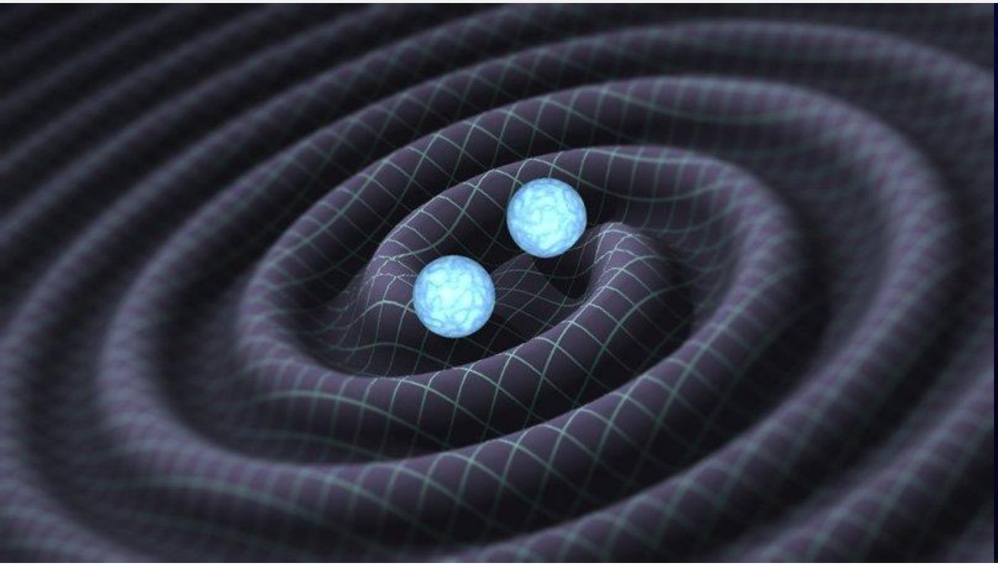
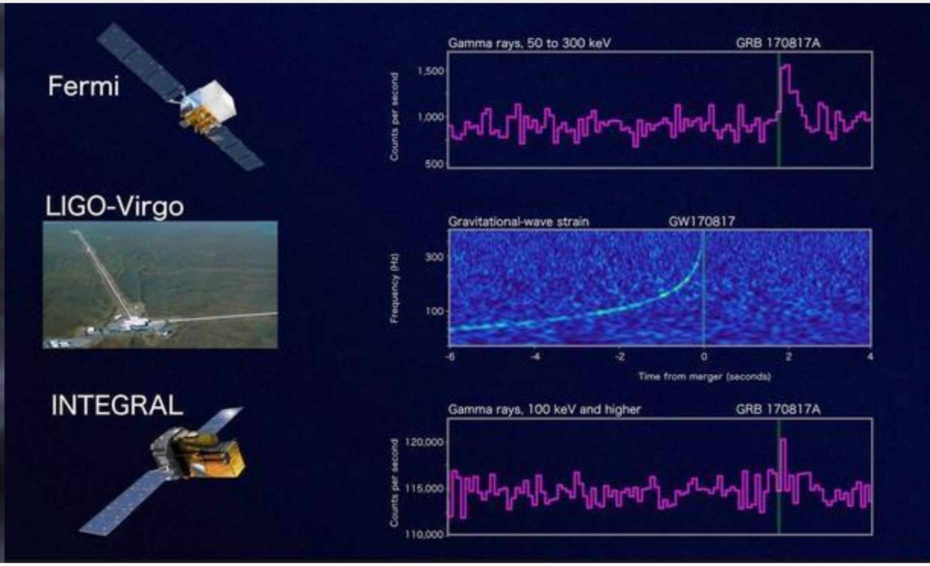
The Fermi/GBM as γ-ray transient monitor and more

Multi-Messenger Studies with Gravitational Wave Event(s)





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4 topics in gamma-ray astrophysics

- GRB 170817A was unusual
- γ-ray localizations – GBM can do better
- γ-ray spectra – constraining the emission mechanism
- γ-dream: polarization

Nomenclature: the event was on 17. August 2017

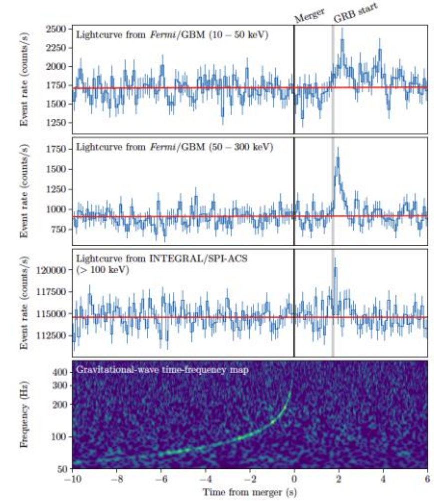
→ GRB 170817A -- gamma-ray burst
→ GW 170817 -- gravitational wave event
→ AT 2017gfo -- kilonova

Contemporaneous GW & γ-ray Detection

“Importance” of GBM (Rossi-Prize)

- no LIGO auto-detection due to noise glitch
- manual LIGO check after <u>automatic</u> GBM trigger
  ➔ after 27 min: the coincidence was recognized

“New era had begun because of GBM trigger!”



To be fair:

Without GW detection this GRB would be just another among 2000 Fermi/GBM GRBs with nothing than γ-ray data:
No kilonova, no afterglow, no distance, no jet structure and geometry details, no wondering about low luminosity

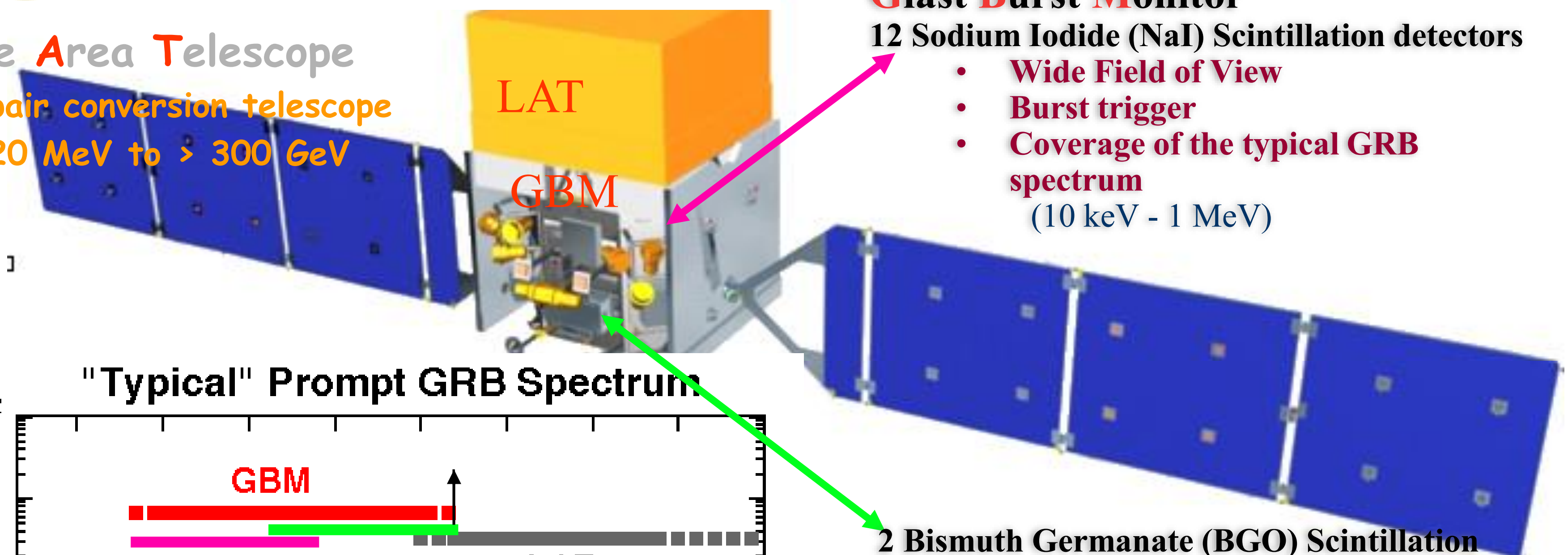
➔ truly multi-messenger event

Fermi: Gamma-ray Space Telescope

Large Area Telescope

pair conversion telescope

20 MeV to > 300 GeV



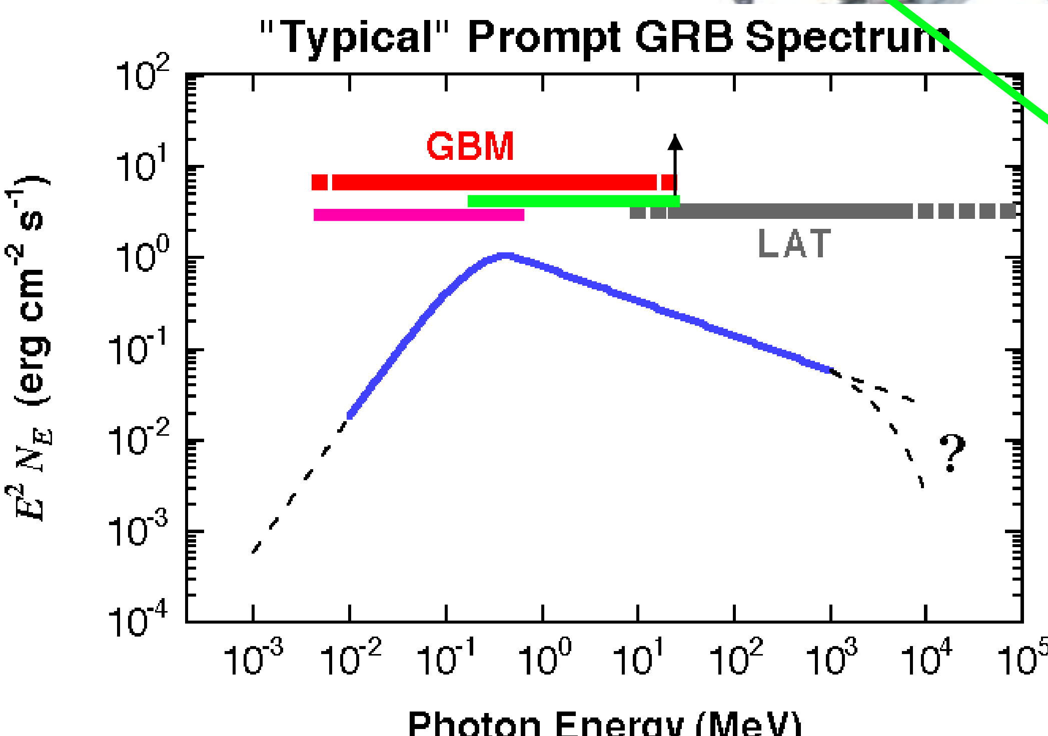
Glast Burst Monitor

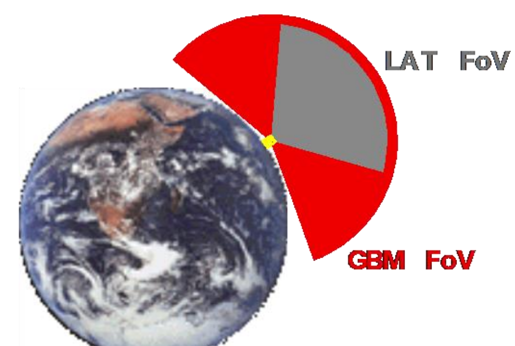
12 Sodium Iodide (NaI) Scintillation detectors

- **Wide Field of View**
- **Burst trigger**
- **Coverage of the typical GRB spectrum**
  (10 keV - 1 MeV)

2 Bismuth Germanate (BGO) Scintillation detectors

- **Spectral overlap with the LAT**
  (150 keV - 30 MeV)





GLAST Burst Monitor (GBM)

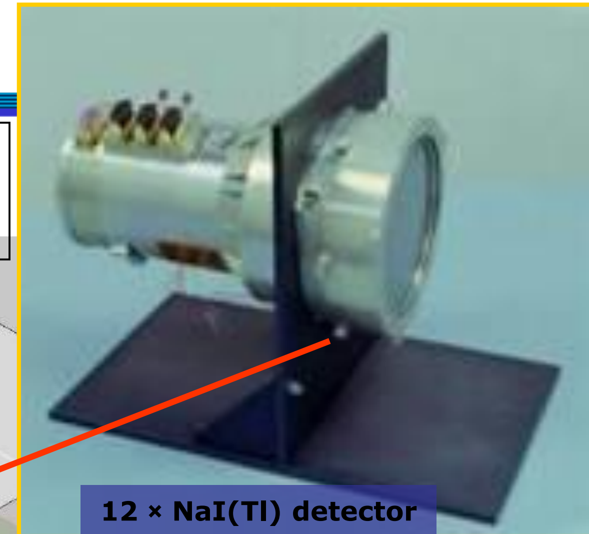
team effort involving physicists and engineers from Germany (MPE, Jena-Optronik) and U.S. (NASA/MSFC)

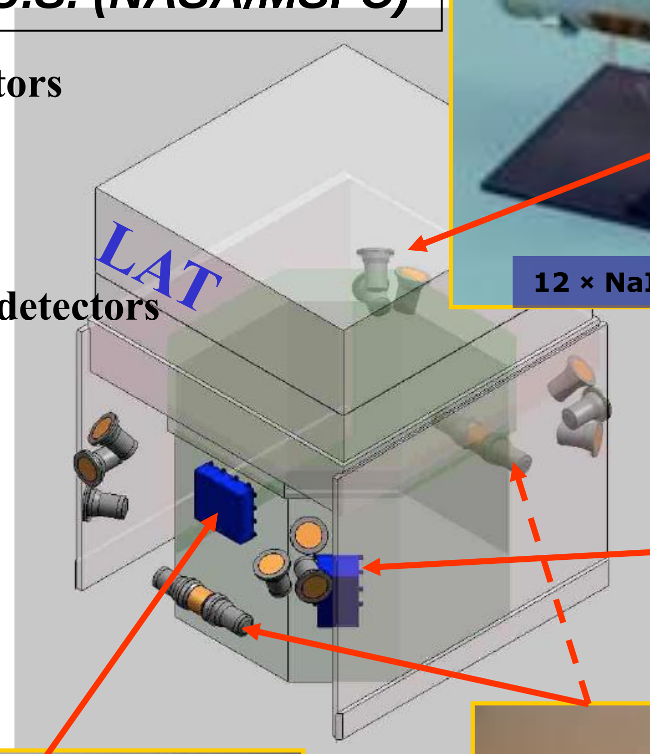
12 × Sodium Iodide NaI(TL) scintillation detectors
- Wide Field of View
- Burst Trigger
- Cover typical GRB spectrum: 8 – 1000 keV

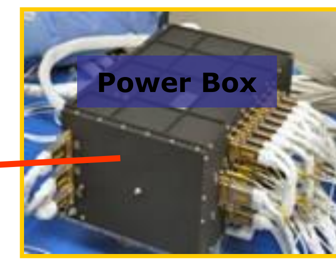
2 × Bismuth Germanate (BGO) scintillation detectors
- Energy range: 150 keV-40 MeV
- Spectral overlap with NaI and LAT

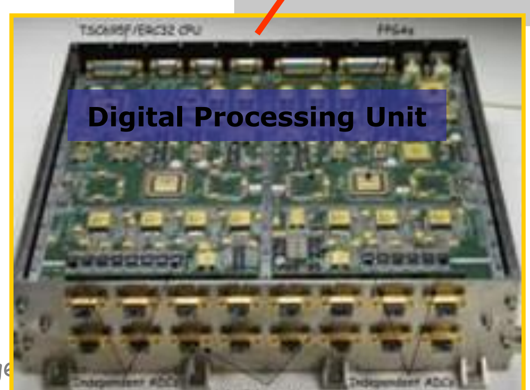
1 × Power Box (PB)

1 × Digital Processing Unit (DPU)







