May. 24-27, 2022, ICRR high-energy astrophysics group workshop

GRB jets in multi-wavelength observations and numerical simulations

多波長観測と数値シミュレーションから迫る GRBジェットの全体像

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

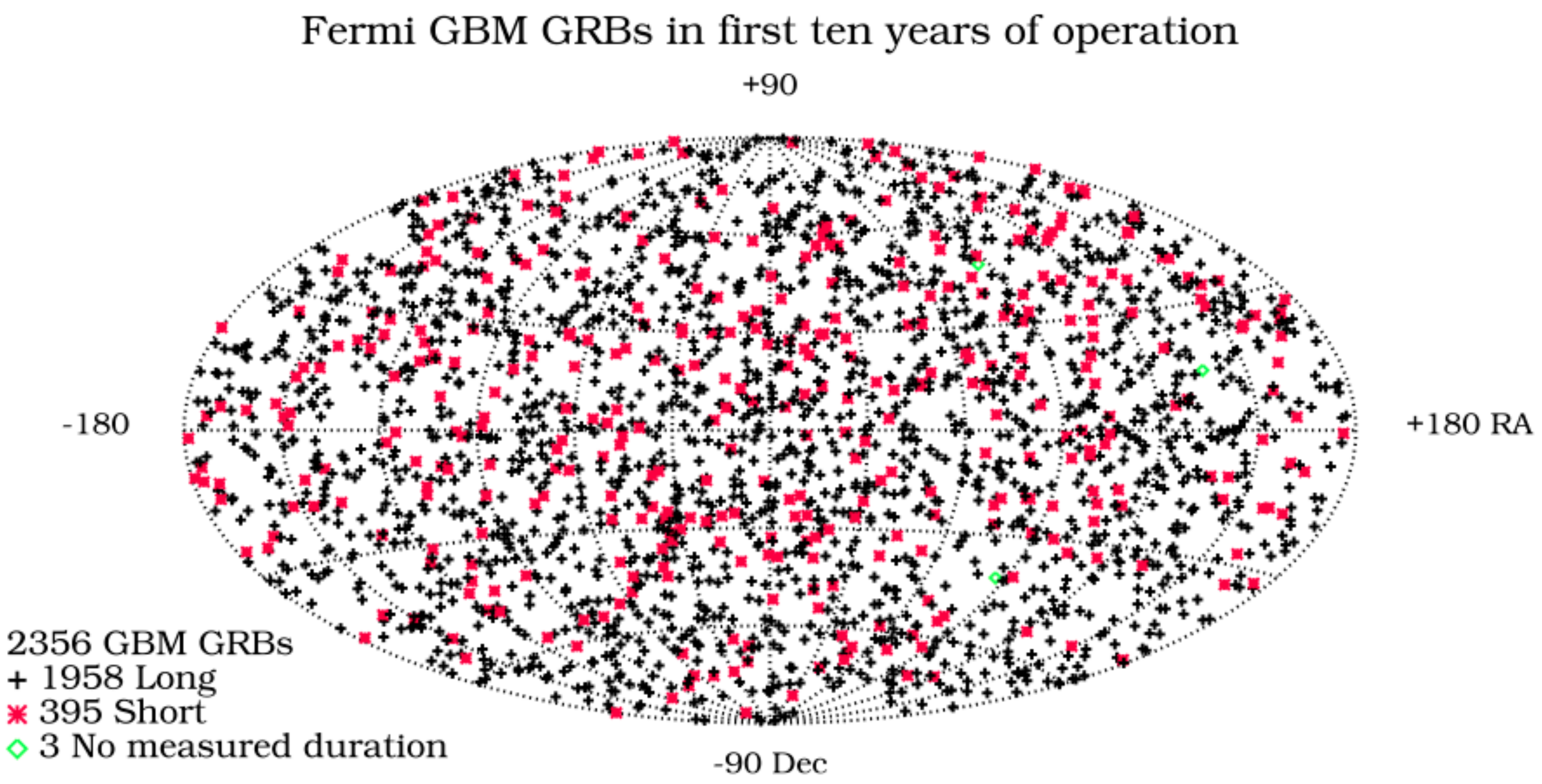
collaborator: Keiichi Maeda (Kyoto U.)

based on Suzuki & Maeda (2022), arXiv: 2111.12914 + α

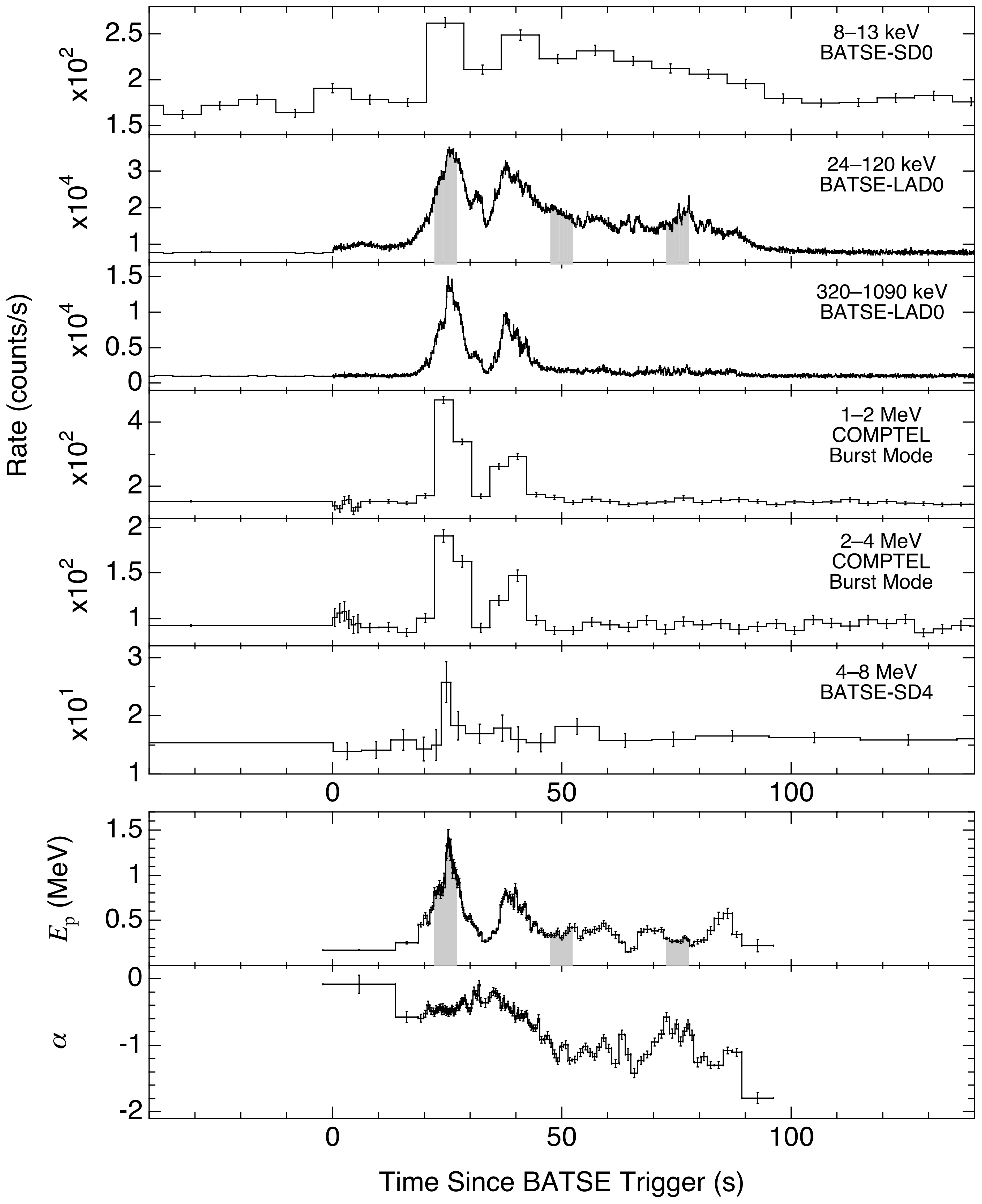
Introduction

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)



GRB gamma-ray light curve, Briggs+ (1999)

