High-energy emission from Gamma-Ray Bursts

A decade of Fermi-LAT observations

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Outline

- Brief introduction to Gamma-ray bursts (GRBs)
- Fermi-LAT observations
- GRBs and gravitational waves (GWs)
- Current status of searches for GW counterparts

Gamma-ray bursts

The keV emission kicked off the GRB show in the '70s!

VELA-5B satellite (1969) in low earth orbit

THE ASTROPHYSICAL JOURNAL, 182:L85–L88, 1973 June 1

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

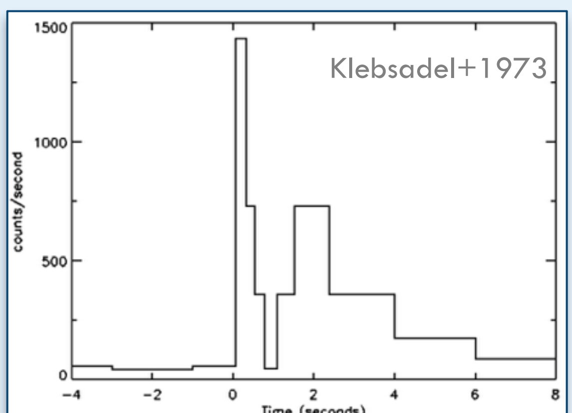
RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

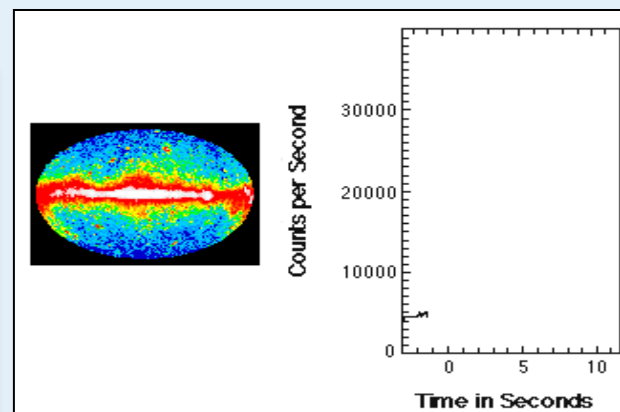
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
Received 1973 March 16; revised 1973 April 2

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 $\sim$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.

Light curve of the first Gamma-Ray Burst





Gamma-ray bursts

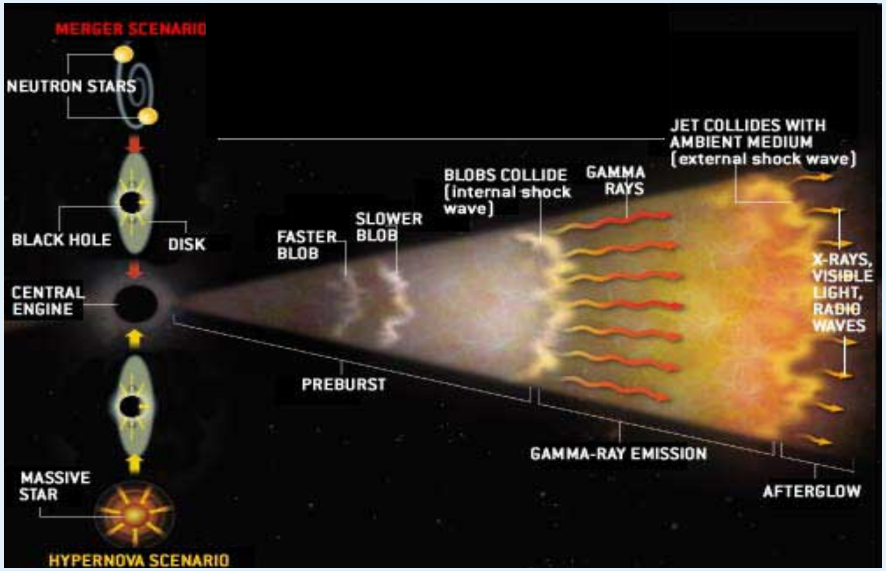
The keV emission kicked off the GRB show in the '70s!

What we know now:

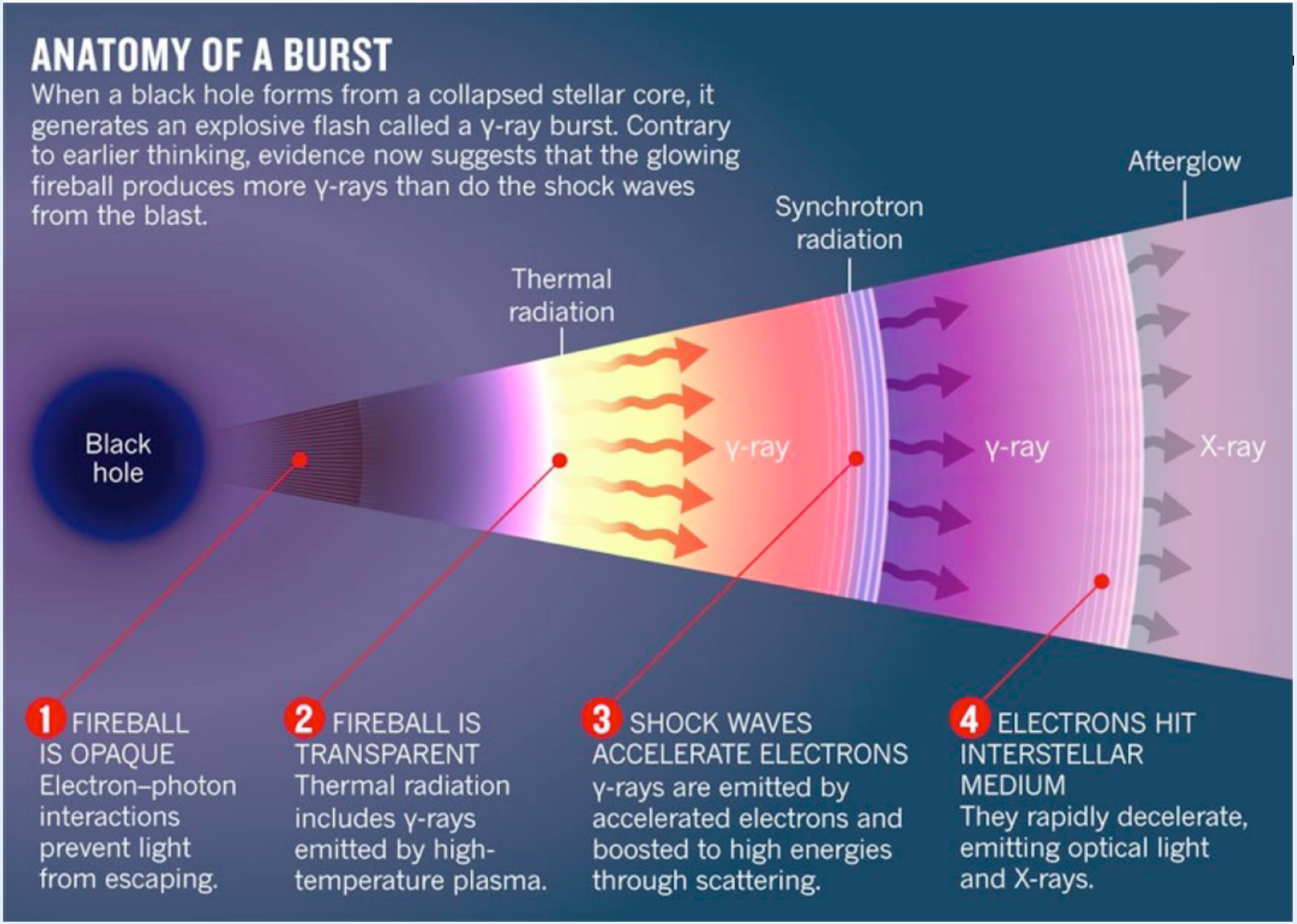
1. GRBs are cosmological *Optical*
2. GRBs have large bulk Lorentz factors *Radio/GeV*
3. 2 emission phases: Prompt and afterglow *Optical/GeV*
4. Long and short GRBs *keV/MeV*
5. Supernova connection *Optical*
6. Common behaviors and trends *X-ray/keV*

"Pillars of knowledge" (Ghisellini 2010)

Multi-wavelength observations have always been key to GRB science!



Many potential emission regions/mechanisms



Open questions

Unveiling the GRB phenomenon still represents a large field of research

- Multi-wavelength/multi-messenger observations crucial to answer many open questions
  - What is the physics behind?
    - Prompt: mechanism, jet properties, central engine
    - Early afterglow: mechanism (plateau phase), particle acceleration, B field generation
  - Tools to probe the Universe
    - Cosmological relations
    - Extragalactic background light (deeper than AGN)
  - Tests of UHECR origin, fundamental physics
    - Signatures of accelerated hadrons
    - Lorentz invariance violation

Previous GRB observations in gamma-rays

- Past and present observations
  - **BATSE** [1991–2000; 20–2000 keV]
    2704 GRBs **(~300 GRBs/yr)**
  - **BeppoSAX** [1996–2003; 40–700 keV]
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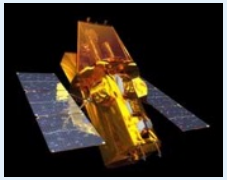
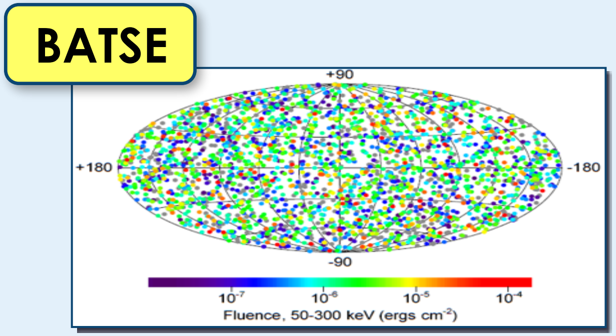
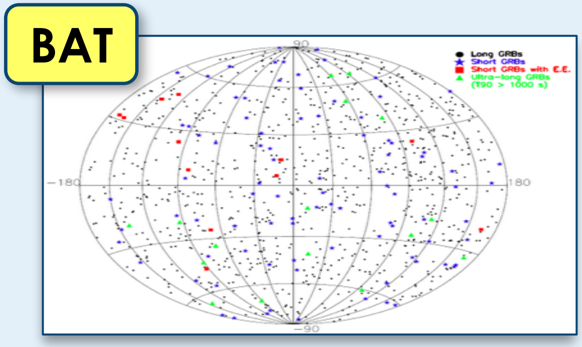
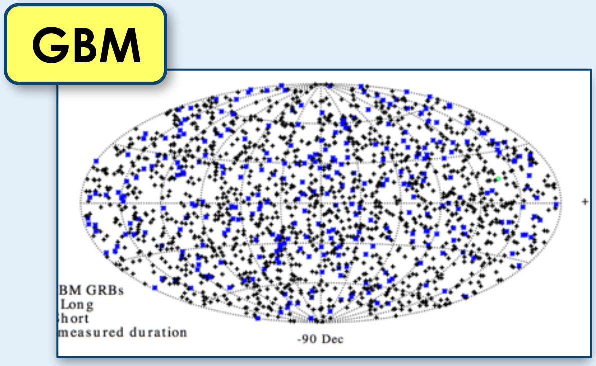
  - **Fermi-GBM** [since 2008; 8 keV–40MeV]
    ~2600 GRBs **(~240 GRBs/yr)**
  - **Other Missions:** HETE-2, INTEGRAL, Konus, Suzaku, AGILE, MAXI-GSC, Astrosat-CZTI, Insight-HXMT, CALET-GRBM **(~150 GRBs/yr)**

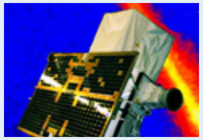
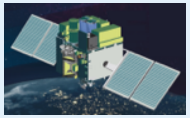
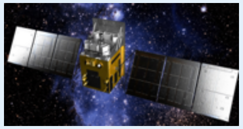
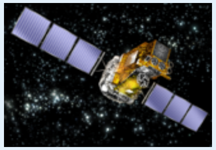
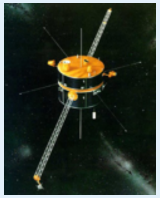








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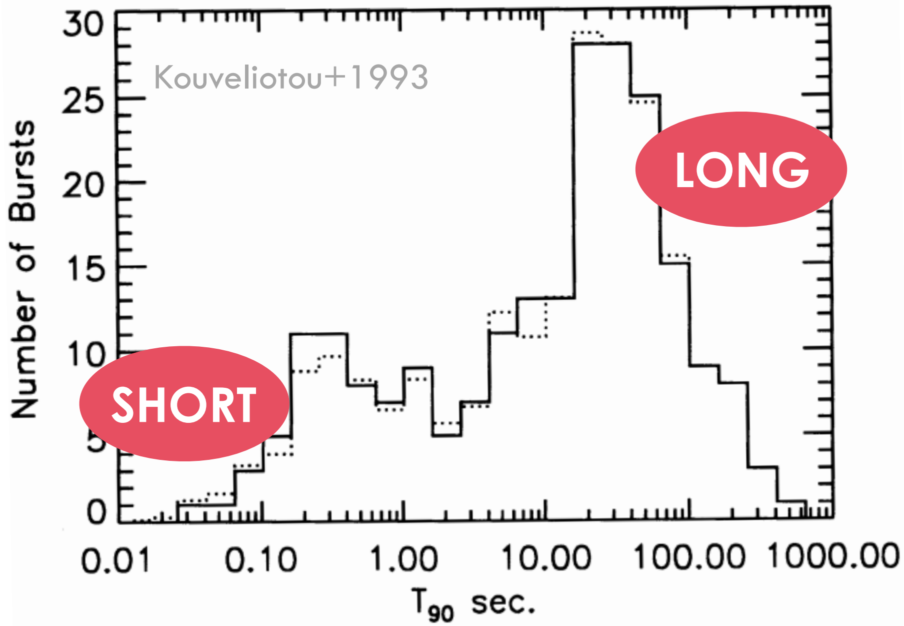
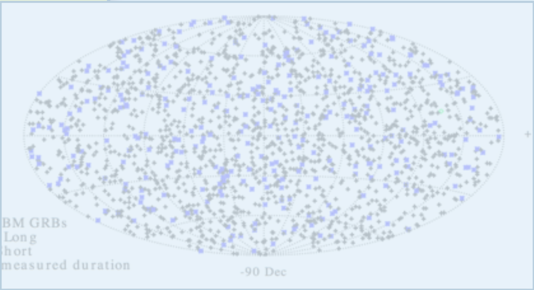
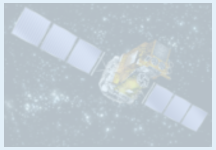
Duration distribution of the first BATSE GRB catalog







