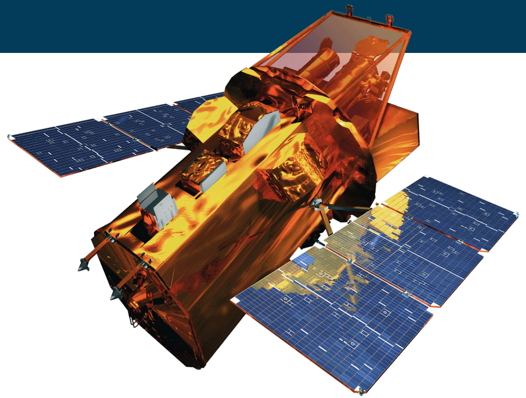
Optical darkness in short-duration γ-ray bursts



Caden Gobat

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Images: NASA GSFC; NSF

Gamma-ray bursts (GRBs): an overview

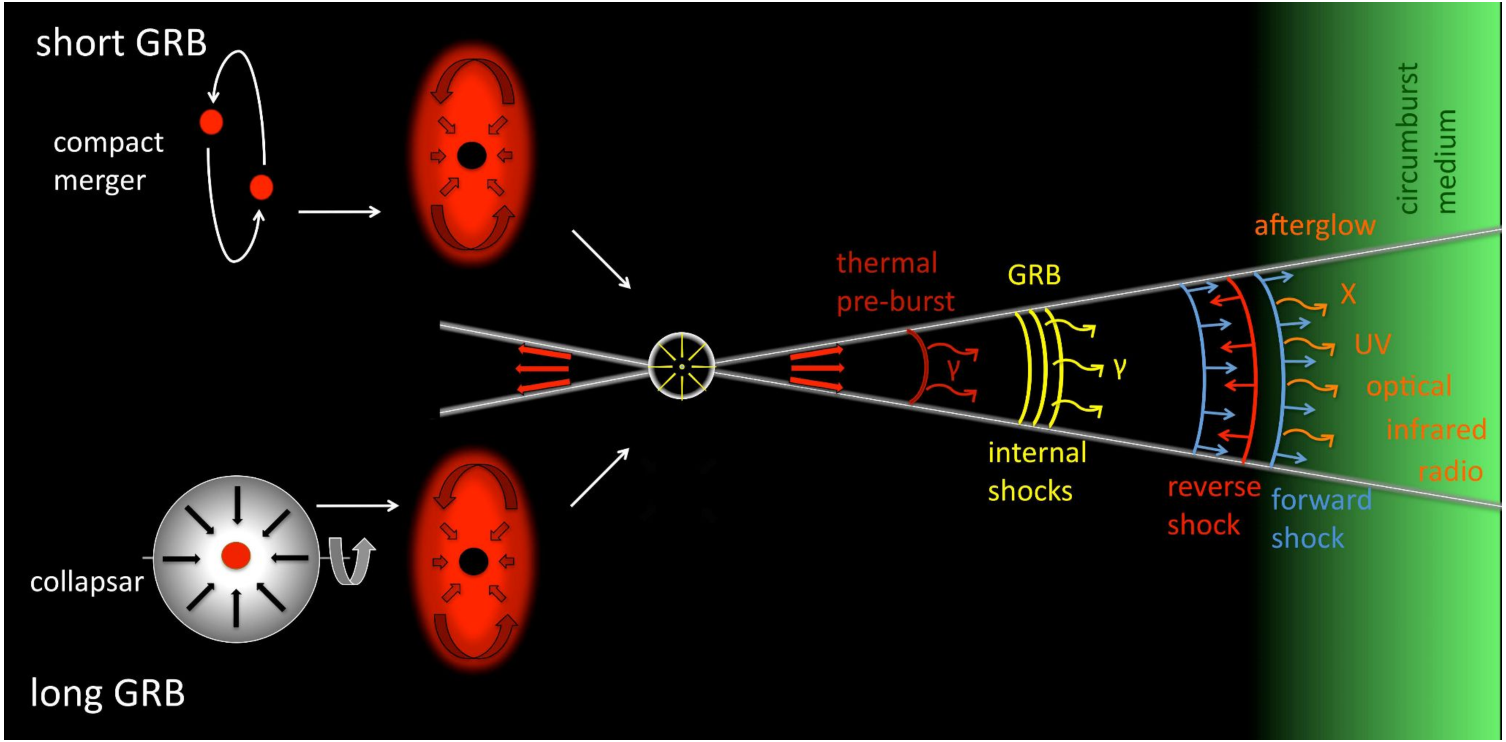
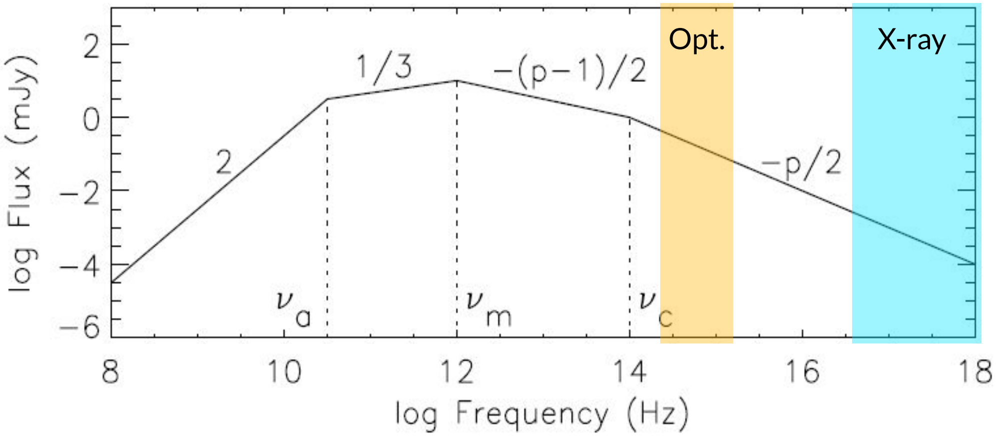


Figure from [Gomboc (2012)]

