10 years of the Fermi Gamma-Ray Space Telescope

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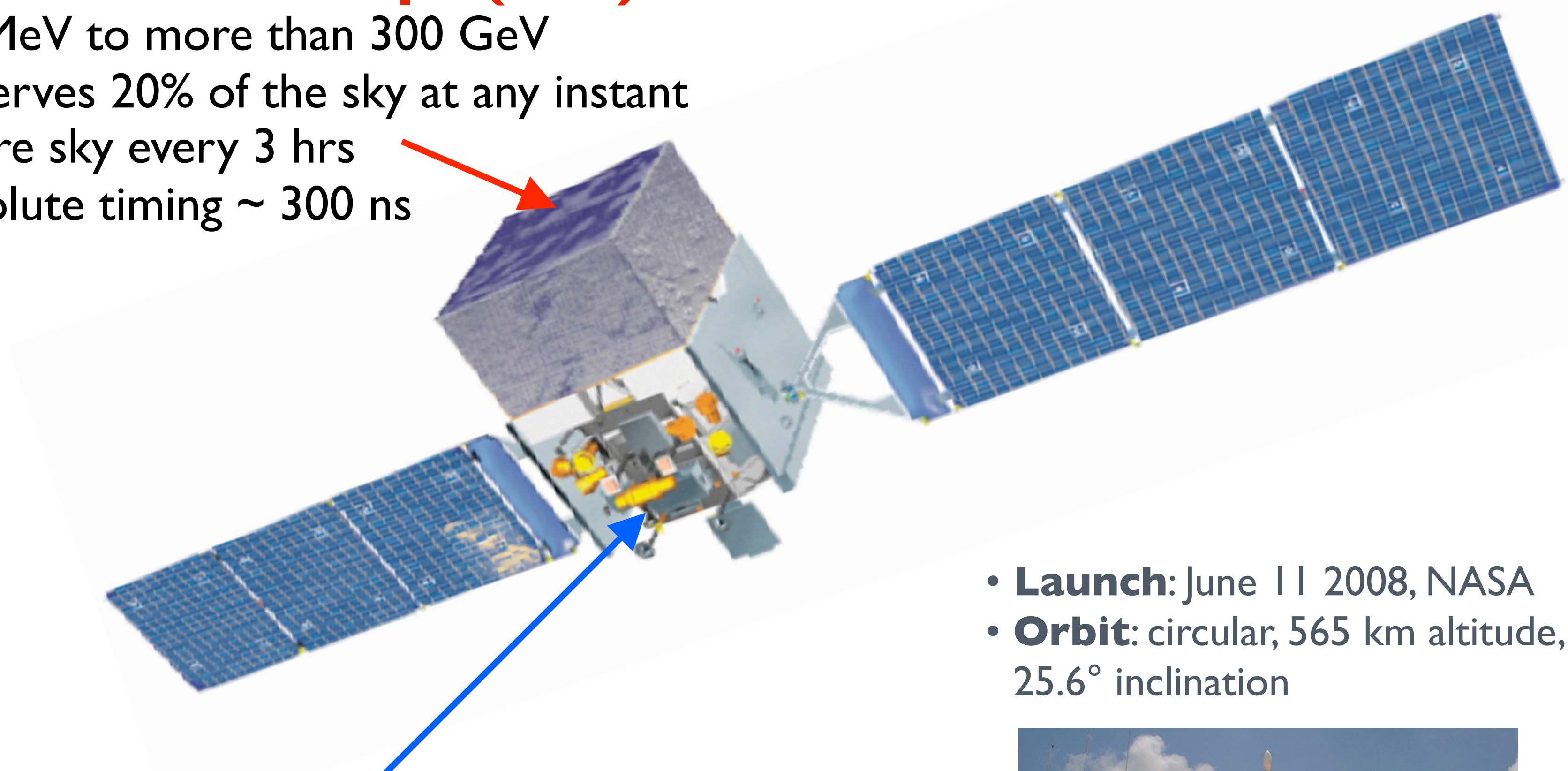
on behalf of the Fermi-LAT Collaboration

CRiS 2018
11th Cosmic Ray International Seminar

The Fermi observatory

Large Area Telescope (LAT):

- 20 MeV to more than 300 GeV
- observes 20% of the sky at any instant
- entire sky every 3 hrs
- absolute timing ~ 300 ns



- **Launch**: June 11 2008, NASA
- **Orbit**: circular, 565 km altitude, 25.6° inclination

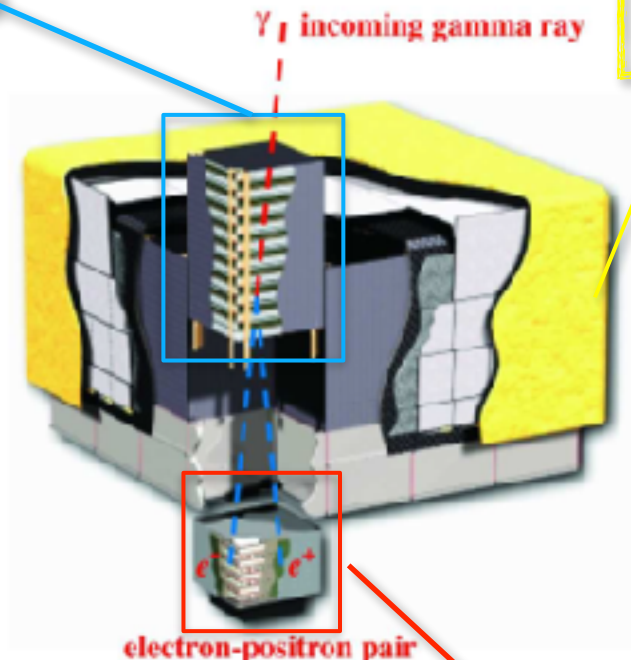
Gamma-ray Burst Monitor (GBM):

- 8 keV to 40 MeV
- observes entire unocculted sky
- absolute timing ~ 2μs
- compute burst location to allow re-orienting Fermi

The Fermi LAT detector

TRACKER-CONVERTER
- Incoming particle direction
- 18 x, y tracking planes: SSD
- 16 planes of tungsten:
  - "FRONT" -> first 12 "thin" layers of 3% radiation length tungsten converters
  - "BACK" -> next 4 "thick" layers of 18% radiation length tungsten converters

ANTICOINCIDENCE DETECTOR
- Charged-particle bkg rejection
- Plastic scintillator, WLS fibers
- Segmented tiles



CALORIMETER
- energy deposition
- shower development imaging
- 96 CsI(Tl) crystals

Pass8 = complete revamp of event reconstruction algorithms (2015)
- Improved performances and IRF
- Retroactively updated entire data archive
- Open new discovery space

Fermi operational anomaly

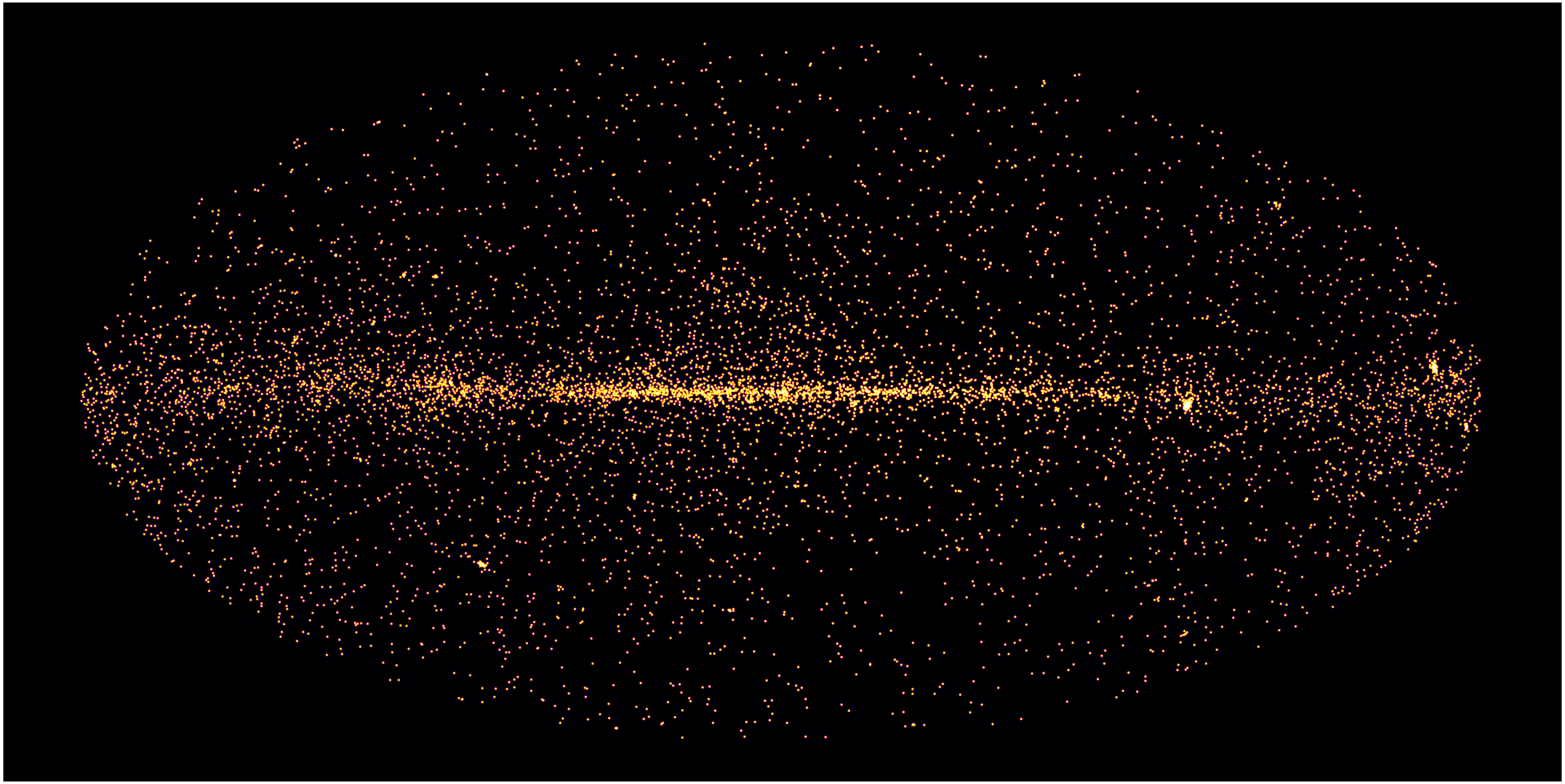
- *On March 16, 2018:* one of the two **solar panels** of Fermi got stuck, as a consequence the observatory went into **safe hold** → instruments powered off and **science data taking stopped**

- *On April 3, 2018:* both GBM and LAT have been **returned to operational status and are actively collecting science data**.
  - GBM has immediately returned to full functionality.
  - LAT started getting back to normal operation temperature (5 days needed to complete the recovery)

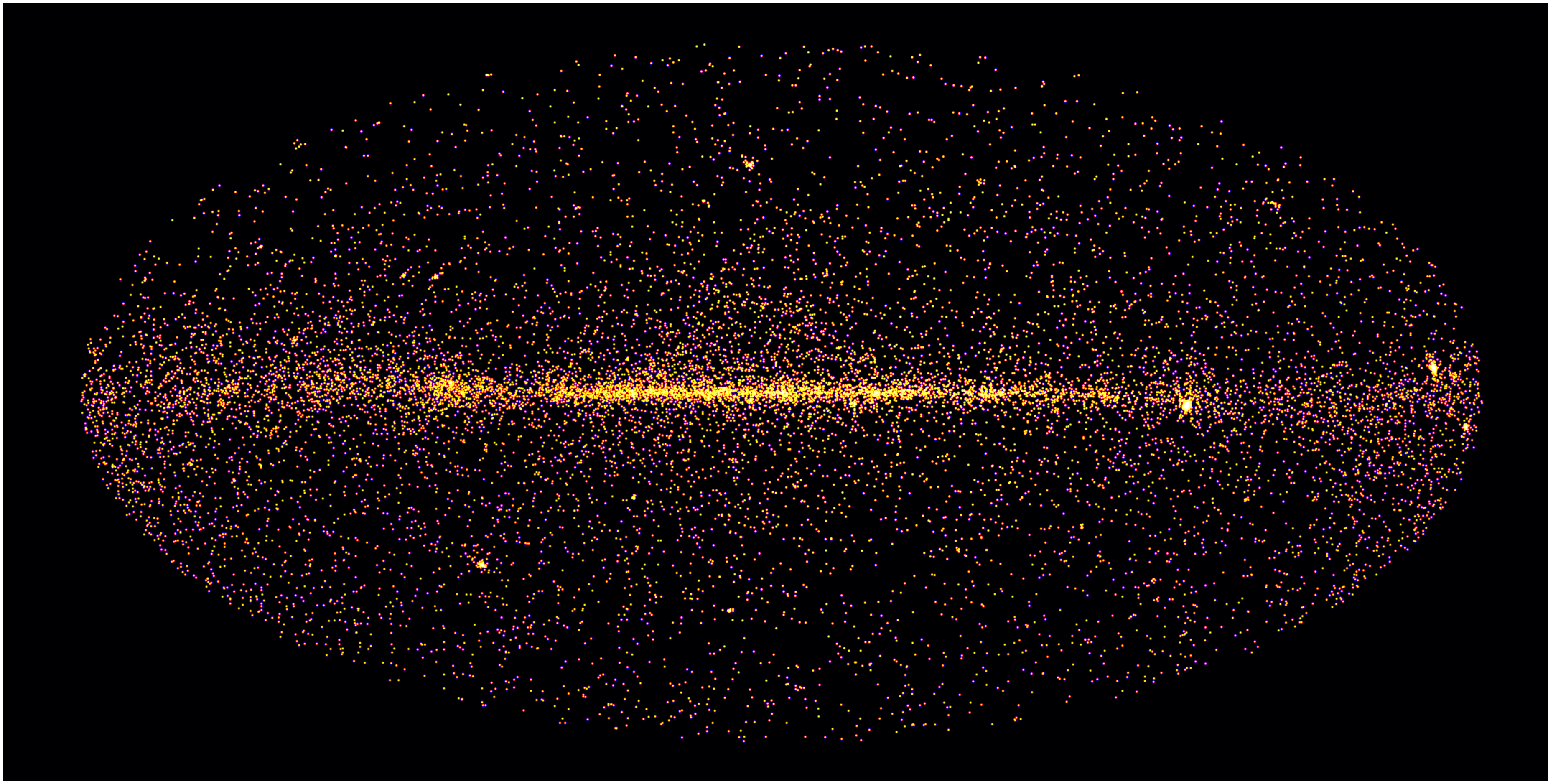
- *Since April 8, 2018:* the LAT operates normally again, a new observing strategy is under study

