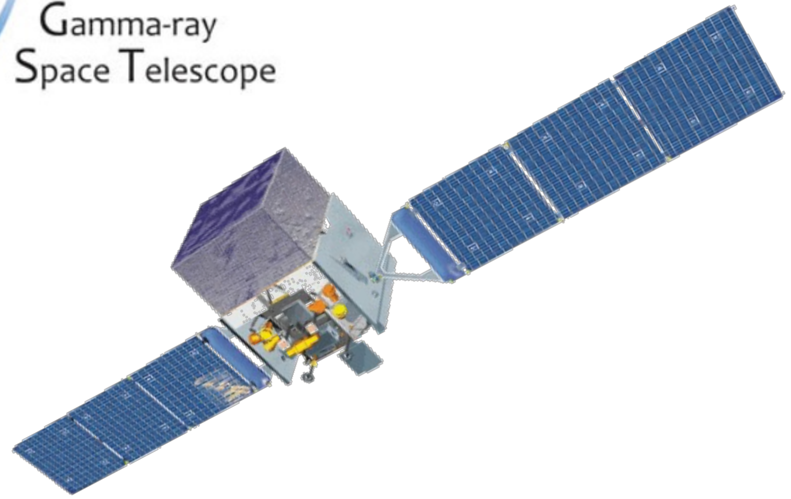
About me

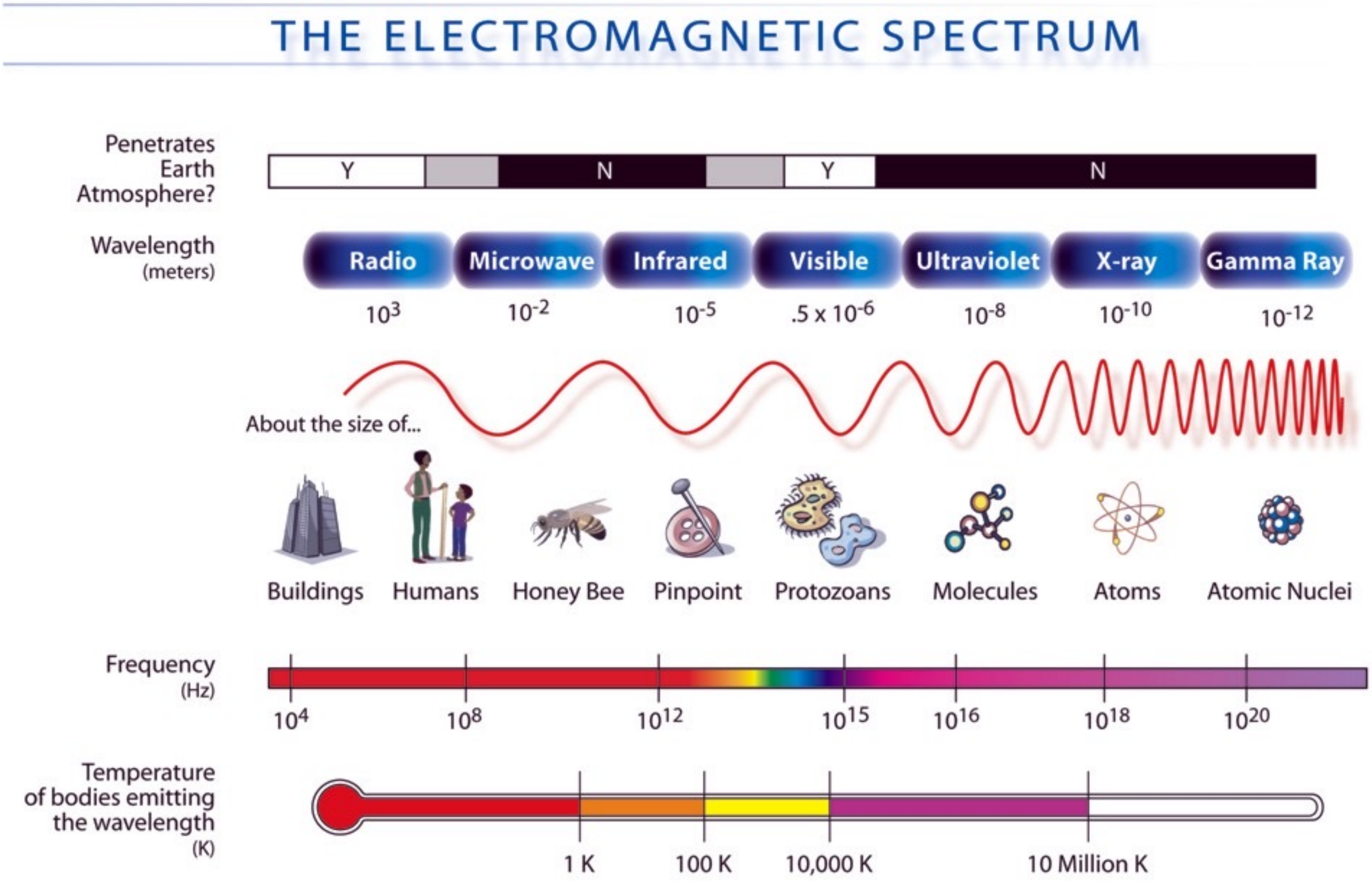
- Physics Major, Cornell U.
  - Discovered astrophysics and a love for experiments through senior level classes and internships
- Ph. D. in Physics from Univ. Maryland, College Park
  - Searched for variability in the very-high-energy gamma-ray sky using Milagro, a water Cherenkov telescope
- Post Doc U. Chicago/Argonne
  - Integrated data acquisition for VERITAS imaging atmospheric Cherenkov telescope array and hunted cosmic-ray signatures in Cherenkov light
- NASA Goddard Research Astrophysicist
  - Flight performance and simulation studies, variability and spatial analysis studies using Fermi LAT data
  - Project Scientist/former deputy for Fermi Gamma-ray Space Telescope; Chief, Astroparticle Physics Laboratory

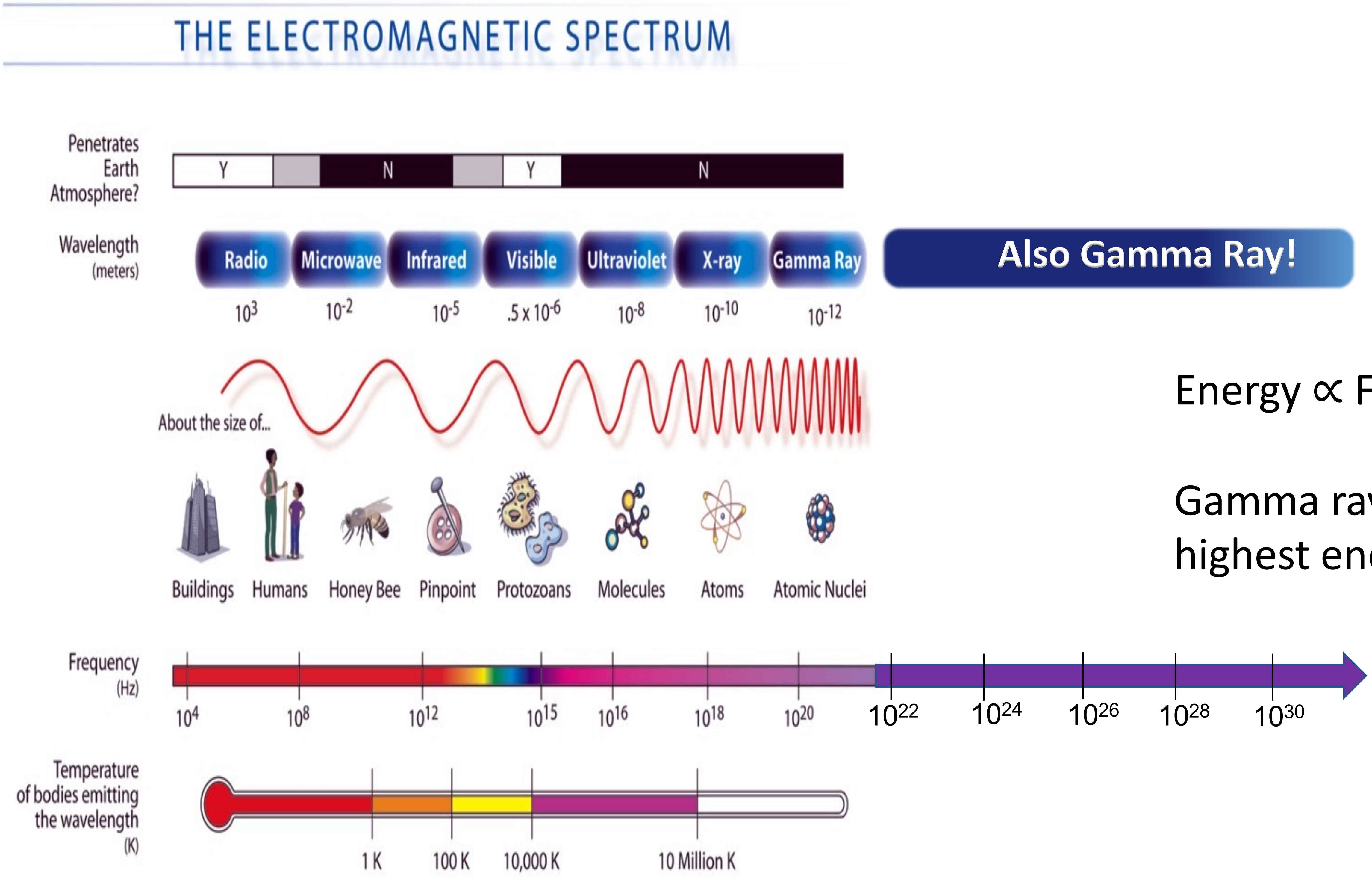


An Introduction to Fermi

Liz Hays

Fermi Summer School 2024


THE ELECTROMAGNETIC SPECTRUM
Penetrates Earth Atmosphere?
Y
N
Y
N
Wavelength (meters)
Radio
Microwave
Infrared
Visible
Ultraviolet
X-ray
Gamma Ray
10^3
10^-2
10^-5
.5 x 10^-6
10^-8
10^-10
10^-12
About the size of...
Buildings
Humans
Honey Bee
Pinpoint
Protozoans
Molecules
Atoms
Atomic Nuclei
Frequency (Hz)
10^4
10^8
10^12
10^15
10^16
10^18
10^20
Temperature of bodies emitting the wavelength (K)
1 K
100 K
10,000 K
10 Million K



Energy ∝ Frequency

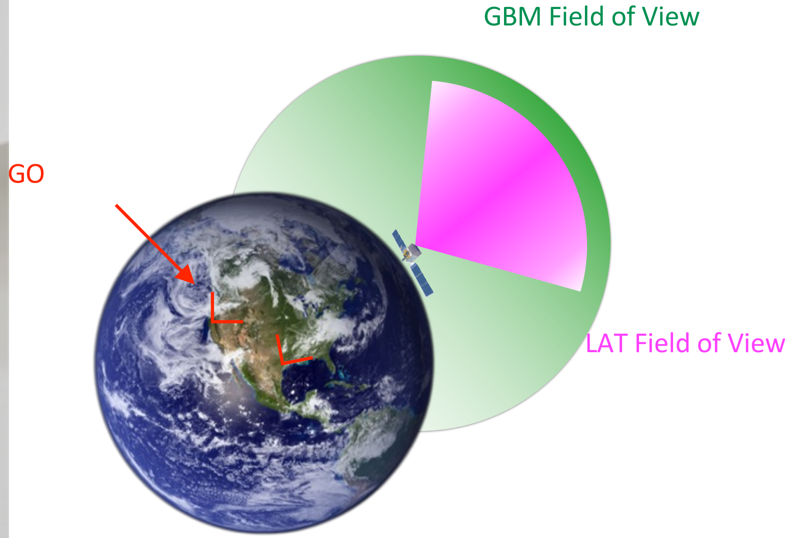
Gamma rays are the highest energy light

The Fermi

Large Area Telescope (LAT)

Large field of view
- 1/5 of the sky
- >85% of the sky in 3 hrs

Broad energy range (20 MeV - >300 GeV)



Gamma-ray Burst Monitor (GBM)

Views entire unocculted sky

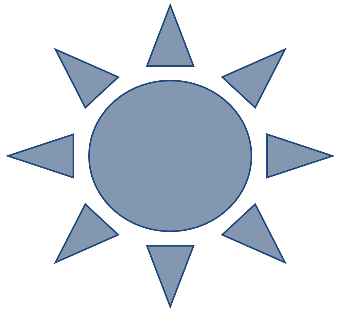
NaI: 8 keV - 1 MeV

BGO: 150 keV - 30 MeV

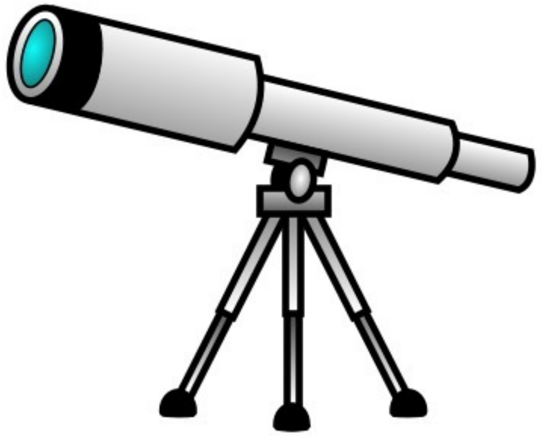
Wait a minute…

You may think of a typical telescope like this

Source

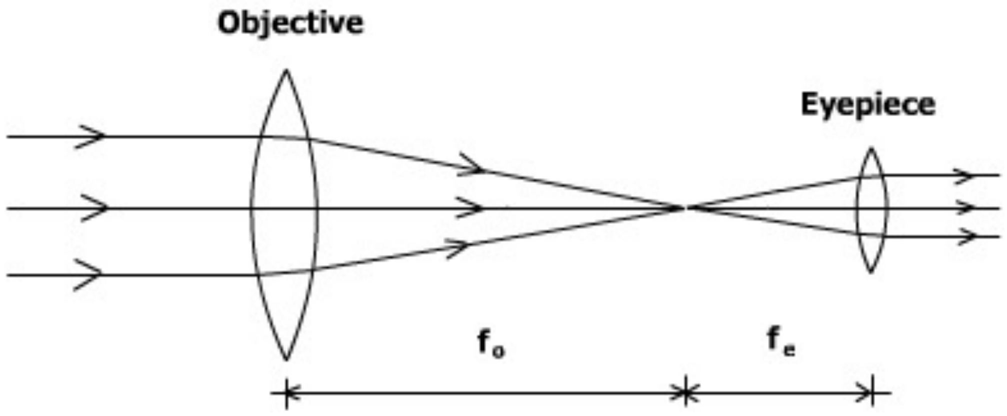


Telescope



Observer

Galaxies and Stars



Collect light through reflection or refraction and record the image

Gamma rays do not reflect or refract easily

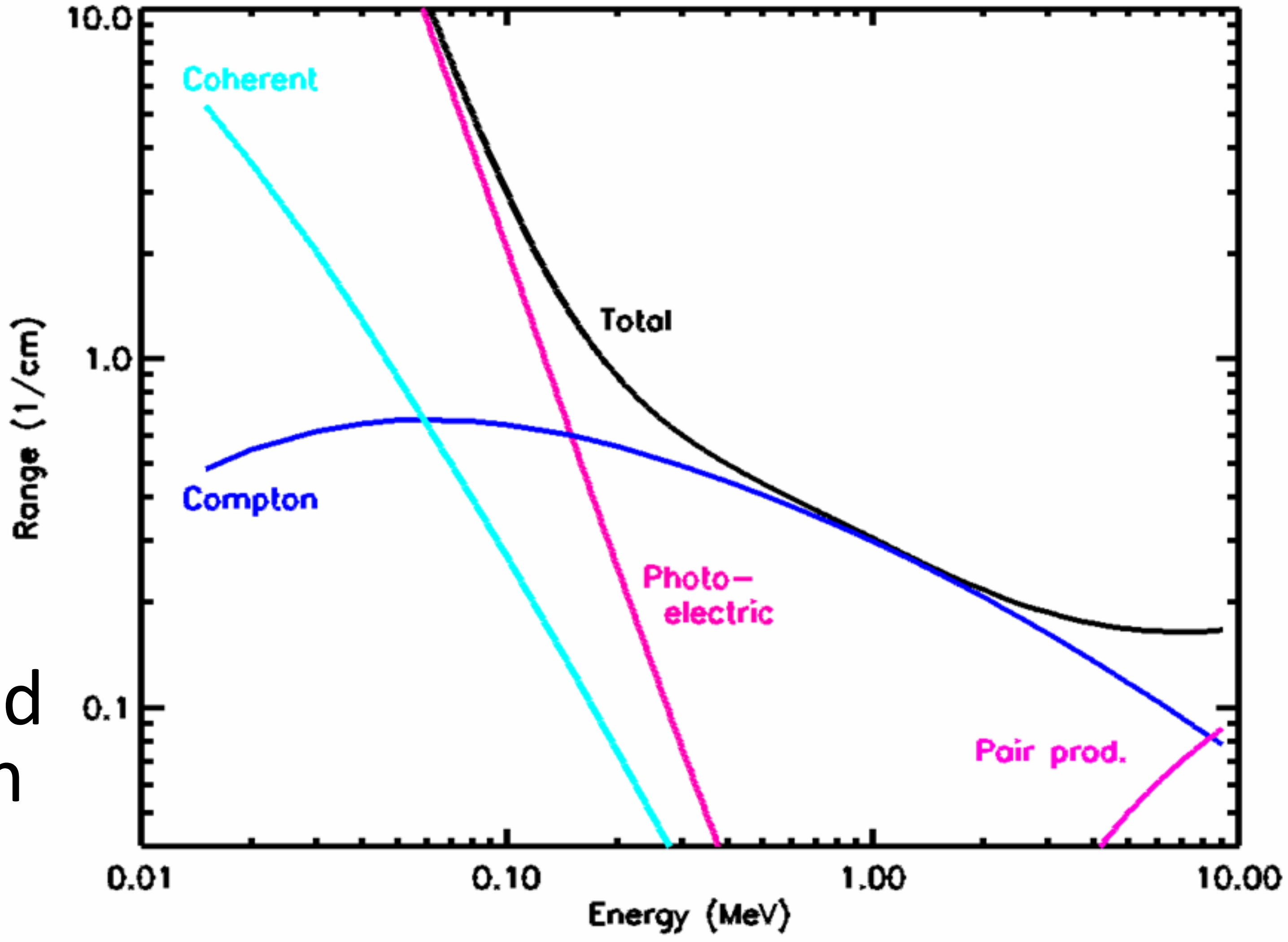
Difficult to focus onto a camera or even detect. Blame physics!

