Wyrd Engines

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THE ROYAL SOCIETY

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wyrd

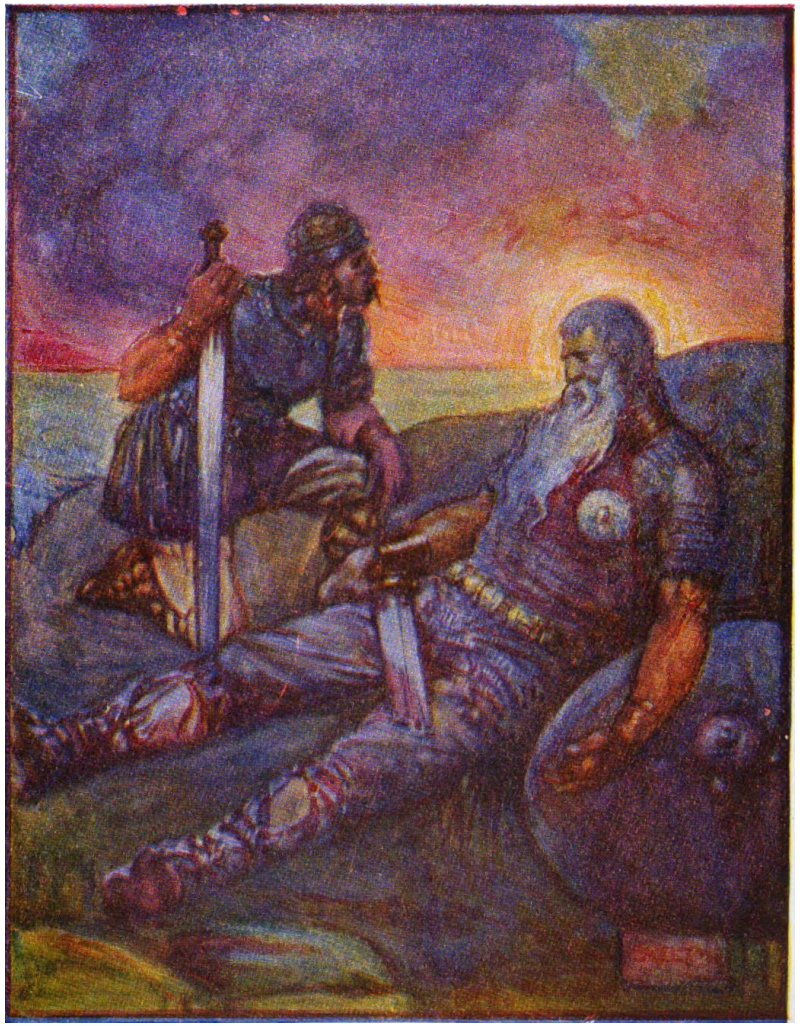
Beowulf, line 455b;

Gæð ā **wyrd** swā hīo sċel.

“**Fate** always goes as it must.”

"He knew his days upon this earth were past"

Wiglaf speaking to Beowulf after his battle with the dragon. Beowulf is mortally wounded



By J. R. Skelton - Marshall, Henrietta Elizabeth (1908) Stories of Beowulf, T.C. & E.C. Jack

Credit: Soheb Mandhai

Yukawa Institute for Theoretical Physics – Nuclear Physics, and Compact Star Mergers 2016

T_{90}: The duration from 5% to 95% for the arrival of the total energy, at the detector

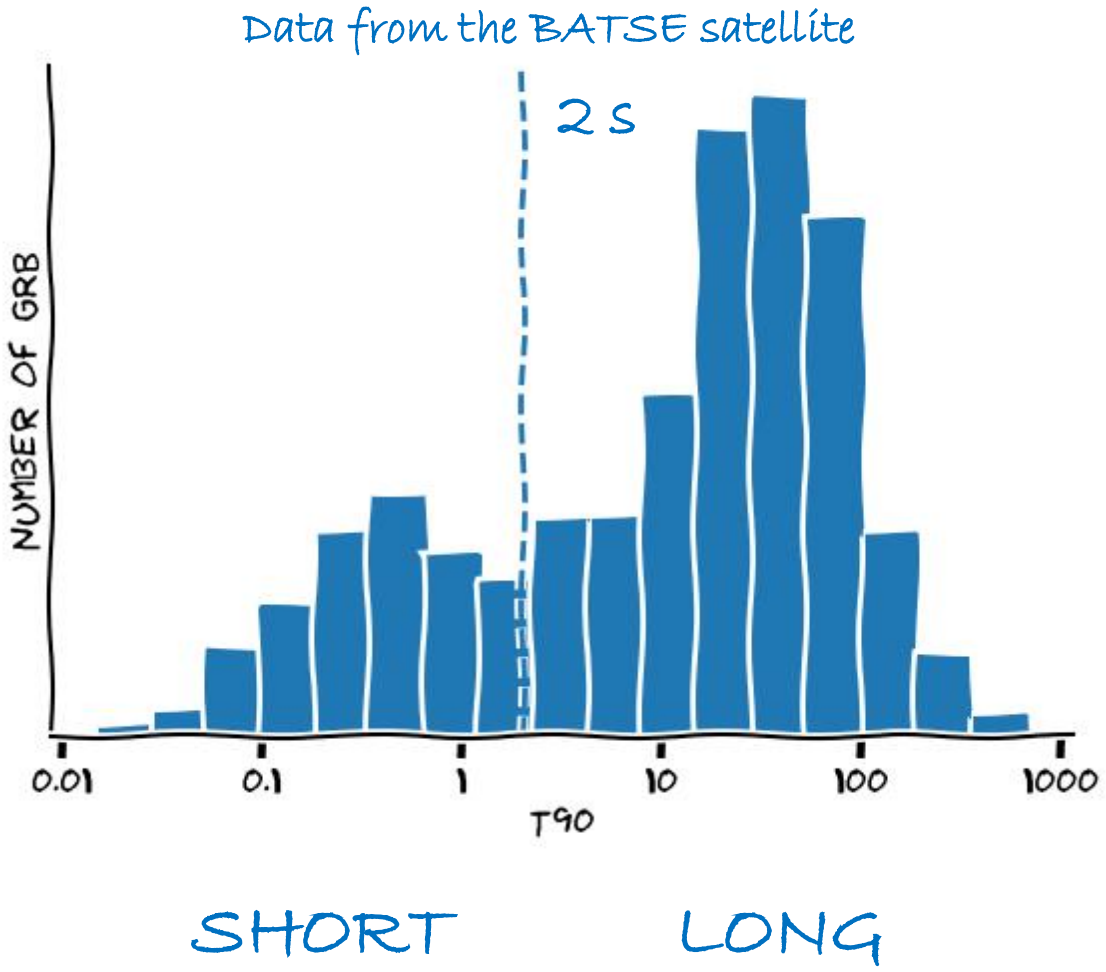
Two distinct populations

GRBs have a statistically significant bimodal distribution of $\log_{10} T_{90}$

An extragalactic origin, and a *required* ultra-relativistic "fireball"

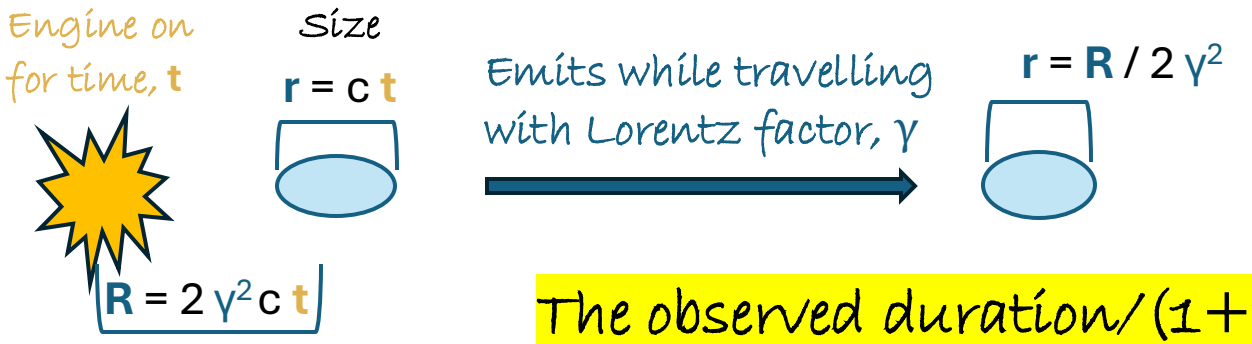
Cataclysmic accretion powered transient

1. Core collapse of massive stars (long)
2. Merger of binary neutron stars (short)



An Aside: Understanding the engines

- GRB prompt emission is measured at the detector as a fraction of the total flux; typically, the duration for the central 90% to arrive is used (5% to 95%). This is the T_{90}
- This timescale sets the minimum timescale that the engine is active
- $T_{90}/(1 + z) = t_{duration}$ in the lab frame*



Observed time is, $t_{obs} = R / (2 \gamma^2 c)$ and $r = c\,t$,

$t_{obs} = R / (2 \gamma^2 c) = r\,2\gamma^2 / (2 \gamma^2 c) = r / c = t$

$t_{obs} = t$

The observed duration/(1+z) = the (minimum) engine duration

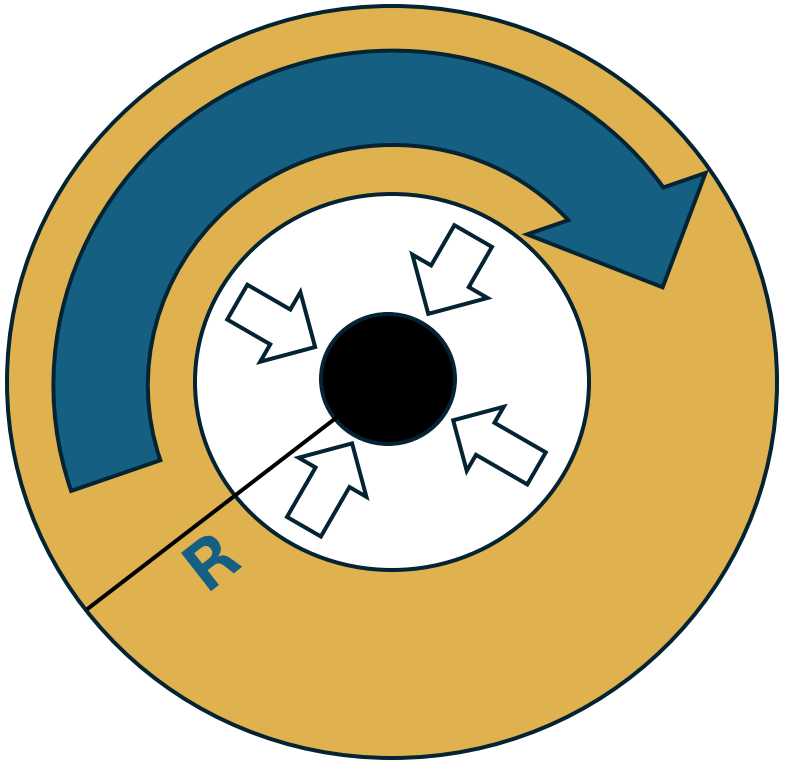
Note; static engine relativistic emission region

*(1 + z) corrects for cosmological time dilation

Understanding the engines

- Analytically, accretion timescale can be described by a **Shakura-Sunyaev α-accretion disk**[1] model
  - Turbulent, viscous accretion disks
  - Dimensionless parameter, **α** ~ 0.01 to 0.1, and represents the "*efficiency of angular momentum transport via turbulence*"
  - Viscosity is parameterized as $v_* = \alpha\, c_s\, H$, where c_s is the sound speed and H is the disk scale height
- The lifetime of a disk is the **viscous time** (t_{visc})

$$t_{visc} = R^2 / v_* = R^2 / (\alpha\, c_s\, H)$$



[1] see Shakura & Sunyaev 1973, 1976 etc.

Engine basics

Note - Disks as GRB engines have turbulence that is likely driven by magneto-rotational instabilities (MRI) - this is a distinct mechanism when compared to the hydrodynamical, viscous process of α-disks. However, the α-disk description still provides an effective prescription, and timescale arguments remain the same.

Short duration bursts

- T_{90} < 2s, typically 0.6s
- Merger of neutron stars, total mass ~3 $M_\odot$
- Small disk mass, 1-10% $M_\odot$
- **Compact size, 10-100 km**

Long duration bursts

- T_{90} > 2s, typically ~30s
- Core-collapse of massive star, ~20-40 $M_\odot$
- Disk mass can be several $M_\odot$
- **Disk is large, ~10^6 km**

$$t_{visc} = \mathbf{R}^2 / v_* = \mathbf{R}^2 / (\alpha\, cs\, H)$$

The viscous time is typically the longest timescale for an accretion disk and sets the maximum lifetime
Generally, the timescale is ordered, dynamical time < thermal time < viscous time
The radius, R, has the strongest dependence on this timescale – short GRBs are small, long GRBs are much larger

Here we assume $\alpha = 0.1$

Relativistic disk

- Newtonian Keplerian motion is invalid near the innermost stable circular orbit
- Requires relativistic angular velocity from **General Relativity***. However, **order-of-magnitude** comparison is sufficient

Short, merger GRB

- Disk, **R** ~ 100 km

$t_{visc} \sim \mathbf{R} / (\alpha\, c) \sim (100\ \text{km}) / (0.1 \times 3\times10^5\ \text{km/s})$

$t_{visc} \sim 100 / 30{,}000\ \text{s} \sim \mathbf{0.003\ s}$

Extremely short timescale consistent with the minimum variability timescale in short duration bursts

Long, collapsar GRB

- Disk, **R** ~ 10^6 km

$t_{visc} \sim \mathbf{R} / (\alpha\, c) \sim (10^6\ \text{km}) / (0.1 \times 3\times10^5\ \text{km/s})$

$t_{visc} \sim 1{,}000{,}000/30{,}000\ \text{s} \sim \mathbf{33\ s}$

A timescale that aligns perfectly with long GRB timescales

The duration of the GRB is fundamentally set by the size of the accretion disk, which is a direct consequence of the progenitor system

*For a Kerr black-hole,
$\Omega = (G M_\bullet)^{1/2} / [R^{3/2} + a (G M_\bullet)^{1/2}]$
Where $0 << a \leq 1$, for a GRB engine

Here we assume α = 0.1

Relativistic disk

- Newtonian Keplerian motion is invalid near the innermost stable circular orbit
- Requires relativistic angular velocity from **General Relativity***. However, **order-of-ma** is sufficient

We can make the disk bigger – say 1,000 km
And we can change the viscosity*, α~0.01
And we get to t_{visc} ~ 0.3 s

Short, merge

- Disk, **R** ~ 1

t_{visc} ~ **R** / (α c) ~

t_{visc} ~100 / 30,000 s ~ **0.003 s**

Extremely short timescale consistent with the minimum variability timescale in short duration bursts

g, collapsar GRB

- isk, **R** ~ 10^6 km

~ **R** / (α c) ~ (10^6 km) / (0.1 × 3×10^5 km/s)

sc ~ 1,000,000/30,000 s ~ **33 s**

A timescale that aligns perfectly with long GRB timescales

The duration of the GRB is fundamentally set by the size of the accretion disk, which is a direct consequence of the progenitor sys

*it isn't the same disk material as a collapsar, so why the same viscosity?

Hayashi et al. 2025

The α-disk - it hides all our physics

Stress (turbulence/magnetic) : $S_{r\phi}$

Pressure (gas + radiation) : P

So, $\alpha = S_{r\phi} / P$

Merger disk: mostly neutrons

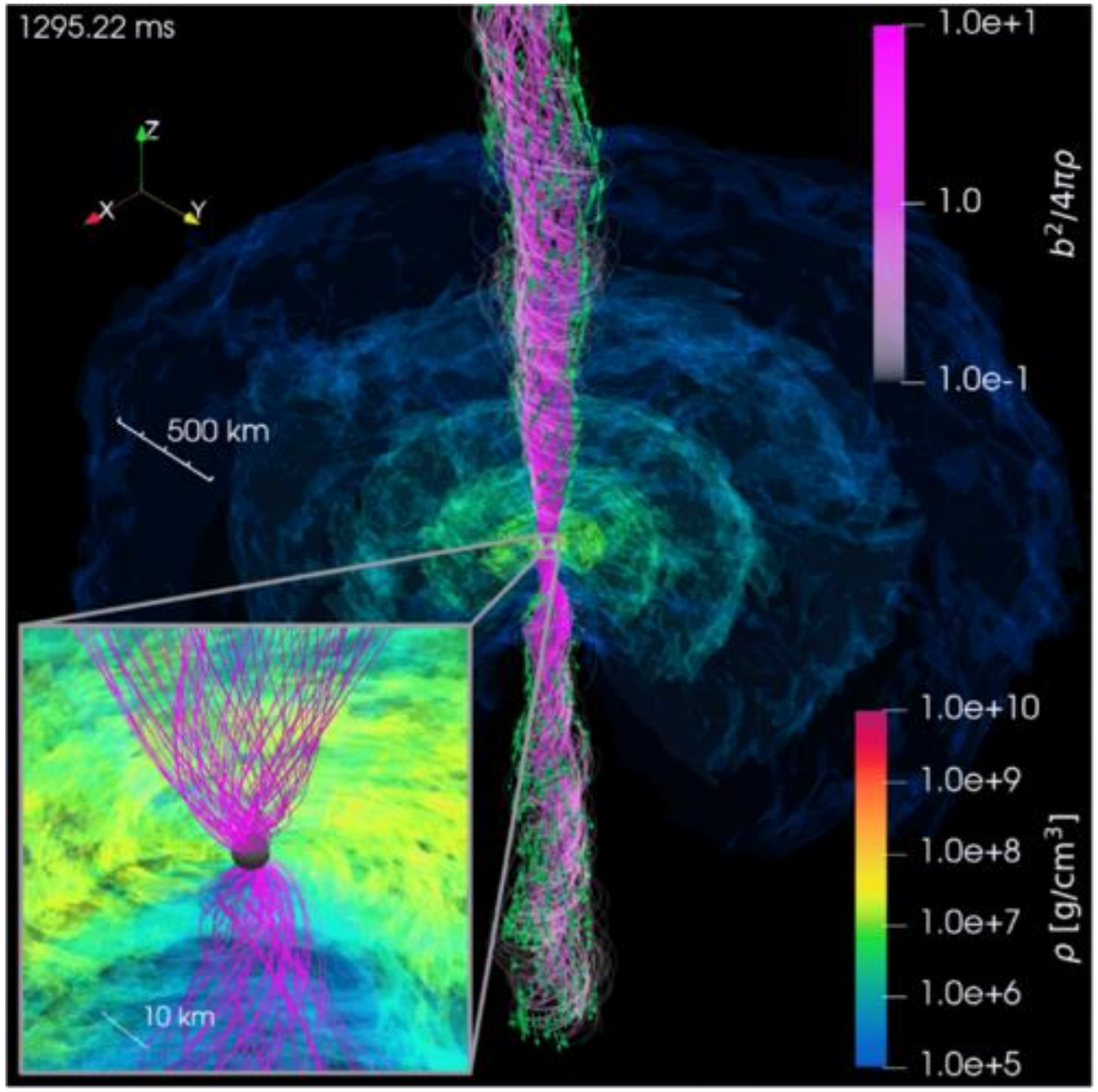
- Low opacity – poor radiative cooling
- Low ionization fraction – reduced MRI

Both $S_{r\phi}$ and P can be lower

- Low ionization = high magnetic diffusivity, and suppressed MRI

Without another source of turbulence, $S_{r\phi}$ will by much smaller for a neutron dominated disk and so α can be smaller

Figure for interest and something amazing to look at



The 3D snapshot at $t-t_{merger\approx1.3}$ s in a domain of ~10^3 km and ~10^2 km. The rest-mass density (contours), magnetic-field lines penetrating the apparent horizon (lines), and the outflow in the magnetosphere (arrows) are shown. The black sphere at the center shows the apparent horizon.

Two types of GRB – our favourite assumptions

TYPE I

- Duration is < 2 s, **SHORT**
- Short spike then extended emission
- No supernova
- Large offset from host
- Host has low star-formation rate
- Uniform medium
- Small energy

TYPE II

- Duration is > 2 s, **LONG**
- Spectral lag
- **Supernova**
- No offset from host
- Host has high star-formation rate
- Uniform or wind medium
- Large energy

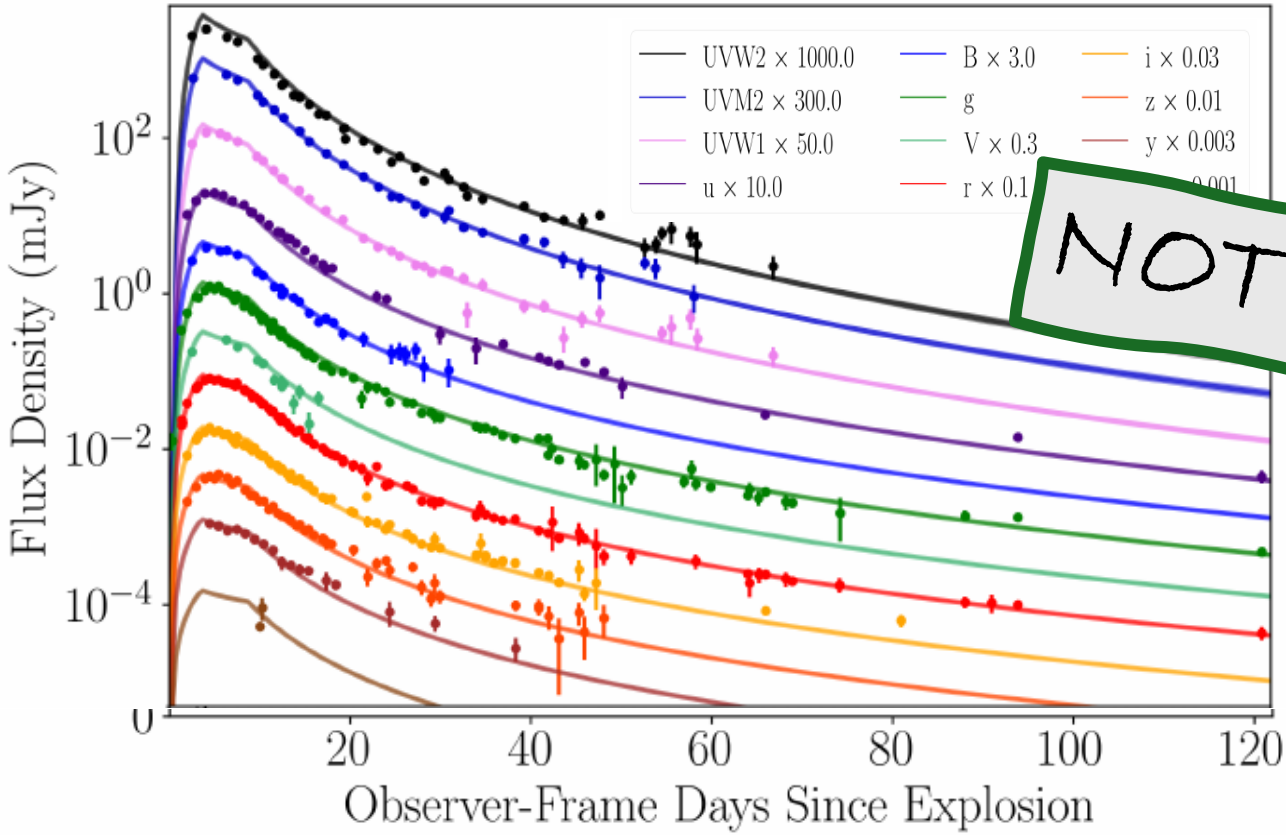
A walk back over the last couple of years…

- The resurgence of the x-ray burst – some Einstein Probe events
  - High redshift transients
  - Nearby x-ray rich bursts
  - GRBs and XRBs
  - Fast X-ray Transients (FXTs)
- The continued finds of Luminous Fast Blue Optical Transients (LFBOTs – not GRBs but quite distracting)
- Long GRBs, short GRBs, and long GRBs that are really "short" GRBs – and the other way

The rise of the Luminous Fast Blue Optical Transients (LFBOTs) - what is it?

