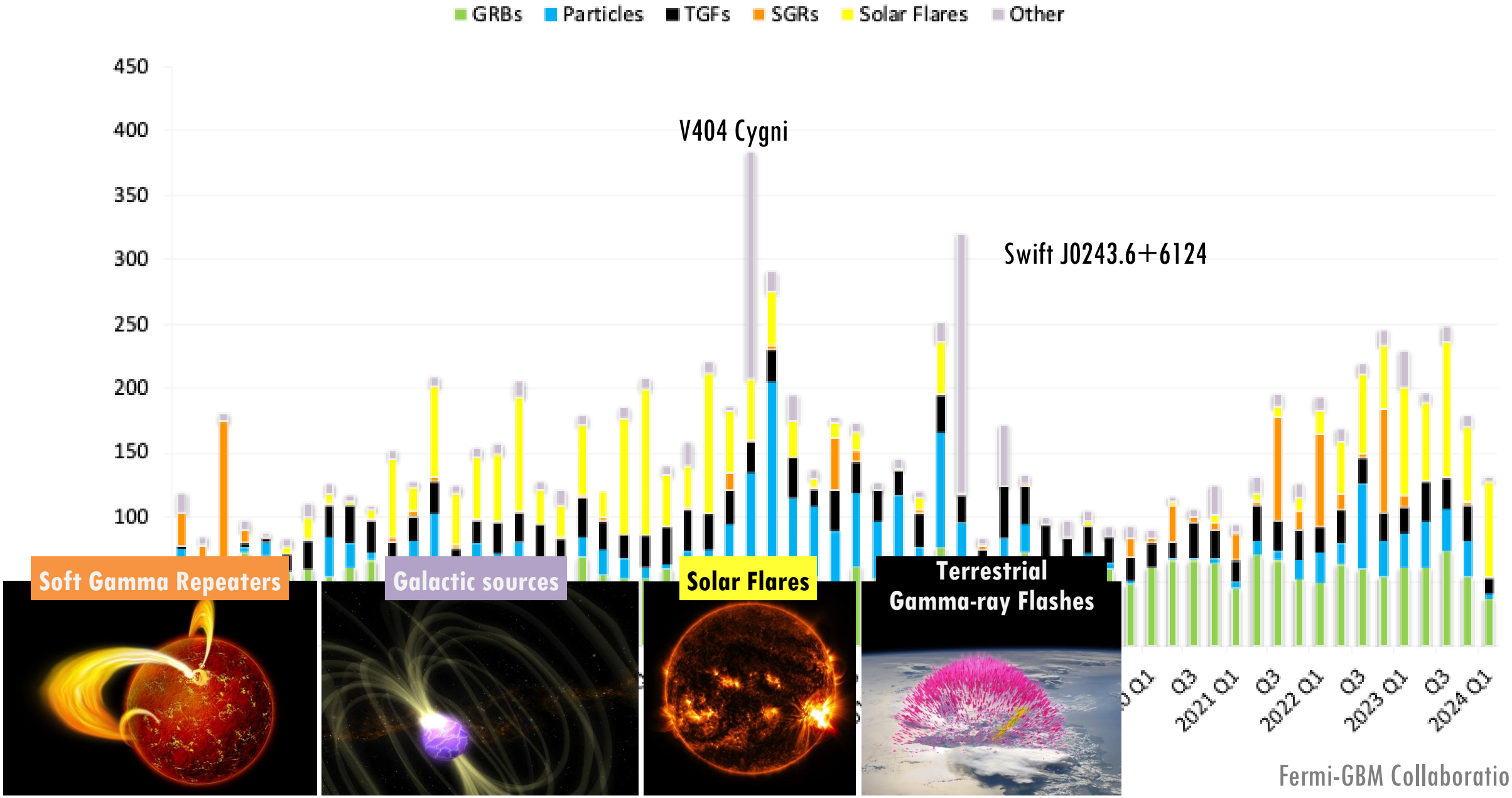
Fermi GBM GRBs in first ten years of operation

As of today
3816 GRBs



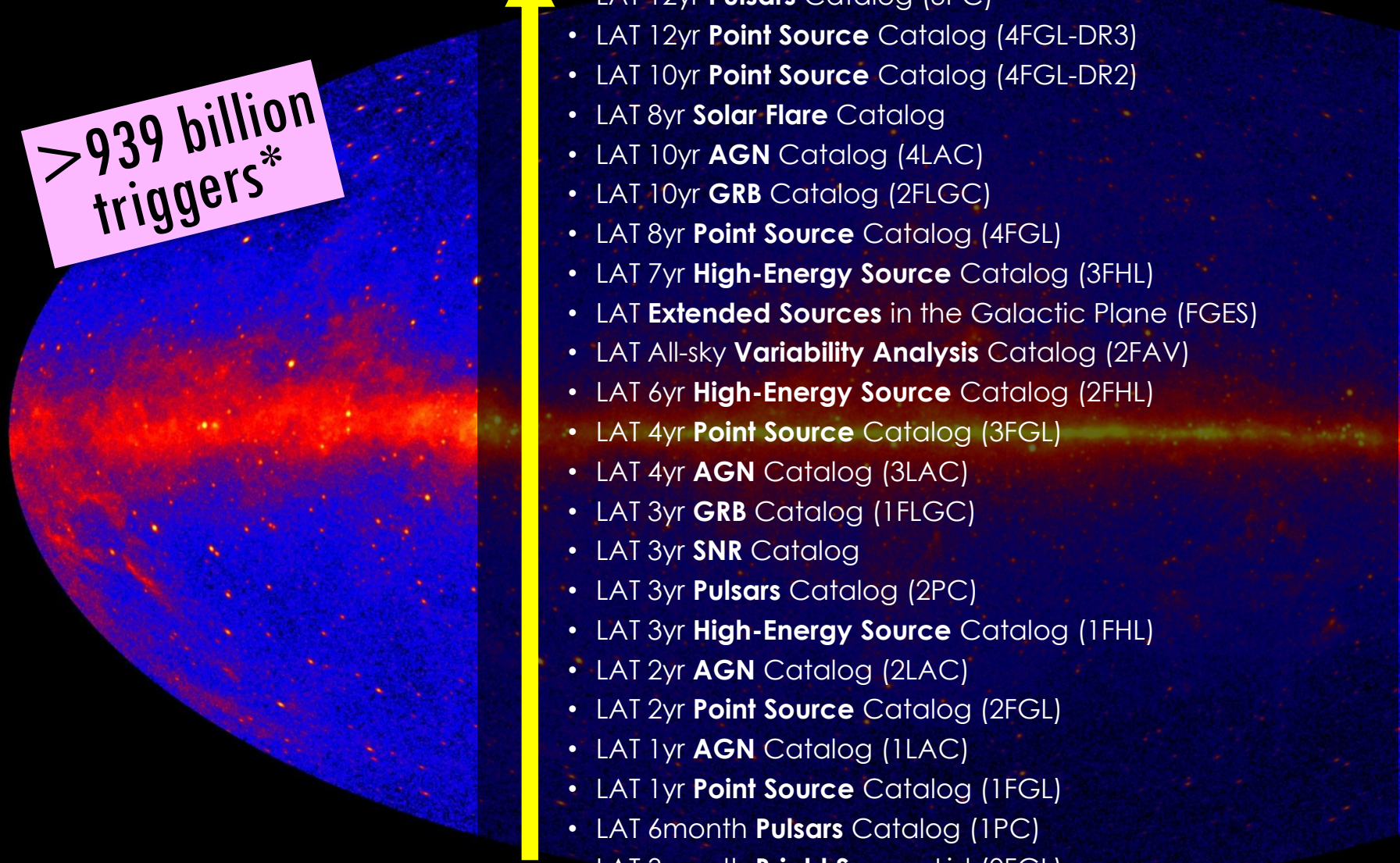
Von Kienlin+2020

Fermi-GBM trigger history



Fermi-GBM Collaboration 2024

The Fermi-LAT sky



>939 billion triggers*

2024

- LAT 14yr **Point Source** Catalog (4FGL-DR4) **(7194 sources)**
- LAT 12yr **Pulsars** Catalog (3PC)
- LAT 12yr **Point Source** Catalog (4FGL-DR3)
- LAT 10yr **Point Source** Catalog (4FGL-DR2)
- LAT 8yr **Solar Flare** Catalog
- LAT 10yr **AGN** Catalog (4LAC)
- LAT 10yr **GRB** Catalog (2FLGC)
- LAT 8yr **Point Source** Catalog (4FGL)
- LAT 7yr **High-Energy Source** Catalog (3FHL)
- LAT **Extended Sources** in the Galactic Plane (FGES)
- LAT All-sky **Variability Analysis** Catalog (2FAV)
- LAT 6yr **High-Energy Source** Catalog (2FHL)
- LAT 4yr **Point Source** Catalog (3FGL)
- LAT 4yr **AGN** Catalog (3LAC)
- LAT 3yr **GRB** Catalog (1FLGC)
- LAT 3yr **SNR** Catalog
- LAT 3yr **Pulsars** Catalog (2PC)
- LAT 3yr **High-Energy Source** Catalog (1FHL)
- LAT 2yr **AGN** Catalog (2LAC)
- LAT 2yr **Point Source** Catalog (2FGL)
- LAT 1yr **AGN** Catalog (1LAC)
- LAT 1yr **Point Source** Catalog (1FGL)
- LAT 6month **Pulsars** Catalog (1PC)
- LAT 3month **Bright Source** List (0FGL)

2008

0/1/2/3/4FGL:
full energy range
(50 MeV-1 TeV)
1/2/3FHL:
high-energy only (> 10/50 GeV)

Each generation uses
improved data/calibration:
P6 → P7 → P7Rep → P8

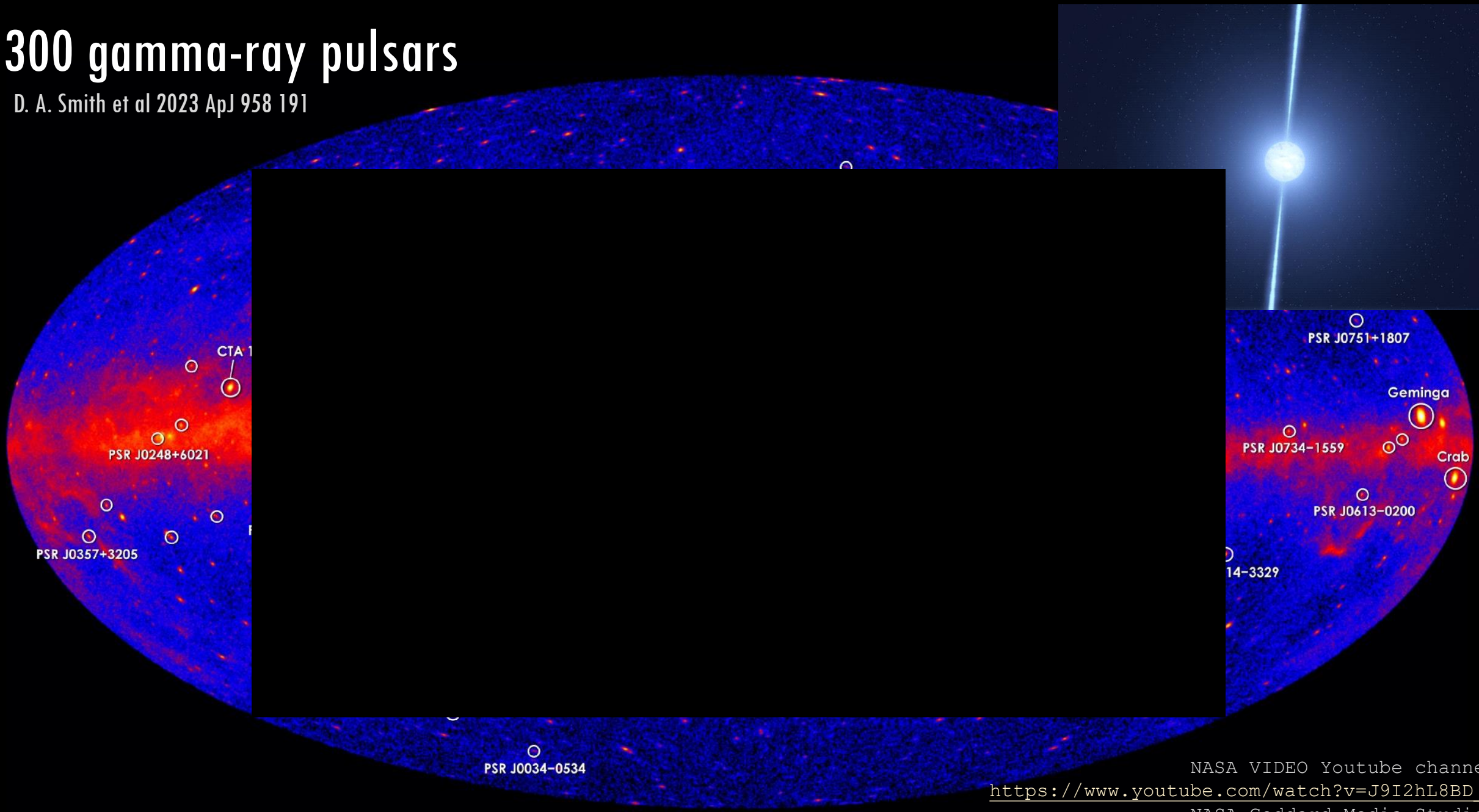
*4.53 billion LAT events
available at FSSC

