Fermi Gamma-ray Space Telescope

The Fermi Observatory Legacy to the Science Community: Papers and Public Analysis Tools

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Pisa, 15 March 2018

Outline

- **Introduction**
- **Scientific Legacy***
- **Public Analysis Tools**

* I will take ‘paper’ to mean ‘scientific result’

Introduction

I can't take credit for any of it

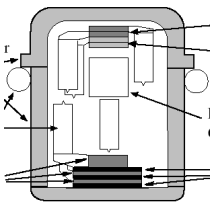
- **The LAT instrument and GLAST/Fermi mission were the right idea at the right time**
- **The LAT and the spacecraft 'just worked', and continue to work well**

- **The LAT is a huge advance for high-energy (~GeV) astronomy**
- **So good that it is difficult to imagine doing a lot better in this energy range**
- **The mission is far from over but it is already clear that Fermi will have a lasting legacy**

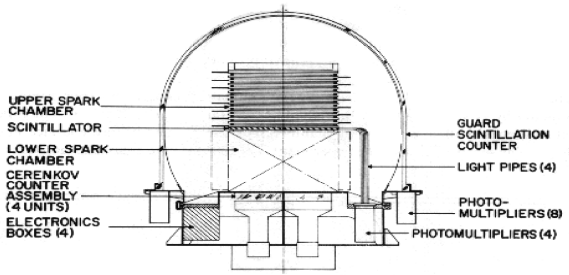
Aside: Brief History of High-Energy Gamma-Ray Detectors Pre-LAT

- 1967-1968, OSO-3 detected Milky Way as an extended γ-ray source, 621 γ-rays
- 1972-1973, SAS-2, ~8,000 celestial γ-rays
- 1975-1982, COS-B, large and variable background of charged particles, ~200,000 γ-rays
- 1991-2000, EGRET, large effective area, good PSF, excellent background rejection, and >1.4 × 10^6 γ-rays
- 2007-, AGILE, like 1/16-th LAT, with small calorimeter, sensitivity ~EGRET