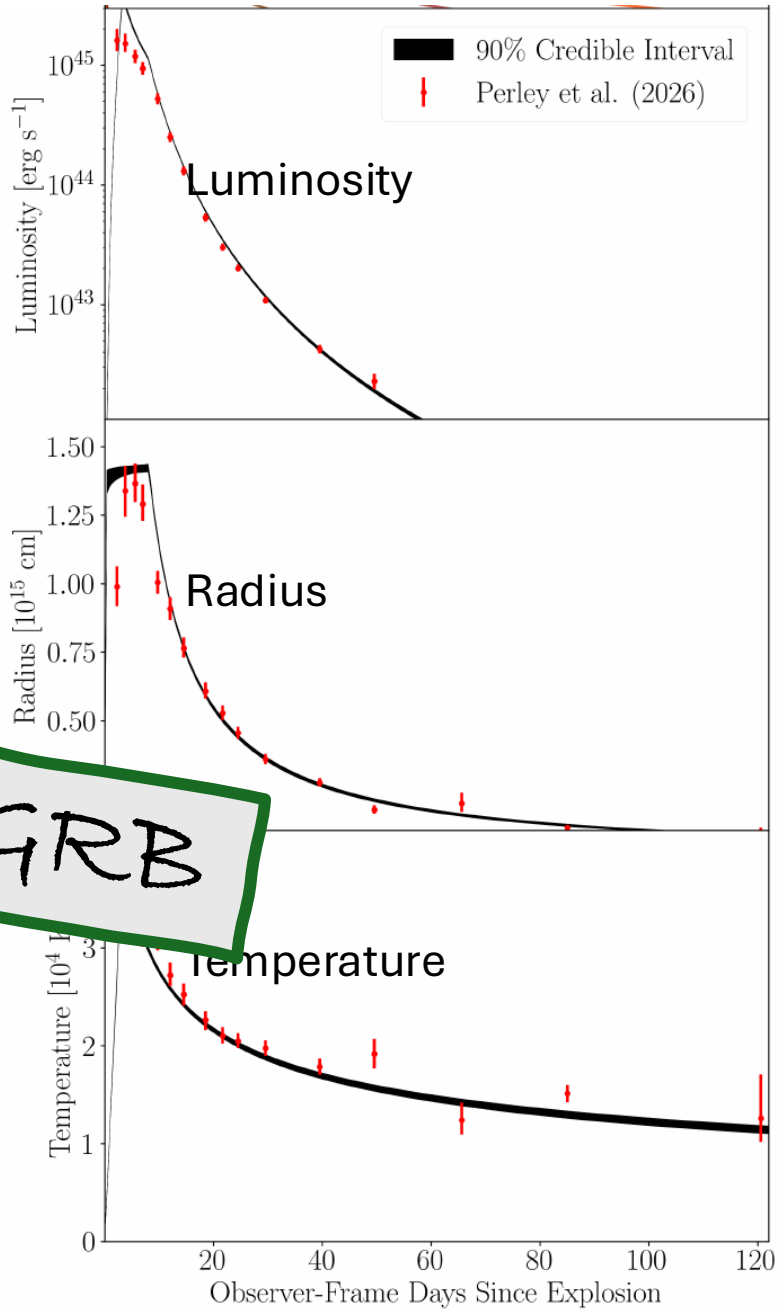
- **See poster by Conor Omand** (week 5), AT2024wpp WOMBAT

Conor Omand



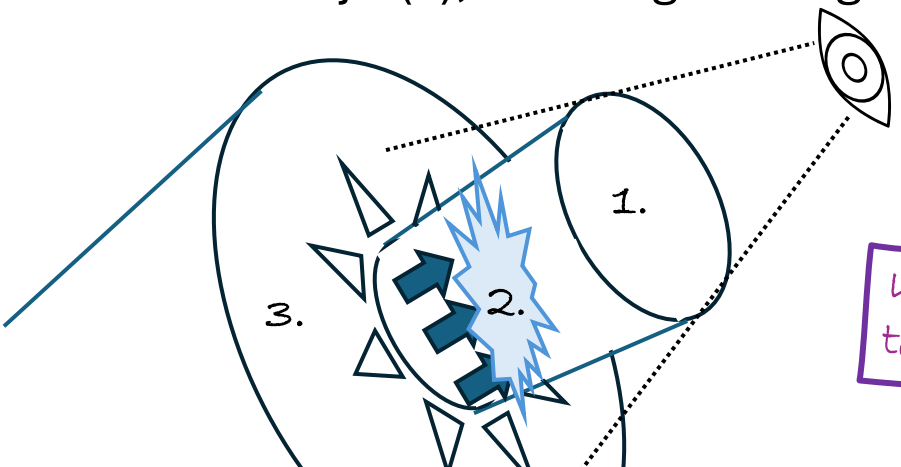
NOT A GRB

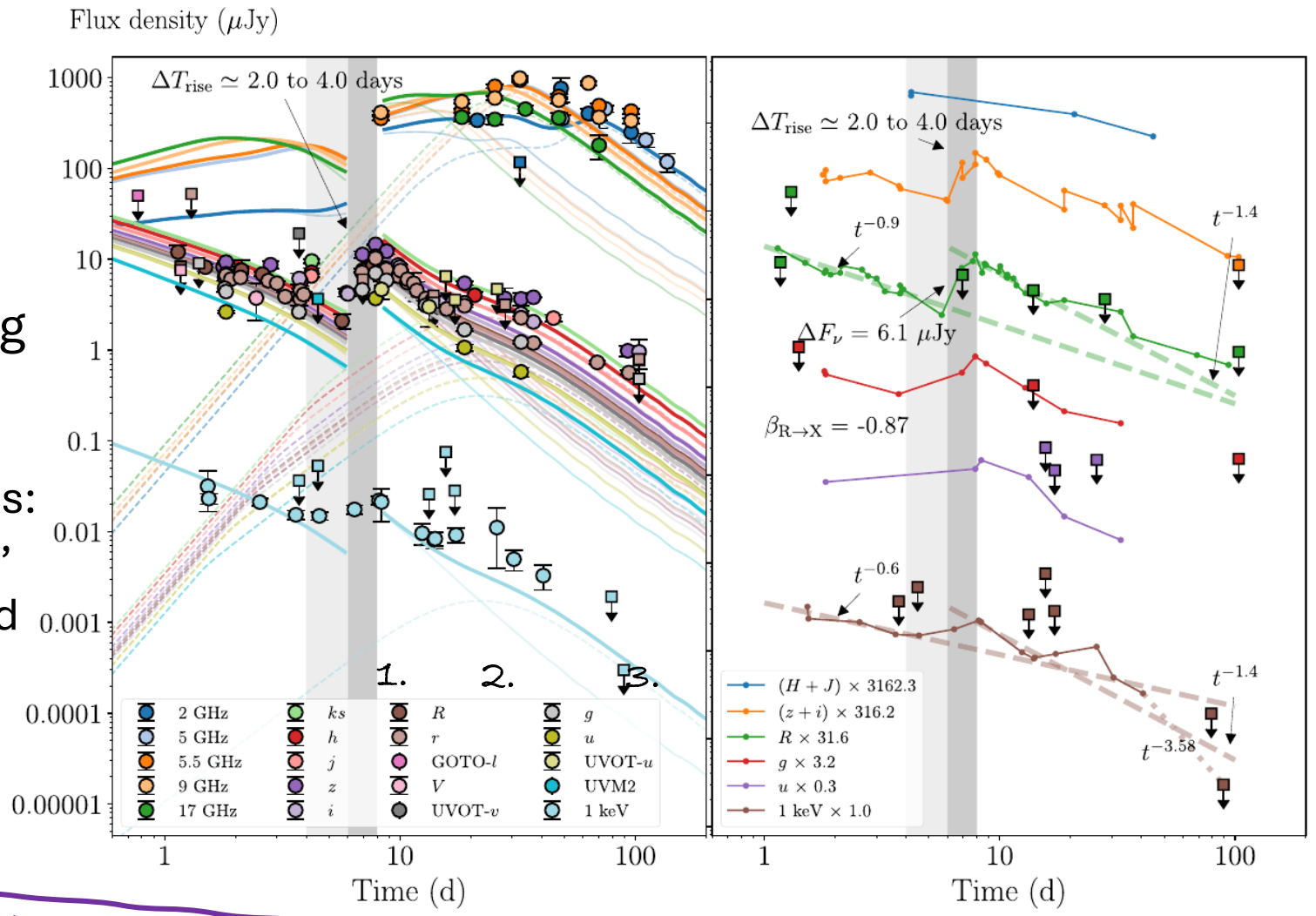
Omand (incl. Lamb) et al. 2026



EP241021a

- No gamma-rays
- A redshift of z=0.75
- An anomalous rebrightening that is too rapid, ΔT/T < ¼
- *And* a supernova!
  - I tried so many different ideas: refreshed and strong shocks, reverse shock, hot-spots, multiple mini-jets, structured jet(s), an energetic ring…





Used two/three components to recreate the afterglow shape

Quirola-Vasquez (incl. **Lamb**) et al. 2026

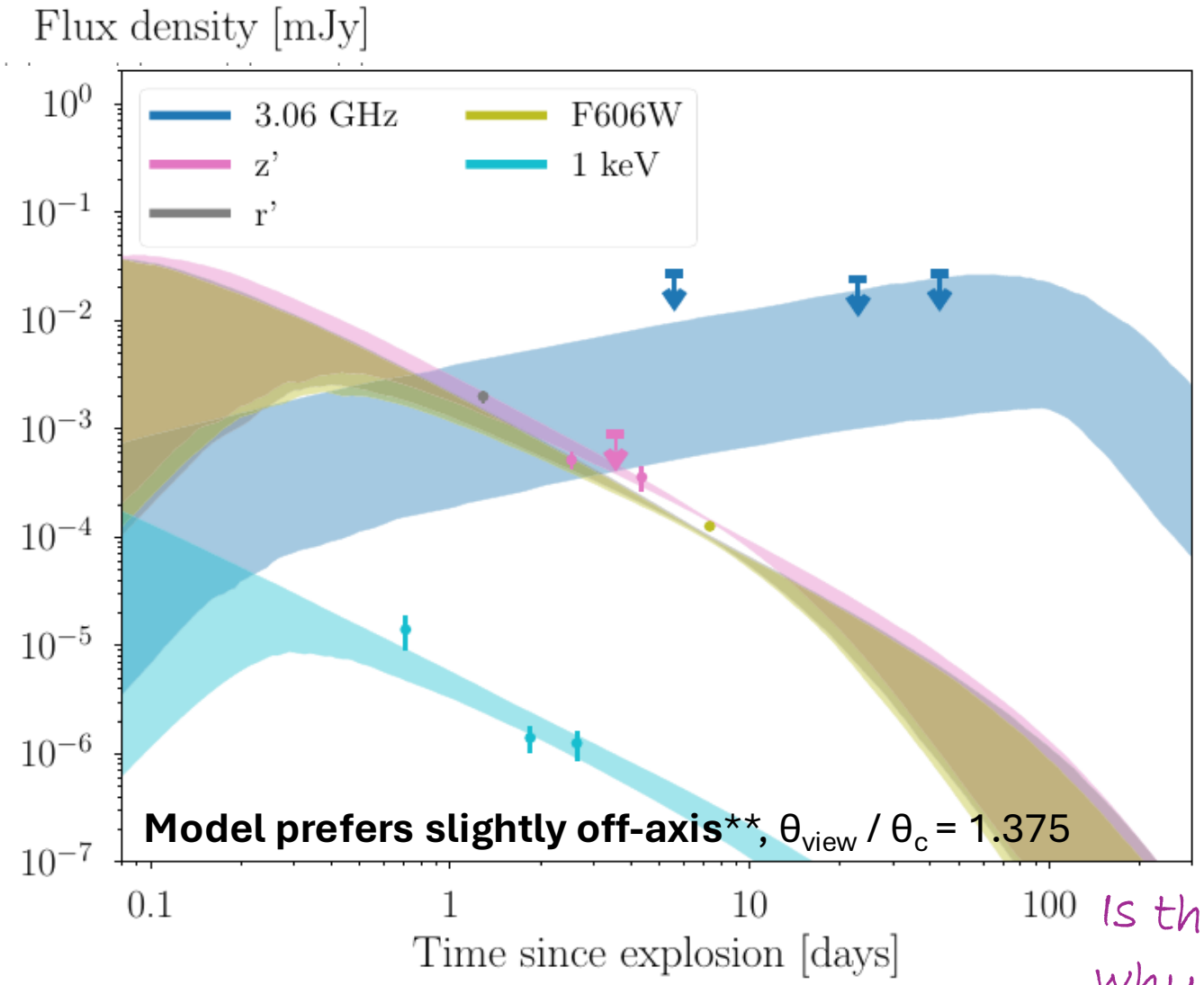
Jonker (incl. **Lamb**) et al. 2026

EP250207b

- At a redshift, z=0.082

...maybe...

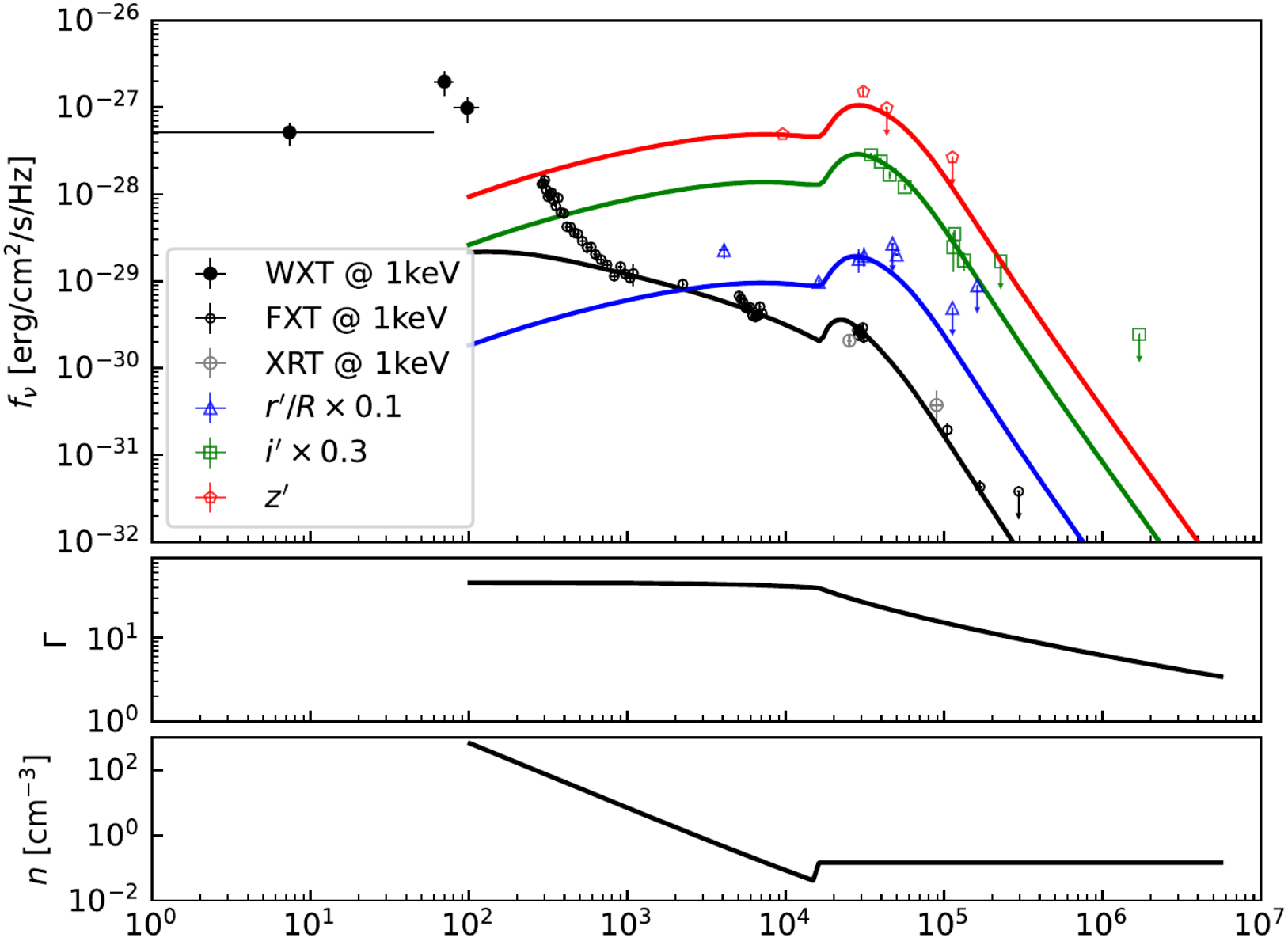
- Or a redshift, z =2.1824
- Galaxies at both
  - Chance alignment higher for z=0.082
  - Offset for z=2.18, ~50 kpc
- Both cases likely non-collapsar origin
  - No supernova, z=0.08
  - High offset, z=2.18
- No gamma-rays from GECAM
  - Fermi GBM Earth occulted



Is this why it's an XRB?

EP241217a

- Redshift, z=4.59
- Below gamma-ray detection threshold
- Likely long (type II) GRB with a bump – is this a termination shock!?*

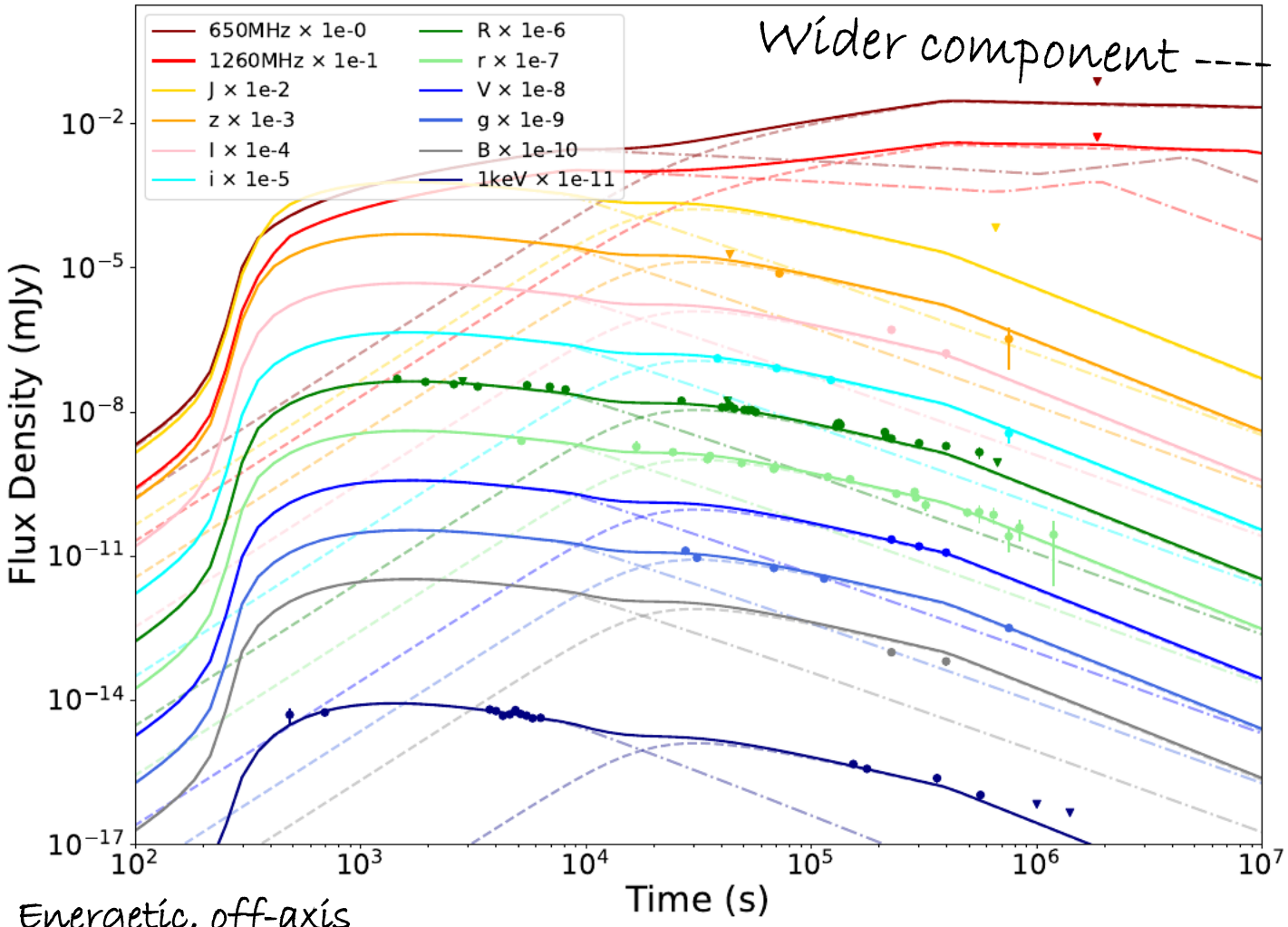


*you can model this as a refreshed shock, but the post refreshed decline is a bit steep

Zhou (incl. **Lamb**) et al. 2025

EP240801a/XRF 240801B

- Redshift, z=1.67
- Long duration
- Two-component jet used to model – maybe like the BOAT



Jiang (incl. **Lamb**) et al. 2025

EP241021a : on-axis, highly variable, ~3+ components, and a supernova

Type II (collapsar)

Quirola-Vasquez et al. 2026

EP250207b : mildly off-axis, possibly one of two redshifts, ambiguous type I or II, but looks more like a type I for both redshifts

Type I (merger?)

Jonker et al. 2026

EP241217a : wind medium and possible termination shock crossing, likely type II, high redshift

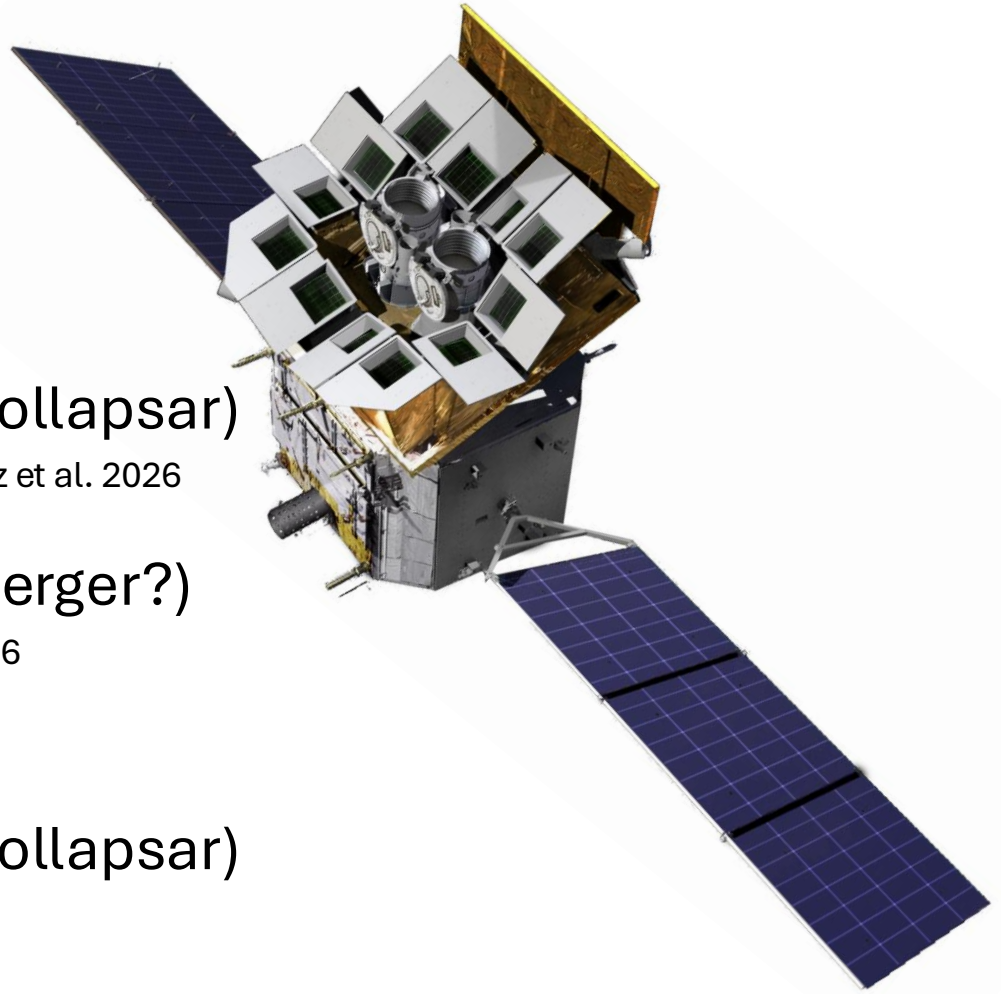
Type II (collapsar)

Zhou et al. 2025

EP240801a: off-axis narrow core, wider second component, is this a BOAT analogue!?

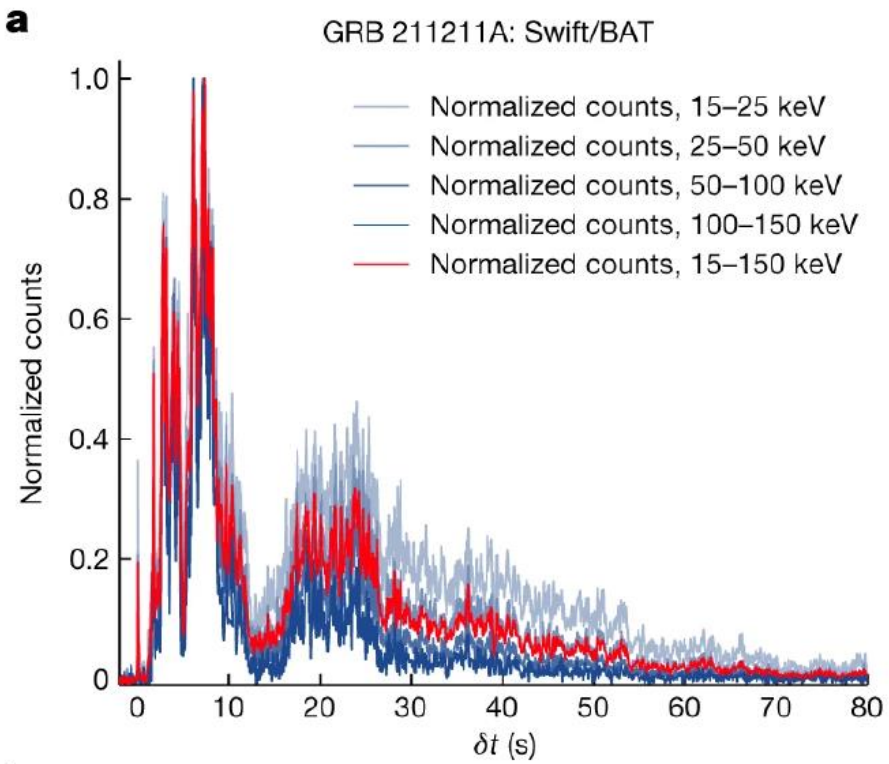
Type II (collapsar)

