

GRB Jets in CSM **& Recent EP Events**

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With:

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References:

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

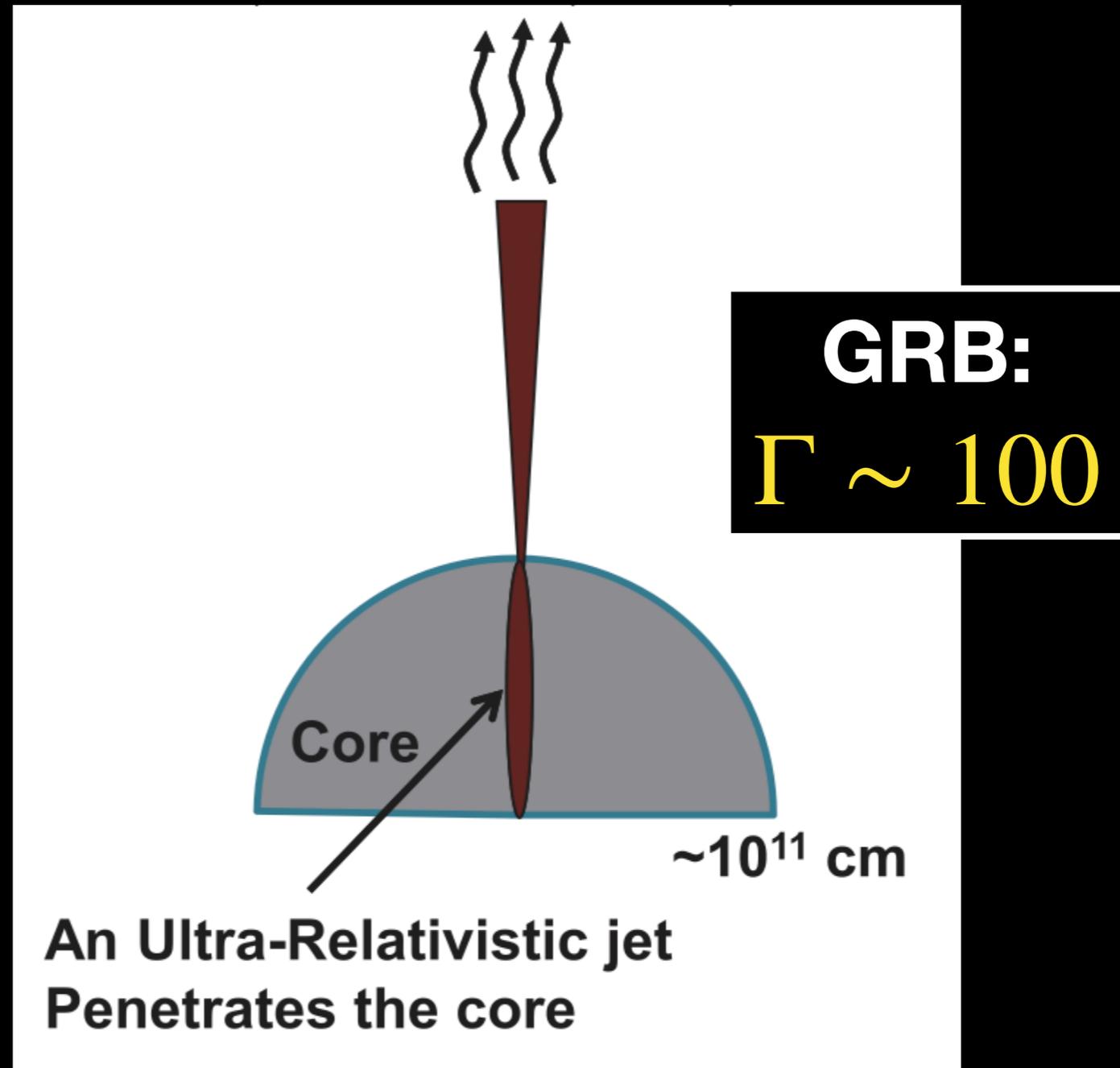
<https://arxiv.org/abs/2503.16243>

<https://arxiv.org/abs/2504.17516>

YITP long-term workshop
January 26 - February 27, 2026 YITP, Kyoto University

Collapsar Scenario

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



Credit: Nakar 15

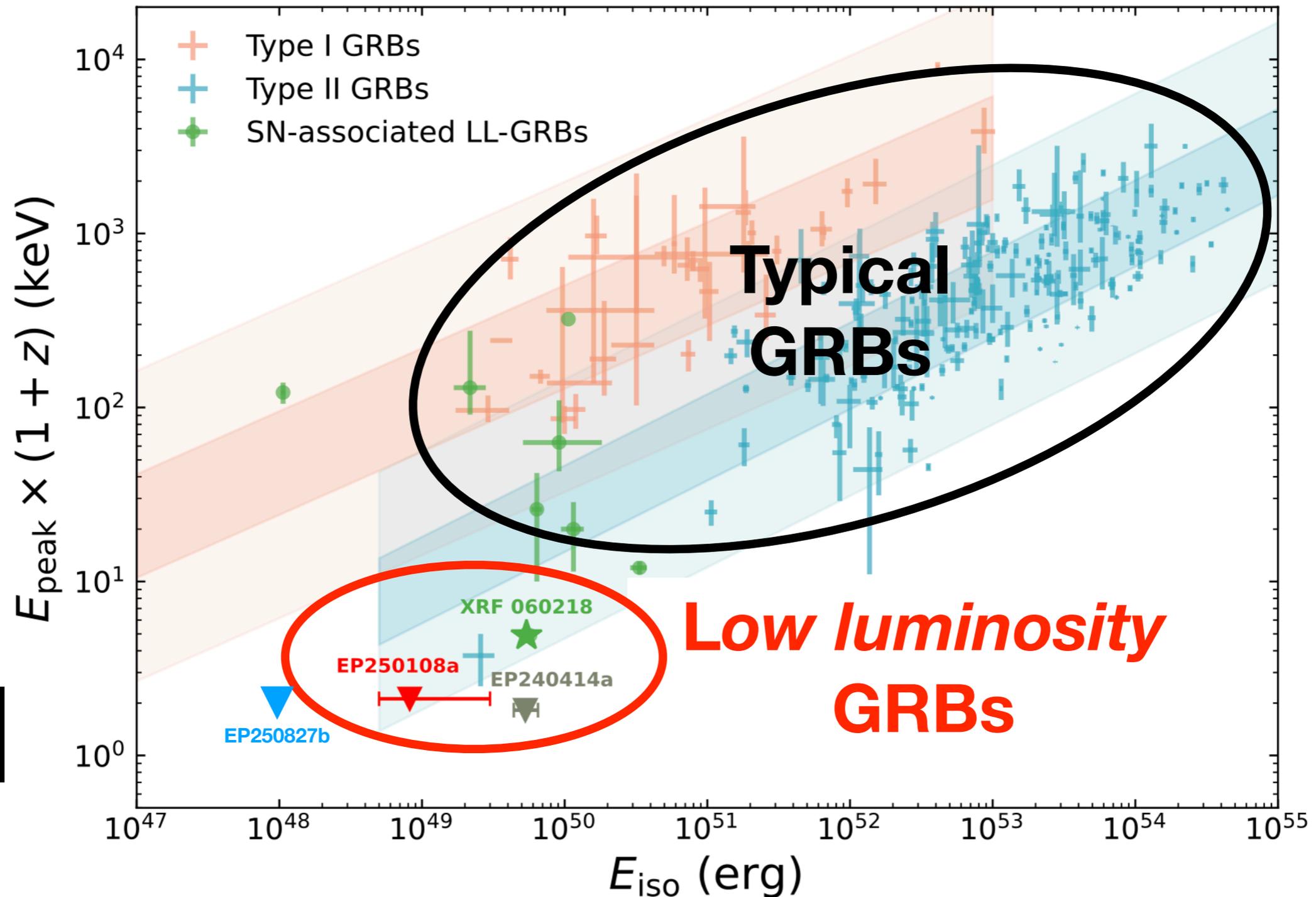
Key point: **We need a stripped/compact Wolf-Rayet Star!**

Credit: MacFadyen+99

Einstein Probe 2024-



Updated [with EP]

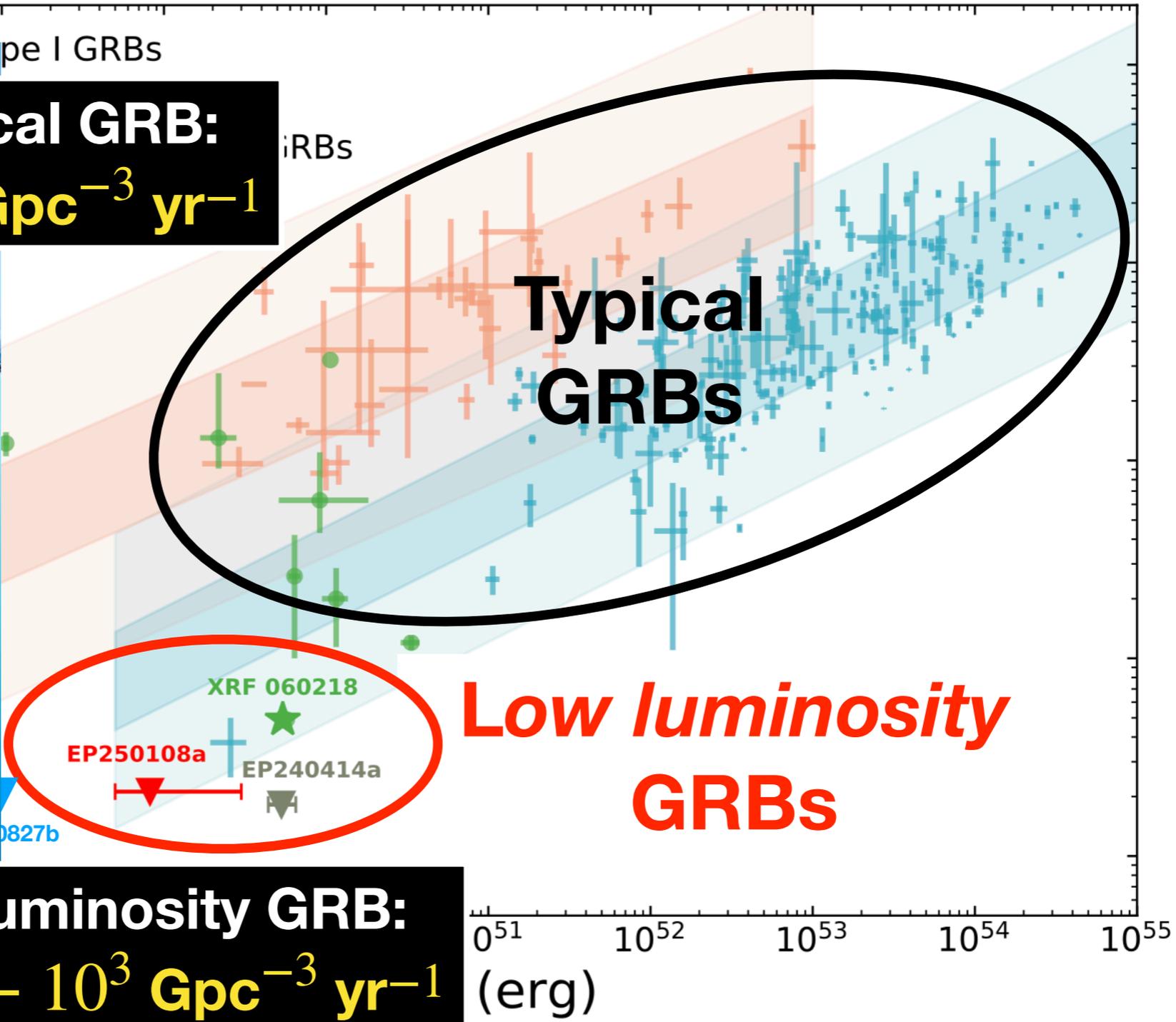


Updated [with EP]



Typical GRB:
 $\sim 1 \text{ Gpc}^{-3} \text{ yr}^{-1}$

Low Luminosity GRB:
 $\sim 10^2 - 10^3 \text{ Gpc}^{-3} \text{ yr}^{-1}$



Typical GRBs

Low luminosity GRBs



Obs. Driven Motivation:

More obs. of weak/LL GRBs

→ **We need to revisit LLGRBs**

Model: Star + “CSM”

Credit: Nakar 15

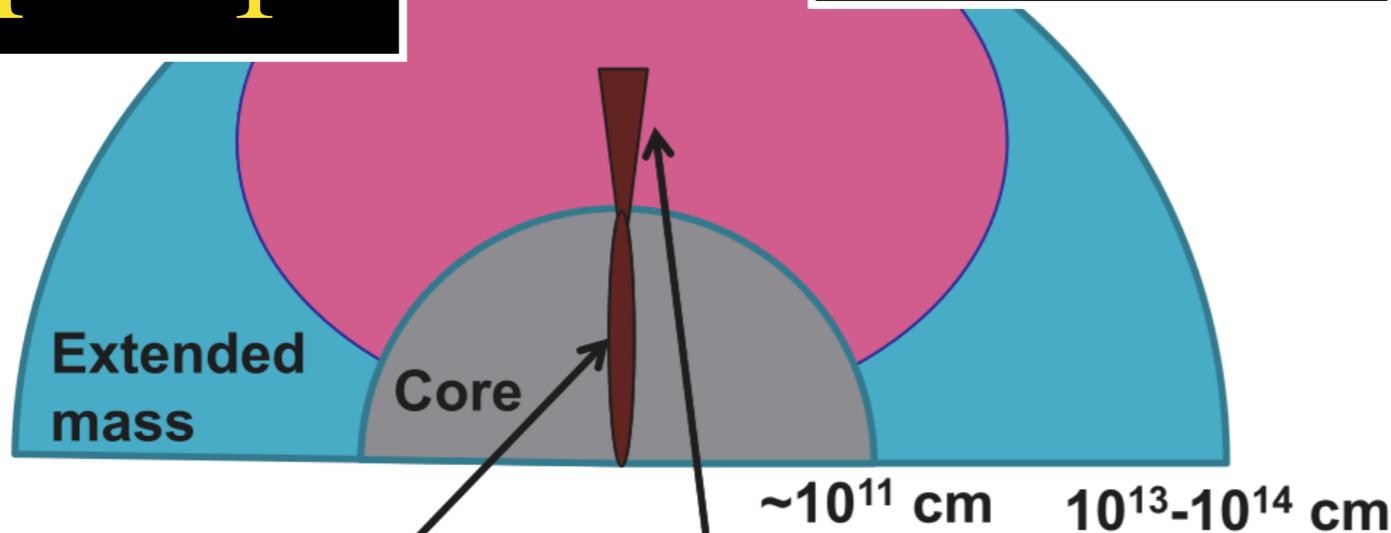
Low-Luminosity GRB

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

LLGRB:

$\Gamma \sim 1$

Shock breakout
see Chris' Talk



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

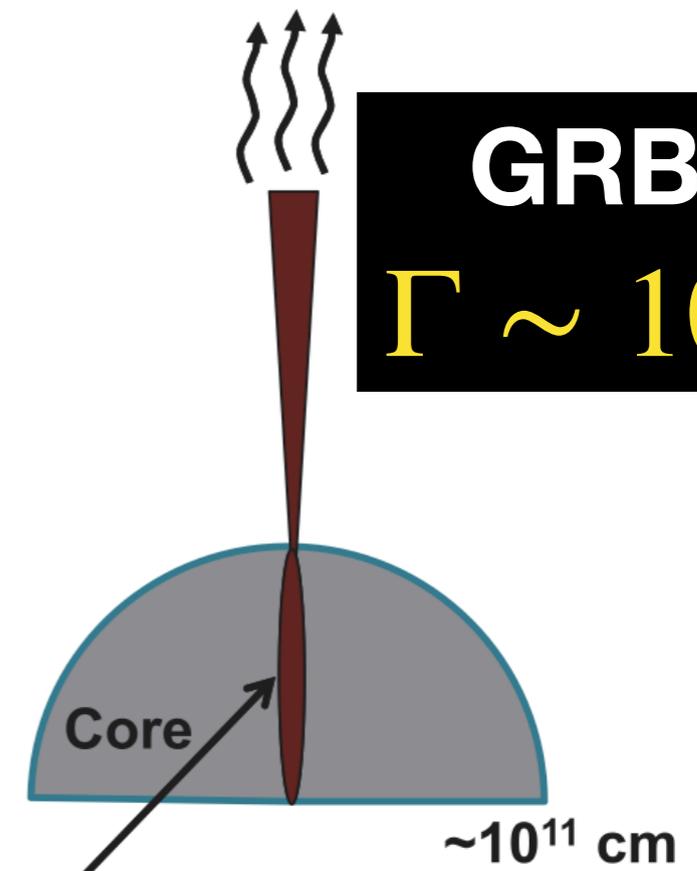
Wolf-Rayet + “CSM”

