An Overview of Gamma-ray Bursts Detections

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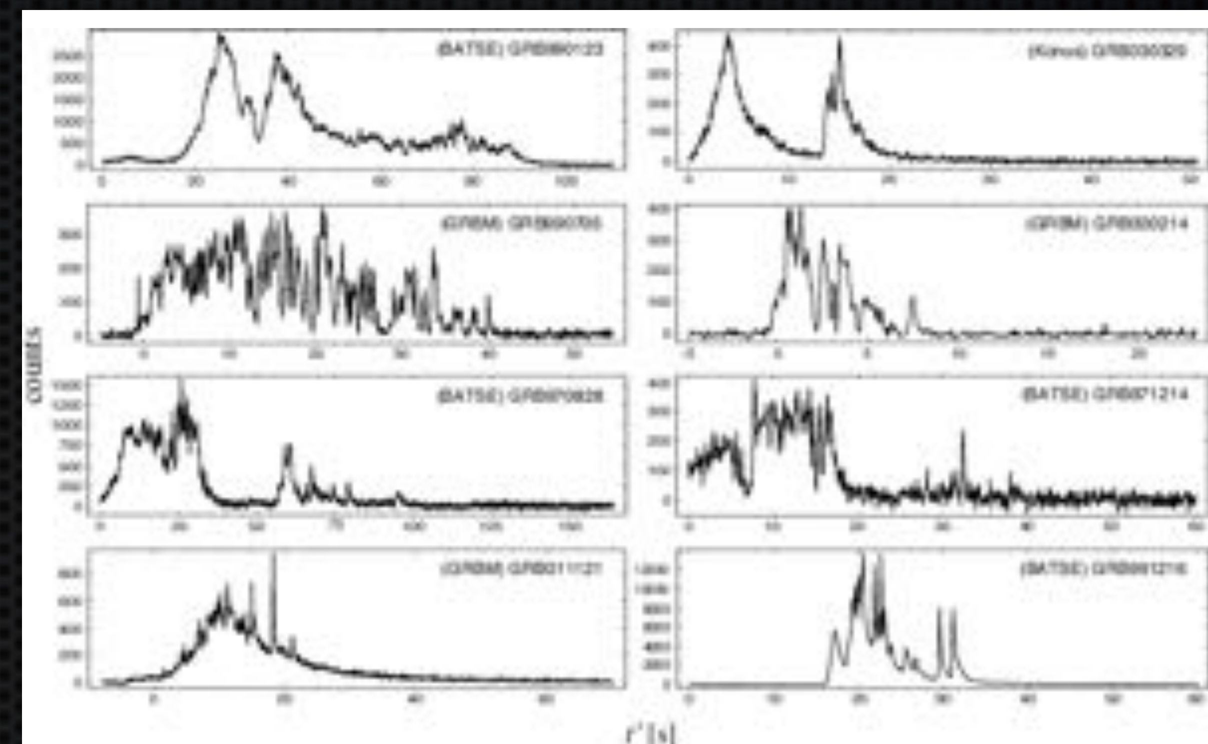
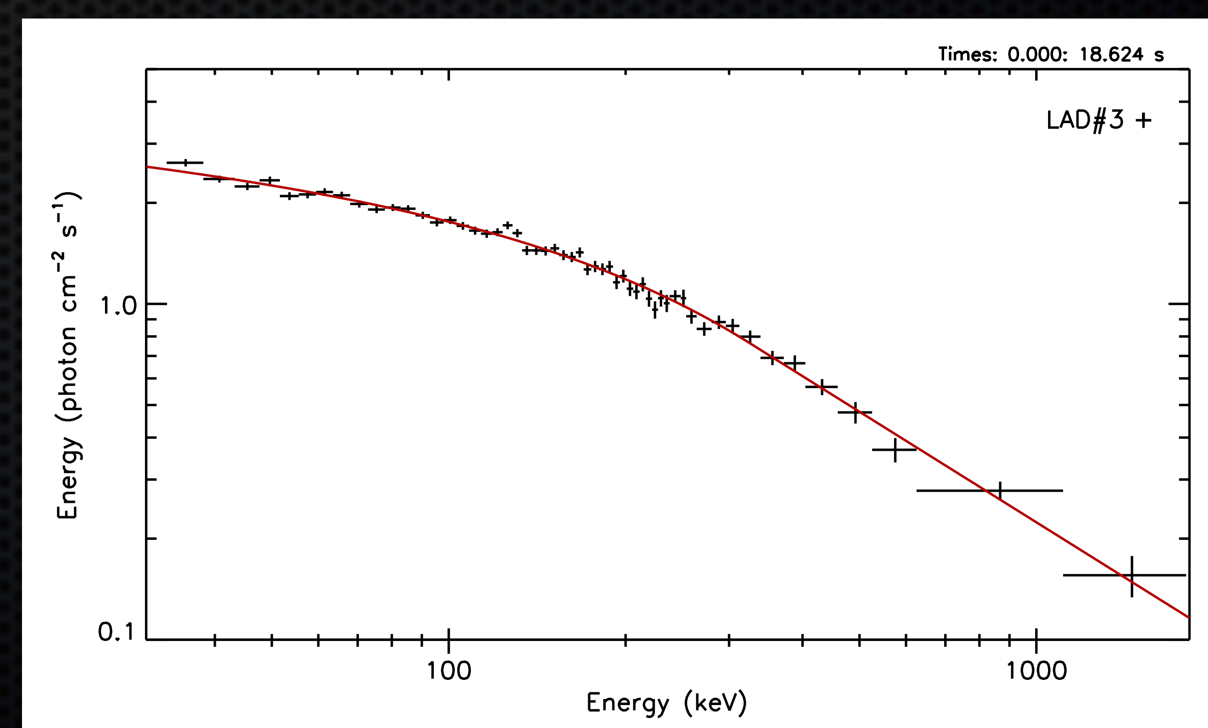
Gamma-ray Burst Overview

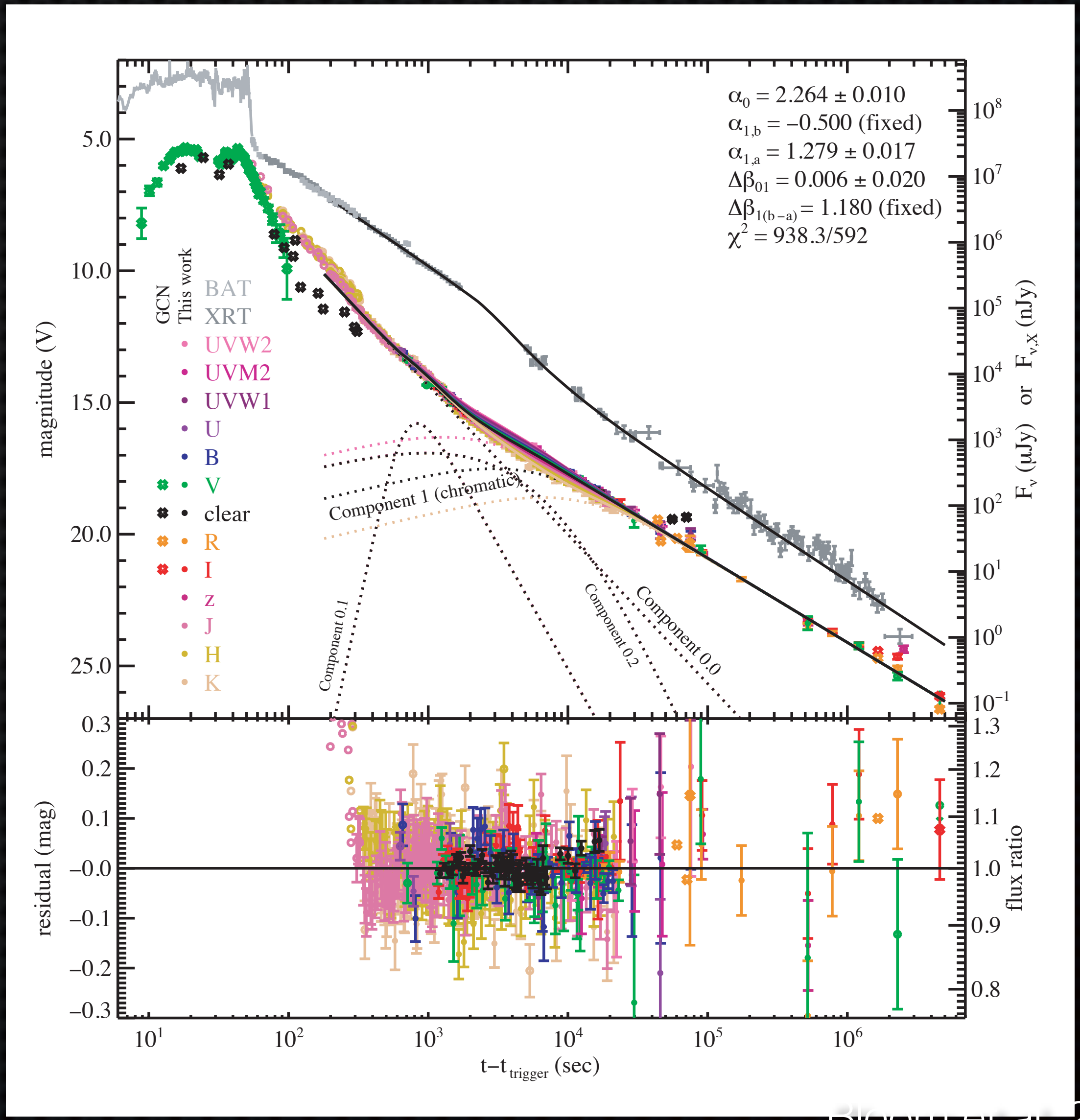
- Intense flashes of gamma-rays
  - Observed rate ~ 1/day
  - Highly time variability
  - Total durations of 1s-100s
- High energies, fast variability
  - Assumed relativistic
- Homogenous, non-thermal spectra
  - Peak νF_ν ~ 250 keV
- Isotropic sky distribution





Long Lived Afterglows

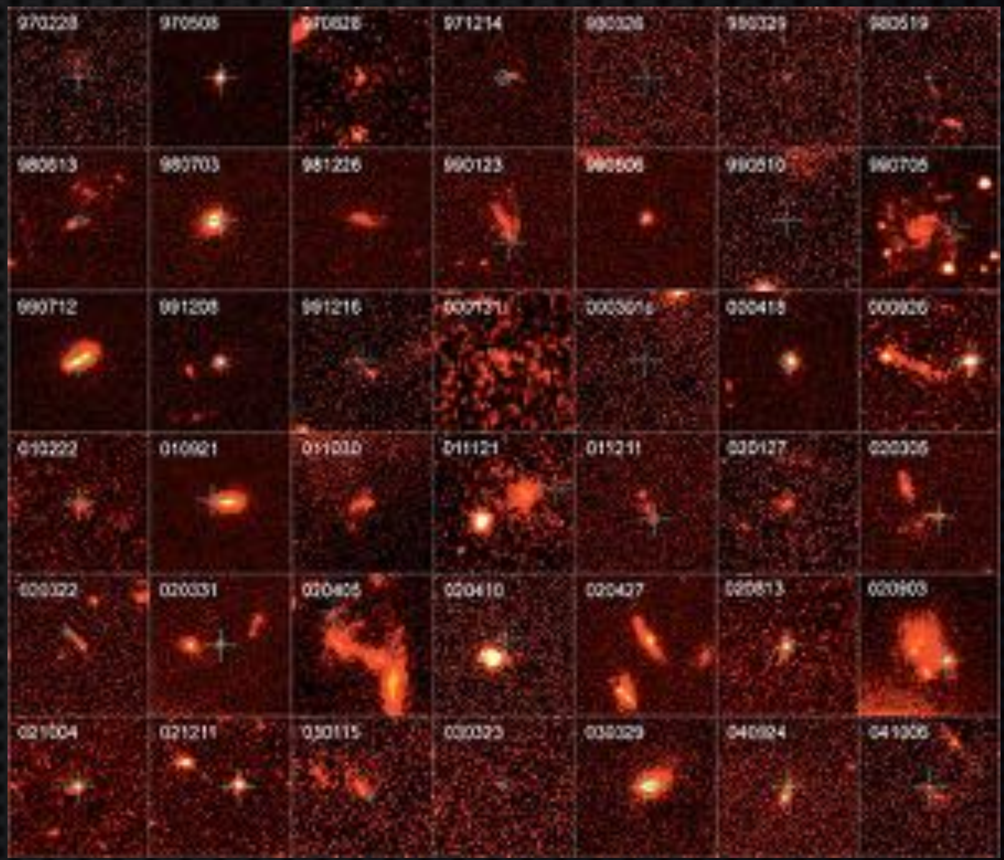
- Long-lived afterglows (x-rays, optical, radio)
  - Lasting days, weeks, months
- Localizations & redshift determinations
  - Absorption spectroscopy of afterglow
  - Emission lines of host galaxies
- Cosmological in origin ($z \sim 0.084$ to 8.2)
  - Enormous energy output $E_{iso} \sim 10^{53}$ ergs
  - Collimation-corrected $E\gamma \sim 10^{51}$ ergs



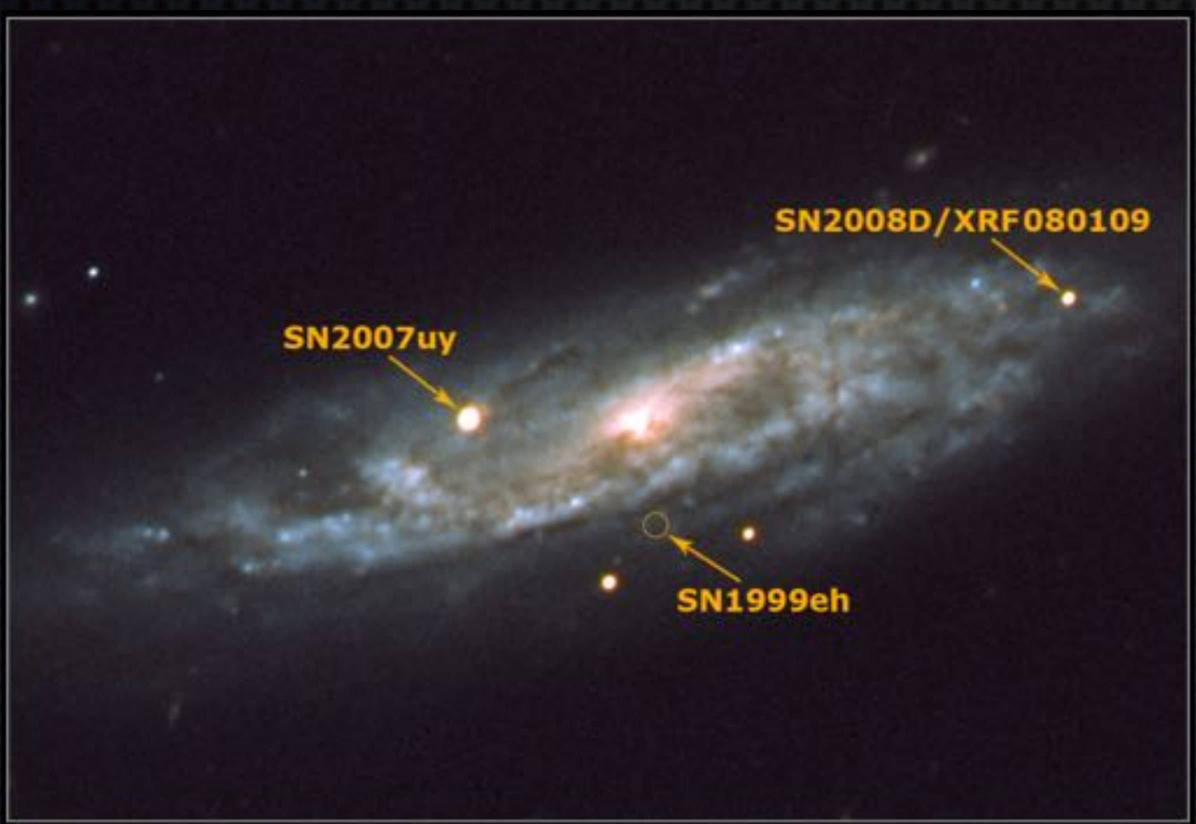
Bloom et al. 2008

Host Galaxies

- Associated with star formation
  - Faint, blue, low mass irregular galaxies
- High specific star formation rates

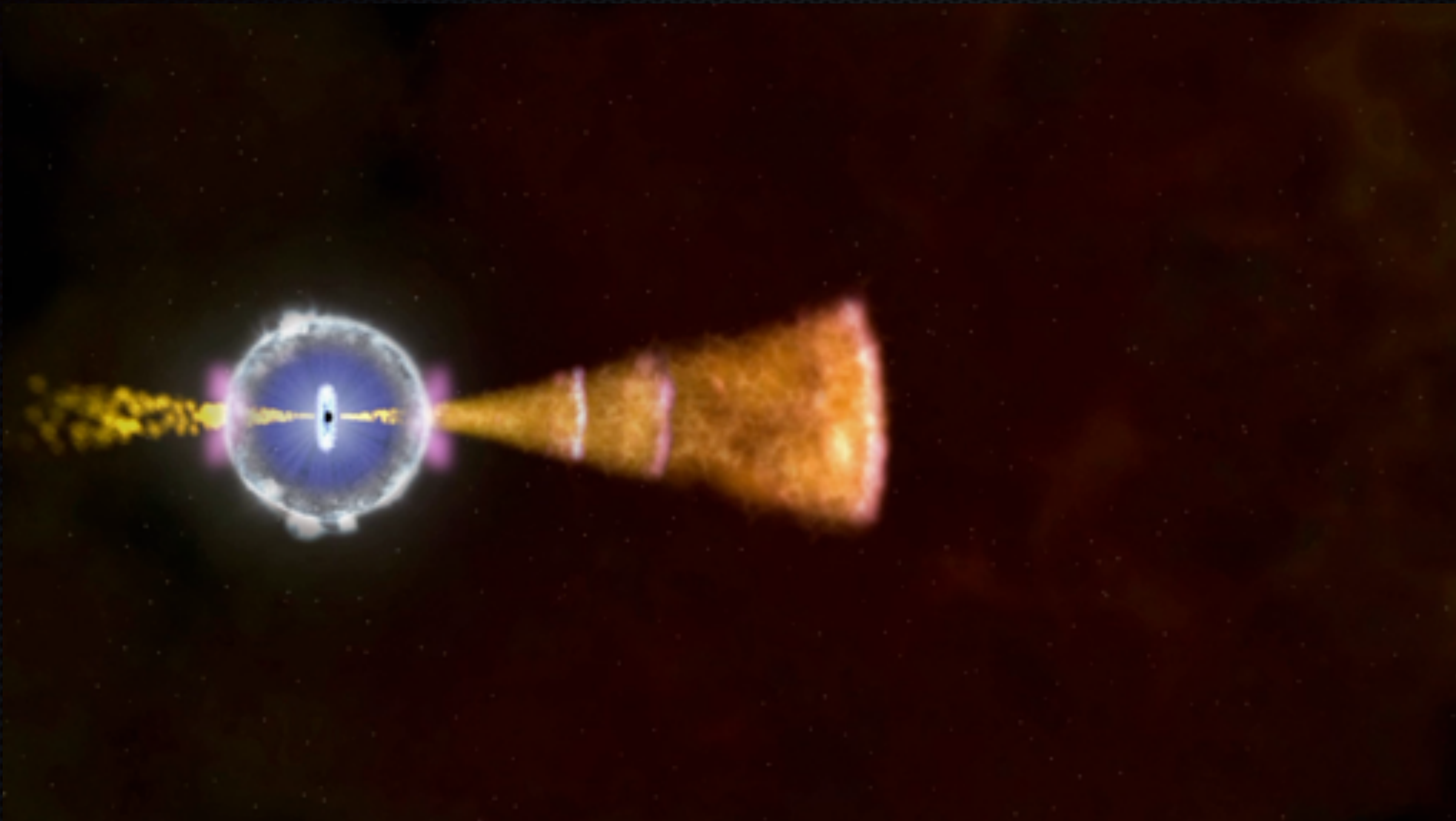


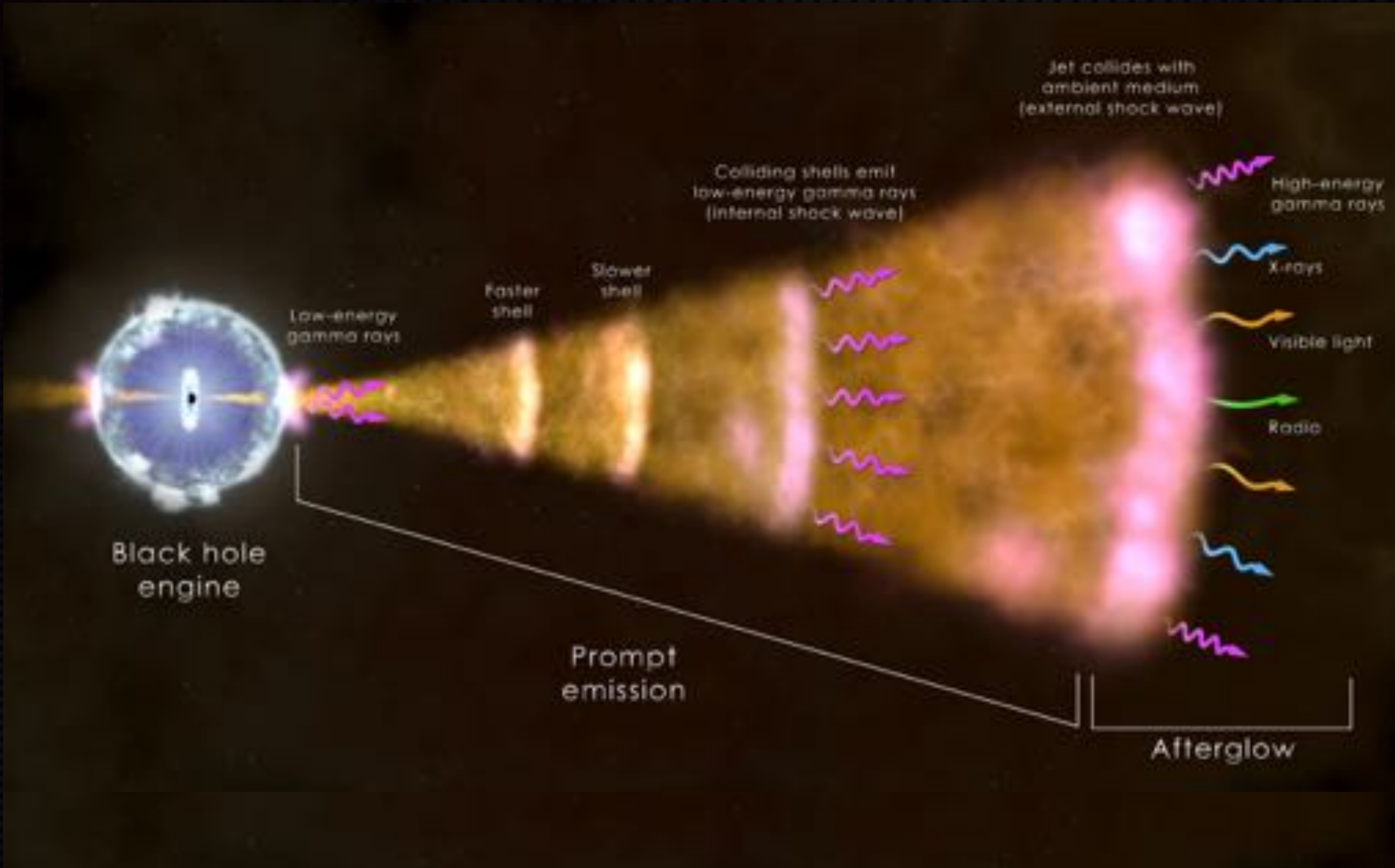
Fruchter et al. 2006



Supernova Factory

- Some have been associated with Broad-lined SN Ib/c events

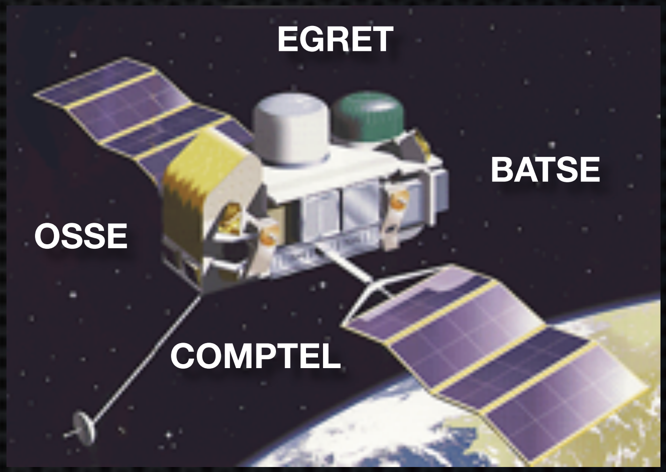




Jet collides with
ambient medium
(external shock wave)
Colliding shells emit
low-energy gamma rays
(internal shock wave)
High-energy
gamma rays
X-rays
Visible light
Radio
Faster
shell
Slower
shell
Low-energy
gamma rays
Black hole
engine
Prompt
emission
Afterglow

High Energy Observations

- CGRO-BATSE (1991-2000)
  - Large NaI Detectors: 20 keV to 1800 keV
  - Detected over 2700 GRBs
  - Limited localization capability ~ 5 deg
- Swift (2004)
  - BAT & XRT: 0.2 keV to 150 keV
  - Rapid localization capability ~ arcmin
  - Detected over 400 GRBs (100 yr^{-1})
  - 90% detected in X-rays, 60% in optical

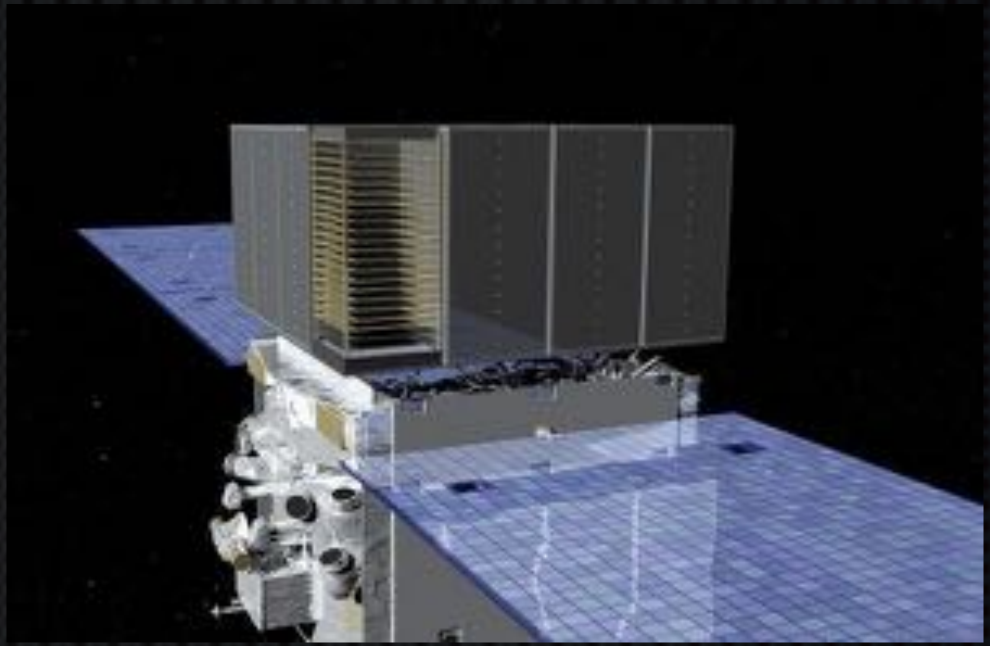


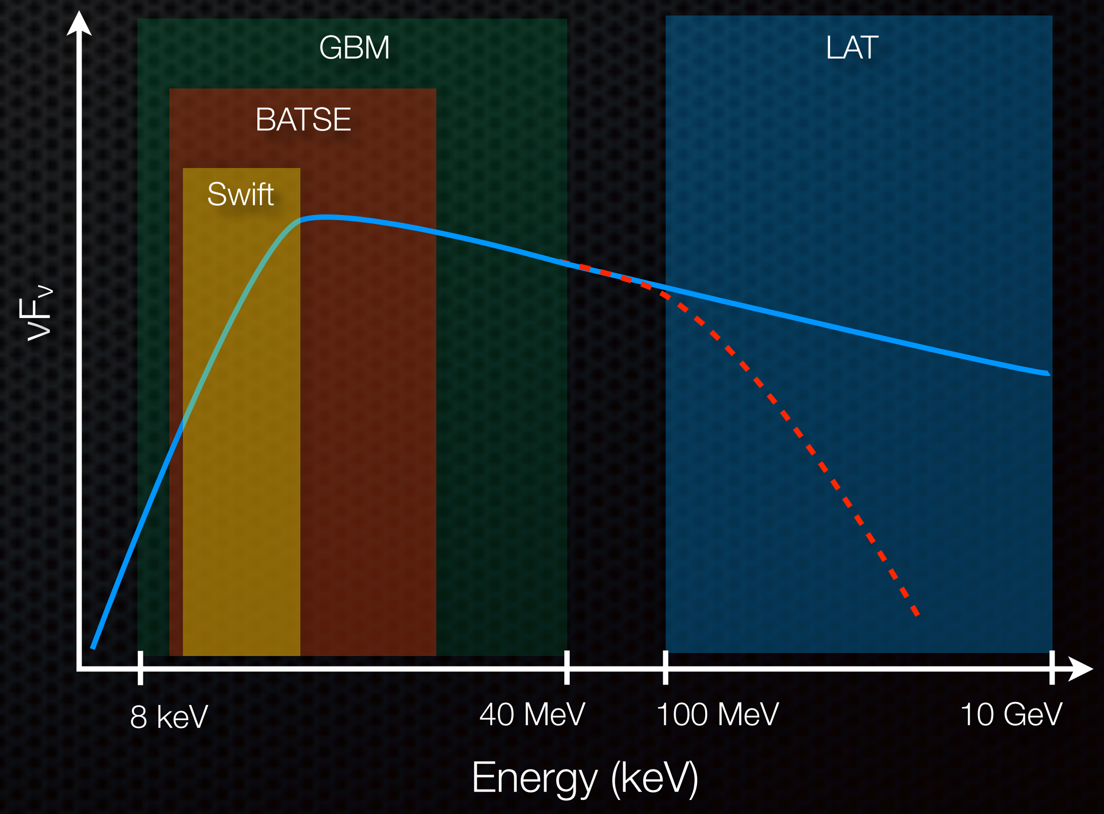
Unresolved Questions Prior to 2008

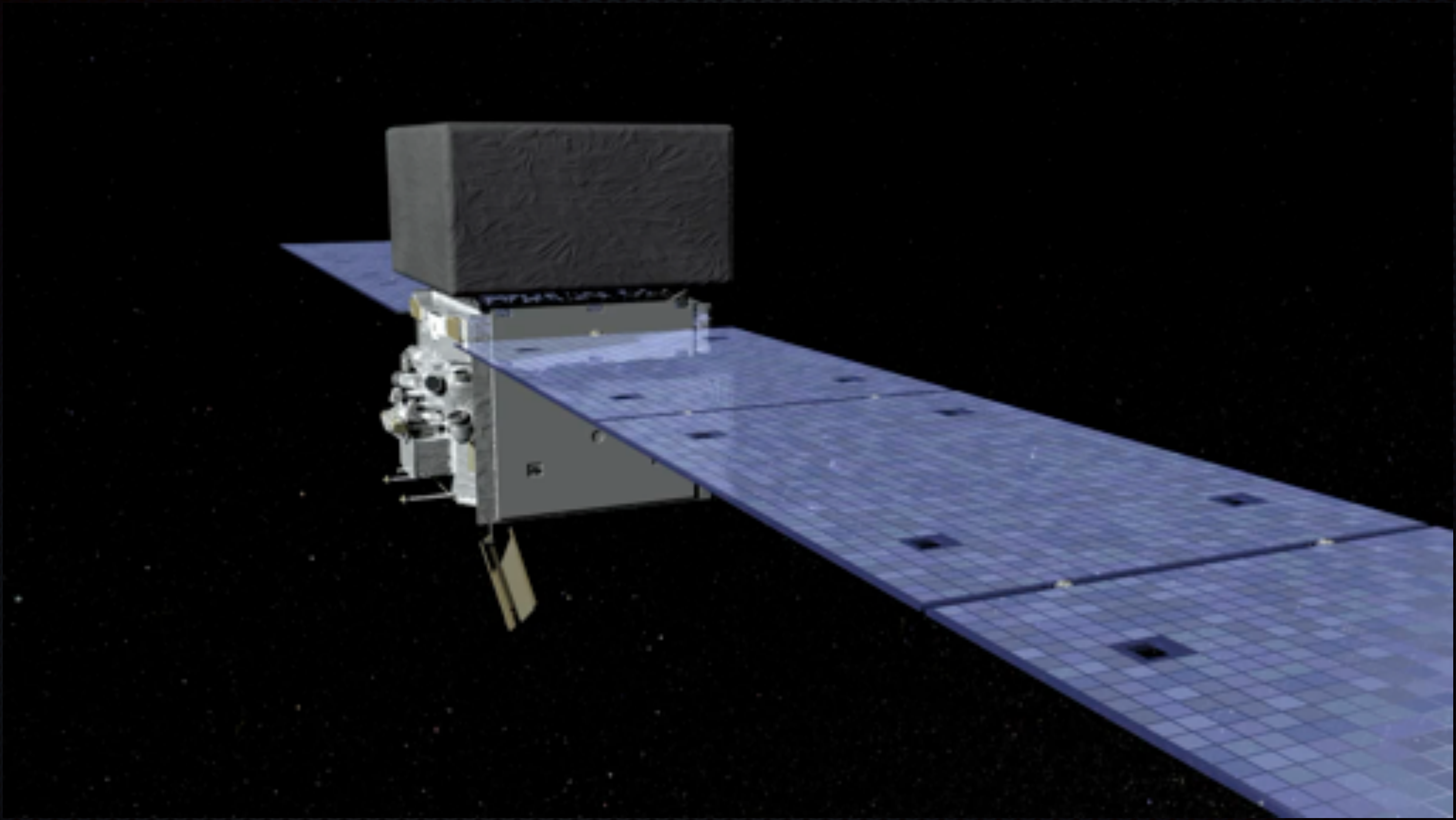
- Band model adequately fits a large majority of bursts
  - No physical emission mechanisms predicts this spectral shape
- Relatively narrow vFv peaks (Epk)
  - Expect large variation if Epk is a synchrotron frequency (Epk ~ $B_{\perp}\Gamma_{rel}$)
- Bursts with very steep spectra below Epk (the synchrotron “line of death”)
- Where is the evidence for pair attenuation?
- Where is the photospheric (blockbody) emission?
- How common is the long lived GeV emission seen by EGRET?
- Where are the IC and SSC components?
  - Is E_{pk} the SC or the IC/SSC peak or are those peaks at GeV/TeV energies

The Fermi Spacecraft

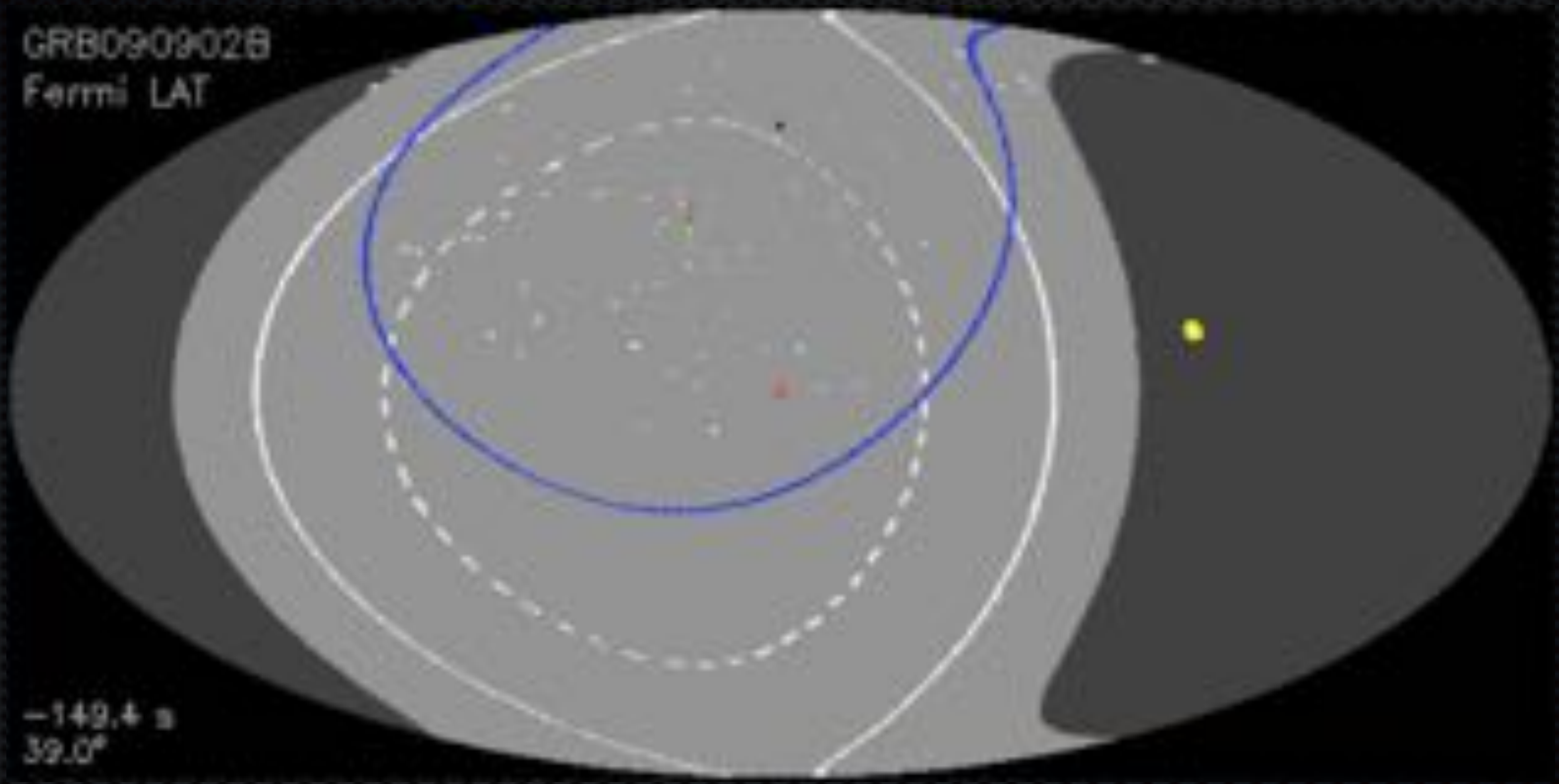
- Launched June 11th, 2008
- Triggering began Aug 7, 2008
- Fermi Gamma-ray Burst Monitor (GBM)
    - Scintillation detectors
    - 12 NaI: 8 keV - 1 MeV
    - 2 BGO: 200 keV - 40 MeV
- Fermi Large Area Telescope (LAT)
    - Pair conversion telescope
    - Energy coverage: 0.1 to >300 GeV







