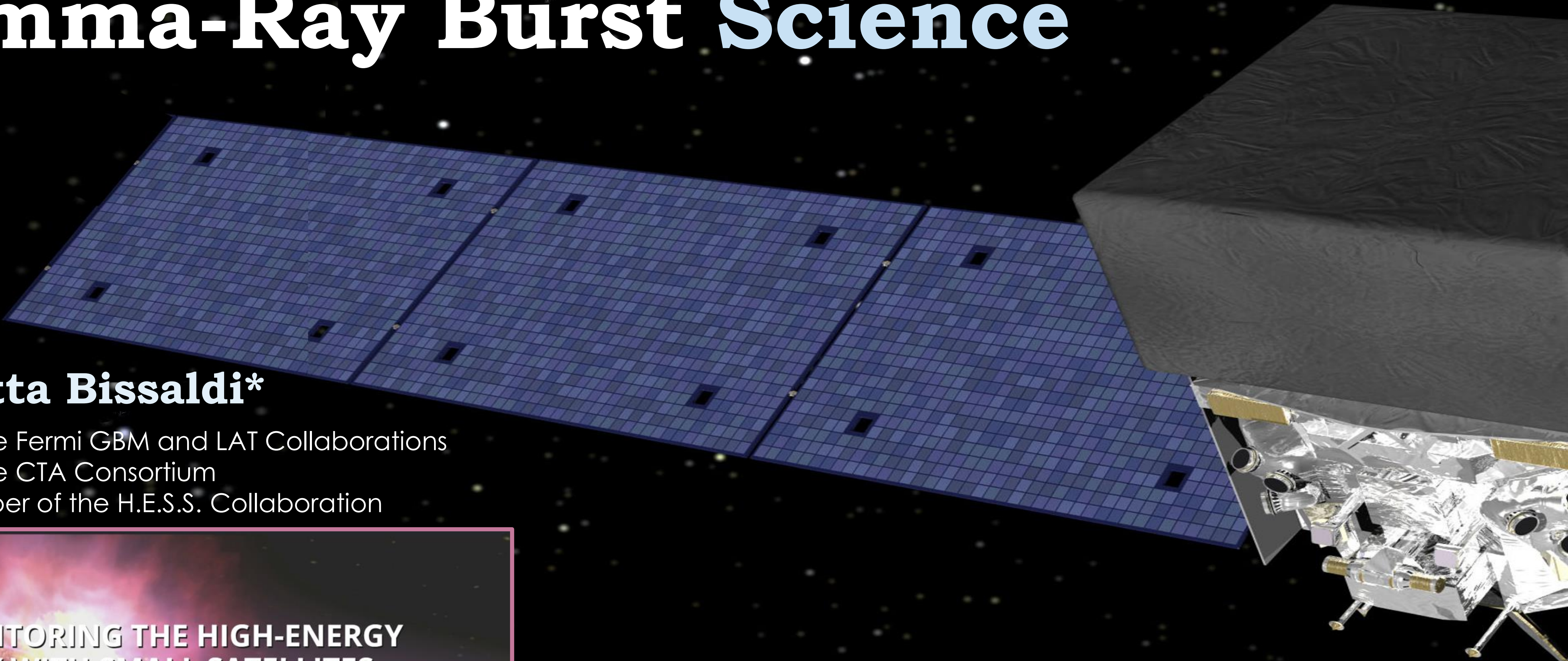
Gamma-Ray Burst Science

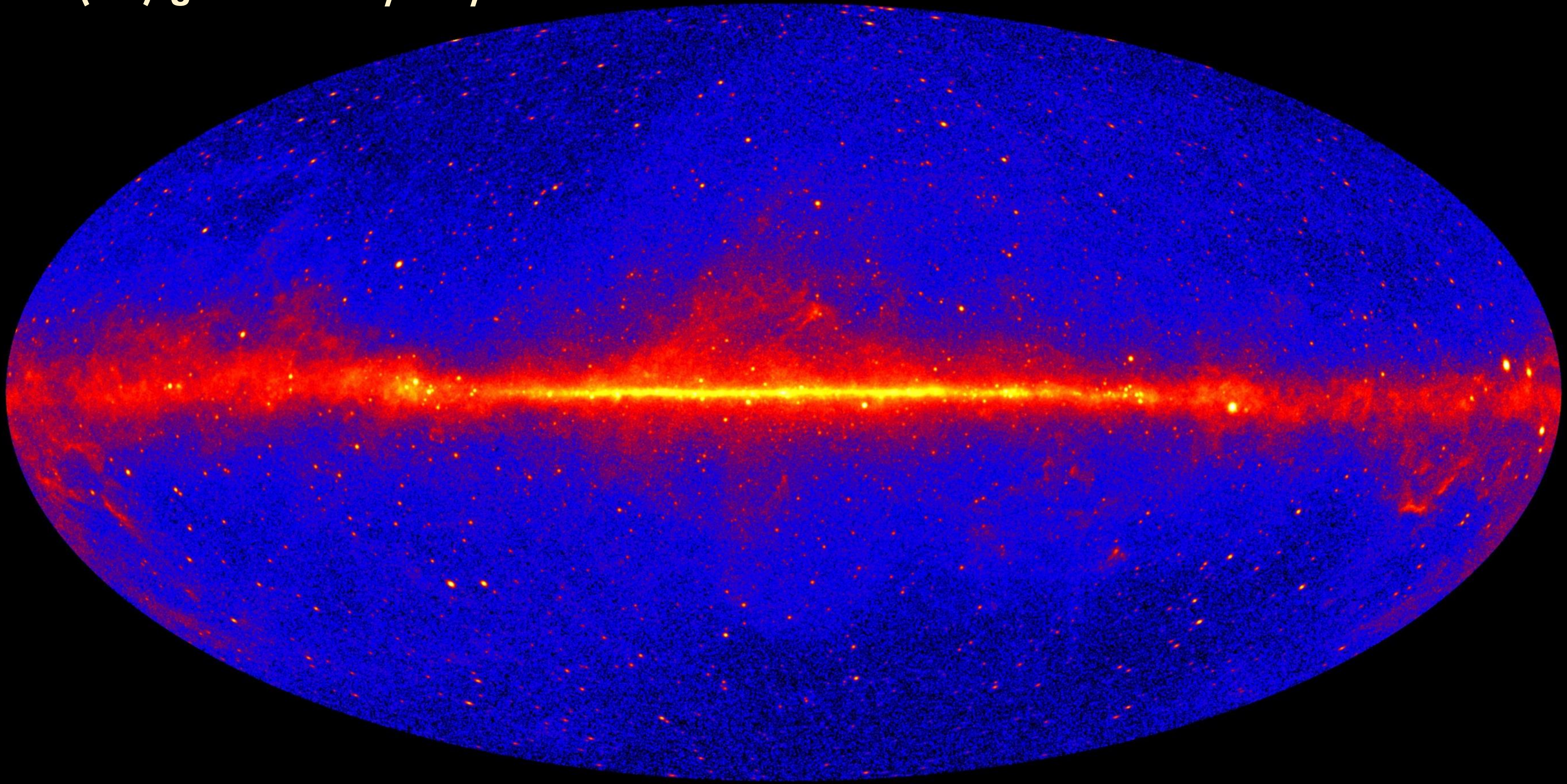


Elisabetta Bissaldi*

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

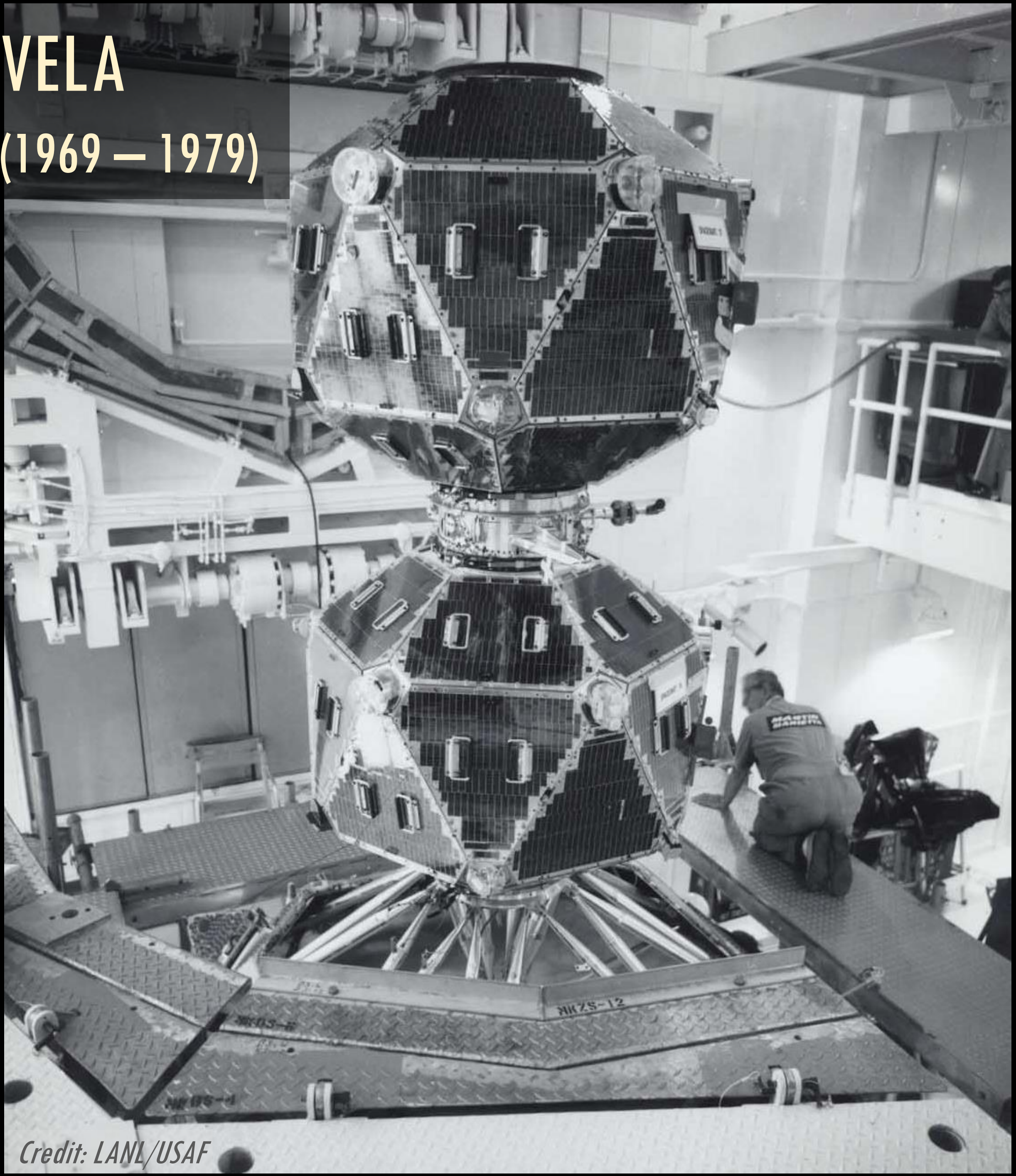
*Dipartimento Interateneo di Fisica "M.Merlin" – Politecnico & INFN Bari
elisabetta.bissaldi@ba.infn.it

The (HE) gamma-ray sky



Credit: NASA/DOE/Fermi LAT Collaboration

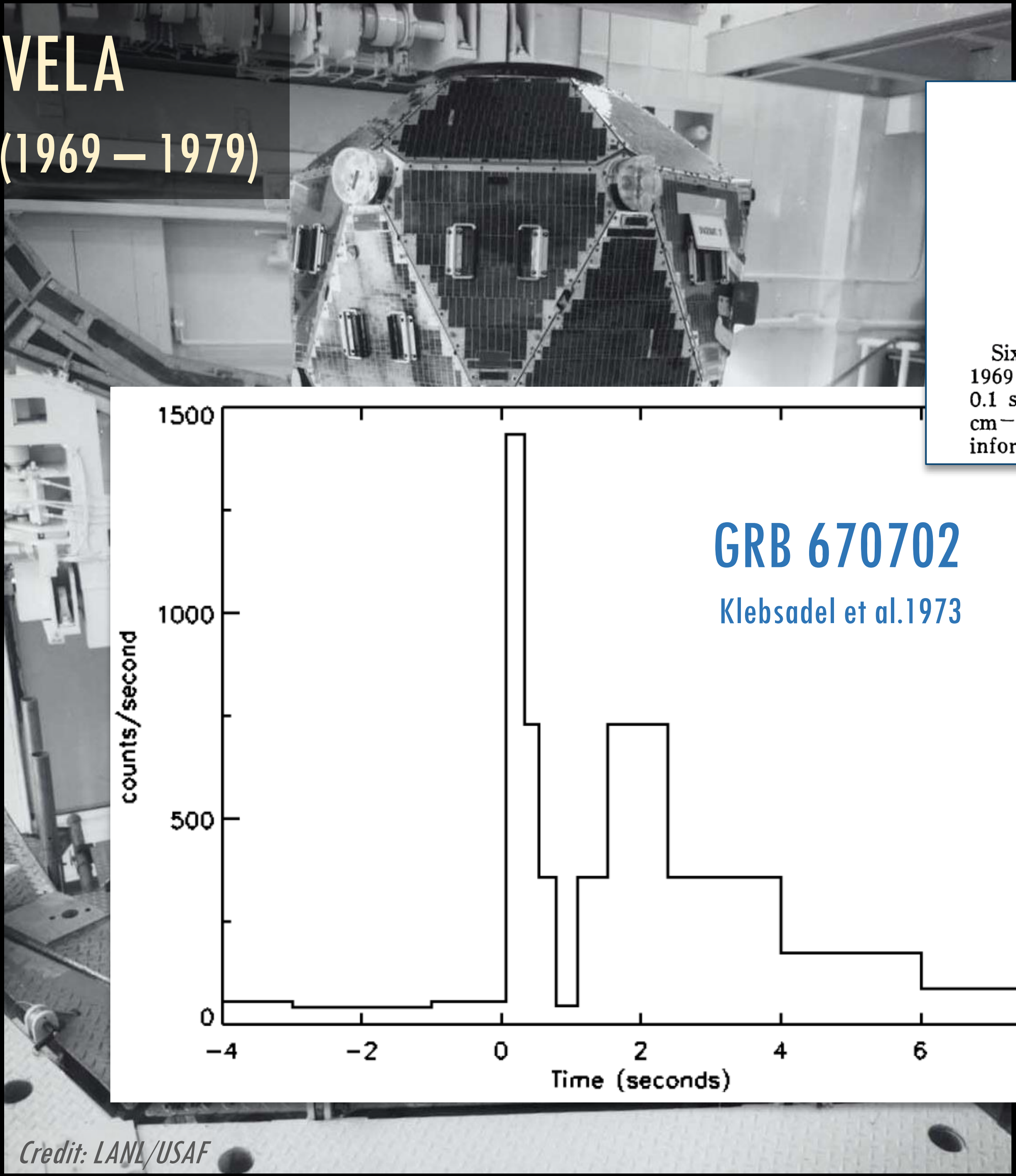
VELA
(1969 – 1979)



Credit: LANL/USAF

VELA

(1969 – 1979)



The Astrophysical Journal, 182:L85–L88, 1973 June 1

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

Ray W. Klebesadel, Ian B. Strong, and Roy A. Olson

University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico

Received 1973 March 16; revised 1973 April 2

ABSTRACT

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ∼30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

THE «DARK» ERA (1973–1991)

- The discovery paper (Klebsadel et al. 1973)
  - **16 GRBs** observed between 1969 and 1972
    - VELA Energy range of 0.2–1.5 MeV
    - Time durations ranged from <1 s to ~30 s
    - Some light curves with **no structure** and others with clearly resolved peaks, as observed in the first GRB
- The VELA satellites were not able to give a GRB spectrum
- Between July 1969 – April 1979:
  - Four VELA satellites (5A & 5B, 6A & 6B) recorded **73 GRBs**
- Detection of **bursts of gamma-rays** soon confirmed by other satellites (*IMP*-6 and Russian *Konus*)
  - New space missions were dedicated to gamma-ray and X-ray observations
  - For the 20 years following the publication of the GRB discovery, **a few hundreds of brief gamma-ray flashes** were observed,
    - **Only roughly localized, vanished too soon, leaving no traces**

THE «DARK» ERA (1973–1991)

- **Interpretation:**
  - In one famous review article at the ***1975 Texas Symposium on Relativistic Astrophysics***, **more than 100 different possible theoretical models** of GRB were listed
    - Possible **GRB origin** from **Galactic neutron stars**
      - On the basis of the **low-energy absorption features**, explained as cyclotron resonance lines (indicating strong magnetic fields), seen by Ginga satellites, and of **high-energy emission features**, interpreted as the 511 keV annihilation line originating near the surface of a solar-mass neutron star
- All experimental results collected in the **1980s** were not sufficiently conclusive
  - It was not possible to detect **any counterpart** of the GRB phenomenon at any wavelength, due to the **large error boxes** of the positions given by the gamma-ray instruments
    - GRBs acquired a special “aura”, mainly due to their mysterious nature which persisted for decades

THE «DARK» ERA

(1973–1991)

- **Interpretation:**
  - In one famous review article at the ***1975 Texas Symposium on Relativistic Astrophysics***, **more than 100 different possible theoretical models** of GRB were listed
    - Possible **GRB origin** from **Galactic neutr**
      - On the basis of the **low-energy** as cyclotron resonance lines (indi by Ginga satellites, and of **high-energy** the 511 keV annihilation line origin mass neutron star
- All experimenta in the **1980s** were not sufficiently conclusive
  - It was not po to detect **any counterpart** of the GRB phenomenon at any wavelength, due to the **large error boxes** of the positions given by the gamma-ray instruments
    - GRBs acquired a special "aura", mainly due to their mysterious nature which persisted for decades

There are no two identical GRBs:
duration, number of peaks, maximum brightness…
in fact, every parameter can be different!