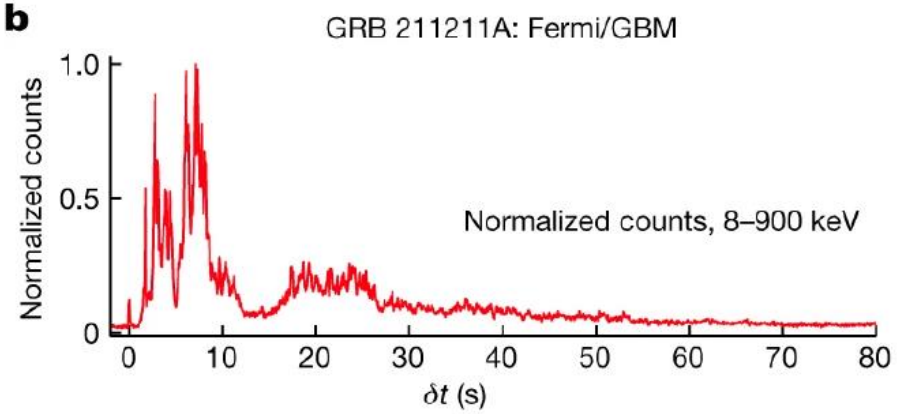
Jiang et al. 2025

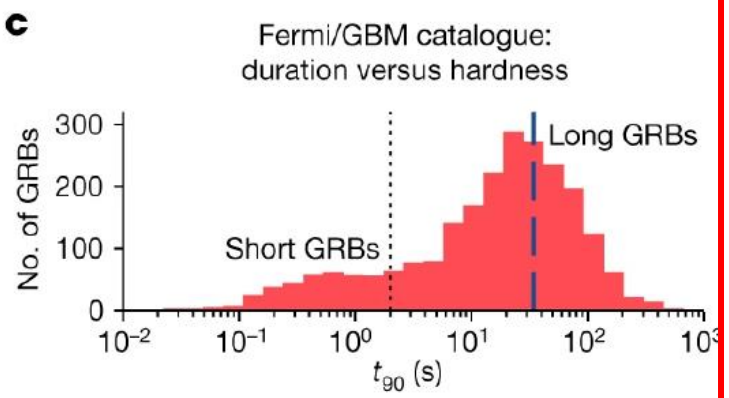


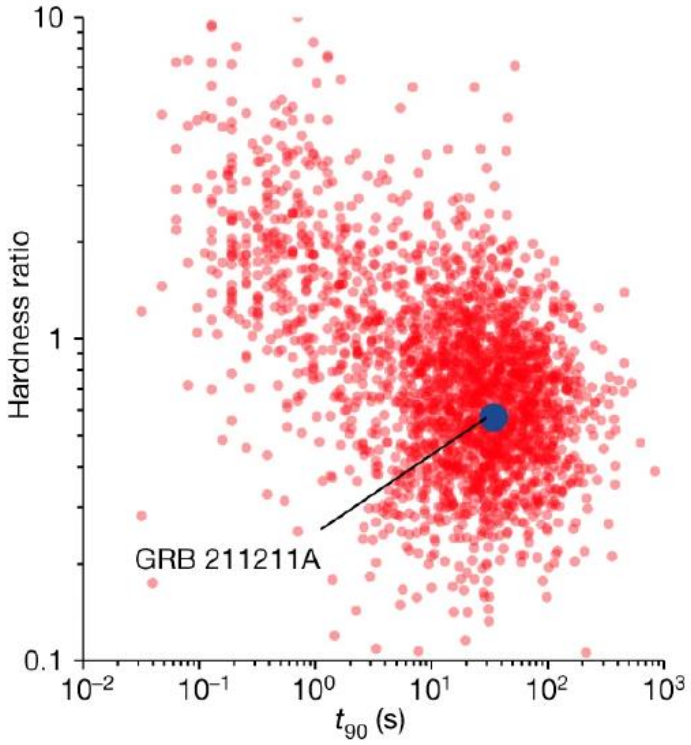
Credit: Soheb Mandhai

Rastinejad, …(incl. **Lamb**) et al. 2022







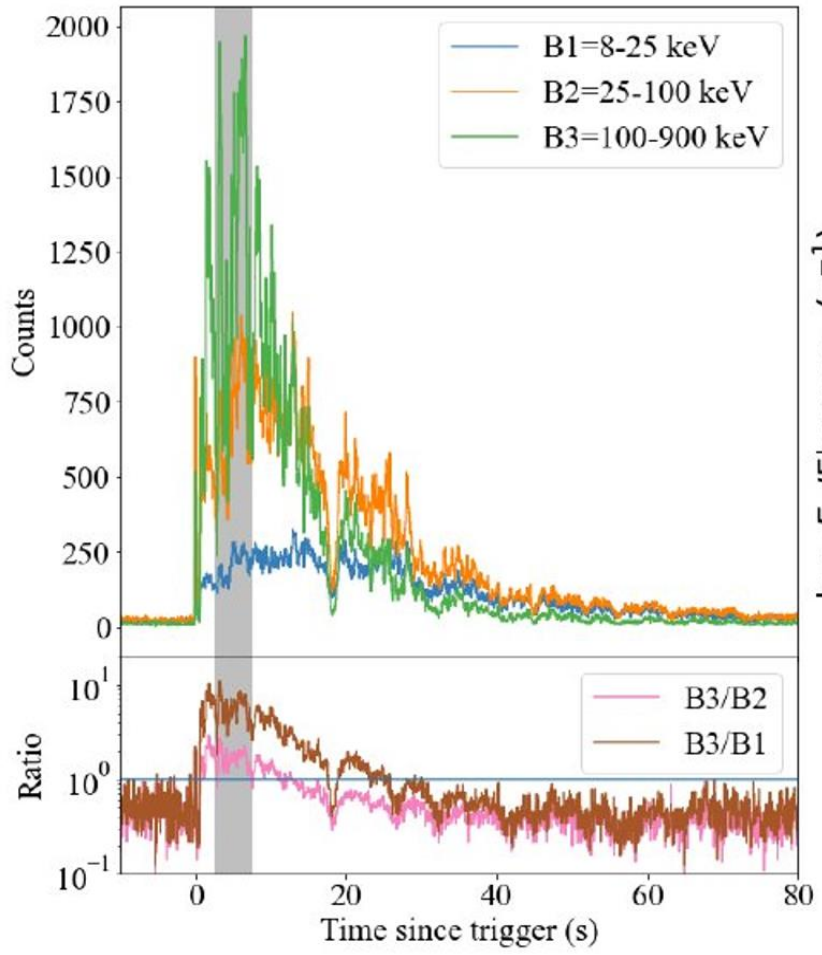


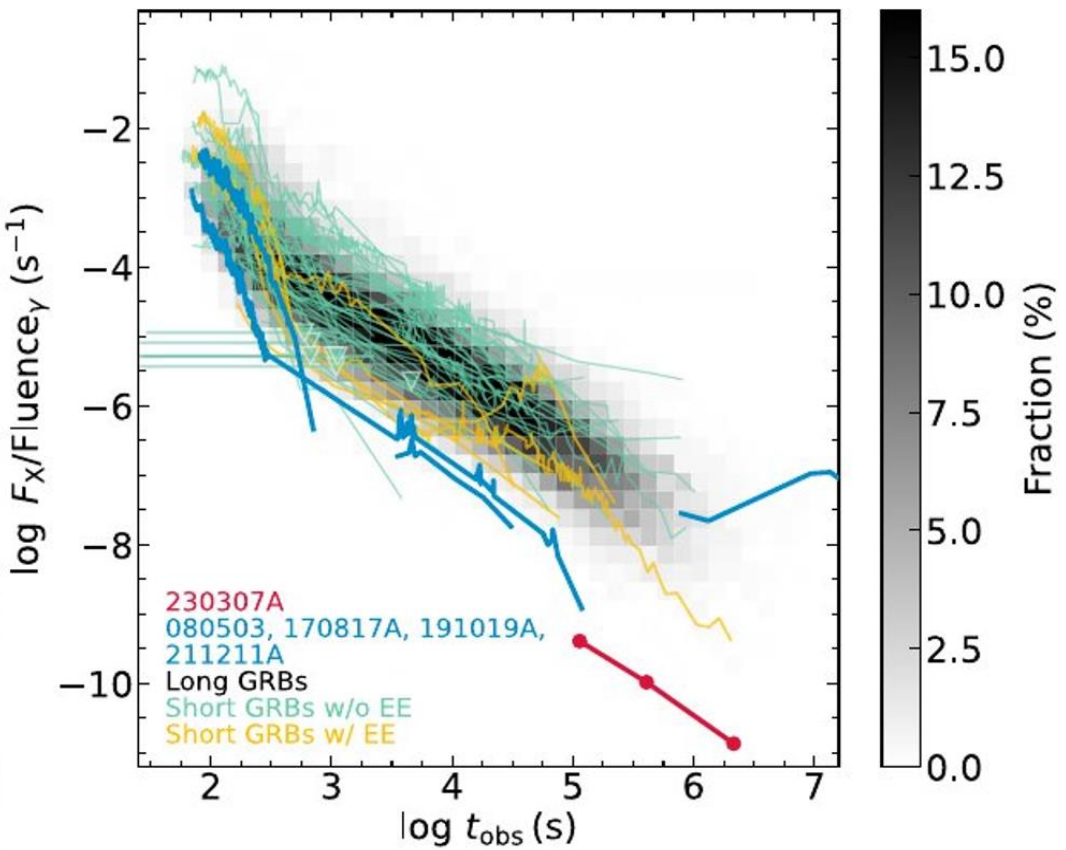
GRB 211211A sits in the middle of the long-duration GRB population, in terms of duration and spectral hardness (ratio of high to low energy within the gamma-ray emission)

So, GRB 211211A is a **long** GRB.
And as such it should be near a star forming region… and have a supernova

GRB 230307A – Another long GRB

But…





Levan (incl. **Lamb**) et al. 2023

remember Two types of GRB

TYPE I

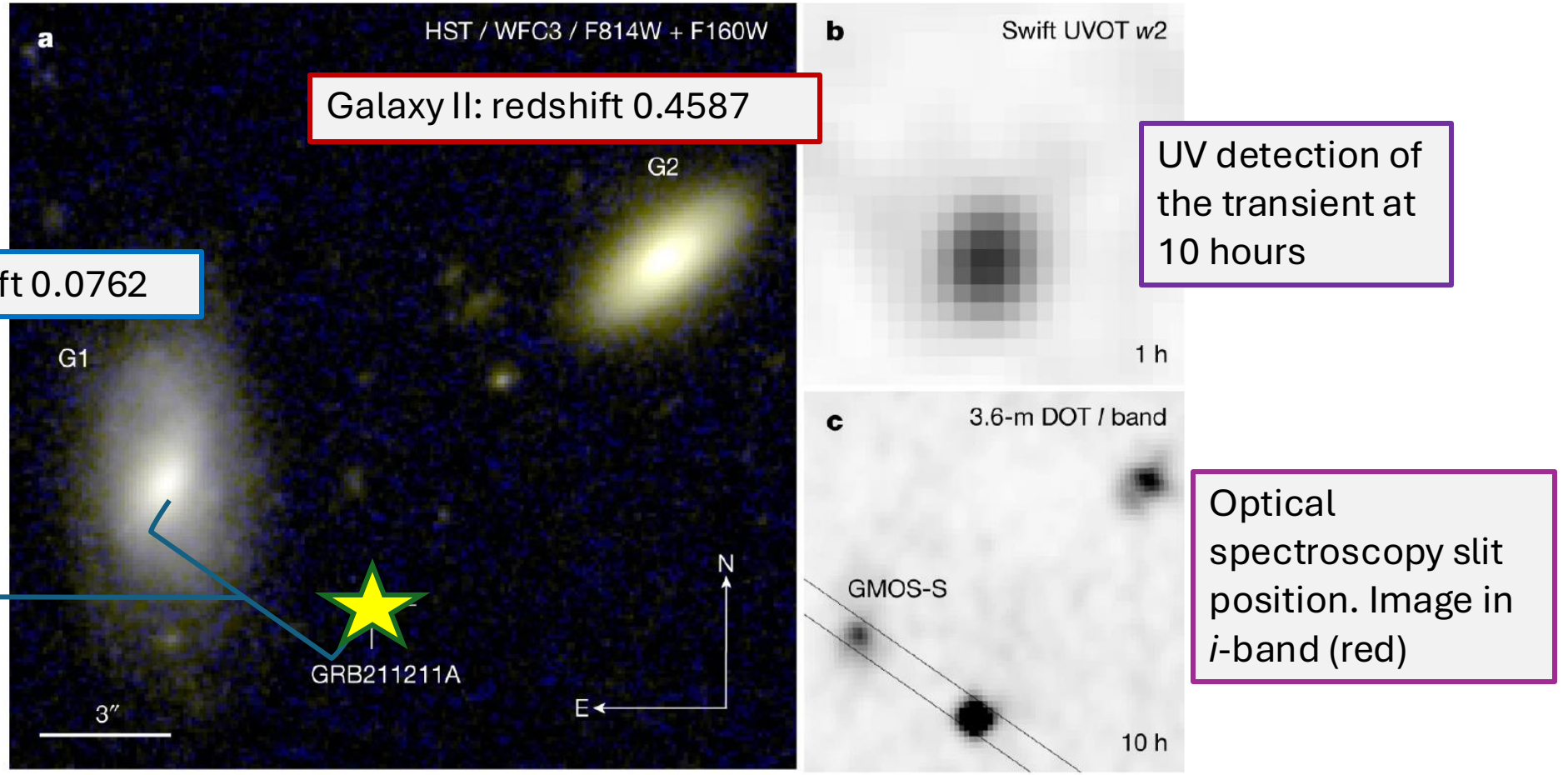
- Duration is < 2 s, **SHORT**
- Short spike then extended emission
- No supernova
- Large offset from host
- Host has low star formation rate
- Uniform medium
- Small energy

what

TYPE II

- Duration is > 2 s, **LONG**
- Spectral lag
- Supernova
- No offset from host
- Host has highstar formation rate
- Uniform or wind medium
- Large energy

GRB 211211a – our favourite assumption, in a break-up story



Galaxy II: redshift 0.4587

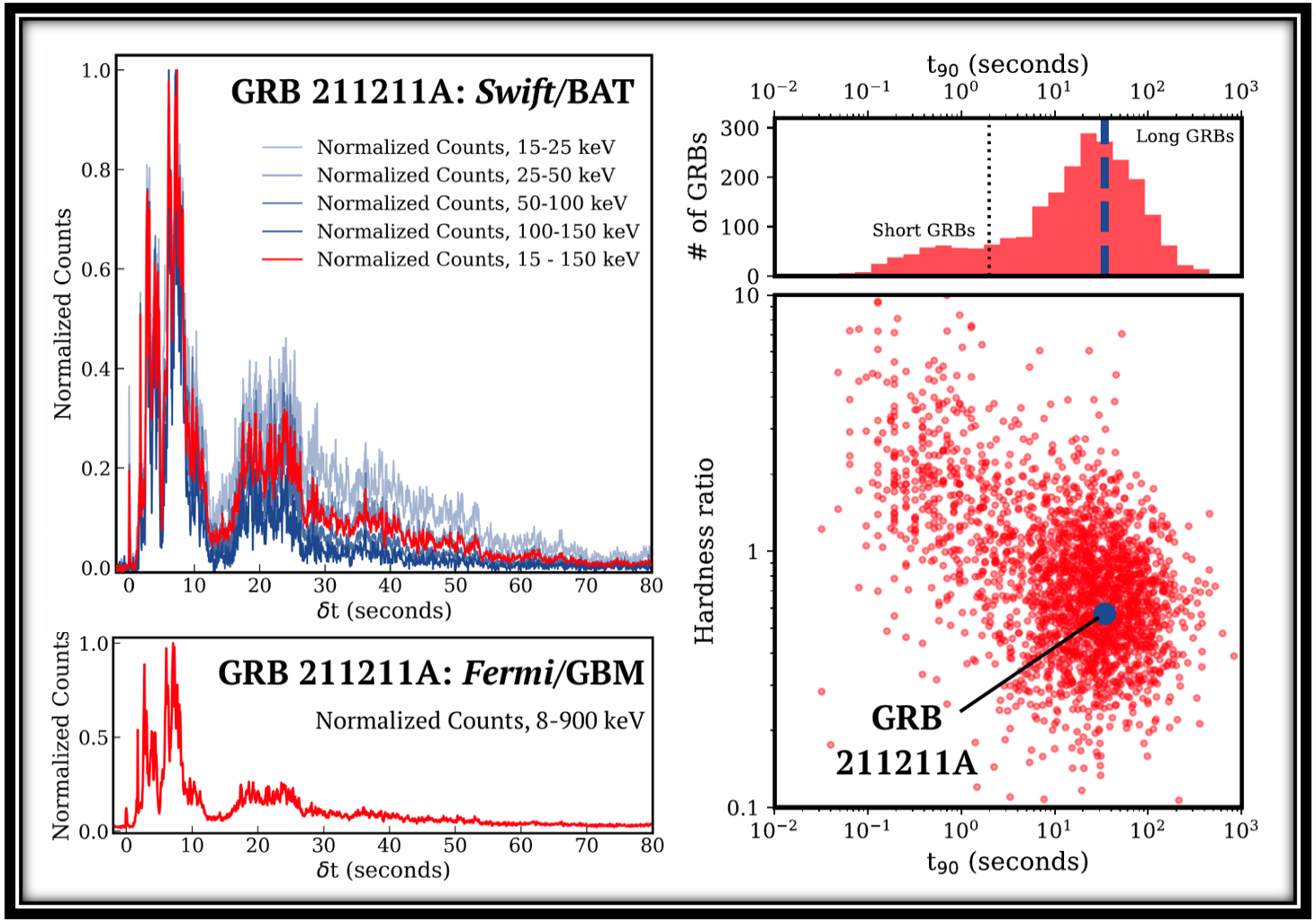
Galaxy 1: redshift 0.0762

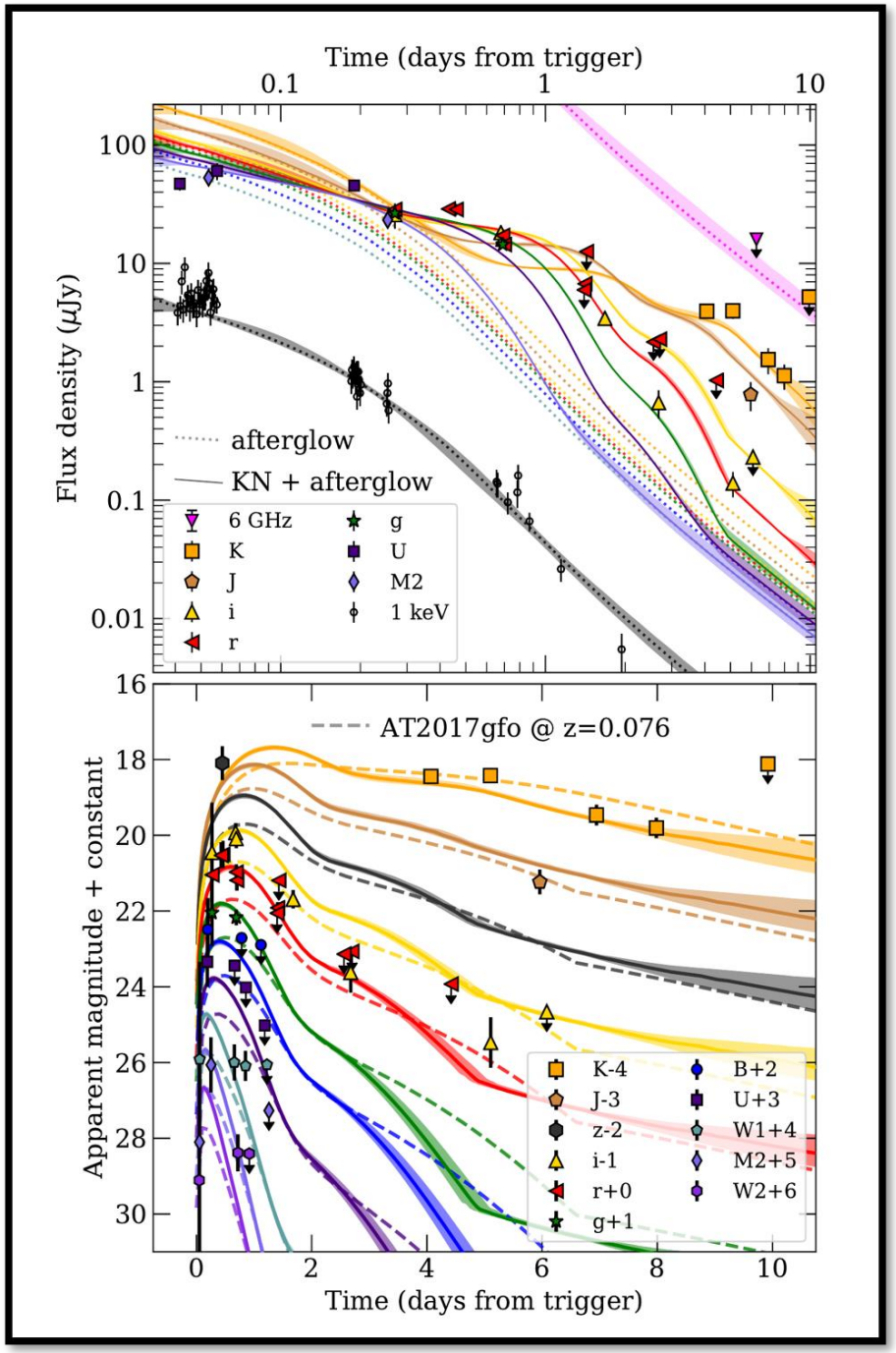
Offset (in projection) is 8 kpc for galaxy I – the largest offset for a long duration GRB

UV detection of the transient at 10 hours

Optical spectroscopy slit position. Image in *i*-band (red)

Rastinejad, …(incl. **Lamb**) et al. 2022

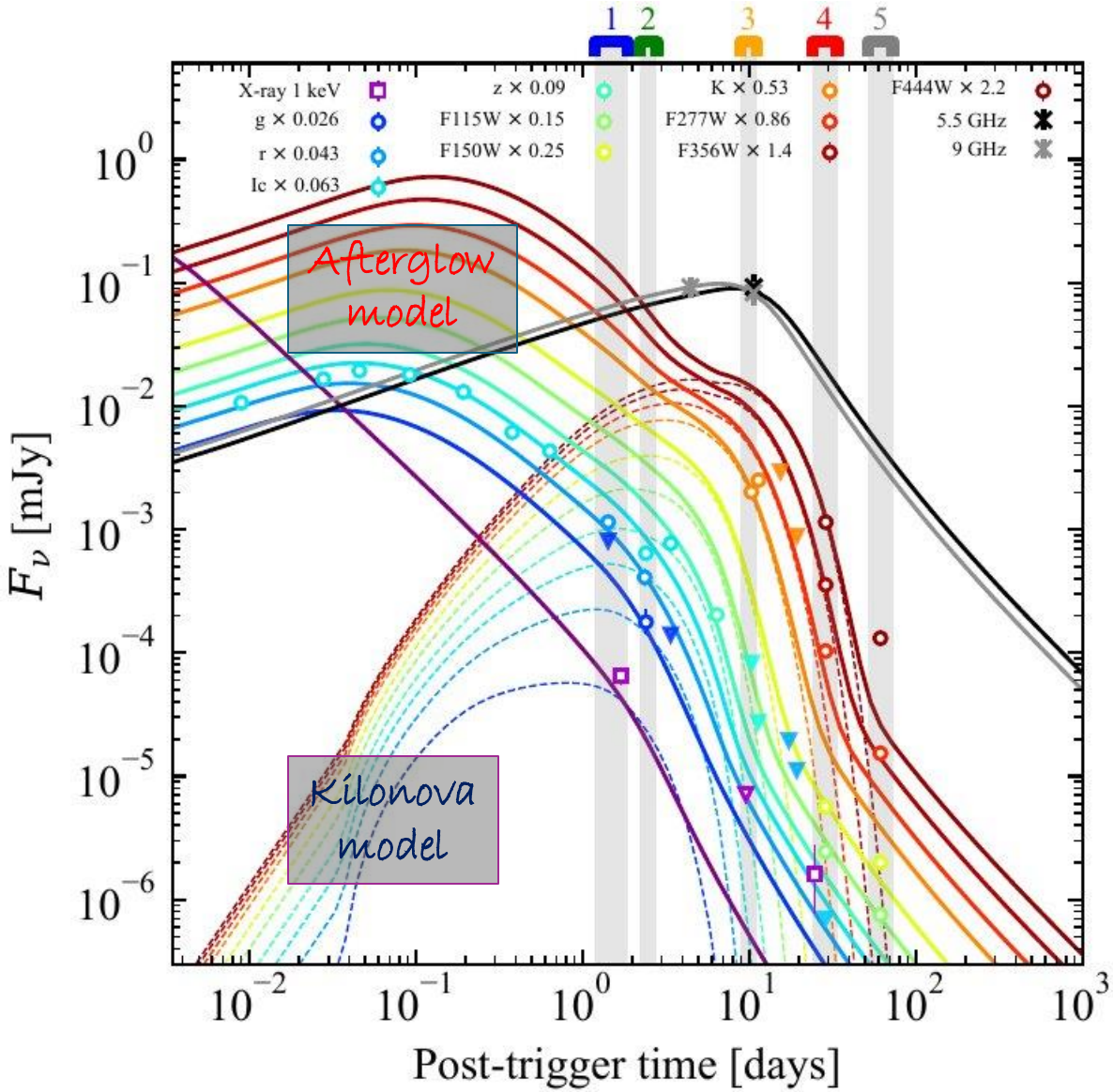


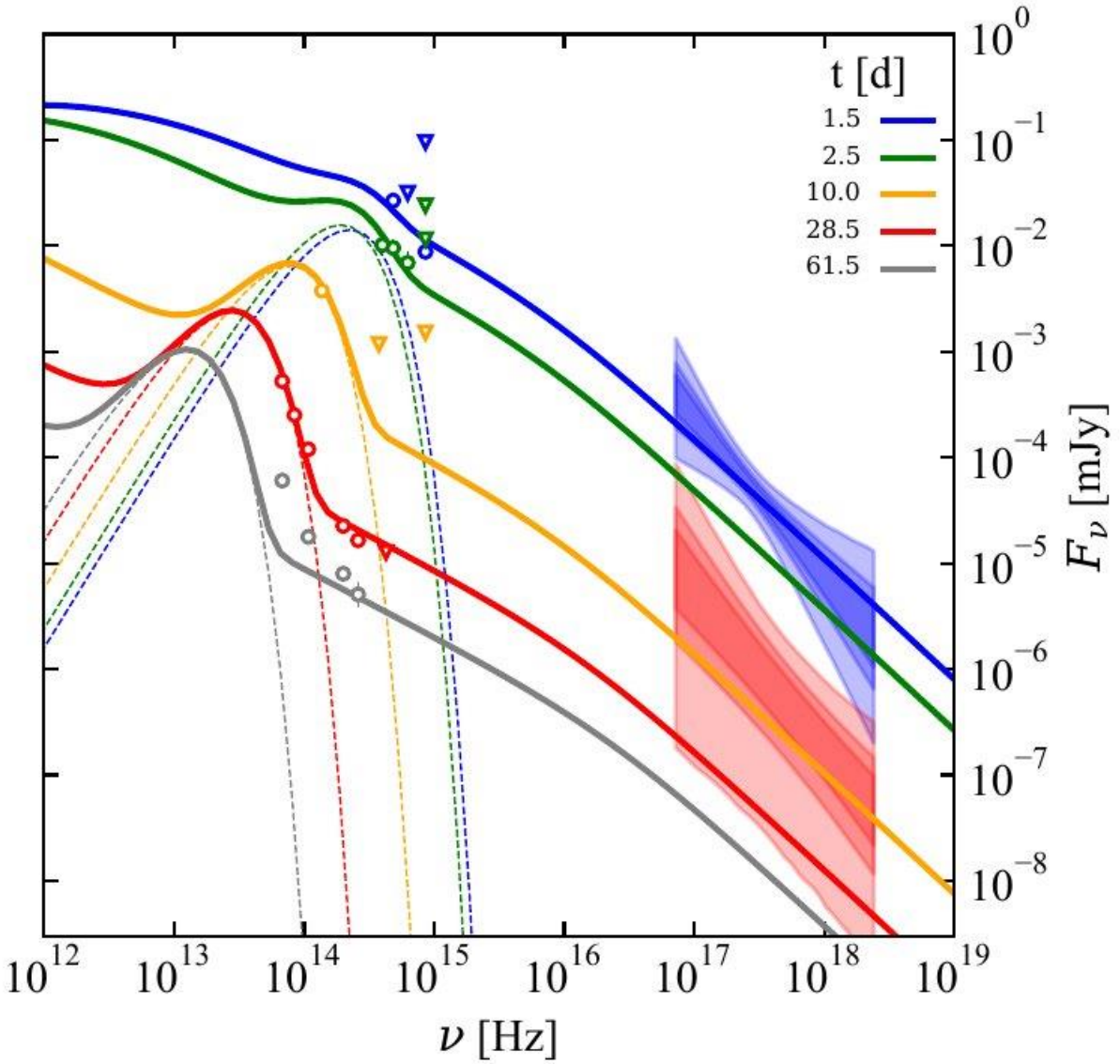


- Prompt, initial burst is >10 s
- Duration and spectral hardness, as a long 'collapsar' GRBs
- Afterglow has **excess at red** wavelengths from 4 days
- Afterglow model subtracted, looks like **AT2017gfo**
- **GRB 211211A is NOT a collapsar! Merger!?**

Rastinejad (incl. **Lamb**) et al. 2022

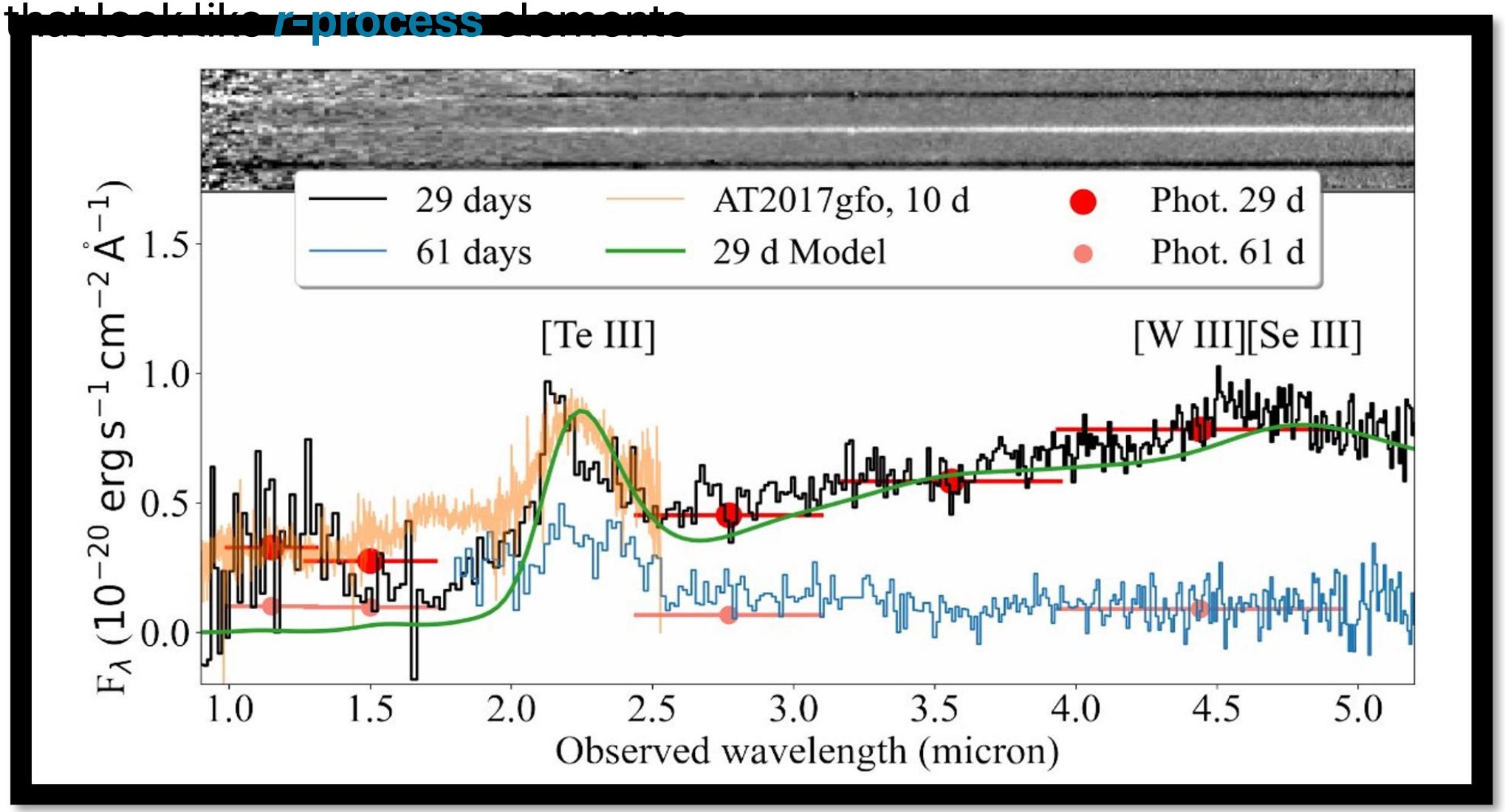
GRB 230307A tells the same story!





