Nov. 1-2, 2023, ICRR multi-messenger astronomy symposium

Jet models for low-luminosity GRBs and multi-messenger astronomy

低光度ガンマ線バーストのジェットモデルとマルチメッセンジャー天文学

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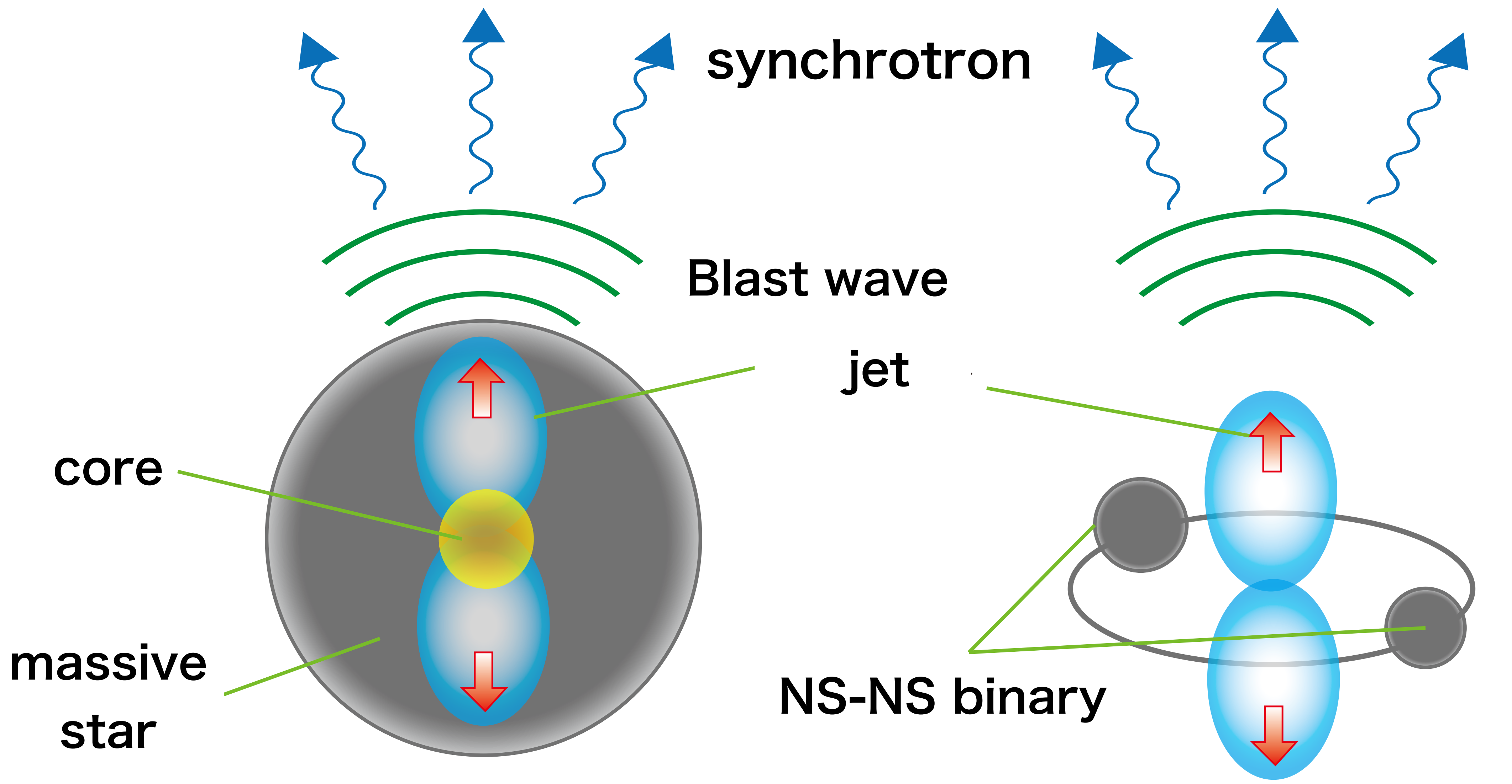
collaborator: Keiichi Maeda (Kyoto U.), Chris Irwin (RESCEU)

Refs.
- **Suzuki** & Maeda (2022), ApJ 925, 148
- Maeda, **Suzuki**, & Izzo (2023), MNRAS 522, 2267
- **Suzuki**, Irwin, & Maeda (2023?), in prep.

Gamma-ray bursts

- a burst of gamma-rays in the sky
- duration > 2 sec → long-duration GRB
- massive stars' explosive death → relativistic jet
- association with supernovae (SNe), in particular, broad-lined SNe-Ic

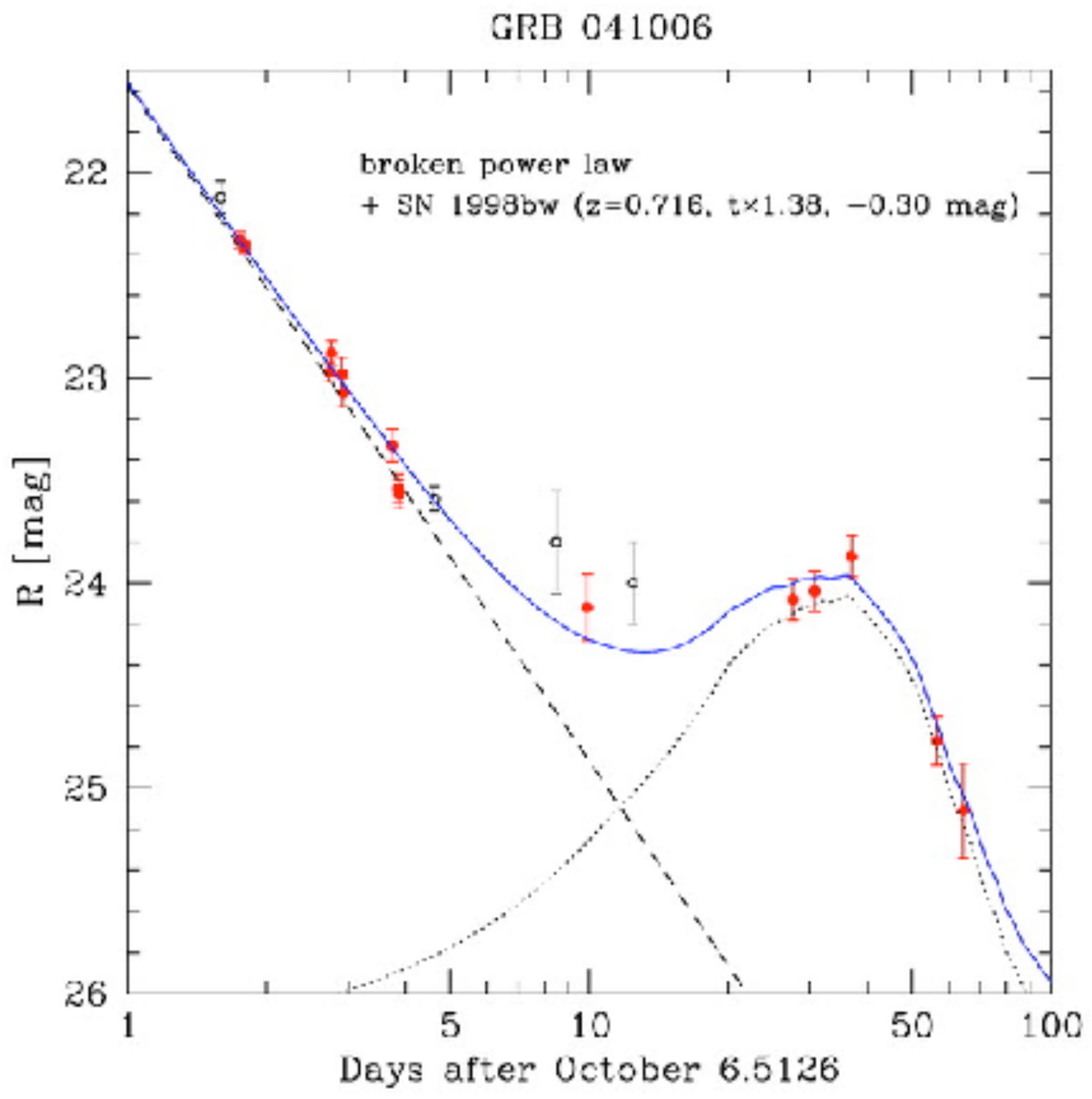


long-soft GRBs short-hard GRBs

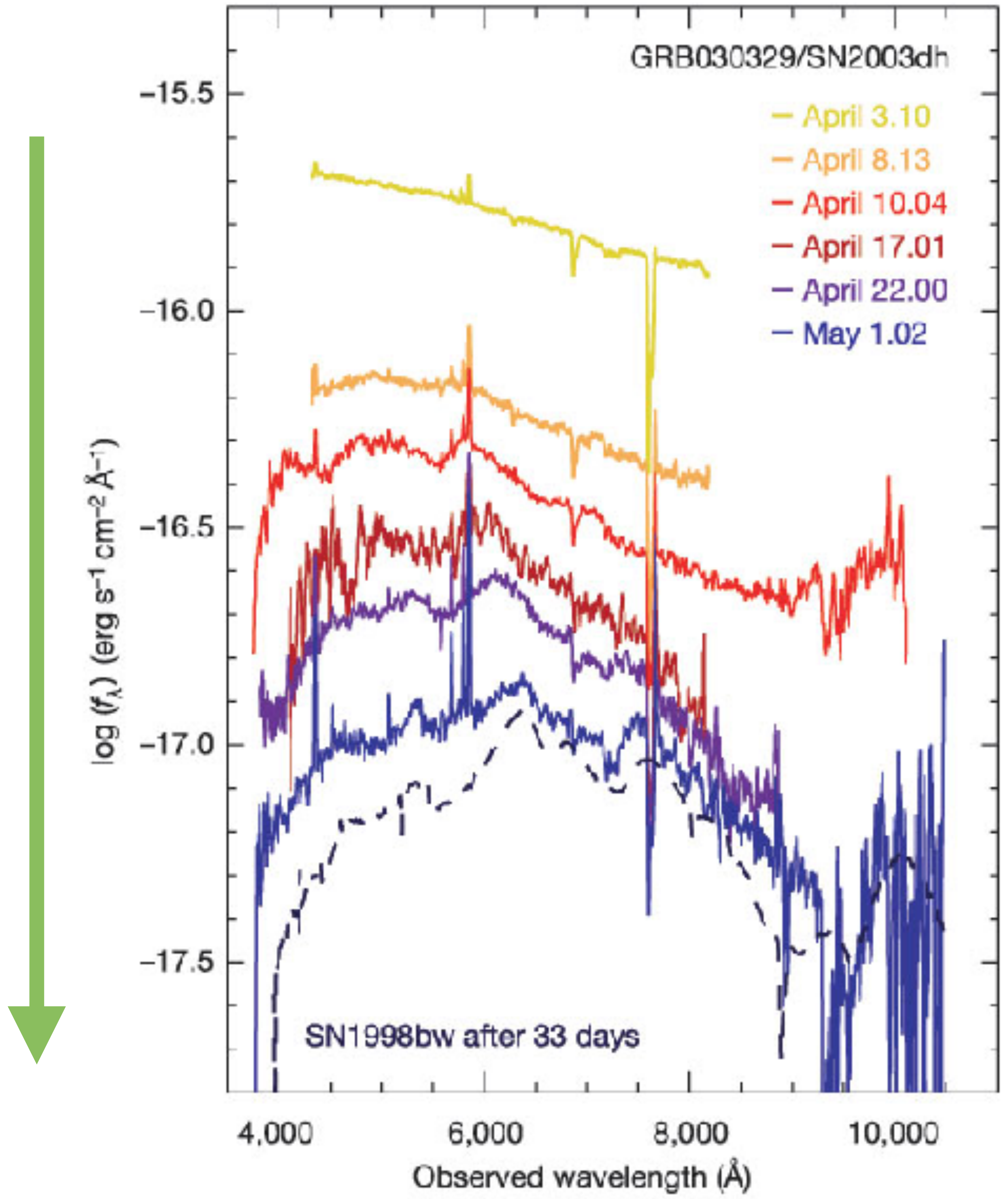
	long GRBs	short GRB
duration T_{90}	> 2 sec	< 2 sec
γ-ray spectrum	soft	hard
origin	massive star's collapse	NS-NS merger
optical counterpart	core-collapse supernova	kilonovae
after-glow	bright	dark
host galaxy	star-forming	old population
location	associated with stellar lights	outskirt

long-duration Gamma-ray bursts

- GRB-SN association
- energetic SNe-Ic with E~10^{52}erg (i.e., hypernovae)
- various chemical elements found in the SN spectra
- important tracers of explosion mechanism and progenitor system
- chemical enrichment



GRB afterglow + SN light: Stanek+ (2005)

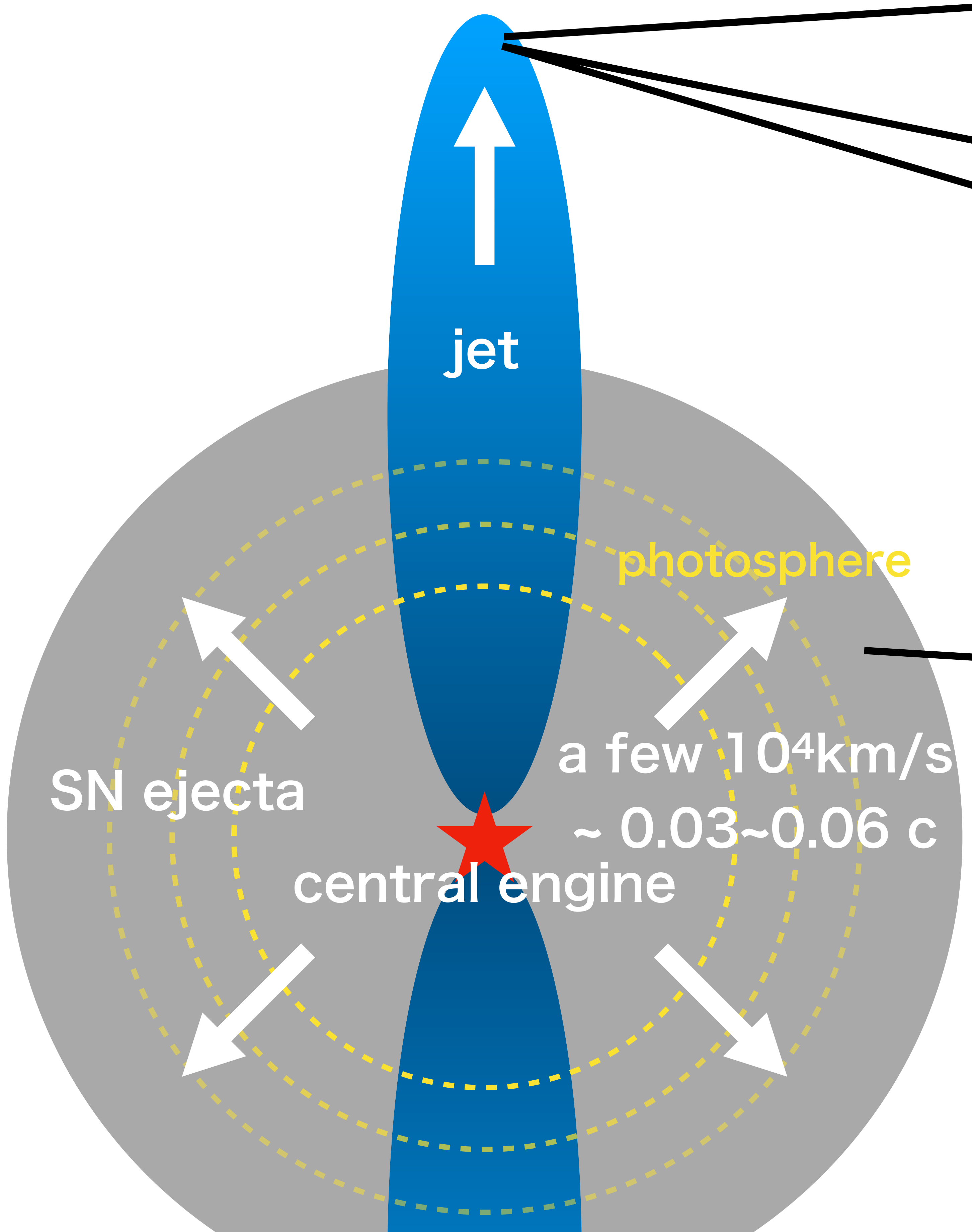


selected GRB-SNe with spectroscopic confirmation

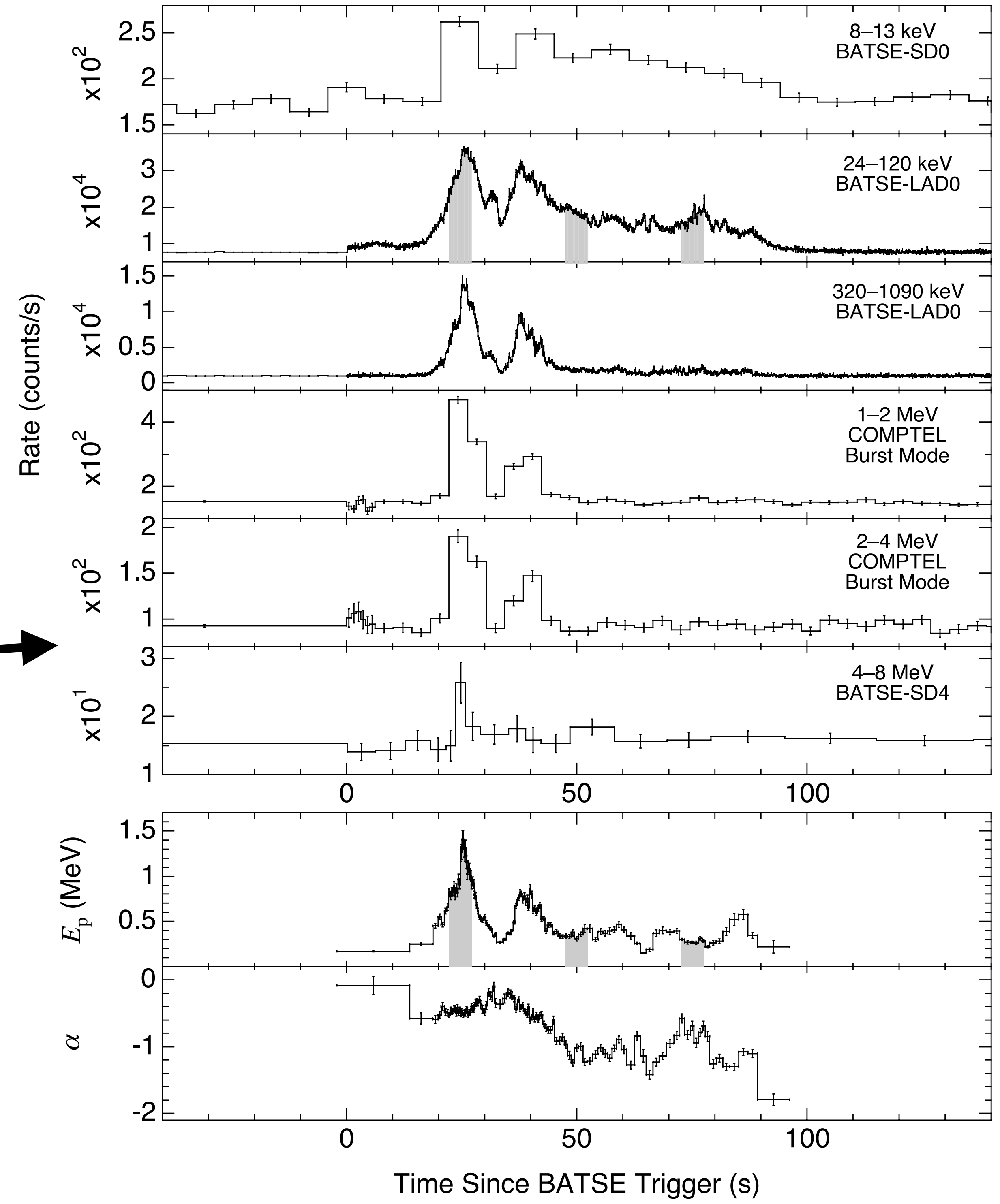
	associated SN	redshift
GRB 980425	SN 1998bw	z=0.0085
GRB 030329	SN 2003dh	z=0.1685
GRB 031203	SN 2003lw	z=0.1055
GRB 060218	SN 2006aj	z=0.0334
GRB 100316D	SN 2010bh	z=0.0591
GRB 120425A	SN 2012bz	z=0.283
GRB 130702A	SN2013dx	z=0.145
GRB 140606B	iPTF4bfu	z=0.384
GRB 161219B	SN 2016jca	z=0.1475
GRB 171205A	SN 2017iuk	z=0.037

long-duration Gamma-ray bursts

- multi-wavelength observations are essential
- prompt γ-ray detection
- afterglow from radio to TeV