Software: Fermitools
latest version is 2.2.0

Credit: NASA/Fermi LAT Collaboration

300 gamma-ray pulsars

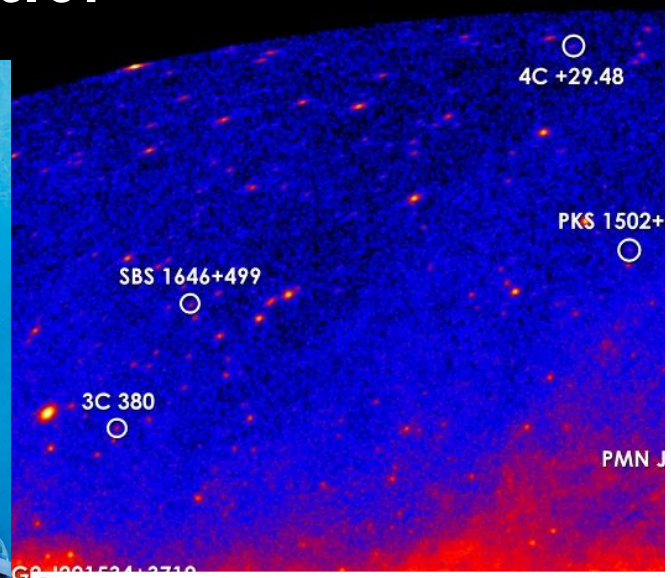
D. A. Smith et al 2023 ApJ 958 191

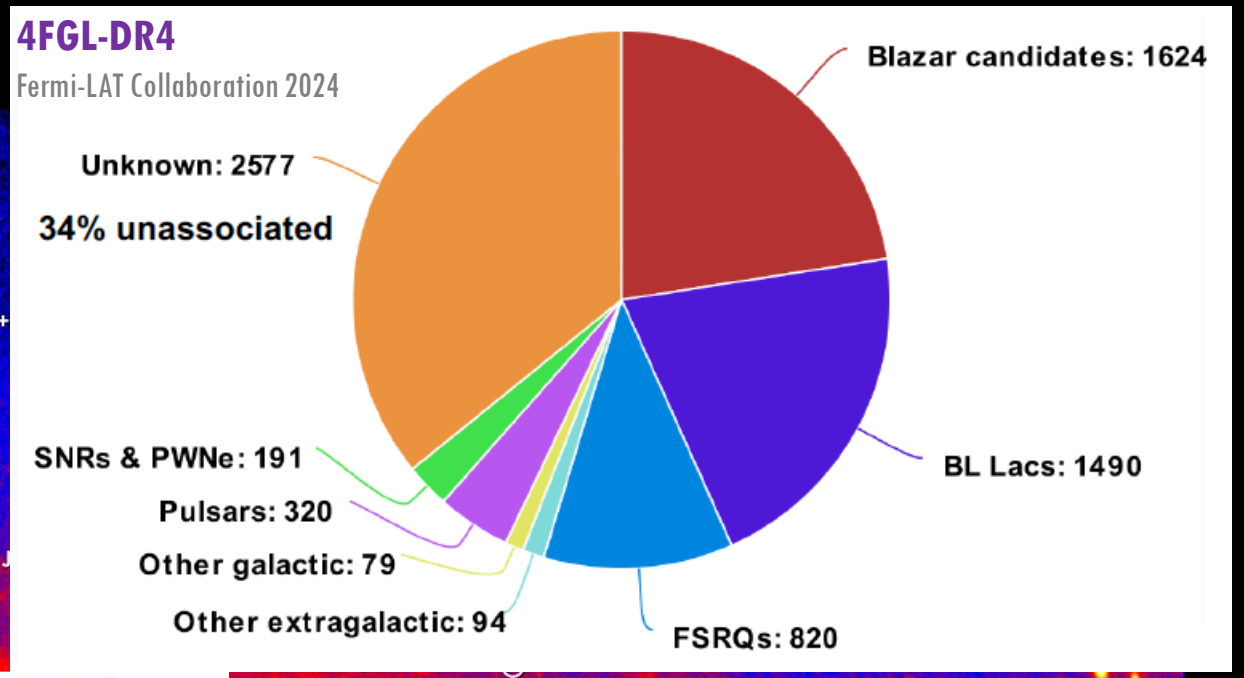


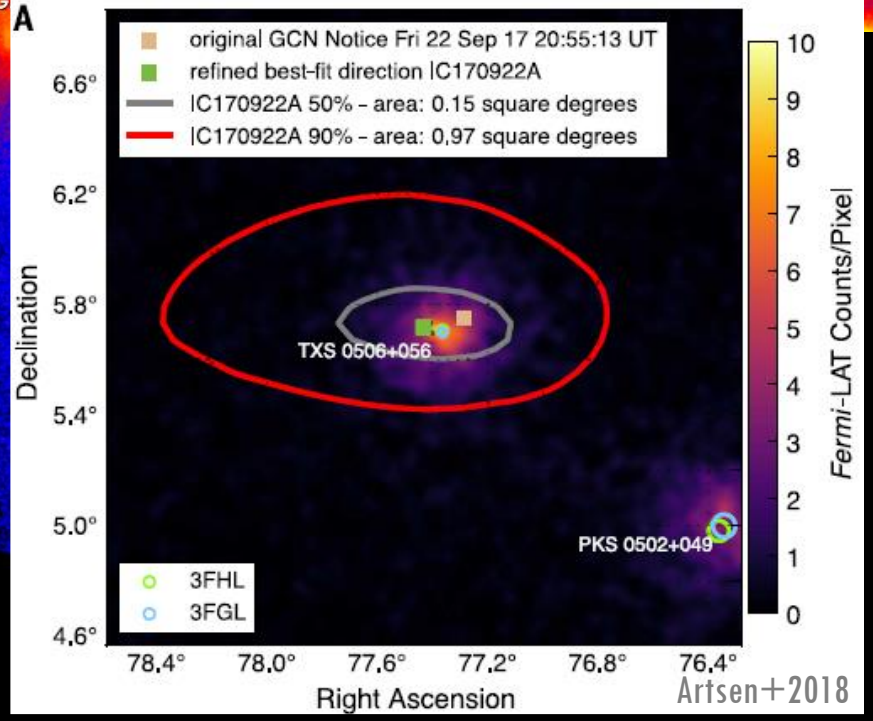
NASA VIDEO Youtube channel
https://www.youtube.com/watch?v=J9I2hL8BD_E
NASA Goddard Media Studios
https://svs.gsfc.nasa.gov/14434