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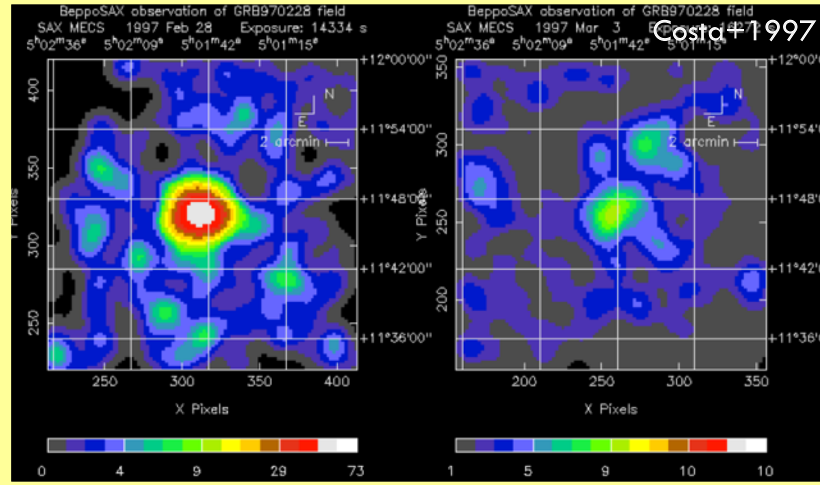
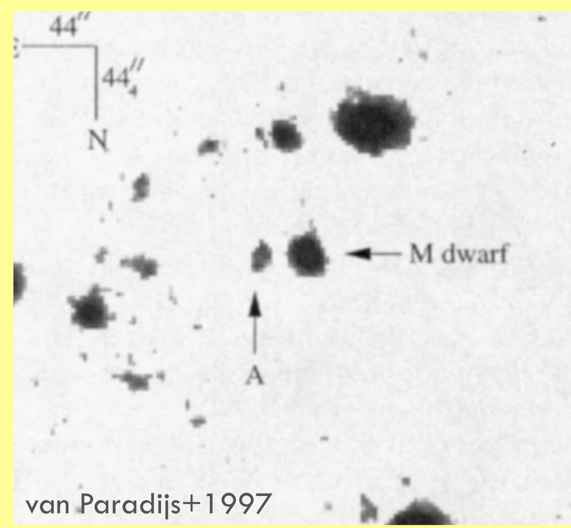
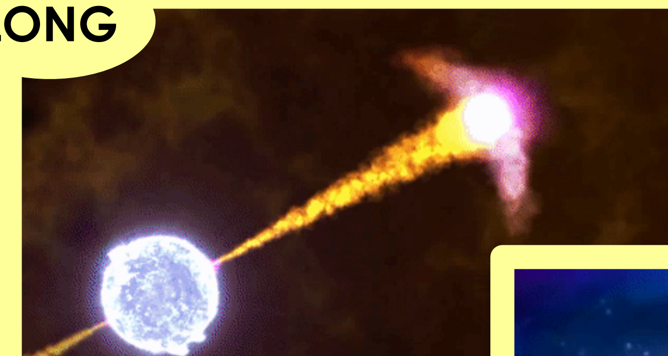
  - 0 keV]
  - keV–40MeV]
  - Suzaku, AGILE, MA
    Insight-HXMT, CALET





LONG



SHORT

Previous GRB observations in gamma-rays

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    Suzaku, AGILE, MAX
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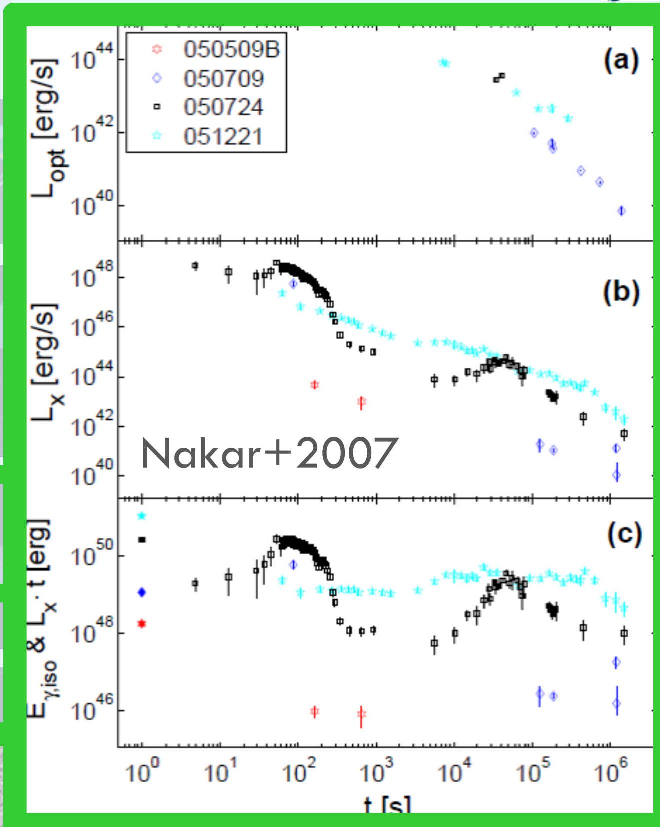
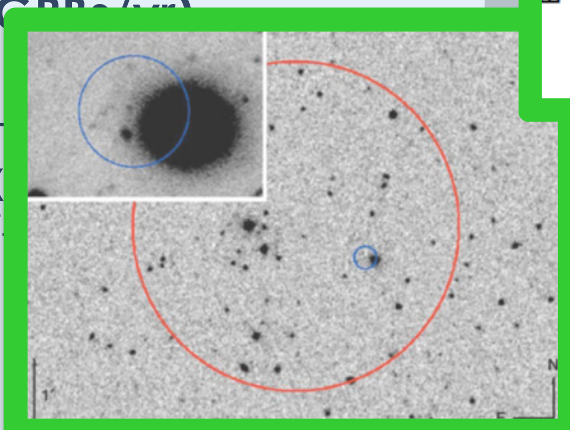
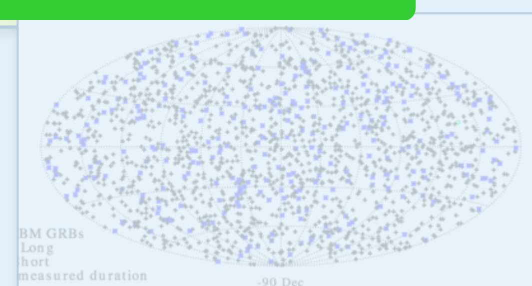






Fermi Gamma-ray Space Telescope

- Launched on June 11, 2008
- GBM detects about 240 GRBs/year
- LAT detects about 20 GRBs/year

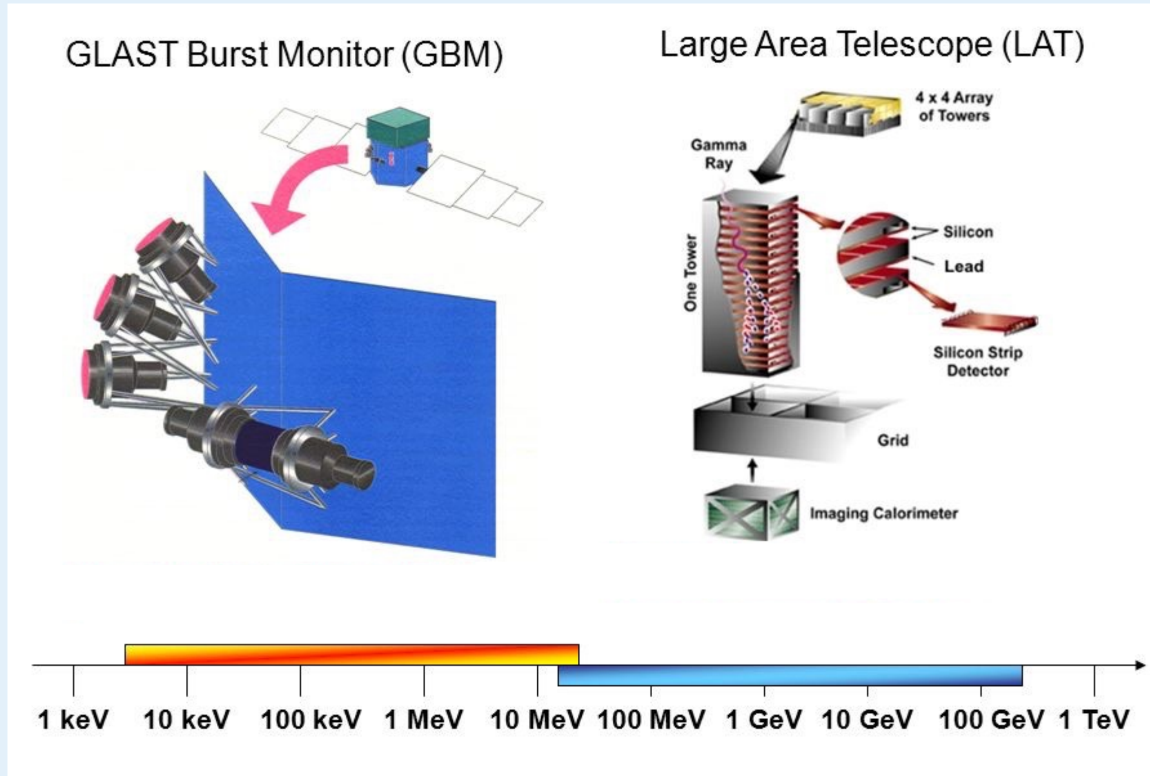


Image: NASA

GBM

NaI: 8 – 900 keV
BGO: 250 keV – 40 MeV

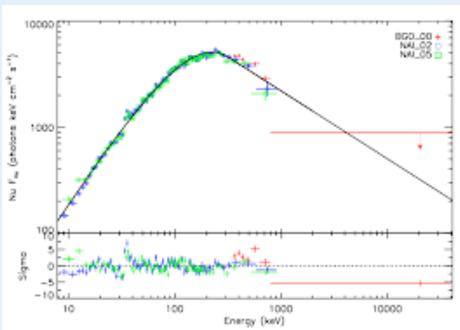
LAT

LLE: 20 MeV – 1 GeV
Std: 100 MeV – 300+ GeV

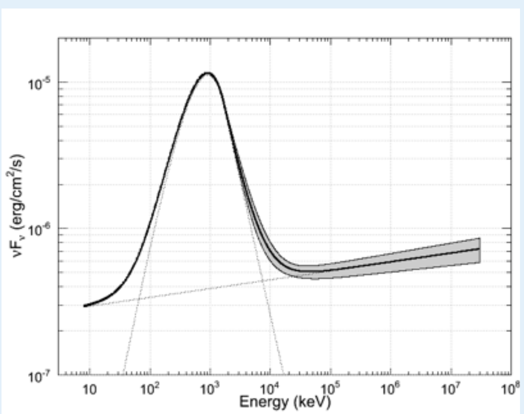
Differences and similarities

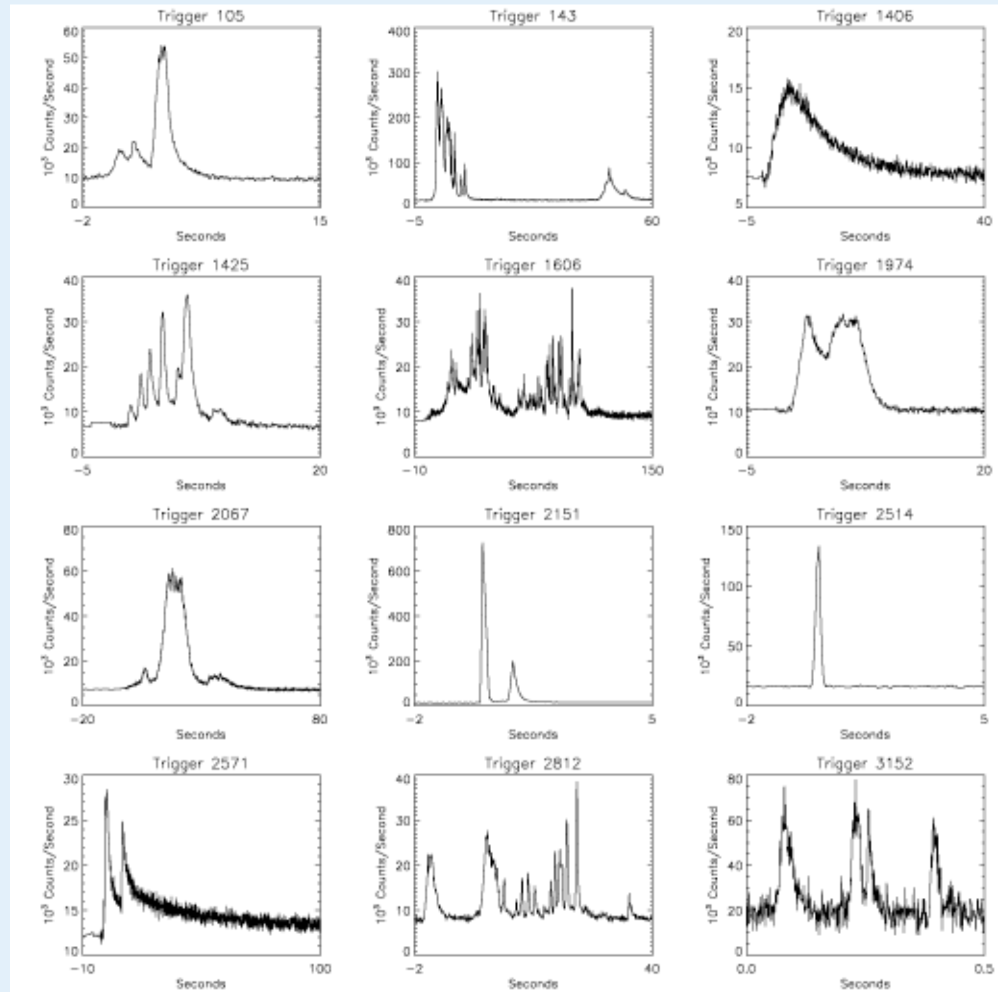
- "When you've seen one gamma-ray burst, you've seen one gamma-ray burst"

Light curves



Spectra



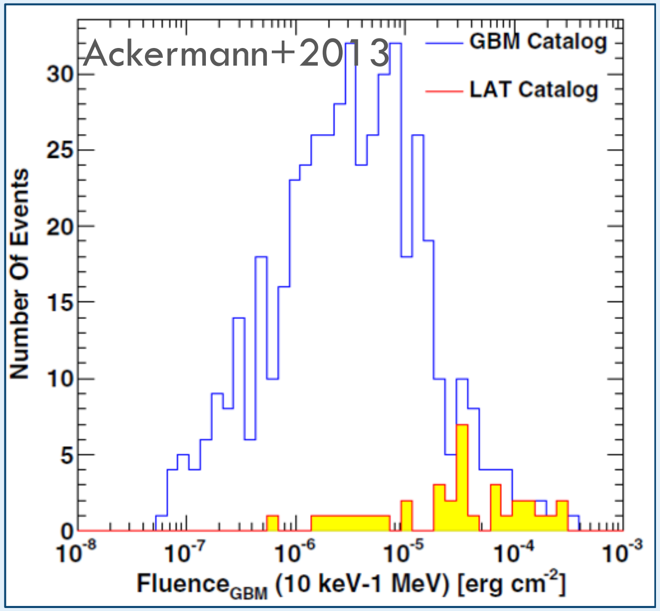


Population studies help
to identify common properties

The 1st LAT GRB Catalog (2013 - *1FLGC*)

- First **systematic study** of **HE** emission of GRBs
  - **35 GRBs** (28 >100 MeV, 7 LLE only <100 MeV)
- High-energy features:
  a) Emission >100 MeV systematically **delayed**
  b) Emission >100 MeV systematically **longer**
  c) Emission >100 MeV decays smoothly as a power law **(index -1)**

LAT GRBs considered among the brightest GBM ones!



