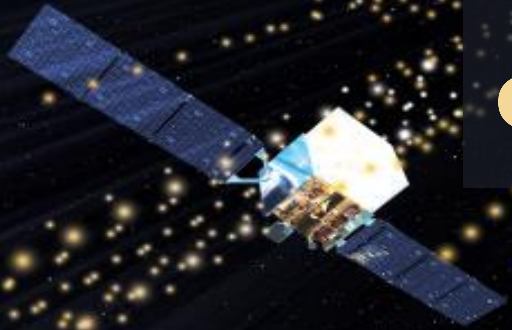
Towards 15-years of Gamma-Ray Burst observations with Fermi



SEXTEN CENTER FOR ASTROPHYSICS RICCARDO GIACCONI

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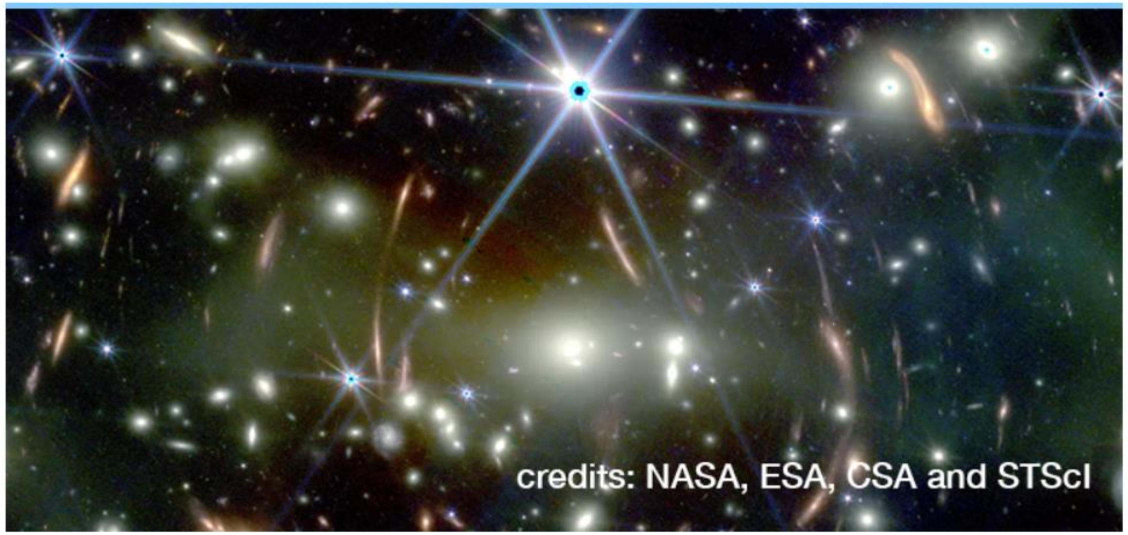
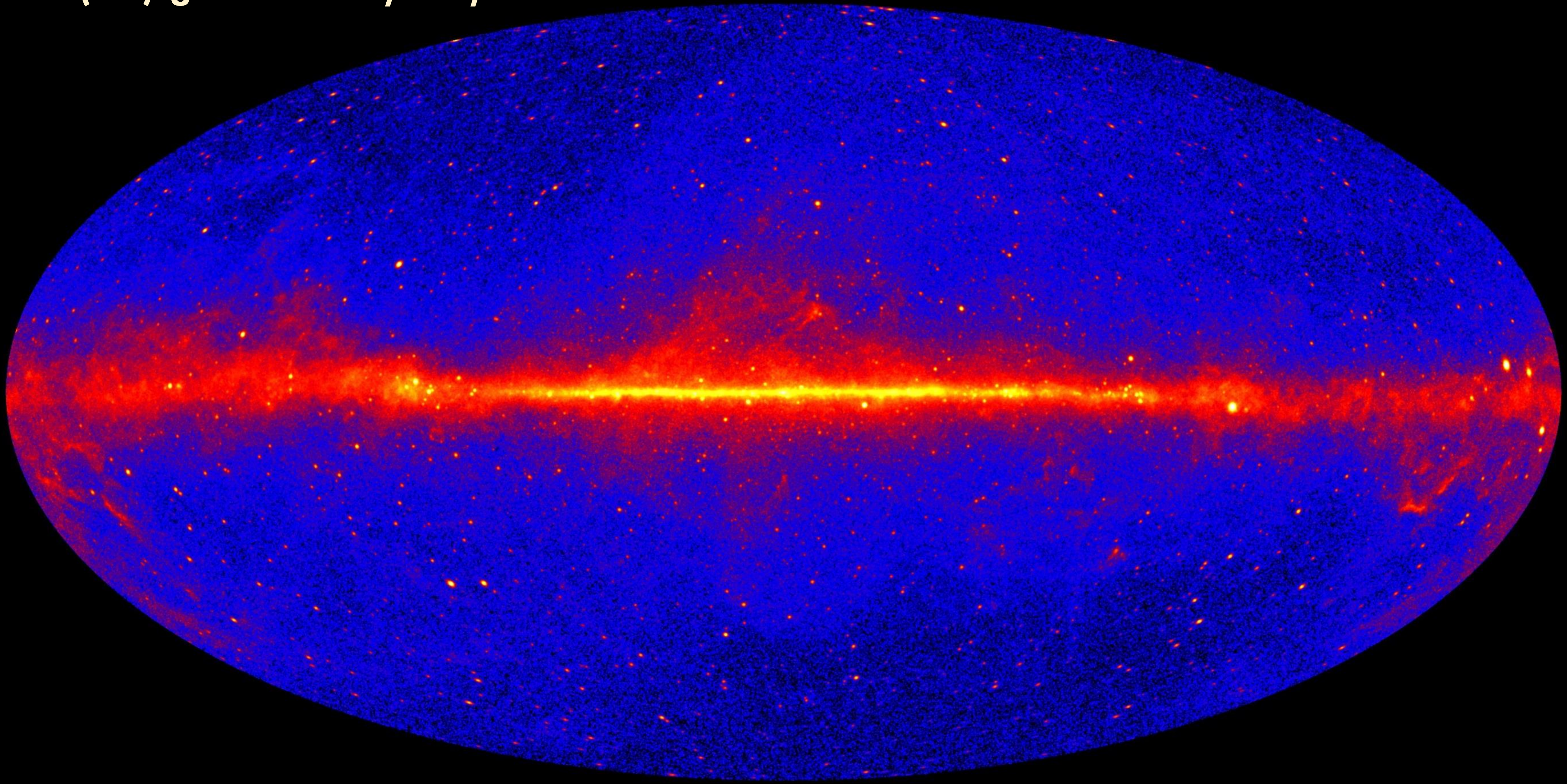
Member of the Fermi GBM and LAT Collaborations
Member of the CTA Consortium
Affiliate member of the H.E.S.S. Collaboration



HIGH REDSHIFT GAMMA-RAY-BURSTS IN THE JWST ERA

The (HE) gamma-ray sky



Credit: NASA/DOE/Fermi LAT Collaboration

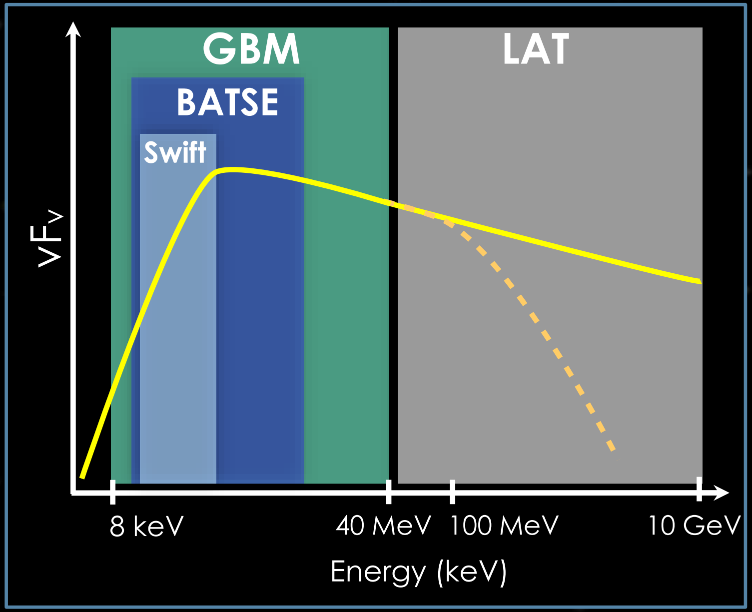
The Fermi Mission

Launched on June 11, 2008

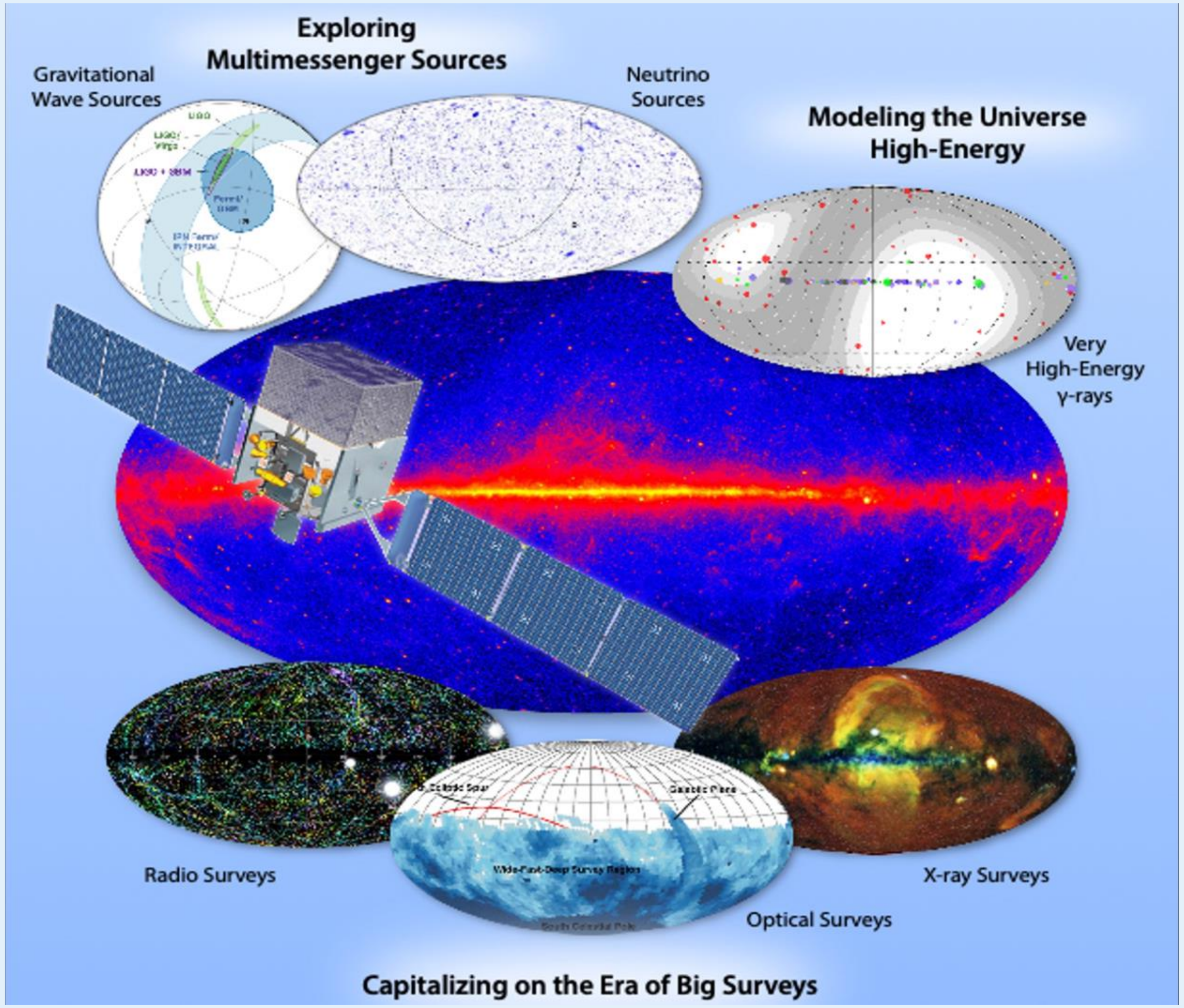
Key features
huge **FoV**
&
large **energy range**

Large Area Telescope (LAT)
Pair conversion telescope
20 MeV → 300 GeV

Gamma-ray Burst Monitor (GBM)
14 Plastic scintillator detectors
8 keV – 40 MeV



NASA Senior Review (SR) of Operating Missions



- NASA Senior Review (SR) 2022
  - Fermi recommended for continuation for 3 years until next SR in 2025
    - *"Fermi provides unique access to the gamma-ray portion of the electromagnetic spectrum and the largest simultaneous field-of-view of any space telescope.*
      Its data give us a time-domain view of the entire gamma-ray sky and are a crucial asset for gravitational-wave and multi-messenger astrophysics."
  - Strongly tied to Astro 2020 decadal survey theme "New Messengers and New Physics"

