GRB Jets in CSM: Dynamics, Breakout, and Diversity of Transients

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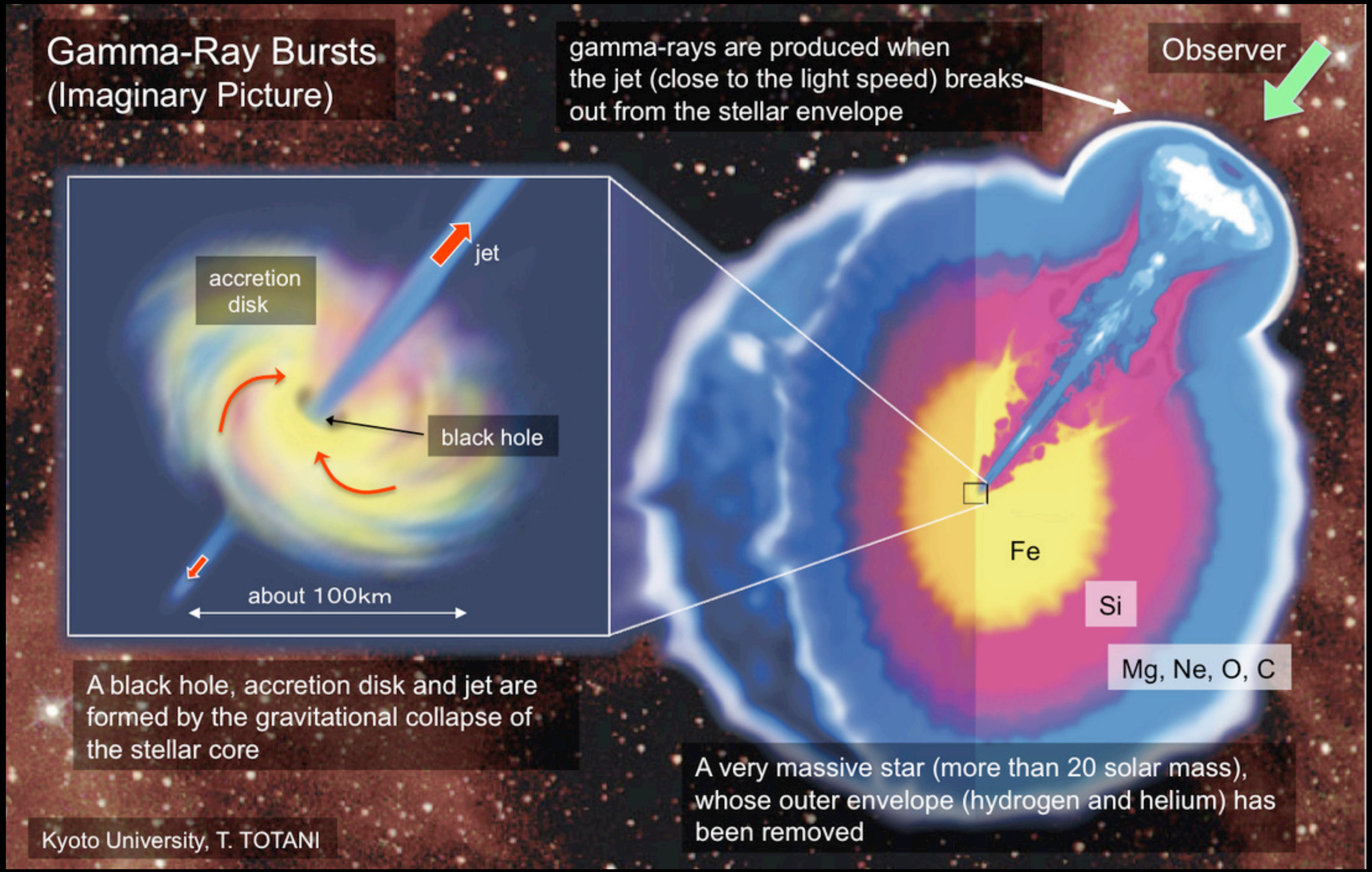
References:
https://arxiv.org/abs/2503.16242
https://arxiv.org/abs/2503.16243

Relativistic Fluids around Compact Objects, May 5-7, 2025

Collapsar Model

Observer:
Long GRB

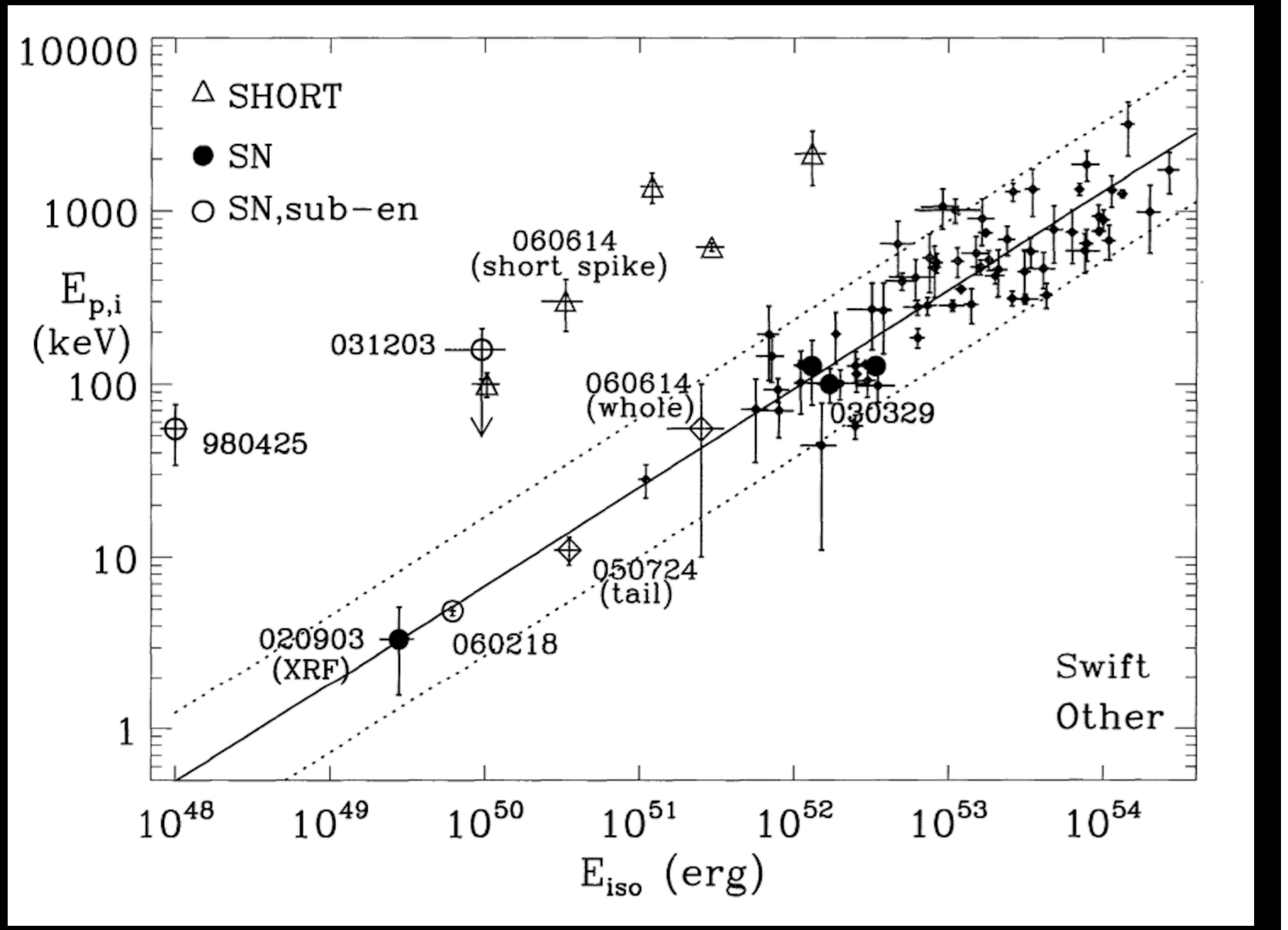


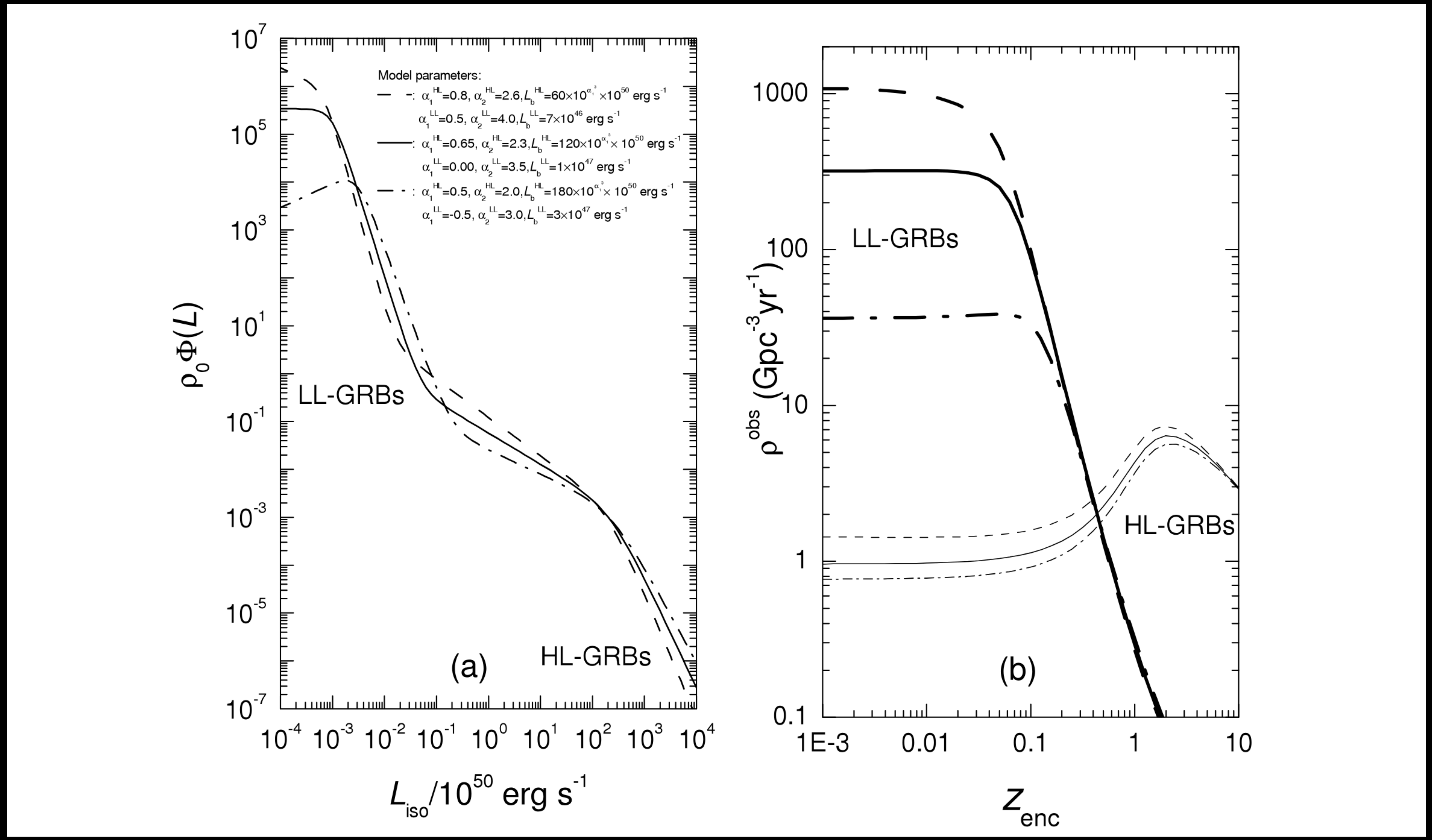
Stripped Wolf-Rayet Star

Question: How common are Long GRB jets?