Automated Repoint Request



- Red cross = GRB 09092B
- Dark region = Occulted Earth
- White Line = LAT field of view
- Blue lines = Earth avoidance angle
- White points = LAT transient events

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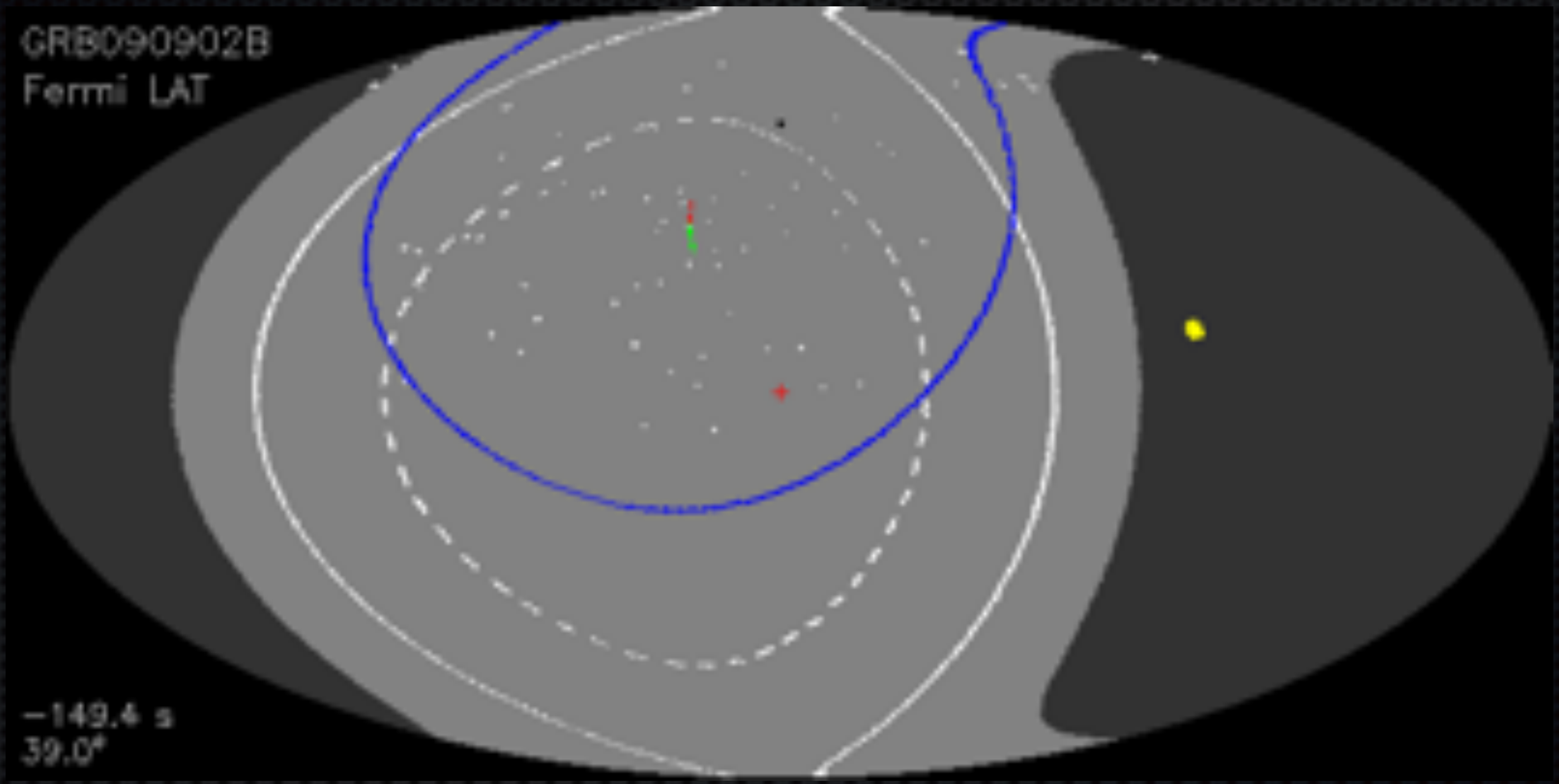

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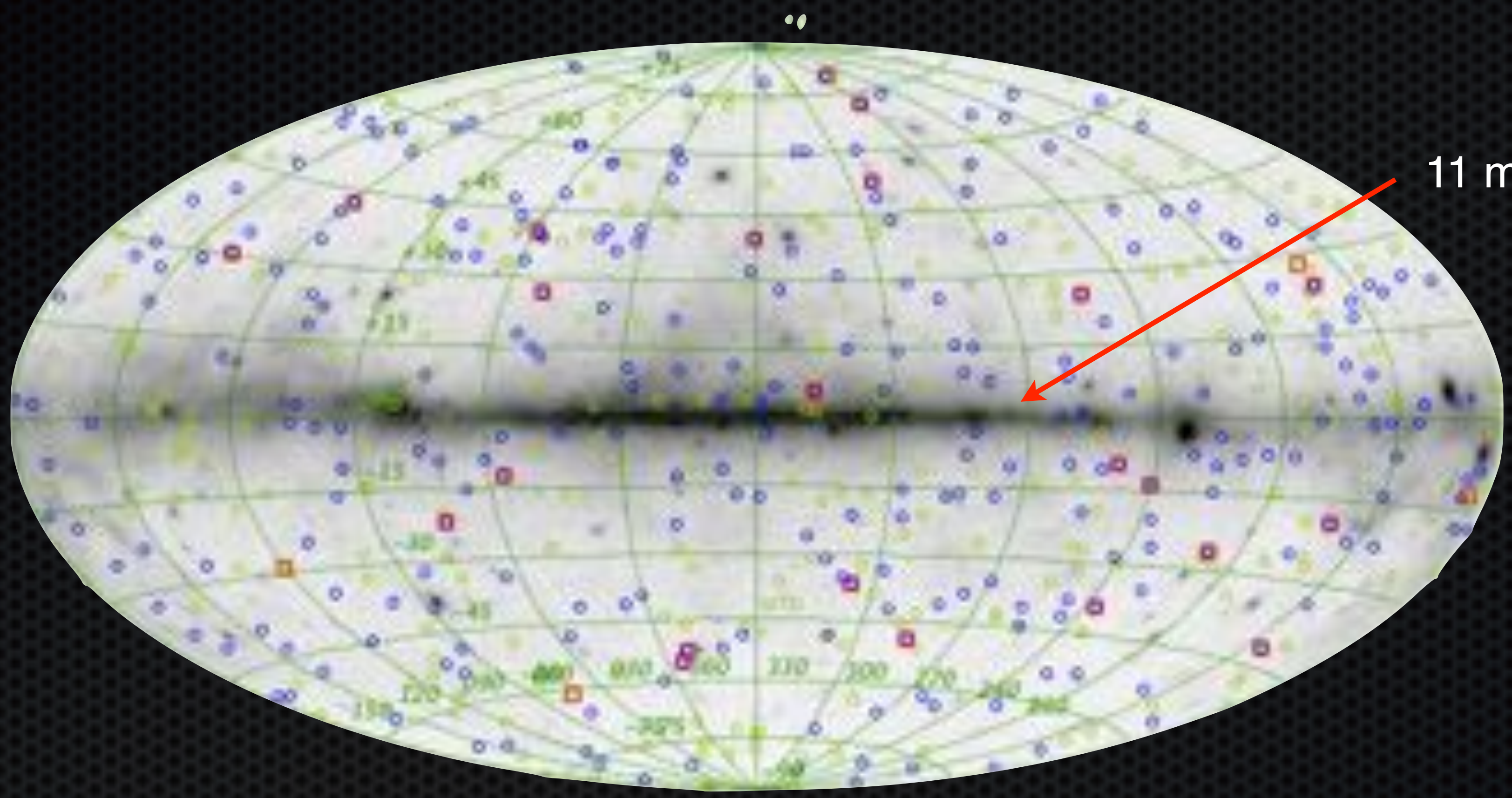
Fermi GRB Detections

GBM 2-year catalog
LAT 3-year catalog

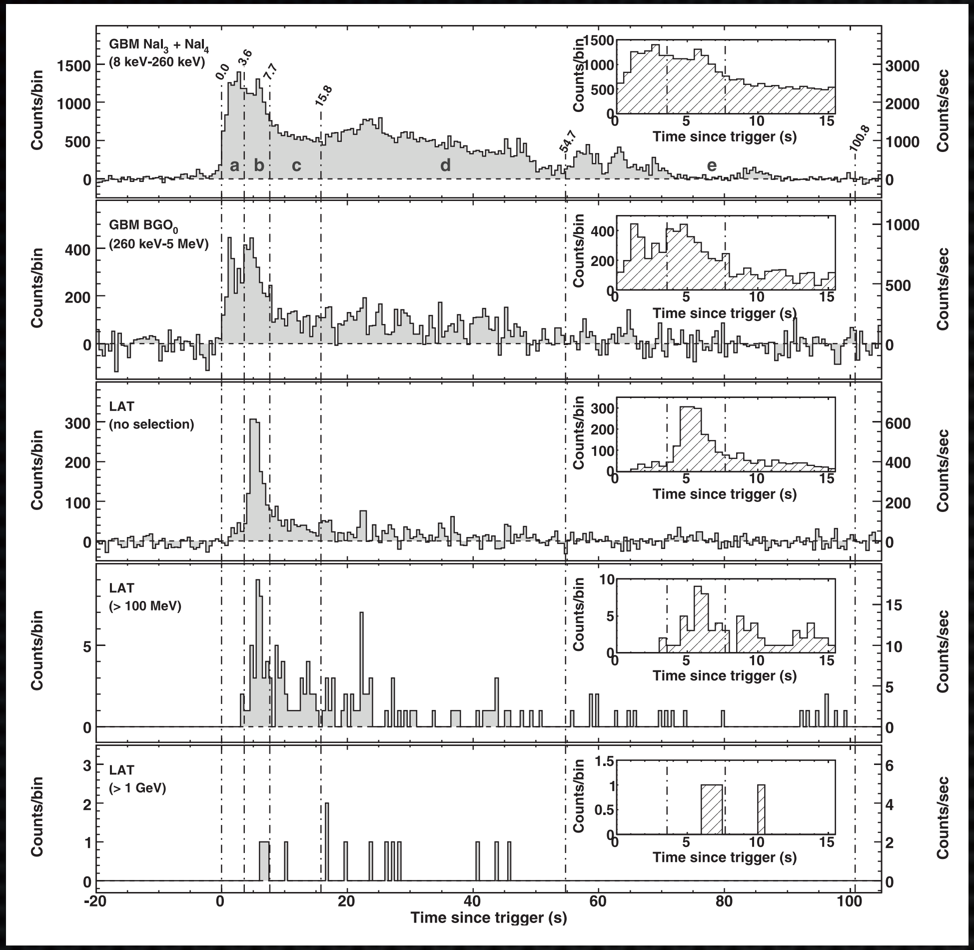


11 month LAT count map

- GBM Detected GRBs: ~250 GRBs/yr (~1200 GRBs) - Blue
- GRBs in LAT FOV: ~ 46% (~600 GRBs) - Green
- LAT Detected GRBs (>100 MeV): 8% (~85 GRBs) - Red

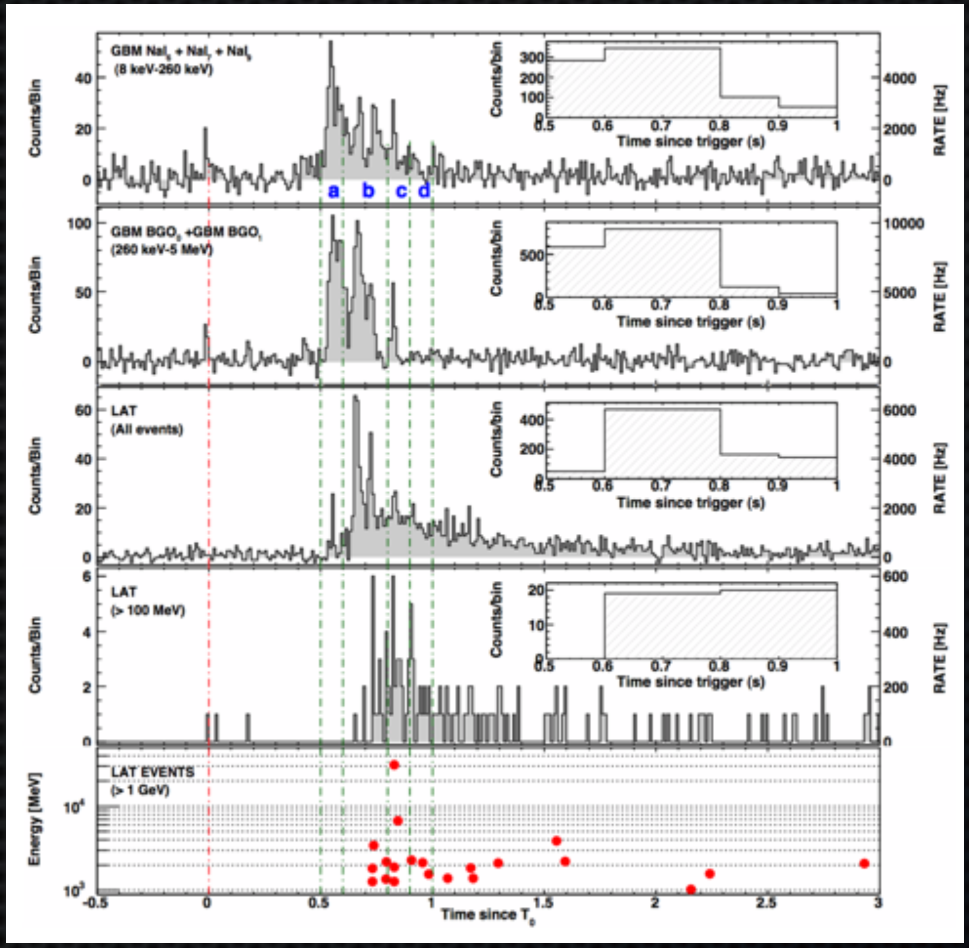
Delayed High Energy Emission

GRB 080916C



Abdo et al. 2009

GRB 090510

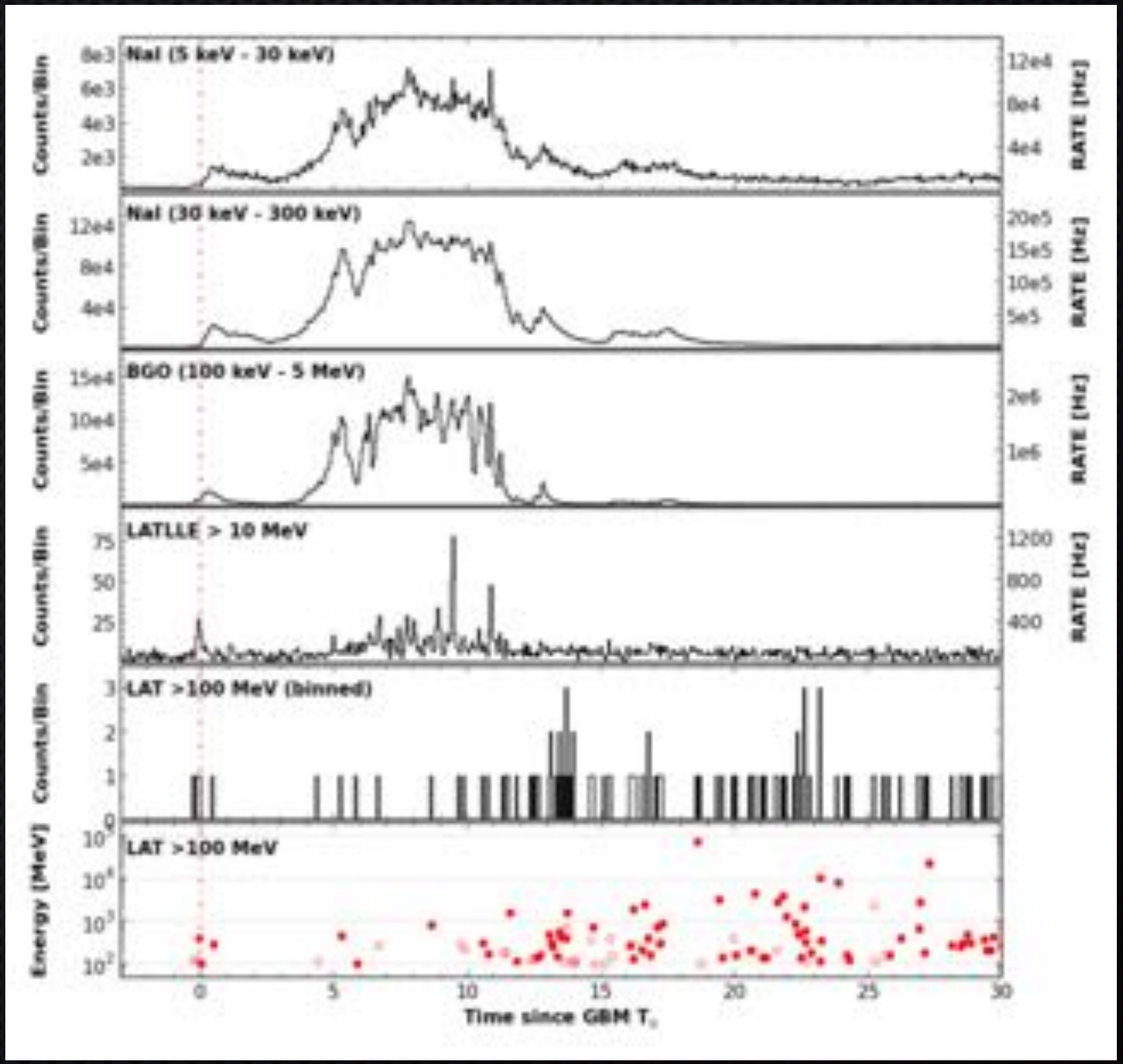


Ackermann et al. 2010

- High energy emission (>100 MeV) is typically delayed emission
- Seen in majority of LAT detected bursts, but not all (e.g. 090217)

Long Lived High Energy Emission

- Longer lived emission > 100 MeV than emission at keV energies
- Seen in a majority of LAT detected bursts, but not all (e.g. 090217)
- Activity lasting thousands of seconds



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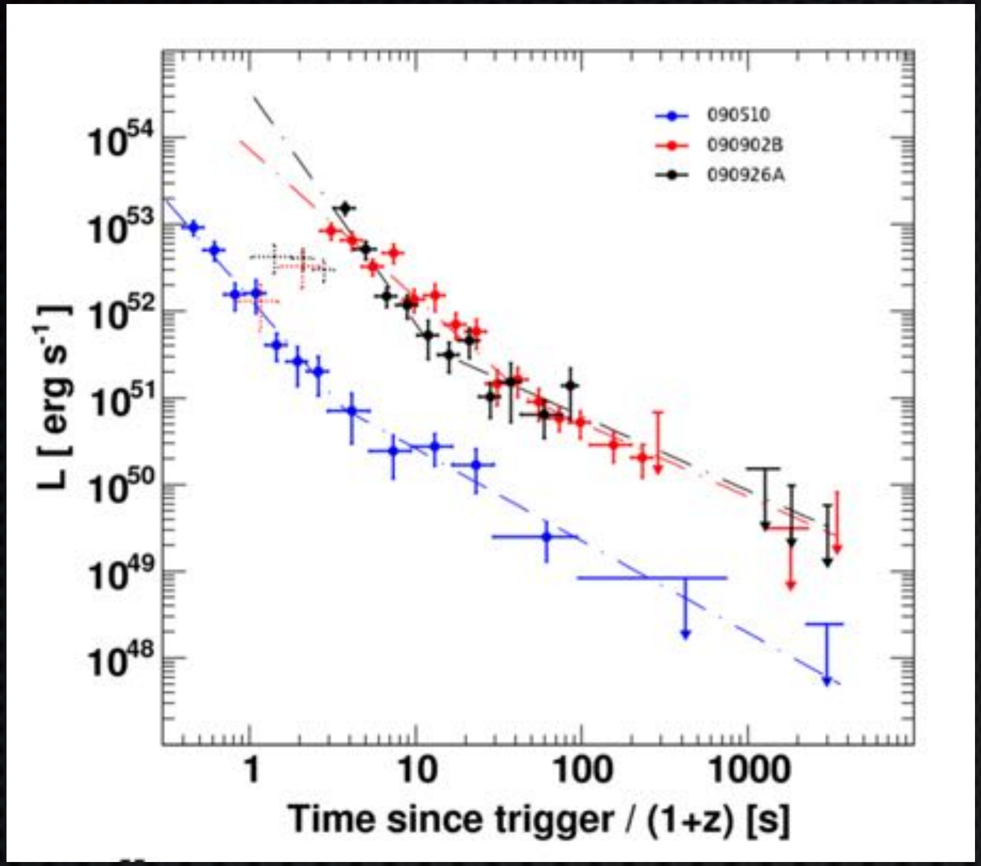
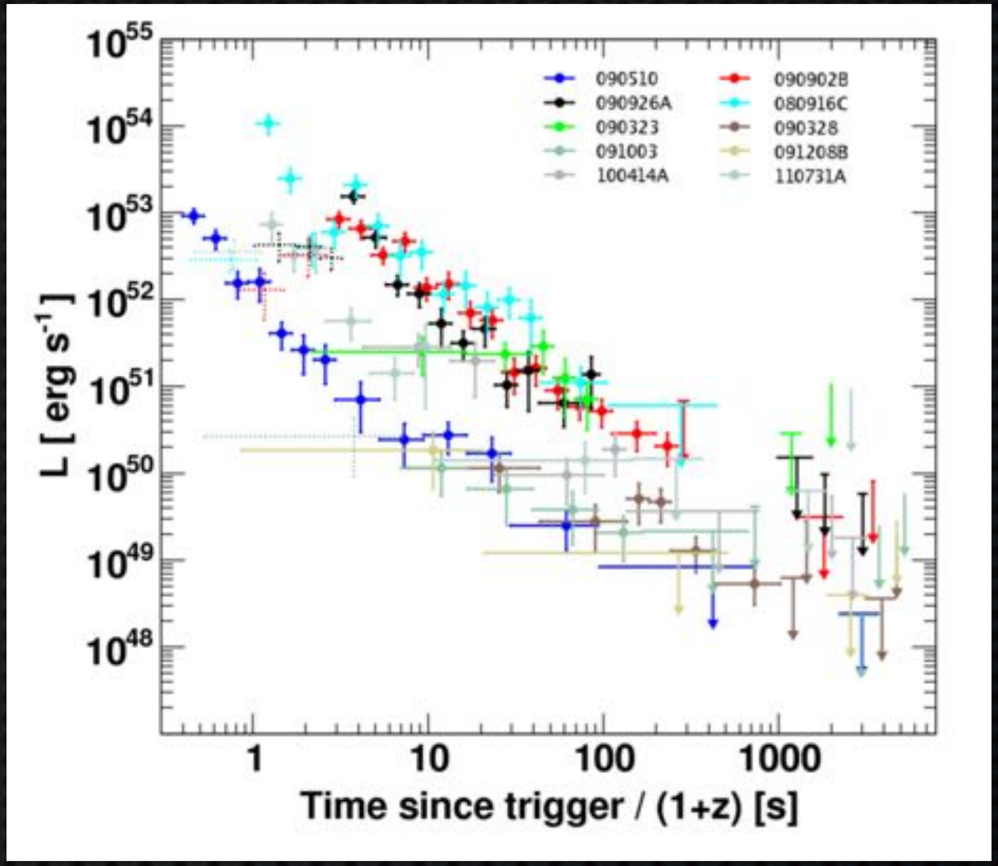


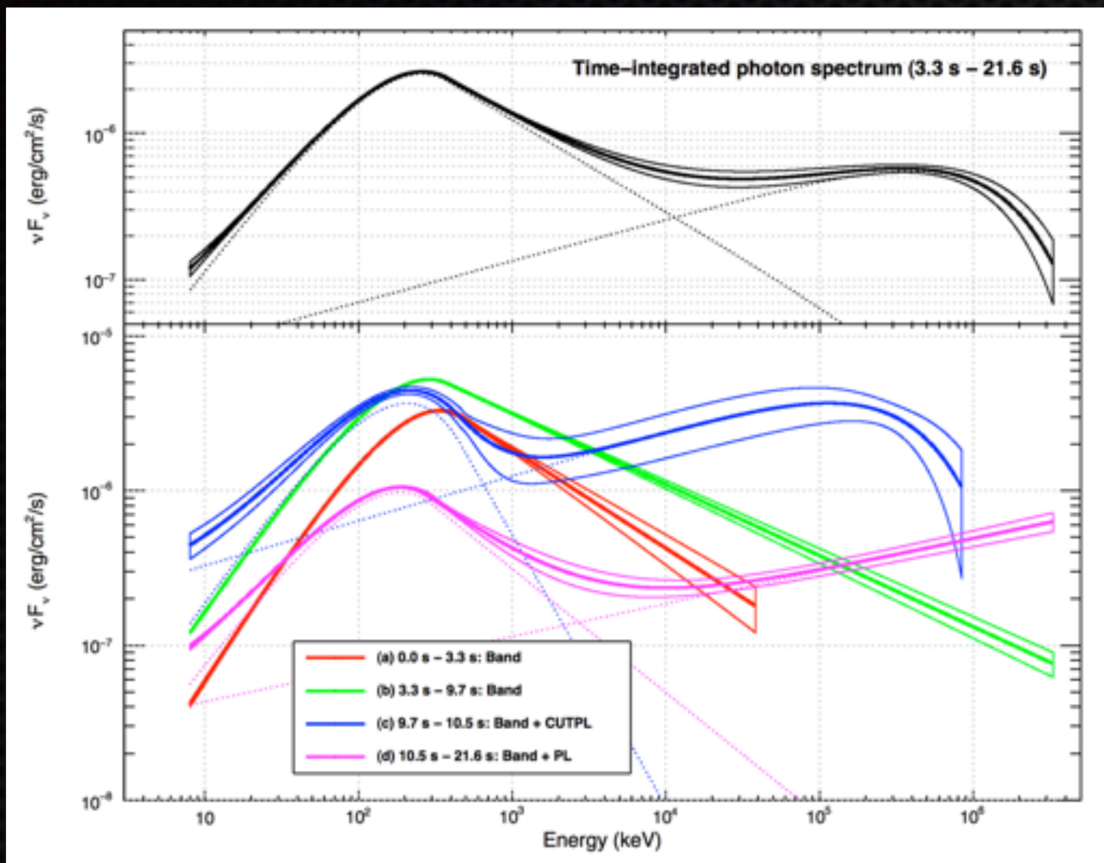


Abdo et al. 2009

- Longer lived emission > 100 MeV than emission at keV energies
- Seen in a majority of LAT detected bursts, but not all (e.g. 090217)
- Power-law decays, with slopes that resemble afterglow decays

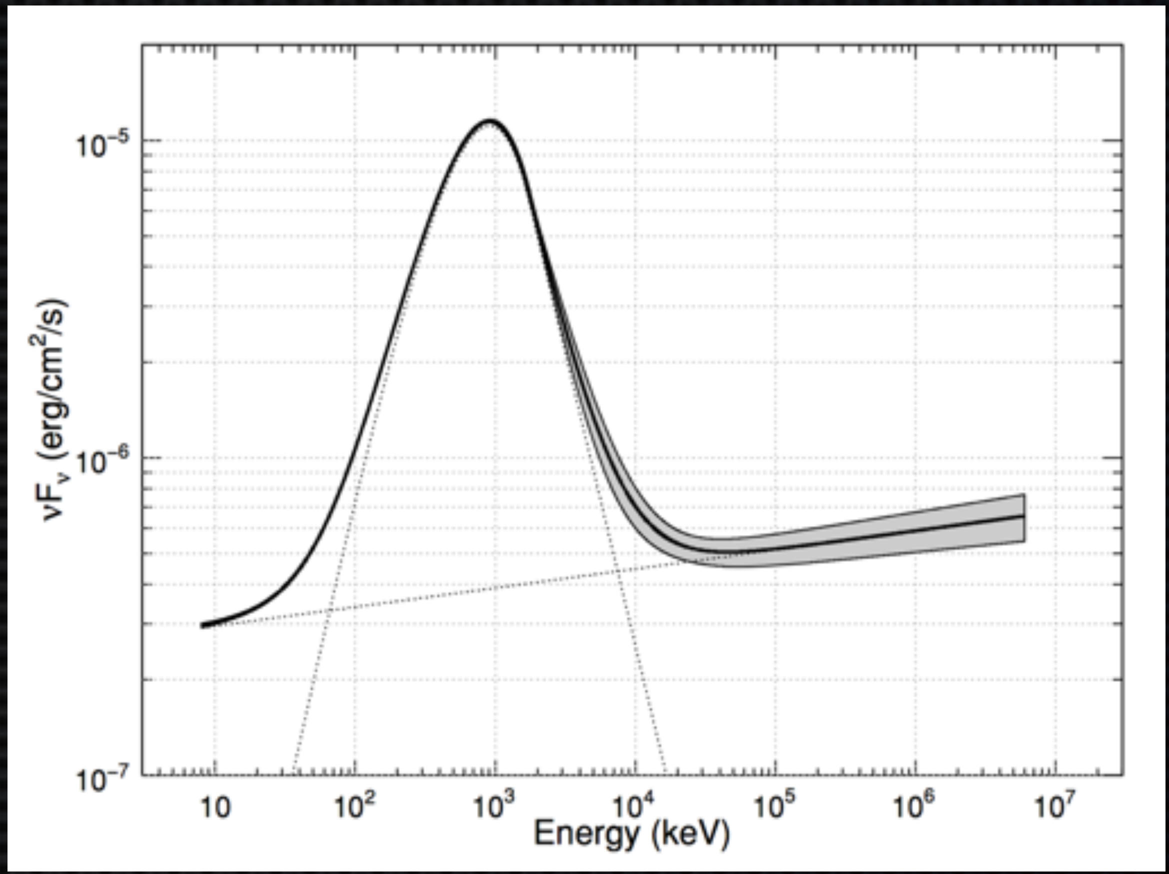
Additional Spectral Components

GRB 090926A



Ackermann et al. 2011

GRB 090902B

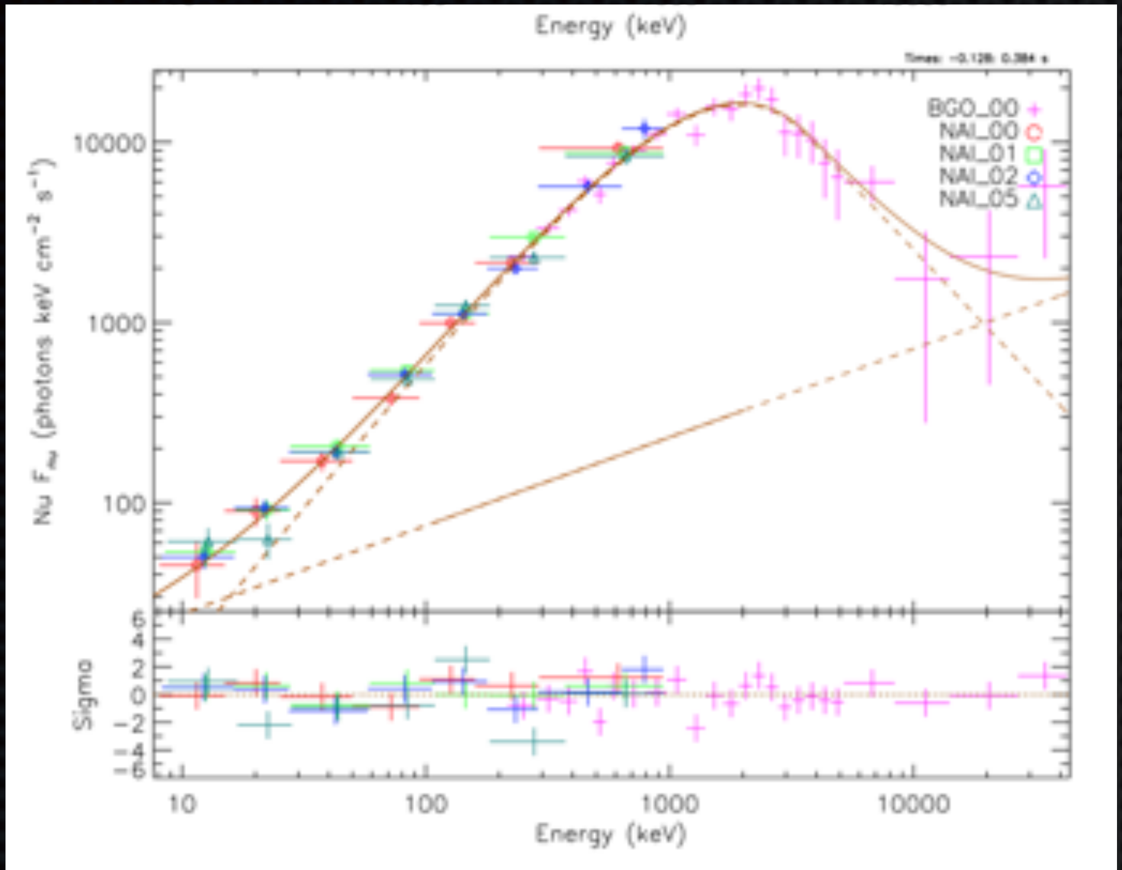


Abdo et al. 2009

- Delayed emission characterized by extra spectral components
- Evidence for attenuation of the power-law component in 090926A
  - First signs of attenuation due to pair-production!

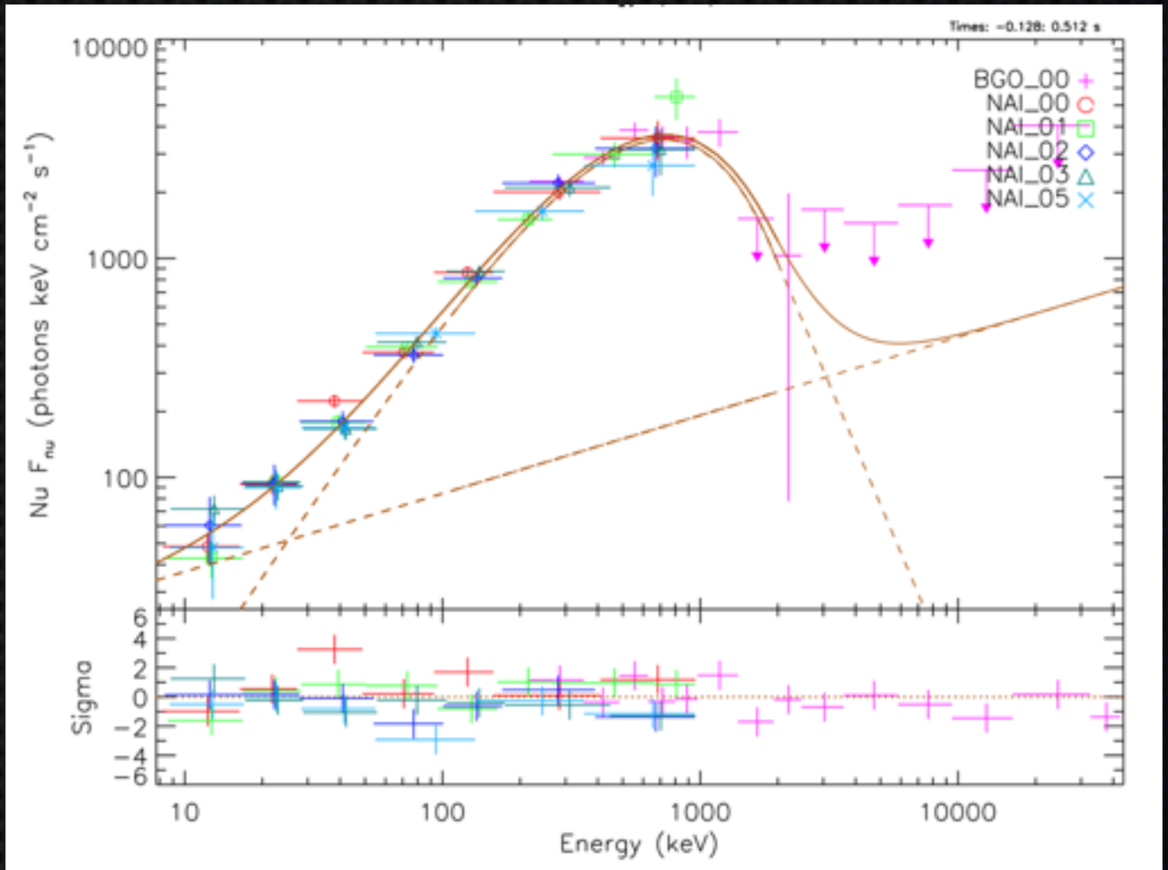
Low Energy Power-Law Components

GRB 090227B



Guiriec et al. 2010

GRB 090228



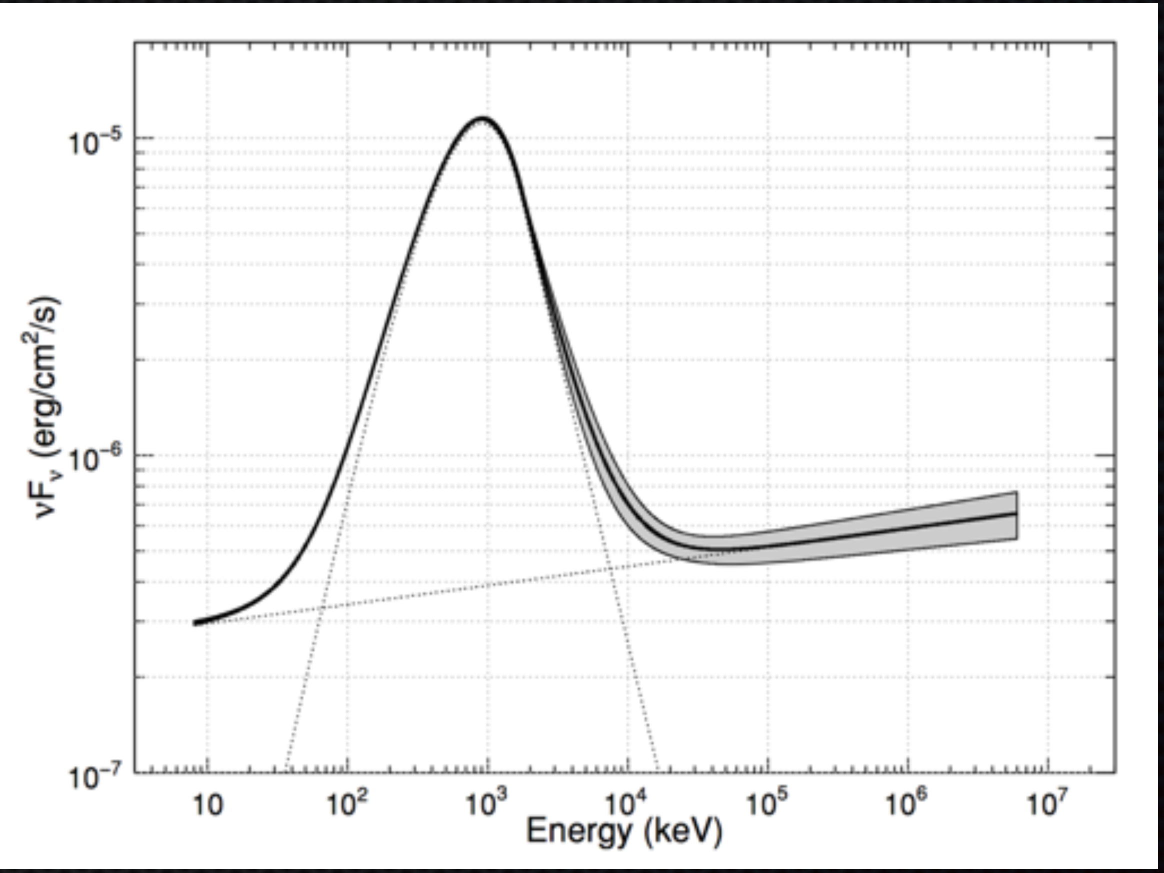
Guiriec et al. 2010

- Clear evidence for power-law contributions at low energies
- Disfavors an IC or SSC explanation
    - Low energy extension and delayed high energy emission

Photospheric Signatures?