Fermi Transient Searches

Pipeline
Method
Timescale
Distribution
Status

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

***Fermi* All-sky Variability Analysis (FAVA)**
Aperture Photometry, 1 week
ATels, FAV catalogs

***Fermi* LAT Light Curve Repository**
Likelihood LAT Catalog Sources
3 days, Weekly

***Fermi* LAT Monitored Sources**
Daily, Weekly above 10^{-6} cm^{-2}s^{-1}

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

GBM Targeted Search
ground search
ms - s
Temporal/Spatial Input

GBM Untargeted Search
ground search
ms - s
GCN Notices

GBM Onboard Triggers
rate triggers
16 ms - minutes
GCN Notices

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

LAT Catalogs
Likelihood, associations
FGL, FHL, LAC, FLE, PSR

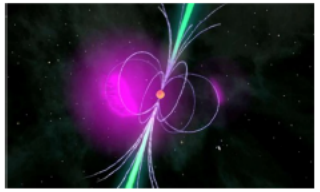
Transients Timescale Pipelines

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

Photon Timing

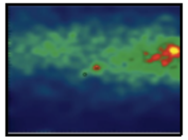
All Sky Cadence

Pulsars

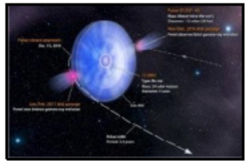


Solar Flares

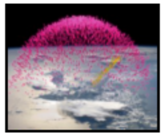
Novae



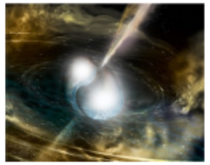
γ-ray Binaries



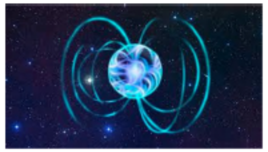
Terrestrial γ-ray Flashes



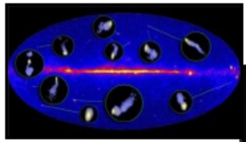
GRBs



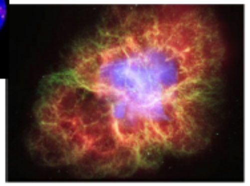
Magnetar Flares



Blazar Flares



Crab Flares



Not to scale

GRB studies through history

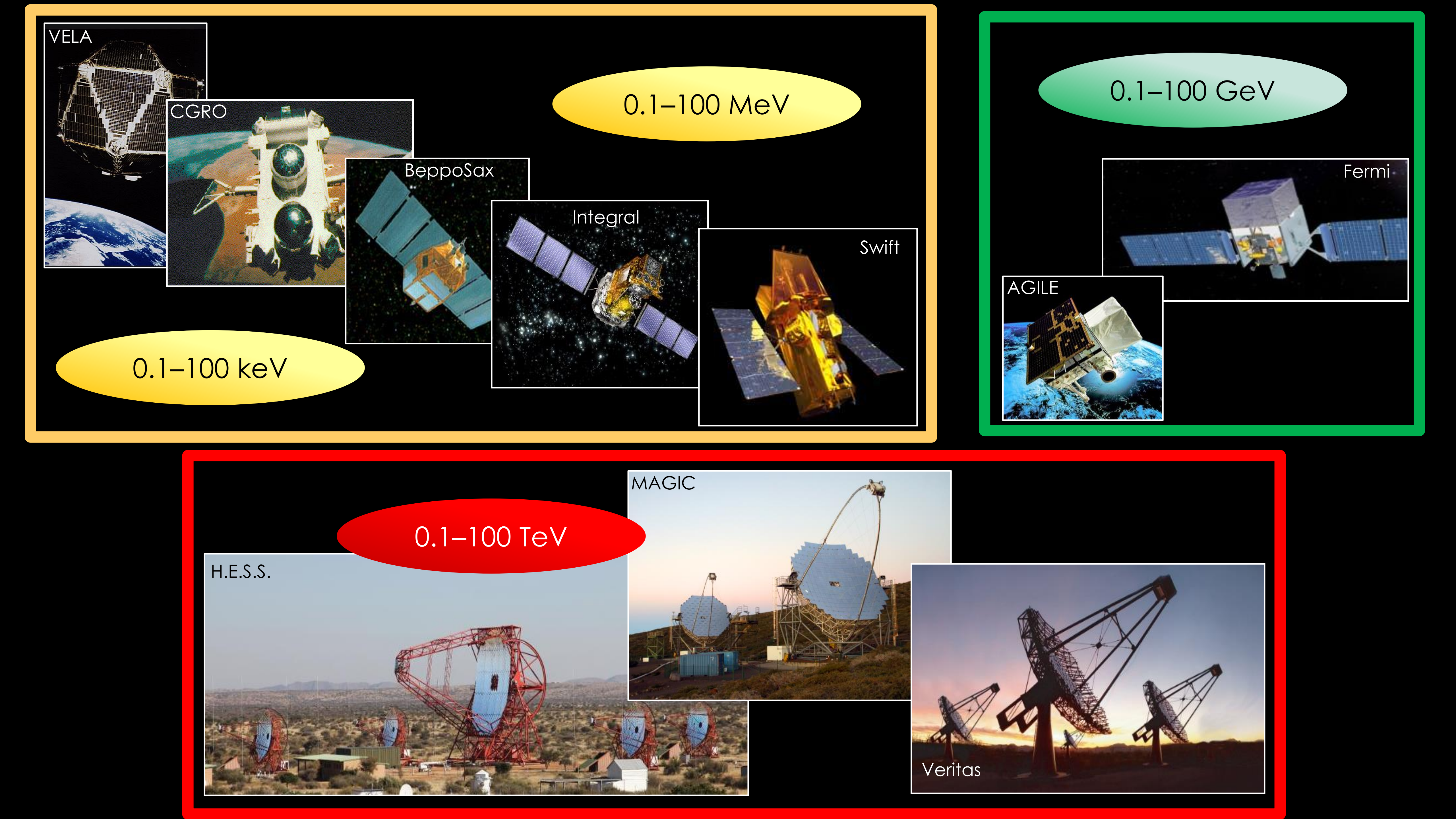
Adapted from F.Longo

Seven eras

Adapted from L.Amati

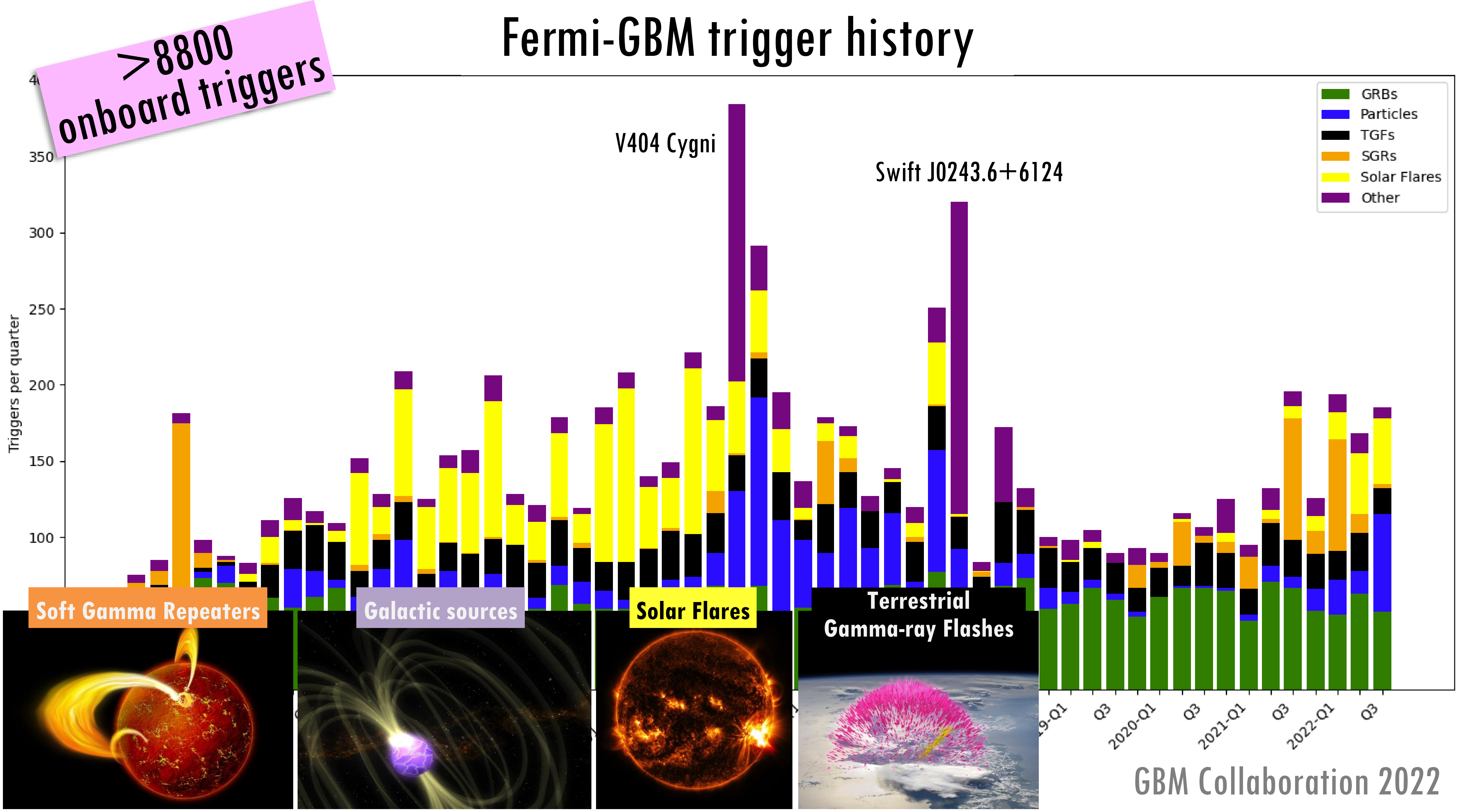
1) "Dark" era (1973-1991): discovery
   Klebesadel, Strong & Olson's discovery (1973);
2) BATSE era (1992-1996): spatial distribution
   Meegan & Fishman's discovery (1992),
   detection rate: ~1 to 3 /day, ~3000 bursts;
3) BeppoSAX era (1997-2000): afterglows
   van Paradijs, Costa, Frail's discoveries (1997);
4) HETE-2 era (2001-2004): origin of long bursts
   Observations on GRB030329/SN2003dh
5) Swift era (2005-): very early afterglows, short-GRB afterglow, GRB subclasses? GRB cosmology?

6) Fermi era (2008–): High energy emission component, GW
7) Multimessenger era (2015–): origin of short GRB
8) VHE era (2019–): VHE emission component from GRB!



VELA
CGRO
BeppoSax
Integral
Swift
0.1–100 MeV
0.1–100 keV
0.1–100 GeV
Fermi
AGILE
MAGIC
0.1–100 TeV
H.E.S.S.
Veritas

Fermi-GBM trigger history

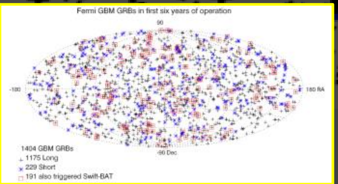


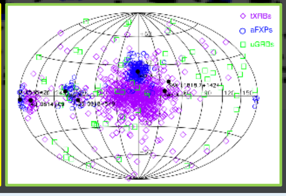
Fermi-GBM catalogs

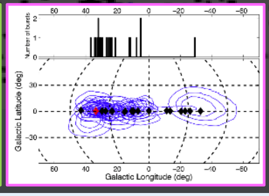
2023

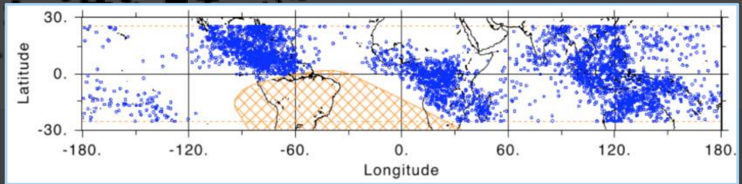
- GBM 10yr **GRB spectral** Catalog Poolakkil+2021.ApJ913
- GBM 10yr **GRB trigger** Catalog von Kienlin+2020.ApJ893
- GBM 10yr **Accreting Pulsar** Catalog Malacaria+2020.ApJ896
- GBM 8yr **TGF** Catalog Roberts+2018.JGRA123
- GBM 6yr **GRB trigger** Catalog (3FGBM) Bhat+2016.ApJSS223
- GBM 5yr **Magnetar** Burst Catalog Collazzi+2015.ApJSS218
- GBM 4yr **GRB time-res. spectral** Catalog Yu+2016.A&A588
- GBM 4yr **GRB spectral** Catalog Gruber+2014.ApJSS211
- GBM 4yr **GRB trigger** Catalog (2FGBM) von Kienlin+2014.ApJSS211
- GBM 3yr **X-ray Burst** Catalog Jenke+2016.ApJ826
- GBM 3yr **EOM** catalog Wilson-Hodge et al. 2012
- GBM 2yr **GRB spectral** Catalog Goldstein+2012.ApJSS199
- GBM 2yr **GRB trigger** Catalog (1FGBM) Paciesas+2012.ApJSS199

2008





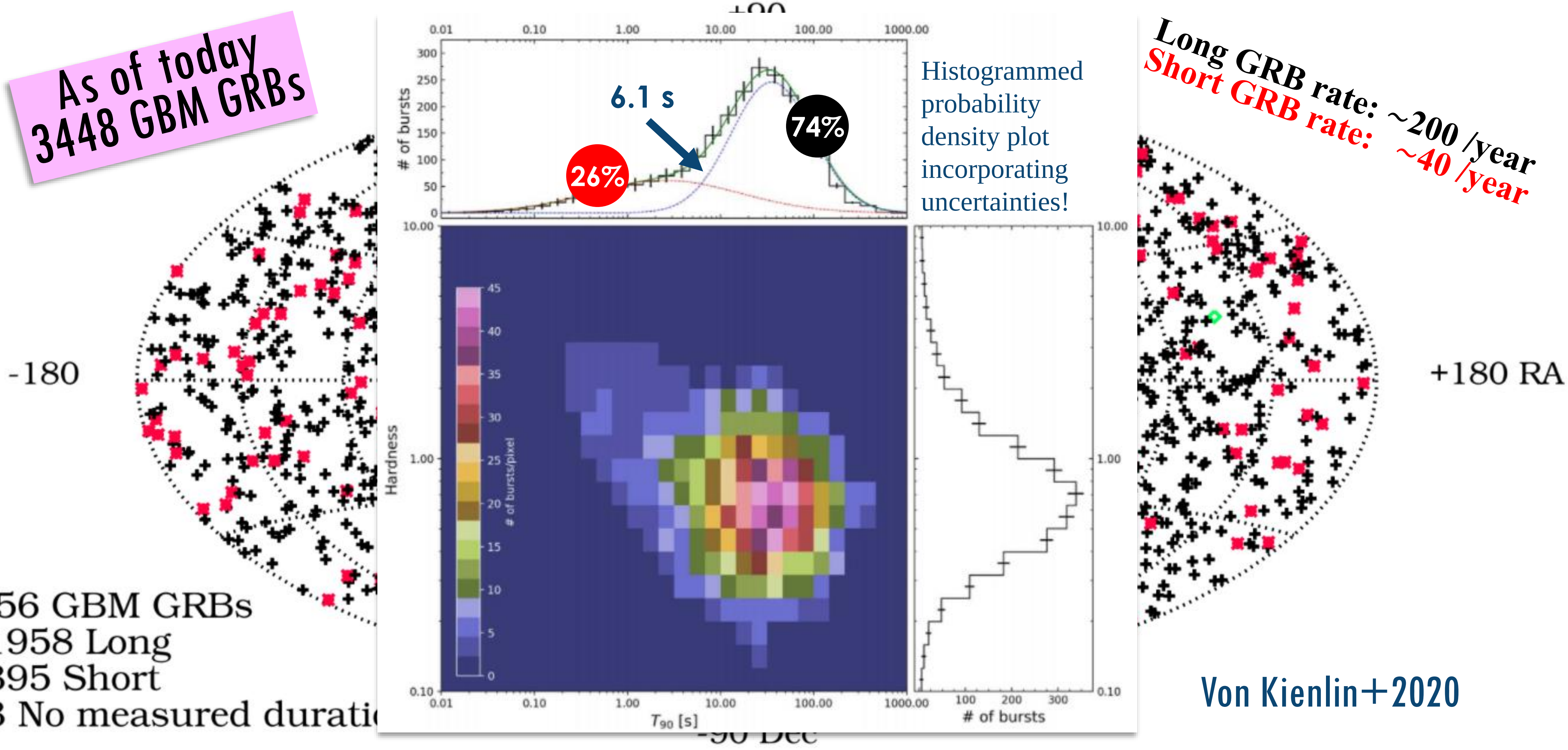




Fermi GBM GRBs in first ten years of operation

As of today
3448 GBM GRBs

Long GRB rate: ~200 /year
Short GRB rate: ~40 /year



Histogrammed probability density plot incorporating uncertainties!

Von Kienlin+2020

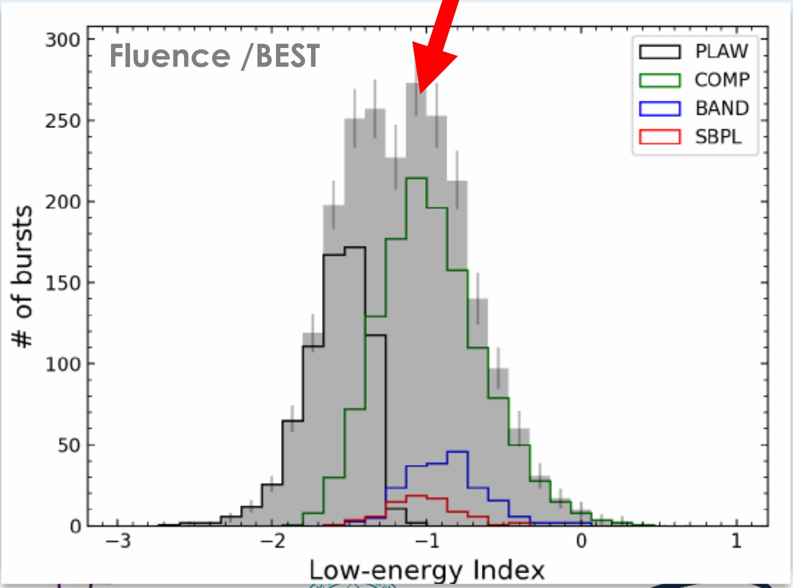
Spectral properties @MeV energies

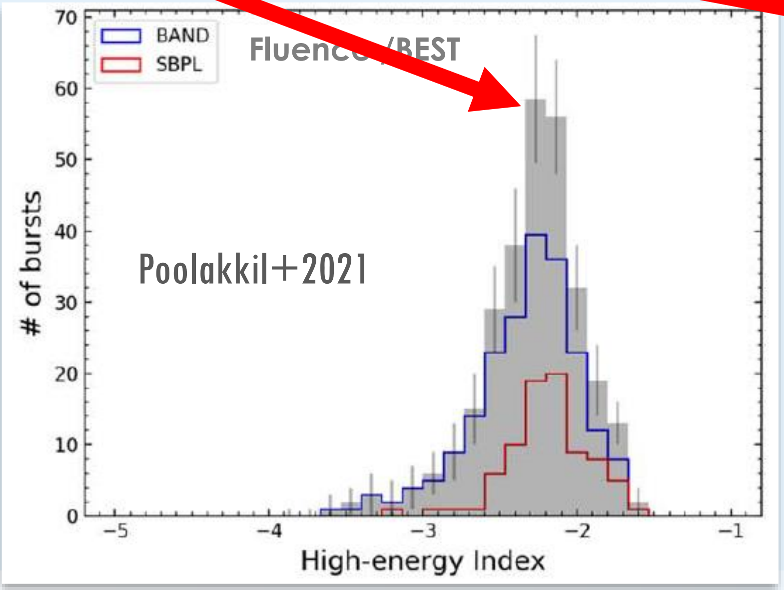
- **Parameter distributions**
  - Fluence and peak flux spectra from Fermi-GBM catalogs

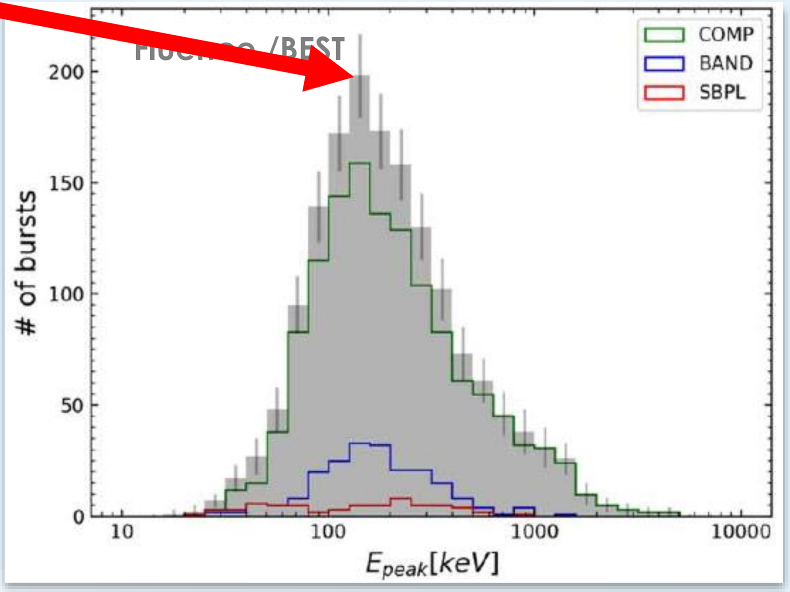
Data Set	Low-energy Index	High-energy Index	E_{peak} (keV)
This Catalog BEST	$-1.08^{+0.45}_{-0.44}$	$-2.20^{+0.26}_{-0.29}$	180^{+307}_{-88}
Gruber et al. (2014)	$-1.$[illegible]$8^{+0.43}_{-0.44}$	-2.14[illegible]	196[illegible]$_{-100}$
Goldstein et al. (2012)	$-$[illegible]$05^{+0.44}_{-0.45}$	$-2.25^{+0.34}_{-0.73}$	[illegible]$^{+359}$
Kaneko et al. (2006)	$-$[illegible]$.14^{+0.20}_{-0.22}$	$-2.33^{+0.24}_{-0.26}$	251^{+122}_{-68}

GOOD and BEST GRB Models

	PLAW	COMP	BAND	SBPL
Fluence Spectra				
This Catalog GOOD	2295 (99.9%)	1616 (70.3%)	666 (29.0%)	1013 (44.0%)
Gruber et al. (2014) GOOD	941 (99.7%)	684 (72.5%)	342 (36.2%)	392 (41.5%)
This Catalog BEST	693 (30.2%)	1311 (57.0%)	209 (9.0%)	82 (3.5%)
Gruber et al. (2014) BEST	282 (29.9%)	516 (54.7%)	81 (8.6%)	62 (6.6%)
Peak Flux Spectra				
This Catalog GOOD	2287 (99.5%)	1047 (45.5%)	328 (14.2%)	522 (22.6%)
Gruber et al. (2014) GOOD	932 (98.7%)	430 (45.6%)	153 (16.2%)	196 (20.8%)
This Catalo[illegible]EST	1248 (54.3%)	931 (40.5%)	79 (3.4%)	29 (1.2%)
Gruber et al. (2014)BEST	514 (54.4%))	375 (39.7%)	25 (2.6%)	18 (1.9%)