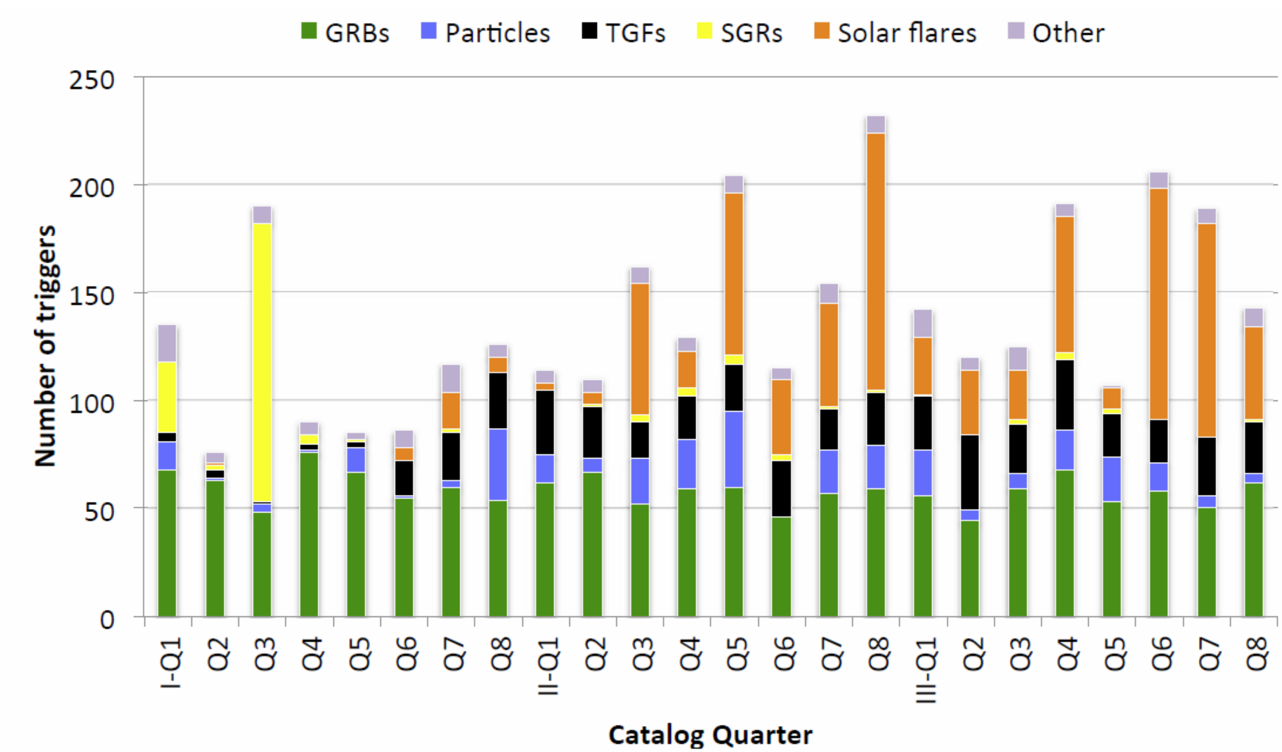


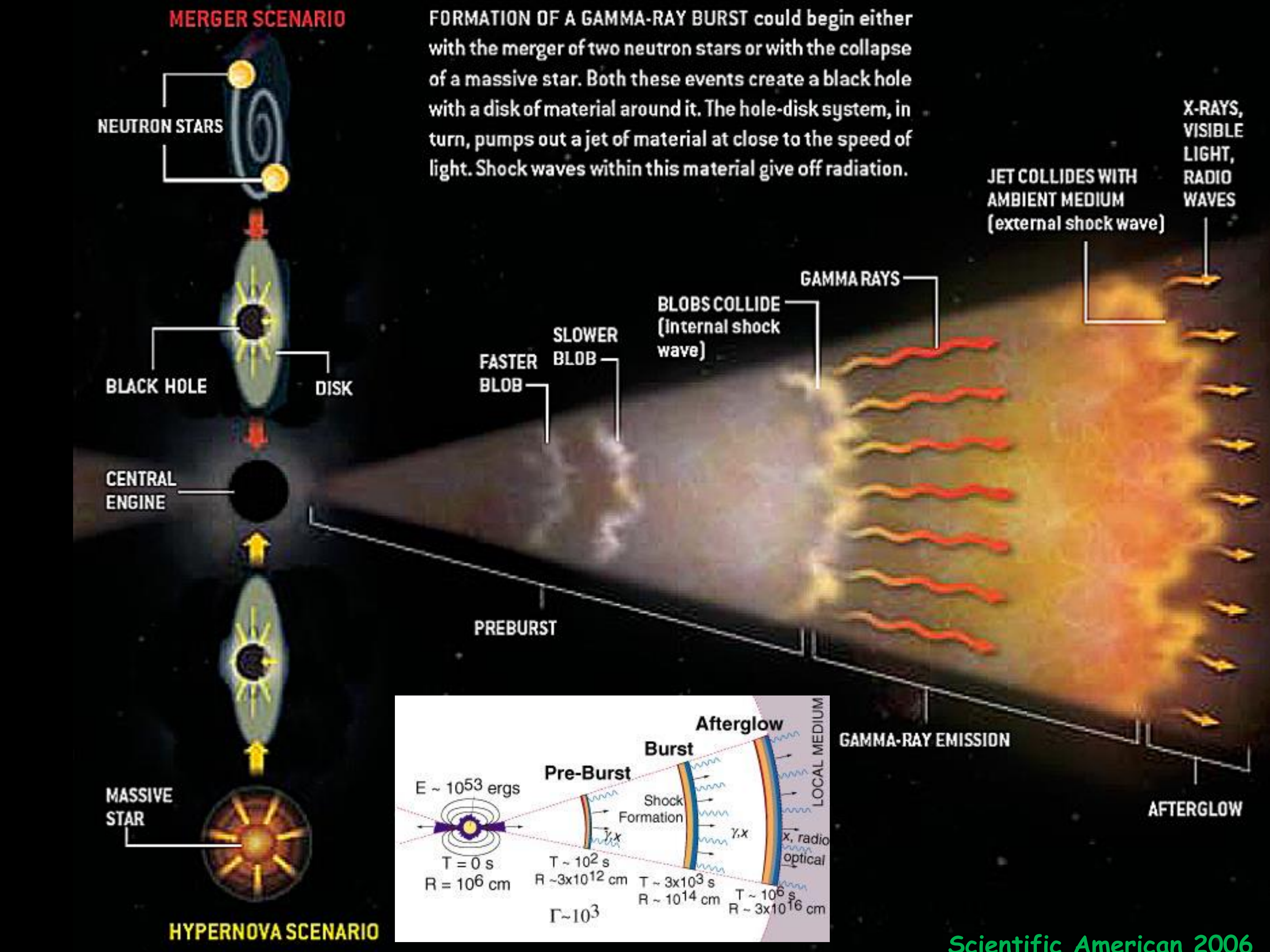
GBM is most prolific burst detector

GBM triggers (automatically) on-board when 2 or more detectors exceed background by n sigma over t timescale in e energy band.

70 algorithms operating simultaneously.

- $4.5 \leq n \leq 7.5$
- $16\ \mathrm{ms} \leq t \leq 8.096\ \mathrm{s}$
- e = one of 25 - 50 keV, 50 - 300 keV, 100 - 300 keV, > 300 keV

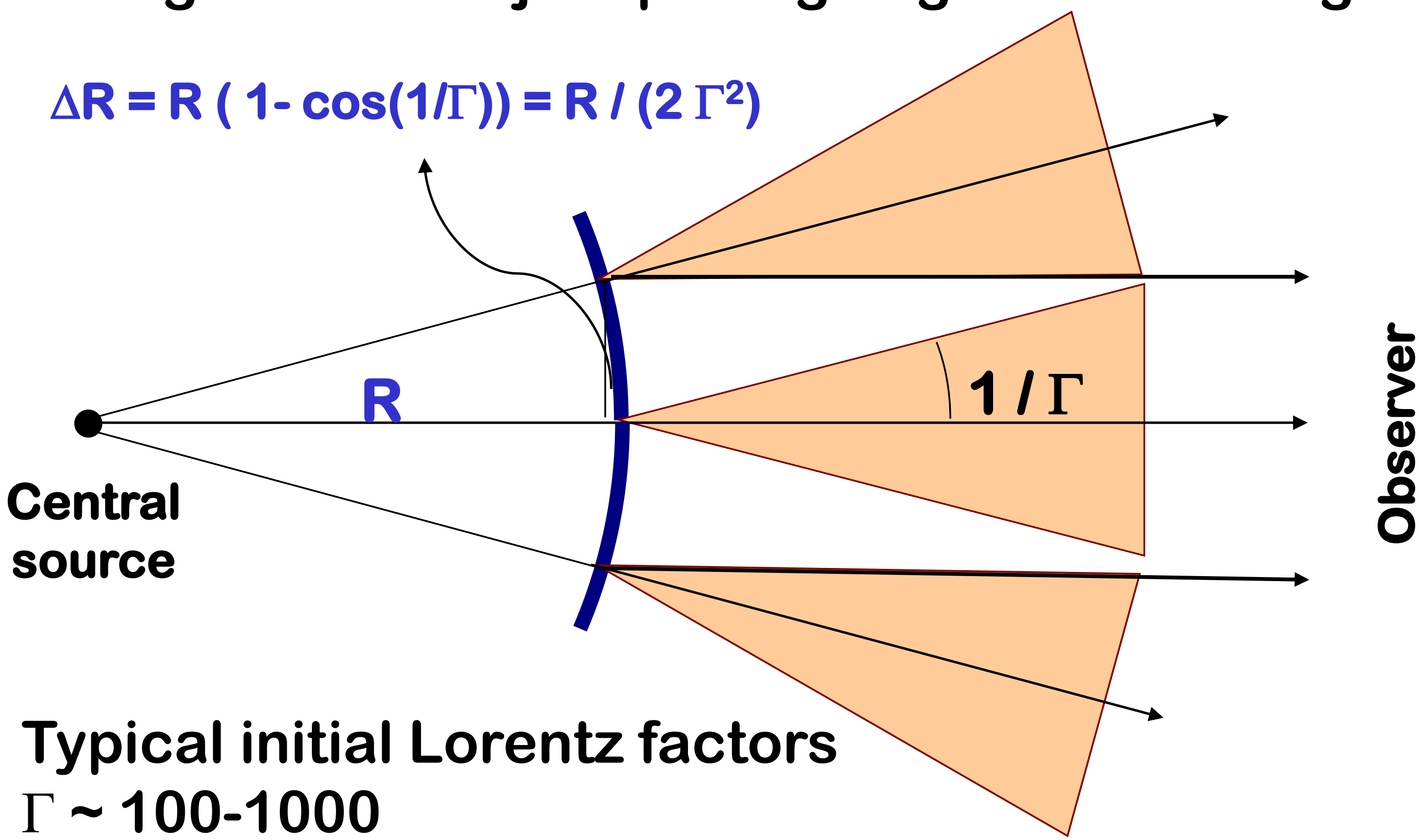



MERGER SCENARIO
FORMATION OF A GAMMA-RAY BURST could begin either with the merger of two neutron stars or with the collapse of a massive star. Both these events create a black hole with a disk of material around it. The hole-disk system, in turn, pumps out a jet of material at close to the speed of light. Shock waves within this material give off radiation.
NEUTRON STARS
BLACK HOLE
DISK
CENTRAL ENGINE
MASSIVE STAR
HYPERNOVA SCENARIO
FASTER BLOB
SLOWER BLOB
BLOBS COLLIDE (internal shock wave)
GAMMA RAYS
JET COLLIDES WITH AMBIENT MEDIUM (external shock wave)
X-RAYS, VISIBLE LIGHT, RADIO WAVES
PREBURST
GAMMA-RAY EMISSION
AFTERGLOW
Afterglow
Burst
Pre-Burst
LOCAL MEDIUM
E ~ 10^{53} ergs
Shock Formation
γ,x
γ,x
x, radio
optical
T = 0 s
R = 10^6 cm
T ~ 10^2 s
R ~3x10^{12} cm
T ~ 3x10^3 s
R ~ 10^{14} cm
T ~ 10^6 s
R ~ 3x10^{16} cm
Γ~10^3
Scientific American 2006

Prompt emission

internal shocks in narrow (~5° opening angle) jets

Note: geometrical jet opening angle vs. beaming angle

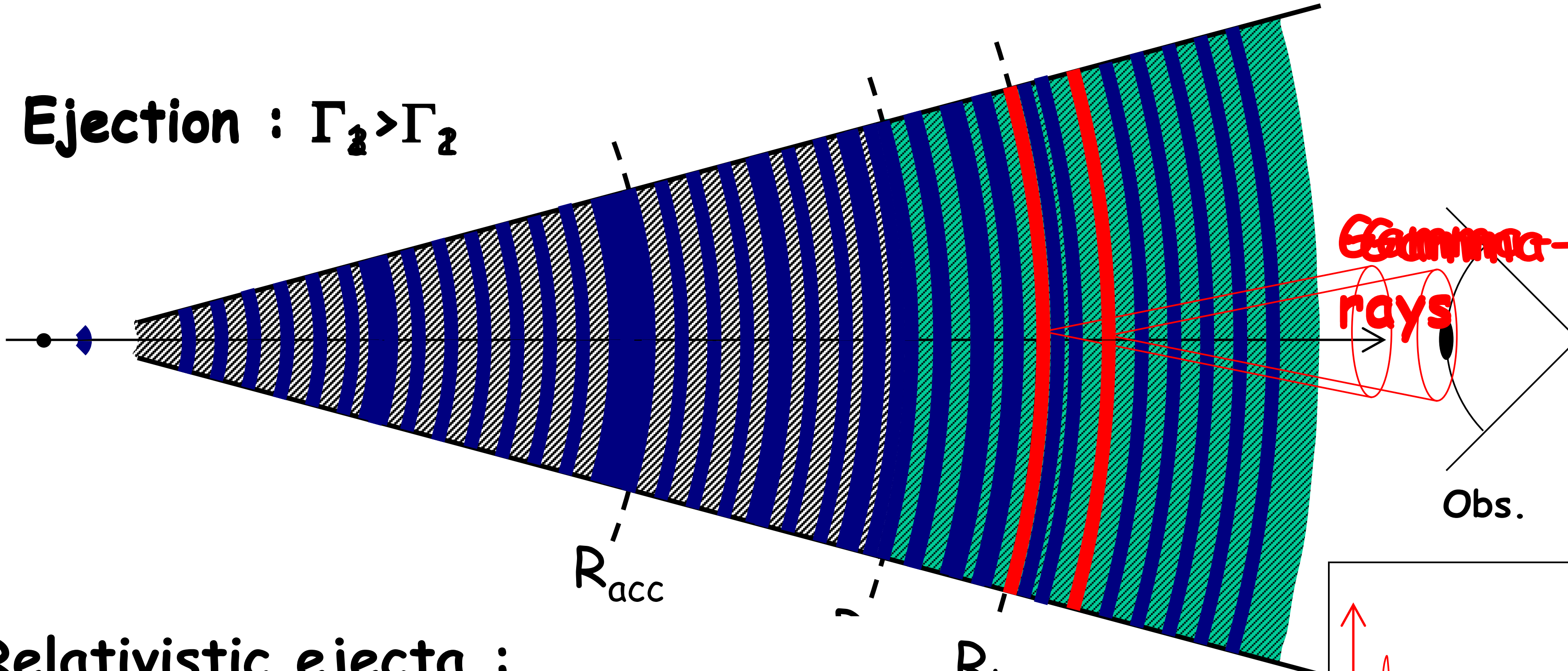


Typical initial Lorentz factors
$\Gamma \sim 100\text{-}1000$

Adopted from Daigne

Internal shocks

Ejection : $\Gamma_1 > \Gamma_2$

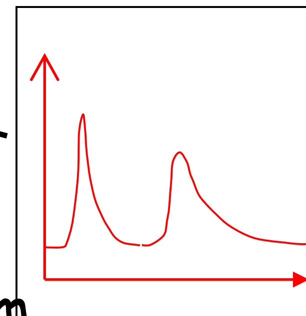


Relativistic ejecta :

- Width $\sim 3.10^{10}\ t_{w,s}$ cm
- Variable Lorentz factor ($\Gamma \geq 100$)
- Kinetic energy $L_{kin,4\pi} \sim 10^{51}$- 10^{54} erg/s

R_{is} : **internal shocks**

$R_{is} \sim 6.10^{14}\ \Gamma_2^2\ t_{var,s}$ cm



GRB time profile

Adopted from Daigne

Models for prompt gamma-ray emission

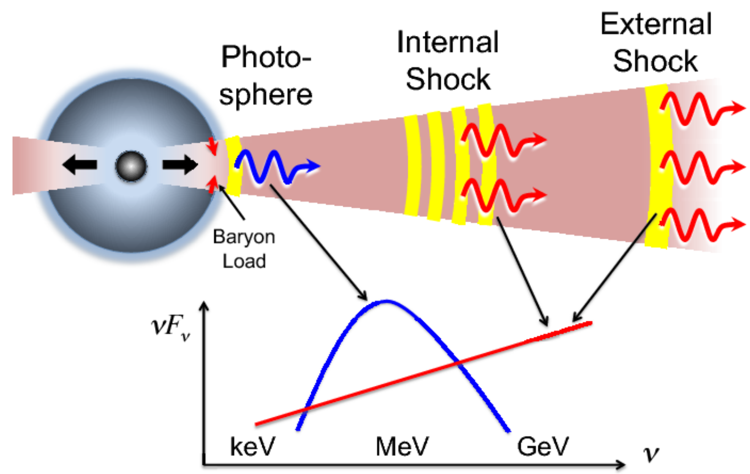
• Standard model: synchrotron emission from Fermi-accelerated electrons in these internal shocks Paczynski 1986, Meszaros & Rees 1994

but not undisputed: main problem is the high efficiency needed

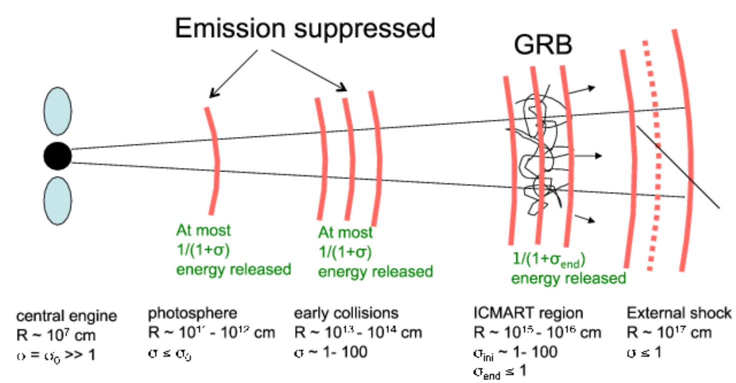
• Alternative models

❖ Photospheric emission:
sub-photospheric heating leads to broadening of Planck spectrum

Ryde et al. 2002; Pe'er et al. 2008



❖ Magnetically dominated jet:
magnetic reconnection leads to broad-band spectrum Zhang et al. 2006



4 topics in gamma-ray astrophysics

- γ-ray spectra – constraining the emission mechanism
- GRB 170817A was unusual
- γ-ray localizations – GBM can do better
- γ-dream: polarization

