GRB Jets in CSM Material:

Dynamics & Diversity of Transients

Hamid Hamidani

(Tohoku University, Japan)

With:

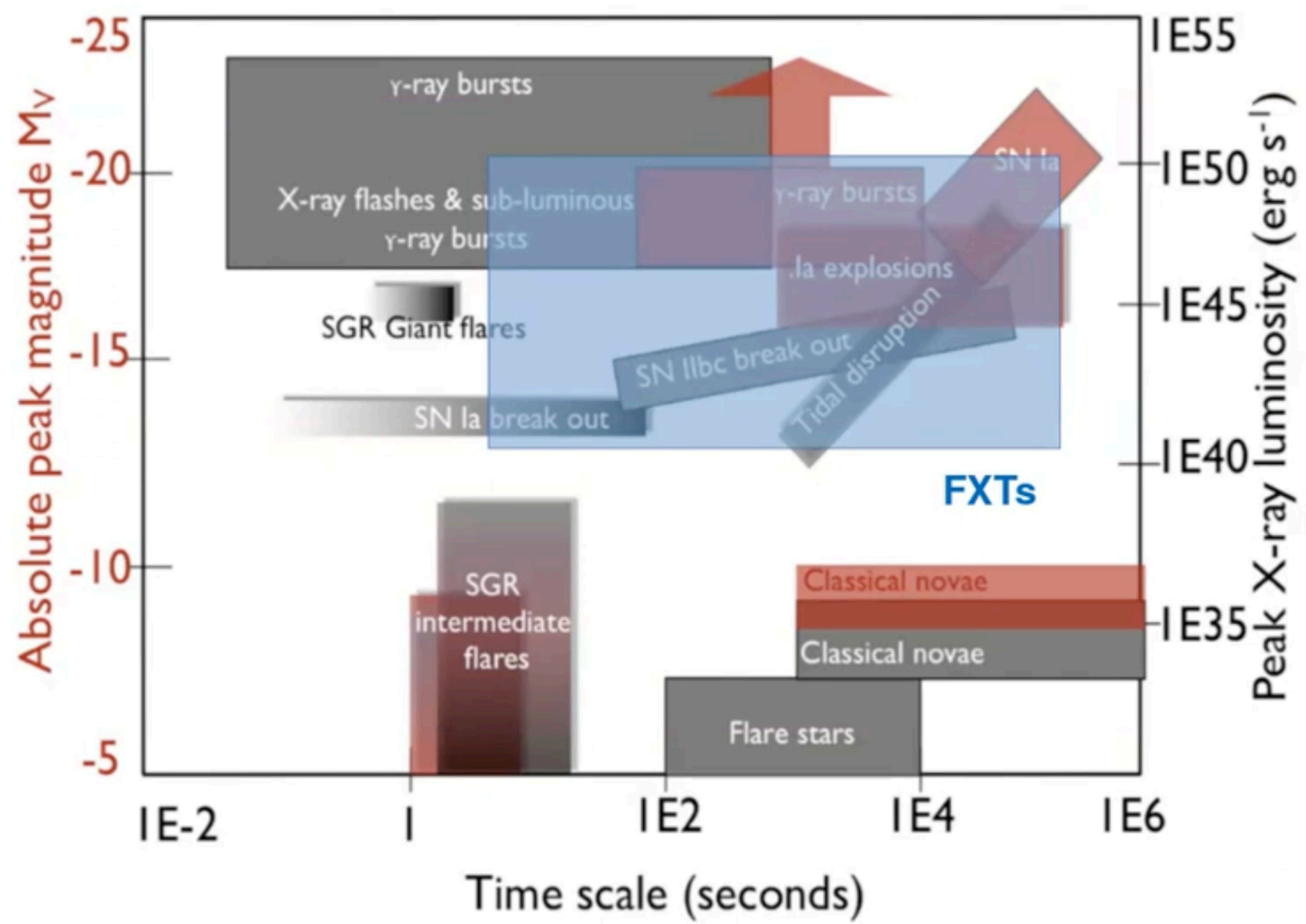
Masaomi Tanaka, Kazumi Kashiyama, Kunihito Ioka,
Yuri Sato, Gokul Srinivasaragavan & Shigeo S. Kimura

References:

https://arxiv.org/abs/2503.16242
https://arxiv.org/abs/2503.16243
https://arxiv.org/abs/2504.17516

Grant-in-Aid for Transformative Research Areas (A), "Multimessenger Astrophysics":
The third annual conference, November 18-20, 2025

Gamma-Ray Bursts (GRBs)

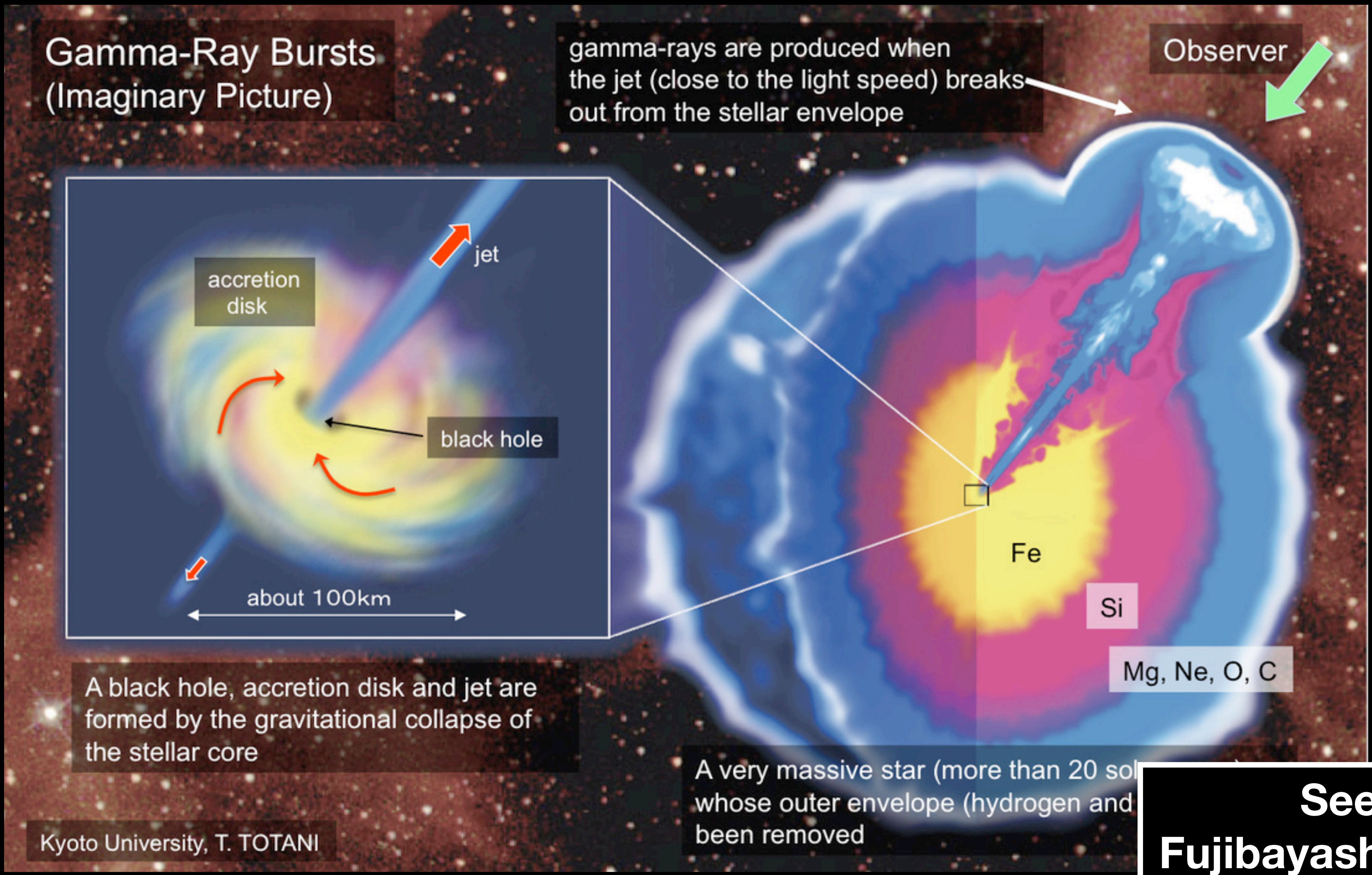


The majority of the diagram is theoretical 3

<u>Too Extreme</u>: We need a jet!

Credit: Jonathan Quirola

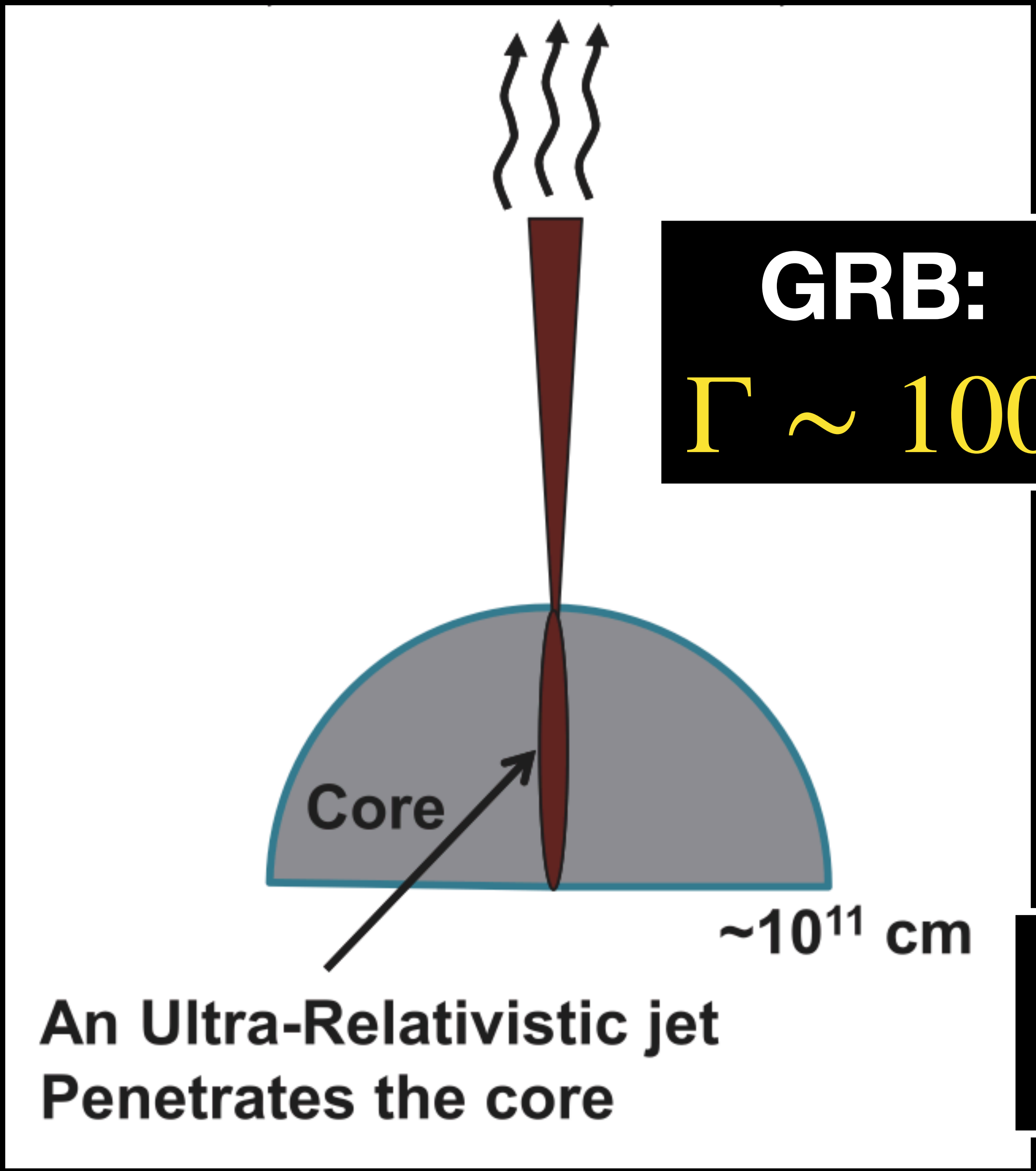
Collapsar Model



See Fujibayashi-san's Talk

<u>Progenitor</u>: Wolf-Rayet Star (fast rotating)