Gamma rays are scattered and absorbed in matter

- Coherent Scattering (electron remains bound to atom)
- Photoelectric Effect
- Compton Scattering
- Electron (e^-) positron (e^+) Pair Production

- Details depend on composition and density of the material and photon energy

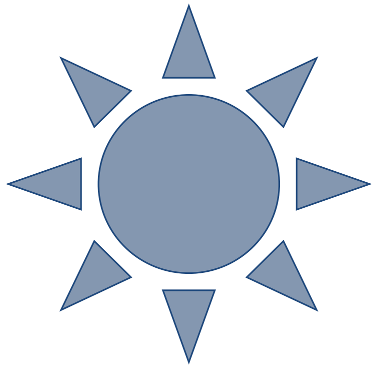
Gamma-ray attenuation in Germanium



Credit: Richard Kroeger

Gamma-ray telescopes are more like this

Source



Matter

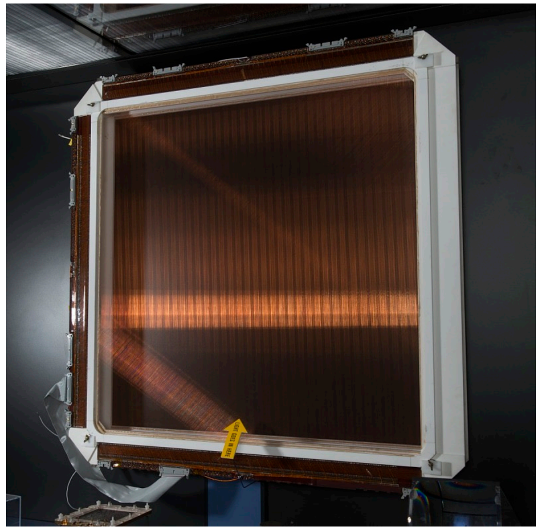
Radiation

Electron

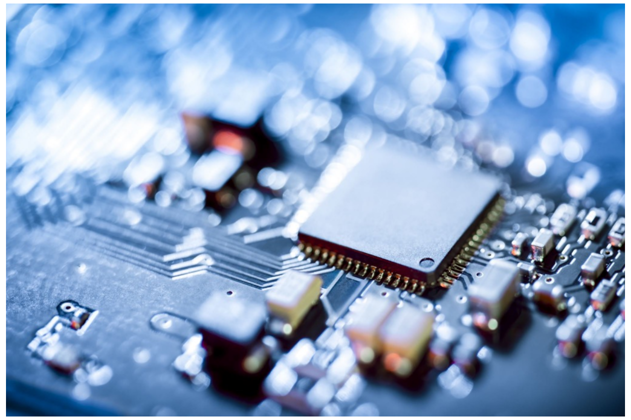
Electron + Positron

Photons

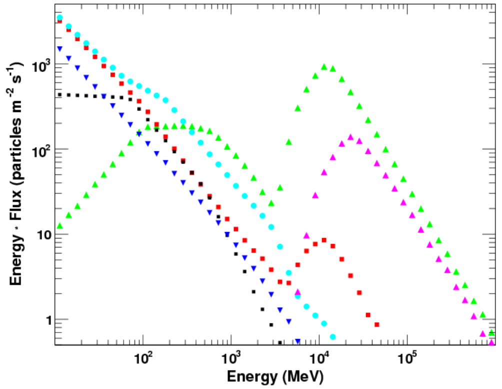
Sensors/Electronics



Computers



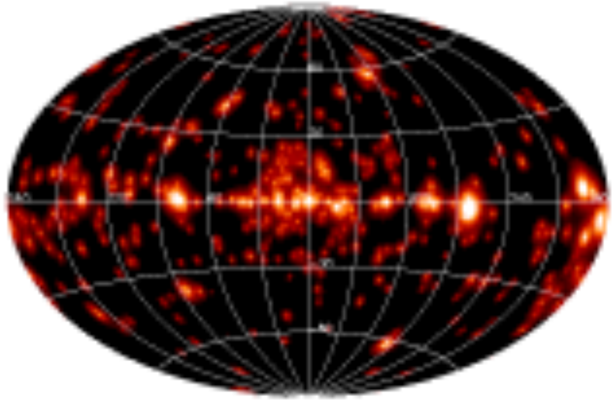
Instrument simulations, background models



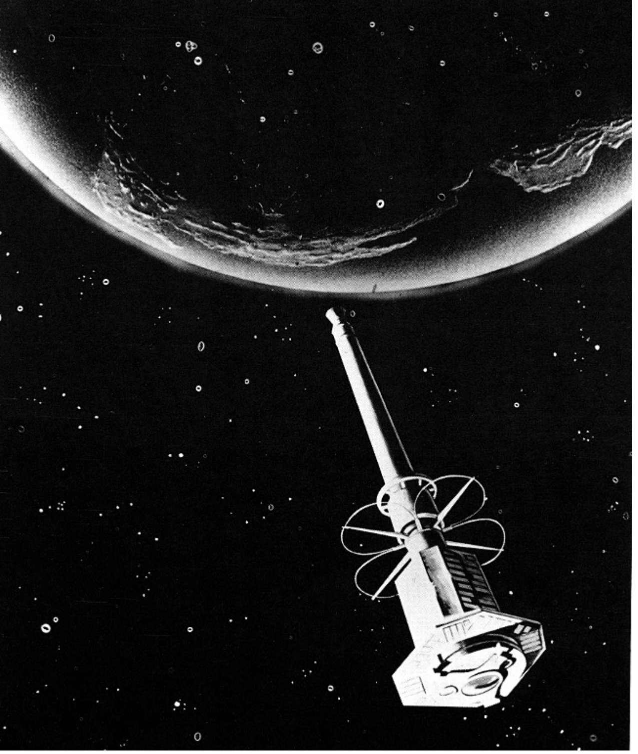
More computers

Observer

Black Holes, compact objects, effects of stellar explosions…

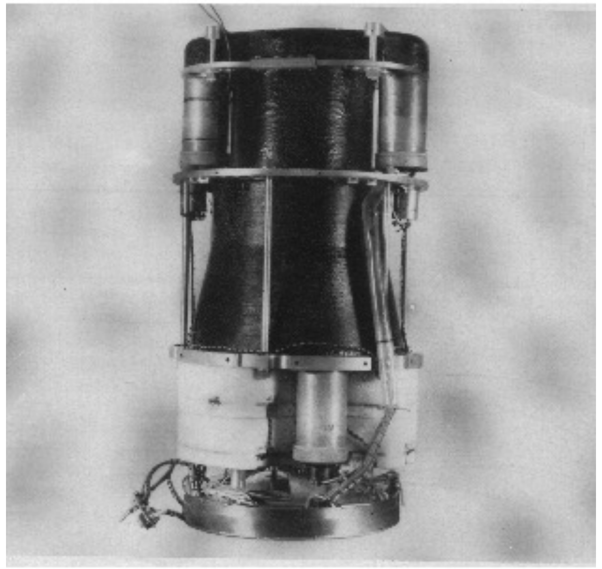


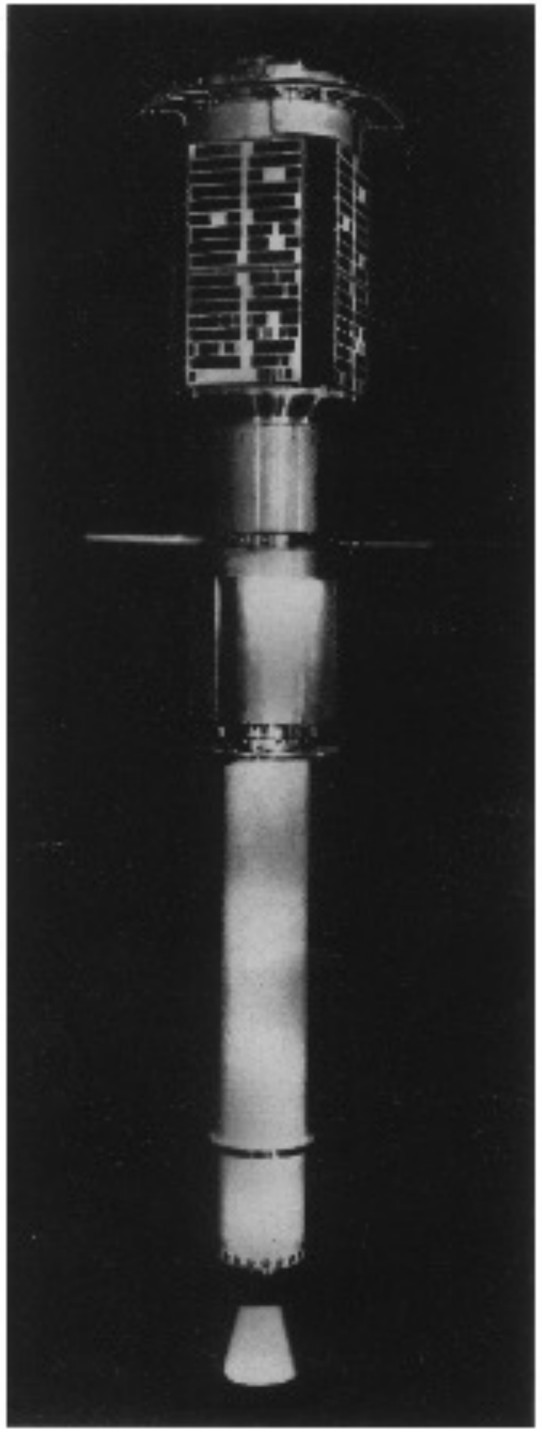
Collecting light through creative absorption



NASA's Explorer XI detected cosmic gamma rays

10 in.



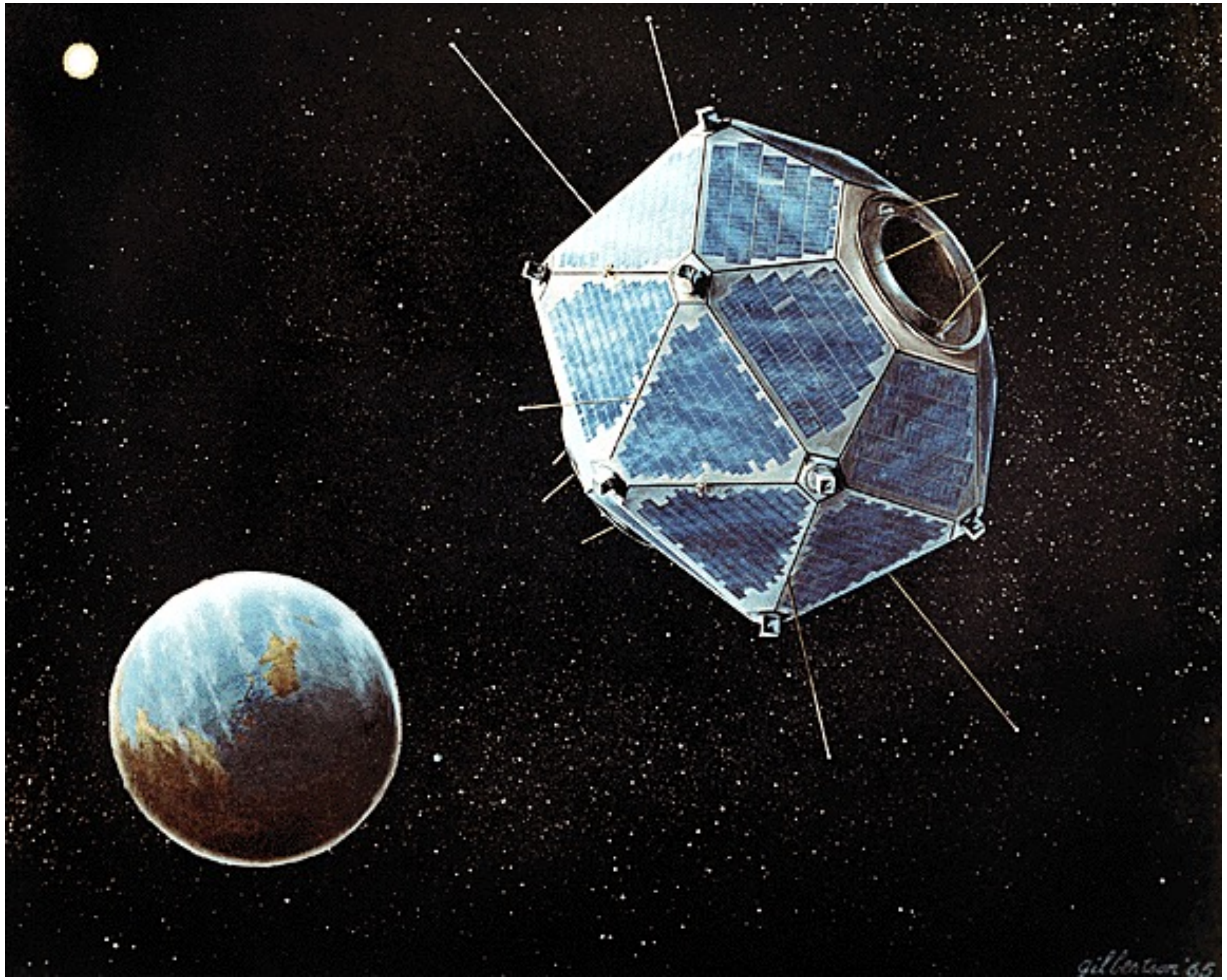


Launched April 1961

- First gamma-ray satellite.
- Flew about 6 months and detected about 30 nonterrestrial gamma rays.
- Detector consisted of sandwich of crystal scintillator, CsI and NaI, in coincidence with a Cherenkov counter

Kraushaar et al., 1965

VELA Program discovers cosmic transients!

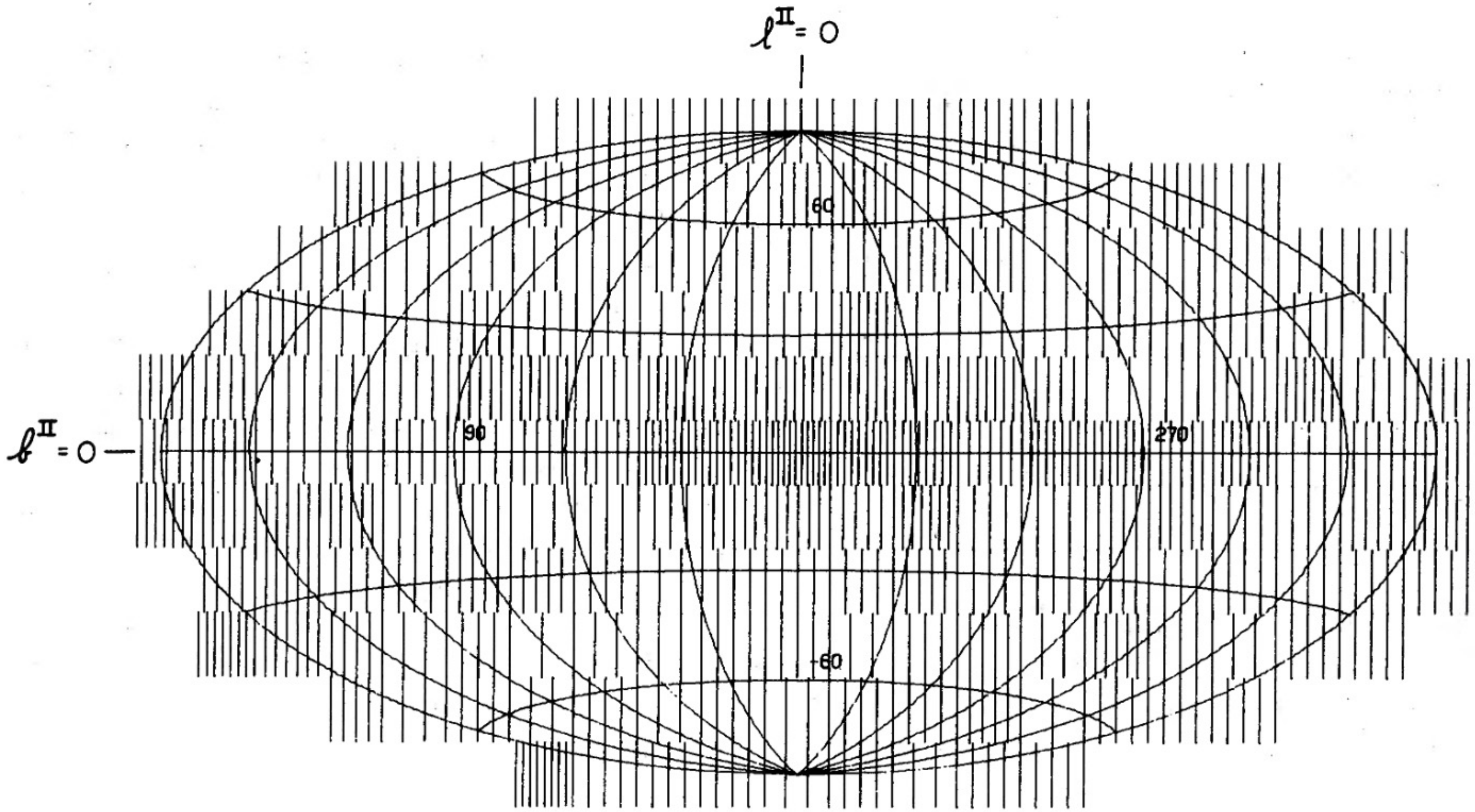


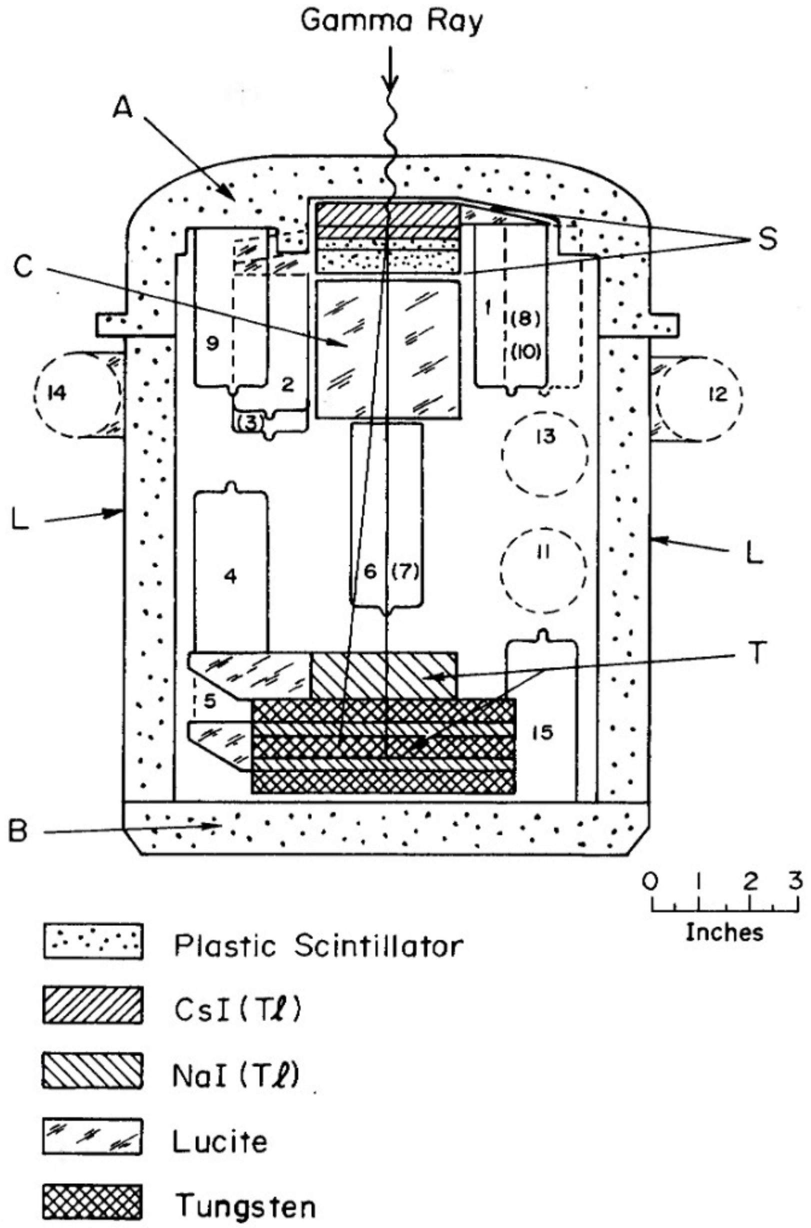
- Vela 5B gamma-ray detector operated from 1969 – 1979.
- Crystal scintillator gamma detectors (NaI and CsI)
- Great for counting, but not much spatial information.

June 1, 2023, was the **50th** anniversary of the discovery paper on gamma-ray bursts

Klebesadel, Strong and Olsen, 1973, ApJ, 182, L85. doi:10.1086/181225 "Observations of Gamma-Ray Bursts of Cosmic Origin."

