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, August 5-8, 2025

Outline:

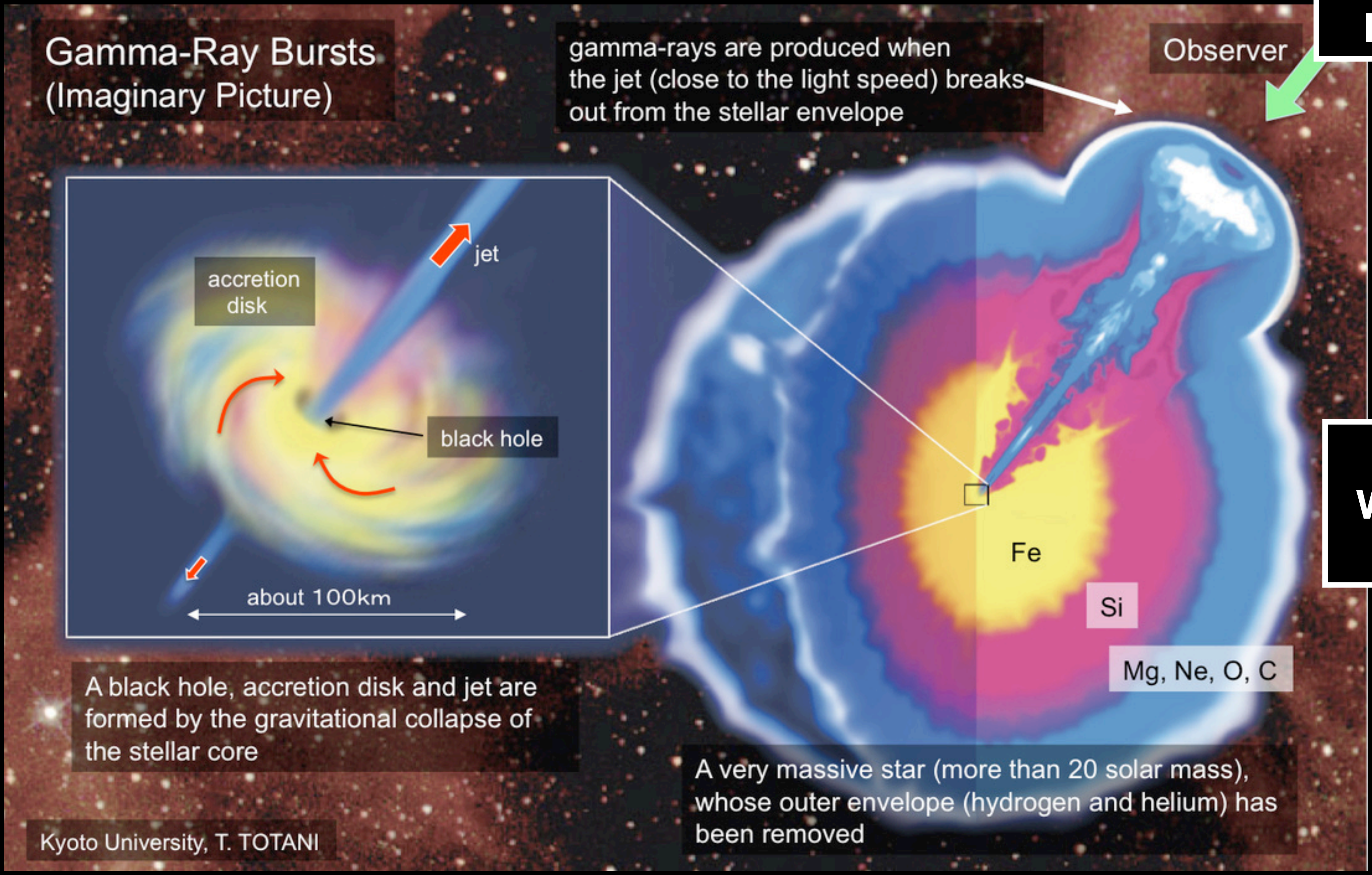
Part I: New modeling for GRB jets

Part II: Application to recent EP events

Part III: Application to LRDs (in prep)

Part I:
New modeling for GRB jets

Long GRBs: "Clean" Relativistic jet



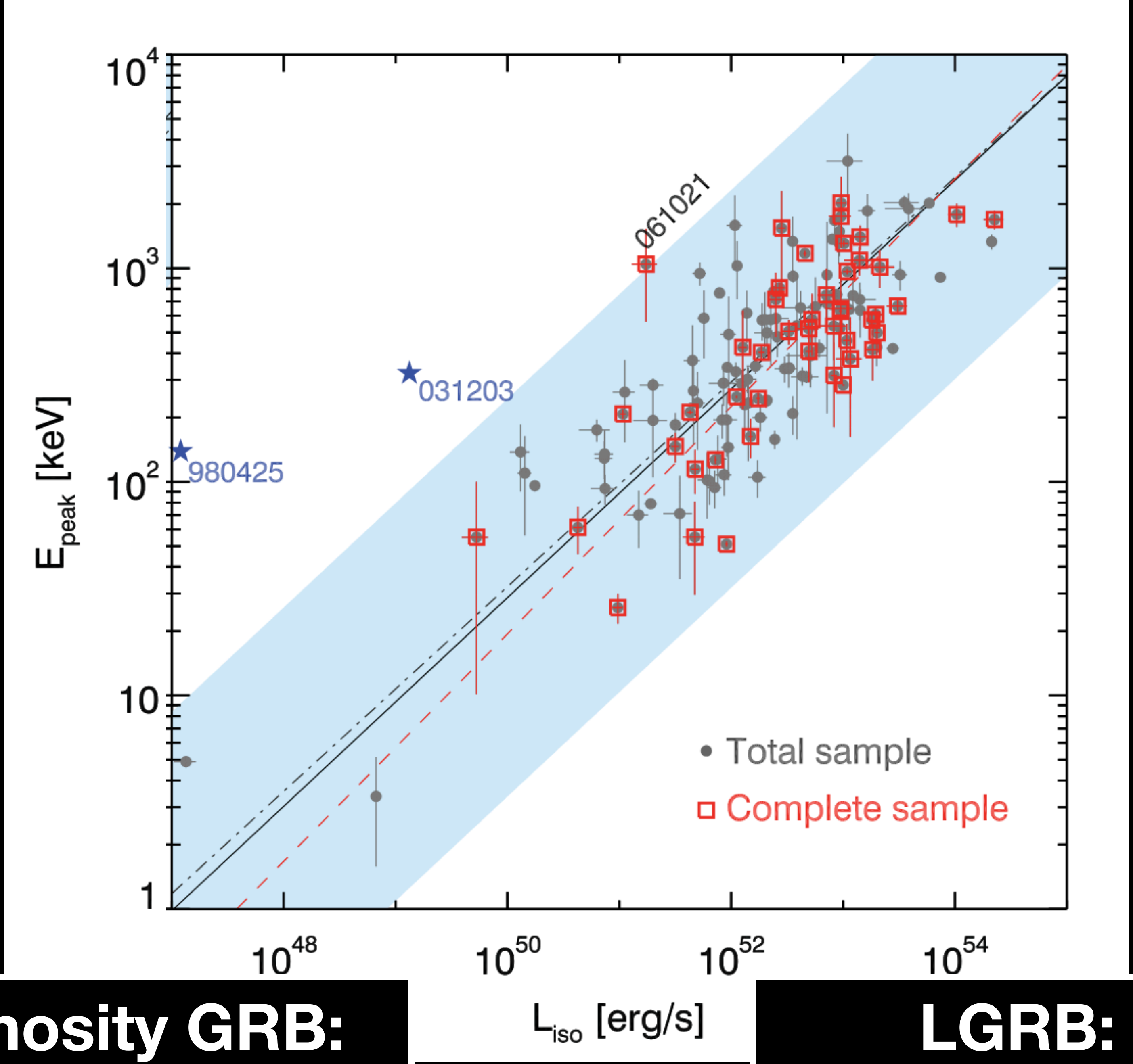
Observer: Long GRB

Stripped Wolf-Rayet Star

Question: Is this a typical system in nature?

Credit: T. Totani

Low Luminosity GRBs



Credit: Yonetoku+04; Nava+12

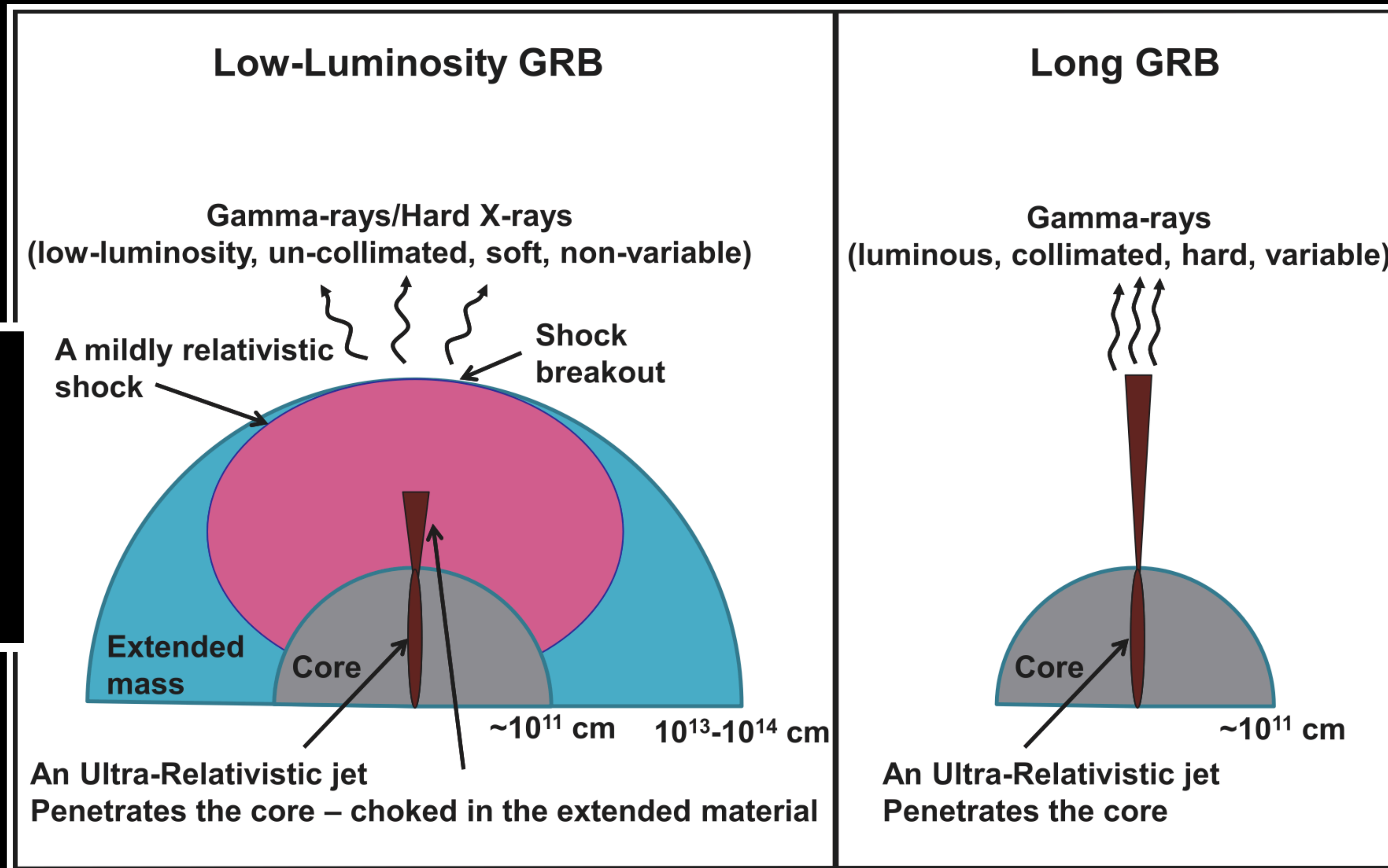
Low Luminosity GRB: $\sim 10^2 - 10^3$ **Gpc**$^{-3}$ **yr**$^{-1}$

LGRB: ~ 1 **Gpc**$^{-3}$ **yr**$^{-1}$

Question: What is the origin of LLGRBs?

