東京大学 大学院
理学系研究科·理学部
SCHOOL OF SCIENCE, THE UNIVERSITY OF TOKYO

Exploring Extreme Transients @YITP 2024/08/06

GRB jets colliding with massive circum-stellar materials and associated electromagnetic transients

Akihiro Suzuki (Research Center for the Early Universe, Univ. of Tokyo)

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

Refs.

- **Suzuki** & Maeda (2022), ApJ 925, 148
- Maeda, **Suzuki**, & Izzo (2023), MNRAS 522, 2267
- **Suzuki**, Irwin, & Maeda (2024), PASJ, arXiv:2406.06939

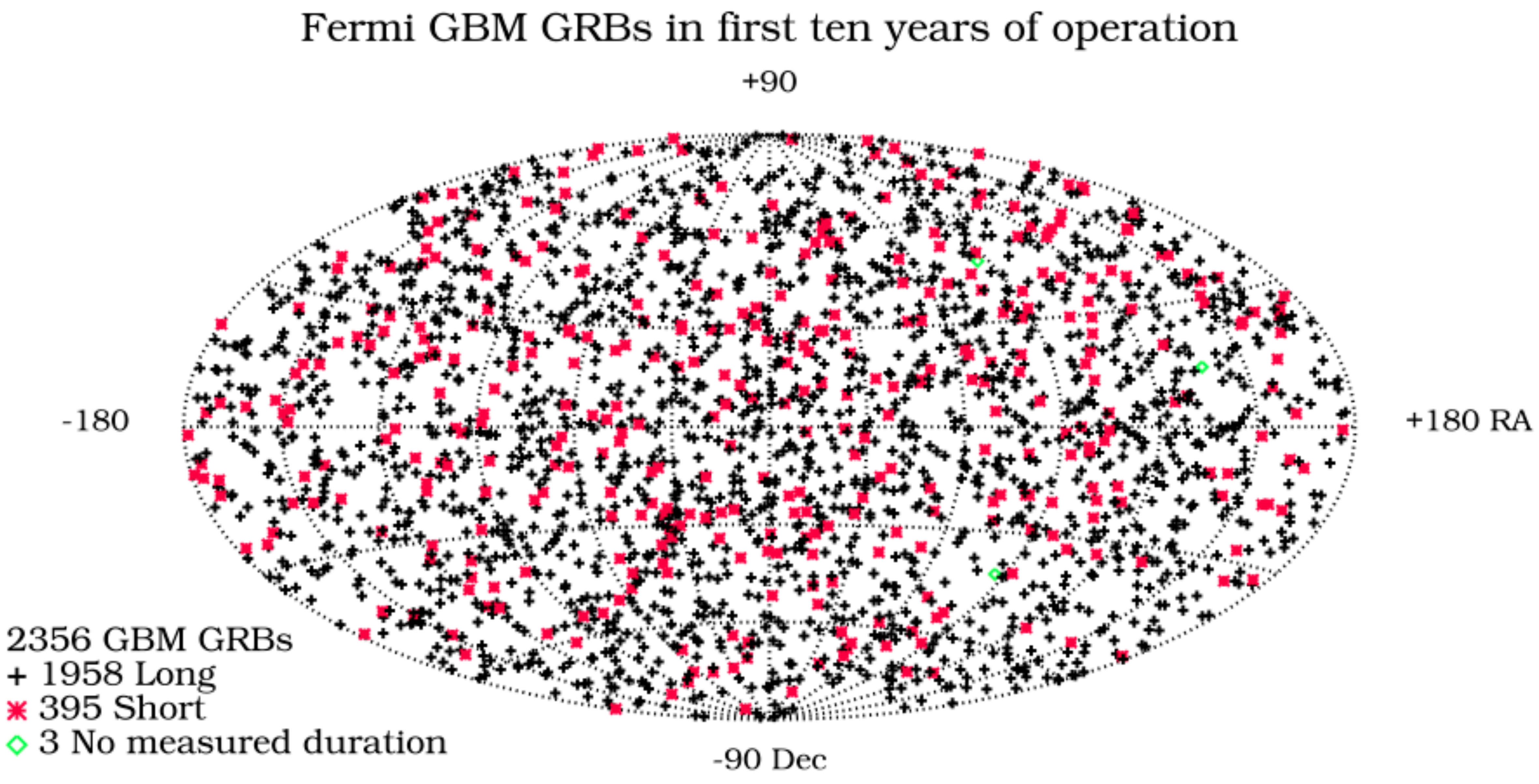
and more

RESEARCH CENTER FOR THE EARLY UNIVERSE
THE UNIVERSITY OF TOKYO
RESCEU

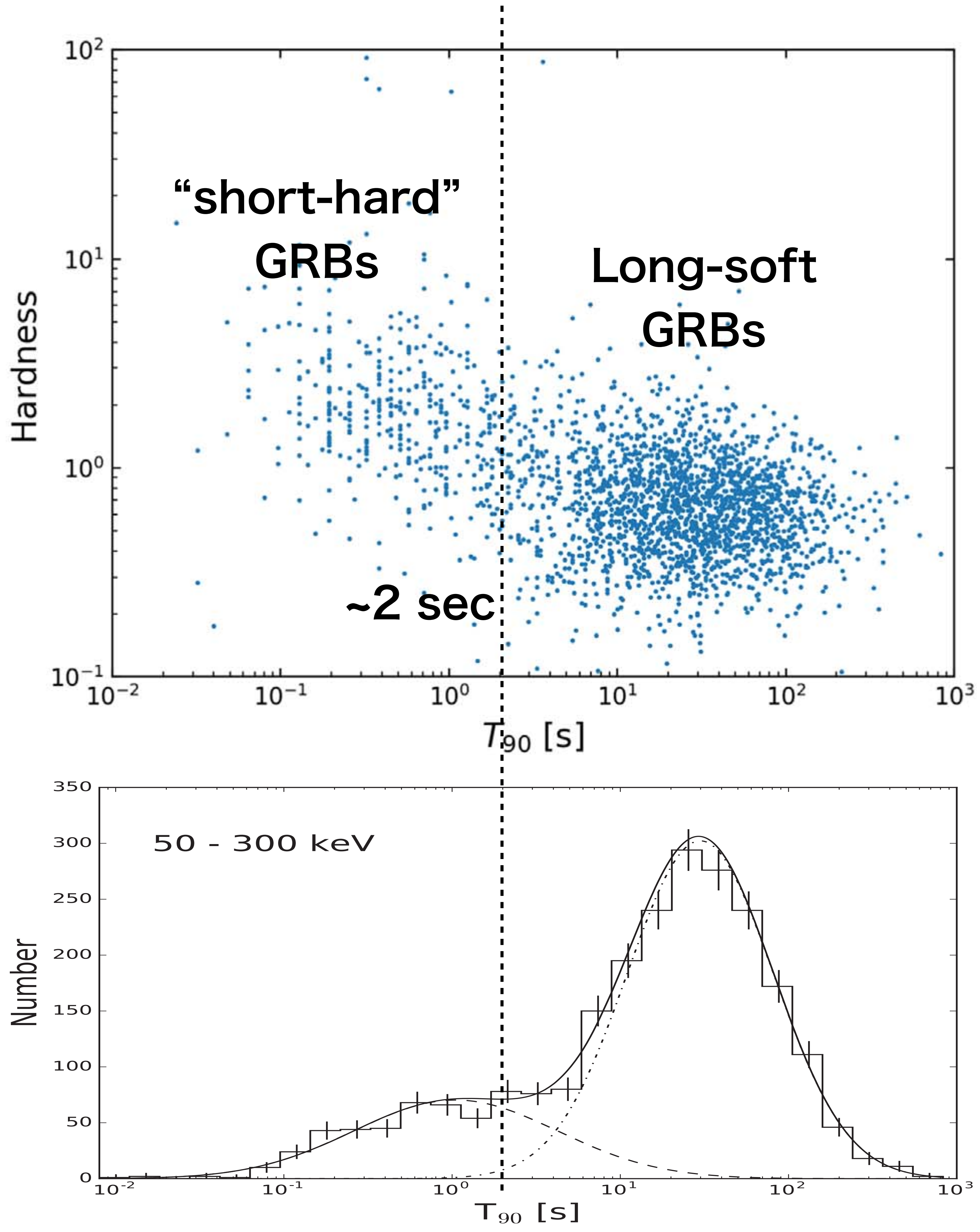
Introduction

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, SNe-Ic



distribution of Fermi GRBs on the celestial sphere
(4th Fermi GBM catalog, von Kienlin+ 2020)



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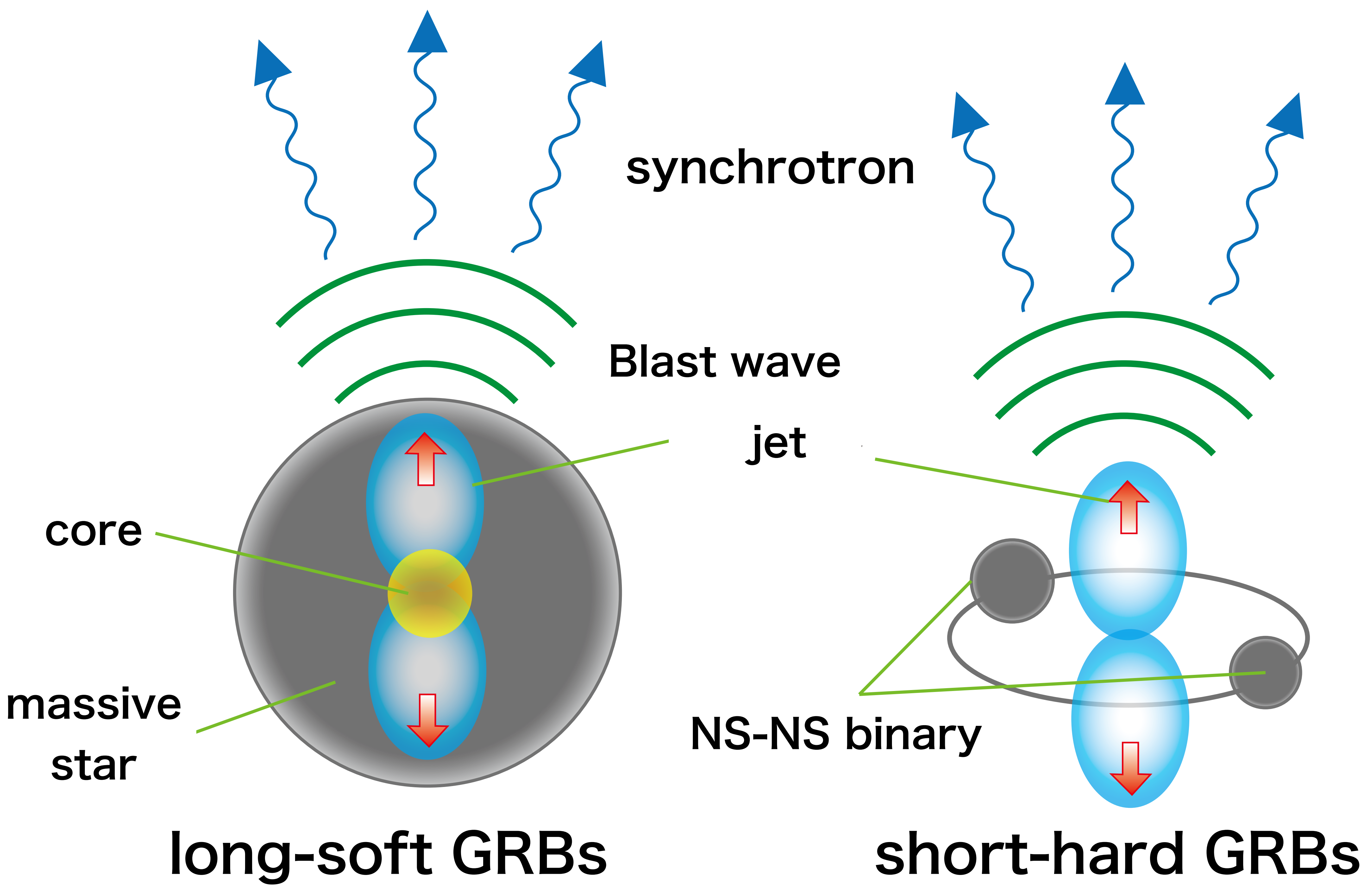


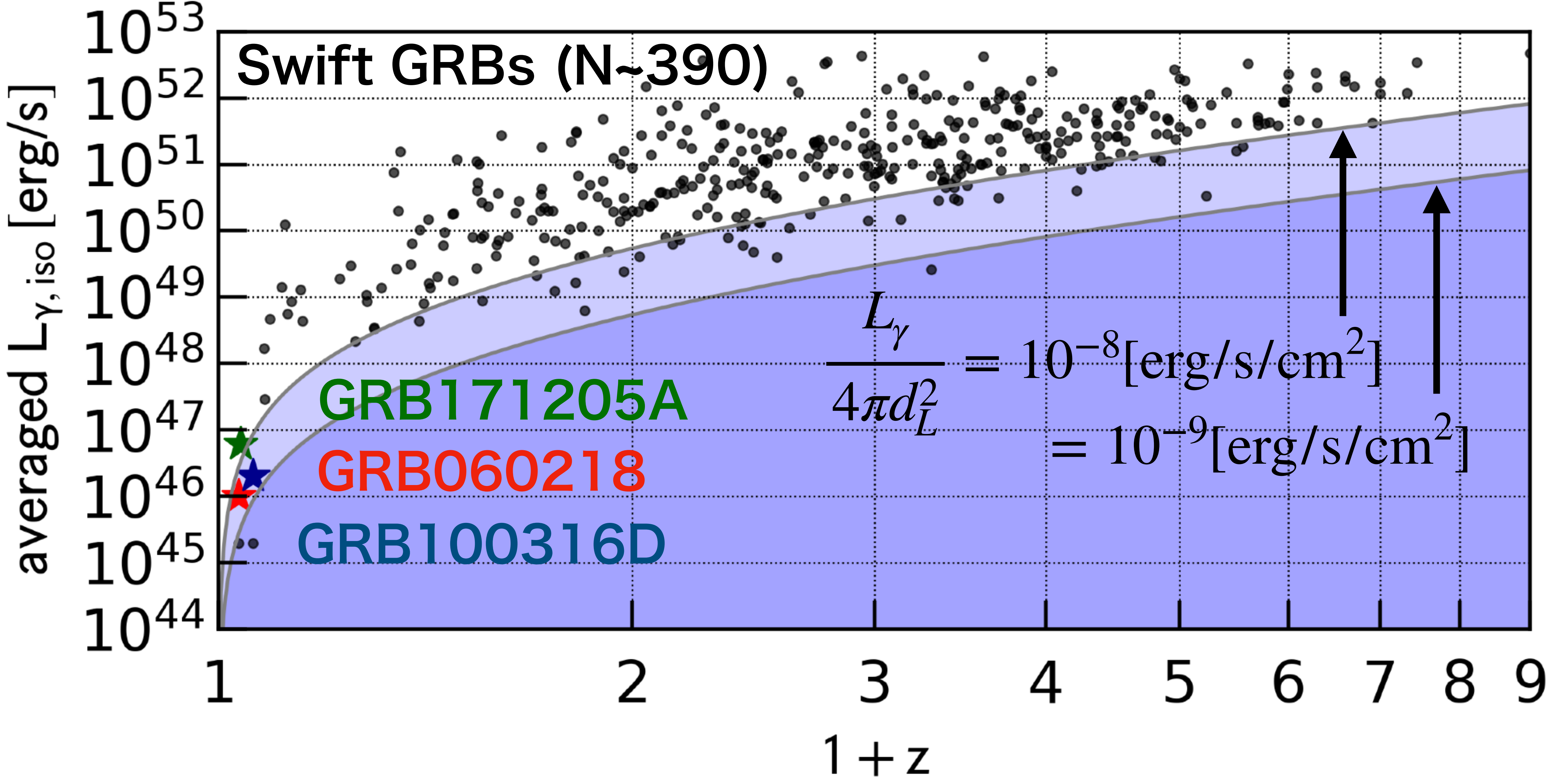
	long GRBs	short GRB
duration T_{90}	> 2 sec	< 2 sec
γ-ray spectrum	soft	hard
origin	massive star's collapse	NS-NS merger
optical counterpart	core-collapse supernova	kilonovae
after-glow	bright	dark
host galaxy	star-forming	old population
location	associated with stellar lights	outskirt

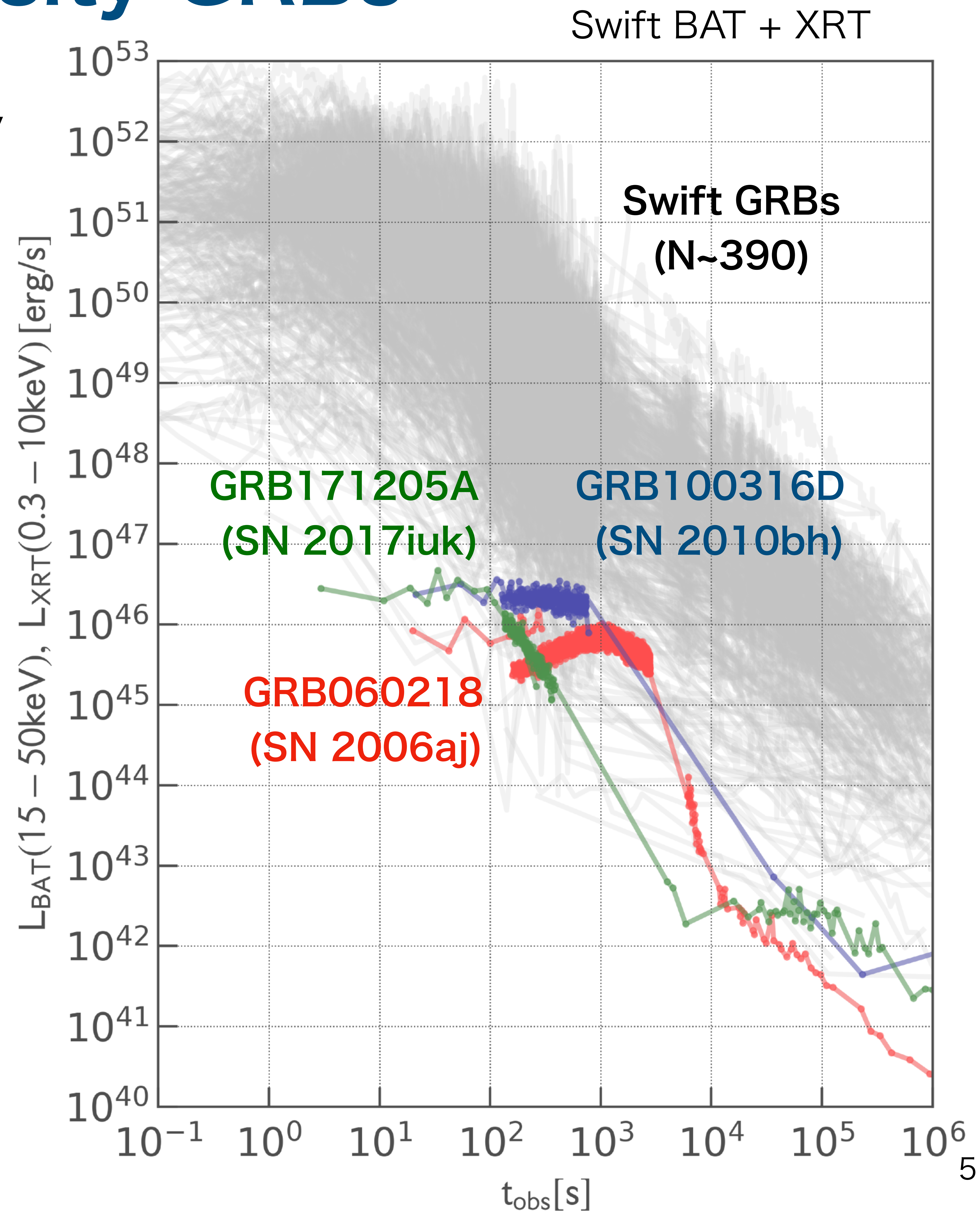
➡ Talks on Friday

(GRB060218-like) 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} $\mathrm{Gpc^{-3}\,yr^{-1}}$ (Soderberg+ 2006),
100-1800 $\mathrm{Gpc^{-3}\,yr^{-1}}$ (Guetta&Della Valle 2007)





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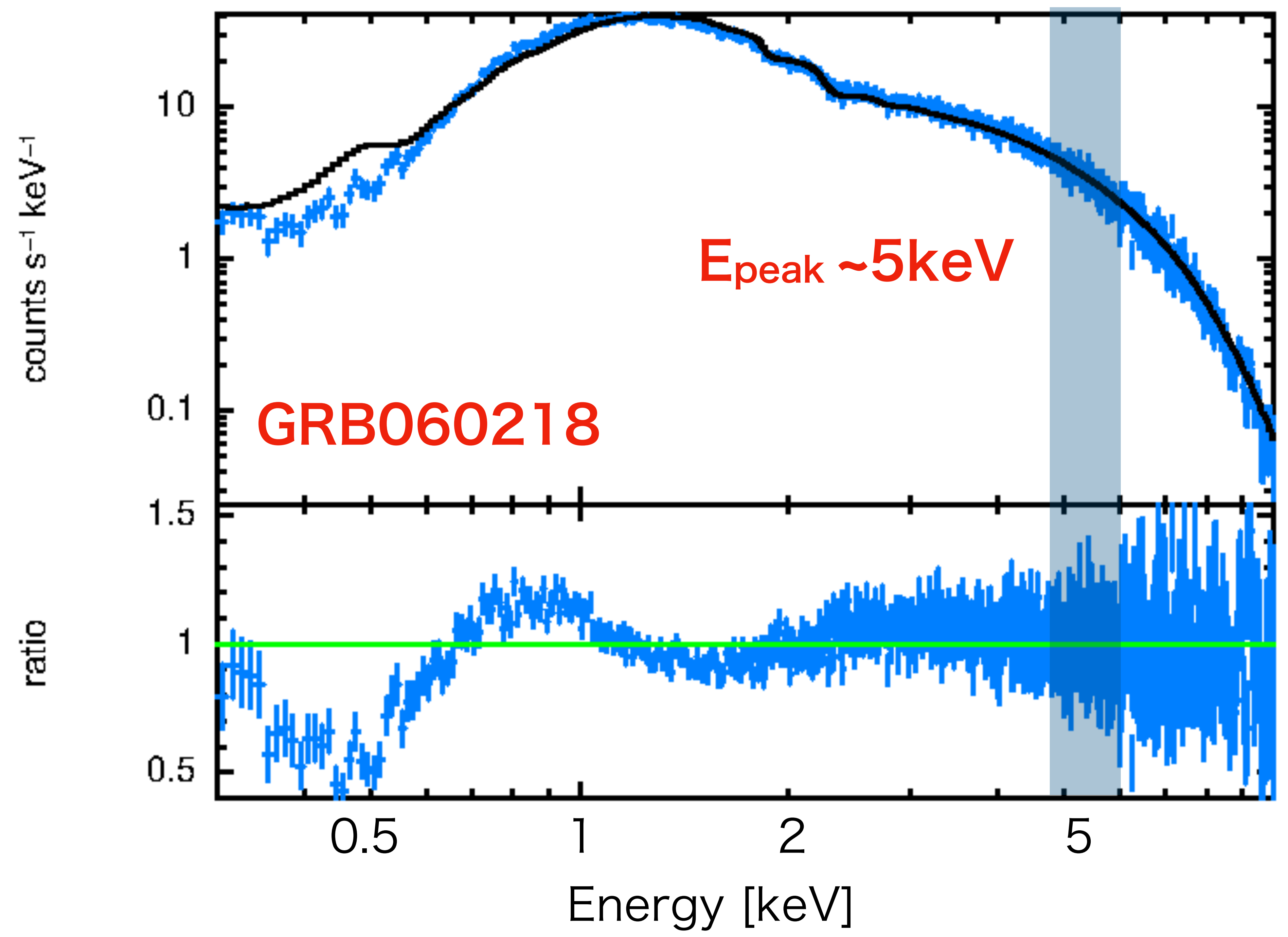
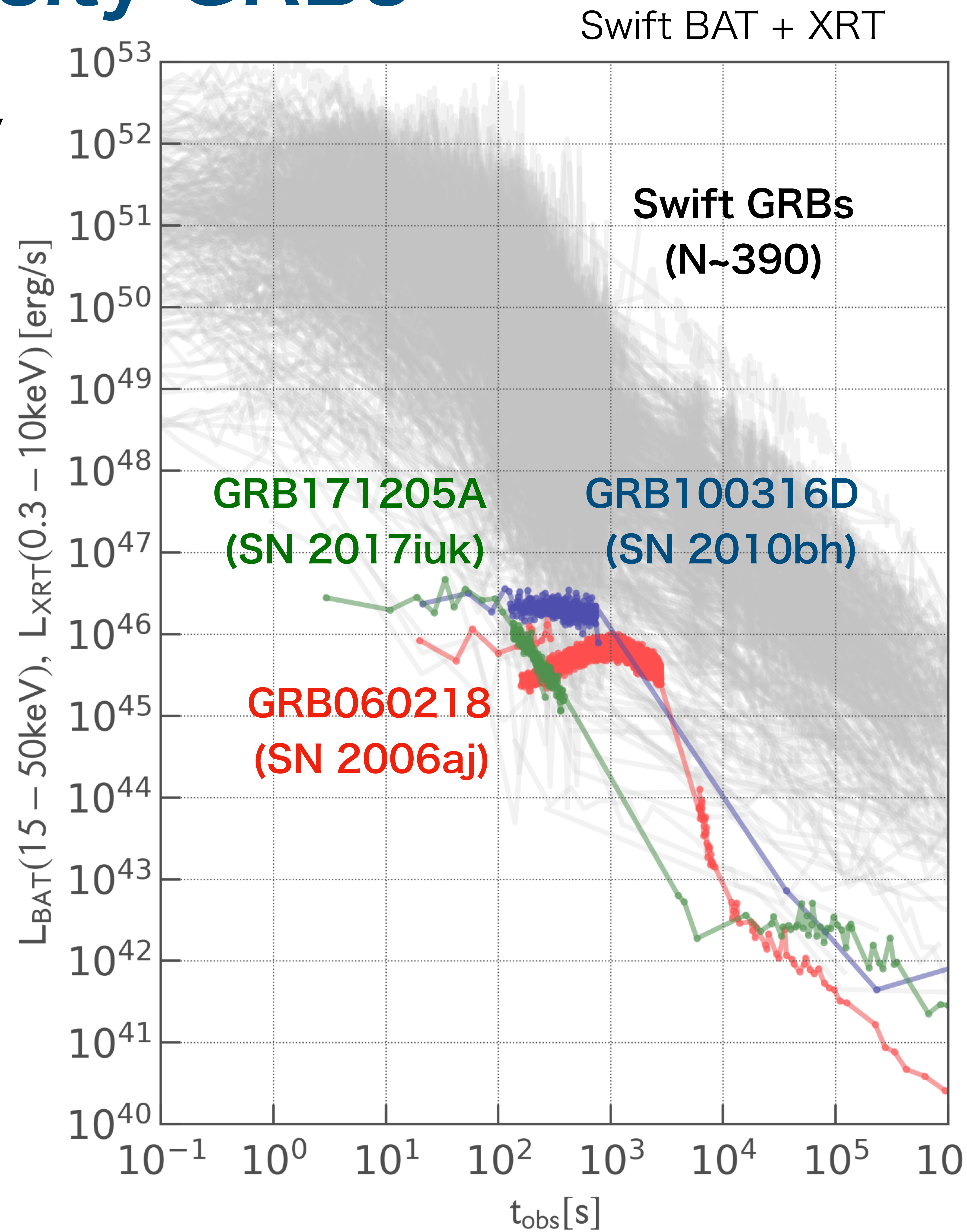
- count/s/keV

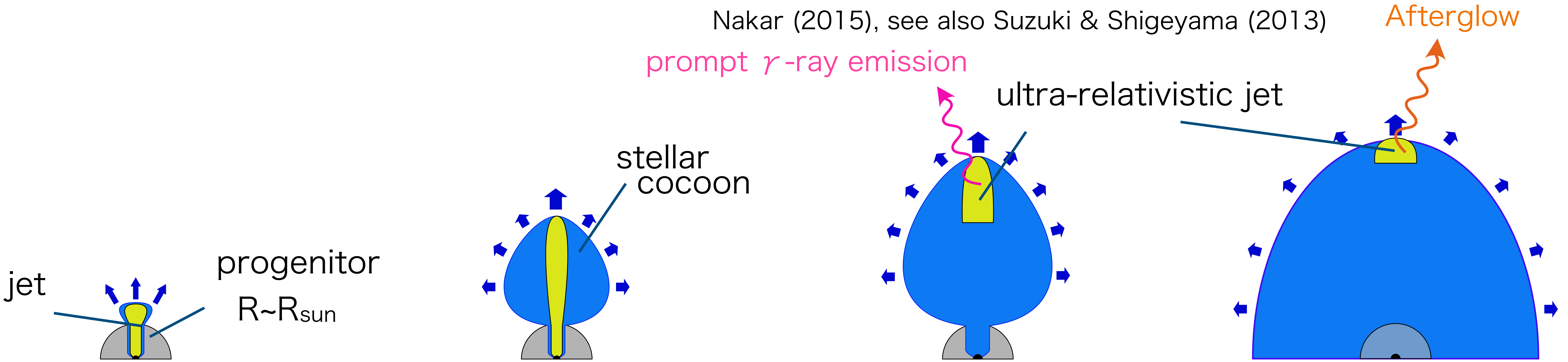
Swift–XRT WT spectrum of GRB 060218





low-luminosity GRBs are failed jets?

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



successful jet without CSM

failed jet with massive CSM

CSM = Circum-Stellar Materials

➡ Talks by K. Maeda and others on Wed.