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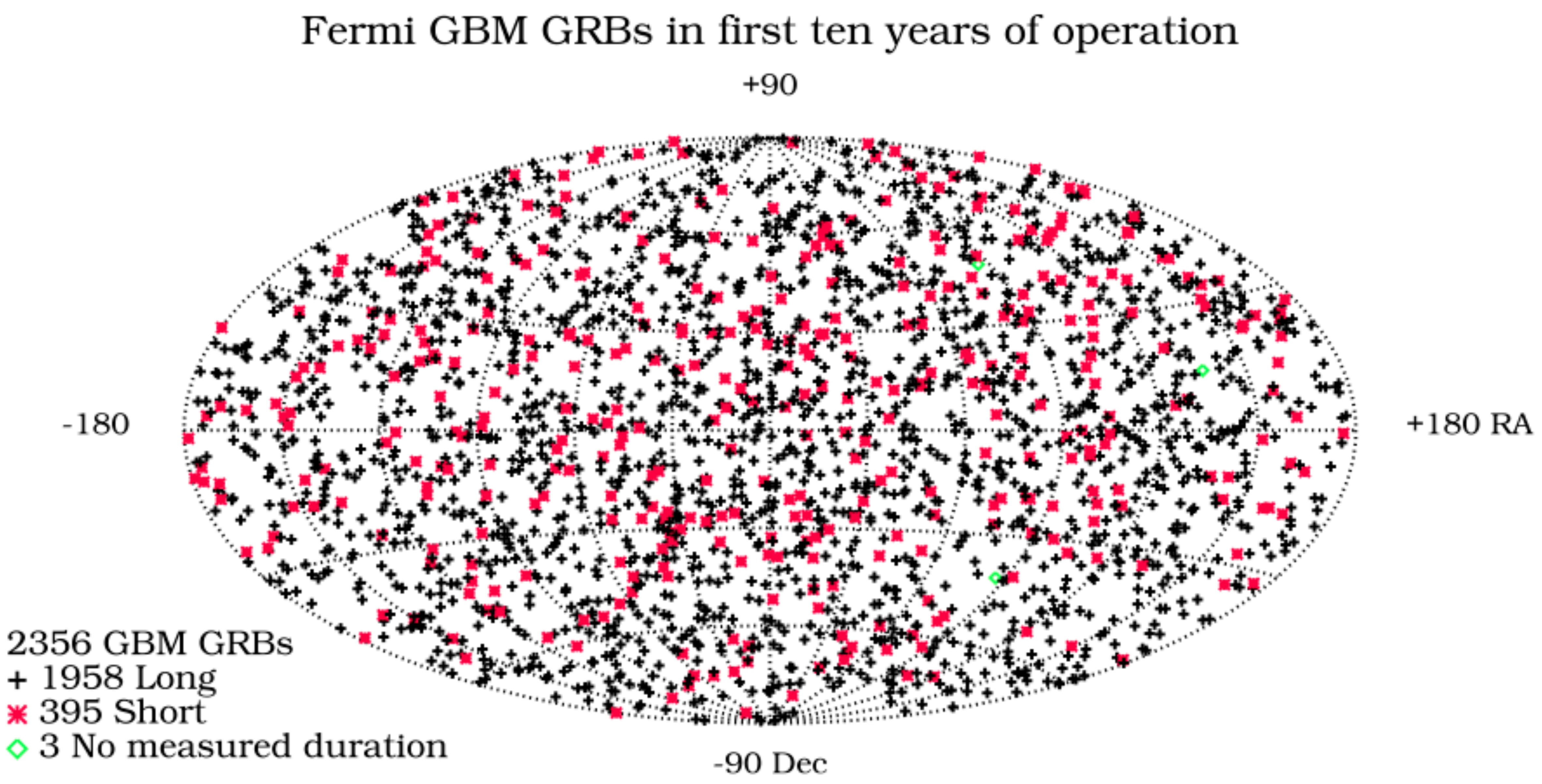

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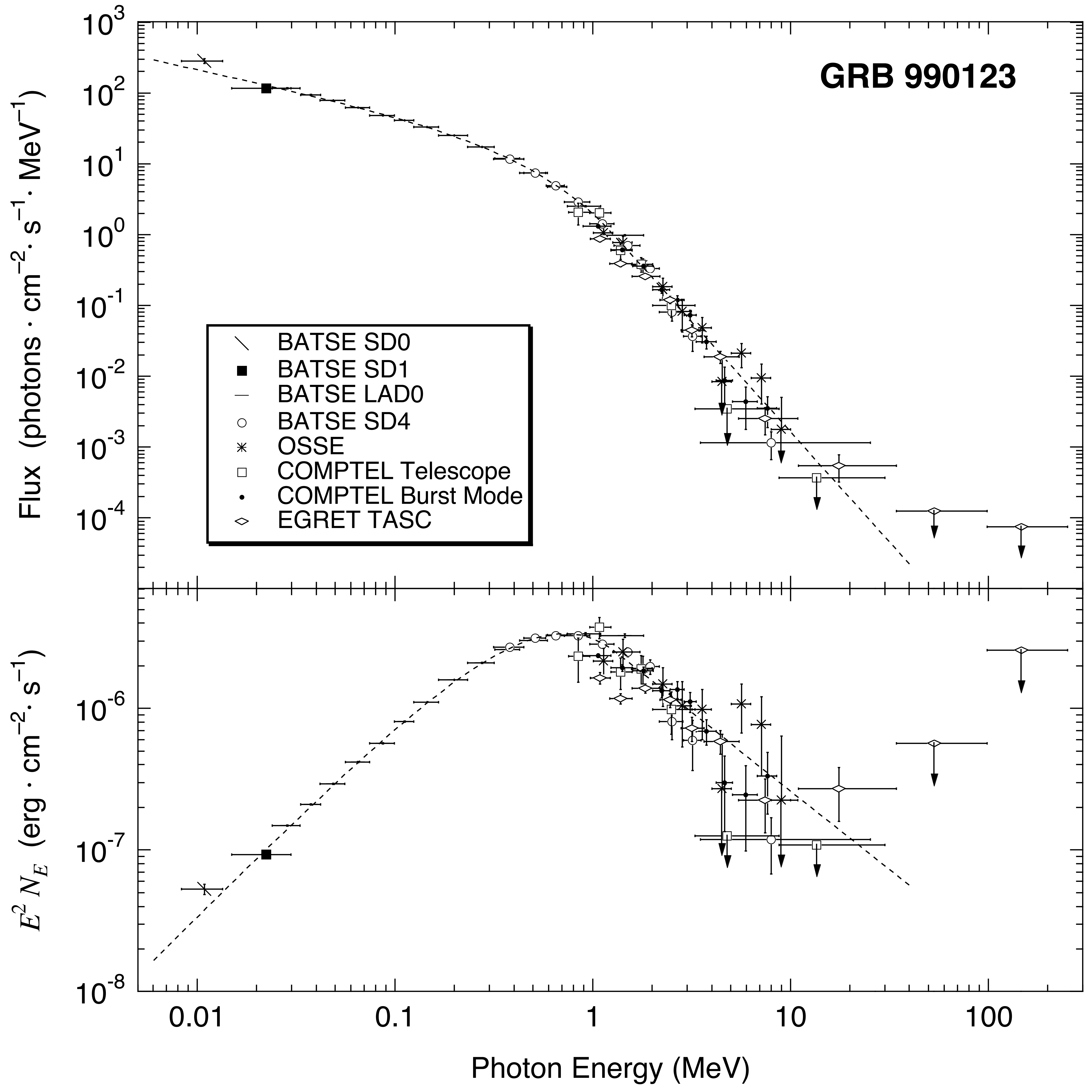

Typical GRB gamma-ray spectrum, Briggs+ (1999)

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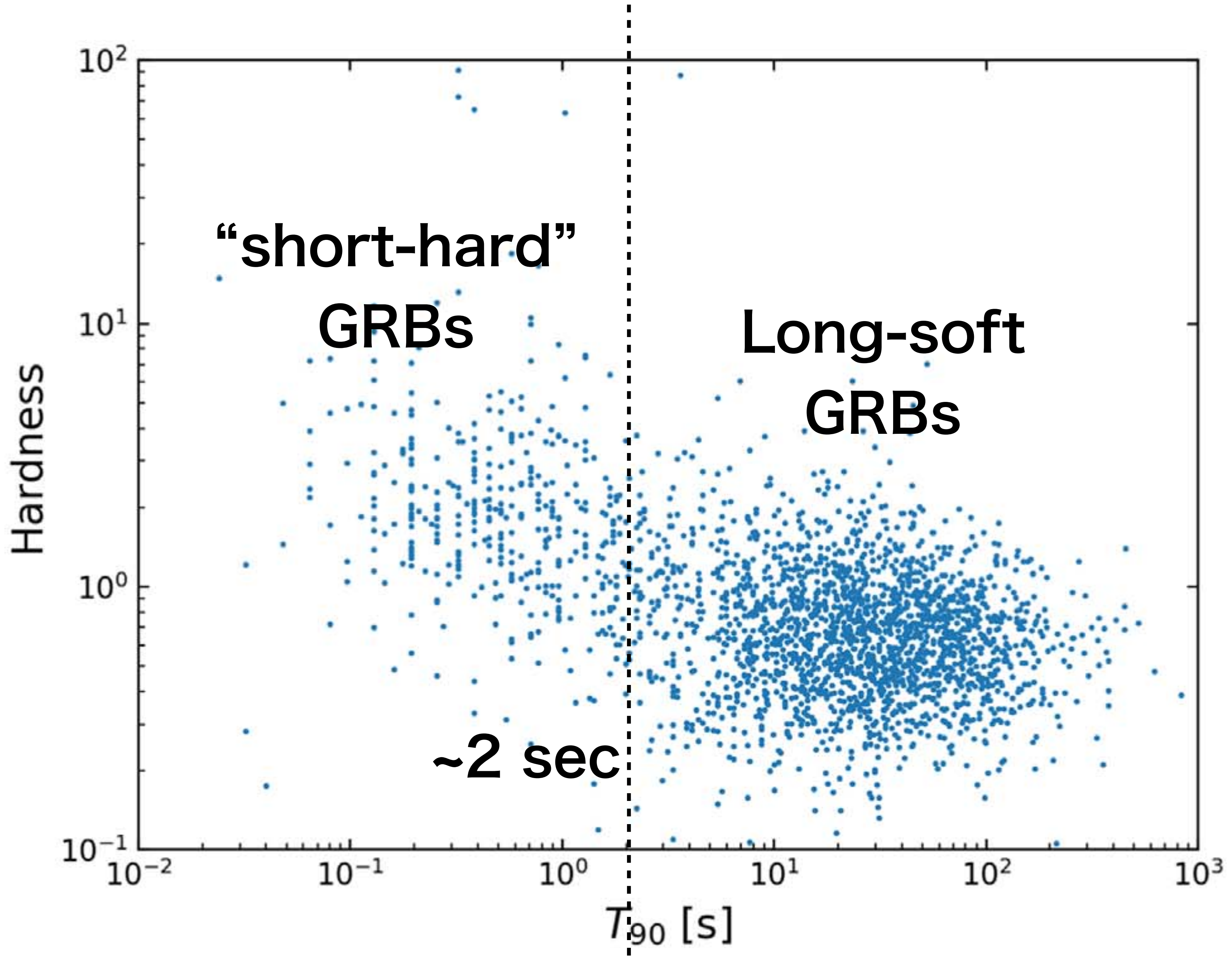