Possible cause: "CSM"

Credit: Nakar 15

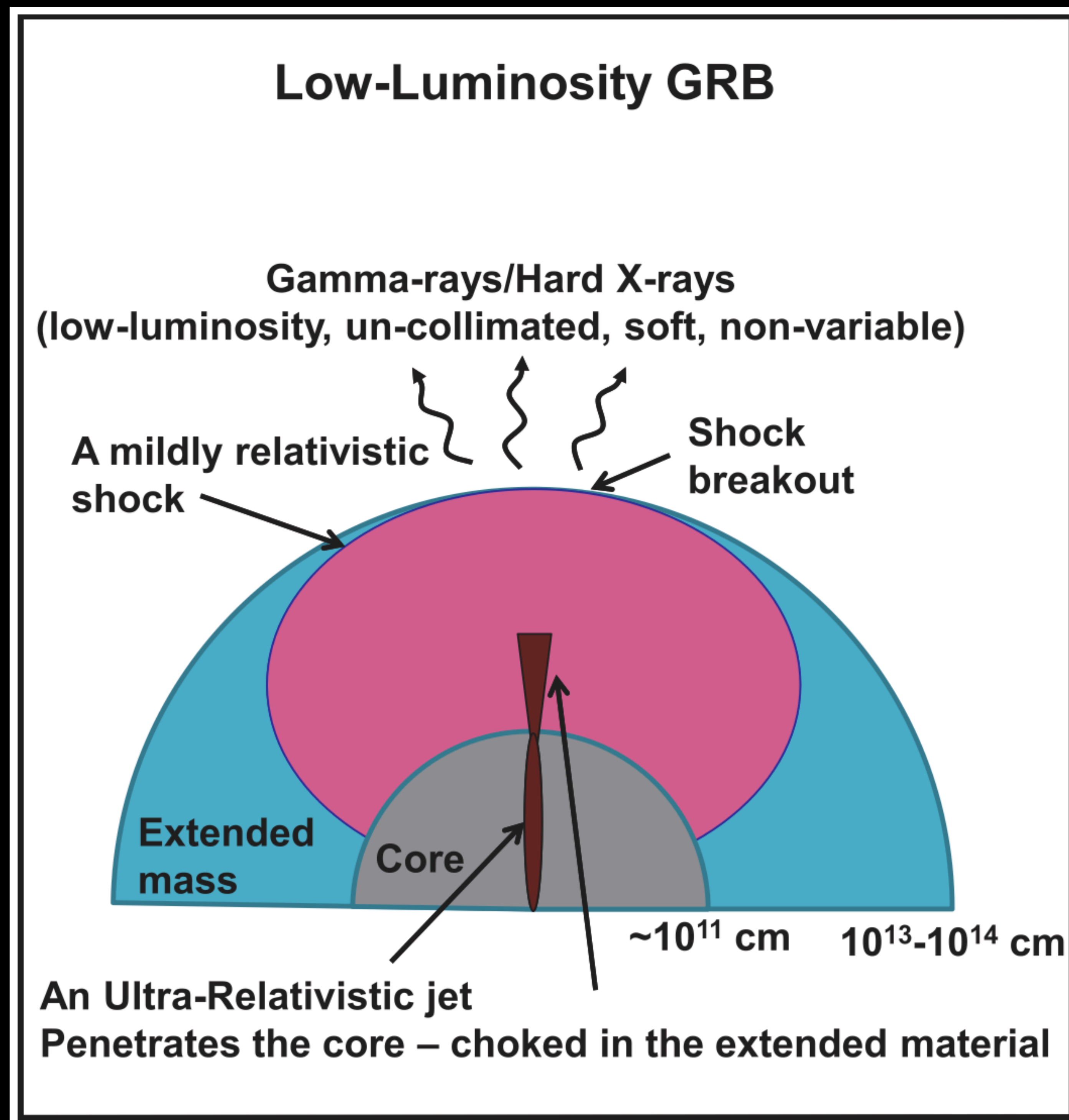


Process: pre-explosion mass-loss ? => CSM

Rate: LLGRBs >> LGRBs

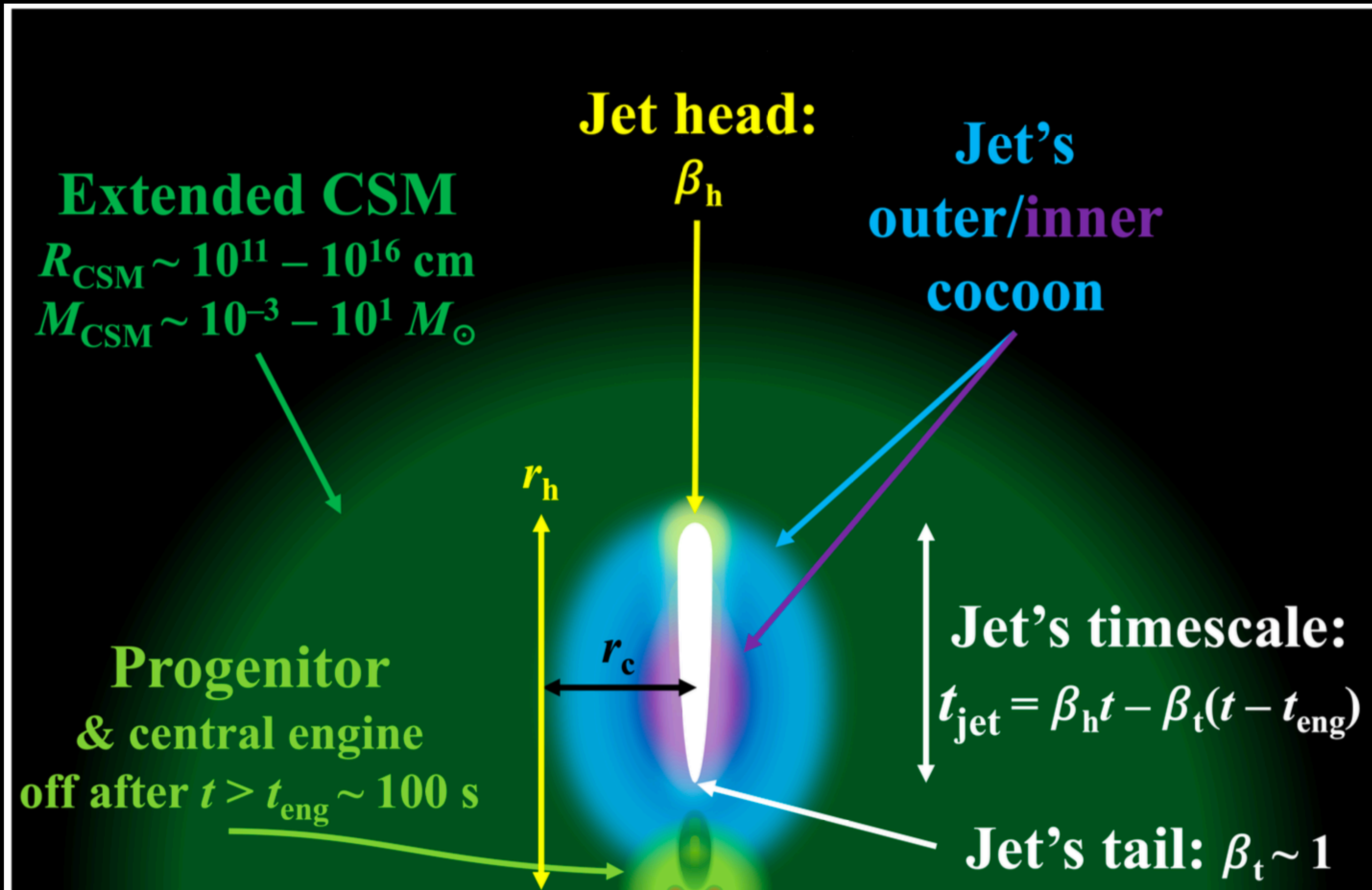
Key Point: Even a low-mass CSM can make a clean jet dirty