- **Ongoing investigation** to understand the problem on the engineering side

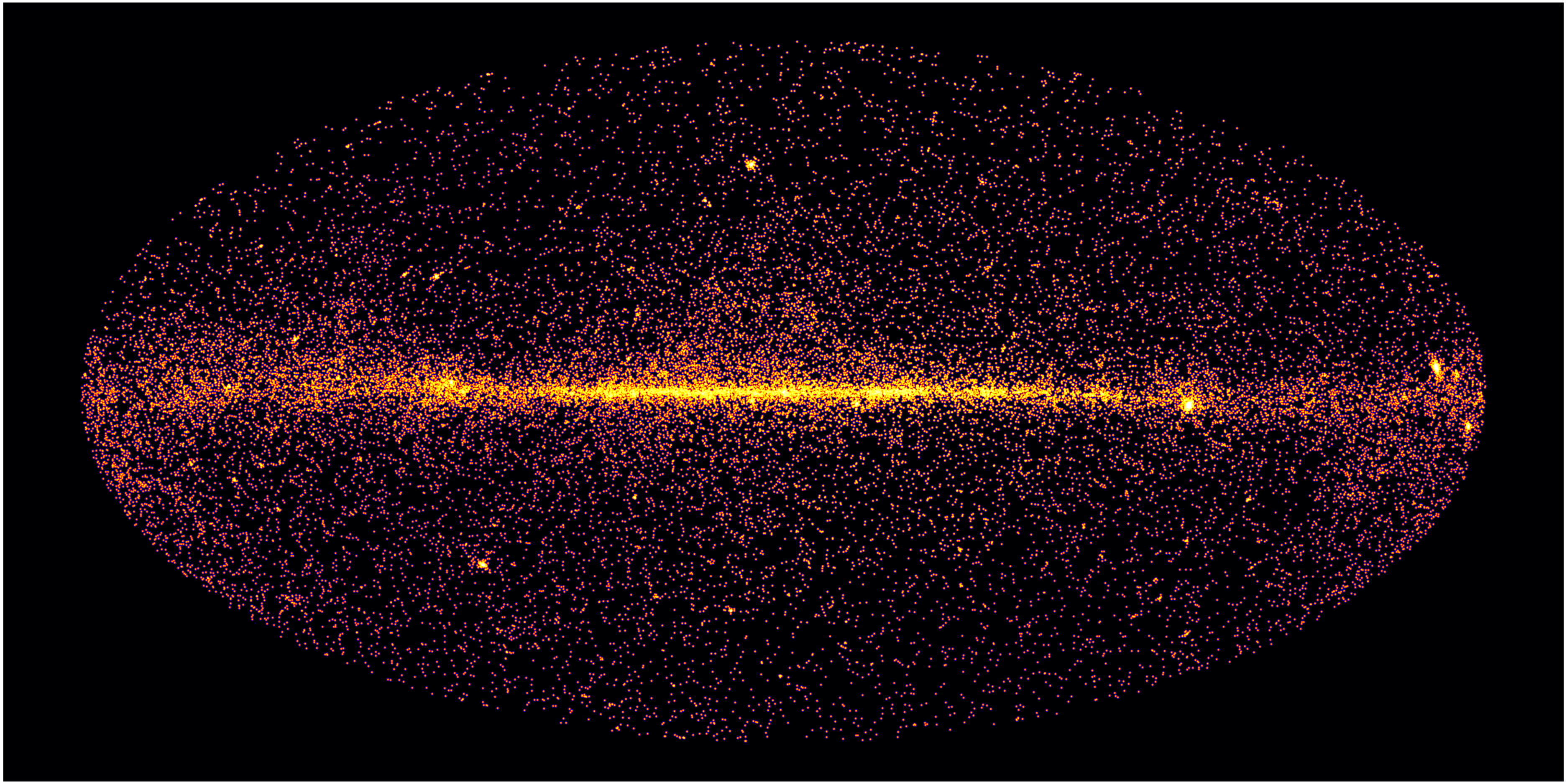
Fermi sky in **30 hours**



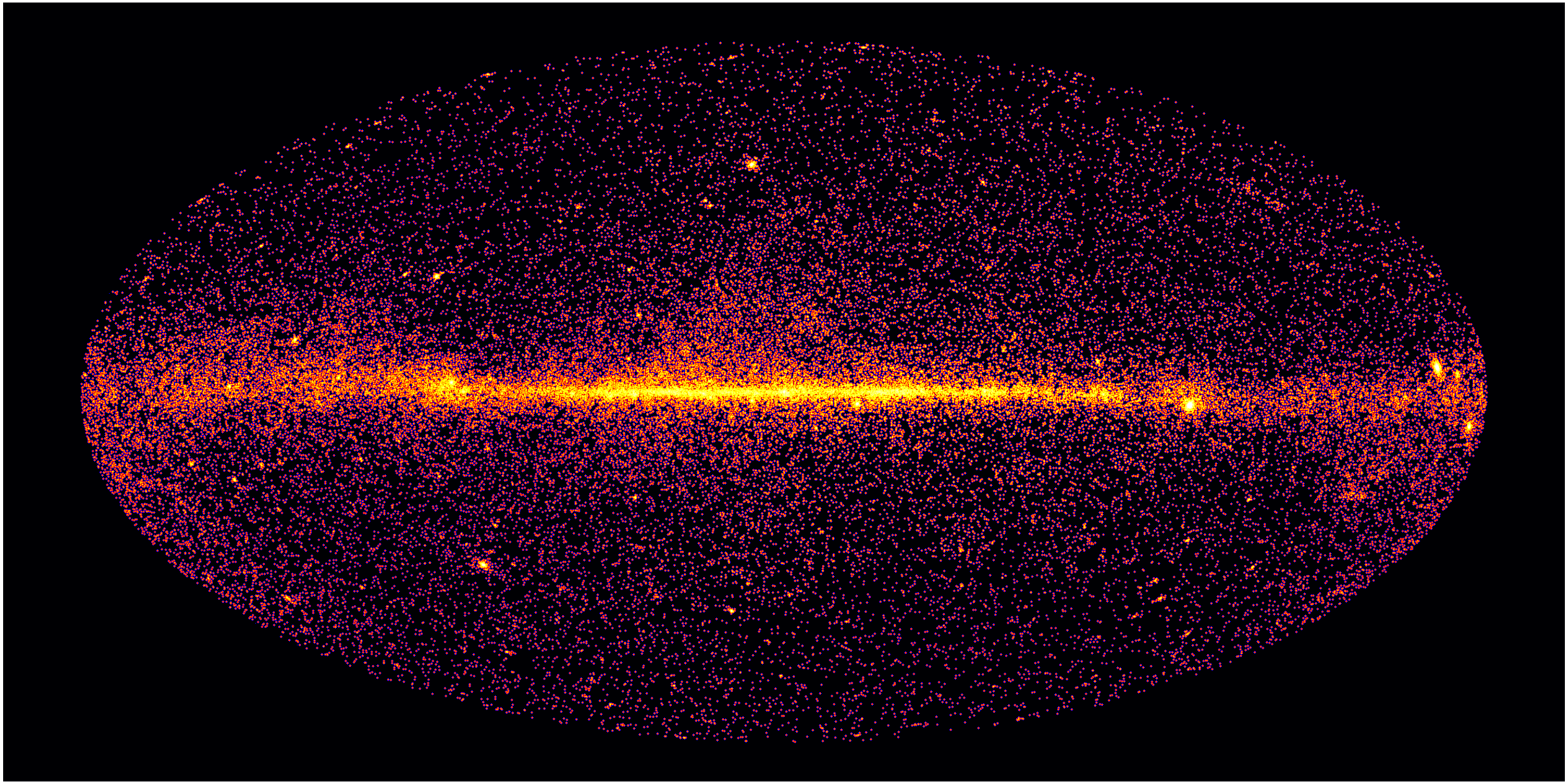
Fermi sky in **60 hours**



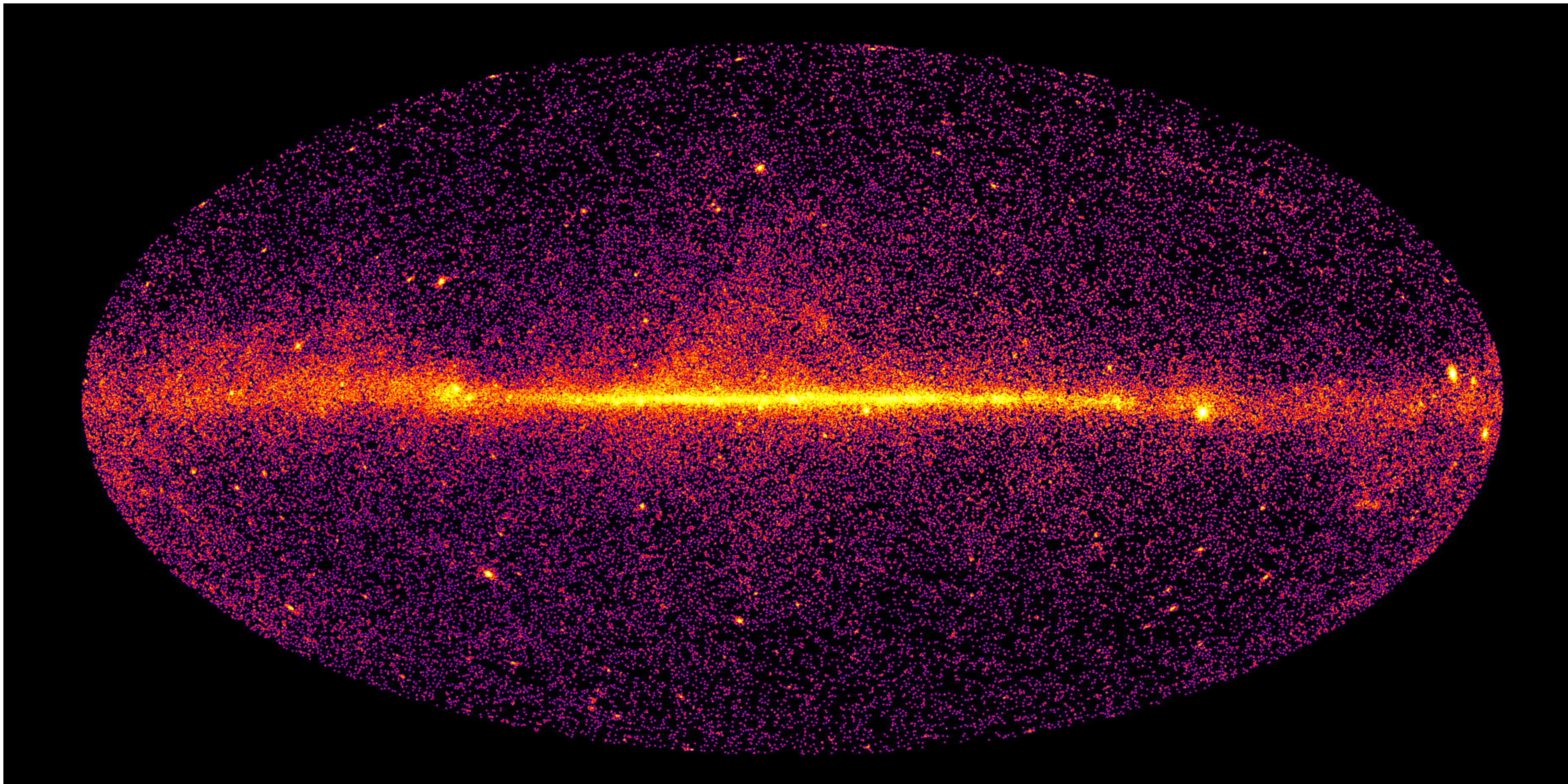
Fermi sky in **5 days**



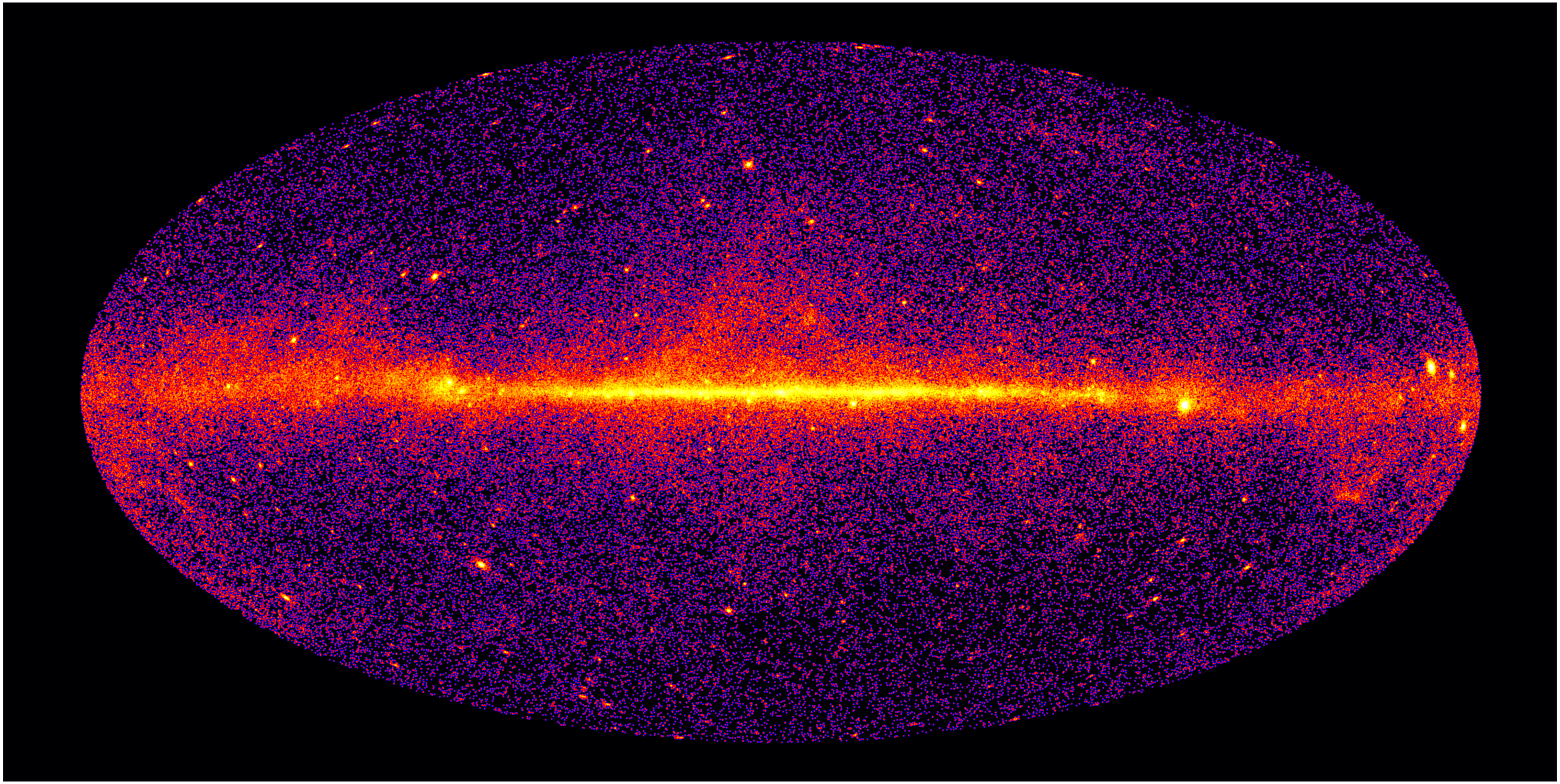
Fermi sky in **10 days**



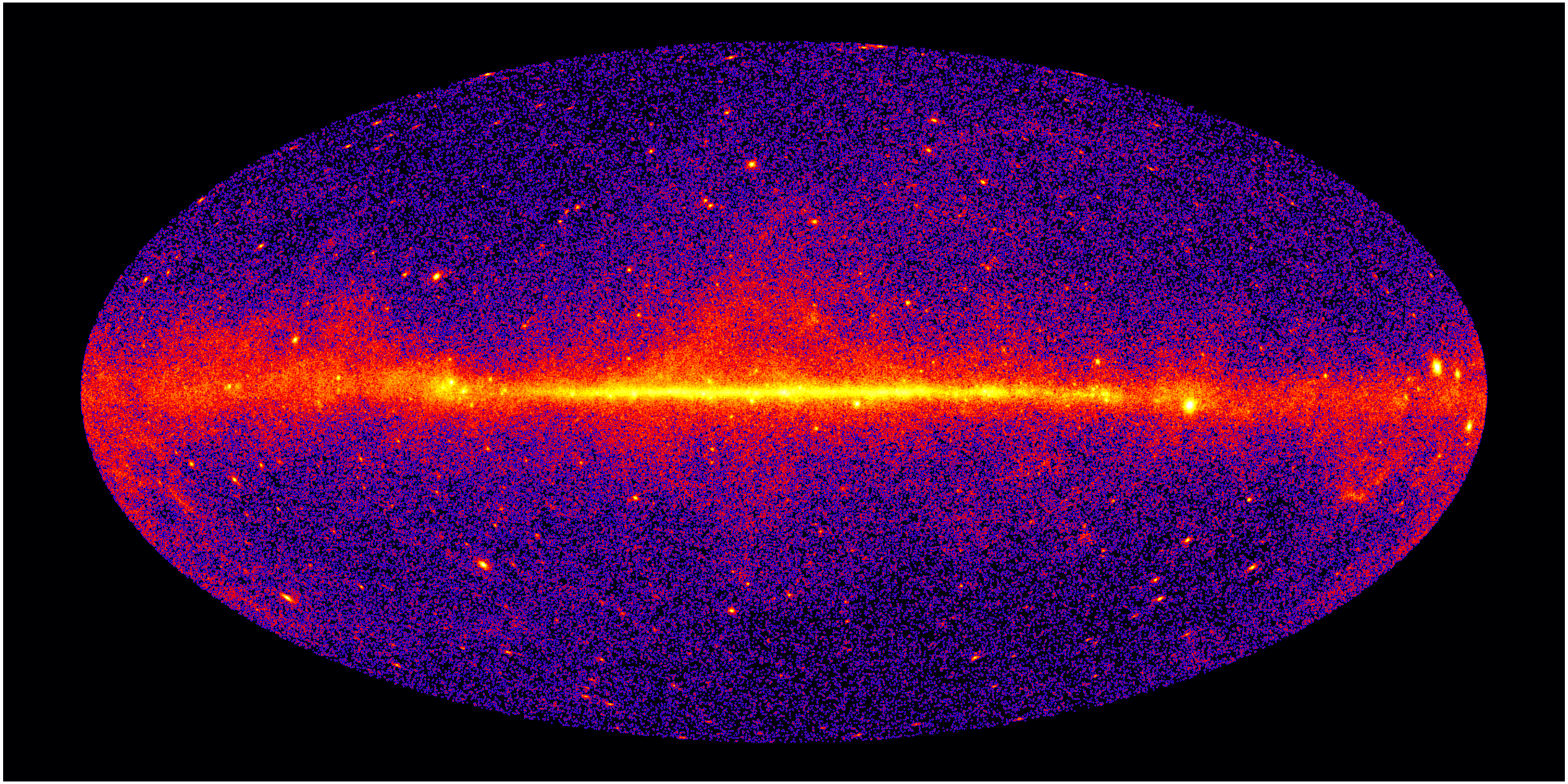
Fermi sky in **20 days**



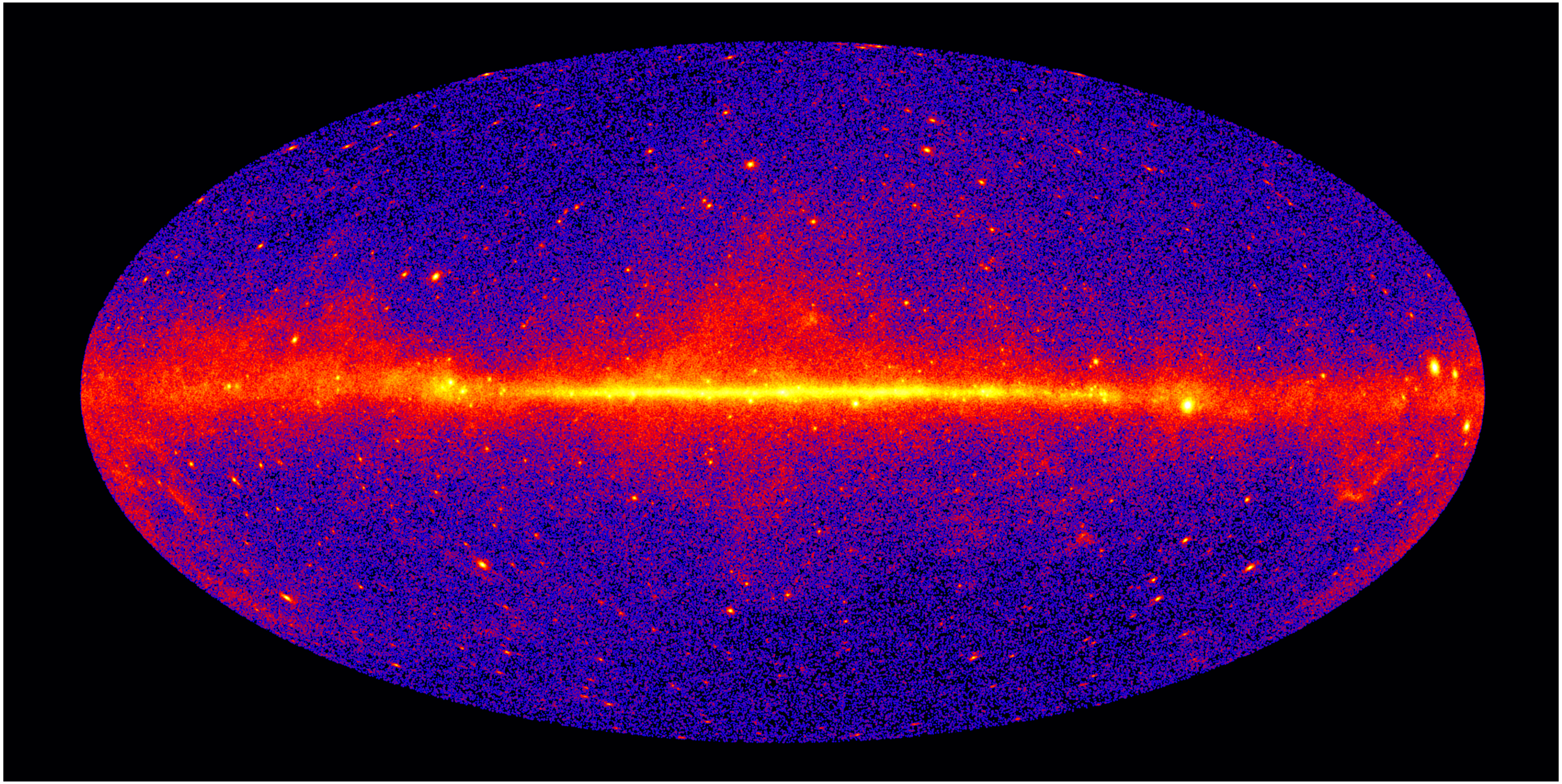
Fermi sky in **40 days**



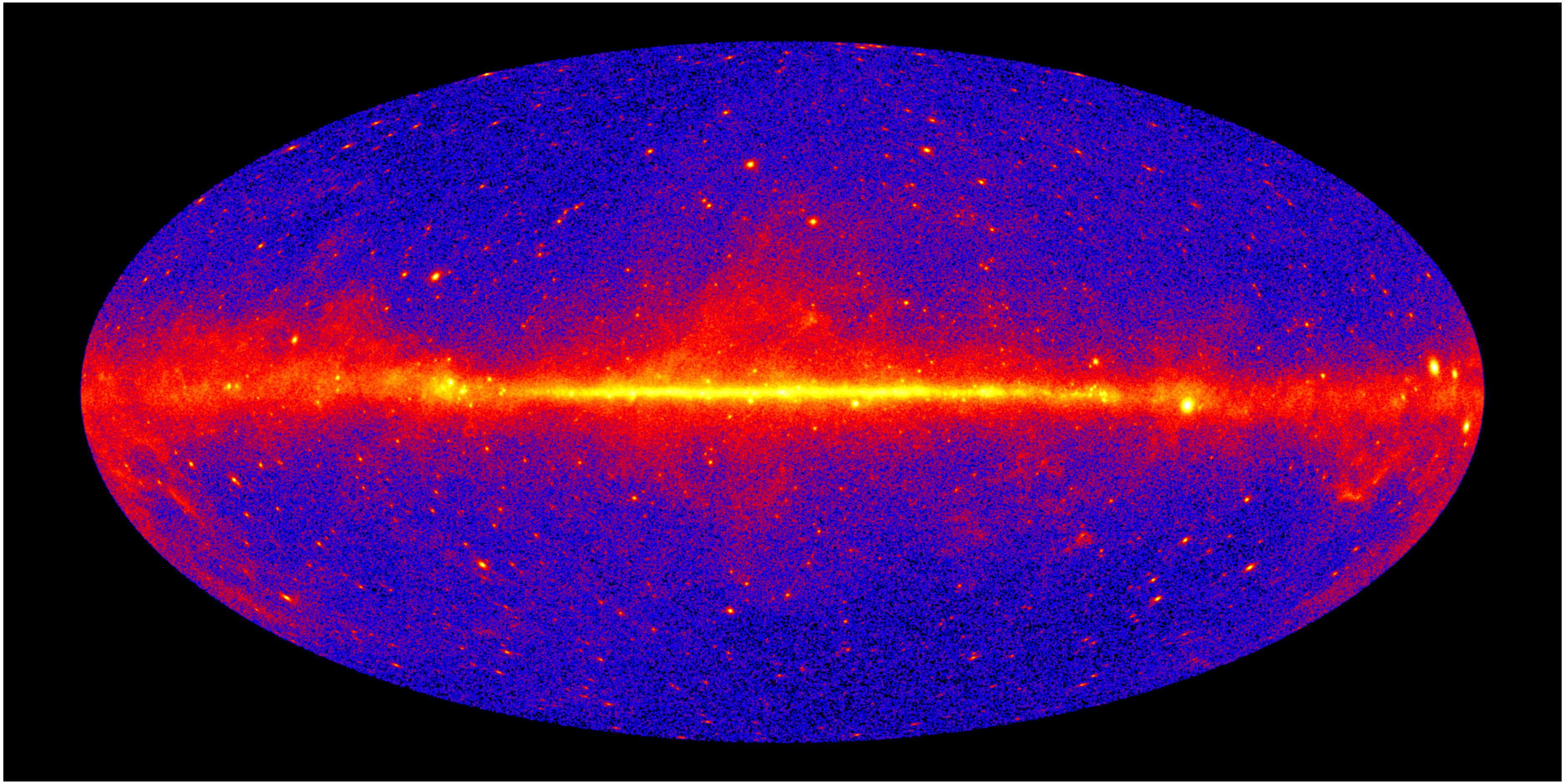
Fermi sky in **80 days**