History

- Synchrotron was one of the early (mid 70ies) contenders for the emission mechanism, but was criticized
  - Because low-E power law slope was too steep to be compatible with S. (so-called line-of-death problem)
    Note: last 30 years fitting of broken powl, not S.!
  - Large (>90%) efficiency needed
- Many alternative models proposed; leading competitor is "photospheric emission"
- 2014: first example for a good fit with a proper synchrotron model
- 2015/2016: new "measures" of curvature suggest S. too wide
- Today: the following story

GBM Data

Data Type	Time Resolution	Energy Resolution
TRIGDAT	1024/256/64 ms	8 channels
CTIME	256/64 ms	8 channels
CSPEC	4096/1024 ms	128 channels
TTE	2 μs	128 channels
CTTE (New!)	2 μs	8 channels

TRIGDAT: used primarily for localization & quick look

CTIME: temporal analysis

CPSEC: spectral analysis

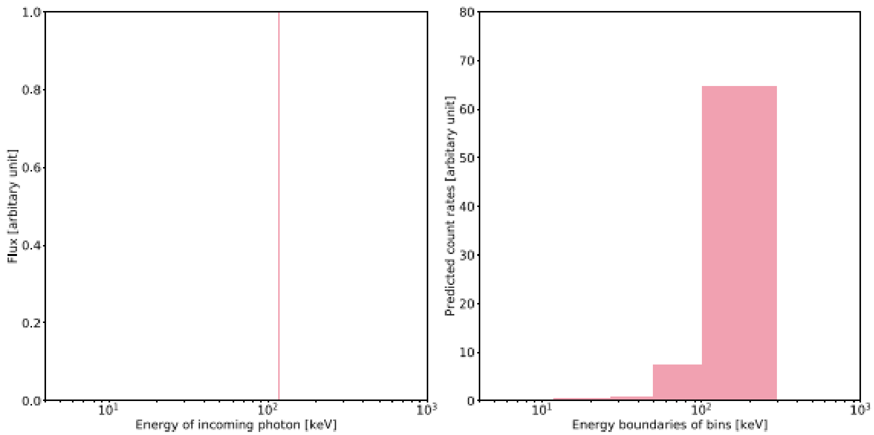
Initially TTE was available ~30s pre-trigger - ~300 s post-trigger

Continuous TTE (CTTE) implemented on November 26, 2012

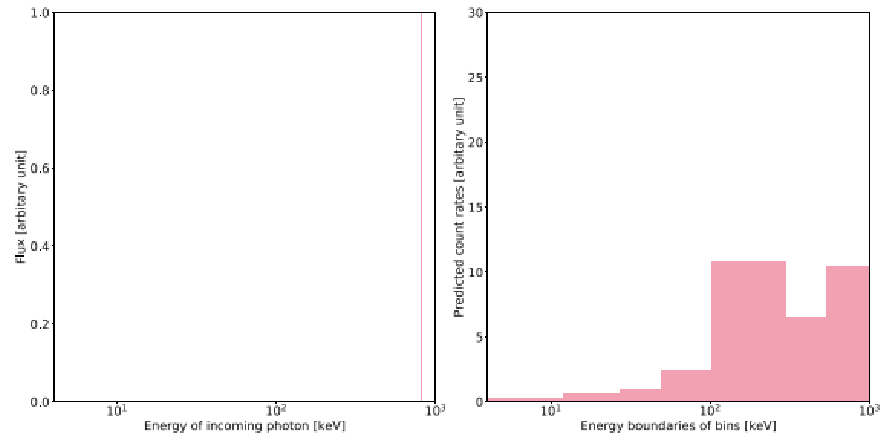
What data do we have?

- The raw count spectrum is indexed in channel energy and has units of electronic count per second.
- Scintillation detectors suffer energy dispersion: there is no direct mapping of channel energy to photon energy!
- …and this is energy-dependent!

115 keV

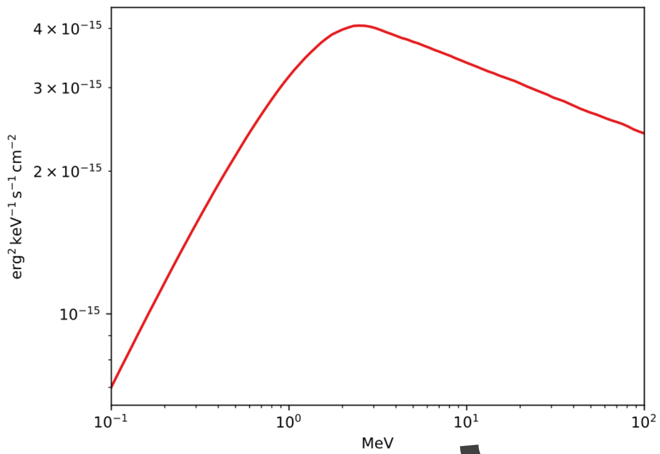


805 keV

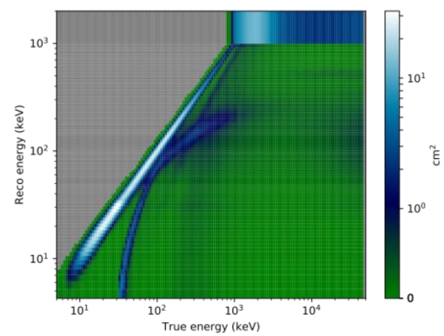


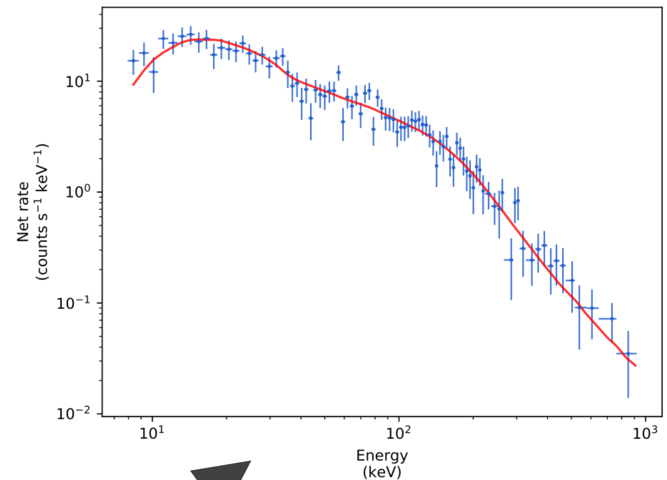
- So never co-add count-rate light curves of different detectors

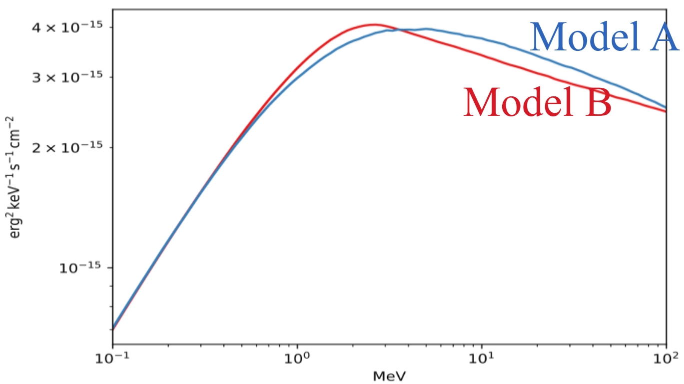
What to infer?

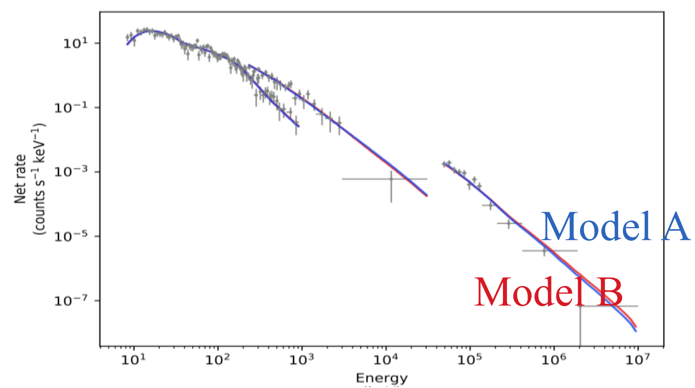


Thus, we need to do forward-folding









Models that appear different in νF_ν can be very similar in data space due to the effect of the response. Thus (1) we should preferentially fit physical models (Burgess+2014), and (2) we must pay attention to the statistical procedures during fits (Vianello+2017)

Fitting synchrotron rather than power laws

$Q(\gamma) \propto \gamma^{-p} \forall \gamma \geq \gamma_{\mathrm{inj}}$ power law injection

$C(\gamma) = -\frac{\sigma_{\mathrm{T}}}{6\pi m_e c} B^2 \gamma^2$ synchrotron cooling

$$n_\nu(\varepsilon; t) = \int_1^{\gamma_{\max}} \mathrm{d}\gamma\, n_e(\gamma, t) \Phi\left(\frac{2\varepsilon b_{\mathrm{crit}}}{3B\gamma^2}\right)$$

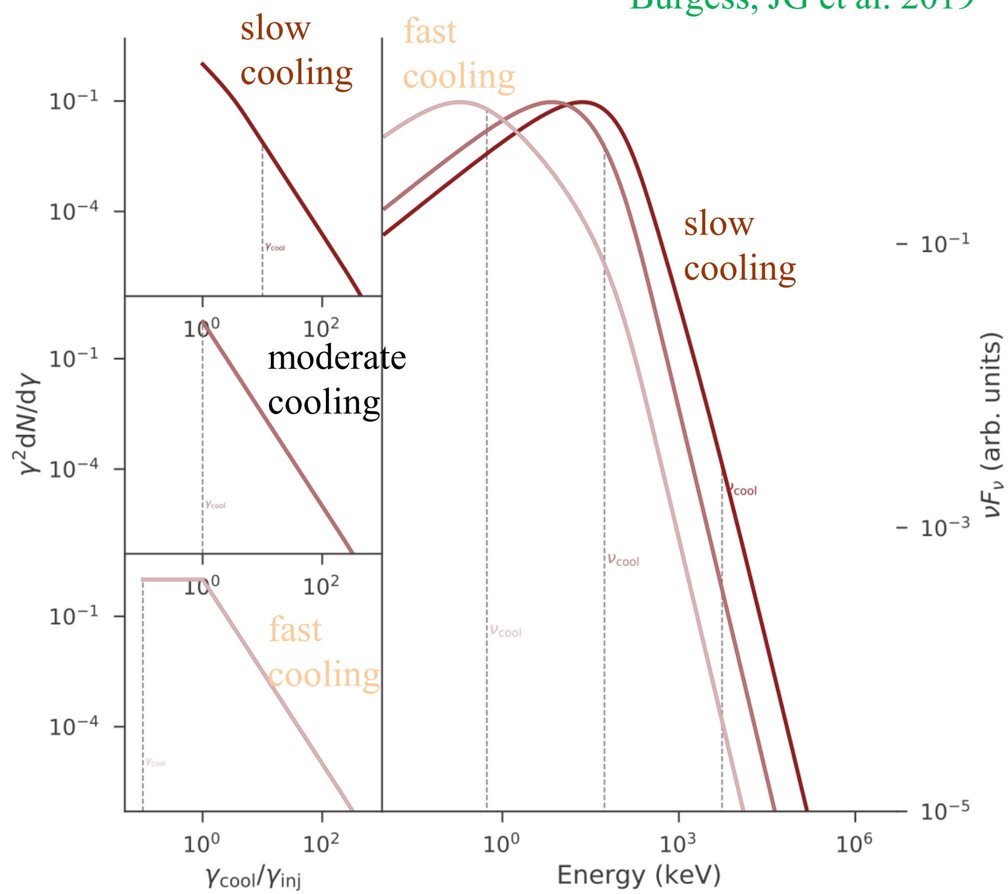
$\Phi(w) = w \int_w^\infty K_{5/3}(x) dx$ synchrotron emission

γ_{inj}	Injection electron energy
γ_{cool}	Cooling electron energy
p	Injection spectral index
B	Magnetic field strength

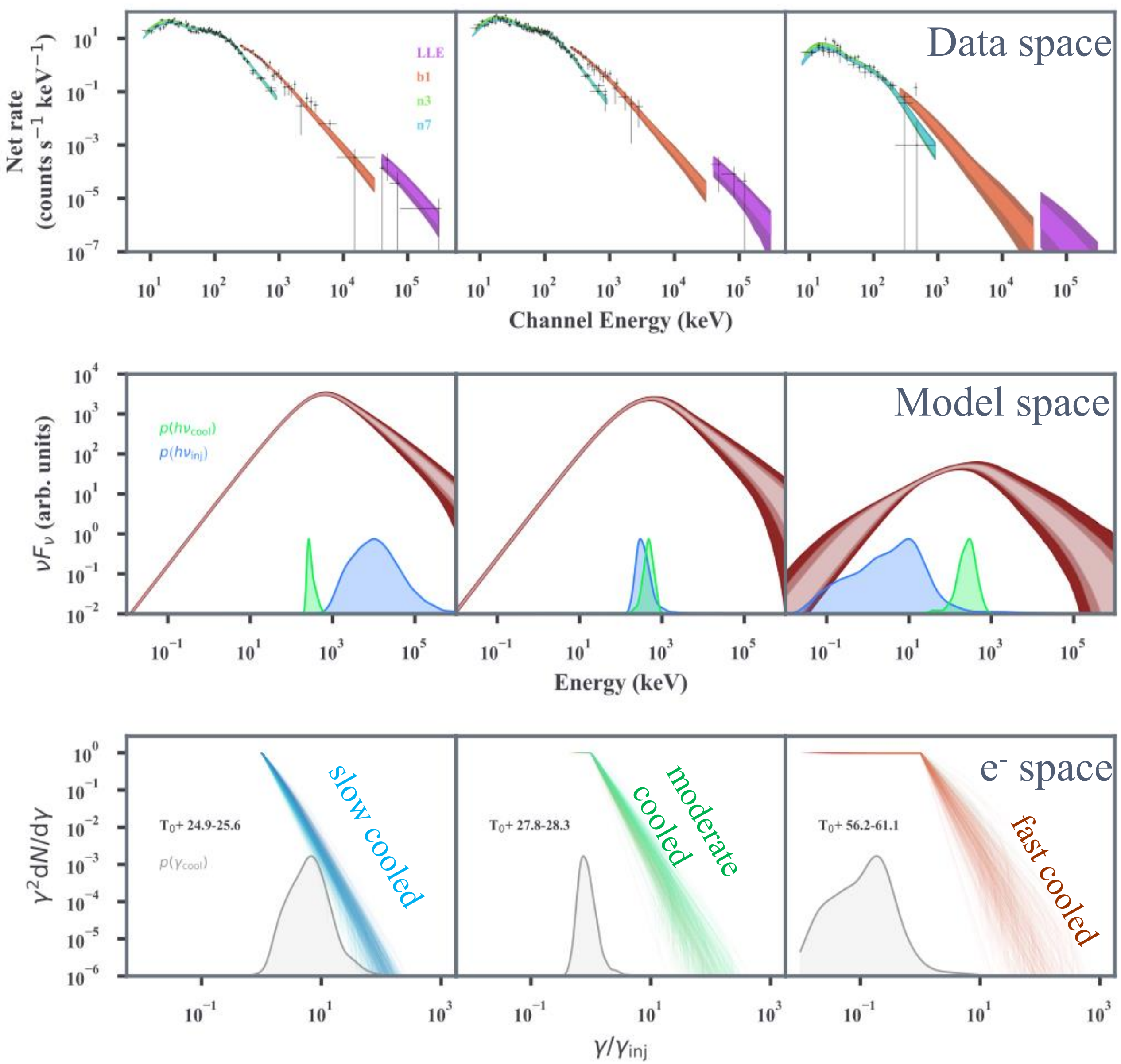
Same number of free parameters as the Band function

Standard synchrotron emission model. The model allows us to test all synchrotron cooling regimes as a parameter!

