The Fermi Large Area Telescope: status and recent results

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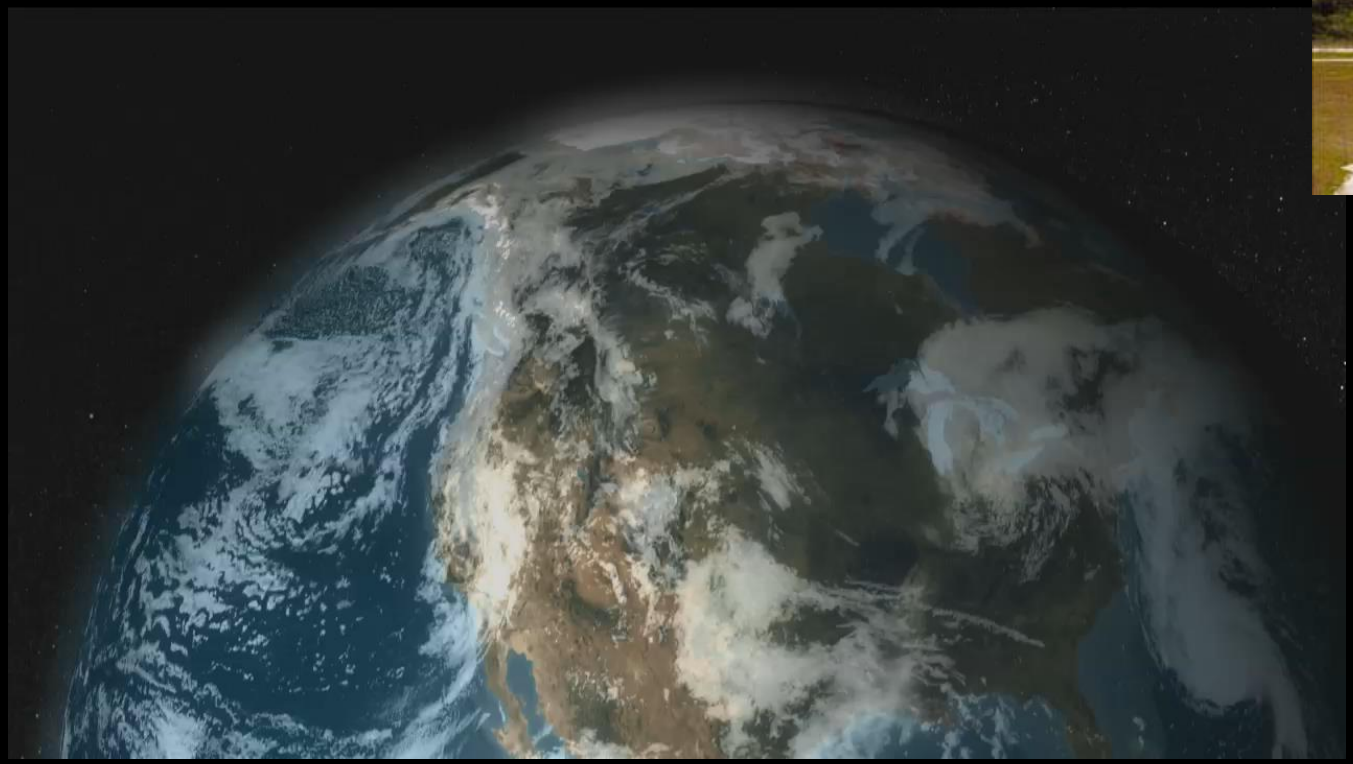
On behalf of the Fermi-LAT Collaboration

RICAP-24
Frascati, 23-27 september 2024

The NASA Fermi satellite

- Lauched on June 11 2008 from Cabo Cañaveral.
- $800M mission led by NASA/DOE.
- Two instruments aboard:
  - Gamma-ray Burst Monitor (GBM; 8 keV – 40 MeV)
  - **Large Area Telescope** (**LAT**; 20 MeV – >1 TeV)



Mission status

Spacecraft and instrument performance are excellent at 16 years!

The mission continues to be operationally healthy, scientifically productive, and engaged with the community and the public.

- No consumables or rapid degradation of spacecraft or instrument components.
  → Gradual degradation is compensated by calibration.

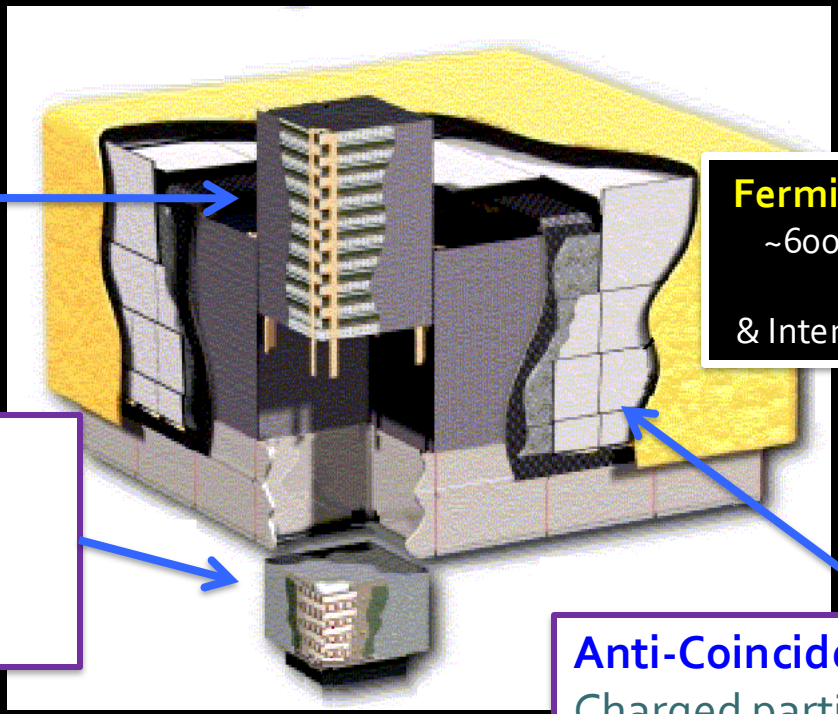
- One solar array drive no longer rotates.
  → modified survey strategy maintains power margin without losing observational efficiency.

- Plans to raise the observatory orbit altitude to a circular orbit at ~563 km.
  - Will lower planning frequency for collision avoidance maneuvers.
  - Frequency of maneuver planning for collision avoidance has increased due to increasing number of objects for this orbit (last maneuver was past Jan 31).

- Formally approved till the end of 2025. About to face a new Senior Review evaluation.

The Fermi Large Area Telescope

Si-Strip Tracker:
convert γ->e^+e^-
reconstruct γ direction
EM v. hadron separation



[1.8 m x 1.8 m x 0.7 m]

Fermi-LAT Collaboration
~600 Scientific Members,
NASA / DOE
& International contributions

Hodoscopic CsI Calorimeter:
measure γ energy
image EM shower
EM v. hadron separation

Anti-Coincidence Detector:
Charged particle separation

Sky Survey:
2.5 sr field-of-view
whole sky every 3 hours

Trigger and Filter:
Reduce data rate from ~10kHz to 300-500 HZ

Public Data Release:
All γ-ray data made public within 24 hours (usually less)

The Fermi-LAT Collaboration

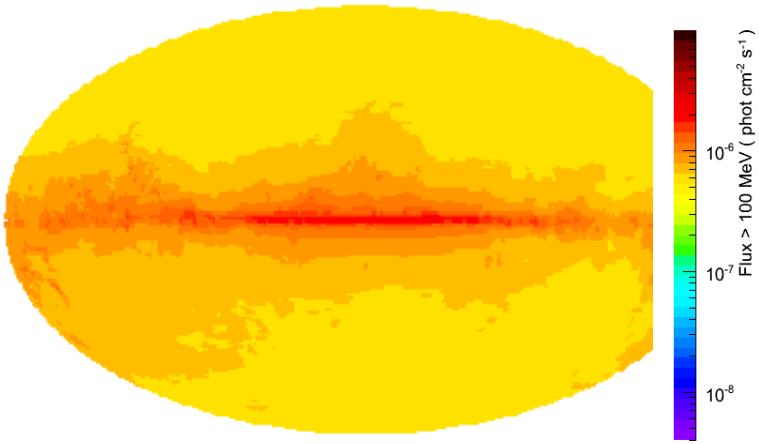
- A very busy and very productive collaboration more than 16 years after launch!
- Recent Collaboration Meeting in Madrid last March 11-15, 2024.
- Next (virtual) Collaboration Meeting will happen this upcoming week.

Fermi-LAT Collaboration @ RICAP

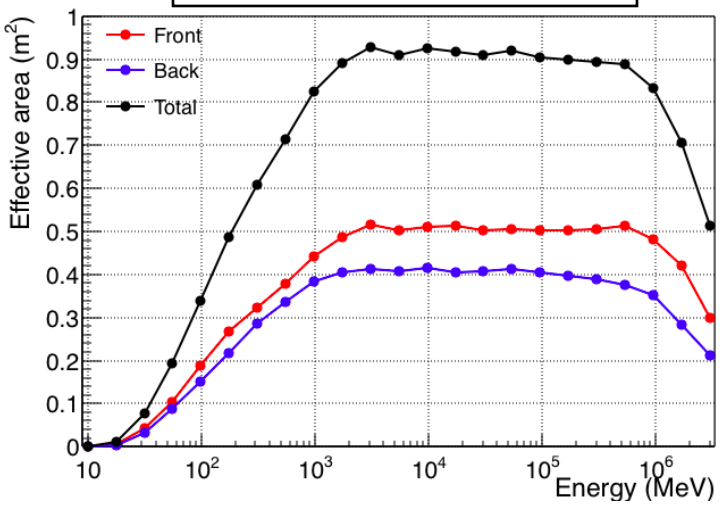
1. GRBs in the Swift and Fermi era – Bissaldi
2. Selection of Cosmic Ray Electrons in Fermi-LAT data with Unsupervised ML techniques – Bonino
3. Search of dark matter annihilation in stellar streams with the Fermi LAT – Fernández-Suárez
4. The population of neutrino blazar candidates from real-time high-energy neutrino alerts – Garrappa
5. Fermi-LAT Discovery of a γ-ray Outburst from the Peculiar Compact Radiogalaxy 3C 216 – Giacchino
6. Multi-class classification of unassociated Fermi LAT sources with ML and dataset shifts – Malyshev
7. The Quiet Sun with Fermi LAT – Orlando
8. Exploring NGC 3603 non-thermal emission through a realistic modelling of its environment – Rocamora-Bernal
9. High-energy variability of the gravitationally lensed blazar PKS 1830-211 – Wagner
10. The Fermi Large Area Telescope: status and results – MASC