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



Credit: Nakar 15
Also: Suzuki+22; 24

Modeling Jets in CSM

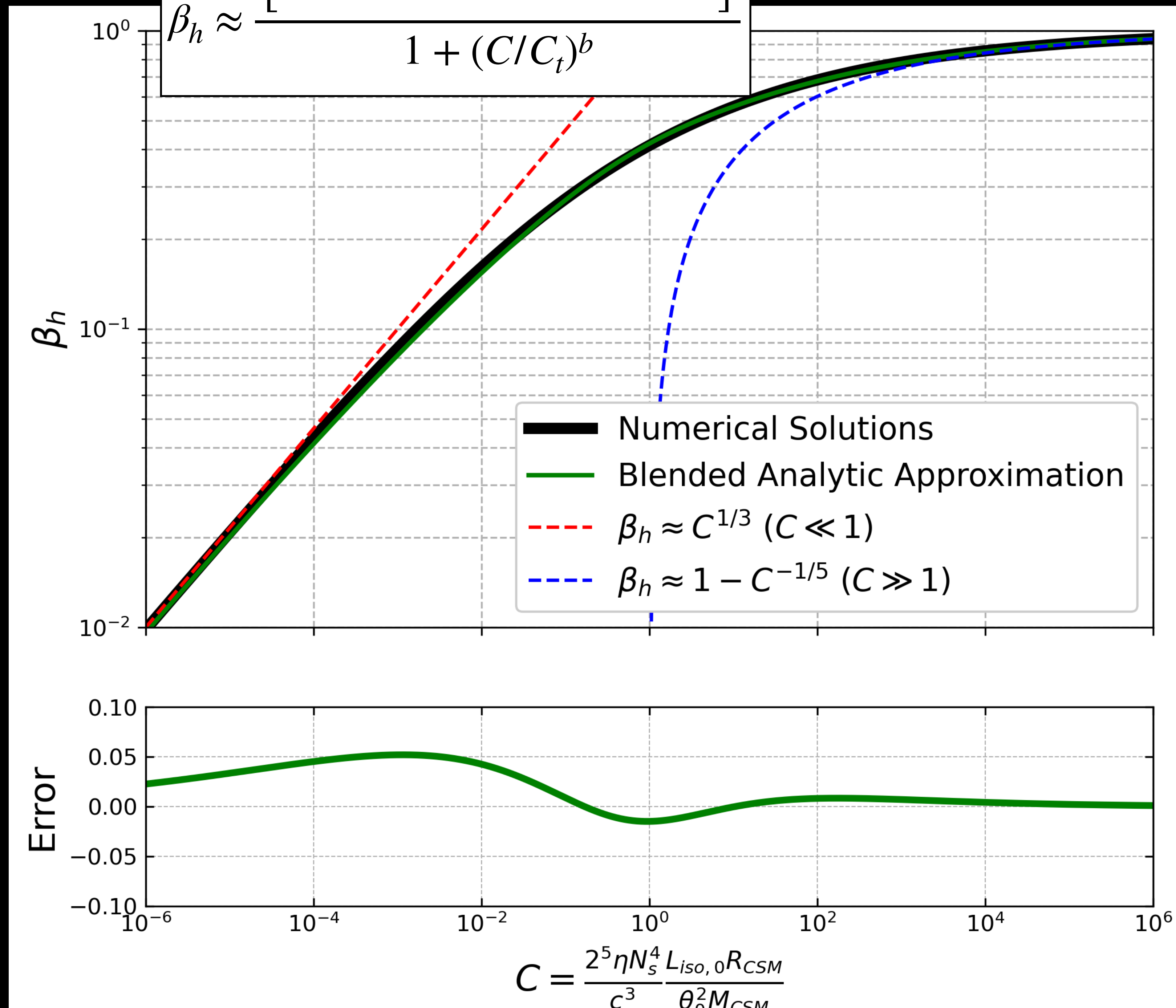


Universal Solution

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

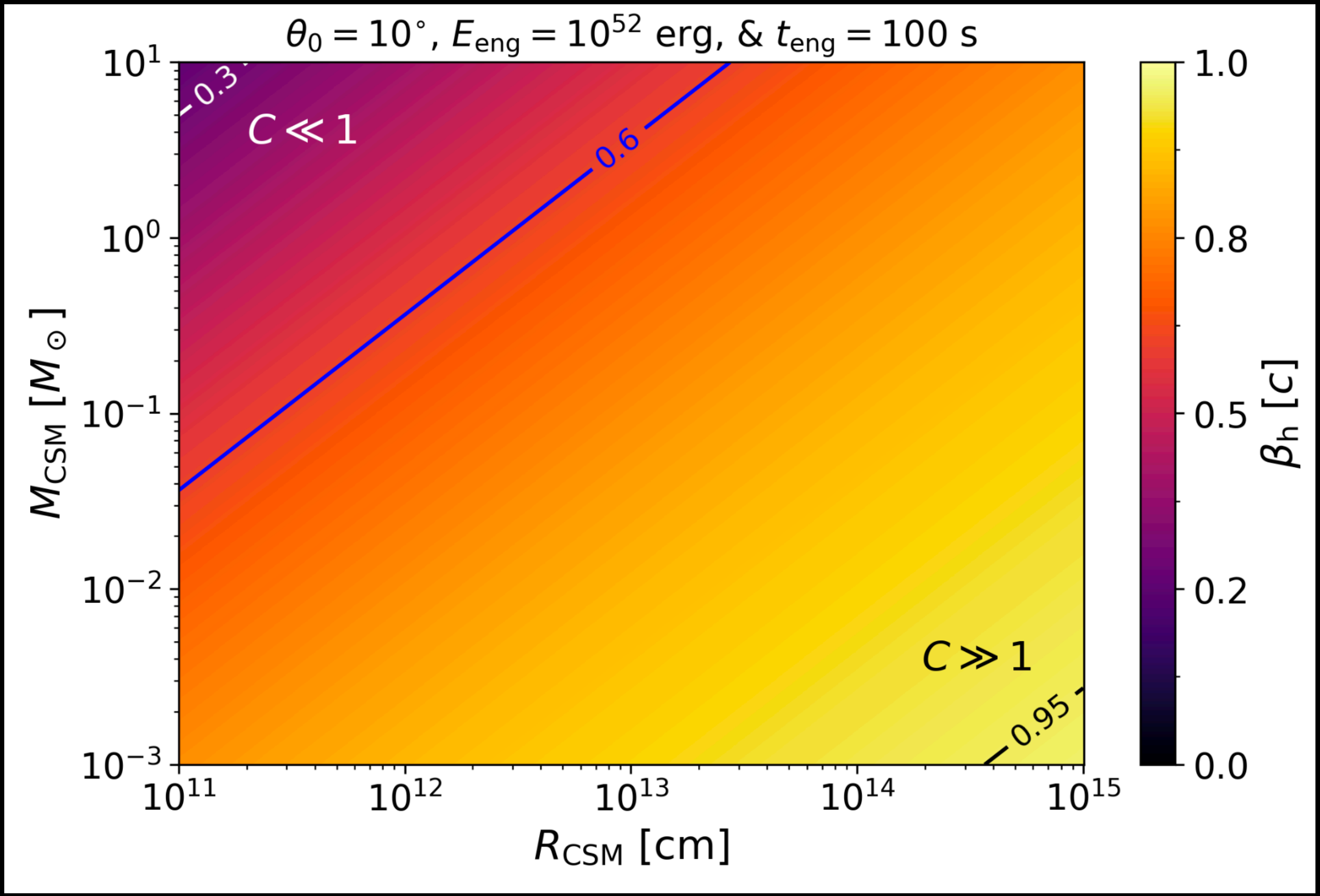
Credit: HH+25

Jet head velocity (β_h)



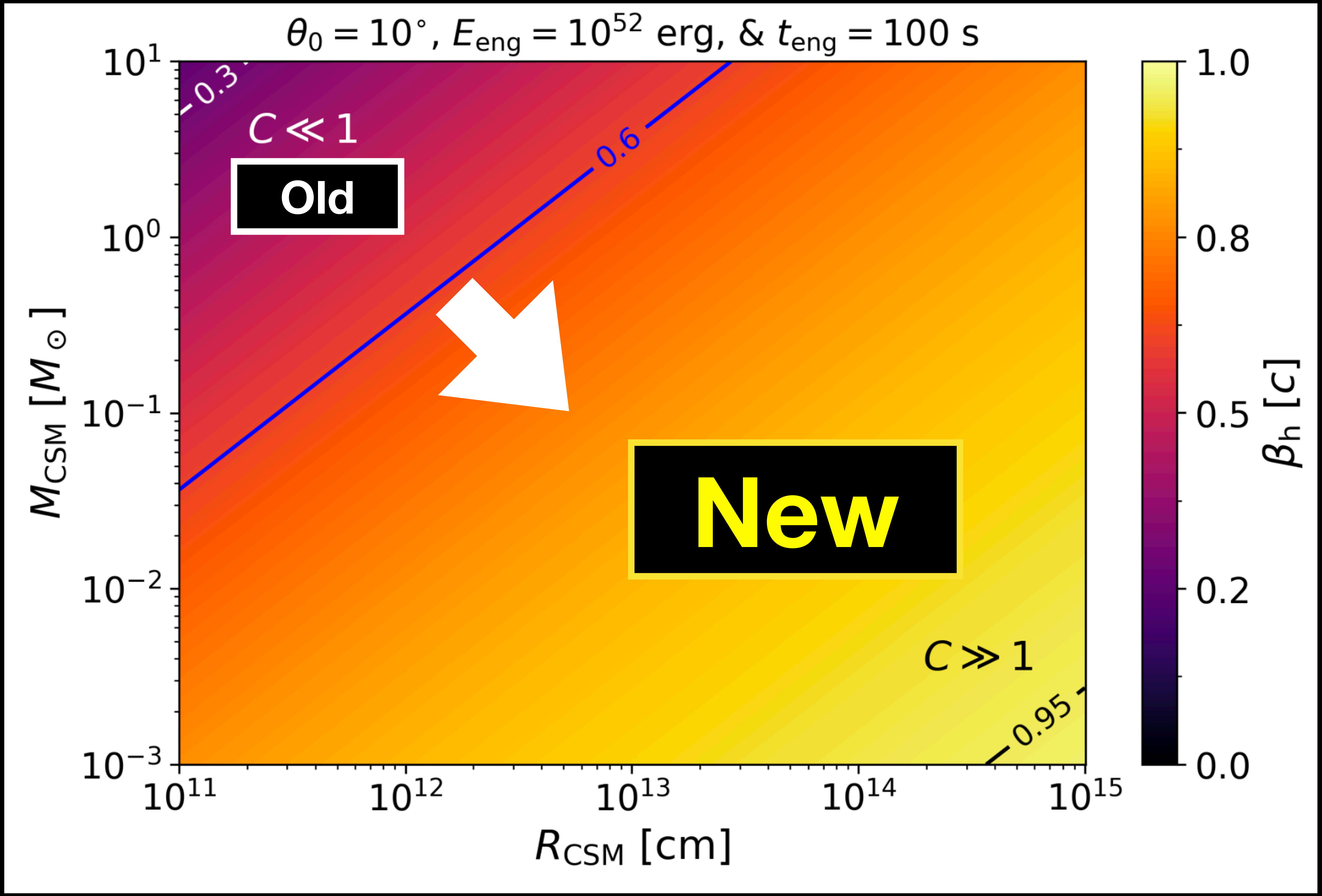
CSM presence: $C \propto \dfrac{E_{\rm eng}}{t_{\rm eng}\theta_0^2} \dfrac{R_{\rm CSM}}{M_{\rm CSM}}$

Results: Jet head velocity



Credit: HH+25

Results: Jet head velocity



Credit: HH+25

New expression for the breakout time

Hamidani+25:

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

Bromberg+12:

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

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

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

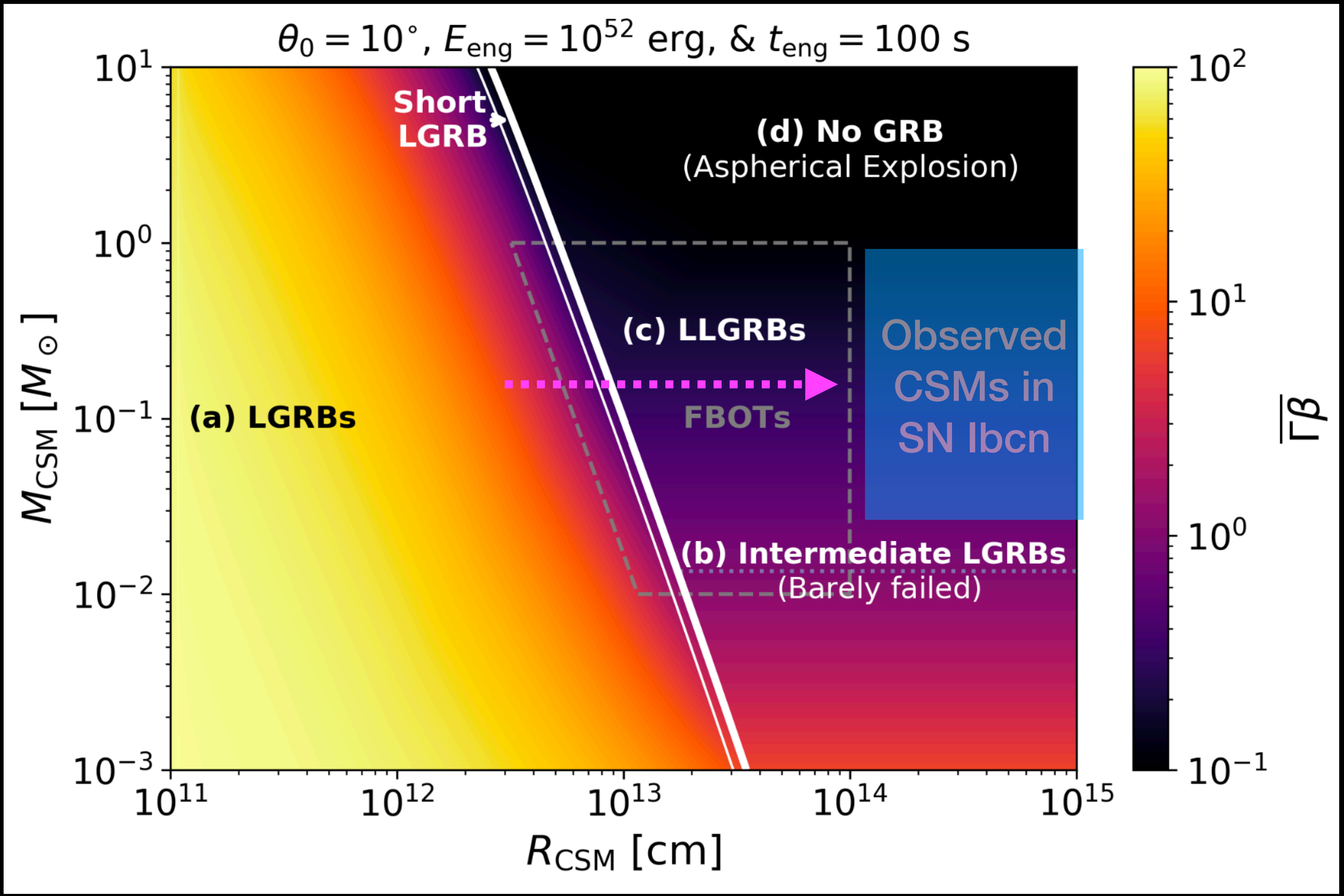
With

Energy weighted

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

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

Diversity of transients



Credit: HH+25

Summary I

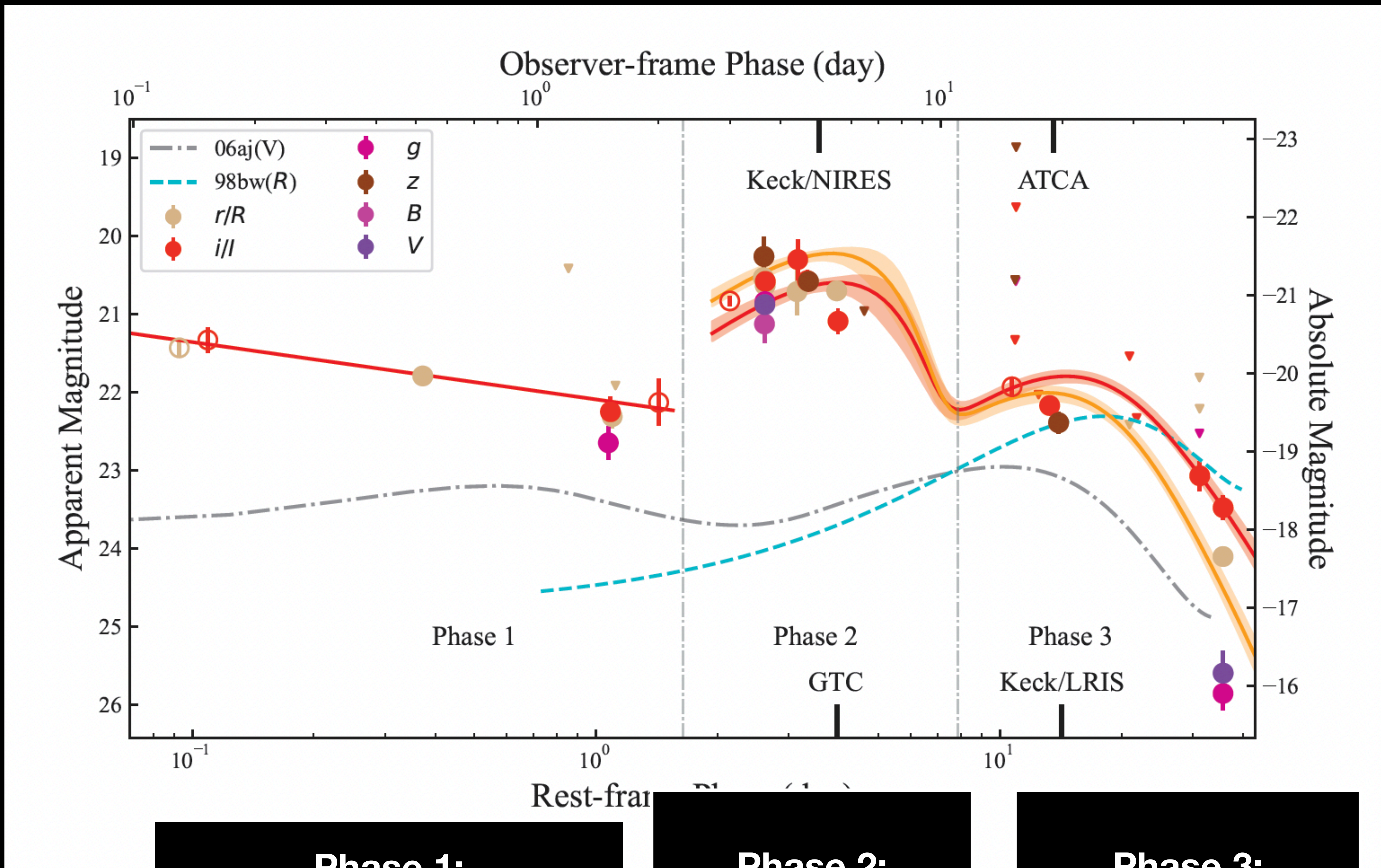
- Fully analytic model for jet dynamics in CSM
  - Jet/CSM parameters
    ⇒ Je propagation (β_h, t_b, …)
    ⇒ Cocoon properties/emission ($L_{\rm bol}$, $r_{\rm ph}$, $T_{\rm ph}$, …)
  - Public in Python: https://github.com/hamidhamidani/cocoon-cooling-model (1 model: < 100ms)
- Can be used to probe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

Part II:
Application to recent events

Recent Einstein Probe (and Future HiZ-GUNDAM) Events

CREDIT: EP

EP240414a [GRB+Fast transient]



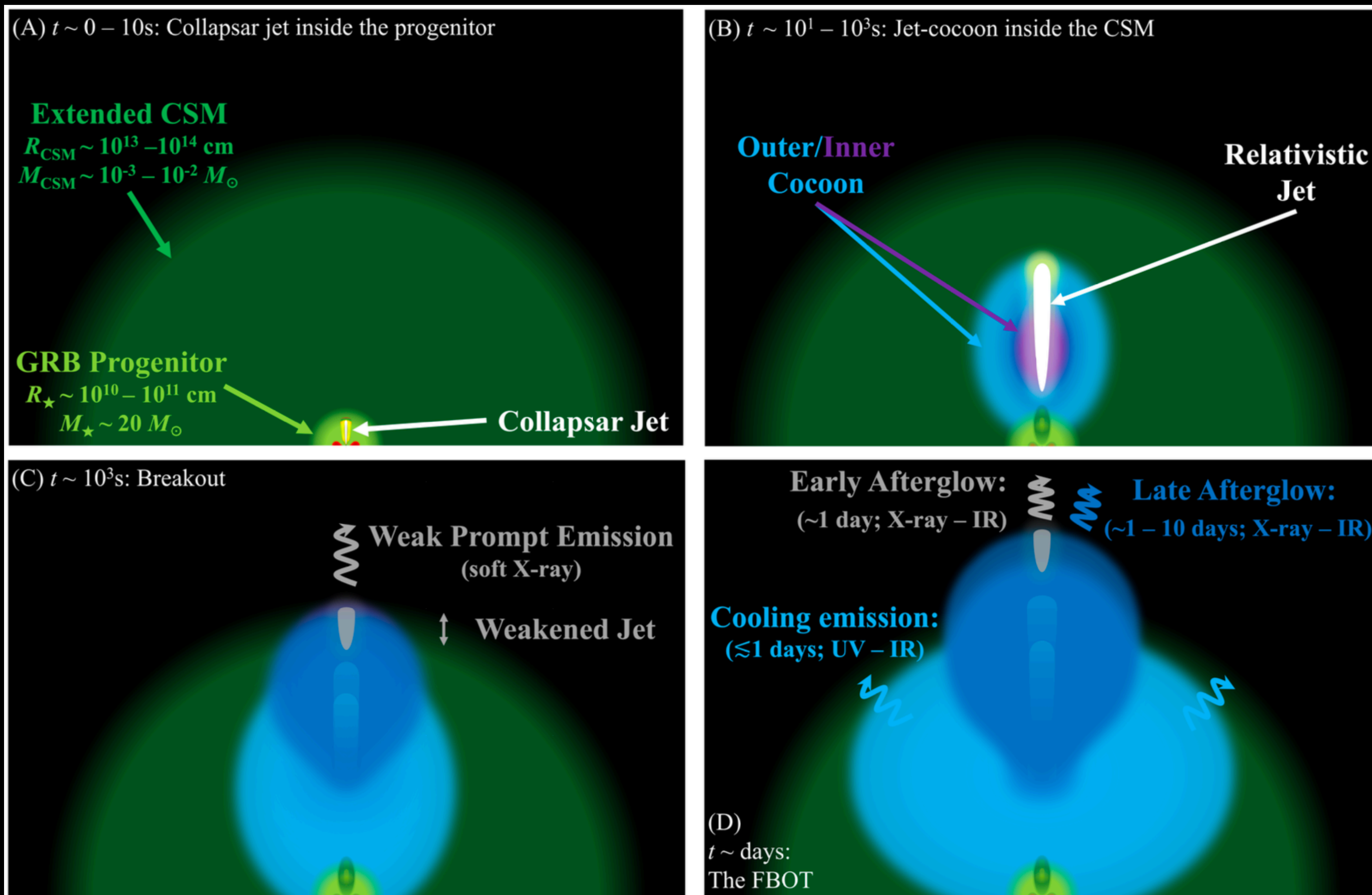
Phase 1: thermal?

Phase 2: non-thermal?

