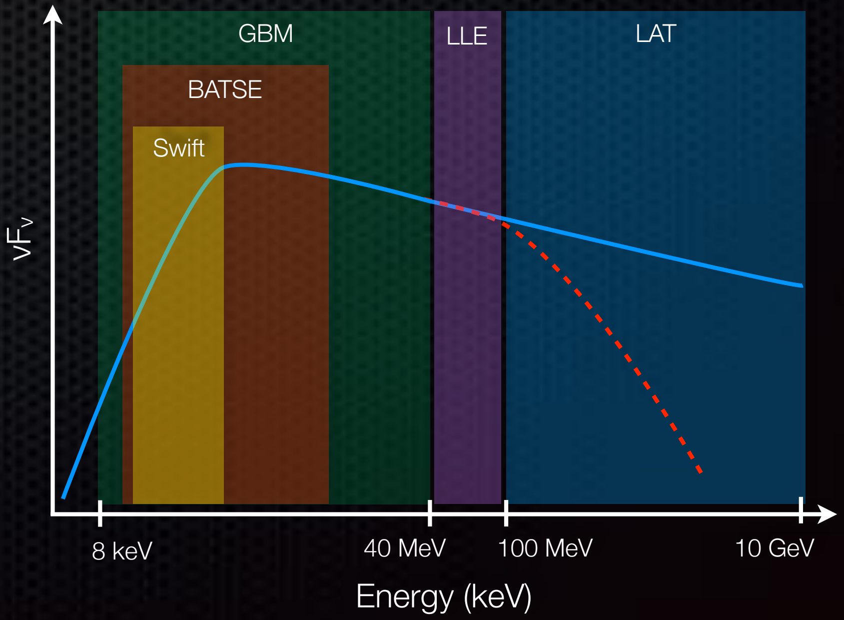
Searching for the origin of the high-energy emission from GRB 170817A

Daniel Kocevski

Marshall Space Flight Center

Fermi Gamma-ray Burst Monitor (GBM)

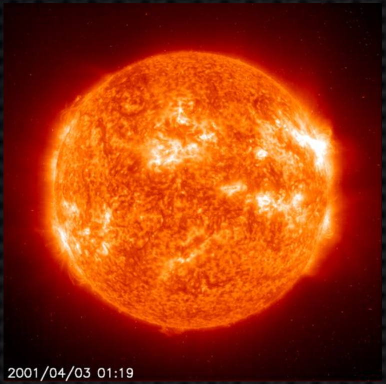
- Scintillation detectors
  - 12 NaI: 8 keV - 1 MeV
  - 2 BGO: 200 keV - 40 MeV
- Field of View
  - > 8 Src (unocculted sky)
- Energy/Temporal Resolution
  - CTTE: 2μs, 128 energy channels
- Triggering algorithms
  - Count rate increase in 2+ NaI detectors
  - 10 timescales: 16ms up to 4.096s
  - Energy ranges: 50-300, 25-50, >100, >300 keV



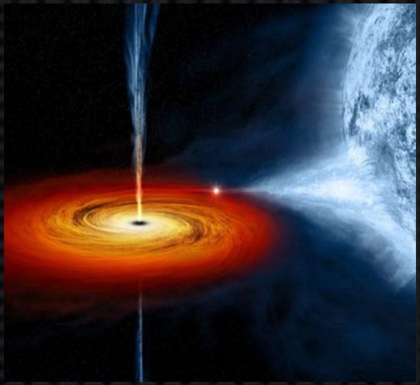
Transient Gamma-ray Sources

Terrestrial
γ-ray Flashes

Solar
Flares



X-ray Binaries

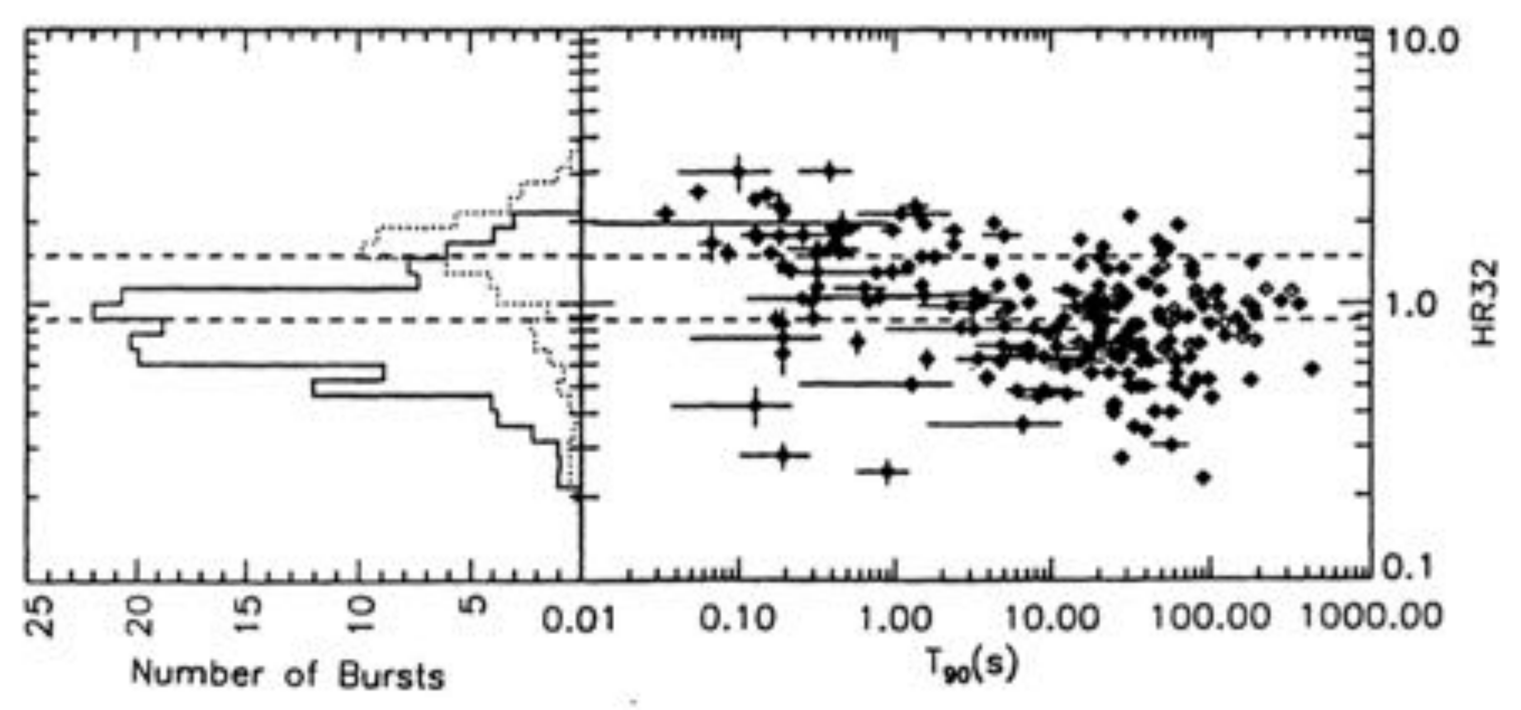


SGRs

Gamma-ray
Bursts

240 GRBs/year
(40 sGRBs/year)

Two GRB Populations

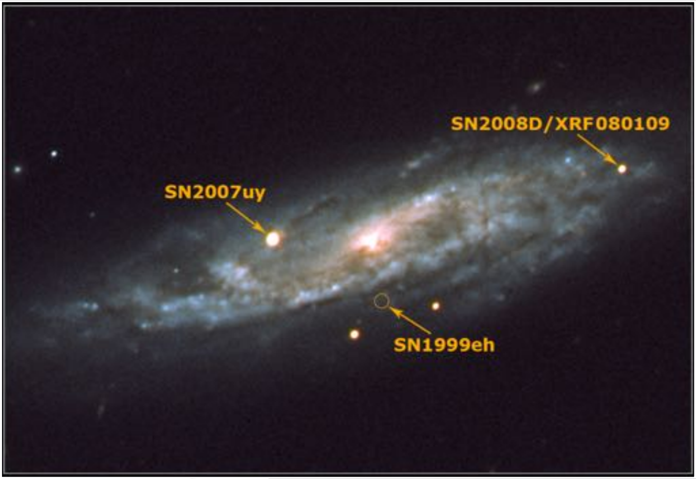


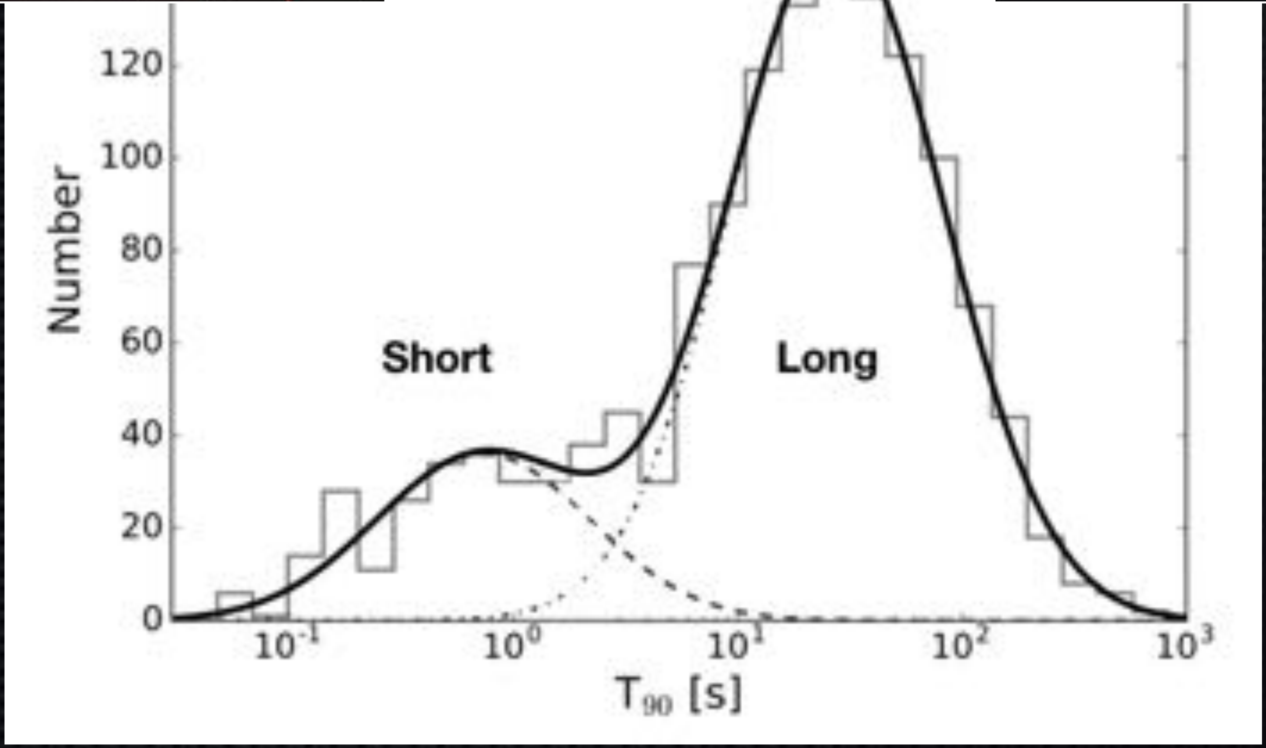
Kouveliotou et al. 1993

- Two populations of GRBs has long been understood to exist
- Evidence observed in Vela, KONUS, ISEE-3, PHEBUS and BATSE data
- Jay Norris and Tom Cline observed duration bimodality in Norris et al. 1984

