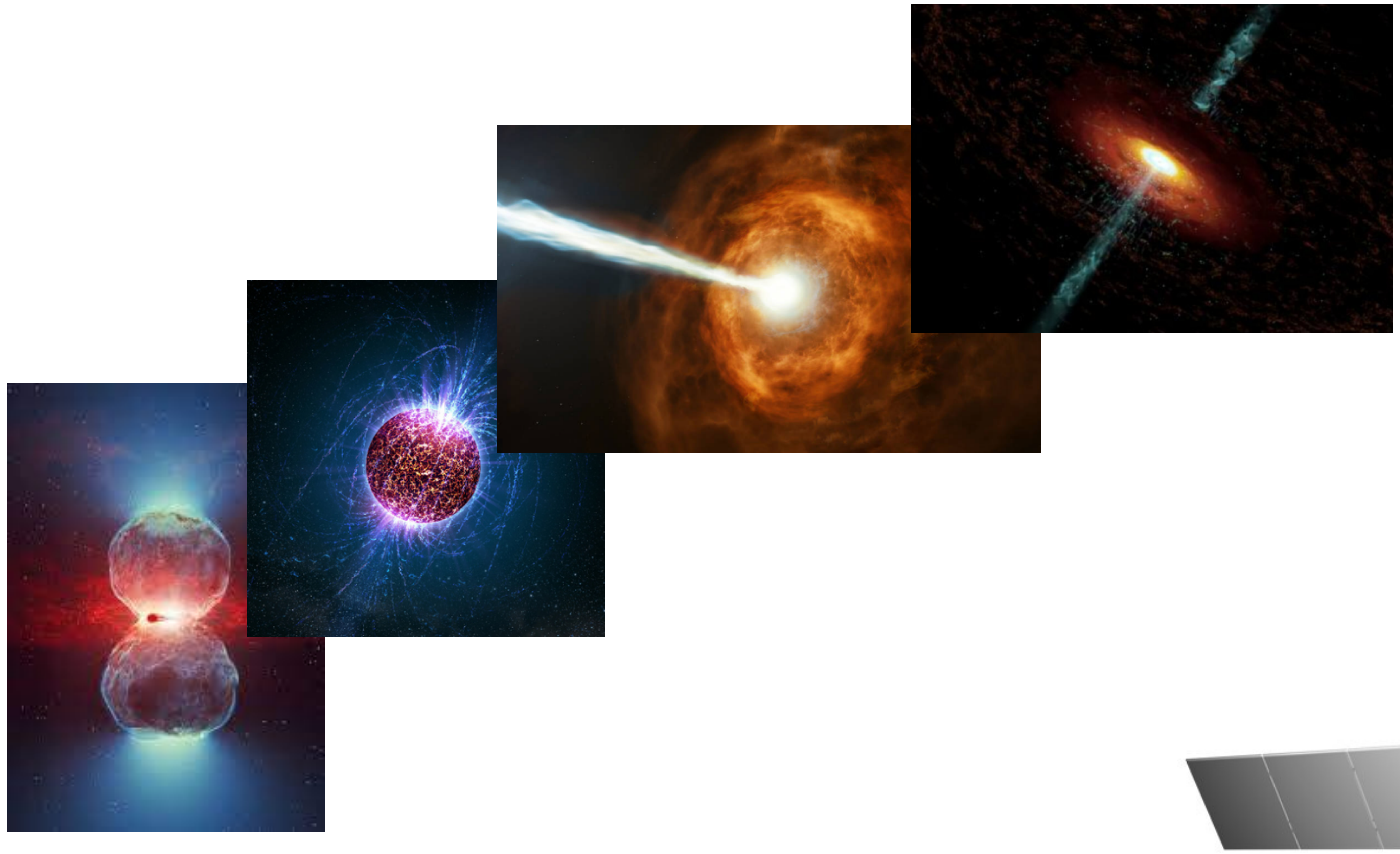
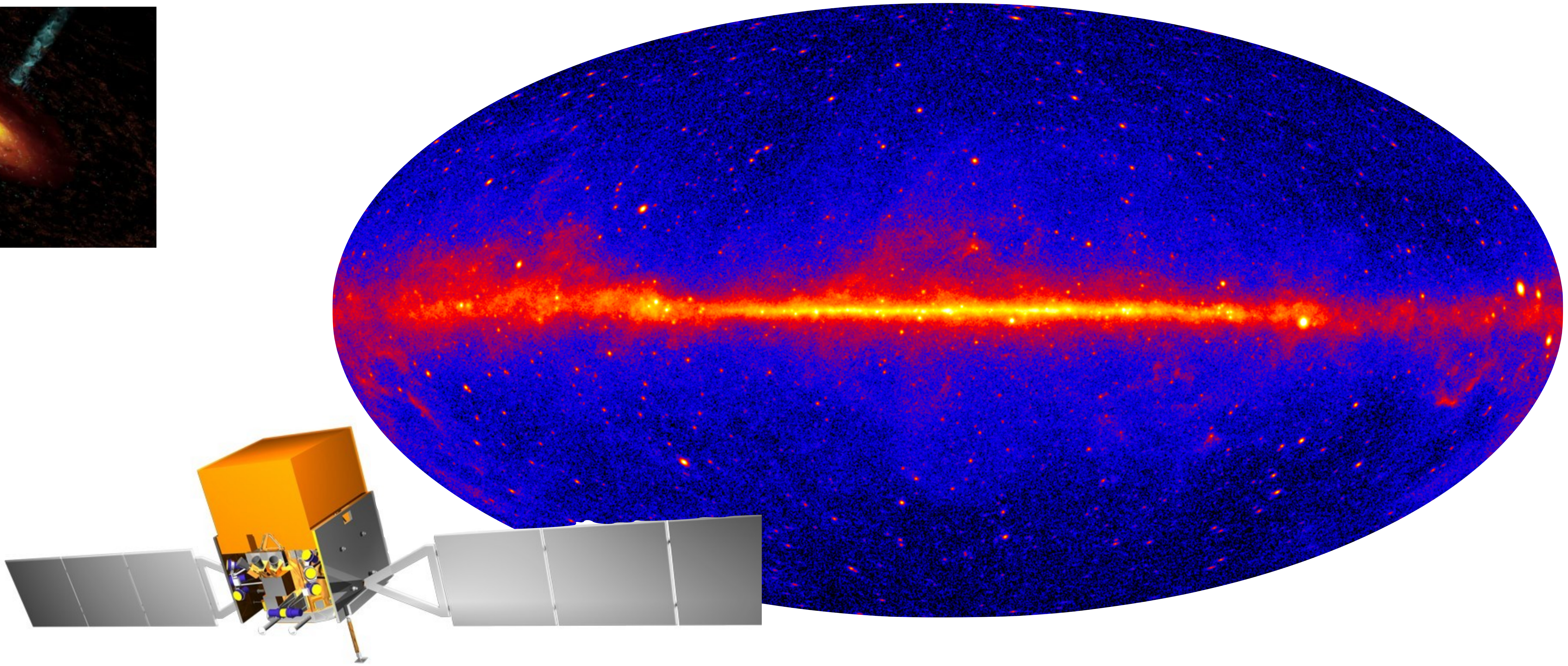
Transient observations with the Fermi LAT/GBM





Markus Ackermann, DESY

Polish-German Heraeus seminar: “The variable multi-messenger sky”

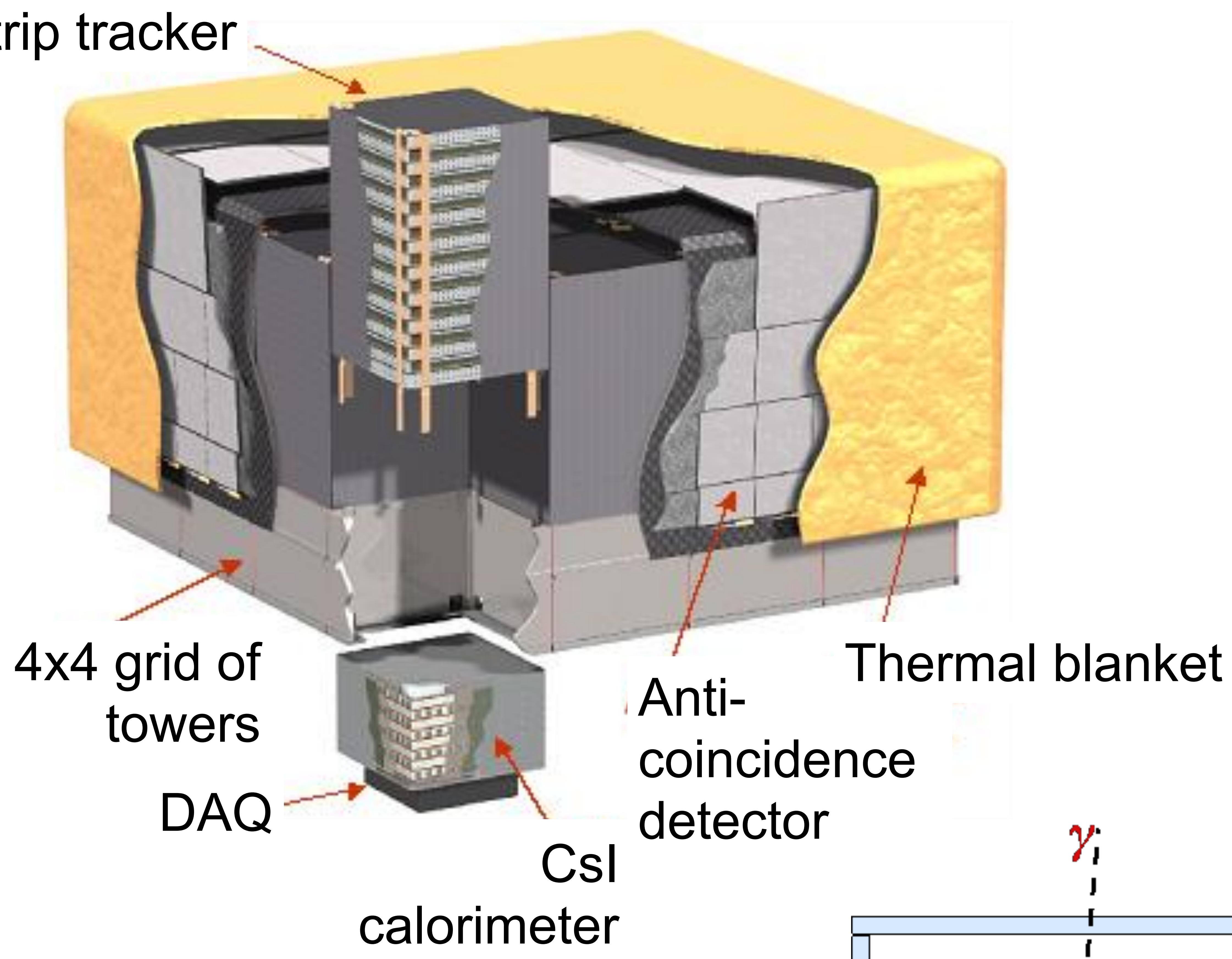
08.11.2022

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

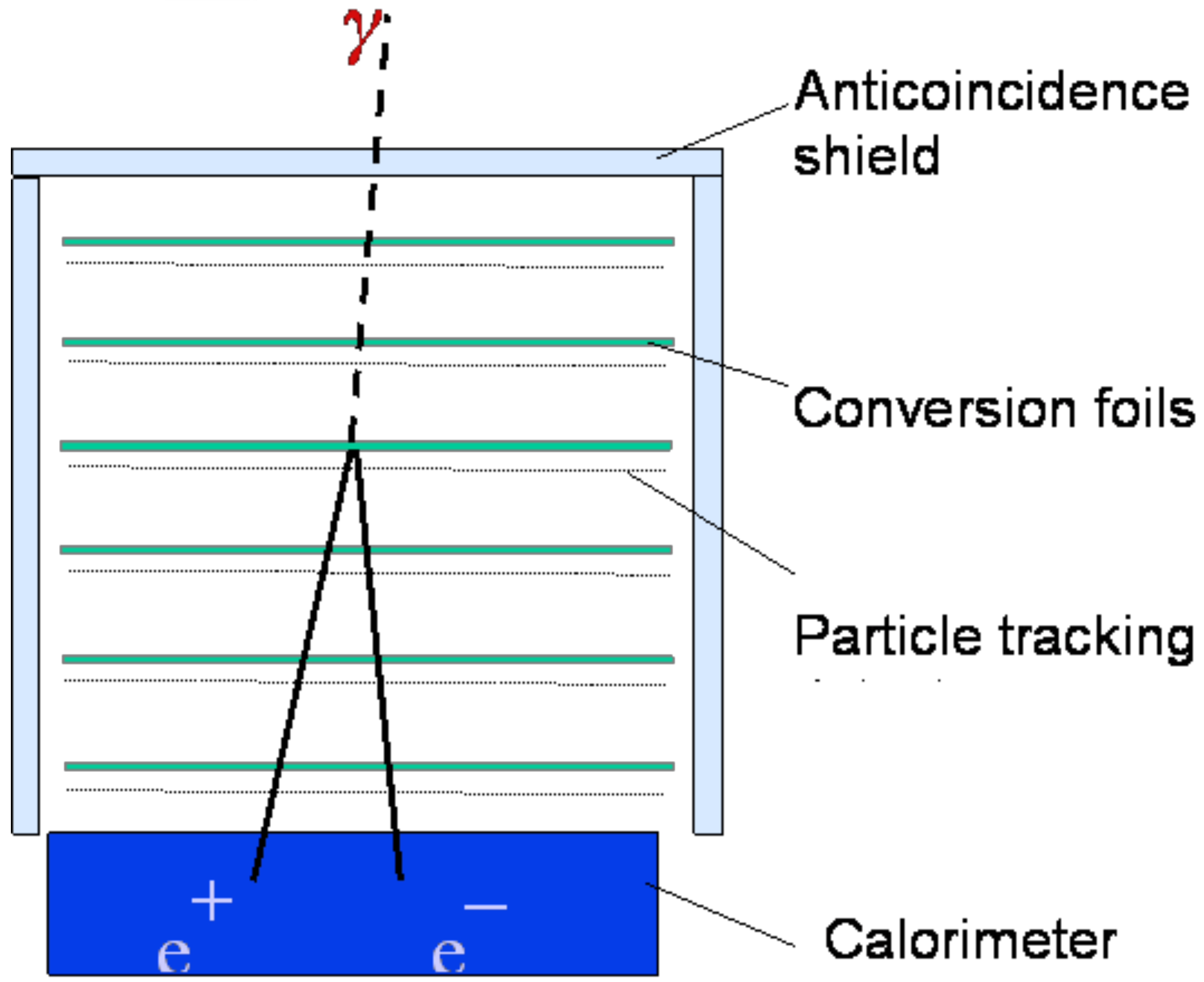
DESY

The Fermi satellite

The Large Area Telescope (LAT)

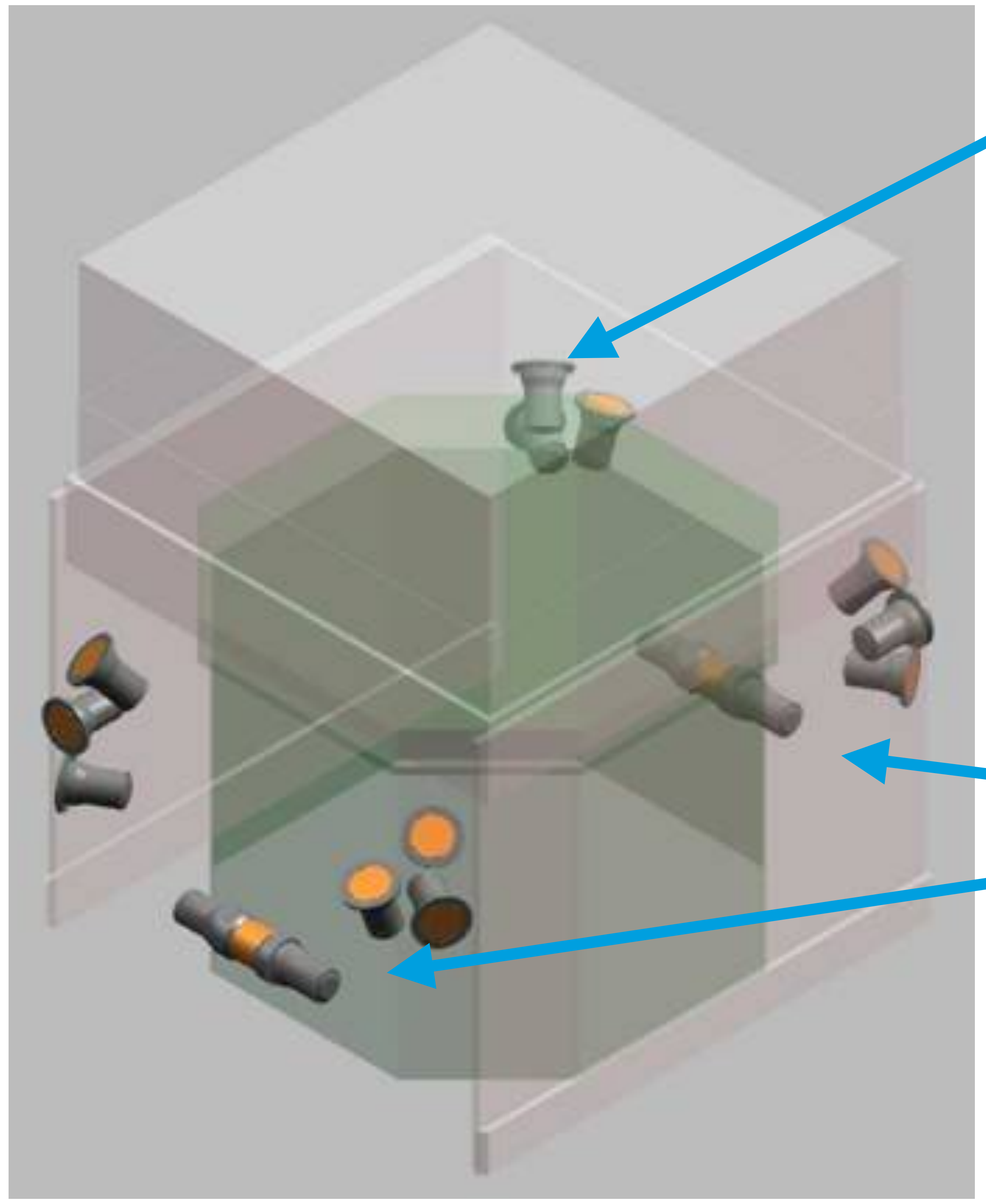


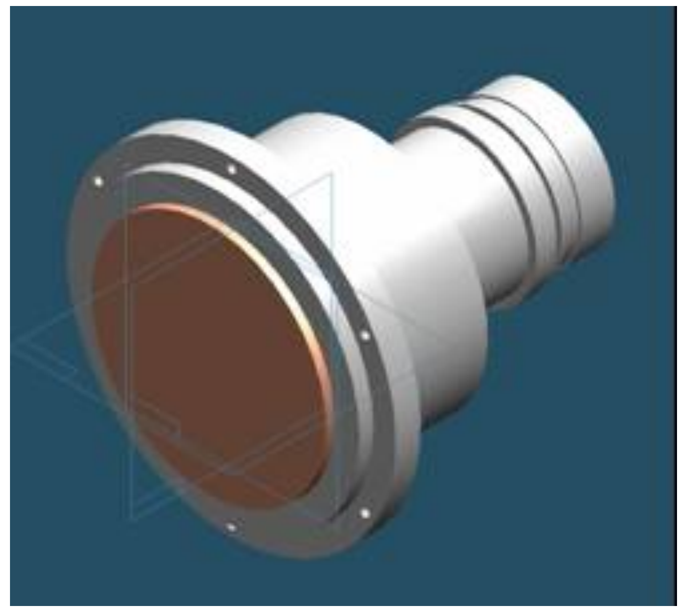
- Launch: June 2008 to low-earth orbit (550 km)
- Energy range:
  30 MeV — 1 TeV
- Field-of-view: 2.4 sr
- Default operation: sky survey



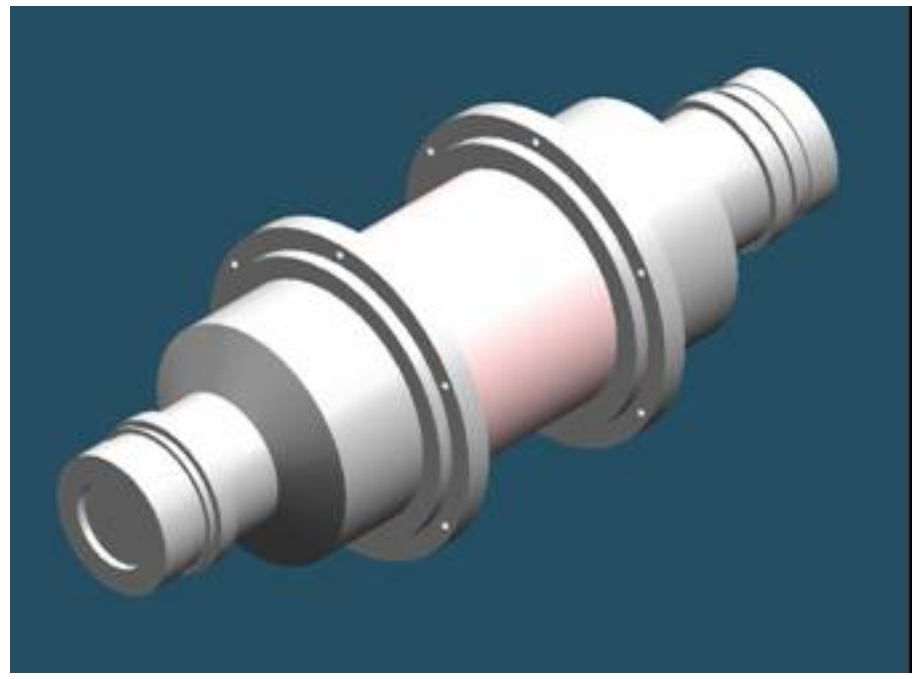
The Fermi satellite

The Gamma-ray burst monitor (GBM)





4 x 3 NaI detectors
8 keV - 1 MeV



2 BGO detectors
150 keV - 40 MeV

- **Field-of-view:** 9.5 sr
- **Sensitivity:** 0.7 ph / cm^2 s^{-1}

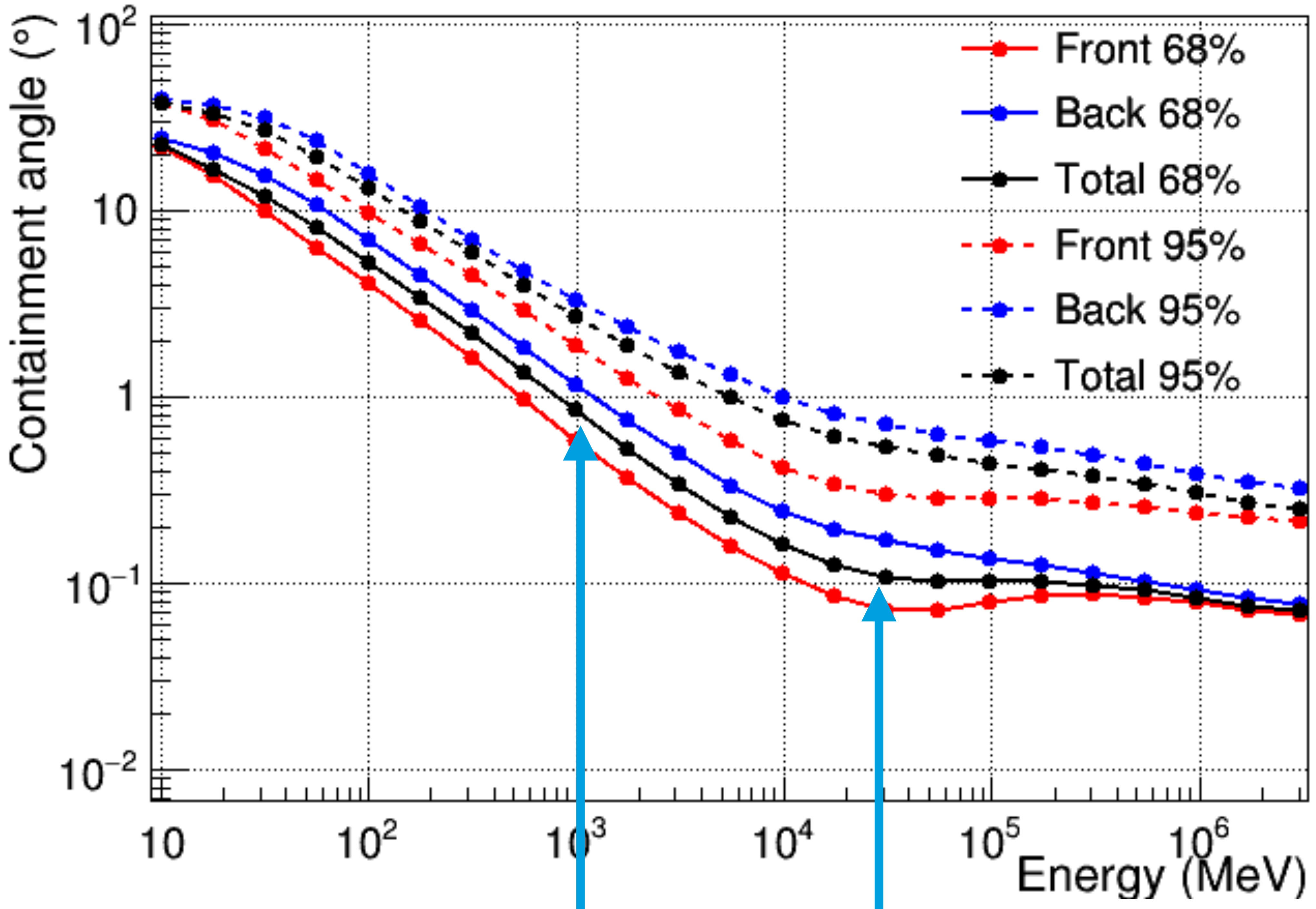
- **Energy resolution:** <12% FWHM @ 511 keV
- **Localization:** < 15 deg

DESY.