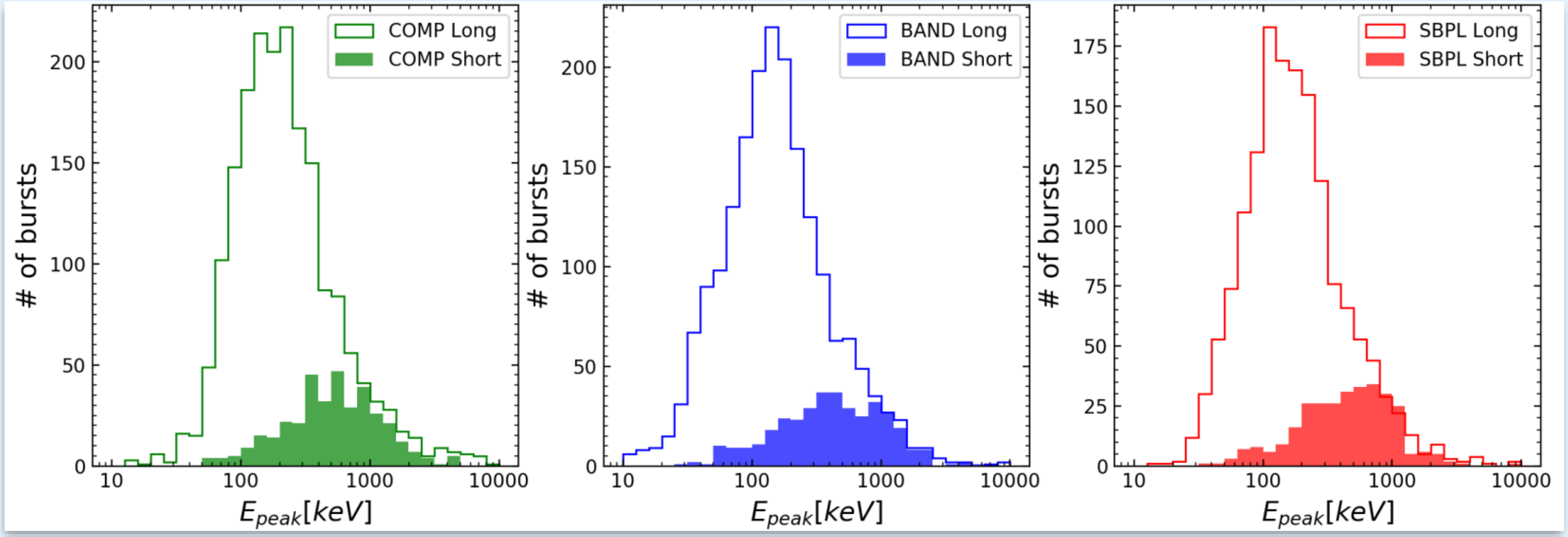


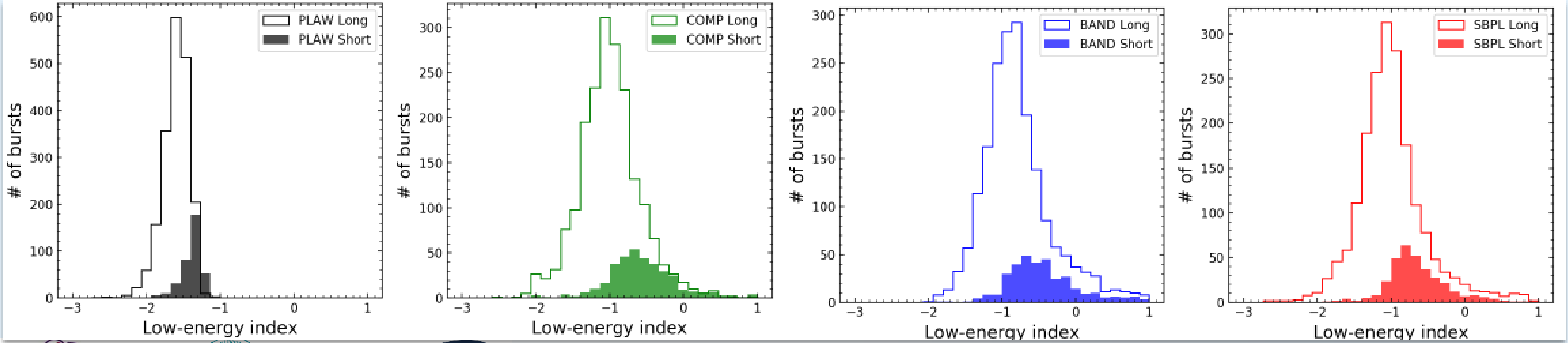
Spectral properties @MeV energies

Long vs. Short GRBs

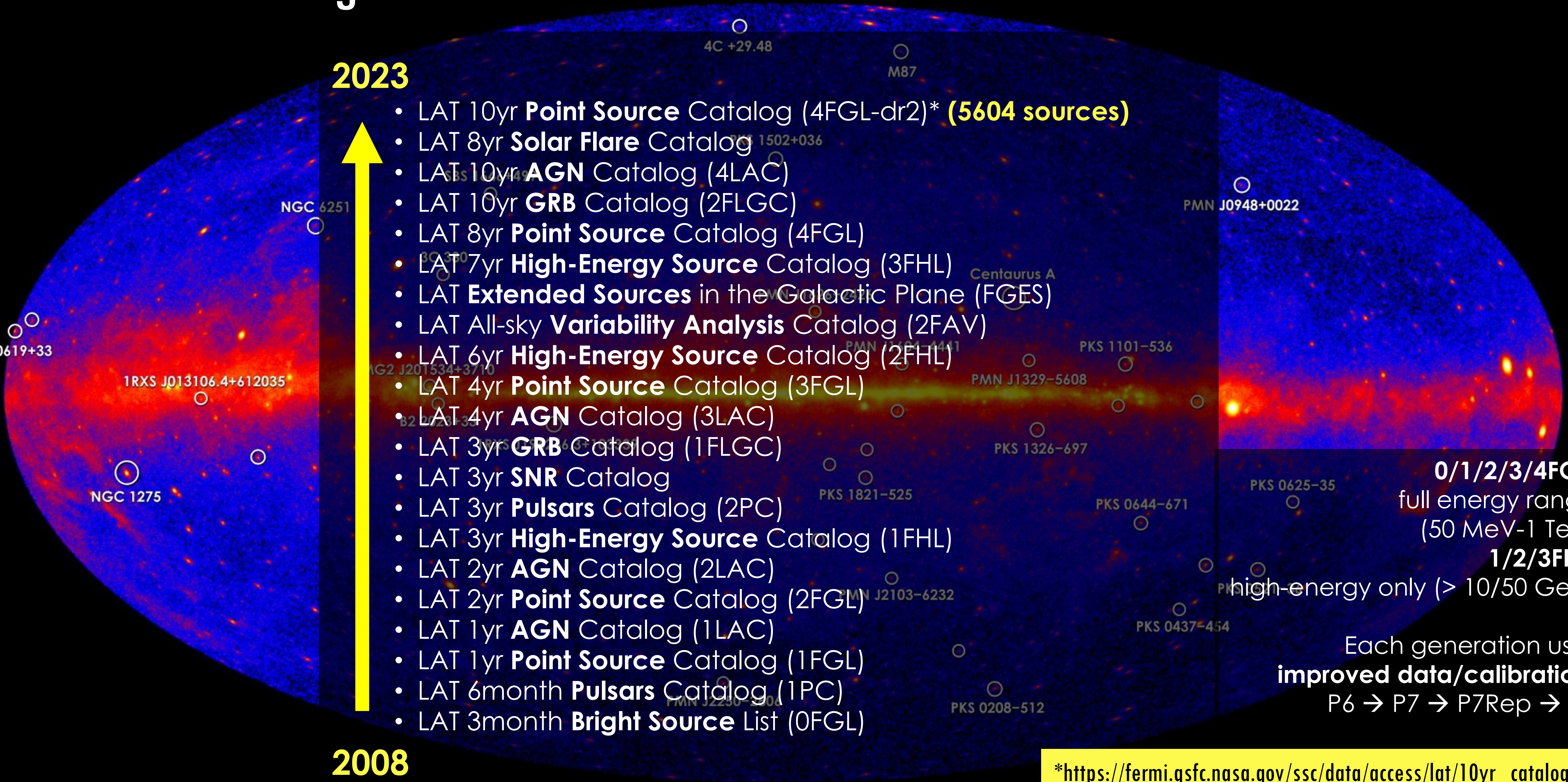
- Short bursts show a **higher median value of Epeak** and a **harder low-energy power law index**

Poolakkil+2021





Fermi-LAT catalogs



2023

- LAT 10yr **Point Source** Catalog (4FGL-dr2)* **(5604 sources)**
- LAT 8yr **Solar Flare** Catalog
- LAT 10yr **AGN** Catalog (4LAC)
- LAT 10yr **GRB** Catalog (2FLGC)
- LAT 8yr **Point Source** Catalog (4FGL)
- LAT 7yr **High-Energy Source** Catalog (3FHL)
- LAT **Extended Sources** in the Galactic Plane (FGES)
- LAT All-sky **Variability Analysis** Catalog (2FAV)
- LAT 6yr **High-Energy Source** Catalog (2FHL)
- LAT 4yr **Point Source** Catalog (3FGL)
- LAT 4yr **AGN** Catalog (3LAC)
- LAT 3yr **GRB** Catalog (1FLGC)
- LAT 3yr **SNR** Catalog
- LAT 3yr **Pulsars** Catalog (2PC)
- LAT 3yr **High-Energy Source** Catalog (1FHL)
- LAT 2yr **AGN** Catalog (2LAC)
- LAT 2yr **Point Source** Catalog (2FGL)
- LAT 1yr **AGN** Catalog (1LAC)
- LAT 1yr **Point Source** Catalog (1FGL)
- LAT 6month **Pulsars** Catalog (1PC)
- LAT 3month **Bright Source** List (0FGL)

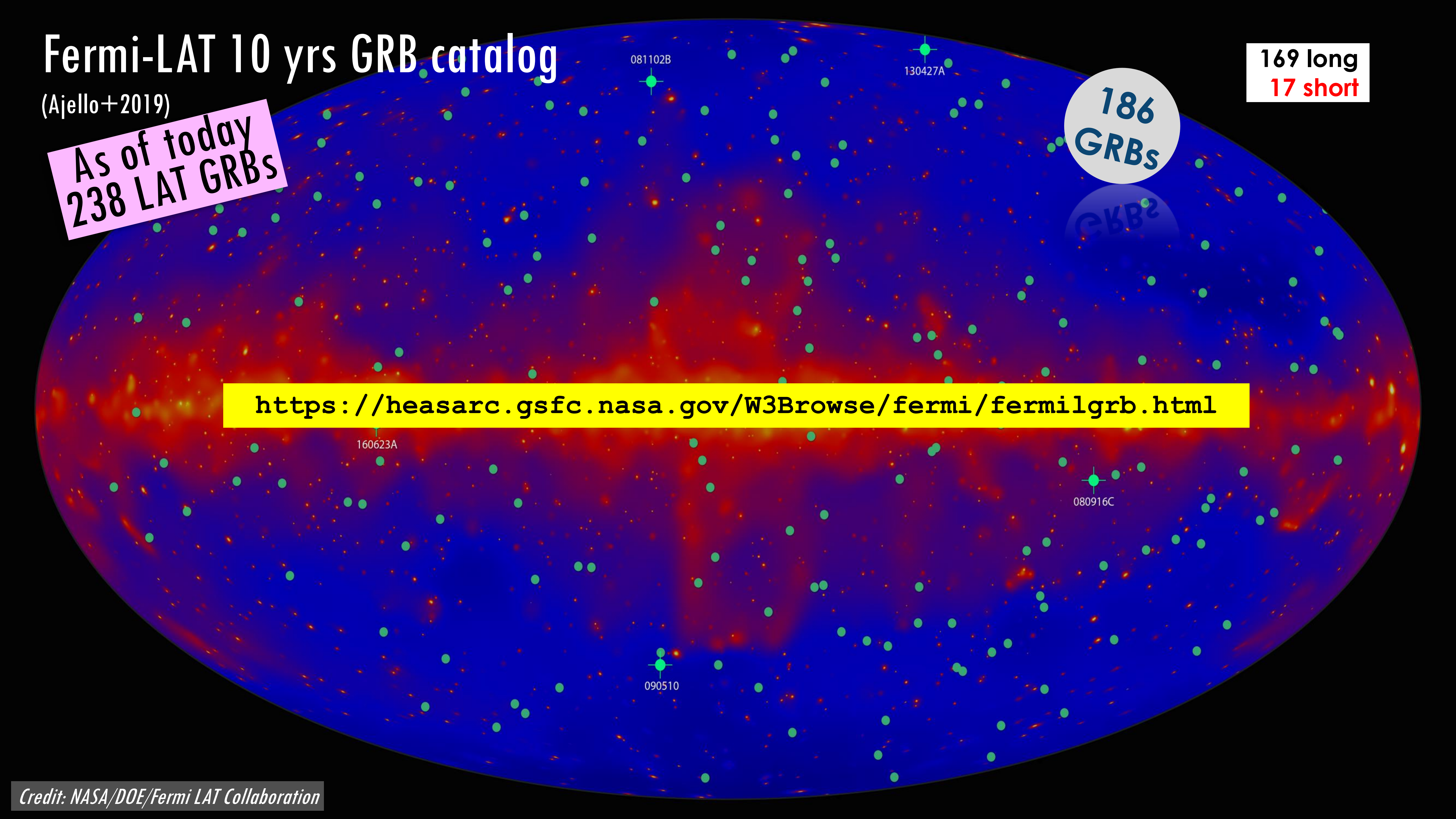
2008

0/1/2/3/4FGL:
full energy range
(50 MeV-1 TeV)
1/2/3FHL:
high-energy only (> 10/50 GeV)

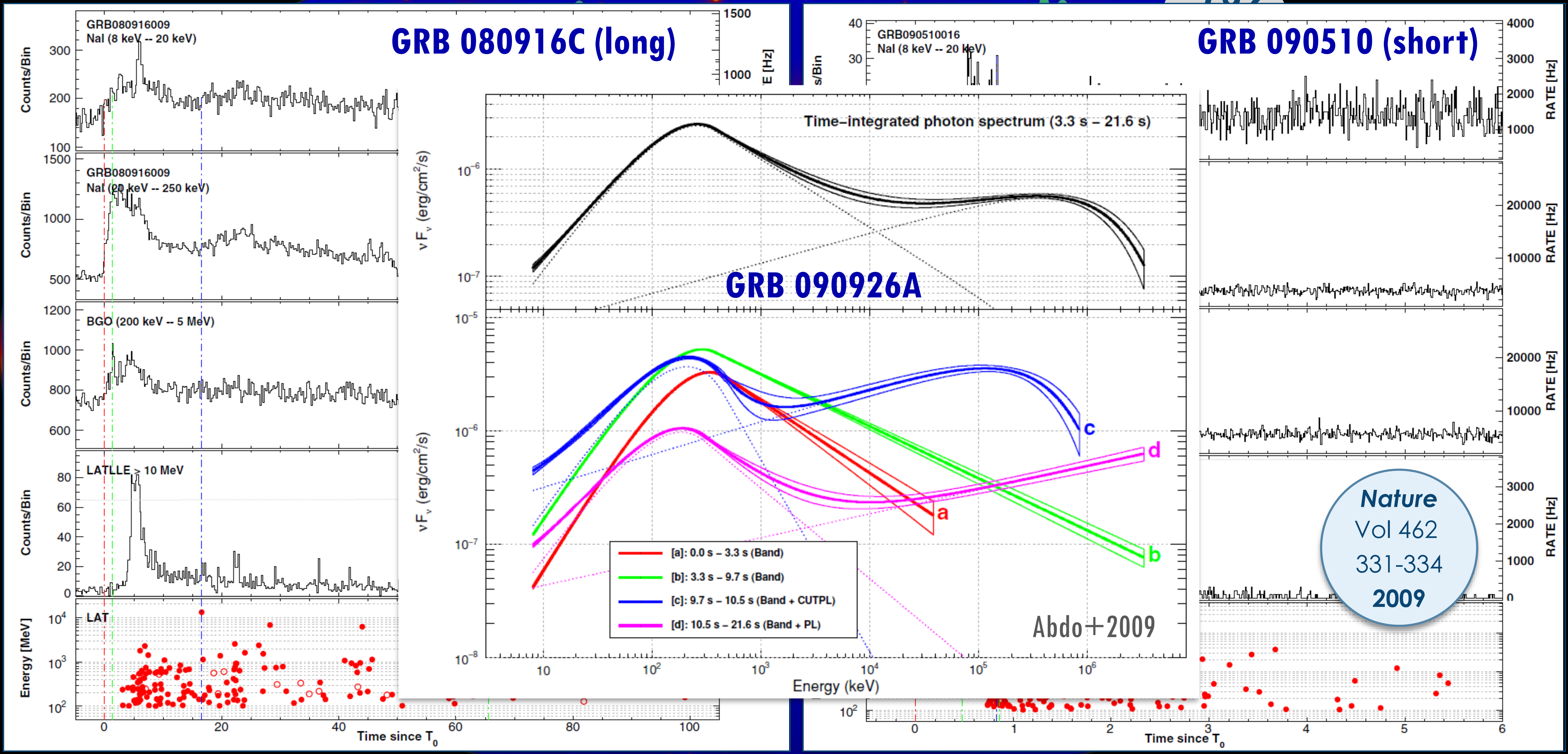
Each generation uses
improved data/calibration:
P6 → P7 → P7Rep → P8

*https://fermi.gsfc.nasa.gov/ssc/data/access/lat/10yr_catalog/
https://arxiv.org/pdf/2005.11208.pdf