Early-type galaxies

Late-type galaxies

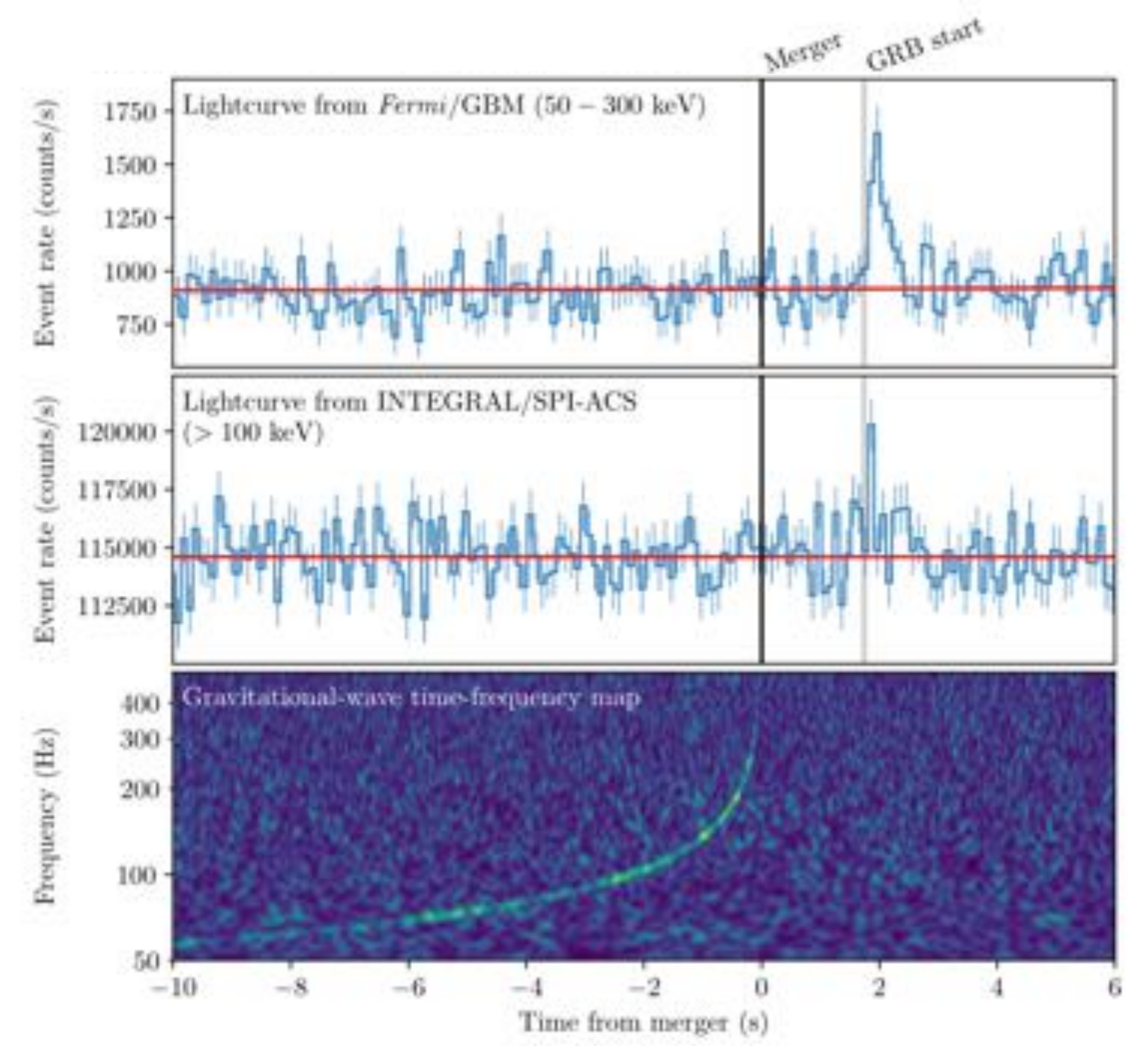




GBM Partnership With LIGO/Virgo

- GBM-LIGO MoU allows for a unique data sharing agreement
- GBM provides sub-threshold GRBs in low-latency for GW follow-up
- LIGO provide “sub-threshold” GW candidates below EM Follow-up threshold
  - In low-latency for autonomous targeted (seeded) GRB follow-up
- GBM detections would provide increased confidence in weak GW detections, effectively increasing the volume of the Universe accessible to LIGO/Virgo

GW170817 - First Joint GW/GRB

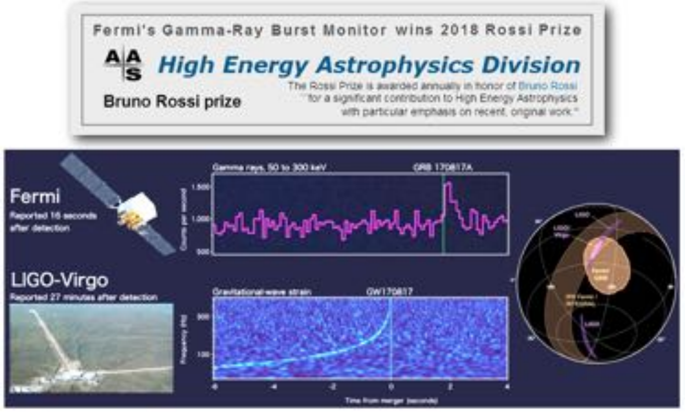


Abbot et al. 2017

GRB 170817A

- >80 papers coordinated for release
  - >3500 Authors, >900 Institutions
- GBM Team paper (Goldstein et al. 2017)
  - Summarized GBM observations
- Joint GBM/LIGO paper (Abbot et al. 2017)
  - Focused on joint EM-GW science
  - GRB theory, Speed of gravity, NES
- The detection was named the 2017 breakthrough of the year by Science
- Colleen Wilson-Hodge and the GBM team received the AAS 2018 Rossi price for the work
- Interesting questions remain about this event!

angular
tum



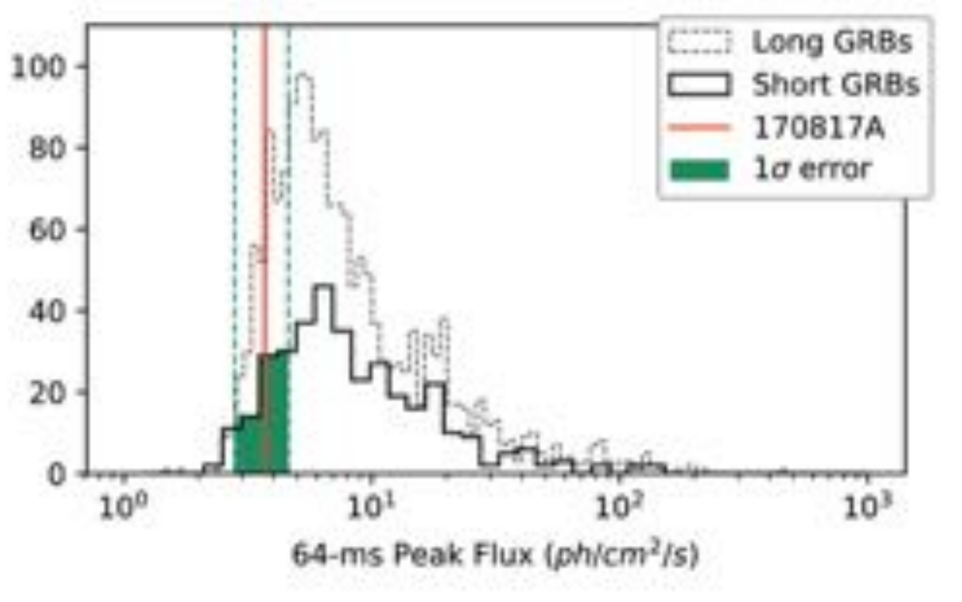
Fermi's Gamma-Ray Burst Monitor wins 2018 Rossi Prize

High Energy Astrophysics Division

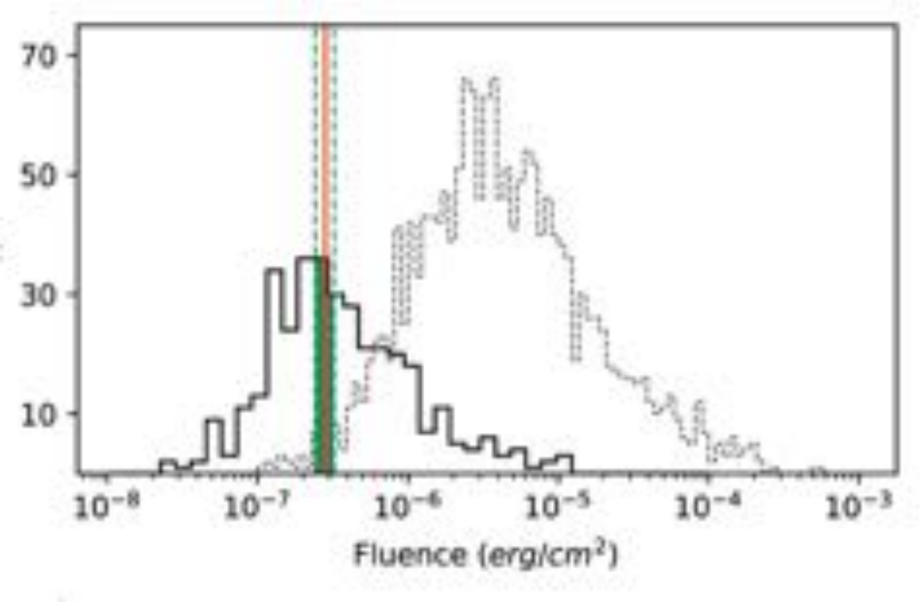
Bruno Rossi prize

The Rossi Prize is awarded annually in honor of Bruno Rossi "for a significant contribution to High Energy Astrophysics with particular emphasis on recent, original work."

