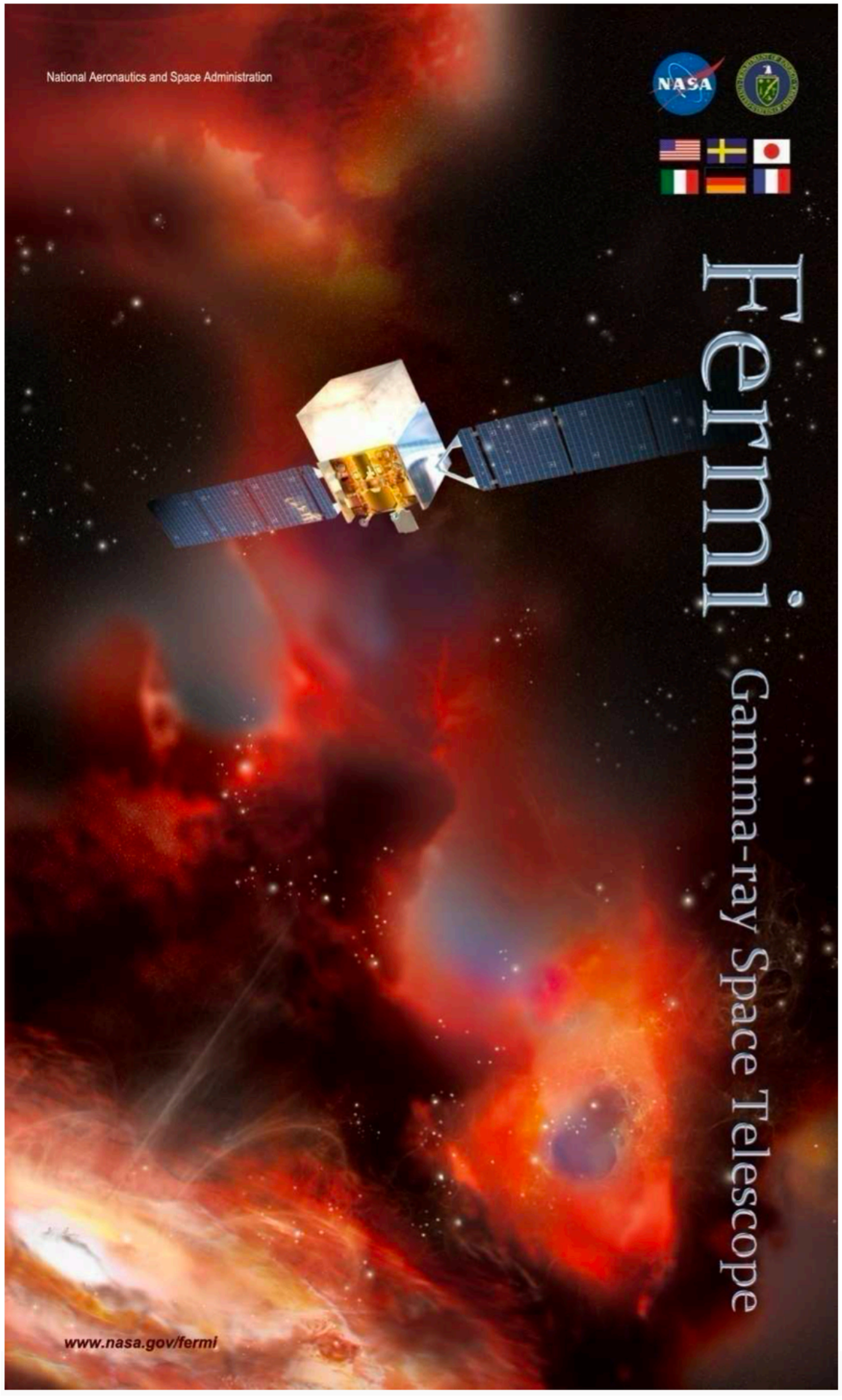


Fermi
Gamma-ray
Space Telescope

Fermi-LAT and its role in the era of time domain astrophysics

Deirdre HORAN on behalf of the *Fermi*-LAT Collaboration

3rd Astro-COLIBRI multi-messenger astrophysics workshop,
Institut Pascal, Orsay
16 - 20 September 2024

Outline

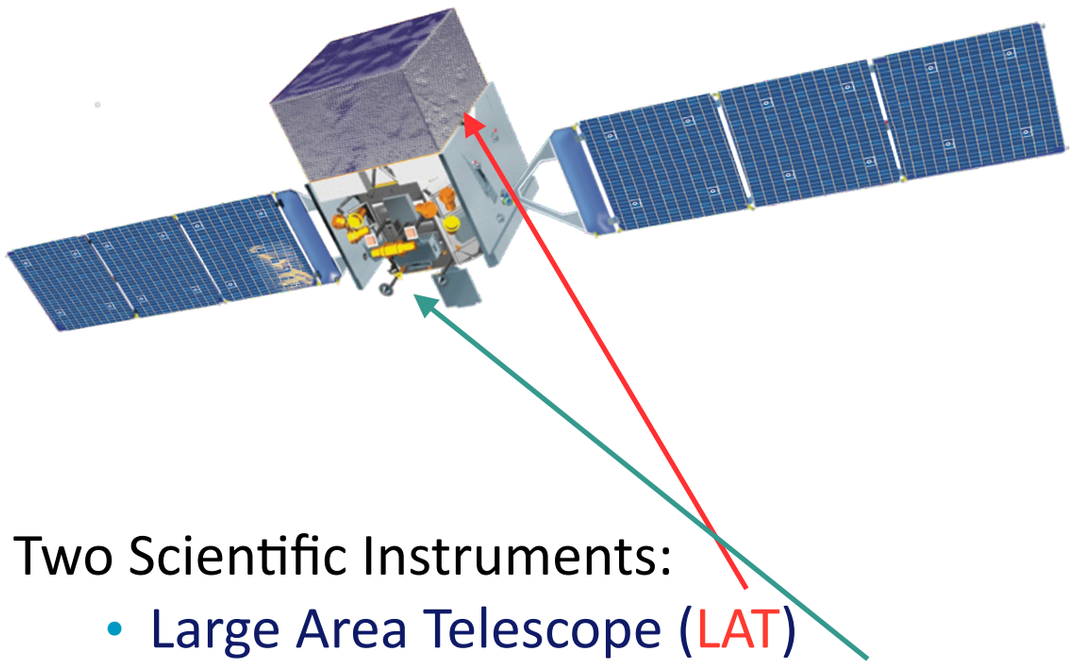
- Reminder/introduction - *Fermi*-LAT and its capabilities for time-domain astro
- Flare advocate and burst advocate shifts
- Monitored source list
- Lightcurve repository
- Gravitational wave follow-up

Fermi Mission Overview

The *Fermi* Space Telescope is a "Probe class" mission to study the extreme high-energy Universe

Launch:

- 11 June 2008, Cape Canaveral, Florida
- 16+ years of science!



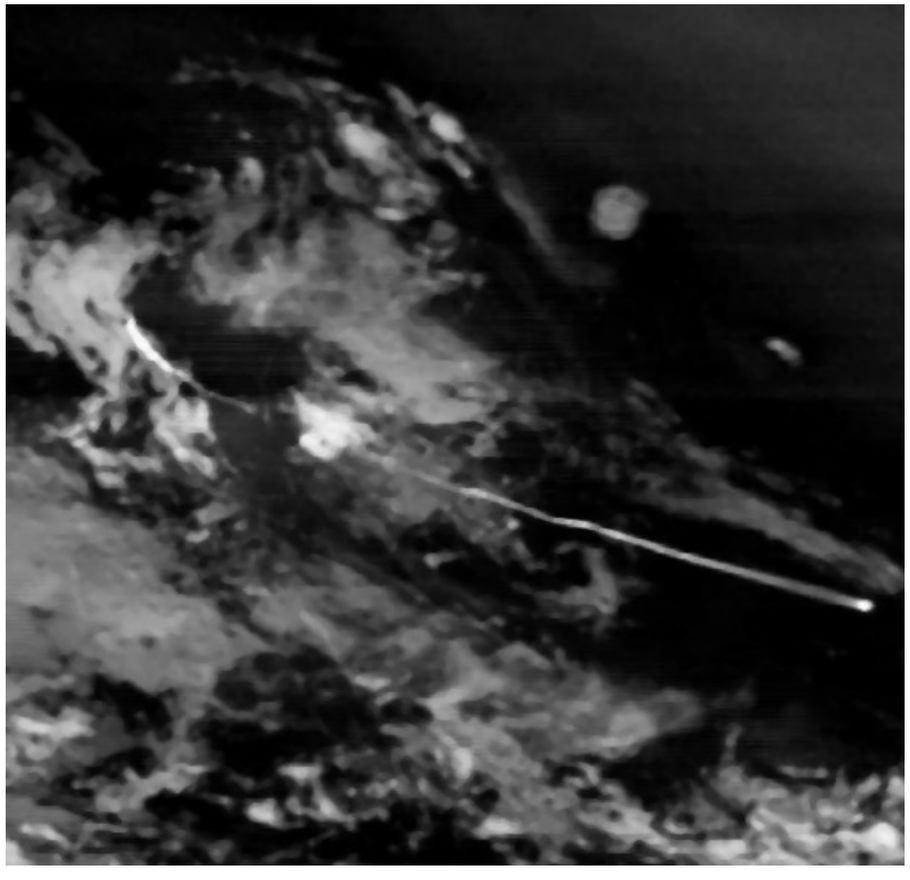
Two Scientific Instruments:

- Large Area Telescope (LAT)
- Gamma-ray Burst Monitor (GBM)

Energy range:

- 8 keV to above 40 MeV (GBM)
- 20 MeV to above 300 GeV (LAT)

NASA

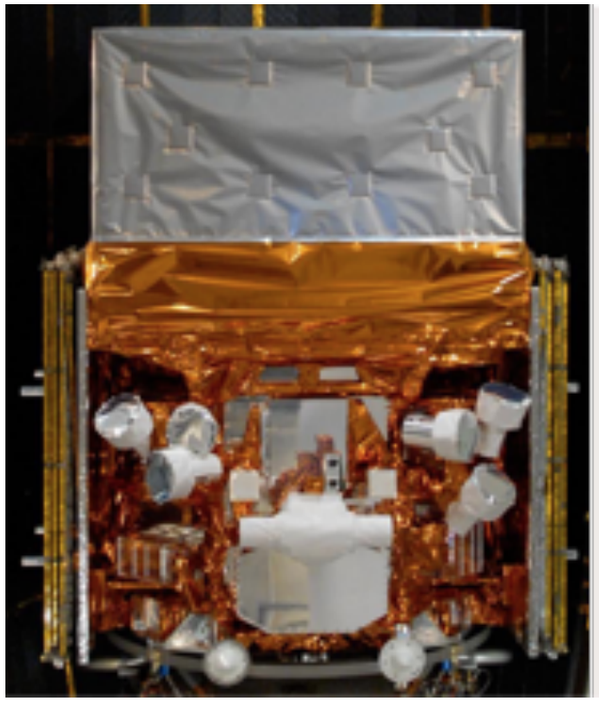


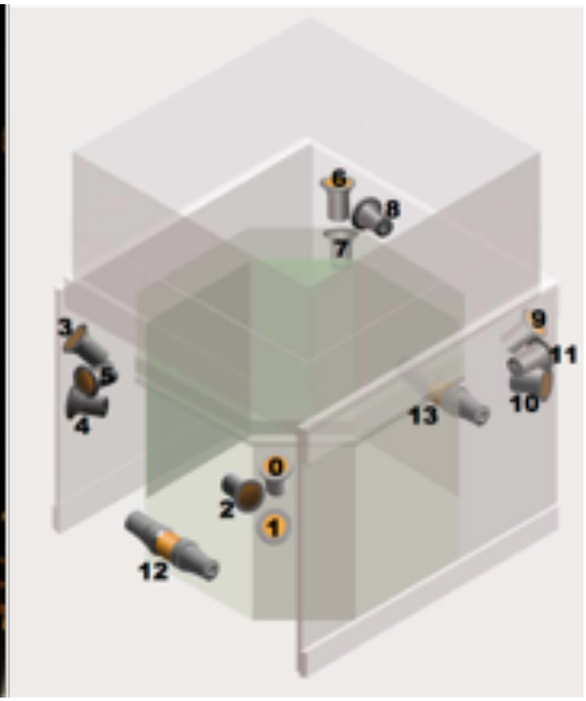
U.S. Air Force/Space Command/Space-Based Infrared Systems Wing