GRB afterglows: spectral models

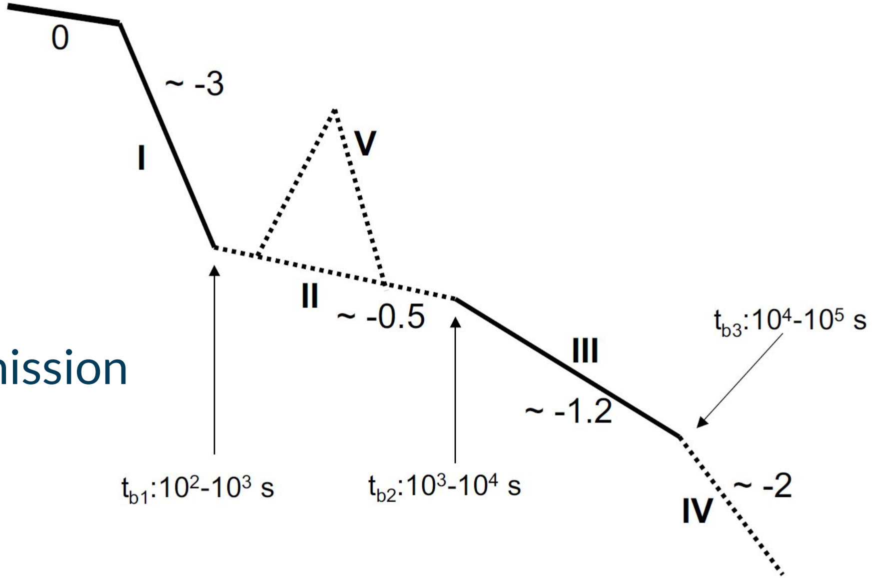
- Fireball model: relativistic outflow/jet $\longrightarrow$ strong shocks
- Synchrotron emission: relativistic electrons (with energy distribution $n_e(\gamma) \propto \gamma^{-p}$) spiralling around magnetic field lines produce EM radiation
- Observed spectrum (and spectral index β) depends on p
- Broken power law spectrum: $F_\nu \propto \nu^{-\beta}$
  - Models inform expectations for β
- Evolution over time $\longrightarrow$ light curves

At right: schematic view of broadband afterglow spectrum from van der Horst (2007)



GRB afterglows: temporal evolution

- Afterglows fade over time, following a (broken) power law decay: $F \propto t^{-\alpha}$
- X-ray lightcurve stages arise from physical evolution of GRB jet
    - Prompt emission
    I. Steep decay
    II. Shallow decay (not ubiquitous)
    III. Normal decay
    IV. Jet break (not ubiquitous)
    V. X-ray flare (not ubiquitous)
- Depending on when we look, we see emission from different physical processes



Canonical X-ray afterglow light curve from Zhang et al. (2006), showing typical decay indices for various emission phases

Optical darkness: context & motivation

- Afterglow: typically multiwavelength/broadband emission, but in some cases…
- Optical darkness: optical emission dimmer than expected based on X-rays

Possible explanation	Long GRBs	Short GRBs
Redshift (cosmological expansion)	*Short lives → collapsars possible within ~1 Gyr after the big bang*	*Mergers systems take a long time to evolve → not possible in early universe*
Gas/dust extinction in host galaxy	*Found in dense regions of star-forming activity*	*"Natal kick" propels system away from active region where it formed*
Extra emission mechanism	*Distinct physical process (?) violates assumptions about relationship between X-rays & optical*	

Questions:

- What is the rate of optical darkness in short GRBs as compared to long ones?
- Can we identify physical explanations for optically-dark short GRBs?

Procedural roadmap

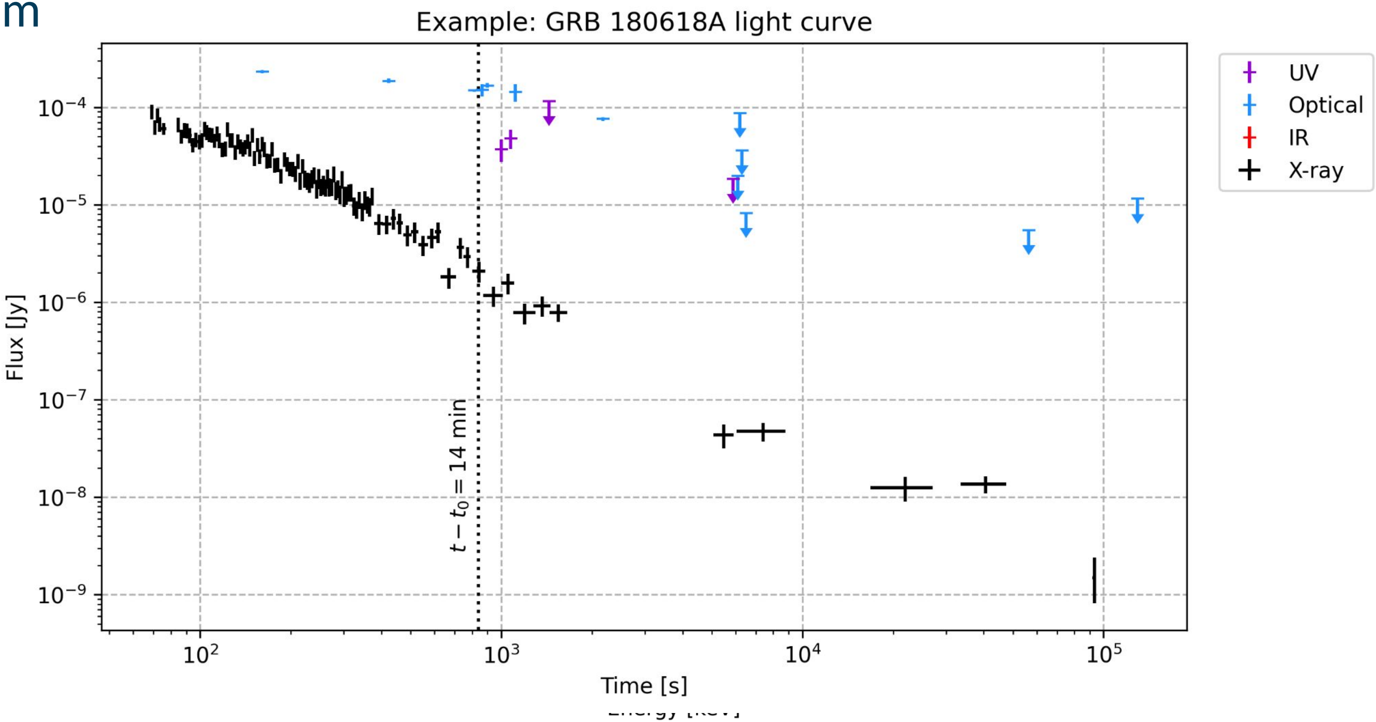
1. Compile sample of bursts/events
2. For every GRB, collect data from both X-ray and optical telescopes
3. Identify contemporaneous data points
4. Calculate spectral index between optical and X-rays: β_{ox}
5. Use steepness of β_{ox} to classify which/when bursts are dark
6. Analyze results for possible explanations