- Extremely narrow spectrum with α ~ 0.55 seen in GRB 090902B
- Consistent with a multi-color blackbody plus a power-law component
- Not narrow enough for a Planck function, but close
  - Traditional blackbody shape can be broadened by geometric effects or subphotopheric dissipation
- Power-law component would come from optically thin synchrotron at larger radii than the thermal emission

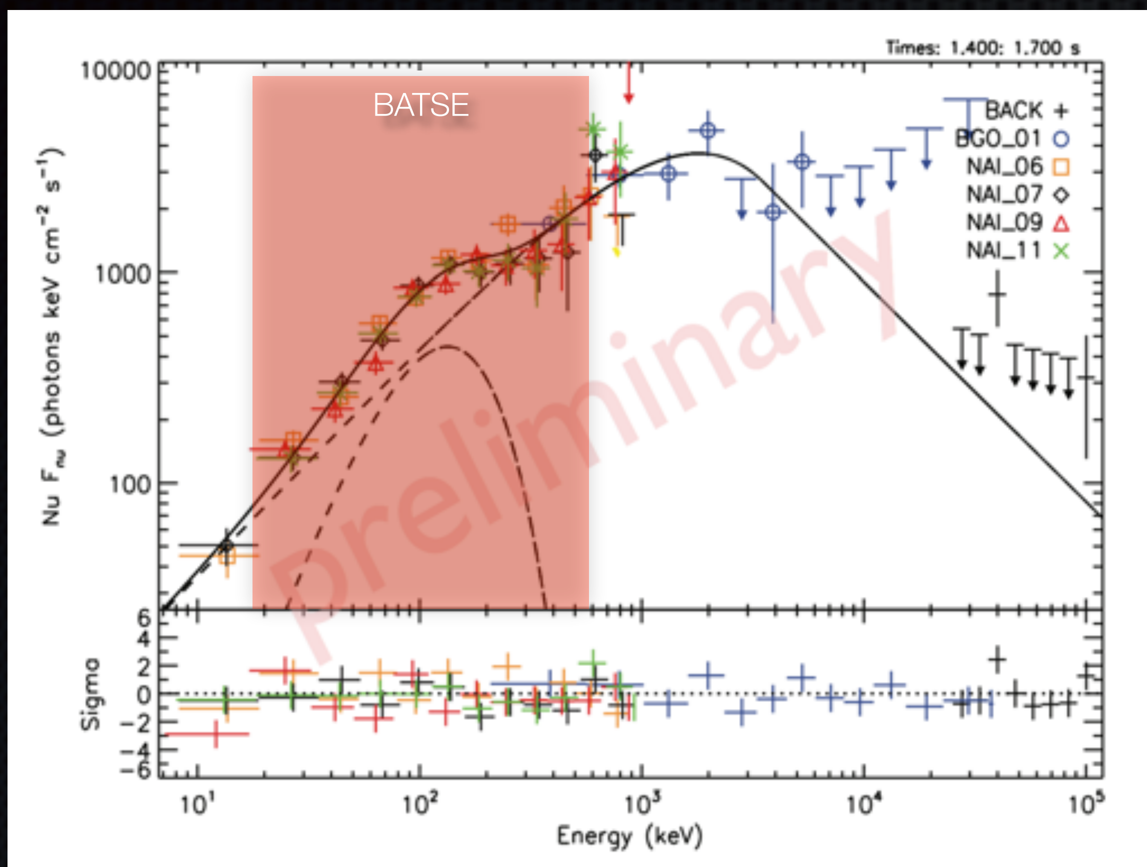
GRB 090902B



Abdo et al. 2009

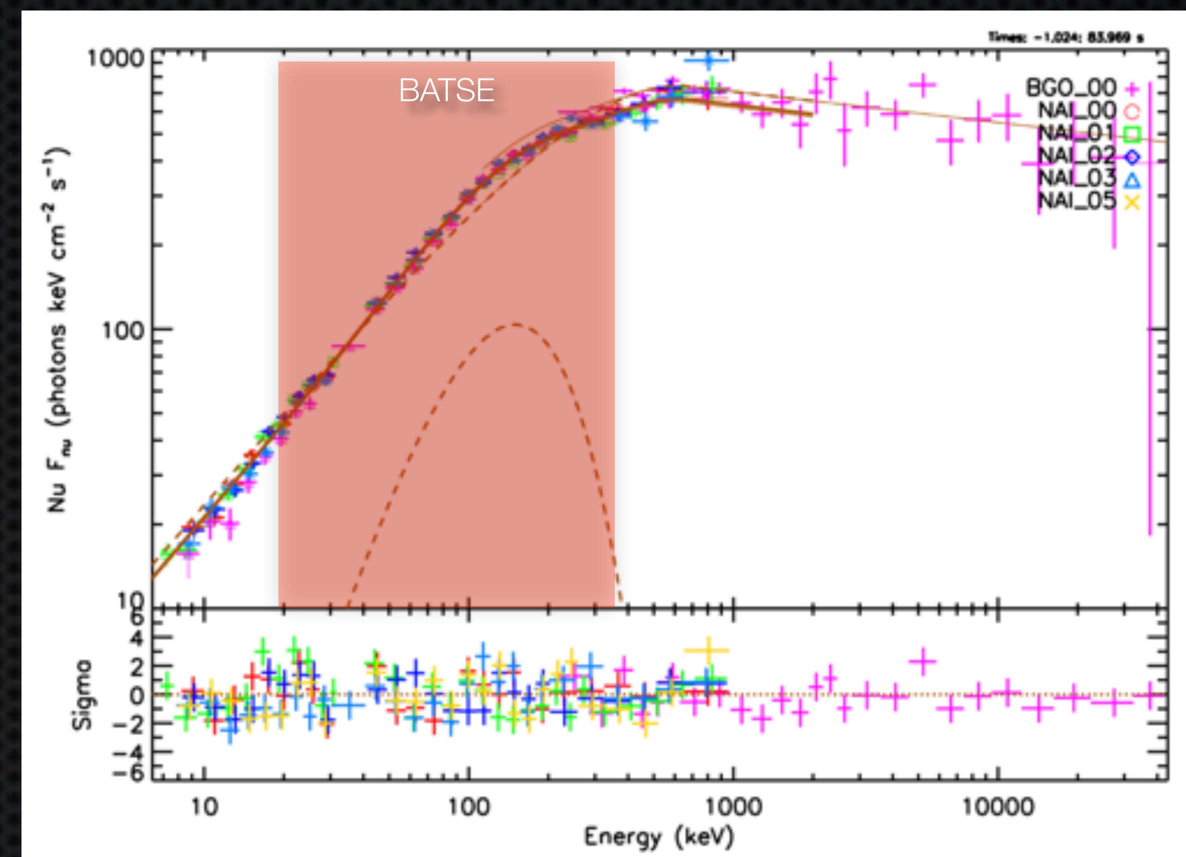
Blackbody Components

GRB 110721A



Ryde 2012

GRB 100724B



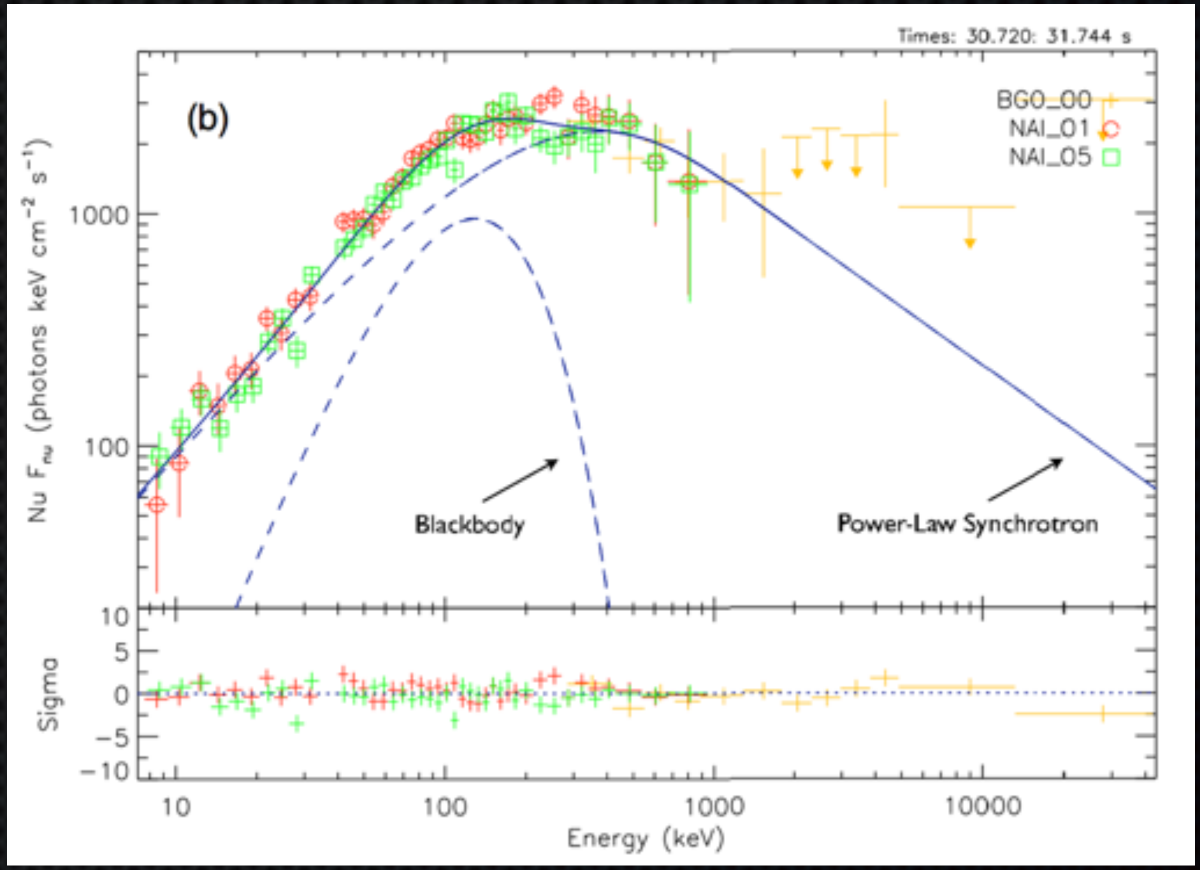
Guiriec et al. 2011

- 110721A: Subdominant blackbody component plus a Band function to explain deviations from a power-law at low energies
- 100724B: Not as pronounced, but consistent with the photospheric interpretation
- Both these bursts would have appeared as $\beta > -2$ spectra in the BATSE era

Synchrotron Models Revisited

- Direct fits to blackbody and synchrotron spectra
- Line-of-death issue can be overcome naturally with this combination
- The Planck like spectral contribution allows for steeper νF_ν spectra near the peak than is allowed by synchrotron alone
- This approach directly constrains physical model parameters as opposed to phenomenological ones

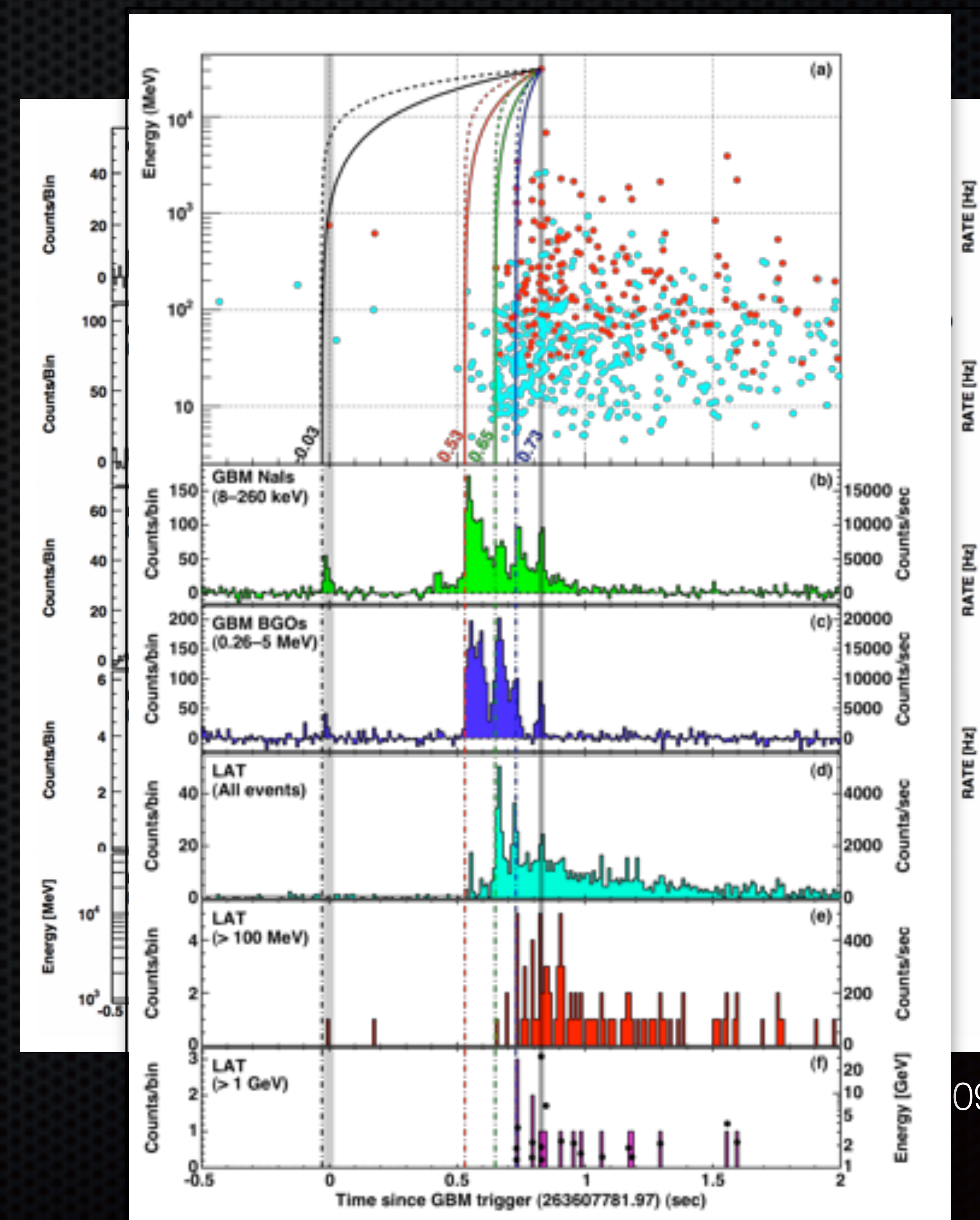
GRB 090820A



Burgess et al. 2011

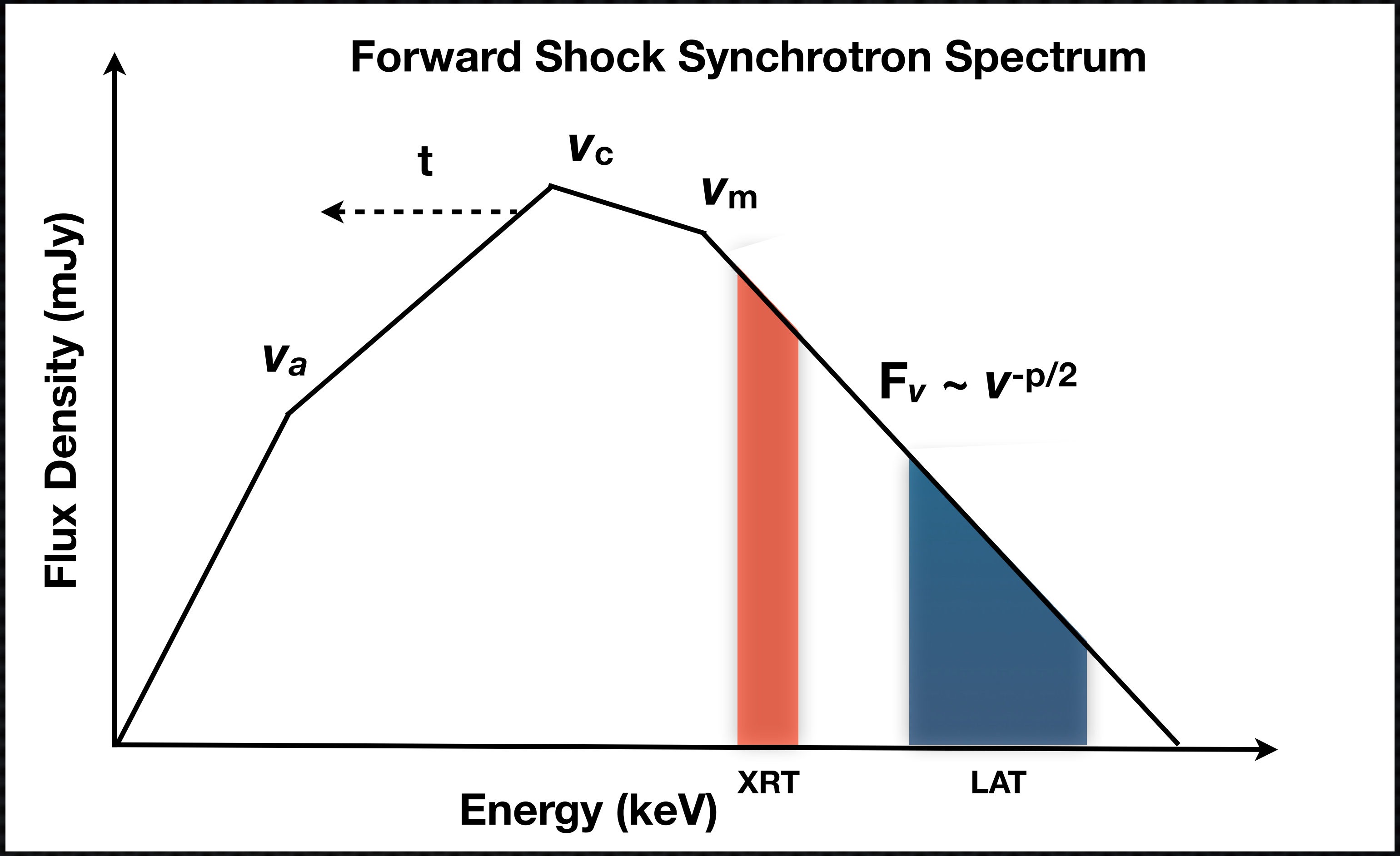
GRB 090510

- Short GRB (T90 ~ 2 sec)
- z_{phot} ~ 0.903
- Emax = 31 GeV
- Γ_{min} ~ 1200
- M_{QG} / M_{planck} > 5.63
- Delayed LAT emission
  - > 100 MeV begins T0 + 0.63 s
- Extended LAT emission
  - 0.1 GeV detected to T0+200s



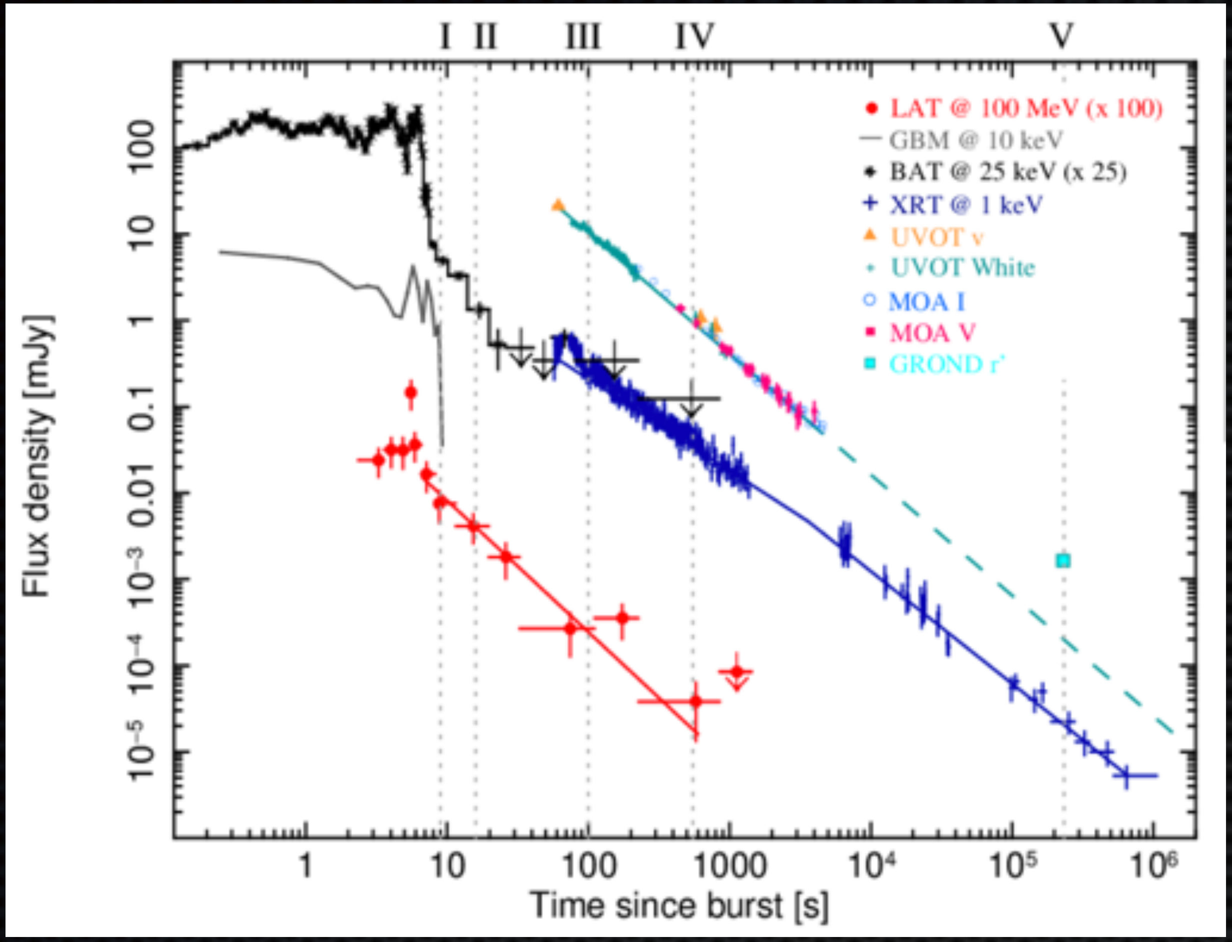
Abdo et al. 2009

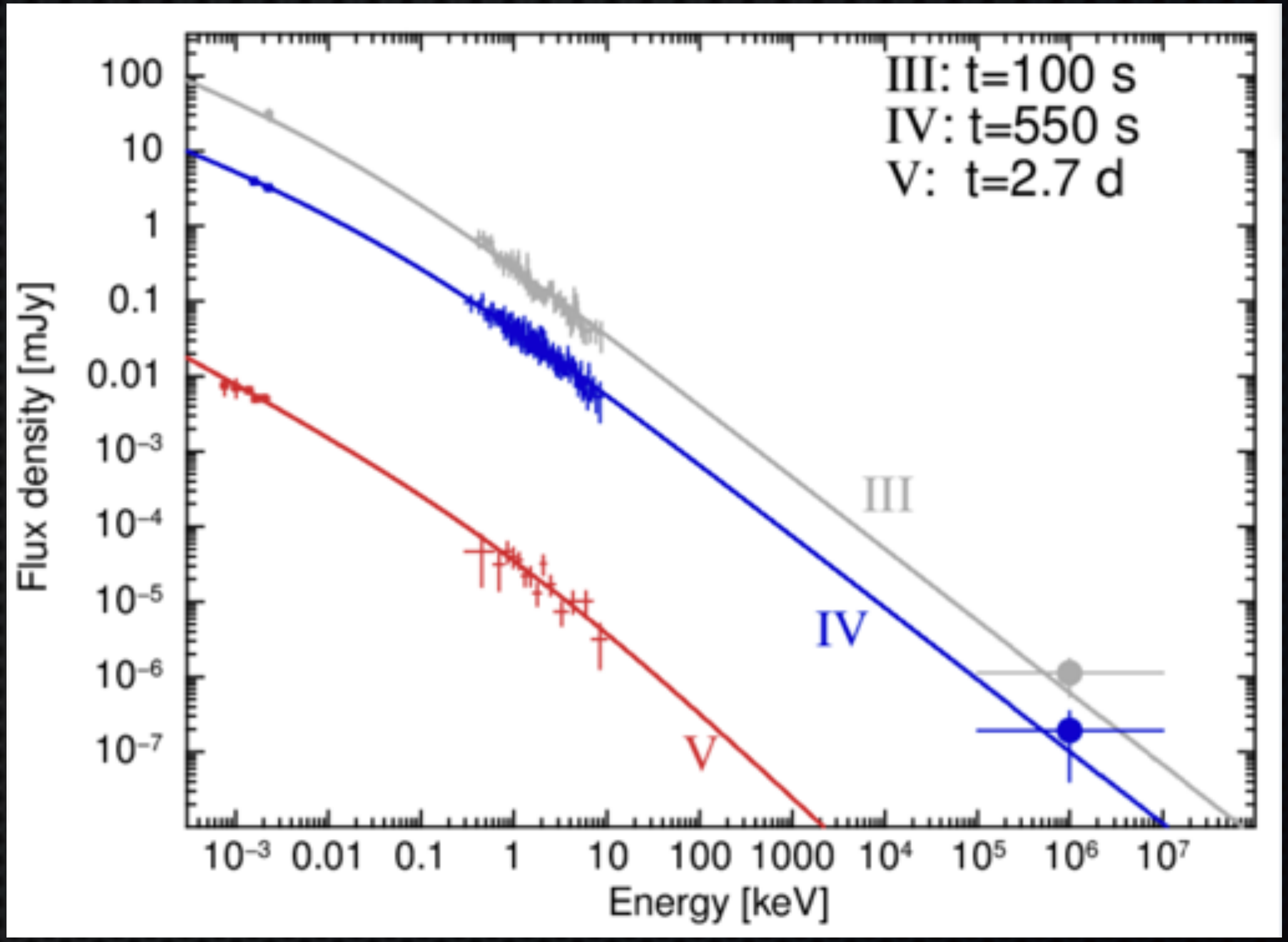
Origin of long live GeV emission?



- Kumar & Barniol Duran 2009
  - Extended emission for 080916C, 090510, 090902B are the tail of the forward shock synchrotron spectrum
  - GeV spectrum and temporal decay satisfy the forward shock “closure” relations: $t^{-(3p-2)/4}$

GRB 110731A

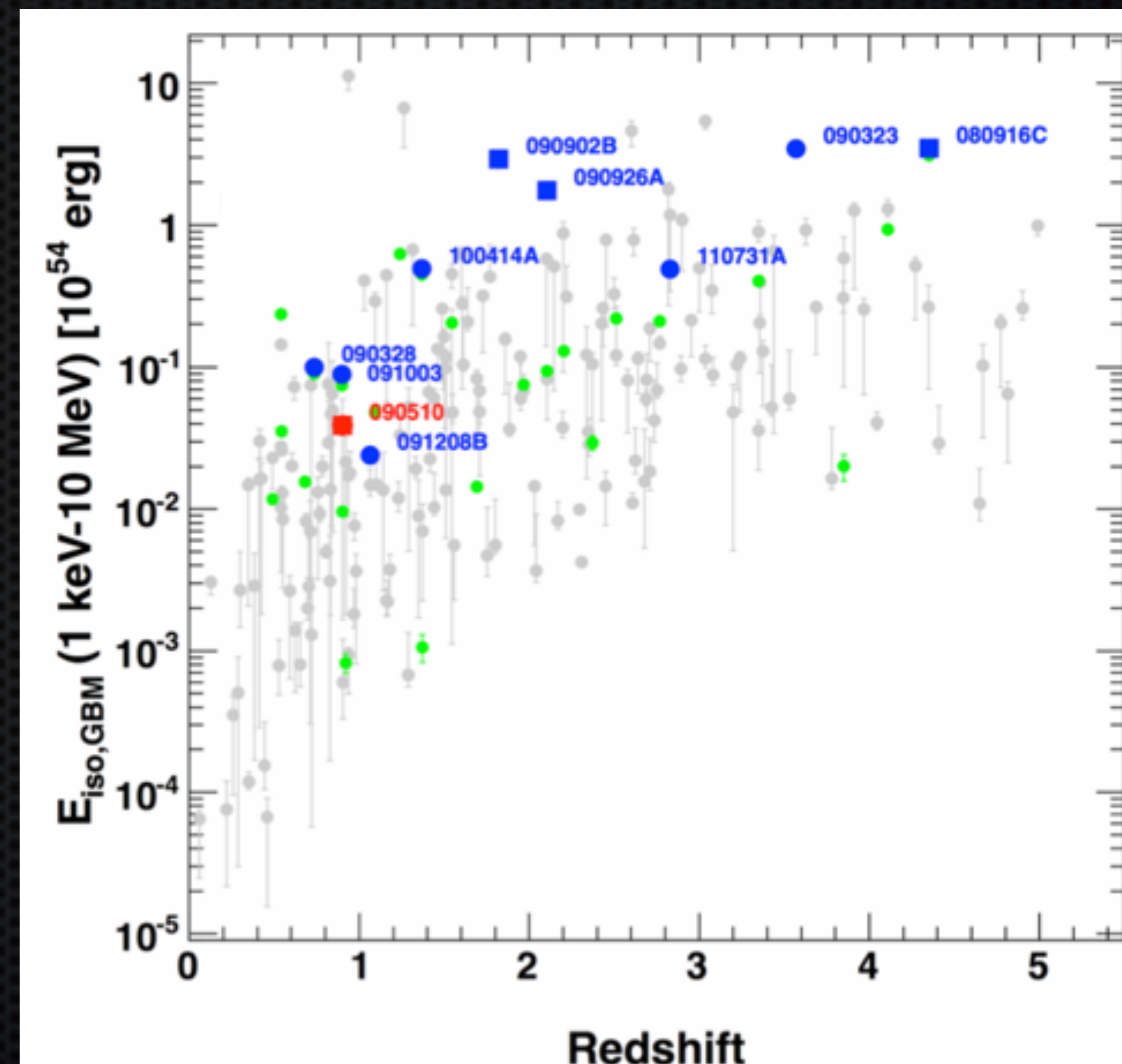


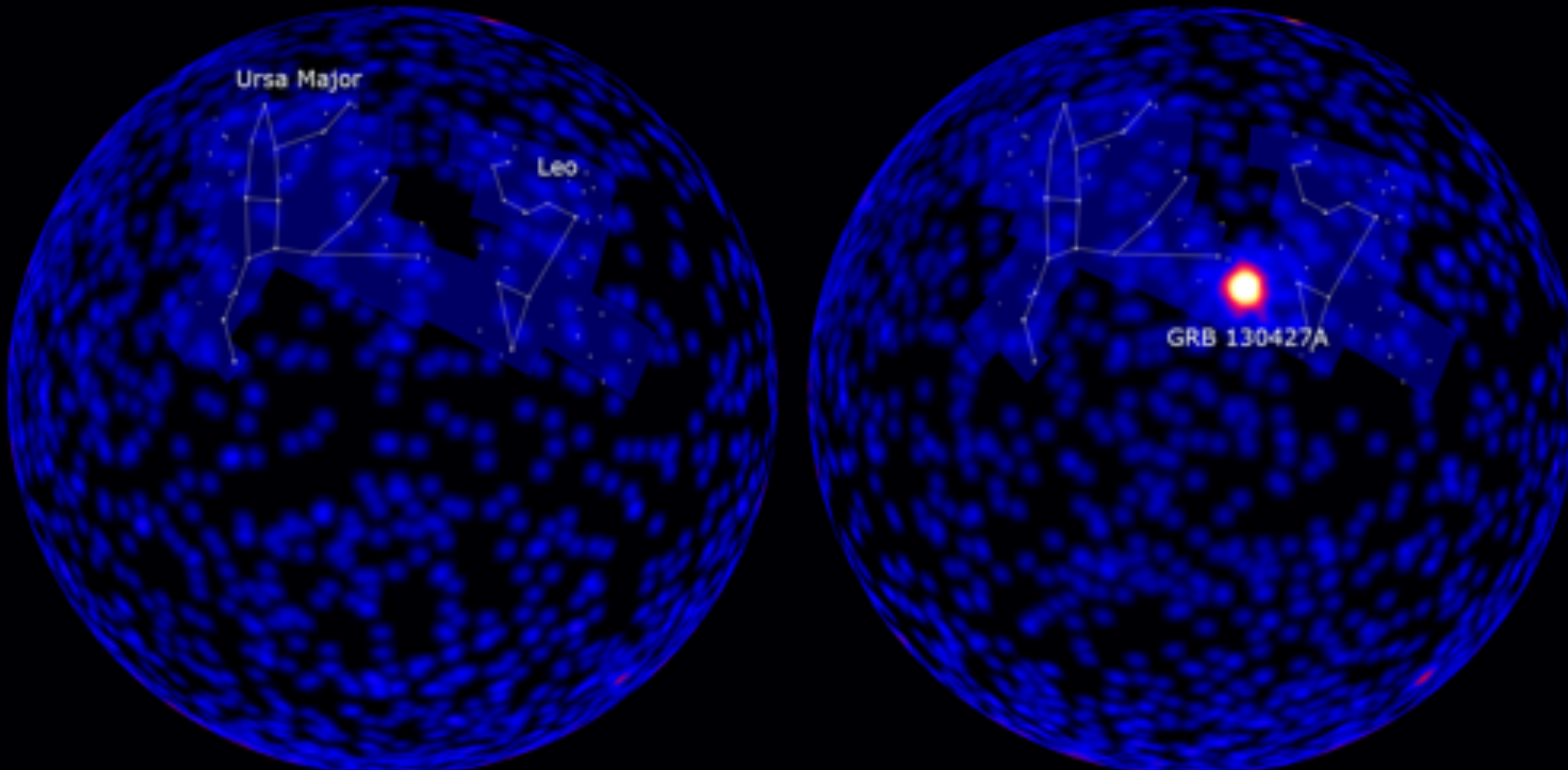


- Simultaneous XRT, LAT, optical observations
- Forward shock model can reproduce the spectrum from the optical to GeV
- Non-thermal synchrotron emission from the decelerating blast wave

Cosmological Context

- LAT detected GRBs tend to be the most energetic of the population
- Luminous events are rare, so are preferentially seen at large redshifts where the sampling volume is greater
- Nearby GRBs are typically under-luminous and unusual
- GRB 130427A
  - An ordinary GRBs at extremely low redshift
  - Incredibly bright!