Low Luminosity GRBs

- Rate of LGRBs: ~ 1 Gpc^{-3} yr-1
- Rate of low luminosity GRBs (LLGRBs): $\sim 10^2 - 10^3$ Gpc^{-3} yr-1



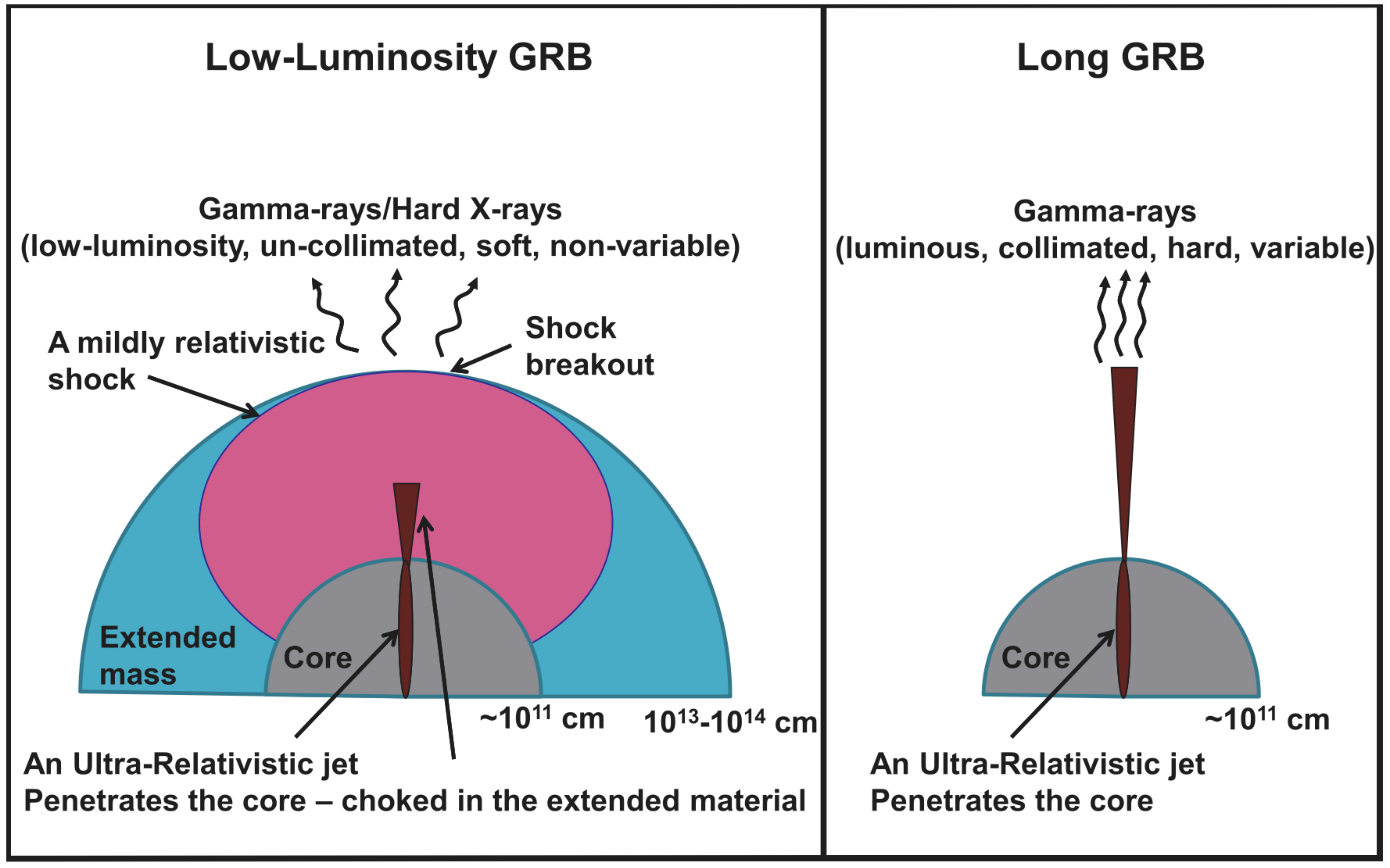


Question: What is the difference between LLGRBs & LGRB?

Credit: Amati+09; Li+07

One possibility: "CSM"

Cause:
Intense pre-explosion mass-loss



Rate: **LLGRBs** **>>** **LGRBs**

Key Point: Even a low-mass CSM can significantly affect the jet

Credit: Nakar 15

Evidence of CSM in Stripped Envelope SNe

SWIFT AND *CHANDRA* DETECTIONS OF SUPERNOVA 2006jc: EVIDENCE FOR INTERACTION OF THE SUPERNOVA SHOCK WITH A CIRCUMSTELLAR SHELL

S. Immler,[1,2,3] M. Modjaz,[4] W. Landsman,[1] F. Bufano,[1,5] P. J. Brown,[6] P. Milne,[7] L. Dessart,[7] S. T. Holland,[1,2,8]

SN 2006jc: A WOLF-RAYET STAR EXPLODING IN A DENSE He-RICH CIRCUMSTELLAR MEDIUM

Ryan J. Foley, Nathan Smith, Mohan Ganeshalingam, Weidong Li, Ryan Chornock, and Alexei V. Filippenko
Department of Astronomy, University of California, Berkeley, CA; rfoley@astro.berkeley.edu, nathans@astro.berkeley.edu,

SUPERNOVA 2002ic: THE COLLAPSE OF A STRIPPED-ENVELOPE, MASSIVE STAR IN A DENSE MEDIUM?

S. Benetti,[1] E. Cappellaro,[1] M. Turatto,[1] S. Taubenberger,[2] A. Harutyunyan,[1] and S. Valenti[3,4]

SN 2017dio: A Type-Ic Supernova Exploding in a Hydrogen-rich Circumstellar Medium*

Hanindyo Kuncarayakti[1,2], Keiichi Maeda[3,4], Christopher J. Ashall[5,6], Simon J. Prentice[5], Seppo Mattila[2], Erkki Kankare[7],
Claes Fransson[8], Peter Lundqvist[8], Andrea Pastorello[9], Giorgos Leloudas[10], Joseph P. Anderson[11], Stefano Benetti[9],
ias-Rosa[9],

LSQ13ddu: a rapidly evolving stripped-envelope supernova with early circumstellar interaction signatures

Peter Clark[1★] Kate Maguire,[1,2] Cosimo Ir

Massive stars exploding in a He-rich circumstellar medium – II. The transitional case of SN 2005la

A. Pastorello,[1★] R. M. Quimby,[2†] S. J. Smartt,[1] S. Mattila,[1,3] H. Navasardyan,[4]

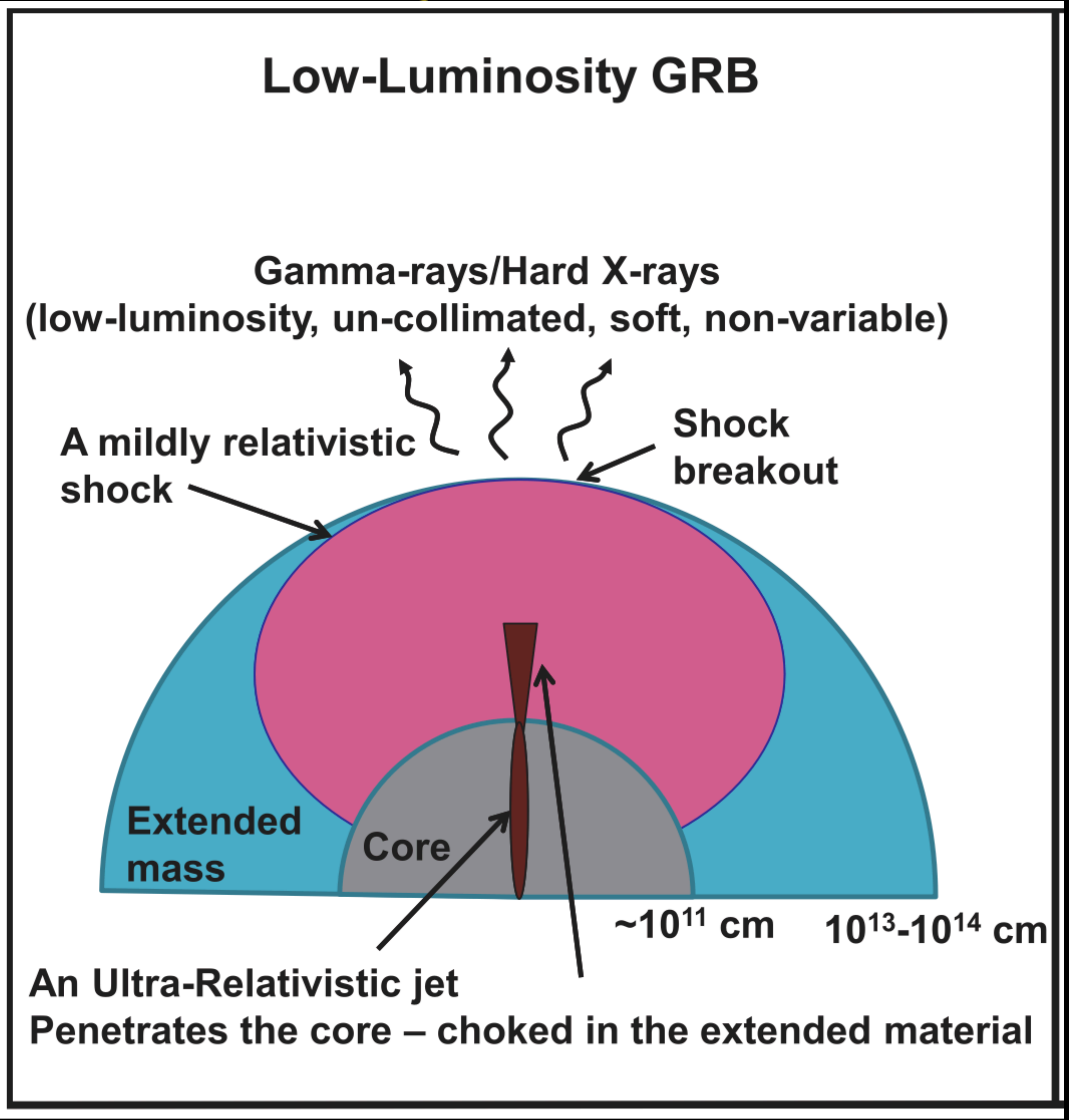
Two stripped envelope supernovae with circumstellar interaction

But only one really shows it

J. Sollerman[1], C. Fransson[1], C. Barbarino[1], C. Fremling[2], A. Horesh[3], E. Kool[1], S. Schulze[4], I. Sfaradi[3], S. Yang[1],

...