Fermi Mission Overview

Gamma-ray Burst Monitor (GBM):

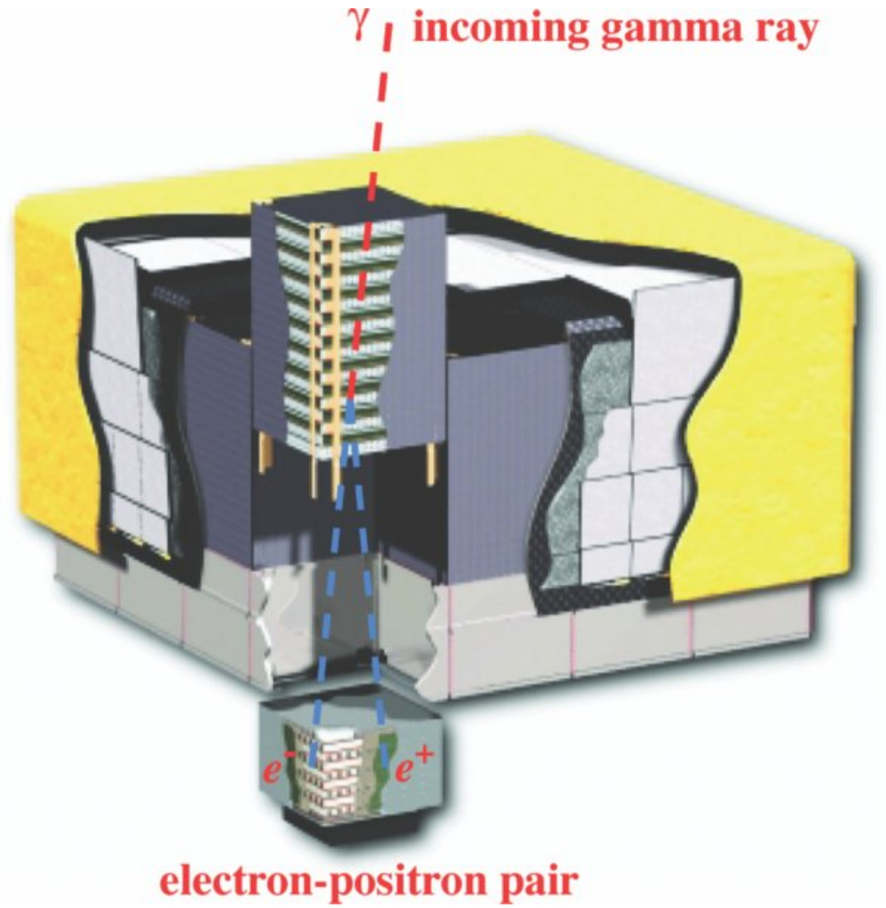
- 8 keV to 40 MeV
- Views unocculted sky
- 12 (four sets of 3) NaI detectors - up to 1 MeV
- 2 BGO detectors for higher energy coverage





Large Area Telescope (LAT):

- 20 MeV to more than 300 GeV
- Views 20% of the sky at any instant
- Entire sky in ~3 hrs
- Segmented anti-coincidence shield + silicon tracker + calorimeter



Guest Investigator Program

Topical Evolution of the Guest Investigator Program ...

The Fermi Guest Investigator Program provides funding for:

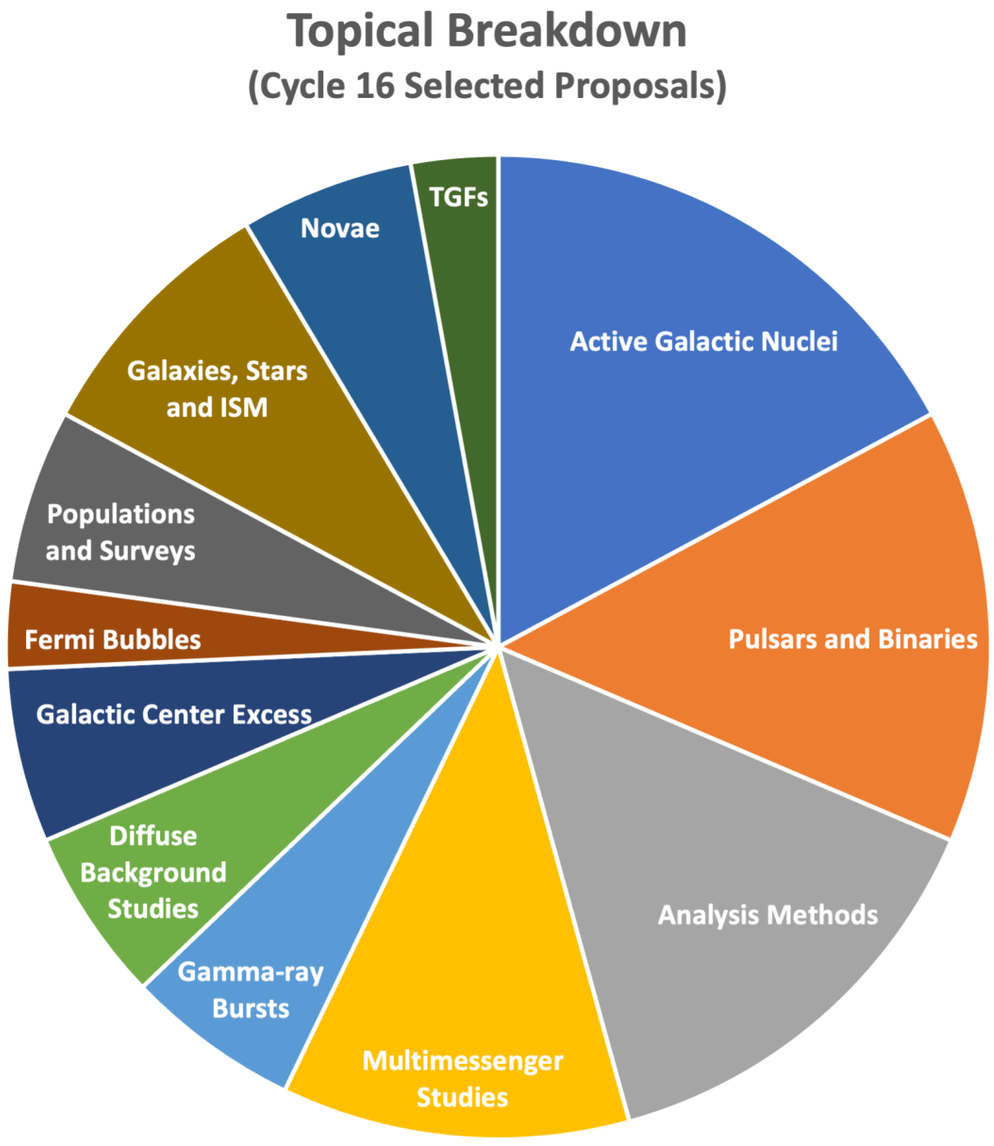
- Analysis of LAT and GBM data
- Supporting observations in other wavebands
- Joint programs include NRAO, NOIRLab, VERITAS, Integral, and TESS
- Complementary theoretical studies
- Analysis methods

Awarded topics have evolved throughout the mission

- growing emphasis on multimessenger studies and analysis methods

New trend for Cycle 16:

- 11% of proposals incorporate machine learning



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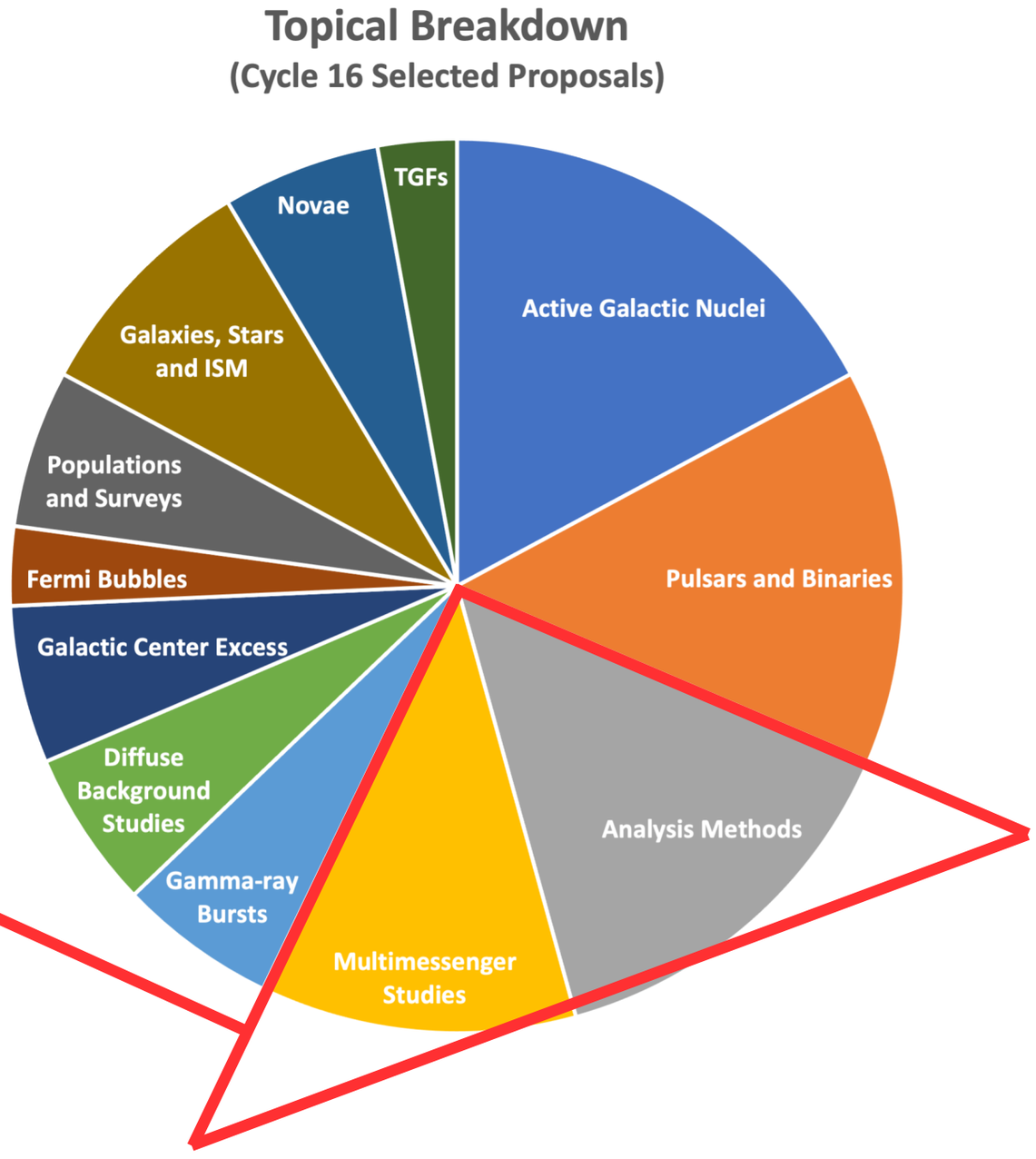

Fermi at 16 !

Fermi turned 16 on the 11th of June !

- Spacecraft and instrument **performance** is **excellent** at 16 years!
  - No consumables or rapid degradation of spacecraft of instrument components
  - One solar array drive no longer rotates; modified survey strategy maintains power margin while avoiding loss of observational efficiency
  - Gradual degradation in instrument components is compensated by calibration

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- Orbit outlook:
  - Lifetime of orbit extends into the **mid-2030s**
  - The *Fermi* mission team is preparing for a series of maneuvers to **raise** the observatory **orbit altitude** following the completion of O4
  - Studies underway to raise the observatory altitude to a **circular orbit at ~563 km**
    - a series of 5 maneuvers: 3 for calibration and circularisation and 2 longer burns to raise the altitude
  - The orbit adjustment 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
    - Have not had to execute a maneuver since 2012, but planning impacts operations even when the maneuver is waived

Fermi Science at 16 years

The era of time-domain astrophysics!