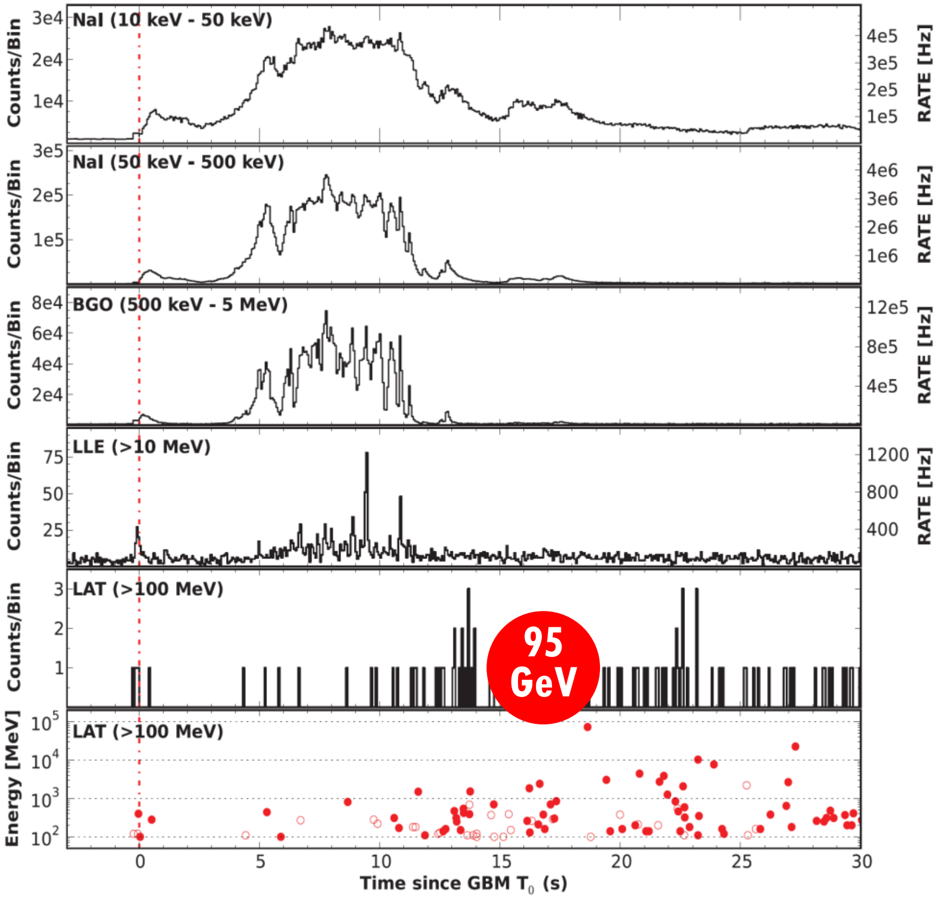
Credit: NASA/DOE/Fermi LAT Collaboration/GSFC

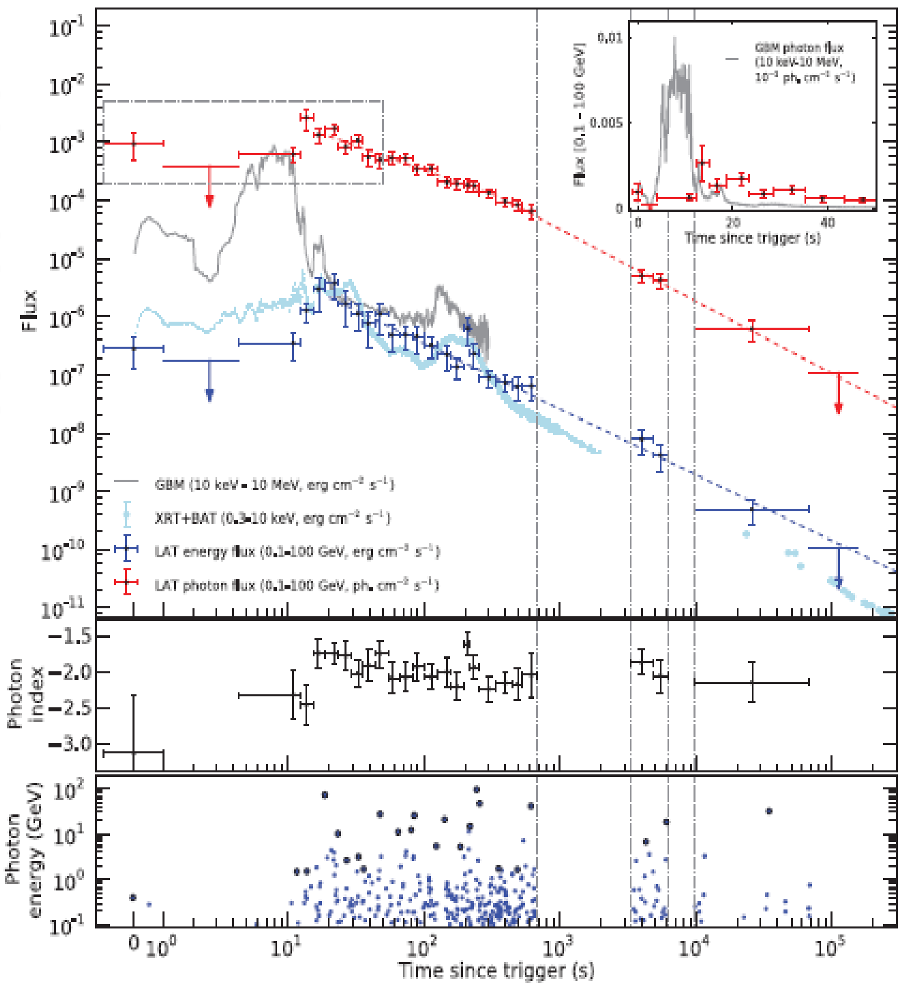

Fermi-LAT 10 yrs GRB catalog
(Ajello+2019)
As of today
238 LAT GRBs
169 long
17 short
186
GRBs
081102B
130427A
https://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermilgrb.html
160623A
080916C
090510
Credit: NASA/DOE/Fermi LAT Collaboration

Fermi-LAT 10 yrs GRB catalog



Credit: NASA/DOE/Fermi LAT Collaboration

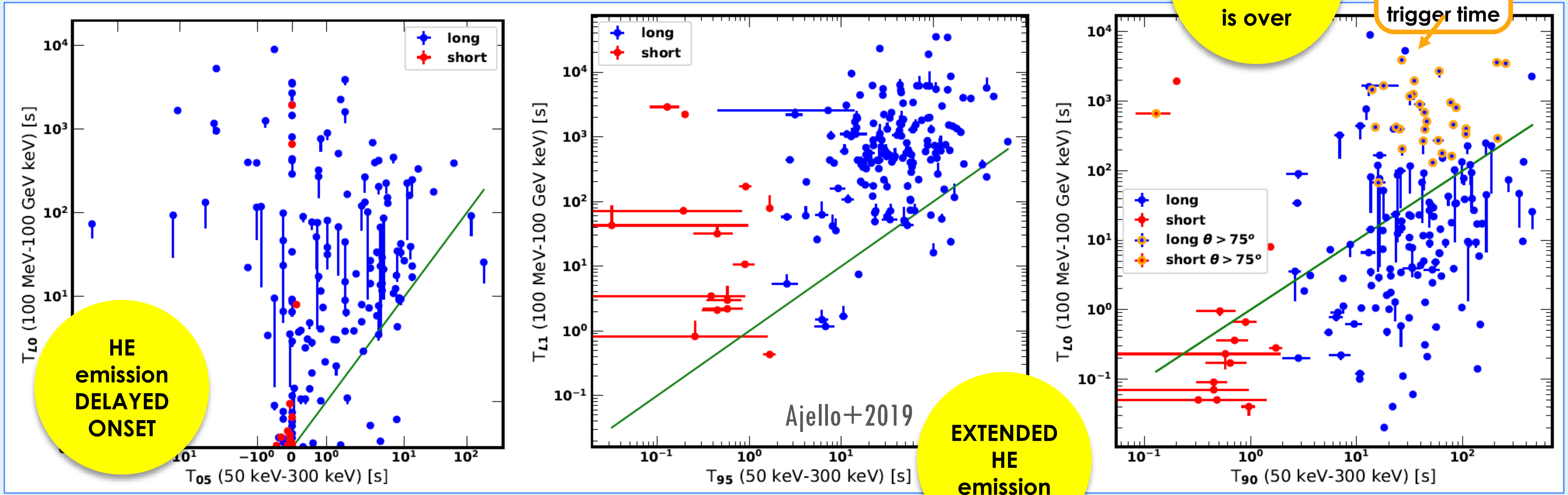




Fermi-LAT Observations of the Gamma-Ray Burst GRB 130427A – Ackermann+2014

Temporal properties at @GeV energies

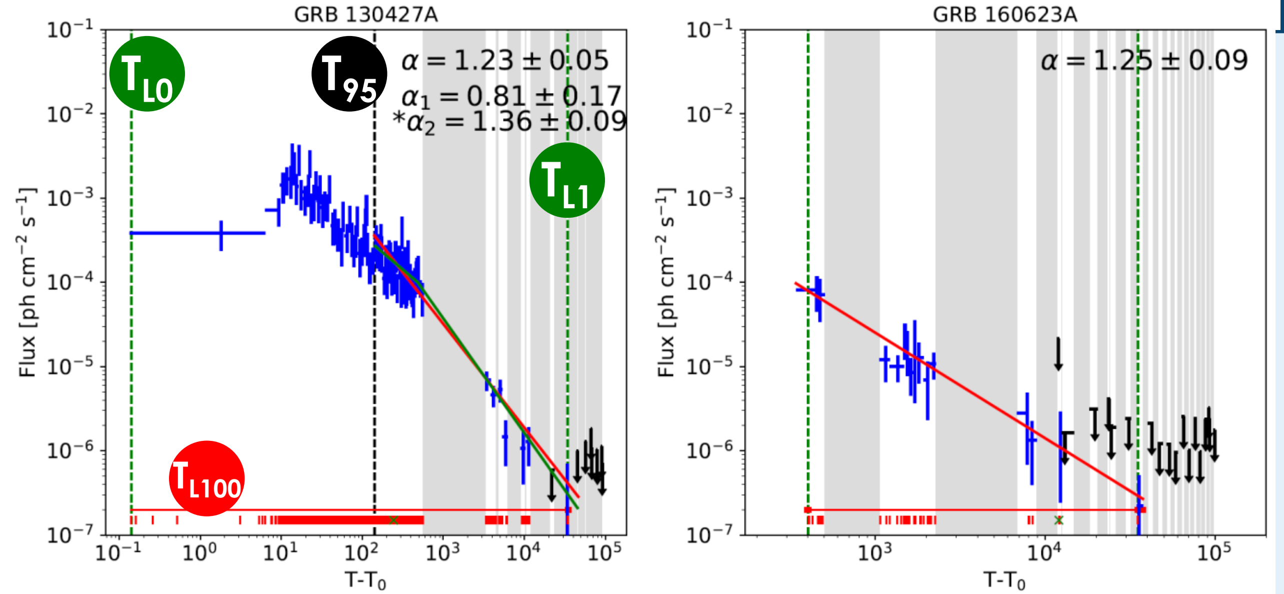
- Detailed study of the **onset** and **duration** of the high-energy emission
  - T_{L100} = GRB duration measured by LAT [**100 MeV – 100 GeV**]
  - T_{L100} = $T_{L1} - T_{L0}$ (Arrival time of last and first photon, respectively)
- **High-energy Emission** (>100 MeV)
  - Systematically **delayed** and **longer** wrt the low-energy emission



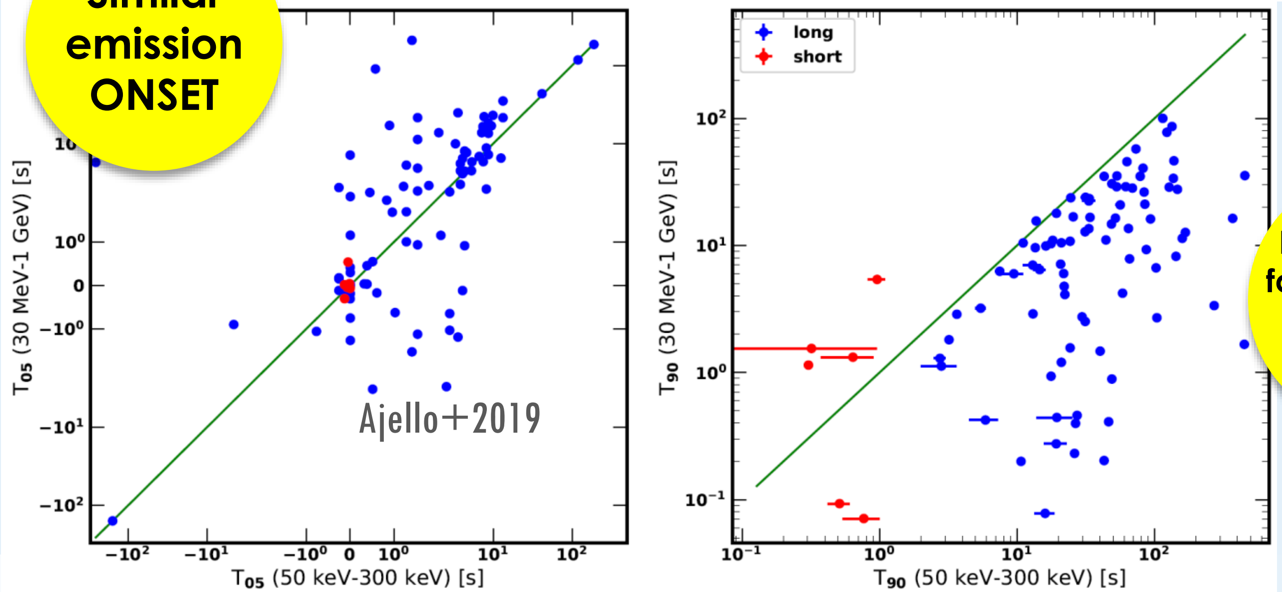
Temporal properties at @GeV energies

- **Longest** bursts
  1. GRB 130427A
     T_{L100} = 34 ks
  2. GRB 160623A
     T_{L100} = 35 ks

- At lower energies (LLE: **30 MeV – 1 GeV**)
  - Definition of duration similar to the GBM
  - Behavior similar to low-energy emission



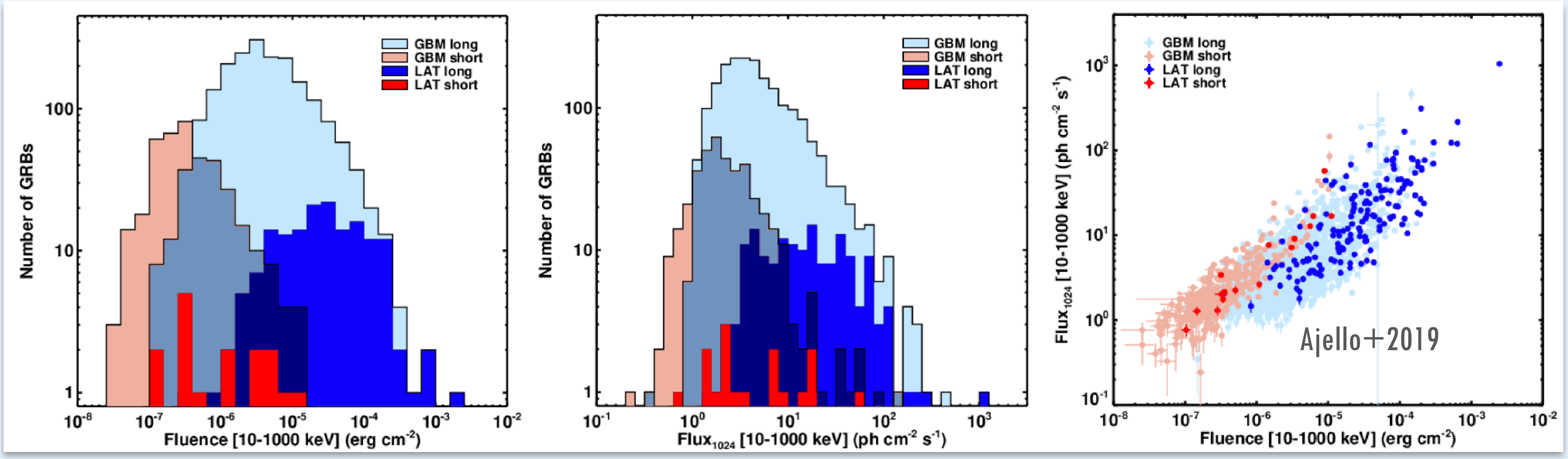
Similar emission ONSET



LLE emission fading FASTER than LE emission

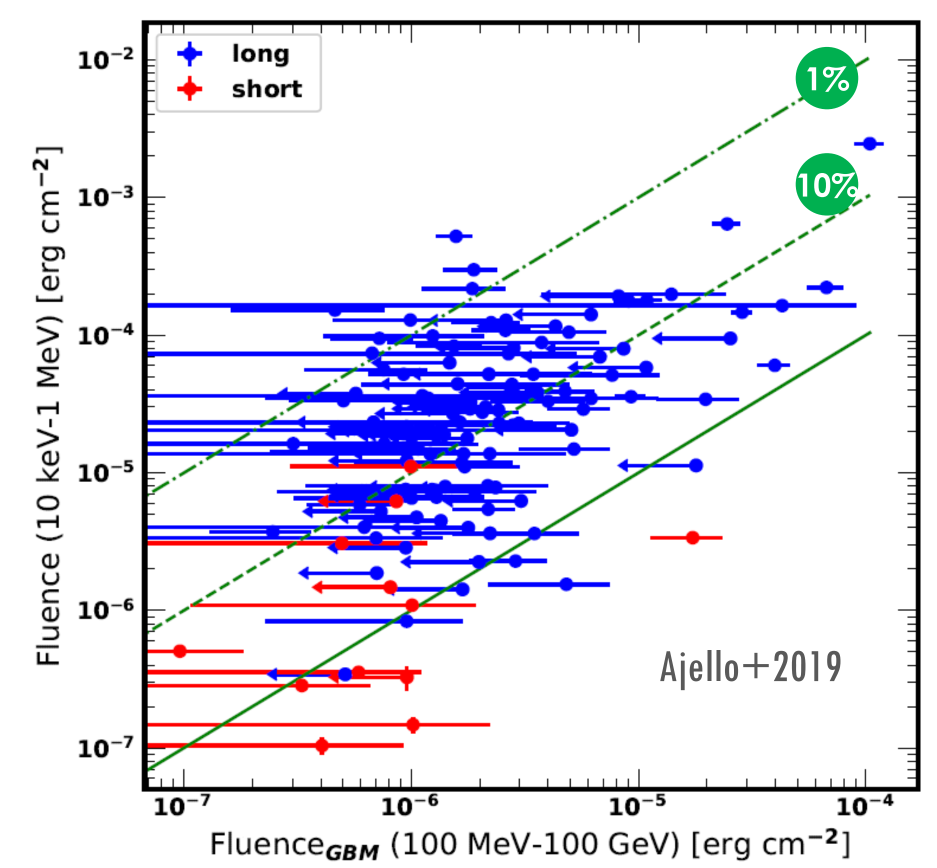
Spectral properties at @GeV energies

- Comparison of low-energy (LE) properties of LAT-detected GRBs with the entire **10yr GBM sample** (**~2400 GRBs**)