Let's Systematically investigate:
GRB-Jet dynamics in CSM



Credit: Nakar 15

Parameters

Jet

$E_{\rm eng}$: Jet energy

$t_{\rm eng}$: Jet timescale

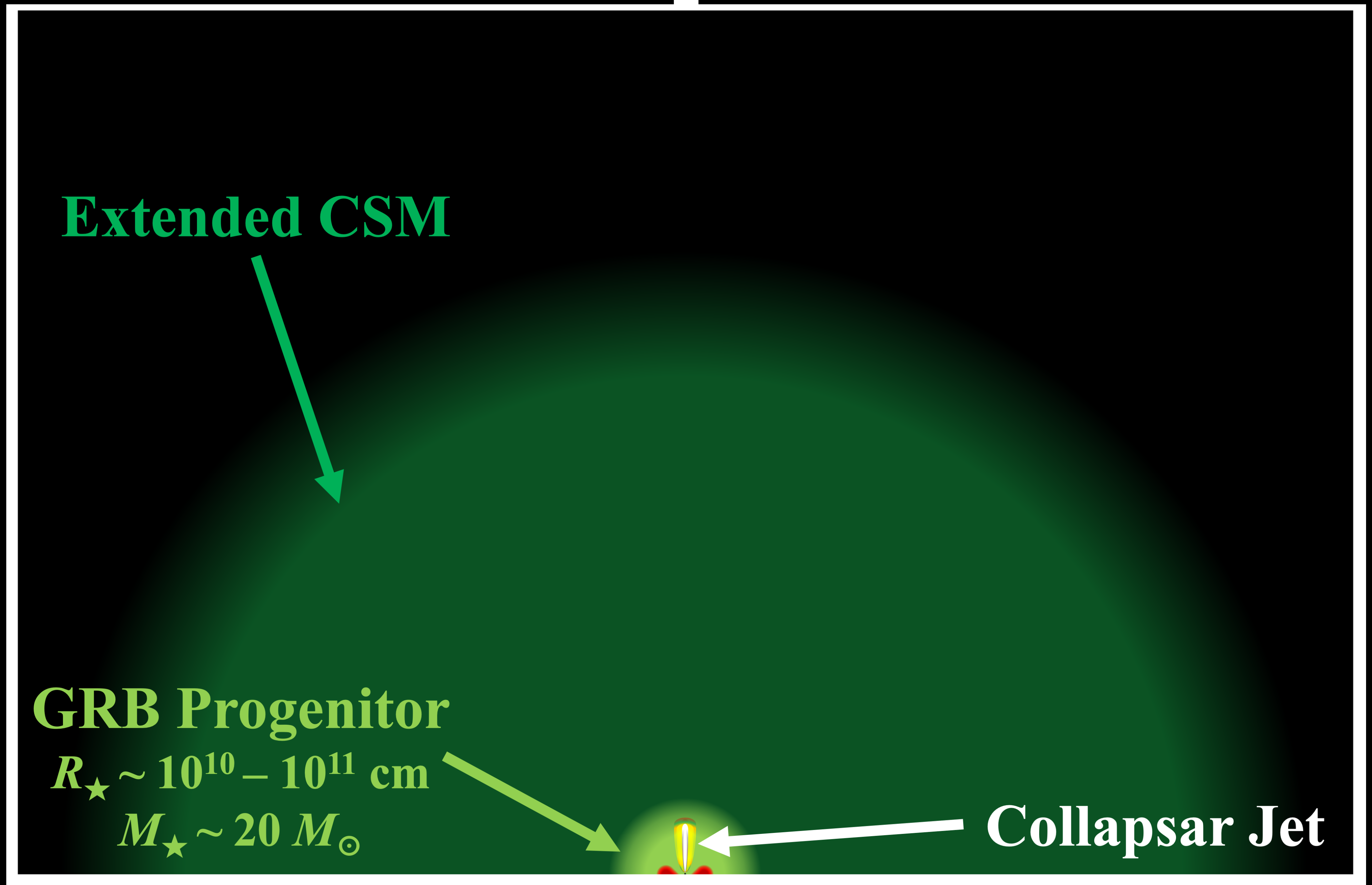
θ_0: Opening angle

CSM

$R_{\rm CSM}$: Radius

$M_{\rm CSM}$: Mass

n: Power-law index ($\rho \propto r^{-n}$)



Values

Conventional LGRBs

$\sim 10^{52}$ erg

$\sim 10^{2}$ s

$\sim 10^{\circ}$

CSM

?

?

~ 2: Constant mass loss

Framework [Bromberg+11]

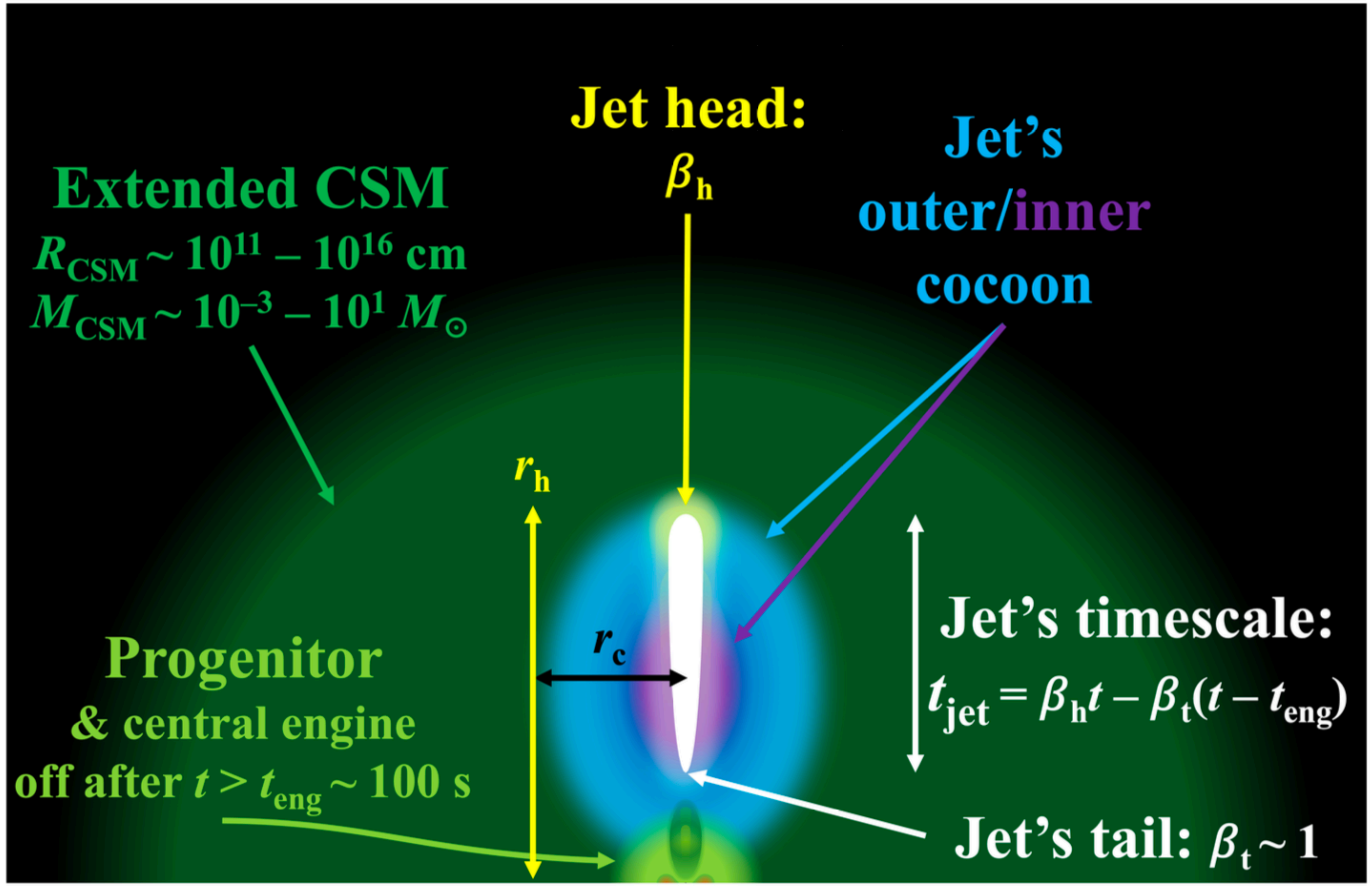
Jet collimation:

$$r_c(t) = c\beta_\perp(t - t_0),$$

$$\beta_\perp = \sqrt{\frac{P_c}{\rho_a(r_h/2)c^2}},$$

$$P_c = \eta\frac{E_c}{3V_c},$$

$$\Sigma_j(t) = \frac{L_j\theta_0^2}{4cP_c},$$



Jump conditions: $\tilde{L} \simeq \dfrac{L_j}{\Sigma_j(t)\rho_a c^3\Gamma_a^2}$, Jet head velocity: $\beta_h = \dfrac{1}{1 + \tilde{L}^{-1/2}}$

Jet head velocity β_h

Following Bromberg et al. (2011):

$$\frac{\beta_h^3}{(1-\beta_h)^5} = C,$$

where: $C = \frac{2^6 \eta N_s^4}{c^3} \frac{E_{\rm eng}}{t_{\rm eng}\theta_0^2} \frac{R_{\rm CSM}}{M_{\rm CSM}} \propto \frac{R_{\rm CSM}}{M_{\rm CSM}}$

No analytic solution!

=> Numerically??

Universal Solution

Solution for non-relativistic jet head with $C \ll 1$

$$\beta_h \approx C^{1/3}$$

Solution for relativistic jet head with $C \gg 1$

$$\beta_h \approx 1 - C^{-1/5}.$$

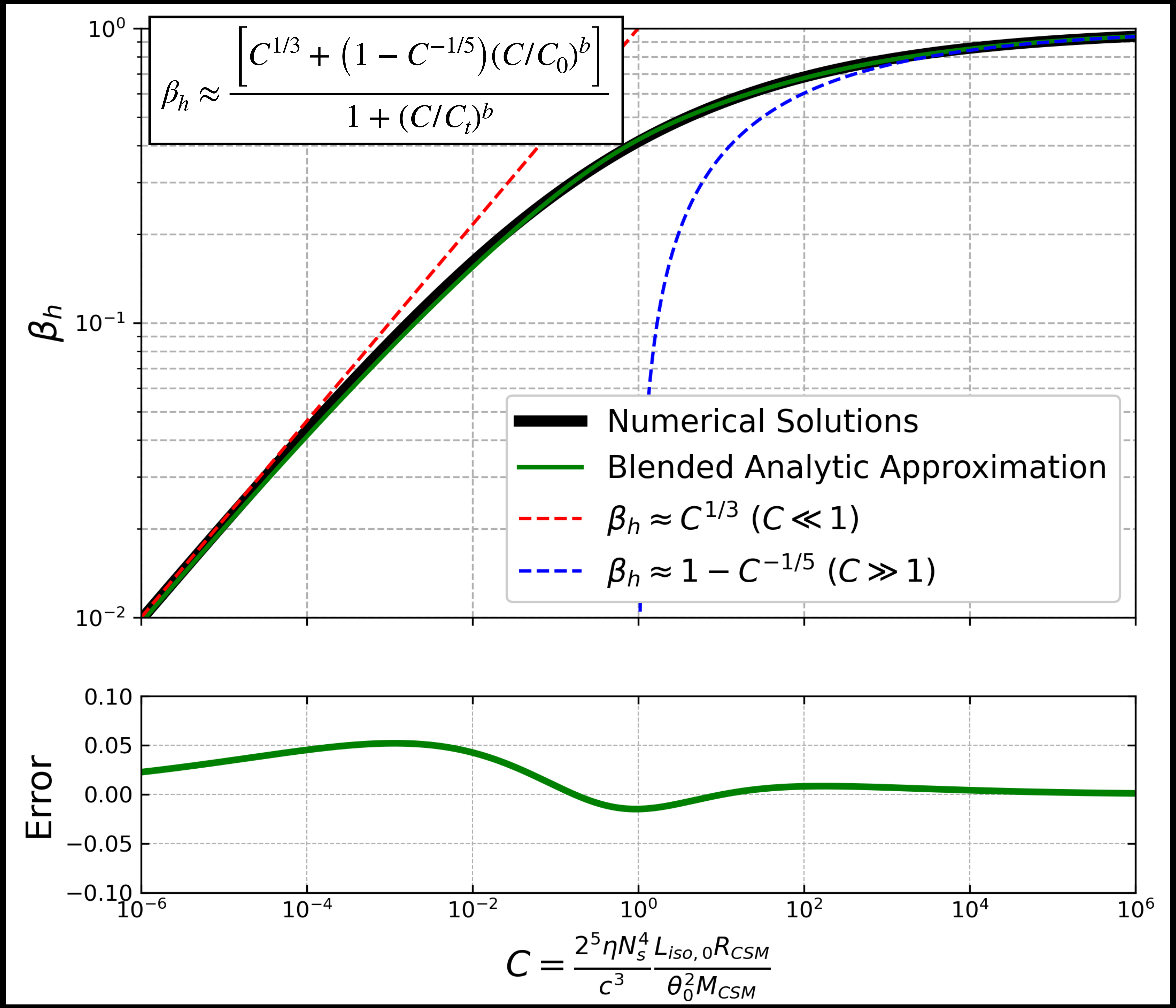
Blended together to:

$$\beta_h \approx \frac{\left[C^{1/3} + \left(1 - C^{-1/5}\right)(C/C_0)^b\right]}{1 + (C/C_t)^b},$$