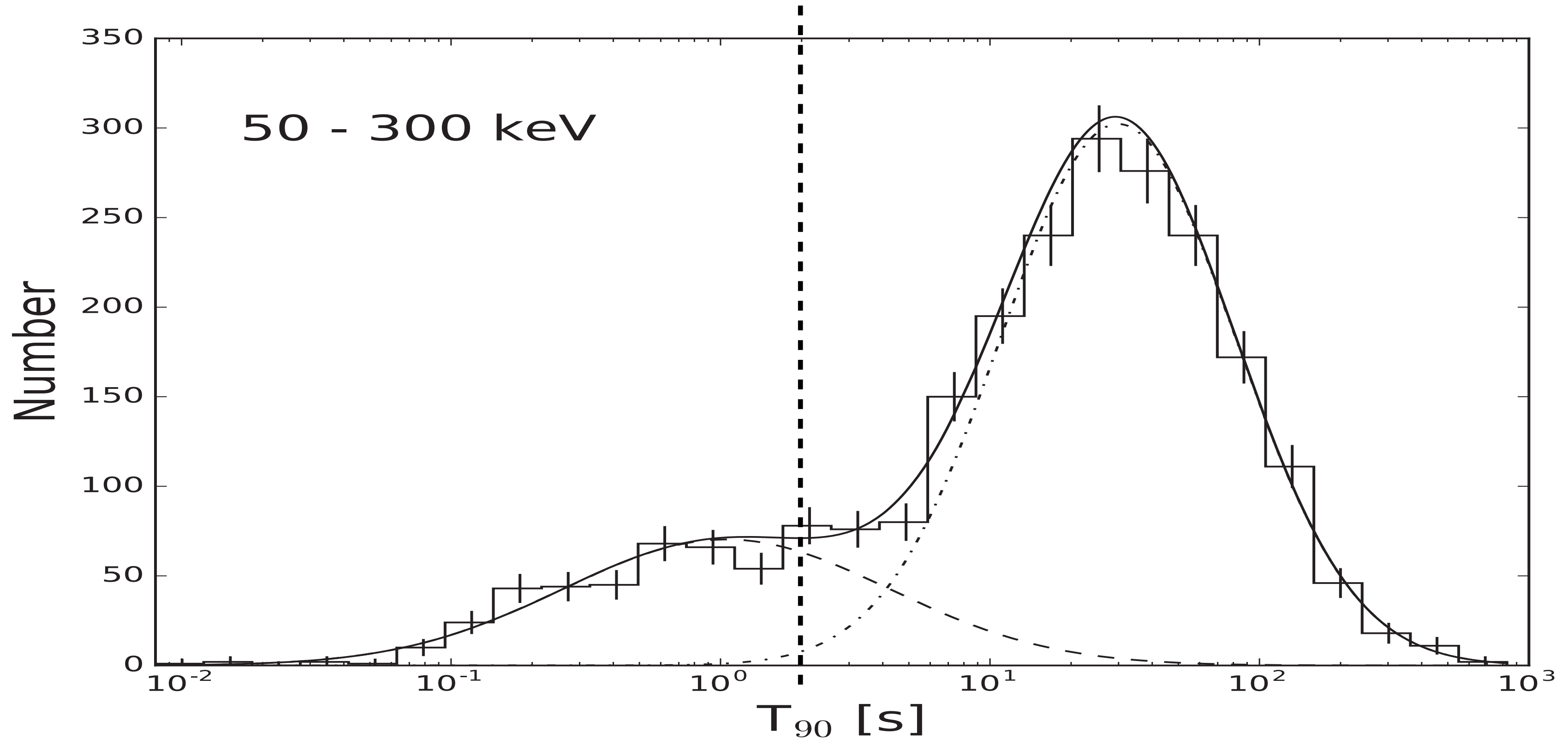

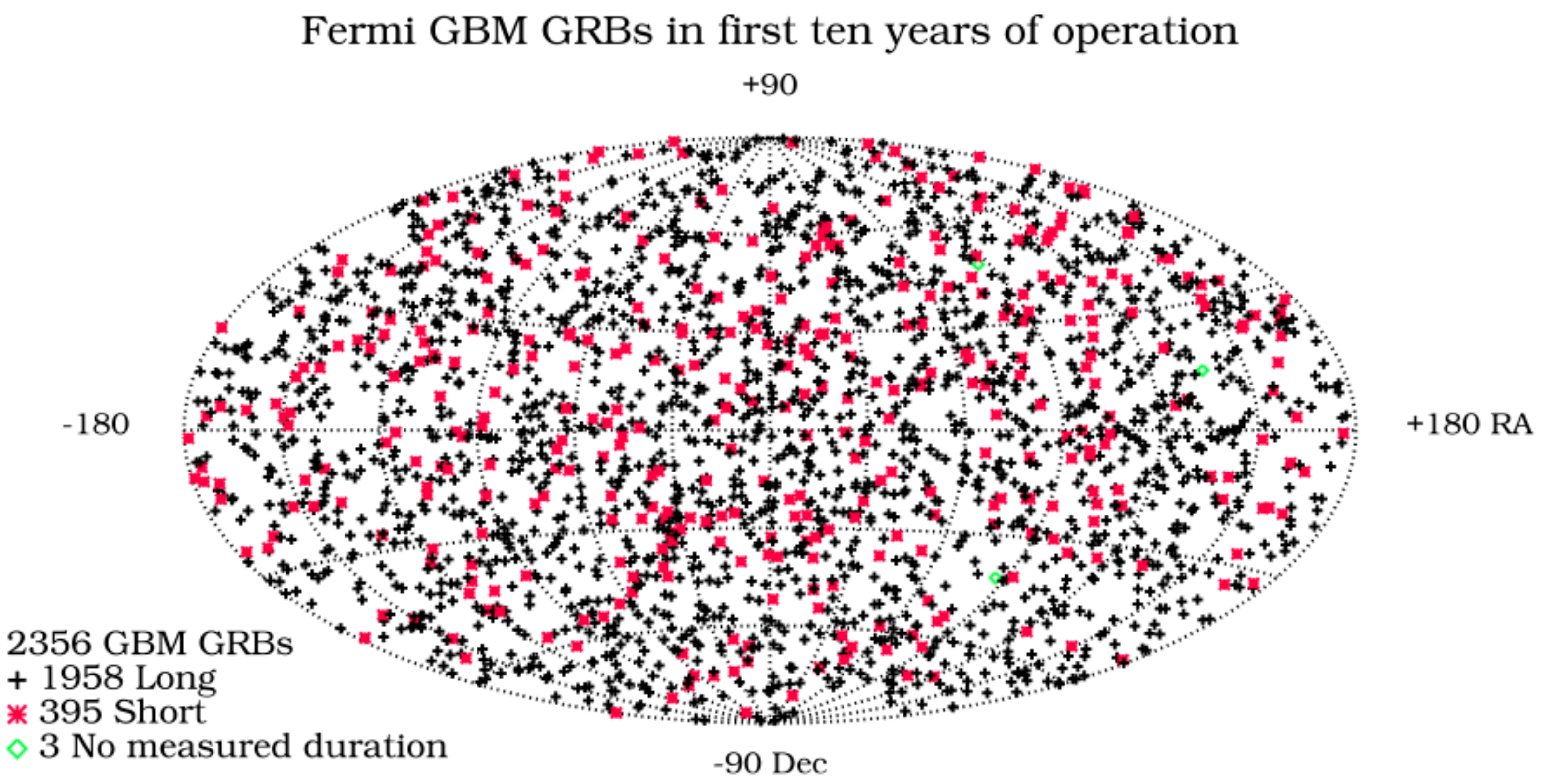

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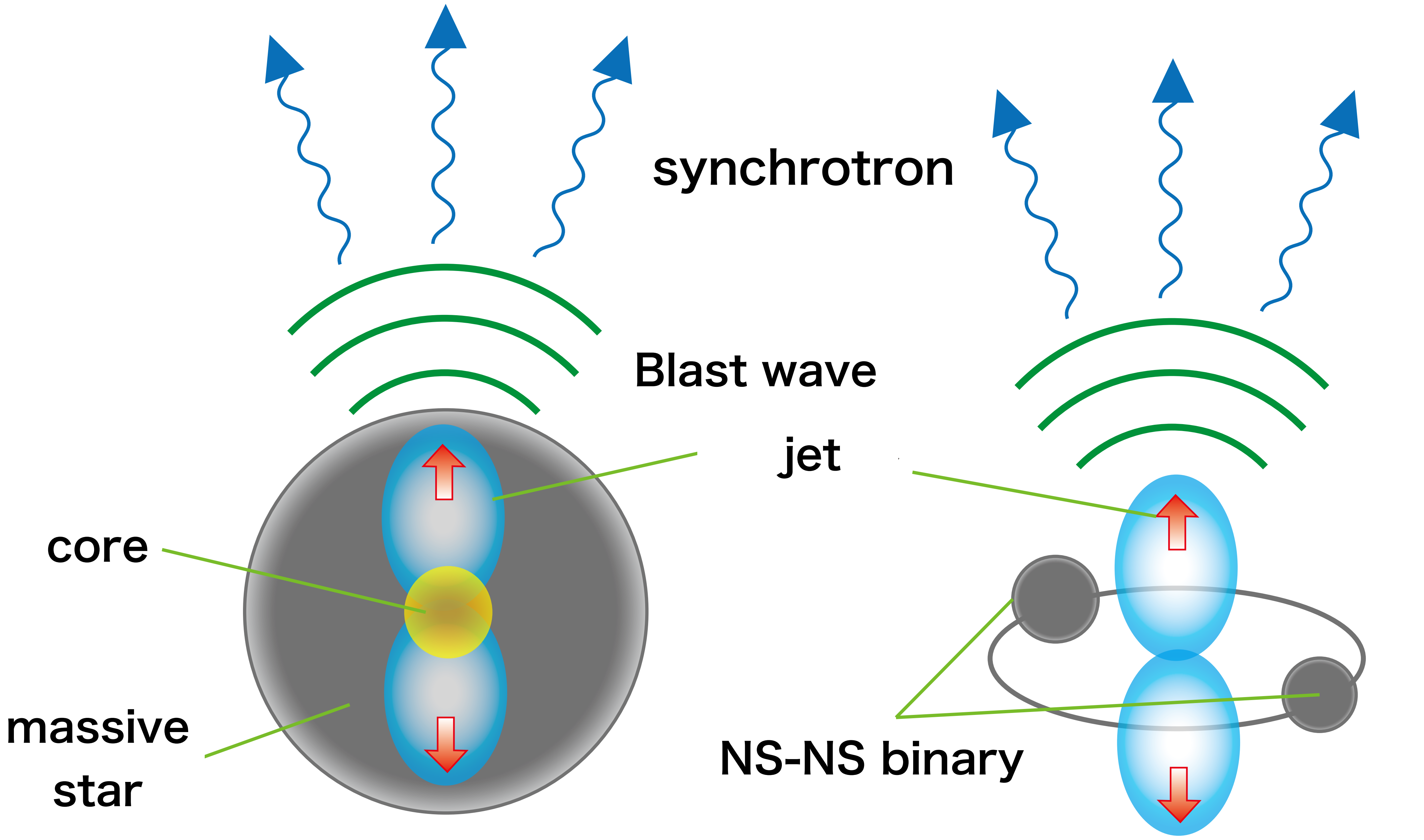
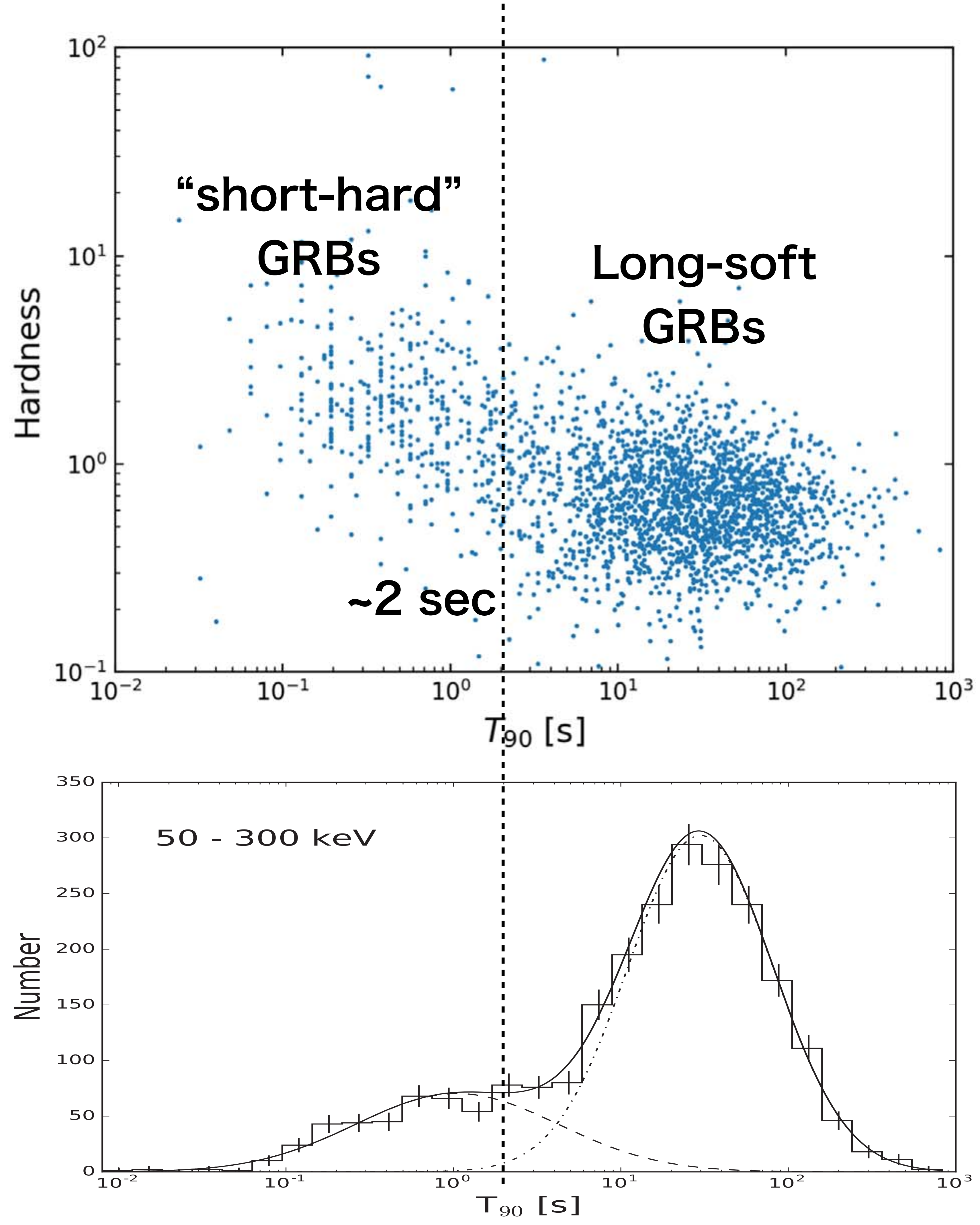


long-soft GRBs short-hard GRBs



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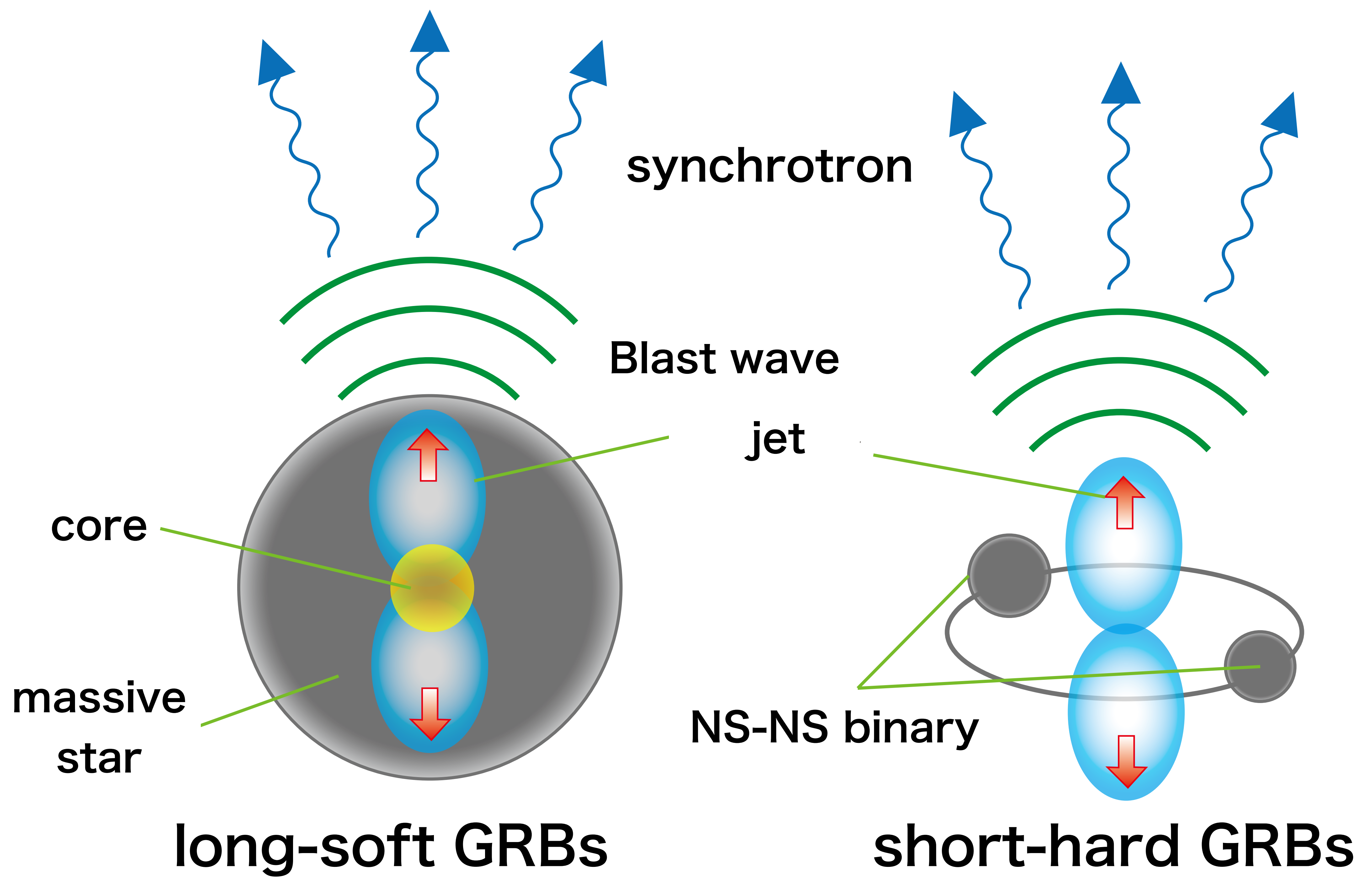

	long GRBs	short GRB
duration T_{90}	> 2 sec	< 2 sec
γ-ray spectrum	soft	hard
origin	massive star's collapse	NS-NS merger
optical counterpart	core-collapse supernova	kilonovae
after-glow	bright	dark
host galaxy	star-forming	old population
location	associated with stellar lights	outskirt