Steps 1 & 2: Sample definition; data compilation

1. Automated pipeline $\longrightarrow$ search for/select short GRBs from online catalogs (195 bursts)
2. Retrieve X-ray light curve and X-ray spectral data from *Swift*-XRT online repository (>5500 data points)
3. Manually compile optical data from GCN Circulars and published literature (>3000 data points)
4. Correct and convert data into comparable flux units

Steps 3 & 4: temporal matching; spectrum reconstruction

- Need temporally matching X-ray and optical data points to build a broadband picture of spectrum
- X-ray from *Swift* X-Ray Telescope
- Optical from ground- and space-based observatories around the world



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Steps 3 & 4: temporal matching; spectrum reconstruction

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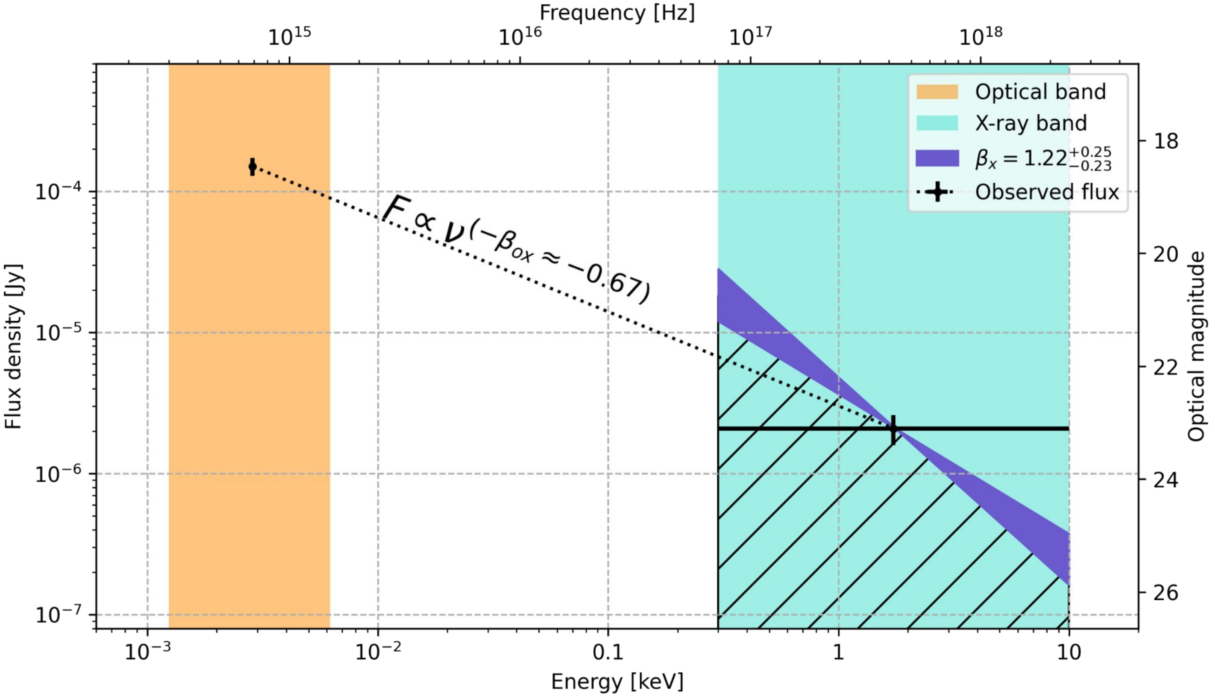
Example: GRB 180618A spectrum @ $t_x \approx t_o \approx 14$ min



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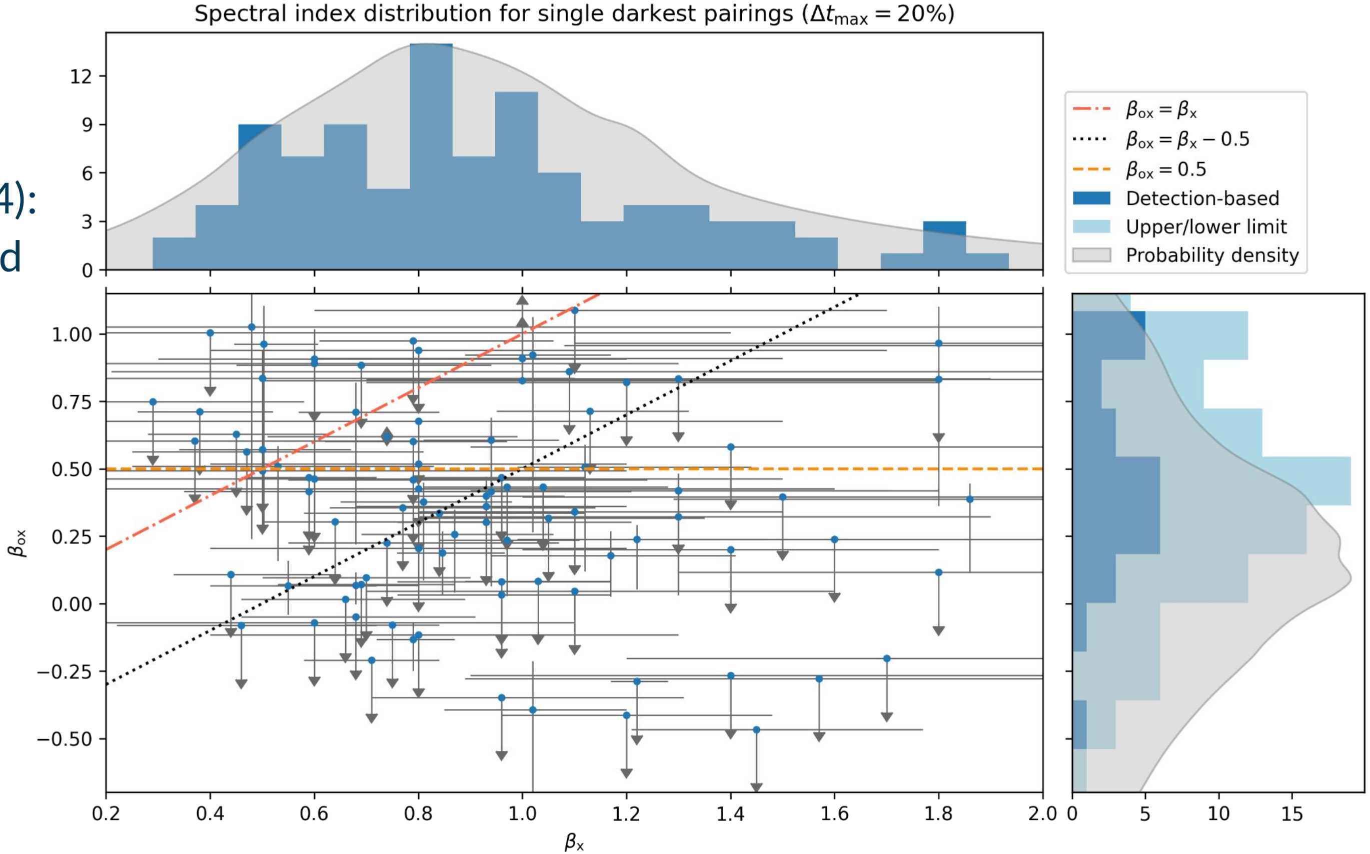
Step 5: Darkness defined by β_x and β_{ox} for each burst