least squares fitting gives: $C_t \approx 0.66,$ & $b \approx 0.79.$

Universal Solution

Jet head velocity

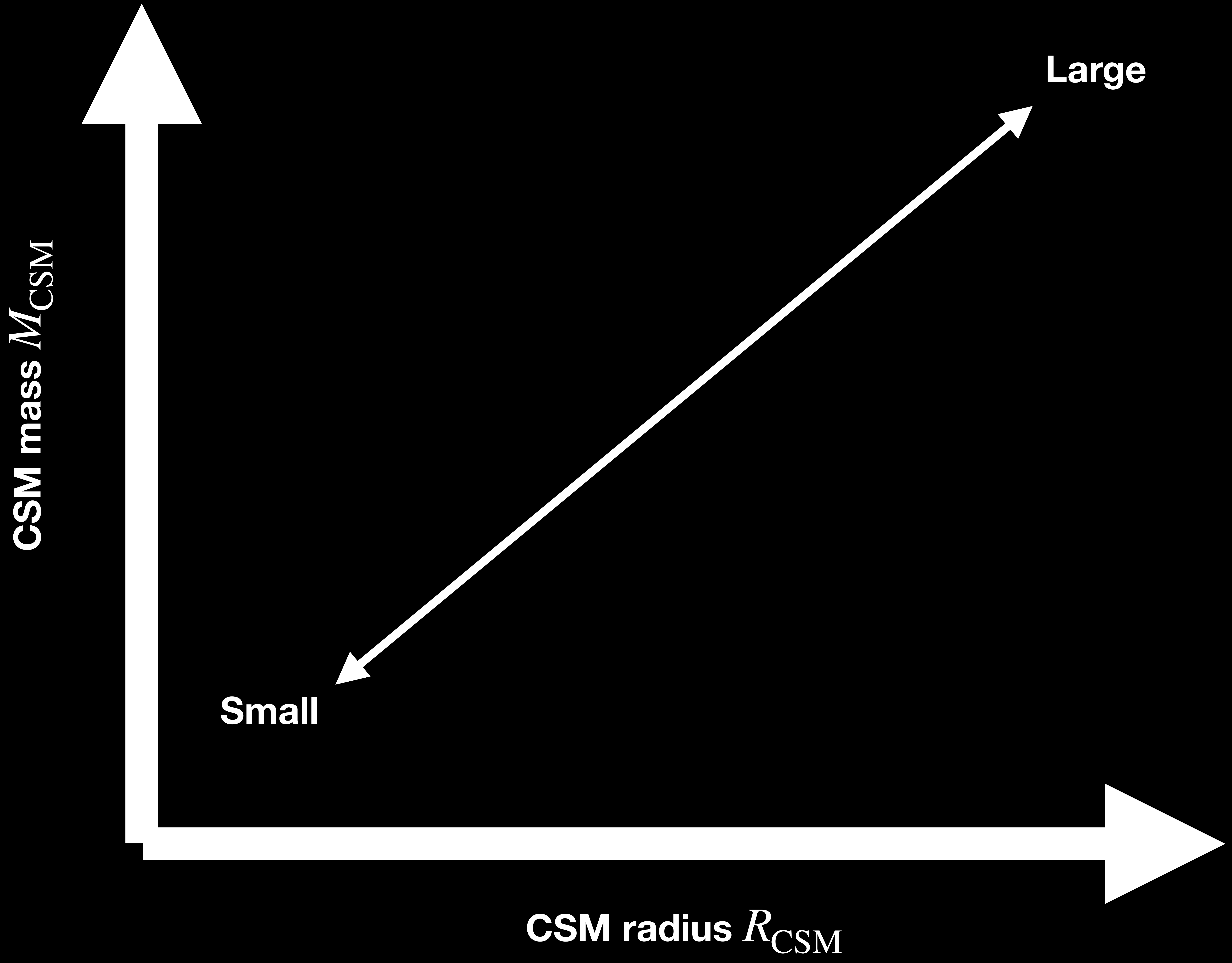


$$C \propto \frac{E_{\rm eng}}{t_{\rm eng}\theta_0^2} \frac{R_{\rm CSM}}{M_{\rm CSM}}$$

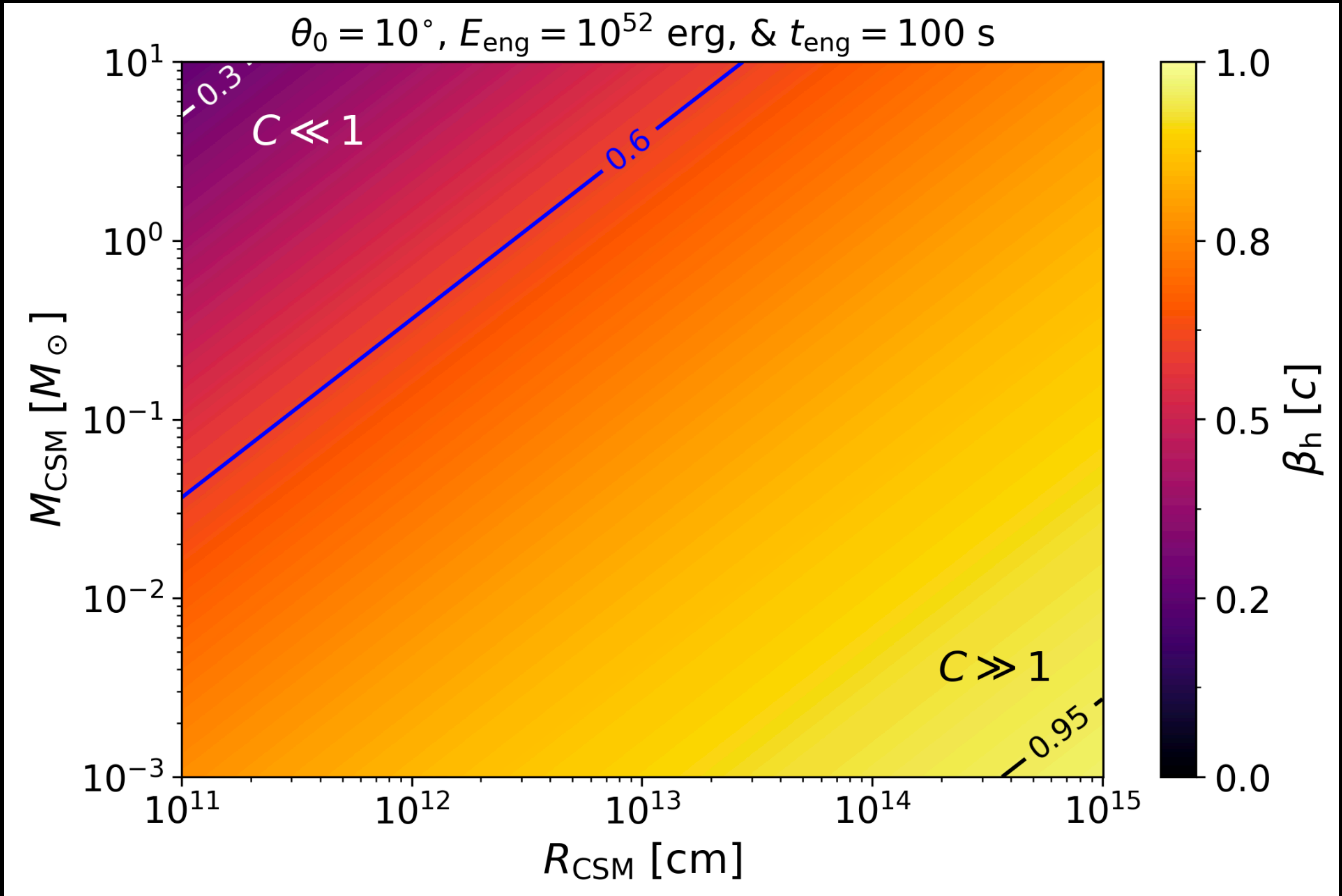
Credit: HH+25

CSM parameters

(for a conventional LGRB jet)



Jet head velocity



Credit: HH+25

New expression for the breakout time

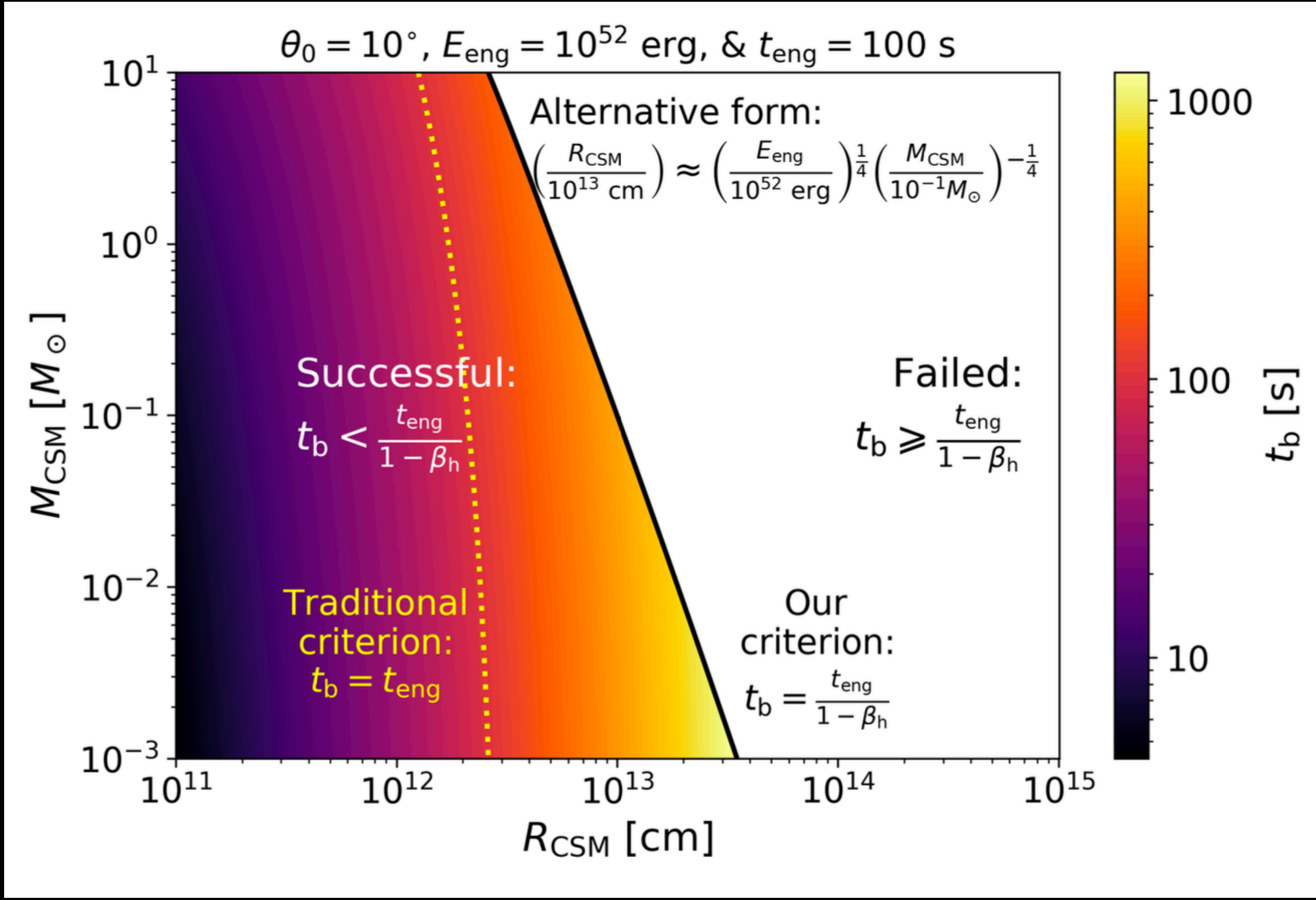
Hamidani+25:

$$t_{\rm b} \approx 430\ {\rm s} \left(\frac{\theta_0}{10^\circ}\right)^{\frac{2}{3}} \left(\frac{E_{\rm eng}/t_{\rm eng}}{10^{50}\ {\rm erg}}\right)^{-\frac{1}{3}} \left(\frac{R_{\rm CSM}}{10^{13}\ {\rm cm}}\right)^{\frac{2}{3}} \left(\frac{M_{\rm CSM}}{0.1 M_\odot}\right)^{\frac{1}{3}} \underline{\left(\frac{1-\beta_{\rm h}}{0.23}\right)}^{-\frac{5}{3}}$$