(GRB060218-like) low-luminosity GRBs

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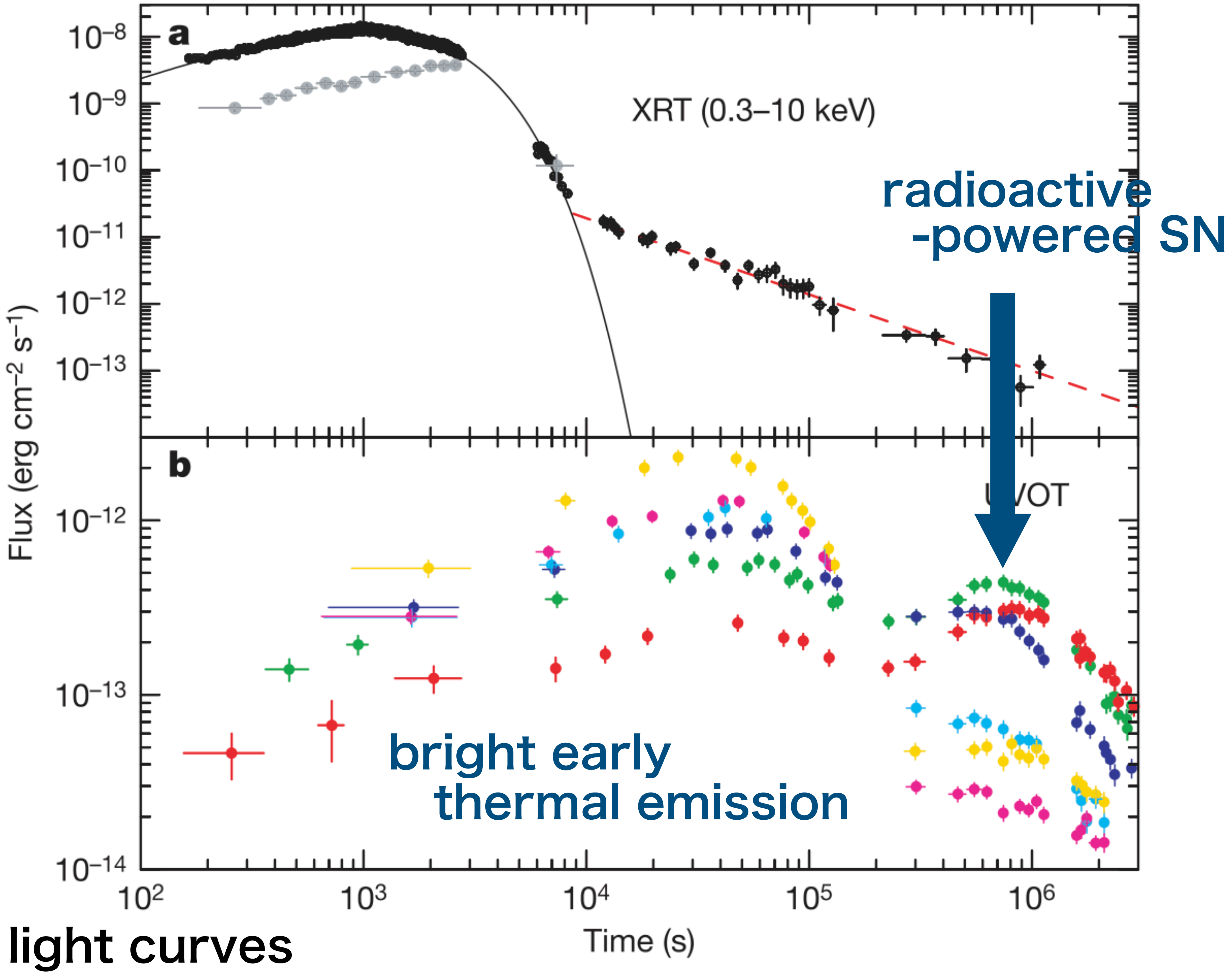
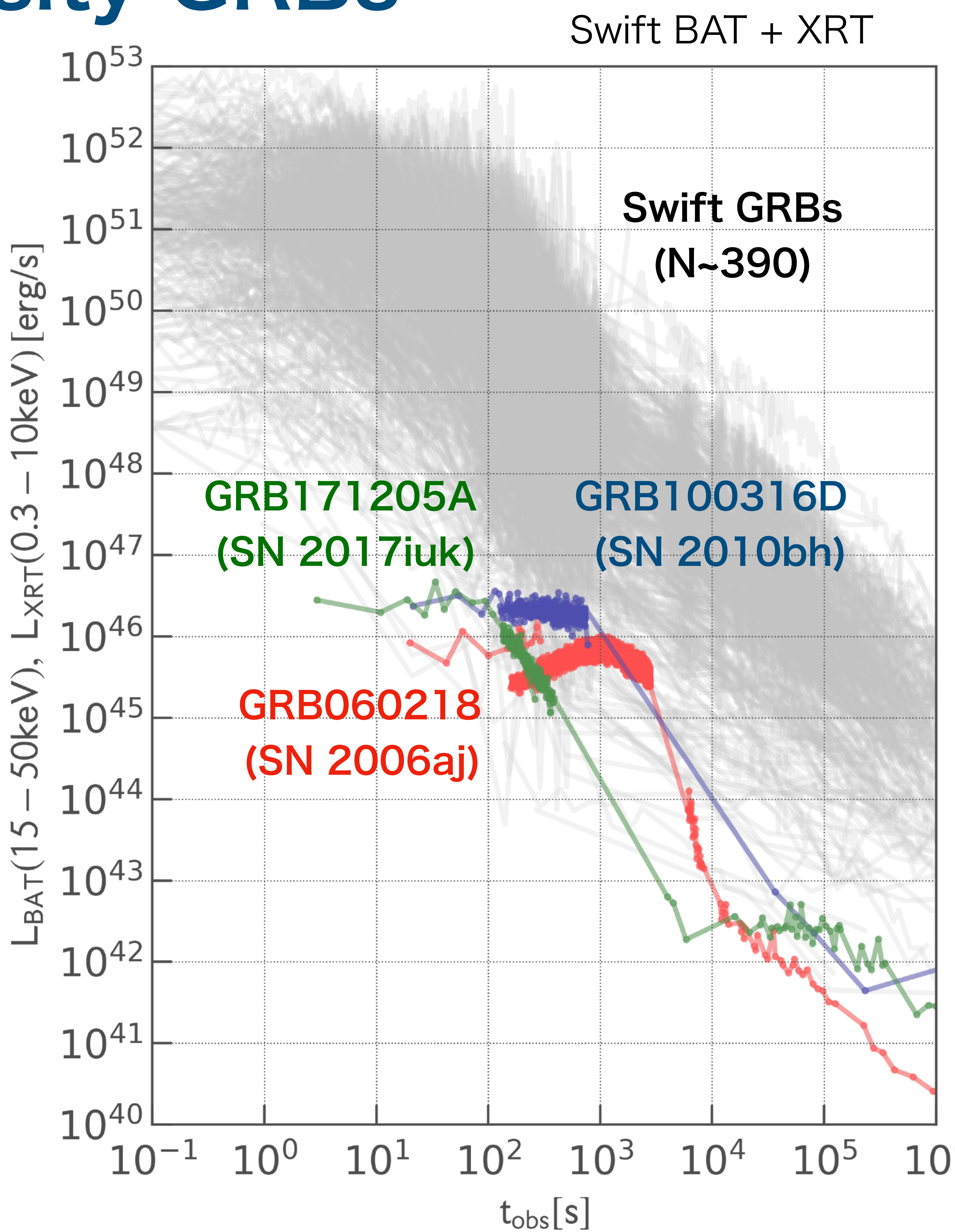


radioactive -powered SN

bright early thermal emission

UV-opt-IR light curves



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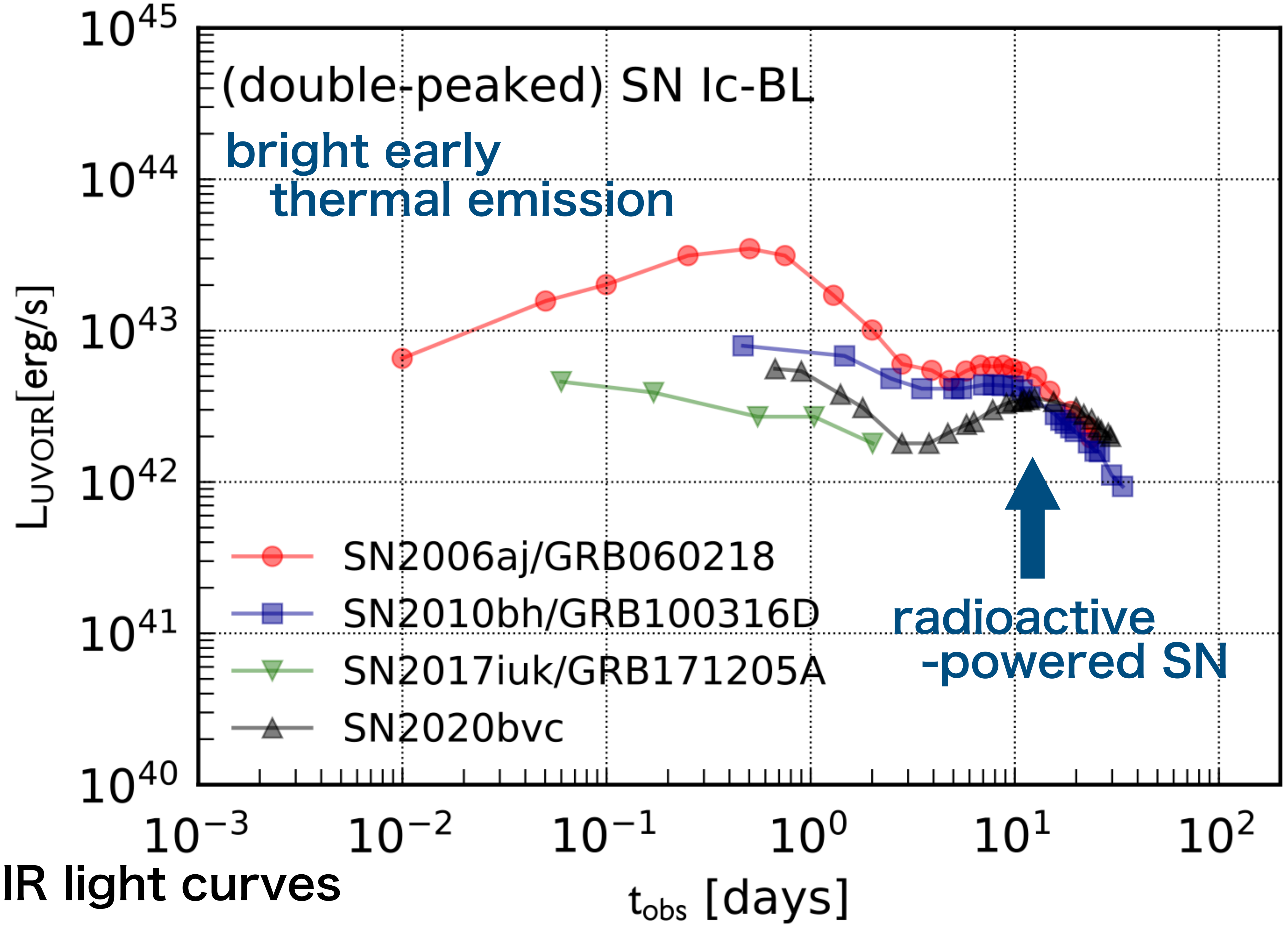
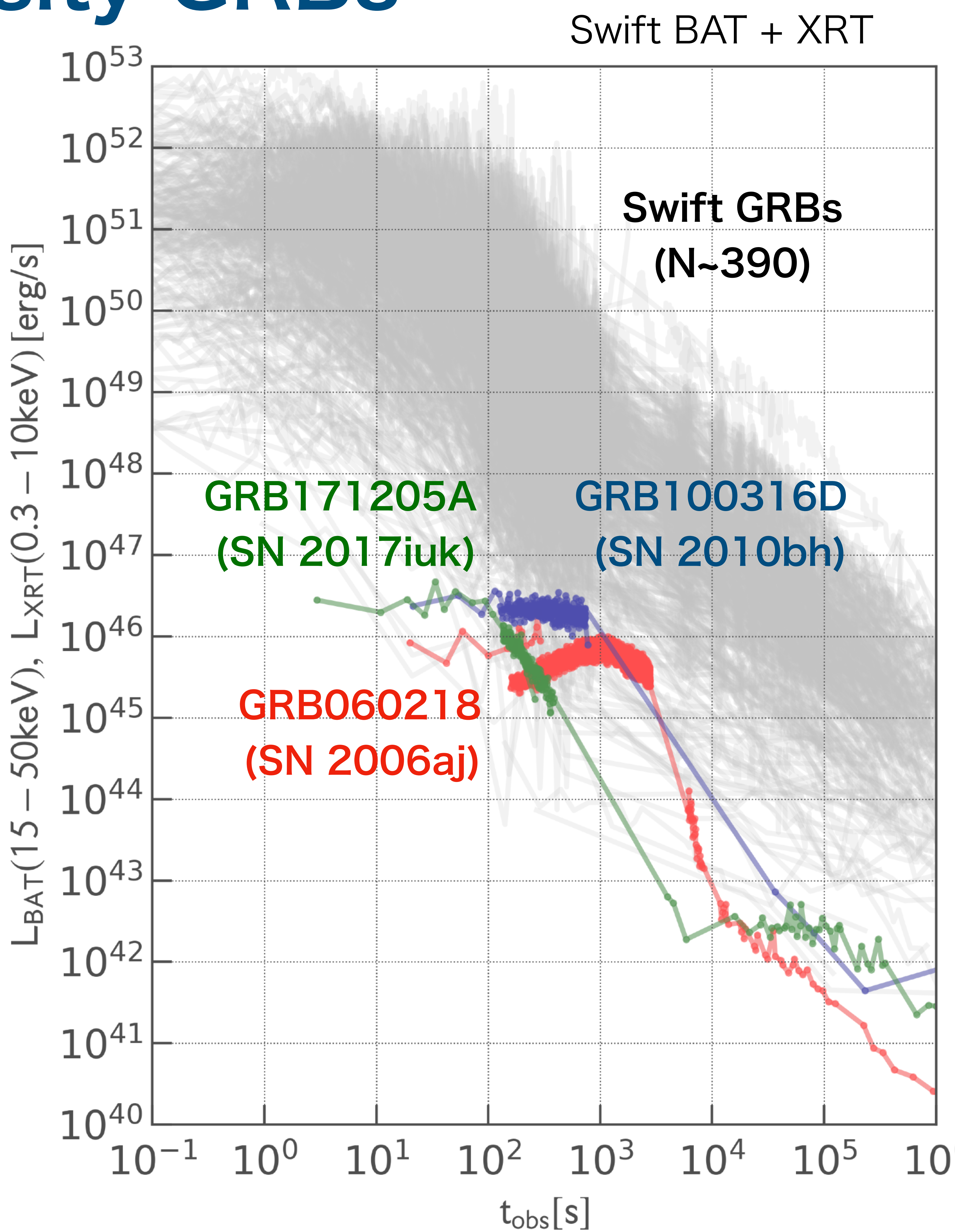


UV-opt-IR light curves

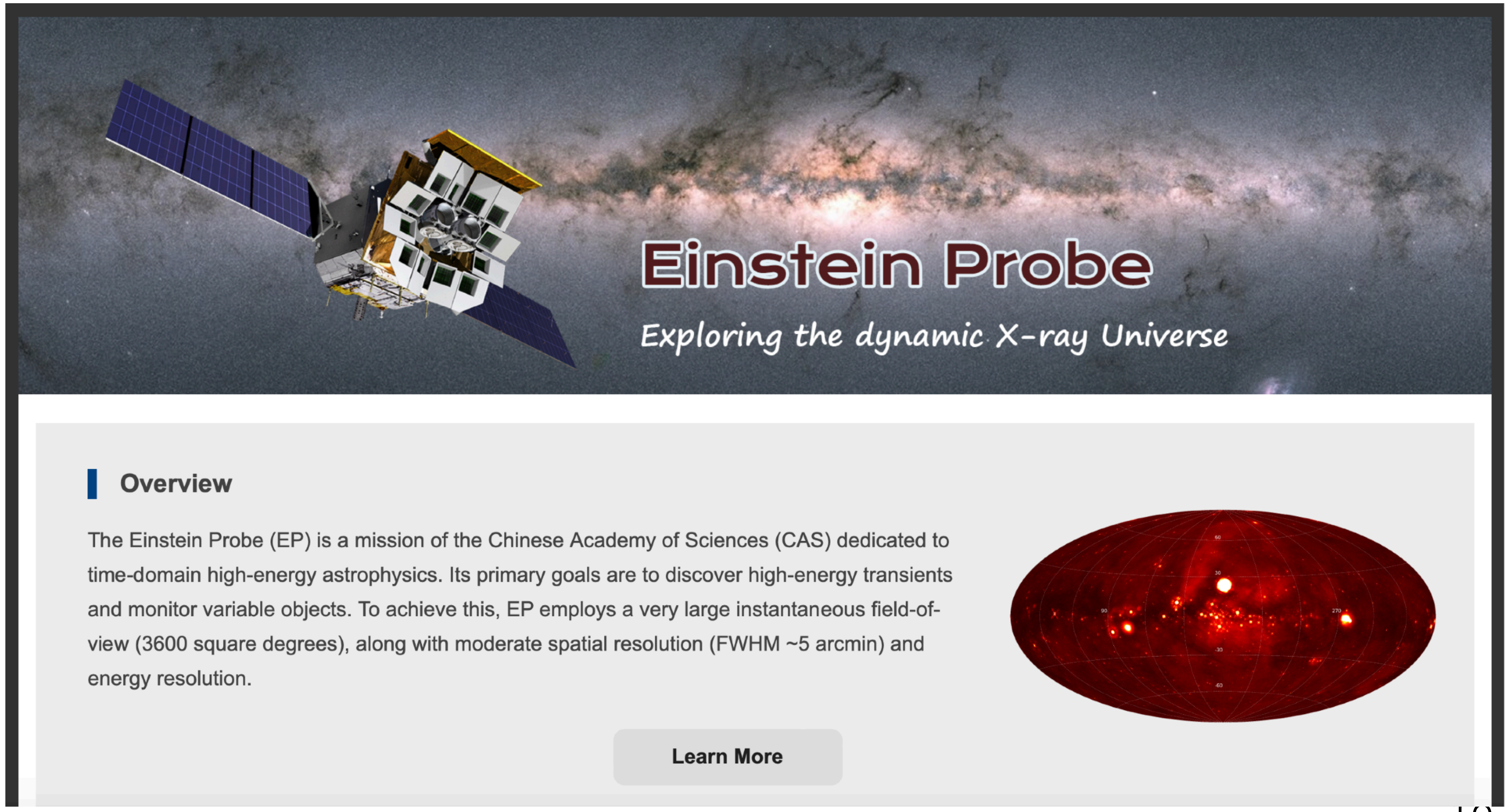


X-ray transient missions: Now and Future

- **Swift BAT(2004-)** :can miss soft X-ray-dominated transients like llGRBs
- **Einstein Probe**: launched in 2024/1 and now in the commissioning phase
- **SVOM** (Space-based multi-band astronomical Variable Objects Monitor) mission: launched in 2024/6

	BAT/Swift	WXT/EP	ECLAIRs/ SVOM
Energy range [keV]	15-150	0.4-5	4 - 250
FoV [str]	1.4	0.35	2
Sensiviity [erg/cm^2/s]	~10^{-8} (for a GRB)	1.2x10^{-10} (for 100s)	several 10^{-8}?
localization accuracy [']	~4	~2-3	3-10

https://swift.gsfc.nasa.gov/about_swift/bat_desc.html
https://arxiv.org/abs/2209.09763
https://irfu.cea.fr/Projets/SVOM/svom.html



Overview

The Einstein Probe (EP) is a mission of the Chinese Academy of Sciences (CAS) dedicated to time-domain high-energy astrophysics. Its primary goals are to discover high-energy transients and monitor variable objects. To achieve this, EP employs a very large instantaneous field-of-view (3600 square degrees), along with moderate spatial resolution (FWHM ~5 arcmin) and energy resolution.

low-luminosity GRBs are UHECRs and ν source?

- cosmological GRBs had been promising ν sources

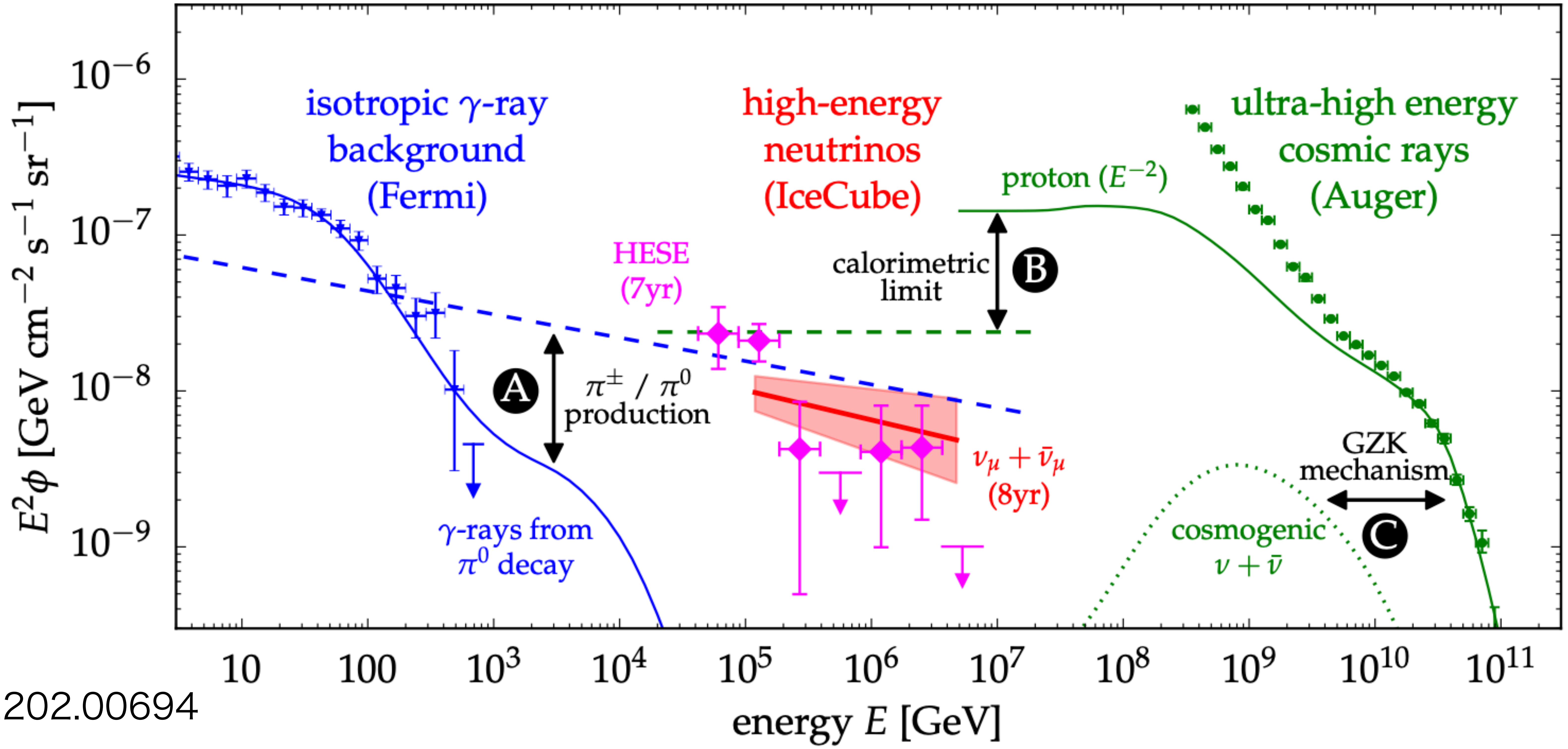
Waxman&Bahcall(1997), Rachen&Meszaros(1998), Ahlers+(2011)

- 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 more common

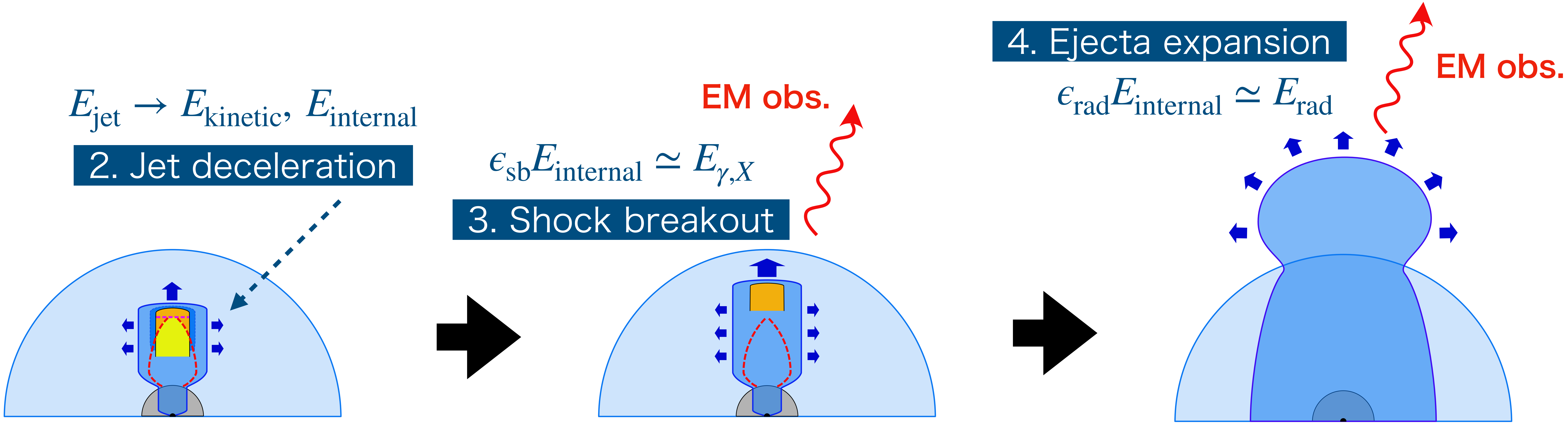
e.g., 230^{+490}_{-190} Gpc^{-3} yr^{-1} (Soderberg+ 2006), 100-1800 Gpc^{-3} yr^{-1} (Guetta&Della Valle 2007)



Halzen&Kheirandish (2022), arXiv:2202.00694

low-luminosity GRBs are failed jets?

- 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



1. Jet formation

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

GW, ν obs.

2. Jet deceleration

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

3. Shock breakout

$\epsilon_{\rm sb} E_{\rm internal} \simeq E_{\gamma,X}$

EM obs.

4. Ejecta expansion

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

EM obs.

5. particle acceleration

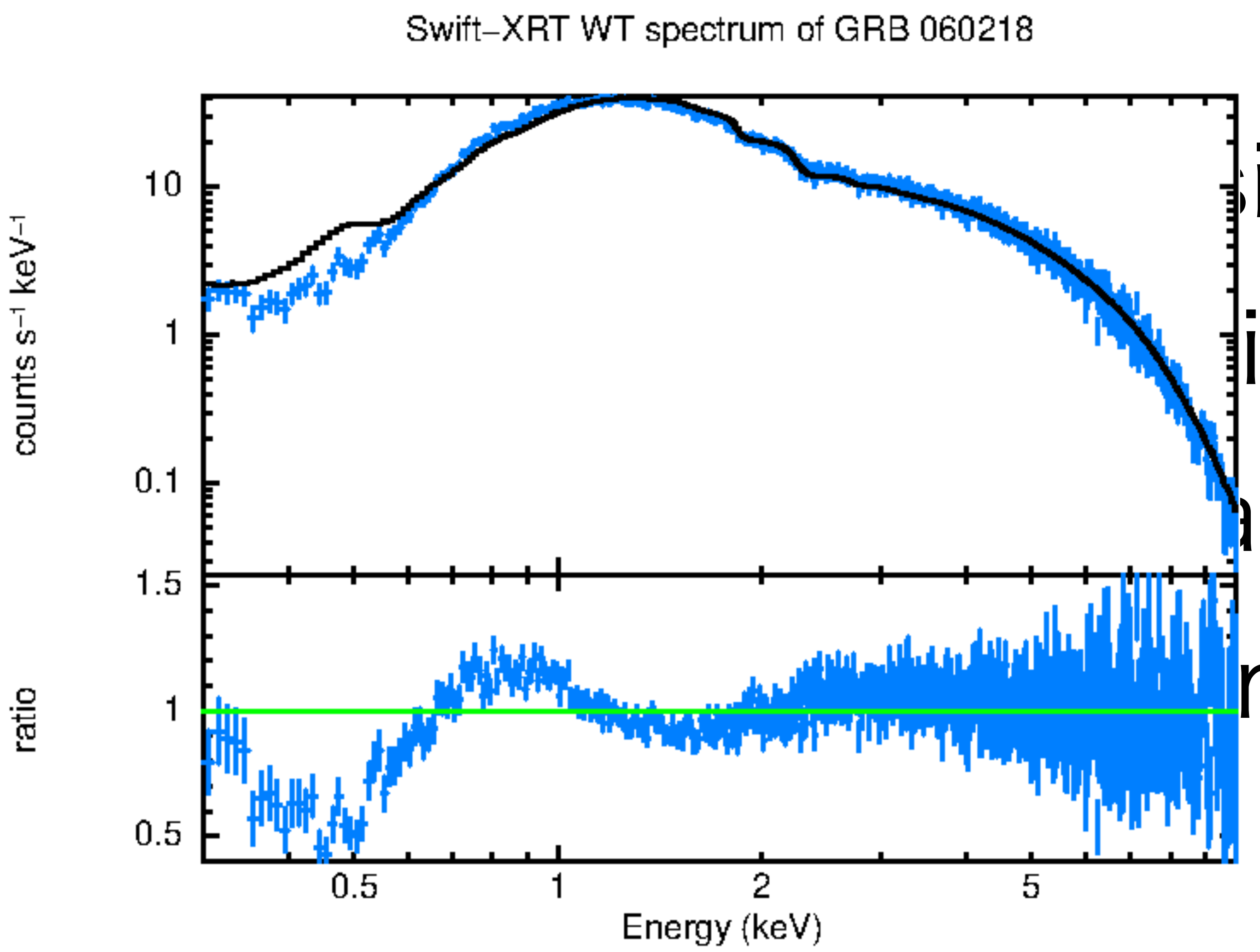
$\epsilon_{\rm acc} E_{\rm internal} \simeq E_{\rm CR} + E_\nu$

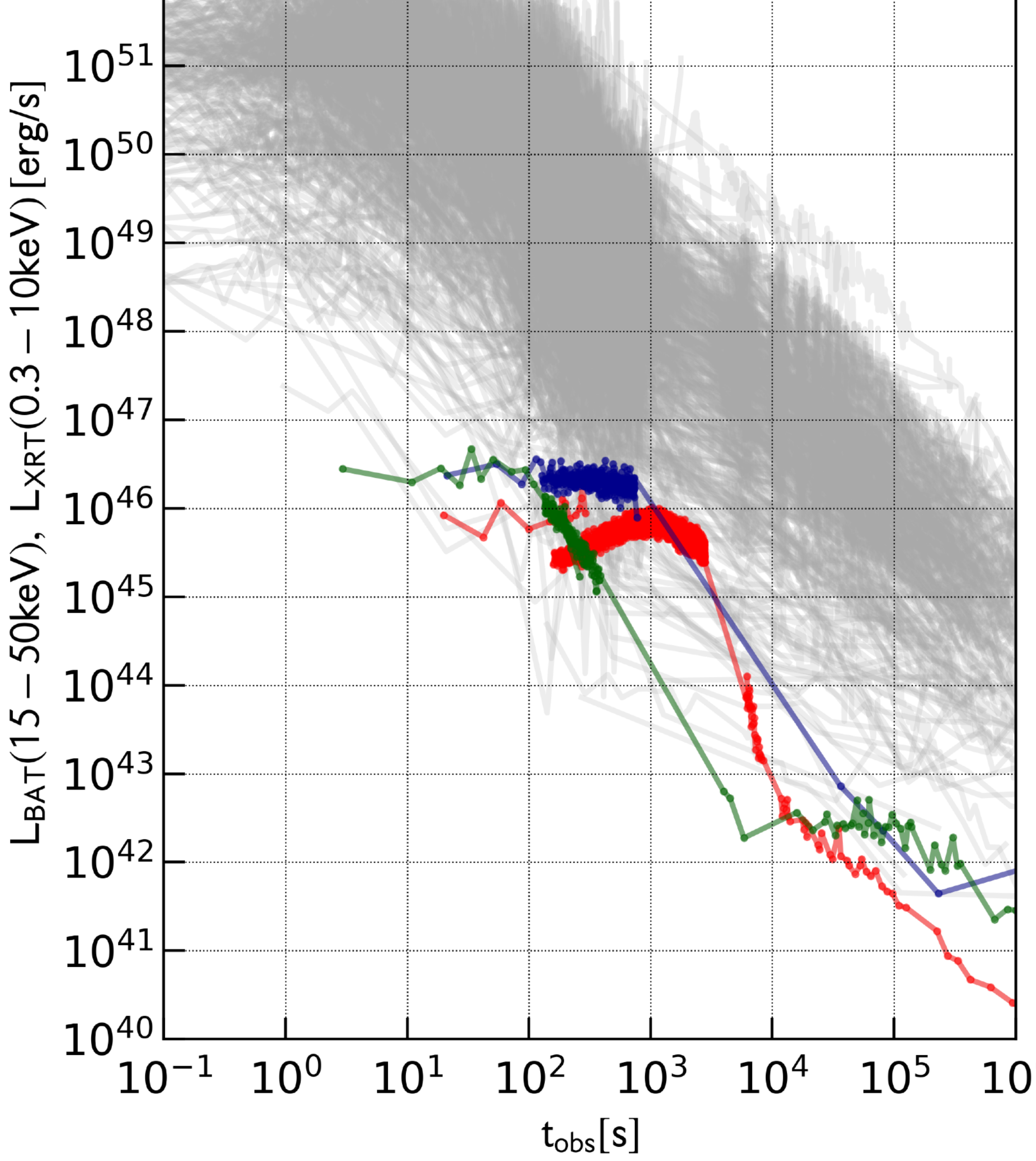
CR, ν obs.