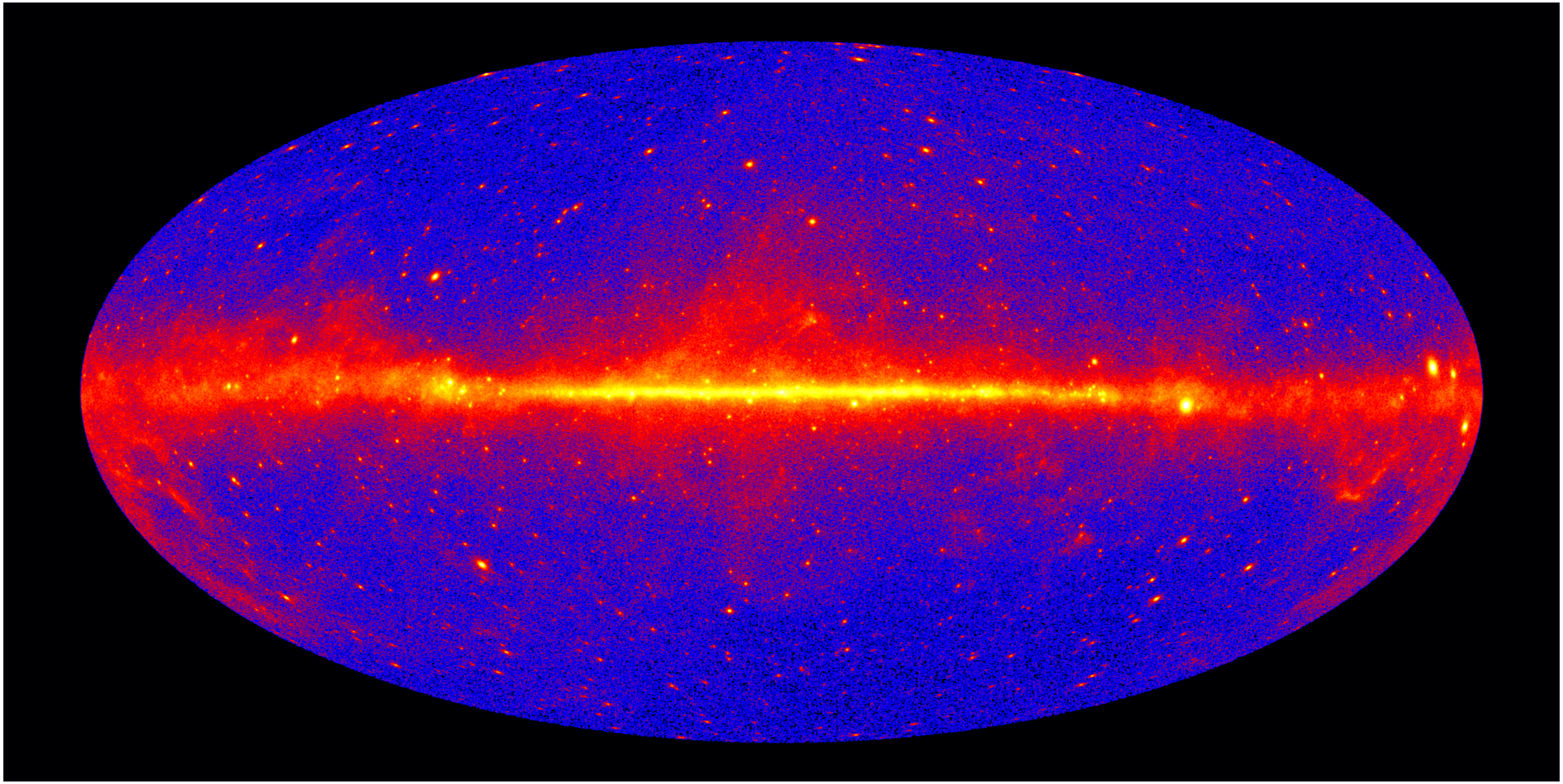
Fermi sky in **160 days**



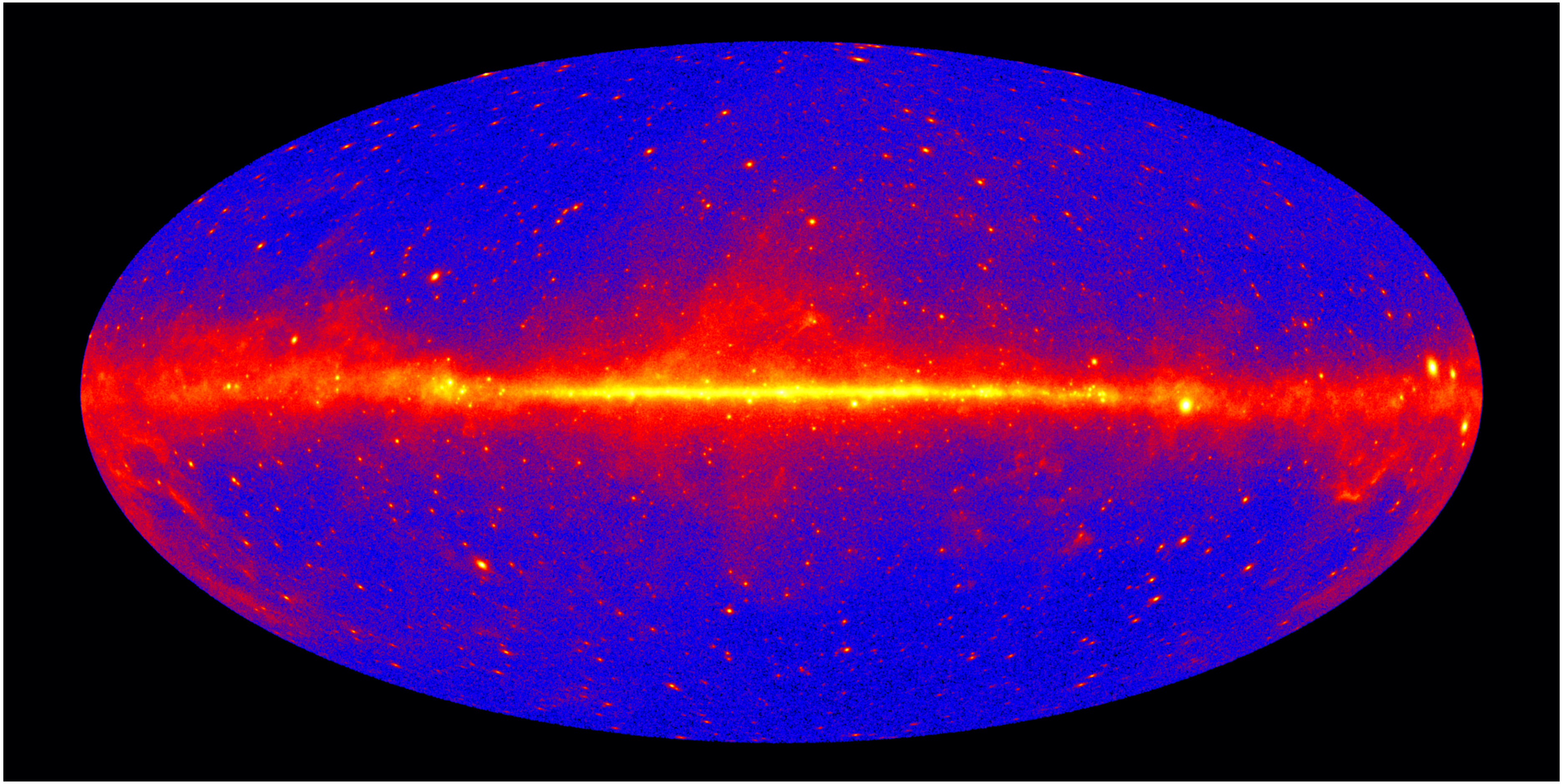
Fermi sky in **320 days**



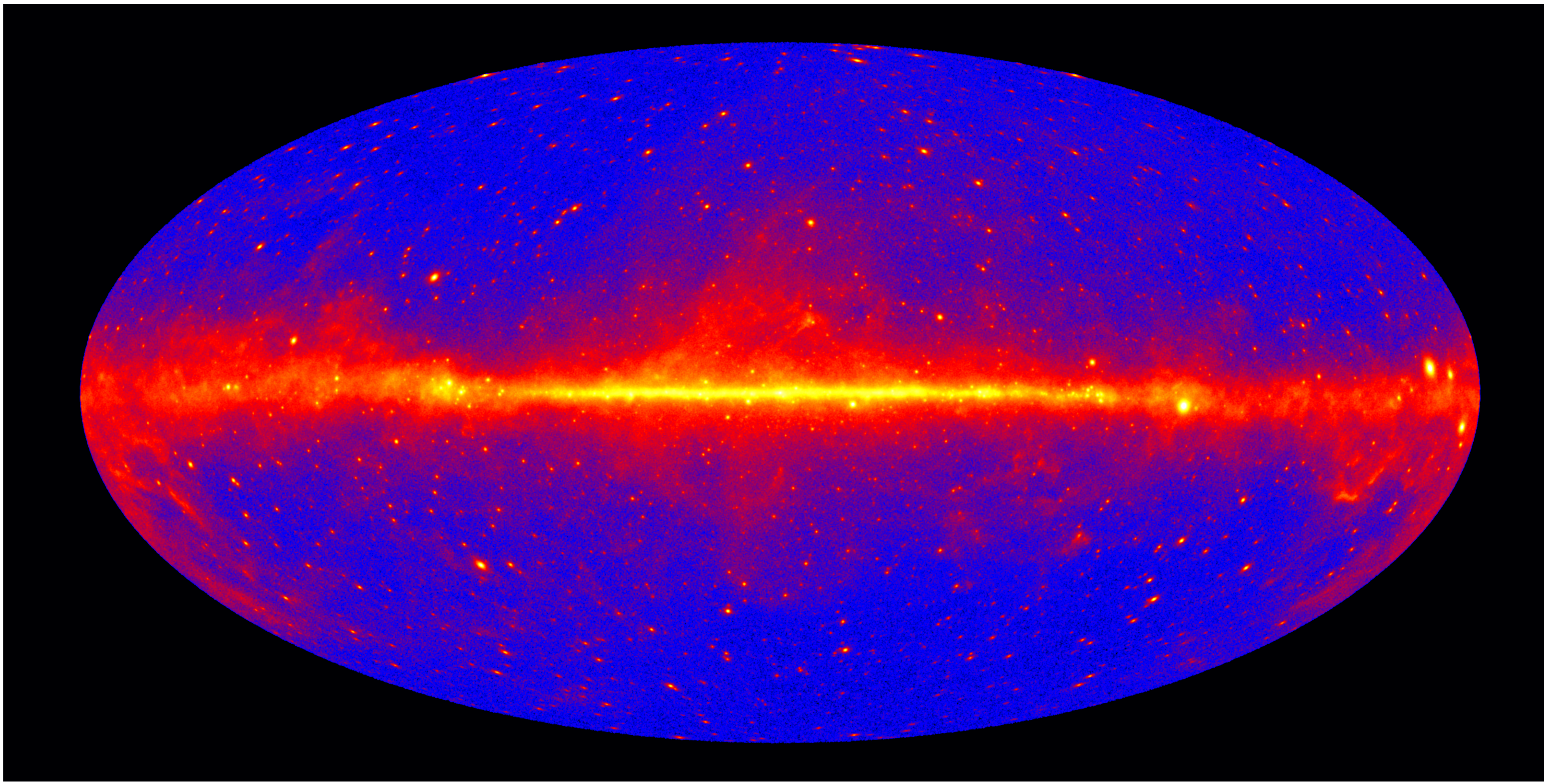
Fermi sky in **640 days**



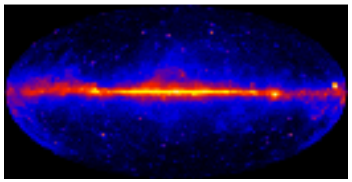
Fermi sky in **1280 days**

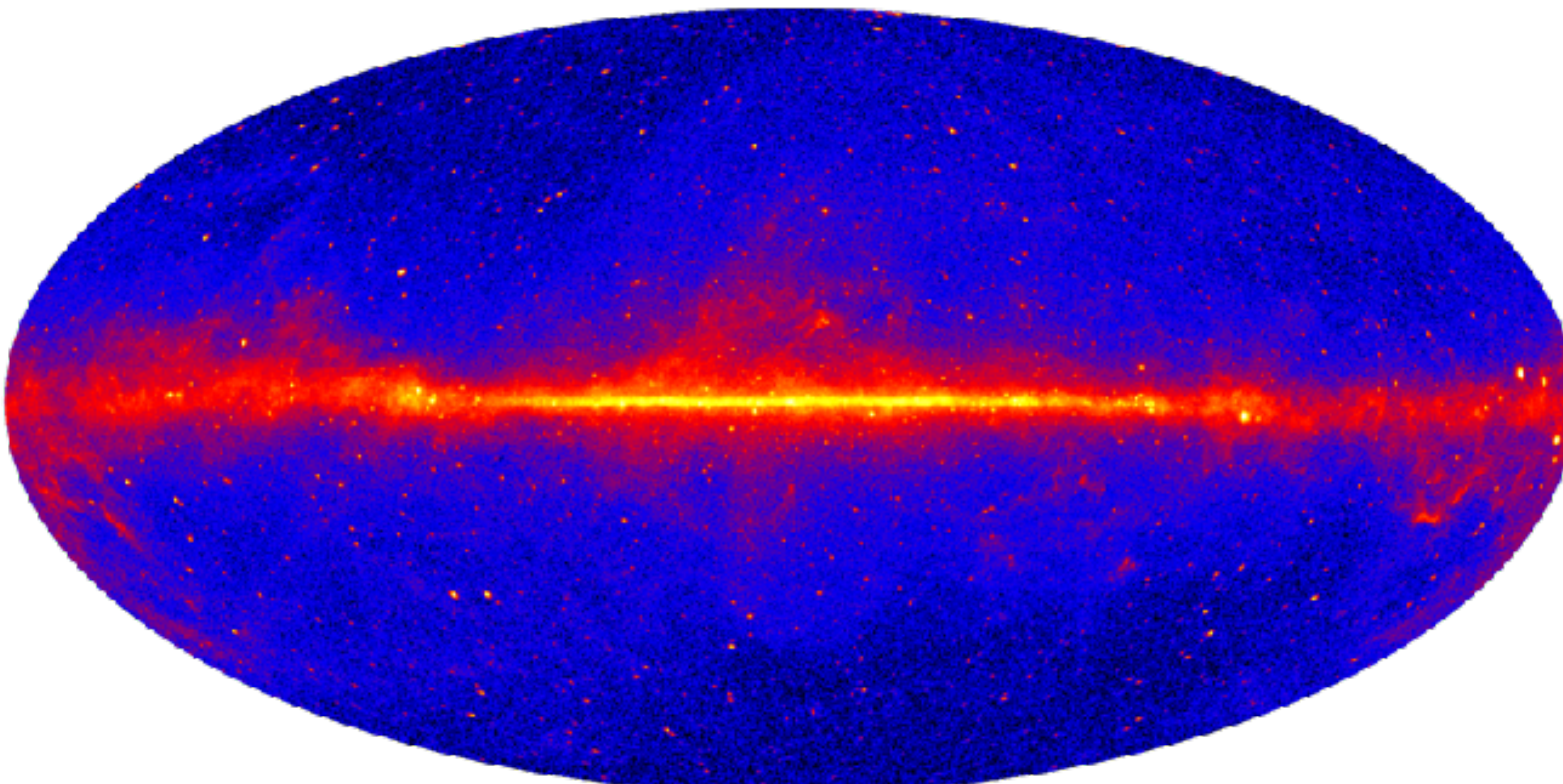


Fermi sky in **7 years**

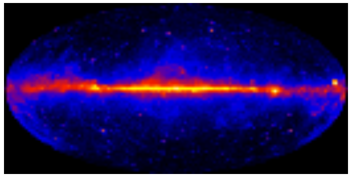


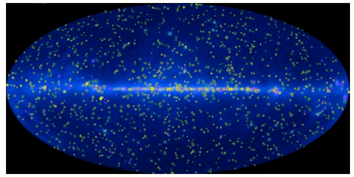
Decomposing the Fermi-LAT Sky

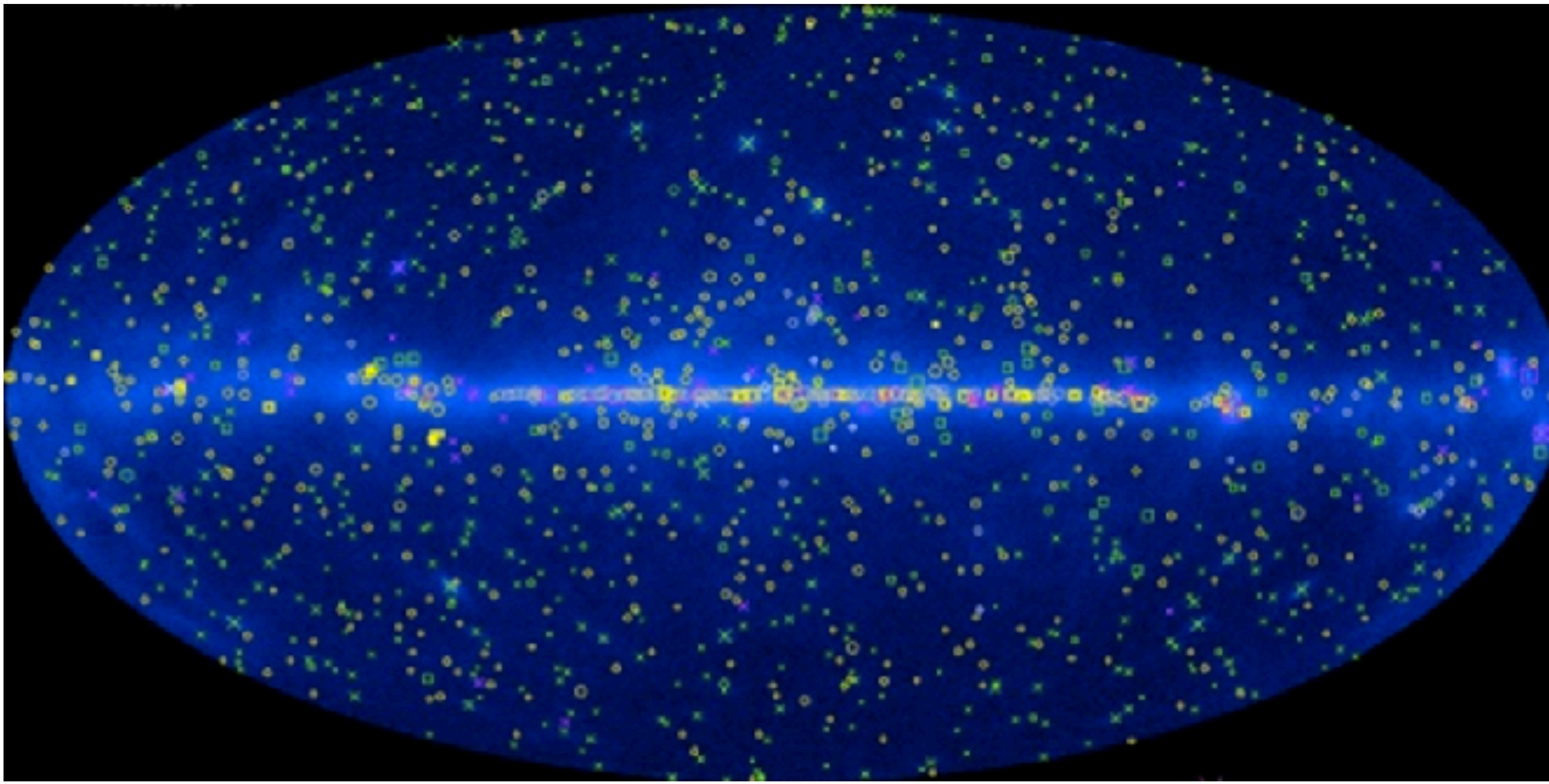
 = ? + ? + ?



Point Sources