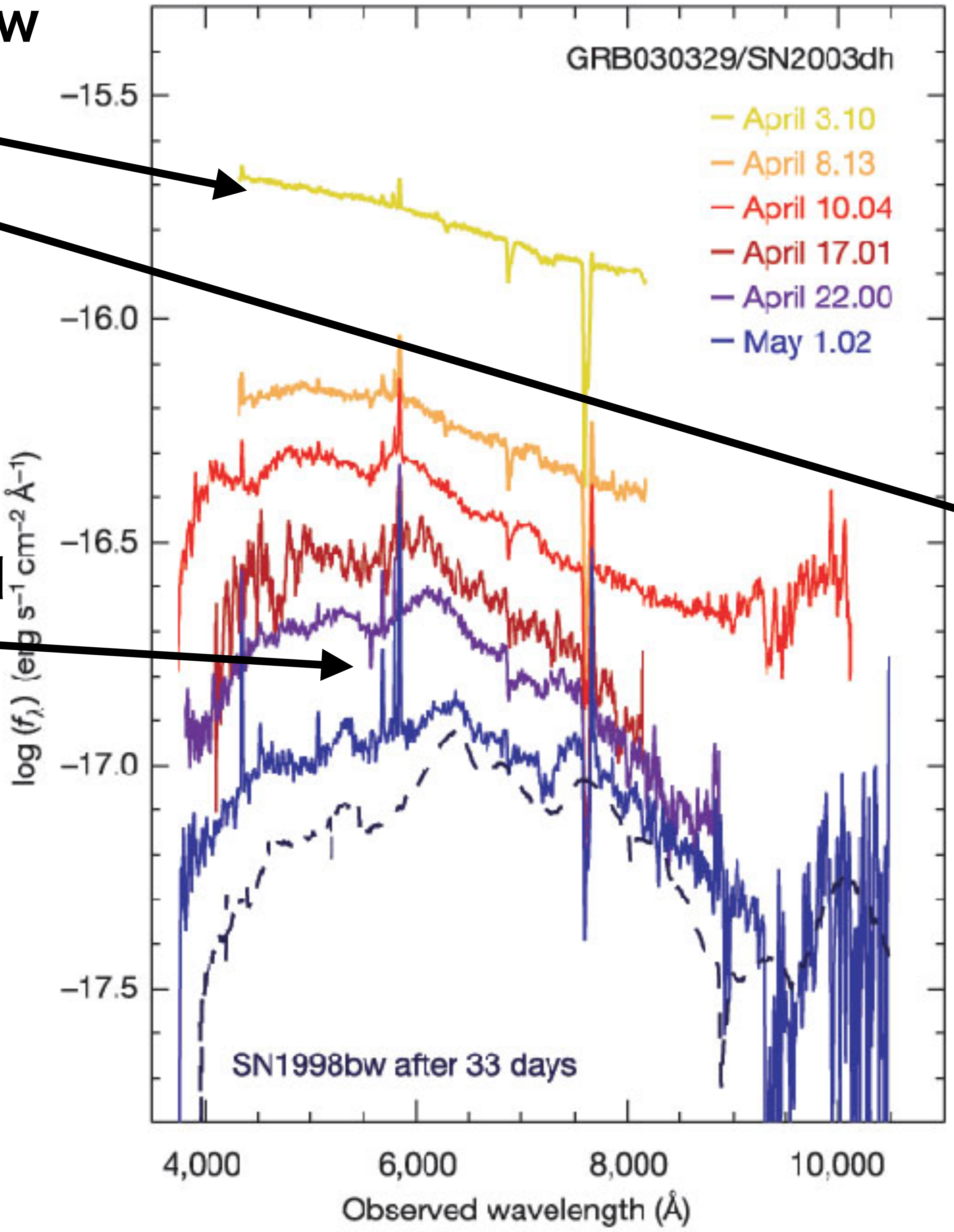


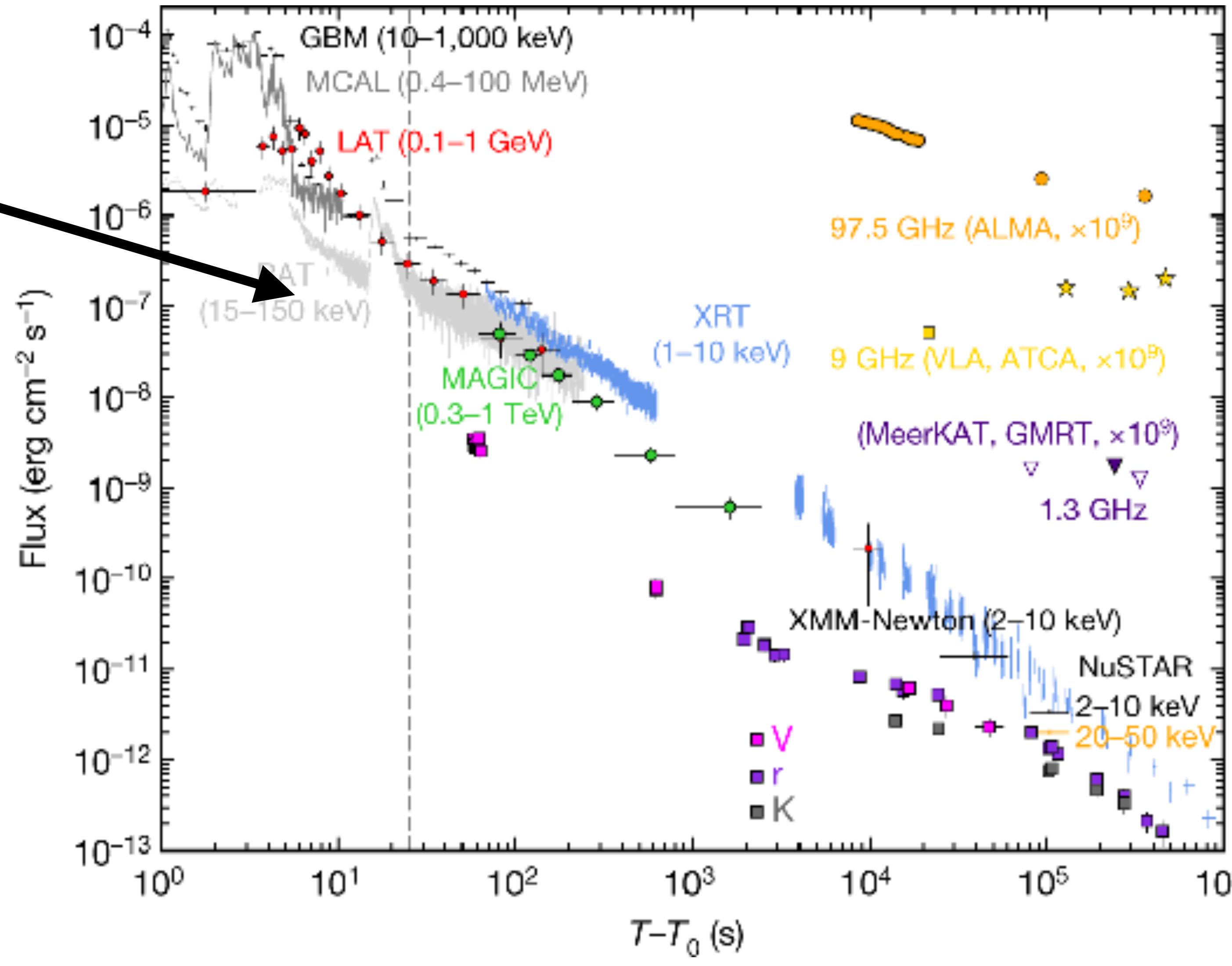
Prompt



Afterglow

Thermal

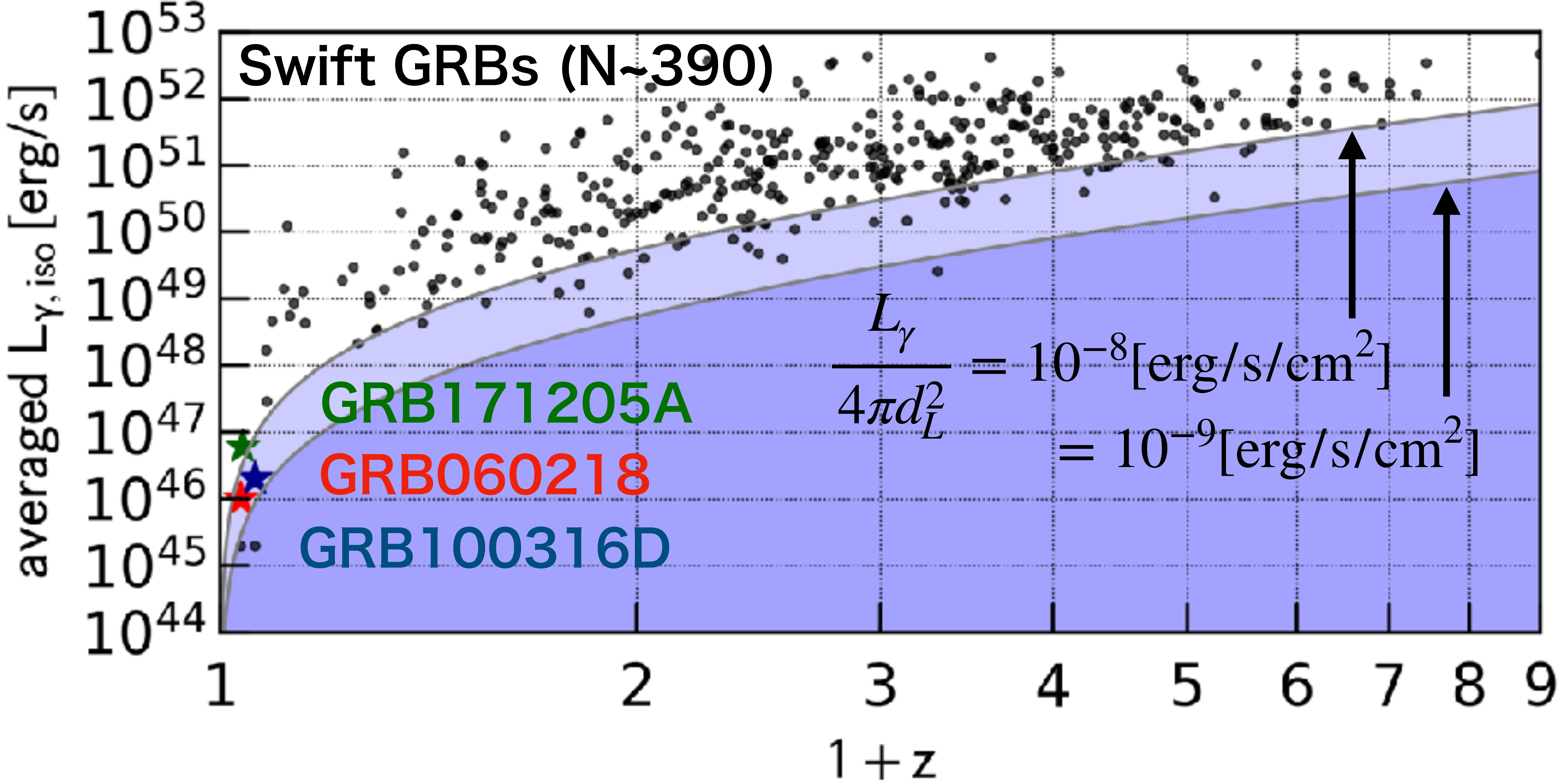


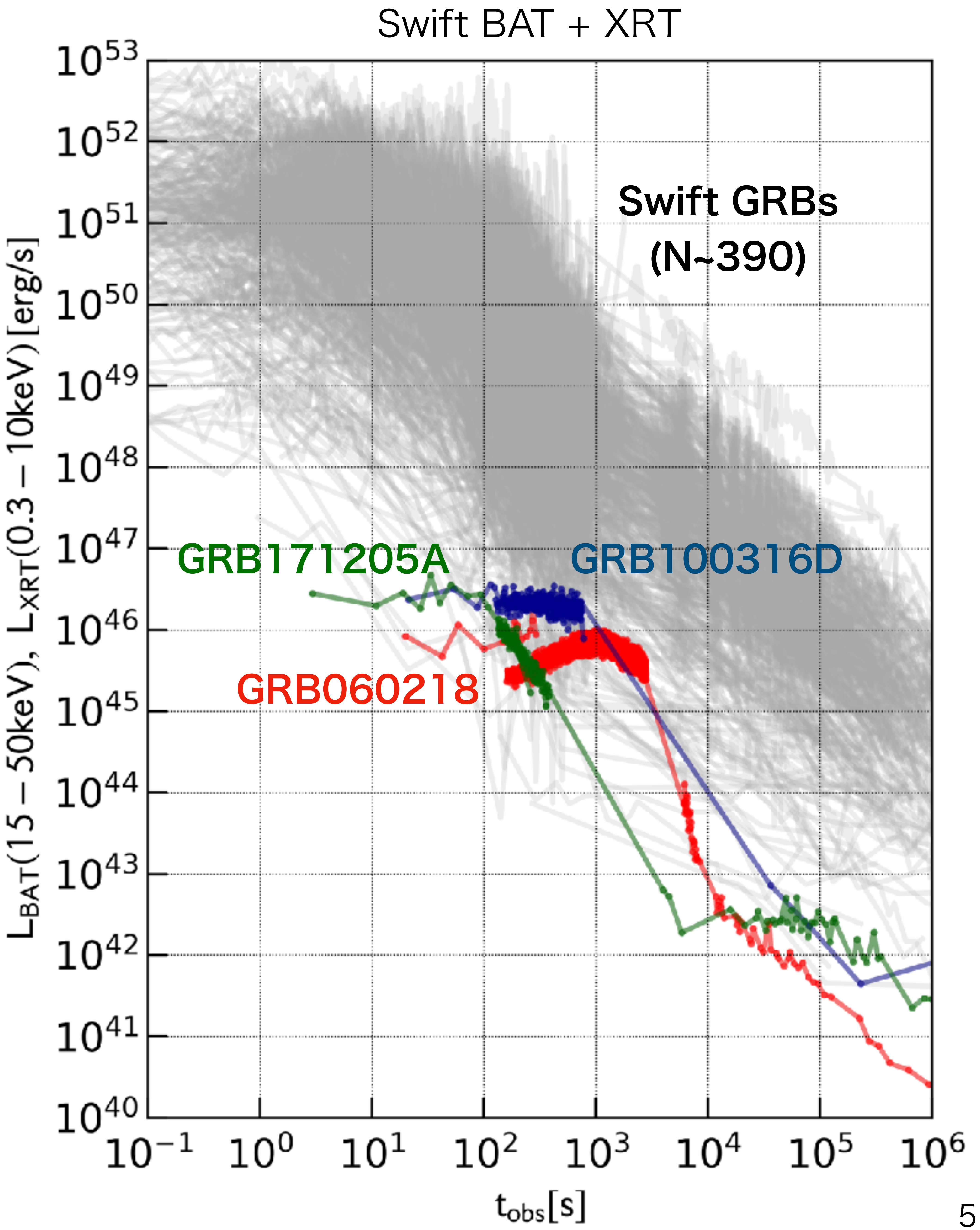


low-luminosity GRBs

- nearby GRBs (< a few 100Mpc) are low-luminosity GRB
- smaller $L_{\gamma,\mathrm{iso}}$ and $E_{\gamma,\mathrm{iso}}$ by 5-6 orders of magnitudes
- outliers in E_{peak}-E_{iso} relation
- more common than normal GRBs

e.g., 230^{+490}_{-190} Gpc^{-3} yr^{-1} (Soderberg+ 2006),
100-1800 Gpc^{-3} yr^{-1} (Guetta&Della Valle 2007)





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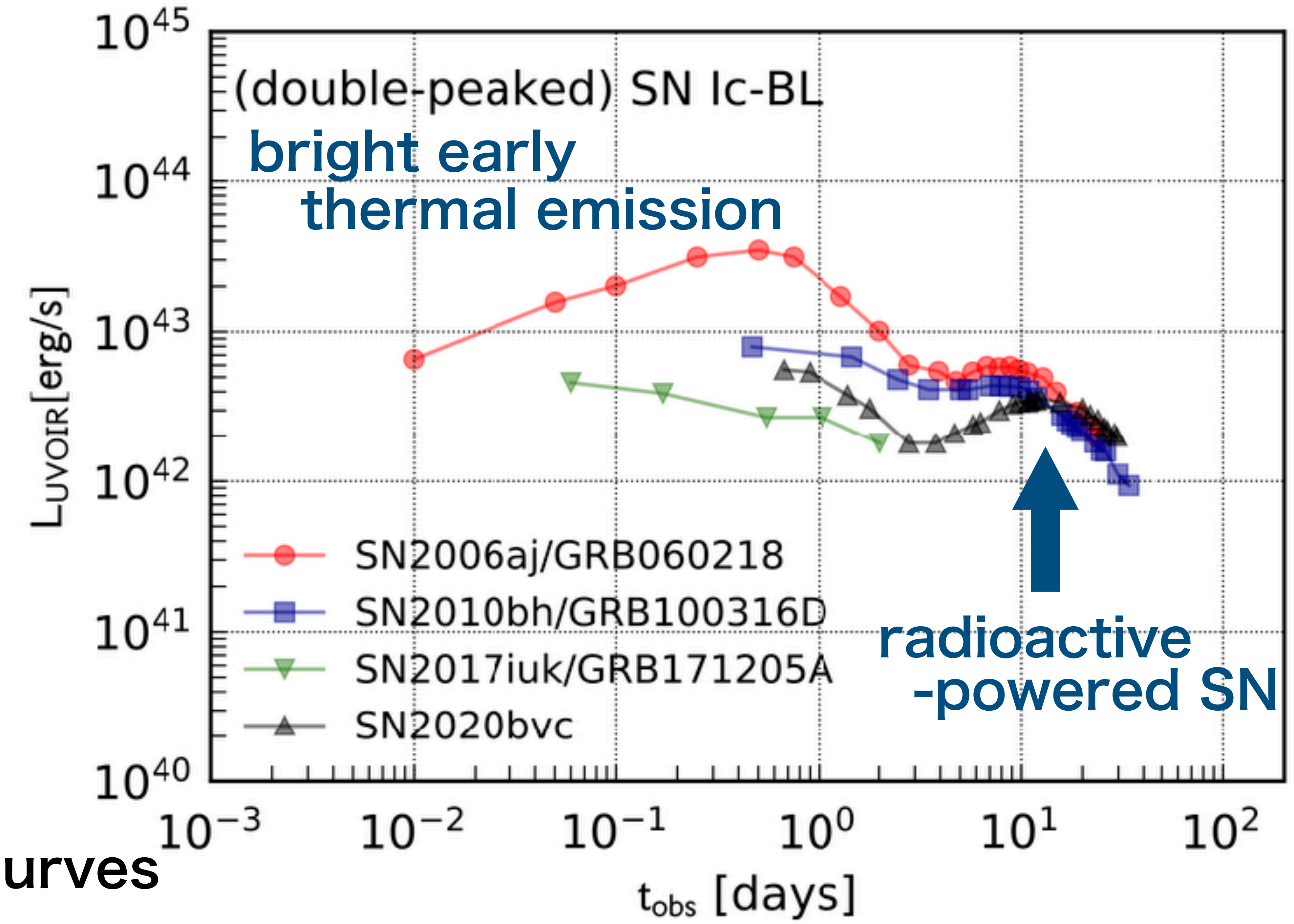
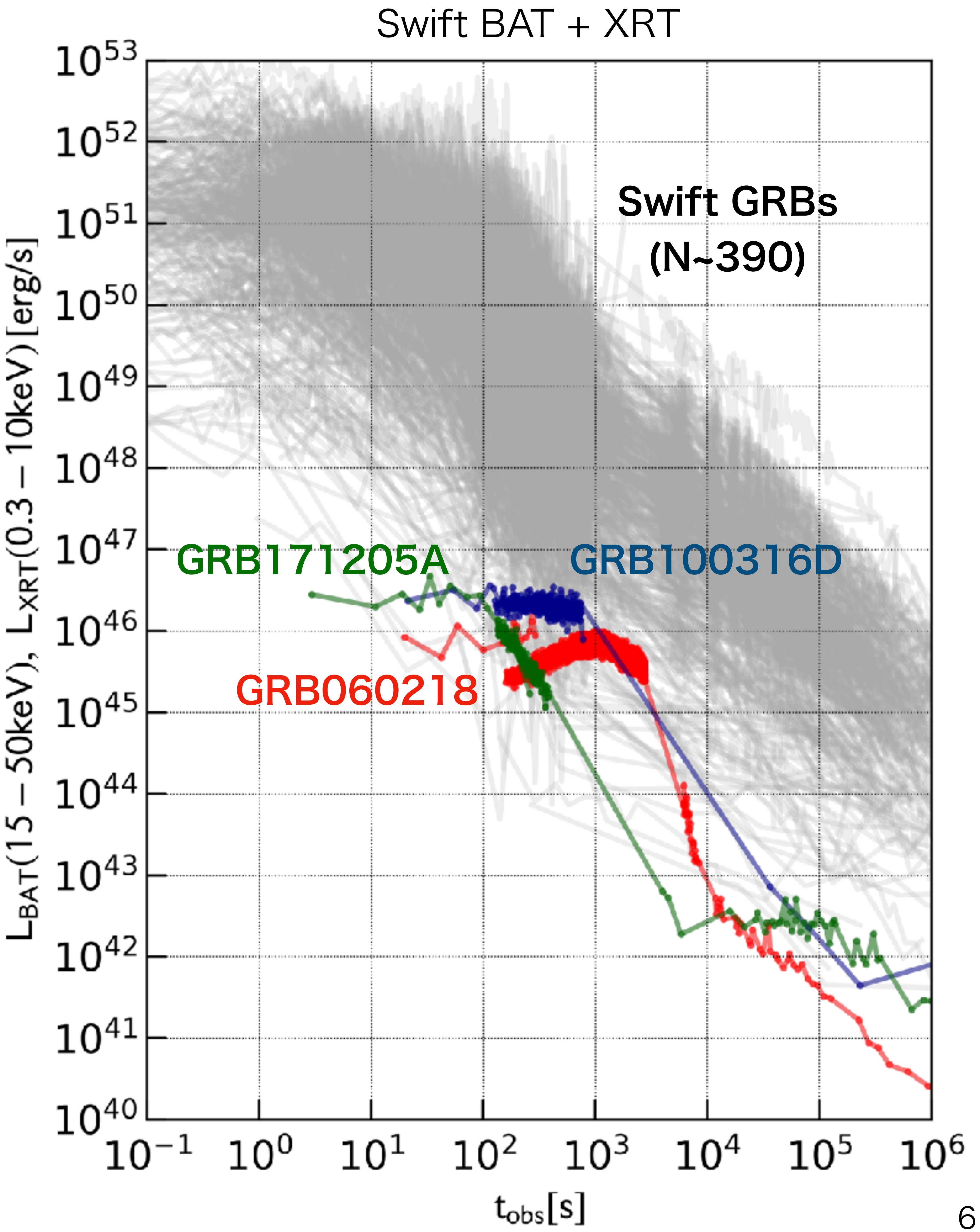

(double-peaked) SN Ic-BL

bright early thermal emission

radioactive -powered SN

UV-opt-IR light curves


Swift BAT + XRT

Swift GRBs (N~390)

GRB171205A

GRB100316D

GRB060218

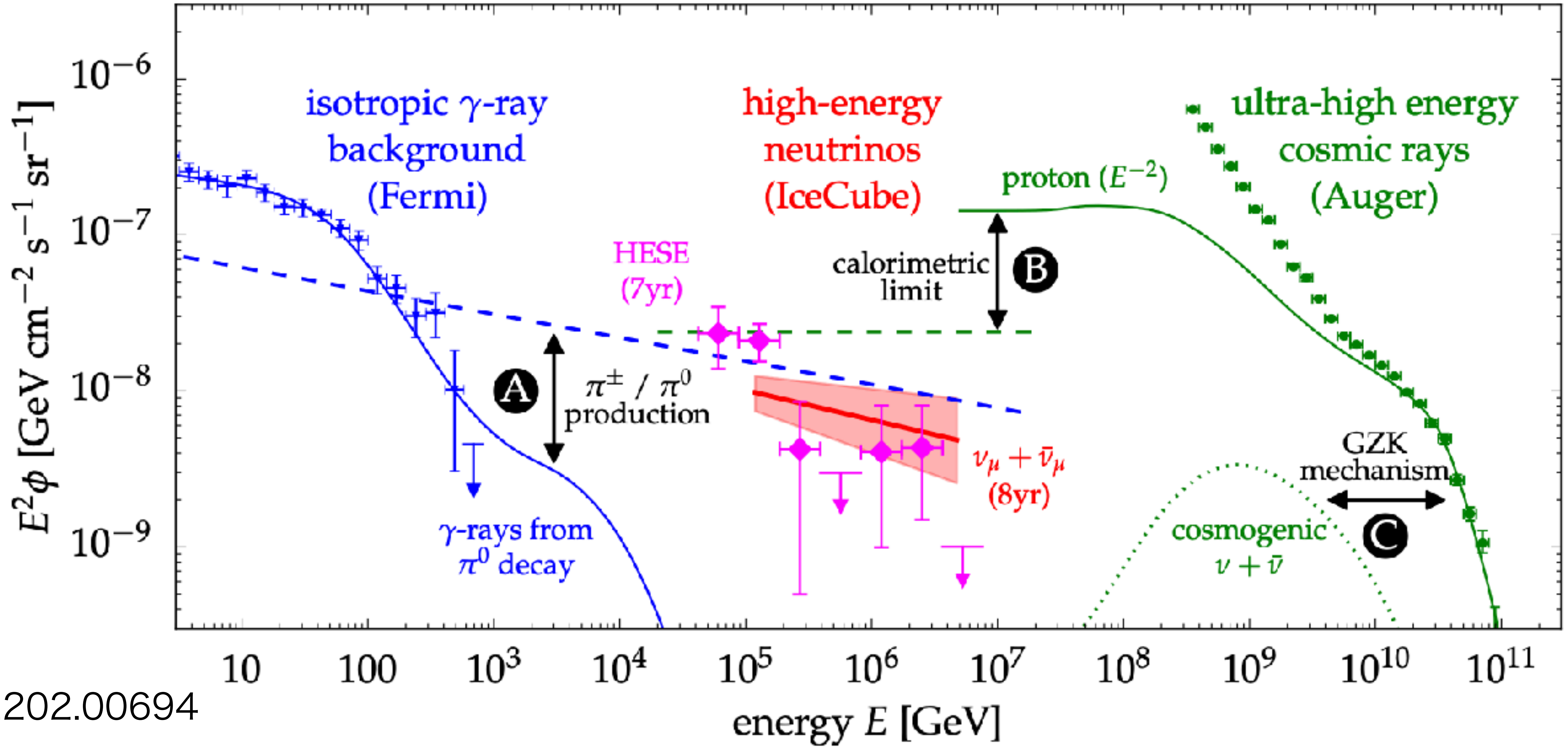
low-luminosity GRBs are UHECRs and ν source?

- cosmological GRBs have been promising ν sources

  Waxman&Bahcall(1997), Rachen&Meszaros(1998), Ahlers+(2011)
- So far, IceCube found no association of ν events with (powerful) GRBs.

  Abbasi+(2012,21,22), Aartsen+(2015,16,17)
- (powerful) GRBs contribute only up to 1% of diffuse ν flux at ~0.1-1 PeV?
- unlike cosmological GRBs, llGRBs are dark in γ-ray, but seem more common

  e.g., 230^{+490}_{-190} Gpc^{-3} yr^{-1} (Soderberg+ 2006), 100-1800 Gpc^{-3} yr^{-1} (Guetta&Della Valle 2007)



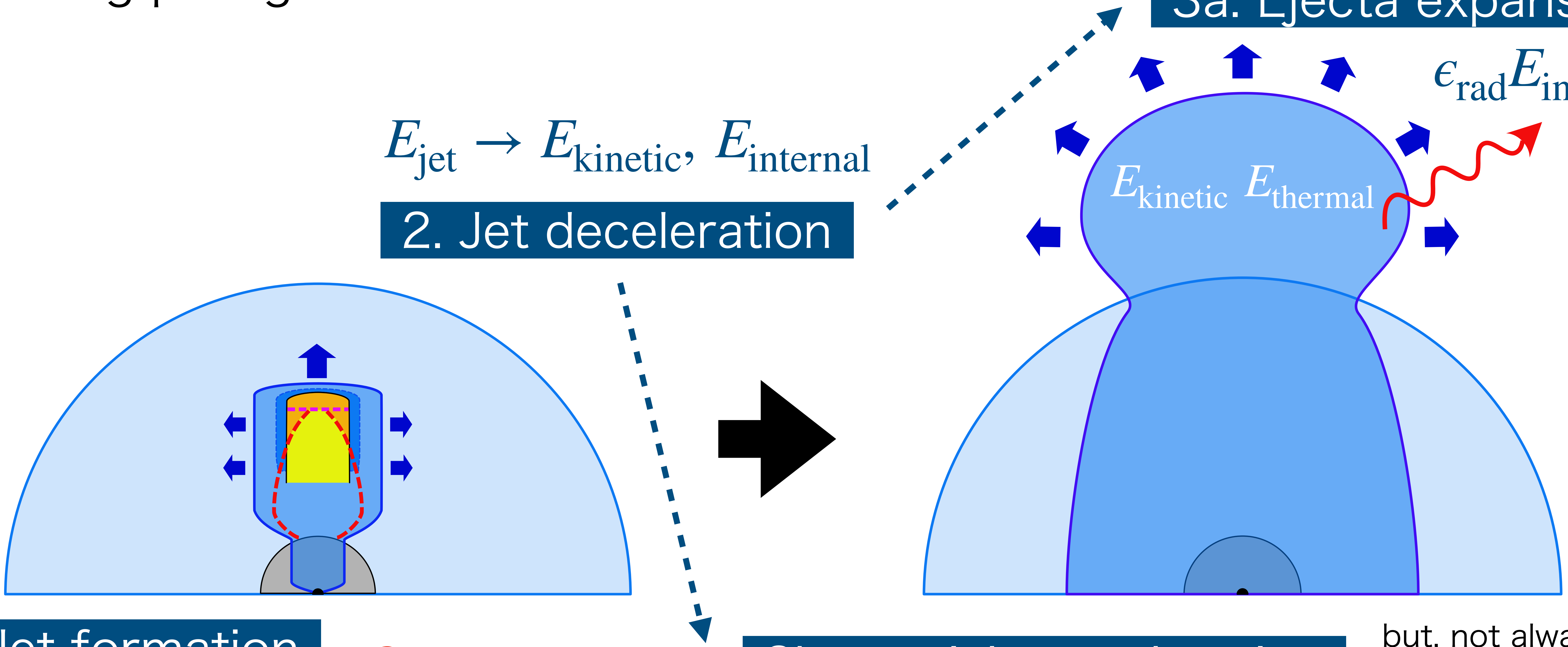
Halzen&Kheirandish (2022), arXiv:2202.00694

low-luminosity GRBs are failed jets?

Nakar (2015), see also Suzuki & Shigeyama (2013)

low-luminosity GRBs are failed jets?

- jet deceleration = energy dissipation
- the jet energy goes into kinetic and thermal energies of expanding CSM
- a small fraction of the thermal energy goes into CRs and ν
- remaining part goes into thermal radiation



3a. Ejecta expansion **EM obs.**

$\epsilon_{\rm rad} E_{\rm internal} \simeq E_{\rm rad}$

$E_{\rm jet} \rightarrow E_{\rm kinetic}, E_{\rm internal}$

2. Jet deceleration

$E_{\rm kinetic}$ $E_{\rm thermal}$

1. Jet formation **GW, ν obs.**

$E_{\rm grav}$ (or $E_{\rm rot}$) $\rightarrow E_{\rm jet}, E_{\rm SN}, E_{\nu}, E_{\rm GW}$

3b. particle acceleration

but, not always (e.g, radiation condition,
Murase&Ioka 2013, Senno+2016)