Bromberg+12:

$$t_b \simeq 15\ {\rm s} \left(\frac{\theta}{10^\circ}\right)^{2/3} \left(\frac{L_{\rm iso}}{10^{51}\ {\rm erg\ s^{-1}}}\right)^{-1/3} \left(\frac{R_*}{5\ R_\odot}\right)^{2/3} \left(\frac{M_*}{15\ M_\odot}\right)^{1/3}$$

Breakout times



Credit: HH+25

Typical $\Gamma\beta \equiv \overline{\Gamma\beta}$ of the system

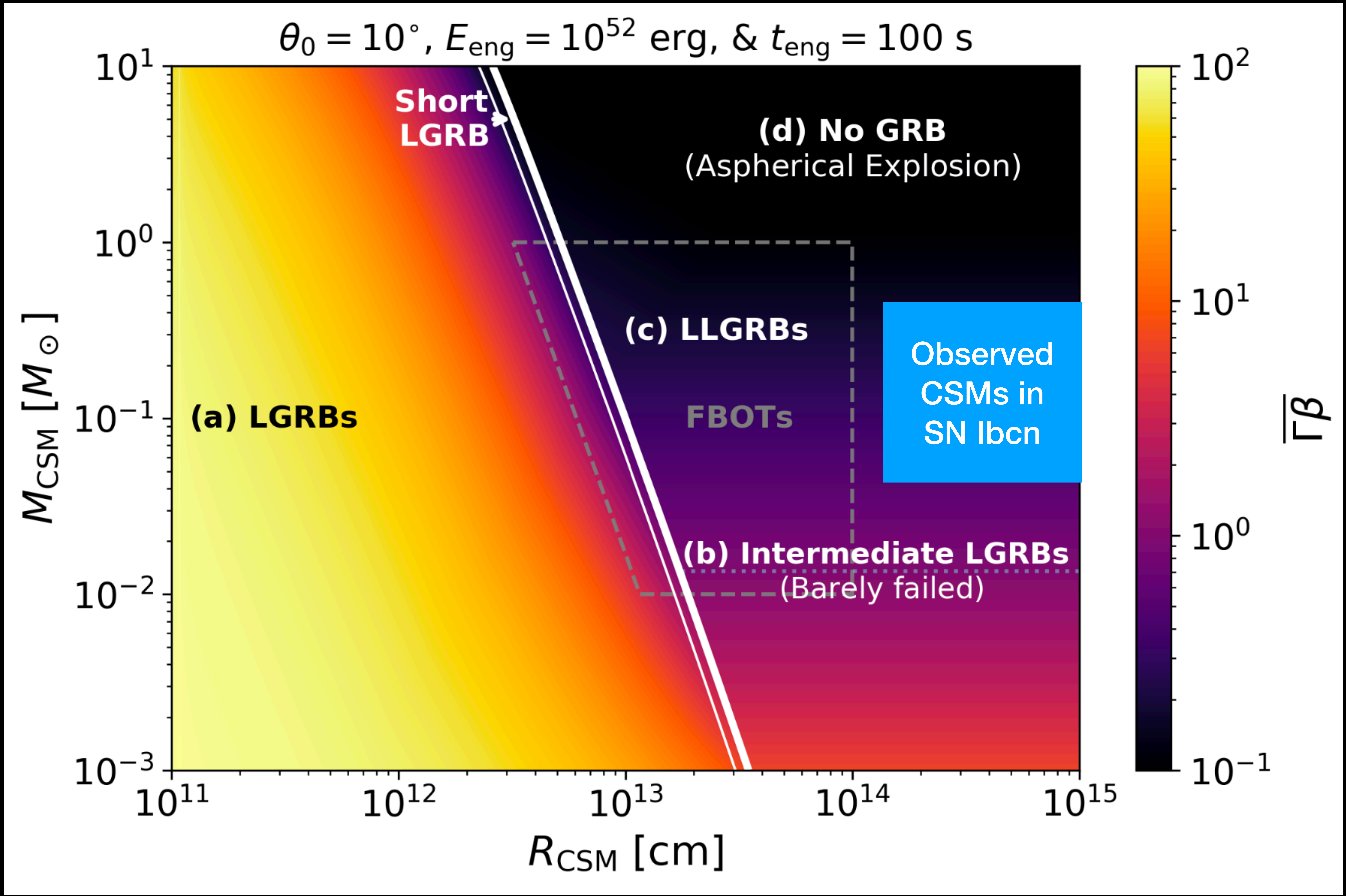
$$\overline{\Gamma\beta} = 10^{\langle \log(\Gamma\beta) \rangle},$$

With

Energy weighted

$$\langle \log(\Gamma\beta) \rangle = \underbrace{\langle \log(\Gamma\beta) \rangle_{\mathrm{j}} \frac{E_{\mathrm{j}}}{E_{\mathrm{eng}}}}_{\textbf{Jet}} + \underbrace{\langle \log(\Gamma\beta) \rangle_{\mathrm{c}} \frac{E_{\mathrm{c}}}{E_{\mathrm{eng}}}}_{\textbf{Cocoon}}$$

Diversity of transients

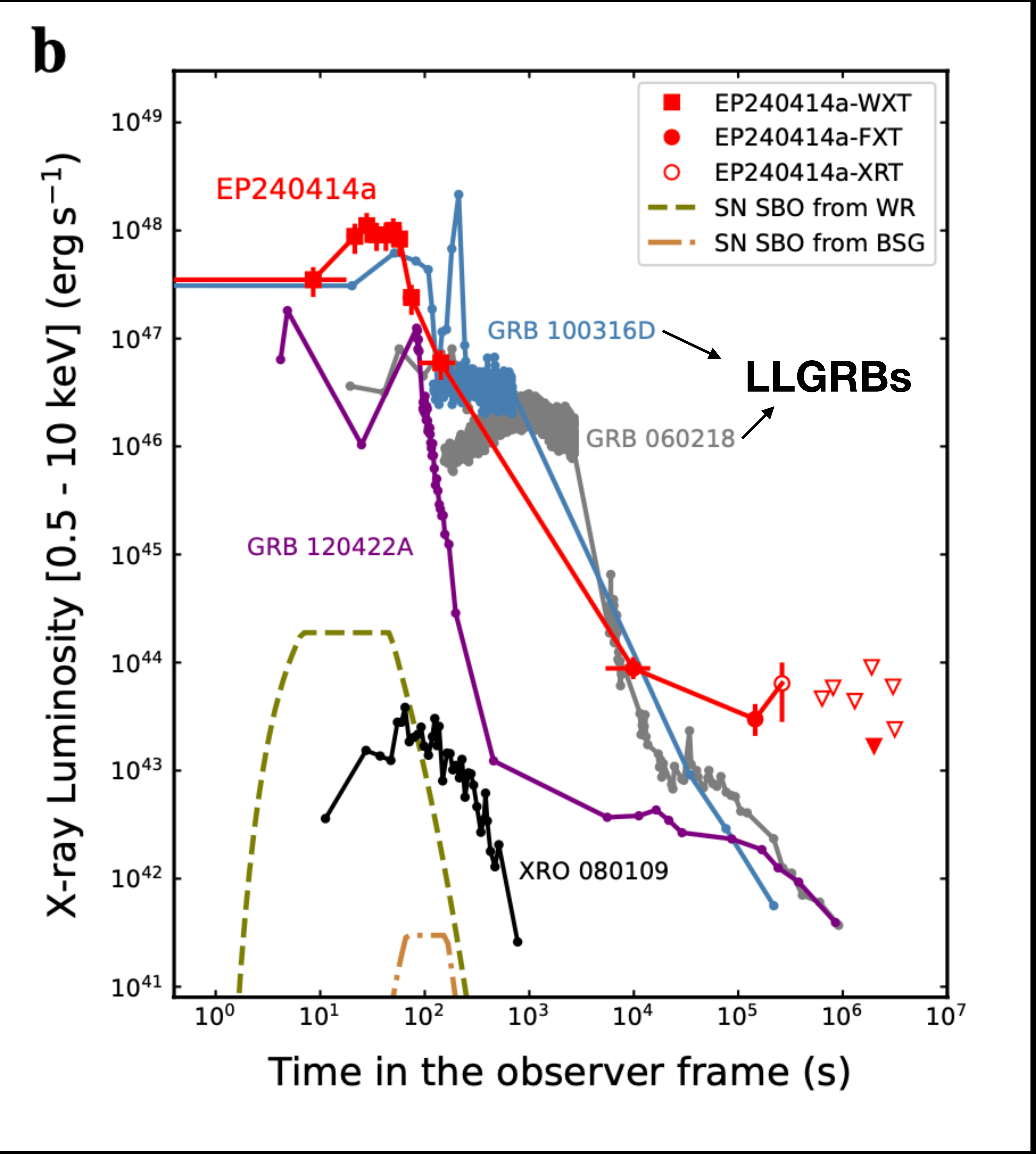


Credit: HH+25

Summary I

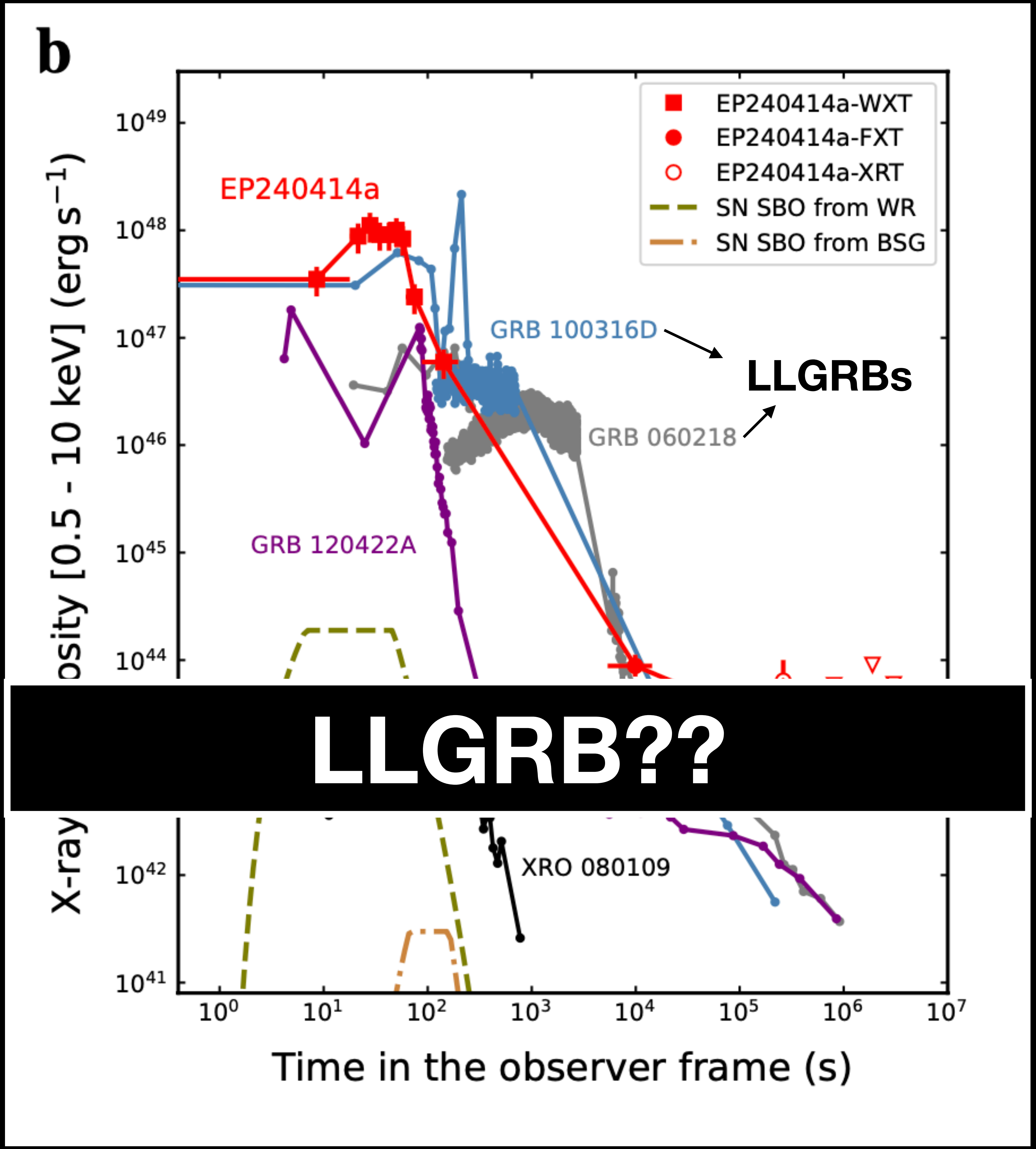
- Fully analytic model for jet dynamics in CSM
  - Jet/CSM parameters
    => $\beta_h, t_b, \ldots$
    => Jet/Cocoon properties
  - Implemtented in Python: https://github.com/hamidhamidani/cocoon-cooling-model
- Constraints on the CSM in LGRBs/LLGRBs