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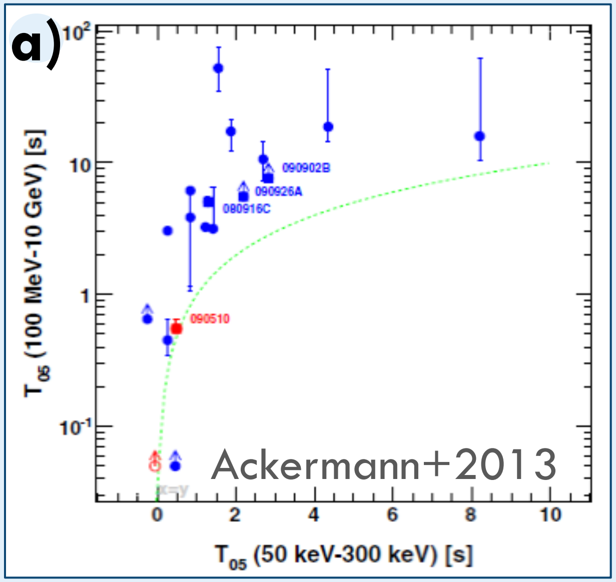
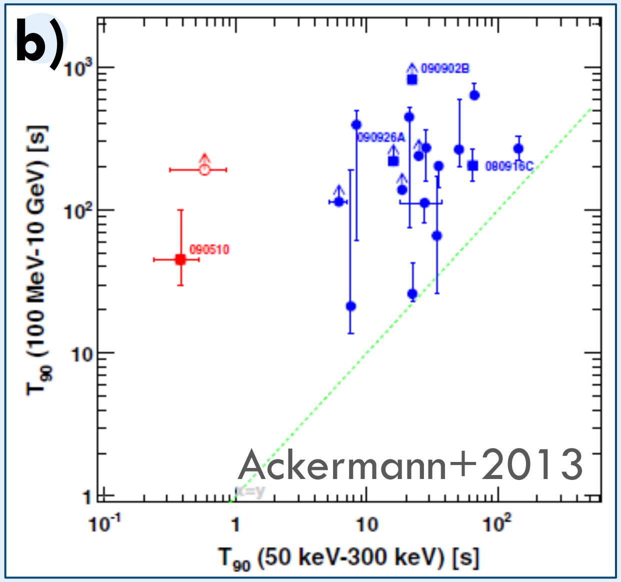
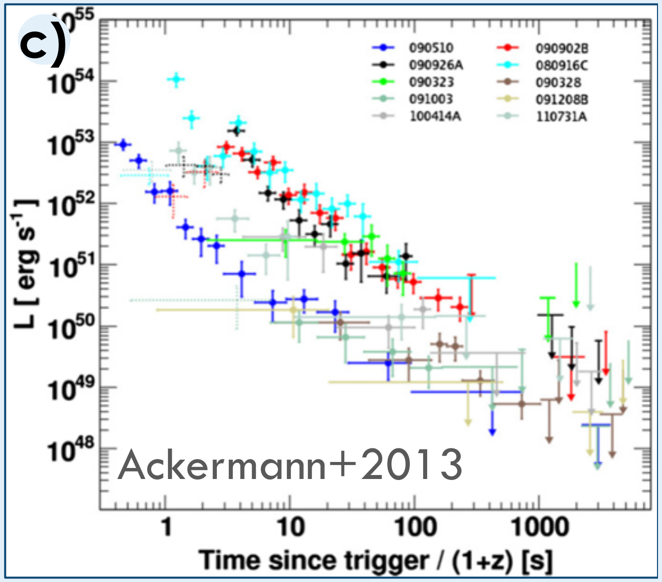


b)


c)


2nd catalog (2FLGC) analysis pipeline

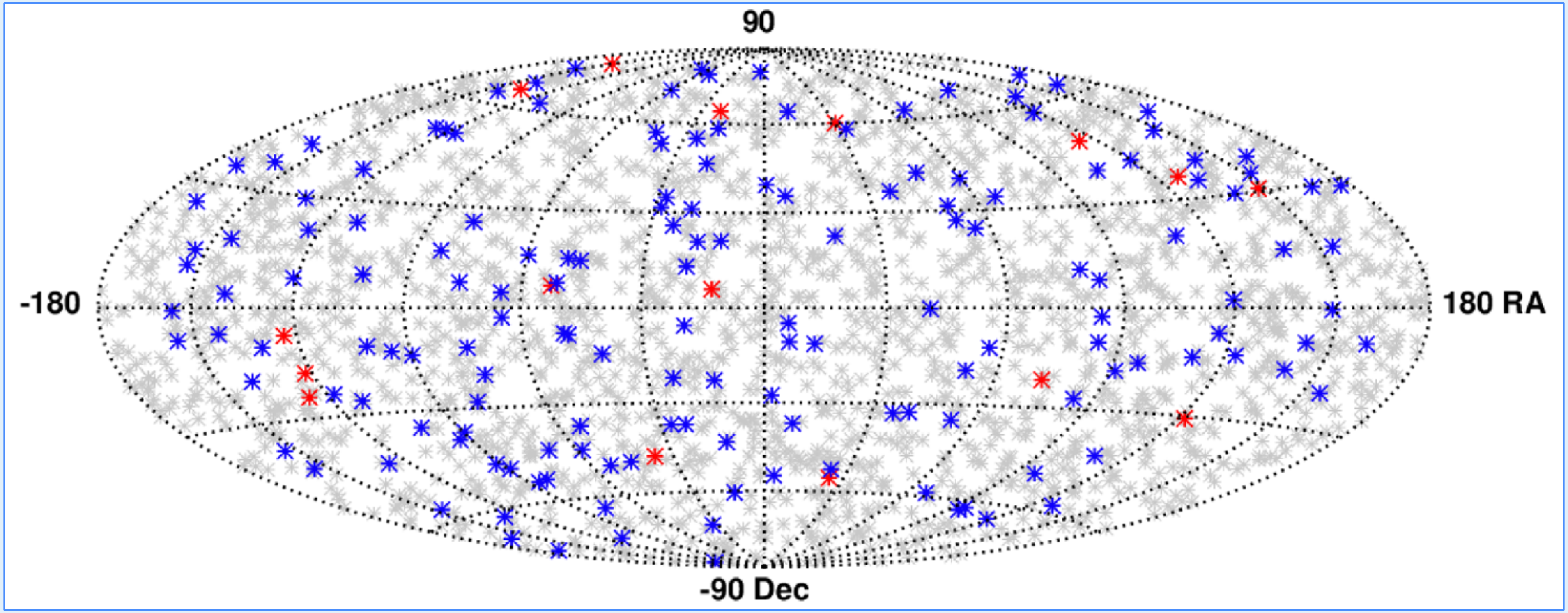
- Time period: August 2008 to 2018 (10 years)
- Search for emission from 3044 GRBs triggered by other instruments (GBM, Swift, Integral, AGILE, IPN)
- Detection algorithm searching five time windows, from 10 s to 10 ks (LTF: Vianello et al. 2015).
- Every detection analysed by a standardized analysis pipeline.

Compared with the 1FLGC

- New detection algorithm: 50% improvement
- Using Pass8 data: 10% improvement

GRB detections

- **186 LAT** detections (169 **long**, 17 **short**)
  - **91 LLE** GRBs (85 long, 6 short), with **17 LLE only** GRBs (15 long, 2 short)



  - 176 joint detections with GBM (160 long, 16 short)
    - 2 Swift-BAT, 8 IPN
  - 34 GRBs have redshift measurements

Temporal properties (1)

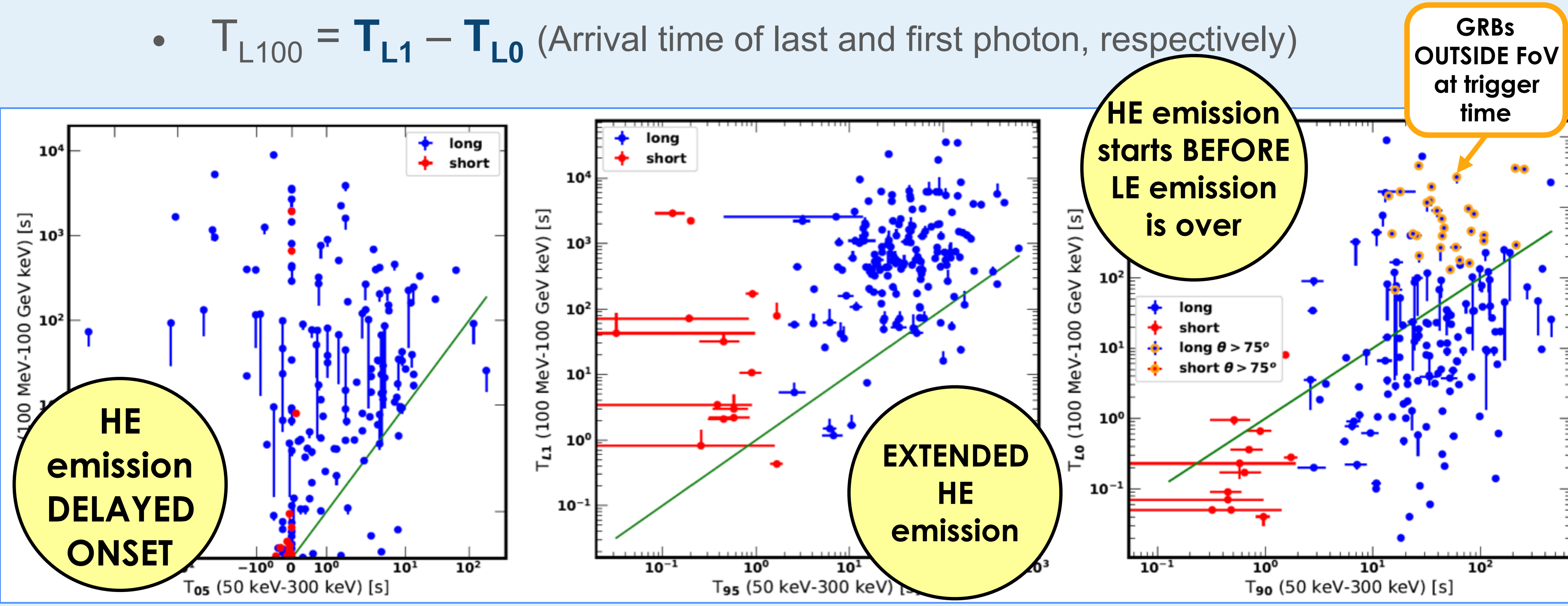
- **GRB duration definitions**

  $\mathbf{T_{90}}$: Canonical GRB duration measured by GBM [**50 – 300 keV**]

  - $T_{90} = \mathbf{T_{95}} - \mathbf{T_{05}}$

  $\mathbf{T_{L100}}$: **new** GRB duration measured by LAT [**100 MeV – 100 GeV**]

  - $T_{L100} = \mathbf{T_{L1}} - \mathbf{T_{L0}}$ (Arrival time of last and first photon, respectively)



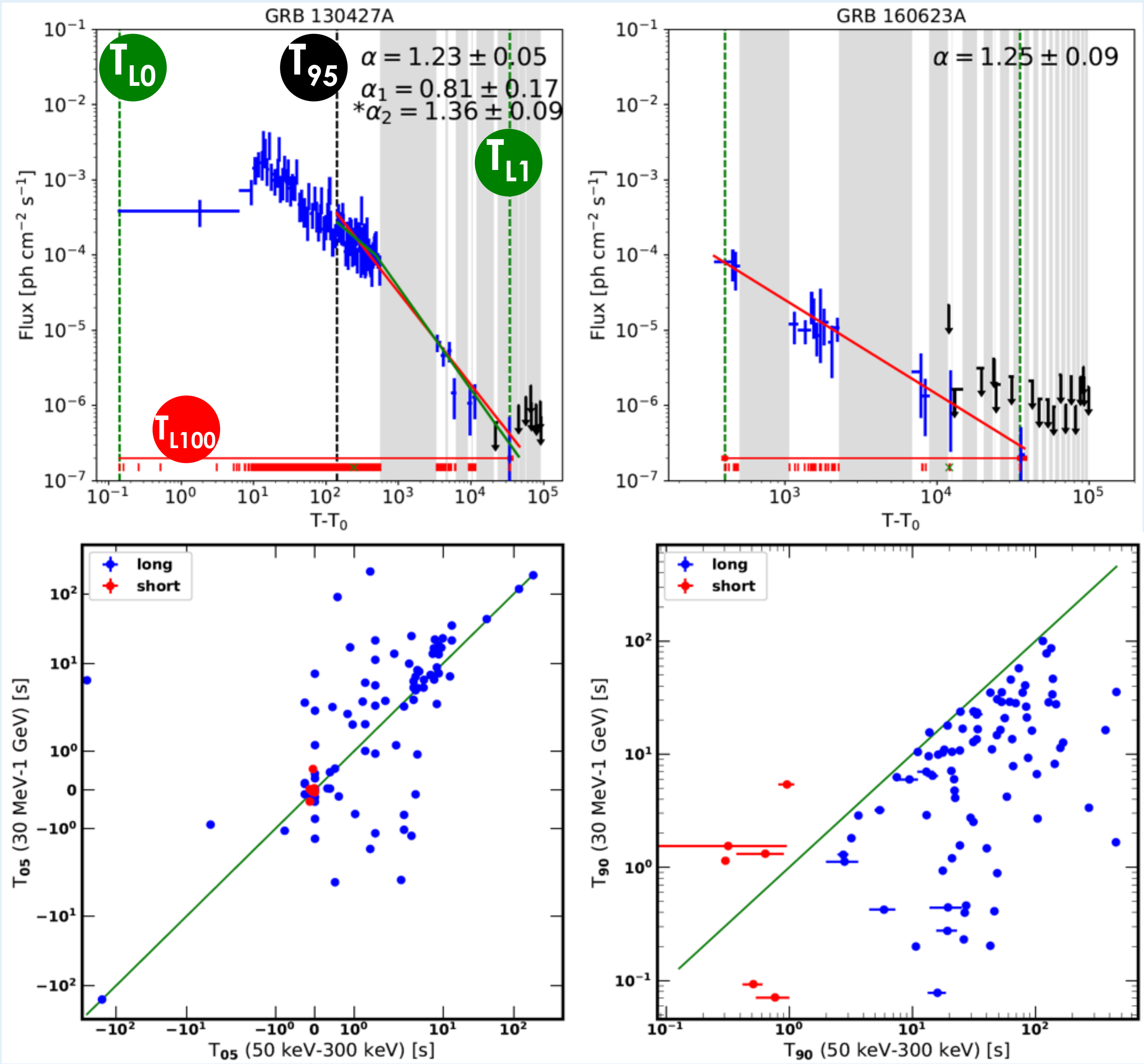
Temporal properties (2)

Longest bursts

1. GRB 130427A
   T_{L100} = 34 ks
2. GRB 160623A
   T_{L100} = 35 ks

LLE bursts

- [**30 MeV – 1 GeV**]
- Definition of duration similar to the GBM
- Behavior similar to low-energy emission