Compton Gamma Ray Observatory

(1991 – 2000)

Credit: NASA/GSFC

Astronaut Jay Apt
1991

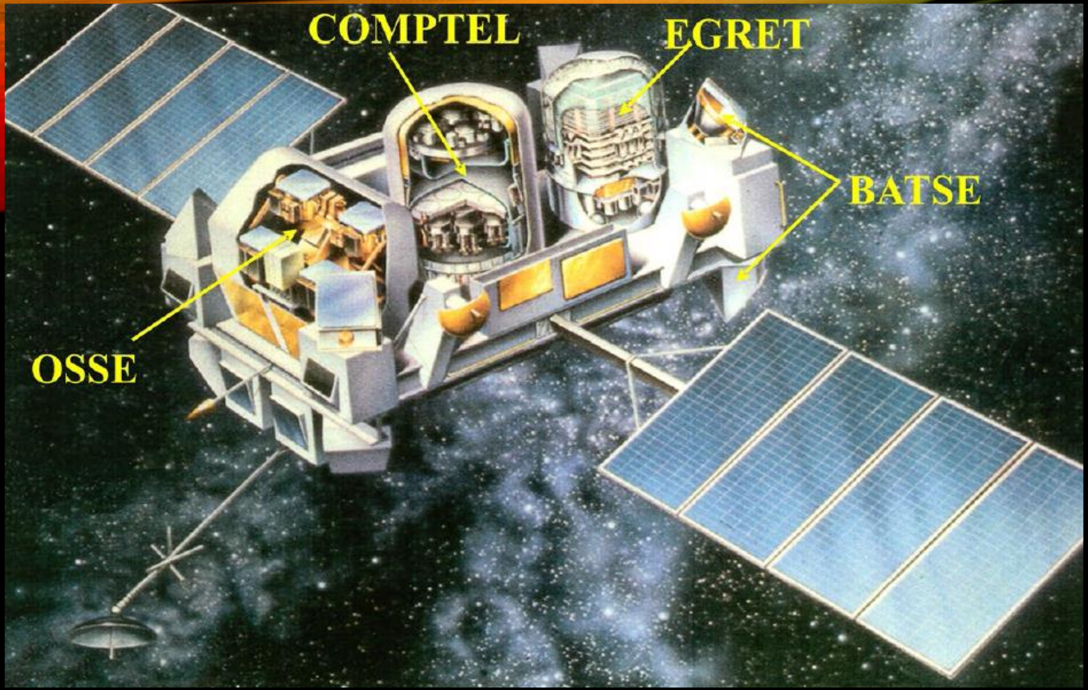
Credit: NASA

Astronaut Jerry Ross
1991

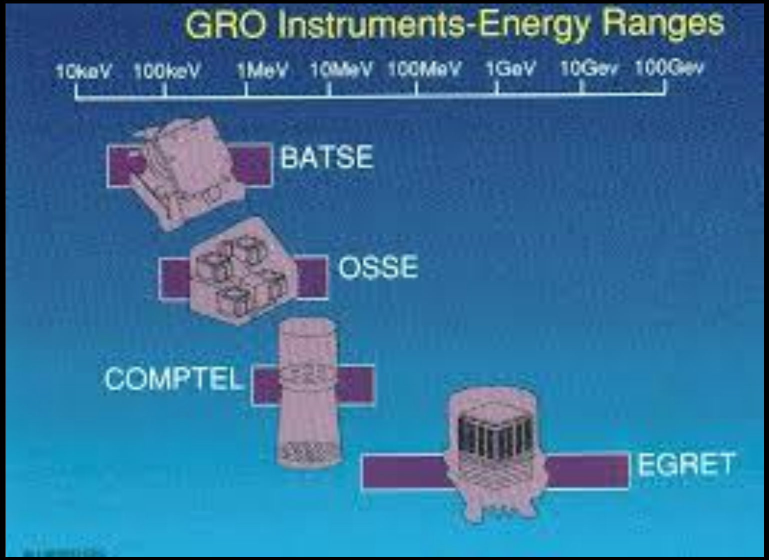
Credit: NASA/Steve Nagel

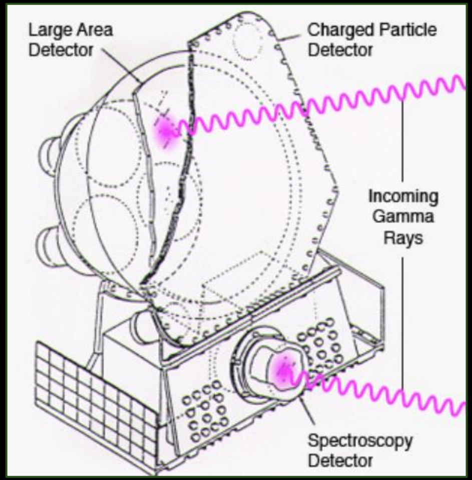
THE BATSE ERA (and milestones)

(1992 – 1996)



Credit: NASA

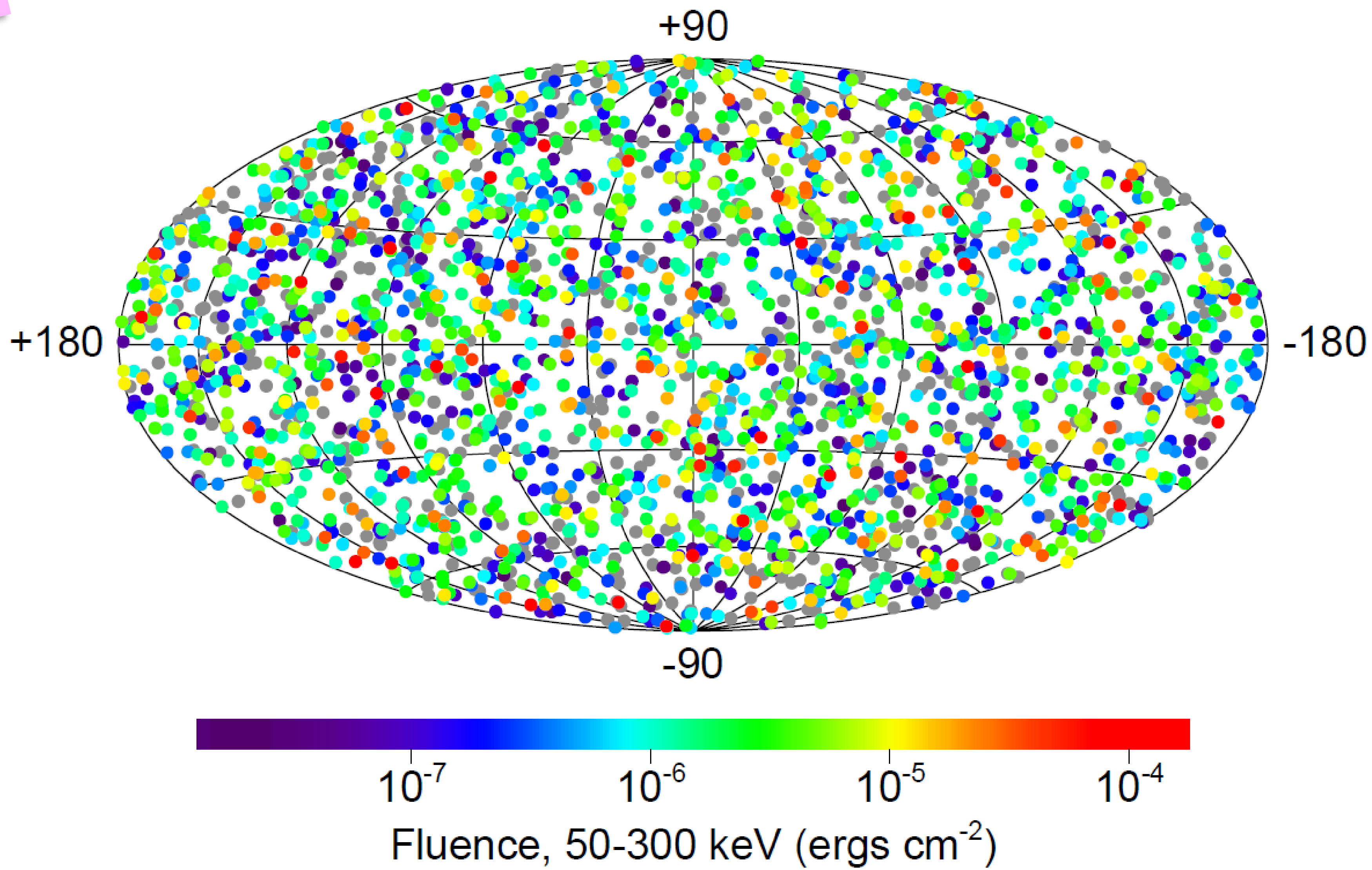




	OSSE	COMPTEL	EGRET	BATSE LARGE AREA	BATSE SPECTROSCOPY
ENERGY RANGE (MeV)	0.06 to 10.0	0.8 to 30.0	20 to 3 x 10^4	0.03 to 1.9	0.015 to 110
ENERGY RESOLUTION (FWHM)	12.5% at 0.2 MeV 6.8% at 1.0 MeV 4.0% at 5.0 MeV	8.8% at 1.27 MeV 6.5% at 2.75 MeV 6.3% at 4.43 MeV	~20% 100 to 2000 MeV	32% at 0.06 MeV 27% at 0.09 MeV 20% at 0.66 MeV	8.2% at 0.09 MeV 7.2% at 0.66 MeV 5.8% at 1.17 MeV
EFFECTIVE AREA (cm^2)	2013 at 0.2 MeV 1480 at 1.0 MeV 569 at 5.0 MeV	25.8 at 1.27 MeV 29.3 at 2.75 MeV 29.4 at 4.43 MeV	1200 at 100 MeV 1600 at 500 MeV 1400 at 3000 MeV	1000 ea. at 0.03 MeV 1800 ea. at 0.1 MeV 550 ea. at 0.66 MeV	100 ea. at 0.3 MeV 127 ea. at 0.2 MeV 52 ea. at 3 MeV
POSITION LOCALIZATION (STRONG SOURCE)	10 arc min square error box (special mode; 0.1 x Crab spectrum)	0.5 - 1.0 deg (90% confidence 0.2 x Crab spectrum)	5 to 10 arc min (1s radius; 0.2 x Crab spectrum)	3_ (strong burst)	—
FIELD OF VIEW	3.8_ x 11.4_	~ 64_	~ 0.6 sr	4 π sr	4 π sr

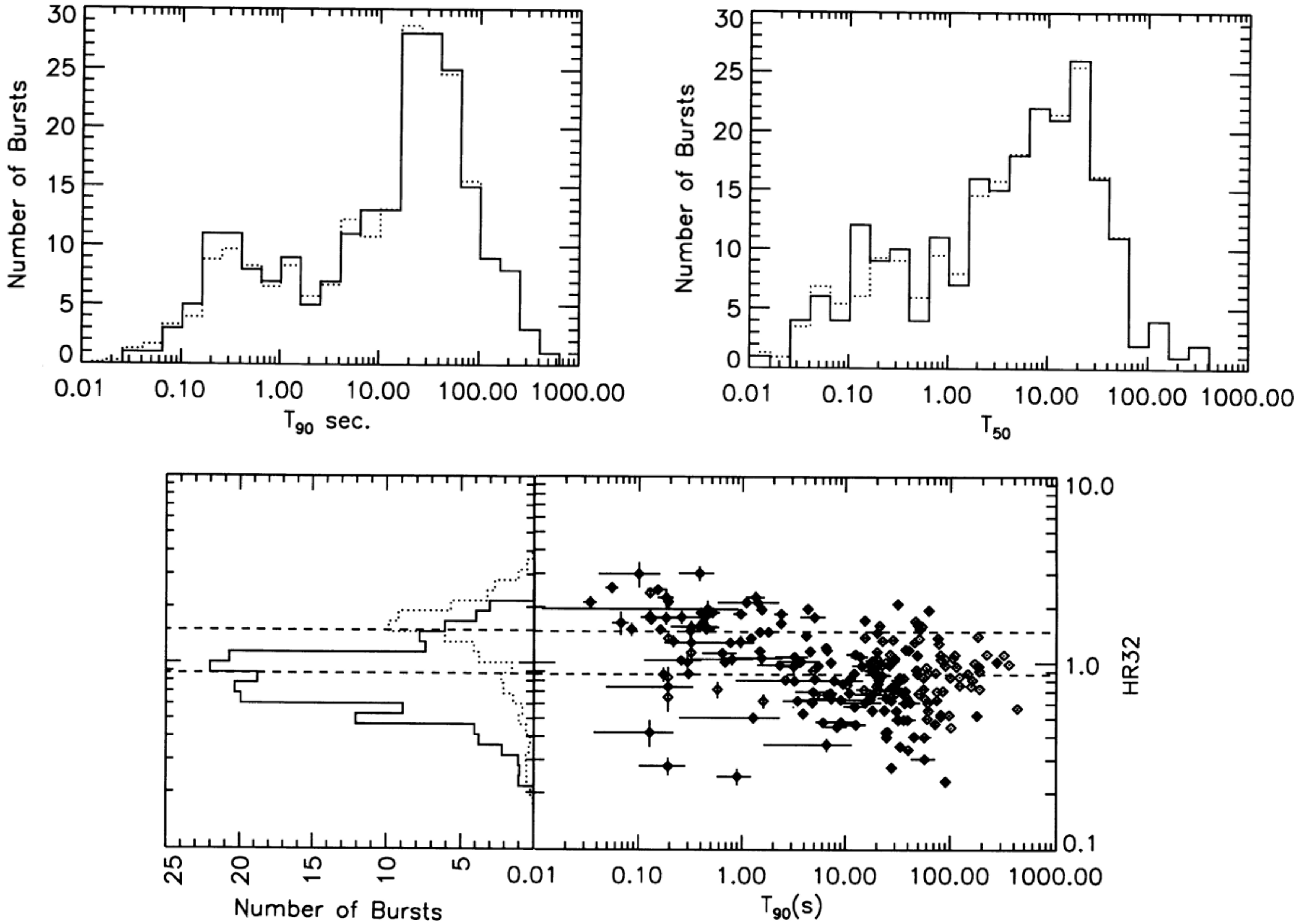
Angular distribution

2704 BATSE Gamma-Ray Bursts



The Fourth BATSE Gamma-Ray Burst Catalog – Paciesas+1999

Temporal properties



Identification of Two Classes of Gamma-Ray Bursts – Kouveliotou+1993

Spectral properties

$$N_E(E) = A\left(\frac{E}{100\ \mathrm{keV}}\right)^{\alpha} \exp\left(-\frac{E}{E_0}\right),$$

$$(\alpha - \beta)E_0 \geq E\,,$$

$$= A\left[\frac{(\alpha-\beta)E_0}{100\ \mathrm{keV}}\right]^{\alpha-\beta} \exp\,(\beta-\alpha)\left(\frac{E}{100\ \mathrm{keV}}\right)^{\beta},$$

$$(\alpha - \beta)E_0 \leq E\,,$$

which we call the GRB model.

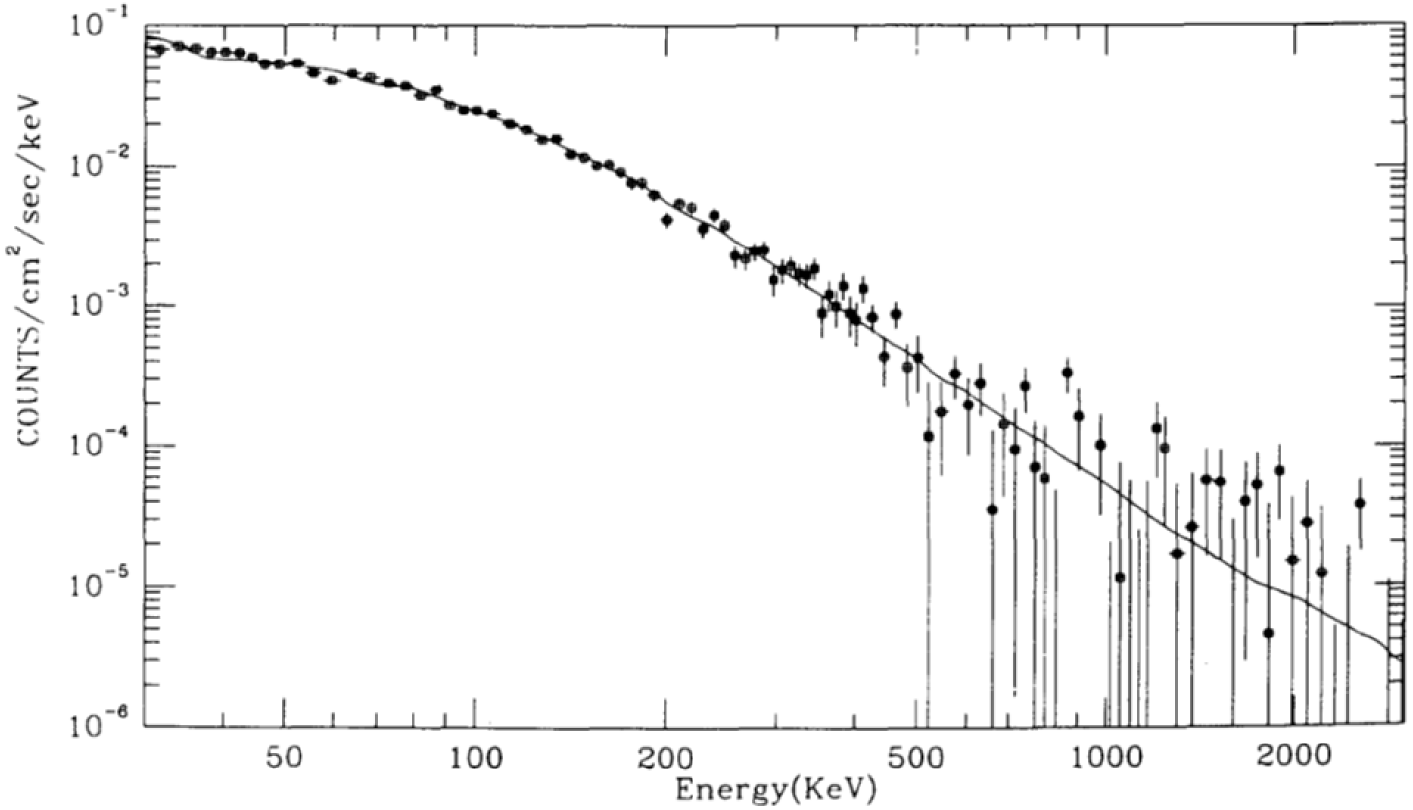
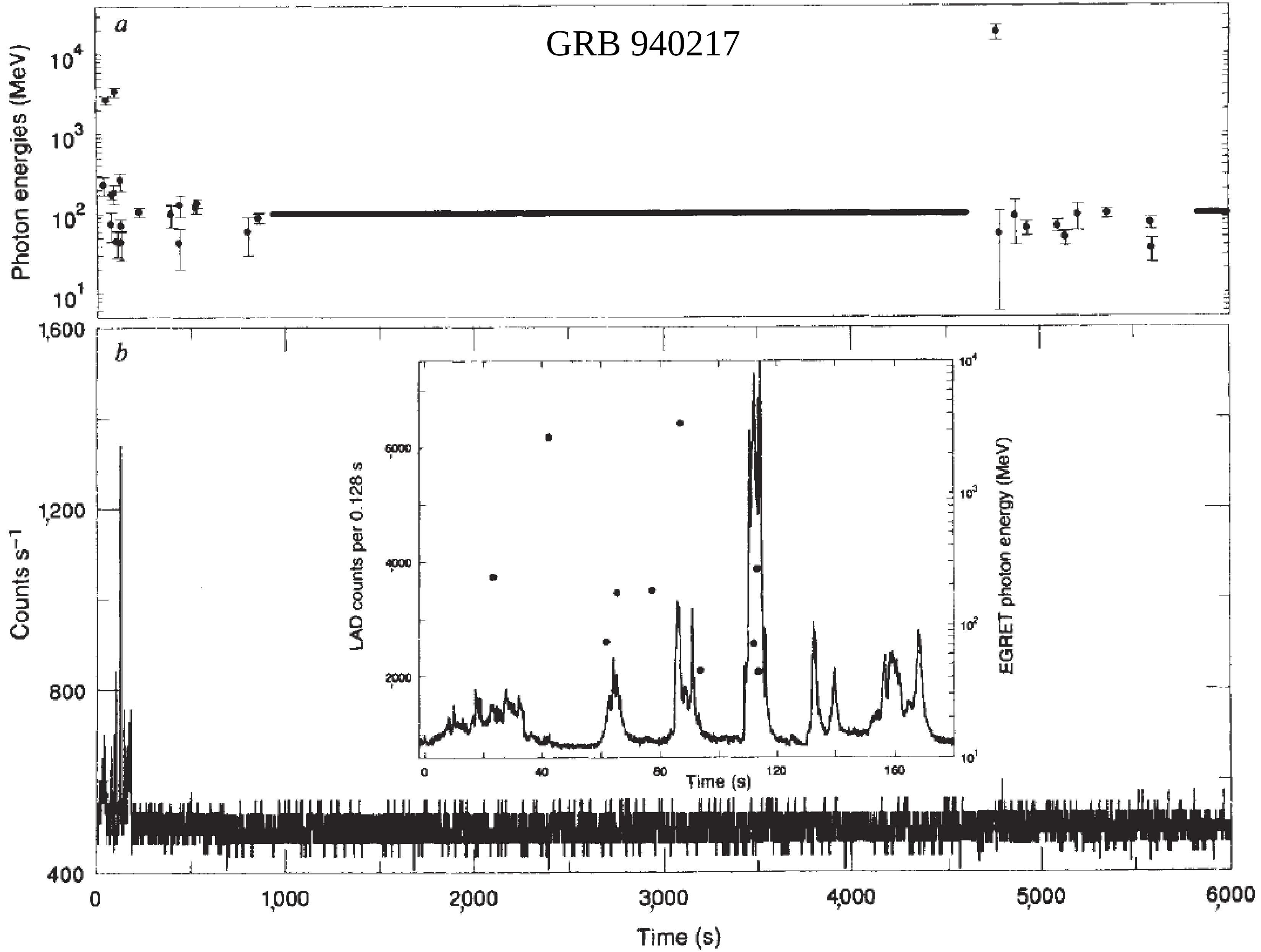


FIG. 1.—Example of a spectral fit. The GRB model (eq. [1]) was fitted to the average spectrum of 1B 911127. The low-energy spectral index is $\alpha = -0.968 \pm 0.022$, the high-energy spectral index $\beta = -2.427 \pm 0.07$, and the break energy $E_0 = 149.5 \pm 2.1$. With 100 degrees of freedom, $\chi^2 = 121.58$.