Spectral Properties



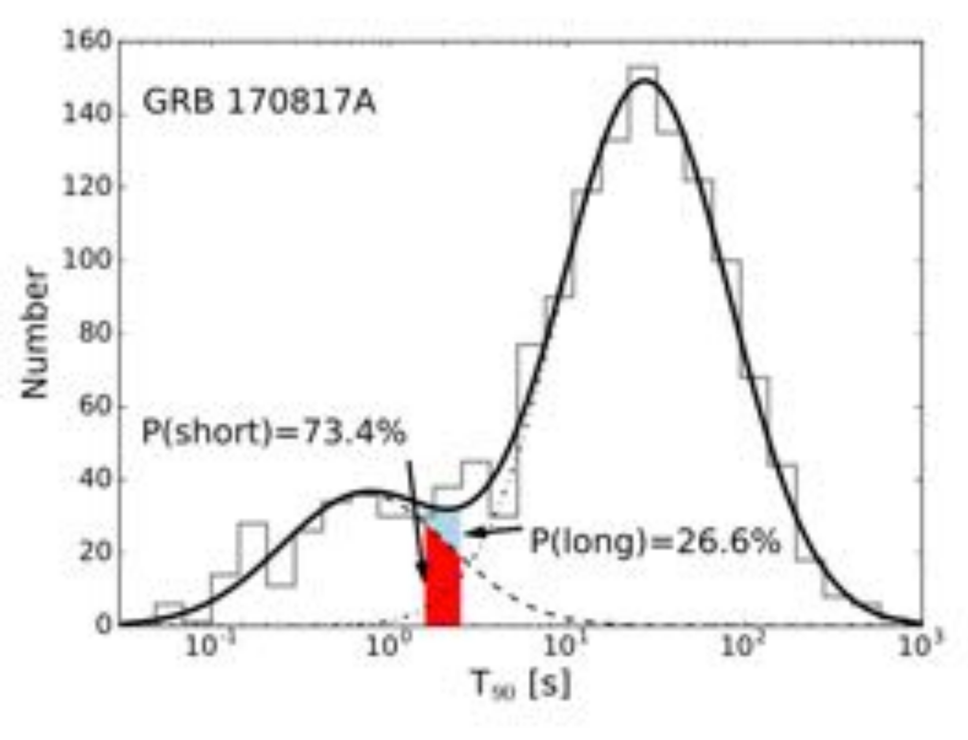
Goldstein et al. 2017

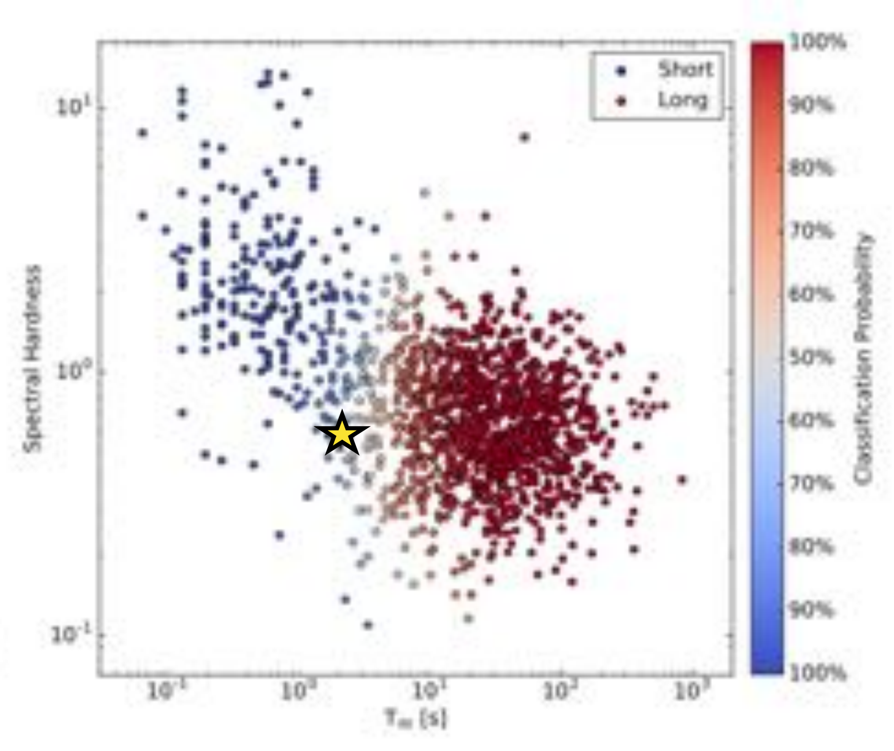


Goldstein et al. 2017

- Using the standard GBM catalog analysis, GRB 170817 does not look particularly unique
- Average fluence for a short GRB compared to the catalog distribution
- Relatively weak in peak flux
    - In the lower third in the 64ms peak flux distribution
- It appears as a typical SGRB in the observer frame

Duration/Hardness

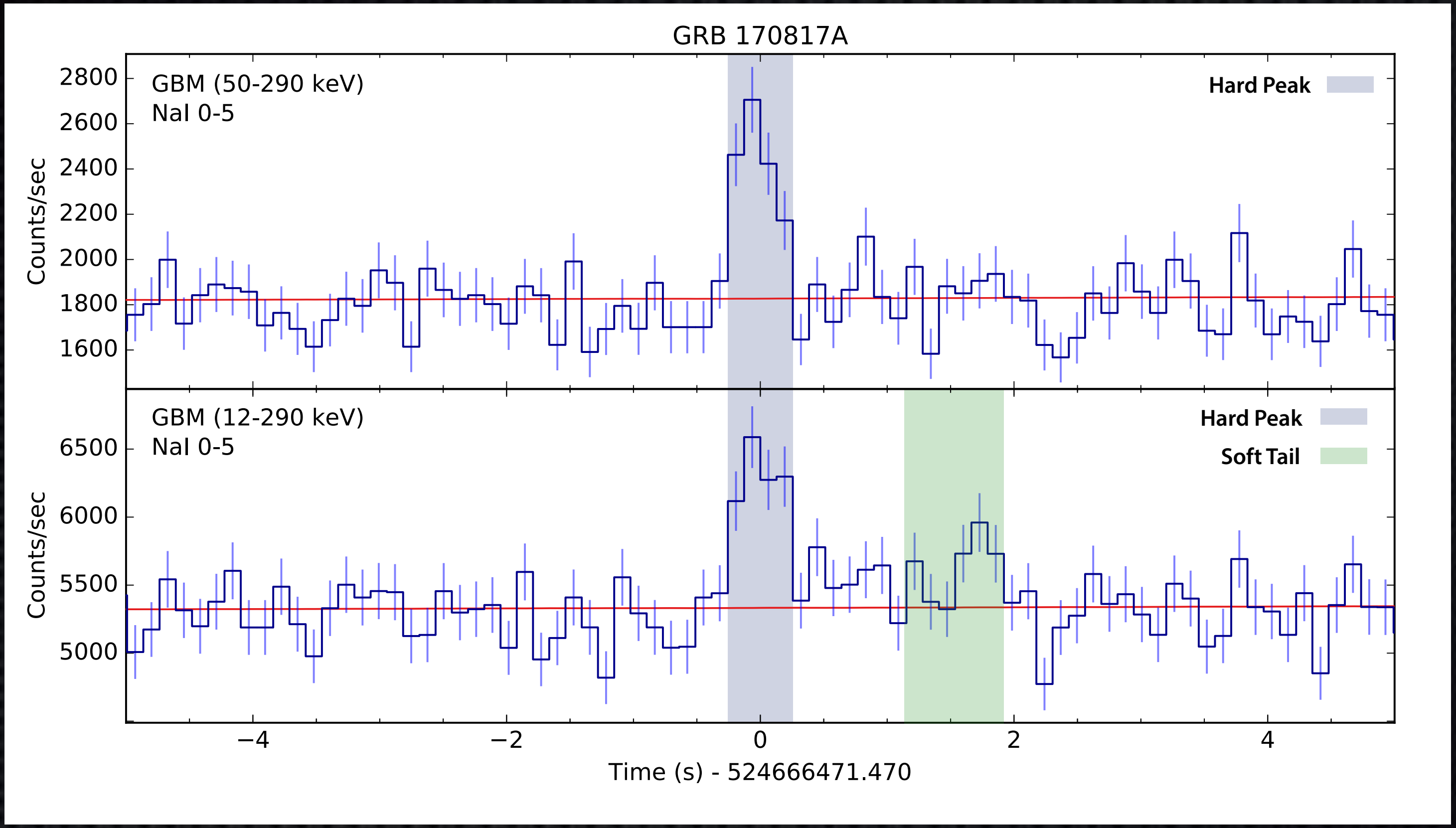




Goldstein et al. 2017

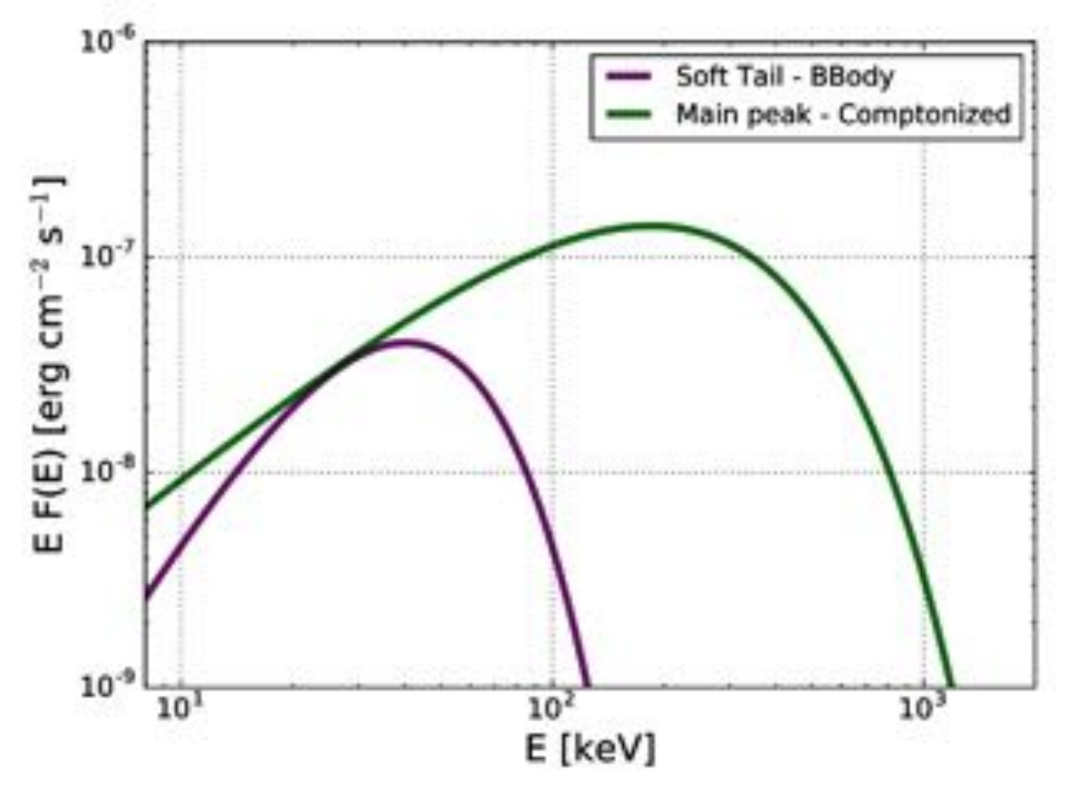
- A standard catalog analysis using 50-300 keV photons yields a $T_{90} = 2.0 \pm 0.5$
- Combining both the duration and hardness information, we get $P_{short} = 73.4\%$
- Hardness ratio between the 50-300 keV and 10-30 keV photons yields a relatively soft burst

