Flares, energy injection, and decoding broadband GRB afterglows via XRT observations

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…and all my great collaborators

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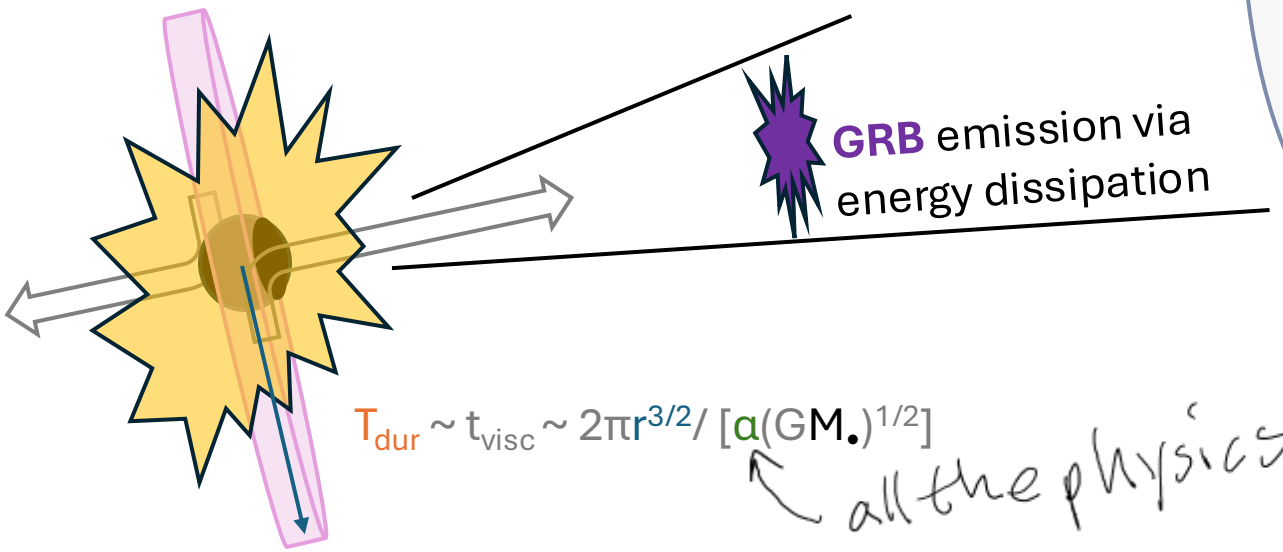
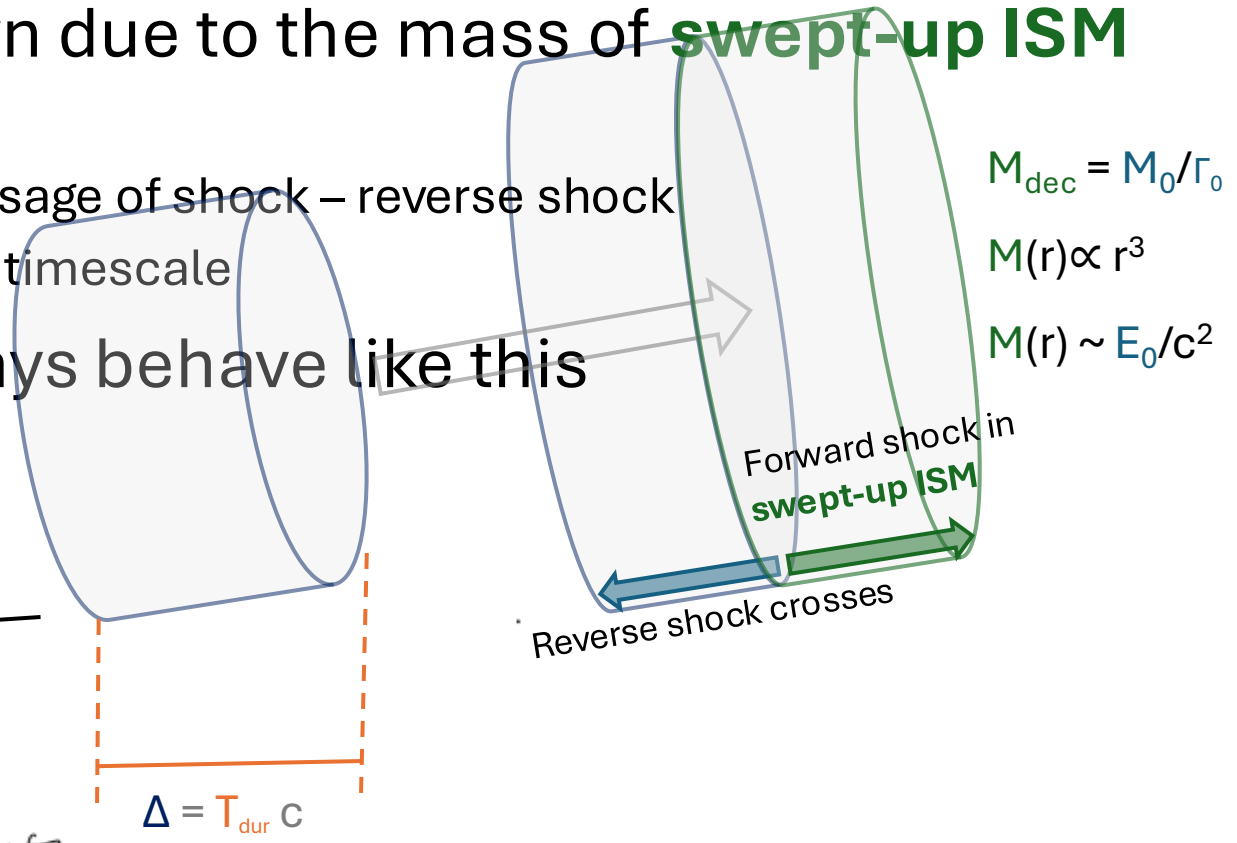
Flares and energy injection in the afterglow

- The classic picture of an afterglow is a **homogeneous** '**puck**' of relativistic plasma slowing down due to the mass of **swept-up ISM** material
  - **Homogeneous** because of the passage of shock – reverse shock
  - '**Puck**', because of the short engine timescale
- But the afterglow does not always behave like this