Long GRB

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

GRB:

$\Gamma \sim 100$



An Ultra-Relativistic jet
Penetrates the core

Wolf-Rayet

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*

CrossMark

Hanindyo Kuncarayakti^{1,2} , Keiichi Maeda^{3,4}, Christopher J. Ashall^{5,6}, Simon J. Prentice⁵ , Seppo Mattila² , Erkki Kankare⁷ ,
Claes Fransson⁸ , Peter Lundqvist⁸ , Andrea Pastorello⁹, Giorgos Leloudas¹⁰ , Joseph P. Anderson¹¹ , Stefano Benetti⁹,

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

Peter Clark¹ , 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

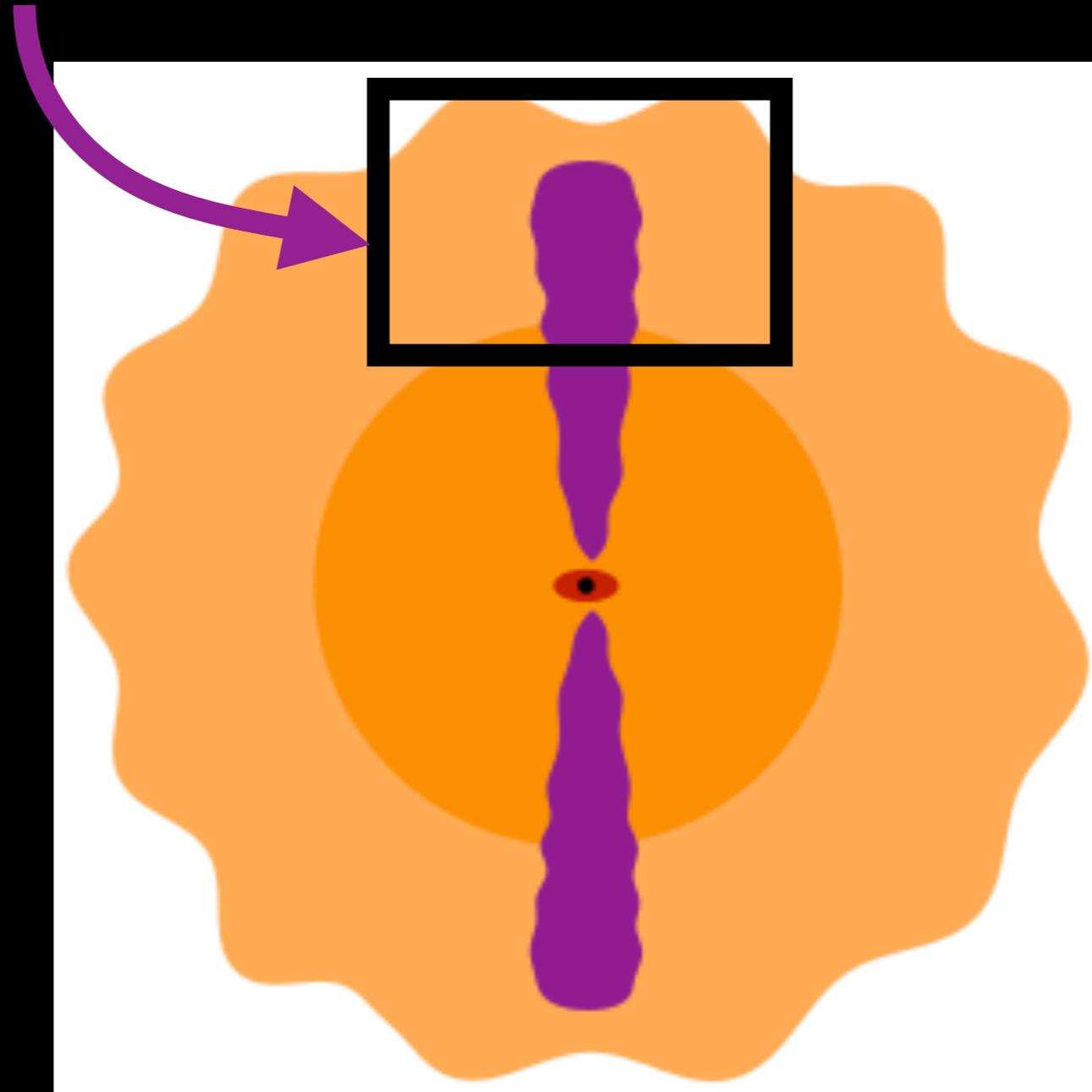
Two stripped envelope supernovae with circumstellar interaction

But only one really shows it

J. Sollerman¹, C. Fransson¹, C. Barbarino¹, C. Fremling², A. Horesh³, E. Kool¹, S. Schulze⁴, I. Sfaradi³, S. Yang¹,

Important Point:

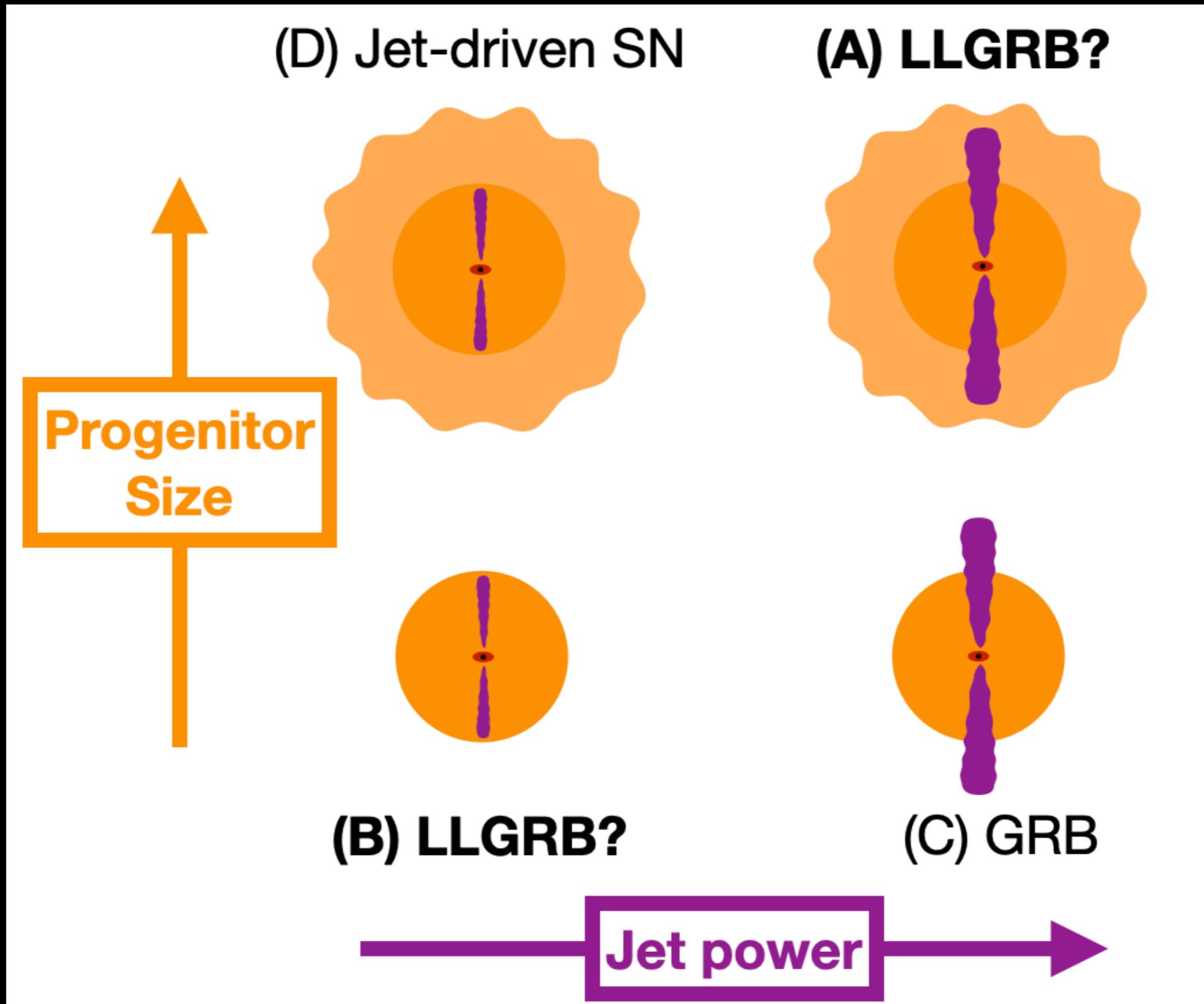
Understand (quantify) how the CSM affects the jet



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)

Z [cm]

4.5e+10

4.0e+10

3.5e+10

3.0e+10

2.5e+10

2.0e+10

1.5e+10

1.0e+10

5.0e+09

0.0e+00



β at $t-t_0 = 0.00$ s

1

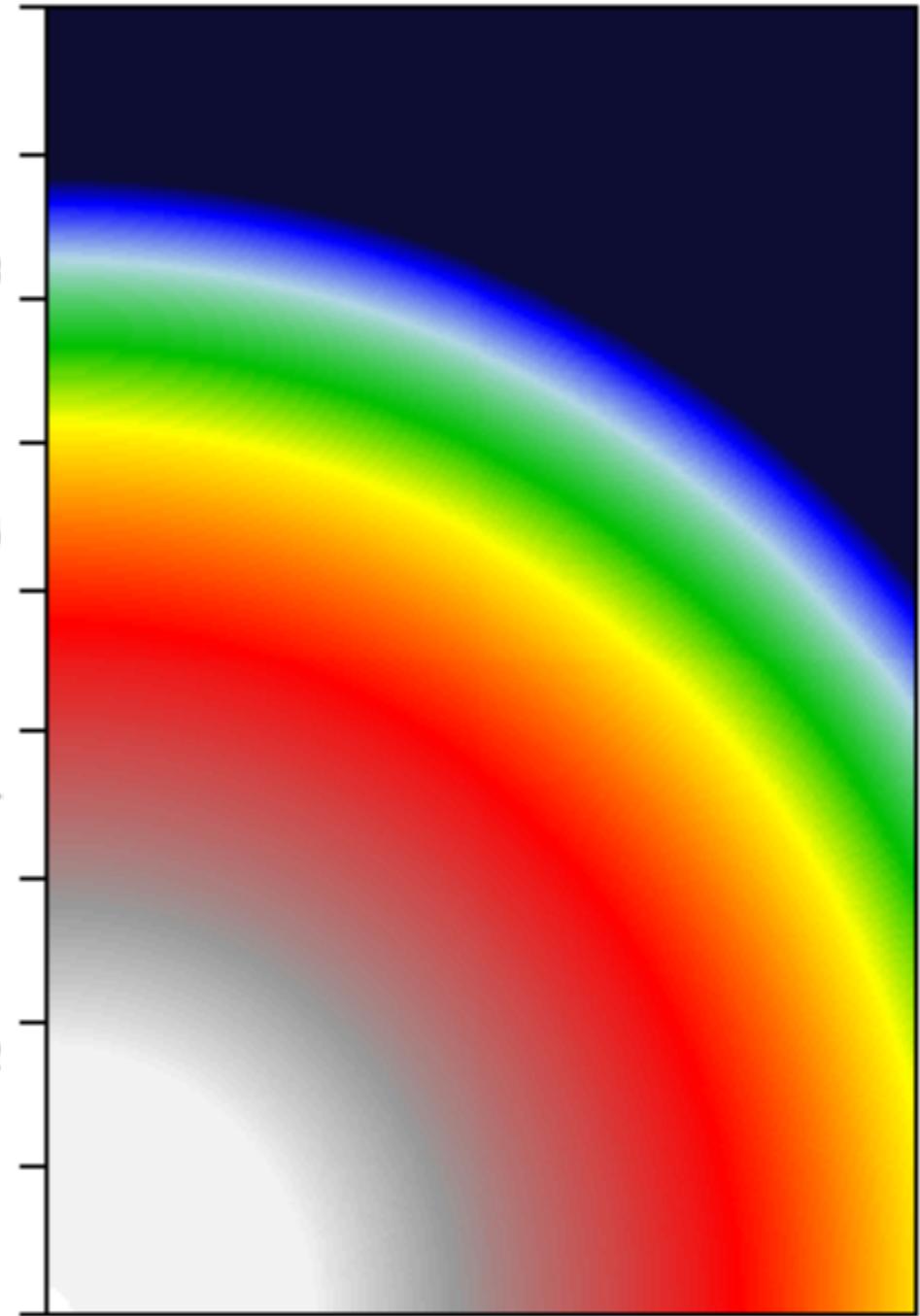
0.8

0.6

0.4

0.2

0



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

3

2

1

0

-1

-2

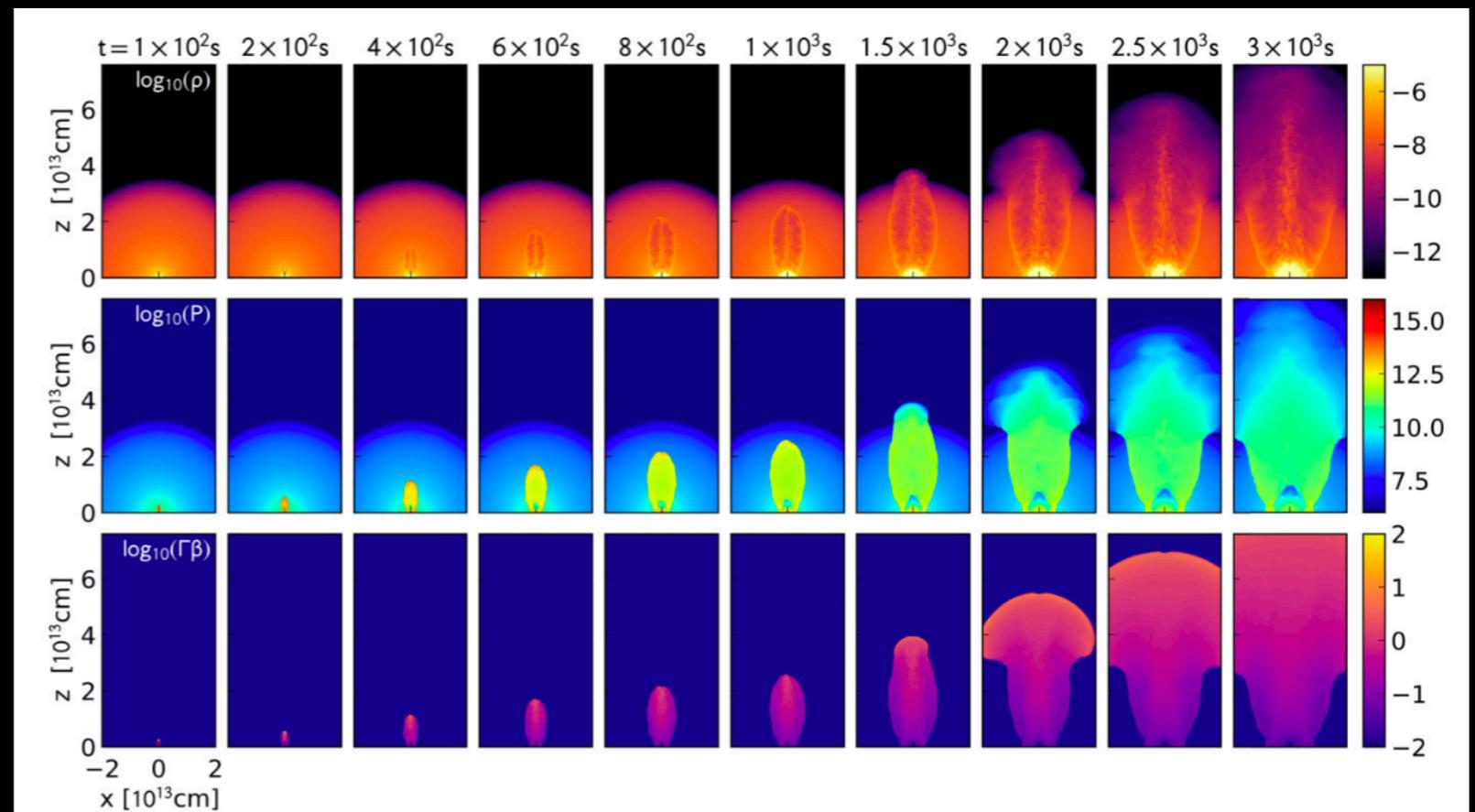
-3

Method:

→ Simulations “difficult”