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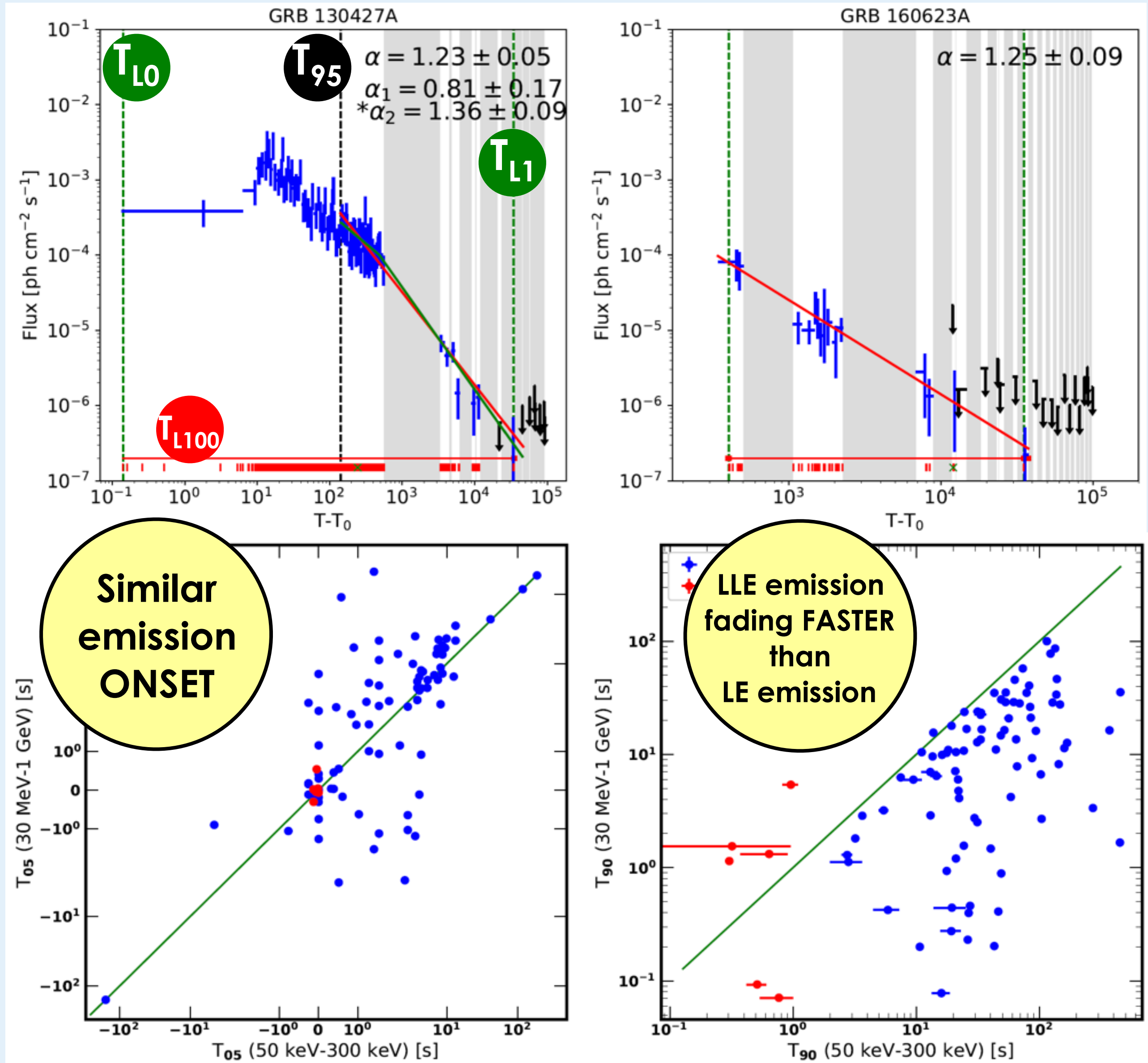
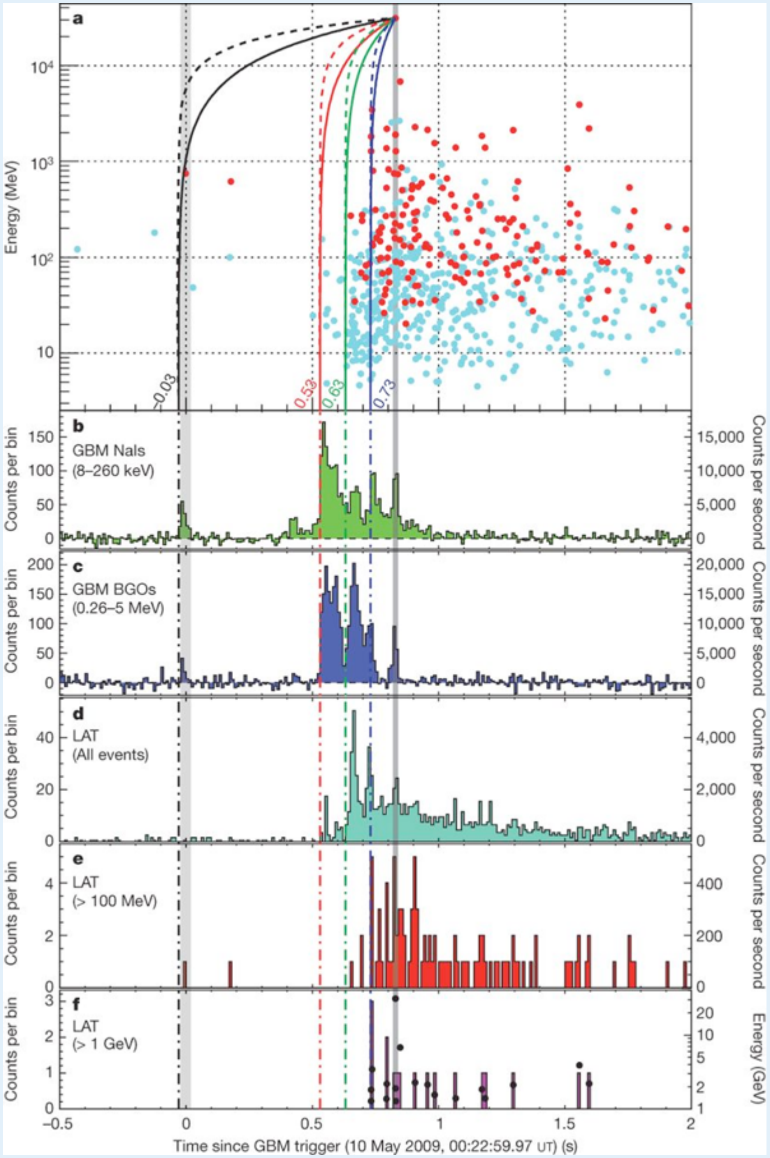


GRB090510

- Duration at low E: ~1 s
- Duration at high E: ~3 min
- Optical follow-up gave redshift 0.903±0.003
- Max energy: 31 GeV observed at 0.83 s

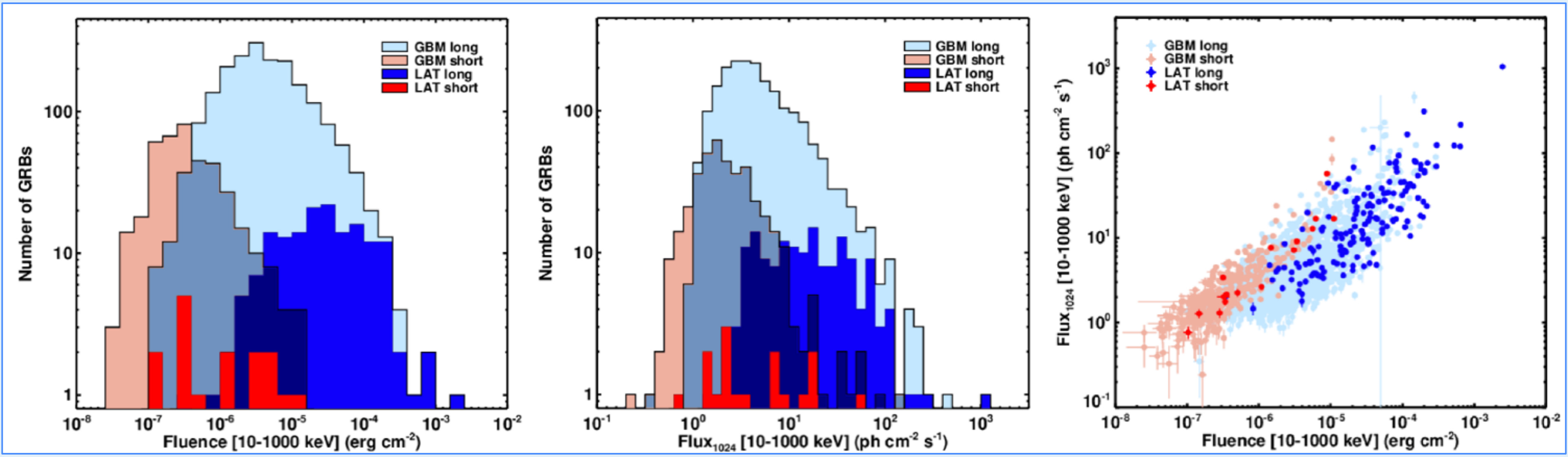
- Delay of high-energy emission clearly seen (~0.2 s)
- Analyzing arrival time of high-energy photon gives constraints on time lags by Lorentz invariance ($|\Delta t/\Delta E| < 30$ ms/GeV)



Abdo et al. 2009

Energetics (1)

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

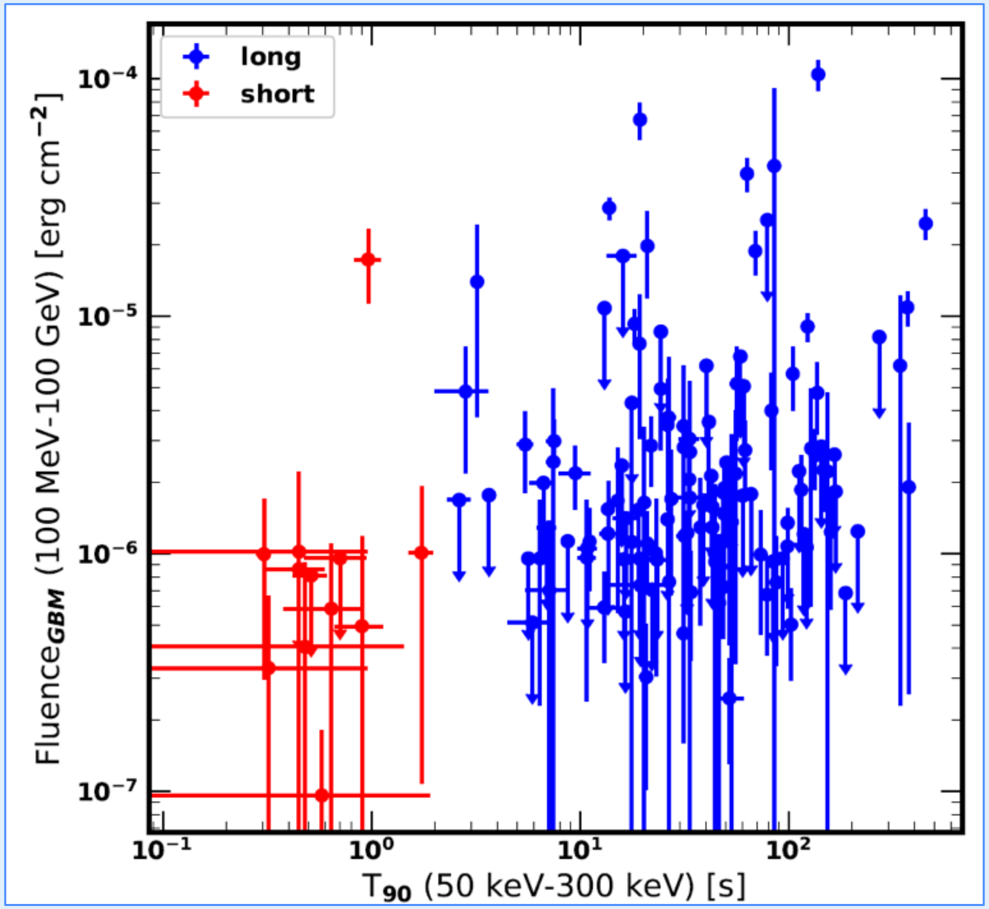


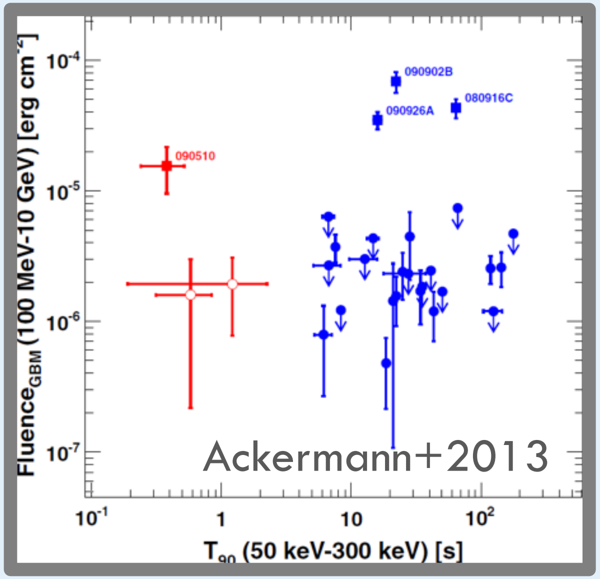
- Distribution of short and long bursts are **different**
- LAT tends to sample brighter bursts
    - BUT: **MUCH LARGER SPREAD** now than in the first LAT catalog!
    - We now detect HE emission also from **weak GBM bursts**!

Energetics (2)

LAT Fluence calculated over the prompt time window (T_{90}) vs duration

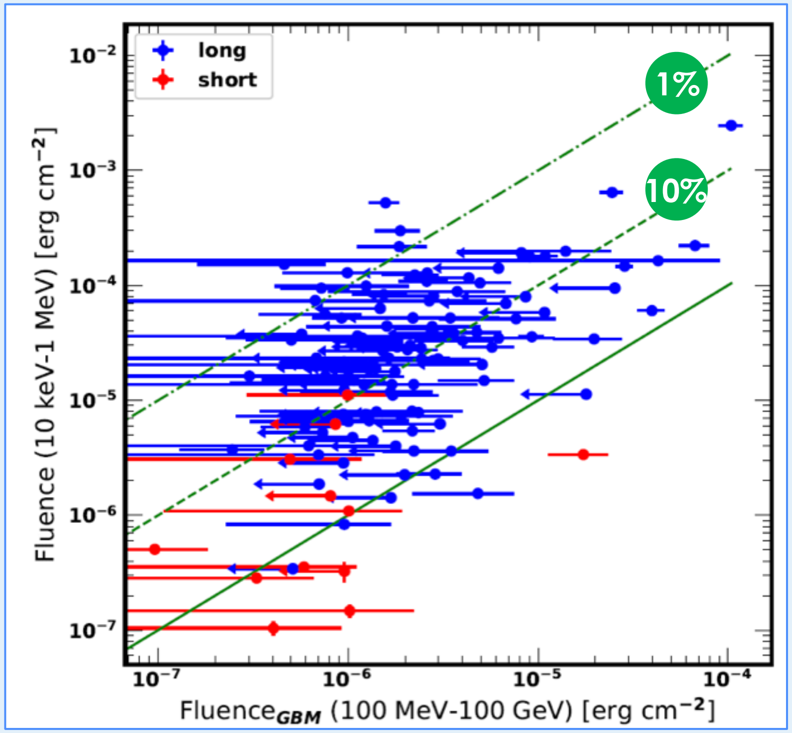
- No clear correlation
- Hint of **distinction** between short and long bursts
- Comparing 1FLGC: Much wider range and **no more clear outliers**!





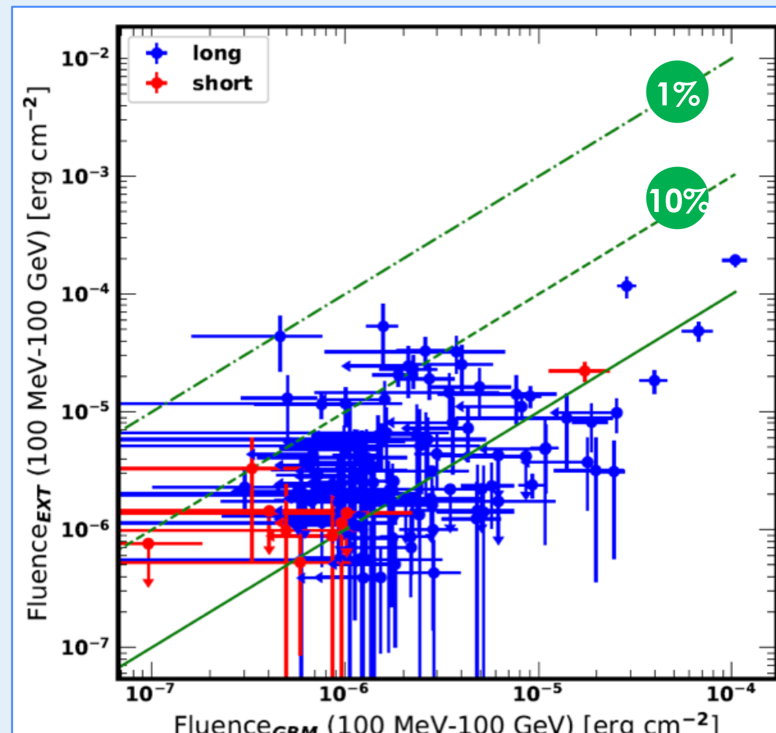
Ackermann+2013

Energetics (3)



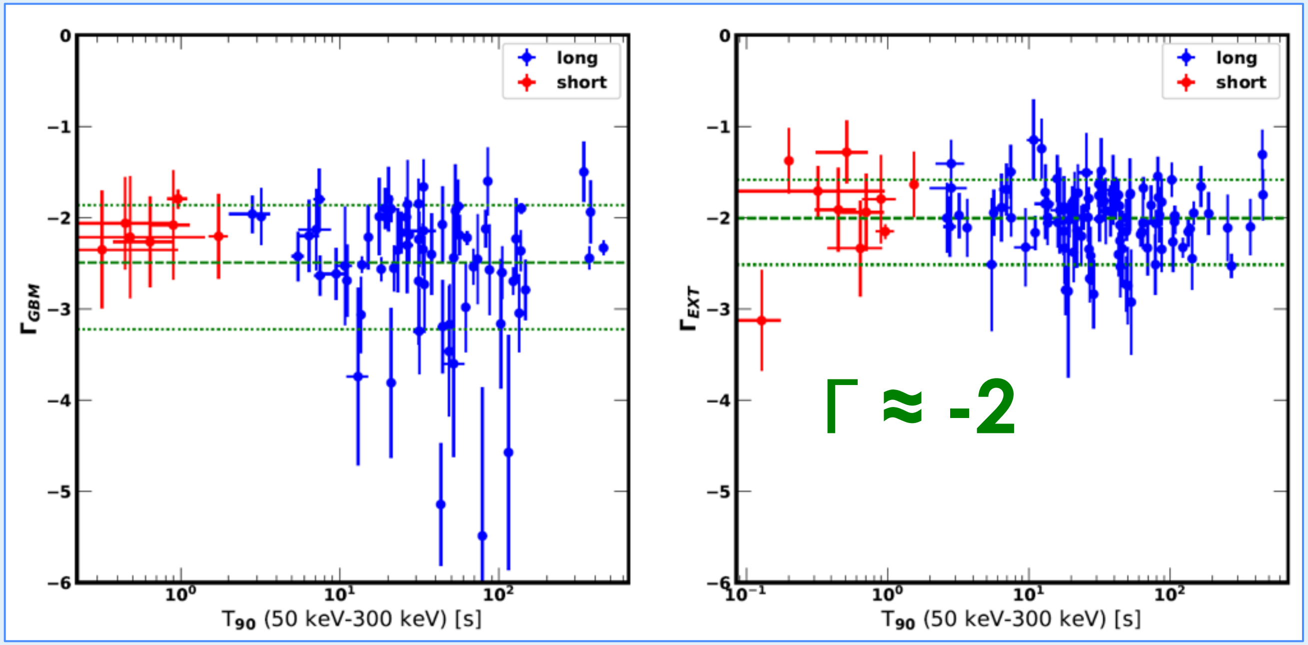
- In **prompt phase** GBM (10-1000 keV) fluence is >10 times larger than LAT (100 Mev-100 GeV) fluence
  - The majority of the burst energy is emitted at lower energies!

