GRBs and Gravitational Waves

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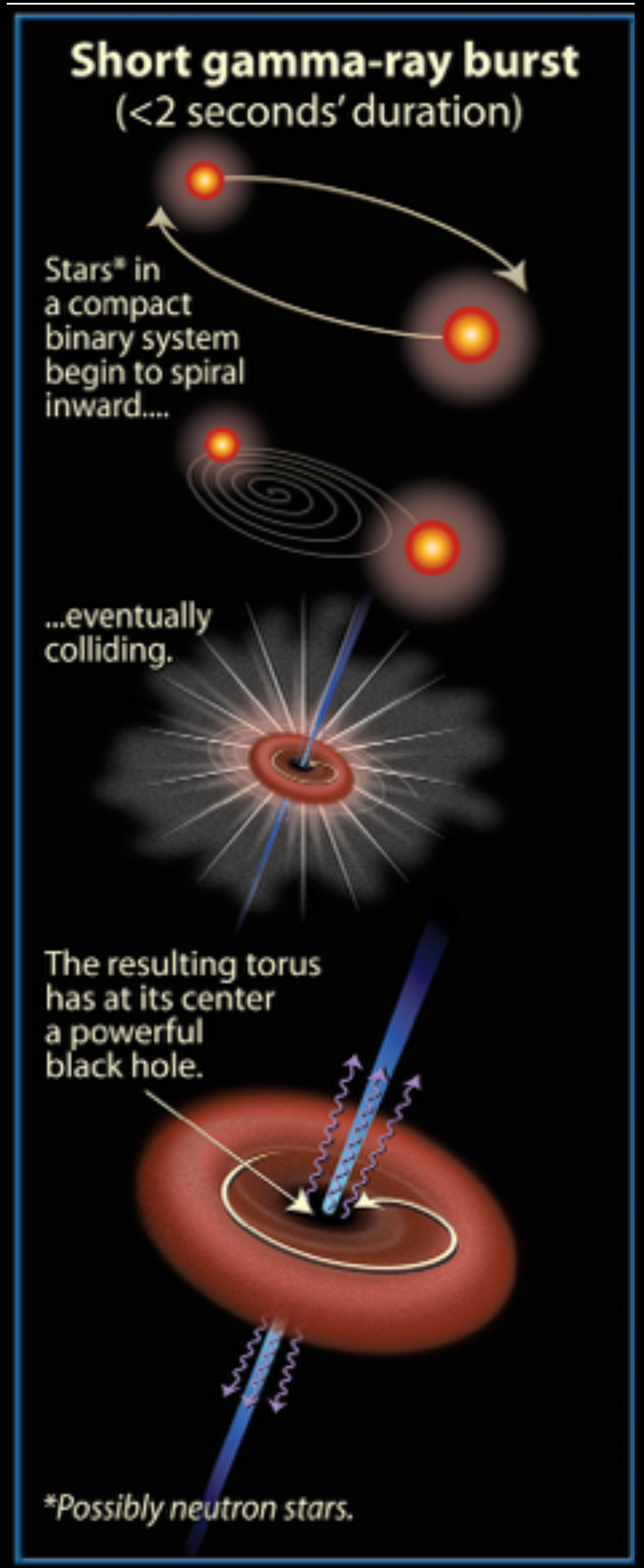
Fermi
Gamma-ray Space Telescope

BNS—GRB Association

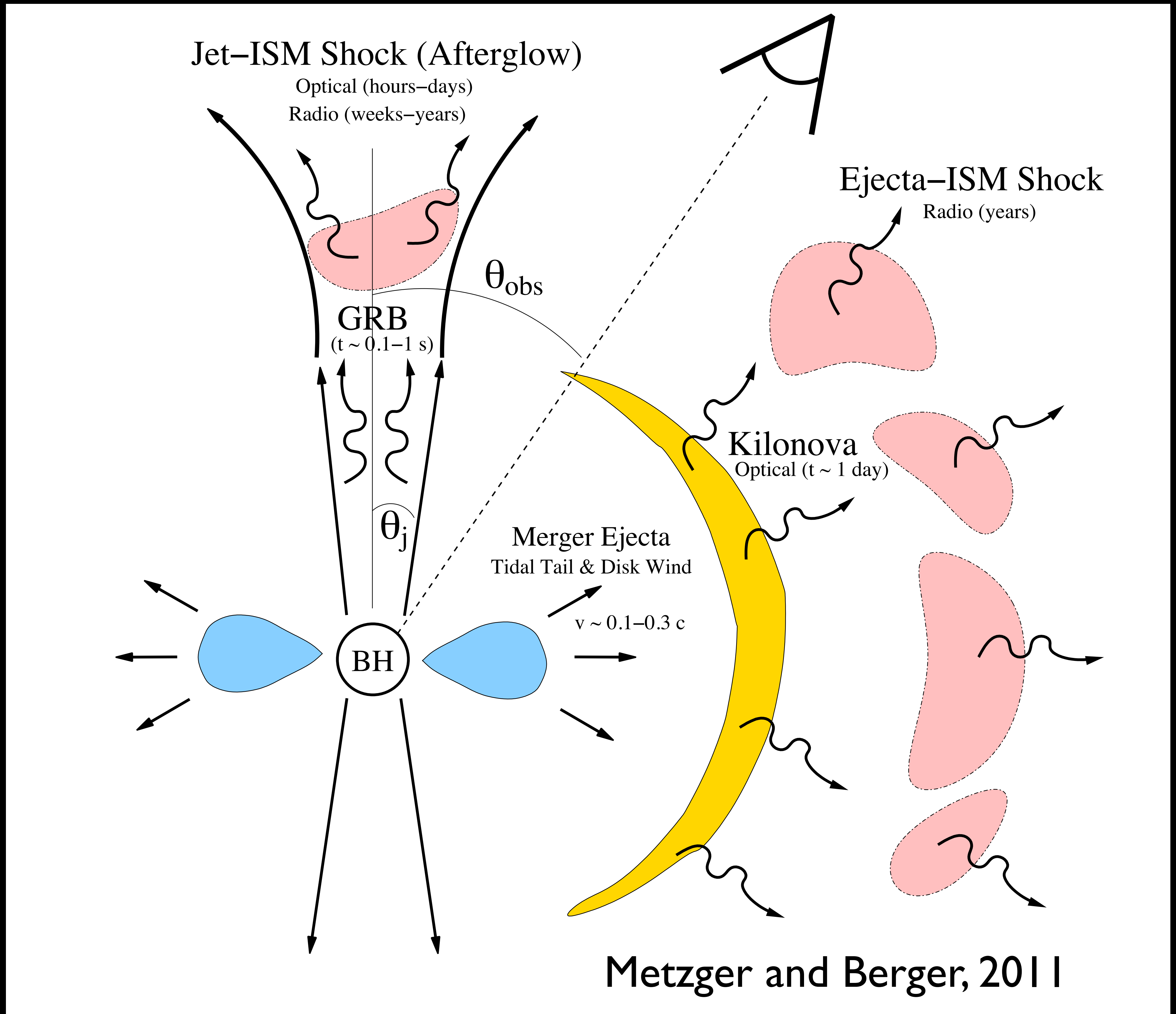


GW

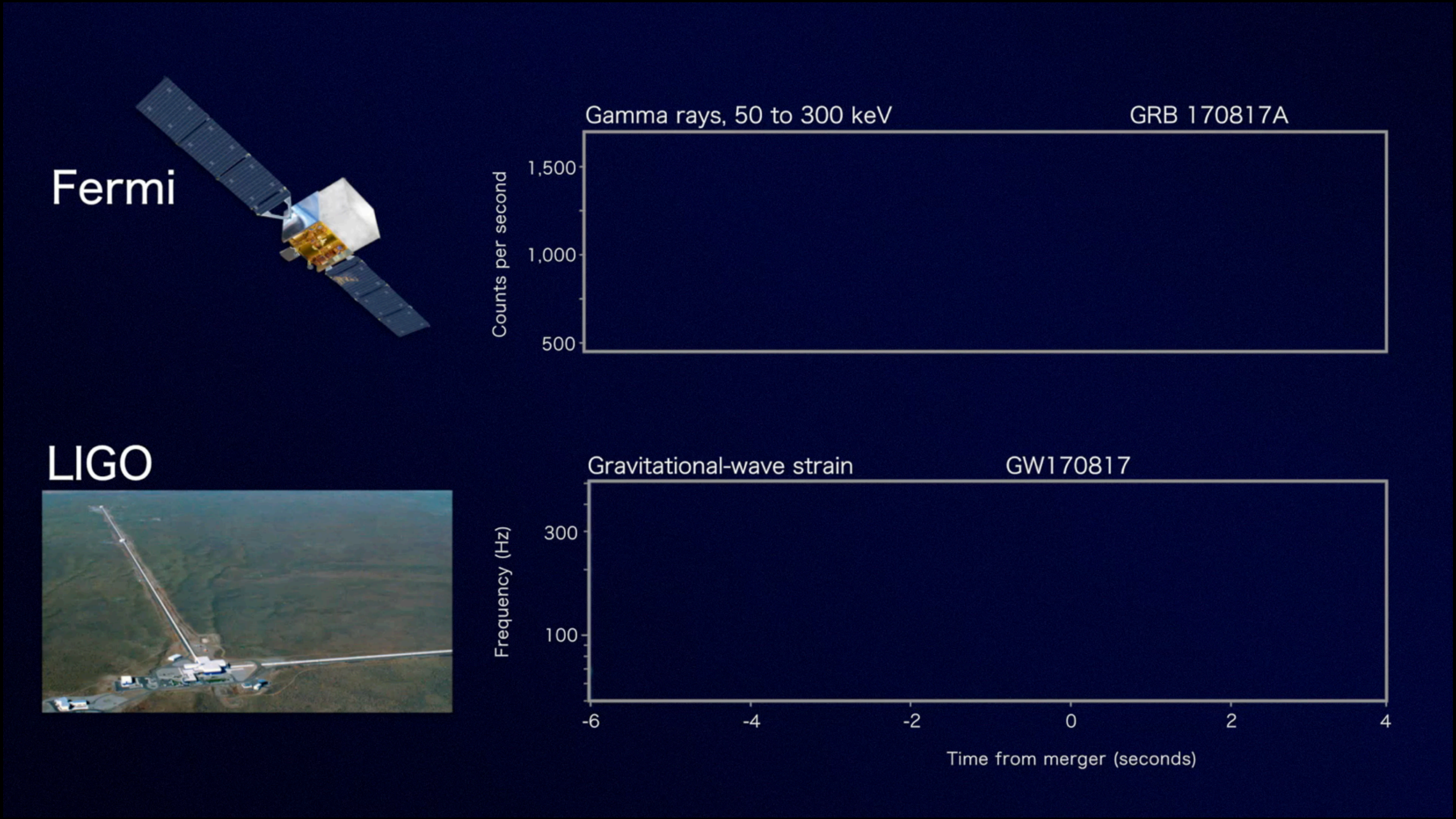
- In-spiral confirms CBC progenitor model
- Information about binary system parameters
- precise merger time
- standard candle -> luminosity distance

EM

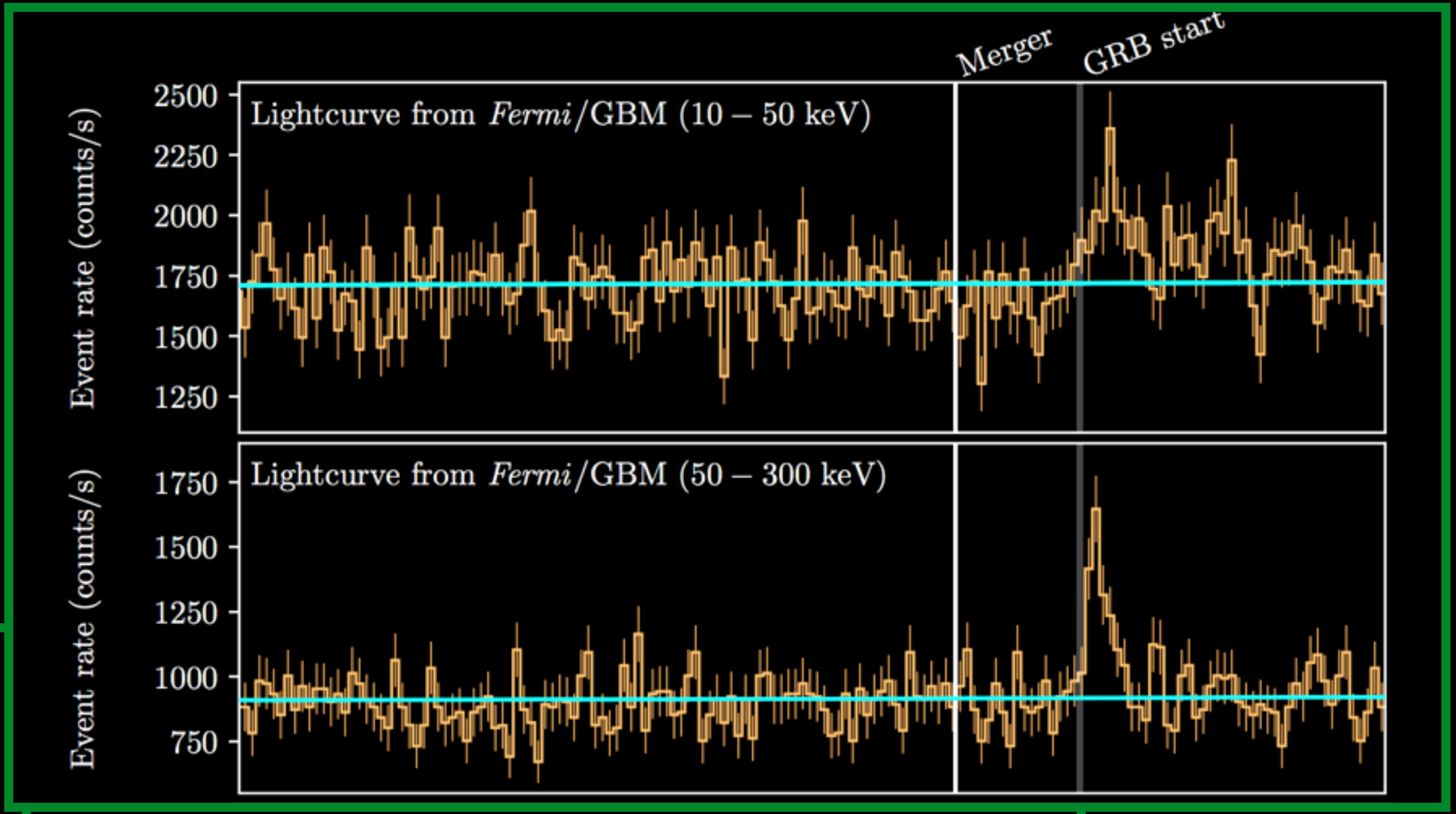
- Detection confidence
- EM energetics
- X-ray or optical afterglow gives precise location
- Breaks degeneracy in binary parameter estimation
- Host galaxy/redshift
- Local environment information

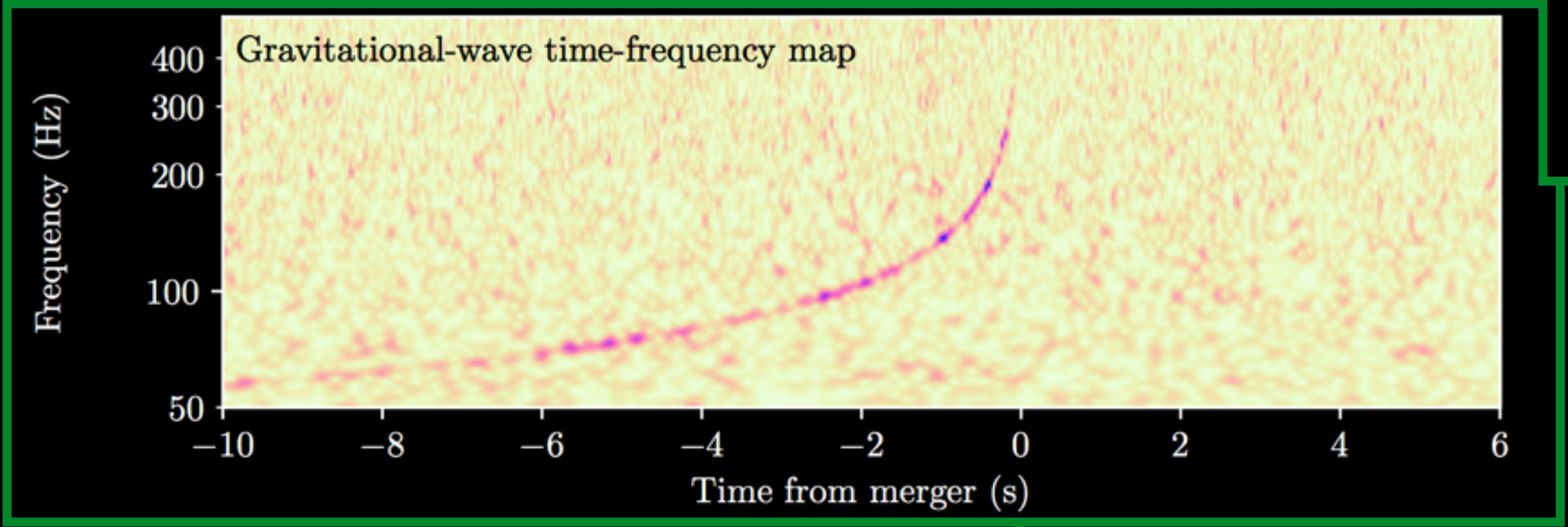


GW170817—GRB 170817A



August 17: Timeline of Events (Abridged)