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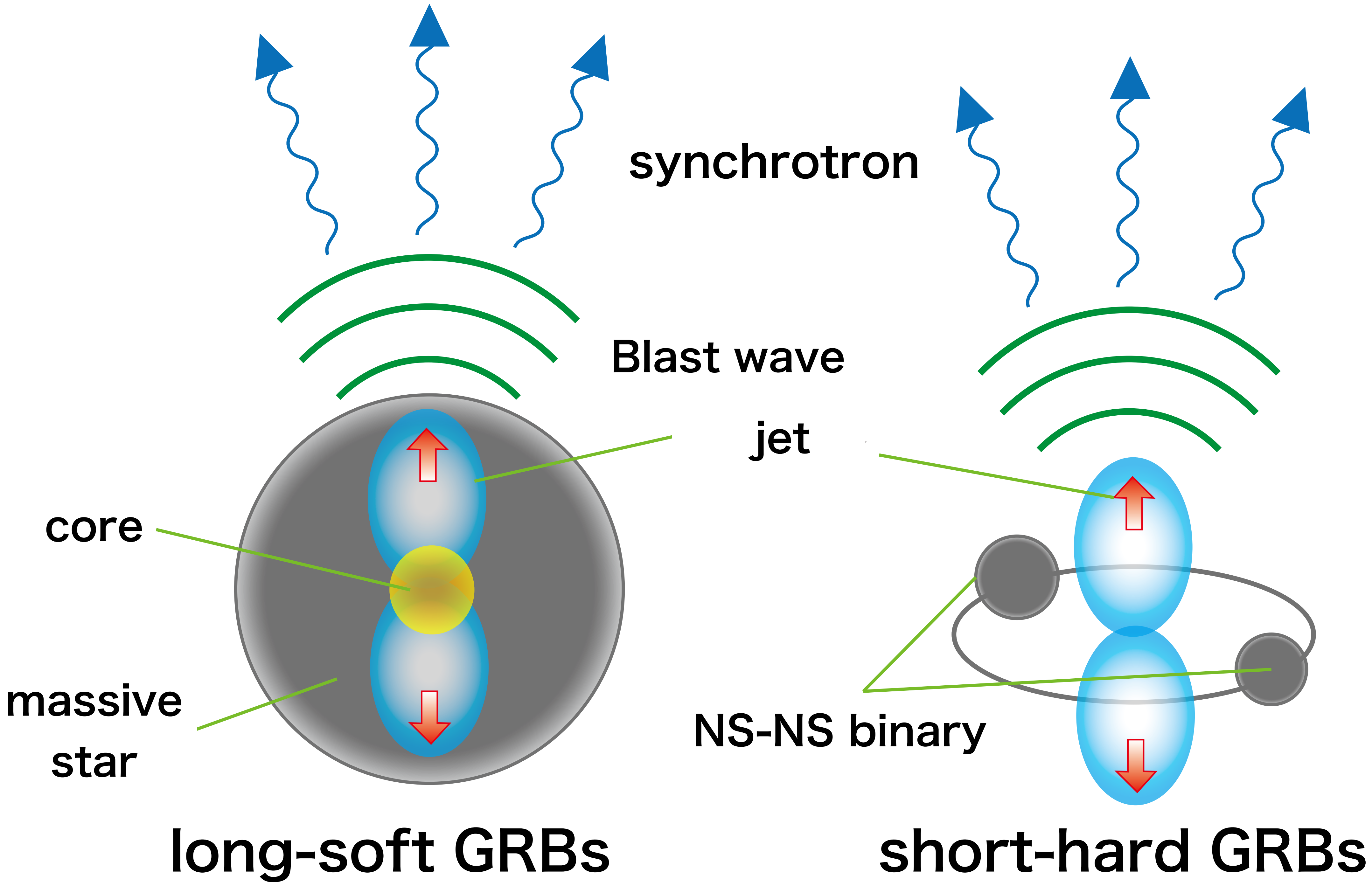

A Kilonova Following a Long-Duration Gamma-Ray Burst at 350 Mpc

Jillian Rastinejad[1*], Benjamin P. Gompertz[2], Andrew J. Levan[3], Wen-fai Fong[1], Matt Nicholl[2], Gavin P. Lamb[4], Daniele B. Malesani[3,5,6], Anya E. Nugent[1], Samantha R. Oates[2], Nial R. Tanvir[4], Antonio de Ugarte Postigo[7], Charles D. Kilpatrick[1], Christopher J. Moore[2], Brian D. Metzger[8,9], Maria Edvige Ravasio[3,10], Andrea Rossi, Genevieve Schroeder[1], Jacob Jencson[12], David J. Sand[12], Nathan Smith[12], José Feliciano Agüí Fernández[13], Edo Berger[14], Peter K. Blanchard[1], Ryan Chornock[15], Bethany E. Cobb[16], Massimiliano De Pasquale[17], Johan P. U. Fynbo[5,6], Luca Izzo[18], D. Alexander Kann[13], Tanmoy Laskar[3], Ester Marini[19], Kerry Paterson[1,20], Alicia Rouco Escorial[1], Huei M. Sears[1] and Christina C. Thöne[21]

Rastinejad+ (2022, arXiv: 2204.10864)

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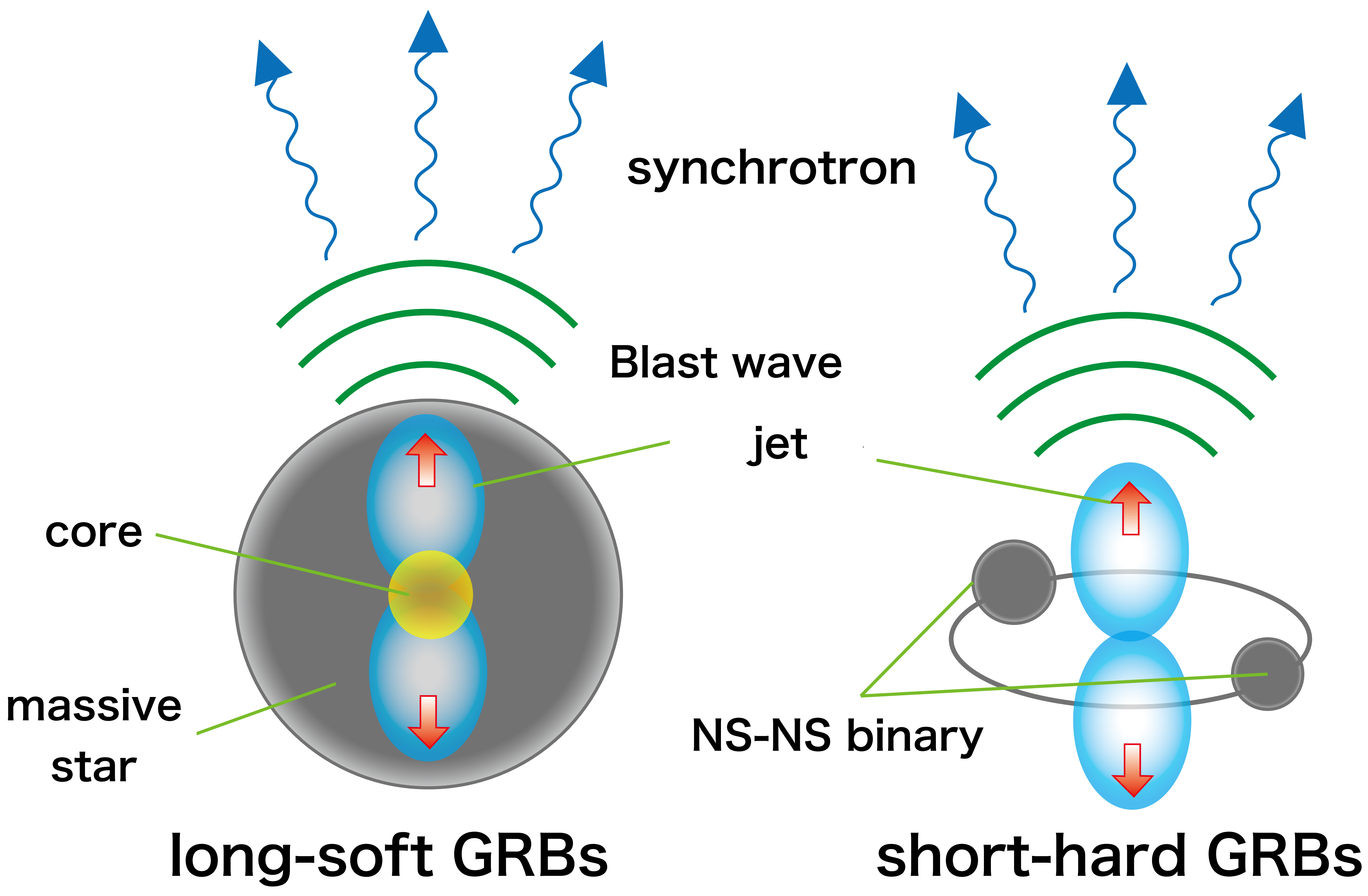

