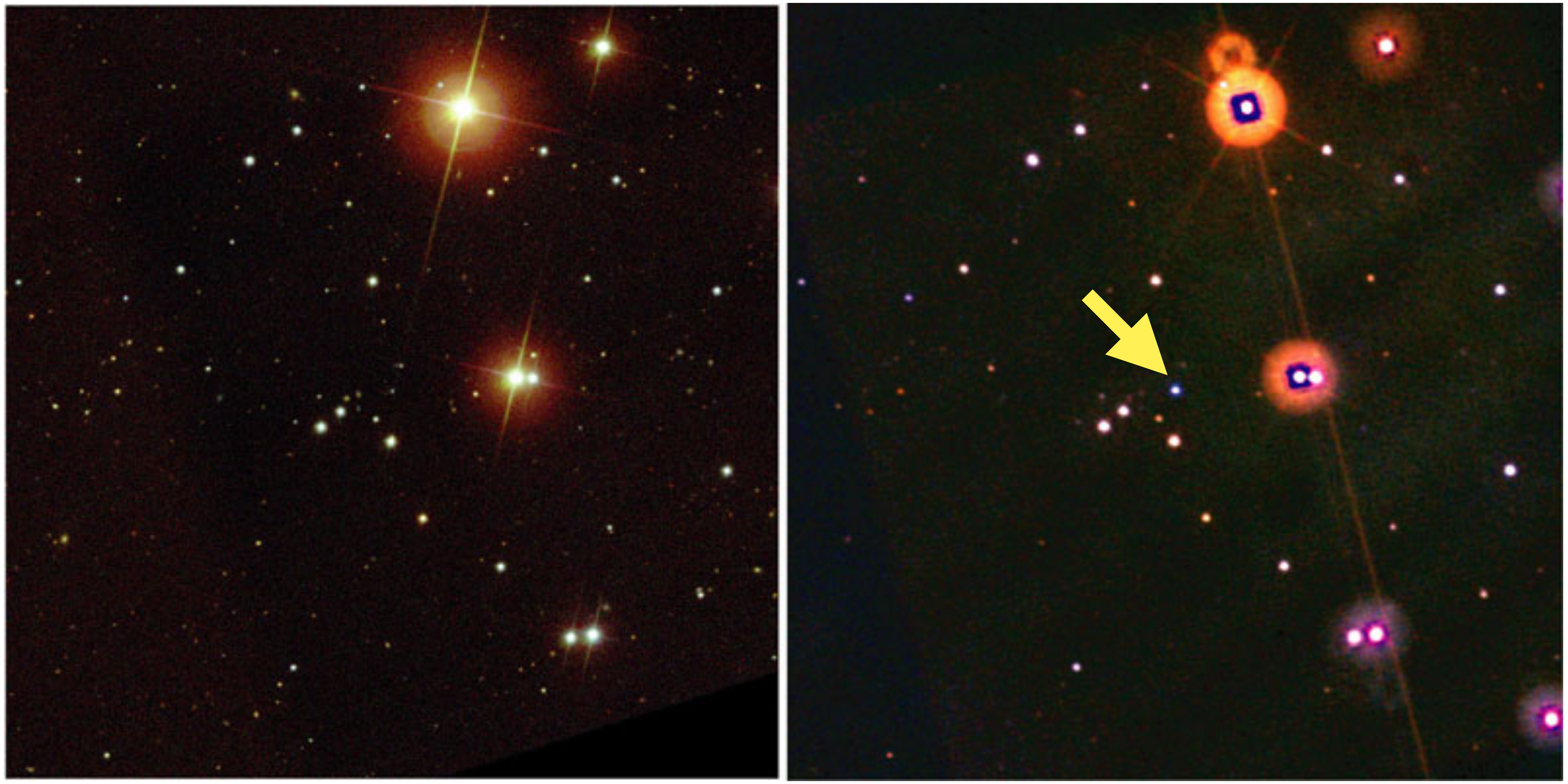
Are Low-Luminosity GRBs Powered by Shock Breakout?

A Revised Shock Breakout Model for GRB 060218

Based on Irwin & Hotokezaka
arXiv:2412.06733
arXiv:2412.06734
arXiv:2412.06736



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東京大学
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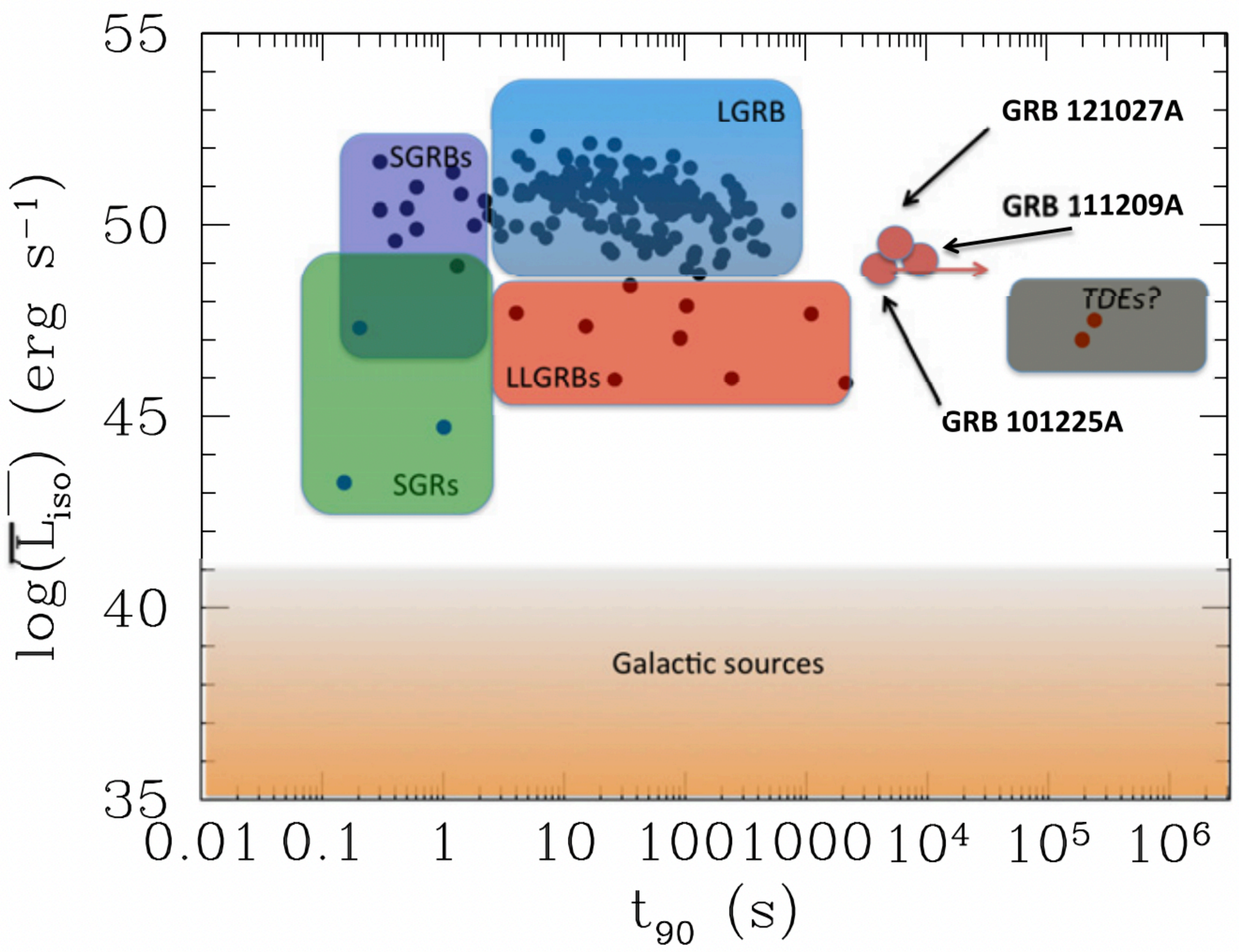
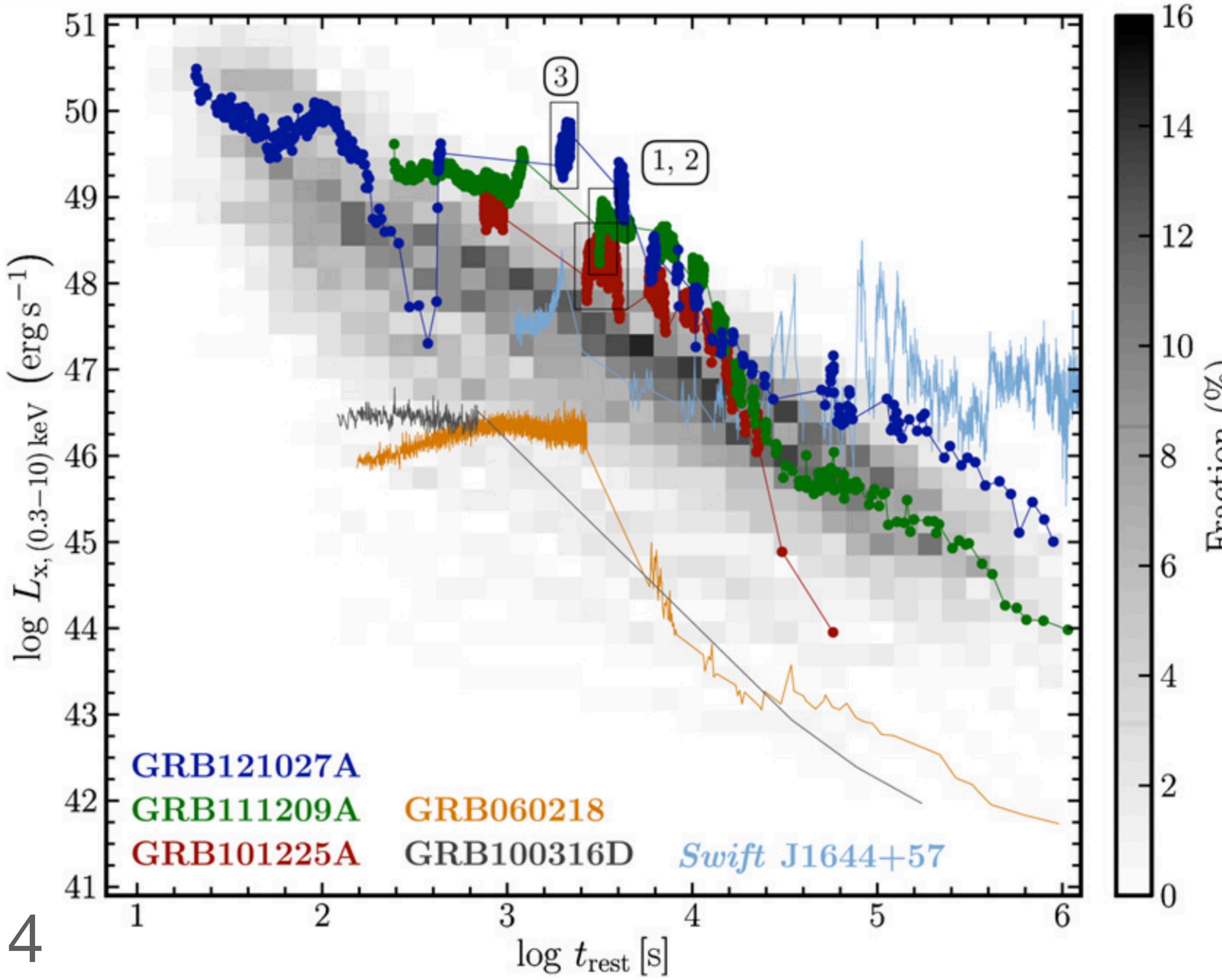
YITP 2016