- Two definitions of optical darkness
  - Jakobsson et al. (2004): $\beta_{ox} < 0.5$ (below dashed yellow line)
  - van der Horst et al. (2009): $\beta_{ox} < \beta_x - 0.5$ (below dotted black line)



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Step 6: Results

195 candidate short GRBs

165 w/ XRT lightcurves

158 w/ optical follow-up

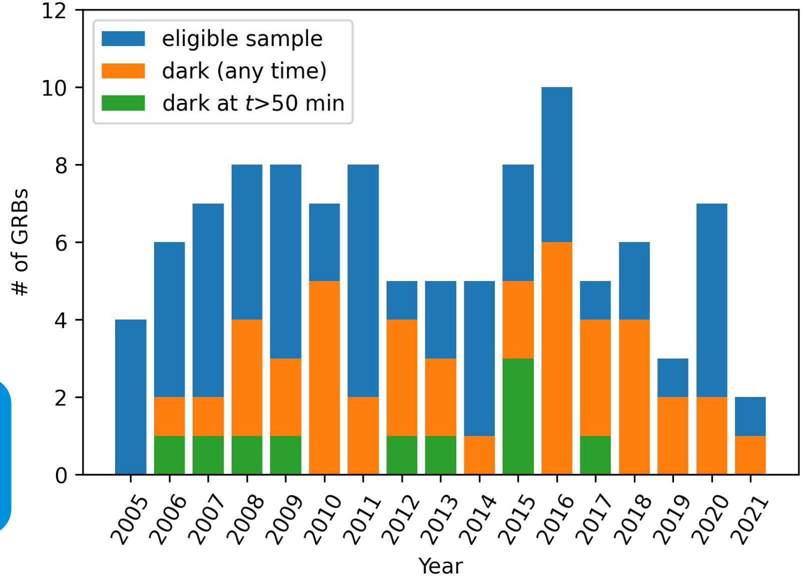
138 w/ both → 101 w/ temporal matches (6.1±0.5 per year)

50 w/ at least one "dark" point (2.9 ±0.4 per year)

23 w/ dark point at t>5 min; 10 w/ dark point at t>50 min

Q: How many short GRBs are dark?

A: About 48% ± 8% of our sample has at least one "dark" data pair



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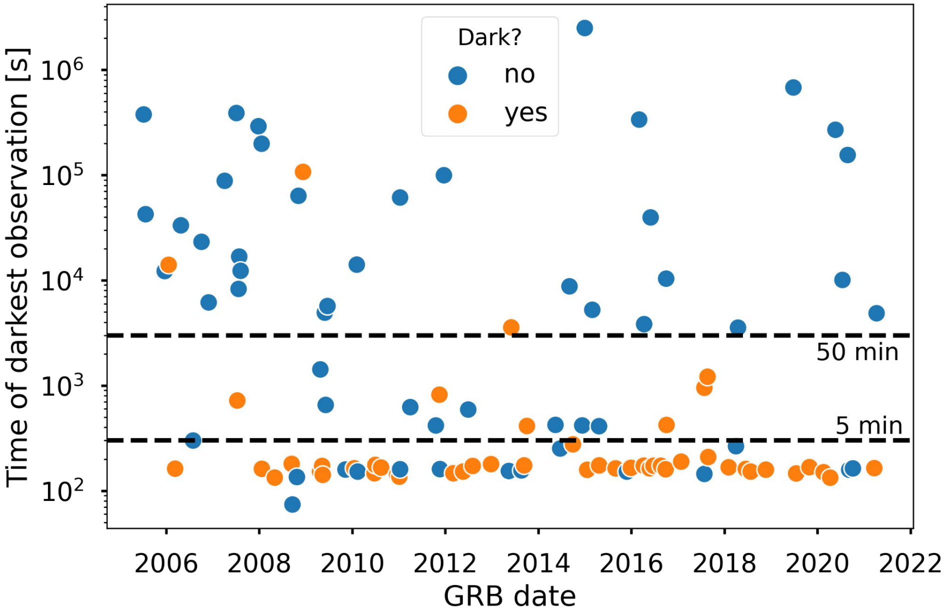
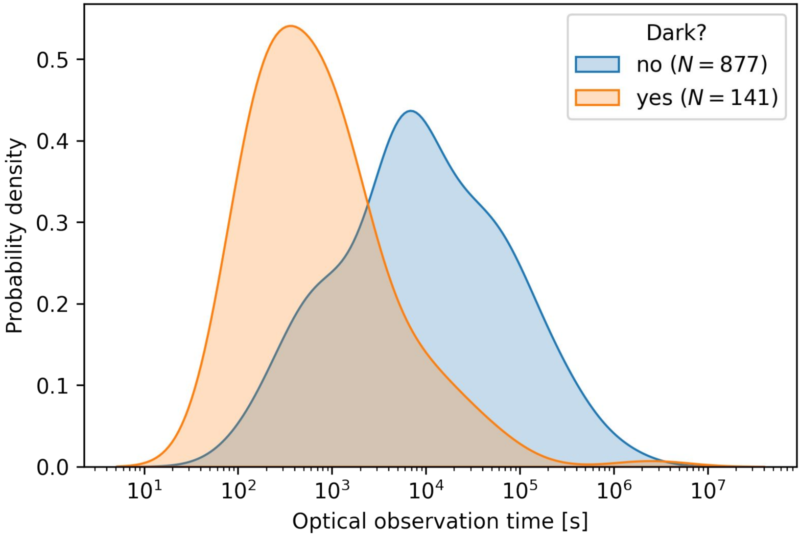
When are GRBs dark?