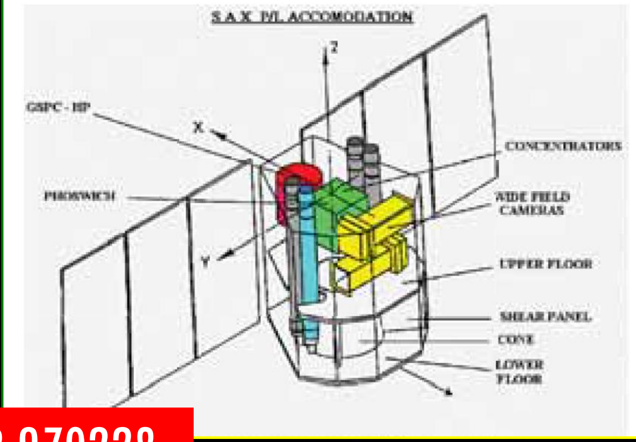
BATSE Observations of Gamma-Ray Burst Spectra. I. Spectral Diversity – Band+1993

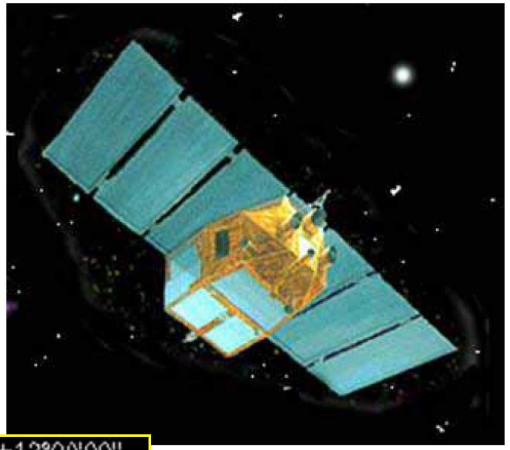
High-energy emission



Detection of a γ-ray burst of very long duration and very high energy – Hurley+1994

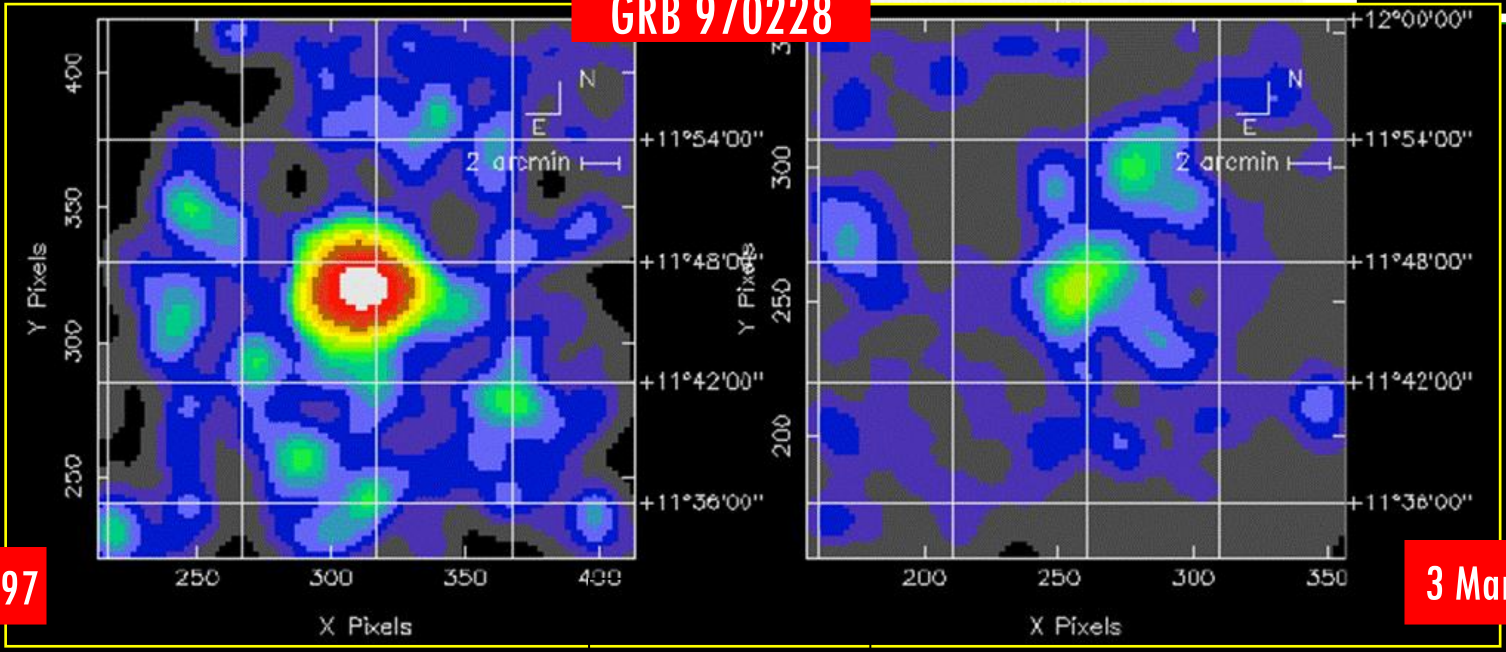
THE AFTERGLOW ERA
(1997–2007)





Credit: BeppoSAX Team

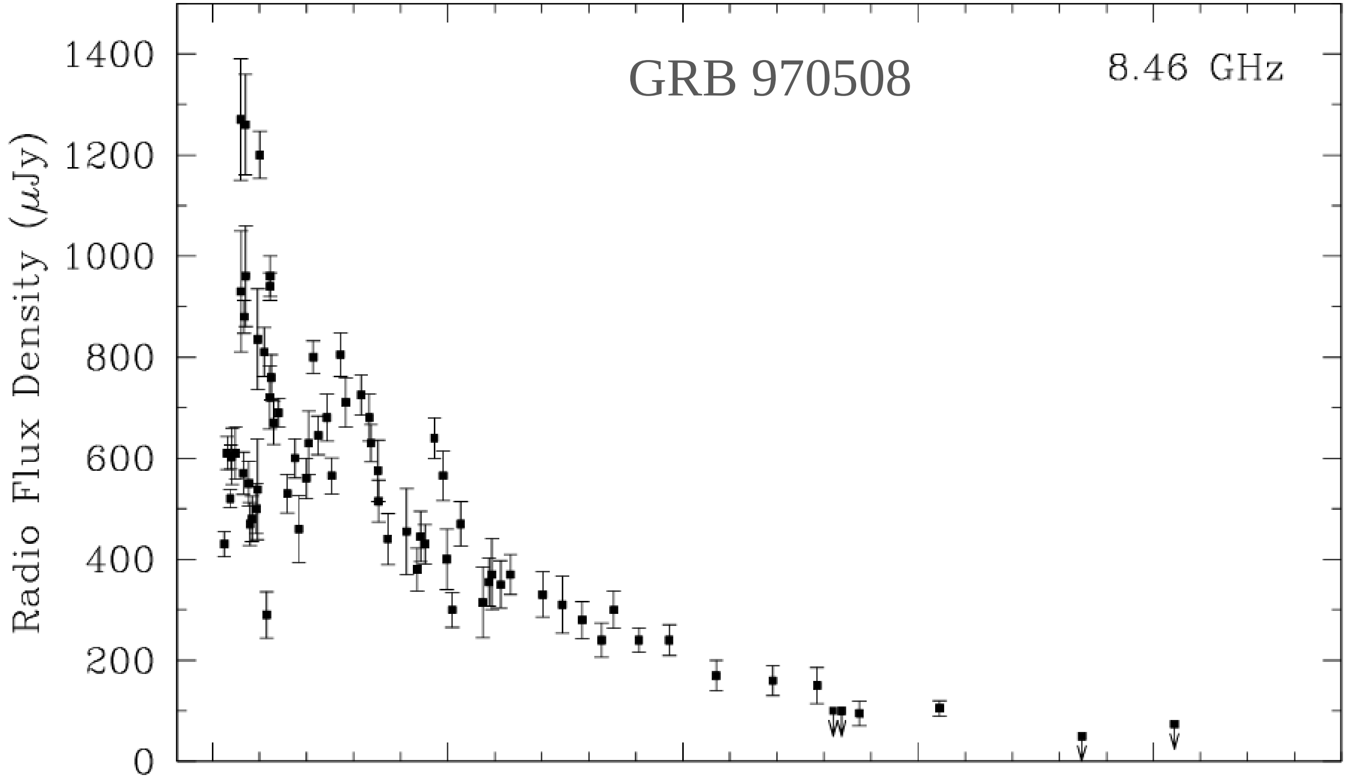
GRB 970228



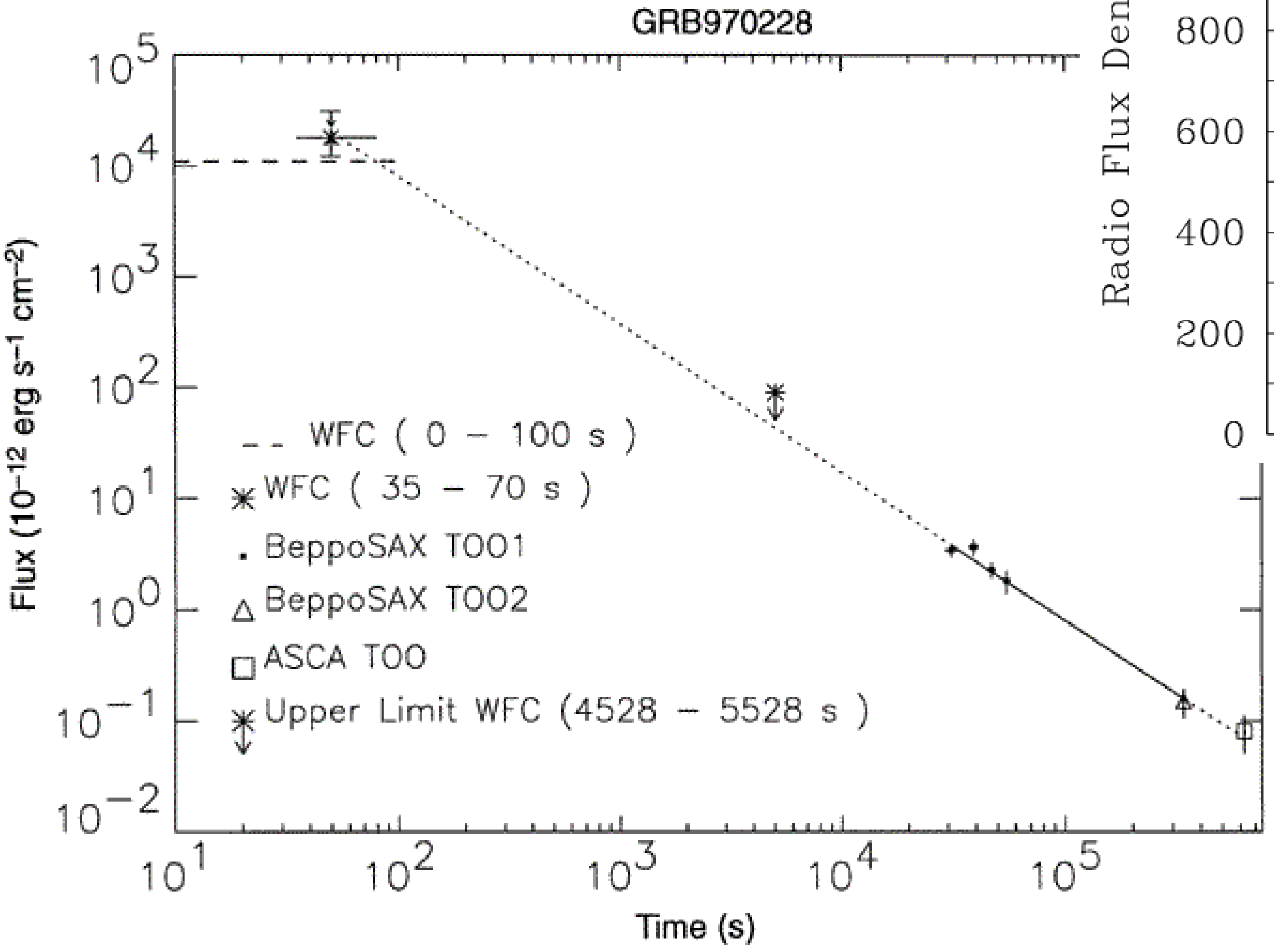
28 Feb 1997

3 Mar 1997

GRB emission phases

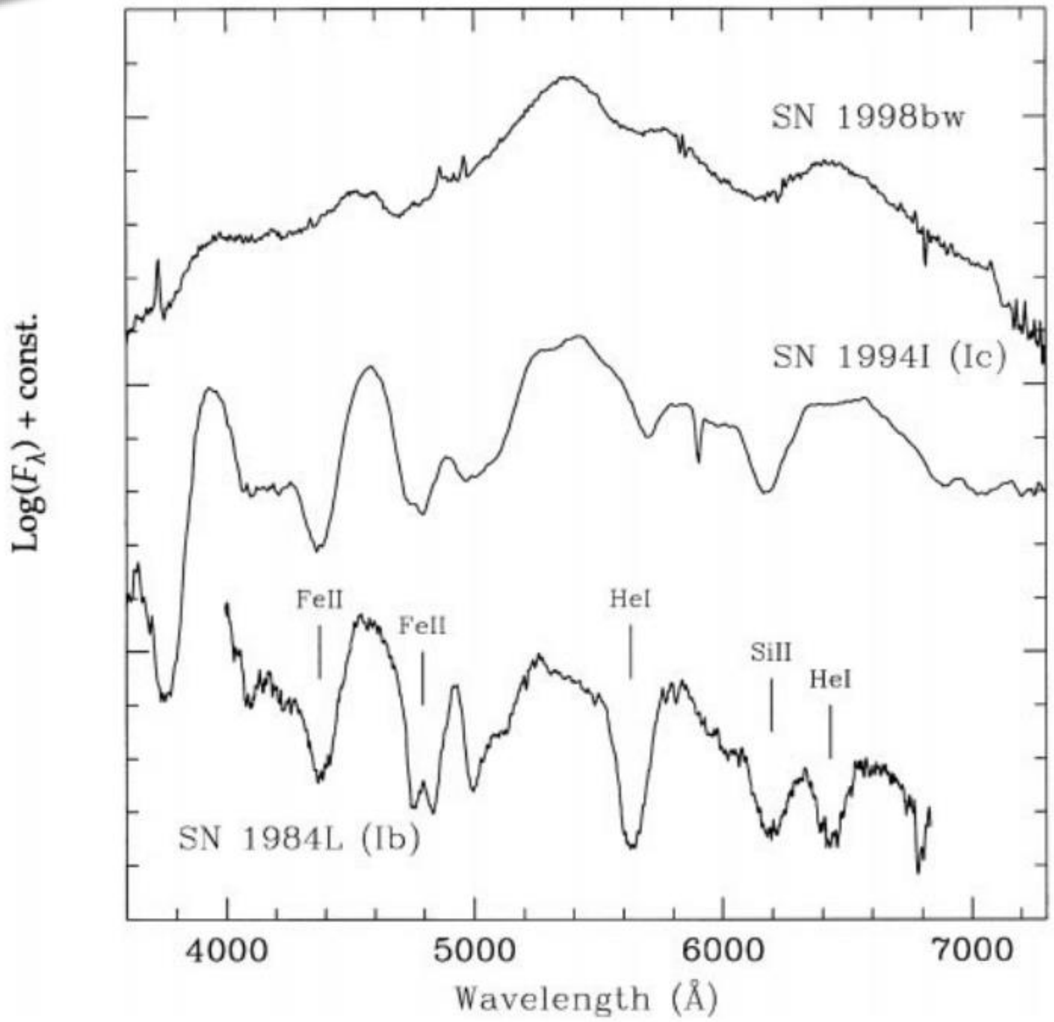


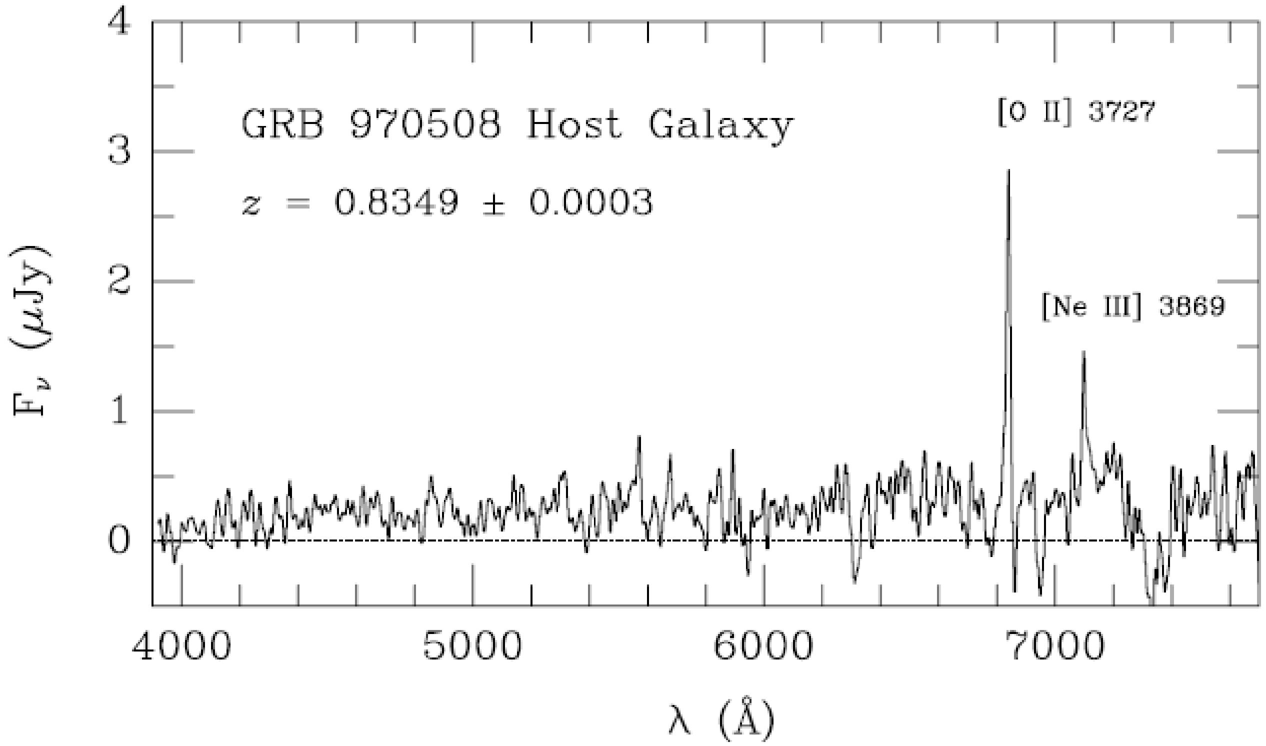
A 450 Day Light Curve of the Radio Afterglow of GRB 970508: Fireball Calorimetry – Frail+2000