→ **Analytic Modeling ?**

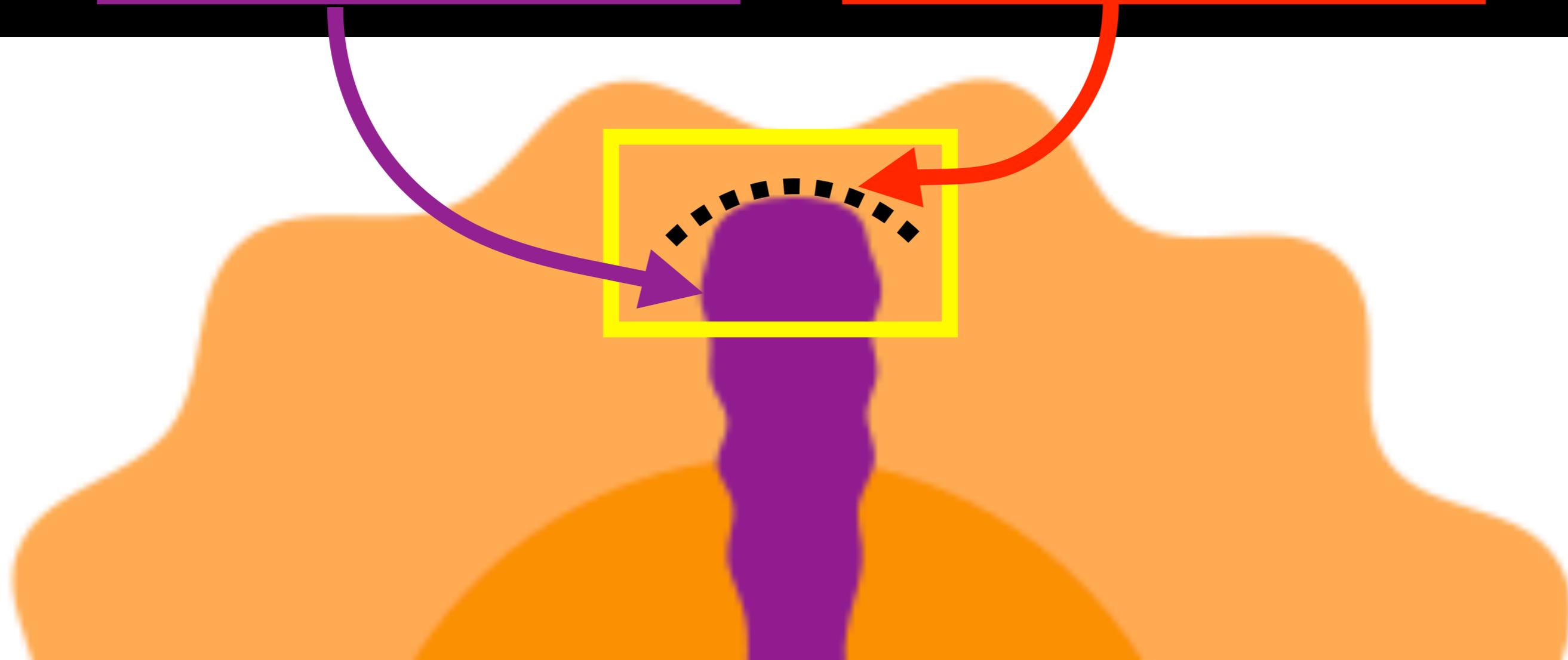
Side note:
Despite nice work
by Suzuki+24



Jet Dynamics

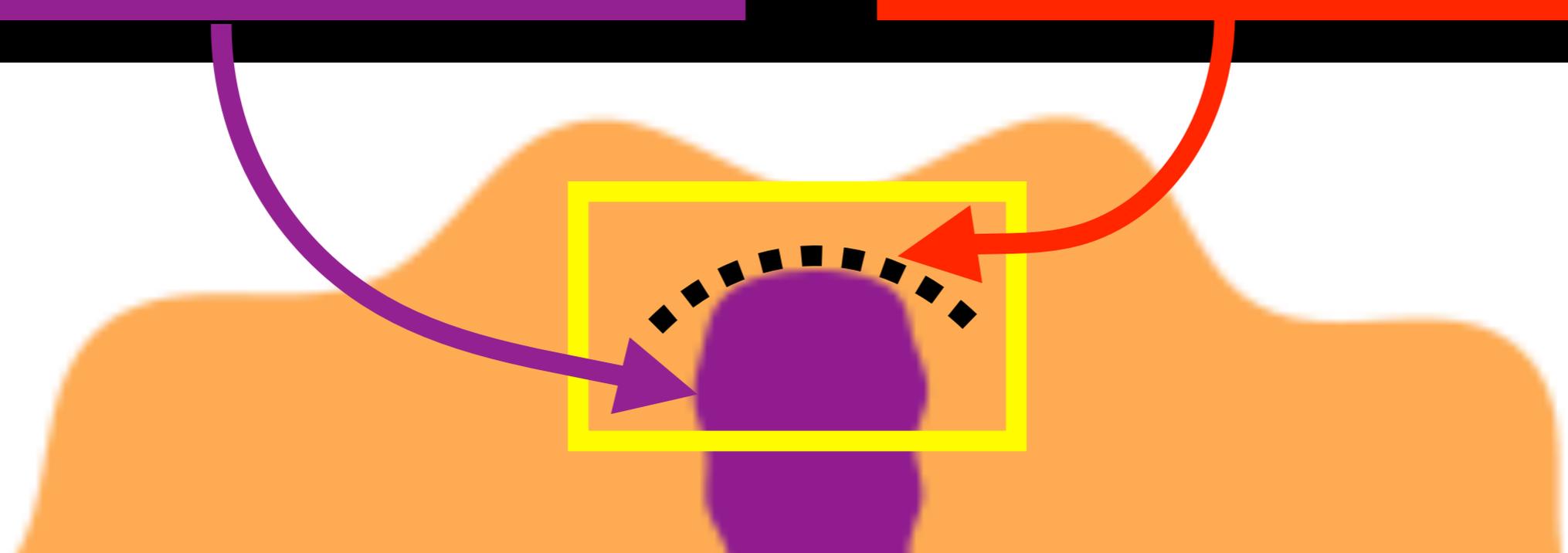
Jump conditions: (Begelman & Cioffi 1989)

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



Jet Dynamics

Jump conditions:

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


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

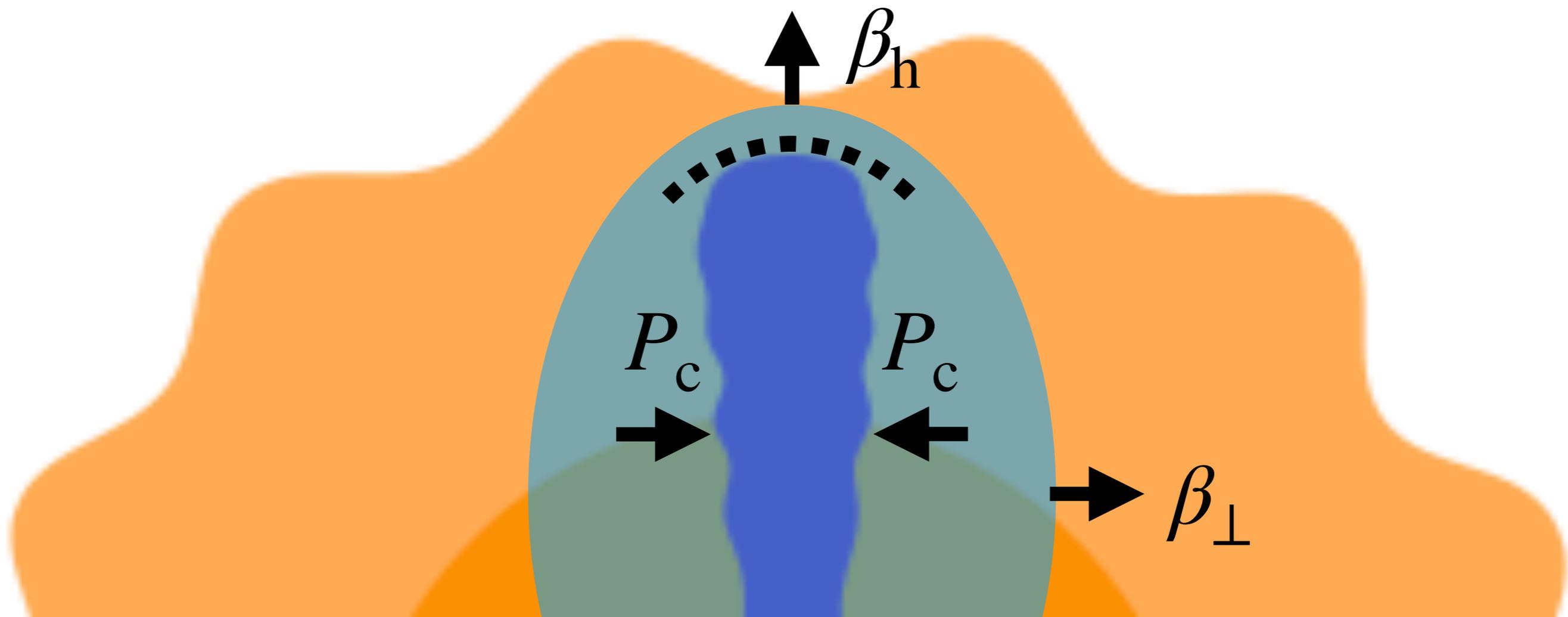
Cocoon & Collimation

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

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

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

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



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

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

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

For relativistic jet head with $C \gg 1$

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

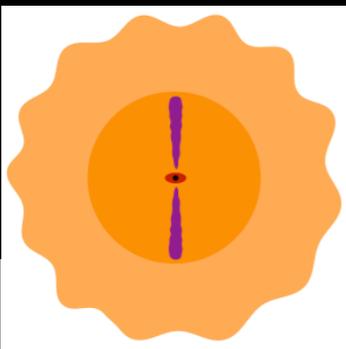
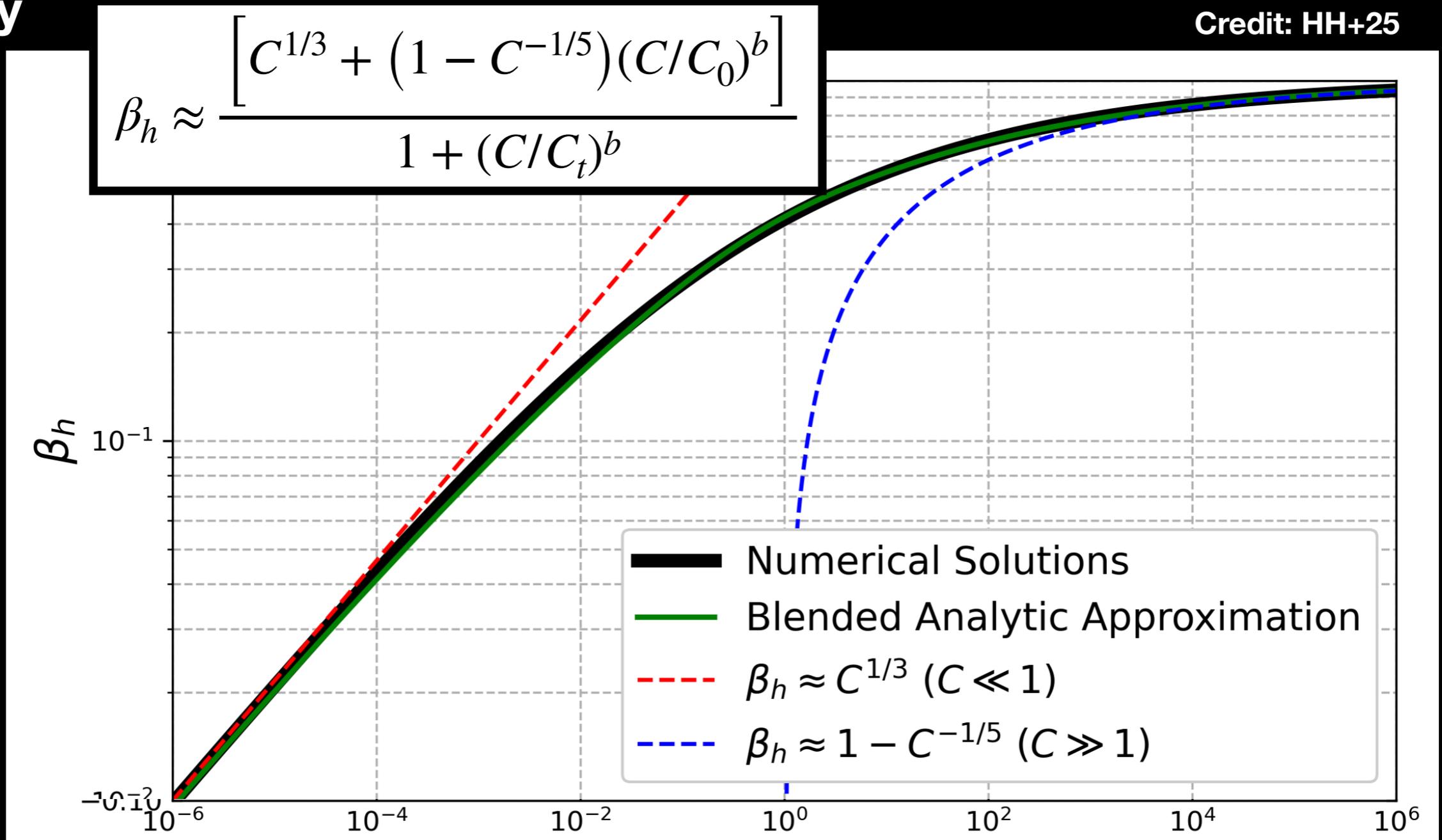
Blended together to ($C_t \approx 0.66$, & $b \approx 0.79$):

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

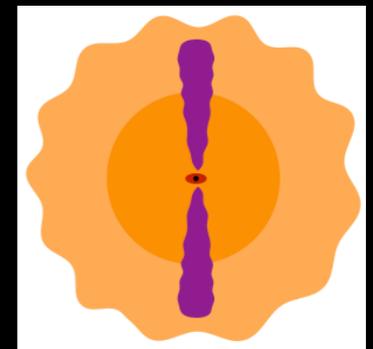
Universal Solution

Jet head
velocity
(β_h)