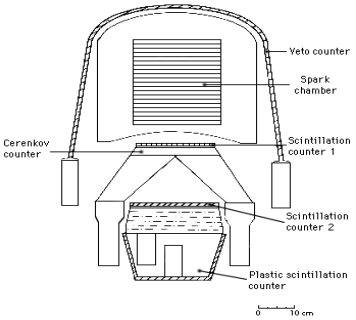
OSO-3



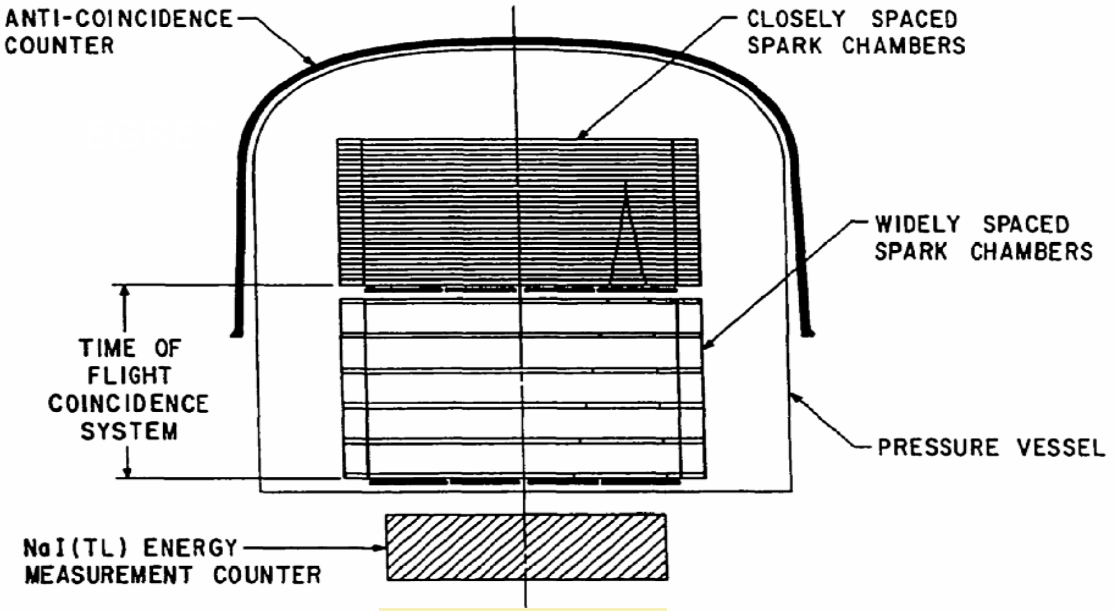
SAS-2



COS-B



EGRET



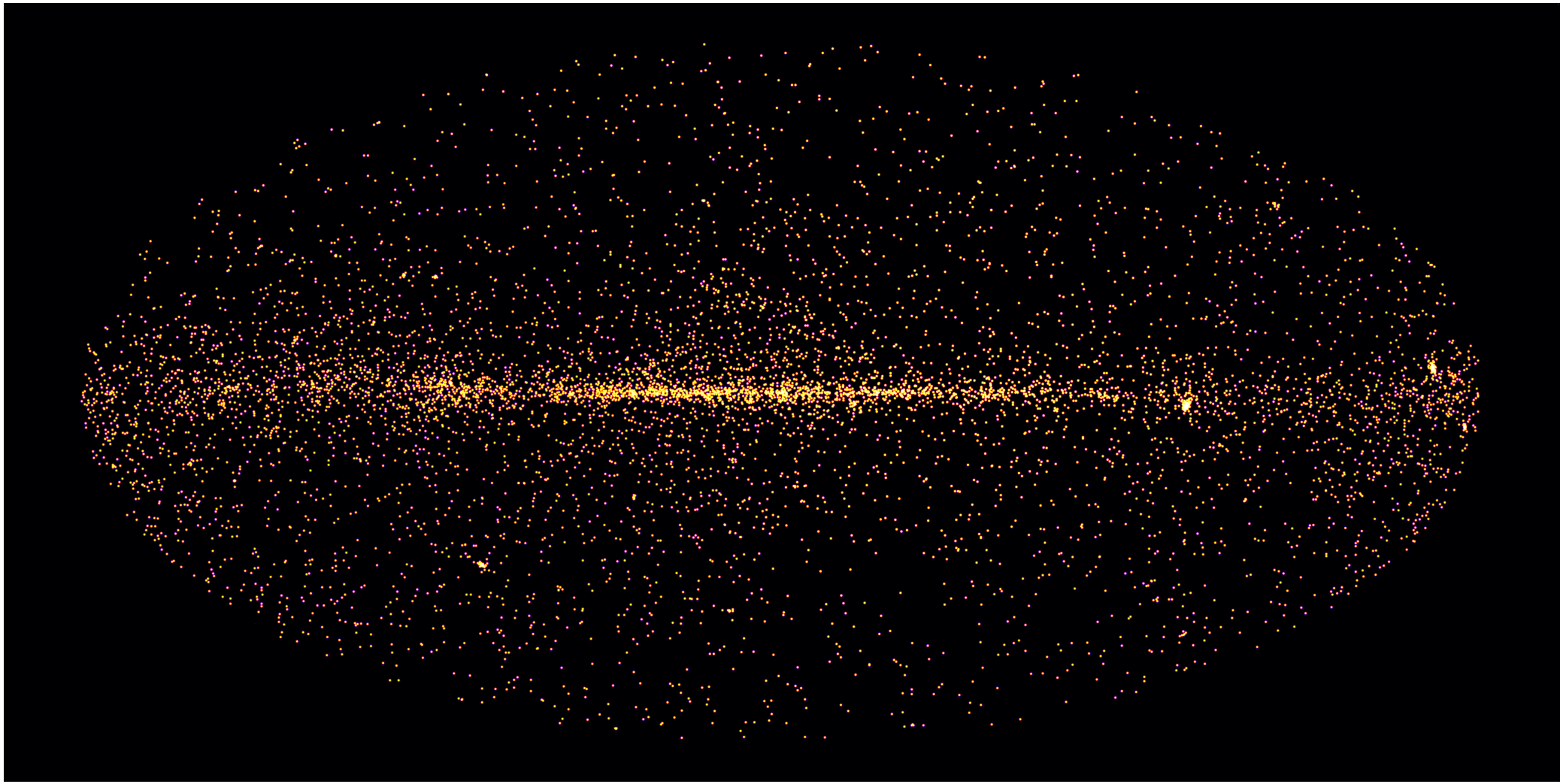
AGILE

Surveying (and Monitoring) the Sky

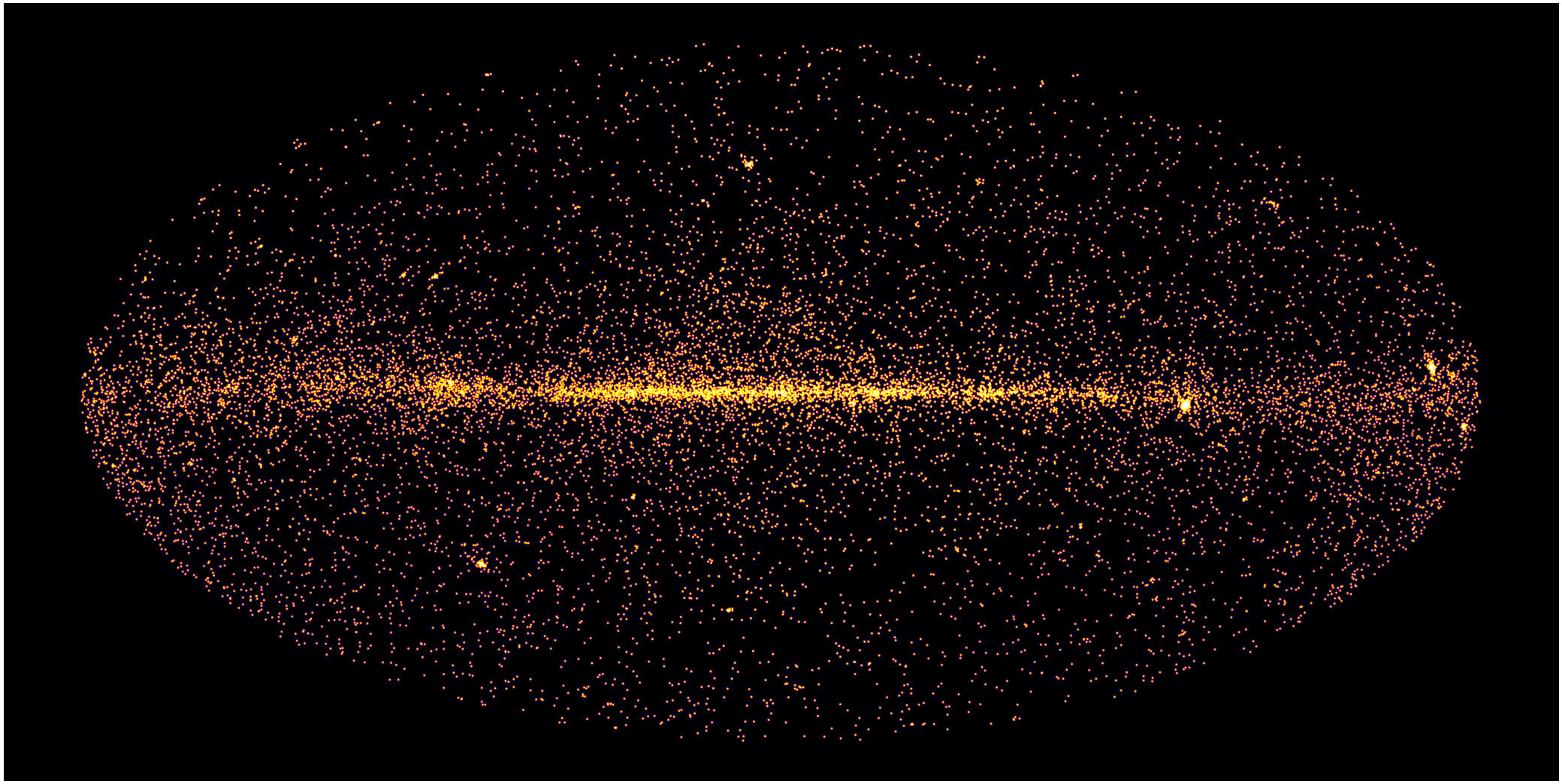
- **Building up deeper and deeper exposure (~2 Hz of celestial photons)**
- **…while monitoring the entire sky with complete coverage 8x per day**

https://apod.nasa.gov/apod/ap120315.html

30 hours (~20 orbits)

