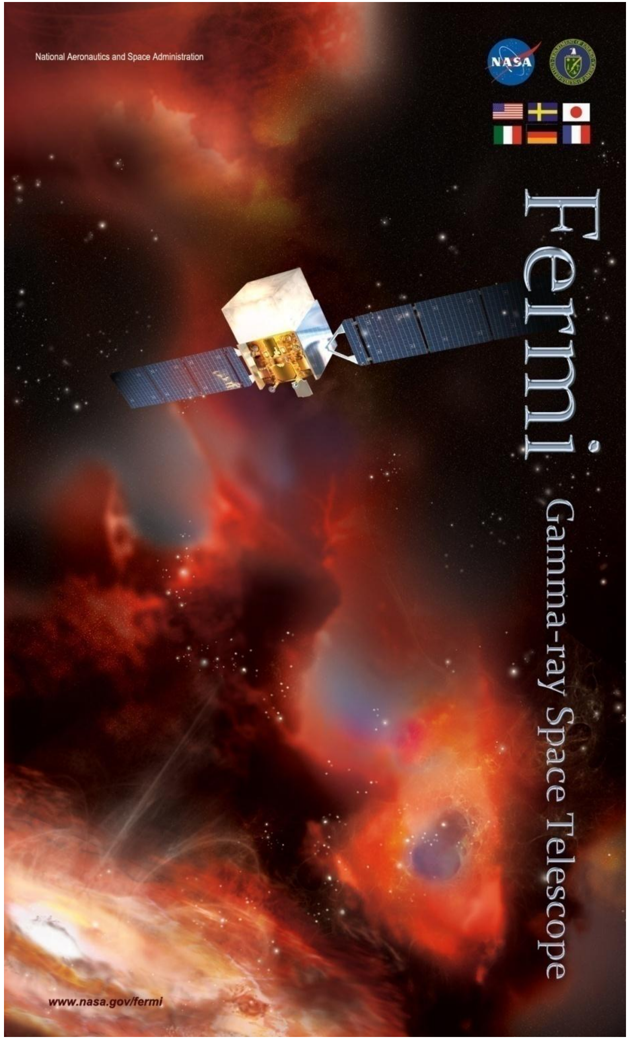


Fermi
Large Area Telescope

CENBG : Denis Dumora, Marie-Hélène Grondin, Marianne Lemoine-Goumard, Benoît Lott, Thierry Reposeur, David Smith
LLR : Denis Bernard, Philippe Bruel, Stephen Fegan, Deirdre Horan
LUPM : Johann Cohen-Tanugi, Eric Nuss, Frédéric Piron, Mathieu Renaud

Outline

- Presentation of the Fermi mission, instrument, collaboration
- IN2P3 contributions
  - Design and construction
  - Pre-launch activities
  - Science results overview
- Responsibilities, human resources, funding
- Assessment

Fermi Gamma-ray Space Telescope

- NASA mission
- Two instruments

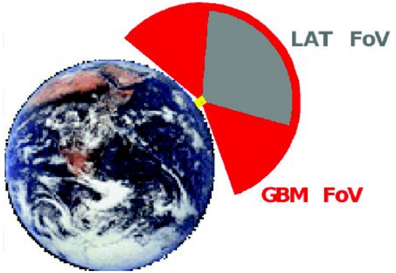
LAT (Large Area Telescope)
- Formerly known as GLAST
- ~30 MeV → ~1 TeV
- FoV ~ 2.5 sr
- IN2P3 “Master projet”
- CNES support

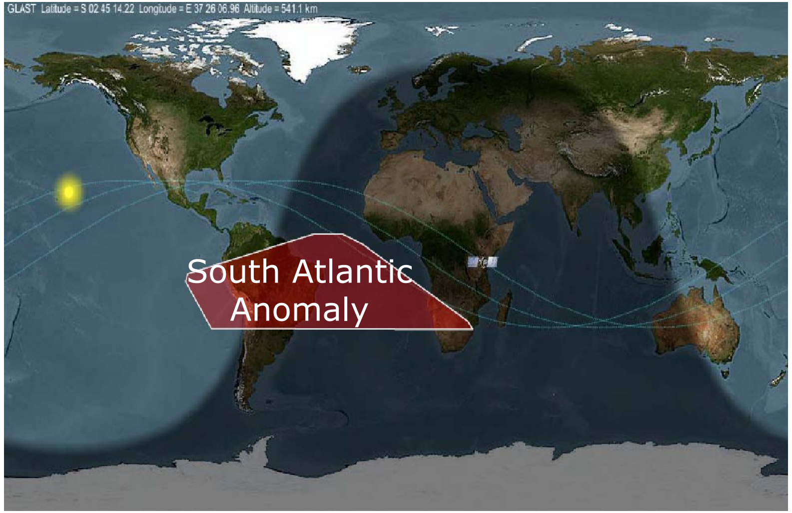
GBM (Gamma-ray Burst Monitor)
- → Gravitation Burst Monitor
- 12 NaI (1 keV -1 MeV)
- 2 BGO (200 keV – 40 MeV)
- FoV > 8 sr
- IN2P3 not involved

Fermi mission

- In operation since June 11 2008
- Originally planned for 5 yr + 5 yr
- Since 2014, a NASA Senior Review every 2 to 3 years.
- The mission was extended in 2014, 2016 and 2019. Next SR in 2022.
- Currently, no competitor/replacement for the LAT.

- Period : 1.5h
- Survey mode
  - Rocks between hemispheres each orbit
  - Full sky in 3h
  - each source: ~30min every 3h
- Altitude : 565 km
- Inclination : 25.6deg





LAT instrument

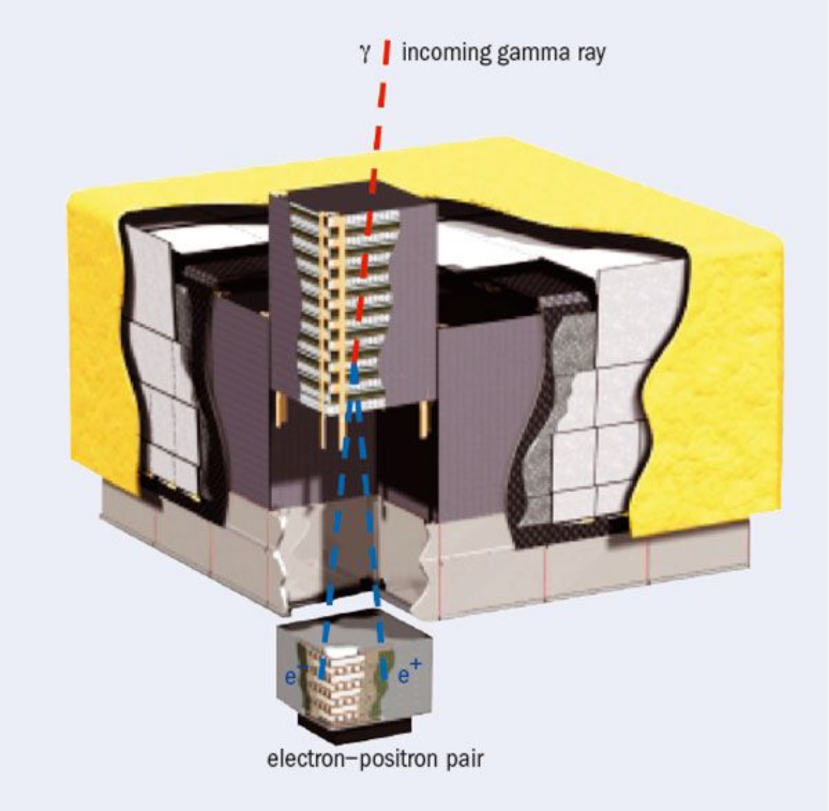
Gamma-ray detection:

- Pair conversion
- Measure direction and energy
- Reject huge cosmic ray background

3 subsystems:

- Tracker
  - Si-strips + W converters
  - Direction measurement
- Calorimeter
  - CsI crystal hodoscope
  - Energy measurement
- Anti-Coincidence Detector
  - Plastic scintillator tiles
  - Charged particle bkgd rejection

Data = list of photons (direction, energy, time)



Fermi-LAT science

- Fermi-LAT covers most of gamma-ray astronomy, a keystone of astroparticle physics

- General goals:
  - map/monitor the gamma-ray sky as fully as possible
  - Characterize the gamma-ray sources
  - Understand the emission mechanisms