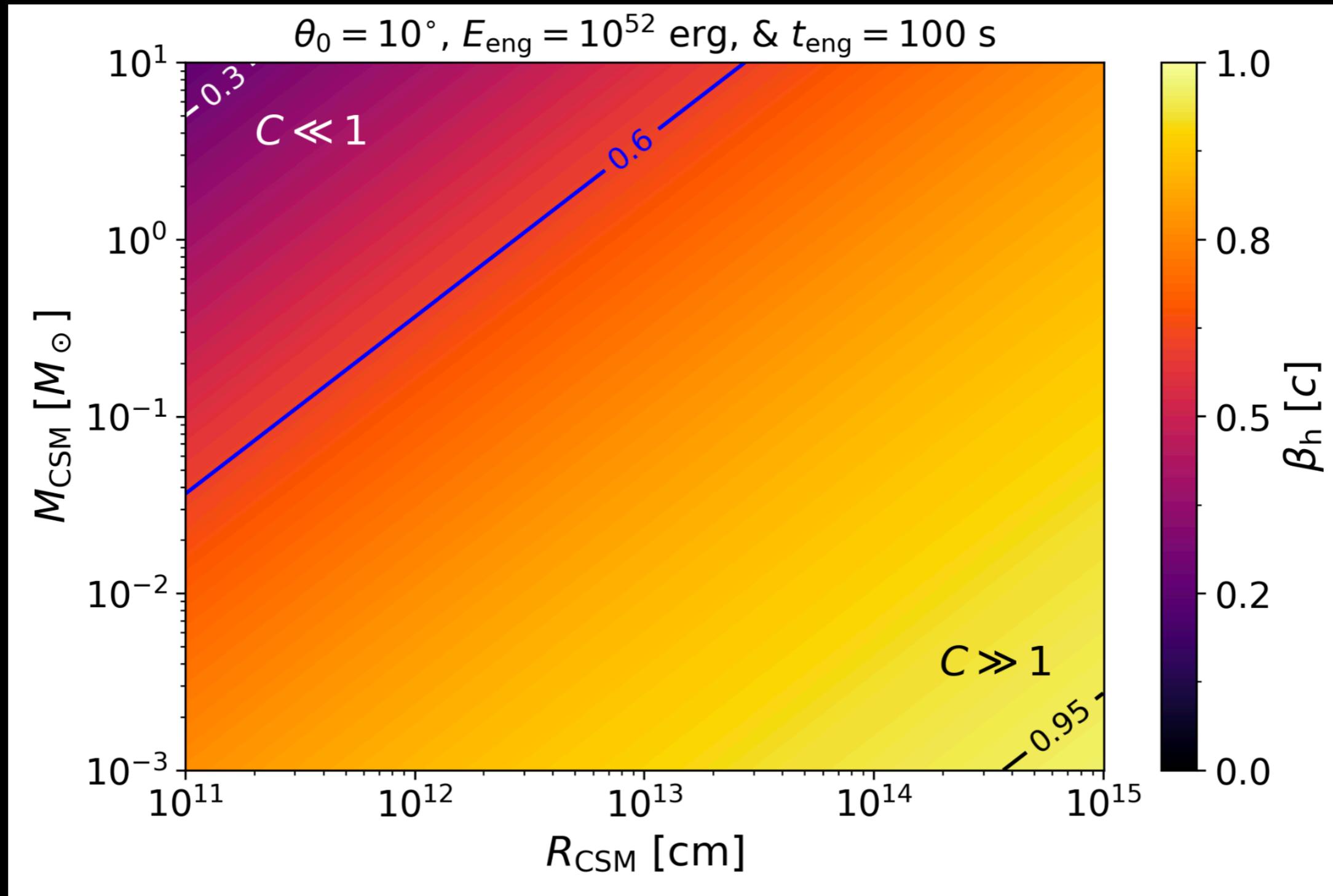
Credit: HH+25



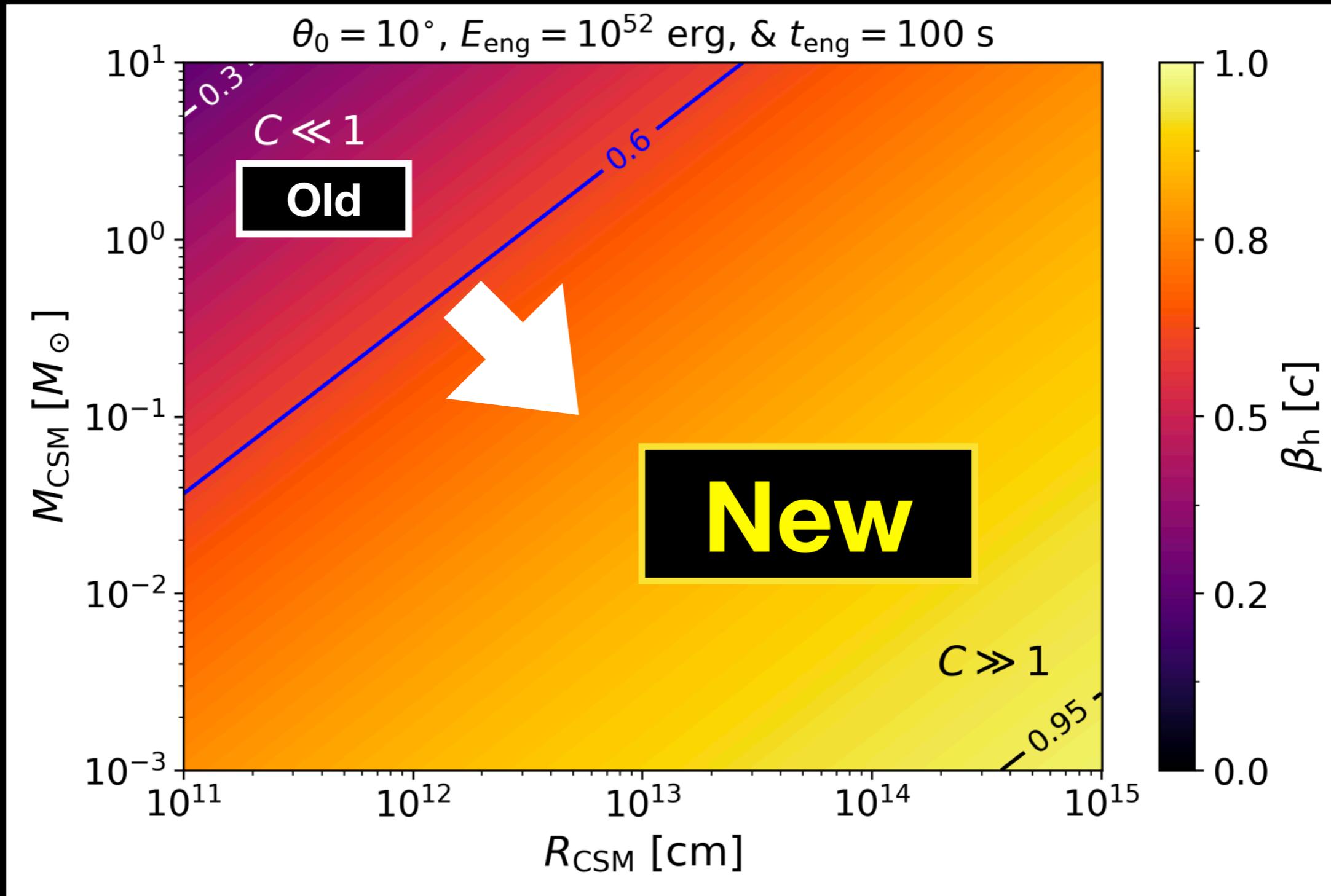
CSM presence: $C \propto \frac{E_{\text{eng}}}{t_{\text{eng}} \theta_0^2} \frac{R_{\text{CSM}}}{M_{\text{CSM}}}$



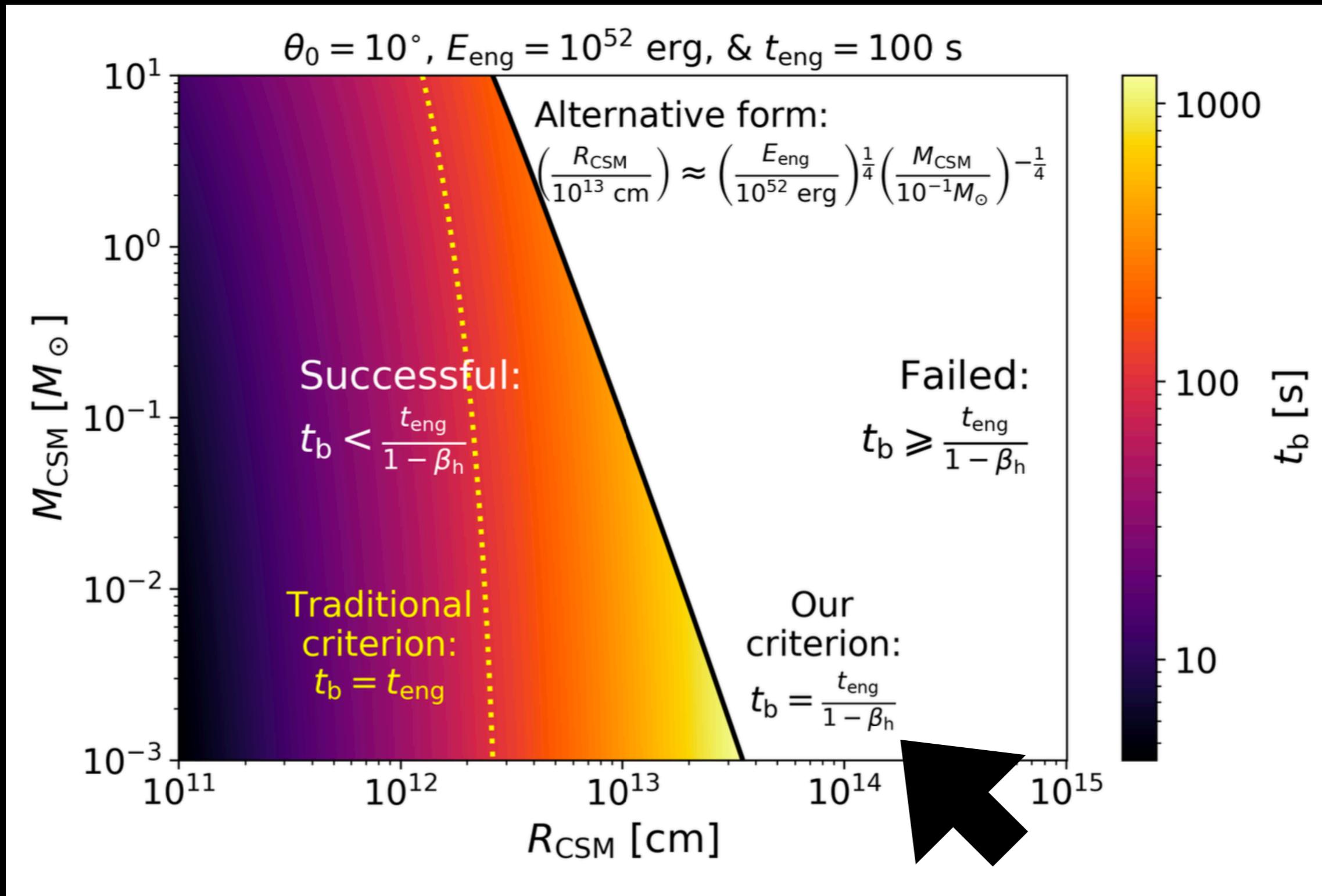
Jet head velocity quantified



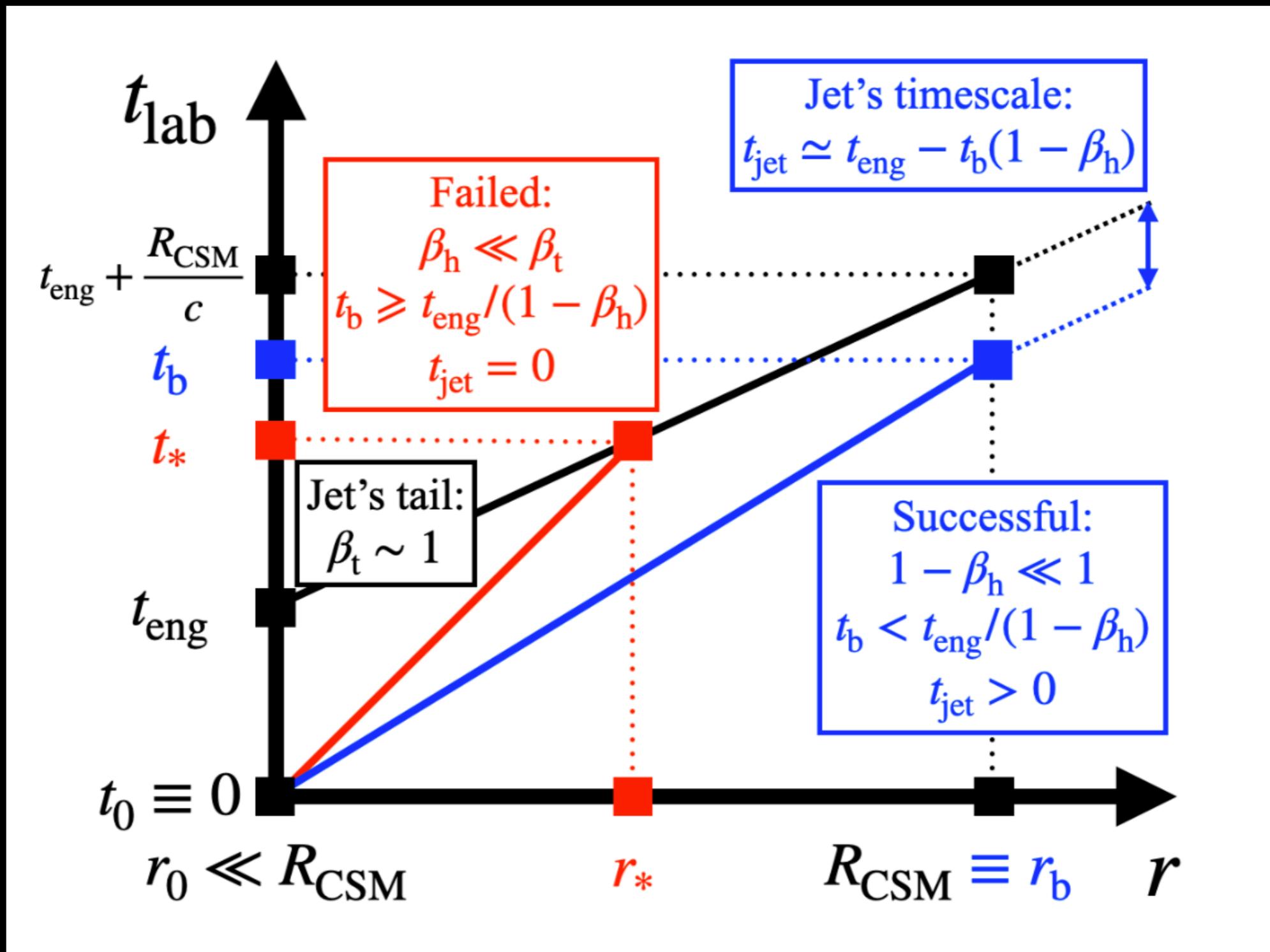
Jet head velocity quantified



Breakout & Success criteria



The term $1 - \beta_h$



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:

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

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

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

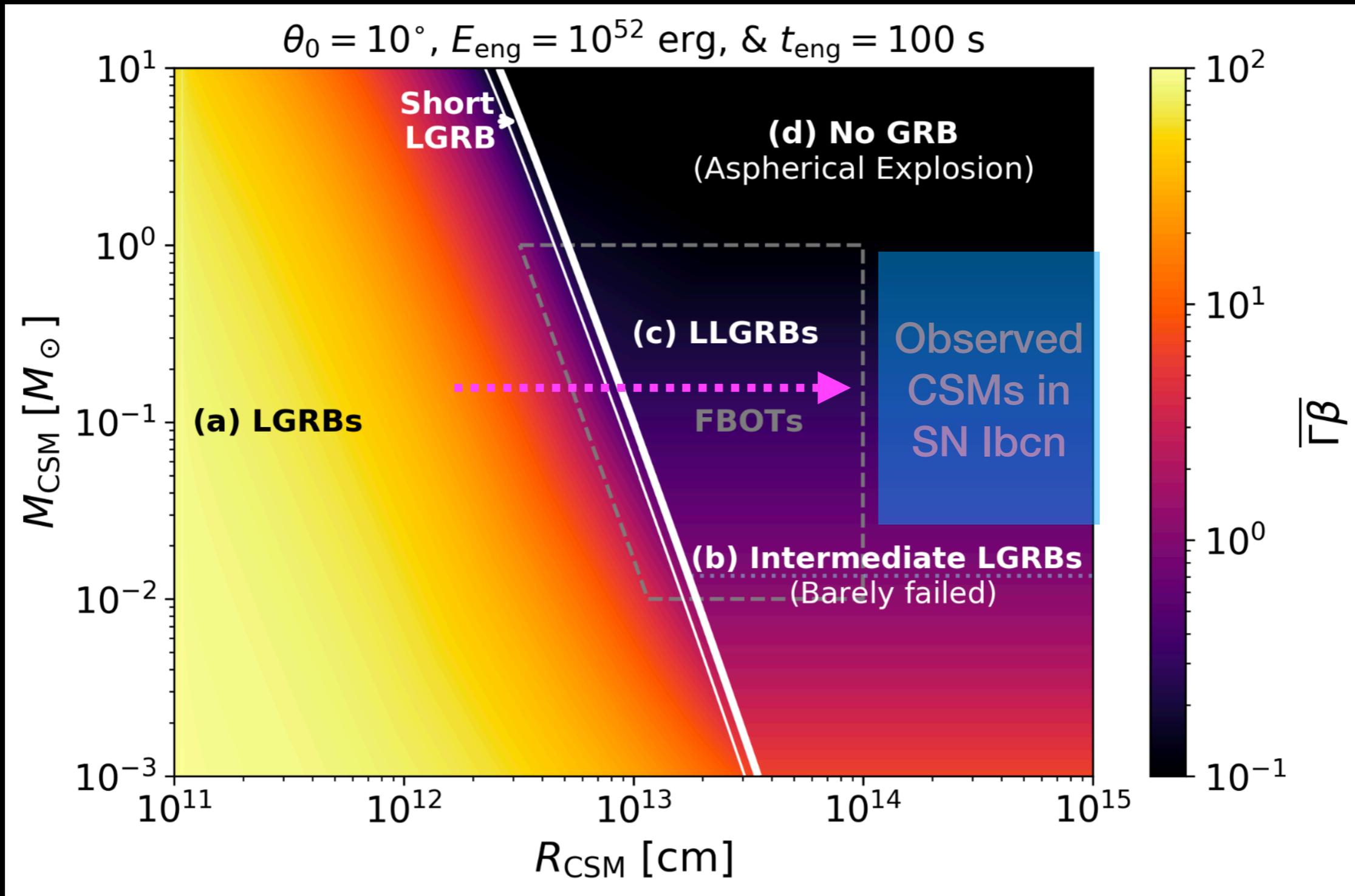
With

Energy weighted

$$\langle \log(\Gamma\beta) \rangle = \underbrace{\langle \log(\Gamma\beta) \rangle_j}_{\text{Jet}} \frac{E_j}{E_{\text{eng}}} + \underbrace{\langle \log(\Gamma\beta) \rangle_c}_{\text{Cocoon}} \frac{E_c}{E_{\text{eng}}}$$