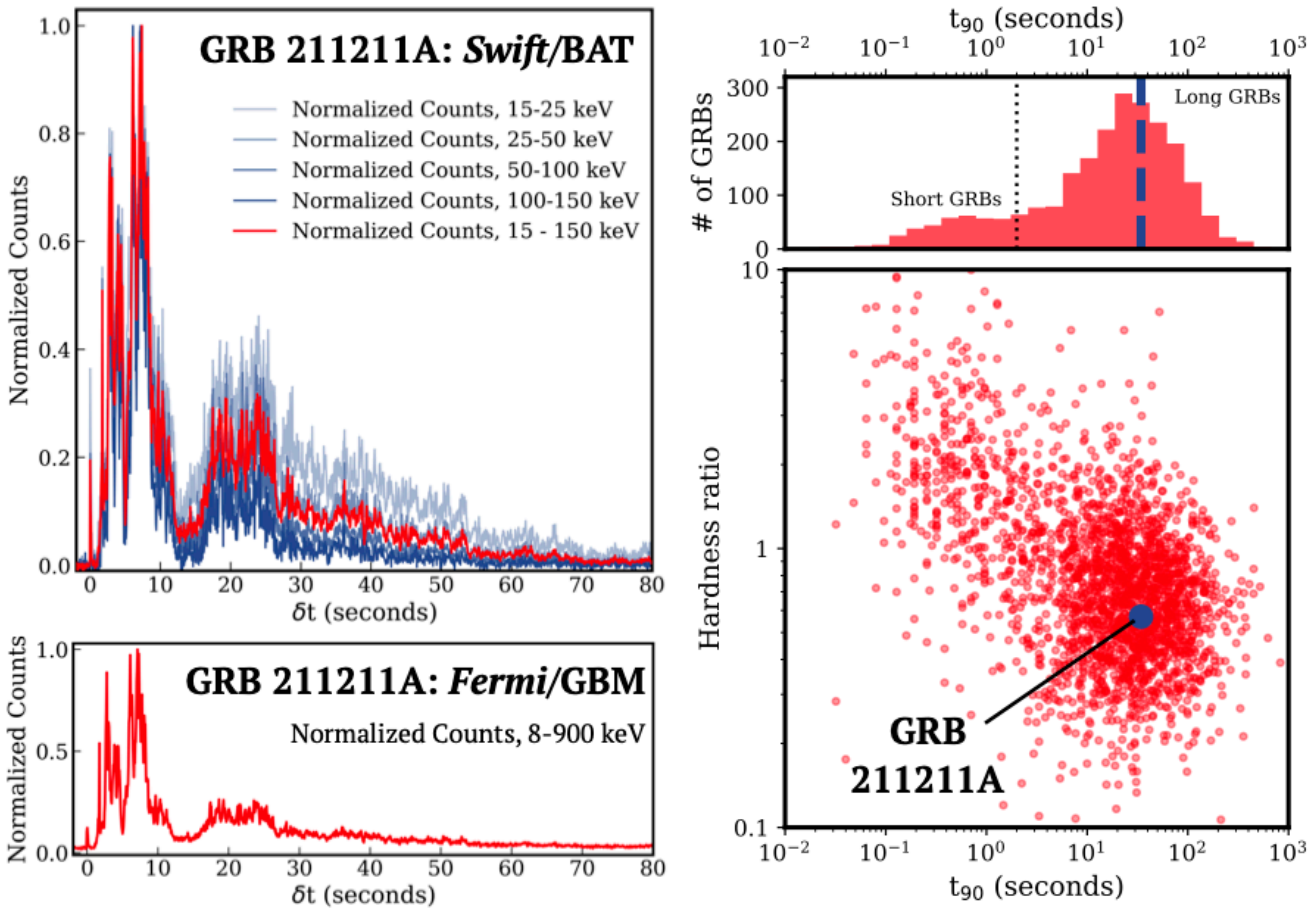

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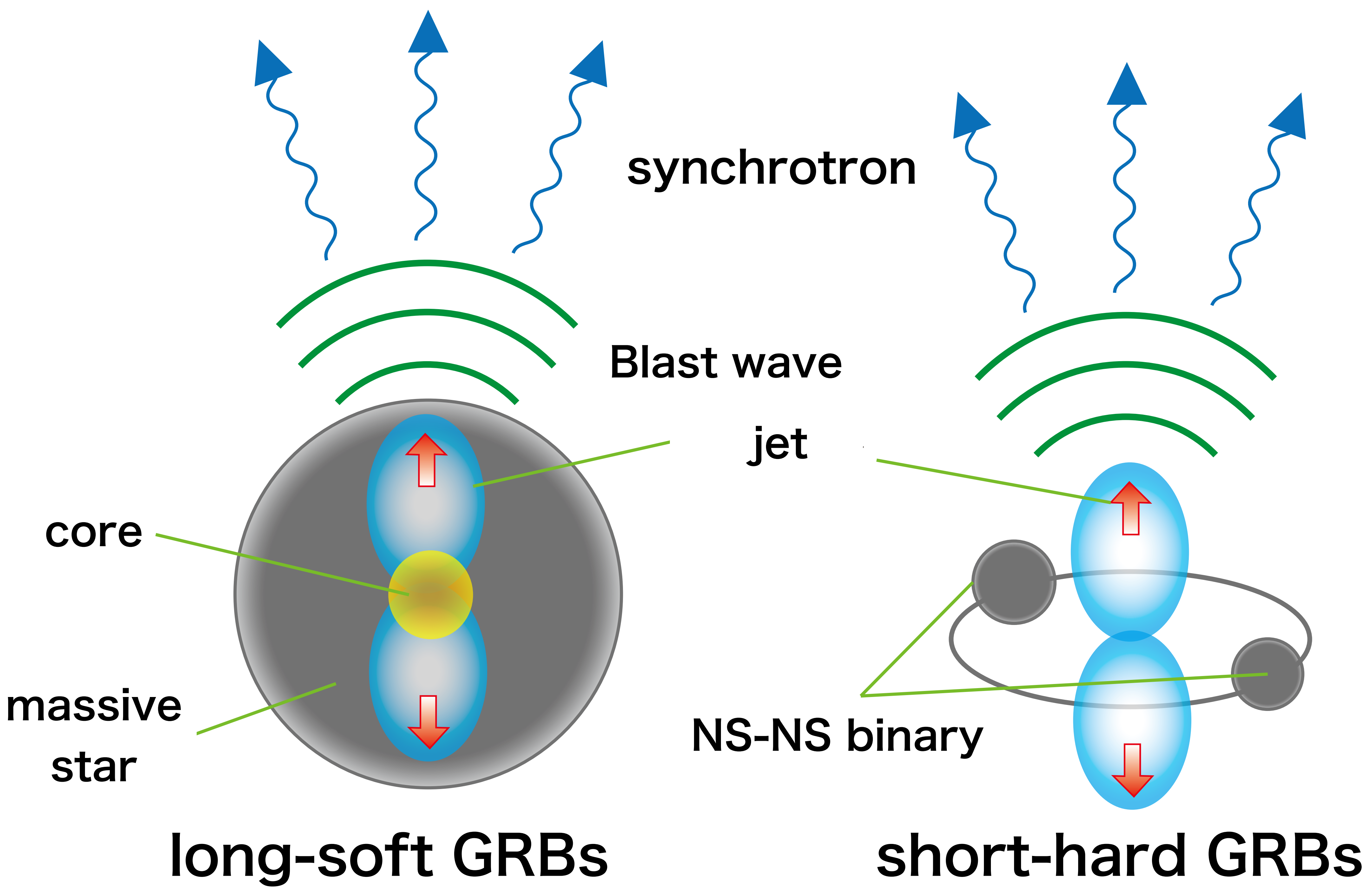

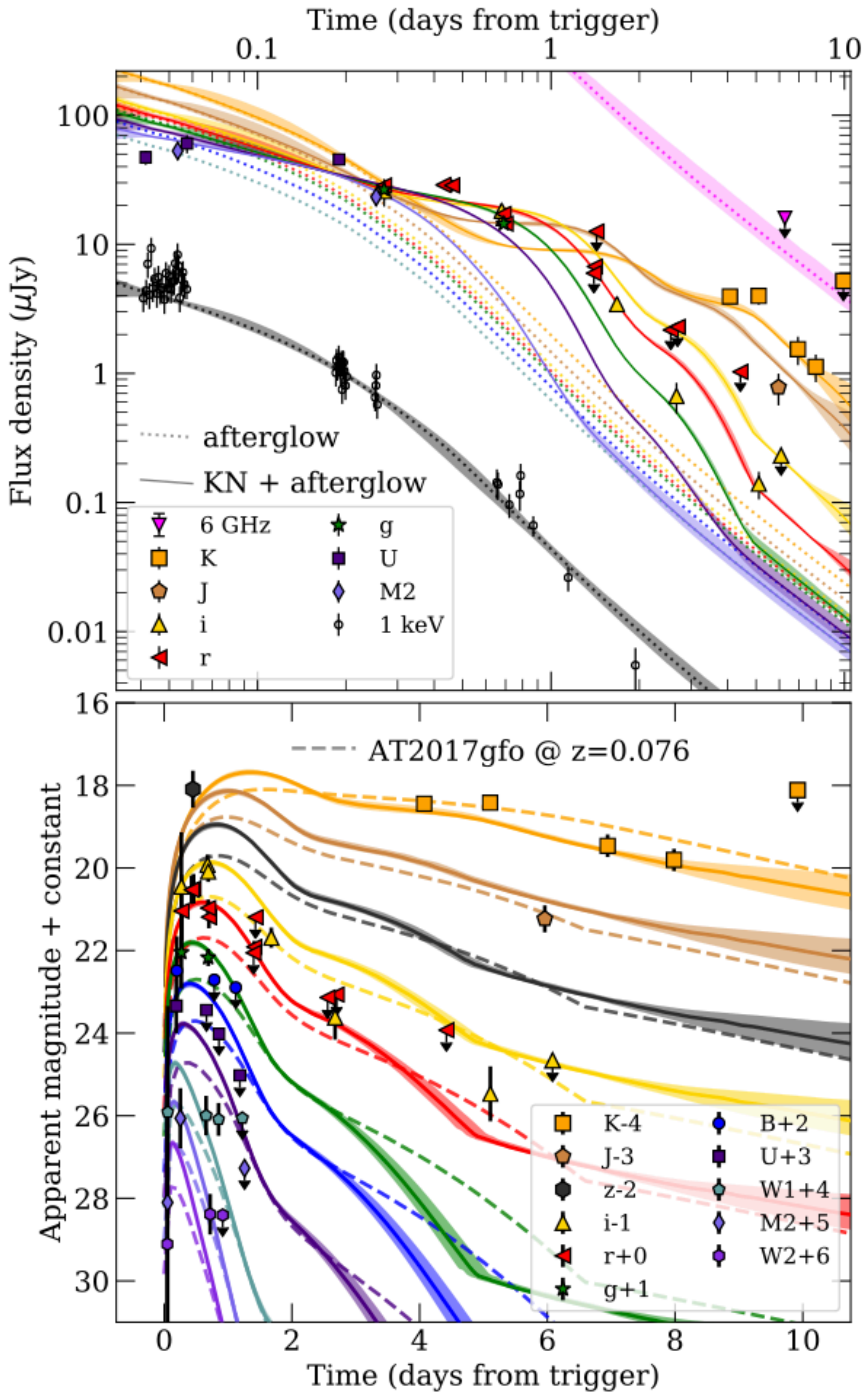

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Progress in (long-)GRB studies

past

- GRB 670702: first GRB detected by Vela satellite (but, classified at first)
- GRB 970228: first optical afterglow detection and redshift determination
- GRB 980425: first SN detection in the optical afterglow