Collapsar Scenario



GRB:
$\Gamma \sim 100$

See
Fujibayashi-san's
Talk

Credit: Nakar 15

$$\Gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$\beta = v/c$$

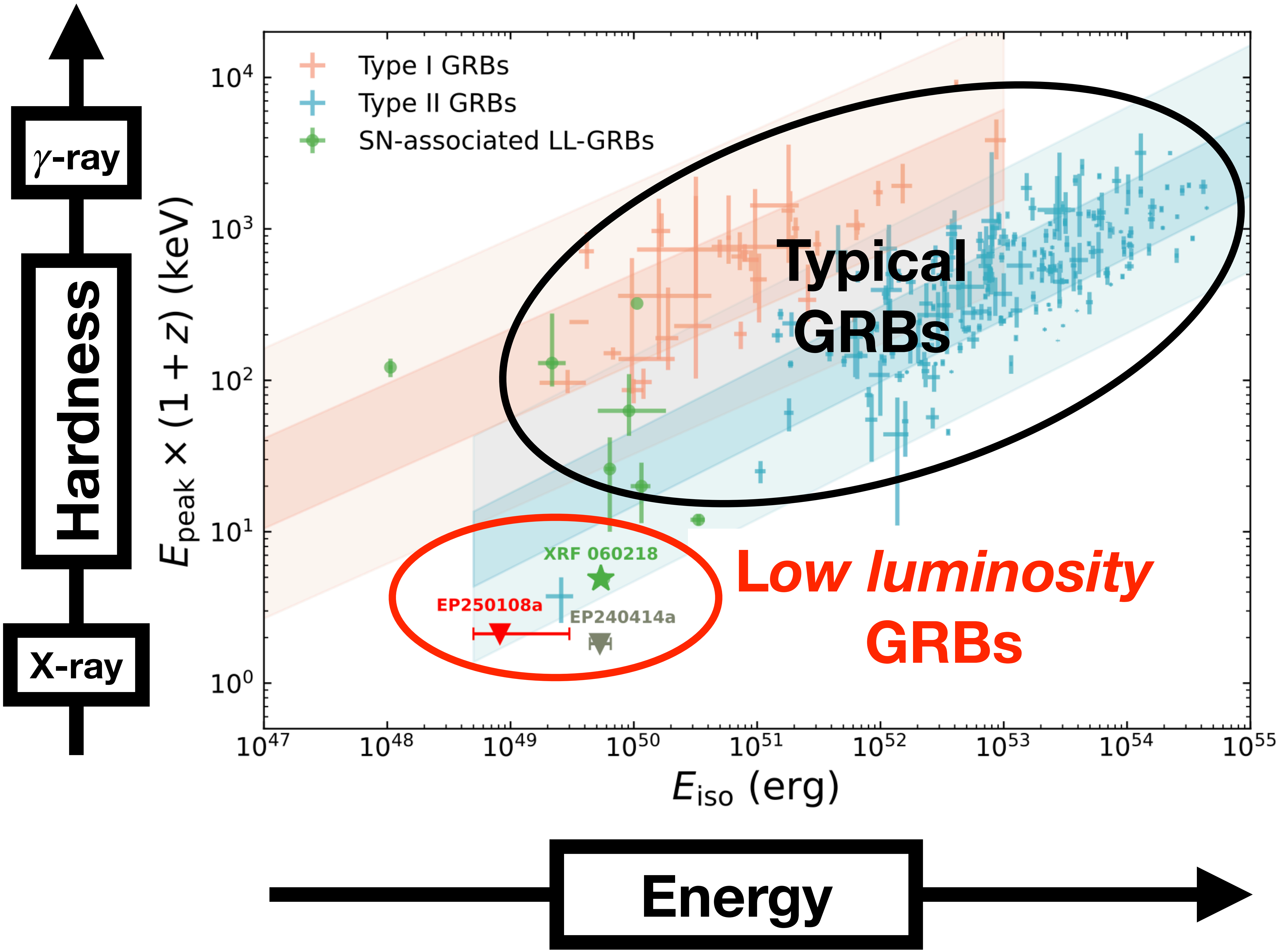
Key point: We need a stripped/compact Wolf-Rayet Star!

Einstein Probe 2024-

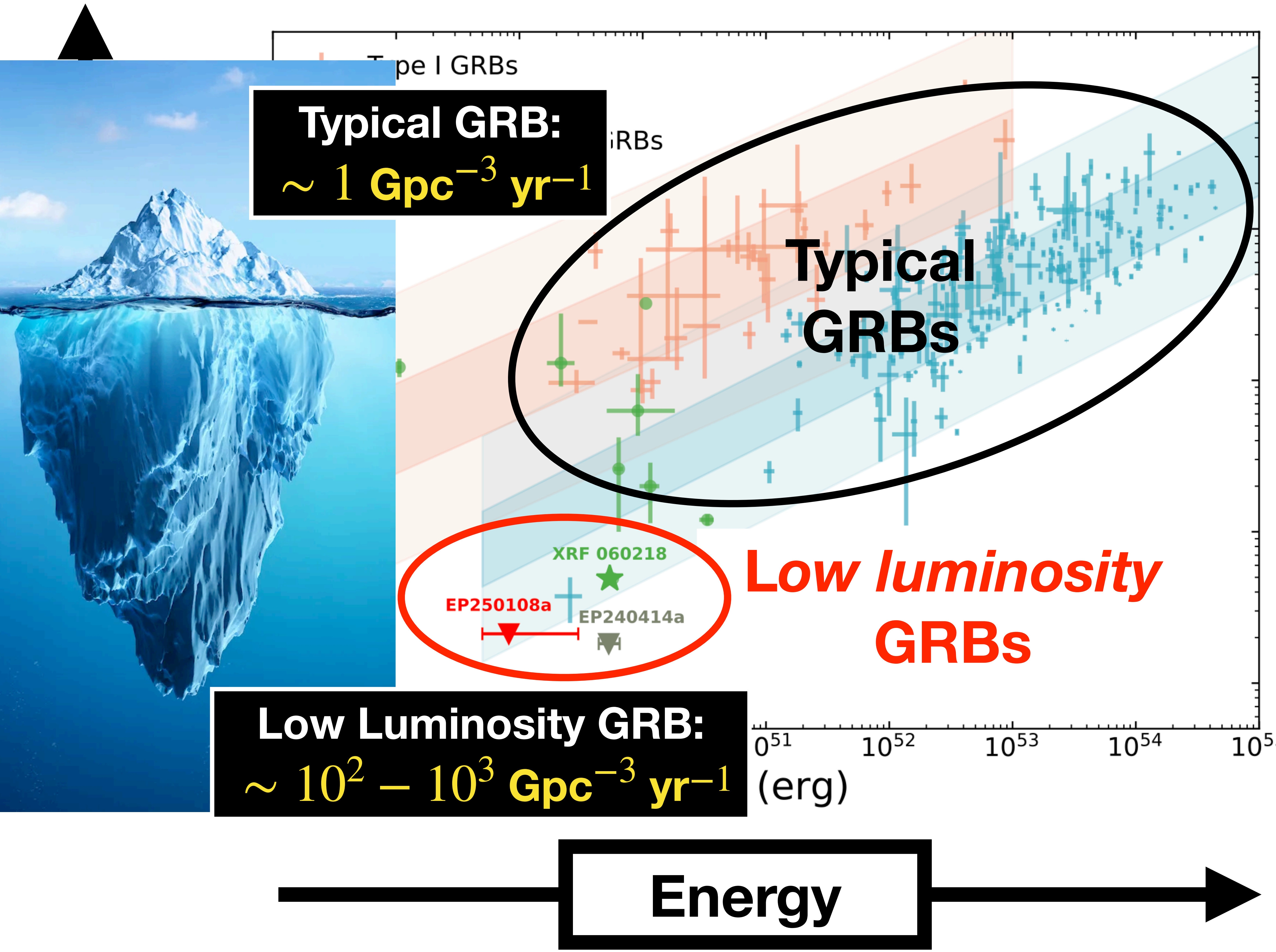
See Arimoto-san's Talk

Credit: EP

Updated [with EP]



Updated [with EP]



Obs. Driven Motivation:

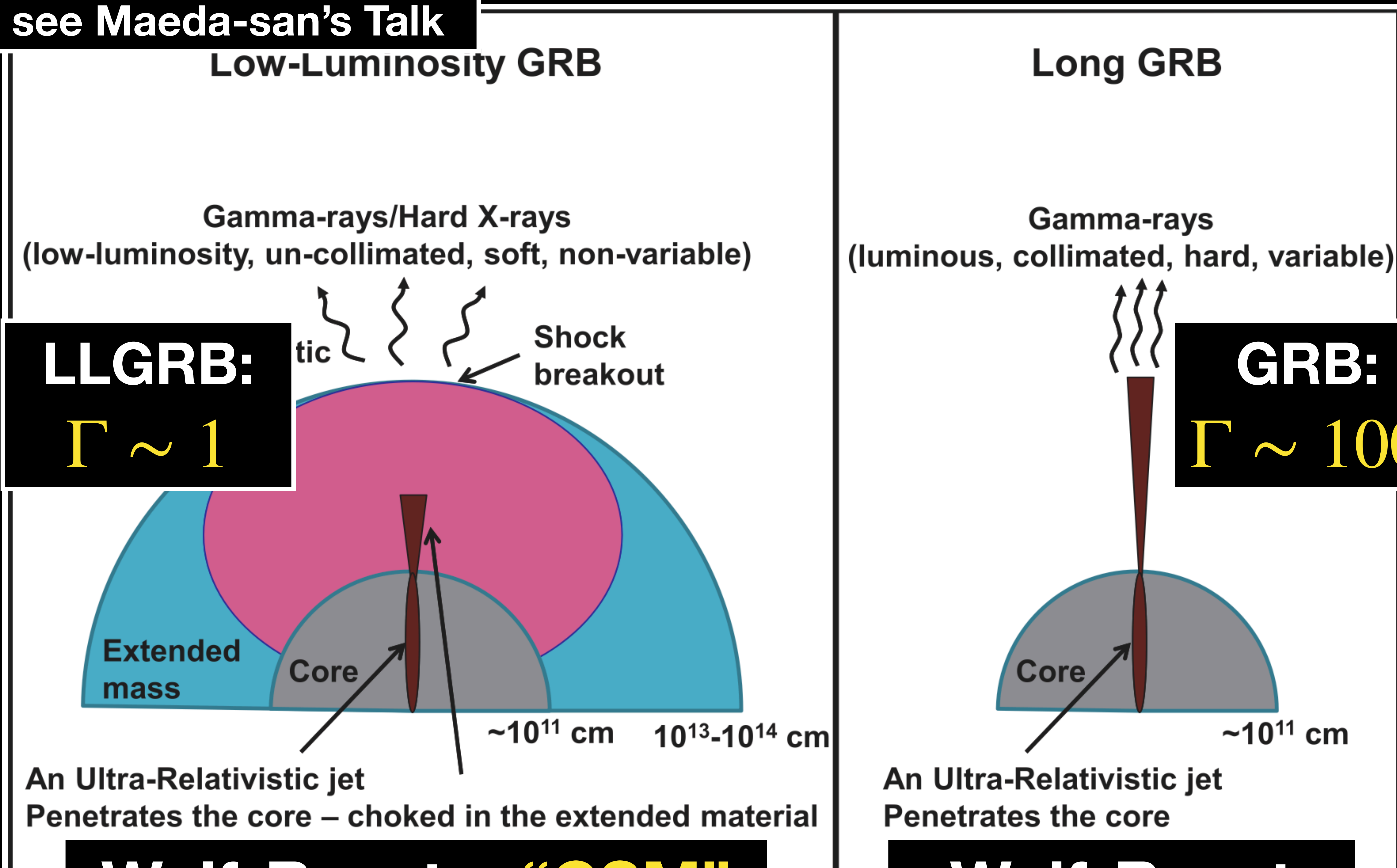
More obs. of weak/LL GRBs

→We need to revisit LLGRBs

Model: Star + “CSM”

Credit: Nakar 15

see Maeda-san’s Talk



LLGRB: $\Gamma \sim 1$

GRB: $\Gamma \sim 100$

Wolf-Rayet + “CSM”

Wolf-Rayet

Consistent w/ Recent Obs. Trend: 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]

Received 2006 August 25; accepted 2006 November 7; published 2006 December 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 In

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

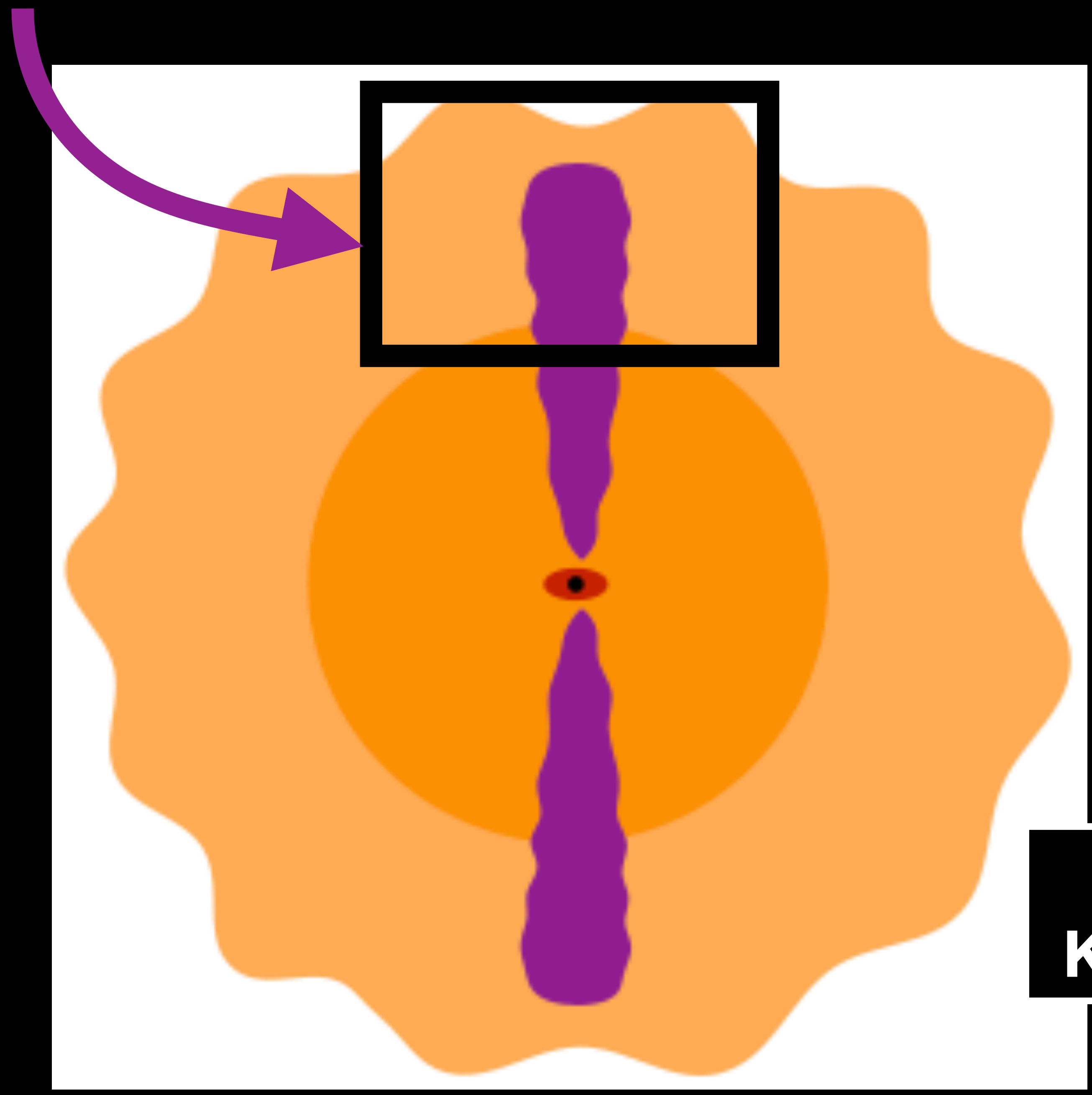
But only one really shows it

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],

...