$\epsilon_{\rm acc} E_{\rm internal} \simeq E_{\rm CR} + E_{\nu}$ **CR, ν obs.**

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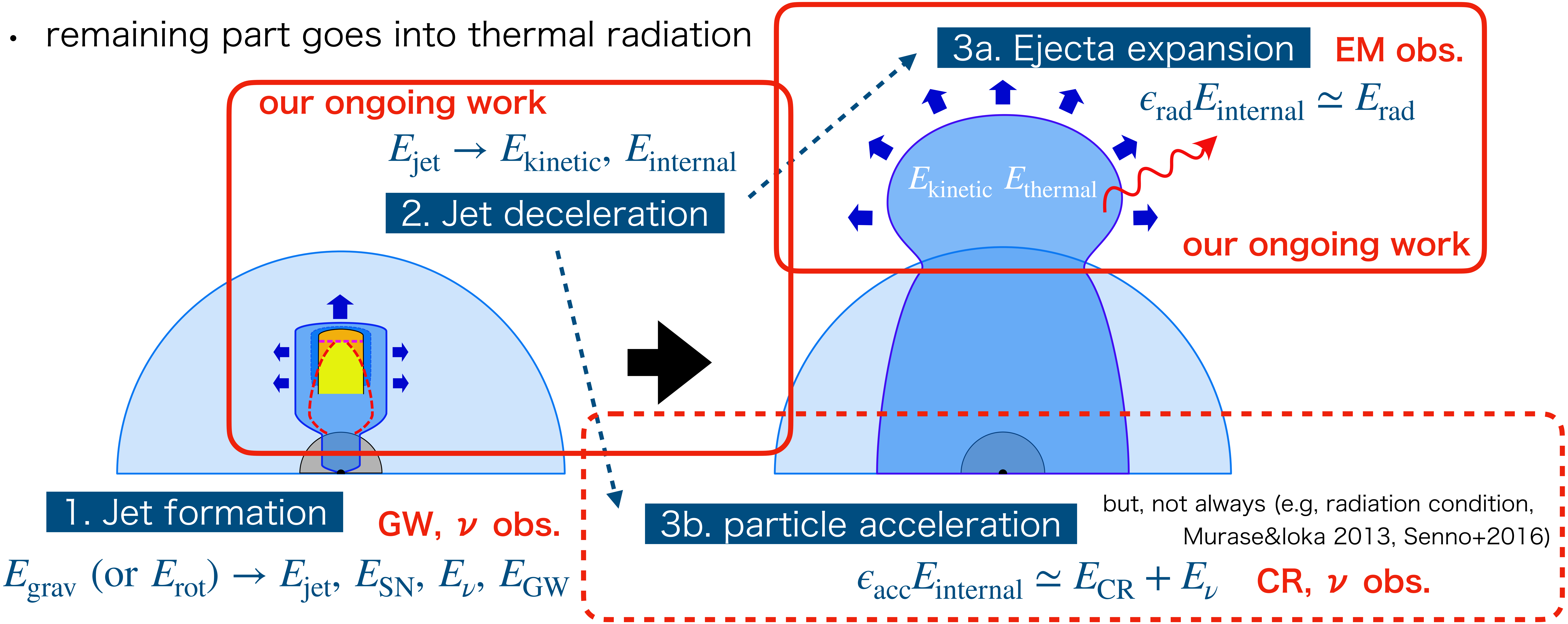

our ongoing work

$E_{\rm jet} \rightarrow E_{\rm kinetic}, E_{\rm internal}$

2. Jet deceleration

3a. Ejecta expansion

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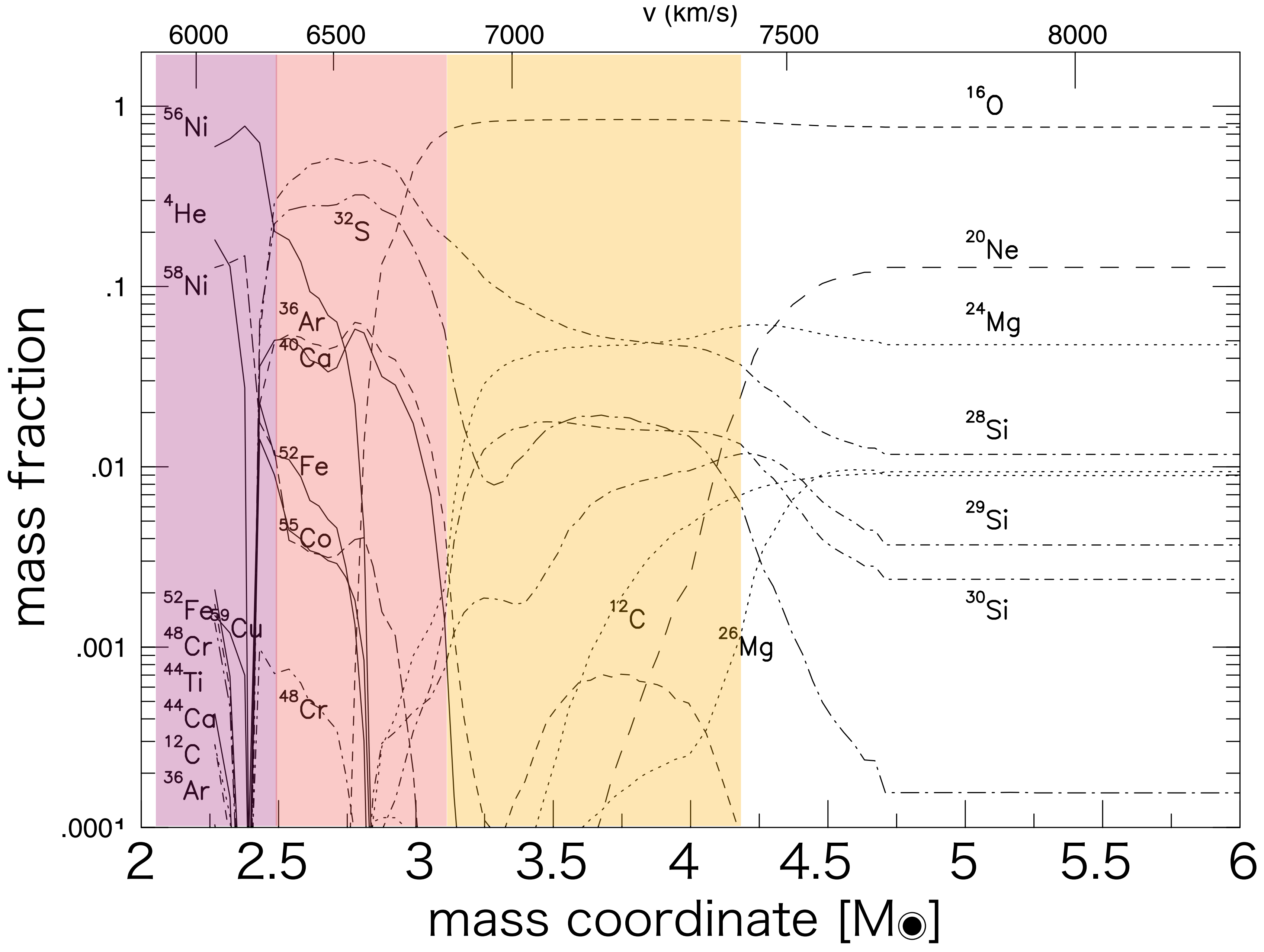
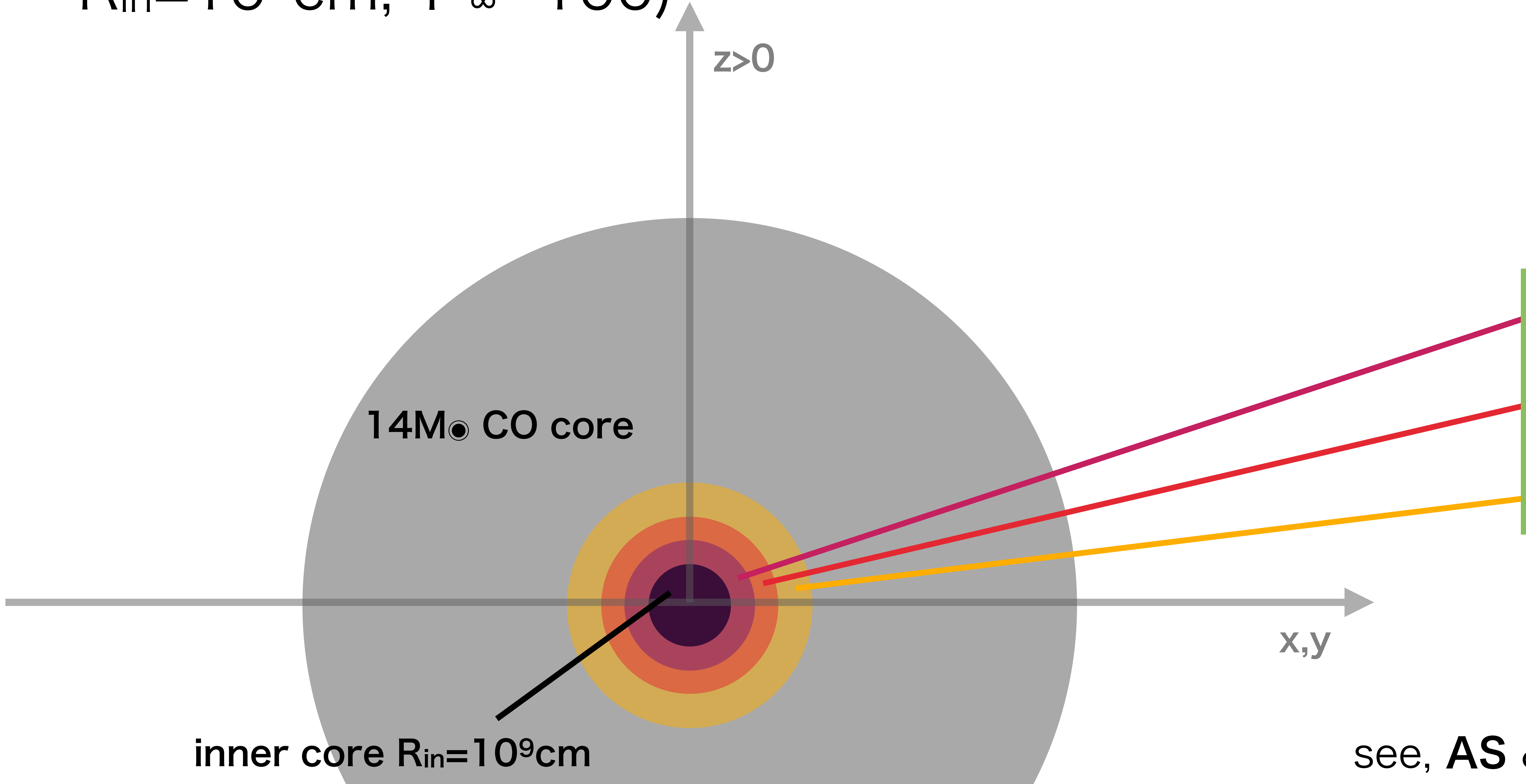
CR, ν obs.

GRB jet simulations: setups

- 3D special relativistic hydrodynamic simulation in (x,y,z)
- 14 M$_{sun}$ CO core (16TI; Woosley&Heger 2006)
- chemical composition: hypernova-like (e.g., Iwamoto+ 2000)
- thermal bomb (5x10^{51} erg, R$_{in}$=10^{9}cm)
- relativistic jet (5x10^{51}erg per jet, t$_{jet}$=20s, θ_{jet}=10 deg, R$_{in}$=10^{9}cm, Γ_{∞}~100)



10M◉ CO core+ 10^{52} erg model by Iwamoto+ (2000)



- Layer 1: Fe-peak elements, 0.4M$_{sun}$
- Layer 2: incomplete Si burning, 0.6M$_{sun}$
- Layer 3: O burning, 1.0M$_{sun}$

see, **AS** & Maeda (2022) for more detail

GRB jet simulations: setups

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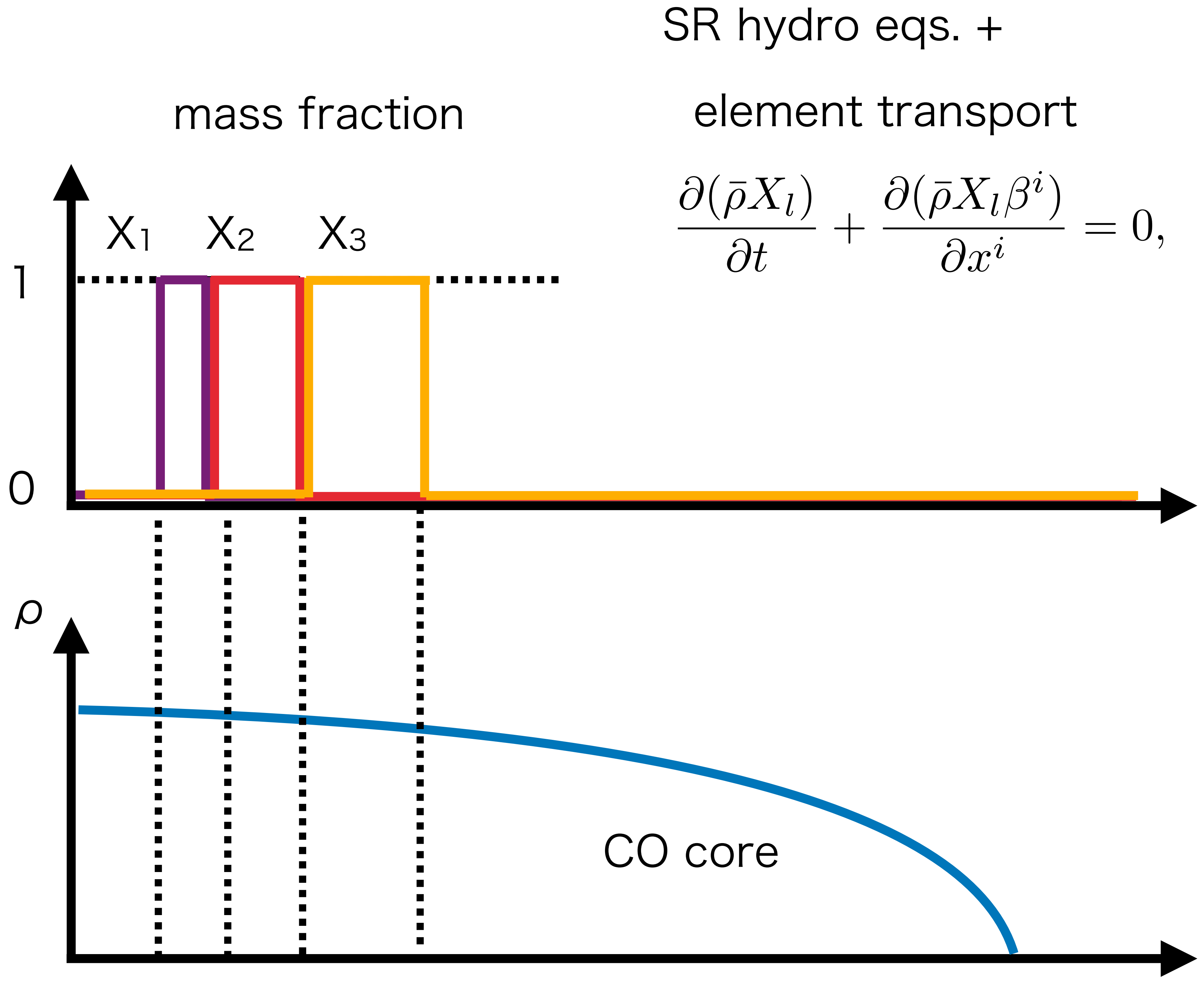
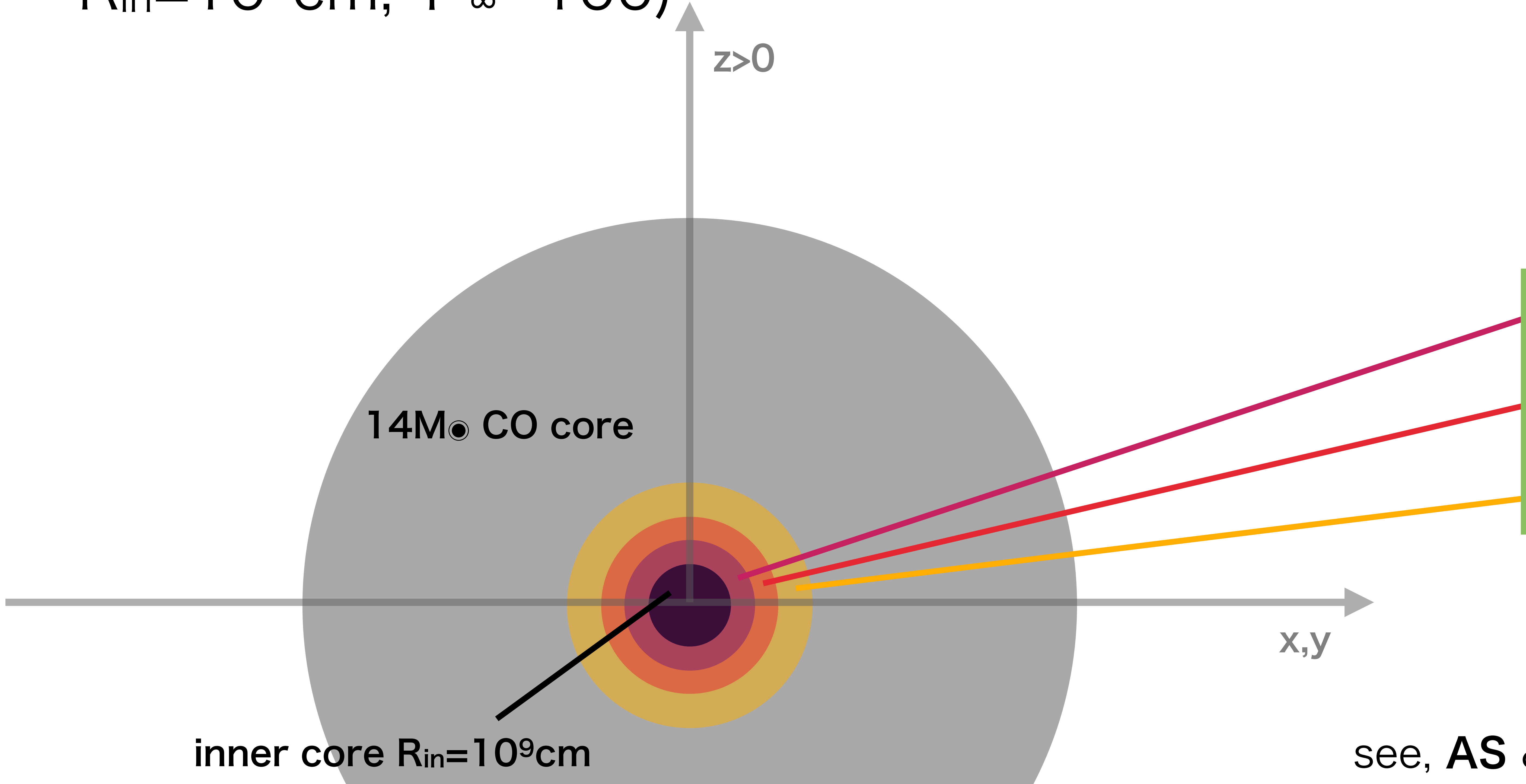


$$\frac{\partial(\bar\rho X_l)}{\partial t}+\frac{\partial(\bar\rho X_l\beta^i)}{\partial x^i}=0,$$



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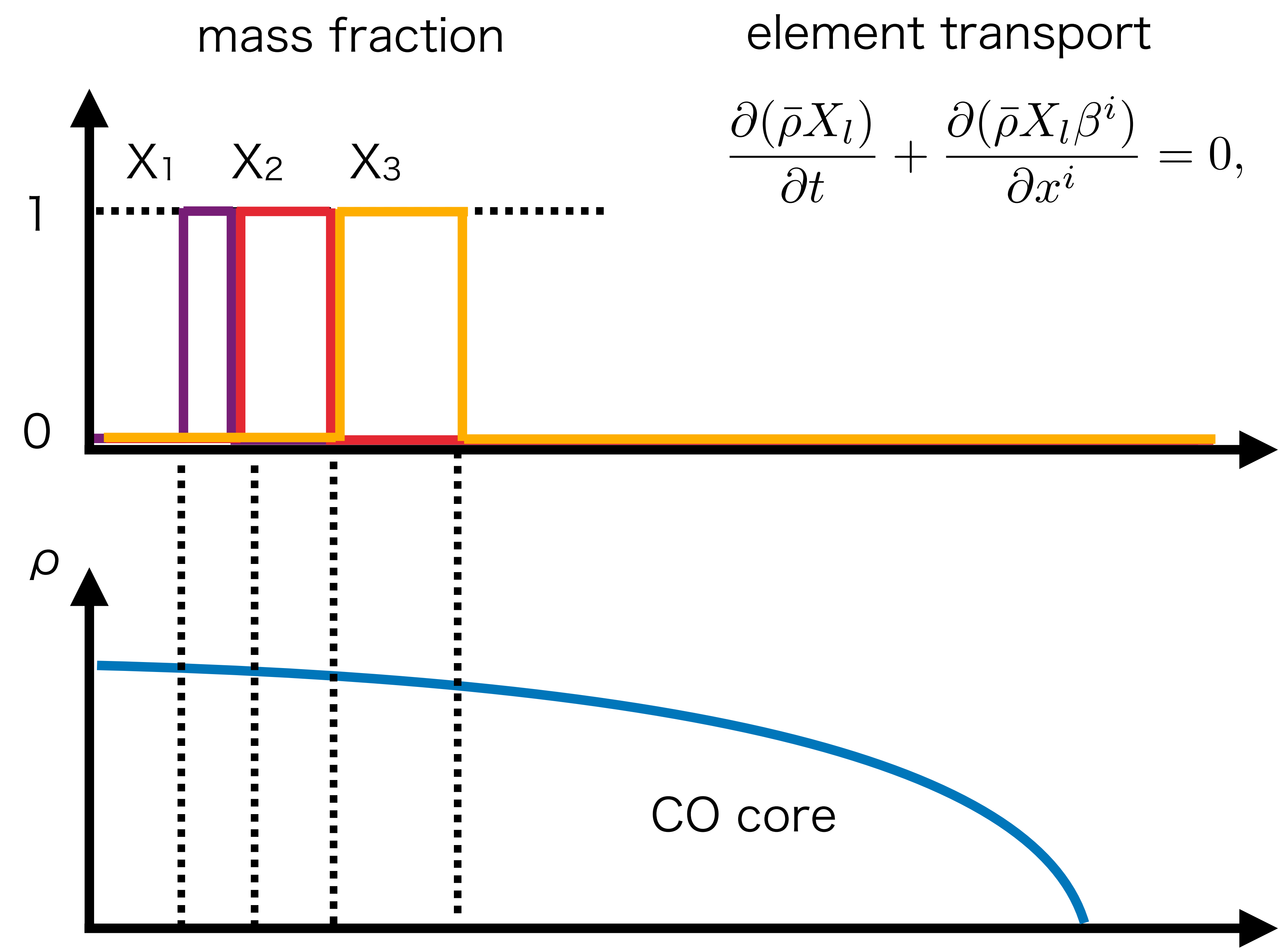
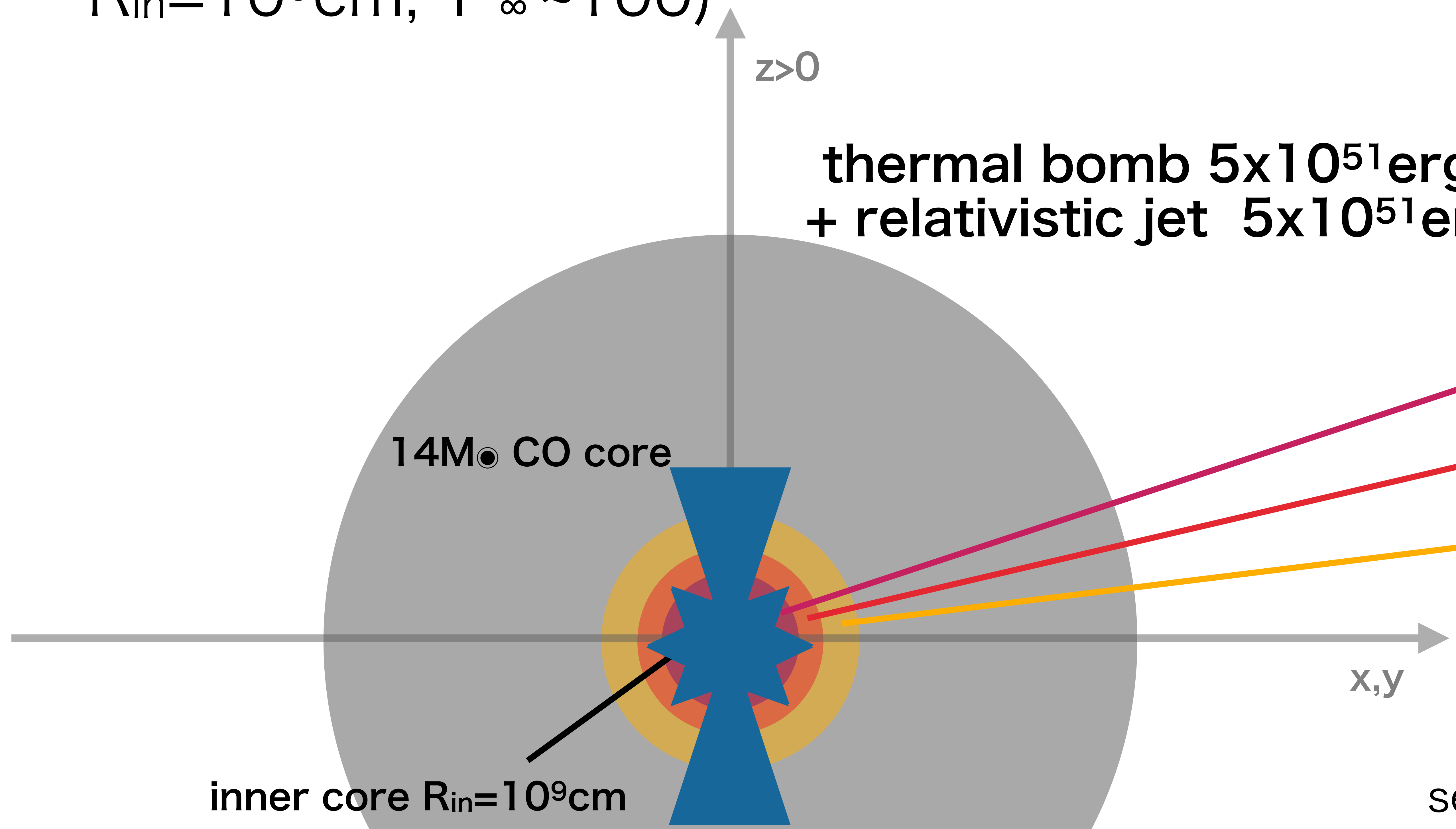
SR hydro eqs. +

element transport

$$\frac{\partial(\bar\rho X_l)}{\partial t}+\frac{\partial(\bar\rho X_l\beta^i)}{\partial x^i}=0,$$





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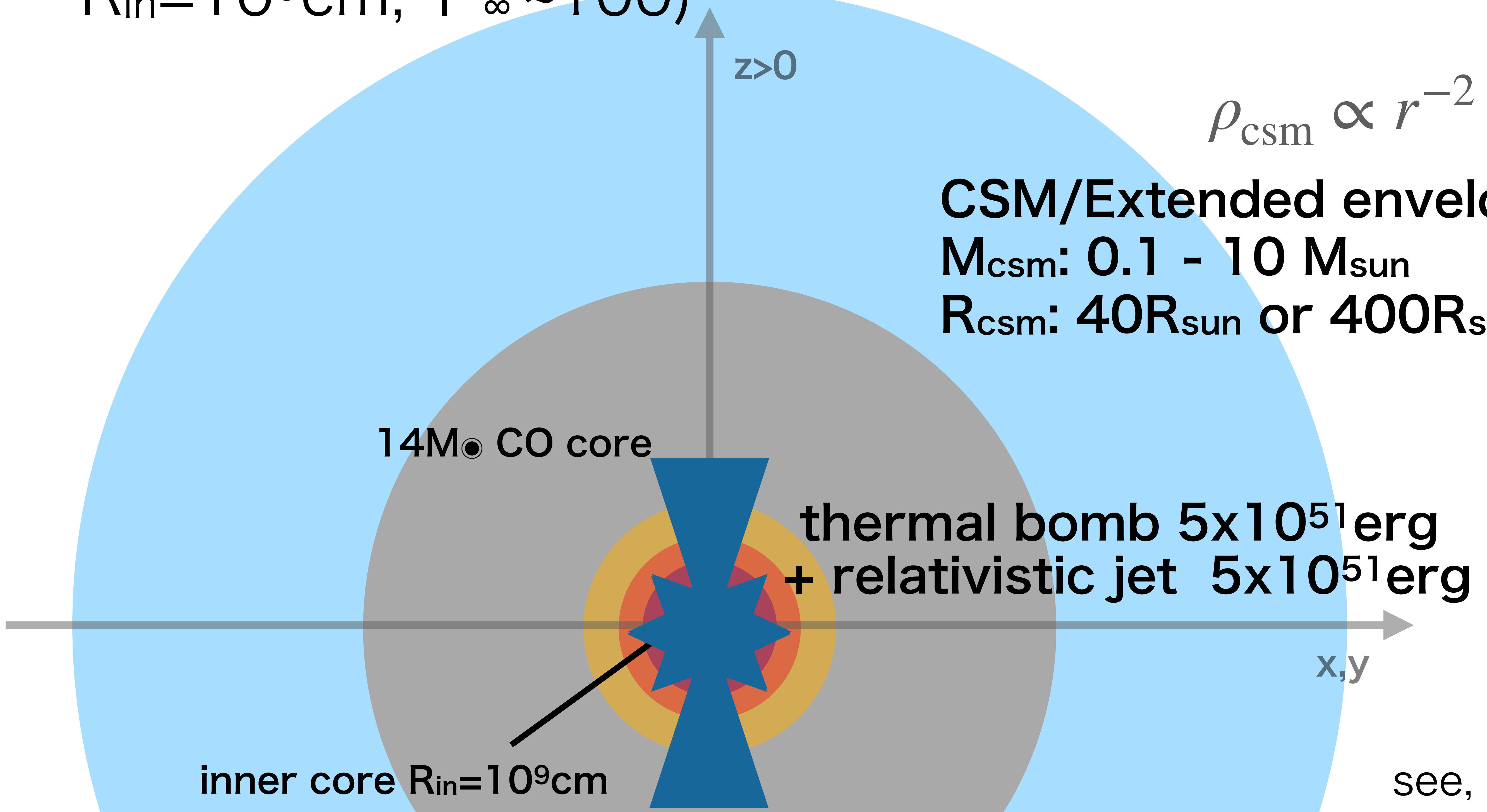


$\rho_{\rm csm} \propto r^{-2}$

CSM/Extended envelop
M_{csm}: 0.1 - 10 M_{sun}
R_{csm}: 40R_{sun} or 400R_{sun}

14$M_\odot$ CO core

thermal bomb $5x10^{51}$erg
+ relativistic jet $5x10^{51}$erg

inner core $R_{in}=10^9$cm

model	M_{csm}[M_{sun}]	R_{csm}[R_{sun}]
M01R40	0.1	40
M03R40	0.3	40
M1R40	1.0	40
M3R40	3.0	40
M10R40	10	40
M01R400	0.1	400
M03R400	0.3	400
M1R400	1.0	400
M3R400	3.0	400
M10R400	10	400

see, **AS** & Maeda (2022) for more detail

GRB jet simulations: jet dynamics

AS, Irwin, &Maeda, in prep.