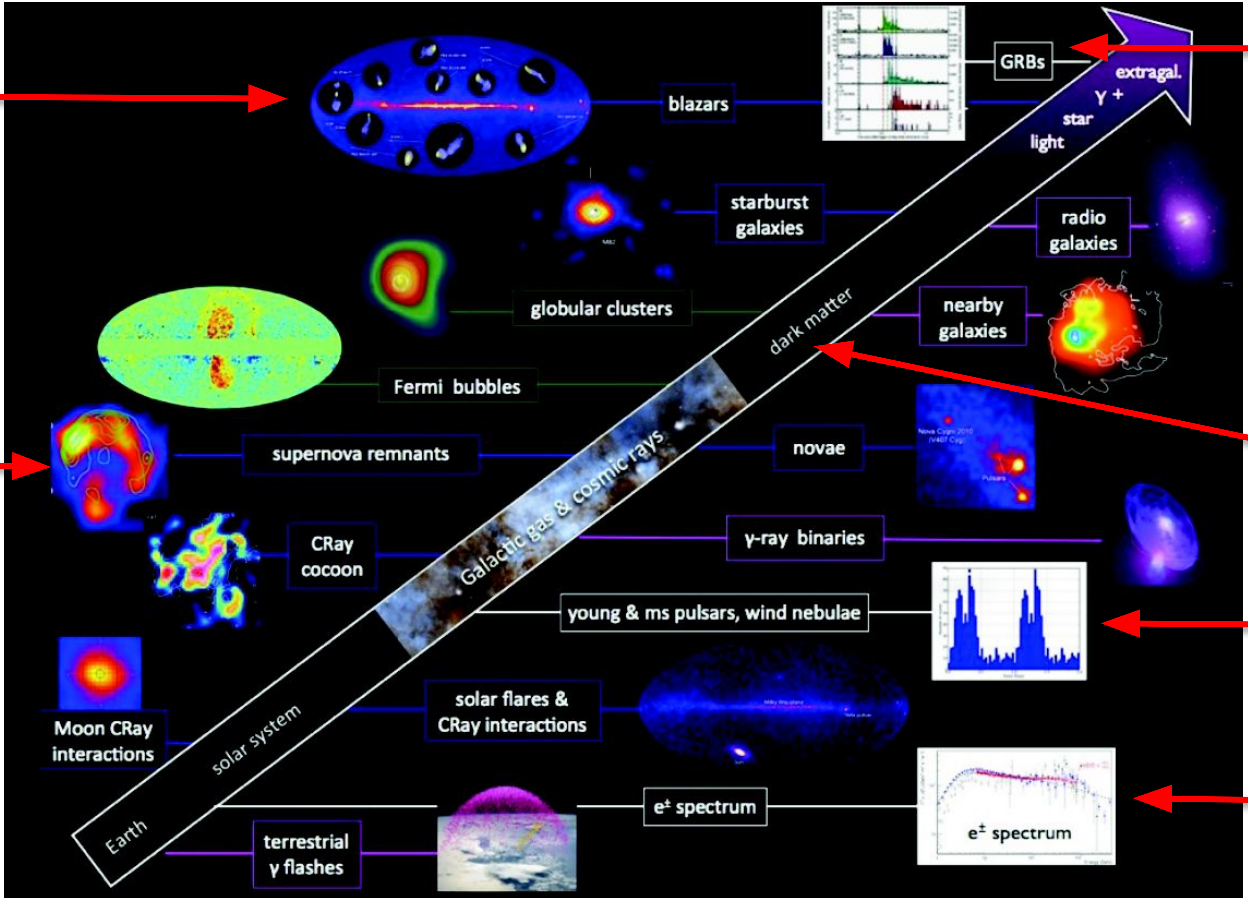
- Some features of gamma-ray sources:
  - Often variable (~h → ~yr)
  - Multi-λ emission from radio to TeV

- Fermi has contributed a lot to connect gamma-ray astronomy to the other domains of astrophysics

Fermi-LAT science

CENBG, LLR

CENBG, LUPM



LUPM

LUPM

CENBG, LLR

LLR

Fermi-LAT collaboration

- Began in 1998 when NASA+DOE selected the GLAST project (P. Michelson (Stanford, Principal Investigator) and W. Atwood (SLAC))
    - Design and build the LAT
    - Process and release the data (data are public)
    - Data analysis and publication
- Currently ~150 members
    - Full members vs affiliated members
- Eight science groups:
    - Zoom meetings every 1 or 2 weeks
    - 2 coordinators rotating every 1 to 2 years
- Two collaboration meetings per year
- Maintenance and operations duties (shifts):
    - Data Quality Monitoring
    - All-sky source monitoring (Flare/Burst advocates)

Collaboration		
	2013	2020
USA	52%	36%
Italy	21%	23%
France	8%	12%
Japan	7%	5%
Sweden	3%	2%
others	9%	22%

Science groups
Instrument/analysis
Catalog
Diffuse emission
Solar system
Galactic sources
Active Galactic Nuclei
Gamma-Ray Bursts
Dark matter and new physics

Public data

- Since project start, NASA required that data be made public as soon processed
  - Except for the first year data, released at the end of the first year

- The LAT collaboration is also responsible for the development and public release of all the tools and ancillary products necessary to analyse LAT data.
  - Basic LAT data analysis: finding a sky model = list of gamma-ray sources (positions and spectra) that, after convolution with the instrument response, predicts the observed counts in a given Region Of Interest of the sky.

- Public data products:
  - Instrument Response Functions (effective area, point spread function, energy redistribution)
  - Galactic diffuse emission and isotropic emission template
  - Catalog of gamma-ray sources
  - Software tools to handle and fit the data
  - Documentation (NASA Fermi Science Support Center web site)

- Each new product version (data, IRFs, templates, software,...) has to be released soon after it is used by the collaboration

IN2P3 involvement timeline

- 1994-2003:
  - It all started in 1994 thanks to Eric Paré and Patrick Fleury
  - 1999: presentation at the IN2P3 Conseil Scientifique
  - French collaboration IN2P3+CEA
    - LLR + PCC (A. Djannati-Ataï) + CENBG
    - Designing and building the calorimeter
  - CNES funding and reviewing
    - In 2001, CNES decision that CEA would be in charge of PCC's part. PCC left the collaboration.
  - 2003: CNES faced a budget crisis and stopped funding Fermi (among others)
    - IN2P3 decision to continue to contribute to the calorimeter and to remain in the collaboration. 3 labs involved (LLR, CENBG, LUPM).
- 2003-2008 (launch)
  - Instrument construction, calibration, beam tests, event reconstruction
  - Data analysis preparation
- 2008-now
  - Instrument optimization
  - Data analysis

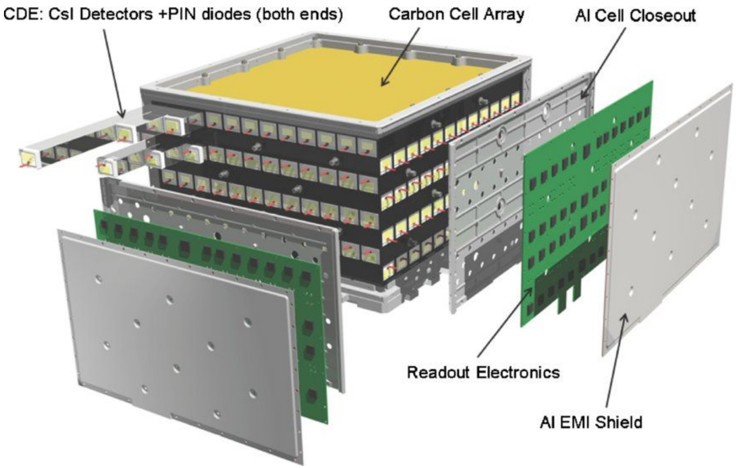
LAT calorimeter

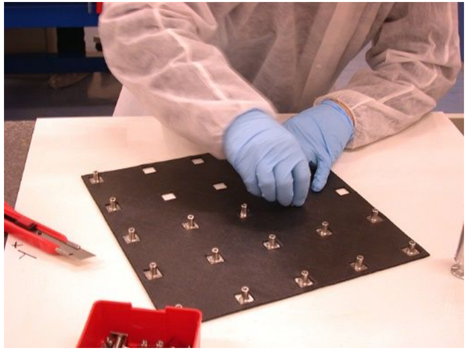
- IN2P3 contribution to the instrument construction

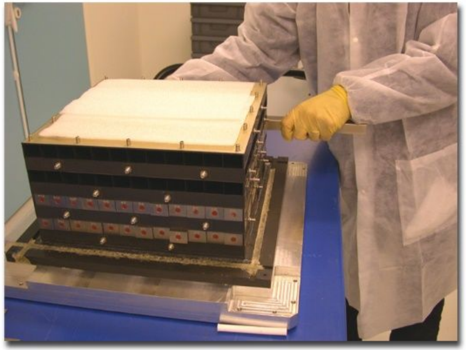
- Design phase
  - Carbon fiber structure (LLR, from CMS)
  - Crystal wrapping (LLR)
  - Photodiode size and bonding (C. Chapron, PCC)

- Structure fabrication (O. Ferreira, LLR)
  - Purchase of an autoclave (180 k€) to improve polymerization + clean room
  - Metrology (LLR) + vibration tests (externalized)
  - 24 structures delivered to NRL (~2 per month)

- Quality/system engineering:
  - Standard in spatial activities
  - A kind of revolution for IN2P3
  - 2 engineers were hired
    - P. Prat (PCC)
    - S. Couturier (LLR)