Fermi-LAT performance

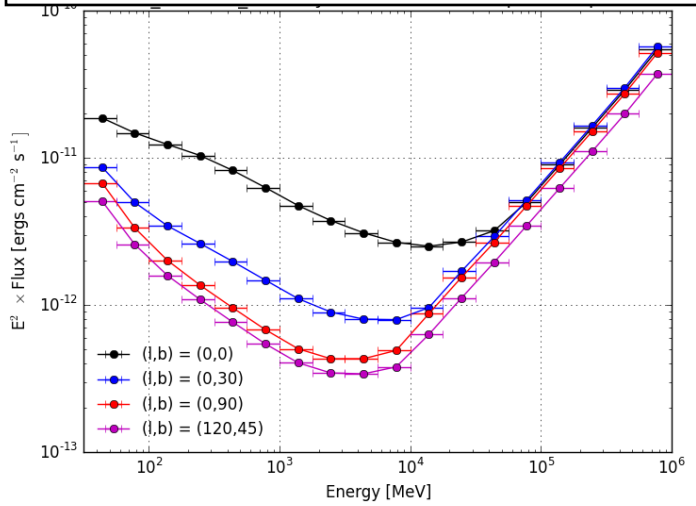
All-sky coverage



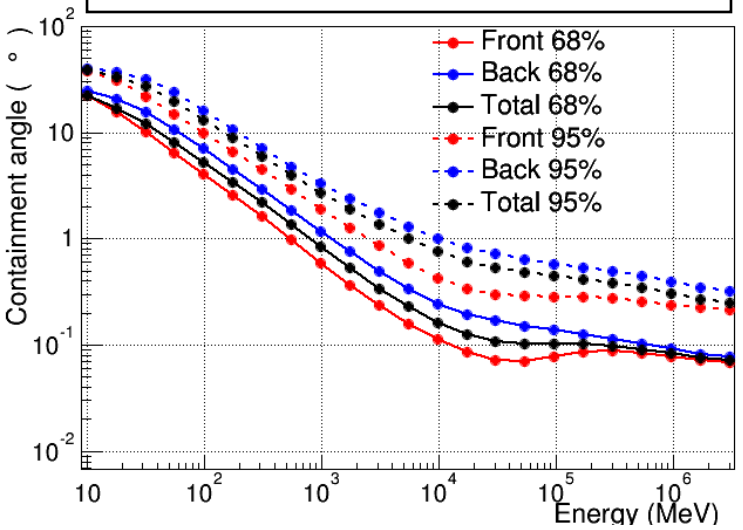
Effective area



Point source sensitivity

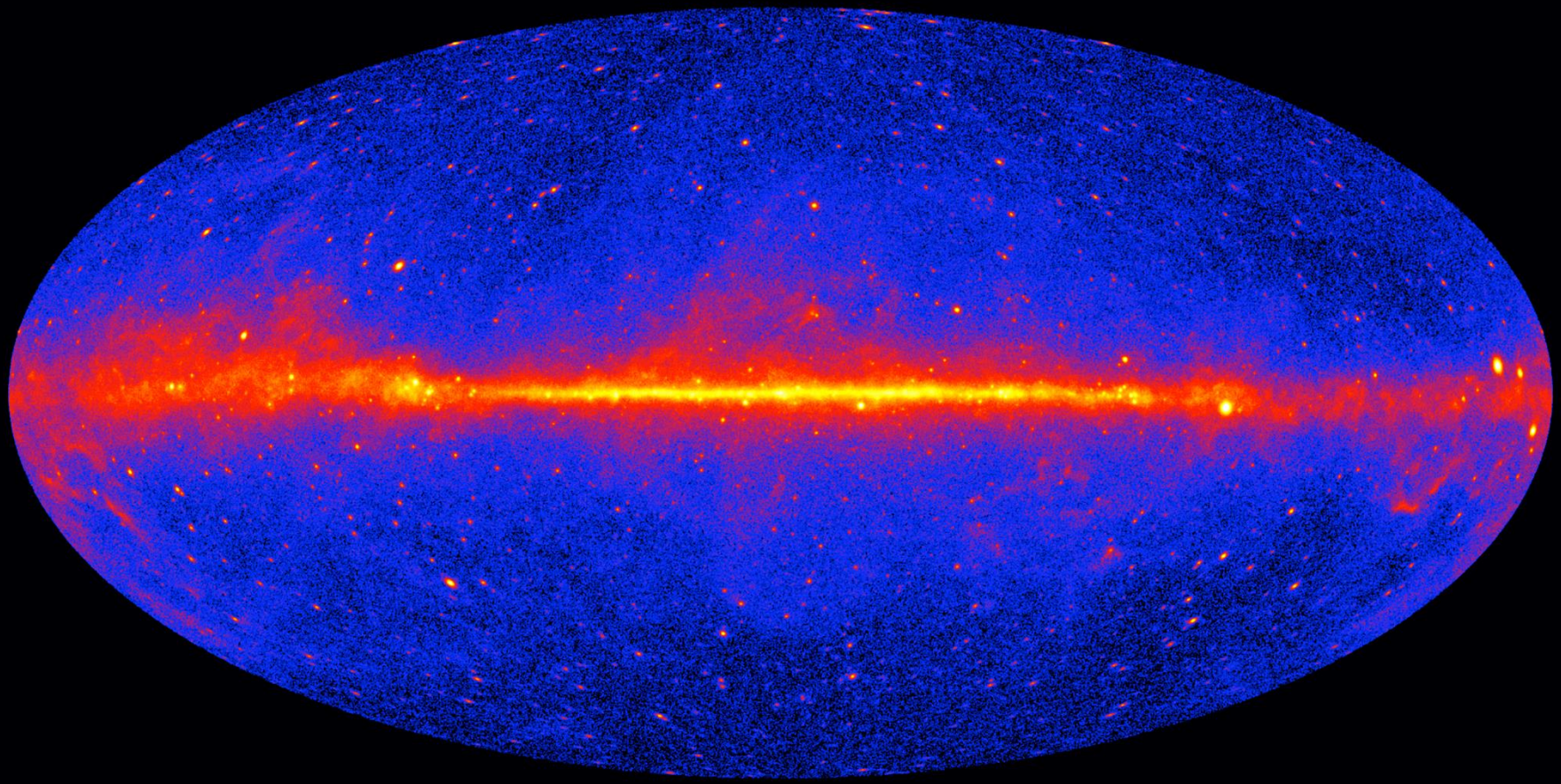


Angular resolution (PSF)

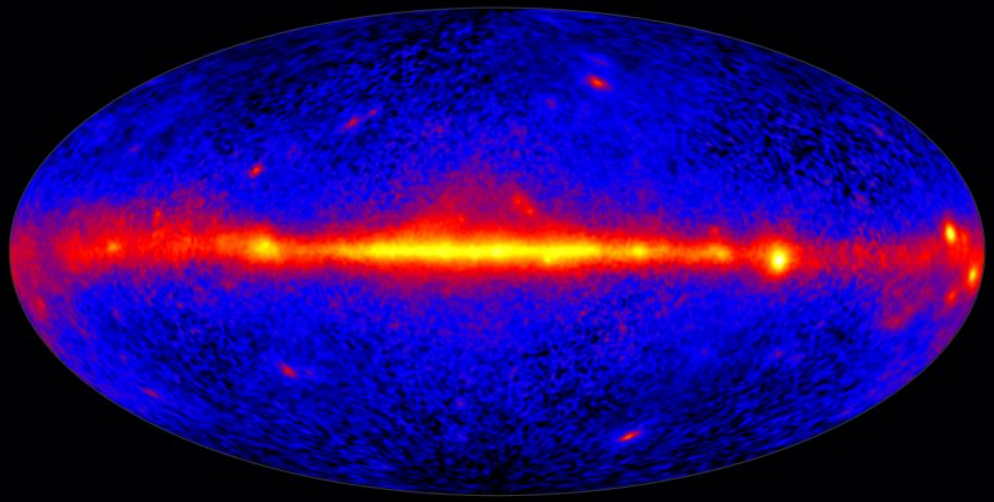


THE GAMMA-RAY SKY above 1 GeV

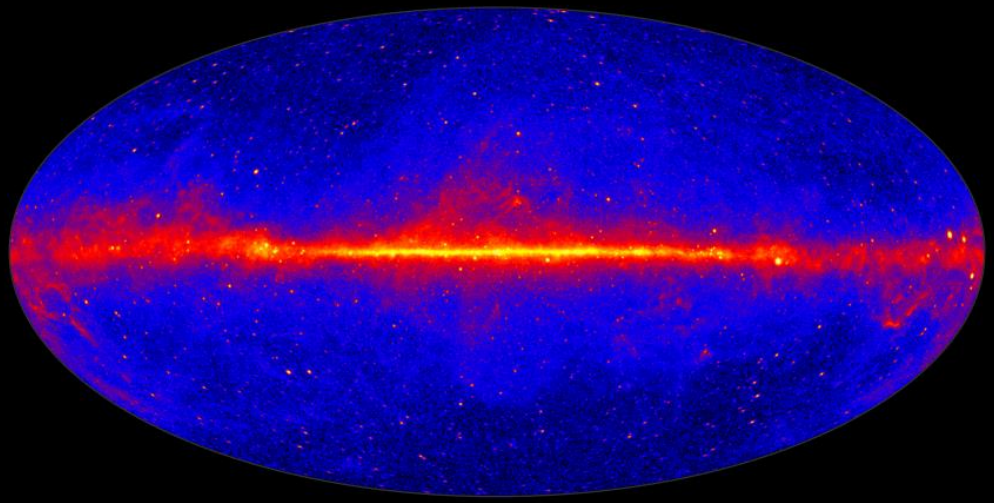
as seen by Fermi LAT



The Fermi-LAT revolution



EGRET all-sky map of gamma rays above 100 MeV



Fermi LAT 12-year all-sky map of gamma rays above 1 GeV

EGRET
[Fermi's predecessor, 1991-1996]

Fermi LAT
[2008-today]

Fermi
aka champion of 'transients'

- All-sky survey provides both instantaneous access and history.
  - Real-time or near real-time observation data of events anywhere in the sky.
  - GBM within 1.5 hrs; LAT within ~ 3 hrs (~1000 s to cover 80% of a GW event region).
  - Archival searches from ms to years available for 16 years.

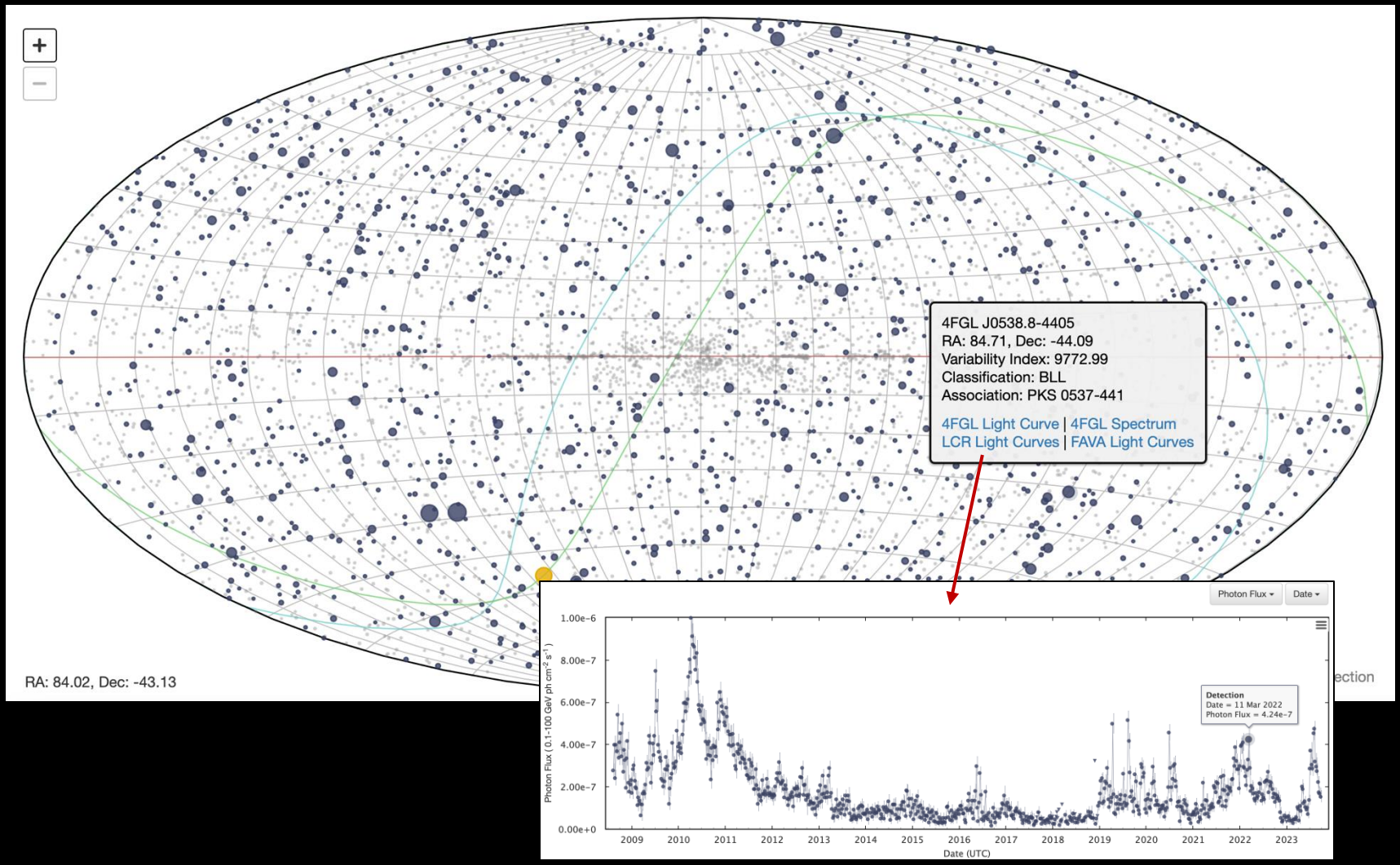
- Unique and highly dynamic energy range.
  - 8 keV - >300 GeV covers a wide variety of energetic astrophysical events.

- Data available immediately after processing.
  - Catalogs + public data products provide insight and context for MW/MM studies.
  - Team-operated science pipelines generate added alerts and information.
    - 'Flare Advocates' search for flaring sources, follow up neutrino alerts… → ATels
    - 'Burst Advocates' perform follow up analyses for GRBs with the LAT FoV → GCNs
    - Monitoring of sources of interest on a daily/weeky basis here.

- Partnerships among science support center, instrument teams, MW/MM observational facilities and community enable innovations in analysis and tools.