Fermi LAT performance

Effective area and angular resolution

Angular resolution

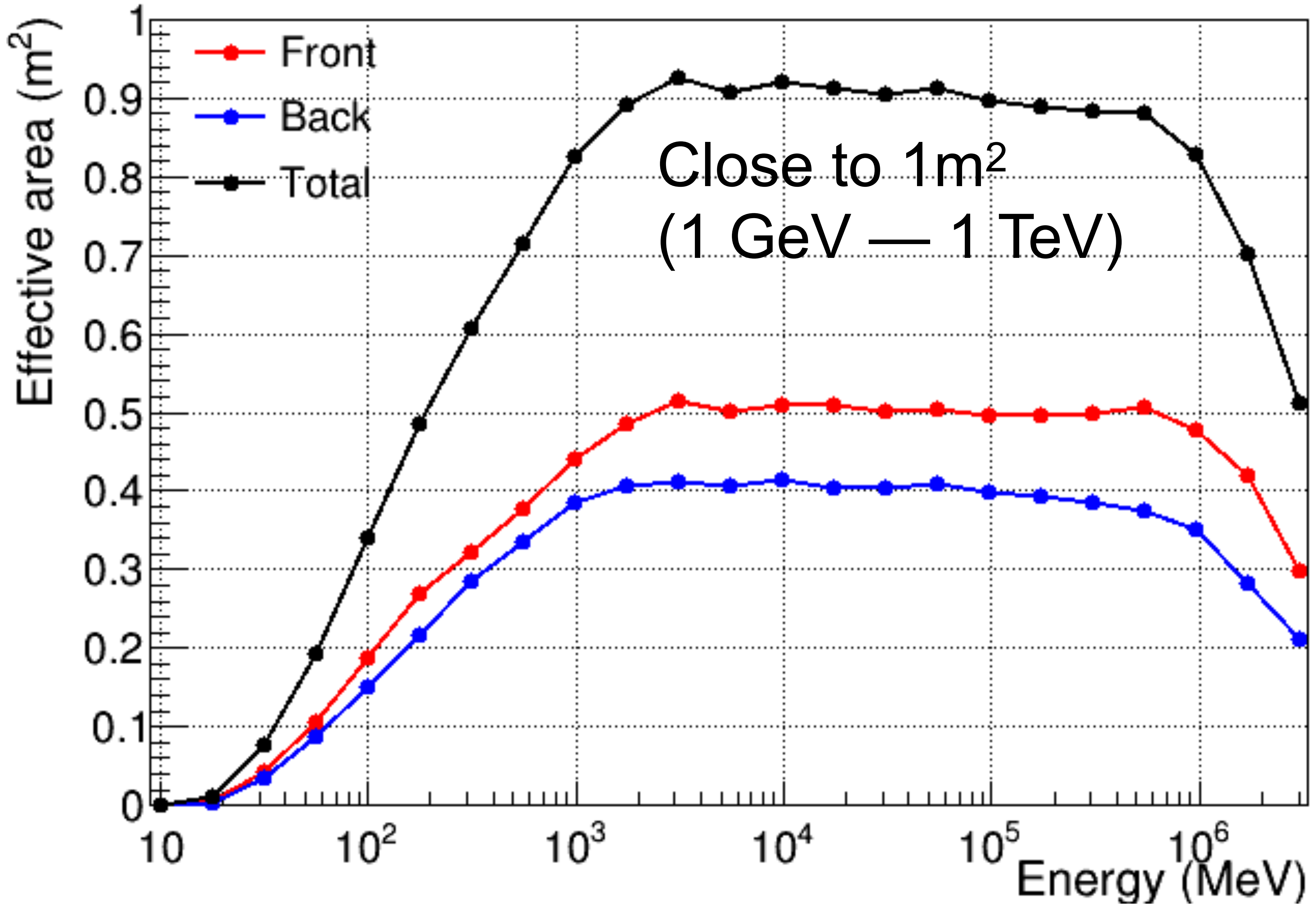


> 1 deg below 1 GeV

< 6 arcmin above 30 GeV

- Two in-flight re-processings of entire LAT datasets to improve performance (latest: pass8)

Effective area

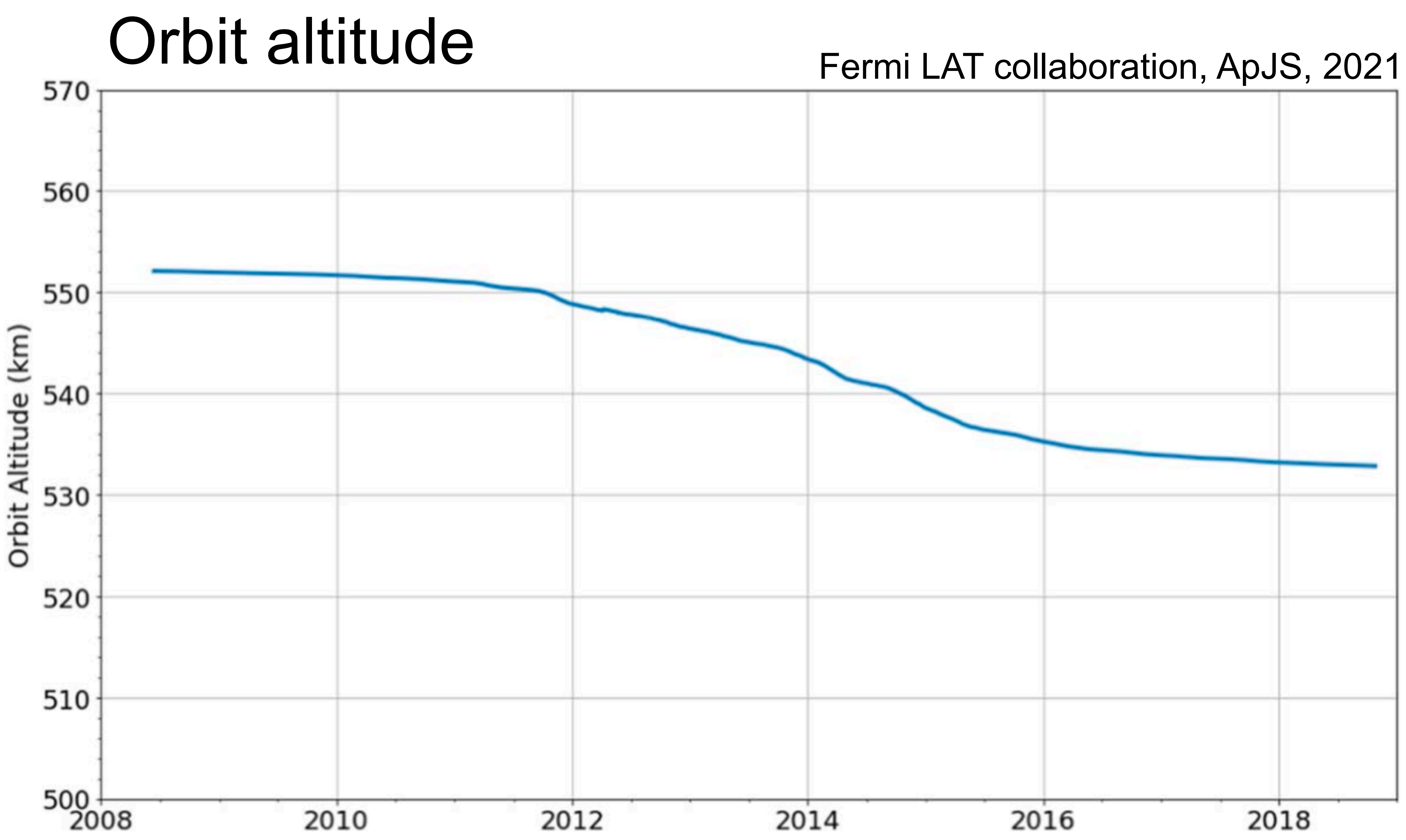


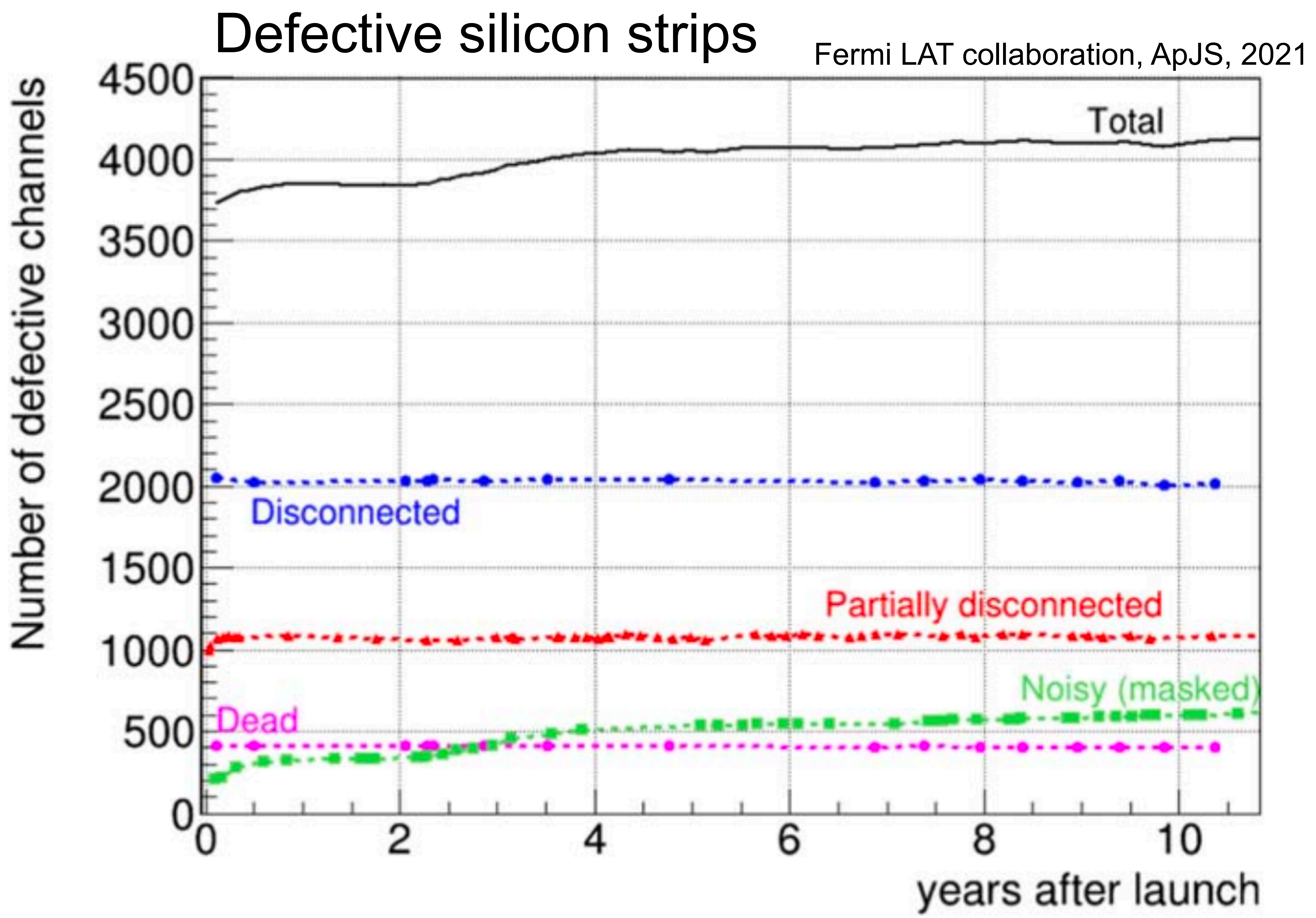
Close to $1 m^2$
(1 GeV — 1 TeV)

- Tungsten converter foils of different thickness in front and back part of tracker lead to different angular resolution for associated events.
- Energy resolution: < 10 % between 1 GeV and 500 GeV

Fermi LAT mission status

Current status and expectations for the future





- LAT continues to perform well, orbit can be maintained at least until the mid-2030s
- One major anomaly: One of two solar array drive motor failed in March 2018.
- Some impact on transient science:
  - For 1/3 of total observation time only 80% sky coverage within 1.5h, but full sky coverage only after 1 week (before: full sky coverage every 3 h)
  - No ToO or automated repointing of the satellite

Public tools for the community

- NASA and the LAT collaboration provide and maintain a series of analysis tools for easy access to the LAT data

Fermi LAT Light Curve Repository - Source Report

Light Curve Options

Data Cadence:

3 day | 1 week | 1 month

Analysis Options:

Minimum Detection Significance: TS = 4 (2σ)

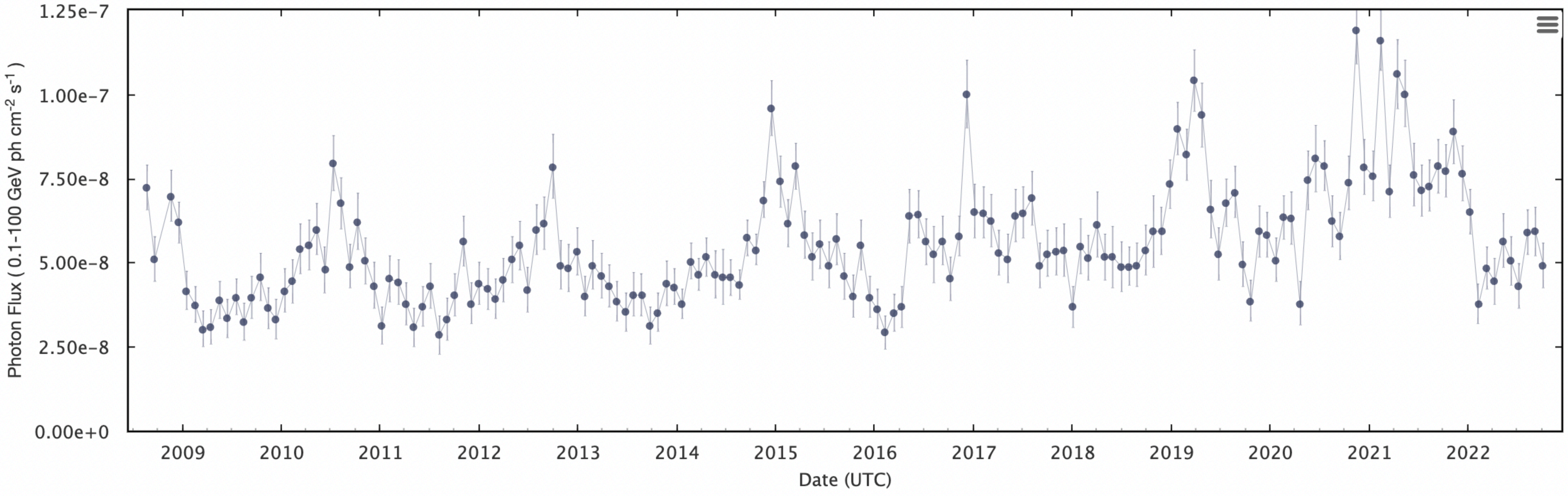
Spectral Fitting: Fixed Index

Plotting Options:

- [x] Upper Limits
- [x] Error Bars
- [x] Connector Line
- [x] Data Tooltips
- [ ] Show Non-Convergent Fits
- [ ] Show Unconstrained Fits

Light Curve Data

Photon Flux | Date



4FGL Catalog Data

Source Information

Catalog Name:	4FGL J1555.7+1111
RA:	238.931°
Dec:	11.188°
Galactic l:	21.908°

Ancillary Data

Photon Index | Date

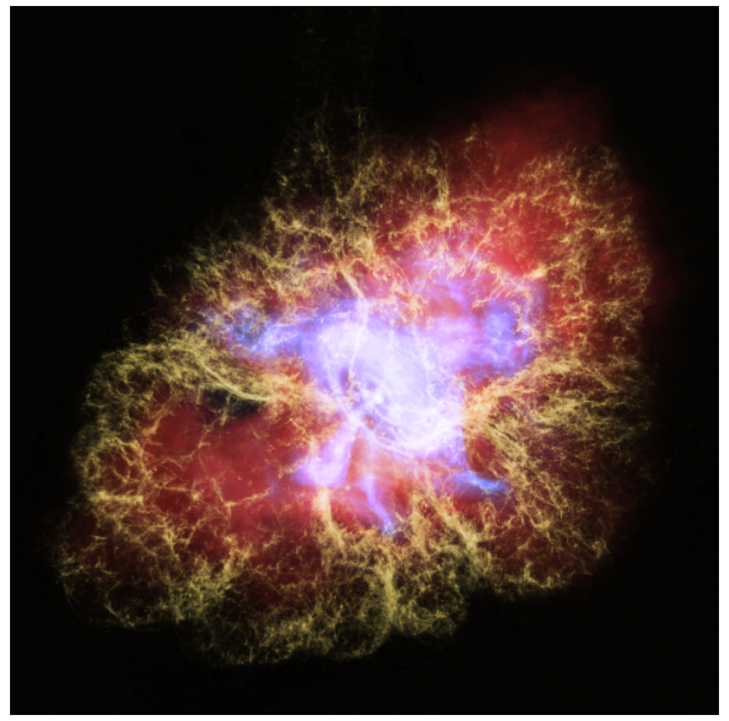
Galactic transients

Overview

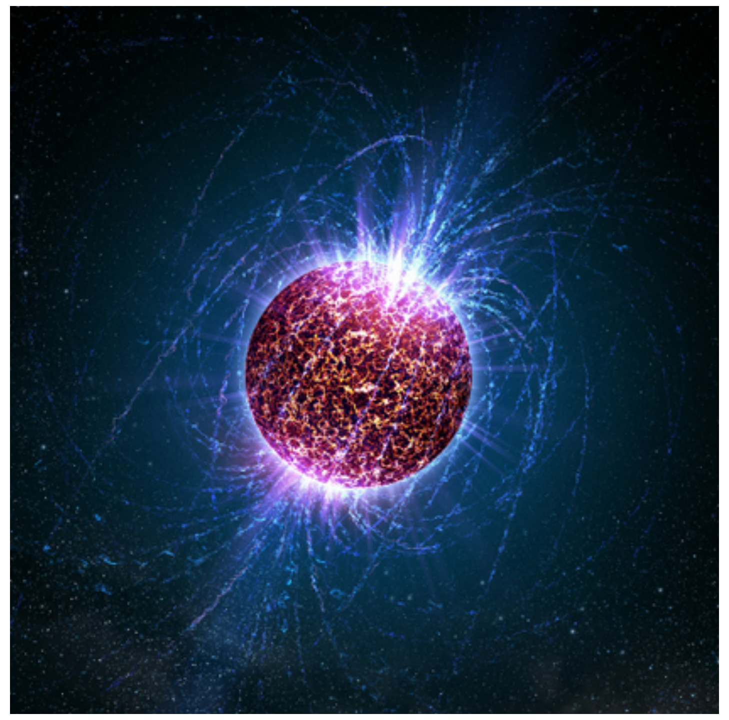
Colliding wind binaries
Two massive stars in close orbit

Novae
Thermonuclear explosions from accretion onto a white dwarf in a binary system

Gamma-ray binaries
Microquasars
Binary systems with a neutron star / black hole orbiting a star



Crab Nebula
Pulsar wind nebula with variable synchrotron emission

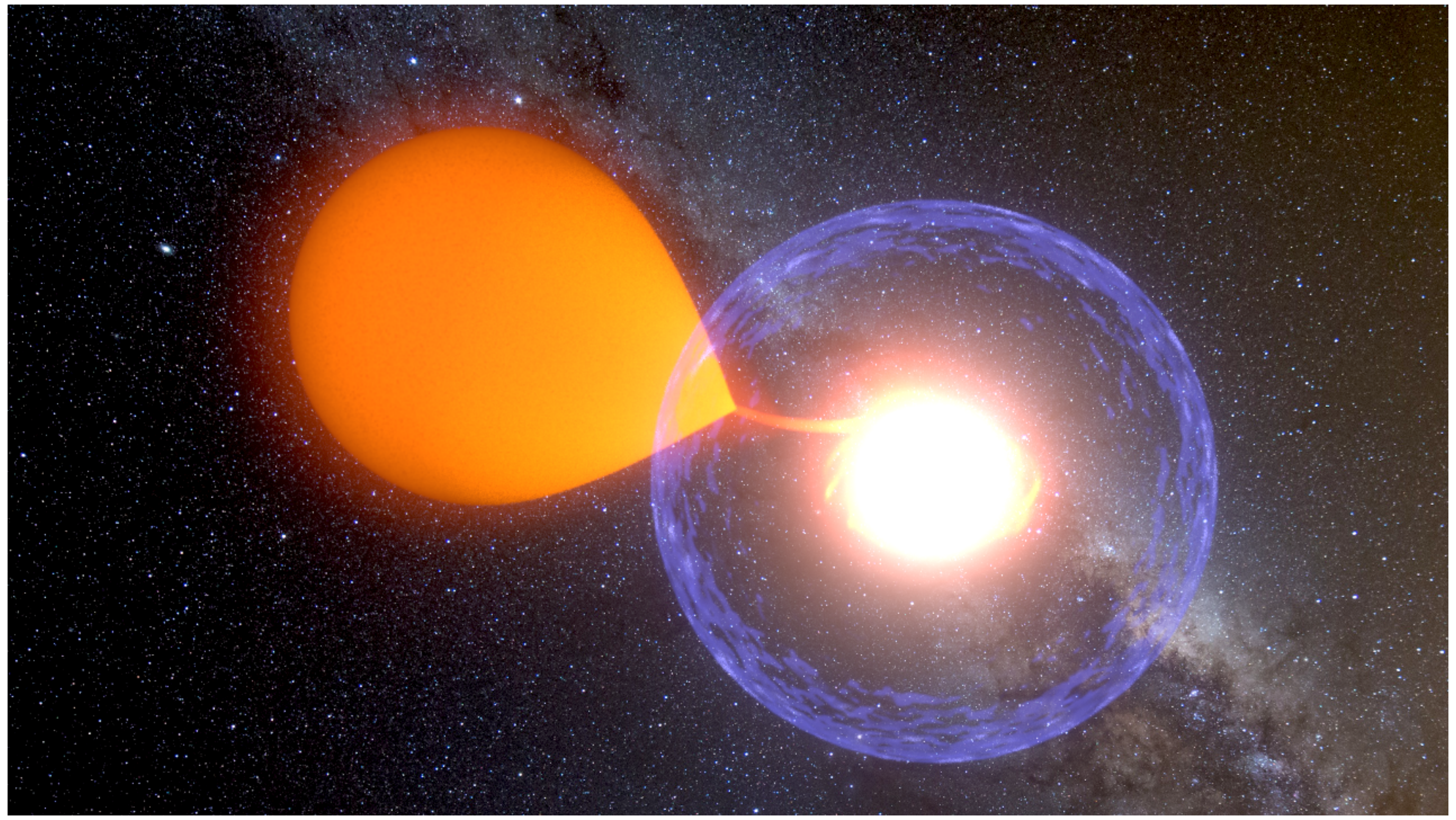


Pulsars and Magnetars
Pulsed emission of rotating neutron stars and magnetar flares

- Many transient phenomena in the Galaxy are linked to binary systems (but not all)
- I will only highlight a few interesting results (need to cover extragalactic transients as well…)

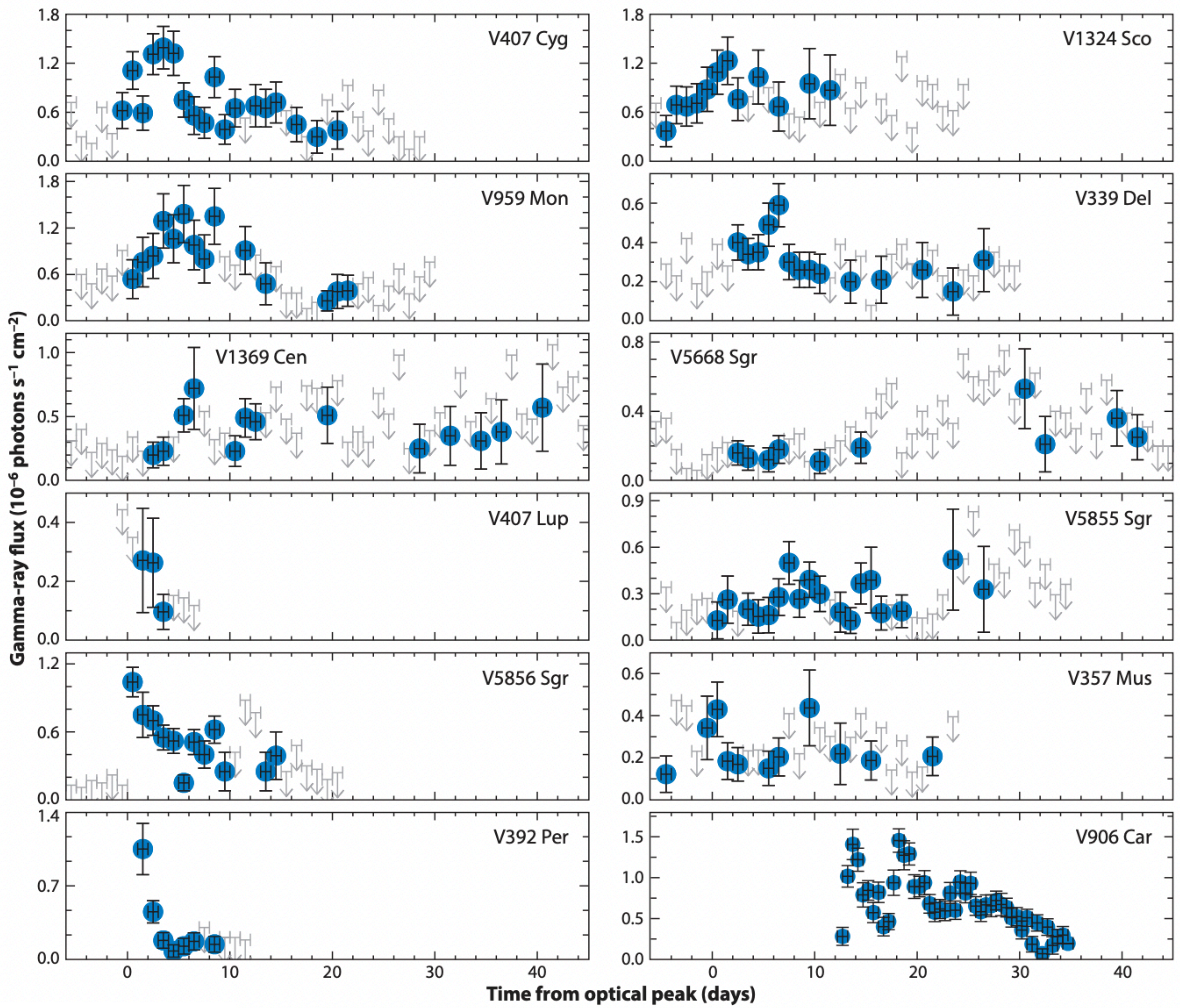
Disclaimer: I will mostly focus on Fermi LAT/GBM results here leaving the discussion of VHE results to the respective talks…

Classical Novae as a population of gamma-ray sources



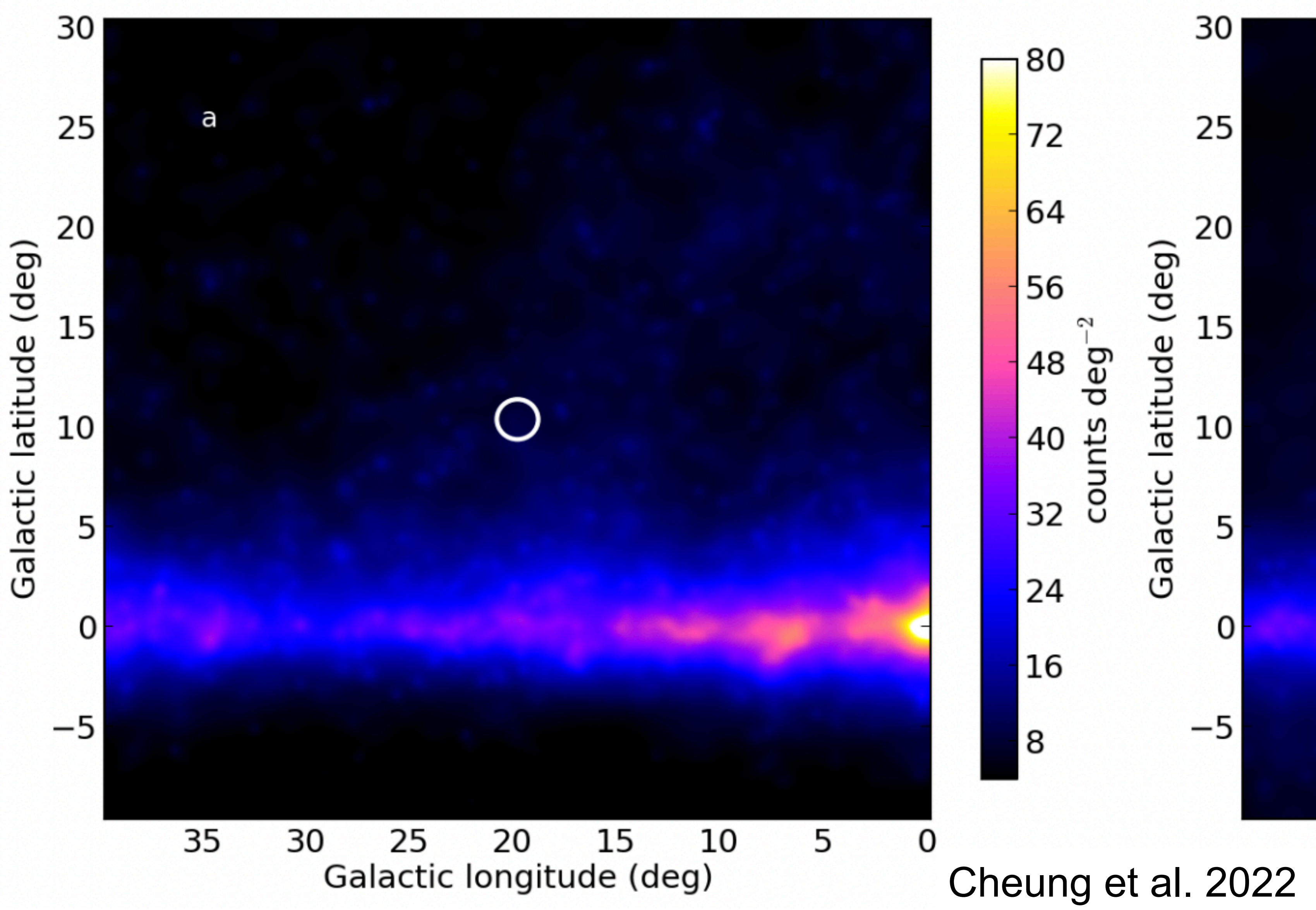
Credit: K. Ulaczyk / Warsaw University Observatory