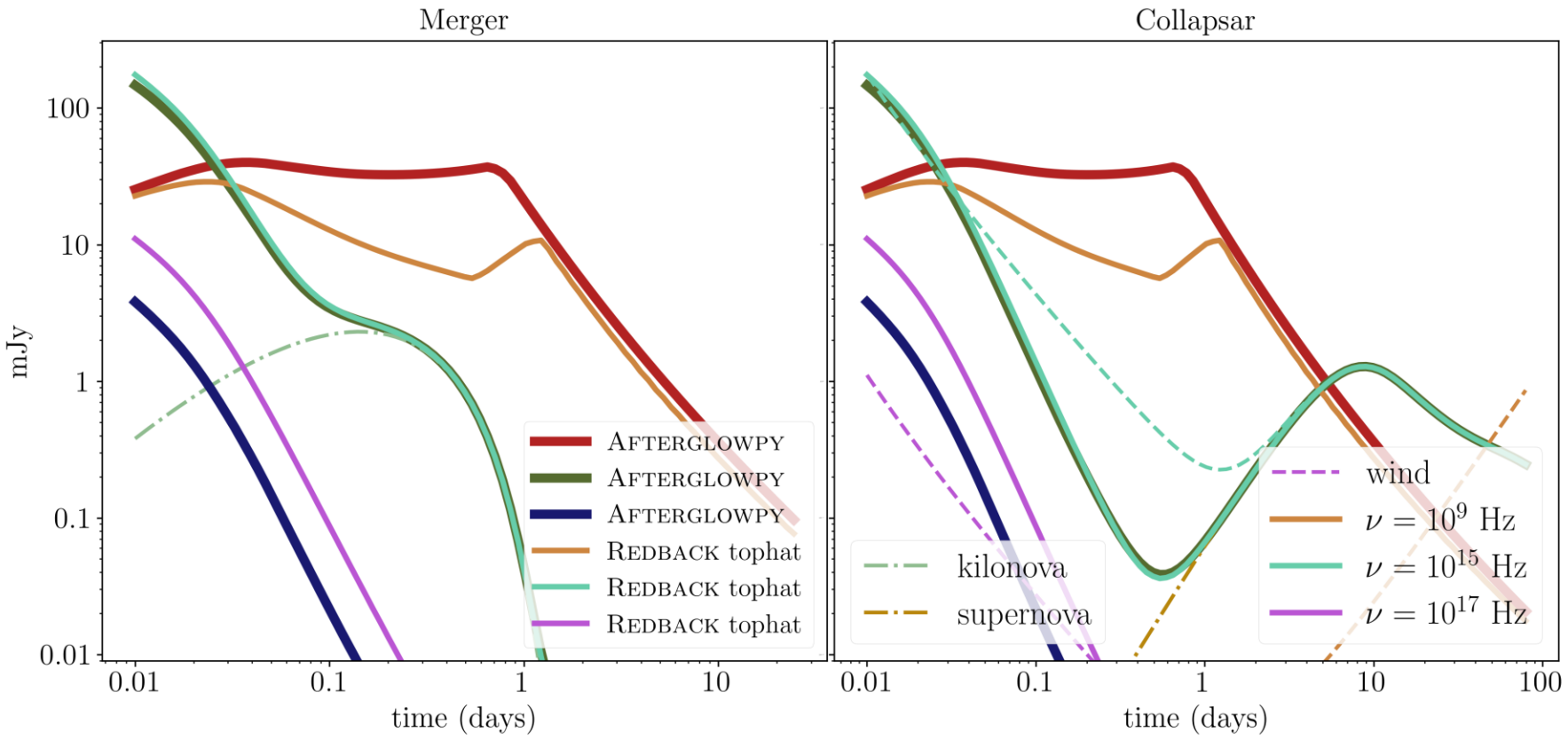


$T_{dur} \sim t_{visc} \sim 2\pi r^{3/2} / [\alpha (G M_\bullet)^{1/2}]$

all the physics



The trouble with idealistic afterglow models

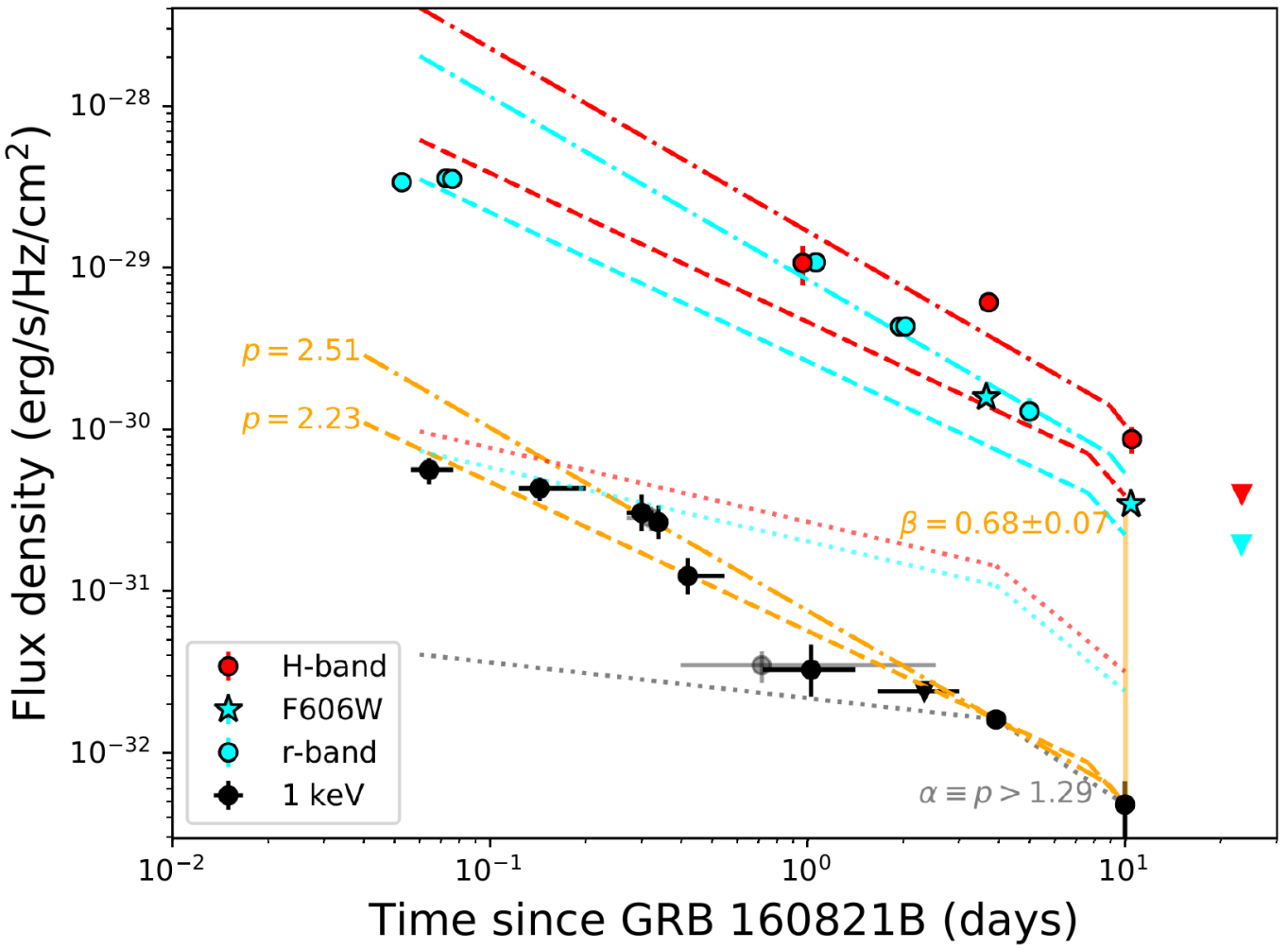


- Afterglow model lightcurves from `Redback` (Sarin,...**GPL**, et al. 2024)
- `Afterglowpy` and `redback_tophat`, plus a kilonova (left) and supernova (right)
- Lightcurves at Radio, optical, x-ray frequencies
- Time scale is 14 minutes to 30 (left) or 100 (right) days

- Observations*, typically start after ~1 hour
- Early radio is complicated by scintillation (not shown)
- And self-absorption – the difference between `redback_tophat` and `afterglowpy` at 1 GHz
- Optical has rapid decline, but thermal transients can become prominent
- Other than spectral break differences, x-ray is well behaved