Levan (incl. **Lamb**) et al. 2023

GRB 230307A – and* nebular phase spectra with **JWST** reveals features that look like ***r*-process** elements



*rubbing salt in the wounds

The two GRBs that broke traditions

GRB 211211A

- GRB duration: T_{90} = 51 s
- Afterglow: ✓
- Host galaxy redshift, z = 0.0763
- Supernova: ✗
- Kilonova: ✓

GRB 230307B

- GRB duration: T_{90} = 35 s
- Afterglow: ✓
- Host galaxy redshift, z = 0.0646
- Supernova: ✗
- Kilonova: ✓

LIGO/Virgo/Kagra were all turned off at the time of both these events

On wibbly-wobbly pre-cursors

Another distraction...

The Peculiar Precursor of a Gamma-Ray Burst from a Binary Merger Involving a Magnetar

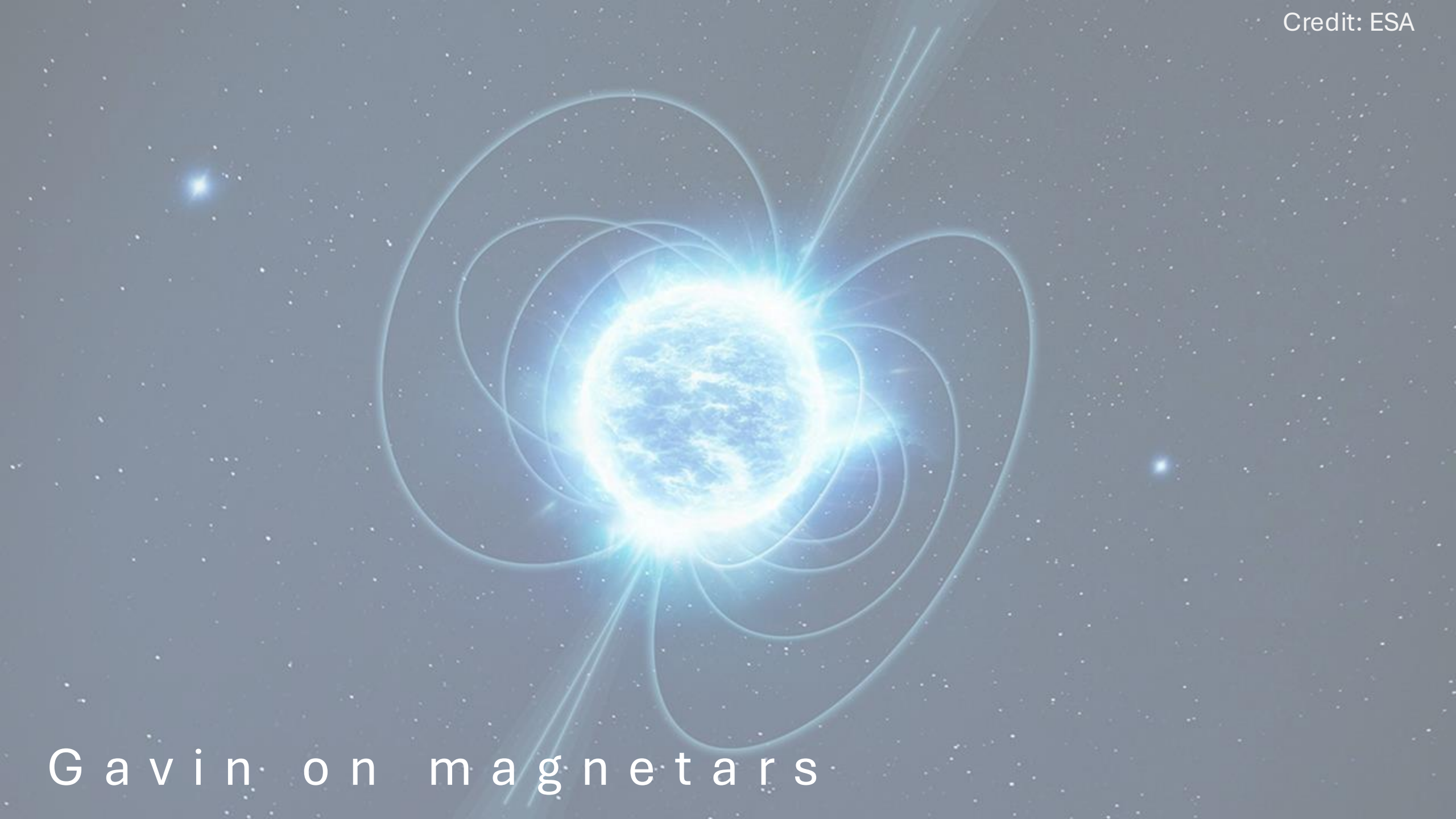
Power

Shuo Xiao[1,2,3], Yan-Qiu Zhang[2,3], Zi-Pei Zhu[4,5], Shao-Lin Xiong[2], He Gao[6], Dong Xu[4], Shuang-Nan Zhang[2], Wen-Xi Peng[2], Xiao-Bo Li[2], Peng Zhang[7], Fang-Jun Lu[2], Lin Lin[6], Liang-Duan Liu[8], Zhen Zhang[2], Ming-Yu Ge[2], You-Li Tuo[2], Wang-Chen Xue[2,3], Shao-Yu Fu[4], Xing Liu[4,9], Jin-Zhong Liu[10,11], An Li[6], Tian-Cong Wang[6], Chao Zheng[2,3], Yue Wang[2], Shuai-Qing Jiang[4], Jin-Da Li[6], Jia-Cong Liu[2,3], Zhou-Jian Cao[6], Xi-hong Luo[1], Jiao-jiao Yang[1], Shu-Xu Yi[2], Xi-Lu Wang[2], Ce Cai[2,3,12], Qi-Bin Yi[2,13], Yi Zhao[2,6], Sheng-Lun Xie[2,8], Cheng-Kui Li[2], Qi Luo[2,3], Li-Ming Song[2], Shu Zhang[2], Jin-Lu Qu[2], Cong-Zhan Liu[2], Xu-Fang Li[2], Yu-Peng Xu[2], and Ti-Pei Li[2,3,14]

Abstract

The milestone discovery of GW170817-GRB 170817A-AT 2017gfo has shown that gravitational waves (GWs) could be produced during the merger of a neutron star–neutron star/black hole and that in electromagnetic (EM) waves, a gamma-ray burst (GRB) and a kilonova (KN) are generated in sequence after the merger. Observationally, however, EM properties before the merger phase are still unclear. Here we report a peculiar precursor in a KN-associated long-duration GRB 211211A, providing evidence of the EM before the merger. This precursor lasts ∼0.2 s, and the waiting time between the precursor and the main burst is ∼1 s, comparable to that between GW170817 and GRB 170817A. The spectrum of the precursor could be well fit with a nonthermal cutoff power-law model instead of a blackbody. In particular, a ∼22 Hz quasiperiodic oscillation candidate (∼3σ) is detected in the precursor. These temporal and spectral properties indicate that this precursor is probably produced by a catastrophic flare accompanied with magnetoelastic or crustal oscillations of a magnetar in a binary compact merger. The strong magnetic field of the magnetar can also account for the prolonged duration of GRB 211211A. However, it poses a challenge to reconcile the rather short lifetime of a magnetar with the rather long spiraling time of a binary neutron star system only by the GW radiation before the merger.

A MAGNETAR DID IT!!!!

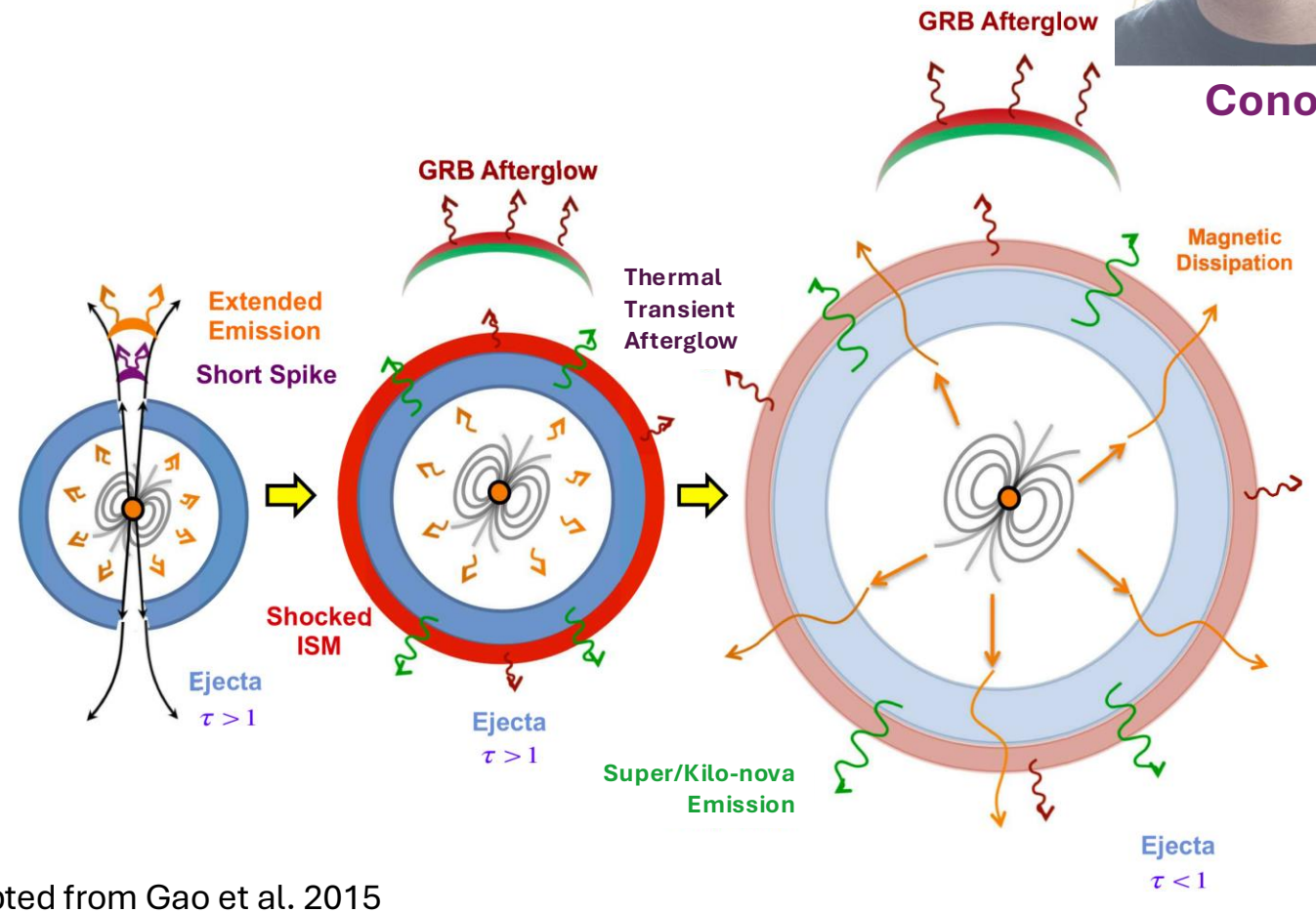


Gavin on magnetars

See and talk to Conor Omand
He's here (looking less like a pirate) and his work is mostly on magnetars

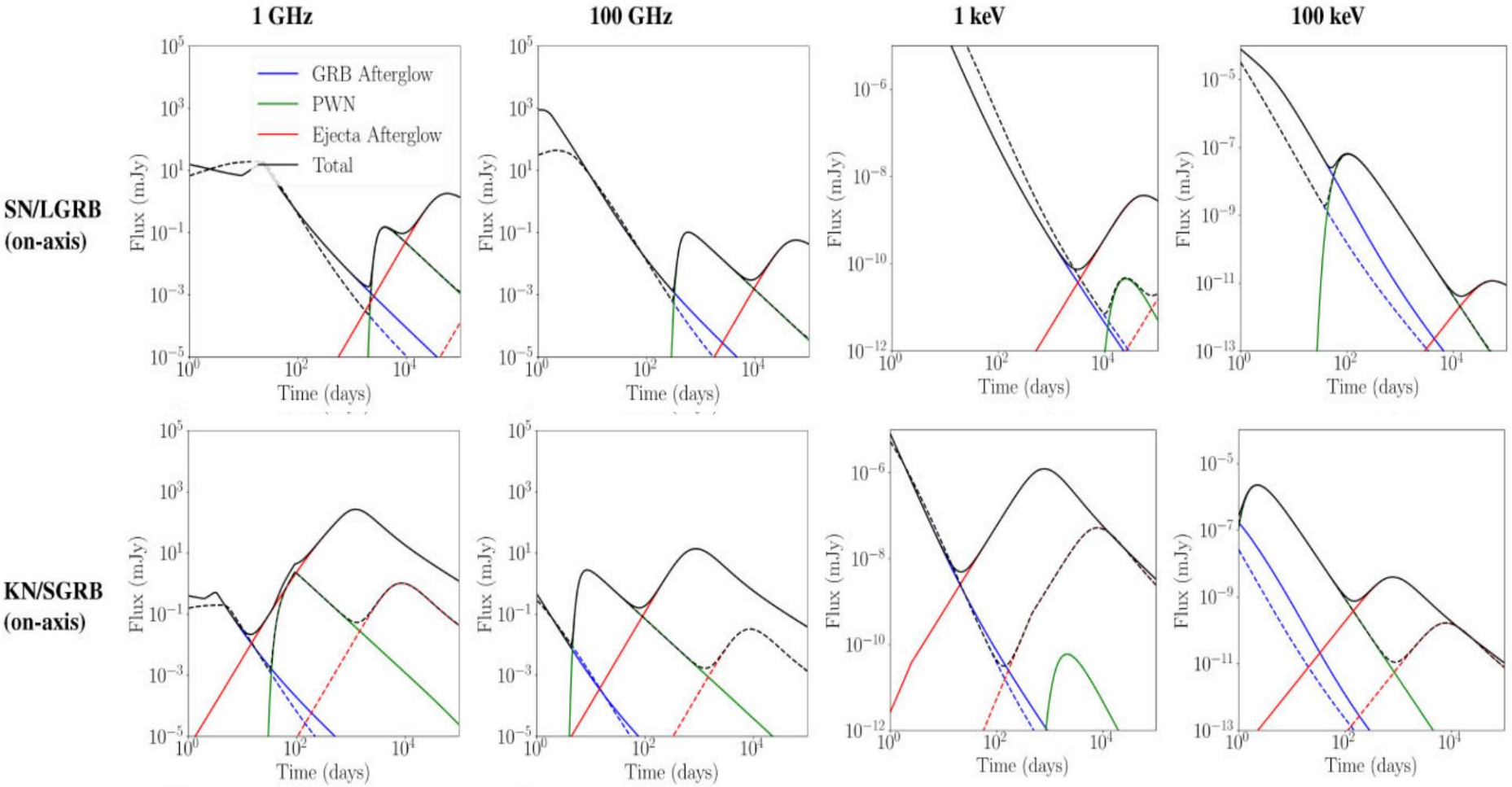
Conor Omand

- Magnetars are highly magnetised, "new" neutron stars
- Both collapsars and mergers can result in magnetar formation
- Unlike a black-hole central engine, a magnetar will produce a "pulsar wind nebular"
- This can create additional transients on the timescale of the afterglow



Adapted from Gao et al. 2015

THE TIME I JOINED IN...



Conor Omand

- Radio and X-ray transients from the ejecta and pulsar wind nebula (PWN)
- PWN from 6 years for SNe-GRBs, and 100 days for KNe-GRB
- X-ray may contribute at late times from ejecta afterglow *and* PWN

Omand, Sarin & **Lamb** 2025

An aside on an aside...
Searching for a magnetar after GRB 211211A

No Sign of a Magnetar Remnant Following the Kilonova-Producing Long GRB 211211A ~ 1.7 Years Later

Genevieve Schroeder,[1] Ben Margalit,[2] Brian D. Metzger,[3,4] Wen-fai Fong,[5] Benjamin P. Gompertz,[6,7] Kate D. Alexander,[8] Edo Berger,[9] Tanmoy Laskar,[10,11] Gavin P. Lamb,[12] Andrew Levan,[13] Charles D. Kilpatrick,[5] and Jillian C. Rastinejad[14,*]

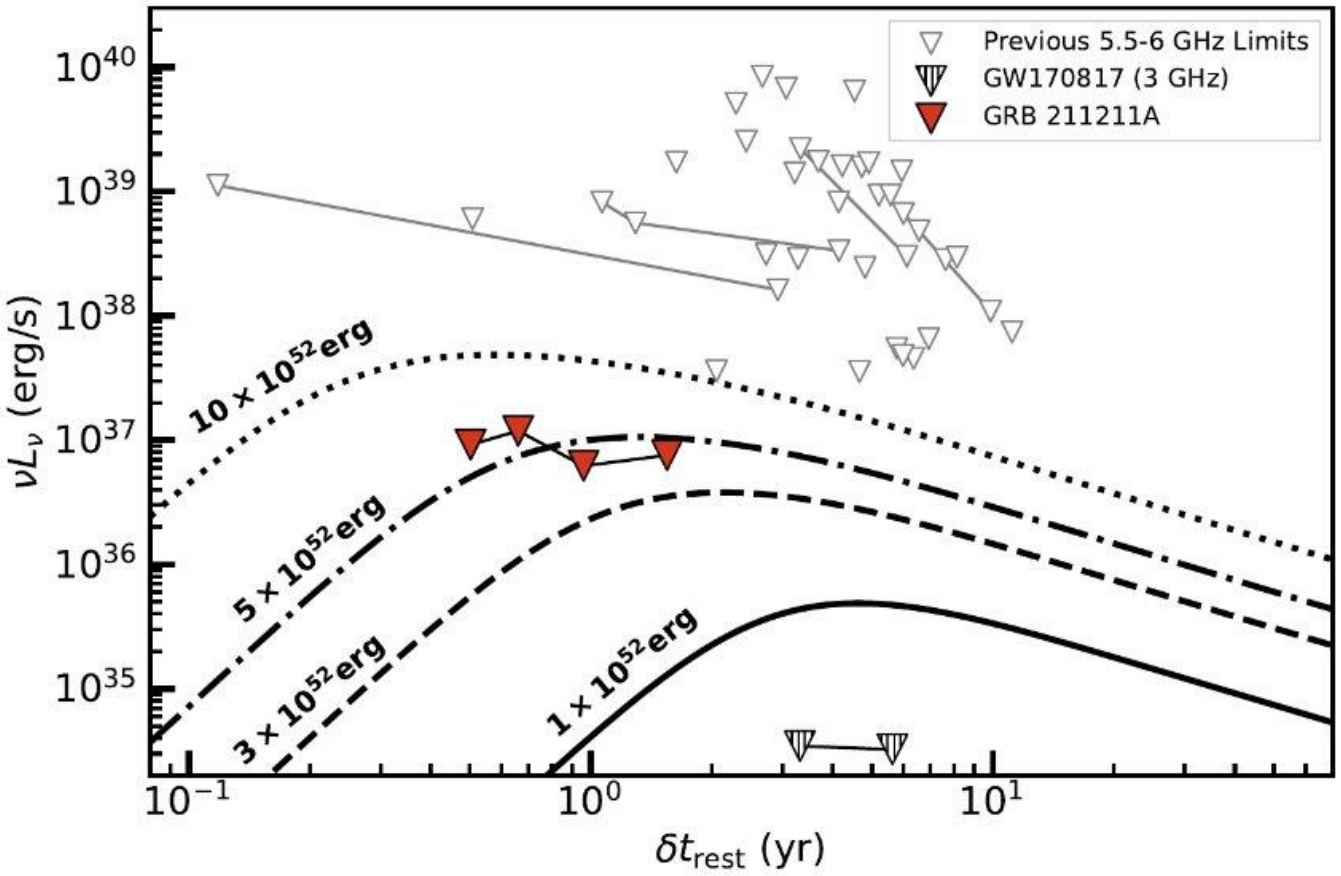
ACCEPTED

An aside on an aside…
Searching for a magnetar after GRB 211211A

ACCEPTED

No Sign of a Magnetar Remnant Following the Kilonova-Producing Long GRB 211211A ∼ 1.7 Years Later

Genevieve Schroeder,[1] Ben Margalit,[2] B
Kate D. Alexander,[8] Edo Berger,[9]
Charles D. Kilpa'



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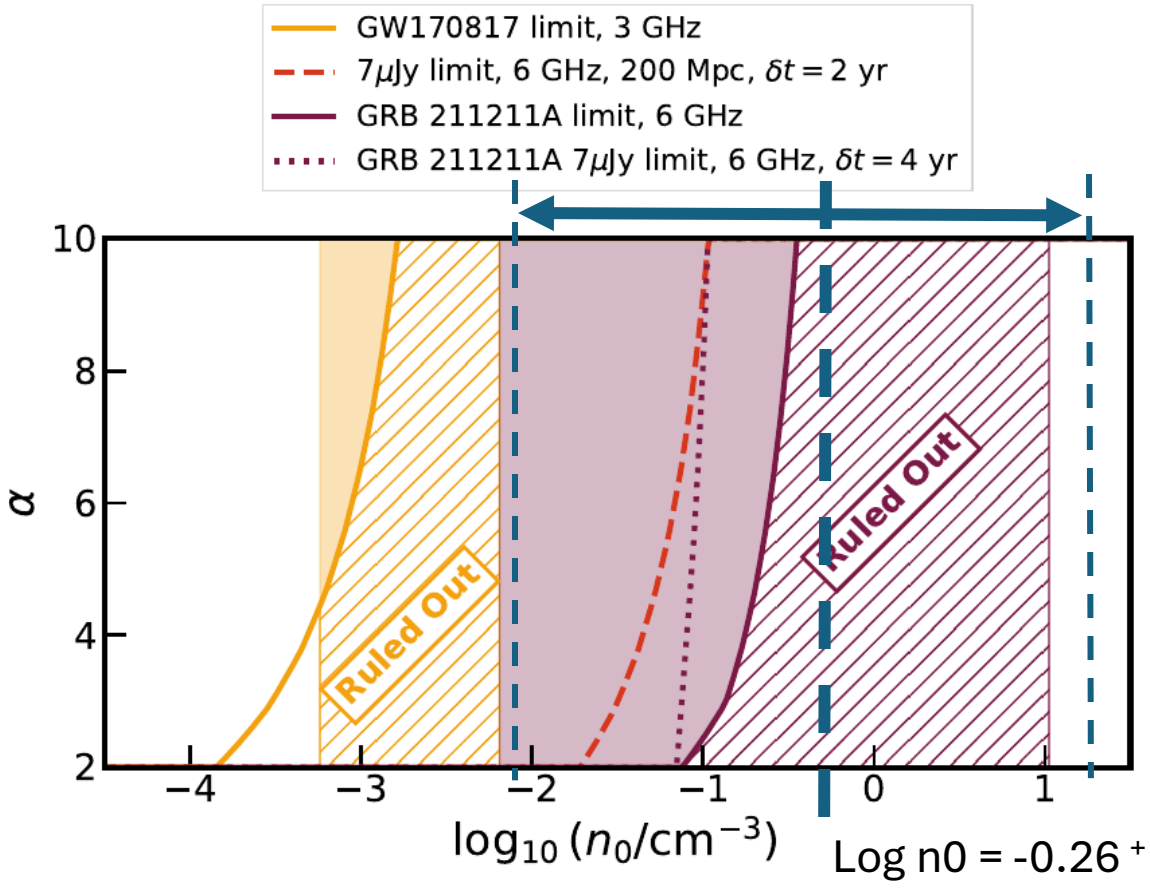
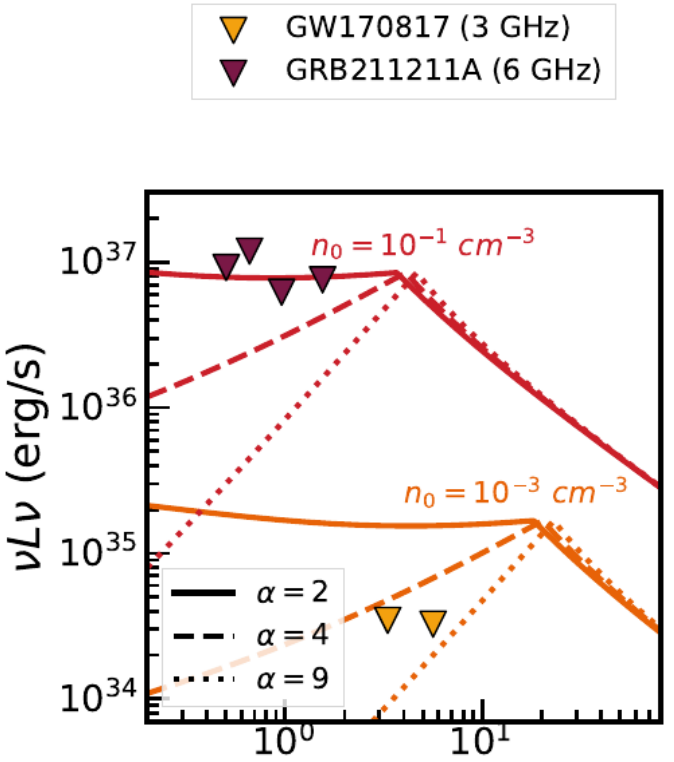