Discovery of an X-ray afterglow associated with the γ-ray burst of 28 February 1997 – Costa+1997

GRB redshifts & SN connection

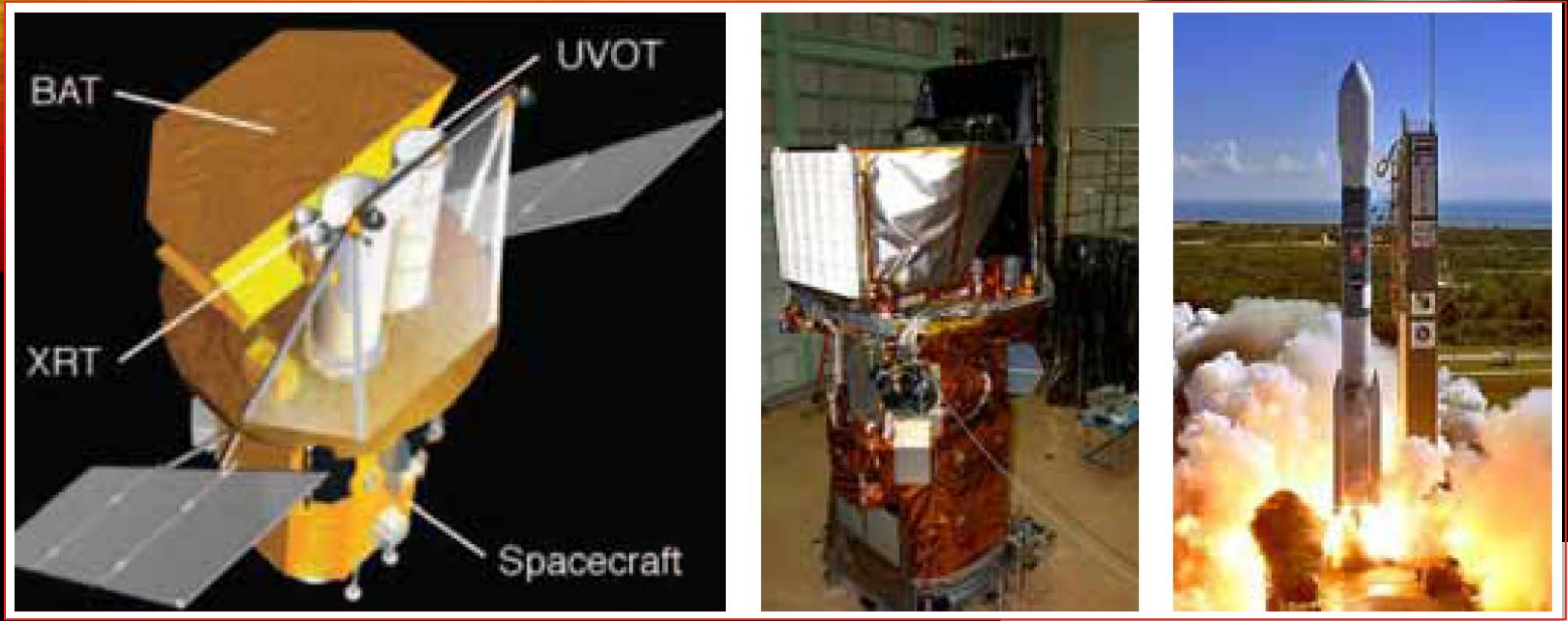




The Host Galaxy of GRB 970508 – Bloom+1998

A hypernova model for the supernova associated with the γ-ray burst of 25 April 1998 – Iwamoto+1998

THE AFTERGLOW ERA (1997–2007)

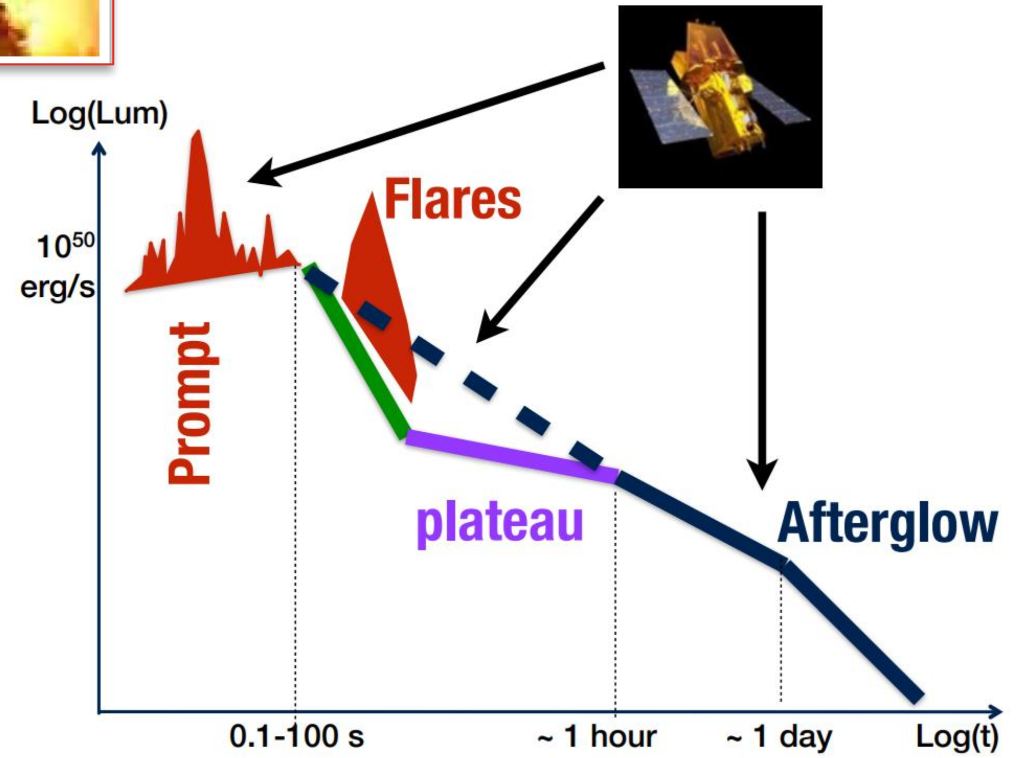


Credit: NASA/GSFC

Swift was specifically designed to study GRBs and their afterglows in multiple wavebands:
MULTI-WAVELENGTH MISSION

Success of the Swift mission
Since November 2004, the *Neil Gehrels Swift Observatory* is contributing to key results in the GRB field, especially in the study of the afterglow emission

- **"canonical"** X-ray light curve (steep-**plateau**-normal) in ~ 1/2 GRBs
- **X-ray flares** in ~ 1/3 GRBs

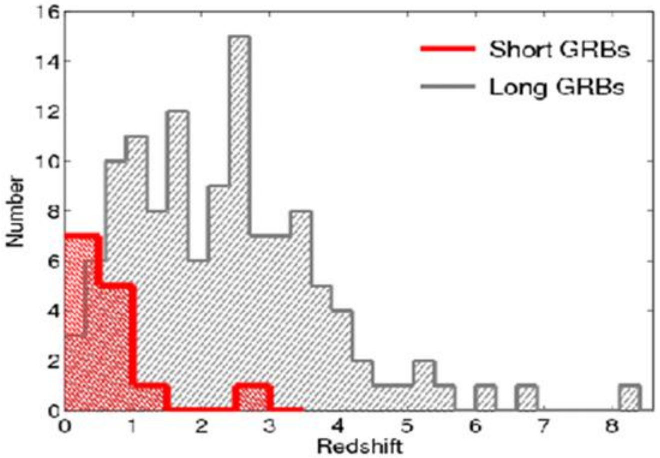


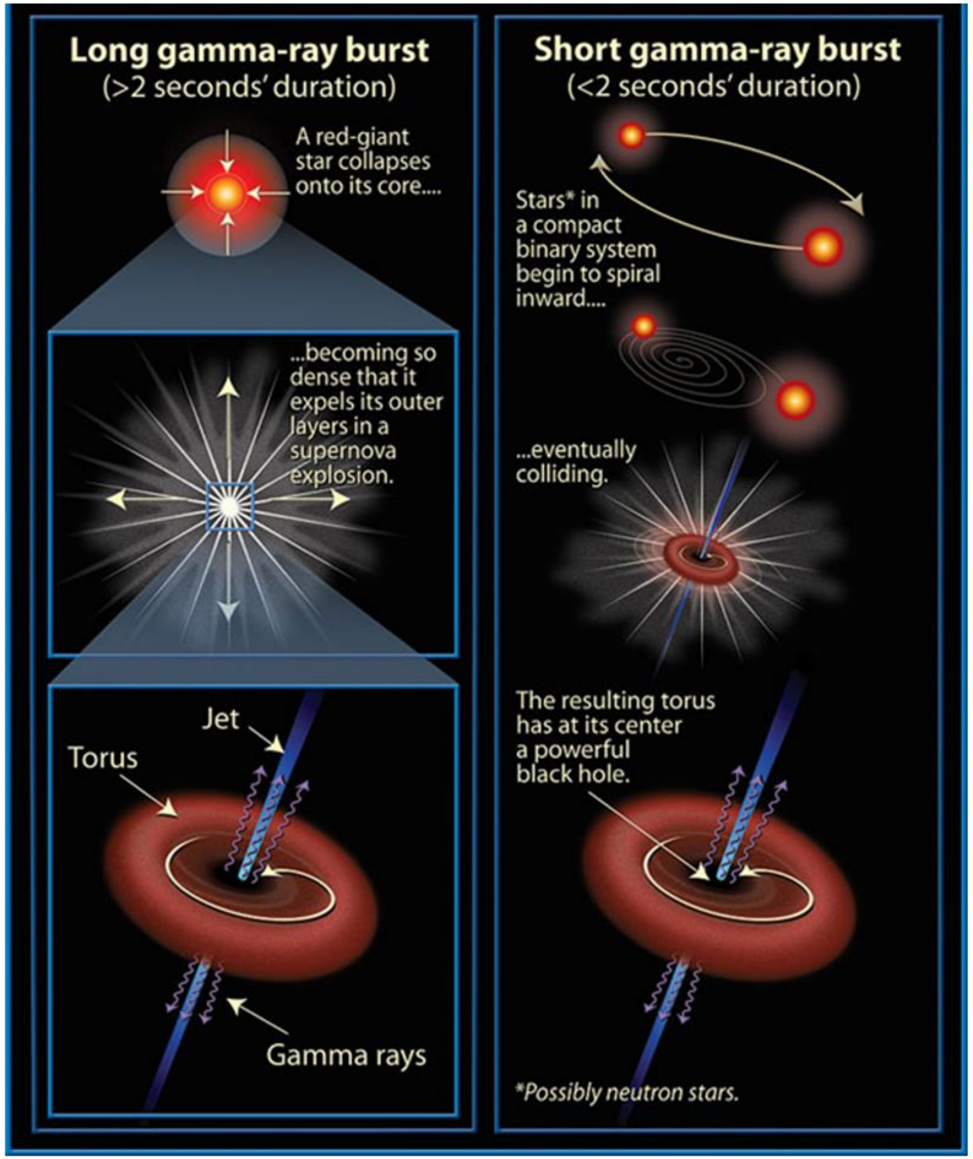
Credit: M.G.Bernardini

Gamma-Ray Bursts: the most extreme phenomena in the Universe

Long GRBs: core collapse of pecular massive stars, **association with SN**

Short GRBs: NS-NS or NS-BH mergers, **association with GW sources**



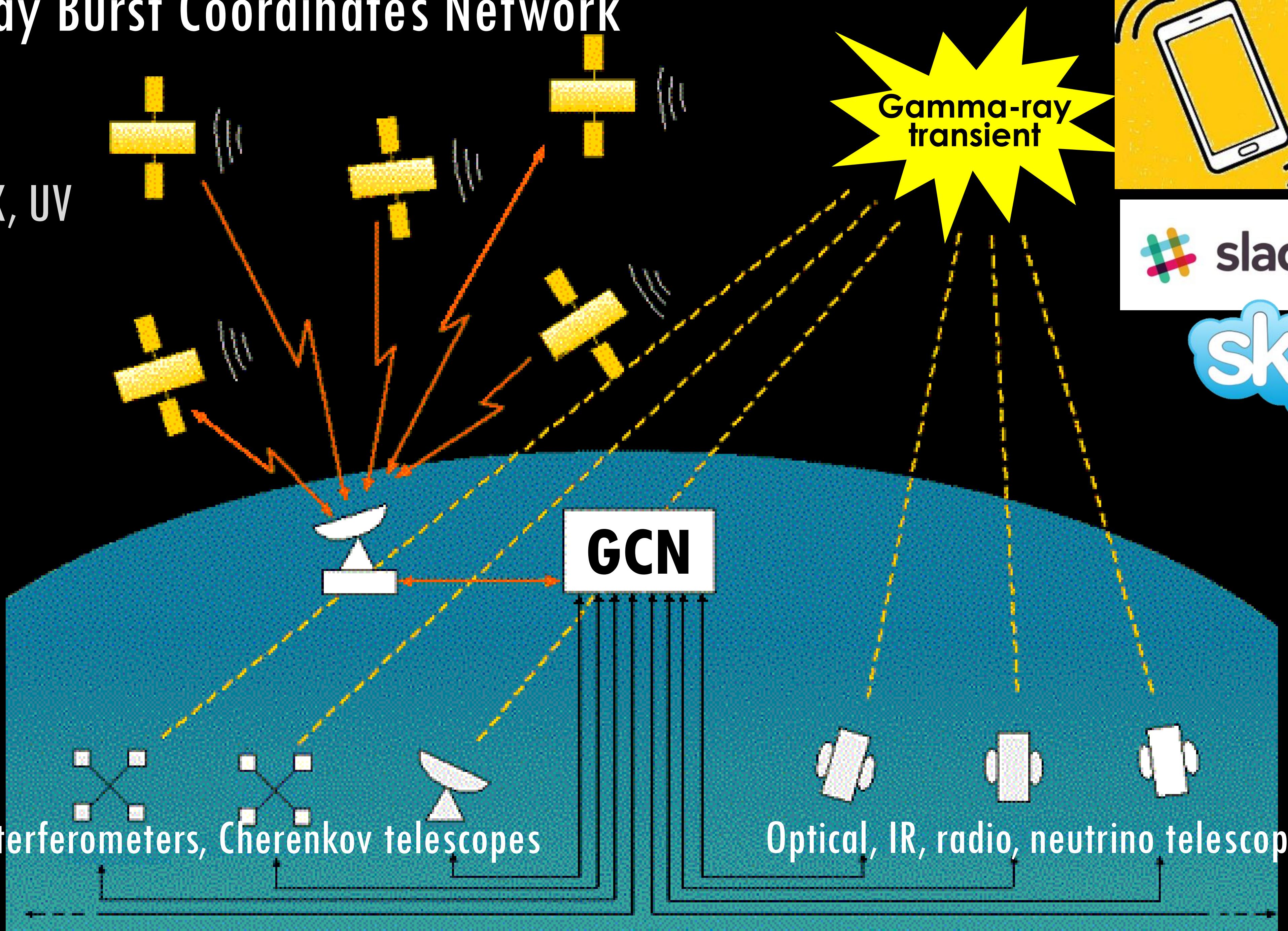


Credit: L. Amati

Gamma-Ray Burst Coordinates Network

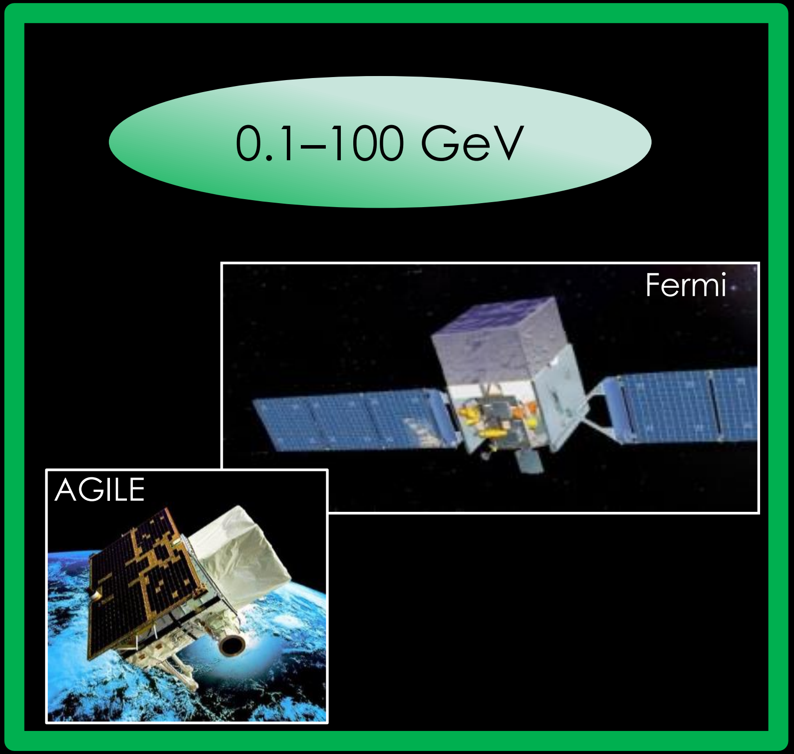
(since 1997)