*from the ground

The case of GRB 160821B

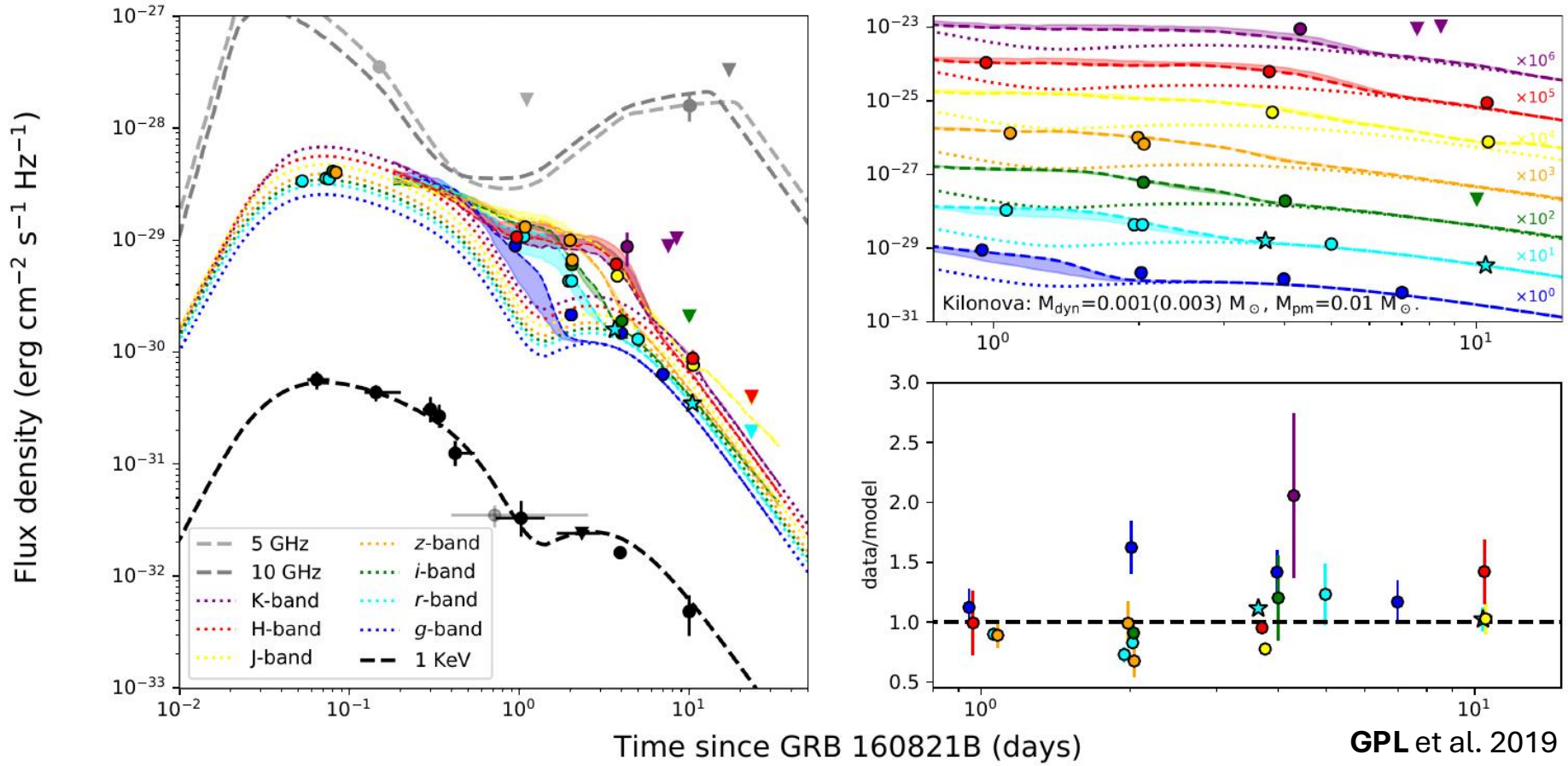


- Observations start at about 1 hour
- All are declining
- But not as a single power law
- Okay, but not even as two power laws

- Use the estimated decline at optical or x-ray to infer the other – dotted, dashed, dash-dotted
- Nothing looks right!?

- Ignore it and carry on?
- Take a closer look at the x-ray, as photon collecting (time error bars are not uncertainties, but bin sizes)
- Re-bin critical x-ray observations!
- It dips more than expected – rebrightening before declining.
- Optical still doesn't fit, but…

- Energy injection into the afterglow at ~1 day
- Optical at the same time is thermal – a kilonova!
- The optical afterglow can be inferred from the x-ray
- And subtracted from the data
- Fitting a kilonova model – although slightly lower mass, this is consistent with the kionova following GW170817



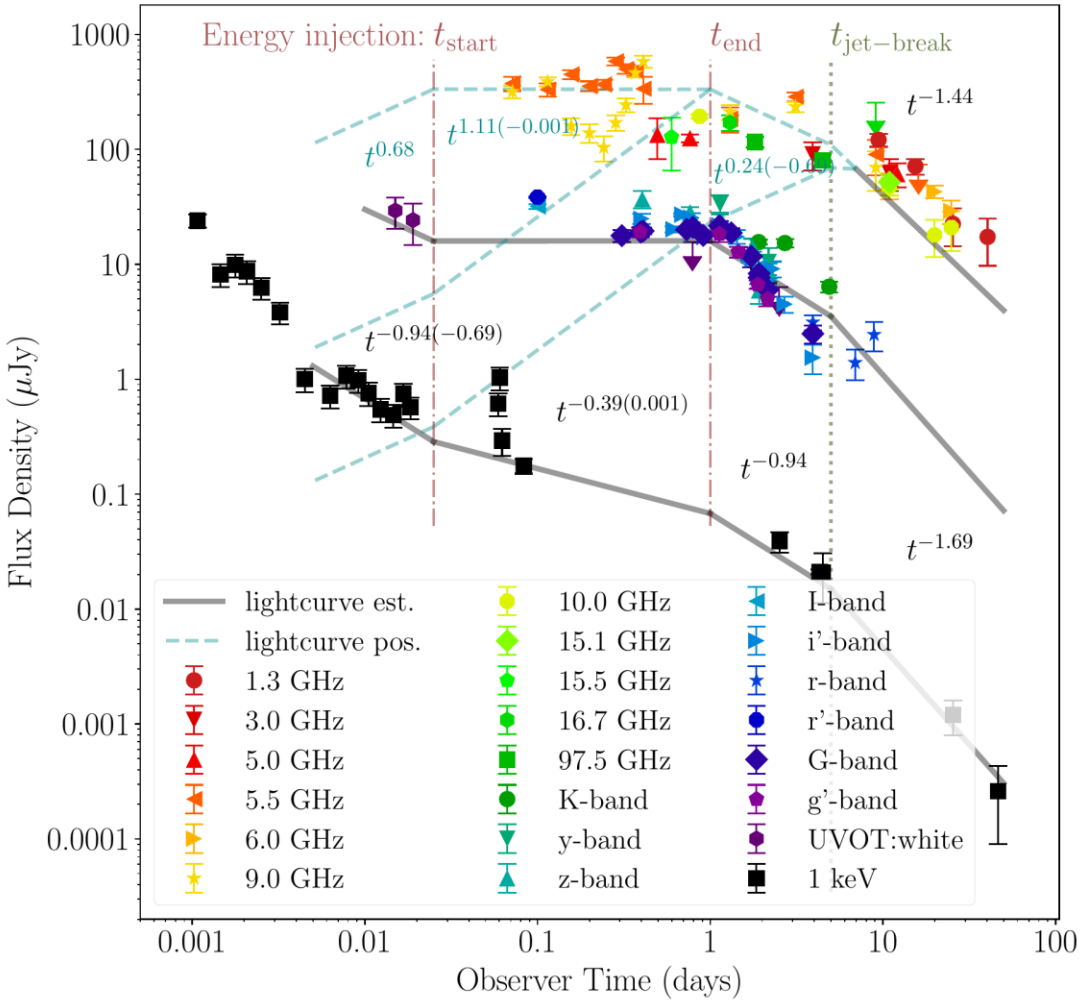
GPL et al. 2019

The x-ray observations of Swift-XRT (and XMM Newton) were essential in decoding the afterglow, revealing a fairly "standard" kilonova.
The x-ray traces the afterglow evolution, even when it is complicated!!!