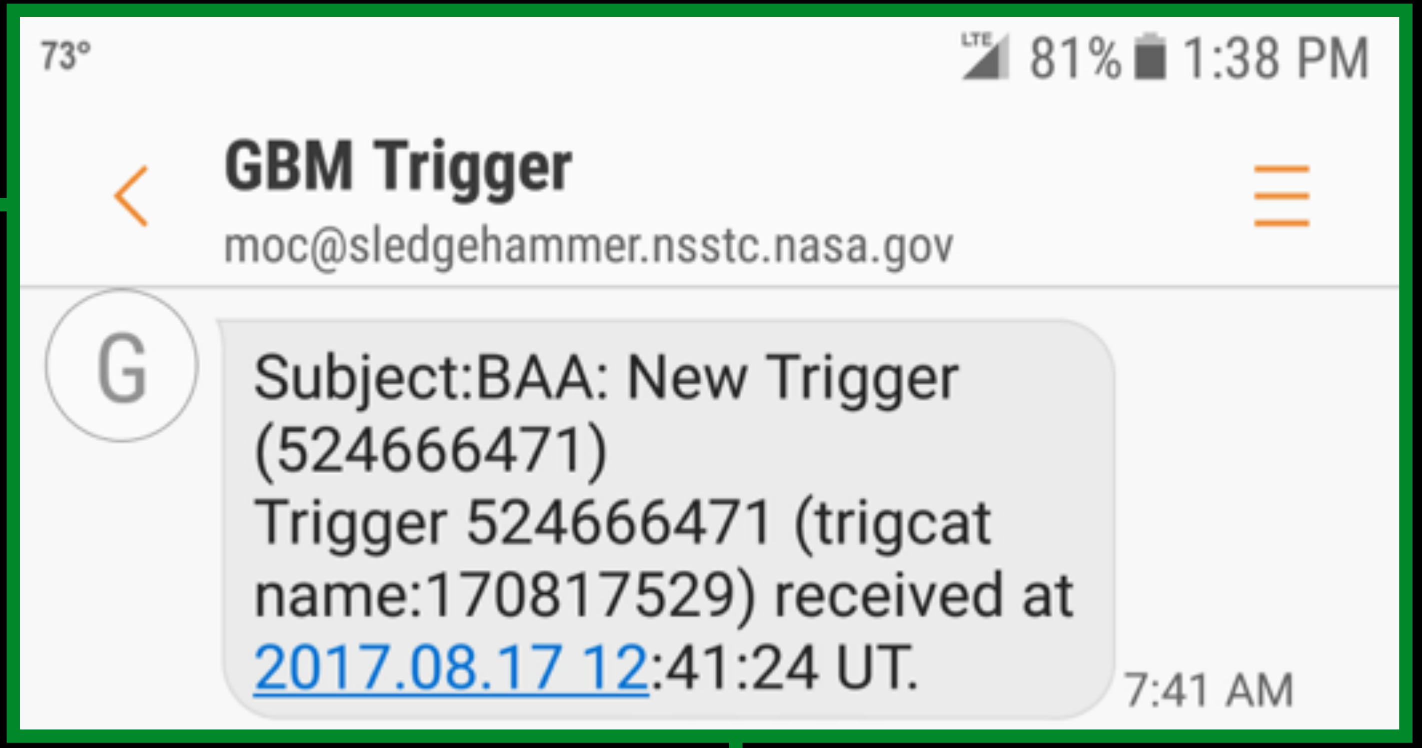
T_{GW}

T_{GW} +1.7 s

GBM Trigger - The **First** Notice

https://gcn.gsfc.nasa.gov/other/524666471.fermi

```
//////////////////////////////////////////////////////////////////////
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
DETECTORS:       0,1,1, 0,0,1, 0,0,0, 0,0,0, 0,0,
LC_URL:          http://heasarc.gsfc.nasa.gov/FTP/fermi/data/gbm/triggers/2017/bn170817529/quicklook/glg_lc_medres34_bn170817529.gif
COMMENTS:        Fermi-GBM Trigger Alert.
COMMENTS:        This trigger occurred at longitude,latitude = 321.53,3.90 [deg].
COMMENTS:        The LC_URL file will not be created until ~15 min after the trigger.
```



First On-board Localization and classification

+16 s

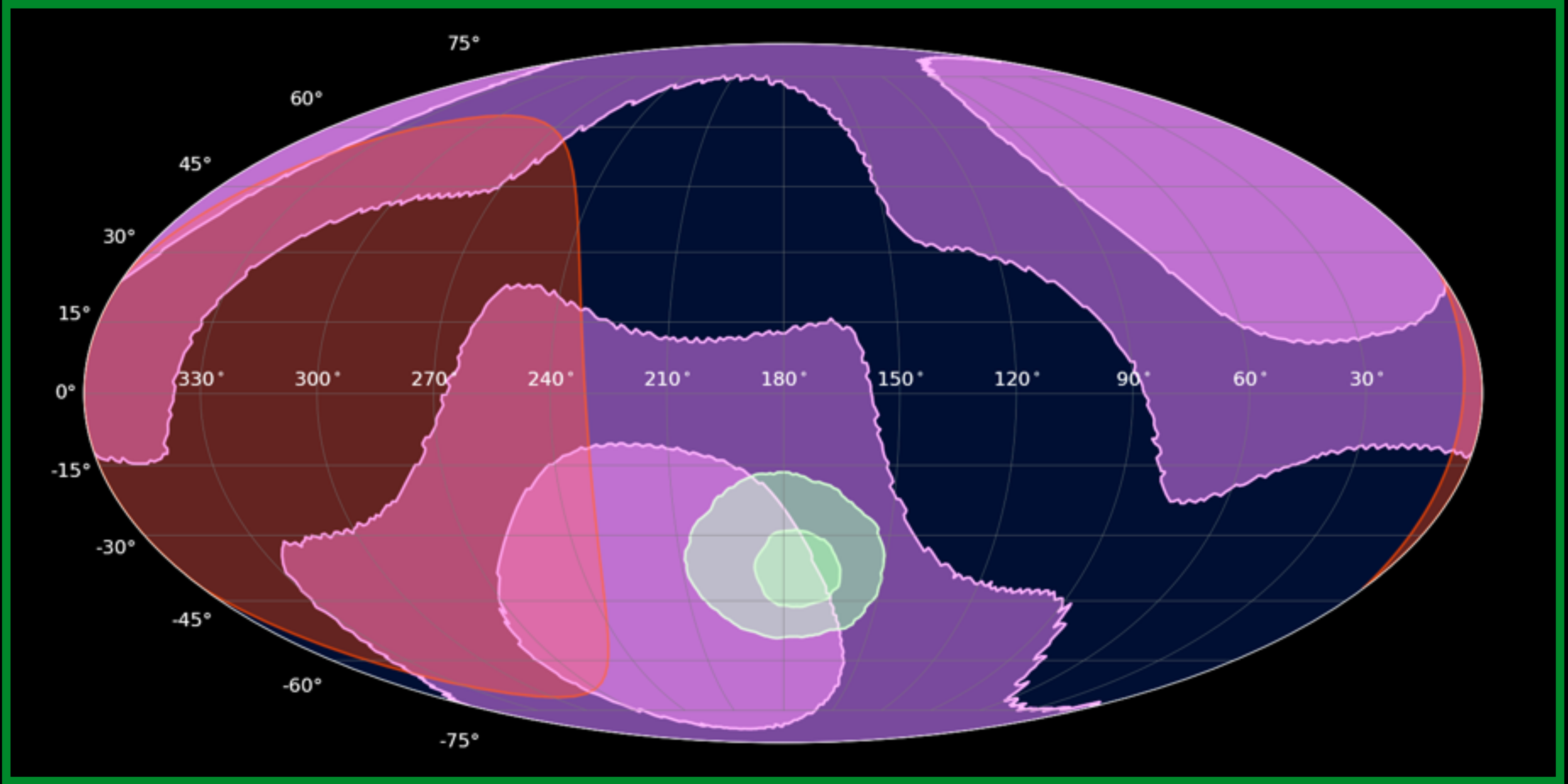
+27 s

GBM Localization

Subject:[gbm+ligo] WAKE UP
Date: Thu, 17 Aug 2017 13:23:13 +0000
From: Littenberg, Tyson B. (MSFC-ST12) <[redacted]>
To:GBM+LIGO <[redacted]>

ivo://nasa.gsfc.gcn/Fermi#GBM_Gnd_Pos_2017-08-17T12:41:06.47_524666471_57-431

this morning's GBM trigger has a friend....



WAKE UP!

Automated On-ground Localization

LIGO Report on GW Trigger Coincident with GRB

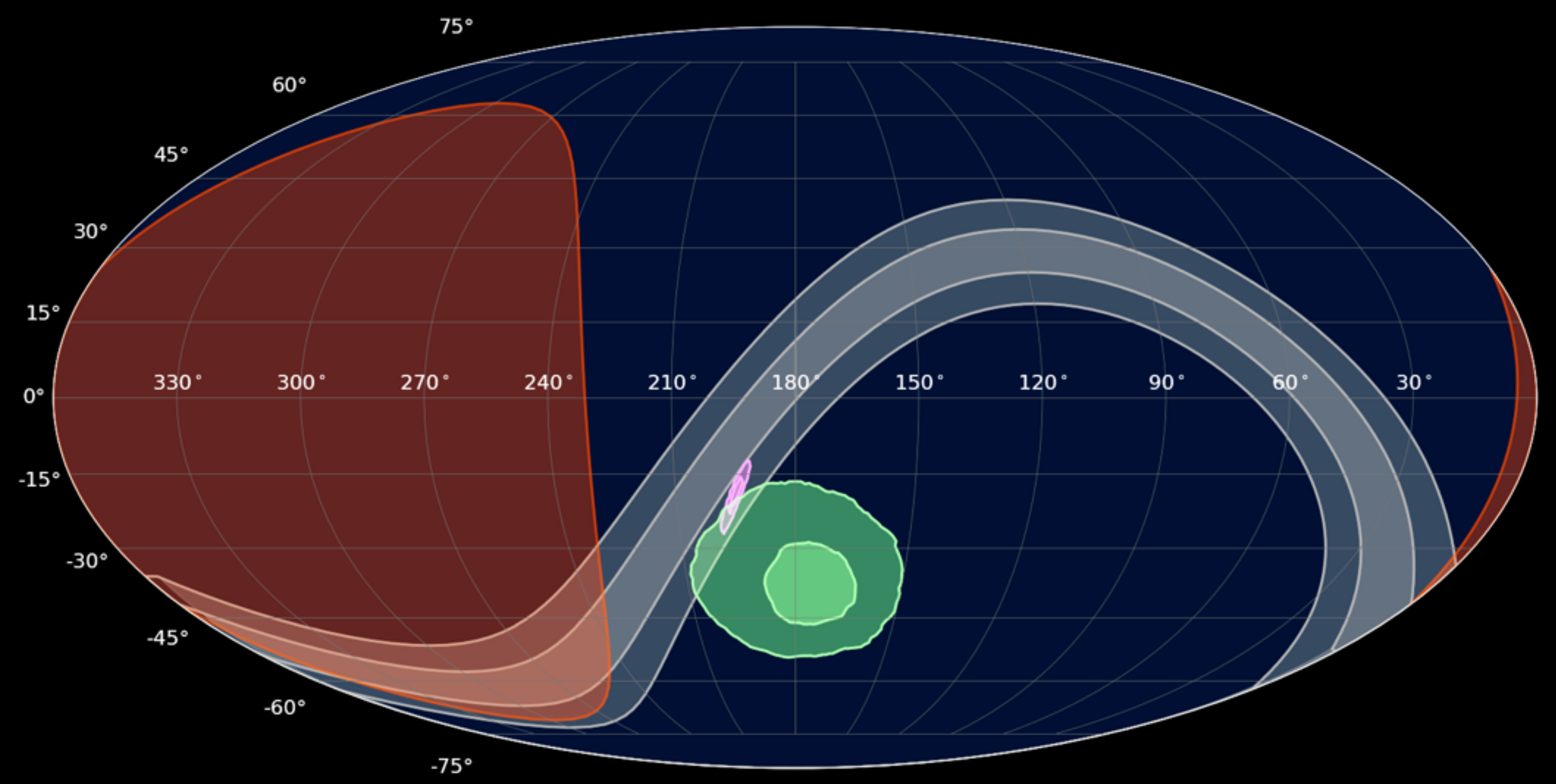
Human-in-the-Loop Localization

+40 s

+40 min

+45 min

More Reporting/Updates



GBM Report on localization and short duration GRB

INTEGRAL SPI-ACS report of a coincident weak GRB signal

Pre-planned LV-EM telecom

Mistaken report on IceCube neutrino candidates

First LIGO/Virgo sky map using all 3 detectors

IPN report on timing annulus between GBM & SPI-ACS

+67 min

+77 min

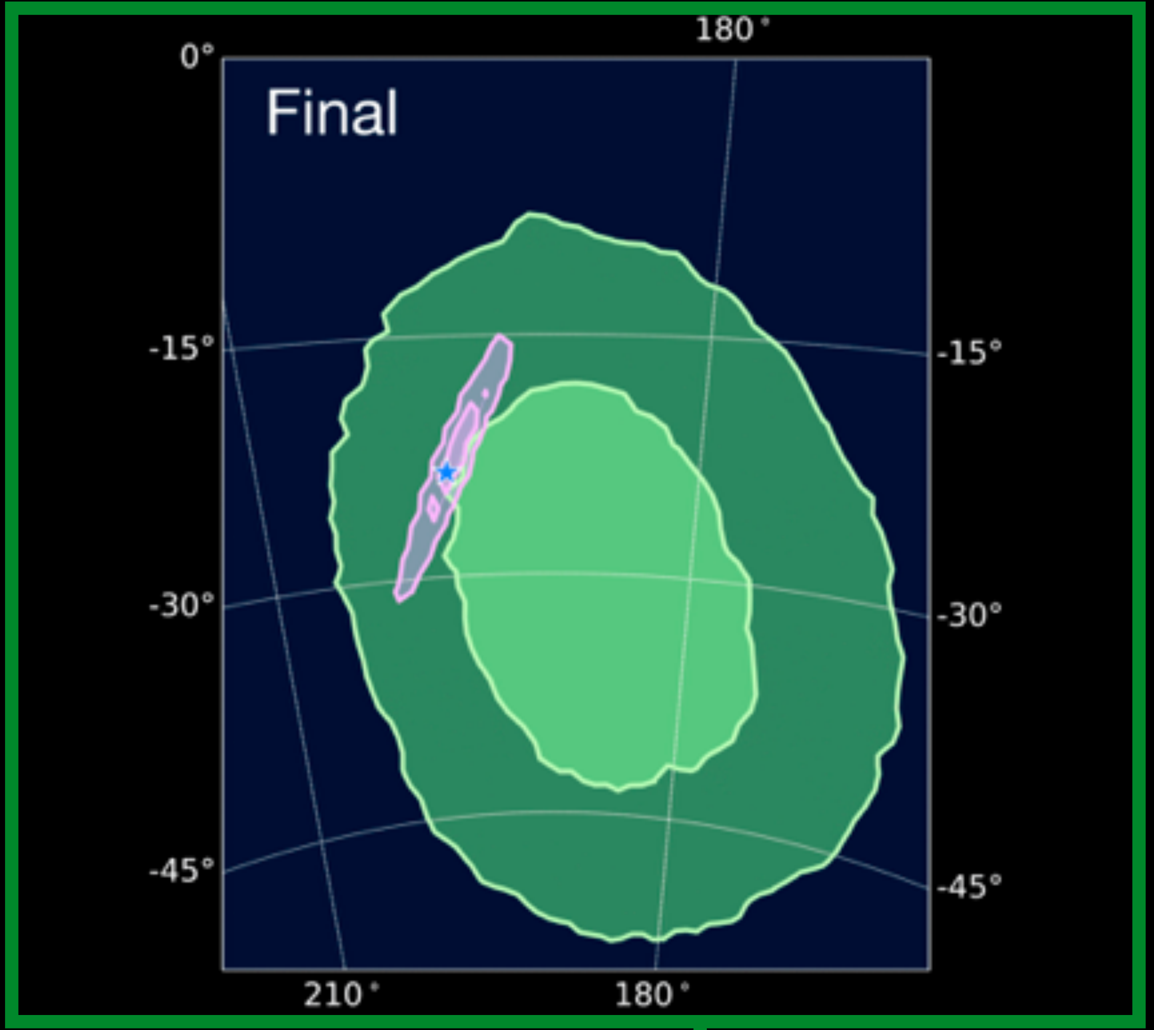
+84 min

+5 hr

+6 hr

Continued Reporting

```
TITLE:   GCN CIRCULAR
NUMBER:  21520
SUBJECT: GRB 170817A: Fermi GBM detection
DATE:    17/08/17 20:00:07 GMT
FROM:    Andreas von Kienlin at MPE  <azk@mpe.mpg.de>
```