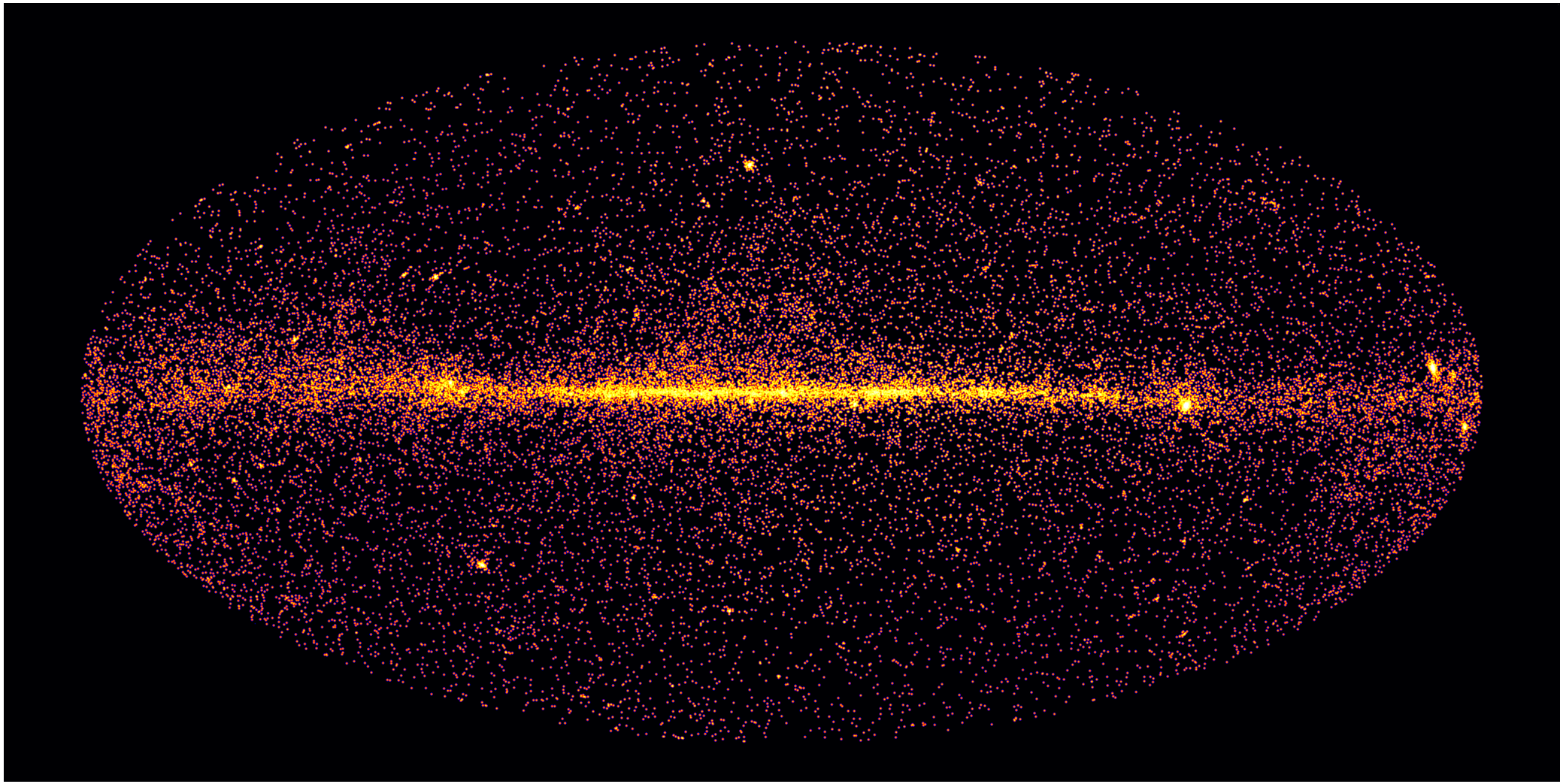


60 hours



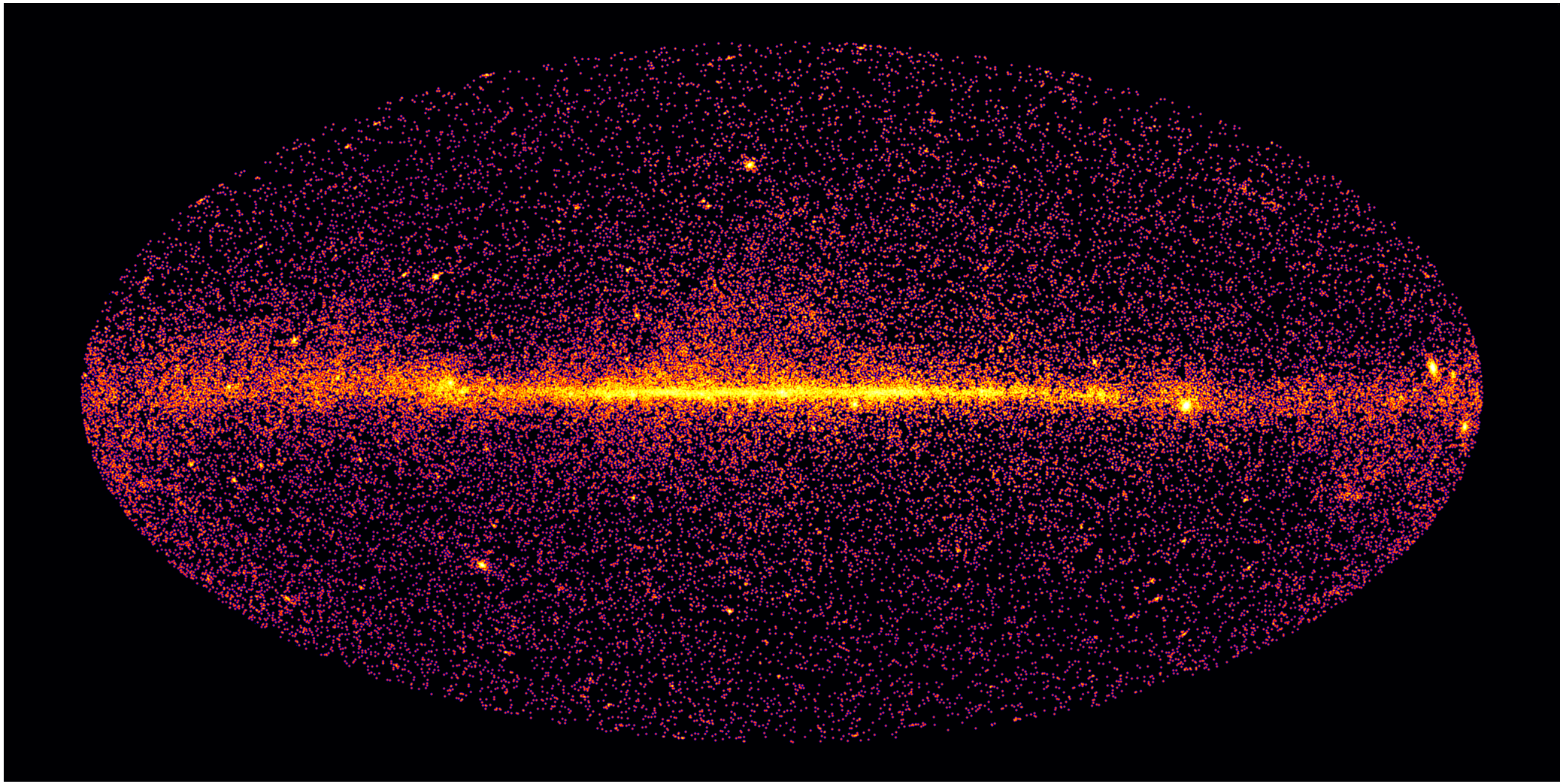
Fermi Gamma-ray Space Telescope

5 days



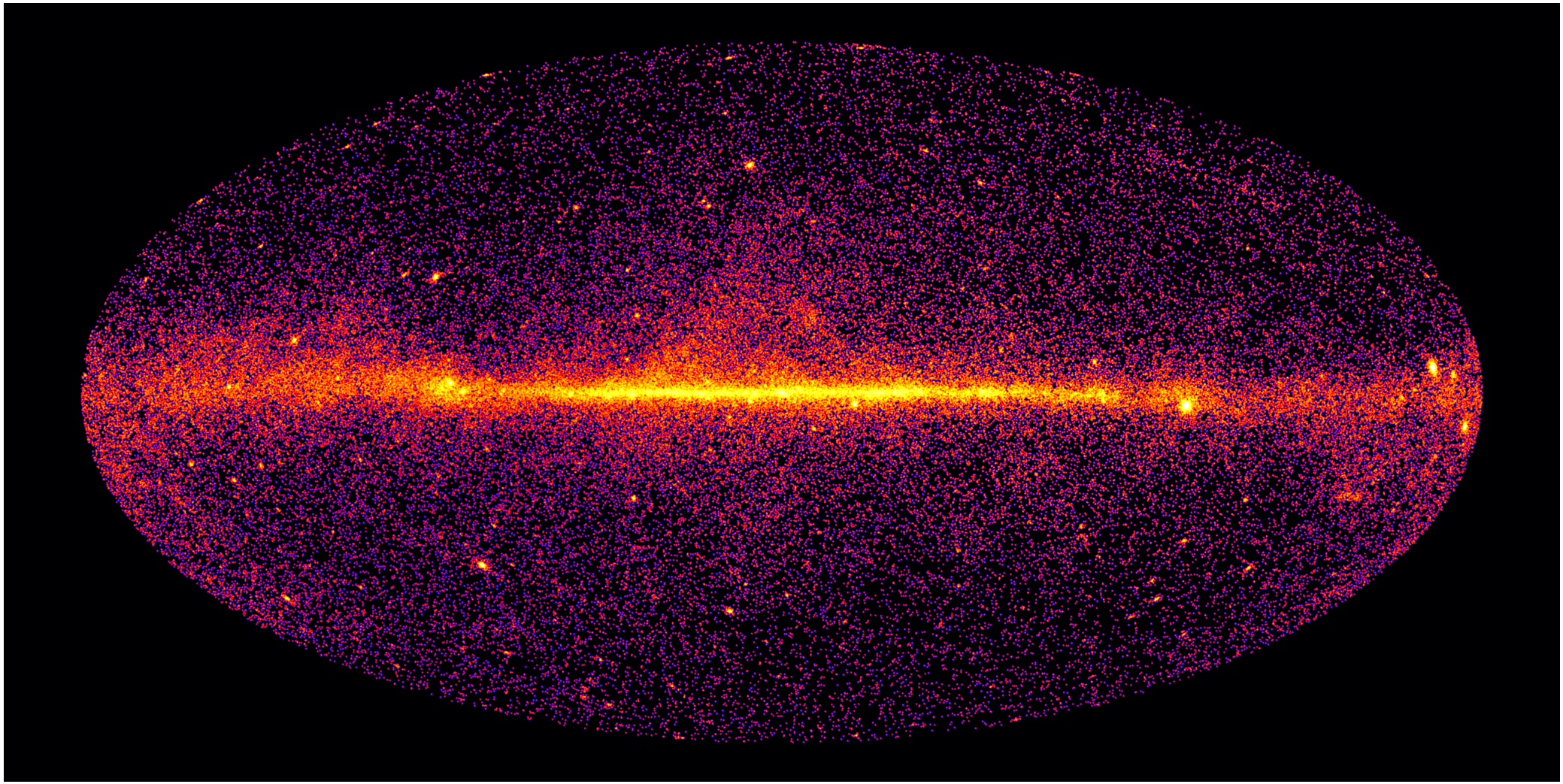
Fermi Gamma-ray Space Telescope

10 days

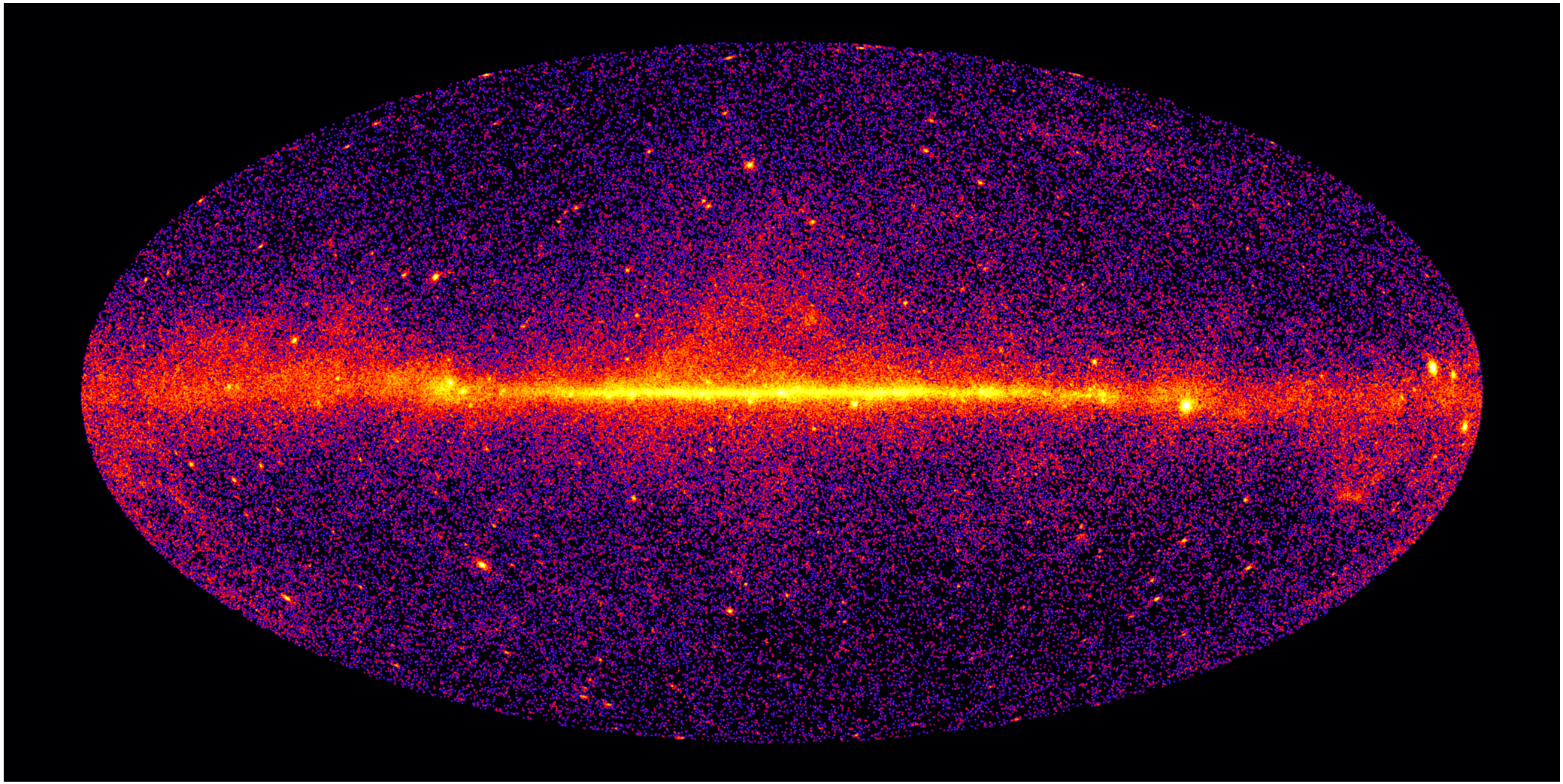


Fermi Gamma-ray Space Telescope

20 days

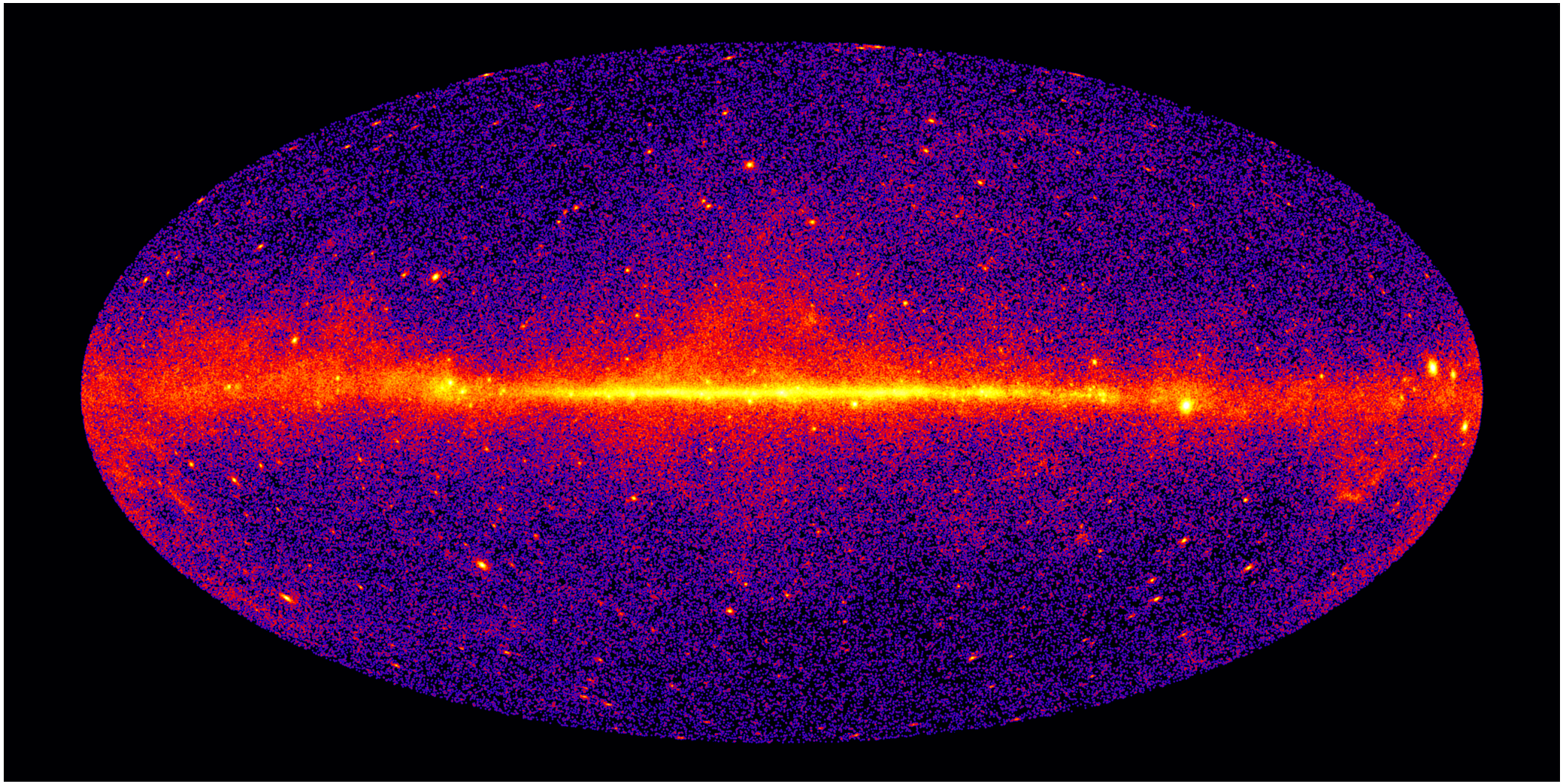


40 days



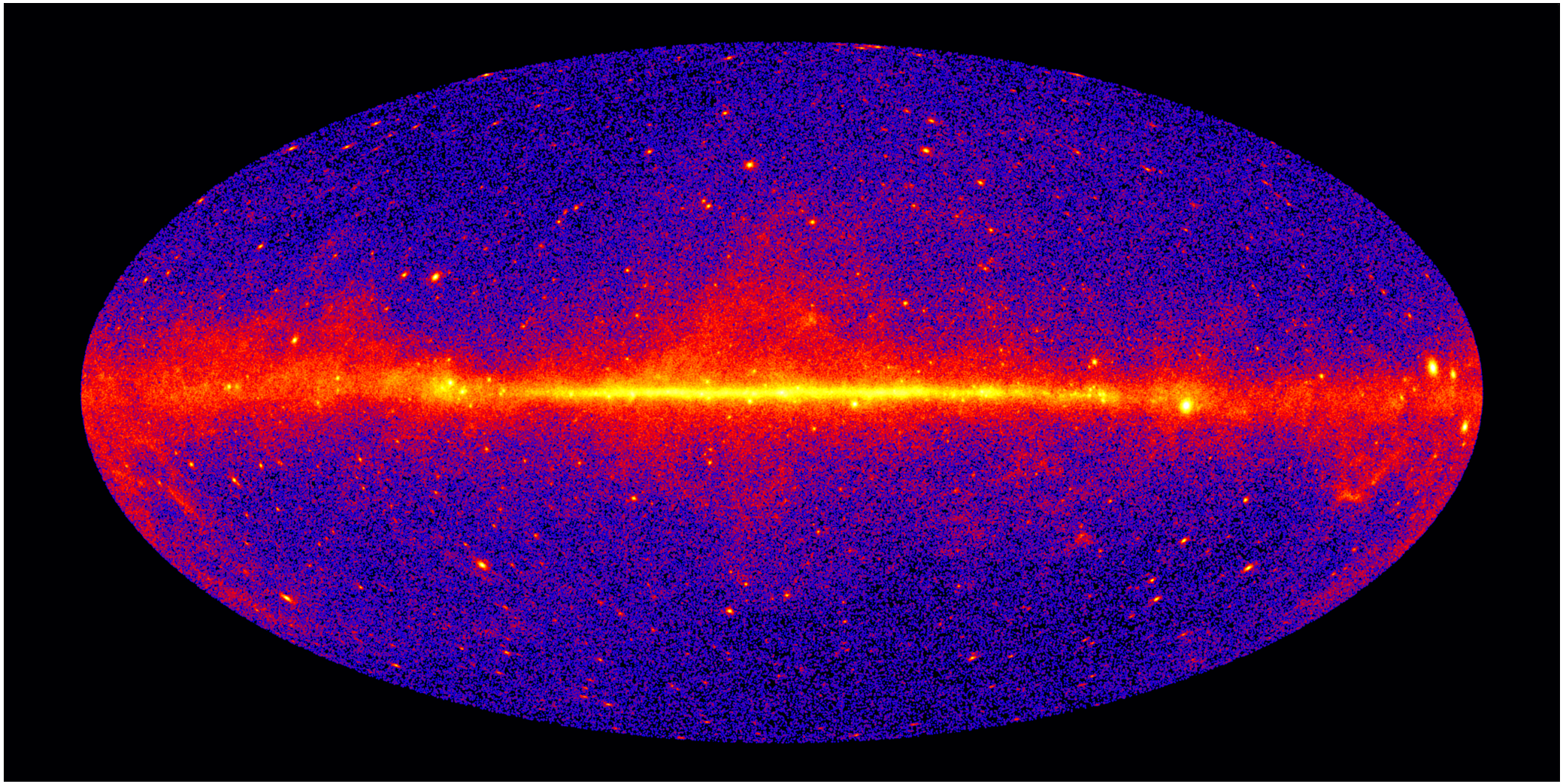
Fermi Gamma-ray Space Telescope

80 days

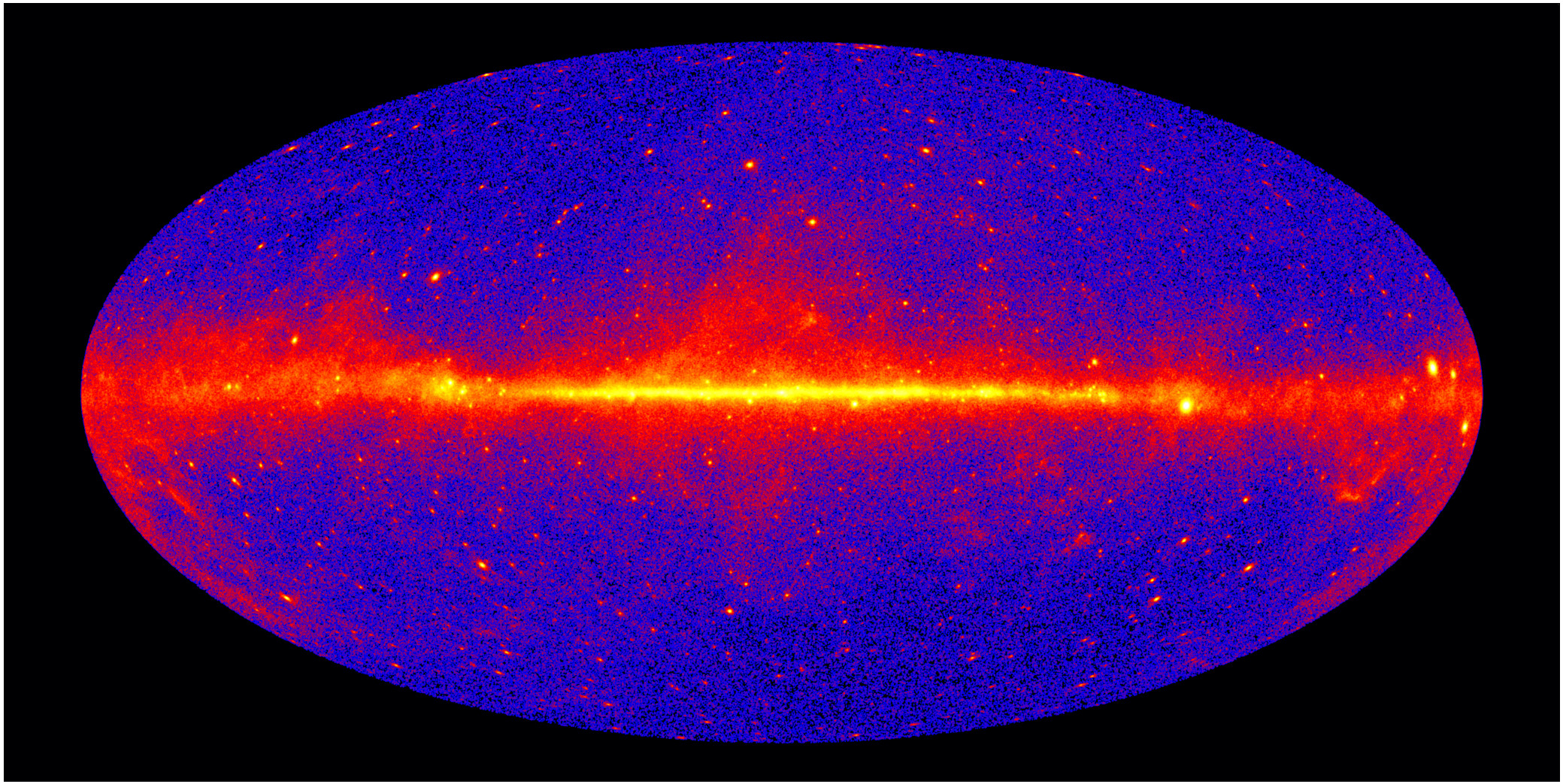


Fermi Gamma-ray Space Telescope

160 days