- Unique and highly dynamic **energy range**
  - 8 keV - >300 GeV provides triggers and observations for a wide variety of energetic astrophysical events

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  - Real-time or near real-time observation data of events anywhere in the sky
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  - Catalogs + public data products provide insight and context for multiwavelength and multimessenger studies
  - Team-operated science pipelines generate added alerts and information

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  - Team-operated science pipelines generate added alerts and information
- **Partnerships** among science support center, instrument teams, MW/MM observational facilities and community enable innovations in analysis and tools

Fermi Science at 16 years

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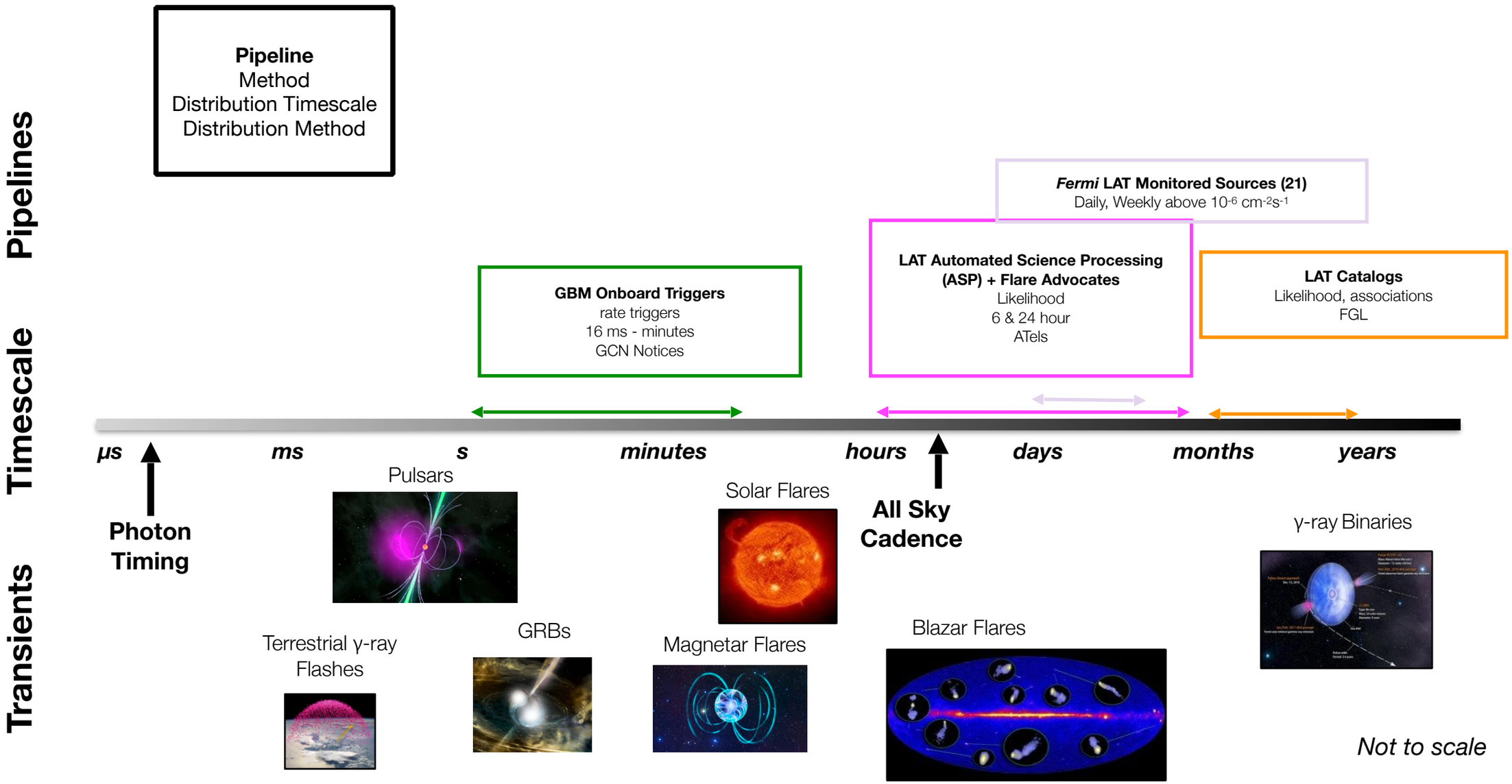
Fermi Transient Searches 2008-2009



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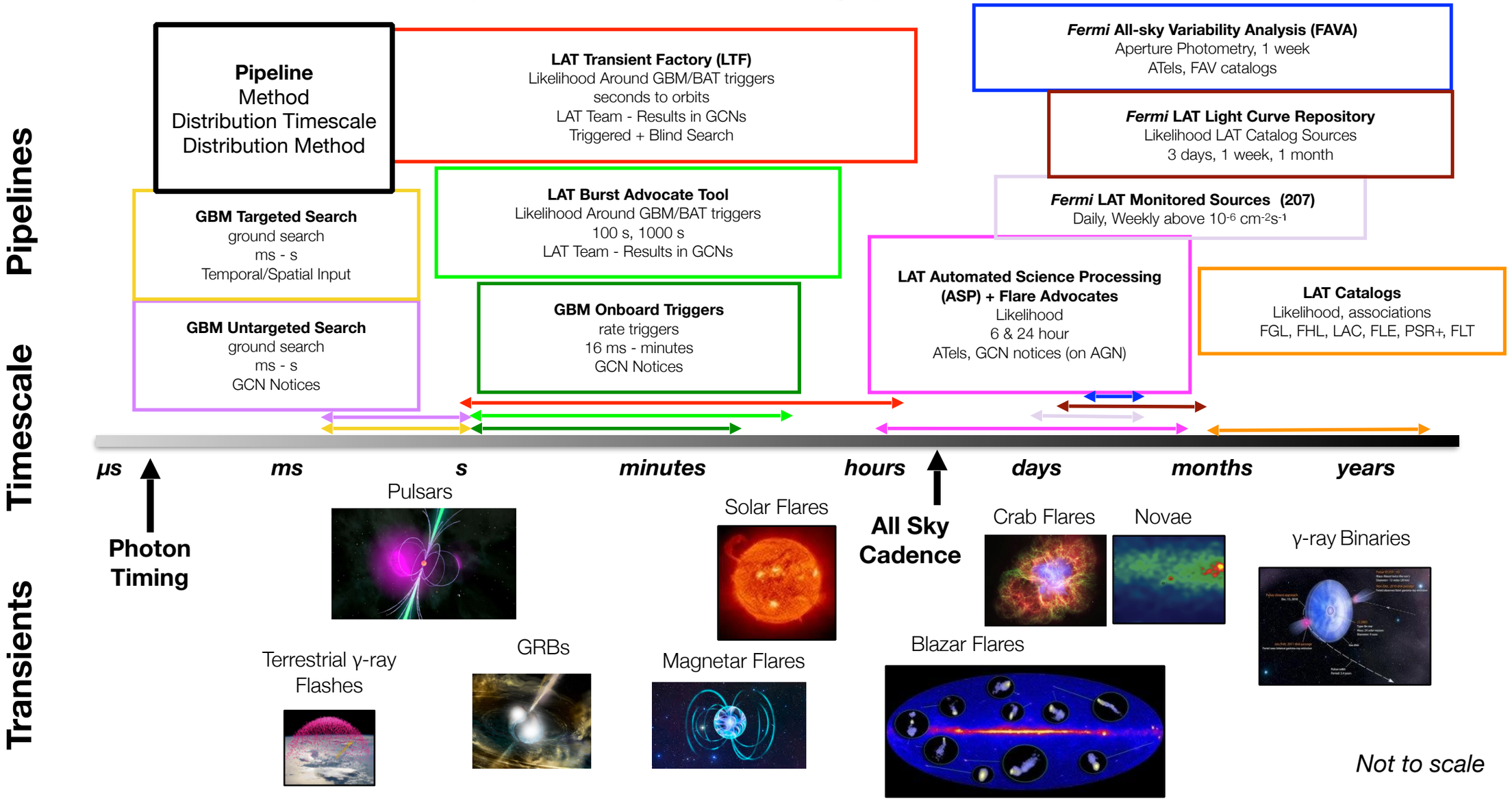


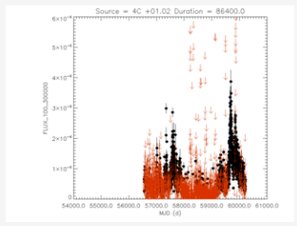
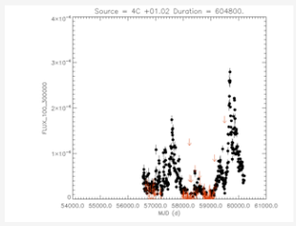
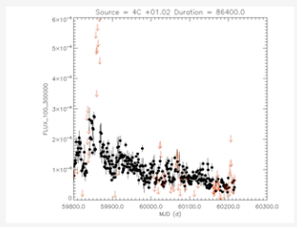
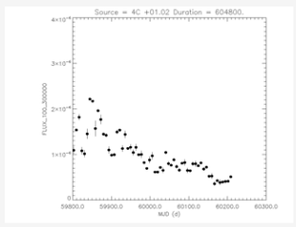
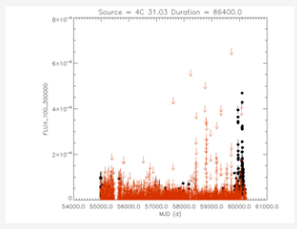
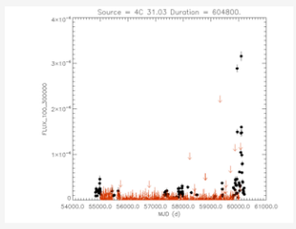
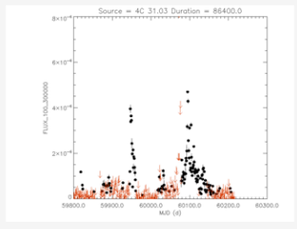
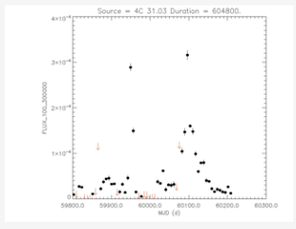
Flare and Burst Advocates

- Flare Advocates:
  - search on 24-hour and 6-hour timescales for flaring activity / new sources
  - alert the multiwavelength community about gamma-ray transients through ATels or GCN
  - trigger MWL observations (ToOs / alert the VHE community)
  - follow up on neutrino alerts
  - follow up on novae

- Burst Advocates:
  - perform dedicated follow-up analysis on any GRB within the FoV of LAT
  - prepare GCN circular