- In the LAT energy range, the fluence at late times is comparable to the prompt phase



Energetics (4)

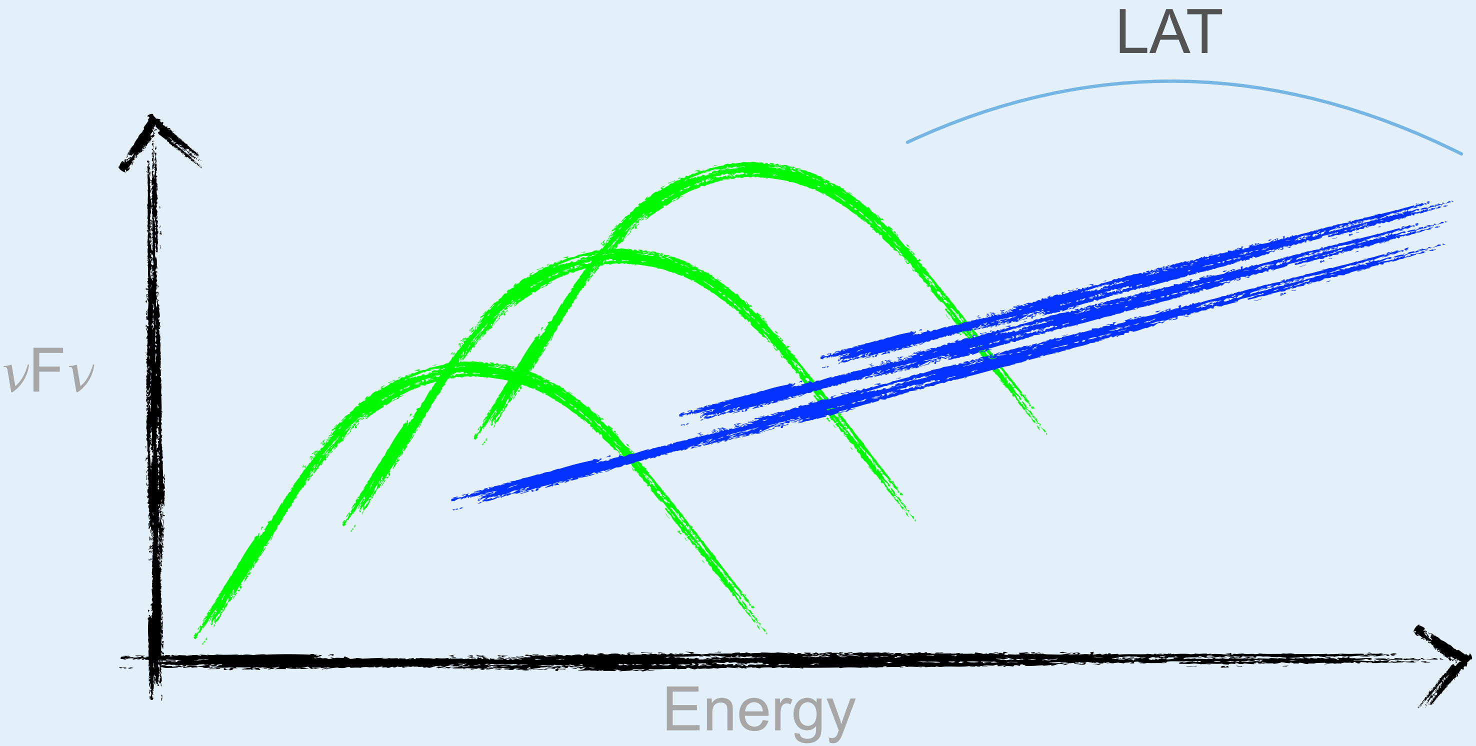
Photon index Γ vs duration in the prompt and late time windows



- No sign of correlation
  - Slightly **harder** at late times
- **Same component at work** in the LAT energy range the whole time
  - Possible **contamination** from the component that dominates in the **10-1000 keV** energy range?

What does this mean?

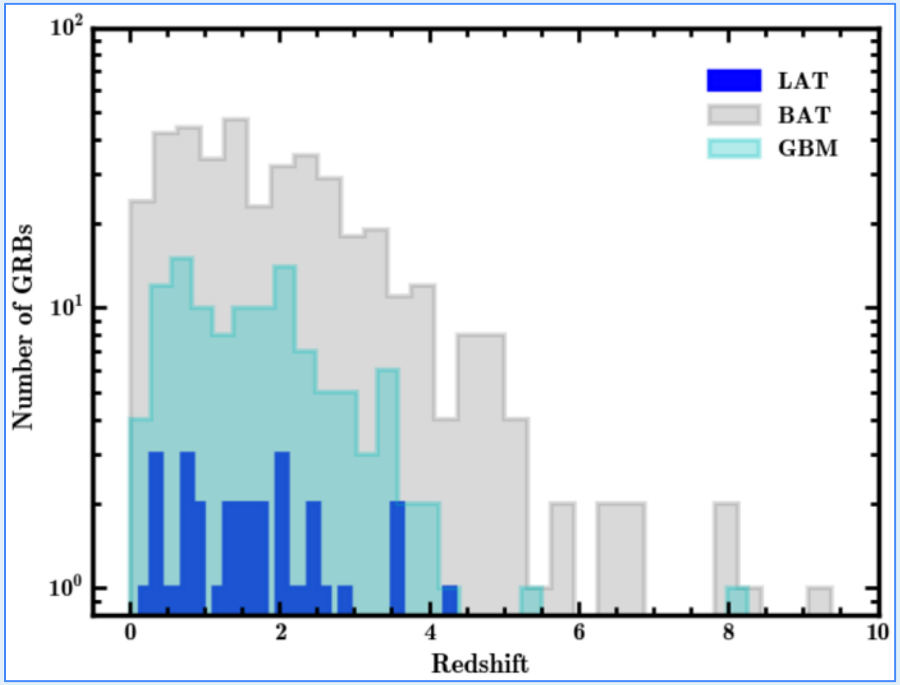
- Strong spectral evolution at low energies
- High-energy emission fairly stable
- Very different temporal behaviour at low and high energies
- Separate emission components!
- Is LAT component an “early afterglow”?



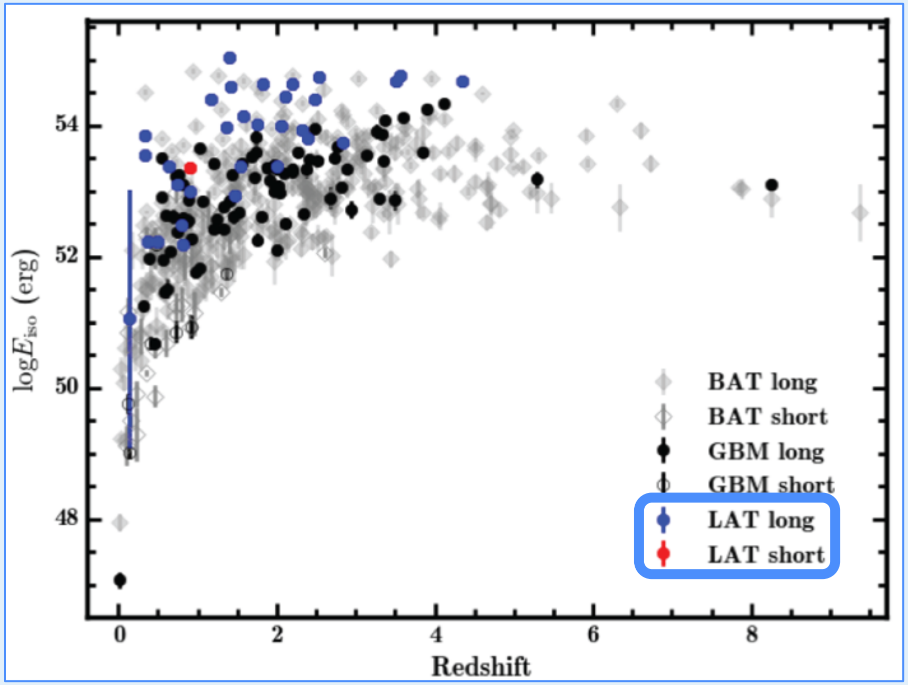
The LAT redshift sample

- **34 GRBs** (33 long and 1 short) have an estimated redshift
  - Study of properties in the **source** frame

➔ Comparing with ***Swift*** and **GBM samples** we detect **intrinsically** brighter bursts!

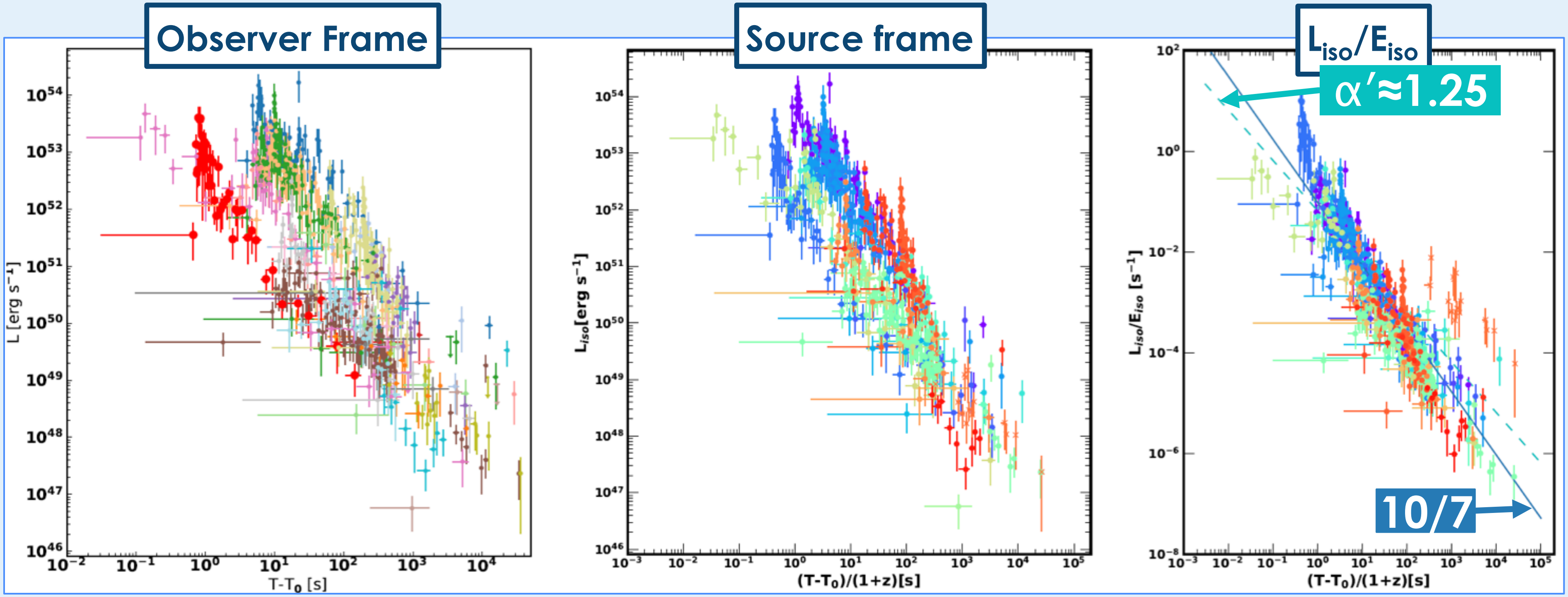


E_{iso} [1 keV – 10 MeV]



The LAT redshift sample

- Study of the temporal decay in **the source frame**

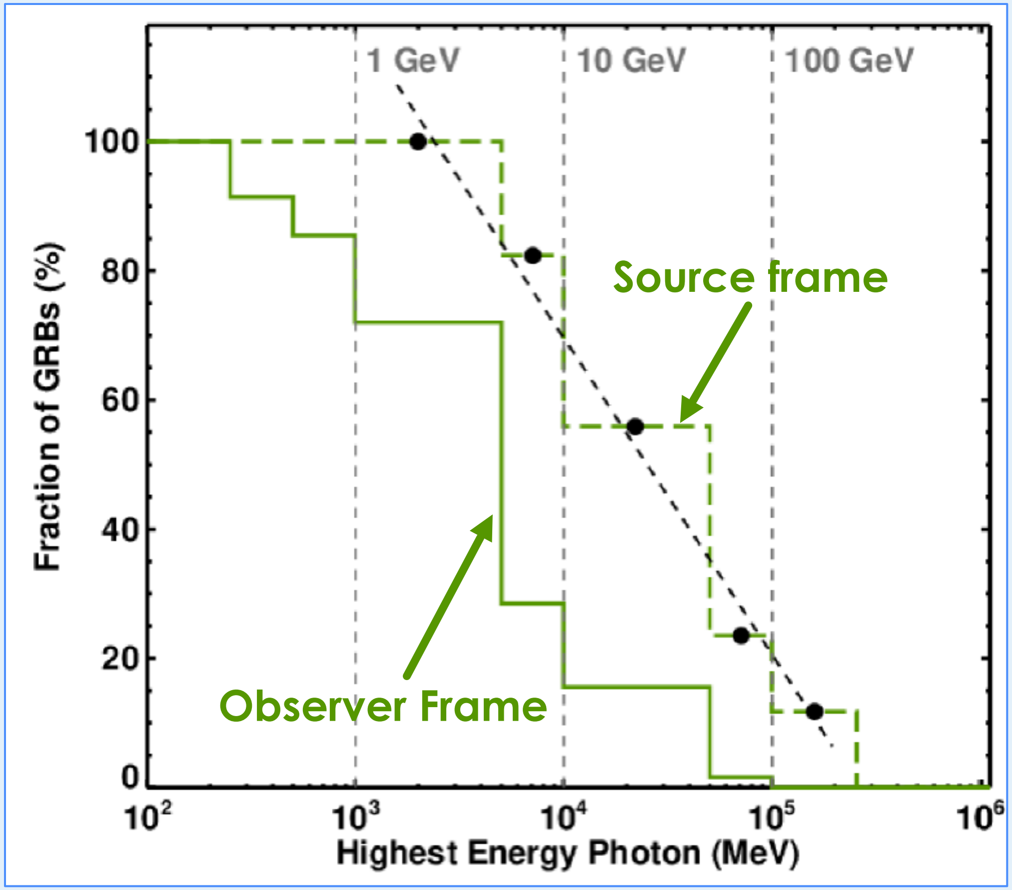


- For each correction, the **spread is reduced** and all points seem to **line up** (Ghisselini et al. 2010, Nava et al. 2014)
  - *In the rightmost plot: division by* $\boldsymbol{E_{iso}}$ *(proxy for* ***total energy budget****)*
    - ***Fit result*** *shown together with* ***theoretical*** *expectation of radiative fireball in constant density environment (index 10/7)*