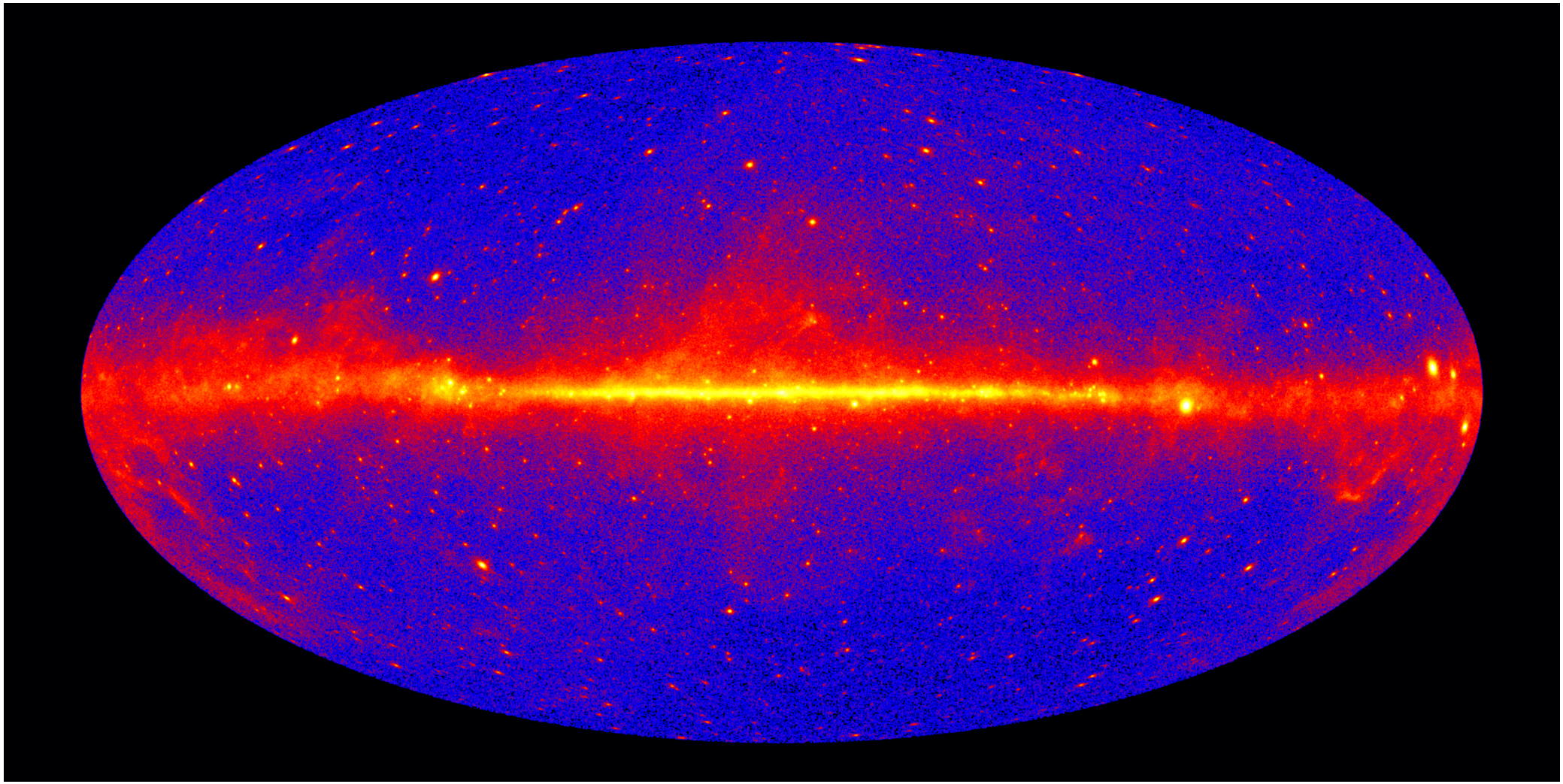


320 days



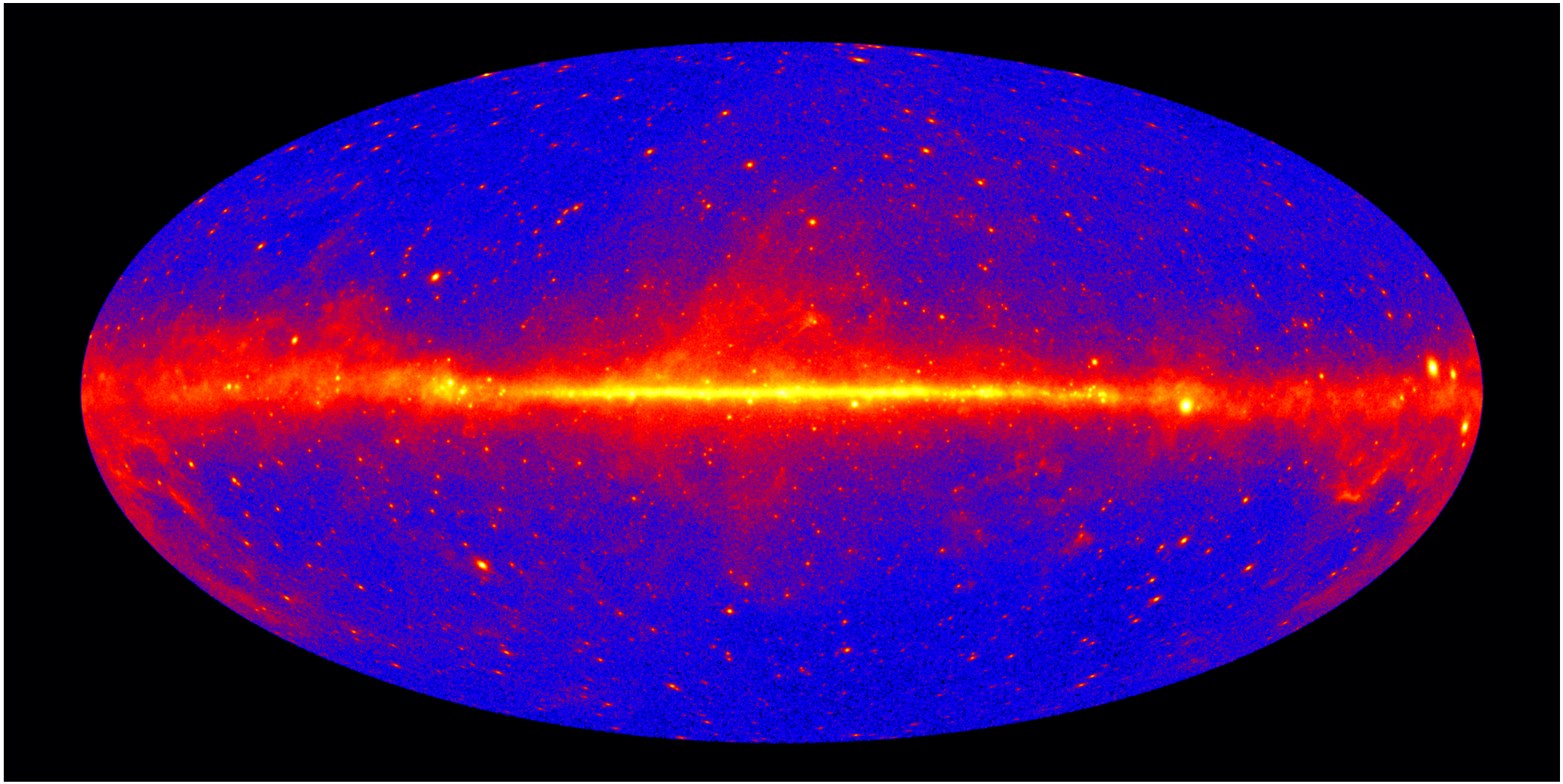
Fermi Gamma-ray Space Telescope

640 days



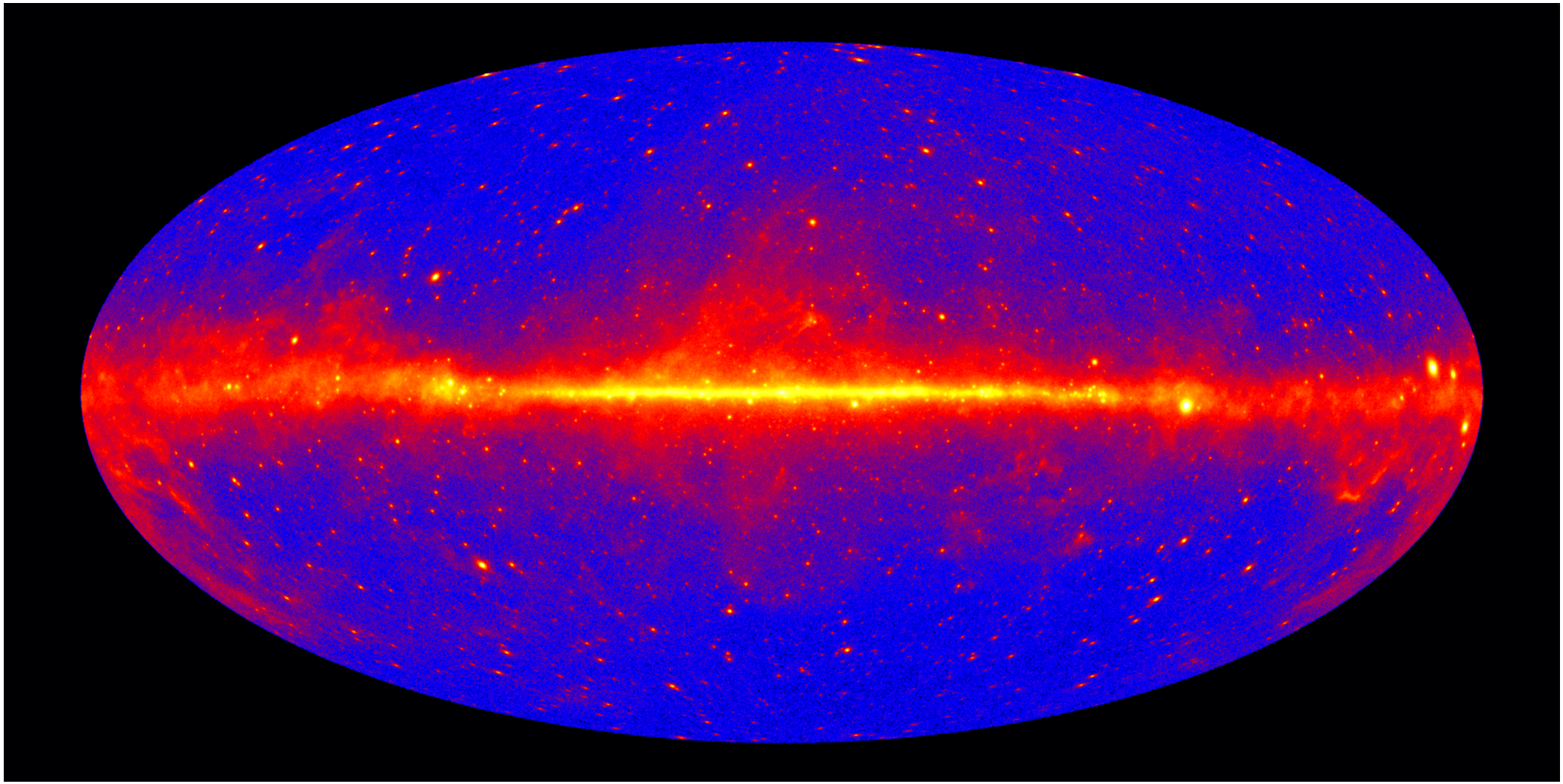
Fermi Gamma-ray Space Telescope

1280 days



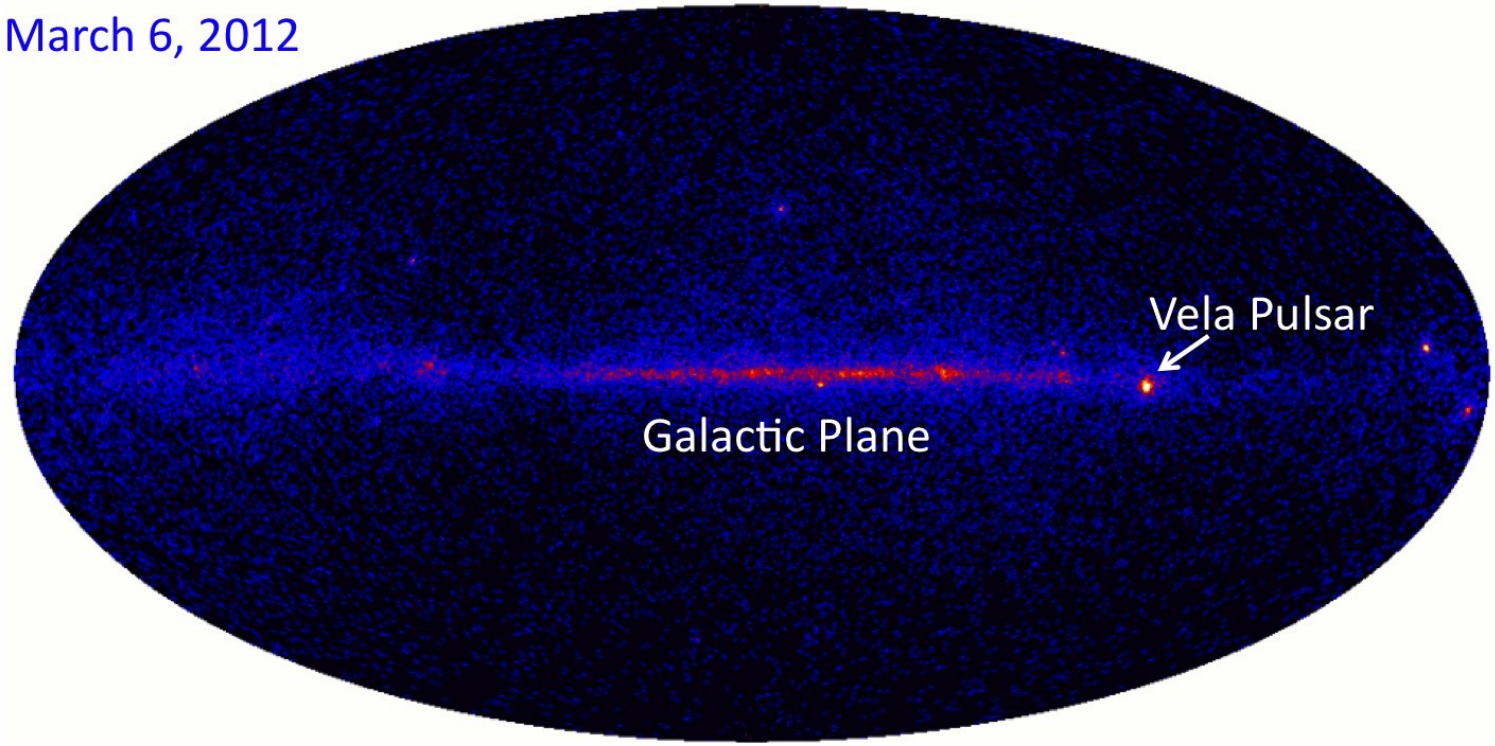
Fermi Gamma-ray Space Telescope

~7 years



Surveying (and Monitoring) the Sky

- **Monitoring the transient gamma-ray sky**
  - **This example is a bright solar flare**
  - **Transient source classes abound – variability has been measured on scales of seconds to years**