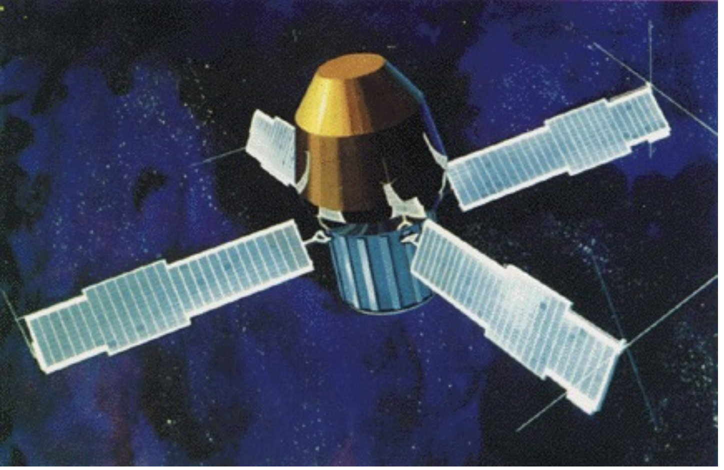
NASA OSO 3 made the first all-sky gamma-ray map



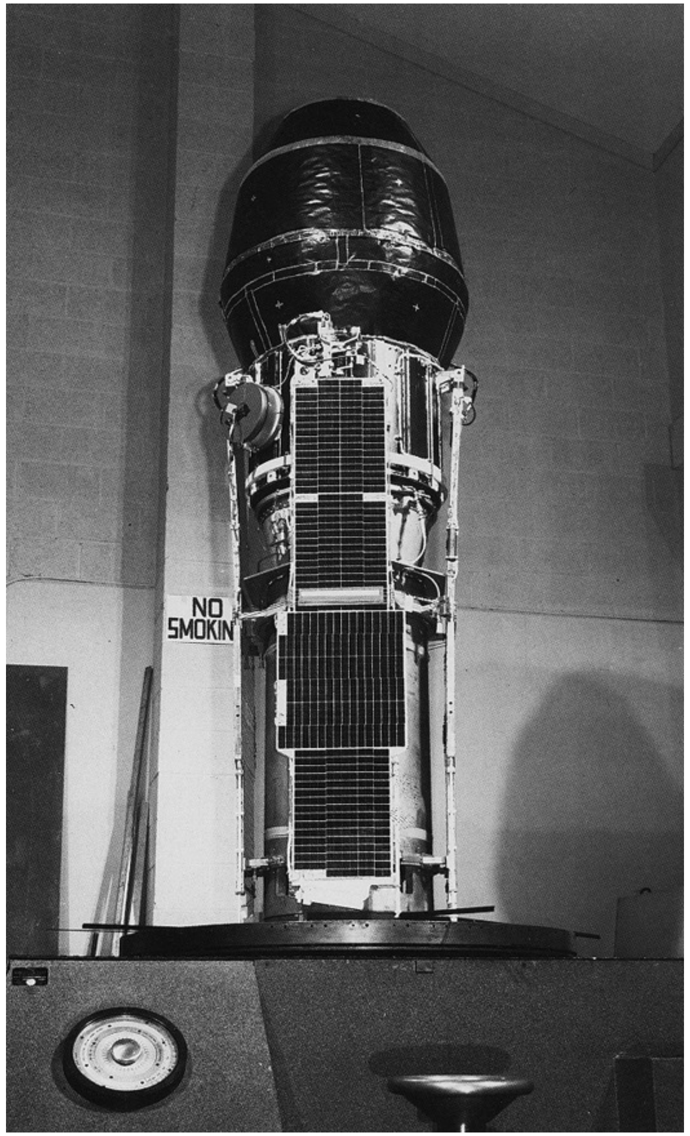


- Operated from March 1967 to July 1968
- Detected 621 gamma rays >50 MeV

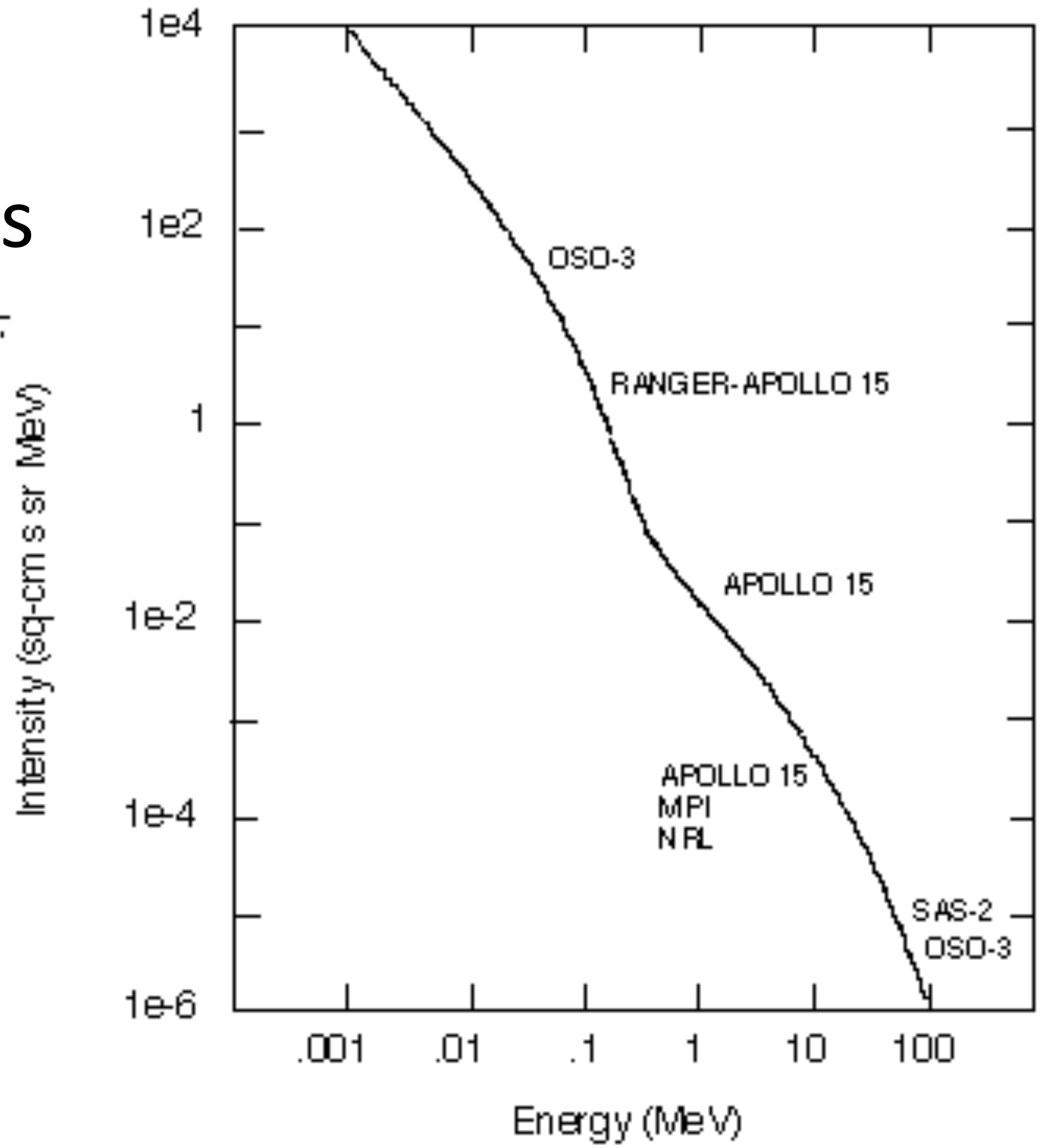
Kraushaar et al., 1972, ApJ, 177, doi:10.1086/151713.



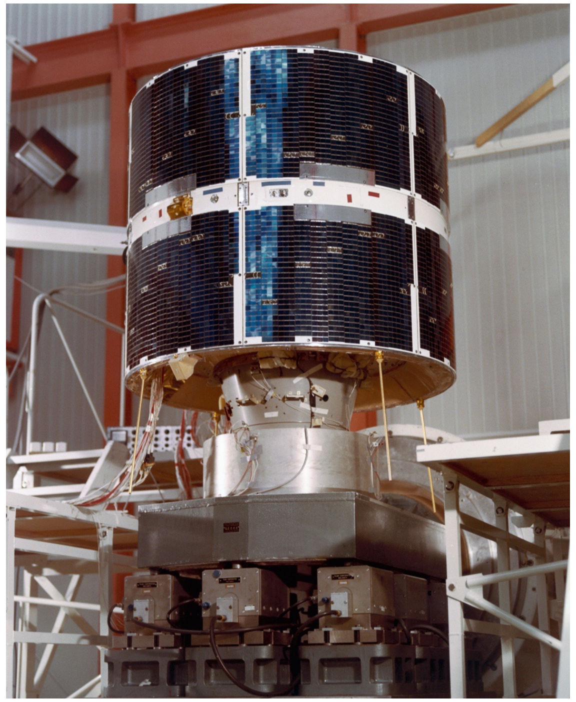
NASA SAS-2 studied Galactic emission



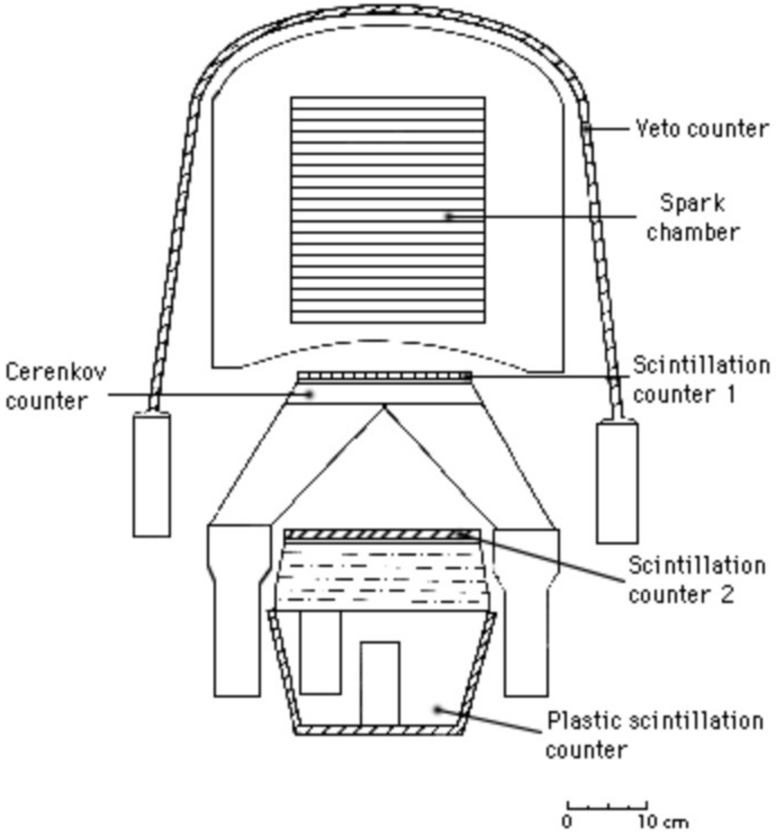
- Nov 1972 – Jun 1973
- 35 MeV – 1 GeV gamma rays
- Emphasis on Galactic plane following OSO-3 results
- Introduced spark chamber for tracking the electron-positron pair
- 4 radio pulsars and Cen A radio galaxy among other sources detected

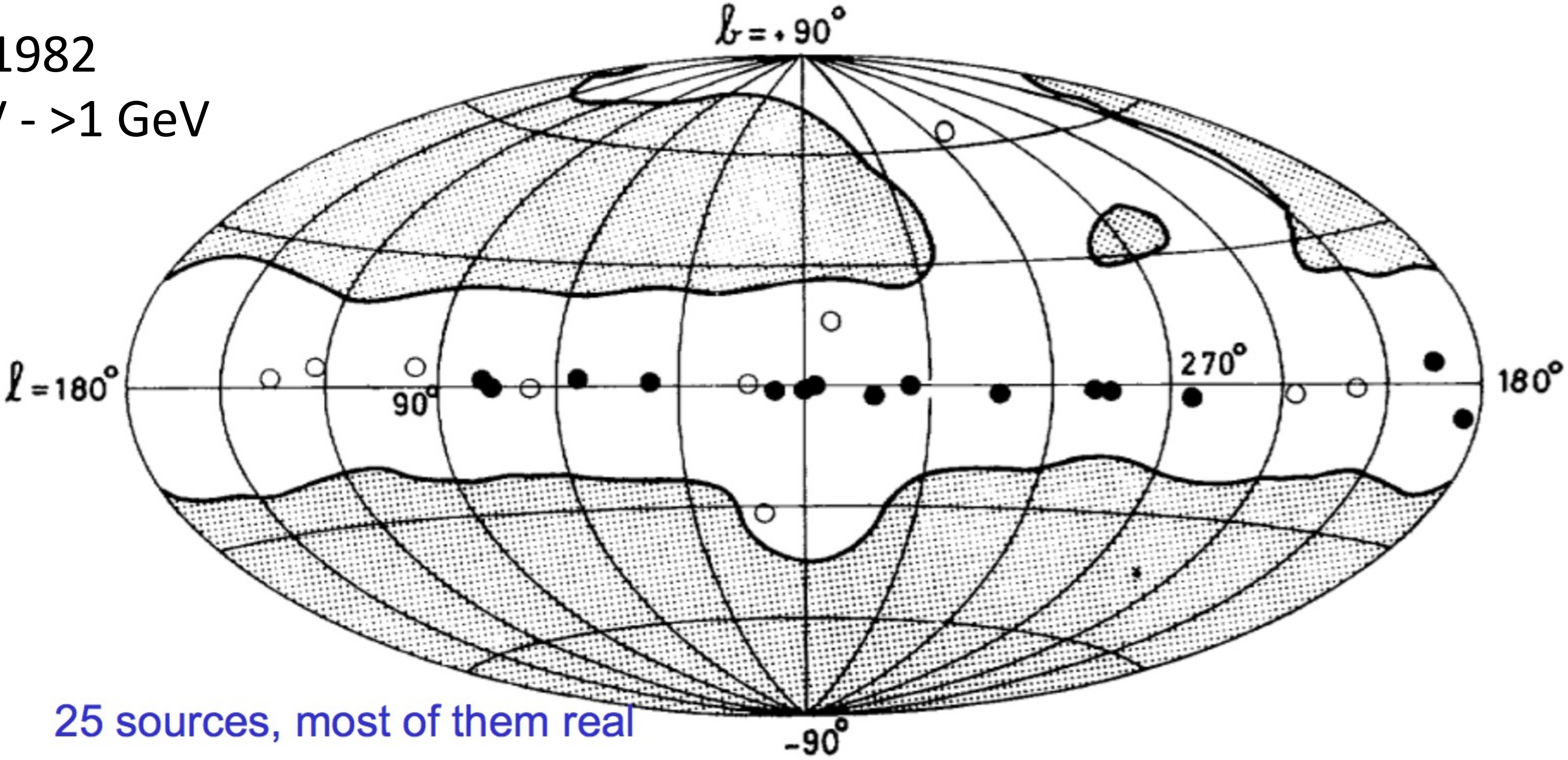


ESA's COS-B catalogued the sky and mapped the Galaxy



1975 - 1982
30 MeV - >1 GeV





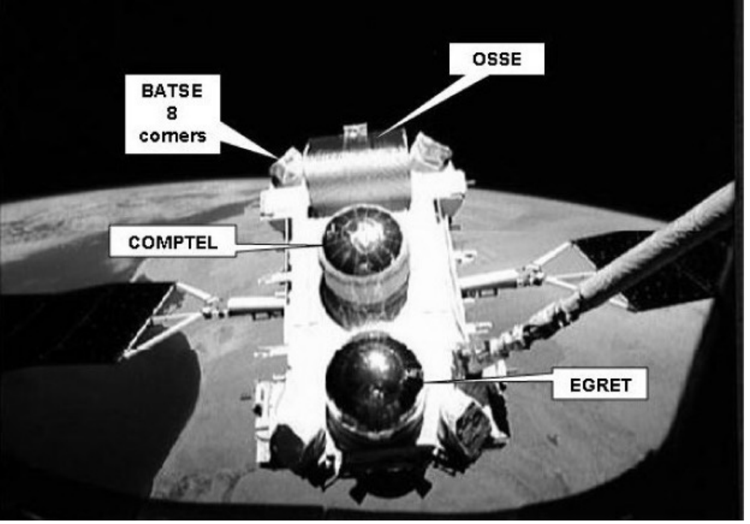
25 sources, most of them real

Swanenburg et al. 1981, ApJ

Balloon Era and SN 1987:
GRIS goes up!

and down…

GRIS – Gamma-ray Imaging Spectrometer flew 9 times between 1988 and 1995. It measured gamma-ray lines from SN 1987A.

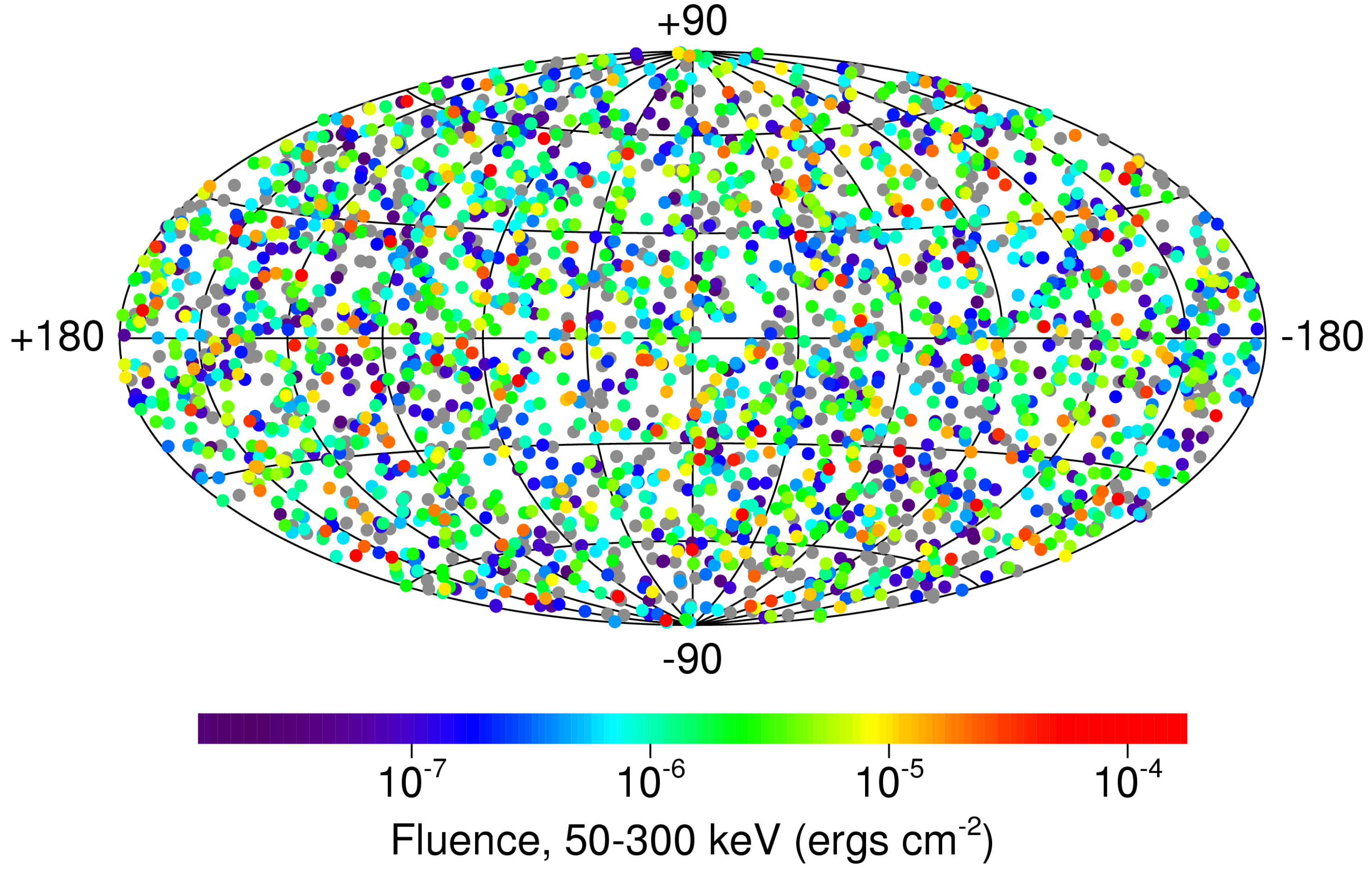


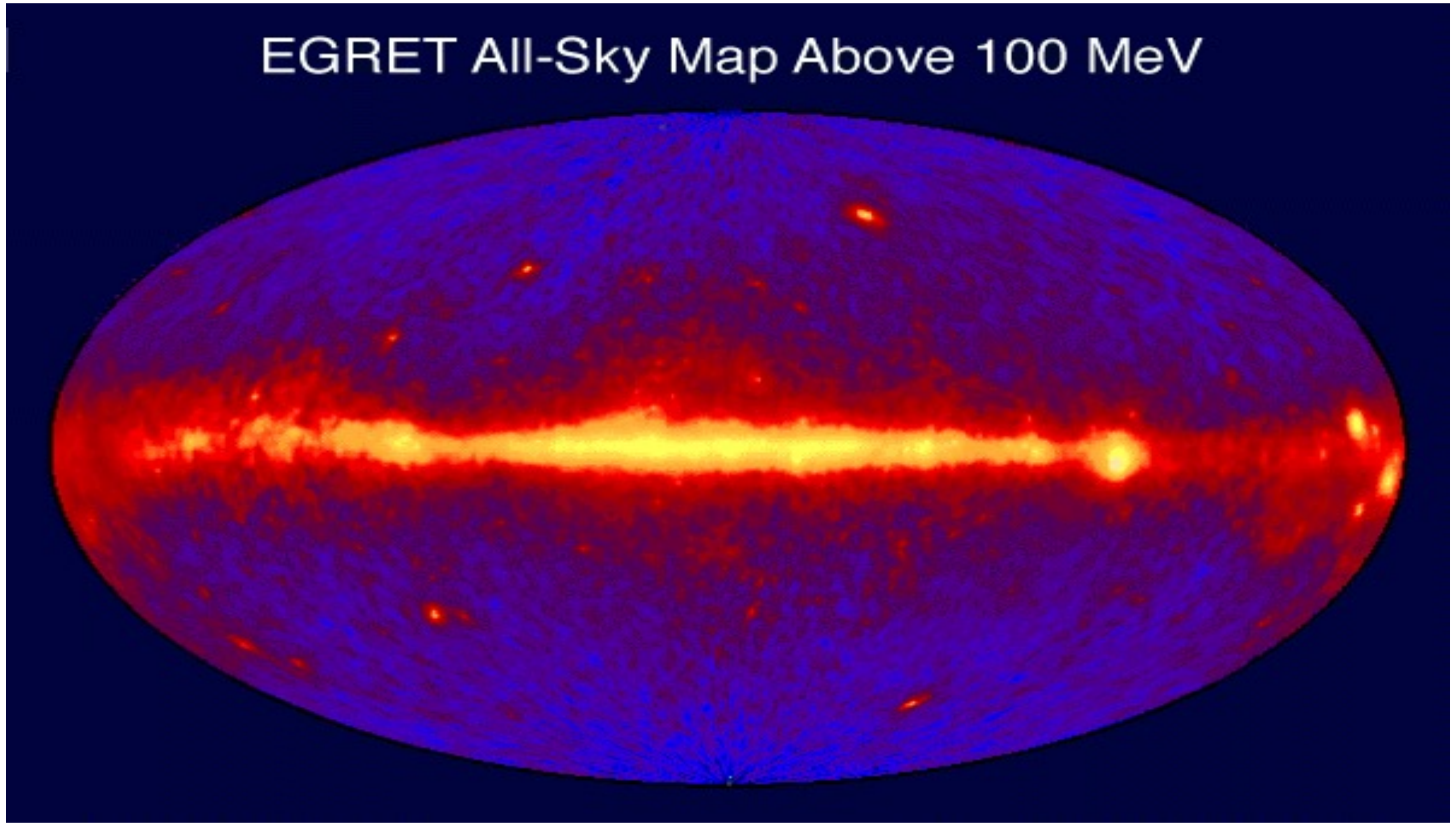
BATSE and EGRET on NASA's Compton Gamma-ray Observatory