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

Diversity of transients



Recap

Fully analytic model for jet dynamics in CSM

For Jet/CSM parameters, Gives:

⇒ Jet propagation (β_h, t_b, \dots)

⇒ Shocked CSM cooling emission ($L_{\text{bol}}, r_{\text{ph}}, T_{\text{ph}}, \dots$)

Code Publicly available in Python:

<https://github.com/hamidhamidani/cocoon-cooling-model>

Can be used to probe the CSM in LGRBs/LLGRBs

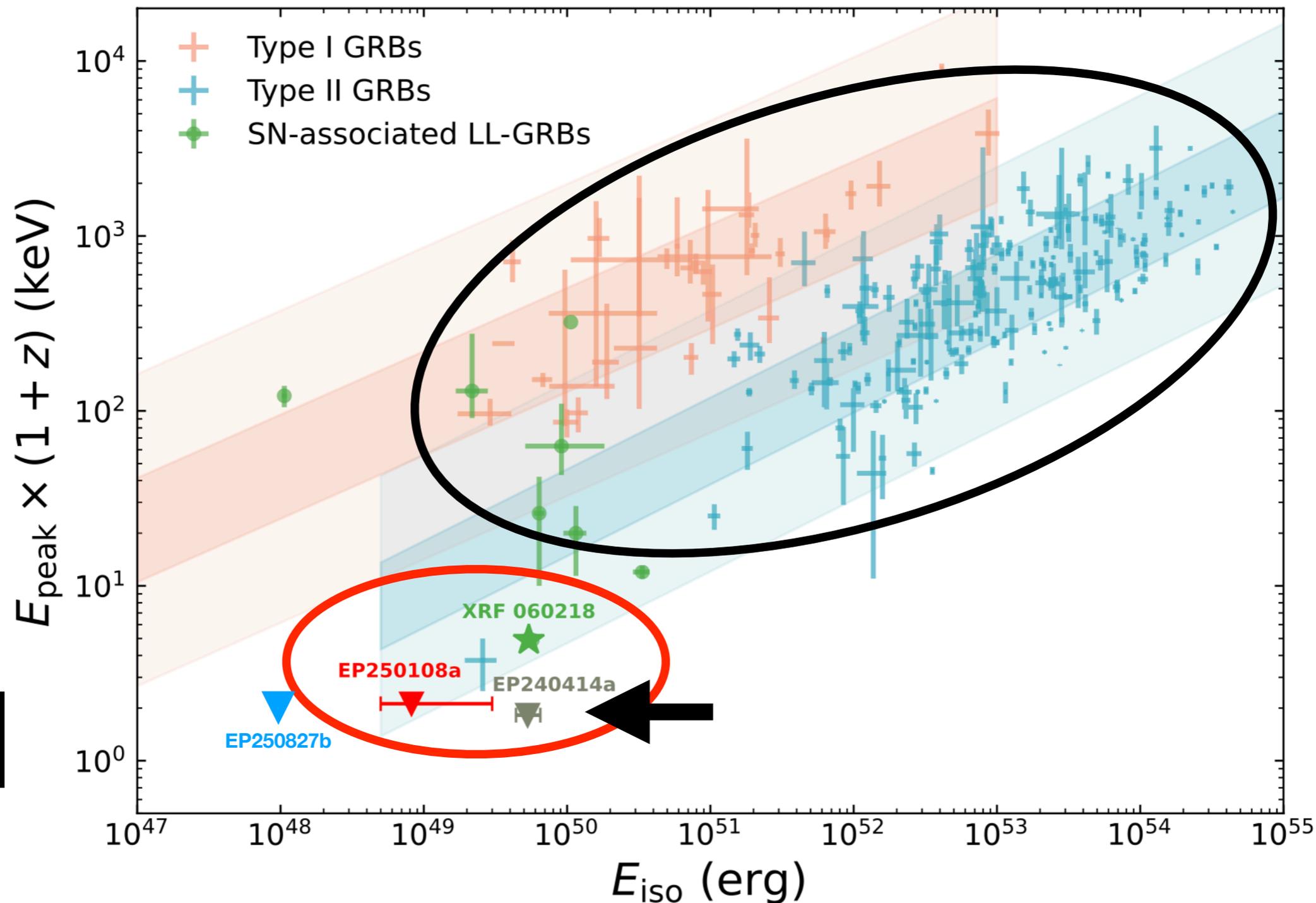
Caveat: We only consider hydrodynamical jets

A Look at Recent EP Events

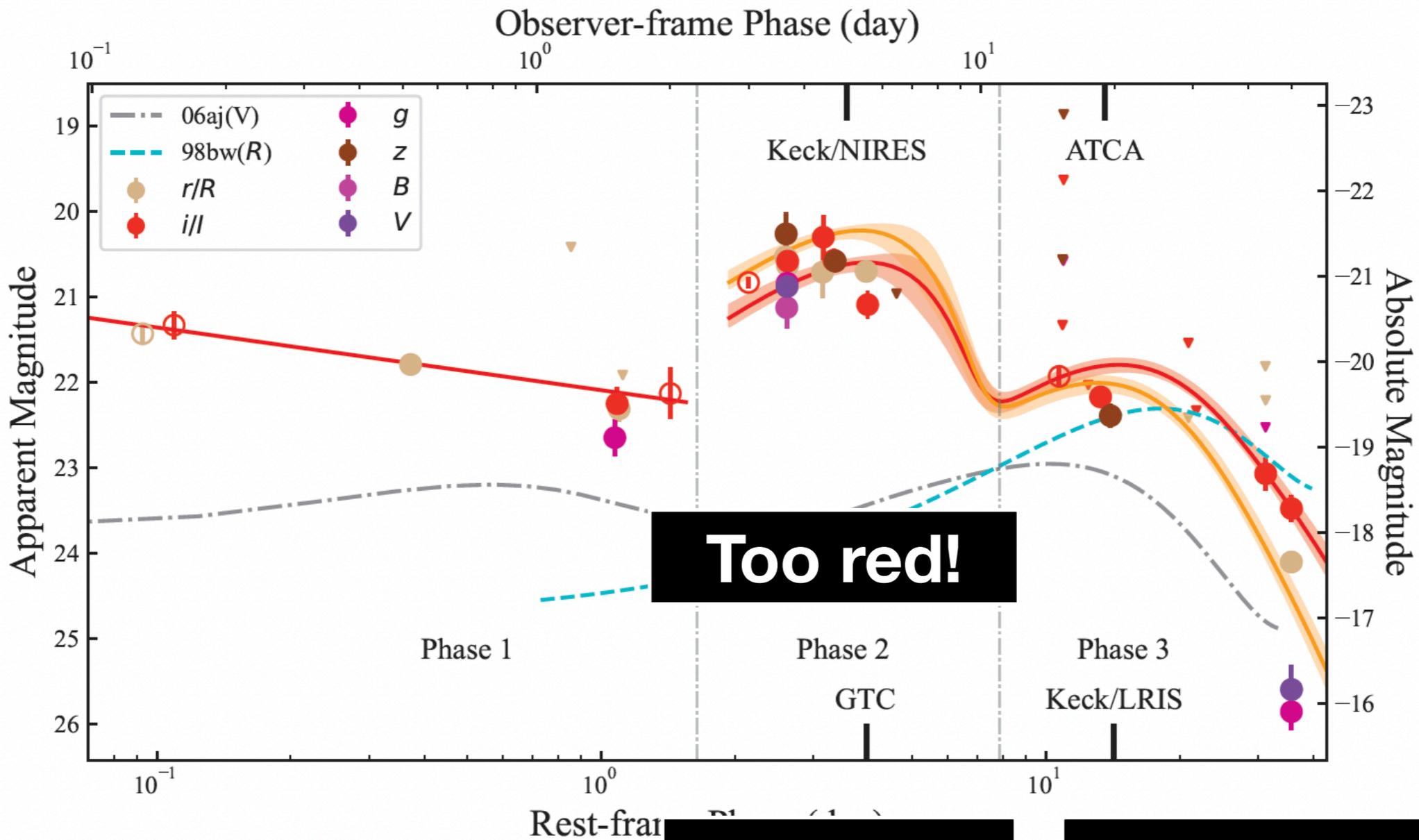


CREDIT: EP

Updated [with EP]



EP240414a [Unique transient]

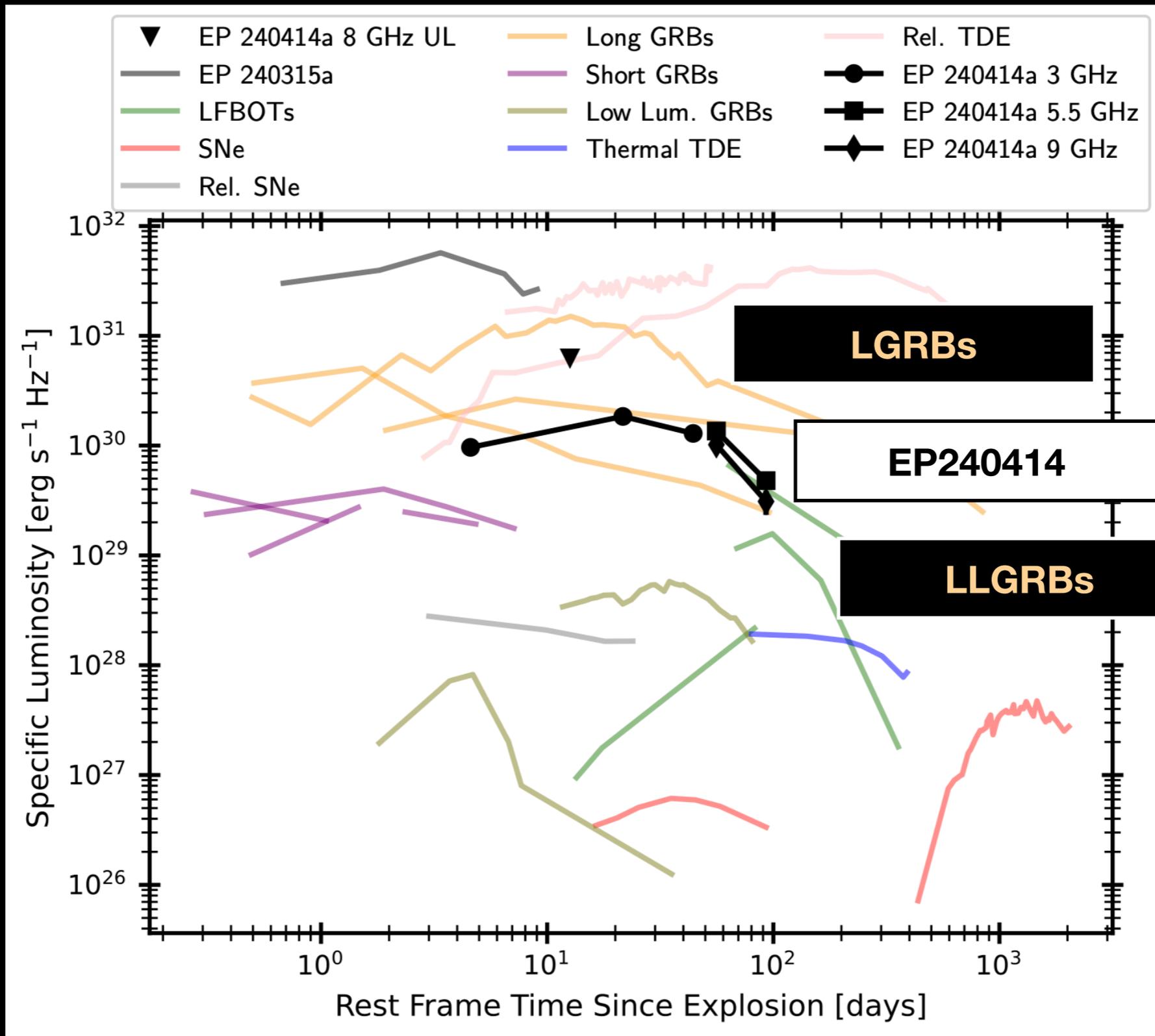


Phase 1:
thermal?

Phase 2:
non-thermal?

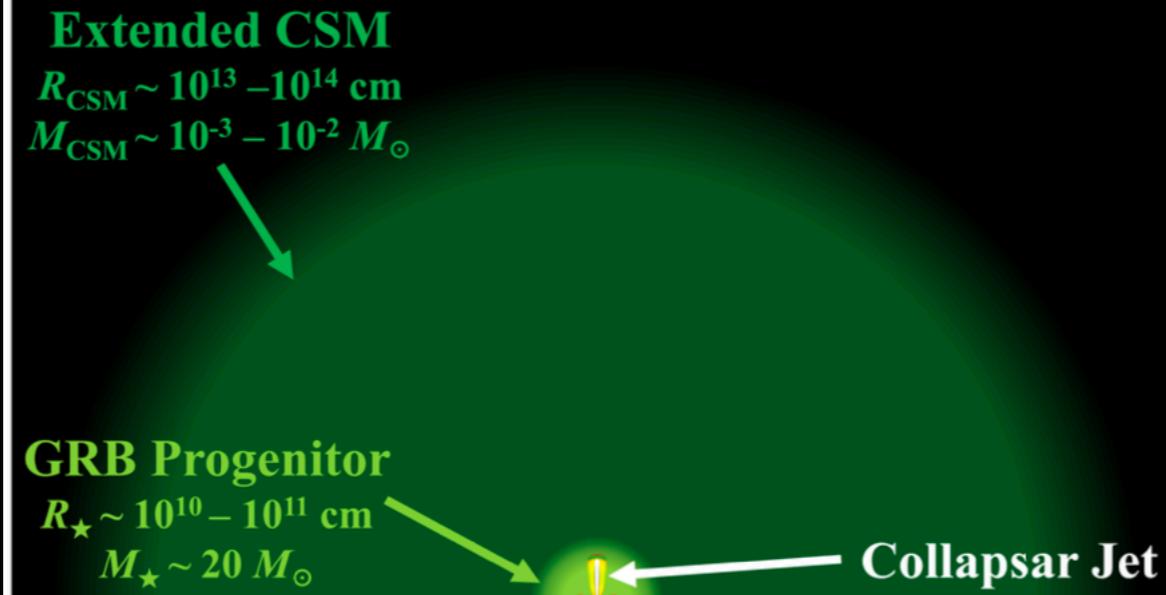
Phase 3:
Ic-BL SN (Ni56)

Radio [EP240414a]