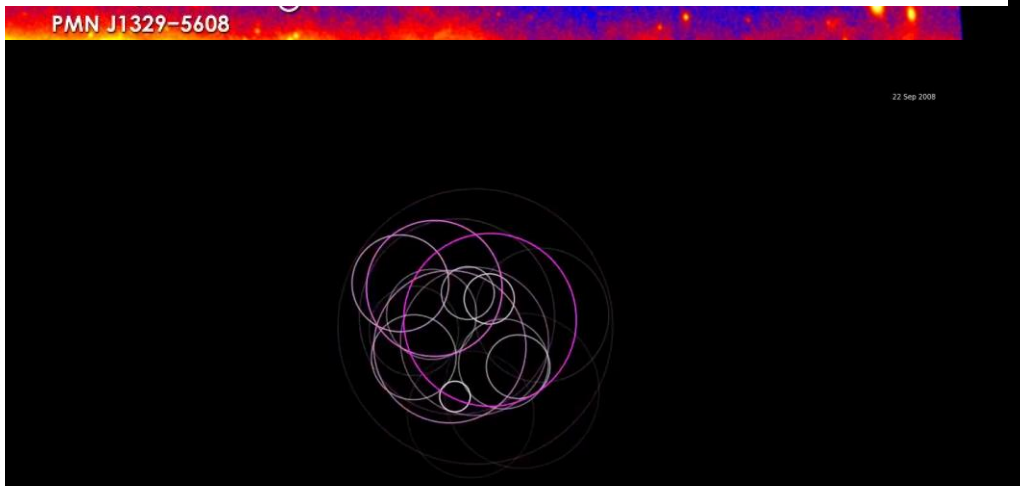
Credit: NASA/Fermi LAT Collaboration

Active Galactic Nuclei





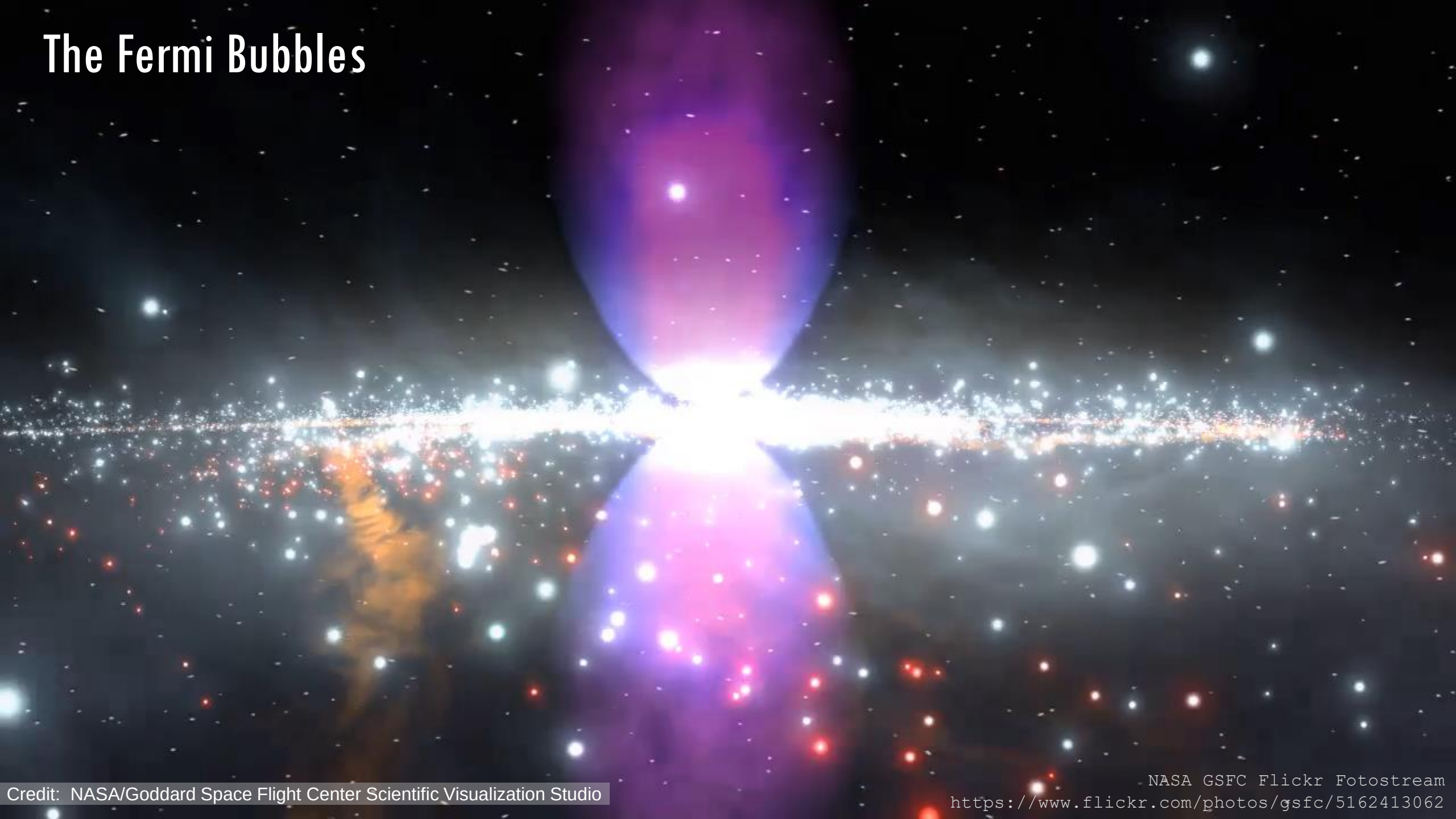




Credit: NASA/Fermi LAT Collaboration

NASA Goddard Media Studios
https://svs.gsfc.nasa.gov/12994

The Fermi Bubbles

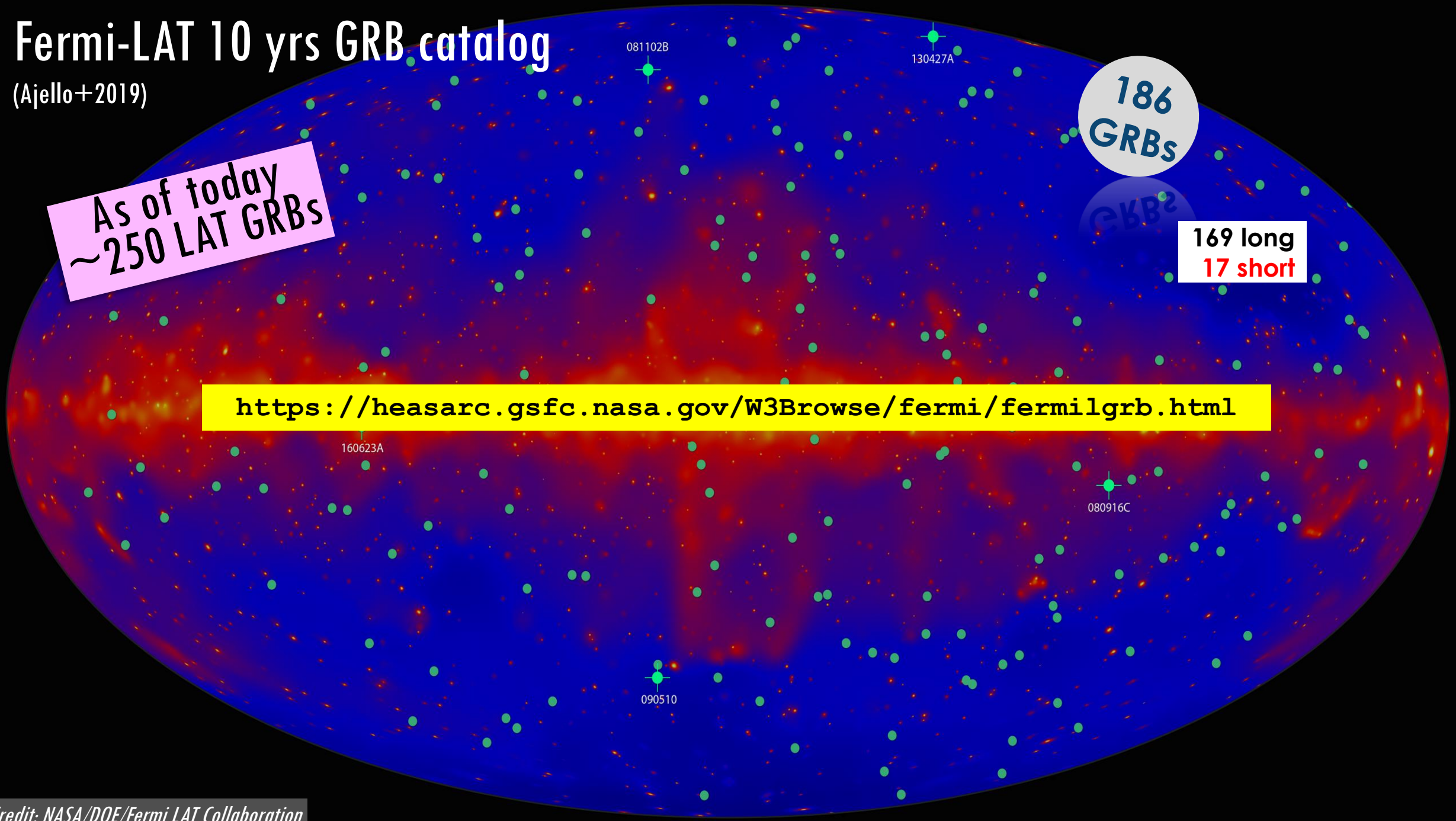


Credit: NASA/Goddard Space Flight Center Scientific Visualization Studio

NASA GSFC Flickr Fotostream
https://www.flickr.com/photos/gsfc/5162413062

Fermi-LAT 10 yrs GRB catalog

(Ajello+2019)



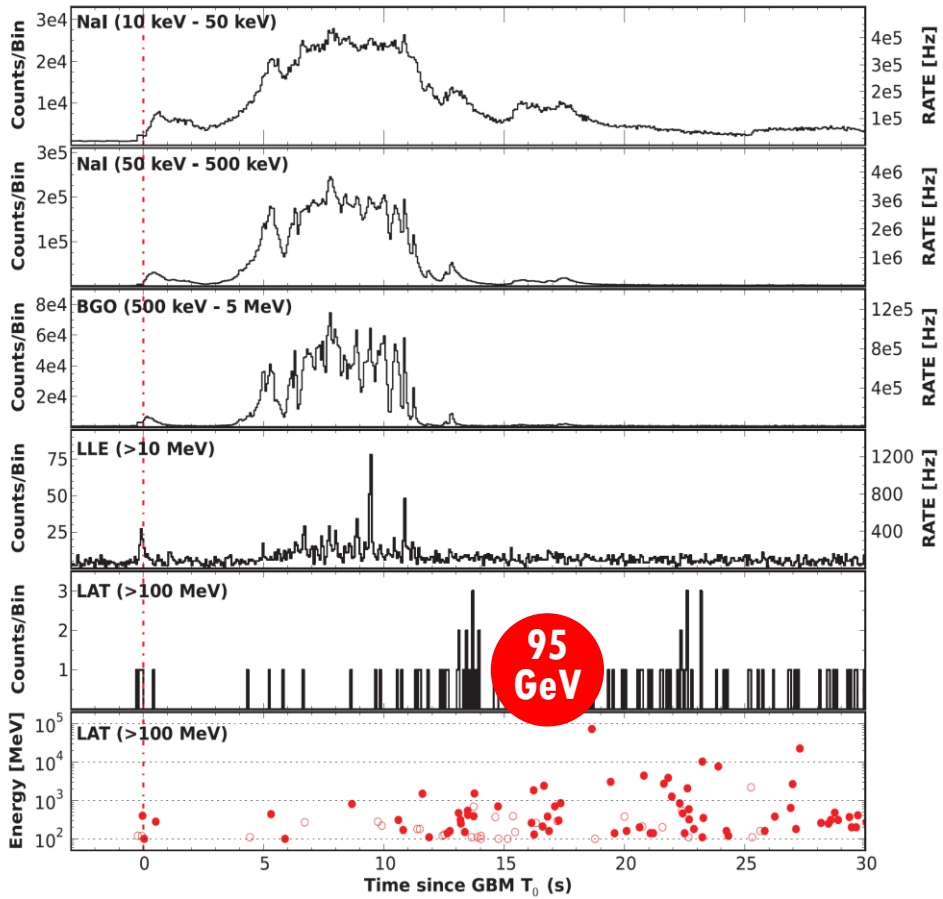
As of today
~250 LAT GRBs

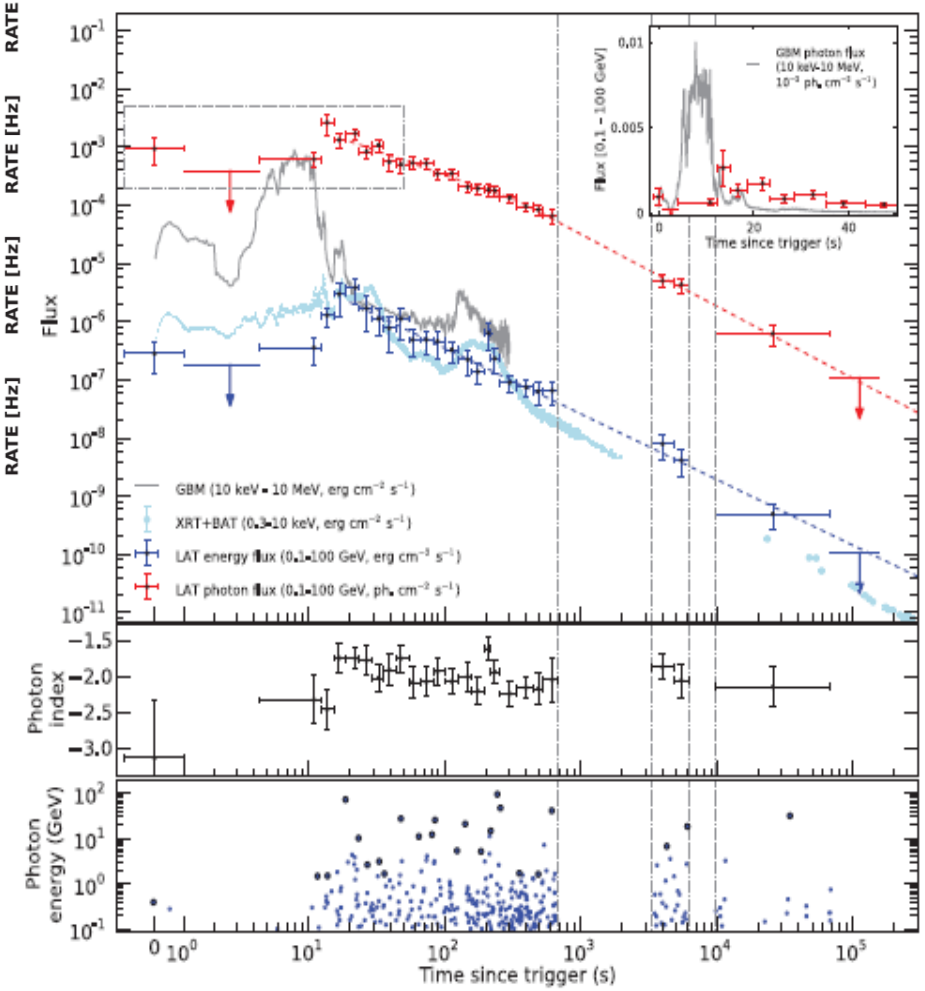
186 GRBs

169 long
17 short

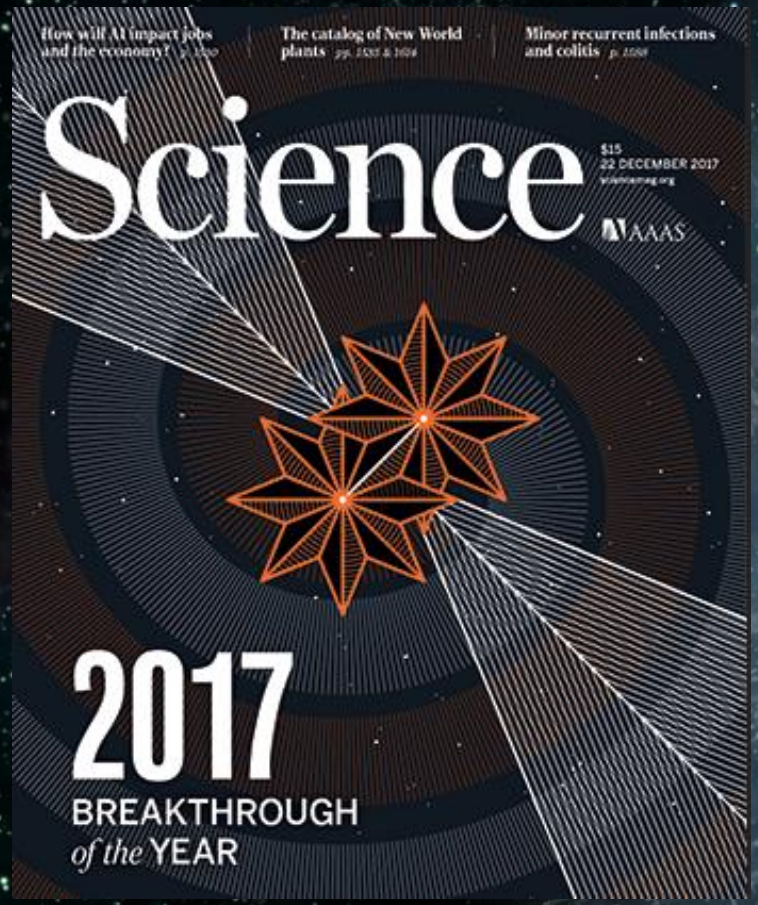
https://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermilgrb.html