1991 – 2000

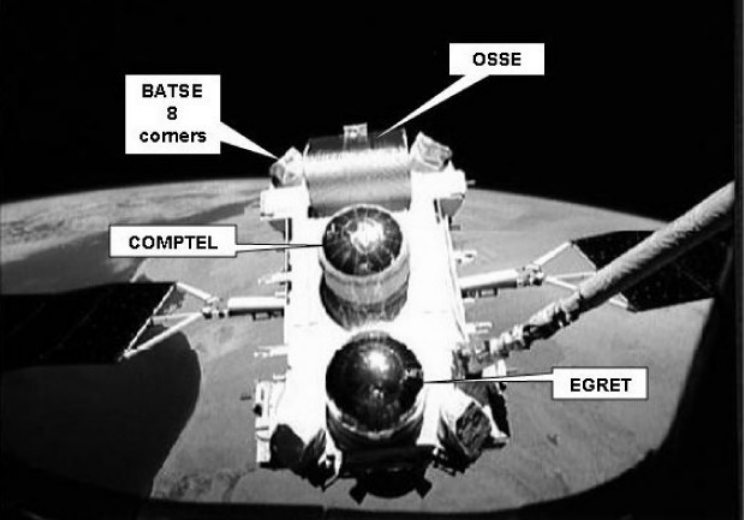
1991 – 1996

2704 BATSE Gamma-Ray Bursts

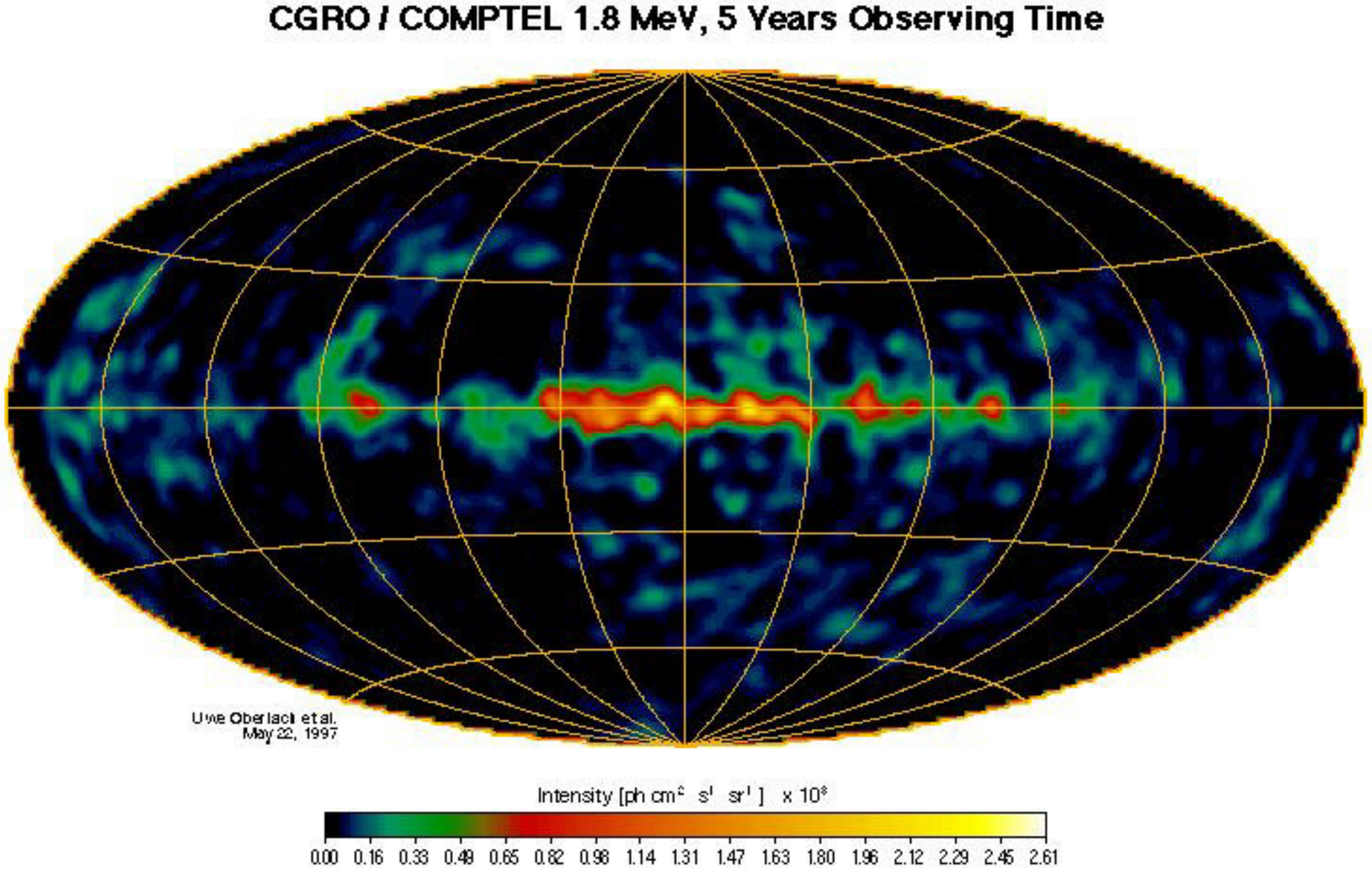


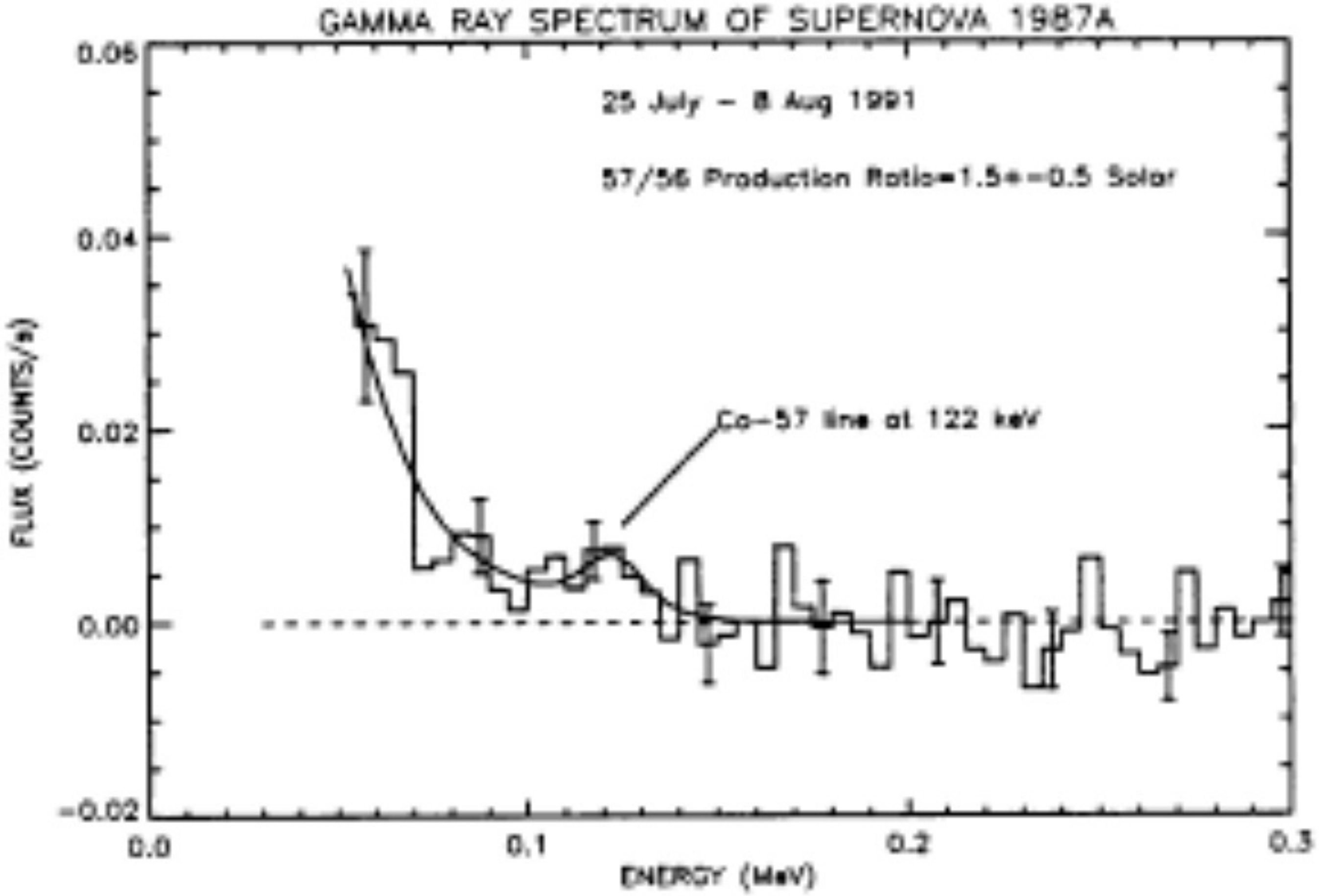


E > 100 MeV intensity map



COMPTEL and OSSE on CGRO



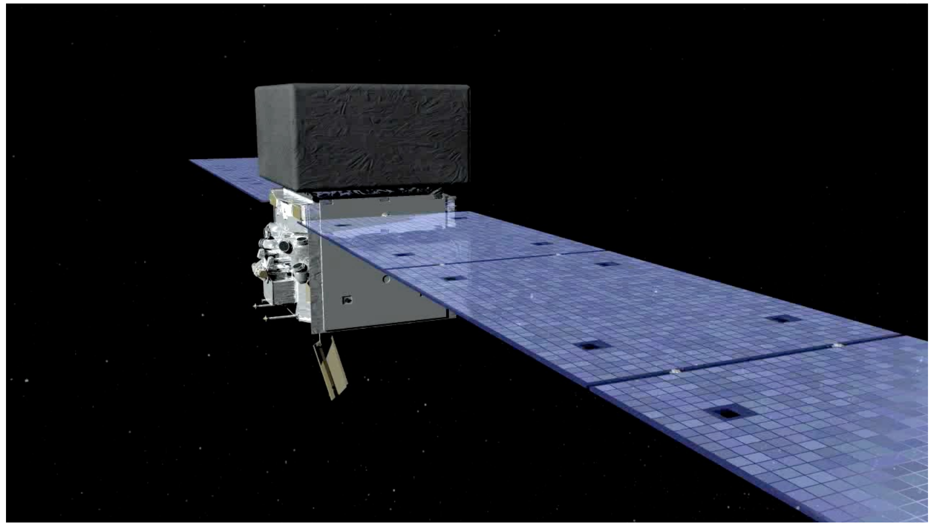


1.8 MeV line emission

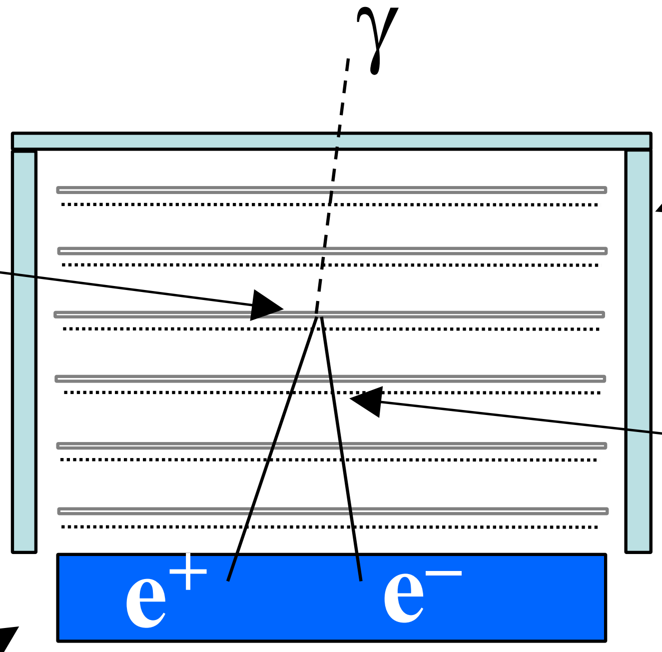
And now back to your regularly scheduled programming

- Physics makes gamma-ray observations hard
  - Gamma-ray telescopes are all about stacking cleverly instrumented materials
  - There is a bright side -- low attenuation makes gamma rays appealing for study of sources obscured at other wavelengths
- Earth's atmosphere requires most of the waveband to be observed from space (but not all!)
- Since the 1960s, we have learned that
  - The gamma-ray sky is highly variable even on very short timescales
  - Numerous sources from within our Galaxy and even distant extragalactic objects across the cosmos emit impressively short wavelengths
  - How do they do that? Stay tuned.

LAT is a Pair Conversion Telescope



Gamma ray **converts** to an e^+ e^- pair in a high density foil layer.



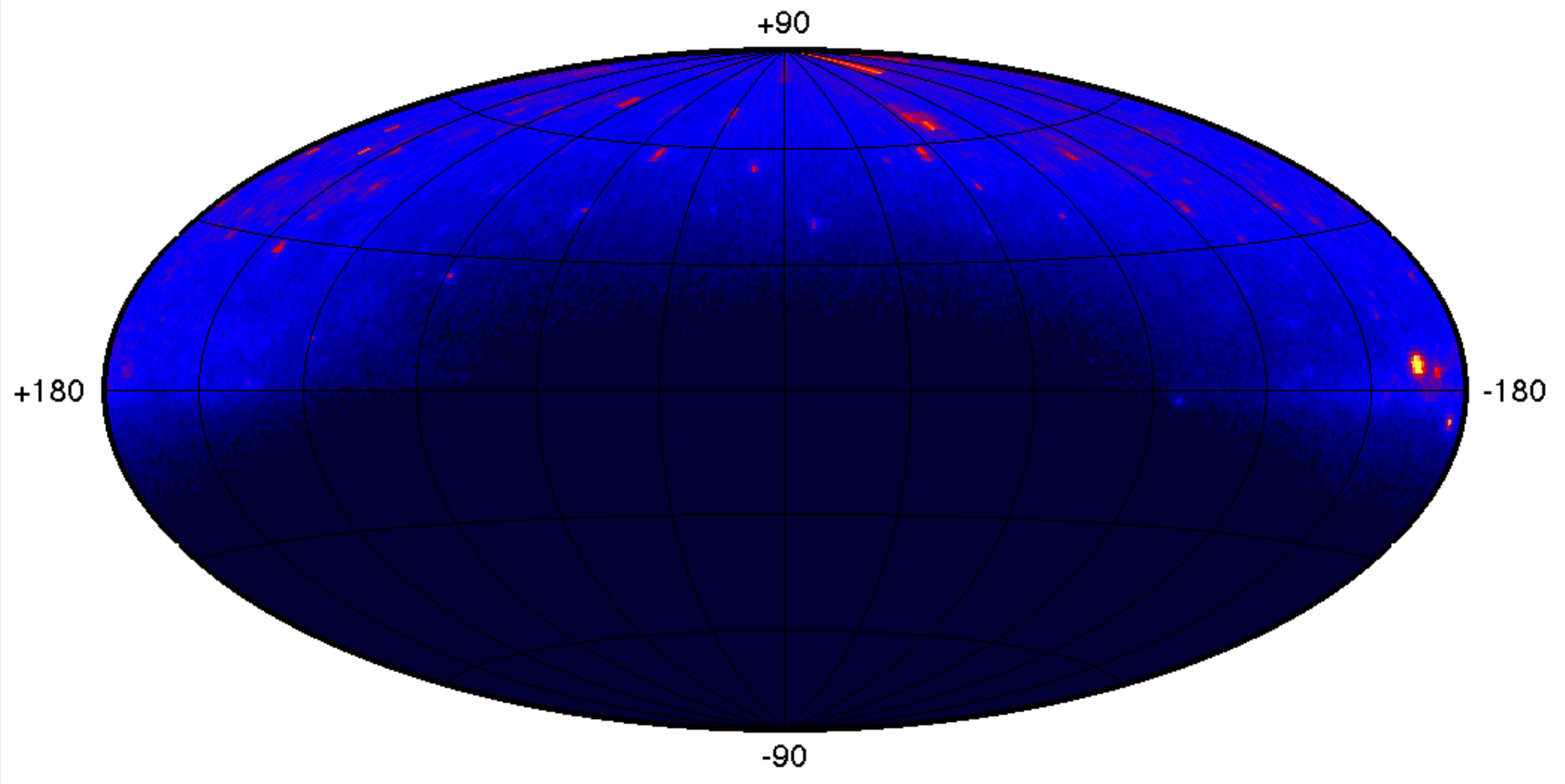
An **anti-coincidence detector** identifies and rejects incoming charged particles.

The **tracks** of charged particles in the instrument are recorded by sensors.

The photon energy is determined from measured energy deposited in the **calorimeter**.

The tracks are used to determine the direction of the gamma-ray source.

LAT Sky Coverage

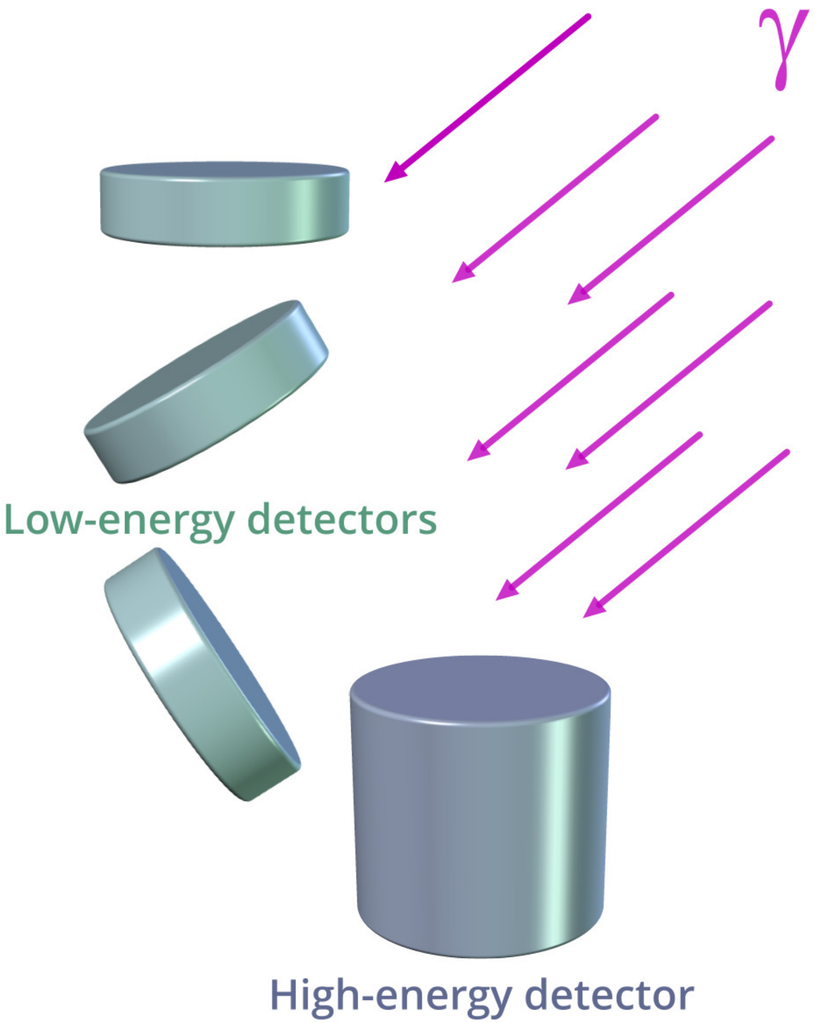


Gamma-ray Burst Monitor Detectors

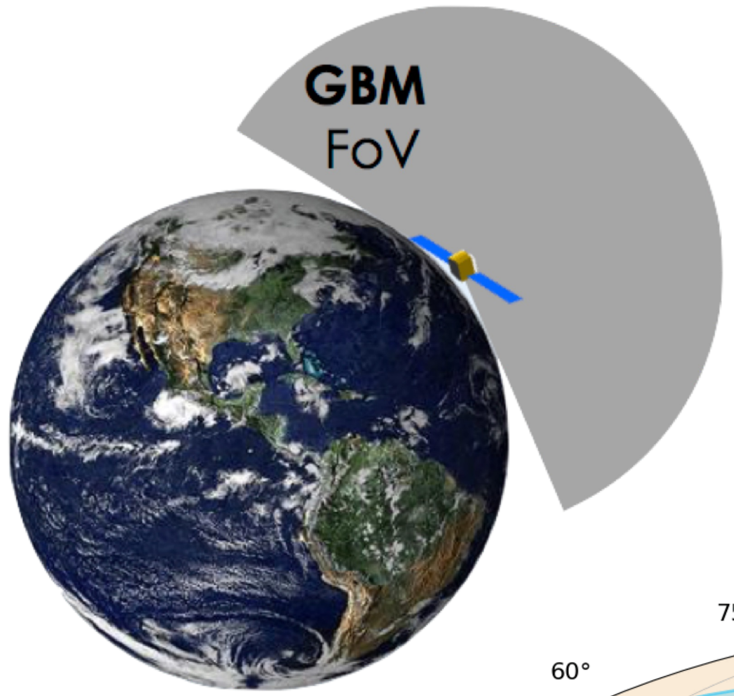
The GBM detectors are made of scintillator material, sodium iodide (NaI) or bismuth germanate (BGO), that produce light when gamma rays strike them.