EP240414a [X-ray]



Credit: Sun+24

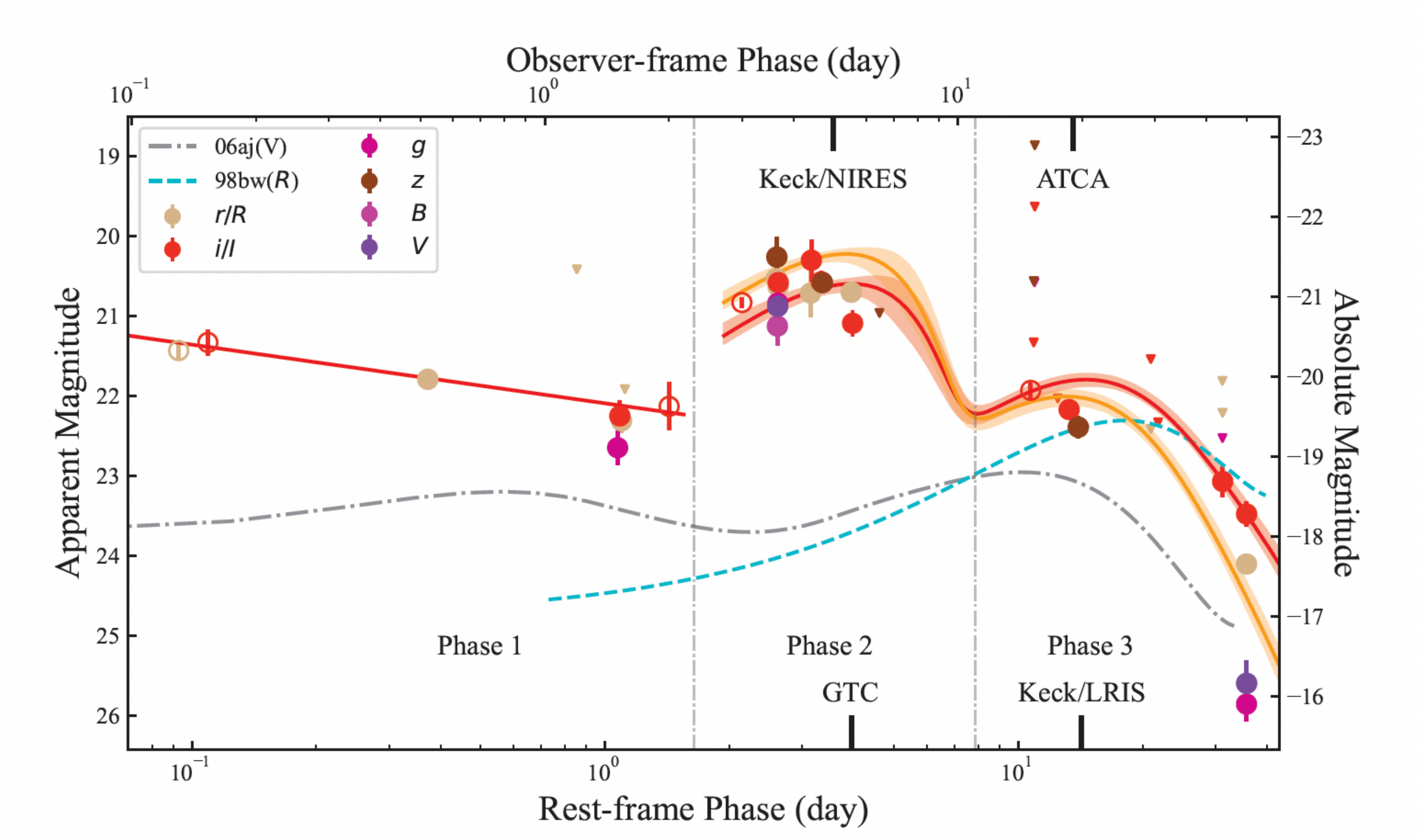
EP240414a [X-ray]



LLGRB??

Credit: Sun+24

Optical [EP240414a]



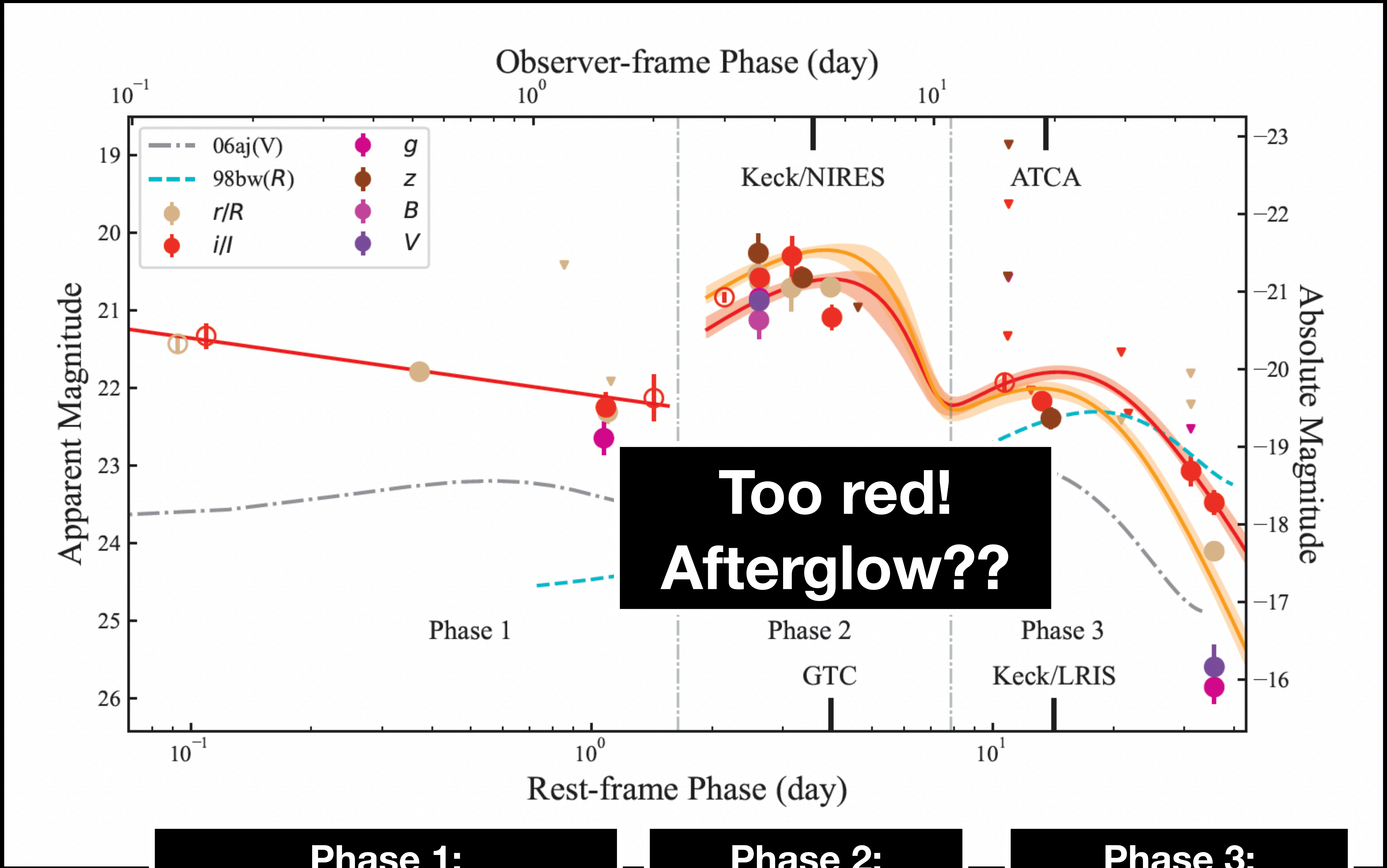
Phase 1: thermal?

Phase 2: non-thermal?

Phase 3: Ic-BL SN (Ni56)

Credit: Sun+24

Optical [EP240414a]



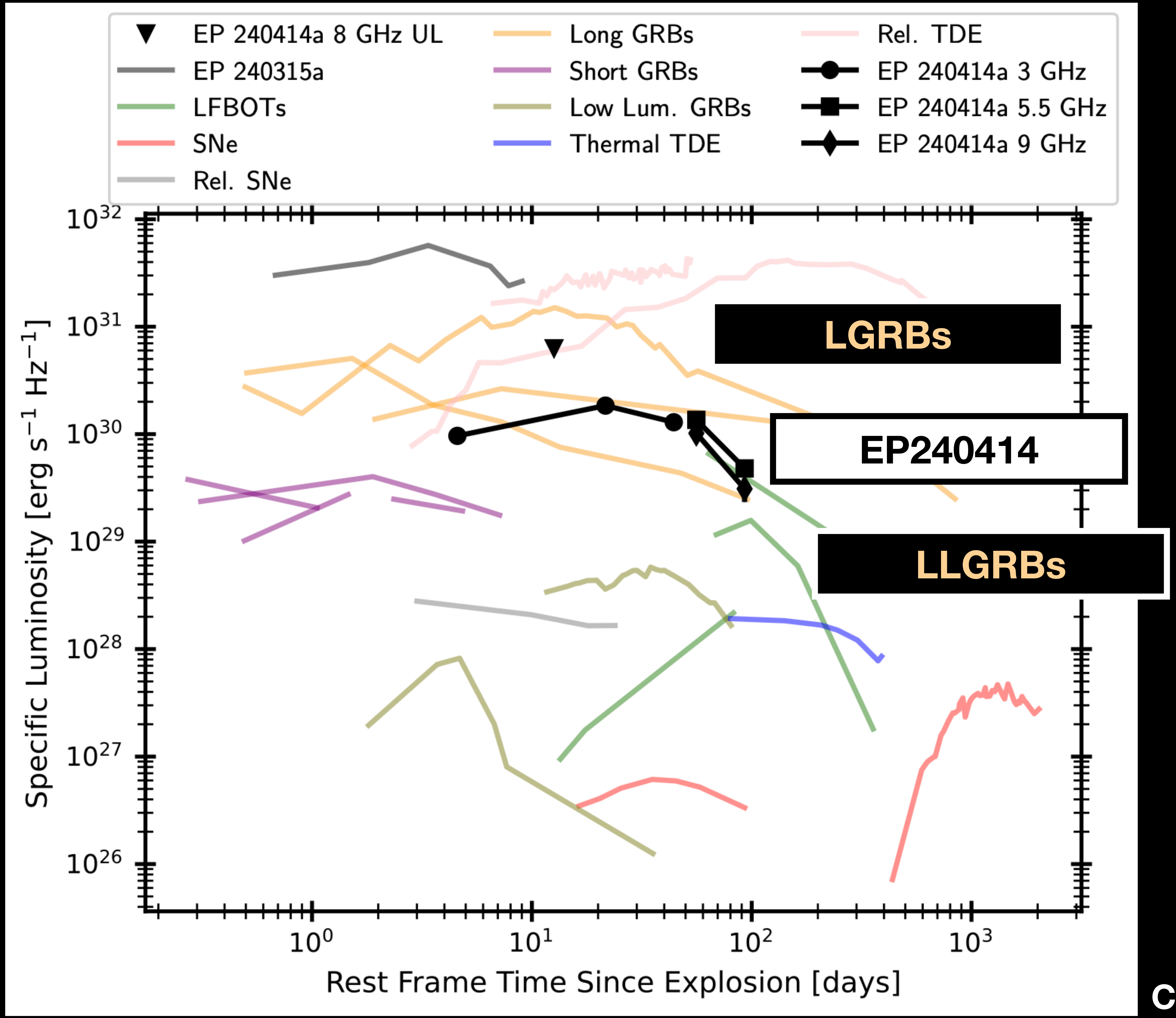
Phase 1: thermal?