- First LAT detection of a Nova in 2010 came as a surprise
- 17 Novae detected by Fermi LAT up to 2021
- Typical **duration**: days to weeks
  Typical **spectral cut-off**: ~1-10 GeV
- Classical and symbiotic/recurrent novae detected
- Particle acceleration in internal and external shocks

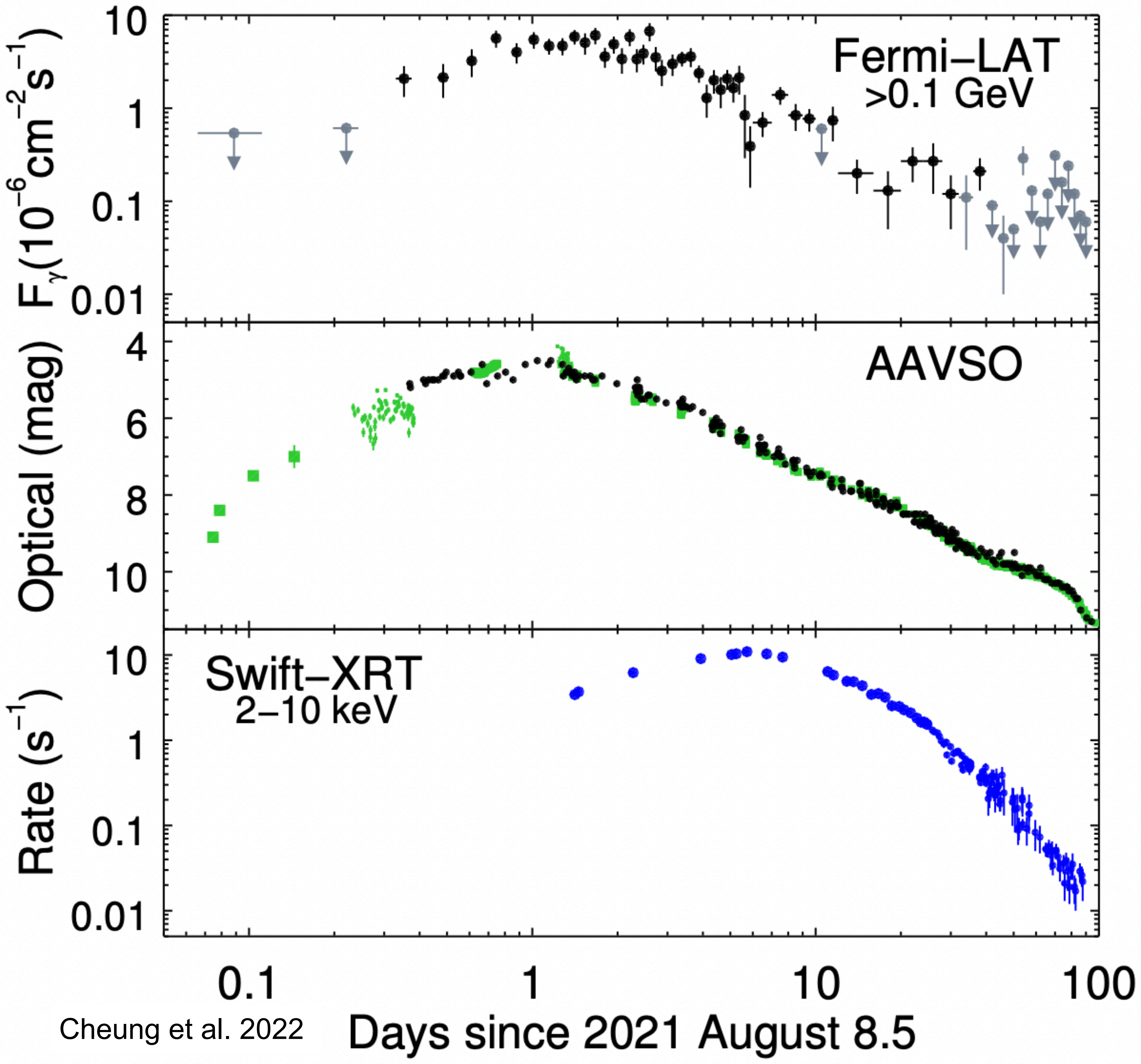


Chomiuk et al. 2021

Recent observations of the recurrent Nova RS Ophiuchi



Cheung et al. 2022



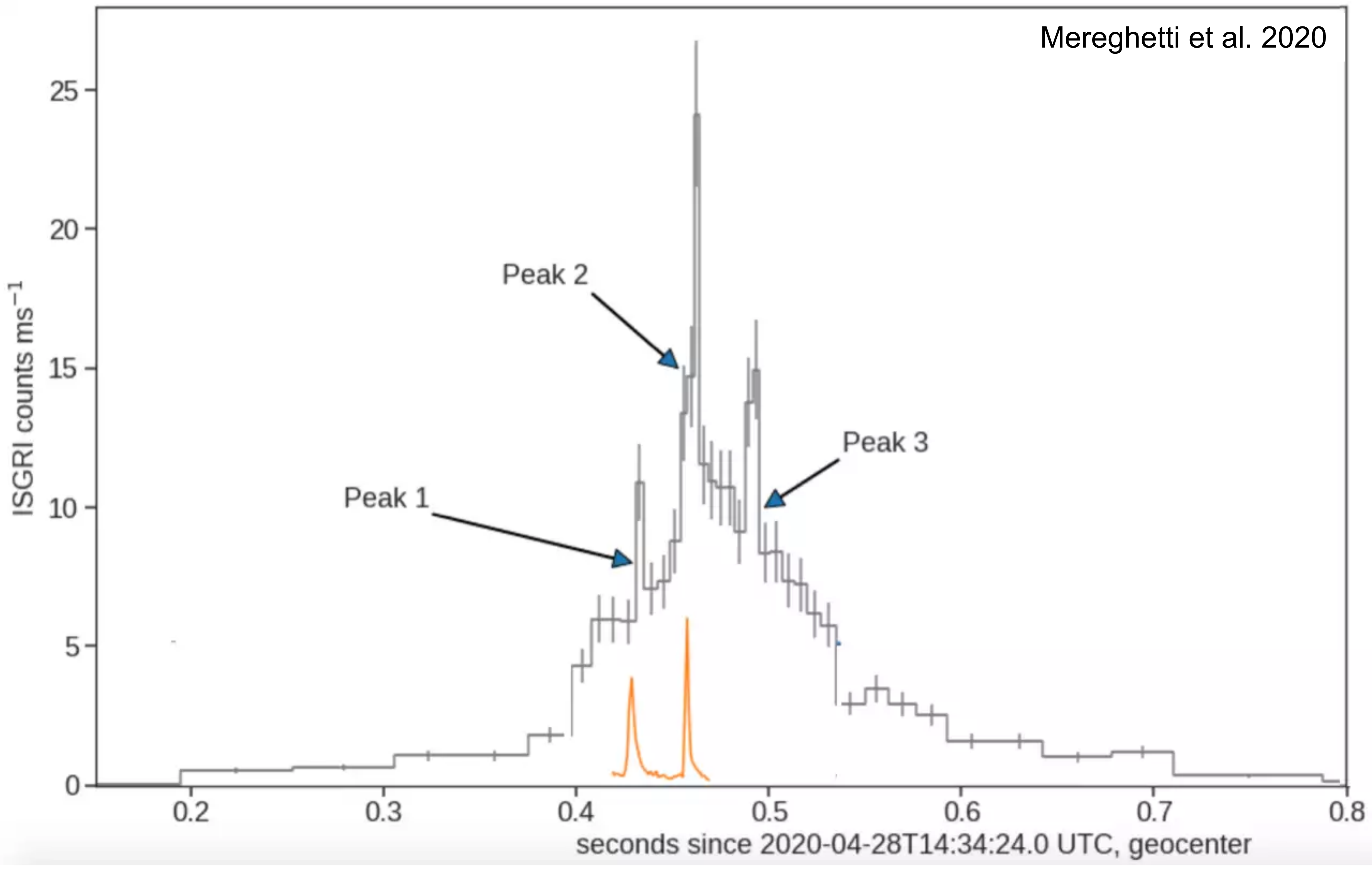
Cheung et al. 2022

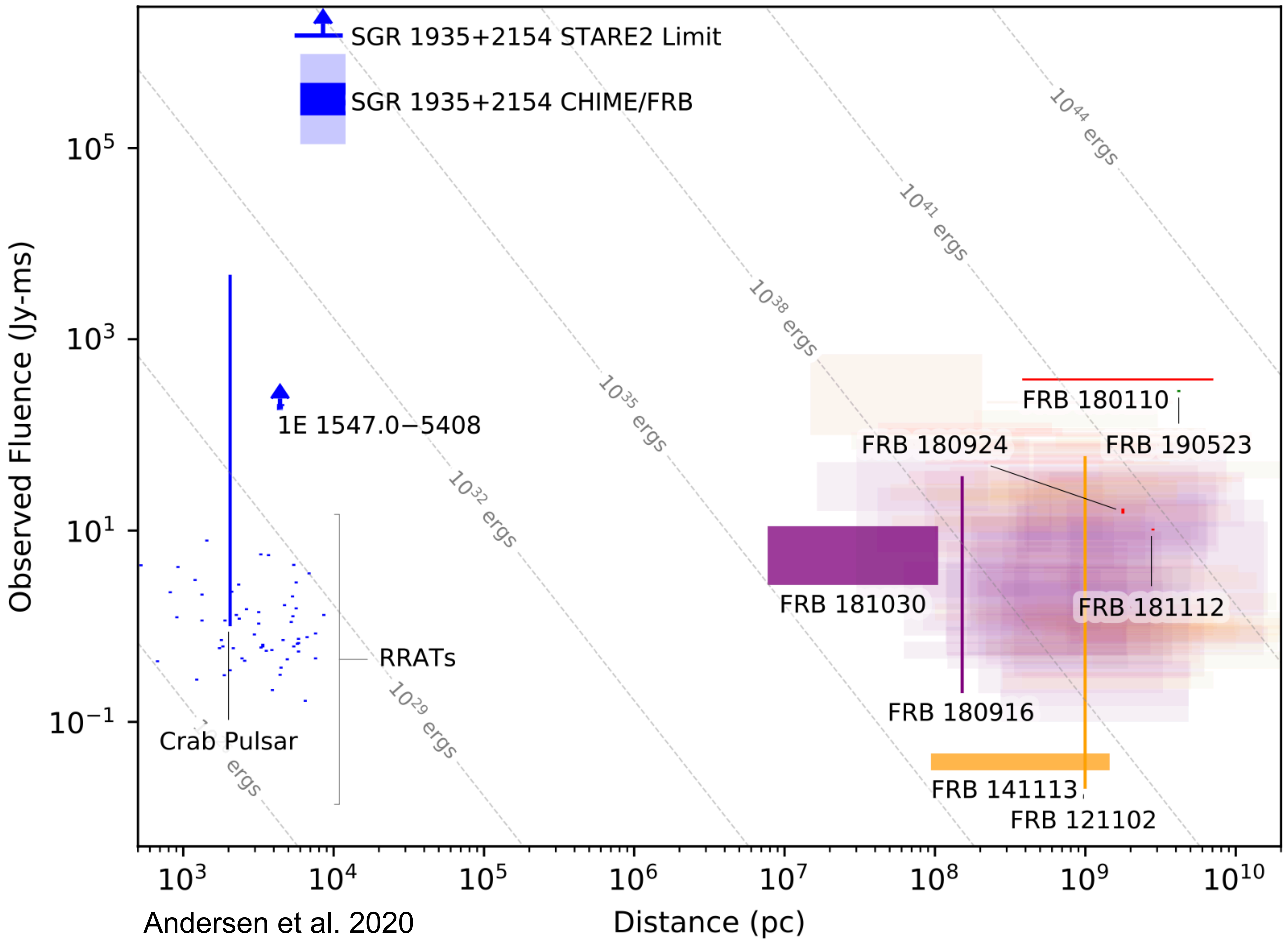
- Recurrent novae: Multiple observed outbursts
- RS Oph recurrence rate: every 9-27 years, last outbreak in 2006 (observed since 1898!)
- Outbreak in 2021: Brightest LAT detected nova so far, detection up to 20 GeV
- More about this nova (probably) in Jim’s talk

A magnetar flare with an associated fast radio burst

SGR 1935+2154

- Series of x-ray/gamma-ray flares detected for the soft gamma-ray repeater SGR 1935+2154 in 2020
- Observed by GBM, INTEGRAL, NICER….
- Hardest spectrum INTEGRAL flare overlays with FRB-like radio burst detected by CHIME / STARE2

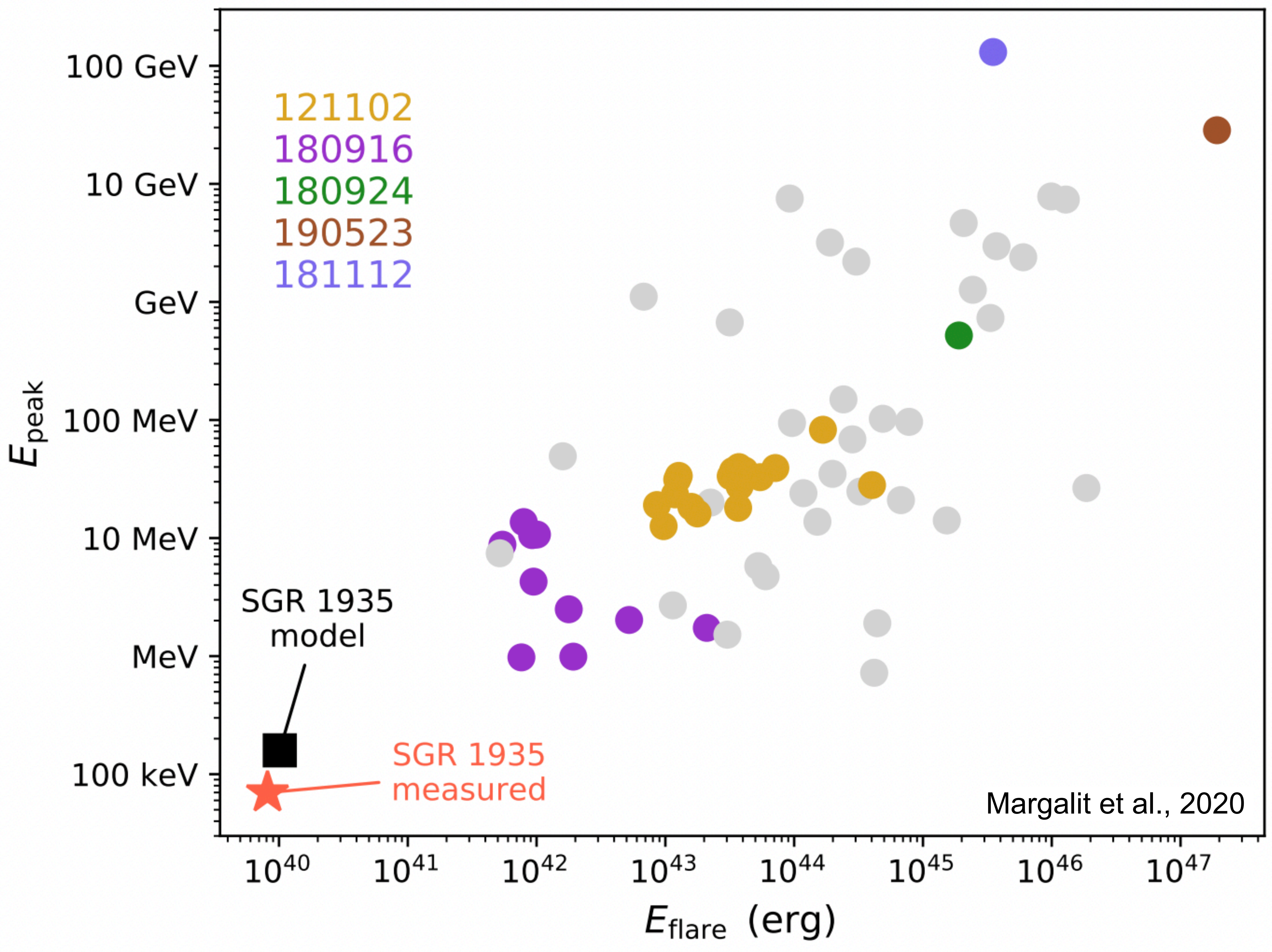




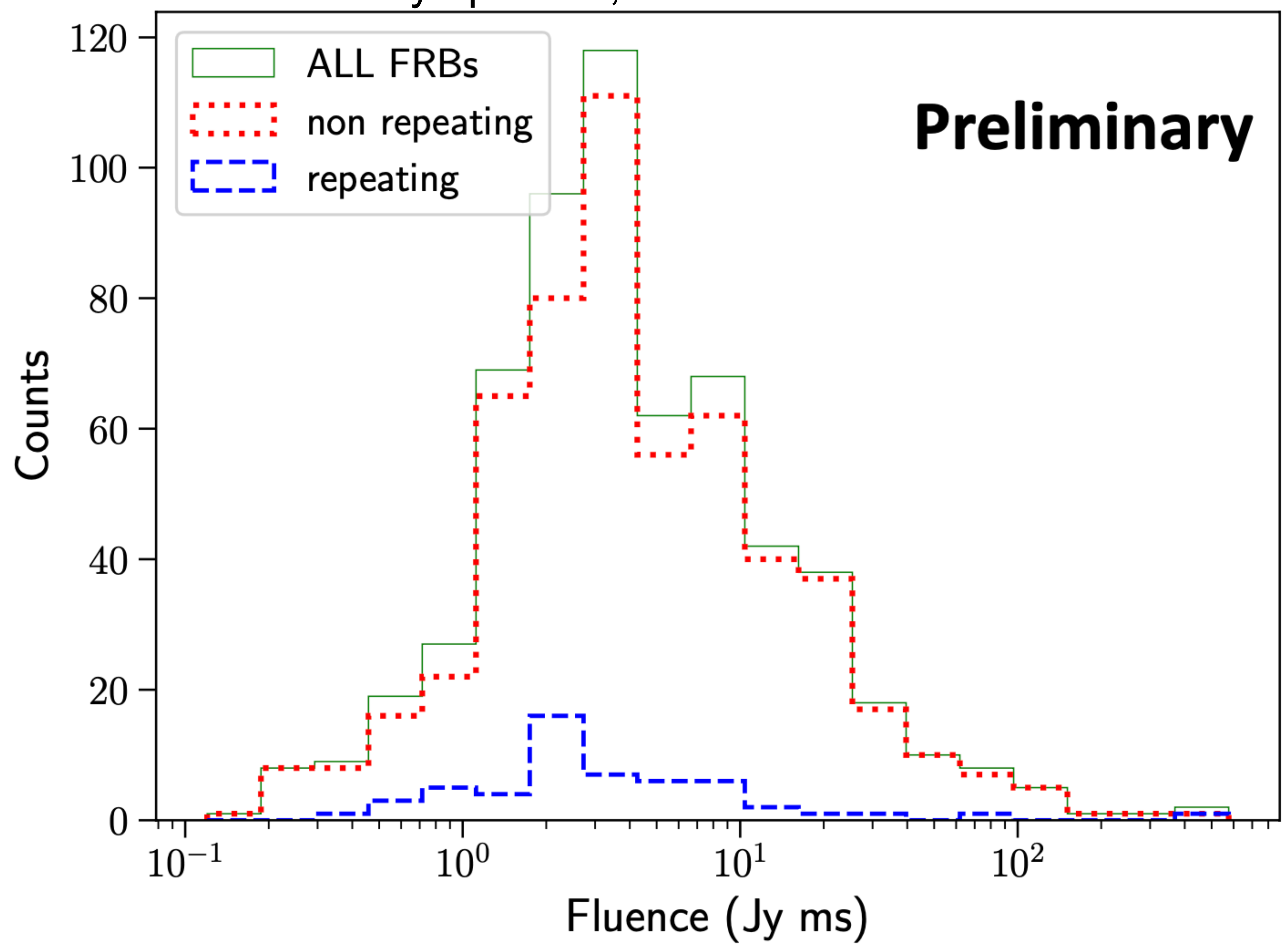
- Similar energetics as extragalactic FRBs
- Connects for the first time an FRB-like burst to a Galactic magnetar

Searches for Fast Radio Bursts with the LAT

GeV gamma-rays connected to FRBs ?



F. Longo for the LAT collaboration
10th Fermi Symposium, 2022

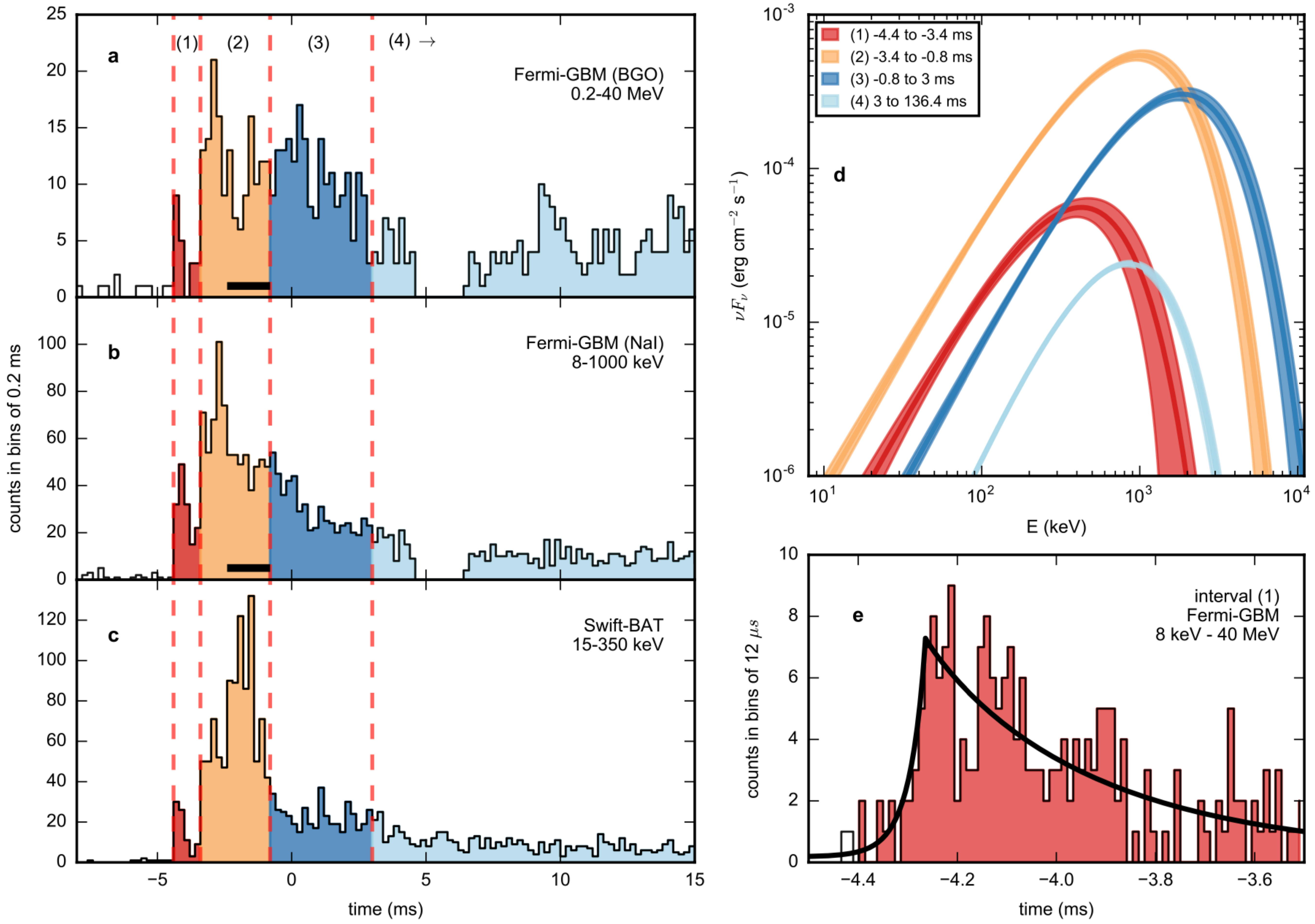


- SGR 1935+2154 was only visible at GBM energies
- Certain classes of models expect the peak of the gamma-ray emission to correlate with the flare energy
- Stacking analysis with 1020 FRBs (repeating and non-repeating) finds no gamma-ray signal in LAT data

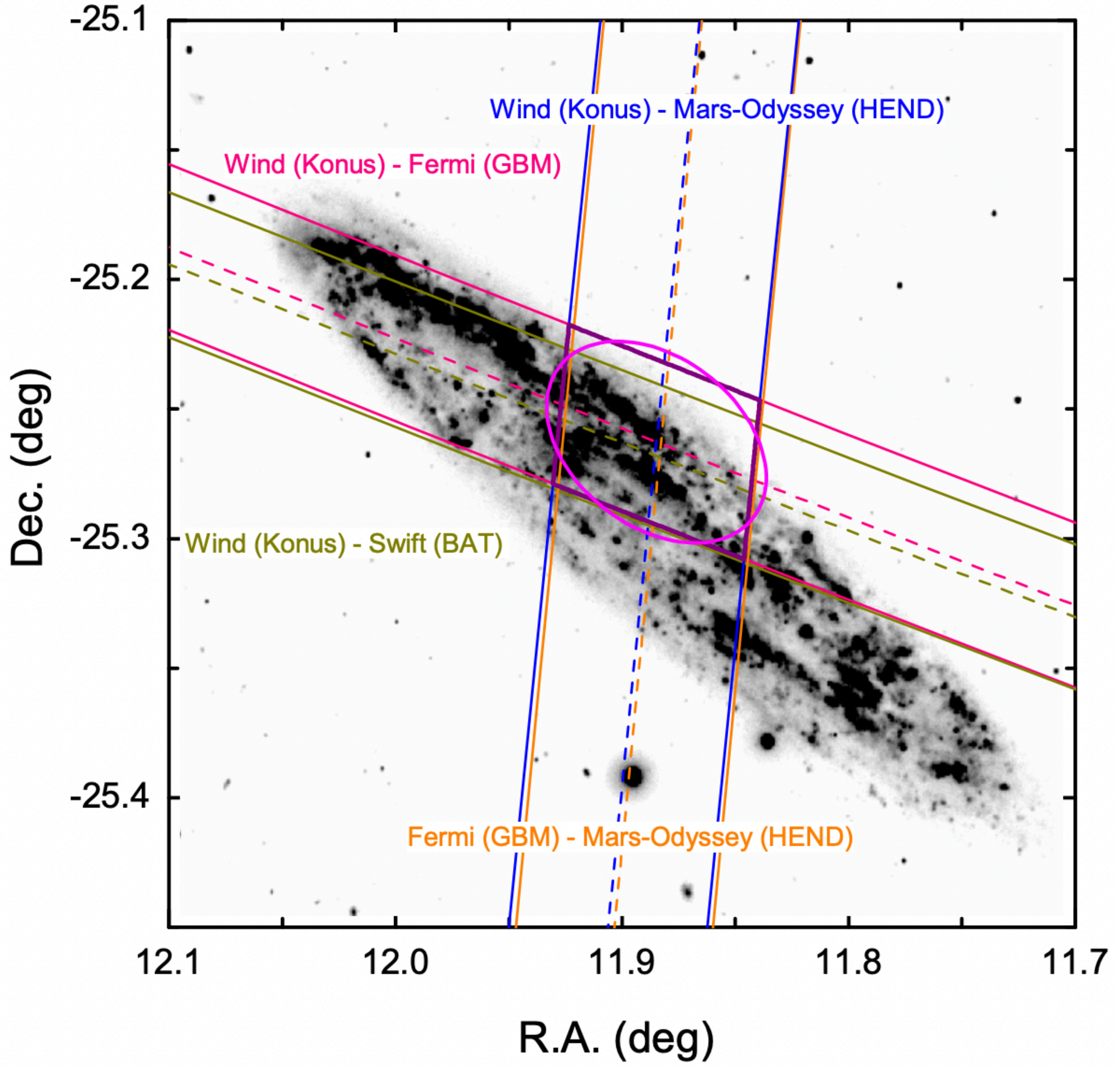
A giant magnetar flare observed by GBM and LAT