https://apod.nasa.gov/apod/ap120315.html

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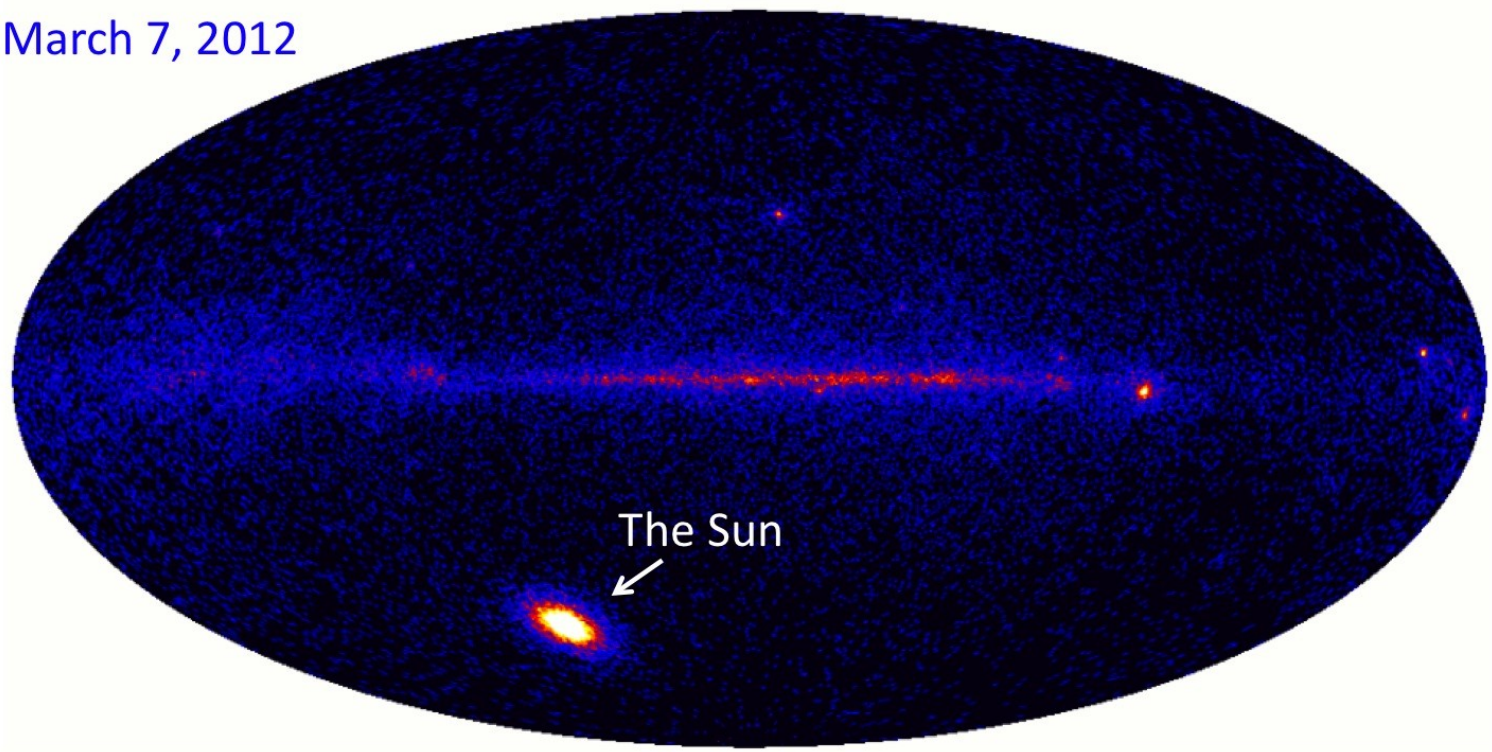


https://apod.nasa.gov/apod/ap120315.html

LAT Legacy to the Scientific Community

- **Will answer this in three ways:**
  - **Catalogs**
  - **Surprises**
  - **New source classes**
- **and hit only some of the highlights***

* I am not covering diffuse gamma-ray emission of the Milky Way (~2/3rds of the celestial gamma rays) at all

Why Make (LAT) Catalogs?