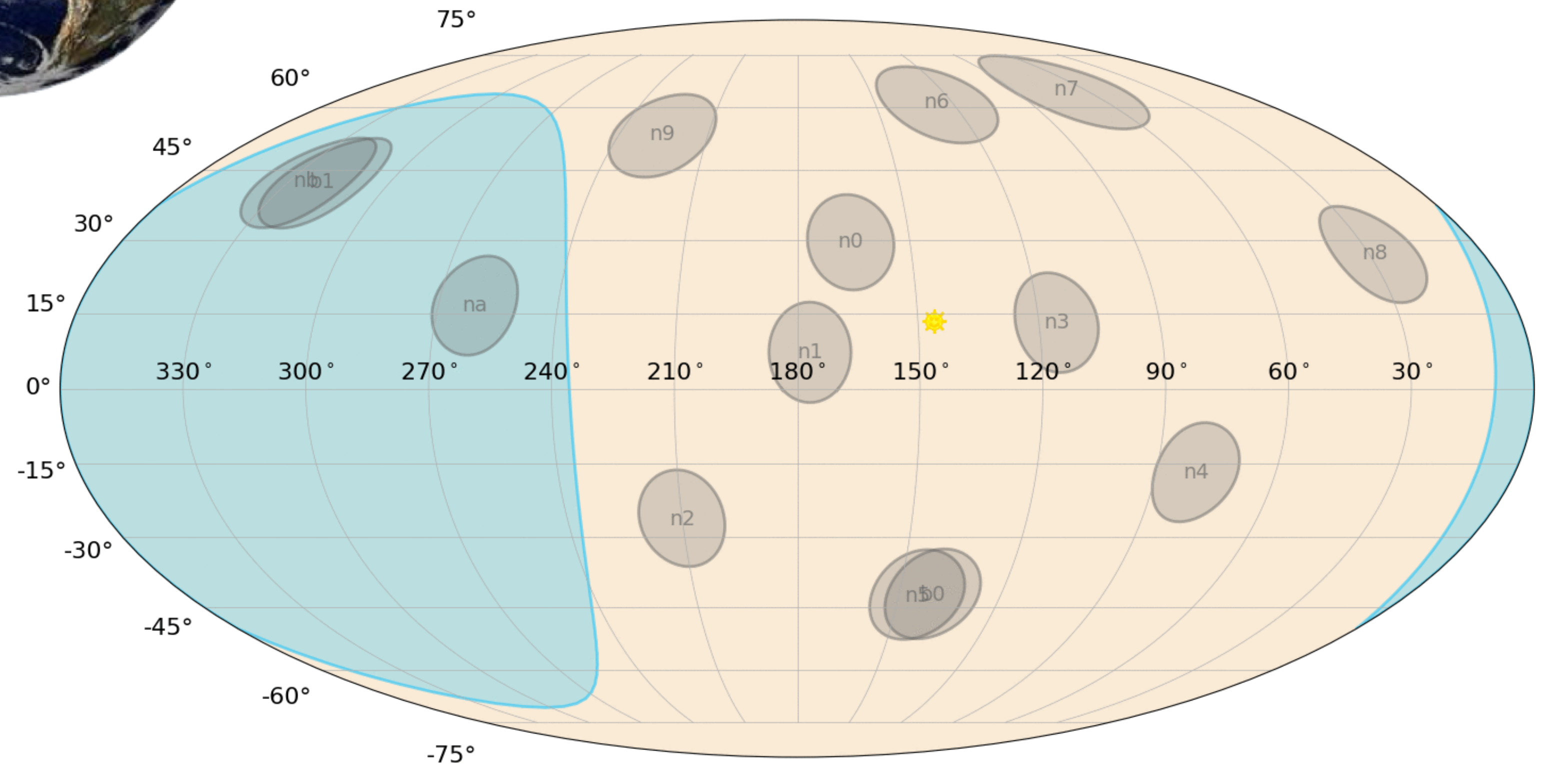
The low-energy detectors (NaI) are placed in different positions and directions. Transients are located using the difference in gamma-ray rates.

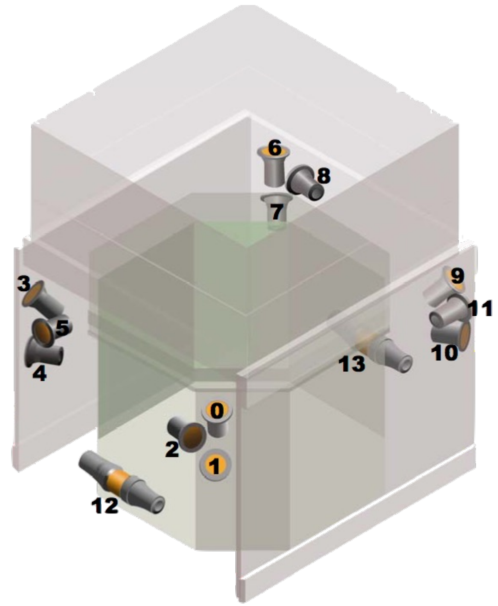
The high-energy detectors (BGO) provide sensitive spectral information that overlaps with the NaI detectors and extends measurements to higher energy.



GBM Sky Coverage



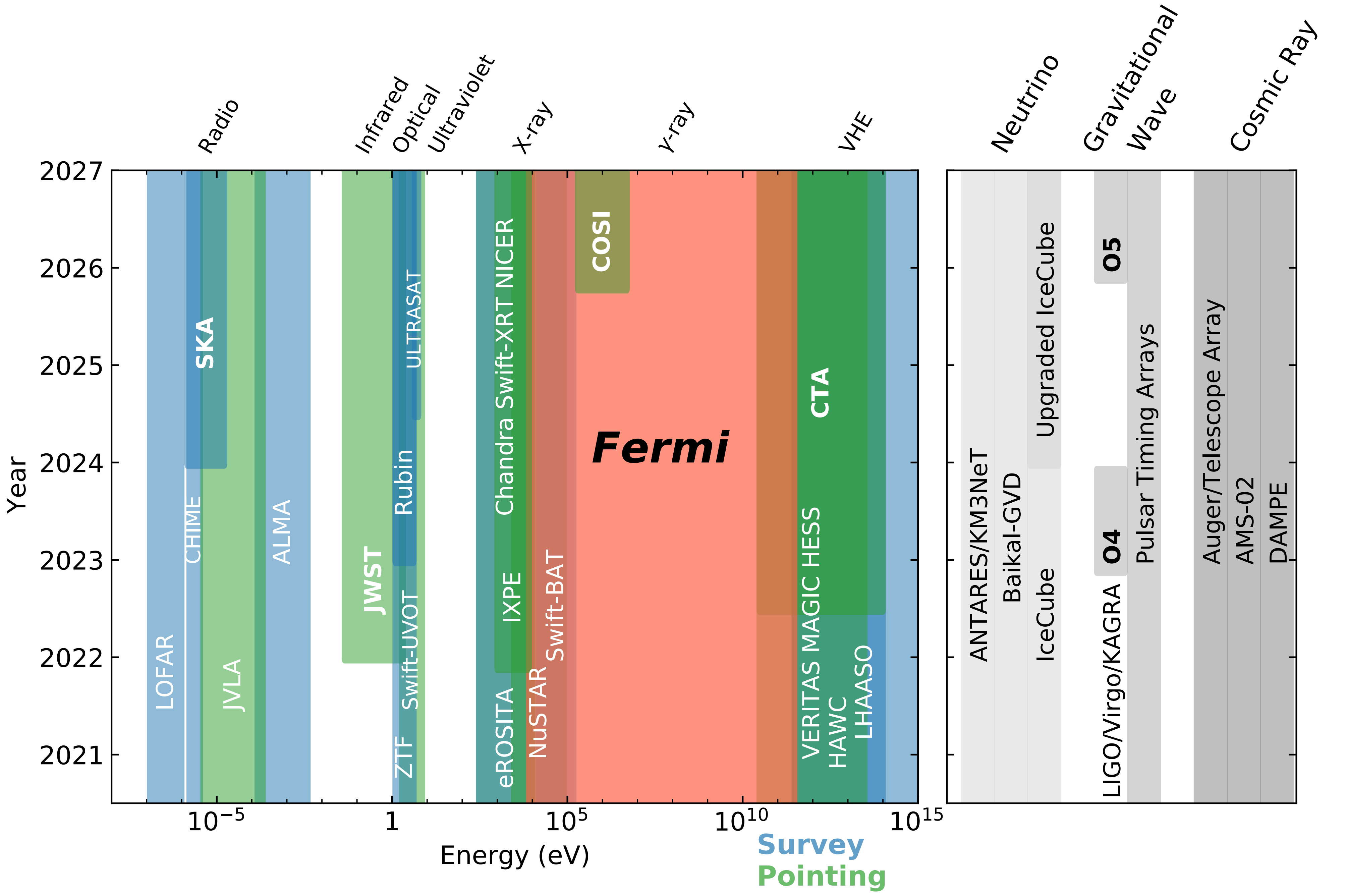




GBM instantaneous field of view: ~70% of the sky

~87% uptime (off during South Atlantic Anomaly)

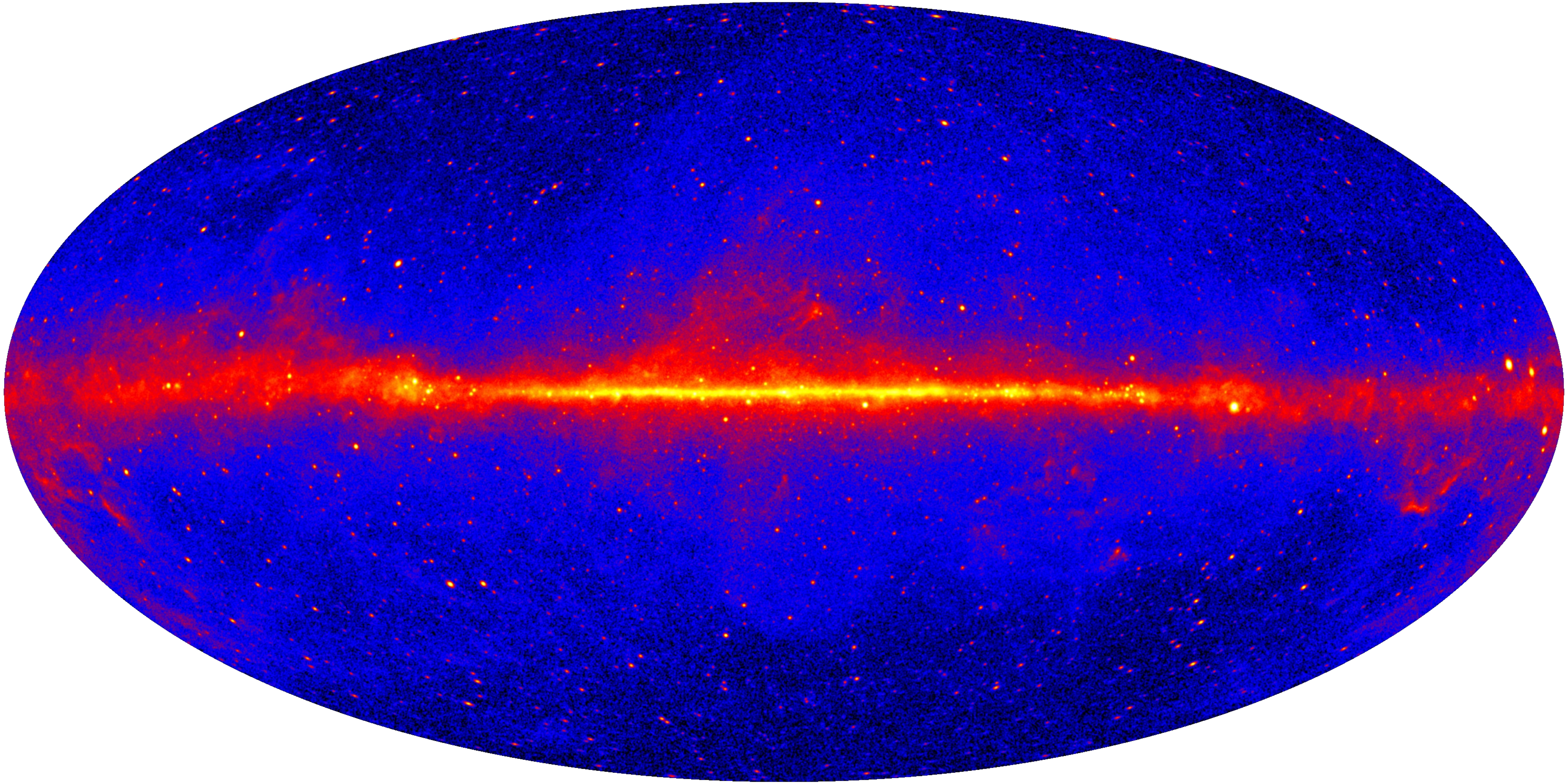
Fermi's spectral coverage



Fermi instruments cover **8 decades** of the electromagnetic spectrum.

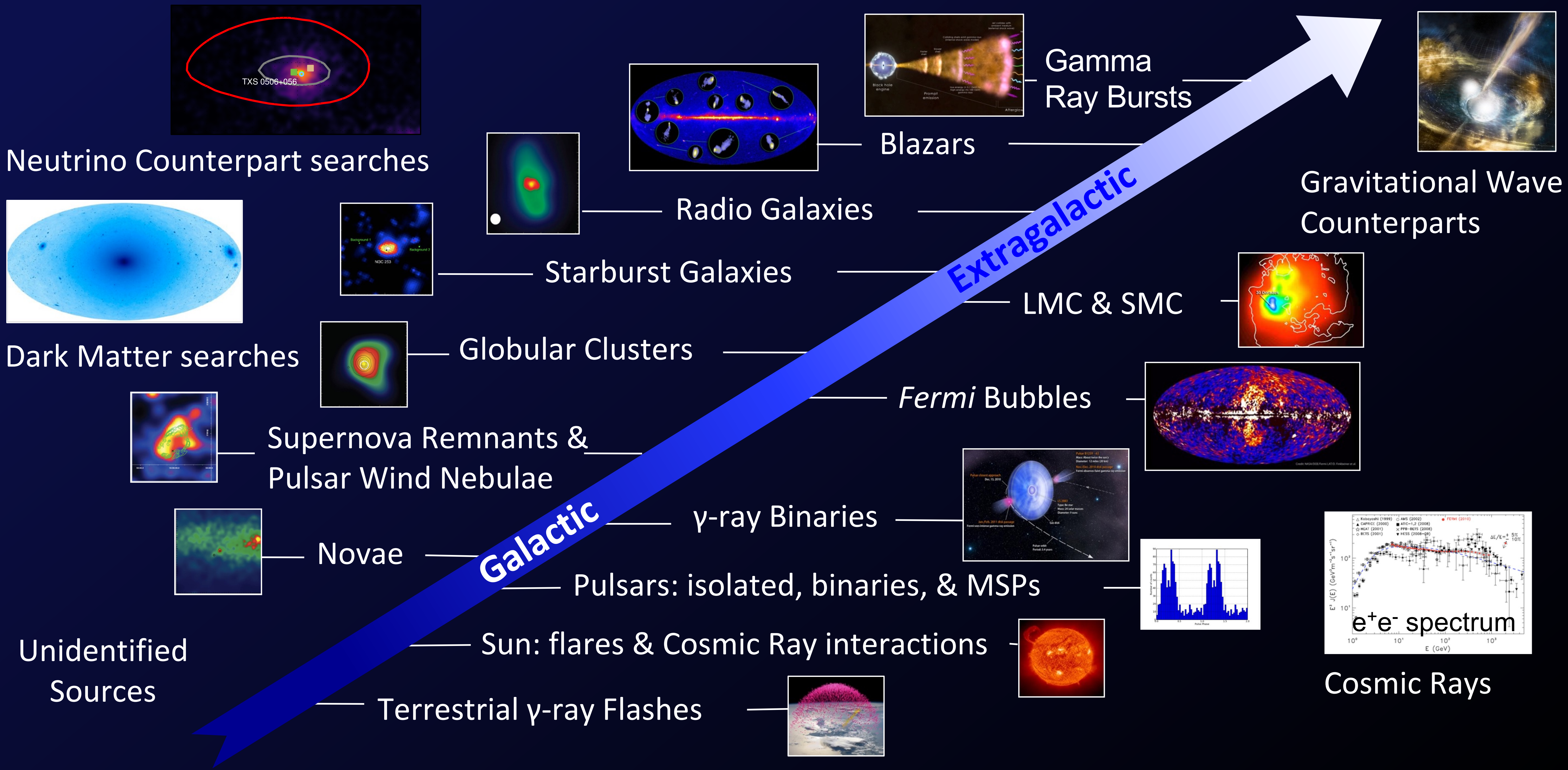
Fermi results complement observations across the full spectrum and beyond.

The Fermi Sky

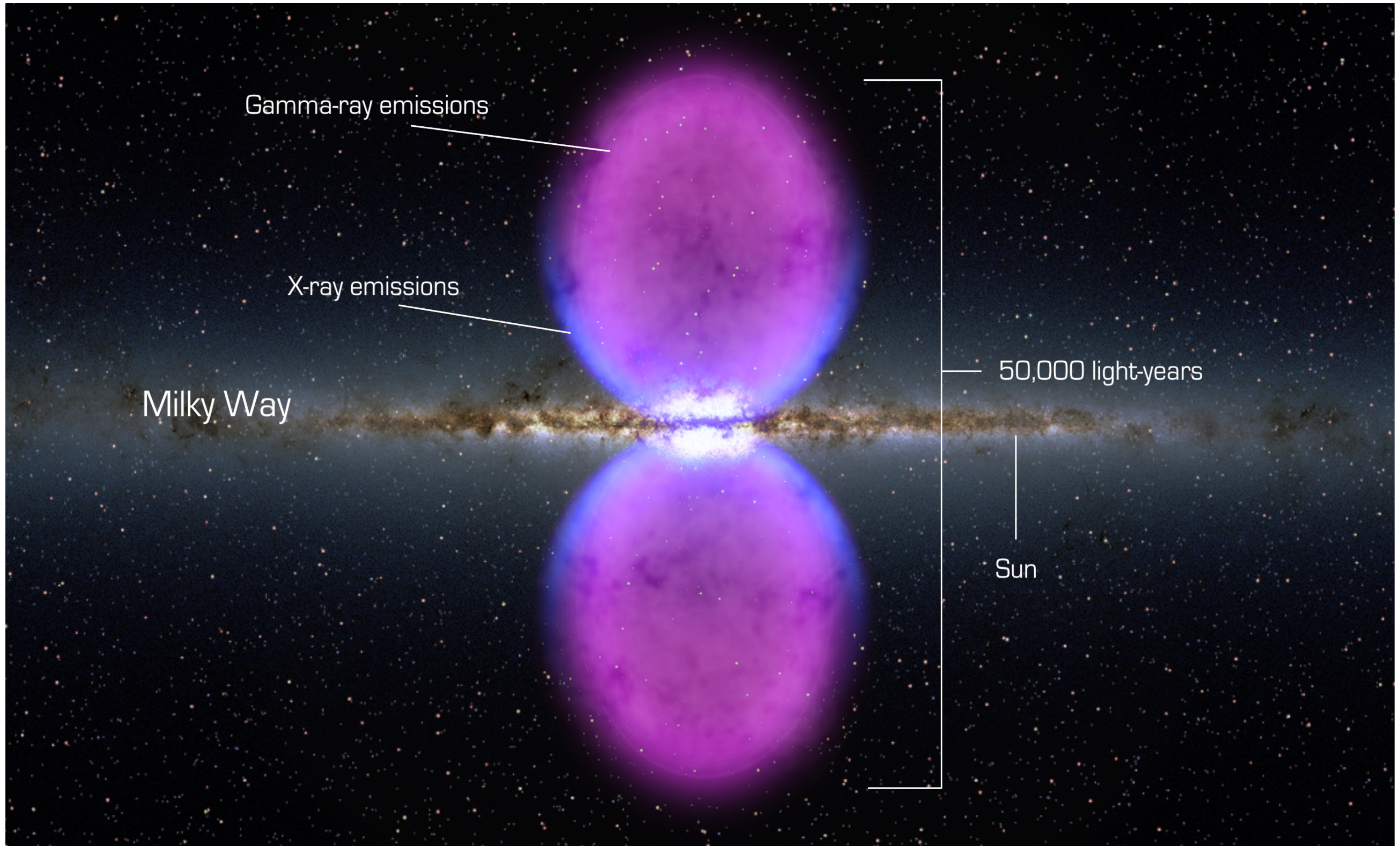


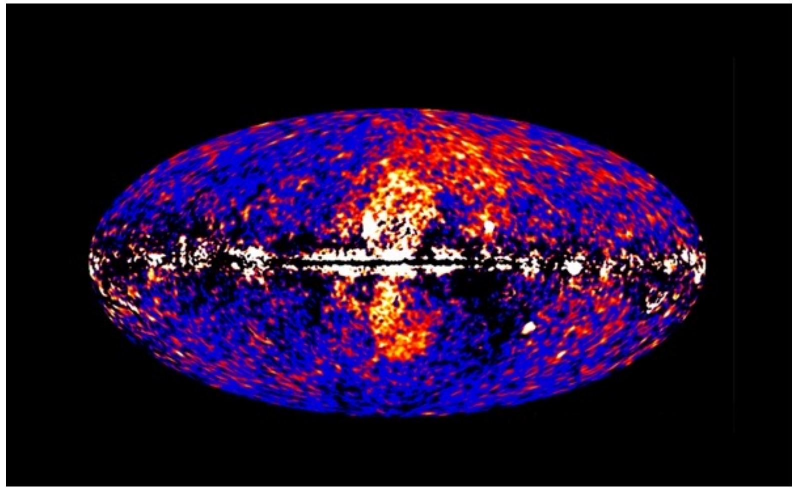
Fermi LAT, Energy > 1 GeV, 12 years of data (7,464,664 photons)