List of 15 host galaxies in LIGO/Virgo sky map volume

GBM science data arrives - GCN Circular giving GRB official name

Updated LIGO/Virgo sky map

GBM report of energetics and initial False Alarm Rate

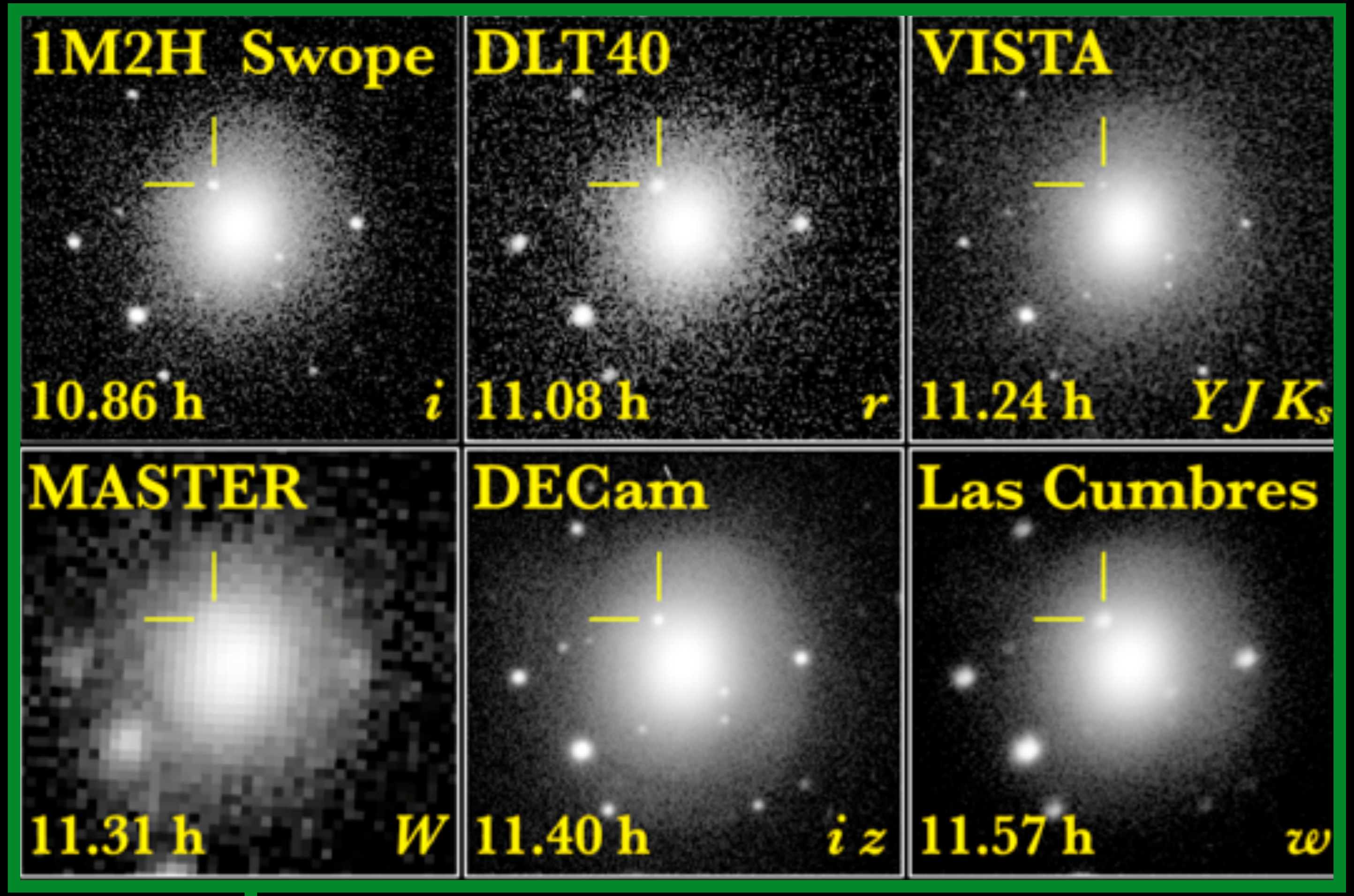
+6 hr

+7 hr

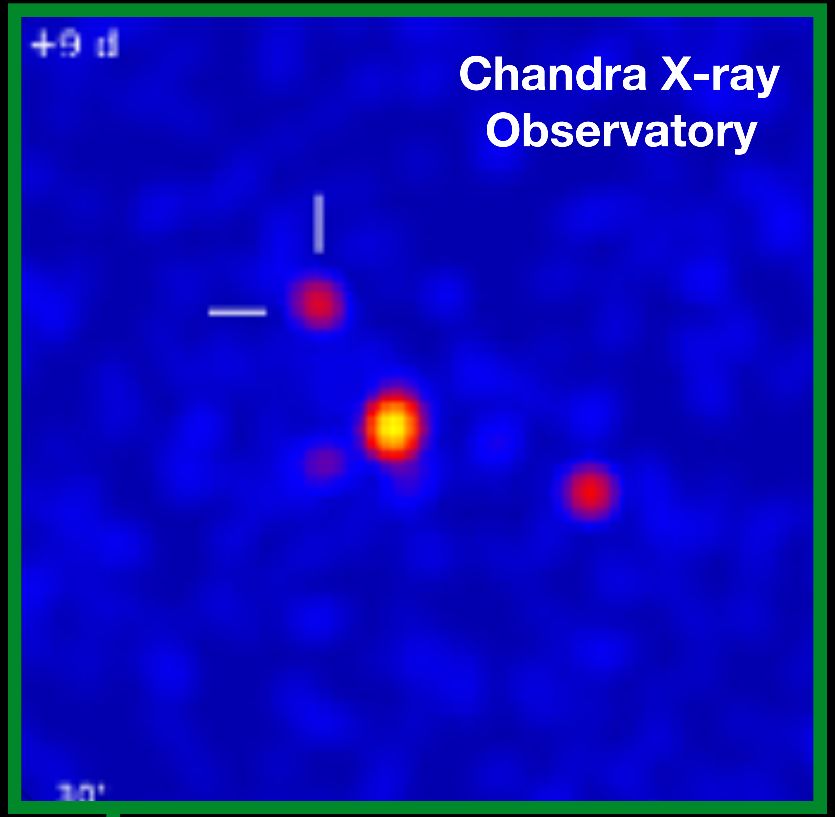
+11 hr

+12 hr

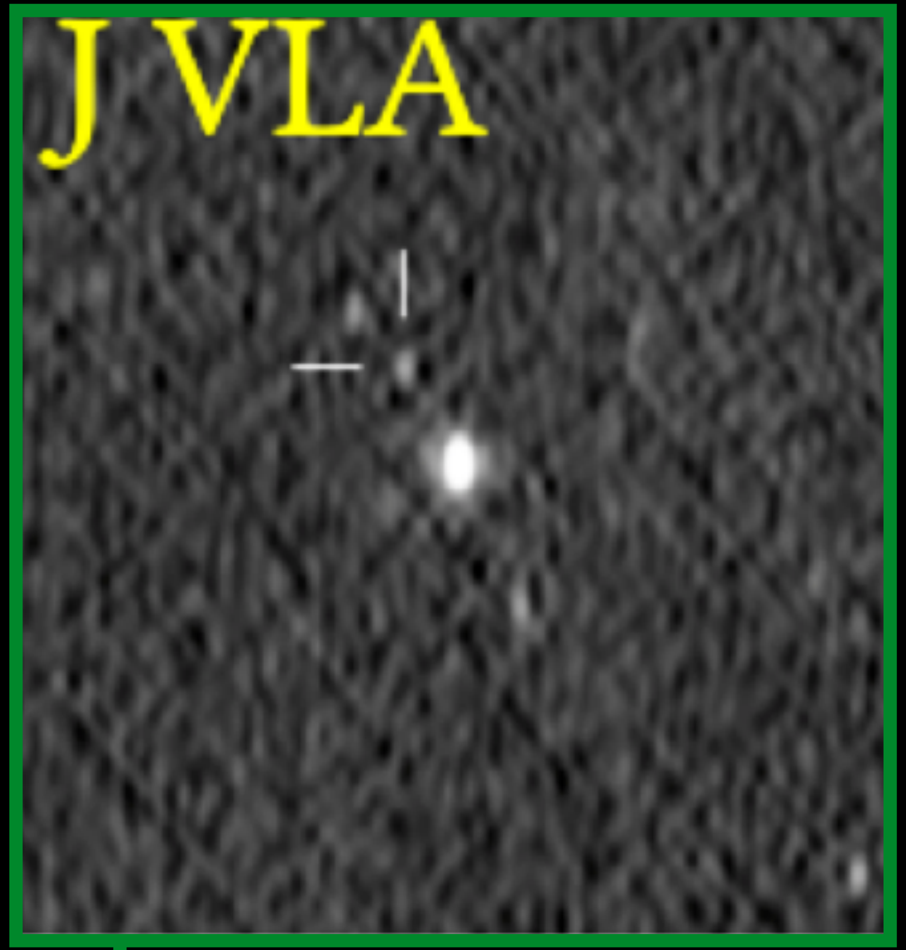
Electromagnetic Follow-up



Report of Optical Transient by three independent telescopes



X-ray counterpart reported by Chandra



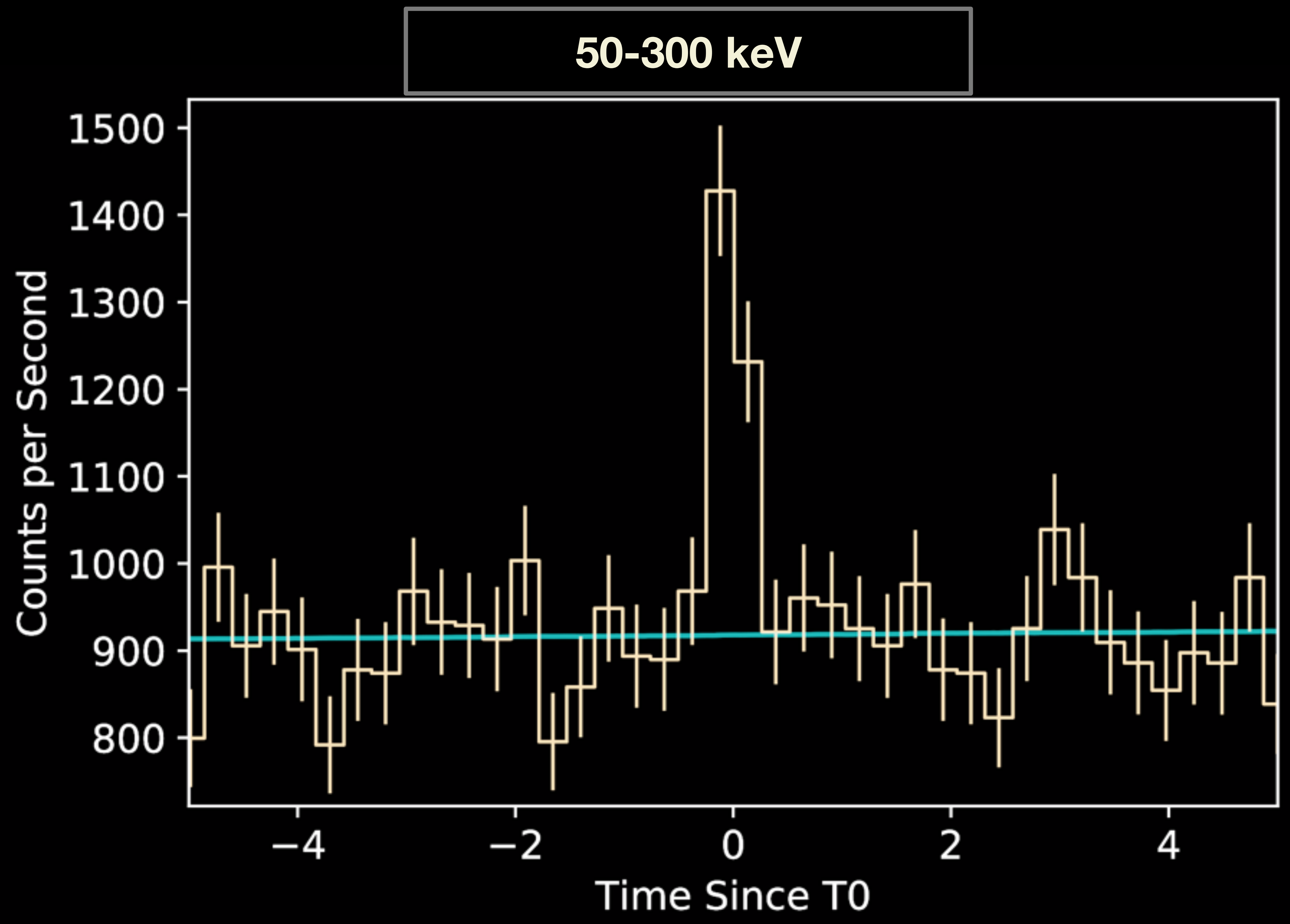
Radio counterpart reported by VLA