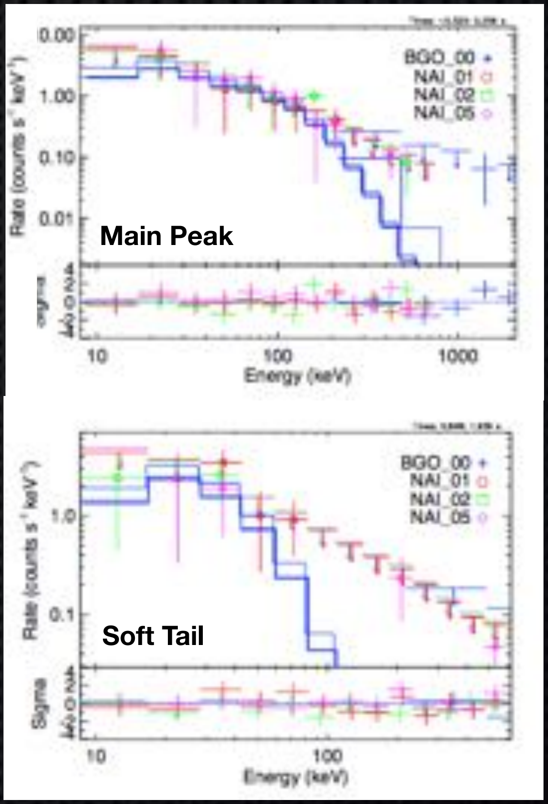
Hard Pulse and Soft Thermal Tail



- Burst appears as a single component in the 50-300 keV energy range
- Two components emerge when including photons in the 10-50 keV energy range
- Initial hard pulse with a delayed and much softer tail

Spectral Properties

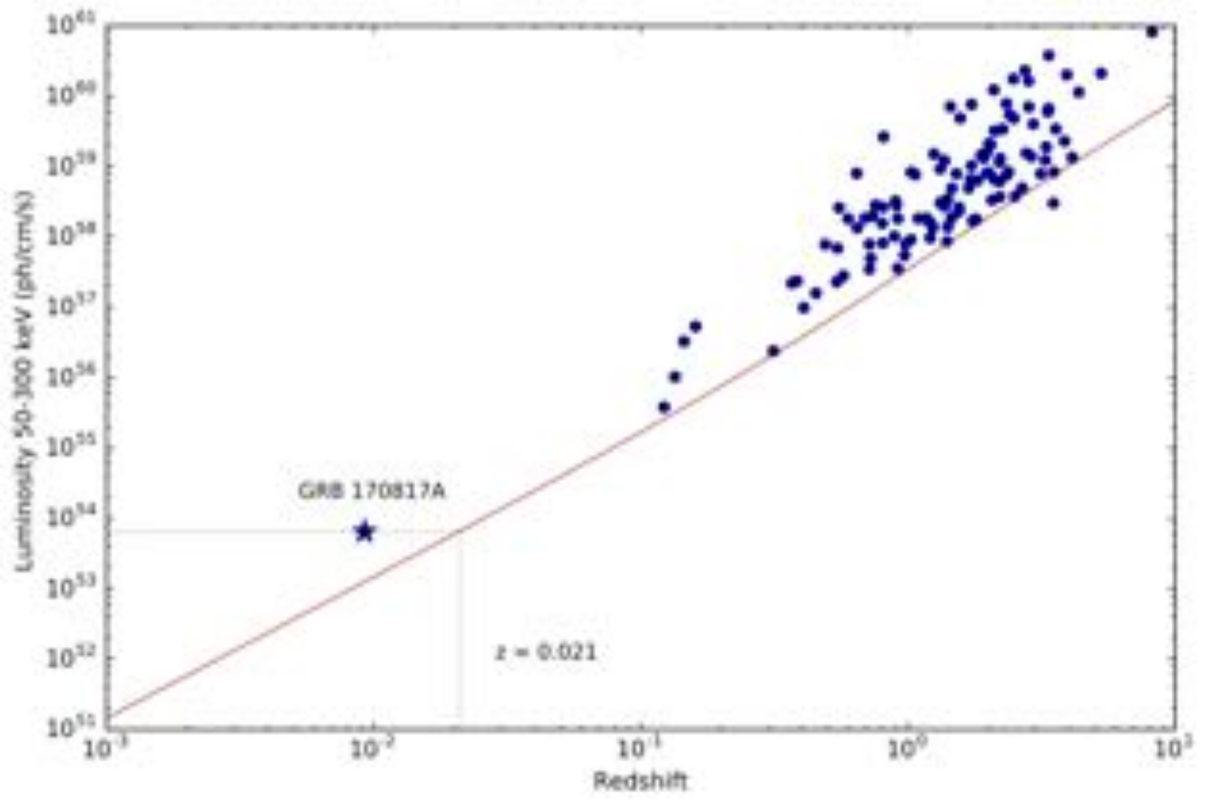




Goldstein et al. 2017

- The main hard peak is best fit with a Comptonized model with E_{pk} = 185 ± 62 keV
- The soft tail is best fit by a black body with kT = 10.3 ± 1.5 keV
- Spectra with photospheric components have been seen (e.g. Ryde, Guiriec, etc), but not in this order

Source Frame Energetics



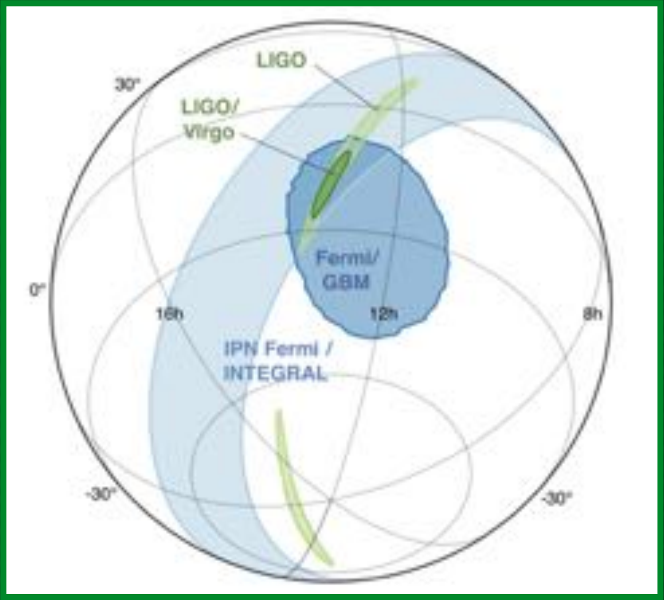
- GRB 170817 was extremely under luminous compared to other GRBs
  - It was the closest and least luminous GRB ever detected
- Estimated isotropic-equivalent energy is ~2-3 orders of magnitude lower than previous observations
- This observations combined with the late-time emission hints at the viewing geometry

```
//////////////////////////////////////////////////////////////////////
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.
```

GBM Alert

First On-board GBM Localization

LIGO Report of coincident GW/GRB



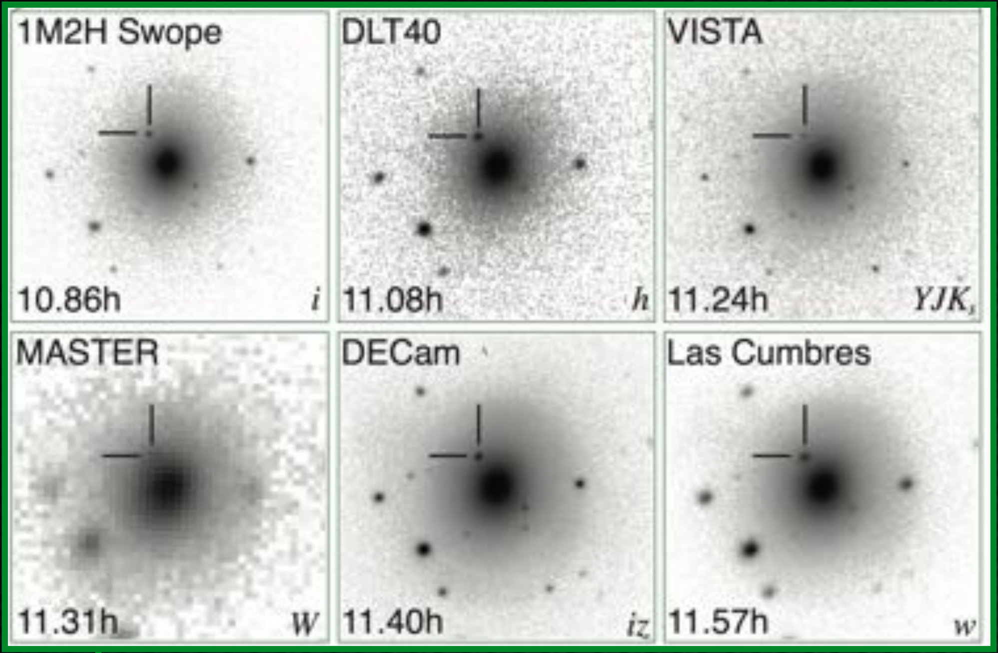
Joint LIGO/ Virgo sky map

+16 s

+27 s

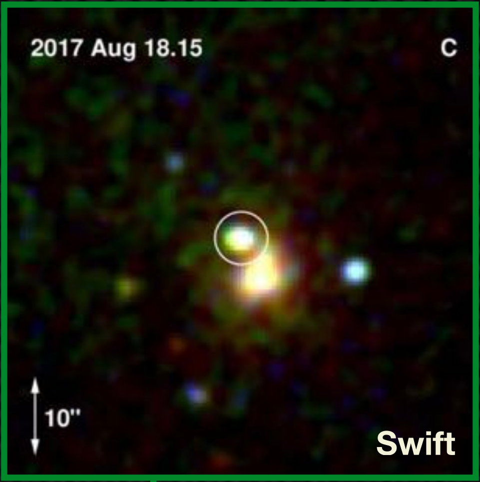
+45 min

+5 hour



Reports of a blue optical transient near an elliptical S0 type galaxy NGC 4993 at ~40 Mpc (Abbot et al. 2017).