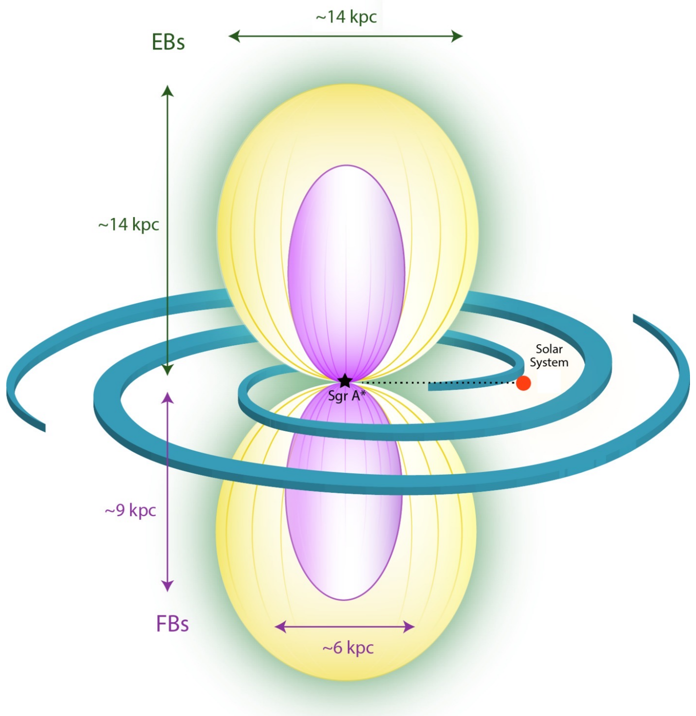
Fermi's Science Menu



The Fermi Bubbles:
Evidence of past activity in the center of the Milky Way



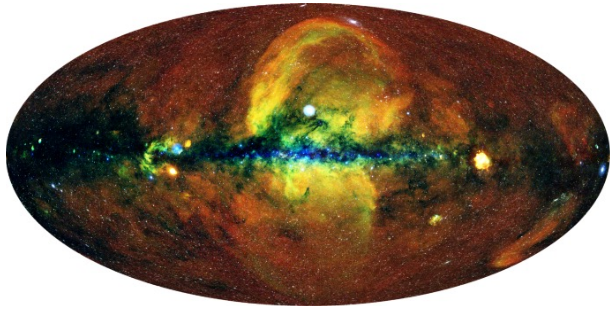




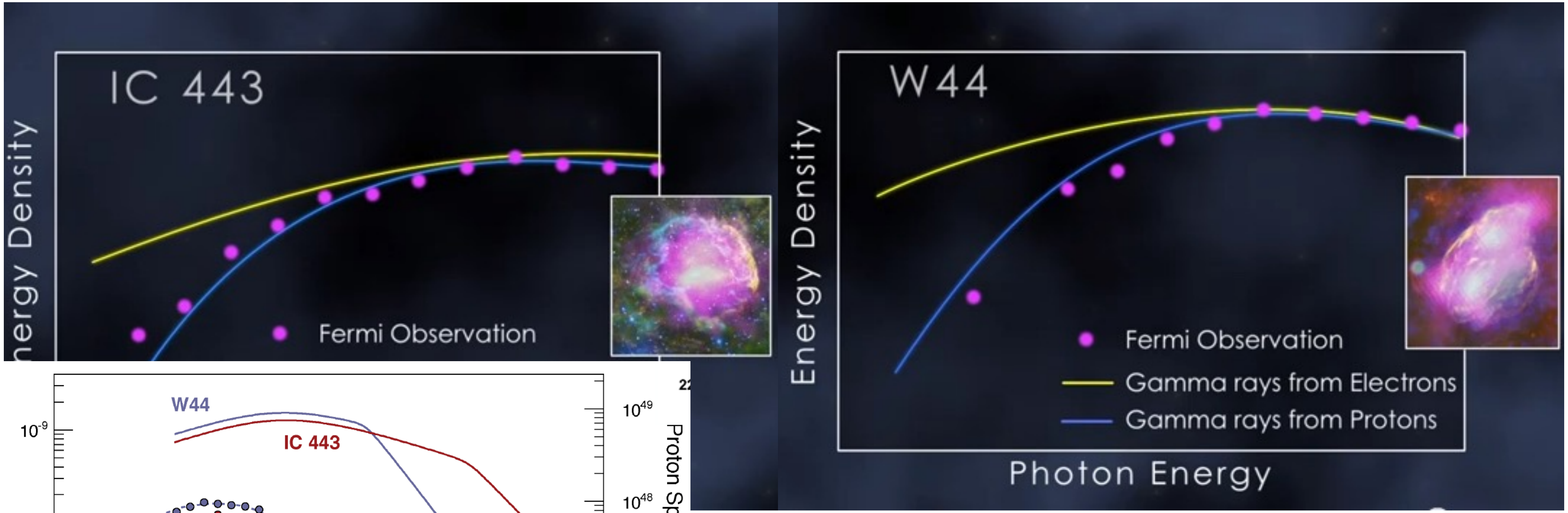
Su, Slatyer, Finkbeiner, 2010, ApJ

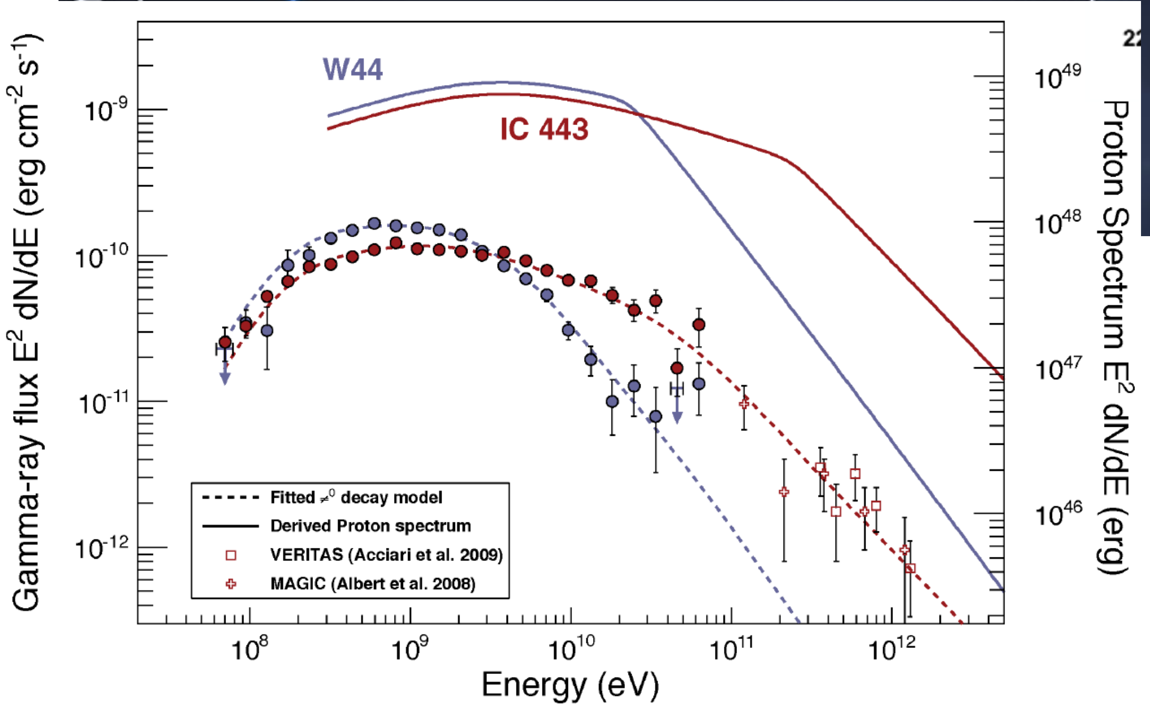
Detected in x-rays by eROSITA!

Predehl et al. 2020, Nature



Supernova Remnants, Pulsar Wind Nebulae, and gamma-ray binaries probe Galactic particle acceleration





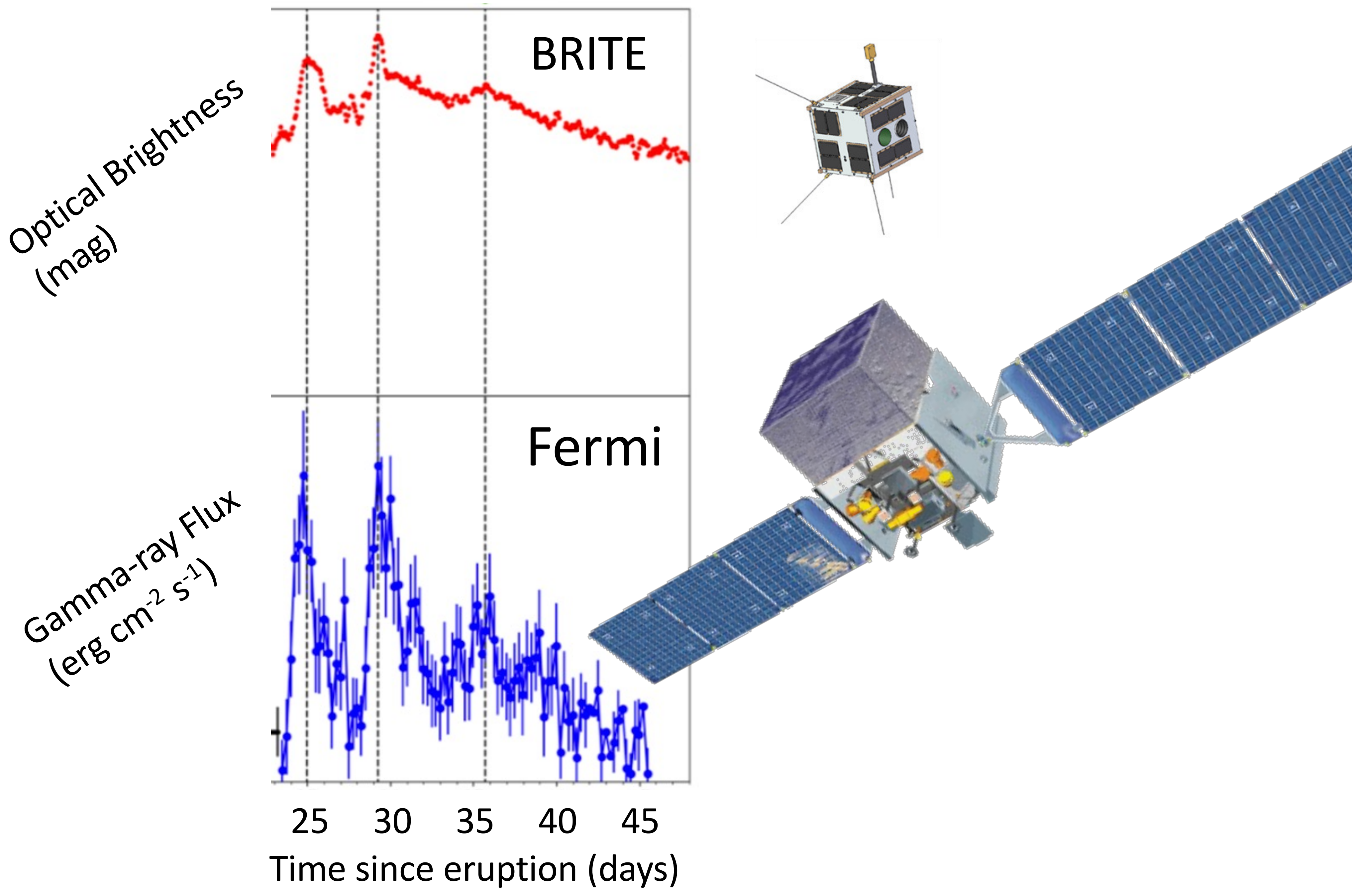
Abdo+ 2010, Science

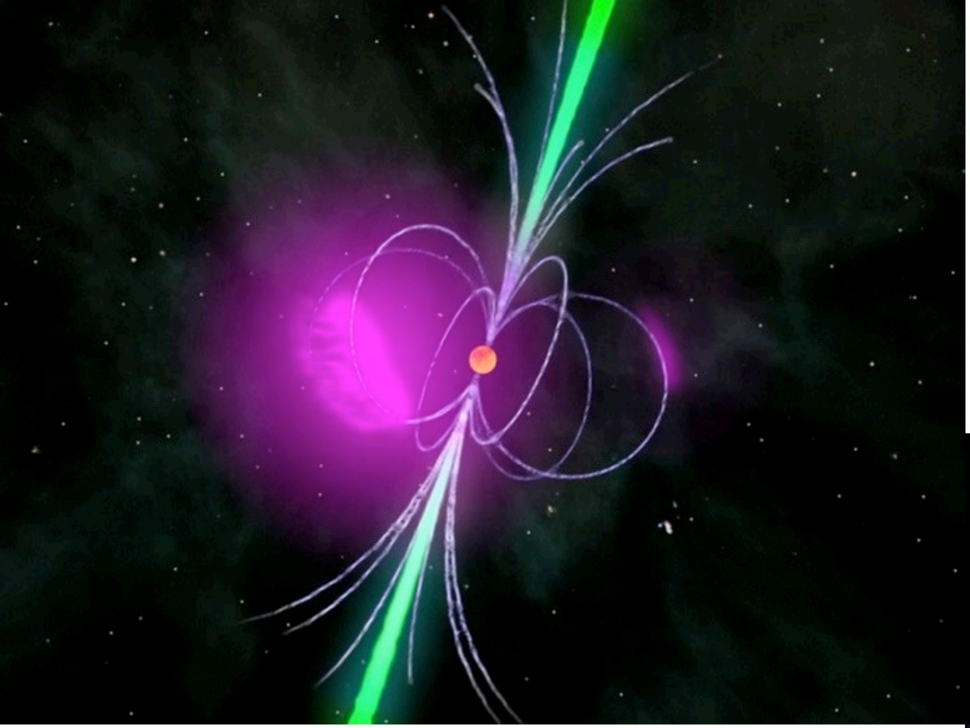
Ackermann+ 2013

Optical and gamma-ray signals reveal a common origin in novae

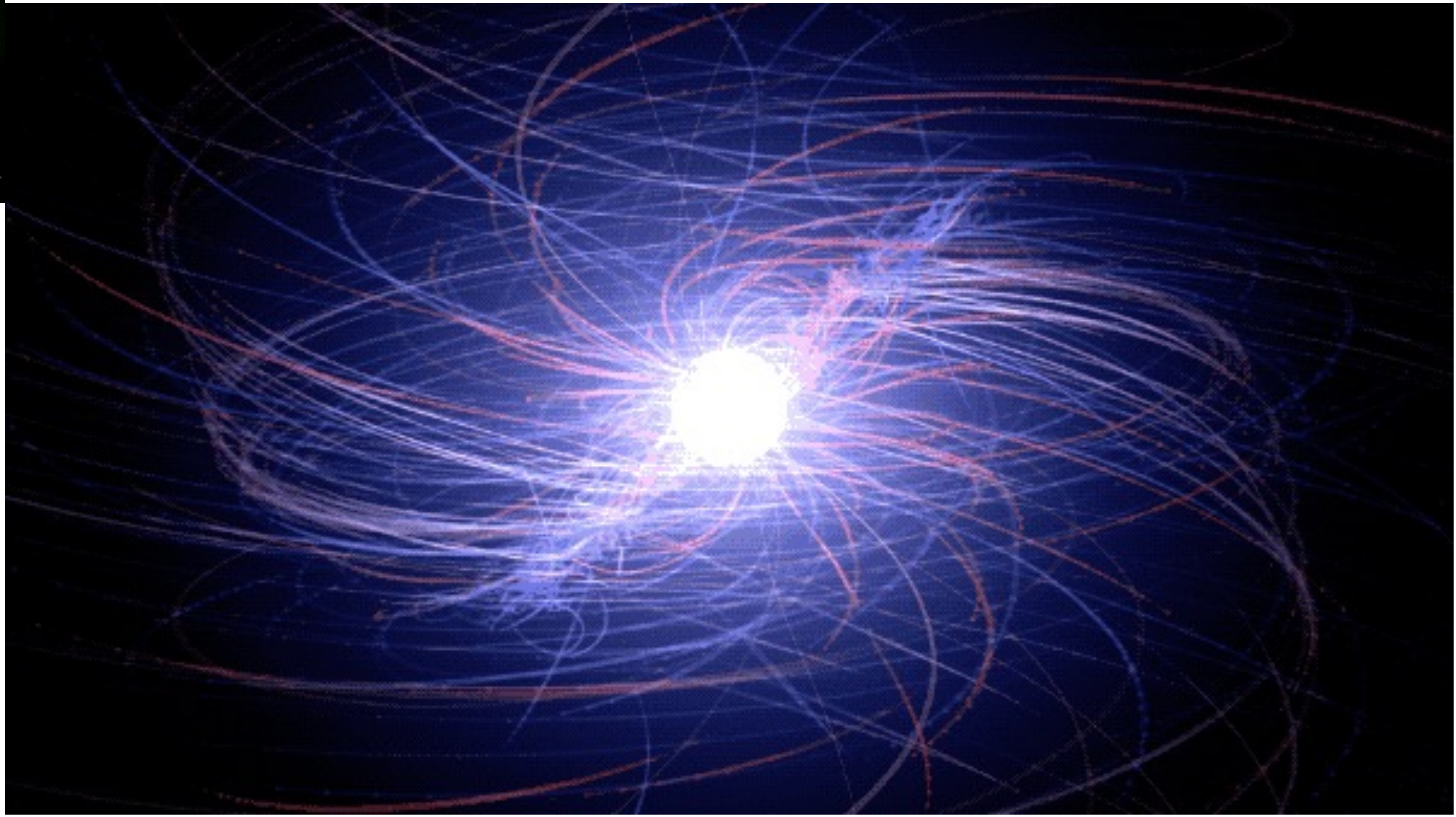
Most of the optical light from the nova comes from the shockwave producing the gamma rays

Aydi et al. 2020, *Nature Astronomy*





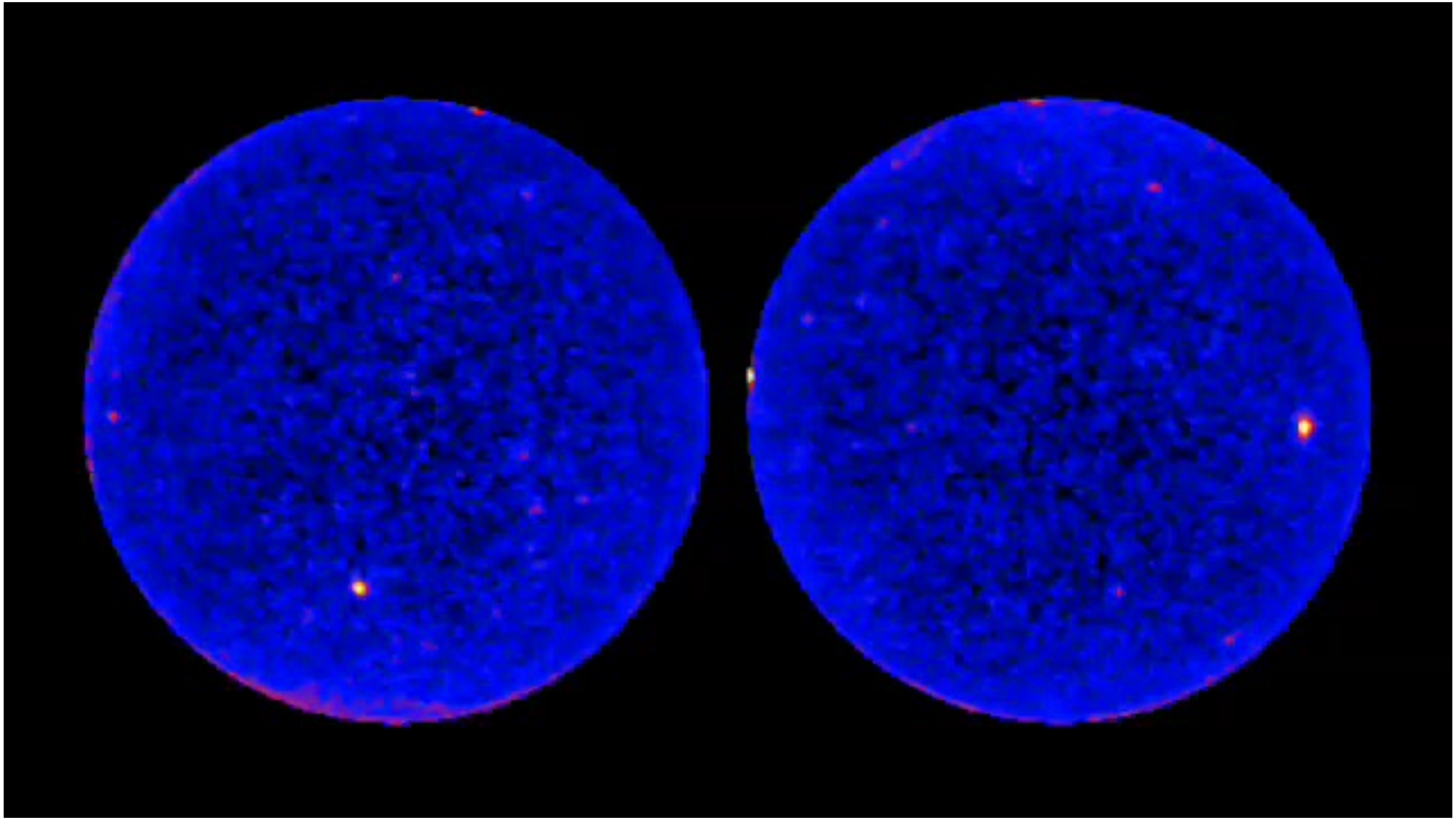
Pulsars are particle accelerating machines