- Rare super-flares of magnetars, orders of magnitude brighter than flares during SGR stage
- Can be observed from nearby galaxies
- GRB 200415A localization overlaps with nearby galaxy NGC 253

Roberts et al., 2021



Svinkin et al., 2021

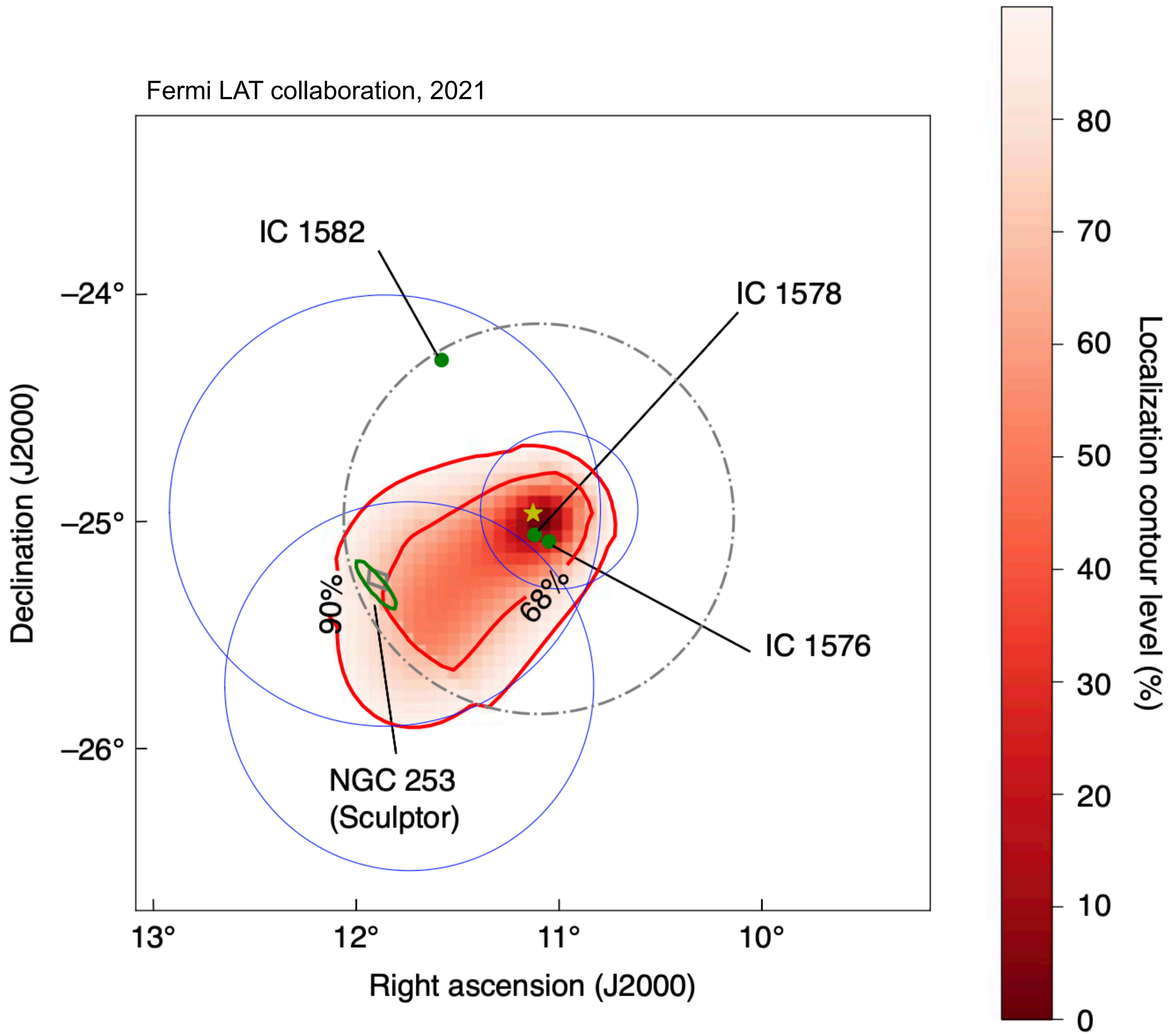


- Shortest measured time scales in gamma rays (77 us), detailed spectral analysis in GBM
- Archival magnetar giant flare (MGF) searches find about 2% of short GRBs to be associated with MGF (Burns et al., 2021)

LAT observations of the giant magnetar flare

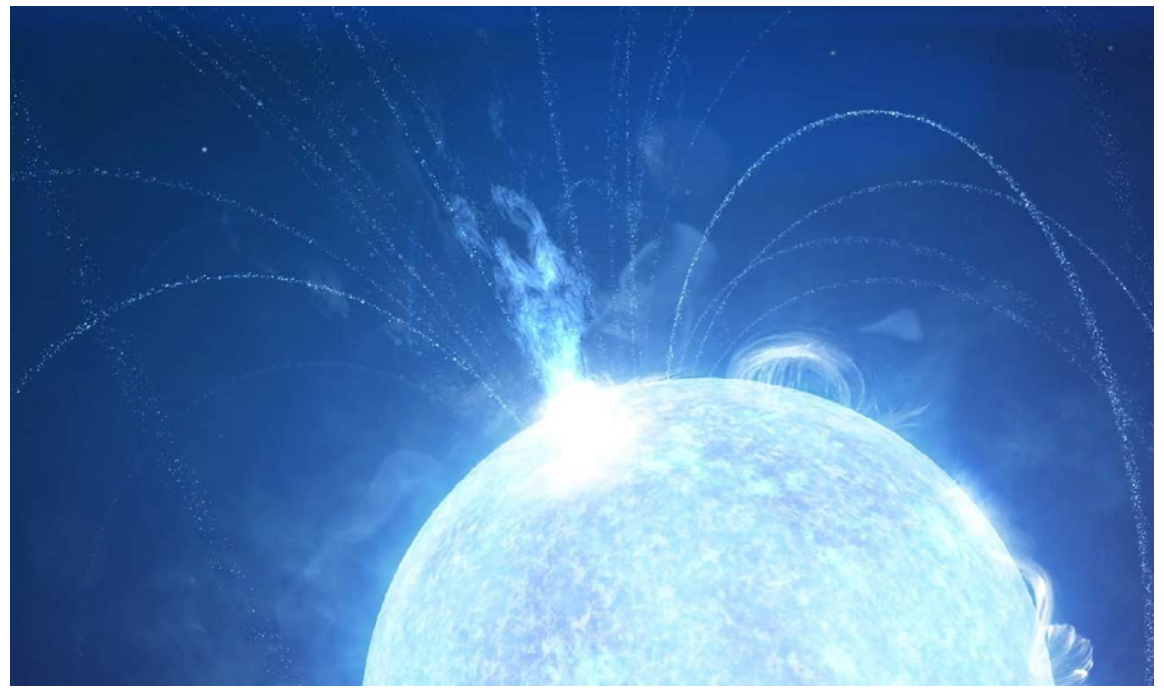
- 3 events observed in the LAT, 19s, 180s and 284s after the flare with energies of 480 MeV — 1.7 GeV
- FAR for an event triplet in spatio-temporal coincidence with the short GRB is < 10^{-7} / year
- Observation suggest relativistic outflows connected to giant magnetar flares

Fermi LAT collaboration, 2021



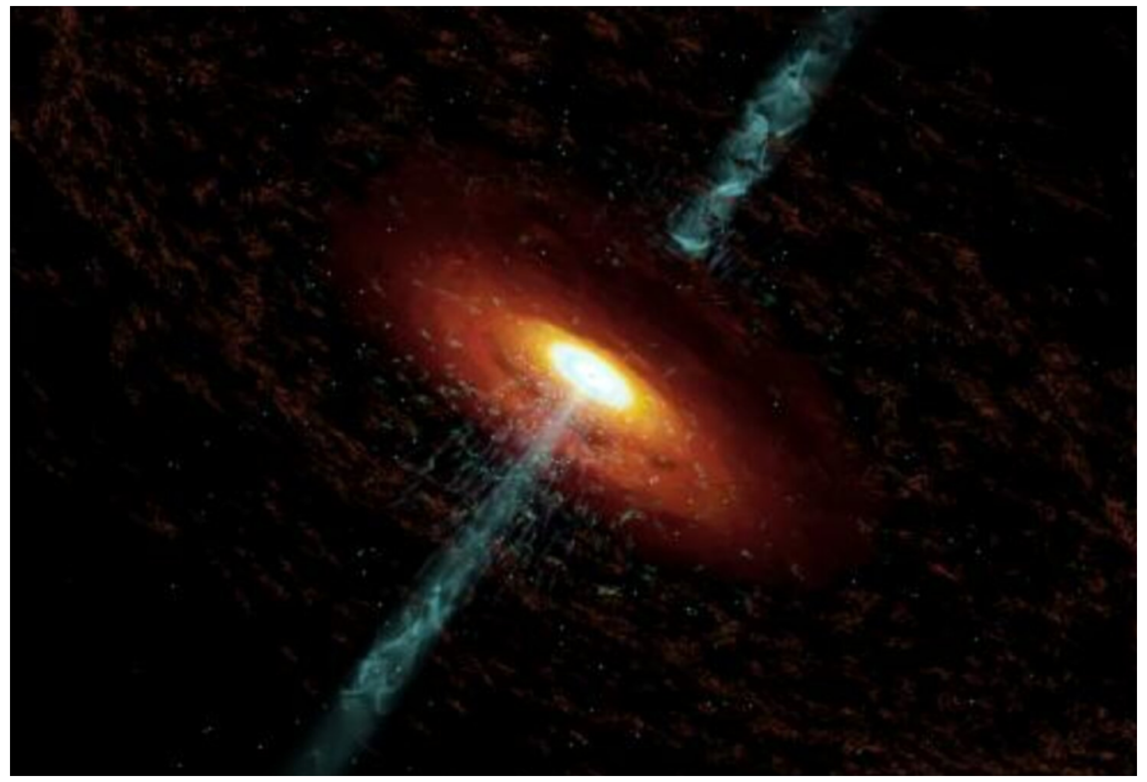
Extragalactic transients

Overview



Giant magnetar flares
Visible from nearby galaxies
Very short gamma-ray transients

Gamma-ray bursts (GRB)
Short duration O(1s) GRB linked to compact object mergers
Long duration O(100s) GRB linked to extreme supernova explosions

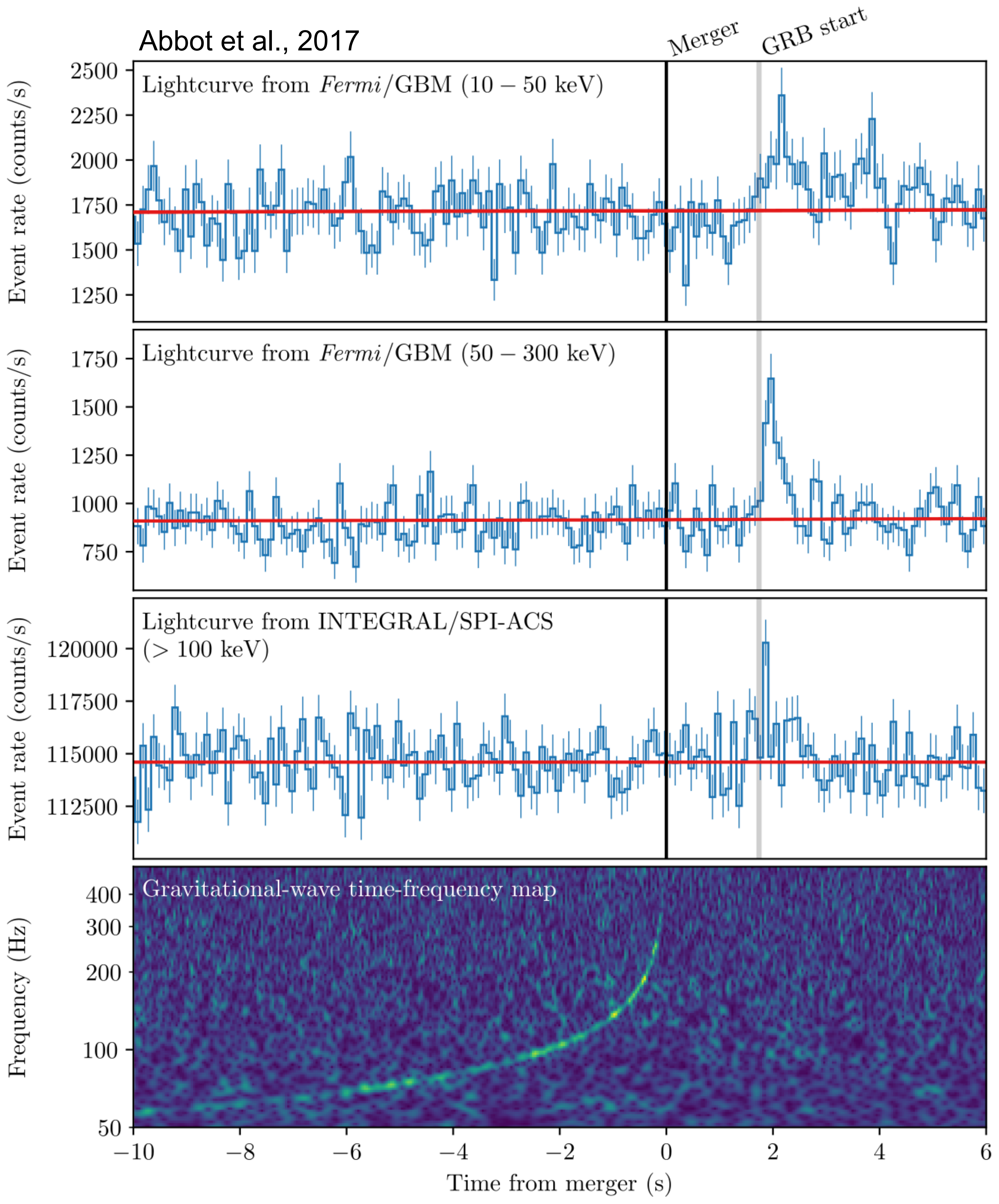


Blazar flares
Emission from relativistic jets of active galactic nuclei accreting matter
Flare durations of minutes to months
Quasi-periodic flares might be linked to binary super-massive black holes

- Again: leaving VHE results to dedicated talks…

Short GRBs and compact object mergers

GW170817



Detection of GRB 170817A / GW170817 provided invaluable new information on a variety of topics:

- Binary neutron star (BNS) mergers are progenitors of short GRBs
- Constraints on gamma-ray emission region
- Constraints on fundamental physics, e.g., speed of gravity
- Origins of heavy elements via subsequent kilonova

Still many open questions:

- rate of short GRB / Kilonova production in BNS mergers
- Structure of the off-axis emission in GRBs
- Expected time delay between GW and GRB onset

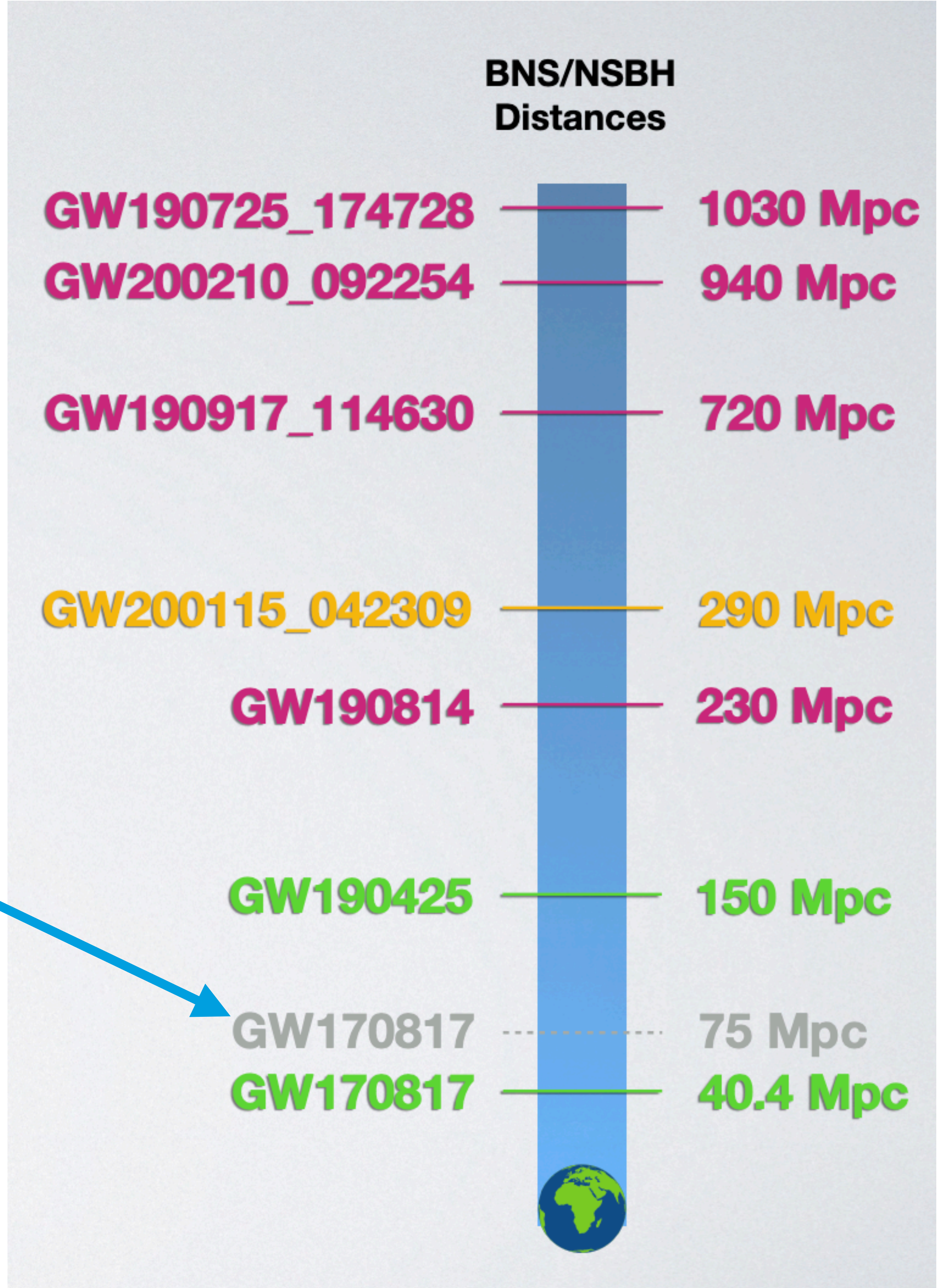
More multi-messenger observations of BNS mergers needed.

Short GRBs and compact object mergers

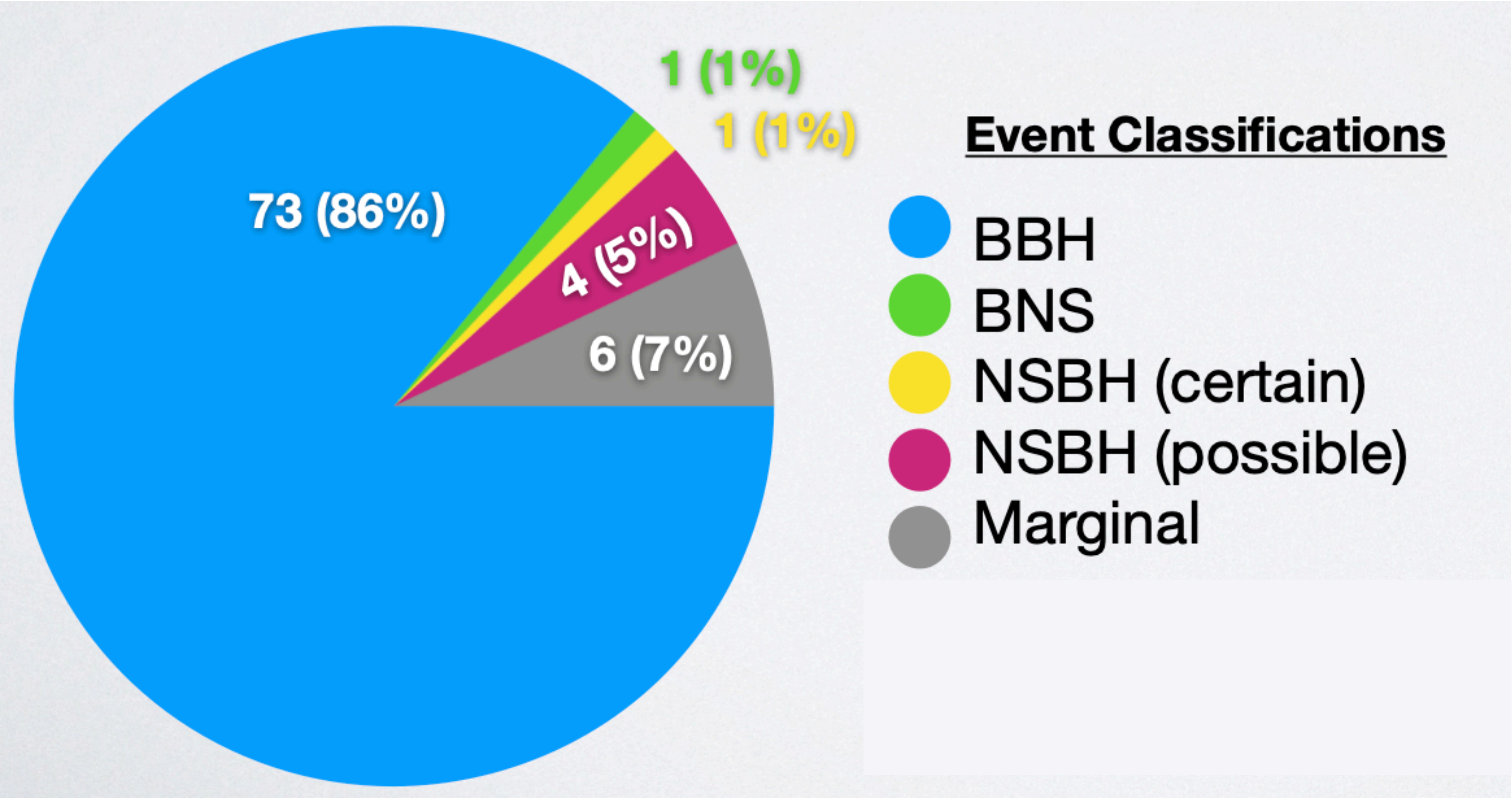
O3 and beyond

- LIGO/Virgo/KAGRA observing run #3 from Apr 2019 to Mar 2020
- No new coincident detections in O3 of BNS or neutron-star/black hole (NSBH) mergers associated with a gamma-ray burst
- Not surprising for observed merger parameters
- Non-observations of binary-black hole mergers associated with GRB are constraining for some models that predict HE emission
- O4 is approaching: expected BNS merger / GRB coincidence rate is 1.04 +/- 0.27 / year (arXiv:2111.03608)