Beam tests and calibration

Several beam tests (SLAC, CERN) during design phase (LLR, PCC)

For calibration and performance validation (IN2P3 lead):

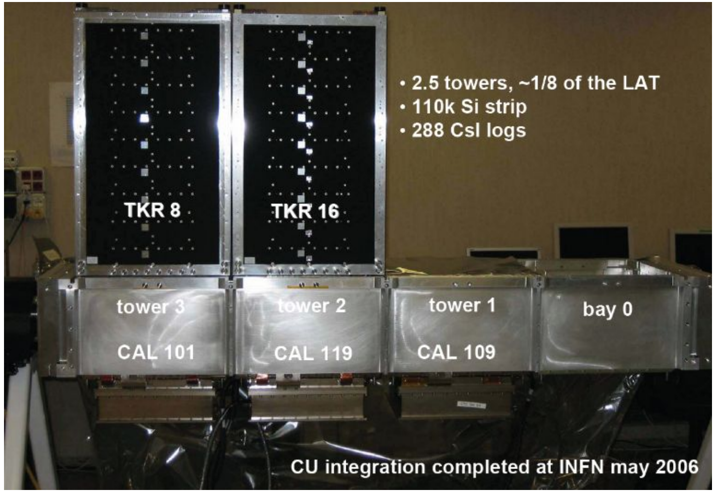
- GANIL, GSI (CENBG) :
  - MIP peak of cosmic ions useful for on-orbit calibration
  - Beam tests found anti-quenching for light ions (alpha, C, O) in relativistic domain
- CERN PS+SPS (CENBG, LLR, LUPM)
  - Test of the Calibration unit (2.5 towers)
  - Photons and electrons
  - Check direction and energy measurement

Software for the in-flight calibration (LUPM)

- Selection of MIP cosmic ions that are used for the inter-calibration of the 2 crystal ends

Verification of the GPS timing (CENBG)

- Bug fix thanks to a cross-check with muons



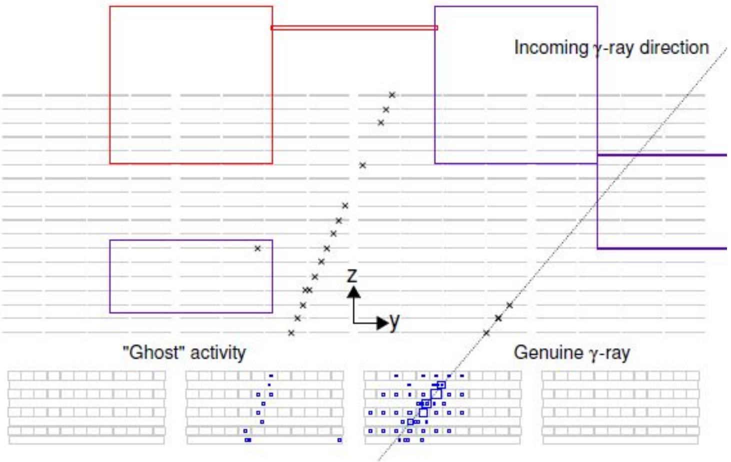
Event reconstruction/selection

Energy reconstruction (the calorimeter is only 8.6 X0 but longitudinally segmented)

- Development of several algorithms (PCC,LLR) to cover the full energy range ($\rightarrow$2 TeV)

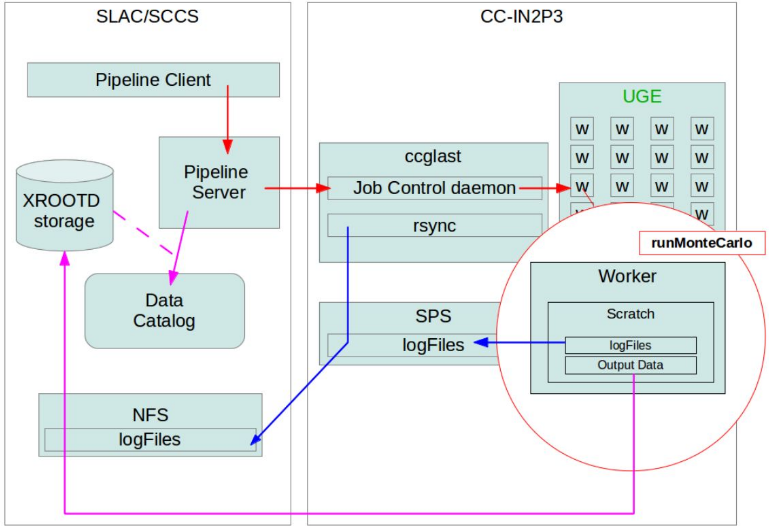
Data version timeline

- Pass 6: developed before launch
  - Meets performance requirements
  - First data: effective area loss (10-30%) due to off-time pile-up of cosmic protons
- Simulation changed to include pile-up
  - Correction of the Instrument Response Functions
- Pass 7: same reconstruction, optimized selection
  - Public release in 2011
  - Reprocessing with improved calibration (2013)
- Pass 8: full reworking of the reconstruction (2015)
  - New tracking + clustering in calorimeter
  - Increased energy range
  - >+25% of effective area
  - Data partition according to direction quality
- Strong IN2P3 contribution to these developments

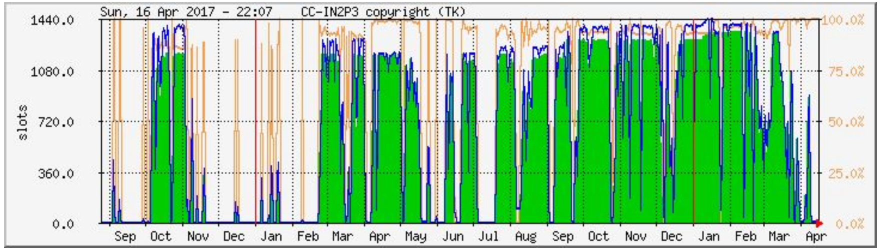


Simulation at CC-IN2P3

- LAT pipeline branch at CC-IN2P3 (LUPM): development, exploitation & maintenance
  - 1300 to 1600 cores at any time
  - Virtualization (Singularity containers) in 2017-2018
- All MC simulations performed at CC-IN2P3 since launch:
  - Event reconstruction optimization, IRFs production, backgrounds
  - 380 millions of CPU hours (HS06 units)
- IN2P3 in-kind contribution to the common funds: 0.4-1.9 M€ since 2009 (1-5 k€/MHS06)
- CNES support: 4 engineering contractors at LUPM in 10 years



Number of running jobs (09/2015-04/2017):



Pre-launch science activities

In parallel with instrument construction and event reconstruction, the LAT collaboration prepared for science analysis.

Science working groups

- Preparing dedicated analysis tools
- Multi-wavelength collaboration
- Connections with theorists

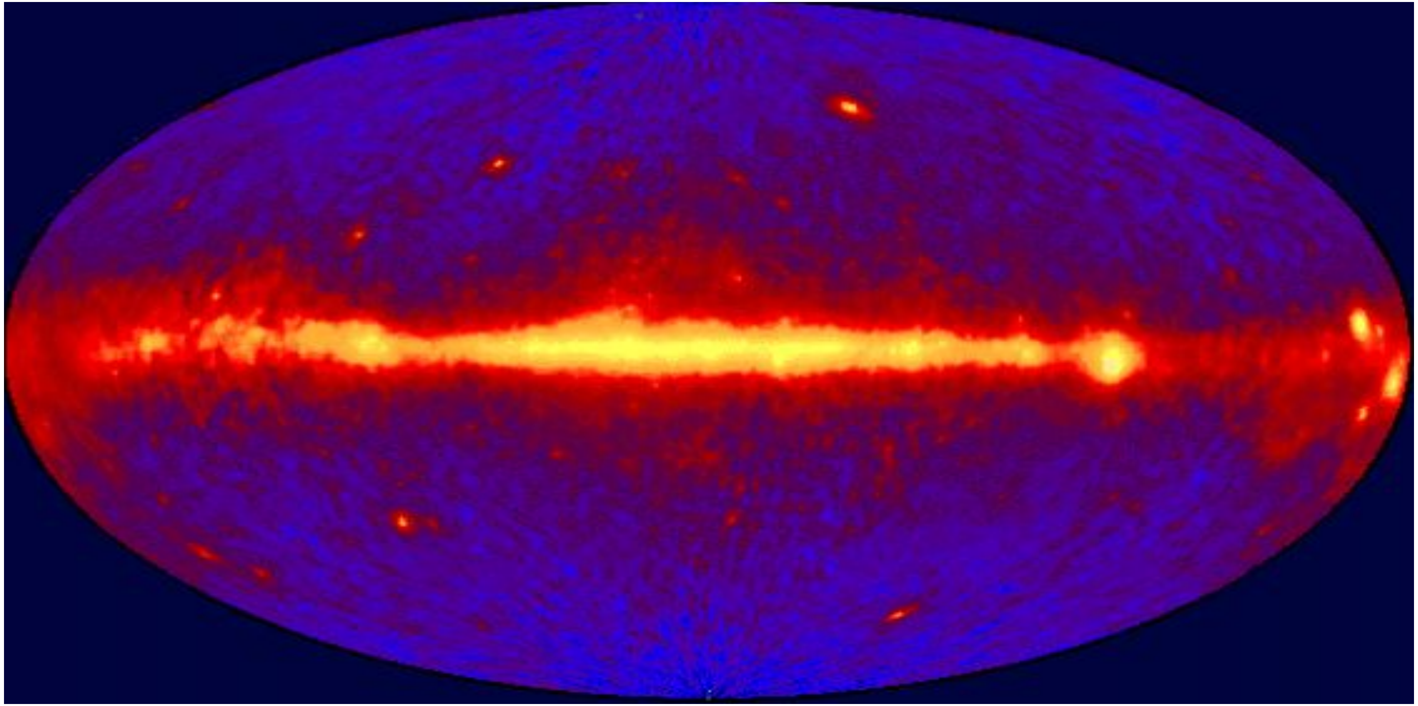
End-to-end simulation of data taking and science analysis