Link

NASA Goddard Space Flight Center

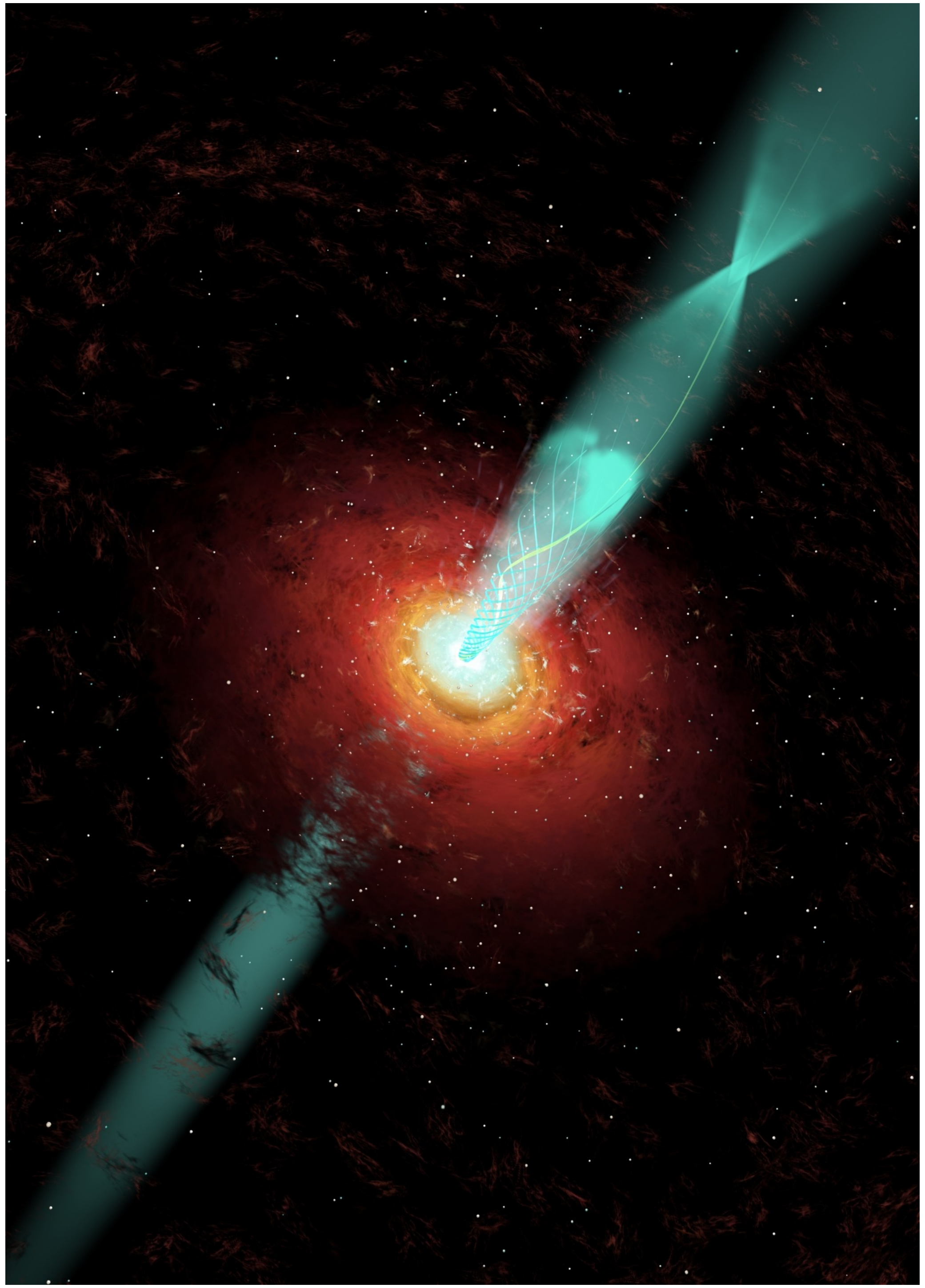
The Dynamic Gamma-ray Sky

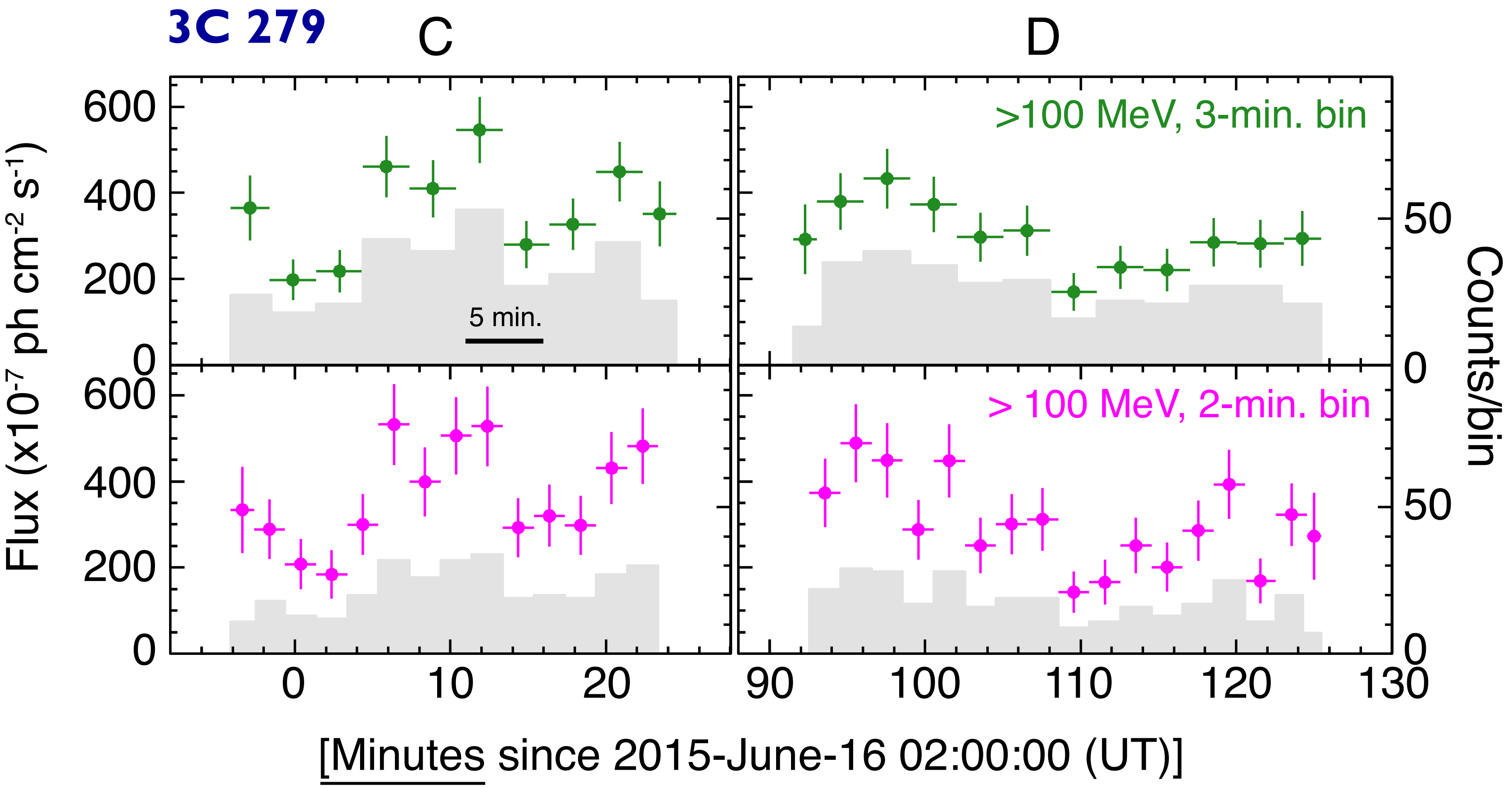


Northern Hemisphere Southern Hemisphere

This movie shows 1 day frames of LAT data over 1 year

Gamma-ray blazars reveal supermassive black hole activity



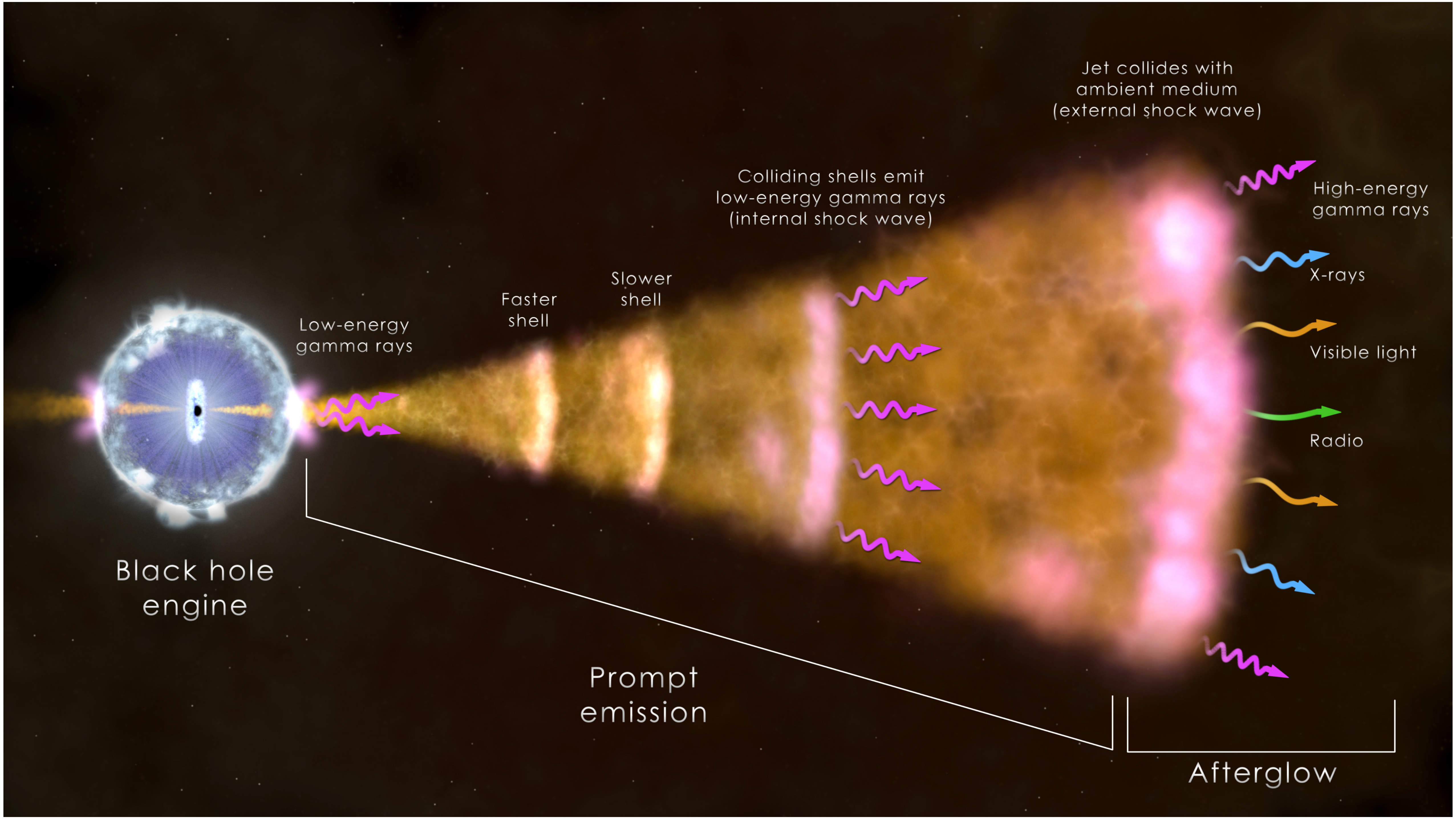


Variability over minutes probes very small regions within a plasma jet 5 billion light years away.

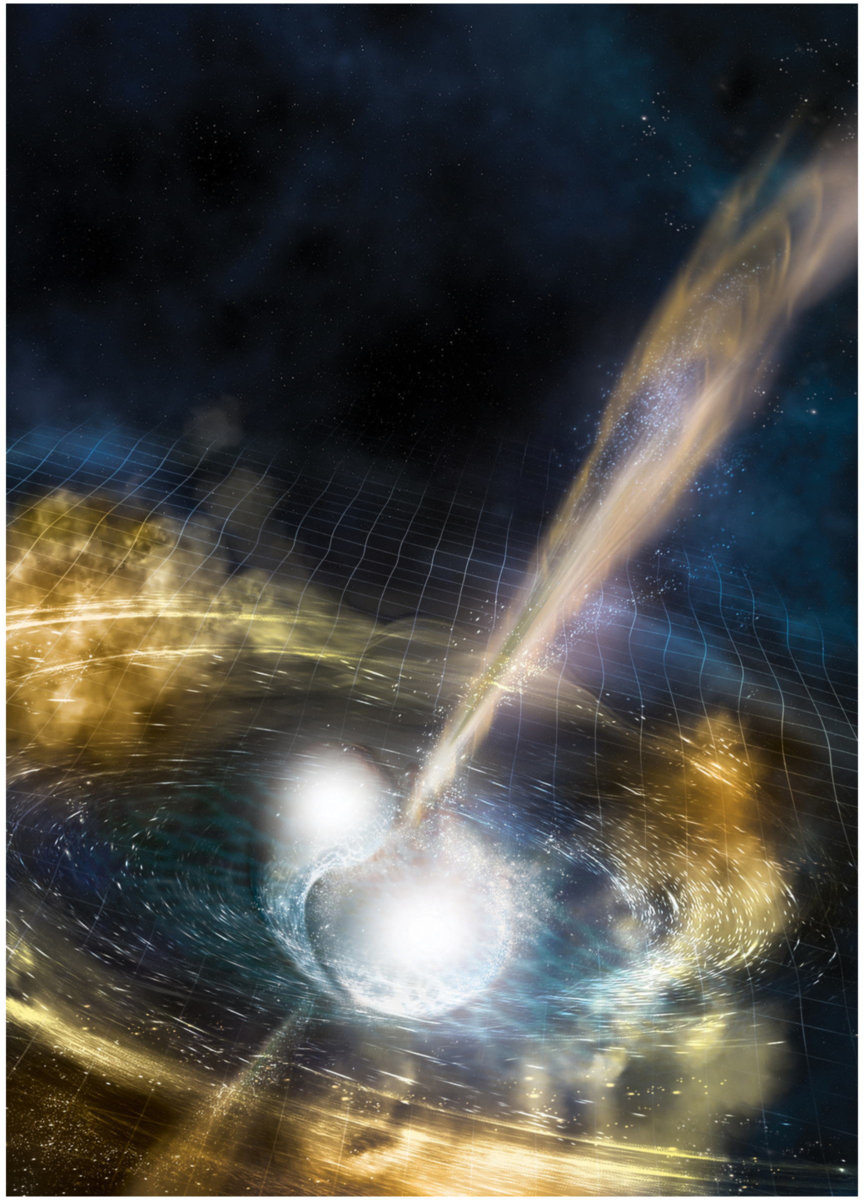
Too small for shocks? Could this be magnetic-driven acceleration in the jet?

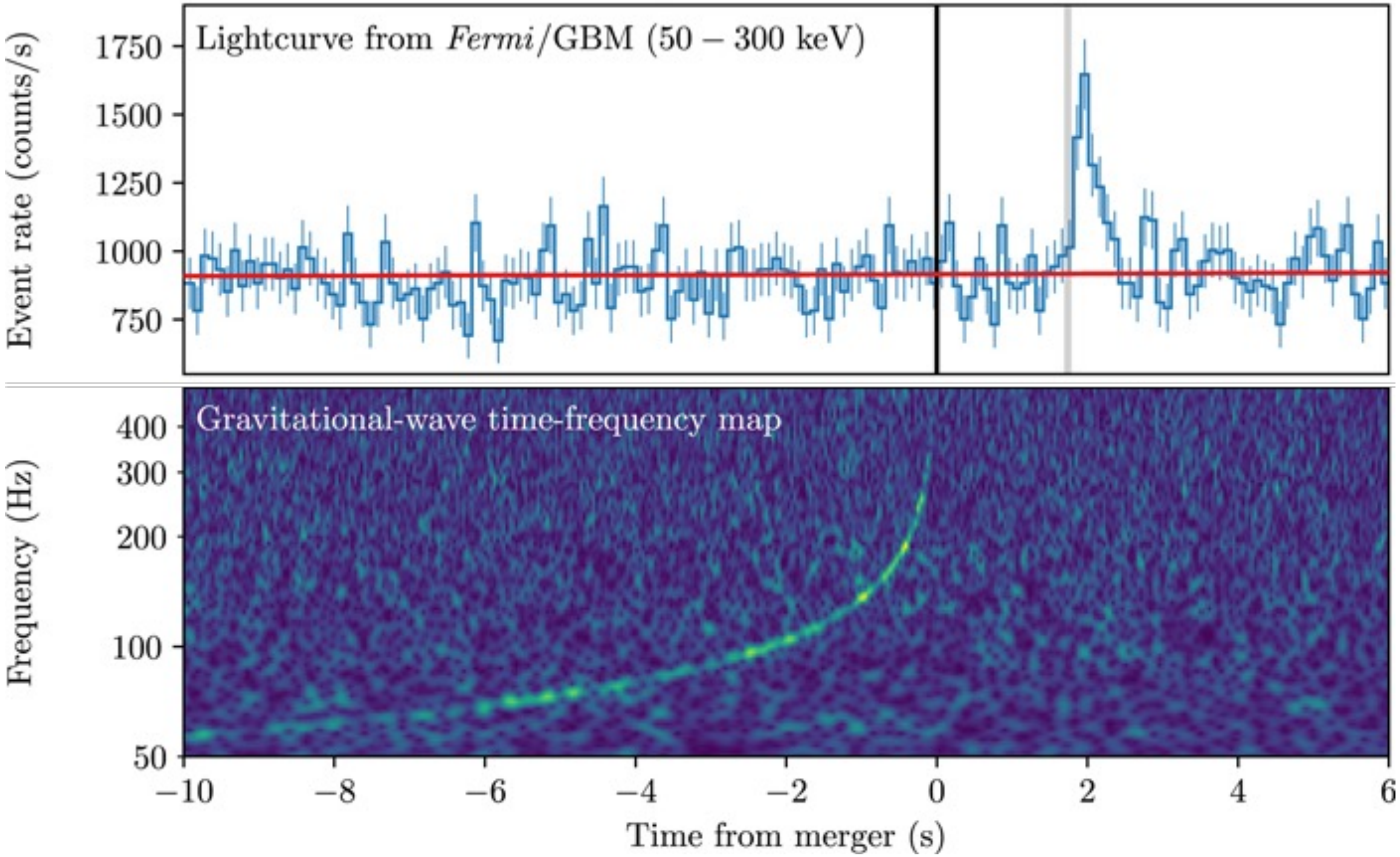
Ackermann et al. 2016, ApJL

Probing the structure of gamma-ray bursts



Gravitational Waves and Light





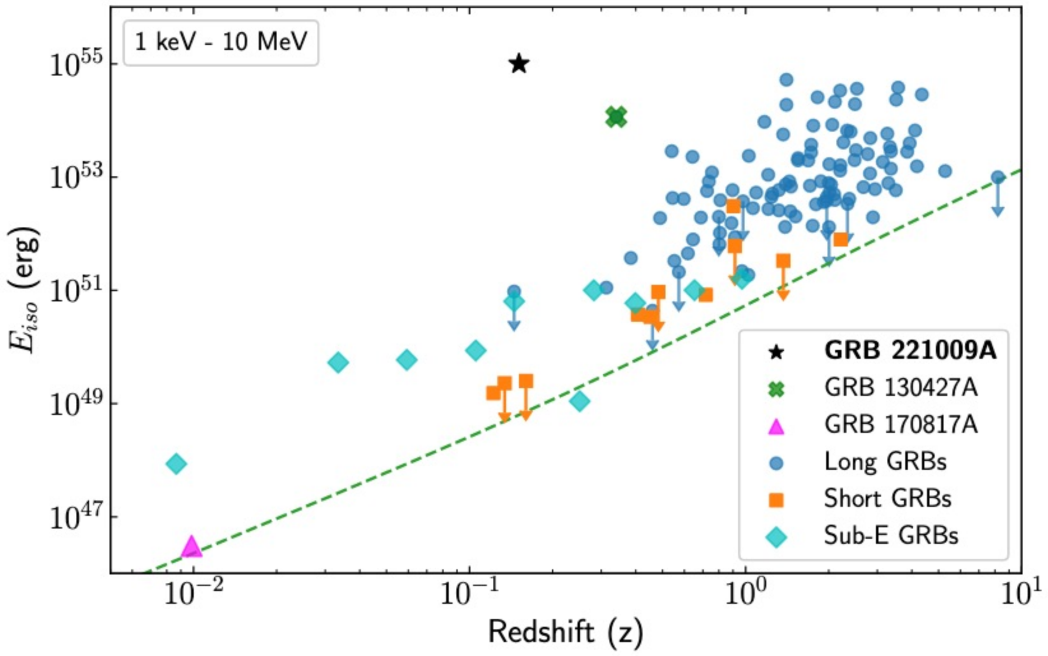
Abbott et al. 2017, ApJL, 848, 2

Game-changing Gamma-ray Burst Observations

First joint detection of a gamma-ray burst and a binary neutron star merger seen in gravitational waves – GRB 170817A