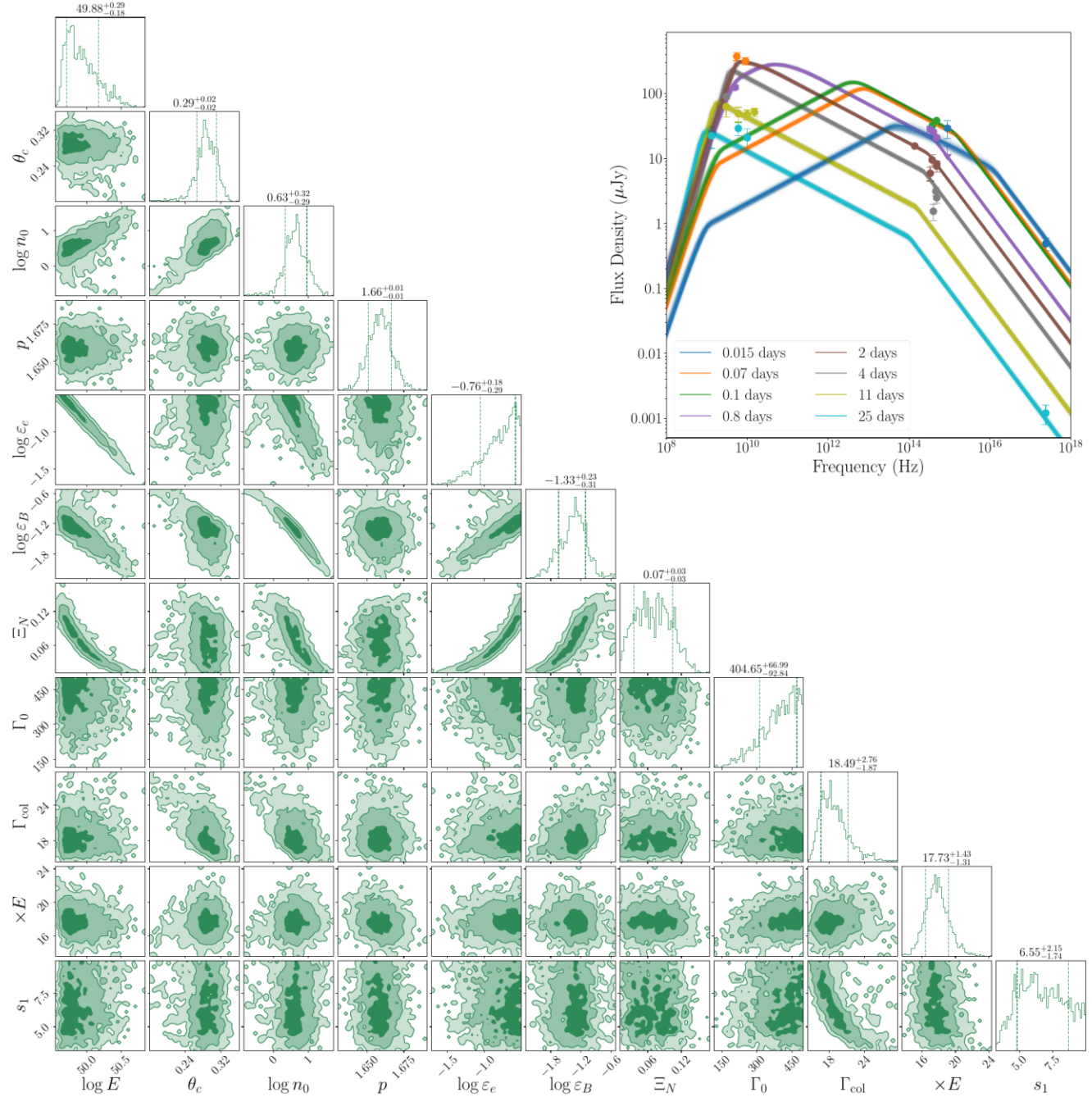
Yes, really! Watch this…

GRB 231117A – it looks like energy injection but…

- Excellent radio, optical, and x-ray coverage
- Use the closure relations to estimate the temporal and sed behaviour – energy injection, but not as we know it
- That x-ray flare at 1-2 hours!?
- That radio excess – scintillation?
- Other than the flare, the x-ray appears as a regular refreshed shock



Anderson… **GPL** et al. (in prep), see also Schroeder et al. 2025



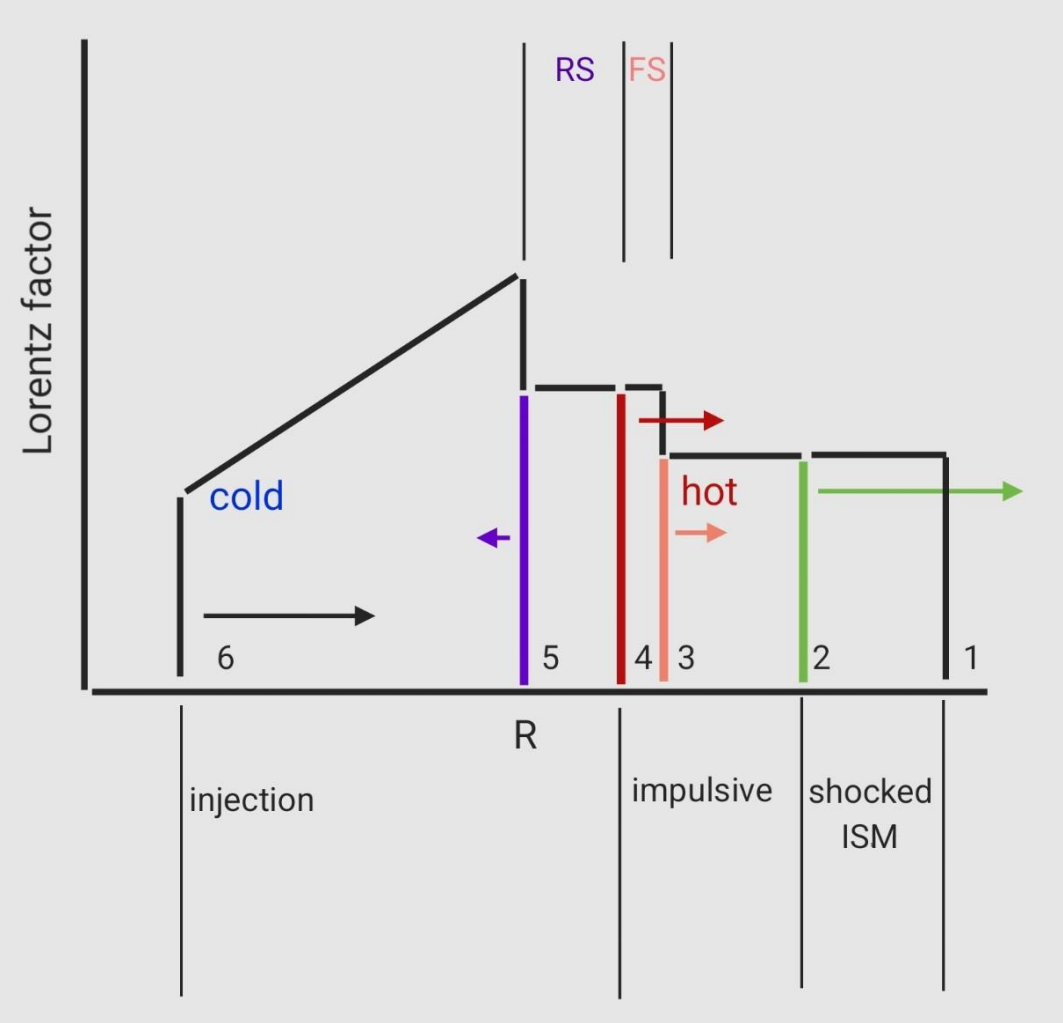
Looking at radio… but that flare!