YITP 2016

Low-luminosity GRBs

- LLGRBs are a faint, soft, long-lived subclass of long GRBs
  - Unlike typical GRBs, some LLGRBs have a smooth, single-peaked light curve
- LLGRBs may be more common than standard GRBs, but owing to their faintness they are difficult to detect
  - Estimated rate is ~230 Gpc^{-3} yr^{-1}, roughly ~10-100 times larger than standard GRBs (Soderberg+ 2006)
  - Swift: one per ~5 years
  - EP: several per year



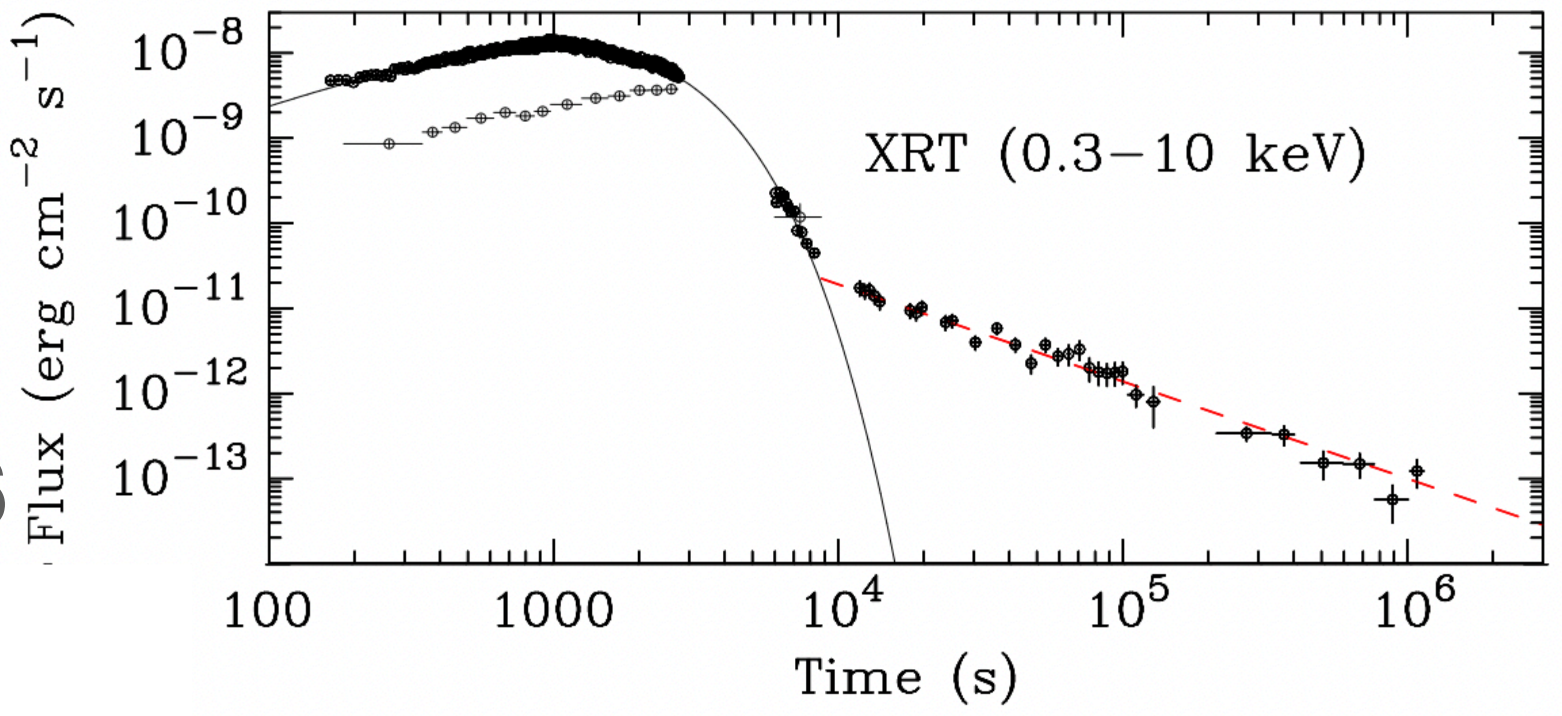


Levan+ 2014

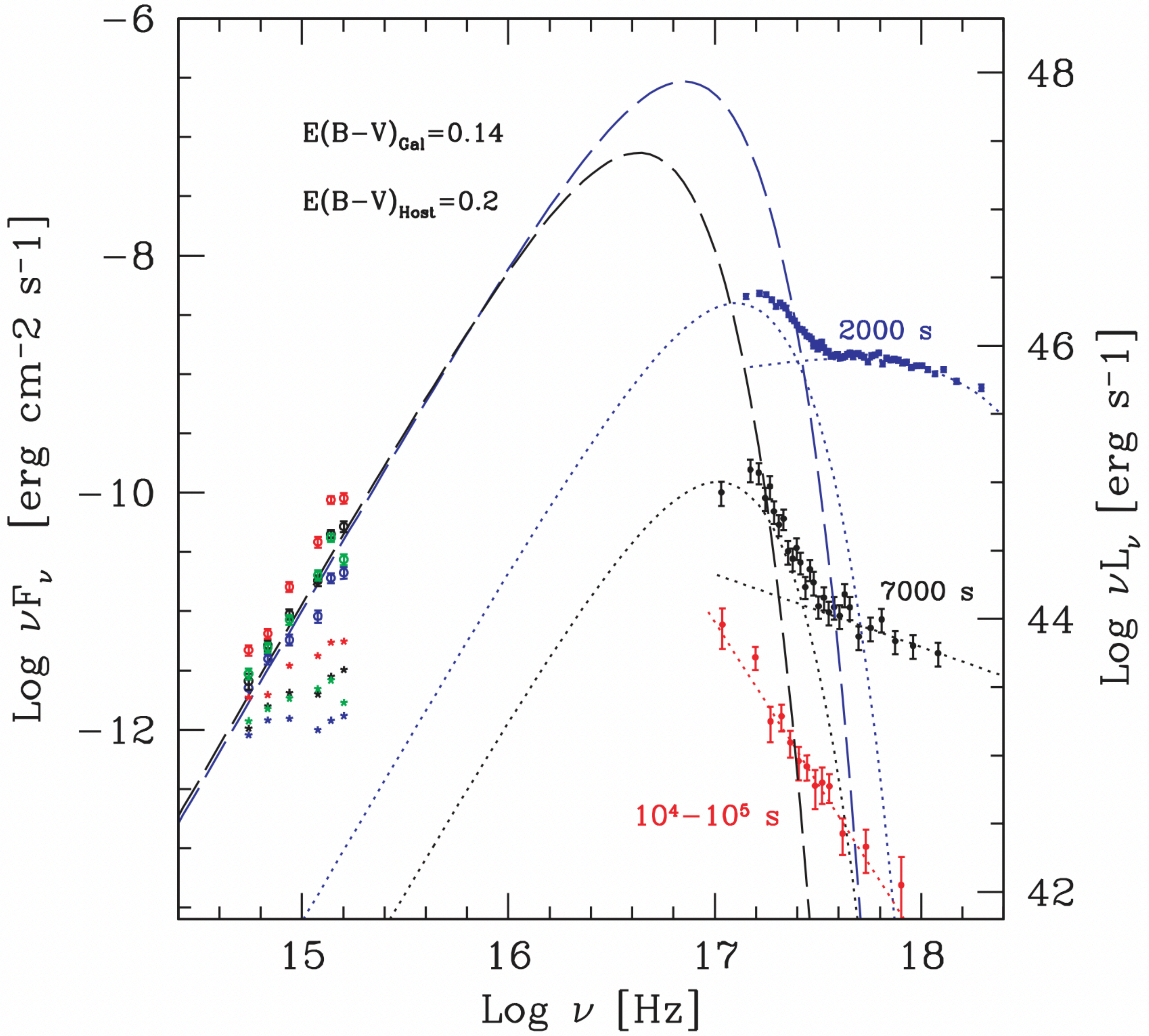
GRB 060218

- Among LLGRBs, two—GRB 060218 and GRB 100316D—share a unique set of peculiar X-ray features
  - Smooth light curve lasting ~thousands of seconds
  - Excess of soft X-rays around ~0.1 keV, interpreted as a thermal component
    - The contribution of the thermal component to the total prompt flux is uncertain—estimates range from 0.13% (Kaneko 2007) to 15% (Campana 2006)
  - The thermal emission dominates at late times
  - Very low peak energy, ~30 keV, which evolves rapidly in time