Phase 3: Ic-BL SN (Ni56)

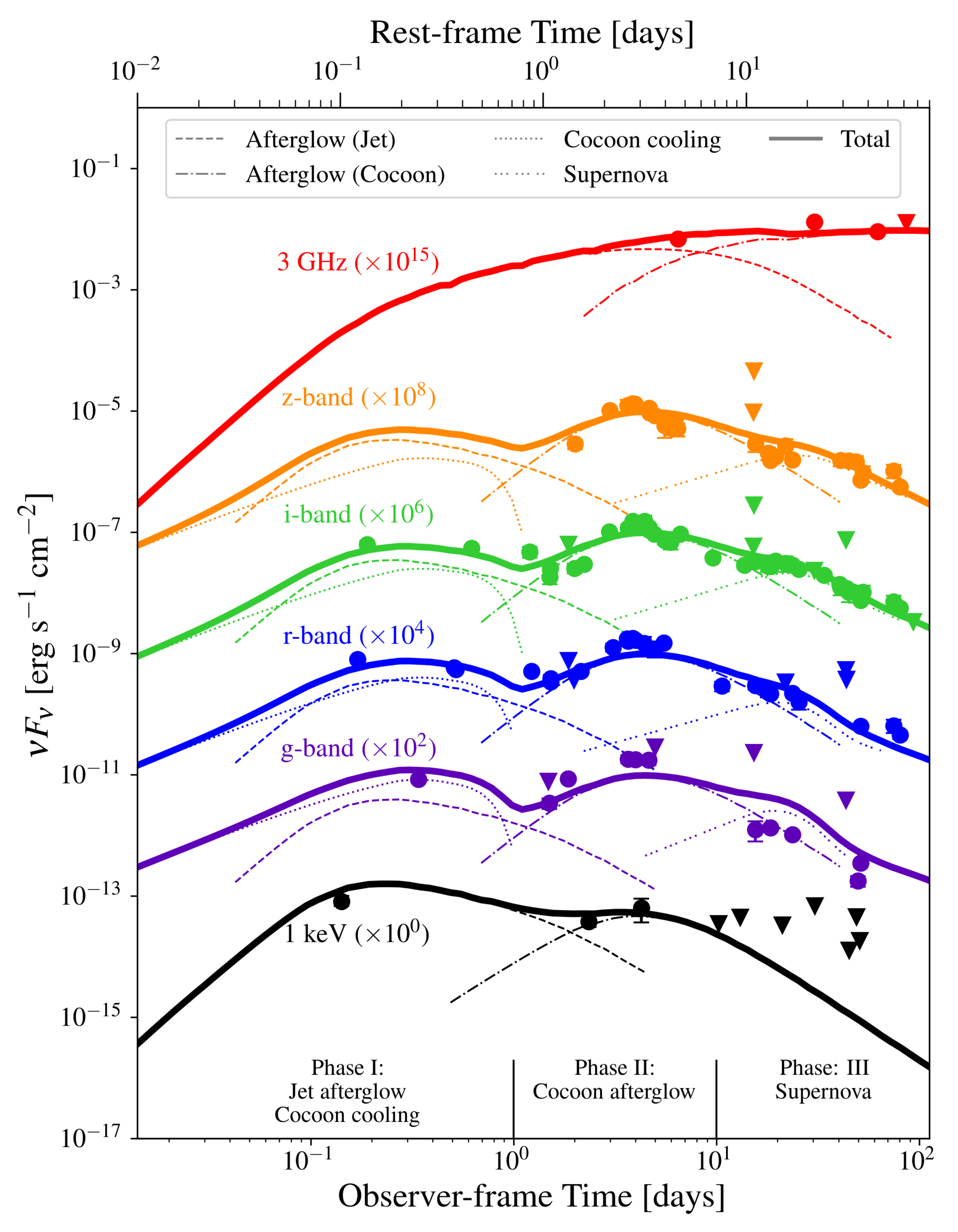
Credit: Sun+24

Our scenario for EP240414a



Credit: HH+25

Results
[EP240414a]



CSM:

$\sim 0.03\, M_\odot$

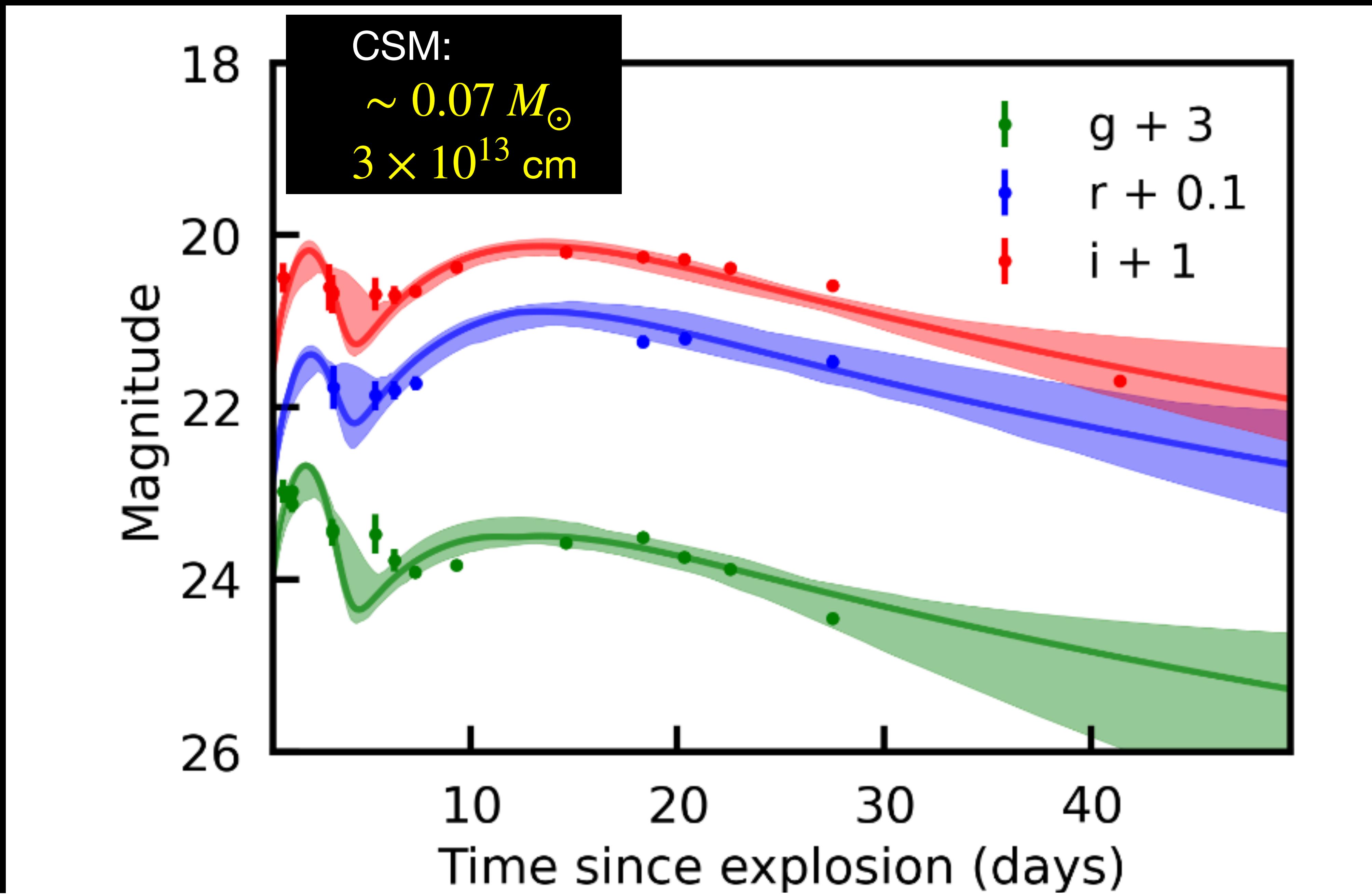
3×10^{13} cm

Jet:

Conventional

Credit: HH+25

EP250108a [LLGRB+FBOT]

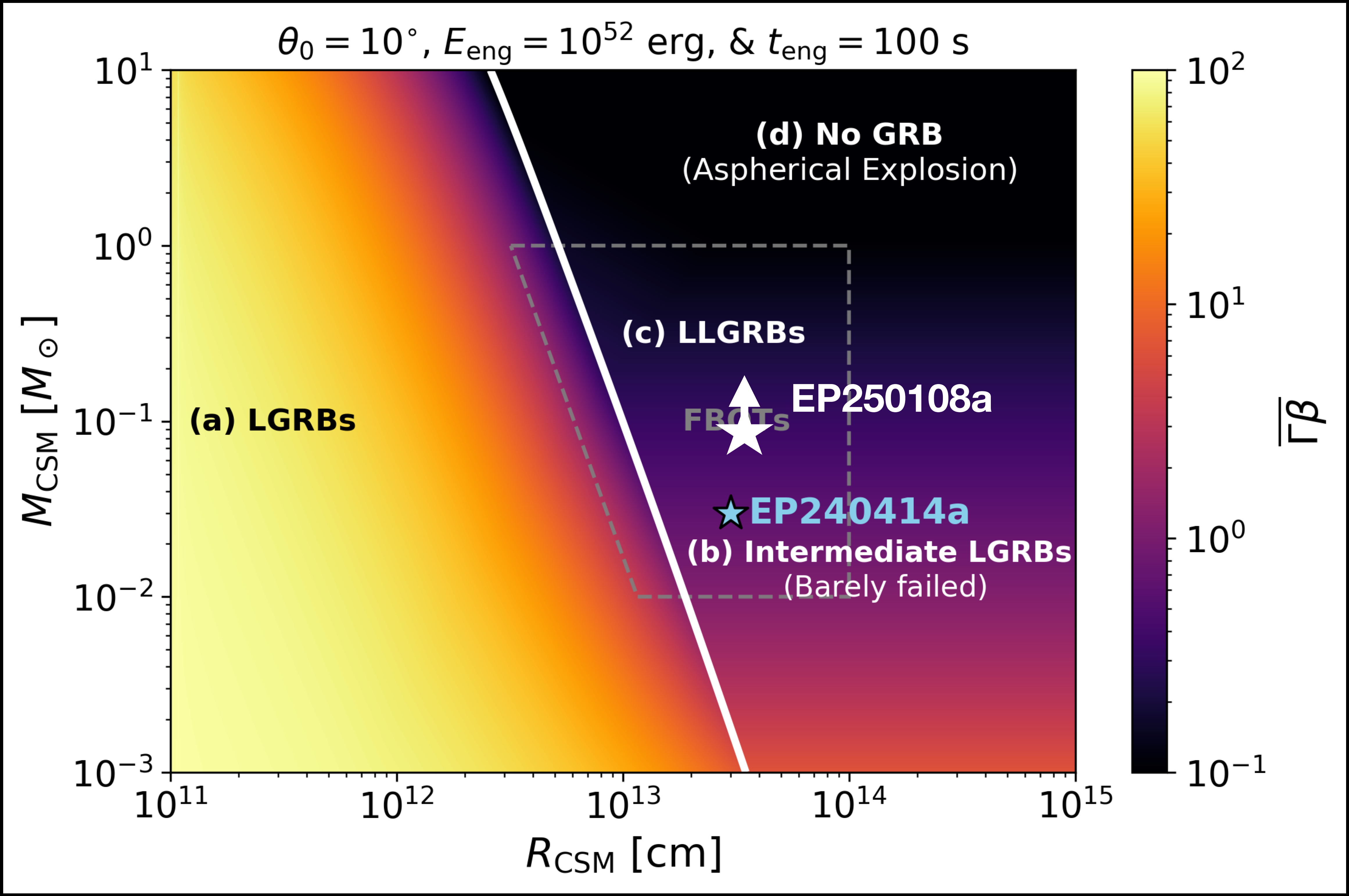


Phase 1:
FBOT (thermal)

Phase 2:
Ic-BL SN (Ni56)

Credit: Srinivasaragavan+24

Intermediate GRB for EP240414a



Credit: HH+25

Summary II

Early follow-up observations allows us see the relativistically diverse composition of GRB explosions (jet, rela. cocoon, non-rela. cocoon)

and constrain the CSM/environment around GRB progenitor

So far, observations consistently point to a CSM of $\sim 0.03 M_\odot$ and $\sim 3 \times 10^{13}$ cm

Part III:
Application to LRDs

What are LRDs?

High-z red objects $z \gtrsim 4$

Compact/Unresolved (PSF): ~ 100p

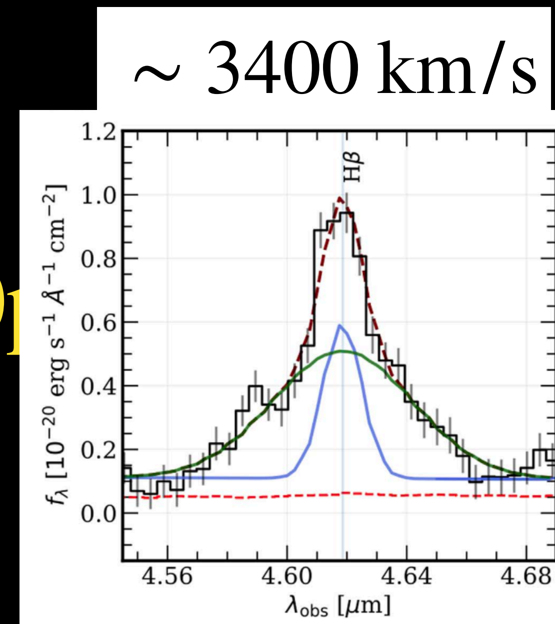
Broad lines: ~ 1000 km/s (?)

