Gamma-Ray Bursts & Extreme Electrodynamics

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Simons Collaboration on Extreme Electrodynamics of Compact Sources

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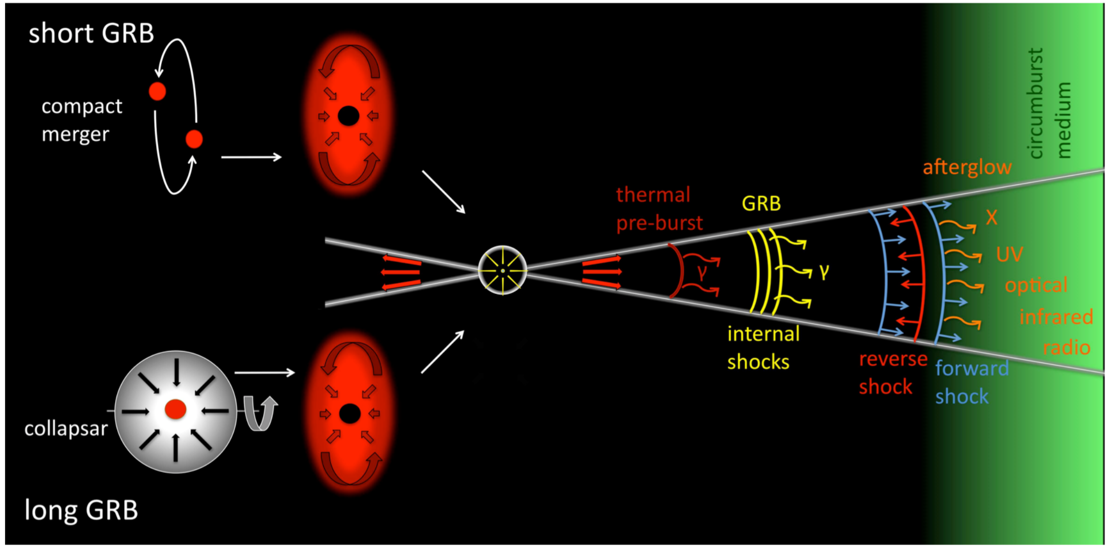
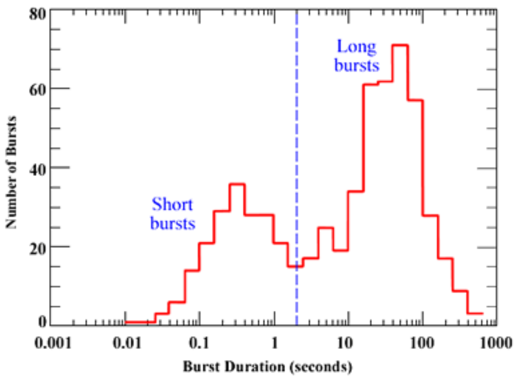
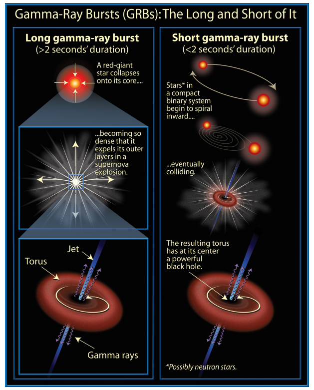
GRB Theoretical Framework:



- **Progenitors**:
  - ❖ **Long**: massive stars
  - ❖ **Short**: binary mergers (NS-NS, BH-NS?)
- **Acceleration**: fireball or magnetic?
- **Prompt γ-rays**: **dissipation – internal shocks or magnetic reconnection?** Emission mechanism?
- **Deceleration**: the outflow decelerates (by a reverse shock for $\sigma \lesssim 1$) as it sweeps-up the external medium
- **Afterglow**: from the long lived forward shock going into the external medium; as the shock decelerates the typical frequency decreases: X-ray → optical → radio

Progenitors: Long GRBs (LGRBs) vs Short GRBs (SGRBs)

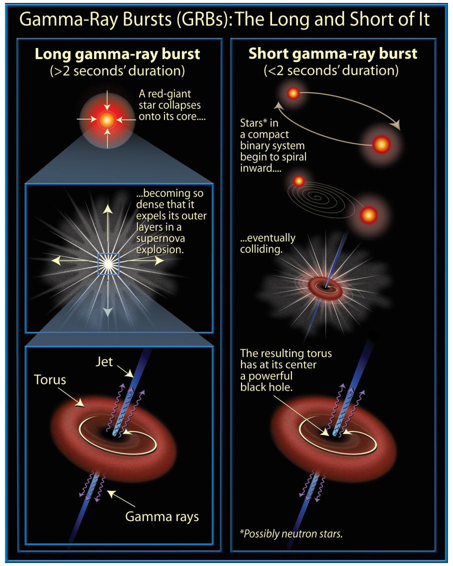




- **Massive stars**: host galaxy type & SFR, location within the host, SN associations
- Some spectroscopic associations to SNe Ic ⇒ core collapse of massive stars stripped of their hydrogen & helium ⇒ BH or NS formation
- Some Open Questions: role of progenitor's rotation, mass, metallicity, binarity; LGRBs without bright SN; local low-luminosity LGRBs; XRFs
- **Binary mergers** (NS-NS, NS-BH**?**): small SFR in hosts, large offsets, no SN associations, one "smoking gun" (GRB170817A/GW170817)
- Some Open Questions: extended emission (soft tails), late flares, collimation (true energy + event rate), long SGRBs, subclasses (e.g. GFs)?

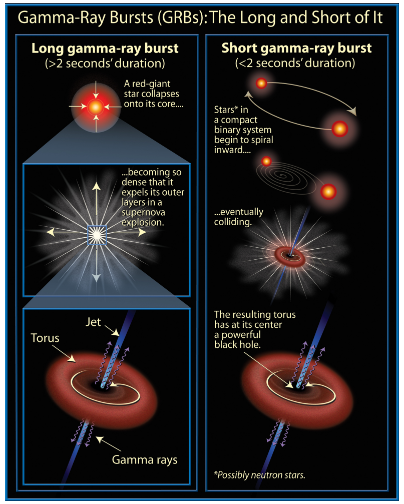
Central Engine: Long GRBs (LGRBs)

- **Accreting BH**: $T_{GRB} \sim t_{ff}(\text{core})$; fast rotation needed to form an accretion disk
  - Jet launching: magnetic (Blandford-Znajek?), neutrino annihilation?
  - Collimation: by the cocoon formed as jet propagates in progenitor's envelope
  - Can provide $\lesssim 10^{54}(M_{acc}/5.6\,M_{\odot})(\varepsilon/0.1)$ erg (ε = efficiency; enough for GRB jet + SN)
- **Millisecond Magnetar**: if $t_{sd} \sim T_{GRB} \Rightarrow B \sim 10^{15.5}$ G (if $t_{sd} \sim T_{plateau}$, what powers GRB?)
  - Powered by the NS rotational energy $\Rightarrow E \lesssim 10^{51.5}(\varepsilon/0.1)$ erg (might not be enough to power very energetic GRB + SN)
  - Jet launching: pulsar-type relativistic MHD wind (high-σ needed)
  - Collimation: similar to BH case

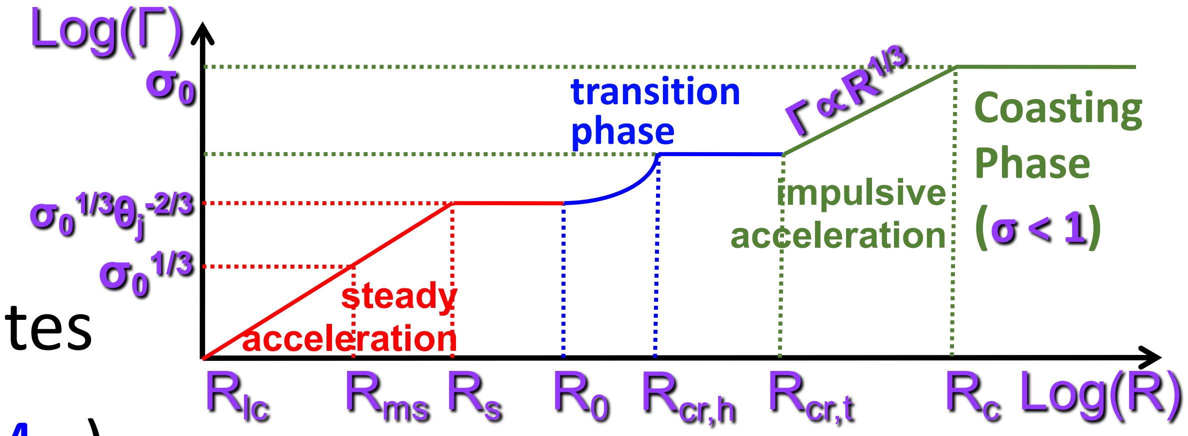


Central Engine: Short GRBs (SGRBs)

- **Accreting BH**: $T_{GRB} \sim t_{visc}$?; variability from disk/propagation instabilities?
  - ❖ Jet launching: magnetic (Blandford-Znajek?), neutrino annihilation?
  - ❖ Collimation: disc wind? cocoon form propagation in merger ejecta?
  - ❖ What powers extended emission or late flares? Late-time fallback?
- **Millisecond Magnetar**: if $t_{sd} \sim T_{GRB} \Rightarrow B_{dip} \sim 10^{16.5}$ G (for dipole spindown)
  - ❖ Strong neutrino-driven wind up to ~10-30 s $\Rightarrow$ may reduce the required B_{dip} but leads to low-$\sigma \Rightarrow$ sub-relativistic outflow
  - ❖ Perhaps a short-lived HMNS $\Rightarrow$ collapses to a BH $\Rightarrow$ accreting BH powers SGRB

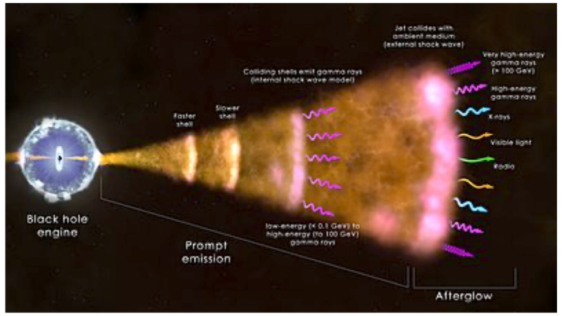


Outflow Acceleration & Composition:

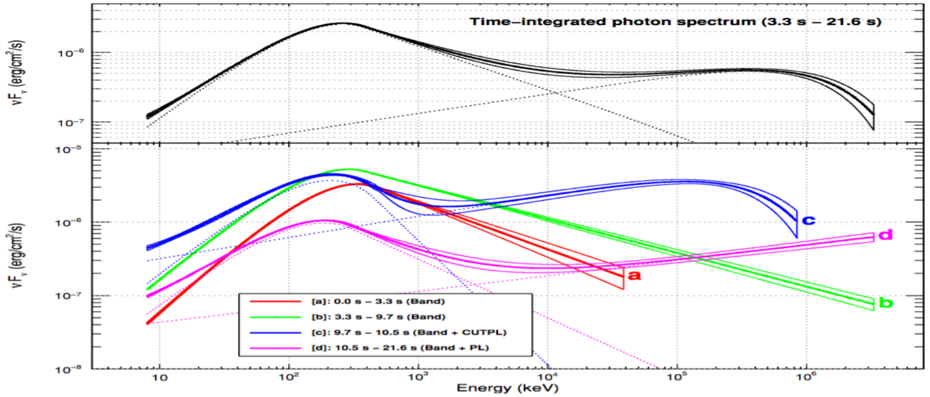


- **Fireball**: thermal (P_{rad}) acceleration
  - ❖ Fast ($\Gamma \propto R$), robust, internal dissipation
  - ❖ Baryon kinetic energy eventually dominates
  - ❖ Requires a small baryon loading ($\sim 10^{-5} M_\odot$)
- **Magnetic acceleration**: Poynting flux dominated jets (high-σ)
  - ❖ Steady, axisymmetric magnetic acc. is slow & not robust or very efficient
  - ❖ Strong time dependence (or reconnecting a stiped wind) can lead to $\sigma < 1$
  - ❖ Much work is still needed on this topic (clearer & more robust predictions)
- **Composition**:
  - ❖ baryons (n-rich?), $e^{\pm}$ pairs, B-field, in different ratios; hard to tell apart

