

GRB Jets in CSM

Material:

Dynamics & Diversity of Transients

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With:

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Yuri Sato, Gokul Srinivasaragavan & Shigeo S. Kimura**

References:

<https://arxiv.org/abs/2503.16242>

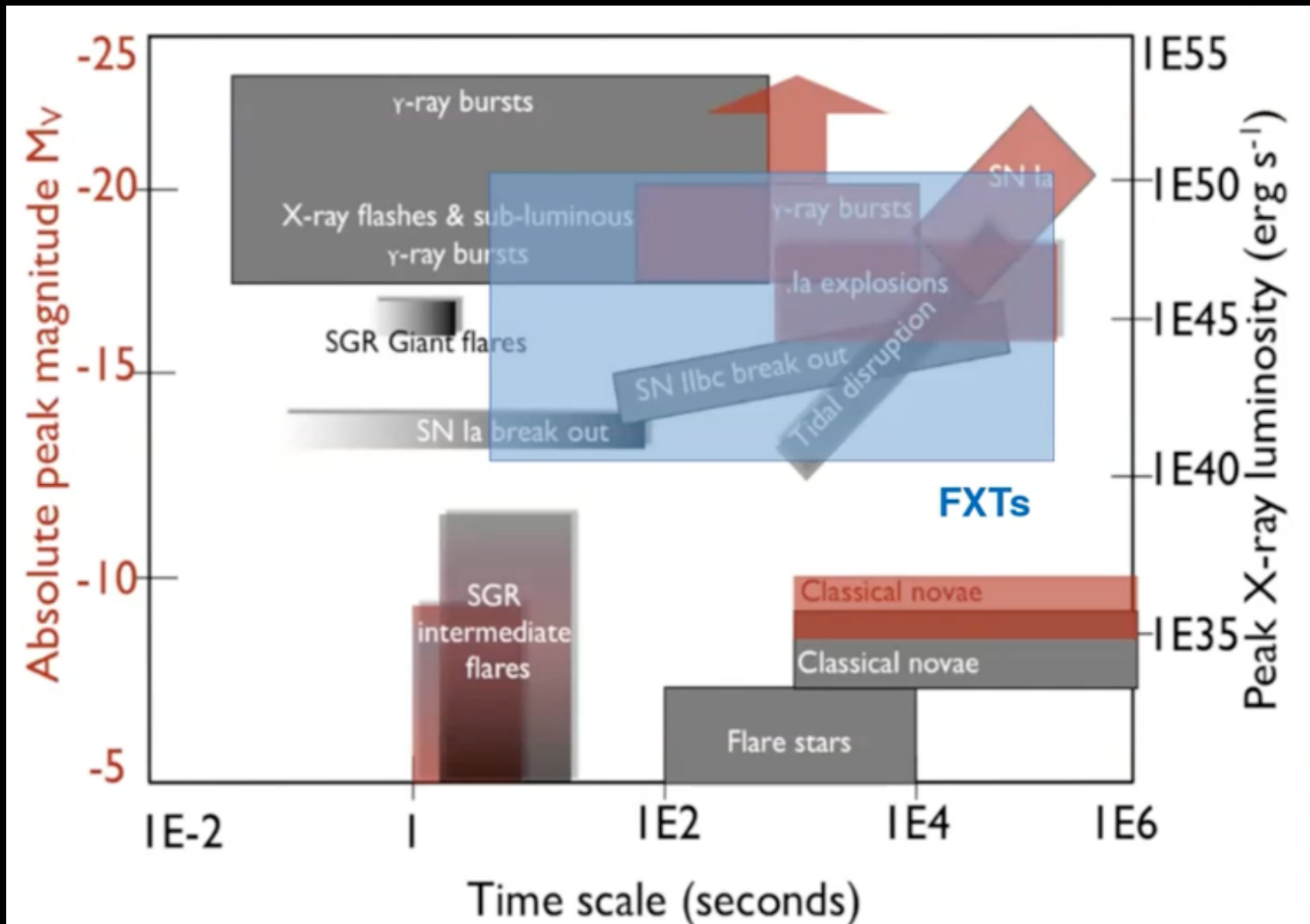
<https://arxiv.org/abs/2503.16243>

<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)



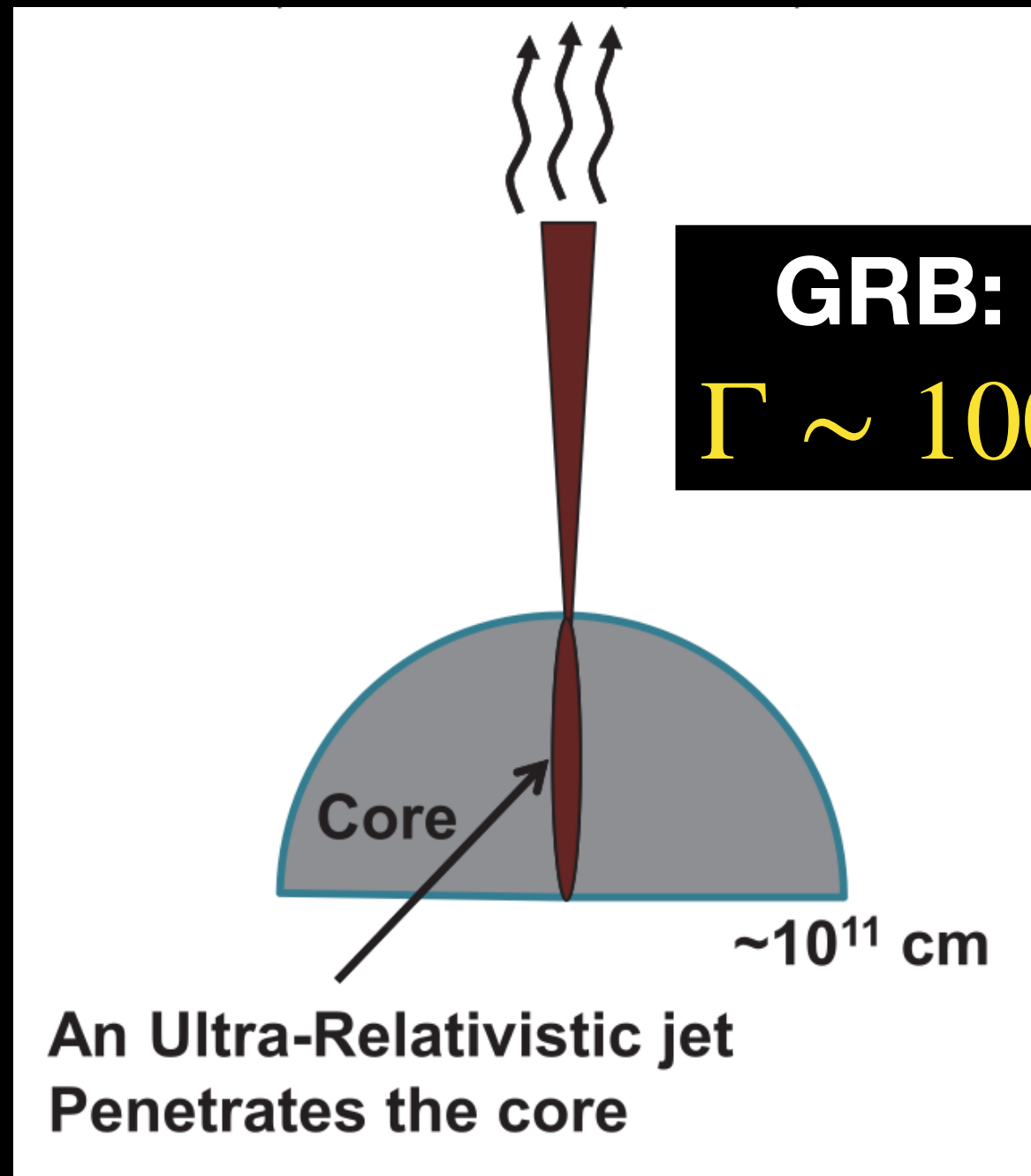
The majority of the diagram is theoretical