Important Point:

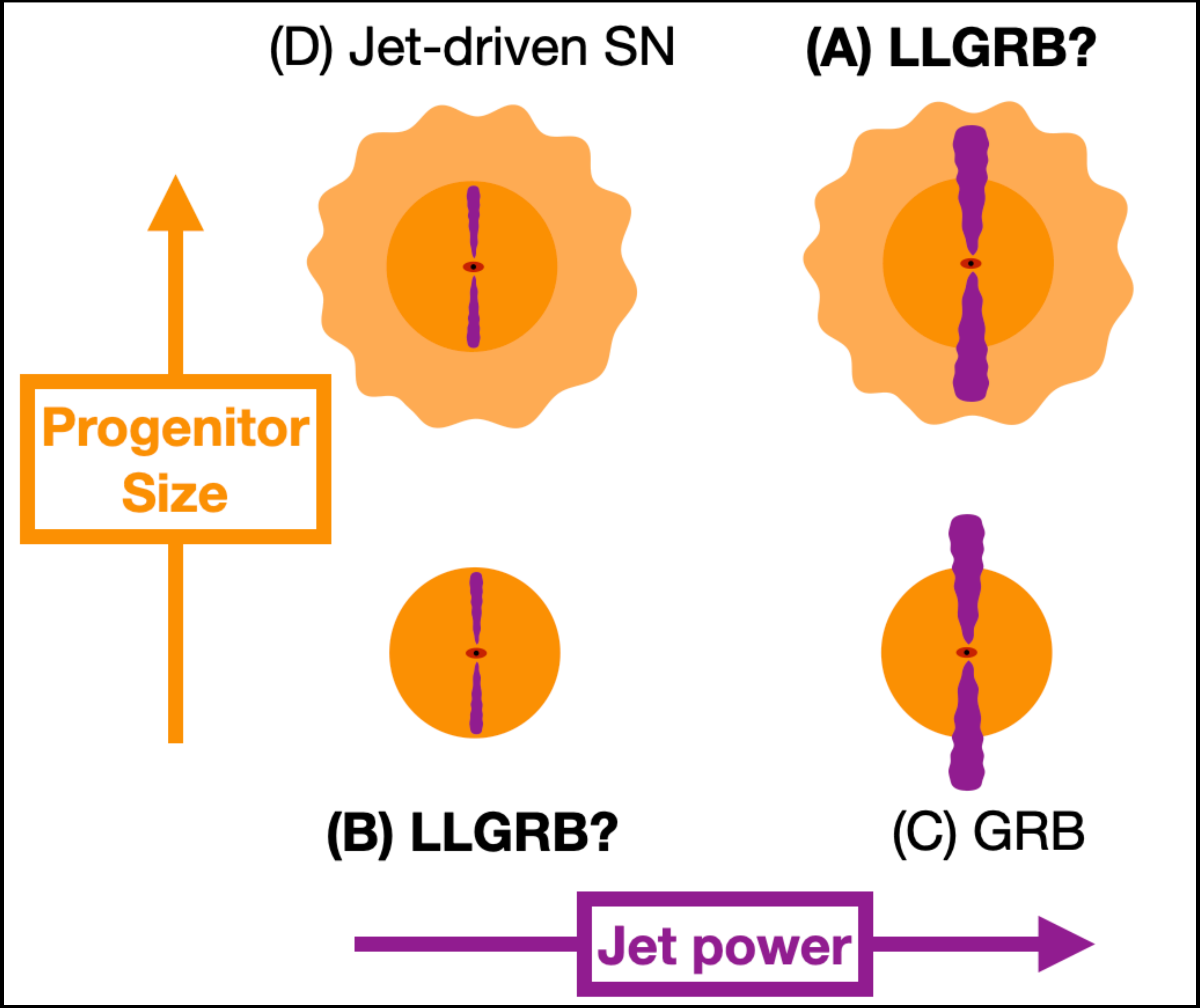
Understand (quantify) how the CSM affects the jet



Nick's Talk
Kuze-san's Poster

i.e. Quantify the effect of
e.g., CSM mass, radius, on the jet dynamics

Ultimate Goal:
What makes LLGRBs so weak?

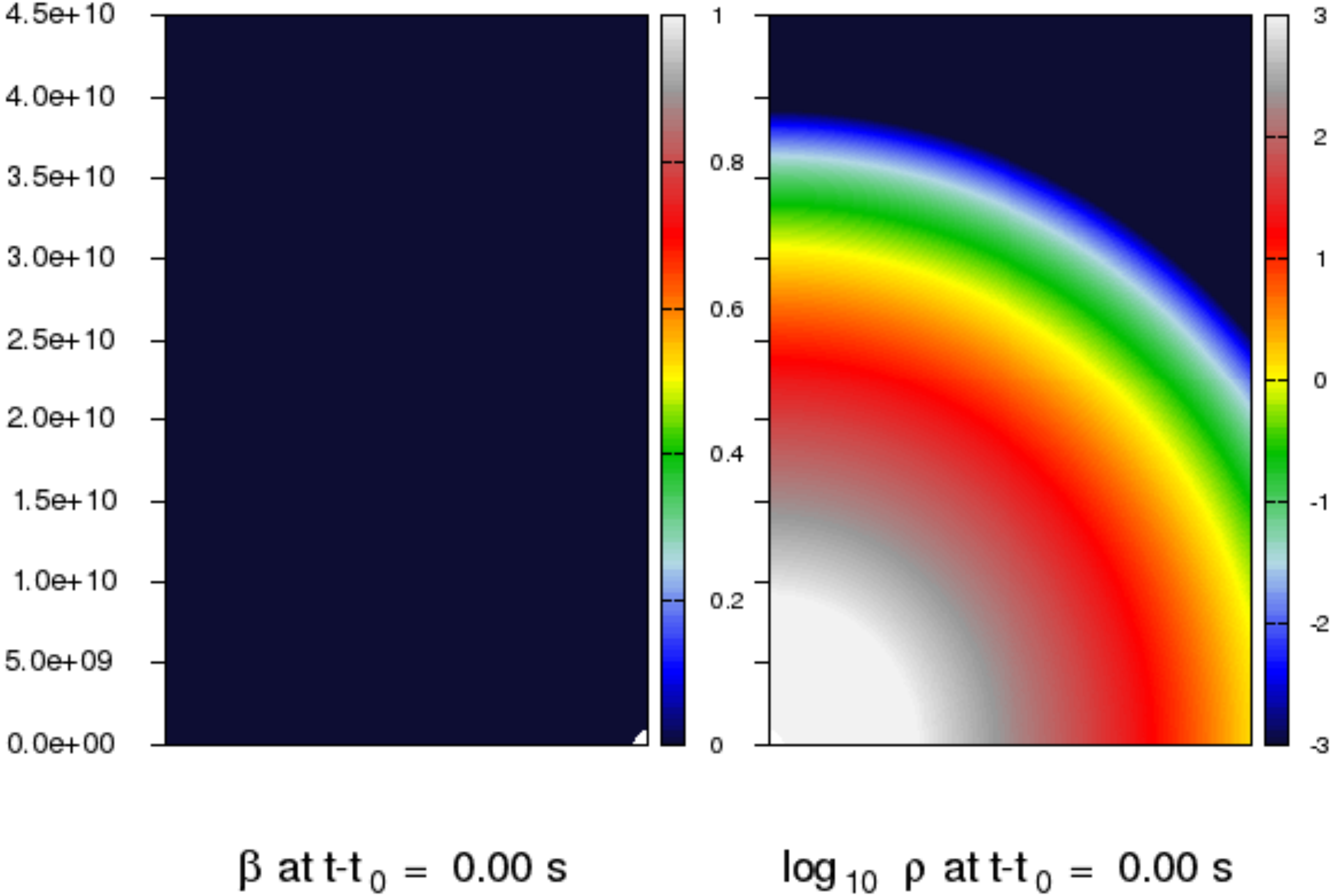


Method:
Numerical Simulations?

In massive Stars (*long* GRBs)

Wide Jet case

$t_b - t_0 = 8.310s$

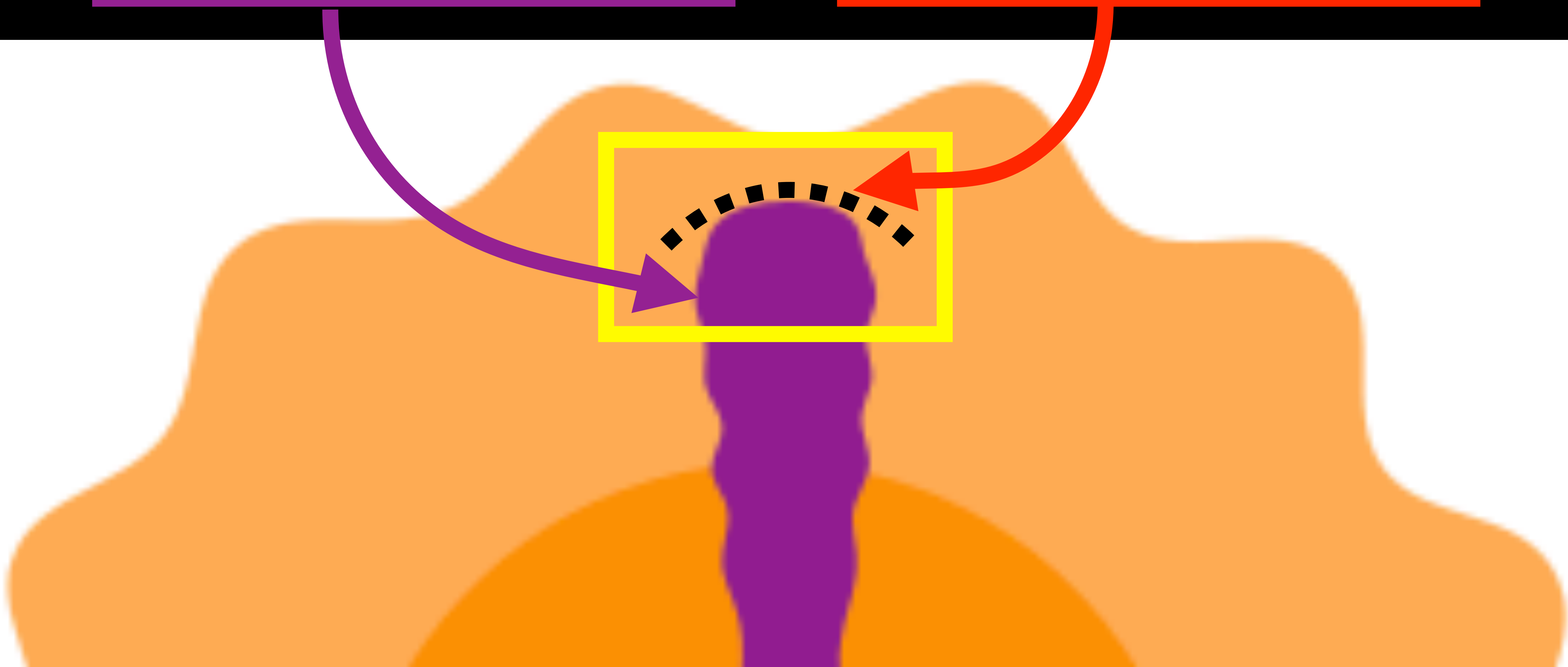


Method:
→ Analytic Modeling

Jet Dynamics

Jump conditions:

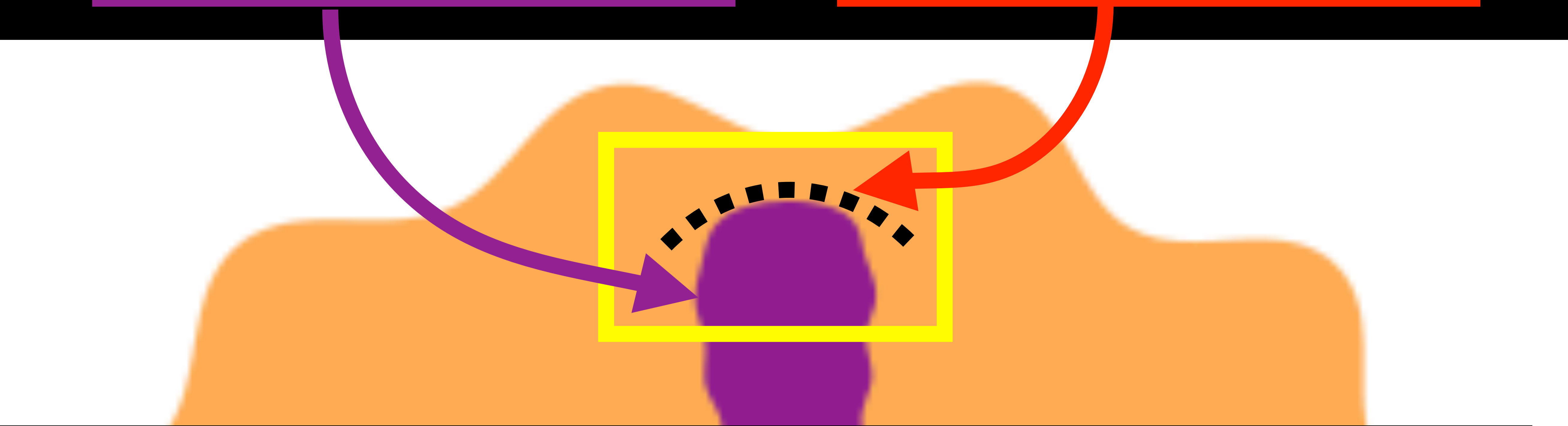
$$\underbrace{h_j\rho_j c^2(\Gamma\beta)^2_{jh} + P_j}_{} = \underbrace{h_a\rho_a c^2(\Gamma\beta)^2_{ha} + P_a}_{}$$



Jet Dynamics

Jump conditions: **(Begelman & Cioffi 1989)**

$$\underline{h_j\rho_j c^2(\Gamma\beta)^2_{jh} + P_j} = \underline{h_a\rho_a c^2(\Gamma\beta)^2_{ha} + P_a}$$



Jet head velocity: $\beta_{\rm h} = \dfrac{1}{1+\tilde{L}^{-1/2}}$, with $\tilde{L} \simeq \dfrac{L_{\rm j}}{\Sigma_{\rm j}(t)\rho_{\rm a}c^3\Gamma_{\rm a}^2}$

Bromberg et al. 2011

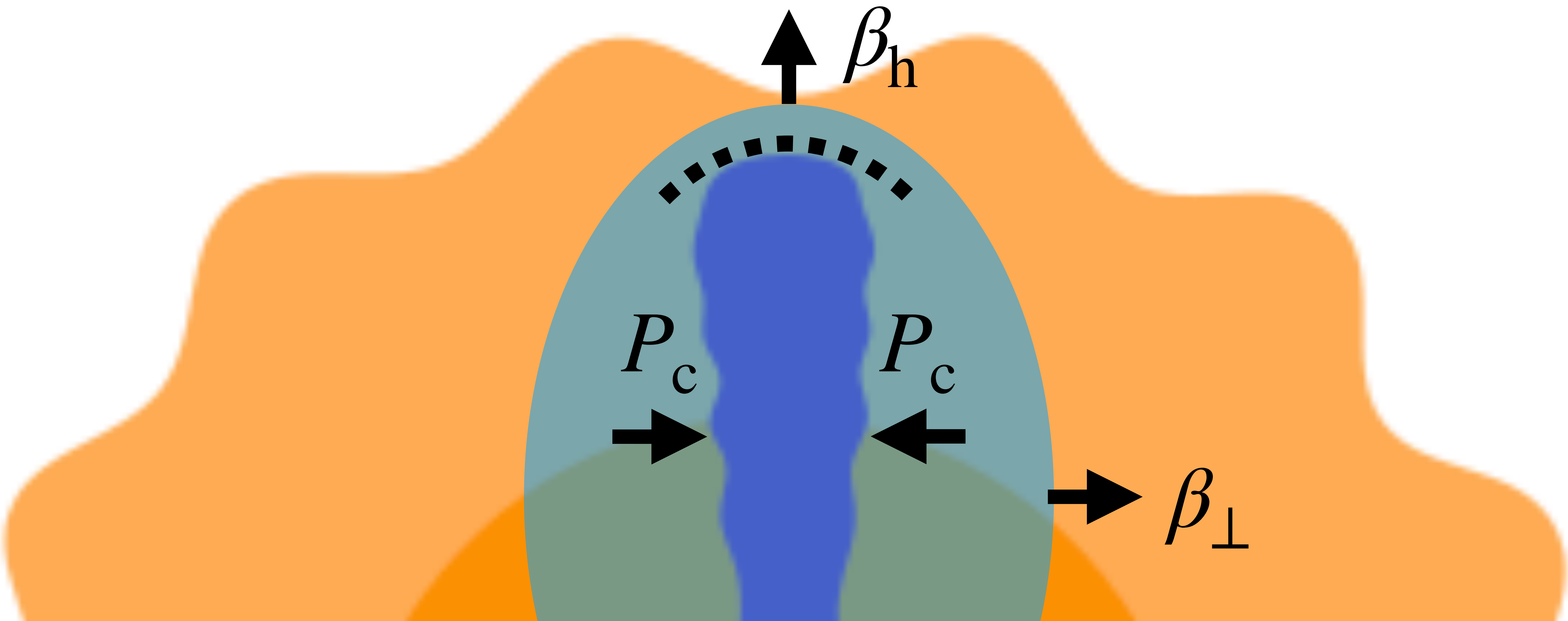
Cocoon & Collimation

$$r_{\mathrm{c}}(t) = c\beta_{\perp}(t - t_0),$$

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

$$P_c = \eta \frac{E_{\mathrm{c}}}{3V_{\mathrm{c}}},$$

$$\Sigma_{\mathrm{j}}(t) = \frac{L_{\mathrm{j}}\theta_0^2}{4cP_{\mathrm{c}}},$$



Jet head velocity β_h

Following Bromberg et al. (2011):

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

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

No analytic solution!

⇒ Numerically??

Universal Solution

For non-relativistic jet head with $C \ll 1$

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

For relativistic jet head with $C \gg 1$

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

Blended together to ($C_t \approx 0.66$, & $b \approx 0.79.$):

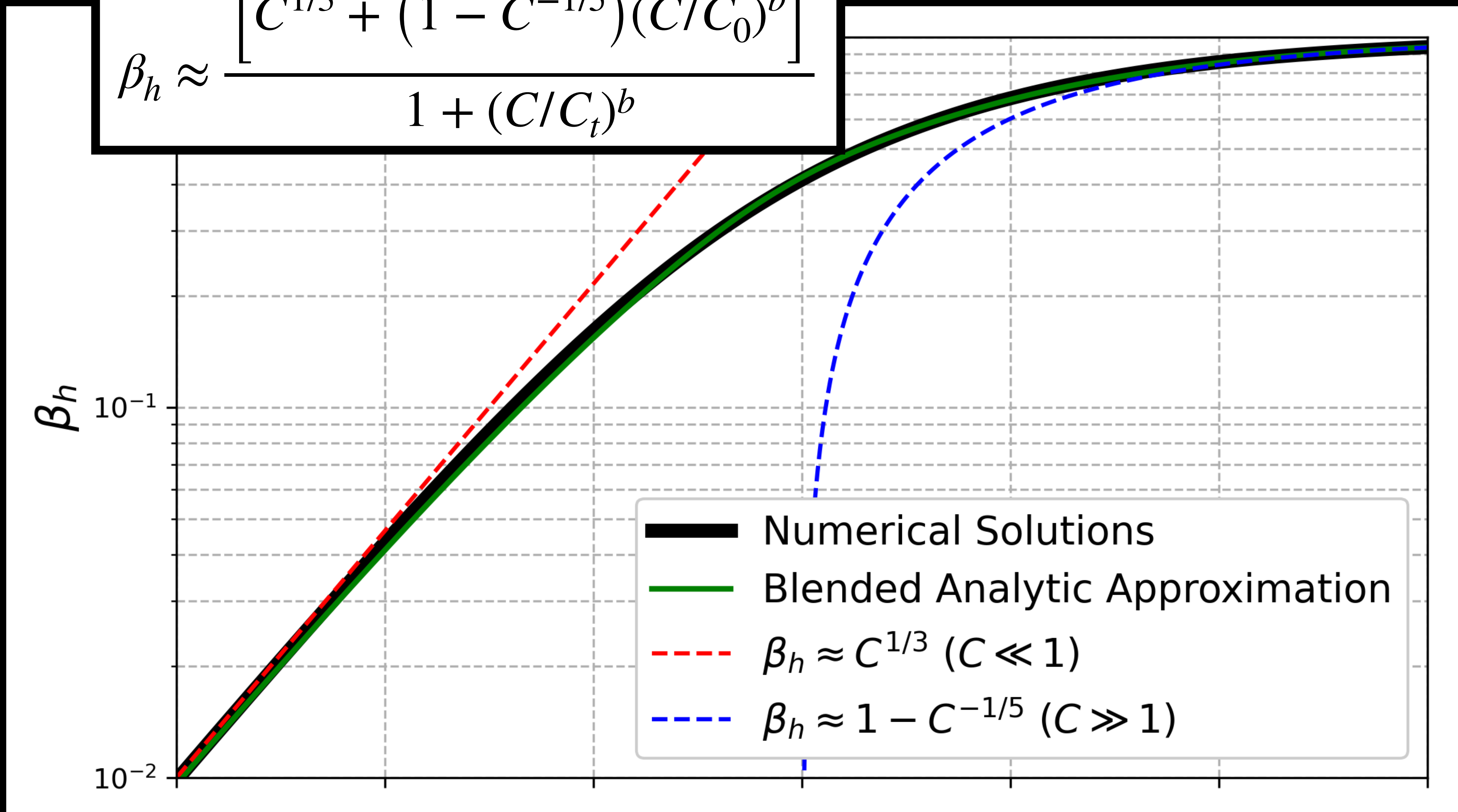
$$\beta_h \approx \frac{\left[C^{1/3} + \left(1 - C^{-1/5}\right)(C/C_0)^b\right]}{1 + (C/C_t)^b},$$

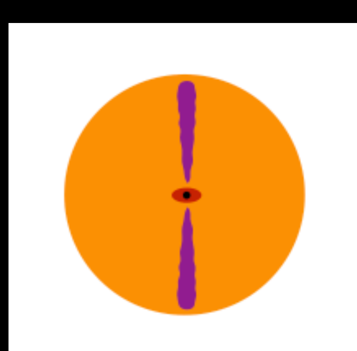
Universal Solution

Jet head velocity (β_h)

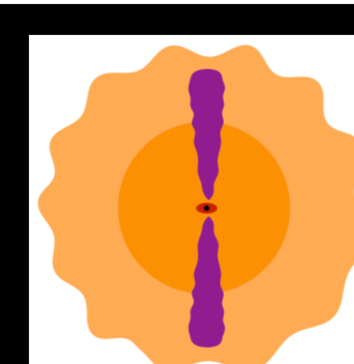
$$\beta_h \approx \frac{\left[C^{1/3} + \left(1 - C^{-1/5}\right)(C/C_0)^b\right]}{1 + (C/C_t)^b}$$

Credit: HH+25

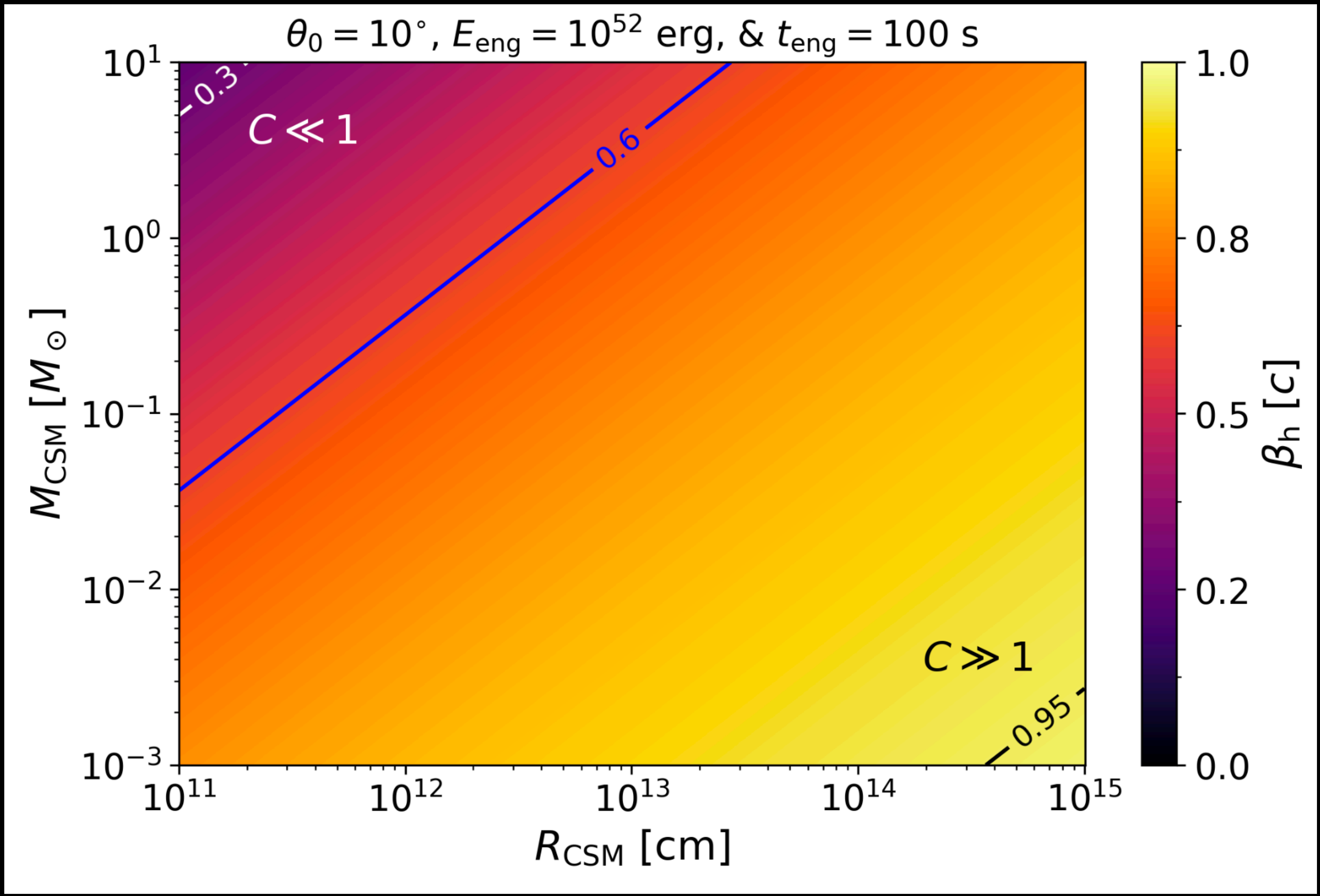




CSM presence: $C \propto \dfrac{E_{\rm eng}}{t_{\rm eng}\theta_0^2} \dfrac{R_{\rm CSM}}{M_{\rm CSM}}$