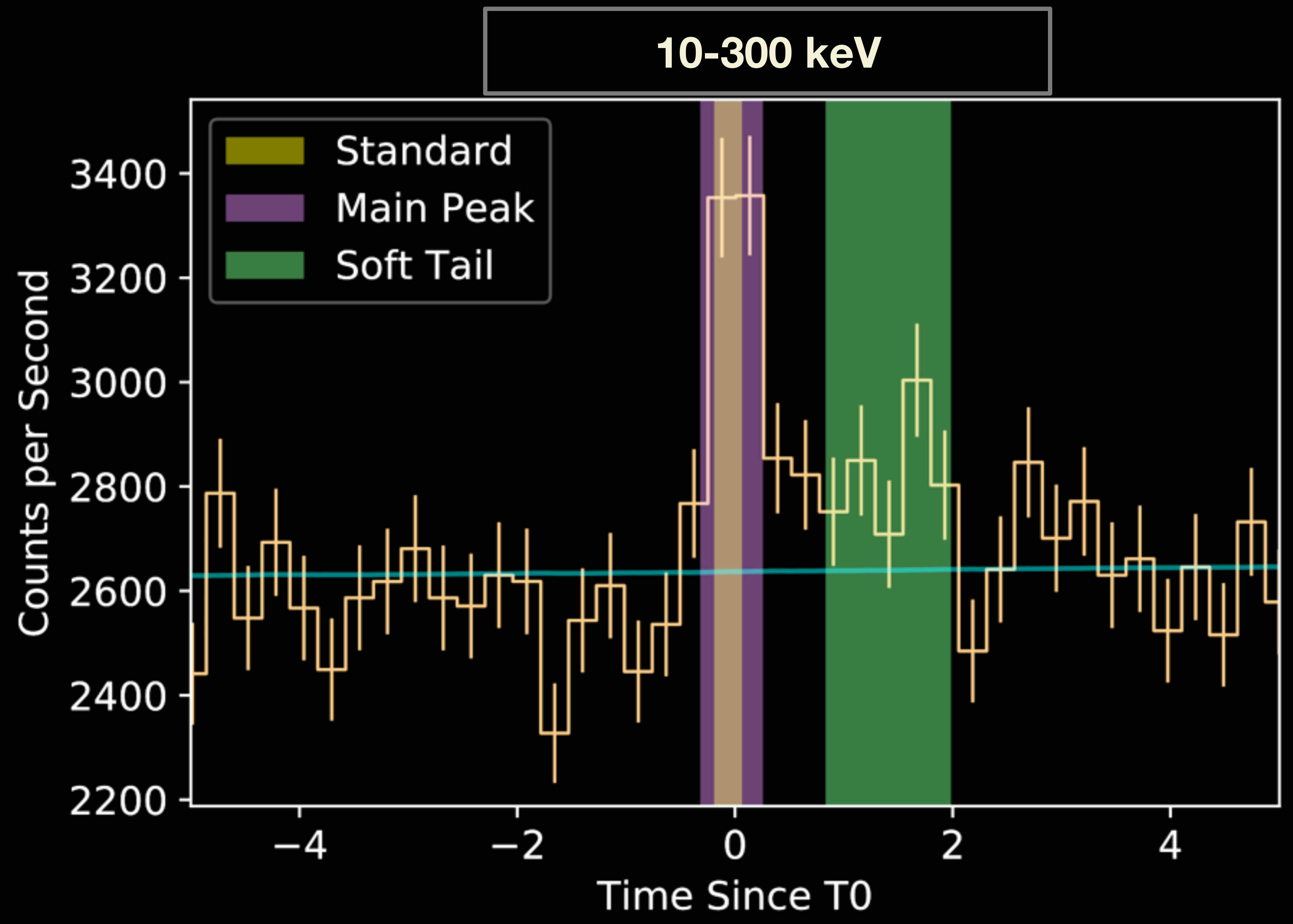
+12-13 hr

+9 day

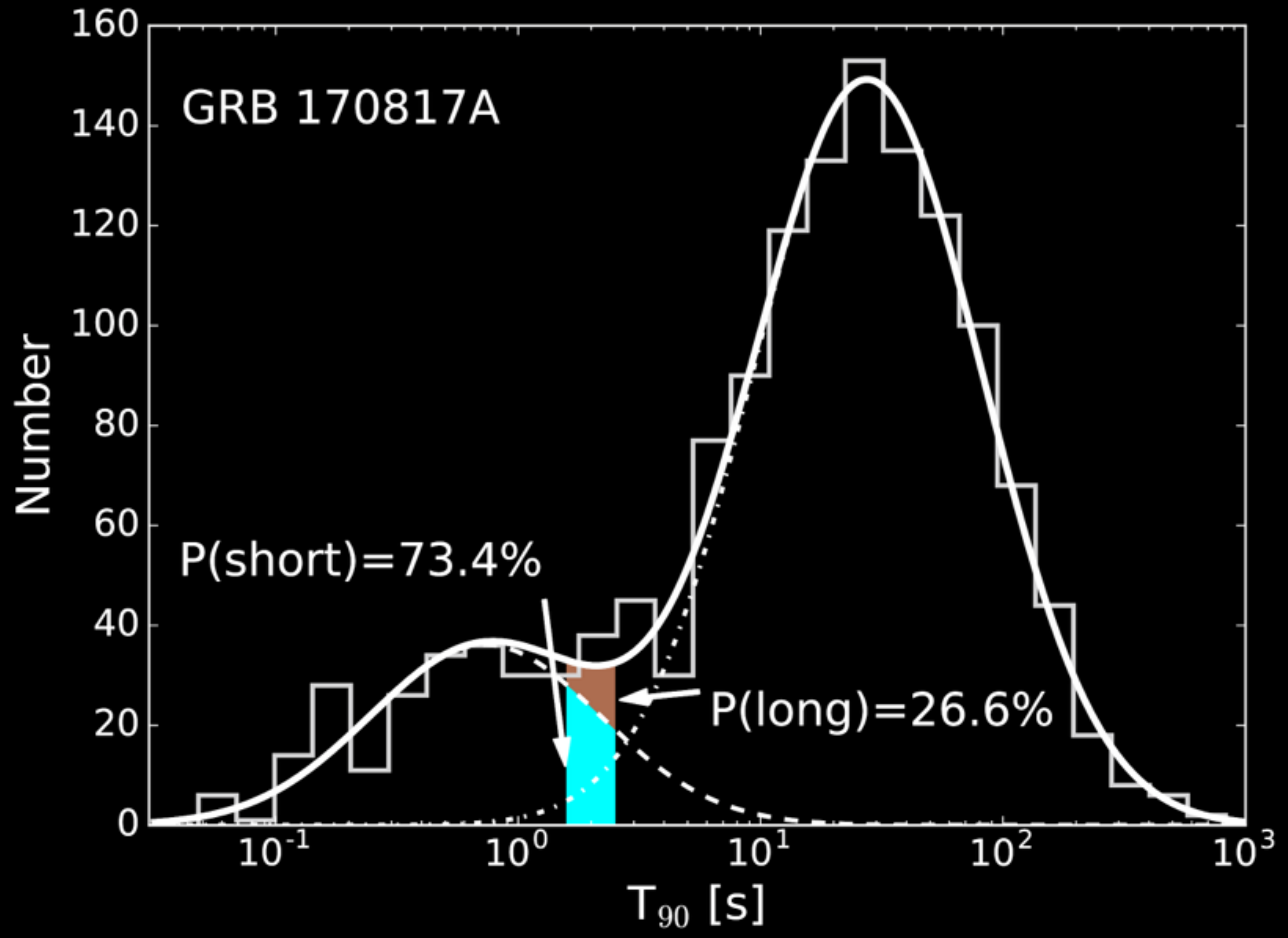
+16 day

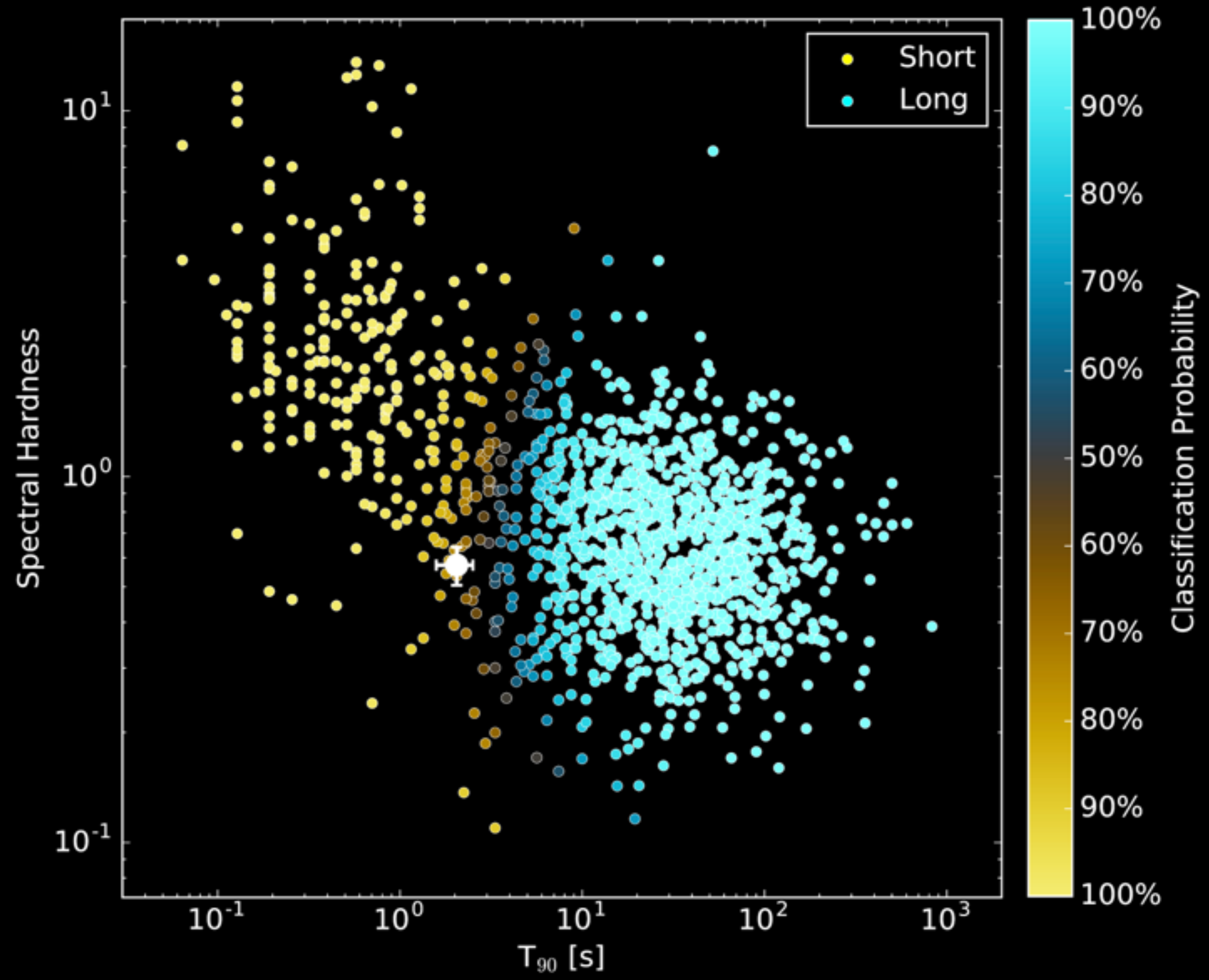
GRB 170817A: A Tail





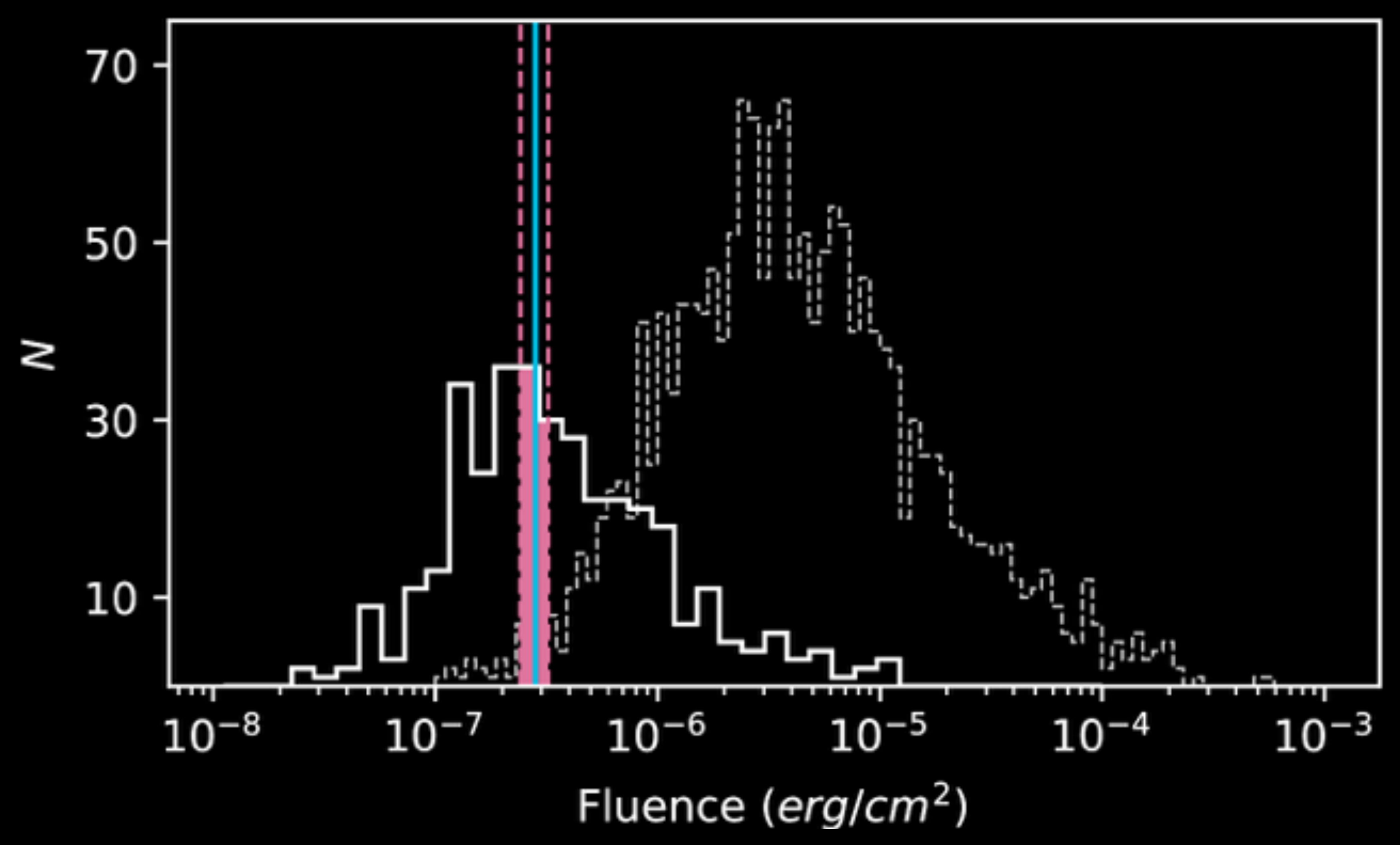
GRB Type: Short or Long?

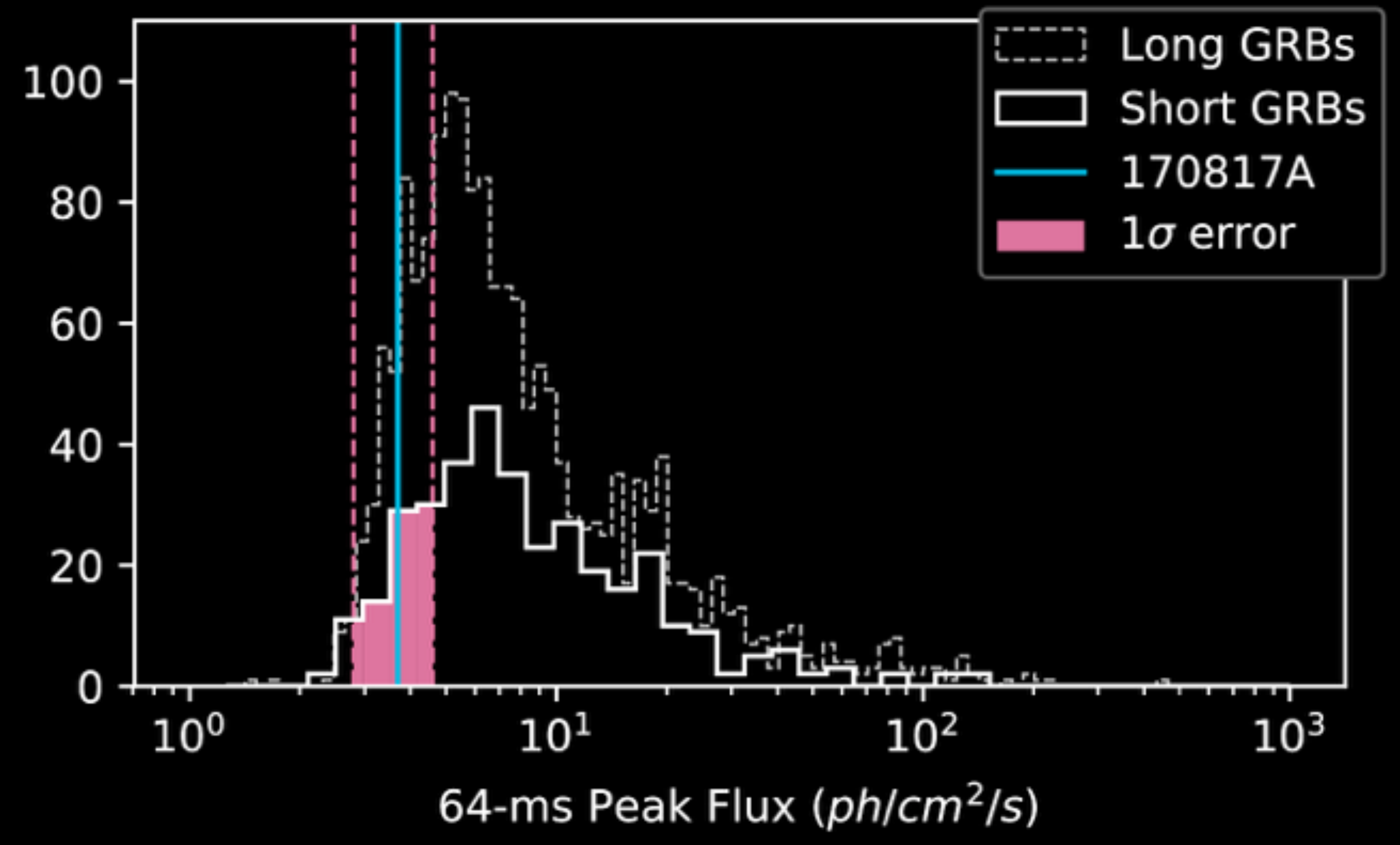


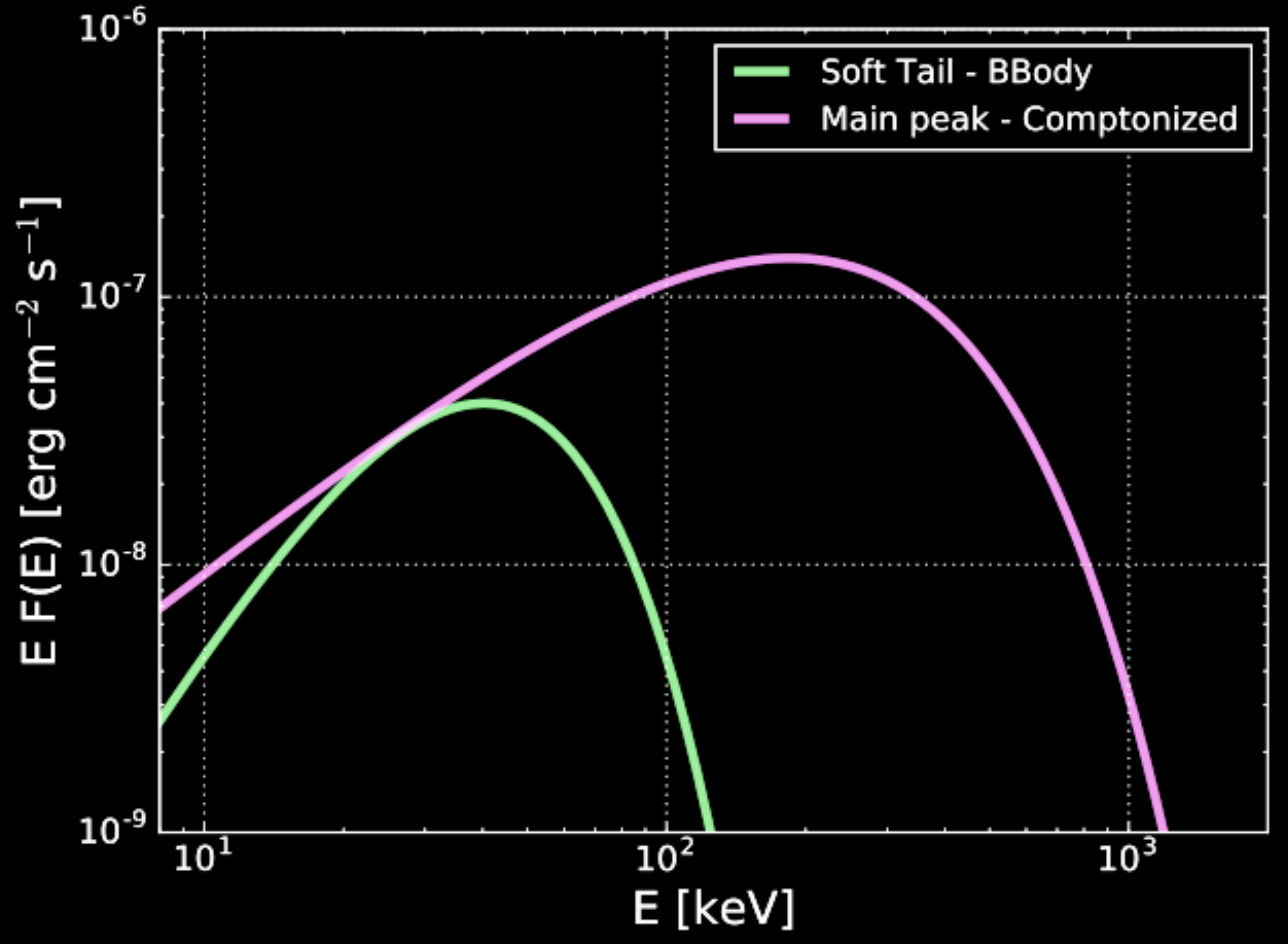


- Two classes of GRBs: short (mergers) and long (collapsars)
- These two classes are also spectrally different: short-hard and long-soft
- This GRB is most likely classified as short, although it is spectrally softer than many short GRBs

Spectra: Average or Peculiar?