Maximum distance for detection of GW170817 with Fermi GBM

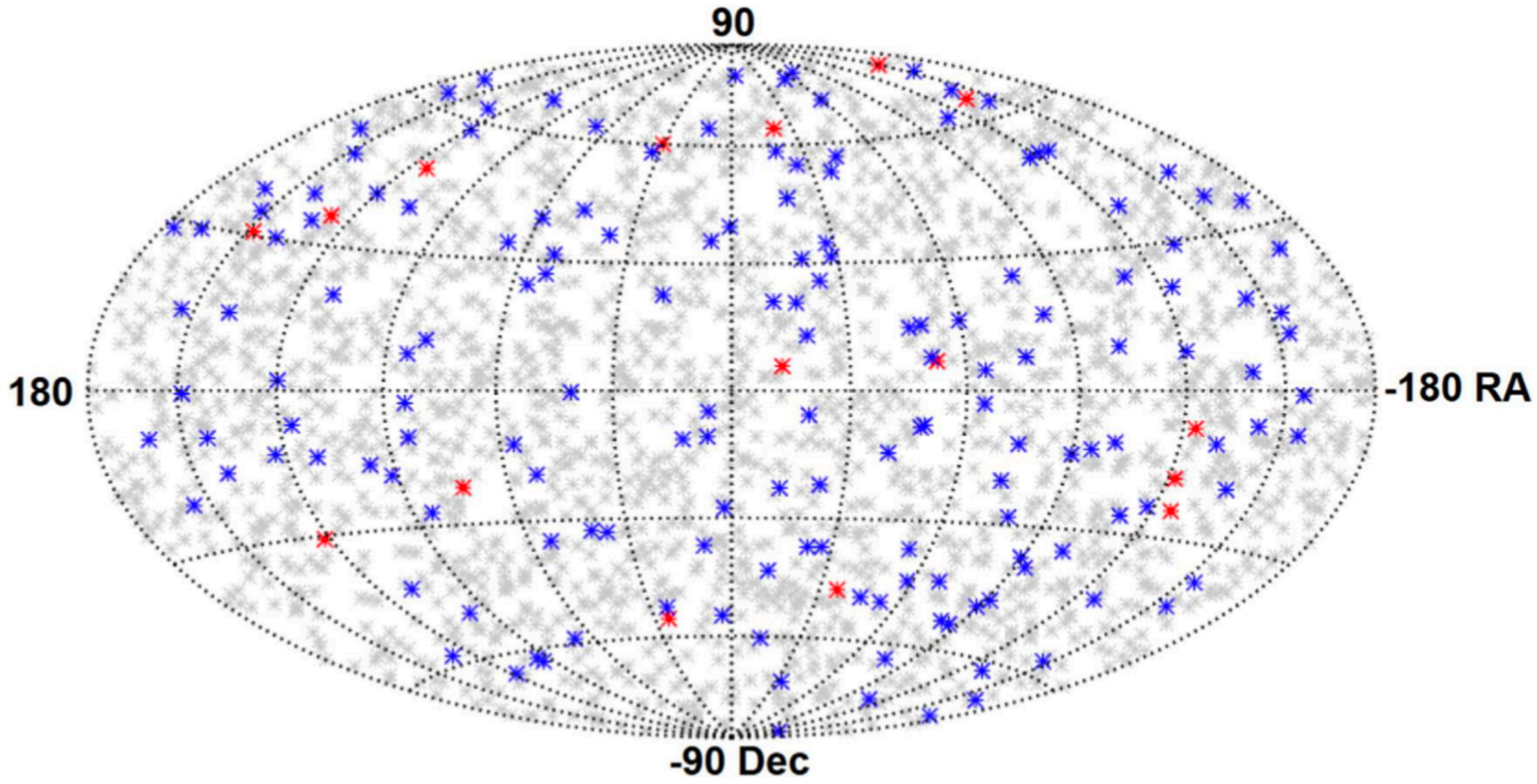


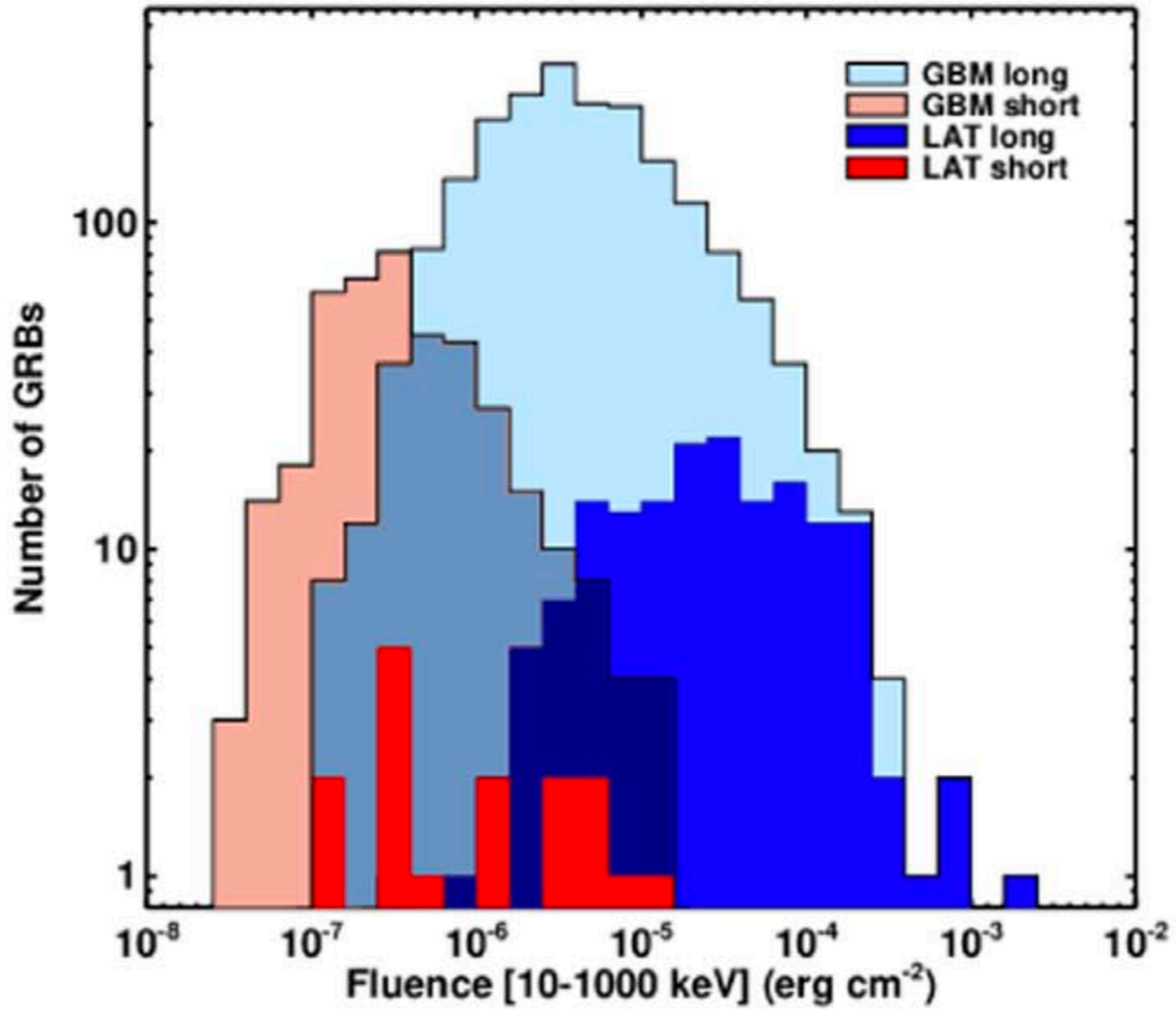
Joshua Wood, 10th Fermi Symposium, 2022

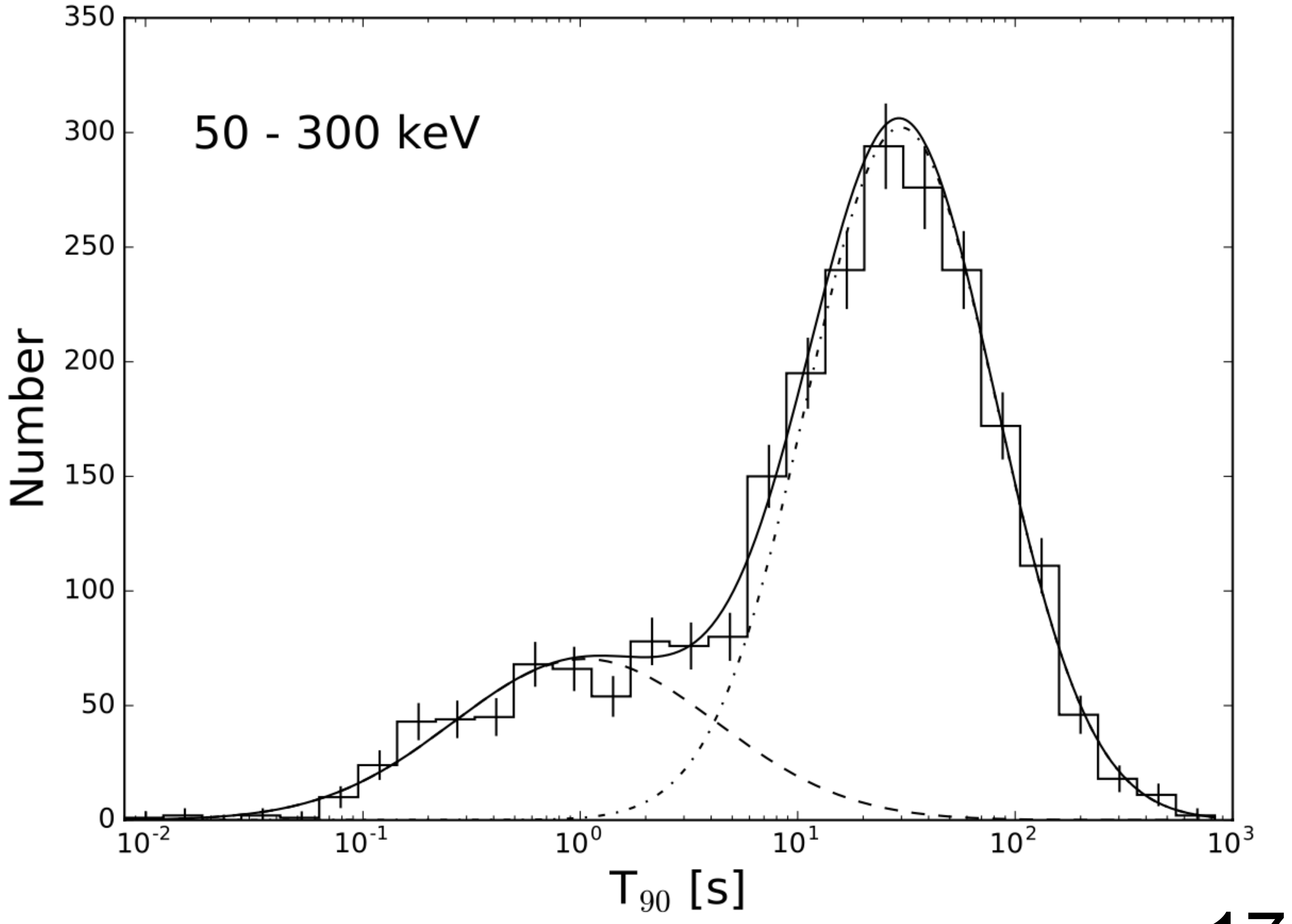


The LAT and GBM GRB populations

10 year catalogs





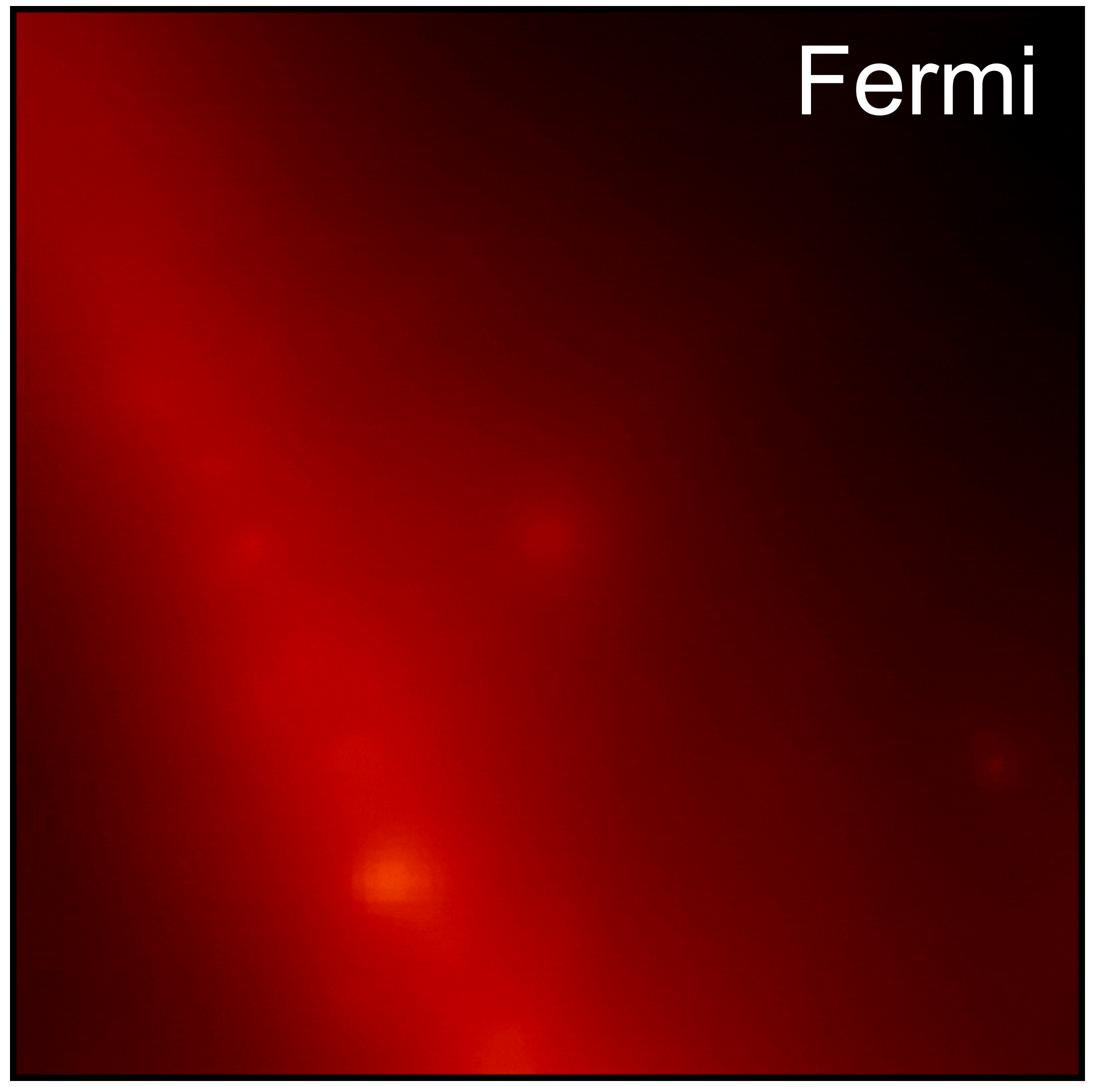


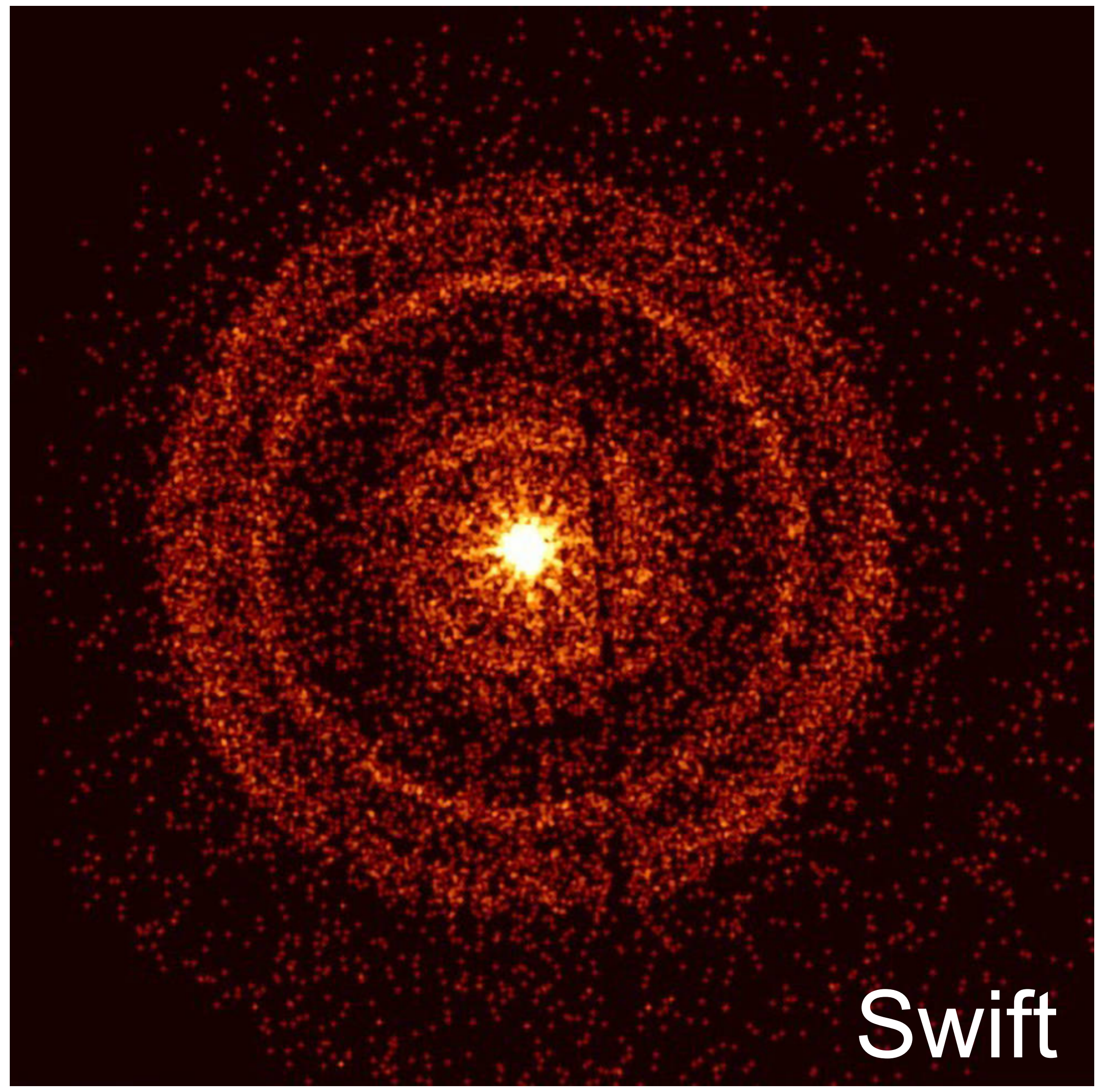
10 year catalogs for LAT and GBM (2008-2018) are milestones for the Fermi mission:

- 2nd LAT GRB catalog: 169 long +17 short GRBs
- 4th GBM catalog: 2356 GBM bursts (1958 long + 395 short)

GRB 220710A

A brief summary of events



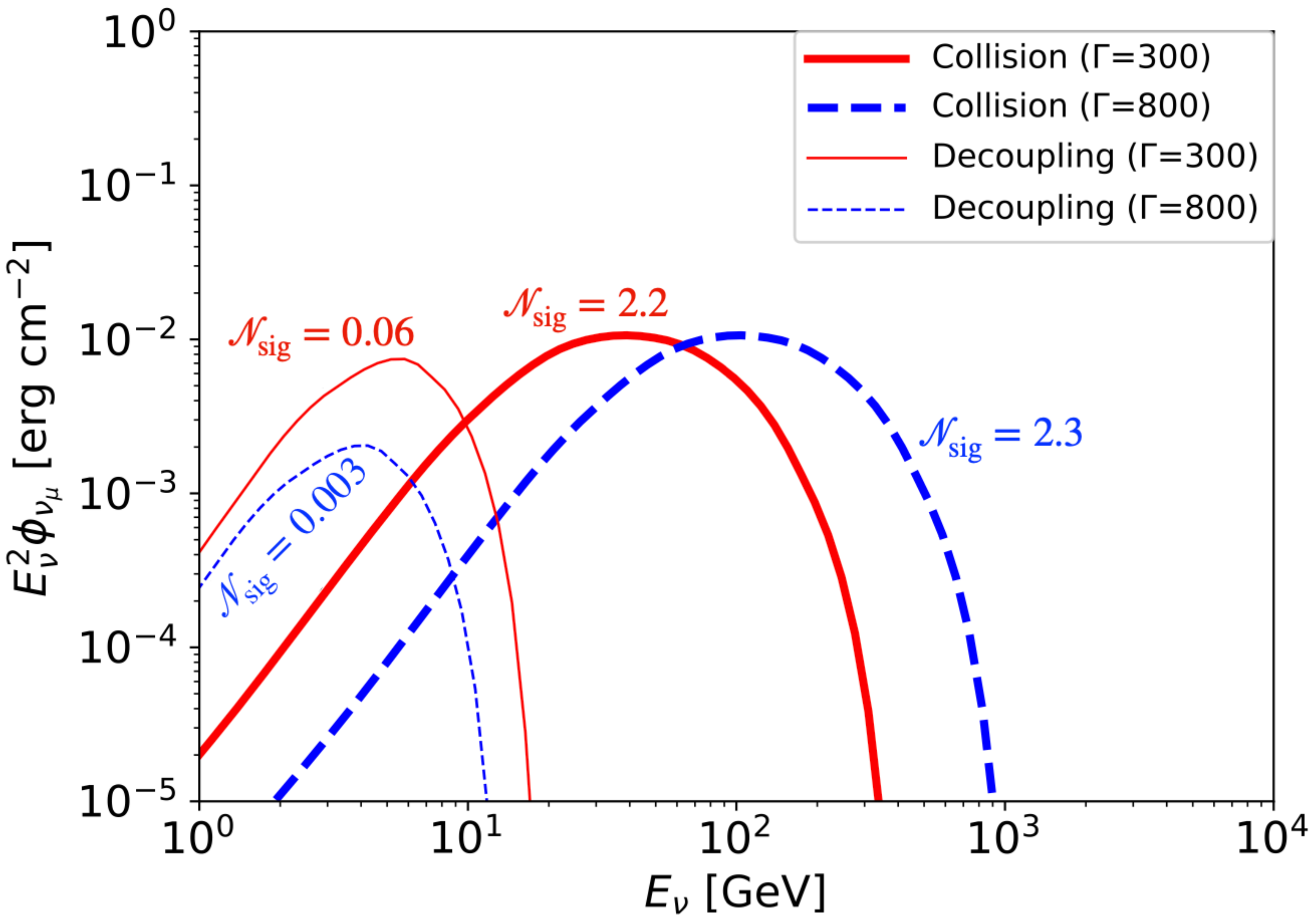


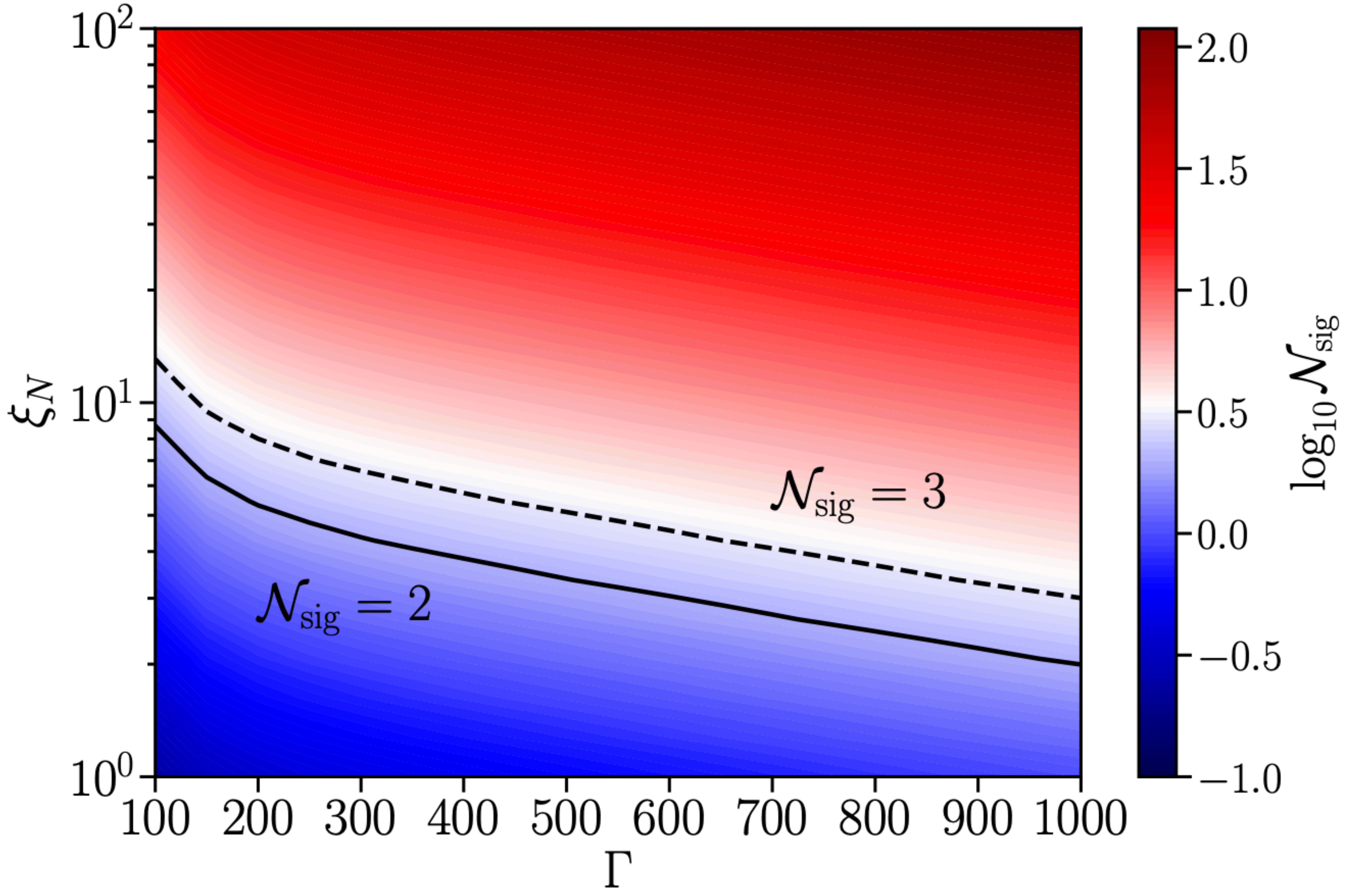
- Brightest gamma-ray burst ever detected by GBM (T_{90} = 327s)
- Brightest afterglow observed by Swift / XRT
- Highest-energy photon ever observed from a GRB by Fermi LAT (99 GeV, 240 s after start of burst)
- LHASSO detects 5000 VHE photons up to around 18 TeV
- Redshift determined by X-shooter/VLT as z = 0.151, $E_{iso} > 2 \times 10^{54}$ erg (saturation / pile-up issues for GBM and other instruments)
- Isotropic energy is among the highest observed ones
- Observations with IACT difficult due to full moon conditions

Neutrinos from GRB 220710A?

The multi-messenger connection

- No TeV neutrinos observed in coincidence with GRB (GCN 221009A)
- Authors suggest that under certain conditions a measurable flux of sub-TeV neutrinos is produced in this burst and recommend dedicated searches.