- Disproportionately early



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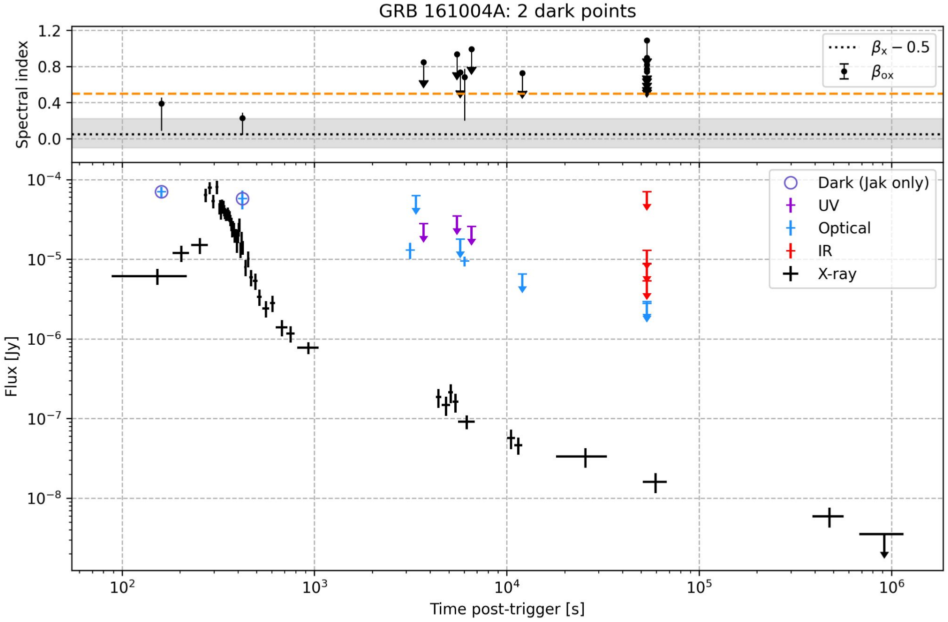
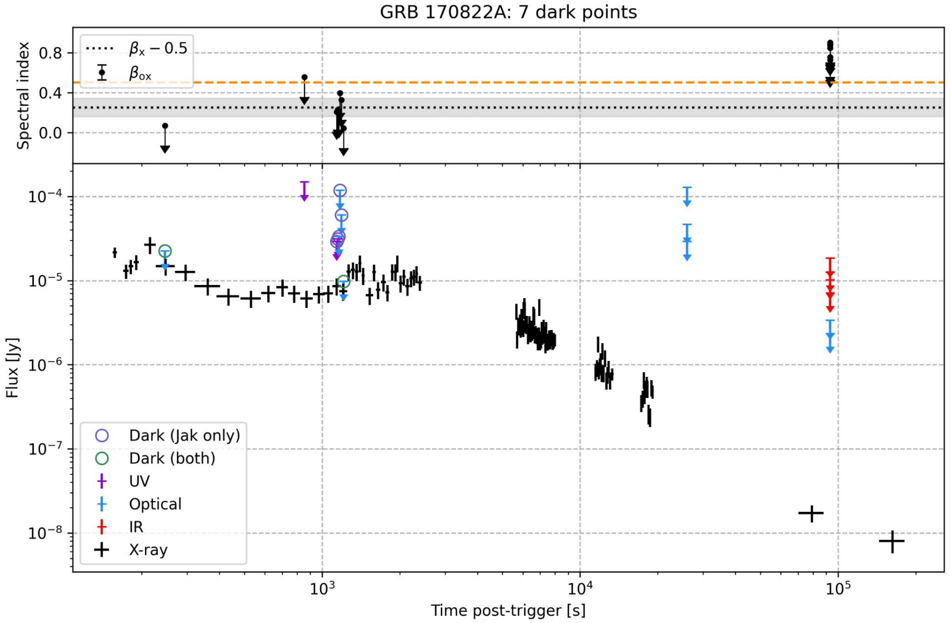
Anomalous X-ray behavior



- Lightcurve weirdness: flares, plateaus, steep decay



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Actually dark short GRBs

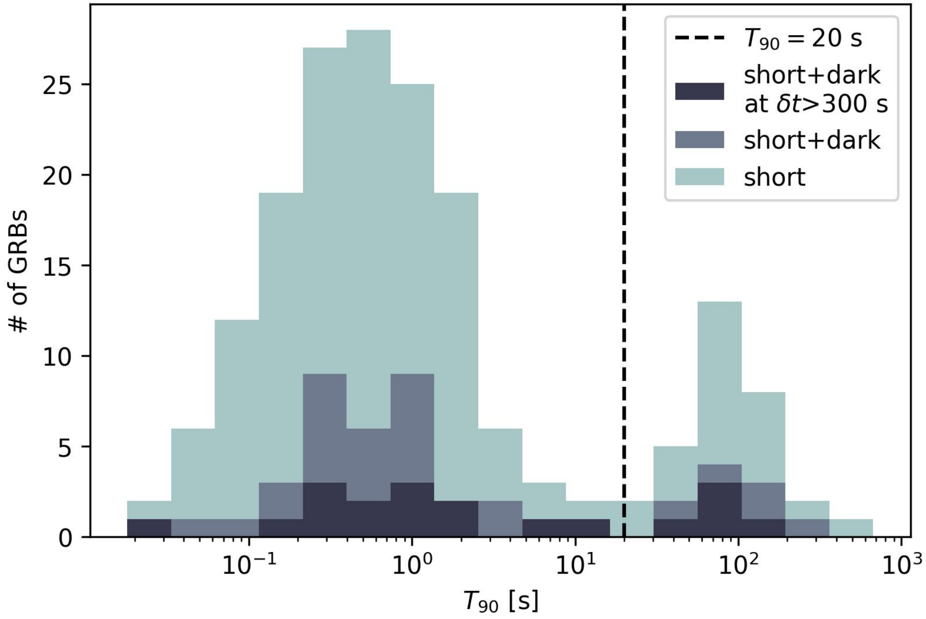
GRB	Darkest β_{ox}	Explanation
060121	$0.18^{+0.09}_{-0.15}$	Redshift or extended emission
090423	<-0.21	Long GRB, high redshift
130603B	$0.23^{+0.07}_{-0.21}$	Magnetar/late-time X-ray excess
170728B	$-0.13^{+0.06}_{-0.11}$	Extended emission