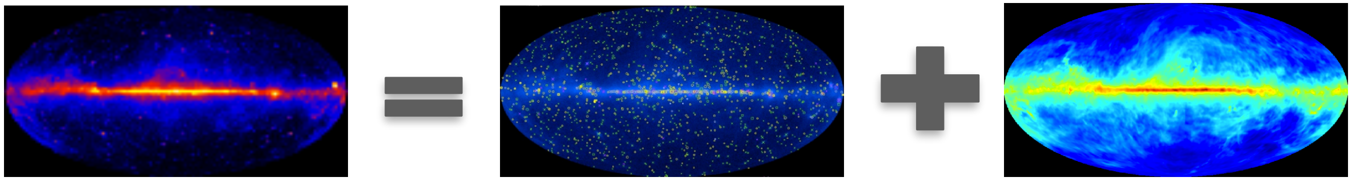


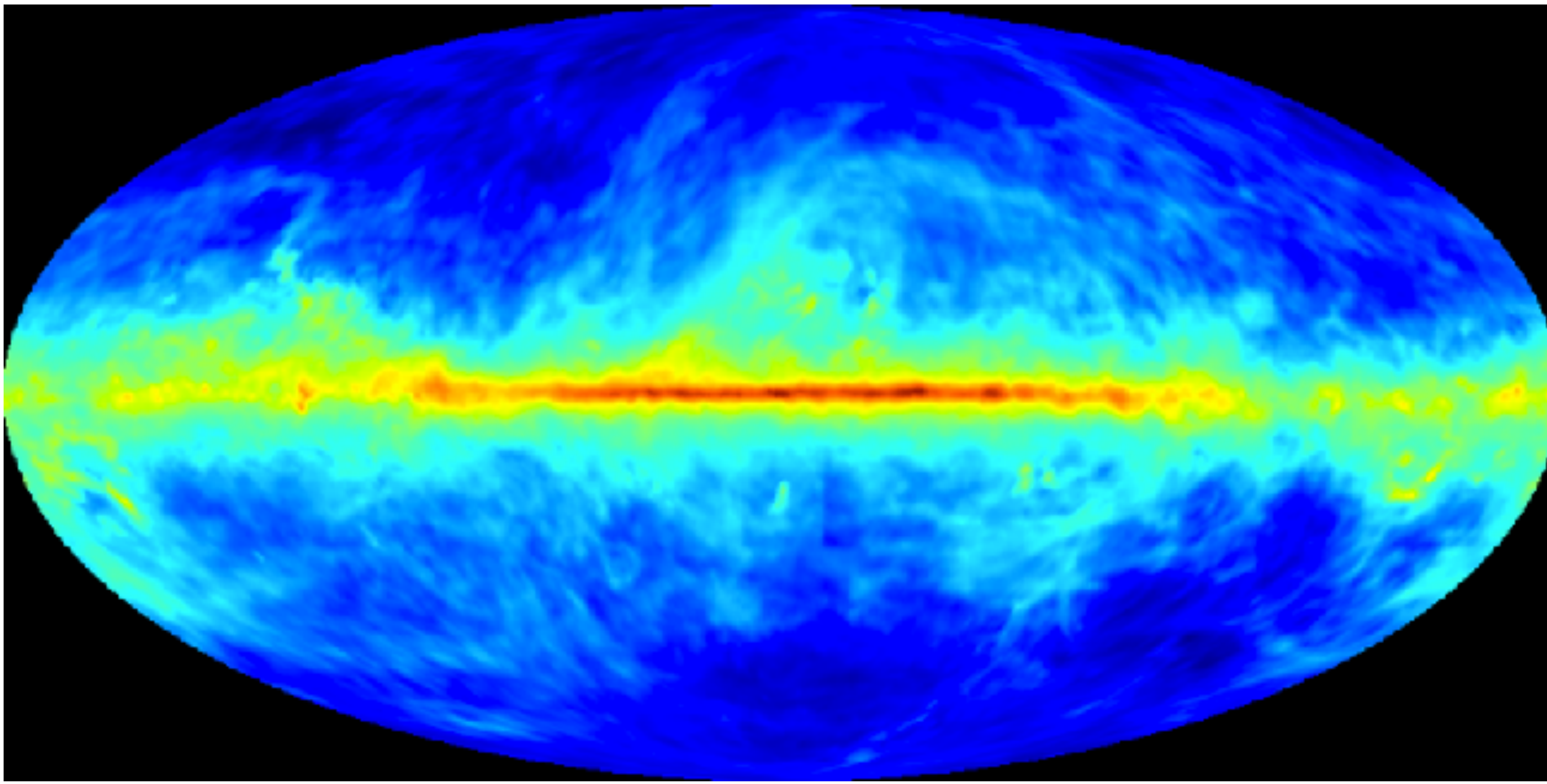




5000+ γ-ray sources: several source classes, including AGN, PSRs, SNR and more

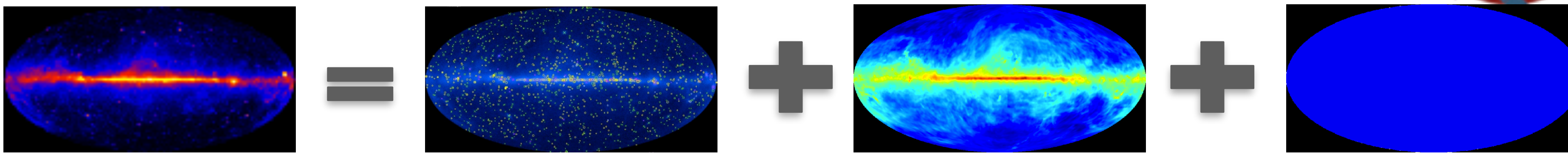
Diffuse Emission

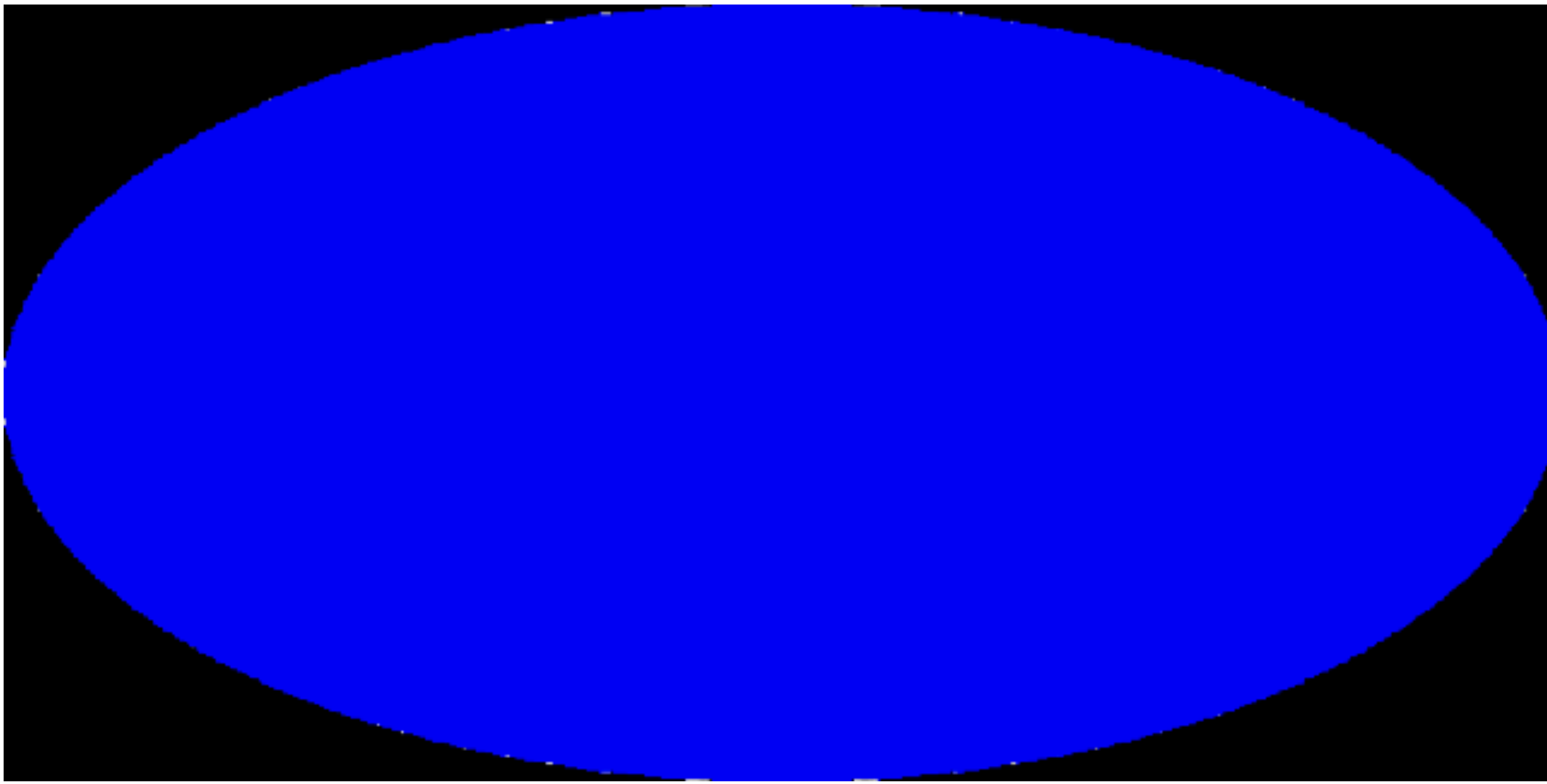




Gamma rays from high-energy **cosmic rays interacting** with dust, gas and radiation fields in the Galaxy

Isotropic Emission

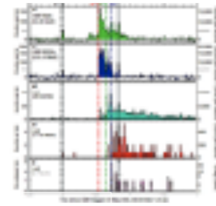




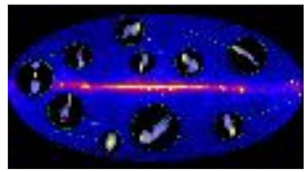
Unresolved emission from extra-Galactic sources, possibly other contributions