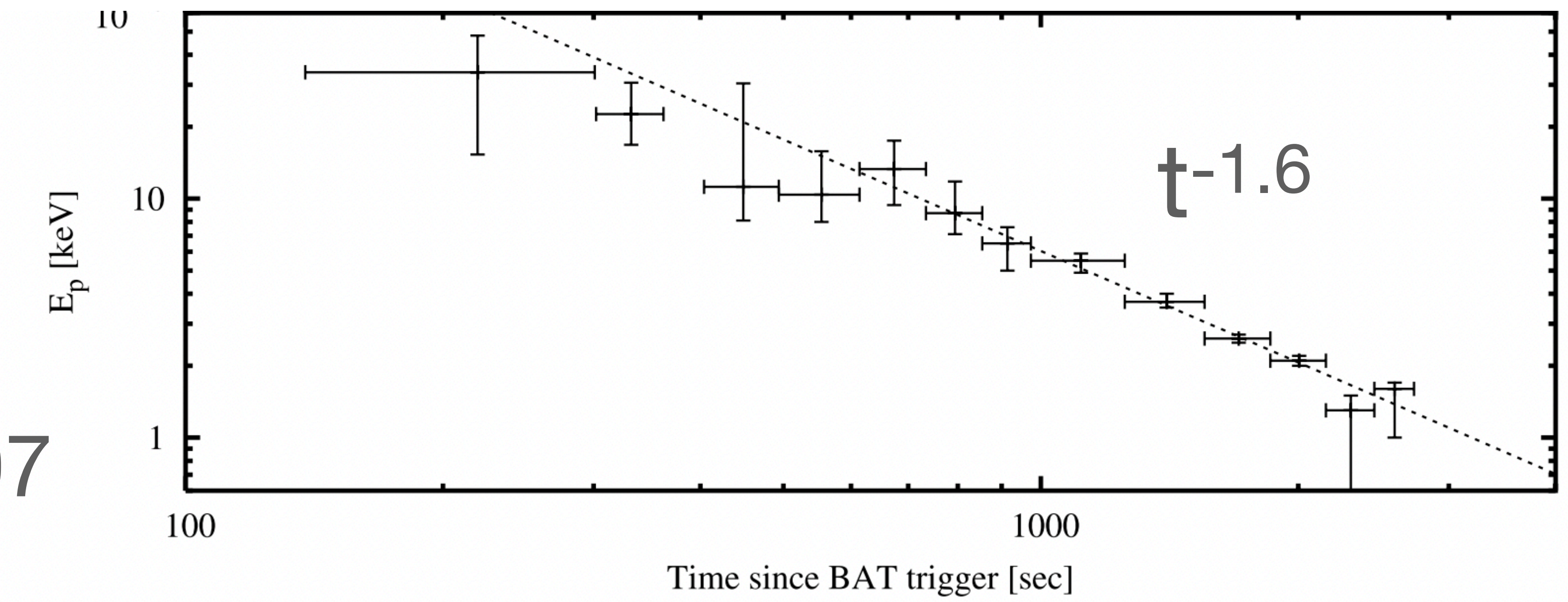
Campana+ 2006



Ghisellini+2007

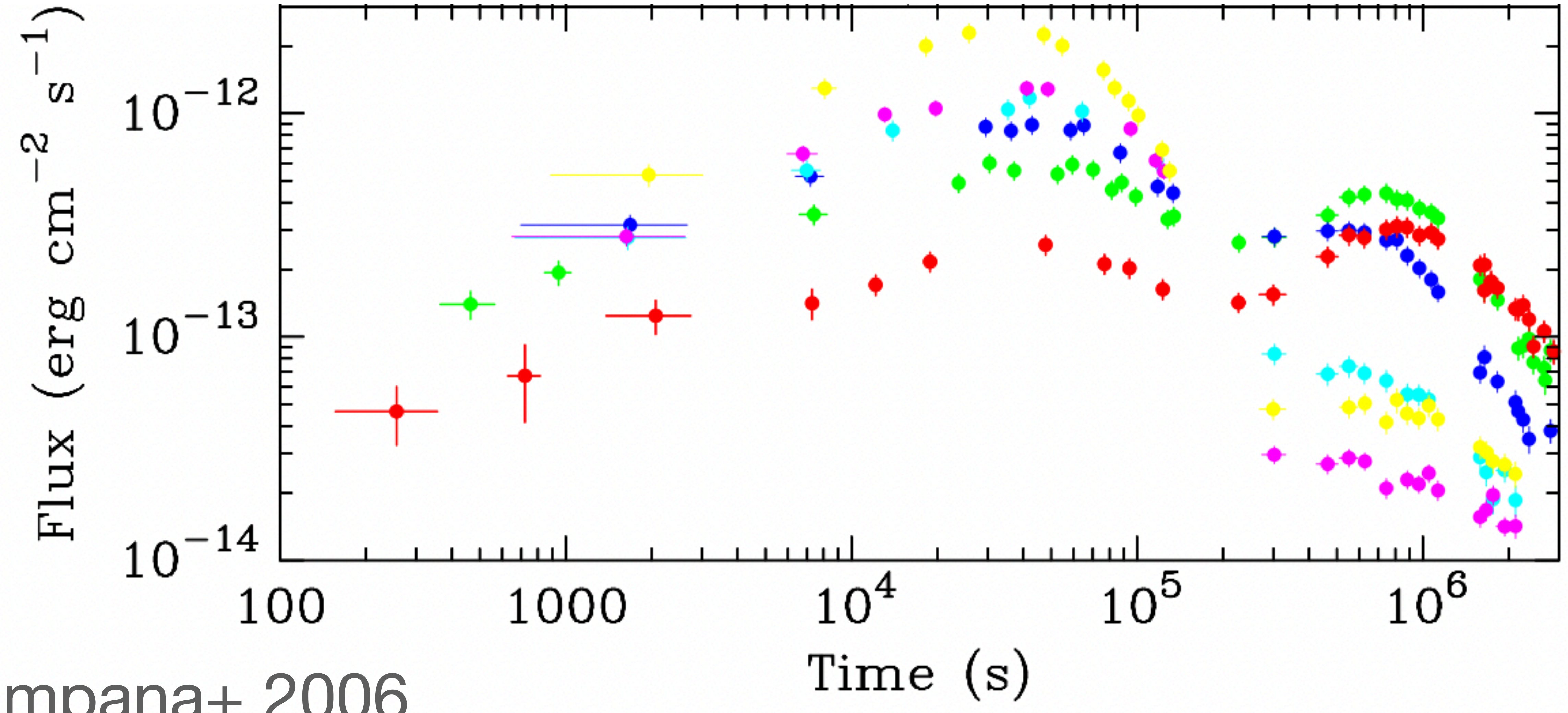


Toma+ 2007

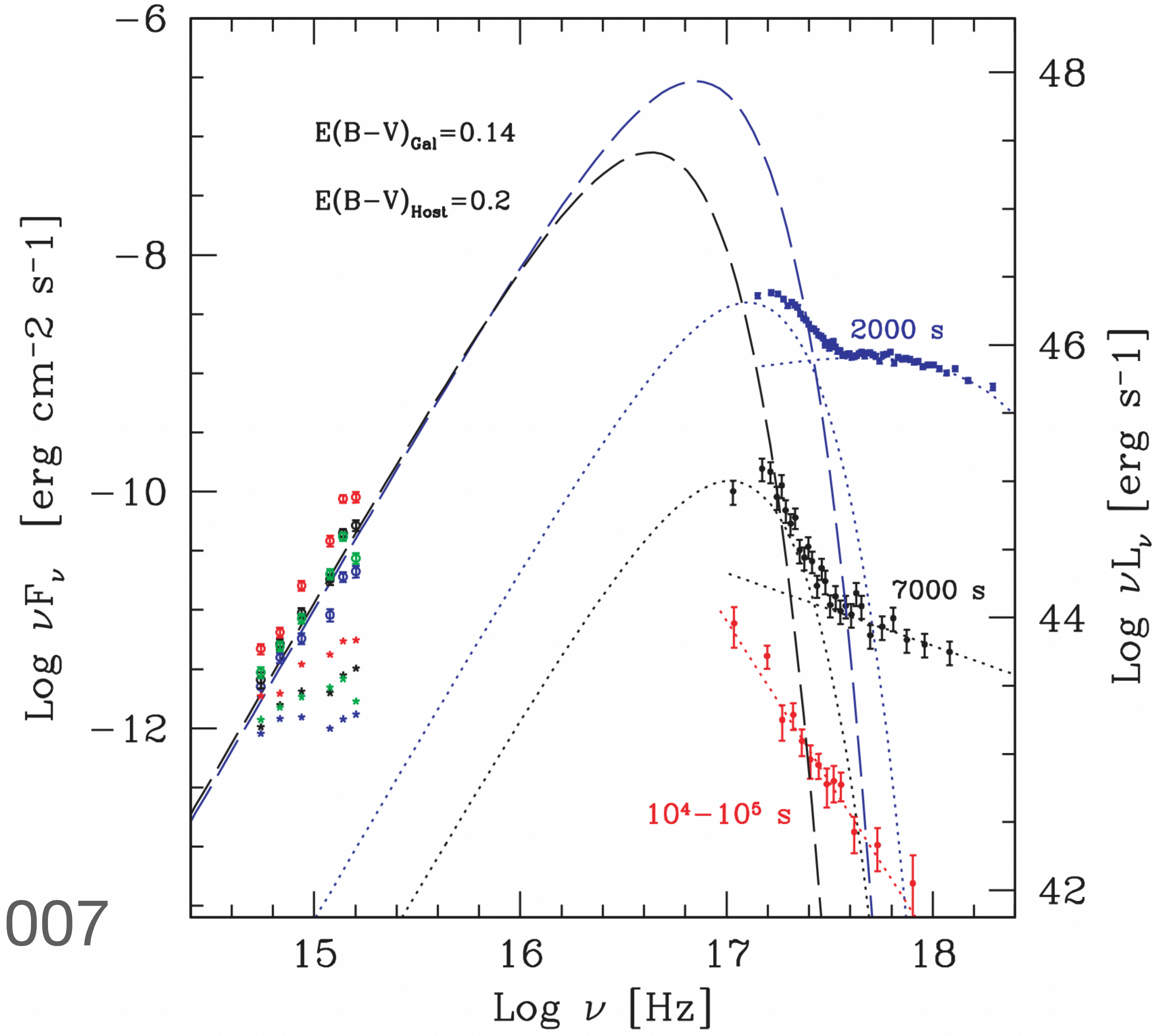


Multiwavelength Observations

- Strong optical emission is observed from early times
- Optical emission rises to an early peak at ~30000 s, well before the SN peaks
  - This double-peaked feature has since been observed in several other Type Ibc SNe (e.g., 2011dh, 2013df, iPTFbeo, 2017iuk, 2024gsa, 2025kg)