Discovery credit goes to Coulter et al. (2017) who observed the region with the 1m Swope telescope at Las Campaas Observatory



Swift observations reveal bright, but quickly fading, UV source with no evidence of X-ray emission (Evans et al. 2017)

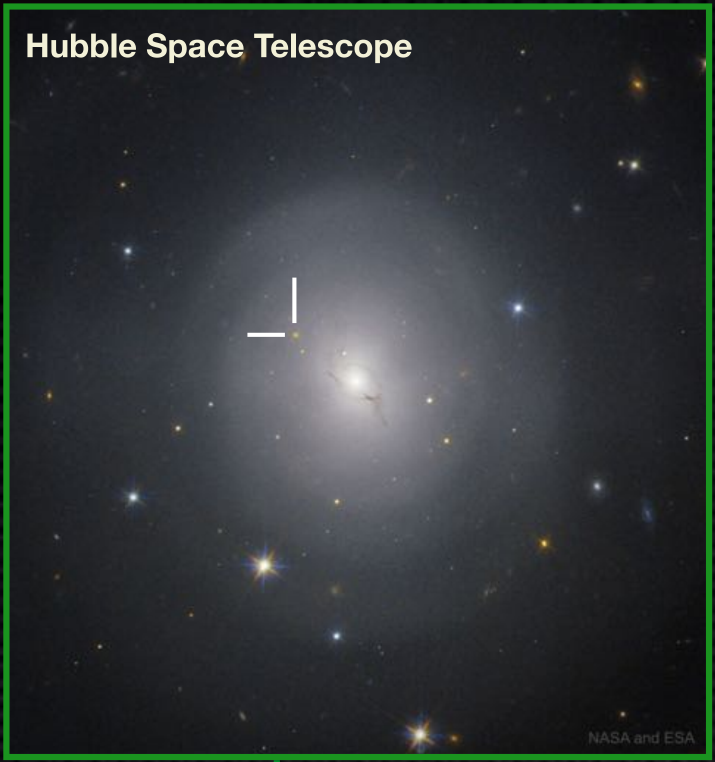
NuStar observations show no X-ray emission (Evans et al. 2017)

+12 hours

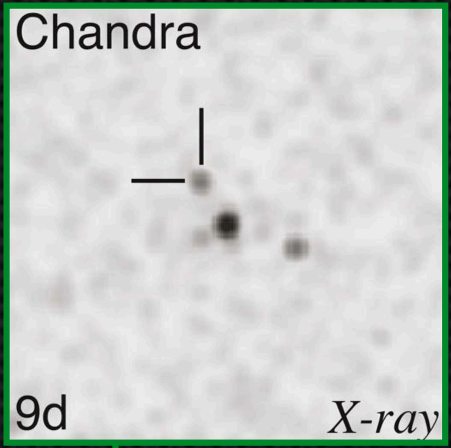
+13 hours

+14 hours

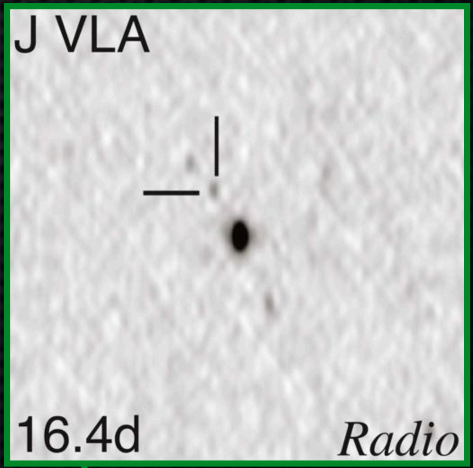
Chandra observations show no X-ray emission (Fong et al. 2017)



Hubble observations reveal a reddening source (Adams et al. 2017)



Chandra observations reveal first evidence of delayed X-ray emission (Troja et al. 2017)



Radio counterpart reported by VLA (Mooley et al. 2017)