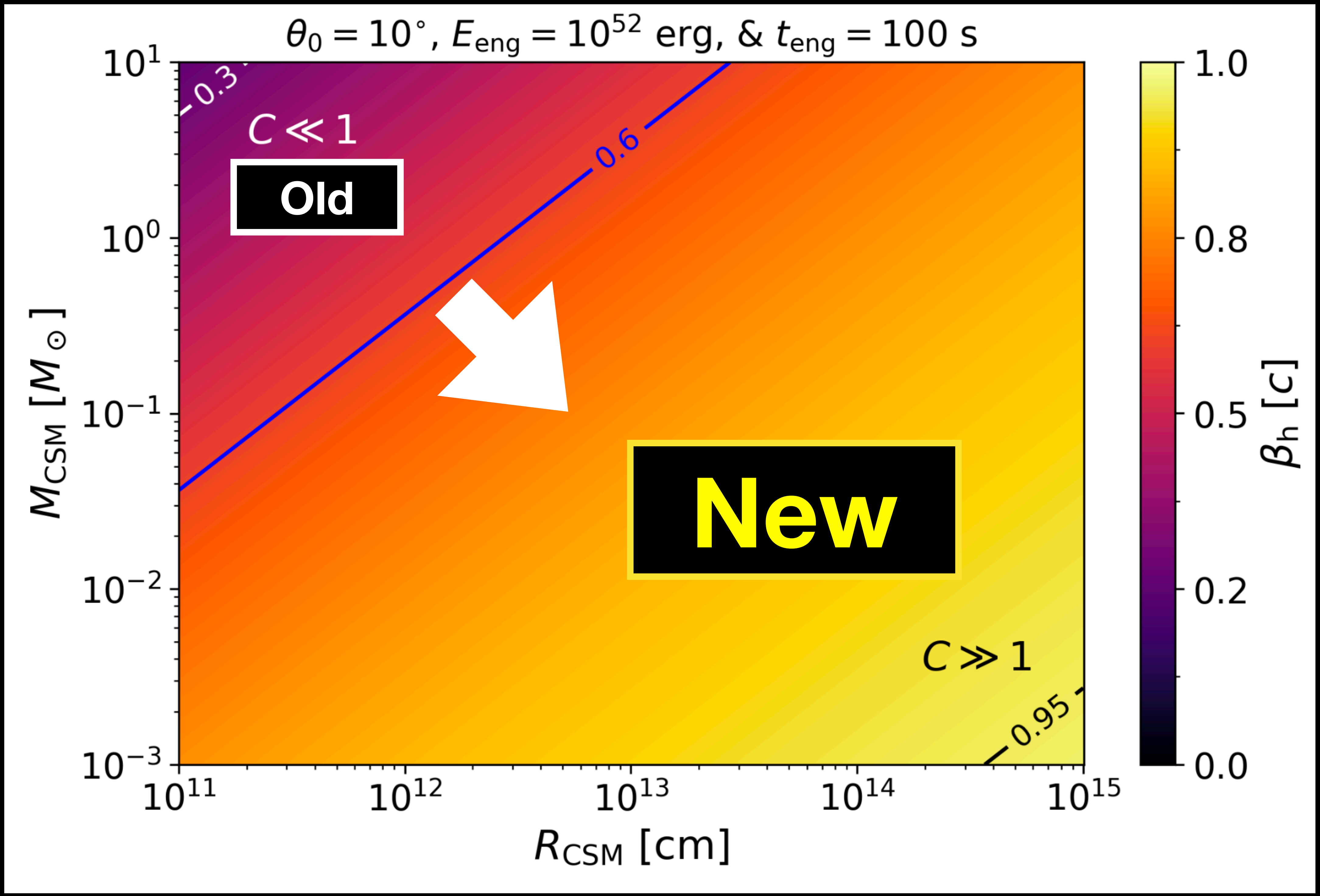


Jet head velocity quantified



Credit: HH+25

Jet head velocity quantified



Credit: HH+25

New Generalised Expression for the breakout time

Hamidani+25:

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

Important for $\beta \lesssim 1$

Bromberg+12:

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

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

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

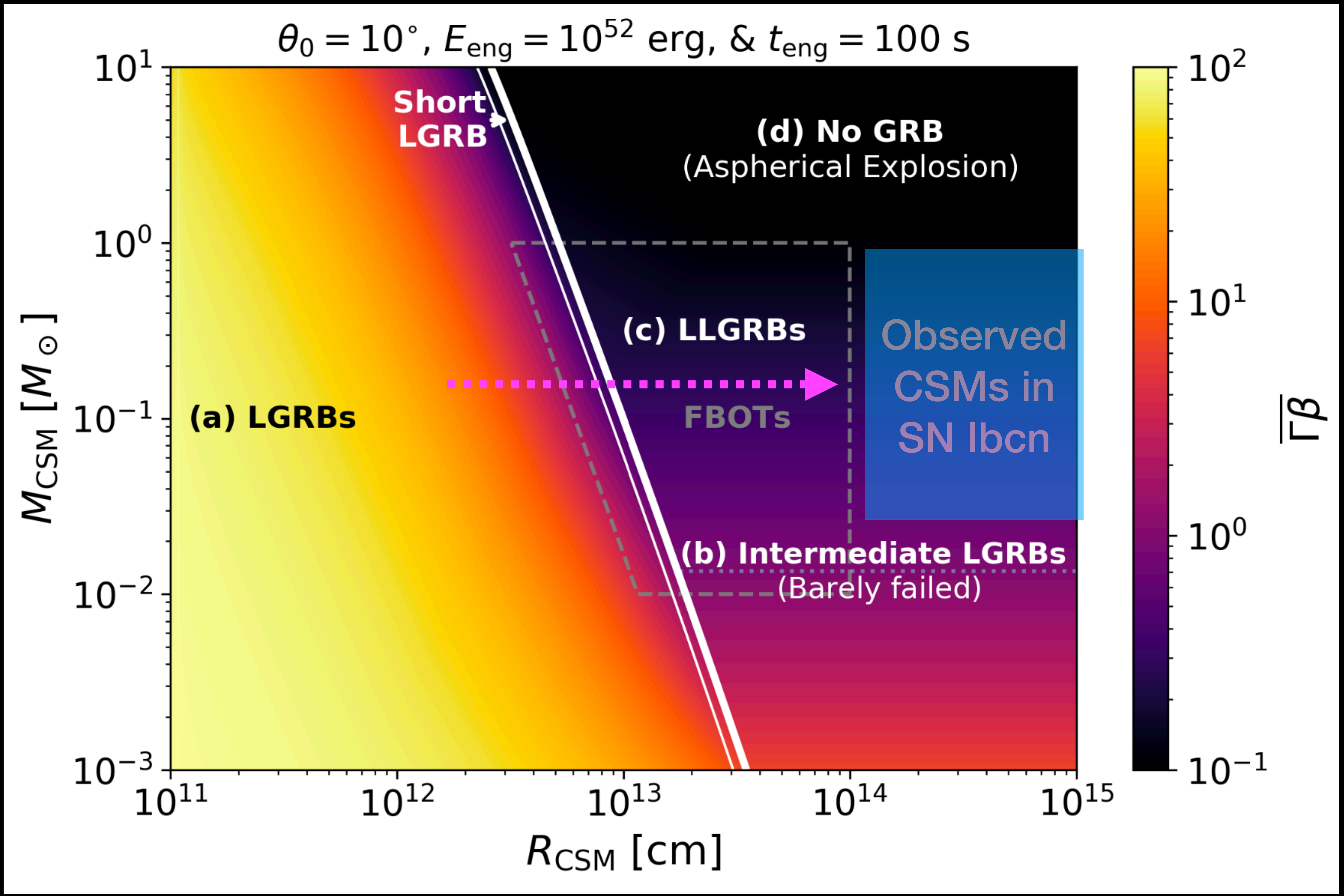
With

Energy weighted

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

$$\overline{\Gamma\beta} = \begin{cases} \gg 1 \text{ (Jet dominated: LGRB)} \\ \ll 1 \text{ (Cocoon dominated: LLGRB)} \end{cases}$$

Diversity of transients



Credit: HH+25

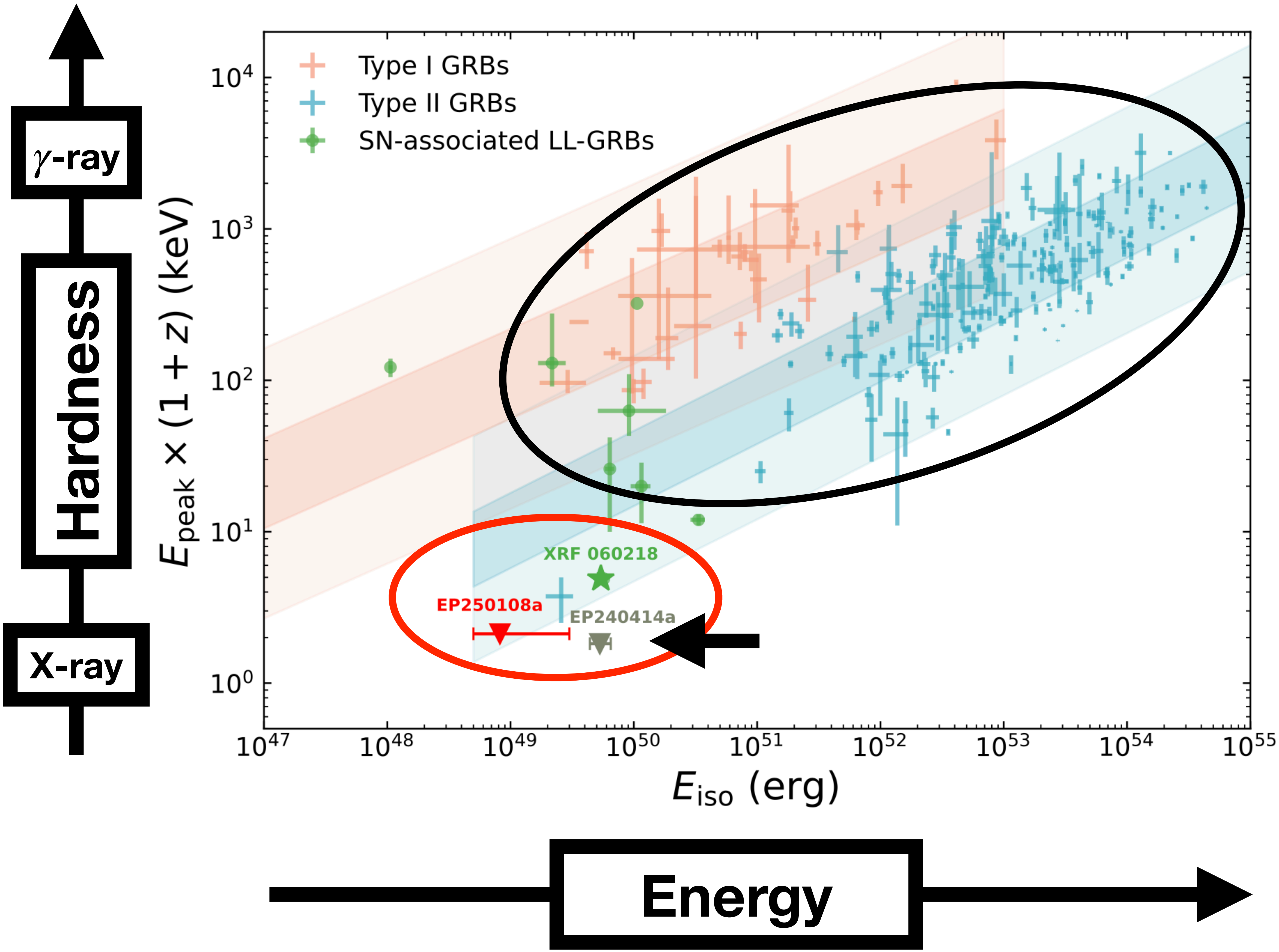
Summary I

- Fully analytic model for jet dynamics in CSM
  - Jet/CSM parameters
    ⇒ Je propagation (β_h, t_b, …)
    ⇒ Cocoon properties/emission ($L_{\rm bol}$, $r_{\rm ph}$, $T_{\rm ph}$, …)
  - Public in Python: https://github.com/hamidhamidani/cocoon-cooling-model (1 model: < 100ms)
- Can be used to probe the CSM in LGRBs/LLGRBs