- Data challenge I (2003): one day of observation
- Data challenge II (2005): 55 days, 1719 sources (pulsars, variable AGN, GRBs)
- Service challenges (2006-2008):
  - Data processing → data server → automatic analysis pipelines
  - Validation of automatic GRB detection
  - Flare/Burst advocate monitoring

All these activities also served as very efficient team building exercises.

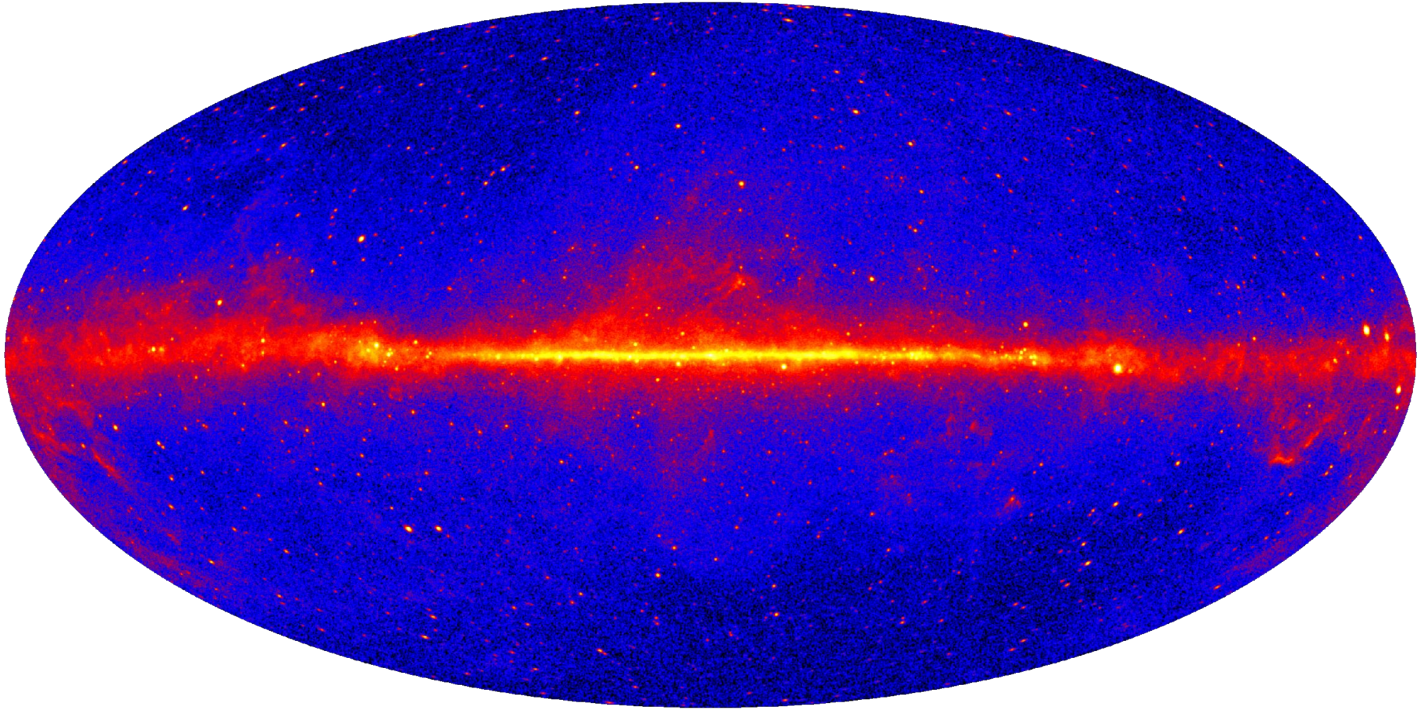
EGRET: 9 years

E>100 MeV, Galactic coordinates, 271 sources in 3EG catalog

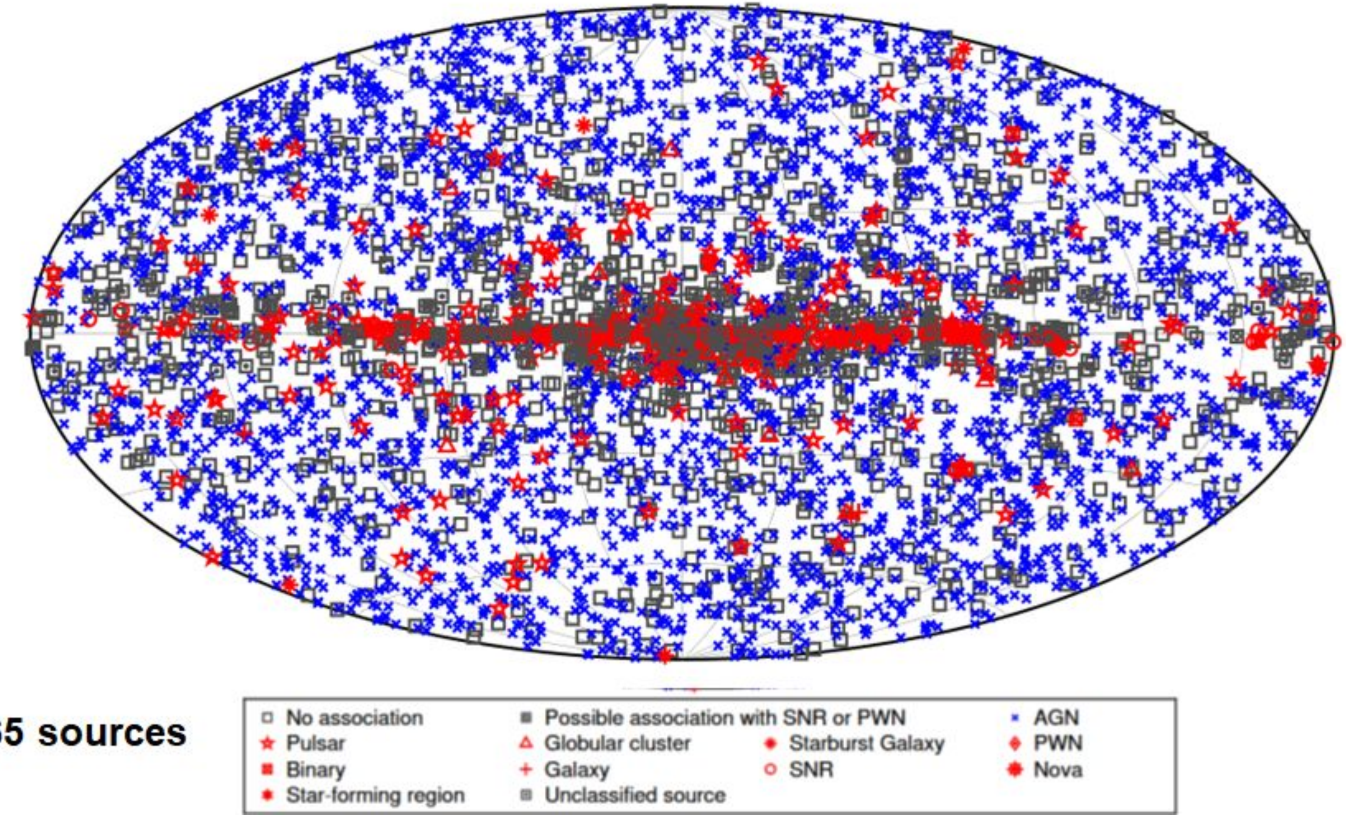


Fermi-LAT: 9 years

E>1 GeV, ¼ of data with best PSF, Galactic coordinates, >5000 sources



4FGL catalog



5065 sources

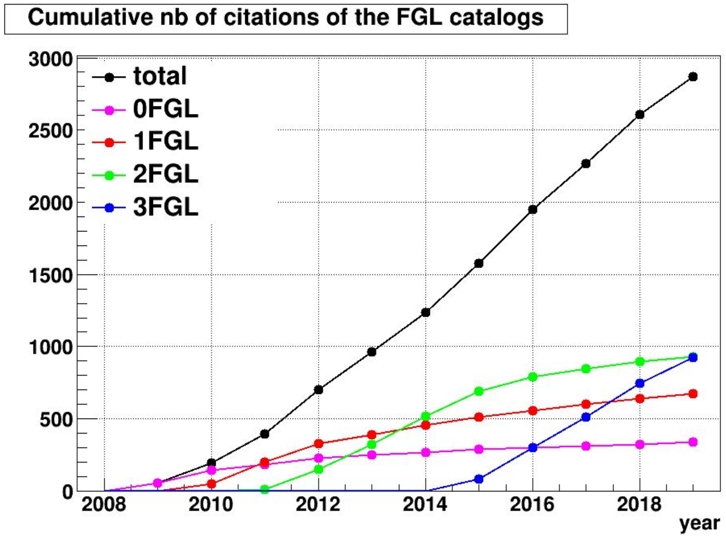
Catalogs

Latest general catalog (10yr): 5786 sources

- Association (B. Lott, CENBG)

Many other specific catalogs

The catalogs are used/cited a lot by the external community.