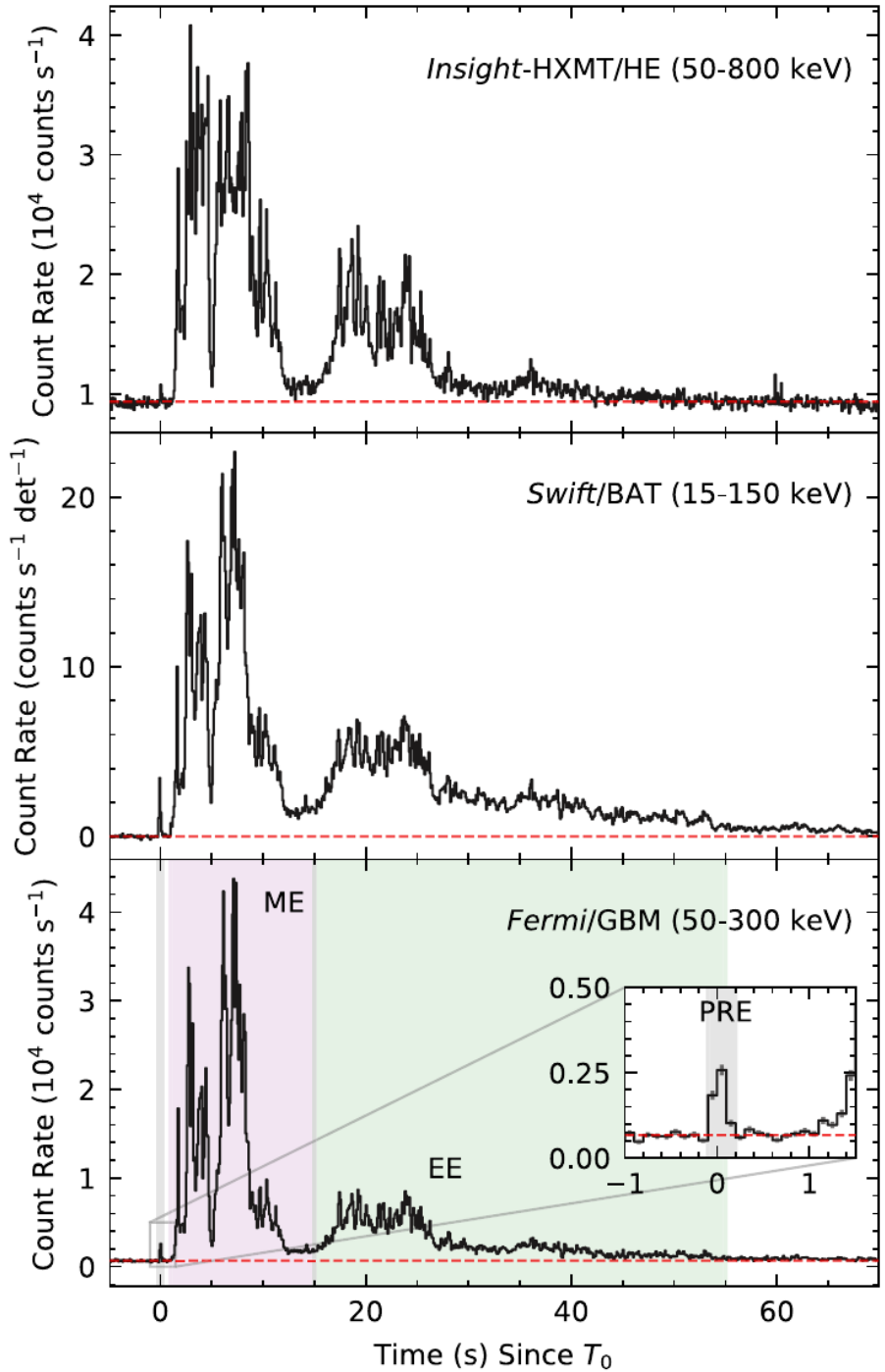
Log n0 = -0.26 $^{+1.29}_{-1.93}$

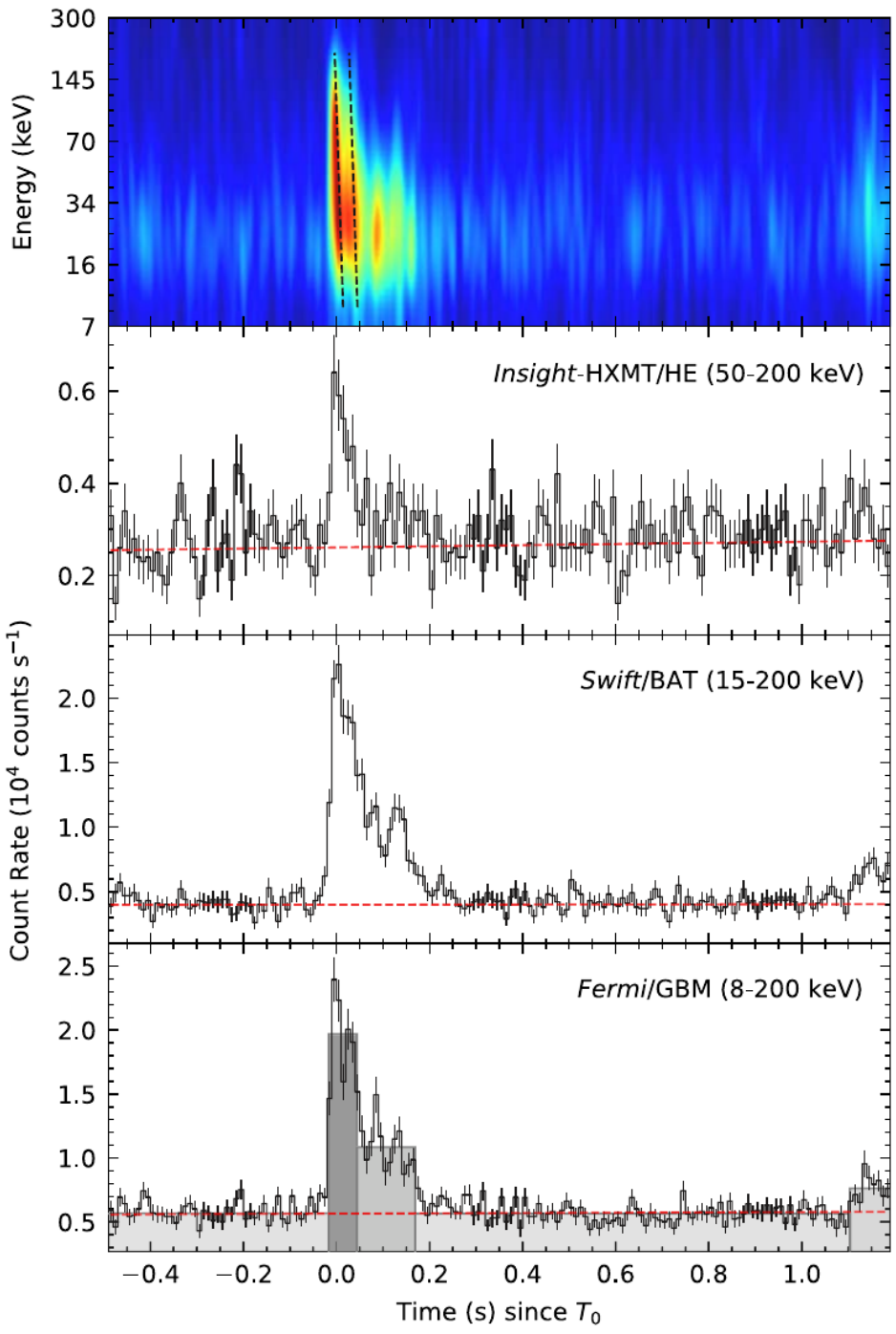


Rastinejad (incl. **Lamb**) et al. 2022

The radio results are the best we could get…
…but even I admit that they're not the most constraining

Schroeder (incl. **Lamb**) et al. 2026





Xiao et al. 2024

First checks…
is it there?

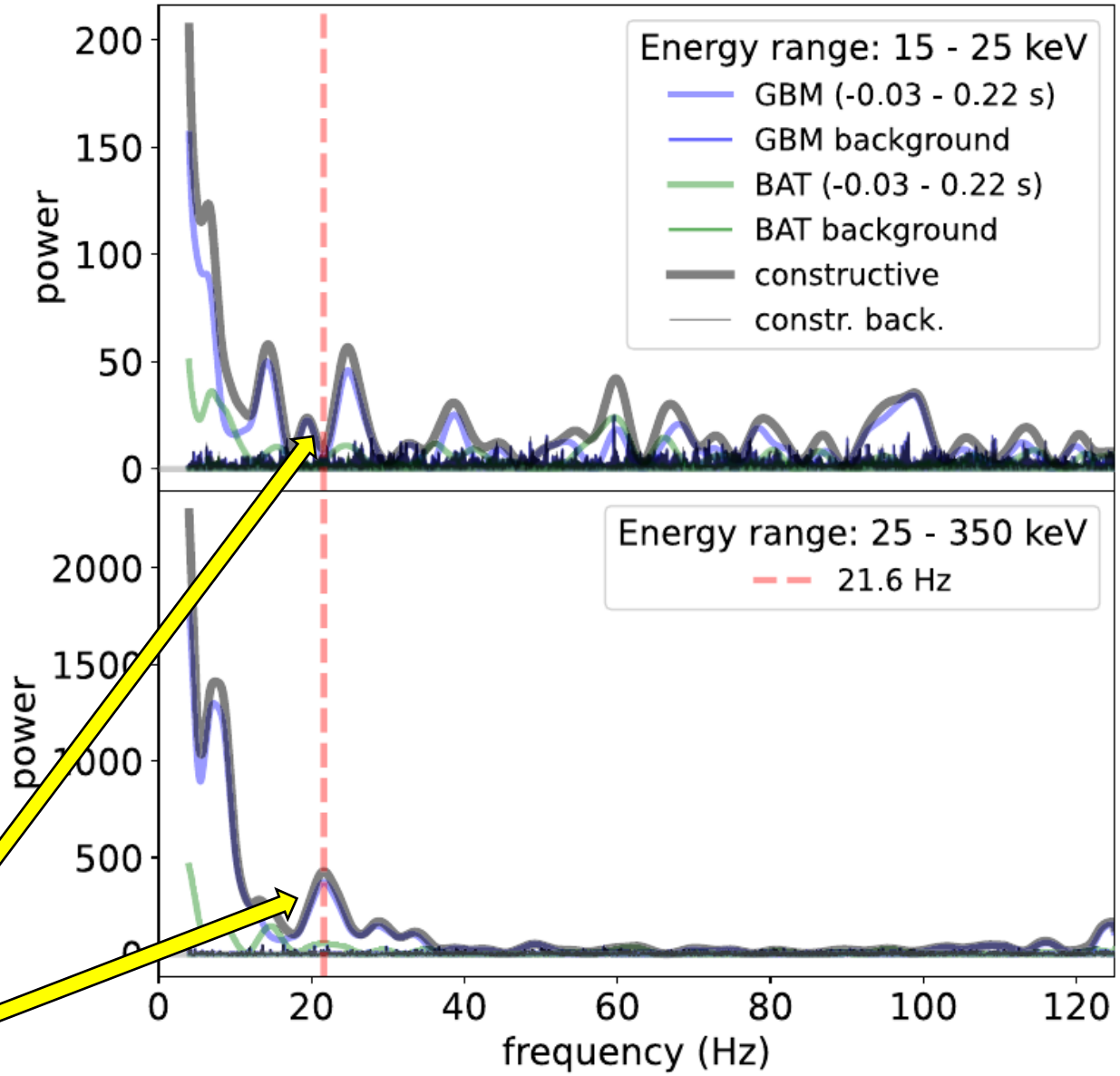
Lomb-Scargle periodogram of 4ms binned Fermi GBM and Swift BAT precursor data in the energy ranges 15-25 keV and 25-350 keV

Duration of data: -0.03 to 0.22 s

Frequency range: 4 – 125 Hz

Low (15-25 keV): **No periodicity**

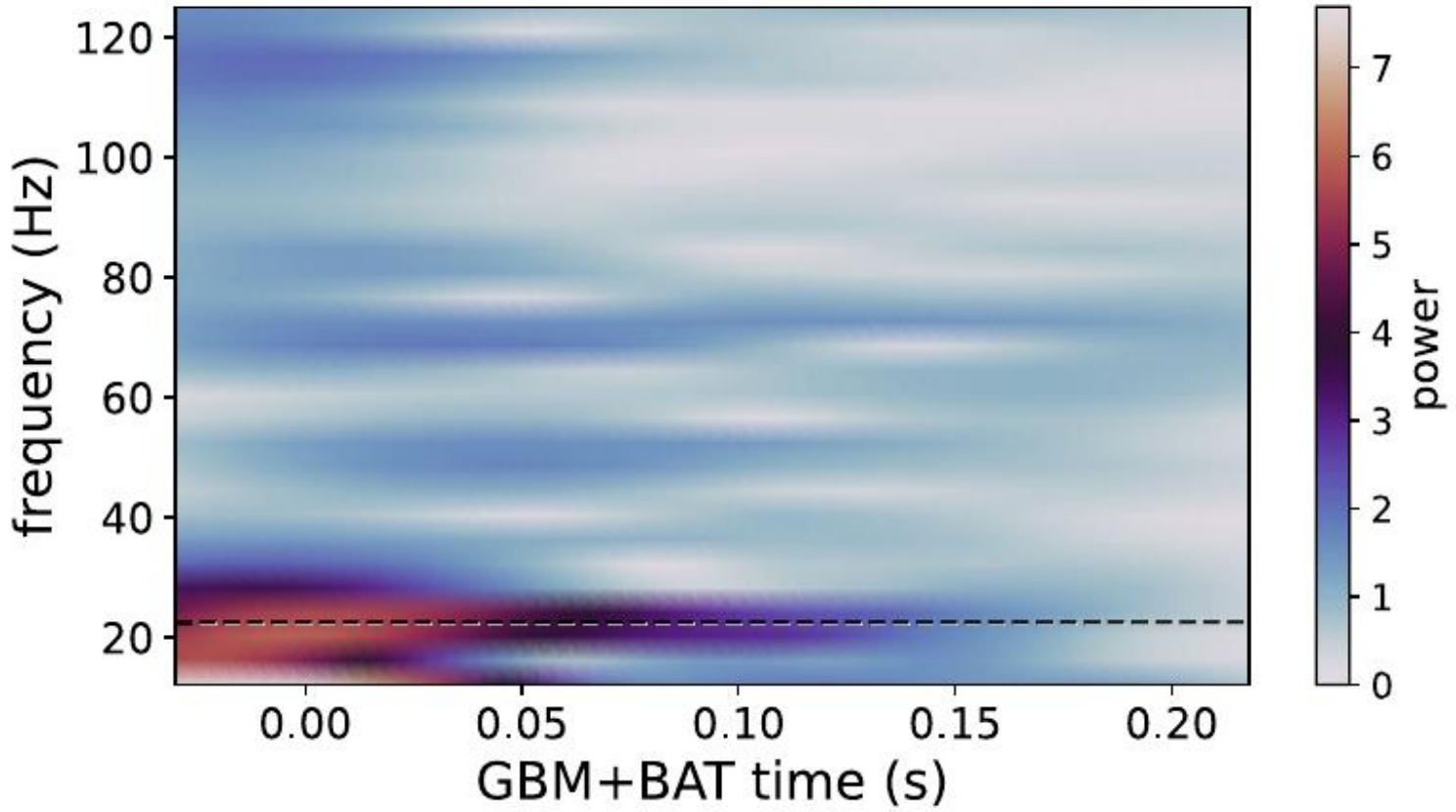
High (25-350 keV): **Yes, at 21.6 Hz**



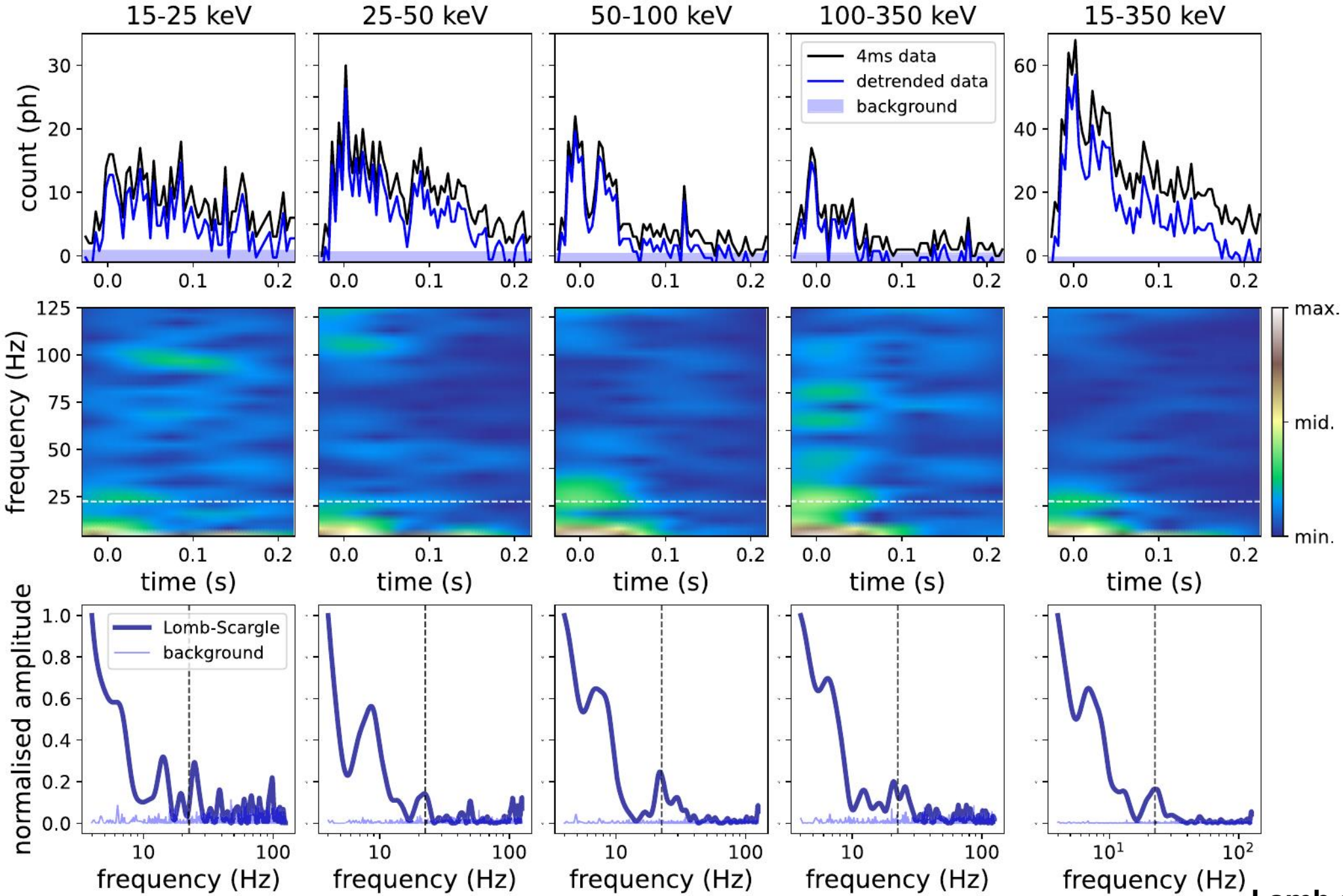
Lamb et al. 2025

...and with time?

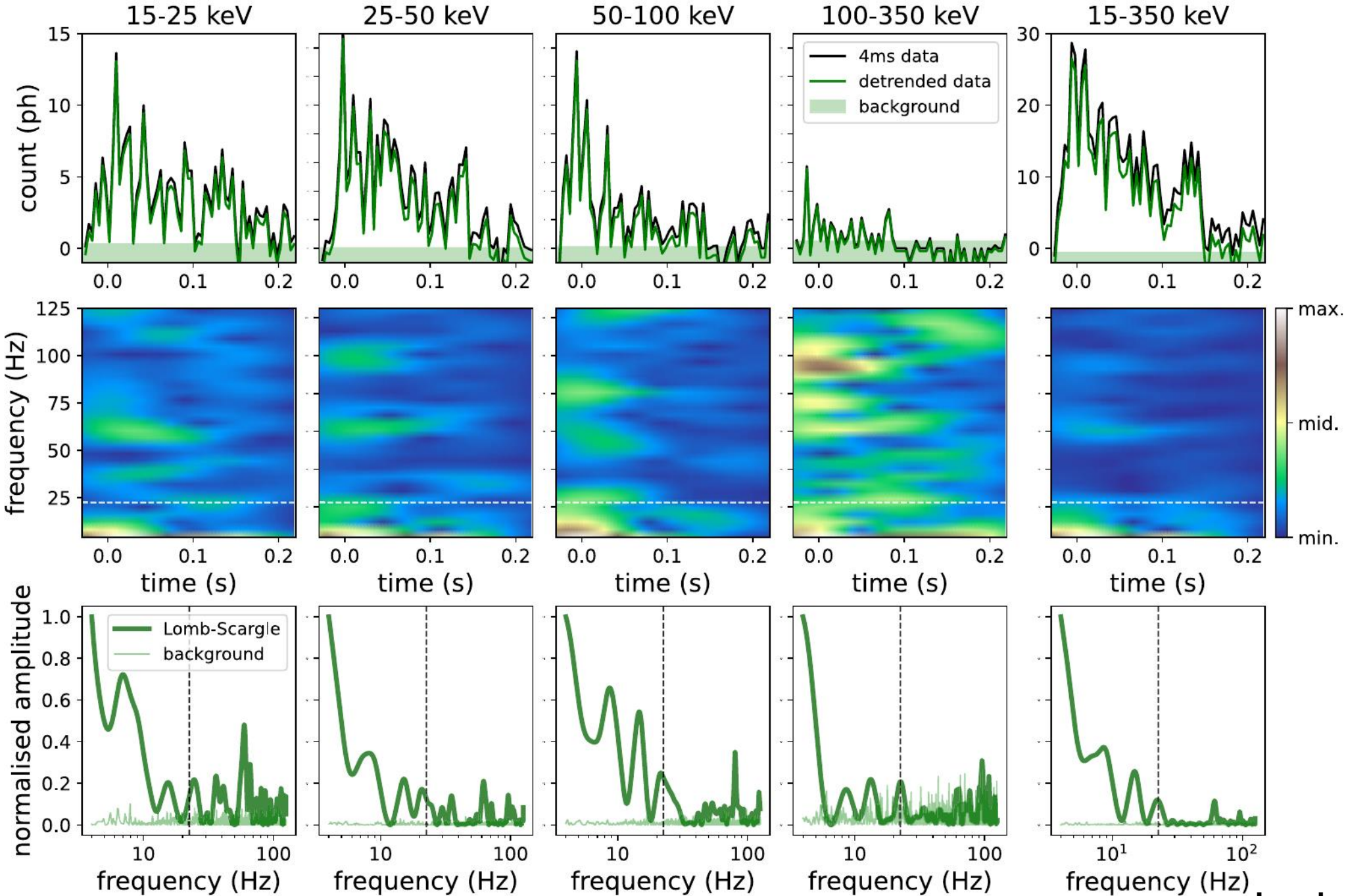
- A **Short Time Fourier Transform** (STFT)
  - **Hanning window** at each 4ms bin centroid
  - Individual **Power Spectral Density** (PSD)
  - PSD at each step is dominated by signal centred on the time step
  - Combine in time-frequency-power



Lamb et al. 2025



Lamb et al. 2025



Lamb et al. 2025

What makes the precursor wobble?

We consider one of two engines:

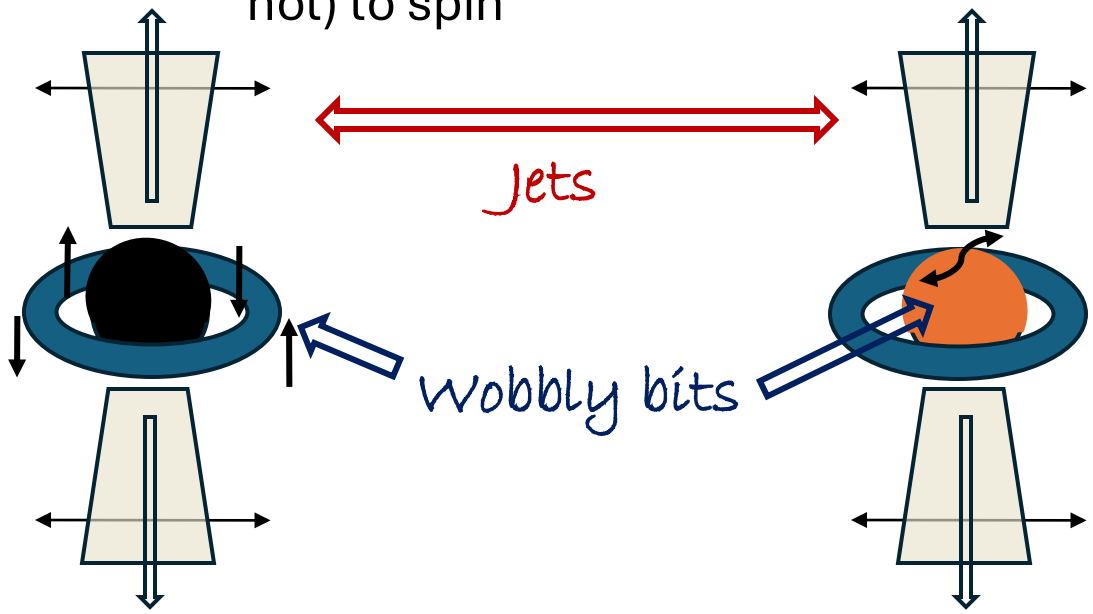
1. Stellar mass black hole
2. Magnetar engine

BLACK HOLE ENGINE CASE

- Minimum variability timescale and required Lorentz factor – jet origin to emission
- Periodicity – jet is coupled to the precession mechanism
- Blandford-Znajek jet
- Precession process:
  - **Lense-Thirring**
  - **Keplerian motion** – discoseismology, orbital resonance, blobs
  - Magnetohydrodynamic (MHD) **magnetototational instability** (MRI)

MAGNETAR ENGINE CASE

- Newly formed magnetars have rapid rotation and strong magnetic fields
- Periodicity in a jet will be coupled to the precession mechanism
- Precession process:
  - **Alfven waves in magnetosphere**
  - **Dipole radiation** coupled (or not) to spin

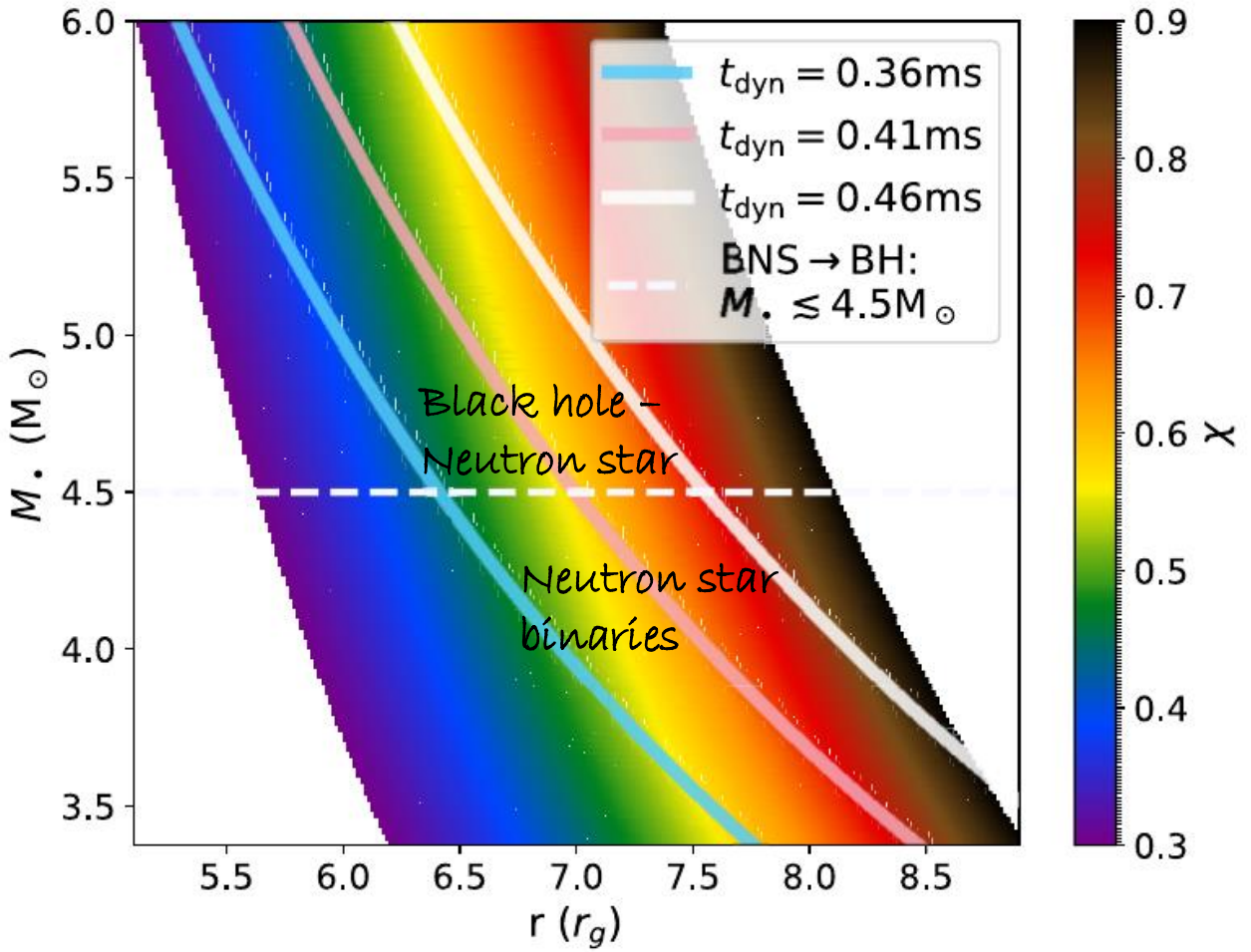


Lense-Thirring

Lense–Thirring (LT) precession is the result of frame dragging within the disc of a black hole with spin $\chi > 0$

Precession at 22 Hz

$$\nu_{\rm LT} = \frac{\omega_{\rm LT}}{2\pi} = \frac{\chi G^2 M_\bullet^2}{\pi c^3 r_{\rm id}^3},$$