Gamma, X, UV satellites



slack
WhatsApp
skype
zoom

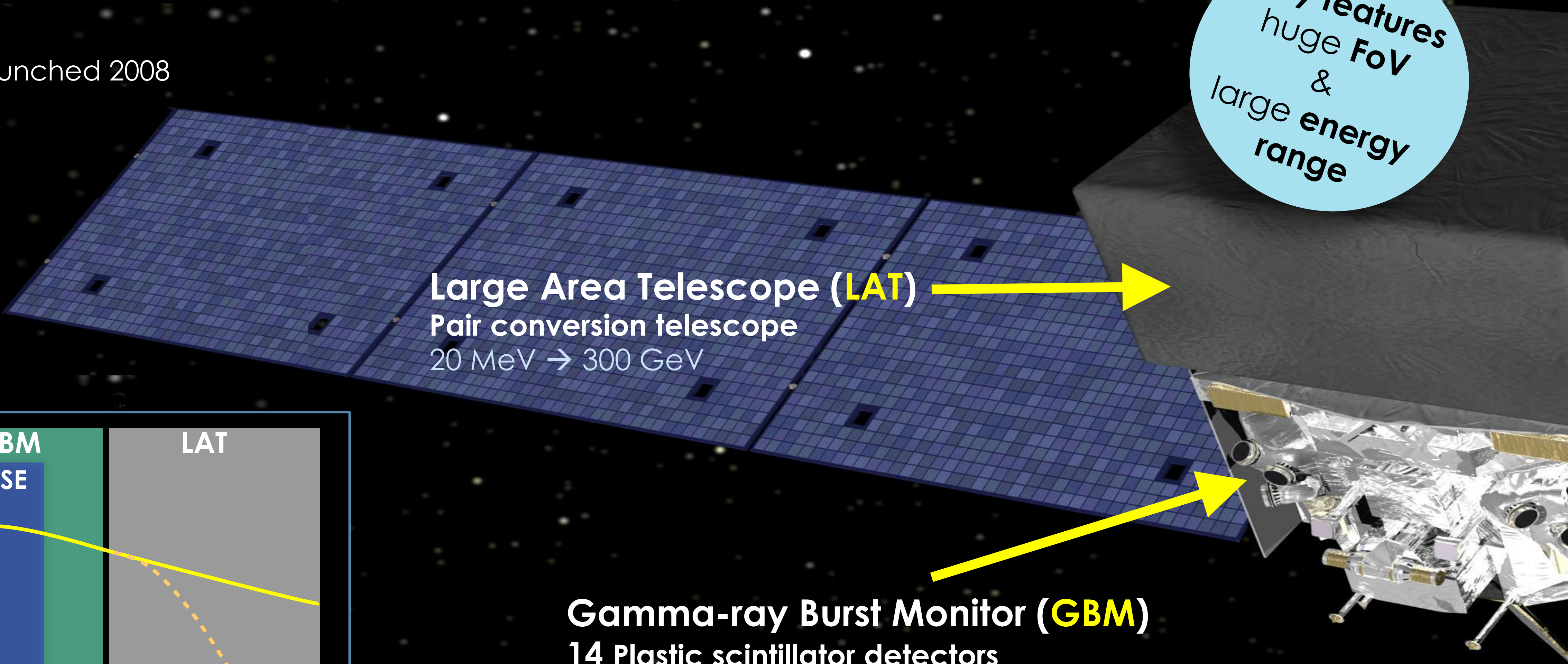

VELA
CGRO
BeppoSax
Integral
Swift
0.1–100 MeV
0.1–100 keV


0.1–100 GeV
Fermi
AGILE


0.1–100 TeV
MAGIC
H.E.S.S.
Veritas

The Fermi mission

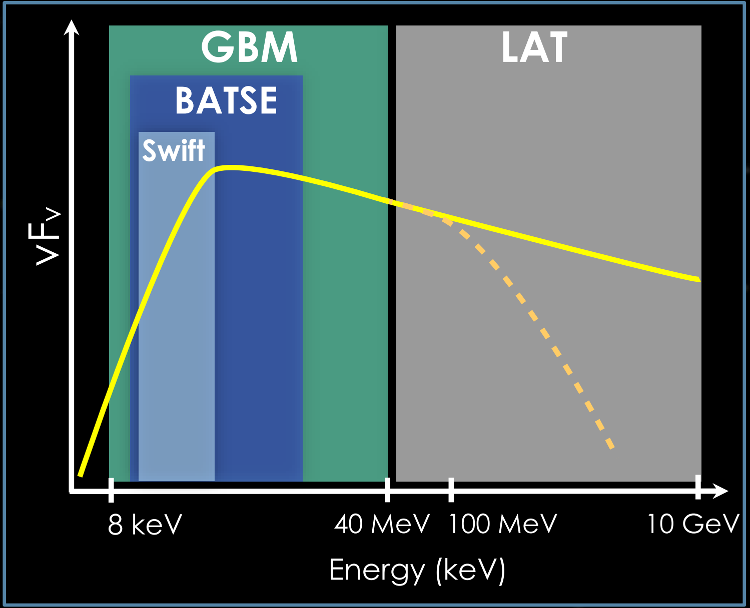
Launched 2008

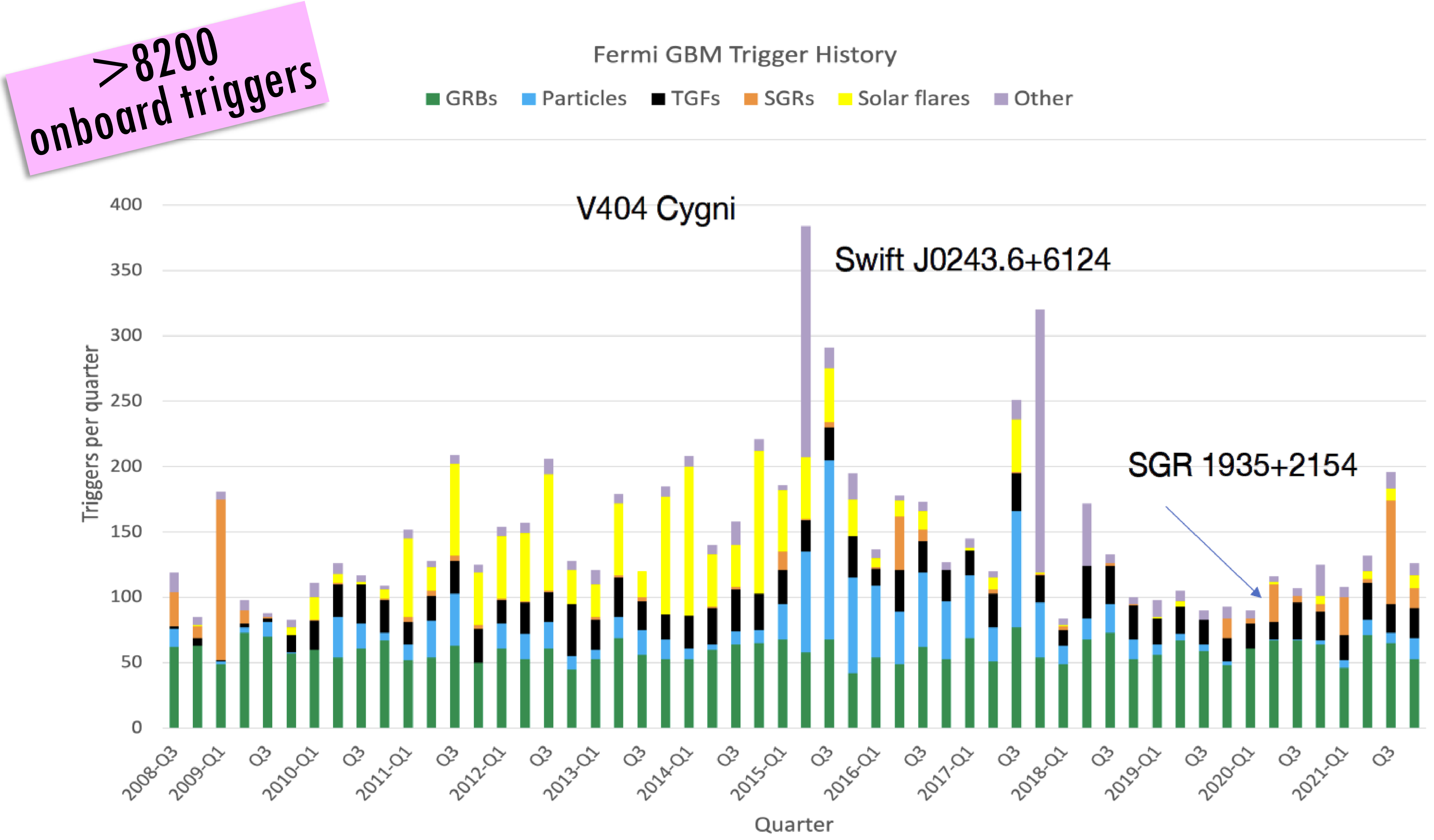


Key features
huge **FoV**
&
large **energy range**

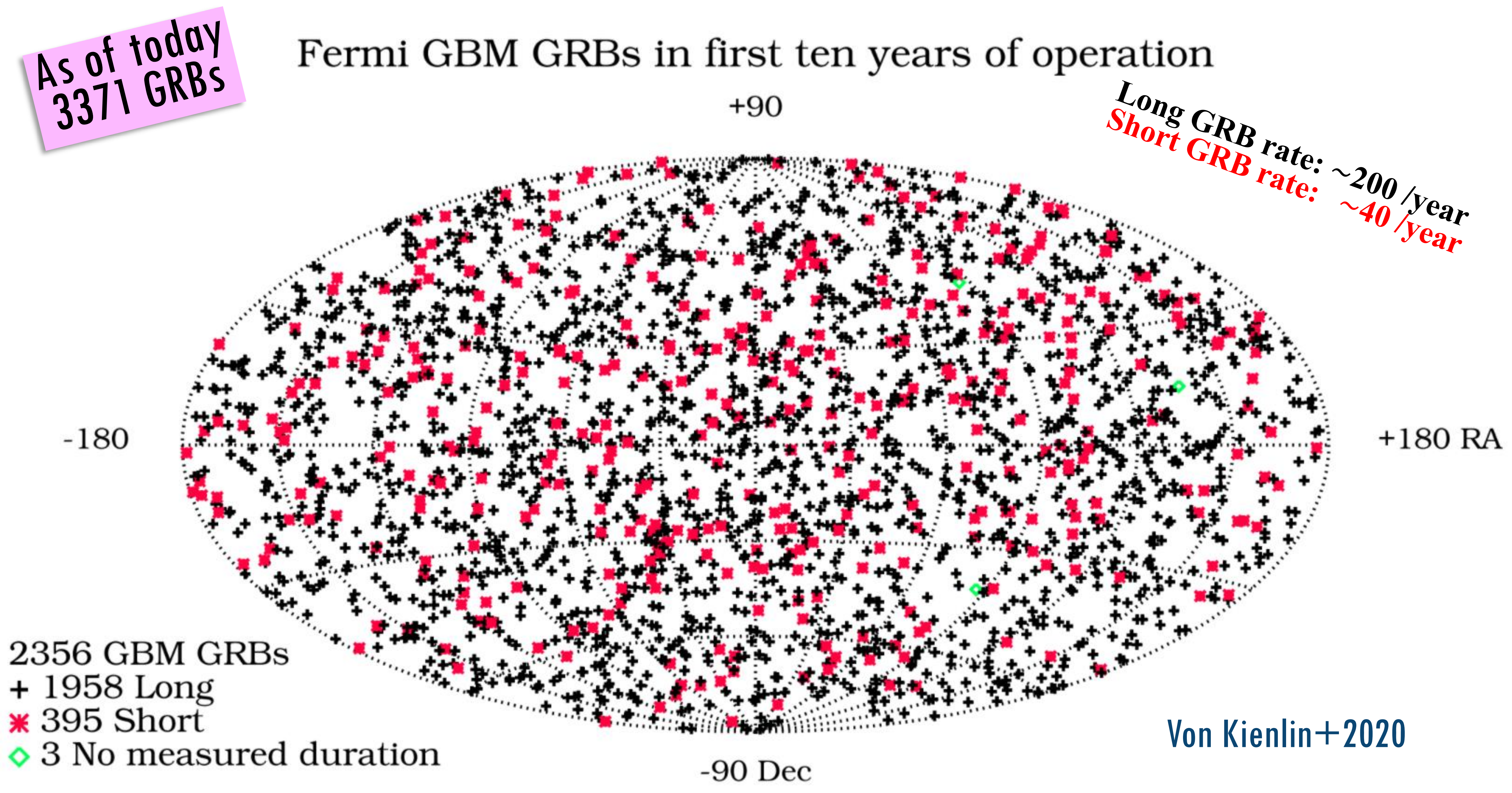
Large Area Telescope (LAT)
Pair conversion telescope
20 MeV → 300 GeV

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



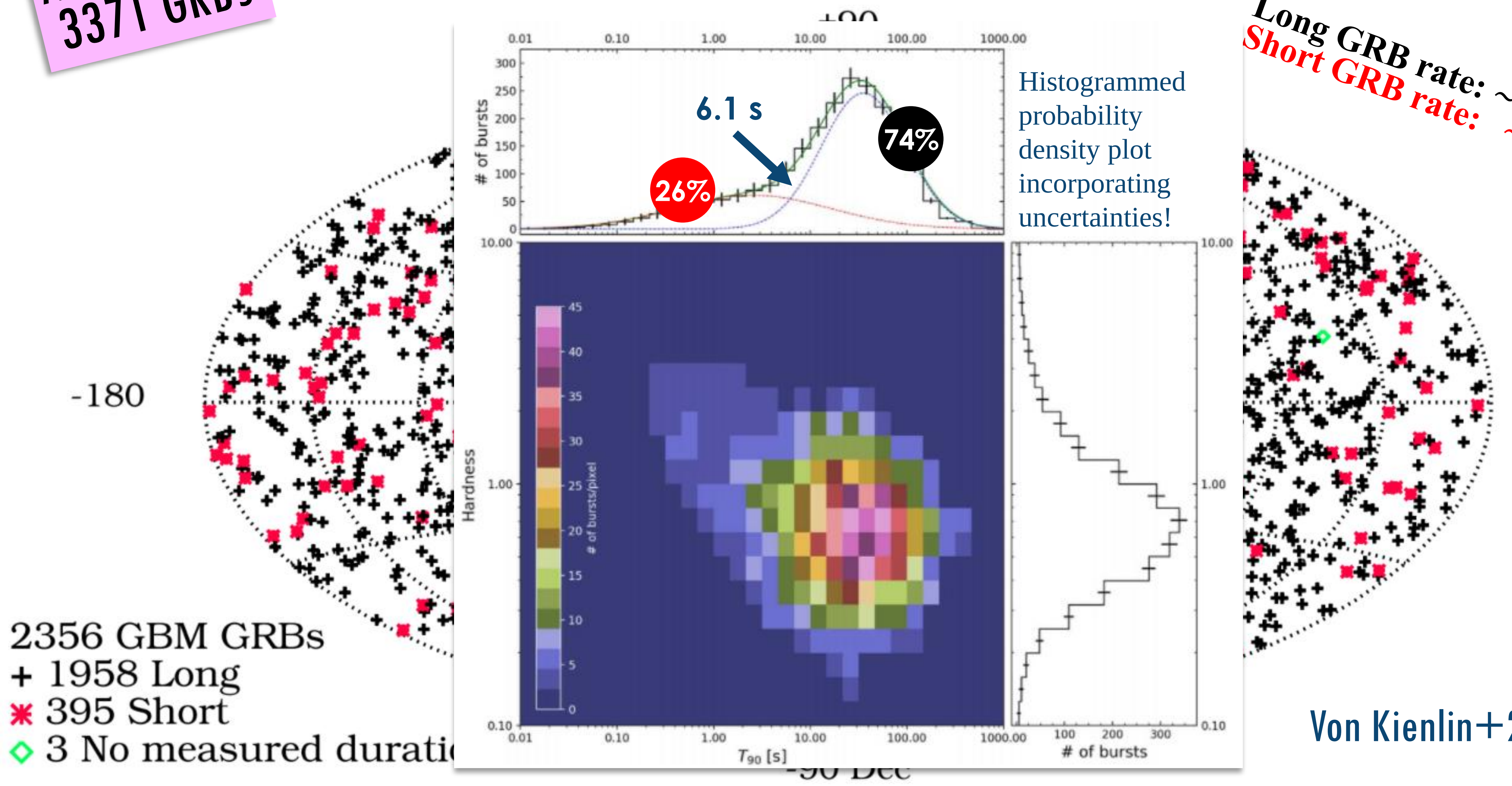


>8200
onboard triggers
Fermi GBM Trigger History
GRBs
Particles
TGFs
SGRs
Solar flares
Other
V404 Cygni
Swift J0243.6+6124
SGR 1935+2154
Triggers per quarter
400
350
300
250
200
150
100
50
0
2008-Q3
2009-Q1
Q3
2010-Q1
Q3
2011-Q1
Q3
2012-Q1
Q3
2013-Q1
Q3
2014-Q1
Q3
2015-Q1
Q3
2016-Q1
Q3
2017-Q1
Q3
2018-Q1
Q3
2019-Q1
Q3
2020-Q1
Q3
2021-Q1
Q3
Quarter


As of today
3371 GRBs
Fermi GBM GRBs in first ten years of operation
+90
-180
+180 RA
-90 Dec
Long GRB rate: ~200 /year
Short GRB rate: ~40 /year
2356 GBM GRBs
+ 1958 Long
395 Short
3 No measured duration
Von Kienlin+2020

Fermi GBM GRBs in first ten years of operation

As of today
3371 GRBs

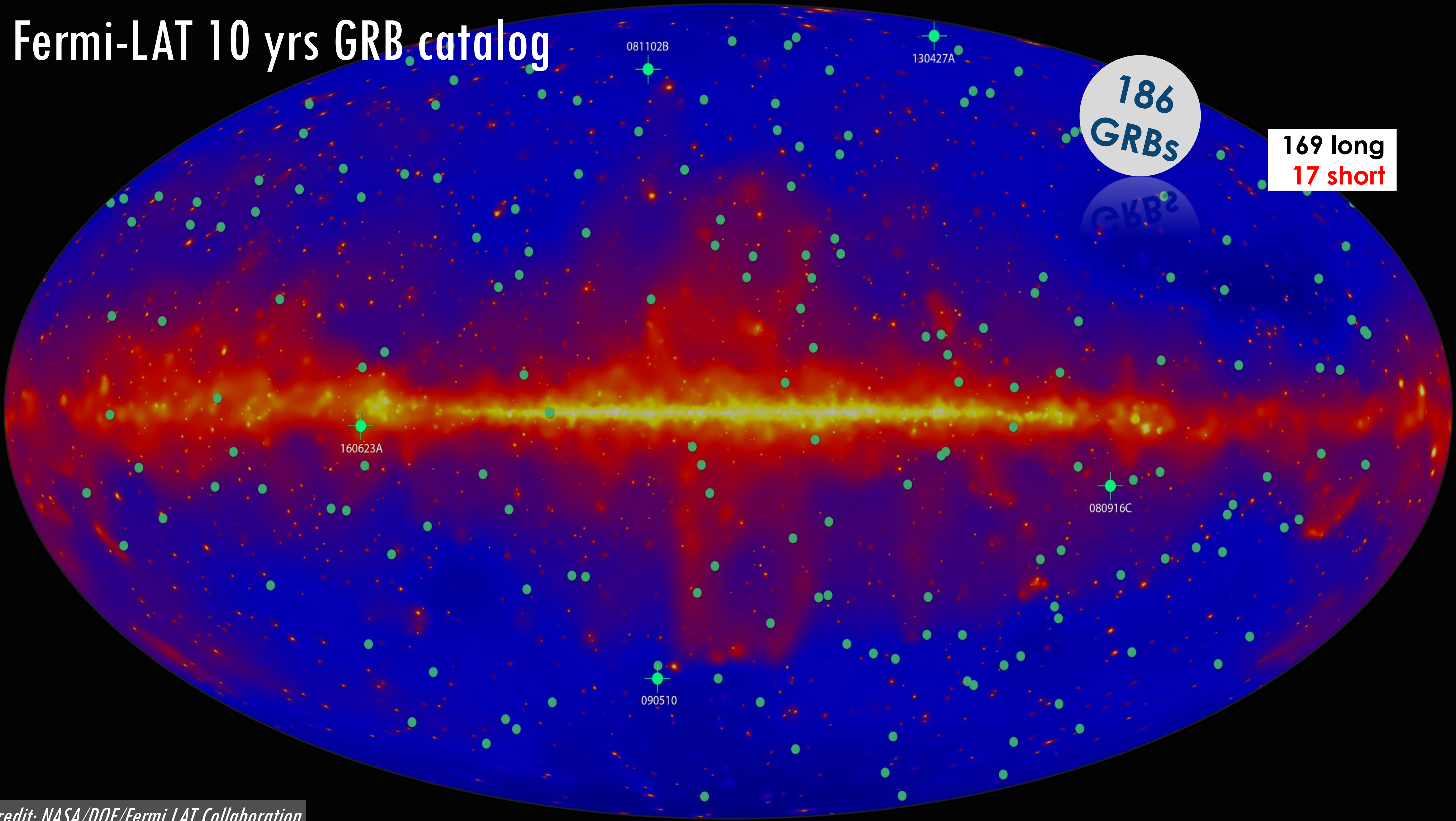


Histogrammed probability density plot incorporating uncertainties!