- a GRB jet-CSM collision in meridional slice (x-z plane) from t=1.0 to t=22.0 s

$E_{jet}=5\times10^{51}$erg

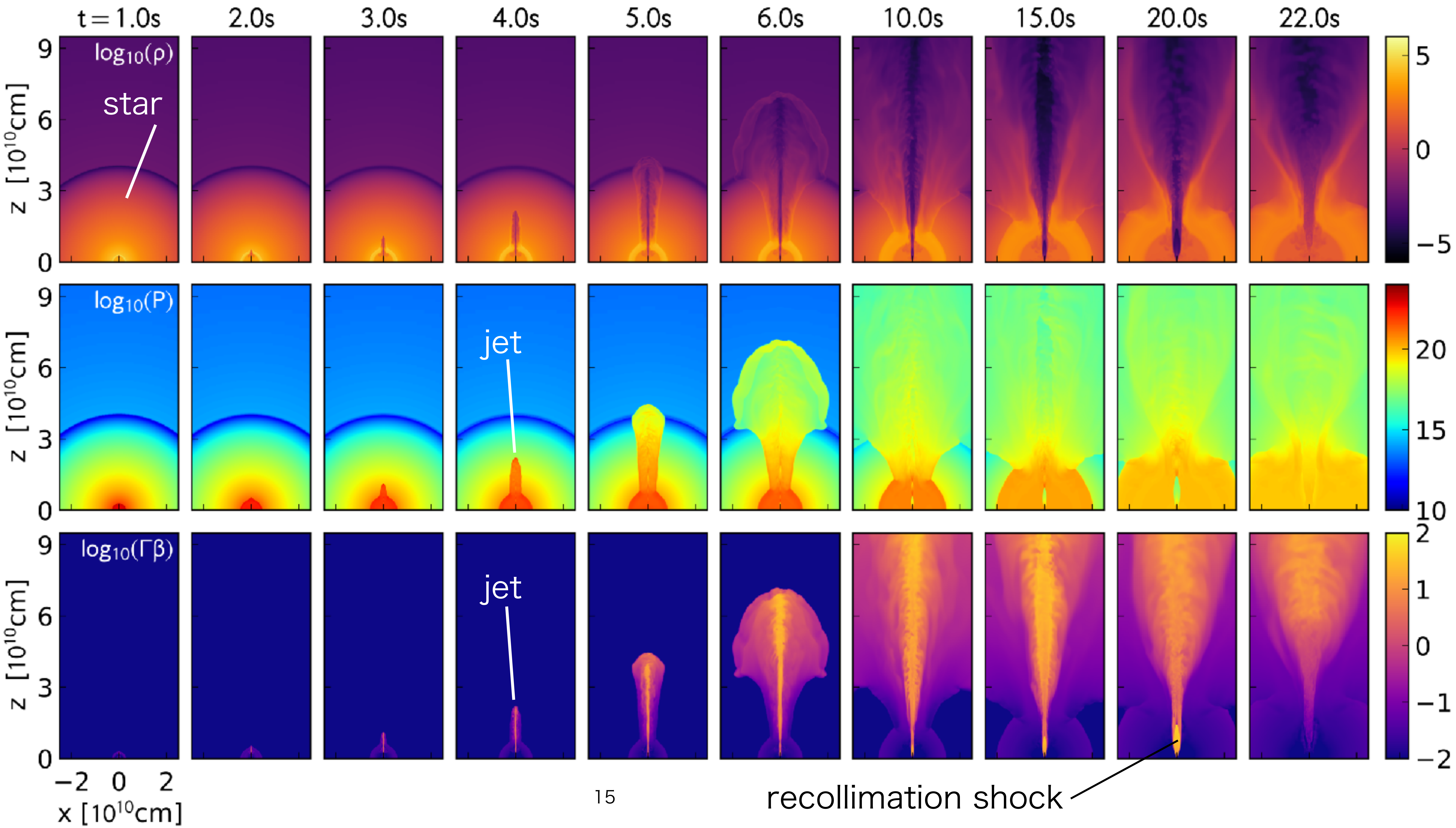
$M_{csm}=1M_{sun}$

$R_{csm}=400R_{sun}$

density

pressure

4-velocity



GRB jet simulations: jet dynamics

AS, Irwin, &Maeda, in prep.

- a GRB jet-CSM collision in meridional slice (x-z plane) from t=30 to t=200 s

$E_{jet}=5\times10^{51}$erg

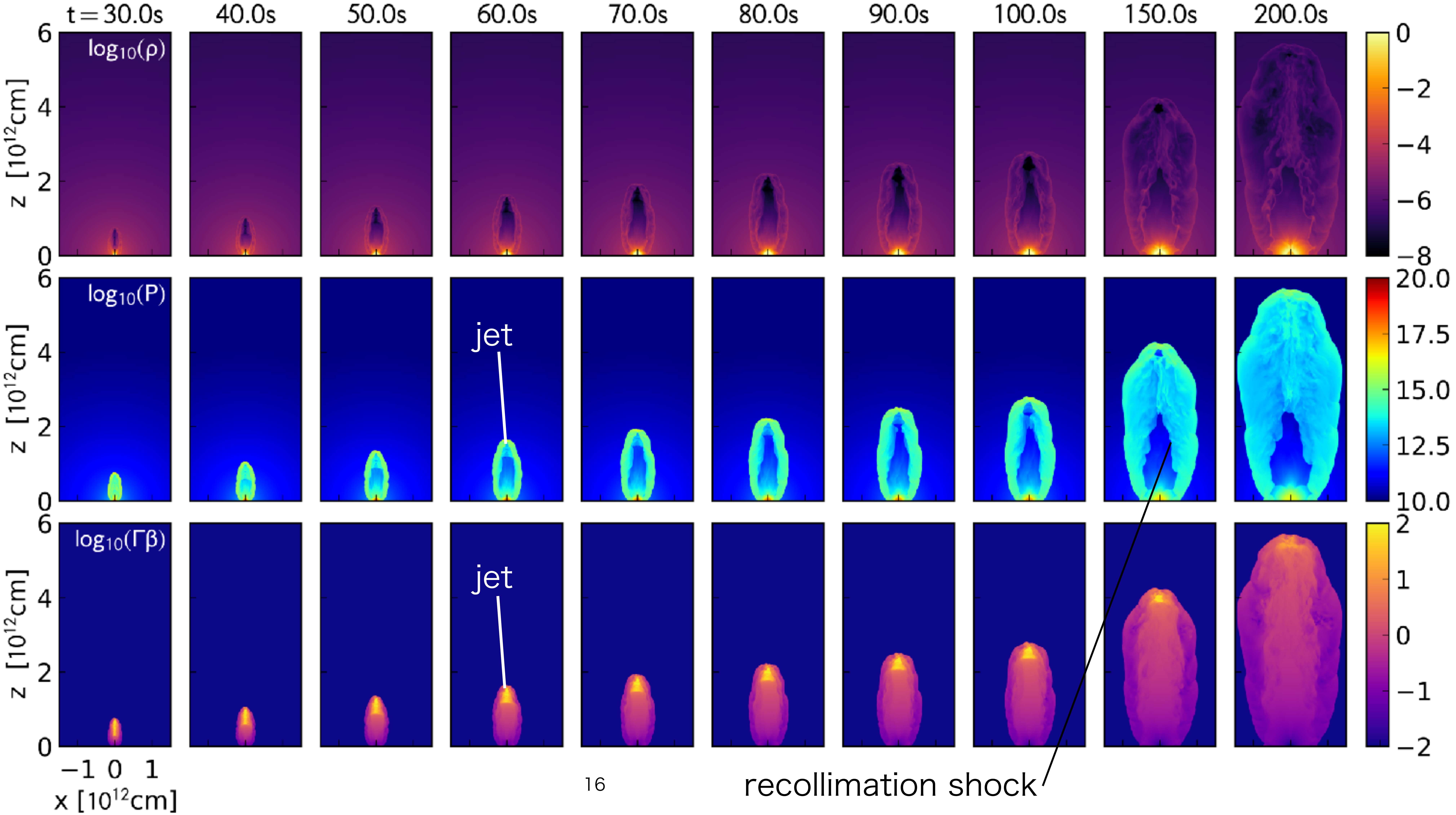
$M_{csm}=1M_{sun}$

$R_{csm}=400R_{sun}$

density

pressure

4-velocity



recollimation shock

GRB jet simulations: jet dynamics

AS, Irwin, &Maeda, in prep.

- a GRB jet-CSM collision in meridional slice (x-z plane) from t=100 to t=3x10^3 s

E_{jet}=5x10^{51}erg

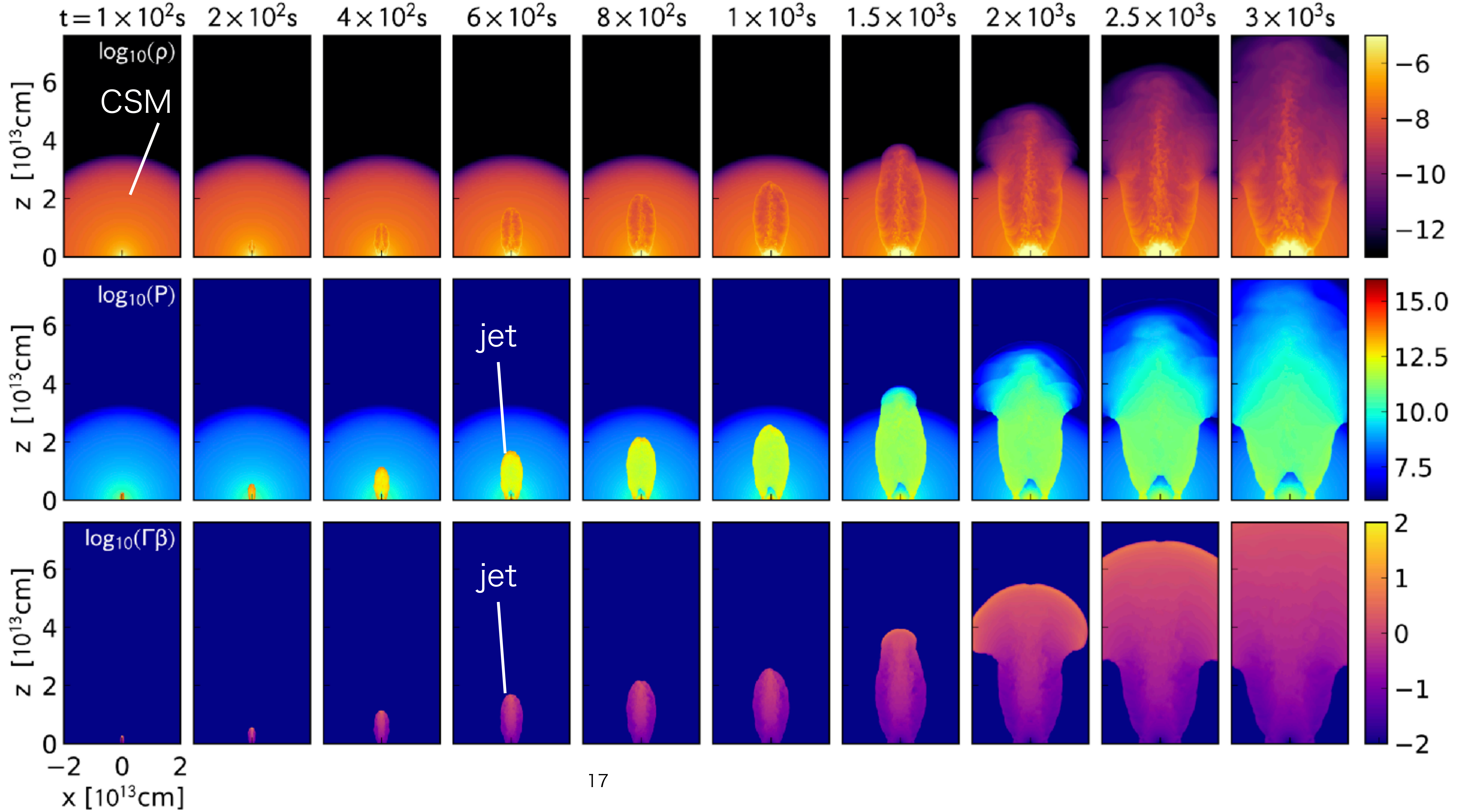
M_{csm}=1M_{sun}

R_{csm}=400R_{sun}

density

pressure

4-velocity



GRB jet simulations: jet dynamics

AS, Irwin, &Maeda, in prep.

- a GRB jet-CSM collision in meridional slice (x-z plane) from t=2x10^3 to t=9x10^3 s

E$_{jet}$=5x10^{51}erg

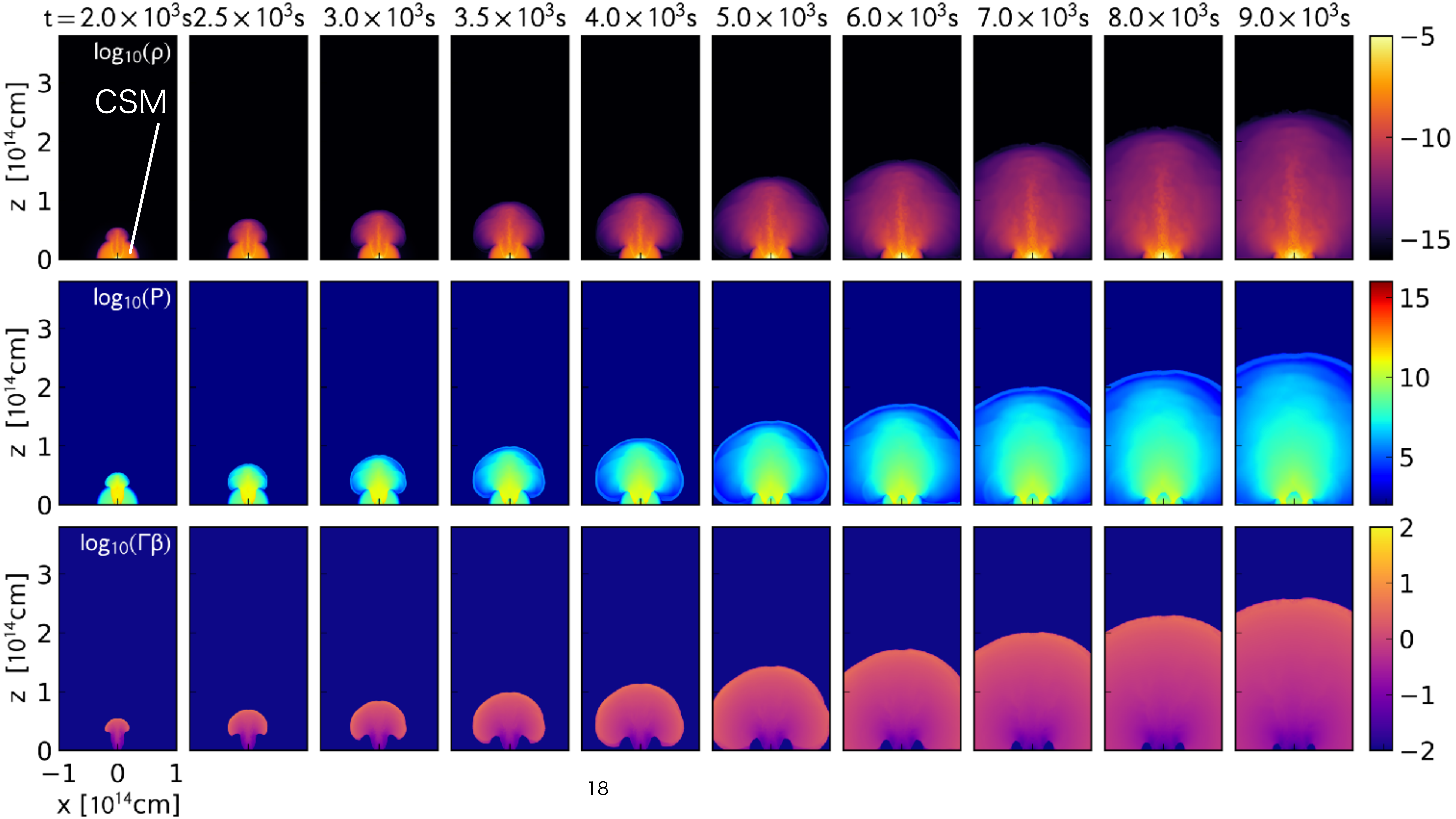
M$_{csm}$=1M$_{sun}$

R$_{csm}$=400R$_{sun}$

density

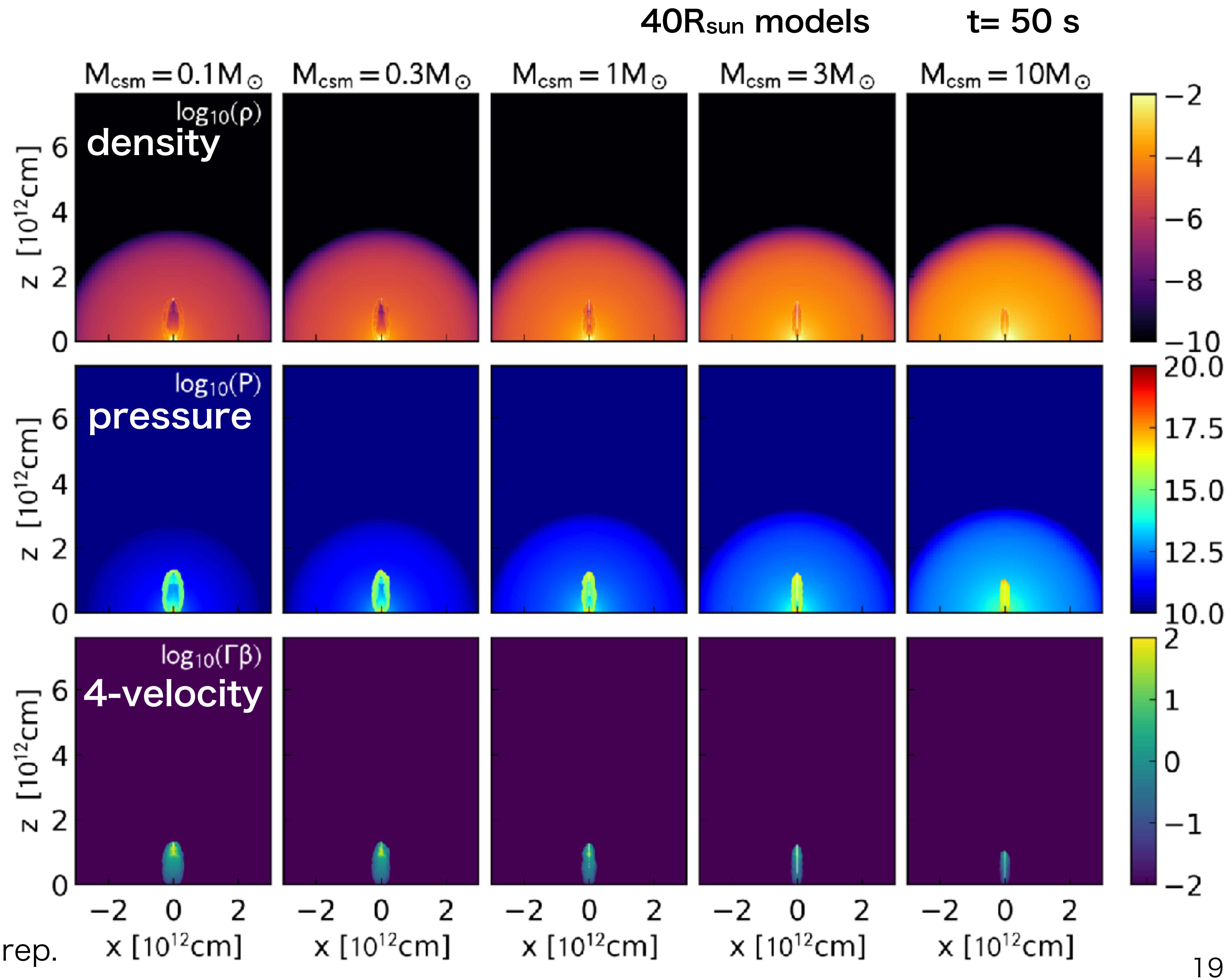
pressure

4-velocity



GRB jet simulations: CSM mass dependence

- 40R_{sun} models: M_{csm}=0.1-10M_{sun}
- massive CSMs decelerate the jet efficiently
- massive CSMs collimate the jet
- M_{csm}=10M_{sun}: non-relativistic jet head.



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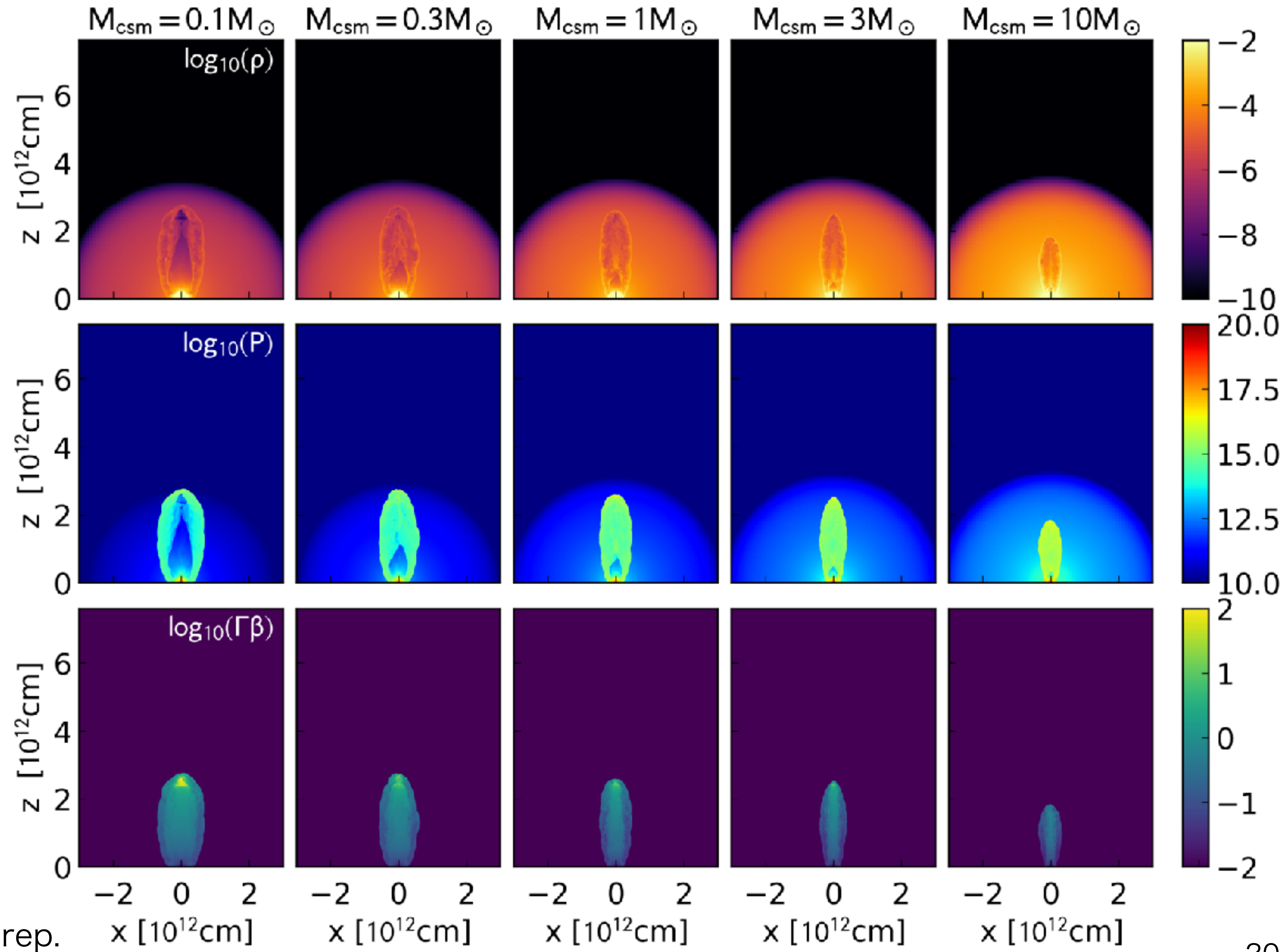
40R$_{sun}$ models t=100 s



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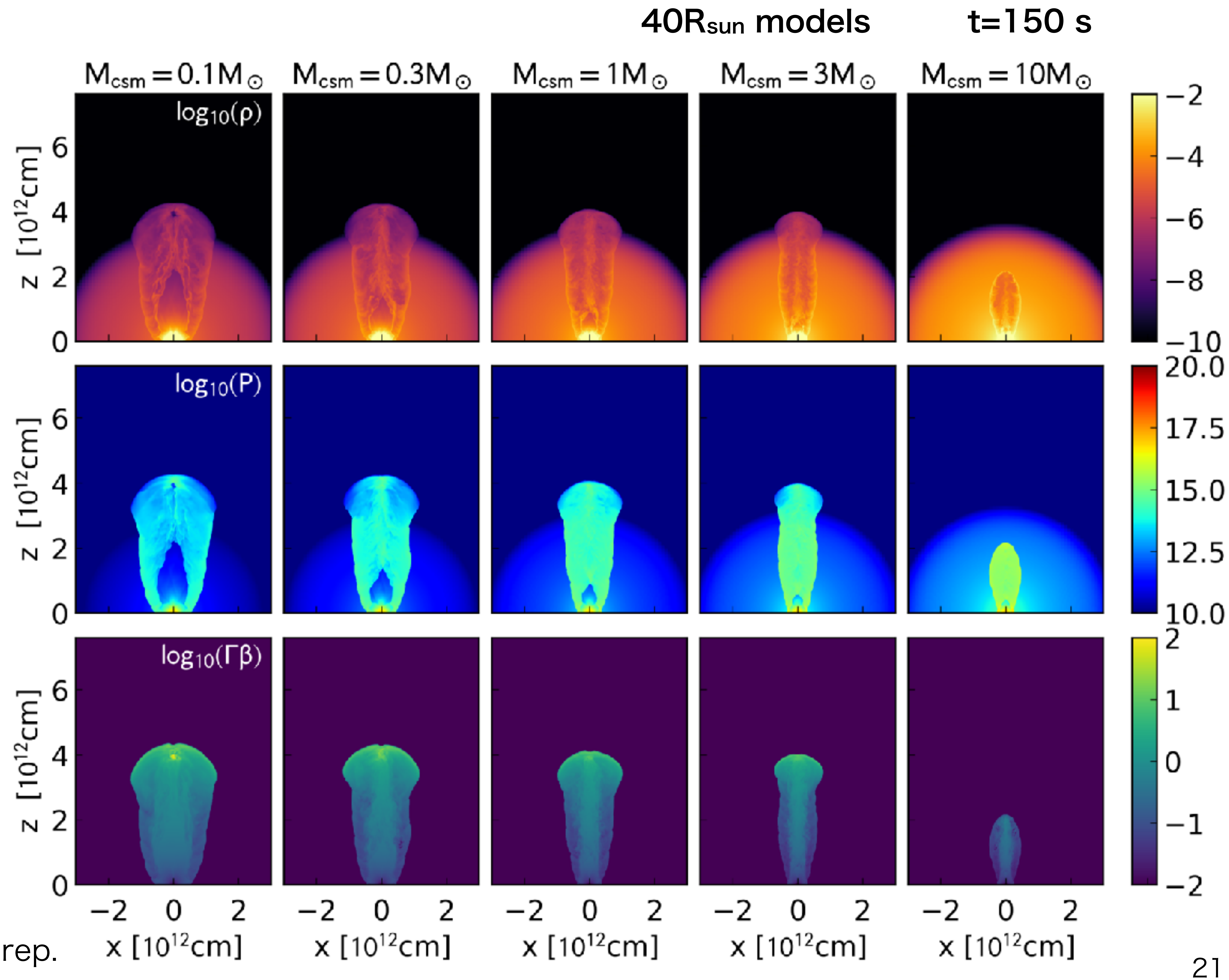

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GRB jet simulations: CSM mass dependence