+2 days

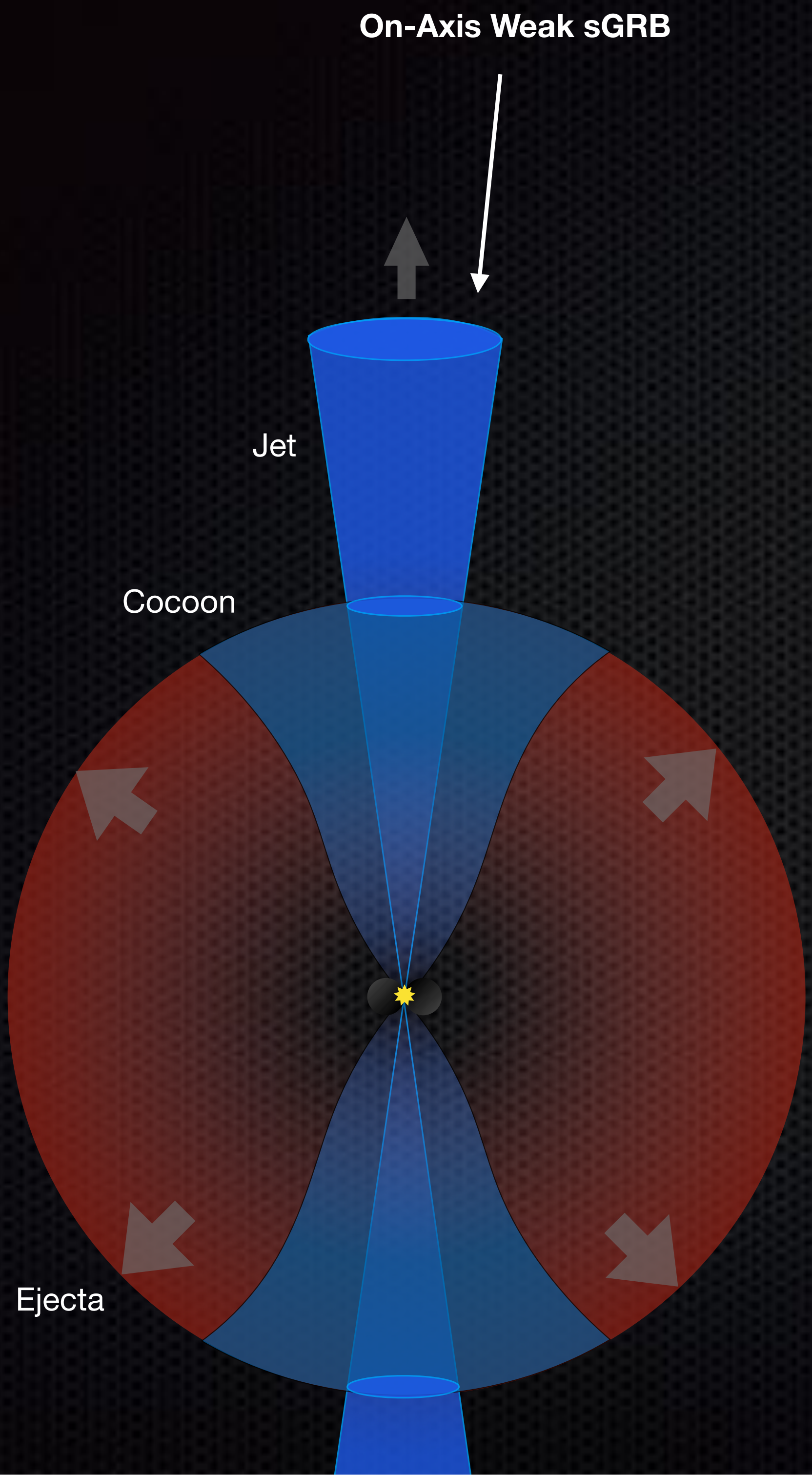
+5 days

+9 days

+16.4 days

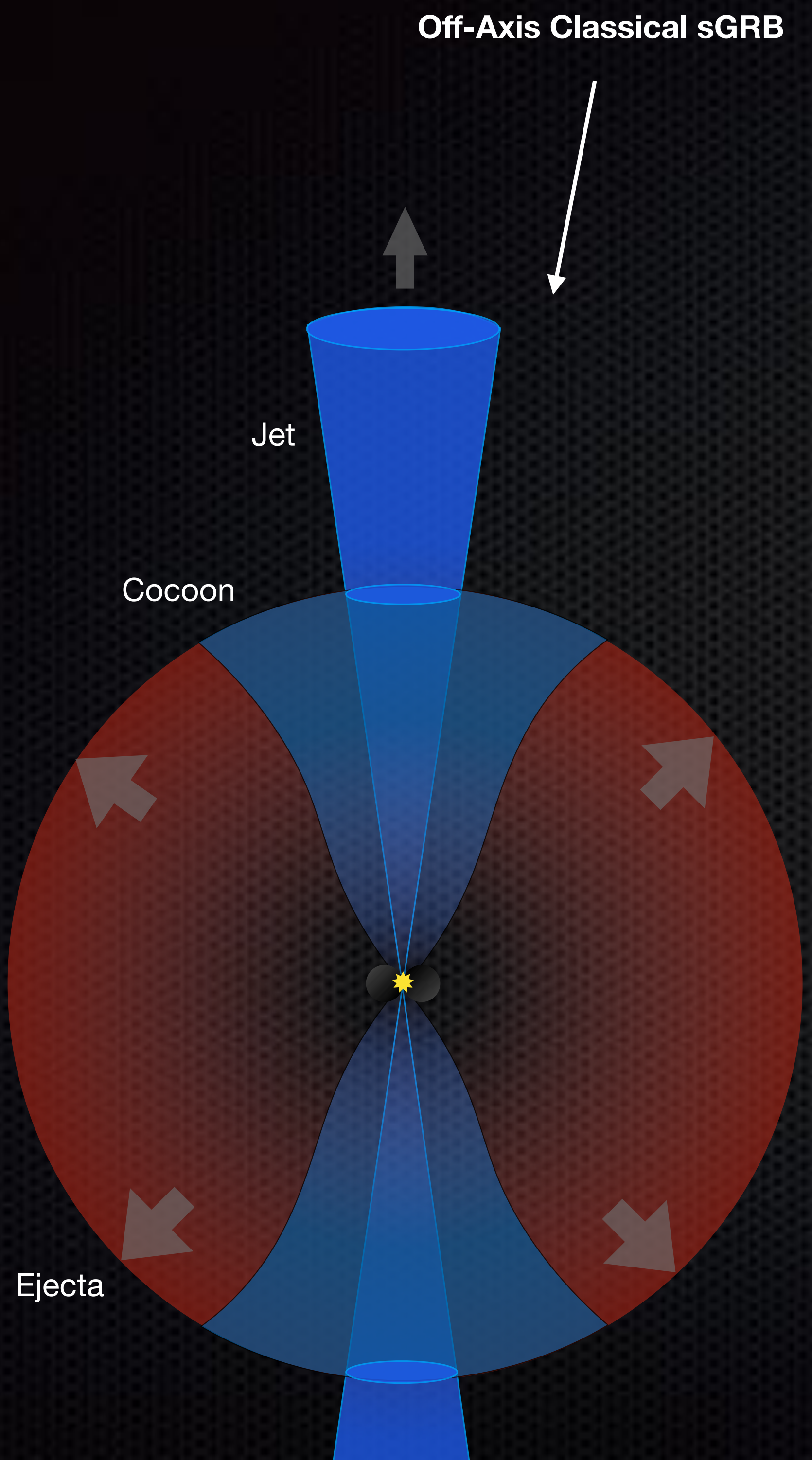
Kilonova

- The production of heavy elements through rapid neutron capture (r-process) and their eventual decay
- Red kilonova is expected from lanthanide-rich dynamical ejected via processes such as tidal forces
- Blue kilonova could be due a lanthanide-poor wind driven outflow or cooling of shock-heated ejecta
- What does this tell us about the gamma-ray emission? There are multiple plausible explanations



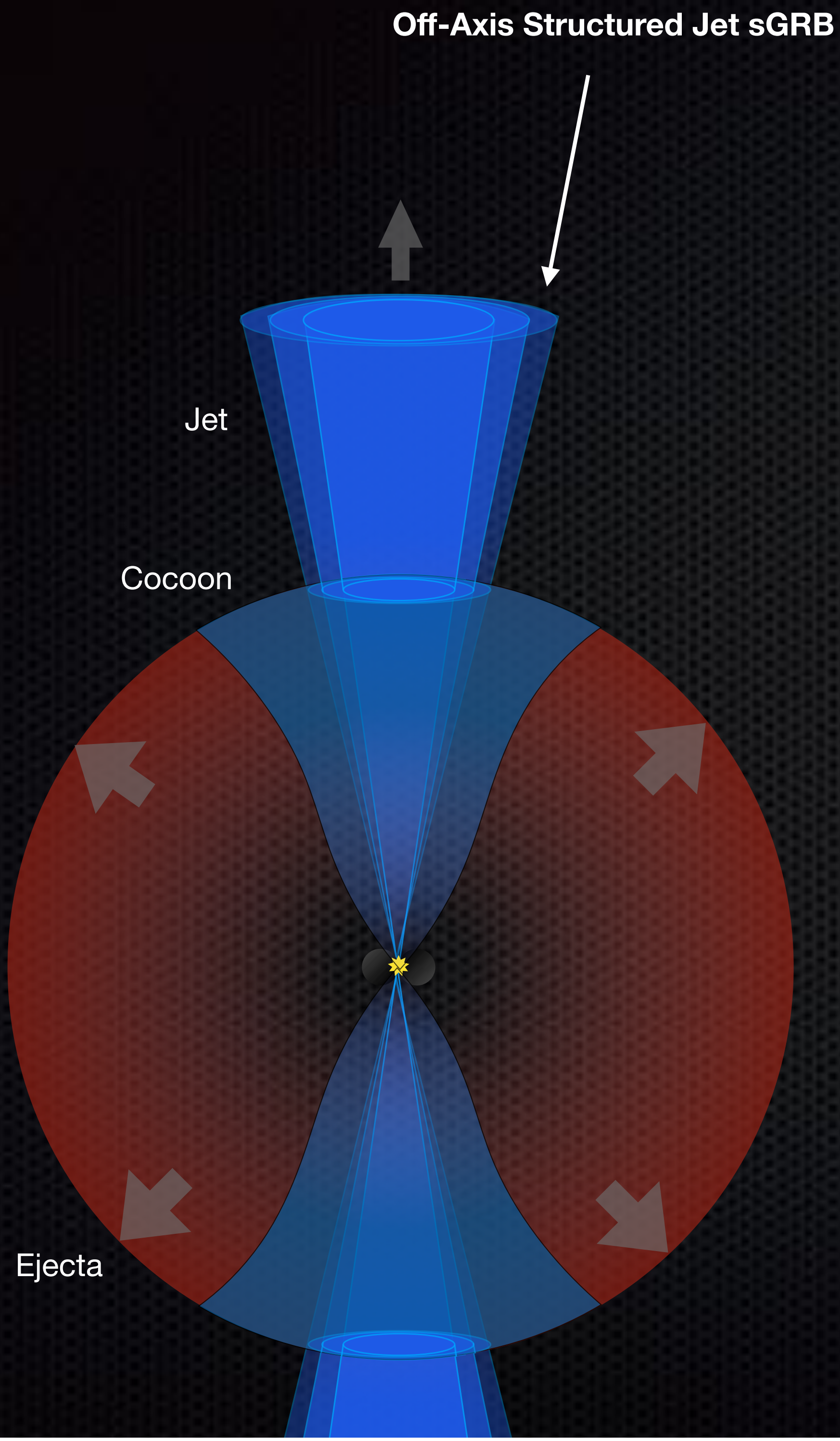
On-Axis Weak sGRB

- We simply observed a top hat jet on the low end of the GRB luminosity function
- Pros:
  - Logical starting point
  - GW-EM delay is on the order of T90
- Cons:
  - Cannot explain the late-time X-ray and radio observations
  - Not clear how to produce delayed thermal emission
  - Would require very low ejecta mass to allow the low-energy jet to successfully breakout
- GW: $\theta_v \sim 29^\circ +15^\circ/-10^\circ$ (LIGO - arXiv:1805.11579v1)
  - Average sGRB is $\theta_{jet} \sim 16^\circ$ (Fong et al. 2015)



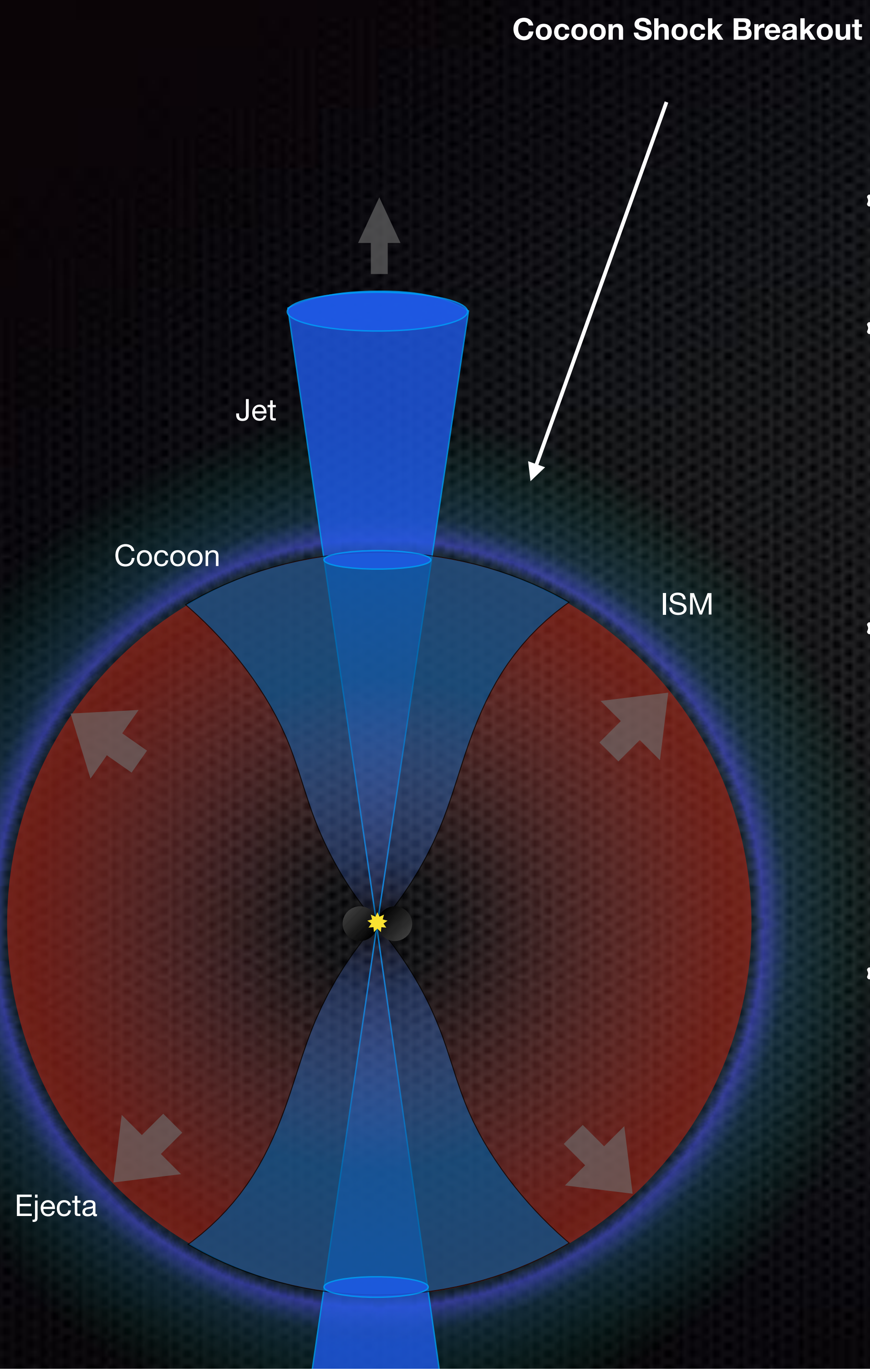
Off-Axis Classical sGRB

- We observed outside the jet of a classical sGRB
- Pros:
    - Can naturally explain the lower energetics
    - Thermal emission could be from the GRB photosphere or the cocoon
- Cons:
    - Observed Epk & Eiso drop very quickly outside θ_{jet}
        - θ_v would need to be just outside the jet edge
    - The on-axis Epk would be on the high end of the observed GBM catalog distribution
    - Expect bright afterglow in X-ray after ~1 day