Prompt GRB Dissipation & Emission Mechanism:



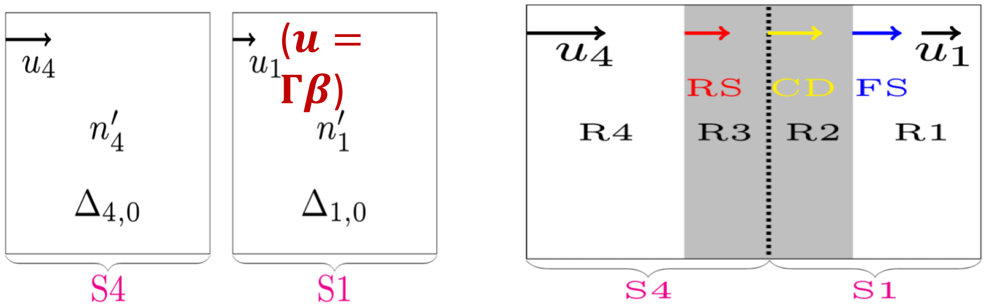
- **Dissipation**: Internal Shocks
  - ❖ Widely explored, may produce variability + some correlations
  - ❖ Limited efficiency, challenged to explain some observations
- **Magnetic Reconnection**: (related ideas: Rel. turbulence / mini-jets / ICMART …)
  - ❖ May potentially reach high radiative efficiency
  - ❖ Not sufficiently worked out yet, so not many testable robust predictions
- **Emission Mechanism**: **?** (leptonic: synchrotron, SSC, Compt., photospheric; hadronic: p-syn, π-decay, $e^{\pm}$ cascades)
- **Some Open Questions**: the dominant dissipation & emission mechanisms, identity of distinct spectral components at high/low energies, …



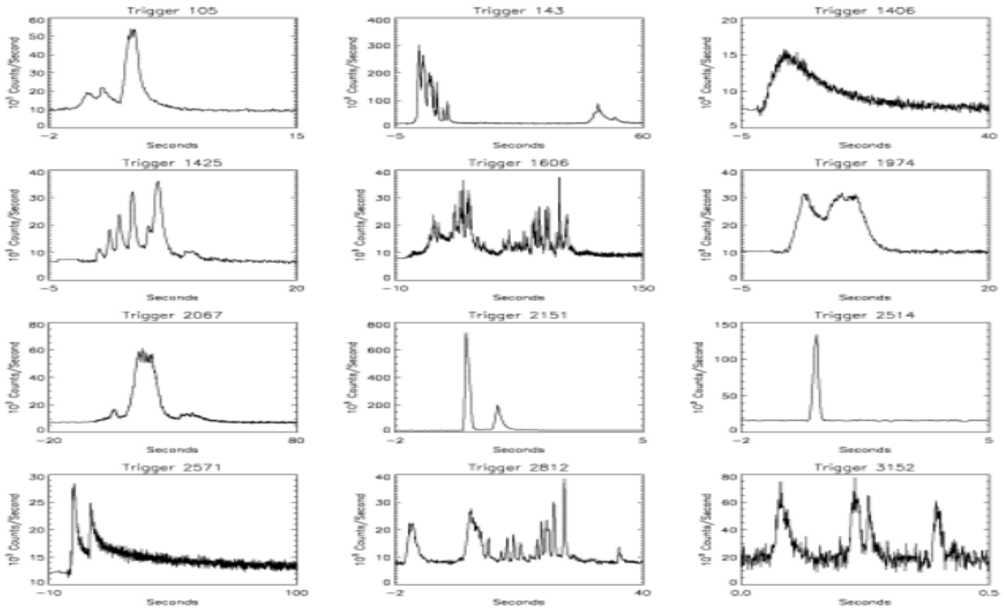
Prompt GRB Emission from Internal Shocks:

(Rahaman, JG & Beniamini 2024a)

Pre-collision **Post collision**

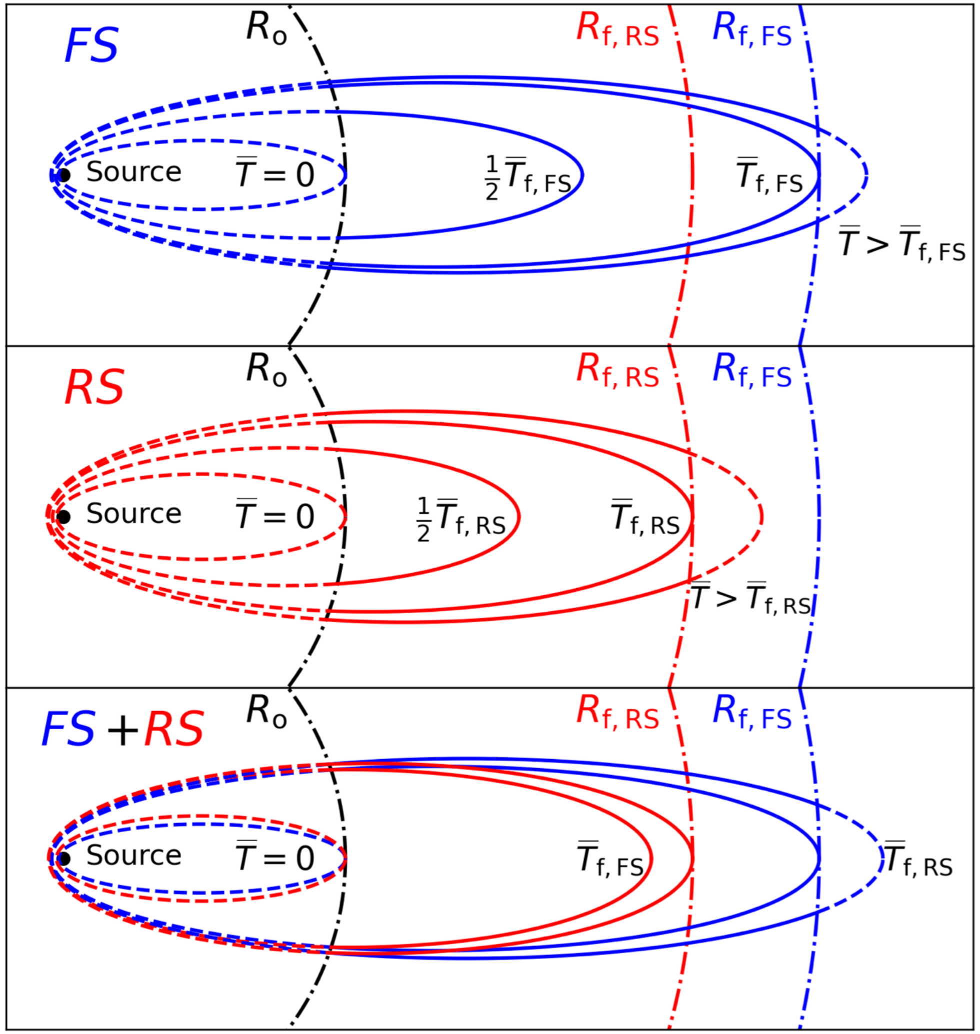


1 collision ⇒ 1 pulse in the lightcurve



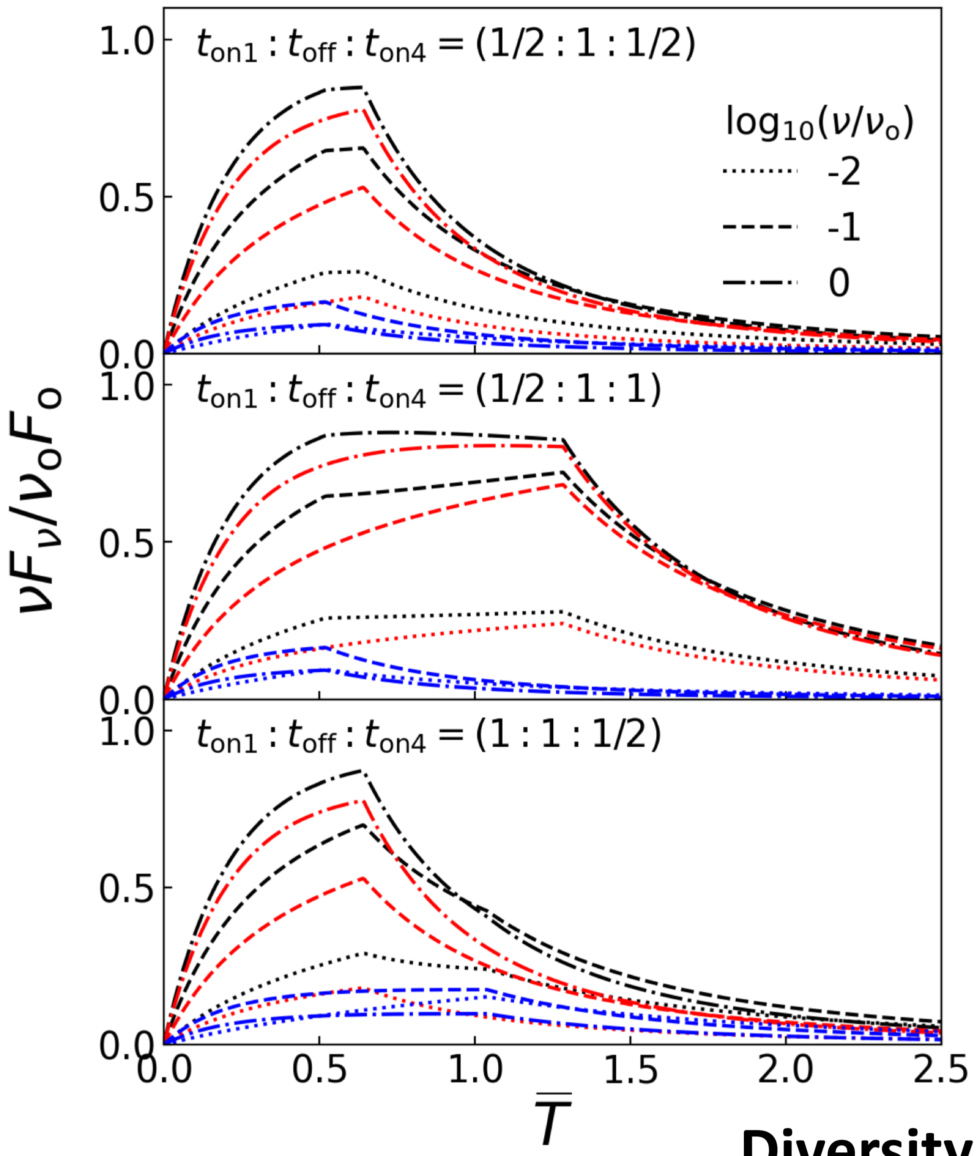
(Credit: J.T. Bonnell (NASA/GSFC))