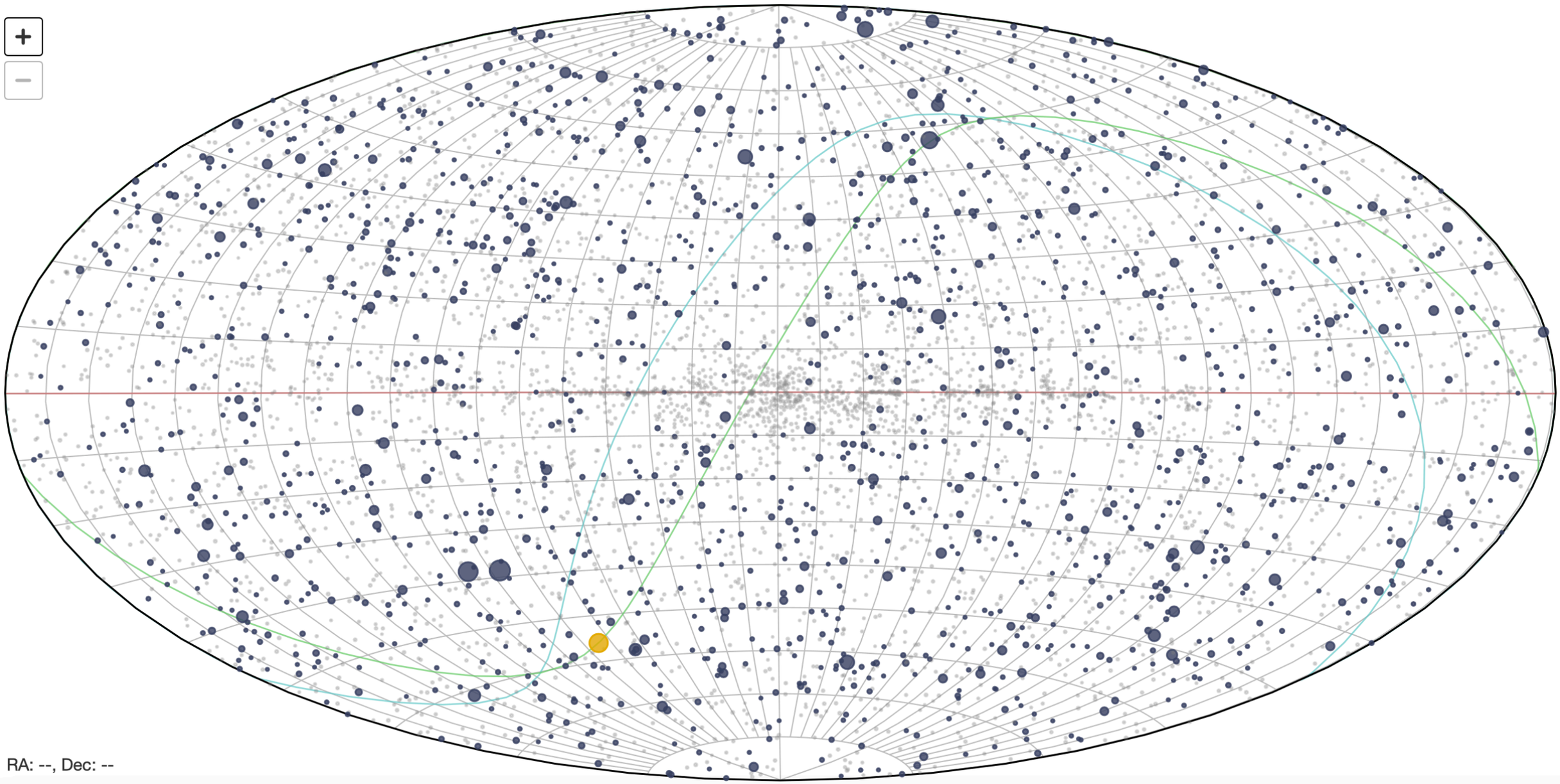
Monitored sources

- The *Fermi* LAT table of monitored sources provides daily and weekly fluxes for sources of interest as described here
- List is updated with new sources regularly (when source exceeds daily averaged flux of 1e-6)
- Started as a list of **25** - now, there are **207**
- Daily and Weekly fluxes for the monitored source list are sent to the FSSC each day

4C +01.02 (RA = 17.1620, Dec = 1.58300) • Daily Light Curve • Daily Light Curve (1yr) • Daily Light Curve Fits File • Weekly Light Curve • Weekly Light Curve (1yr) • Weekly Light Curve Fits File		
	 (most recent 1-year data segment)	 (most recent 1-year data segment)
4C 31.03 (RA = 18.2100, Dec = 32.1380) • Daily Light Curve • Daily Light Curve (1yr) • Daily Light Curve Fits File • Weekly Light Curve • Weekly Light Curve (1yr) • Weekly Light Curve Fits File		
	 (most recent 1-year data segment)	 (most recent 1-year data segment)

Fermi-LAT Lightcurve repository

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



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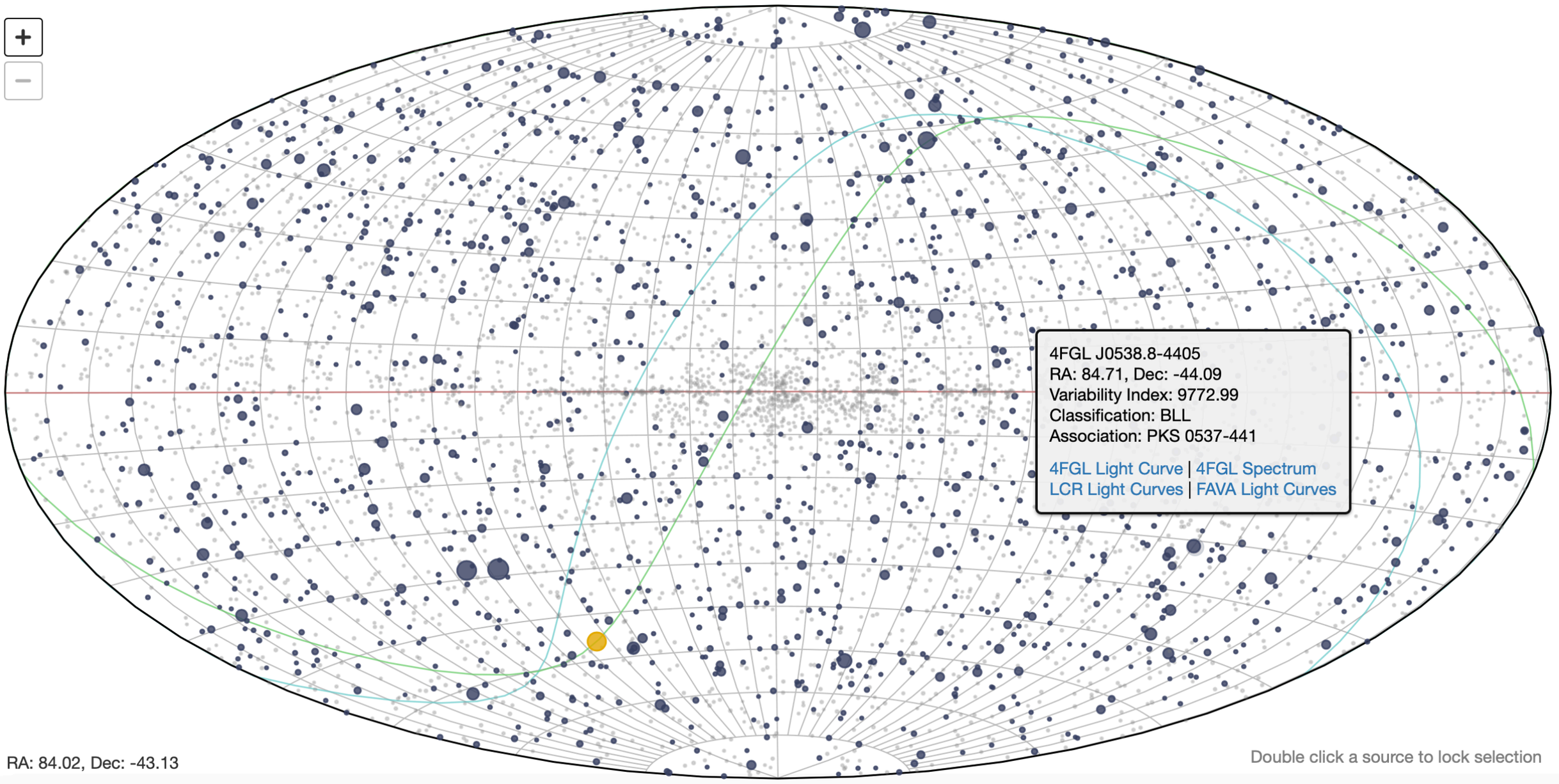

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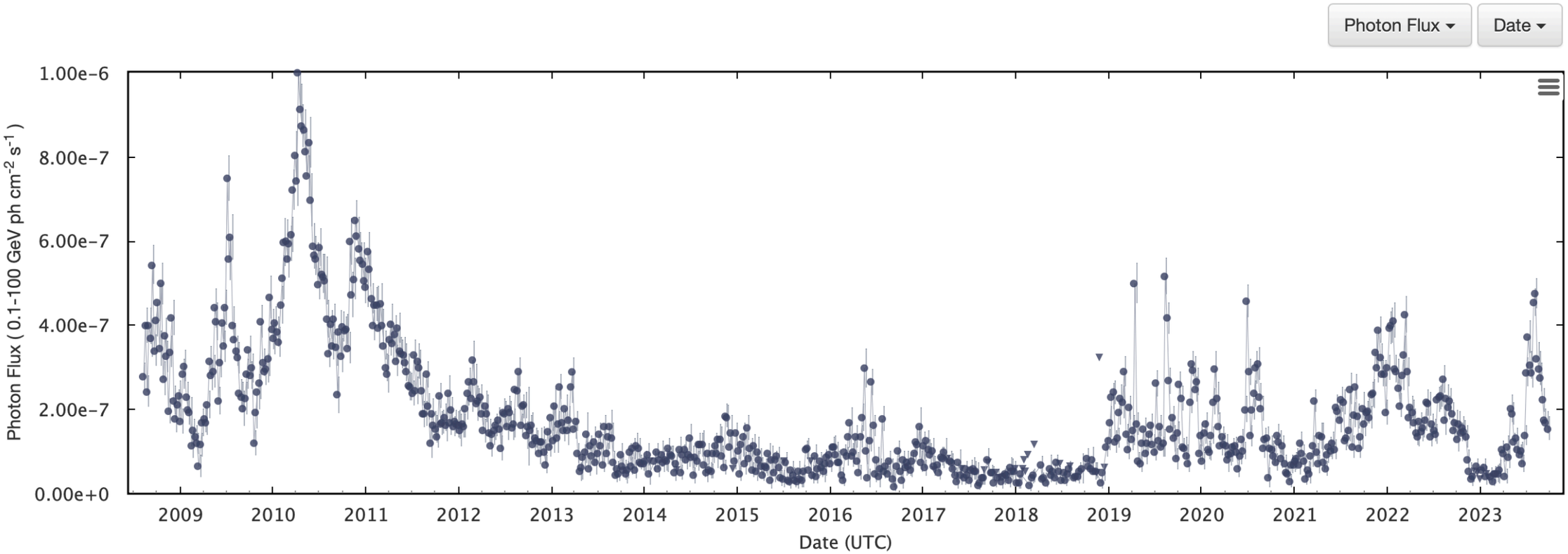

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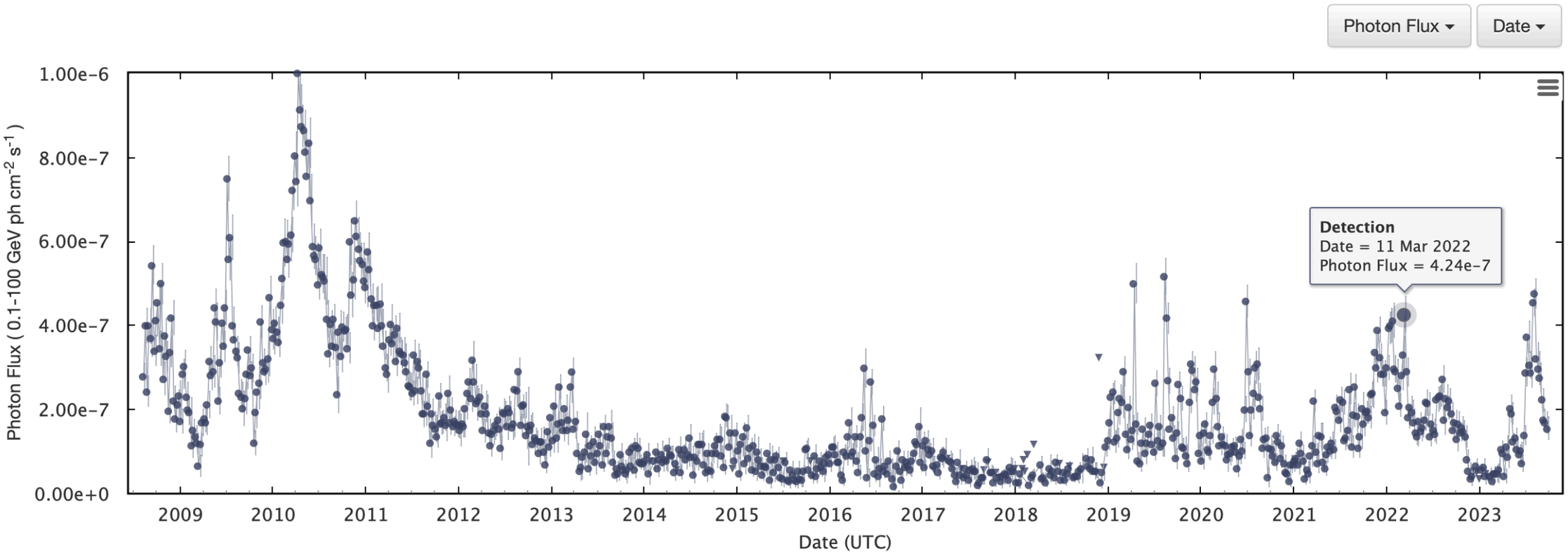