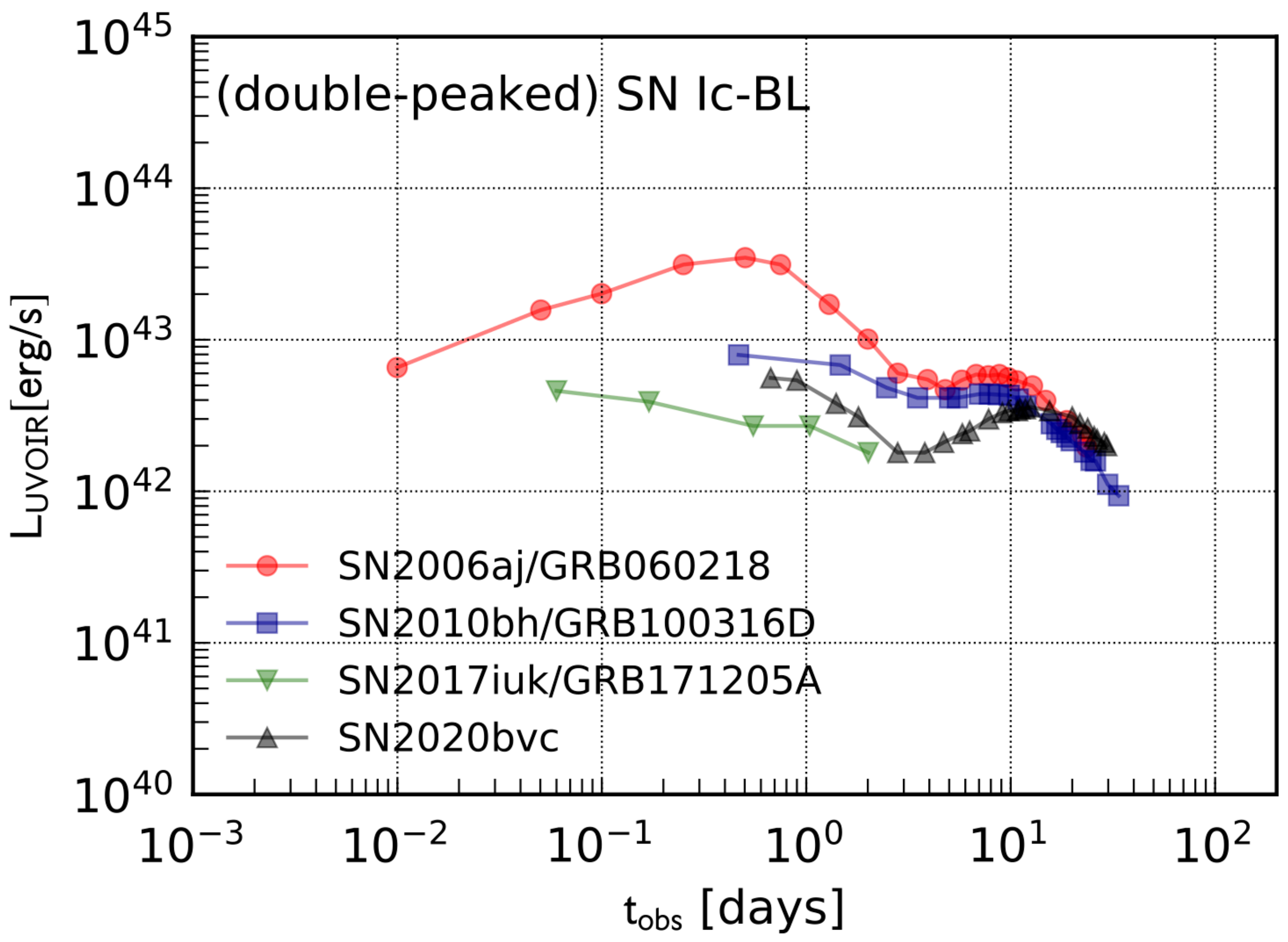
but, not always (e.g, radiation condition, Murase&Ioka 2013, Senno+2016)

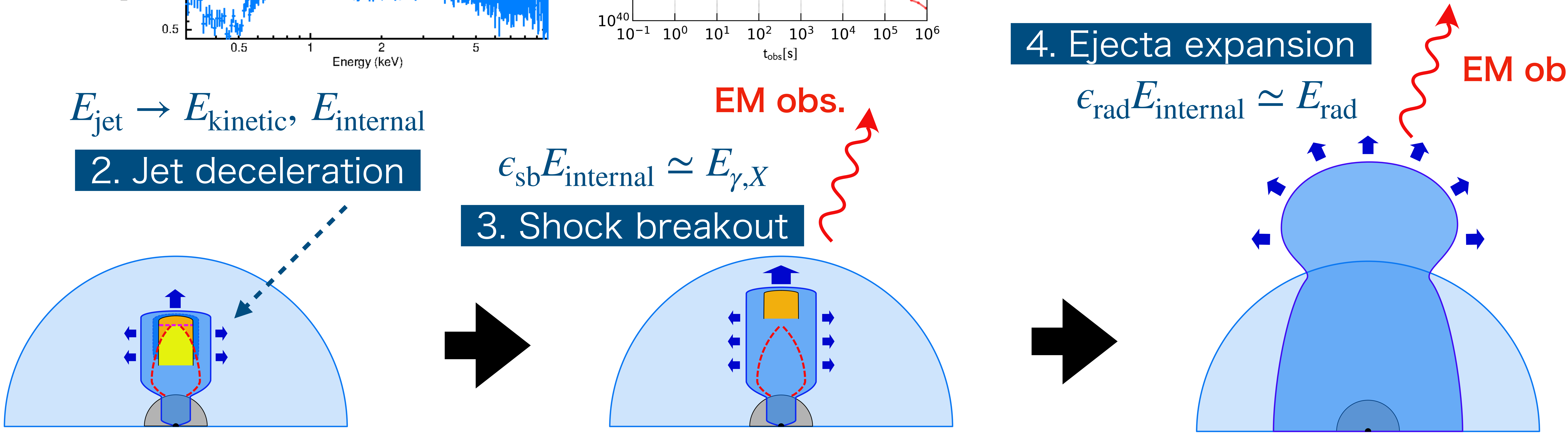
low-luminosity GR ets?

- jet ip
- the ic f expanc
- a s al nd ν
- ren m









4. Ejecta expansion

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

EM obs.

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

2. Jet deceleration

EM obs.

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low-luminosity GR ts?

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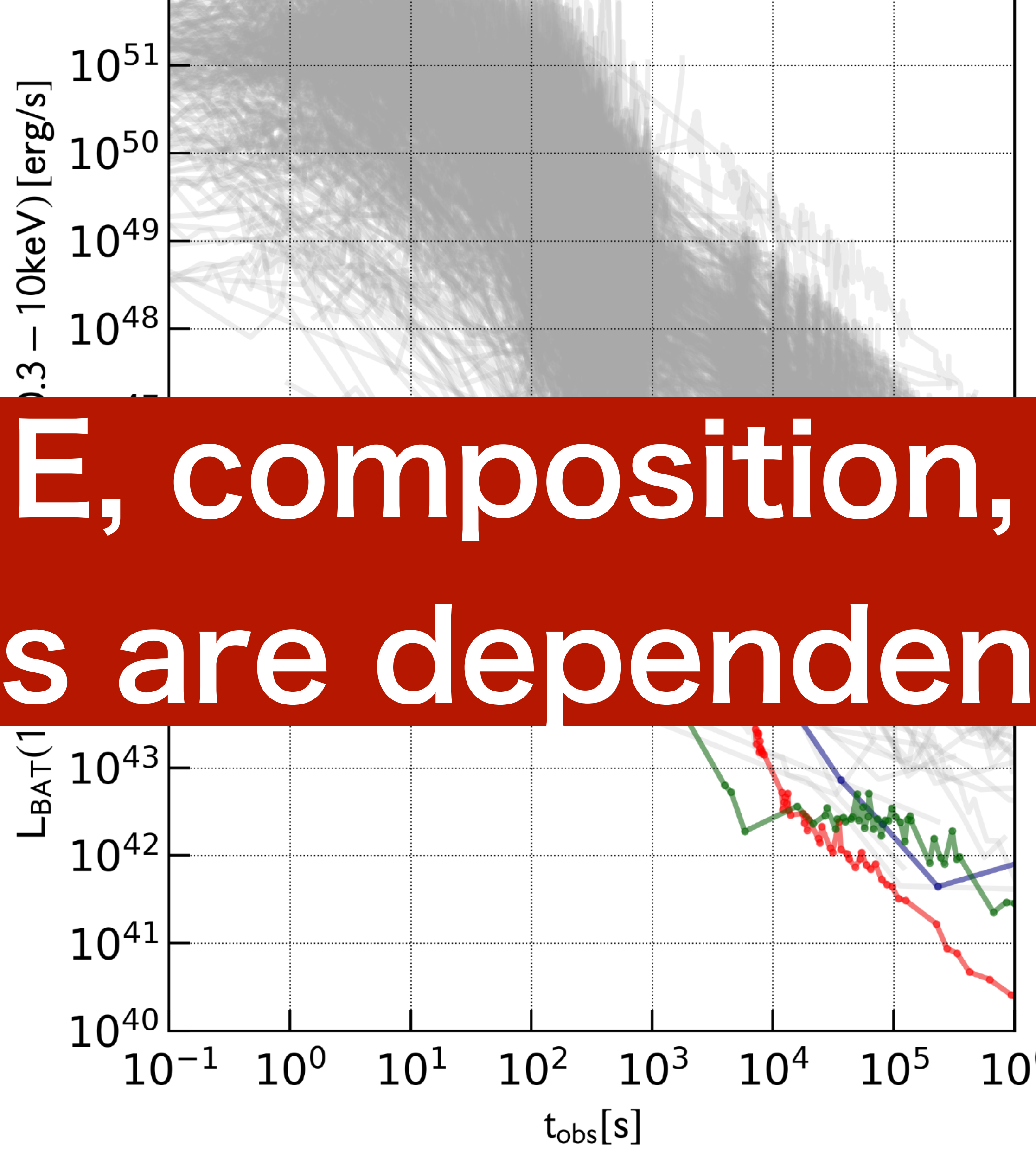
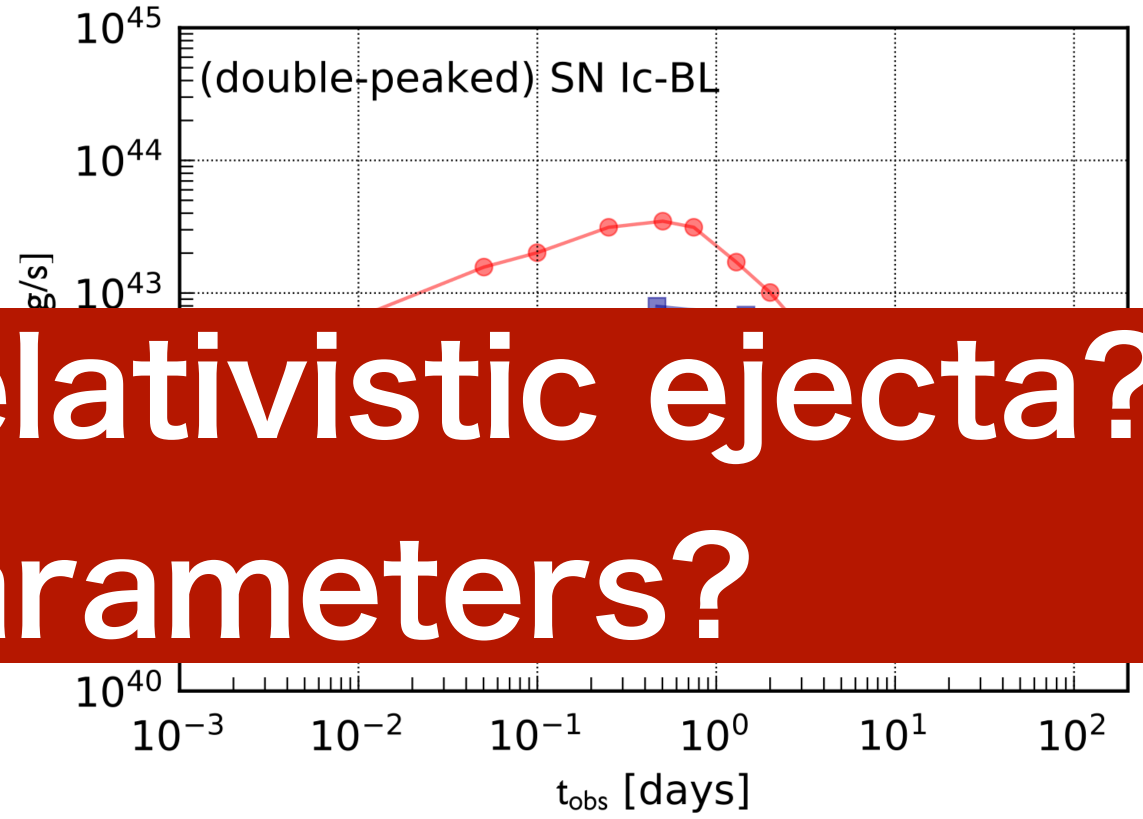
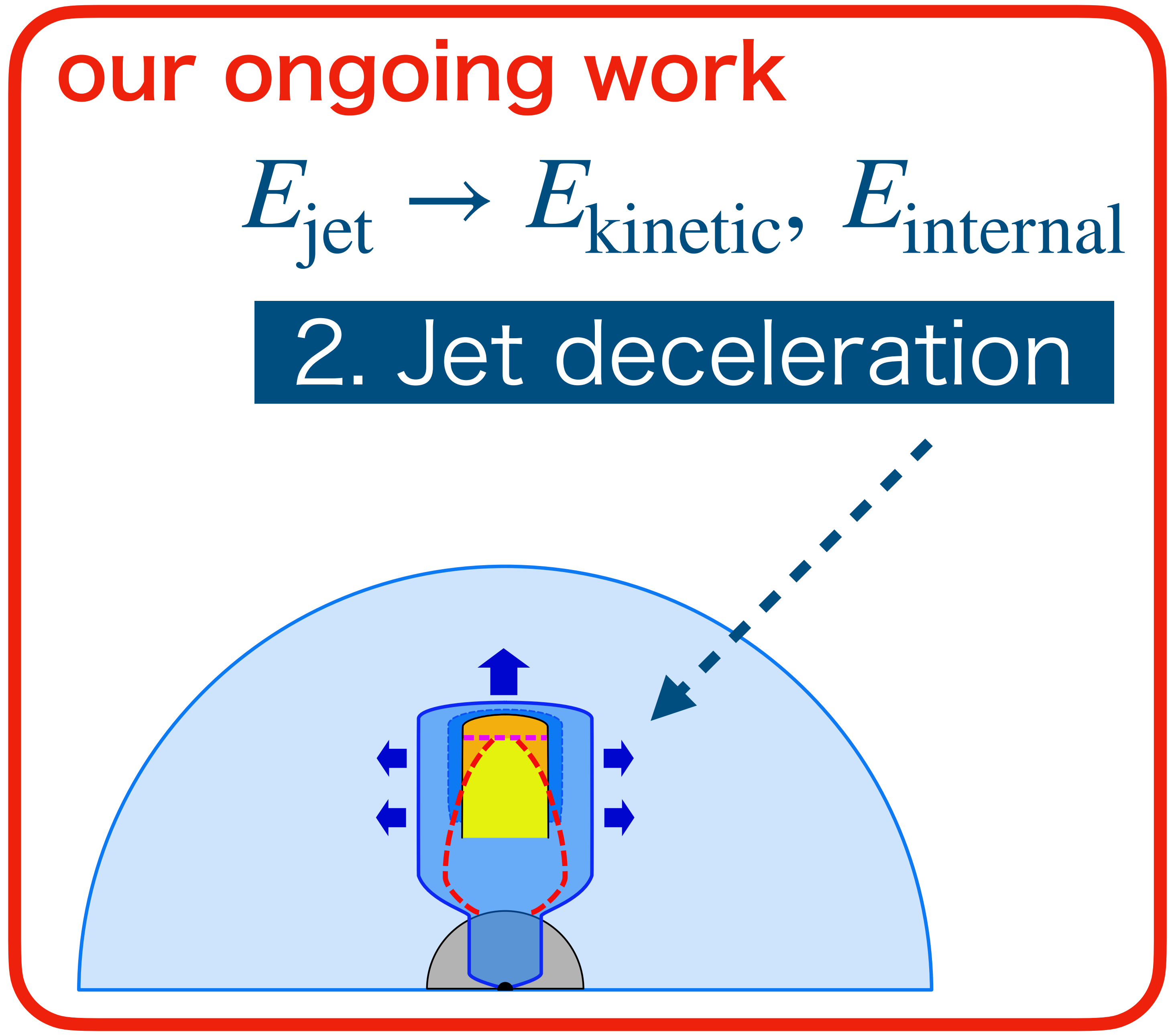




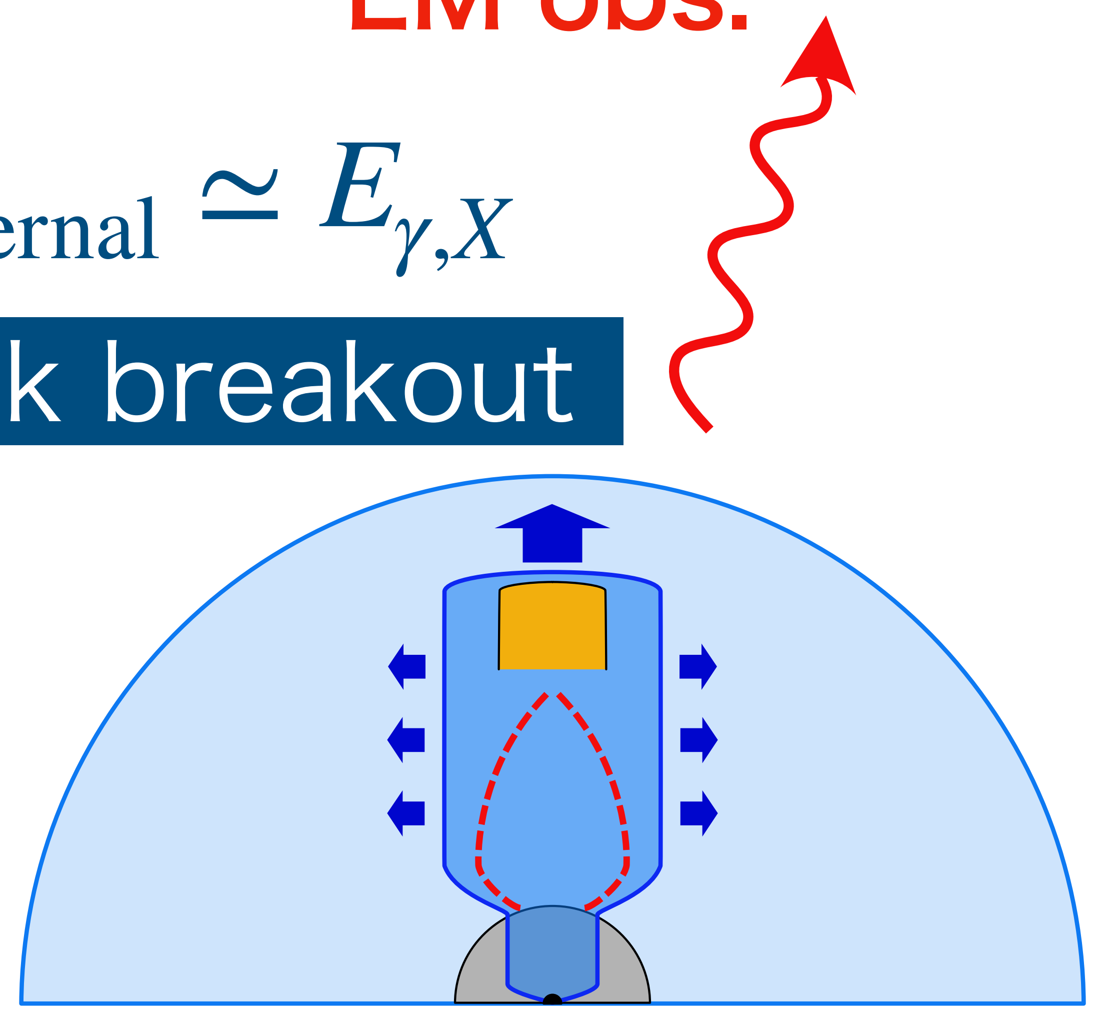
What is the property (M, E, composition, …) of the relativistic ejecta?
How the ejecta properties are dependent on CSM parameters?



our ongoing work

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

2. Jet deceleration



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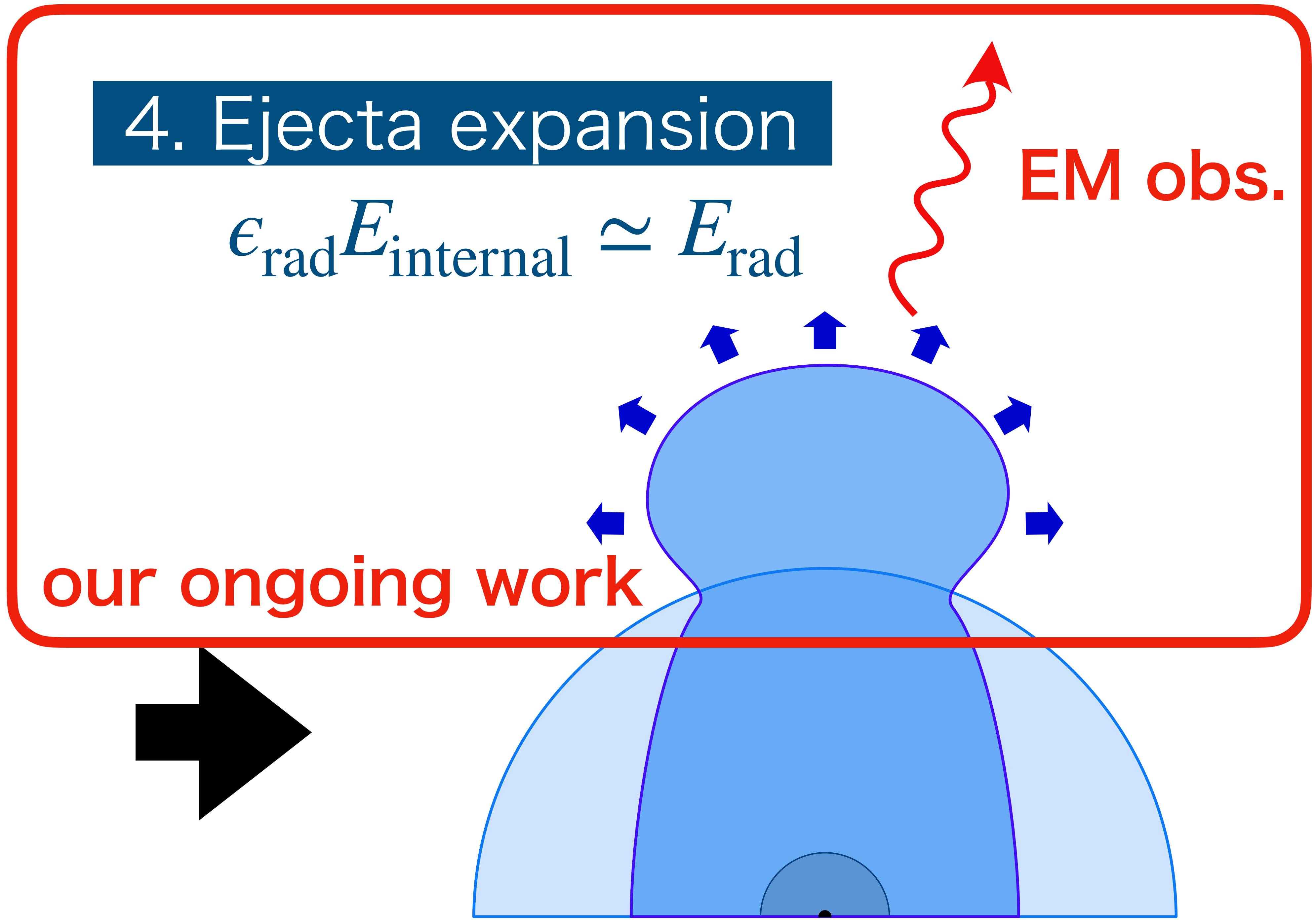

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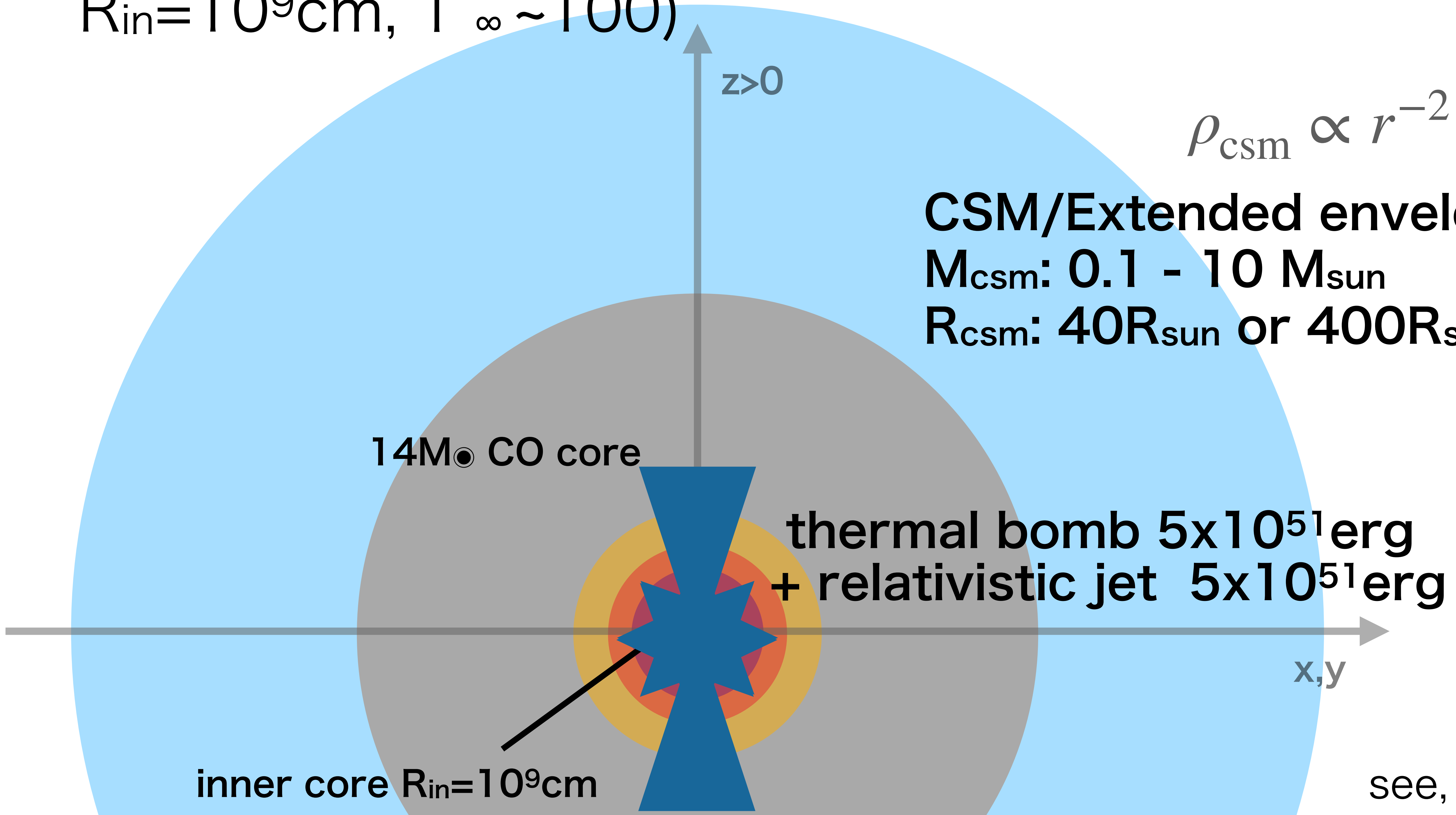
but, not always (e.g, radiation condition,
Murase&Ioka 2013, Senno+2016)

CR, ν obs.