Credit: NASA/DOE/Fermi LAT Collaboration





Fermi-LAT Observations of the Gamma-Ray Burst GRB 130427A – Ackermann+2014



Credit: Dana Berry/SkyWorks Digital, Inc./Harvard-Smithsonian Center for Astrophysics

Fermi

Gamma rays, 50 to 300 keV

GRB 170817A

Counts per second

1,500

1,000

500

LIGO

Gravitational-wave strain

GW170817

Frequency (Hz)

300

100

-6

-4

-2

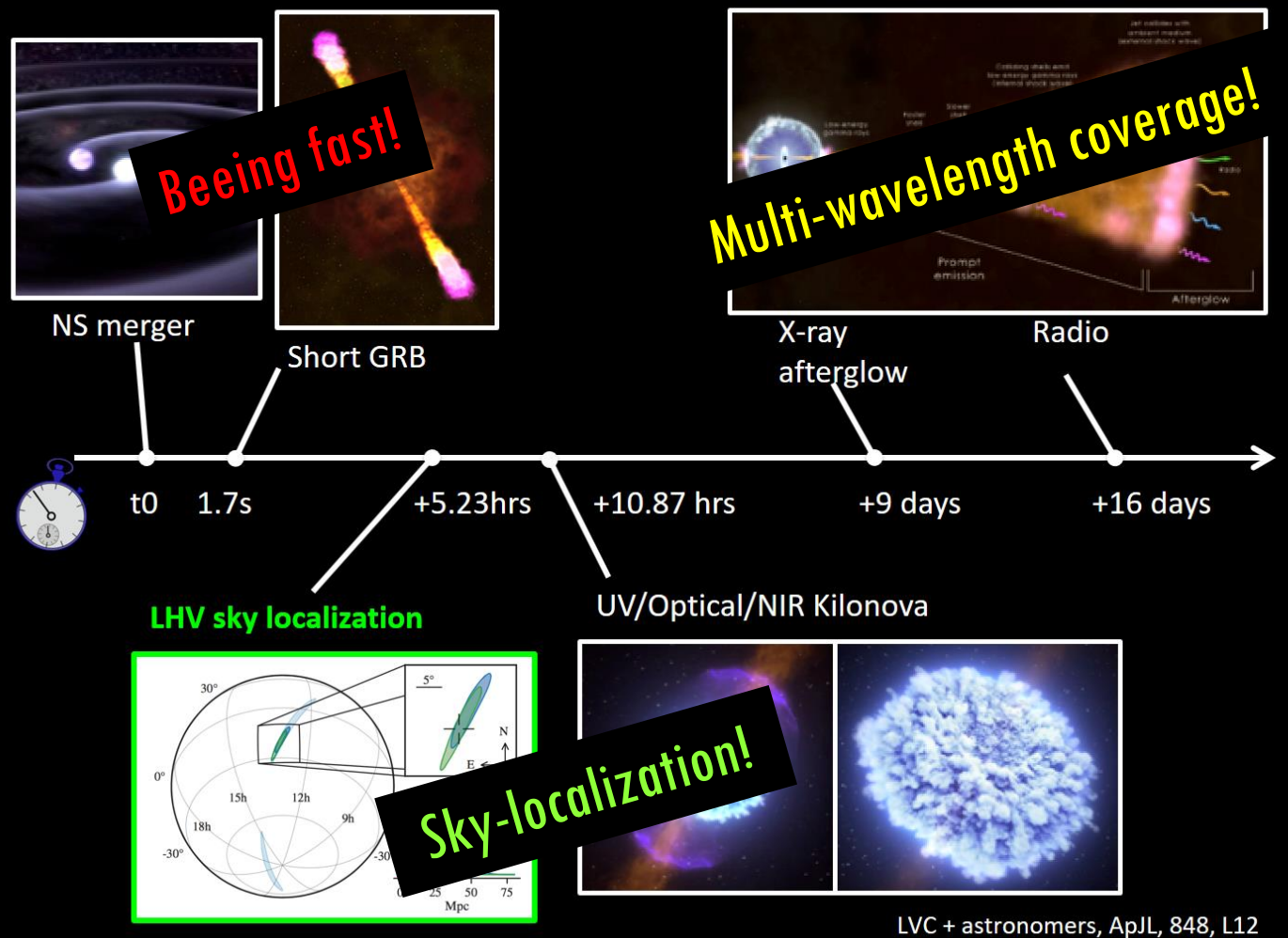
0

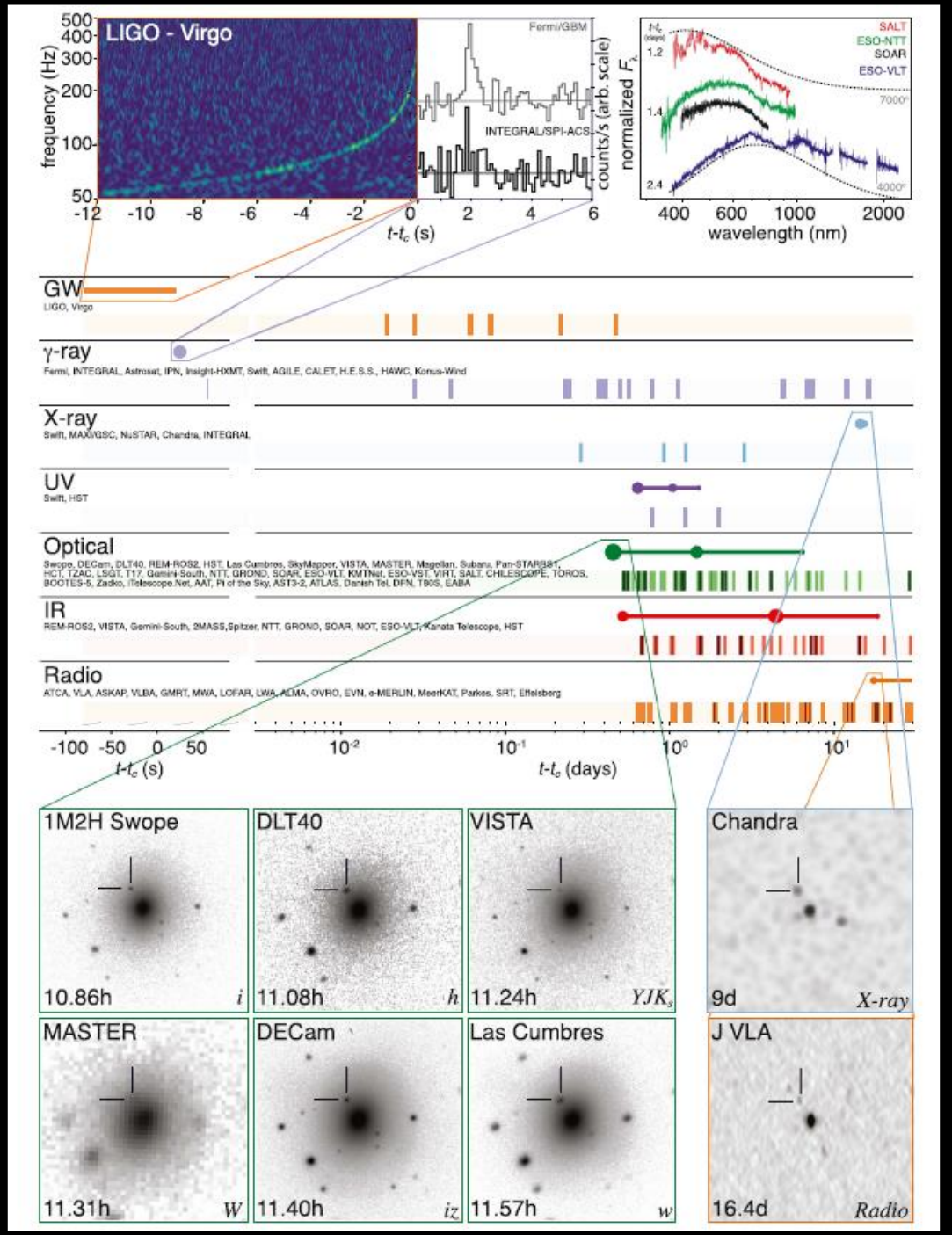
2

4

Time from merger (seconds)

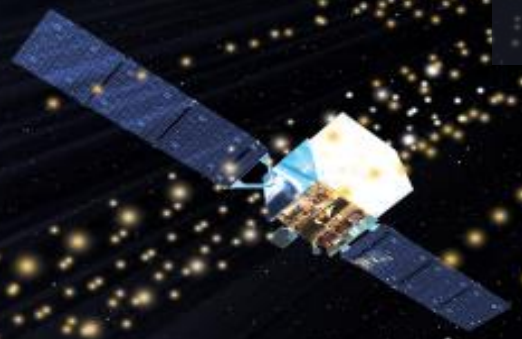
Credit: NASA‘ Goddard/Fermi Collaboration/LIGO Collaboration