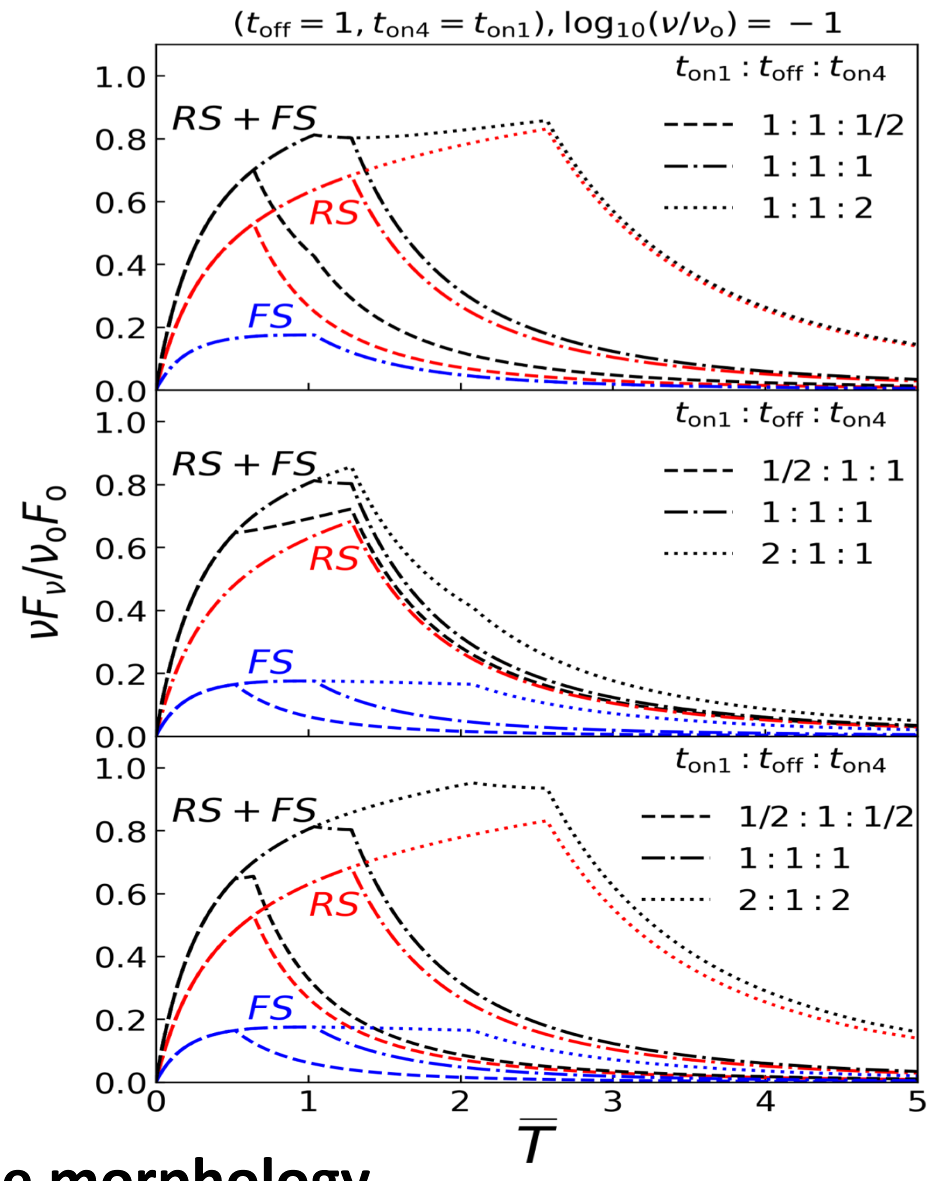
Equal-Arrival-Time Surfaces (EATS)



Contribution of both EATS must be taken at a given observed time.

Lightcurves (single pulse; **Rahaman, JG & Beniamini 2024a**):

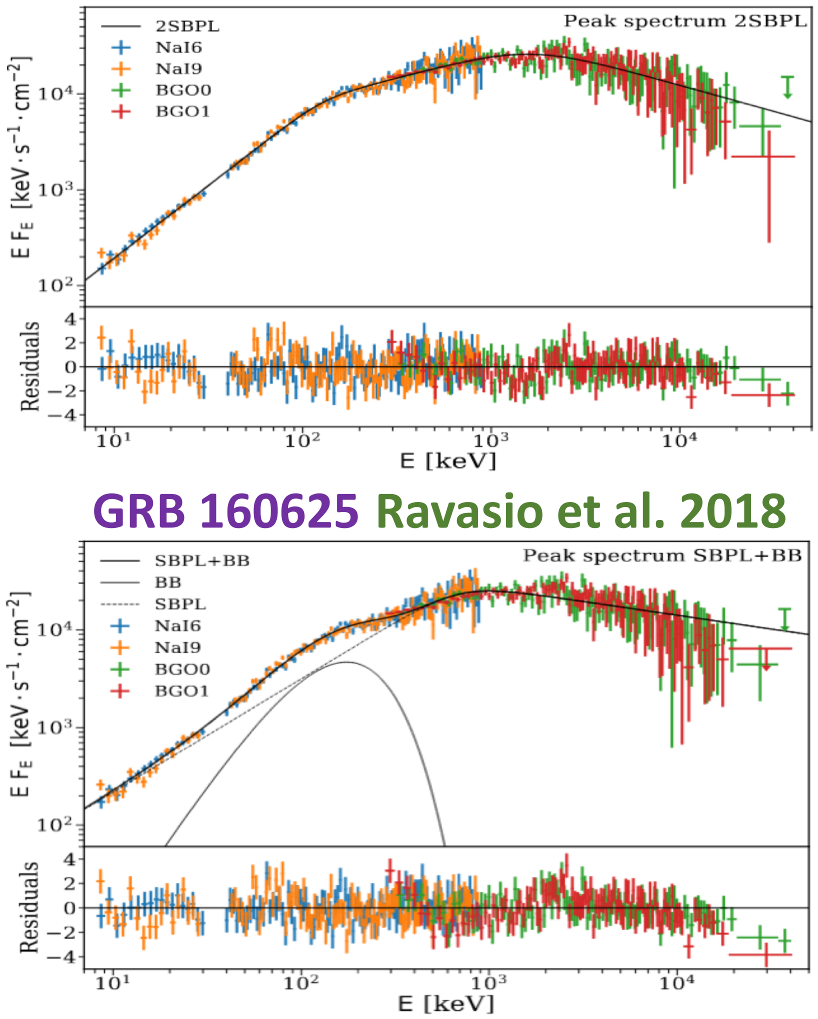




Diversity in pulse morphology

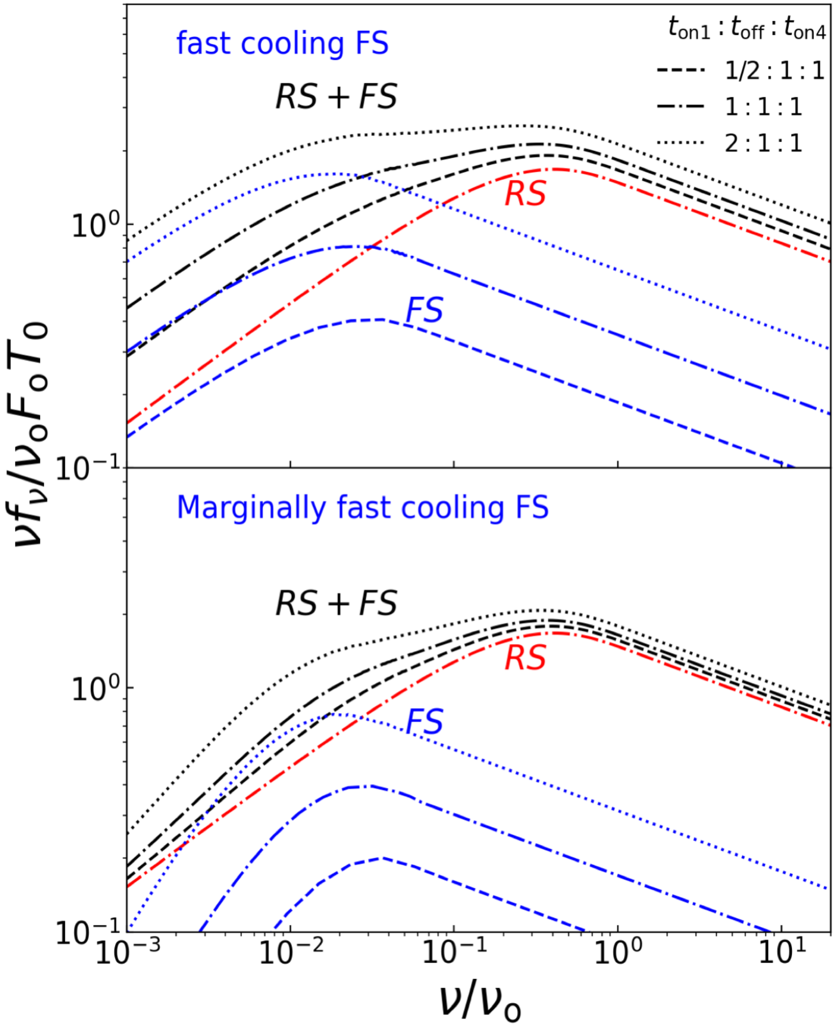
Spectra (Rahaman, JG & Beniamini 2024a):