Short GRBs with extended emission

- Classical short cutoff: $T_{90} < 2$ seconds

	T_{90} >20s	T_{90} ≤20s
dark at $\delta t > 300$s	5 (17 ± 8 %)	14 (9 ± 3 %)
dark at any time	10 (34 ± 13 %)	36 (24 ± 4 %)
entire sample	29 (100%)	151 (100%)

Histogram of T_{90} durations in our sample



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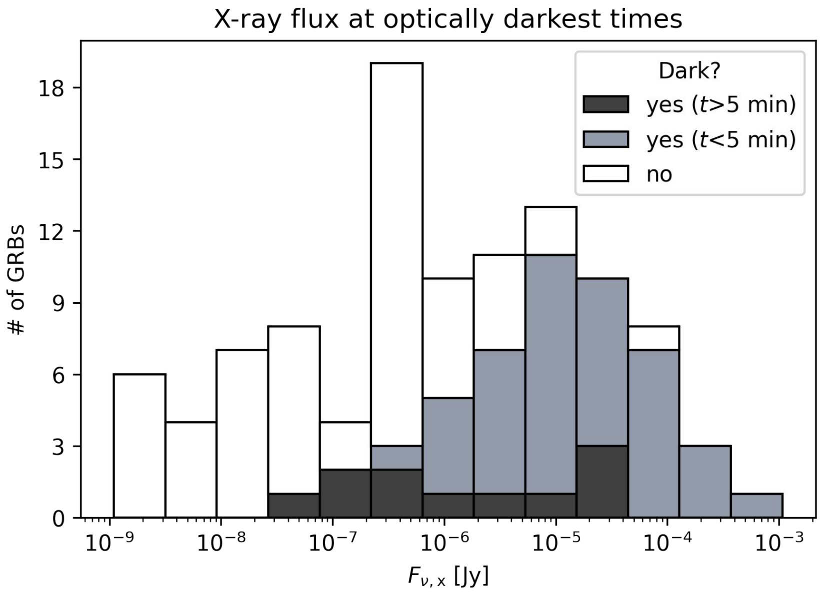
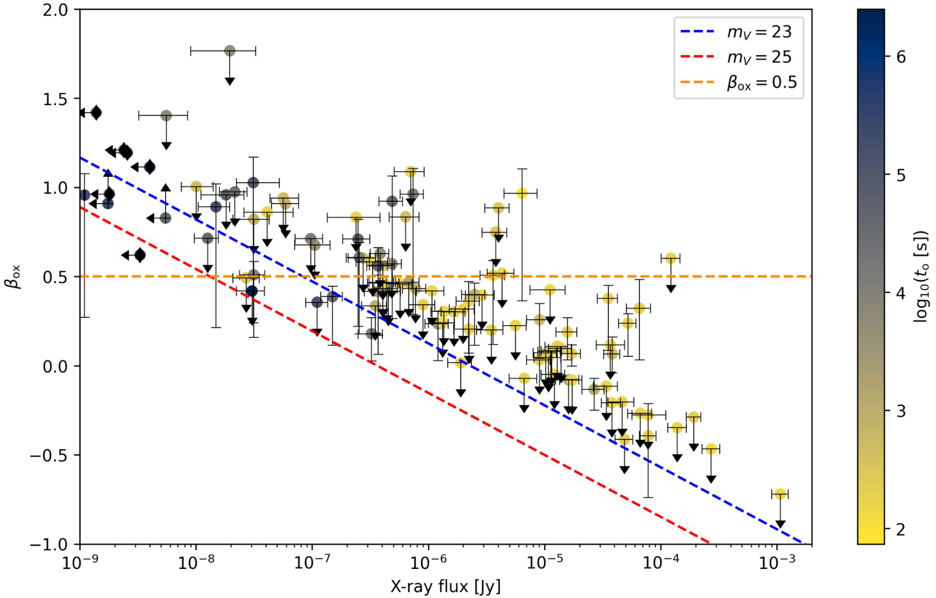
Correlations? No, just observational effects



- Are dark GRBs just brighter in X-rays as a rule?
- Not necessarily.



It looks like dark GRBs skew brighter than the population as a whole in X-rays…

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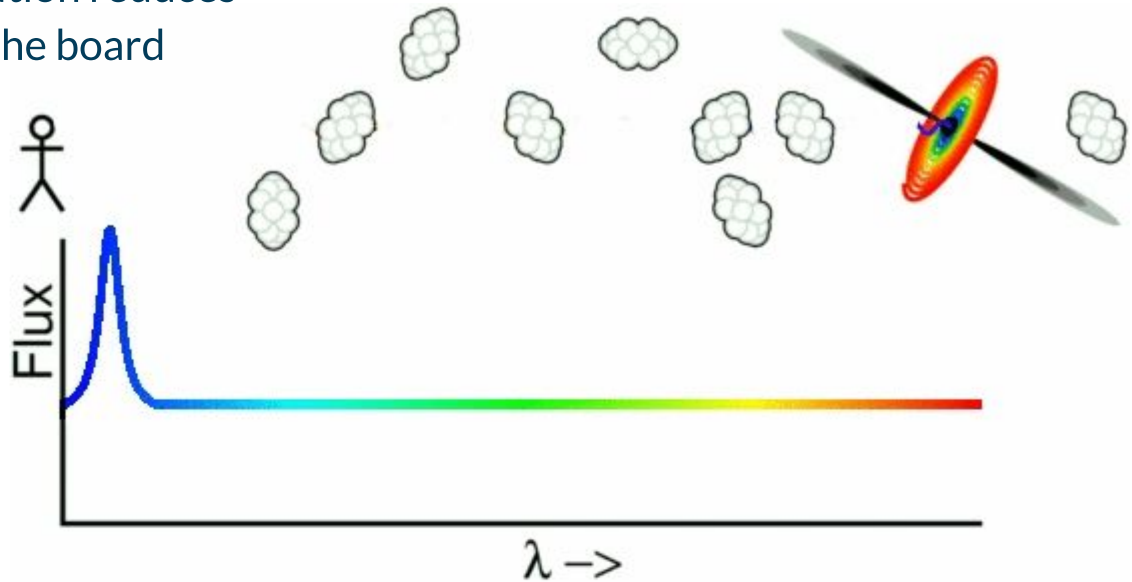
Summary & takeaways