3

Too Extreme: **We need a jet!**

Collapsar Scenario

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



Credit: Nakar 15

See
Fujibayashi-san's
Talk

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

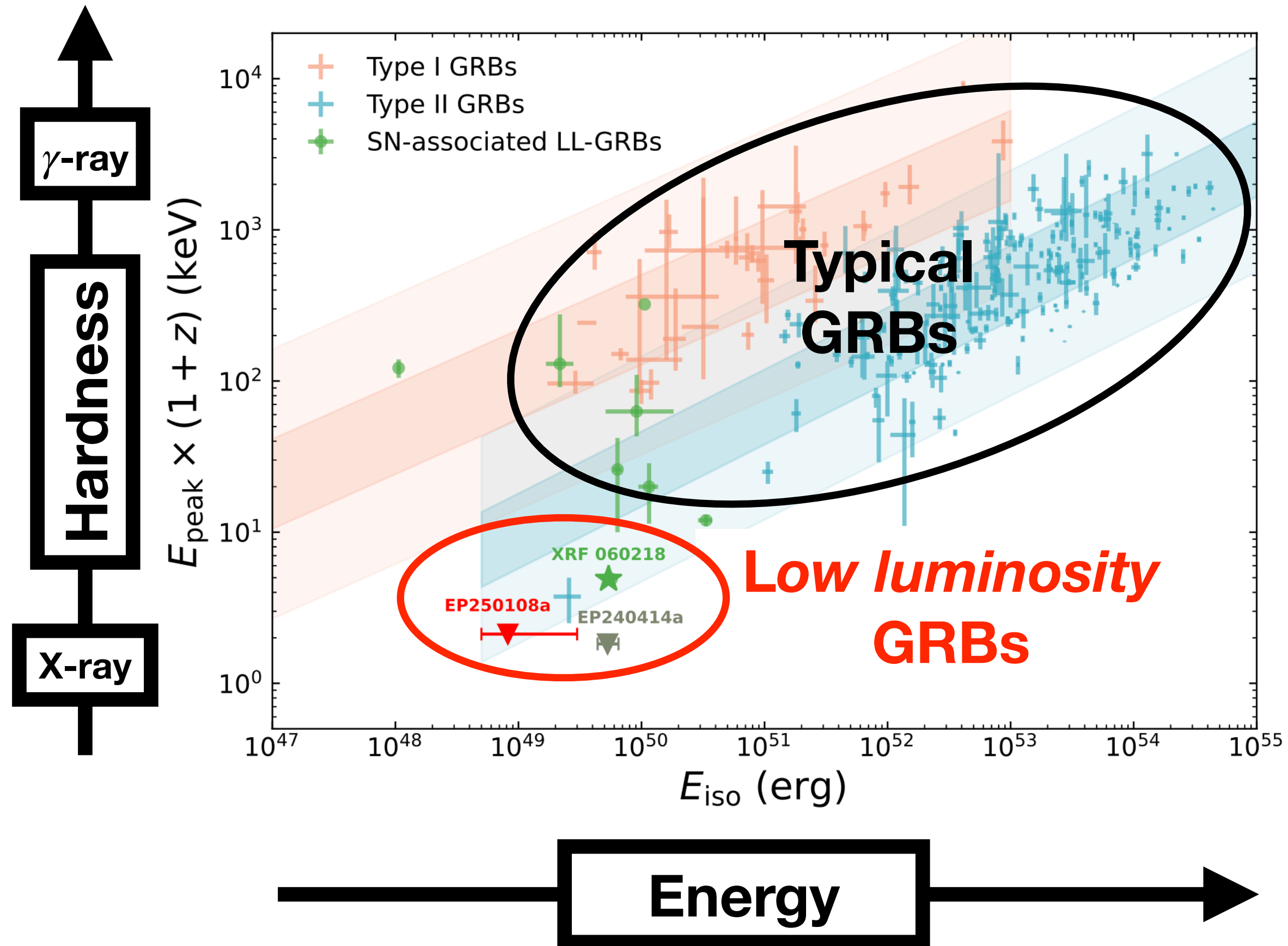
Einstein Probe 2024-



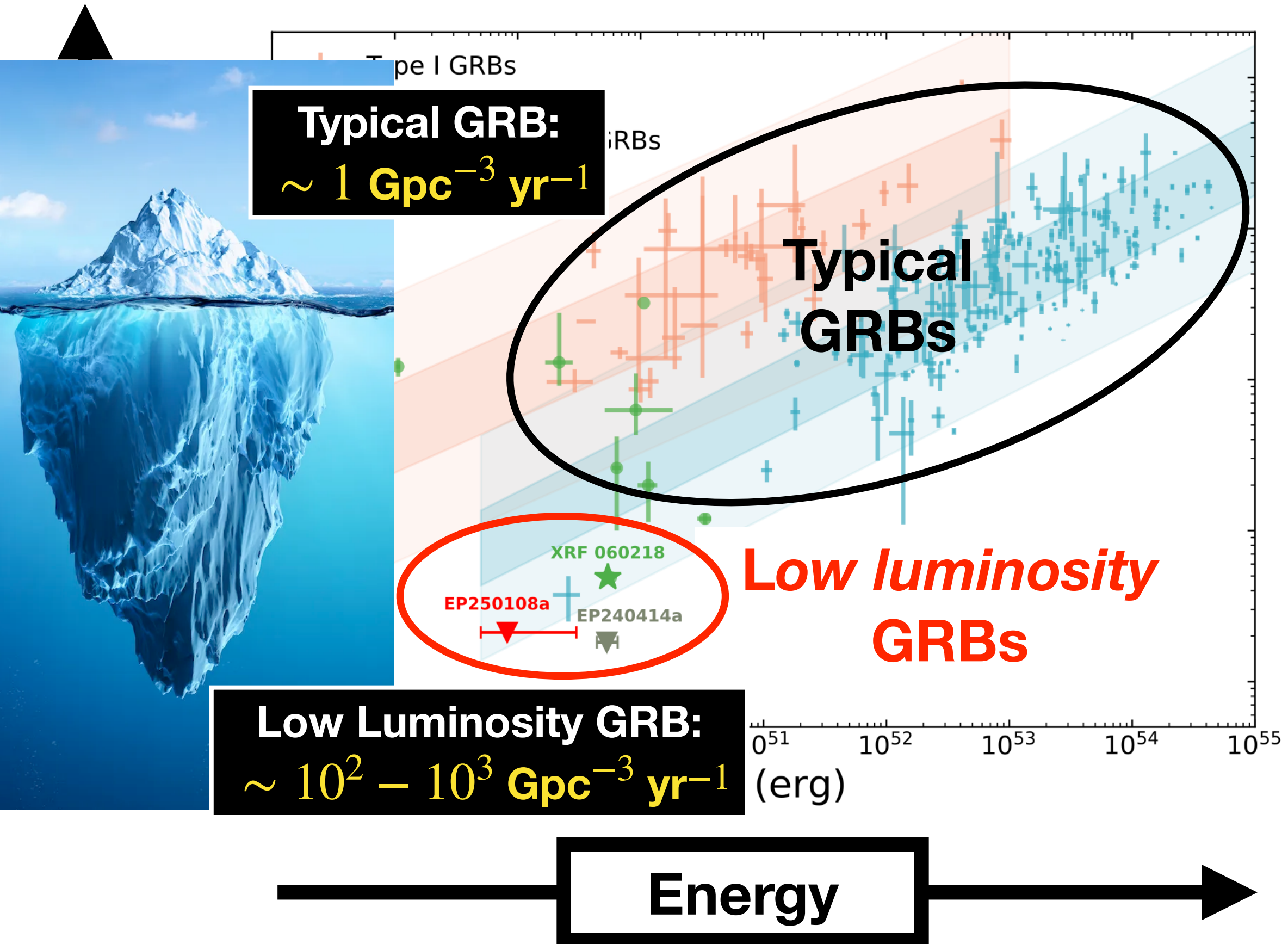
**See Arimoto-san's
Talk**

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

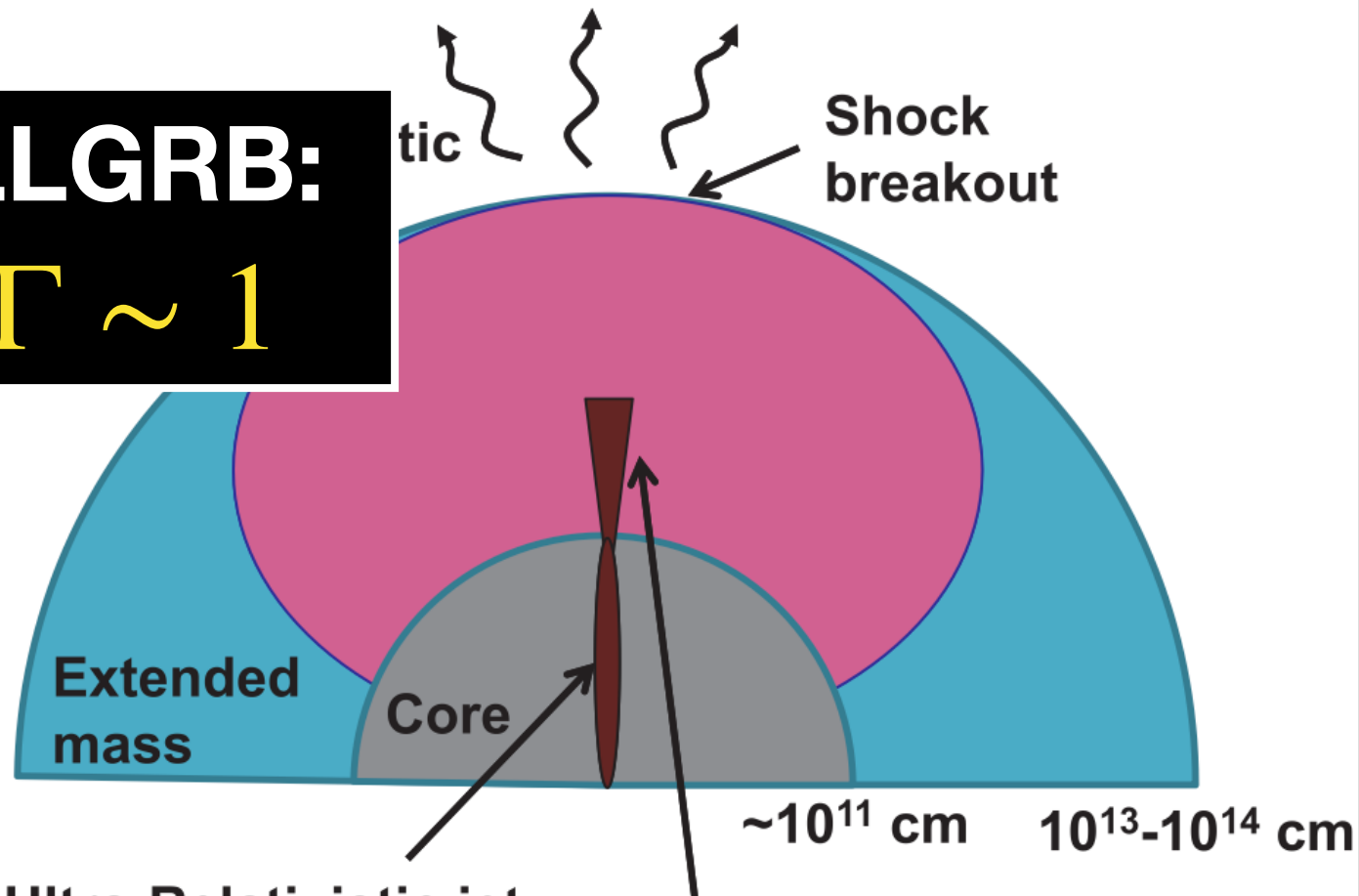
see Maeda-san's Talk

Low-Luminosity GRB

Gamma-rays/Hard X-rays
(low-luminosity, un-collimated, soft, non-variable)

LLGRB:

$$\Gamma \sim 1$$



An Ultra-Relativistic jet
Penetrates the core – choked in the extended material

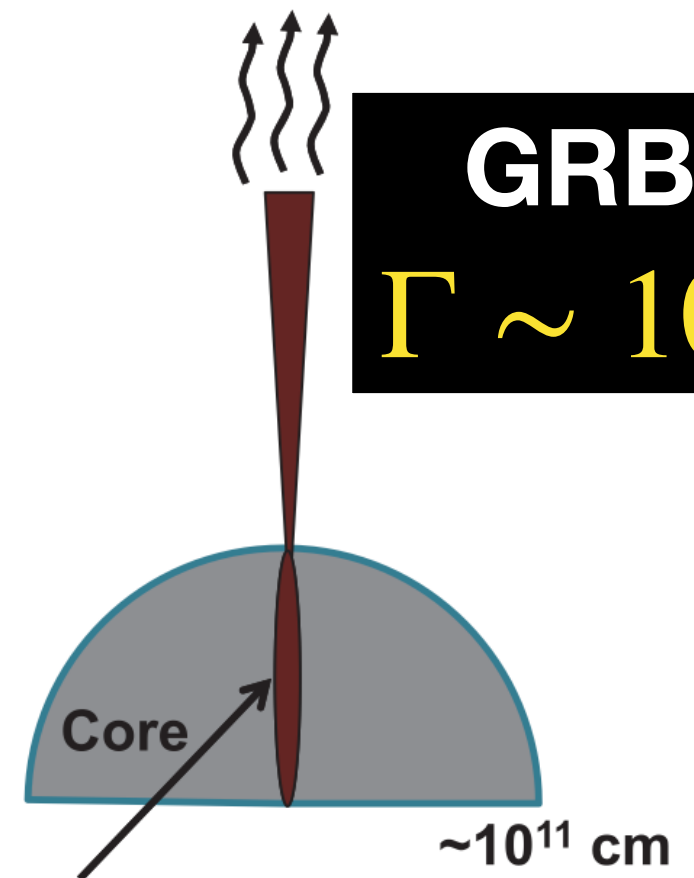
Wolf-Rayet + “CSM”

Long GRB

Gamma-rays
(luminous, collimated, hard, variable)

GRB:

$$\Gamma \sim 100$$

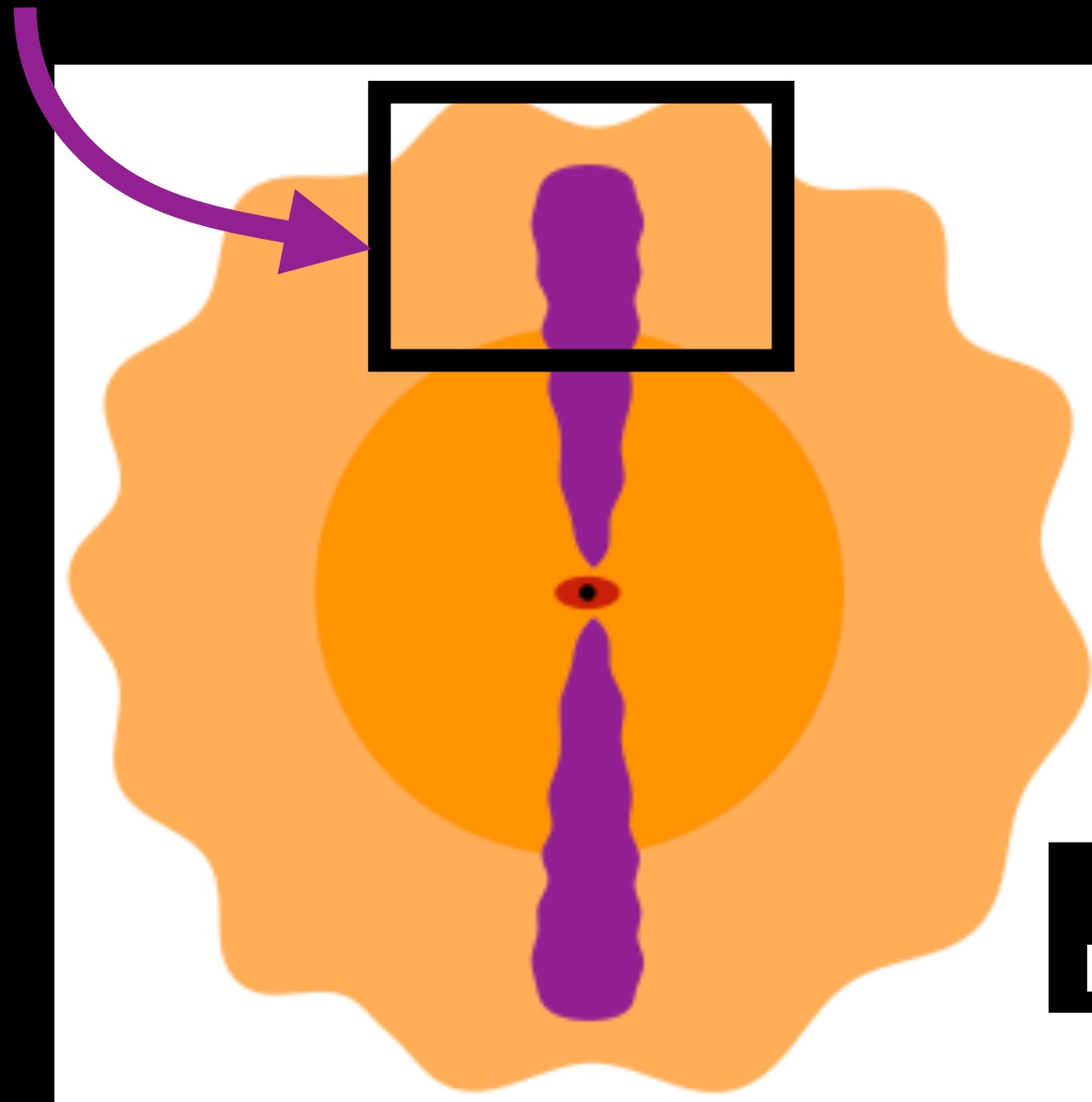


An Ultra-Relativistic jet
Penetrates the core

Wolf-Rayet

Important Point:

Understand (quantify) how the CSM affects the jet

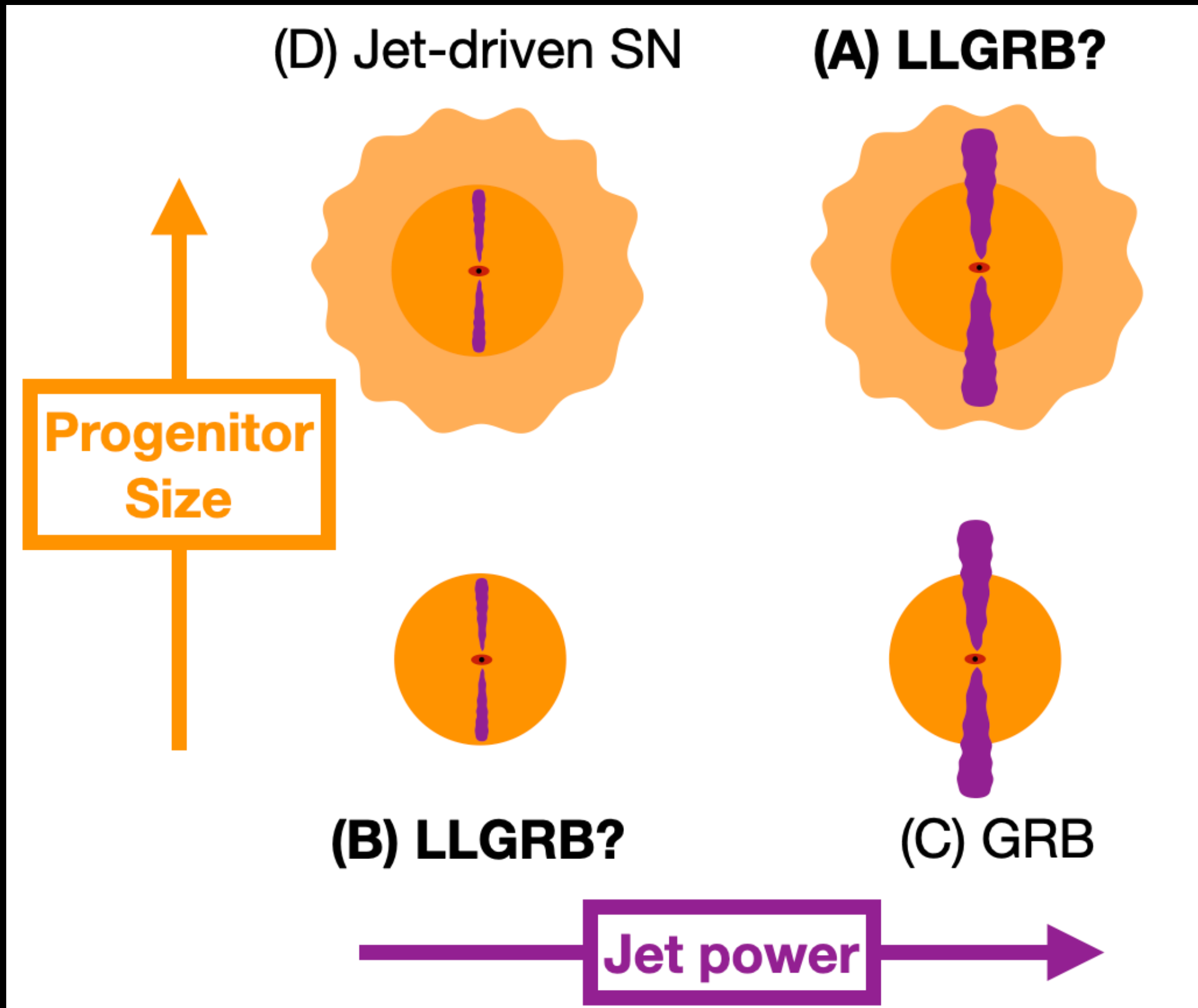


Nick's Talk
Kuze-san's Poster

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

Ultimate Goal:

What makes LLGRBs so weak?

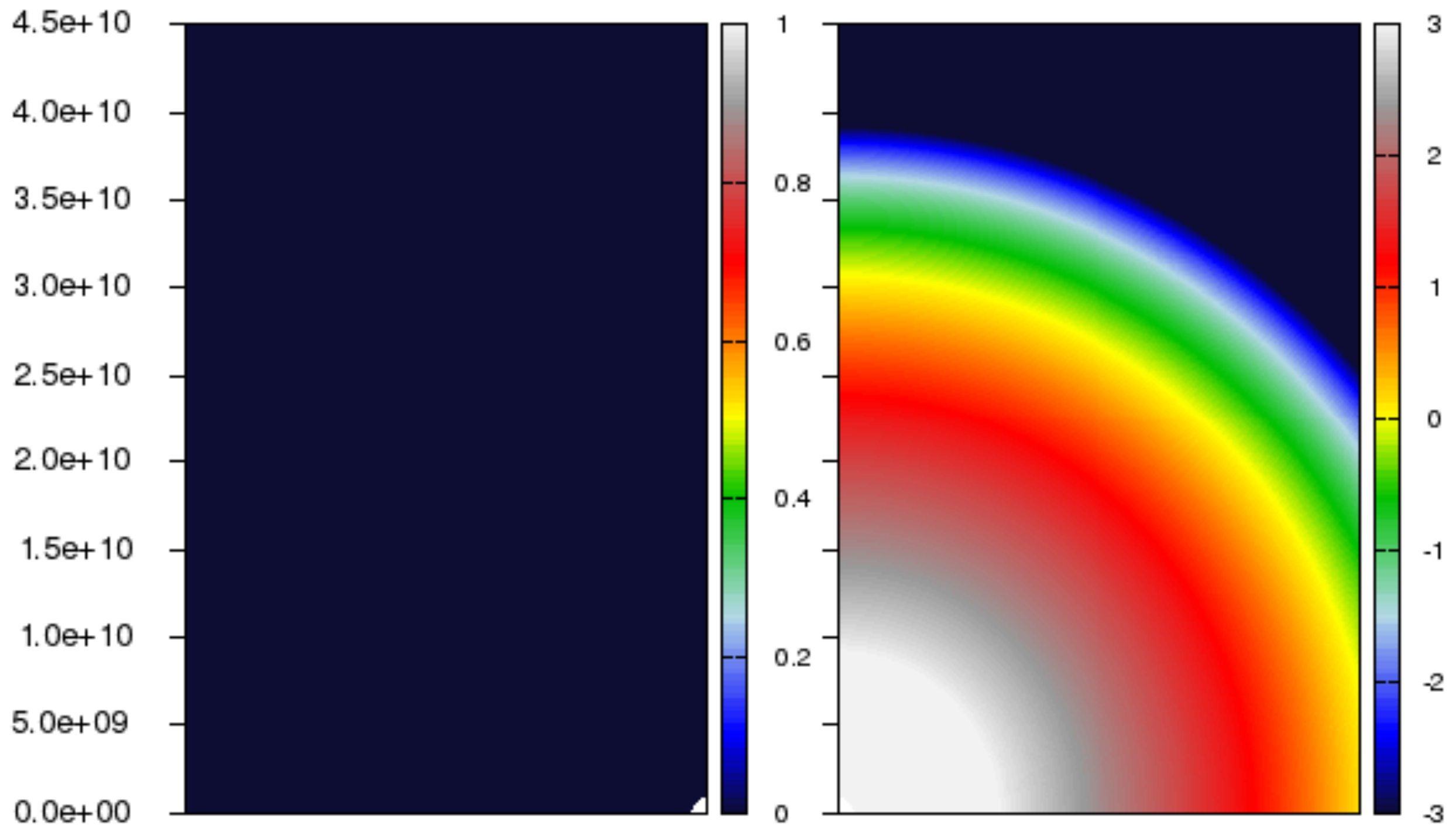


Method:
Numerical Simulations?

In massive Stars (*long* GRBs)

Wide Jet case

$$t_b - t_0 = 8.310s$$



β at $t - t_0 = 0.00$ s

$\log_{10} \rho$ at $t - t_0 = 0.00$ s

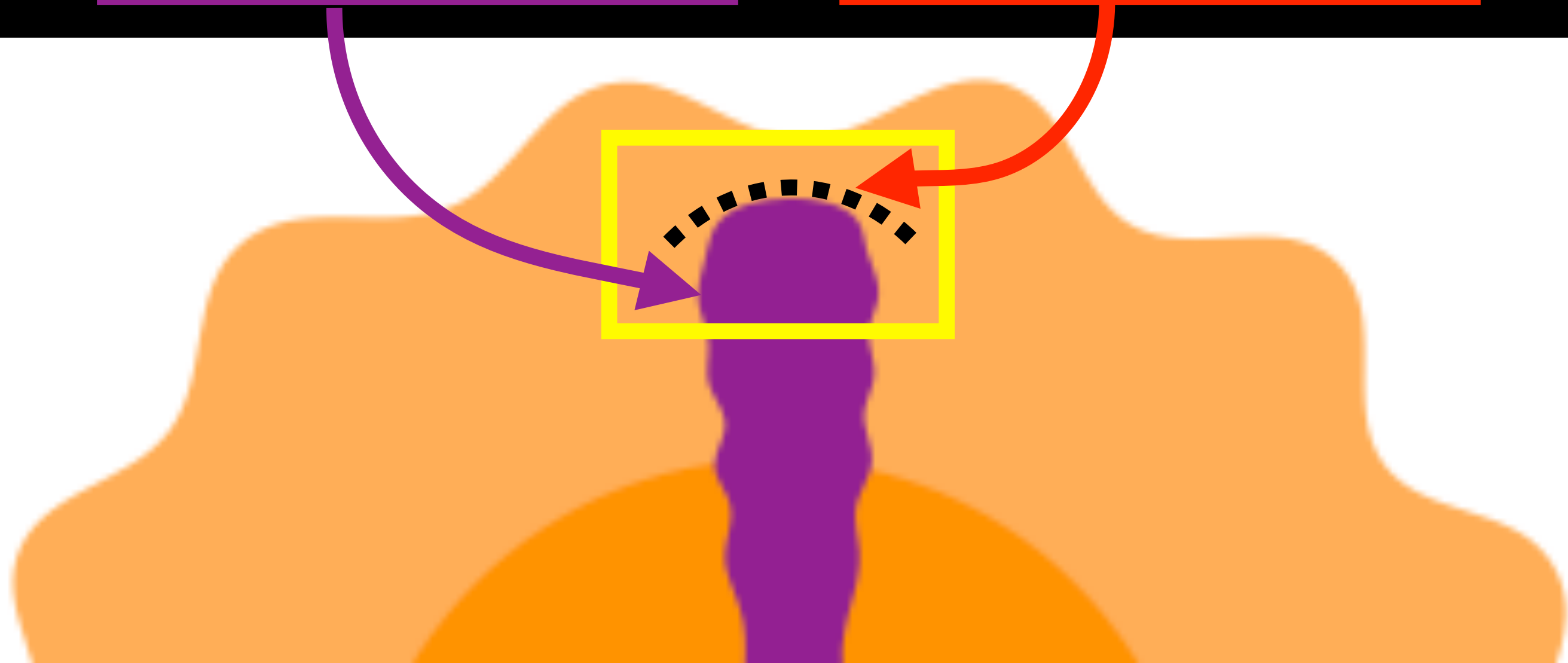
Method:

→ Analytic Modeling

Jet Dynamics

Jump conditions:

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



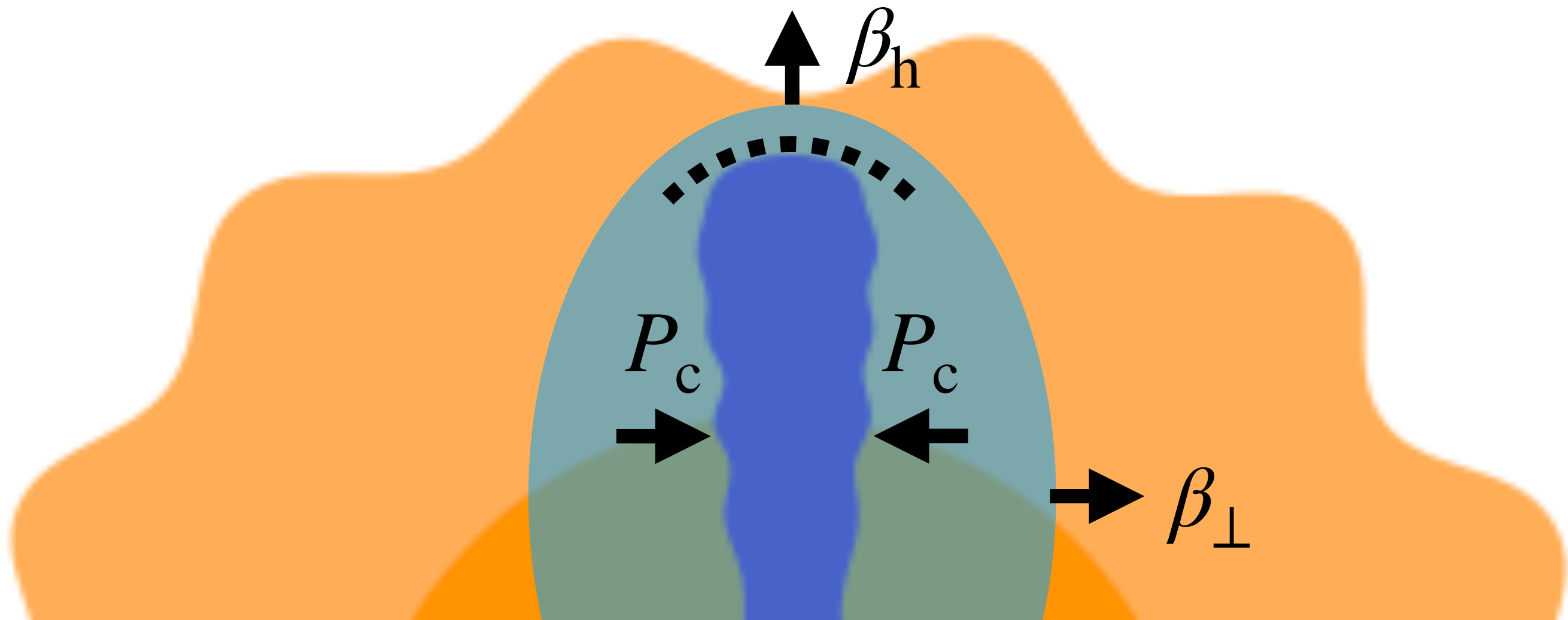
Cocoon & Collimation

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

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

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

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



Jet head velocity β_h

Following Bromberg et al. (2011):

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

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

No analytic solution!

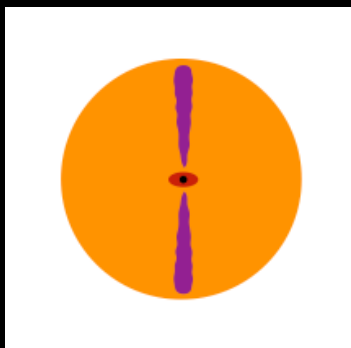
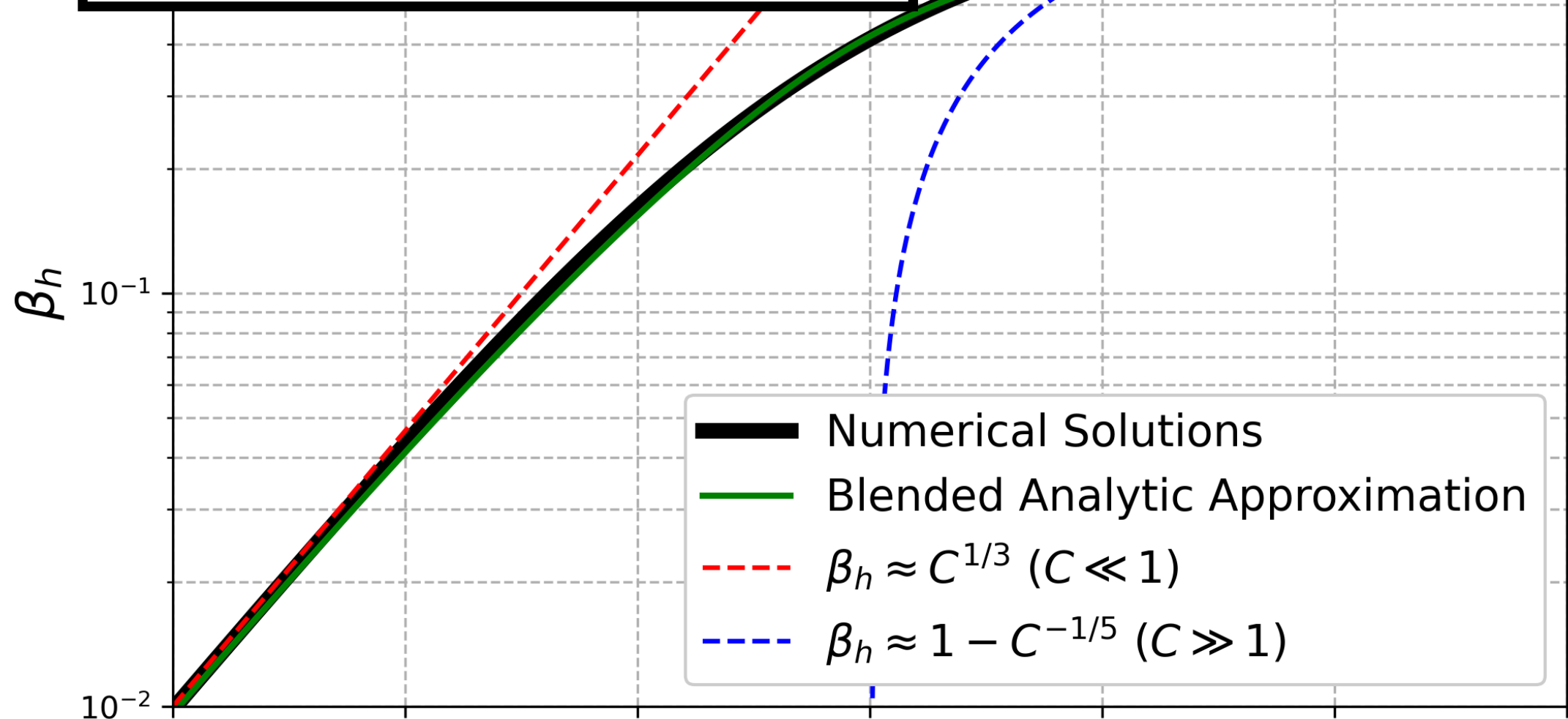
⇒ Numerically??

Universal Solution

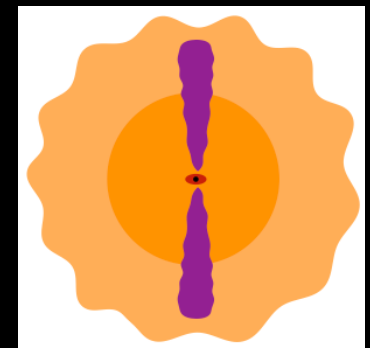
Jet head
velocity
(β_h)

Credit: HH+25

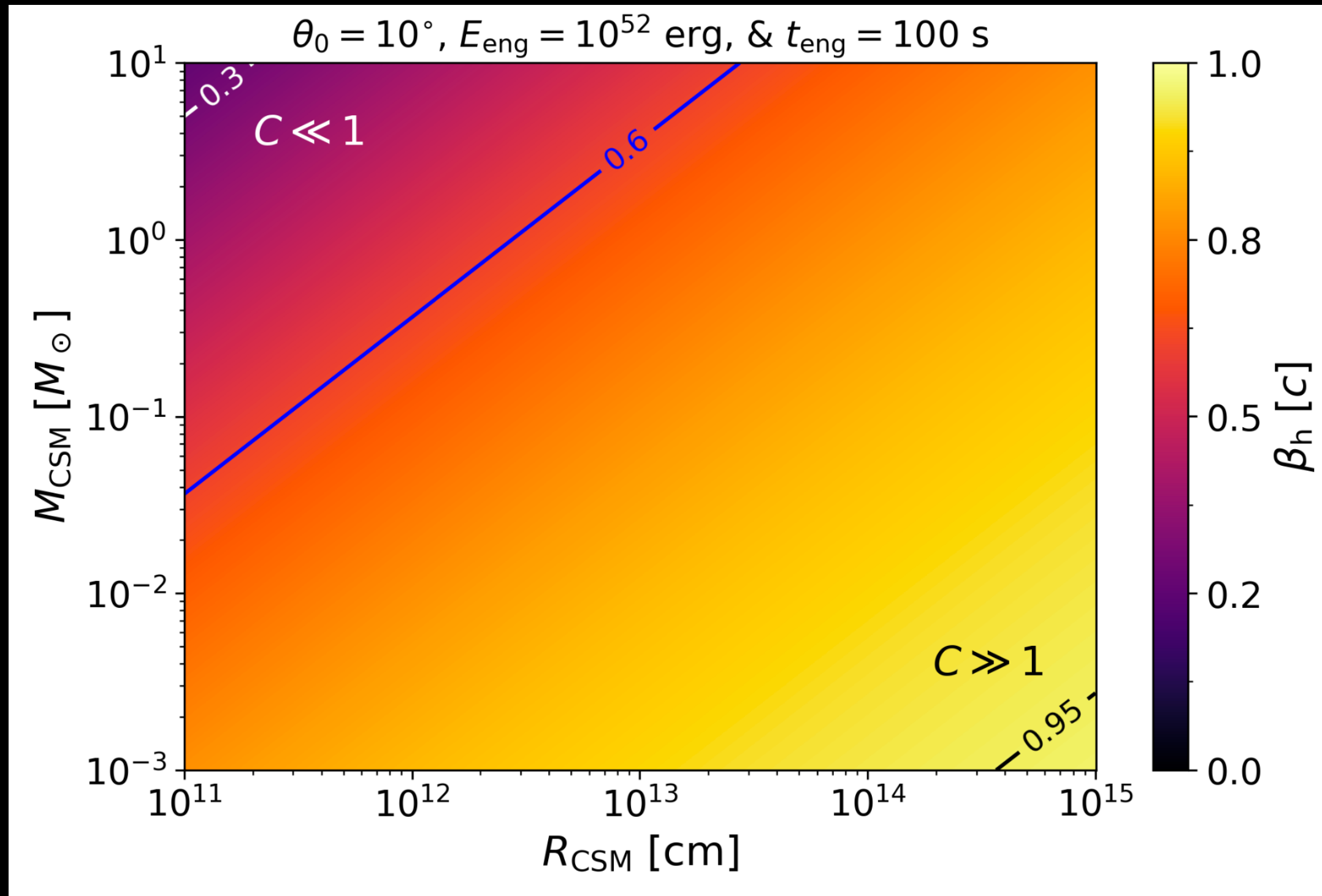
$$\beta_h \approx \frac{\left[C^{1/3} + (1 - C^{-1/5})(C/C_0)^b \right]}{1 + (C/C_t)^b}$$