Example of Observations

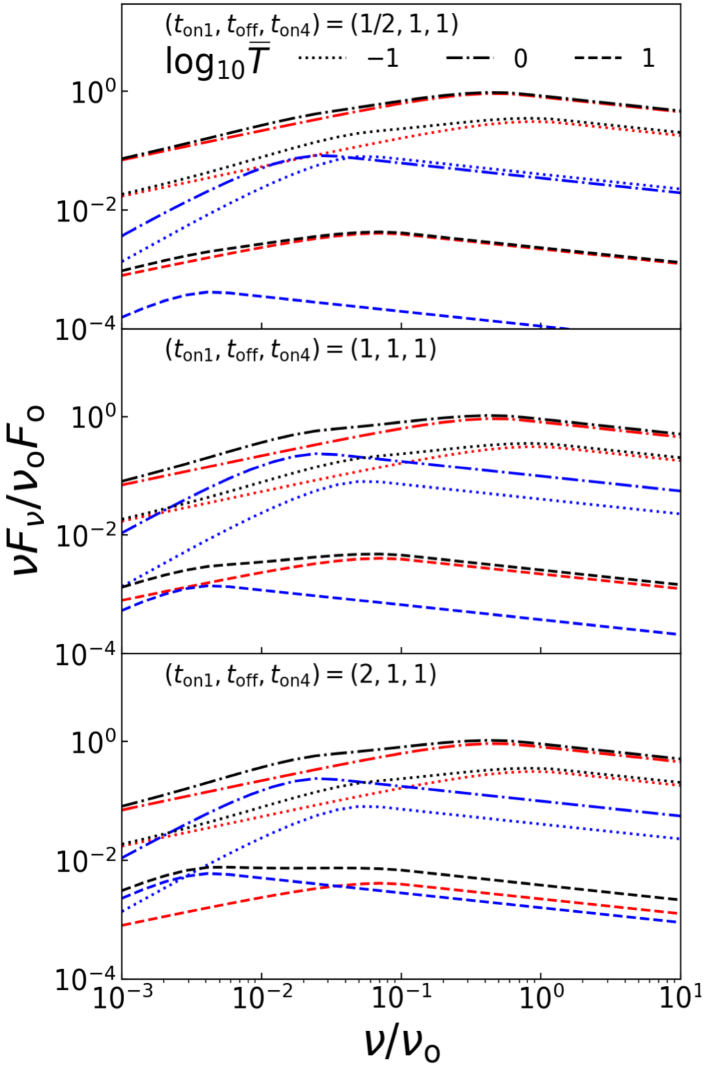


GRB 160625 Ravasio et al. 2018

Time-Integrated

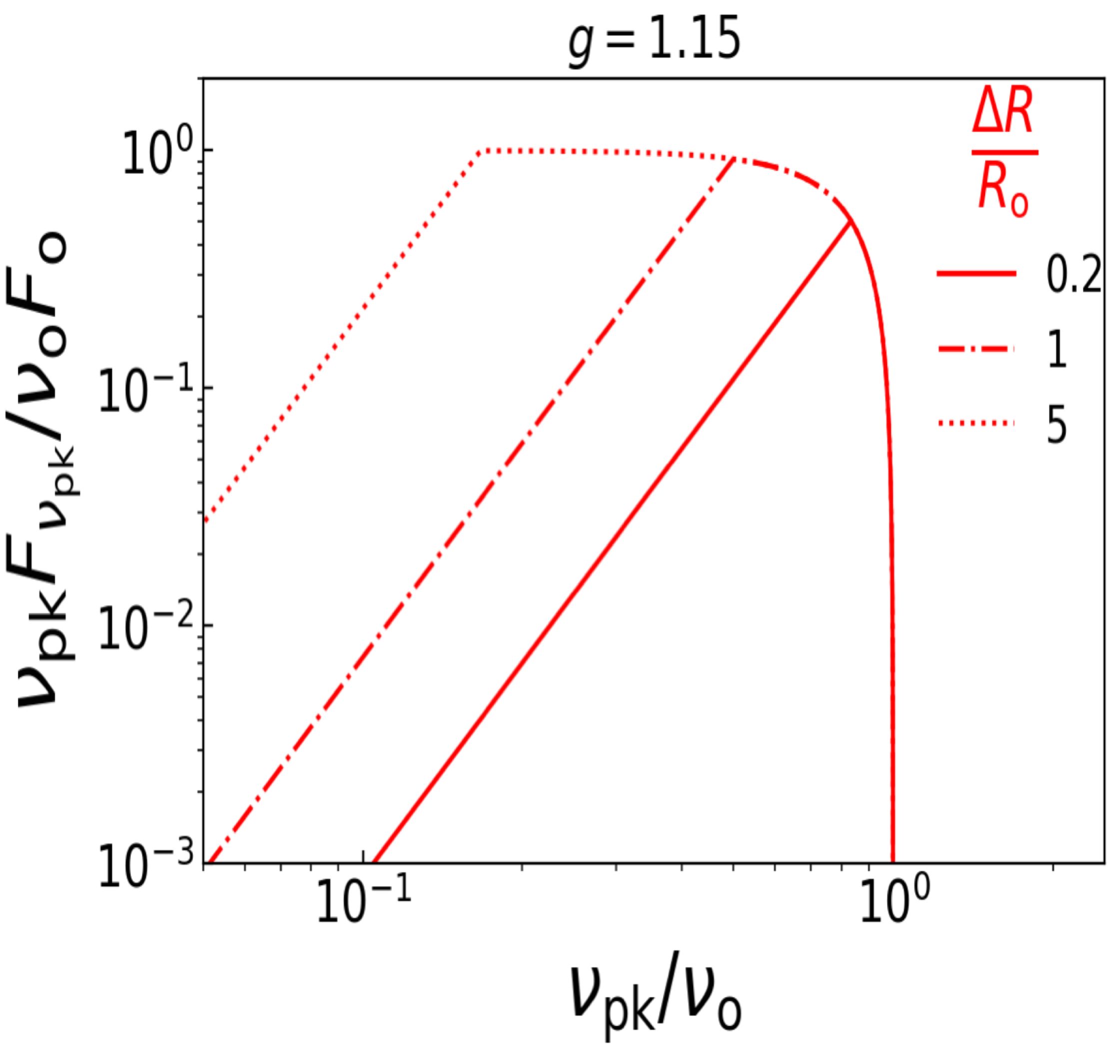


Time-resolved

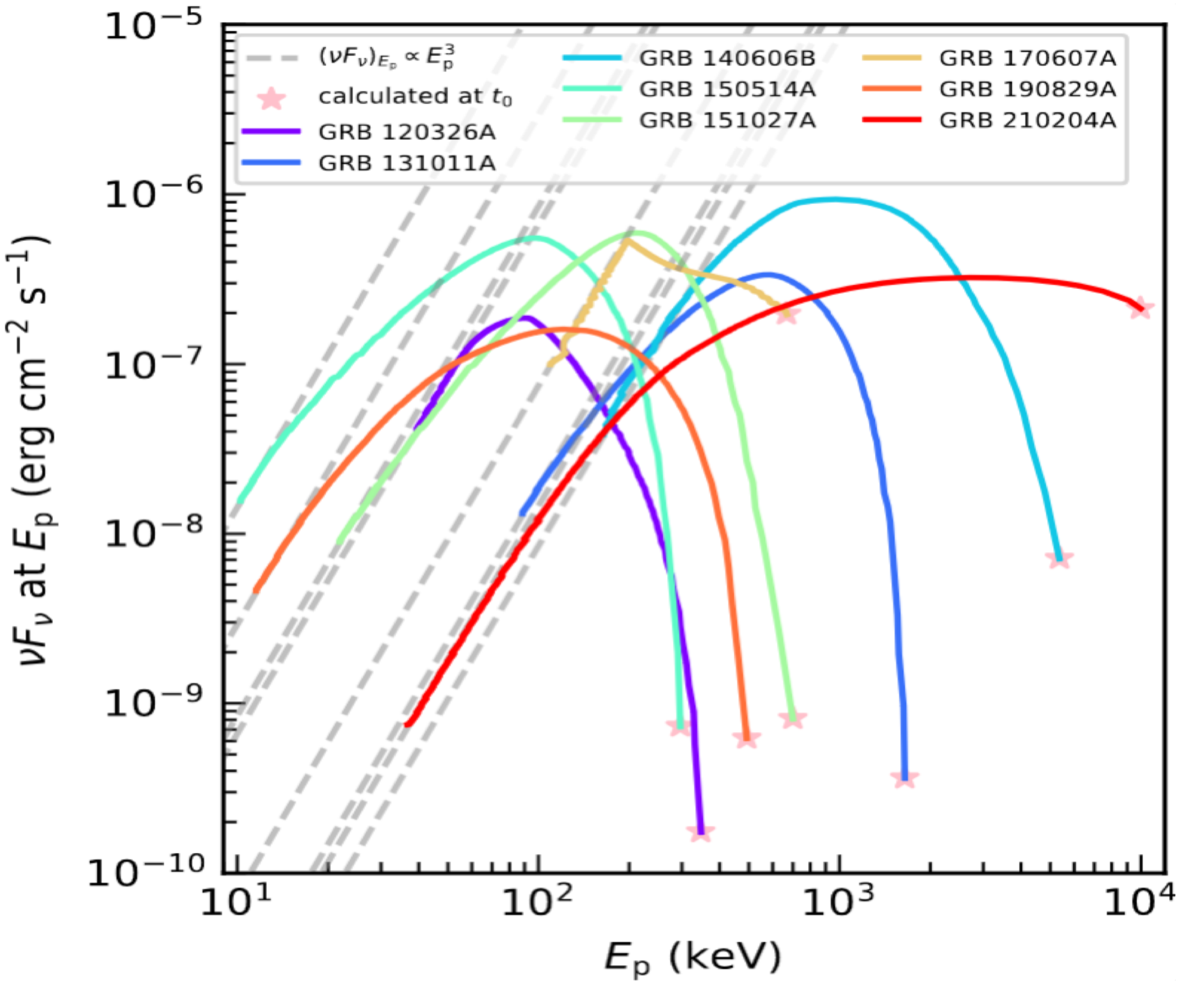


The weaker FS emission may mimic a "photospheric" quasi-thermal component or a low-E_{ph} spectral break – features that have been inferred in an increasing number of GRBs

Relating $F_\nu(t)$ to the colliding shells properties:

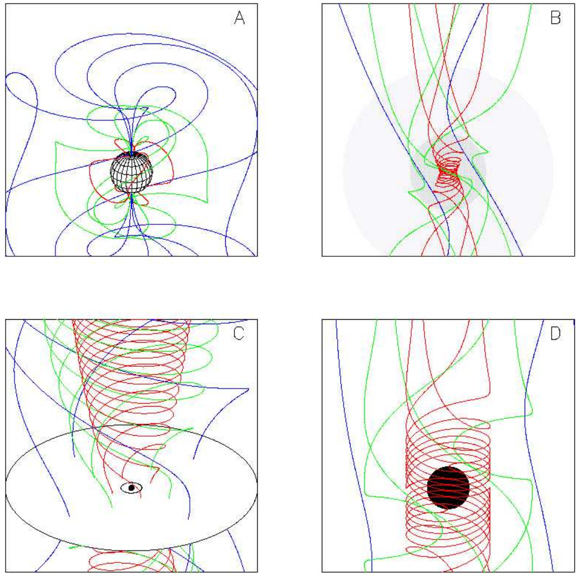


(Rahaman, JG & Beniamini 2024a)



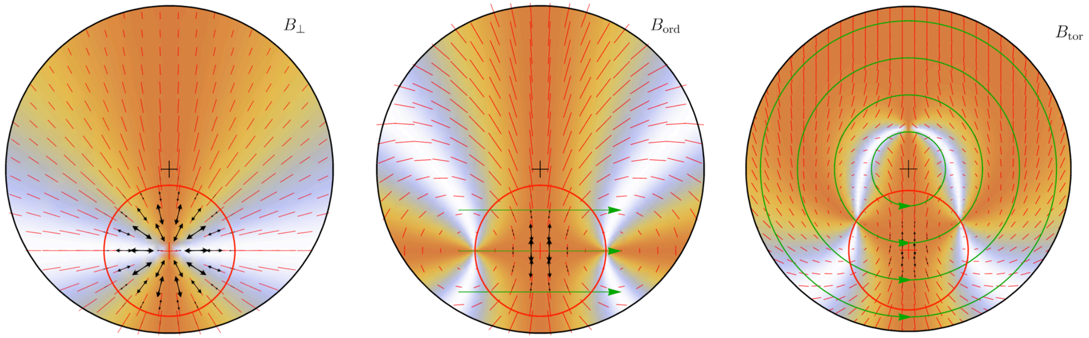
(Yan et al. 2023)

Magnetic Fields Play Many Key Roles in GRBs:



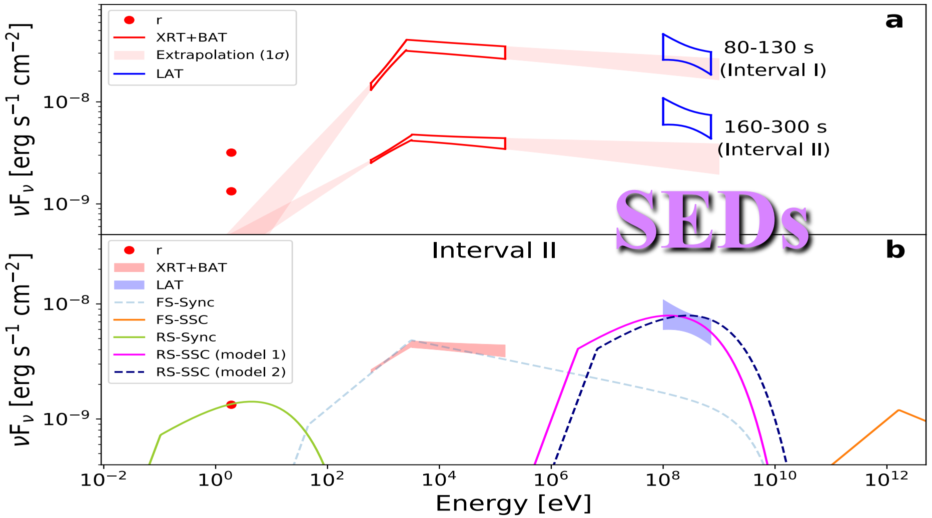
- **Accretion:** instabilities (e.g. MRI), angular momentum transport, stop accretion (MAD),…
- **Jet/wind launching**: Blandford-Znajek/Payne,…
- **Acceleration**: steady state collimation induced, stripped wind + reconnection, time-variability
- **Jet dynamics**: inside a star ($t_{breakout}$, stability, dissipation, mixing / mass loading)
- **Prompt GRB emission**: Affects dissipation (reconnection vs shocks), emission
- **Particle acceleration** in all of the emission regions
- **Polarization**: prompt GRB, reverse shock, afterglow

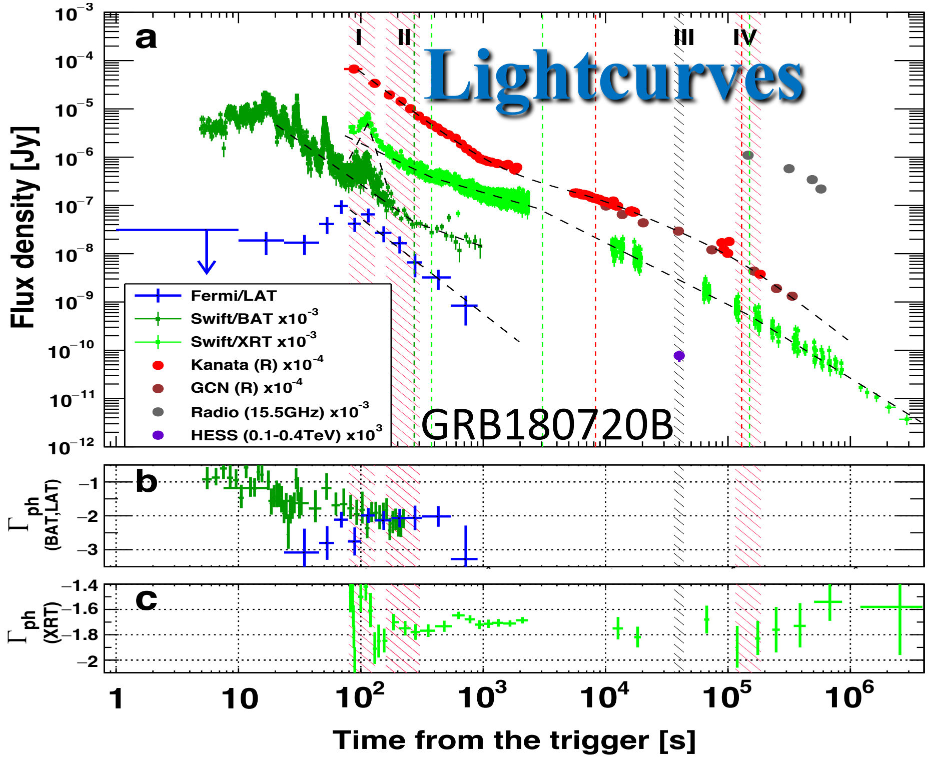
GRB Polarization probes the B-field & Jet structures:



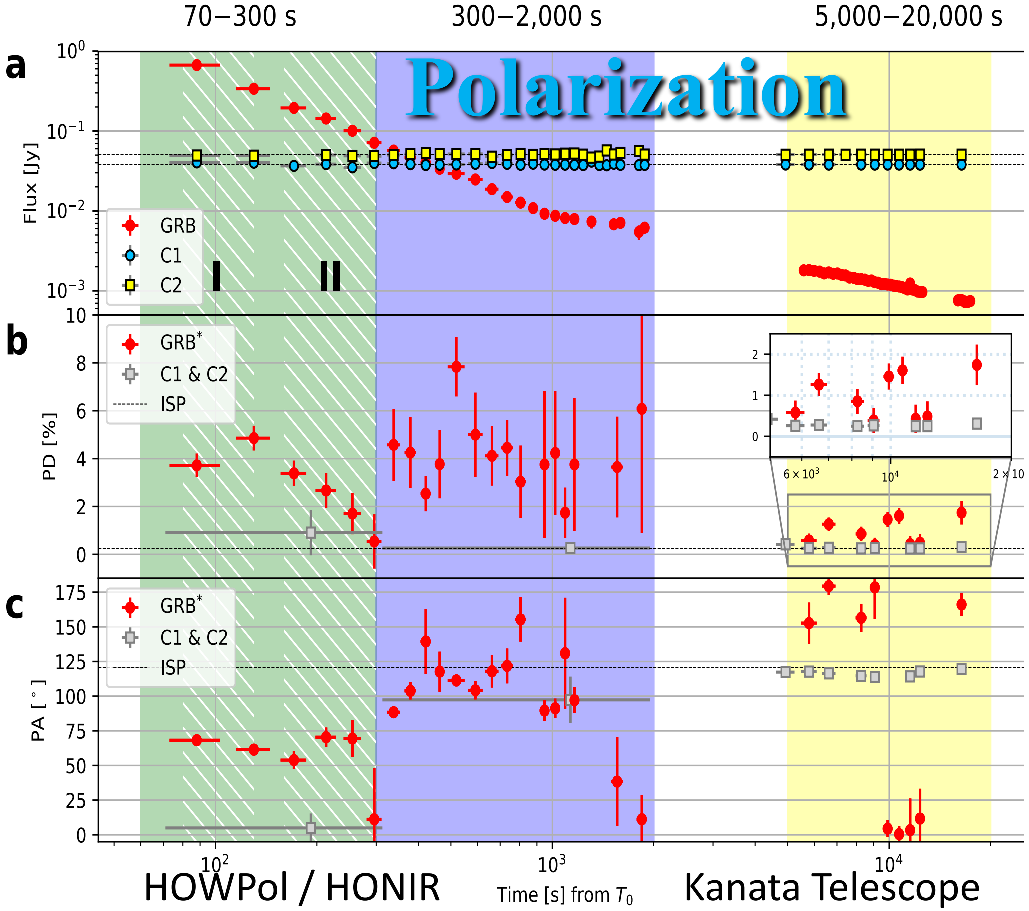
- **Prompt GRB**: hard X-ray – soft $\boldsymbol{\gamma}$-ray
  ⇒ hard to measure ⇒ no clear detections
- **Reverse Shock**: also probes original ejecta, but in optical to radio ⇒ detections
  - ❖ Probes B-field structure & turbulence in the ejecta near the deceleration epoch
  - ❖ $P_{8.5\rm GHz}$(1 day) < 7% ⇒ rules out ordered B-field (of coherence length $\theta_B \gtrsim 1/\Gamma$) or toroidal B-field + $dE/d\Omega \propto \theta^{-2}$ structured jet, allowing $\theta_B \lesssim 10^{-2}$patches (JG & Taylor 2005)
  - ❖ ALMA detected reverse shock polarization @97.5 GHz: P ≈ 0.9 ➜ 0.6%, Δθp ≈ 54° (2.2 ➜ 5.2 hr); 1st GRB radio pol. ⇒ favors patches with $\theta_B{\sim}10^{-3}$ (Laskar et al. 2019)
- **Afterglow**: optical & radio – probes jet angular structure & B-field structure in collisionless relativistic shocks

Reverse + Forward Shock Polarization: (Arimoto et al. 2023)



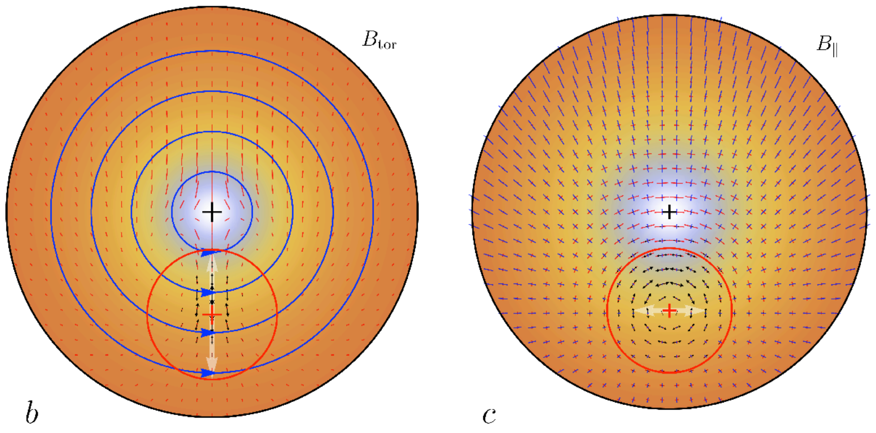


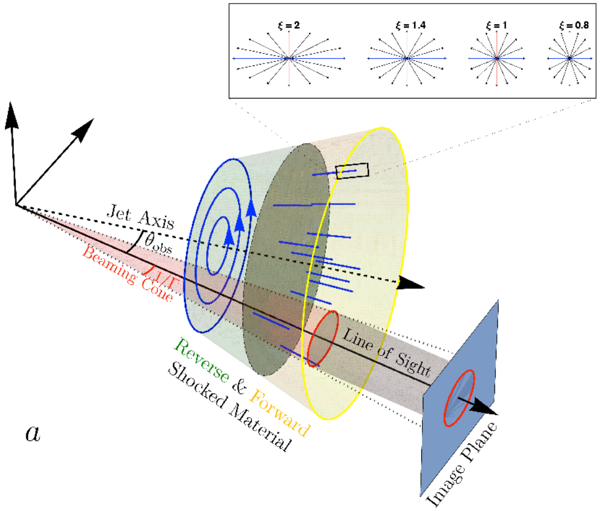
- < 300 s: RS; P: 5 → 1%, θp ≈ 70°
- 0.3-2 ks: P ~ 2-8%, θ_p varies
- 5-20 ks: FS; P ~ 0.5-2%, θ_p ≈ 160°
- RS → FS dominance @ ~10^3 s



Reverse + Forward Shock Polarization: (Arimoto et al. 2023)

- < 300 s: ejecta; B_{tor} + turbulence
- 0.3-2 ks: turbulence-induced P
- 5-20 ks: CSM; radial stretching