Fermi-LAT light curve repository

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



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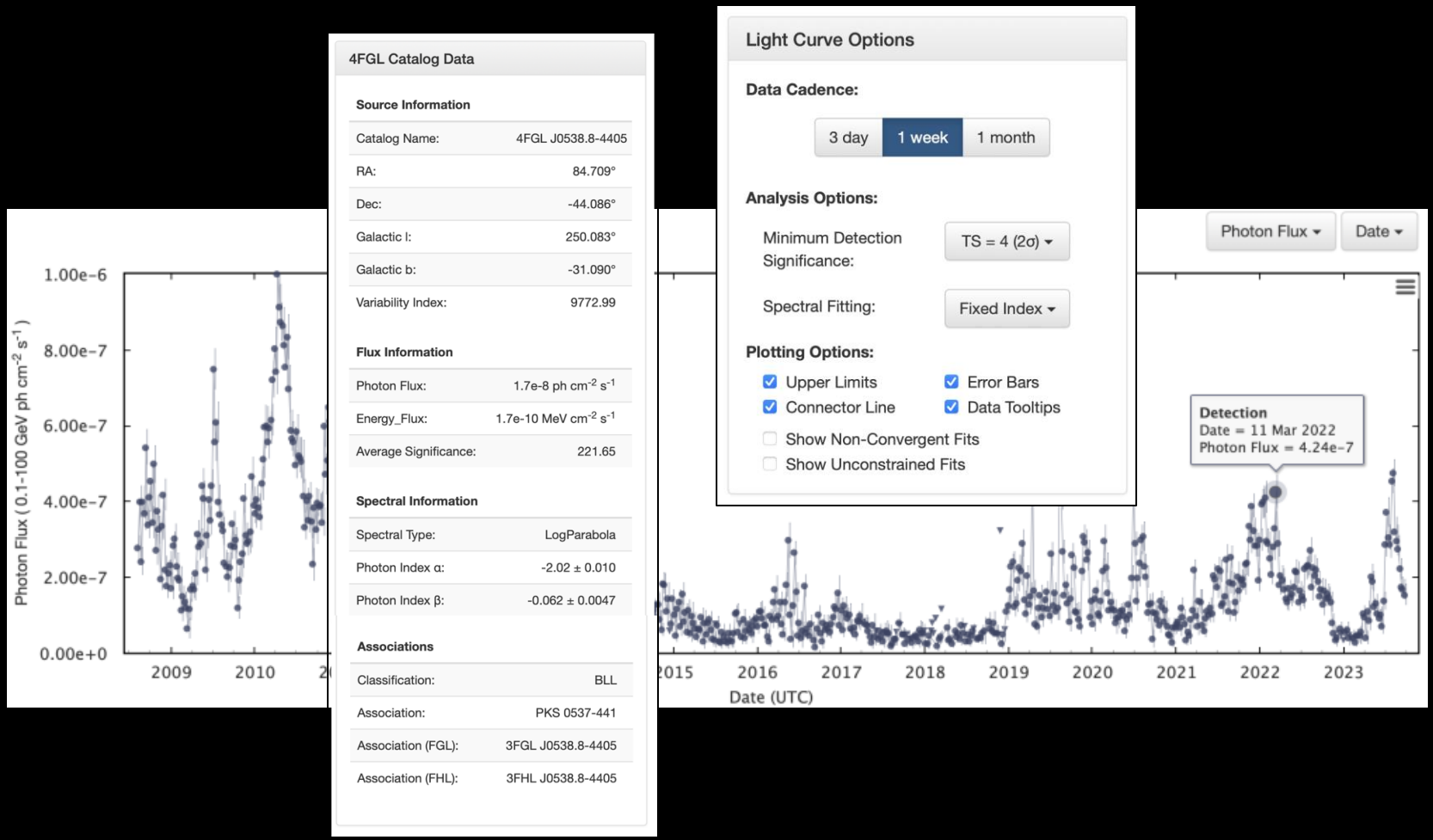
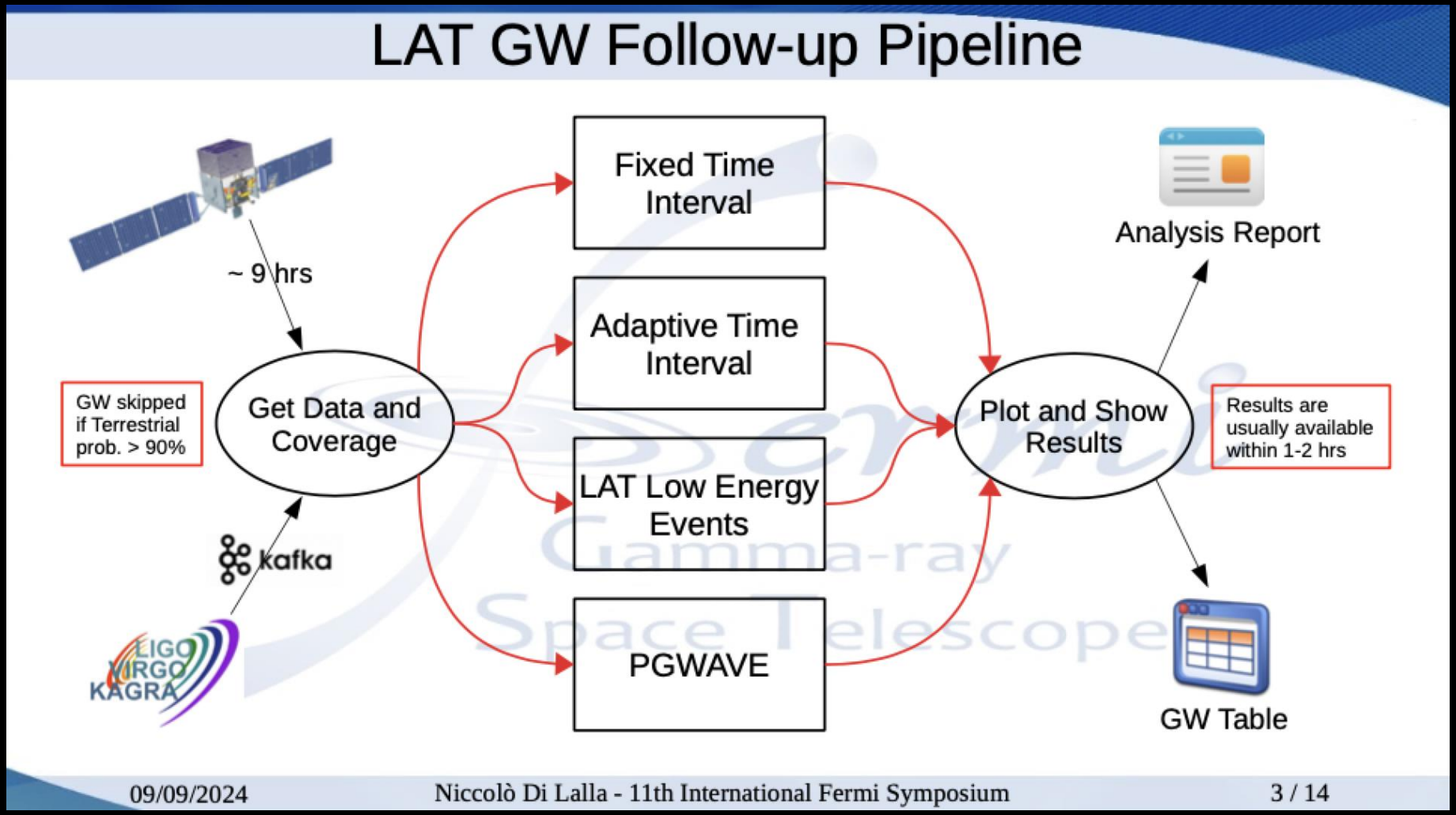


Fermi LAT follow up of GW events

Fermi-LAT follows up most significant GW events searching for electromagnetic counterparts.



GWs: O4 and Fermi LAT

- LAT follow up analyses publicly available at http://fermigrb.stanford.edu/GWTable/
- Page created and maintained by Niccolò Di Lalla at Stanford.

Stanford University

Fermi-LAT Gravitational Waves Table

This page displays the outcomes of the Fermi-LAT automatic follow-up analysis pipeline used to search for electromagnetic counterparts of gravitational waves (GW). For a detailed explanation of the analysis techniques, please refer to 2017ApJ...841L..16V. Furthermore, the Fermi-LAT Collaboration has published additional papers on GW events such as GW150914, LVT151012 and GW151226, GW170104, and GW170817

All analysis results presented here should be considered preliminary, unless otherwise stated. If you have any questions, please write to Niccolò Di Lalla.

Click on the following buttons to access the table associated with the corresponding observing cycle:

O3 | O4

Stop your mouse cursor over the table headings to view a short explanation of the columns in the table or check the legend here.

* Information taken from GraceDB (LIGO-Virgo-KAGRA Collaboration).

Trigger Name*	Date*	Time (UTC)*	GraceDB*	FAR (Hz)*	Highest Probability*	Has NS? (%)*	Has Remnant? (%)*	Has MassGap? (%)*	Inst. Coverage (%)	FTI TS max	ATI TS max	Flux UB (erg/cm2/s)	Analysis report
S240902bq	2024-09-02	14:33:06	Link	2.5e-09	BBH: 100.0%	0.0	0.0	0.0	0.0	10.2	9.8	5.3e-10	Link (v02)
S240830gn	2024-08-30	21:11:20	Link	6.3e-10	BBH: 89.1%	0.0	0.0	0.1	26.0	5.9	9.9	1.3e-09	Link (v02)
S240825ar	2024-08-25	05:51:46	Link	3.2e-09	BBH: 96.5%	0.0	0.0	7.1	83.2	9.2	9.5	2.8e-10	Link (v02)
S240813d	2024-08-13	04:39:13	Link	1.8e-18	BBH: 100.0%	0.0	0.0	0.0	27.4	12.4	11.1	1.4e-09	Link (v02)
S240813c	2024-08-13	03:45:48	Link	2.6e-09	BBH: 99.8%	0.0	0.0	2.8	41.8	19.5	23.4	5.9e-10	Link (v02)
S240807h	2024-08-07	21:45:59	Link	2.0e-11	BBH: 100.0%	0.0	0.0	28.3	39.9	**37.1**	**35.4**	5.7e-10	Link (v02)
S240716b	2024-07-16	03:49:00	Link	7.9e-16	BBH: 100.0%	0.0	0.0	0.0	6.6	22.5	19.6	5.7e-10	Link (v02)
S240705at	2024-07-05	05:32:15	Link	7.1e-16	BBH: 100.0%	0.0	0.0	0.0	2.4	7.9	8.1	6.5e-10	Link (v02)
S240703ad	2024-07-03	19:13:55	Link	1.2e-13	BBH: 100.0%	0.0	0.0	0.0	6.9	20.7	18.2	4.5e-10	Link (v02)
S240630t	2024-06-30	10:17:03	Link	1.9e-12	BBH: 100.0%	0.0	0.0	0.0	92.4	22.0	24.7	5.6e-10	Link (v02)
S240629by	2024-06-29	14:52:56	Link	3.2e-10	BBH: 91.5%	0.0	0.0	0.0	0.5	11.0	5.7	4.7e-10	Link (v02)
S240627by	2024-06-27	13:16:22	Link	1.2e-08	BBH: 99.2%	0.0	0.0	8.1	SAA	15.8	16.5	5.2e-10	Link (v01)
S240622h	2024-06-22	00:40:08	Link	1.2e-08	BBH: 98.5%	0.0	0.0	0.0	0.1	12.7	14.4	3.5e-10	Link (v02)

Maximum significance

Analysis report

Fermi-LAT catalogs

The production of very diverse gamma-ray catalogs **remains a priority**:

- **4FGL-DR4**, main catalog with nearly 7200 sources (Ballet et al. 2023).
- **3PC**, with 294 pulsars (Smith et al. 2023).
- Other recent catalogs include the 4LAC-DR3 (Ajello et al. 2022), 1FLT (Baldini et al. 2021); FLSF (Ajello et al. 2021), FERMILGRB (Ajello et al. 2019), FGES (Ackermann et al. 2017).

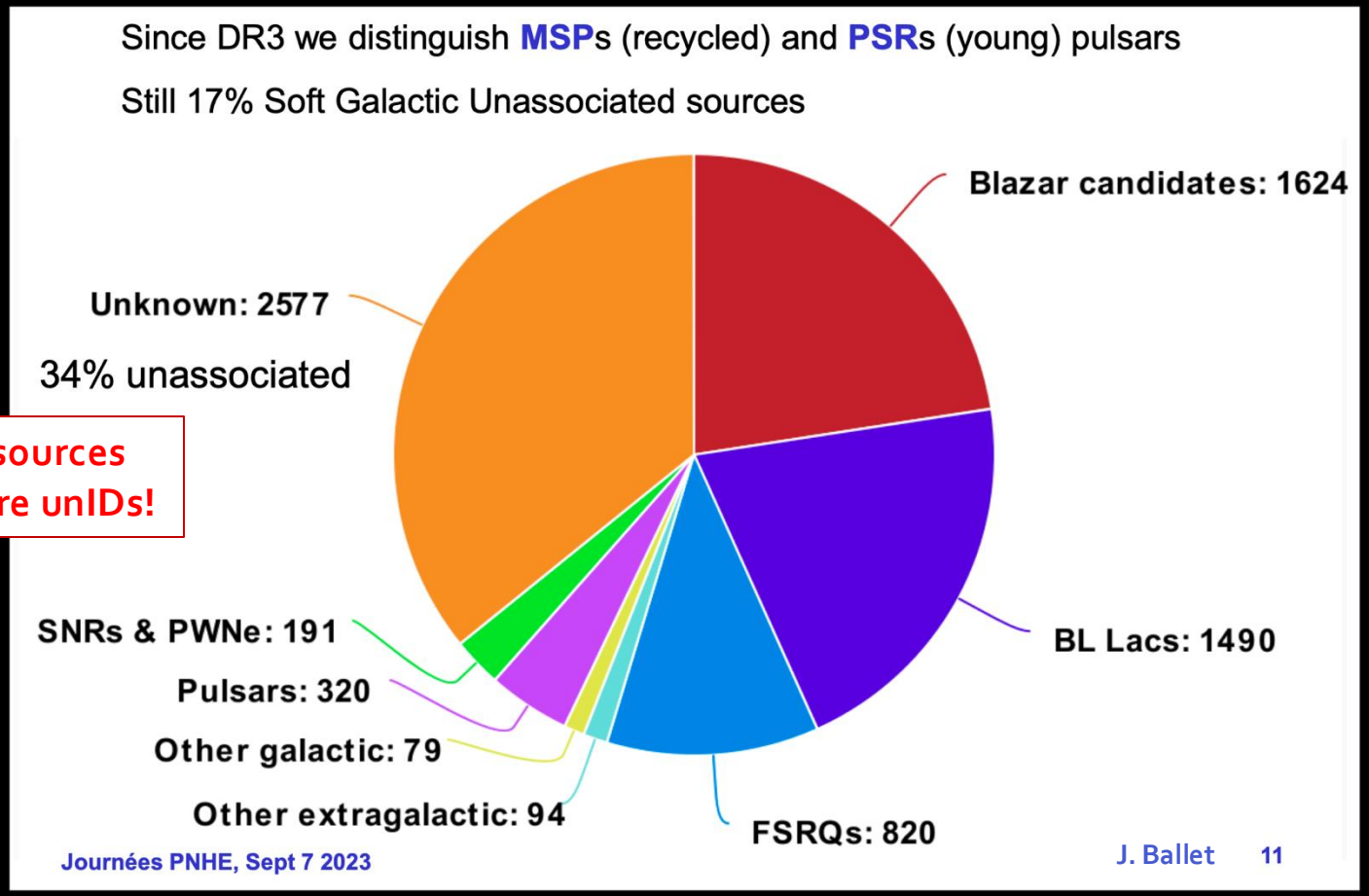
Several catalogs currently **under production**:

- 5FGL based in a new Galactic diffuse emission model.
- 2FGES catalog of extended sources.
- 2FLE catalog of low-energy sources.
- PWN catalog.
- 4FHL catalog of 'hard' sources.

The 4FGL-DR4 point-source catalog

[Ballet et al. (2023), arXiv: 2307.12546; LAT Collab. ApJS 260, 53 (2022)

7195 entries (DR3 had 6658).
All of the data available at the FSSC: https://fermi.gsfc.nasa.gov/ssc/data/access/lat/14yr_catalog/



57% of new sources in the DR4 are unIDs!

GRB221009A – "The B.O.A.T."