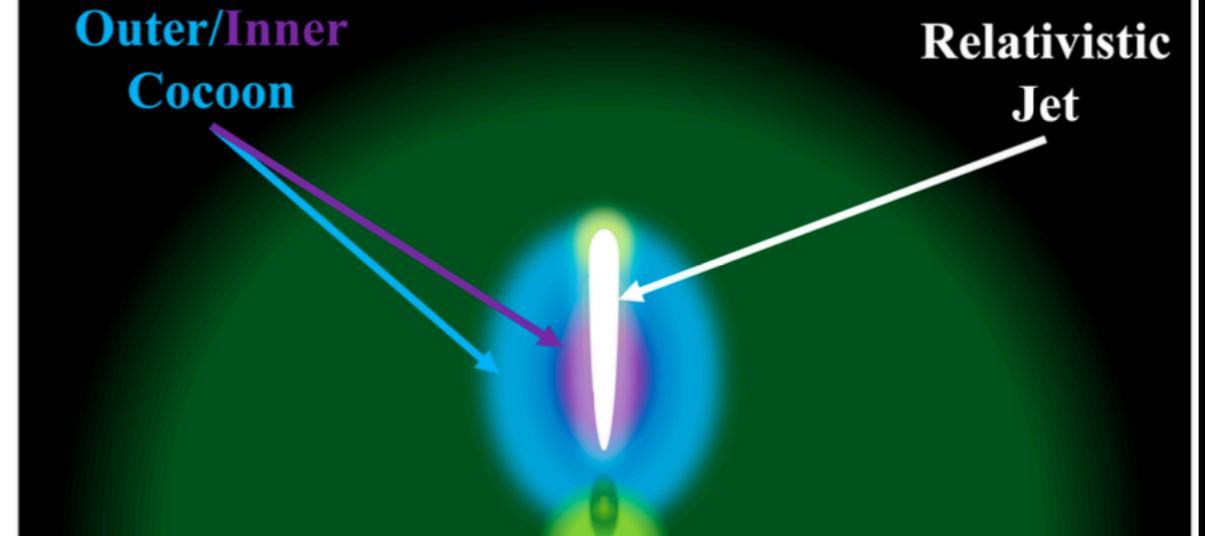


Scenario for EP240414a

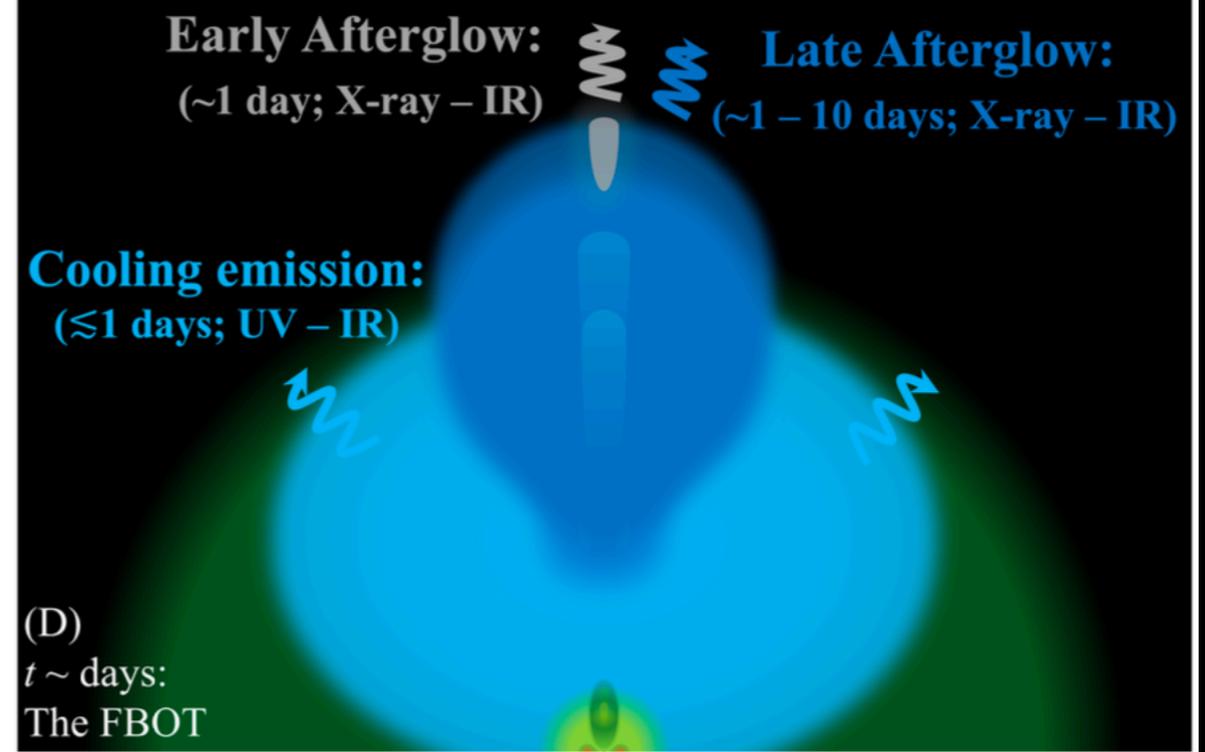
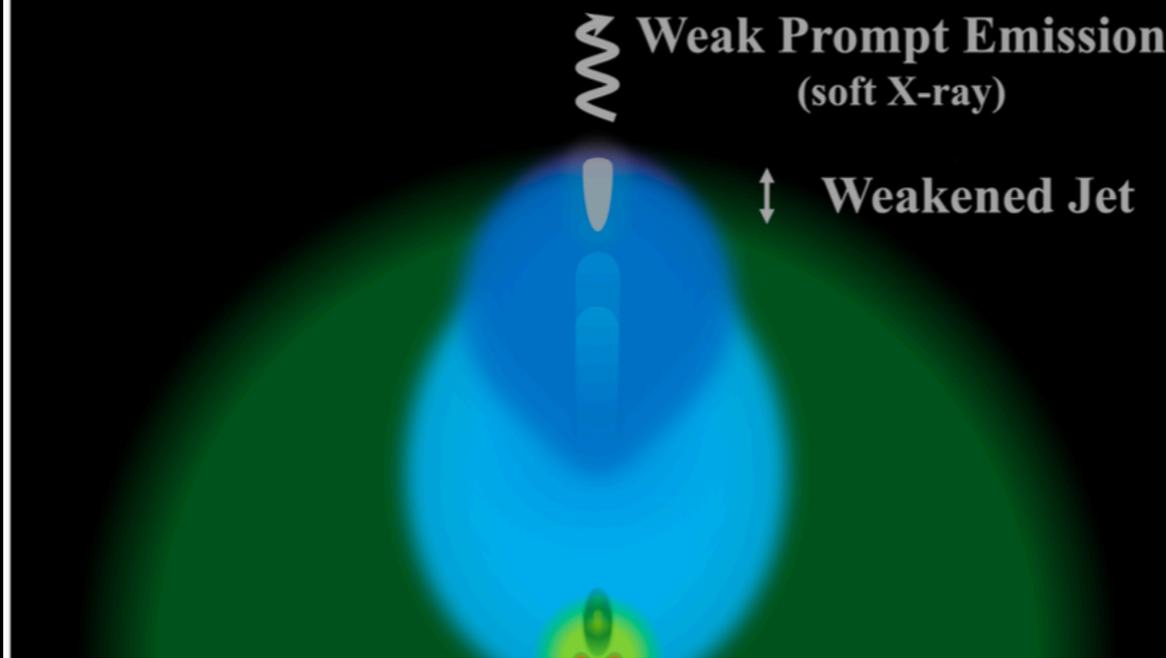
(A) $t \sim 0 - 10$ s: Collapsar jet inside the progenitor



(B) $t \sim 10^1 - 10^3$ s: Jet-cocoon inside the CSM



(C) $t \sim 10^3$ s: Breakout

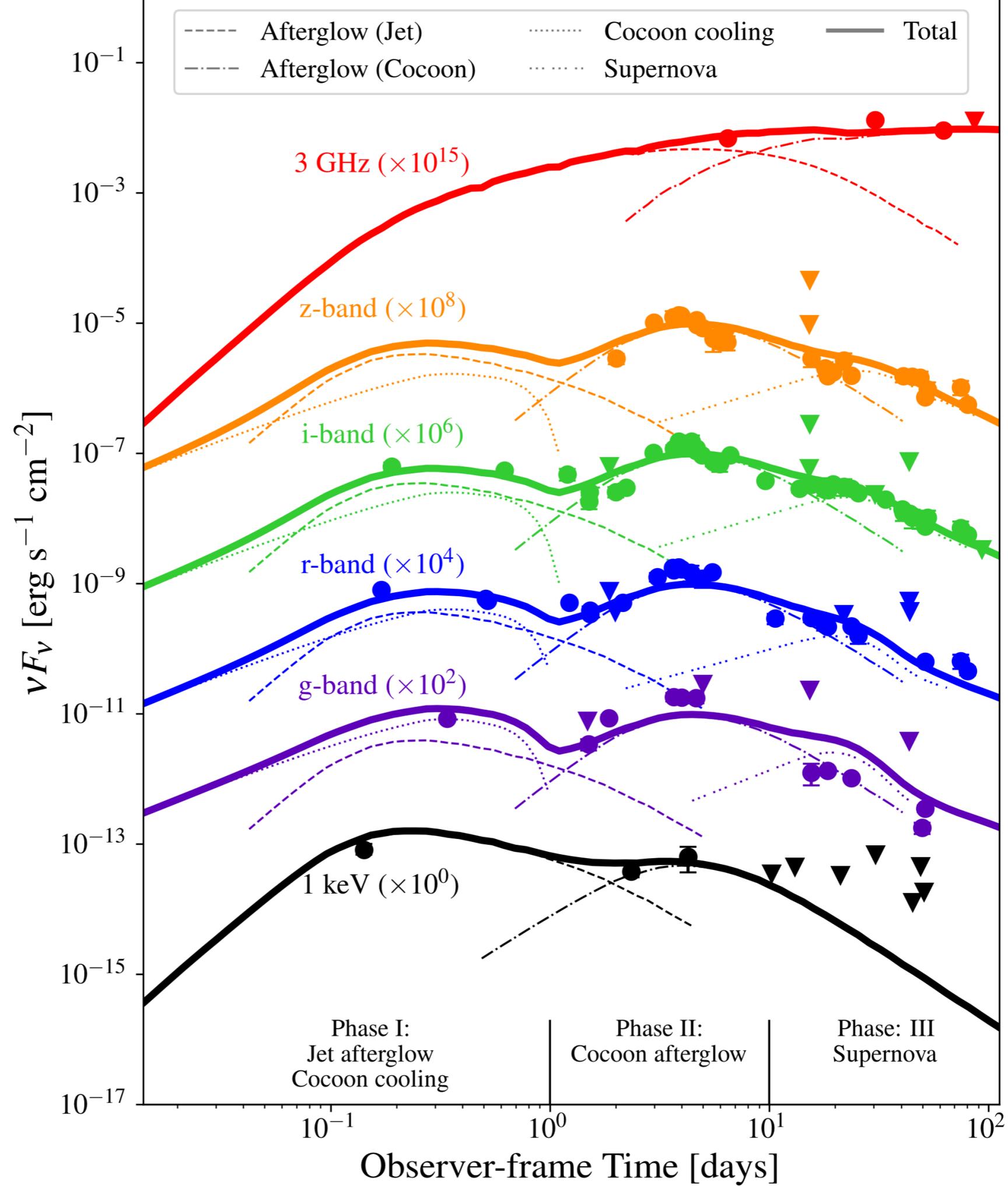


Results

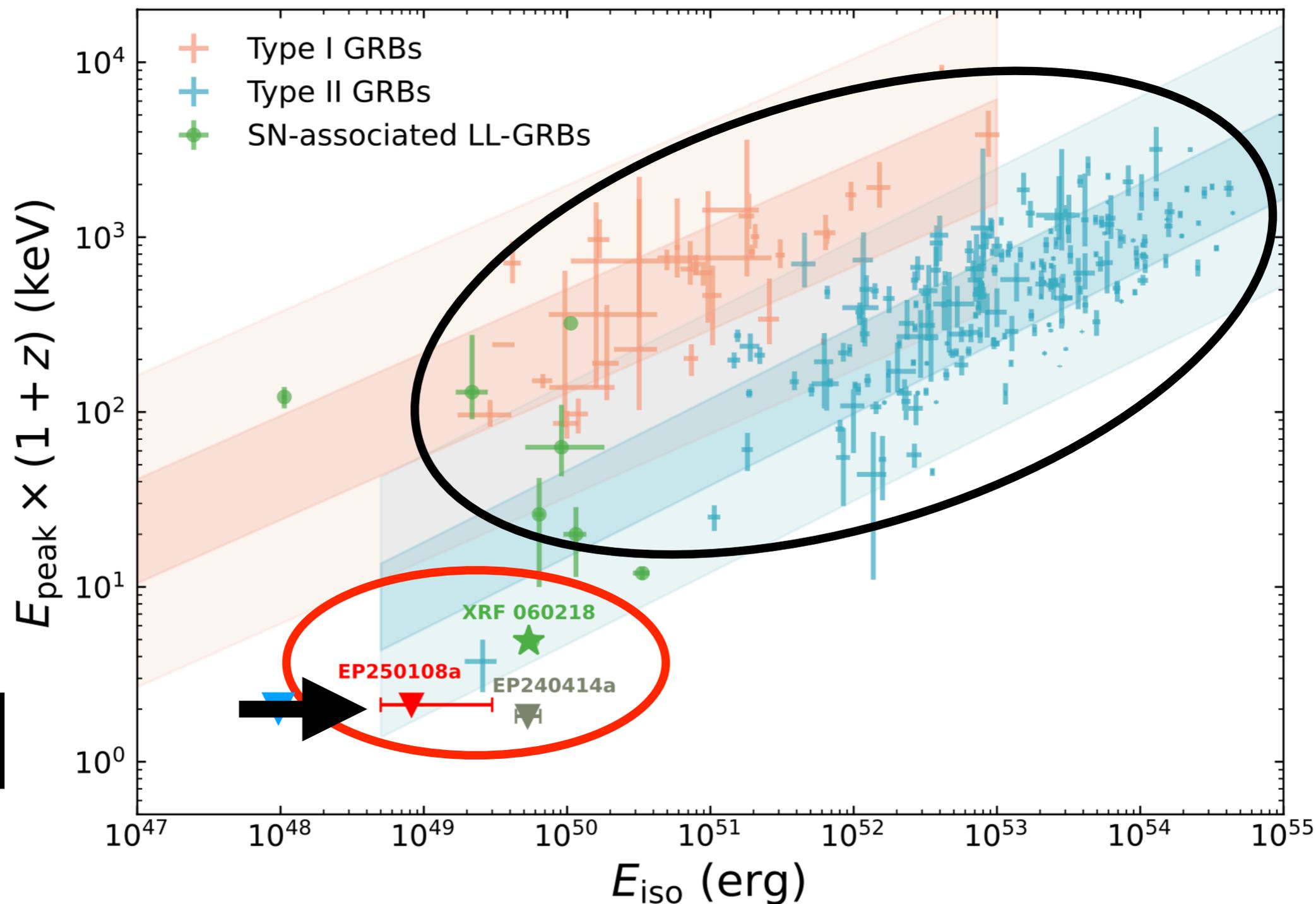
[EP240414a]

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

Jet:
Conventional



Updated [with EP]