Fermi sources classes

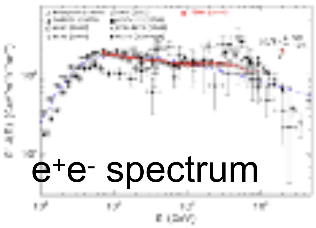
GRBs



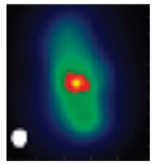
Blazars

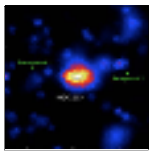


Radio Galaxies



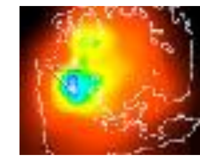
e+e- spectrum



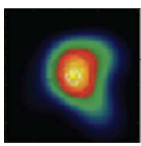


Starburst Galaxies

LMC & SMC

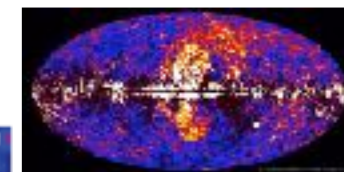


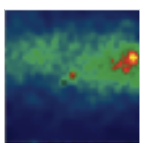
Extragalactic



Globular Clusters

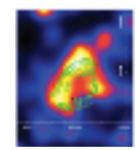
Fermi Bubbles

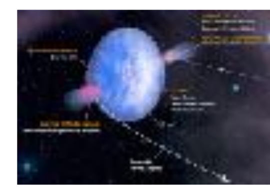




Nova (1)