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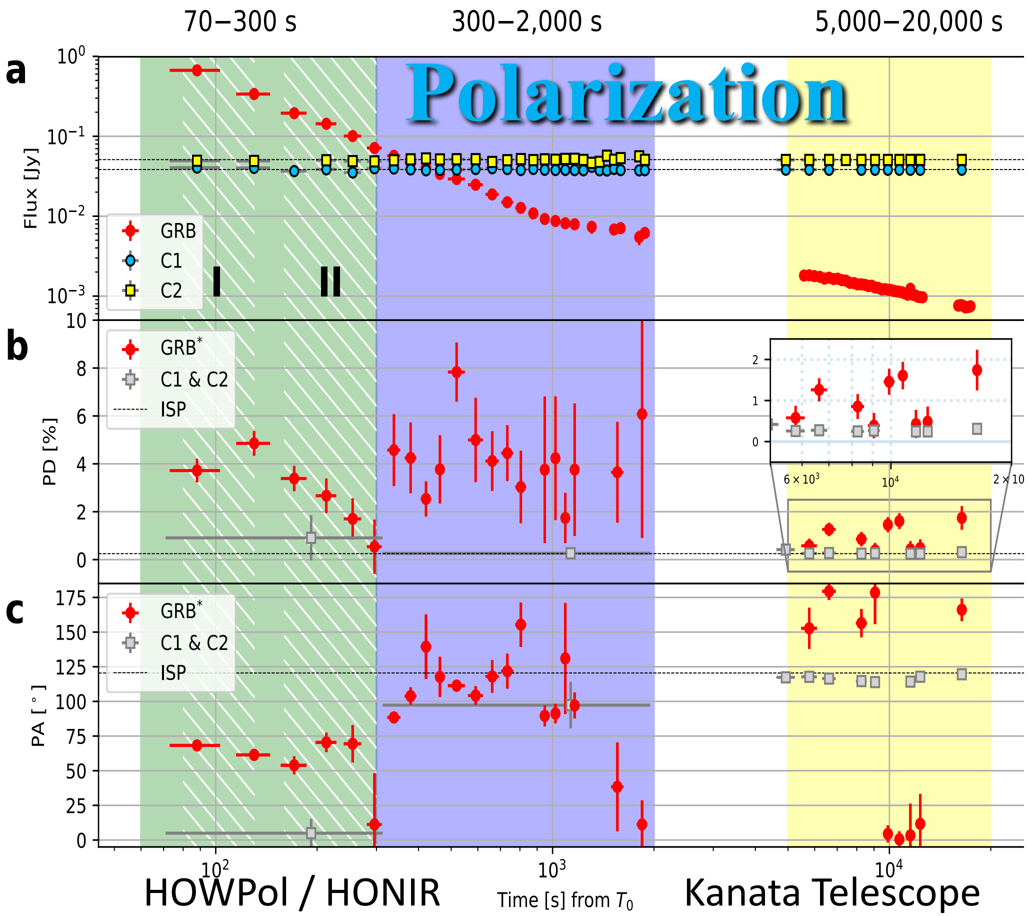
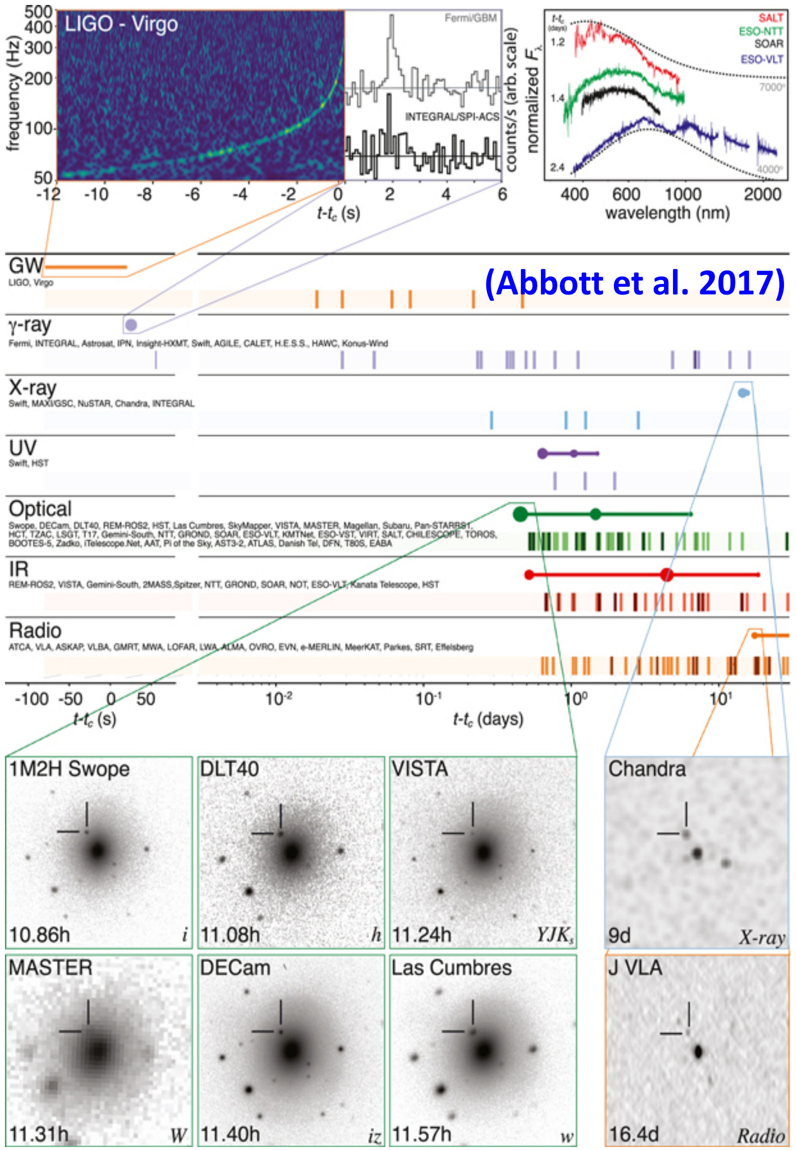


GRBs & Multi-Messenger Astronomy:

- **Gravitational Waves**: SGRBs (GRB170817A/GW170817)
  - ❖ GW chirp signal (**NS-NS merger**) + SGRB + kilonova + afterglow
  - ❖ Other emission components also possible (initial fast dynamical ejecta, late emission from tidal tails afterglow, extended emission,…)
- **Neutrinos & Cosmic Rays**: no detections – increasingly stronger upper limits
  - ❖ Neutrino emission from prompt GRB $\lesssim 10^{-2} \times$ the most optimistic predictions
  - ❖ GRBs disfavored as the source of UHECRs

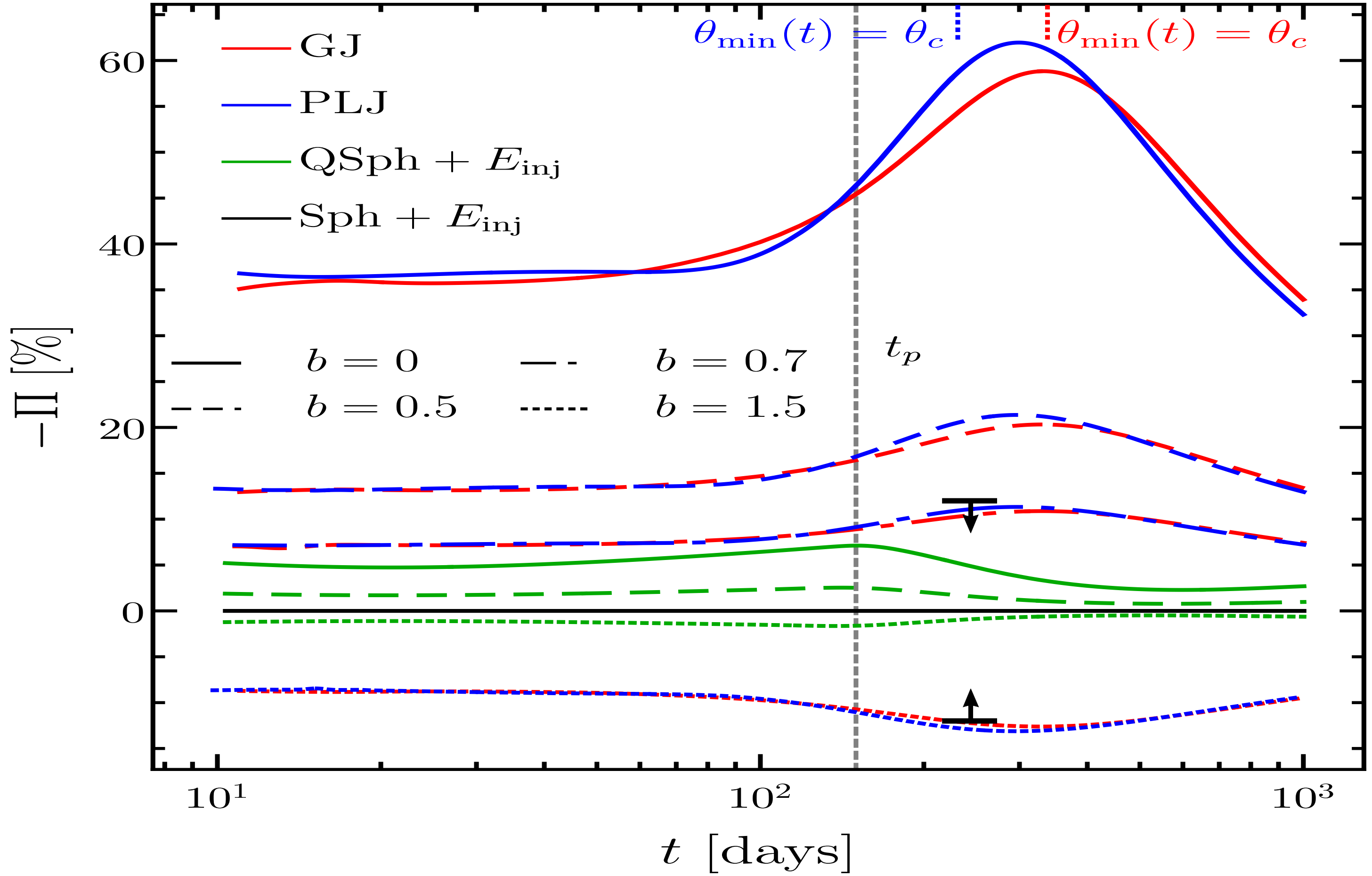


GW 170817 / GRB 170817A: D ≈ 40 Mpc:

- 1^{st} **GW detection** of **NS-NS** merger; 1^{st} electromagnetic counterpart to GW signal
  - S**GRB**170817A (very low-luminosity), 1.74 s γ-GW delay; ⇒ $\left|\frac{v_{GW}}{c} - 1\right| \lesssim 4 \cdot 10^{-16}$
  - 1^{st} clear-cut **kilonova** (IR to UV, few weeks) ⇒ NS-NS mergers may dominate the r-process nucleosynthesis; X-ray to radio **afterglow** (up to hundreds of days)
- **1^{st}** direct **association** of a SGRB & NS-NS merger
- **Remnant**: BH – either direct collapse or 1^{st} short-lived ($\lesssim$ 1 s) HMNS
- **Kilonova**: 2 components needed – blue/fast, lanthanide-poor $M_{ej}/M_{\odot} \sim$ 1–2%, $v_{ej} \sim$ 0.2–0.3c & red/slow, lanthanide-rich $M_{ej}/M_{\odot} \sim$ 3–5%, $v_{ej} \sim$ 0.05–0.2c
- **Afterglow**: structured jet with sharp edges (Gaussian or $\frac{dE}{d\Omega} \propto \theta^{-a}$ & a ≈ 4 – 5) viewed from well outside of its core ($\theta_{\rm obs}/\theta_c \sim 3-5$; $\theta_{\rm obs} \sim 15° - 25°$)

GRB 170817A: polarization UL ⇒ post-shock B-field

- Jet angular structure & $\theta_{\rm obs}$ well constrained ⇒ breaks degeneracies
- Assuming a shock-produce B-field with $b \equiv 2\langle B_\parallel^2\rangle/\langle B_\perp^2\rangle$ (JG & königl 03; Gill & JG 18)