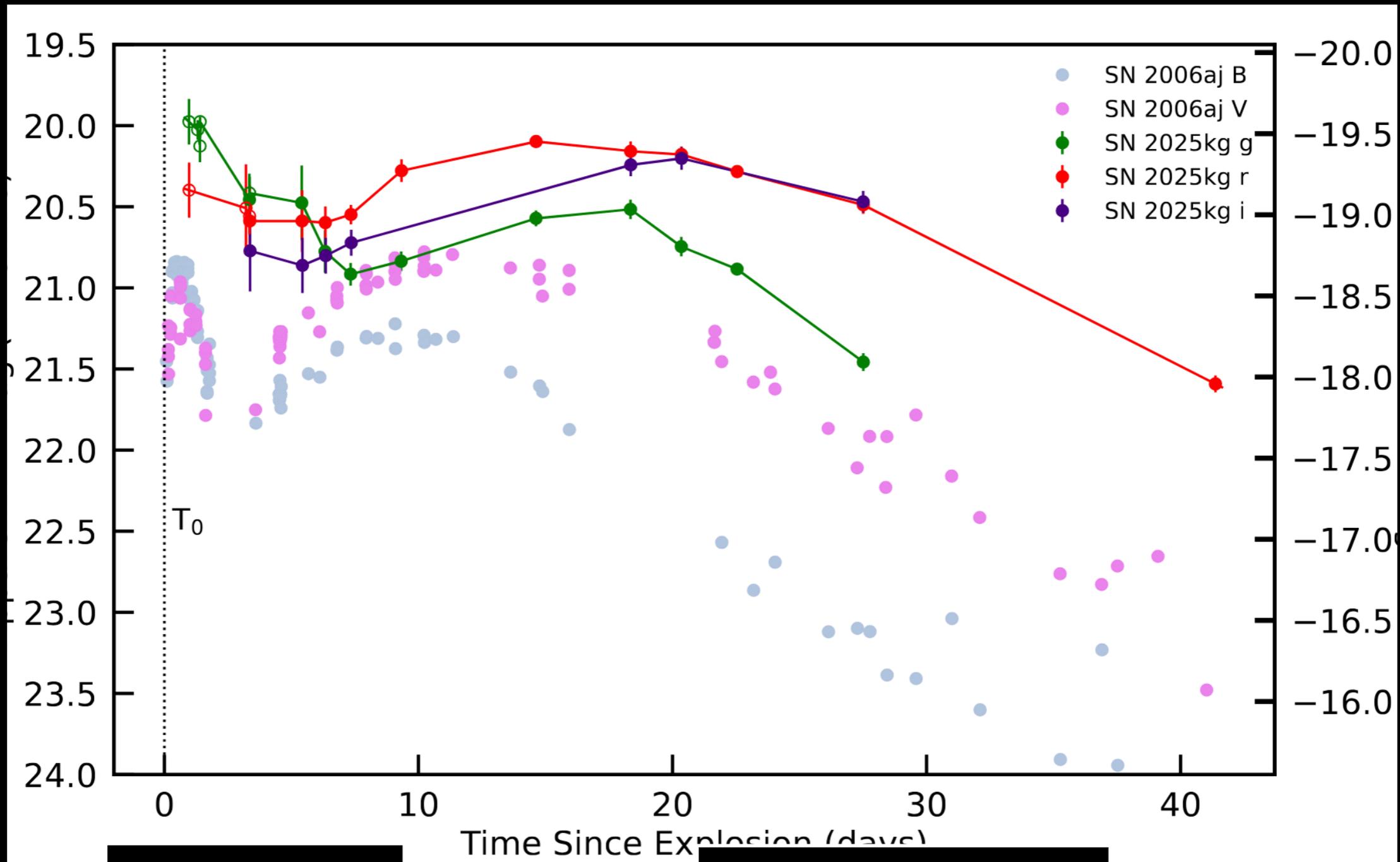
γ -ray

Hardness

X-ray

Energy

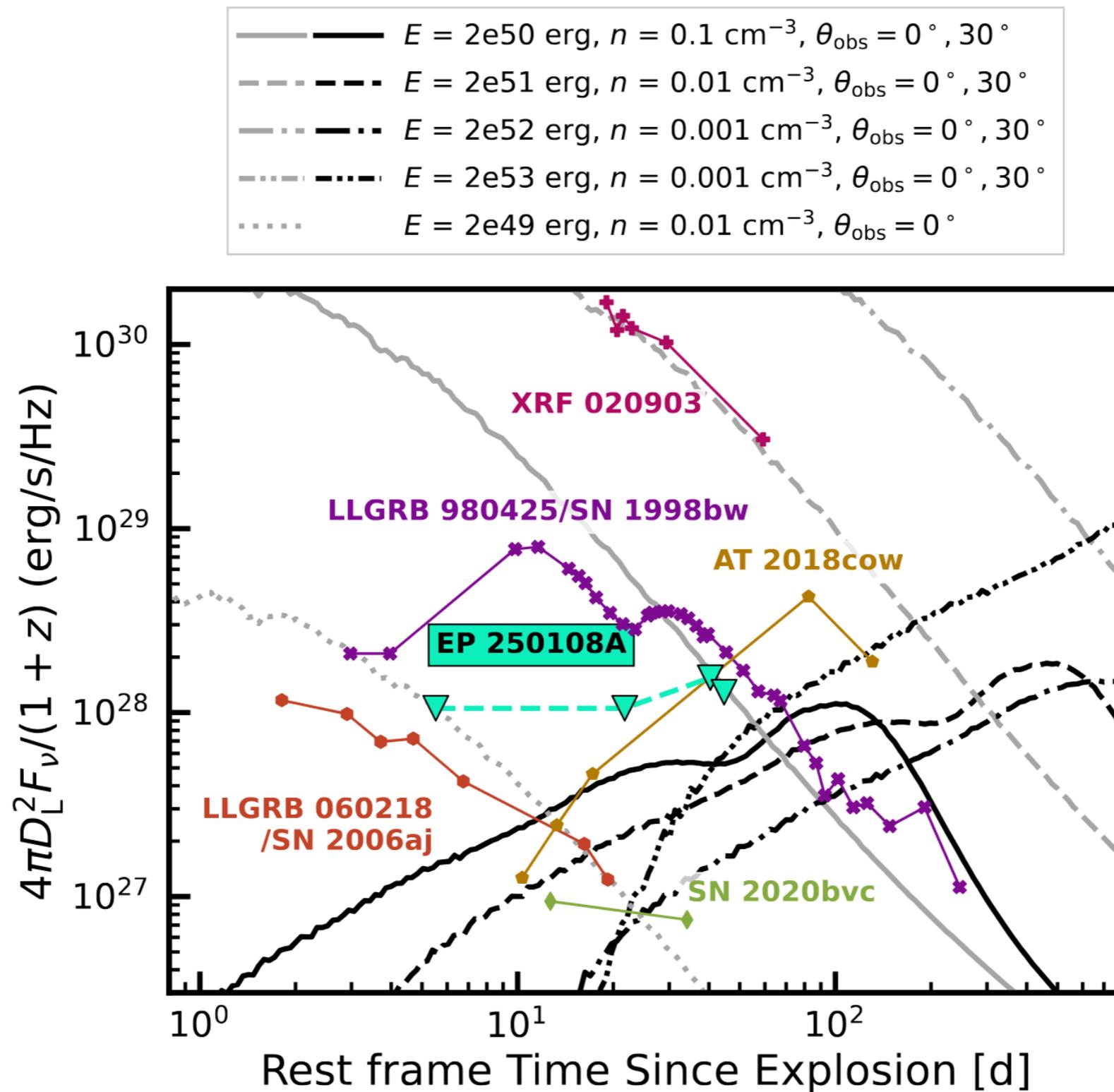
EP250108a [LLGRB+FBOT]



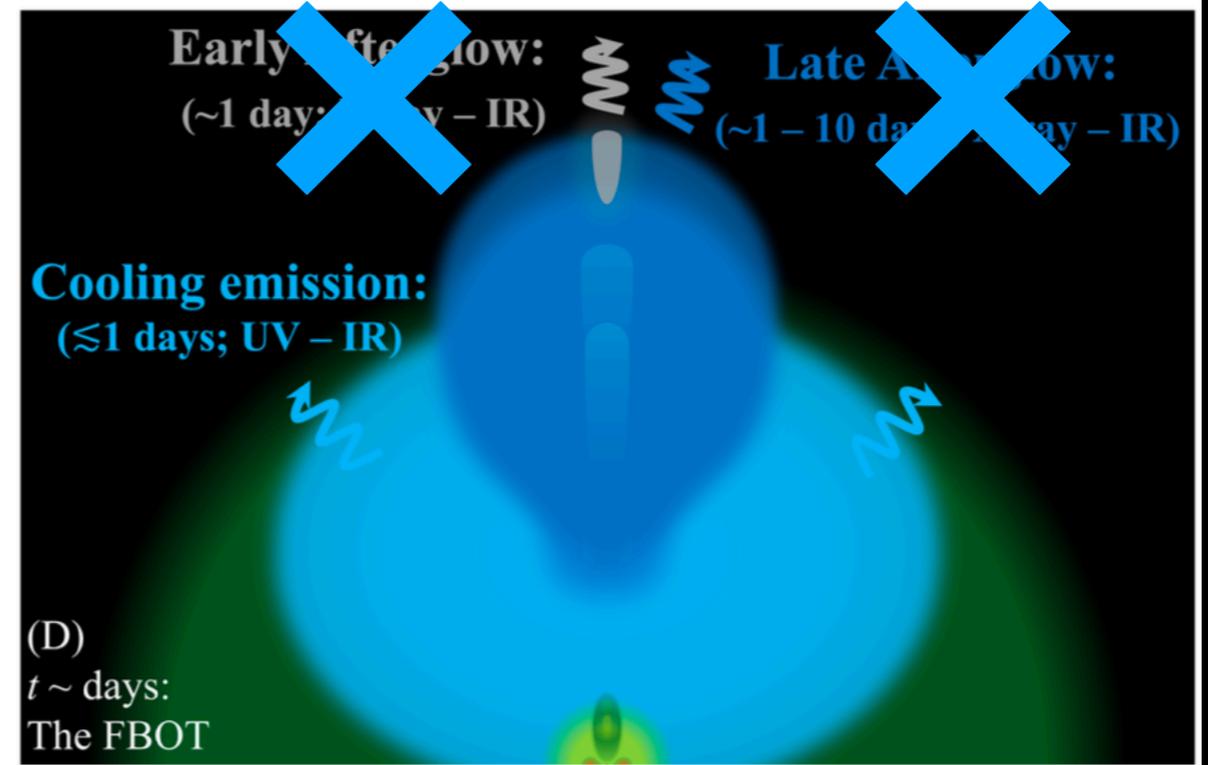
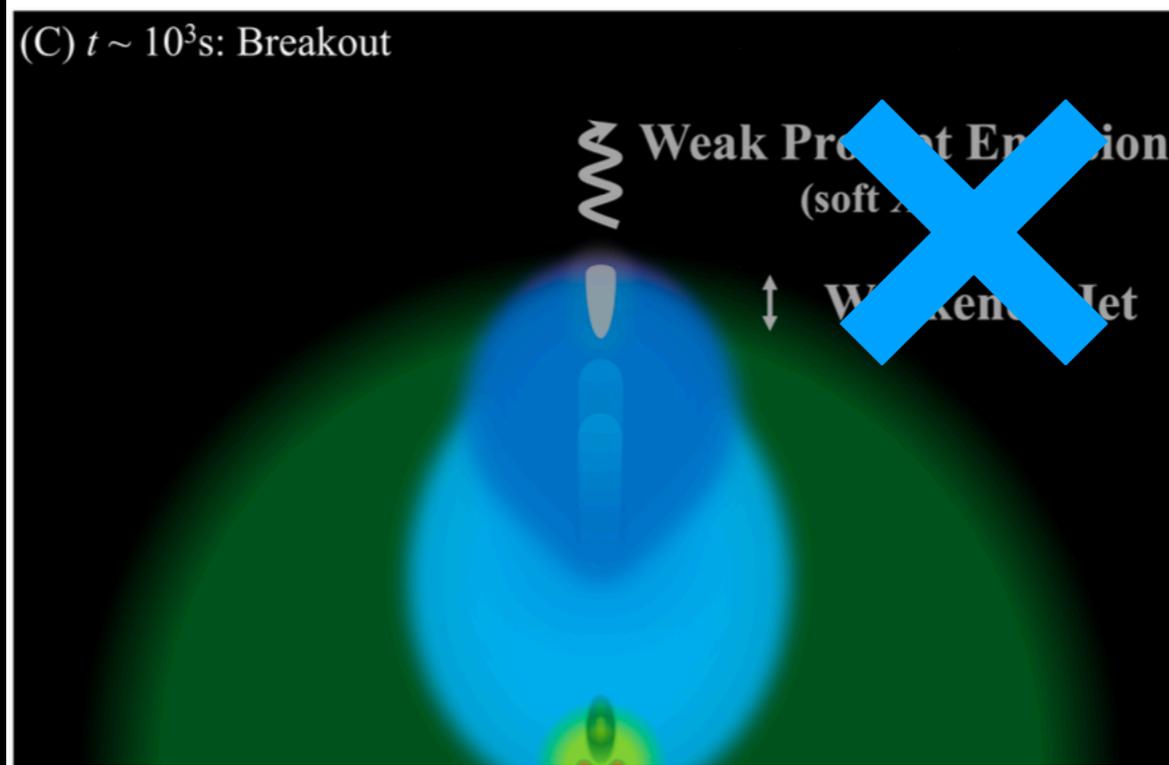
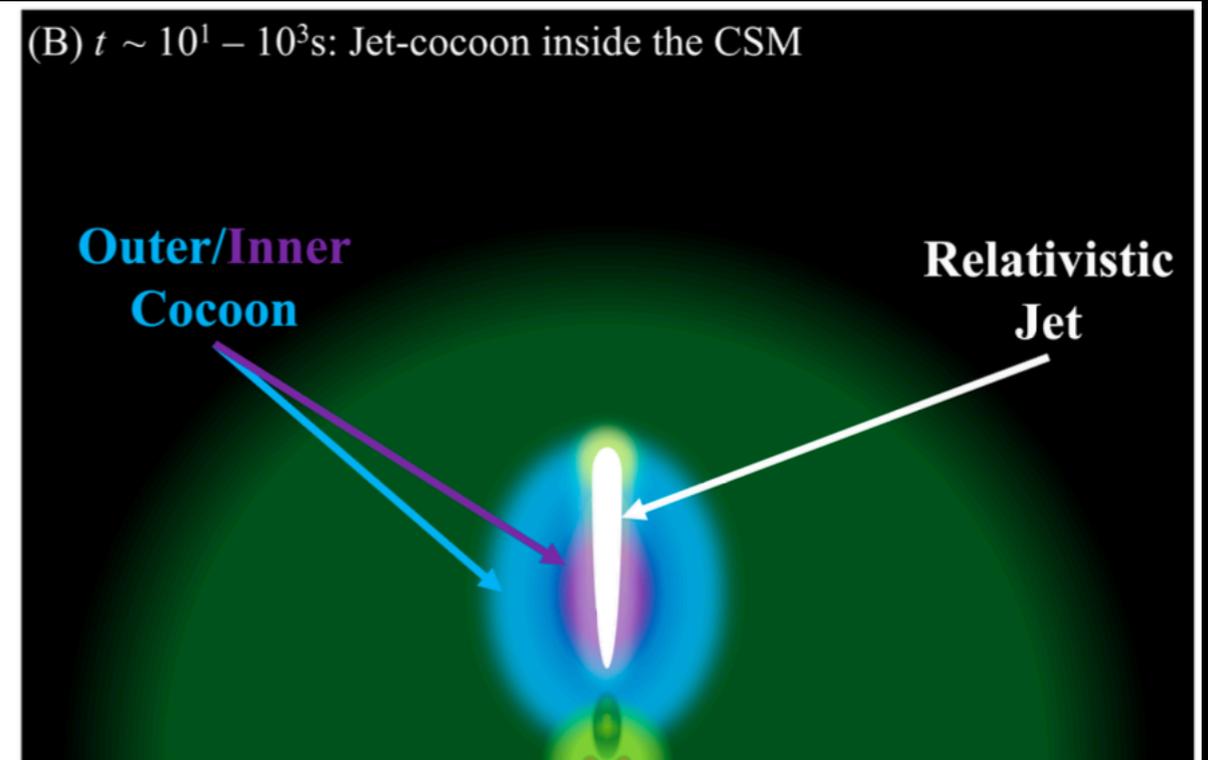
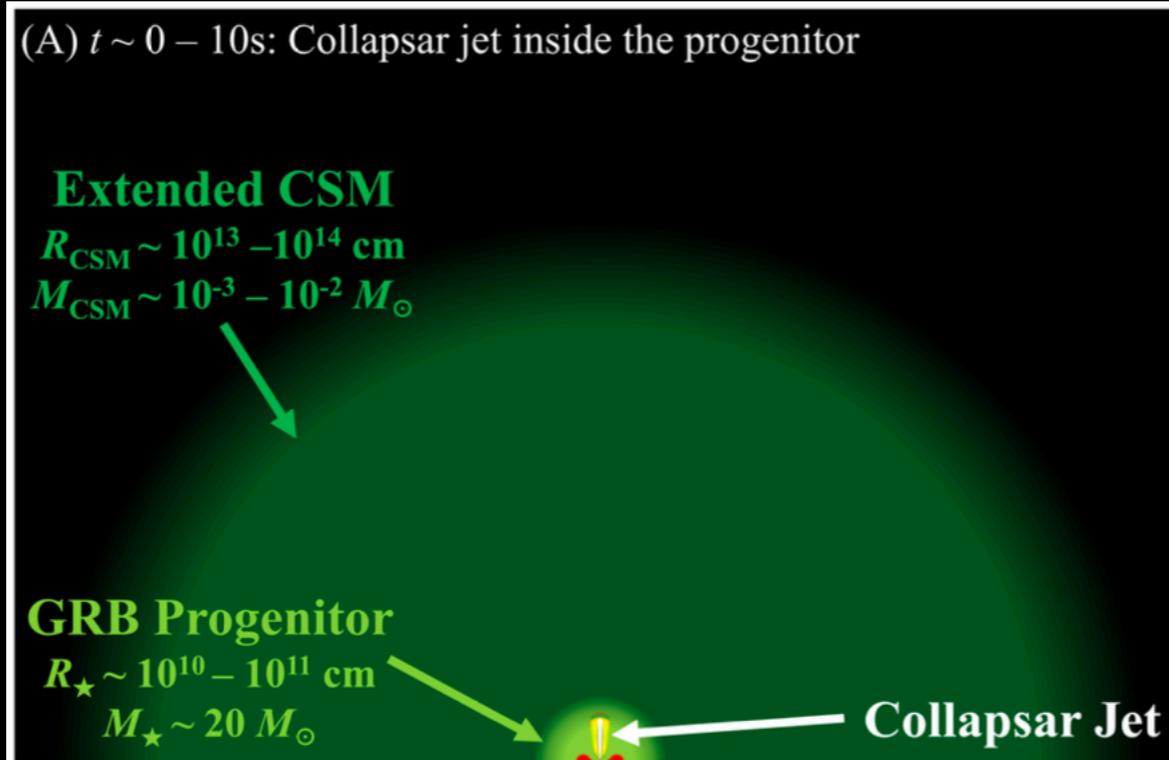
**Phase 1:
Thermal**