Phase 2: non-thermal?

Phase 3: Ic-BL SN (Ni56)

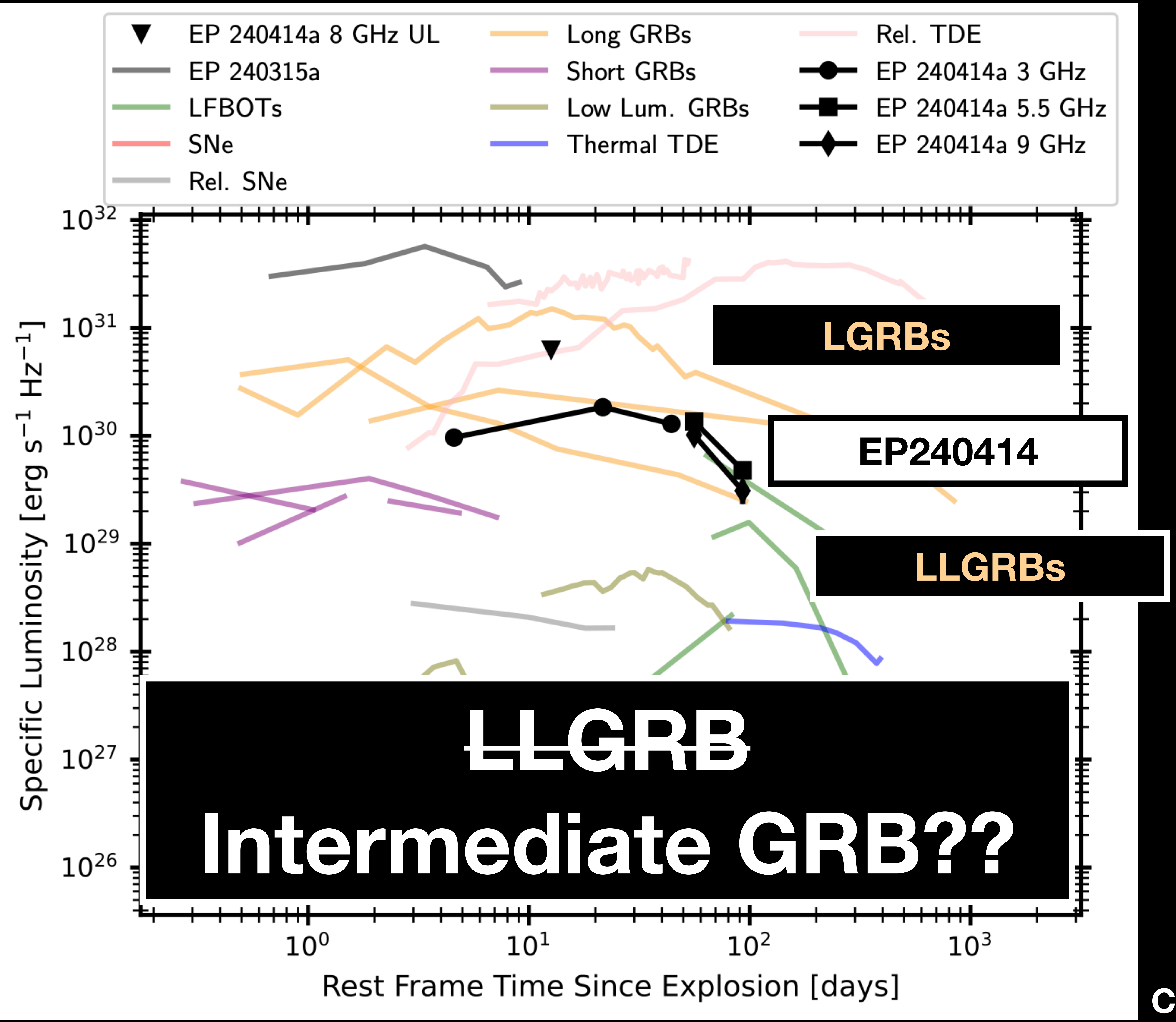
Credit: Sun+24

Radio [EP240414a]



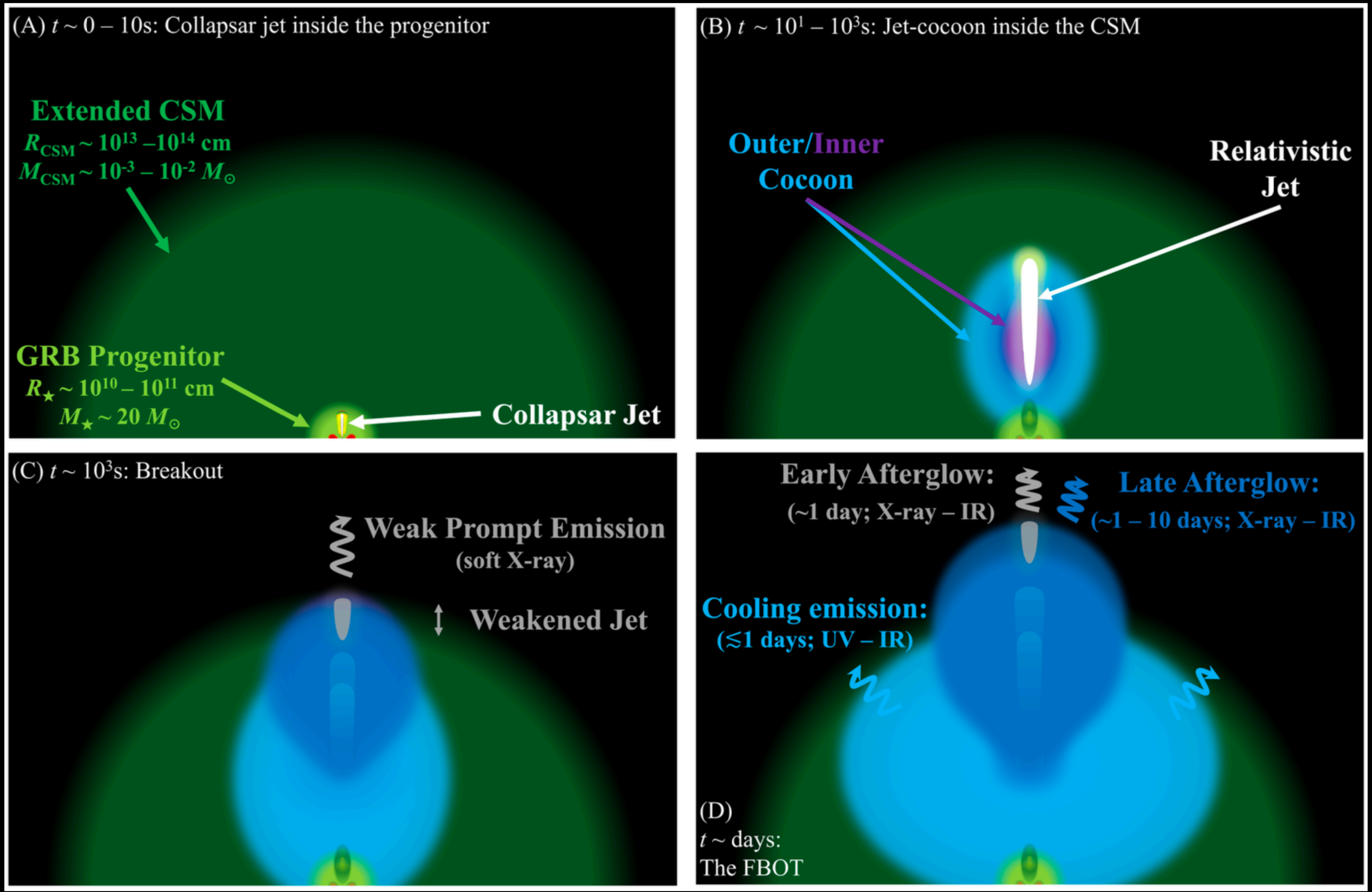
Credit: Bright+24

Radio [EP240414a]



Credit: Bright+24

Our scenario [EP240414a]

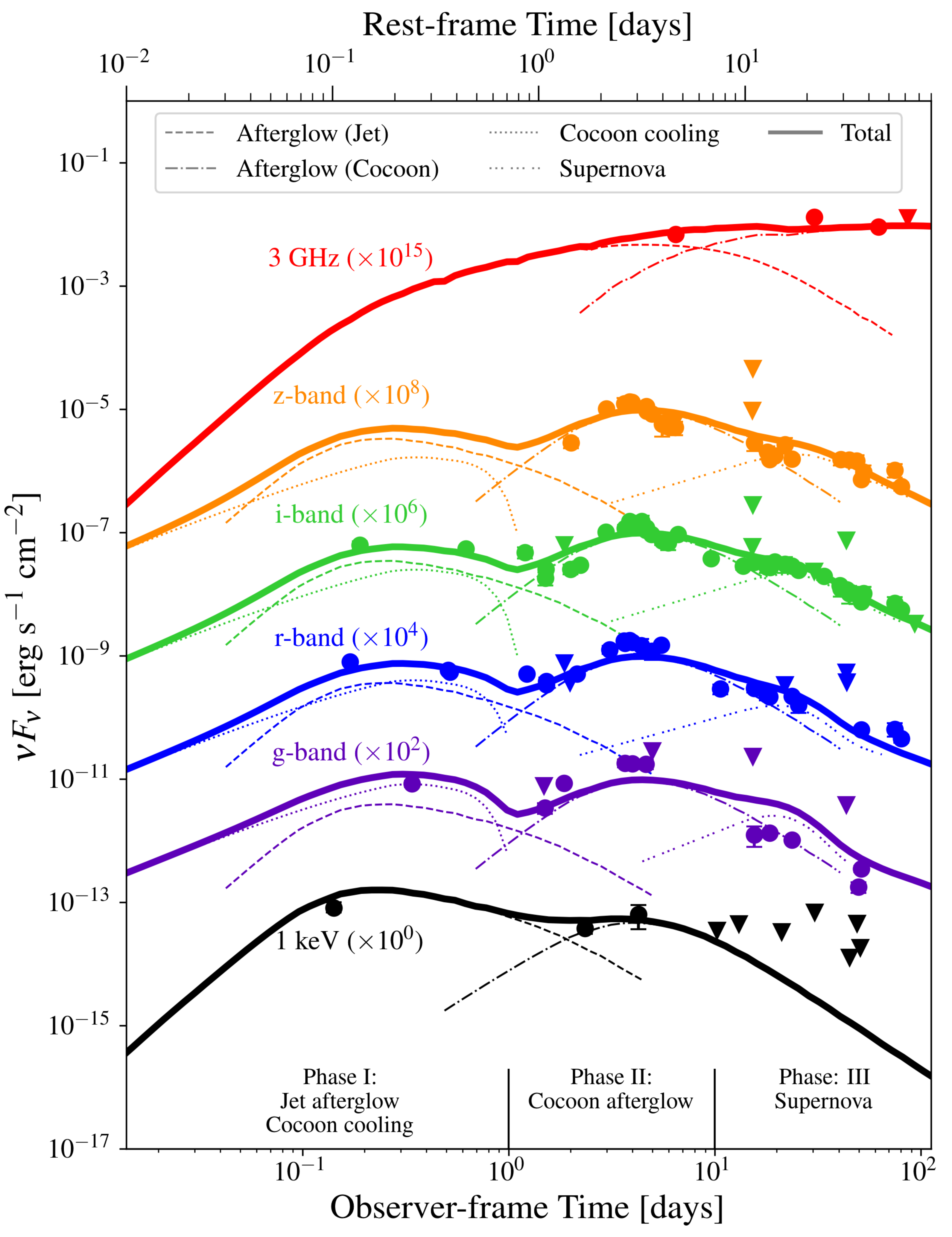


Credit: HH+25

Parameters [EP240414a]

- Jet: Conventional LGRB jet
- CSM: $\sim 0.03\, M_\odot$ and 3×10^{13} cm
- Outcome: Barely failed jet
  - Mildly relativistic jet-cocoon $\Gamma \sim 5 - 20$ and $\sim 10^{50}$ erg (Afterglow)
  - Non-relativistic cocoon $\sim 10^{52}$ erg (thermal cooling emission)