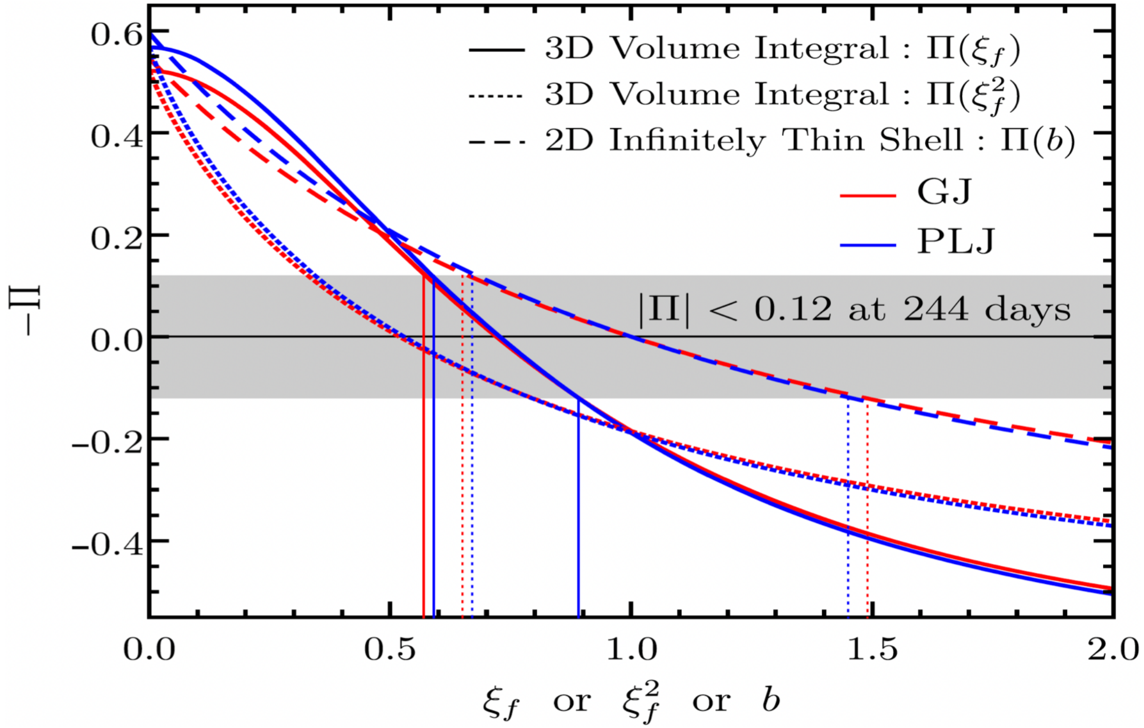
$0.7 \lesssim$ b $\lesssim 1.5$ for jet models

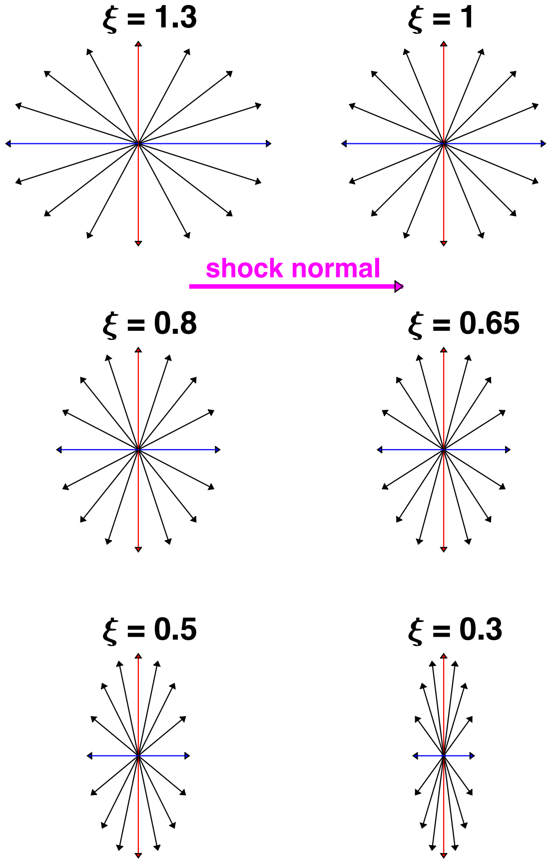
New: upper limit $P_{\rm lin} < 12\%$ @ ν = 2.8 GHz, t = 244 days (Corsi + 2018)

GRB 170817A: polarization UL ⇒ post-shock B-field

More realistic assumptions ⇒ B-field in collisionless shocks: (Gill & JG 2019)

- 2D emitting shell → 3D emitting volume (local BM76 radial profile)
- B-field evolution by faster radial expansion: $L'_r / L'_{\theta,\phi} \propto \chi^{(7-2k)/(8-2k)}$
- B-field isotropic in 3D with $B'_r \rightarrow \xi B'_r$ (Sari 1999); $\xi = \xi_0 \chi^{(7-2k)/(8-2k)}$

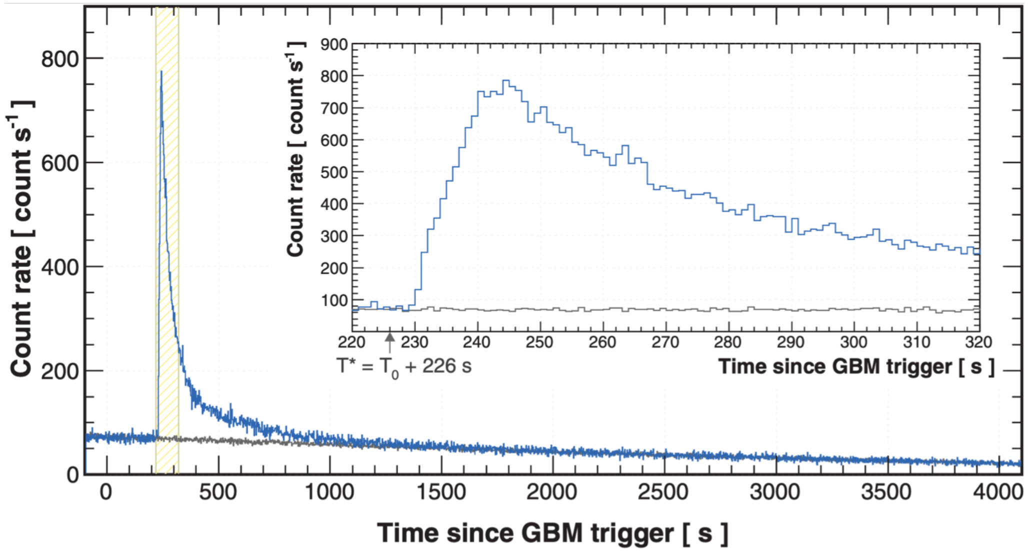


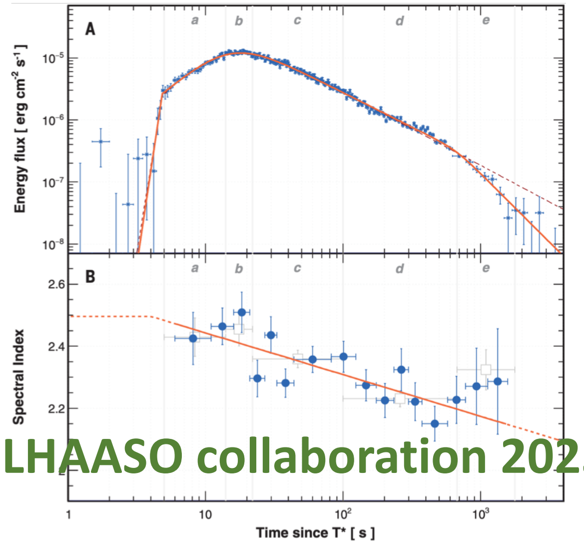


$0.57 \lesssim \xi_f \lesssim 0.89$

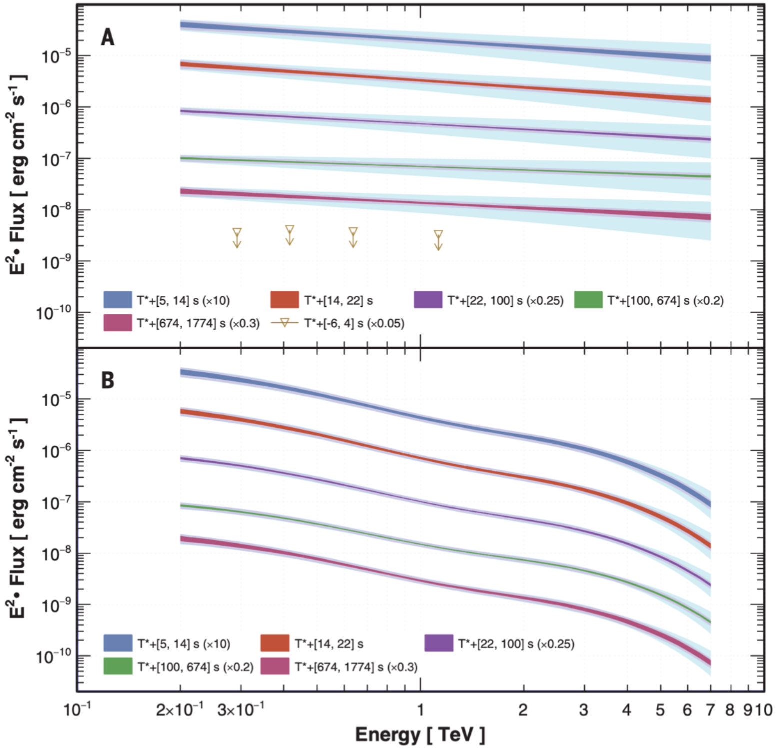
GW 221009A: $z = 0.151$ ($D_L \approx 720$ Mpc); $E_{\gamma,iso} \approx 1.2\times10^{55}$ erg

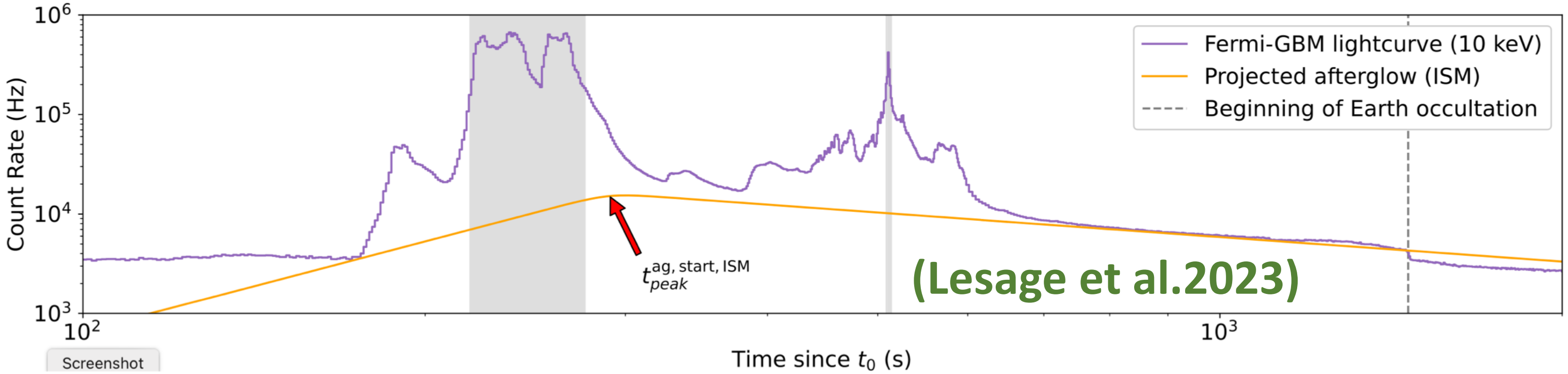
- Huge gamma-ray energy output, long GRB (≈ 600 s), $E_{kin} \gtrsim 10^{52.5}$ erg
- Strong TeV emission (LHAASO); saturated in MeV-GeV