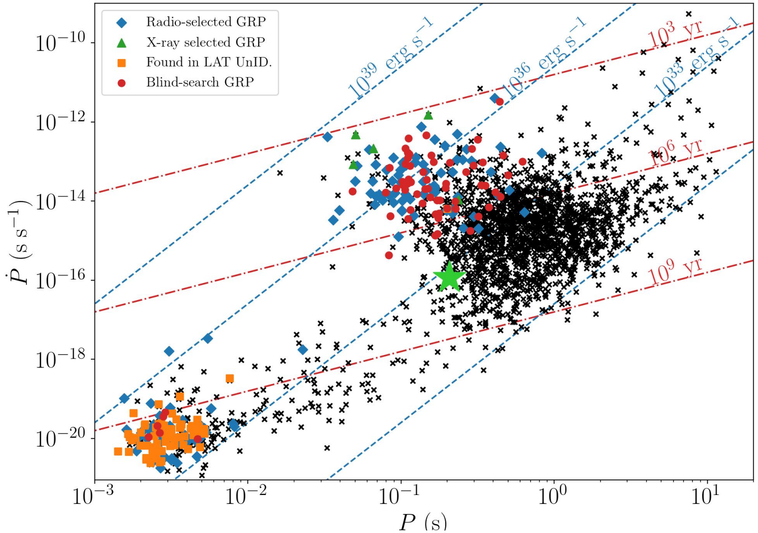


code	objects	entries	data	status	France/IN2P3
0FGL	General (> 100 MeV)	205	3 m	ApJS	co-lead
1FGL	General (> 100 MeV)	1451	11 m	ApJS	co-lead
2FGL	General (> 100 MeV)	1873	2 yr	ApJS	co-lead
3FGL	General (> 100 MeV)	3033	4 yr	ApJS	co-lead
4FGL	General (>50 MeV)	5065	8 yr	ApJS	co-lead
1FHL	General (>10 GeV)	514	3 yr	ApJS	co-lead
2FHL	General (>50 GeV)	360	6.7 yr	ApJS	----
3FHL	General (>10 GeV)	1556	7 yr	ApJS	co-lead
0LAC	Active galactic nuclei	106	3 m	ApJ	co-lead
1LAC	Active galactic nuclei	709	11 m	ApJ	co-lead
2LAC	Active galactic nuclei	1017	2 yr	ApJ	co-lead
3LAC	Active galactic nuclei	1557	4 yr	ApJ	co-lead
4LAC	Active galactic nuclei	2863	8 yr	ApJ	co-lead
1PC	Pulsars	46	1 yr	ApJS	co-lead
2PC	Pulsars	117	3 yr	ApJS	co-lead
1FLGC	Gamma-ray bursts	35	3 yr	ApJS	co-lead
2FLGC	Gamma-ray bursts	186	10 yr	ApJS	participation
PWN	Pulsar wind nebulae	30+28	3.75 yr	ApJ	co-lead
SNR	Supernova remnants	31	3 yr	ApJ	participation

Pulsars

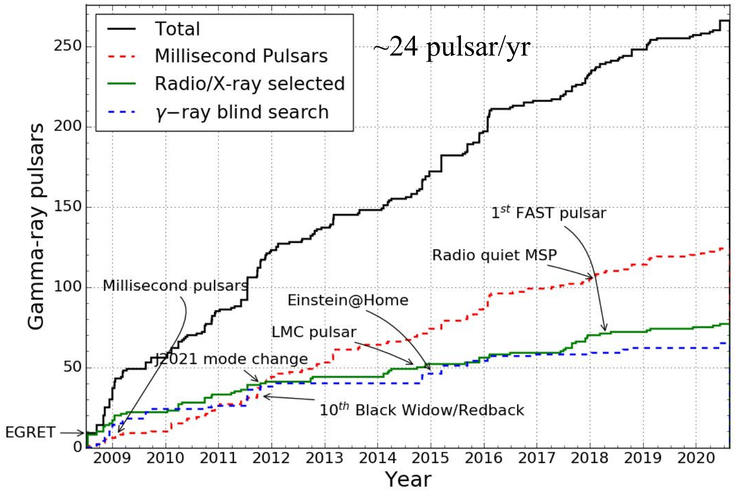
EGRET → LAT: 6 → 260

CENBG, LLR



Diversity of pulsar types

- Young pulsars / Milli-Second Pulsars
- Radio loud / radio quiet
- MSP: isolated / in binaries



IN2P3 speciality: the faintest ones.

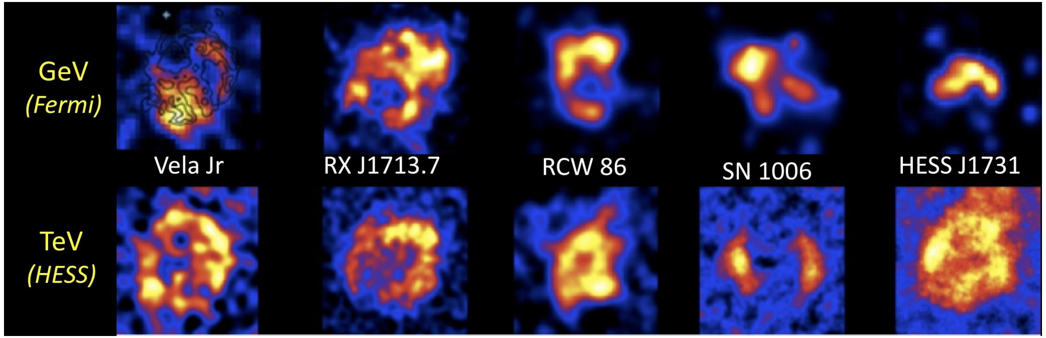
Requires precise radio timing (synergy with Nançay and other radio telescopes) and innovative analysis (e.g. weighting).

SuperNova Remnants/Pulsar Wind Nebulae

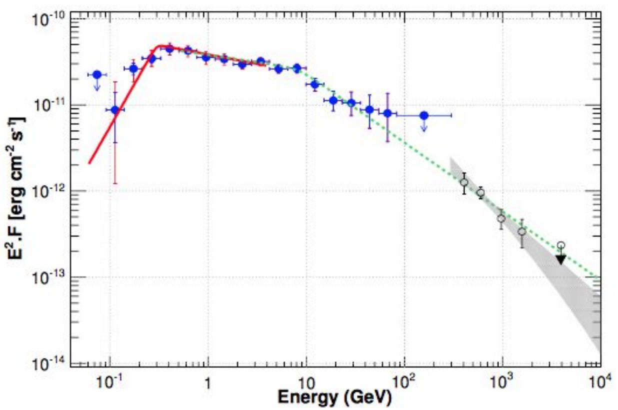
EGRET → LAT: 0 → 35

CENBG, LUPM

- Lead of the PWN catalogs
- Co-lead of the extended source catalog
- Synergy with H.E.S.S. on several unidentified sources
- Proof of acceleration of protons in middle-aged SNRs
- Strong constraints derived for young SNRs:
  - *Fermi* changed the paradigm from: “Is the mechanism leptonic or hadronic” to “In which region of the SNR is the emission hadronic dominated” ?