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

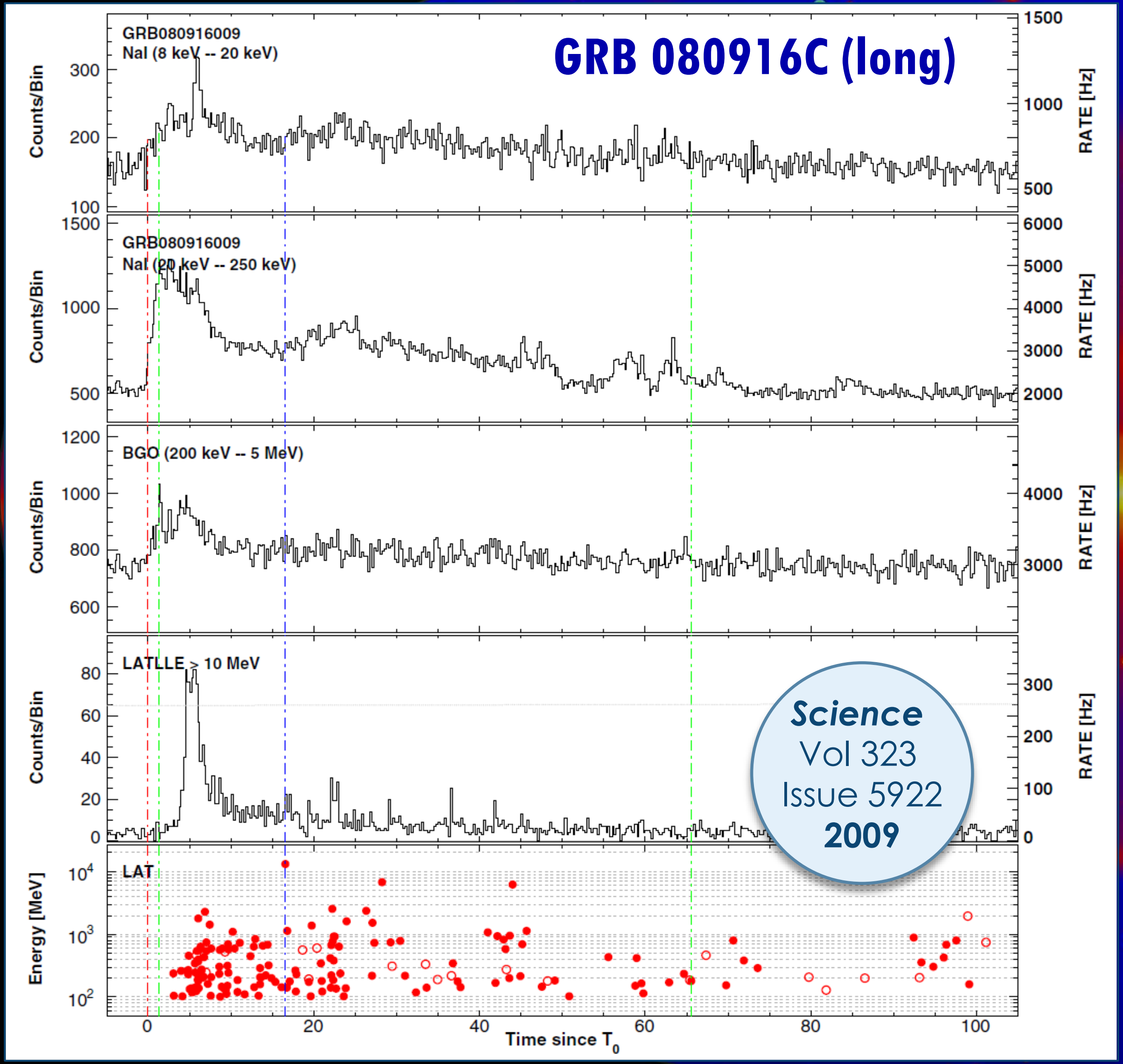
Von Kienlin+2020

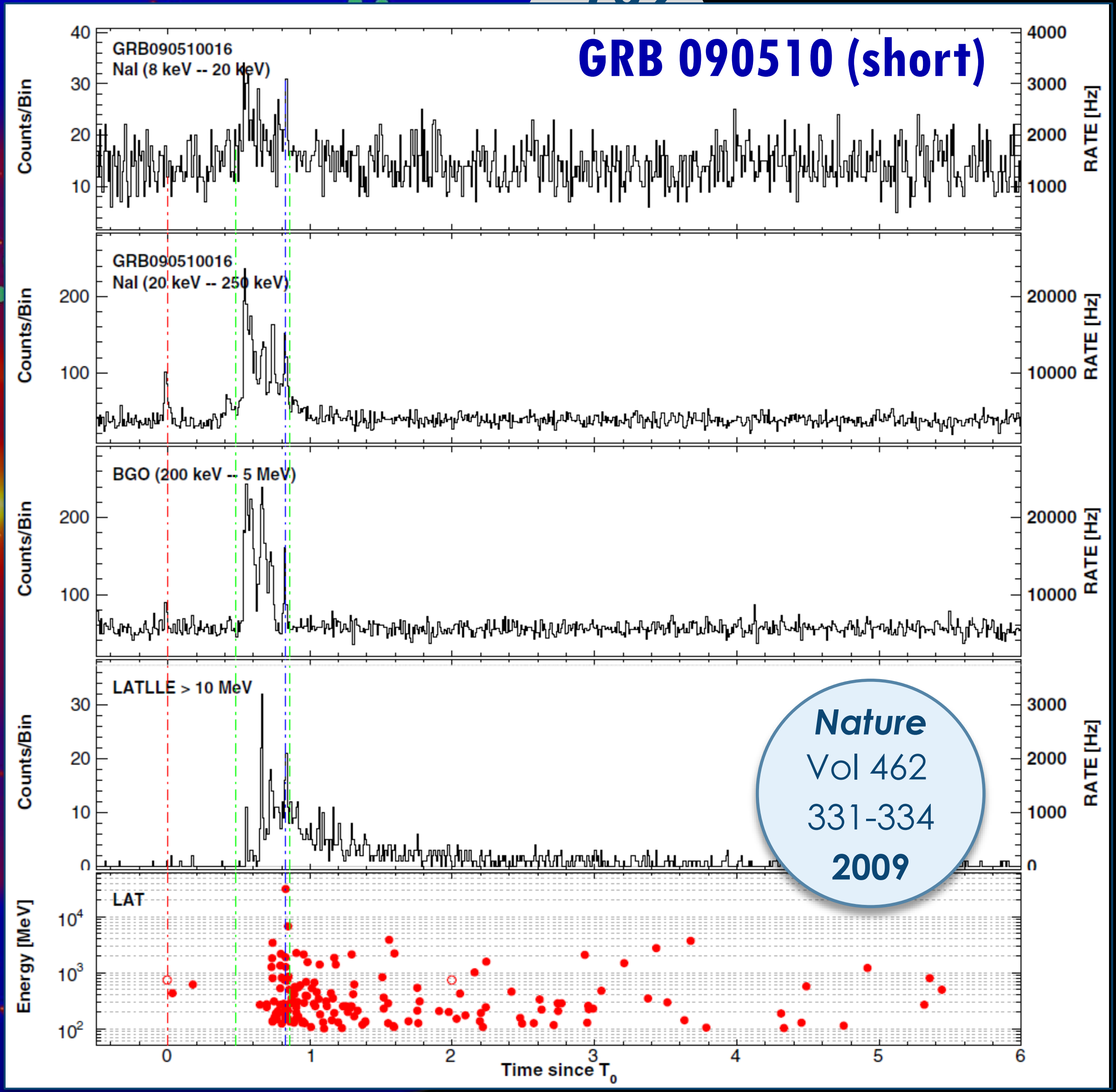
Fermi-LAT 10 yrs GRB catalog



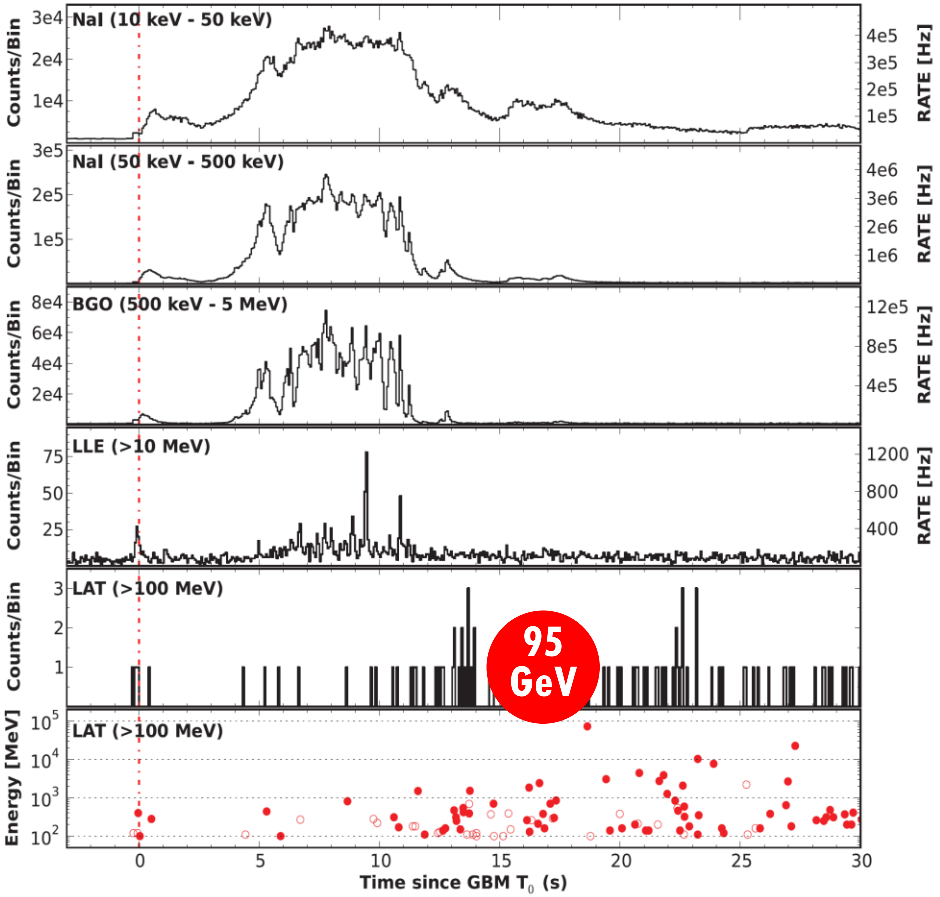
Credit: NASA/DOE/Fermi LAT Collaboration

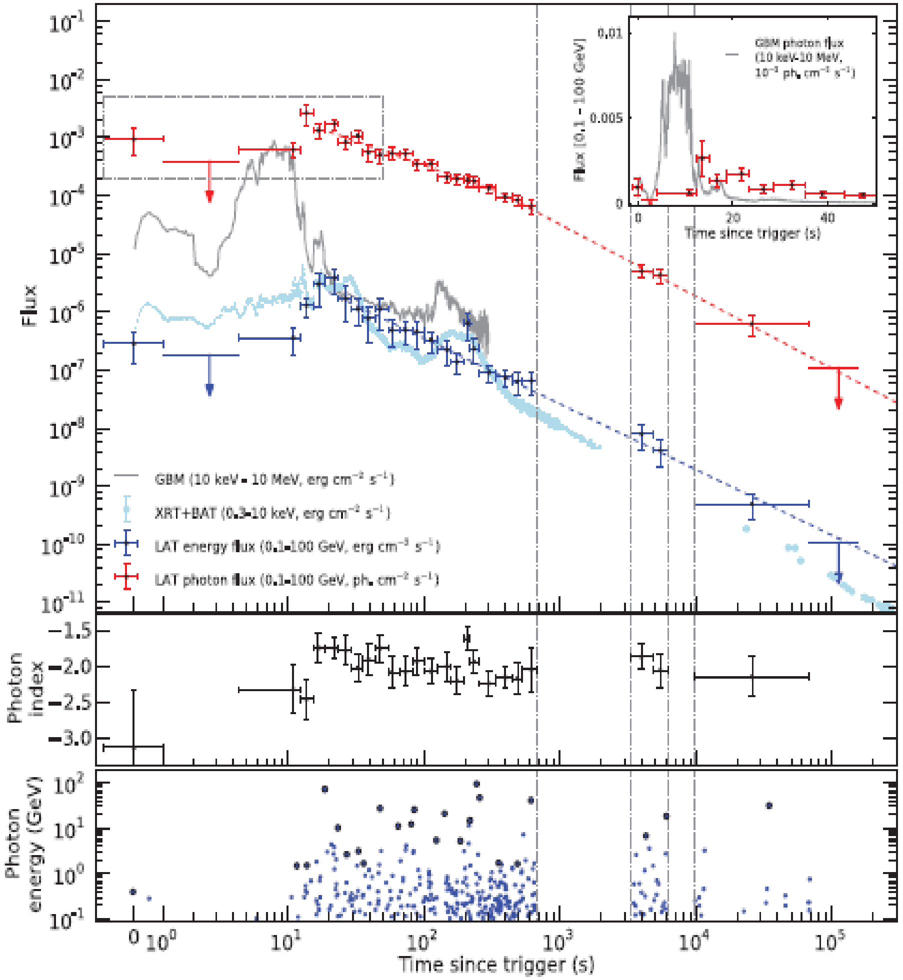
Fermi-LAT 10 yrs GRB catalog



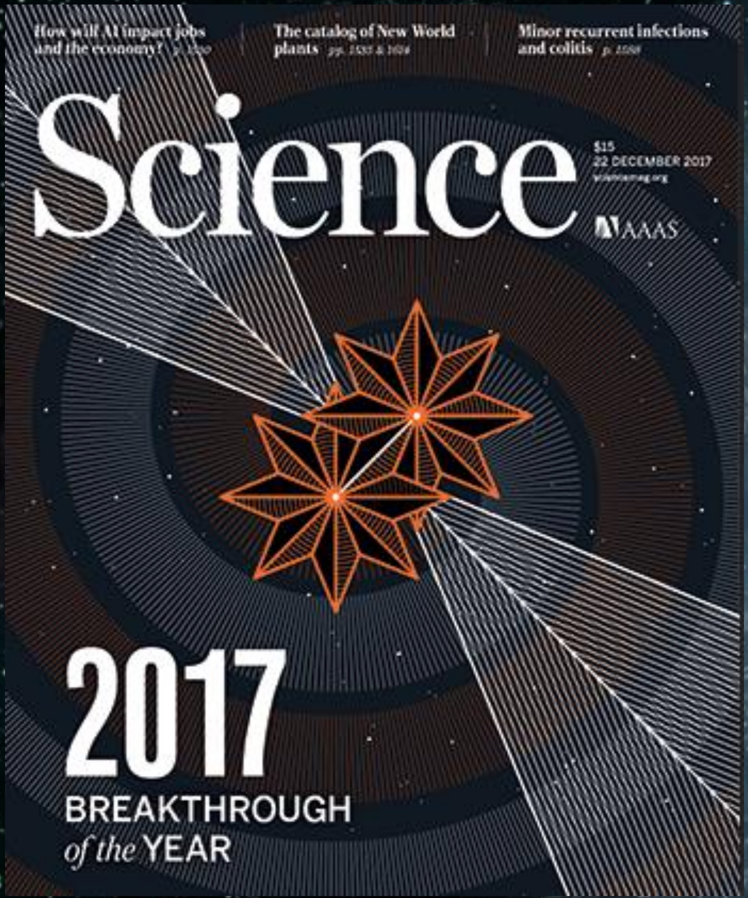


Credit: NASA/DOE/Fermi LAT Collaboration



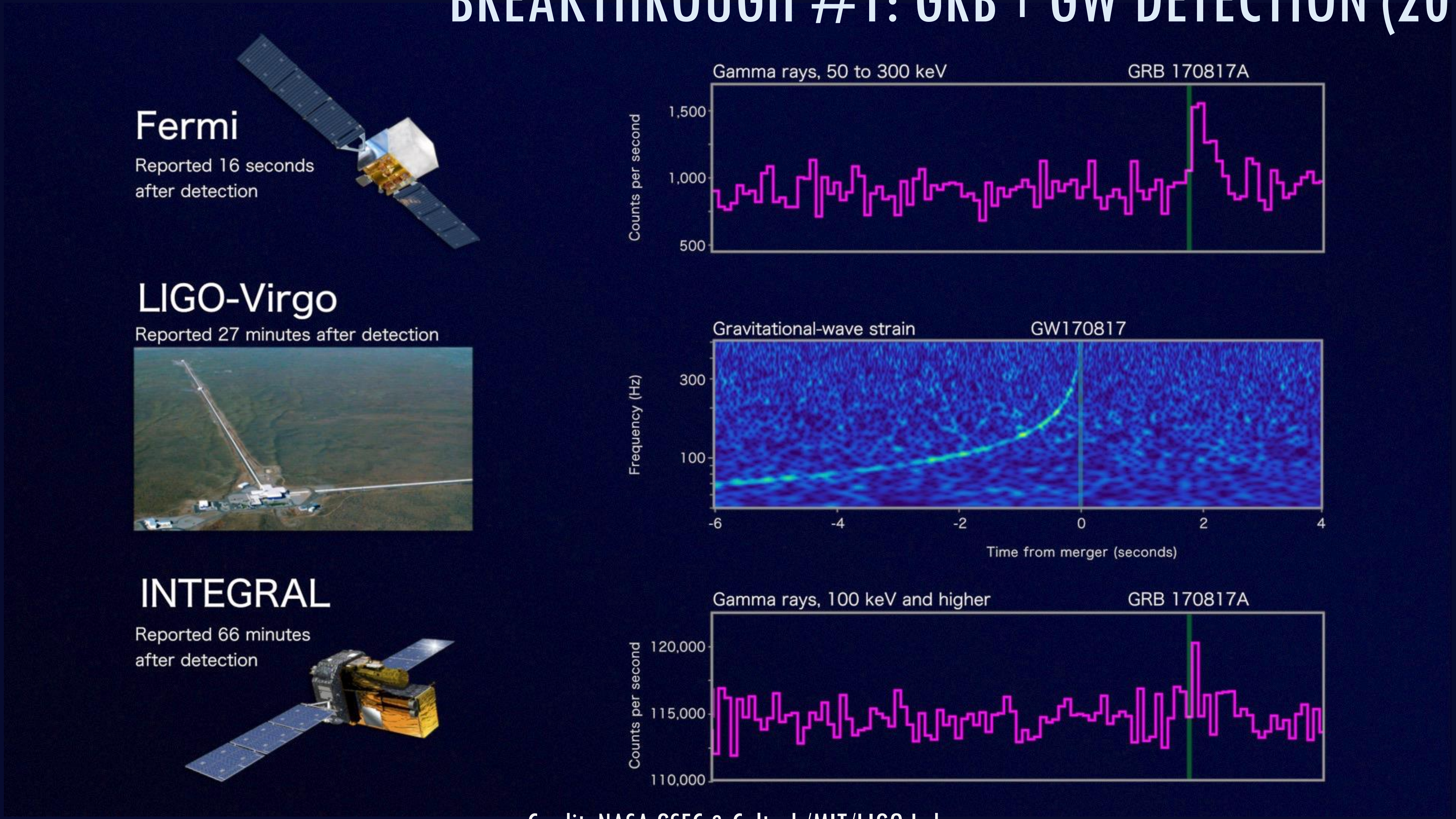


Fermi-LAT Observations of the Gamma-Ray Burst GRB 130427A – Ackermann+2014



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

BREAKTHROUGH #1: GRB+GW DETECTION (2017)