Burgess, JG et al. 2019



Fitting of GBM(+LAT) spectra



Burgess, JG et al. 2019

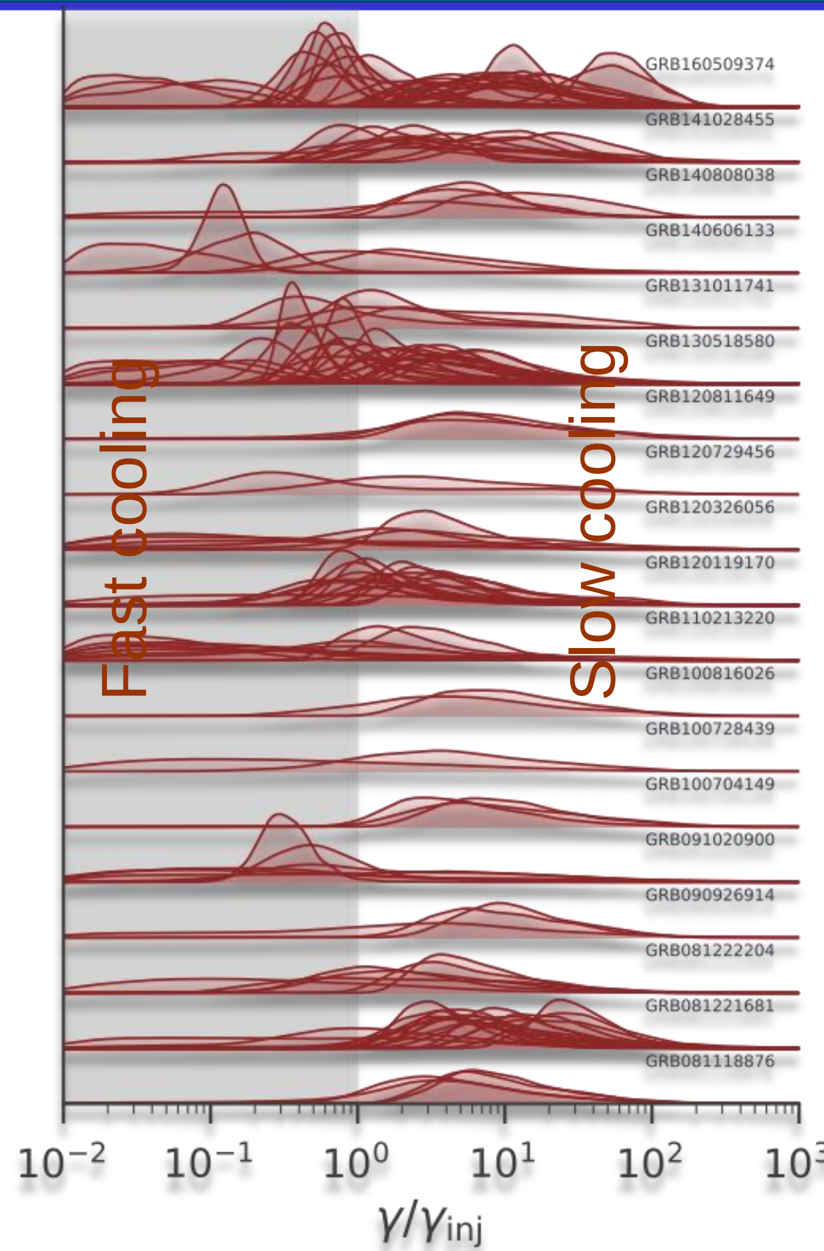
- We fit all (19) single pulse GRBs with redshift
- =168 time-resolved spectra (Bayesian blocks)
- include BGO and LAT-LLE data
- Example: 3 time-bins of GRB 130518580

Mostly slow-cooling

- A diverse population of cooling regimes.
  $\gamma_{cool}/\gamma_{inj} > 1$: slow cooling
  $\gamma_{cool}/\gamma_{inj} < 1$: fast cooling

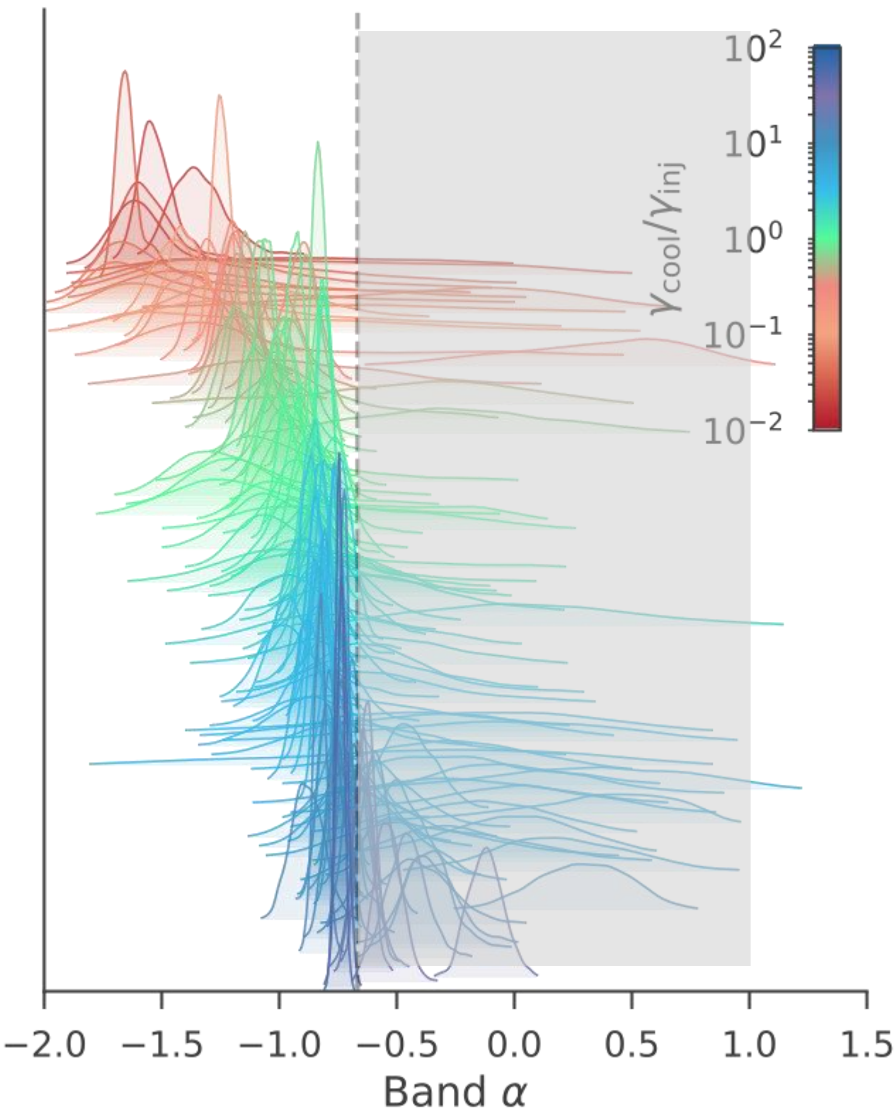
- However, most spectra are in the so-called "slow-cooling regime" (Lack of cooling somewhat unexpected – may indicated re-heating)

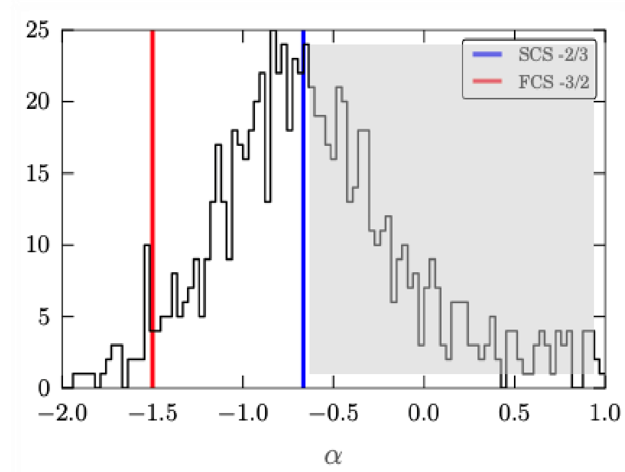
- For canonical emission radius of 10^{14} cm, we obtain:
  $10^{51} < N_e < 10^{56}$
  $10^{-2} < B < 10^{2}$ G
  $p \sim 3.5$ (!) – possibly magnetic reconnection?



Burgess, JG et al. 2019

Test against the Line-of-Death





- 25% of all fits show-2/3<α<1, thus violating the line-of-death
- Yet, the fits are fully consistent with synchrotron emission

➔ The Band function is not a useful probe of physics!

Burgess, JG et al. 2019

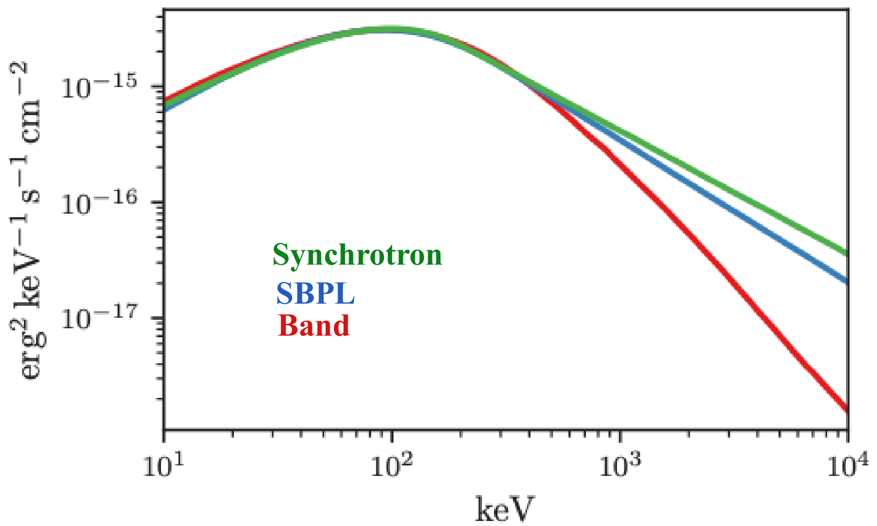
Why does empirical model (Band) go wrong?

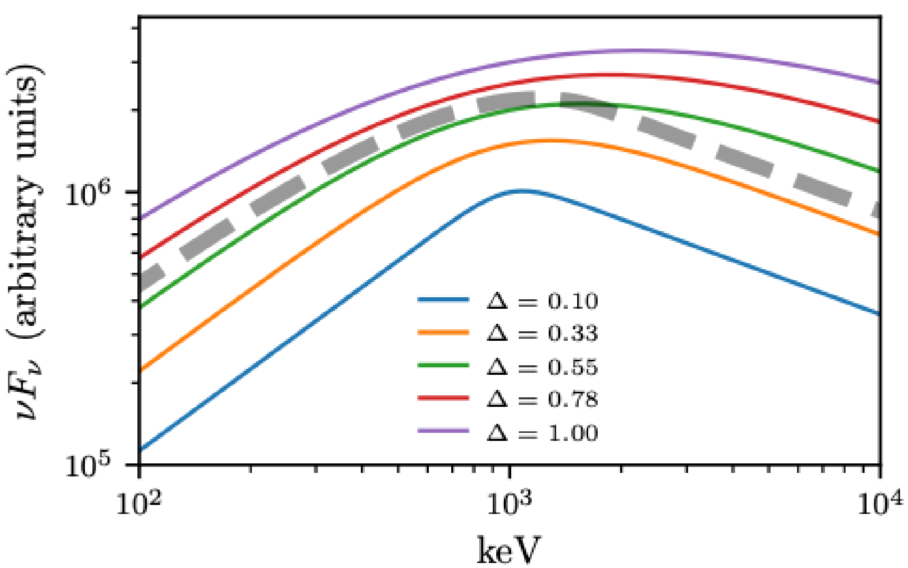
Simulating synchrotron spectra and then fitting with a Band function or a SBPL shows that these empirical models do a poor job of reproducing the spectral shapes.

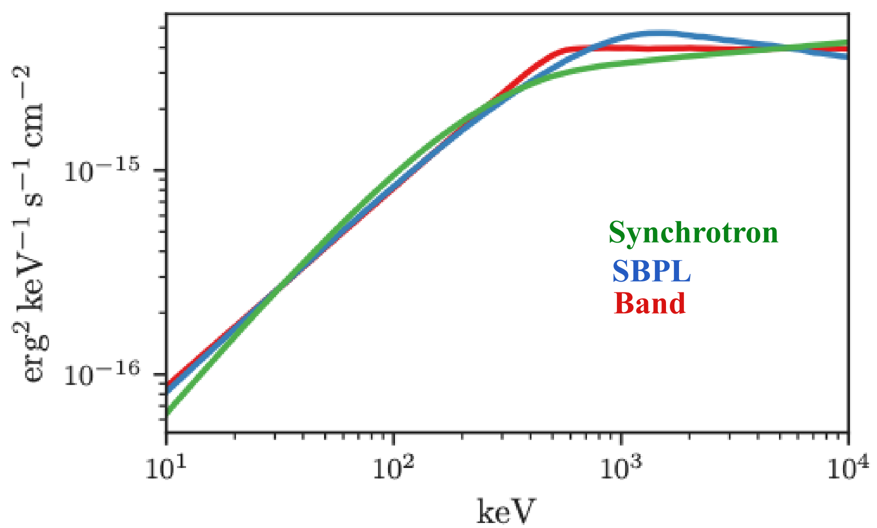
➔ Band: α-β determines curvature

Inferring Line-of-Death from Band-function fit was an over-interpretation

Burgess, JG et al. 2019







Limits for Fireball Model

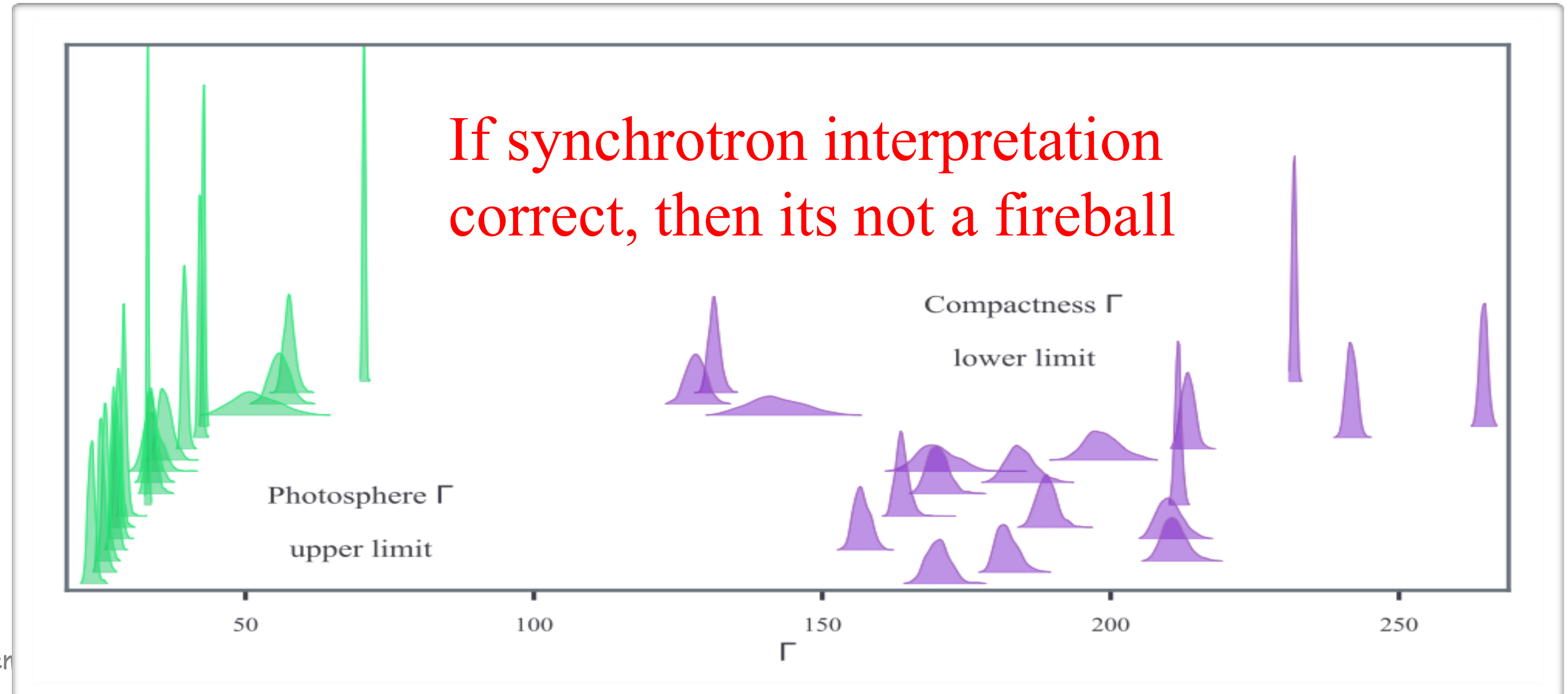
- Use our fits to compute physics about the outflows: Burgess, JG et al. 2019
- Peak of the emission is non-thermal; fits do not require an additional thermal component – but lets assume a sub-dominant thermal component with 50% of flux

$$\Gamma_{\rm obs} \geq \Gamma_{\gamma\gamma} = \left(\frac{f_{\rm p} L_{\rm obs} \sigma_{\rm T}}{r_0^2 m_{\rm e} c^2}\right)^{\frac{1}{4+2\beta}}$$

$$\Gamma_{\rm obs} \leq \Gamma_{\rm photosphere} = \frac{\sqrt{2}}{4} \frac{\varepsilon^{1/8} L_{\rm obs}^{1/4} \sigma_{\rm T}^{1/4}}{\pi^{1/4} r_0^{1/4} (1+z)^{3/2} c^{3/4} m_{\rm p}^{1/4}}$$

•A lower limit from pair-opacity

•An upper limit from lack of a photosphere.



Summary GRB spectroscopy

Burgess, JG et al. 2019, Nat. Astron.