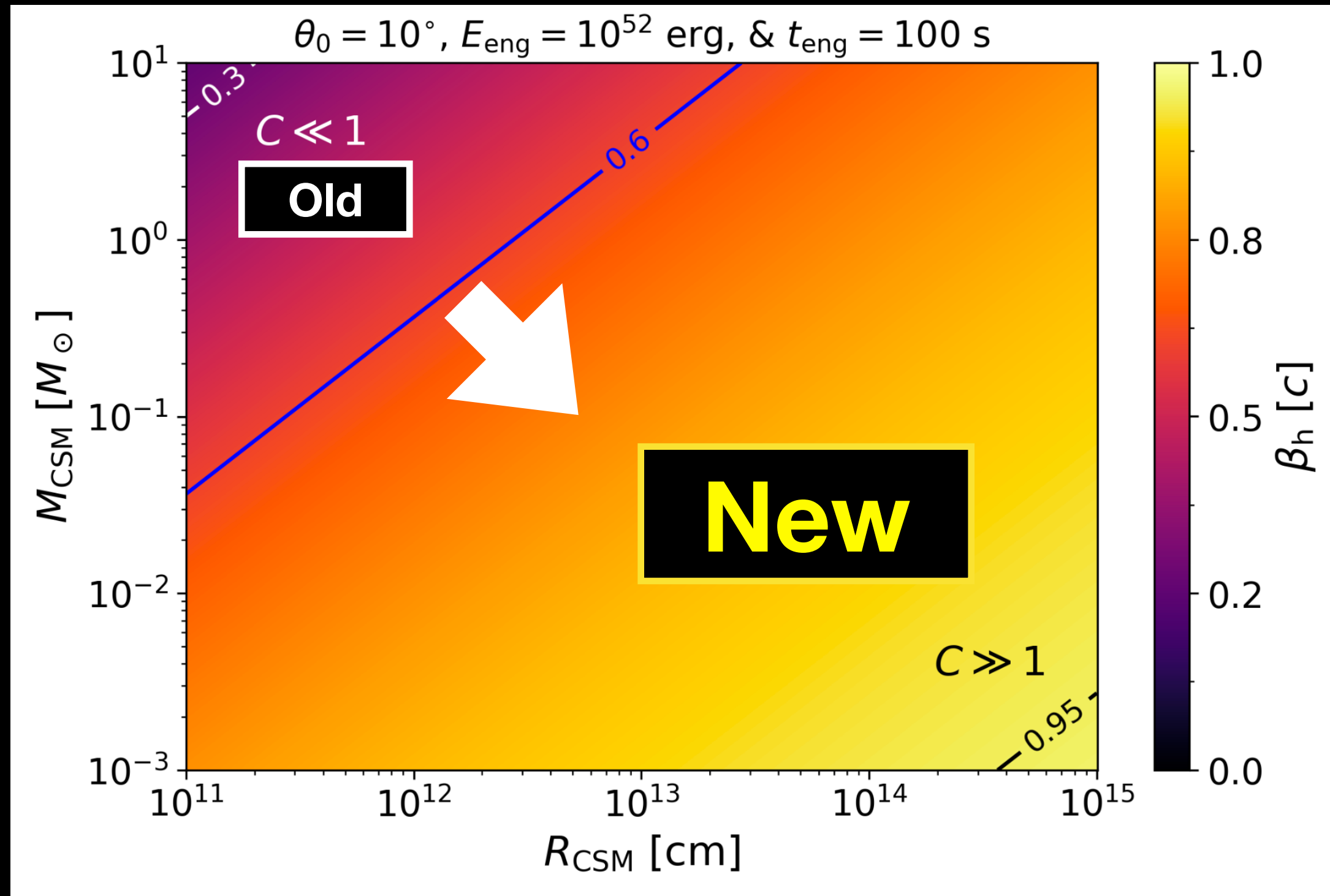
CSM presence: $C \propto \frac{E_{\text{eng}}}{t_{\text{eng}} \theta_0^2} \frac{R_{\text{CSM}}}{M_{\text{CSM}}}$



Jet head velocity quantified



Jet head velocity quantified



New Generalised Expression for the breakout time

Hamidani+25:

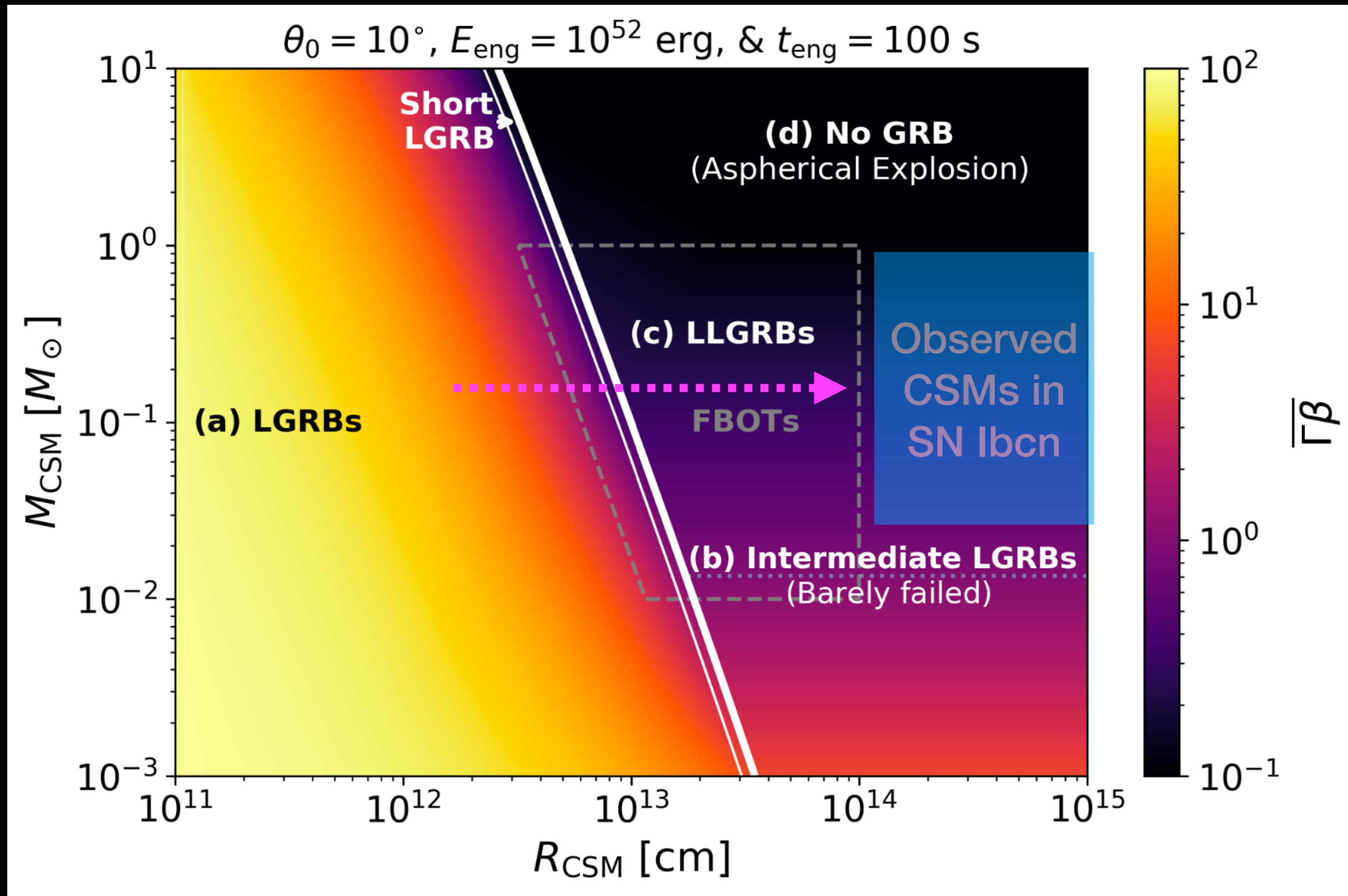
$$t_b \approx 430 \text{ s} \left(\frac{\theta_0}{10^\circ} \right)^{\frac{2}{3}} \left(\frac{E_{\text{eng}}/t_{\text{eng}}}{10^{50} \text{ erg}} \right)^{-\frac{1}{3}} \left(\frac{R_{\text{CSM}}}{10^{13} \text{ cm}} \right)^{\frac{2}{3}} \left(\frac{M_{\text{CSM}}}{0.1 M_\odot} \right)^{\frac{1}{3}}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

**Important
for $\beta \lesssim 1$**

Bromberg+12:

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

Diversity of transients

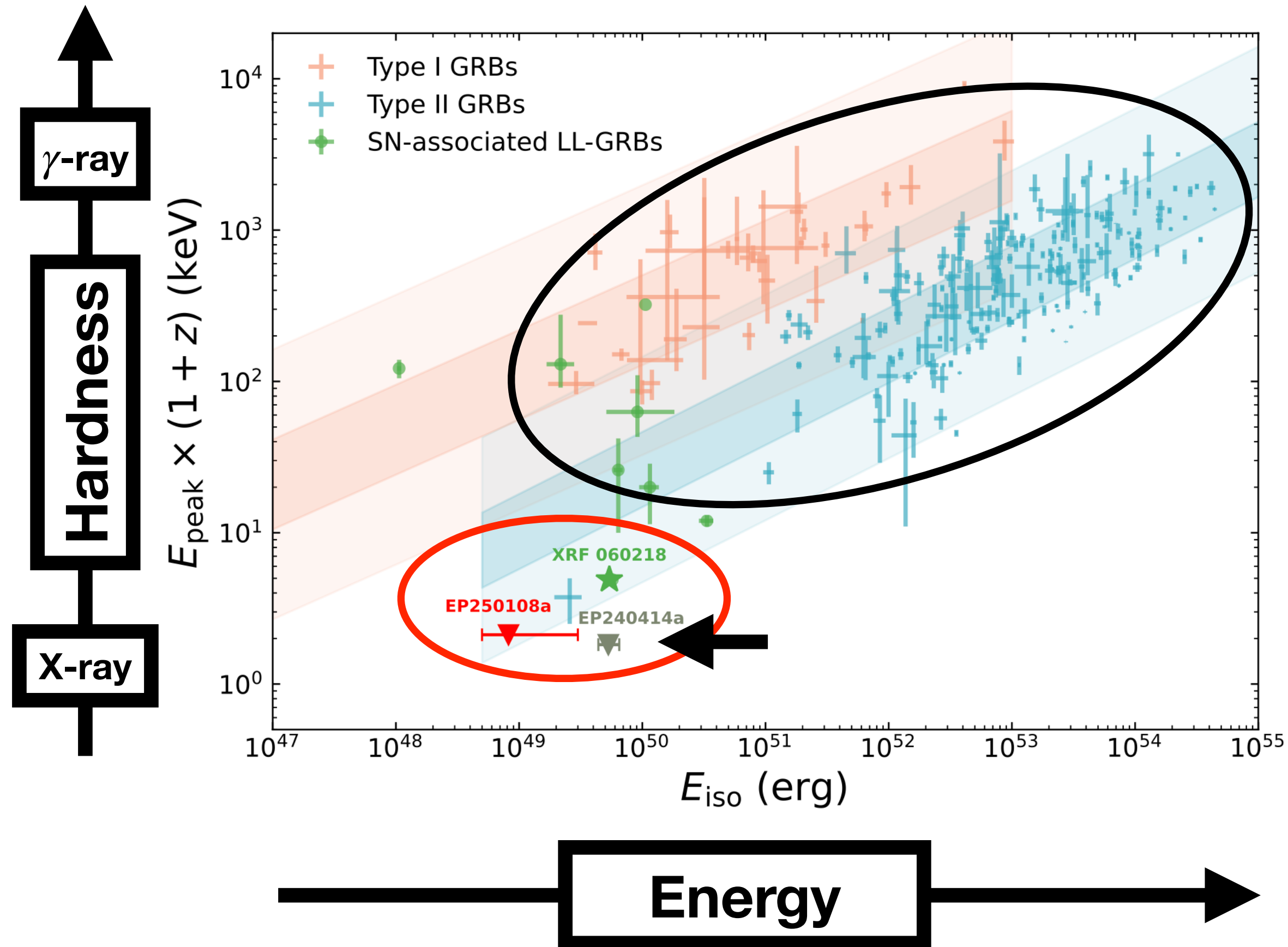


Interpretation of Recent EP Events

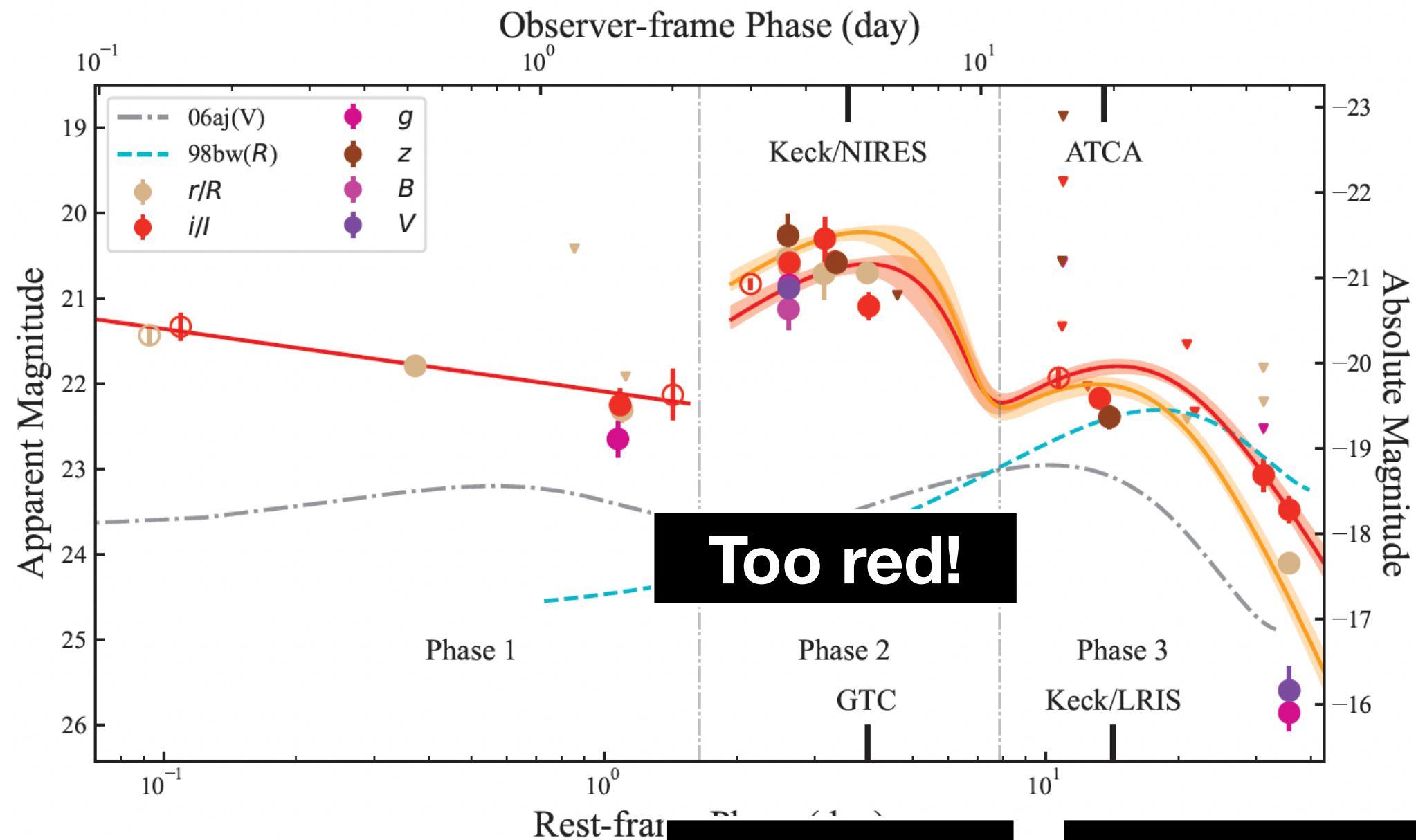


CREDIT: EP

Updated [with EP]