  - It is usually interpreted as cooling emission from a shock-heated CSM or extended, low-mass envelope
- The slope of the optical spectrum is uncertain due to uncertain host extinction/reddening
  - The optical spectrum seems to become bluer after a few thousand seconds
- Radio observations suggest ~10^{48} erg coupled to mildly relativistic (Γ ~ 2) ejecta (Soderberg+ 2006)



Campana+ 2006

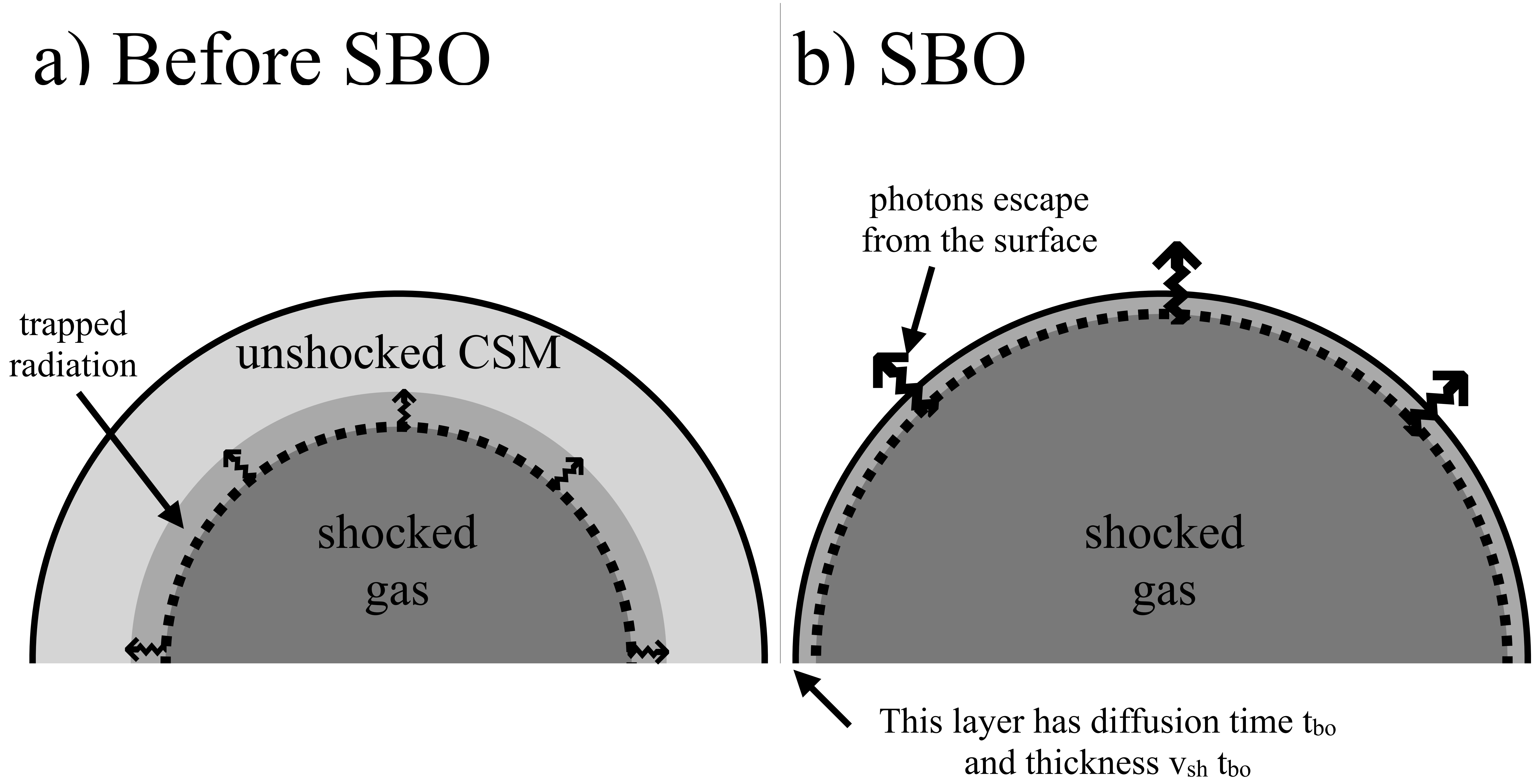


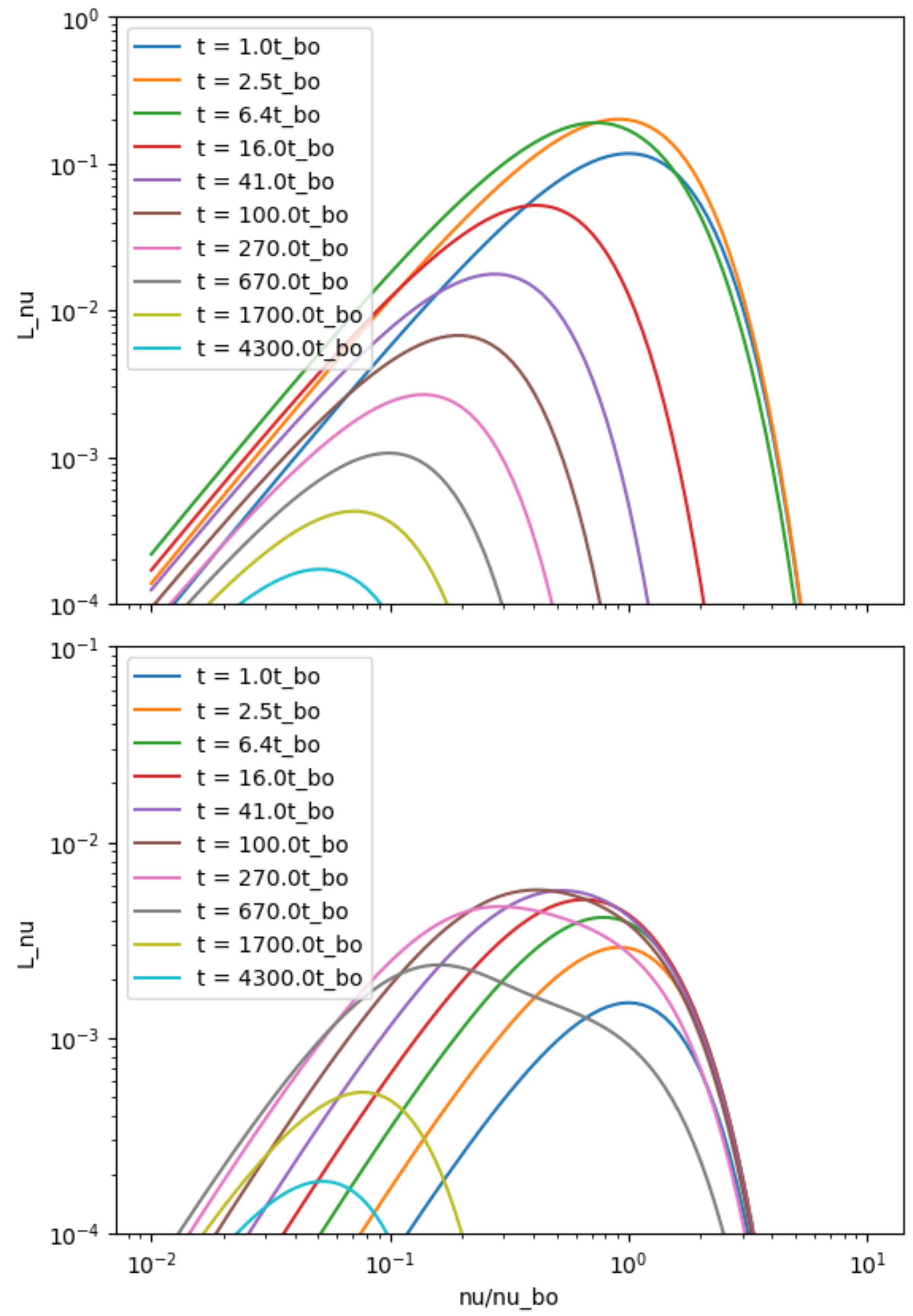
Ghisellini+2007

A Brief History of LLGRB Theory: Shock Breakout?