- 95% of all time-resolved GRB γ-ray spectra are well fit with synchrotron model with slow-cooling electrons
- Problem with high efficiency remains
- Dissipation mechanism likely magnetic, since it can have a large Lorentz factor without a thermal component (but not canonical fireball)
- Sample contains 1 short GRB, so validity for all short GRBs not proven, though likely

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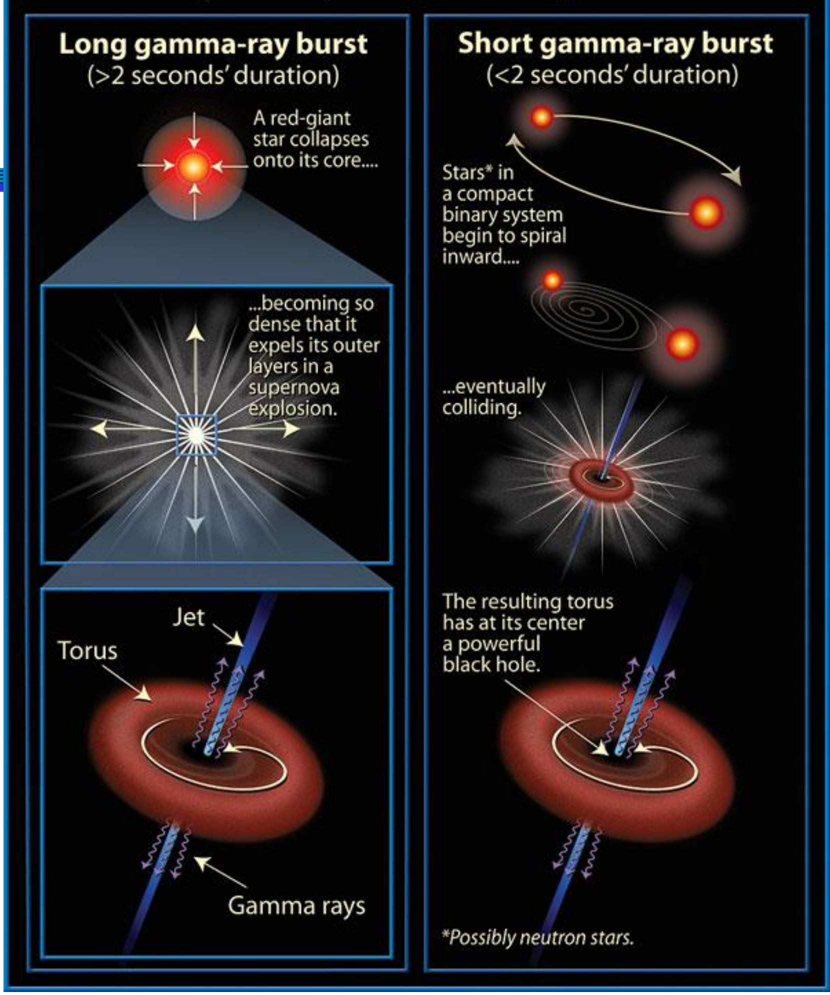
Short GRBs

- due to NS-NS merger (Eichler+1989)
- typical jet opening angles ~5-10^o
- closest known short GRB: 080905 at z=0.1218 (570 Mpc)
- thus, for any short GRB within the aLIGO horizon we expected

  (1) 100-1000 LIGO detections of NS-NS mergers without a GRB

  (2) monster-bright γ-ray emission

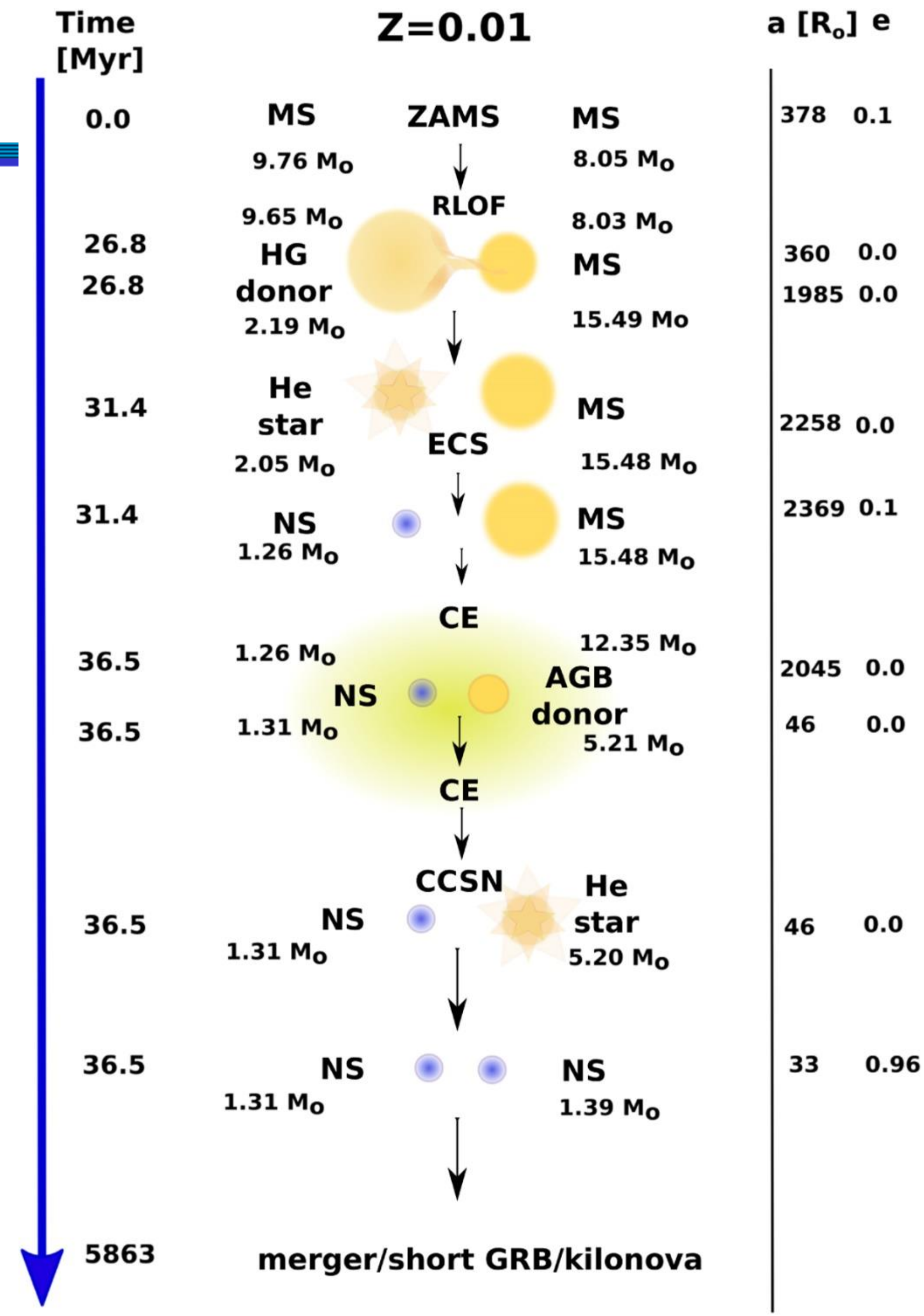


➔ Instead, the first LIGO detection of a NS-NS merger comes with a weak GRB! Total surprise! Shows our incomplete/biased knowledge!

NS-NS merger rate

- LIGO detection suggests rate of $1.5^{+3.2}_{-1.2}$ yr^{-1} (per 100 Mpc^3)
- 3 known channels
  - field binary evolution
  - globular clusters
  - nuclear clusters
- highest rate is from classical isolated binary evolution: 10^{-2} yr^{-1}

➔ Either rare event, or unknown binary channel with more frequent NS-NS mergers

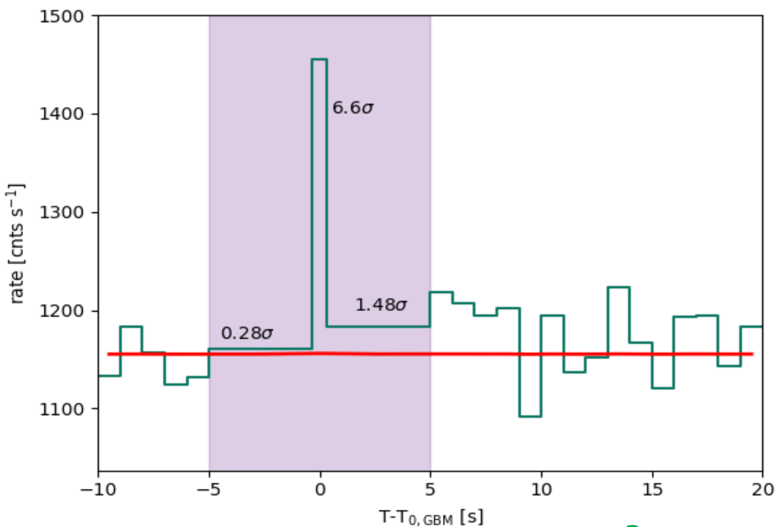


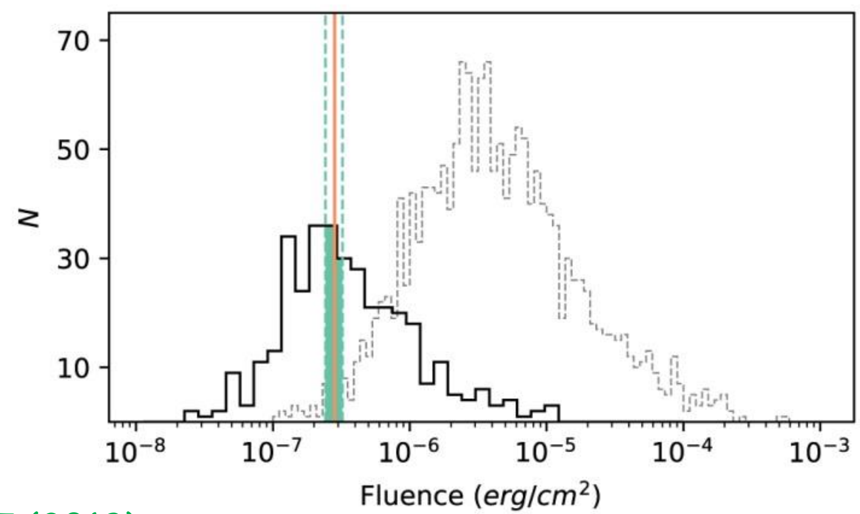
Tauris+2006, Belczynski+2010, Belczynski+2018, A&A

Gamma-ray measurements of GRB 170817A

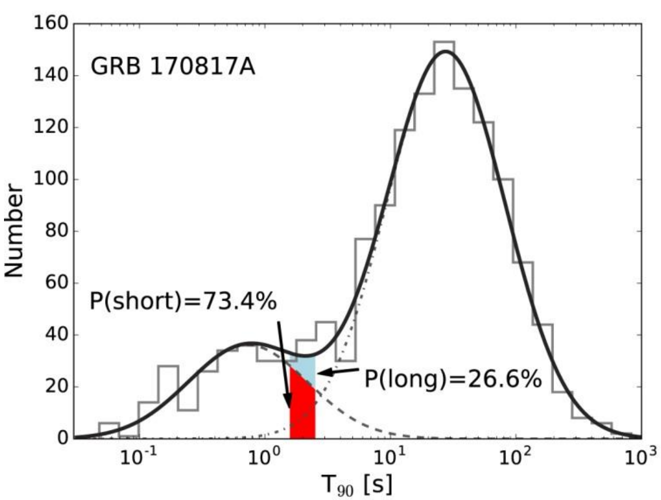
GRB 170817A: not really a typical short GRB!

Goldstein et al. 2017

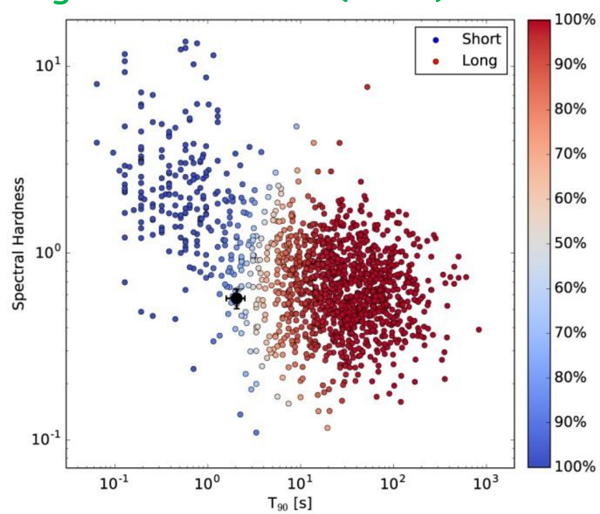




Burgess et al. 2017 (2019)



(a)



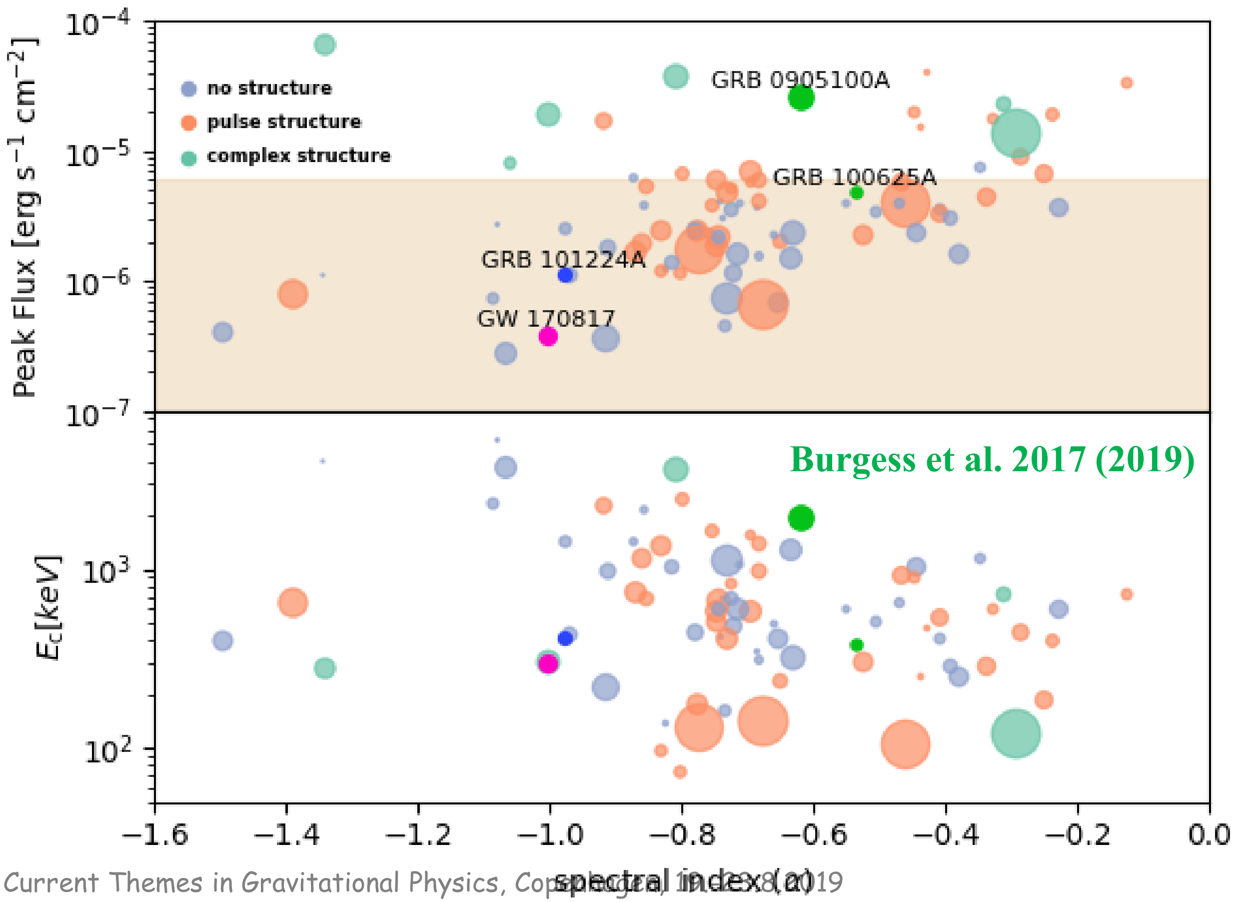
(b)

- ➢ z=0.01, while all other short GRBs 0.1<z<2
  ➔ under-luminous by 10^4x
- ➢ Duration rather long
- ➢ Spectrum very soft

GRB 170817A: Low-L or off-axis?

Questions:

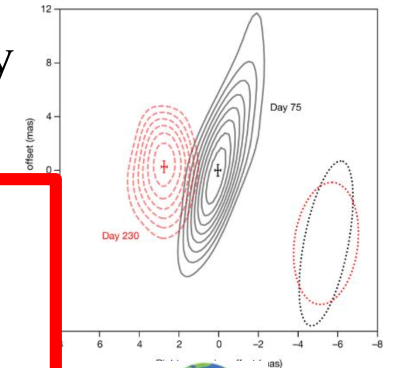
- ➢ A particularly low-luminosity event, or a short GRB seen off-axis?
- ➢ Rarity: lucky detection or other similar events?



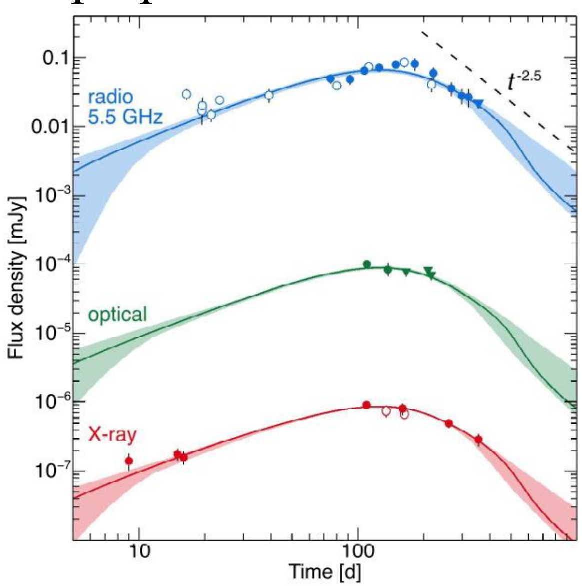
- ➢ low-L difficult: 10^4x difference should have impact on emission mechanism
- ➢ off-axis implies:
  - ○ Lower Γ
  - ○ Softer spectrum
  - ○ Longer duration
  - ○ Smoother lc

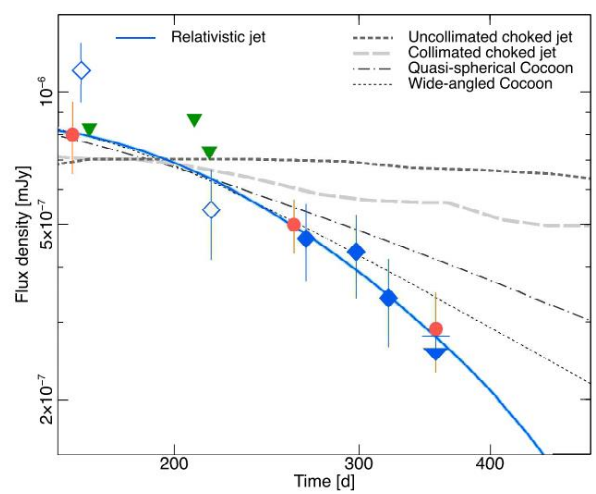
GRB jet structure and viewing geometry

- no afterglow during first 10d: slow rise suggests off-axis geometry
- superluminal motion of compact radio emission from afterglow
- together with flux evolution:
  - jet opening angle: 4°
  - off-axis angle of observer: 20°
- consistent with LIGO limit of <28° for … of orbital plane (under assumption of jet being perpendicular to NS-NS orbit)

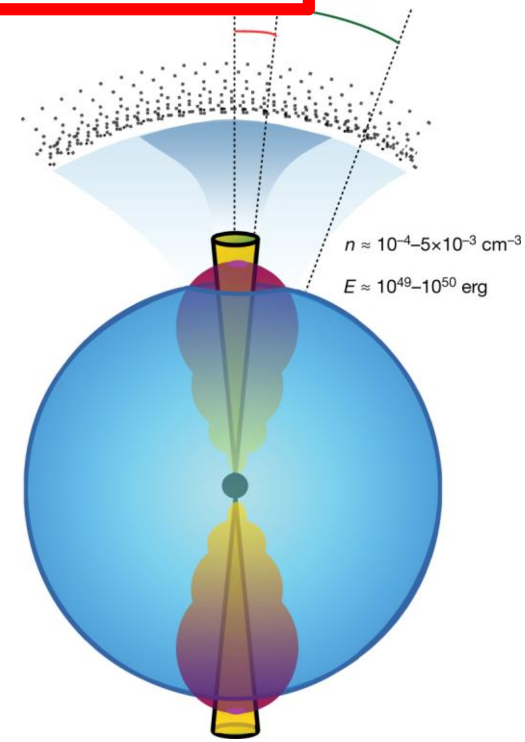


very narrow jet observed far off-axis
➔ inconsistent with previous GRB theory!