Size of LT participation

$$\Delta r \simeq \frac{r}{3\nu_{\rm LT} t_{\rm coh}},$$

Coherence timescale

Damping timescale = viscous time

$$t_{\rm visc} \simeq \begin{cases} \frac{r^2}{\alpha c_s h} & \text{thin disc,} \\ \frac{r}{\alpha c_s} & \text{thick disc,} \end{cases}$$

Lamb et al. 2025

Keplerian

Discoseismology; p and g modes

Blobs oscillate at the Keplerian frequency

pressure

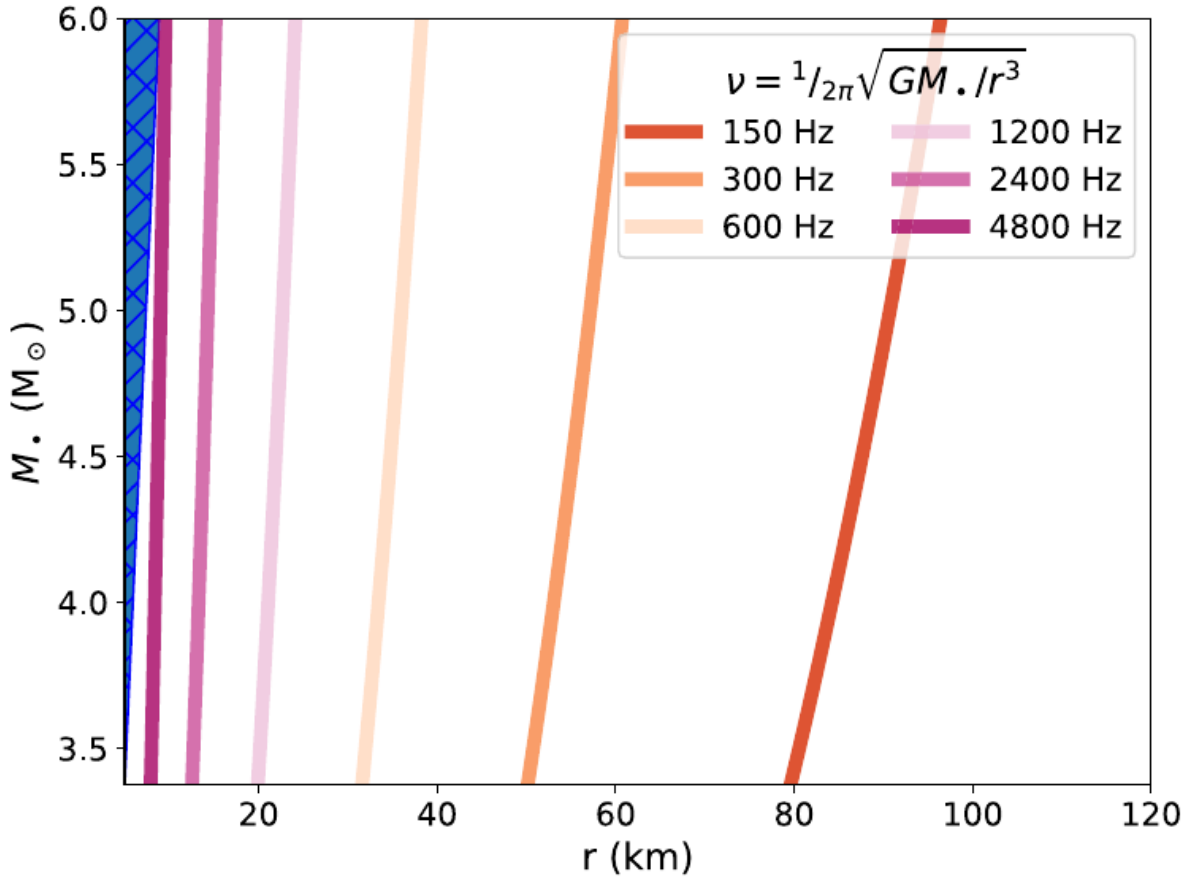
$$\nu_{\mathrm{p-mode}} \simeq \frac{1}{2\pi}\sqrt{\frac{GM_\bullet}{r^3}} = \frac{\omega_{\mathrm{K}}(r)}{2\pi} \equiv \nu_{\mathrm{K}}(r),$$

gravity

$$\nu_{\mathrm{g-mode}} \simeq \nu_{\mathrm{p-mode}}\frac{N_{BV}}{\kappa},$$

Buoyancy / Epicyclic frequency

This is > 1 for the inner radius, and goes to 1 at high radius



Given the black hole mass and radius within the disc, the QPO from the Keplerian frequency ranges from 100 to several 1000 Hz, well beyond the 22.5 Hz of the observed QPO. The blue shaded hatched region gives the lower limit on the radius, $r = r_g(M_\bullet)$.

There are other modes: radial, orbital and vertical – all are equal to or higher than the Keplerian frequency

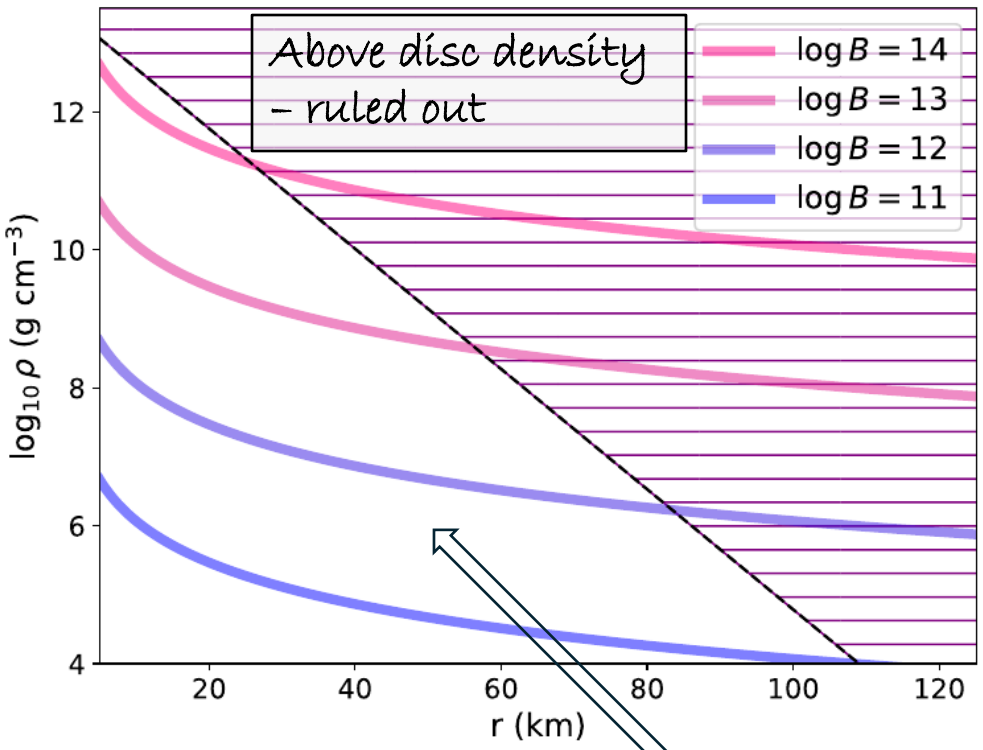
Magnetohydrodynamic

wavenumber

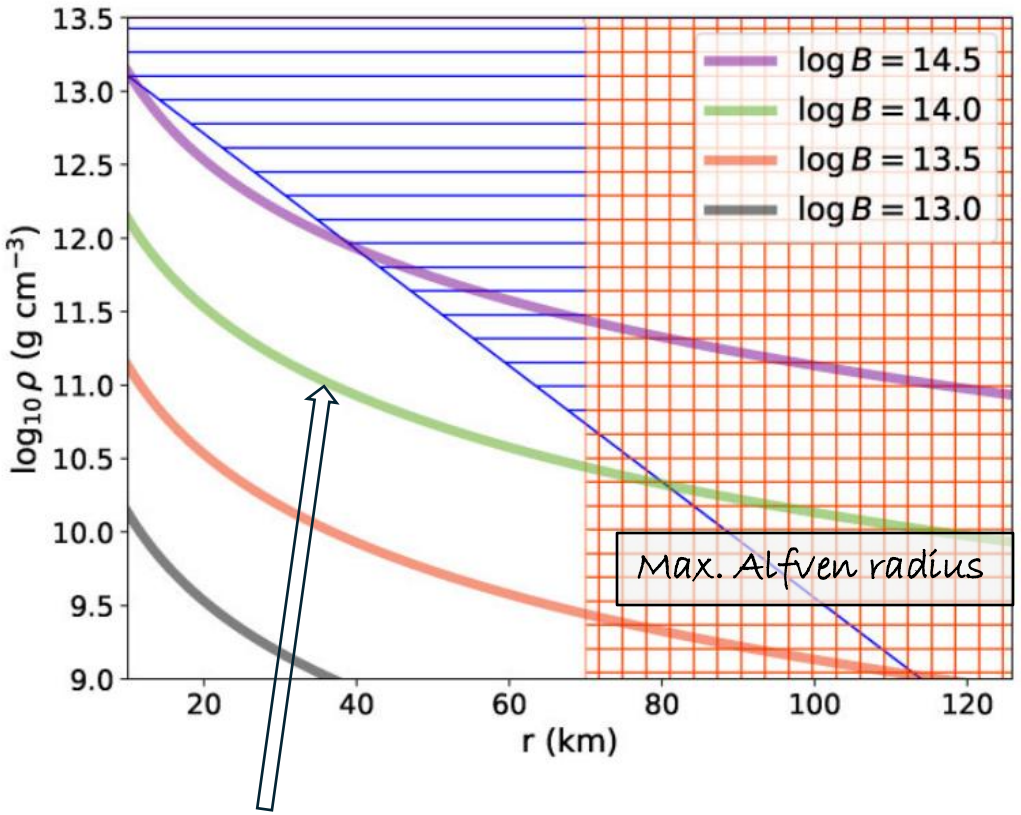
$$\nu_{\mathrm{MRI}} \simeq \frac{k_{\parallel}\, v_A}{2\pi},$$

Alfven frequency

Black hole case: MHD or MRI



Magnetar case



22 Hz MHD QPO viable here

Magnetohydrodynamic

wavenumber

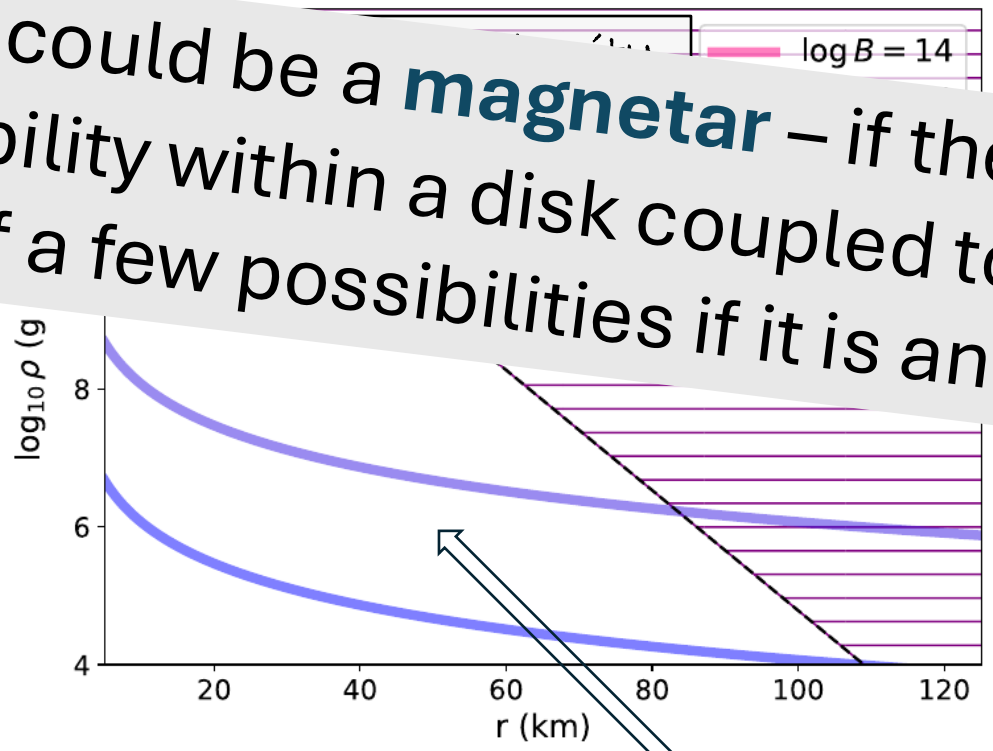
$$\nu_{\rm MRI} \simeq \frac{k_\parallel v_A}{2\pi},$$

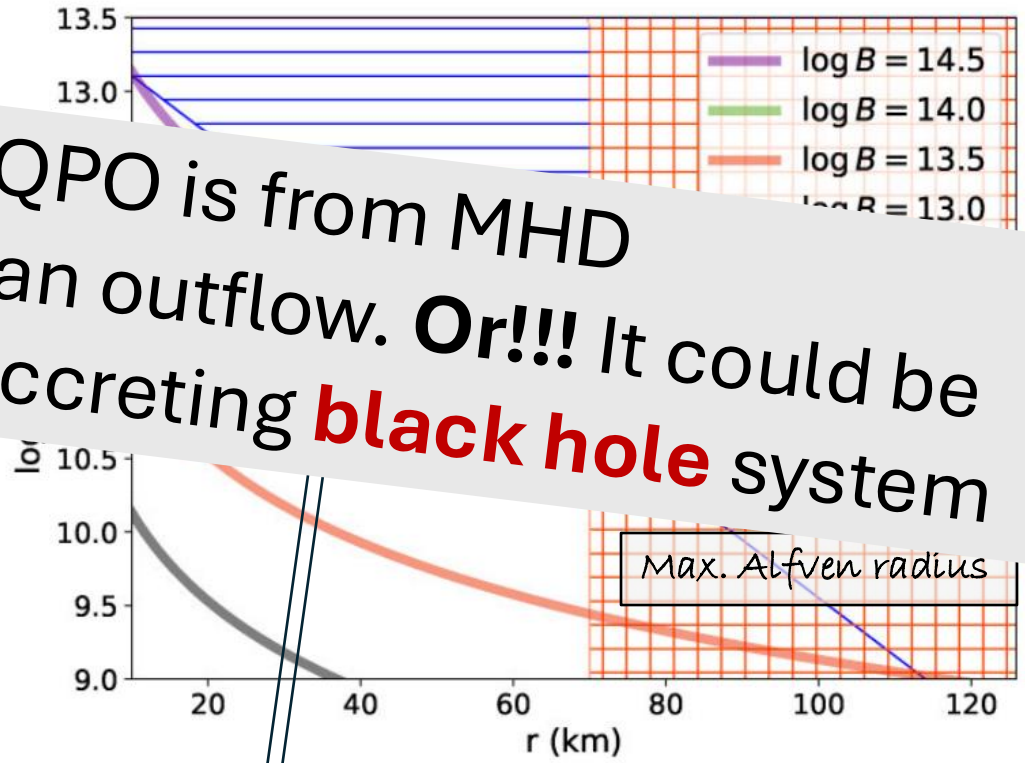
Alfven frequency

Black hole case: MHD or MRI

Magnetar case

So, it could be a **magnetar** – if the QPO is from MHD instability within a disk coupled to an outflow. **Or!!!** It could be one of a few possibilities if it is an accreting **black hole** system





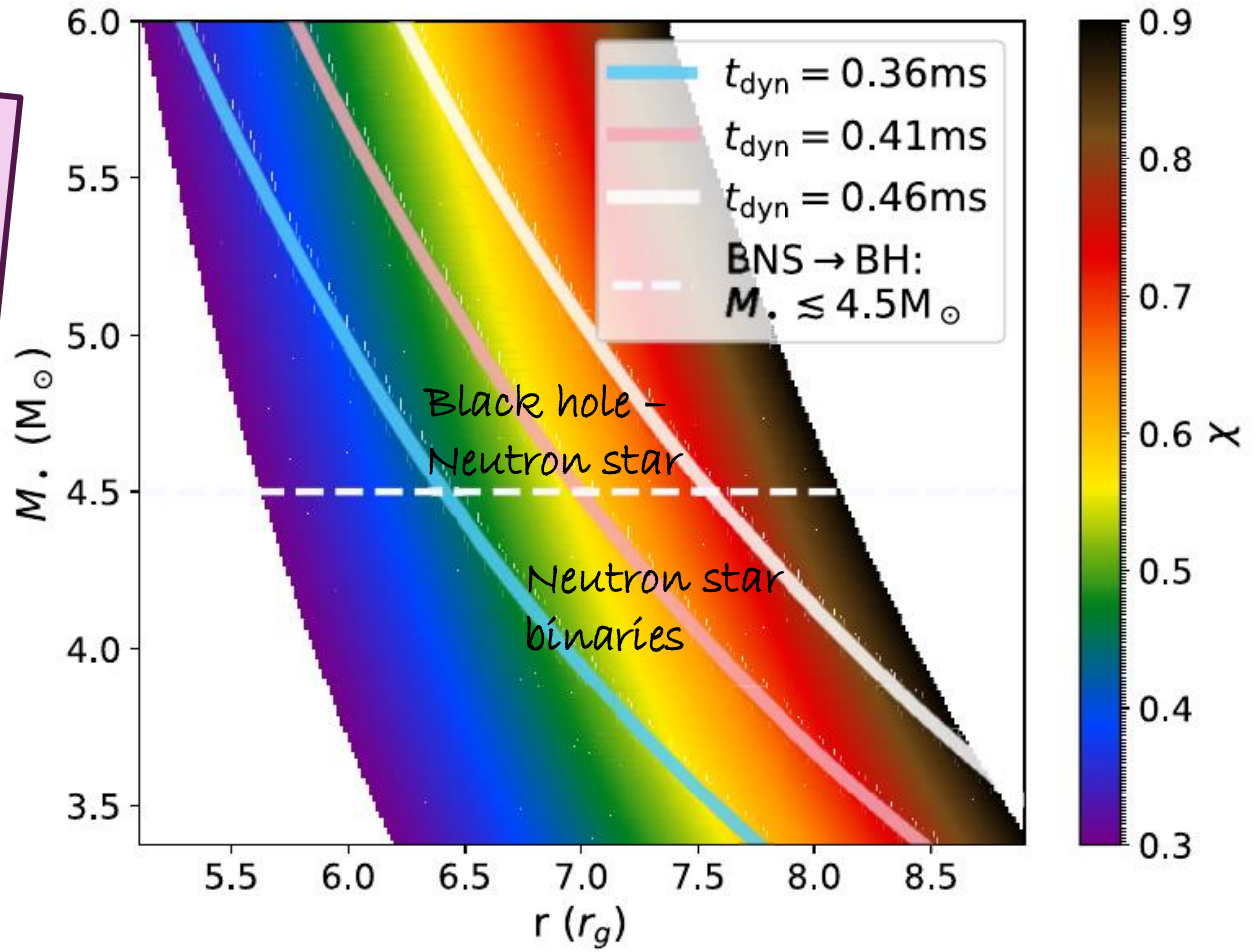
22 Hz MHD QPO viable here

I prefer this explanation: Lense Thirring with some disk tearing and the damping explained by the torn disk crossing

Lense–Thirring (LT) precession is the result of frame dragging within the disc of a black hole with spin $\chi > 0$

Precession at 22 Hz

$$\nu_{\rm LT} = \frac{\omega_{\rm LT}}{2\pi} = \frac{\chi G^2 M_\bullet^2}{\pi c^3 r_{\rm id}^3},$$



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Coherence timescale

Damping timescale = viscous time

$$t_{\rm visc} \simeq \begin{cases} \frac{r^2}{\alpha c_s h} & \text{thin disc,} \\ \frac{r}{\alpha c_s} & \text{thick disc,} \end{cases}$$

Lamb et al. 2025

Other merger weirdos – the short kings

Just in my limited experience, short duration GRBs show evidence for much longer emission than our analytic disk-scale based approximations would lead us to believe

- **GRB 160821B** – energy injection and a kilonova*

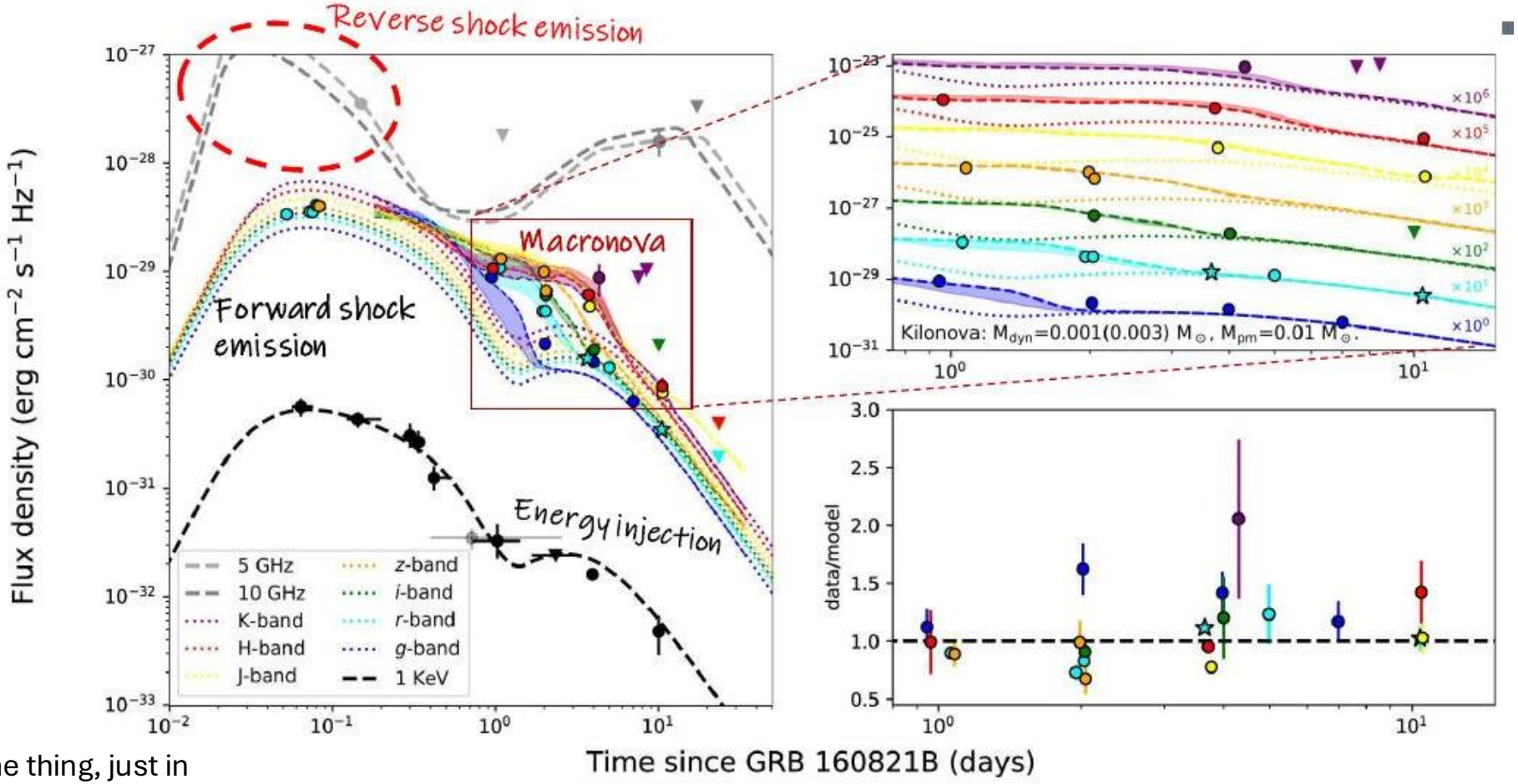


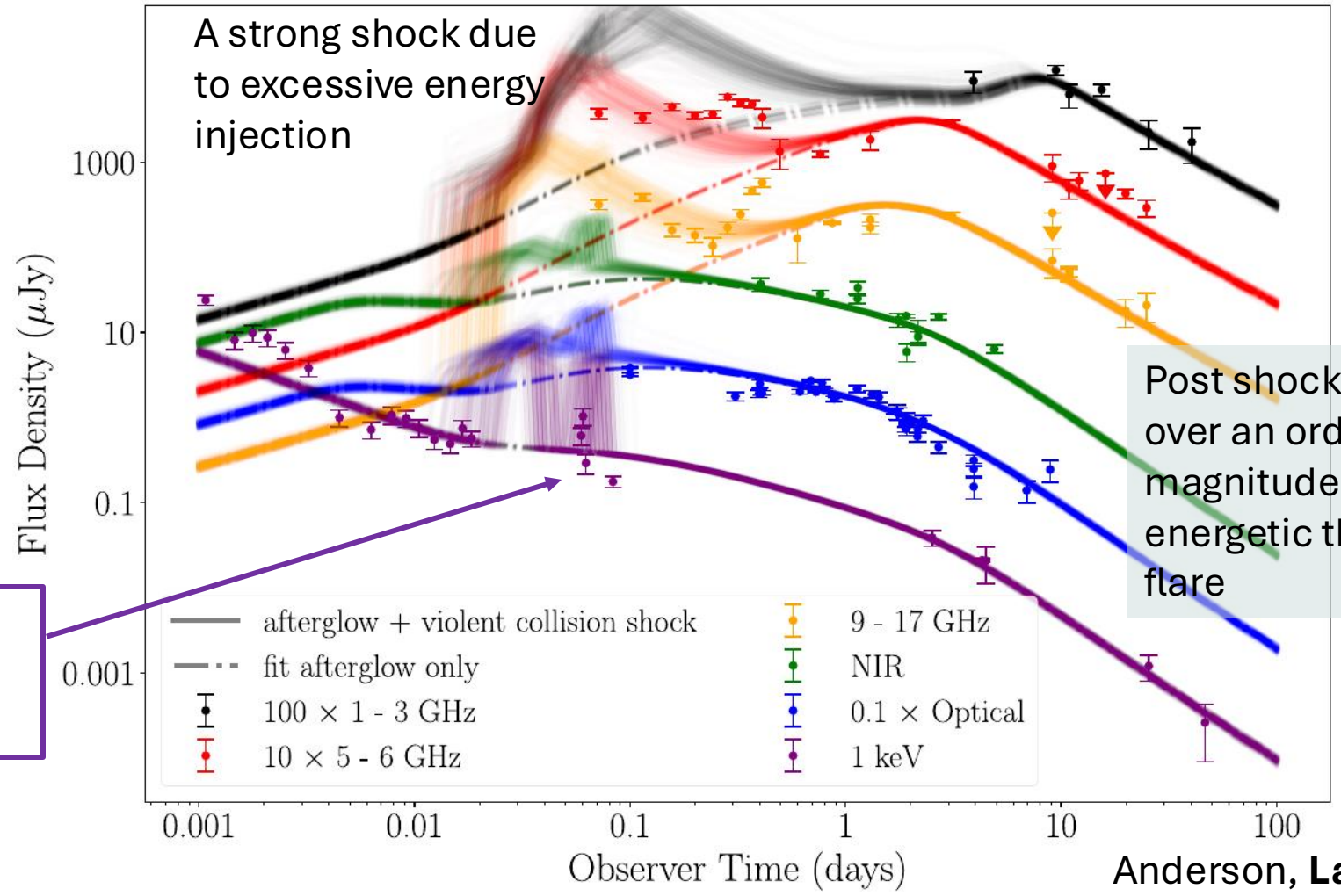
*figure says "macronova", this is the same thing, just in the days of the great naming convention wars

Lamb et al. 2019

Note: the basic afterglow model is fit to the data, however, the radio requires an additional component that is consistent with a strong shock (not modelled) but expected from the model parameter fits

Anderson's short GRB 231117A

A regular short duration GRB, but with very early radio observations (from 0.1 days)



Post shock afterglow over an order-of-magnitude more energetic than the pre-flare

The model unintentionally seems to have explained an x-ray flare at 0.07 days!

Anderson, **Lamb** et al. 2025

Engines here?

These few events all seem to be pointing to processes within the engines of merger-origin GRBs

These engines must be far *more* complex than our naïve assumptions

But probably not any weirder, just "put together in an unexpected way"...