- **Not to collect butterflies, although obviously we all want to know what the LAT has detected**
  - **For the LAT especially making catalogs was one approach for finding and studying new source classes**

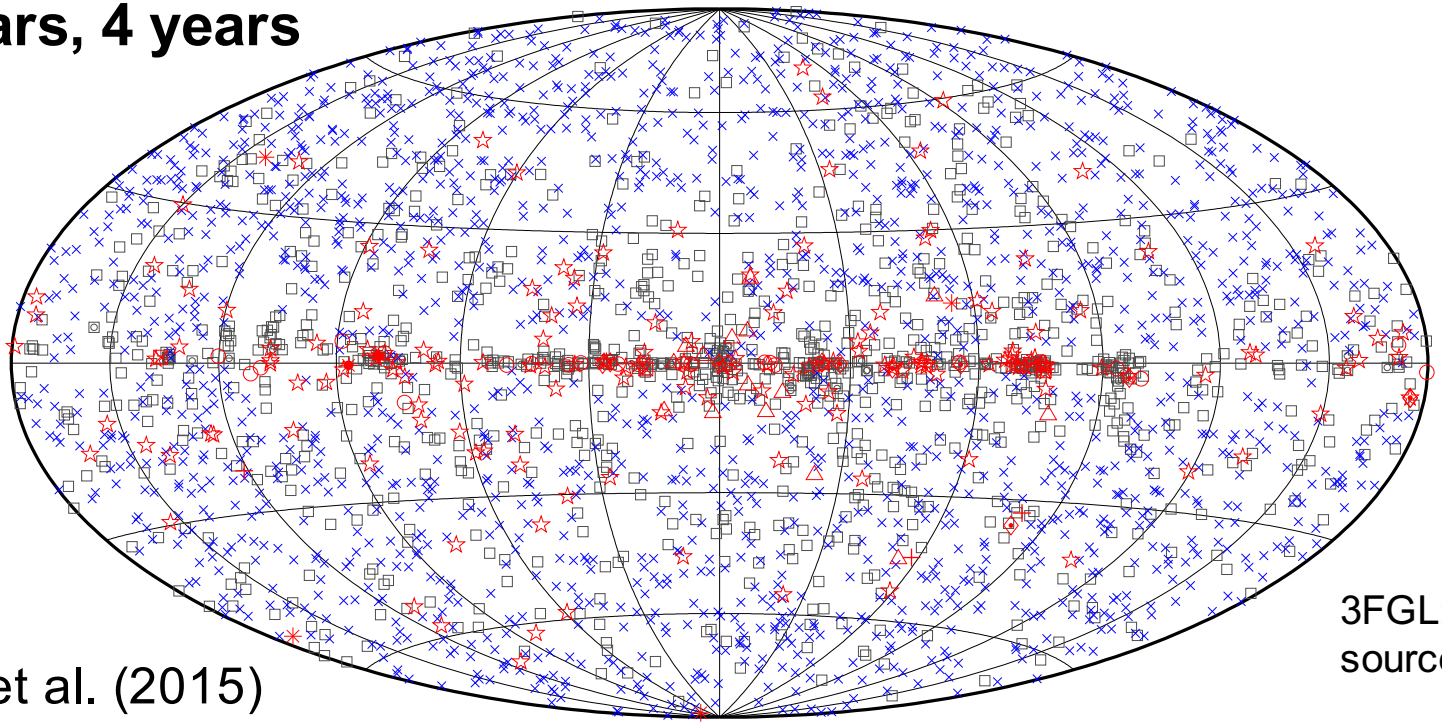
- **Perhaps less obvious is that the systematic analysis of the sky exercised the LAT analysis tools and tested the assumptions of the analysis**
  - **From the definition of the event classes and IRFs on up to the effects of residual Earth limb emission and the impact of the moving Sun**