- Many instances of darkness occur very early
    - X-ray excess rather than optical deficit
- Darkness of individual points depends heavily on how quickly follow-up observations are obtained
- Meaningful optical darkness: better identified at later times once X-ray lightcurve has settled into regular decay
    - Current models/darkness criteria are incompatible with early-time behavior
- Categorically, short GRBs are not as optically dark as long GRBs

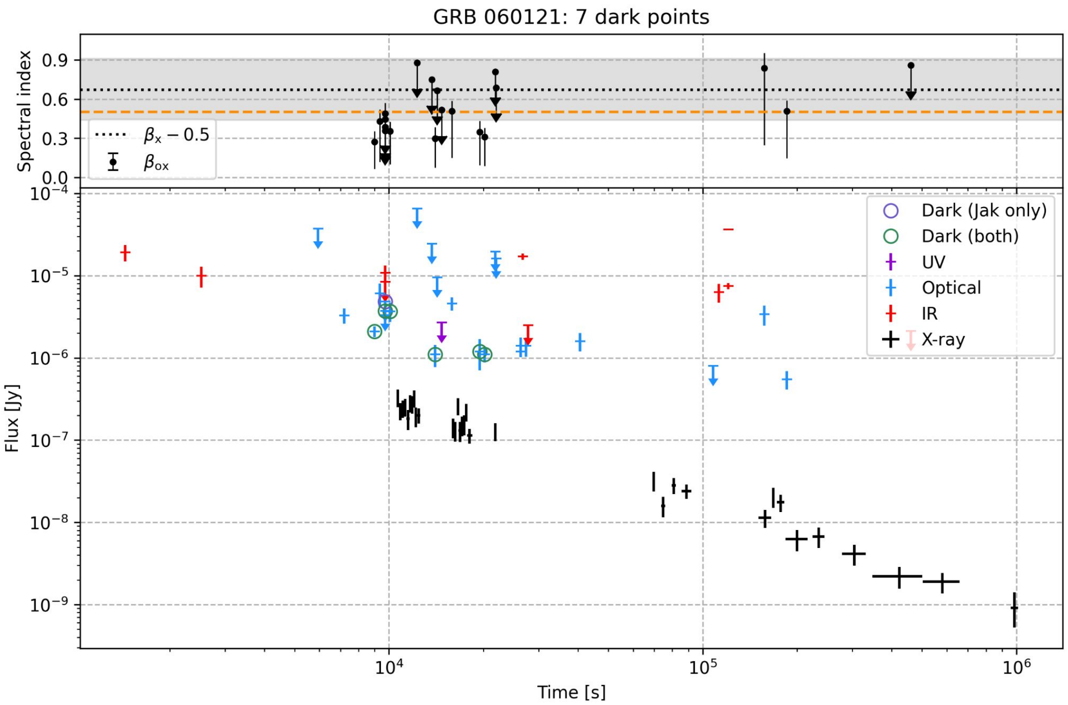
Supplementary material

Redshift and the Lyman-alpha forest

- Expansion of universe → distant objects move away from us
- Wavelengths get stretched: $\lambda_{obs} = (1+z)\lambda_{rest}$
- The same absorption line from matter at a range of redshifts creates a "forest"
  - Isotropic matter distribution reduces optical emission across the board
  - Ly-α: $\lambda_{rest} = 1216$ Å



GRB 060121



- z~ 4.6 or z ~ 1.7; T_{90} = 1.97 s
- Optically dark between 10000s & 20000s post-burst
- Optically dark observations come from Liverpool telescope in $r'i'z'$, OSN in RI, and CAHA 2.2m and Bok 2.3m telescopes in R

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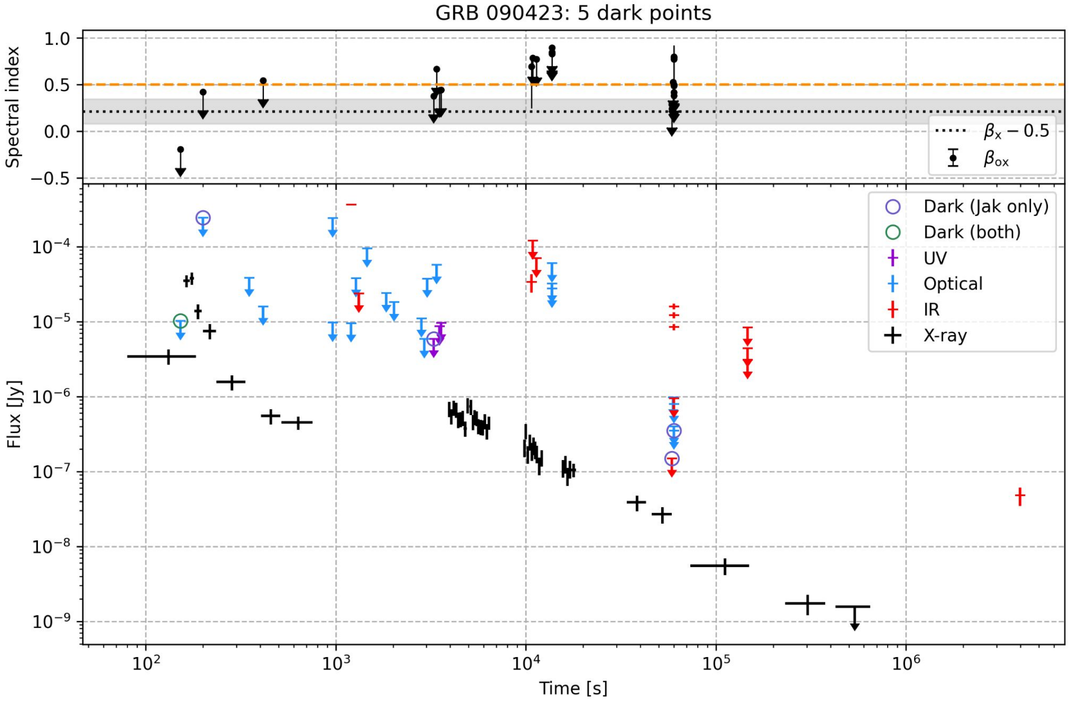
GRB 090423