- Due to the lack of variability in the light curve, many authors have proposed a shock breakout origin for GRB 060218 (e.g., Campana et al. 2006; Waxman et al. 2007; Nakar & Sari 2012; Nakar 2015)
  - The early optical peak can be explained as cooling emission from a low-mass (~10^{-2} M_{sun}) envelope or mass-loss region extending out to ~10^{13} – 10^{14} cm (e.g., Nakar & Piro 2014; Nakar 2015; Irwin & Chevalier 2016)
  - Interestingly, the light-crossing time of the inferred envelope is similar to the duration of the X-ray transient—could the X-ray signal be produced when the shock breaks out of such an extended envelope (Nakar 2015)?

A Brief History of LLGRB Theory: Shock Breakout?





$t_{bo} >> R_{CSM}/c$

$R_{CSM}/c >> t_{bo}$

$$L \approx \frac{(\rho_{CSM} v_{sh}^2)\,[4\pi R_{CSM}^2 v_{sh} t_{bo}]}{t_{bo}} \min\left(1, \frac{t_{bo}}{R_{CSM}/c}\right)$$

A long light-crossing time smears out the signal over R_{CSM}/c,and spreads the emission over multiple temperatures

Not Shock Breakout?

A Brief History of LLGRB Theory: ~~Shock Breakout?~~

- However, so far shock breakout models have struggled to capture several features of GRB 060218 (see Irwin & Chevalier 2016), such as:
  - The coexistence of thermal and non-thermal spectral components
  - The presence of strong optical emission as early as ~100 s
  - The rapid peak energy evolution, $E_p \propto t^{-1.6}$
- These issues have led some authors to suggest that GRB 060218 cannot be a shock breakout event, and to propose alternative models involving jets (e.g., Ghisellini+ 2007a,b; Toma+ 2007; Irwin & Chevalier 2016)

Actually Shock Breakout After All?

~~Not Shock Breakout?~~

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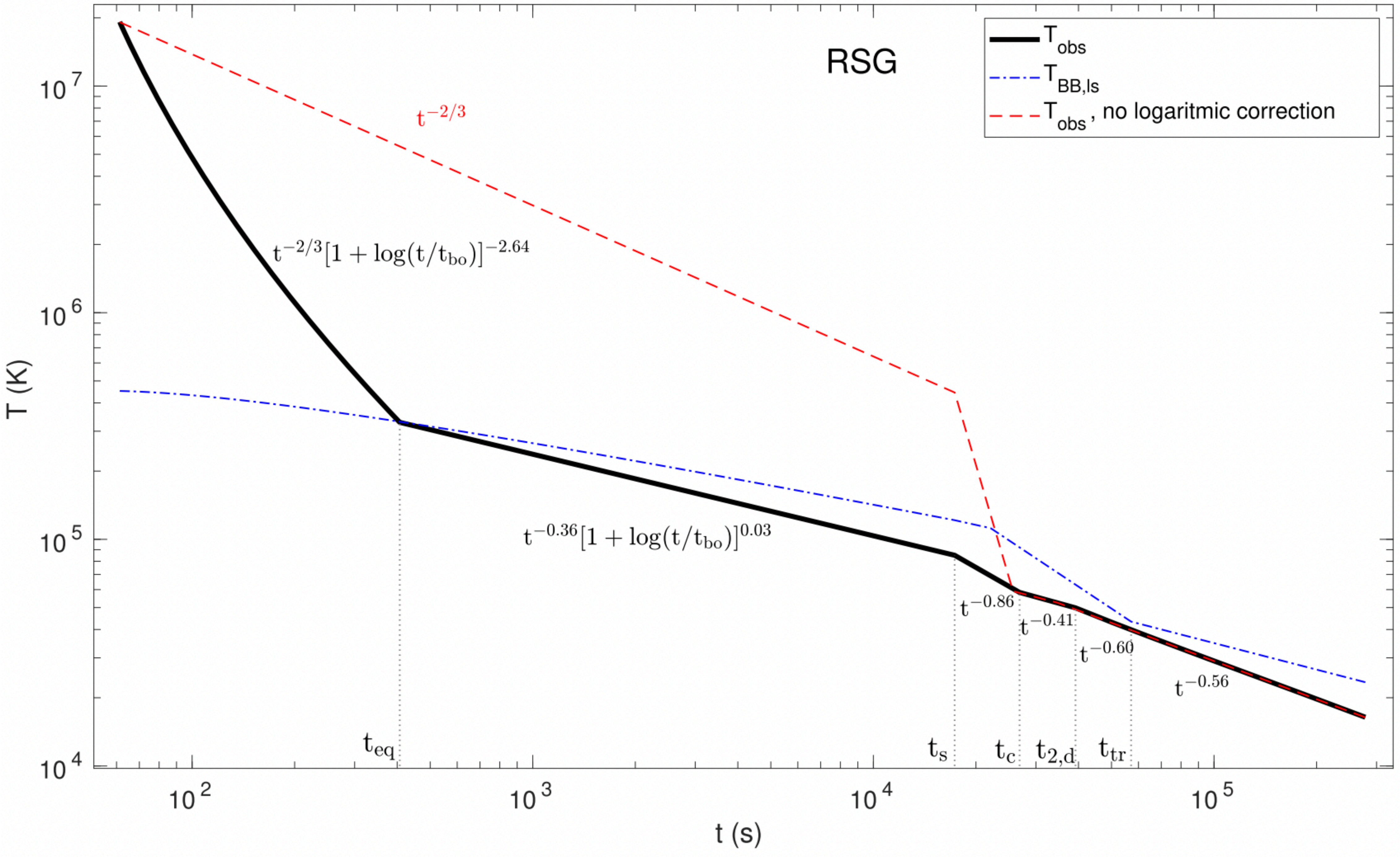
- **It may be possible to overcome these difficulties with an updated shock breakout model** (Irwin & Hotokezaka 2024, 2025a, 2025b)

What Changed?
The Early Temperature Evolution

For fast shocks breaking out of low density environments, the gas and radiation are not in equilibrium in the outer layers of the ejecta.

Deeper and slower shells, which are in equilibrium, are eventually revealed as the outflow expands



Early work ignored a logarithmic term which turns out to be important.

Recently, a self-similar solution of the diffusion equation in the planar phase was obtained, which shows that this correction significantly different temperature evolution

Nakar & Sari 2010

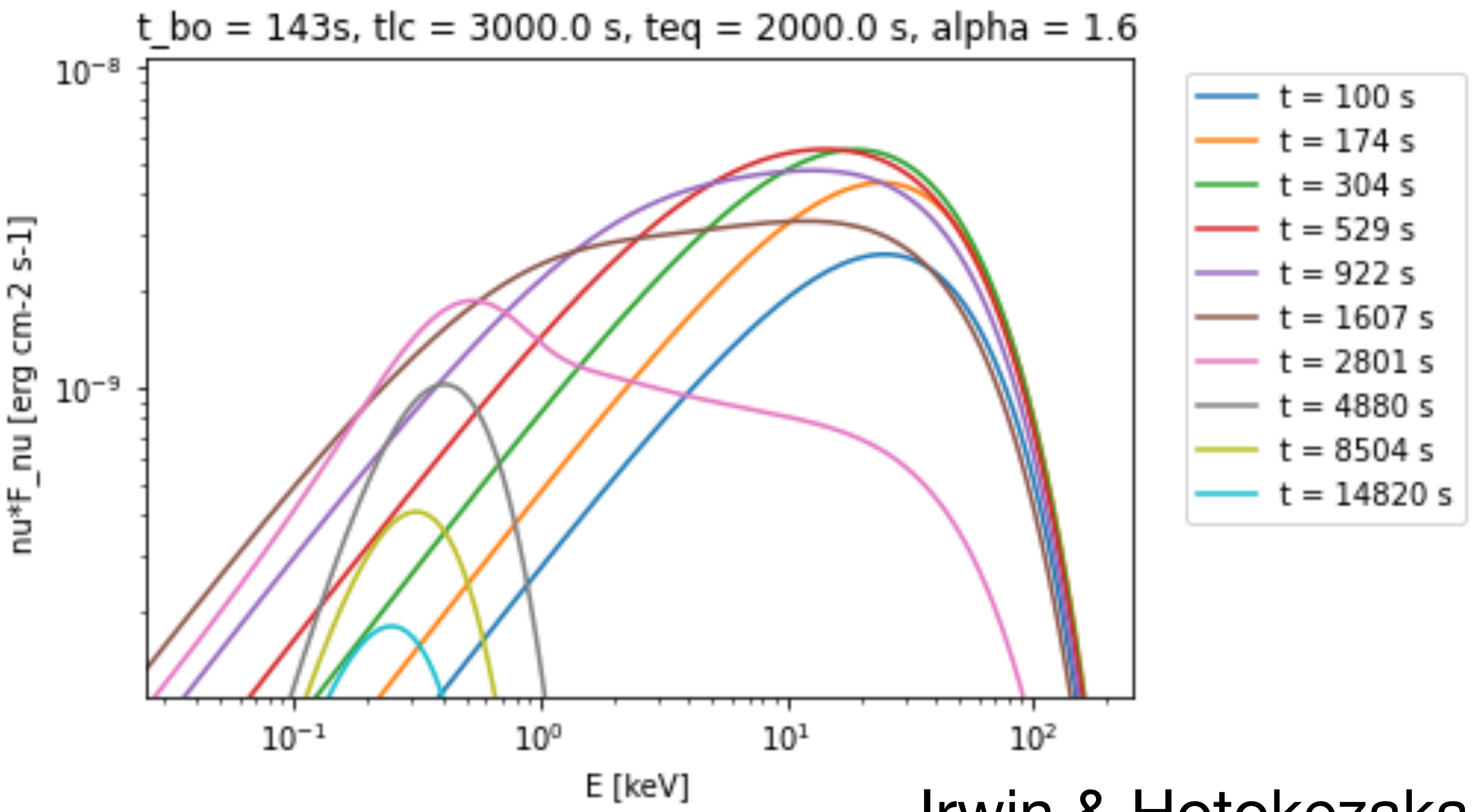
- $T_{obs} \propto t^{-\alpha(n)}$, $1/3 < \alpha < 2/3$