- Fit the model `tophat_redback_refreshed` to the data via `nessai` – a sophisticated, AI powered nested sampler (with hierarchical something or other)
- Posterior, and the sed – all looks good apart from the early radio at 0.07 days
- The x-ray flare was just before this – data not shown

- Could the flare and the radio excess be related?

Anderson… **GPL** et al. (in prep)

Never a new model... let's make a new model!



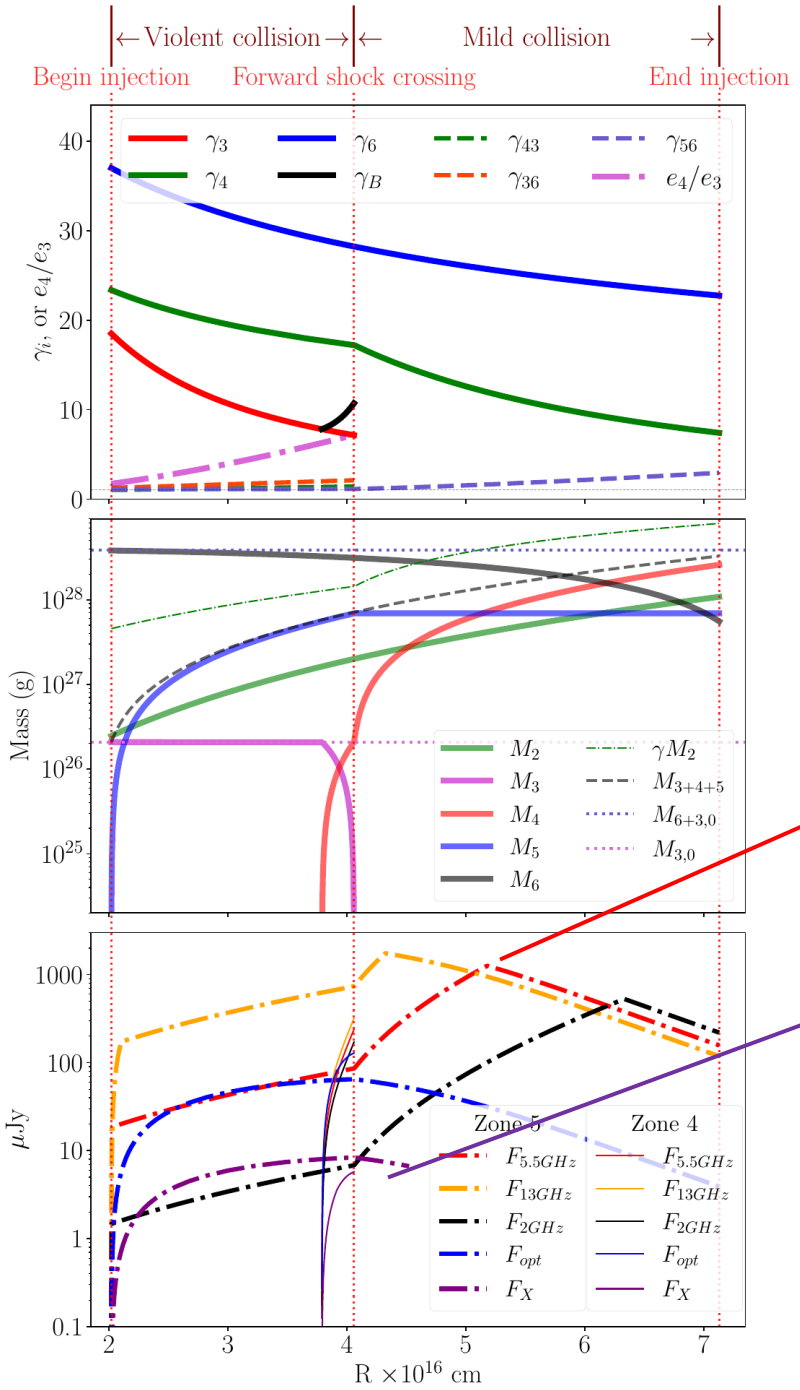
- Not actually "new"... maybe a bit new
- Take Zhang & Meszaros 2002 and apply their collision model to our parameters
- What is new?
  - Stratified velocity profile in catching shell
  - Energy injected is >> impulsive energy
- Careful to conserve mass, energy, and momentum