Jet simulations

GRB jet simulations: setups

- 3D special relativistic hydrodynamic simulation in (x,y,z)
- 14 $M_{\rm sun}$ CO core (16TI; Woosley&Heger 2006)
- chemical composition: hypernova-like (e.g., Iwamoto+ 2000)
- thermal bomb (5×10^{51} erg, $R_{\rm in}=10^9$cm)
- relativistic jet (5×10^{51}erg per jet, $t_{\rm jet}$=20s, $\theta_{\rm jet}$=10 deg, $R_{\rm in}=10^9$cm, $\Gamma_\infty\sim100$)



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

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

14$M_\odot$ CO core

thermal bomb 5×10^{51}erg
+ relativistic jet 5×10^{51}erg

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

model	$M_{\rm csm}$[$M_{\rm sun}$]	$R_{\rm csm}$[$R_{\rm sun}$]
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

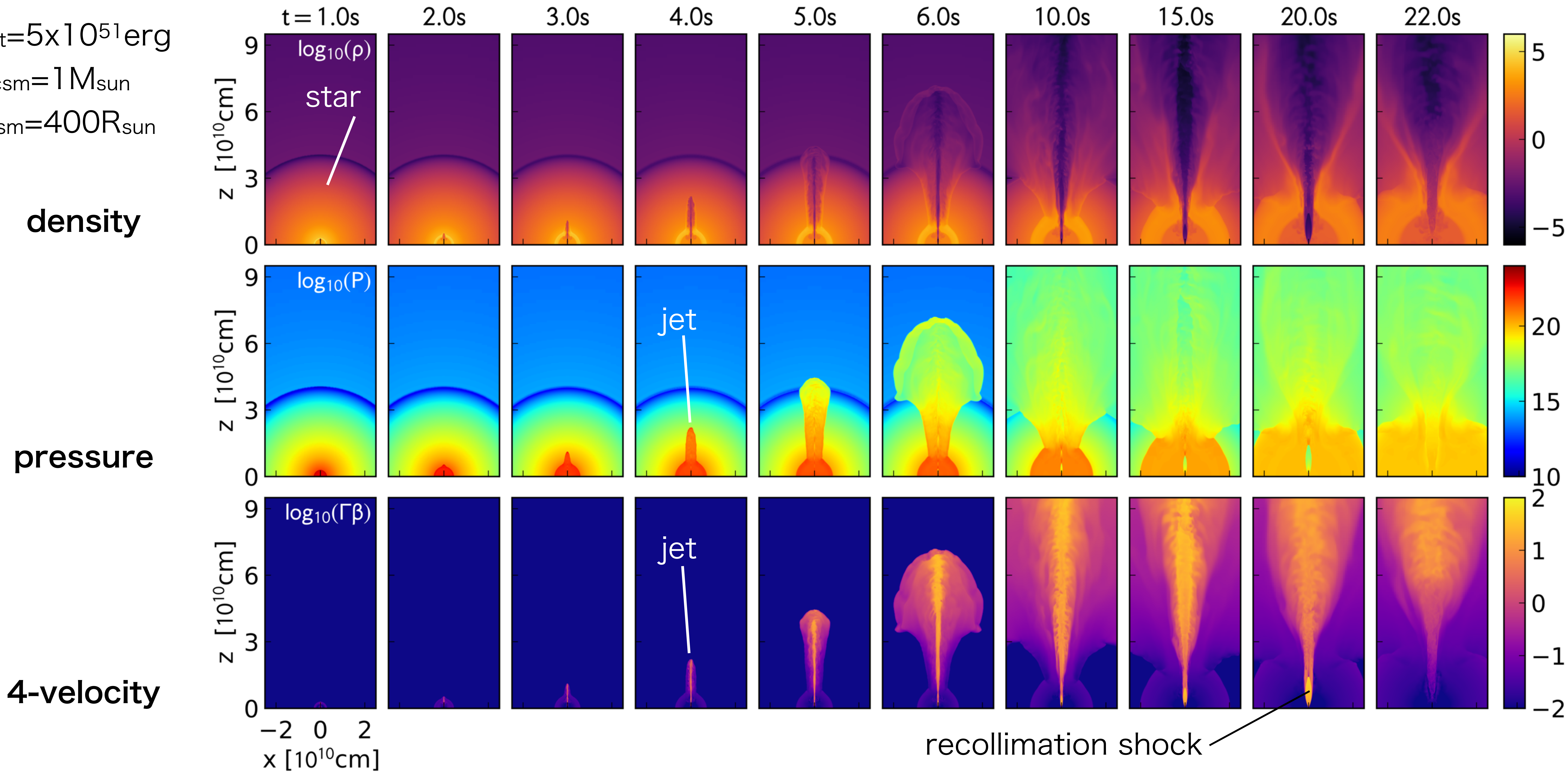
AS, Irwin, &Maeda (2024)

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

$E_{\rm jet}=5\mathrm{x}10^{51}$erg

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

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



GRB jet simulations: jet dynamics

AS, Irwin, &Maeda (2024)

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

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

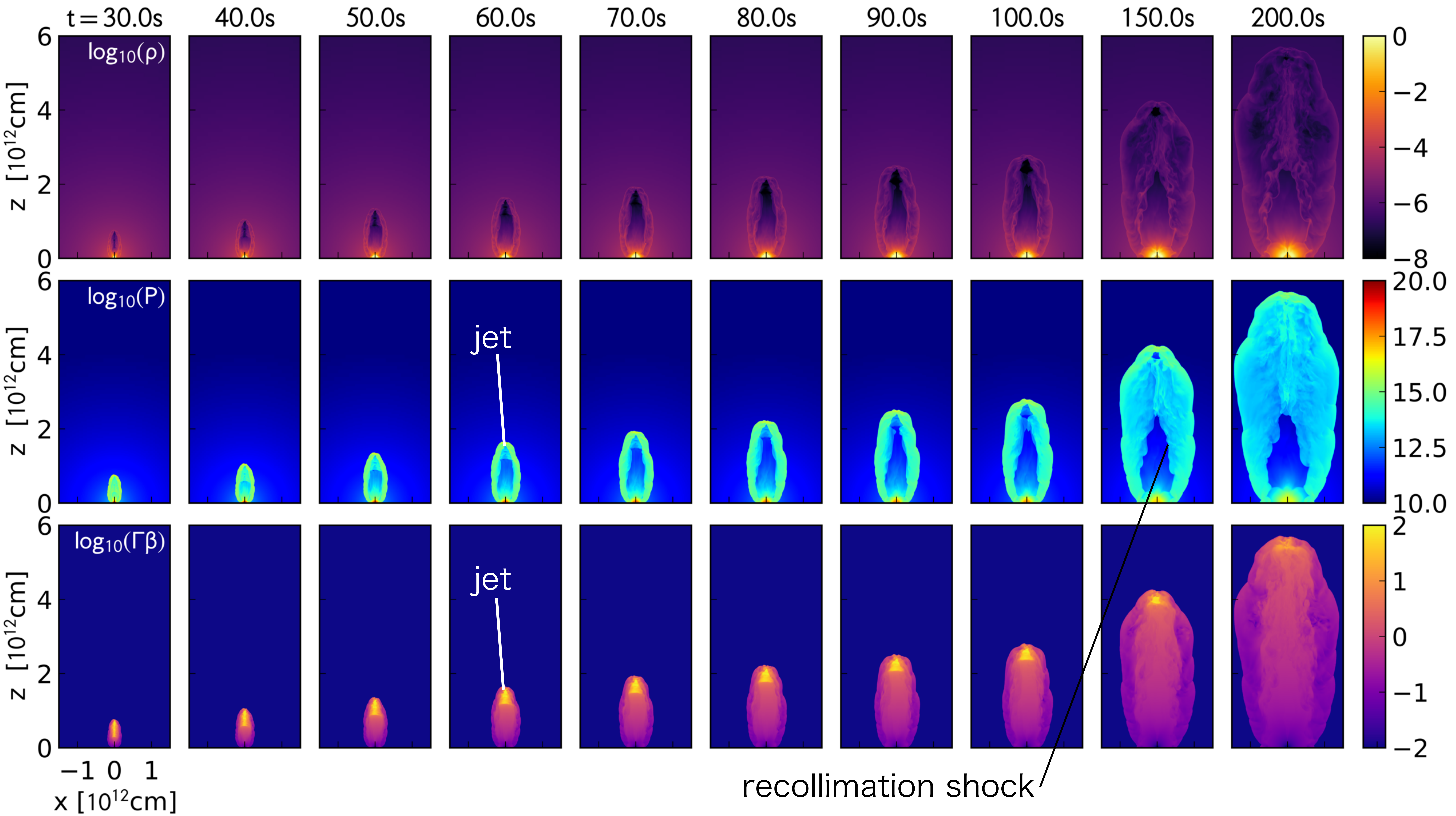
$M_{csm}=1M_{sun}$

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

density

pressure

4-velocity

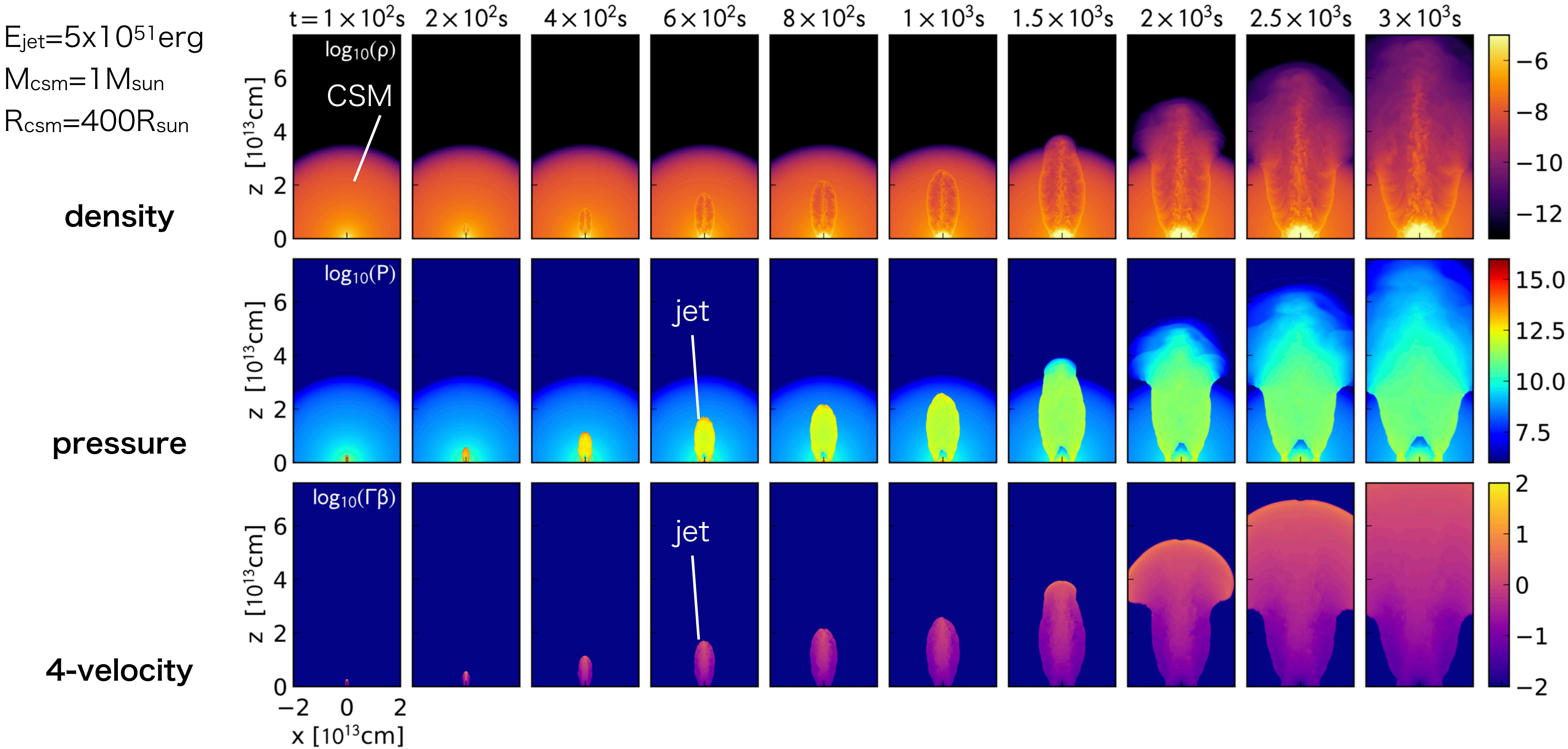


GRB jet simulations: jet dynamics

AS, Irwin, &Maeda (2024)

- 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}



GRB jet simulations: jet dynamics

AS, Irwin, &Maeda (2024)

- 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

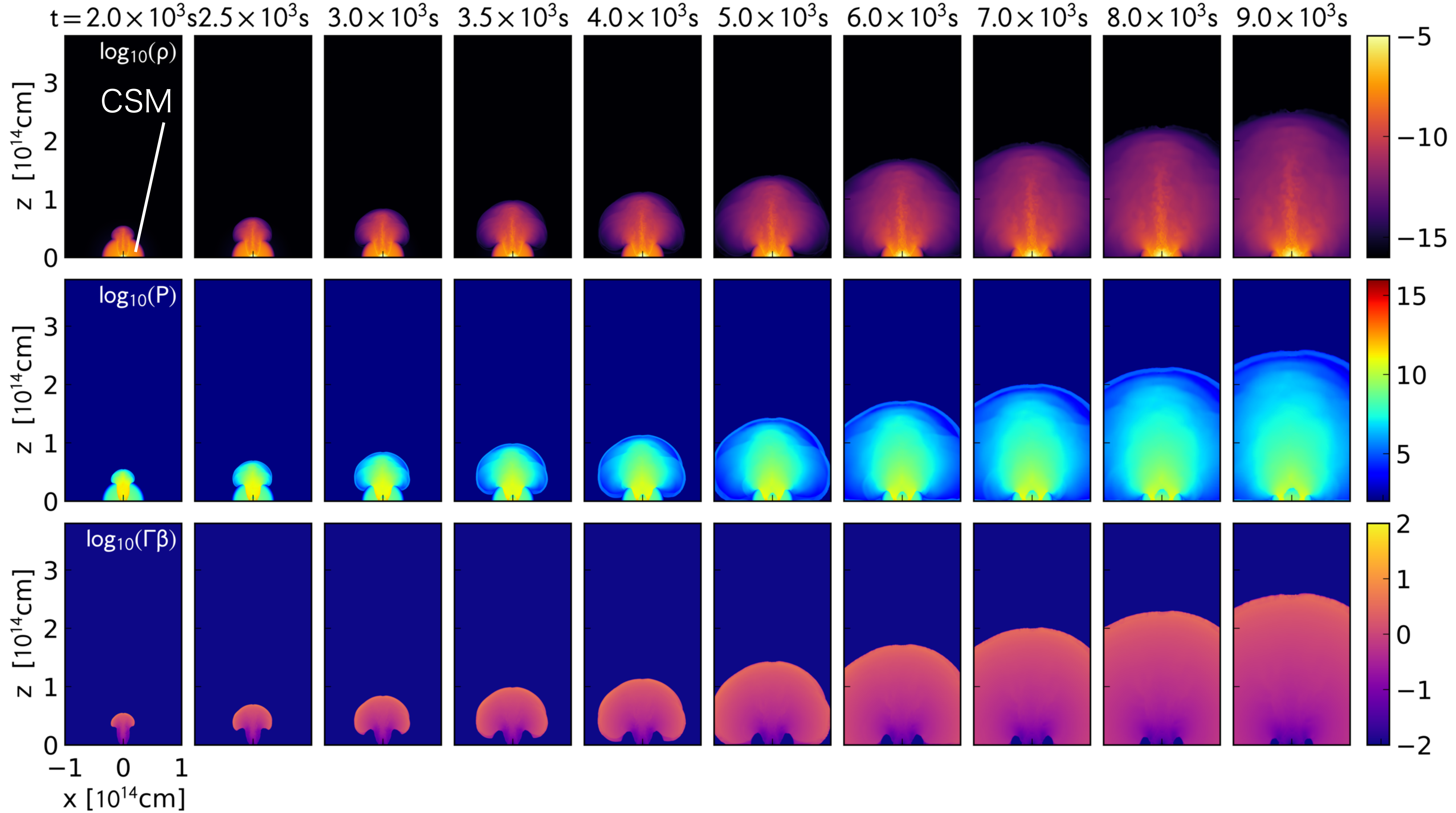
M_{csm}=1M_{sun}

R_{csm}=400R_{sun}

density

pressure

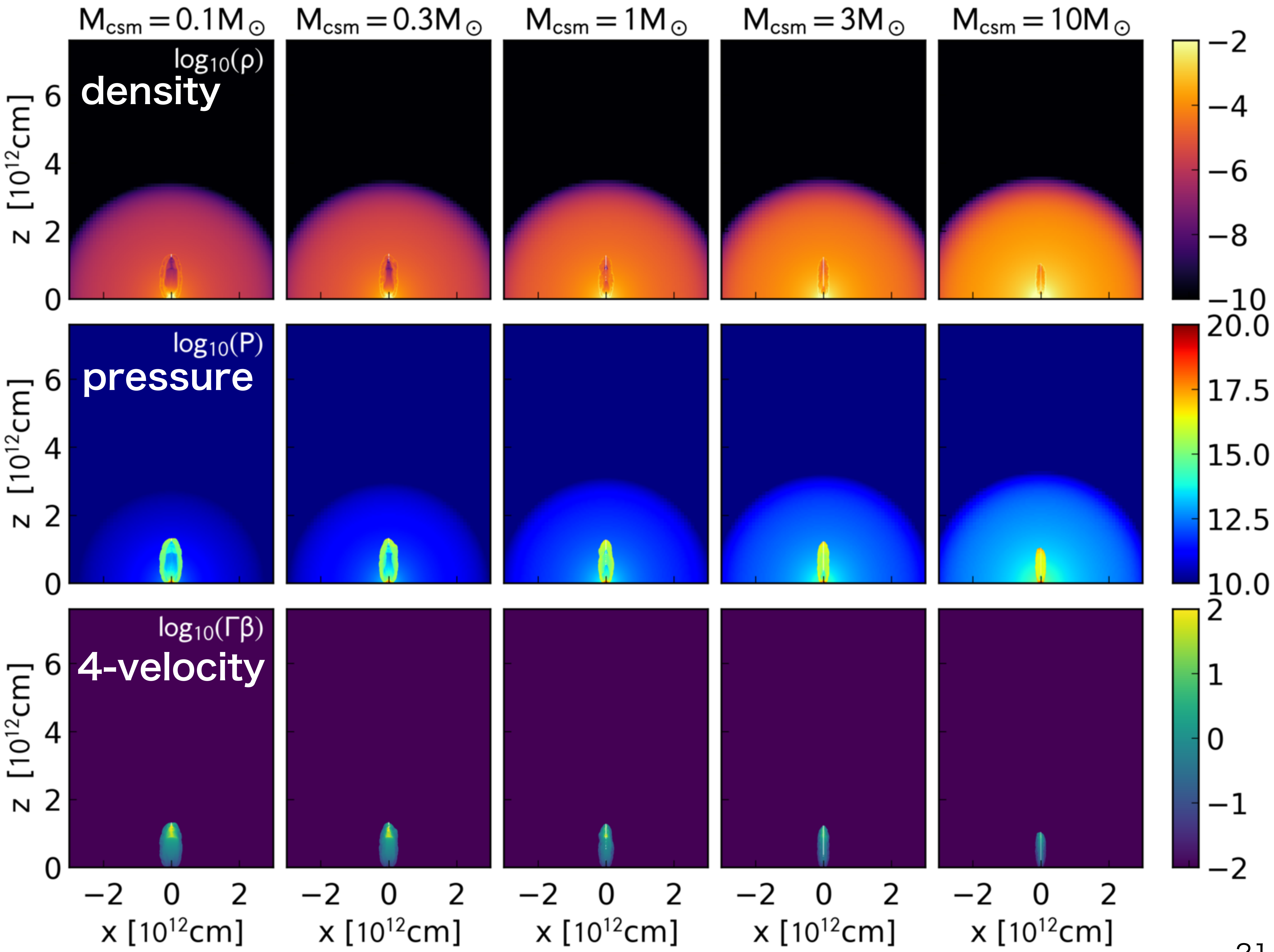
4-velocity



GRB jet simulations: CSM mass dependence

- 40R$_{\rm sun}$ models: M$_{\rm csm}$=0.1-10M$_{\rm sun}$
- massive CSMs decelerate the jet efficiently
- massive CSMs collimate the jet
- M$_{\rm csm}$=10M$_{\rm sun}$: non-relativistic jet head.

40R$_{\rm sun}$ models t= 50 s



AS, Irwin, &Maeda (2024)

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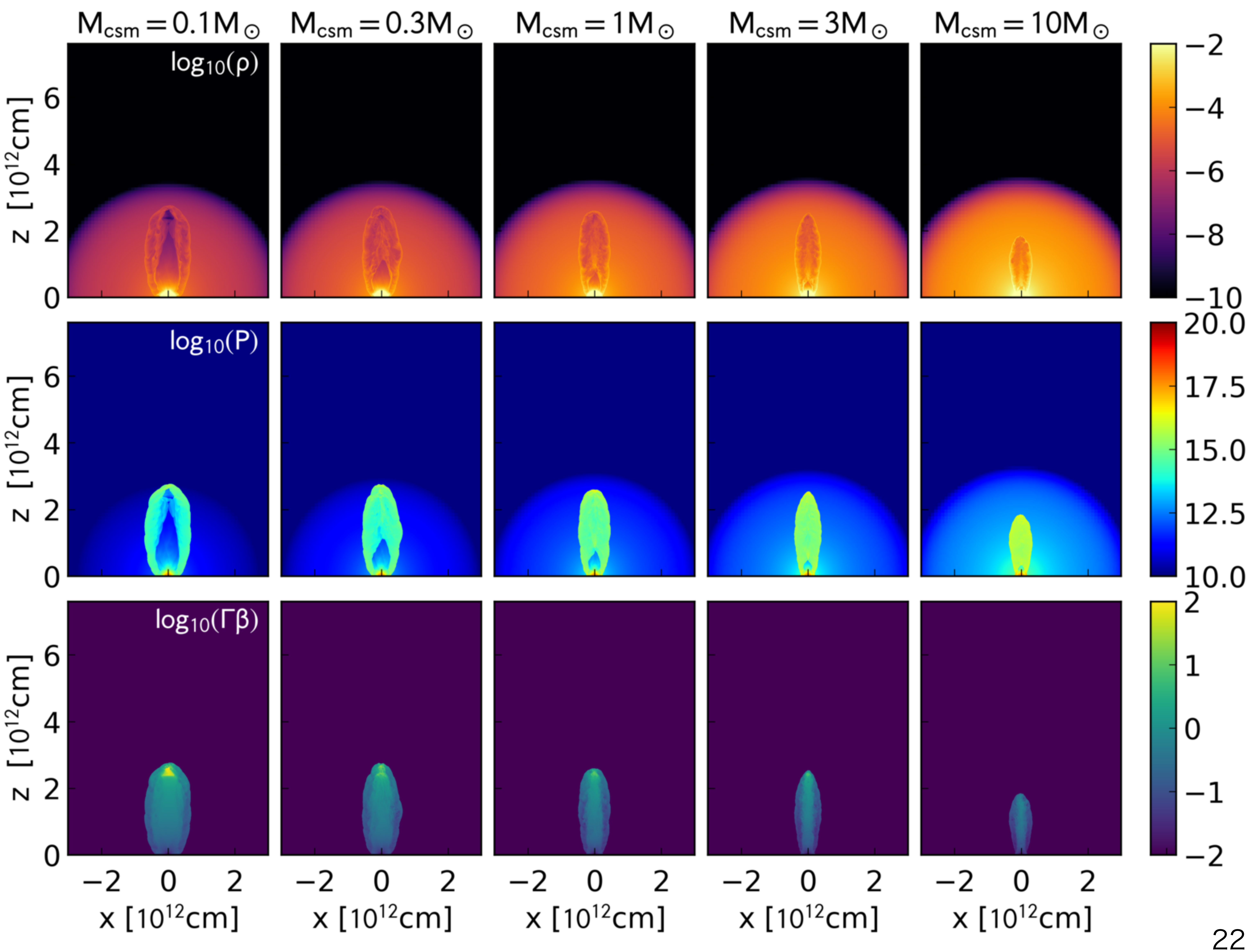
40R_{sun} models t=100 s



AS, Irwin, &Maeda (2024)

GRB jet simulations: CSM mass dependence

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- massive CSMs collimate the jet
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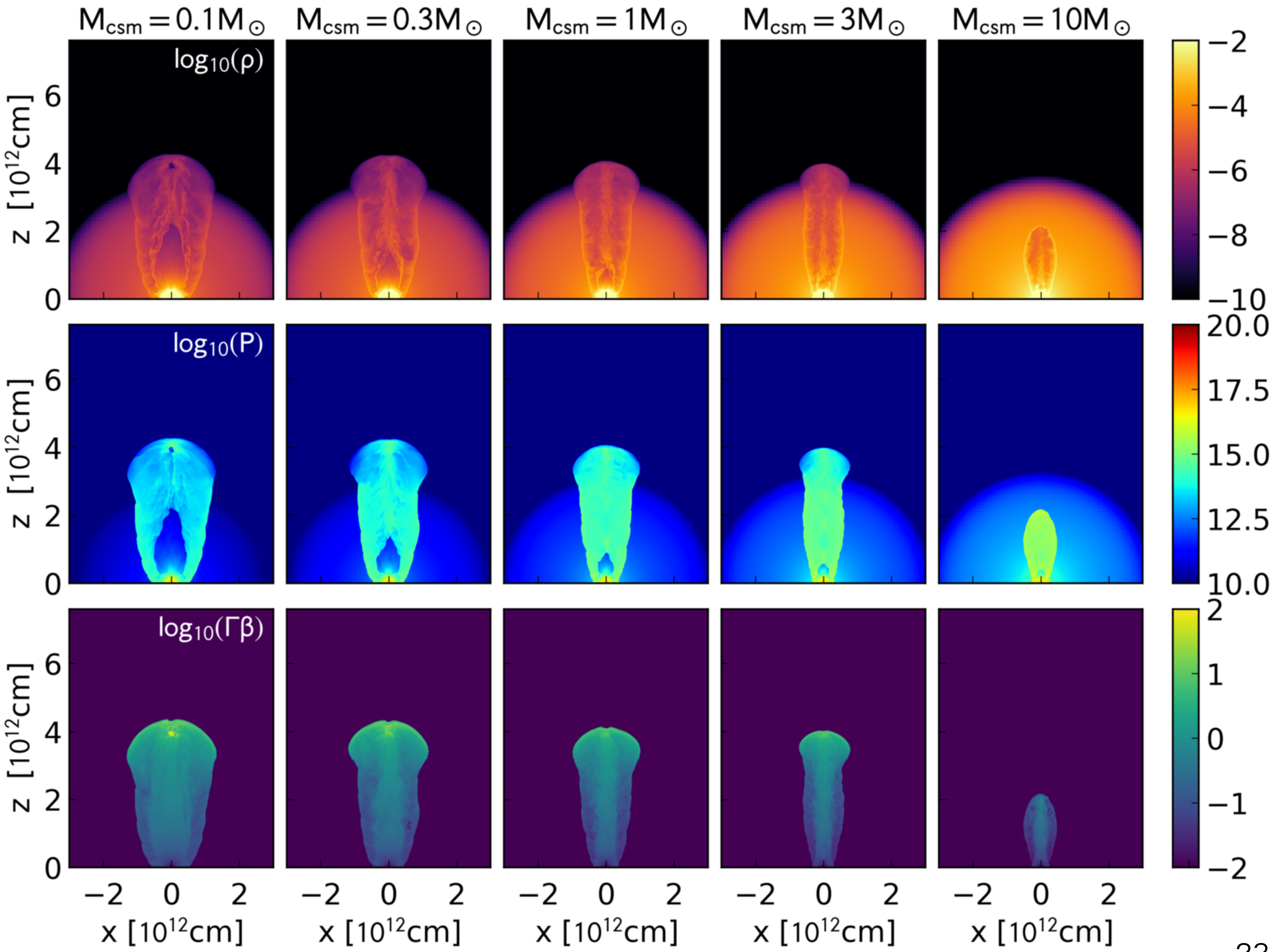
40R$_{\rm sun}$ models t=150 s



AS, Irwin, &Maeda (2024)

GRB jet simulations: CSM mass dependence

- 40R$_{sun}$ models: M$_{csm}$=0.1-10M$_{sun}$
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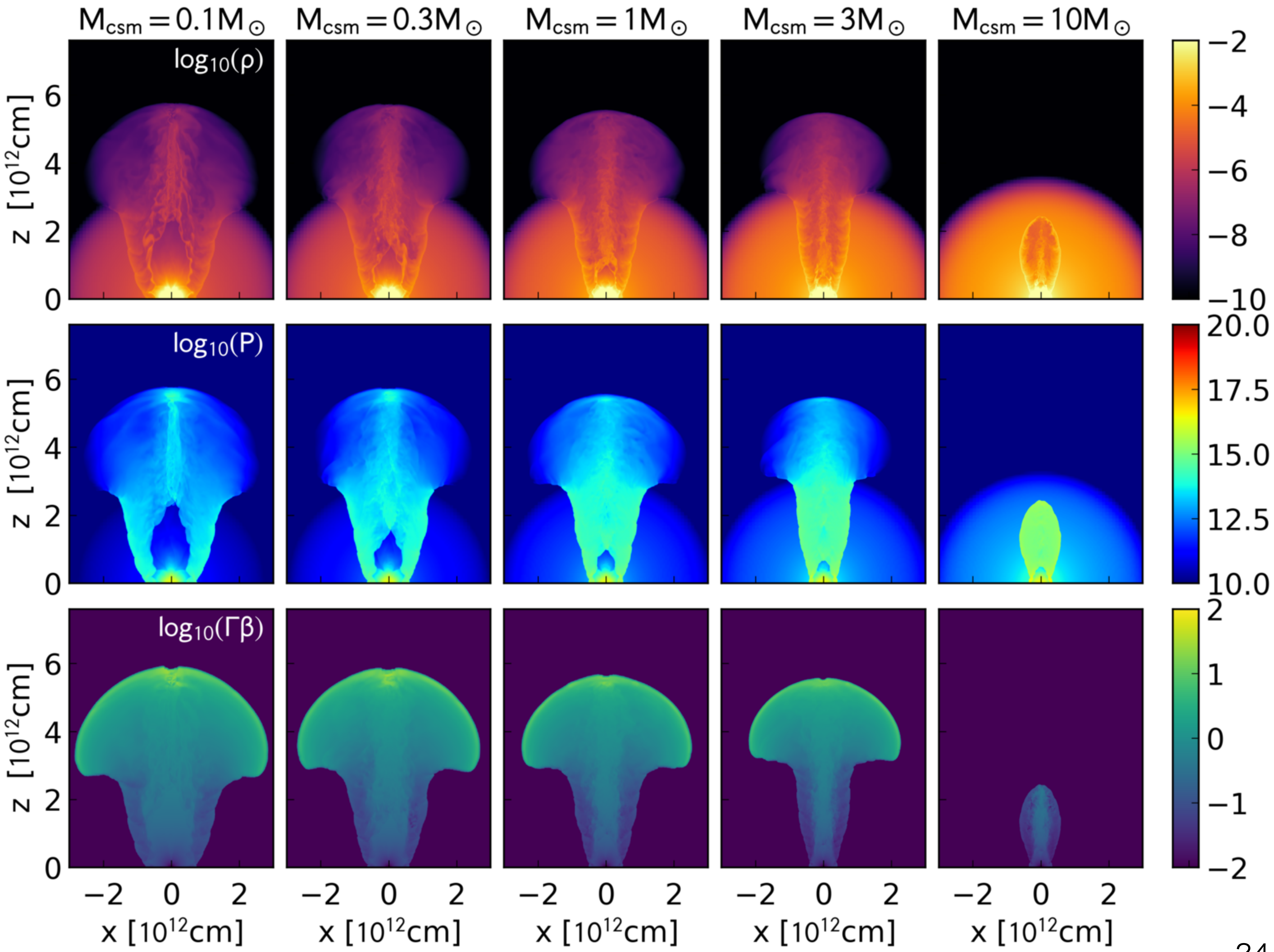
- massive CSMs collimate the jet
- M$_{csm}$=10M$_{sun}$: non-relativistic jet head.

40R$_{sun}$ models t=200 s

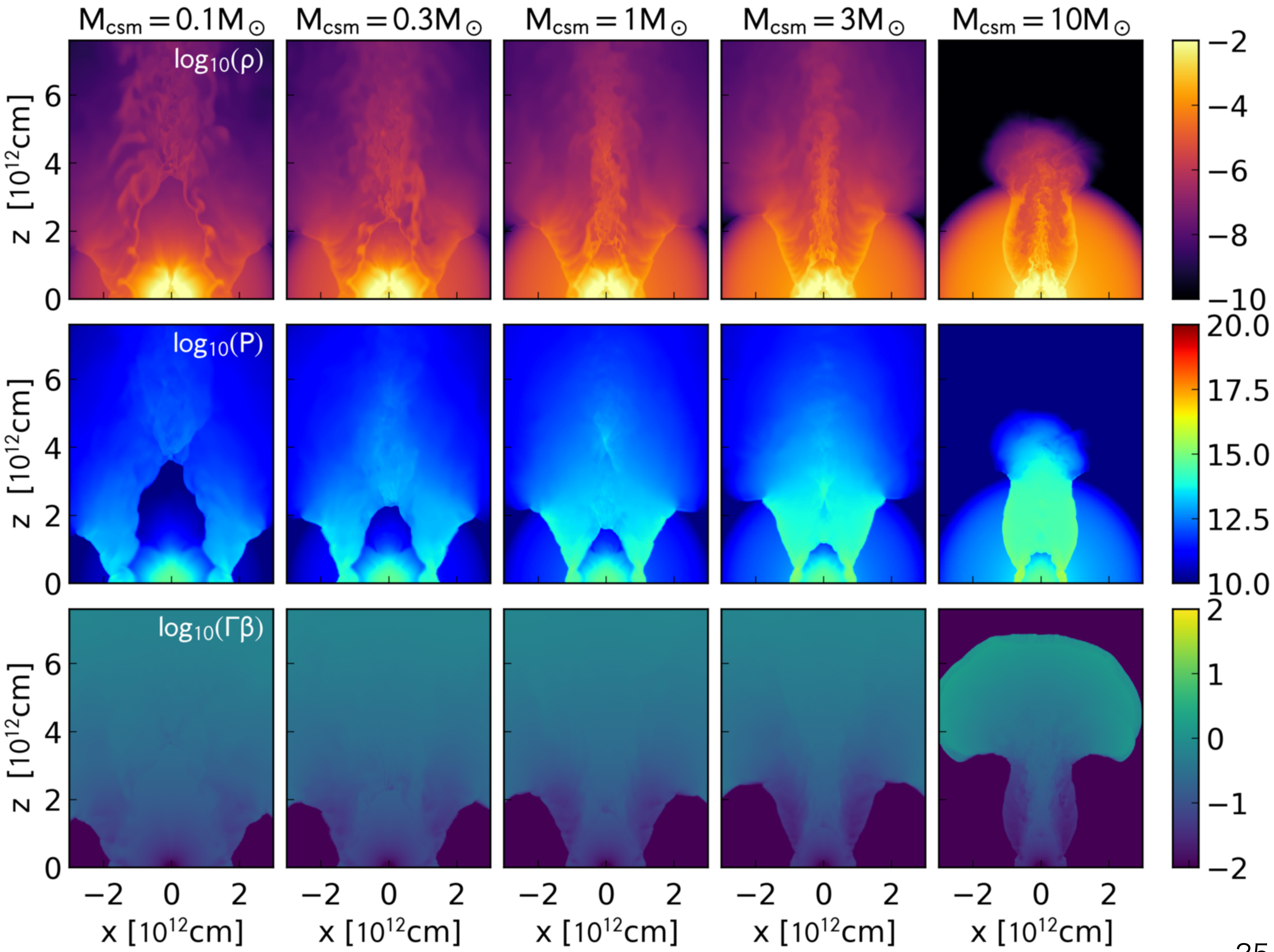


AS, Irwin, &Maeda (2024)

GRB jet simulations: CSM mass dependence

- 40Rsun models: Mcsm=0.1-10Msun
- massive CSMs decelerate the jet efficiently
- massive CSMs collimate the jet
- Mcsm=10Msun: non-relativistic jet head.