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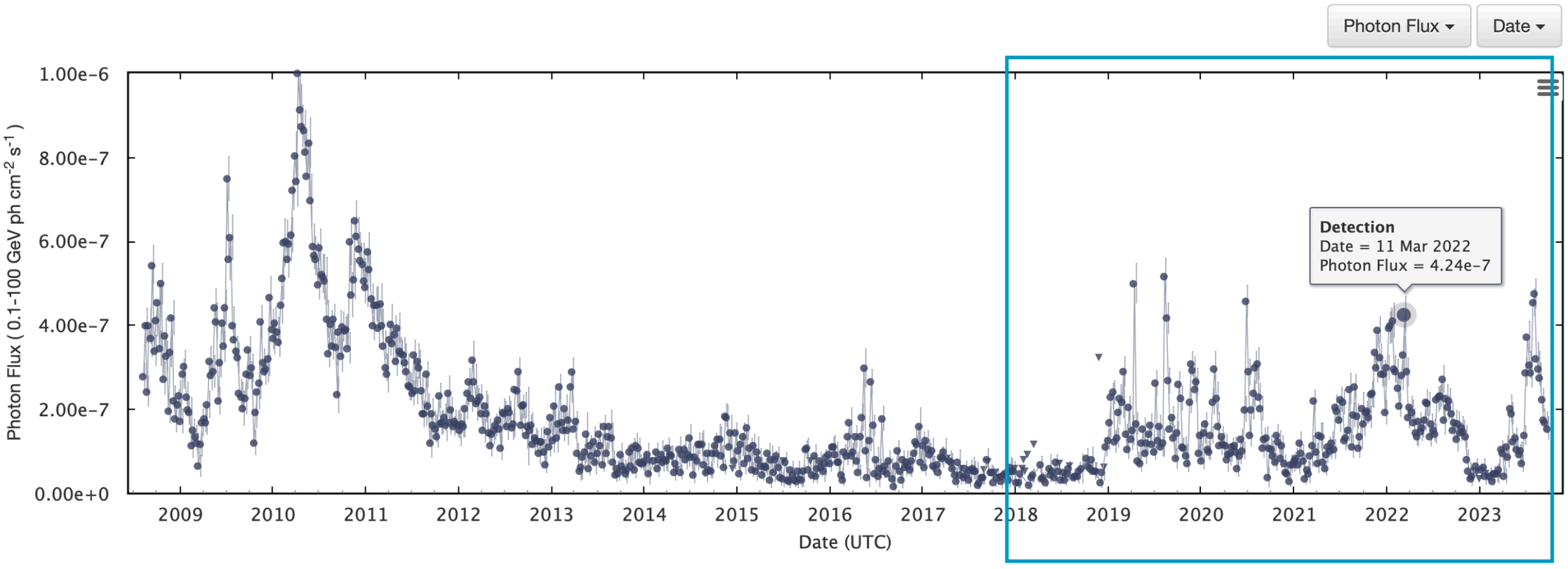

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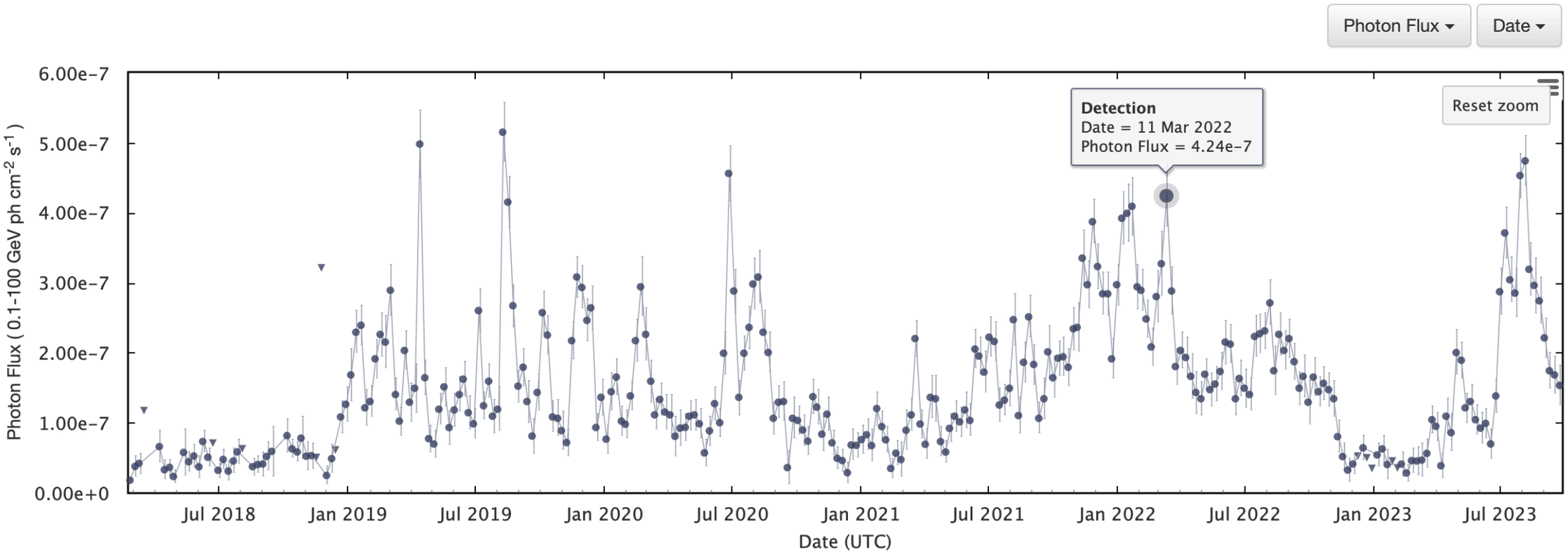

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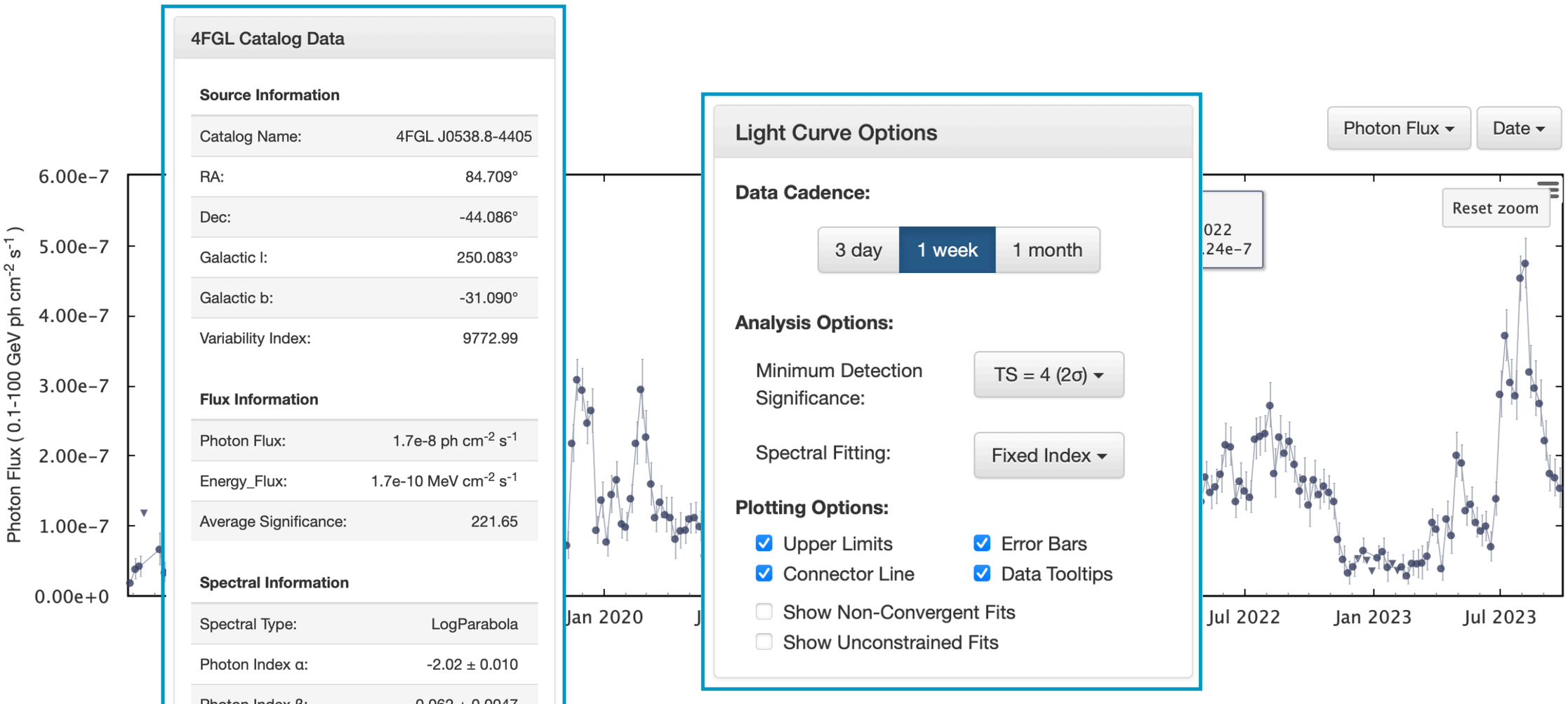
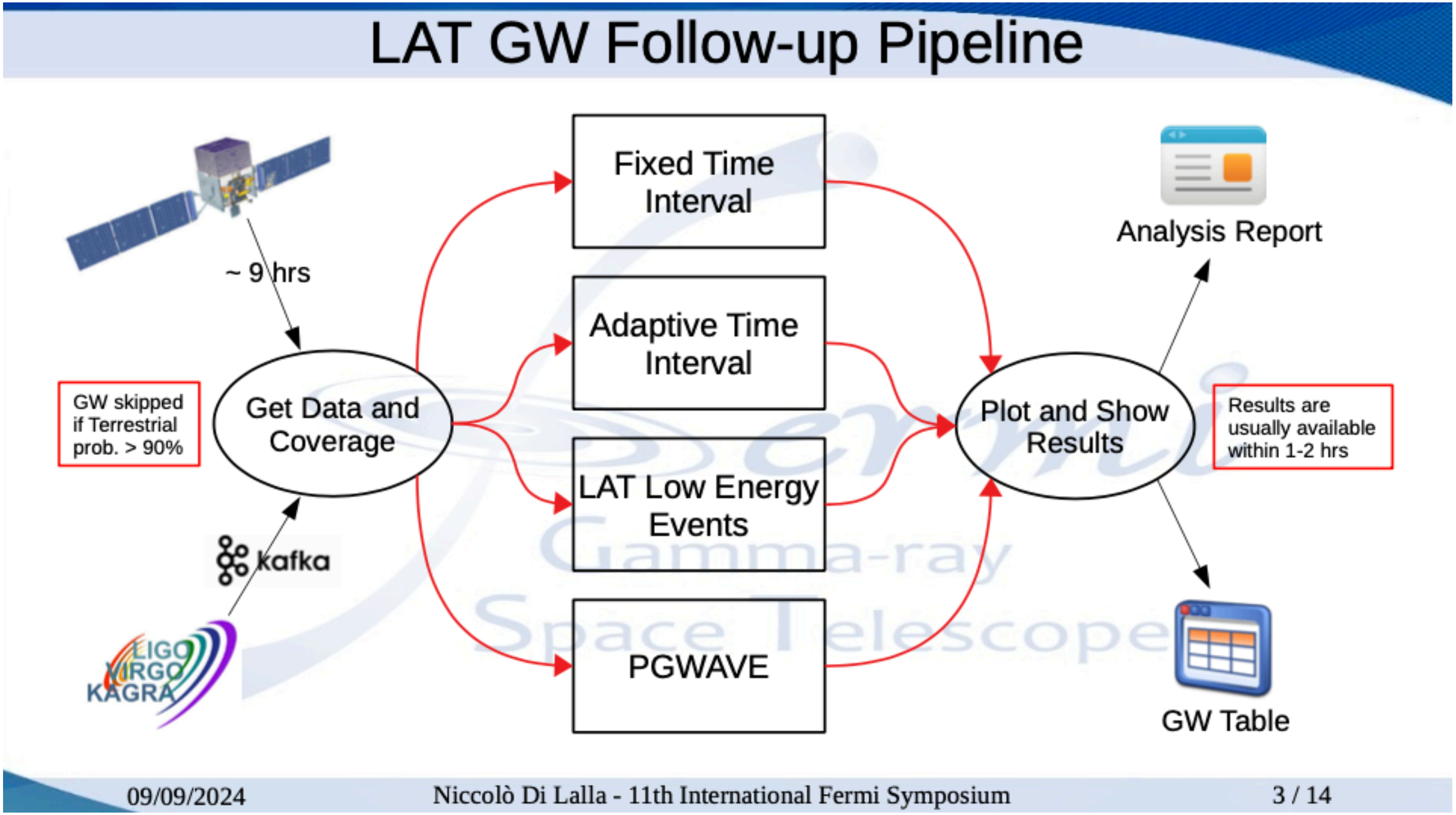