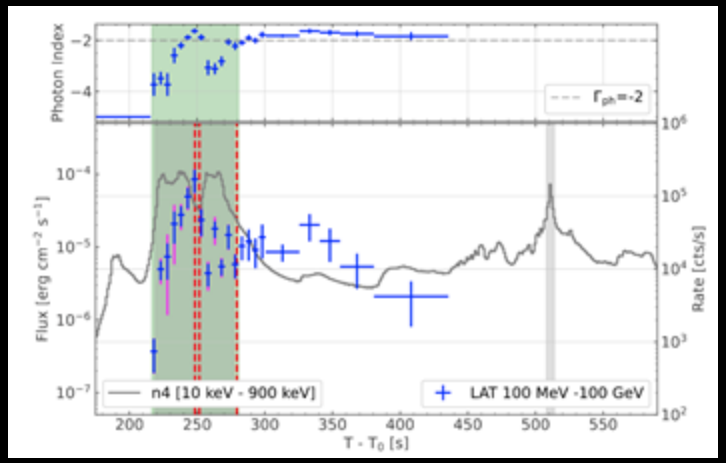
[arXiv:2409.04580]

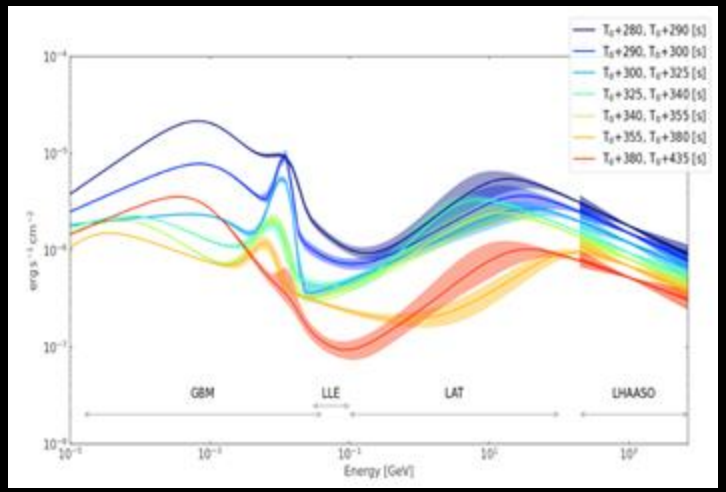
(Bissaldi, Bruel, Di Lalla, Omodei, Pillera; for the LAT Collaboration and the GBM Team)

Comprehensive study on the bright GRB 221009A just submitted (Axelsson et al. 2024).

- Unusable data for standard analysis pipelines recovered and critical for obtained results.
- Flux estimation during the affected LAT time interval.
- Detailed analysis of the light curve, with comparison to TeV emission (LHAASO).
- Temporal evolution of spectrum from GBM to LHAASO, including assessment of the ~10 MeV line.

Additional 'category 2' paper (Tak et al. 2024) submitted that performs a MW analysis (optical, X-rays, γ's).

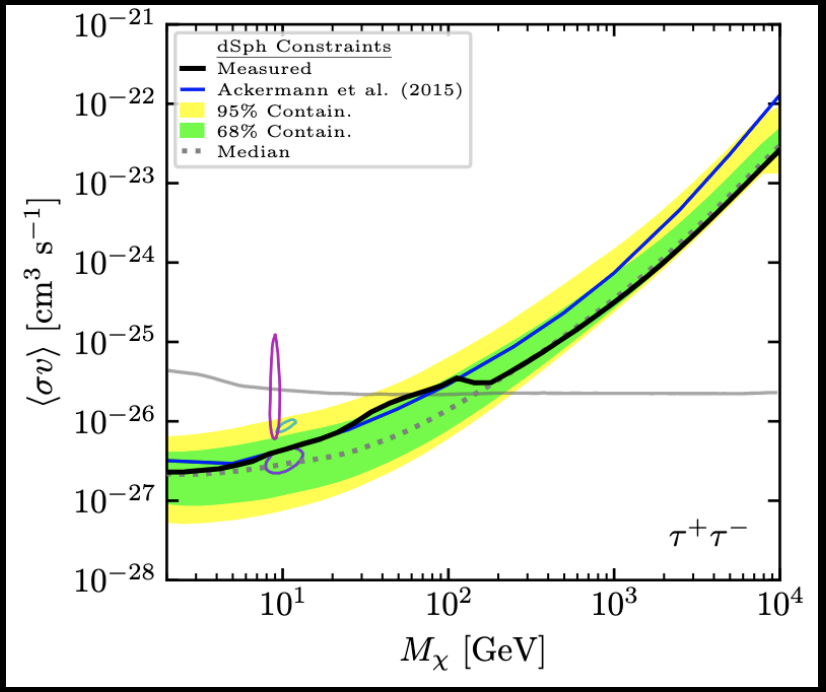


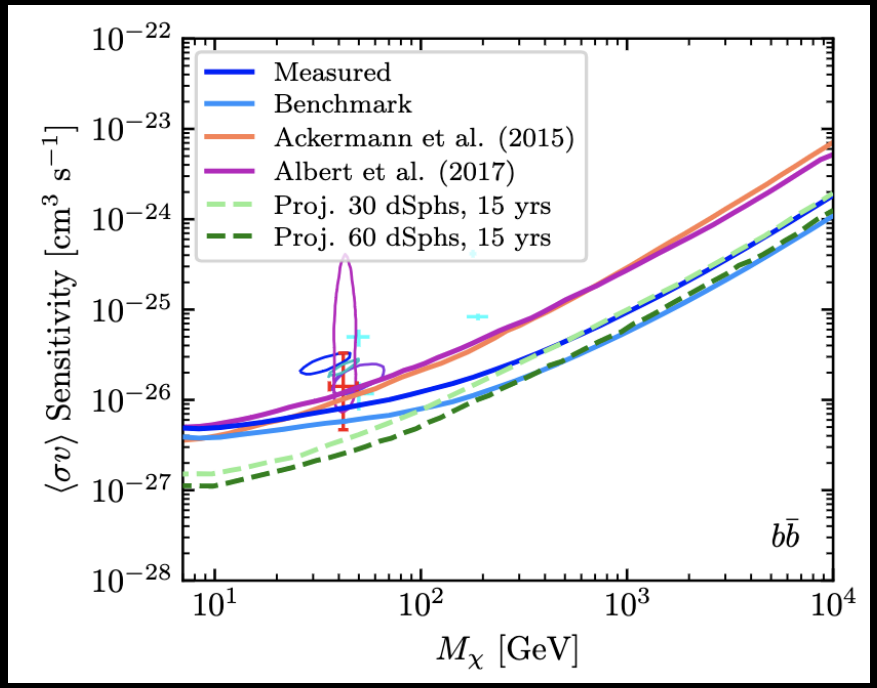


‘Legacy’ dark matter dwarf analysis

[McDaniel et al. (2024) – arXiv:2311.04982; PRD 109, 063024]

- No gamma-ray signal found in the direction of ~50 dwarfs
  → Upper limits to the gamma-ray flux → Upper limits to dark matter (DM) annihilation
- Most significant excess is < 1σ (global) (but see Crocker+22)
- Combined DM limits the most robust and competitive ones so far.
  → Dwarfs as a test of the GeV GC excess.



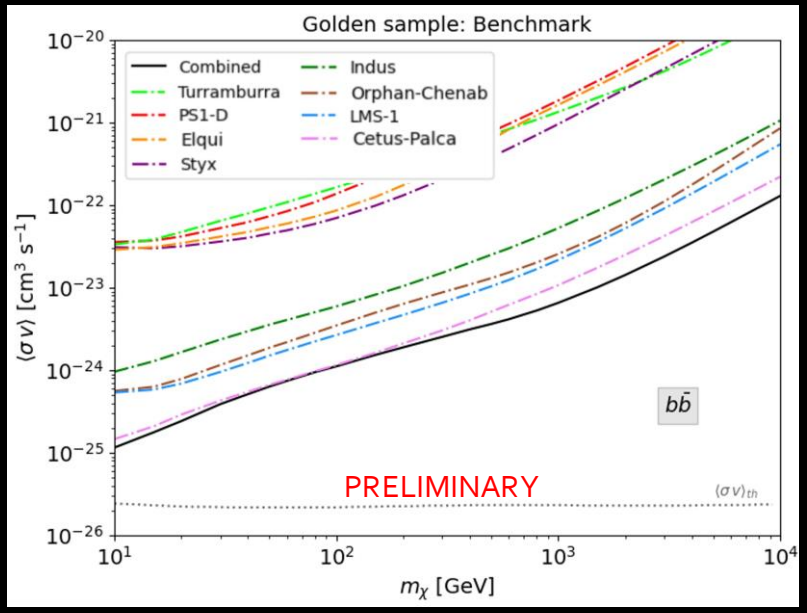


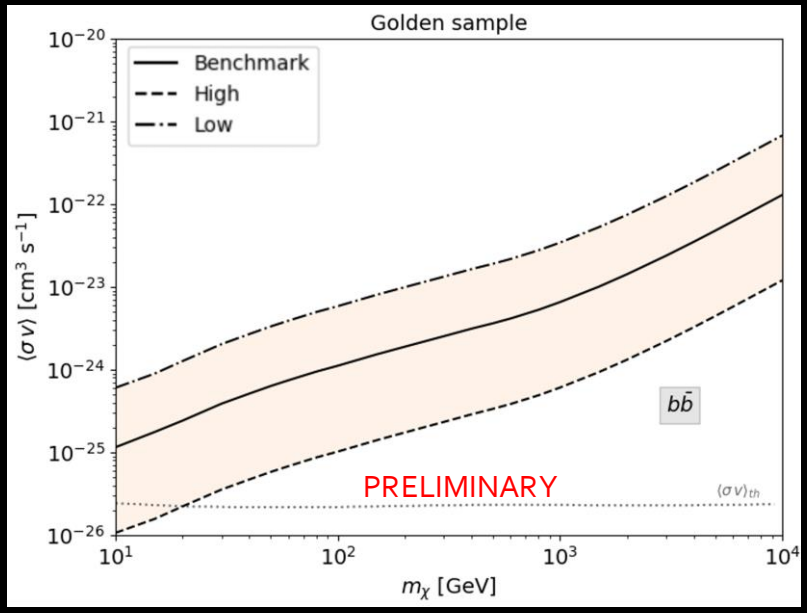
[McDaniel+24]

LAT DM search in stellar streams

[Fernández-Suárez & MASC (2024), for the LAT Collab., in prep.]

- Remnants of globular clusters or dwarf galaxies heavily stripped by tidal forces in the host.
- Those whose progenitors were dwarfs may still contain a significant amount of DM today.
- We search for DM annihilation in LAT data from a selected sample of O(10) streams.
- In the absence of a signal, we set competitive DM constraints for different assumptions of the DM subhalo remnant hosting the stream.





Other ongoing and future efforts

Intense and continuous work to develop a new Galactic diffuse emission model.

- Tightly connected and necessary for the generation of the 5FGL.
- Different approaches under consideration (template fitting, IFT…).

Study of unID sources (>2500 in the 4FGL-DR4).

- Comprehensive multi-wavelength analysis of many unIDs.
- Study of potential mismodeling due to diffuse emission.
- Application of machine learning tools.

Multi-wavelength and multi-messenger studies.

- 3PC and unID follow ups.
- GW EM counterpart localization, LAT follow up analyses publicly available.

Public data release of Flare Advocate analyses soon available.

Will be posted at the FSSC data webpage on a continuous basis.

fermipy
an analysis tool for the community

- *fermipy* is a python package that facilitates analysis of LAT data with the Fermi Science Tools.

- Recently, we established the project organization and defined the key roles and responsibilities:
  - Key personnel within the LAT collaboration took ownership of the *fermipy* project, still fostering participation from the community.
  - Maintenance; issue tracking and community support (via github); development

- Recent development/updates include:
  - Added the *psmap* (code implementation described in Bruel 2021).
  - Updated the documentation to use the latest version of catalogs/data products.
  - Added and updated a series of tutorials (via jupyter notebooks), that are available in the documentation page (https://fermipy.readthedocs.io/en/latest/index.html).
  - Boost in activity and people involved, following a workshop in Madrid past March 2024.

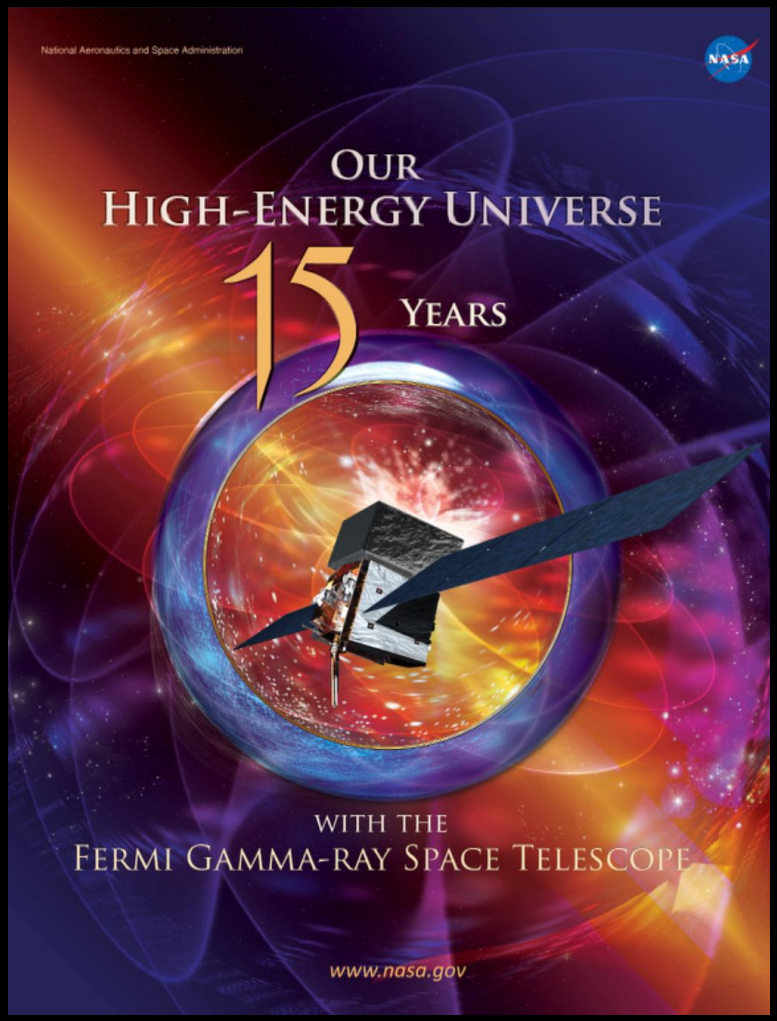
- **New version of Fermipy (v1.3.1) just released!**
  - Available in *pip*, soon will be available in *conda* too.