SNRs & PWN

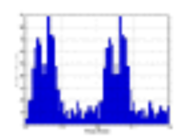




γ-ray binaries

Galactic

Pulsars: isolated, binaries, & MSPs



Sun: flares & CR interactions

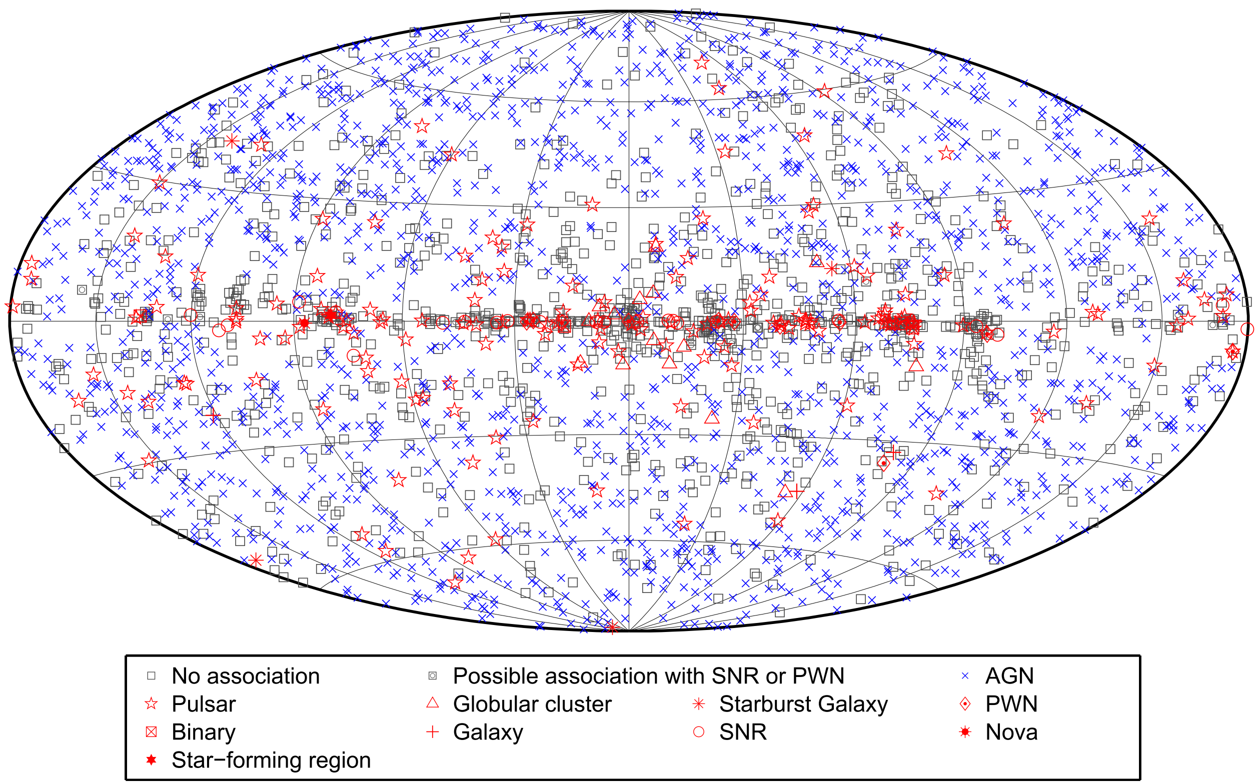
TGFs

Unidentified Sources

Some of the Fermi-LAT HIGHLIGHTS

Catalogs

- One possible approach for **finding and studying new source classes**
- Systematic analysis of the sky **exercised the LAT analysis tools** (e.g. definition of event classes and IRFs) and **tested assumptions of the analysis** (e.g. effects of residual Earth limb emission)
- Good **initial guess for detailed study** of a (newer and longer) data set



- **0FGL** (3 months)
- **1FGL** (11 months)
- **2FGL** (2 years)
- **3FGL** (4 years)
- *coming soon:*

  4FGL *(8 years) with 5000+ sources*

Surprises

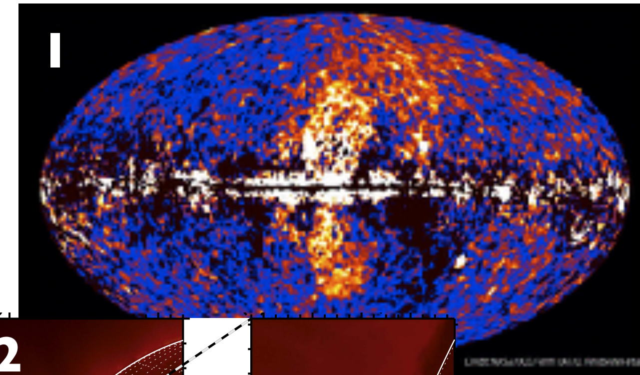
- **Fermi bubbles (1)** – Large lobes of hard-spectrum emission extending +/-60° above and below the Galactic plane in the inner Galaxy *(Su et al. 2010)*

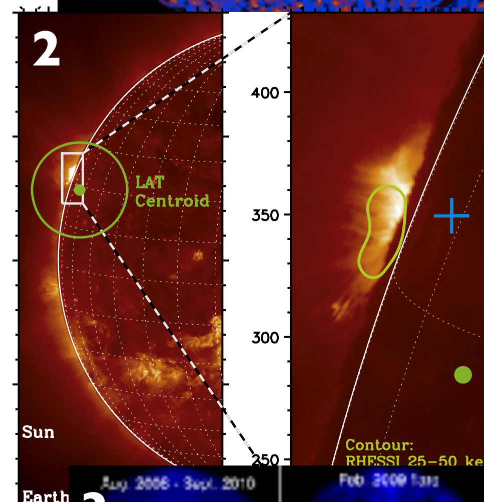
- **GC GeV excess** – A large region around the Galactic center is brighter than expected in GeV gamma rays *(Vitale et al. 2009)*

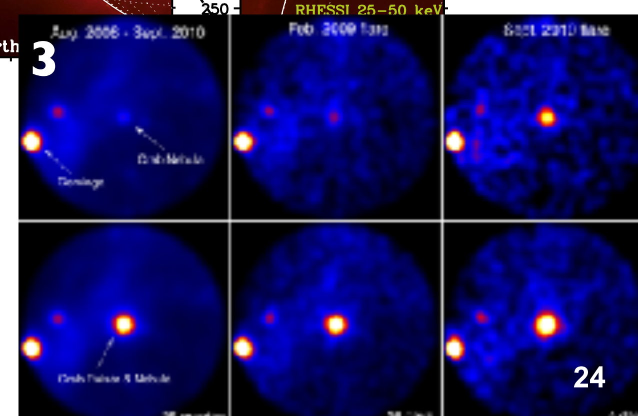
- Behind-the-limb **solar flares (2)** *(Pesce-Rollins+ 2015)*

- **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 (3)** – The Crab nebula, a standard calibration source, is generally 'boiling' and occasionally in outburst *(Tavani et al. 2010)*

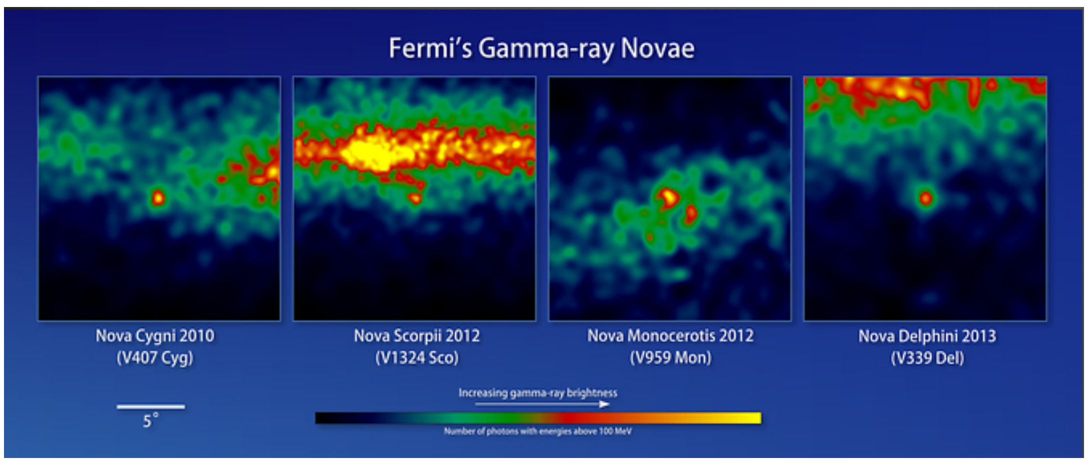


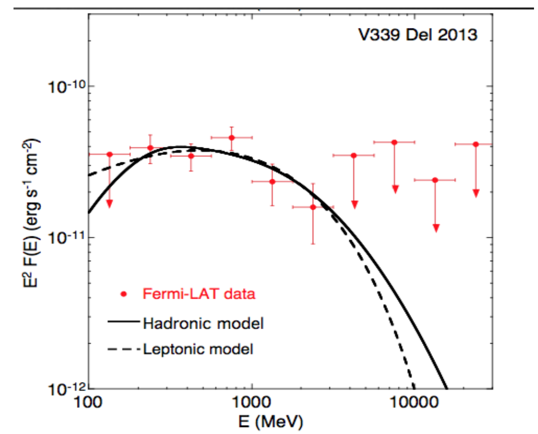




New sources classes

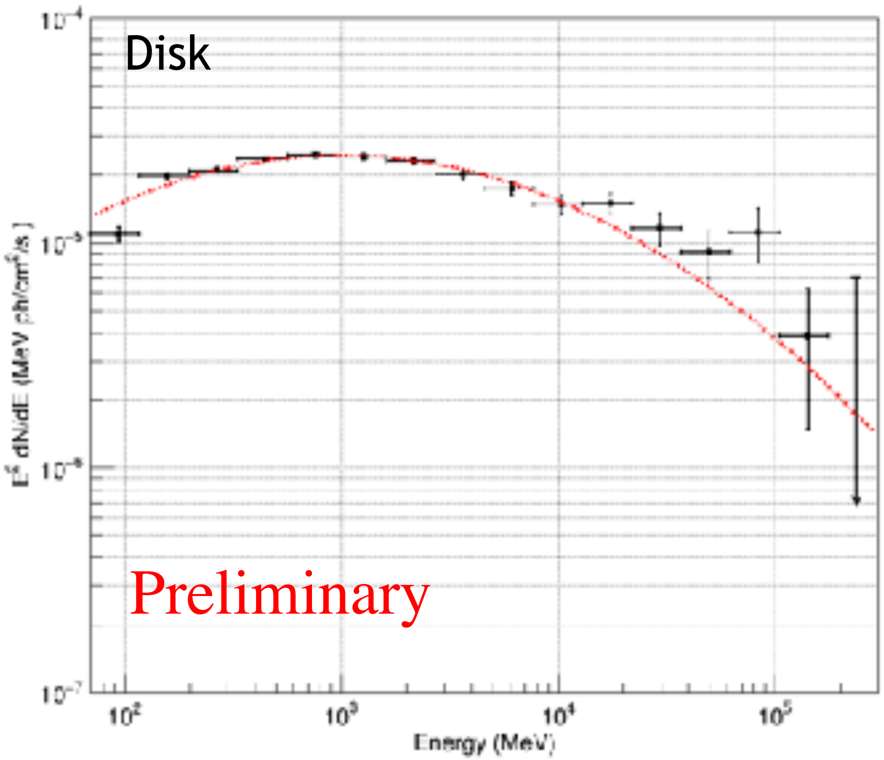
- **Galactic novae** – White dwarf star accreting matter from a companion, detonating, started with V407 Cygni (Abdo et al. 2010), now many
  - Shocks in the expanding nova envelope produce γ rays that appear 1-3 weeks after onset of optical outburst
  - Fermi ToO in response to optical discovery resulted in ~8 new detections
  - Synergy with radio observations that reveal shock sites

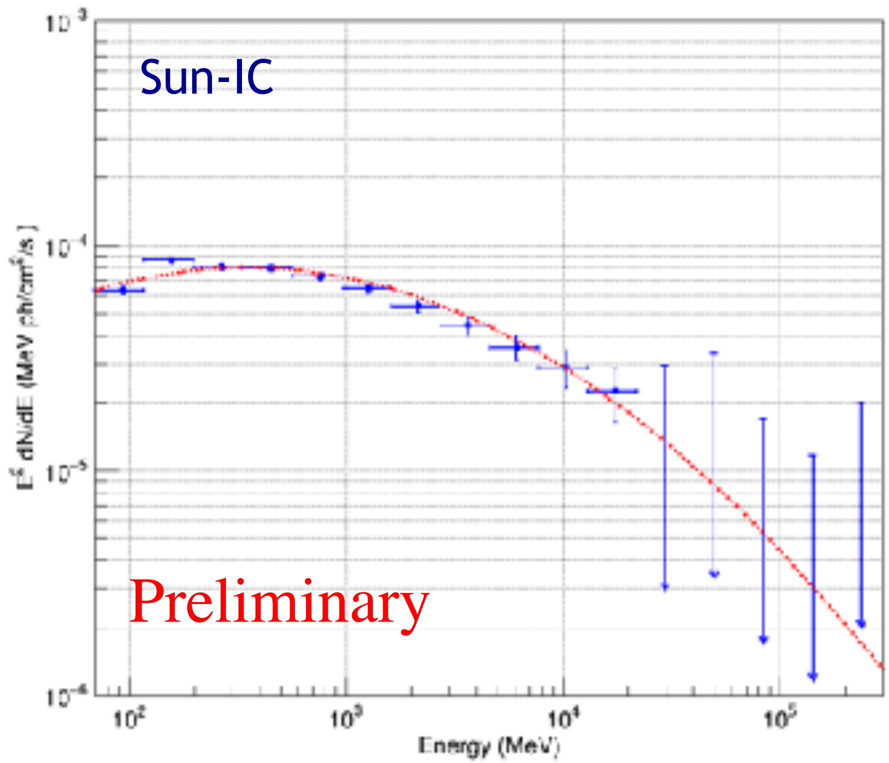




- **High-mass binaries** – Started with PSR B1259-63 (Abdo et al. 2010), gets active at periastron
- **Star-forming galaxies** – Started with M82 and NGC 253 (Abdo et al. 2010), now several
- **Globular clusters** – Started with Abdo et al. (2009), 15 sources in 3FGL
- **Misaligned AGN** – blazar jet not pointed at the Earth; CenA nearby prototype (Abdo et al. 2010)