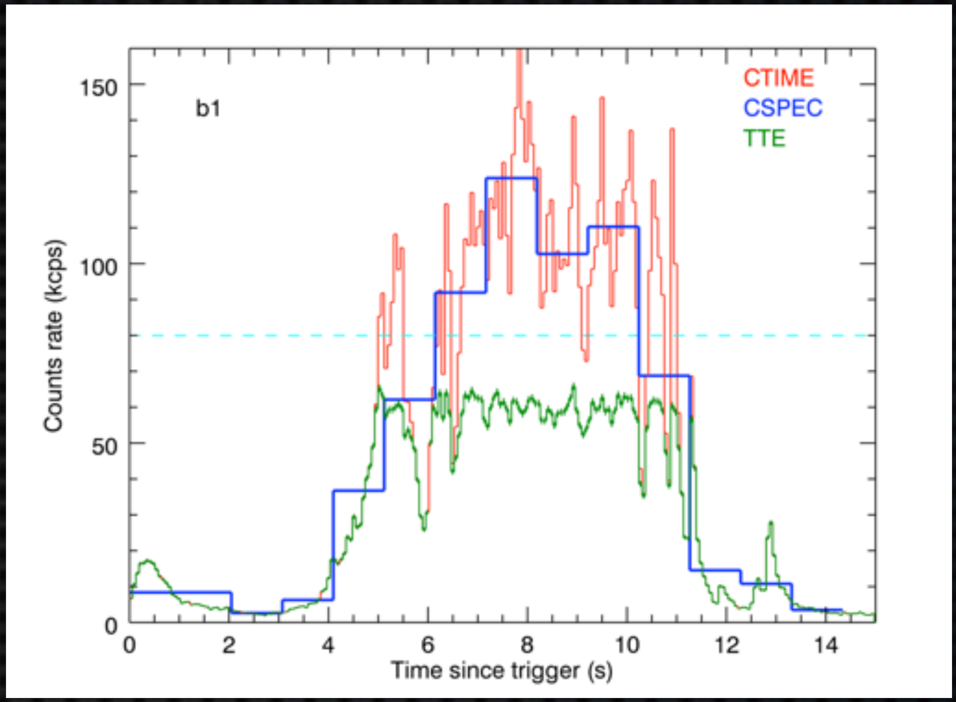
Before and after Fermi LAT views of GRB 130427A, centered on the north galactic pole

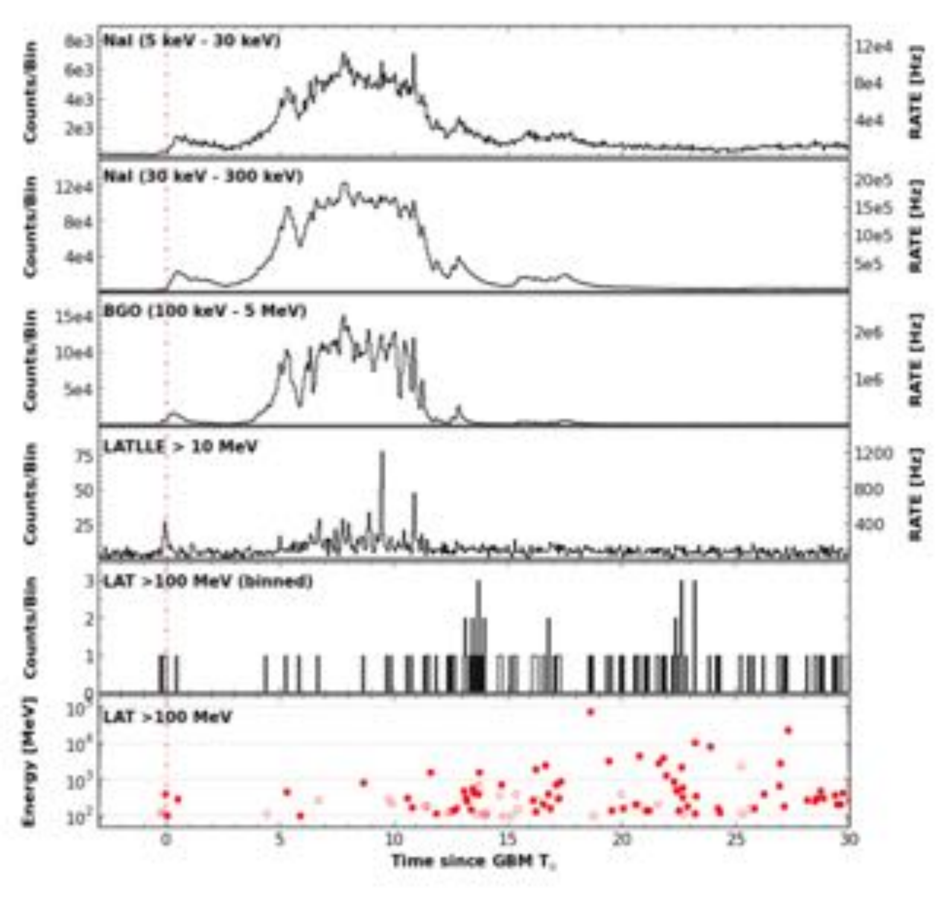
GRB 130427A Overview

- Detected by Swift, Integral, Fermi-GBM, & Fermi-LAT
- Brightest burst detected by both the LAT and the GBM
- Highest gamma-ray fluence ever measured
  - 4.2×10^{-3} erg cm^{-2} in the GBM
- Triggered an Autonomous Repoint Request
- Longest-lasting GeV emission (~1 day in LAT)
  - 32 GeV photon detected >8 hours after burst onset
- Fantastic multi-wavelength coverage
  - 53 observatories, some still observing

Temporal Structure

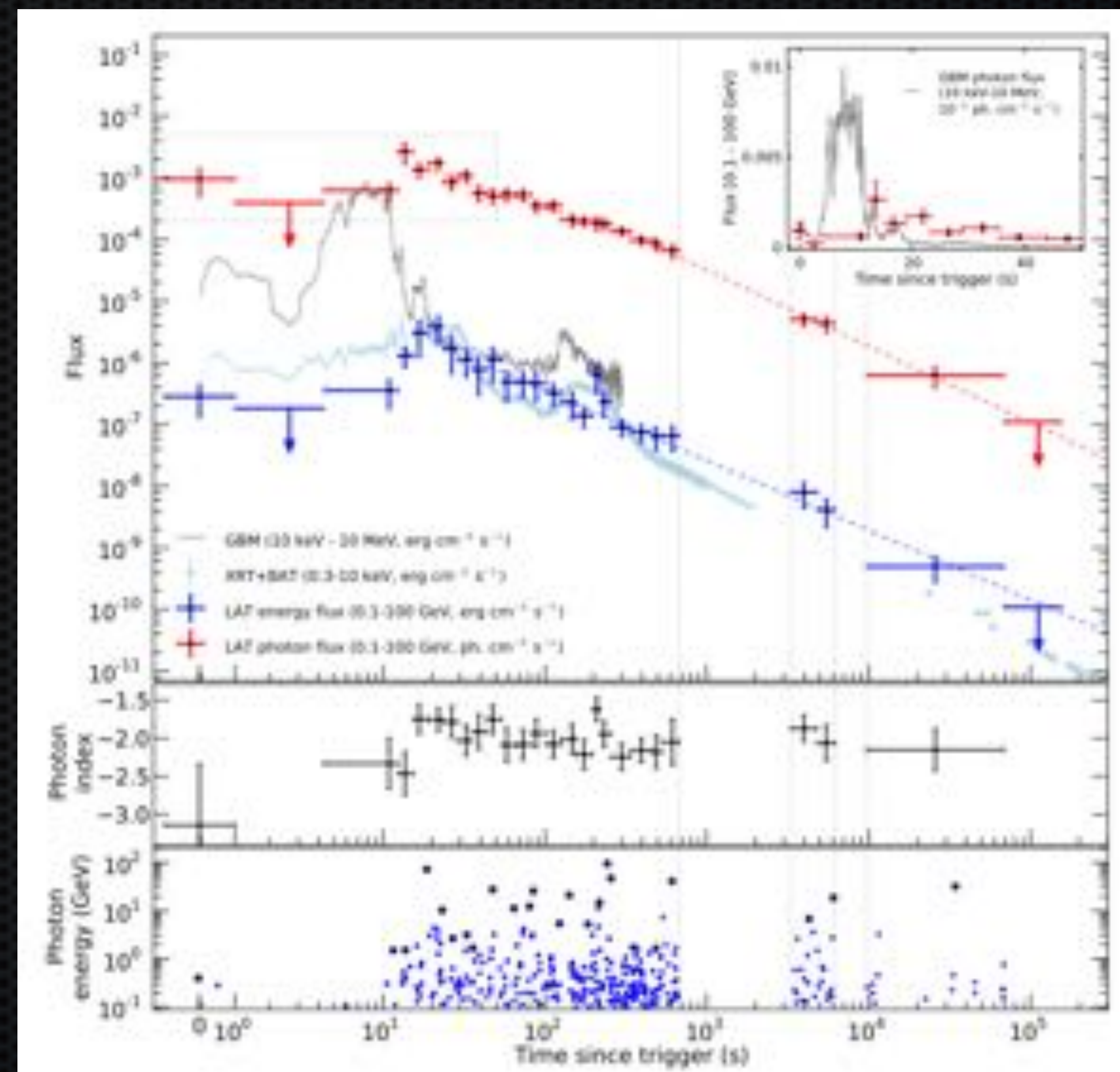
- Initial spike followed by a complex series of pulses
- Brightest portion saturated the GBM bus, resulting in data loss
- Significant pulse pile up in GBM
- This complicates the spectral fitting analysis at high-energies
- Clever tricks were employed to recover the lost information
- Bulk of Fermi-LAT emission starts after the GBM emission





Extended GeV emission

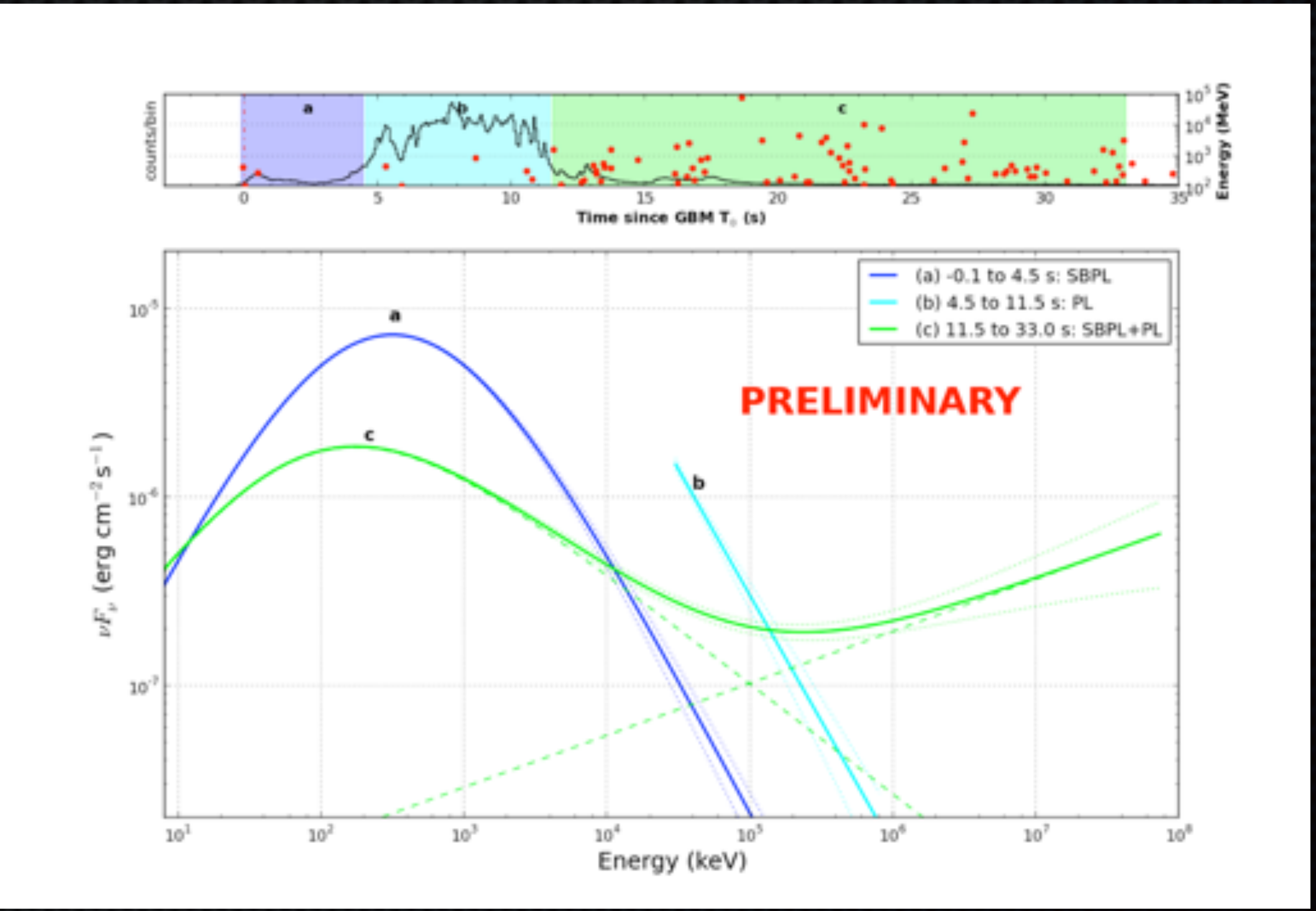
- Long lasting MeV-GeV emission
  - Detected out to ~1 day
- Photon flux (red)
  - Broken power-law ~300s
- Break time and index match that see in the X-rays by Swift-XRT
- Photon index of -2
  - Flat vFv spectrum



Ackermann et al. 2013

Spectral Fitting

- The prompt GBM emission is well fit by a “Band function”
- As the LAT emission increases, an extra power-law component becomes evident.
- Evidence that MeV-GeV emission is distinct from the KeV emission
- No evidence for multiple spectral components at high energies



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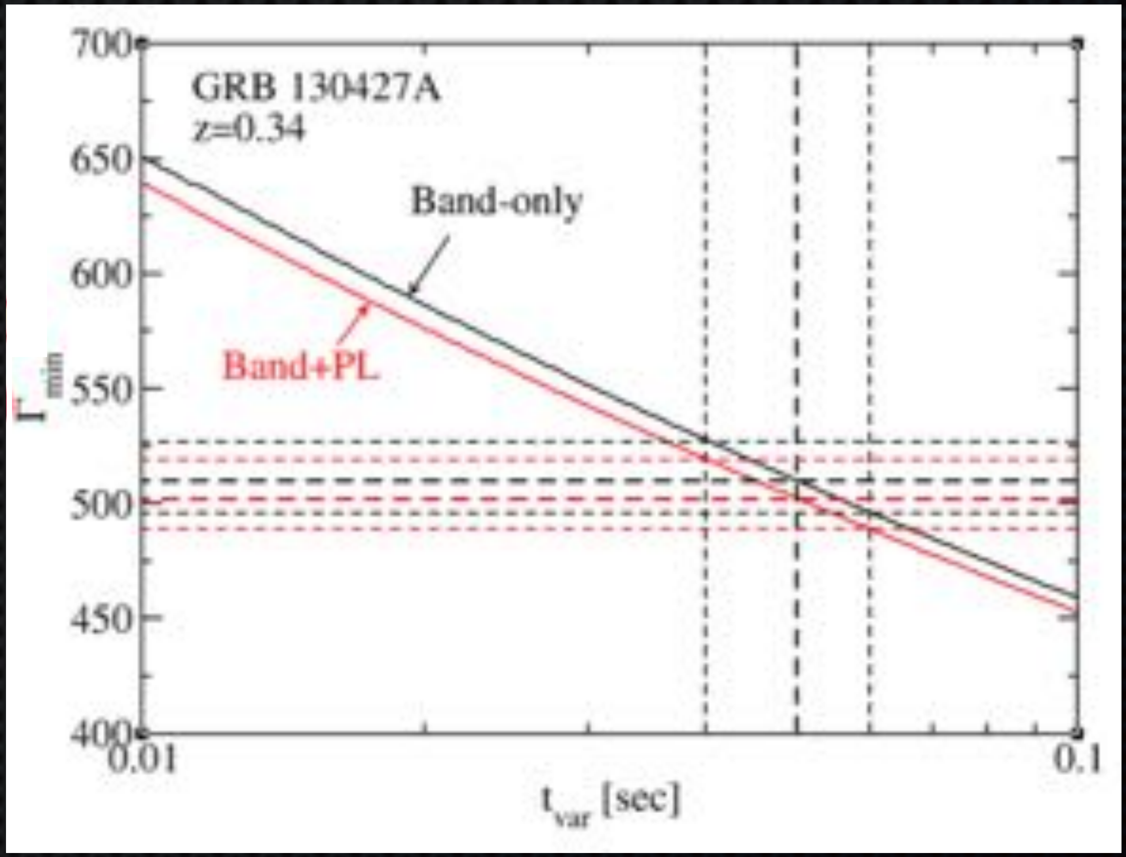
Bulk Lorentz Factor

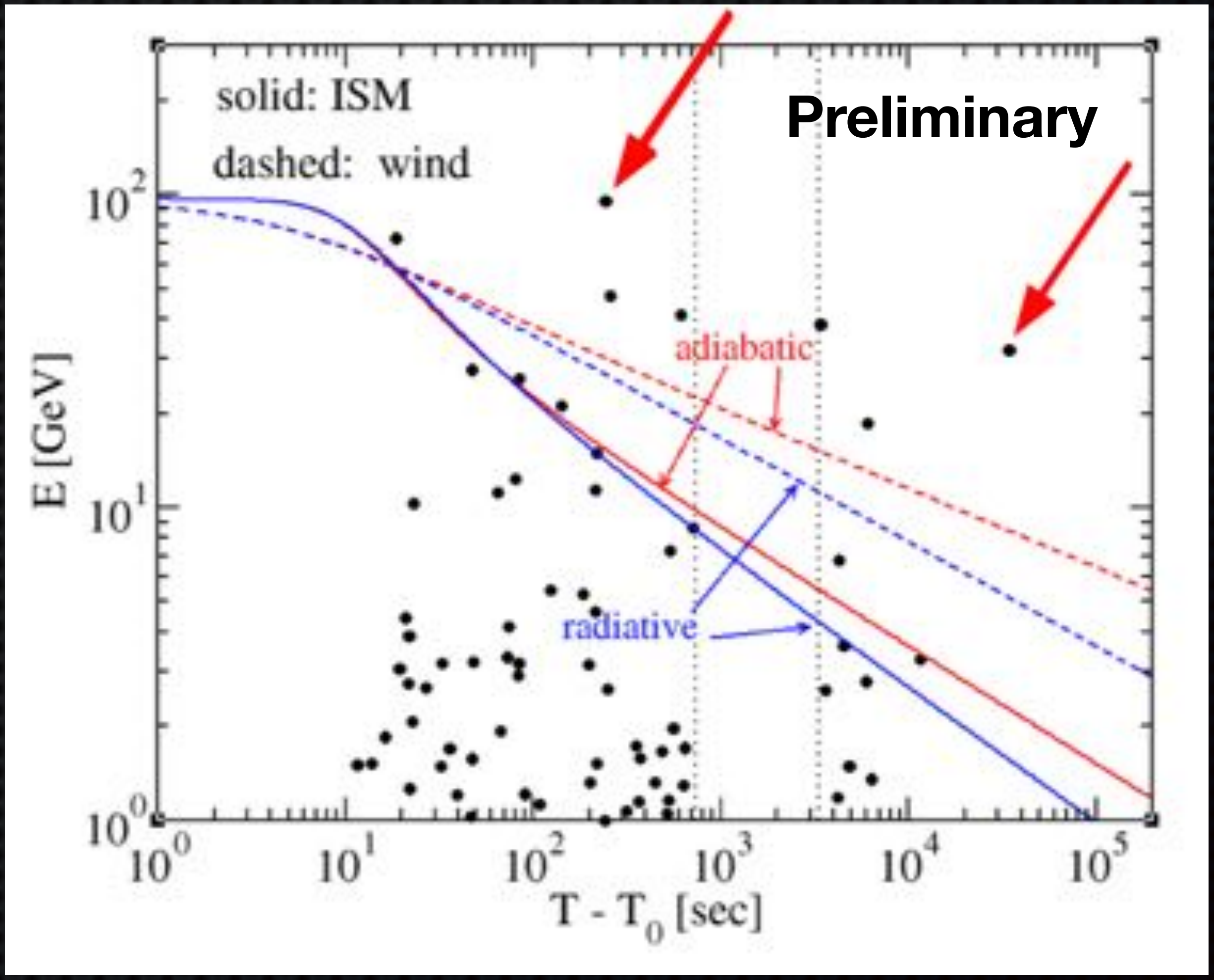
- No evidence for γγ-attenuation
  - Using 73 GeV photon at 19s
  - $\tau_{\gamma\gamma}(E_{max}, z, \Delta t, \Gamma, \beta) < 1$
  - $\Gamma_{min} \sim 500$
- From deceleration timescale Γ
  - $t_{dec} \sim$ 10-20 seconds
  - $\Gamma_{min} \sim 770$



Ackermann et al. 2013

High-energy late-time photons

- The arrival of high-energy emission at very late times is problematic for synchrotron emission
- The highest energy external shock photons should arrive around the deceleration timescale, t_d ~10-20s
- Synchrotron emission is too efficient and the radiating electrons should lose all of their energy very quickly
- Excellent sources for Magic, HESS, Veritas, and CTA!

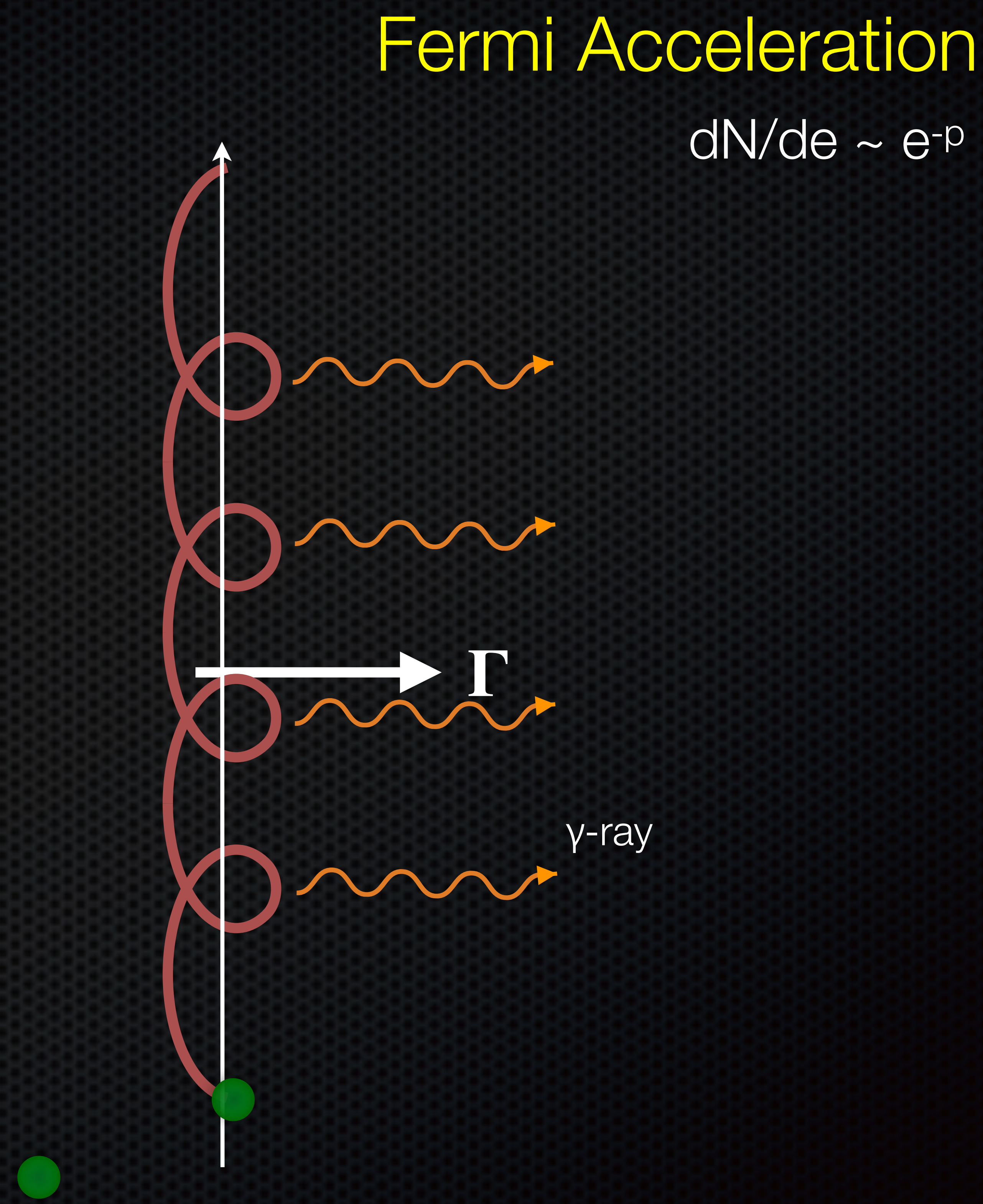


Ackermann et al. 2013

Standouts: 95 GeV (143 s) and 32 GeV (>30 ks)

Maximum Synchrotron Energy

- Radiation-reaction limited ε_{max}:
  - Larmor orbit timescale = timescale for synchrotron losses
  - Extremely hard to produce 100 GeV photons with synchrotron emission
- IC or SSC mechanisms are needed above these energies



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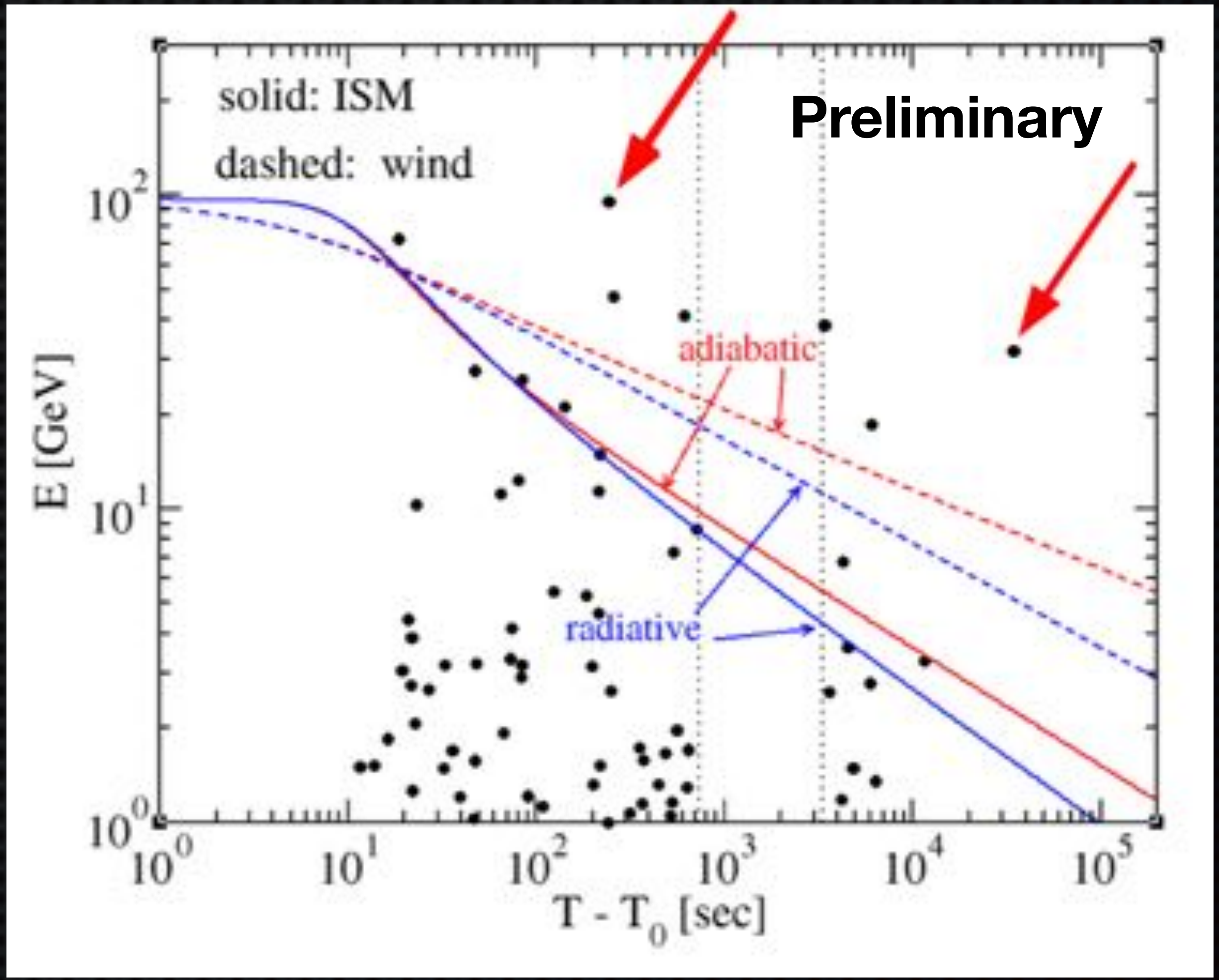
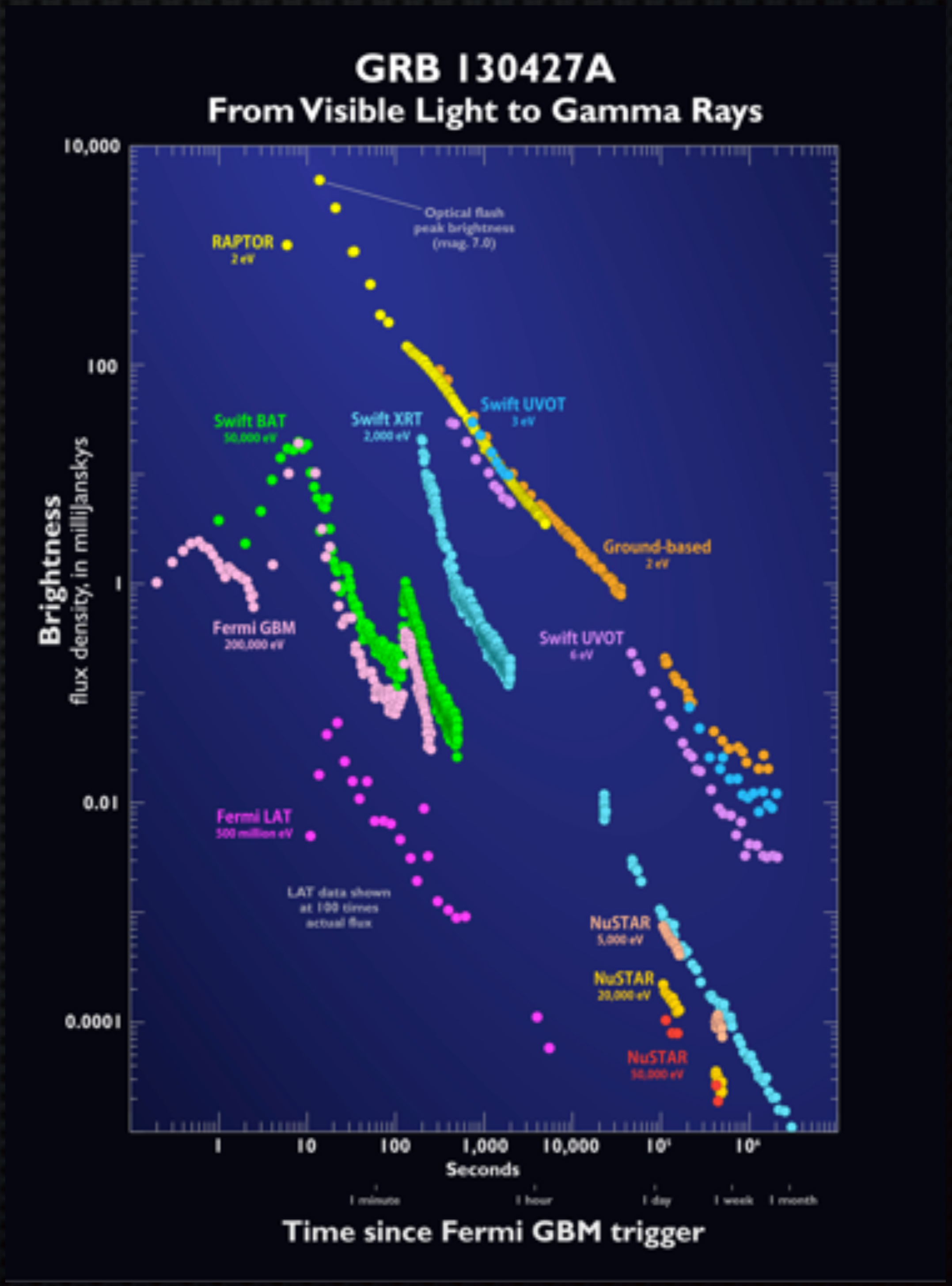


Ackermann et al. 2013

Standouts: 95 GeV (143 s) and 32 GeV (>30 ks)

Multi-wavelength Observations

- Excellent multi-wavelength coverage
- Should be visible in x-rays for ~ year!
- Swift & Nu-Star data support a single spectral component from x-rays to GeV energies
- Optical and radio observations can be fit with a standard afterglow spectrum
- No evidence for inverse Compton and synchrotron self-Compton processes



Afterglow Model Challenges

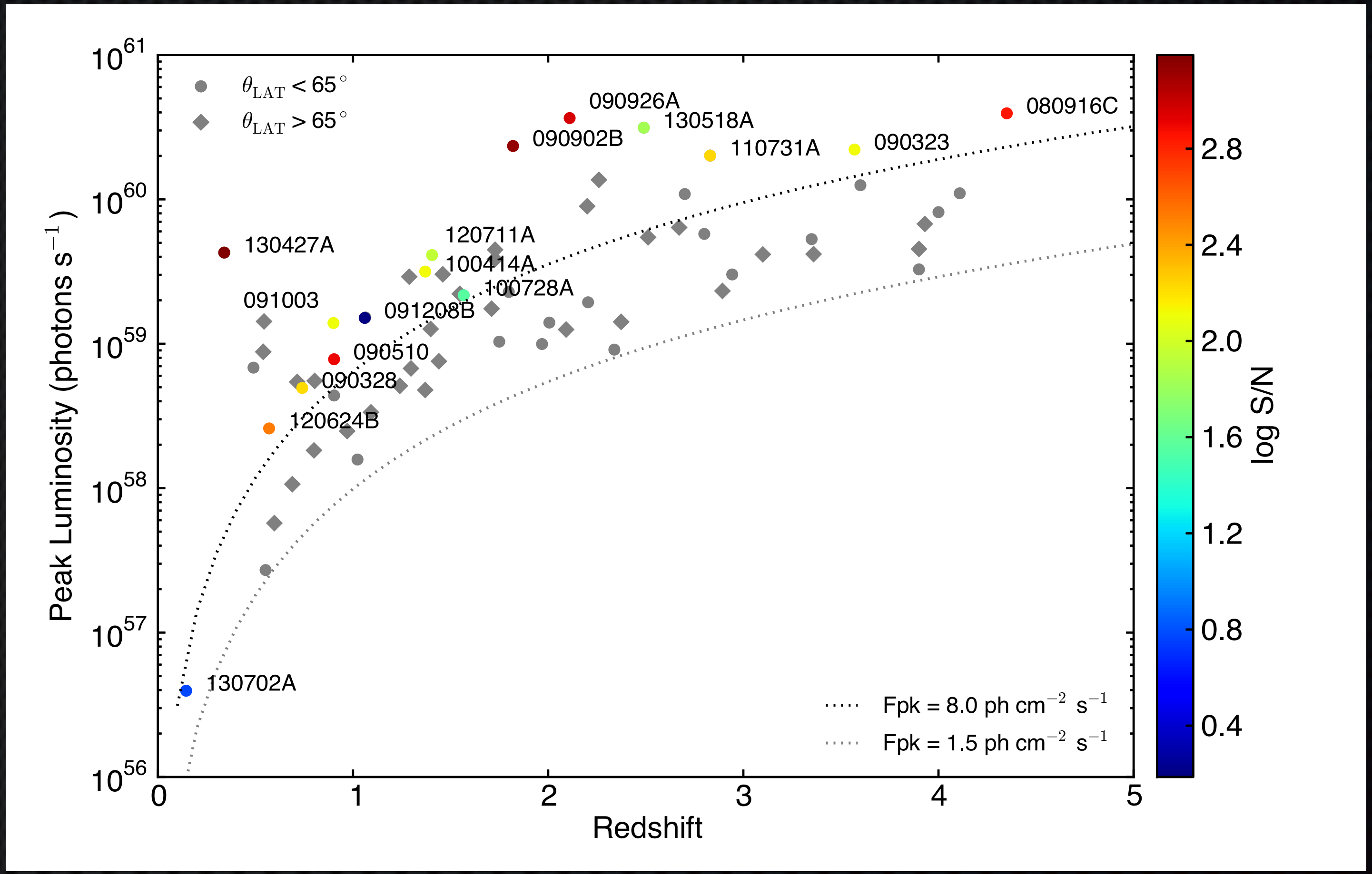
- SSC (synch photons up-scattered by jet electrons)
  - During prompt phase, SSC photons are >TeV. If the environment is optically thin, cannot account for emergence of GeV photons
  - Blast wave decelerates, highest energy SSC photons pass through LAT energy => should see an effect in LAT LC
- “Standard” AG model: LAT GeV emission is non-thermal synchrotron from electrons accelerated at external shock
  - Synchrotron emission above 100 GeV is still possible if an acceleration mechanism faster than the Fermi process is acting, such as magnetic reconnection
  - Gradient in the magnetic field strength
- Electromagnetic cascade
  - Induced by UHE gamma-ray photons

Interpretation

- LAT emission preceding GBM emission during first pulse
  - Simple hard to soft evolution of internal shock emission
- LAT long-lived extended emission
  - Interaction between the blast wave and the circumburst medium, i.e. due to an external shock origin
  - Similarity in temporal and spectral shape to XRT emission supports this interpretation
- Origin of the late-time GeV emission?
  - Unlikely due to inverse Compton or SSC mechanisms
  - Likely not due to simple synchrotron emission though!