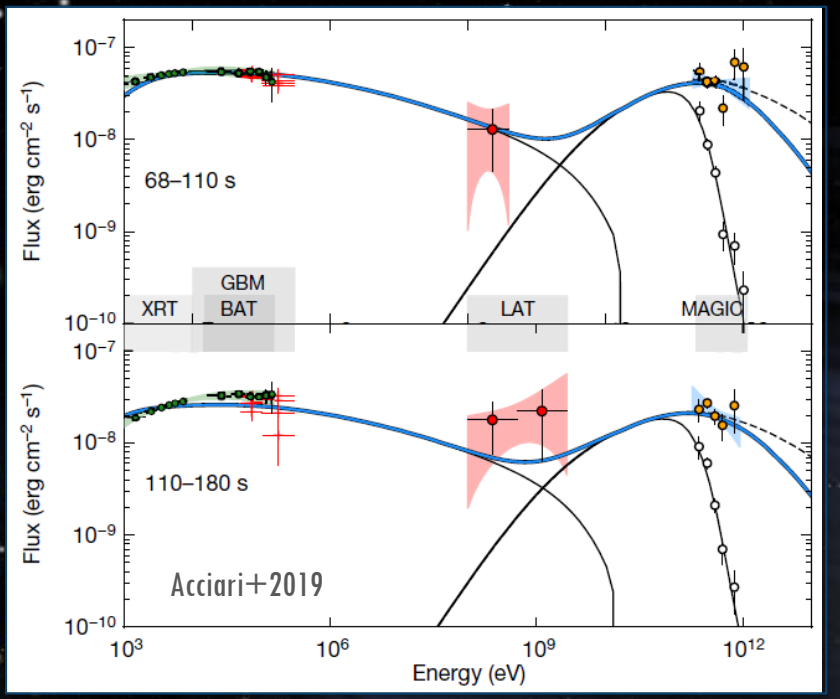


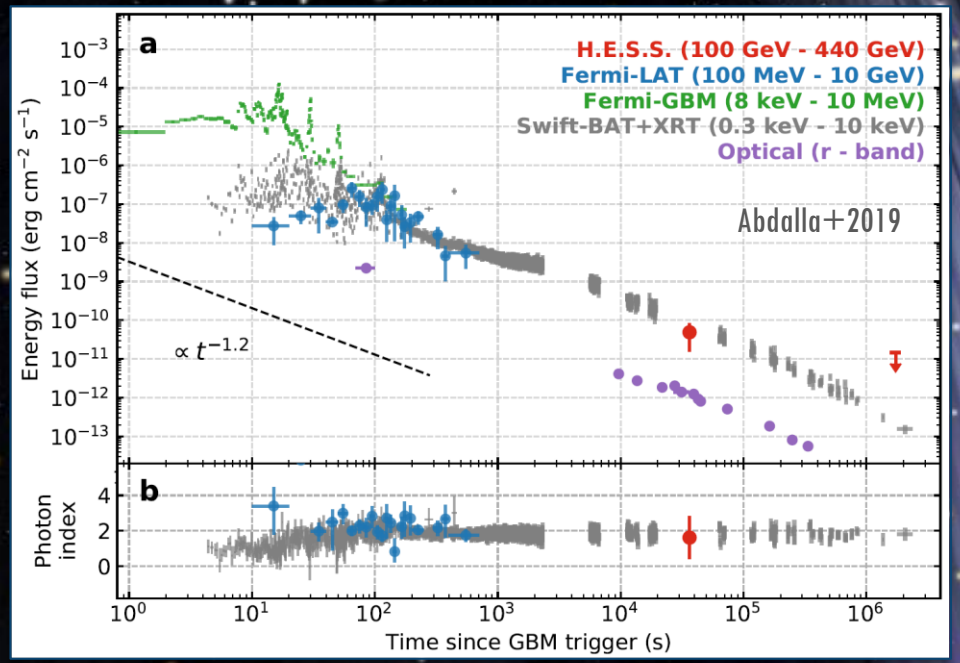


Multi-messenger Observations of a Binary Neutron Star Merger – Abbott+2017

GRBs at TeV energies







nature

Article | Published: 20 November 2019

A very-high-energy component deep in the γ-ray burst afterglow

H. Abdalla, R. Adam, [...] O. J. Roberts

Nature **575**, 464–467(2019) | Cite this article

Abstract

Gamma-ray bursts (GRBs) are brief flashes of γ-rays and are considered to be the most energetic explosive phenomena in the Universe[1]. The emission from GRBs comprises a short (typically tens of seconds) and bright prompt emission, followed by a much longer afterglow phase. During the afterglow phase, the shocked outflow—produced by the interaction between the ejected matter and the circumburst medium—slows down, and a gradual decrease in brightness is observed[2]. GRBs typically emit most of their energy via γ-rays with energies in the kiloelectronvolt-to-megaelectronvolt range, but a few photons with

nature

DOI: 10.1038/s41586-019-1750-x

Article | Published: 20 November 2019

Teraelectronvolt emission from the γ-ray burst GRB 190114C

MAGIC Collaboration

Nature **575**, 455–458(2019) | Cite this article

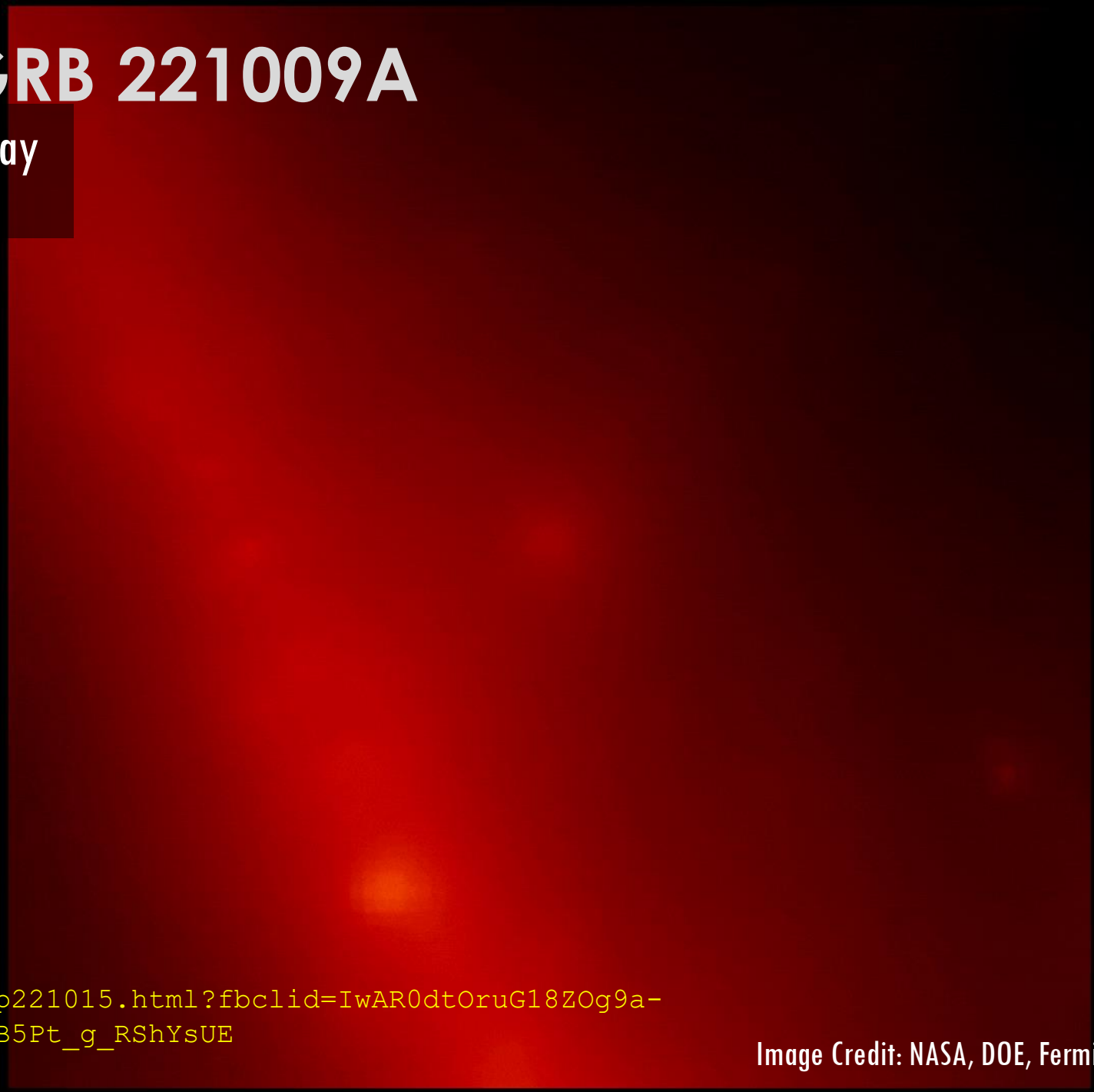
Abstract

Long-duration γ-ray bursts (GRBs) are the most luminous sources of electromagnetic radiation known in the Universe. They arise from outflows of plasma with velocities near the speed of light that are ejected by newly formed neutron stars or black holes (of stellar mass) at cosmological distances[1,2]. Prompt flashes of megaelectronvolt-energy γ-rays are followed by a longer-

The «BOAT» GRB 221009A

Astronomy Picture of the Day

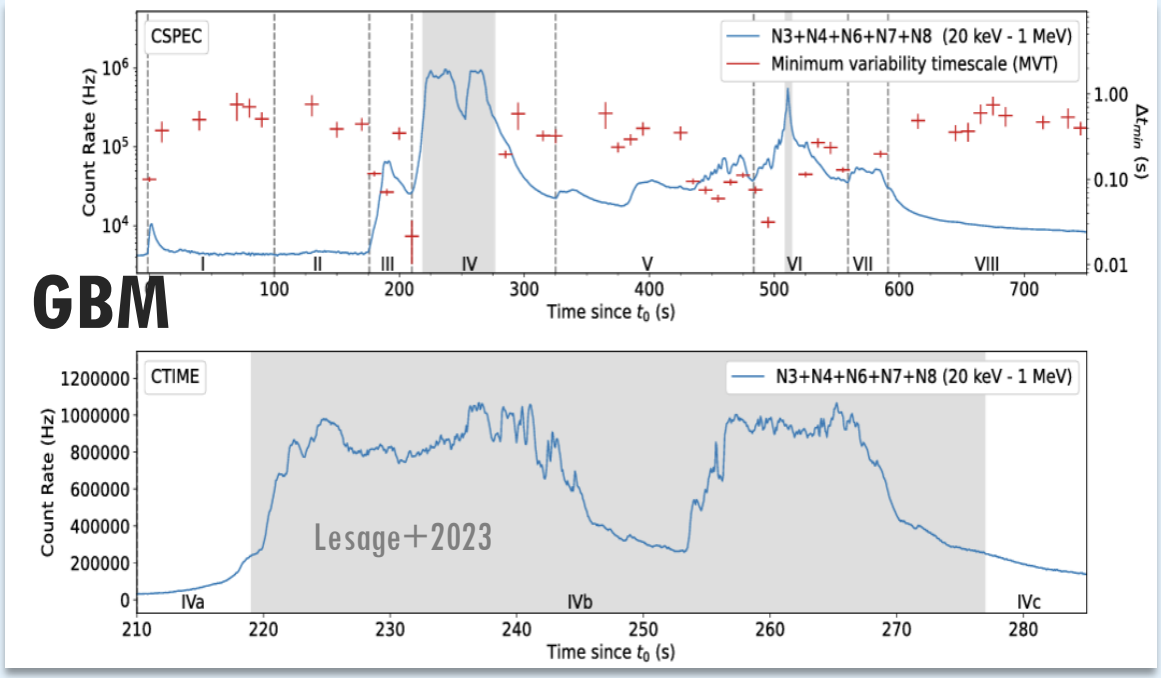
15 October 2022

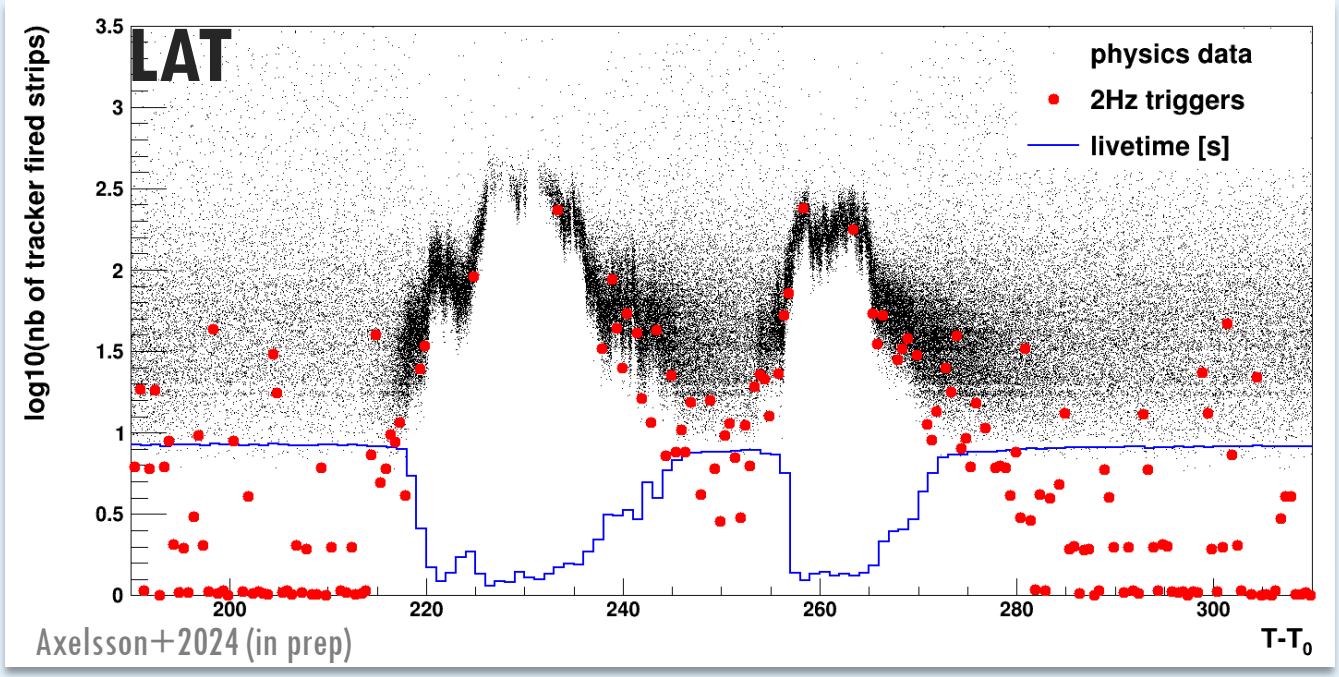


https://apod.nasa.gov/apod/ap221015.html?fbclid=IwAR0dtOruG18ZOg9a-AhjcLkfPfvsok_C5Dvn-sjK7YpBQB5Pt_g_RShYsUE