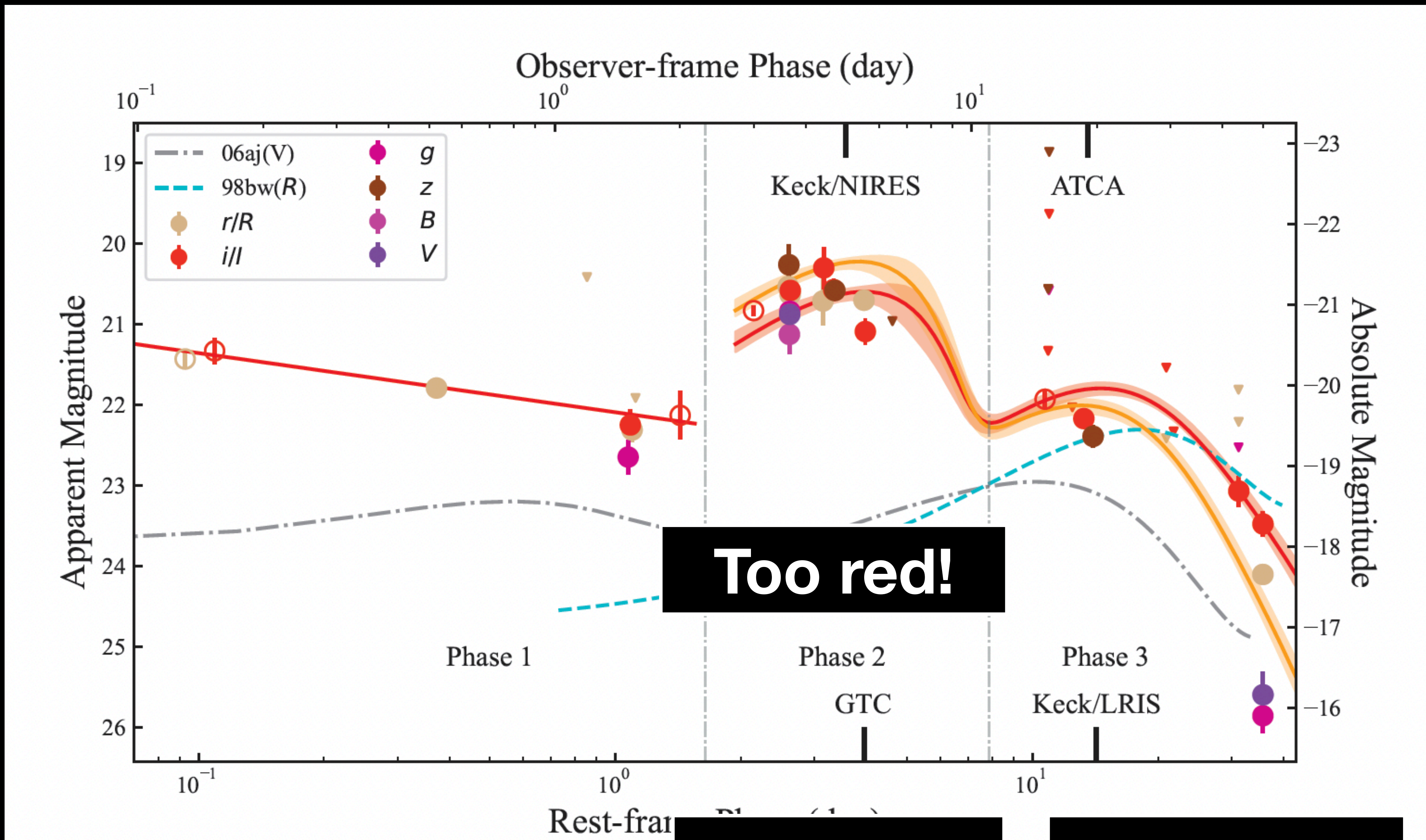
Interpretation of Recent EP Events

CREDIT: EP

Updated [with EP]



EP240414a [Unique transient]



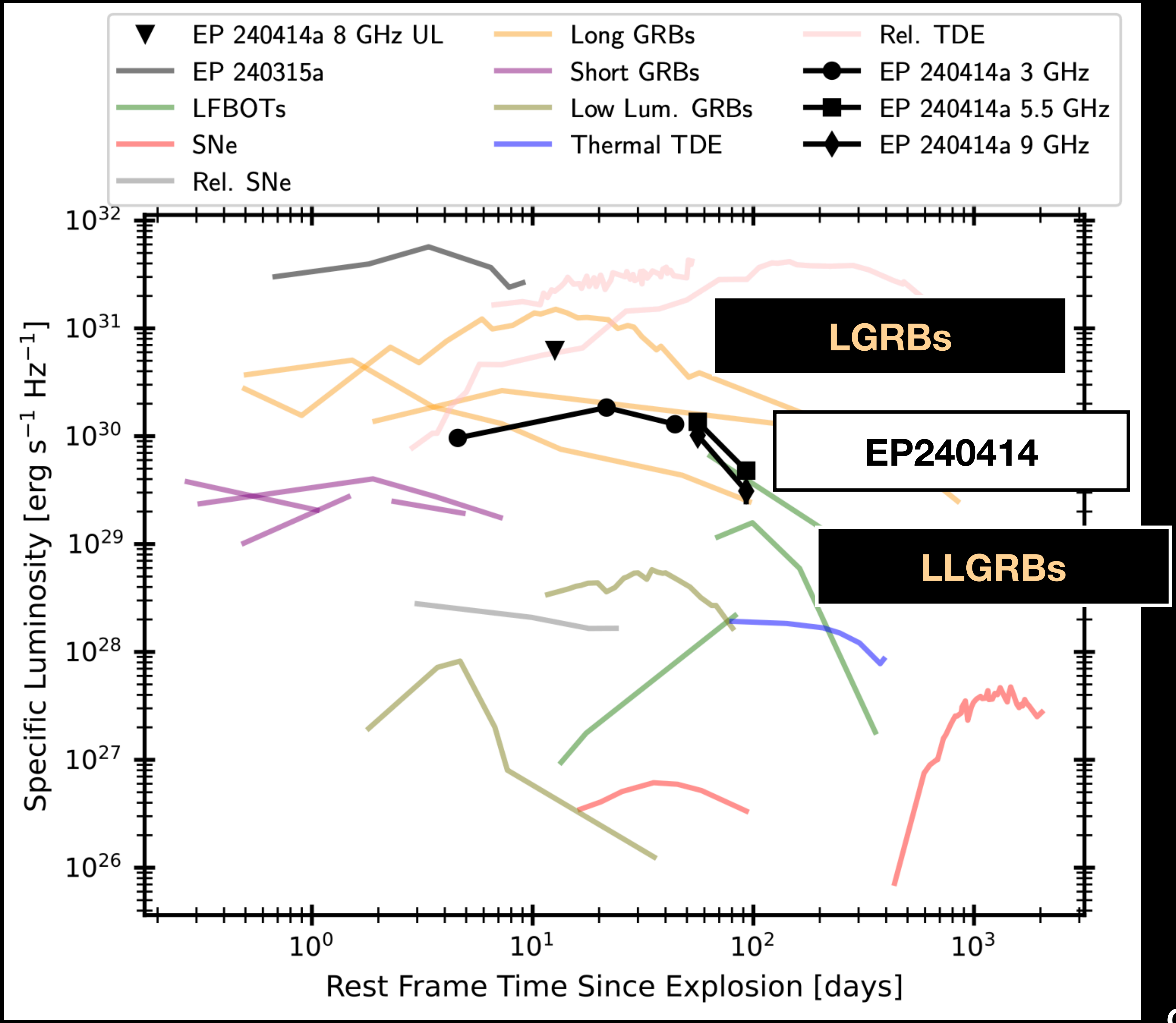
Phase 1: thermal?

Phase 2: non-thermal?

Phase 3: Ic-BL SN (Ni56)

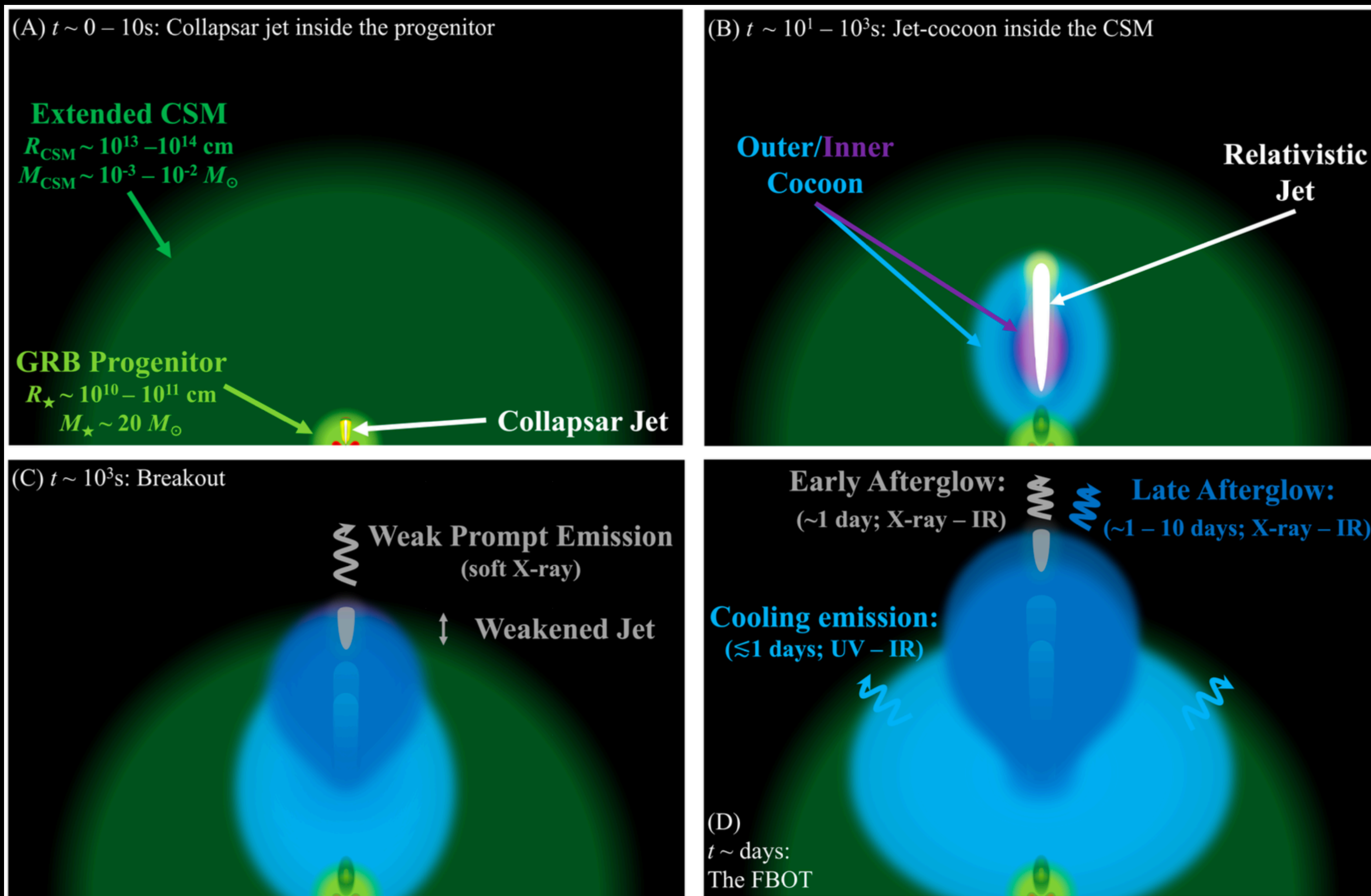
Credit: Sun+24

Radio [EP240414a]