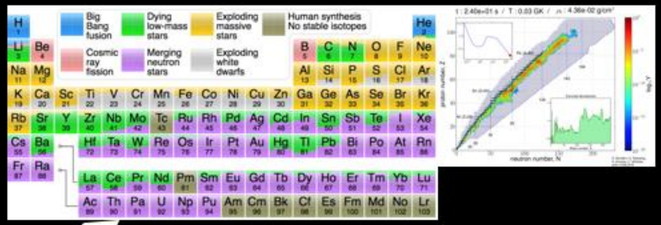
Credit: NASA GSFC & Caltech/MIT/LIGO Lab

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

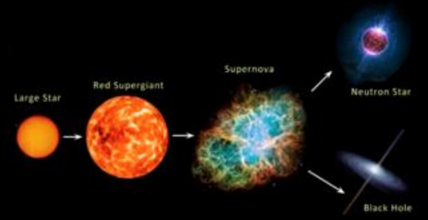
Radioactively powered transients

Relativistic astrophysics

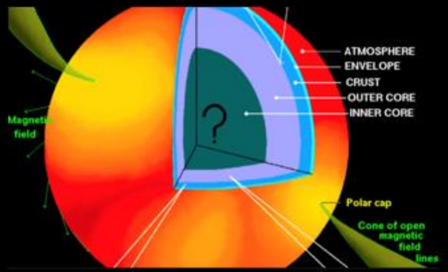
Nucleosynthesis and enrichment of the Universe



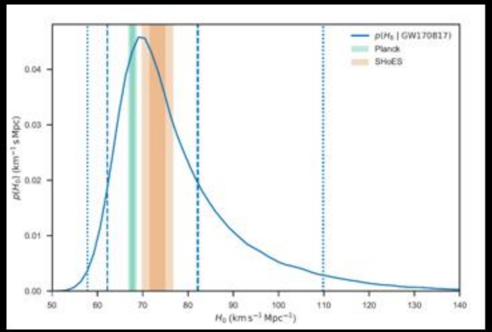
Compact object formation and evolution



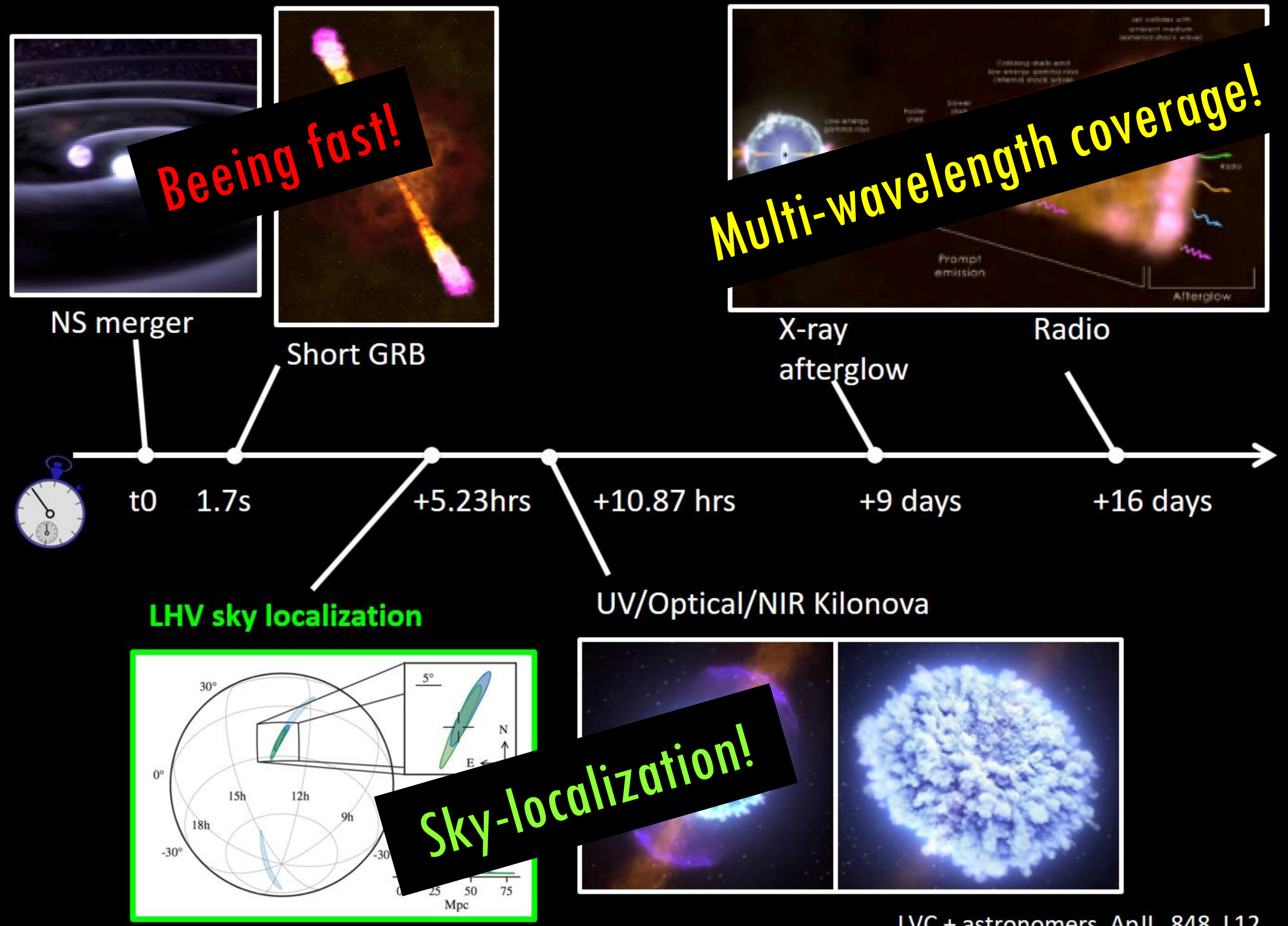
Nuclear matter physics



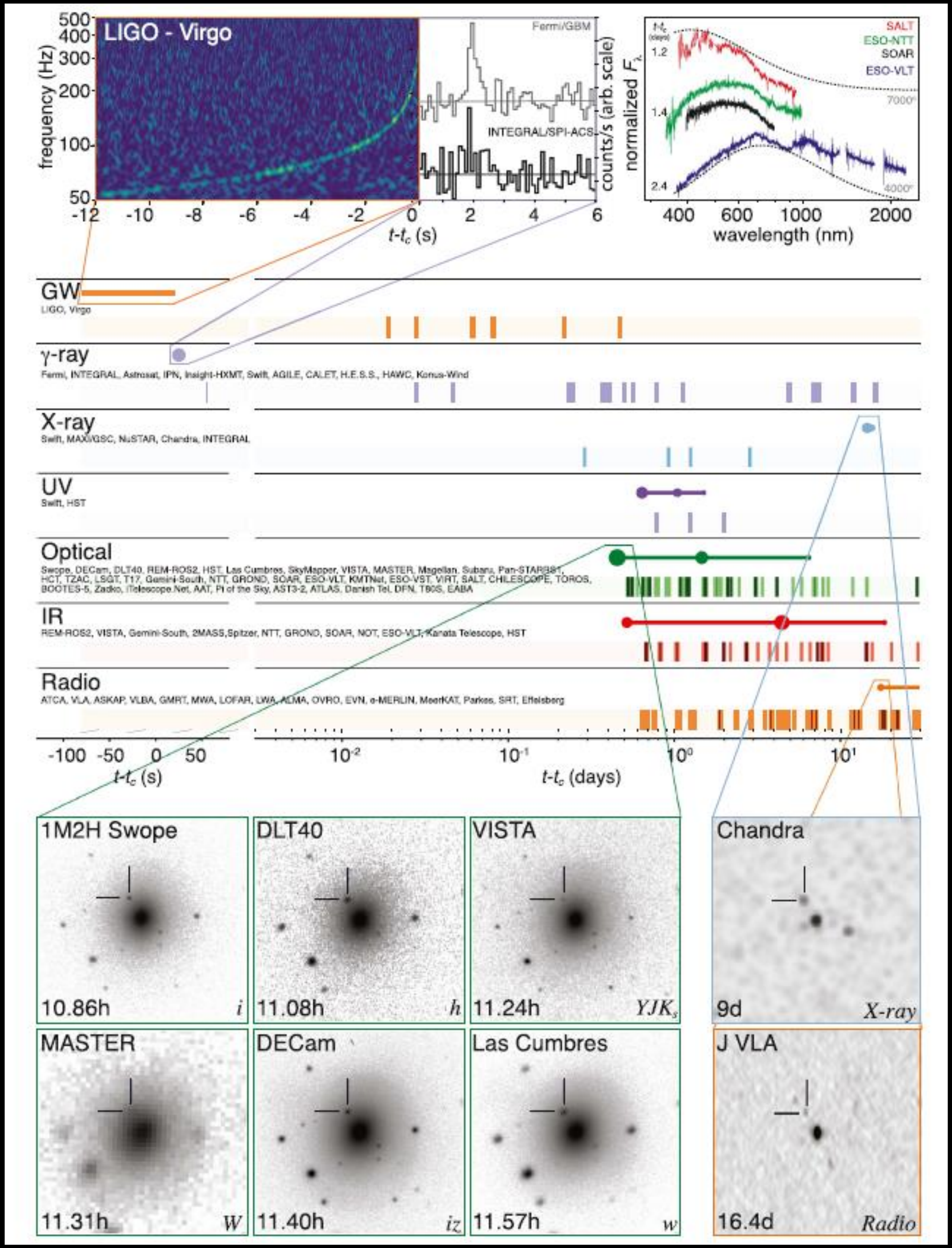
Cosmology



Credit: M. Branchesi

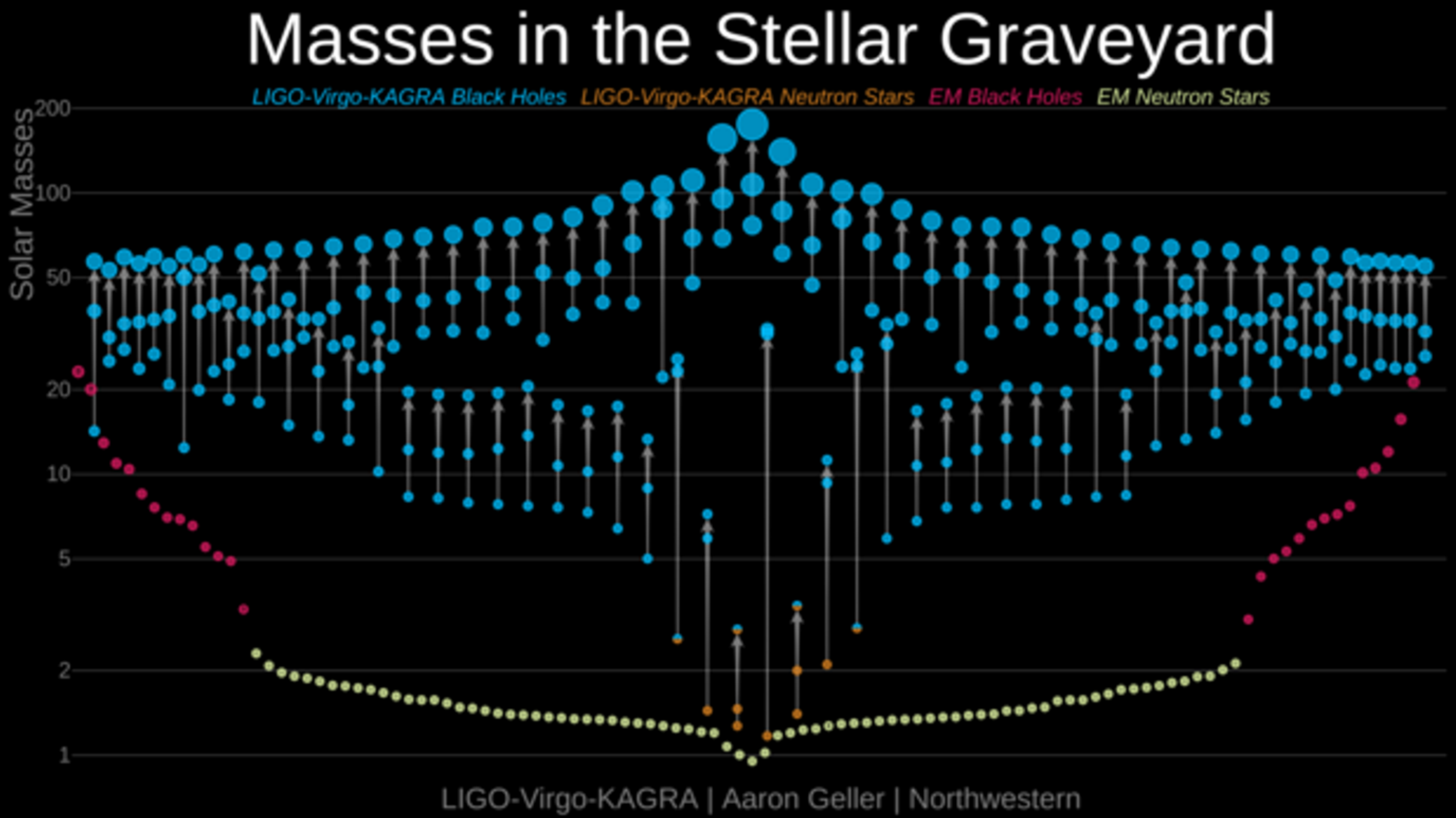


LVC + astronomers, ApJL, 848, L12



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

LIGO, Virgo and KAGRA O1+O2+O3 runs

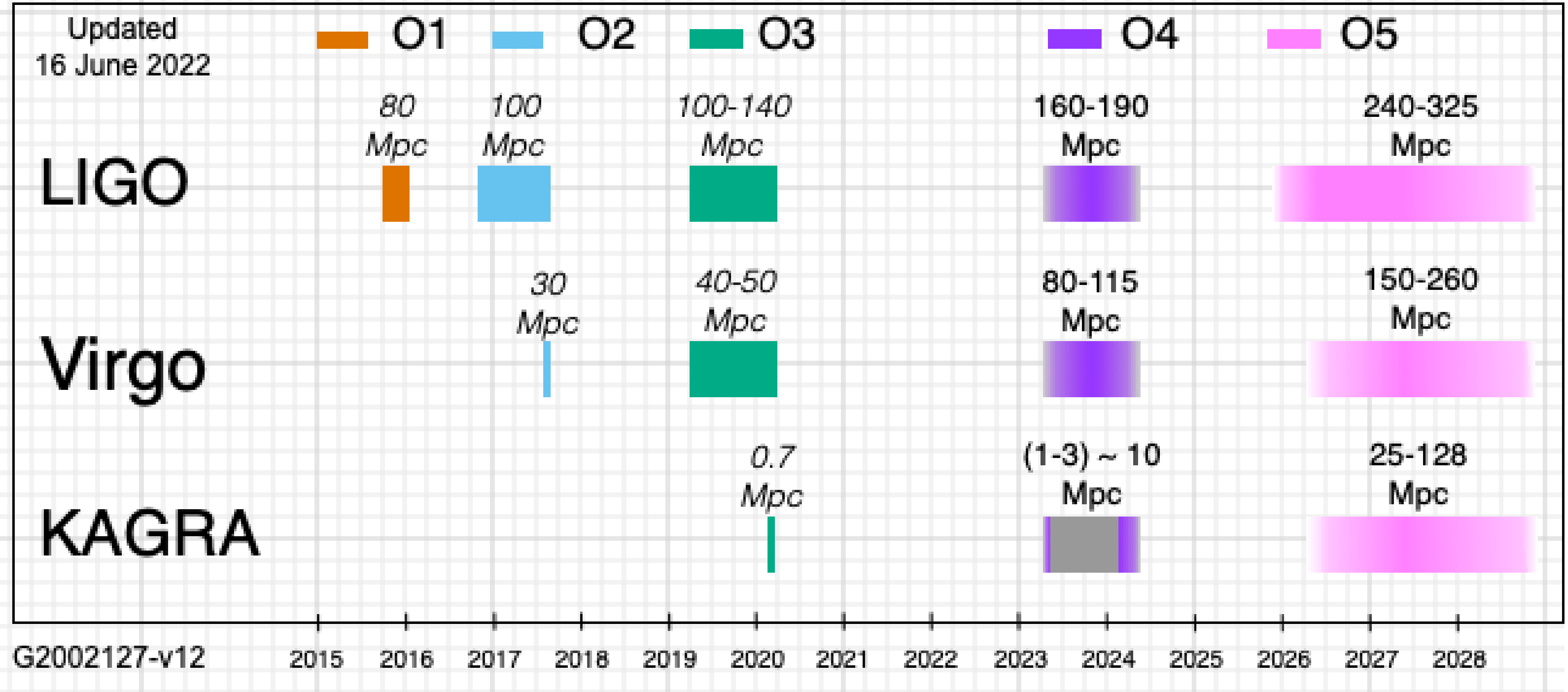


90 GW CANDIDATE EVENTS!

LVK arXiv:2111.03606

BNS range for each observing run

15 June 2022 update

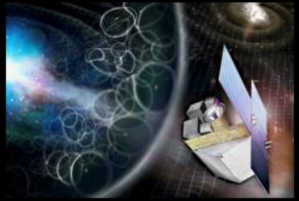


https://observing.docs.ligo.org/plan/

GW + γ-ray joint detections per year

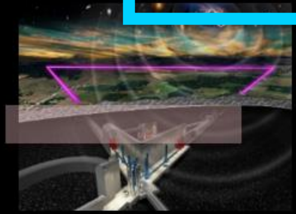
SURVEY MODE

Credit: M. Branchesi



INSTRUMENT	band MeV	F_{lim} erg cm^{-2} s^{-1}	FOV/4π	loc. acc.	Joint ET +γ-ray	N_{JD}/N_{γ}	Joint (ET+CE) +γ-ray	N_{JD}/N_{γ}
Fermi-GBM	0.01 - 25	0.5(*)	0.75	5 deg (^{a})	33^{+14}_{-11}	68^{+13}_{-18}%	47^{+14}_{-14}	95^{+5}_{-7}%
Swift-BAT	0.015 - 0.15	2×10^{-8}	0.11	1-3 arcmin	10^{+3}_{-3}	62^{+11}_{-14}%	13^{+5}_{-4}	94^{+6}_{-7}%
GECAM	0.006 - 5	2×10^{-8}	1.0	1 deg	121^{+84}_{-48}	57^{+8}_{-10}%	205^{+145}_{-72}	92^{+4}_{-5}%
SVOM-ECLAIRs	0.004 - 0.250	1.792(*)	0.16	$<$ 10 arcmin	3^{+1}_{-1}	69^{+10}_{-9}%	4^{+1}_{-1}	95^{+5}_{-4}%
SVOM-GRM	0.03 - 5	0.23(*)	0.16	$\sim$ 5 deg	9^{+4}_{-3}	59^{+6}_{-6}%	14^{+6}_{-4}	92^{+3}_{-3}%
THESEUS-XGIS	0.002 - 10	3×10^{-8}	0.16	$<$ 15 arcmin	10^{+5}_{-4}	63^{+13}_{-13}%	15^{+6}_{-4}	94^{+6}_{-7}%
HERMES	0.05 - 0.3	0.2(*)	1.0	1 deg	84^{+42}_{-30}	61^{+10}_{-11}%	139^{+54}_{-36}	94^{+6}_{-6}%
TAP-GTM	0.01 - 1	1(*)	1.0	20 deg	60^{+24}_{-24}	67^{+13}_{-14}%	84^{+30}_{-24}	95^{+5}_{-6}%