Fermi-H.E.S.S. paper on W49B: “Pion bump”



Active Galactic Nuclei

CENBG, LLR

<u>EGRET → LAT: 94 → 3000</u>

98% blazars (maximum redshift 4.3)

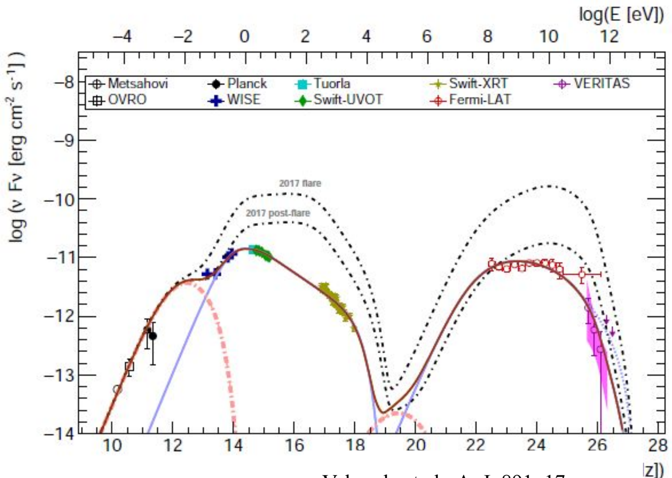
Considerable progress about many aspects:

- Dichotomy between blazar classes
- Emission mechanisms
- Emission location
- Variability at all timescales

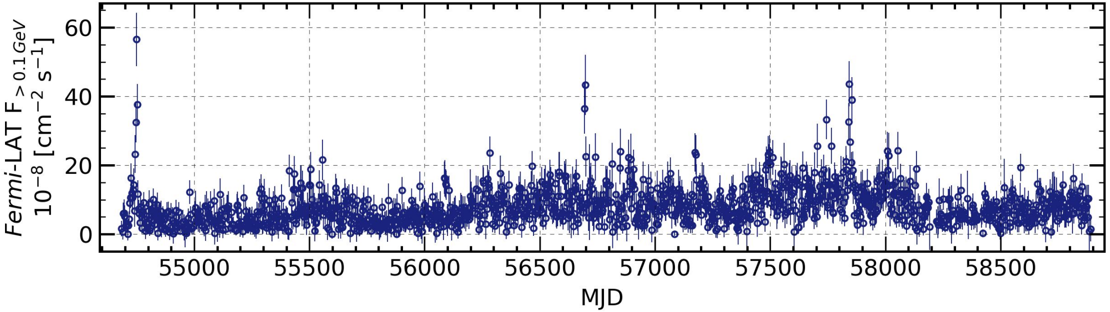
Synergy with other bands/messagers:

- From radio to TeV (including H.E.S.S./CTA)
- Neutrinos, UHECR

Flare Advocate alerts



Valverde et al., ApJ, 891, 17

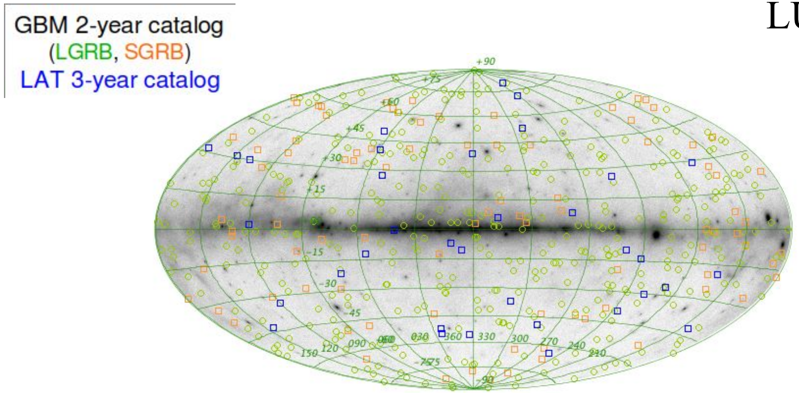


Gamma-Ray Bursts

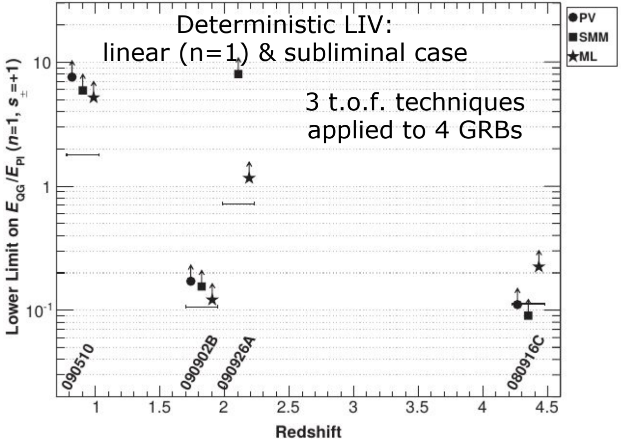
LUPM

EGRET → LAT: 5 → 186

- Co-lead of the first LAT GRB catalog
- Study of the keV-MeV-GeV prompt emission
  - GeV spectral cutoff & variability → location of emission zones & jet Lorentz factor
  - Exploration of the internal shock model
- Best limits on Lorentz Invariance Violation (LIV)
  - Deterministic: $$v_{\rm ph}(E) \simeq c \times \left[1 \mp \frac{n+1}{2}\left(\frac{E}{E_{\rm QG}}\right)^n\right]$$
  - 95% lower limits: $E_{QG} > 7.6\ E_{Planck}$ (n=1) (1.3×10^{11} GeV for n=2)
- Burst Advocate: quick analysis of GRB alerts (mostly from GBM, Swift) → ~40 LAT GCN circulars



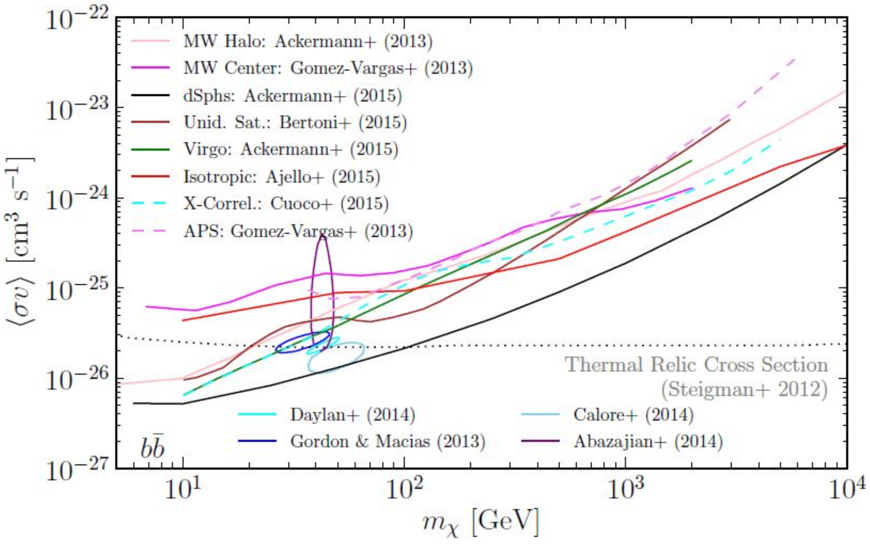
Vasileiou, V. et al. 2013, Phys. Rev. D, 87, 122001

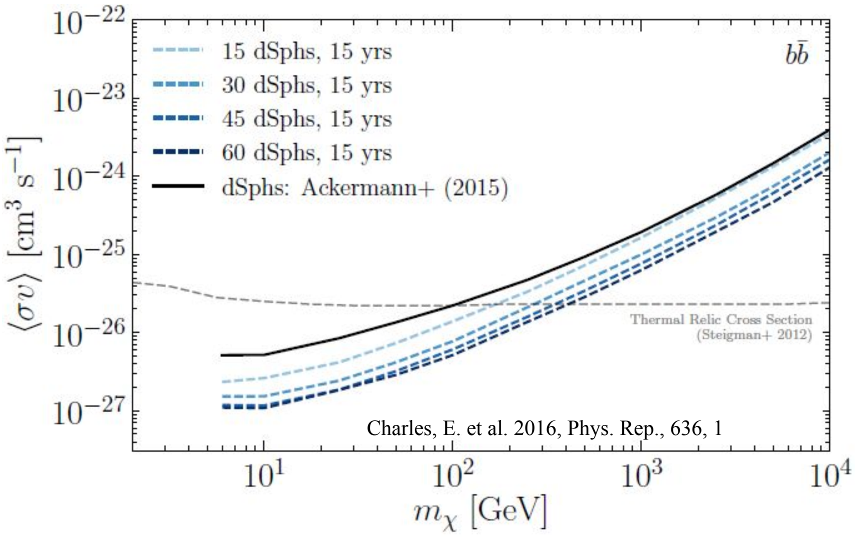


Dark matter

LUPM

- Dwarf spheroidal galaxies are DM-dominated objects in the galactic DM halo
  - No gas or cosmic-ray content → no expected conventional gamma-ray signal
  - The DM content is rather well constrained → simple relation between WIMP annihilation cross-section and gamma-ray signal
  - The number of dSphs increases with time thanks to:
    - Sloan Digital Sky Survey, Dark Energy Survey, Pan-STARRS survey, LSST