Image Credit: NASA, DOE, Fermi LAT Collaboration, R.Pillera

GRB 221009A – Fermi data issues





- **Saturation effects**

  Definition of Bad Time Intervals (BTIs)
  - **GBM** PPU corrections
  - **LAT** Modified reconstruction algorithm

All caveats can be found here: https://fermi.gsfc.nasa.gov/ssc/data/analysis/grb221009a.html

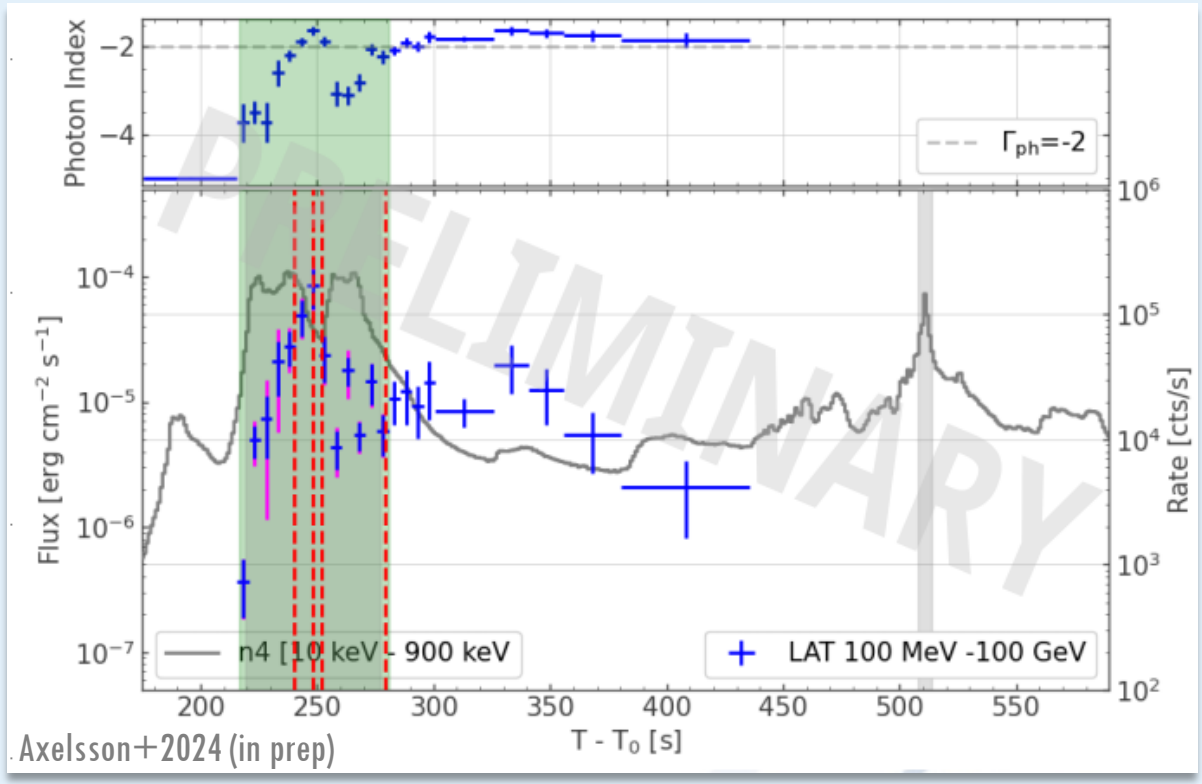
- **Normal data taking conditions**

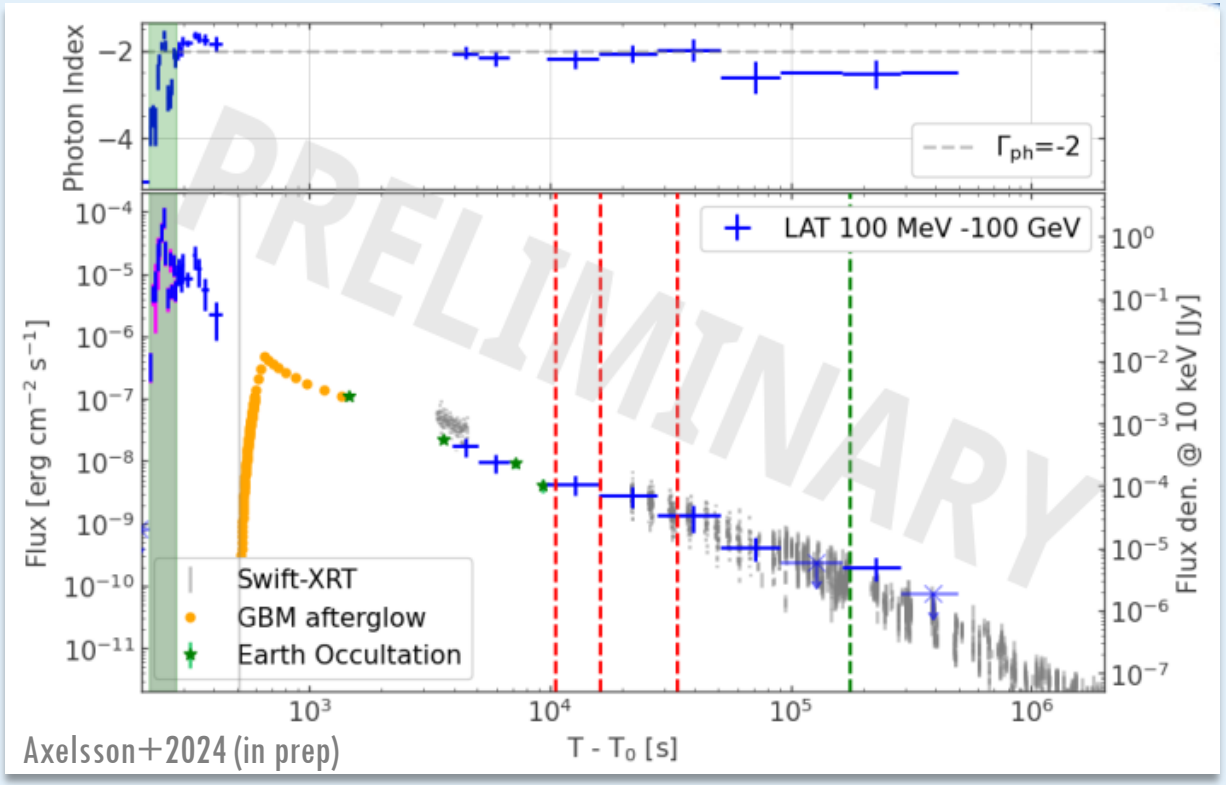
  Before T_0+217 s and after T_0+280 s

- **Bad Time Intervals**

  No standard analysis possible

GRB 221009A – High-energy emission analysis





Early times LLE+LAT analysis

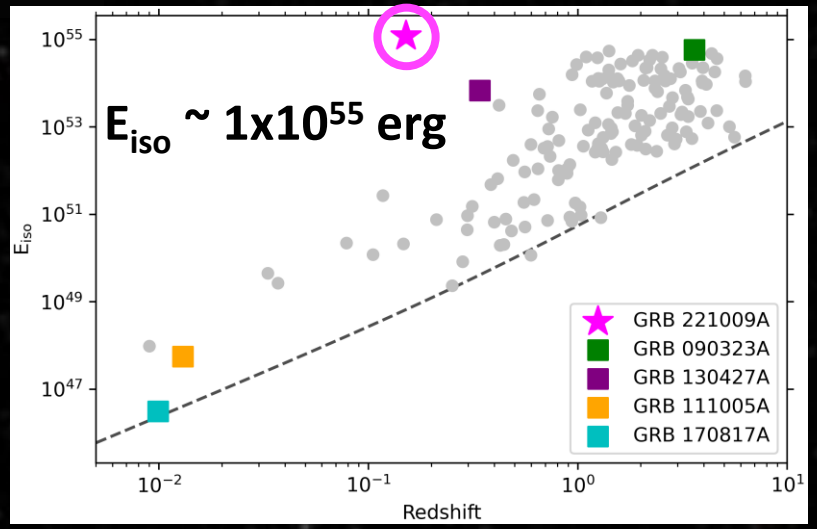
- Estimate flux maximum in the BTI
- Bulk Lorentz factor estimation from opacity arguments: **Γ>450**

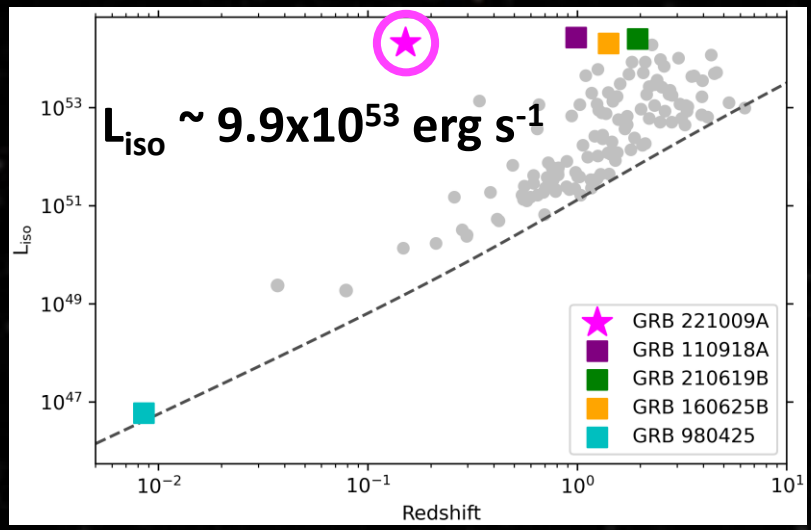
Late times LAT analysis

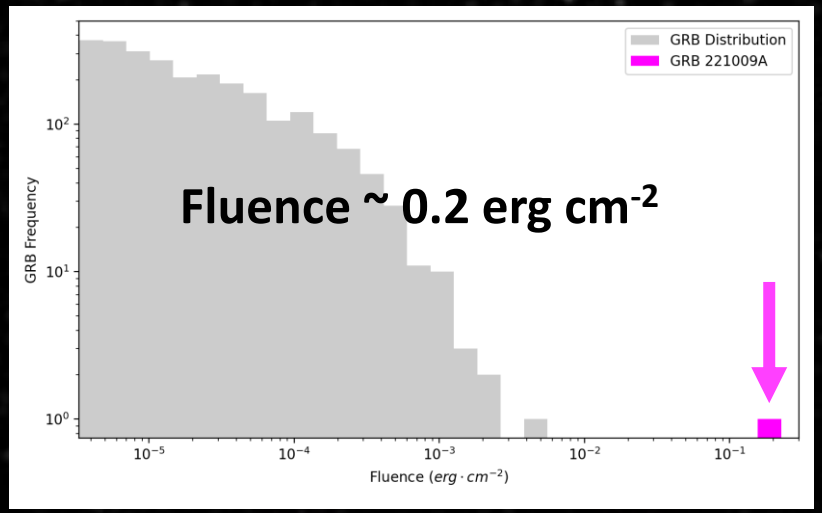
- GRB duration: ~**180 ks** (**2 days: record!**)
- Afterglow flux PL decay (index ~ **−1.3**)
- $t_{peak,\,ag} \gtrsim t_0$+280 s consistent with LHAASO

Is it the B.O.A.T.?