EP240414a [Unique transient]

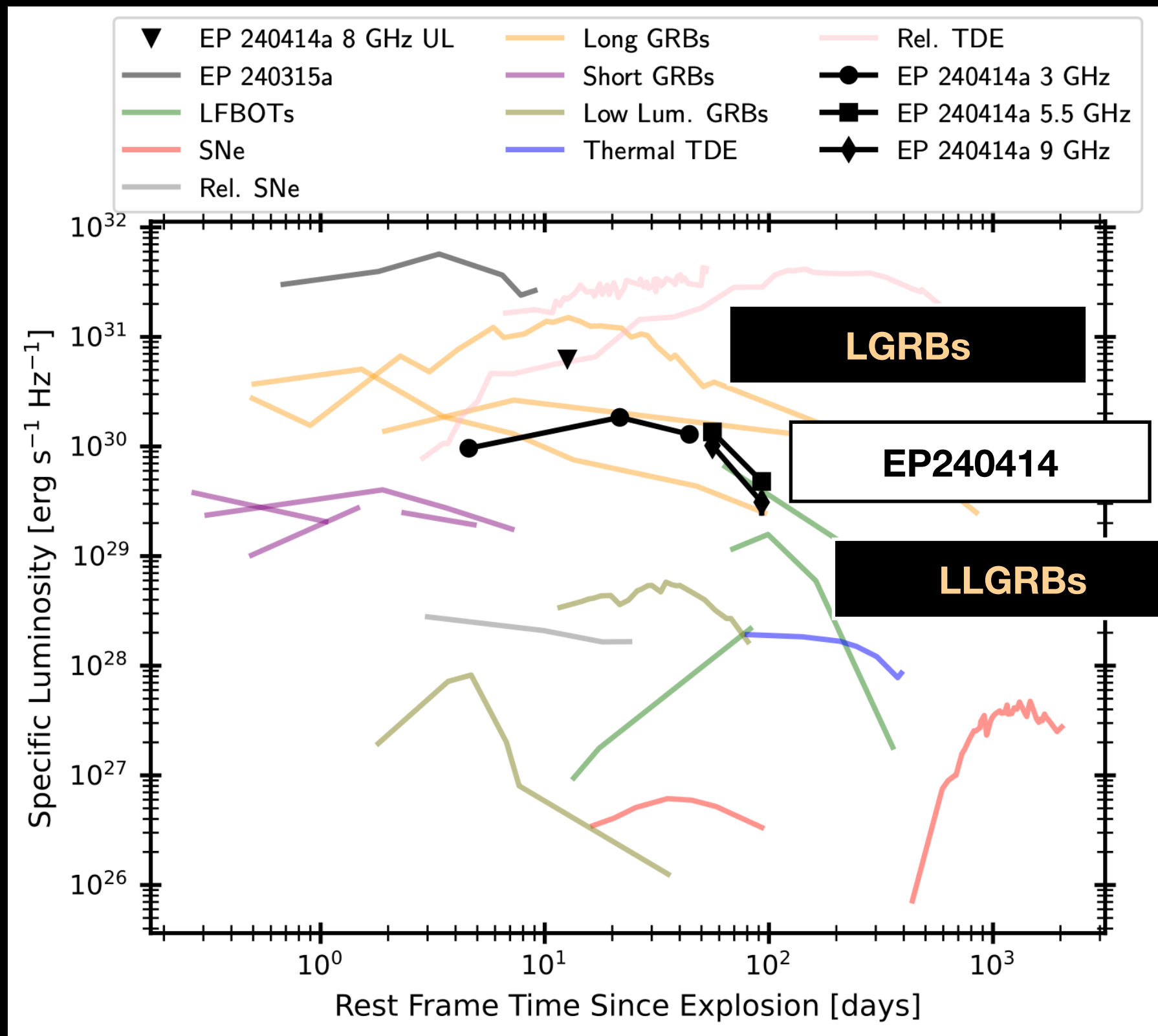


Phase 1:
thermal?

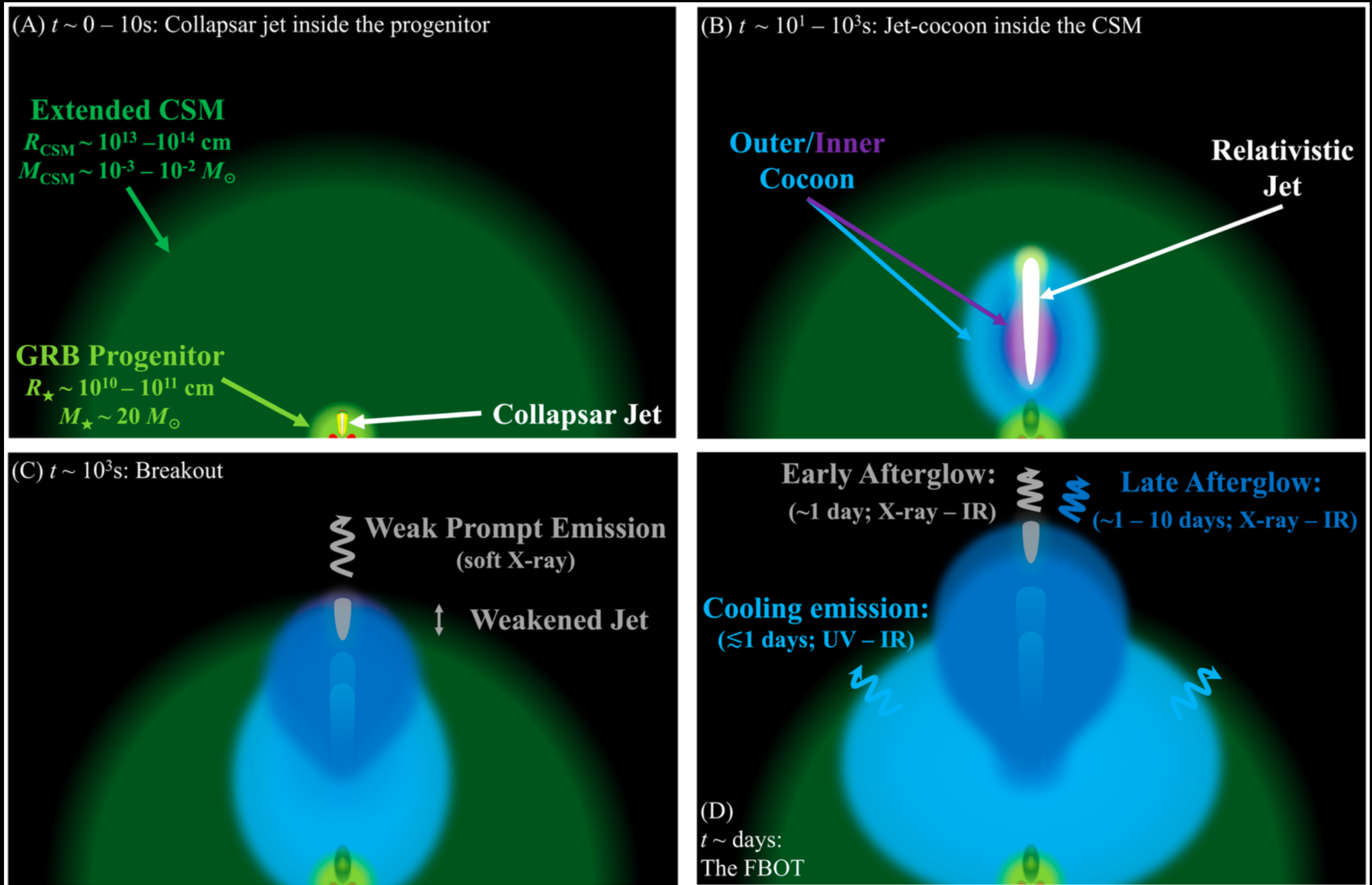
Phase 2:
non-thermal?

Phase 3:
Ic-BL SN (Ni56)

Radio [EP240414a]