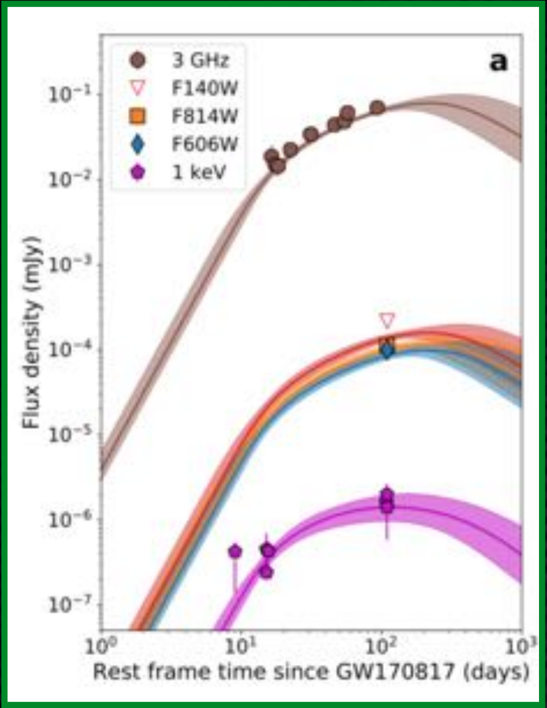
Off-Axis Structured Jet sGRB

- We observed the less energetic region of a structure jet where the Lorentz factor decreases with θv
- Pros:
  - Could produce arbitrary Epk and Eiso values
  - GW-EM delay is on the order of T90
  - Thermal emission could be from the GRB photosphere or the cocoon
- Cons:
  - Not entirely clear how such wings are generated or what their Lorentz profiles look like
  - On-axis Eiso would still need to be relatively low
- Predictions
  - Afterglow should peak and fade as the jet decelerates and we see the more energetic core region of the jet
  - VLBI imaging would reveal proper motion of the jet



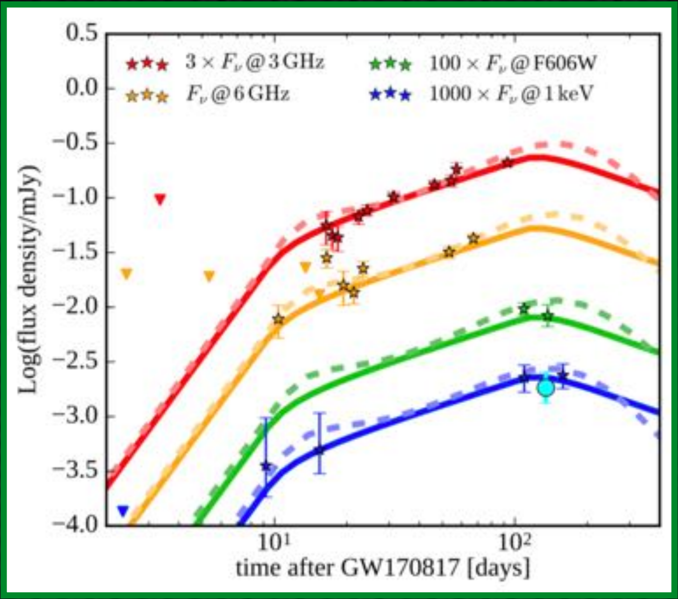
Cocoon Shock Breakout

- Hard emission from mildly-relativistic shock breakout and thermal emission from cocoon
- Pros:
  - Can naturally explain the lower energetics
  - Could naturally explain both hard and thermal components
- Cons:
  - Cannot explain very high Epk values
  - Difficult to explain fast variability
  - Should overproduce look alike sGRBs
- Predictions:
  - Late time x-ray and radio should rise for months to years as the cocoon interacts with the ISM
  - Quasi-spherical outflow should not produce any proper motion in VLBI imaging



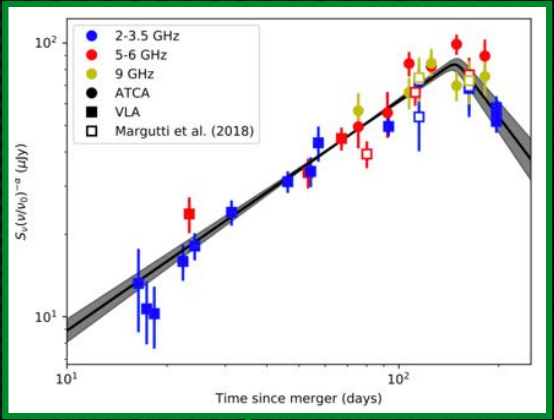
HST and *Chandra* observations continue to show rising afterglow flux (Lyman et al. 2018, Ruan et al. 2018, Troja et al. 2018)

+100 days



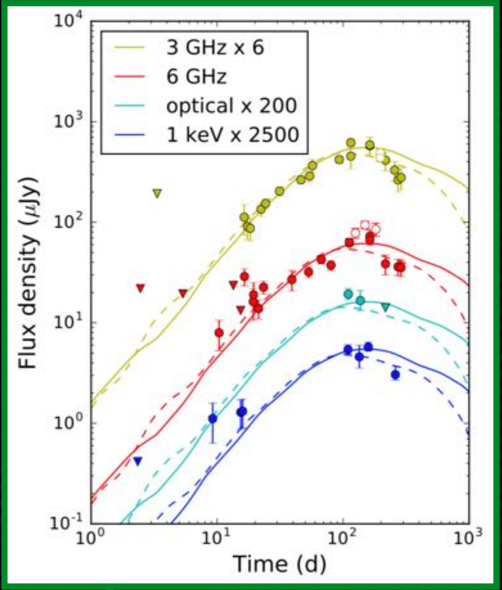
Hints of a plateau in x-rays (D'Avanzo et al. 2018) and radio (Resmi et al. 2018)

+135 days

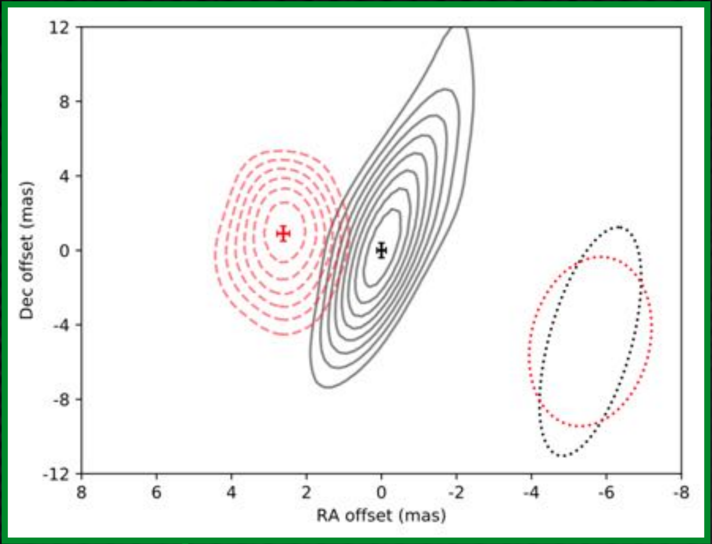


Evidence for a turn over in radio (Dobie et al. 2018)

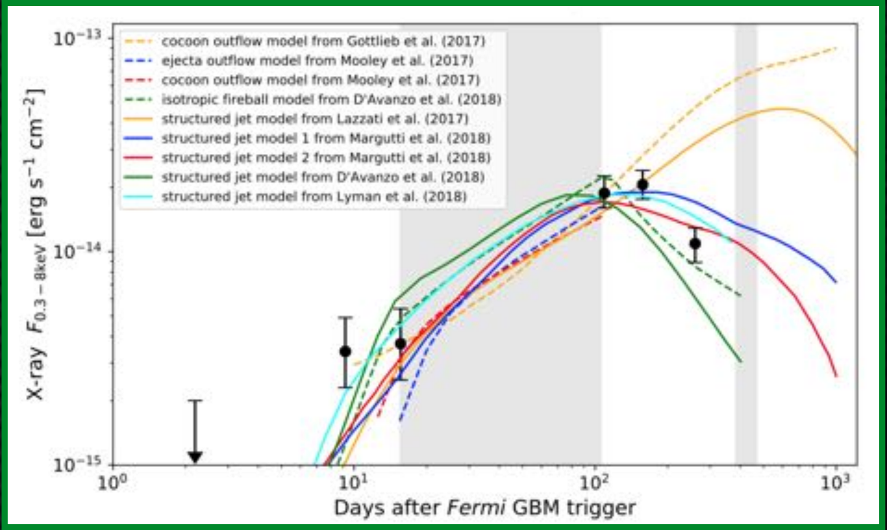
+150 days



Further evidence for a turn over (Alexander et al. 2018)



Superluminal motion of the unresolved radio source and undeniable evidence of a off-axis jet (Mooley et al. 2018)



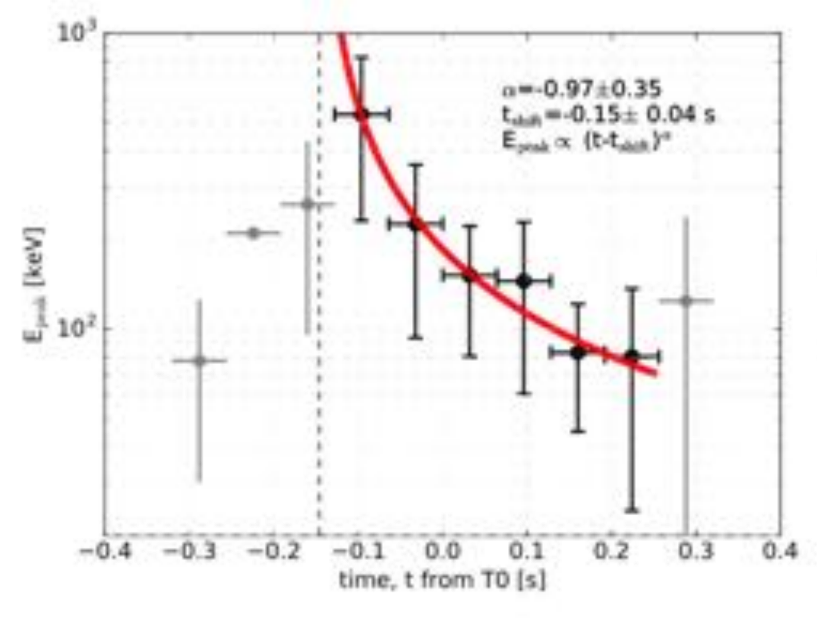
Cocoon is ruled out at late times, but it could still explain prompt and early afterglow (Nynka et al. 2018, Mooley et al. 2018)