40Rsun models t=500 s

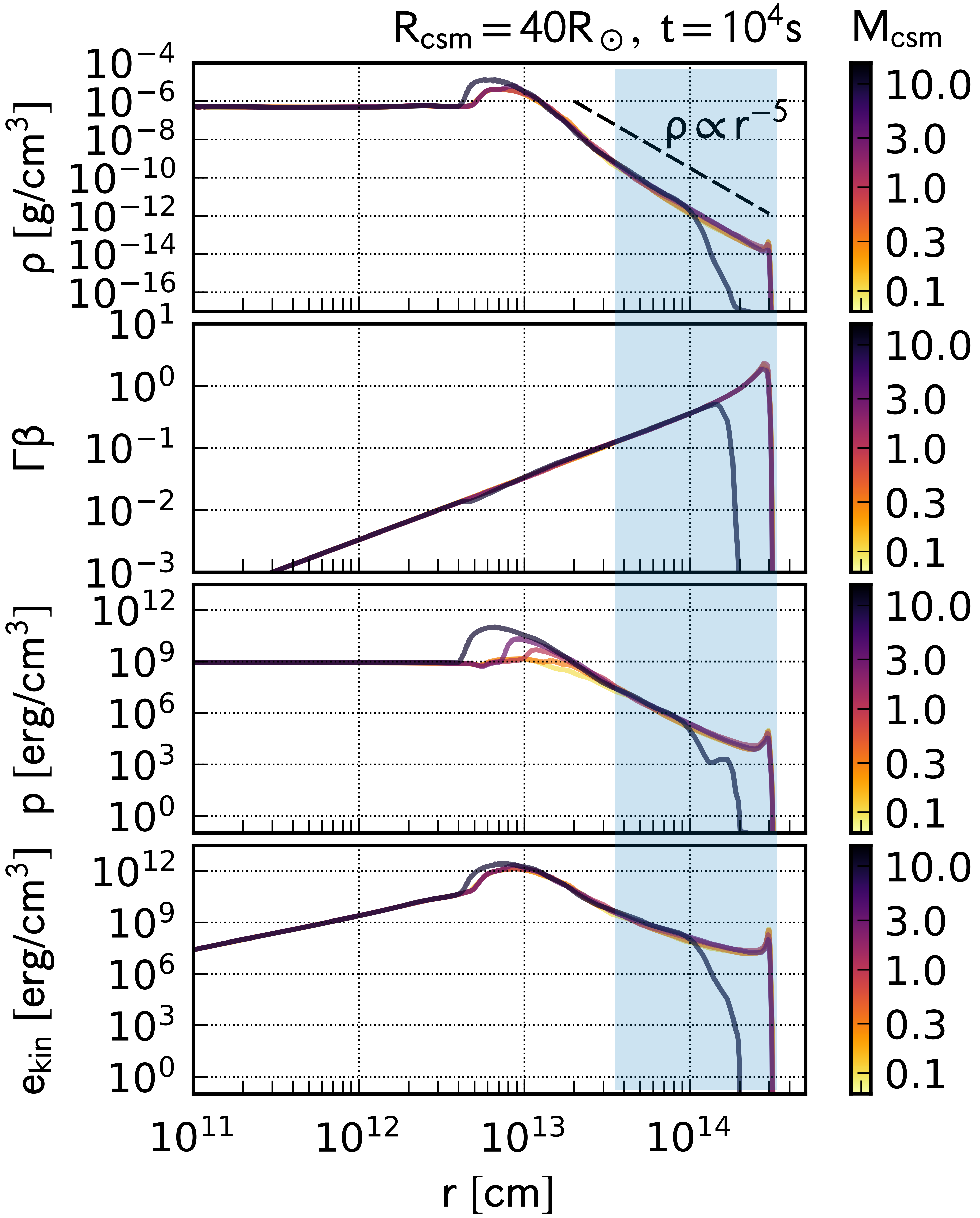


AS, Irwin, &Maeda (2024)

GRB jet simulations: radial profiles

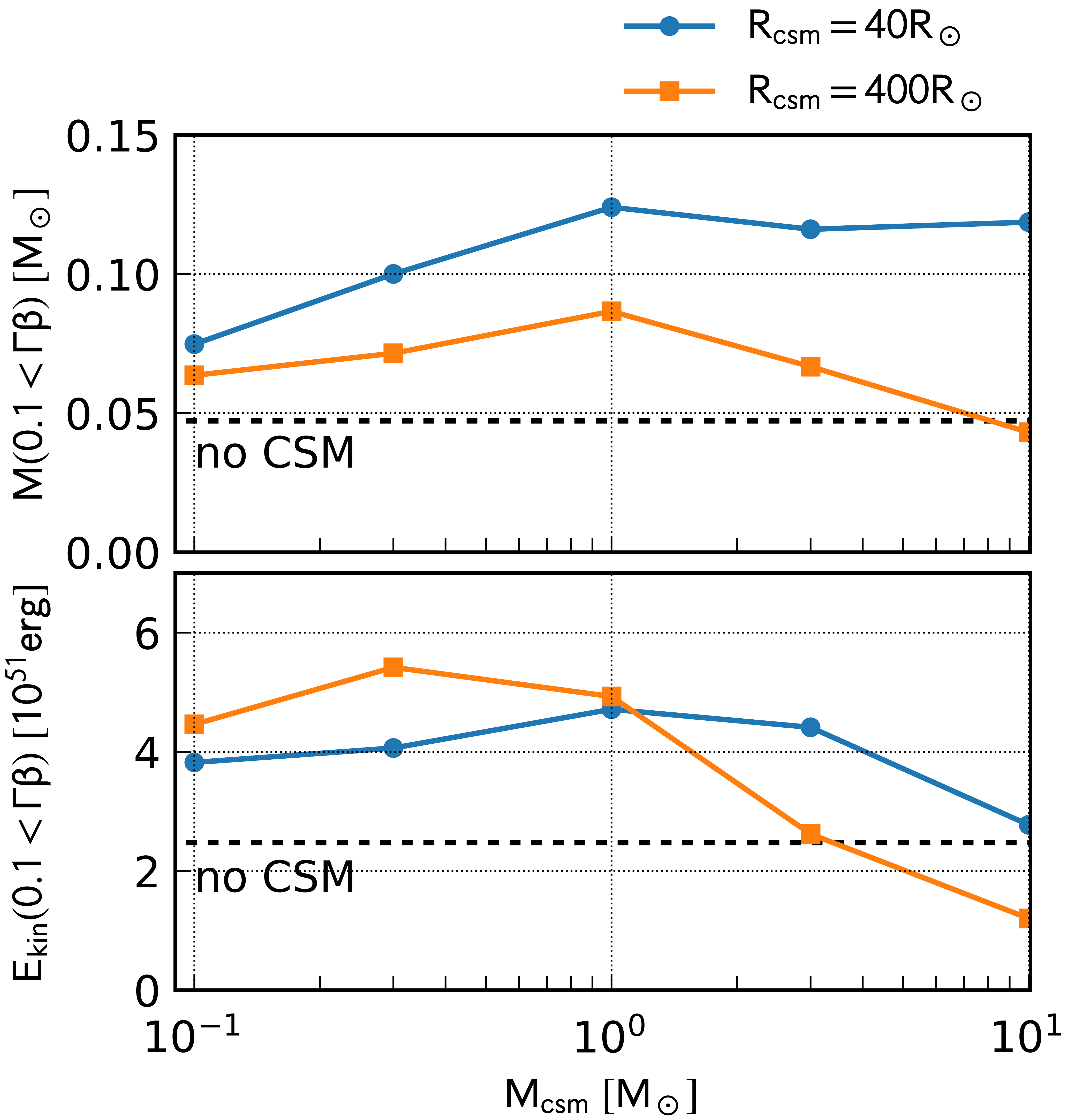
AS, Irwin, &Maeda (2024)

- 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: $\rho \propto v^{-5} \propto r^{-5}$



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) ~ (0.05-0.12)Msun
  - Ekin(v>0.1c) ~ (1-5)x10^{51}erg
- weak dependence on the CSM properties (Mcsm and Rcsm)



AS, Irwin, &Maeda (2024)

EM emission modelings

EM emission from mildly relativistic ejecta

- 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

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

2. Jet deceleration

$\epsilon_{\rm sb} E_{\rm internal} \simeq E_{\gamma,X}$

3. Shock breakout

EM obs.

relativistic ejecta

with $M_{\rm rel}$, $E_{\rm rel}$, $E_{\rm int}$ at R_0

4. Ejecta expansion

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

EM obs.

1. Jet formation

GW, ν obs.

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

5. particle acceleration

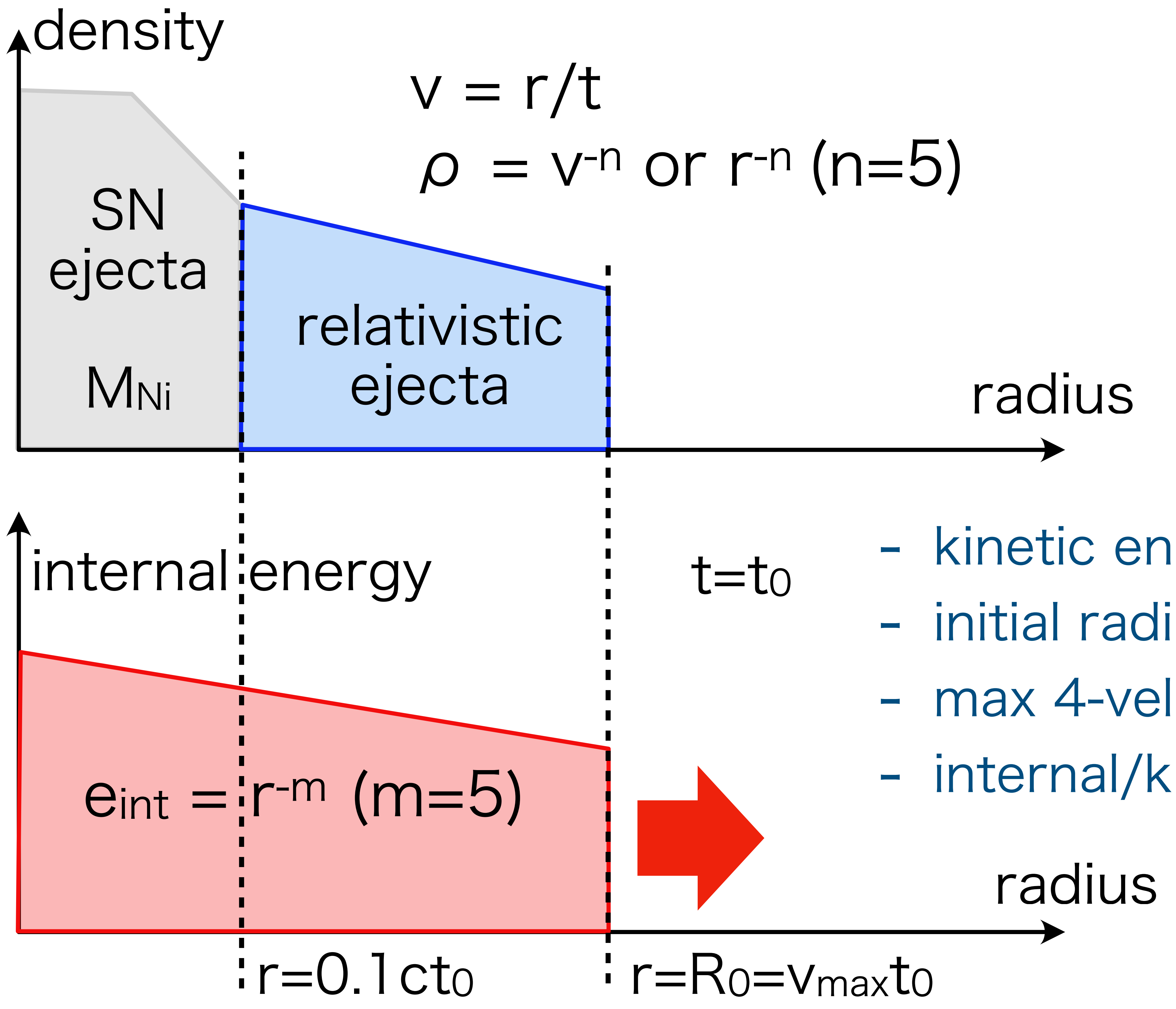
$\epsilon_{\rm acc} E_{\rm internal} \simeq E_{\rm CR} + E_\nu$

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

CR, ν obs.

Thermal emission powered by jet dissipation

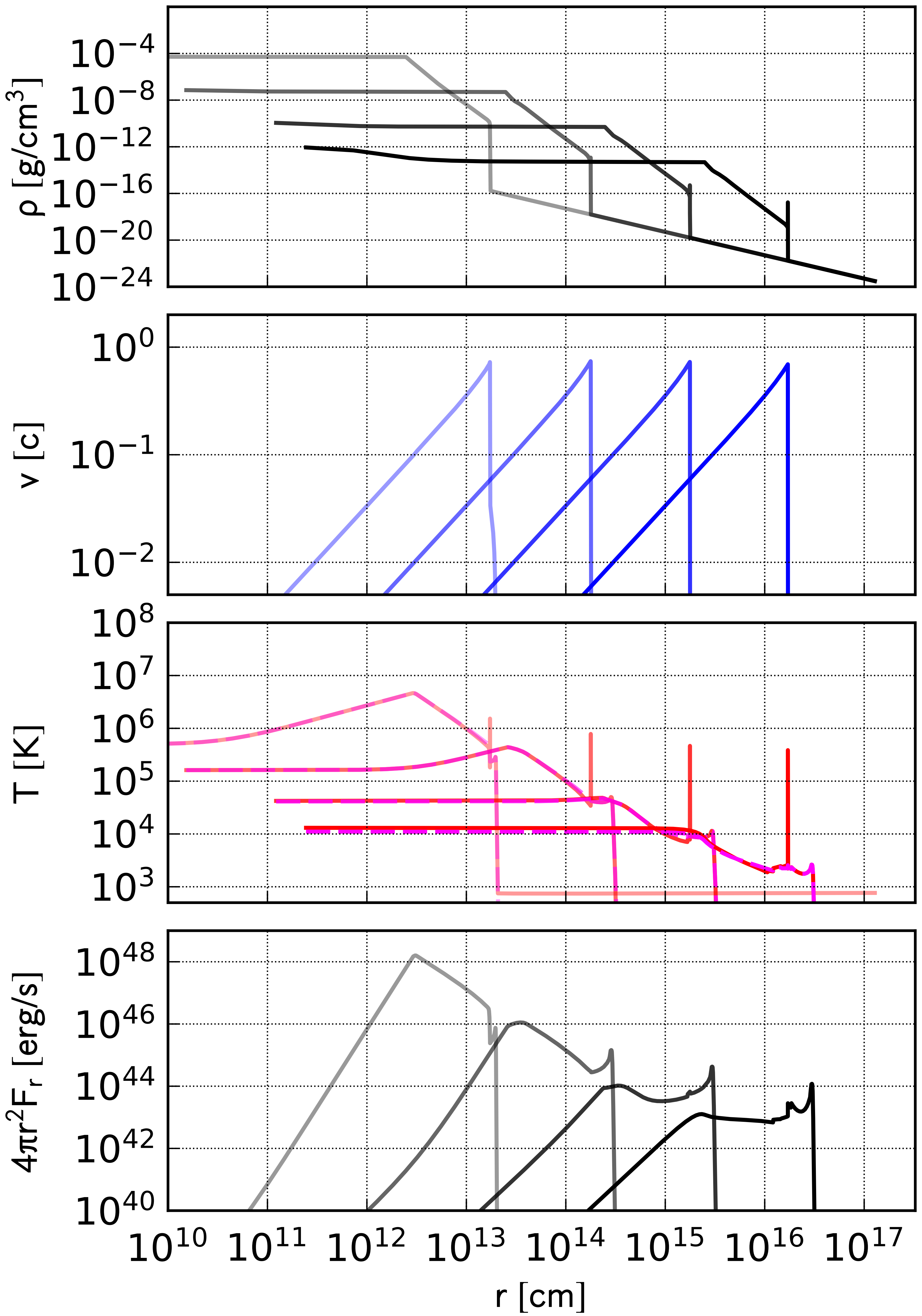
- thermal emission from the fast ejecta can account for the early UV-opt luminosity of llGRBs and SN Ic-BL 2020bvc
- this thermal emission could be common



$v = r/t$

$\rho = v^{-n}$ or r^{-n} (n=5)

- kinetic energy: E_{rel} (or M_{rel})
- initial radius: R_0
- max 4-velocity: $\Gamma\beta=0.7$
- internal/kinetic energy ratio: f=0.5



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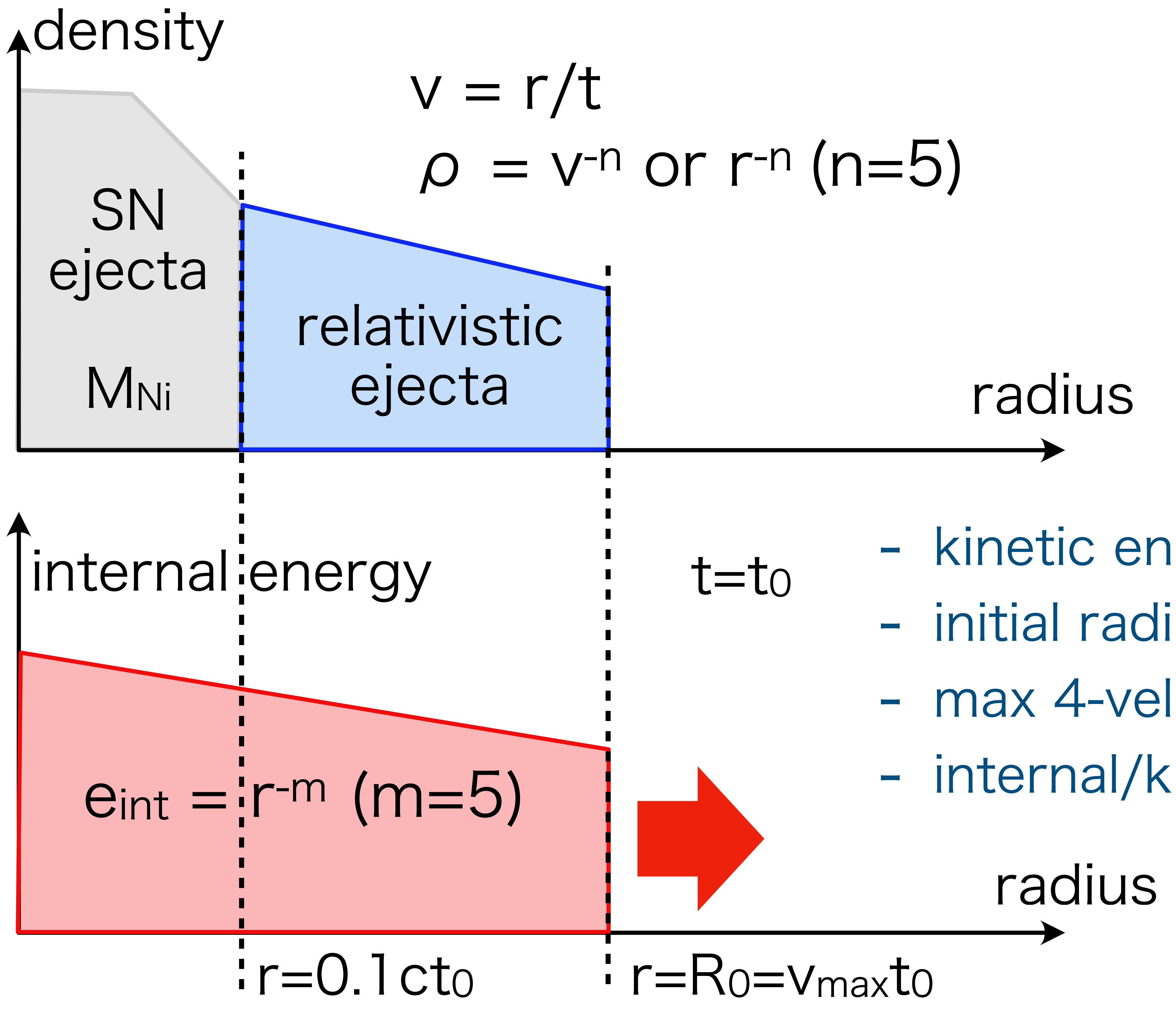

density

$v = r/t$

$\rho = v^{-n}$ or r^{-n} ($n=5$)

SN ejecta

M_{Ni}

relativistic ejecta

radius

internal energy

$t=t_0$

$e_{int} = r^{-m}$ ($m=5$)

radius

$r=0.1ct_0$

$r=R_0=v_{max}t_0$

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- initial radius: R_0
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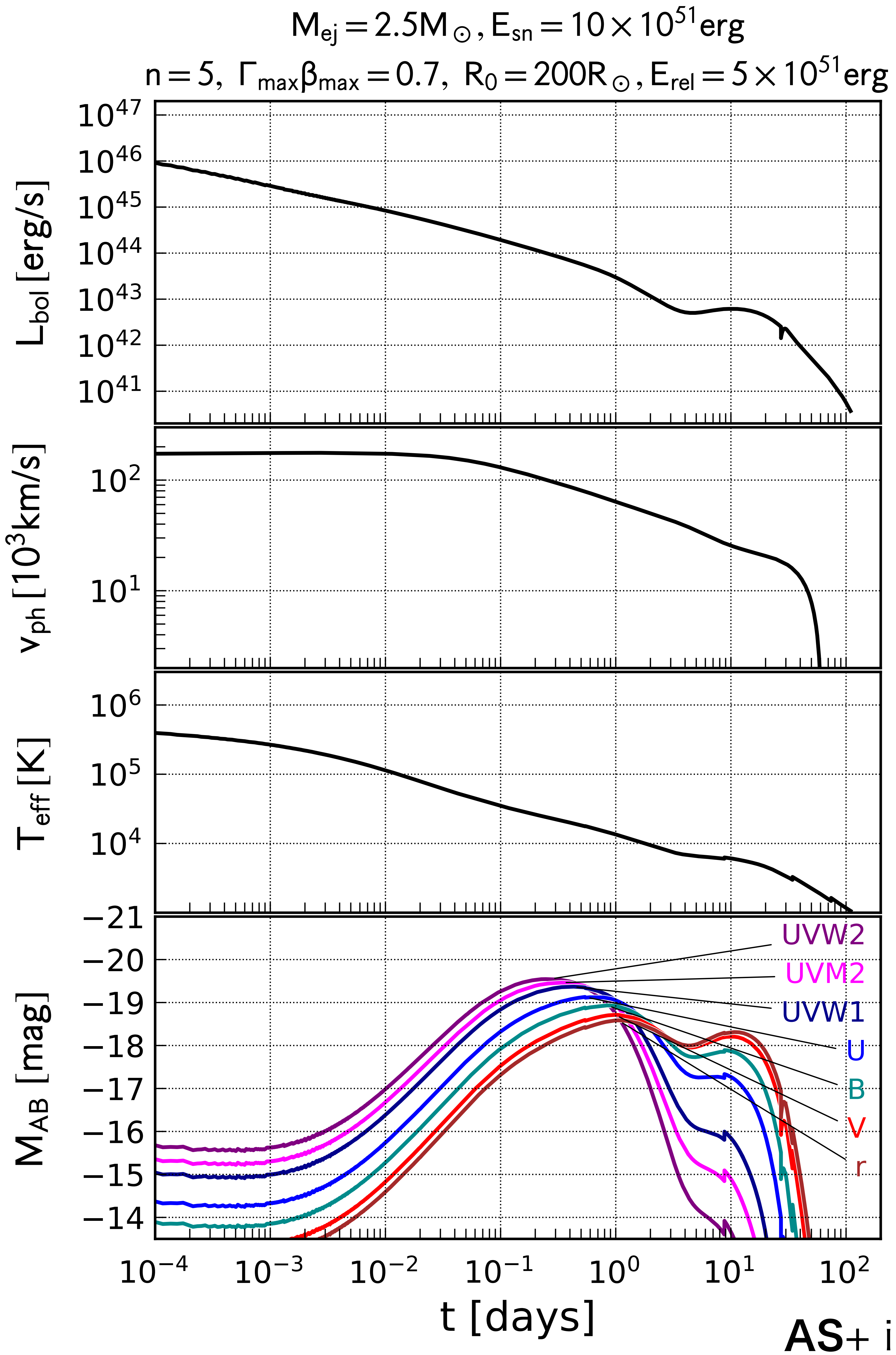

AS+ in prep

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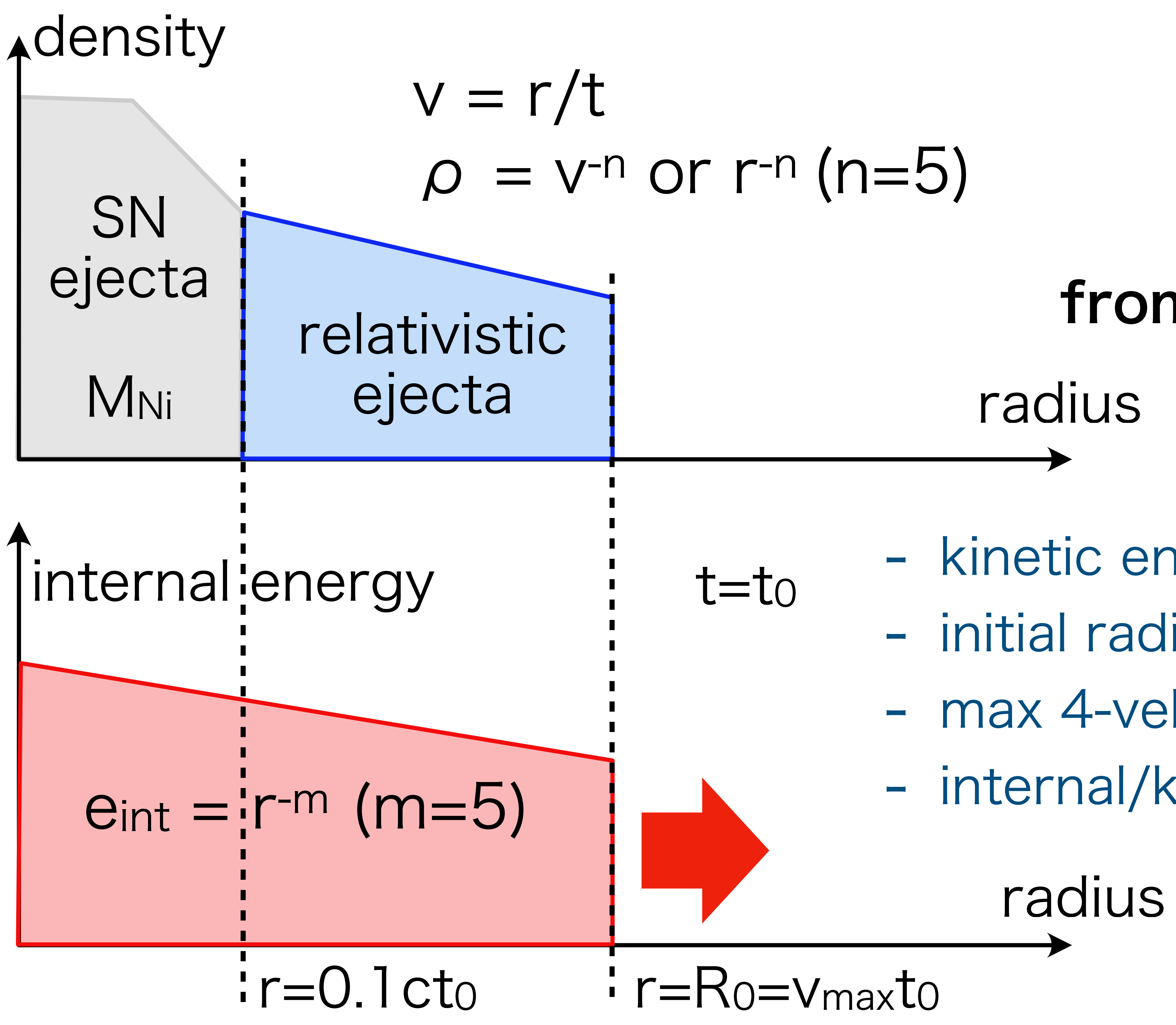

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- kinetic energy: E_{rel} (or M_{rel})
- initial radius: R_0
- max 4-velocity: $\Gamma\beta$=0.7
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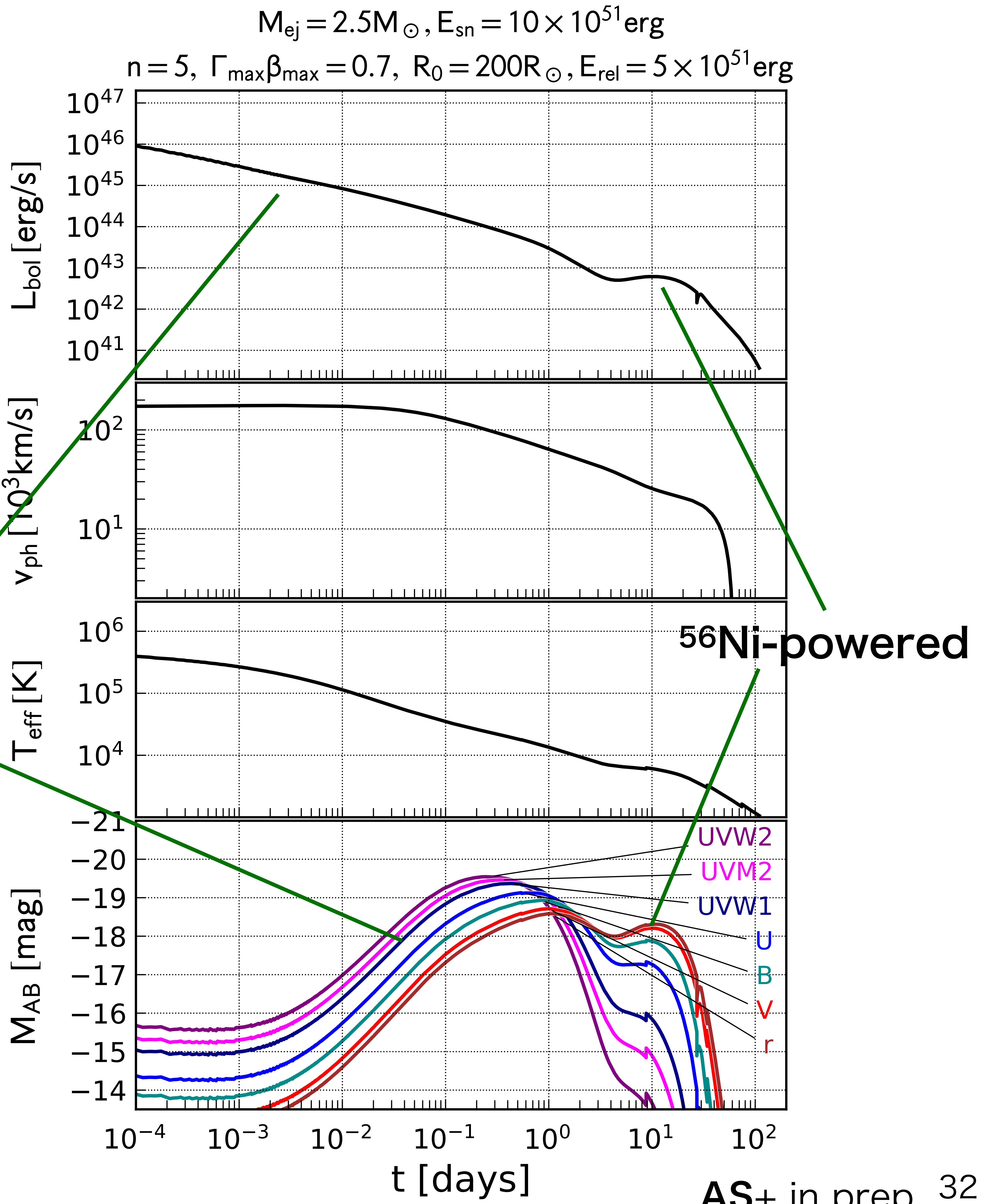
thermal emission from high-velocity ejecta