- **Also, a LAT source catalog provides a good initial guess for detailed study of a (generally newer and longer) data set**

General LAT Source Catalogs

- **0FGL, 1FGL, 2FGL, 3FGL: Based on 3 months, 11 months, 2 years, 4 years**

Prefix for the designators of the individual sources in the catalog; the rest of the name encodes the position of the source



3FGL: 3000+ sources

Acero et al. (2015)

No association	Possible association with SNR or PWN		AGN
Pulsar	Globular cluster	Starburst Galaxy	PWN
Binary	Galaxy	SNR	Nova
Star–forming region			

- **4FGL (8 years) is coming (5000+ sources)**

Specialized General Catalogs

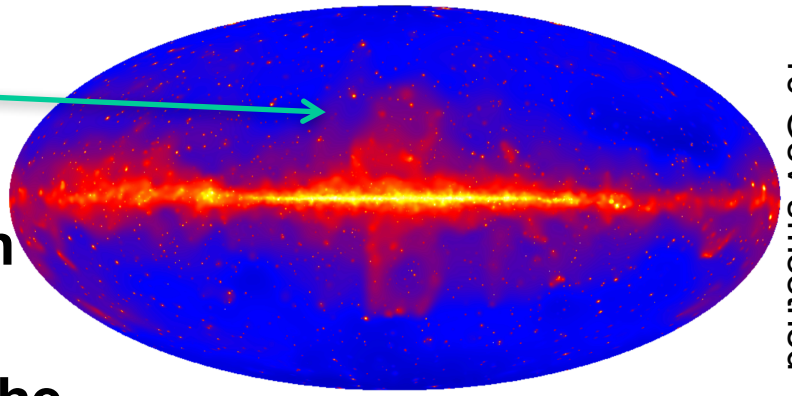
- **1FHL (2013), 2FHL (2016), 3FHL (2017): General (all-sky) catalogs but focused on high energies (>10 GeV, >50 GeV)**
- **1FAV (2013), 2FAV (2017): Flaring sources, diffuse emission model-independent search on weekly time scales**
- **Extended sources: Low-latitude (FGES, 2017), high latitude (FHES, coming soon) – systematic searches for angular extension in 3FGL sources**

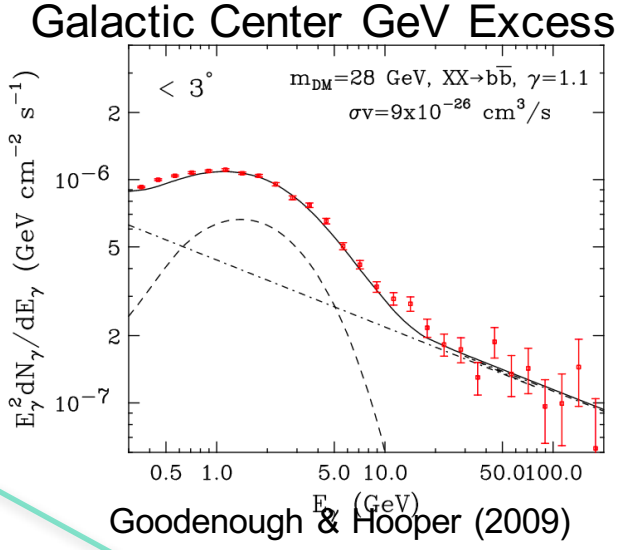
Source Class-Specific Catalogs

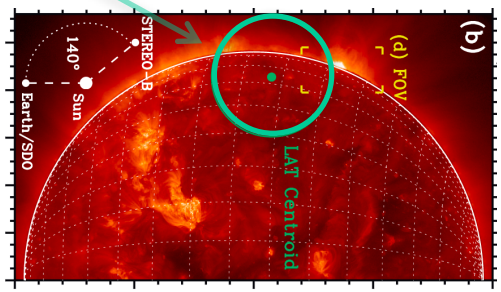
- **1LAC (2010), 2LAC (2011), 3LAC (2015): Companions to the 'FGL' catalogs, compilations of Active Galactic Nucleus (blazar) properties**
- **1PC, 2PC (2013): Pulsar catalogs (young radio loud, young radio quiet, millisecond pulsars), population and multiwavelength properties, 117 total in 2PC (3PC coming)**
- **SNRCAT (2016): 30 detections of supernova remnants in the Milky Way + 14 marginal associations -> population properties**
- **GRB catalog (2013) Systematic search for GRBs detected by GBM**
- **Solar flare catalog (coming)**

Some of the Surprises

- **Fermi bubbles** – Large lobes of hard-spectrum emission extending +/-60º above and below the Galactic plane in the inner Galaxy (Su et al. 2010)
- **GeV excess** – A large region around the Galactic center is brighter than expected in GeV gamma rays (Vitale et al. 2009)
- **Behind-the-limb solar flares** – Pesce-Rollins et al. (2015)
- **Variable pulsars** – Isolated PSR J2021+4026 (Allafort et al. 2016), millisecond pulsar in a binary system PSR J1227-4853 (Johnson et al. 2015)
- **Crab flares** – The Crab nebula, a standard calibration source, is generally 'boiling' and occasionally in outburst (Tavani et al. 2010)
- **Galactic novae** [also a new source class]



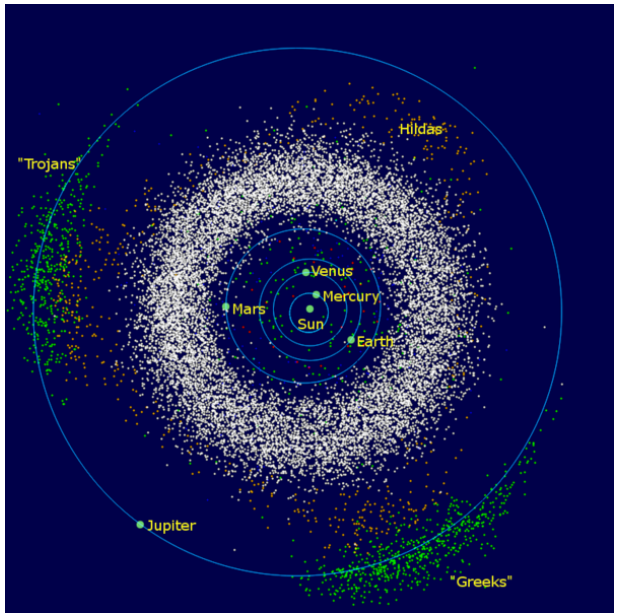




Negative surprises

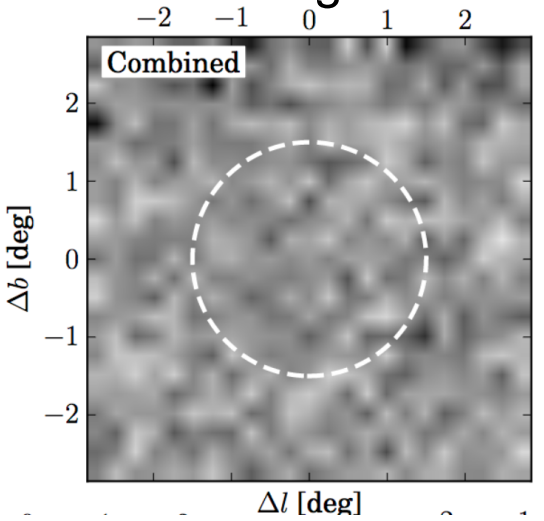
- **Also 'anti-surprises' (signals could have been strong enough, but no convincing detections):**
  - **Asteroid belt – Tracer of size spectrum of asteroids at size scales down to meters**
  - **Galaxy clusters – Accelerate and confine cosmic rays; Ackermann et al. (2013) present a stacking analysis of 50 galaxy clusters**
  - **Dark matter annihilation [limits are at very interesting levels]**