Faran & Sari 2019

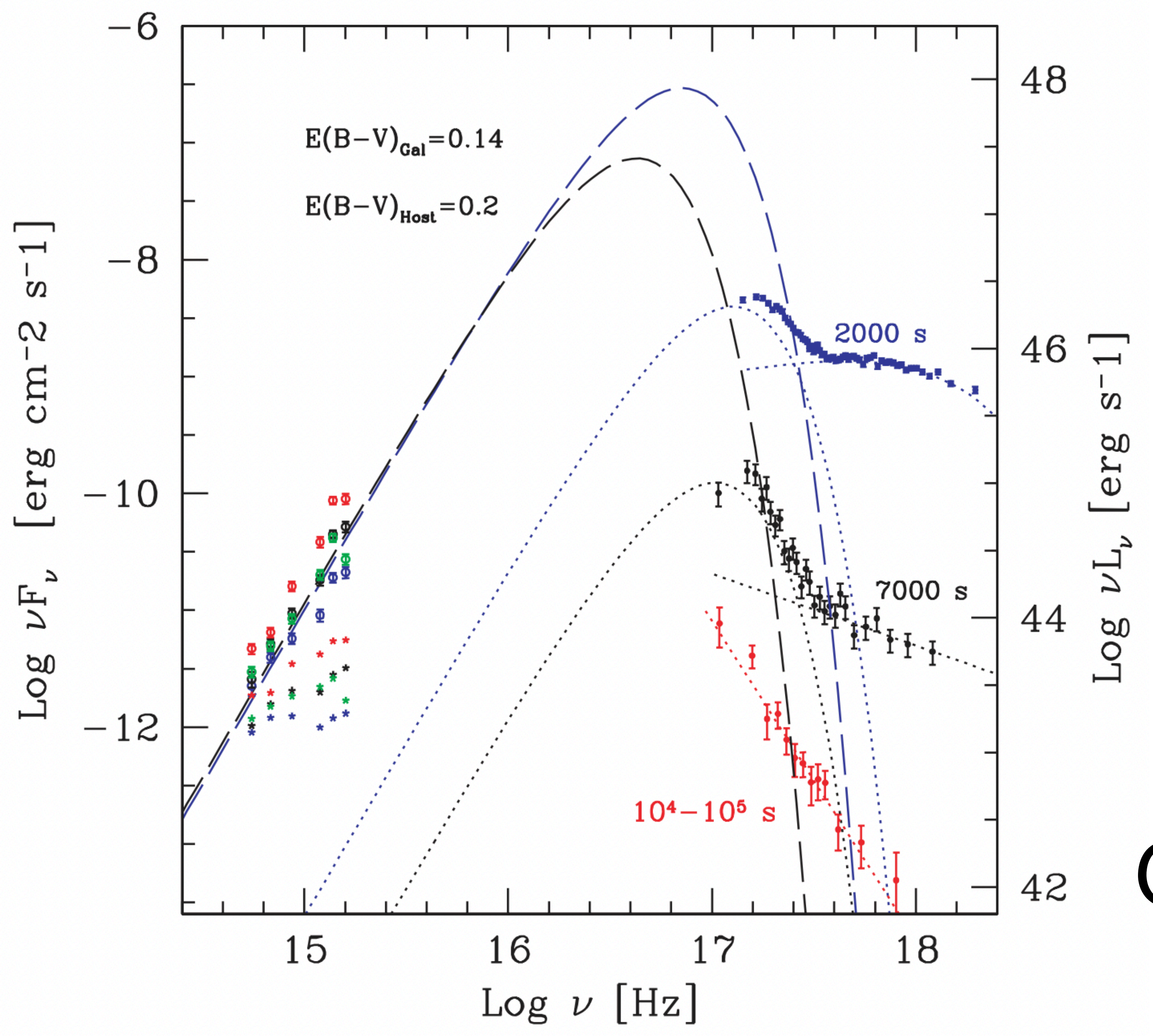
- $T_{obs} \propto t^{-\alpha(n)} [1 + \ln t]^{-\beta(n)}$, β can be large
- Equilibrium is achieved much faster than previously thought

An unexplored regime of shock breakout

- For fast shocks, the postshock gas and radiation are initially out of thermal equlibrium. The spectrum is a free-free spectrum peaking at temperatures >> T_{BB}
- The gas and radiation eventually thermalize on a timescale t_{eq}, and the spectrum becomes a blackbody
- If the breakout is prolonged to > t_{eq} due to a large breakout radius and/or asphericity, the spectrum is a blend of thermal and non-thermal components
- The resulting peculiar spectrum resembles observations of low-luminosity GRBs
    - Excess emission at ~0.1 keV
    - Free-free enhances the optical at early times
    - Steepening optical spectrum at late times



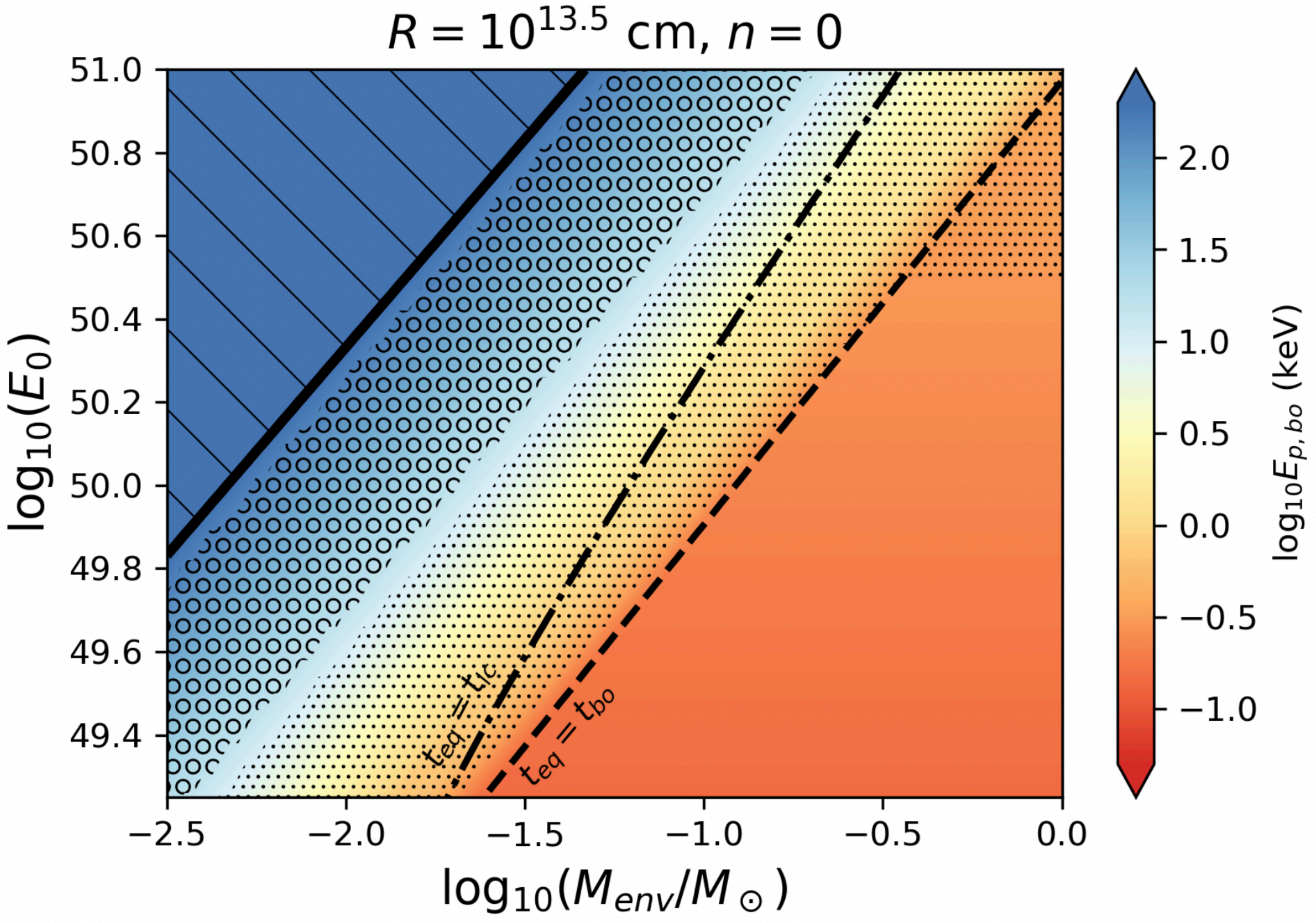
Irwin & Hotokezaka 2024



Ghisellini+ 2007

When does this type of breakout occur?