O4 and *Fermi* LAT

- From Nicollò Di Lalla's presentation last week at the Fermi Symposium:



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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

09/09/2024 Niccolò Di Lalla - 11th International Fermi Symposium 4 / 14

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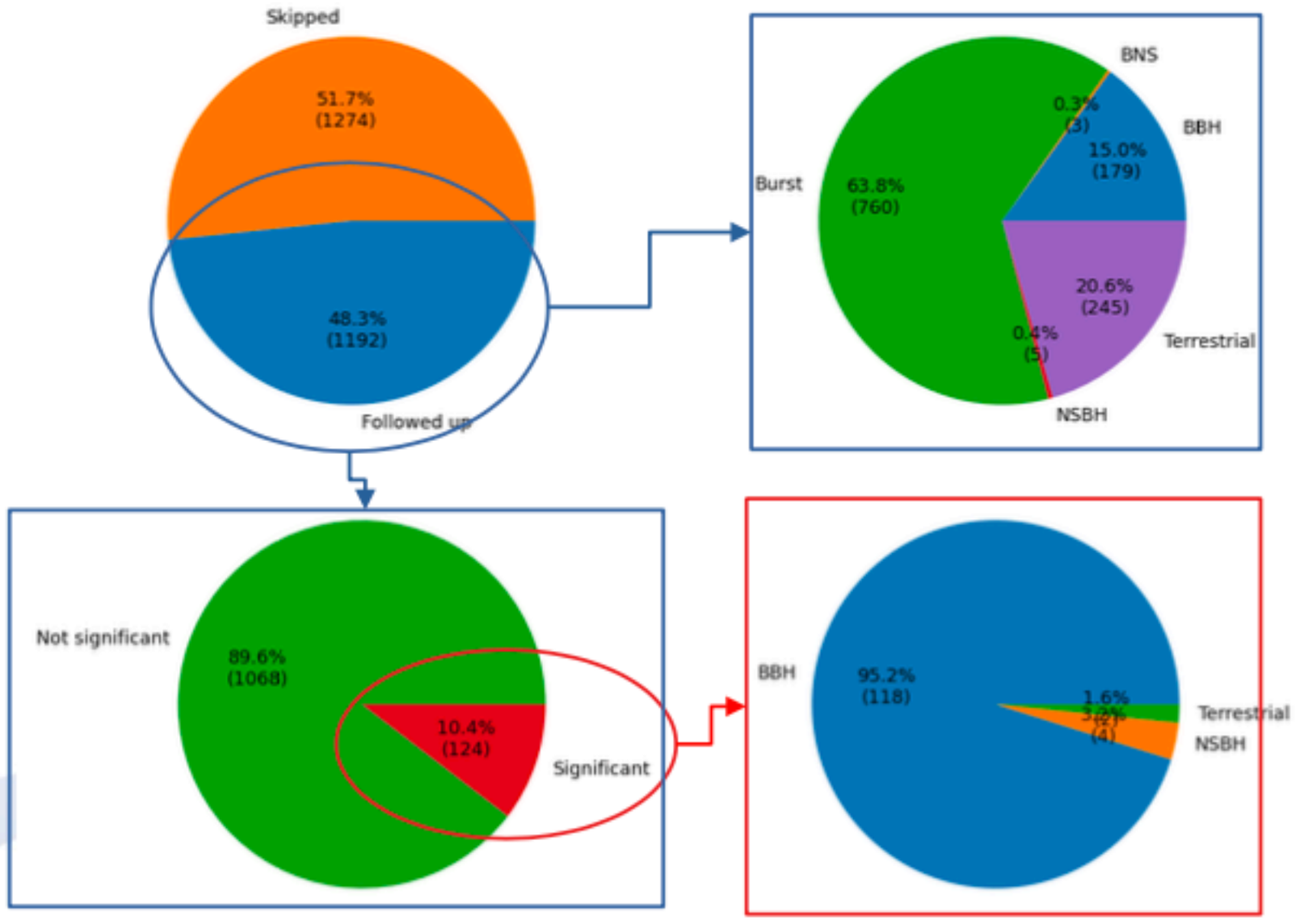
O4a+O4b (so far) in Numbers



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O4 and *Fermi* LAT

- *Fermi*-LAT Gravitational Waves Table! http://fermigrb.stanford.edu/GWTable
- Displays results of LAT follow-up analysis pipeline searching for EM counterparts to GWs
- 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

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O3 | O4

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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	6.9e-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	6.2e-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)

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Trigger Name*	Date*	Time (UTC)*	GraceDB*	FAR (Hz)*	Highest Probability*	Has NS? (%)*	Has Remnant? (%)*	Has MassGap? (%)*	Inst. Coverage (%)	FTI TS ma	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	6.9e-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	6.2e-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 for the Adaptive Time Integral analysis

O4 and *Fermi* LAT

- *Fermi*-LAT Gravitational Waves Table! http://fermigrb.stanford.edu/GWTable
- Displays results of LAT follow-up analysis pipeline searching for EM counterparts to GWs
- 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 repo
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)
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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)
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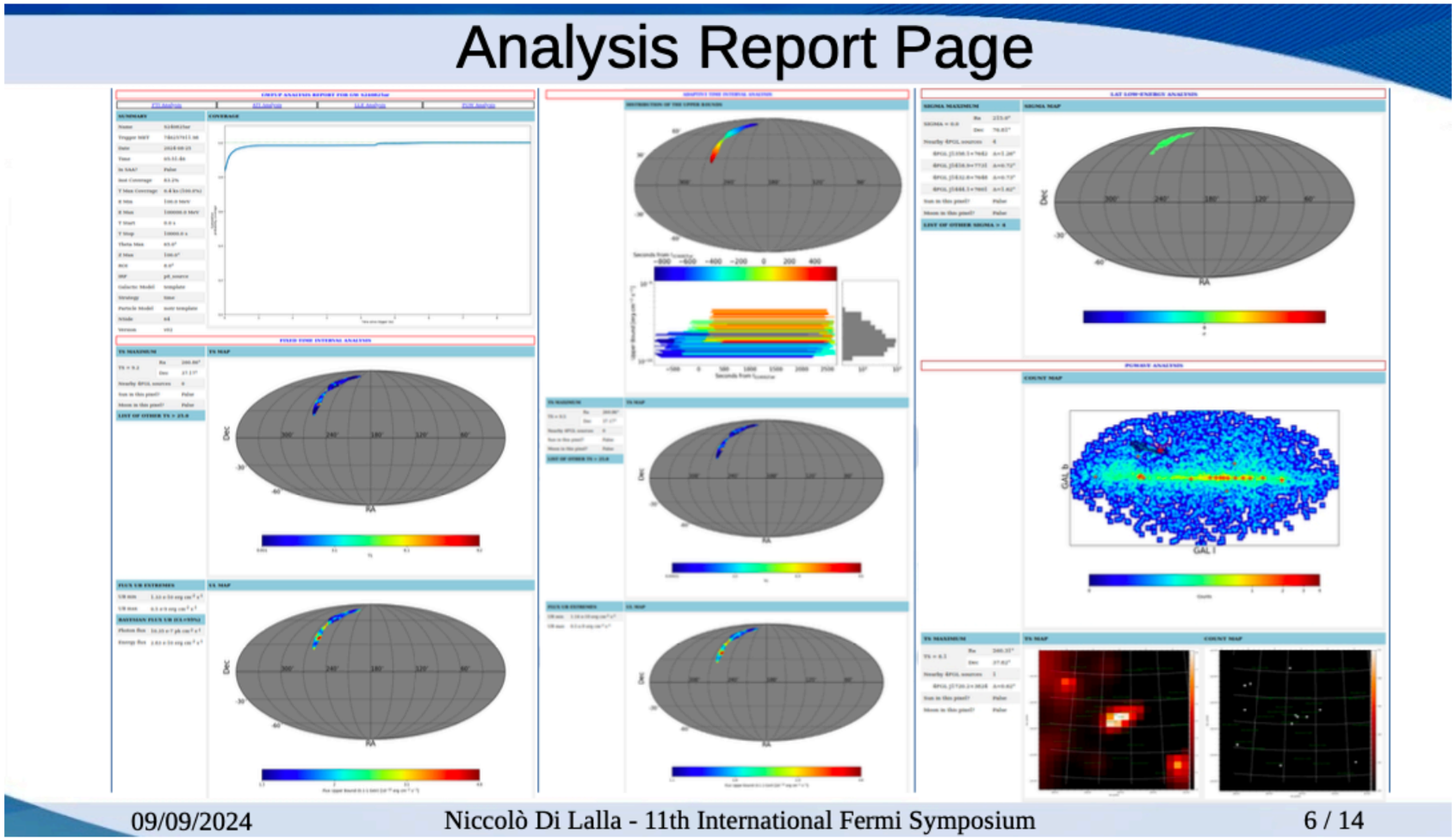
Click on "Link" to go to the analysis report for each event

Analysis report page:

- Automatically generated results for:
  - Fixed Time Interval analysis
  - Adaptive Time Interval analysis
  - PG Wave analysis