The Sun SED



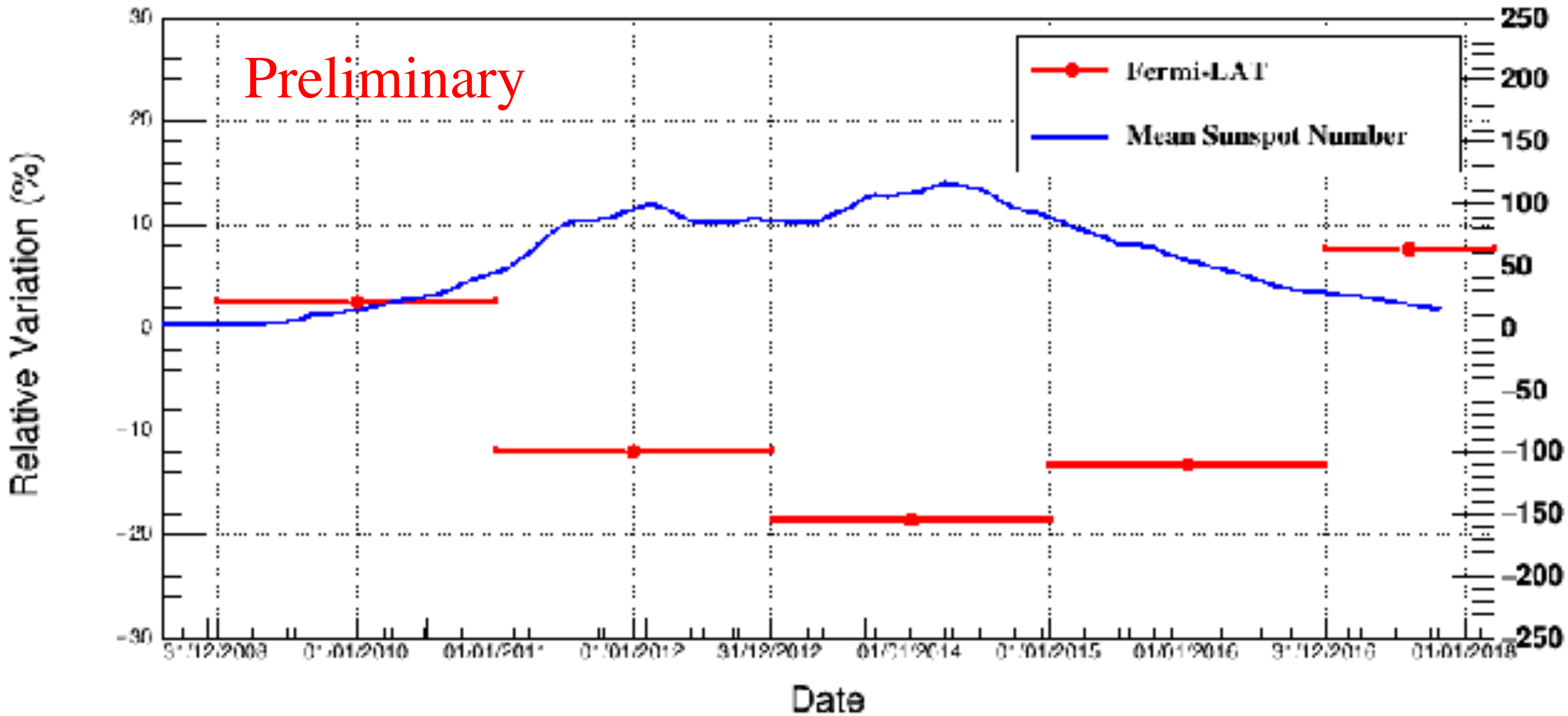


Disk Integral Flux(E>100MeV) = (1.97±0.03) 10^{-7} ph $cm^{-2}s^{-1}$

Sun IC Integral Flux (E>100MeV) = (7.39±0.11)10^{-7} ph $cm^{-2}s^{-1}sr^{-1}$

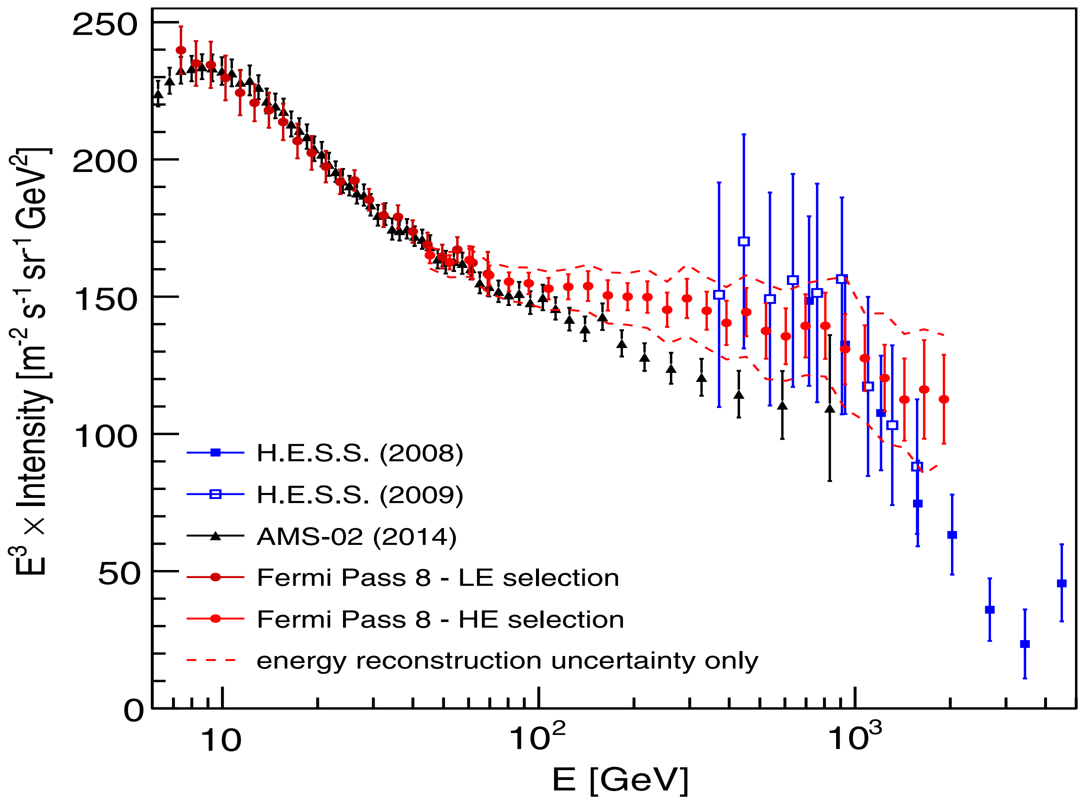
Solar disk modulation

Trend of the relative variation of the disk integral flux (>100MeV) w.r.t. the overall disk integral flux evaluated over the entire ≈10 years time interval.
Superimposed the mean sunspot number trend.



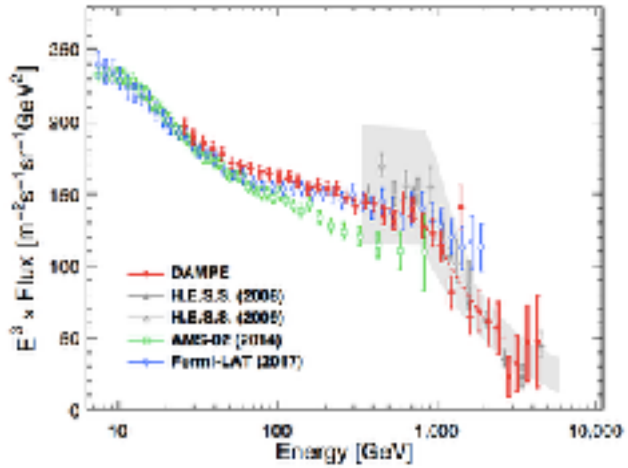
Solar activity source: WDC-SILSO, Royal Observatory of Belgium, Brussels

CRs e^+e^- (CRE) spectrum



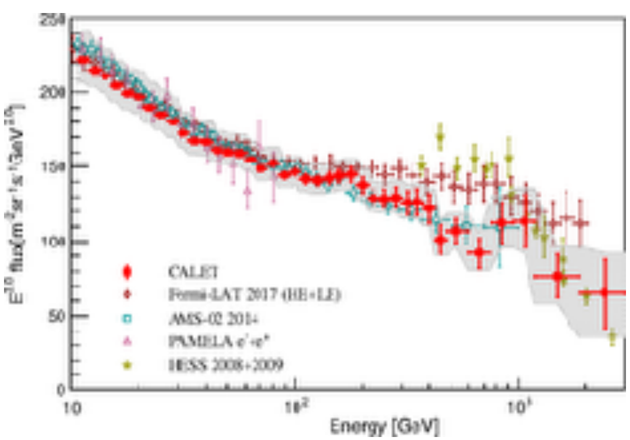
- **Fermi-LAT** CRE spectrum well fitted by a **broken power law:**
  - Hint of a break at 53±8 GeV (significance ~ 4σ)
  - Best fit spectral indices Γ_1=-3.21±0.02 below and Γ_2=-3.07±0.02 above the break
- Exponential **cutoff lower than 1.8 TeV excluded at 95% CL**
- Slightly harder than AMS- 02 spectrum (spectral indices different at 1.7σ level)
- **Syst. uncertainty** on: **energy scale** ~ 2% + **energy rec.** 0% @ 10 GeV → 5% @ 1 TeV

Comparison with recent results



DAMPE:

- Cal. depth 32 X_0, energy res. ~ 1.2%, acceptance: ~ 0.2-0.3 m^2 sr
- Broken power law ($\Gamma_1 \approx -3.1$ - $\Gamma_2 \approx -3.9$), $E_{break} \approx 0.9$ TeV
  - Consistent with Fermi, except the TeV break
  - Overall higher than AMS-02



CALET:

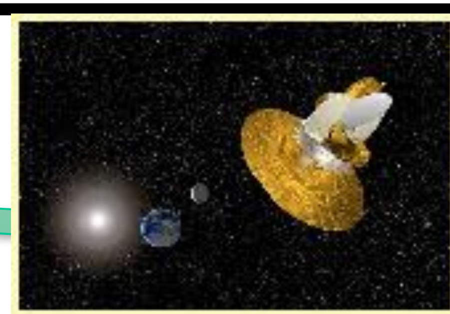
- Cal. depth 30 X_0, energy res. ~ 2%, acceptance: ~ 0.06 m^2 sr
- Single power law above 30GeV ($\Gamma = -3.152 \pm 0.016$)

- Differences might be due in part to the **uncertainty in the absolute energy scale**.
- With increased statistics and improved understanding of detectors' performances, **more consistent measurements** may be achieved in the near future.

MULTI-MESSENGER STUDIES

Synergy with other instruments

Radio: pulsations, synchrotron emission, gas / dust maps, high resolution imaging of host galaxies…



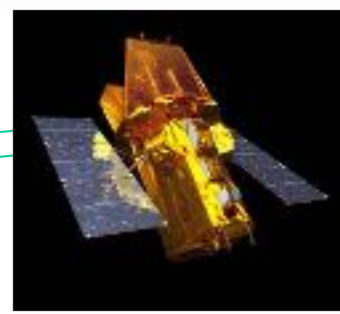
Microwave: diffuse maps & morphology, host galaxy characteristics…

IR: gas/ dust maps, host galaxy characteristics

- **LAT Source Localization better than 0.1°**
- **Great for followups**

Energy

TeV: High-energy spectral breaks, supernovae morphology…



X-ray: GRB afterglows, Galactic source morphology & pulsar association…

Optical: GRB afterglows, AGN/ GRB redshifts…

Transient Searches

Pipelines

Pipeline
Method
Timescale
Distribution
Status

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

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

***Fermi* All-sky Variability Analysis (FAVA)**
Counts Map Aperture Photometry
3 day (coming soon), 1 week
ATels
http://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/

GBM Untriggered Search
ground search
ms - s
GCN Notices
http://gammaray.nsstc.nasa.gov/gbm/science/sgrb_search.html

GBM Onboard Triggers
rate triggers
16 ms - minutes
GCN Notices
Operating

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

LAT Catalogs
Likelihood, associations
3 month (0FGL), 1 year (1FGL), 2 years (2FGL), 4 years (3FGL)
http://fermi.gsfc.nasa.gov/ssc/data/access/
4FGL in progress

Timescale

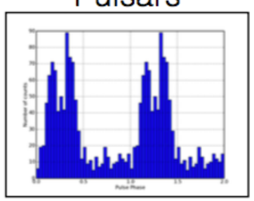
μs — ***ms*** — ***s*** — ***minutes*** — ***hours*** — ***days*** — ***months*** — ***years***

Photon Timing

All Sky Cadence

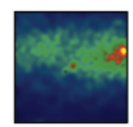
Transients

Pulsars

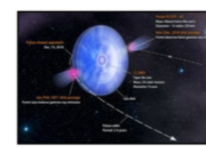


Solar Flares

Novae

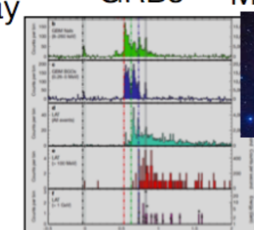


γ-ray Binaries



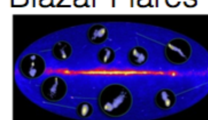
Terrestrial γ-ray Flashes

GRBs

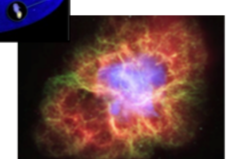


Magnetar Flares

Blazar Flares



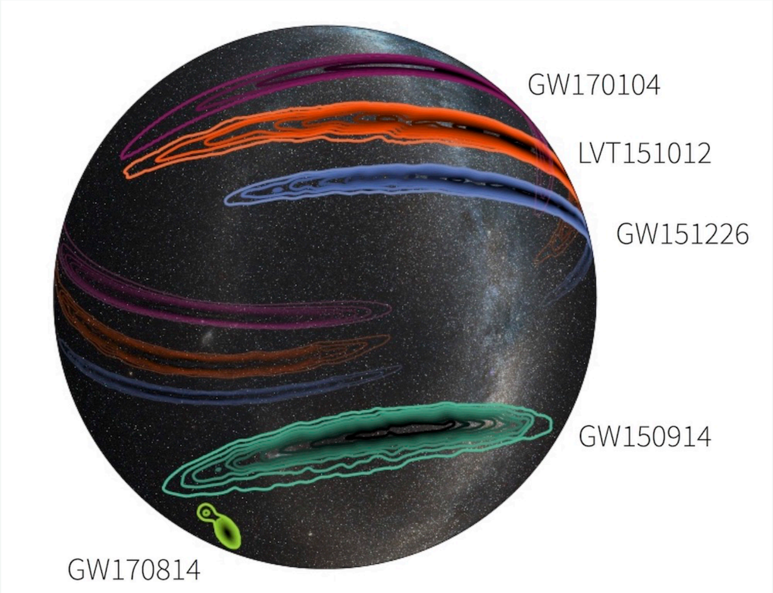
Crab Flares



Not to scale

Gravitational waves

- **6 GW events** announced by the LIGO/VIRGO Collaboration:
  - **5 BH- BH**: GW150914, LVT151012, GW151226,GW170104, GW170814;
  - **1 NS-NS**: GW170817;