(LHAASO collaboration 2023)





(Lesage et al.2023)

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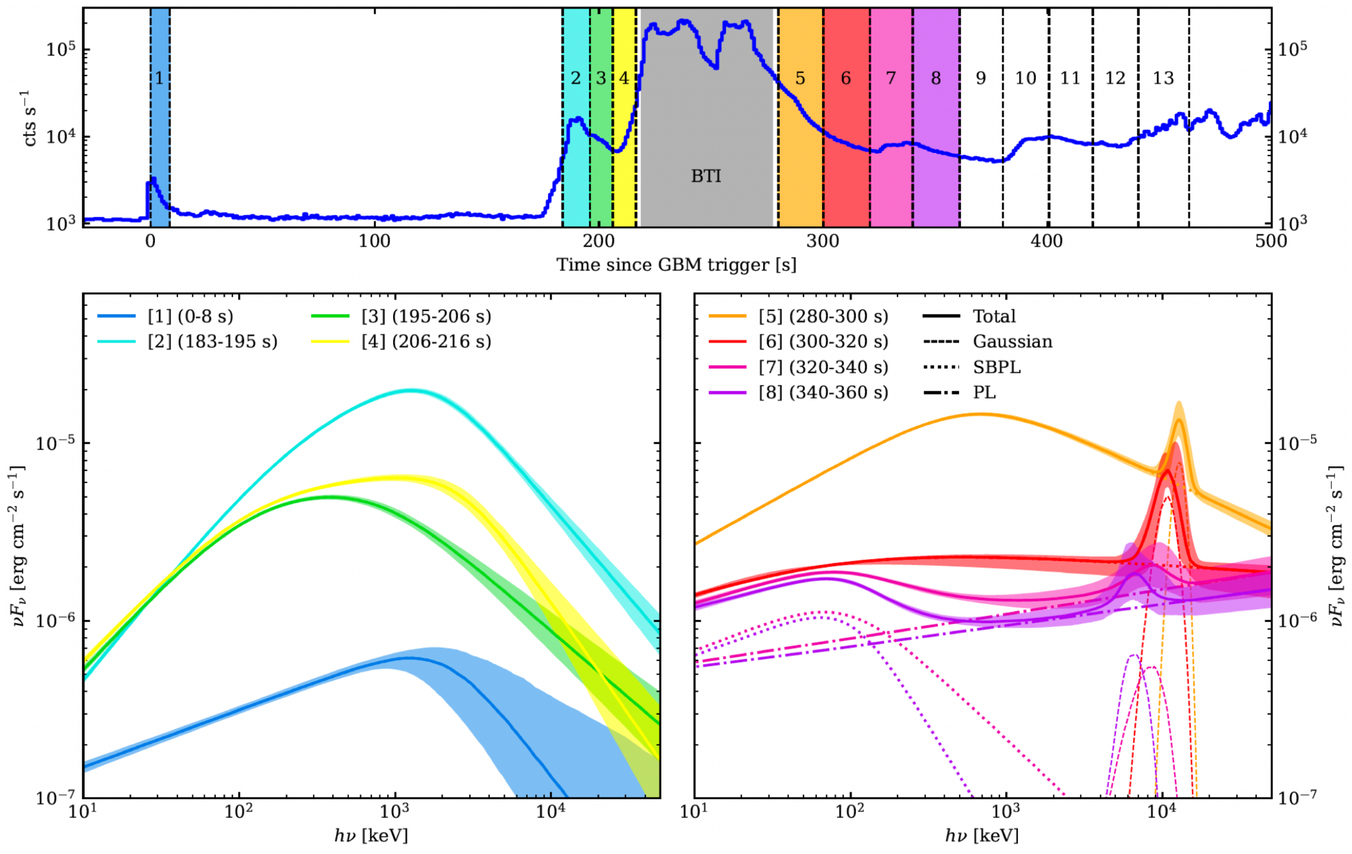
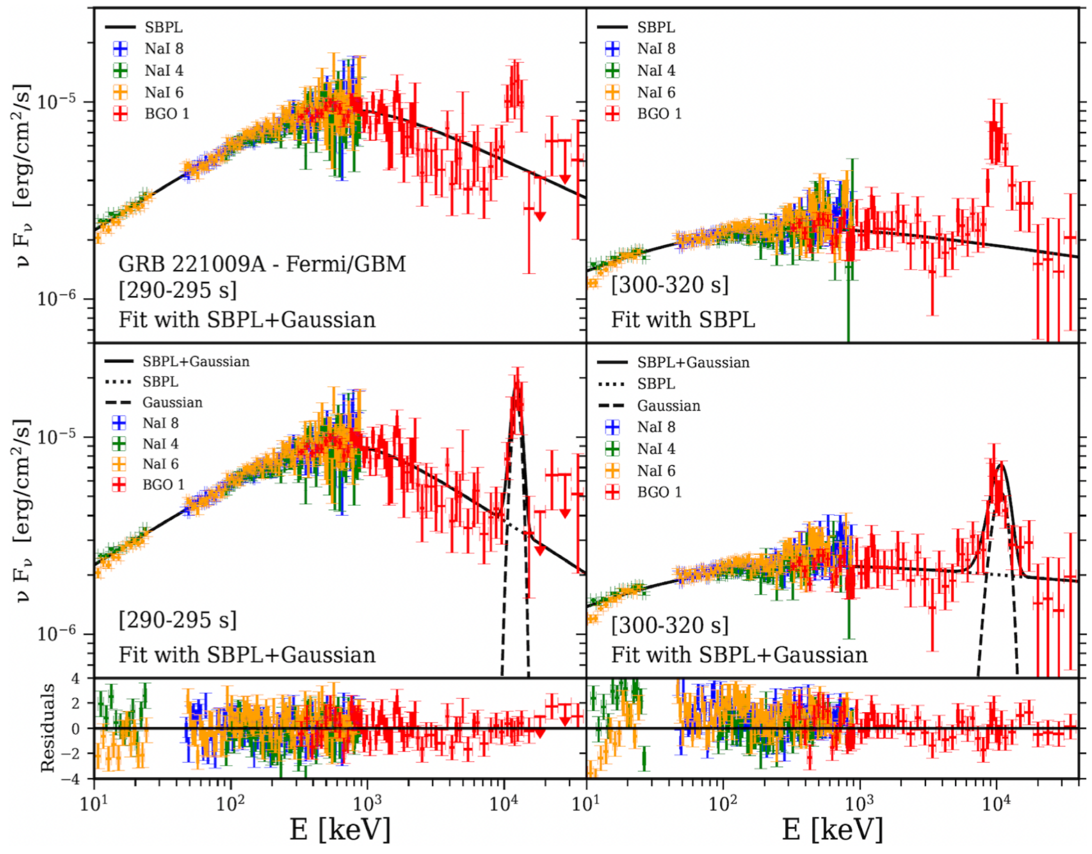
- Huge gamma-ray energy output, long GRB (≈ 600 s), $E_{kin} \gtrsim 10^{52.5}$ erg
- Spectral line feature (Ravasio et al. 2023): E_{ph}:12 → 6 MeV (290 → 320 s)





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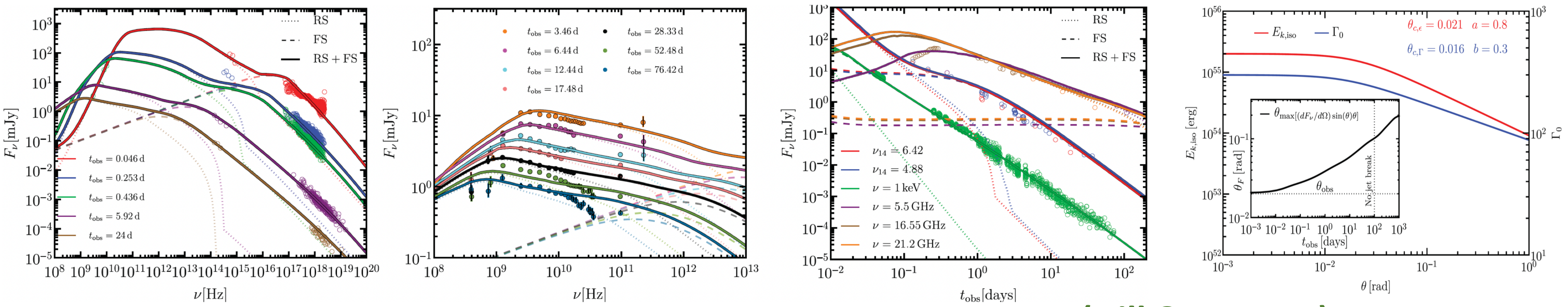
- Huge gamma-ray energy output, long GRB (≈ 600 s), $E_{\mathrm{kin}} \gtrsim 10^{52.5}$ erg
- Shallow Jet angular structure: $\frac{dE}{d\Omega} \propto \theta^{-0.8}$ $\quad \theta > \theta_c \approx 0.02, \quad \theta_{\mathrm{obs}} \sim \theta_c$



(Gill & JG 2023)

GRB Puzzles: possible topics for discussion

- The origin of **X-ray plateaus** (E-injection I/II, structured jet, microphysics evolution,…)
- **"long" SGRBs** (long prompt GRB durations with binary merger origin)
- SGRB **extended emission**
- Recent **polarization** measurements in GRBs
- The **origin of late-time flares** in LGRBs & SGRBs
- Testing **shock acceleration** with **afterglow** observations ($E_{syn,max}$ violating, onset of afterglow / evolution of microphysics parameters, NR transition & deep Newtonian regime)

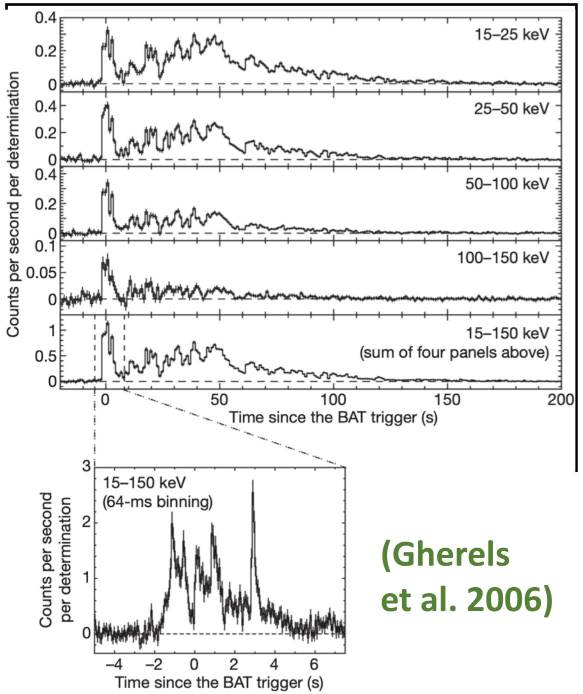


Figure 1 | The light curve of GRB 060614 as observed with the BAT. The

(Gherels et al. 2006)

The End