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- massive CSMs decelerate the jet efficiently
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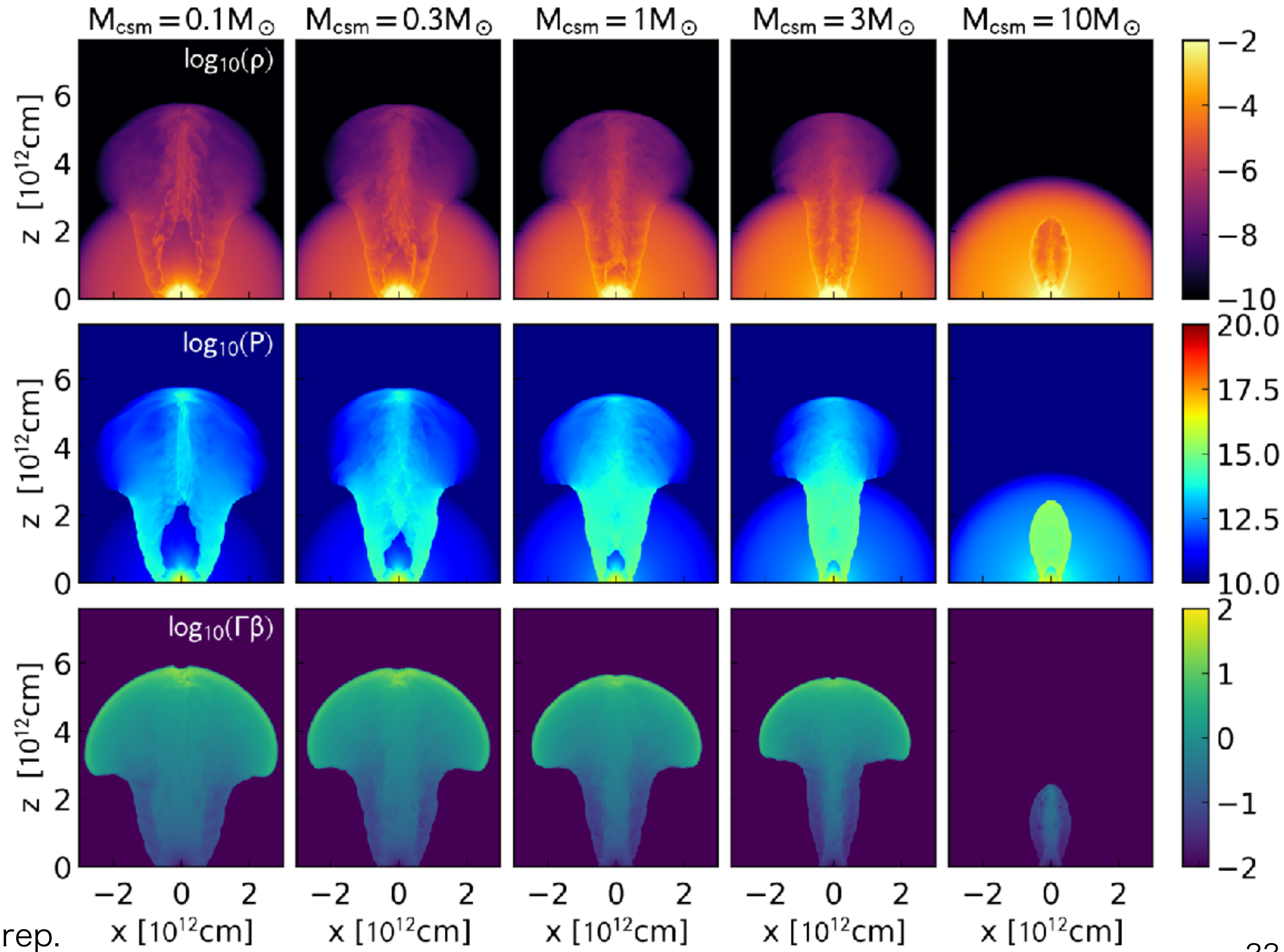
40Rsun models t=200 s



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GRB jet simulations: CSM mass dependence

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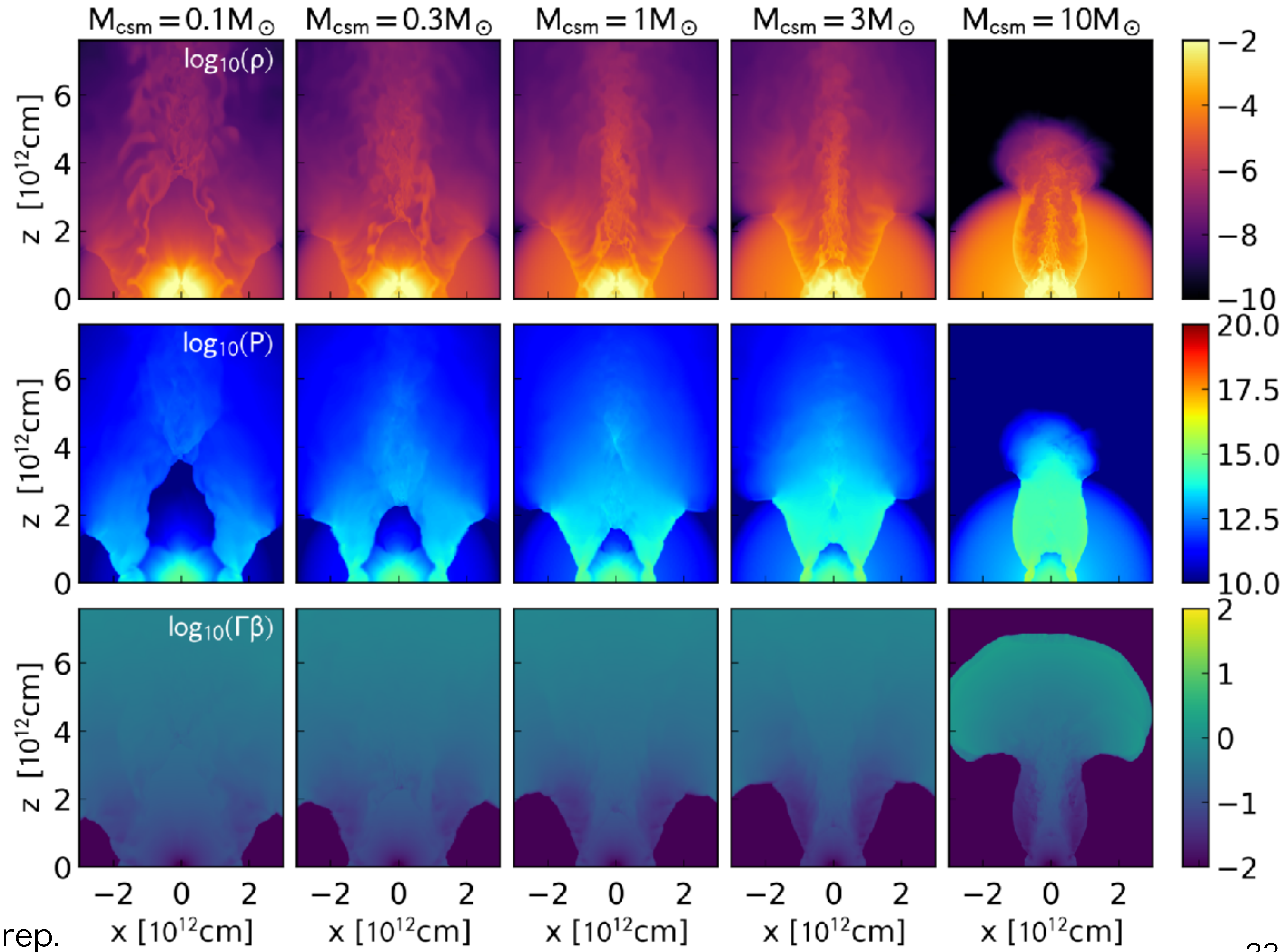
40R$_{sun}$ models t=500 s



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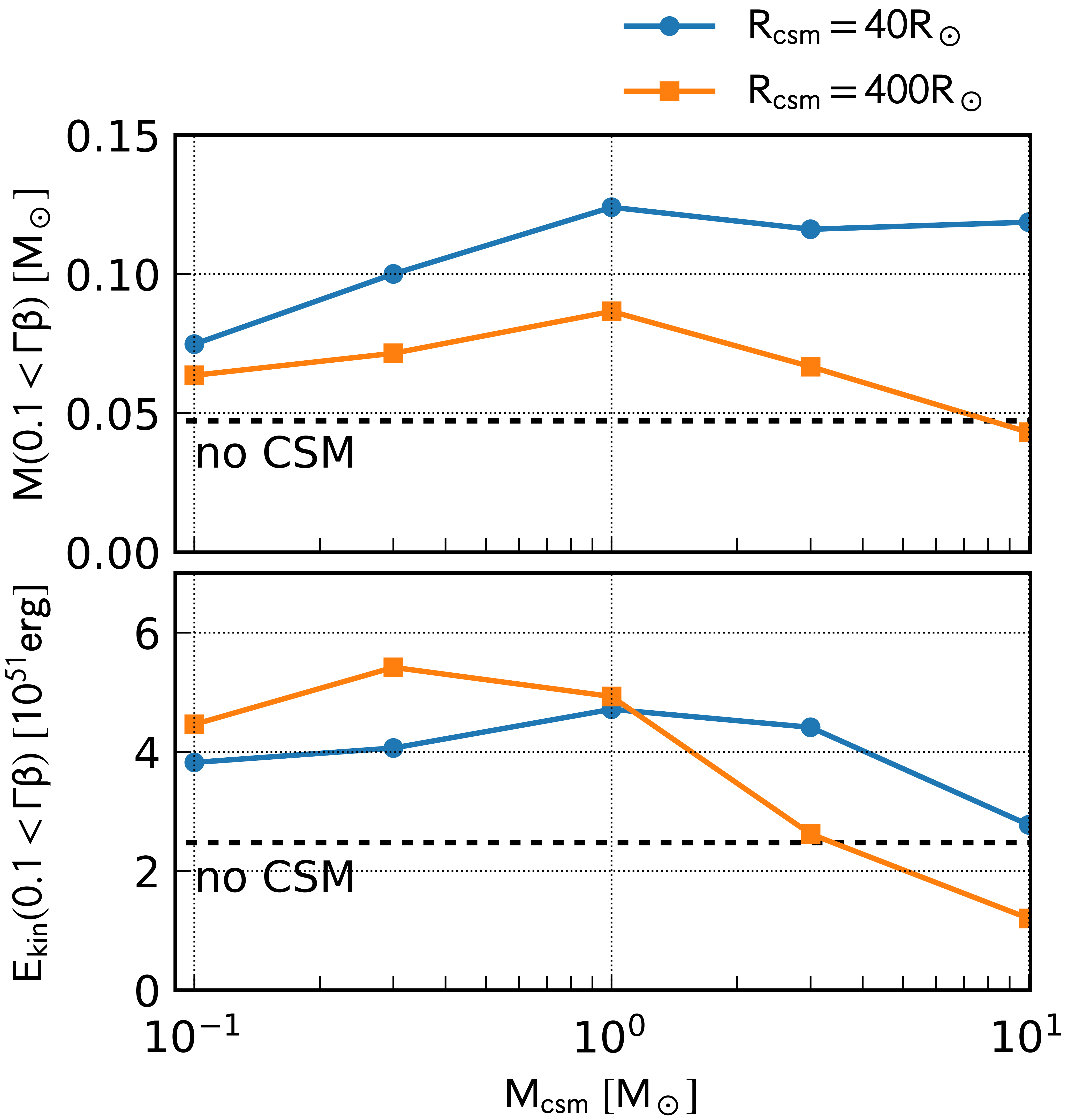
GRB jet simulations: CSM mass dependence

- a fraction of CSM is swept by the shock driven by the jet
- mass and energy of ejecta accelerated beyond v=0.1c:
  - $M(v>0.1c) \sim (0.05\text{-}0.12)M_{sun}$
  - $E_{kin}(v>0.1c) \sim (1\text{-}5)\times10^{51}$erg
- only weakly dependent on the CSM properties (M_{csm} and R_{csm})



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Thermal emission powered by jet dissipation

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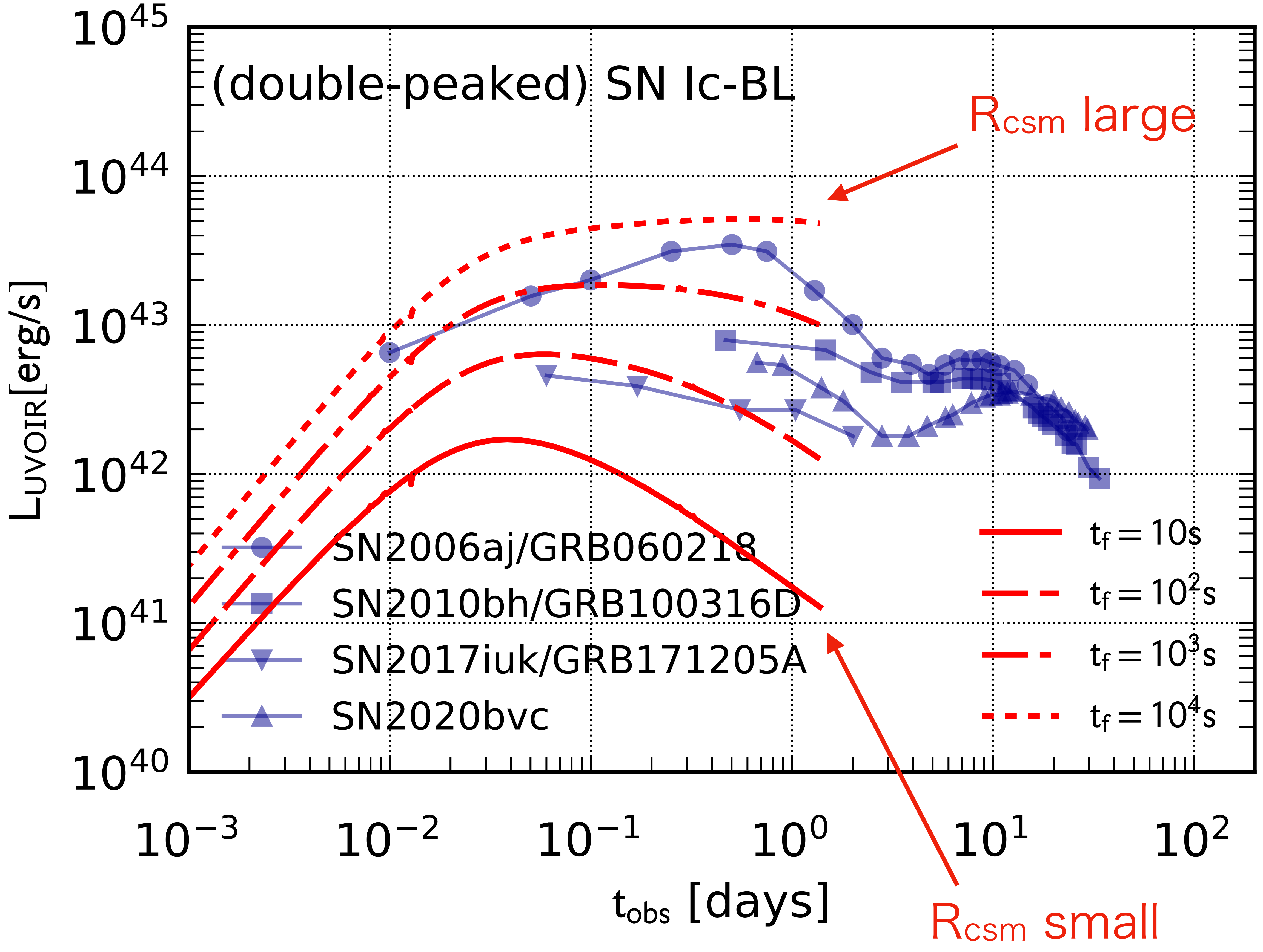
  - $M(v>0.1c) \sim (0.05\text{-}0.12) M_{sun}$
  - $E_{kin}(v>0.1c) \sim (1\text{-}5) \times 10^{51}$ erg
- only weakly dependent on the CSM properties (M_{csm} and R_{csm})
- thermal emission from the fast ejecta can account for the early UV-opt luminosity of llGRBs and SN Ic-BL 2020bvc
- this thermal emission could be common



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Summary: llGRBs in multi-messenger era

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- the jet energy goes into kinetic and thermal energies of expanding CSM
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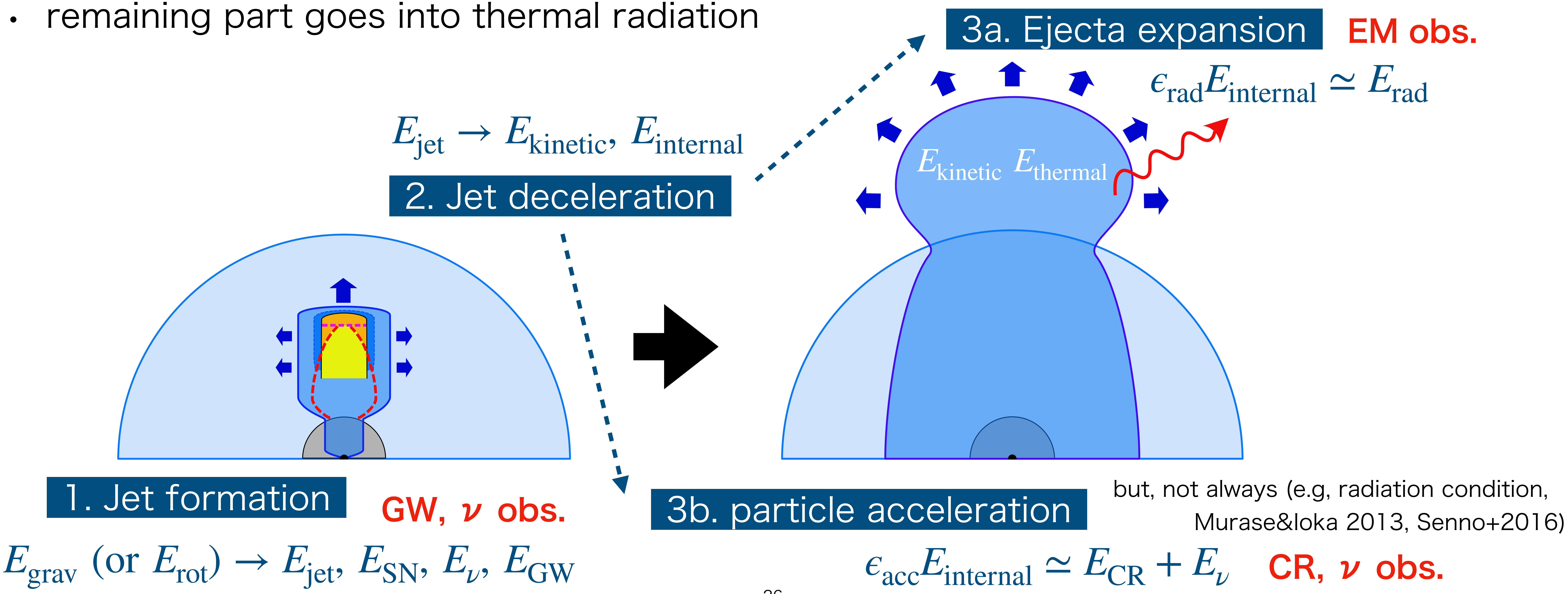

1. Jet formation **GW, ν obs.**

$E_{\rm grav}$ (or $E_{\rm rot}$) $\rightarrow E_{\rm jet}, E_{\rm SN}, E_{\nu}, E_{\rm GW}$

$E_{\rm jet} \rightarrow E_{\rm kinetic}, E_{\rm internal}$

2. Jet deceleration

3a. Ejecta expansion **EM obs.**

$\epsilon_{\rm rad} E_{\rm internal} \simeq E_{\rm rad}$

3b. particle acceleration

but, not always (e.g, radiation condition,
Murase&Ioka 2013, Senno+2016)

$\epsilon_{\rm acc} E_{\rm internal} \simeq E_{\rm CR} + E_{\nu}$ **CR, ν obs.**

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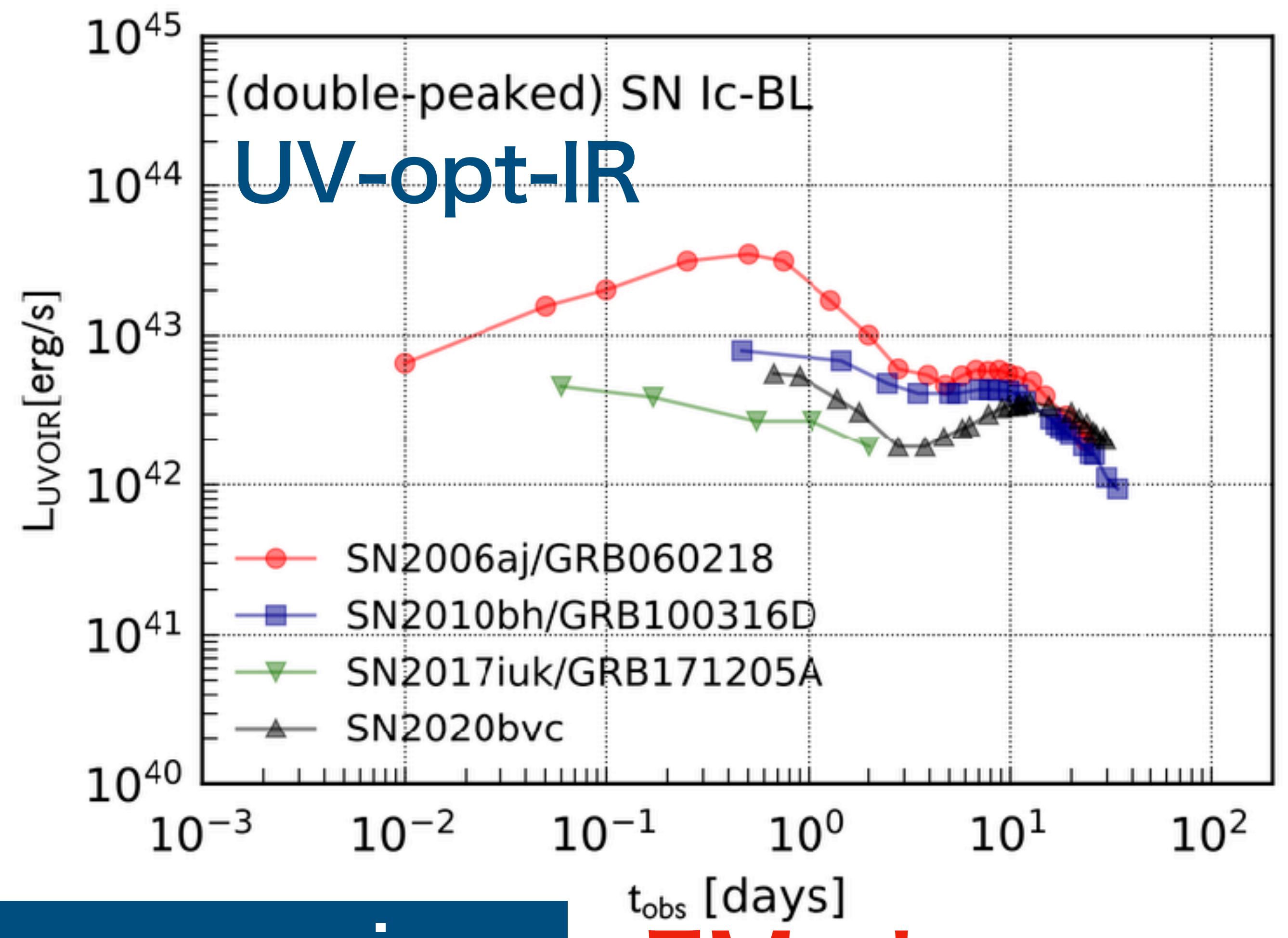

3a. Ejecta expansion

EM obs.

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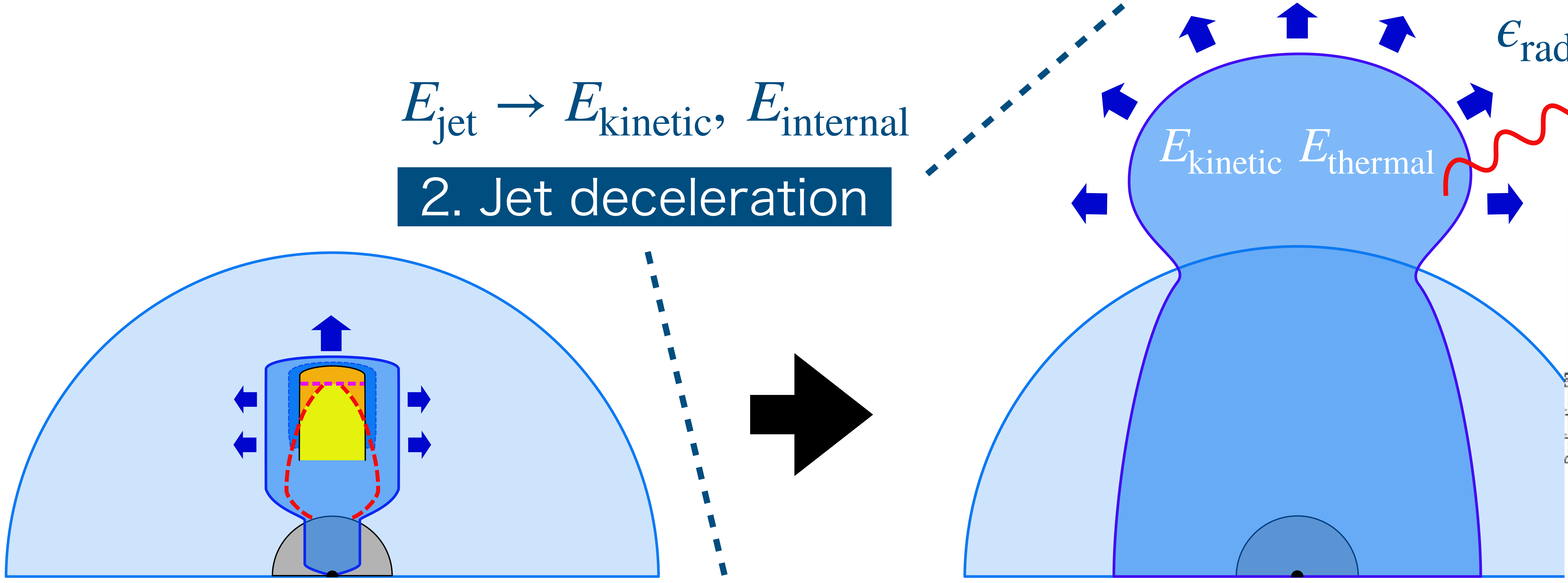
$$E_{\rm jet} \rightarrow E_{\rm kinetic}, E_{\rm internal}$$

2. Jet deceleration



1. Jet formation

GW, ν obs.

$$E_{\rm grav} \text{ (or } E_{\rm rot}) \rightarrow E_{\rm jet}, E_{\rm SN}, E_{\nu}, E_{\rm GW}$$

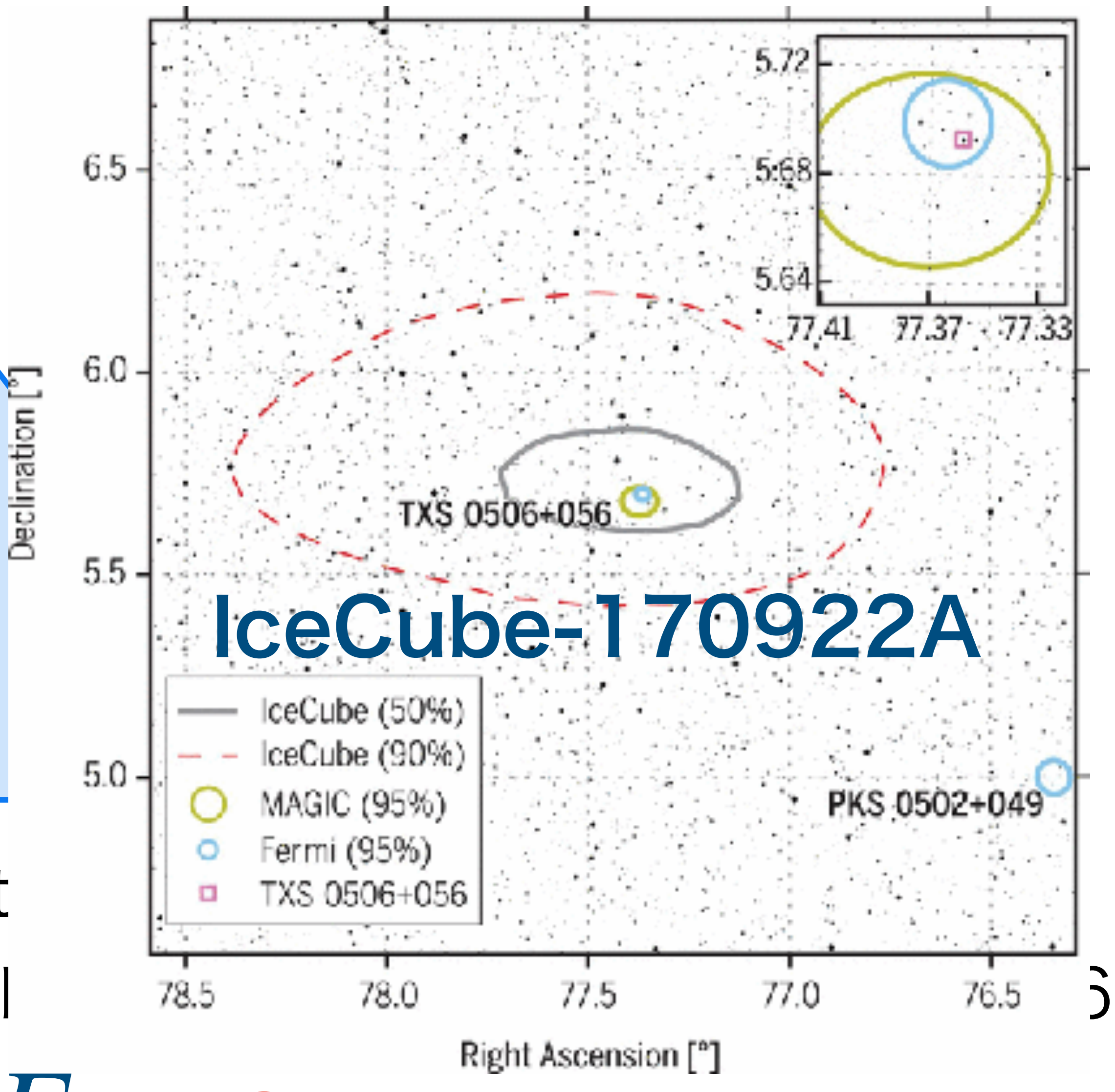
3b. particle acceleration

$$\epsilon_{\rm acc} E_{\rm internal} \simeq E_{\rm CR} + E_{\nu}$$

CR, ν obs.