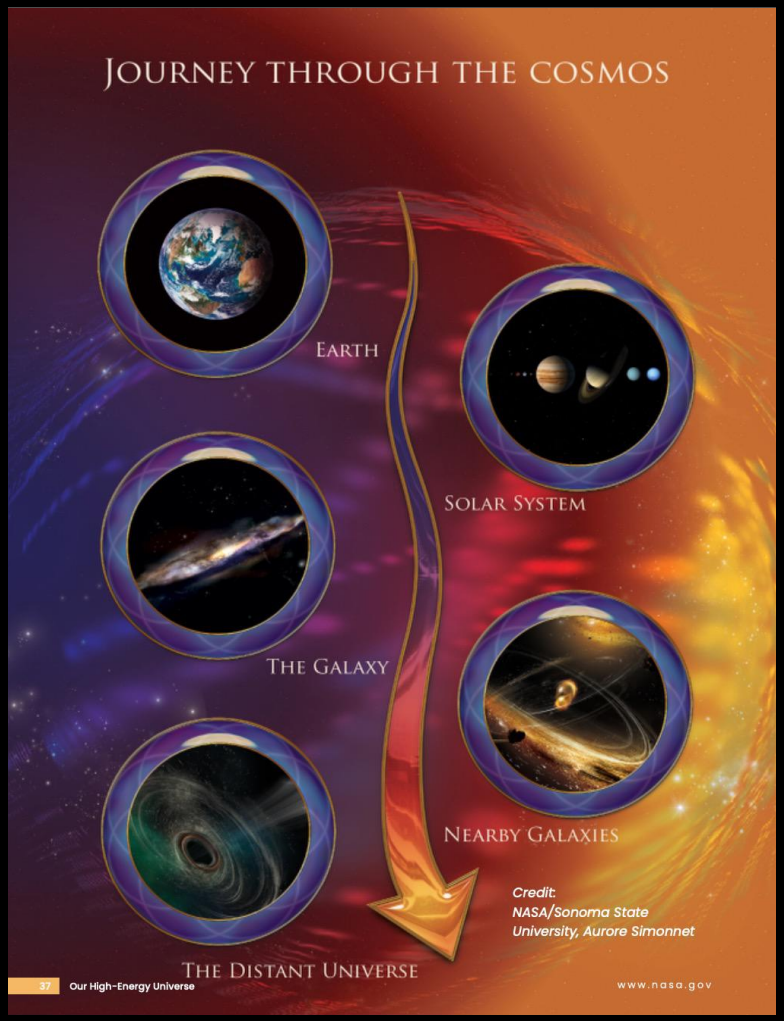
Fermi-LAT: a story of discoveries!

https://fermi.gsfc.nasa.gov/ssc/library/news/

Thousands of new sources in the sky, better understanding of most energetic phenomena, Universe composition, Galactic diffuse emission… and many more in NASA news!

Fermi 15-year e-book





Released in April! Download it here.

Outlook

- **Fermi LAT a very vibrant, healthy collaboration and community!**
  - Main data products publicly available.
- **Fermi LAT the leading instrument in the GeV energy domain**.
  - Mission just turned 16 years and is formally approved through 2025.
  - Performance is excellent.
- **Lots more science!**
  - Fermi LAT key for transients and GW follow ups.
  - Production of catalogs remains a priority. Nearly 7200 sources in the latest 4FGL-DR4.
  - Investigation of unIDs by different methods.
  - Leading gamma-ray dark matter constraints from dwarfs. Novel limits from streams.
- **Fermi LAT will likely run for many more years!**
  - Plan to operate Fermi while the observatory remains functional and the science productivity continues high!

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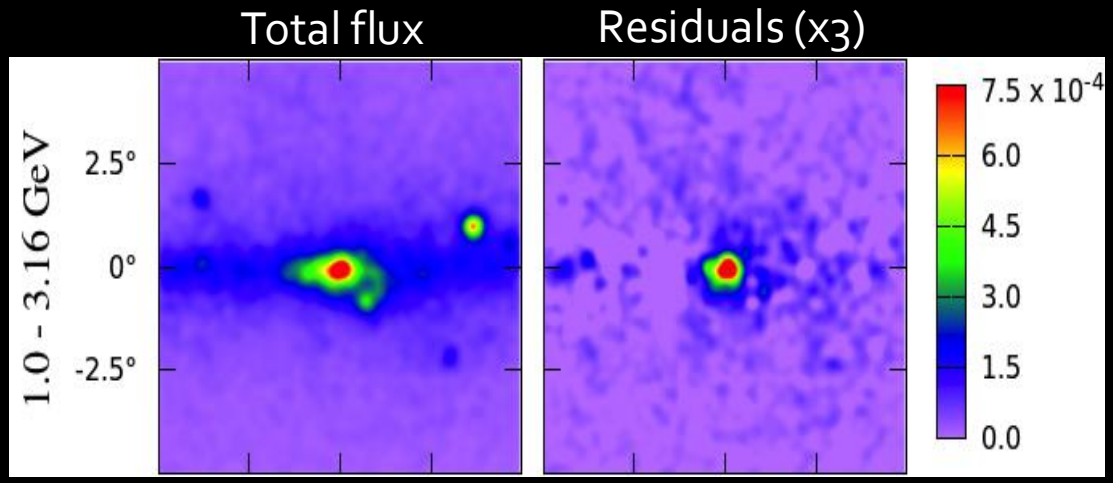
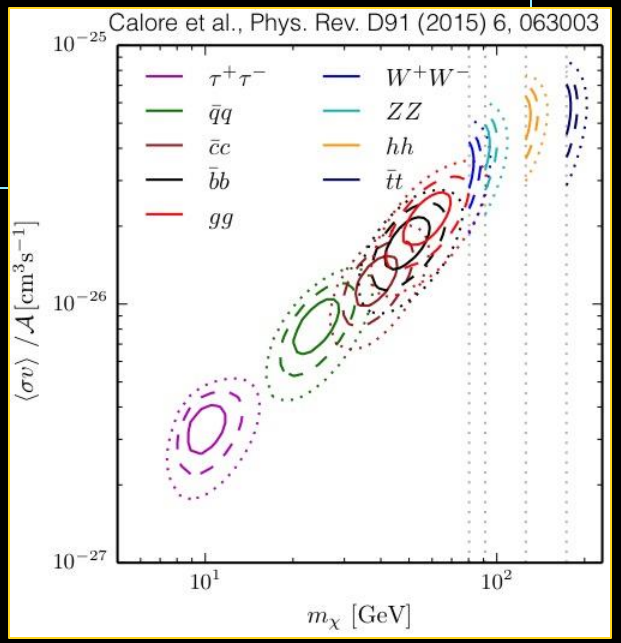
MULTIDARK
Multimessenger Approach for Dark Matter Detection

'GeV excess' in the Galactic center

- **Several groups** reported an excess of GeV photons from the GC region (e.g., Goodenough & Hooper 09, 11; Daylan+14, Abazajian+14, Calore+14; Gordon & Macías 14, Ajello+16)
- General agreement on the excess **peaking at a few GeV** above the ***standard*** diffuse emission models.
- **Interpretation difficult** due to complicated foreground/background modeling.
- **DM annihilation** (still) a plausible and exciting possibility
  - Spatially consistent with gNFW
  - Approx. half the thermal cross section
  - Around 50 GeV DM particle mass (bb)



[Daylan+14]

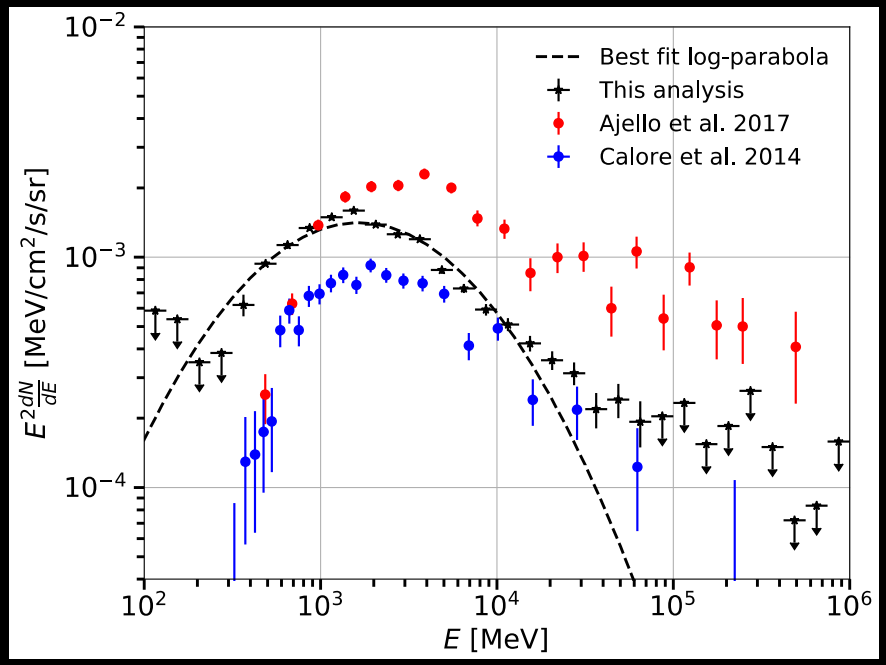


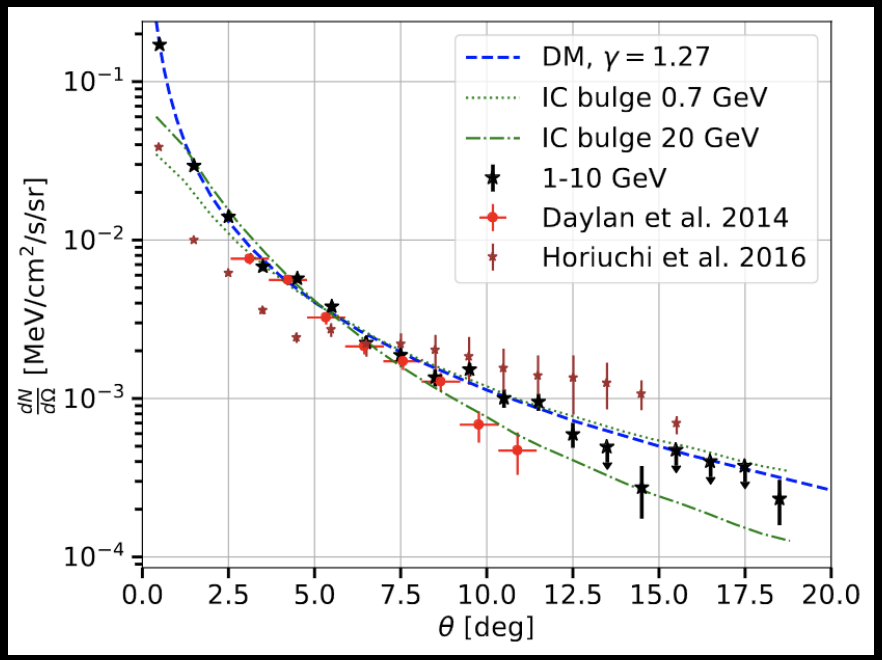
[Calore+14]

GC excess *circa* 2024

- Excess persists. Different explanations possible: pulsars, CR outbursts, DM.
- Pulsar interpretation is strenghtening:
  - Photon counts suggest a point source origin (Bartels+15, Lee+15; Buschmann+20; Malyshev+24; but see also Leane&Slatyer 20).
  - GCE seems to trace stellar densities (Bartels+18; Macias+18)
- Similar excesses at other longitudes along the Galactic Plane (Ackermann+17)

  → not expected from DM; diffuse emission residuals can mimic a DM signal.

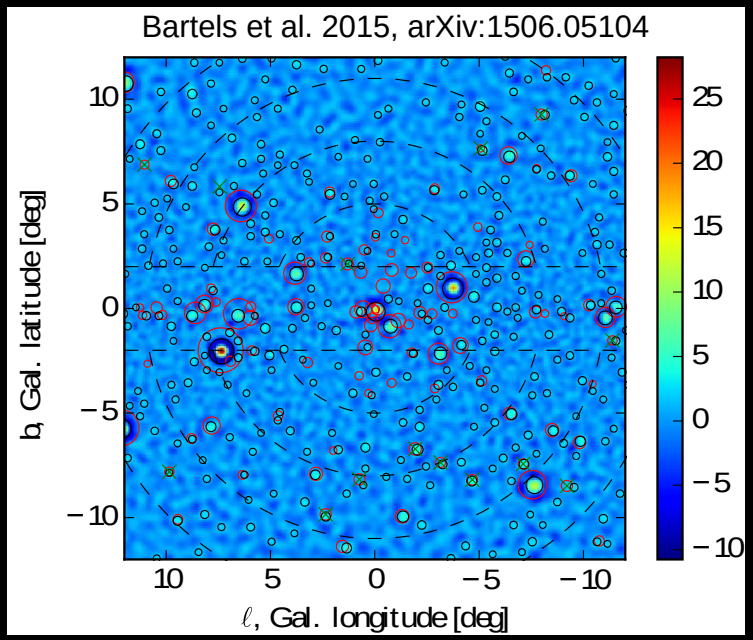




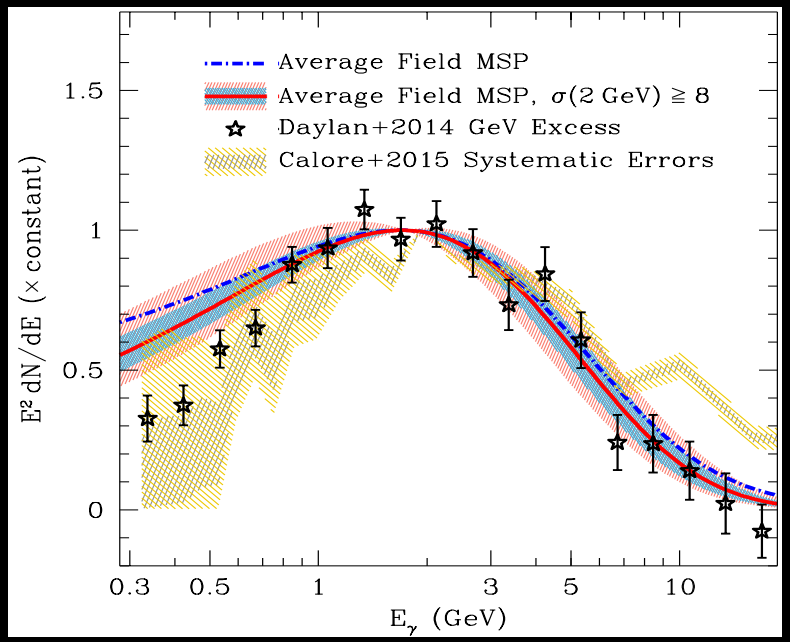
[di Mauro+21]

Interpretation (II): Unresolved sources?