- Confirmed origin of (many) short-duration gamma-ray bursts
- Known mass of initial and final remnants from GW
- Speed of gravity consistent with speed of light
- Measured time lag for jet emergence following merger
- Characterized relativistic jet launched from a newly formed black hole

"Brightest of all time" burst - GRB 221009A

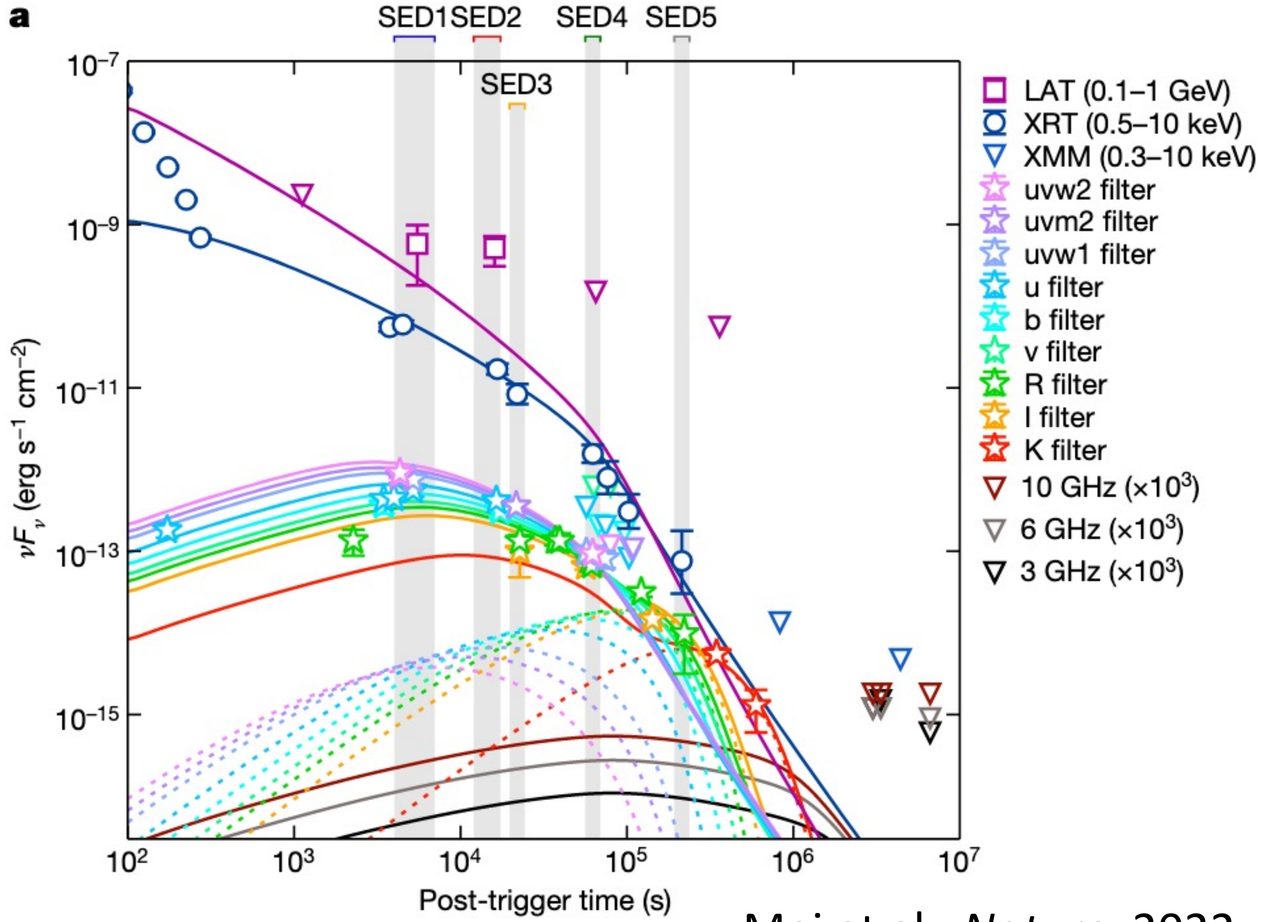


Highest isotropic equivalent energy, fluence and peak flux

Observed variability and evolution of a highly-collimated jet from a collapsar

Kilonova associated with a long-duration gamma-ray burst identified as a binary neutron star merger - GRB 211211A

- Gamma-ray afterglow detected by LAT several hours after the trigger suggests interaction of the jet with the kilonova

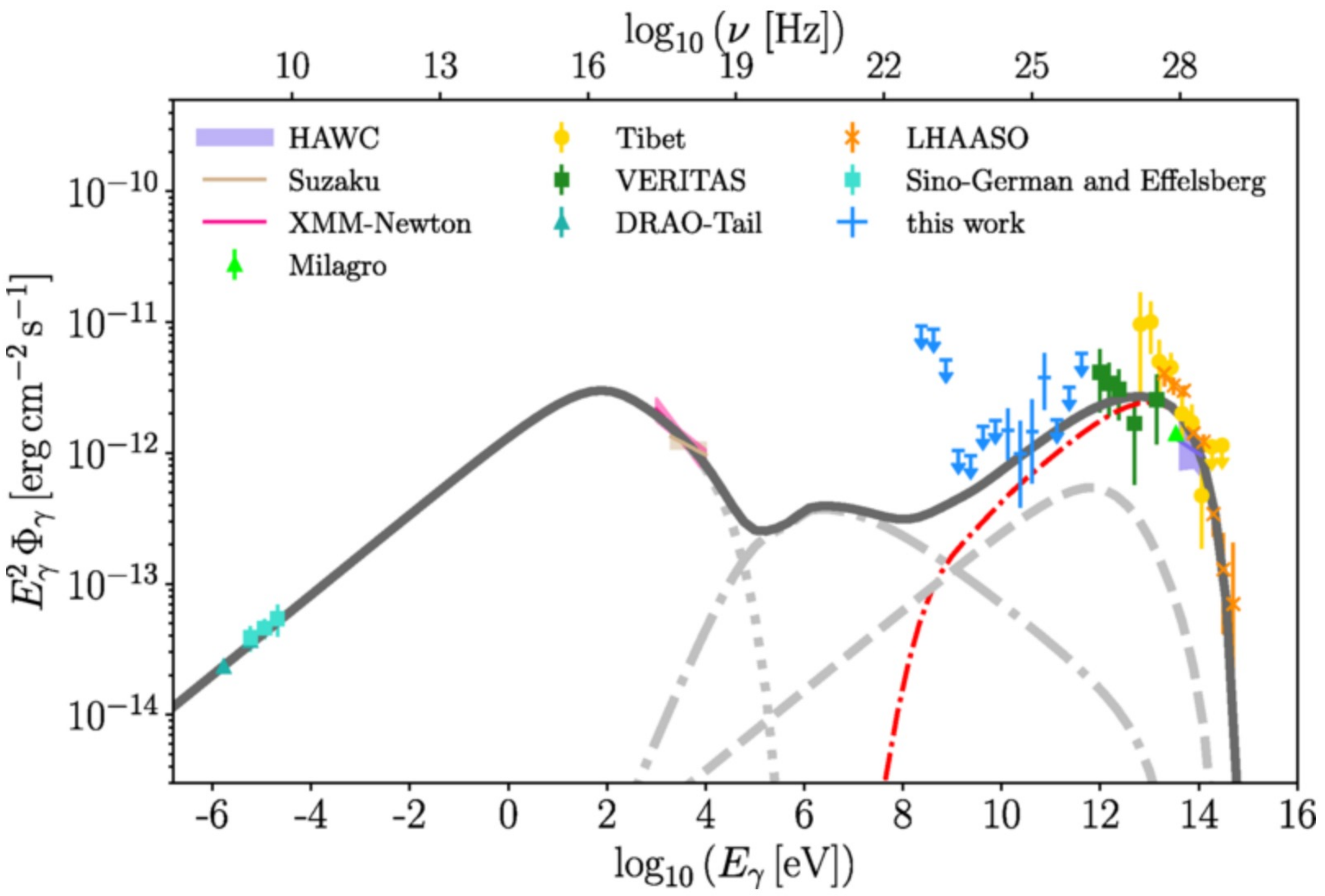


Mei et al., *Nature*, 2022

Cosmic-ray and Neutrino Origins

Fermi data reveal sources of proton acceleration in the Galaxy and candidate sources of extragalactic neutrinos.

Gamma-ray spectrum indicates PeV proton acceleration in SNR G106.3+2.7.

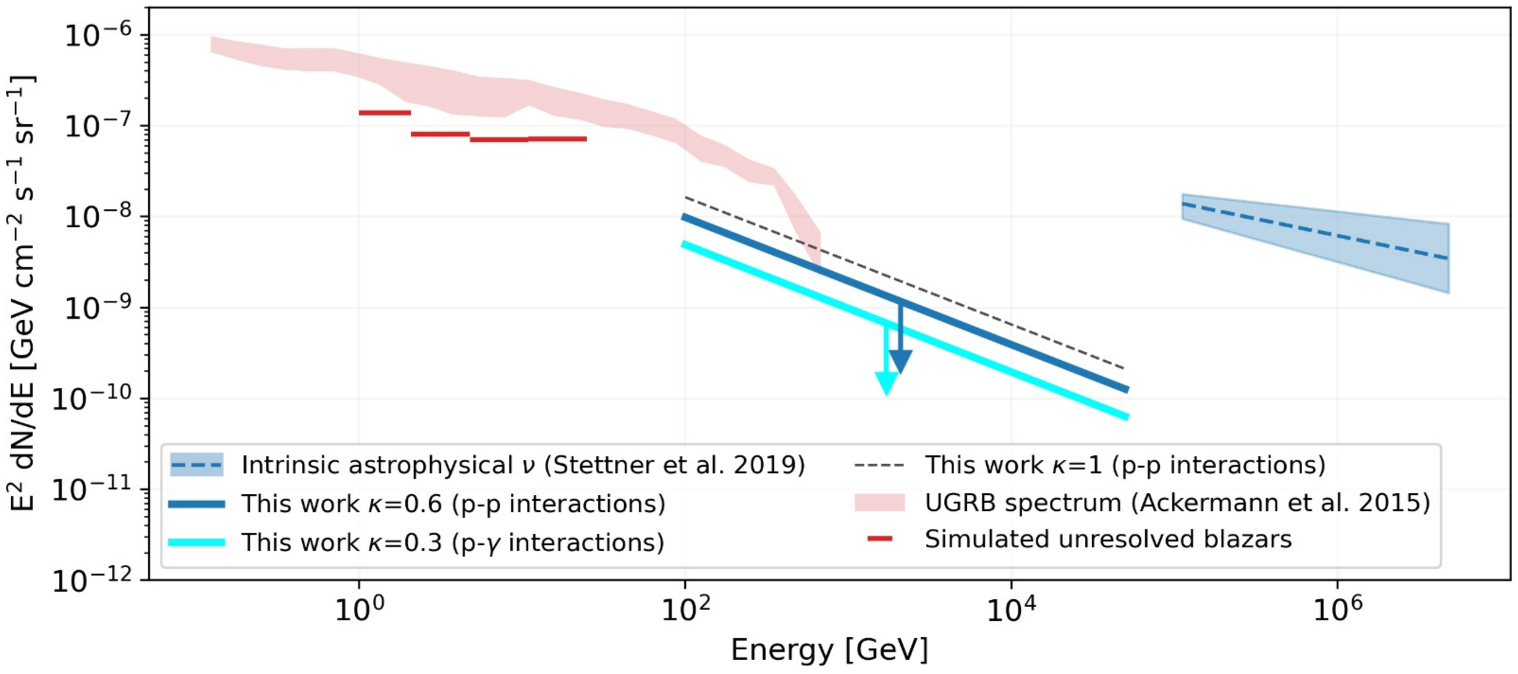


Fang et al., *Phys Rev Letters*, 2022

Neutrino counterpart candidates have been found through follow-up searches of events and catalog correlations, e.g.

- TXS 0506+056, gamma-ray blazar
- NGC 1068, luminous Seyfert II galaxy detected by LAT

2D cross-correlation study of gamma-ray and neutrino data finds that unresolved blazars could contribute up to 1% of the astrophysical neutrino flux at 100 TeV.



Negro et al., *ApJ*, 2023

Fermi Transient Searches

Fermi Gamma-ray Space Telescope

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 Untargeted Search
ground search
ms - s
GCN Notices

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

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

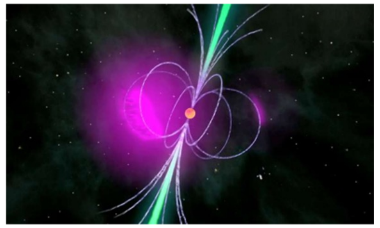
Timescale

Photon Timing

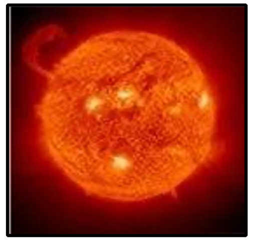
All Sky Cadence

Transients

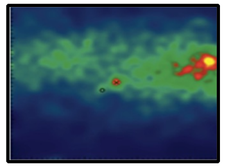
Pulsars



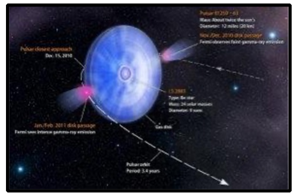
Solar Flares



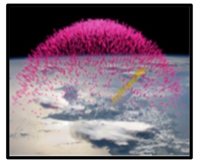
Novae



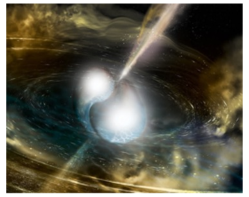
γ-ray Binaries



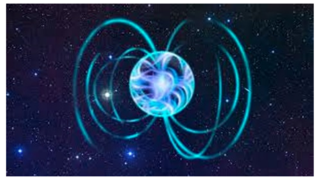
Terrestrial γ-ray Flashes



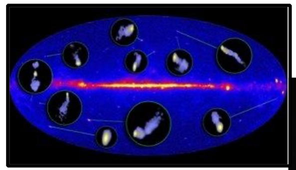
GRBs



Magnetar Flares



Blazar Flares

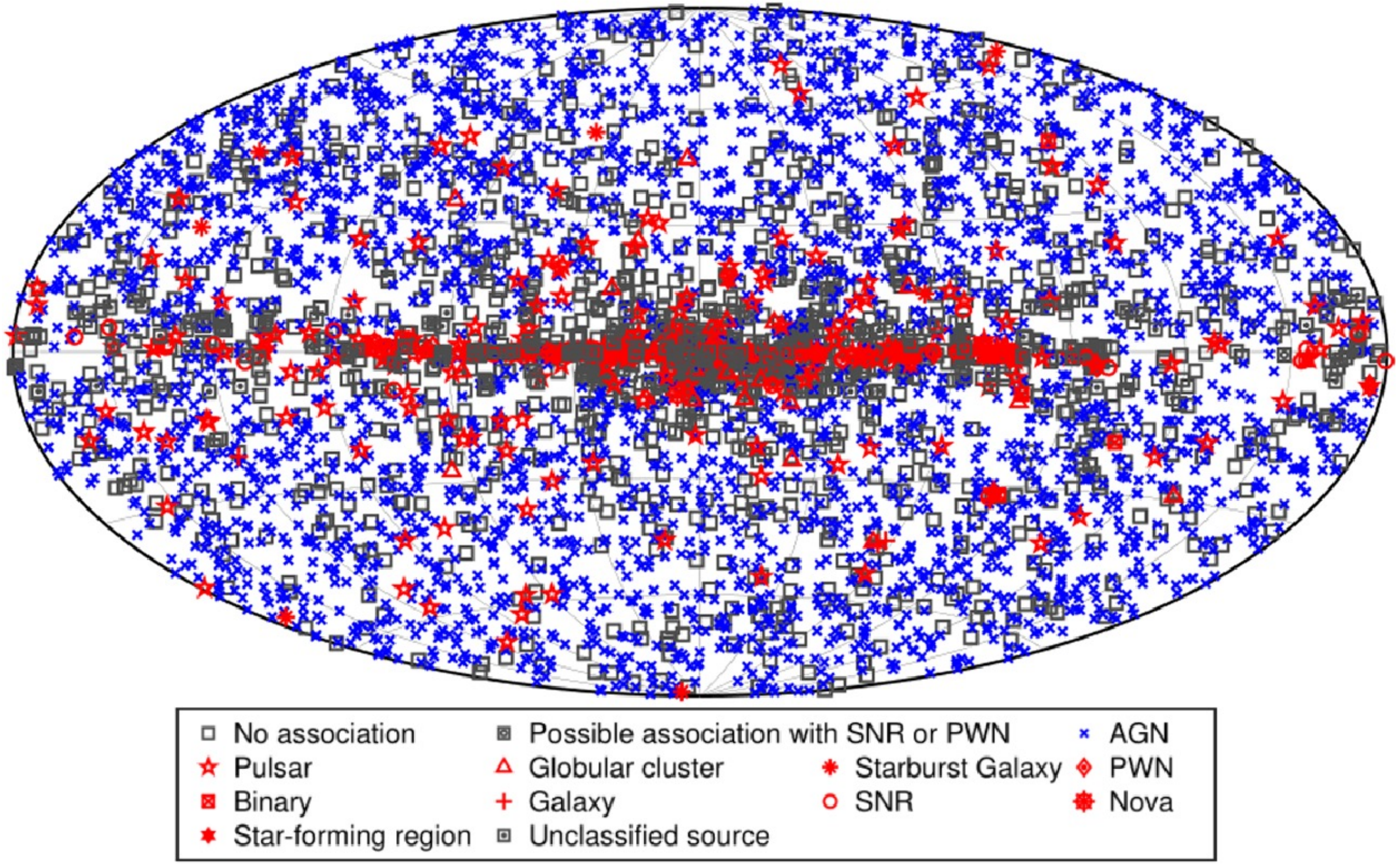


Crab Flares

Not to scale

Update

Catalogs



10-year Catalog (4FGL-DR2)

See also

LAT catalogs:

- 4FGL-DR4 (14 years)
- 4FGL-DR3 (12 years)
- 4LAC-DR3 (AGN)
- 3FHL (high energy)
- FGES (extended sources)
- 2FAV (variable)
- FLT (monthly transients)
- GRB
- SNR (supernova remnants)
- 3PC (pulsars)
- Solar Flares

GBM catalogs:

- GRB
- TGF
- X-ray burst

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

Summary

- The Fermi Observatory carries 2 instruments, LAT and GBM, that observe most of the sky most of the time over 8 orders of magnitude in energy
  - The instruments are more sensitive than when launched (software!)
  - Can continue operating for the foreseeable future (no consumables or notable degradation)
- Gamma-ray science IS multi-wavelength science and multi-messenger science.
- Fermi has generated science results from close to home to some of furthest sources in the Universe
- Some sources in the gamma-ray sky are steady. Some extend over very large regions. The entire sky glows in gamma rays.
- Many sources in the gamma-ray sky vary, sometimes wildly
- Fermi finds new sources all the time. You can find out about them in public catalogs and publications and using online tools at the Fermi Science Support Center.
- During the rest of the school, we'll learn a selection of Fermi science and spend some time on the analysis of data from LAT and GBM.