Credit: Bright+24

Scenario for EP240414a

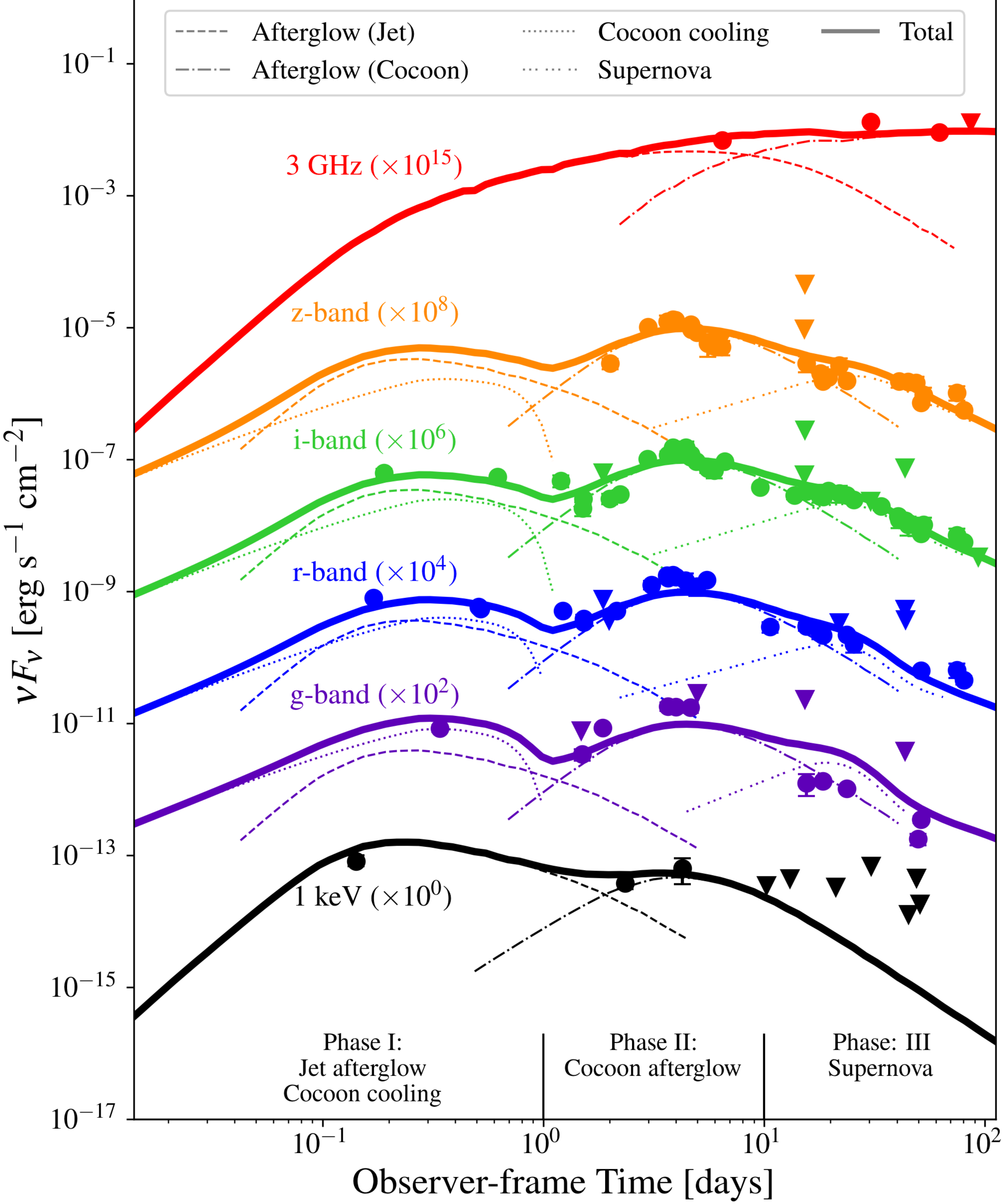


Credit: HH+25

Results
[EP240414a]

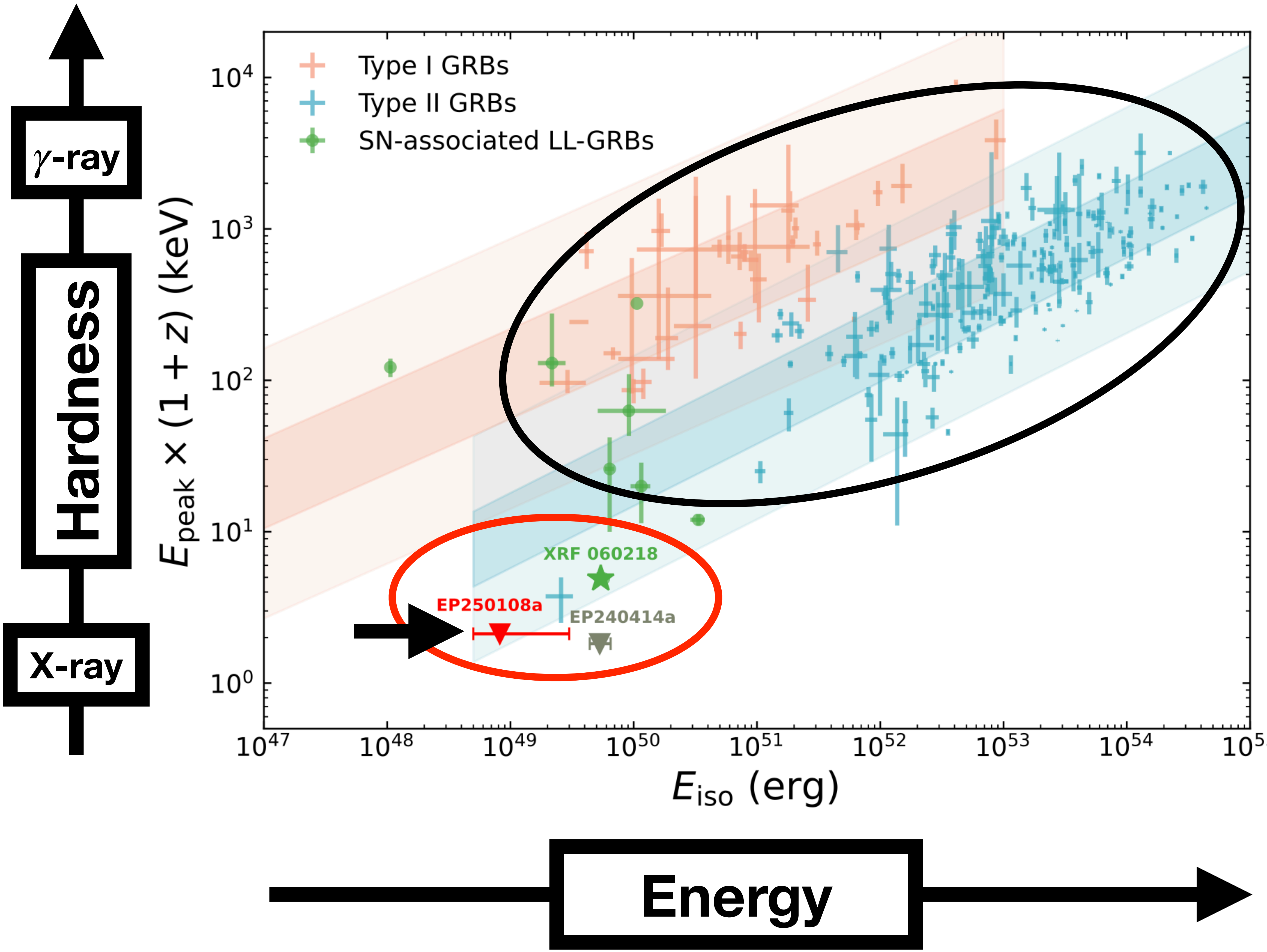
CSM:
$\sim 0.03\,M_\odot$
3×10^{13} cm

Jet:
Conventional

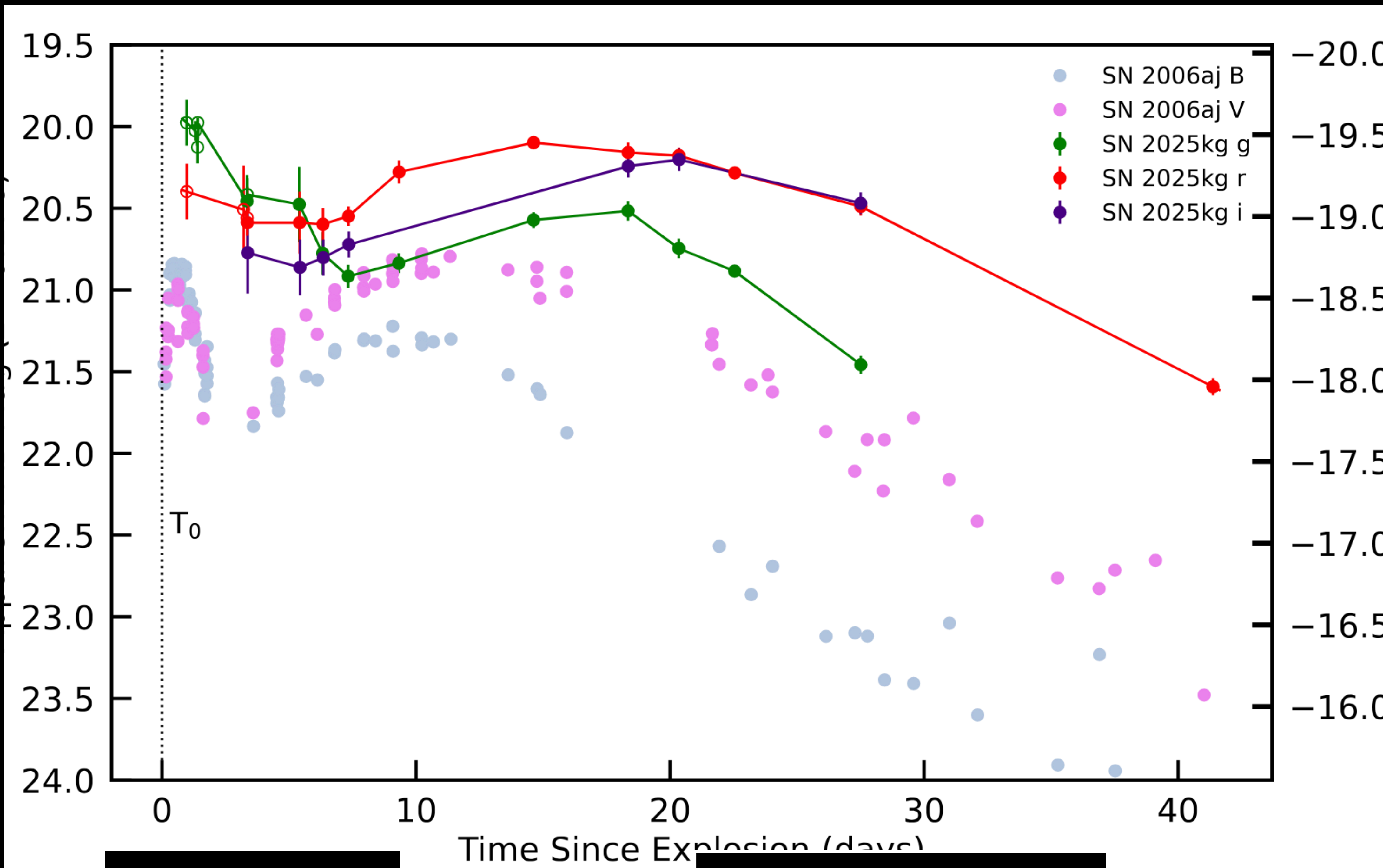


Credit: HH+25

Updated [with EP]



EP250108a [LLGRB+FBOT]

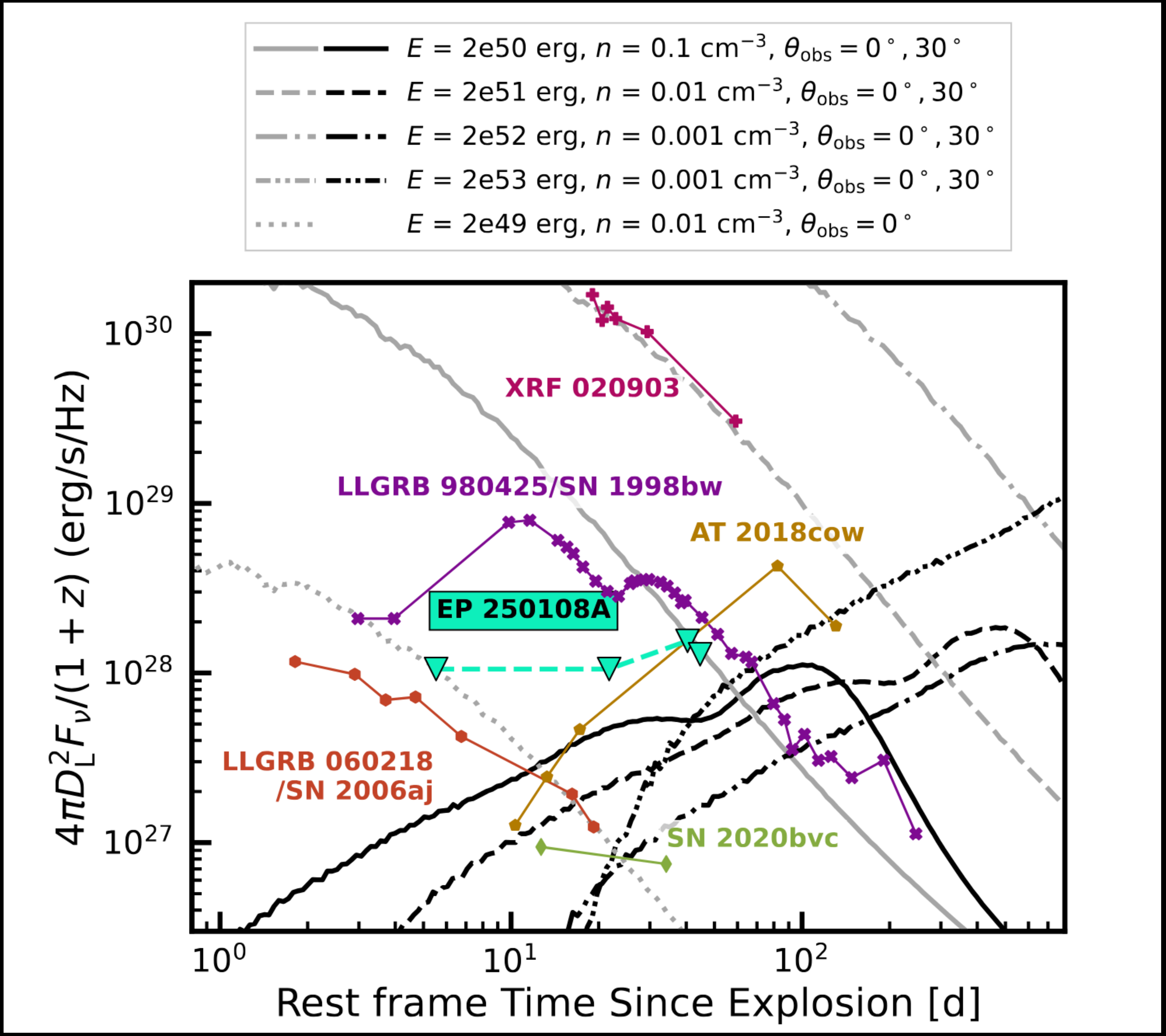


Phase 1: Thermal

Phase 2: Thermal (SN / Ni56)