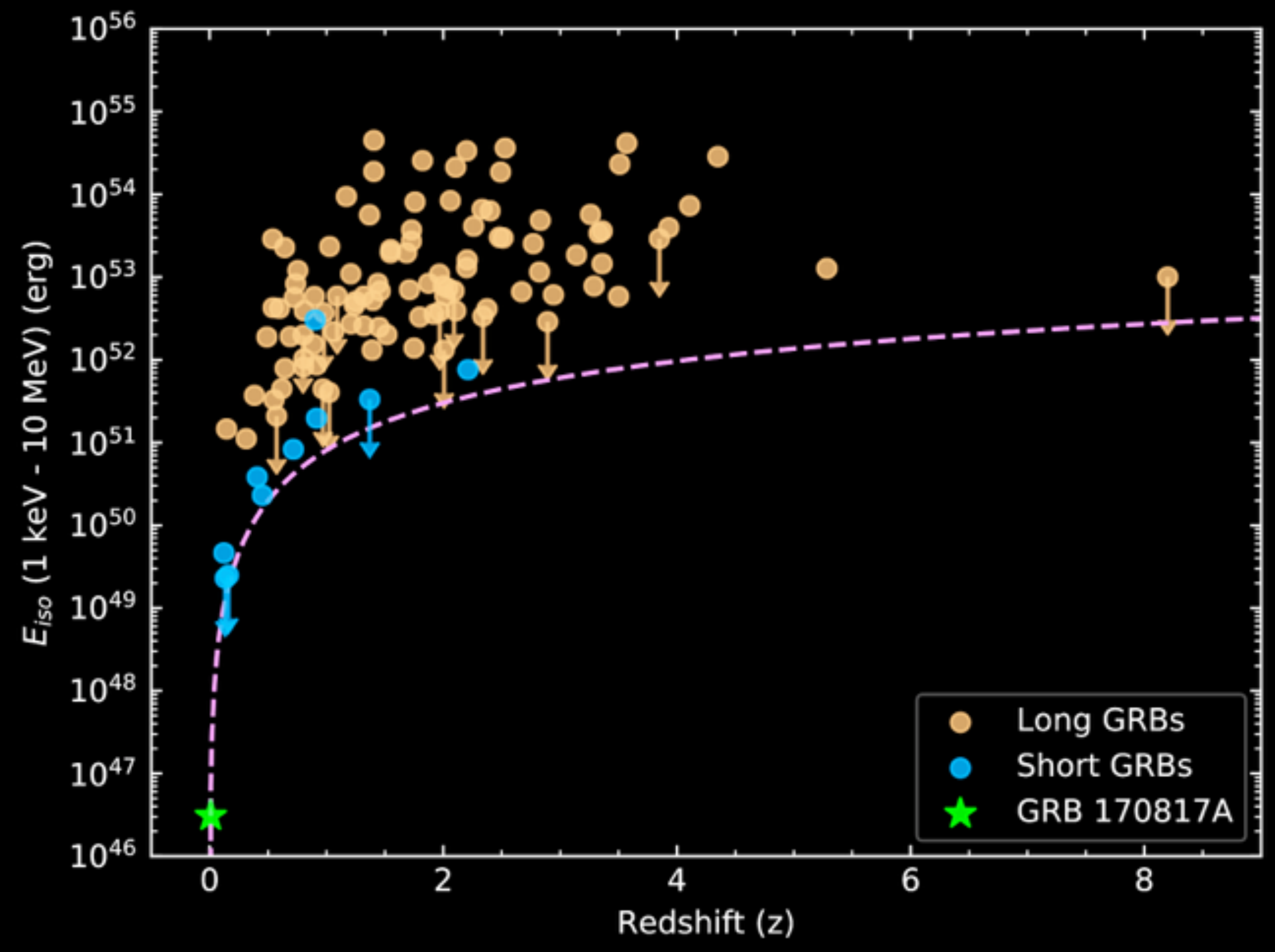
Standard GBM Catalog analysis

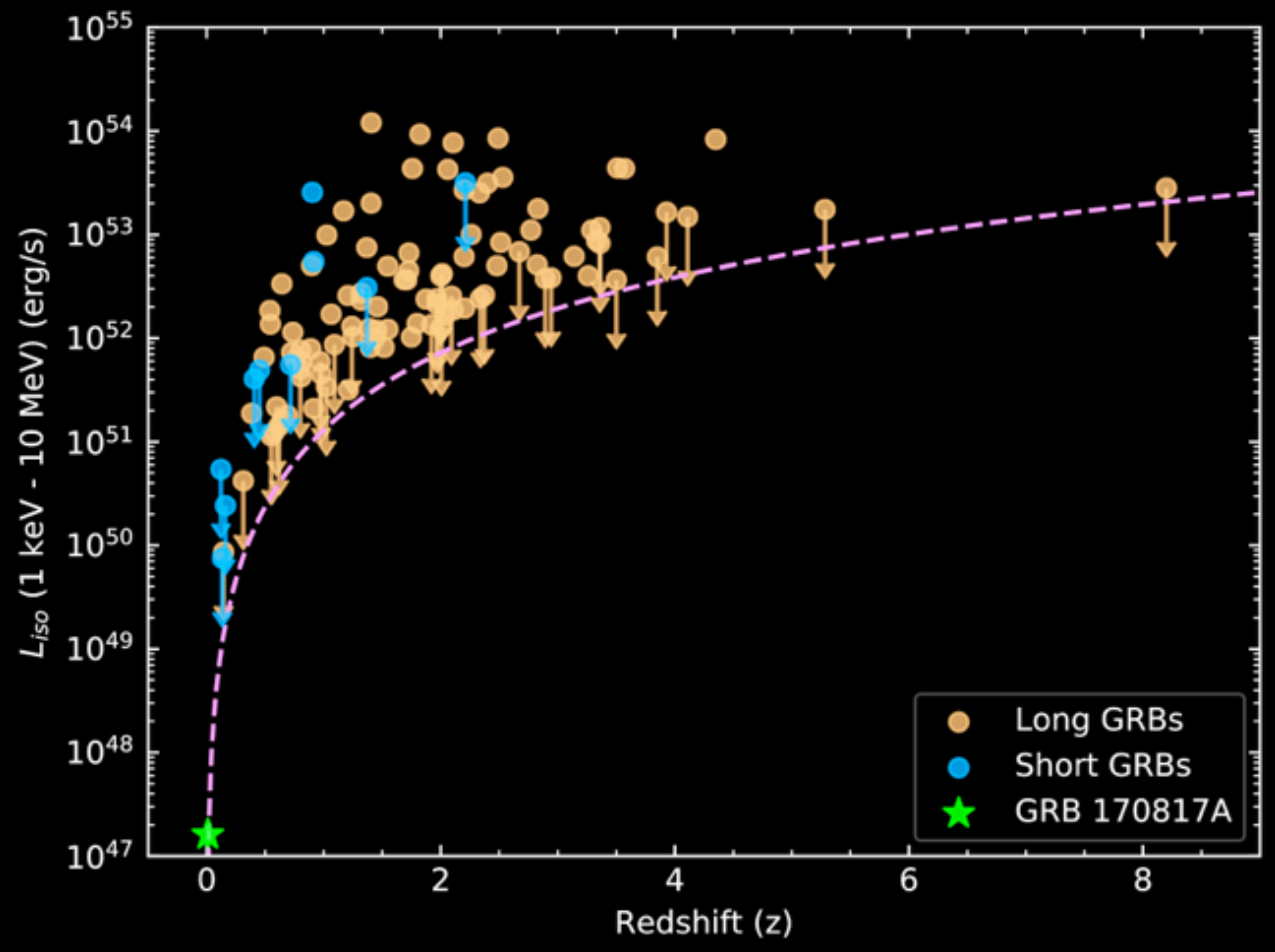
- Average short GRB by fluence
- Lower third in 64 ms peak flux

Refined analysis

- Two components: initial GRB spike & weak soft tail
- Tail appears thermal—blackbody kT~10 keV

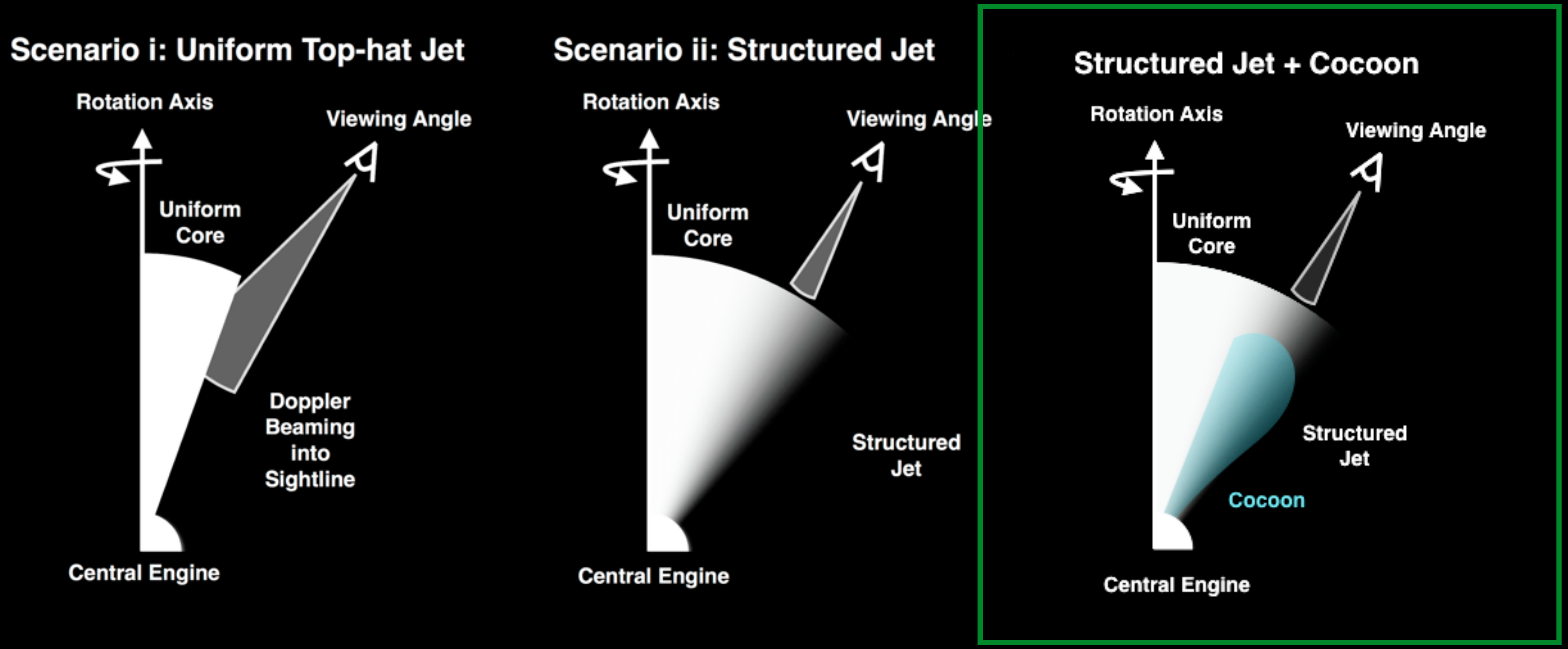
Energetics? Not Very.





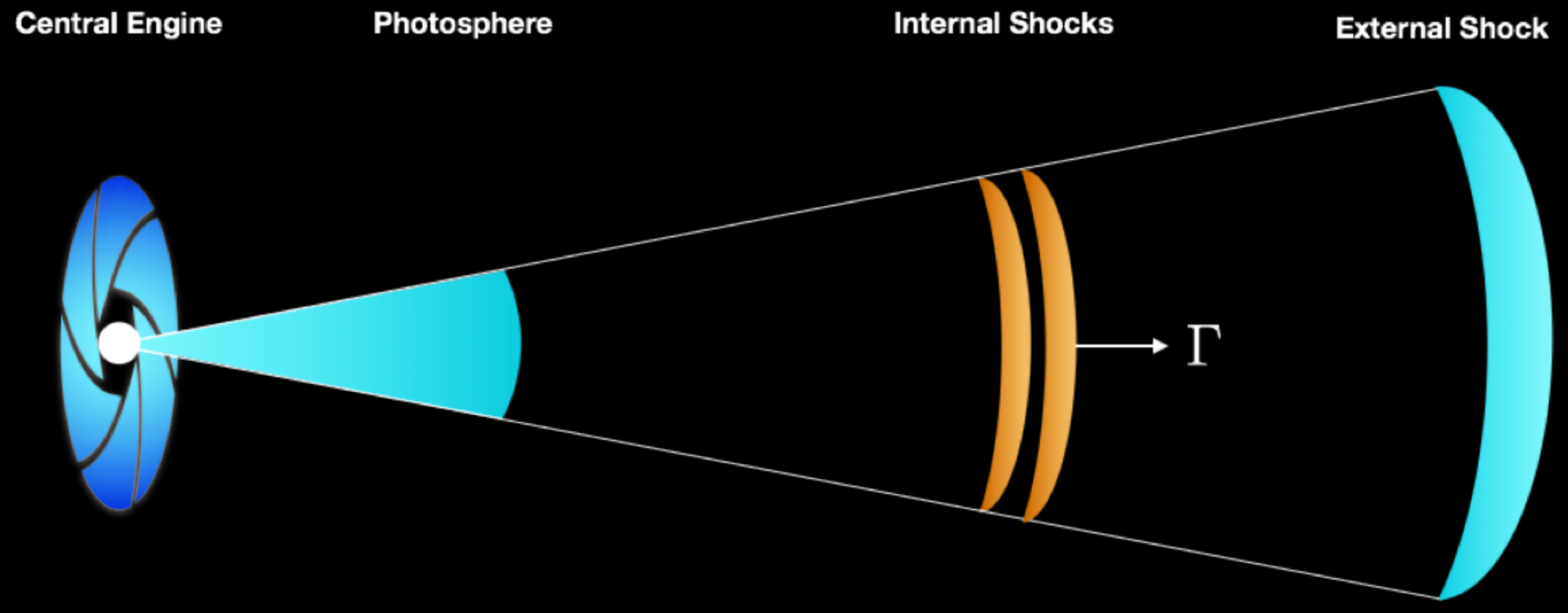
- Estimated peak luminosity and isotropic-equivalent energy is ~2-3 orders of magnitude lower than previous observations
- Why the large gap? Malmquist bias.
    - We see bright things far away that look weak, bright things nearby that look bright, and weak things nearby that look weak. We can’t see weak things far away.

GRB Observing Scenarios



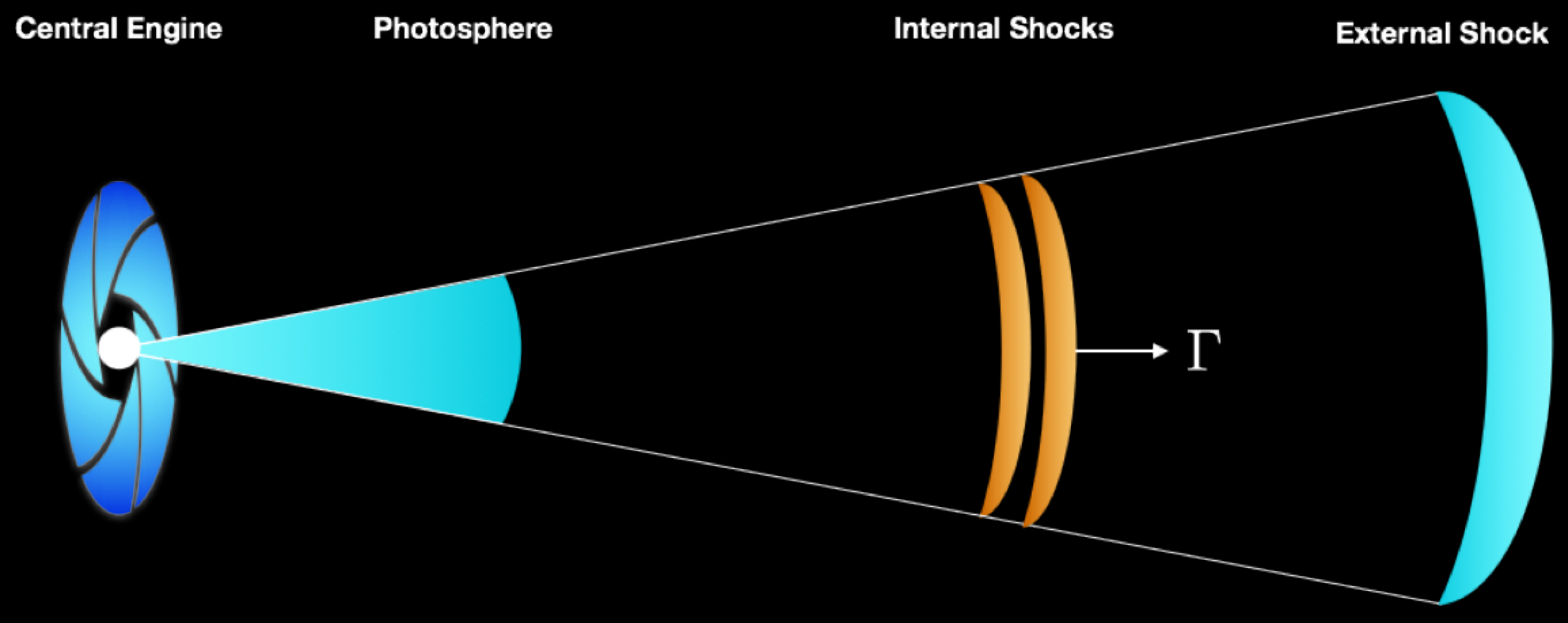
- GW data restricts viewing angle < 56 deg off-axis
- Viewing angle < 36 deg off-axis (20+/-5 Mooley+ ArXiv:1806.09693)
- Could be a structured jet with “wings” of shocked material (e.g. Lazzati+ 2018)
- Could be a shock breakout from a “choked” trans-relativistic jet (e.g. Gottleib+ 2018)

GRB Emission Models—Shocking



- First direct measurement of a GRB central engine
- Typical GRB spike
  - Internal shocks, assuming time delay between GW and GRB is due to propagation time, the radius of the relativistic outflow < 30 au, and the size of emitting region < ~3 au
  - External shocks, assuming time delay is between GW and GRB is propagation time, Lorentz factor ~300, deceleration radius ~200 au