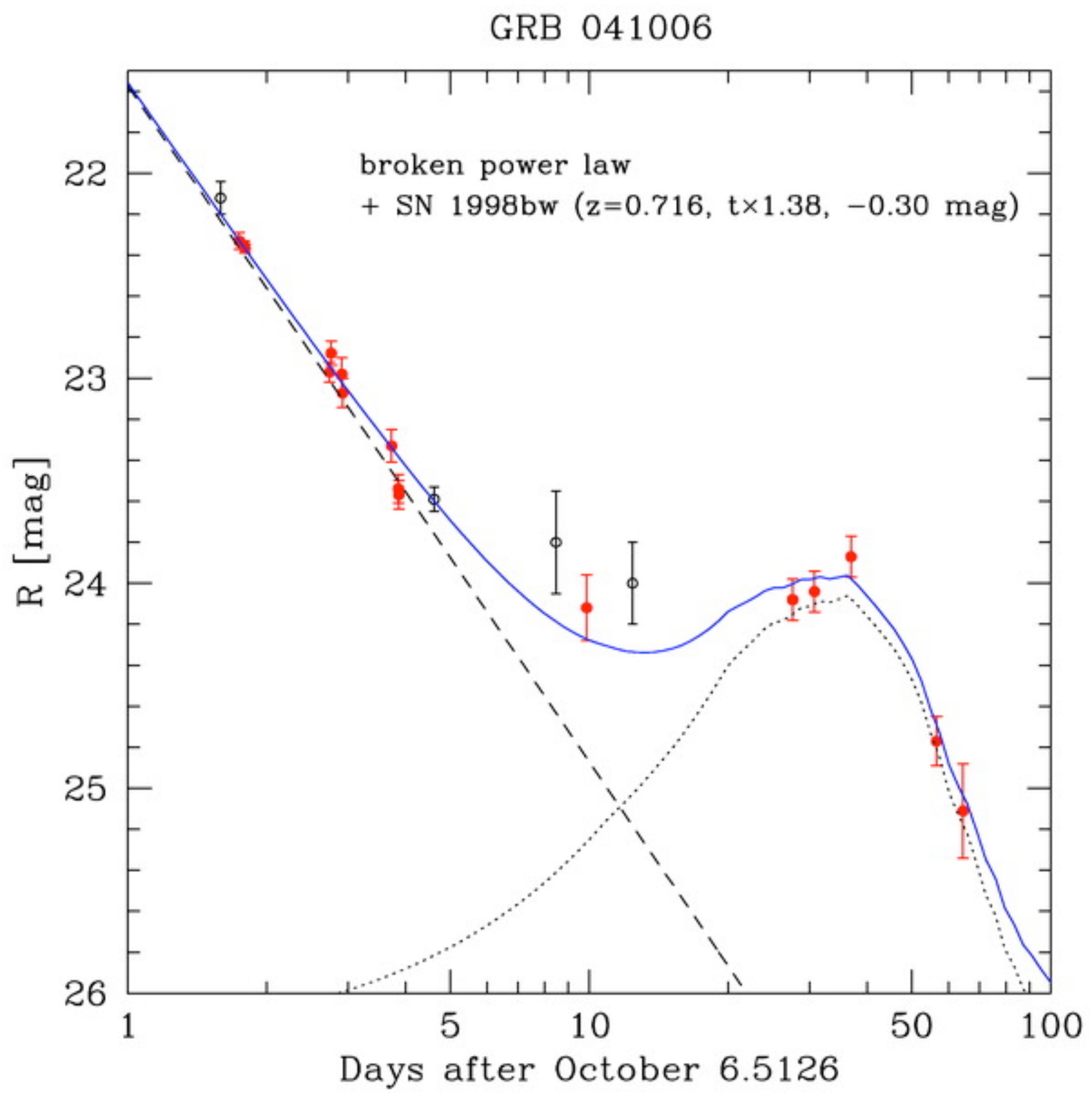
⋮

- GRB 171205A: optical spectroscopic observations within < 1 days.
  Izzo+ (2019) including K. Maeda & AS
- radio polarization observed by ALMA?
  Urata+ (2019), but see Laskar+(2020)
- GRB 181201A: reverse shock emission decomposed in radio afterglow?
  Laskar+ (2019)
- GRB 190114C: first GRB in TeV energy band by MAGIC
  MAGIC collaboration (2019a,b)
- iPTF11agg, AT 2020blt: optically detected afterglow-like transient with no GRB?
  Cenko+(2013), Ho+(2020)