Scenario for EP240414a

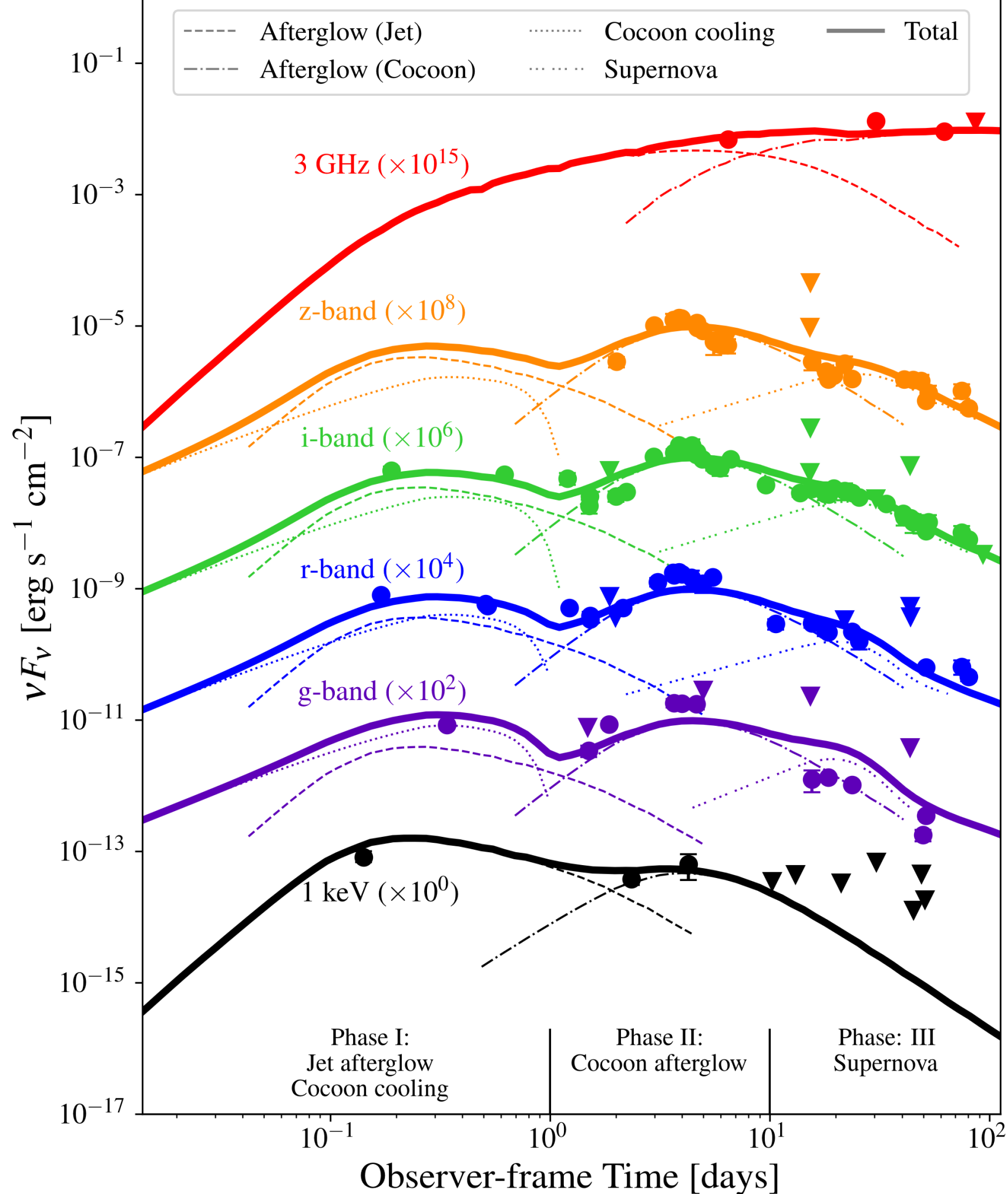


Results

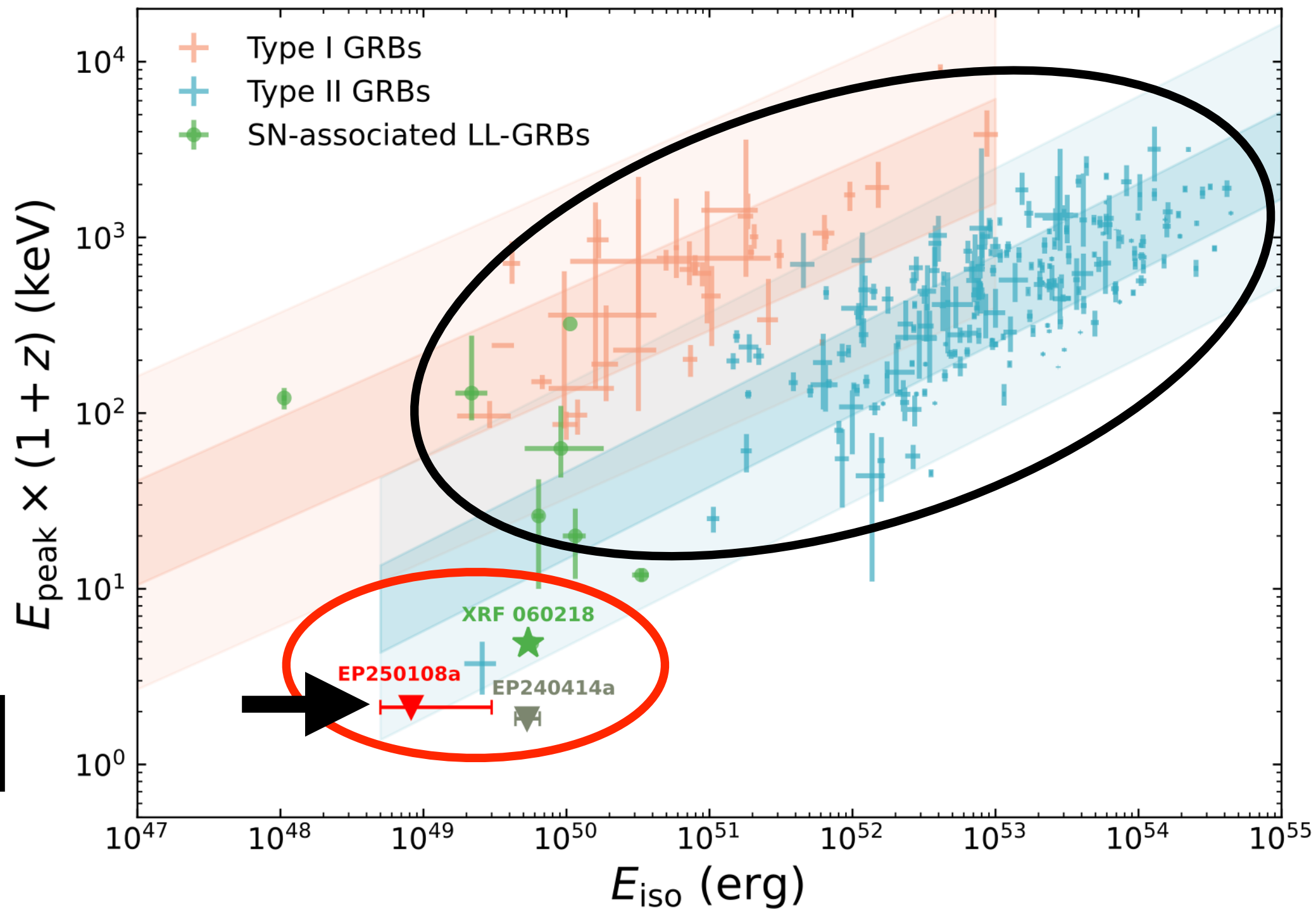
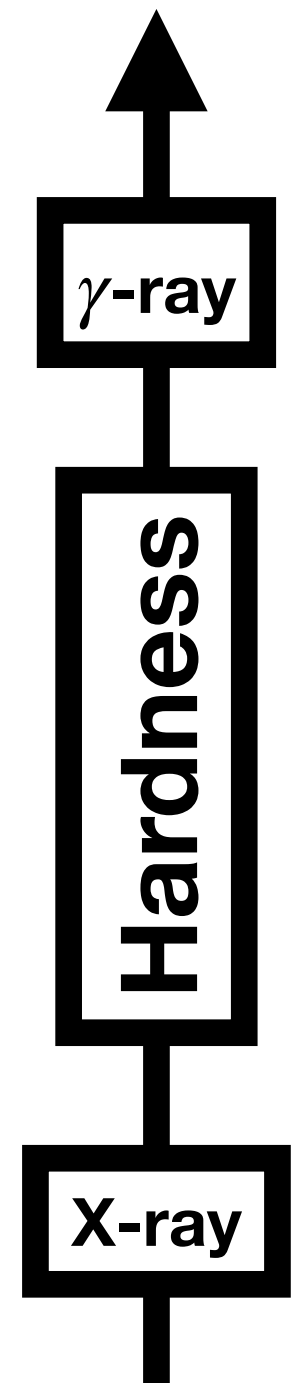
[EP240414a]

CSM:
 $\sim 0.03 M_{\odot}$
 $3 \times 10^{13} \text{ cm}$

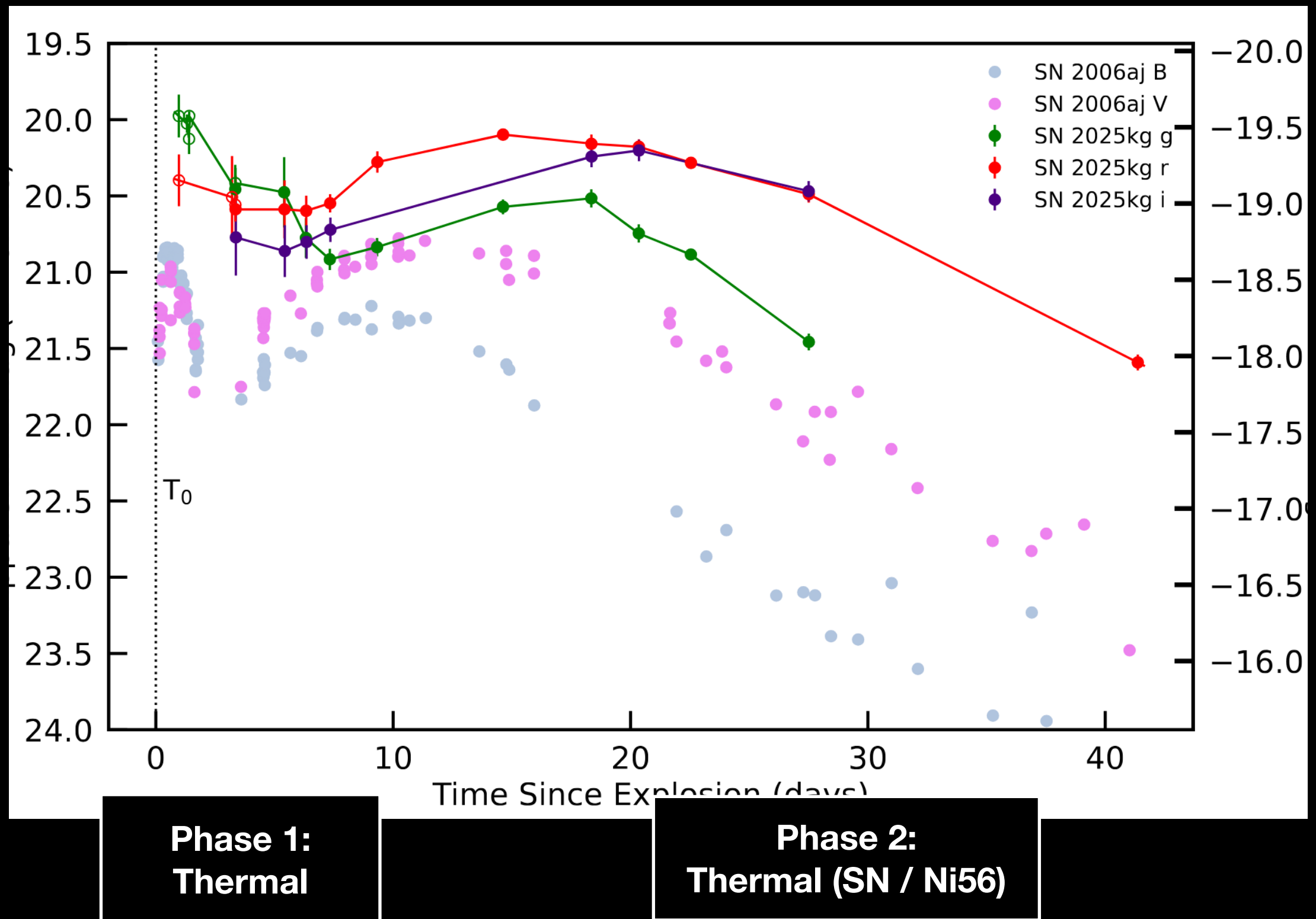
Jet:
 Conventional



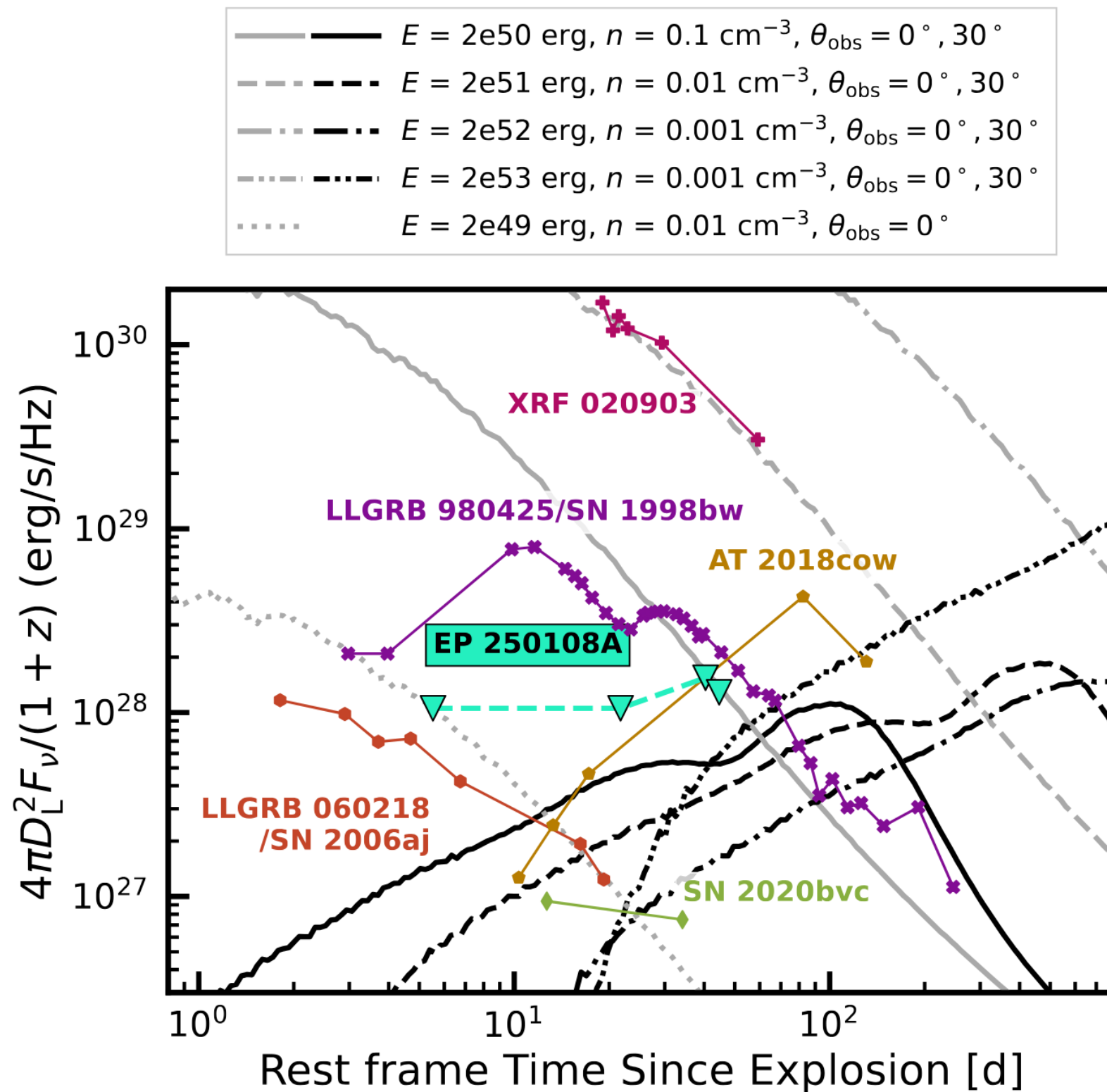
Updated [with EP]