Population Demographics

- Even though 130427A had a high Eiso value, it would have been seen by the GBM out to z ~ 5, but only to z ~ 2 by the LAT.
- The LAT detections follow the GBM detection threshold
- Mechanisms that creates extended emission is directly linked to the prompt
- Whether a burst has LAT emission may simply be a selection effect
- This high energy emission may be common in most bursts



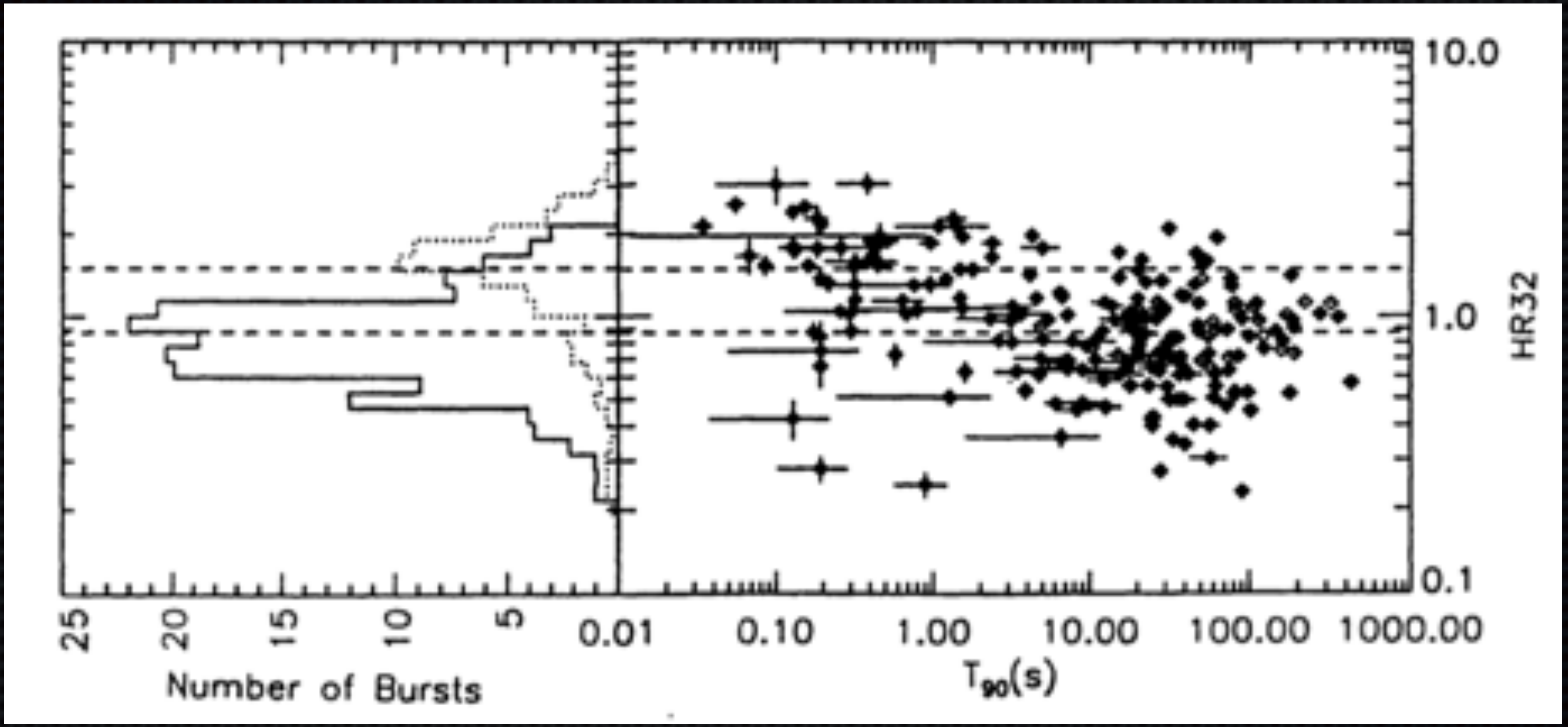
Unresolved Prompt Emission Questions

- Relatively narrow Epk values
    - Much wider and flatter Epk peaks have now been observed
- Where is the evidence for pair attenuation?
    - Definitive detections of spectral turnovers, interpreted as pair attenuation
- Nature of the delayed extra power-law component seen by EGRET?
    - Onset of the afterglow emission at GeV energies?
    - Not a ubiquitous feature in GRB spectra though
- Where are the IC and SSC components?
    - These components are not ubiquitous at GeV energies
- Where is the photospheric emission?
    - Growing evidence for photospheric emission broadband fits

Outstanding Questions!

- What accounts for the delay in the prompt GeV emission
  - Rise of the external shock emission?
  - Hadronic emission (proton synchrotron or photo-meson processes)?
- What is the emission mechanisms for the late GeV emission?
  - Modified synchrotron emission?
- How do we explain the late-time GeV photons at such late times
  - Late-time particle acceleration (i.e. magnetic reconnection)?
- Where is the IC and/or SSC peak?
  - At TeV energies?
- What sets LAT detected GRBs apart from the general population?
  - More energetic? Denser circumburst medium? Simple flux threshold?

Two GRB Populations

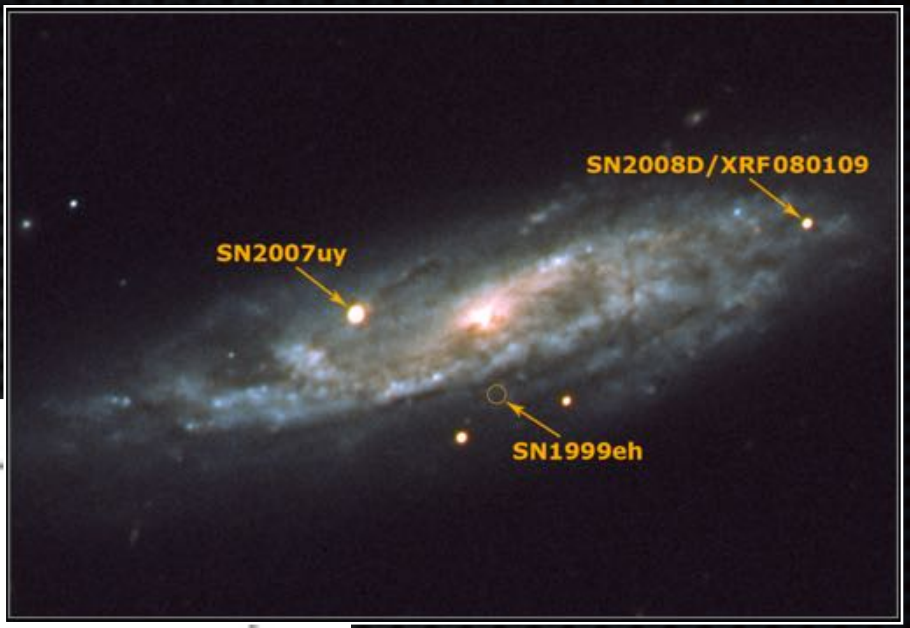


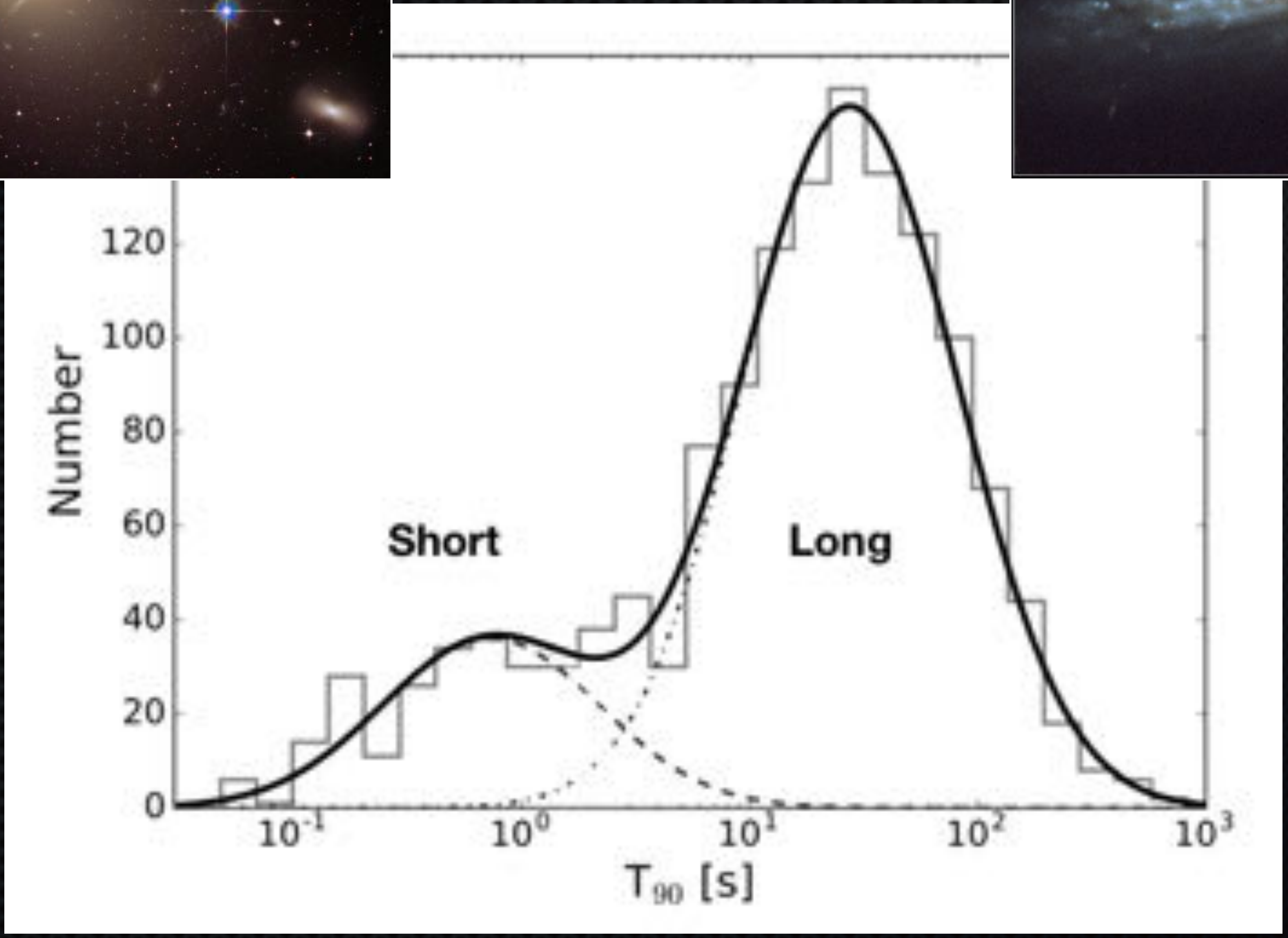
Kouveliotou et al. 1993

- 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

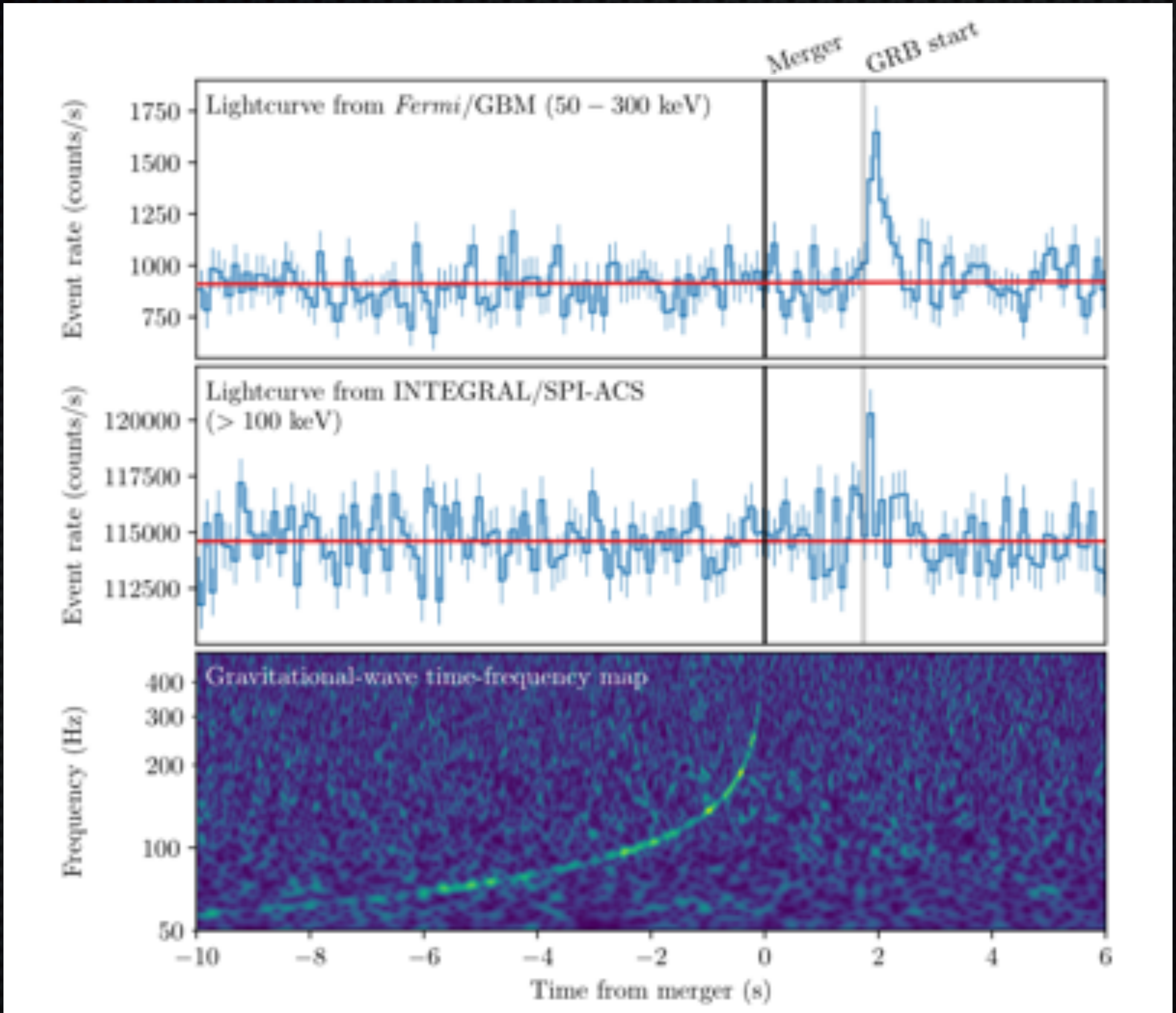




GBM Partnership With LIGO/Virgo

- GBM-LIGO MoU allows for a unique data sharing agreement
- GBM provides sub-threshold GRBs in low-latency for GW follow-up (New in O2)
- LIGO provide “sub-threshold” GW candidates below EM Follow-up threshold
  - In low-latency for autonomous targeted (seeded) GRB follow-up (New in O2)
- GBM detection would provide increased confidence in weak GW detections, effectively increasing the volume of the Universe accessible to LIGO/Virgo

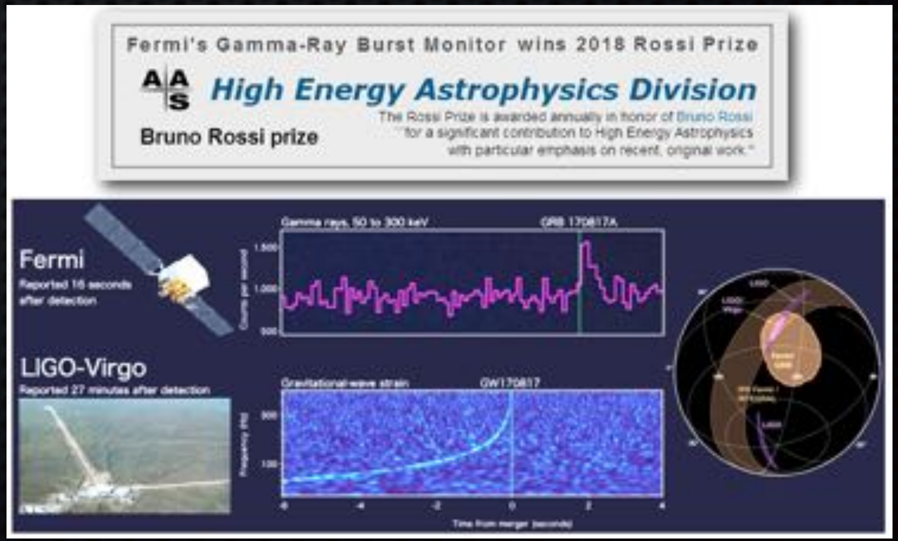
GW170817 - First Joint GW/GRB



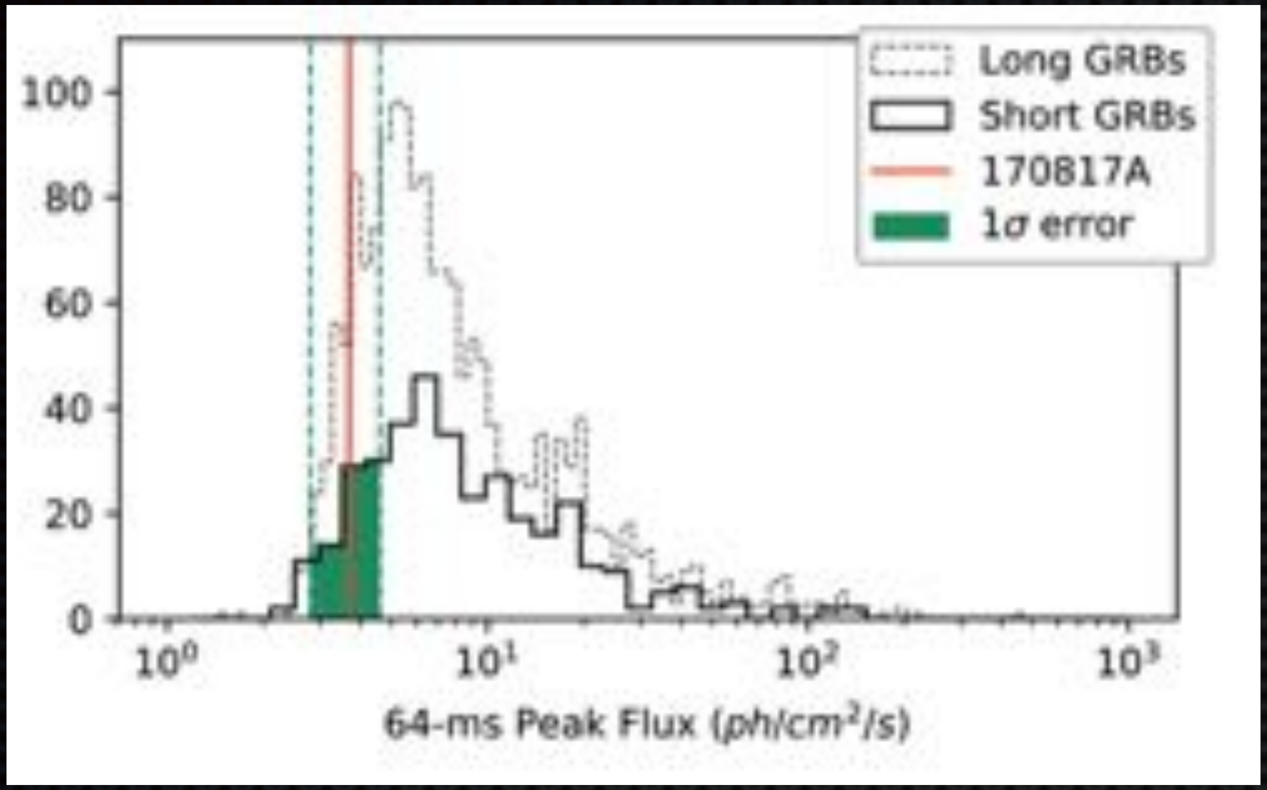
Abbot et al. 2017

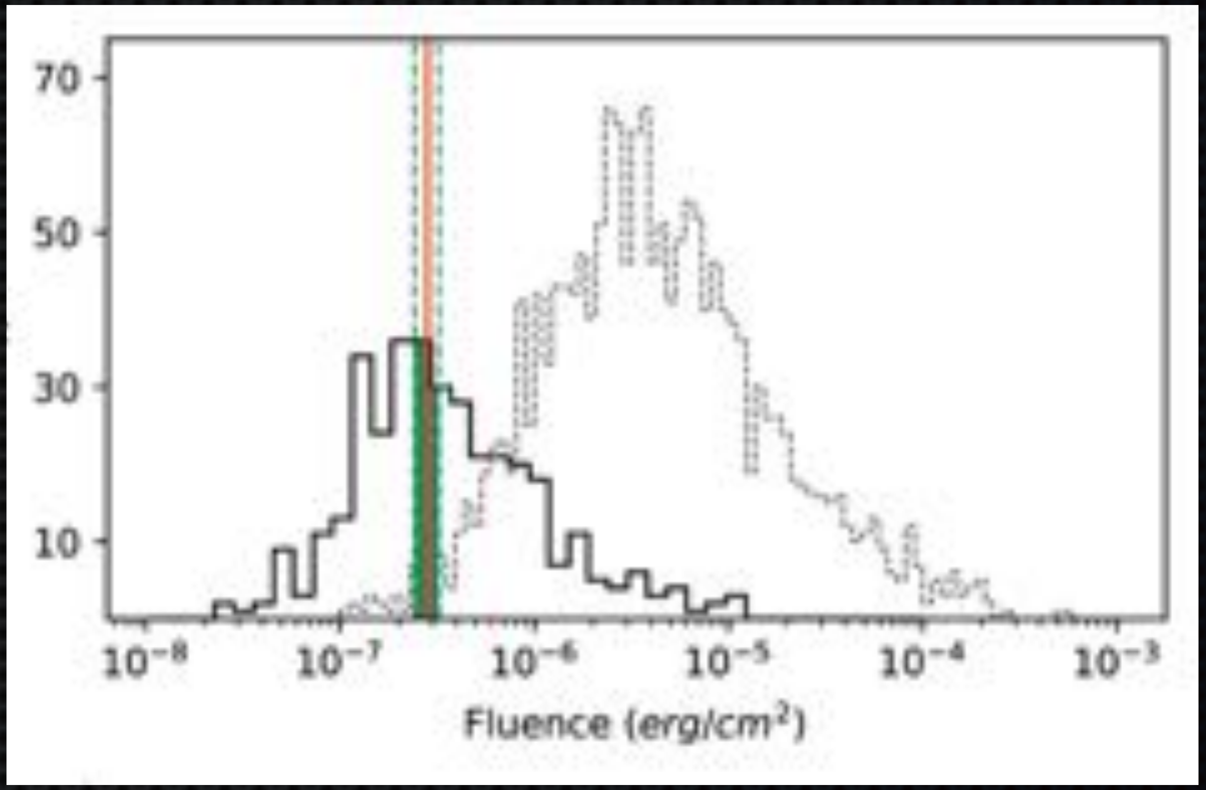
GRB 170817A

- >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!



Spectral Properties

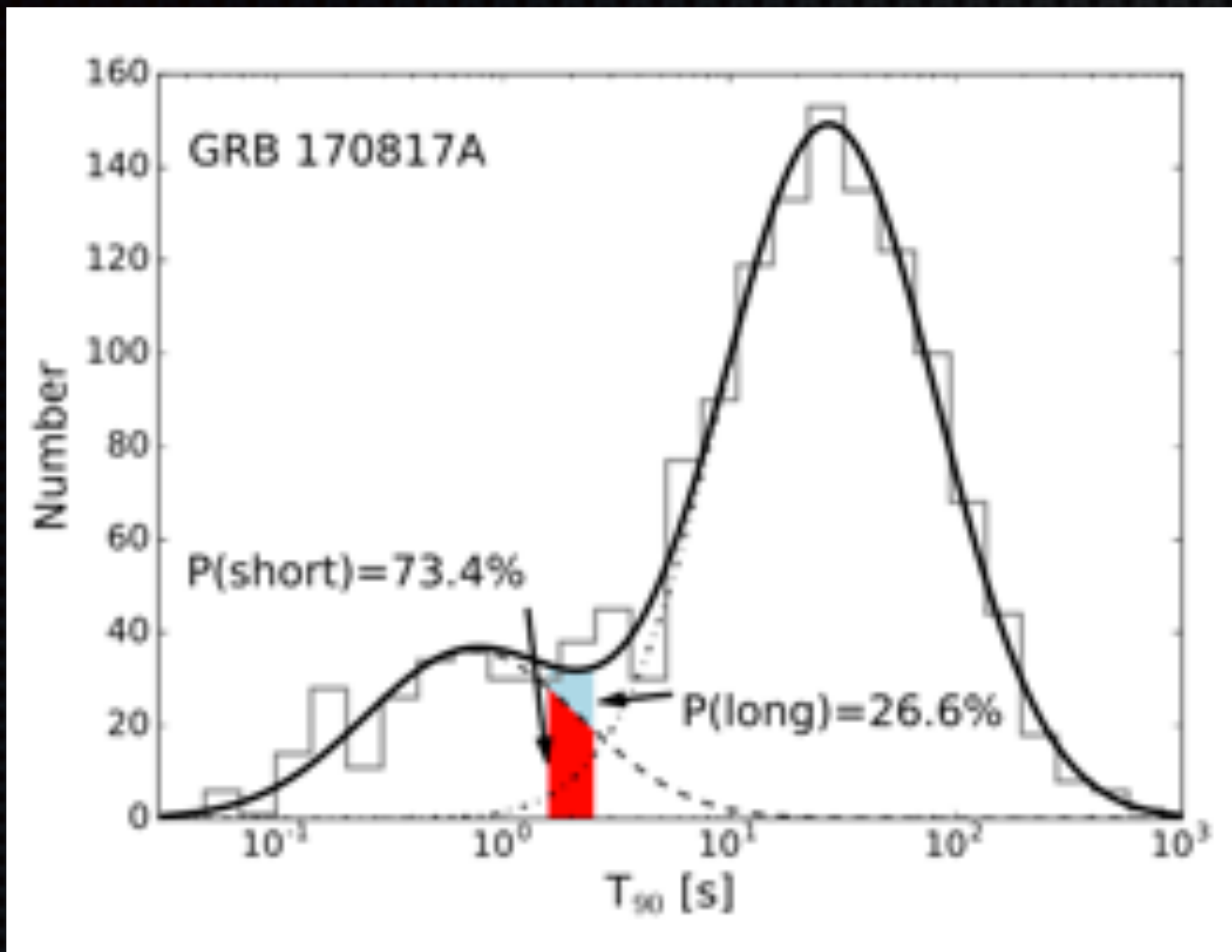


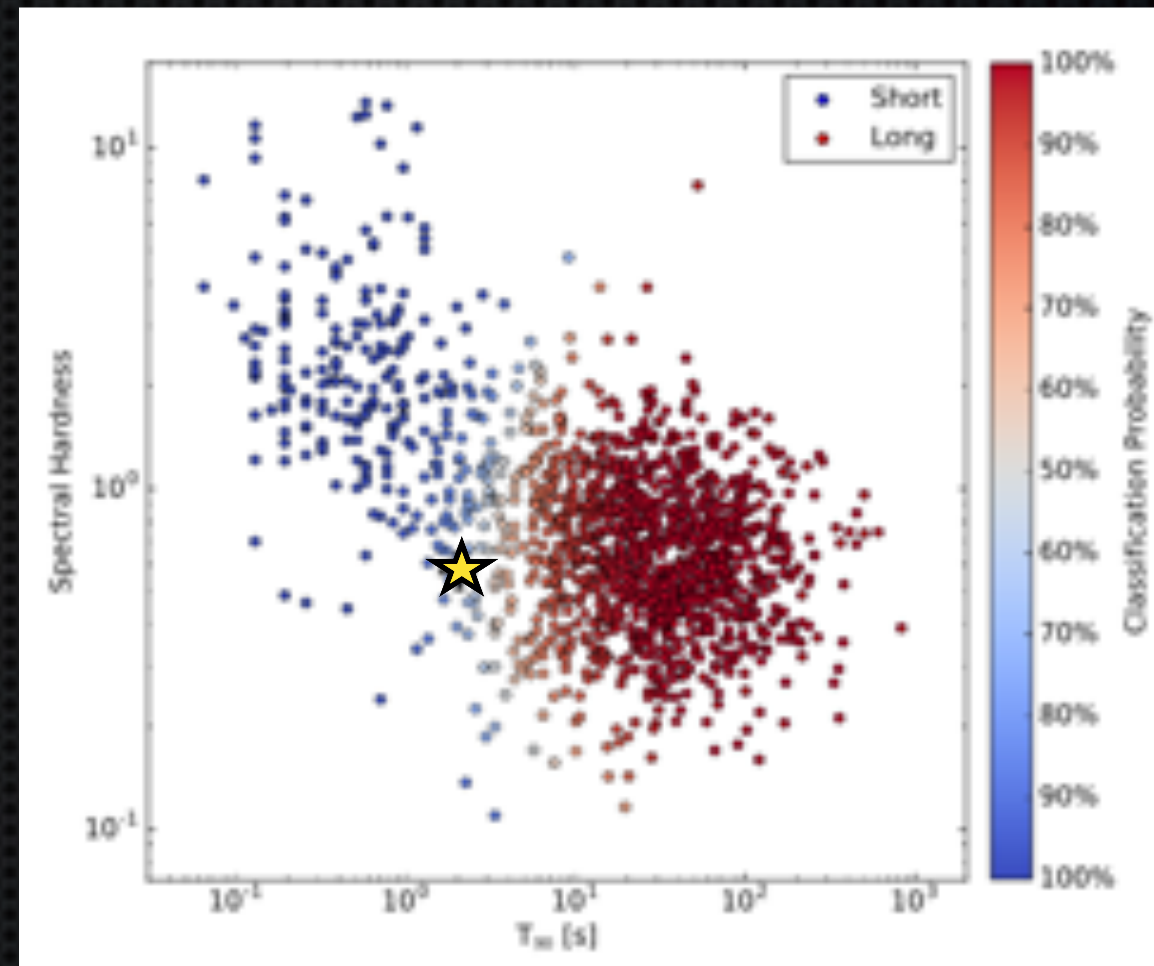


Goldstein et al. 2017

- 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
- So not that unusual of a short GRB

Duration/Hardness

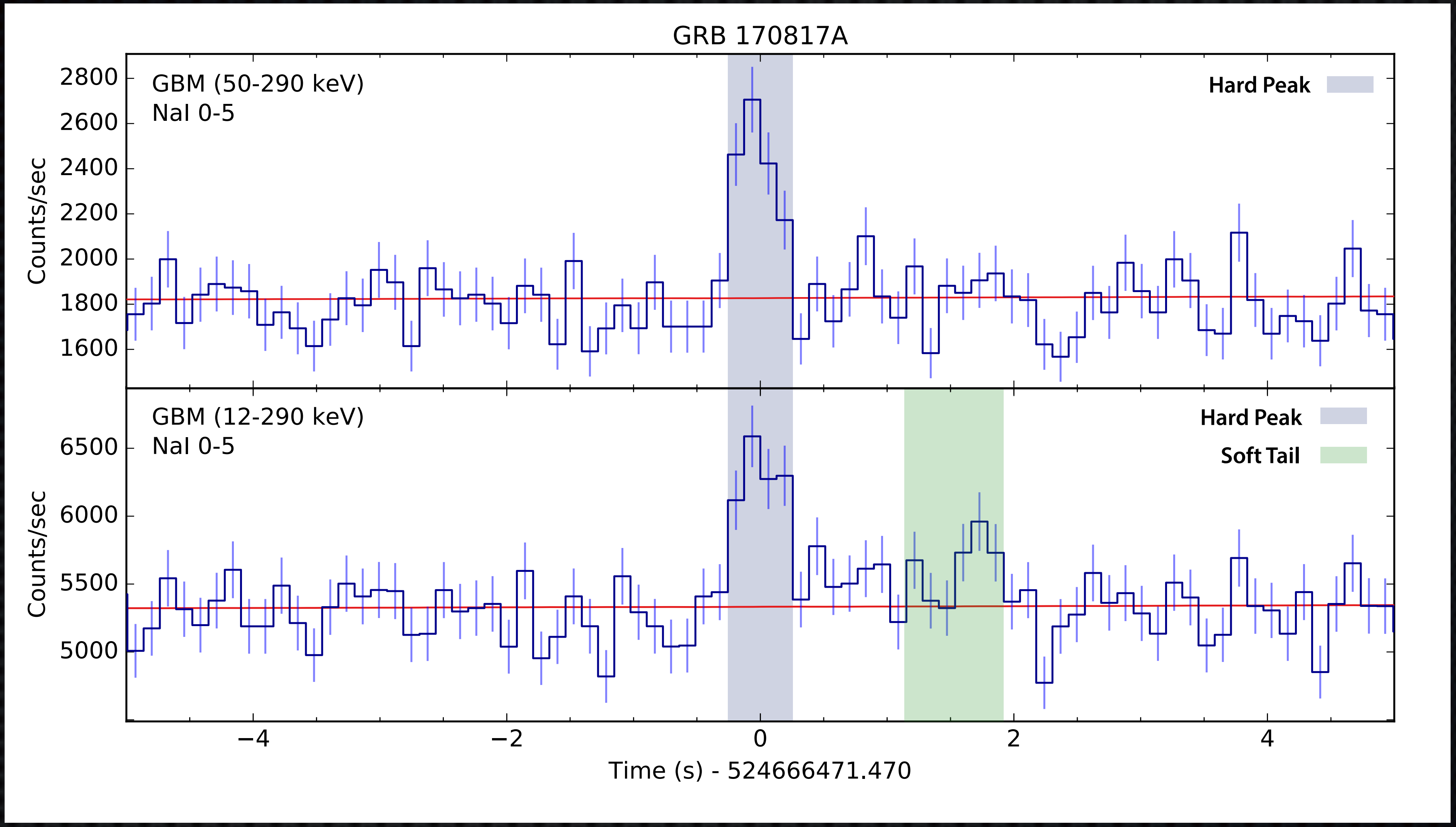




Goldstein et al. 2017

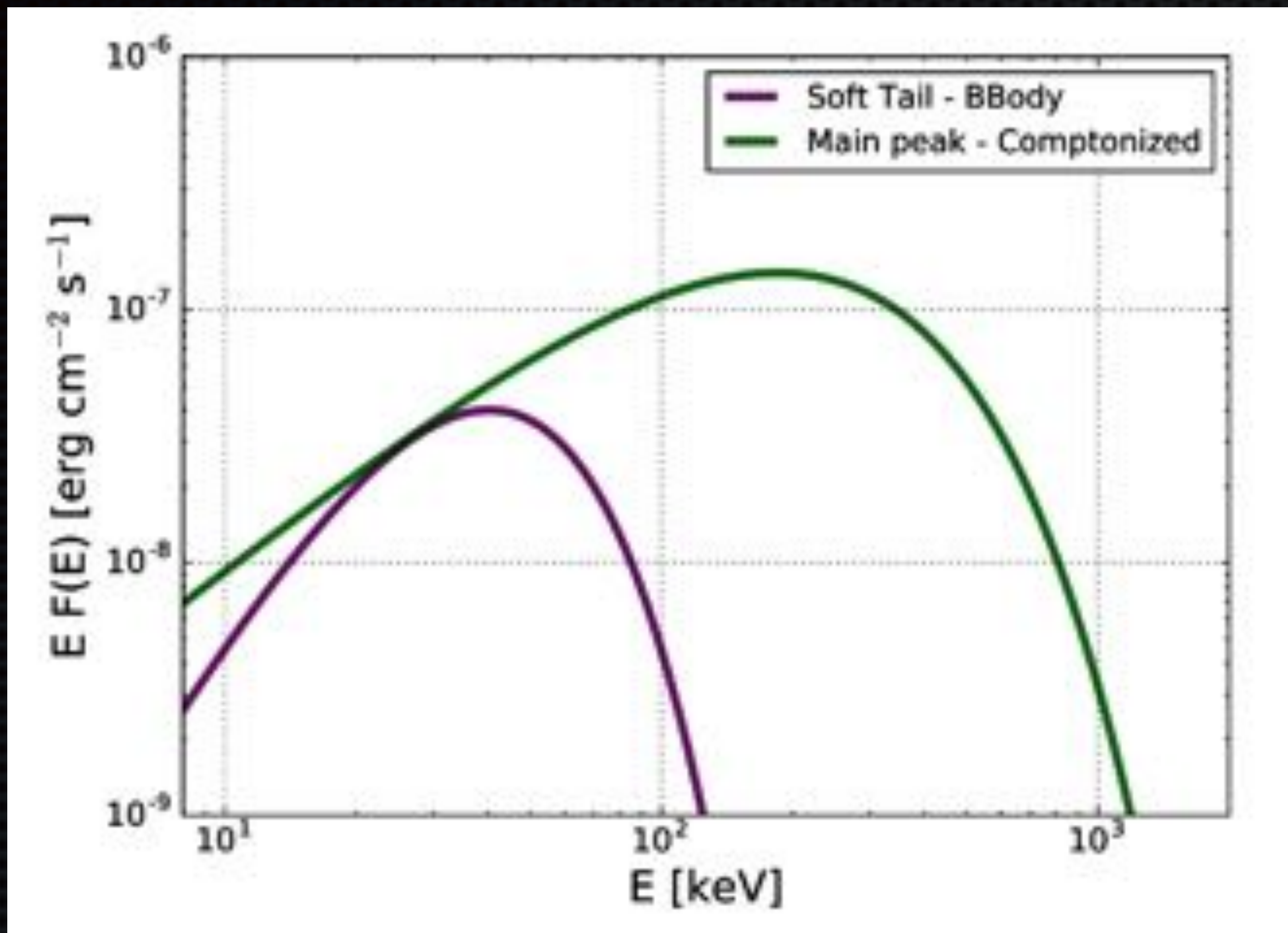
- A standard catalog analysis using 50-300 keV photons yields a T_{90} = 2.0 ± 0.5
- Hardness ratio between the 50-300 keV and 10-30 keV photons yields a relatively soft burst
- Combining both the duration and hardness information, we get P_{short} = 73.4%