Troja et al. 2018



Mooley et al. 2018, Nature

GBM I: The GRB prompt emission spectrum

Constraints on synchrotron emission models

Begue, JG et al. 2017, ApJ

a. Structured or on-axis top-hat jet

$$L_{\rm obs}^{\rm sync} = \frac{4}{3}\sigma_{\rm T} c \left(\frac{2\pi m_{\rm e} c^2}{q_{\rm e}}\right)^2 \frac{E_{\rm p}^2}{8\pi\gamma_{\rm e}^2} \frac{\alpha\xi M_\odot}{\Gamma m_{\rm p}}.$$

Lorentz factor of accelerated e- is $\gamma_e = \kappa m_p/m_e$

κ parametrizes uncertainty of acceleration

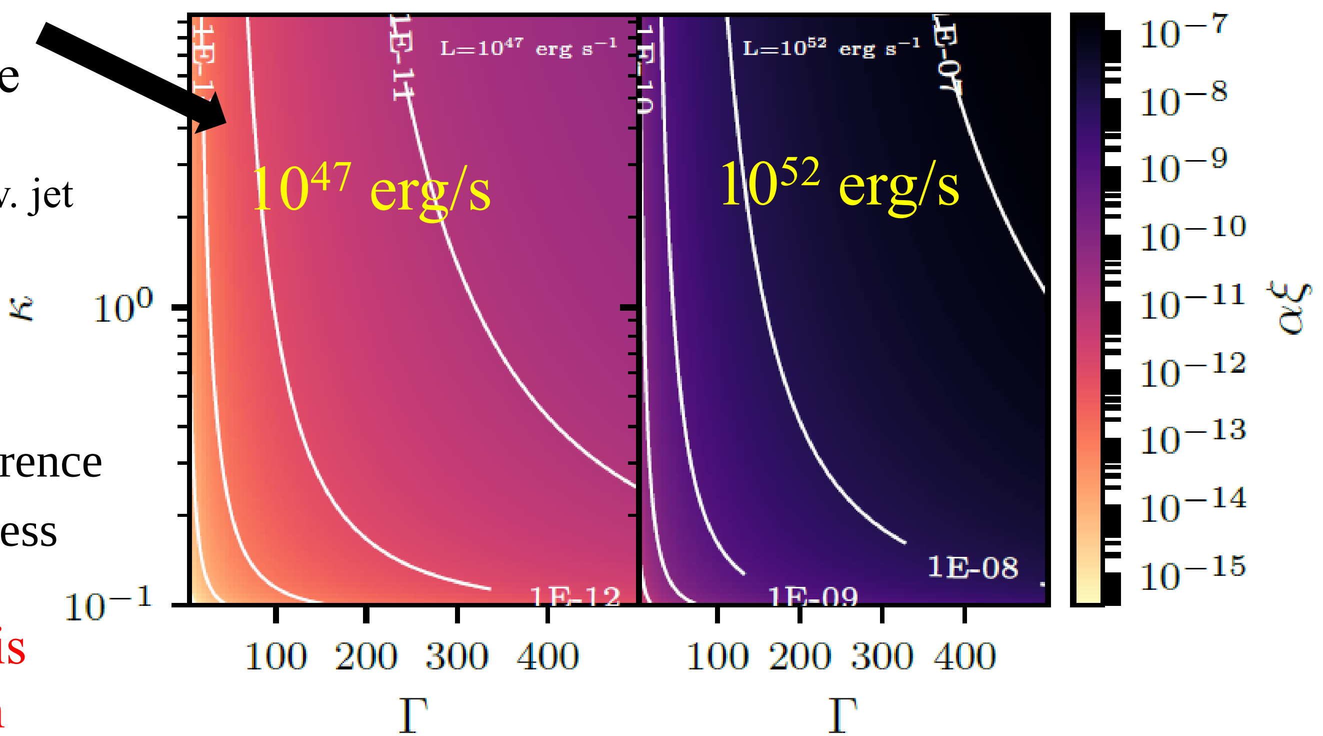
$\xi < 1$ fraction of accelerated e-

$\alpha < 1$ fraction of E turned into radiation

αξ extremely tiny for GRB170817A: impossible

ξ«1 small efficiency

α«0.01 incompatible with relativ. jet

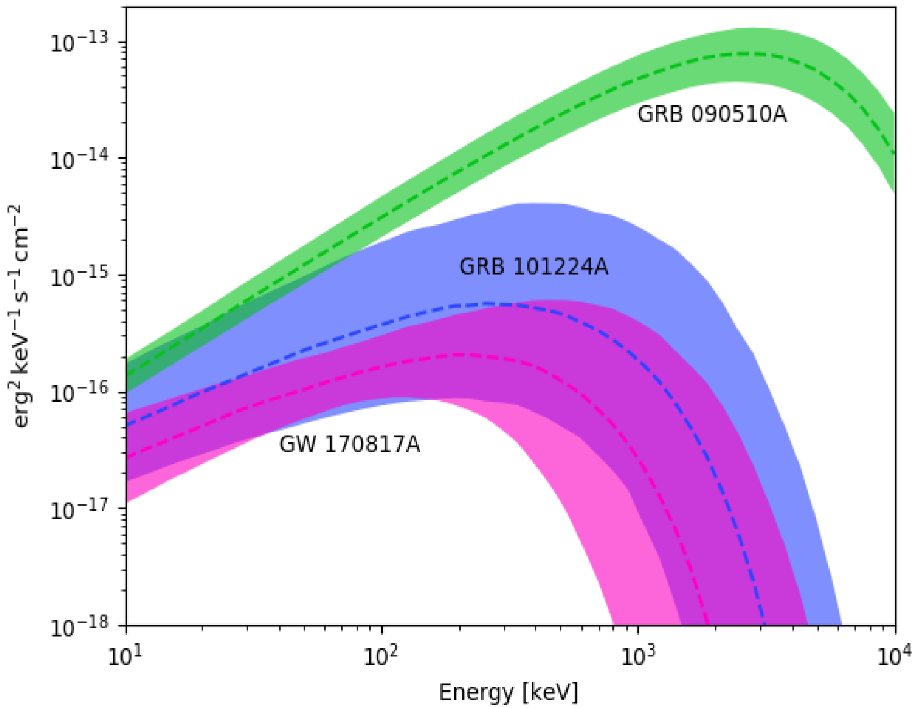


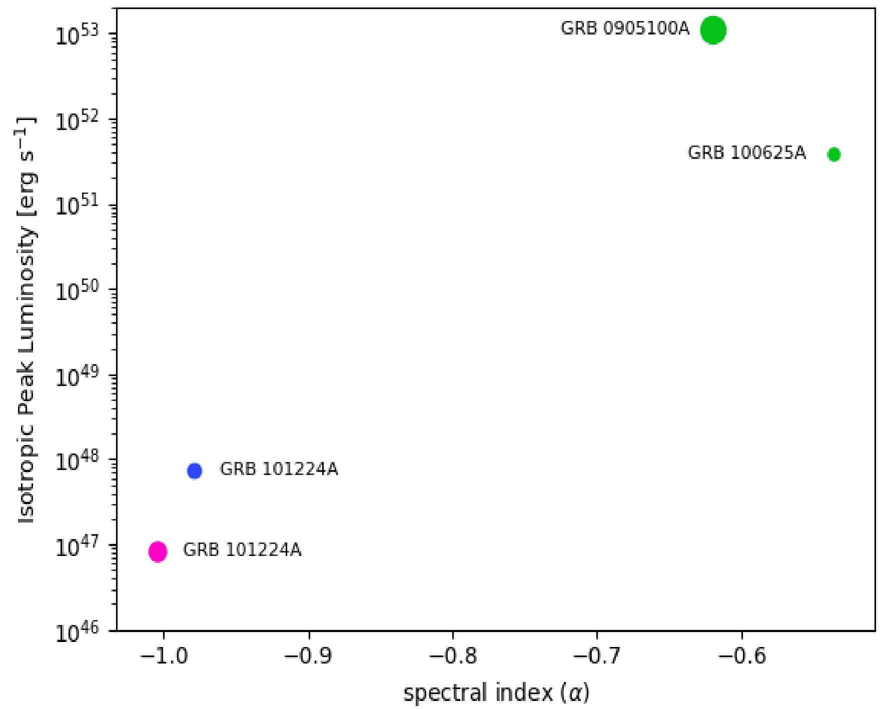
b. off-axis top-hat jet

$\Gamma<20$ at $\theta \sim 10^o$ for E_{peak} difference incompatible with compactness

➔ Emission mechanism is very unlikely synchrotron

Similar short GBM-GRBs

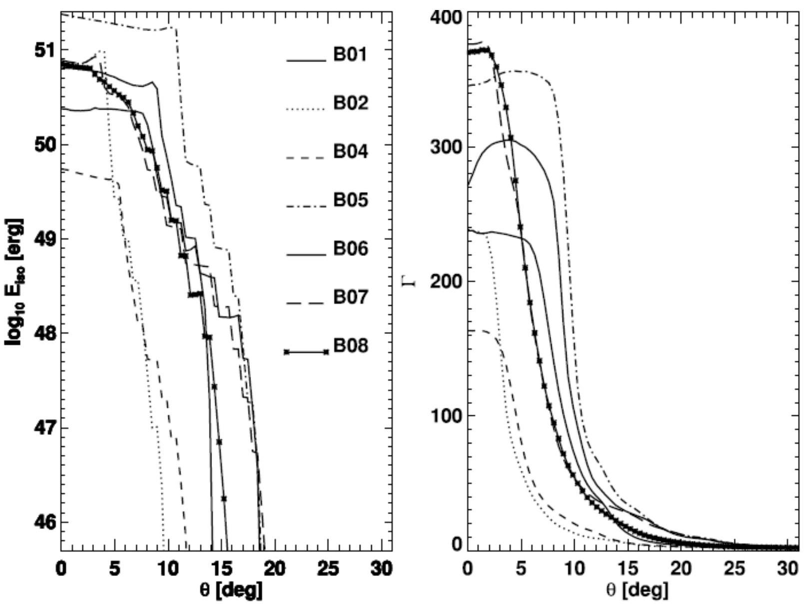




- at least one other good candidate for nearby low-L GRB
- in total ~10 out of 50 short GRBs have similar spectral properties, and thus could be local and off-axis

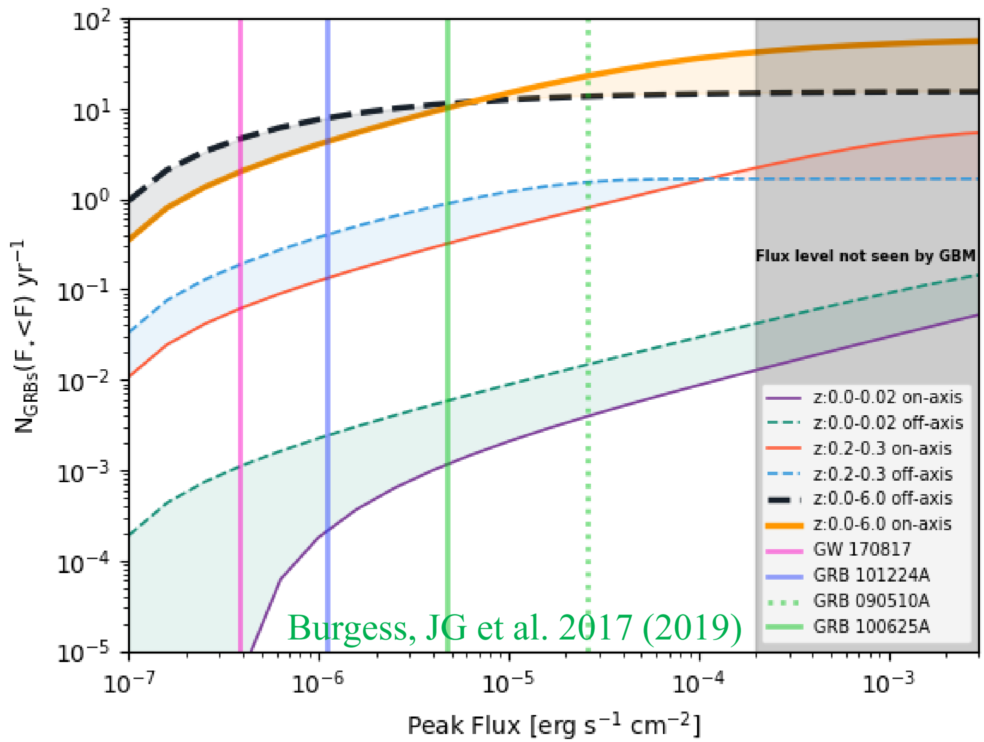
GBM II: Constraint on Rate of nearby GRBs

- if GRBs also emit off-axis, then there will be many more of those
- rate depends on relative luminosity ratio and jet opening angle



Nominal on-axis emission within 10°, beyond power-law decline up to 90°

Janka et al. 2006



➔ at faint flux levels, local off-axis GRBs dominate

Summary GRB 170817A

- Its unusual for its off-axis emission (underluminous & spectral shape)
- Emission mechanism is unlikely to be the same (synchrotron) as for all other short GRBs
- Rates suggest that faint sGRBs are local, while bright sGRBs are distant (viewed along the beam)
- Why have we (Swift) not seen any other local short GRB? The nearest sGRB of last 30 years is 10x further away than 170817A

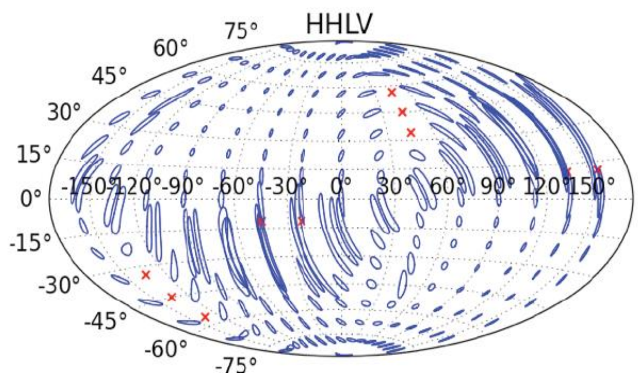
4 topics in gamma-ray astrophysics

- γ-ray spectra – constraining the emission mechanism
- GRB 170817A was unusual
- γ-ray localizations – GBM can do better
- γ-dream: polarization