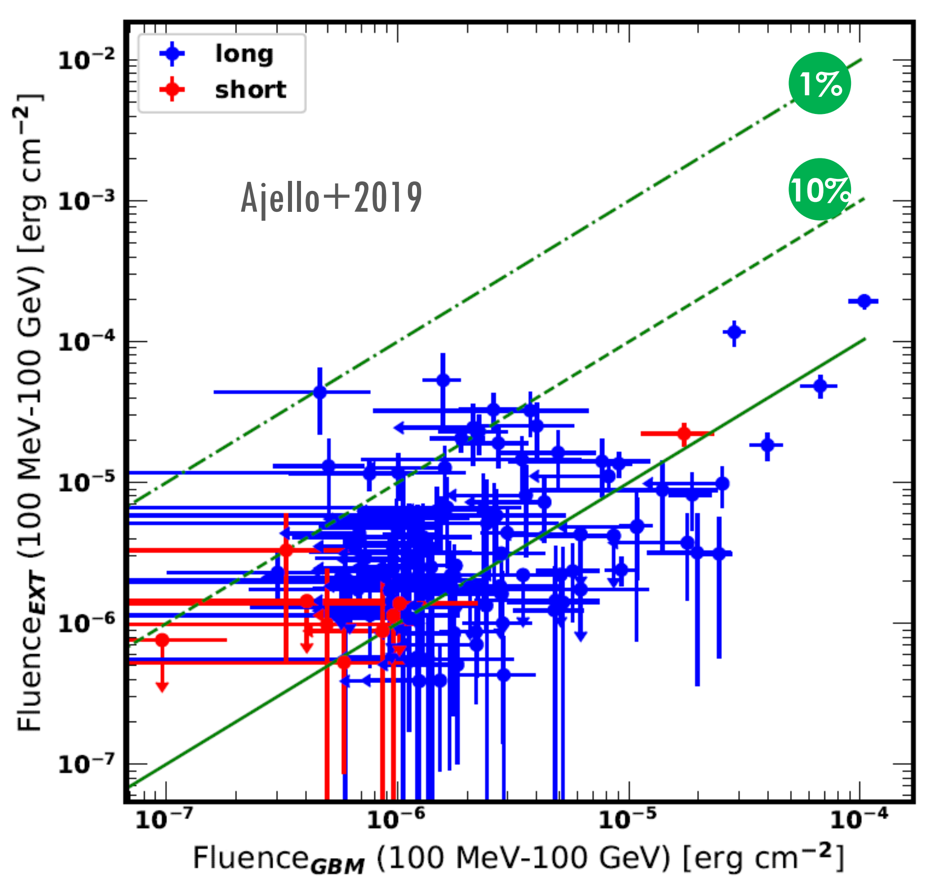


- Distribution of short and long bursts are **different**
- LAT tends to sample brighter bursts
  - BUT: **MUCH LARGER SPREAD** now than in the first LAT catalog!
    - Detection of HE emission also **from weak GBM bursts**!

Spectral properties at @GeV energies



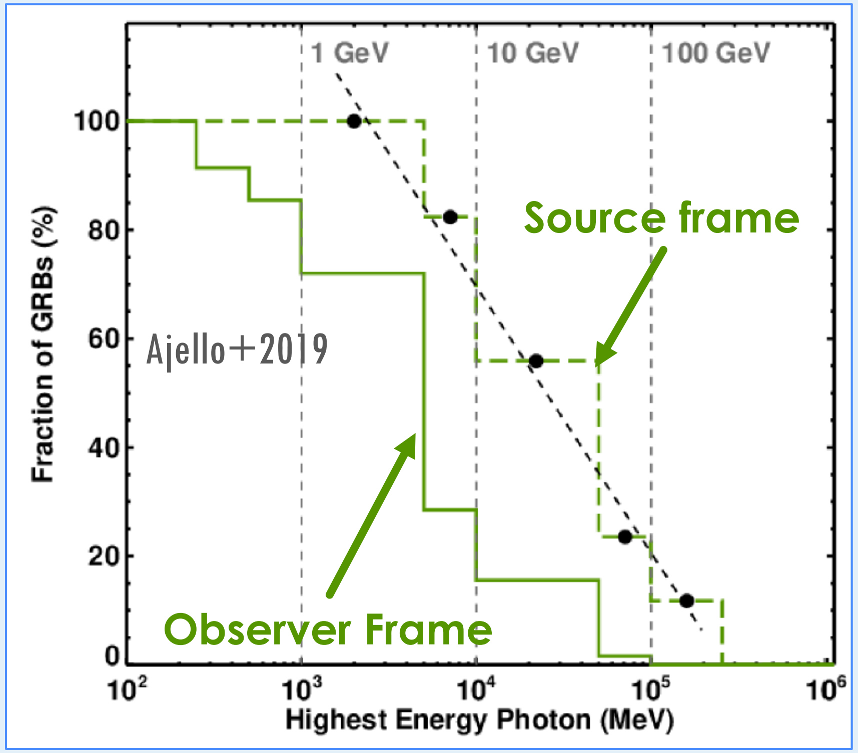
- LE (10-1000 keV) fluence is >10 x larger than HE (100 Mev-100 GeV) fluence in the «GBM» time window
  - The majority of the burst **energy** is emitted at **lower energies**!

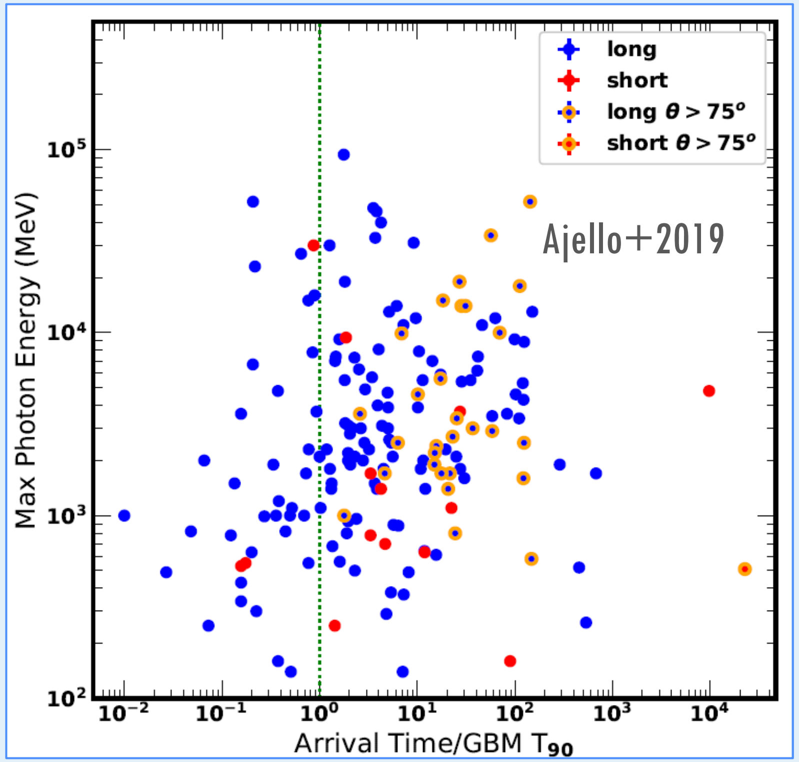


- At HE (100 Mev-100 GeV), the fluence measured at late times («EXT» winodw) is **comparable** to the one measured during the prompt phase («GBM» window)

Spectral properties at @GeV energies

- **Highest-energy photons** from GRBs
  - **<5%** of GRBs have **E > 50 GeV**
  - Sharp drop @5 GeV (obs.frame)
  - Record holder: **GRB 130427A**
    - **95 GeV @243 s, 77 GeV @19s, 34 GeV @34 ks**



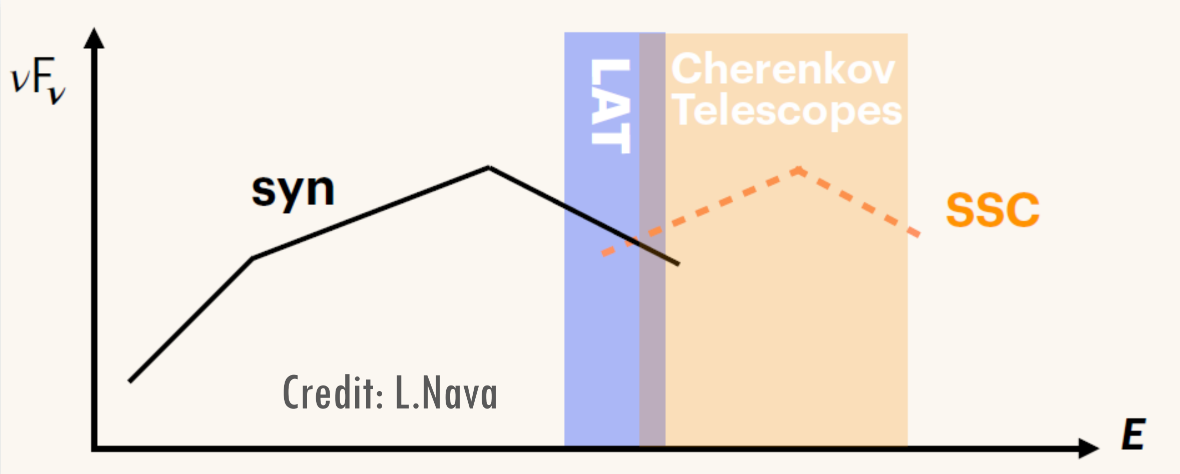


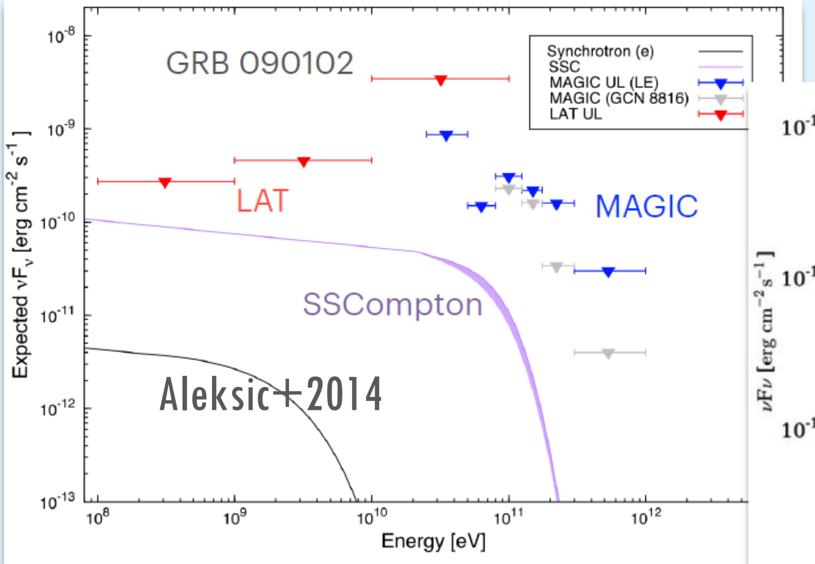
- HE photons often **arrive after the low-energy emission is over, BUT**

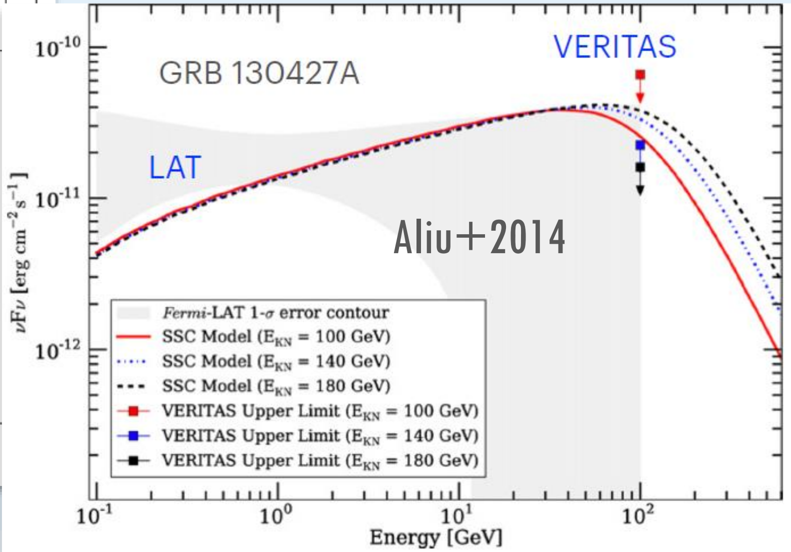
  ➡ Highest energies can be produced either very quickly or very late: challenge for models!

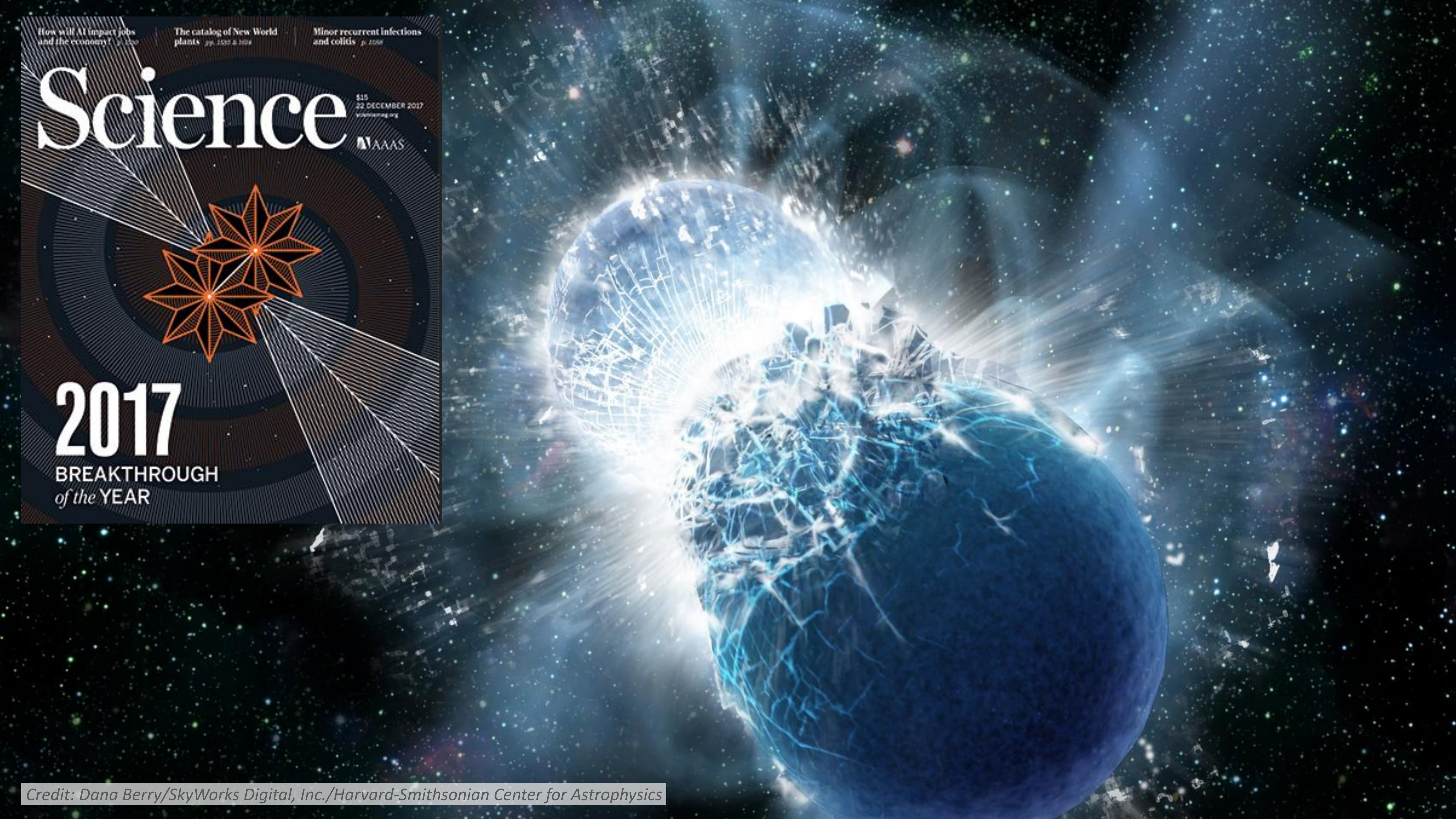
GRBs @ TeV energies

- Evidence for high-energy additional spectral components from GeV observations
- **Current generation on IACTs: MAGIC / HESS / VERITAS**
  - Number of observed GRBs:
    - Hundreds
  - Low-energy threshold:
    - 50 / 50 / 100 GeV
  - Time delay:
    - < 100 s / 100 – 1000 s
- Tev observations until 2019:
  ➔ no detections,
  only upper limits!