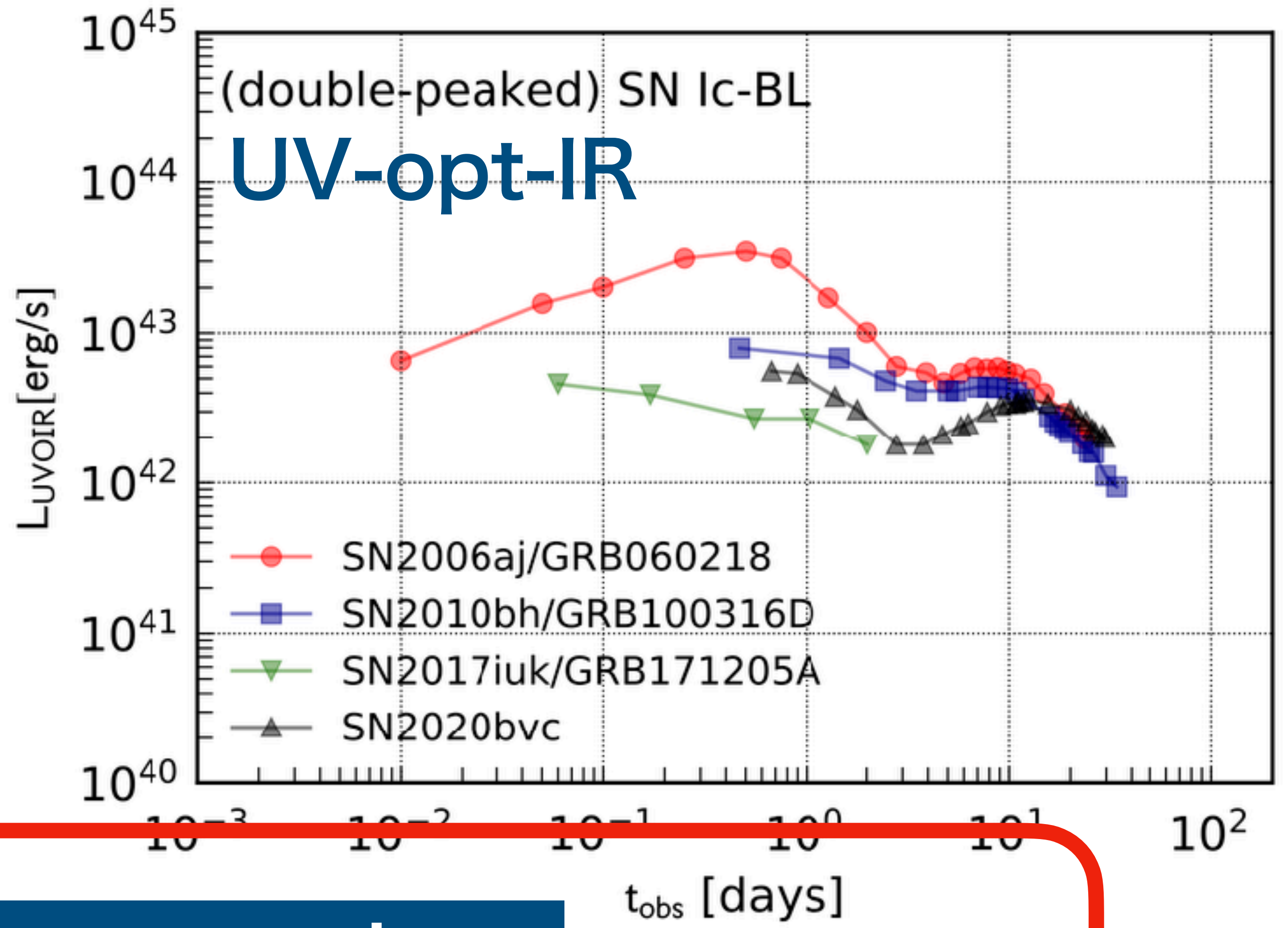
but, not

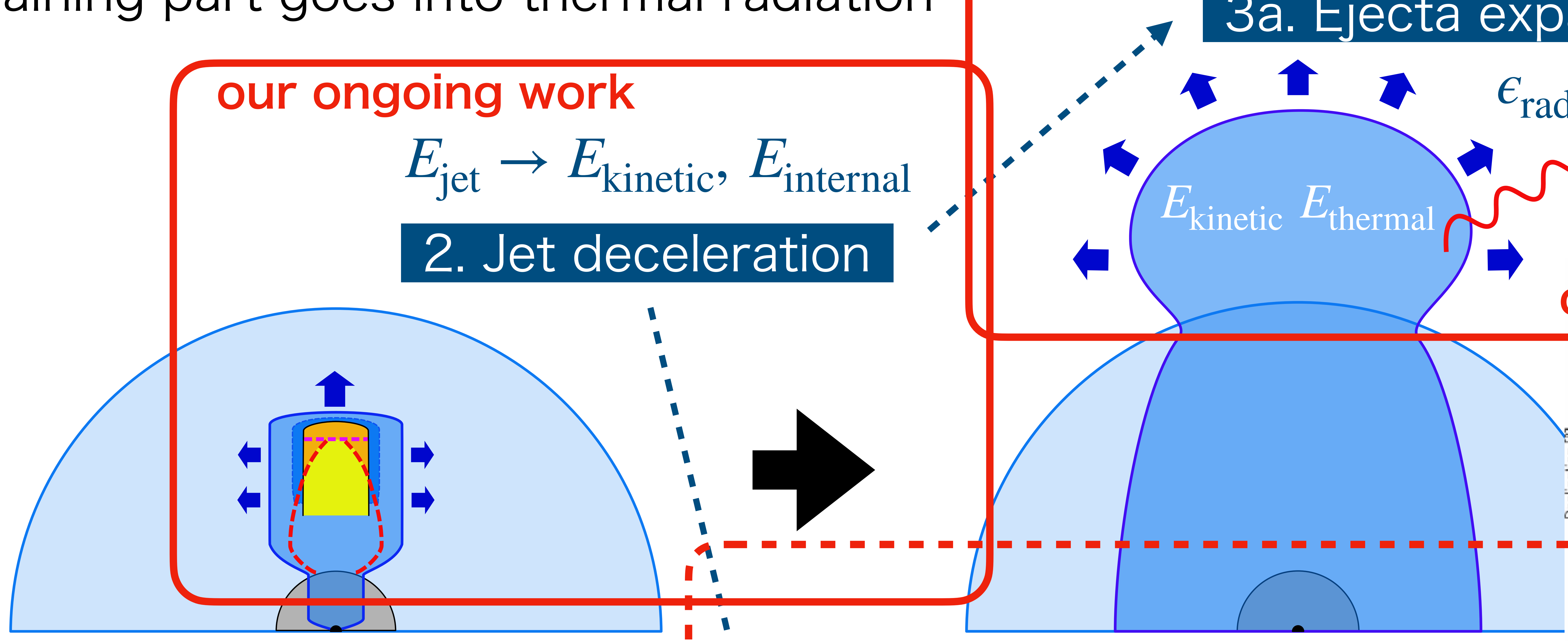
5)



Summary: llGRBs in multi-messenger

- jet deceleration = energy dissipation
- the jet energy goes into kinetic and thermal energies of expandi
- a small fraction of the thermal energy goes into CRs and ν
- remaining part goes into thermal radiation





our ongoing work

$E_{\rm jet} \rightarrow E_{\rm kinetic}, E_{\rm internal}$

2. Jet deceleration

3a. Ejecta expansion

EM obs.

$\epsilon_{\rm rad} E_{\rm internal} \simeq E_{\rm rad}$

$E_{\rm kinetic}$ $E_{\rm thermal}$

our ongoing work

1. Jet formation

GW, ν obs.

$E_{\rm grav}$ (or $E_{\rm rot}$) $\rightarrow E_{\rm jet}, E_{\rm SN}, E_{\nu}, E_{\rm GW}$

3b. particle acceleration

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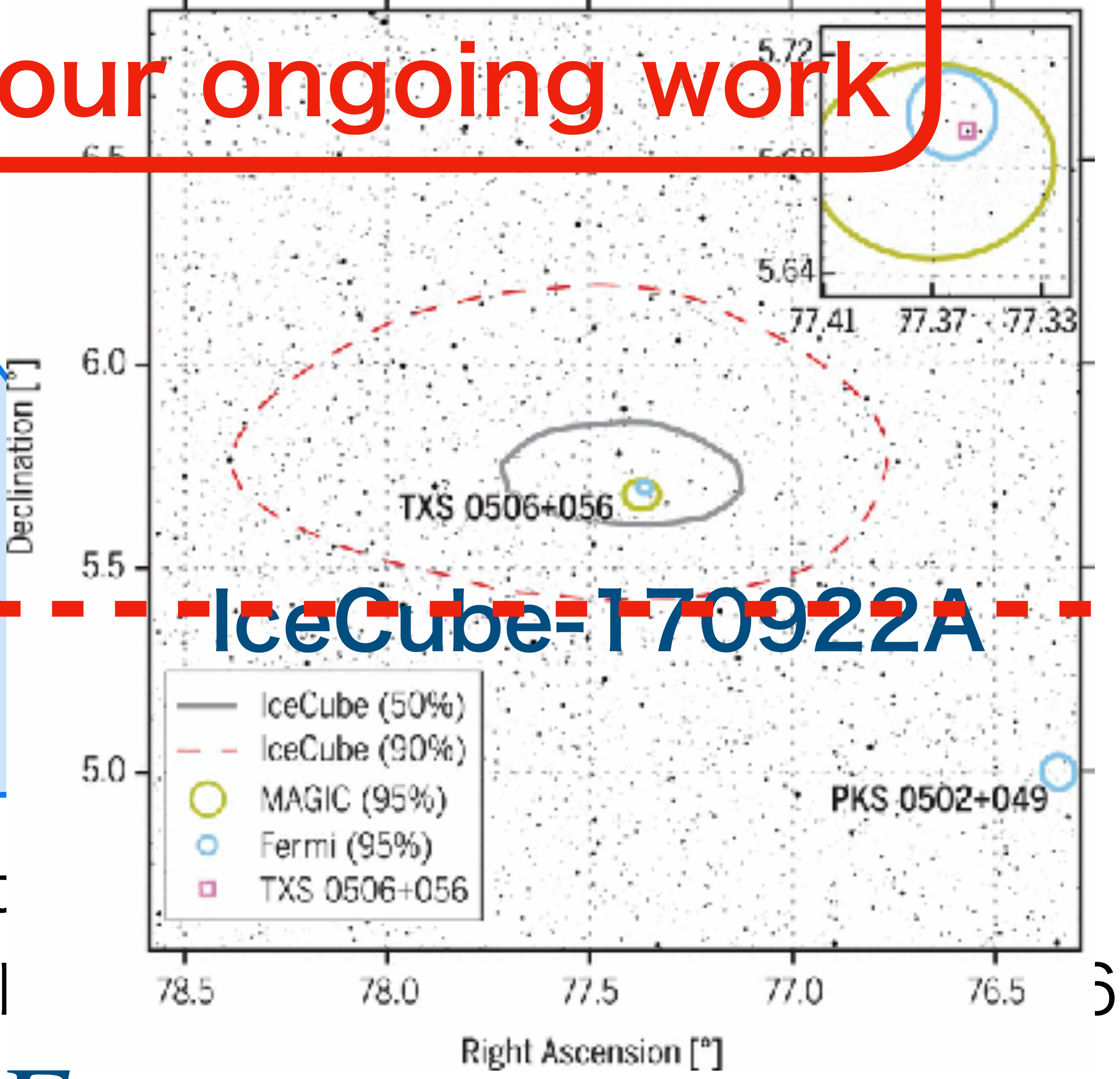


IceCube-170922A

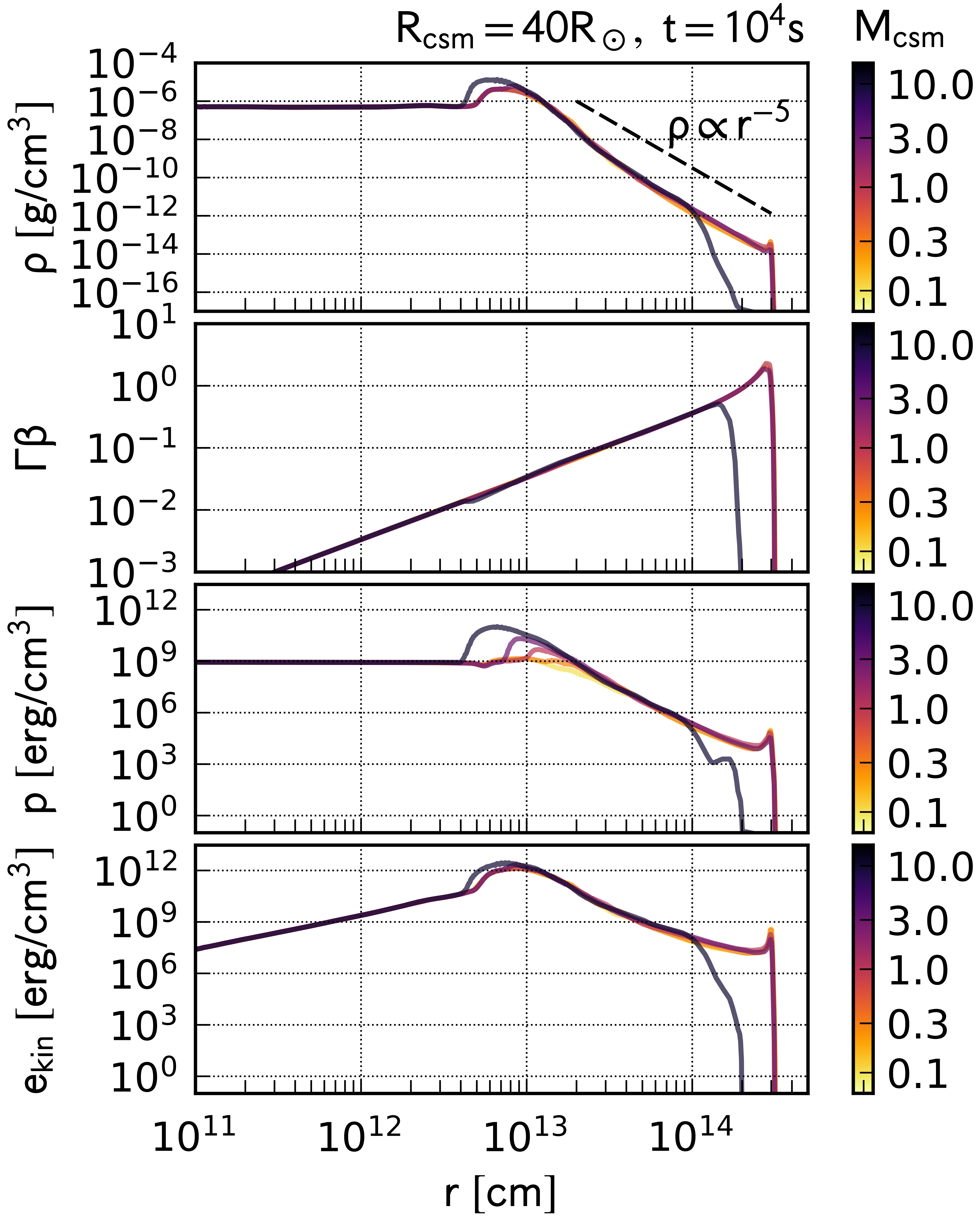
$\epsilon_{\rm acc} E_{\rm internal} \simeq E_{\rm CR} + E_{\nu}$

CR, ν obs.

Backup slides

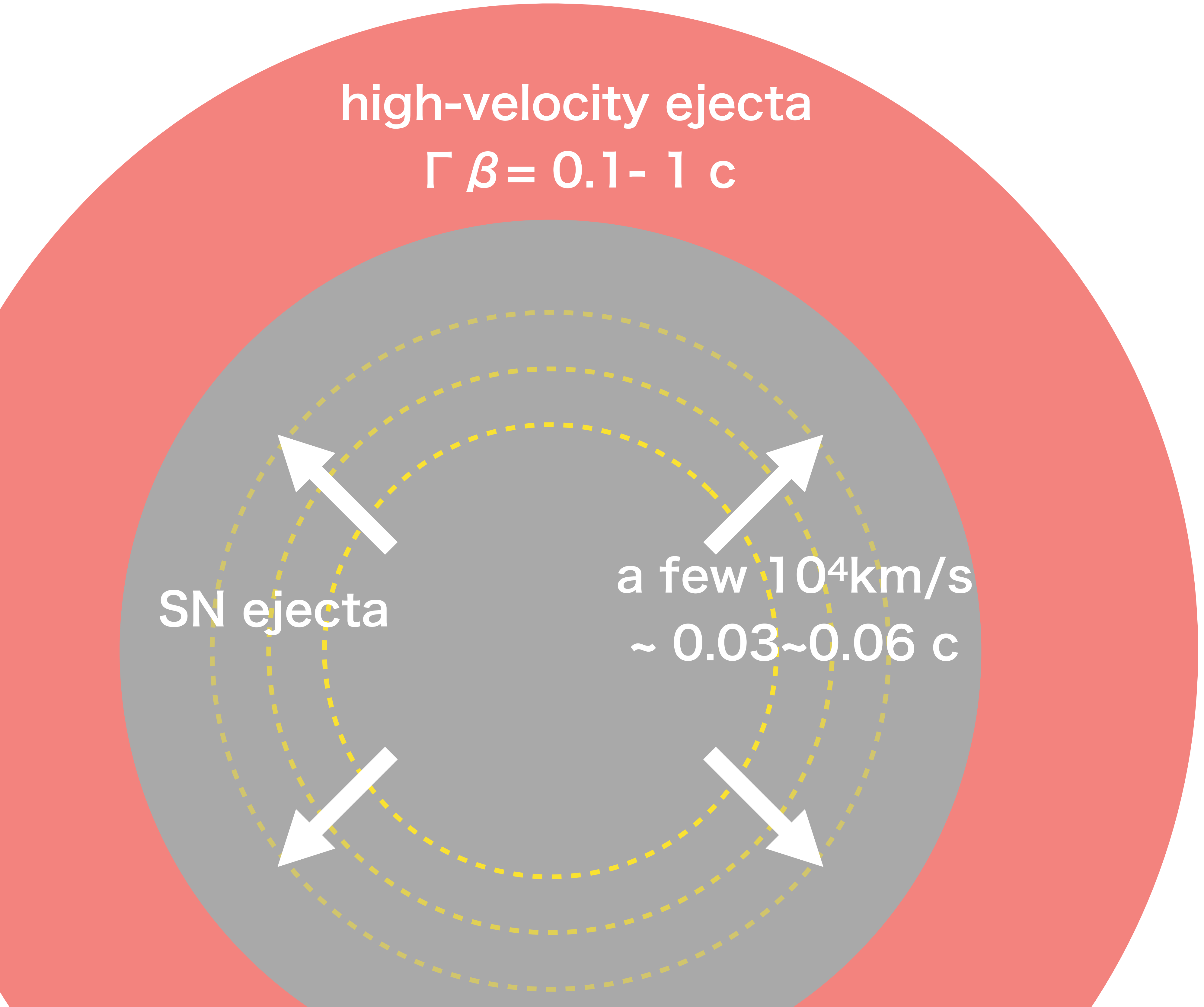
GRB jet simulations: radial profiles

- angle-averaged profiles of density, 4-velocity, pressure, and kinetic energy density
- almost free expansion (v=r/t)
- density structure is remarkably universal
- power-law function of radial velocity with index -5: $\rho \propto v^{-5} \propto r^{-5}$



Future studies

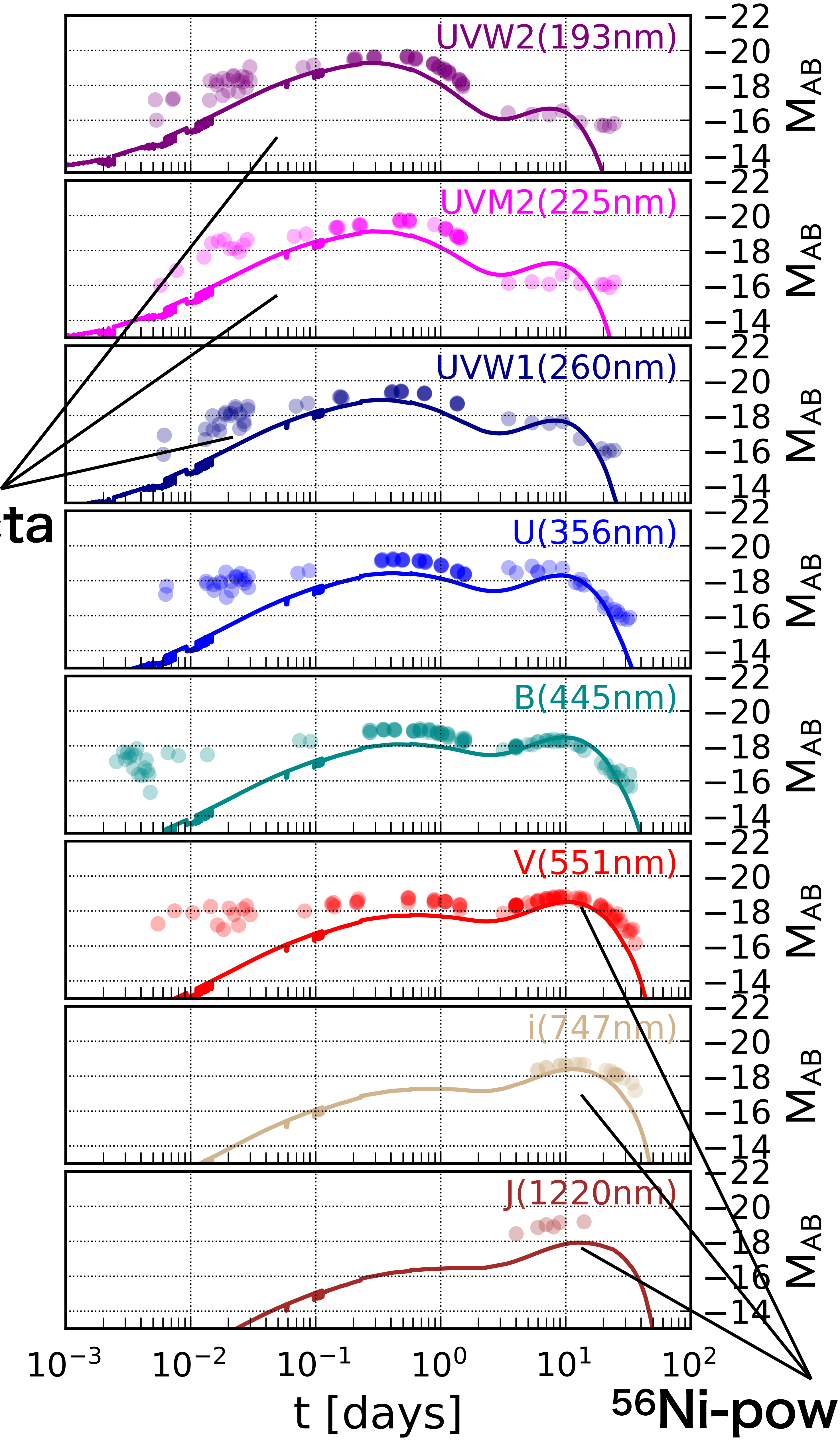
- combined modeling of thermal cocoon emission + SN light
- spherical 1D radiation-hydrodynamic simulations with gray opacity



ejecta properties:

- t_0=200[s]
- $E_{c,kin}$=**15**x10^{51}[erg]
- $E_{c,int}$=**0.05** x $E_{c,kin}$
- $\Gamma\beta_{max}$=1.0
- $\rho \propto (\Gamma\beta)^{-5}$
- E_{sn}=6x10^{51}[erg]
- M_{ej}=2M_{sun}
- M_{ni}=0.3M_{sun}
- free expansion, v=r/t

SN 2006aj multi-band light curve with theoretical model (cocoon + SN)