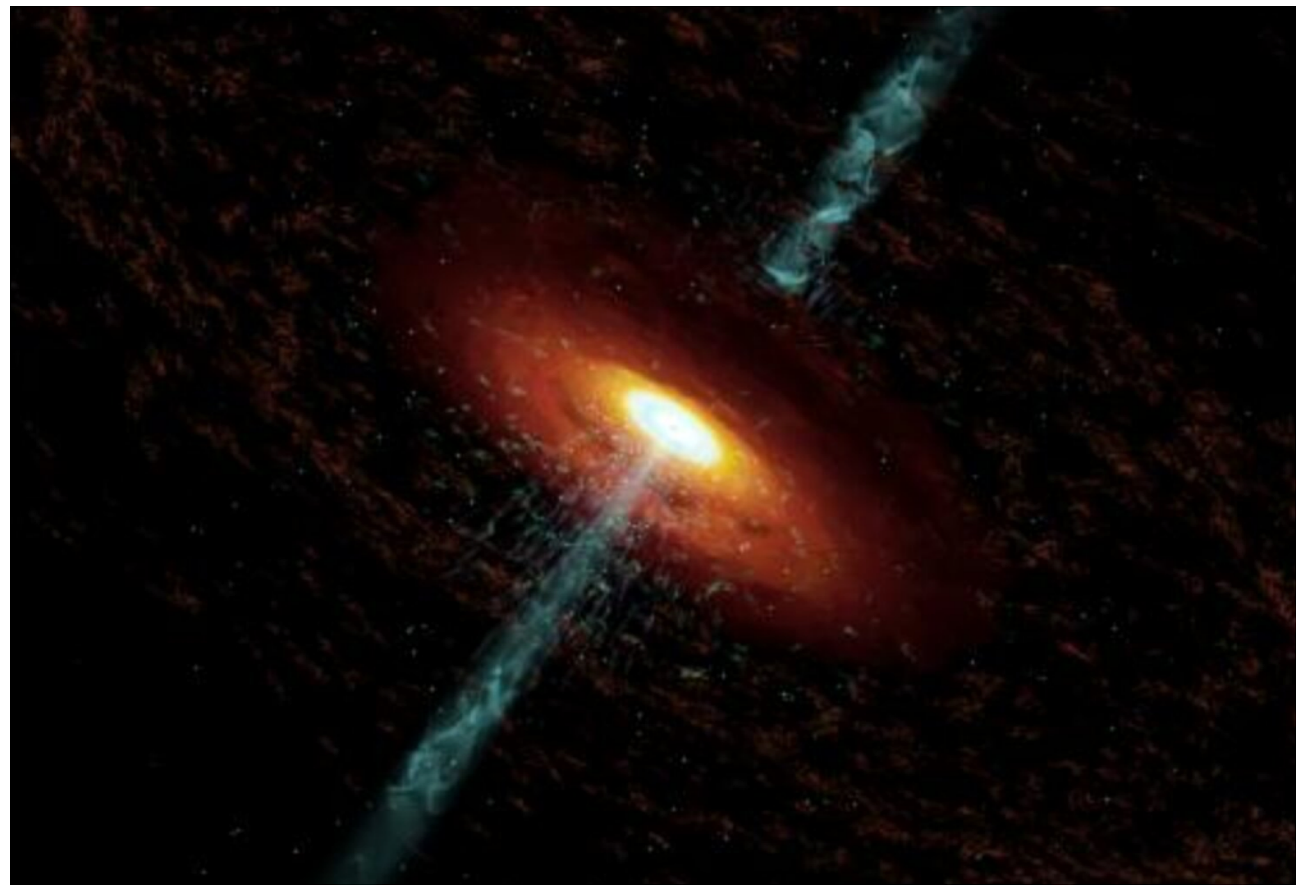


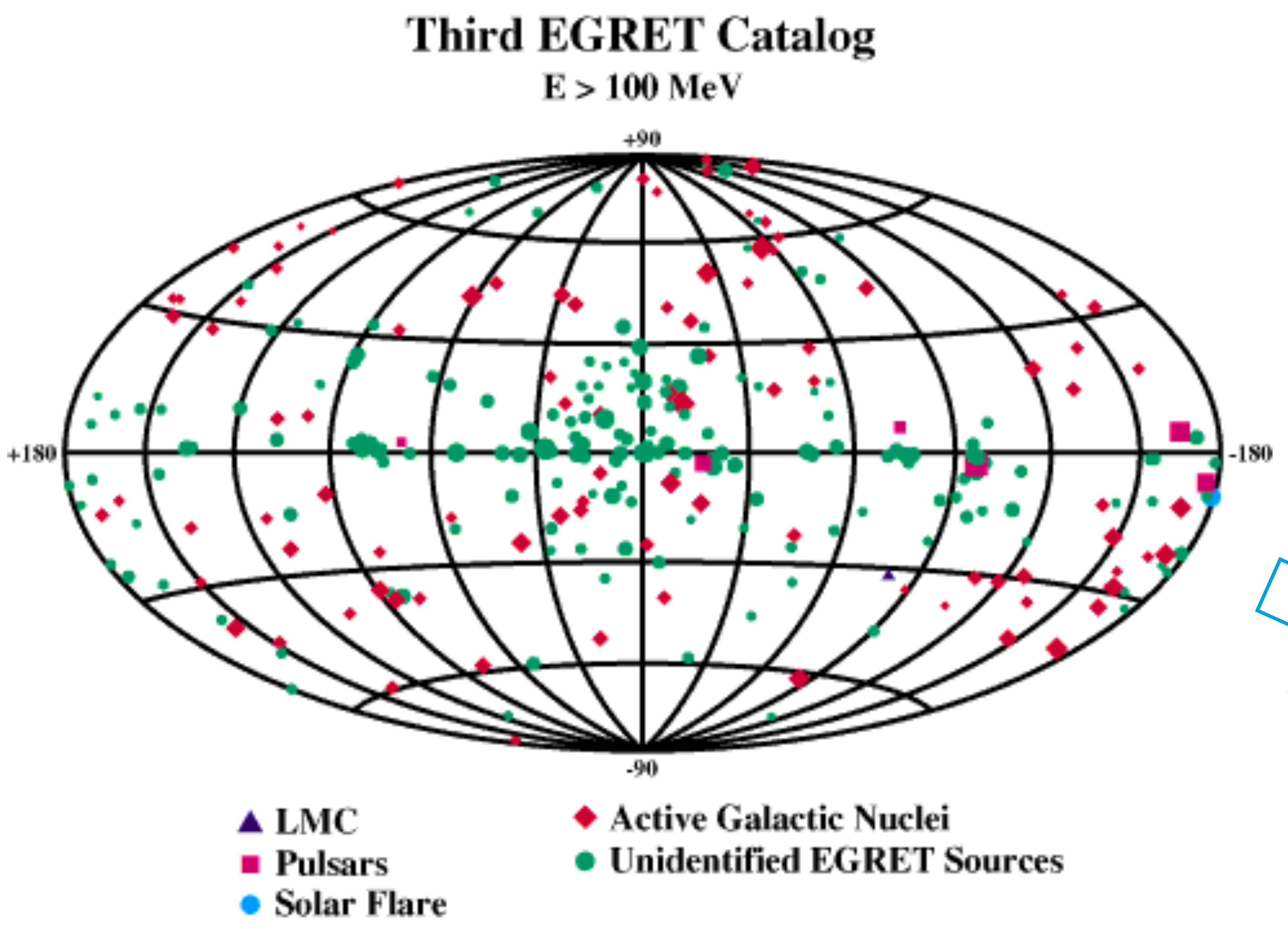


Murase et al., arXiv:2210.15625

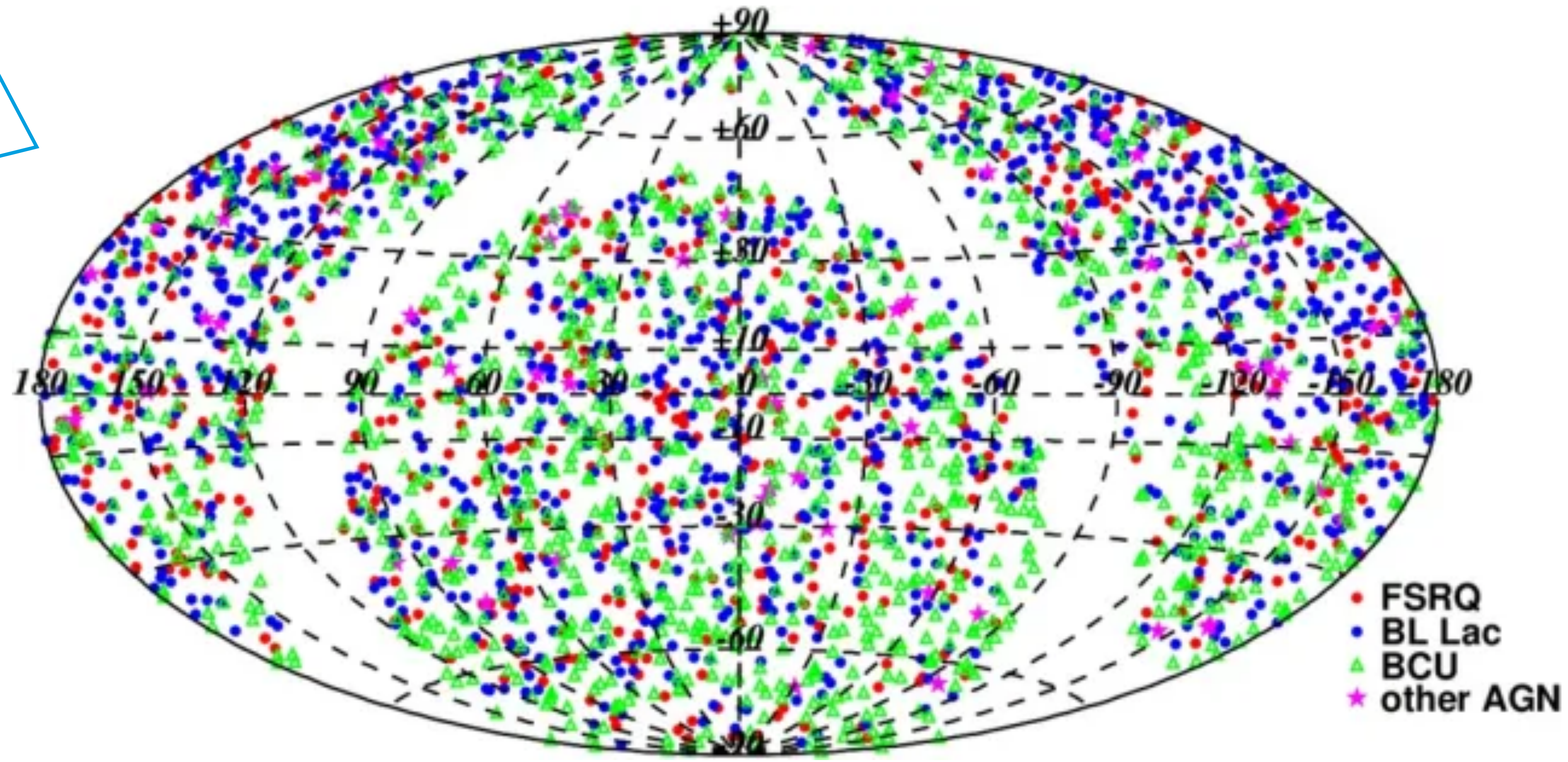
Blazars and their flares

Blazar flares
Emission from relativistic jets of supermassive black holes accreting matter





- Continuous all-sky monitoring of thousands of gamma-ray blazars over more than a decade
- Coordinated multiwavelengths and multi-messenger campaigns spanning years

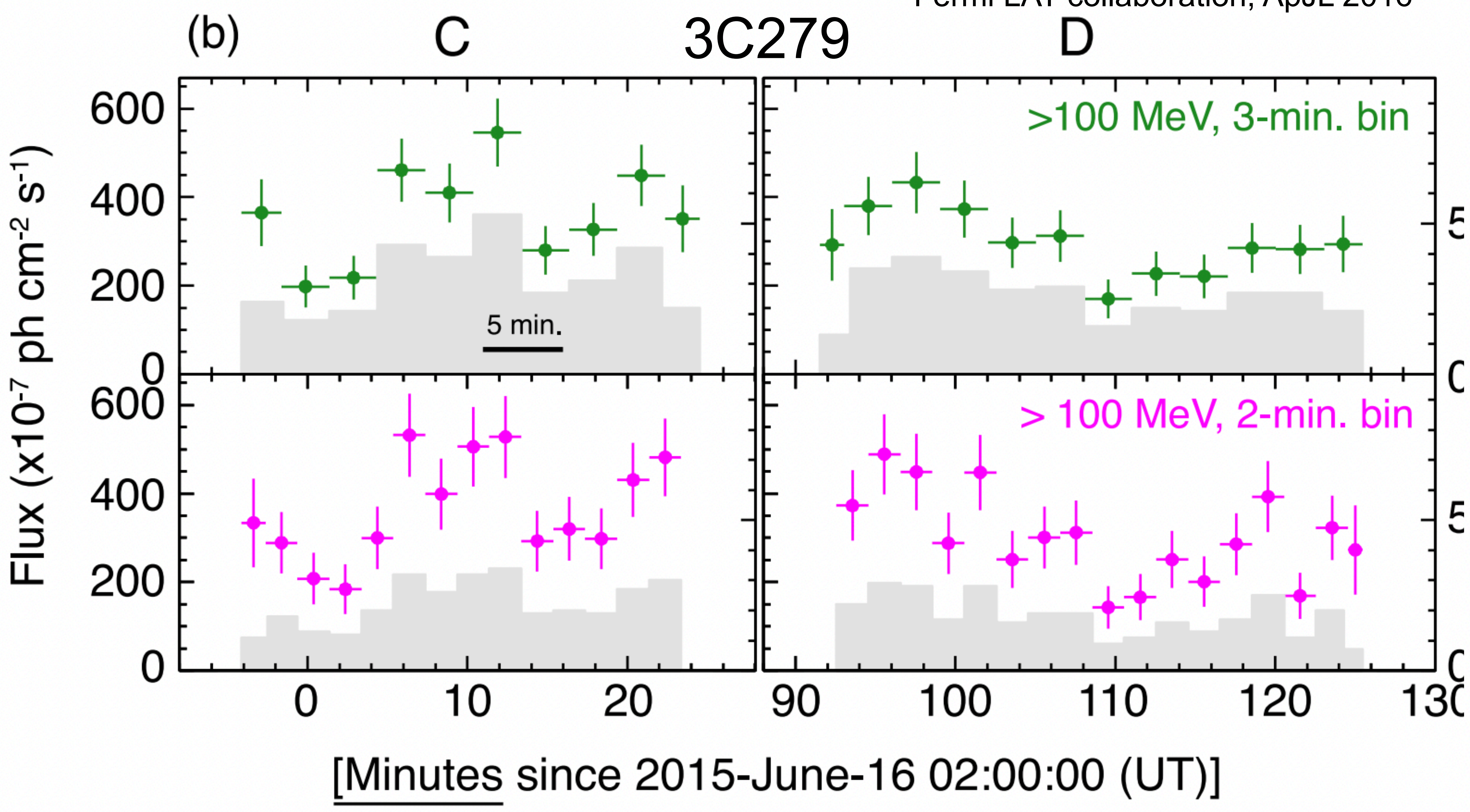


4th LAT AGN Catalog (4LAC)

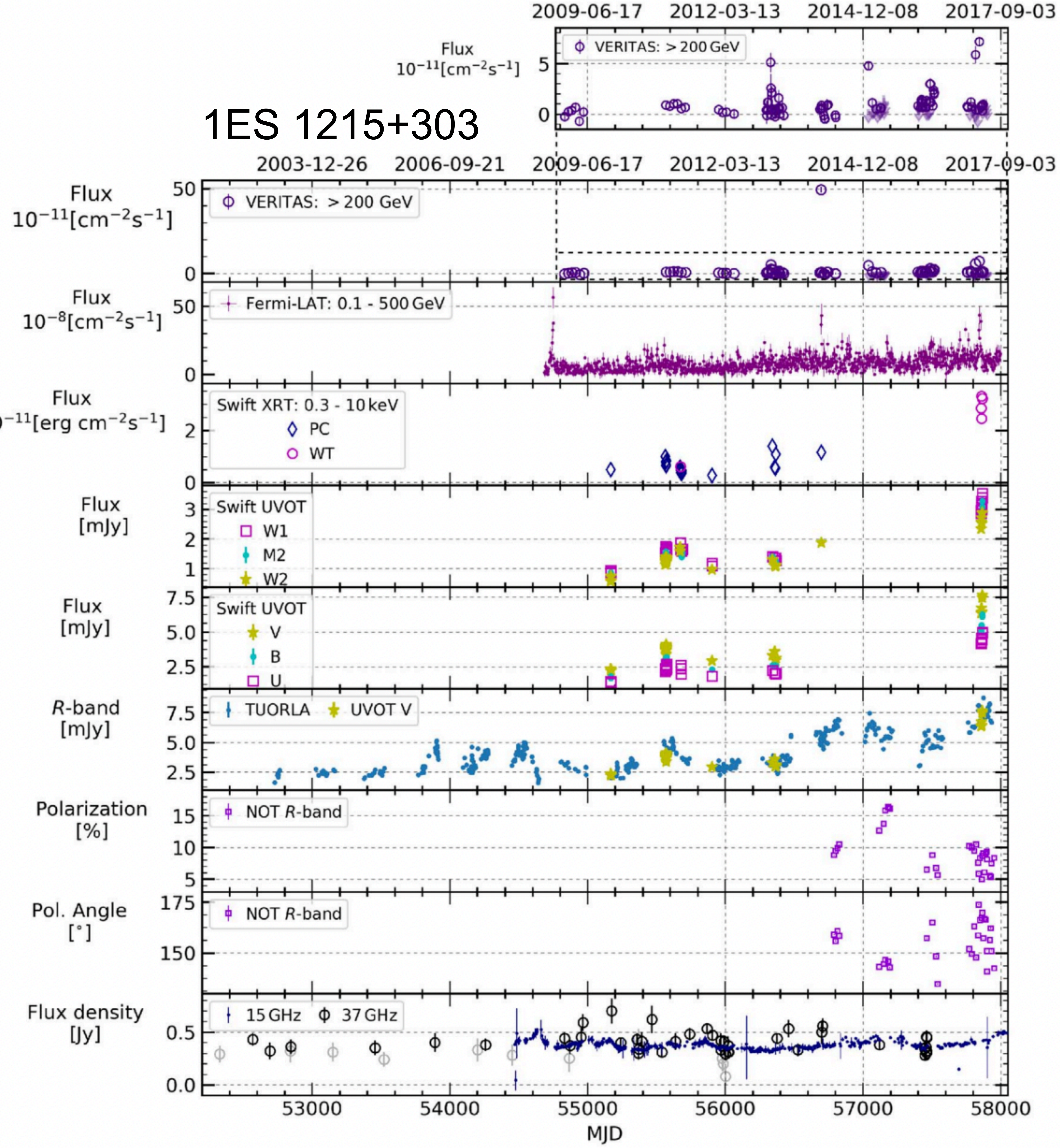
Multiwavelength observations

and variability studies

Fermi LAT collaboration, ApJL 2016



Valverde et al, ApJ, 2020

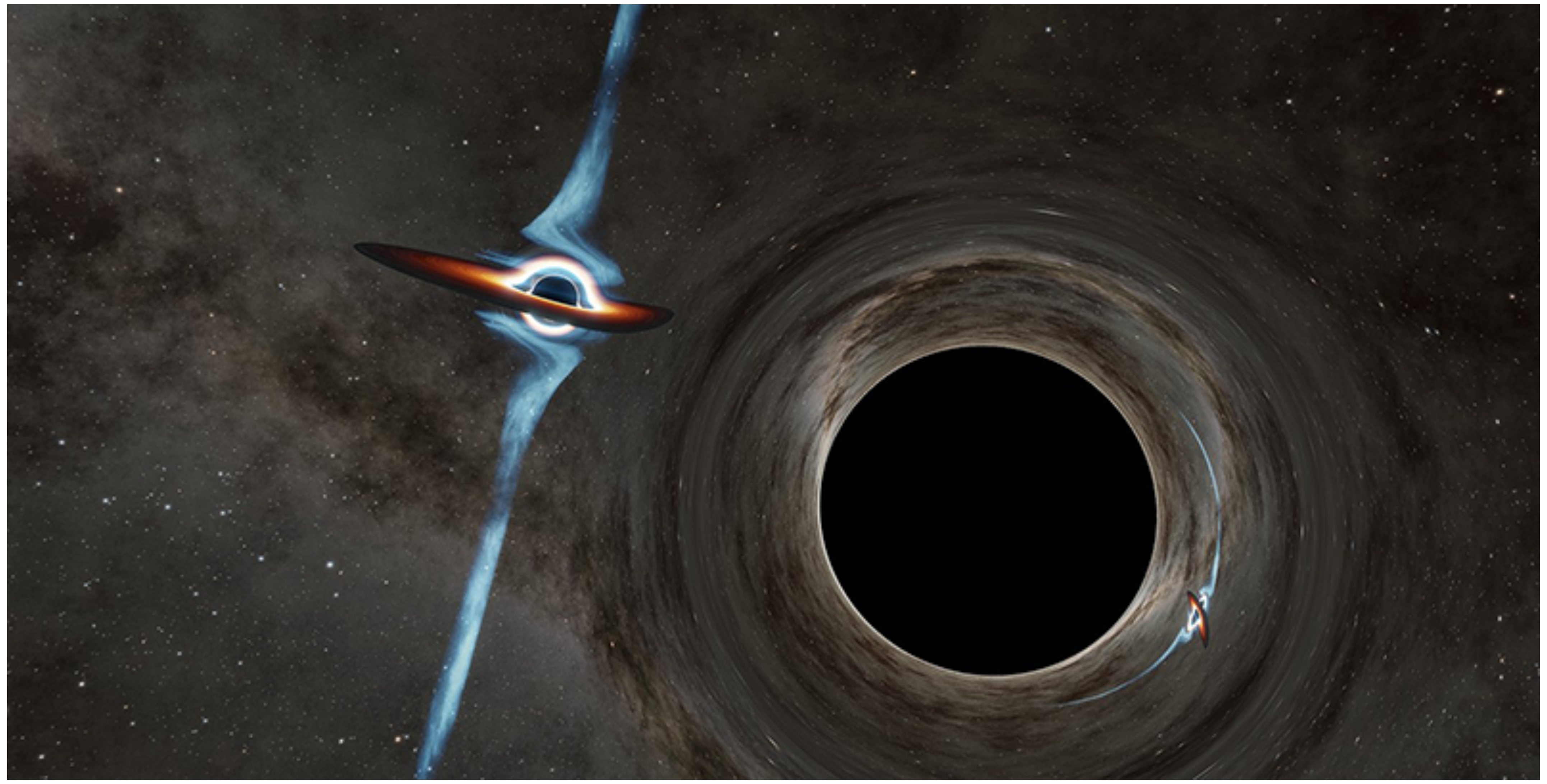


- Multi-wavelength campaigns now stretch over a decade with continuous Fermi LAT data coverage
- Minute scale variability in the GeV band observed for several bright blazars (like at VHE energies)
- Constraints on acceleration / emission models, jet structure, etc.

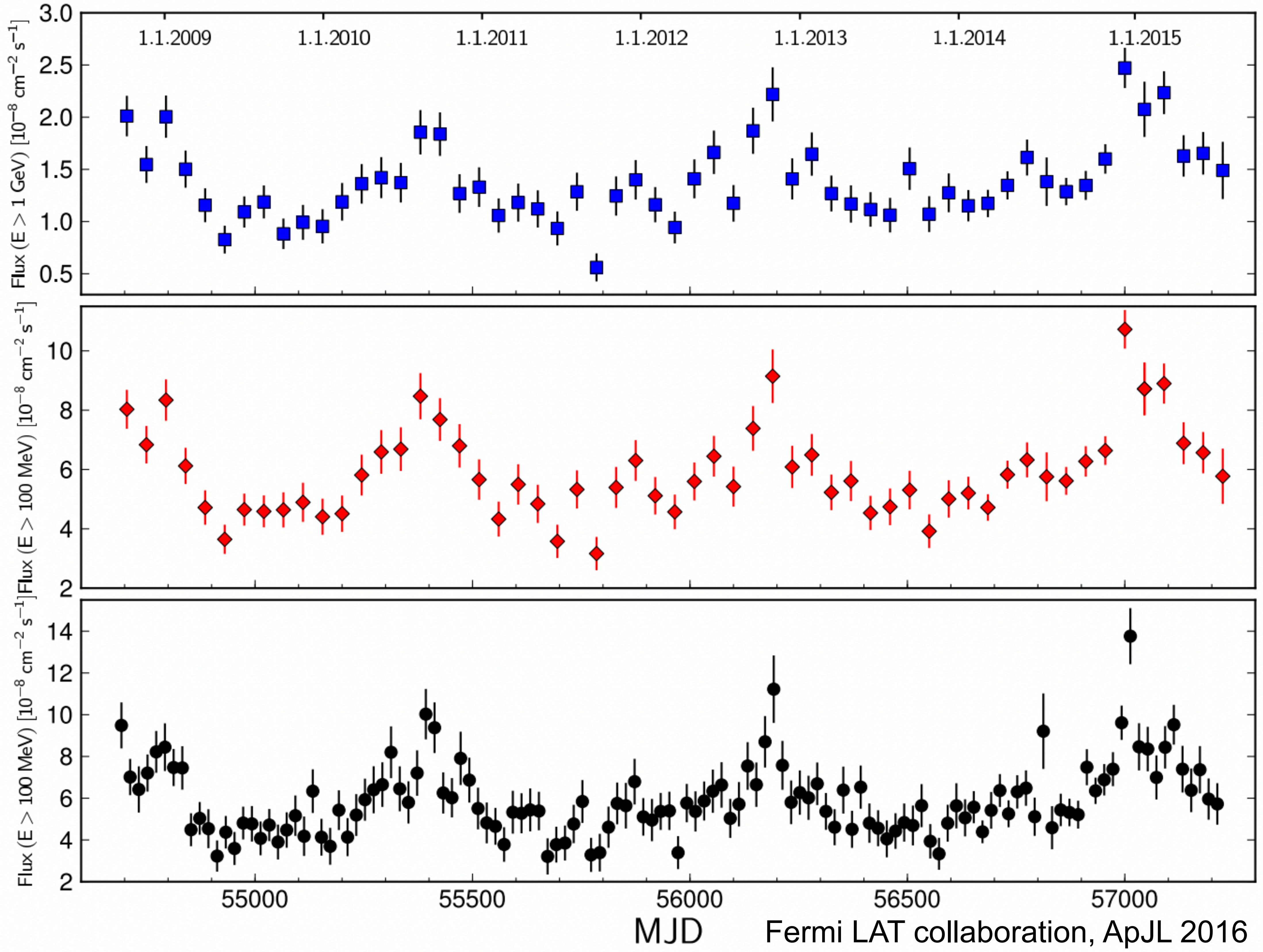
Super-massive binary black holes

PG 1553+113

- Very few candidates known from long-term optical / radio monitoring, e.g. OJ 287, PKS 2131-021
- Several interesting candidates from LAT observations