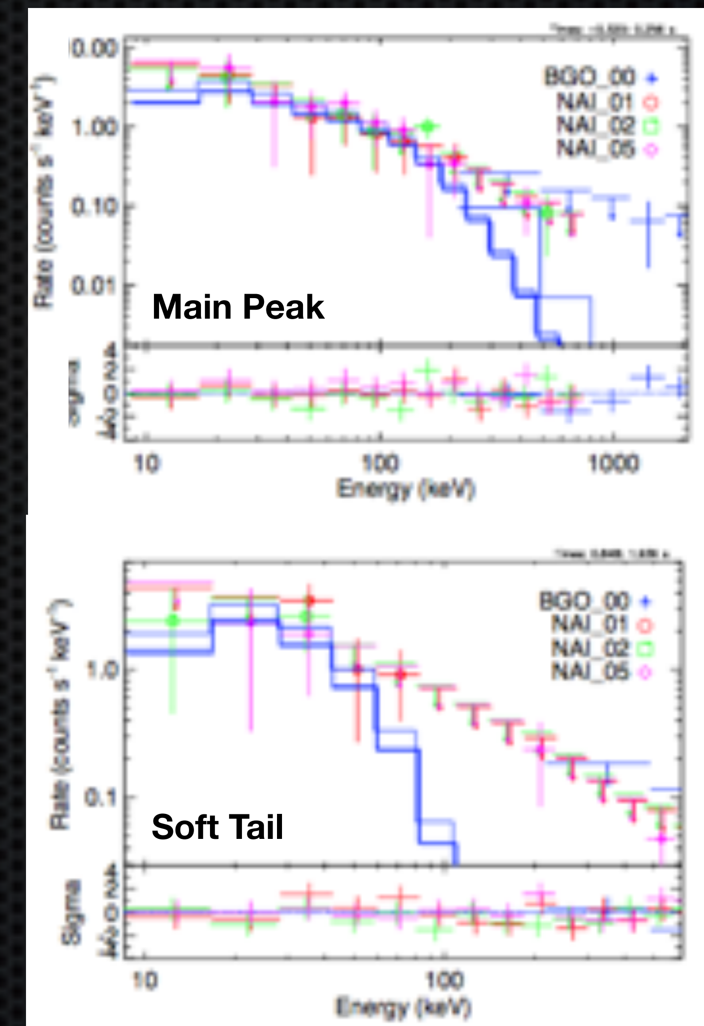
Hard Pulse and Soft Thermal Tail



- 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

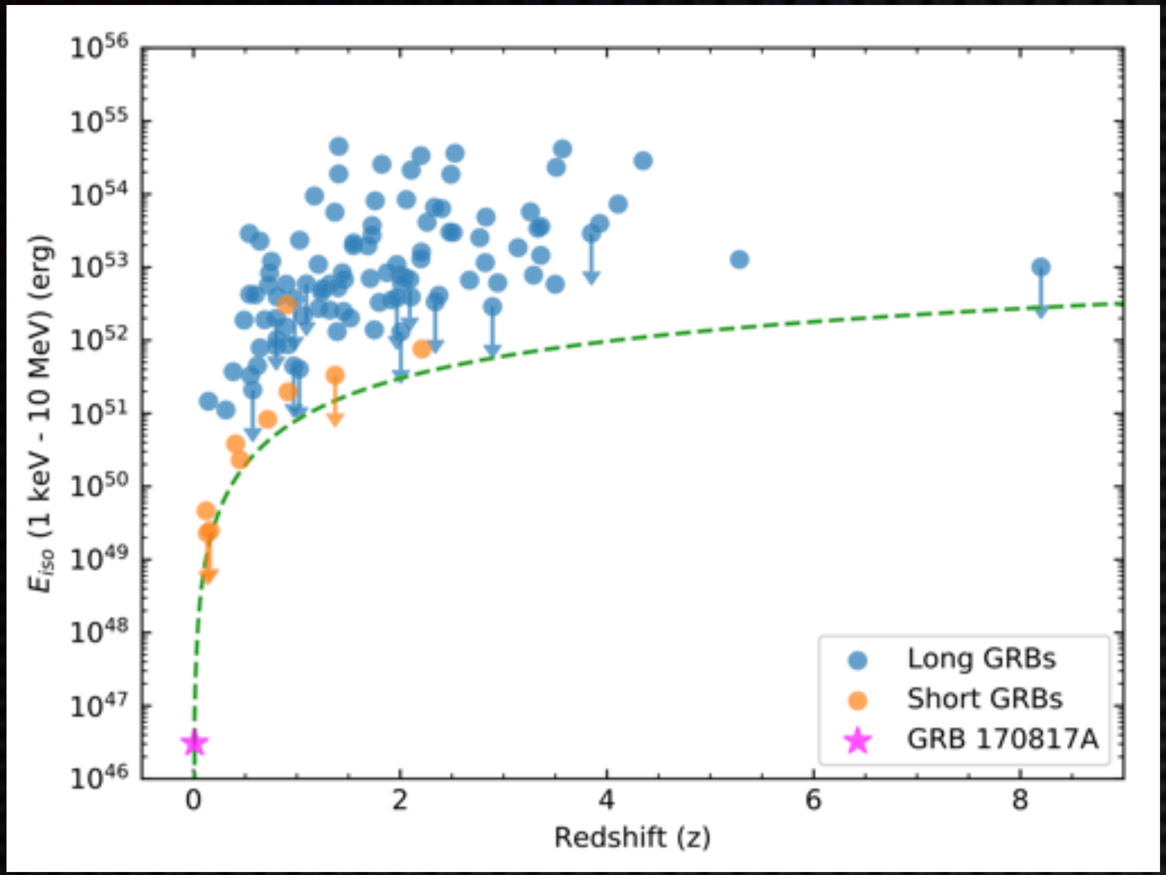


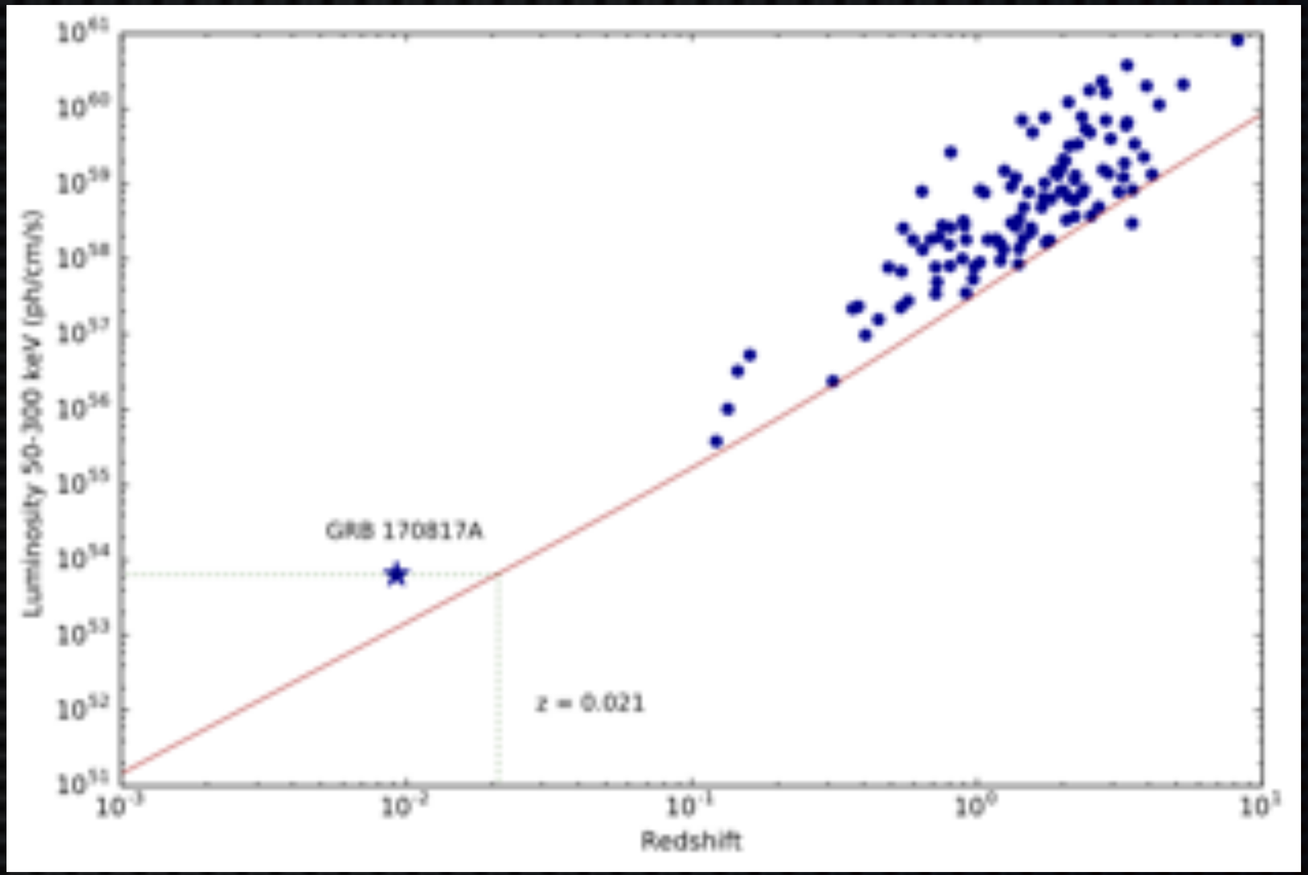


Goldstein et al. 2017

- The main hard peak is best fit with a Comptonized model with E_{pk} = 185 ± 62 keV
  - This is for the time-resolved analysis!
- The soft tail is best fit by a black body with kT = 10.3 ± 1.5 keV

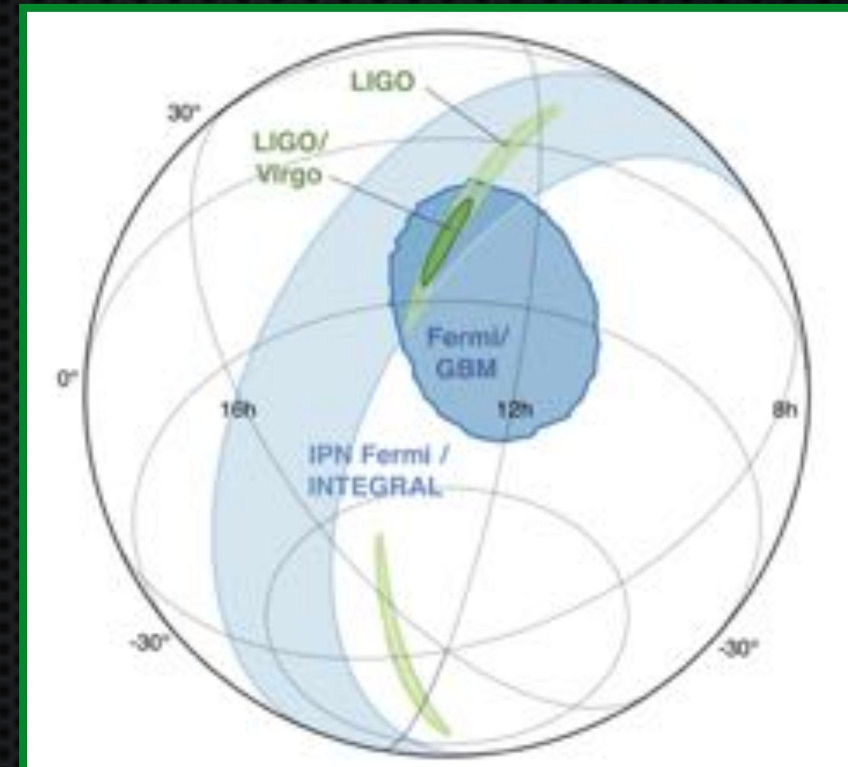
Source Frame Energetics





- GRB 170817 was extremely under luminous compared to other GRBs
  - It was the closest and least luminous GRB every 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

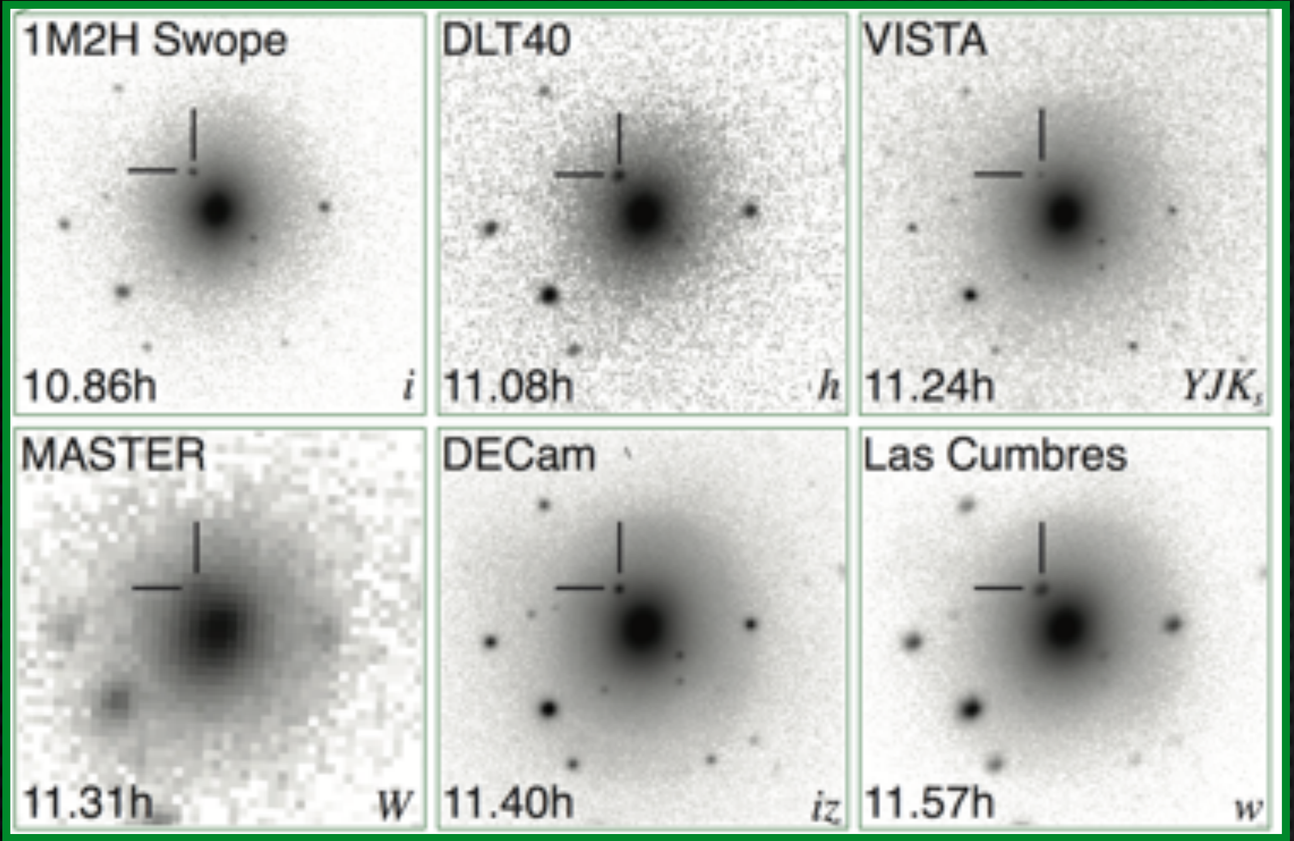
Joint LIGO/ Virgo sky map

+16 s

+27 s

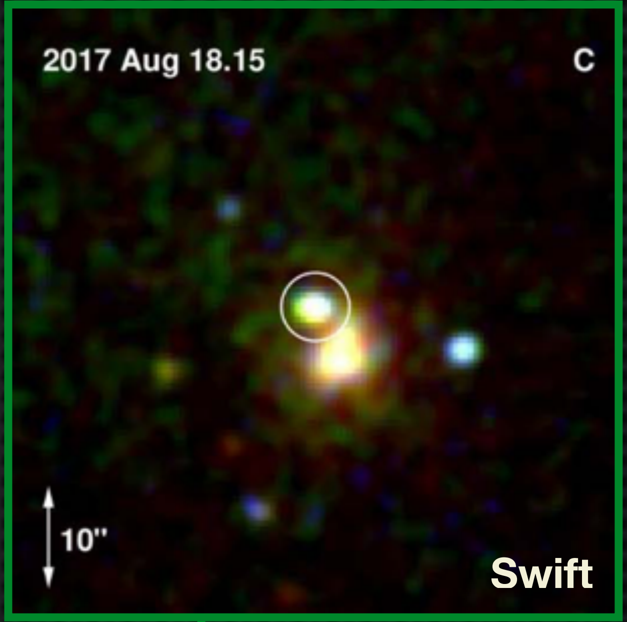
+45 min

+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 Campanas Observatory



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

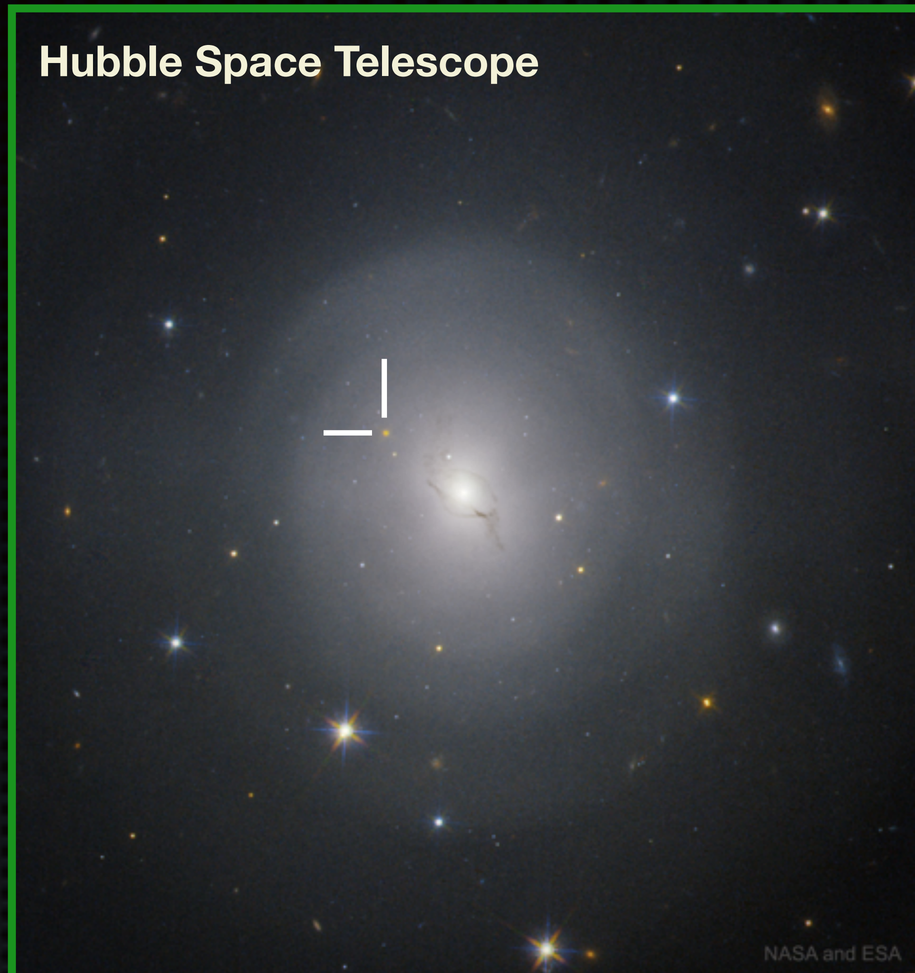
NuStar observations show no X-ray emission (Evans et al. 2017)

+12 hours

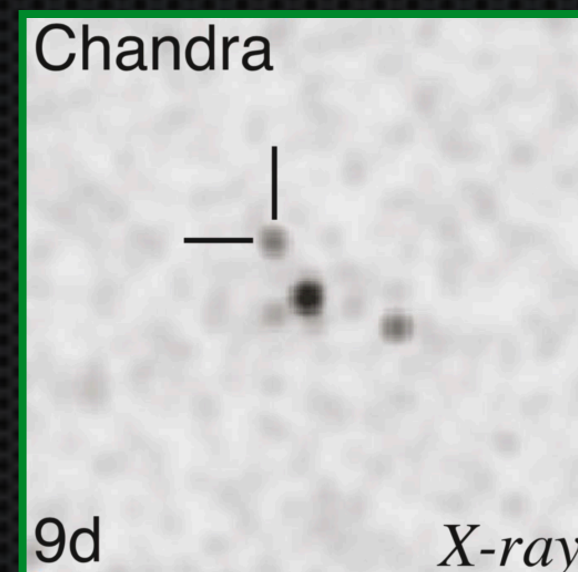
+13 hours

+14 hours

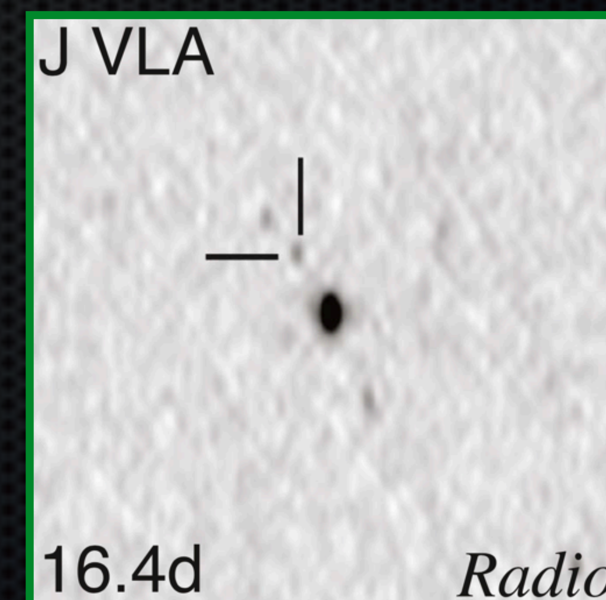
Chandra observations show no X-ray emission (Fong et al. 2017)



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

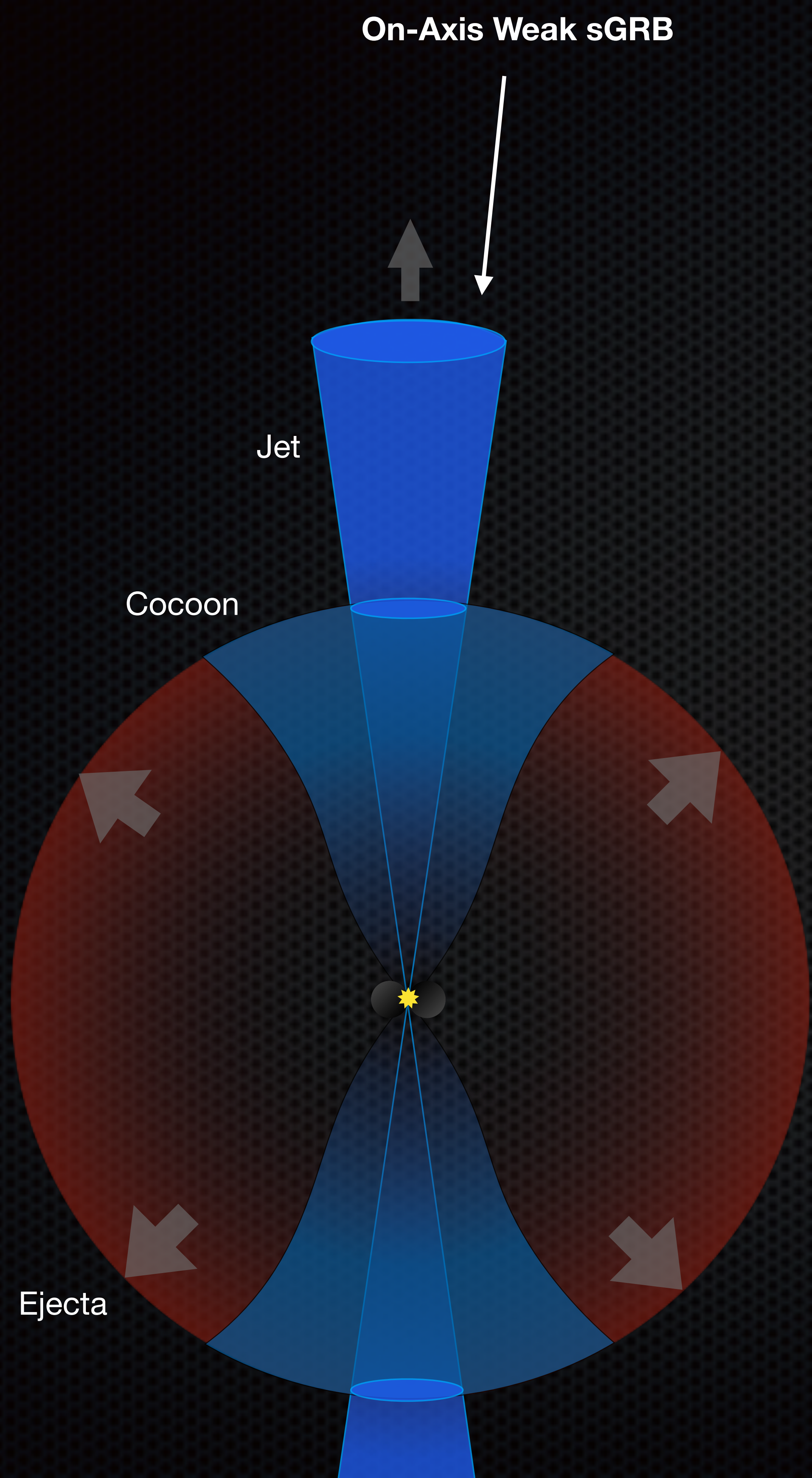
+5 days

+9 days

+16.4 days

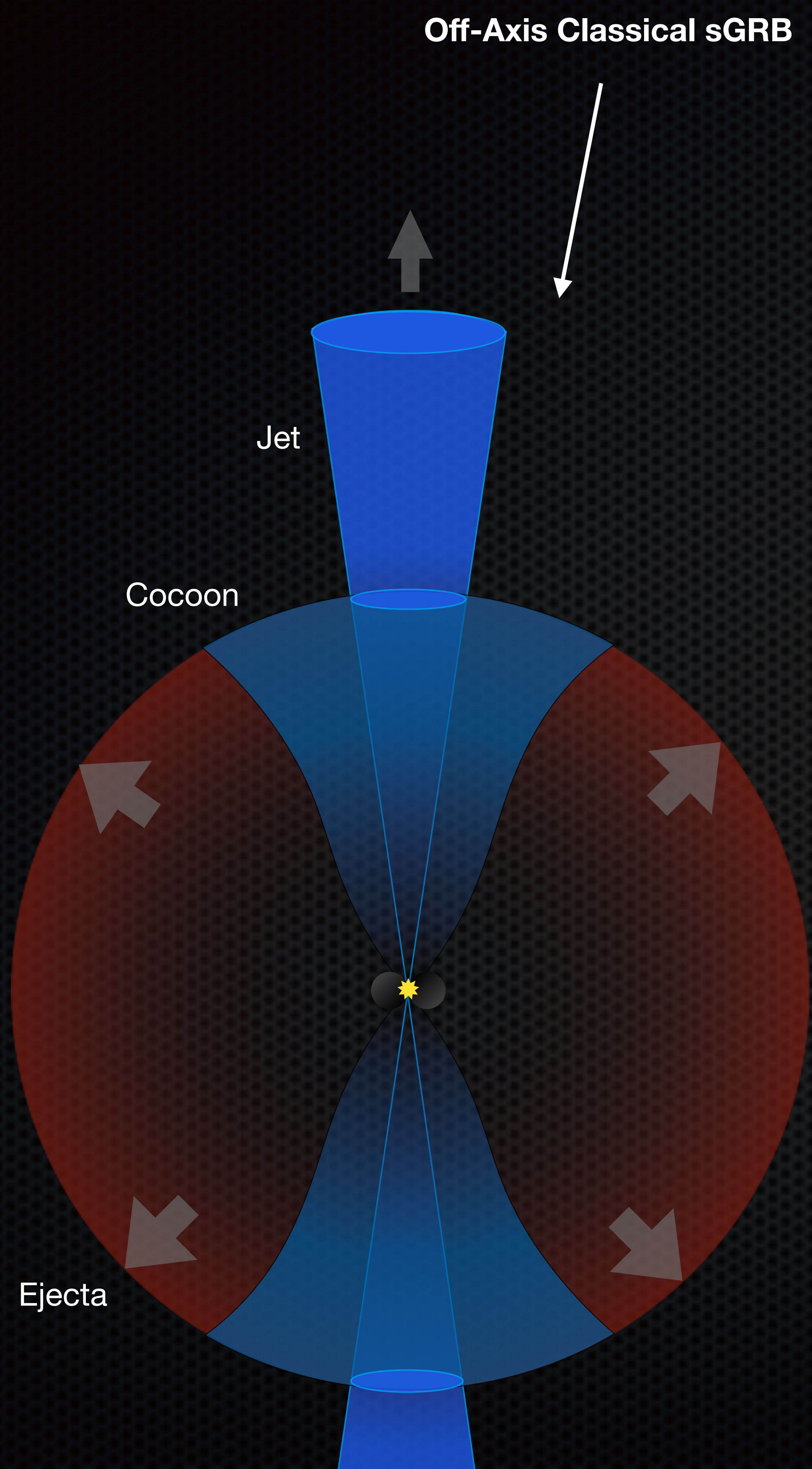
Kilonova

- 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



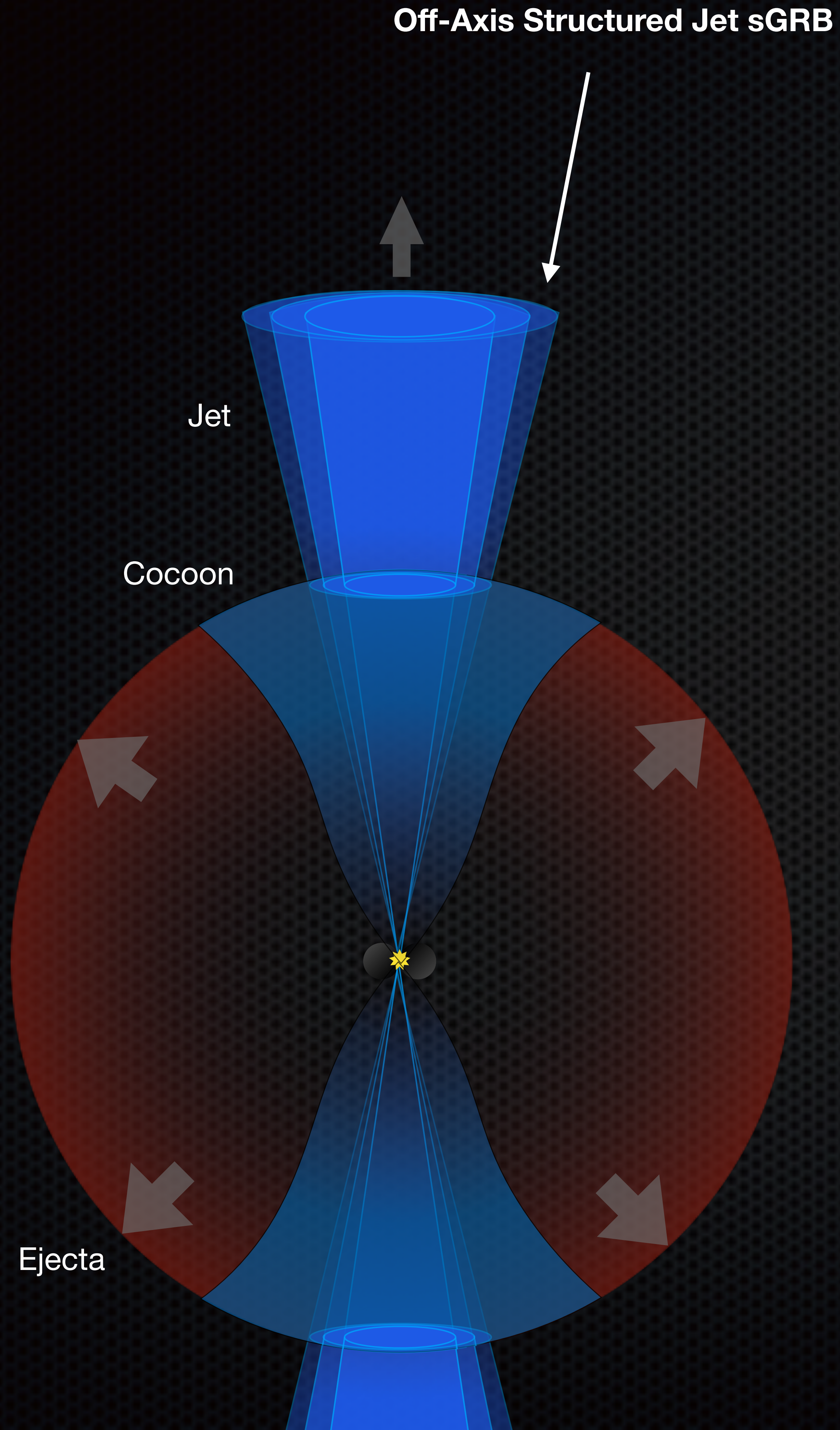
On-Axis Weak sGRB

- 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: θ_v ~ 29° +15°/-10° (LIGO - arXiv:1805.11579v1)
  - Average sGRB is θ_{jet} ~16° (Fong et al. 2015)



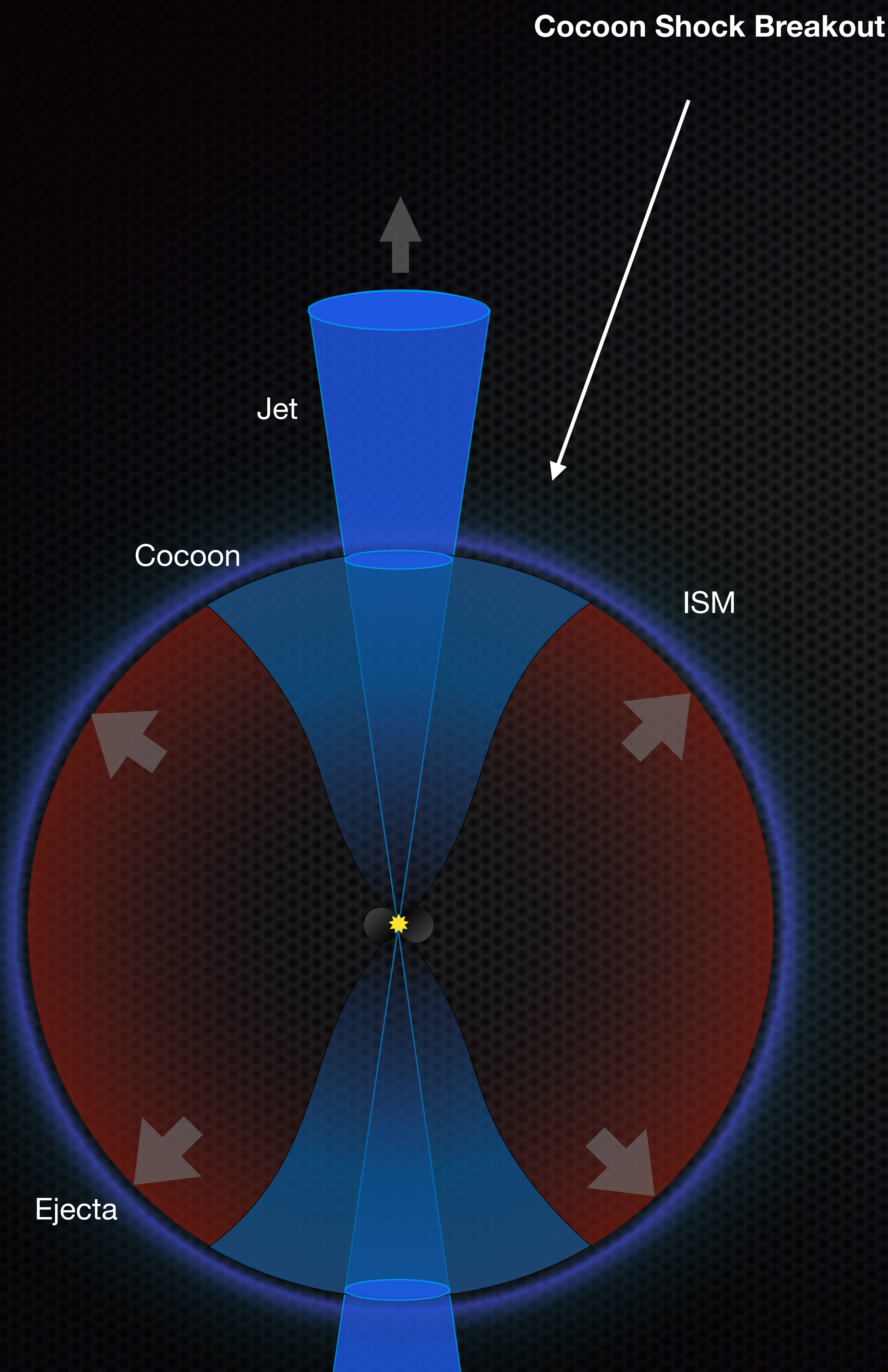
Off-Axis Classical sGRB

- 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



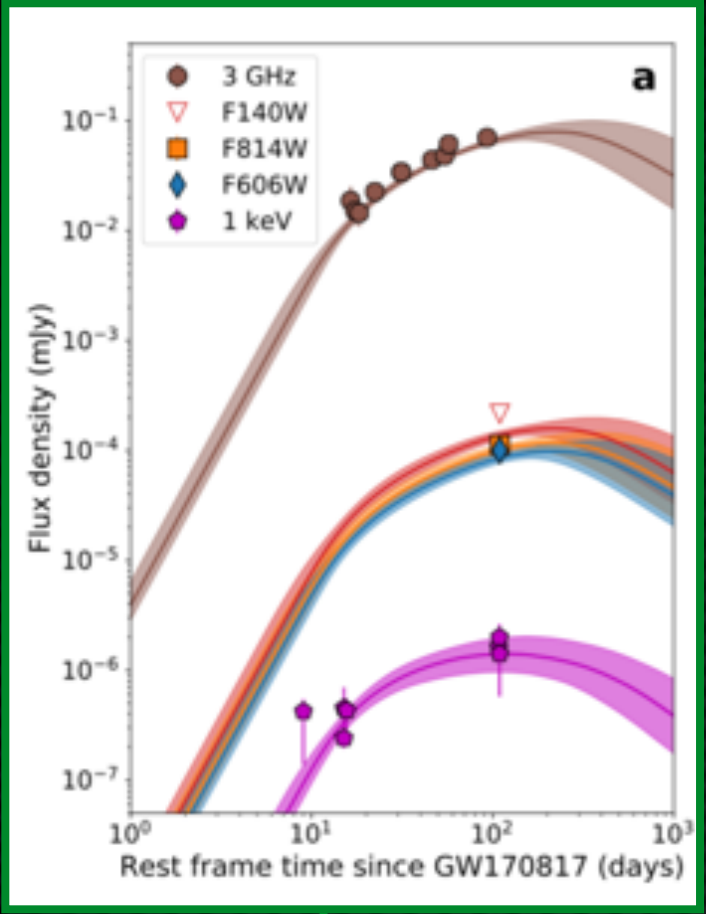
Off-Axis Structured Jet sGRB

- 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

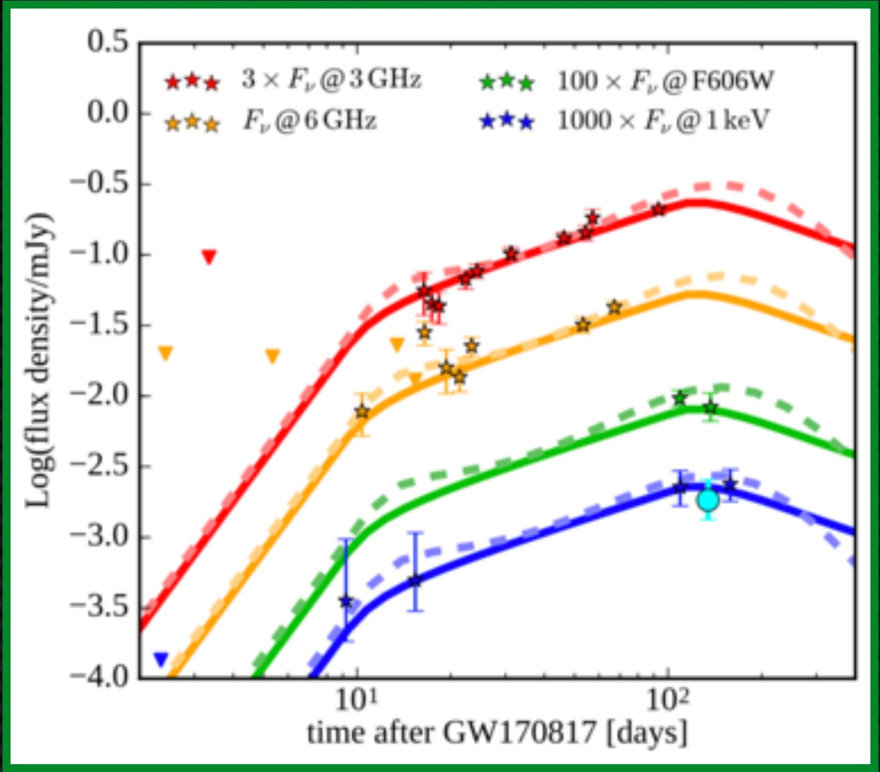


Cocoon Shock Breakout

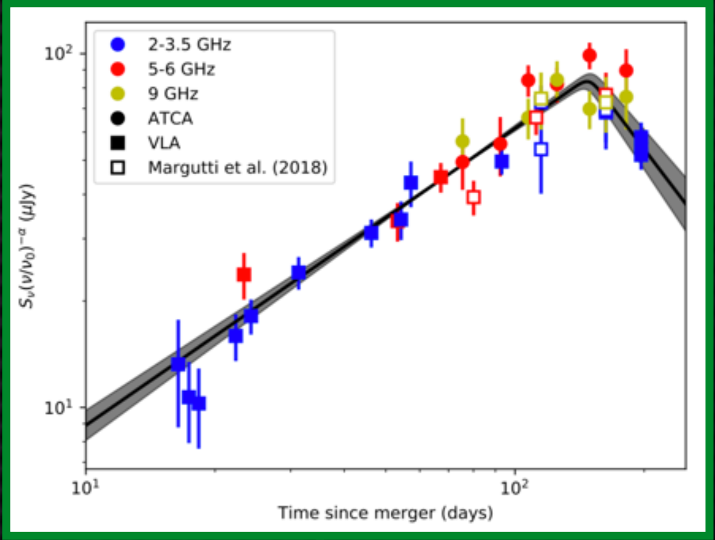
- Hard emission from mildly-relativistic shock breakout and thermal emission from cocoon
- Pros:
  - Can naturally explain the lower energetics
  - Could naturally explain both hard and thermal components
- Cons:
  - Cannot explain very high Epk values
  - Difficult to explain fast variability
  - Should 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)