**Phase 2:
Thermal (SN / Ni56)**

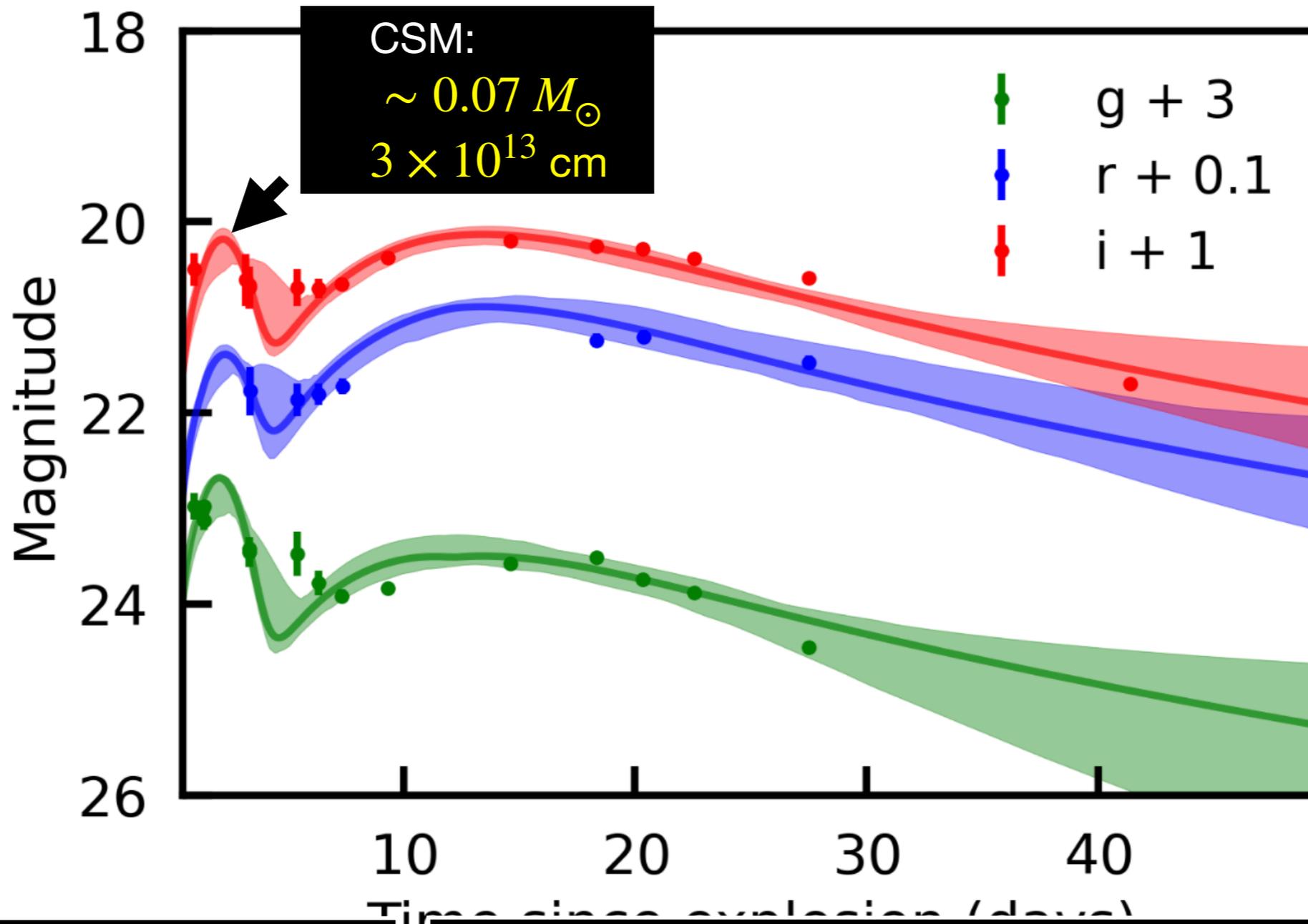
EP250108a [No afterglow]



Our scenario for EP250108a



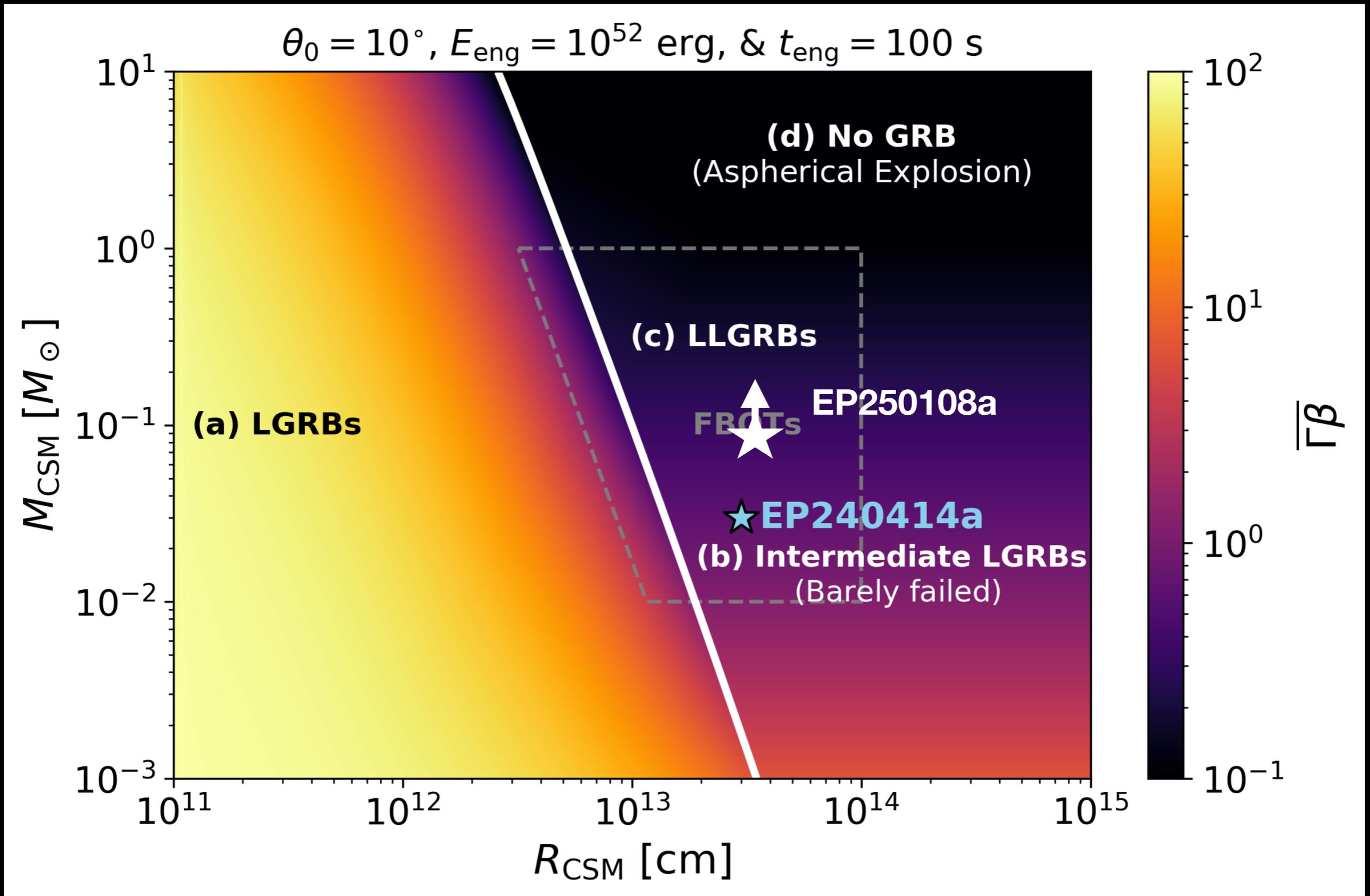
EP250108a [LLGRB+FBOT]



Phase 1:
FBOT (thermal)

Phase 2:
Ic-BL SN (Ni56)

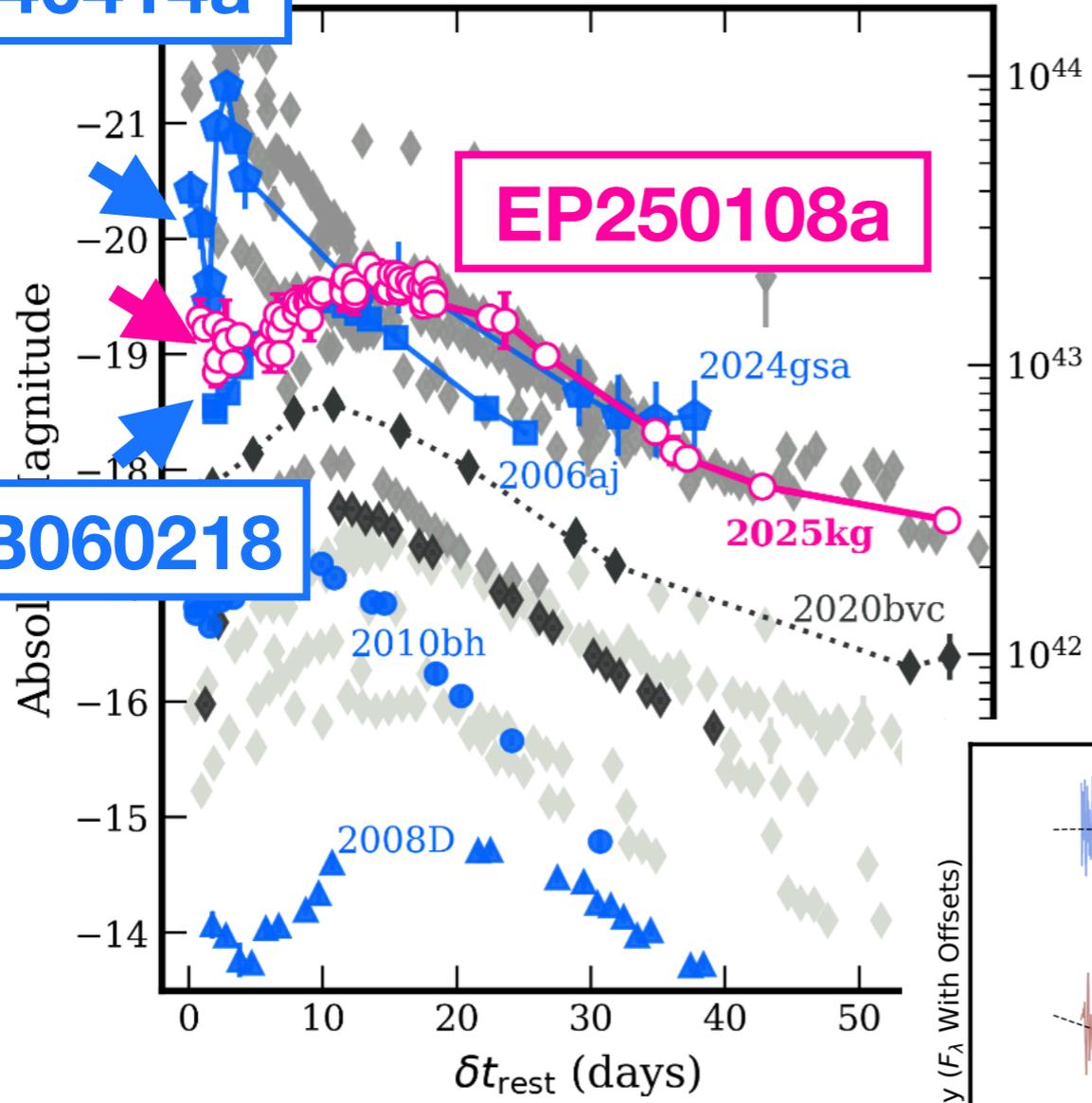
EP240414a & EP250108a



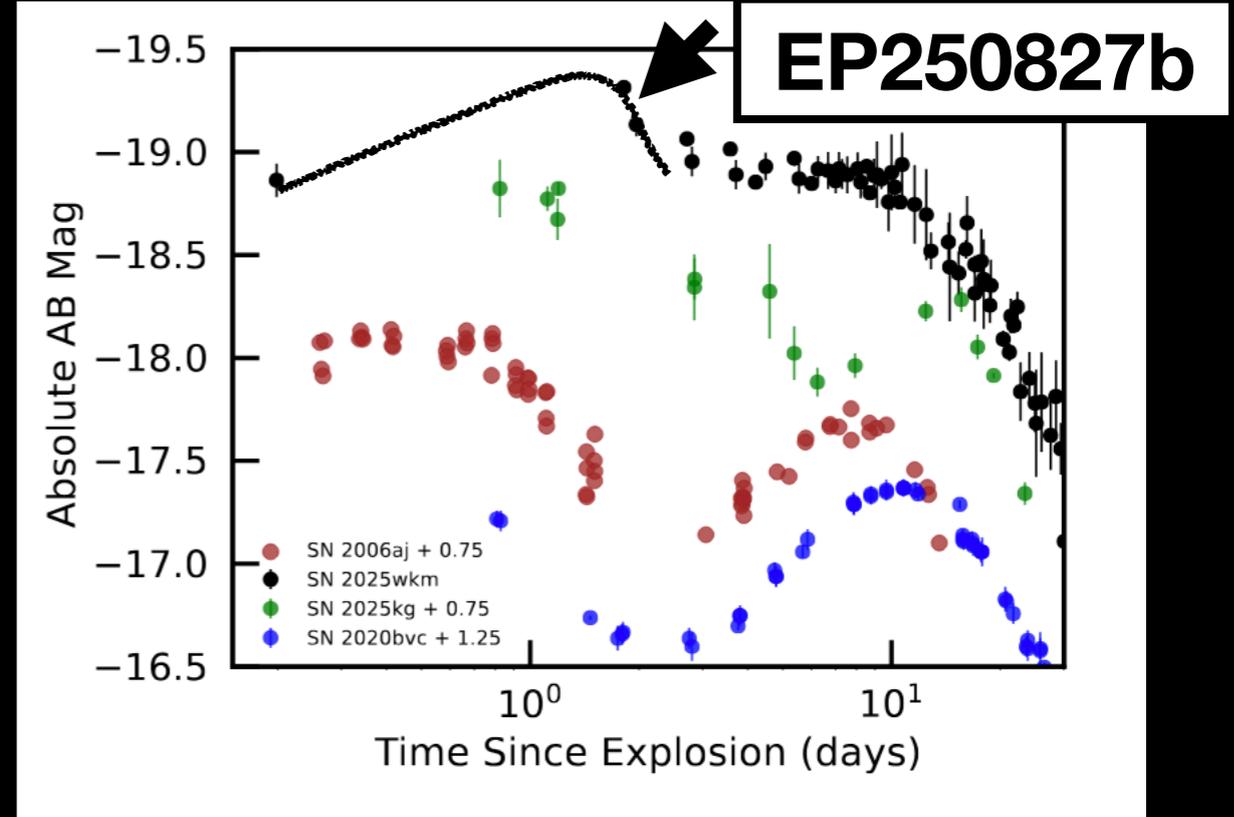
EPs so far: “CSM peak”

EP240414a

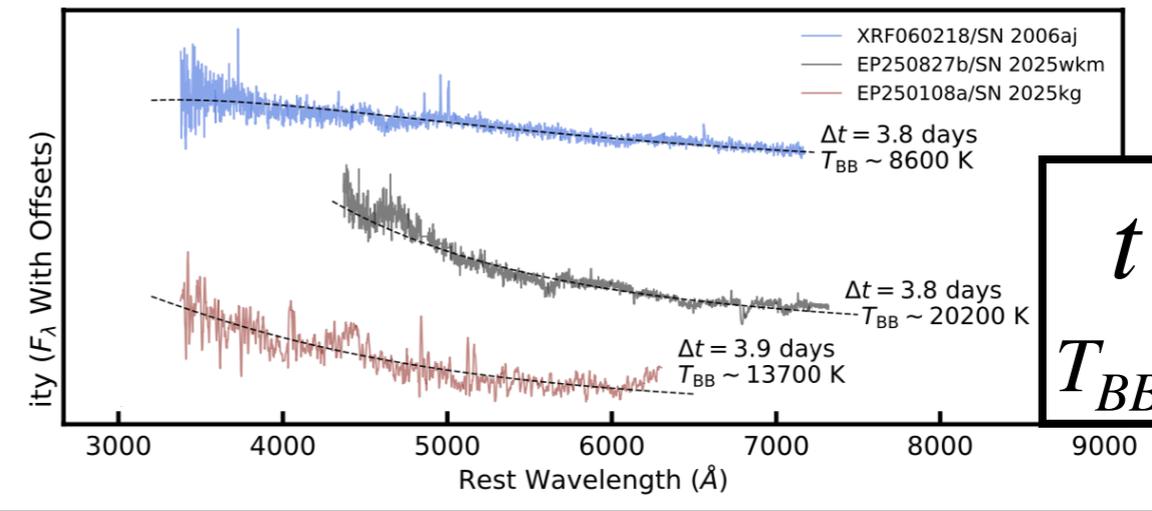
$\lambda_{rest} \approx 0.5-0.58 \mu m$



GRB060218



EP250827b



$t \sim 3.8d$
 $T_{BB} \sim 20\,000K$

Early observations (& lack of bright optical afterglow) consistently show ~ a few days long blue transient! Ubiquitous?

Summary

We **quantified** the effect of the CSM on GRB jets

Follow-up of EPs show that we need an early “**CSM peak**”

Similarity in inferred LLGRB **CSMs** $\sim 10^{-2}M_{\odot}$ and $\sim 10^{13.5}$ cm

LGRBs? [the Afterglow is too bright and hides the CSM peak anyways]

See Om's Talk
Tomorrow
(BOAT GRB)