Asteroid Belt



Wikipedia

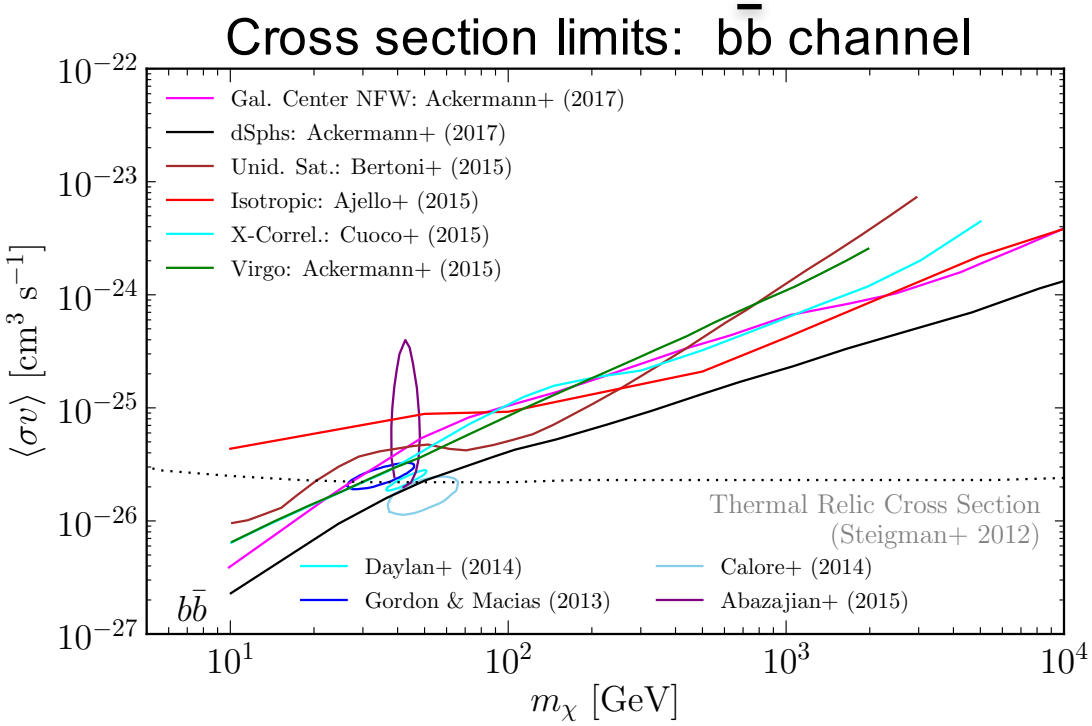
50 Clusters Significance map



+/-3σ range

Indirect Detection Searches for Dark Matter

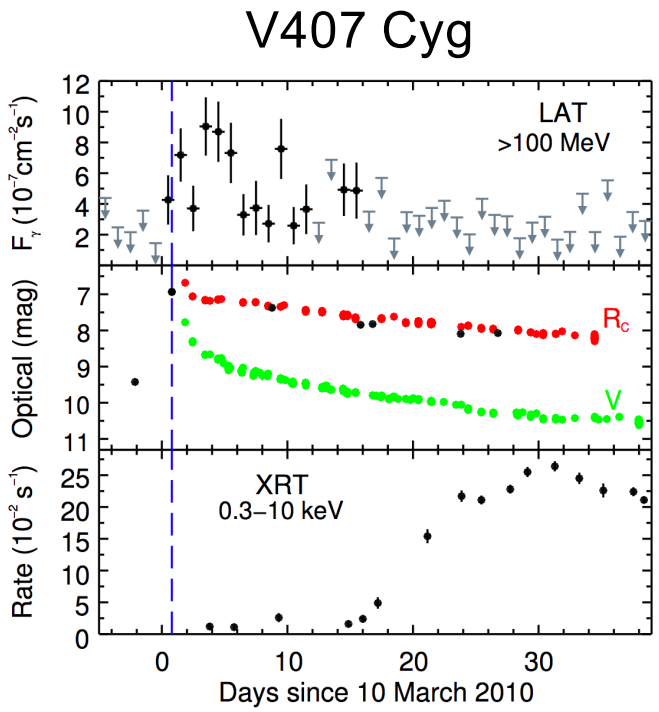
- **The LAT is the first and only experiment to provide WIMP annihilation cross section limits in the 'interesting' range below the thermal relic cross section**
- **Complementary search strategies are possible with the all-sky survey of the LAT – different systematics**

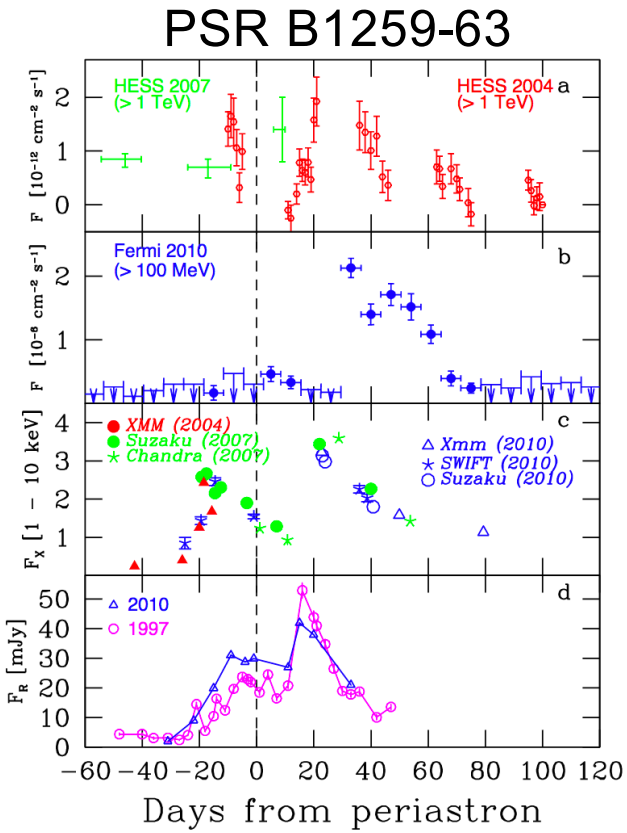


Updated from Charles et al. (2016)

New Source Classes (variable)

- **Galactic novae** – White dwarf star accreting matter from a companion, detonating, started with V407 Cygni (Abdo et al. 2010), now many





- **High-mass binaries** – Started with PSR B1259-63 (Abdo et al. 2010), 3.4-yr period, gets active around periastron

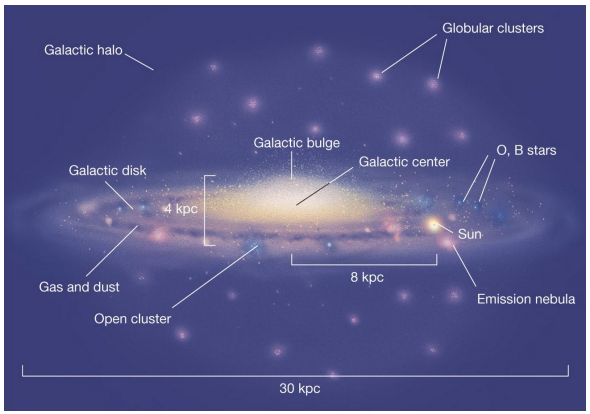
New Source Classes (steady)

- **Star-forming galaxies** – Started with M82 and NGC 253 (Abdo et al. 2010), now several

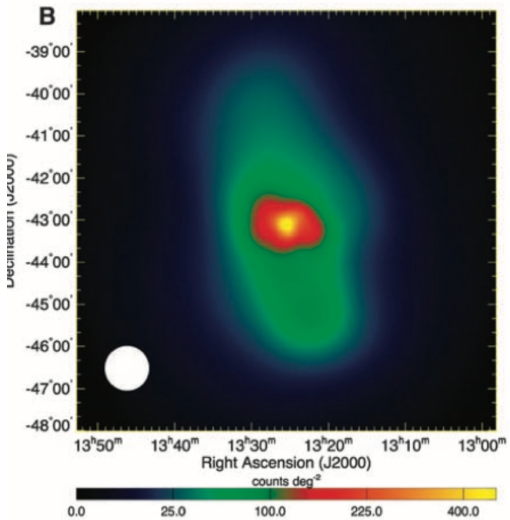
- **Globular clusters** – Started with Abdo et al. (2009), 15 sources in 3FGL

- **Misaligned AGN** – Active Galactic Nuclei with the blazar jet not pointed at the Earth; Centaurus A is a nearby (atypical) prototype (Abdo et al. 2010)

Schematic Globular Clusters



LAT Centaurus A



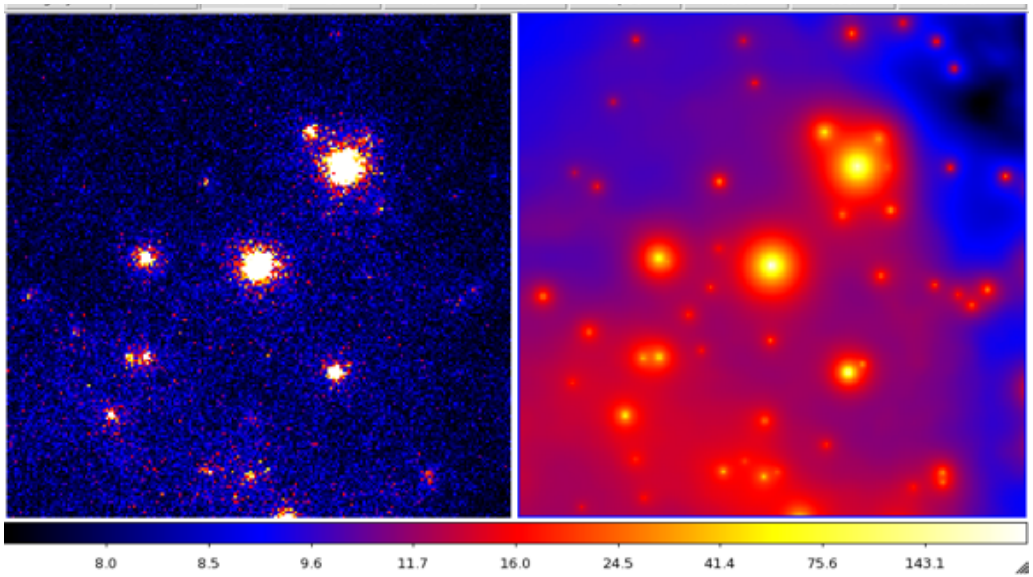
Public Analysis Tools

- **N.B. What I will discuss is the high-level analysis of LAT gamma-ray data; the event reconstruction and classification is essential for science, not via public analysis tools**

- **Public analysis tools were mandated by NASA – interest in maximizing the scientific return from the mission, and maintaining long-term viability of LAT data analysis**
- **And it was enforced by the funding allocation**
  - **GLAST Science Support Center was funded years before launch and much of the programming support for development of the tools was funneled through the SSC**
  - **SSC also enforced HEASARC standards, and participated in the (NASA mandated) Project Data Management Plan**

Public Analysis Tools (2)

- **Drivers for the analysis design: LAT is not an X-ray mission – large, moving FOV, gigantic PSF, low count rates, and actually relatively little background misclassified cosmic rays**
  - **Most source analysis is model fitting – you define the degrees of freedom you want to measure**
  - **Adapted a likelihood function approach, pioneered by Pollack et al. (1981) for COS-B**



FSSC

- **Preparation through simulation:**
  - **High-level simulators to validate the analysis tools**
  - **Instrument (event-level) simulations to define event classes, evaluate instrument response**
- **And later in-flight validation**

Public Analysis Tools (3)

- Developments over time: Pass 8 (with event types), Python interface to the Science Tools, and now Fermipy
- With the analysis being model fitting, source detection tends to be brute force or to rely on some other approach for finding 'seeds'
  - Seed finding has been important for sky monitoring and catalog analyses
- Moore's law has also helped analyses keep pace with the data
- New and coming features include: Weighted likelihood for folding in systematic uncertainties

Looking Ahead

- **This is not the whole story on the legacy from the LAT – it is still being written**
  - **The sensitivity at the highest energies is still improving faster than sqrt(time)**
  - **We are getting more adept at going to lower energies**
- **The LAT is always scanning the sky, and new multi-messenger opportunities are helping to maintain the scientific relevance**

URLS for papers, analysis tools, and LAT data

LAT collaboration bibliography: https://www-glast.stanford.edu/cgi-bin/pubpub
NASA Fermi-wide bibliography: https://fermi.gsfc.nasa.gov/cgi-bin/bibliography_fermi
Fermi Science Support Center: https://fermi.gsfc.nasa.gov/ssc/