Late fall-back material

Magnetic braking/arresting

Much larger disks

varying viscosity/turbulence

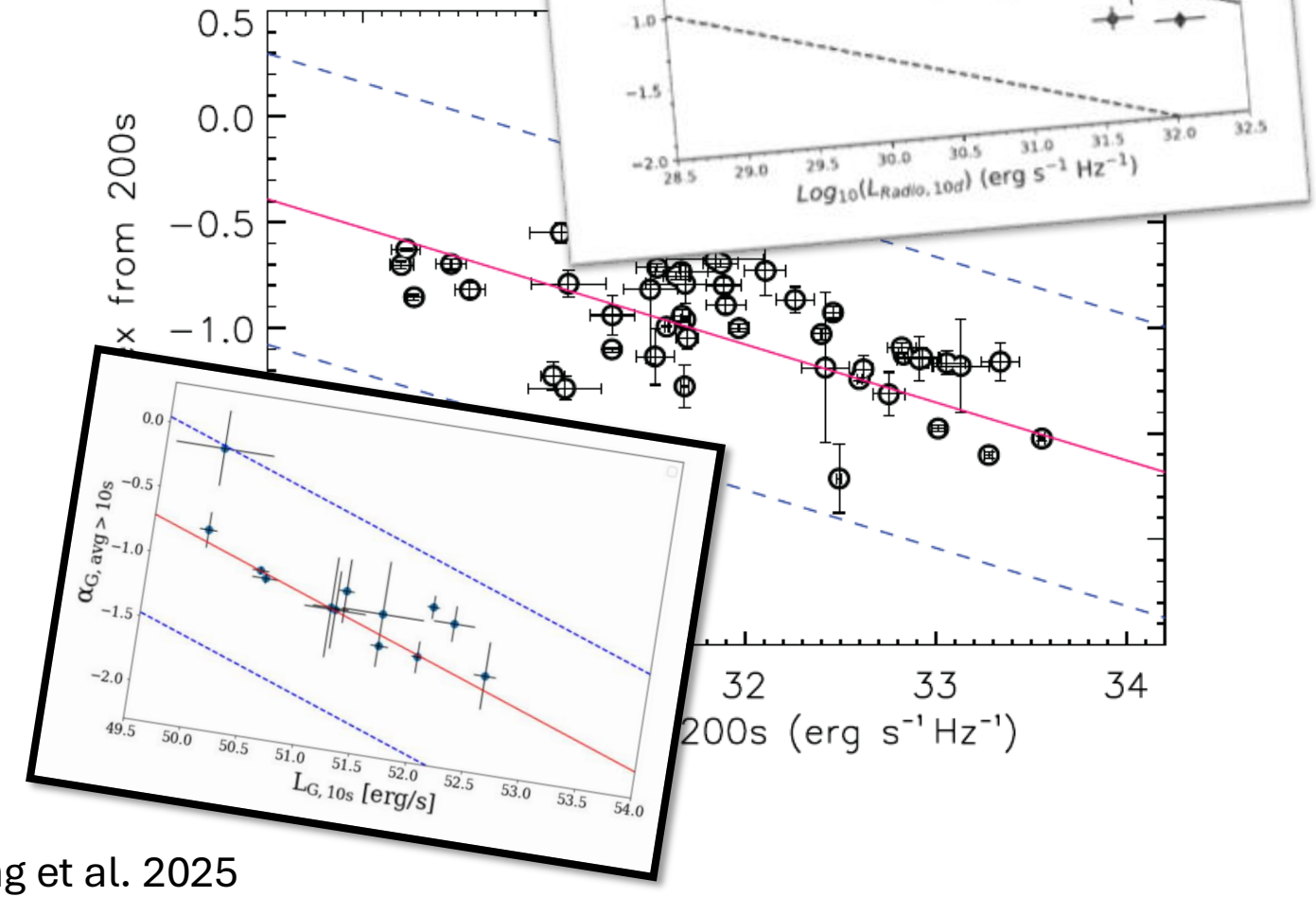
What about the rest?

Long, or more accurately, "collapsar origin GRBs" present their own dramas

Often these dramas are weird!?

Long GRB correlations

- We see multiple empirical correlations for long duration bursts – most famous is the Amati relation
- But see also; Ghirlanda relation, Yonetoku relation, Dainotti relation…
- A less talked about correlation exists between the afterglow "peak" flux and the average temporal decline index



see **talk by Cairns Turnbull for GRB parameters inference via physically modelling an empirical afterglo w correlation (**Friday, week 1**)

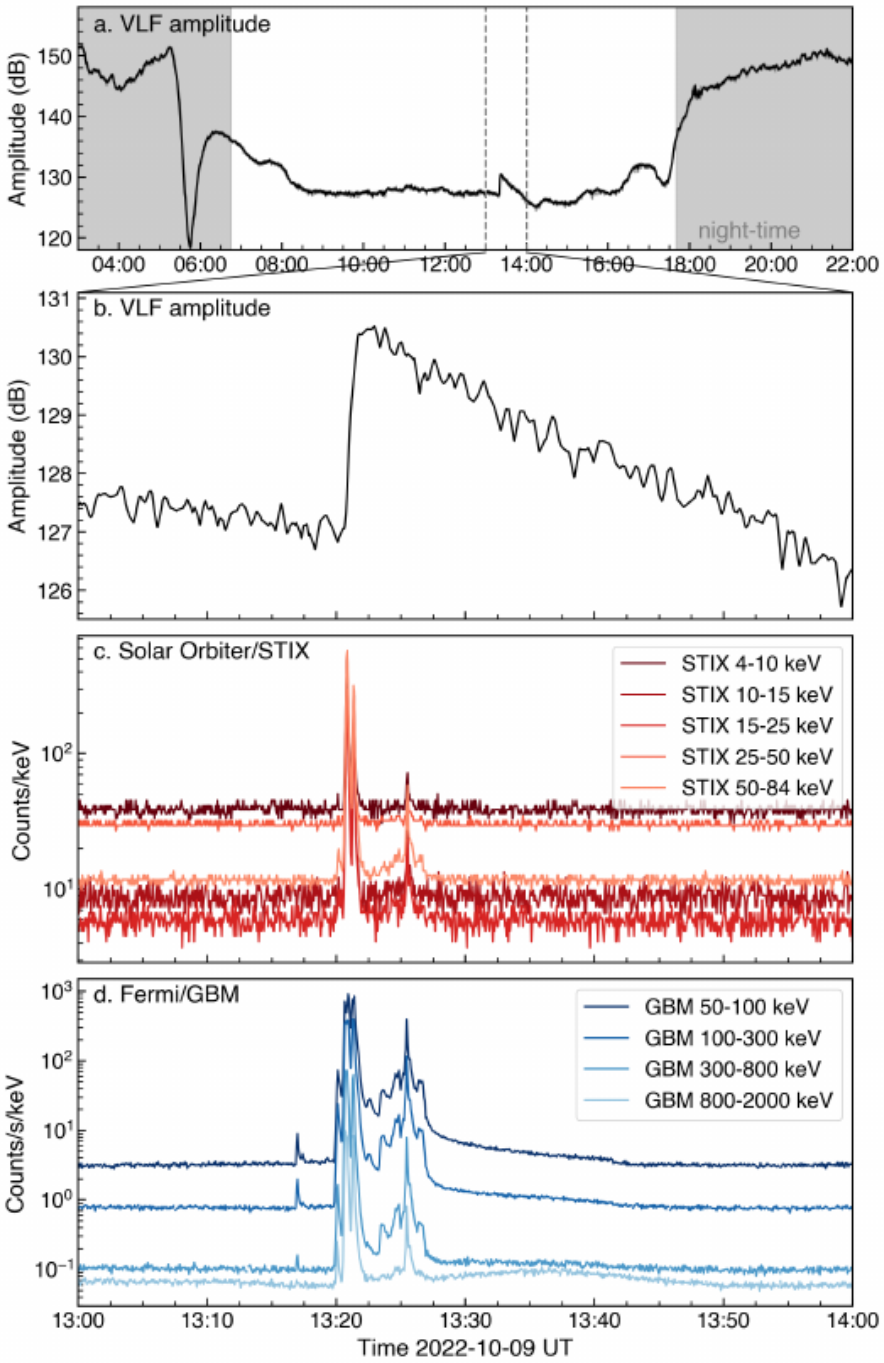
Oates et al. 2015, Hinds et al. 2023, Shilling et al. 2025

The BOAT is a good example of weird, but is it all just dust

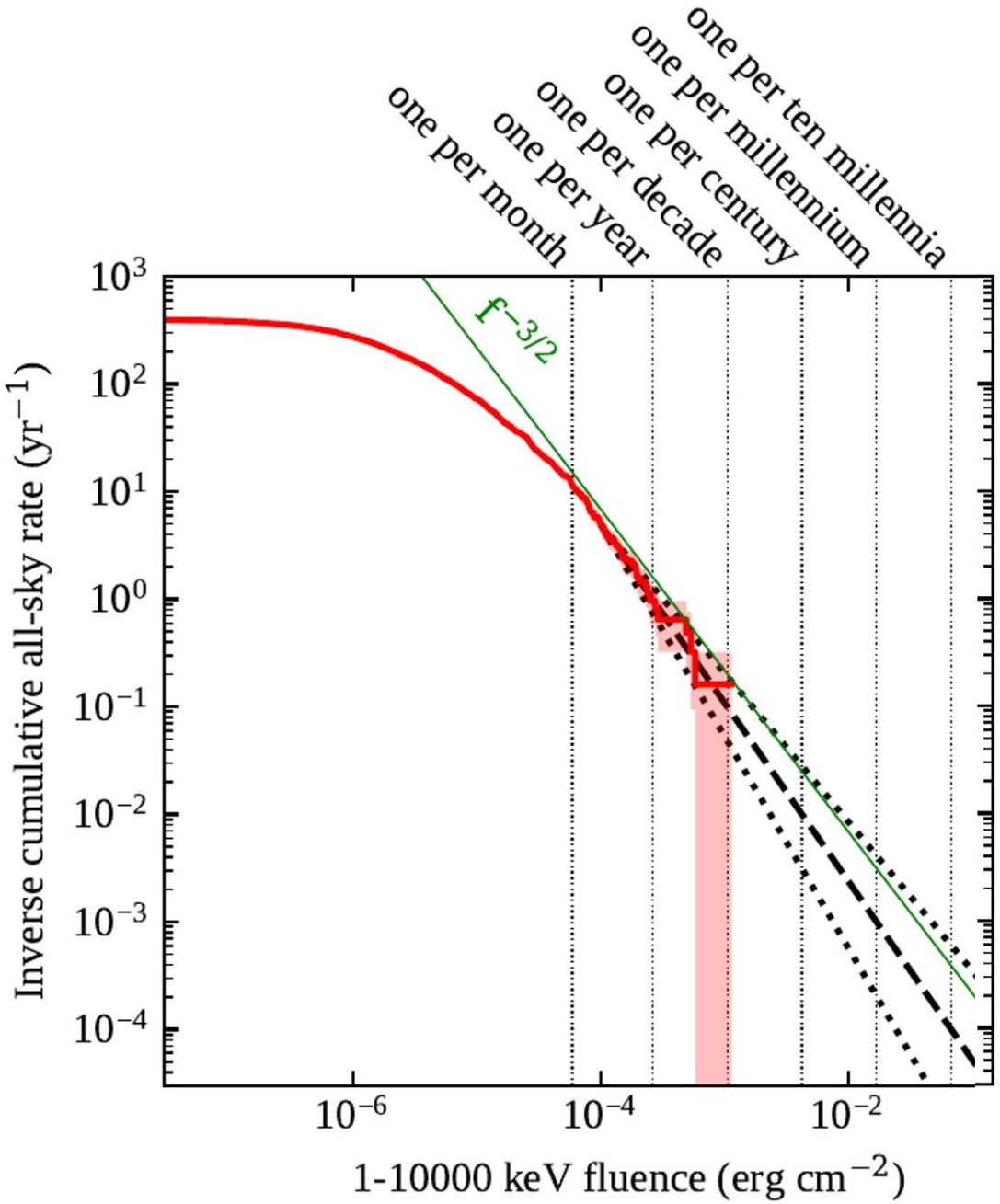
- The Brightest Of All Time – GRB 221009A, the BOAT
- It shined a light through the Milky-Way (which wasn't great news for astronomers)
- It also excited the ionosphere! Which was exciting for solar system plasma people
- It was a target for **JWST** early supernova, r-process searches

...but we saw nothing but power-laws

- **Too blue for regular GRB afterglow models**



Hayes & Gallagher 2022



- At a redshift of $z = 0.151$, the **BOAT** is one of the closest recorded long-duration GRBs
- Despite this relative proximity, the burst is still, intrinsically (amongst) the **most energetic bursts ever discovered**
- An exceptionally rare event that was, unfortunately, observed through the Milky Way dust lanes…

Malesani (incl. **Lamb**) et al. 2025

Levan, **Lamb**, Schneider et al. 2023

The Astrophysical Journal Letters, 946:L28 (14pp), 2023 March 20 https://doi.org/10.3847/2041-8213/acc2c1
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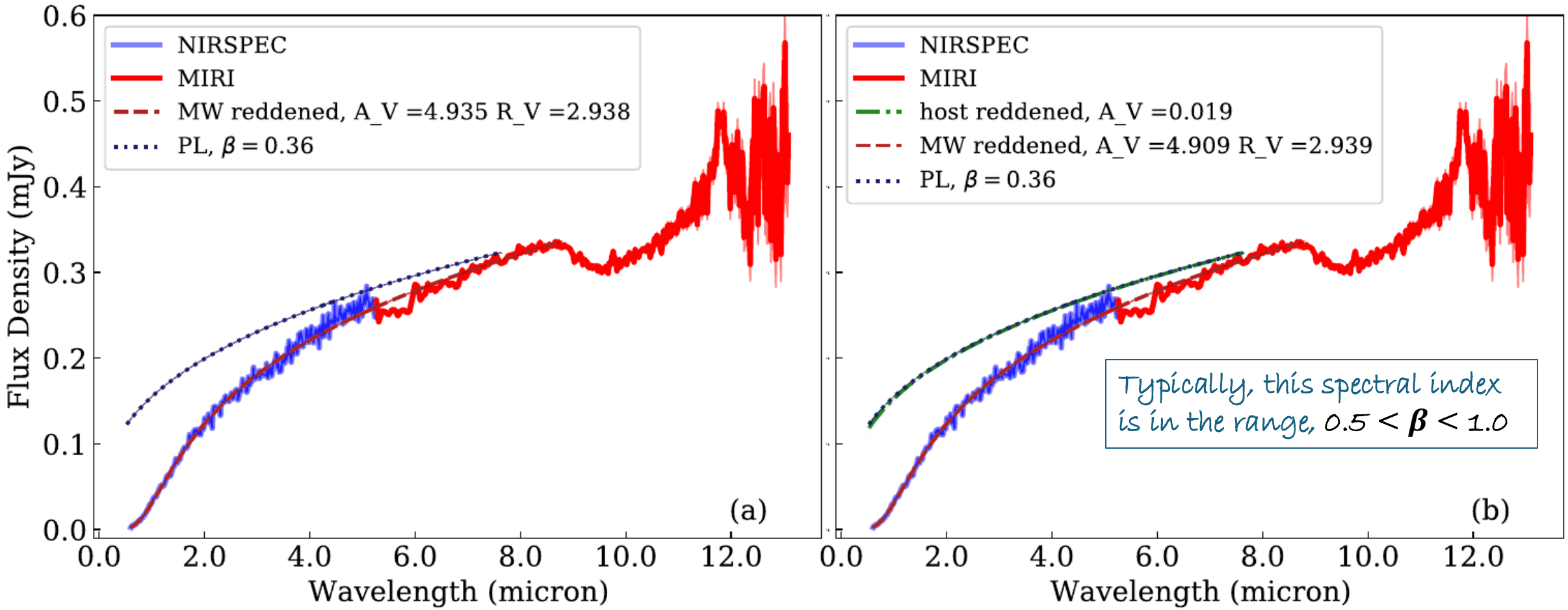
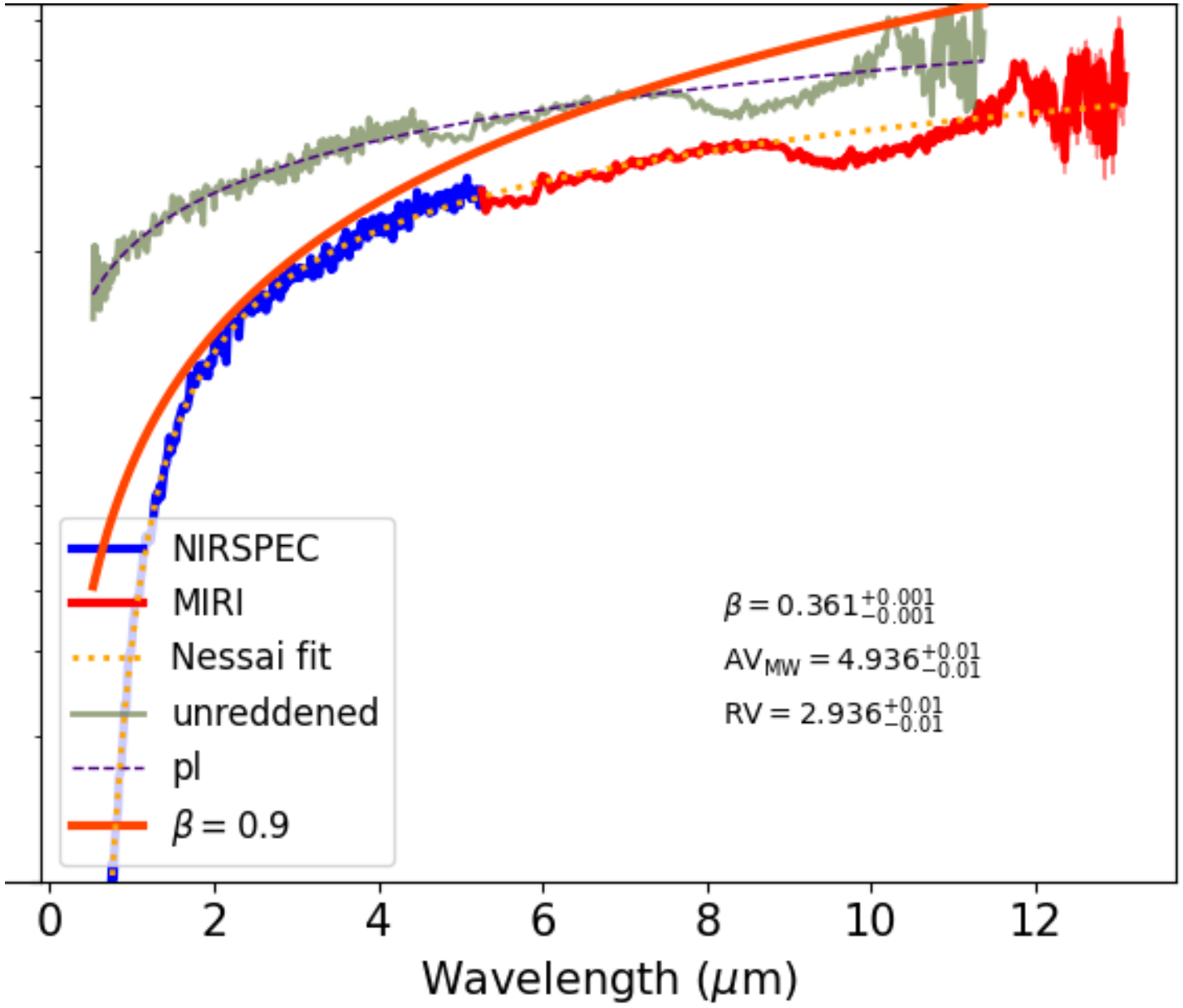
OPEN ACCESS

The First JWST Spectrum of a GRB Afterglow: No Bright Supernova in Observations of the Brightest GRB of all Time, GRB 221009A





Is it really that much **bluer**?

Yes

Orange solid line shows an intrinsic spectral index of **0.9**, as predicted by most of the wind medium models.

Also note that in a wind medium, the cooling frequency increases with time.

The redder part is ever steeper than the observed **MIRI** spectrum

Is there an afterglow solution? Yes

- Shrestha et al. 2023 give an optical decline of $\alpha_1 = 1.425$
- Williams et al. 2023 give an x-ray decline of $\alpha_2 = 1.675$
- Levan et al. 2023 gives an IR spectral index of $\beta = 0.36$
- No consistent solution in a wind or ISM medium pre-jet-break
- Post-jet-break, assuming an edge-effect only*
  - For p = 1.72 (from $\beta = (p-1)/2 = 0.36$),
  - An ISM medium gives a temporal index $\alpha_1 = 1.45$, and $\alpha_2 = 1.7$
  - Consistent with observations at optical/NIR and x-ray
- BUT IS THERE A SUPERNOVA AT 13 DAYS?
  - The answer is "NO"

$$\alpha_1 = \frac{3(p+6)}{16}, \quad (\nu < \nu_c)$$

$$\alpha_2 = \frac{3p+22}{16}, \quad (\nu > \nu_c).$$

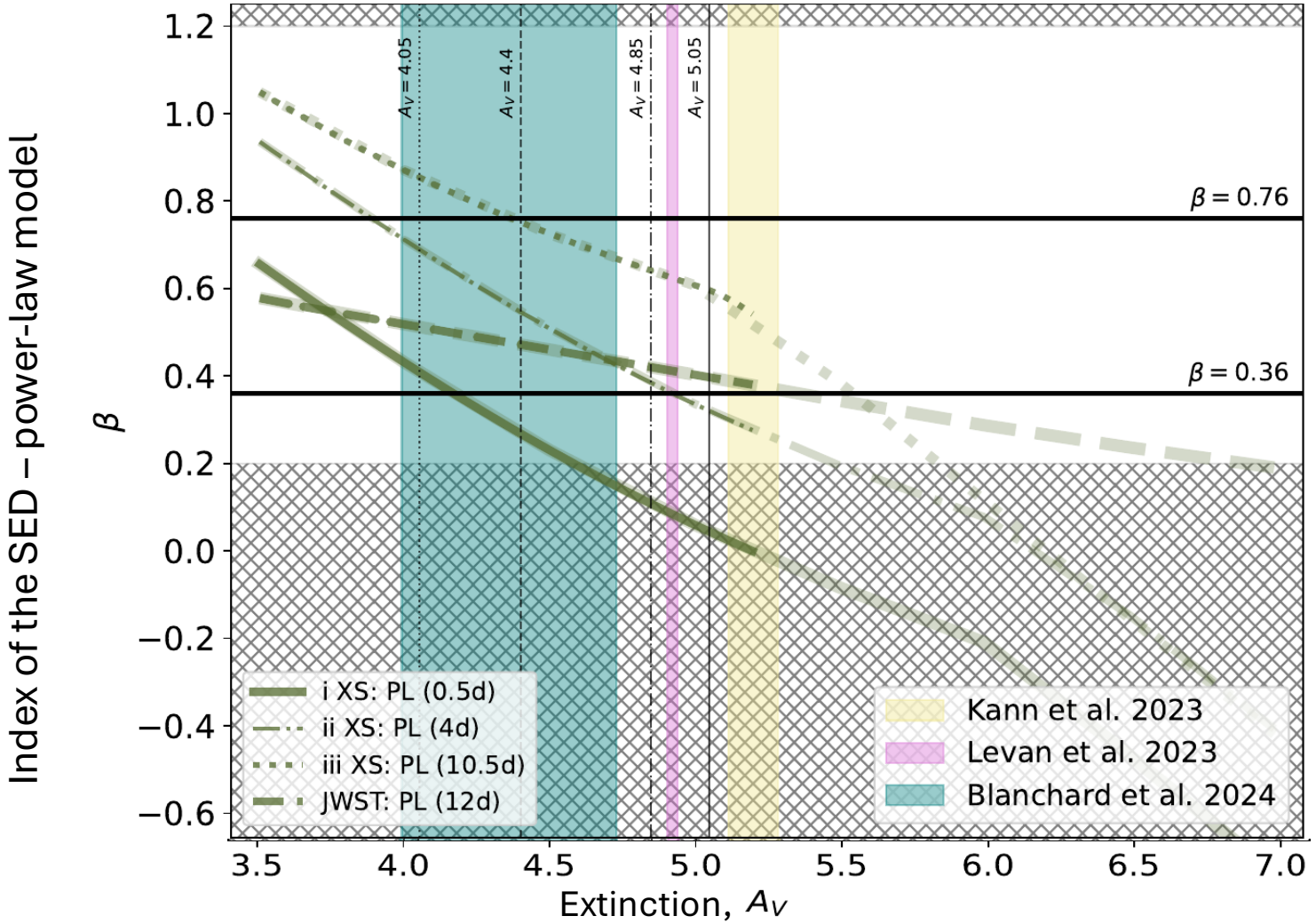
See e.g., Gao et al. 2013

*no sideways expansion of the jet

Khang's work on the boat

See talk on Friday by Nguyen M. Khang – spoilers!

Khang Minh Nguyen



- How **blue** can you go!
- The afterglow has a huge extinction – mostly Milky-Way
- The assumption about either the spectral index *or* the extinction will drive your fit (with this data)

Nguyen, **Grabham** et al. (in prep)

A toy model for the afterglow Grabham et al. (in prep.)