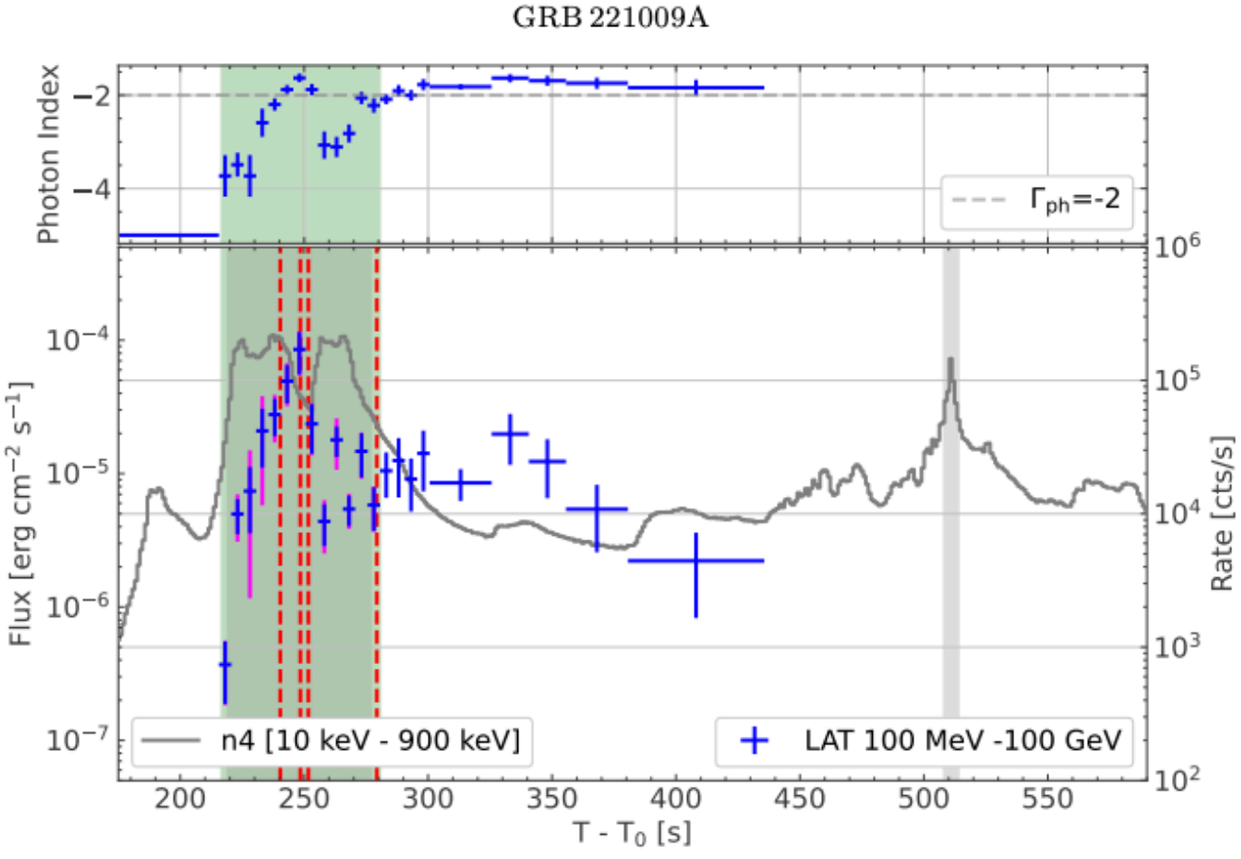
http://fermigrb.stanford.edu/GWTable



from Niccolò Di Lalla's talk at the Fermi Symposium

GRB 221009A - the "BOAT"

- Caveats about LAT data here



arXiv:2409.04580

Draft version September 10, 2024
Typeset using LaTeX **preprint** style in AASTeX631

GRB 221009A: the B.O.A.T Burst that Shines in Gamma Rays

M. Axelsson [1,2] M. Ajello [3] M. Arimoto [4] L. Baldini [5] J. Ballet [6]
M. G. Baring [7] C. Bartolini [8,9] D. Bastieri [10,11,12] J. Becerra Gonzalez [13]
R. Bellazzini [14] B. Berenji [15] E. Bissaldi [16,8,*] R. D. Blandford [17] R. Bonino [18,19]
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A. Dinesh [34] R. Di Tria [16] L. Di Venere [8] A. Domínguez [34] S. J. Fegan [20]
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F. Giacchino [26,27] N. Giglietto [16,8] M. Giliberti [8,16] R. Gill [40,41] F. Giordano [16,8]
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H. Tajima [72,73] D. Tak [74] J. B. Thayer [17] D. F. Torres [75,76] J. Valverde [56,22]
G. Zaharijas [77]

(Fermi LAT collaboration)

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W. H. Cleveland [81] S. Dalessi [82,83] C. de Barra [84] M. Gibby [85] M. M. Giles [85]
R. Hamburg [86] B. A. Hristov [87] C. M. Hui [88] D. Kocevski [88] B. Mailyan [89]
C. Malacaria [90] S. McBreen [84] S. Poolakkil [91,79] O.J. Roberts [81]
L. Scotton [78,79] P. Veres [91,79] A. von Kienlin [92] C. A. Wilson-Hodge [88]
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[5] *Università di Pisa and Istituto Nazionale di Fisica Nucleare, Sezione di Pisa I-56127 Pisa, Italy*
[6] *Université Paris-Saclay, Université Paris Cité, CEA, CNRS, AIM, F-91191 Gif-sur-Yvette Cedex, France*

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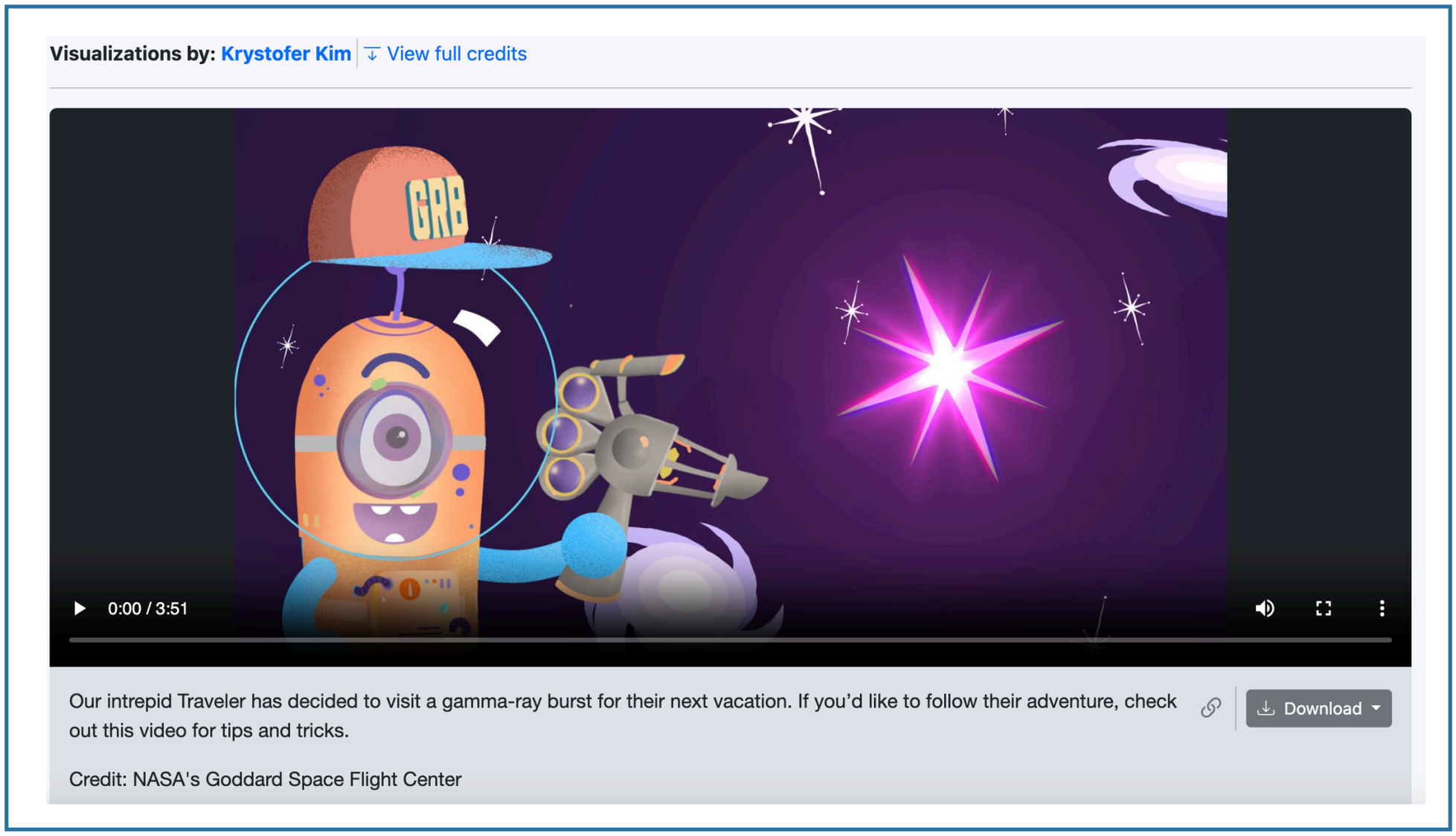
GRB 221009A

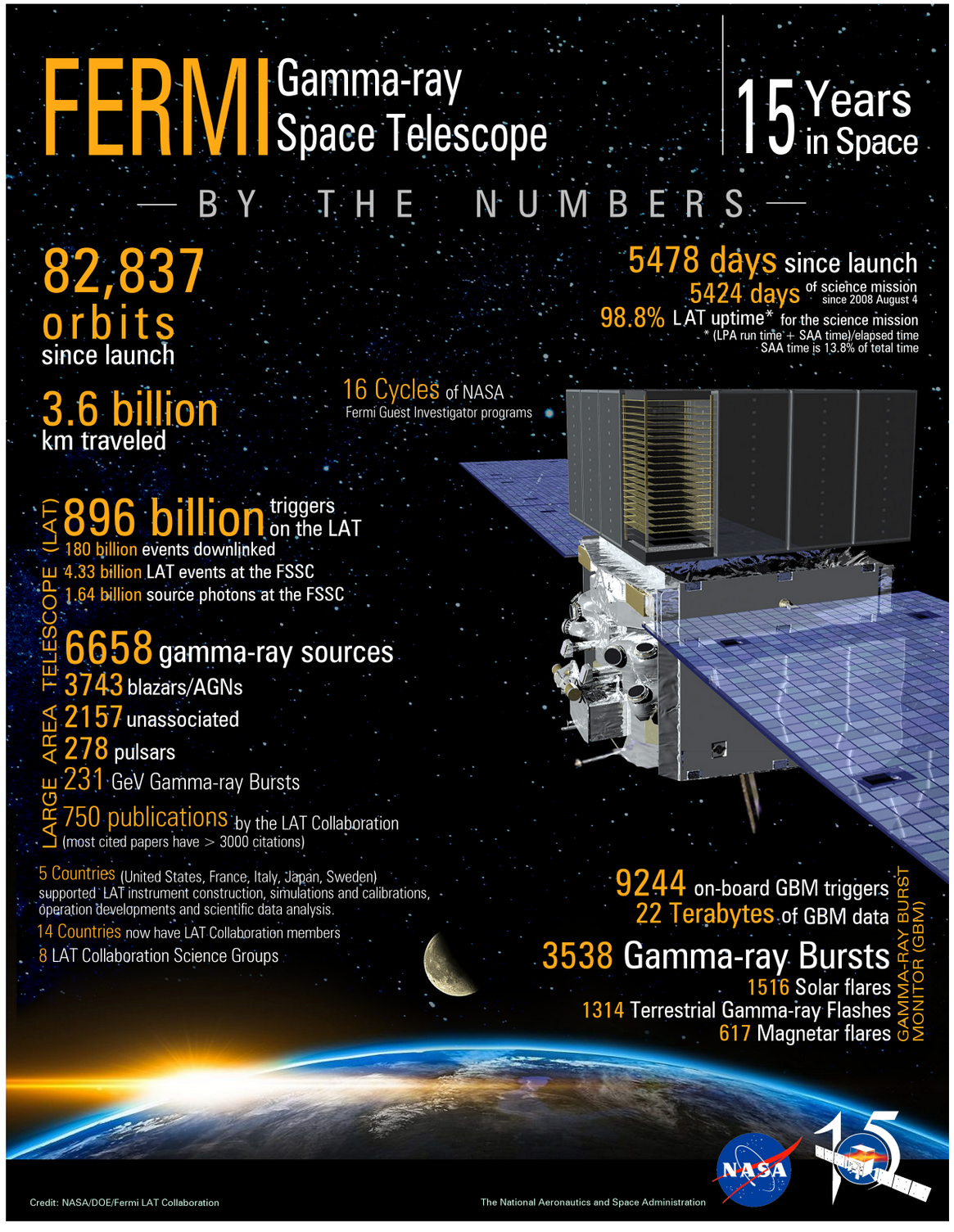
A "guide" to visiting a gamma-ray burst!! Yes - really :-)

- Fermi is a current contributor to 50 years of breakthrough observations of gamma- ray bursts. For this milestone NASA created a “guide” to visiting a gamma-ray burst:
  - https://svs.gsfc.nasa.gov/14355