(4 measures)

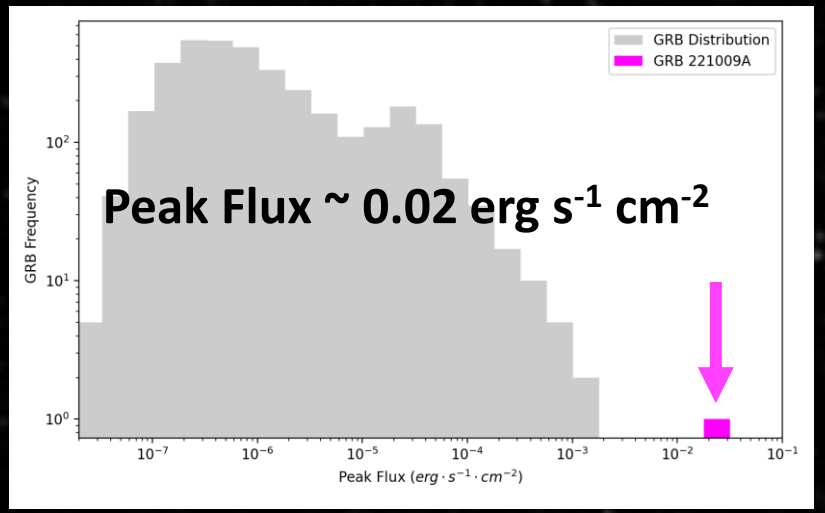






55 years of data

Burns+2023



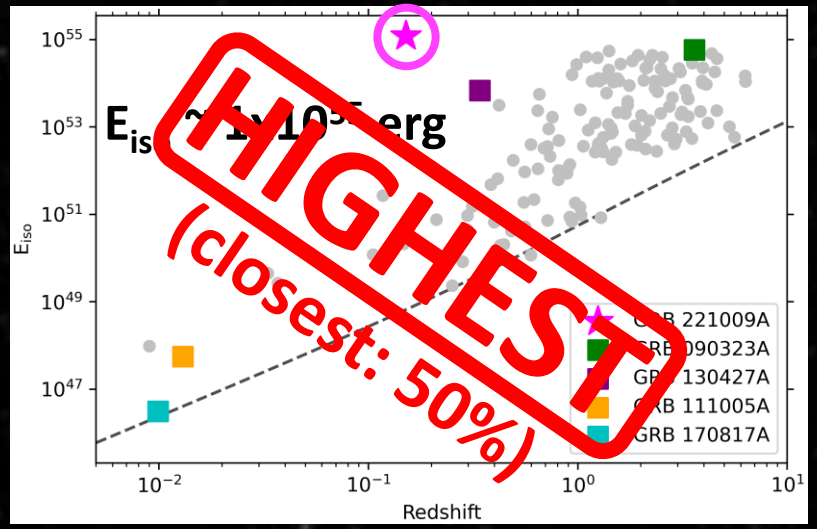
Slide courtesy of S. Lesage, *Fermi*-GBM | GRB50

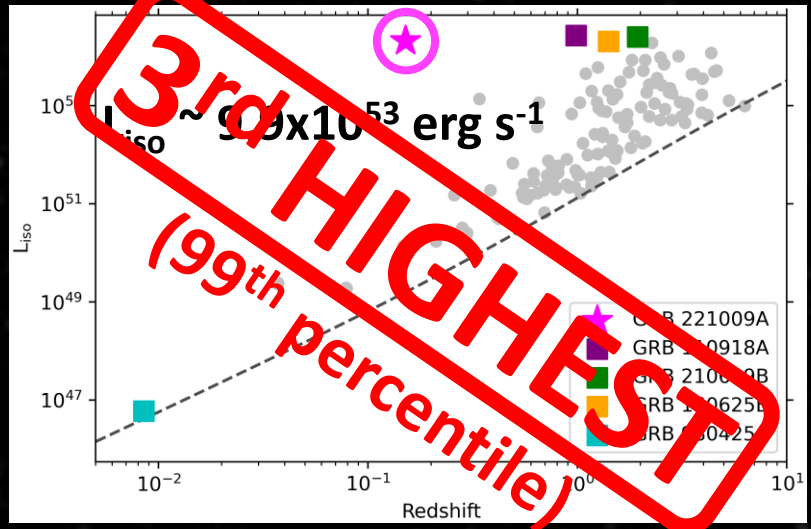
Is it the B.O.A.T.?

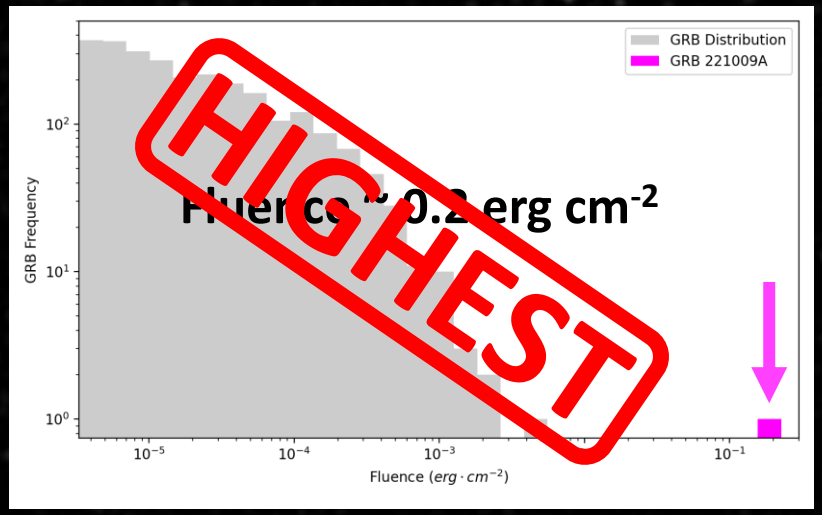
(4 measures)

YES!

YES!



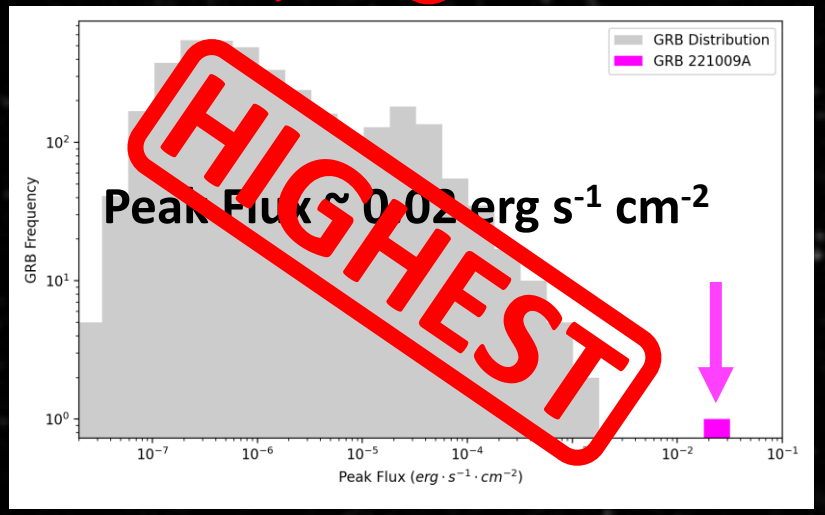




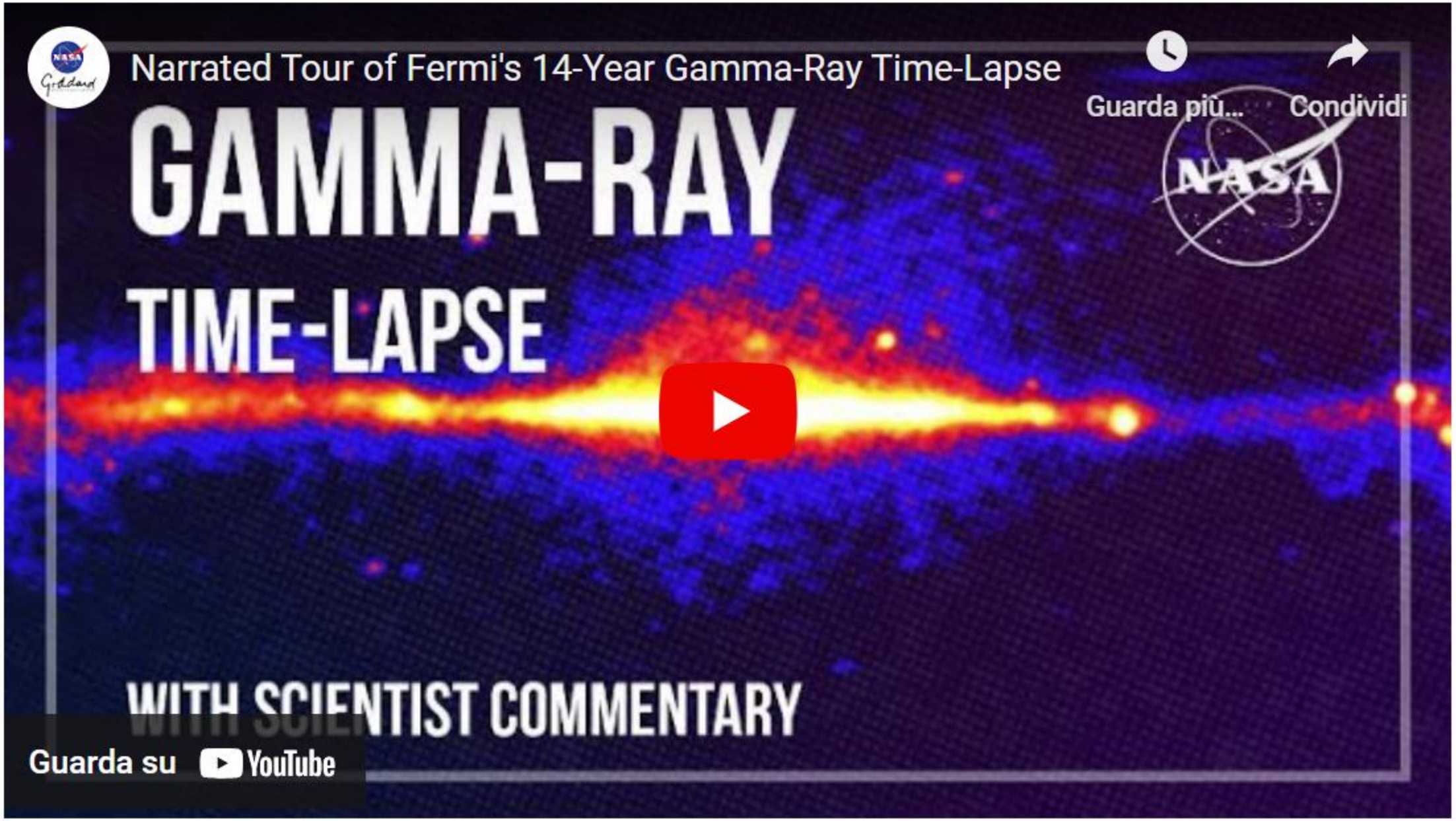
¾ measures of brightness

55 years of data

Burns+2023



Slide courtesy of S. Lesage, *Fermi*-GBM | GRB50

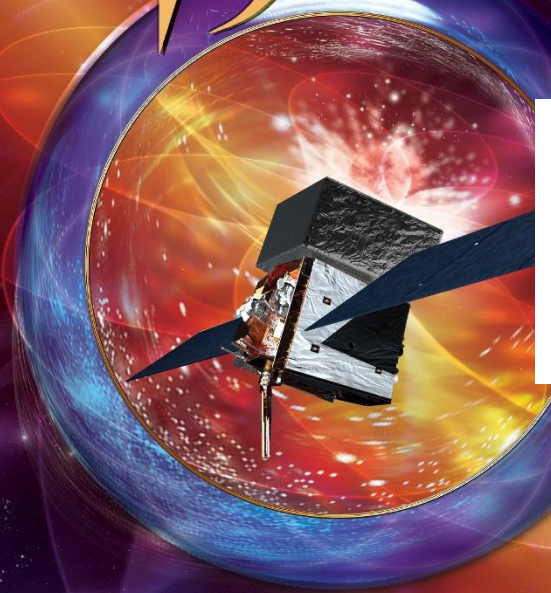


https://science.nasa.gov/centers-and-facilities/goddard/nasas-fermi-mission-creates-14-year-time-lapse-of-the-gamma-ray-sky/