Charles, E. et al. 2016, Phys. Rep., 636, 1

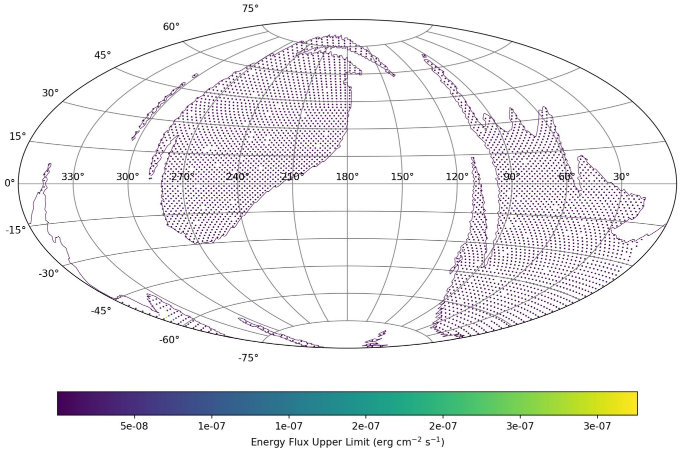
Multi-messengers

Burst Advocates:

- monitor LIGO-Virgo alerts and check the automatic analyses by the LAT GW pipelines
- 11 LAT GCN circulars (flux upper limits) during LIGO-Virgo O3 run

Flare Advocates:

- monitor IceCube neutrino alerts, look for possible LAT counterparts in the error region
- run dedicated analyses on the candidates (over various timescales) and issue ATels or GCNs



LAT scan (in ~5 ks) of the error localization contour (~14700 deg^2) of S190901ap (86% Binary Neutron Star merger, 240±80 Mpc) detected by LIGO-Virgo

Fermi-LAT detection of enhanced gamma-ray activity and hard spectrum of TXS 0506+056, located inside the IceCube-170922A error region

ATel #11419; ***Roopesh Ojha (NASA/GSFC/UMBC), and Janeth Valverde (LLR/Ecole Polytechnique) on behalf of the Fermi Large Area Telescope Collaboration***
on ***14 Mar 2018; 20:16 UT***

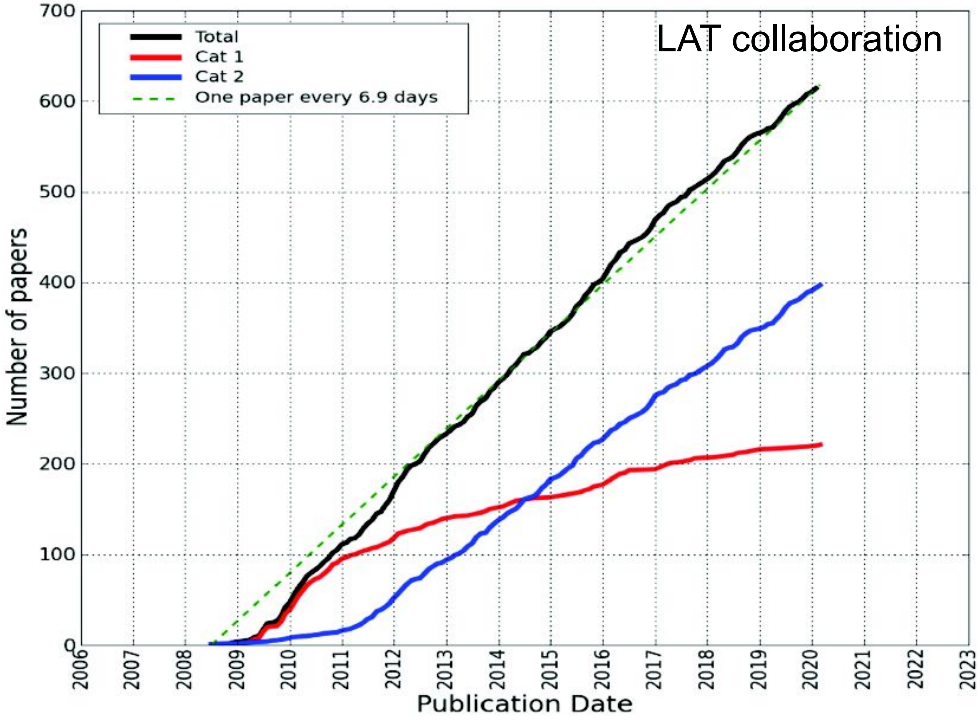
Publications

Two paper categories :

- 1 = major results, signed by all full members
- 2 = signed by small teams

~steady rate since 2009 (~55/yr)

IN2P3: 74 publications with at least one IN2P3 scientist as contact author

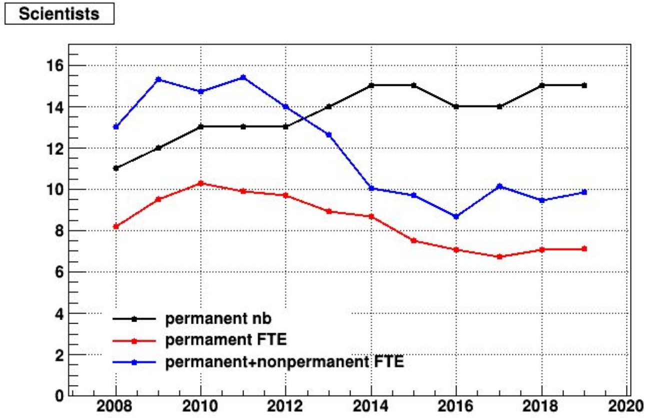


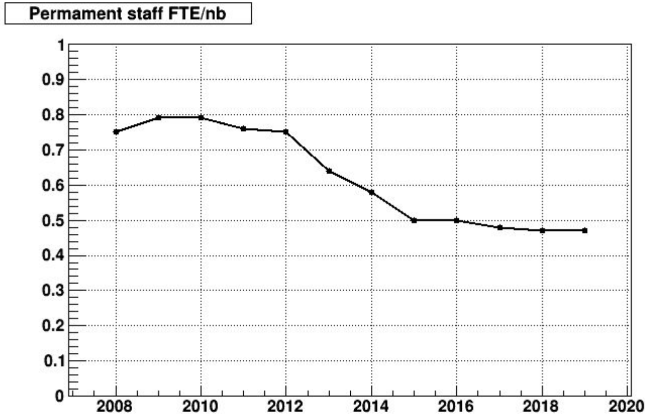
Responsibilities and coordination

- Design of the calorimeter: O. Fereira, G. Bogaert (LLR), P. Charon, A. Djannati (PCC)
- Construction of the calorimeter structures: O. Fereira (LLR)
- Energy reconstruction: PCC, LLR
- Simulation pipeline: LUPM
- Beam tests:
  - GSI and CERN-SPS: B. Lott (CENBG)
  - CERN data analysis: P. Bruel (LLR)
- Science working groups:
  - Instrument : P. Bruel (LLR), J. Brégeon (LUPM)
  - Catalog: B. Lott (CENBG)
  - Diffuse emission : J. Cohen-Tanugi (LUPM)
  - Galactic sources: D. Smith (CENBG), M. Lemoine-Goumard (CENBG)
    - SNR/PWN: M. Lemoine-Goumard (CENBG), M.H. Grondin (CENBG)
  - AGN: B. Lott (CENBG), S. Fegan (LLR), D. Horan (LLR)
  - GRBs : F. Piron (LUPM), V. Vasileiou (LUPM)
- Collaboration analysis coordinator: P. Bruel (LLR)

Human resources

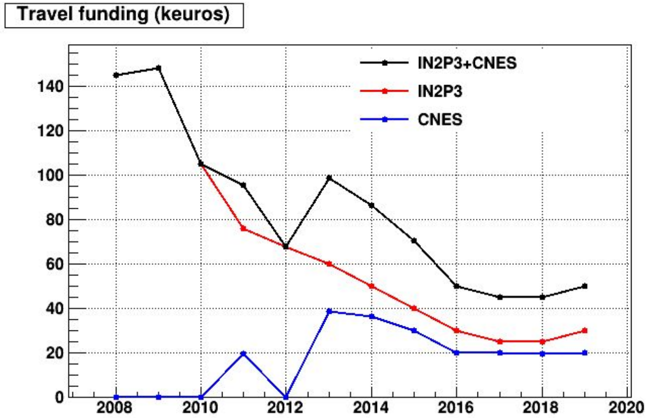
- Total FTE:
  - ~15 at launch to ~10 since 2014
- Permanents:
  - Number: 11 to 15
  - Fraction: 80% to 50%
    - Several still at 100%
- PhD: 20 graduated + 2 ongoing
- Postdocs: 10