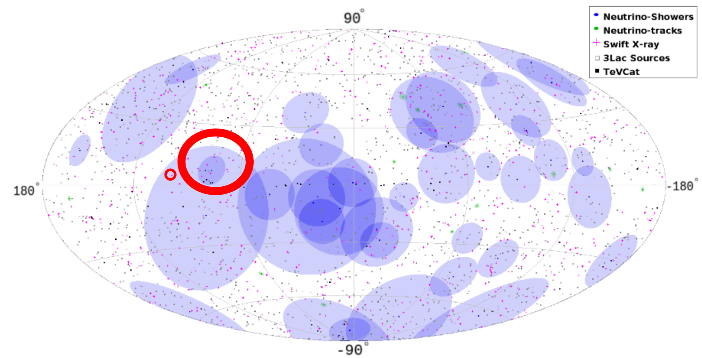
Neutrino or GW Counterpart Search

what matters is: location, location, location…

Abbott+2016, Living Rev. Relativity, 19, 1



Error ellipses with 2 US sites + Virgo

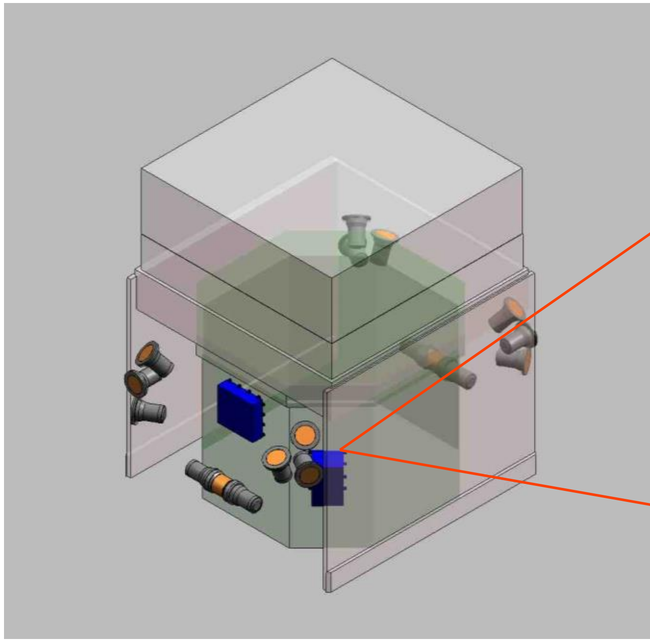


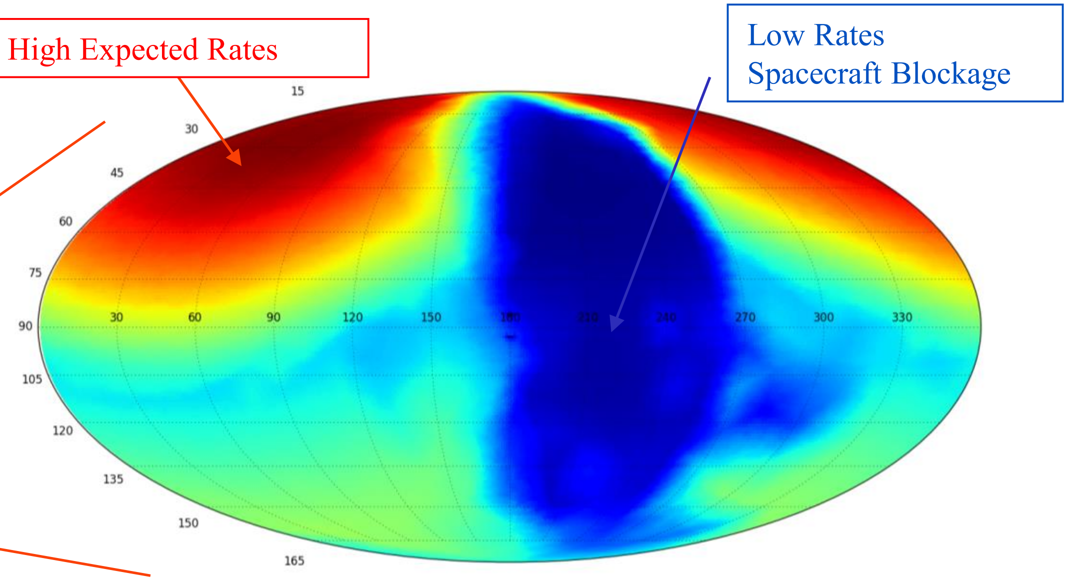
IceCube tracks (1°) vs. showers (~15°)

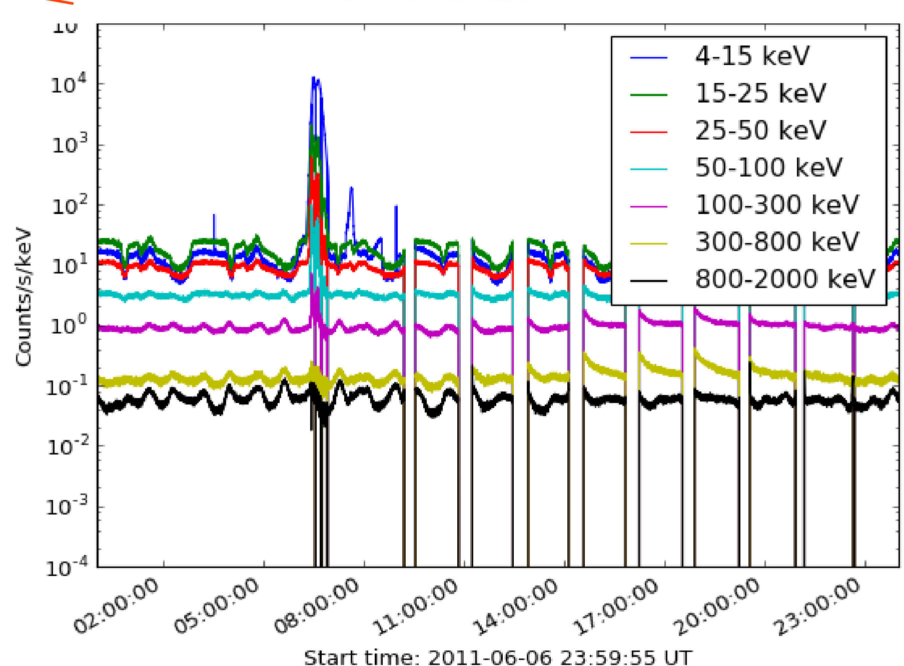
Moharana+2016, PoS ICRC2015, 1122

Previous Fermi/GBM locations do not provide improvements, …but this can be cured

GBM Detection: Sky + Bkg + Earth + Sun





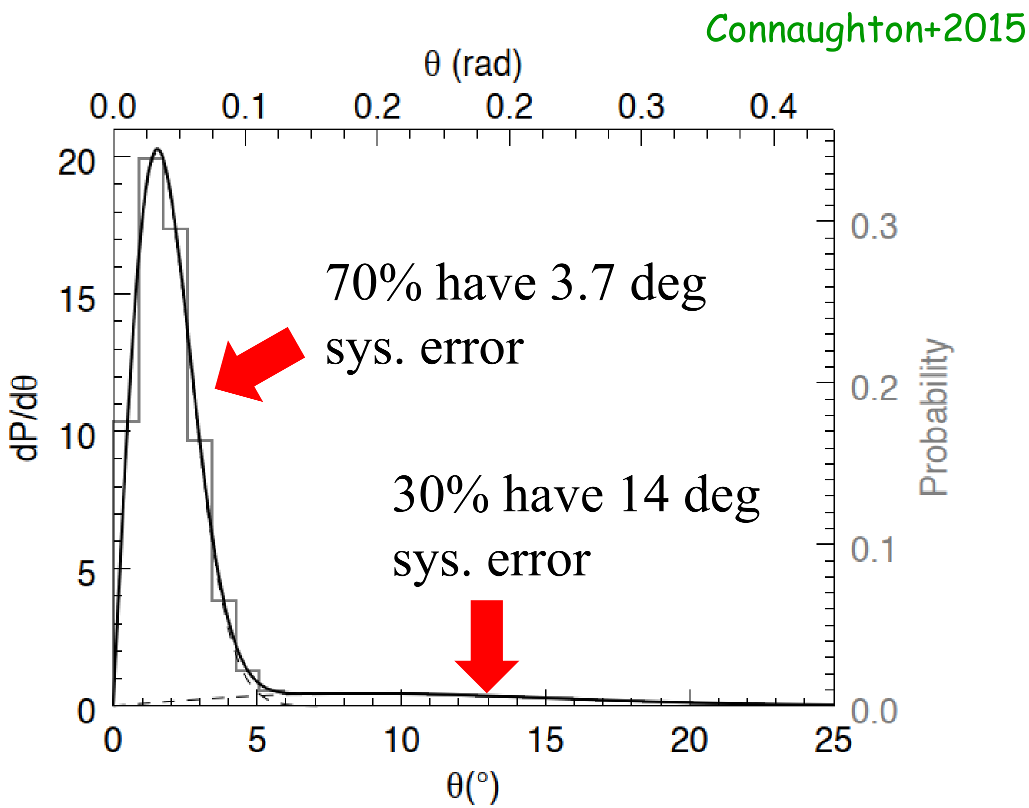


Each detector sees a certain relative fraction of sky (bkg and sources), Earth albedo or blockage, etc

This relative fraction changes with time

At a given time, this fraction is different for each detector

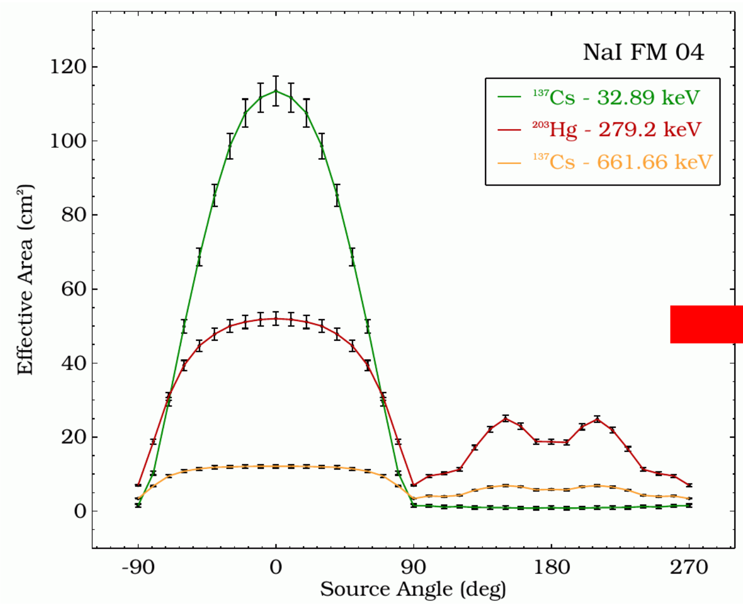
Previous GBM localization performance

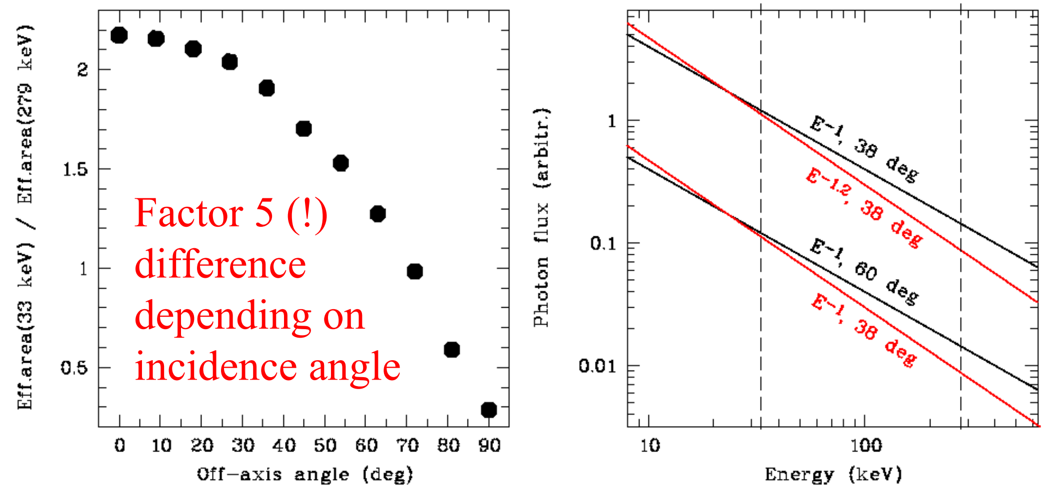


The problem: for a given GRB, we don’t know to which of these two components it belongs?

➔ So we have to adopt the large uncertainty for every GRB in order to be on the safe side (in terms of counterpart search)

GBM localization algorithm



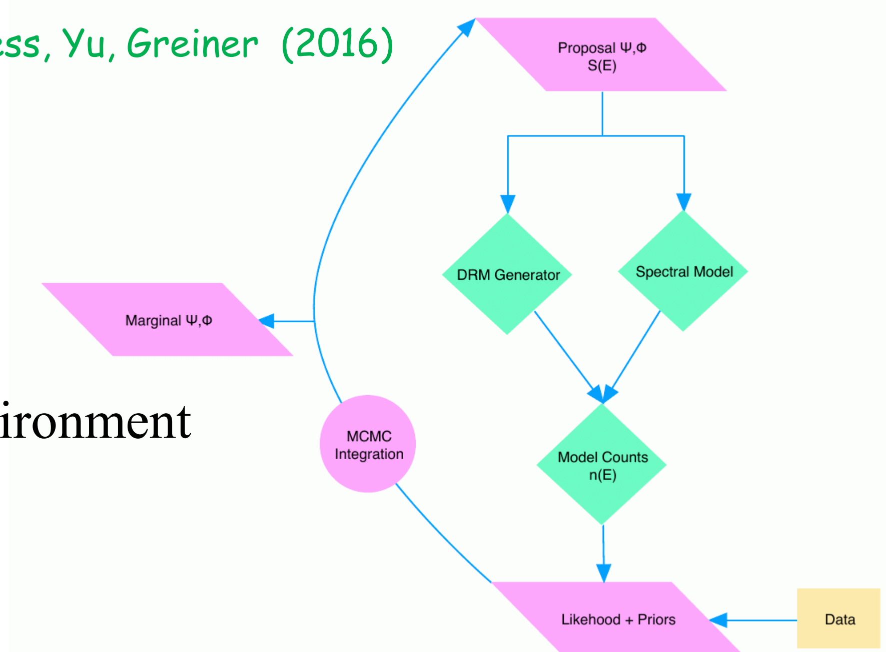


➔ being 0.1 off in slope ≡ 10° off

- Principle: Relative response at different energies varies with off-axis angle
- So far: <u>same</u> spectral template spectrum is assumed for all (long/short) GRBs to compute model rates, and a position is derived via comparison to the relative observed rates in each detector on a 1° grid on the sky
- Previous Fermi/GBM (and CGRO/BATSE) method has large systematic error: 14° for 30% of all GRBs Connaughton+2015
- Correct way: fit spectrum and position at the same time ➔ BALROG

BALROG

Burgess, Yu, Greiner (2016)



- corrects systematics in GBM location
- Easily implemented on desktop/cluster environment with a built in Pythonic user interface
- Dramatic effect on spectral parameters.

Likelihood Model

$$-2\log L = 2\sum_{i=1}^{N} \underline{M_i(\vec{\phi},\vec{p})} + t_s f_i - D_i \log(\underline{M_i(\vec{\phi},\vec{p})} t_s f_i) + \frac{1}{2\sigma^2_{B,i}}(B_i - t_s f_i)^2 - D_i(1-\log D_i)$$

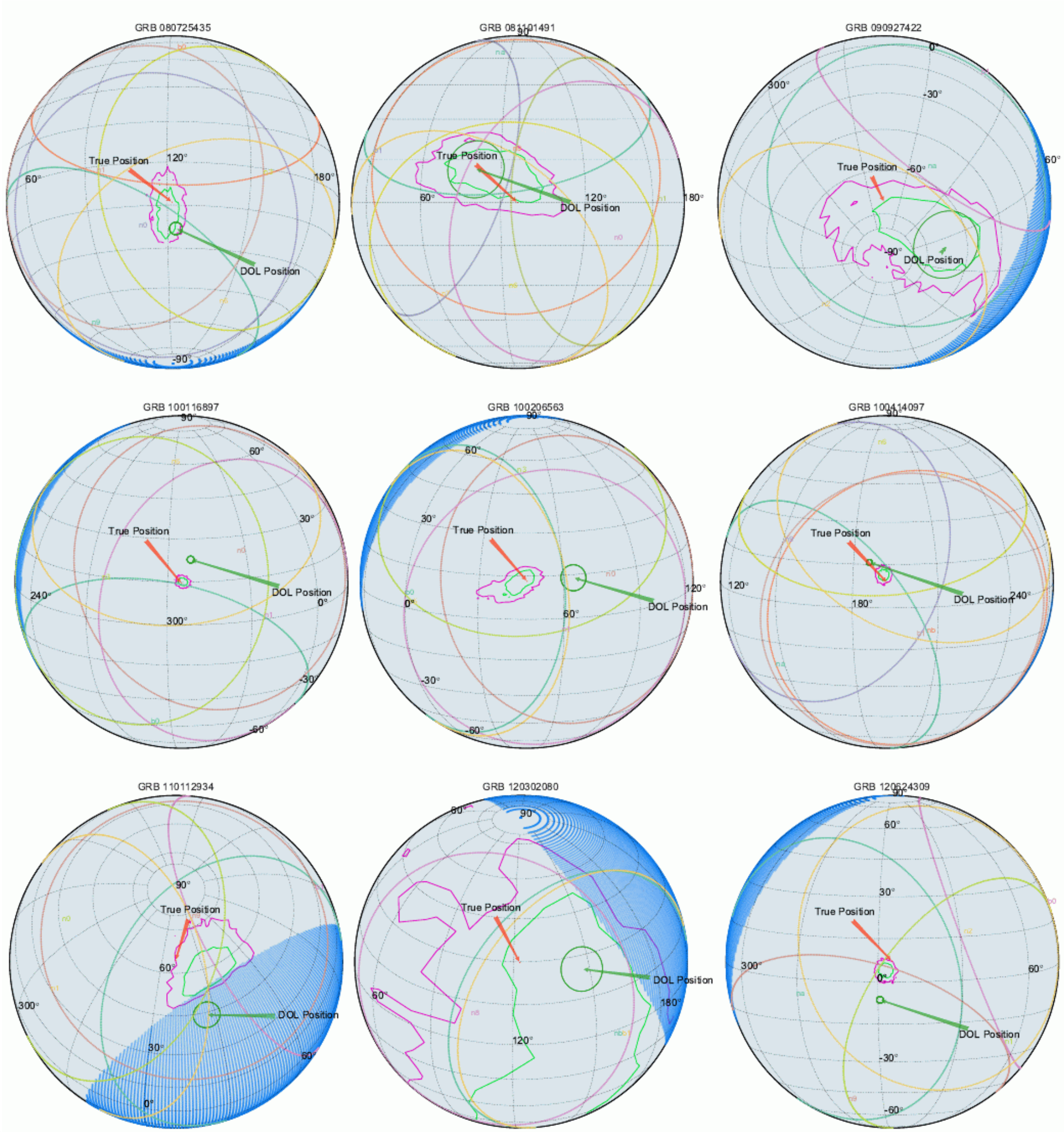
Position-dependent

p=position, Φ=spectral par.