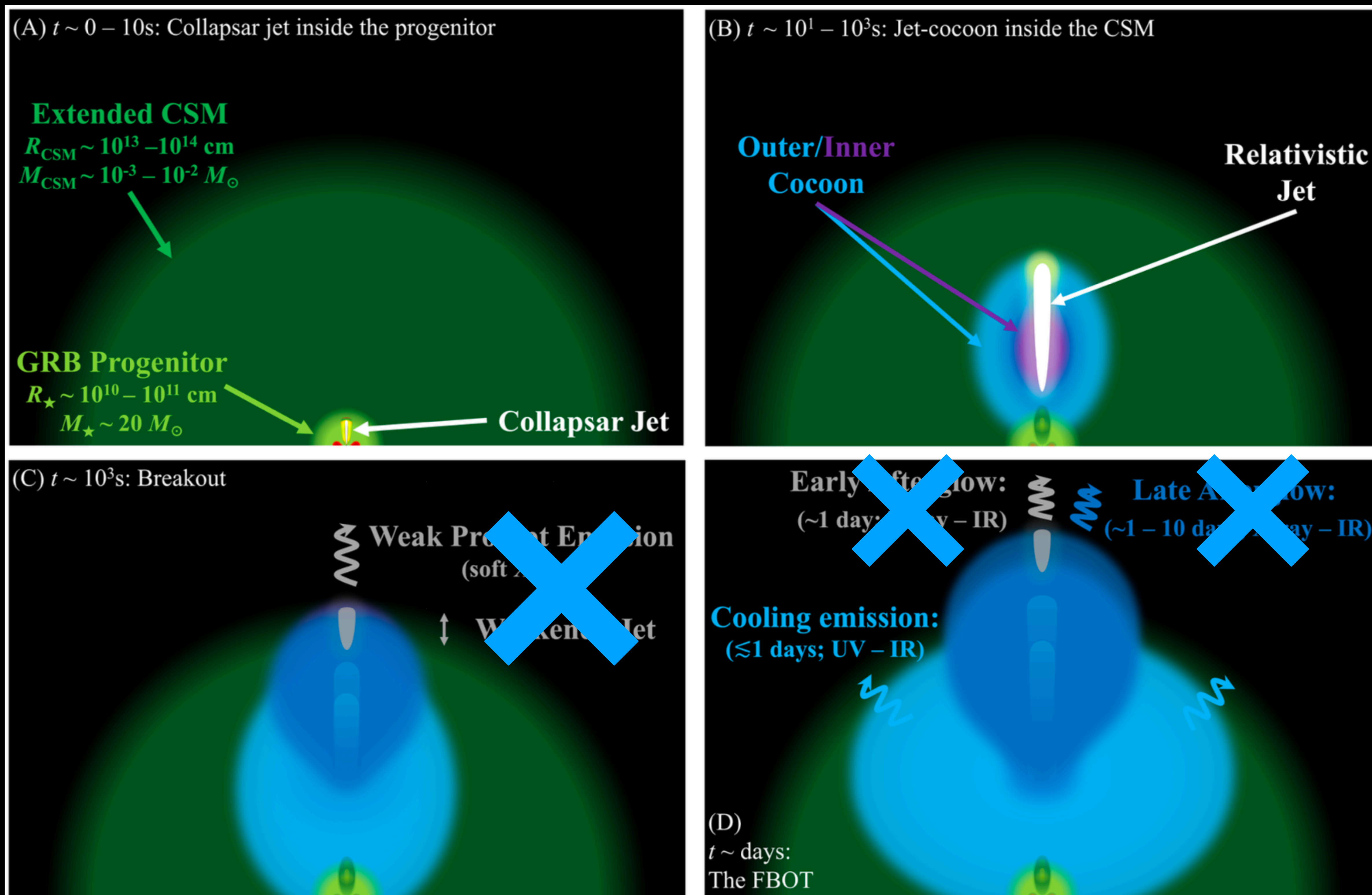
Credit: Srinivasaragavan+25

EP250108a [No afterglow]



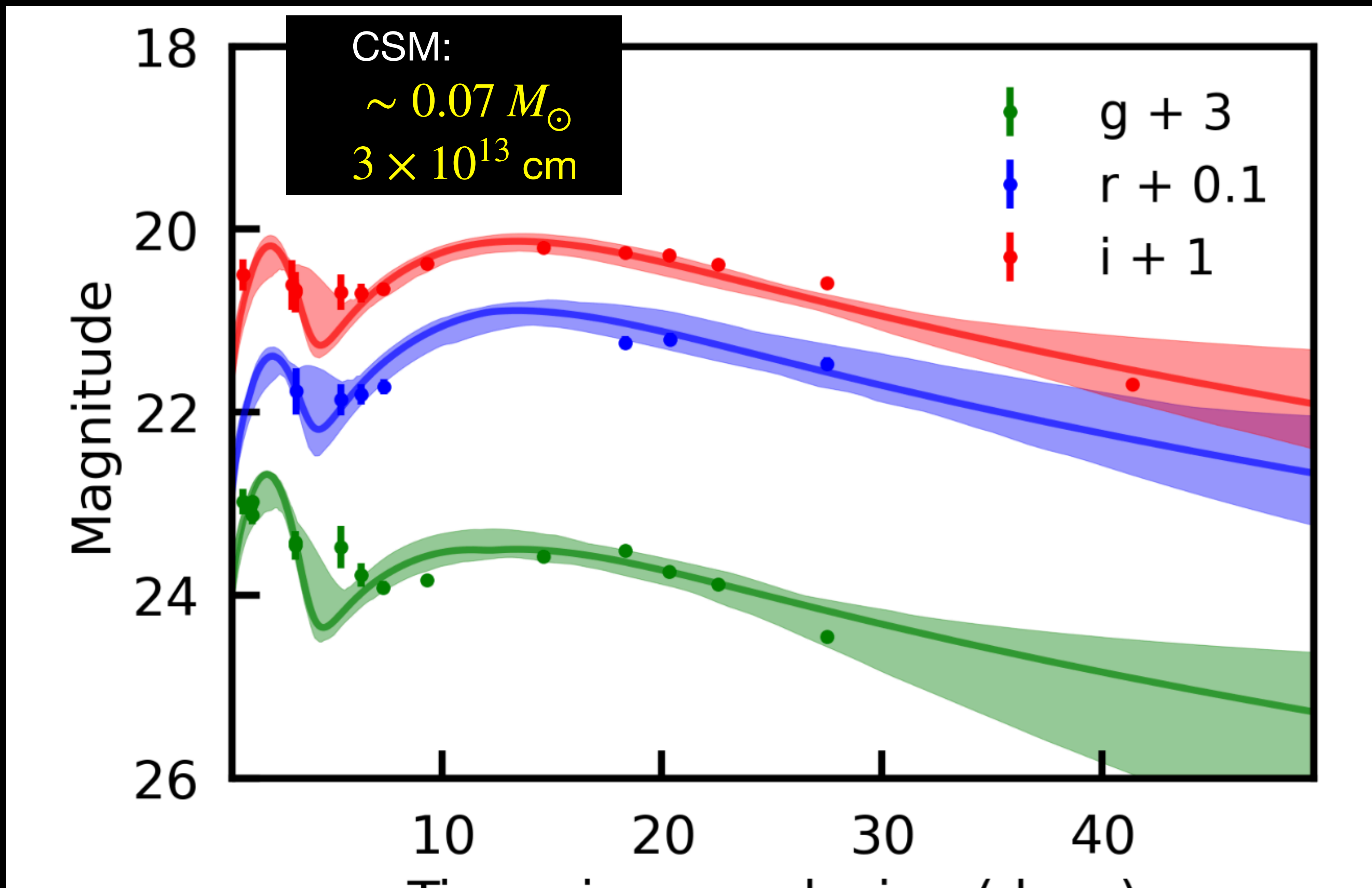
Credit: Srinivasaragavan+25

Our scenario for EP250108a



Credit: HH+25

EP250108a [LLGRB+FBOT]

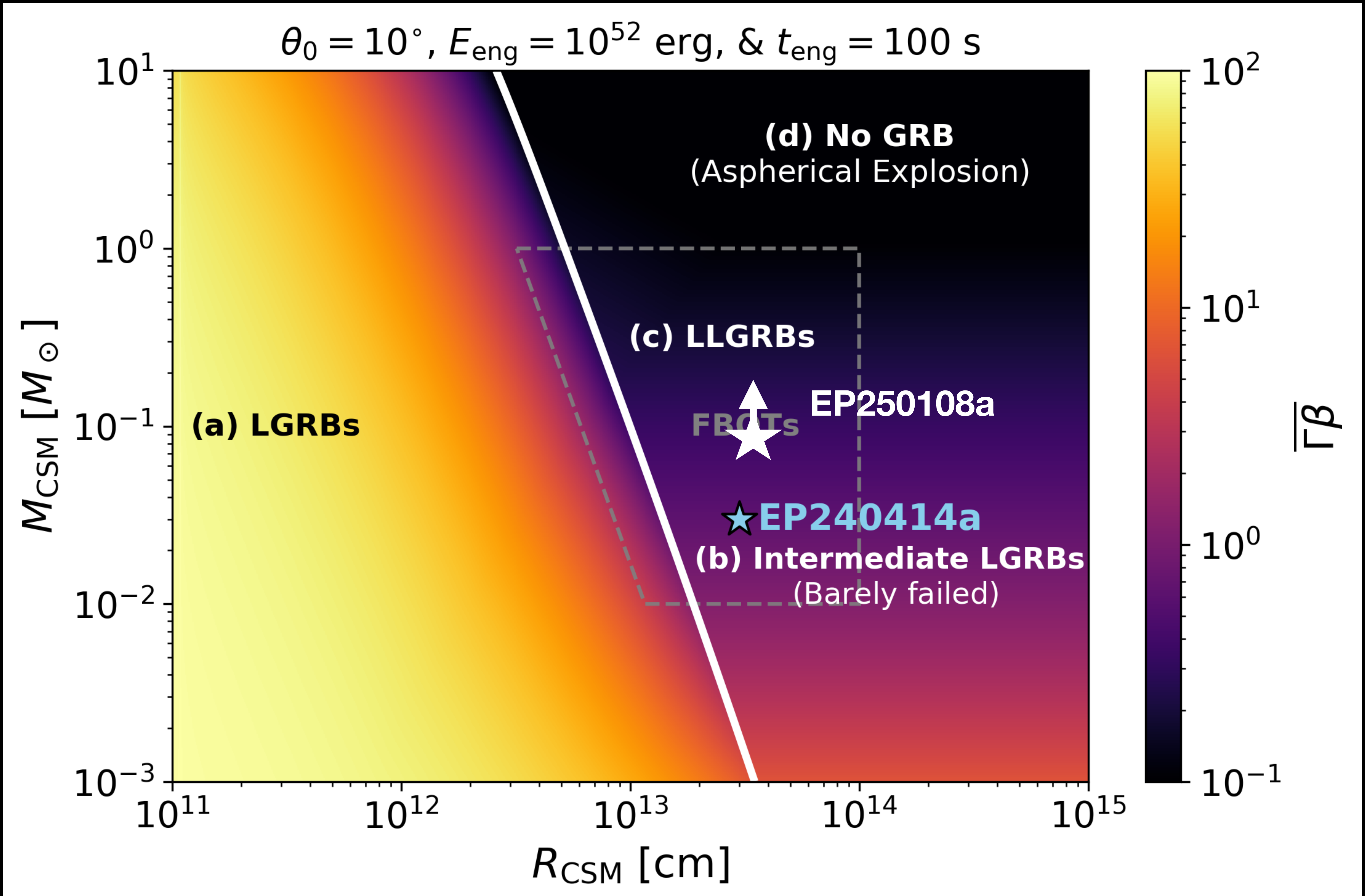


Phase 1:
FBOT (thermal)

Phase 2:
Ic-BL SN (Ni56)

Credit: Srinivasaragavan+25

EP240414a & EP250108a



Credit: HH+25

Summary

We quantified the effect of the CSM on GRB jets

Early follow-up observations of nearby LLGRBs show that we need extended CSM

We see similarity in LLGRB CSM parameters $\sim 0.03 M_\odot$ and $\sim 3 \times 10^{13}$ cm