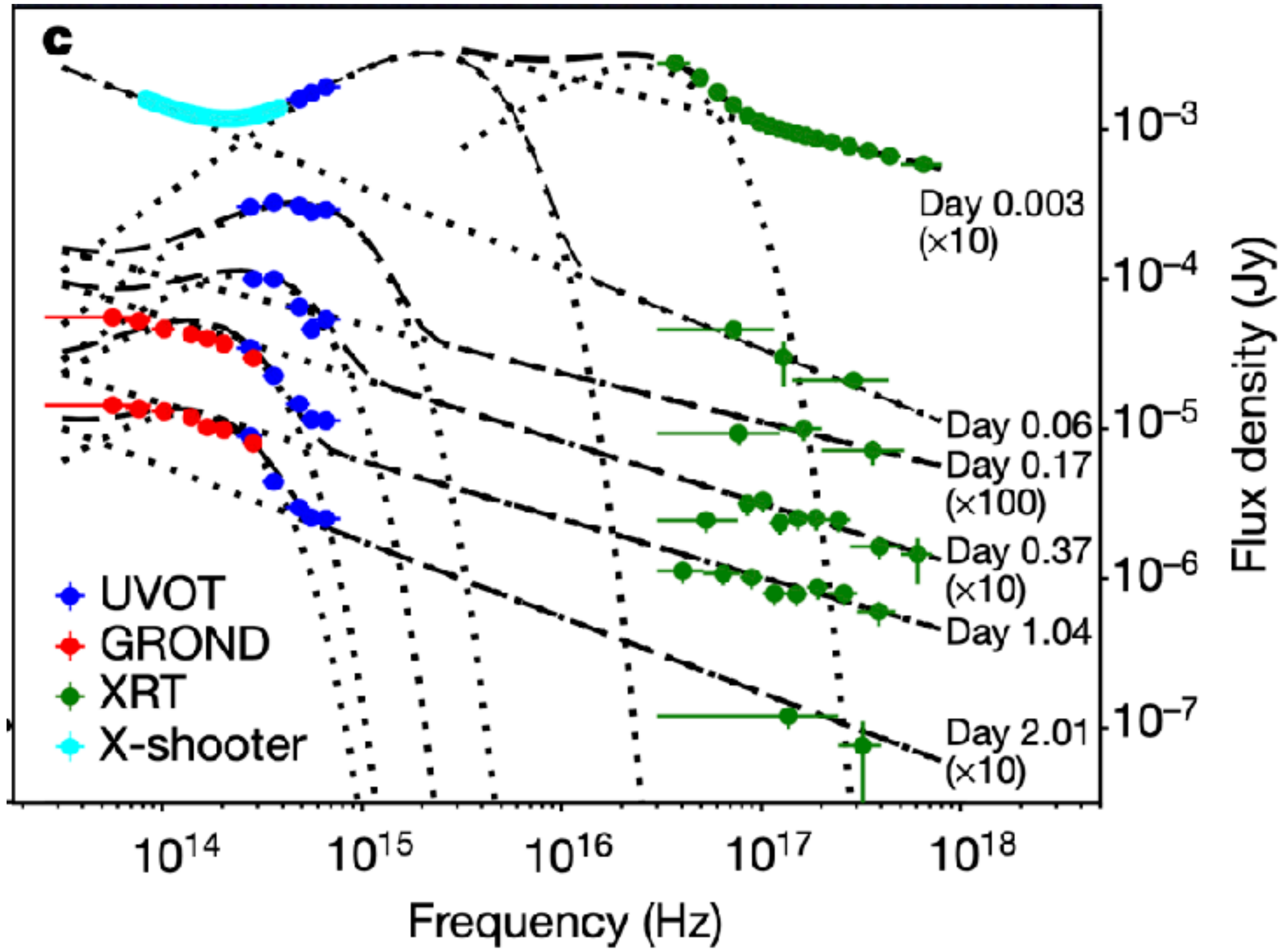


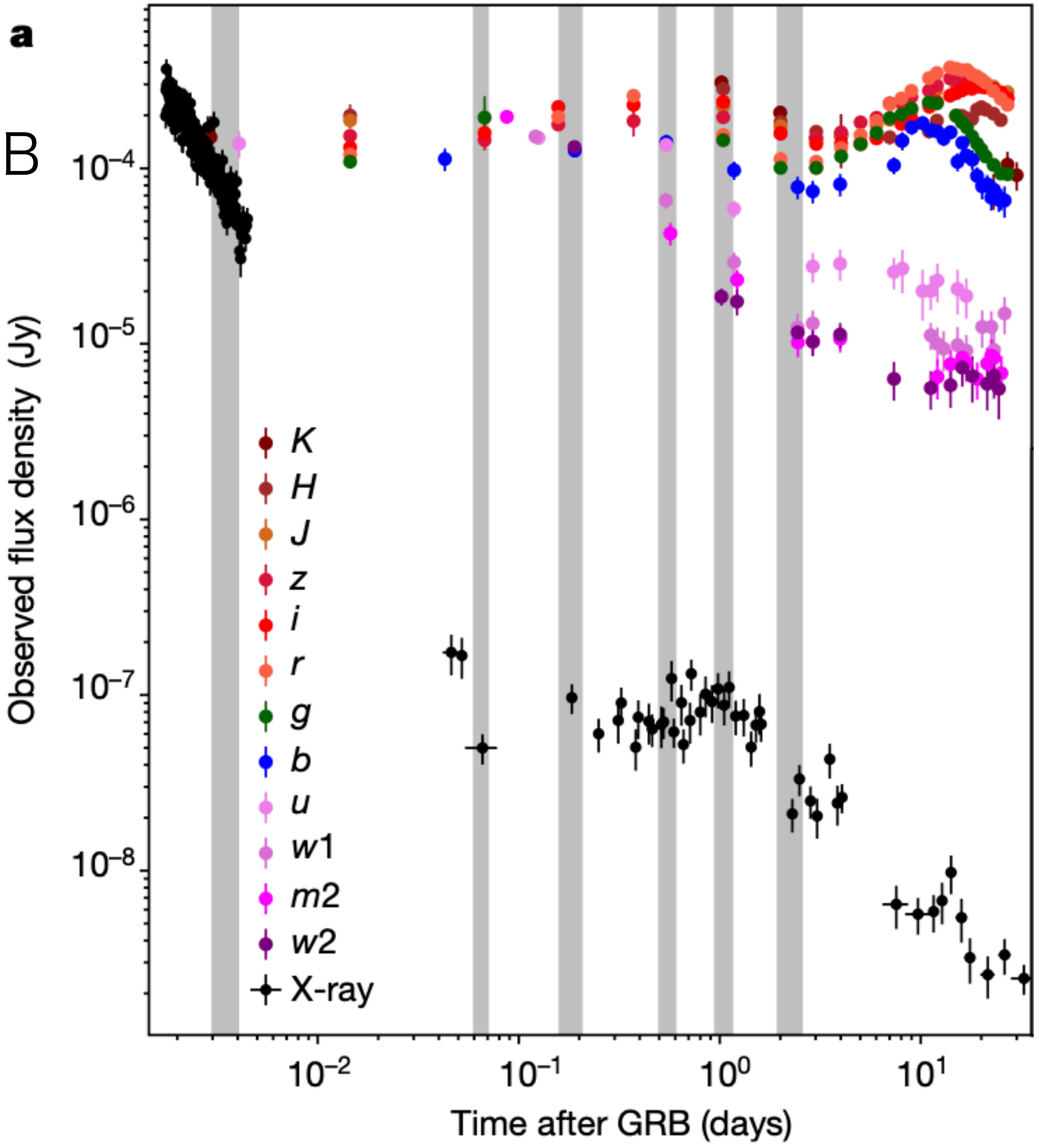
thermal emission from high-velocity ejecta

^{56}Ni-powered

GRB 171205A: a GRB-SN in very early stage

- (low-luminosity) GRB 171205A/ SN 2017iuk at D=163Mpc
- optical spectroscopy as early as 0.06 days after GRB trigger
- E_{iso}~2.2x10^{49}[erg], T_{90}~190[s]





Izzo+ (2019, Nature) including K. Maeda & **AS**

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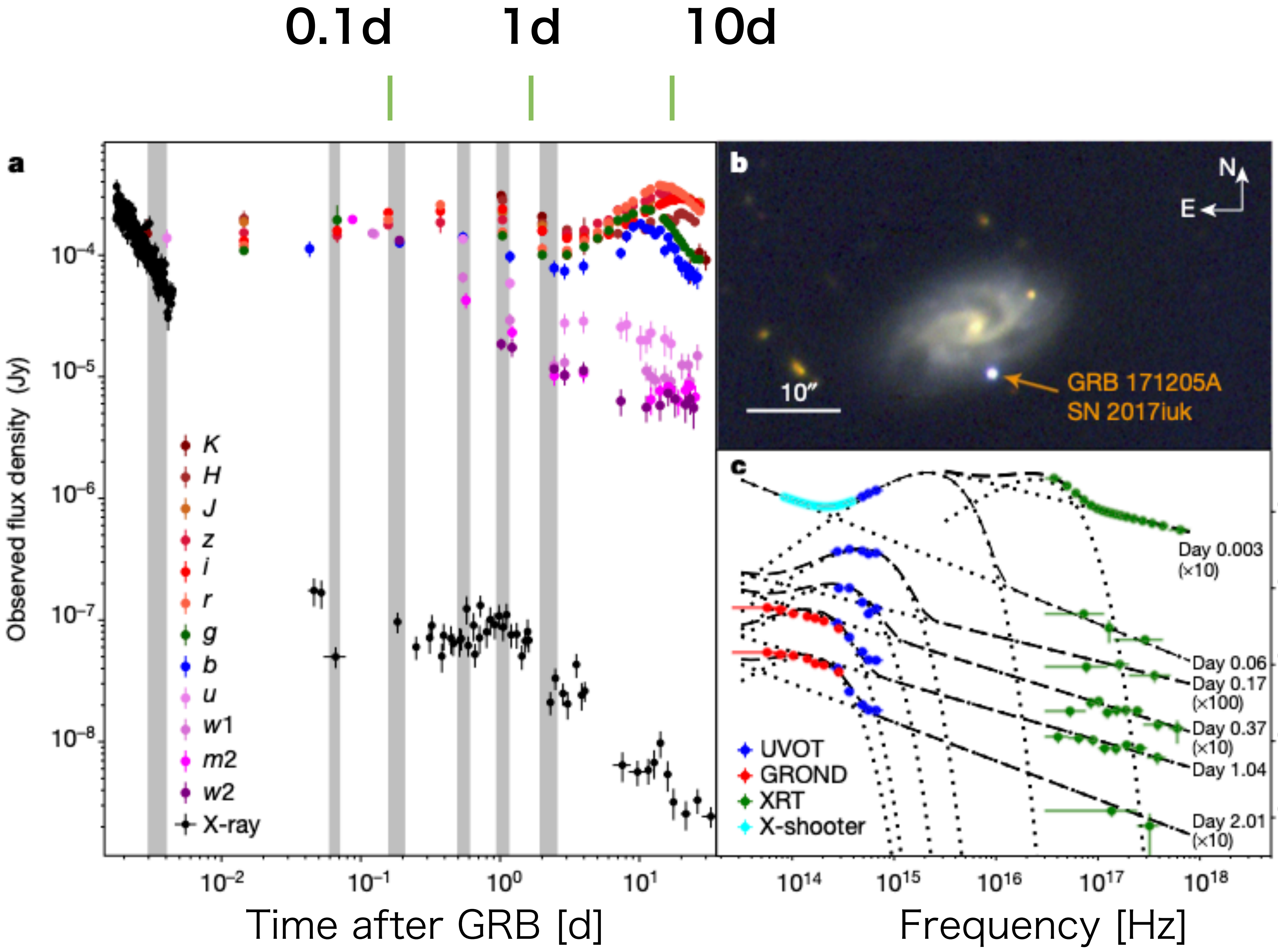

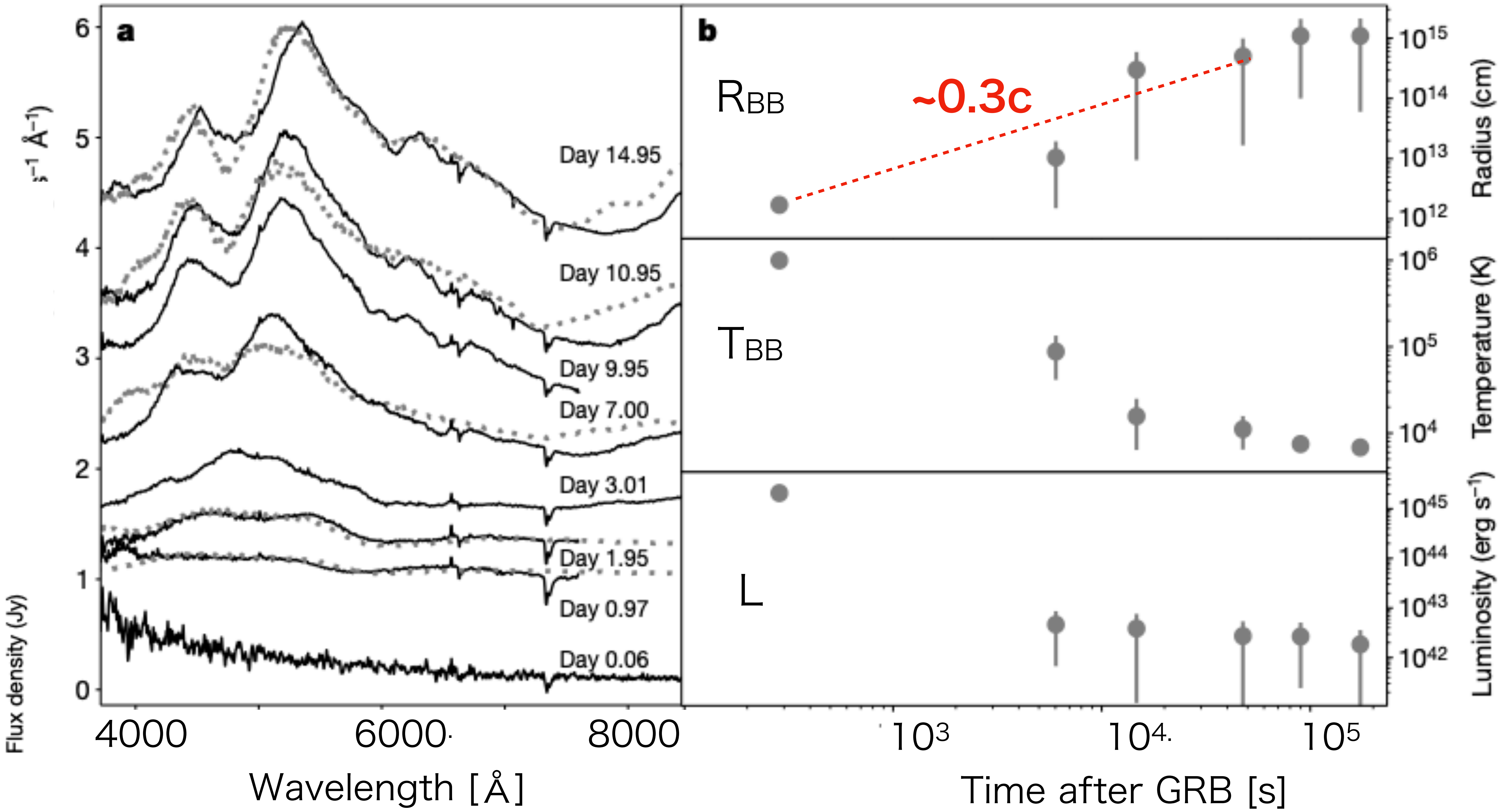

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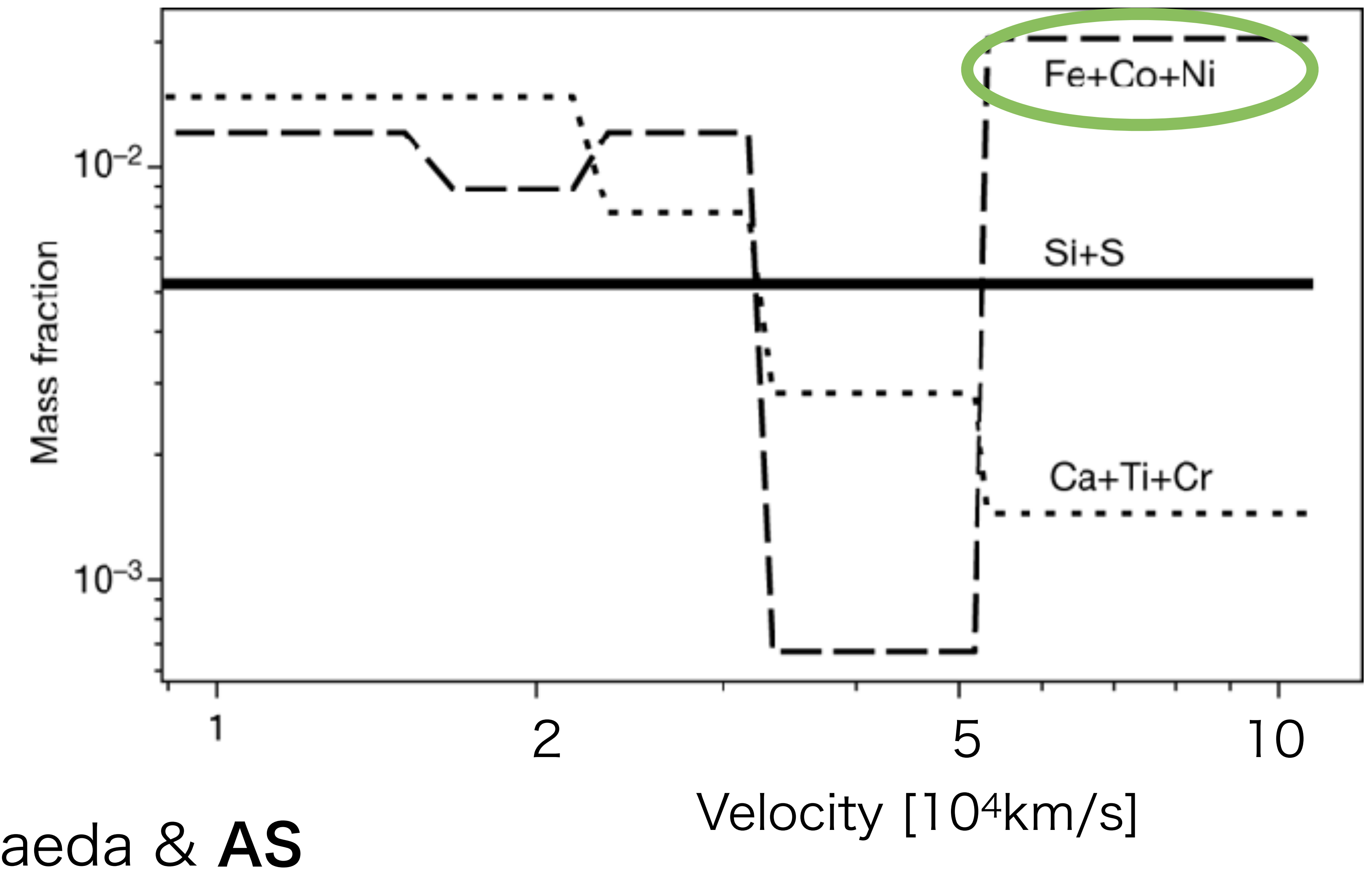
- density profile $\rho \propto v^{-6}$



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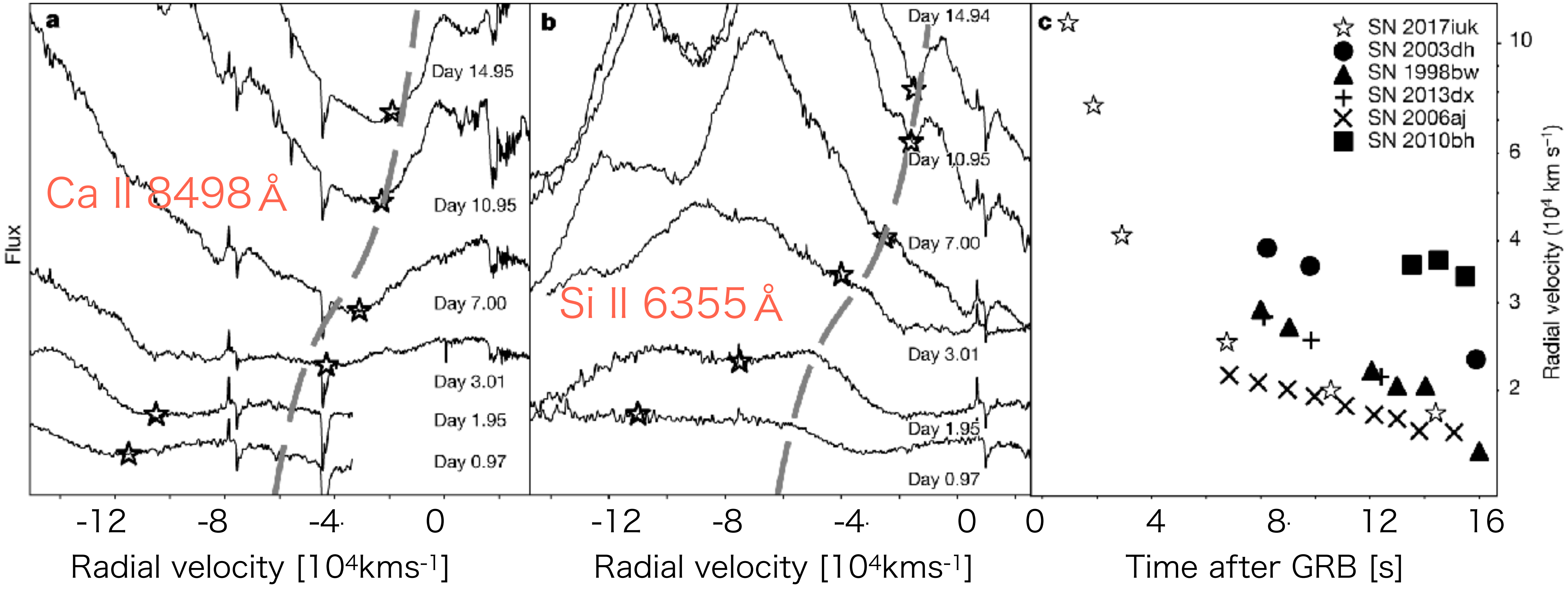
Chemical abundance distribution used for the spectral modeling with the TARDIS code



Early spectral evolution of GRB-SNe

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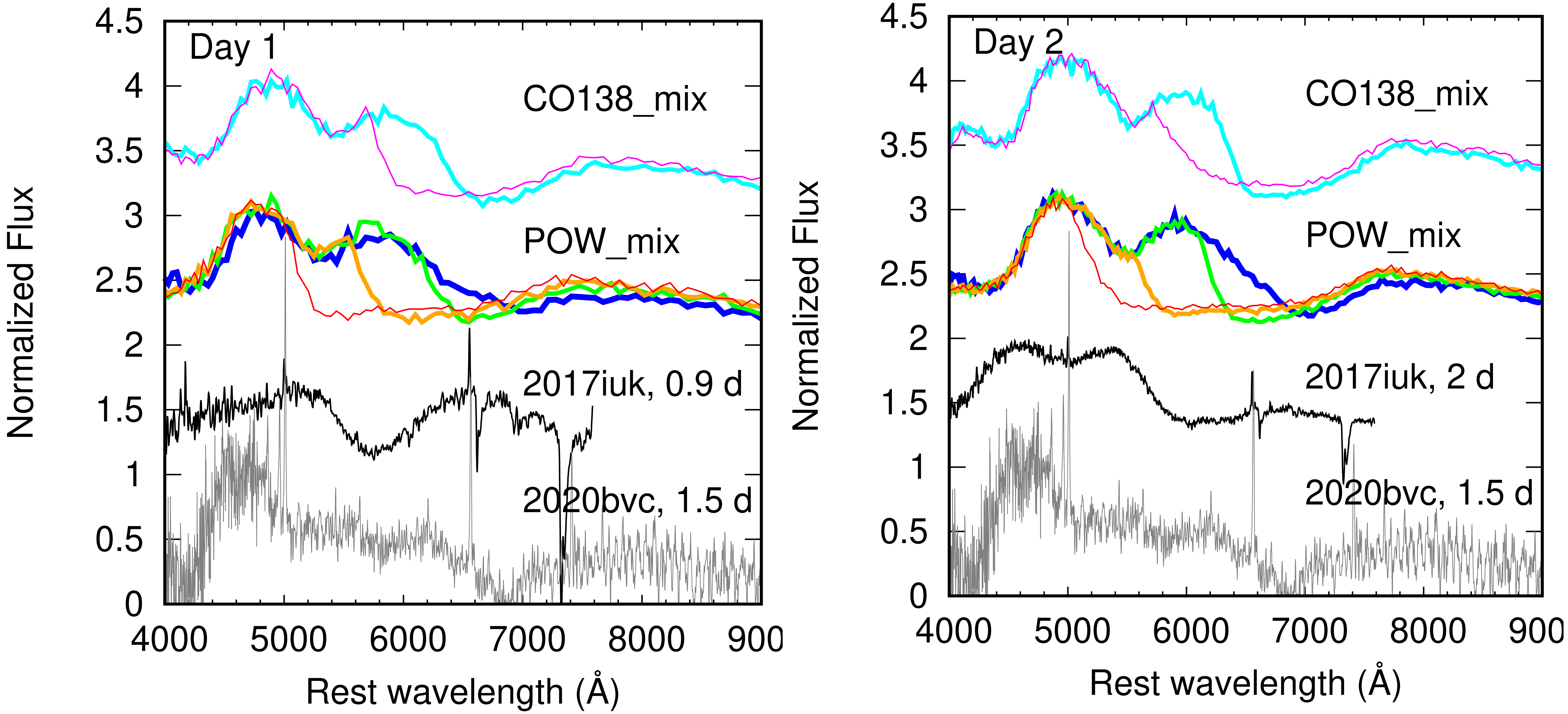
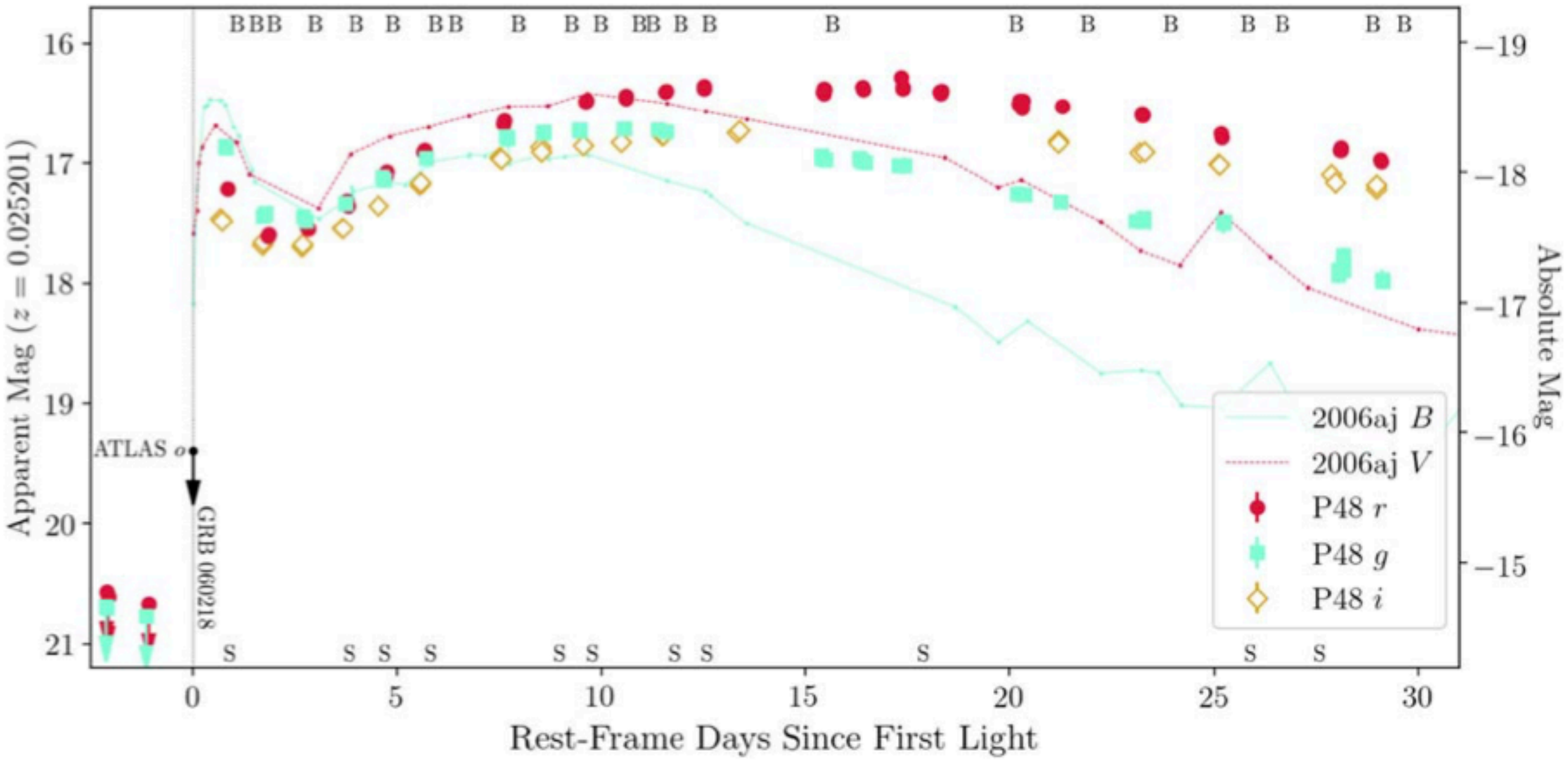


Maeda, **AS**, & Izzo (2023)

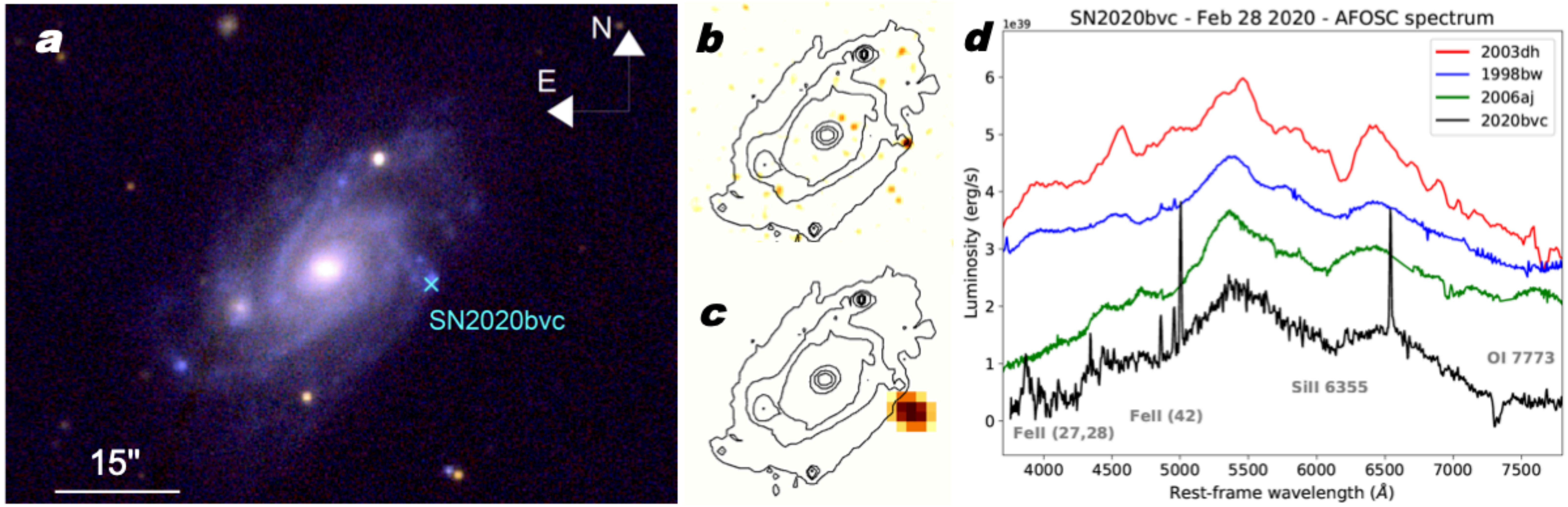
SN 2020bvc: an optically-selected off-axis GRB-SN?