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

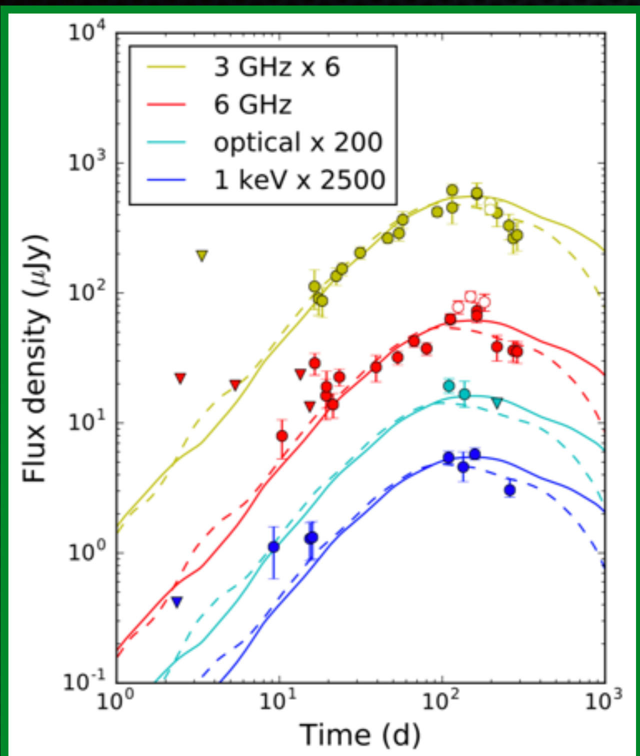


Evidence for a turn over in radio (Dobie et al. 2018)

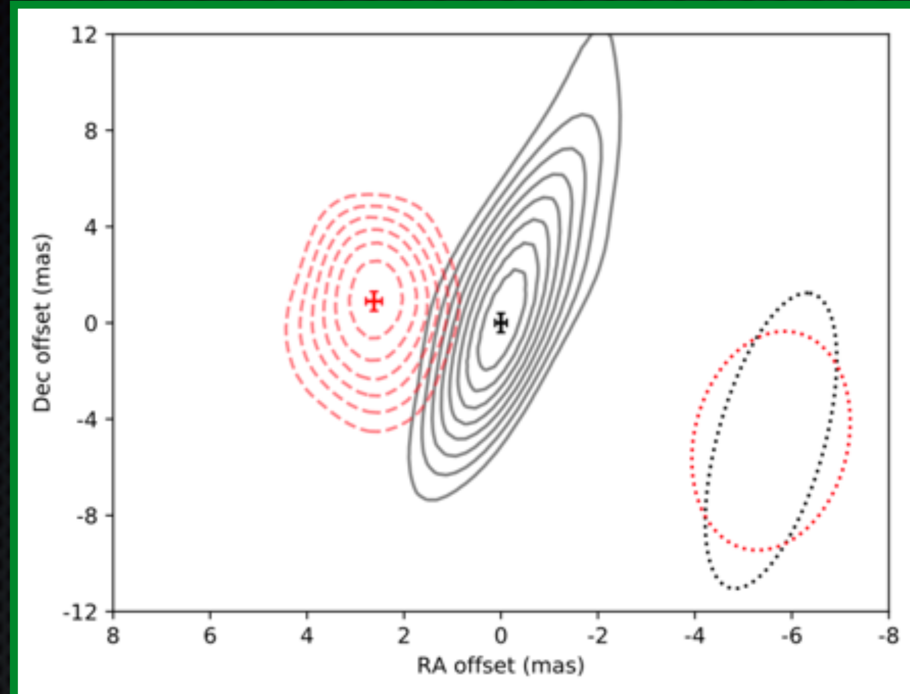
+100 days

+135 days

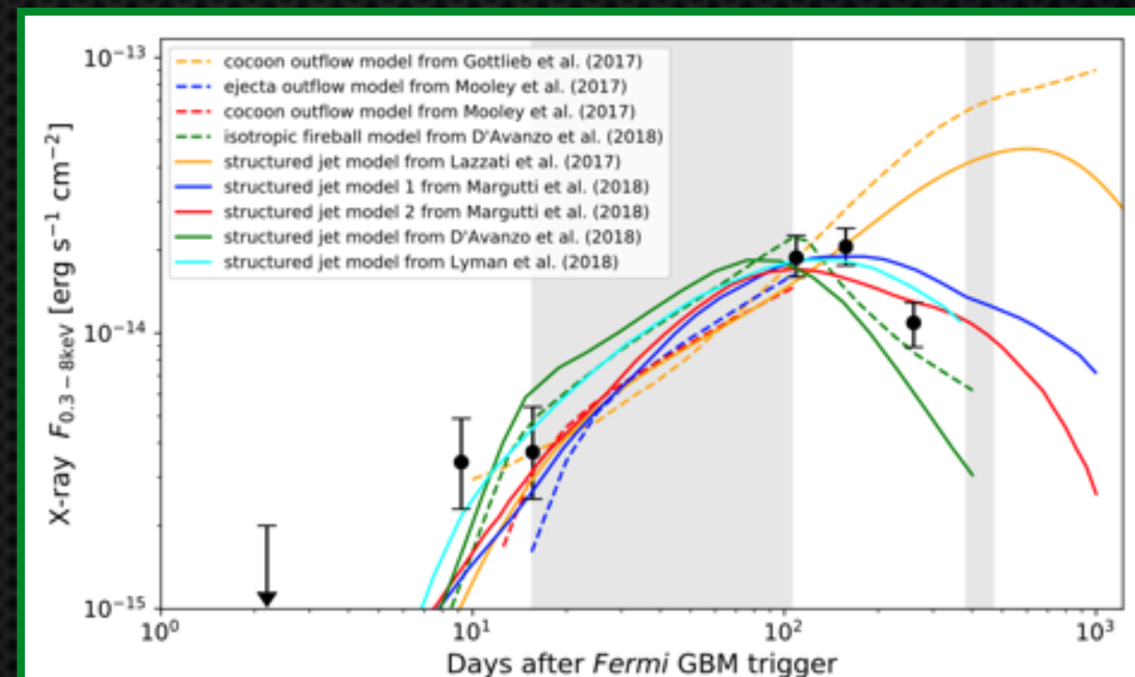
+150 days



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)



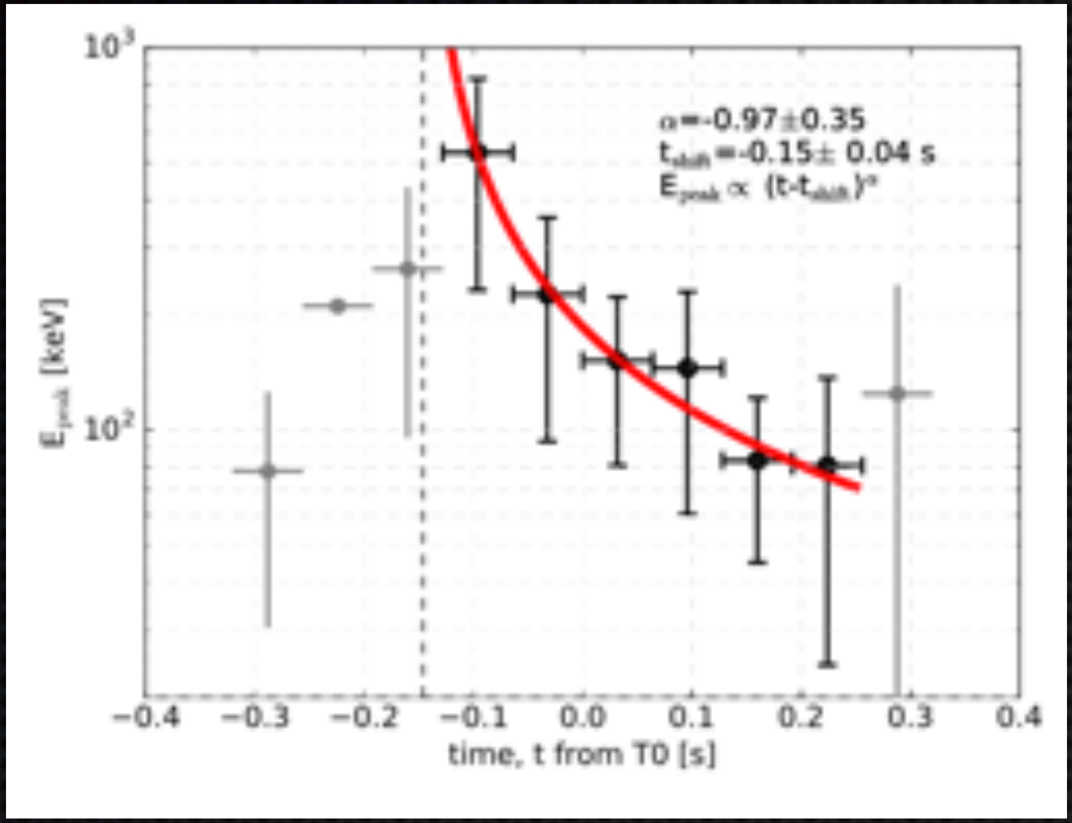
Cocoon is ruled out at late times, but it could still explain prompt and early afterglow (Nynka et al. 2018, Mooley et al. 2018)

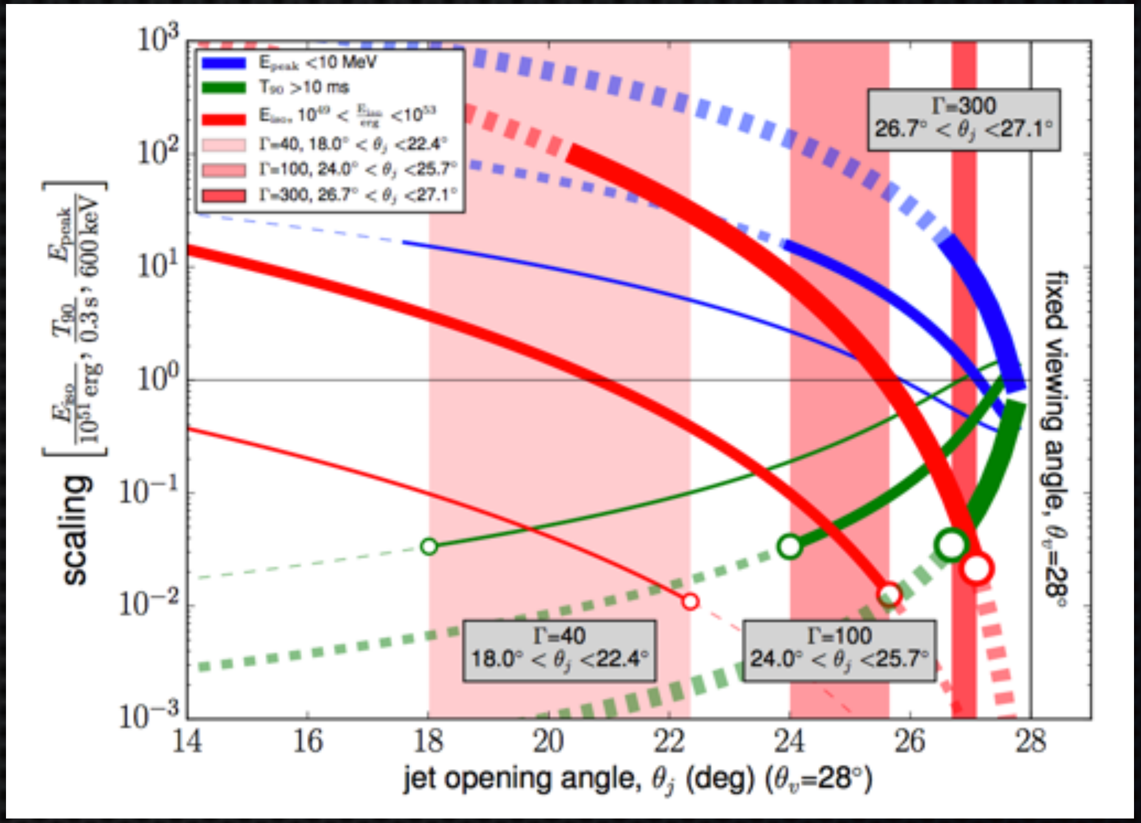
+220 Days

+230 days

+260 days

Time Resolved Spectral Analysis



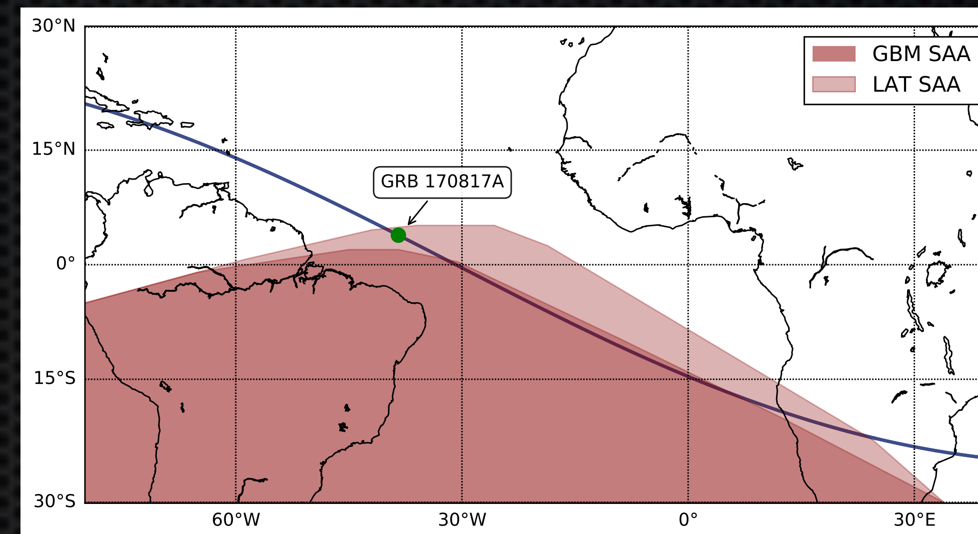


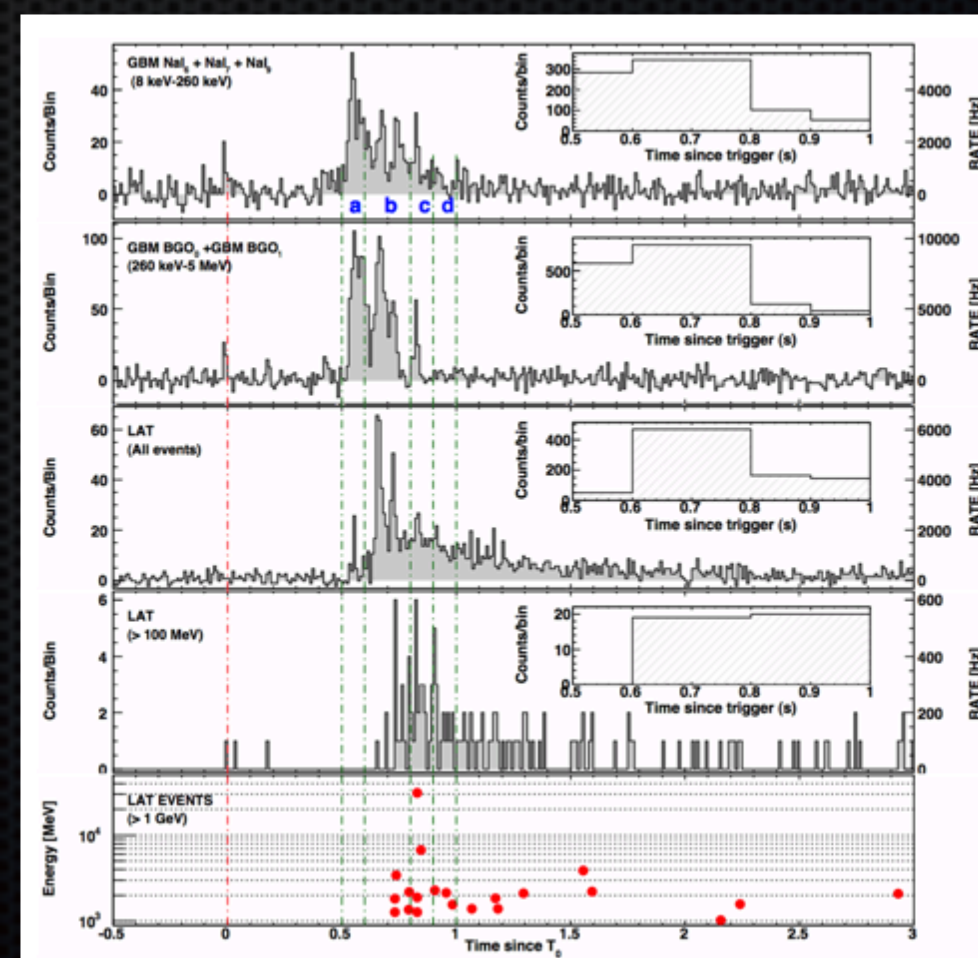
Veres et al. 2018

- 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
- Veres et al. 2018 can reproduce observed values with a wide jet and low Lorentz factor
- Similar results found by Ioka & Nakamura 2018

Things to look for in O3

- Several high-energy observations should be able to help discriminate between jet and shock breakout emission
- The Fermi LAT was famously in the SAA during the GW 170817 event
- 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
- Determining if the gamma-ray emission is due to the cocoon helps constrain the total ejected mass which we can compare to the mass of the system as inferred from GWs
- Ultimately we need more observations of joint NS-NS mergers to definitely address these open questions



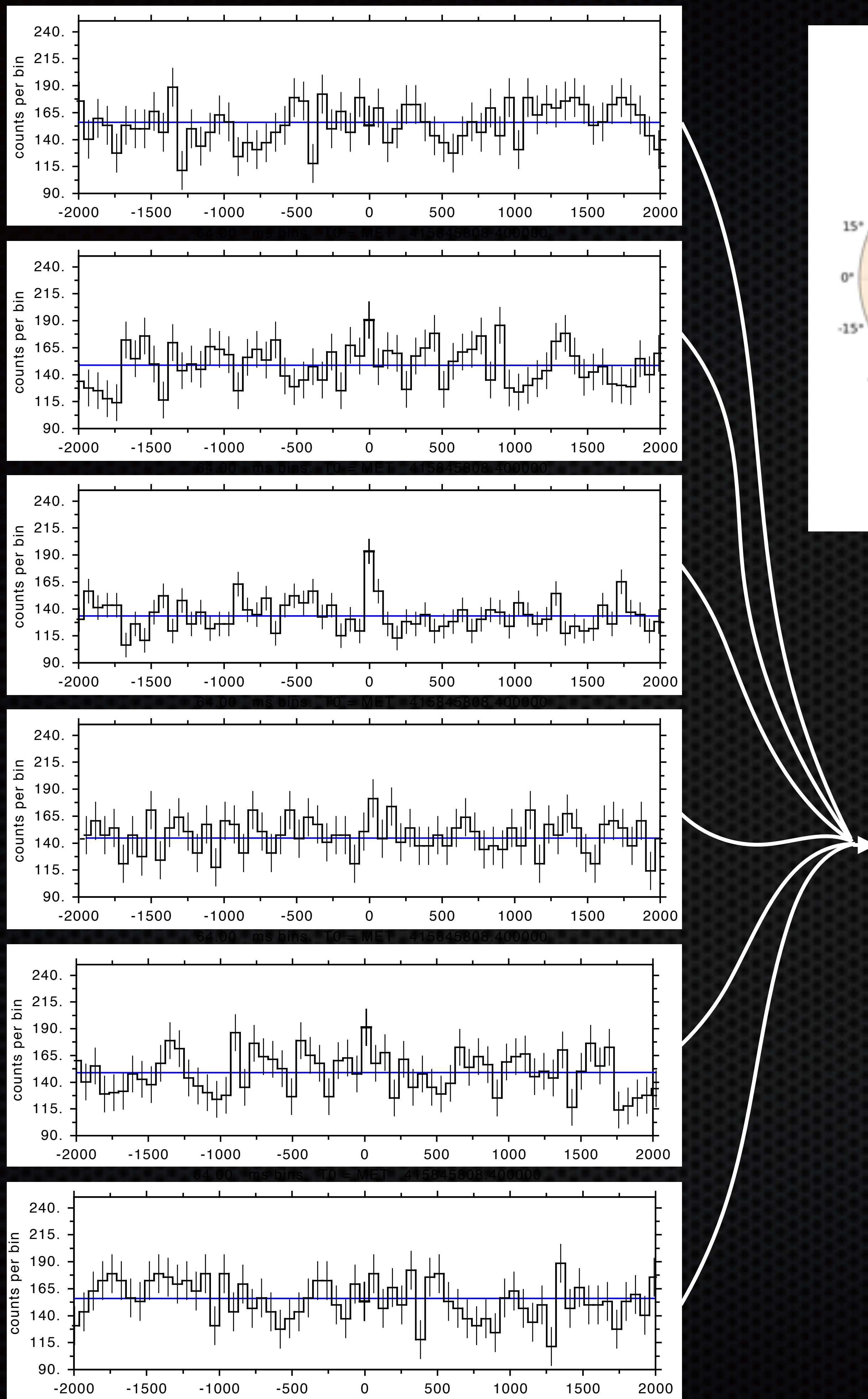


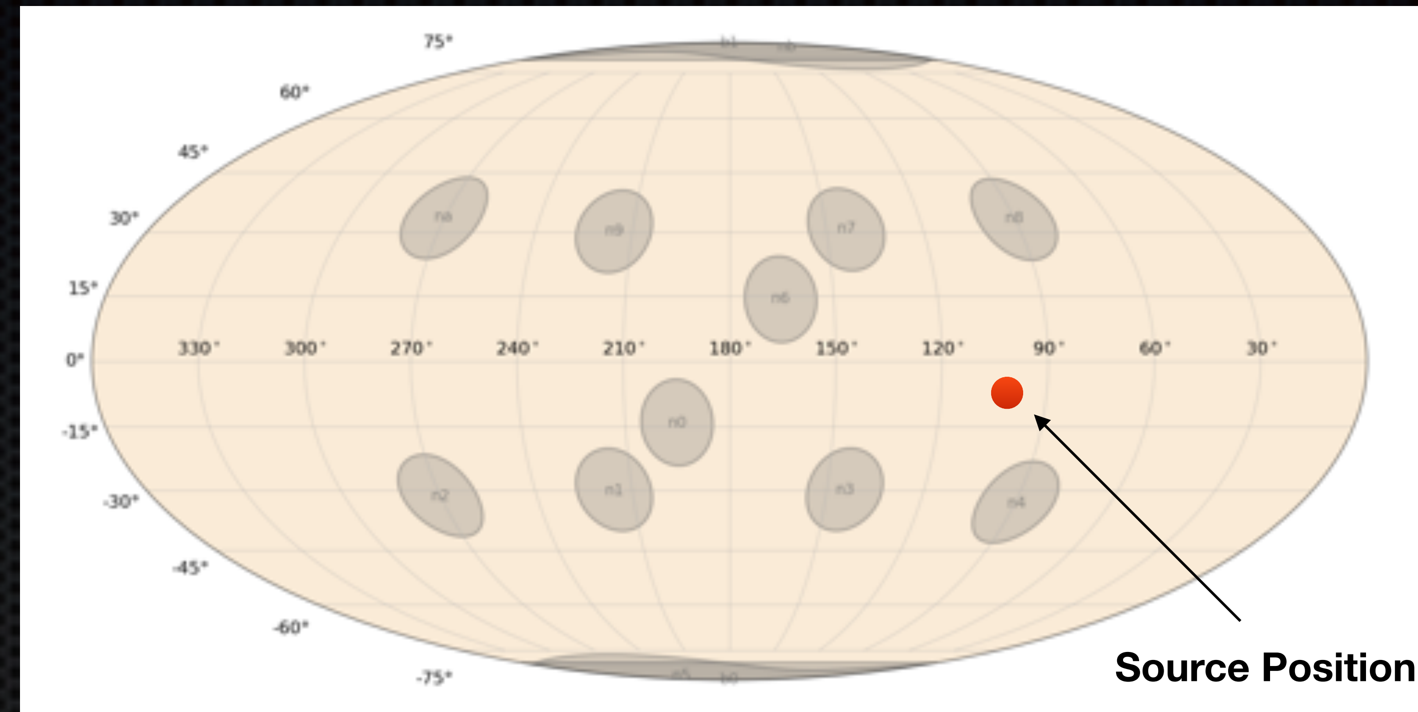
GRB 090510

Ackermann et al. 2010

GBM Triggering Algorithms

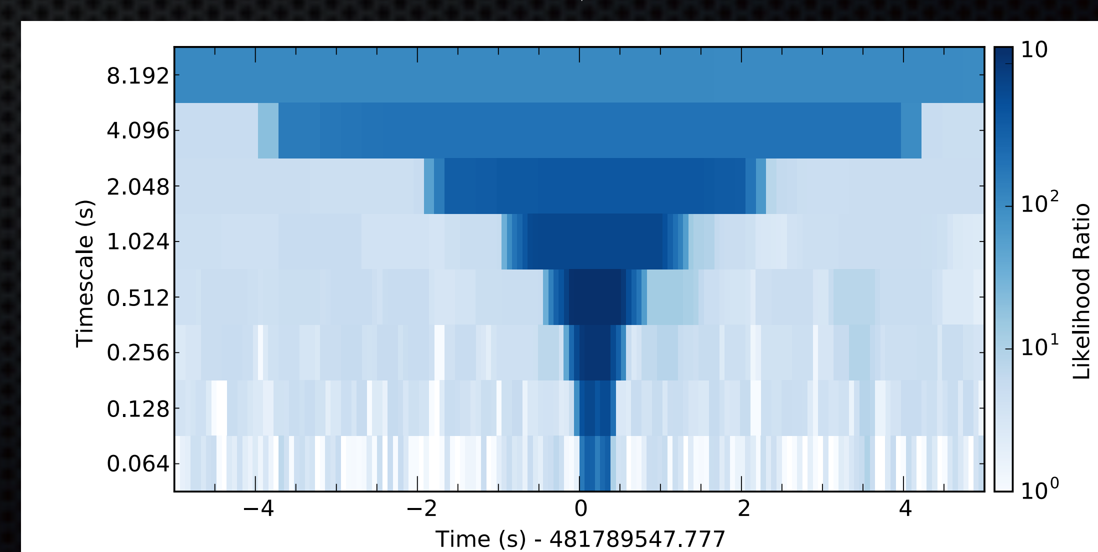
- Onboard Triggering algorithms:
  - Count rate increase in 2+ NaI detectors
  - 10 timescales: 16ms up to 4.096s
  - 4 energy ranges: 50-300, 25-50, >100, >300 keV
- Computing power onboard limits the sophistication of onboard algorithms
- The advent of CTTE data in 2013 allows for additional analysis on the ground
- "Untargeted Search"
  - Perform the rate trigger analysis over a larger range of timescale and energies
- "Targeted Search"
  - Exploit the instrument response to perform a coherent seeded search using all detectors
  - Originally developed by Lindy Blackburn and extended by Eric Burns, Adam Goldstein, Michelle Hui, Rachel Hamburg, Tito Dal Canton and Daniel Kocevski
    - Blackburn et al. ApJS 2015, 217 and Goldstein et al. 2016 arXiv1612202395G



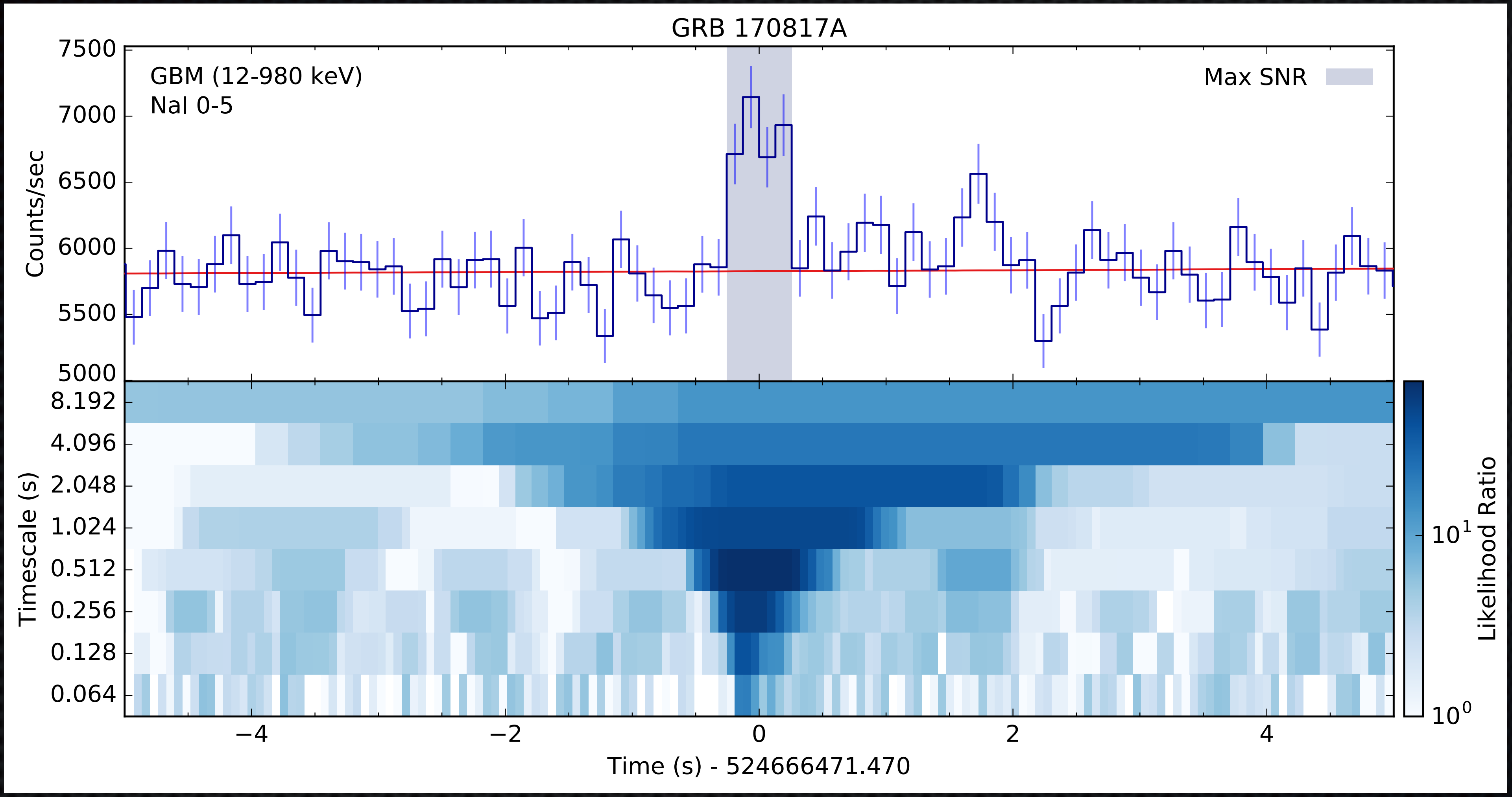


$$P(d_i|H_1) = \prod_i \frac{1}{\sqrt{2\pi\sigma_{d_i}}} \exp\left(-\frac{(\widetilde{d_i} - r_i s)^2}{2\sigma_{d_i}^2}\right)$$

$$\mathcal{L} = \sum_i \left[\ln\frac{\sigma_{n_i}}{\sigma_{d_i}} + \frac{\widetilde{d_i}}{2\sigma_{n_i}^2} - \frac{(\widetilde{d_i} - r_i s)^2}{2\sigma_{d_i}^2}\right]$$



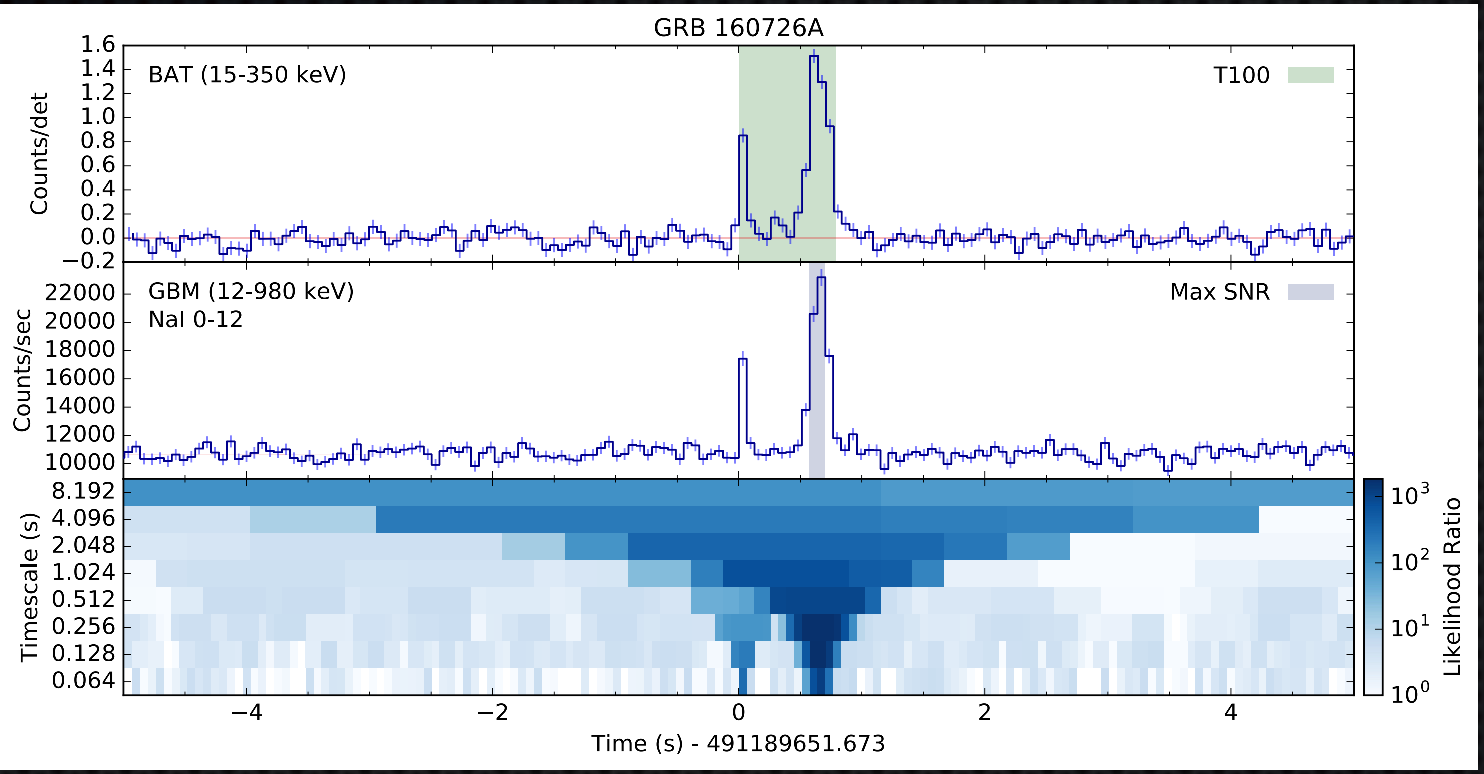
GRB 170817

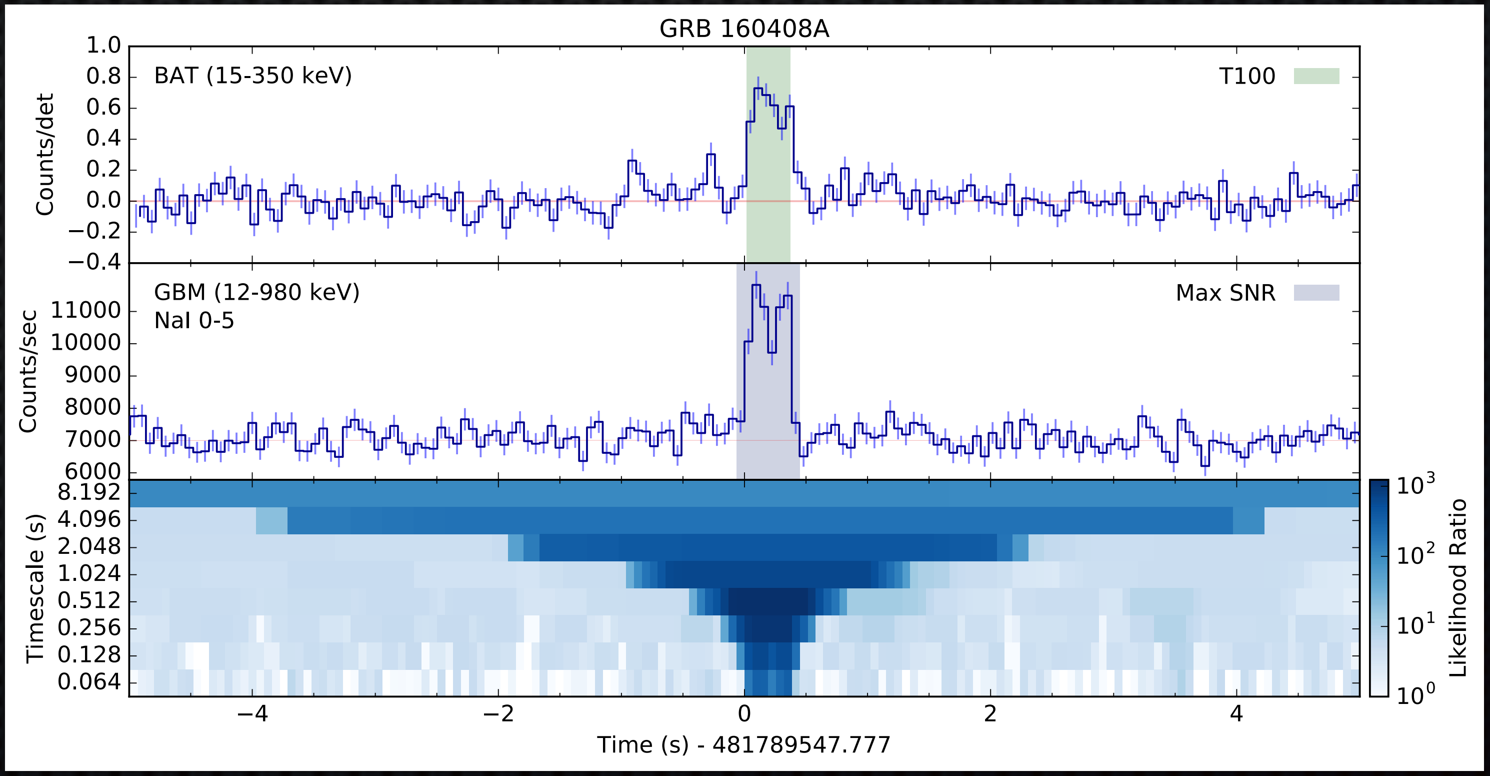


Kocevski et al. 2018

- Well detected onboard the spacecraft and easily picked up by the GBM targeted search
- How far further could we have seen GRB 170817 with the sub-threshold targeted search?
- We can use a control sample of Swift detected GRBs to examine the sensitivity of the search