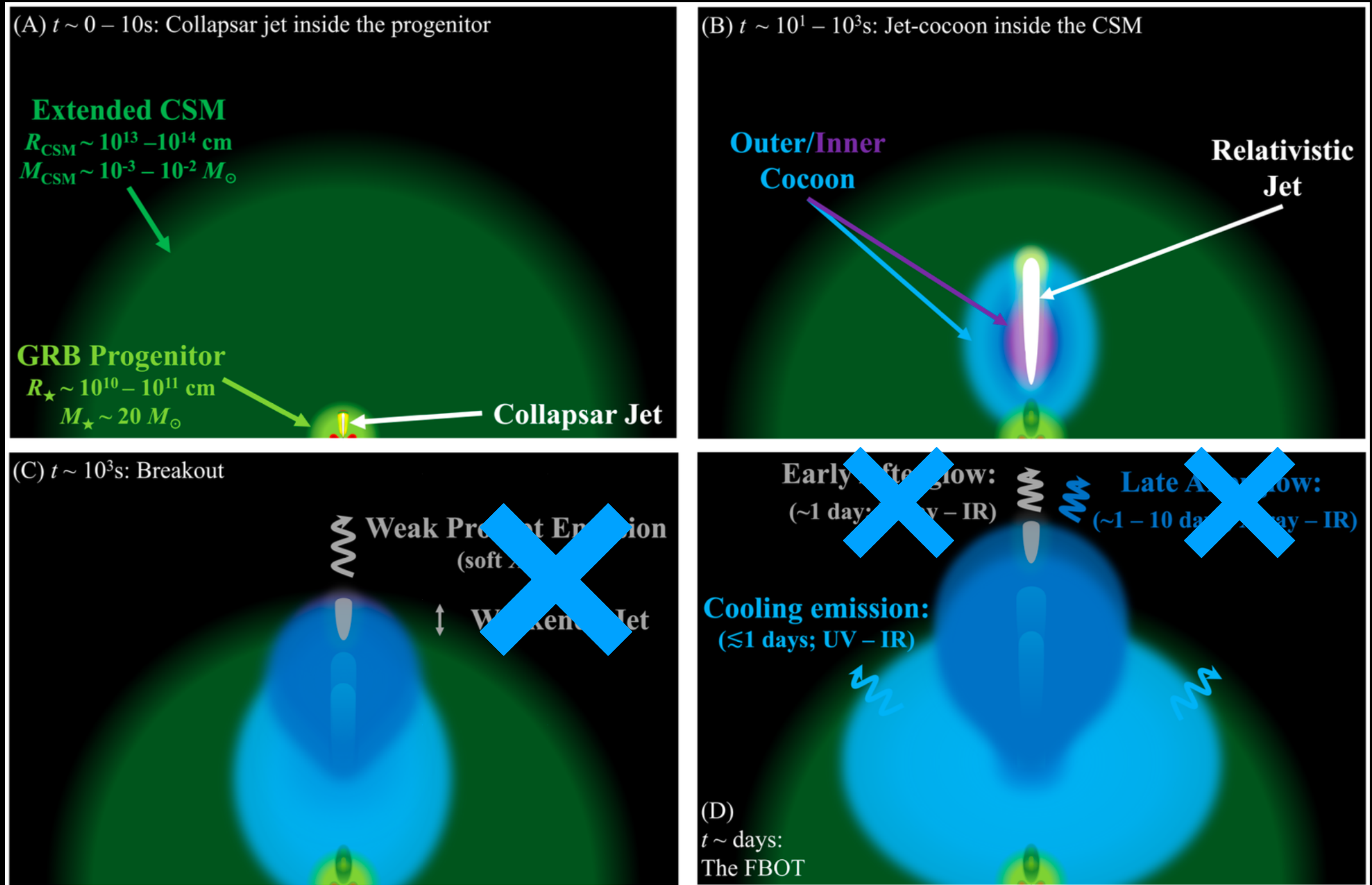
EP250108a [LLGRB+FBOT]



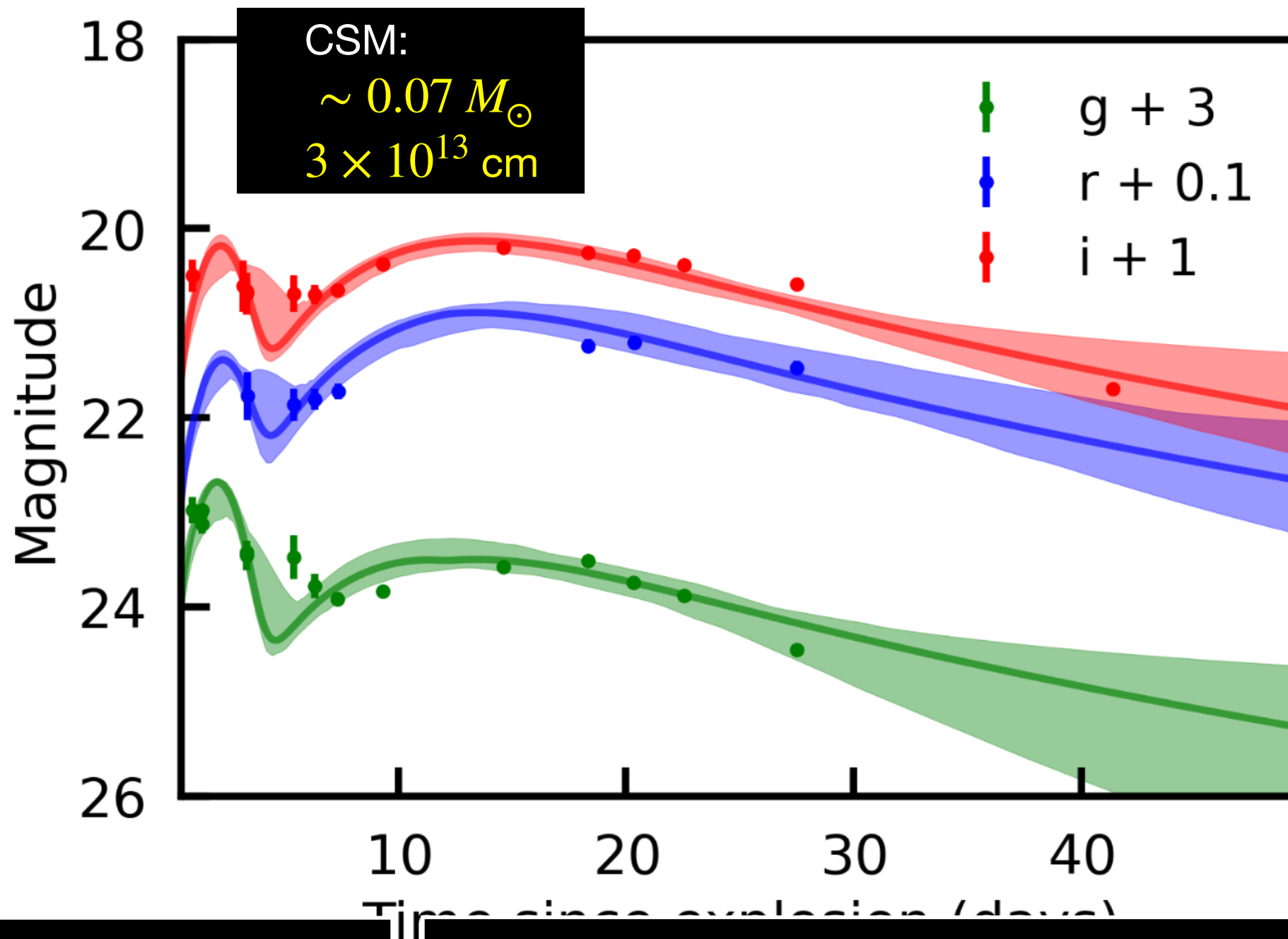
EP250108a [No afterglow]



Our scenario for EP250108a



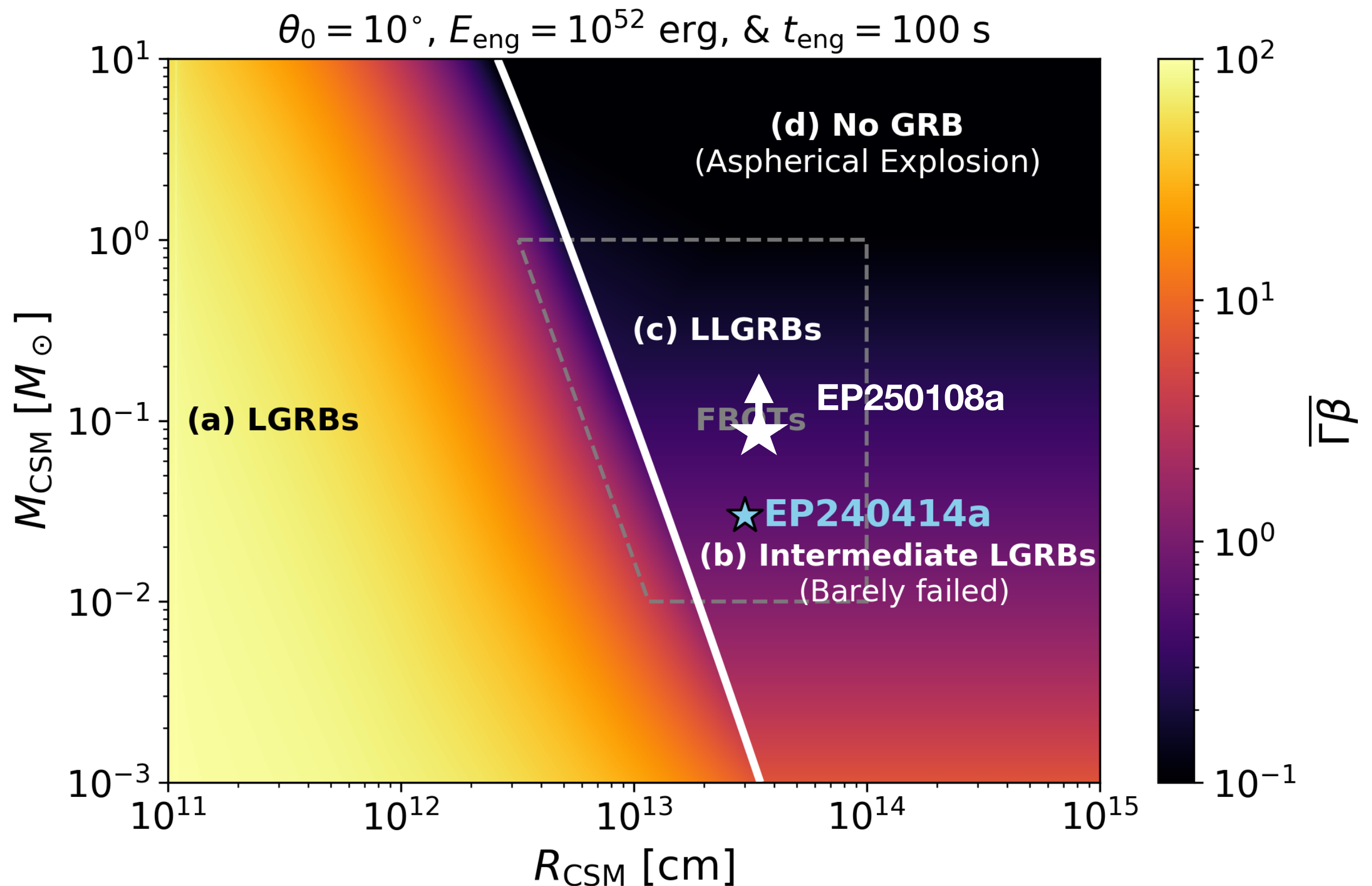
EP250108a [LLGRB+FBOT]



Phase 1:
FBOT (thermal)

Phase 2:
Ic-BL SN (Ni56)

EP240414a & EP250108a



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 $\sim 0.03M_{\odot}$ and $\sim 3 \times 10^{13}$ cm