^{56}Ni-powered

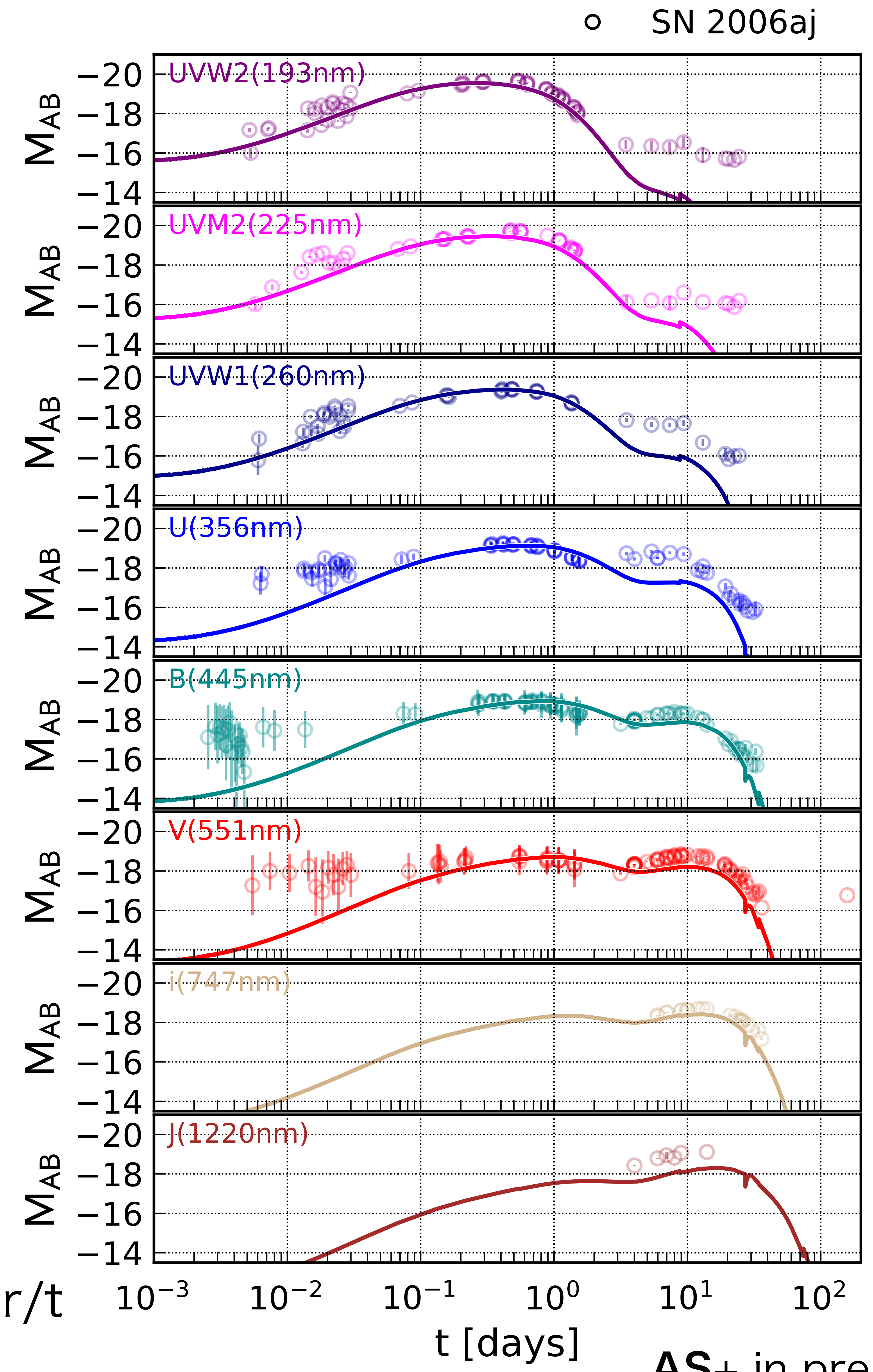
AS+ in prep

The case of GRB 060218/SN 2006aj

- GRB 060218/SN 2006aj: LC fitting looks quite good
- discrepancy in early optical LCs ($<10^4$ sec)
- early UV emission is a good probe of the total energy of the mildly ejecta (and thus the dissipated jet energy)
- constrained parameters are isotropic equivalent values
- non-spherical effects?

ejecta parameters:

- $R_0=200[R_{sun}]$
- $E_{rel}=5\times10^{51}$[erg]
- $\Gamma\beta_{max}=0.7$
- $\rho\propto(\Gamma\beta)^{-5}$
- $E_{sn}=10\times10^{51}$[erg]
- $M_{ej}=2.5M_{sun}$
- $M_{ni}=0.38M_{sun}$
- free expansion, v=r/t



AS+ in prep

The case of GRB 171205A/SN 2017iuk

- GRB 060218/SN 2006aj: LC fitting looks quite good
- discrepancy in early optical LCs (<10^4 sec)
- early UV emission is a good probe of the total energy of the mildly ejecta (and thus the dissipated jet energy)
- constrained parameters are isotropic equivalent values
- non-spherical effects?

ejecta parameters:

- R_0=50[R_{sun}]
- E_{rel}=1x10^{51}[erg]
- $\Gamma\beta_{max}$=0.7
- $\rho \propto (\Gamma\beta)^{-5}$
- E_{sn}=10x10^{51}[erg]
- M_{ej}=2.5M_{sun}
- M_{ni}=0.38M_{sun}
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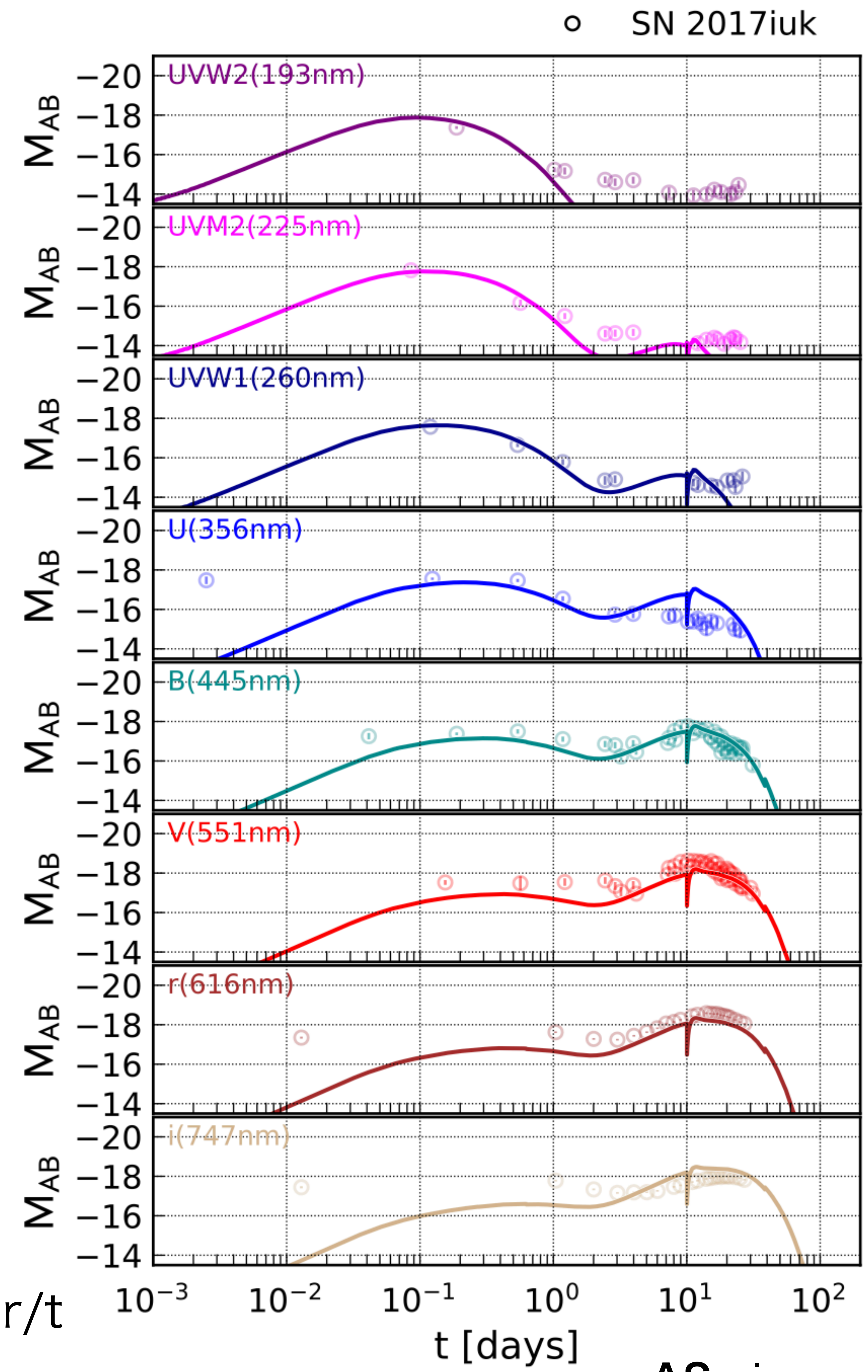


AS+ in prep

Volumetric rate summary

- long GRB rate: $R_{\rm lGRB}$ ~ 1[events/Gpc^3/yr]
- llGRB rate: $R_{\rm llGRB}$ ~ **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)

Einstein probe, SVOM

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

$$\dot{E}_{\rm inj} \simeq 3\times10^{45}\boxed{\left(\frac{E_{\rm diss}}{3\times10^{51}\,[\rm erg]}\right)}\boxed{\left(\frac{R_{\rm llGRBs}}{1000\,[\rm Gpc^{-3}yr^{-1}]}\right)}[\rm erg\,Mpc^{-3}\,yr^{-1}]$$

UV-opt follow-up (ULTRASAT,UVEX)

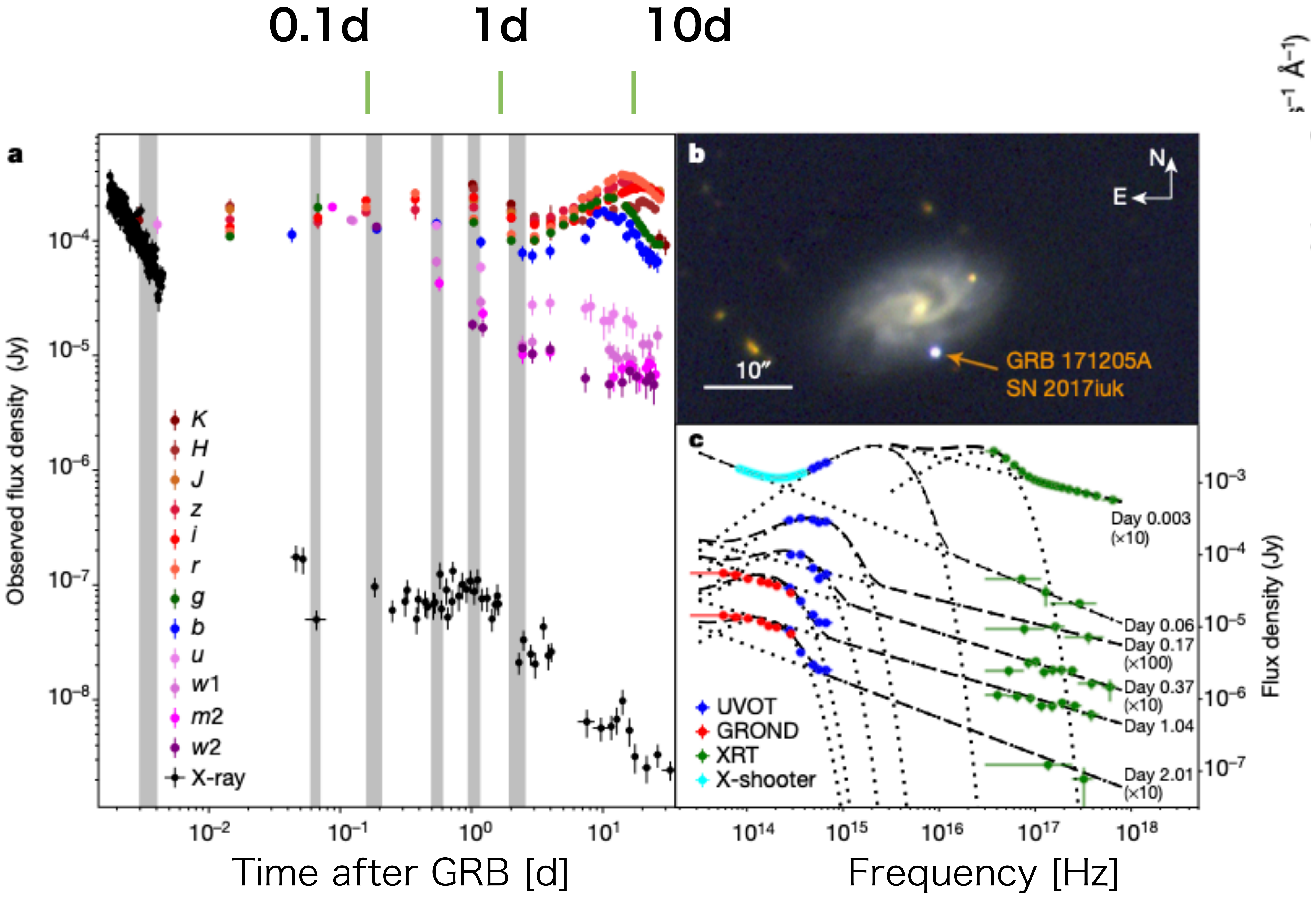
+ LC model grid

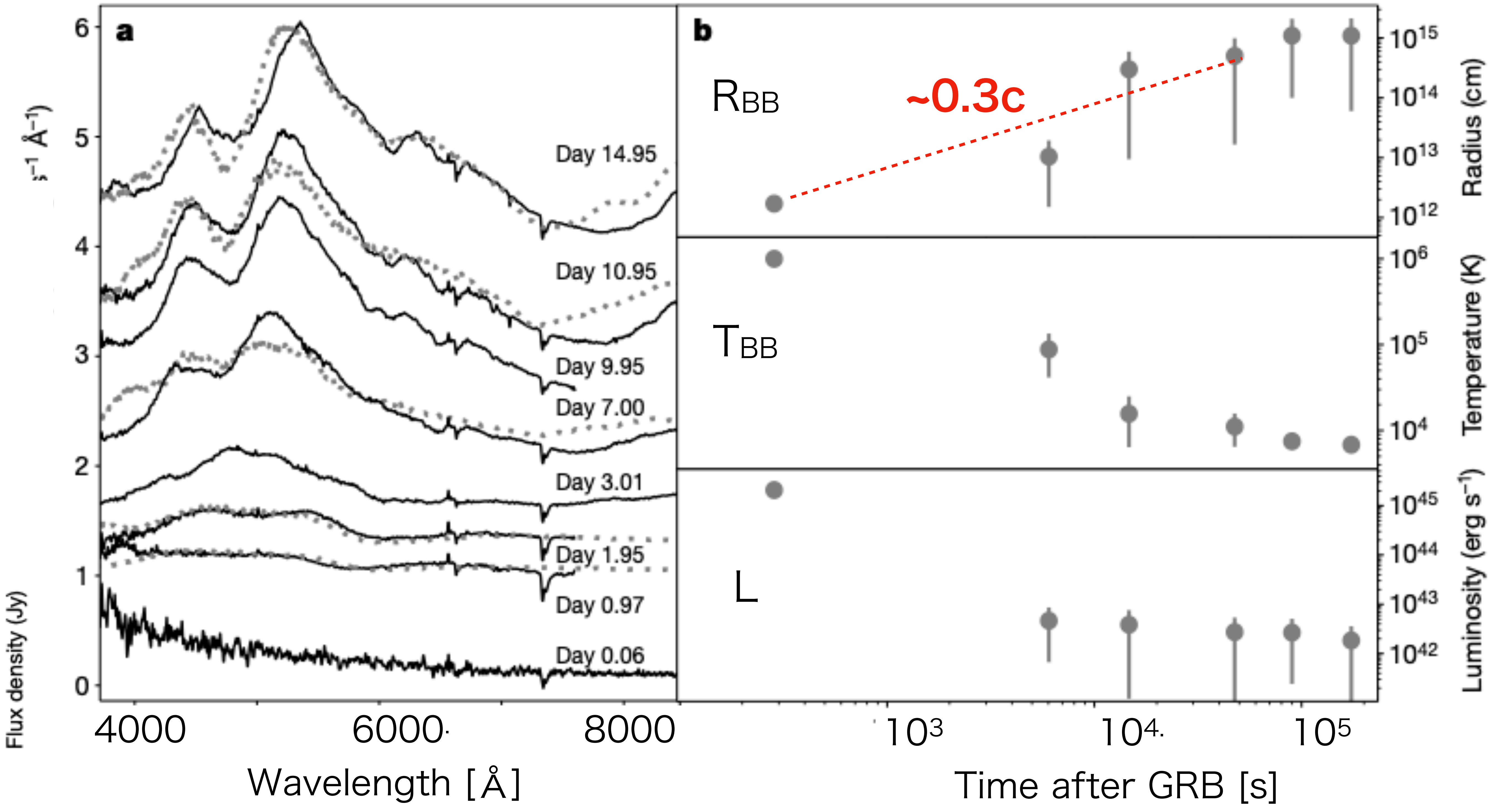
cf.) $\dot{E}_{\nu,\rm PeV} \sim \dot{E}_{\rm UHECRs} \sim 10^{44} - 10^{45}[\rm erg\,Mpc^{-3}\,yr^{-1}]$

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

Early spectral evolution of GRB-SNe

- (low-luminosity) GRB 171205A/ SN 2017iuk at D=163Mpc
- optical spectroscopy as early as 0.06 days after GRB trigger
- E_{iso}~2.2×10^{49}[erg], T_{90}~190[s]





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

Early spectral evolution of GRB-SNe

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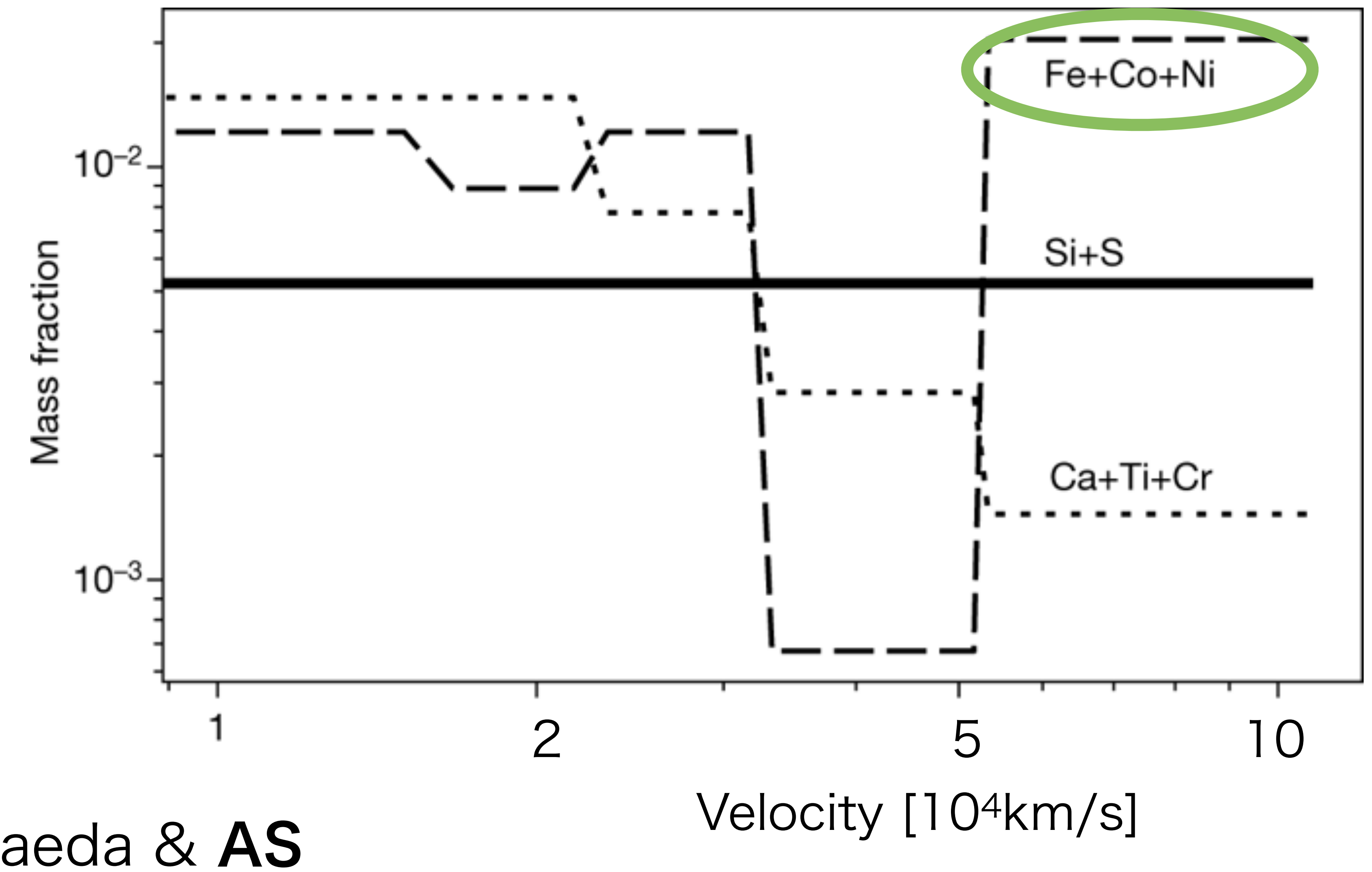
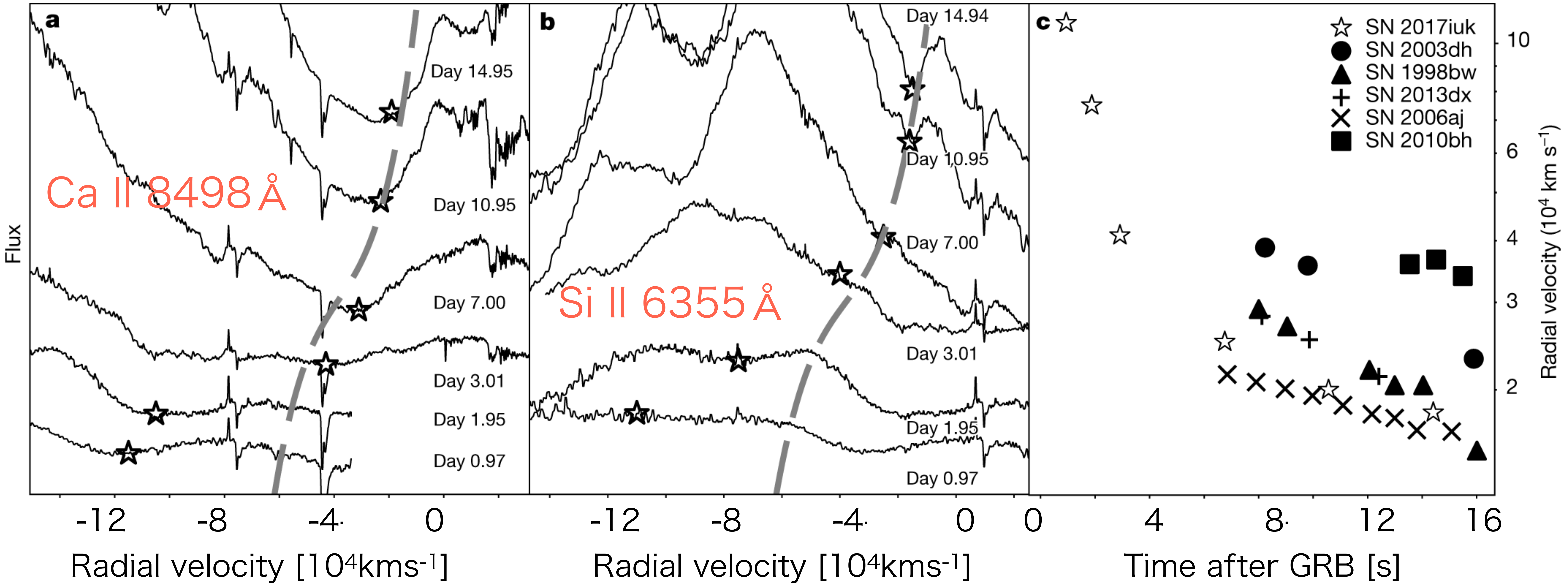
- blue-shifted absorption features with $v=10^5$km/s~0.3c
- Fe,Co,Ni well mixed into the fast component (X~0.01)
- density profile $\rho \propto v^{-6}$



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

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



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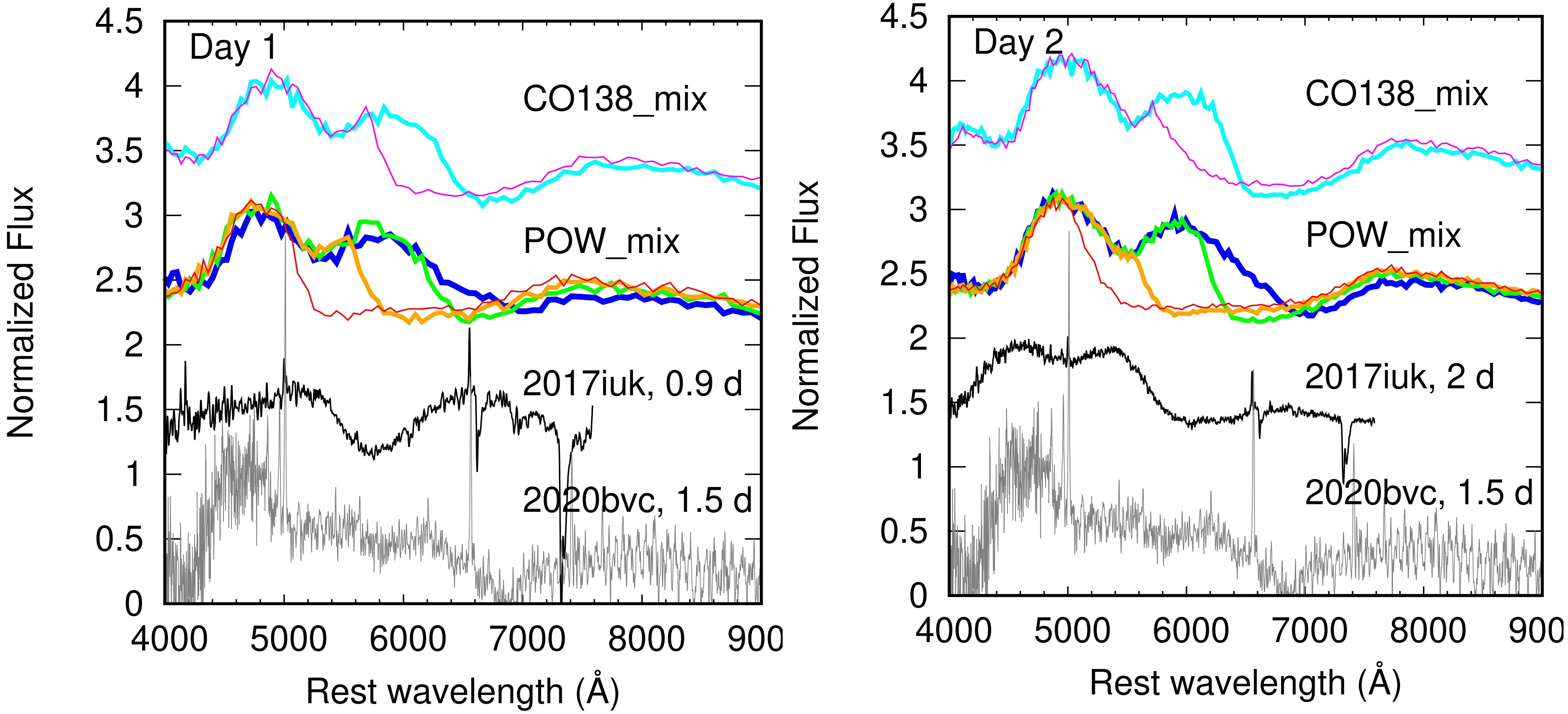
Models with different profile (CO138 or pow) and maximum velocities



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

Summary

Summary: llGRBs in multi-messenger era

- jet deceleration in massive CSM = energy dissipation
- jet energy goes into kinetic and thermal energies of expanding ejecta
- a small fraction of the thermal energy channeled into CRs and ν
- thermal radiation as a probe of the dissipated energy

ULTRASAT, UVEX
+Chronos with UV?

Einstein probe, SVOM
+hiZ-GUNDAM?

EM obs.

4. 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

$\epsilon_{\rm sb}E_{\rm internal} \simeq E_{\gamma,X}$

3. Shock breakout

1. Jet formation

GW, ν obs.