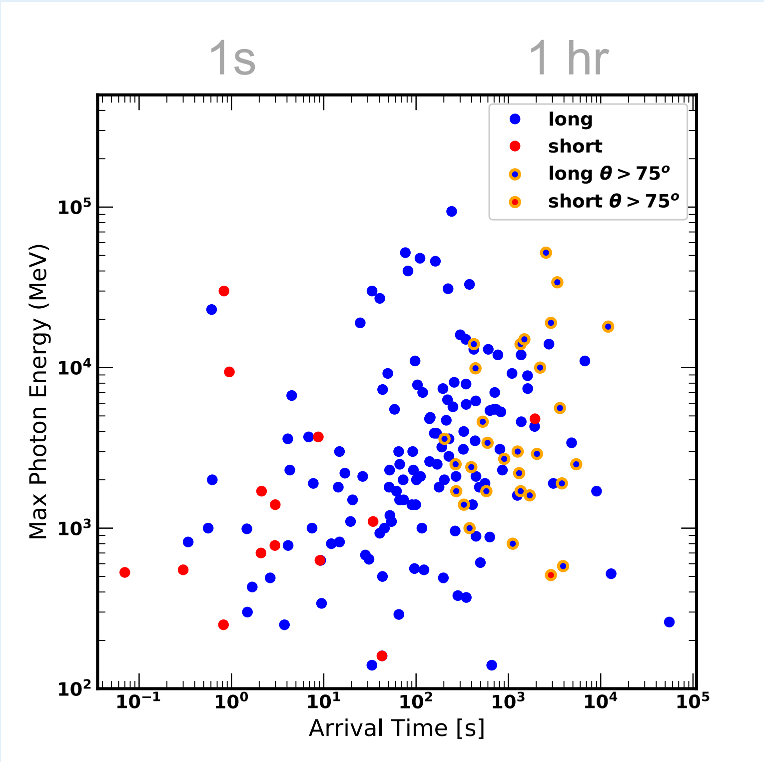
Highest-energy photons from GRBs

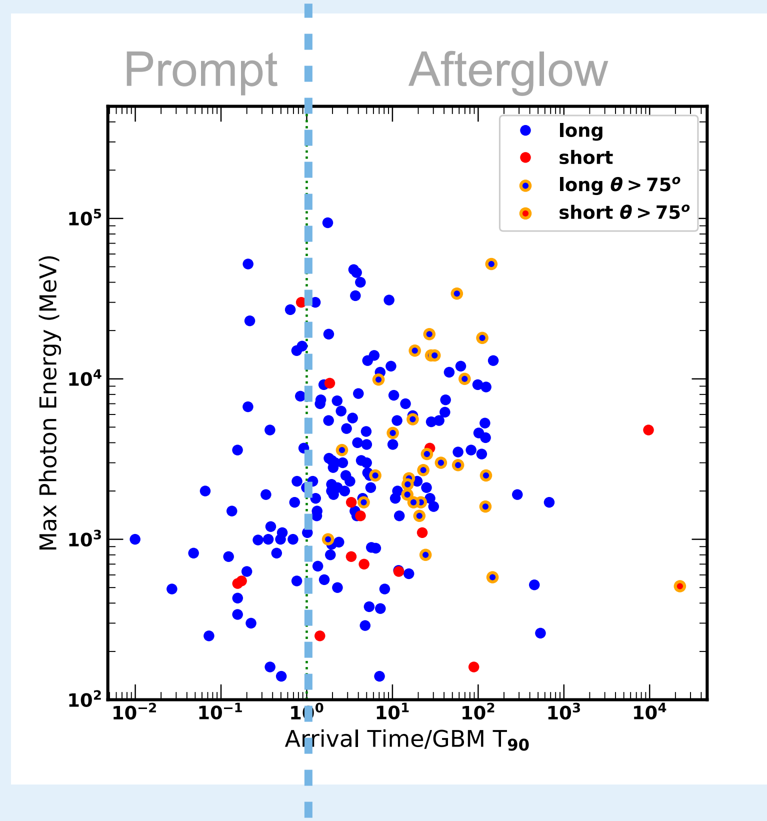
- Sharp drop @5 GeV (obs.frame)
- **<5%** of GRBs have **E > 50 GeV**
  - Record holder: **GRB 130427A**
    - **95 GeV @243 s**
    - **77 GeV @19s**
    - **34 GeV @34 ks**

- In the rest frame, the fraction falls smoothly with energy
- 10% of GRBs reach rest-frame energy >100 GeV
- Observational bias?



When do the highest-energy photons arrive?



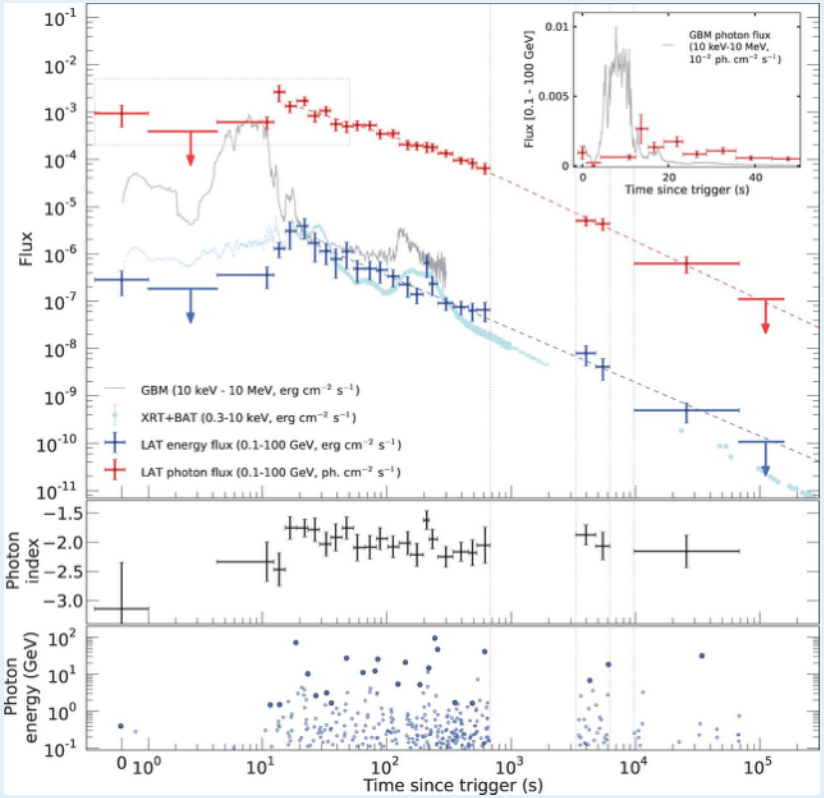


Highest-energy photons can arrive seconds or hours after trigger
→ challenge for models

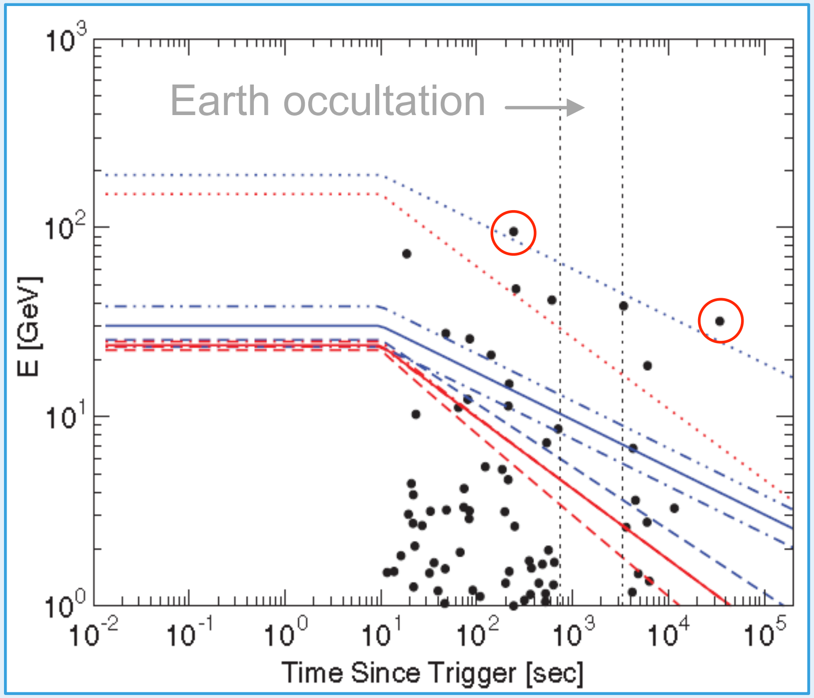
A large fraction arrives during prompt phase
→ acceleration process must be efficient

GRB 130427A

- The brightest GRB yet observed by Fermi
- High-energy emission lasted over 10 hours
- Maximum energy: 95 keV at 243 s.



Ackermann et al. 2014



LAT observations can constrain circumburst medium: wind-like density profile best fit.

Late-time energetic photons are problematic for synchrotron models.

Interpretation

Tricky to simultaneously explain all LAT results!

- Detection of HE emission implies **high Lorentz factors**
- Difficult to explain both delayed onset and long duration at the same time
  - **SSC**: difficulties with **very large delays**
    - Comptonization kicks off very quickly
  - **External Forward shock**: difficulties with **HE seen at very late times**
  - **Pair loading model**: difficulties with very large delays and large differences in **duration between LE and HE emission**
- **Closure relations**: Testing wind and ISM environments
  - ➡ Wind environments favored in a few cases, but no clear trend

Recent discovery of VHE emission

- Until this year, GRB 130427A had the record for highest energy: 95 GeV
- On January 14, MAGIC announced the detection of GRB 190114C at energies above 300 GeV in the prompt phase
- H.E.S.S. has since announced detection of GRB 180720B after 10 hours!
- Additional very high energy spectral component (comptonization?)

TITLE: GCN CIRCULAR
NUMBER: 23701
SUBJECT: MAGIC detects the GRB 190114C in the TeV energy domain
DATE: 19/01/15 01:56:36 GMT
FROM: Razmik Mirzoyan at MPI/MAGIC <Razmik.Mirzoyan@mpp.mpg.de>

R. Mirzoyan (MPP Munich), K. Noda (ICRR University of Tokyo), E. Moretti (IFAE Barcelona), A. Berti (University and INFN Torino), C. Nigro (DESY Zeuthen), J. Hoang (UCM Madrid), S. Micanovic (University of Rijeka), M. Takahashi (ICRR University of Tokyo), Y. Chai (MPP Munich), A. Moralejo (IFAE Barcelona) and the MAGIC Collaboration report:

On January 14, 2019, the MAGIC telescopes located at the Observatorio Roque de los Muchachos on the Canary island of La Palma, detected very-high-energy gamma-ray emission from GRB 190114C (Gropp et al., GCN 23688; Tyurina et al., GCN 23690, de Ugarte Postigo et al., GCN 23692, Lipunov et al. GCN 23693, J. Selsing et al. GCN 23695). The observation was triggered by the Swift-BAT alert and it started about 50s after the Swift T0: 20:57:03.19.

The GRB data of MAGIC shows a clear excess of gamma-ray events with the significance >20 sigma in the first 20 min (starting at T0+50s) for energies >300GeV. The relatively high detection threshold is due to the large zenith angle of observations (~60 deg.) and the presence of partial moon. After the first bright flash the source is quickly fading.

GRBs now detected across the entire electromagnetic spectrum!

A new window on the Universe

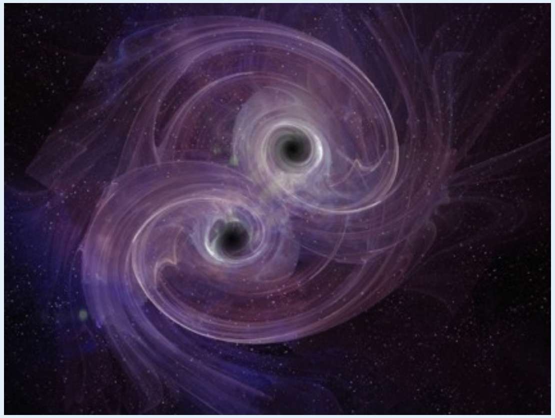
4 km

3 km

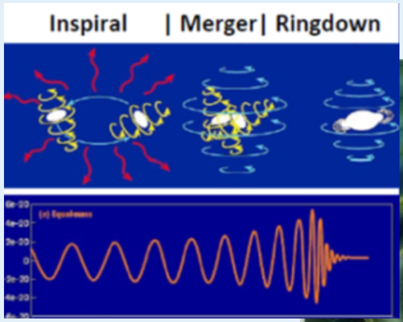
Expected transient GW sources

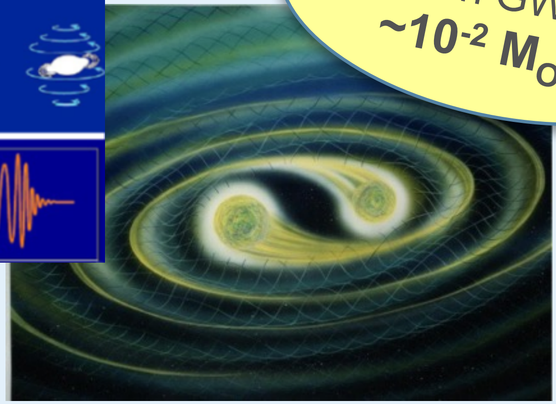
"Transient GW signal": signal with duration significantly shorter than the observation time and that cannot be re-observed

Compact Binary Coalescence (CBC)



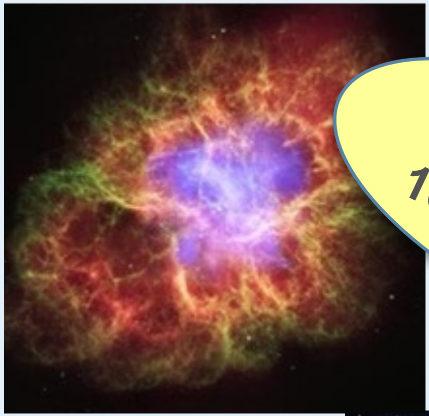
binary system of neutron stars (NS) and/or stellar-mass black-hole (BH)