National Aeronautics and Space Administration

Our High-Energy Universe

15 Years



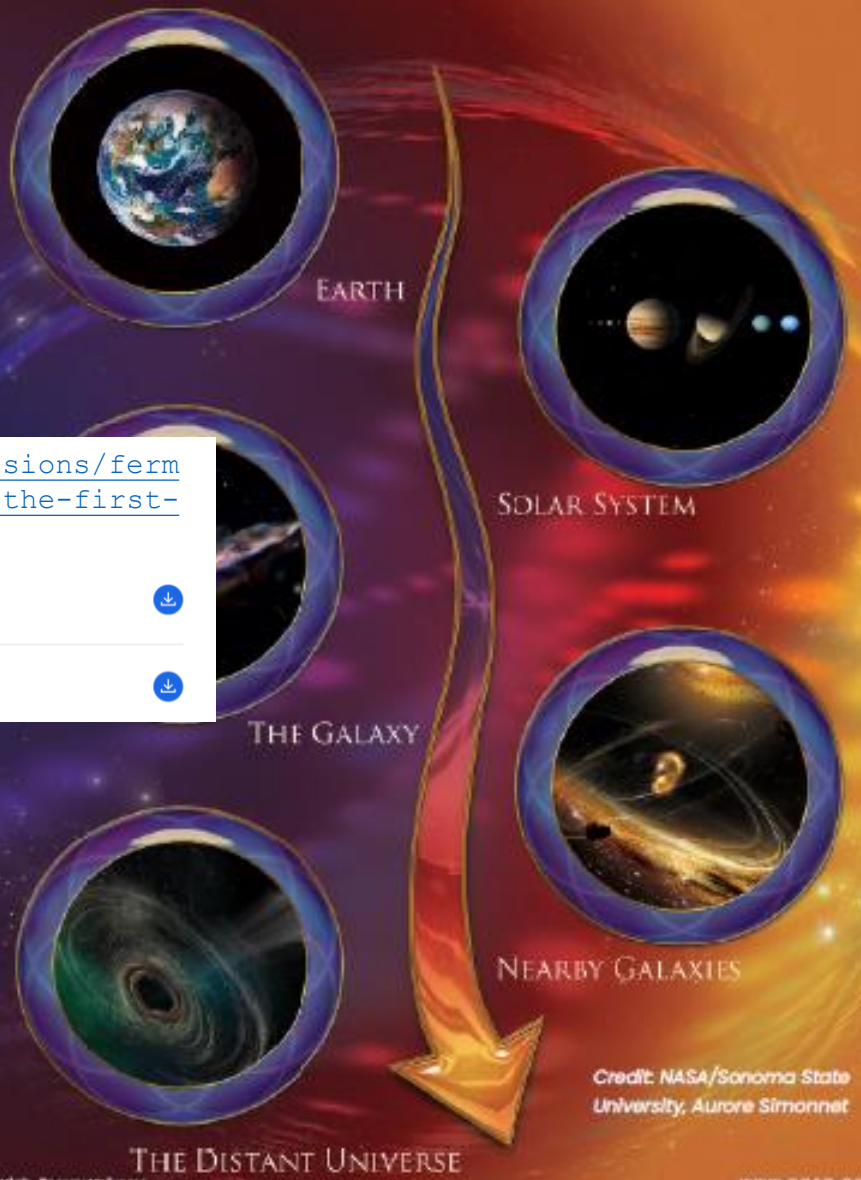
with the Fermi Gamma-ray Space Telescope

www.nasa.gov

https://science.nasa.gov/missions/fermi/explore-the-universe-with-the-first-e-book-from-nasas-fermi/

PDF	(PDF) (44.03 MB)	
EPUB	(EPUB+ZIP) (804.49 MB)	

Journey through the Cosmos



Credit: NASA/Sonoma State University, Aurore Simonnet

www.nasa.gov

Thank you

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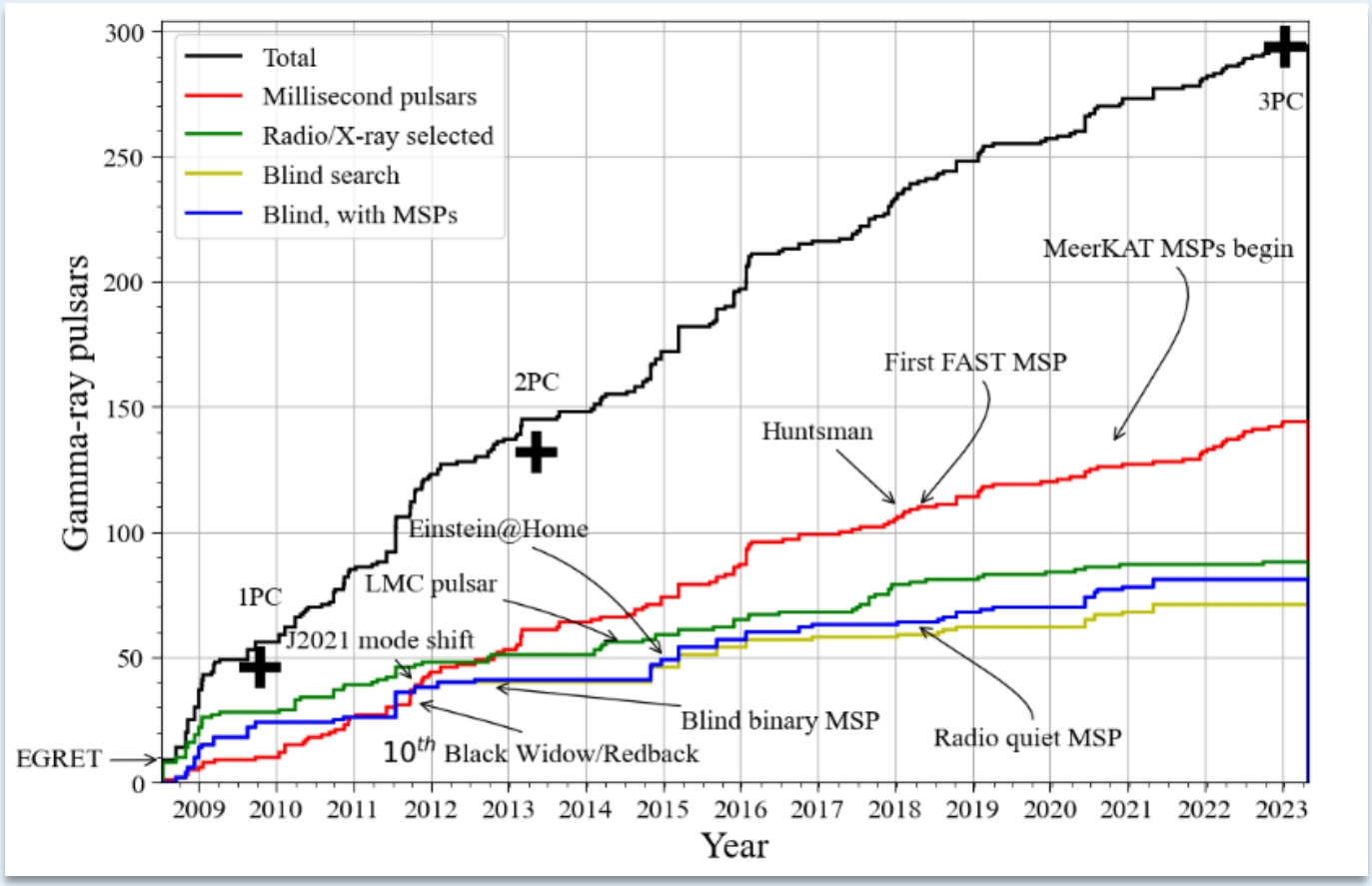
3PC: The latest LAT pulsar catalog

- 294 gamma-ray pulsars
  - Half of them not known before Fermi
  - Emission region location: outer-gap model preferred with respect to the polar-gap
  - Discovery of gamma-ray millisecond pulsars (MSPs)
  - Pulsars, considered stable sources, were discovered to be variable!

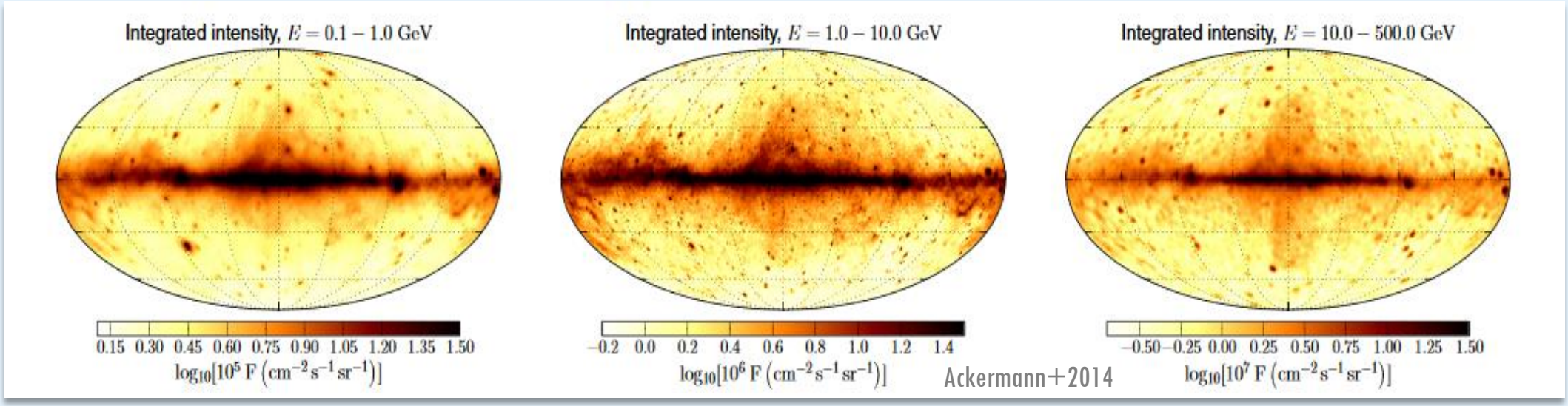
Public list of LAT pulsars

https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars



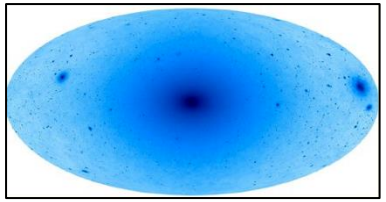
The Fermi bubbles

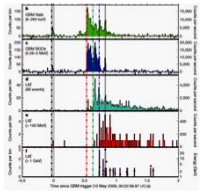
- Excess in the diffuse emission detected between 1 GeV up to 50GeV
- Fermi Bubbles properties:
  - Extension for ~**55**° above and below the Galactic plane
  - Same morphology as the WMAP microwave haze with a magnetic field between 5 and 20 μG ➔ common origin
  - Likely created by some large energy injection in the Galactic Center, such as a past accretion event onto the central black hole SgrA in the last ~10 My



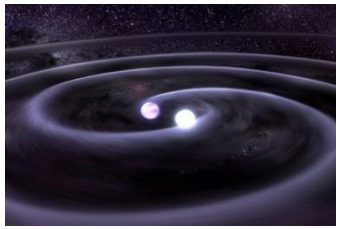
Science with the Fermi-LAT

Dark Matter searches

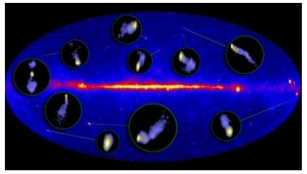




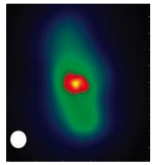
GRBs (see G. Principe and R. Pillera's talks)



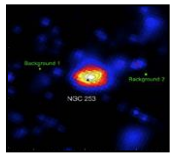
NEW! Gravitational waves



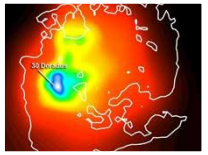
Blazars



Radio Galaxies



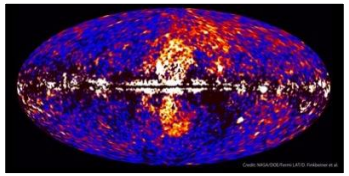
Starburst Galaxies

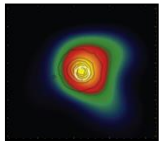


LMC & SMC

Extragalactic

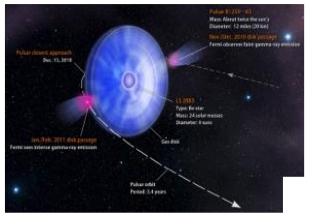
Fermi Bubbles

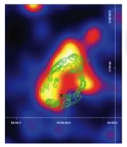




Globular Clusters

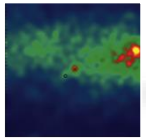
γ-ray Binaries





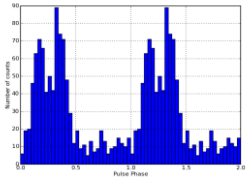
SNRs & PWN

Galactic



Novae

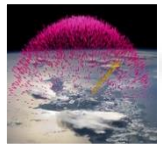
Pulsars: isolated, binaries, & MSPs
(see G. Principe's talk)



Local

Sun: flares & CR interactions

Moon
Earth Limb



Terrestrial γ-ray Flashes