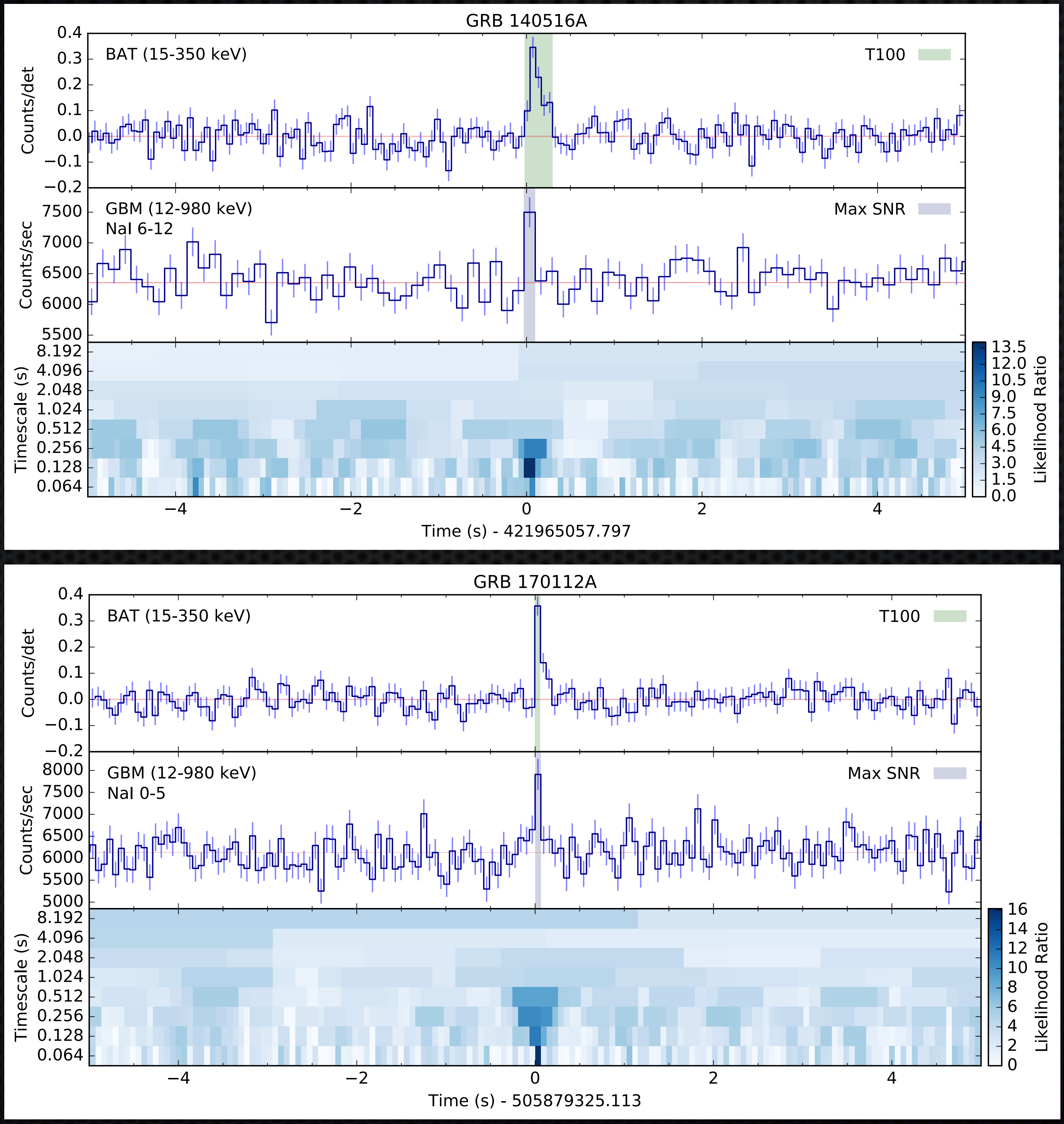
Example results for triggered sGRBs





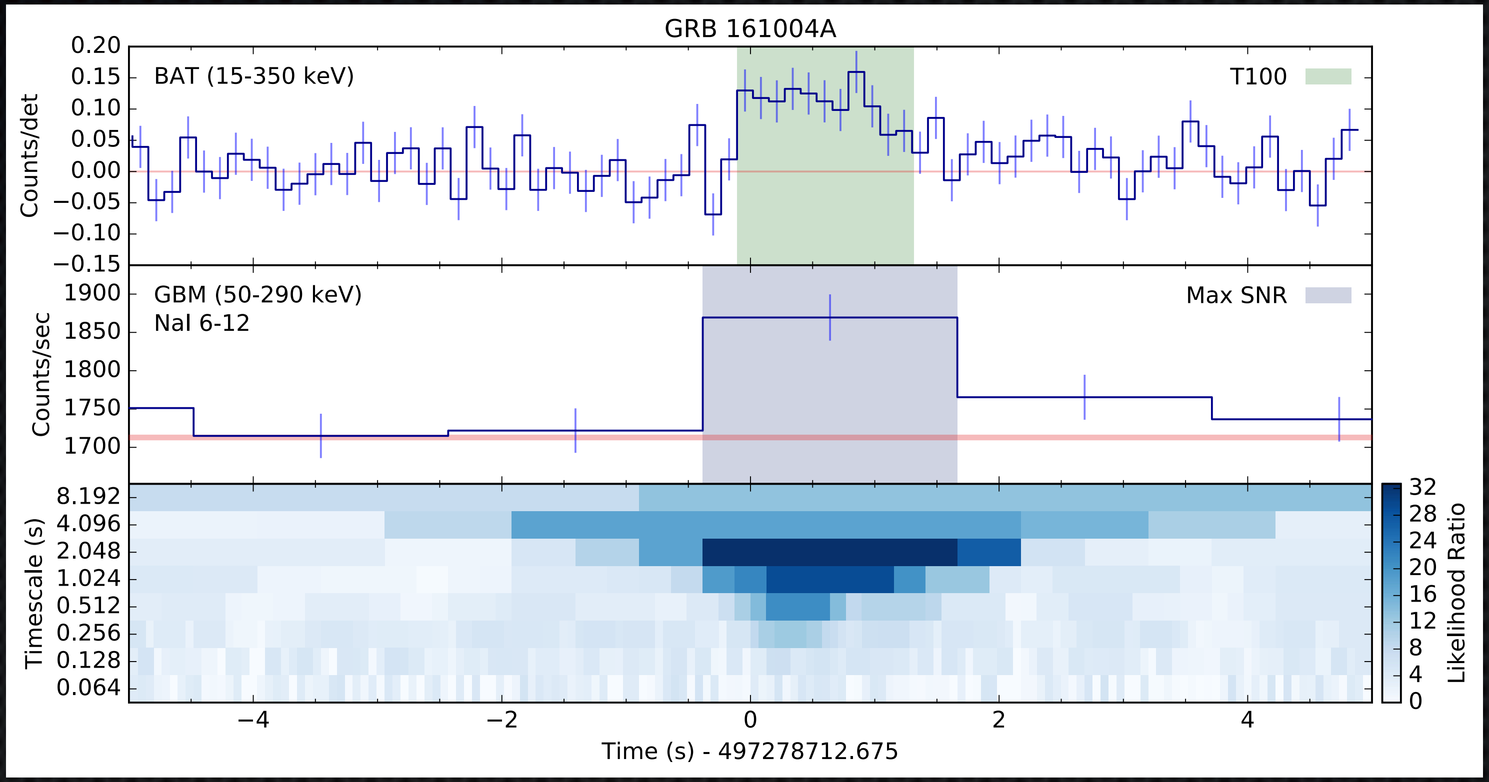
Kocevski et al. 2018

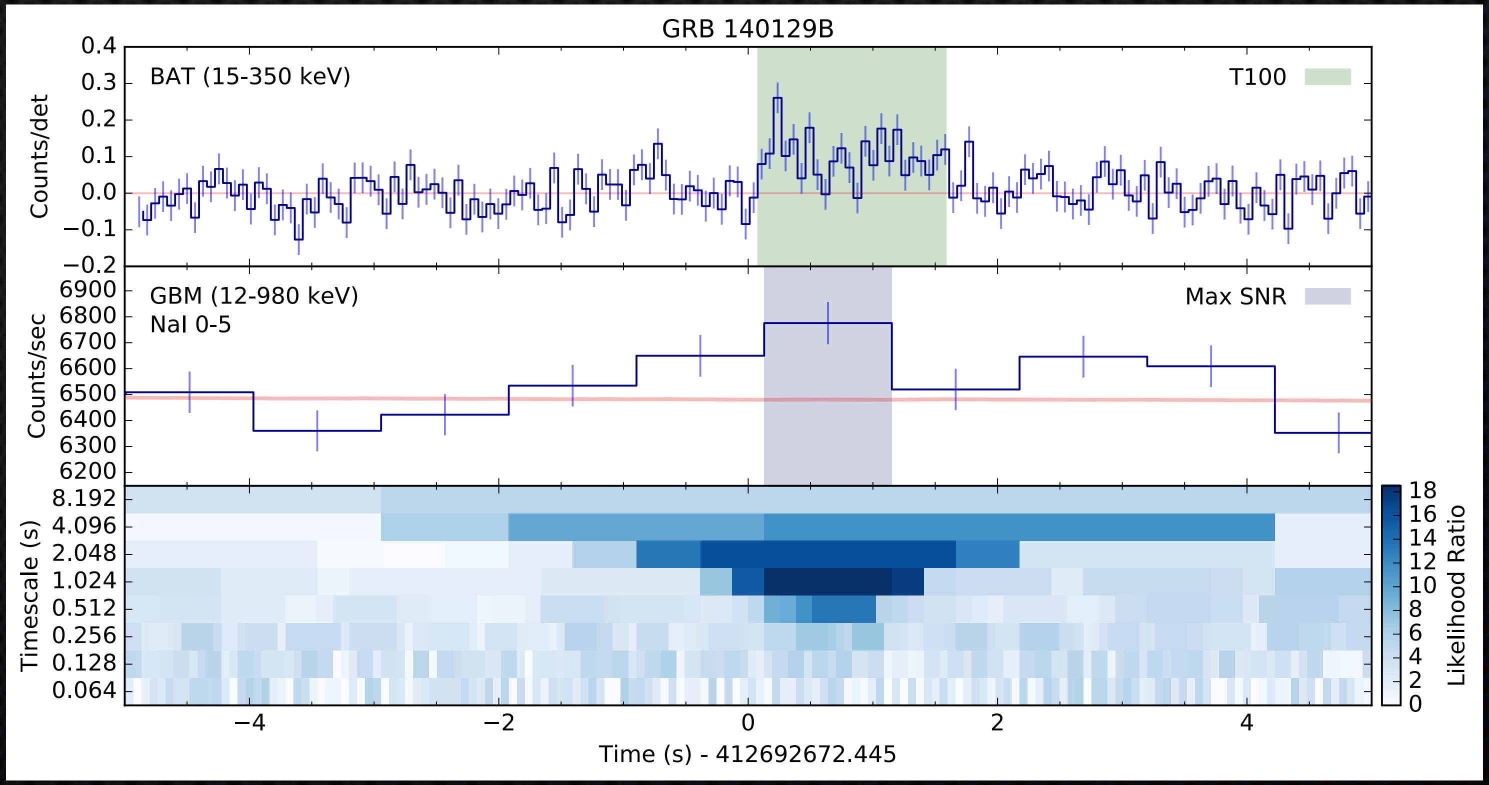
Example Untriggered sGRBs (short)



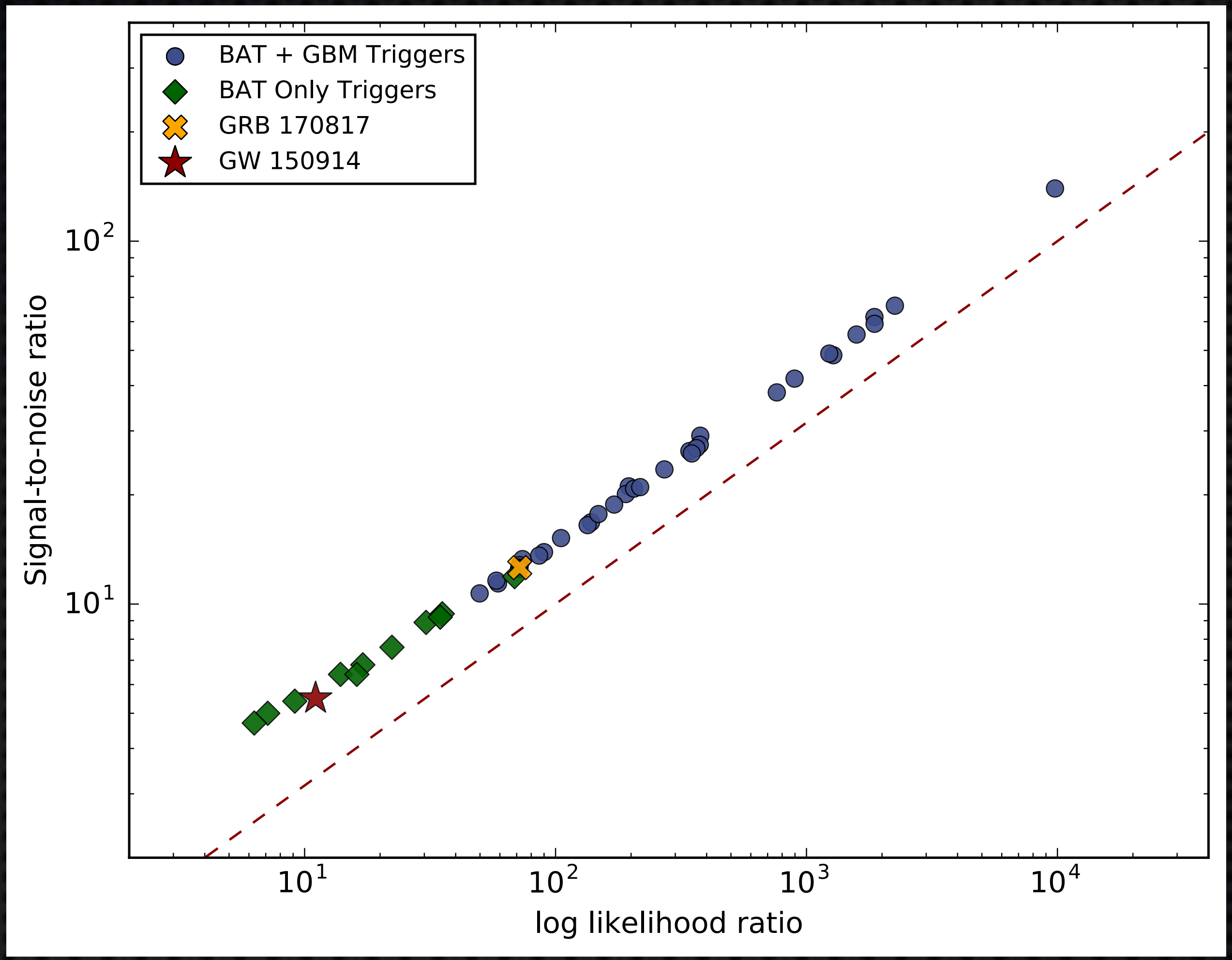
Kocevski et al. 2018

Example Untriggered sGRBs (long)



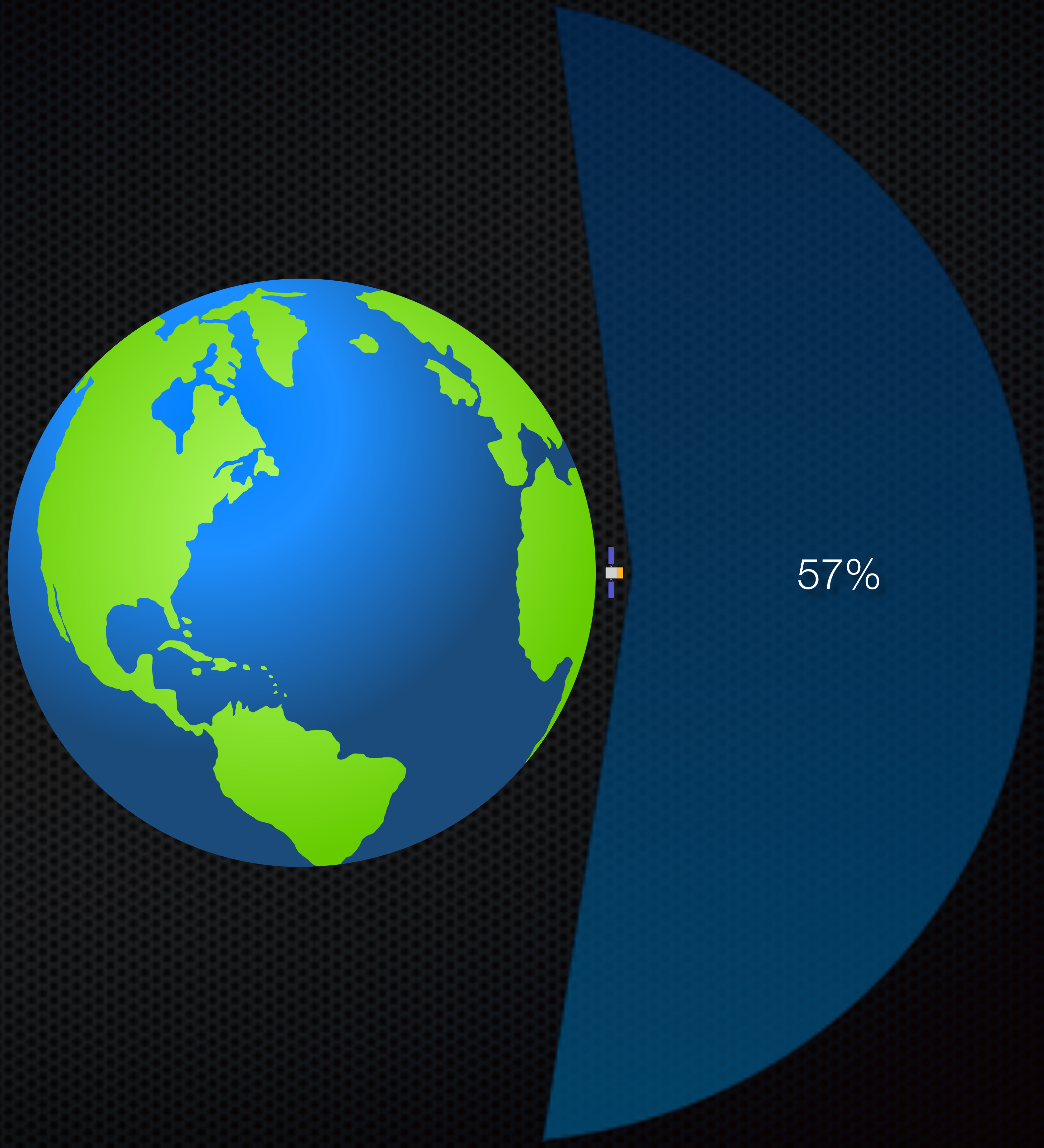


Swift Control Sample



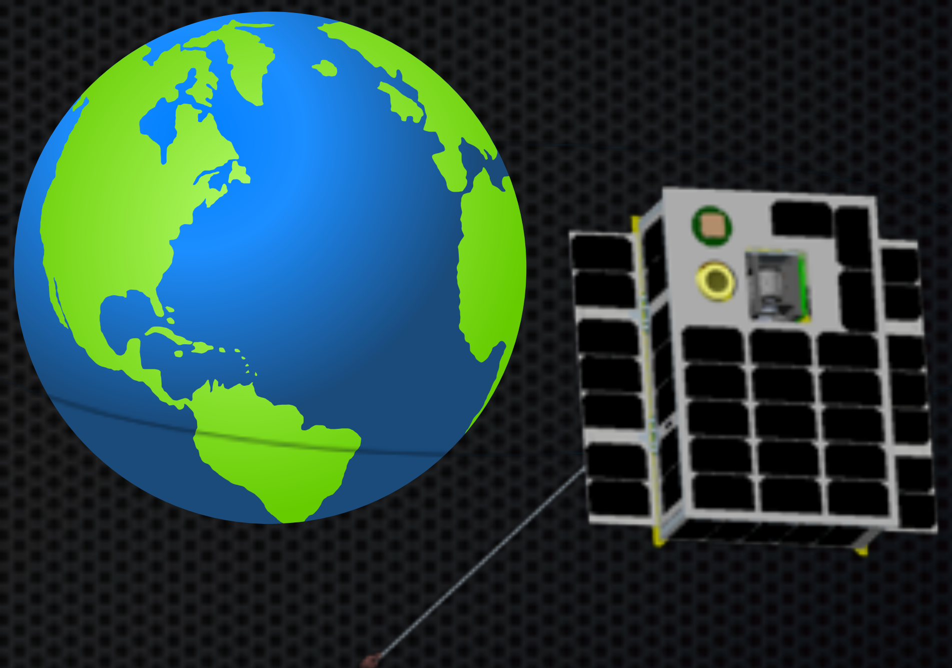
Kocevski et al. 2018

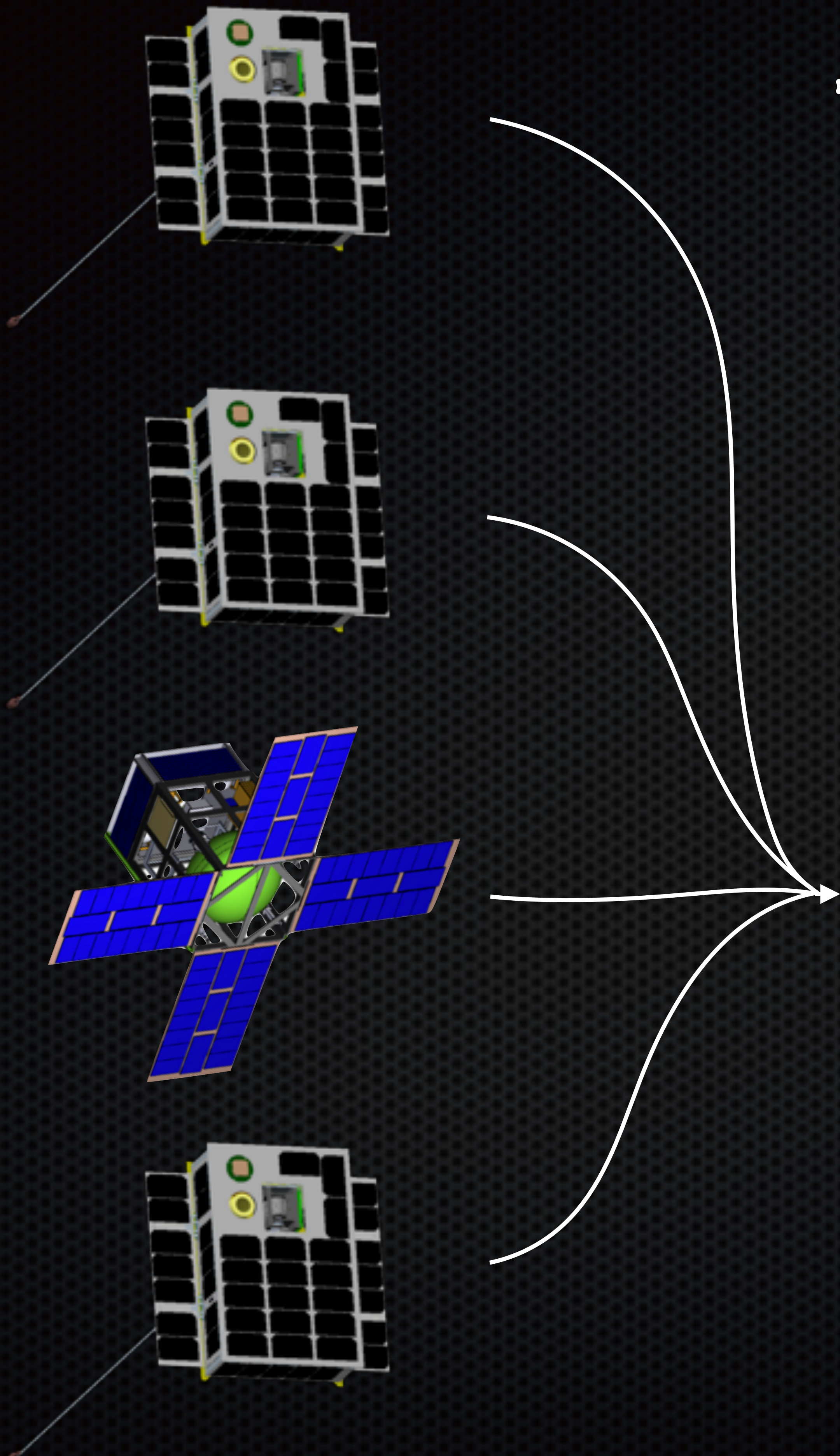
- On-board triggers stop at about SNR ~ 10
- GRB 170817 was detected close to this threshold with SNR ~ 12.7
- The targeted could have recovered it down to SNR ~ 4-5
- This corresponds to a decrease of ~60% of its original brightness
- Increases the volume of the Universe in which GRB 170817 could be detected by factor of 5


57%

CubeSats/SmallSats

- BurstCube
  - PI: Perkins @ GSFC
  - 6U CubeSat with 4 CsI crystals with SiPM
  - Deployed from the ISS with 1-2 year lifetime
  - 70% Fermi-GBM effective area @ 100 keV
  - Currently funded for development through APRA
- MoonBEAM
  - PI: Michelle Hui @ MSFC
  - 12U CubeSat with 4 CsI crystals with SiPM
  - Deployed via the SLS-SM2 in Lunar or L3 orbit
  - Time of flight would provide IPN like localizations
  - Mission concept study funded @ MSFC
- Astrophysics Science SmallSat Studies Call (ROSES D.15)
- Individual Space Grant Consortiums for smaller versions in LEO
- Ultimate goal would be to have a constellation of CubeSats

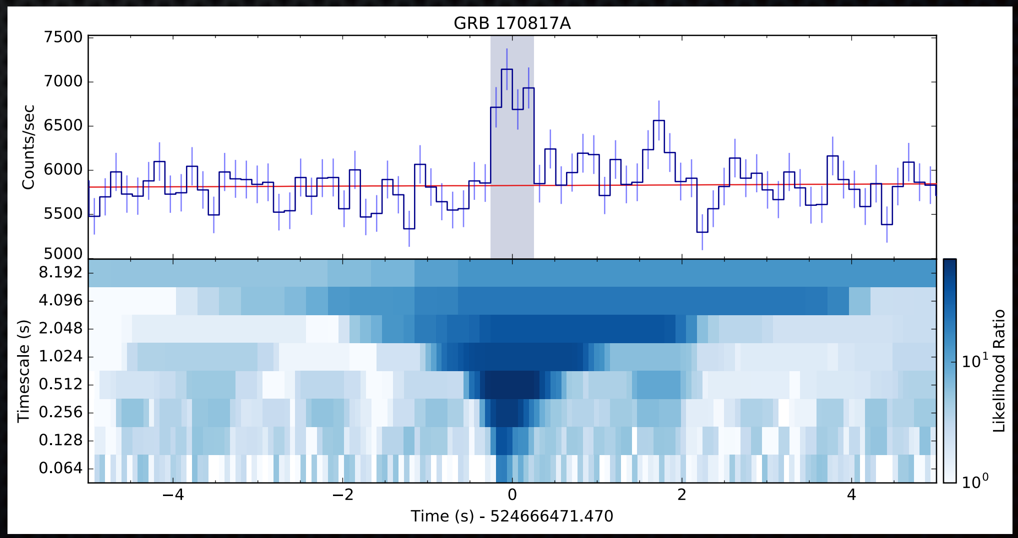




- Use targeted search to coherently combine data from a constellation of CubeSats and SmallSats
  - Need to have good pointing knowledge
  - Need to have good position knowledge
  - Need to have good timing knowledge

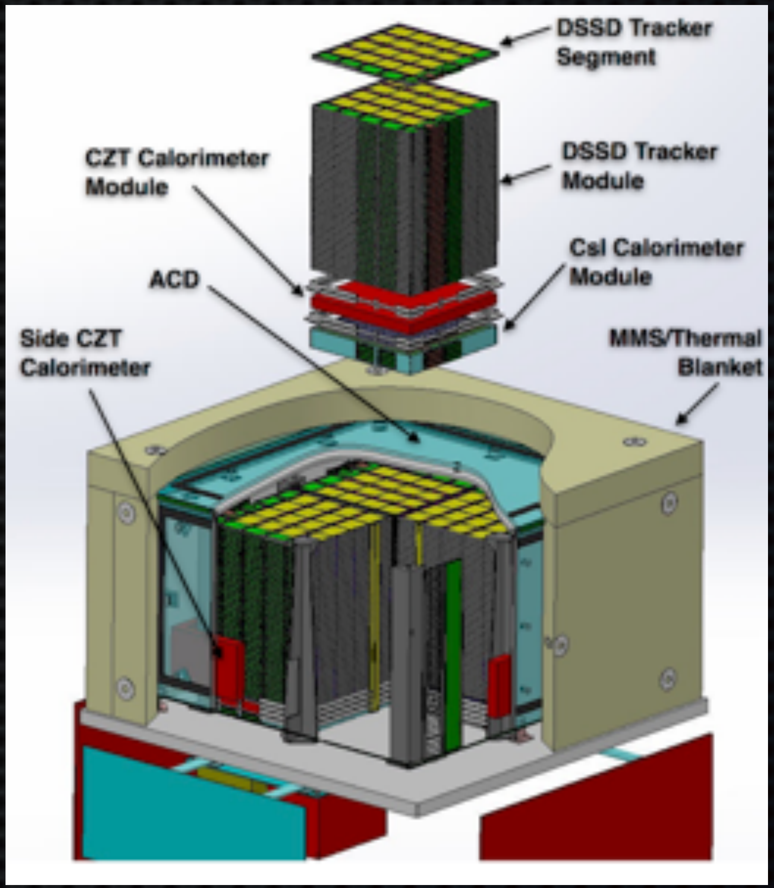
$$P(d\,|H_1) = \prod_i \frac{1}{\sqrt{2\pi\sigma_{d_i}}} \exp\left(-\frac{(\widetilde{d}_i - r_i s)^2}{2\sigma_{d_i}^2}\right)$$

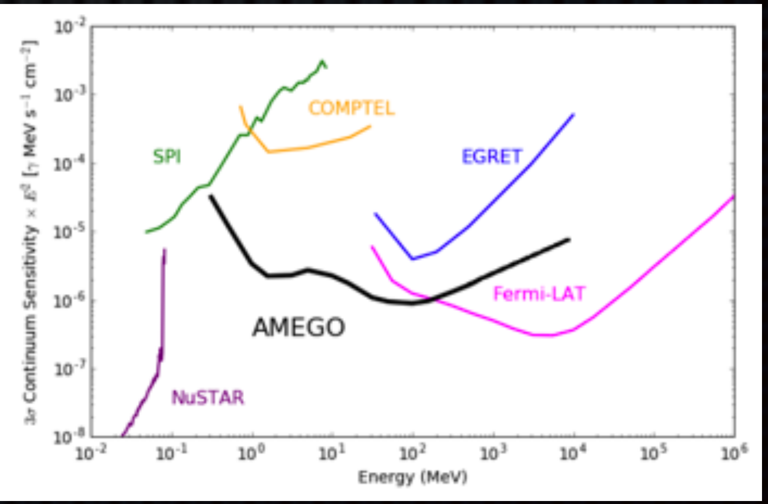
$$\mathcal{L} = \sum_i \left[\ln\frac{\sigma_{n_i}}{\sigma_{d_i}} + \frac{\widetilde{d}_i}{2\sigma_{n_i}^2} - \frac{(\widetilde{d}_i - r_i s)^2}{2\sigma_{d_i}^2}\right]$$



Future Missions

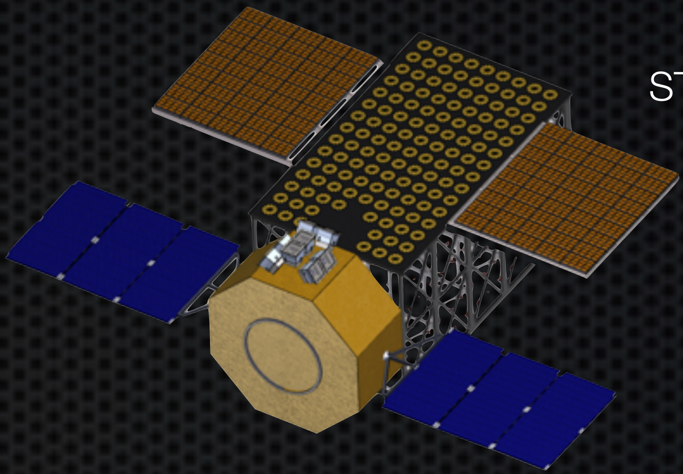
- AMEGO
  - PI: Julie McEnery @ GSFC
  - Solid state detector to study the under-examined MeV domain
  - Enhanced MeV sensitivity compared to Fermi LAT
    - Removal of tungsten pair conversion foils between layers
    - Improved low-energy calorimeter response
  - Compton scattering < 10 MeV and pair production > 10 MeV
  - Continuum sensitivity from 200 keV – 10 GeV >20 times deeper than COMPTEL
  - Polarization sensitivity from 200 keV – 5 MeV
  - Energy resolution of 1–5% (200 keV– 100 MeV) and 10% at higher energies
  - Potential to be a prolific detector of short hard GRBs
    - Other great MeV related science too!





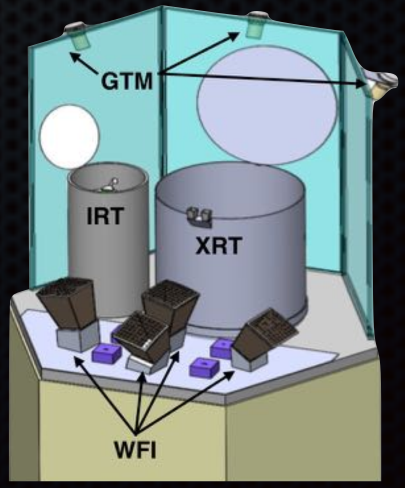
Future Missions

- STROBE-X
  - PI: Paul Ray @ Navel Research Lab
  - Would combine capabilities of NICER and LOFT
  - Wide field X-ray capabilities
  - Selected for astrophysics probe mission concept study
- THESEUS
  - PI: Lorenzo Amati @ INAF-IASF Bologna
  - Wide field x-ray imager, 0.7m infrared telescope, and CsI gamma-ray detector proposed for ESA's M5 opportunity
  - High-redshift GRBs, but also excellent sGRB detector
  - Selected for a "Phase A" equivalent mission concept study
- ISS-TAO/TAP
  - PI: Jordan Camp @ GSFC
  - TAO: Wide-field x-ray monitor ISS - Selected for Phase A
  - TAP: Multi-messenger time-domain - Selected probe concept study



STROBE-X

THESEUS



TAP

Conclusions

- GRB 170817 may have been the best observed transient in the history of astronomy
- Despite this 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!