Energy emitted in GW $\sim 10^{-2}\ M_O\ c^2$

Core-collapse of massive stars



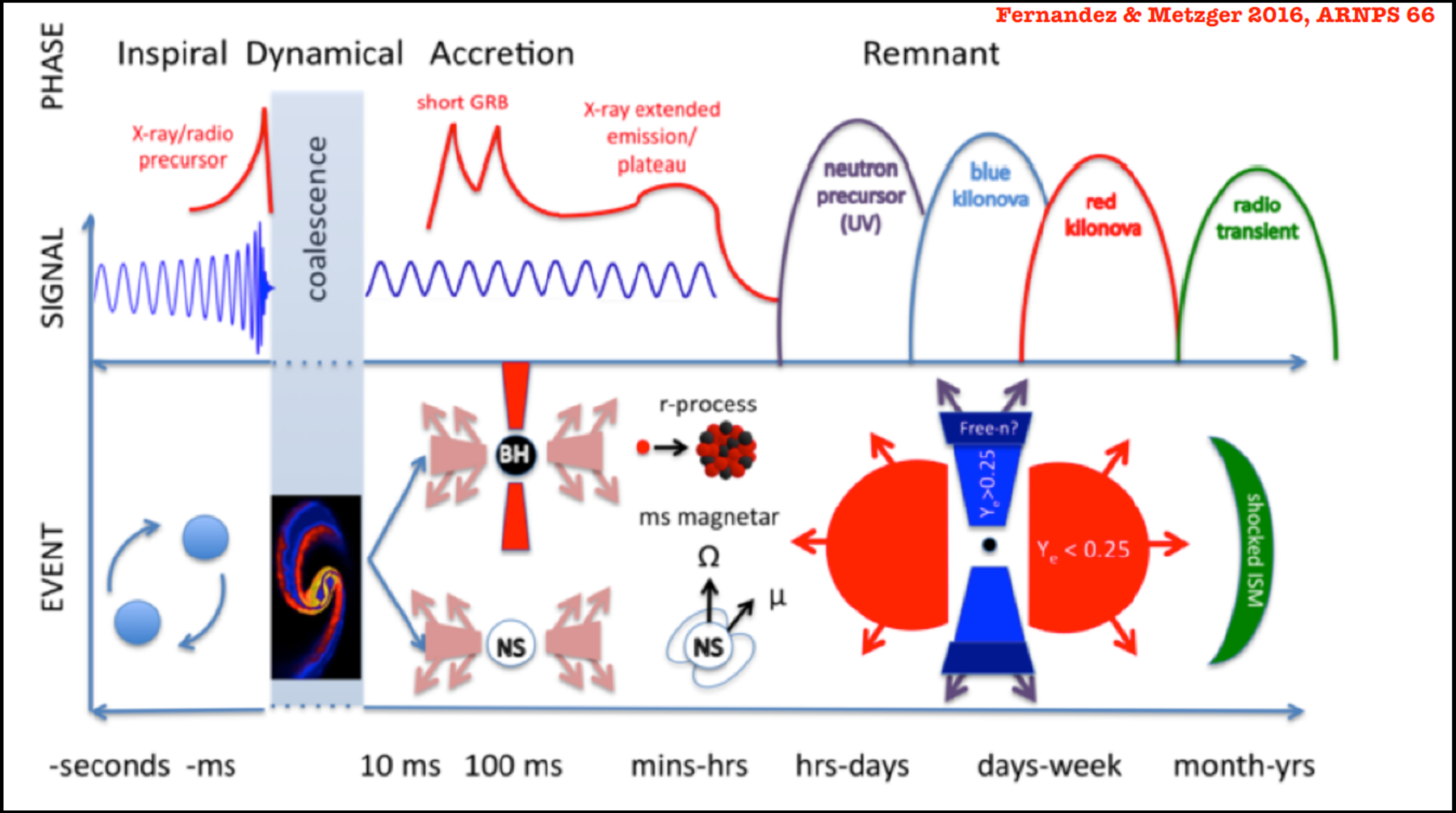
Energy emitted in GW uncertain $10^{-8} – 10^{-4}\ M_O\ c^2$

Isolated neutron-star

NS-NS NS-BH Merger: a global picture

EM

GW



Need for multi-wavelength observatories which cover a large region of the sky and repeat observations over different timescales

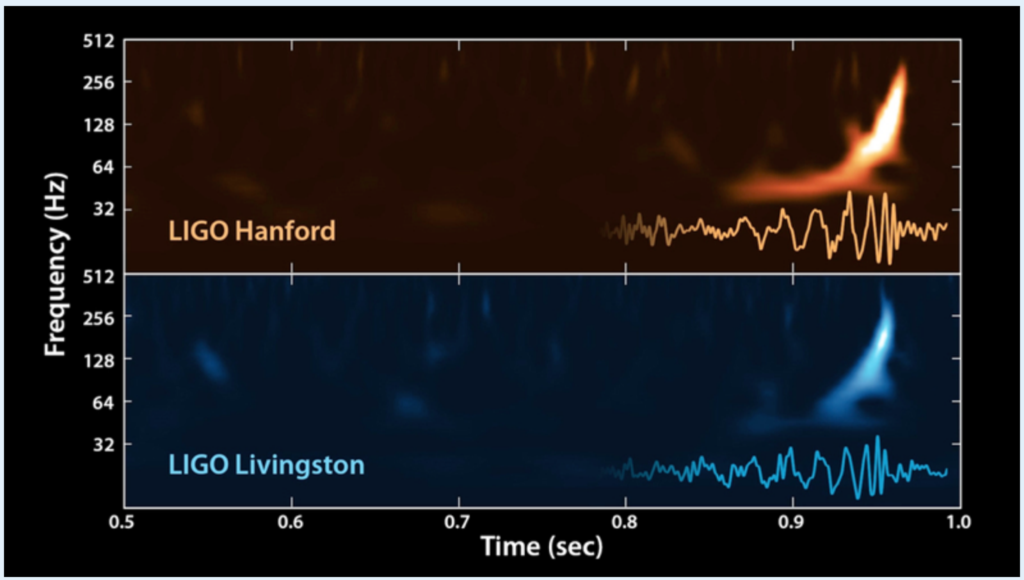
150914: The beginning of the GW era

Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

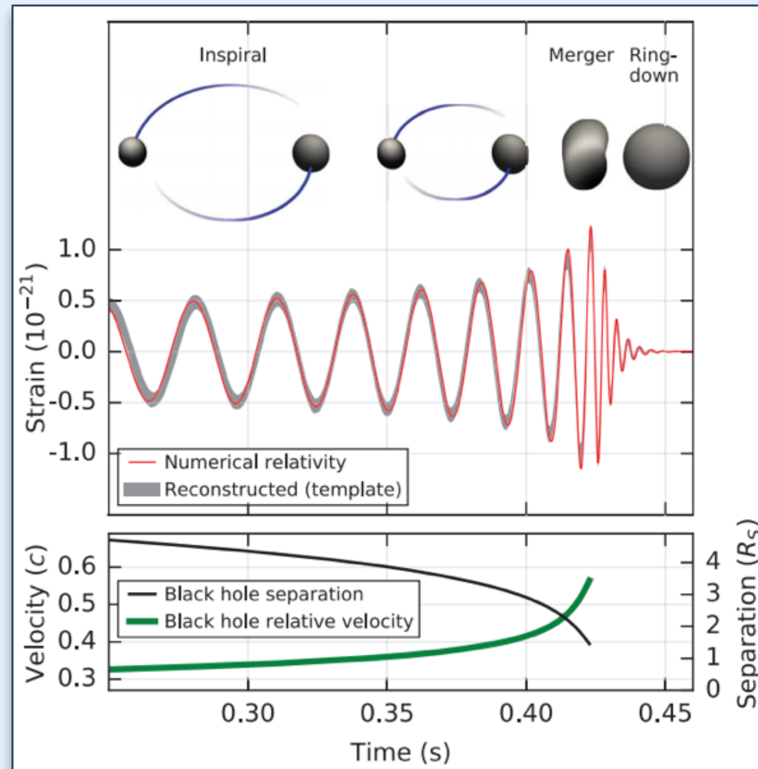
Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)



Credit Caltech/MIT/LIGO Lab

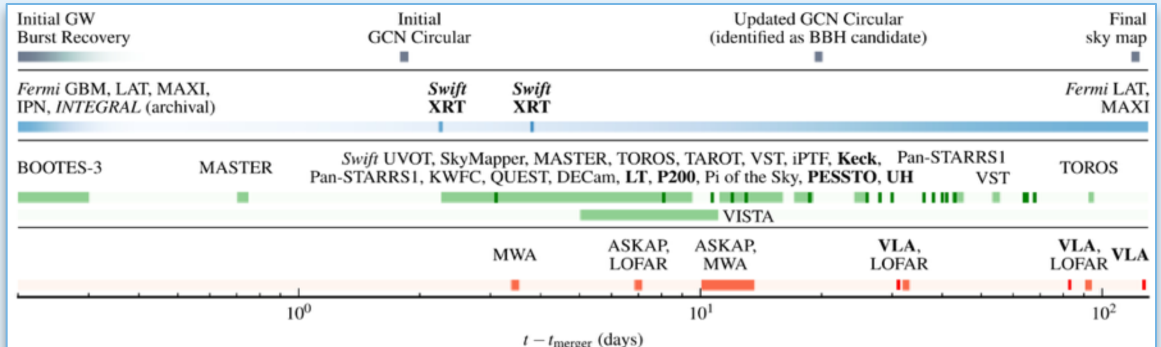


Abbott+2016

EM follow-up of GW150914

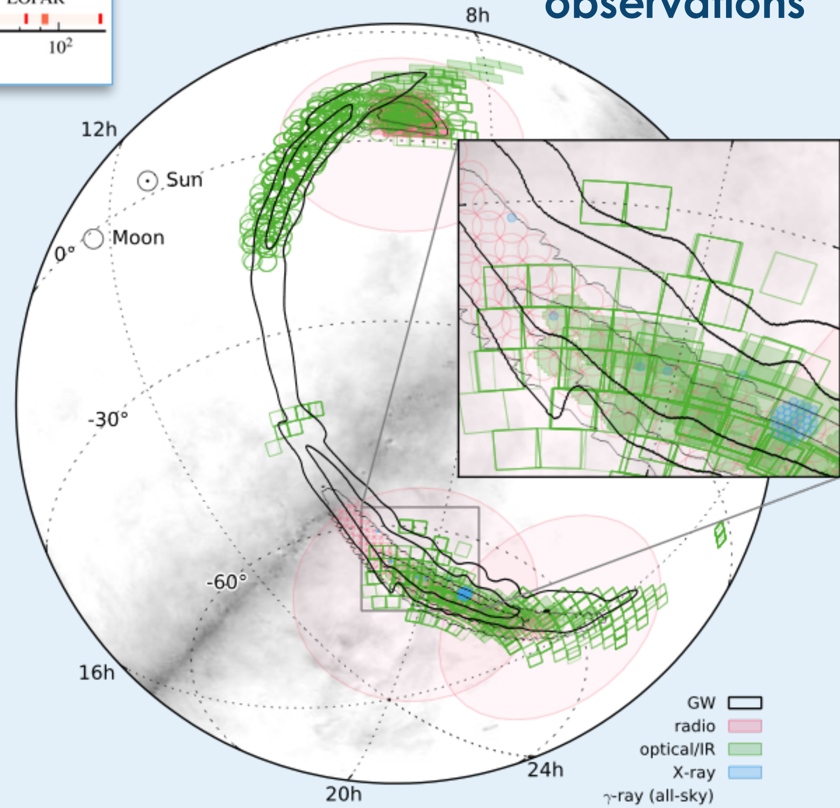
No coincident triggers from space-based observatories!
→ Offline searches

Follow-up observations reported by **25 teams** via **private GCN circulars**



Timeline of observations

Skymap of observations



- Event nature: **Binary black hole (BBH) merger**
  - Little expectation of a detectable electromagnetic (EM) signature

➔ But: **Milestone achieved**!

  - **First broadband campaign** to search for a counterpart of a LIGO source
  - Broad capabilities of the transient astronomy community and **observing strategies**

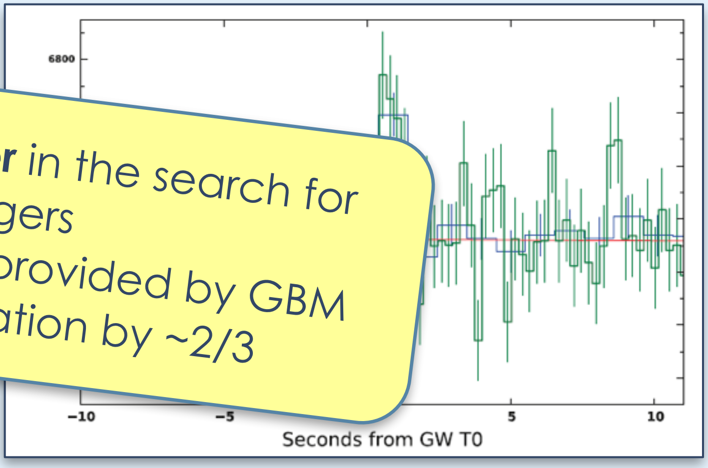
Abbott+2016

GW150914-GBM

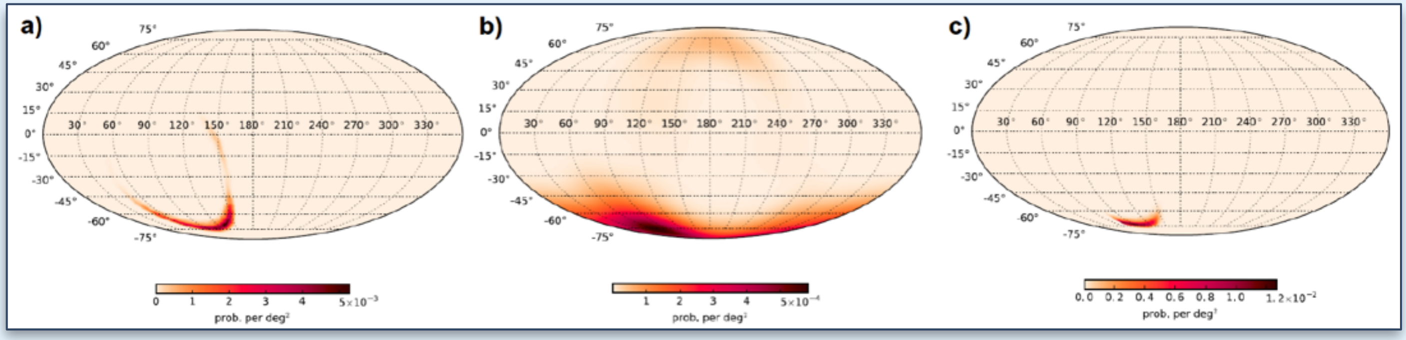
- **Fermi-GBM "Targeted" search** around GW150914:
  - **Best candidate**: Hard transient **0.4 s after GW trigger**
  - **Association significance: 2.9 σ**
  - **Classified as short GRB**
    - Spec … for short GRBs but f … GRB
  - **Localizat … spacecra**
- Association **largely debated**:
  - Lack of corroboration by other experiments (Integral, AGILE, etc…)
  - Nature of the LIGO event was BBH merger

Fermi proves to be **an ideal partner** in the search for EM signals of GW triggers
➔ Even a **large uncertainty region** provided by GBM helps shrinking the LIGO localization by ~2/3