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

5. particle acceleration

IceCUBE (gen2?)
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

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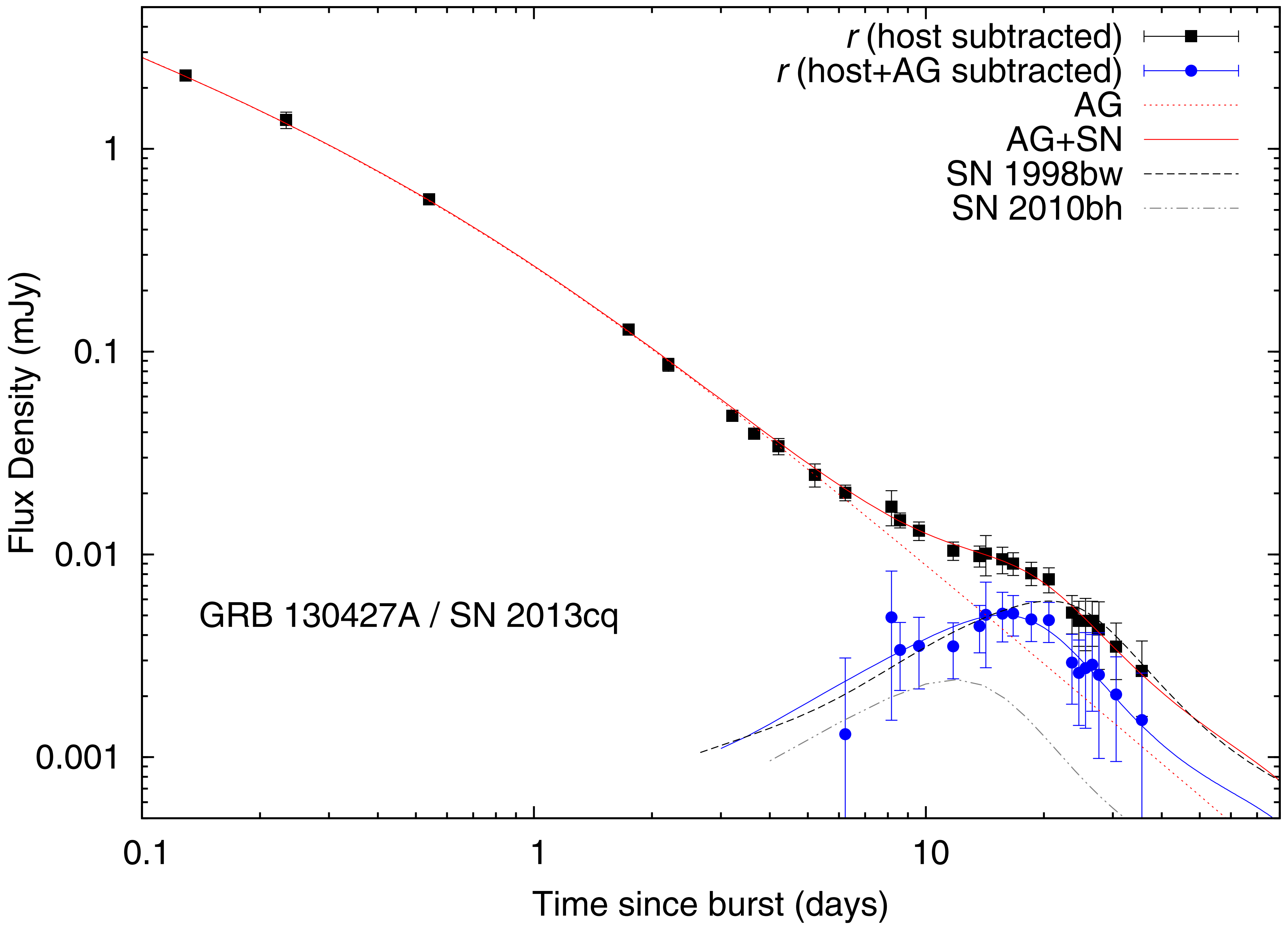
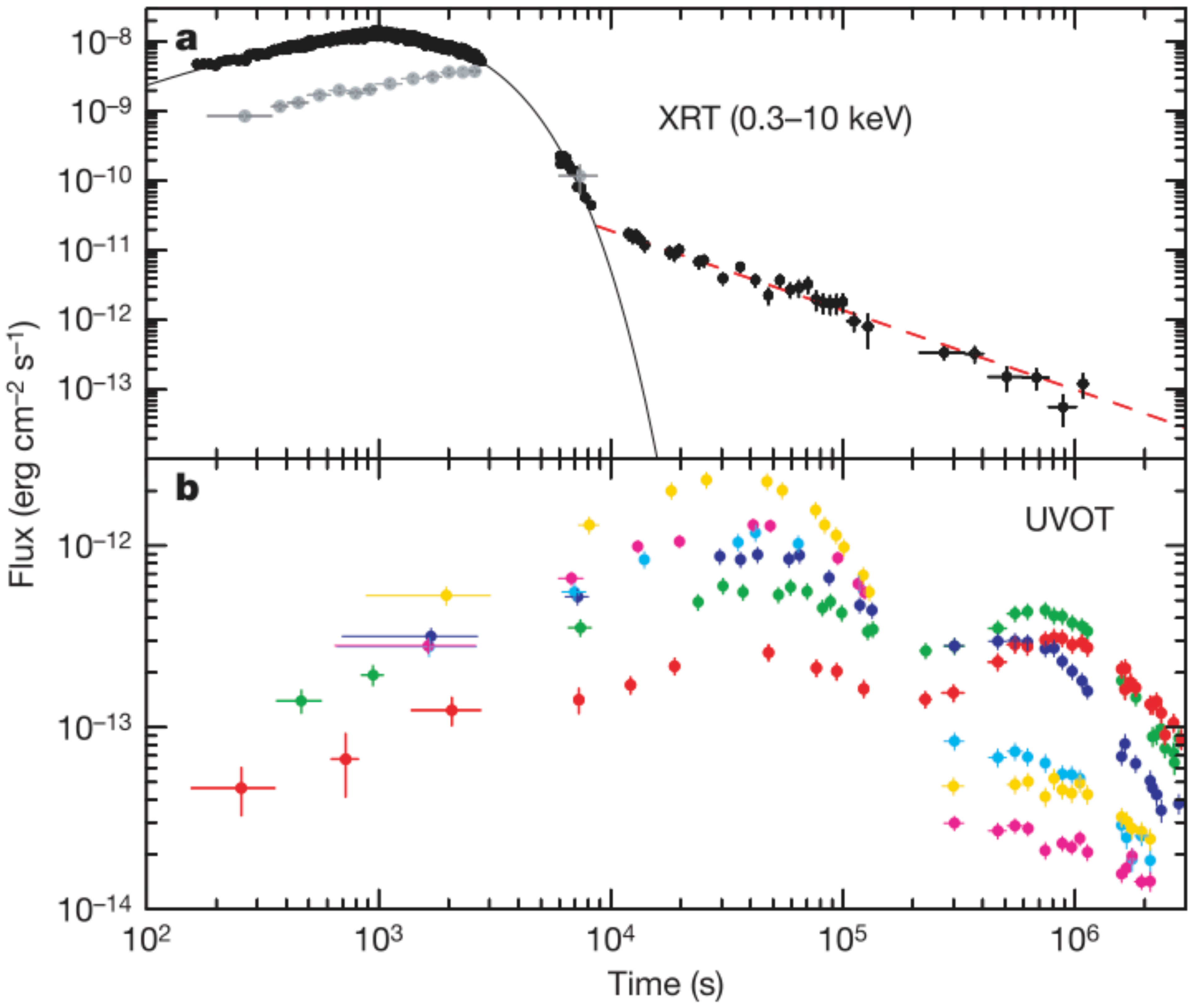
Backup slides

low-luminosity GRB as off-axis GRB?

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



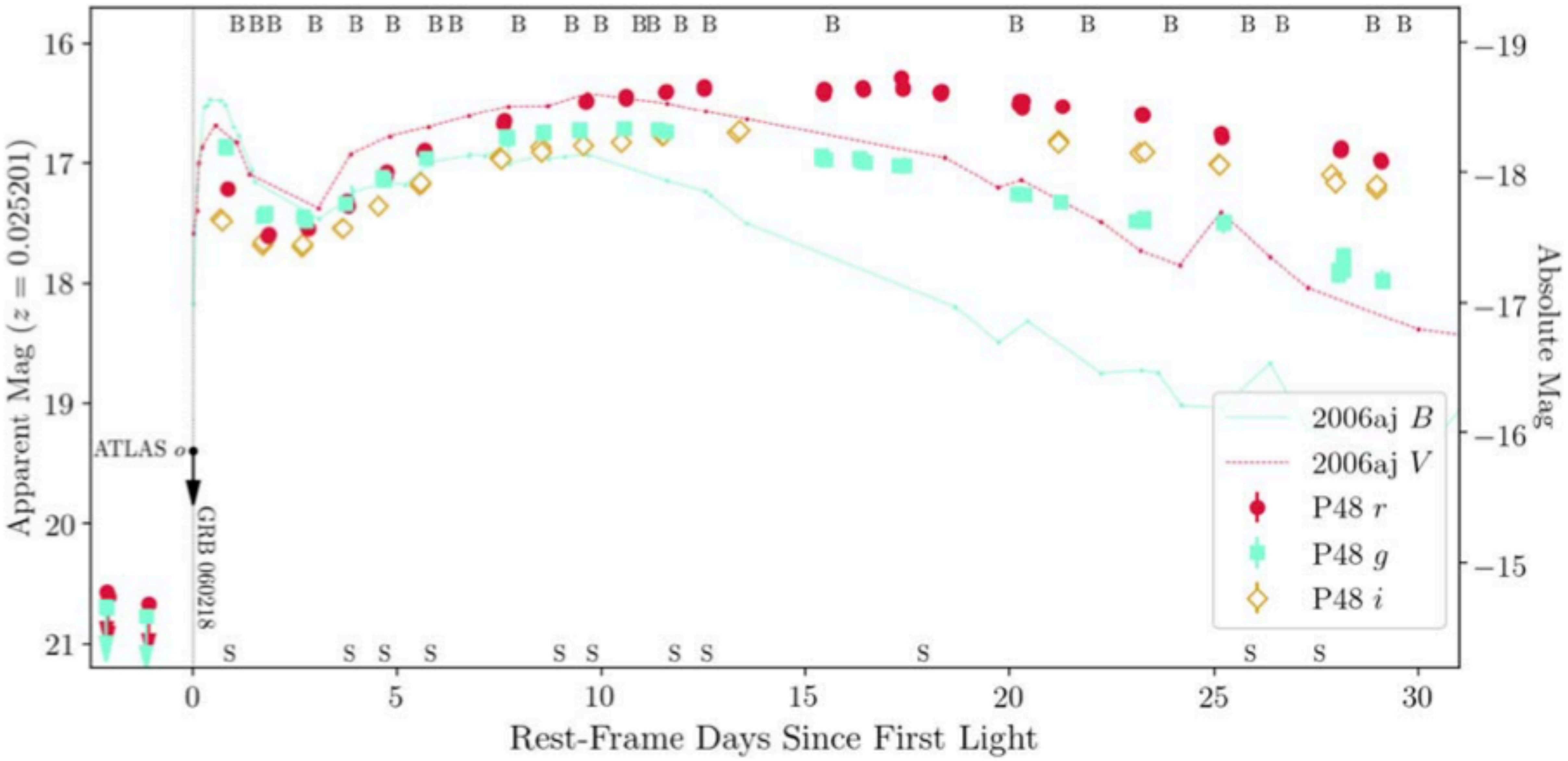
r-band light curve of GRB 130427A/SN 2013cq, Xu+(2013)



Campana+(2006)

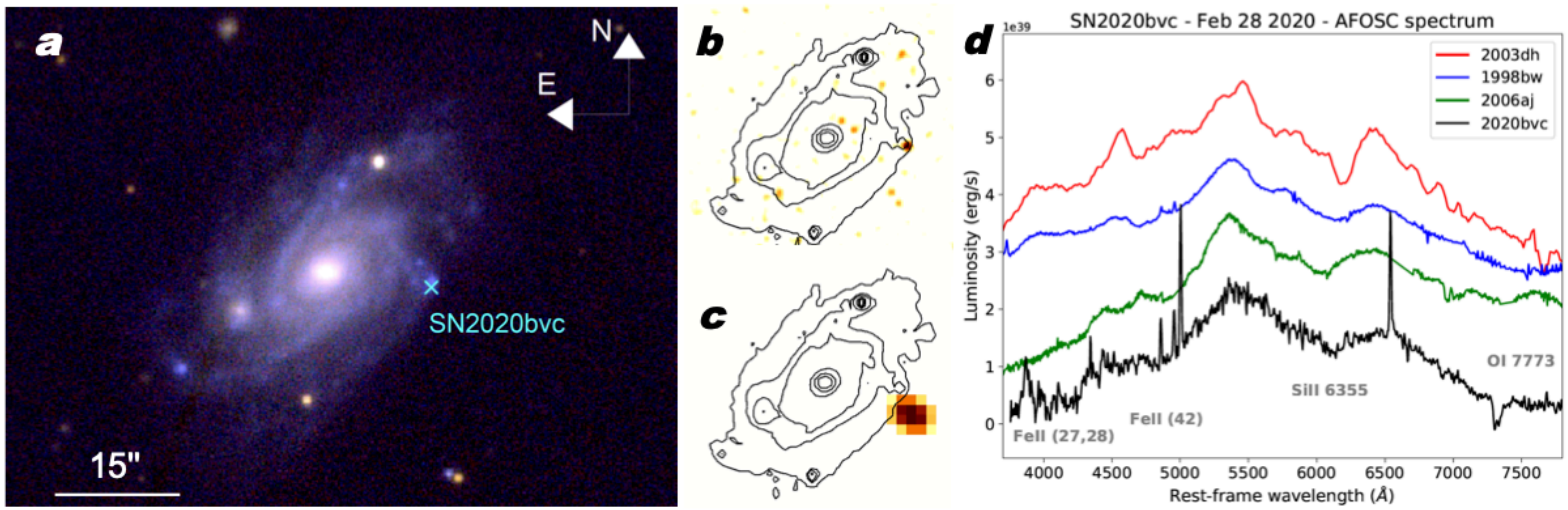
SN 2020bvc: an optically-selected off-axis GRB-SN?

- 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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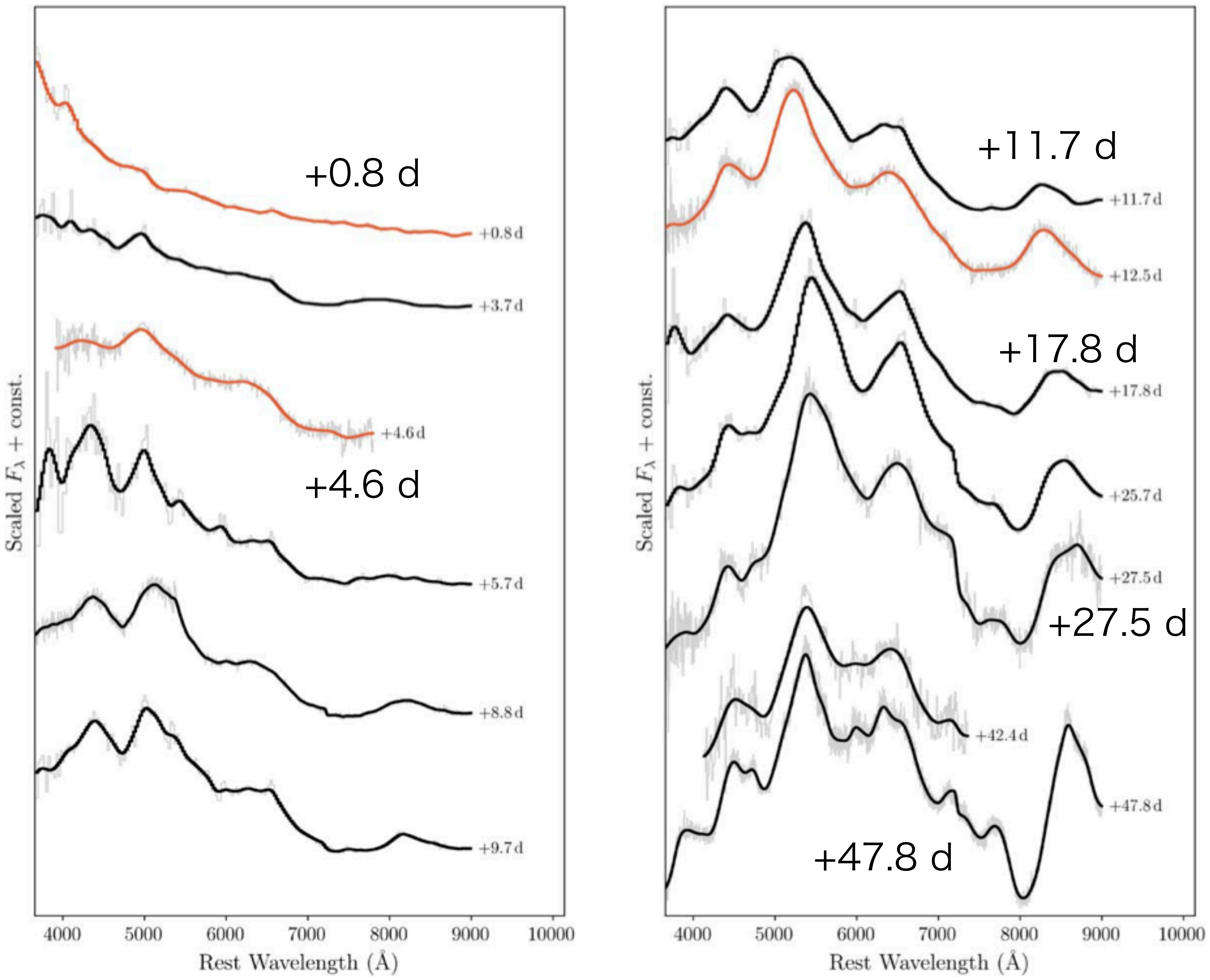

+0.8 d

+4.6 d

+11.7 d

+17.8 d

+27.5 d

+47.8 d

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

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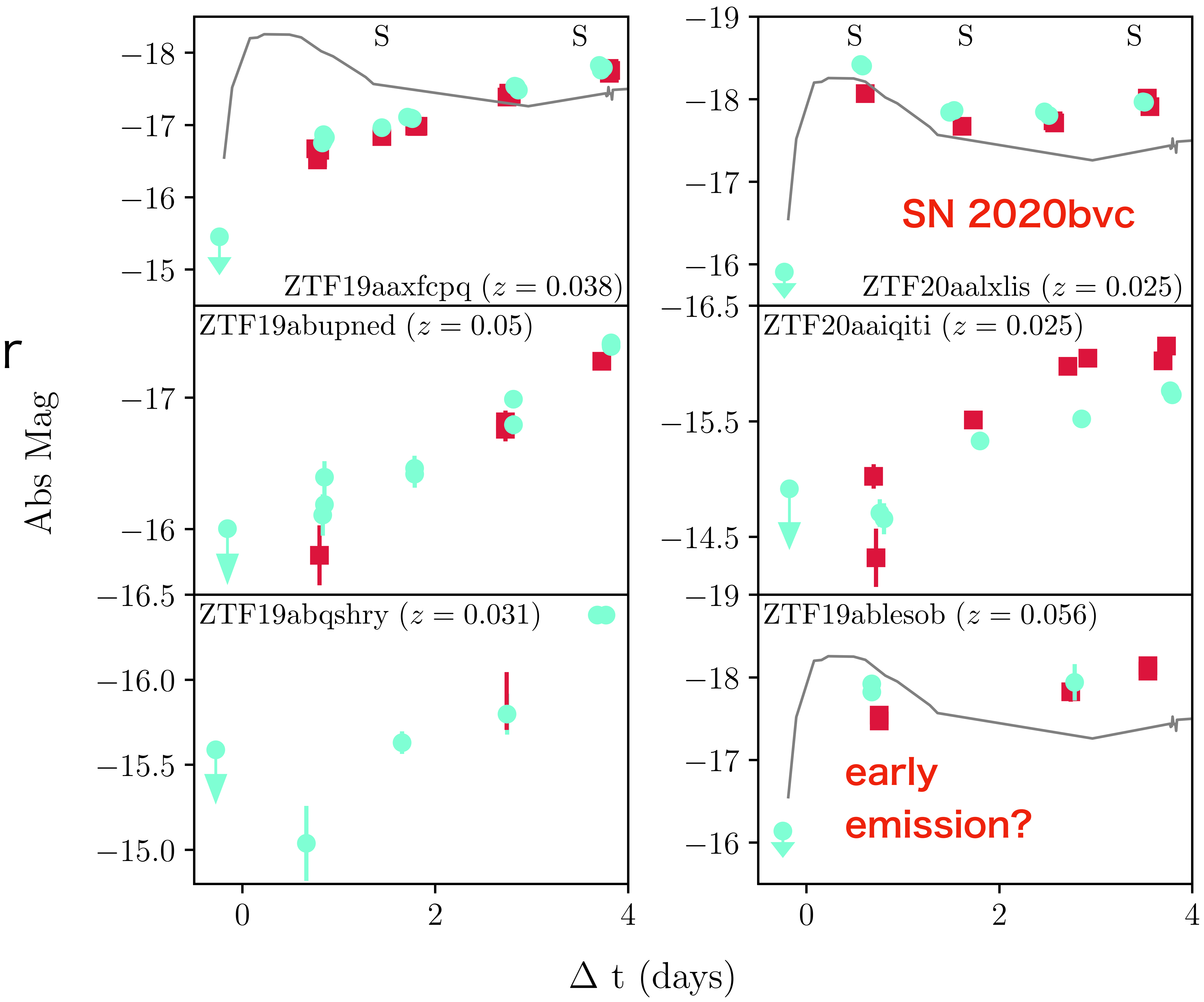
- 1 or 2 out of 6 SNe Ic-BL(z<0.06) are accompanied by early bright emission: 20-30% of SNe Ic-BL show jet signature?

Ho+ (2020)



low-luminosity 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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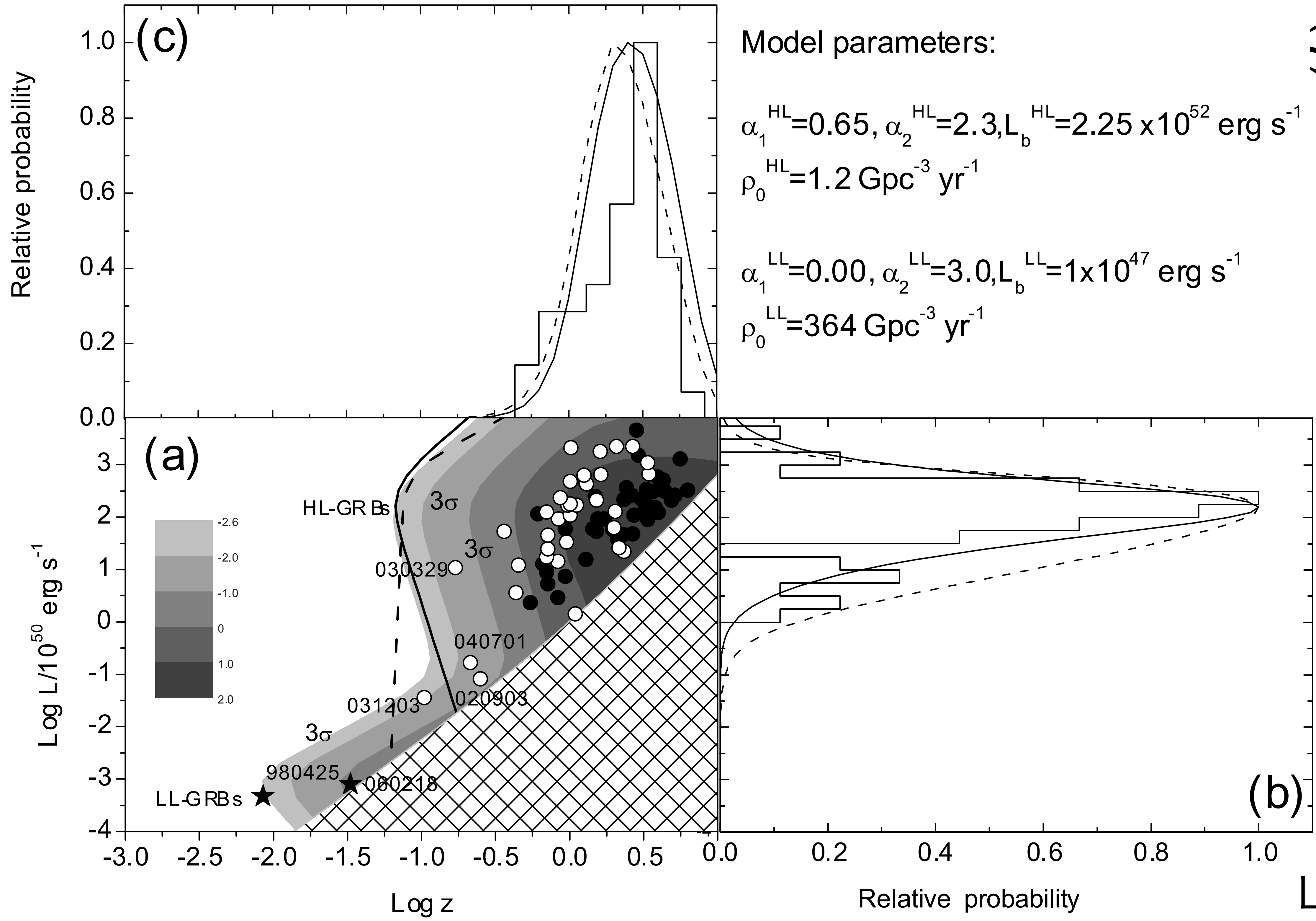
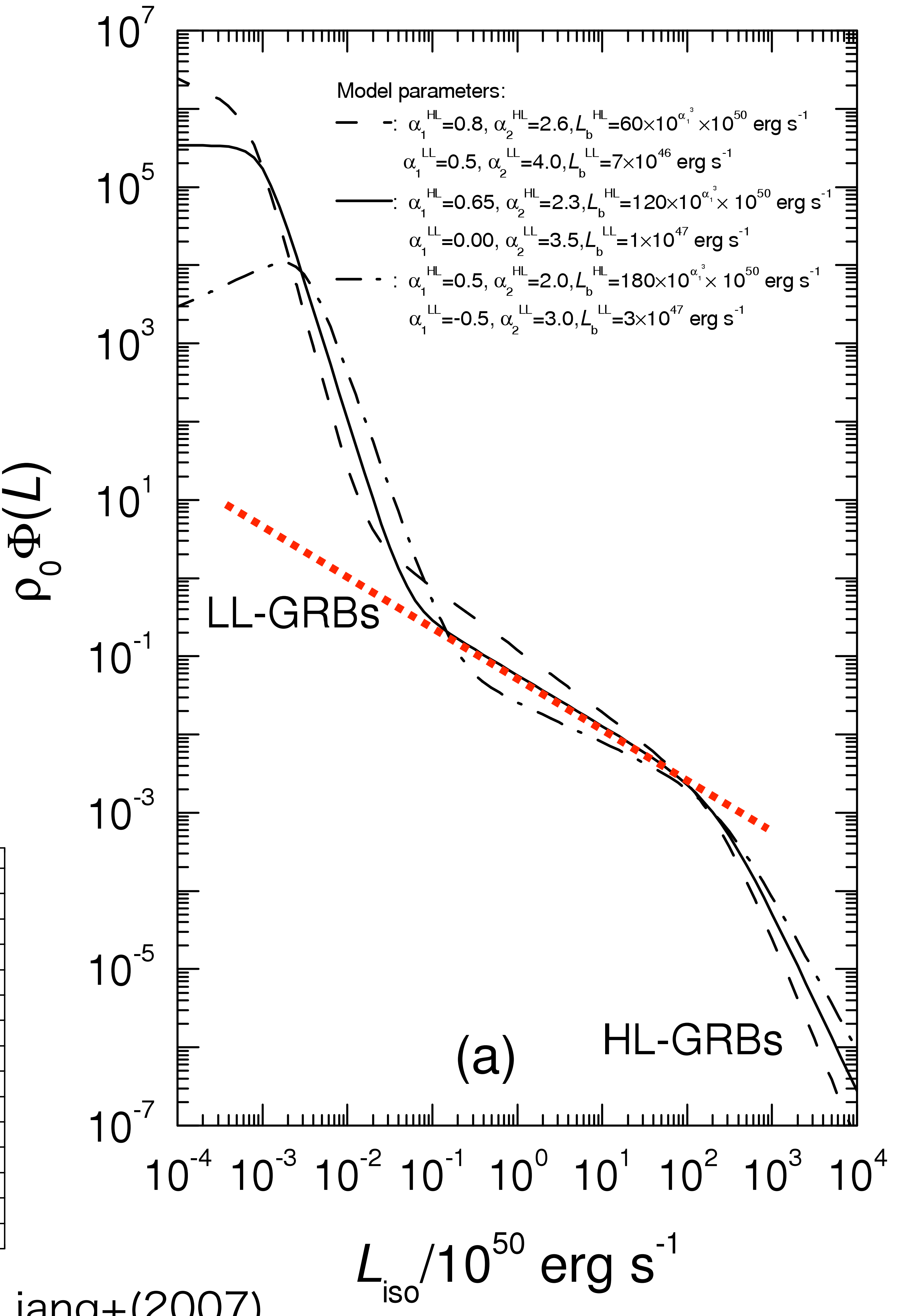


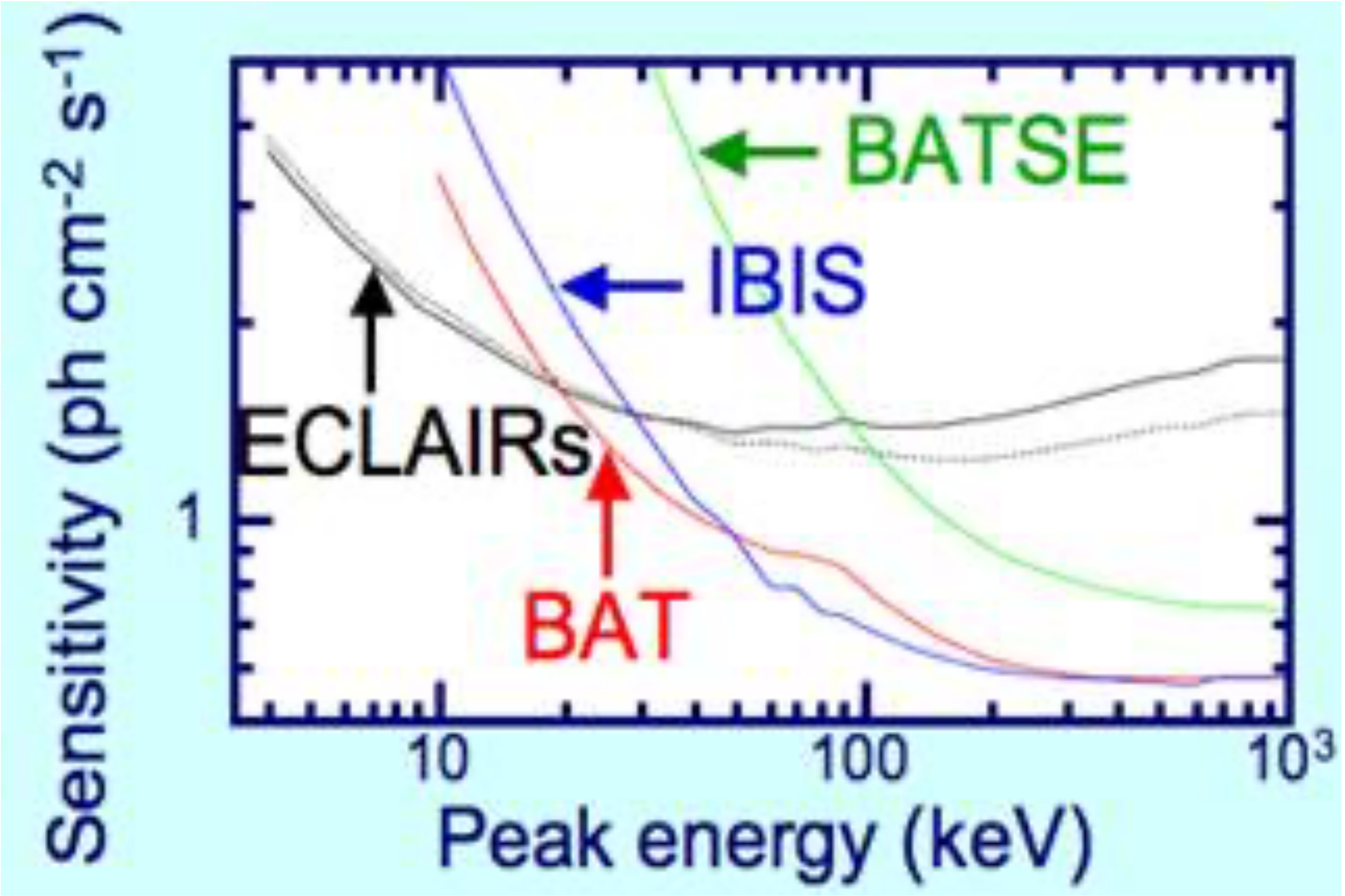


Liang+(2007)

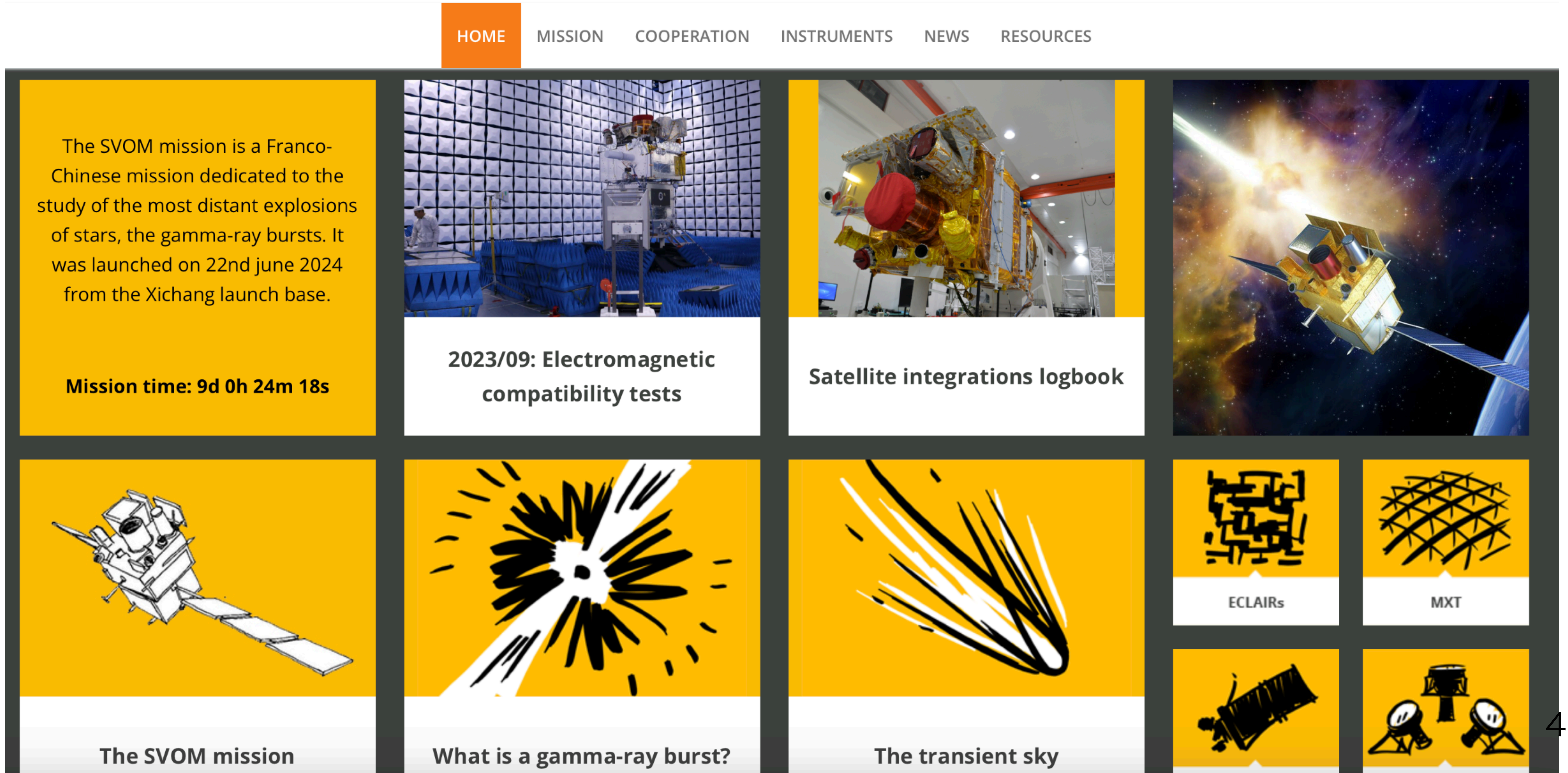
X-ray transient missions: Now and Future

- **Swift BAT(2004-)** :can miss soft X-ray-dominated transients like llGRBs
- **Einstein Probe**: launched in 2024/1 and now in the commissioning phase
- **SVOM** (Space-based multi-band astronomical Variable Objects Monitor) mission: launched in 2024/6

https://www.svom.eu/



https://irfu.cea.fr/Projets/SVOM/payload_complete.html



The SVOM mission is a Franco-Chinese mission dedicated to the study of the most distant explosions of stars, the gamma-ray bursts. It was launched on 22nd june 2024 from the Xichang launch base.