Almost all detected short GRB will have a GW counterpart

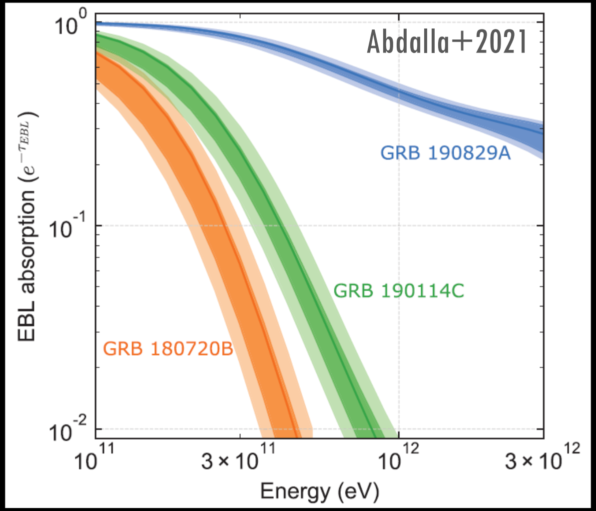


Depending on the satellites, we will have
tens to hunreds of detections per year

Ronchini, MB, Oganesyan, et al. arXiv:2204.01746

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

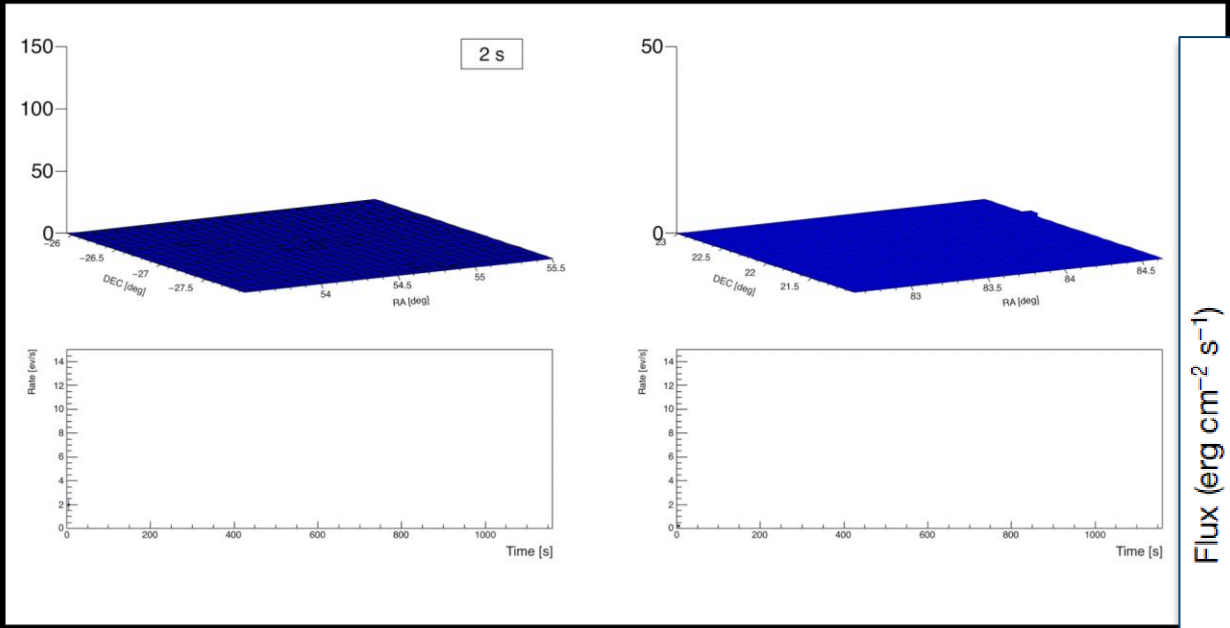
z = 0.0785

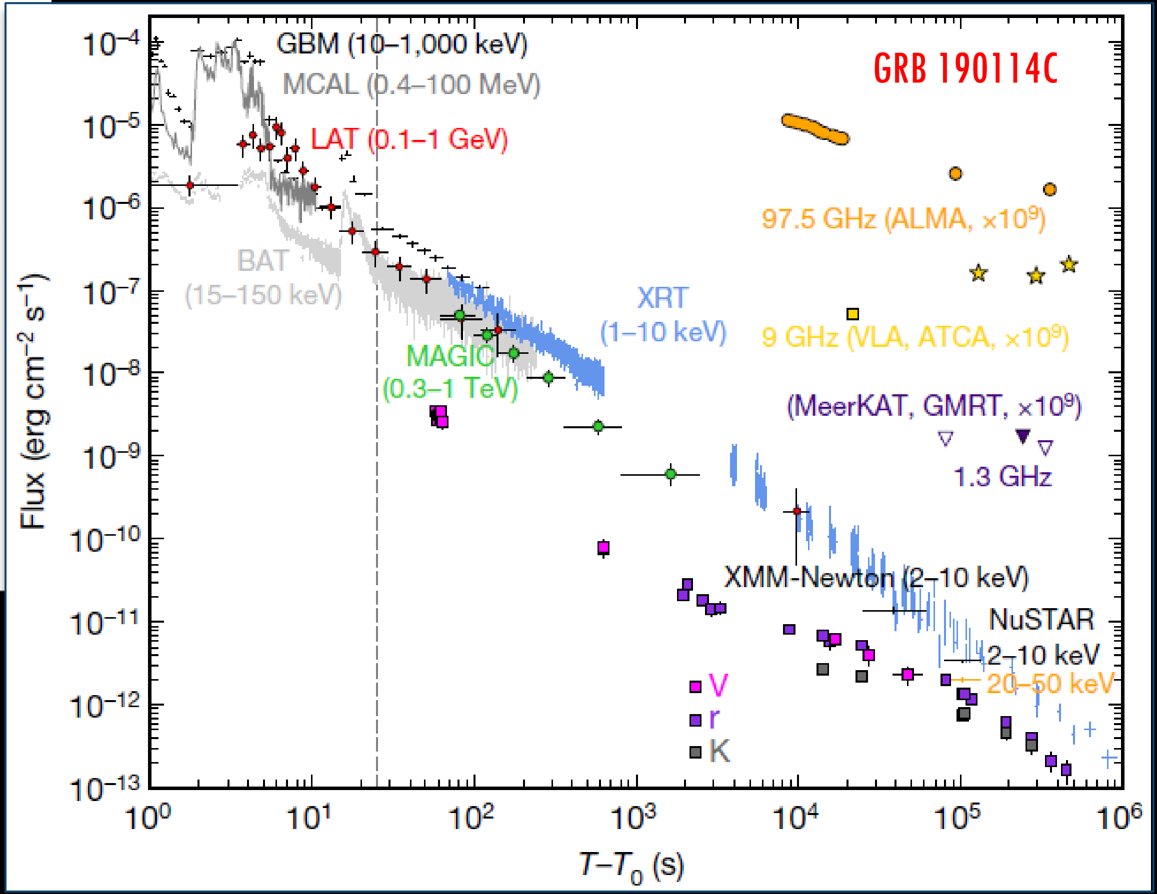
Article | Figures & Data | Info & Metrics | eLetters | PDF

Abstract

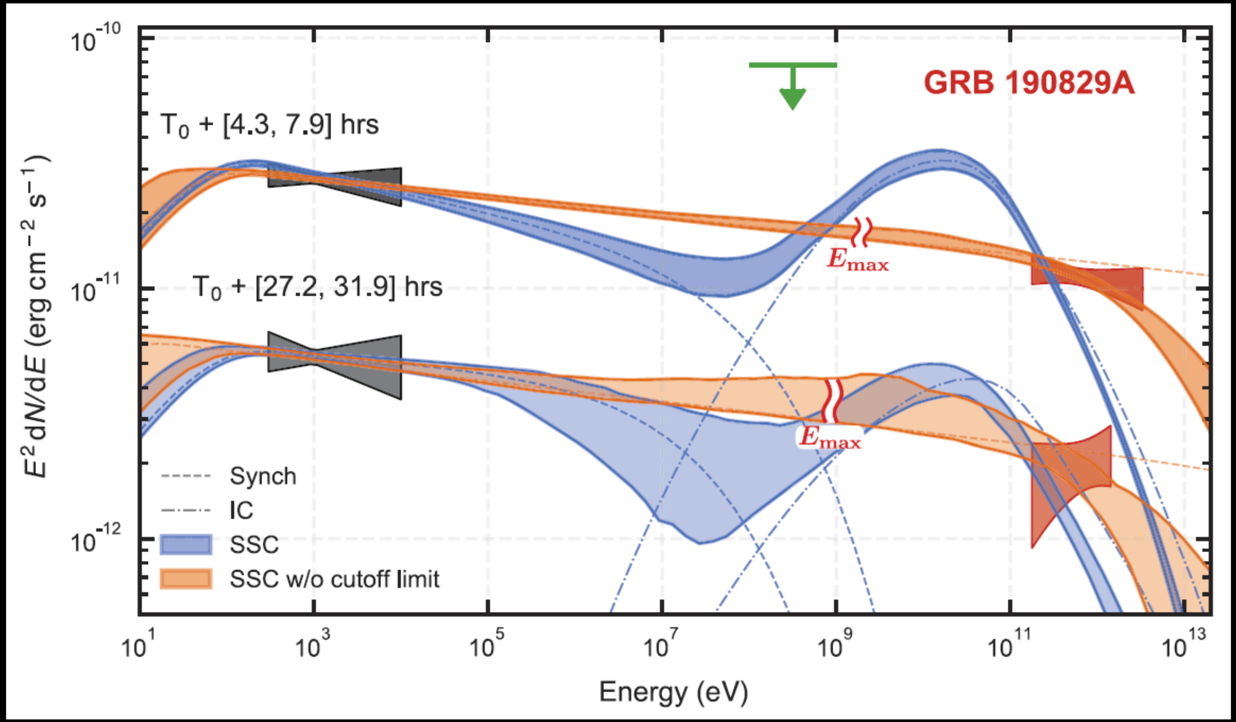
Gamma-ray bursts (GRBs), which are bright flashes of gamma rays from extragalactic sou... followed by fading afterglow emission, are associated with stellar core collapse events. W... report the detection of very-high-energy (VHE) gamma rays from the afterglow of GRB 190829A, between 4 and 56 hours after the trigger, using the High Energy Stereoscopic System (H.E.S.S.). The low luminosity and redshift of GRB 190829A reduce both internal a... 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





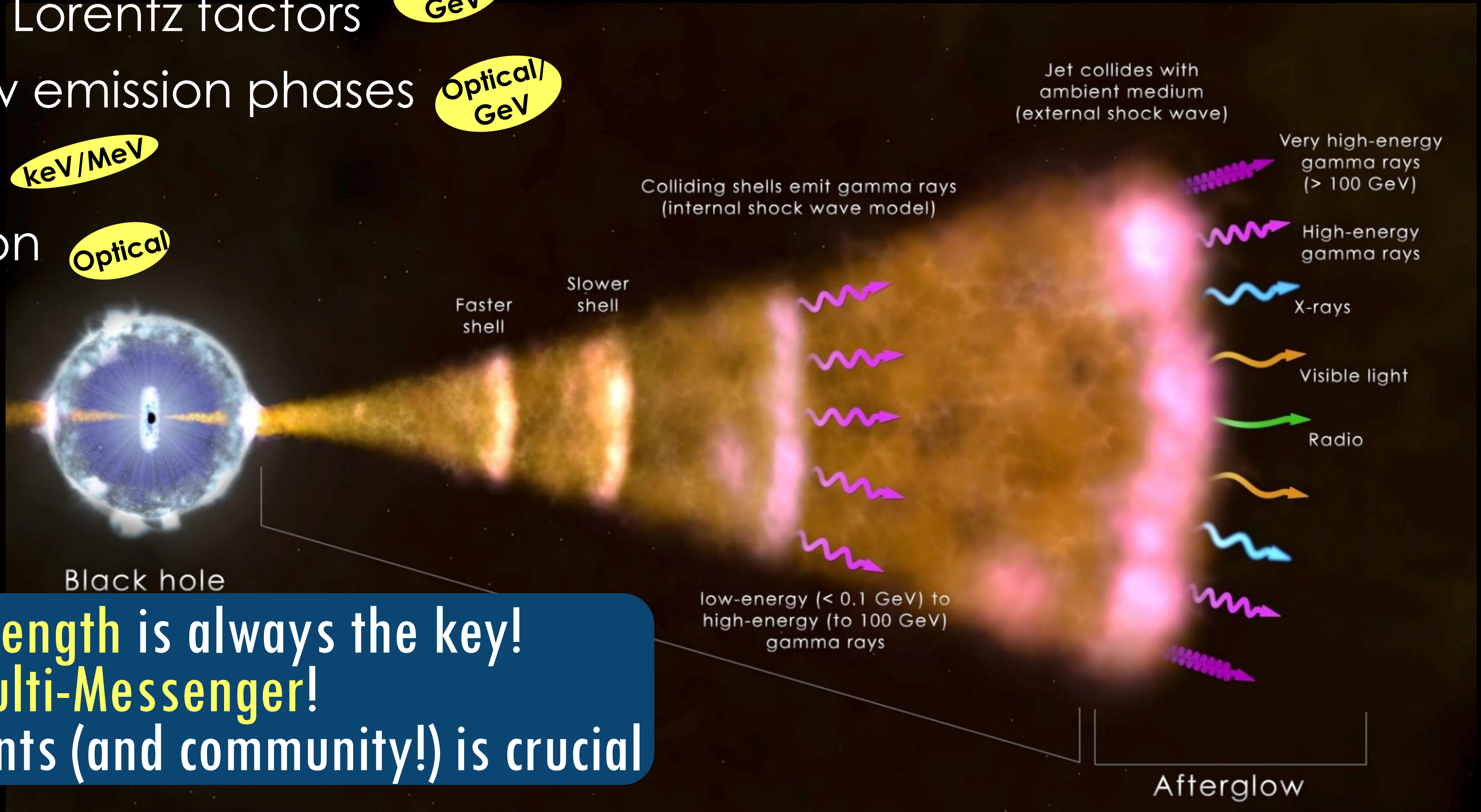
Observation of inverse Compton emission from a long γ-ray burst – MAGIC Collaboration 2019



Revealing x-ray and gamma ray temporal and spectral similarities in the GRB 190829A afterglow – H.E.S.S. Collaboration 2021

GRB "PILLARS OF KNWOLEDGE"

1. GRBs are cosmological *Optical*
2. GRBs have large bulk Lorentz factors *Radio/ GeV*
3. Prompt and afterglow emission phases *Optical/ GeV*
4. Long and short GRBs *keV/MeV*
5. Supernova connection *Optical*
6. Common behaviors and trends *X-ray/keV*



Going for **Multi-Wavelength** is always the key!
Now also **Multi-Messenger**!
Synergy between instruments (and community!) is crucial

Credit: NASA/Goddard Space Flight Center

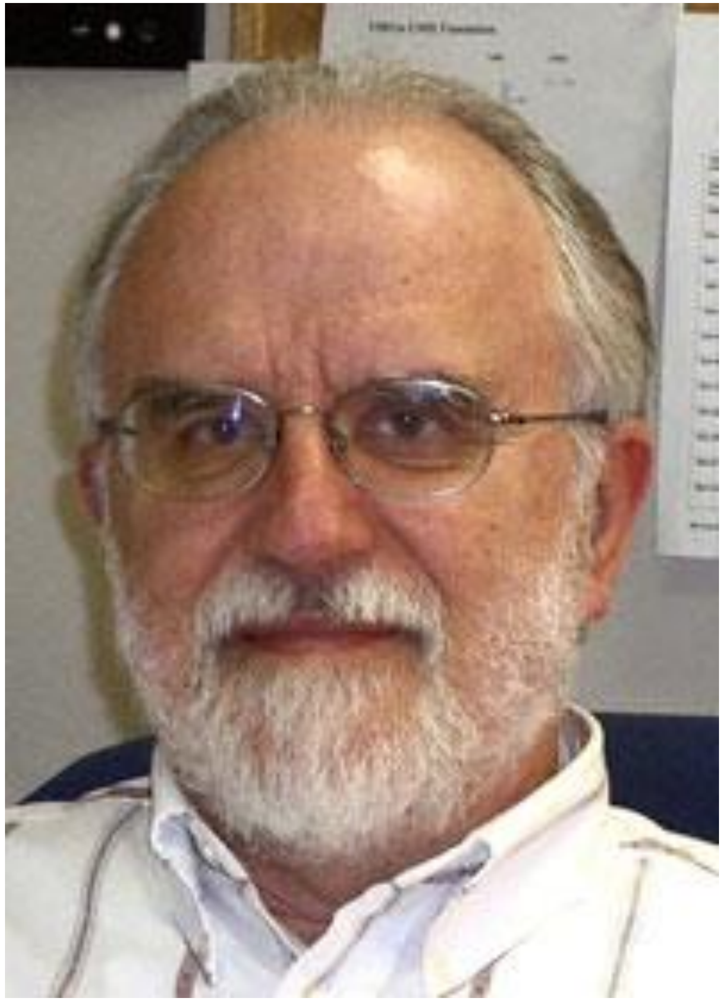
Conclusions

There is still a lot of discovery potential in the GRB field!

- **keV/MeV energy range**: Fundamental triggering and monitoring range for multiwavelength and multimessenger follow-up campaigns!
  Looking forward to many exciting new missions coming online soon!

- **GeV/TeV energy range**: The fun has just began!
  Looking forward to CTA boosting VHE GRB detection rate in both prompt and afterglow emission phases

Williams Paciesas



August 27, 1947 – June 12, 2022

Magnus Axelsson

October 31, 1978 – July 6, 2022

Thank you!


MONITORING THE HIGH-ENERGY
SKY WITH SMALL SATELLITES
2022 September 6-8
Brno, Czech Republic