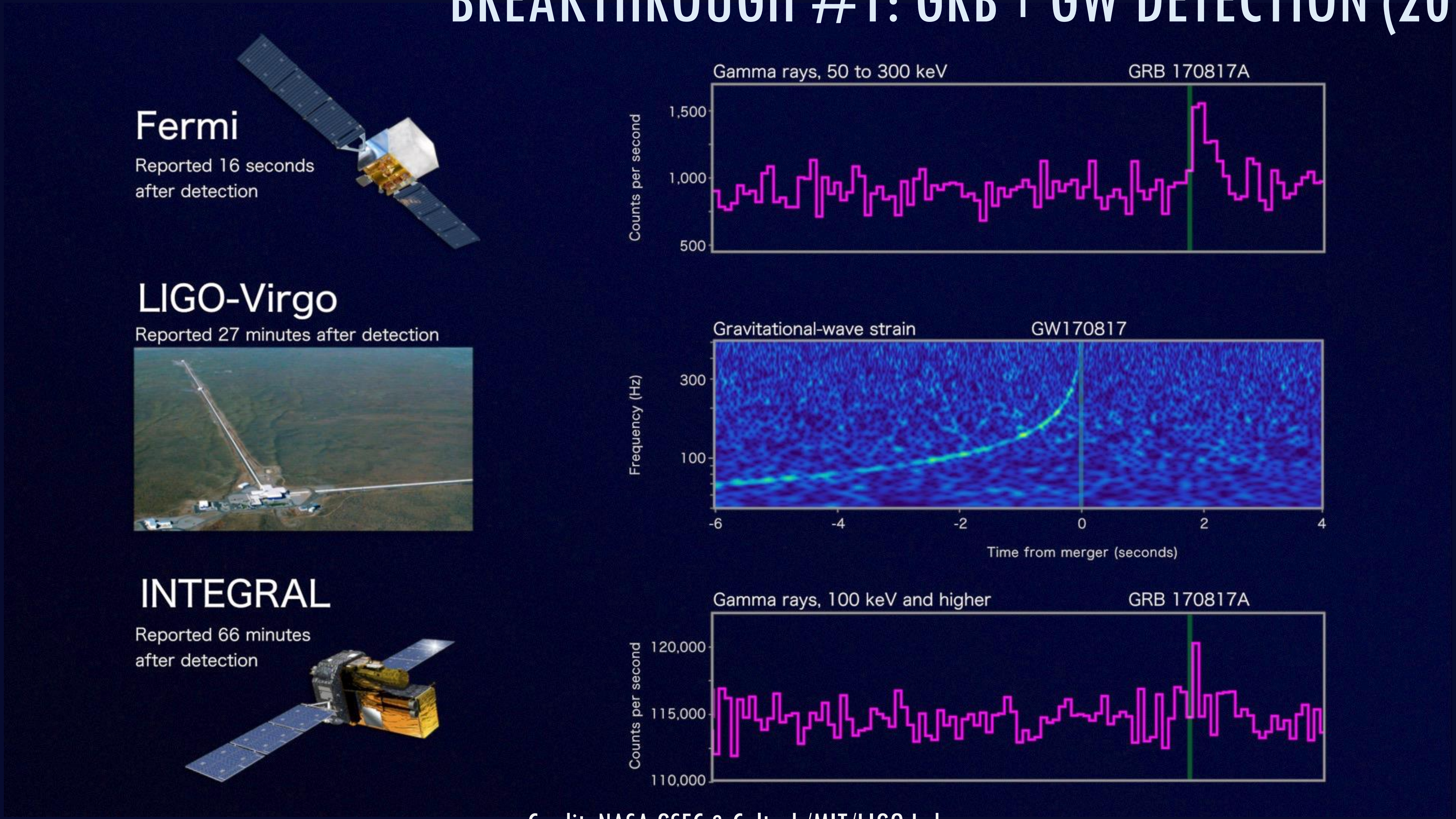






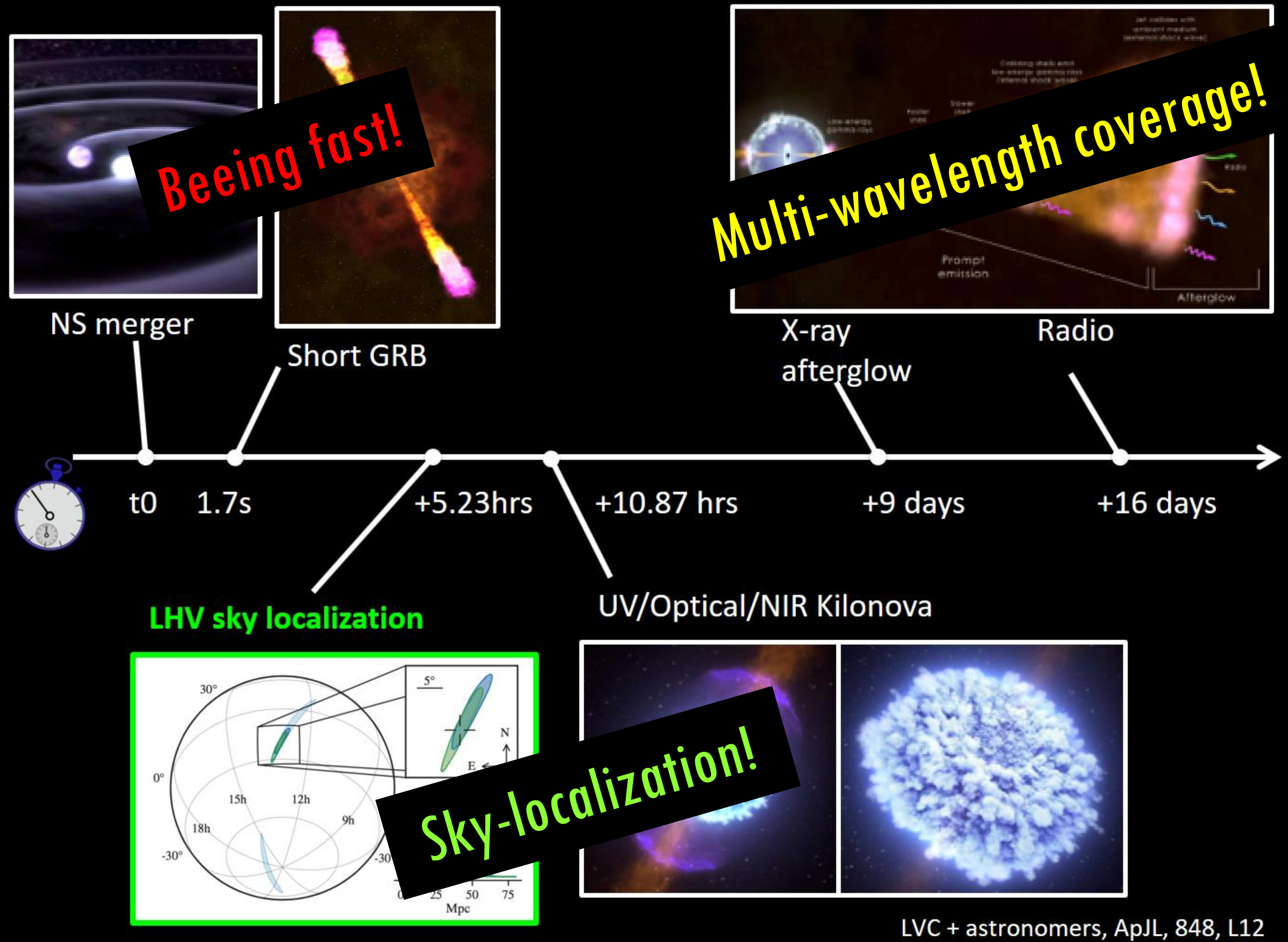
Credit: Dana Berry/SkyWorks Digital, Inc./Harvard-Smithsonian Center for Astrophysics

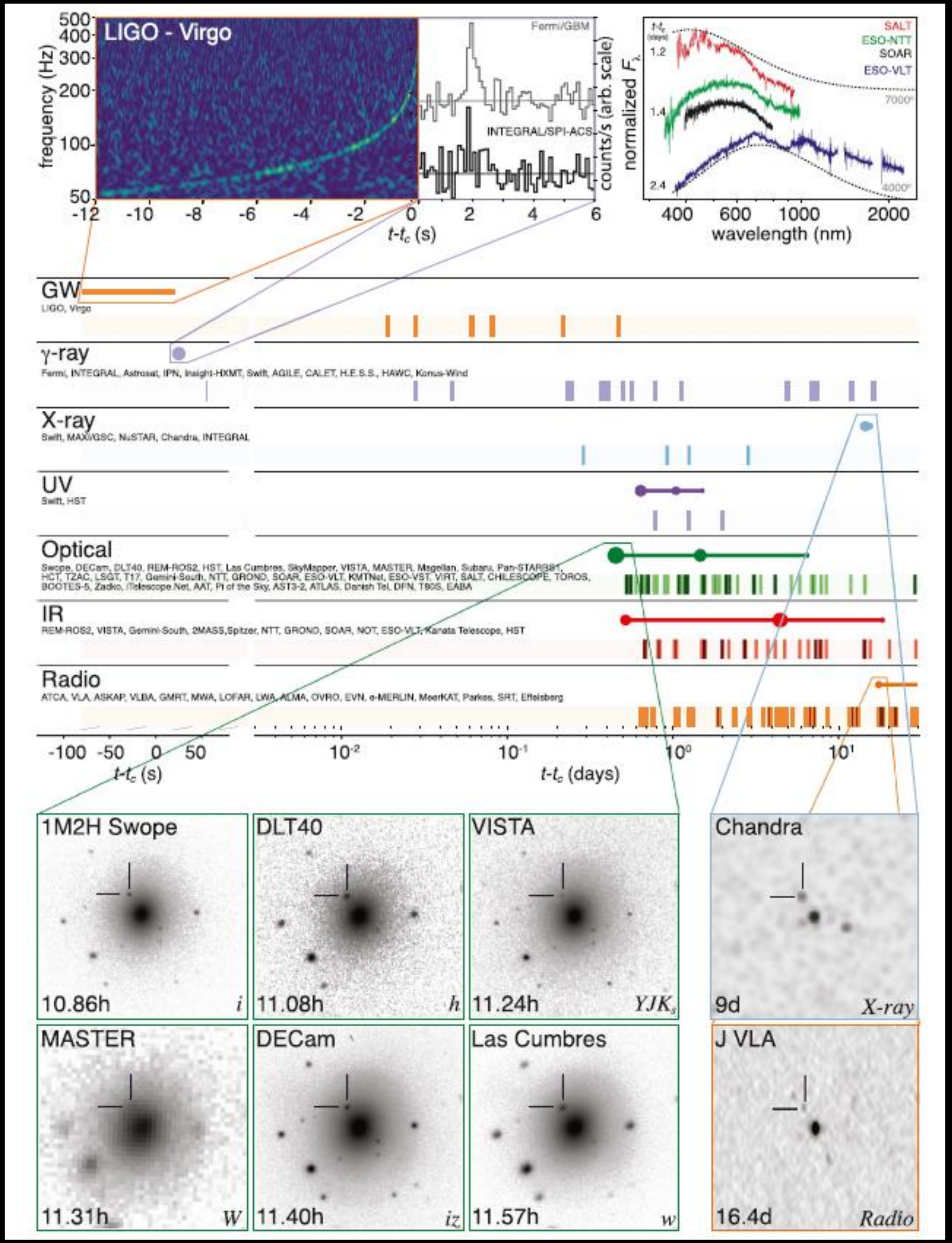
BREAKTHROUGH #1: GRB+GW DETECTION (2017)



Credit: NASA GSFC & Caltech/MIT/LIGO Lab

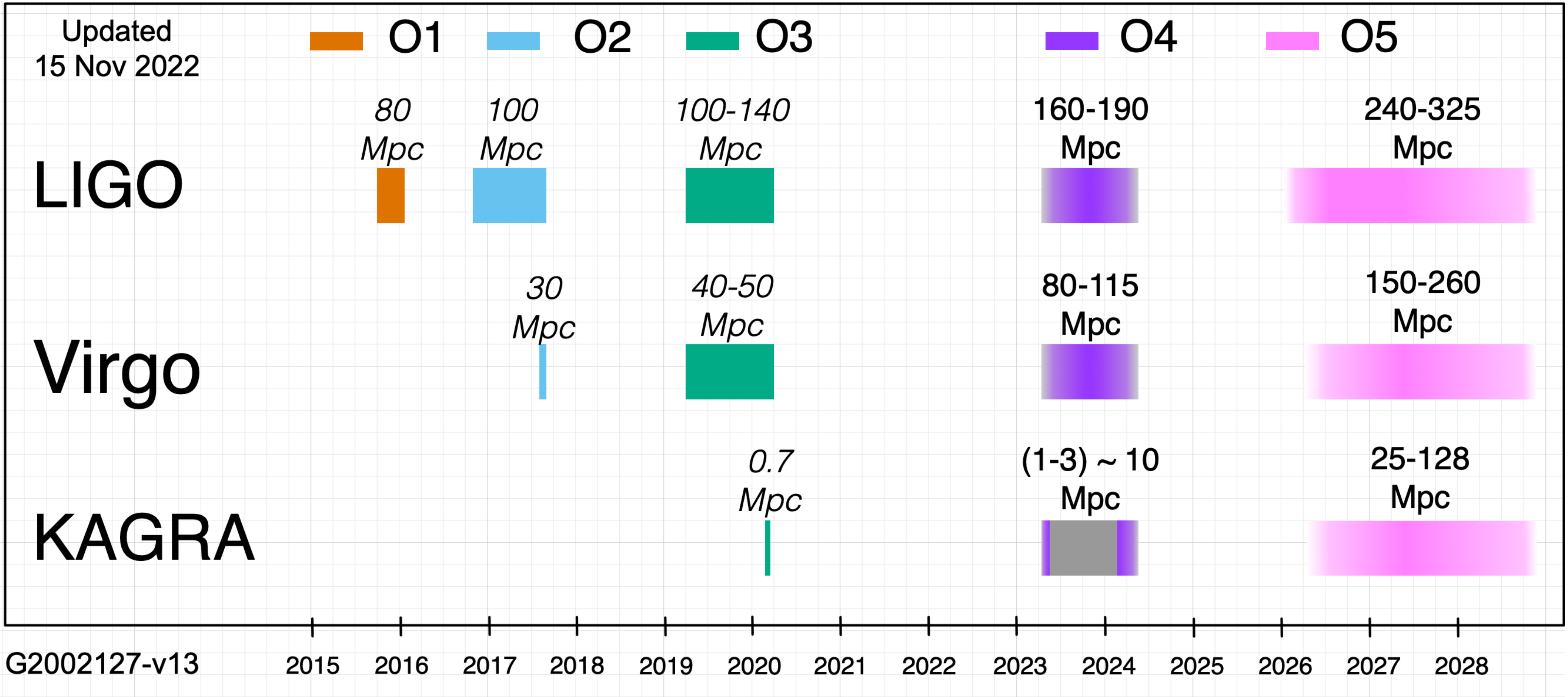
https://www.youtube.com/watch?v=-Yt5EmEgz2w





Multi-messenger Observations of a Binary Neutron Star Merger – Abbott+2017

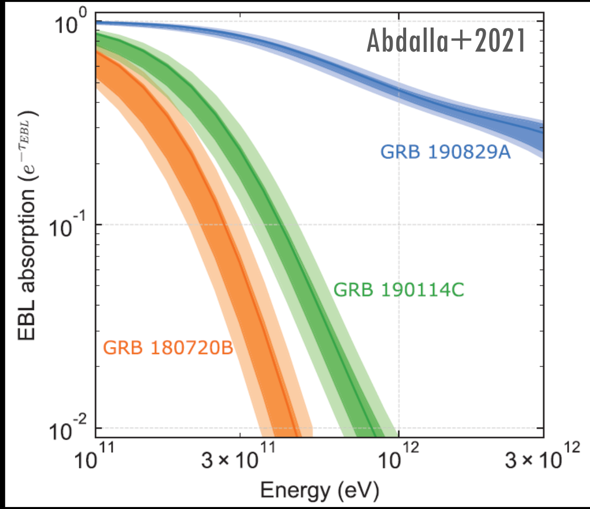
BNS range for each observing run



https://observing.docs.ligo.org/plan/

BREAKTHROUGH #2: GRB DETECTIONS @VHE

- Announcements on 20 Nov. 2019
  1. H.E.S.S. observation of **GRB 180720B**
  2. MAGIC observation of **GRB 190114C**
- Announcement on 4 June 2021
  3. H.E.S.S. observation of **GRB 190829A**



nature

Article | Published: 20 November 2019

A very-high-energy component deep in the γ-ray burst afterglow

H. Abdalla, R. Adam, […] O. J. Roberts

Nature **575**, 464–467(2019) | Cite this article

3478 Accesses | **382** Altmetric | Metrics

z = 0.653

Abstract

Gamma-ray bursts (GRBs) are brief flashes of γ-rays and are considered to be the most energetic explosive phenomena in the Universe[1]. The emission from GRBs comprises a short (typically tens of seconds) and bright prompt emission, followed by a much longer afterglow phase. During the afterglow phase, the shocked outflow—produced by the interaction between the ejected matter and the circumburst medium—slows down, and a gradual decrease in brightness is observed[2]. GRBs typically emit most of their energy via γ-rays with energies in the kiloelectronvolt-to-megaelectronvolt range, but a few photons with

nature DOI: 10.1038/s41586-019-1750-x

Article | Published: 20 November 2019

Teraelectronvolt emission from the γ-ray burst GRB 190114C

MAGIC Collaboration

Nature **575**, 455–458(2019) | Cite this article

4230 Accesses | **493** Altmetric | Metrics

z = 0.4245

Abstract

Long-duration γ-ray bursts (GRBs) are the most luminous sources of electromagnetic radiation known in the Universe. They arise from outflows of plasma with velocities near the speed of light that are ejected by newly formed neutron stars or black holes (of stellar mass) at cosmological distances[1,2]. Prompt flashes of megaelectronvolt-energy γ-rays are followed by a longer-