B_i=bkg cts, $\sigma_{B,i}$=Gaussian error in i^{th} channel

D_i=observed total data cts

BALROG results on GBM/Swift GRBs



- Statistical errors about 30% larger, as they incorporate the location uncertainty
- For all Swift GRBs the statistical 3σ contour includes the true position.
- Paradigm shift: problems since 1991 (CGRO/BATSE)

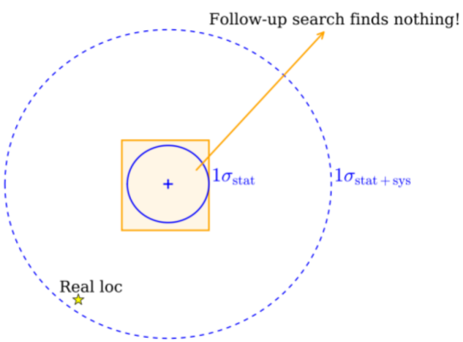
Curre

Fermi/GBM Localizations

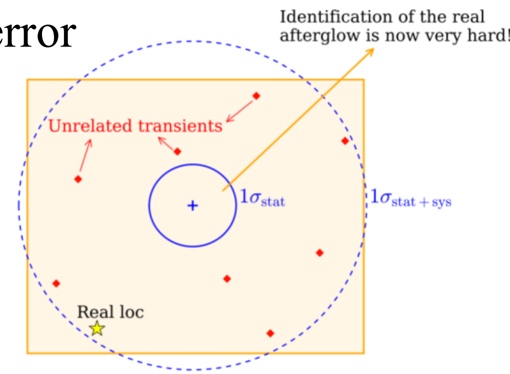
- Previous Fermi/GBM (and CGRO/BATSE) method has large systematic error: 13°-15° for 30% of all GRBs Connaughton+2015

Connaughton+2015

Last 30 years until present ("official" GBM team)

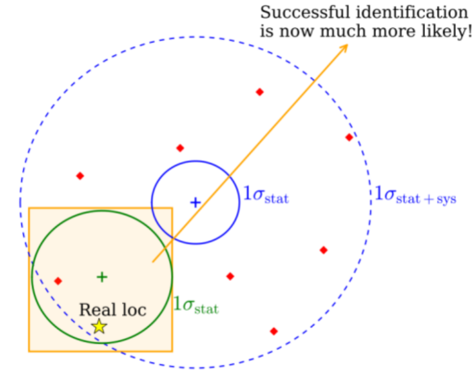


This would be the correct way with the previous systematic error

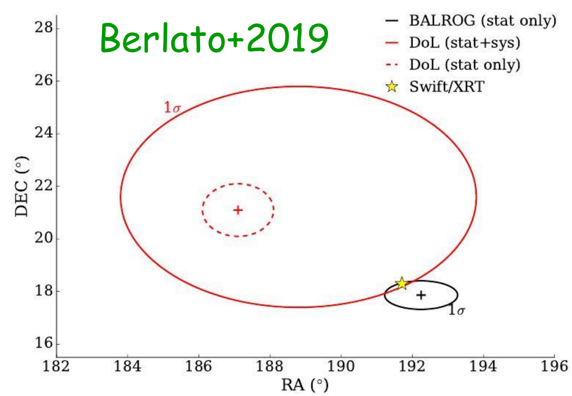


Berlato+2019

Our improved method (BALROG) since 2017



Example from real life: GRB 170705.115



4 topics in gamma-ray astrophysics

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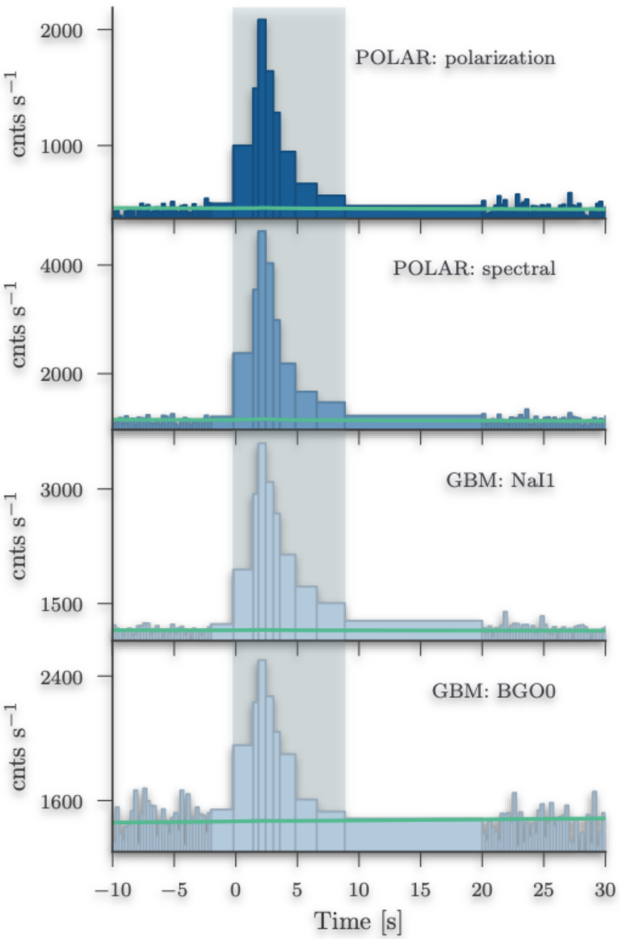
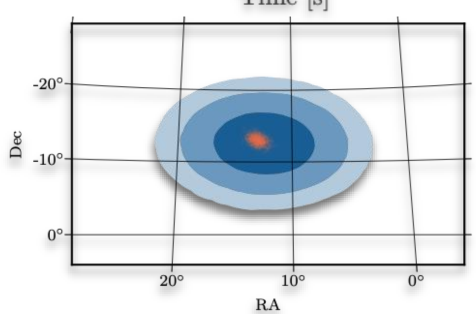
Compton Polarimeter POLAR

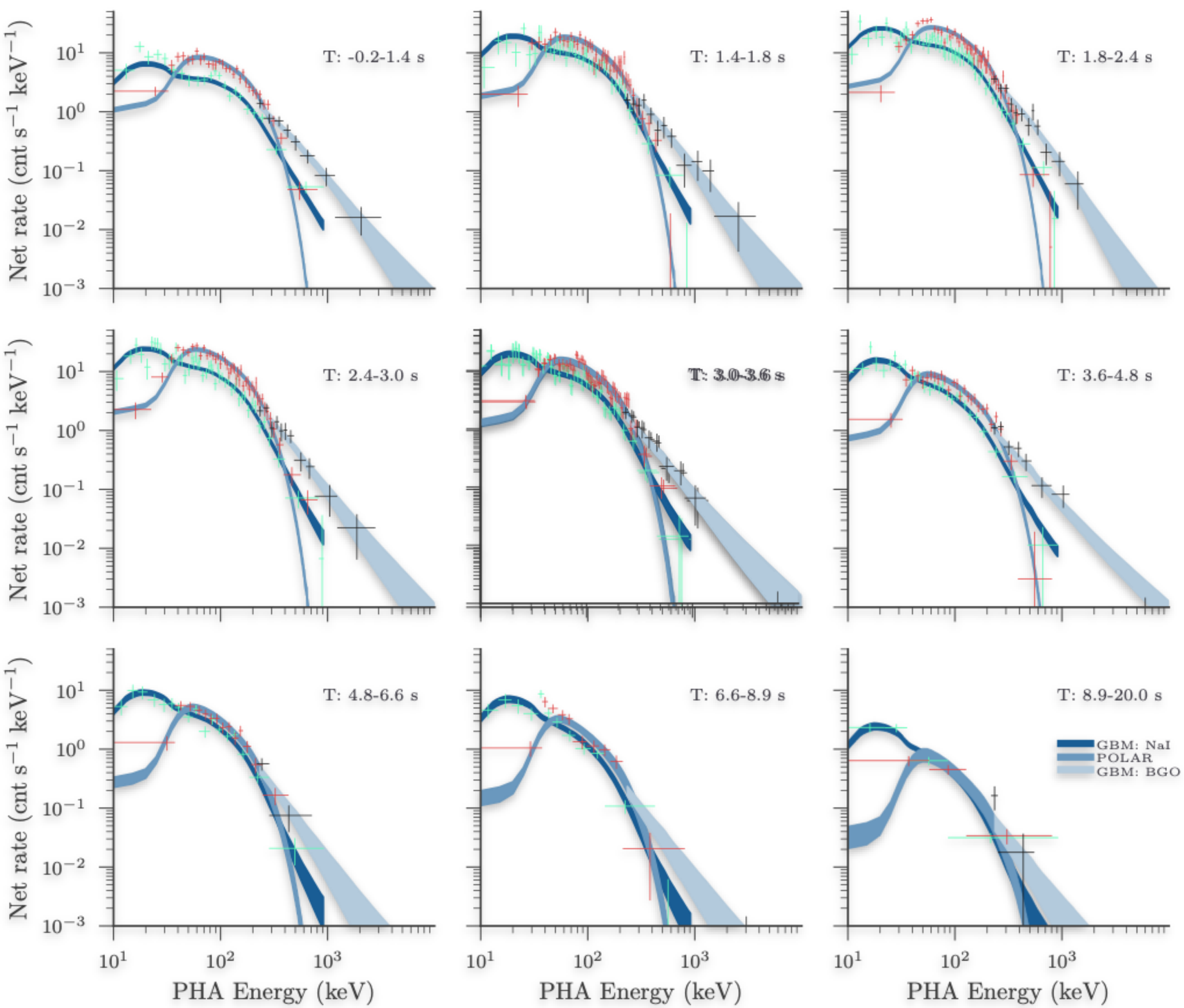




Zhang+2019, Nat. Astron; Kole, Burgess, JG et al. 2019, A&A

- Swiss Compton polarimeter on Chinese Space Station: 6 month lifetime
- 1 (11) bright (fainter) GRBs seen
- Brightest GRB also seen by Fermi/GBM
- Synergy wrt
  - Our vastly-improved GBM positions
  - Our scheme of simultaneously fitting >1 property (spectrum/location; spectrum/polarization)

Combined GBM+POLAR spectral fits

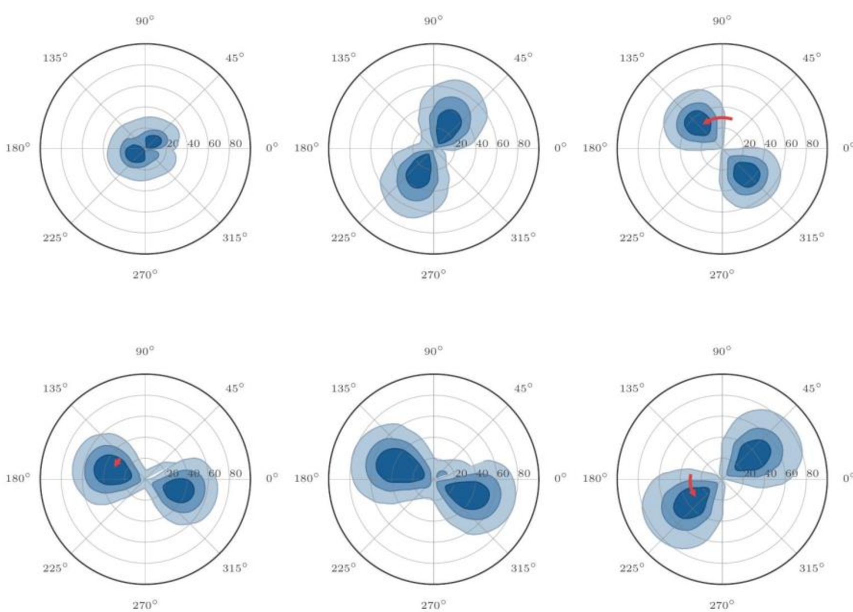


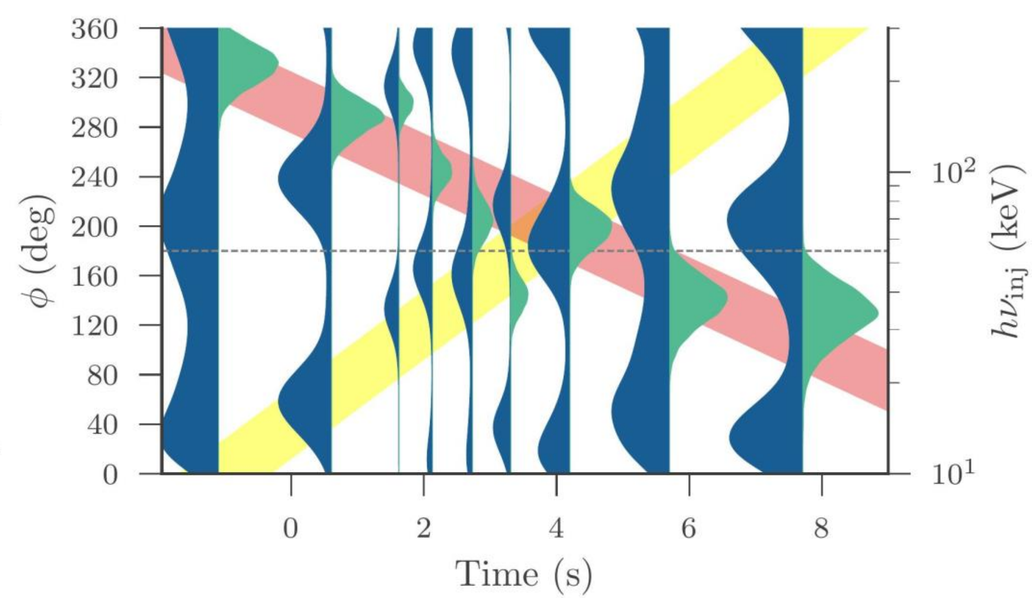
- ➢POLAR+GBM data calibrated well
- ➢Emission described with **synchrotron**
- ➢No Band function!

Polarization of prompt GRB emission

Kole, Burgess, JG et al. 2019, A&A

- first-ever evidence of rotating polarization angle during GRB pulse
- Would "explain" earlier non-detections which all summed over full GRB duration
- Physical mechanism unclear: possibly see helical structure as in blazar jets?

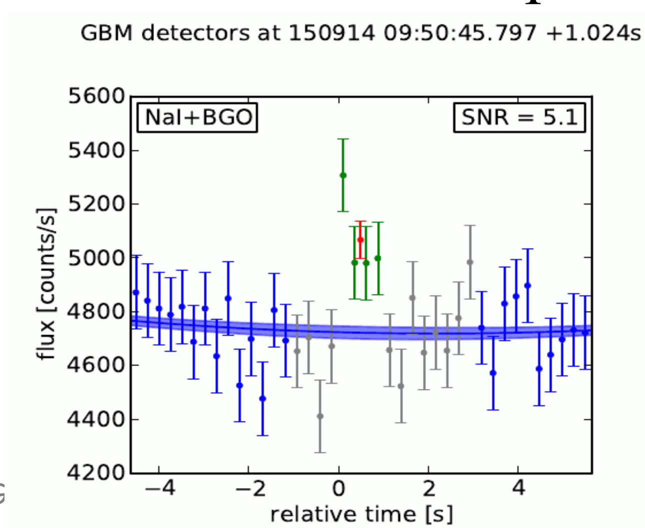


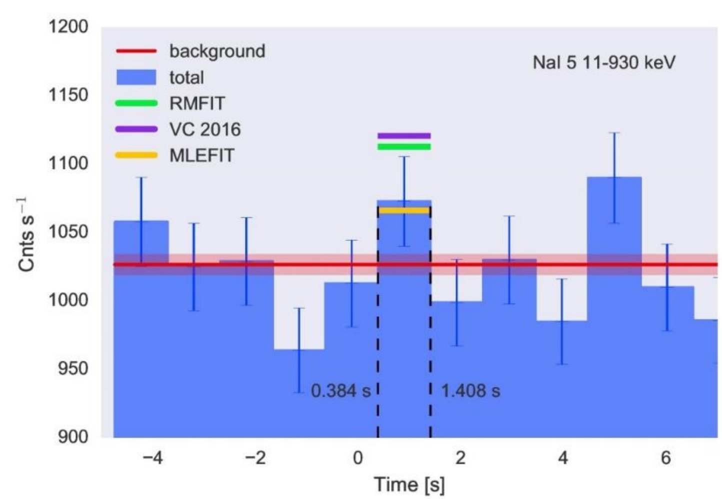


BH-BH and BH-NS merger

- BH-BH mergers
  - O2: None has shown a convincing EM counterpart
    (claim for EM of first merger, GW 150914, disproven)
    this is consistent with many earlier predictions, though 150914 sparked the phantasy of some theoreticians
  - 18+ in O3 seen: none with gamma-ray emission
    (Veres+2019, arXiv:1905.08755 claim to need 40-60 non-detections to accept 150914's γ-ray emission as fluke)
- BH-NS merger: first event observed by aLIGO/Virgo
  case for EM counterpart completely open: keep open-minded

Connaughton+2016





Greiner+2016

Summary

- Many expectations for future: KN, off-axis emission mechanism, BH-NS merger, likely also unexpected surprises
  - GRB Pessimistic view: GW 170817 was unique event; no NS-NS merger(s) with γ-ray emission in O3
  - GRB Optimistic view: off-axis emission and 100x more frequent NS-NS binaries are the rule, then handful of new NS-NS mergers with γ-rays in O3 (2019)
- Prompt GRB emission mechanism is synchrotron
- γ-emission of 170817 cannot have been synchrotron
- Interesting promises for gamma-ray polarization measurements