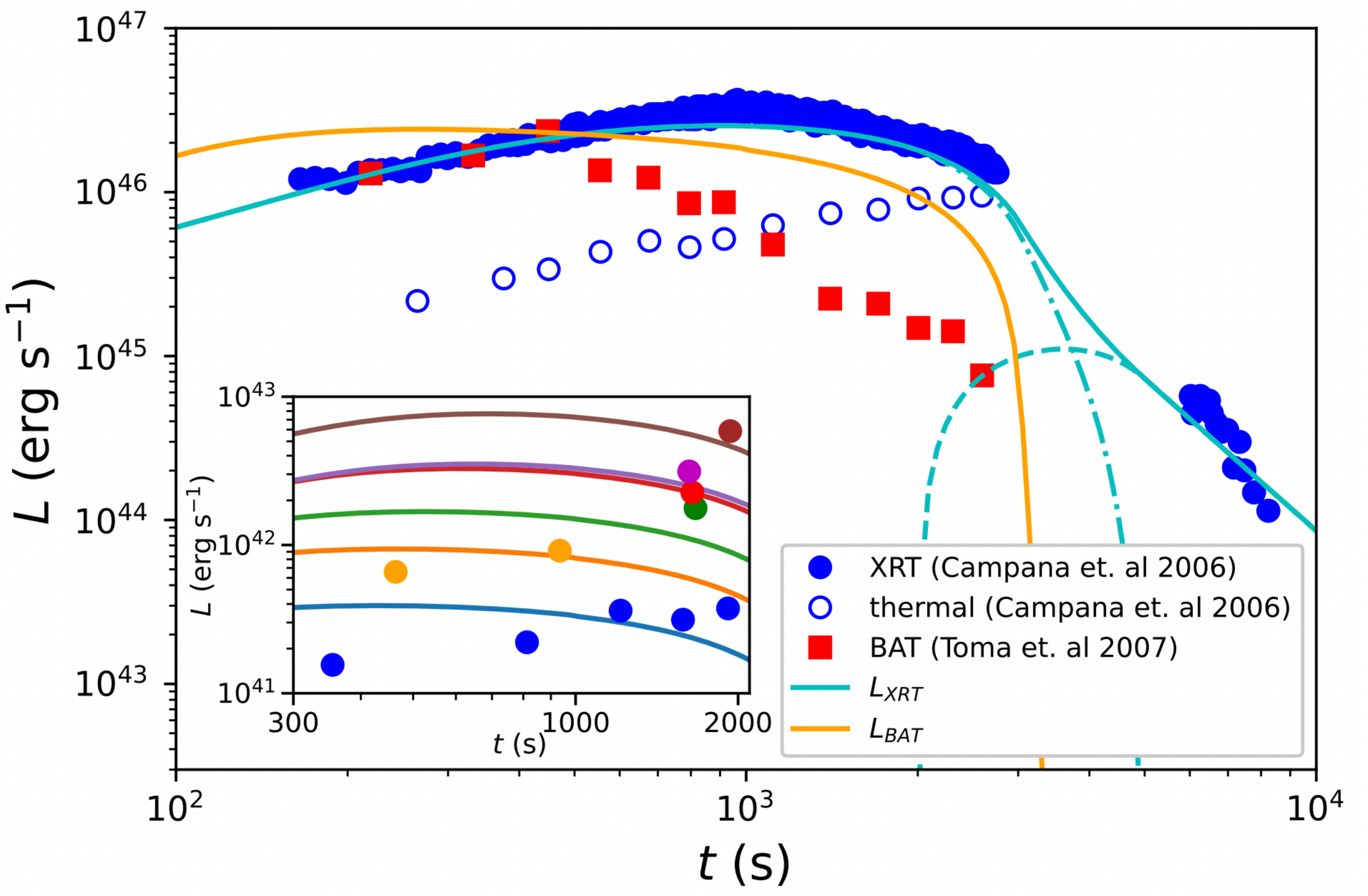
- Velocities around ~0.1c-0.2c almost always results in this type of two-component breakout
- Interestingly, the peak energies in this case significantly overlap the Swift XRT band. In this picture, **it is not surprising that XRT-bright LLGRBs show both blackbody and non-blackbody emission**
- To achieve the desired conditions, **breakout from an extended low-mass medium is preferable**, in which case the radiation escapes before significant shock acceleration takes place



Irwin & Hotokezaka, 2025b

Application to GRB 060218

- We only focus on fitting the 0.3-10 keV XRT light curve
- Yet, we get a satisfactory fit at other wavelengths as well:
  - The BAT timescale and peak luminosity are roughly reproduced (though the shape is different)
  - The optical data within the first hour are also reproduced within a factor of 2-3. (After ~2000 s, the optical is likely powered by cooling of shocked CSM, not by the shock breakout)
- A major caveat is that we assumed spherical symmetry



Irwin & Hotokezaka 2025b

Implications

- Our modeling suggests **$E = 3 \times 10^{50}$ erg, $M_{CSM} = 0.1\ M_{sun}$, and $R_{CSM} = 3 \times 10^{13}$ cm**
- In order to reproduce observations, we require a large energy, ~3×10^{50} erg, to be deposited in fast moving material (~0.1 c) in the extended envelope
    - It is **difficult for the supernova to put this much energy into fast material**, especially since SN 2006aj had an energy of only ~2×10^{51} erg
    - This possibly suggests that the energy may be **deposited by a choked jet**
- The envelope mass and radius we infer are similar to past studies (e.g., Nakar 2015; Irwin & Chevalier 2016) and also agree with recent modeling of EP events associated with Ic-bl SNe (e.g., Srinivasaragavan et al. 2025, and Eyles-Ferris et al. 2025)
    - The basic picture of a shock interacting with an extended low-mass envelope is therefore supported independently by prompt emission models, and models of the optical bump at later times