Science Contents News Careers Journals

REPORT

Revealing x-ray and gamma ray temporal and spectral similarities in the GRB 190829A afterglow

H.E.S.S. Collaboration[*,†], H. Abdalla[1], F. Aharonian[2,3,4], F. Ait Benkhali[3], E. O. Angüner[5], C. Arcaro[6], C. Armand[7], T. Armstro...
+ See all authors and affiliations

Science 04 Jun 2021:
Vol. 372, Issue 6546, pp. 1081-1085
DOI: 10.1126/science.abe8560

z = 0.0785

Article | Figures & Data | Info & Metrics | eLetters | PDF

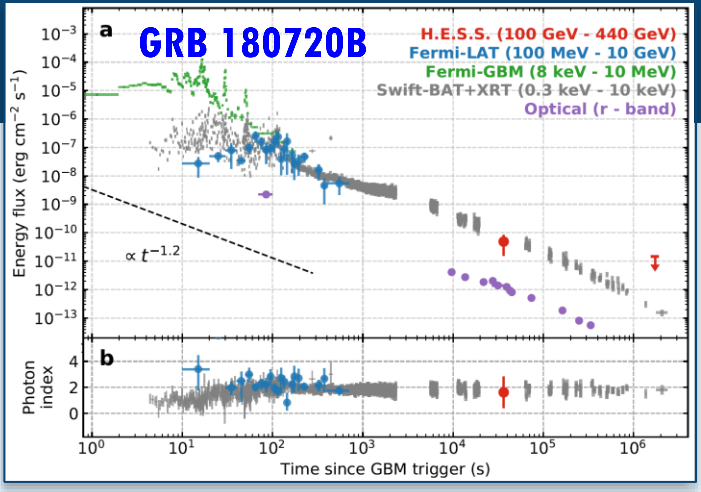
Abstract

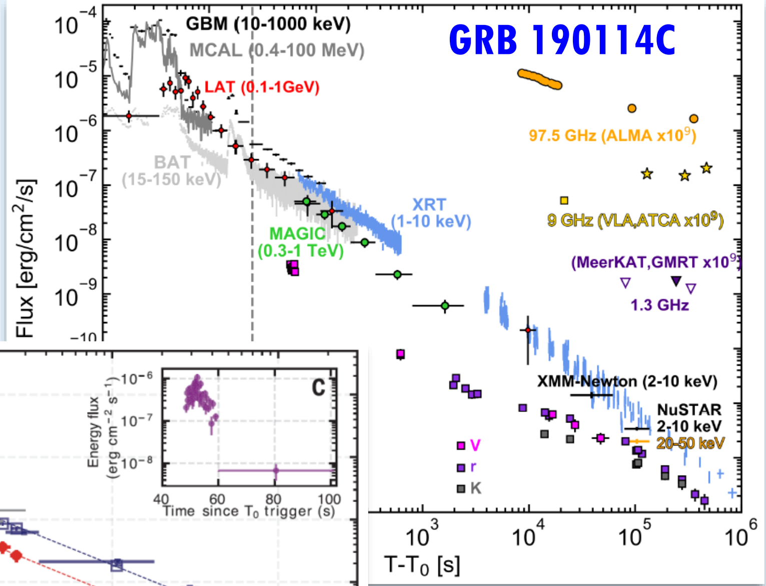
Gamma-ray bursts (GRBs), which are bright flashes of gamma rays from extragalactic sou followed by fading afterglow emission, are associated with stellar core collapse events. W report the detection of very-high-energy (VHE) gamma rays from the afterglow of GRB 190829A, between 4 and 56 hours after the trigger, using the High Energy Stereoscopic System (H.E.S.S.). The low luminosity and redshift of GRB 190829A reduce both internal ar external absorption, allowing determination of its intrinsic energy spectrum. Between energi of 0.18 and 3.3 tera–electron volts, this spectrum is described by a power law with photon index of 2.07 ± 0.09, similar to the x-ray spectrum. The x-ray and VHE gamma-ray light curves also show similar decay profiles. These similar characteristics in the x-ray and gamma-ray bands challenge GRB afterglow emission scenarios.

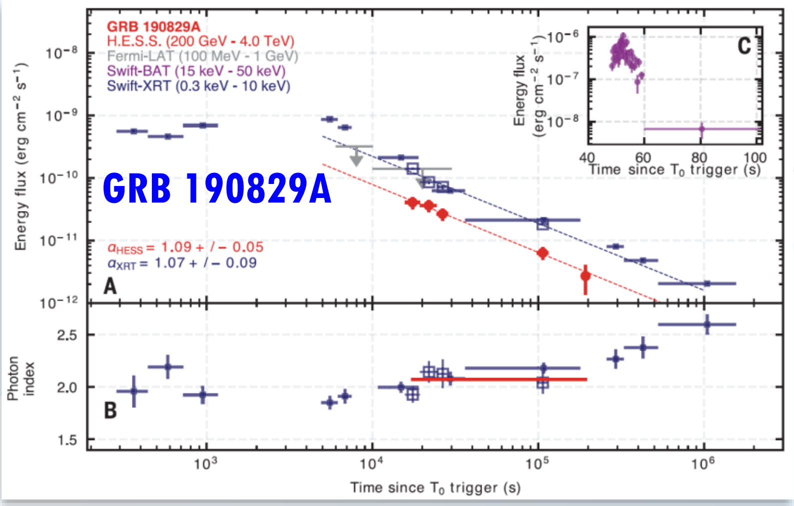
GRB 201216C MAGIC detection

GRBs @ TeV energies

- GRB 160821B **z = 0.162**
  - 3σ detection – short GRB **>0.5 TeV** **4h** post trigger (MAGIC+2021)
- **GRB 180720B** **z = 0.653**
  - 5σ detection – long GRB **>0.1 TeV** **10h** post trigger (HESS+2019 Nature)
- **GRB 190114C** **z = 0.4245**
  - 50σ detection – long GRB **>0.2 TeV** **60s** post trigger (MAGIC+2019 Nature)
- **GRB 190829A** **z = 0.0785**
  - 20σ detection – long GRB **>0.18 TeV** **4-50h** post trigger (HESS+2021 Science)
- GRB 201015A **z = 0.43**
  - >3σ detection – long GRB **40s** post trigger (MAGIC GCN 28659)
- GRB 201216C **z = 1.1**
  - >5σ detection – long GRB **57s** post trigger (MAGIC GCN 29075)



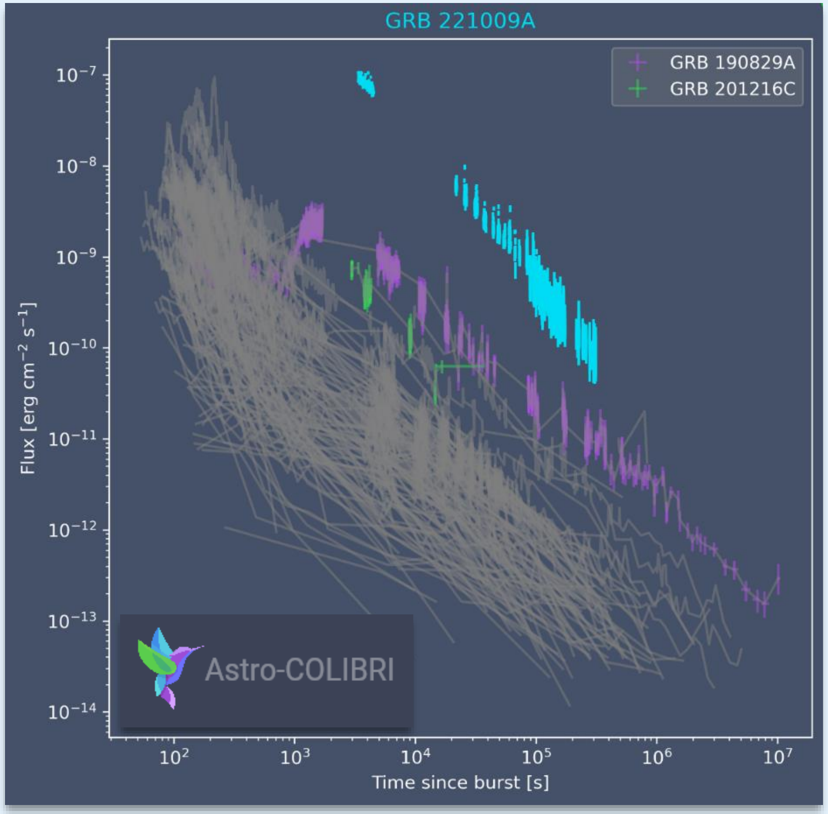


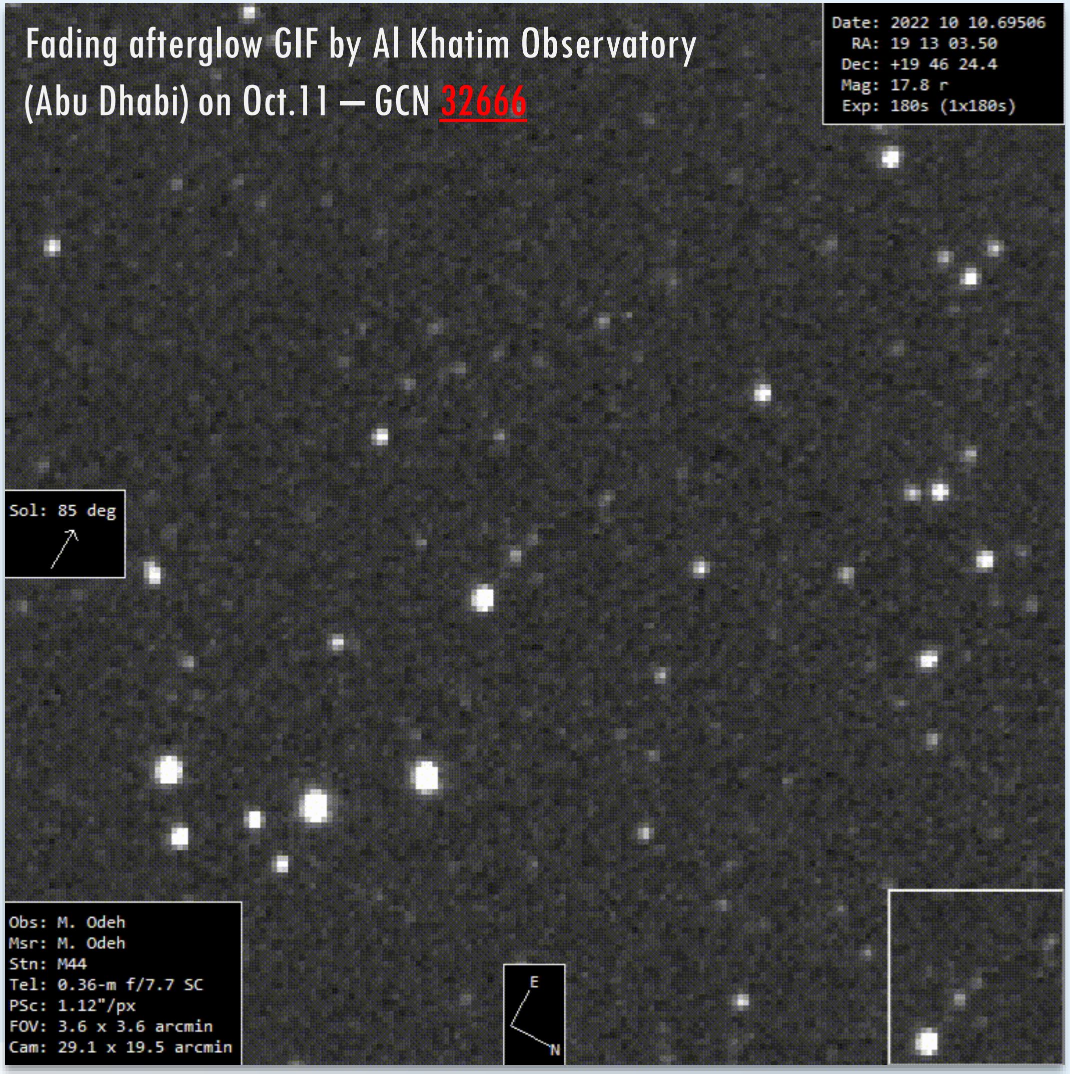


The «BOAT» GRB 221009A

- First announced by **Swift** as a "new bright hard X-ray and optical transient"
  Swift J1913.1+1946 (GCN 32632)

- Until now:
  117 GCNs
  +1 ATEL
  - Latest GCN this morning from **HST**: optical/IR counterpart well detected @30d)





GRB 221009A – Timeline of events

- **Oct.9 2022**
  - 13:16:60 UT **(T_0)** Fermi-GBM trigger 221009553 (no prompt GCN notices)
  - 14:10:17 UT **(T_0+3200s)** Swift trigger (Swift GCN after 20min)
  - 20:54:36 UT Fermi-GBM reports that trigger 221009553 is superbright+long **GRB 221009A** → location consistent with Swift J1913.1+1946 → same event!!!
  - 21:45:05 UT Fermi-LAT reports HE emission (**E_{max}: 8 GeV** @766 s post Swift trigger)
- **Oct.10, 2022**
  - IPN triangulation (Swift-BAT+Fermi-GBM+Fermi-LAT+INTEGRAL/SPI-ACS+Konus-Wind)
  - X-shooter/VLT reports **redshift z = 0.151**
  - Fermi-LAT reports refined analysis (Duration **>25ks** and **E_{max}: 99 GeV** @T_0+240s)
  - IceCube reports neutrino UL (no detection)
  - Konus/WIND reports highest GRB fluence in 28 years of operation) in GCN
- **Oct.11, 2022**
  - LHAASO reports **>500 GeV** emission within T_0+2000s (>100σ) + **18 TeV photon** (10σ)
  - Swift/XRT reports complex system of **bright expanding dust-scattering rings**
  - HAWC reports upper limits 8 hours after trigger
- **Oct.12, 2022**
  - Carpet-2 reports **250 TeV photon**-like air shower

Astronomy Picture of the Day

15 October 2022

Image Credit: NASA, DOE, Fermi LAT Collaboration, R.Pillera

https://apod.nasa.gov/apod/ap221015.html?fbclid=IwAR0dtOruG18ZOg9a-AhjcLkfPfvsok_C5Dvn-sjK7YpBQB5Pt_g_RShYsUE