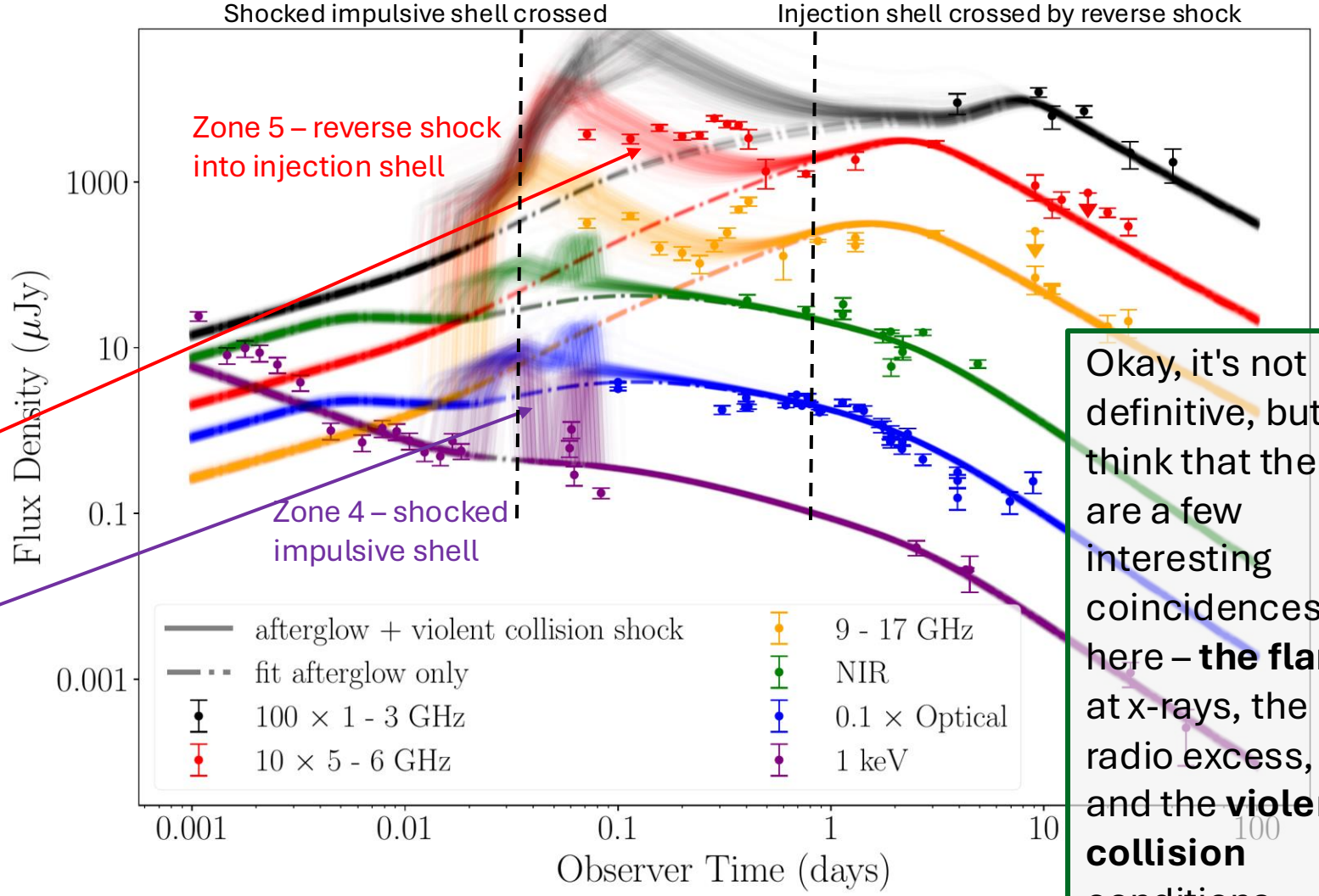
- Many more free parameters, too many
- Use the existing fit posterior (refreshed shock) and tag on the new model

Violent collision model without finetuning →

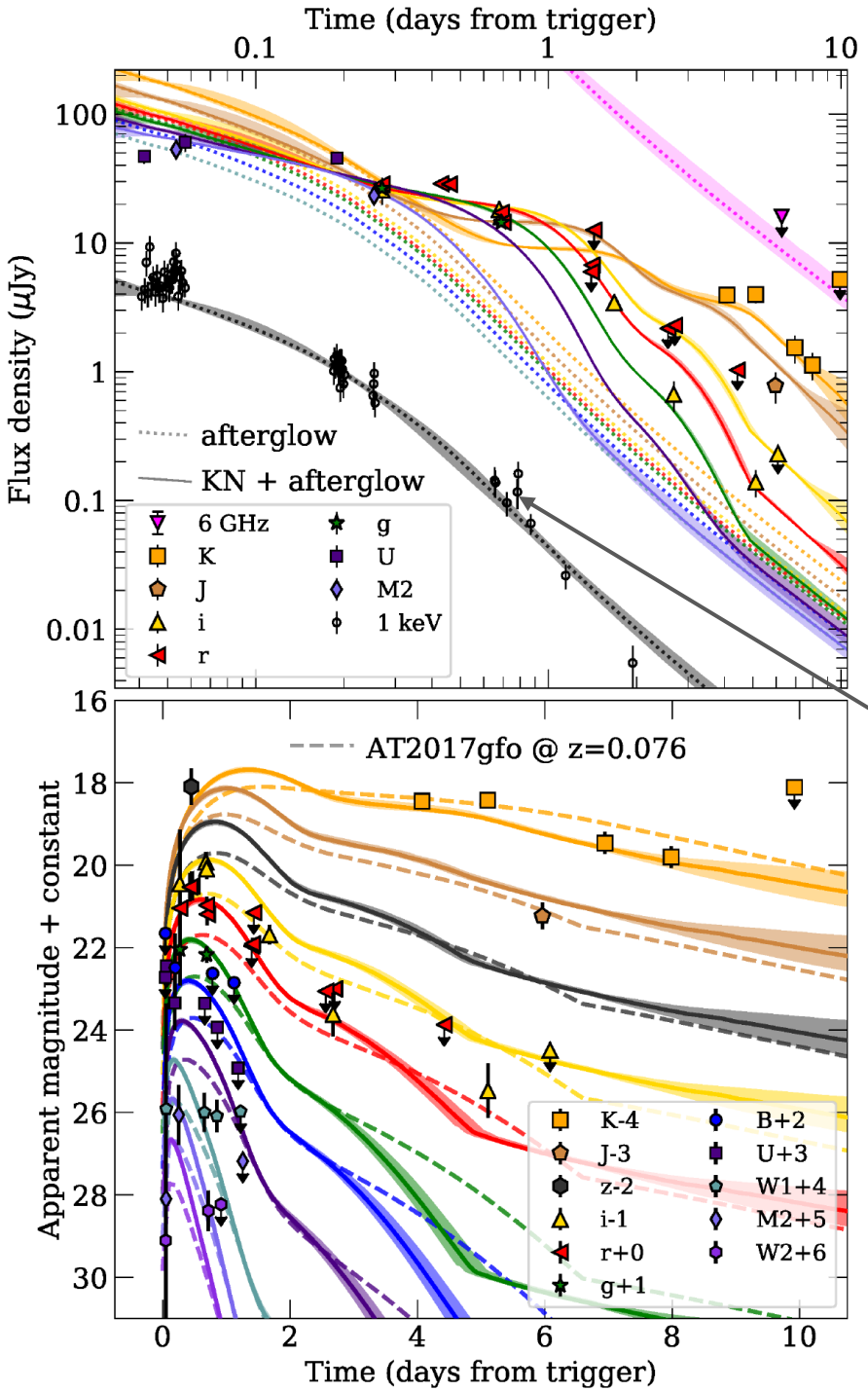
Anderson... **GPL** et al. (in prep) -- this figure relegated to the appendix, Appendix B even!