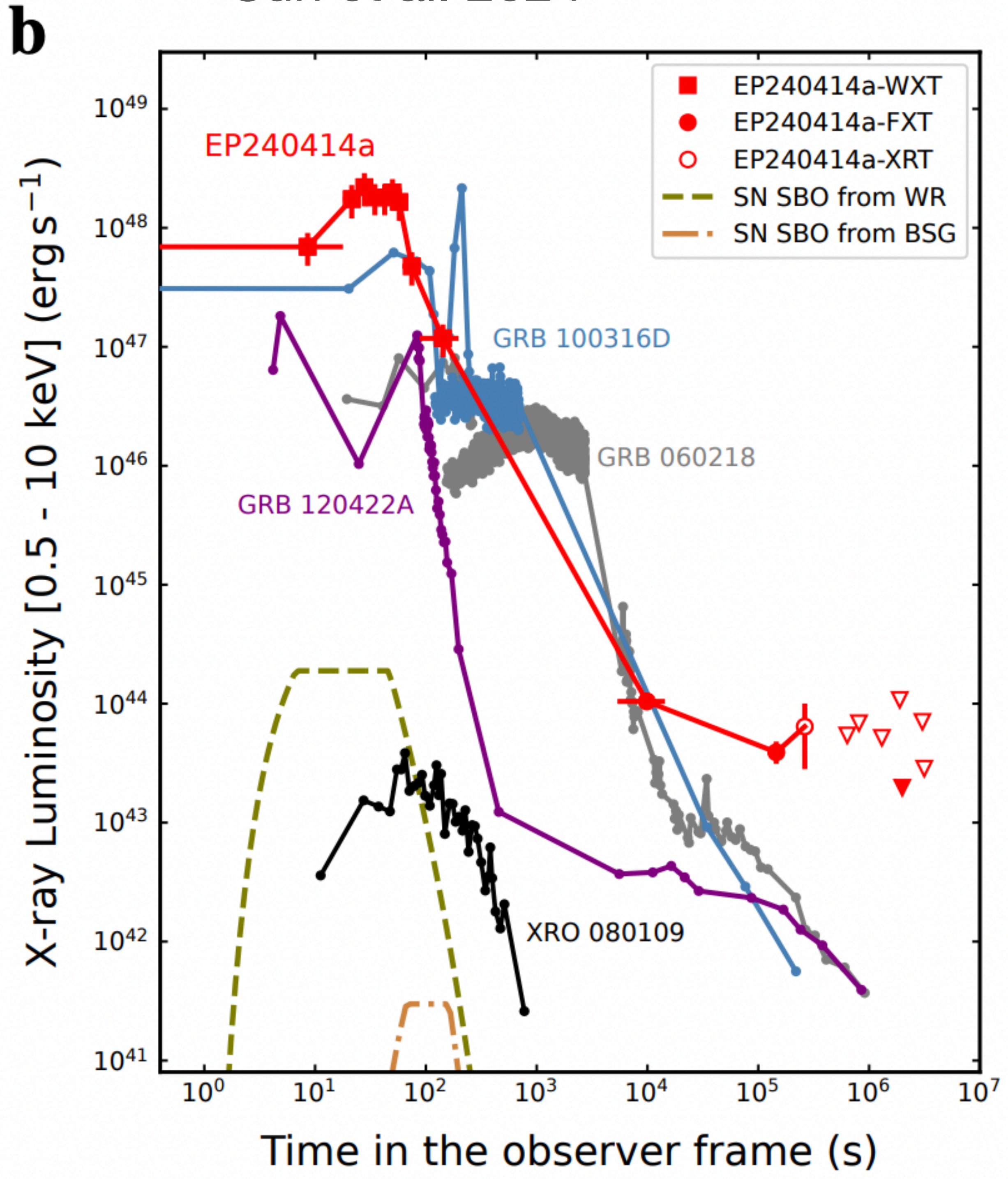
EP events bring new questions

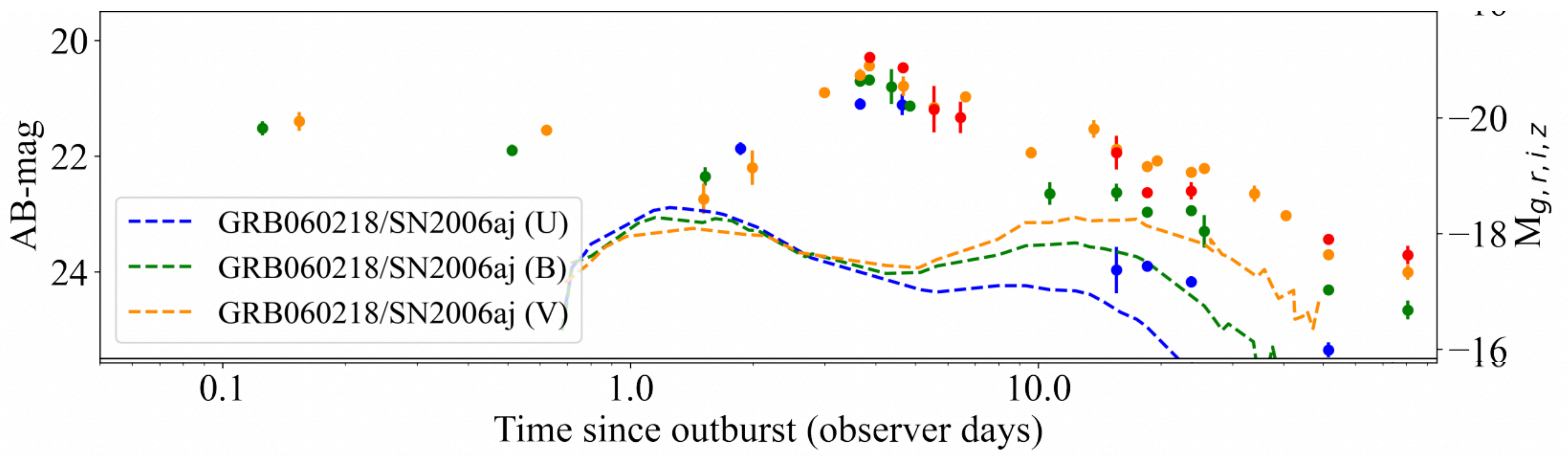
- The model works reasonably well for the prompt emission of the Swift-detected LLGRBs 060218, 100316D, and 171205A
- Recently, Einstein Probe detected two similar events, EP 240414a and EP 250108
    - Their origin is not entirely clear yet, but as ~1000 s X-ray transients associated with double-peaked, broad-lined Type Ic SN, they certainly have a lot in common with Swift LLGRBs

EP events bring new questions

- EP 240414a is very difficult to explain with shock breakout, for two reasons:
  1. The prompt X-ray emission is *shorter, brighter, and softer* than GRB 060218. This combination is not expected to occur in (spherical) shock breakout.
  2. In the shock breakout picture, the duration of the prompt X-rays is $t_X \sim R_{CSM}/c$, while the bolometric luminosity of the pre-SN optical bump is $L \sim R_{CSM}\, v_{sh}^2\, c/\kappa$.
     Because both are $\propto R_{CSM}$, events with longer X-ray durations should have brighter optical bumps. EP 240414 has a brighter bump despite its shorter duration.
- EP 250108a is more similar to GRB 060218. Due to uncertainty in the X-ray duration, the above arguments may not apply.

Sun et al. 2024





van Dalen et al. 2025

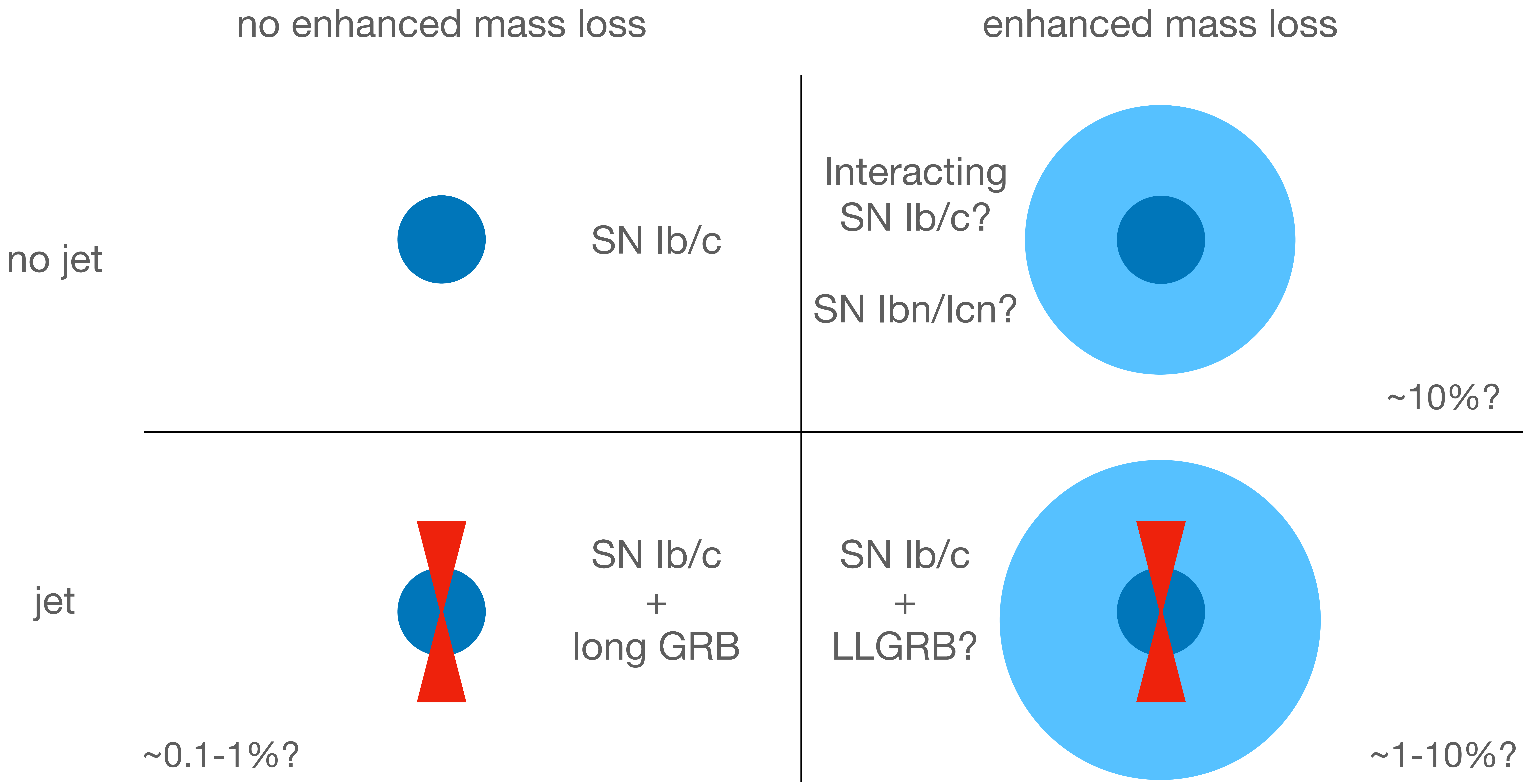
	EP250108a*
X-Ray	
Duration† T_{90} (s)	960^{+3092}_{-208}

Li et al. 2025

Where is the shock breakout in EP240414a?

- Luminous shock breakout is inevitable when an energetic explosion drives a fast shock through an optically thick medium.
- The duration of breakout emission is always at least R_{CSM}/c, so it cannot be too short in the case of an extended CSM
- Asymmetry may be important: this acts to make the breakout emission longer and fainter. The emission can be further suppressed by projected area effects, or relativistic beaming.
- Another mechanism producing a bright thermal X-ray signal (e.g., cooling of a mildly relativistic cocoon) is likely needed
- Combining shock breakout and jet-driven models to explain the diversity of LLGRBs/FXTs is an important work in progress

Progenitor Speculation



Conclusions

- Under the right conditions, it is possible to obtain a **non-standard type of shock breakout where blackbody and free-free components coexist**
  - This can occur when the **shock with a velocity of ~0.1 c breaks out of an extended low-mass medium**
  - The properties of this type of breakout are qualitatively similar to the observed properties of GRB 060218 and GRB 100316D
  - The **soft X-ray excess, early optical emission, and steep peak energy decay**—which are very difficult to explain with standard shock breakout—are all reproduced in this model
- The envelope properties inferred from this non-standard breakout model agree with models for the early pre-supernova optical bump. A similar optical peak is expected at later times in our model.
- **GRB 060218 may be a shock breakout after all**
- Where is the shock breakout component in EP events? More work is needed.