Astronomy Picture of the Day

15 October 2022

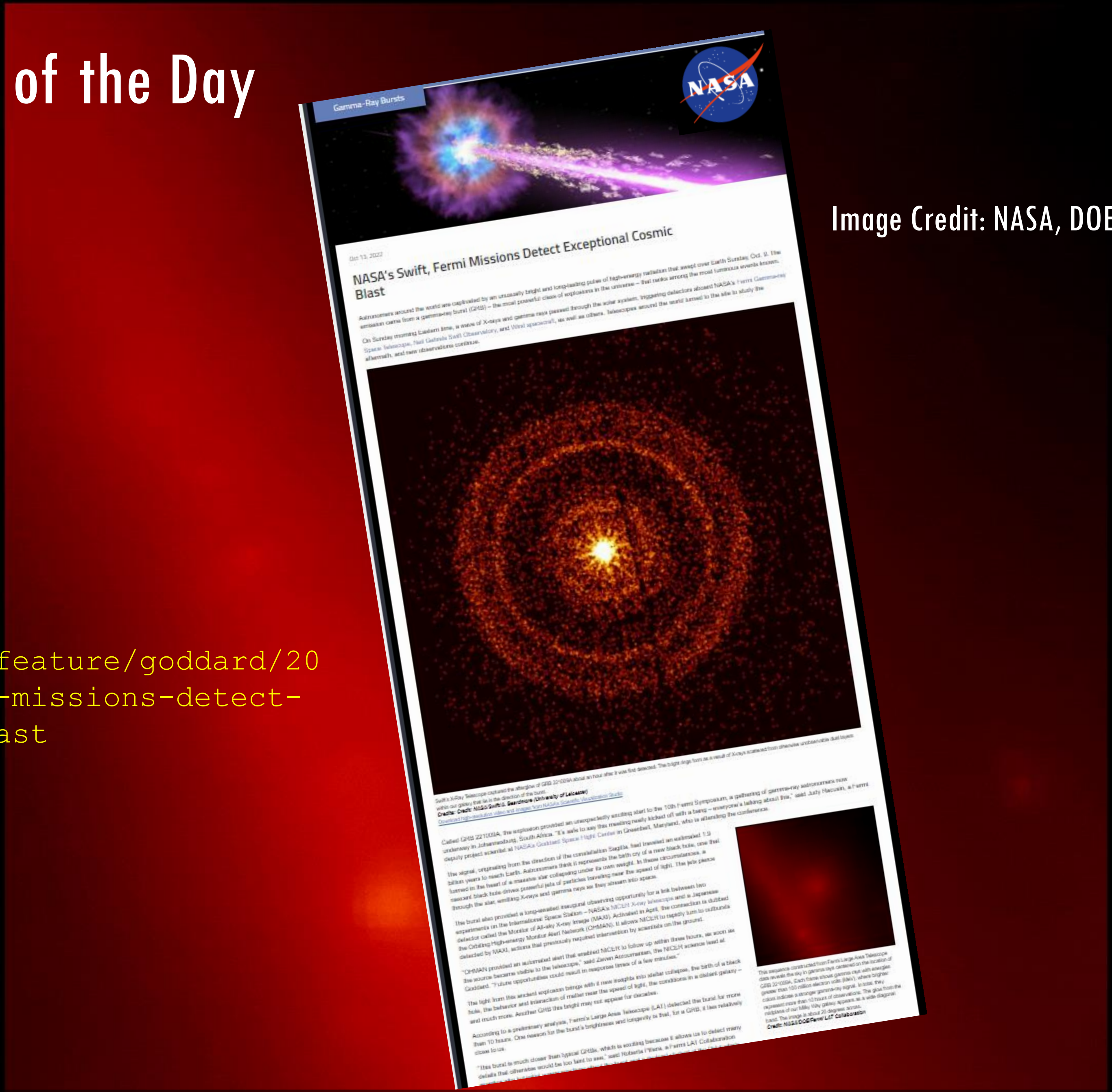


Image Credit: NASA, DOE, Fermi LAT Collaboration, R.Pillera

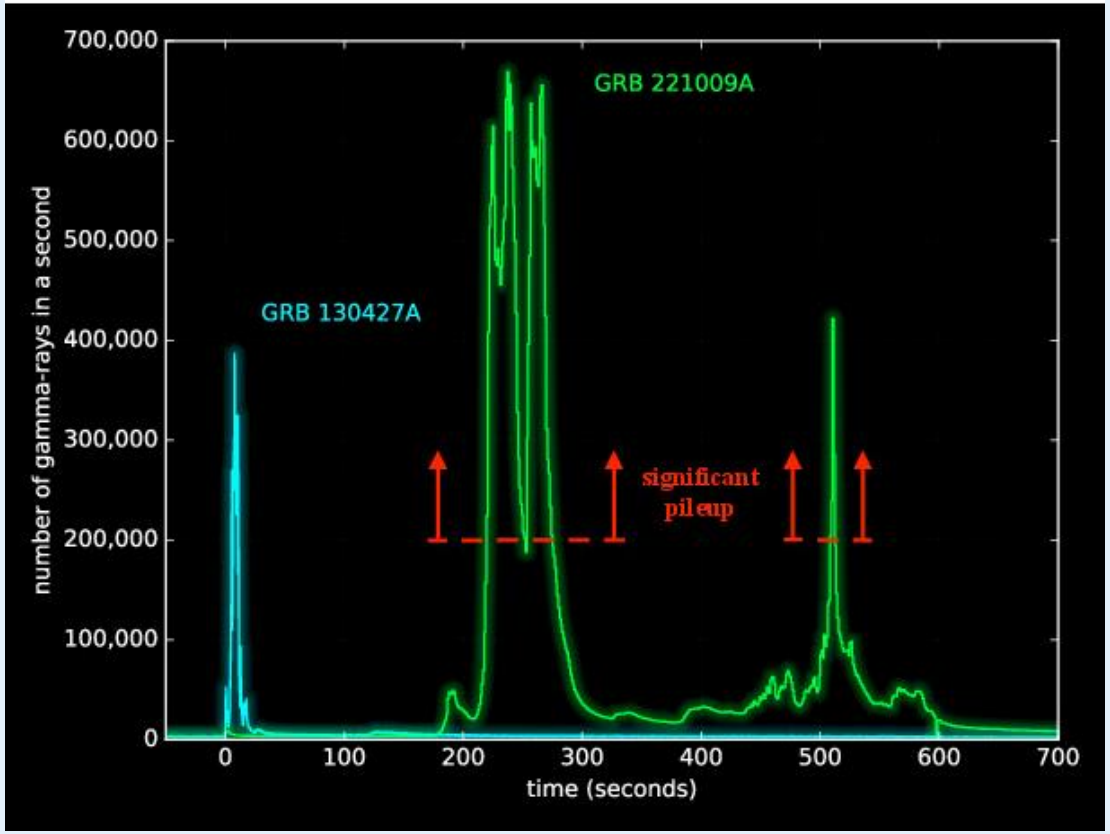
NASA NEWS

13 October 2022

https://www.nasa.gov/feature/goddard/2022/nasa-s-swift-fermi-missions-detect-exceptional-cosmic-blast

https://apod.nasa.gov/apod/ap221015.html?fbclid=IwAR0dtOruG18ZOg9a-AhjcLkfPfvsok_C5Dvn-sjK7YpBQB5Pt_g_RShYsUE

GRB 221009A GBM/LAT lightcurves

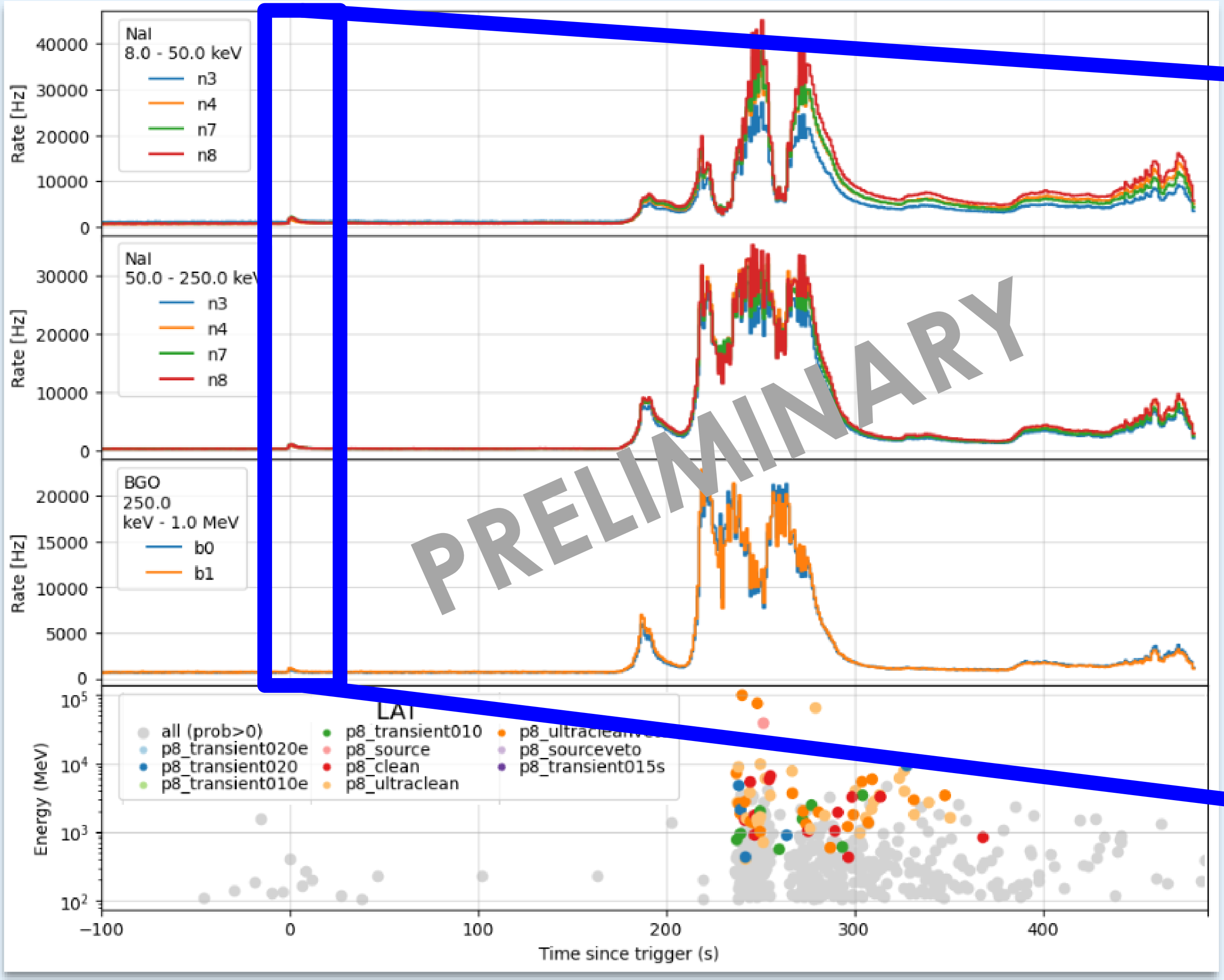


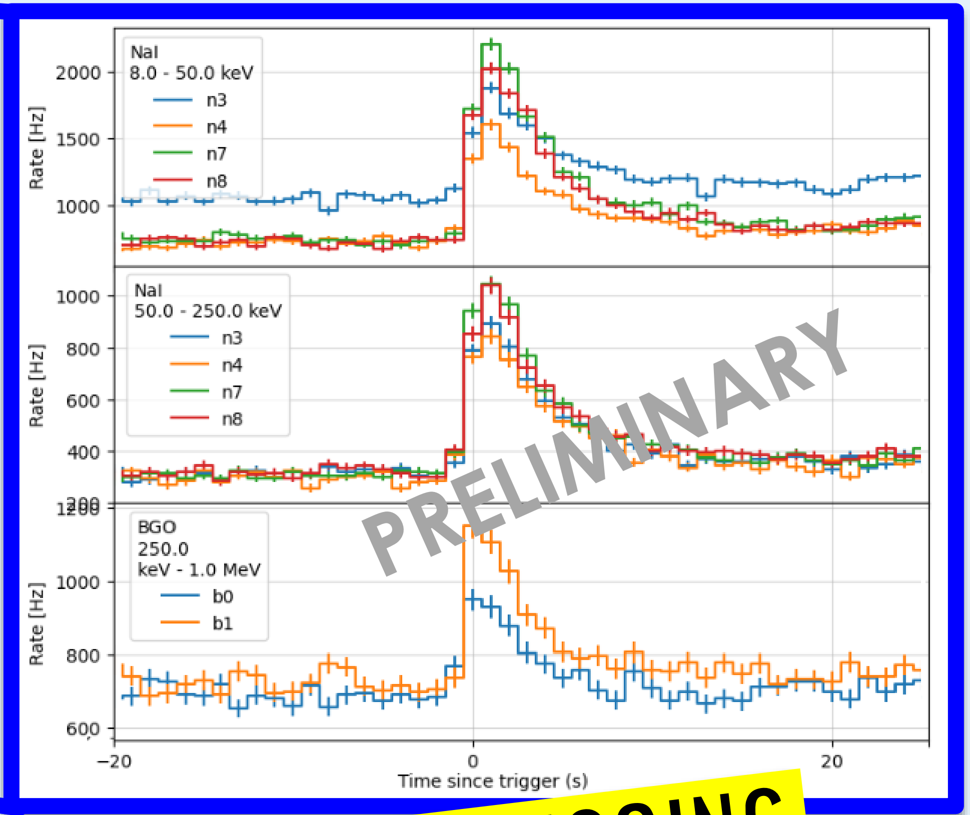
Courtesy of GBM PI – C. Wilson-Hodge

- Dramatically **brighter and longer** than GRB 130427A, the previous record holder
- High count rates **saturating GBM** require **new tools** built upon work with terrestrial gamma-ray flashes
- >30 teams from radio to very high energy gamma-rays and neutrinos studying GRB 221009A

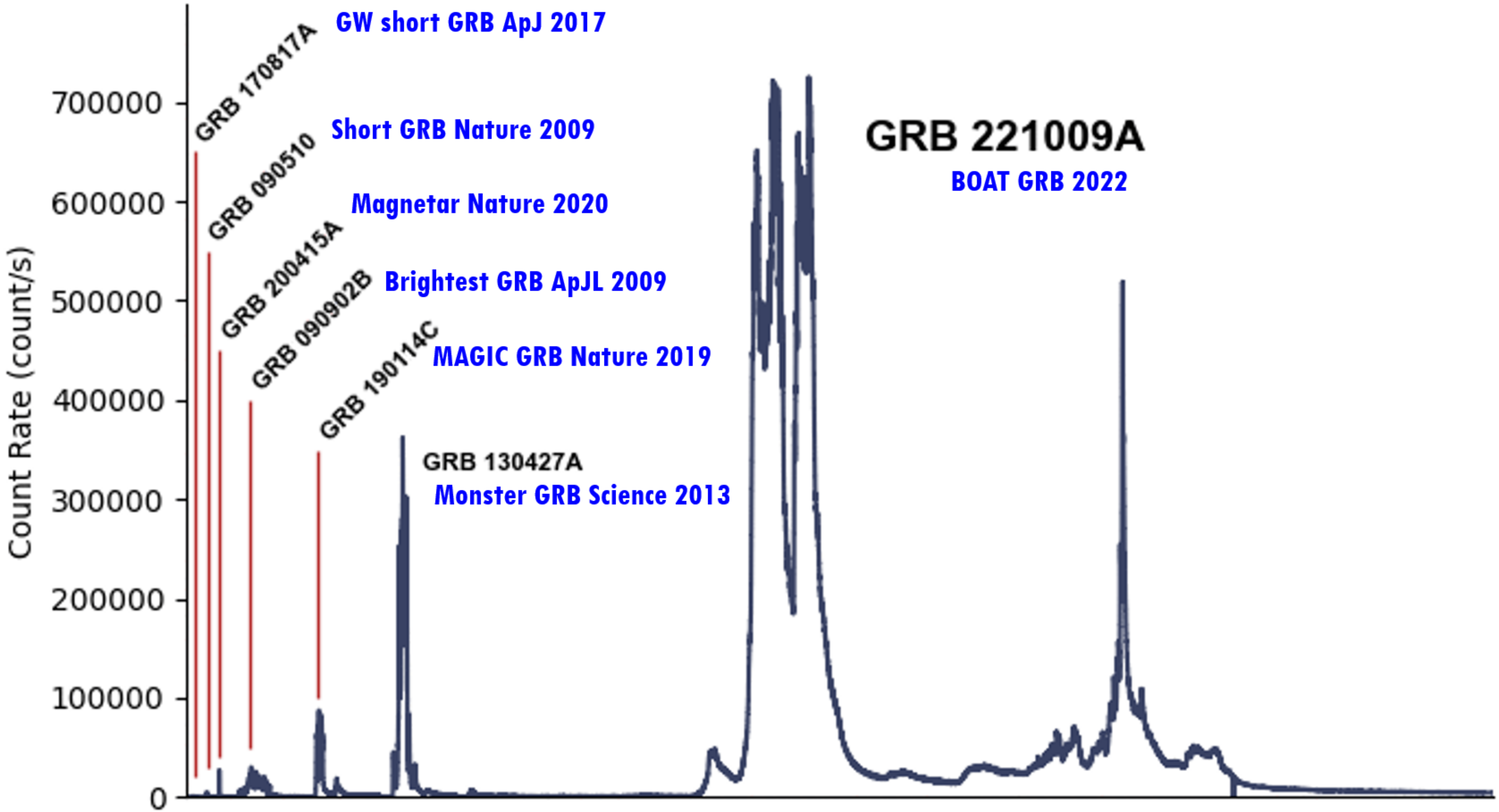
Press Embargo until March!

GRB 221009A GBM/LAT lightcurves





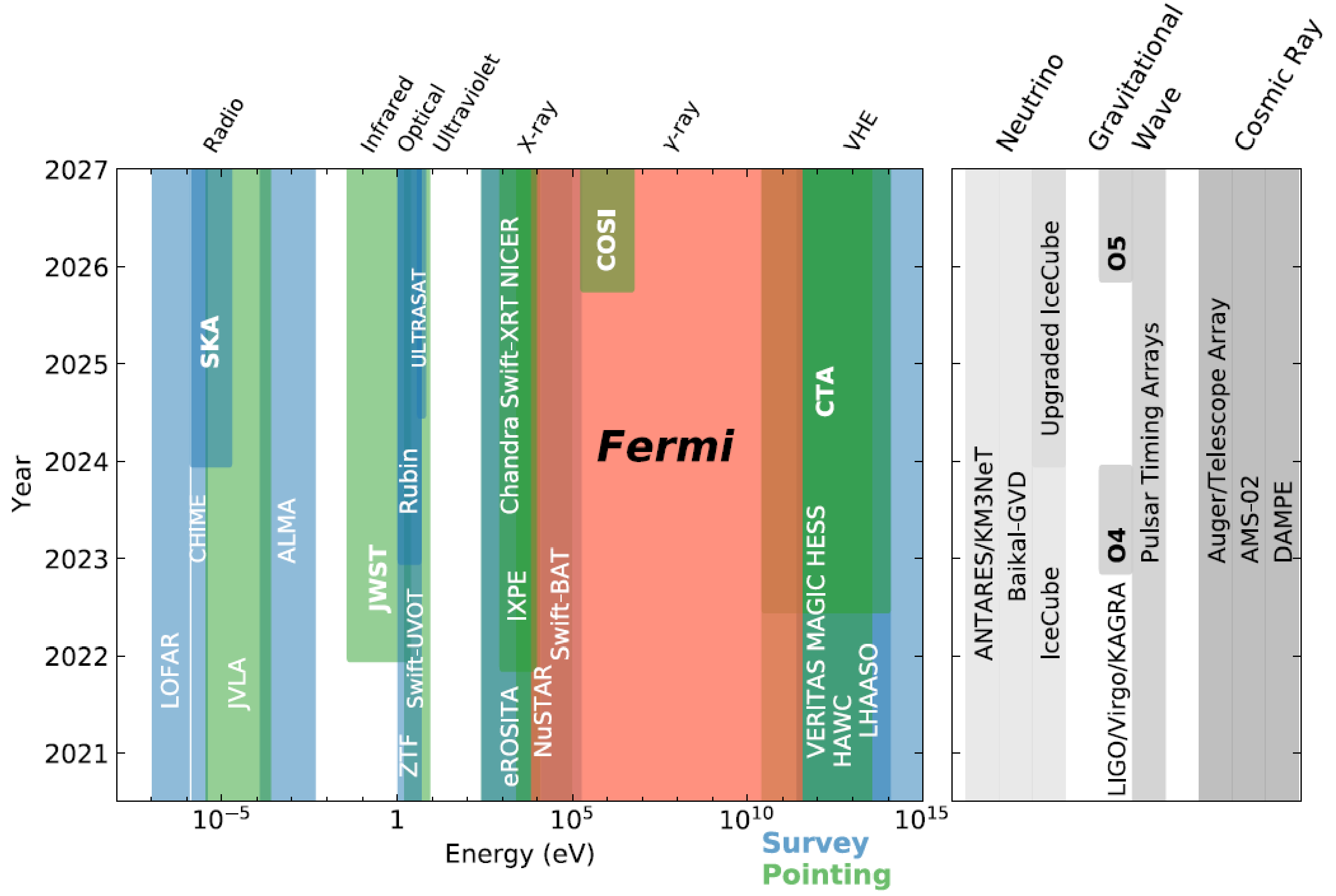
ANALYSIS ONGOING
STAY TUNED!!!



Credit: A. Goldstein/Fermi-GBM

Fermi Opportunities over the next 5 years

- Senior Review Themes
  - Exploring Multimessenger Sources
  - Capitalizing on the Era of Big Surveys
  - Modeling the High-Energy Universe



Credit: J. Racusin @Fermi Symposium 2022

THANK YOU!