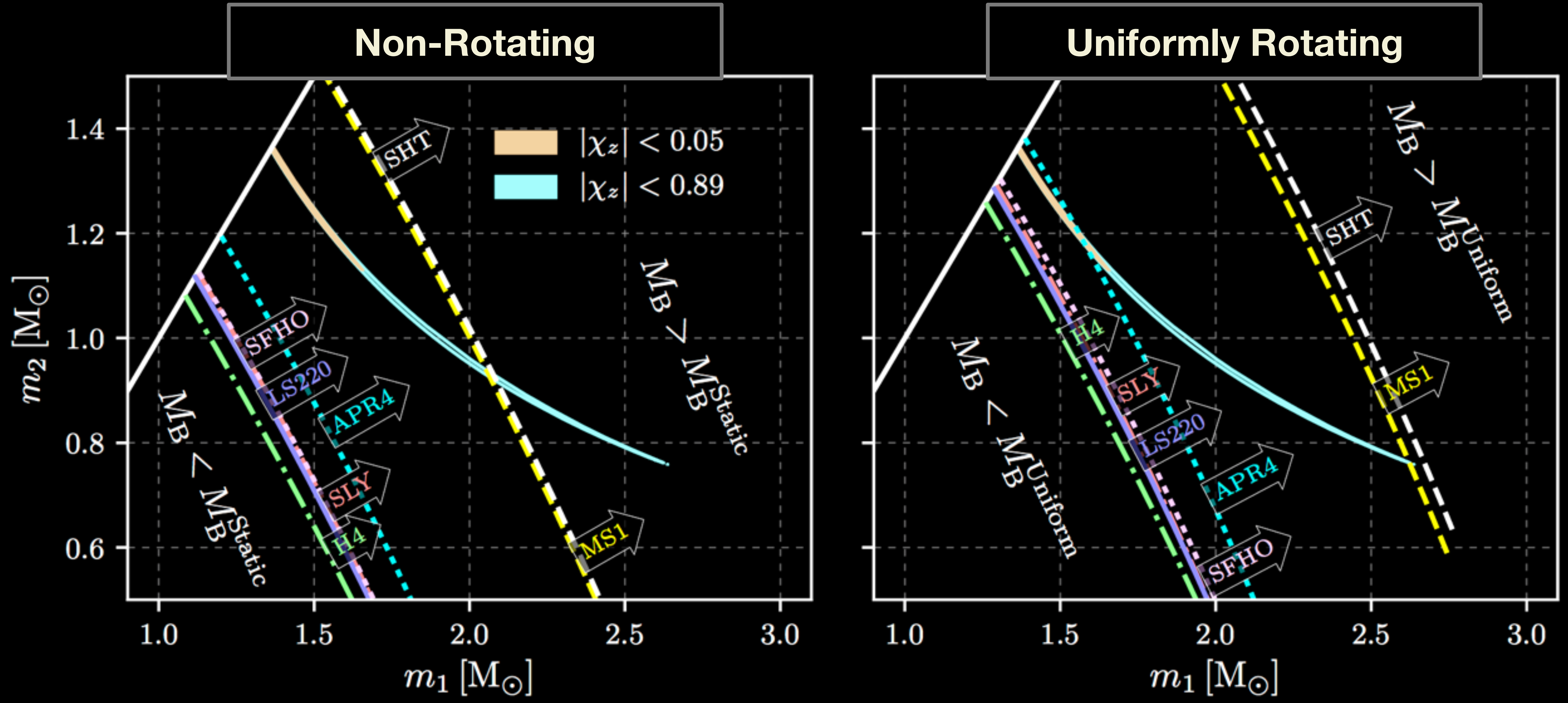
GRB Emission Models—Shocking



- Soft blackbody tail
  - Photospheric emission can explain this if assume the delay time is the time required for photosphere to become optically thin -> photospheric radius ~ 1 au
  - Photospheric emission has difficulty in explaining non-thermal spike + thermal emission
  - Cocoon emission radius ~3000-14000 km, supported by off-axis x-ray observations of trans-relativistic cocoon

A Cool Video

Neutron Star Equation of State



- Testing the “flufiness” of neutron star material
- Gamma-ray/X-ray upper limits on post-merger emission indicate that any remnant emission must be 2-3 orders of magnitude weaker
- Assuming remnant is a black hole (and not a stable magnetar), the mass of a non-rotating neutron star < 3.2-3.7 solar mass
- Most massive pulsar: (2.01+/-0.04) solar masses from Antoniadis et al. 2013

A Race Between Gravity and Light: It's a Tie

- Conservative estimate
- Assume distance = 26 Mpc (lower bound GW 90% credible interval)
- Assume GWs and gamma-rays emitted at same time, OR
- Assume gamma-rays emitted 10 s **after** GWs
- Gravitational waves travel at *c* to within one part in one quadrillion
- Rules out some Modified Newtonian Dynamics theories

$$-3 \times 10^{-15} \leq \frac{\Delta v}{v_{\mathrm{EM}}} \leq +7 \times 10^{-16}$$

The Equivalence Principle

- Equivalence Principle: Gravitational mass == inertial mass
- Can test using Shapiro delay
  - Propagation time of massless particles traveling in curved spacetime (through gravitational fields) will be slightly increased compared to flat spacetime

$$\delta t_{\mathrm{S}} = -\frac{1+\gamma}{c^3} \int_{\mathbf{r_e}}^{\mathbf{r_o}} U(\mathbf{r}(l))dl$$

δt_S = Shapiro delay using the same time bounds
$\mathbf{r_o}$ = observation position, $\mathbf{r_e}$ = emission position
$U(\mathbf{r})$ = gravitational potential (here the Milky Way's)
l = wave path
γ = deviation from Einstein-Maxwell theory
(where γ_{EM} and γ_{GW} are both equal to 1)

$$-1.2 \times 10^{-6} \leq \gamma_{\mathrm{GW}} - \gamma_{\mathrm{EM}} \leq 2.6 \times 10^{-7}$$

This is 1-2 orders of magnitude lower than the best **absolute** bound on γ_{EM} based Shapiro delay of radio waves

ApJ Letters Focus Set

THE ASTROPHYSICAL JOURNAL LETTERS

Focus on the Electromagnetic Counterpart of the Neutron Star Binary Merger GW170817

OPEN ACCESS

Multi-messenger Observations of a Binary Neutron Star Merger

B. P. Abbott *et al.* 2017 *ApJL* **848** L12

+ View abstract   View article   PDF

OPEN ACCESS

Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A

B. P. Abbott *et al.* 2017 *ApJL* **848** L13

+ View abstract   View article   PDF

An Ordinary Short Gamma-Ray Burst with Extraordinary Implications: *Fermi*-GBM Detection of GRB 170817A

A. Goldstein *et al.* 2017 *ApJL* **848** L14

+ View abstract   View article   PDF

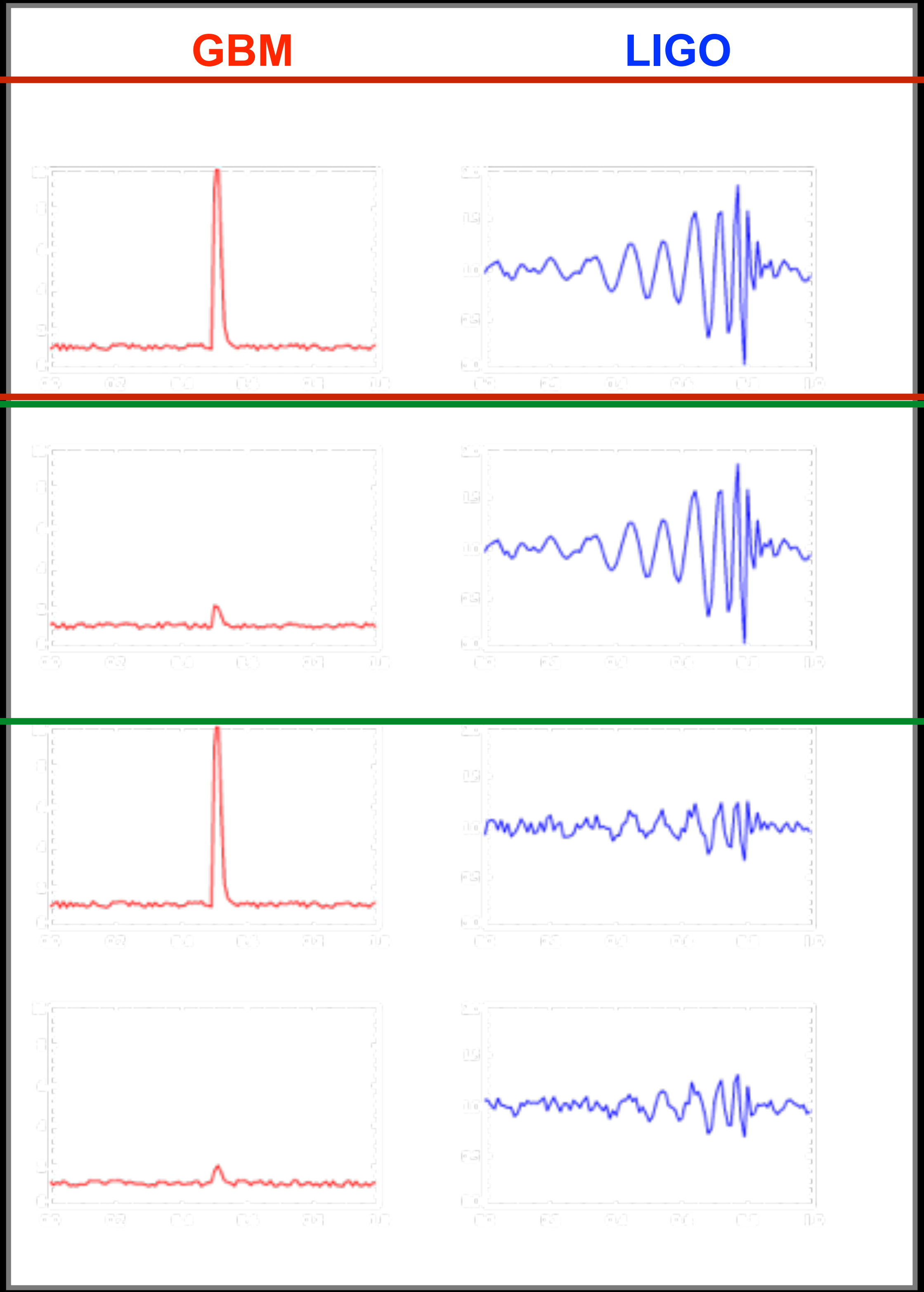
Fermi Science from GW170817

Many exciting results from ONE observation!

- Relativistic Jet physics — emission radius/timescale, deceleration radius/timescale
- Stellar populations — rate of NS-NS mergers/short GRBs
- Condensed matter physics — Neutron Star Equation of State
- Fundamental physics — measurement of the speed of gravity
- General Relativity — testing the Equivalence Principle between gravity and EM, and Lorentz Invariance Violation

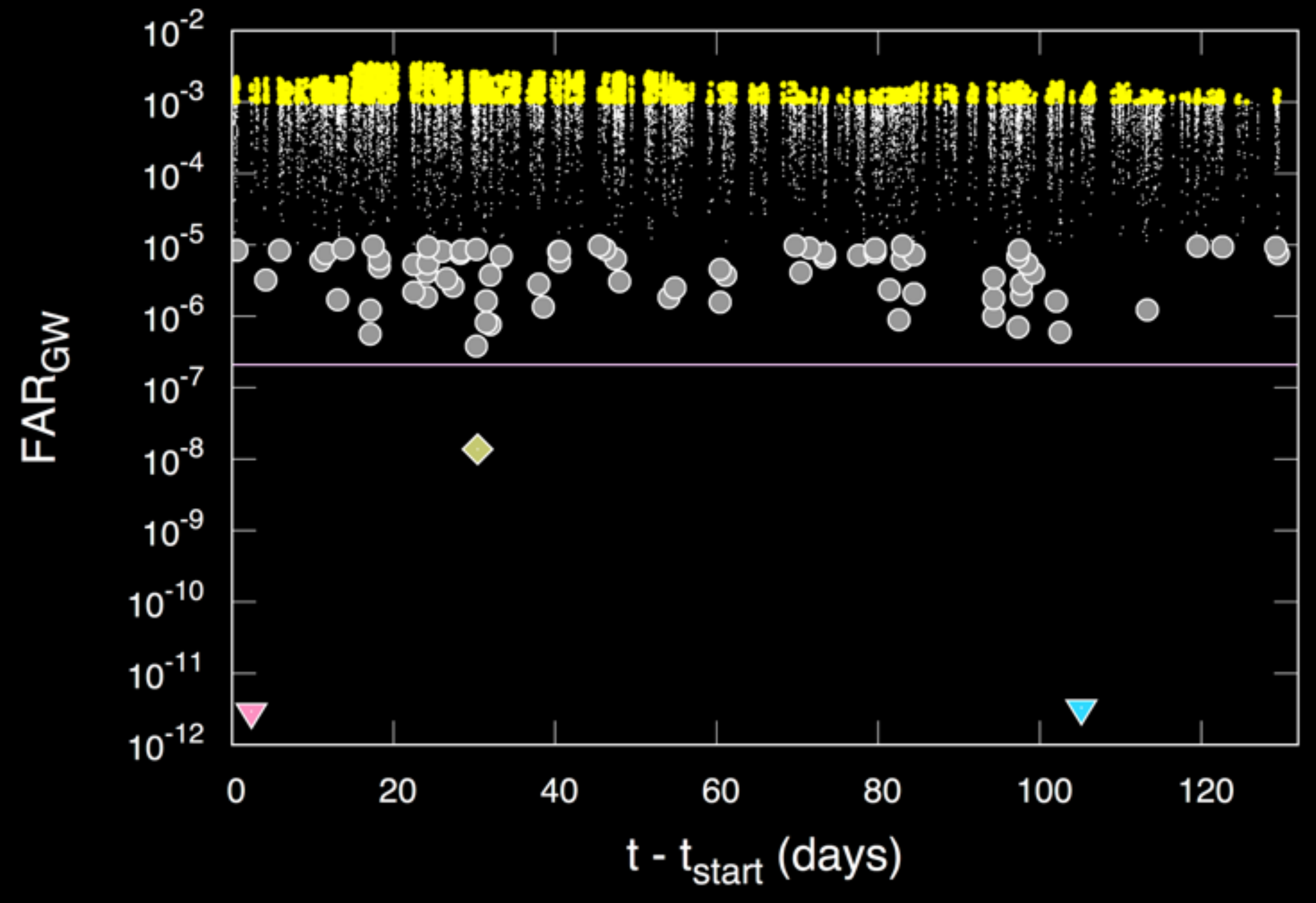
Joint Sub-threshold Search

Ideal Scenario GRB 170817A!	Bright GBM	Bright LIGO
GW150914 Scenario Connaughton+ 2016, ApJL 826, L6	Sub-threshold GBM	Bright LIGO
Typical more distant short GRB	Bright GBM	Sub-threshold LIGO
Both Sources Faint	Sub-threshold GBM	Sub-threshold LIGO

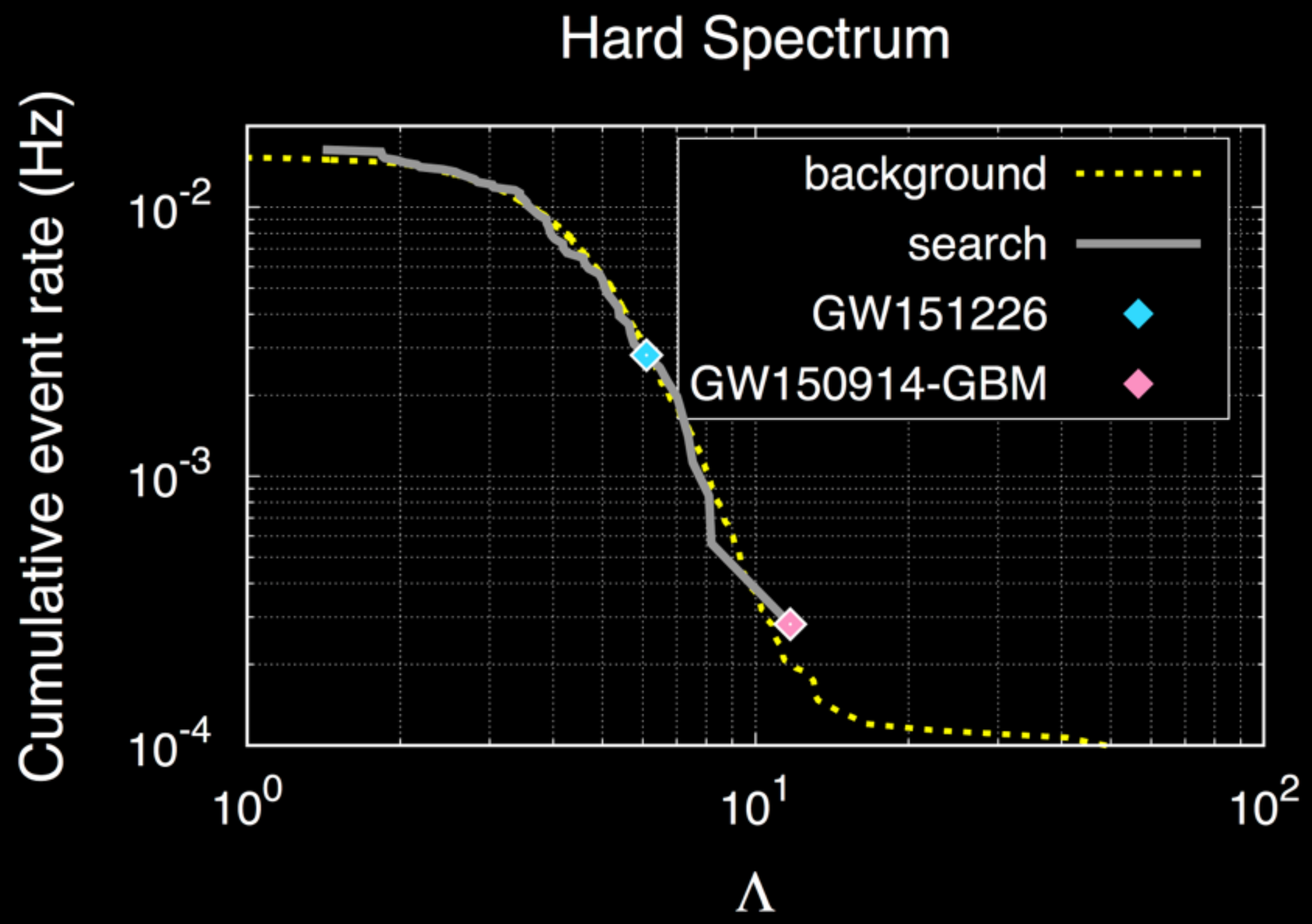


- GBM and LIGO teams working together to develop automated pipelines to search for sub-threshold signals
  - Untargeted Search—offline, searches all continuous data, latency ~few hours: https://gcn.gsfc.nasa.gov/fermi_gbm_subthresh_archive.html
  - Targeted Search—searches window around target of interest, deep detector and spectral coherent search
- Detection of sub-threshold signals can push the GW detection distance deeper
- GW/GRB 170817A inspired formulation of joint detection statistic: Ashton+ 2018, ApJ 860, 6