- O(1000) Millisecond pulsars (MSPs) within ~1kpc of the GC [Abazajian+14]
- Young MSPs [O'Leary+15]
- MSPs from globular clusters' disruption [Brandt+15]
- Non-poissonian photon statistics template analysis [Lee+15]
- Wavelet decomposition of the gamma-ray sky [Bartels+15]



[Bartels+15]



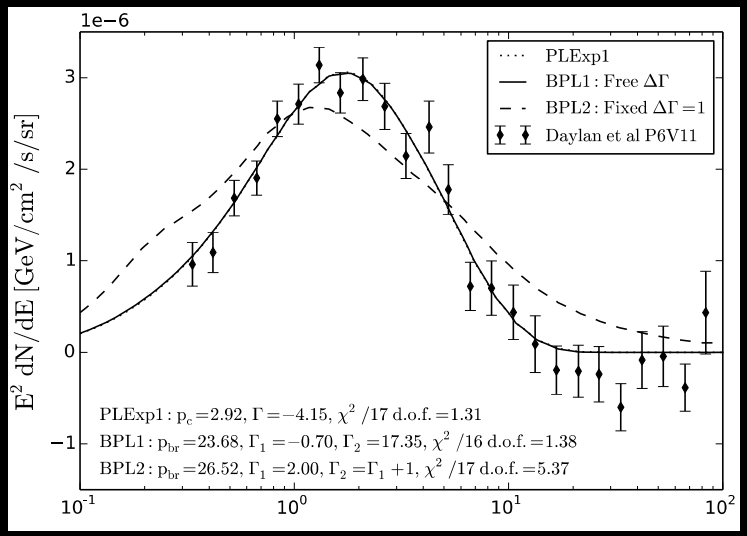
[Brandt+15]

Interpretation (III): Cosmic-ray outbursts?

CR-induced emission may vary with time due to outburst events (black hole, starbursts)

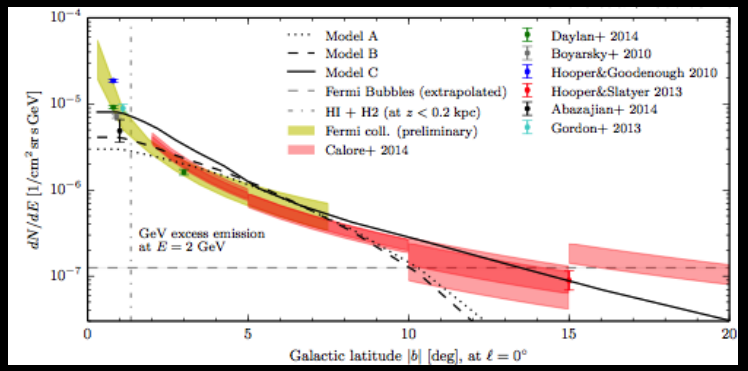
1) HADRONIC

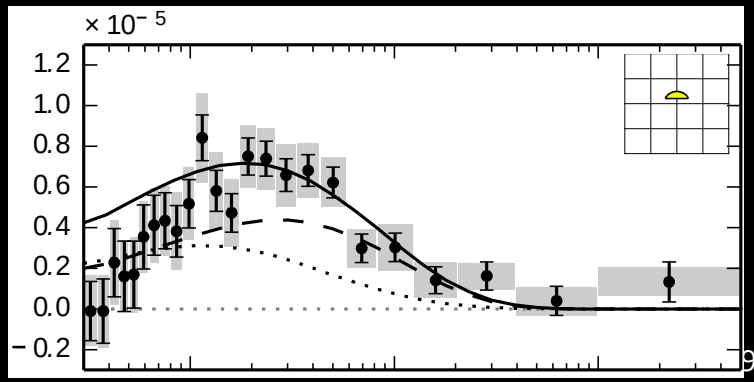
E.g., protons from supernova remnants
[Carlson&Profumo 14]



2) LEPTONIC

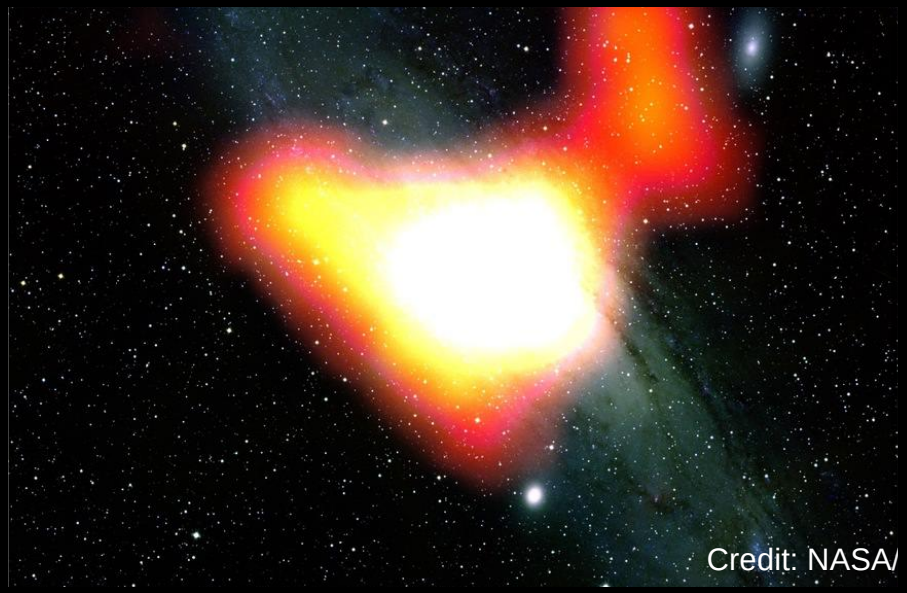
E.g., multiple burst events injecting electrons
[Petrovic+14, Cholis+15]

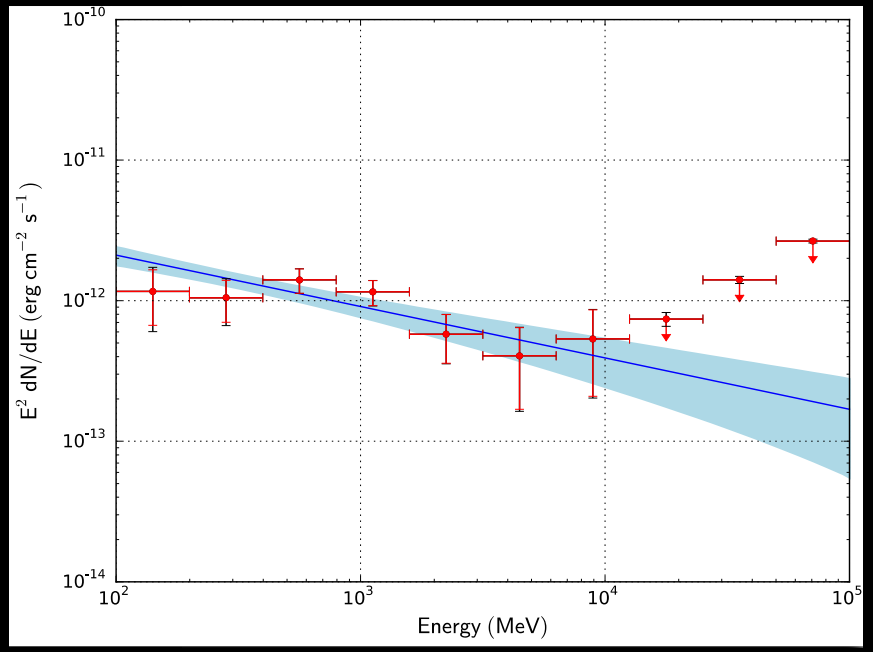




[Cholis+15]

A gamma-ray excess in M31 too?





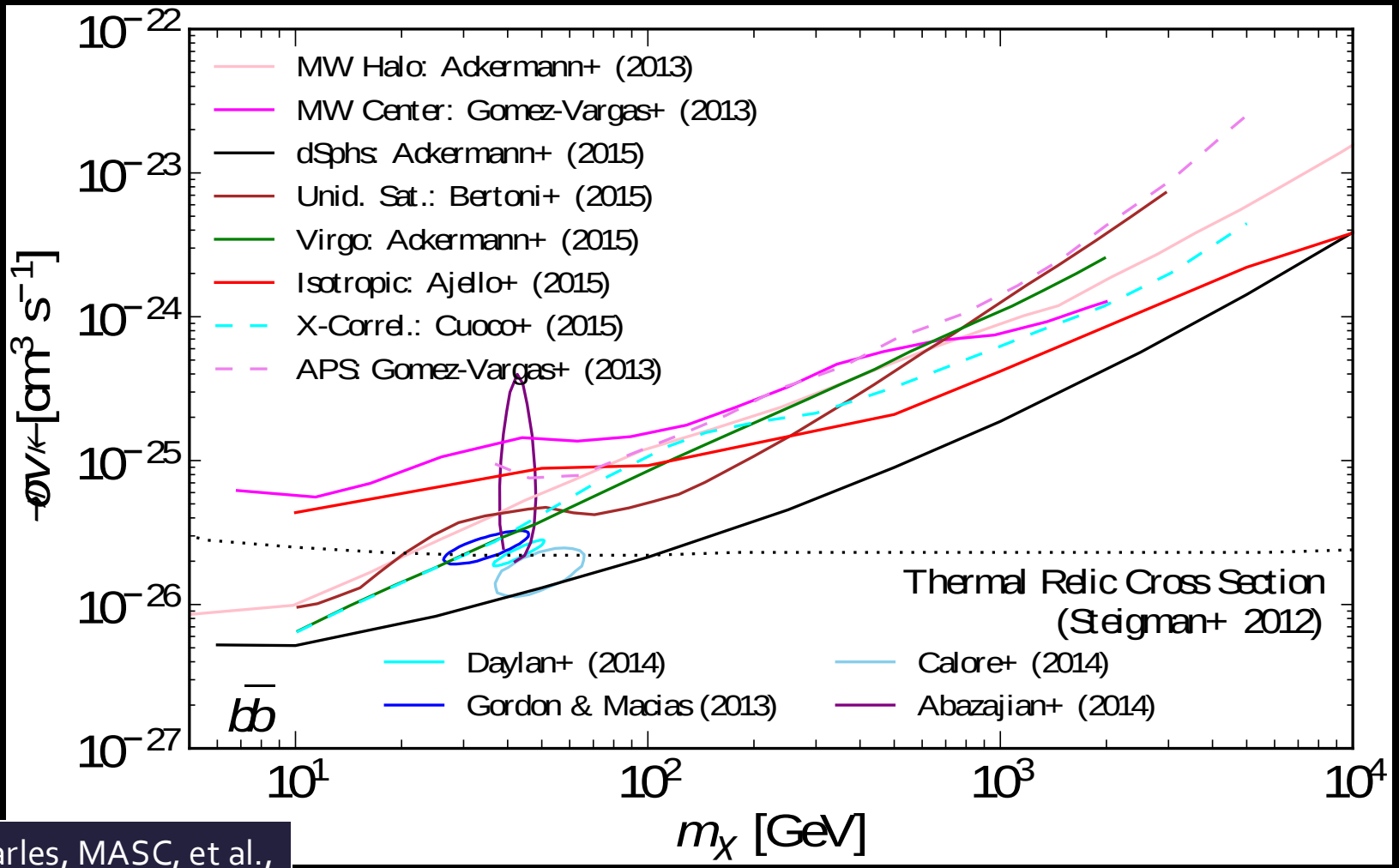
Ackermann+17

- The LAT has detected Andromeda at 10σ significance.
- 4σ significance of extended (0.4°) emission.
- Confined to the inner (<5kpc) regions of the galaxy.
- Not correlated with interstellar gas and star formation regions.
- Galactic disk not detected.
- ORIGIN OF THIS EMISSION IS UNCLEAR

  → MSPs could explain it, but they under predict the signal (factor ~2; Eckner+17)

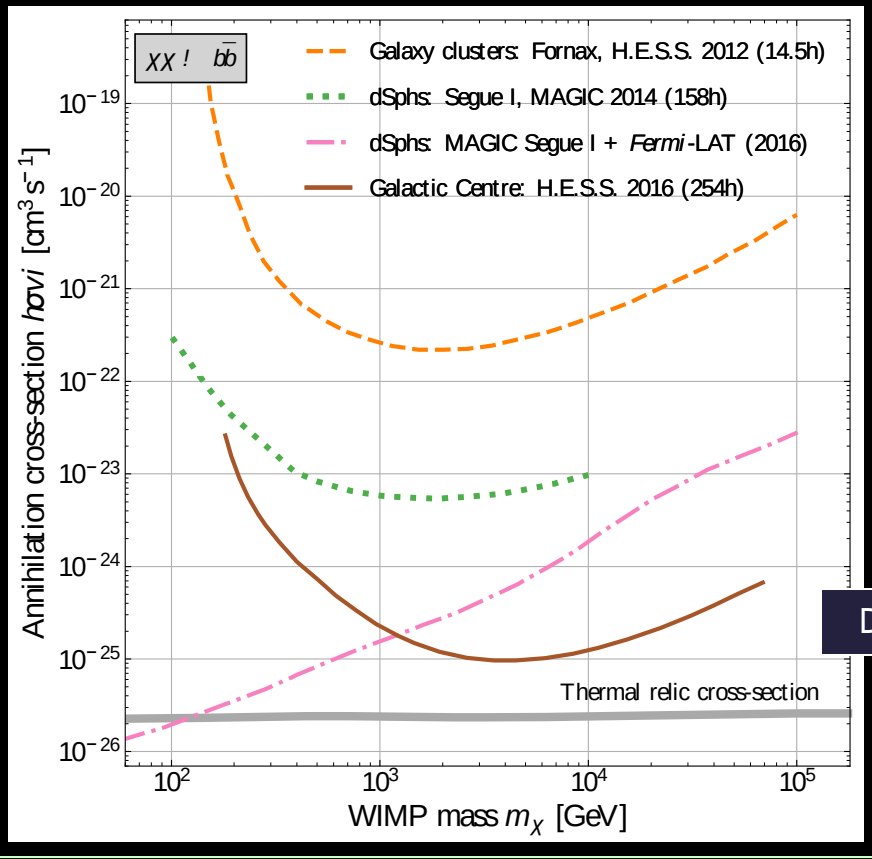
Fermi-LAT : a lot of DM targets explored so far

[many DM limits and some signal hints]



Charles, MASC, et al., [1605.02016]

γ-ray DM annihilation searches: today



Doro, MASC, Hütten (2021)

Different targets observed, different DM scenarios explored.