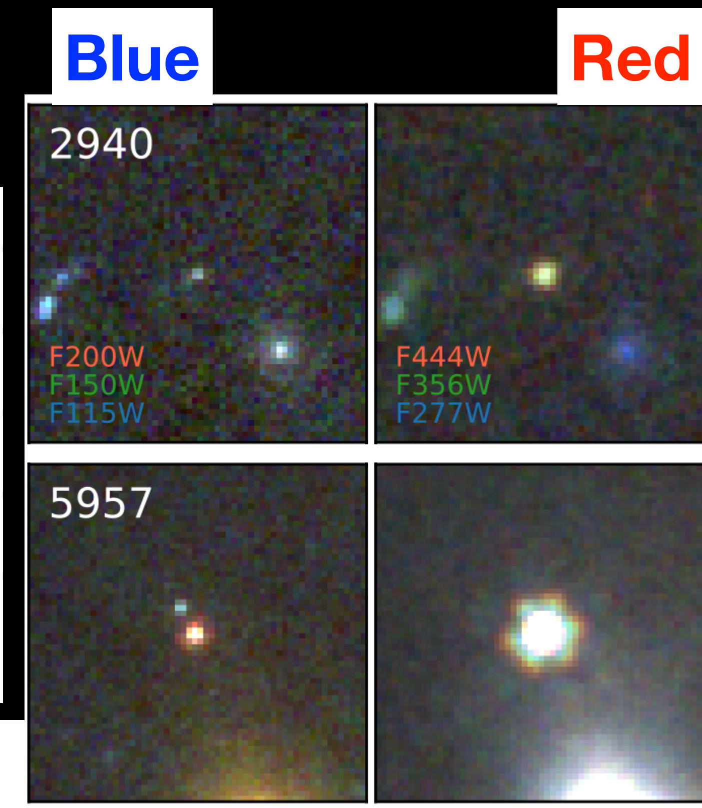
SED: V-shape

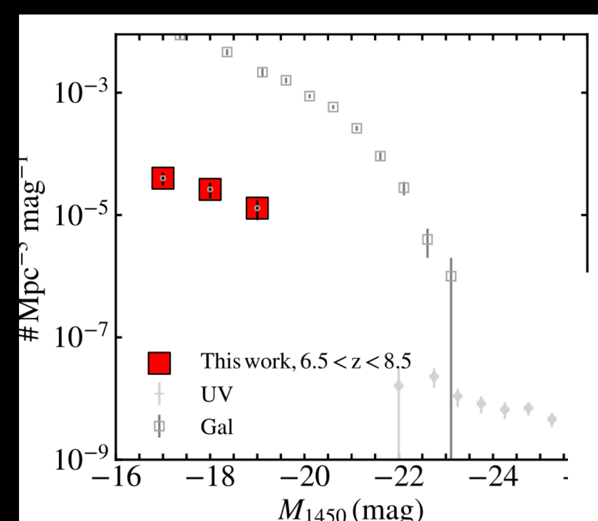
X-ray / Radio: No/Weak

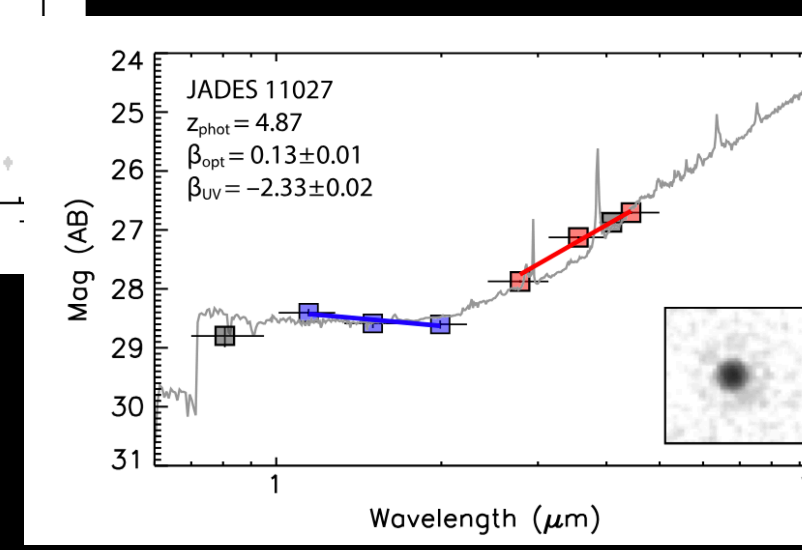
~No variability

Number density (relative to AGNs)
$\sim 10^{-5}\mathrm{Mpc}^{-3}$ (~1% of galaxies)



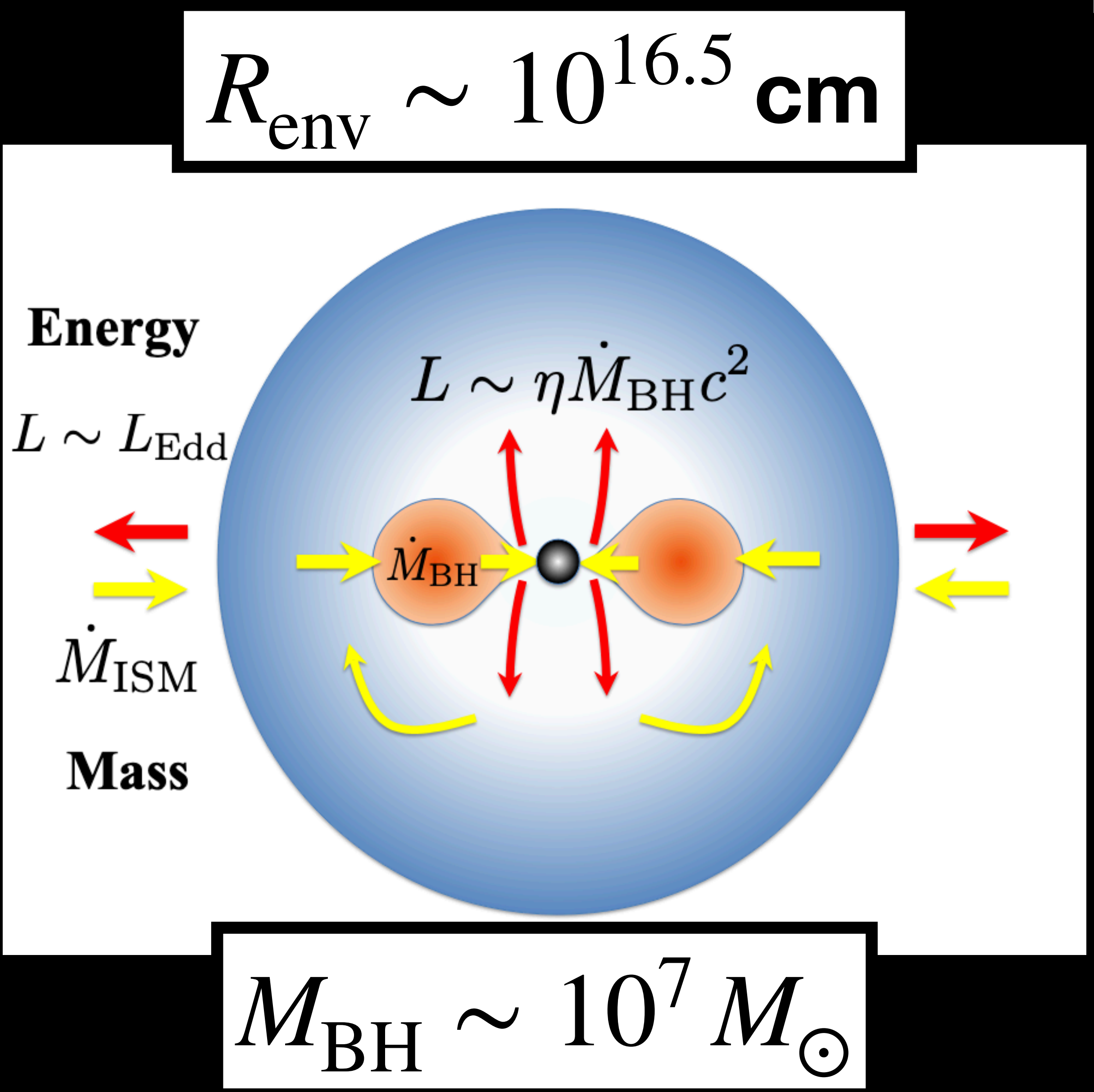




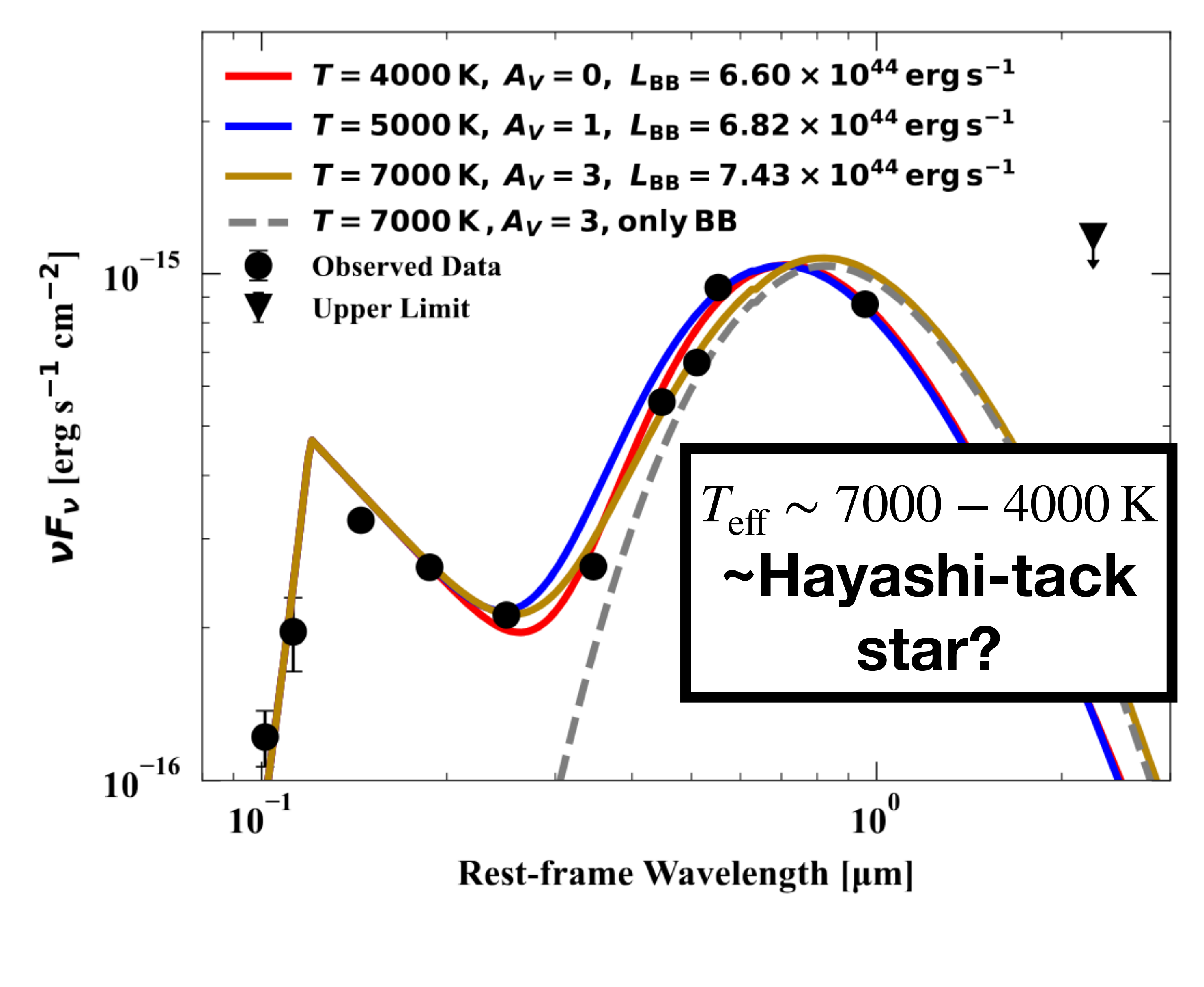


Labbe+2023; Greene+25; Harikane+23 etc.