- The radio afterglow to GRB 221009A is not self-consistent across all bands – this suggests an additional element that dominates the radio afterglow

A two-component model with independent microphysical parameters, see also Sato et al. 2023

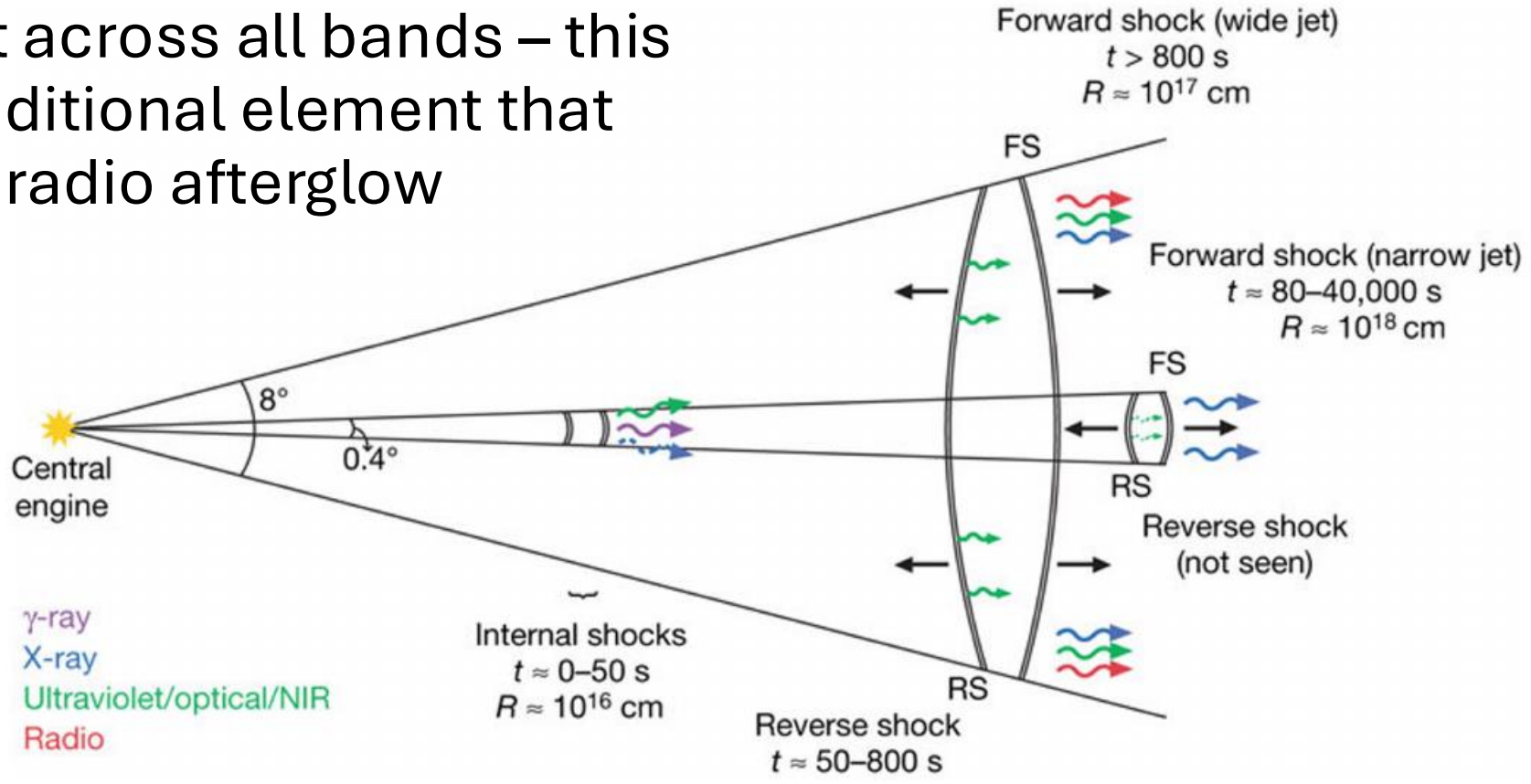
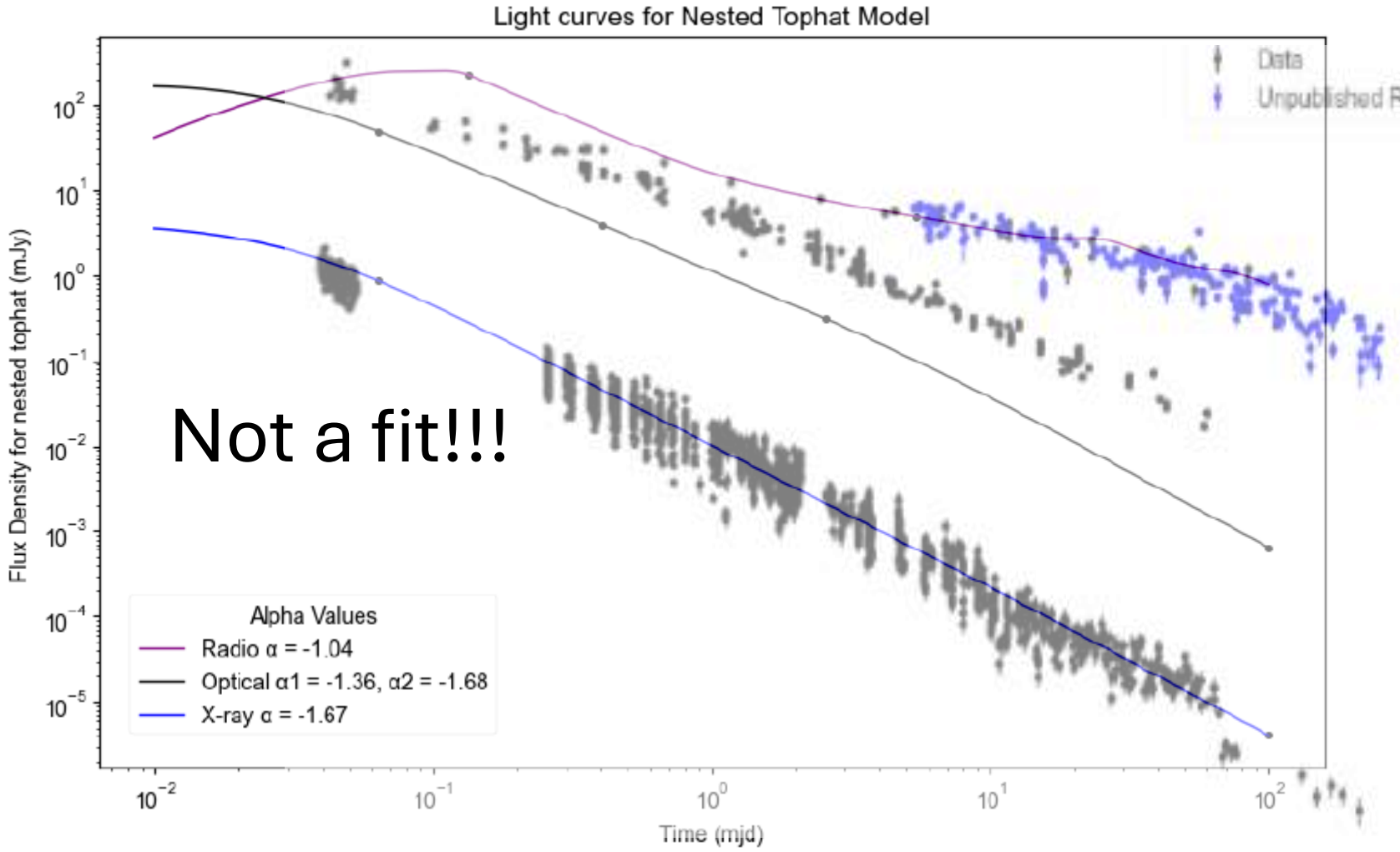


Diagram is courtesy of J.D. Myers (NASA) (Racusin et al. 2008)

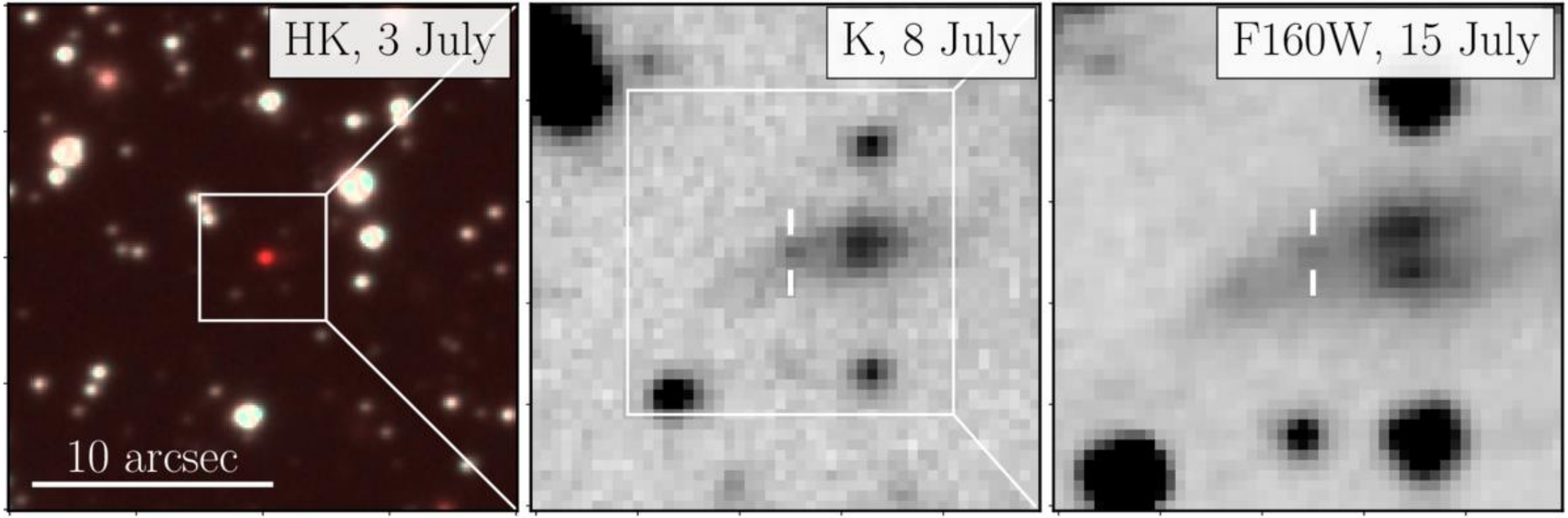
A two-component, or "nested top-hat" jet – proof of principle

- Model tests indicate that the model can produce three distinct regimes that evolve with three distinct temporal indices



Work in prep by Nell Grabham

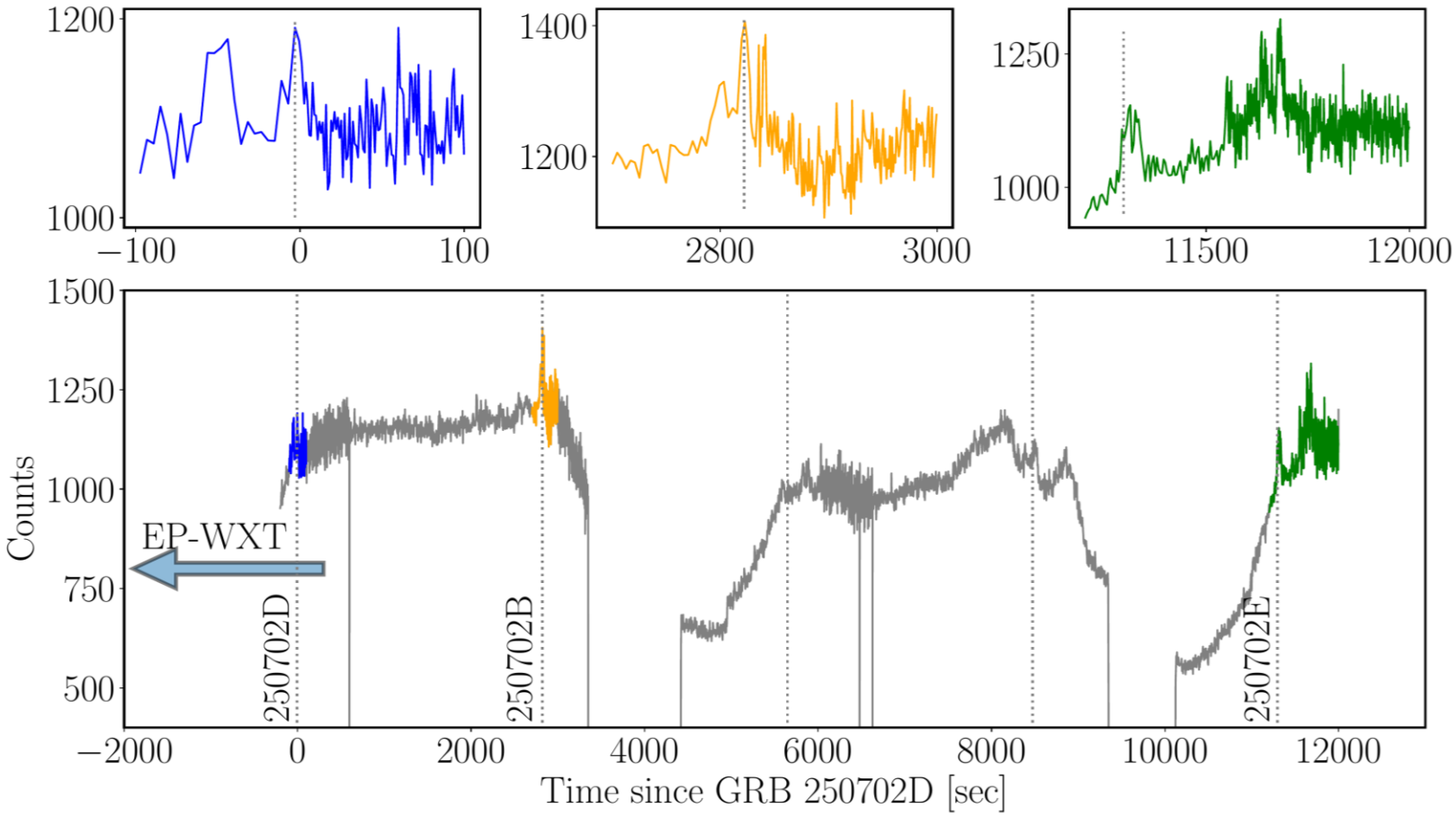
And what about this bad boy!? **GRB 250702B**



Levan, (incl. **Lamb**) et al. 2025

GRB 250702B

- The ultra-*ultra*-long burst – with **3 distinct burst components**
- The **longest duration GRB ever** – and distinct from other ultra-longs



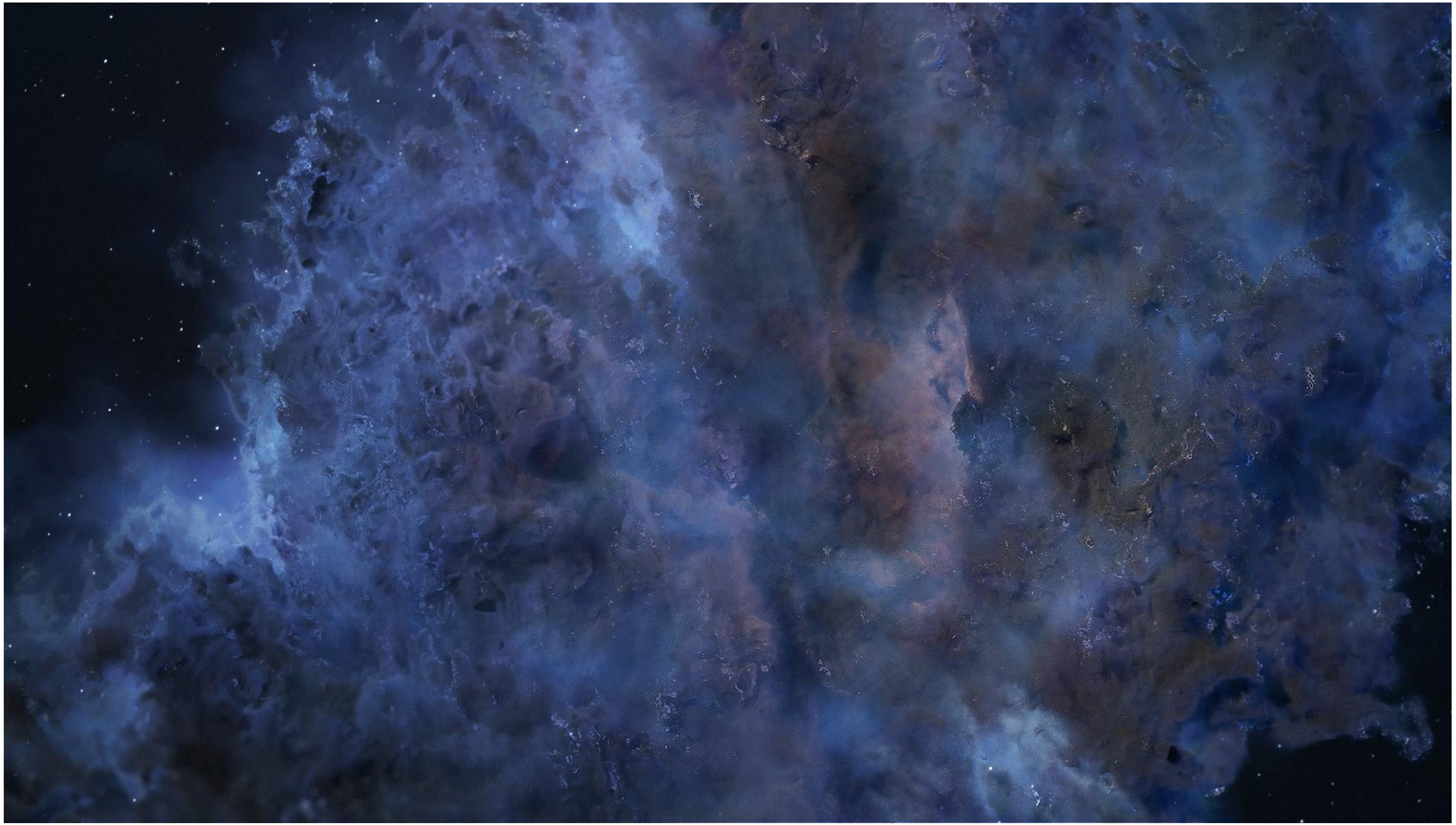
GRBs typically have a bright flare and a long tail – especially long, or ultra-long GRBs, However, GRB 250702B is unusual in that all episodes are significant. The preceding x-ray emission has not been seen in GRBs before, however, this may be due to a lack of facilities capable of discovering such a precursor

Levan, (incl. **Lamb**) et al. 2025

	Engine Duration (s)	Minimum Variability Timescale (s)	Maximum Photon Energy (MeV)	Power & Profile	Viable (Y/N)
X-ray Binaries	1,000,000	-	0.5	Y	N
Magnetar Giant Flare	0.01–0.1	0.001–0.1	5	N	N
Neutron Star Mergers	0.01–10	0.001–1	10	N	N
White Dwarf Mergers	100–10,000	-	-	N	N
Tidal Disruption Event	250,000	$\gtrsim$40	1	Y	N
IMBH Tidal Disruption Event	~10,000	$\gtrsim$10	1	N	N
Micro Tidal Disruption Event	10,000-100,000	0.01–10	10	Y	Y
Carbon-Oxygen Collapsar	1–1,000	0.01–10	10	N	N
Helium Collapsar	1–1,000	0.01–10	10	N	N
Binary Helium Star Merger	1–1,000	0.01–10	10	N	N
Helium Merger	~100,000	0.01–10	10	Y	Y
GRB 250702B	~100,000	0.5	10	-	-

- The minimum variability timescale requires an ultra-relativistic jet
- The duration requires a massive and large engine with significant angular momentum
- The best candidates for this are Helium Mergers – these are the merger of a massive helium star with a black-hole companion. The black-hole is "swallowed" by the He-star and makes its way to the core, where it destroys the star and forms a long-lasting GRB engine
- An alternative is a micro-tidal disruption event, which is a similar mechanism but the star and the black-hole are the result of dynamical interactions within, say, a dense star cluster

Neights, (incl. **Lamb**) et al. 2025



https://svs.gsfc.nasa.gov/vis/a010000/a014900/a014916/NASA_GRB_Sequence_Final_v01.mp4

The ARI, LJMU is looking for researchers…

Interested candidates are advised to contact the ARI's head of research, **Prof Robert Crain** at the earliest opportunity.

We usually request an expression of interest (EOI) from interested candidates 3 months prior to the fellowship deadline. EOIs typically consist of a **one** page summary of your proposed research project, a statement motivating the ARI as the chosen host institute, a CV and a publications list.

Currently, all successful senior fellowships will convert into a permanent position at the ARI – this is essentially a "UK tenure track"

https://www.ljmu.ac.uk/research/centres-and-institutes/astrophysics-research-institute/research-fellowship-opportunities

Round up of the weirdest – challenging our understanding

- The "new" class of x-ray transients – weird variability follows these around; watch out for more to come!!!
- Long GRBs that appear like mergers
- QPO in a pre-cursor (not necessarily a magnetar, not necessarily real)
- Short GRBs that support long-lasting or stratified outflows
- Magnetar engines will have signatures – in the afterglow, at late times
- Extremely long lasting long GRBs – new or niche engines

Conclusions

- X-ray bursts add to the GRB population, are they more of the same or something quite distinct?
- The long-short diagnostic that we held onto for so long is dead
- Two long duration bursts have cemented a challenge to our assumptions
- And long, long bursts that sit at an extreme

Gæð ā **wyrd** swā hīo sċel.

“**Fate** always goes as it must.”

GRB engines are not weird, they are wyrd challenging our assumptions

Credit: Soheb Mandhai

Temporal variability

What does the light-curve look like?

Combined Fermi-GBM and Swift-BAT counts

Fit with three toy models:

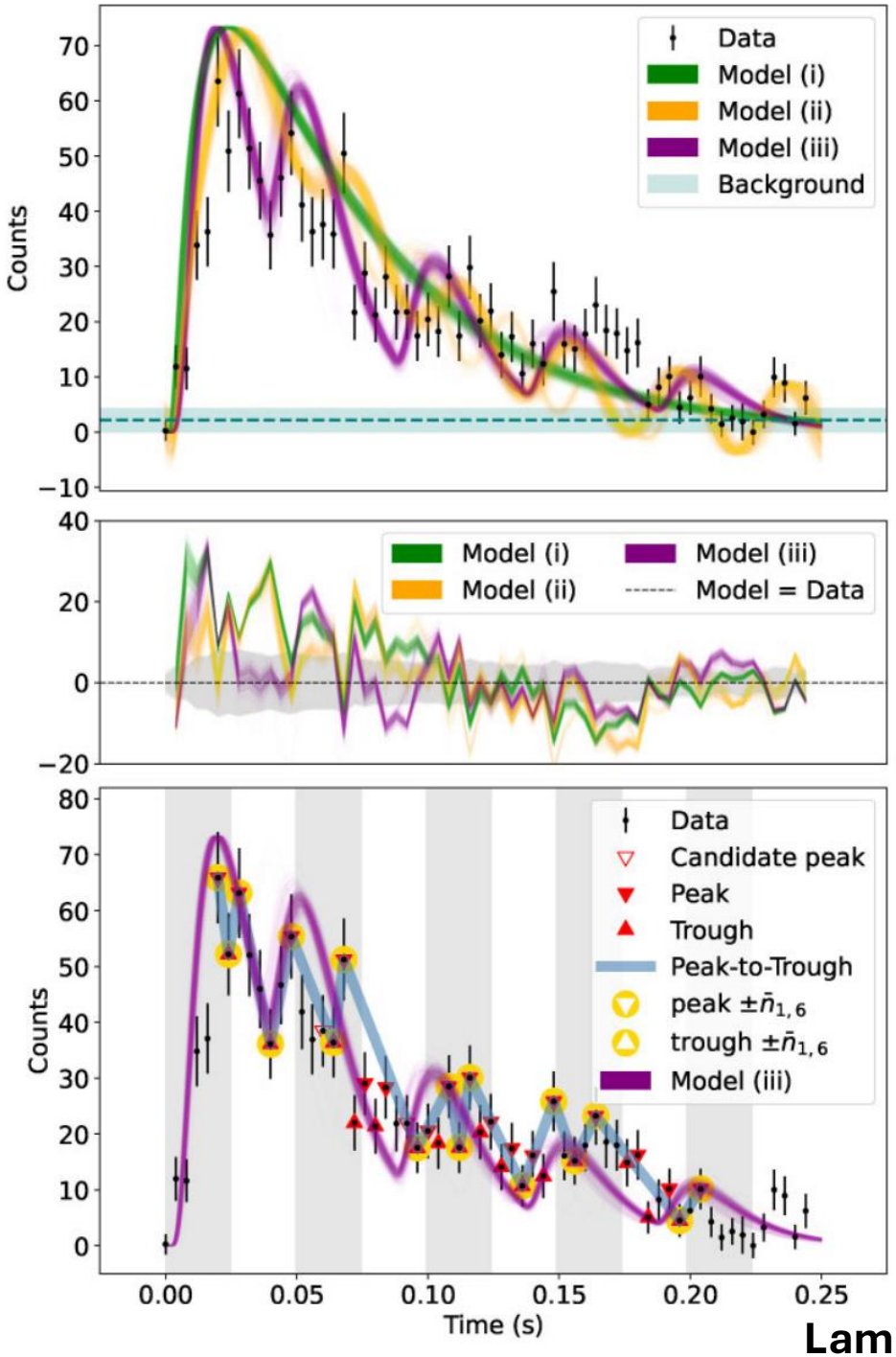
(i) Single pulse (FRED)

(ii) Single pulse + sinusoid

(iii) **Multiple pulses and damping**

Model	τ_1 (ms)	τ_2 (ms)	x	ν_ω (Hz)
(i)	10^{+1}_{-1}	56^{+2}_{-2}	–	–
(ii)	13^{+1}_{-1}	55^{+2}_{-2}	$0.52^{+0.06}_{-0.06}$	$24.29^{+0.60}_{-0.45}$
(iii)	$\mathbf{26^{+3}_{-2}}$	$\mathbf{15^{+0}_{-1}}$	$\mathbf{0.56^{+0.02}_{-0.02}}$	$20.13^{+0.14}_{-0.08}$
$\log \mathcal{B}$	(i)	(ii)	(iii)	
(i)	0	−9.248	−22.357	
(ii)	0.248	0	−13.109	
(iii)	**22.257**	**13.109**	**0**	

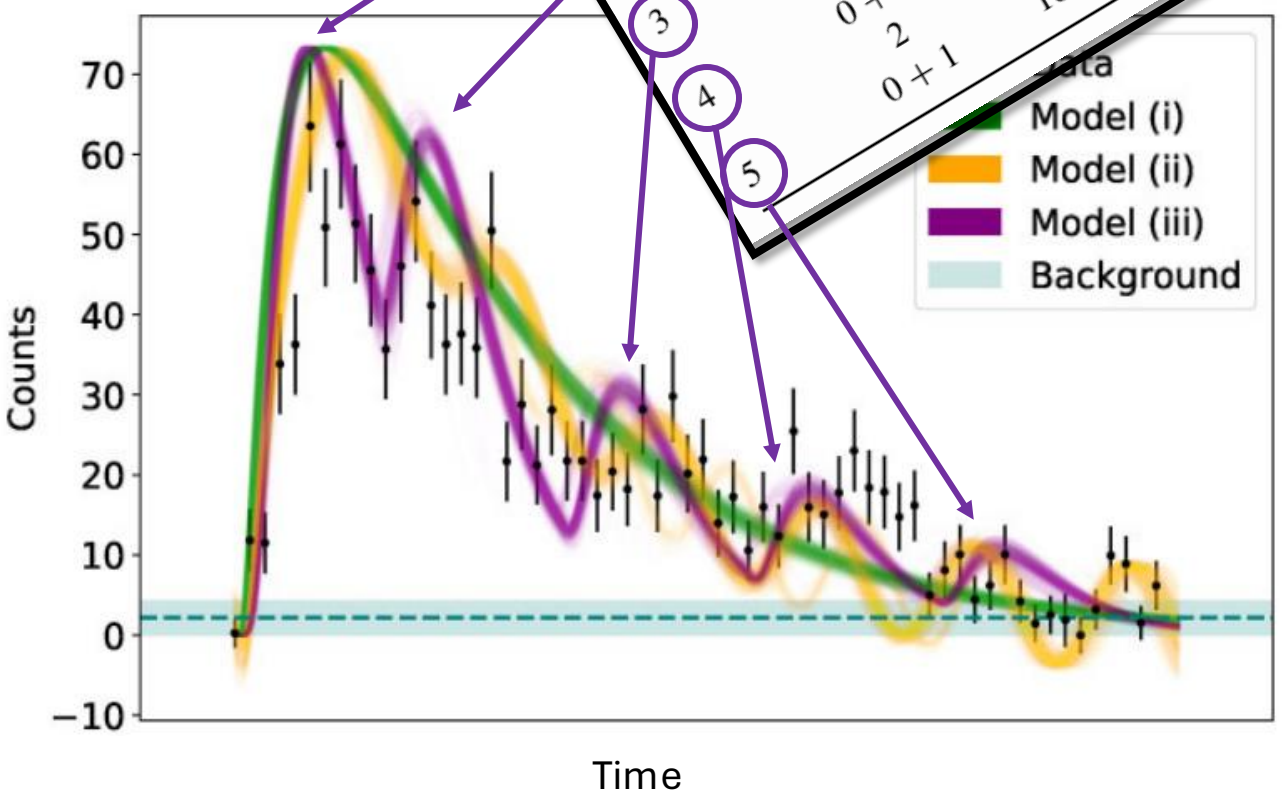
Log Bayes



Lamb et al. 2025

> 14 shells

Pulse	n_{peak}	$t_{0,collision}$ ms	Γ
1	0 + 1	0	86
	2	22	163
2	0 + 1	37	112
	2	59	148
3	0 + 1	89	87
	2	104	134
4	0 + 1	126	78
	2	145	92
5	0 + 1	182	90
	2		
	0 + 1		



What do these pulses tell us?

By assuming an internal shock, shell collision origin for these pulses

Given the energy required, and the short timescales – we put estimates on the minimum Lorentz factor required

All return high values consistent with an engine on/off cycle at the observed QPO

High Lorentz factor requires the source to be jetted and emission region 'far' from source (relative to the size of the engine, re. $R_{GRB} \sim 2\,\Gamma^2\,c\,\Delta t$)

Lamb et al. 2025

Why a wombat and not a whippet?

- Australian
- Marsupial
- Cooler

Orphans: AT2021any, AT2021lcr, AT2021blt, AT2023lcr, AT2021lfa, AT2019pim

- Li et al. 2025, Perley et al. 2025, Sarin et al. 2022