Mission time: 9d 0h 24m 18s

2023/09: Electromagnetic compatibility tests

Satellite integrations logbook

The SVOM mission

What is a gamma-ray burst?

The transient sky

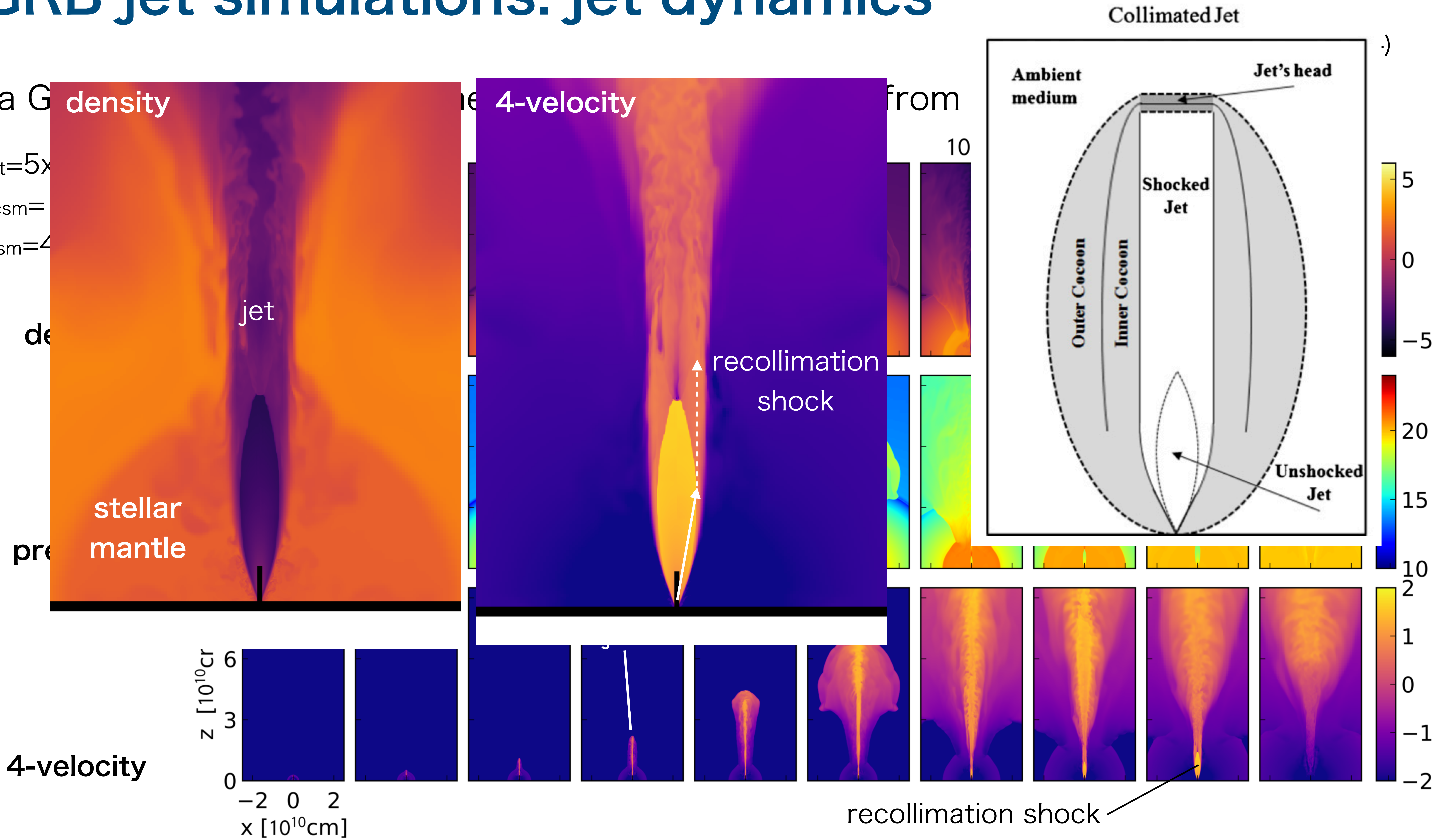
GRB jet simulations: jet dynamics

- a G ne from

Ejet=5x

Mcsm=

Rcsm=4



Bromberg+(2011)

GRB jet simulations: jet dynamics

AS, Irwin, &Maeda (2024)

- a GRB jet-CSM c sli 30 to t=200 s

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

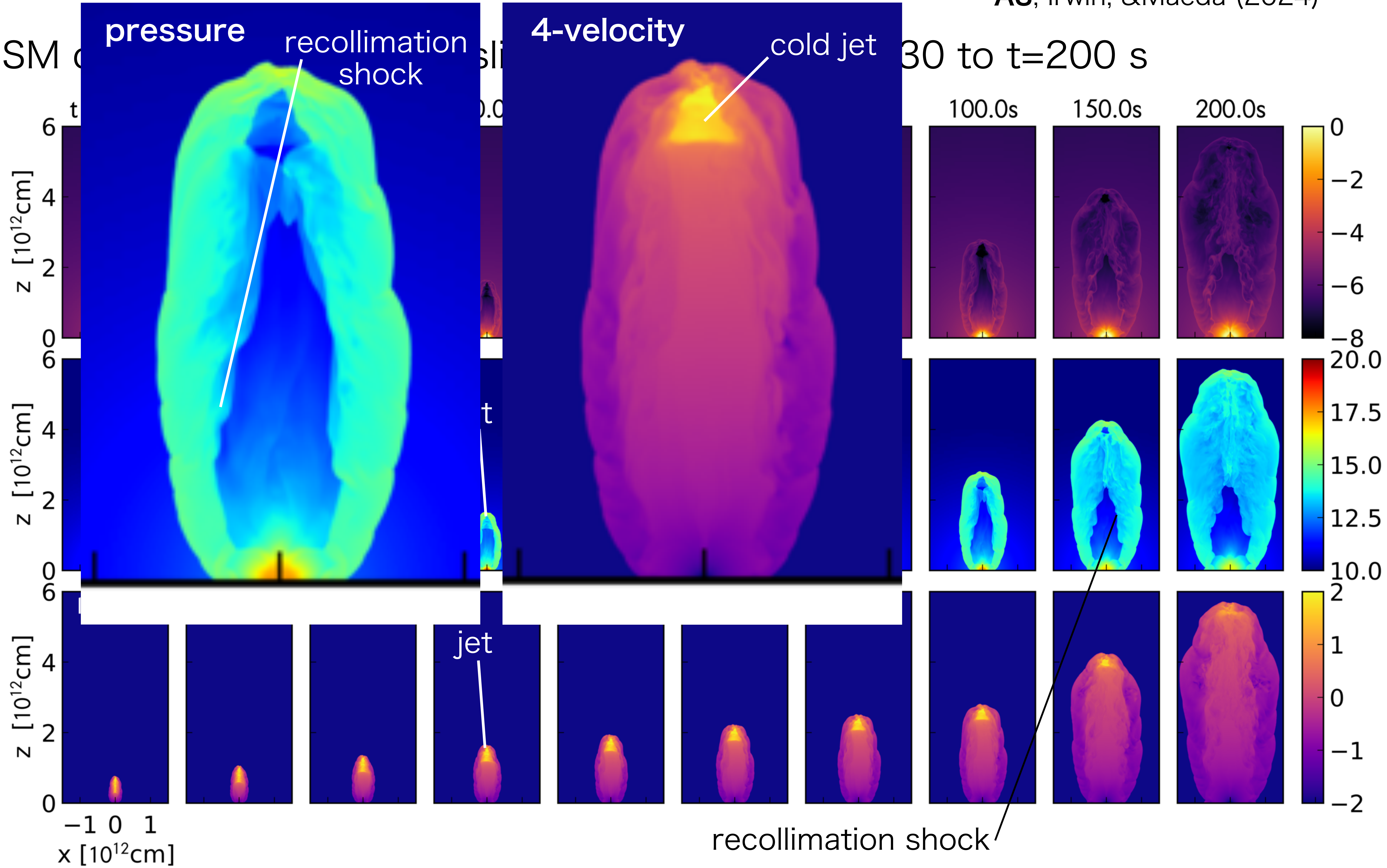
$M_{csm}=1M_{sun}$

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

density

pressure

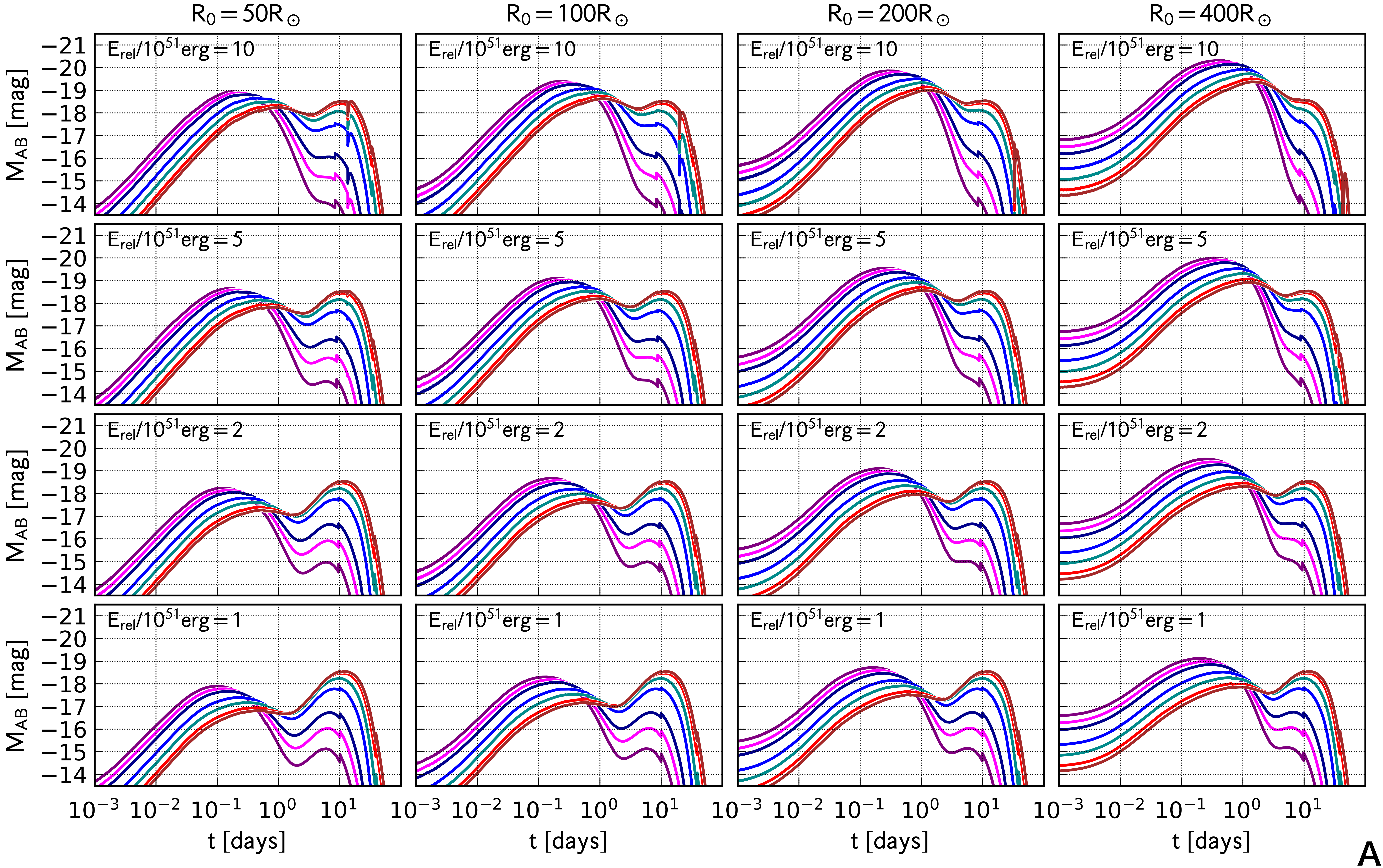
4-velocity



Thermal emission powered by jet dissipation

- dependence on energy and initial radius (E_{rel} or M_{rel}, R_0)

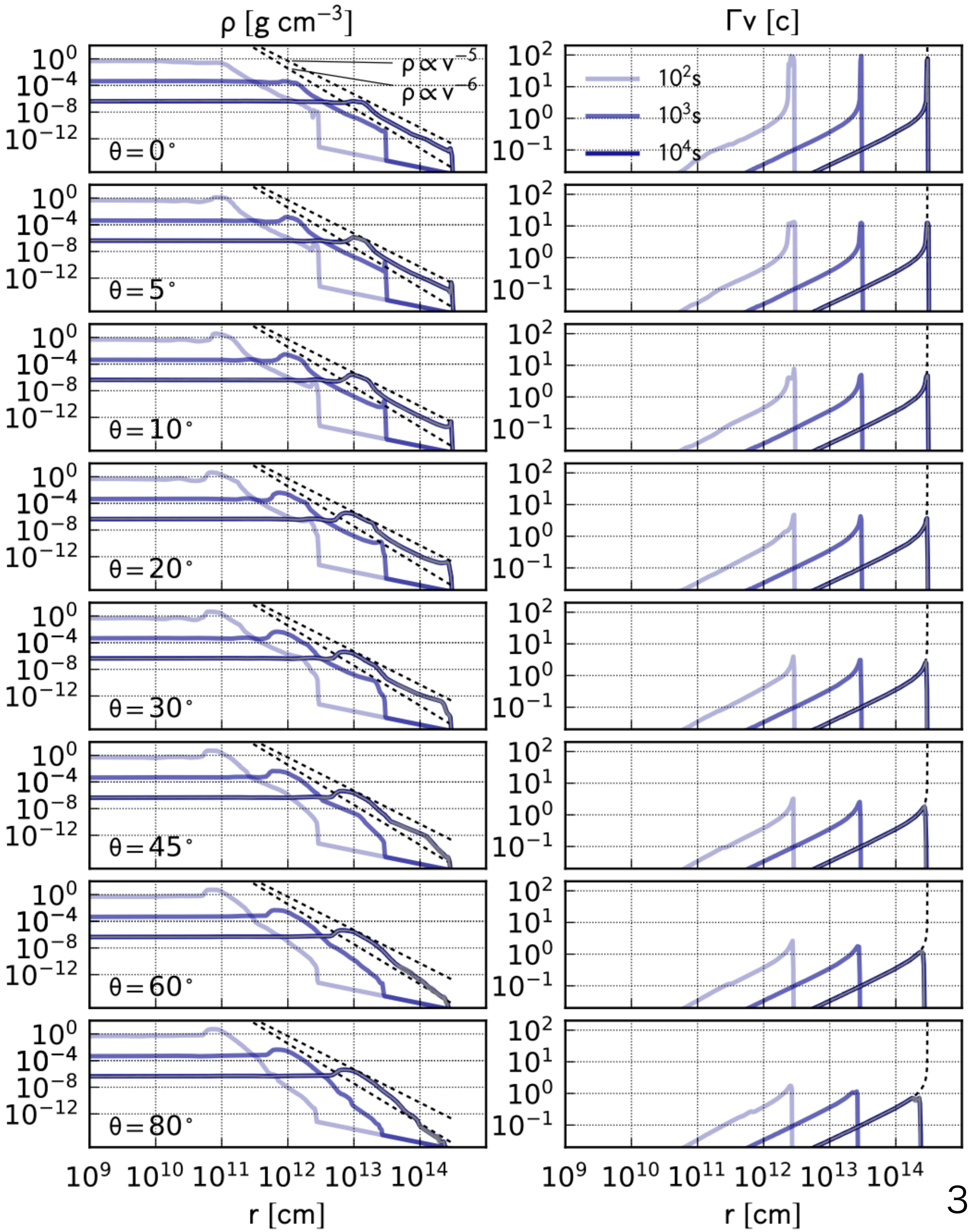
Larger initial radii R_0



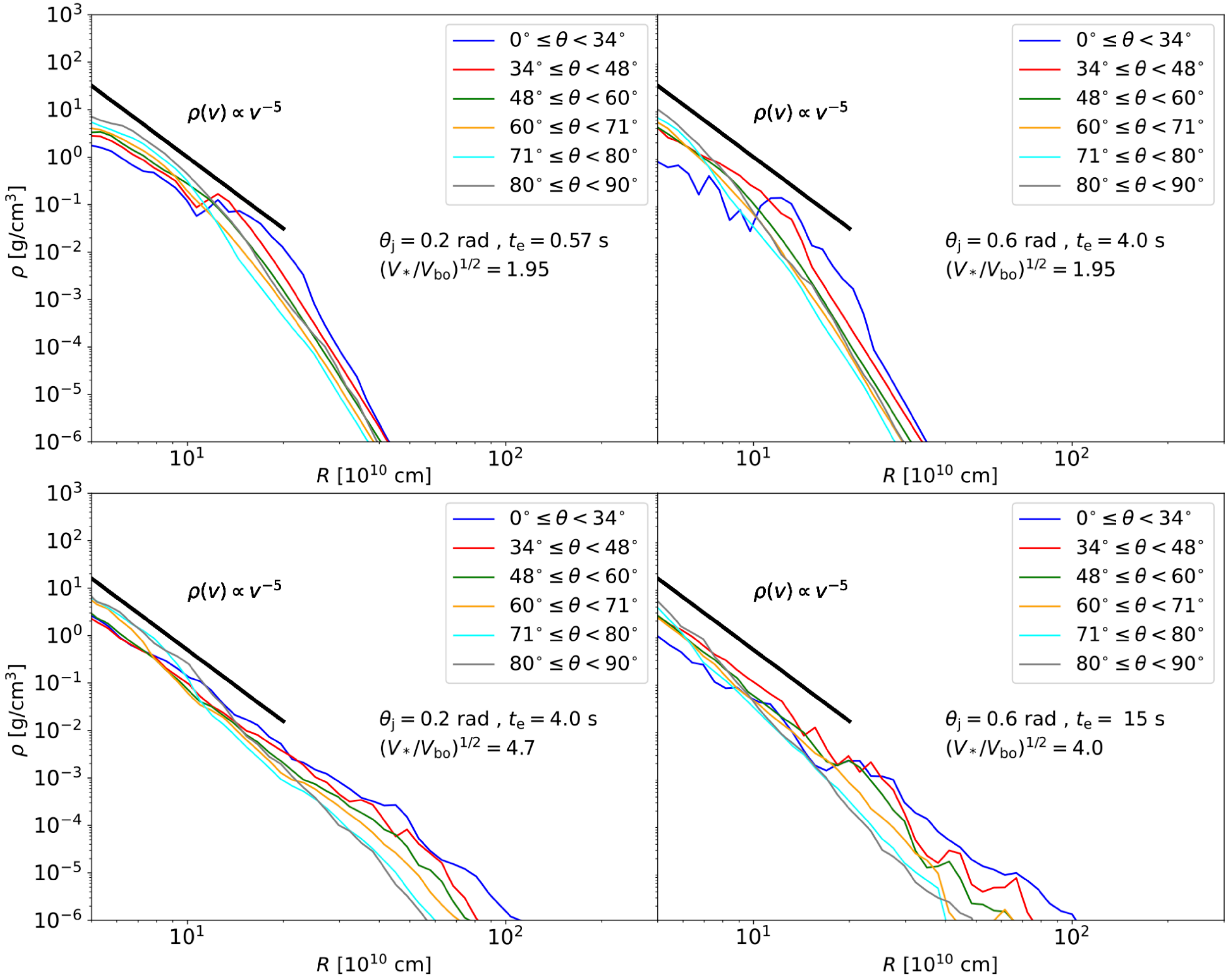
Larger E_{rel} or M_{rel}

AS+ in prep

Universal density profile v^{-5} or r^{-5}?

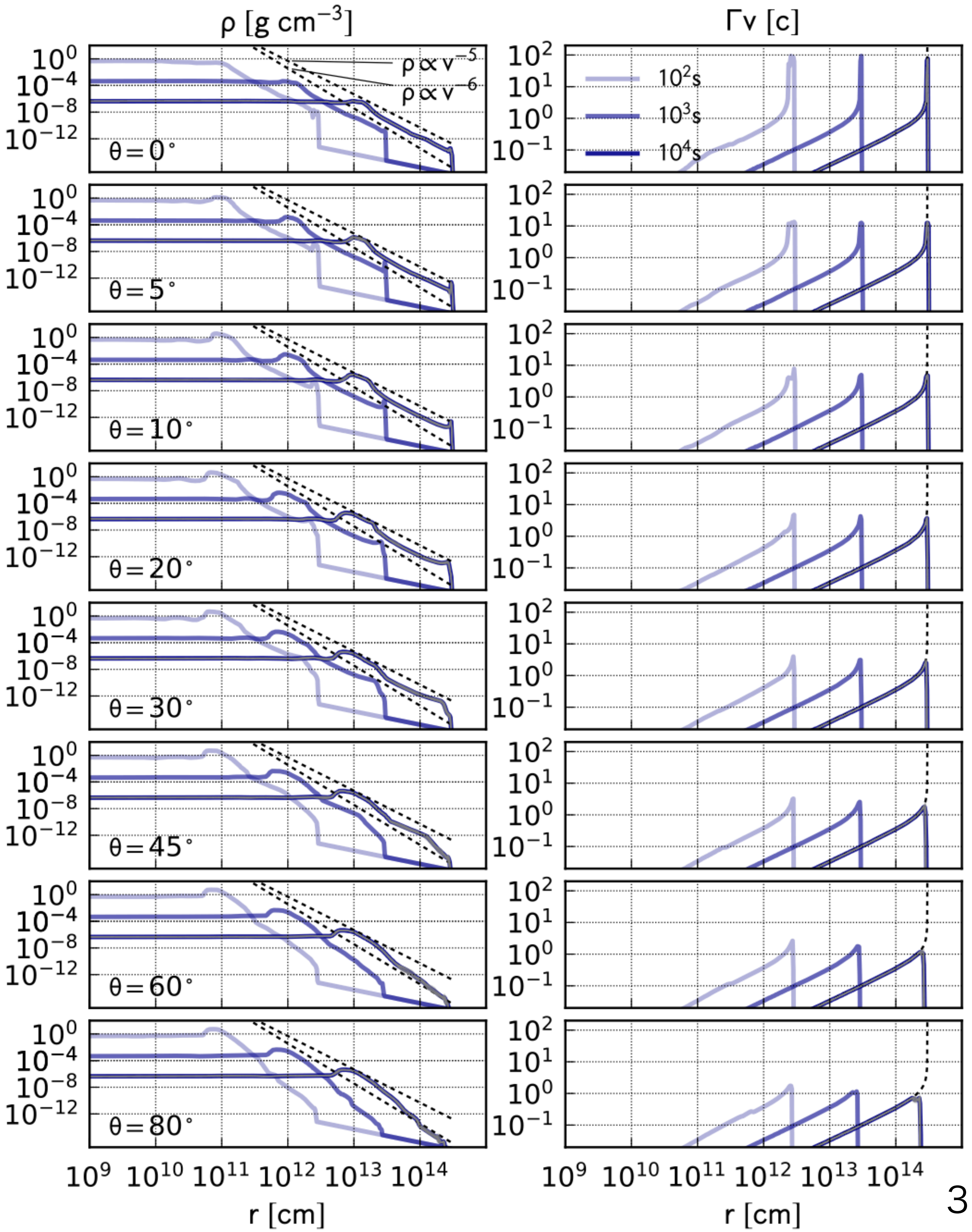


3D simulation: **AS** & Maeda (2022)



2D simulation: Pais+(2023)

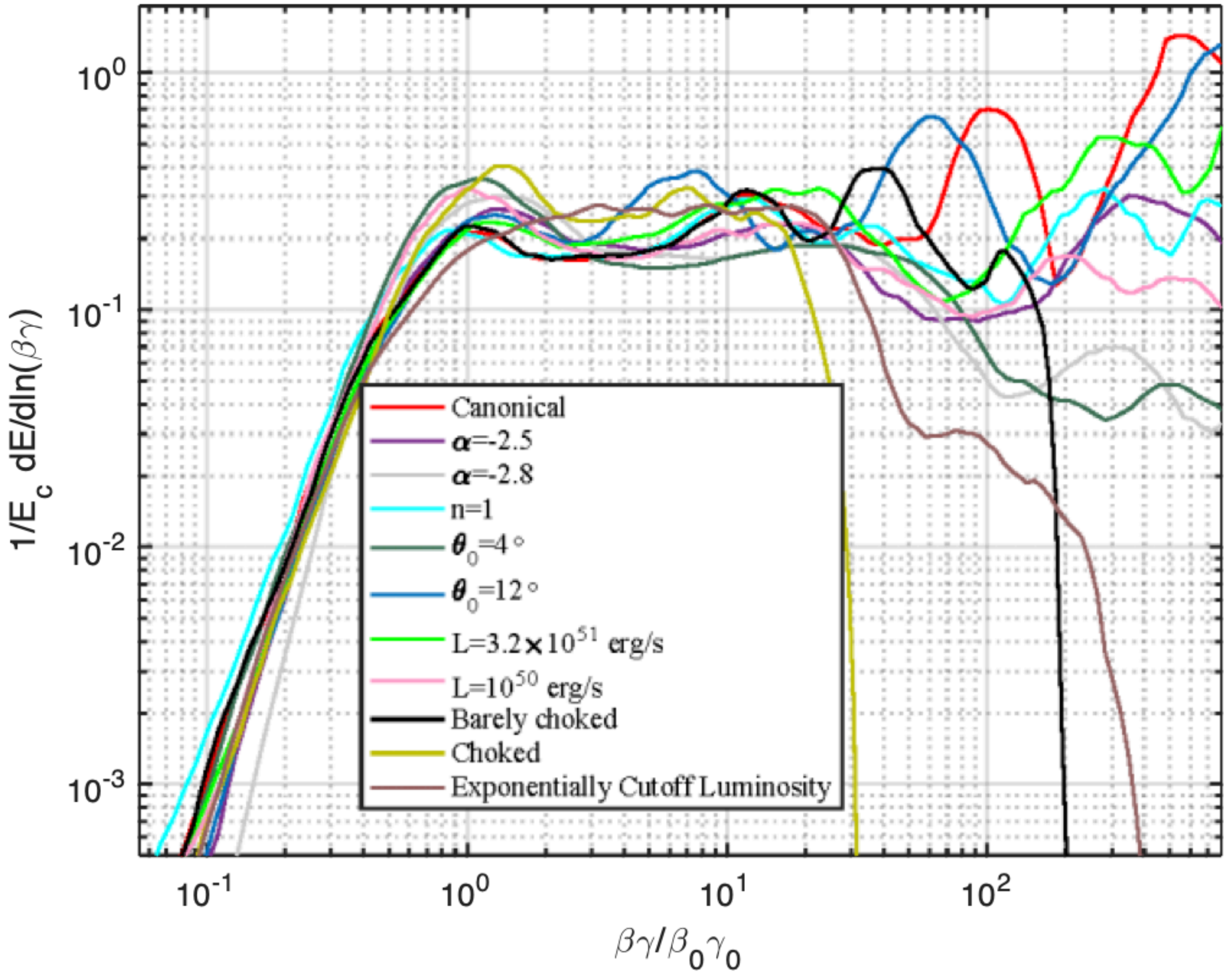
Universal density profile v⁻⁵ or r⁻⁵?



3D simulation: **AS** & Maeda (2022)

$$\rho \propto v^{-5}, r = v/t \quad \Leftrightarrow \quad \frac{dE_{kin}}{d\ln v} \propto v^0$$

$$(dE_{kin} \propto \rho v^2 r^2 dr \propto \rho v^5 d\ln v)$$



2D simulation: Eisenberg+(2022)