“BH envelope” scenario



Stars + BH = V-shaped LRDs



Kido et al. 2025

Scenario Elegance

Broad lines: $v_{\rm grav} \equiv v_{\rm BL} \sim 2000~{\rm km~s^{-1}} \left(\frac{M_{\rm BH}}{10^7 M_\odot}\right)^{\frac{1}{2}} \left(\frac{R_{\rm env}}{10^{16.5}~{\rm cm}}\right)^{-\frac{1}{2}}$

Luminosity: $L_{\rm LRD} \equiv L_{\rm Edd} \sim 10^{45}~{\rm erg~s^{-1}} \left(\frac{M_{\rm BH}}{10^7 M_\odot}\right)$

Temperature: $T_{\rm env,eff} \sim 5800~{\rm K} \left(\frac{M_{\rm BH}}{10^7 M_\odot}\right)^{\frac{1}{4}} \left(\frac{R_{\rm env}}{10^{16.5}~{\rm cm}}\right)^{-\frac{1}{2}}$

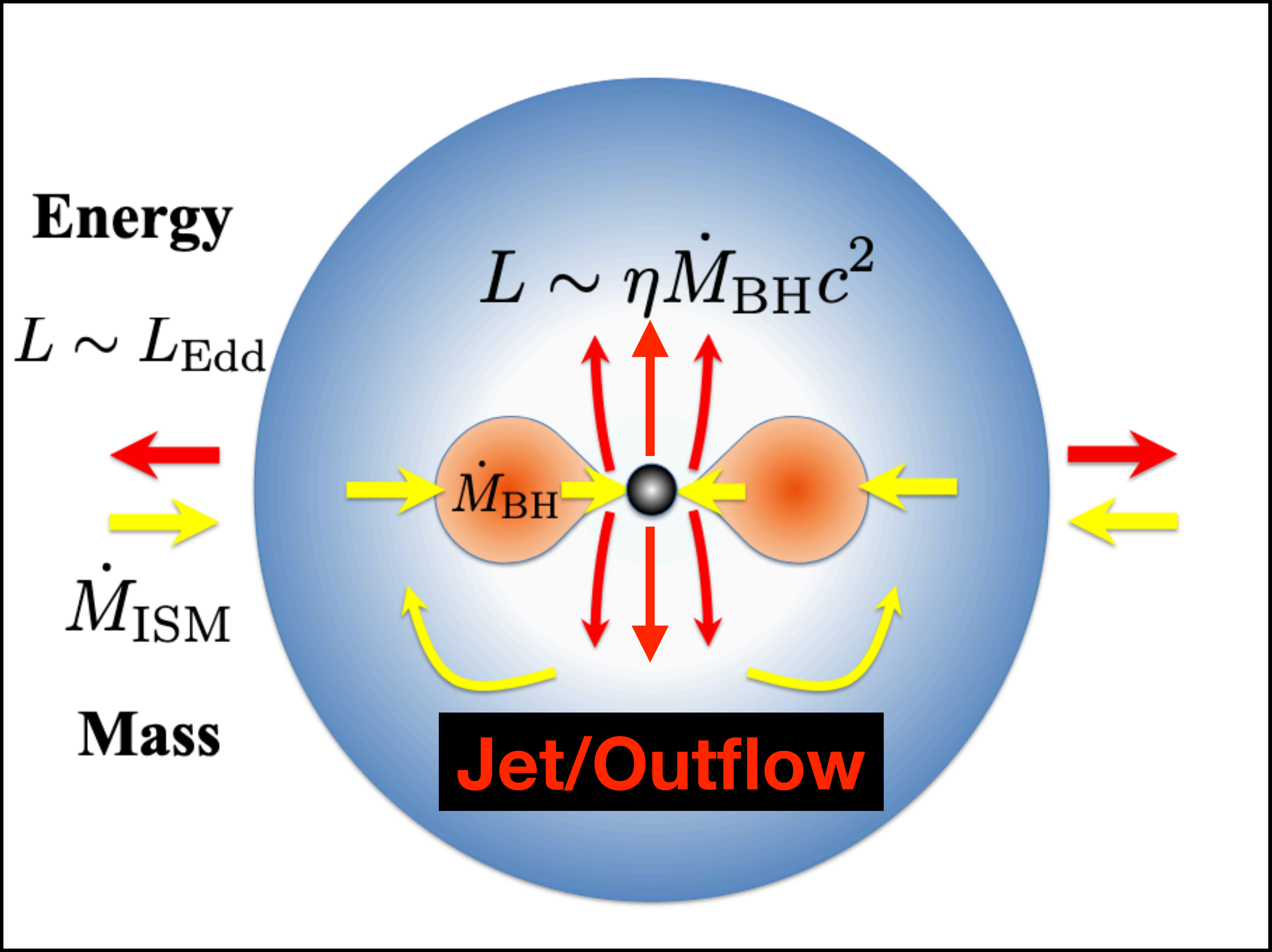
Number density: $\frac{N_{\rm LRD}}{N_{\rm Gal}} \sim \frac{t_{\rm Cosmic}}{t_{\rm Sal}} \sim 10^{-2}$

$t_{\rm Cosmic}(z \sim 4-7) \sim 10^9~{\rm yr}$

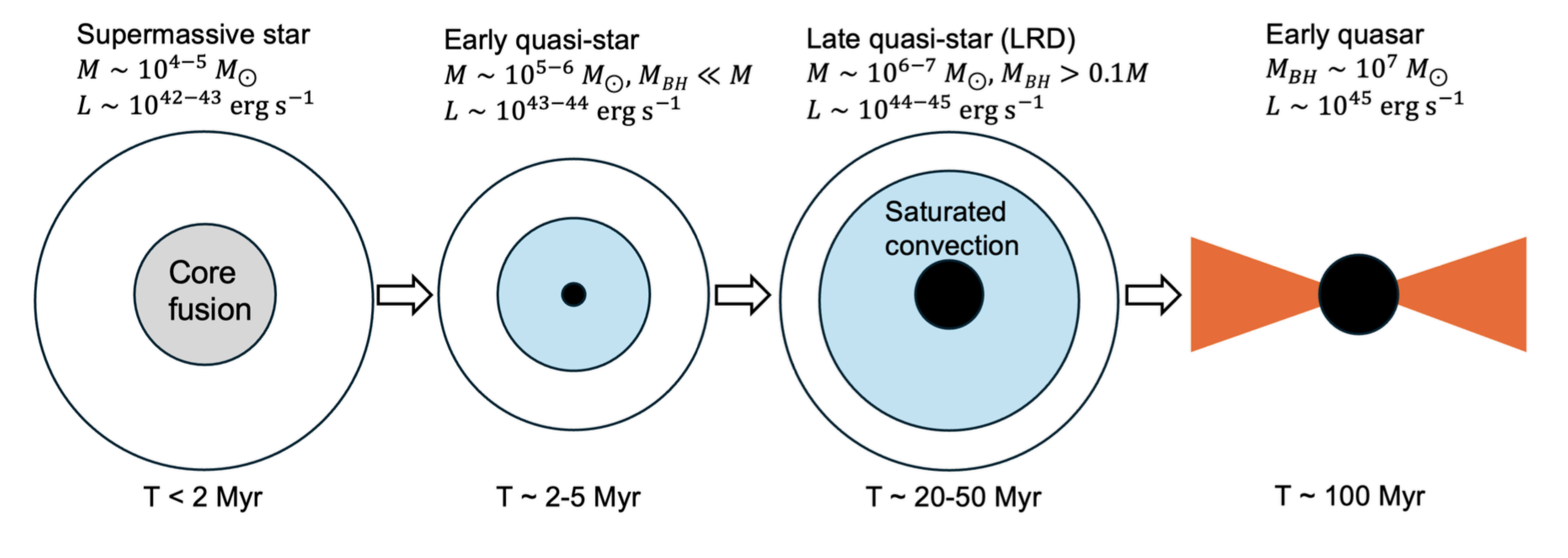
$$t_{\rm age} \approx \frac{M_{\rm env}}{\dot{M}_{\rm Edd}} \sim t_{\rm Sal} \sim 4.5 \times 10^7~{\rm yr} \left(\frac{M_{\rm env}}{10^{6-7} M_\odot}\right)$$

Jet launch?

Kido et al. 2025



Q: How LRDs evolve to QSO?



i.e., When do LRDs evolve to QSOs?

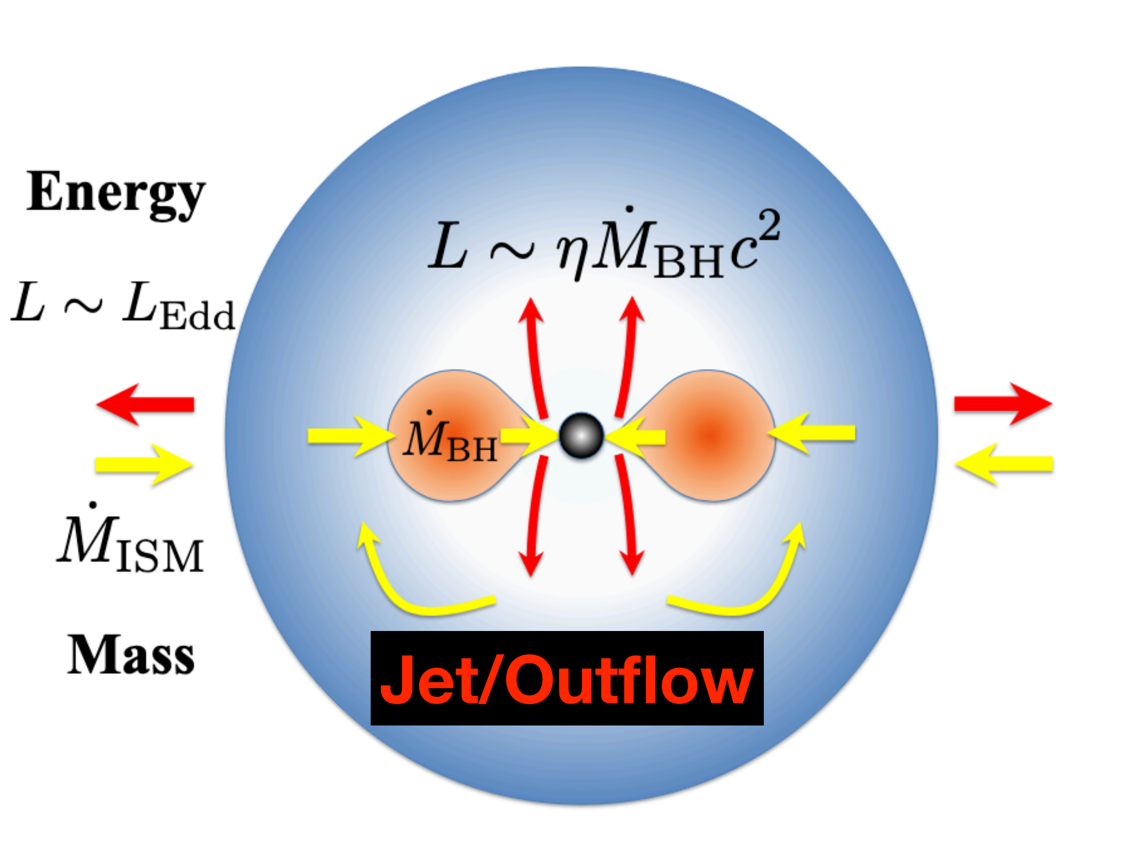
Begelman & Dexter 2025

No X-ray/Radio

No X-ray:

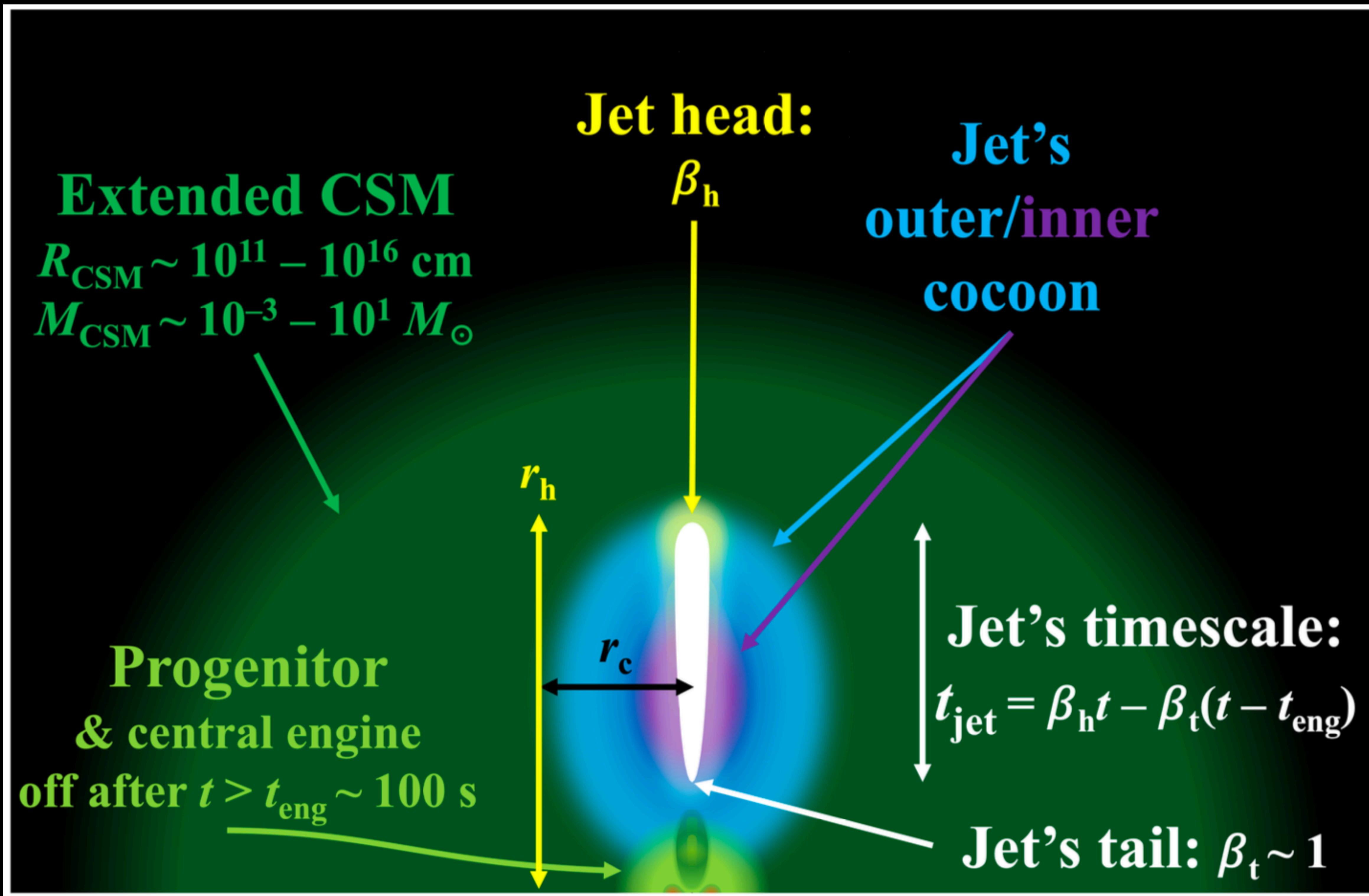
$$N_{\rm H} \approx 3.2 \times 10^{30}\ \mathrm{cm}^{-2} \left(\frac{M_{\rm env}}{10^7\, M_\odot}\right)\left(\frac{R_{\rm env}}{3\times 10^{16}\,\mathrm{cm}}\right)^{-}$$

No radio: Jet is failed in the envelope?



Kido et al. 2025

Same Framework!
CSM => BH-envelope



Jet emergence (in prep)

Jet head velocity:

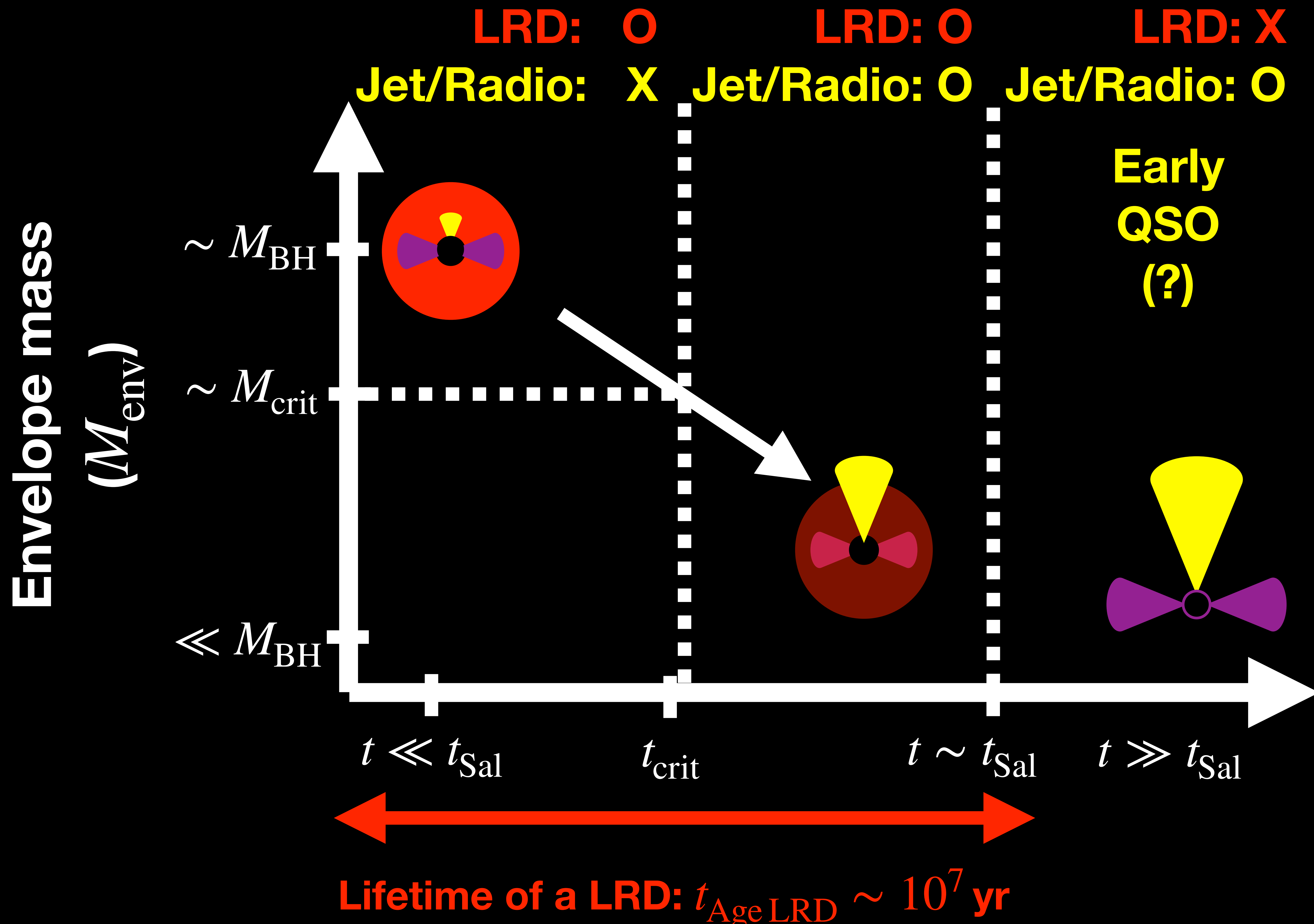
$$\beta_h \approx 4 \times 10^{-3} \times \left(\frac{M_{\rm env}}{10^3 M_\odot}\right)^{-\frac{1}{2}} \left(\frac{r}{10^{16.5}\ \mathrm{cm}}\right)^{\frac{1}{2}}$$

Sound Speed:

$$c_s/c \approx 4 \times 10^{-3} \times \left(\frac{M_{\rm BH}}{10^7 M_\odot}\right)^{-\frac{1}{2}} \left(\frac{r}{10^{16.5}\ \mathrm{cm}}\right)^{-\frac{1}{2}}$$

Critical envelope mass:

$$\begin{cases} M_{\rm env} \gtrsim 10^3 M_\odot \Rightarrow \beta_h \lesssim c_s/c & \text{(Jet stalls),} \\ M_{\rm env} \lesssim 10^3 M_\odot \Rightarrow \beta_h \gtrsim c_s/c & \text{(Jet emergence).} \end{cases}$$



LRD: O
Jet/Radio: X
LRD: O
Jet/Radio: O
LRD: X
Jet/Radio: O
Early QSO (?)
Envelope mass ($M_{\rm env}$)
$\sim M_{\rm BH}$
$\sim M_{\rm crit}$
$\ll M_{\rm BH}$
$t \ll t_{\rm Sal}$
$t_{\rm crit}$
$t \sim t_{\rm Sal}$
$t \gg t_{\rm Sal}$
Lifetime of a LRD: $t_{\rm Age\,LRD} \sim 10^7$ yr

Fraction of Radio loud LRDs (in prep)

Main assumption: ISM accretion time $\lesssim 10^7$yr

Cosmic time: $\sim 10^9$ yr

LRD lifetime: $\sim 10^7$ yr

Duration of LRDs w/ Radio: $\sim 10^3$ yr

Fraction of LRDs w/ Radio: $\lesssim 10^{-4}$

Conclusion:

We have natural fine-tuning for no simultaneous LRD+radio!