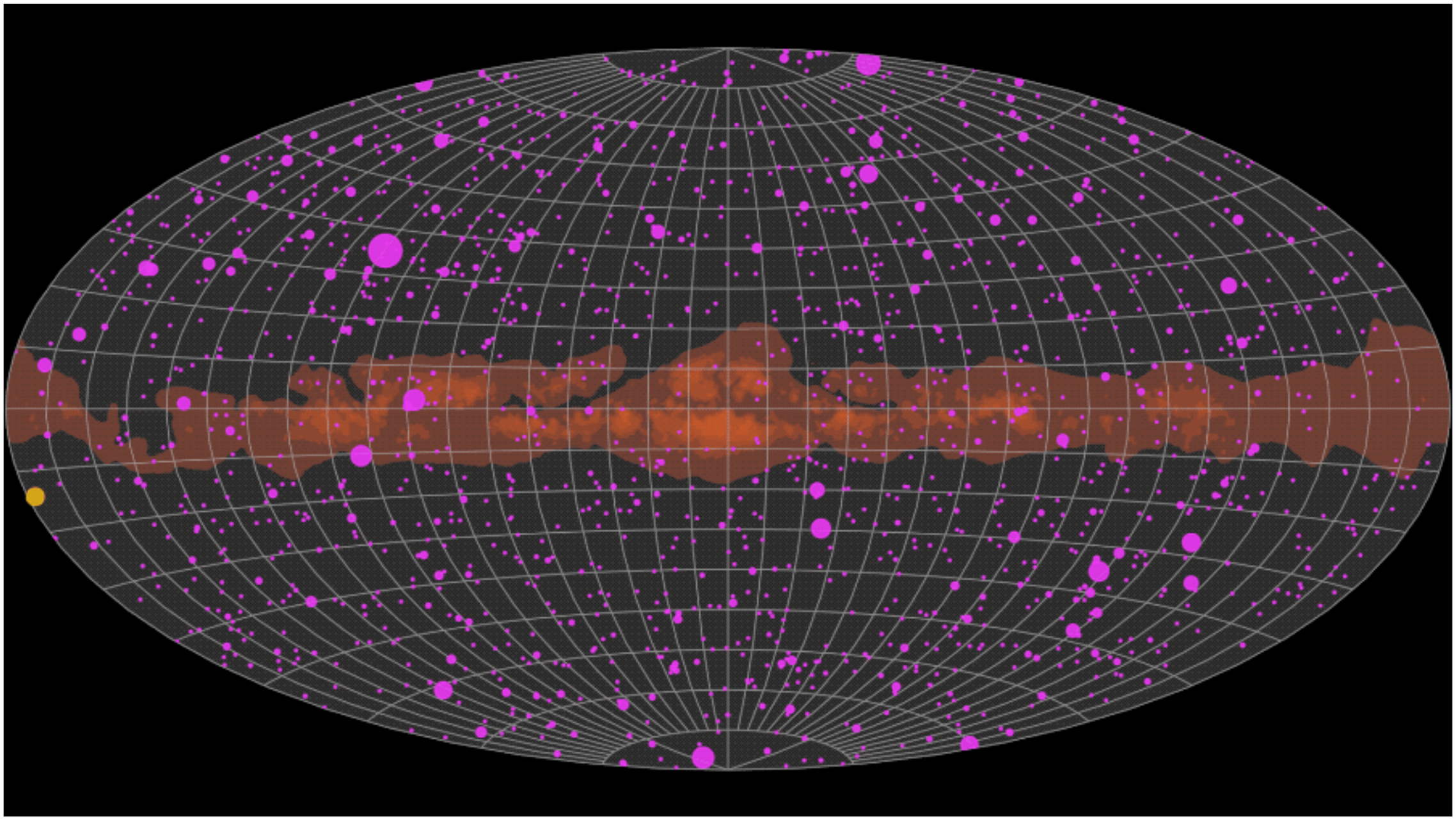


Outlook

- A very **vibrant** collaboration and community !
  - strong engagement with the community
- Era of time-domain multi-messenger astronomy
  - *Fermi*-LAT has big role to play
- Constantly improving
  - in response to needs of community
- Lots more science - performance excellent
  - plan to operate *Fermi* while the observatory remains functional and while the science productivity continues to receive favourable reviews !



Fermi-LAT Lightcurve repository



https://www.nasa.gov/feature/goddard/2023/nasa-s-fermi-captures-dynamic-gamma-ray-sky-in-new-animation

Credit: "NASA’s Marshall Space Flight Center/Daniel Kocevski"

Press release: 15 March 2023

4FGL - DR4

LAT **14-year** Source Catalog (4FGL-DR4) - Ballet et al. (2023), arXiv 2307.12546

Refereed paper: *Fermi*-LAT Collaboration ApJS 260, 53 (2022)

- All of the data are available here at the FSSC
- **7195 entries** in the catalogue (7194 sources since Crab Nebula has 2 entries)

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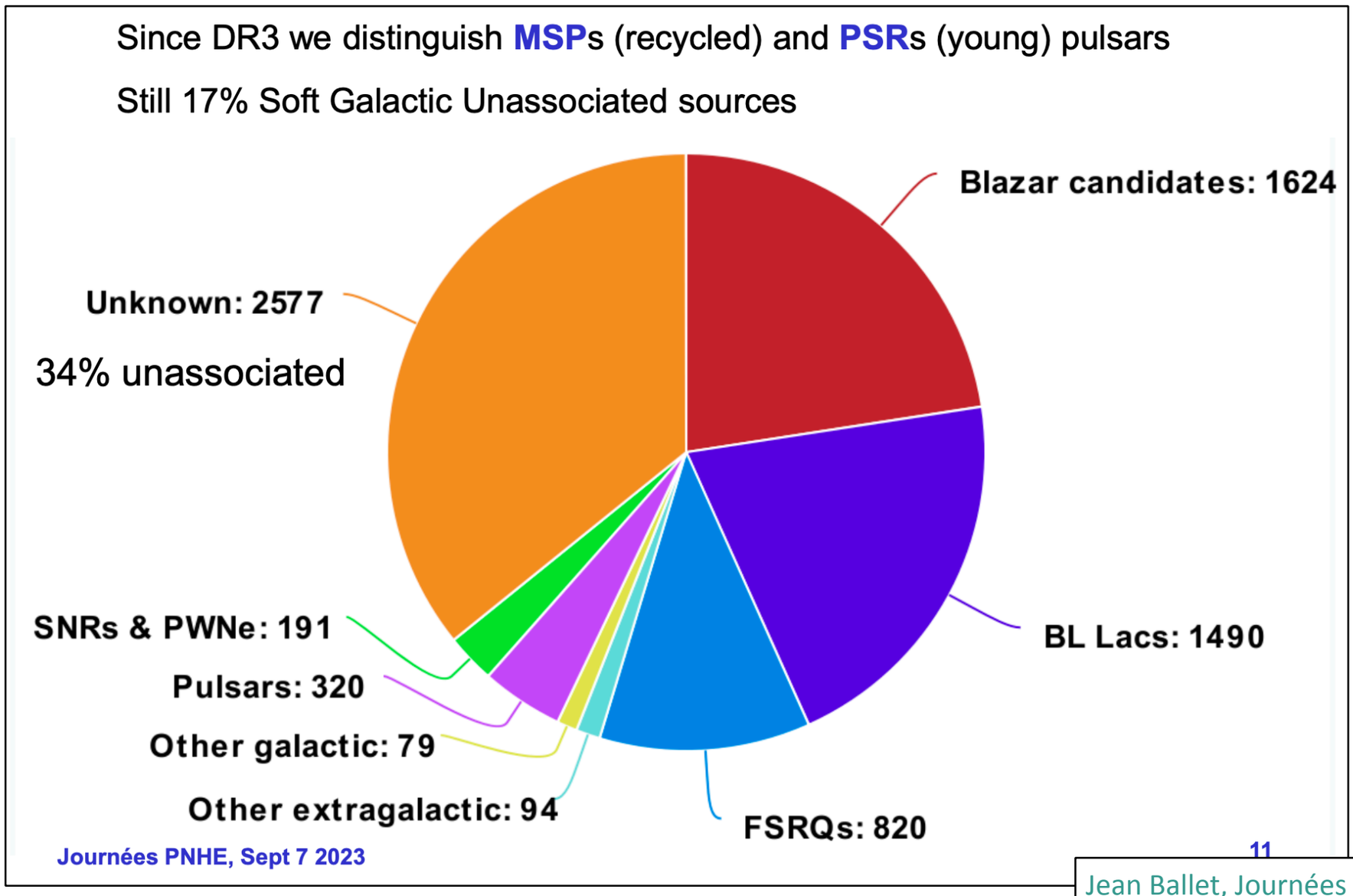

Jean Ballet, Journées PNHE (2023)

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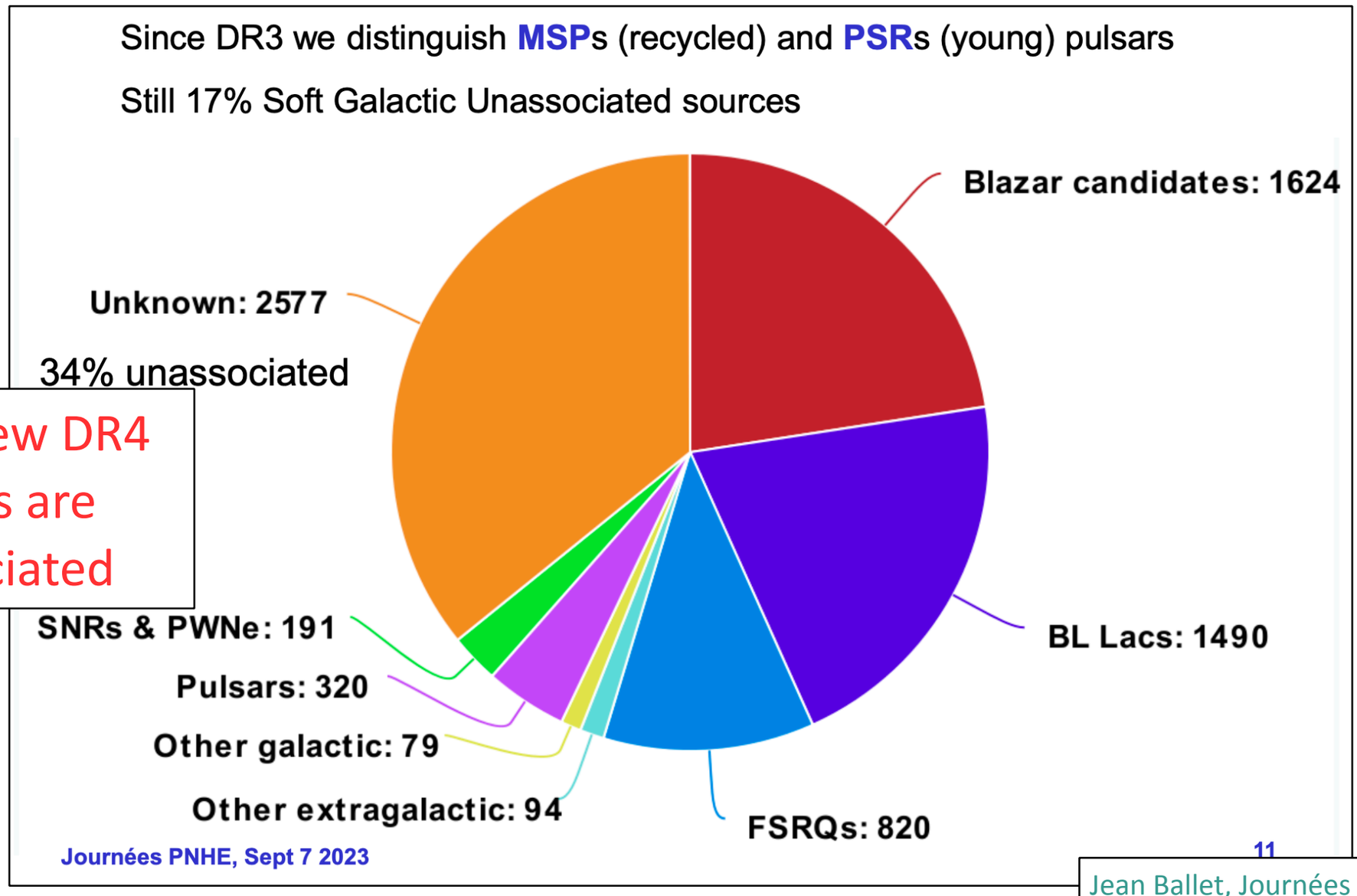

57% of new DR4 sources are unassociated

Jean Ballet, Journées PNHE (2023)