- BH-BH mergers are not expected to produce *EM radiation.*

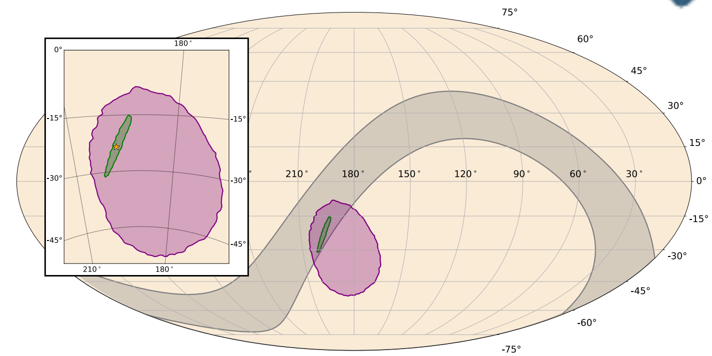
- NS-NS: predicted (and confirmed) to produce *EM radiation.*

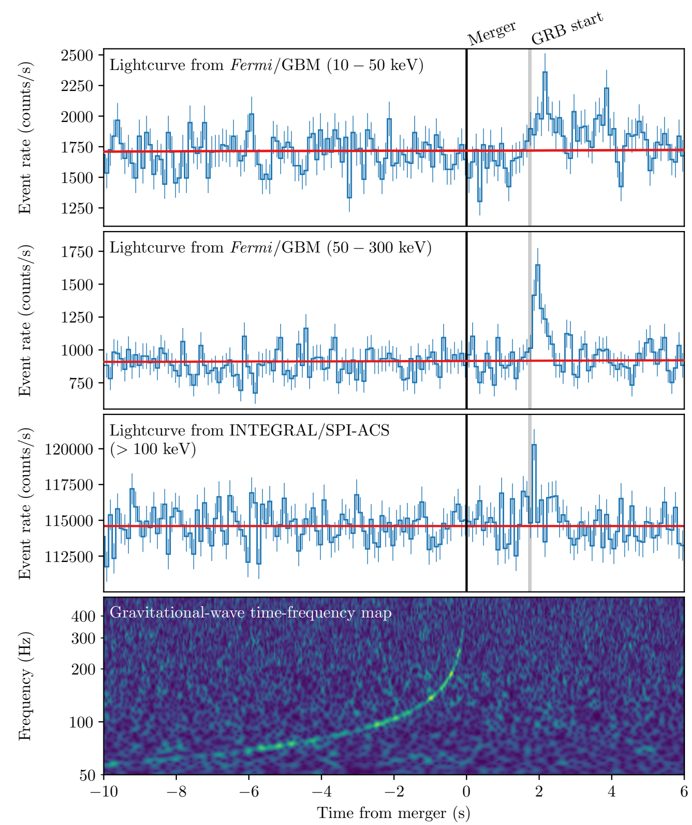
- General **strategy for Fermi-LAT searches** at high- energy:
  - Automated full sky searches of transients
  - Specific searches in the LIGO contours
  - Specific followups of detected counterparts
  - Pipelines to quick alert the community

GW170817/GRB170817A

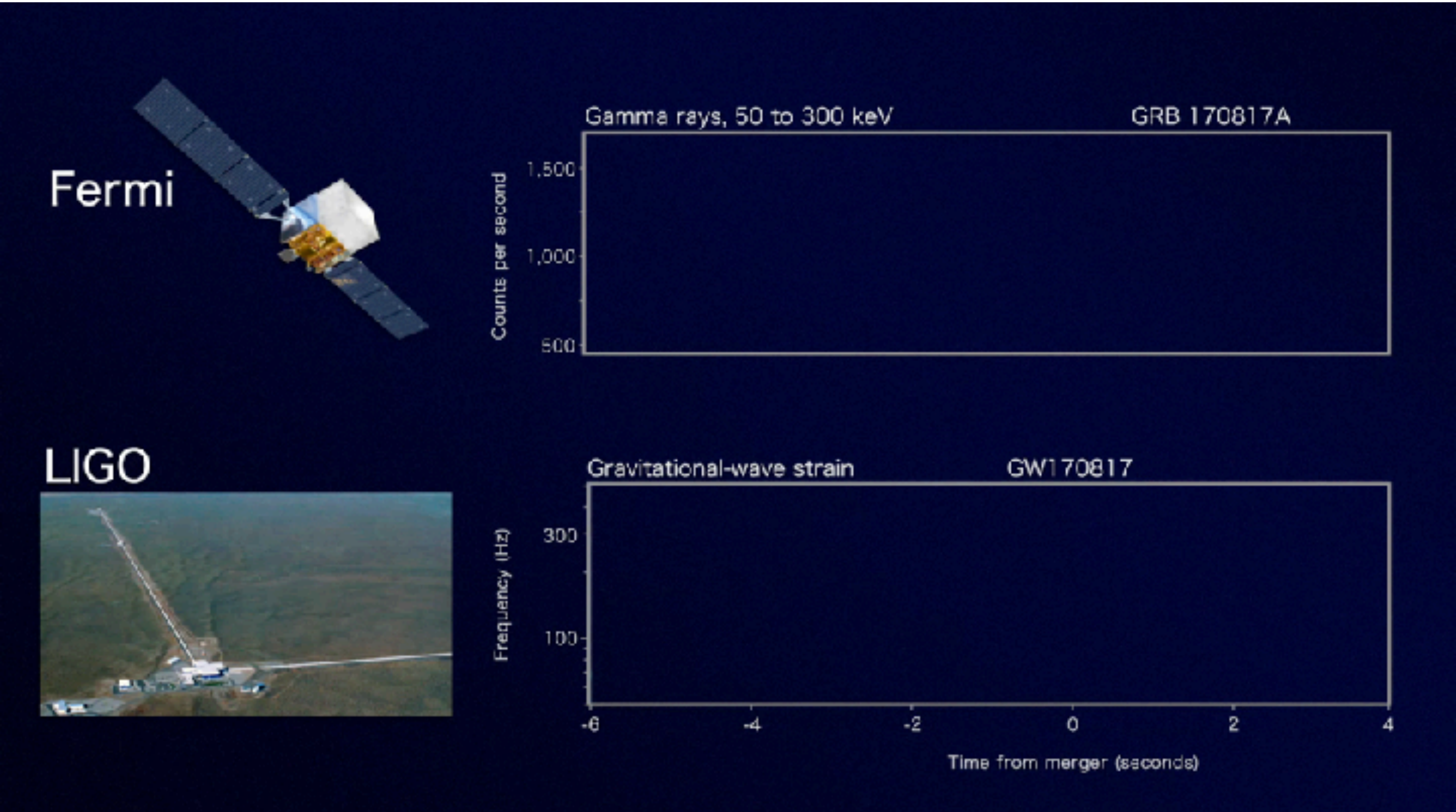
- GW170817 detected on August 17, 2017 by the Advanced LIGO and Virgo observatories.
- 1st signal due to the merger of two NS
- Only 1.7 seconds after the GW detection, **Fermi-GBM and INTEGRAL detected a short GRB 170817A**
- For decades astronomers suspected that sGRB were produced by the merger of two NS or a NS and a BH

➡ The combination of GW170817 and GRB 170817A provides the **1st direct evidence that colliding NS can produce sGRB**.



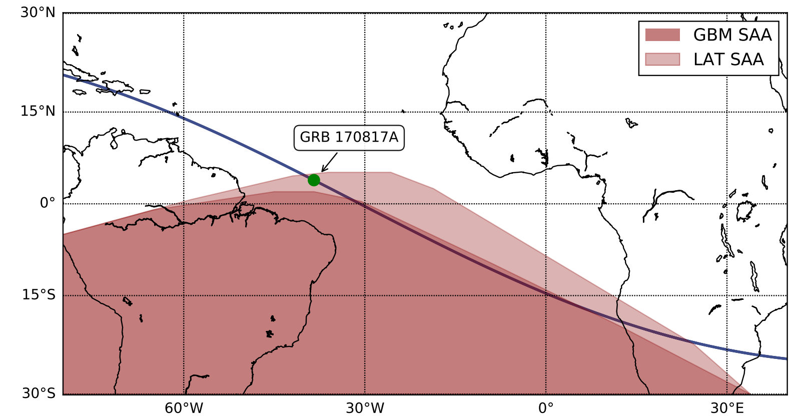


GW170817/GRB170817A

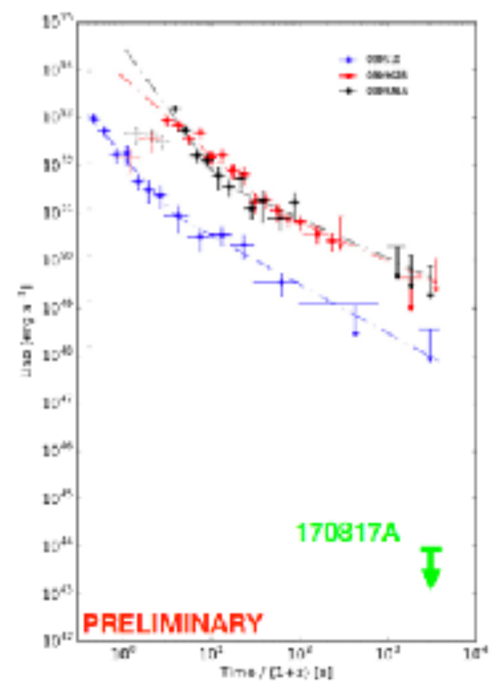


LAT observation of GW170817

- The LAT and the GBM do not collect data when in the SAA
  - SAA definition for the LAT is slightly larger (14%) than the GBM one
  - **At the time of the GW event the LAT was in the SAA**
  - We observe the entire region between t_{GW}+1153 – t_{GW}+2017



- No electromagnetic counterpart above > 100 MeV on timescales of minutes/hours/days after t_{GW}
- Upper bound (0.1-1 GeV): F < 4.5x10^{-10} erg cm^{-2} s^{-1}
  - **L_{iso} < 9.3x10^{43} erg s^{-1}** → strong constraint *(5 orders of magnitude less luminous than GRB090510)*
- Prospects for future LAT detections: assuming a sGRB+GW rate of 1-2/yr → **LAT has a P~5-10% to detect at least 1 event in 1 year**



Neutrinos

- So far only the Sun and SN1987A have been identified as **astrophysical ν sources**

- Mechanisms and environments responsible for the high-energy cosmic neutrinos are still to be identified

- Many potential astrophysical source candidates exist:
  - Heavy black holes (M_{BH}~$10^{8-9}M_{SUN}$) → **AGN**
  - Strong magnetic fields (B ~ 10^{15}G) → **magnetars**
  - Bright explosions (L ~ 10^{52} erg/s) → **GRB**
  - Big gravitationally bounded objects → **Galaxy clusters/groups**

- **AGN** - blazars in particular - are the most promising candidates:
  - Powerful relativistic jets could accelerate particles up to the highest energies
  - Such particles, interacting with radiation and matter, would produce pions that decay into photons and ν
  - ➡ The **coincident observation of ν with electromagnetic flares** would enable the **identification of the sources**

Searching strategies

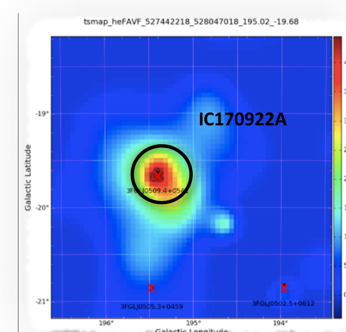
- Correlation with known catalogs of blazars: 3LAC (>100MeV, 4years); 2FHL (>50 GeV, 6years); 2WHSP (most complete list of HSP)
  - no significant evidence for ν signal in none of the catalogs
  - results compatible with bkg fluctuations.

- Searches for time-dependent ν sources
  - IceCube real-time alert system targets ν of likely astrophysical origin
  - ***On Sept. 22, 2017:*** **first detection of gamma-ray excess positionally and temporally consistent with an IC EHE neutrino!**

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*

on 28 Sep 2017; 10:10 UT



MW follow-up of IC170922

- The GCN notice triggered **follow-up** by ground and space-based instruments to help identifying a possible astrophysical source for the candidate ν:
  - **Fermi-LAT**: detected an **increased γ-ray activity of the known γ-ray source TXS 0506+056** (3FGL J0509.4+0541) inside the IC error region, redshift unknown
  - **AGILE**: confirmed the enhanced γ-ray activity
  - ***IACTS:* MAGIC** (detection of VHE γ-rays from direction consistent with ν event), **HAWC** and **HESS** (upper limits)
  - ***Radio:*** detection of flux variability
  - ***X-ray:* Swift-XRT** (detection), **INTEGRAL** (upper limits)
  - ***Optical*: ASAS-SN** (enhanced flux), **Liverpool telescope** (optical spectrum)

➡ These observations suggest that **blazars may be sources of high-energy ν…more details coming soon, STAY TUNED!**

Outreach


Researcher Night


Dual-training
(learning and working)


Masterclass

Outreach

Conclusions

- The Fermi mission is celebrating its **10th anniversary** and continue to work well
- **Public data** and **public analysis tools** maximize the scientific return
- **Huge advance for high-energy astronomy** (exceeding expectations!)
  - current performances are already impressive, but they can be further improved with a new event selection…stay tuned!
- The mission is far from over but it is already clear that Fermi will have a **lasting legacy**
- Some of the **highlights**:
  - catalogs
  - surprises
  - new source classes
  - multi-messenger

➡ Fermi is always scanning the sky, and **new multi-messenger opportunities** are helping to maintain the scientific relevance