- → No DM-induced gamma-ray signal (unequivocally) detected.
- → Fermi LAT ruling out thermal WIMPs below ~100 GeV.
- → GC excess persists (M31 too?). Dwarfs the best independent way to test it.
- → IACTs and HAWC competitive in the TeV energy range.

γ-ray DM decay searches: today

Annihilating DM

$$\frac{d\Phi_{\rm ann}}{dE_\gamma} = \frac{1}{k}\frac{\langle\sigma v\rangle}{4\pi\, m^2_{\rm DM}}\sum_i {\rm BR}_i \frac{dN^i_\gamma}{dE} \times J_{\Delta\Omega}$$

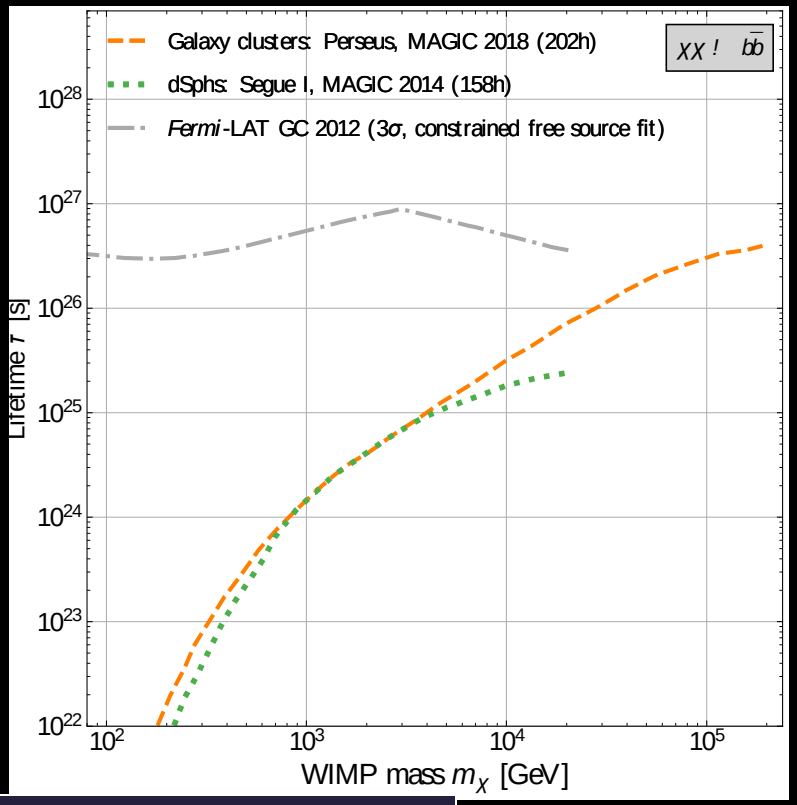
Decaying DM

$$\frac{d\Phi_{\rm dec}}{dE_\gamma} = \frac{1/\tau}{4\pi\, m_{\rm DM}}\sum_i \Gamma_i \frac{dN^i_\gamma}{dE} \times D_{\Delta\Omega}$$

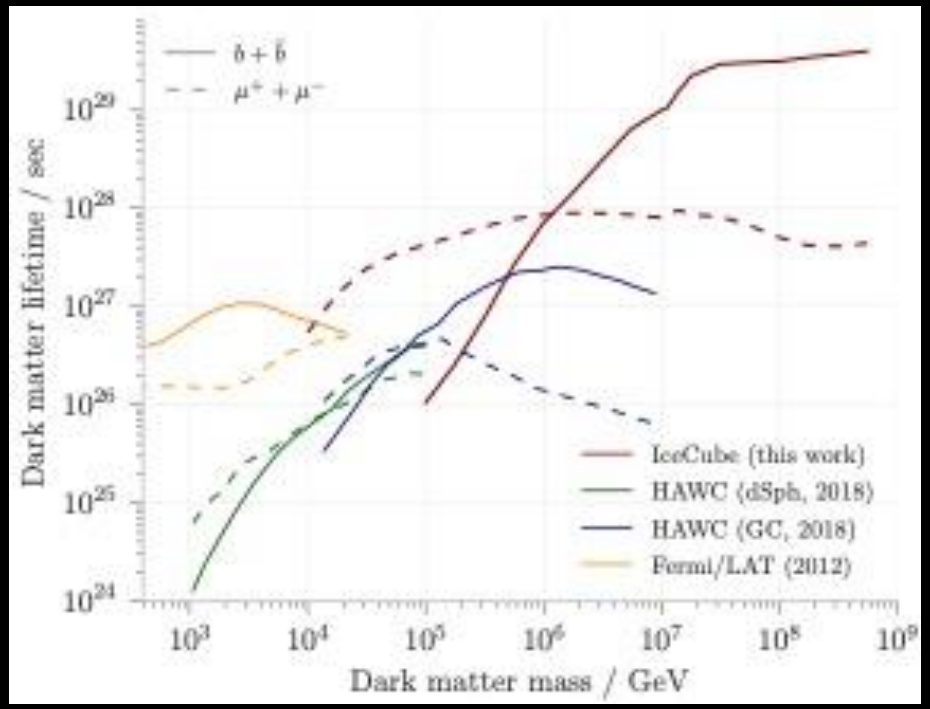
with

$$J_{\Delta\Omega} = \int_{\Delta\Omega}\int_{\rm l.o.s.} \rho^2_{\rm DM}(\ell,\Omega)\, d\ell\, d\Omega$$

$$D_{\Delta\Omega} = \int_{\Delta\Omega}\int_{\rm l.o.s.} \rho_{\rm DM}(\ell,\Omega)\, d\ell\, d\Omega$$



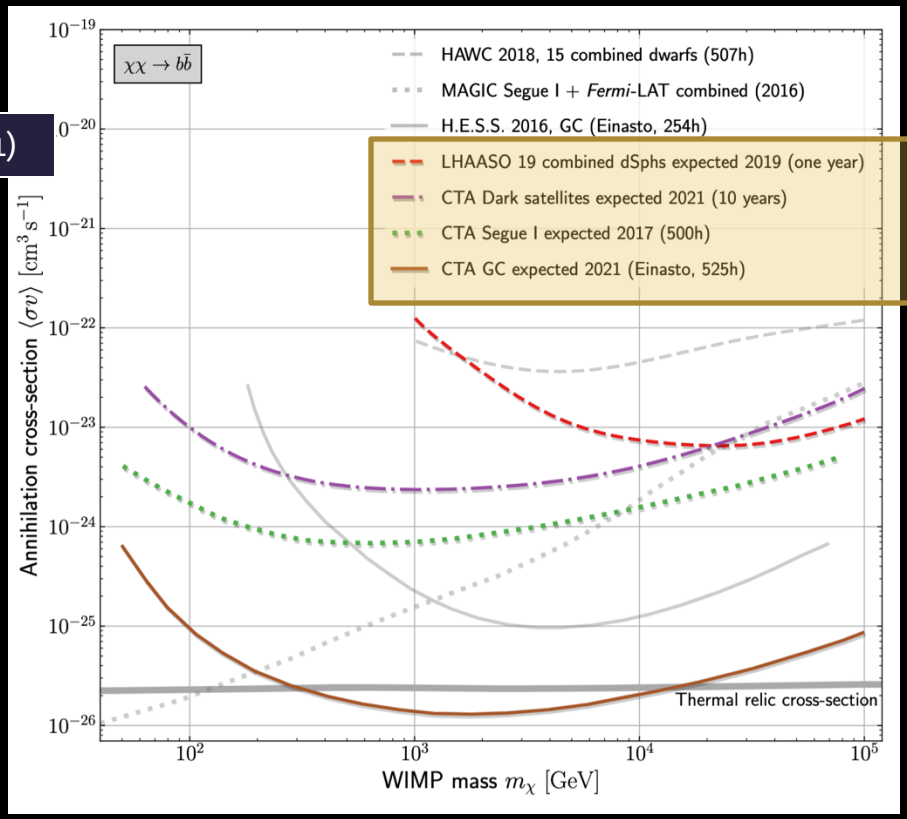
Doro, MASC, Hütten (2021)



[Aartsen+18]

(γ-ray) DM searches: tomorrow

Doro, MASC, Hütten (2021)



Predictions

→ **Fermi + CTA** will (fully?) test the WIMP miracle (~2030?).

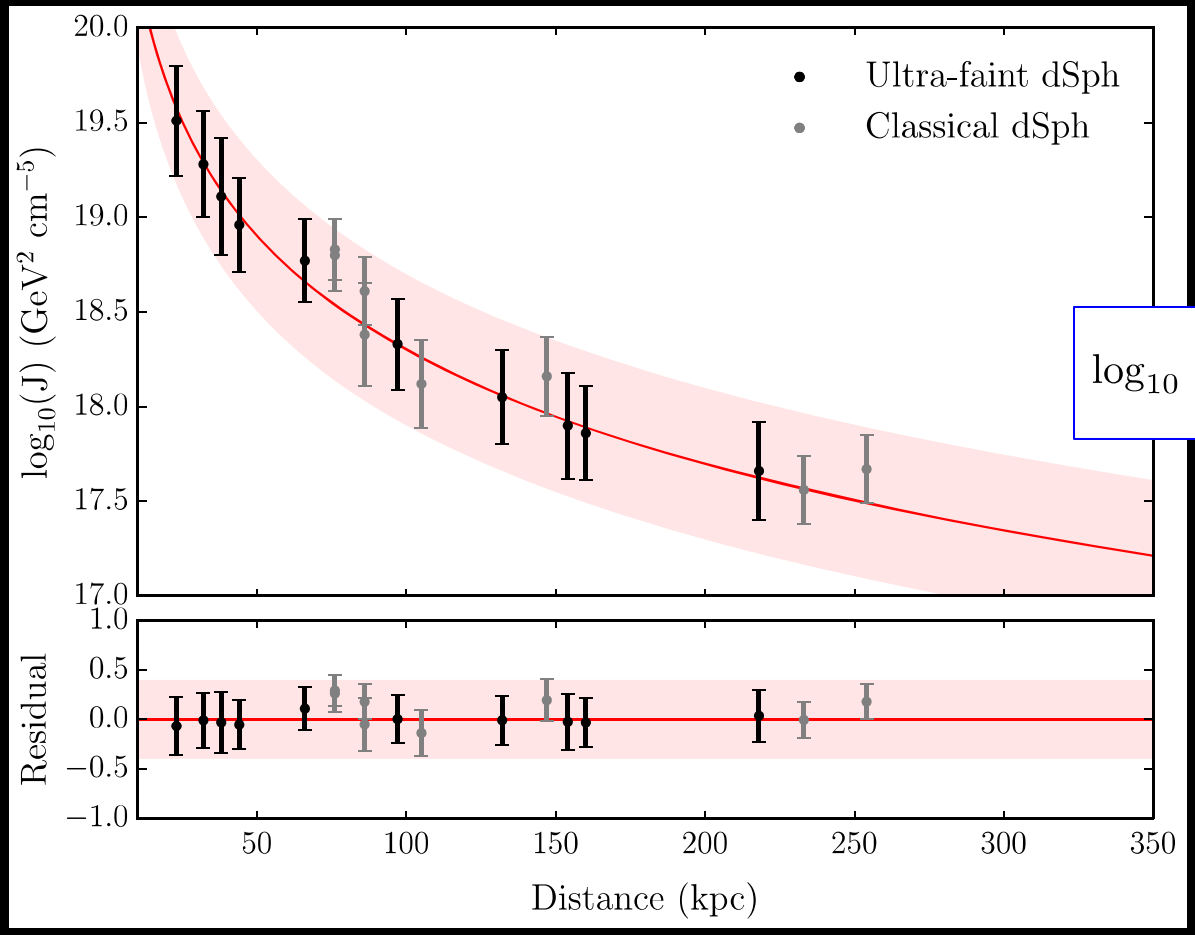
→ Origin of the **GC excess possibly settled** (more dwarfs, radio and MeV measurements)

→ Critical to **keep the diversity** of astrophysical targets, experiments, messengers, DM particle candidates.

Dwarf Galaxies' J-Factors

"J-factor" of MW dwarf satellite galaxies inferred from:

- l.o.s. velocity dispersion profiles
- DM density profile (e.g. NFW)



Drlica-Wagner+15

Parametrization based on current knowledge of J-factors

$$\log_{10}\left(\frac{J_{\mathrm{pred}}}{J_0}\right) = -2\log_{10}\left(\frac{D}{100\,\mathrm{kpc}}\right)$$

with $J_0 = 18.1\ \mathrm{GeV^2cm^{-5}}$

[Albert+17]

Dark satellite search with gammas: general methodology

Around 1/3 of sources in gamma-ray catalogs are unidentified (unIDs)
(e.g., >2000 unIDs in the '4FGL-DR4' Fermi-LAT catalog)

Exciting possibility: some of them may be subhalos annihilating to gammas!

Search for potential DM subhalo candidates by identifying those unIDs compatible with DM subhalo annihilation.