- z ~ 8.2; T_{90} = 10.3 s
- Actually long GRB; present because initially ambiguous
- Very early-time optical darkness (X-ray flare that @ δt = 200s?)
- Also dark at later times
  - UV at δt ≈ 3000s: *Swift*/ UVOT upper limit
  - Optical/nIR at δt ≈ 60000s, from GMOS and GROND

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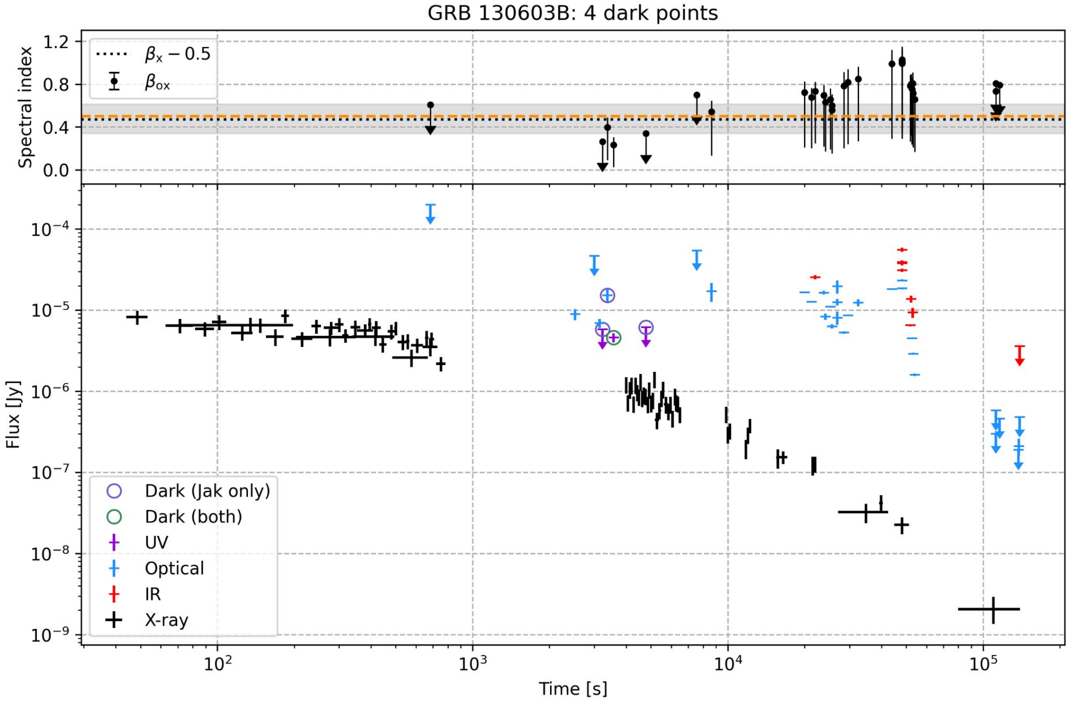
GRB 130603B



- $z \sim 0.36$; $T_{90} = 0.18$ s
- Theorized magnetar merger product; late-time X-ray excess kicks in around δt = 3000s → consistent with timing of our optically dark points

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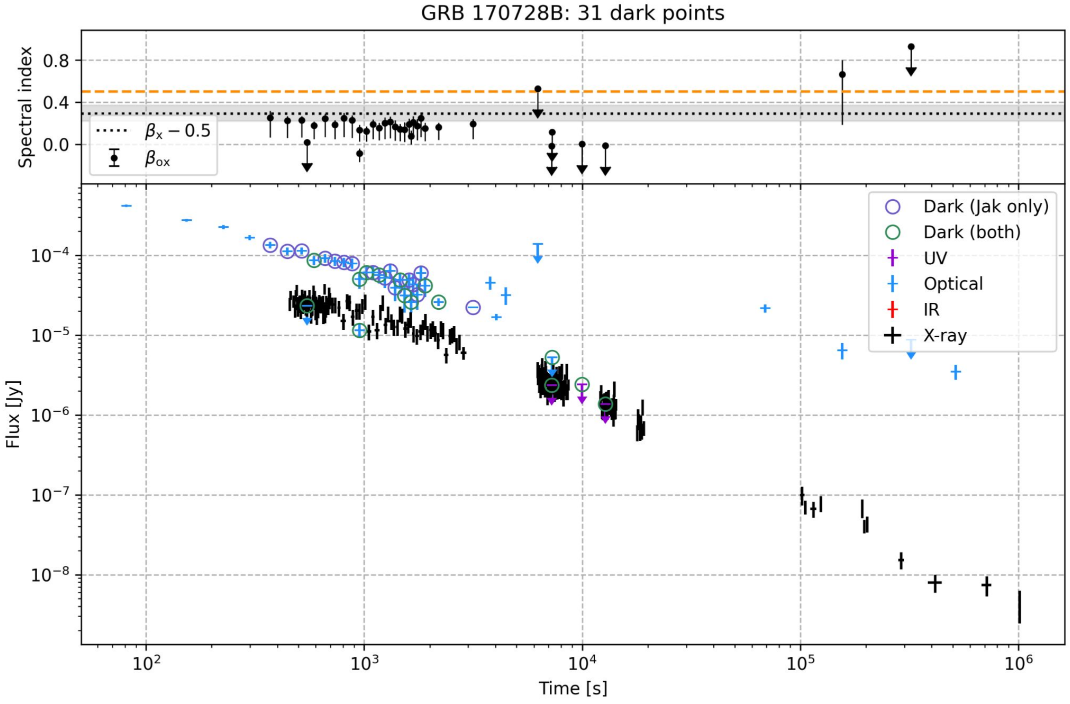
GRB 170728B



- No known host galaxy (z = ?)
- T_{90} = 47.7 s
  - "Short burst with extended emission" (EE)
- Not much else to say

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