- ZTF discovery
- ATLAS non-detection
- follow-up spectroscopic obs. 0.8 days
- early spectrum dominated by blue continuum
- late-time X-ray and radio detection: similar to SN 2017iuk.



Ho+ (2020)

Izzo+ (2020)



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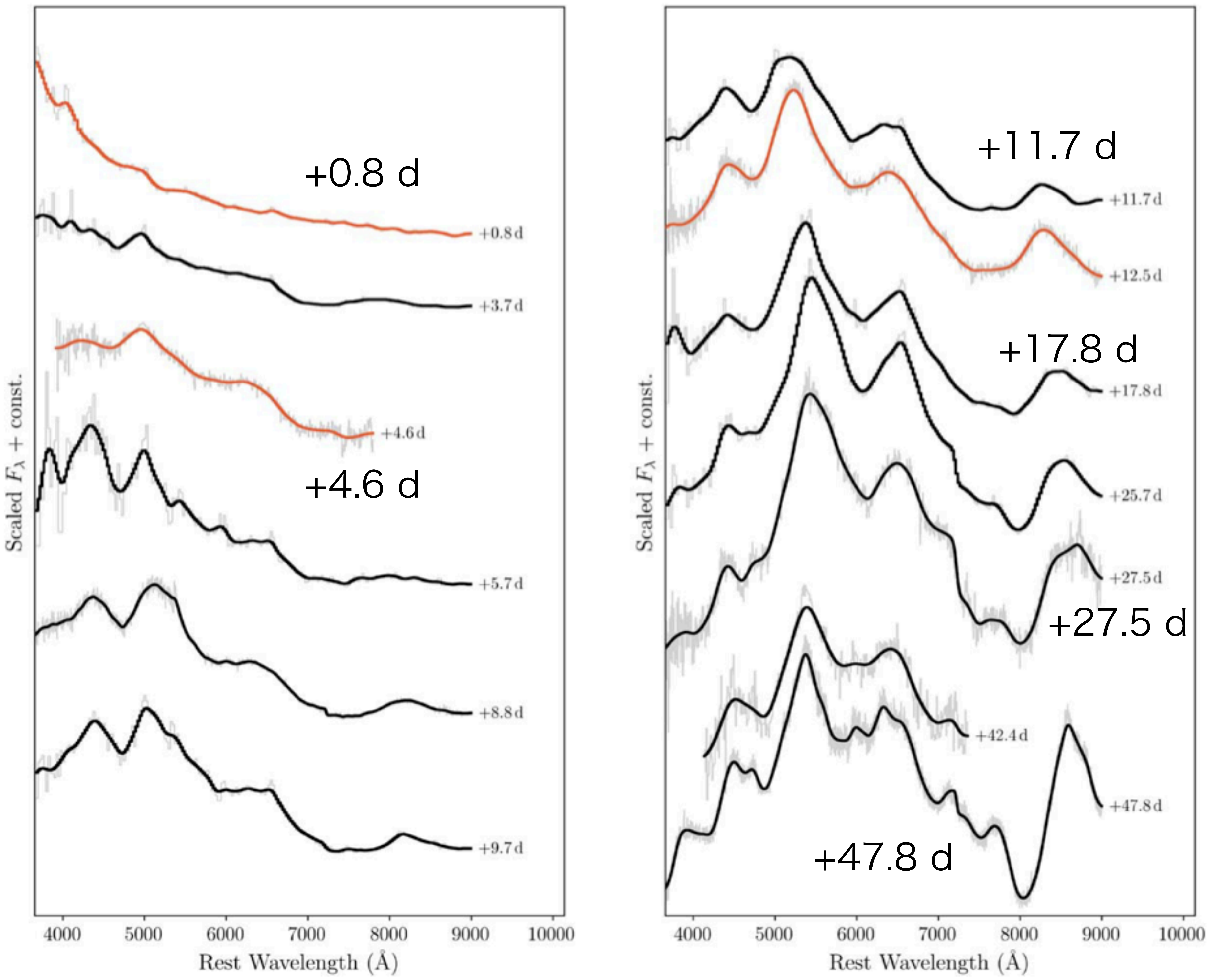

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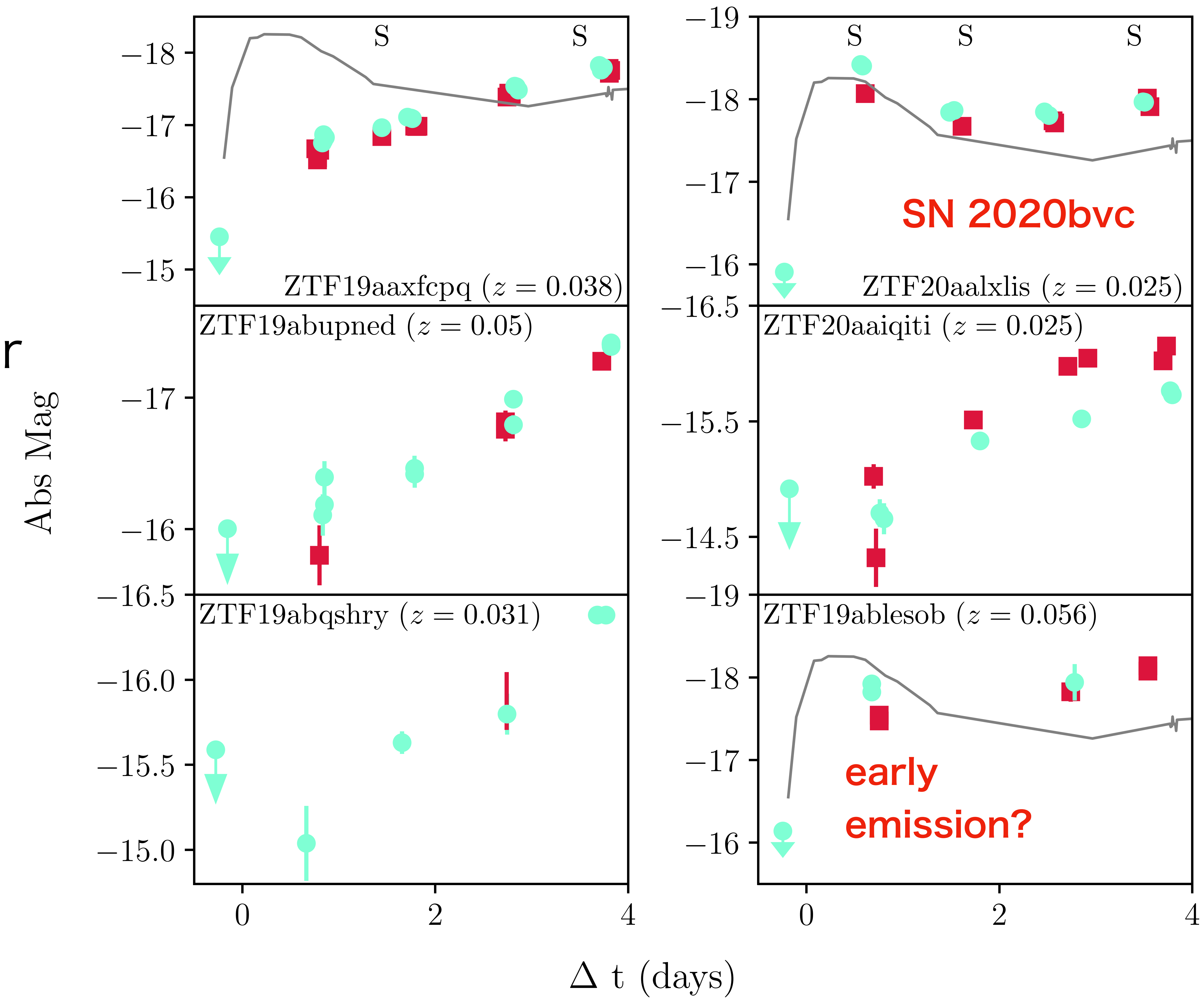
- 1 or 2 out of 6 SNe Ic-BL(z<0.06) are accompanied by early bright emission: 20-30% of SNe Ic-BL show jet signature?

Ho+ (2020)



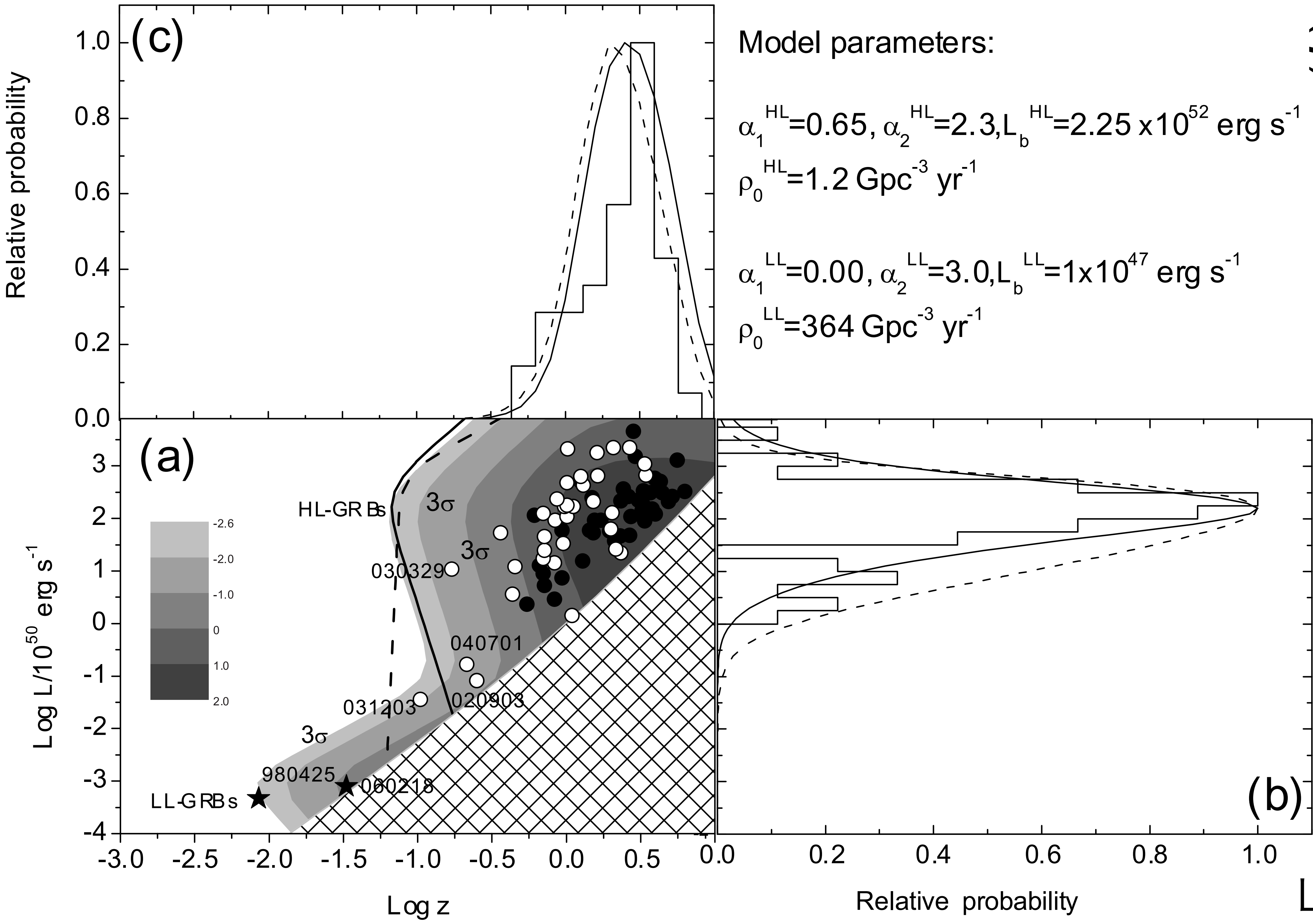
SN 2020bvc

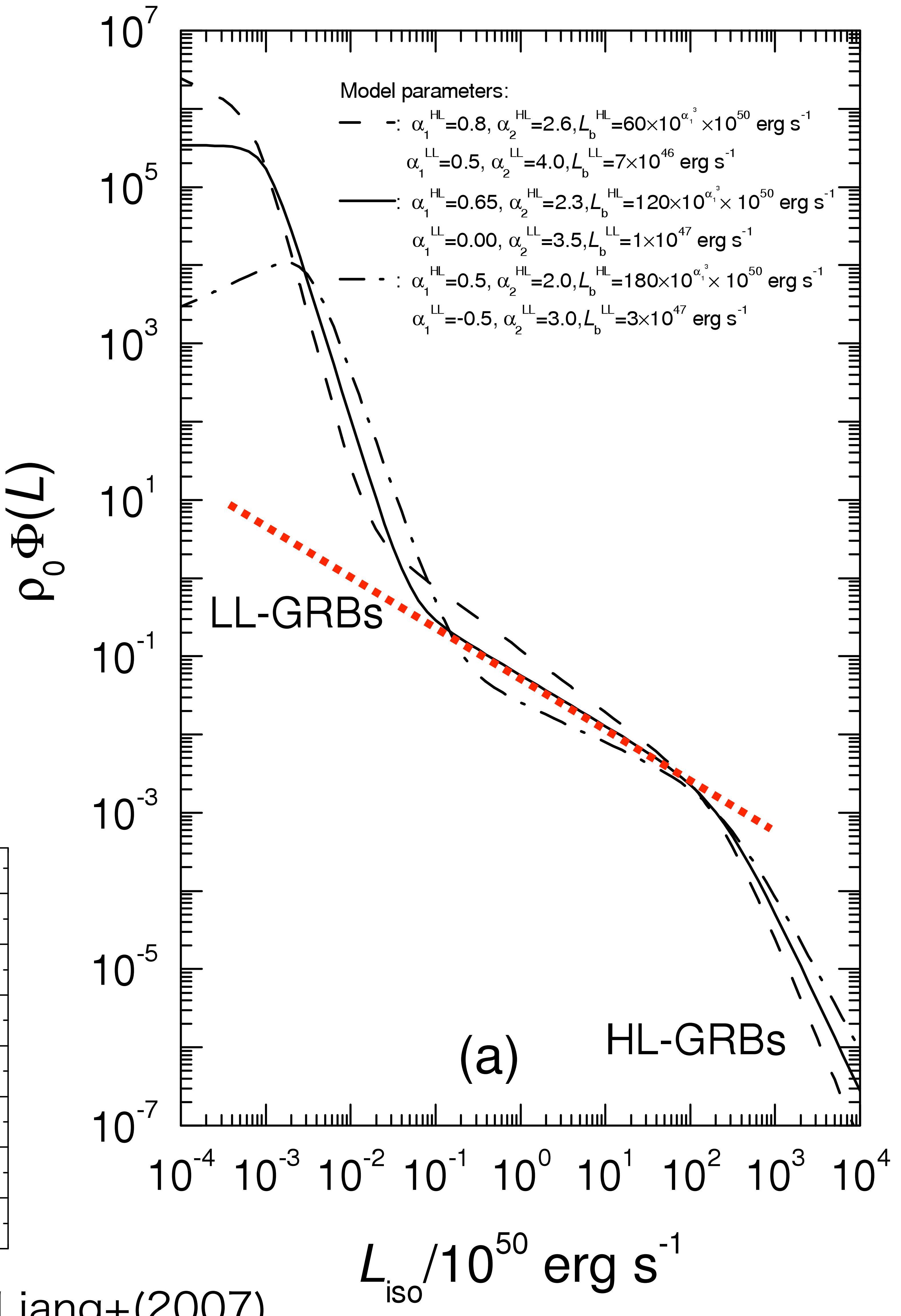
early emission?

low-luminosity GRBs

e.g., 230^{+490}_{-190} Gpc^{-3} yr^{-1} (Soderberg+ 2006),
100-1800 Gpc^{-3} yr^{-1} (Guetta&Della Valle 2007)

- nearby GRBs (< a few 100Mpc) are low-luminosity GRB
- smaller $L_{\gamma,\mathrm{iso}}$ and $E_{\gamma,\mathrm{iso}}$ by 5-6 orders of magnitudes
- outliers in E_{peak}-E_{iso} relation
- what are they?





Liang+(2007)

Volumetric rate summary

- CCSNe: R_{CCSN} ~10^5[events/Gpc^3/yr]
- broad-lined Ic SNe: $R_{\mathrm{Ic\text{-}BL}}$ ~ 2-3% of R_{CCSN} ~ (2-3)x10^3 [events/Gpc^3/yr]
- <u>double-peaked</u> Ic-BL SNe: 1/6 or 2/6 of $R_{\mathrm{Ic\text{-}BL}}$ ~ **300-1000** [events/Gpc^3/yr] ?

ZTF SNe Ic-BL with z<0.06 like 2020bvc (Ho+ 2020)

$R_{\mathrm{Ic\text{-}BL}}$ ~ R_{llGRB},

γ-rays are not so beamed? but, small statistics

- long GRB rate: R_{lGRB} ~ 1[events/Gpc^3/yr]
- llGRB rate: R_{llGRB} ~ **100-1000** [events/Gpc^3/yr] ?

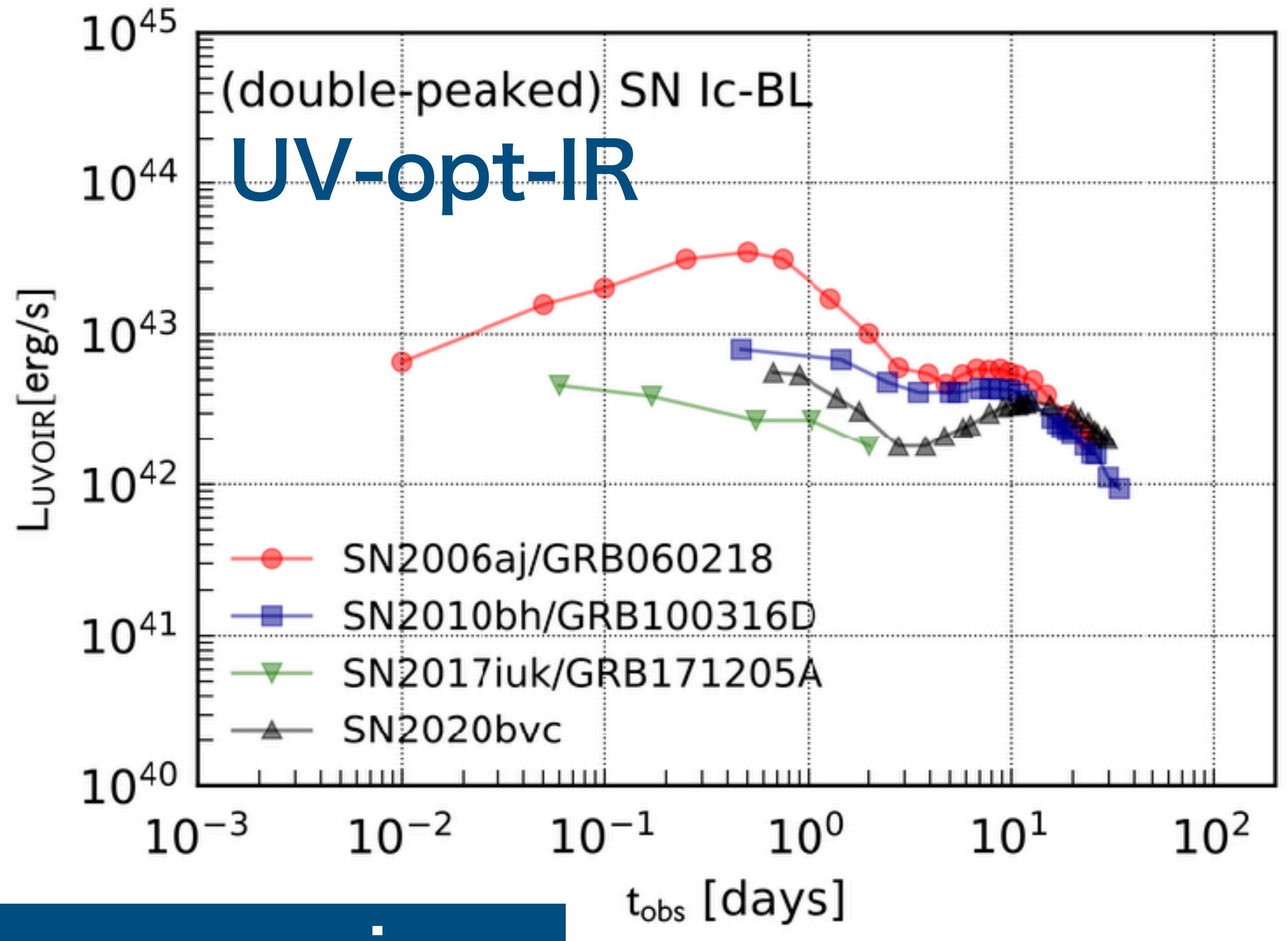
e.g., 230^{+490}_{-190} Gpc^{-3} yr^{-1} (Soderberg+ 2006), 100-1800 Gpc^{-3} yr^{-1} (Guetta&Della Valle 2007)

- Assuming a jet dissipation energy E_{diss} and event rate R, the energy injection rate is

$$\dot{E}_{\mathrm{inj}} \simeq 10^{45}\epsilon_{\mathrm{acc}}\left(\frac{E_{\mathrm{diss}}}{10^{51}\,[\mathrm{erg}]}\right)\left(\frac{R}{1000\,[\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}]}\right)[\mathrm{erg\,Mpc^{-3}\,yr^{-1}}]$$

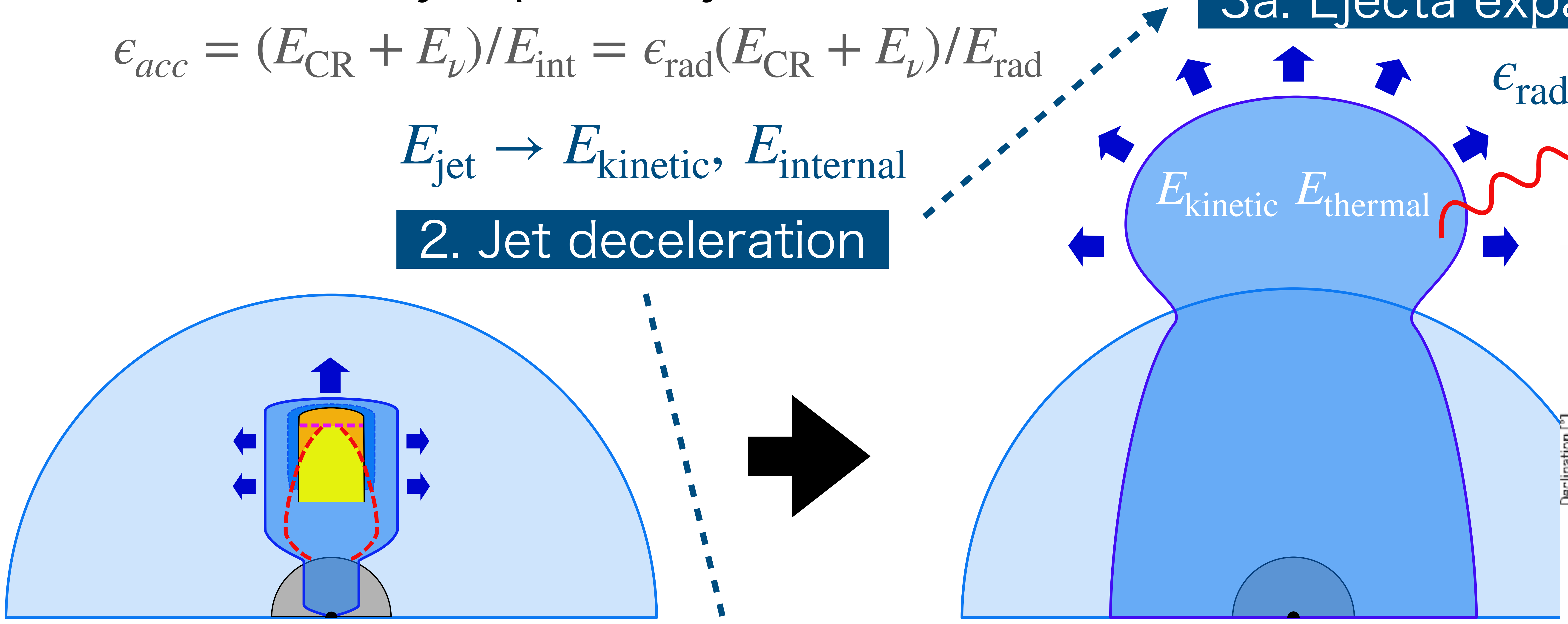
cf.) $\dot{E}_{\mathrm{GeV}\,\gamma} \sim \dot{E}_{\nu} \sim \dot{E}_{\mathrm{UHECRs}} \sim 10^{44} - 10^{45}[\mathrm{erg\,Mpc^{-3}\,yr^{-1}}]$

If we get EM and ν observation…



- UVOIR obs. gives $E_{\rm rad}$
- with ν obs., we can estimate $E_{\rm CR} + E_\nu$
- jet model gives radiation efficiency $\epsilon_{\rm rad} = E_{\rm rad}/E_{\rm int}$
- acceleration efficiency is probably obtained;

$$\epsilon_{acc} = (E_{\rm CR} + E_\nu)/E_{\rm int} = \epsilon_{\rm rad}(E_{\rm CR} + E_\nu)/E_{\rm rad}$$



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