All-O1 Offline Follow-up Analysis



GBM+LVC, 2019

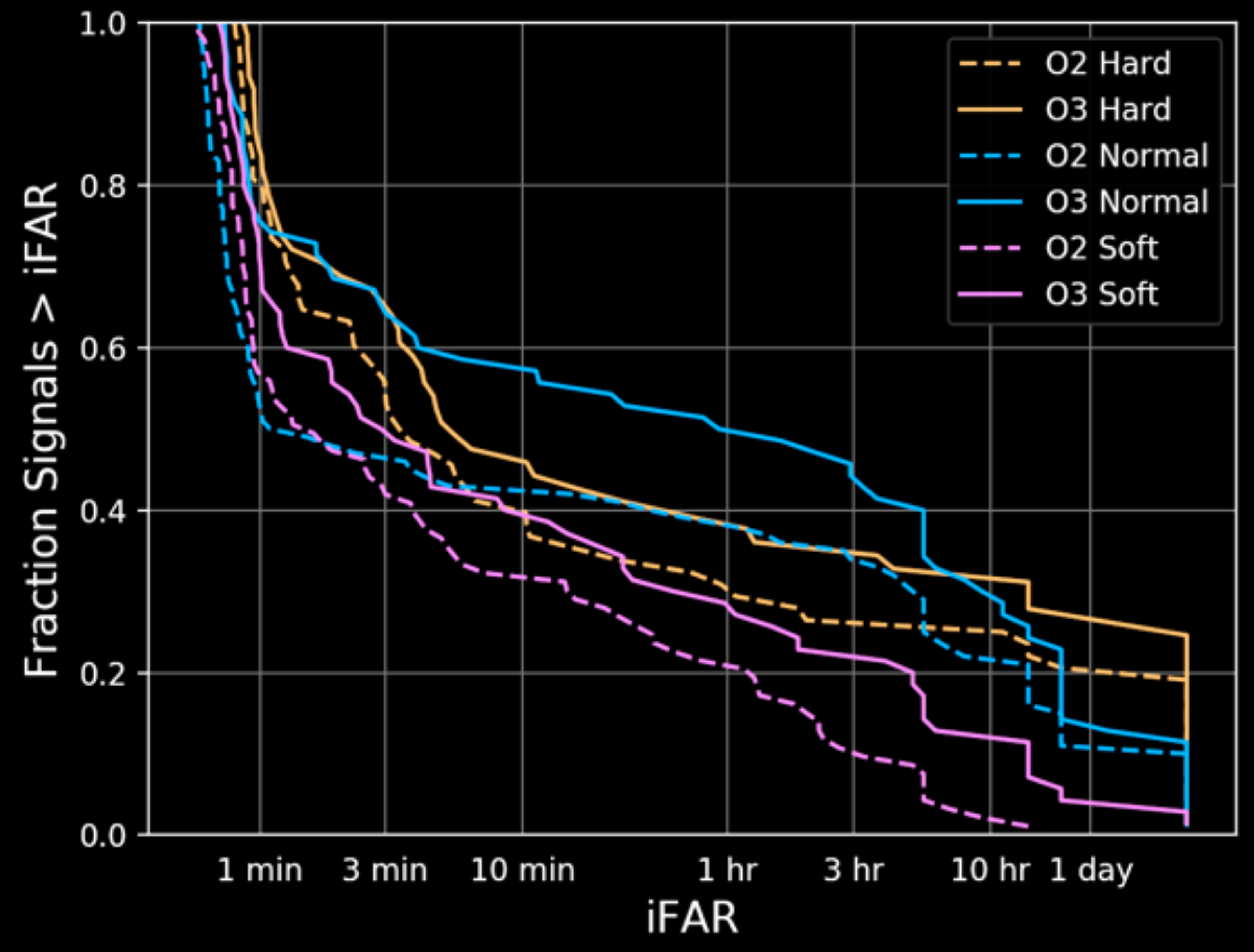


- 59 LIGO triggers
- ~2500 Background triggers (FAR > 1 per 15 min)
- No above threshold or blind sub-threshold gamma-ray counterparts

- Search performed over 3 template spectra
- GW150914-GBM candidate is most significant at FAR ~3×10^{-4} Hz
- GW150914-GBM has lowest post-trials FAP, too high to declare an unambiguous EM counterpart

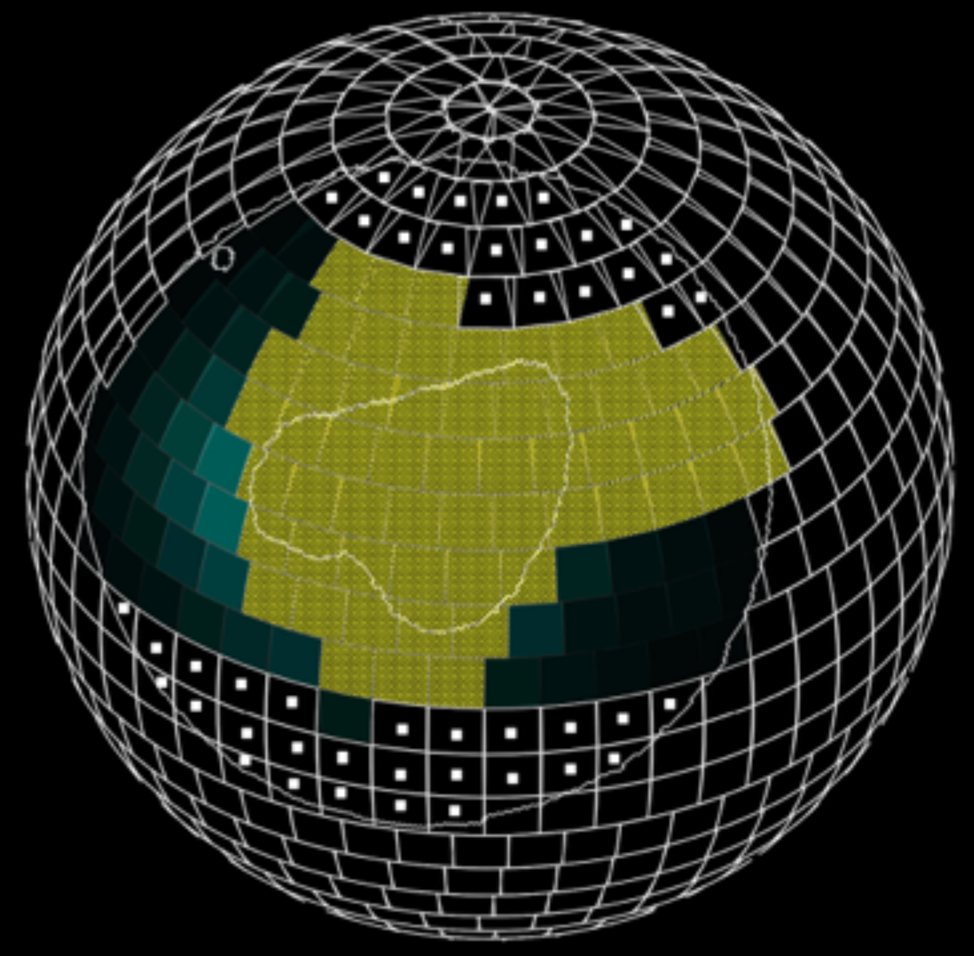
Fermi GBM During O3

- Untargeted Search
  - Over 40 confirmed sub-threshold short GRBs
  - Using as a calibration sample for classification
- Targeted Search
  - >10x faster than in O2
  - More sensitive — lower background FAR, increased detection statistic
- Reporting of coincident triggers
  - Independent triggers
  - Single IFO GW triggers + GBM signal (realtime)
  - Triggers where either GBM or LIGO/Virgo are sub-threshold (~hours delay)
- Prompt, combined skymaps
- Enable follow-up, interested wide-field telescopes: ZTF, GOTO, EveryScope, MASTER

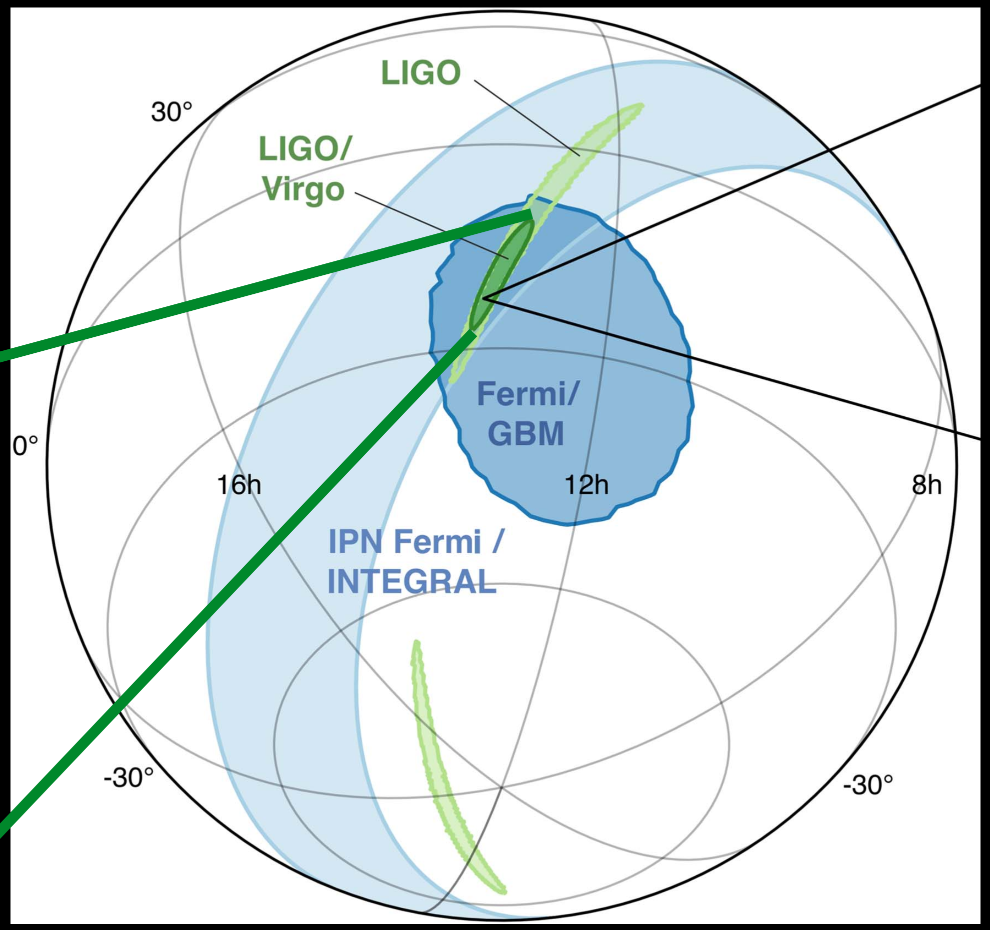


ZTF — 2900 deg^2 followup!

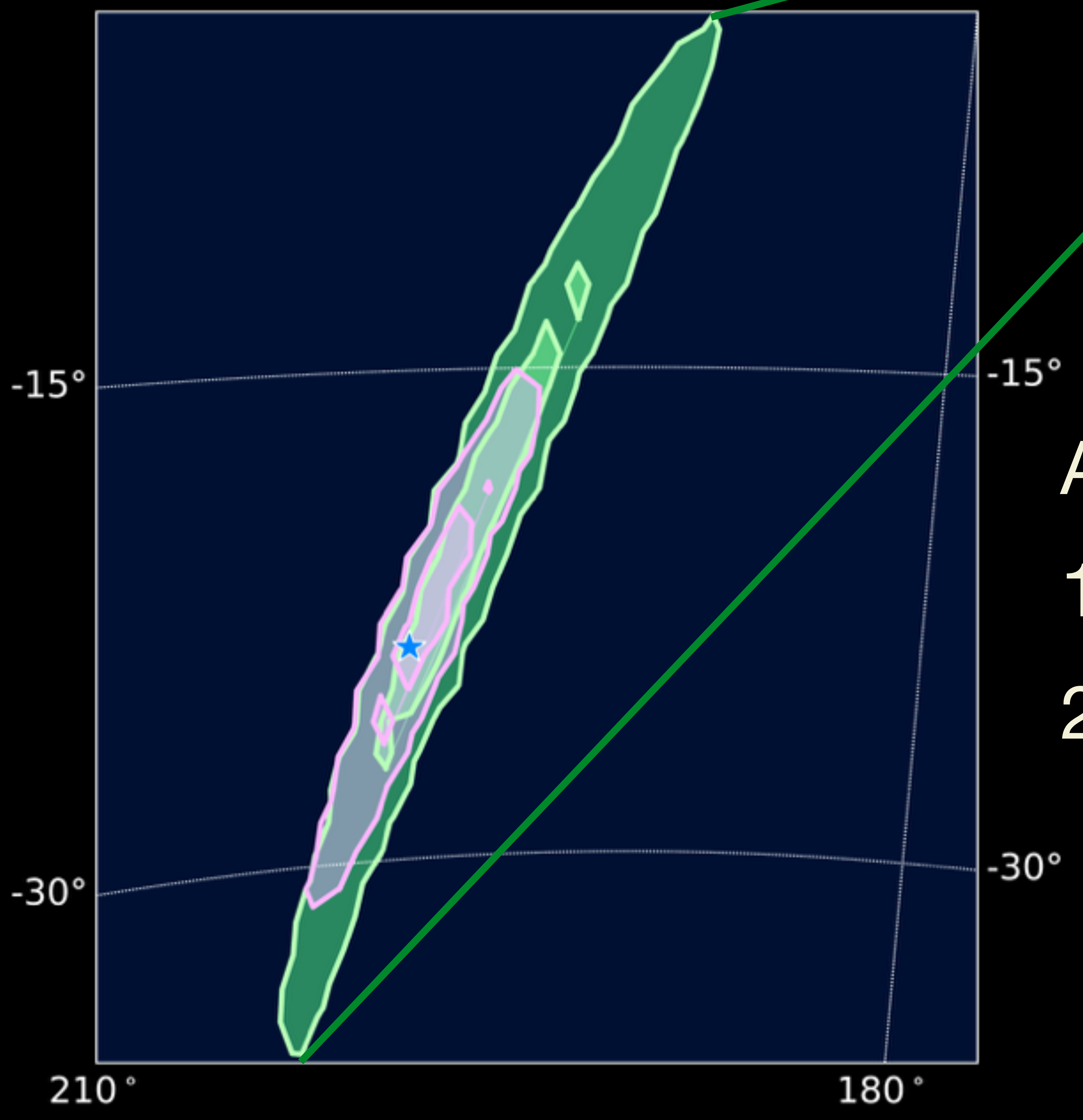
Coughlin+ 2019



Fermi GBM During O3



GBM initial+HL

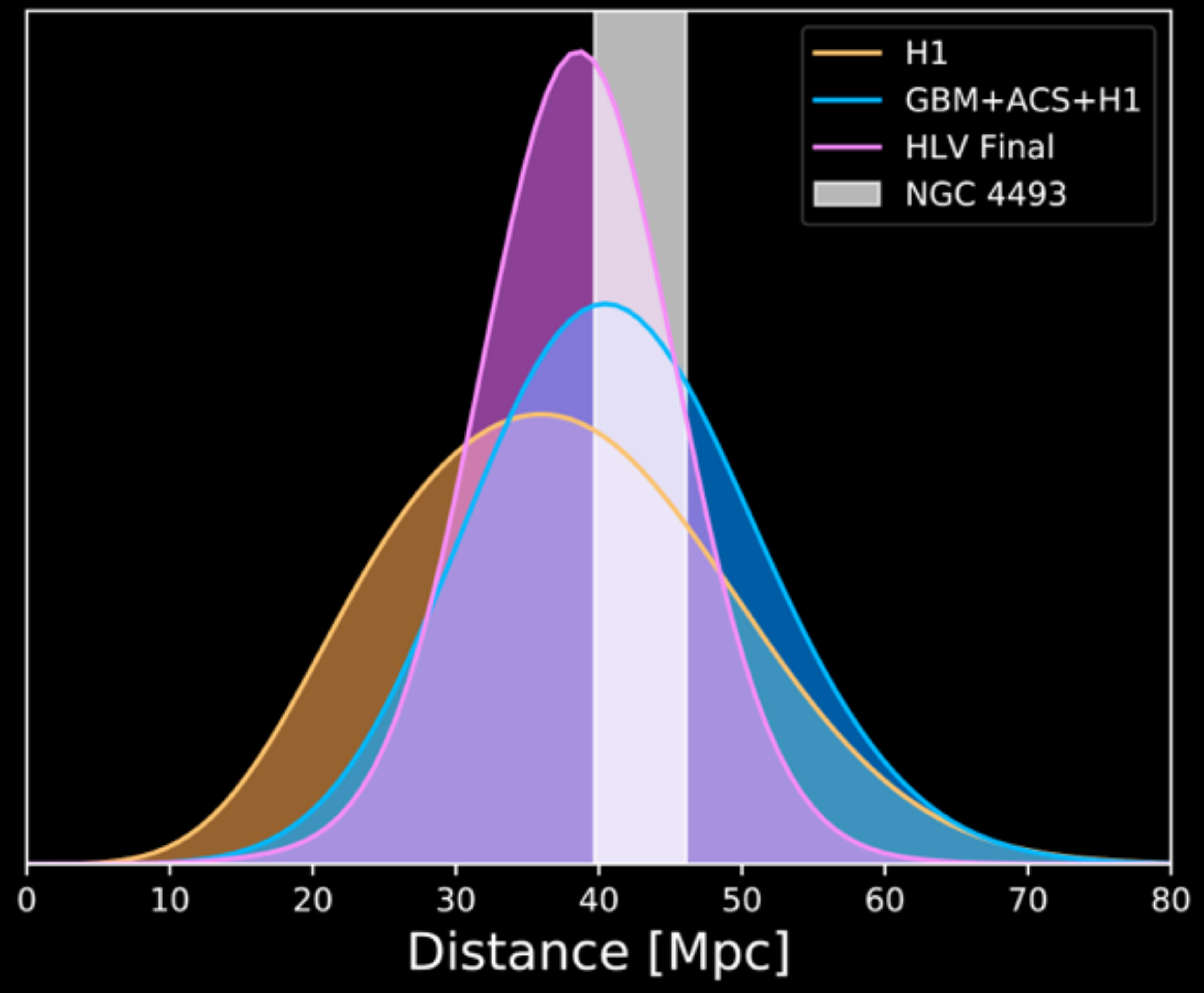


Average localization improvement:

1 interferometer: 90%

2 interferometers: 80%

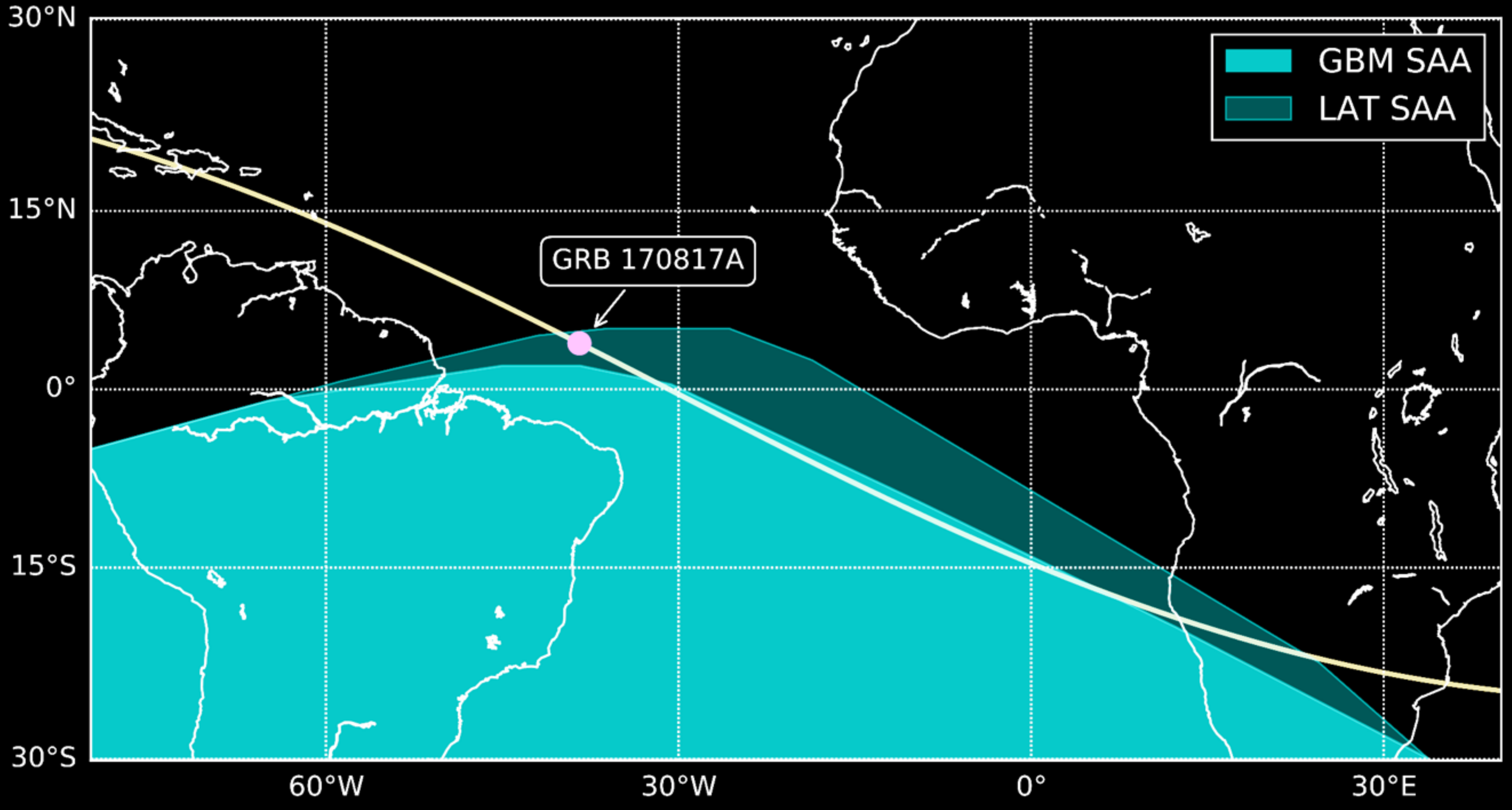
Distance Posteriors



Fermi: The Multi-Messenger Observatory

Backup

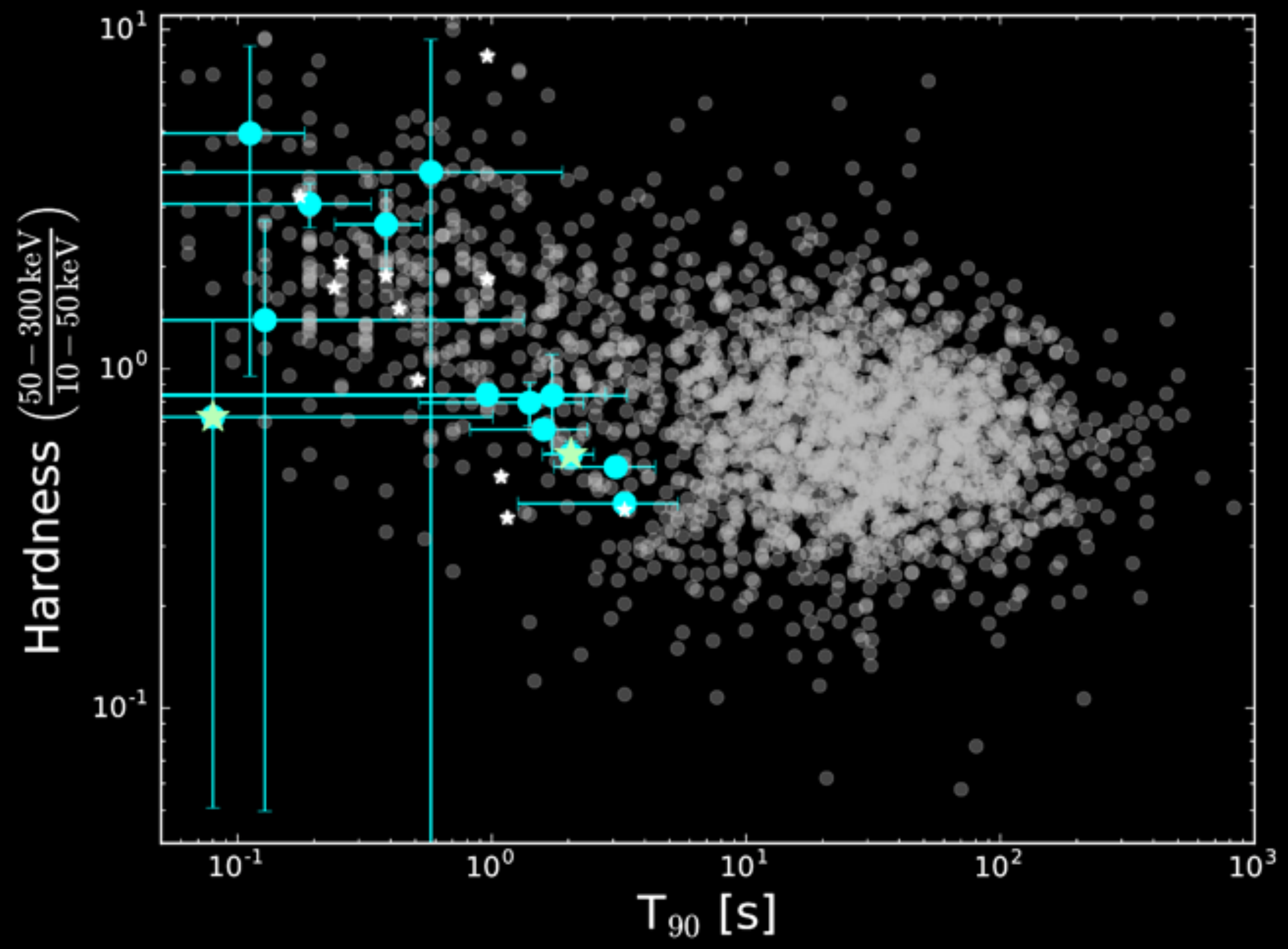
A Cautionary Tale on SAA Boundaries



GRBs Similar to 170817A

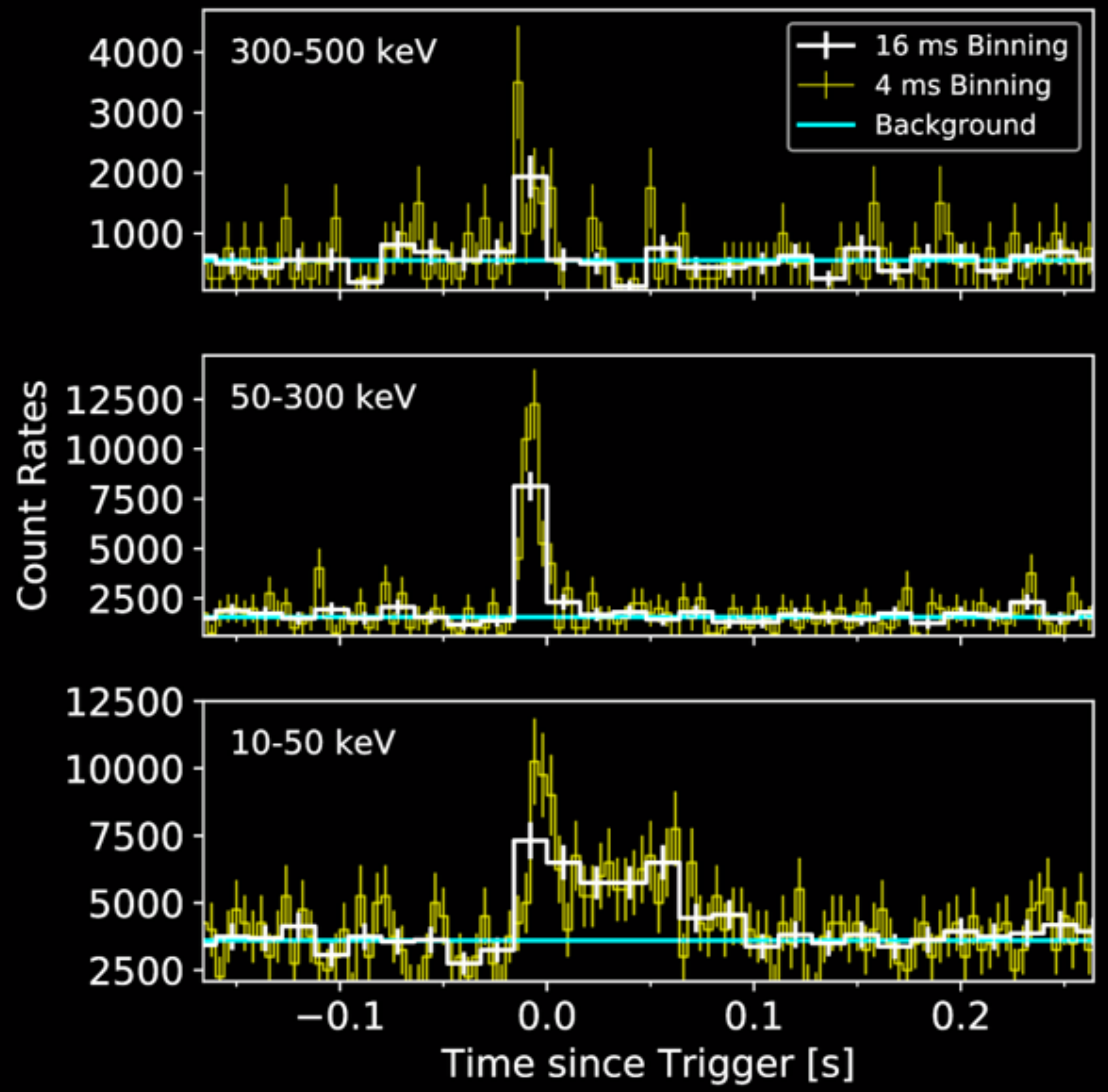
- Similar —> short and has a similar soft (blackbody?) tail
- 12 GRBs similar to 170817A (including 150101B) over 10 years
- Short GRBs ranging in duration from ~0.1 to ~3 s
- Tail not part of natural hard-to-soft spectral evolution observed in many GRBs

- Could be signatures of low-z binary neutron star mergers
- Most short GRBs do not have this observed tail, far away —> too weak to be observed?
- Only 170817A and 150101B have measured redshift



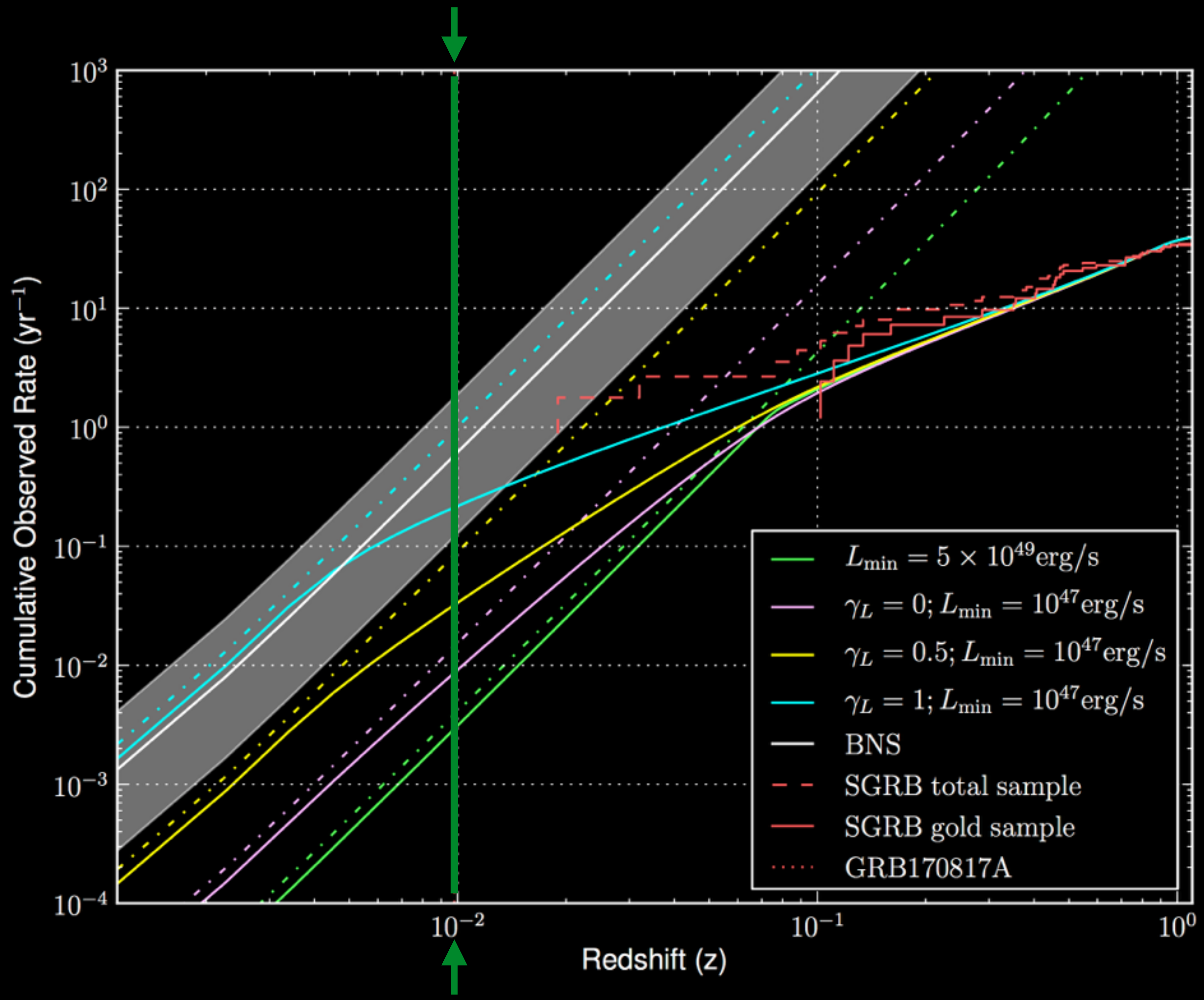
von Kienlin+ 2019, in press
arXiv: 1901.06158

GRB 150101B



Burns+ 2018, ApJL, 863, L34

Will We Ever See Another One?



- Short GRBs at < 40 Mpc are rare
- O3 Predicted Rates
  - GW detections of BNS: 1-50/year
  - GW-GRB detections: 0.1-1.4/year
- LIGO/Virgo Design
  - GW detections of BNS: 6-120/year
  - GW-GRB detections: 0.3-1.7/year