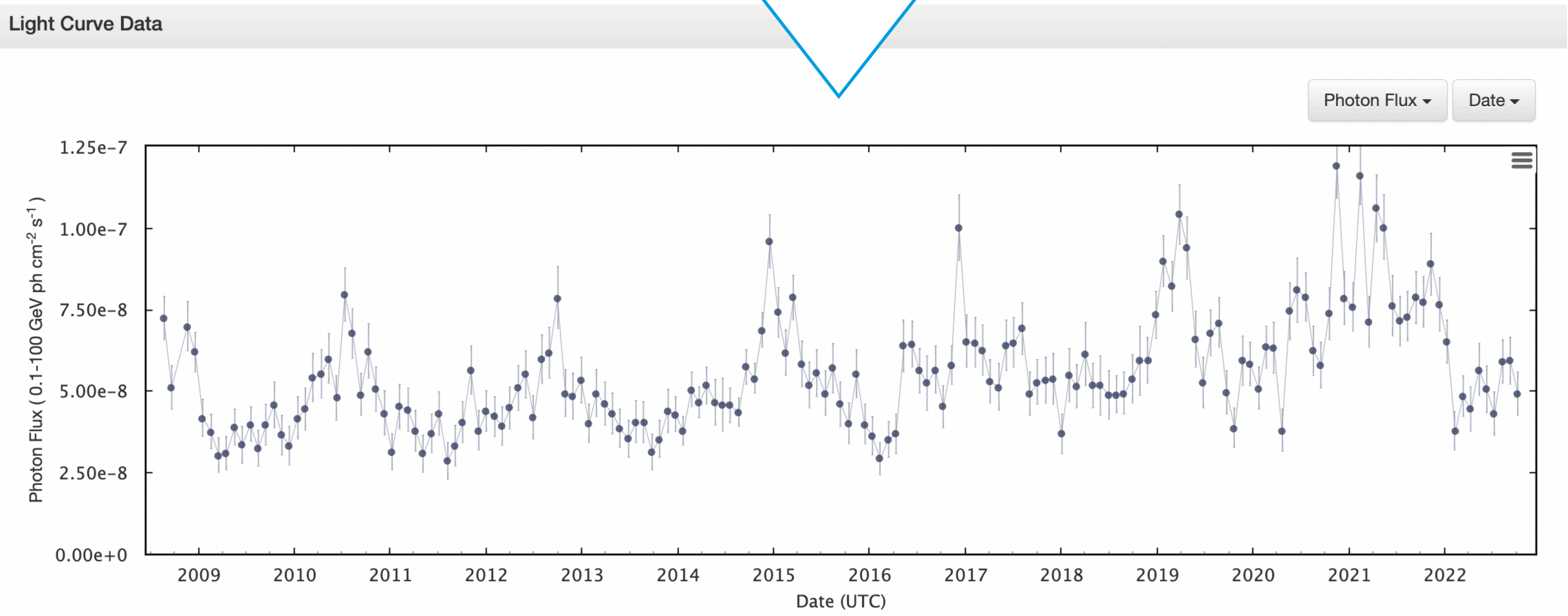


PG 1553+113: 2.2 +/- 0.1 yr period



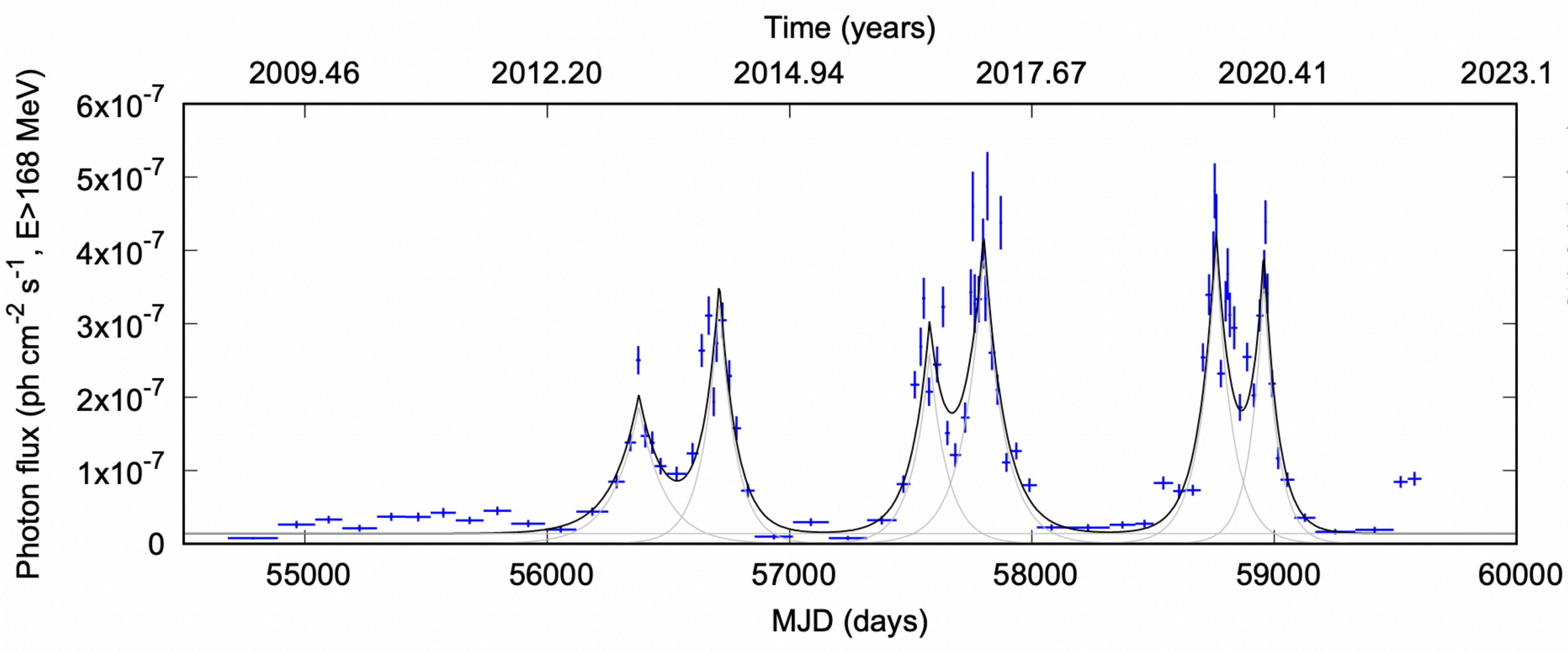
Fermi LAT collaboration, ApJL 2016

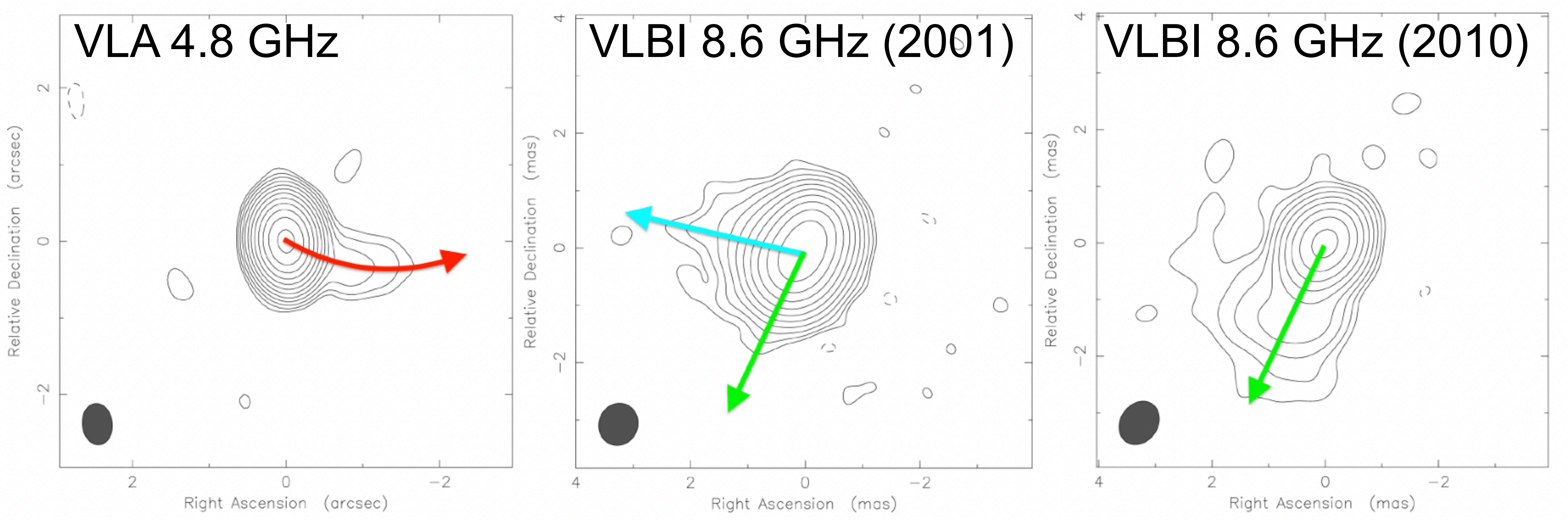
Fermi LAT light curve repository



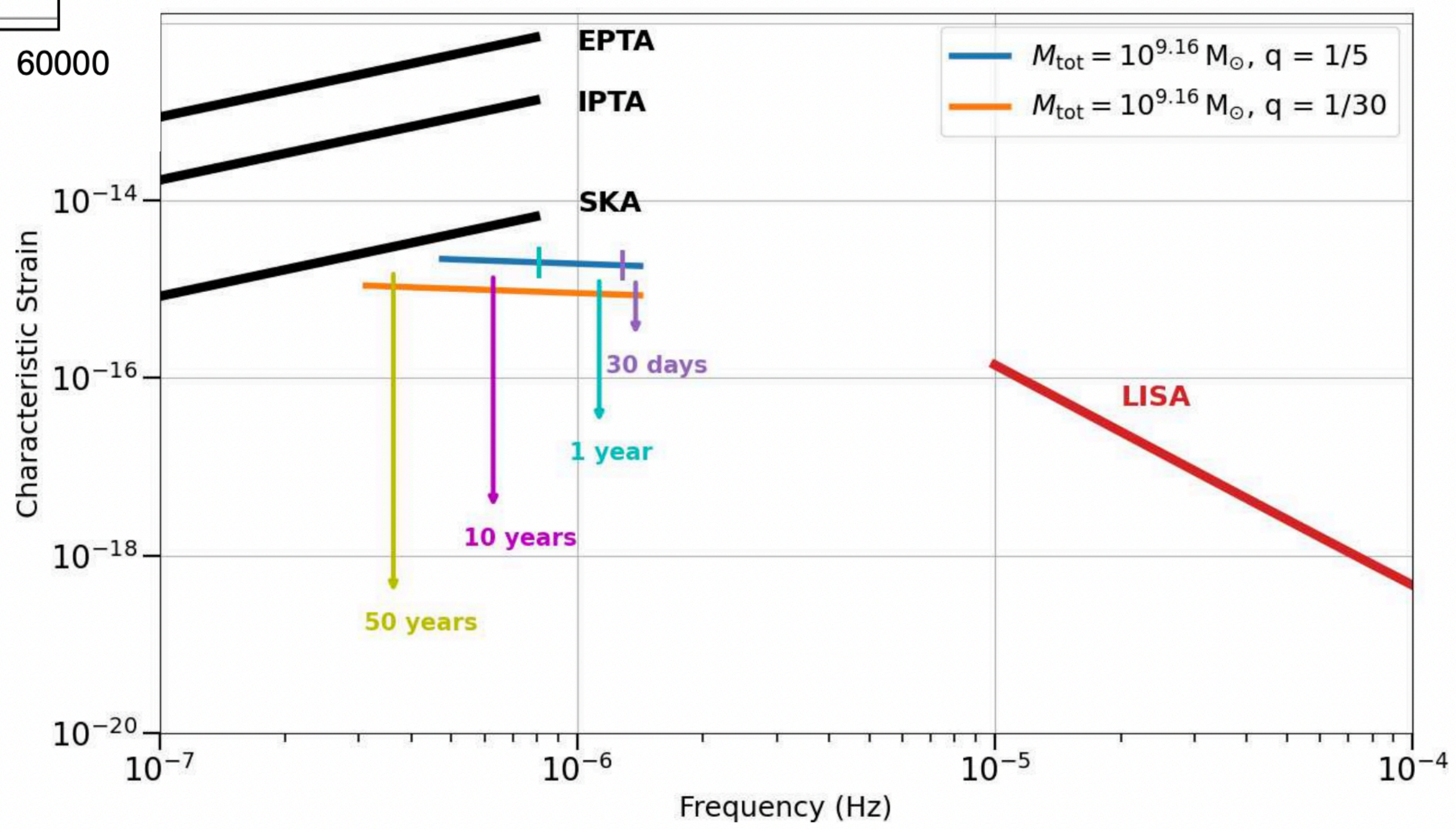
Super-massive binary black hole candidates

from Fermi-LAT observations





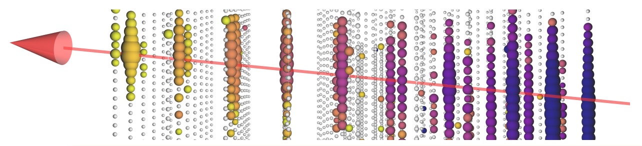
Kun et al., arXiv:2209.05107



- FSRQ J1048+7143 at z=1.15
- Quasi-periodic with a period of 3.05 +/- 0.4 years
- Possible merger in 60 - 80 years
- Derived parameters for SMBBH case do not favor a detection by future pulsar timing arrays or LISA

Blazar flares and high-energy neutrinos

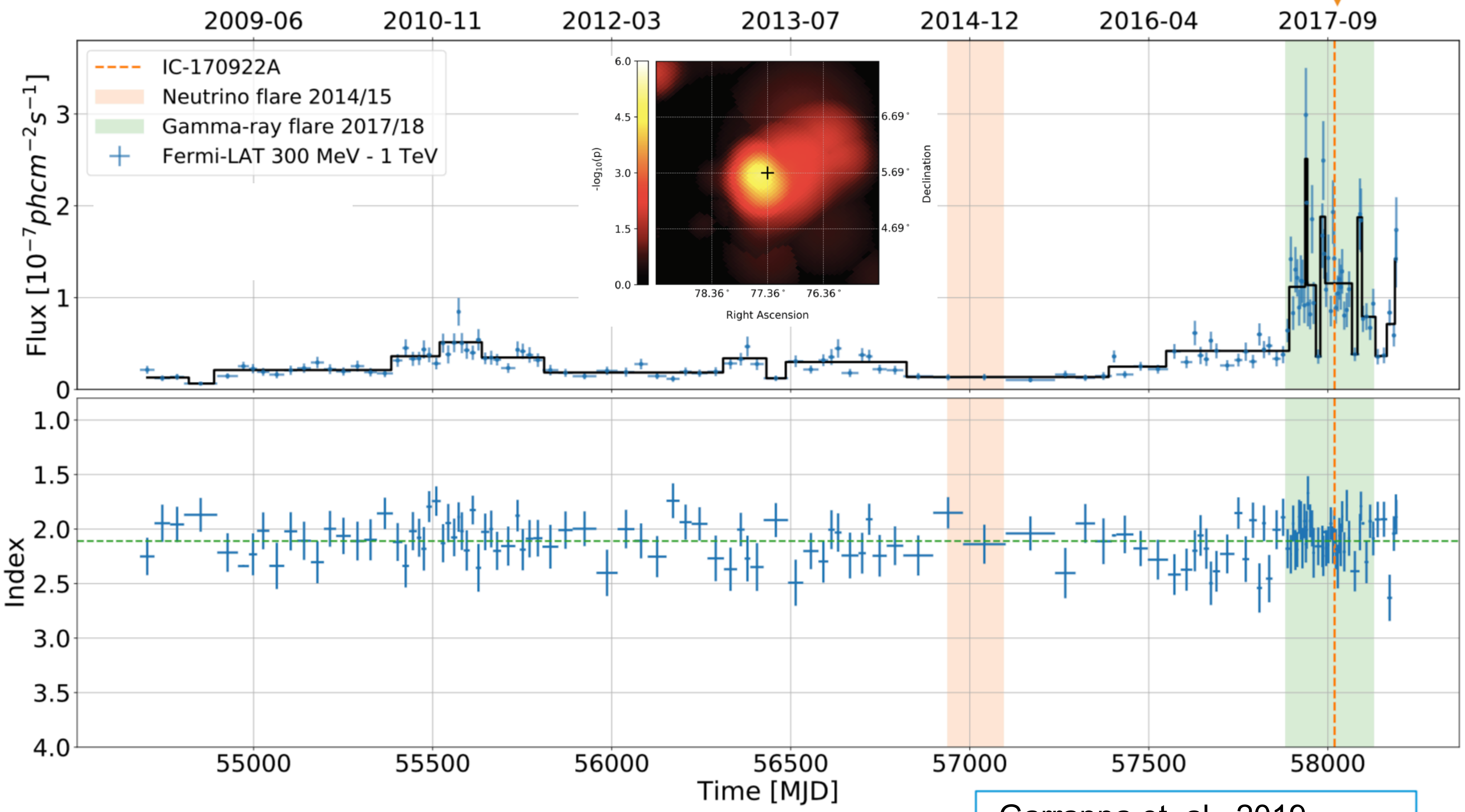
TXS 0506+056



Neutrino Flare
158 days

IC-170922A

- IC-170922A in coincidence with gamma-ray flare of the blazar TXS0506+056
- Excess of O(10) neutrinos over expected backgrounds during a 158 day period in archival data
- Each observation has a significance at the 3 sigma level



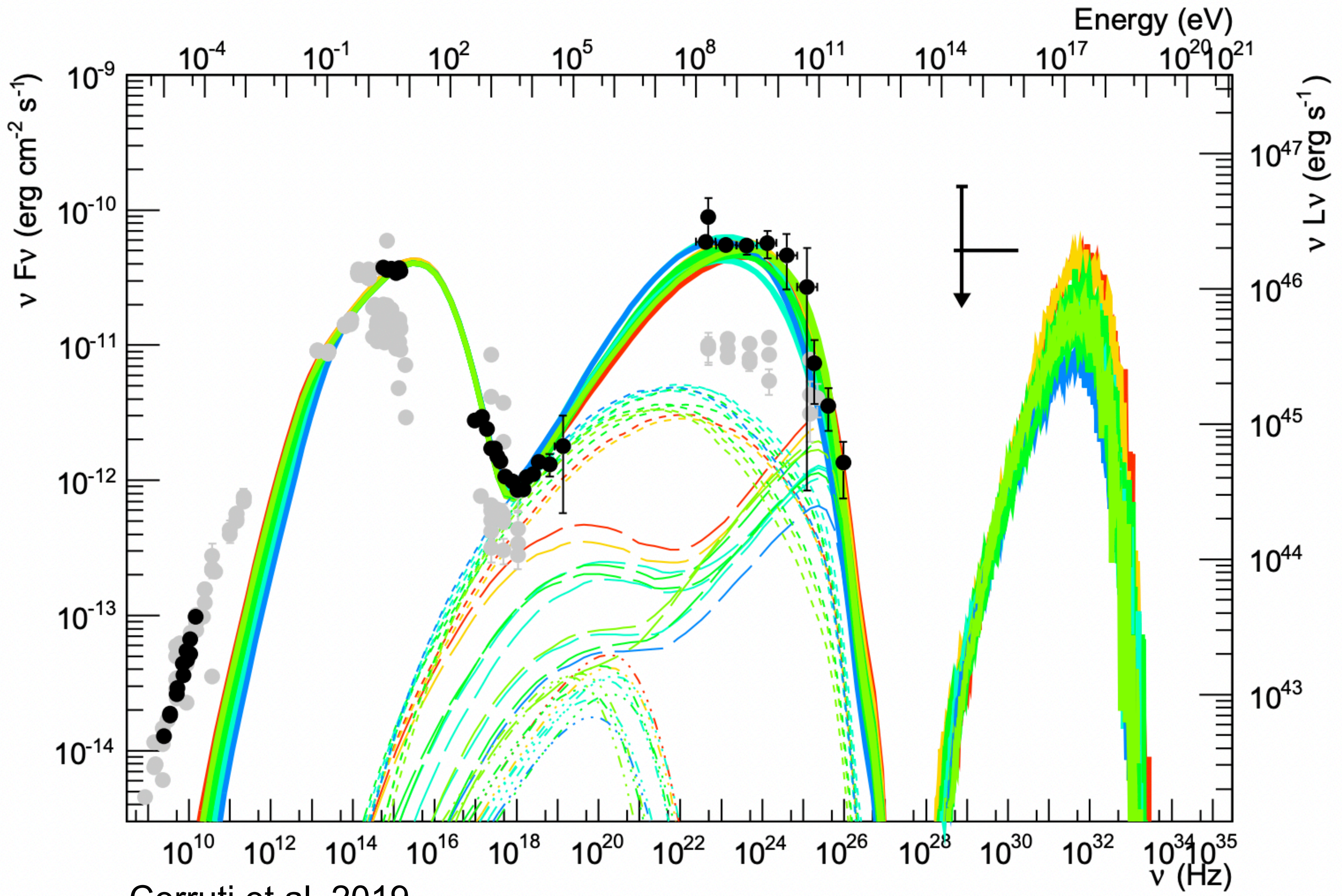
Garrappa et. al., 2019

Blazar flares and high-energy neutrinos

Interpretation

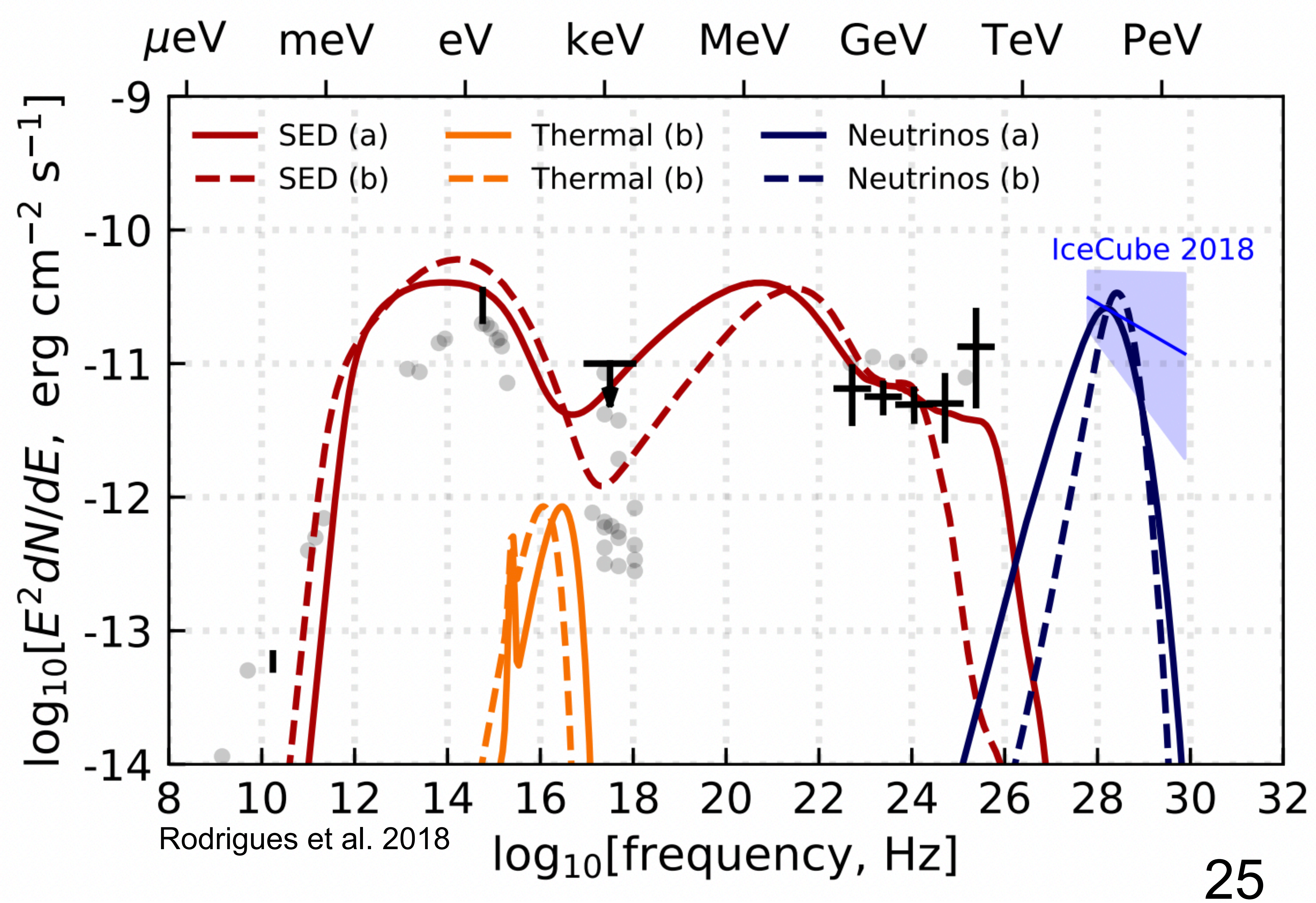
- **O(10) neutrinos** from 2014/2015 neutrino flare implies **several times higher neutrino than gamma-ray luminosity**
- Challenge for modelling, even bigger challenge to reconcile with 2017 observations within a single model
- X-ray and MeV observations key to constrain model space

2017 high-energy neutrino
1-zone leptohadronic model



Cerruti et al. 2019

2014/2015 neutrino flare
external photon fields

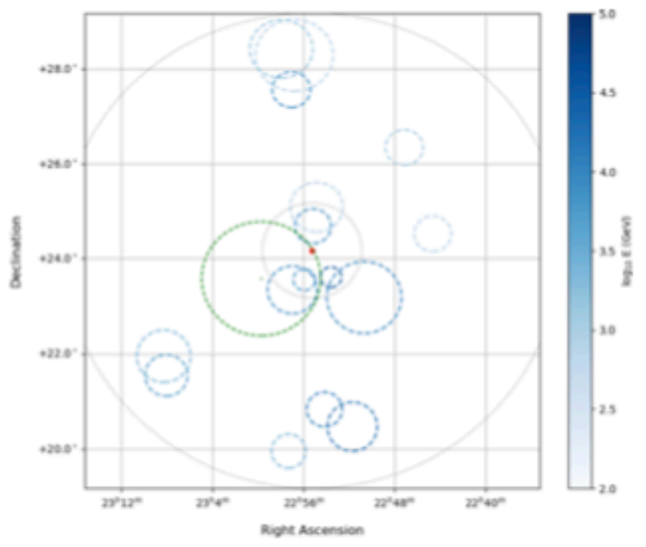


Rodrigues et al. 2018

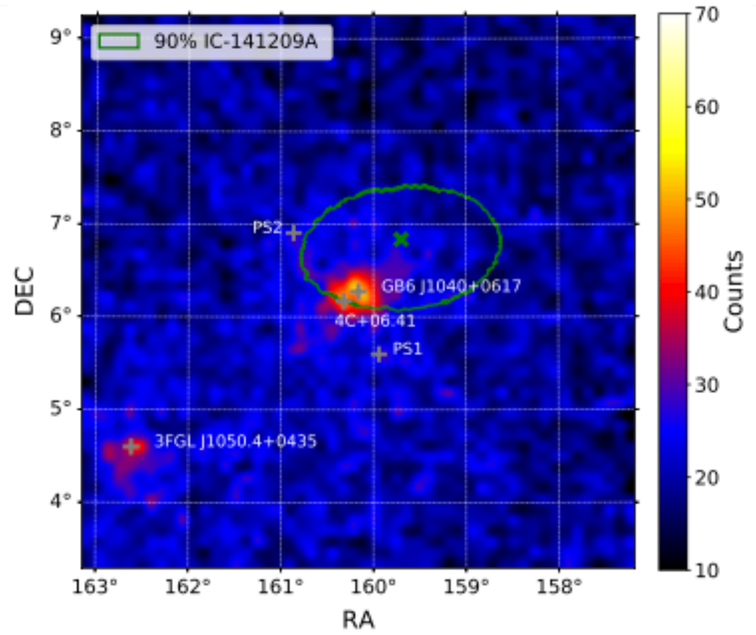
Blazar flares and high-energy neutrinos

Additional correlations

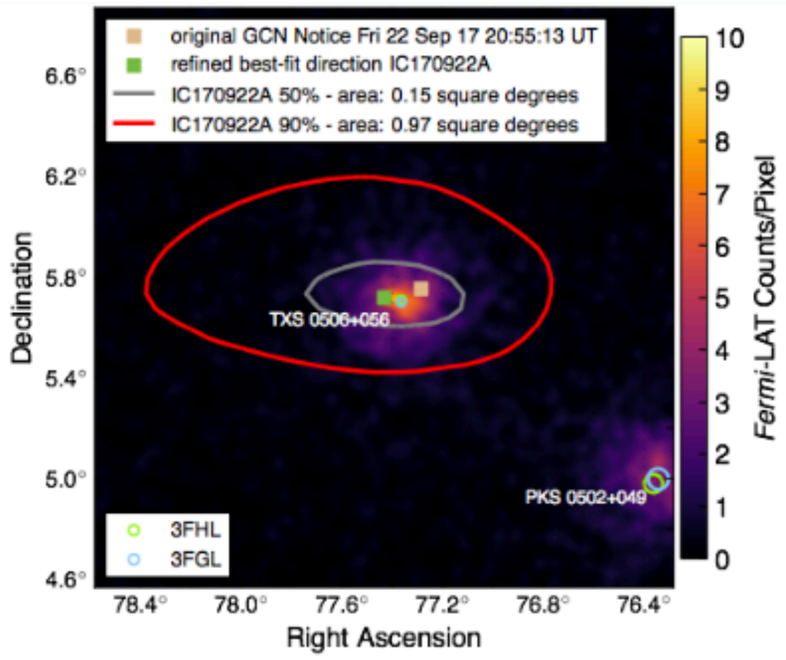
- S. Garrappa, 10th Fermi Symposium, Oct 2022



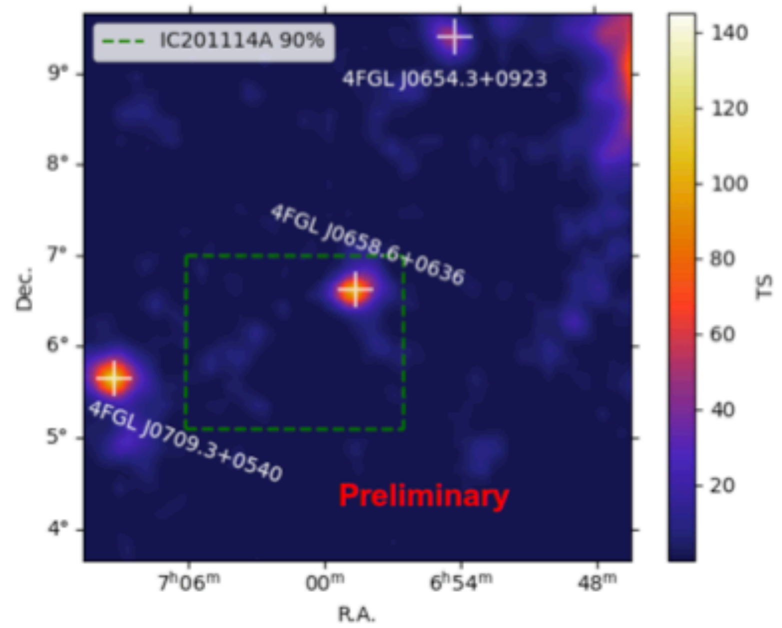
IC-100608A and MG3 J225517+2409
Flaring: Yes
ANTARES Coll. et al. 2021



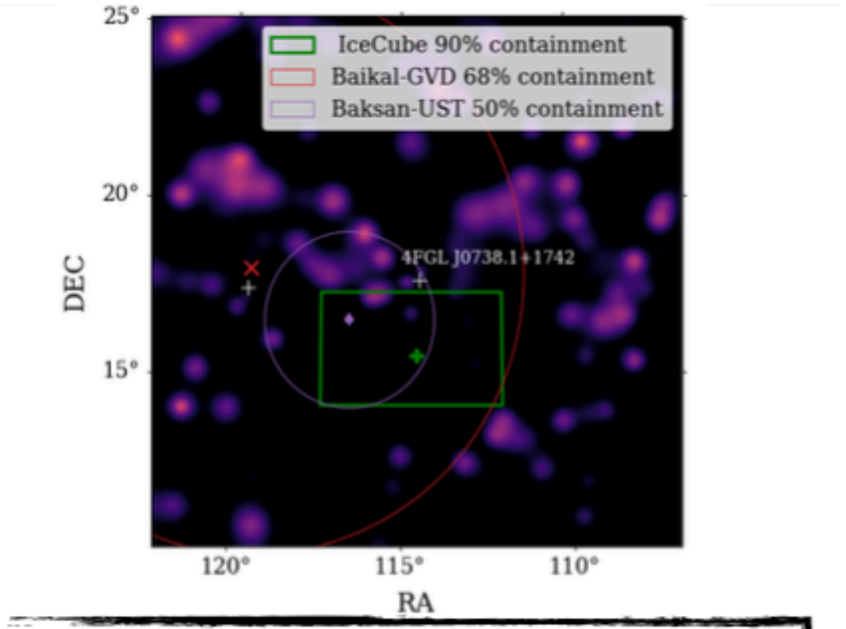
IC-141209A and GB6 J1040+0617
Flaring: Yes
SG et al. 2019



IC-170922A and TXS 0506+056
Flaring: Yes
IceCube Coll. et al. 2018



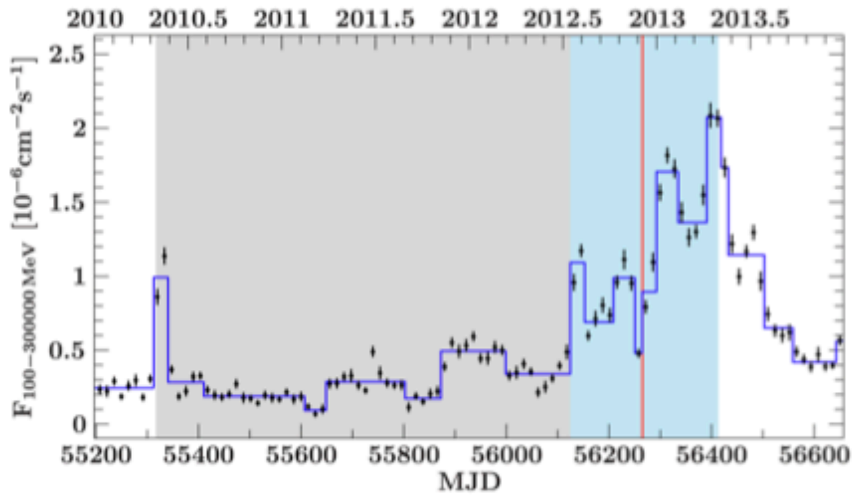
IC-201114A and 4FGL J0658.6+0636
Flaring: No
de Menezes et al. 2021



IC-211208A and PKS 0735+17
Flaring: Yes
SG et al. 2021, ATel #15099
Sahakyan et al. 2022,
Omeliukh, SG et al. (in prep.)