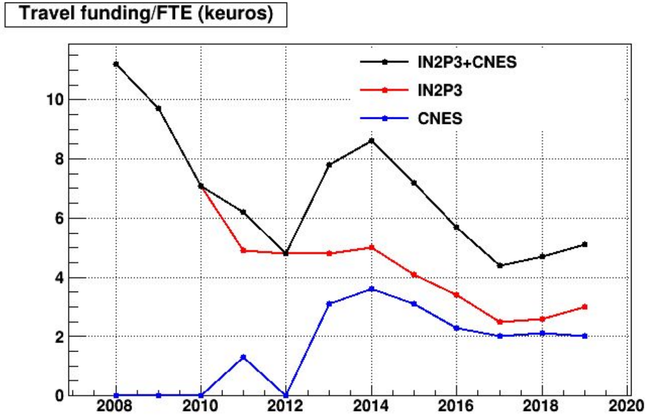




Funding

- Construction (IN2P3/CNRS): 750 k€
  - including 180k€ for the autoclave)
- IN2P3+INSU common funds (covered by IN2P3)
  - Computing at CC-IN2P3:
    - 40-170 k€/yr since 2009
  - 1 computing engineer (LLR) at SLAC
  - CNES funded 4 computing engineers at LUPM
    - 8.5 years in total (~44 k€/yr)
- Travel support
  - IN2P3 + CNES provide together the required 5k€/FTE





Retrospective SWOT analysis

	1998	A posteriori assessment
Strengths	Expertise in particle physics (detector design to event analysis).	It worked very well in all aspects and contributed much to our successful integration in the collaboration.
Weaknesses	No spatial label for instrument construction nor data exploitation.	The starting phase has been difficult but we were able to remain in the project, allowing us to gain the spatial label both on the instrument and science sides.
Opportunities	Moving from first generations Cherenkov telescopes (small number of sources) to a success-guaranteed mission (thousands of sources, x20 better than previous one)	It actually seems that it was a very good move to join Fermi.
Threats	Funding. Political “inferiority” (w.r.t CEA, CNES) Public data.	Yes, but IN2P3/CNRS helped. Yes, but now it has changed. It turned out not to be a problem (see next slide).

Keys to success

- A 20x better sensitivity ensured a lot of science results and a large source/scientist ratio

- The LAT collaboration has always provided (and still does) a very welcome and open environment
  - It allowed us to efficiently contribute at the beginning in our expertise areas and smoothly get up to speed on the rest before launch
  - Opportunity to work with world-wide experts
  - No need to be an established scientist to become a coordinator

- NASA/collaboration relationship: very good, with NASA sometimes acting as the referee
  - client/provider or funder/beneficiary

- Public data and public tools
  - No reserved areas: everyone can contribute
  - Data and tools: public = easy to use, from which we also have benefitted
  - Enough data/topics for both the collaboration and the external community, with a slight advantage for the collaboration because of experimental and theoretical expertise and a ~1yr lead on data analysis

Conclusions

- Fermi was one of the first space missions at IN2P3

- A very good opportunity
  - From instrument to data analysis and science results
  - In a nice environment/collaboration
  - A lot of skills/knowledge transferable to other projects (CTA, SVOM, LSST,...)

- With Fermi, IN2P3 was able to increase its gamma-ray energy coverage
  - Fermi-H.E.S.S./CTA: 30 MeV to 10 TeV
  - Key to understanding the violent universe

- Fermi is an important player of multi-lambda and multi-messenger astrophysics

- It is too early to perform a final assessment:
  - Fermi is still flying ($\rightarrow$2022, $\rightarrow$2025 ?)
    - Continue the GeV-TeV connection with CTA
  - Legacy phase (legacy papers) after the end of the mission

Backup slides

Relationship with NASA

- Flight operation (NASA) and Instrument Science Operation Center (SLAC)

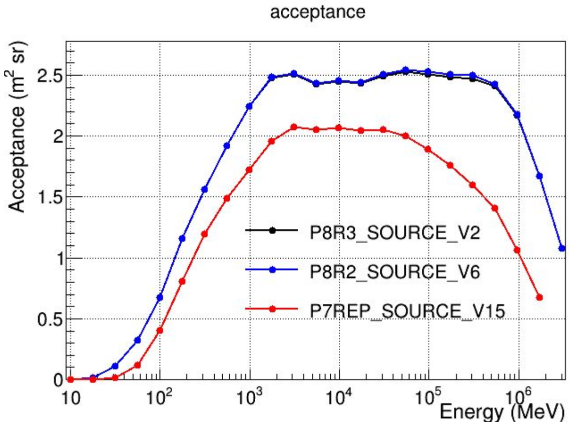
- Public data and software

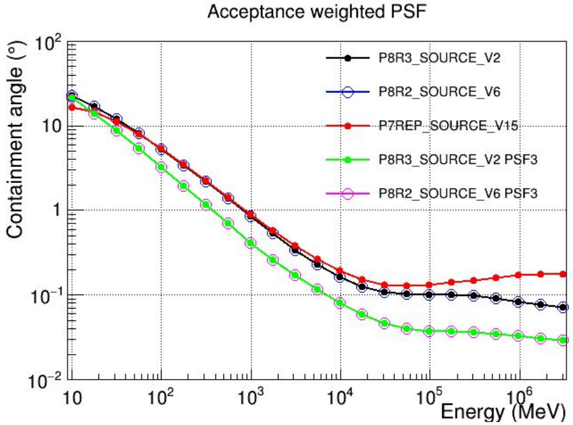
- NASA Fermi user's group: this group of non-LAT members meets twice a year to give feedback to NASA from the external community of Fermi data users

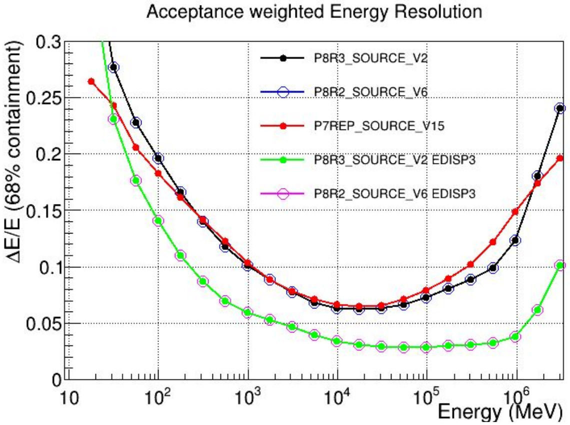
- The collaboration contributes a lot to the preparation of the NASA Senior Review
  - Build the science case to extend the mission 2 to 3 more years
  - Propose improvements (data, analysis, observation)

- Several NASA GSFC physicists (including the Project Scientist) are members of the collaboration

LAT Performance



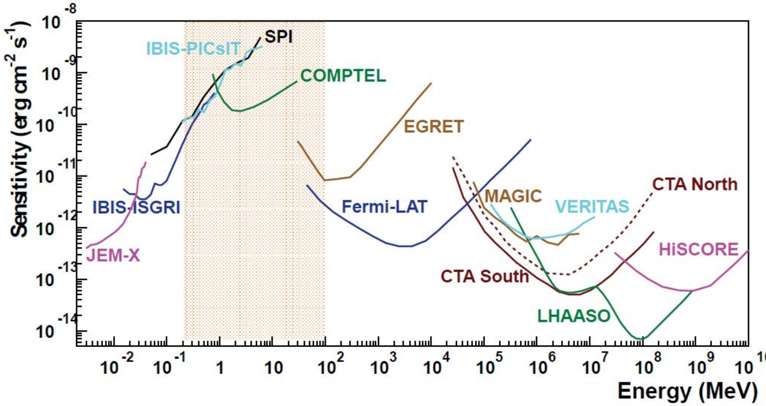




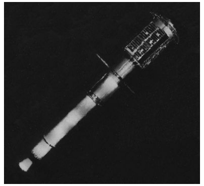
Validation of the performance with in-flight data

Comparison with EGRET

- No consumables → virtually no lifetime limitation
- ACD segmentation → large effective area above 10 GeV
- 5 times larger FoV and survey mode → all-sky monitor
- Smaller deadtime (26 μs vs 0.1s) → fast flare sensitivity
- Larger acceptance and better PSF → 20x source sensitivity

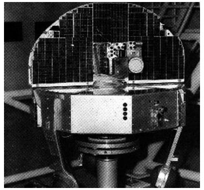


Gamma-ray astronomy from space



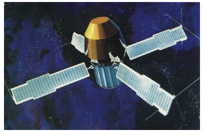
Explorer 11
141h/7months
22 γ-rays

1961



OSO-3
~2 yr
800 γ-rays

1967

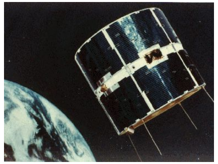


SAS-2
~6 months
8000 γ-rays
3 sources

1972

1975

COS-B
6.7 yr
1e5 γ-rays
25 sources

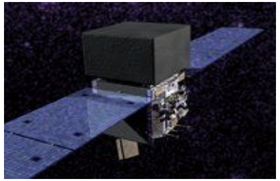


1991

EGRET
9 yr
1.4e6 γ-rays
271 sources

2008

Fermi-LAT
>12 yr
>1e9 γ-rays
>5000 sources



Outreach

COSMIX: muon detectors based on CsI logs used in tests of the LAT calorimeter

COSMAX: suite of scripts enabling non-experts to access the LAT data and create maps, animations. Masterclasses "Black holes seen in gamma-rays" with high-school students.

More than one public lecture per month.