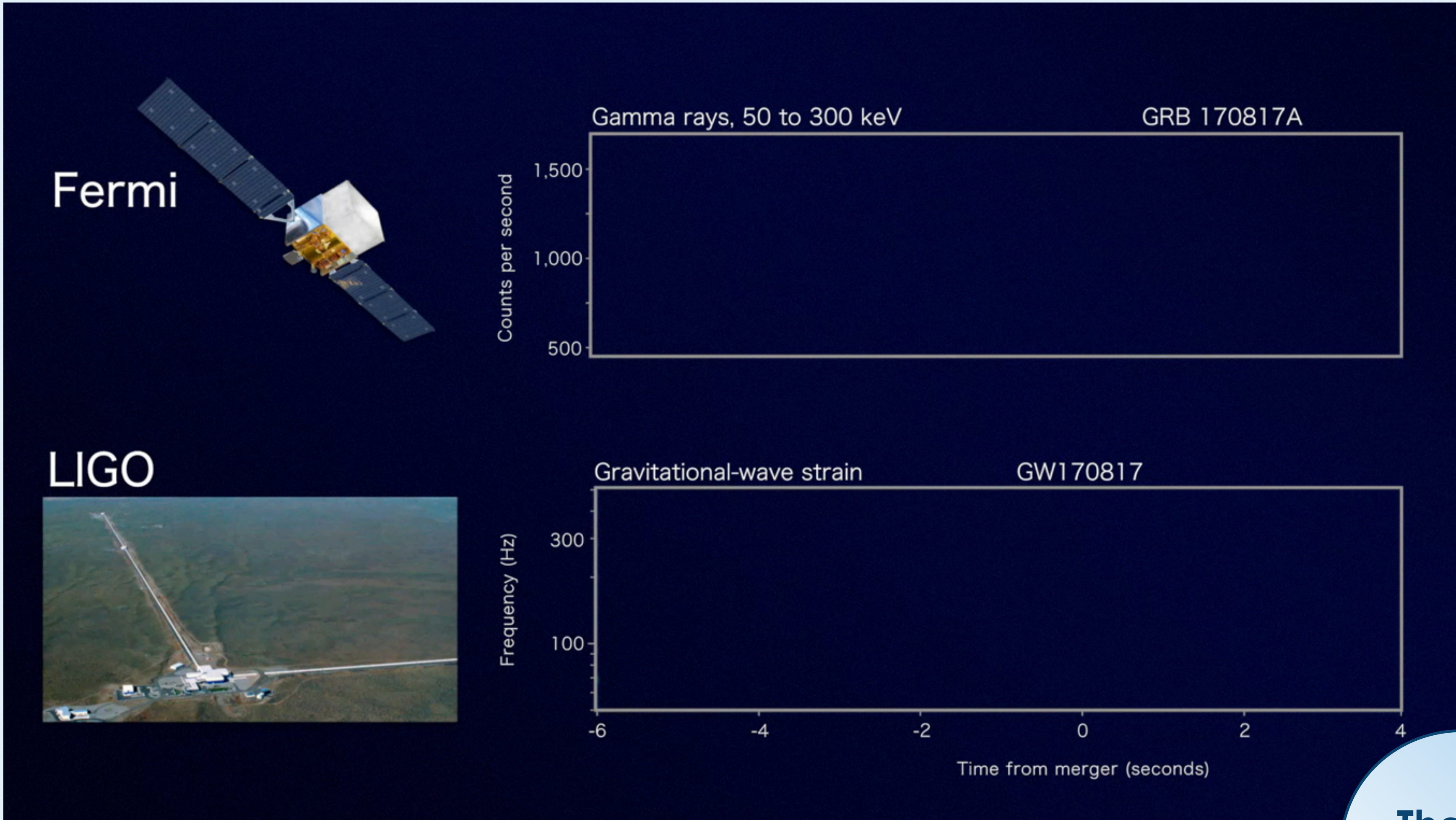
Summed GBM LC



Connaughton+2016

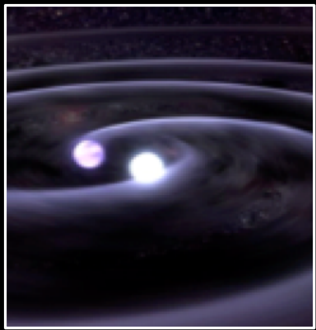


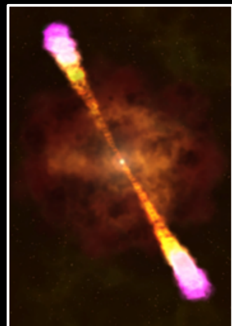
August 17, 2017



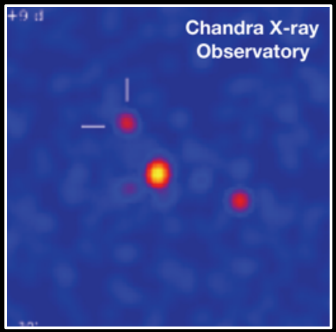
Credit: LIGO; Virgo; Fermi; NASA/DOE; NSF; EGO; ESA

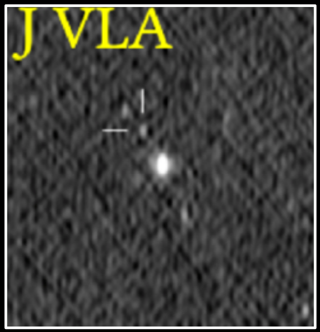
Theory confirmed!





```
///////////////////////////////////
TITLE:            GCN/FERMI NOTICE
NOTICE_DATE:      Thu 17 Aug 17 12:41:20 UT
NOTICE_TYPE:      Fermi-GBM Alert
RECORD_NUM:       1
TRIGGER_NUM:      524666471
GRB_DATE:         17982 TJD;    229 DOY;    17/08/17
GRB_TIME:         45666.47 SOD {12:41:06.47} UT
TRIGGER_SIGNIF:   4.8 [sigma]
TRIGGER_DUR:      0.256 [sec]
E_RANGE:          3-4 [chan]    47-291 [keV]
ALGORITHM:        8
```





NS merger

Short GRB

GBM GCN notice

X-ray afterglow

Radio

T_0 +1.7s +16s +45min +6hrs +11 hrs +9 days +16 days

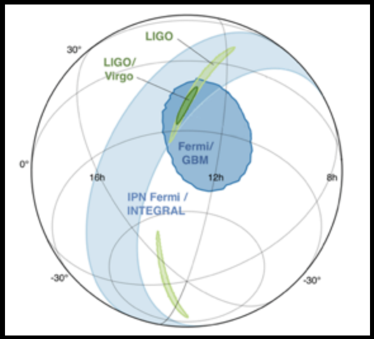
LVC GCN Circular

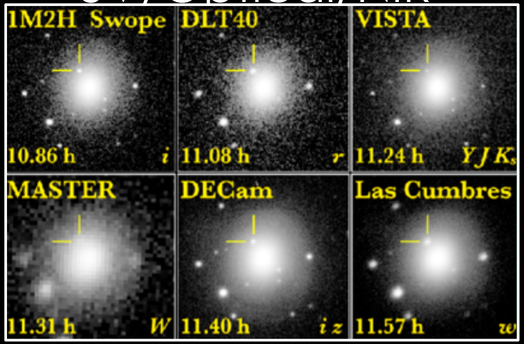
LHV sky localization

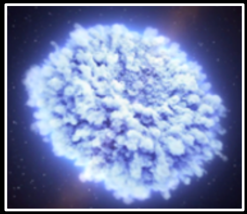
UV/Optical/NIR

```
///////////////////////////////////
TITLE:   GCN CIRCULAR
NUMBER:  21505
SUBJECT: LIGO/Virgo G298048: Fermi GBM trigger
524666471/170817529: LIGO/Virgo Identification of
a possible  gravitational-wave counterpart
DATE:    17/08/17 13:21:42 GMT
FROM:    Reed Clasey Essick at MIT
<ressick@mit.edu>

The LIGO Scientific Collaboration and the Virgo
Collaboration report:
The online CBC pipeline (gstlal) has made a
preliminary identifi-cation of a GW candidate
associated with the time of Fermi GBM trigger
524666471/170817529 at gps time 1187008884.47 (Thu
Aug 17 12:41:06 GMT 2017) with RA=186.62deg
Dec=-48.84deg and an error radius of 17.45deg.
The candidate is consistent with a neutron star
binary coalescence with False Alarm Rate of
~1/10,000 years.
```







40 Mpc away!

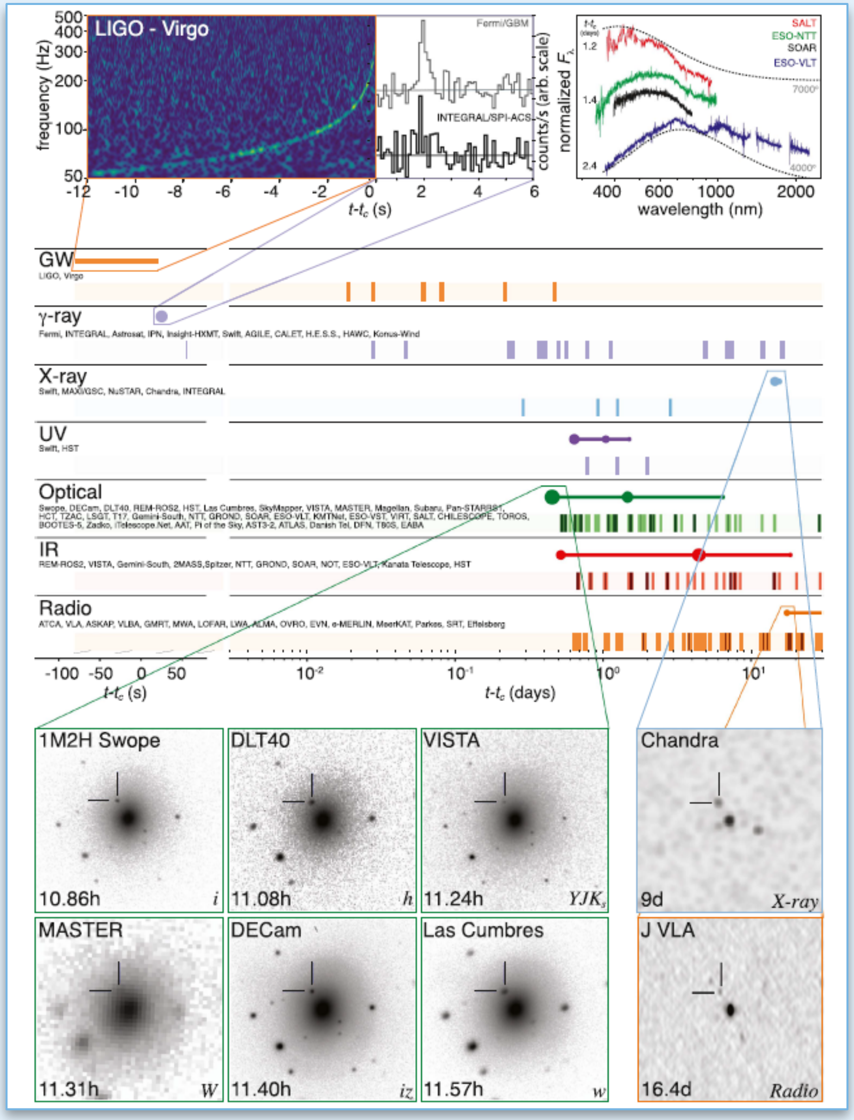
Abbott+2017

The first multi-messenger paper

The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

Multi-messenger Observations of a Binary Neutron Star Merger

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)



Science results

Fundamental physics/Cosmology

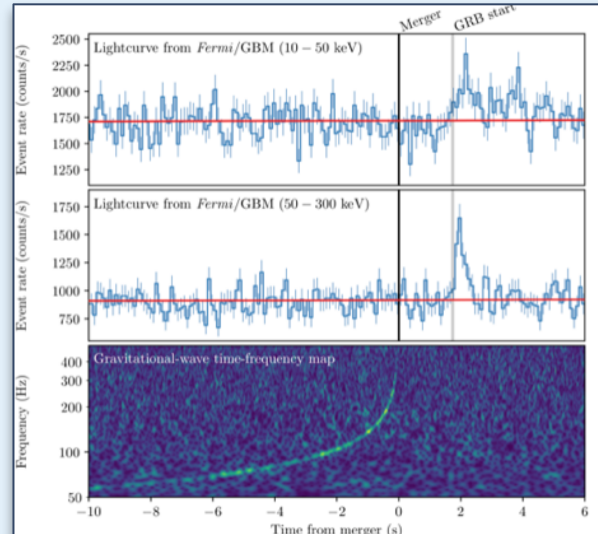
1. Direct measurement of **the speed of gravity**
    - Is the same as the speed of light within one part in one quadrillion
2. Test of **equivalence principle:** Gravitational mass = inertial mass
3. Measure of cosmological constant H0

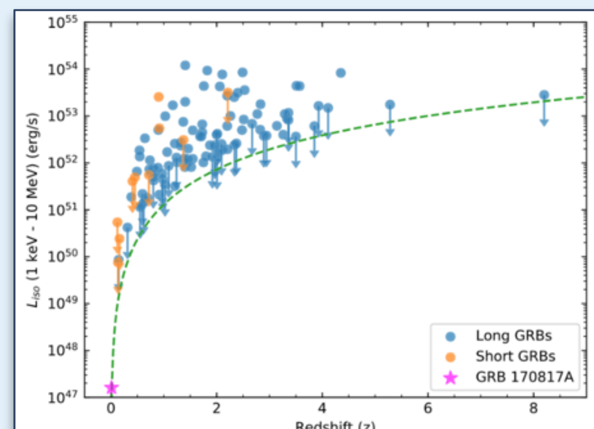
Probe of the **NS equation of state**:

- Joint GW/short GRB observations constrain the maximum mass of a NS

Investigation of the emission physics of relativistic jets and the **engine** that produces **short GRBs**

- GRB 170817A is **extremely under-luminous**
- Very late radio high-resolution imaging unveiling structured jet viewed off-axis





GW170817/GRB170817A: Predictions vs observations

Fermi Gamma-ray Space Telescope

Predicted

- Merging NS are the progenitors of sGRB
- GW and sGRB are separated by ~sGRB duration
- Kilonova producing heavy elements
- Speed of light = speed of gravity

* GBM observations predicted detection sooner than generally expected

Observed

- GWs from merging NS followed by a sGRB, 1.7 s later
- Hours later – kilonova
- > 1 week, X-ray and radio counterparts

Unexpected

- GW detection from NS merger met optimistic predictions*
- Joint GW/sGRB detection was earlier than generally expected*
- GRB 170817A was dim despite being close
- Unusual time-history for a sGRB: hard spike followed by a softer tail
- Optical, X-ray, and radio counterparts brightened instead of fading
- Bright UV counterpart was not predicted by kilonova models

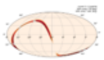
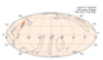
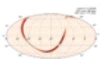
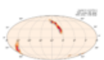
O3 is here!

- Start: 1st of April 2019
- LVC public GW Alerts
  - 22 detection candidates GraceDB
    - 18 BBH, 1 BNS, 3 Other
  - No EM counterpart reported yet
  - Fermi does follow-up analysis for every trigger

LIGO/Virgo Public Alerts

Detection candidates: 20

SORT: EVENT ID (A-Z)

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S190720a	BBH (99%), Terrestrial (1%)	July 20, 2019 00:08:36 UTC	GCN Circulars Notices | VOE		1 per 8.3367 years	
S190718y	Terrestrial (98%), BNS (2%)	July 18, 2019 14:35:12 UTC	GCN Circulars Notices | VOE		1.1514 per year	
S190707q	BBH (>99%)	July 7, 2019 09:33:26 UTC	GCN Circulars Notices | VOE		1 per 6018.9 years	
S190706ai	BBH (99%), Terrestrial (1%)	July 6, 2019 22:26:41 UTC	GCN Circulars Notices | VOE		1 per 16.673 years	
S190701ah	BBH (93%), Terrestrial (7%)	July 1, 2019 20:33:06 UTC	GCN Circulars Notices | VOE		1 per 1.6543 years	

GCN Circulars 21 Jul 2019 11:25 GC

To: magaxe@kth.se

LIGO/Virgo S190720a: No counterpart candidates in Fermi-LAT observations

TITLE: GCN CIRCULAR
NUMBER: 25135
SUBJECT: LIGO/Virgo S190720a: No counterpart candidates in Fermi-LAT observations
DATE: 19/07/21 09:15:18 GMT
FROM: Magnus Axelsson at Stockholm U. <magaxe@kth.se>

M. Axelsson (KTH and Stockholm Univ.) reports on behalf of the Fermi-LAT Collaboration:

We have searched data collected by the Fermi Large Area Telescope (LAT) on July 20, 2019, for possible high-energy (E > 100 MeV) gamma-ray emission in spatial/temporal coincidence with the LIGO/Virgo trigger S190720a (GCN 25115).

Future GW runs

Improved localization!

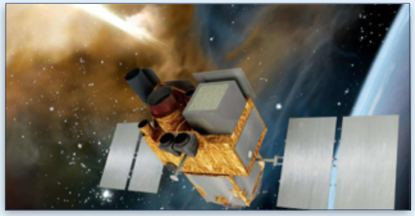
Currently funded GRB missions:

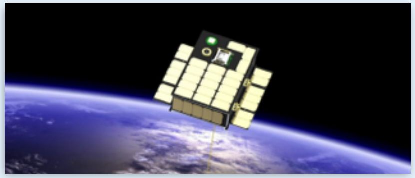
SVOM (2021)

BurstCube (2021)

Glowbug (2023)

Fermi extended to 2022 (with planning >2023)





Conclusion

- GRBs can be seen across the electromagnetic spectrum - and with GW
- Probe emission physics, but also have wider impact, e.g., the extragalactic background light and Lorentz invariance
- The LAT catalog is the largest compilation of high-energy detections
  - A lot of tables and figures
  - Discussion of prospects for GRB detections at VHE (with CTA)
- LAT FITS file is publicly available via HEASARC
- Combined GW-EM observations of (short) GRBs strengthen both fields, and give important scientific return
- Looking forward to new discoveries during O3!

Thank you!