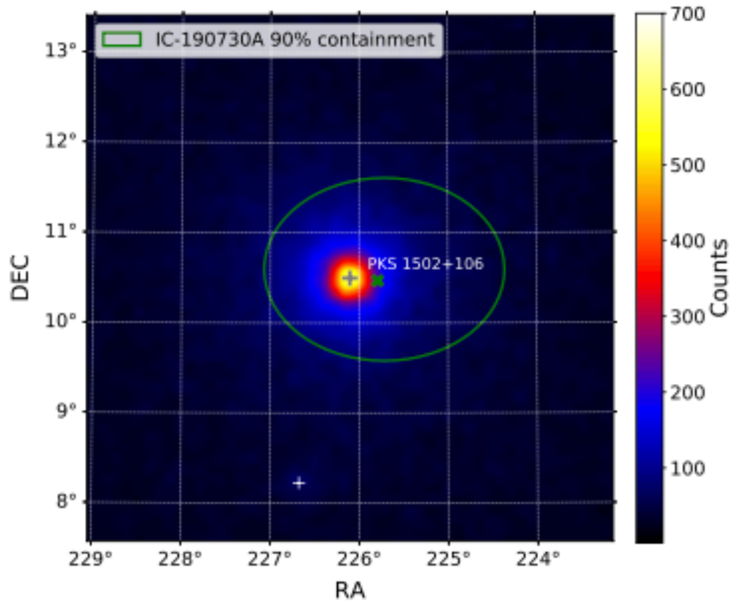
2010 2012 2014 2016 2018 2020 2022

Year

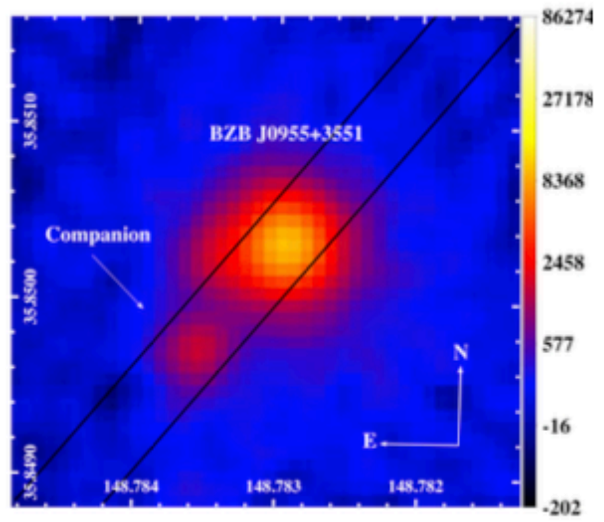


IC-35 and PKS 1424-41
Flaring: Yes
Kadler et al. 2016

IceCube Realtime alert stream



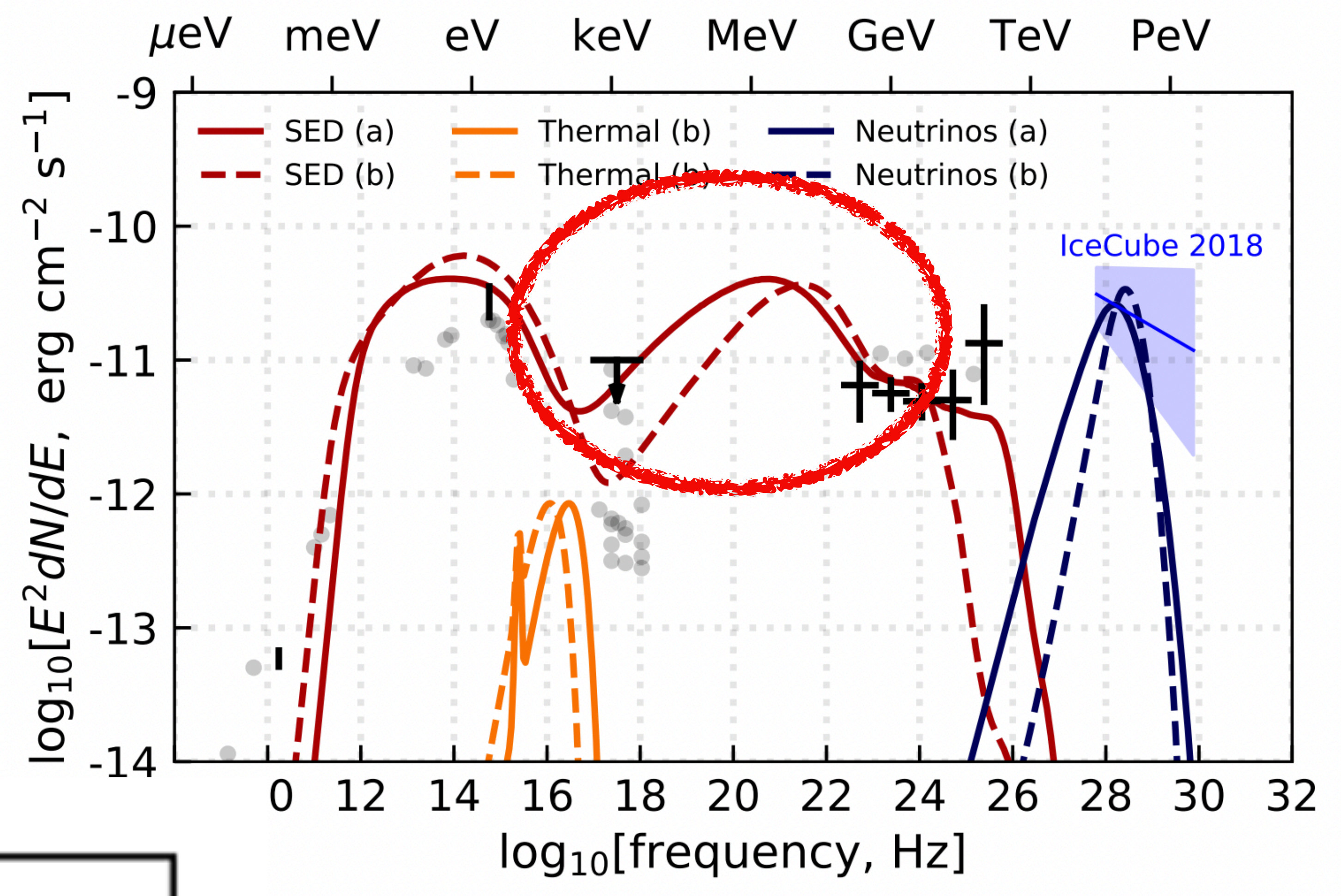
IC-190730A and PKS 1502+106
Flaring: No
Franckowiak, SG et al. 2019

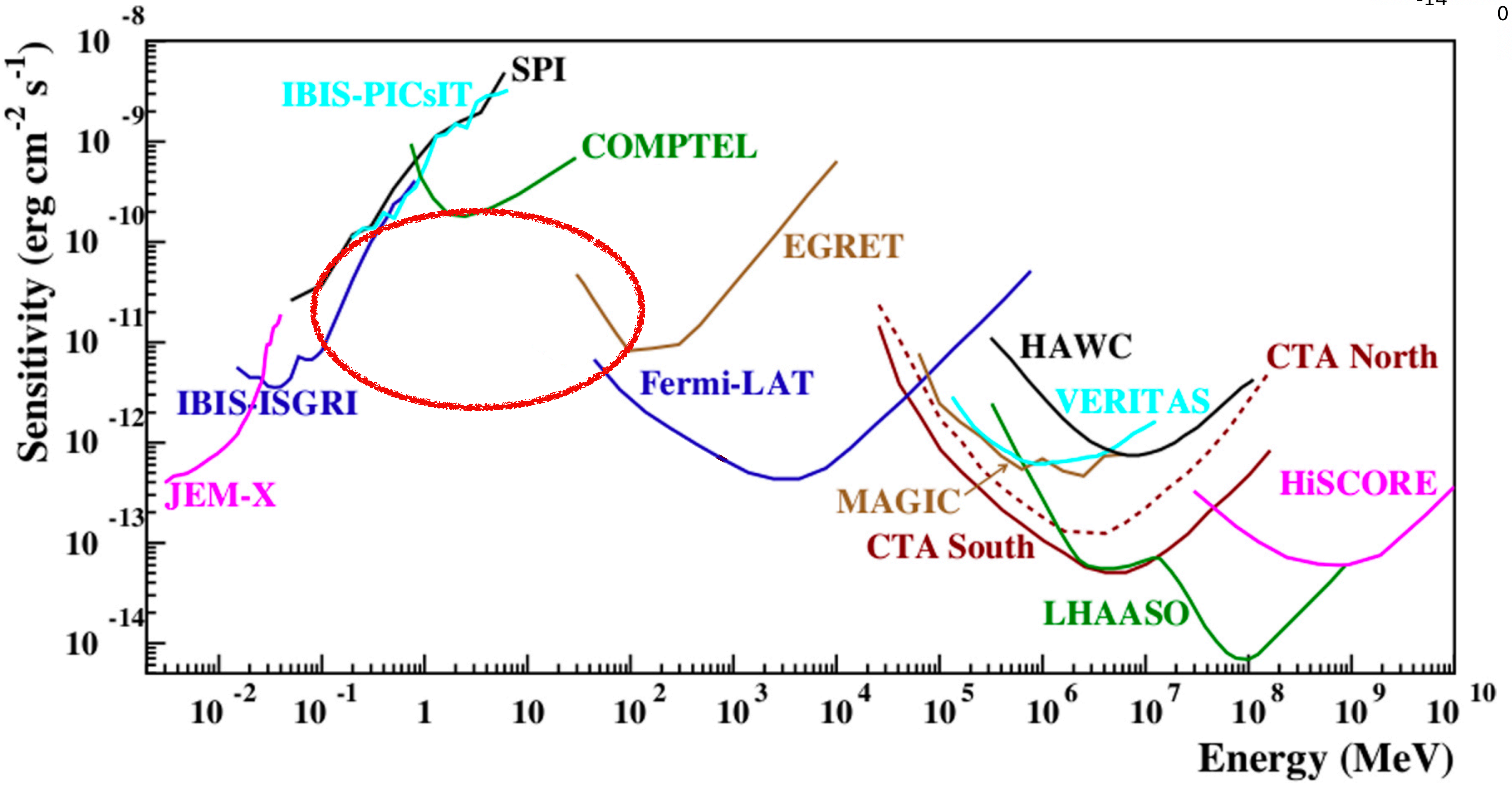


IC-200107A and BZB J0955+3551
Flaring: No
Paliya et al. 2020

13

Future missions: The MeV gap



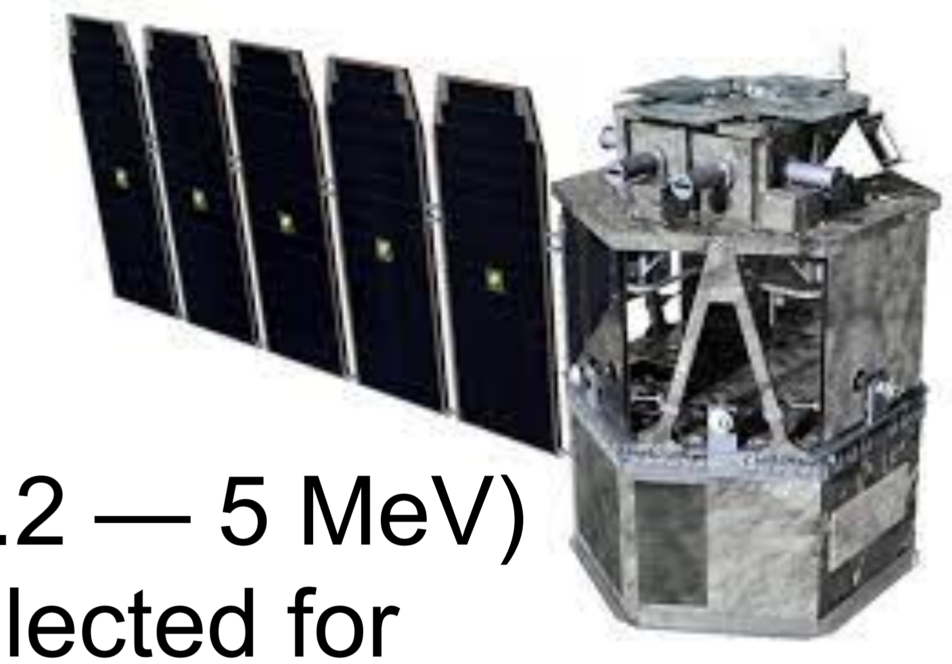


- Sensitivity around 1 MeV is two to three orders of magnitude worse than in the surrounding energy bands
- Should Fermi reach its end-of-life, the MeV gap would extend from 100 keV to tens of GeV

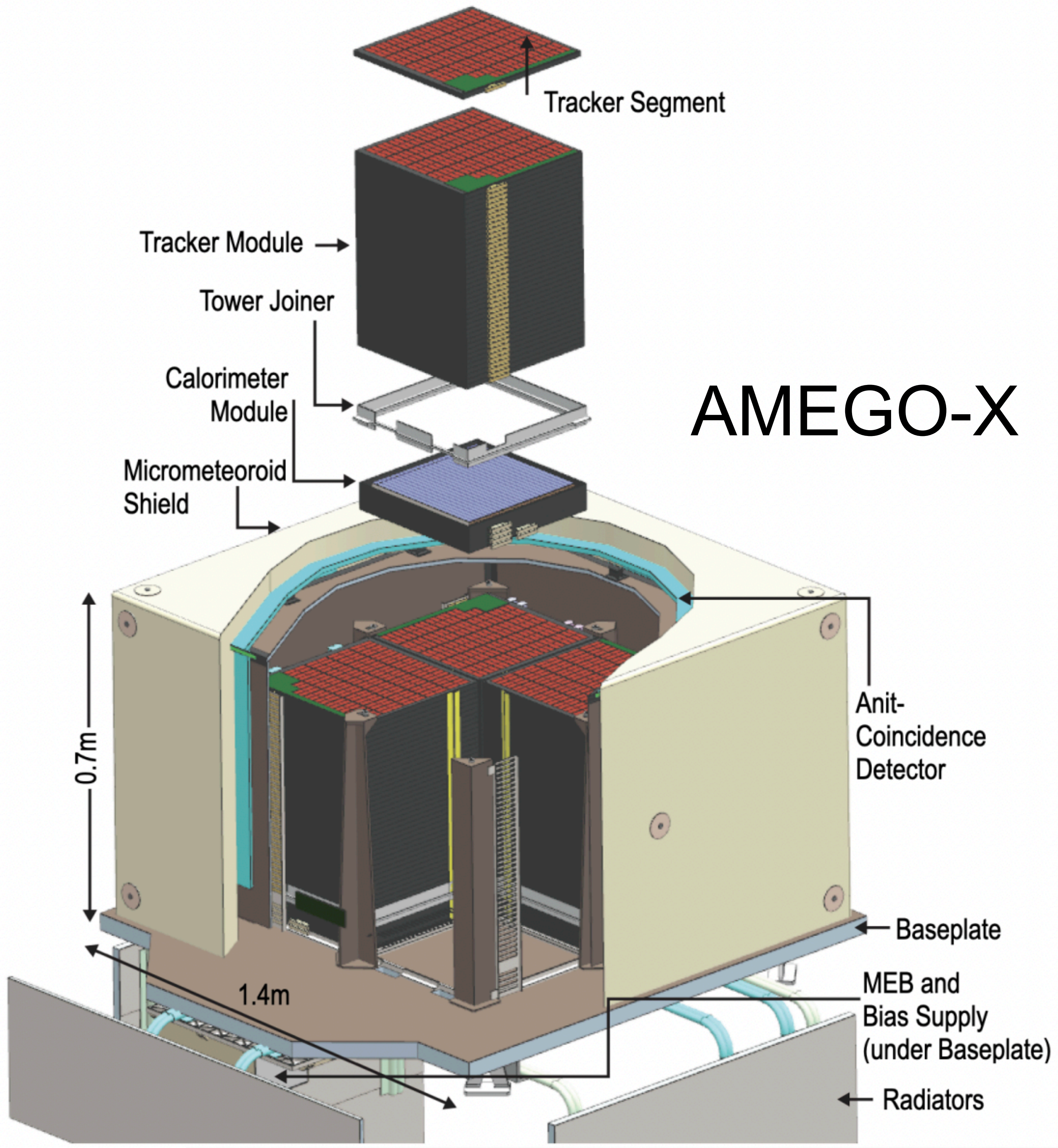
Future missions

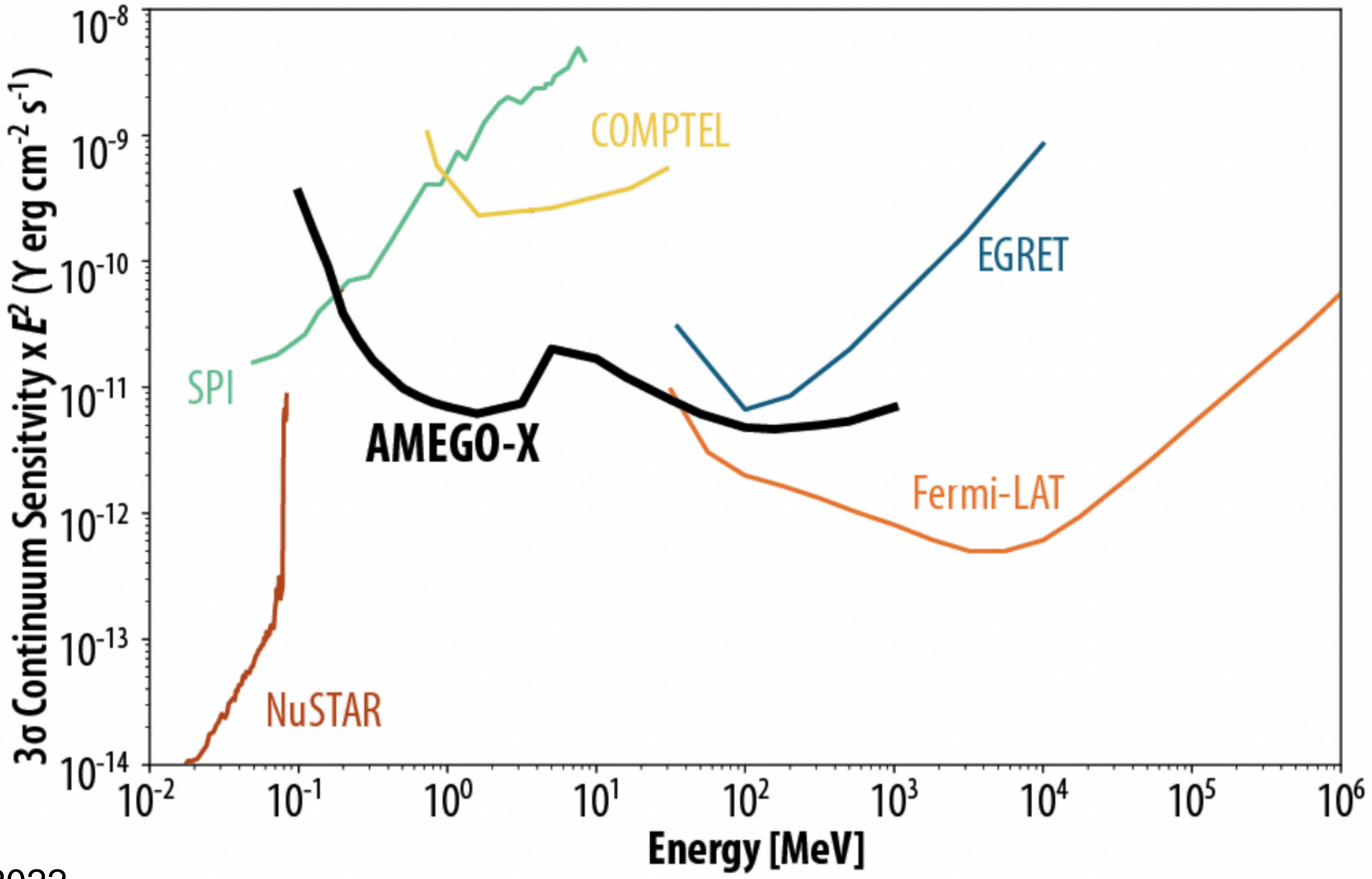
COSI, AMEGO-X, ASTROGAM

COSI

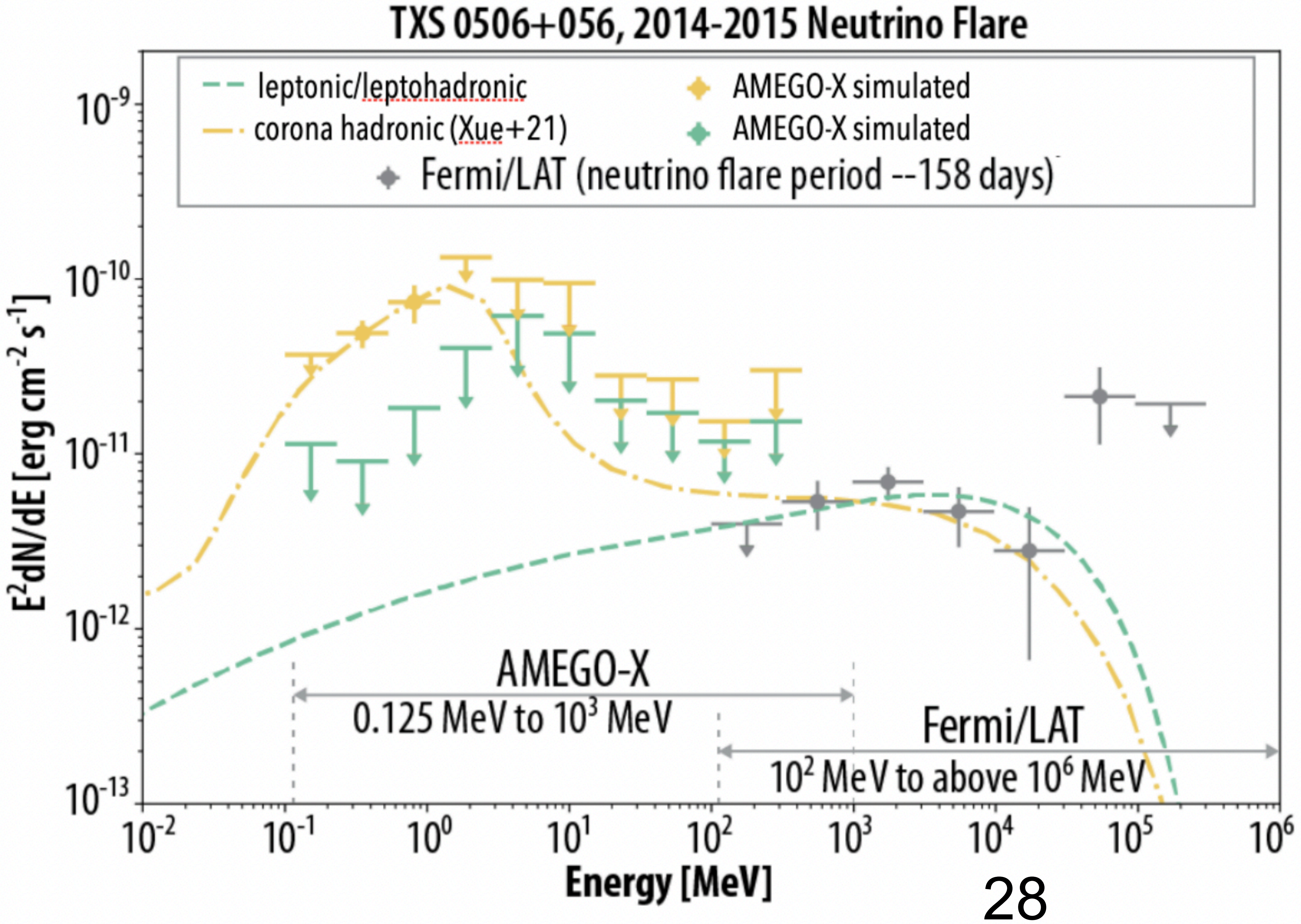


(0.2 — 5 MeV) selected for SMEX mission

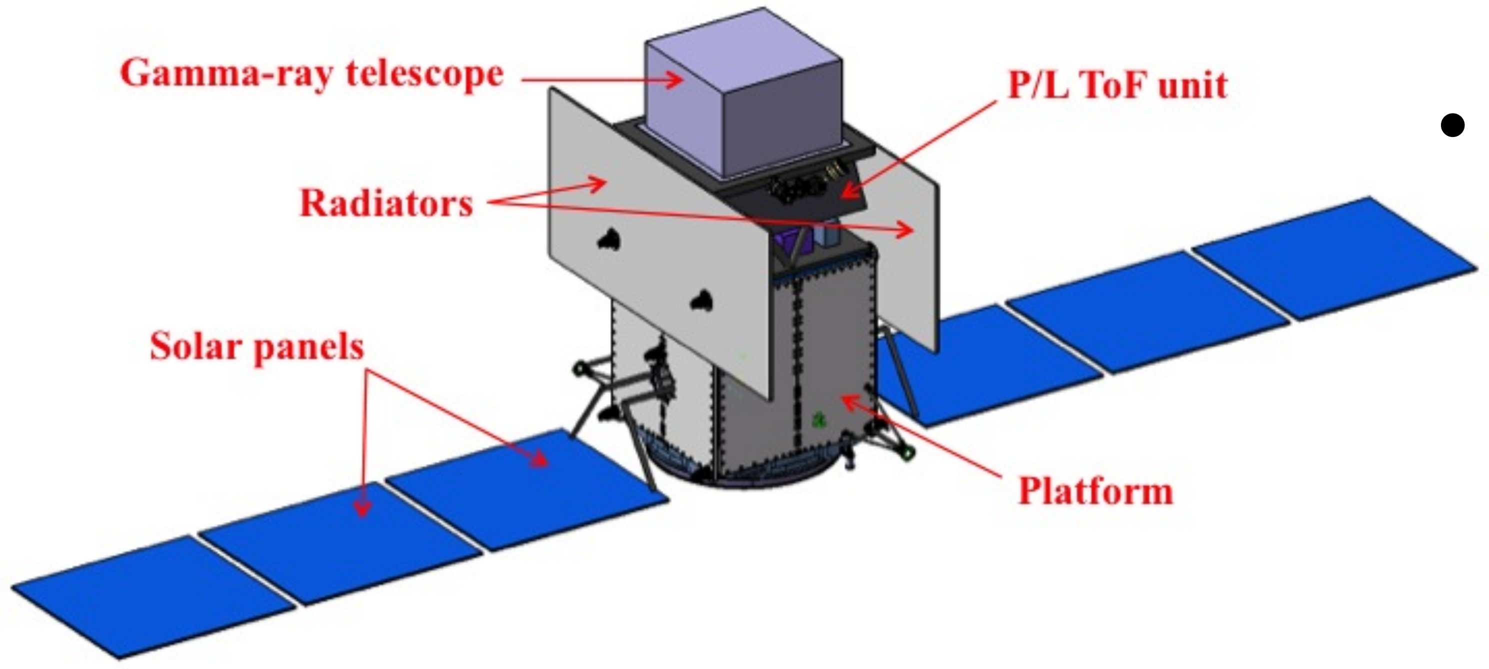




Caputo et al. 2022



e-ASTROGAM



- Mid-scale Compton/Pair telescopes (100 keV — 1 GeV) are ideal multi messenger instruments for the next decade

Conclusions

- More than 14 years after launch science with the Fermi gamma-ray space telescope remains exciting
- Both LAT and GBM are in good health and may continue observations for at least a decade (barring catastrophic failure or loss of NASA support)
- Transients are the main science driver in this extended mission period
- Fascinating results in recent years for many classes of galactic and extragalactic transients
    - Examples shown for observations of Novae, Magnetars, GRBs and Blazar flares
- Fermi LAT and GBM are core instruments for multi-messenger science with both gravitational waves and neutrinos
- Given NASA/ESA time scales it is the time now to join the efforts for a successor mission.
- COSI is a great first step, but a medium-class mission is needed to support multi-messenger science of the 2030s (ideally targeted at the MeV energy range)