Model parameters look like this… and the lightcurves, like this





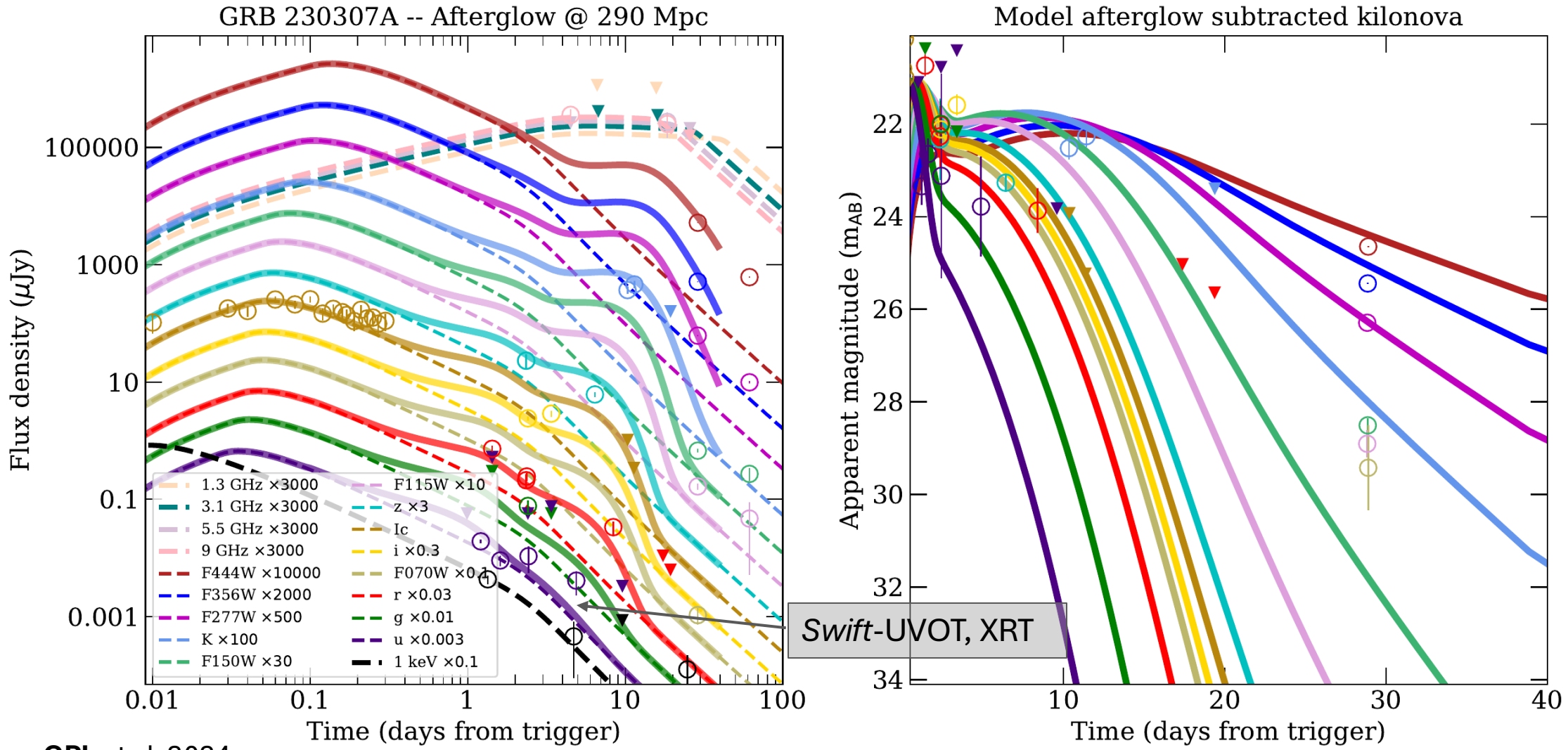
Okay, it's not definitive, but I think that there are a few interesting coincidences here – **the flare** at x-rays, the radio excess, and the **violent collision** conditions



Those long-engined merger GRBs

- …or maybe not (Waxman et al. 2025) 😉
- GRB 211211A and GRB 230307A (Rastinejad… **GPL** et al. 2022, Levan… **GPL** et al. 2024)
- GRB 211211A – the *Swift*-XRT wins again
- GRB 230307A was also controversial… but not as much as a z=4 GRB with that luminosity would have been!