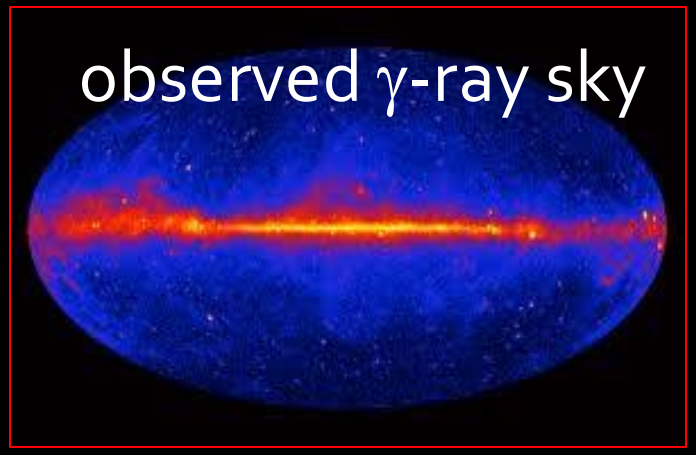
→ Apply a series of '*filters*' based on expected DM signal properties.

Possible results:

1. A few VIP candidates → dedicated data analyses, follow-up campaigns…
2. A few more subhalo candidates (yet uncertain) → set DM constraints
3. No unIDs compatible with DM → best achievable constraints

DM constraints from gamma-ray unID sources?

VS.



dark subhalo J-factors, number density, spatial extension…

instrument sensitivity to DM annihilation, pool of unID sources

Number of predicted detectable subhalos VS. number of unIDs compatible with DM

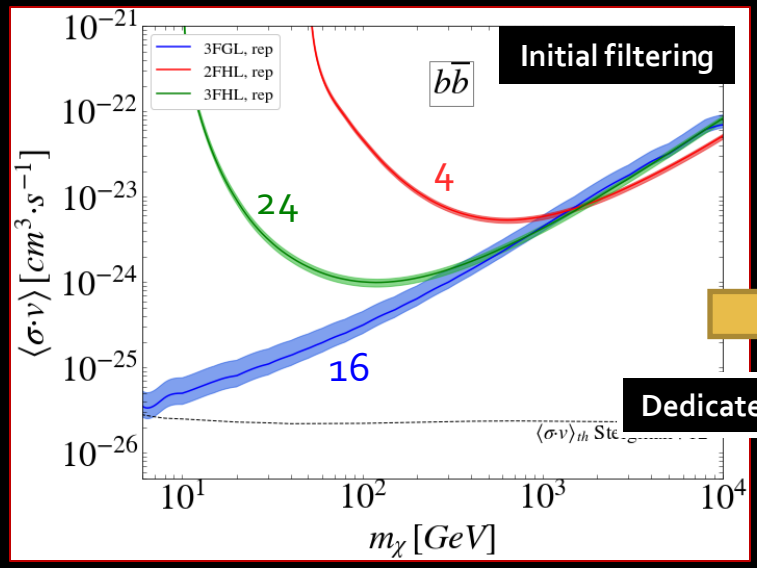
DM CONSTRAINTS

[The less DM candidates among unIDs the better the constraints]

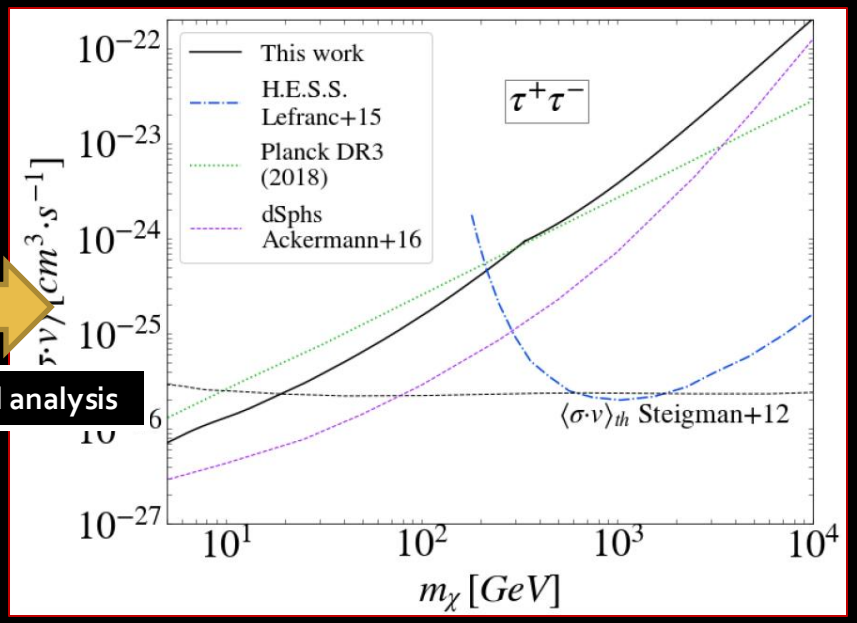
Dark satellite search in Fermi-LAT catalogs (I)

[Coronado-Blázquez, MASC, et al. (2019 a,b) – arXiv:1906.11896; 1910.14429]

- List of O(10) VIP candidates among unIDs in the 2FGL, 2FHL, 3FGL Fermi LAT catalogs.
- Dedicated spectral analysis of best DM subhalo candidates → improved constraints
- DM limits competitive with other targets, reach thermal cross section.
- 4FGL-DR4 search ongoing (Valenciano-Ruano & MASC, in prep.)



[Coronado-Blázquez, MASC+19 – 1906.11896]



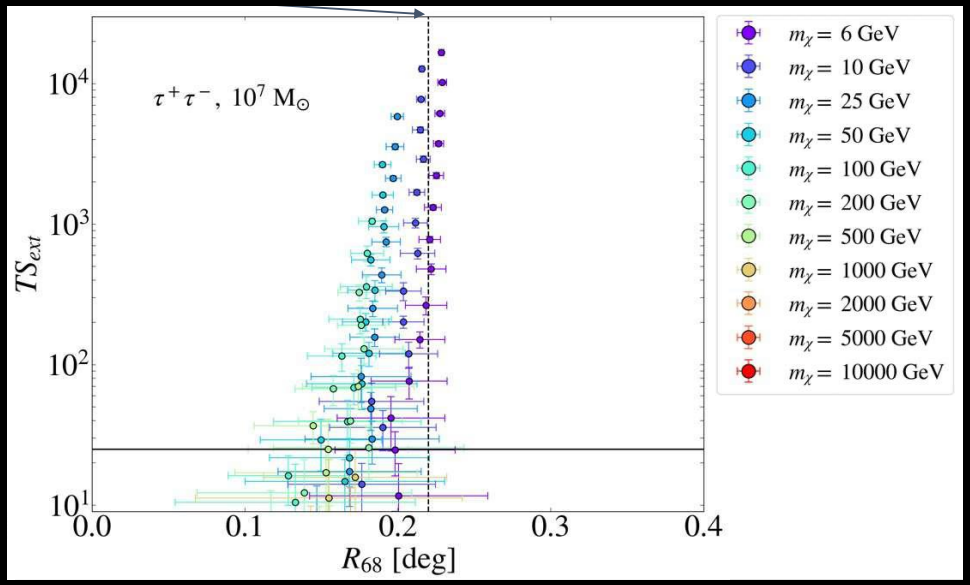
[Coronado-Blázquez, MASC+19b – 1910.14429]

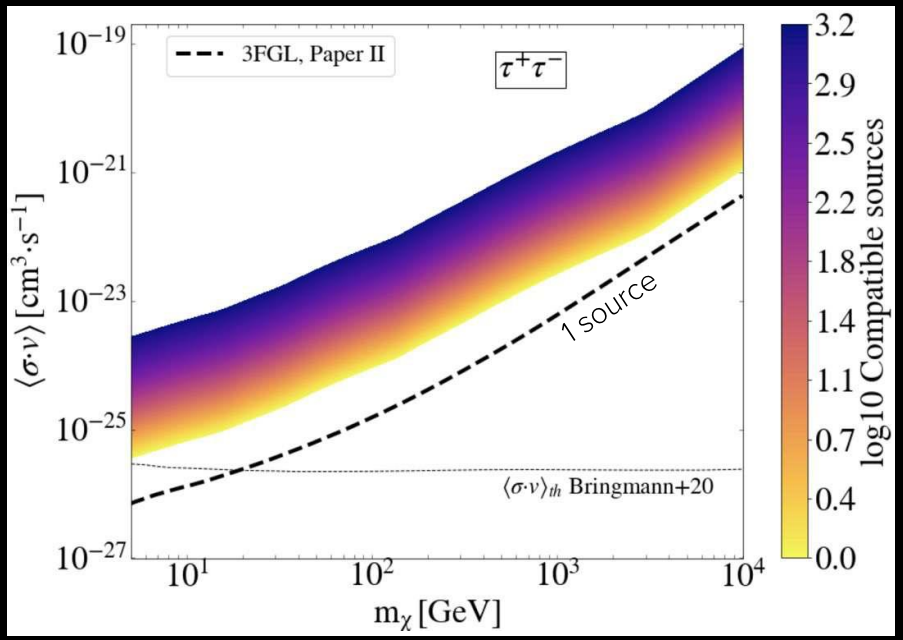
Also: Tasitsiomi&Olinto 02; Pieri+05; Kuhlen+07; Springel+08; Anderson+10; Brun+11; Belikov+12; Ackermann+12; Zechlin+12;+13; Berlin&Hooper 13; Mirabal+16; Hooper+16; Bertoni+16; Schoonenberg+16; Calore+17; Abeysekara+19

Dark satellite search in Fermi-LAT catalogs (II)

[Coronado-Blázquez, MASC, et al. (2023) – arXiv:2204.00267]

- Study of the spatial properties of the expected DM emission and of the implications for Fermi-LAT detectability and DM constraints.
  - Realistic LAT simulations of 'typical', extended subhalos.
  - Careful spatial analysis of previously VIP candidates.
- Typical emission O(0.2 - 0.3 degrees) for the LAT and for the brightest subhalos.
- DM constraints more robust/realistic but weaker than previous ones by a factor 2-3.

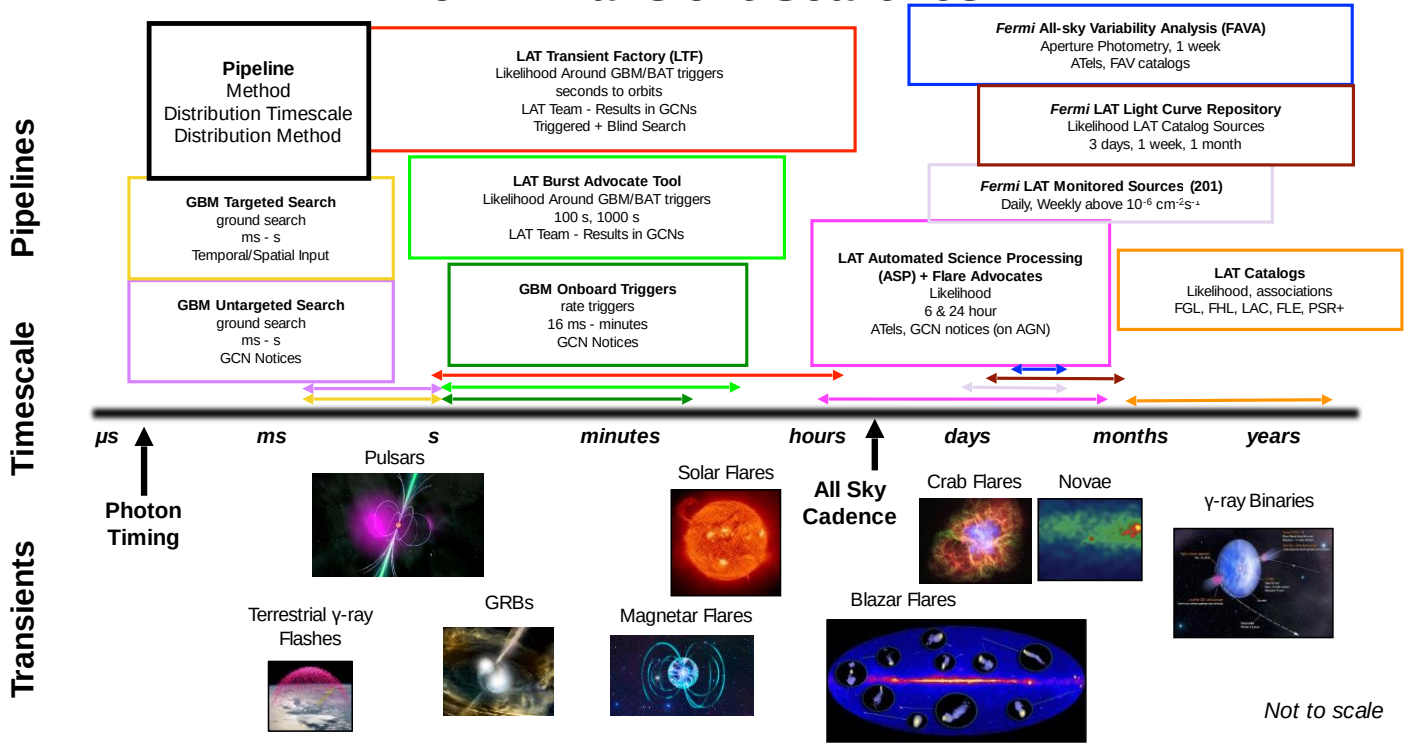




Fermi Science at 16 years

The Era of Time-domain Astrophysics!

Fermi Transient Searches



O4 and LAT: analyses

Implemented Analyses

Fixed Time Interval	• An independent unbinned maximum likelihood analysis is run for each pixel within 90% probability of the GW map in a **fixed time window** of 10 ks after the GW trigger
Adaptive Time Interval	• Similar to the FTI analysis, but the **ATI time window is optimized for each pixel separately** to get the largest exposure closer to the trigger time
LAT Low Energy Events	• LLE data (E < 100 MeV) are extracted for each pixel of the GW map in the LAT FoV at the trigger time and the **significance of the light curves** is estimated respect to the background
PGWAVE	• PGWAVE is run over the count map to **discover candidate sources**, followed by a dedicated likelihood analysis if any of these are within the 90% probability of the GW map

- Leer algo más acerca de casos concretos de ciencia que discuto
  - Assessment on the 10 MeV line for the BOAT
  - Niccoló's presentation
  - Crocker+22
  - IFT based approaches