+220 Days

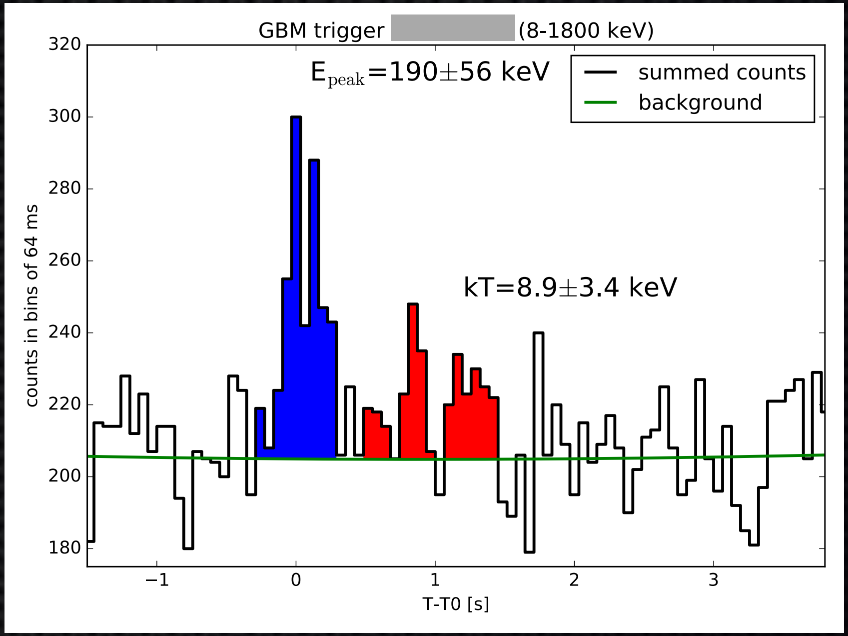
+230 days

+260 days

Challenging Gamma-ray Observations



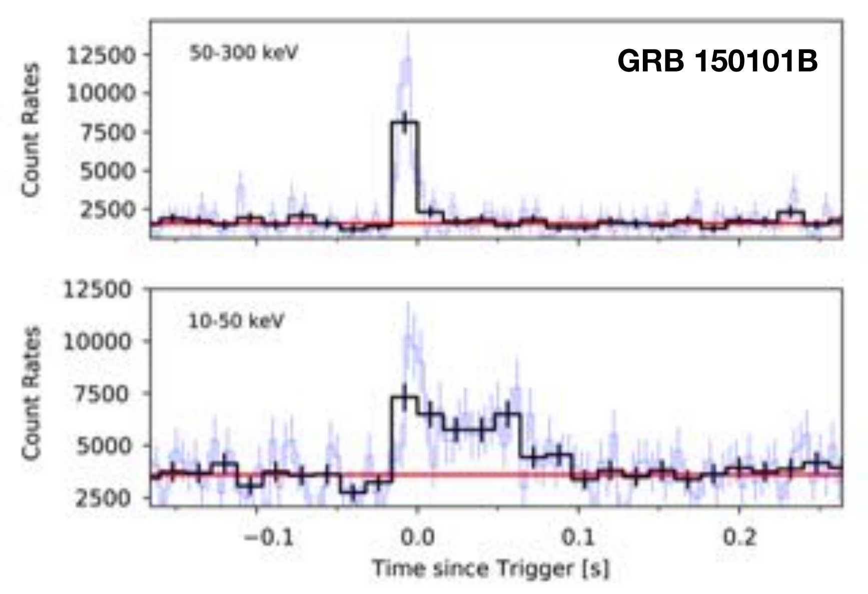
Veres et al. 2018



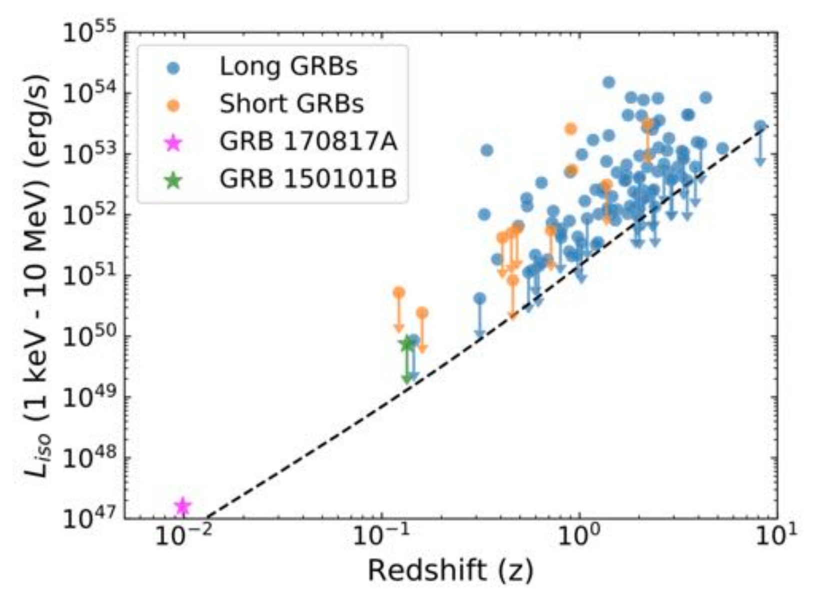
Von Kienlin in prep.

- A time resolved spectral analysis has shown evidence for very high Epk values
- High Epk values become challenging for the cocoon shock breakout model to explain
- We have found bursts that resemble GRB 170817 in BATSE, GBM, and Swift data
- Very preliminary, but evidence for sub-structure in some of these cases

GRB 150101B



Burns et al 2018

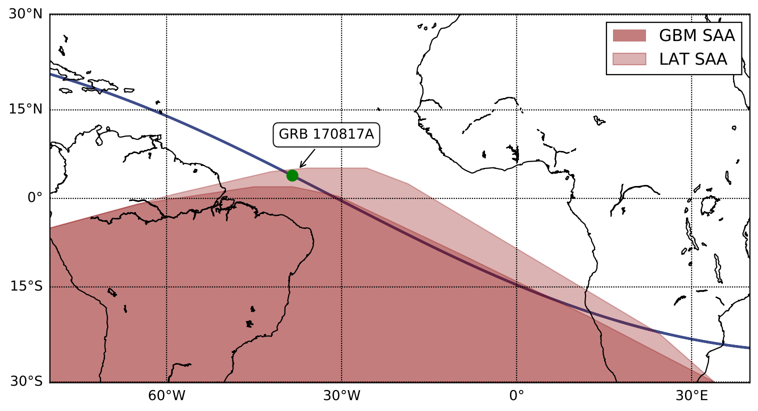


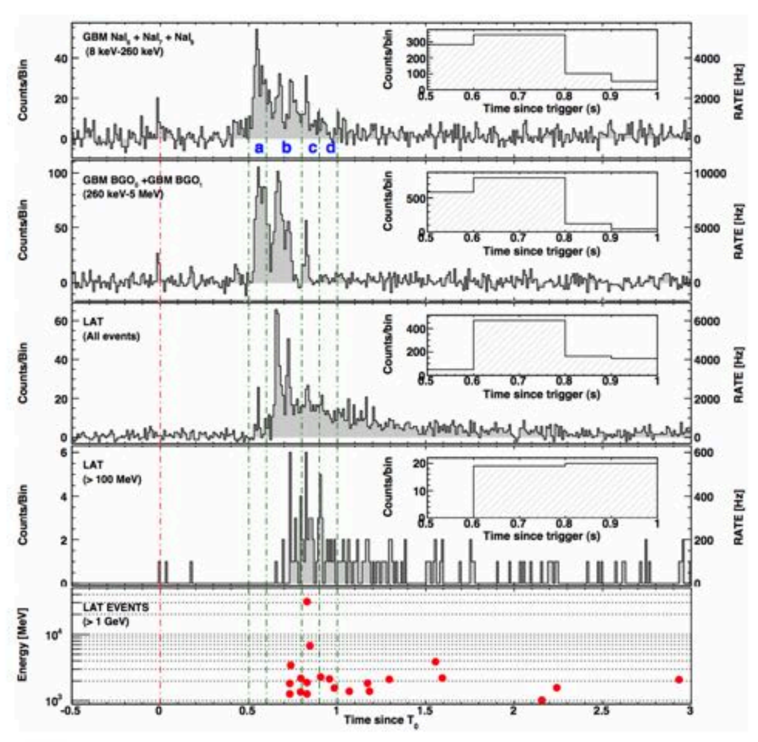
Burns et al 2018

- Eric Burns led a paper on the study on the third closest SGRB with known redshift - GRB 150101B
- Very hard initial pulse with Epk =1280±590 keV followed by a soft thermal tail with kt~10 keV
- Unlike GRB 170817, 150101B was not under luminous and can be modeled as an on-axis burst
- Suggests that the soft tail is common, but generally undetectable in more distant events
- Thermal tail can be explained as GRB photosphere, but degeneracy with the cocoon model still exists

Things to look for in O3

- Several high-energy observations should be able to help discriminate between jet and shock breakout emission
- Observation of MeV/GeV emission from such an event would be impossible to explain from a cocoon alone
  - Would require inverse Compton scattering of the cocoon emission by relativistic particles which would impart a distinct spectral shape
  - We have never seen evidence for IC emission in GRBs
- Observation of high time variability in GBM data would also effectively rule out shock breakout and/or cocoon emission
- Ratio of BNS mergers with/without a gamma-rays will allow us to estimate the average beaming angle of SGRB jets and the isotropy of any cocoon like emission
- Observation of gamma-ray signal with a long tail and no red kilonova would be a evidence for a long lived HMNS
- Ultimately we need more observations of joint NS-NS mergers to definitely address these open questions





GRB 090510

Ackermann et al. 2010

Conclusions

- GRB 170817 may have been the best observed transient in the history of astronomy
- Despite this, many questions regarding its nature still remain
- The GBM observations show GRB 170817 to be a normal sGRB in observer frame
- Source frame energetics and non-standard analysis reveal unique peculiarities
- The exact origin of the observed gamma-ray emission is still in question
- An off-axis structured jet or shock breakout from an energetic cocoon could work
- Recent GBM observations reveal prompt gamma-ray emission that is in tension with the cocoon model
- Late time x-ray and radio observations support an off-axis structured jet as well
- Need to find more sGRB counterparts to GW detections to answer these questions!
- Lots of exciting work to be done in O3!