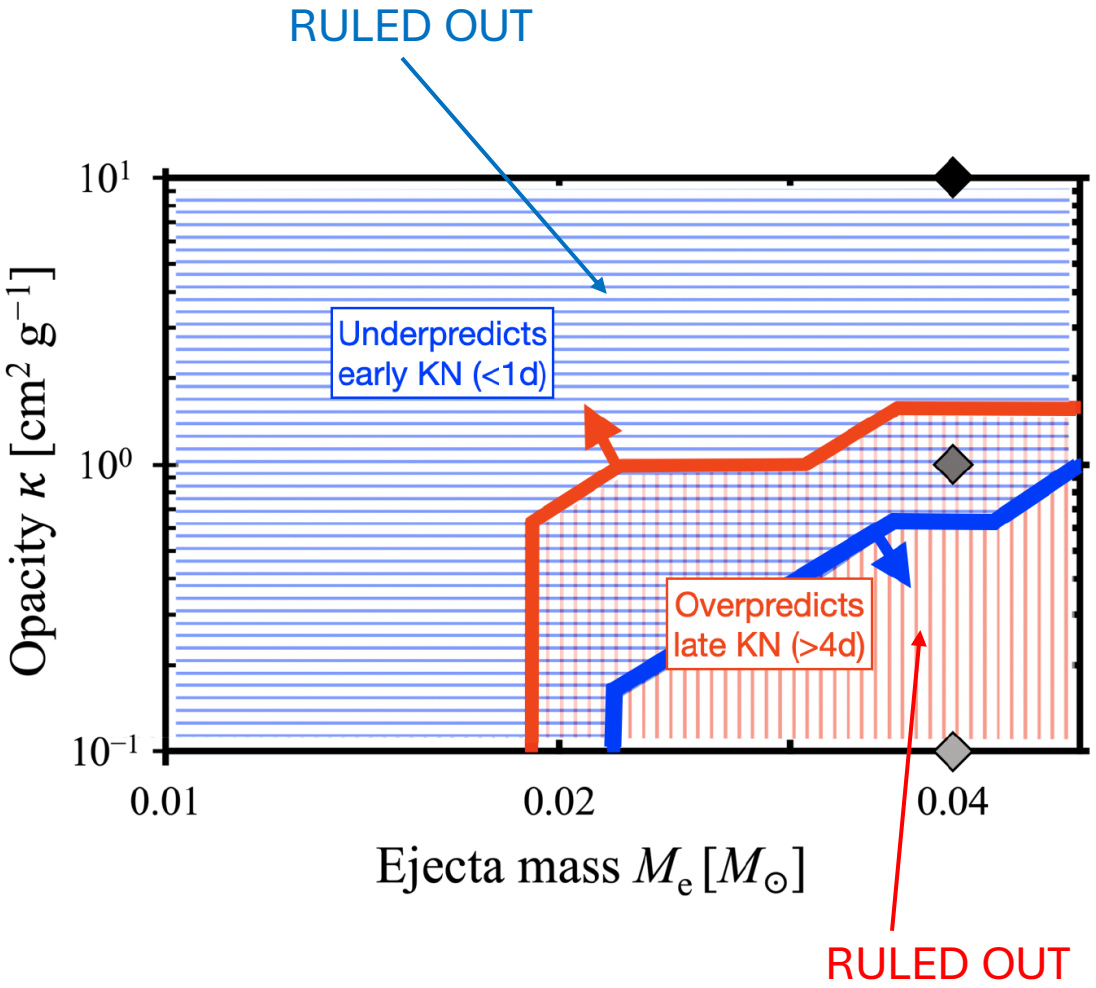
My figure for the GRB 230307A afterglow



Not in Levan… **GPL** et al. 2024

Long lived engine

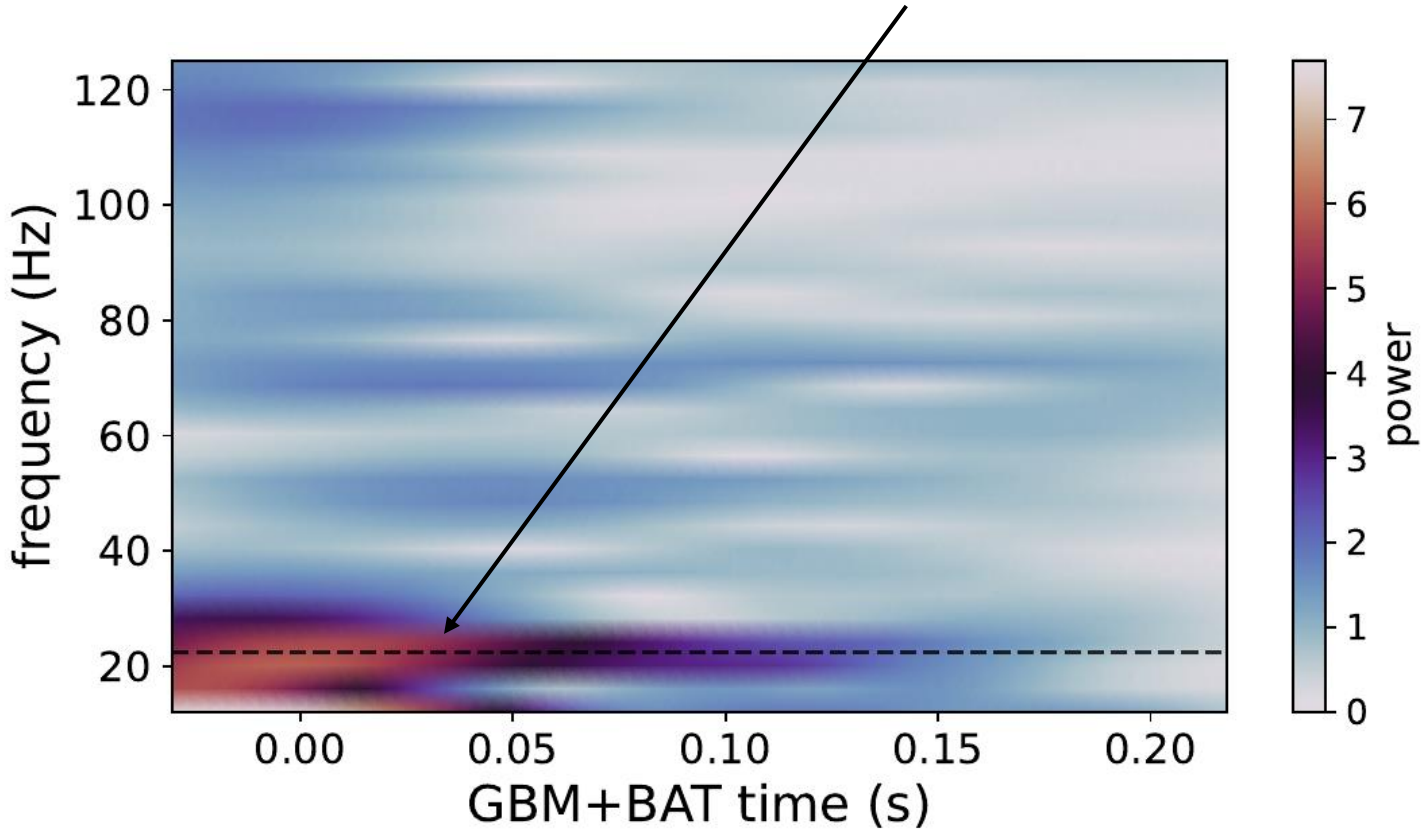
- Not everything as it seems
- The kilonova is difficult to reconcile
- Hamidani… **GPL** et al. 2024 show that red and blue incompatible
- And suggest a long-lived engine, or late jet that inflates a cocoon resulting in the blue component.
- So, the kilonova would just be red? Like from a NS-BH…

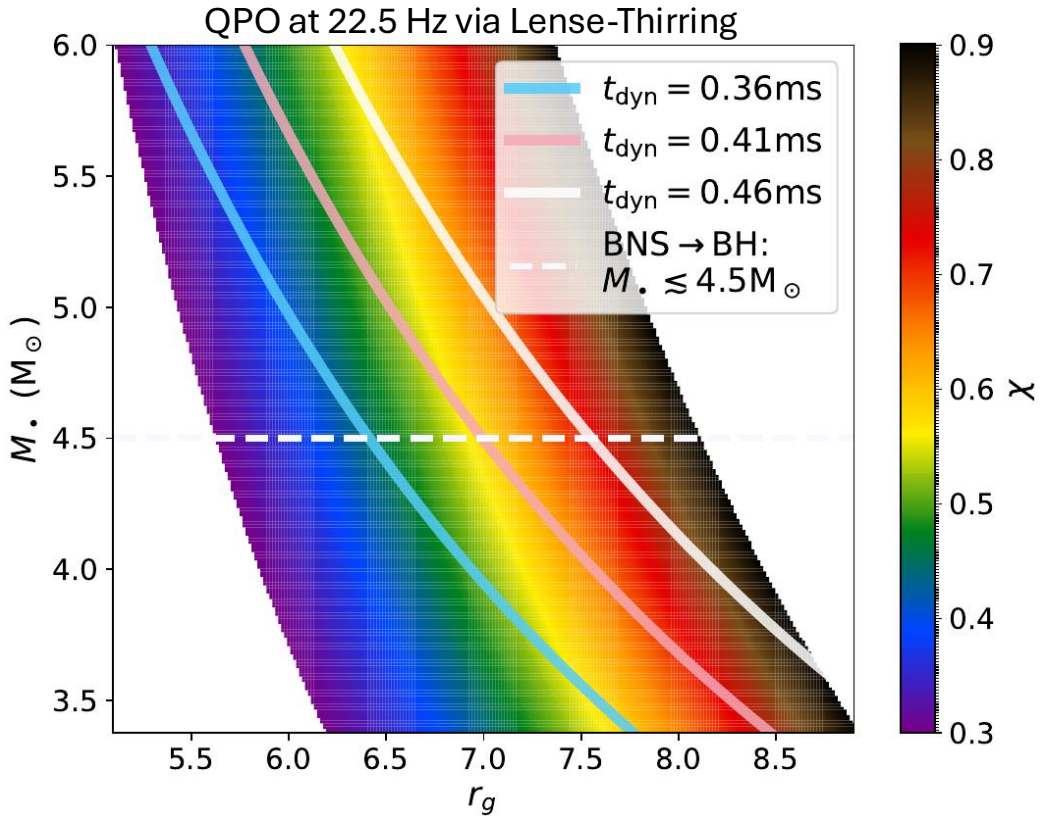


Hamidani… **GPL** et al. 2024

Early QPO – possibly evidence of a warp

- More weirdness… a QPO in the highly variable precursor. Analysis includes *Swift*-BAT data





If it is a NS-BH merger, the QPO is likely Lense-Thirring – which for higher mass black holes with moderate spin seems to produce the expected timescales and length scales

GPL et al. 2025 arXiv:2503.15613

Conclusions

- The x-, gamma-, and UV/optical observations of GRBs made by *Swift* are essential in unlocking the individual afterglow lightcurve data for most GRBs
- The BAT data compliments the data from other gamma-ray burst monitors, and gives unparallelled localisations
- GRB phenomena are complicated, but general trends persist – the details may hold the keys to unlocking their secrets
- XRT observations have been instrumental to our understanding and modelling of GRB afterglows

LONG LIVE *SWIFT* – the original Swifty

Taylor Swift – stolen from the internet. No grasses!