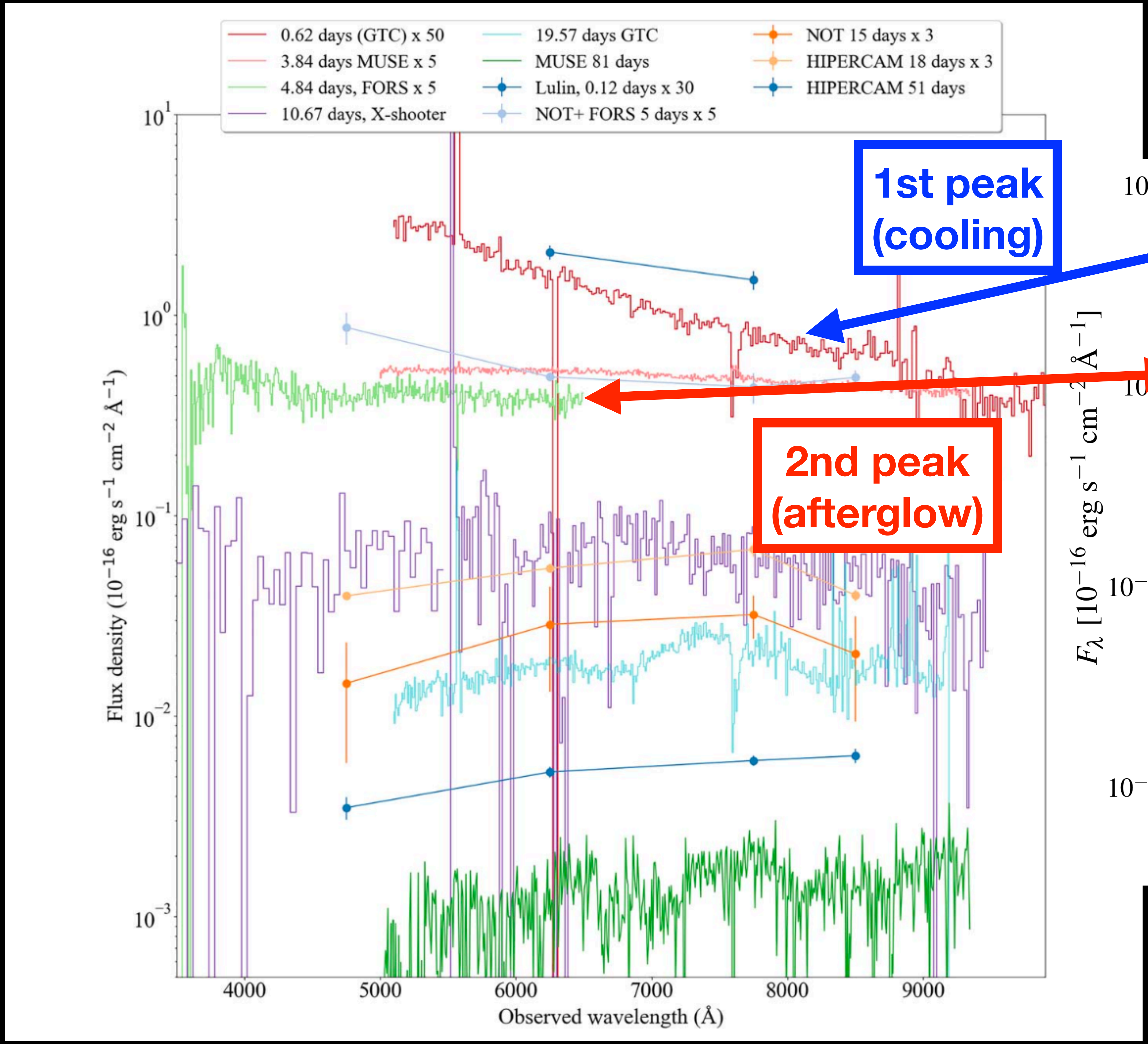
Results
[EP240414a]



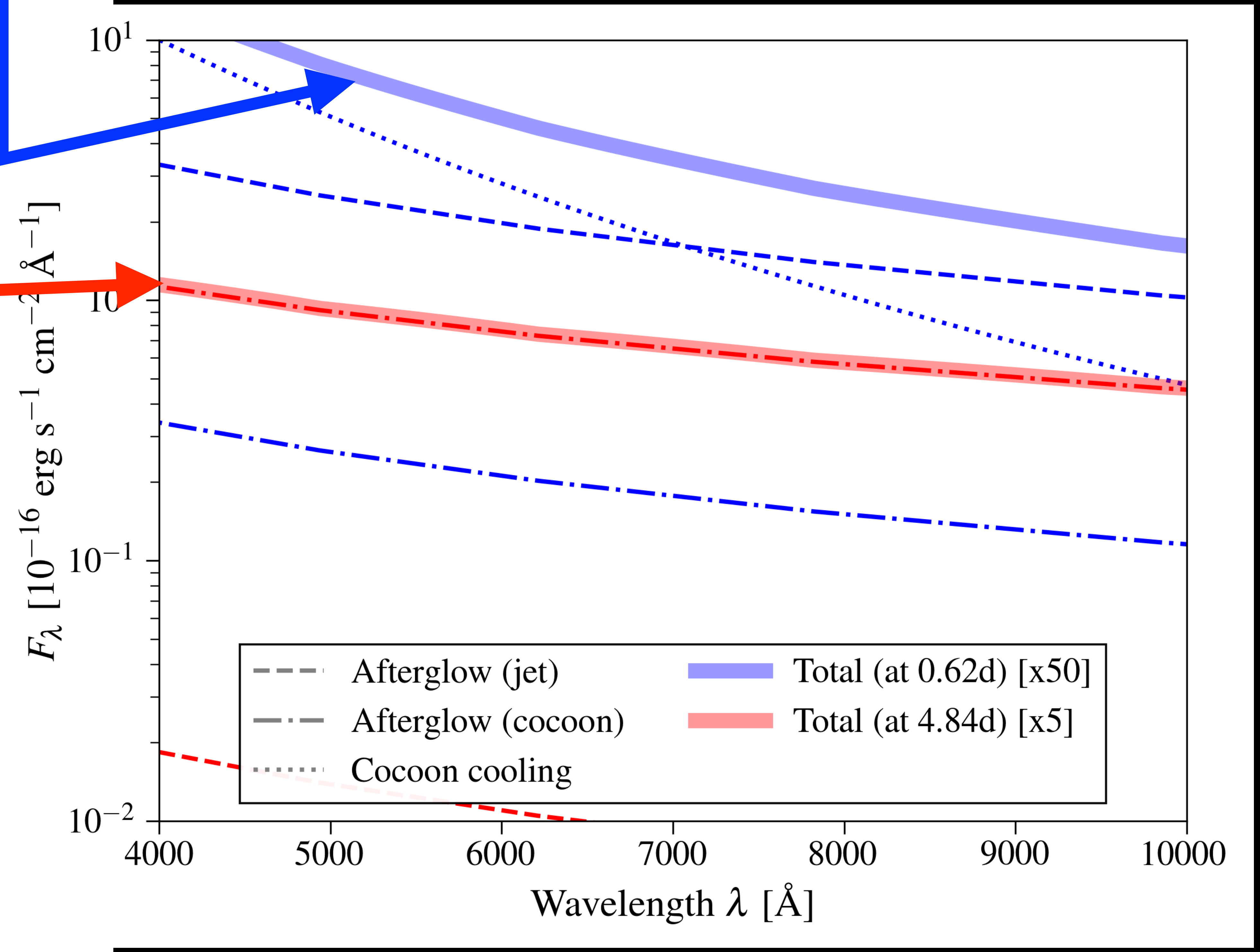
Credit: HH+25

SED of EP240414a

Observations (Absorbed)

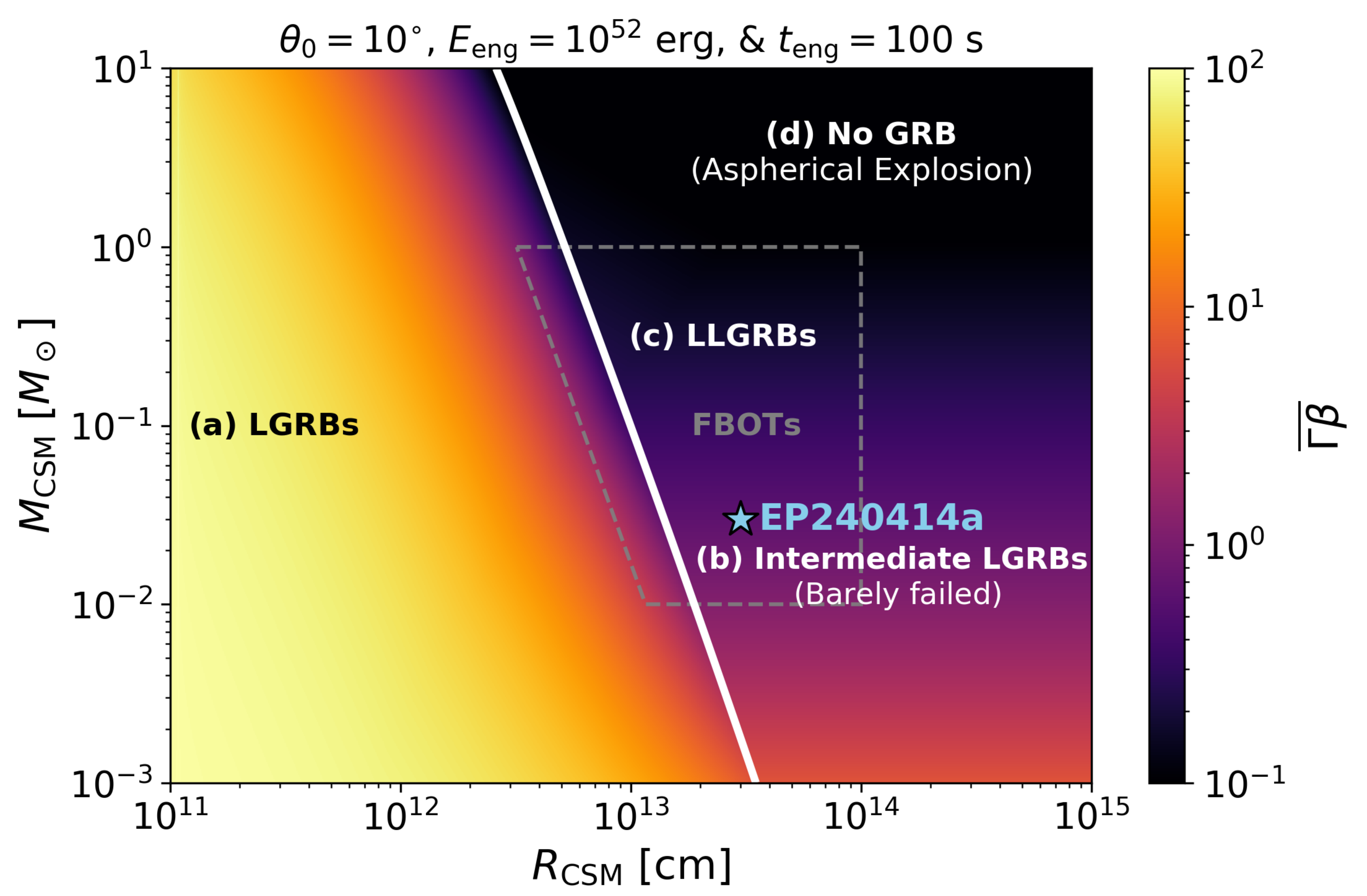


Theory (Unabsorbed)



Credit: Dalen+25; HH+25

Intermediate GRB for EP240414a



Credit: HH+25

Summary II

- EP240414a: intermediate prompt & afterglow properties relative to LGRBs/LLGRBs
- LGRB jet weakened in an extended CSM?
  - An intermediate-class jet/GRB?
- A conventional LGRB jet in a CSM of $\sim 0.03 M_\odot$ and $\sim 3 \times 10^{13}$ cm can explain X-ray / Optical / Radio photometry / SED…
  - May naturally explain the weak/soft prompt emission