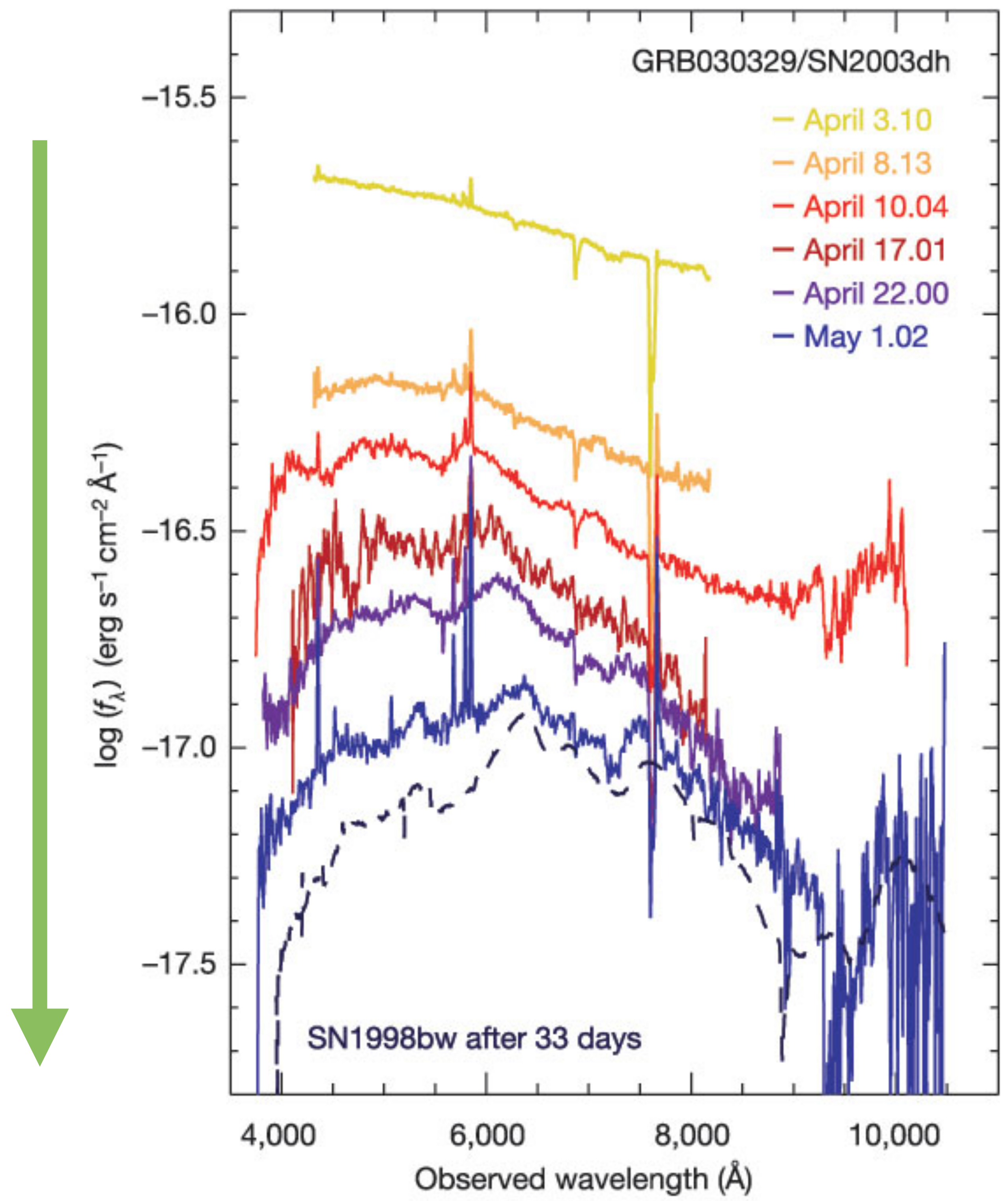
now

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

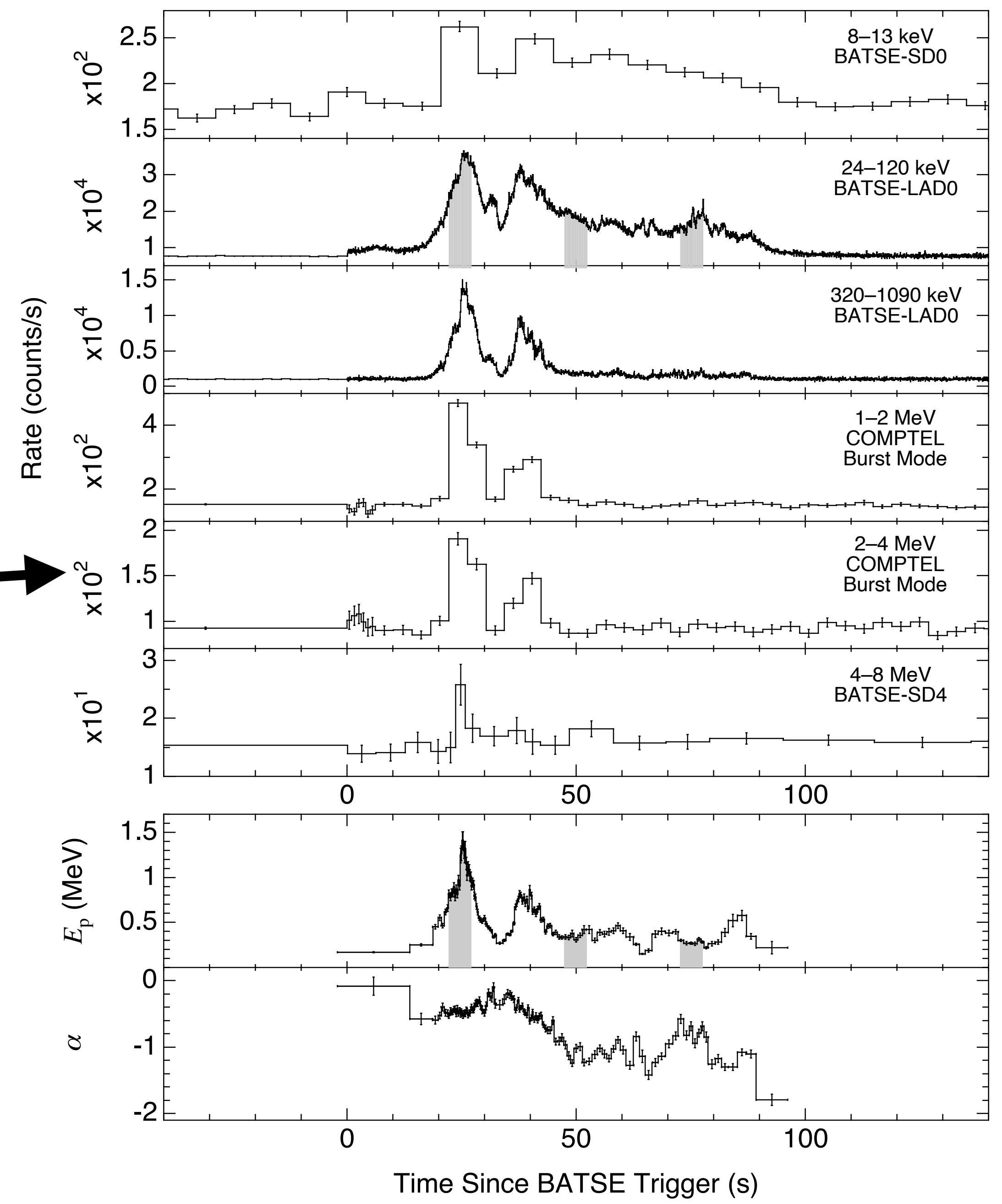
- GRB-SN association
- energetic SNe-Ic with E~10^{52}erg (i.e., hypernovae)
- various chemical elements found in the SN spectra
- important tracers of explosion mechanism and progenitor system
- chemical enrichment
- SN ejecta mass of **2 - 10 M_{sun}**
- Ni mass (SN power source) of **0.1 - 1(?) M_{sun}**

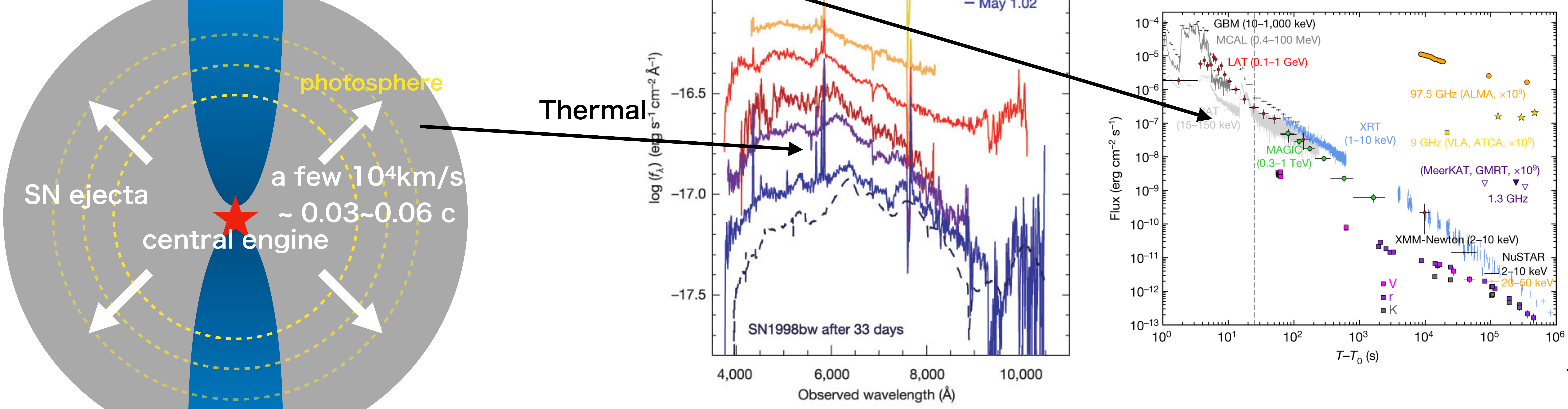
GRB	SN	type	z	E_K (10^{51} erg)	M_{ej} ($M_\odot$)	M_{Ni} ($M_\odot$)	v_{ph} (km s^{-1})
970228		GRB	0.695				
980326		GRB					
980425	1998bw	*ll*GRB	0.00866	$20-30$	$6-10$	$0.3-0.6$	18000
990712		GRB	0.4331	$26.1^{+24.6}_{-15.0}$	$6.6^{+3.5}_{-2.9}$	0.14 ± 0.04	
991208		GRB	0.7063	$38.7^{+44.6}_{-26.0}$	$9.7^{+6.8}_{-5.6}$	0.96 ± 0.48	
000911		GRB	1.0585				
011121	2001ke	GRB	0.362	$17.7^{+8.8}_{-6.4}$	4.4 ± 0.8	0.35 ± 0.01	
020305							
020405		GRB	0.68986	$8.9^{+5.4}_{-3.8}$	$2.2^{+0.6}_{-0.5}$	0.23 ± 0.02	
020410							
020903		*ll*GRB	0.2506	$28.9^{+32.2}_{-18.9}$	$7.3^{+4.9}_{-4.0}$	0.25 ± 0.13	
021211	2002lt	GRB	1.004	$28.5^{+45.0}_{-13.0}$	$7.2^{+7.4}_{-6.0}$	0.16 ± 0.14	
030329	2003dh	GRB	0.16867	$20-50$	$5-10$	$0.4-0.6$	20000
030723							
030725							
031203	2003lw	*ll*GRB	0.10536	60.0 ± 15	13.0 ± 4.0	0.55 ± 0.20	18000
040924		GRB	0.858				
041006		GRB	0.716	$76.4^{+39.8}_{-28.7}$	$19.2^{+3.9}_{-3.6}$	0.69 ± 0.07	
050416A		INT	0.6528				
050525A	2005nc	GRB	0.606	$18.9^{+10.7}_{-7.5}$	$4.8^{+1.1}_{-1.0}$	0.24 ± 0.02	
050824		GRB	0.8281	$5.7^{+9.3}_{-3.7}$	$1.4^{+1.6}_{-0.6}$	0.26 ± 0.17	
060218	2006aj	*ll*GRB	0.03342	1.0 ± 0.5	2.0 ± 0.5	0.20 ± 0.10	20000
060729		GRB	0.5428	$24.4^{+14.3}_{-9.9}$	$6.1^{+1.6}_{-1.4}$	0.36 ± 0.05	
060904B		GRB	0.7029	$9.9^{+5.1}_{-3.7}$	2.5 ± 0.5	0.12 ± 0.01	
070419A		GRB	0.9705				
080319B		GRB	0.9371	$22.7^{+19.1}_{-11.9}$	$5.7^{+2.6}_{-2.2}$	0.86 ± 0.45	
081007	2008hw	GRB	0.5295	19.0 ± 15.0	2.3 ± 1.0	0.39 ± 0.08	12600
090618		GRB	0.54	$36.5^{+20.0}_{-14.2}$	$9.2^{+2.1}_{-1.9}$	0.37 ± 0.03	
091127	2009nz	GRB	0.49044	13.5 ± 0.4	4.7 ± 0.1	0.33 ± 0.01	17000
100316D	2010bh	*ll*GRB	0.0592	15.4 ± 1.4	2.5 ± 0.2	0.12 ± 0.02	35000
100418A		INT	0.6239				
101219B	2010ma	GRB	0.55185	10.0 ± 6.0	1.3 ± 0.5	0.43 ± 0.03	
101225A		ULGRB	0.847	32.0 ± 16.0	8.1 ± 1.5	0.41 ± 0.03	
111209A	2011kl	ULGRB	0.67702	$20-90$	$3-5$		21000
111211A			0.478				
111228A			0.71627				
120422A	2012bz	*ll*GRB	0.28253	25.5 ± 2.1	6.1 ± 0.5	0.57 ± 0.07	20500
120714B	2012eb		0.3984				
120729A		GRB	0.8			0.42 ± 0.11	
130215A	2013ez	GRB	0.597			$0.25-0.30$	6000
130427A	2013cq	GRB	0.3399	64.0 ± 7.0	6.3 ± 0.7	0.28 ± 0.02	35000
130702A	2013dx	INT	0.145	8.2 ± 0.4	3.1 ± 0.1	0.37 ± 0.01	21300
130831A	2013fu	GRB	0.479	18.7 ± 9.0	4.7 ± 0.8	0.30 ± 0.07	
140606B		GRB	0.384	19.0 ± 11.0	4.8 ± 1.9	0.42 ± 0.17	19800
150518A			0.256				
150818A		INT	0.282				
-	2009bb	Rel IcBL	0.009987	18.0 ± 8.0	4.1 ± 1.9	0.19 ± 0.03	15000
-	2012ap	Rel IcBL	0.012141	9.0 ± 3.0	2.7 ± 0.5	0.12 ± 0.02	13000

GRB-SNe properties
Cano+(2017)

Problems in Gamma-ray bursts

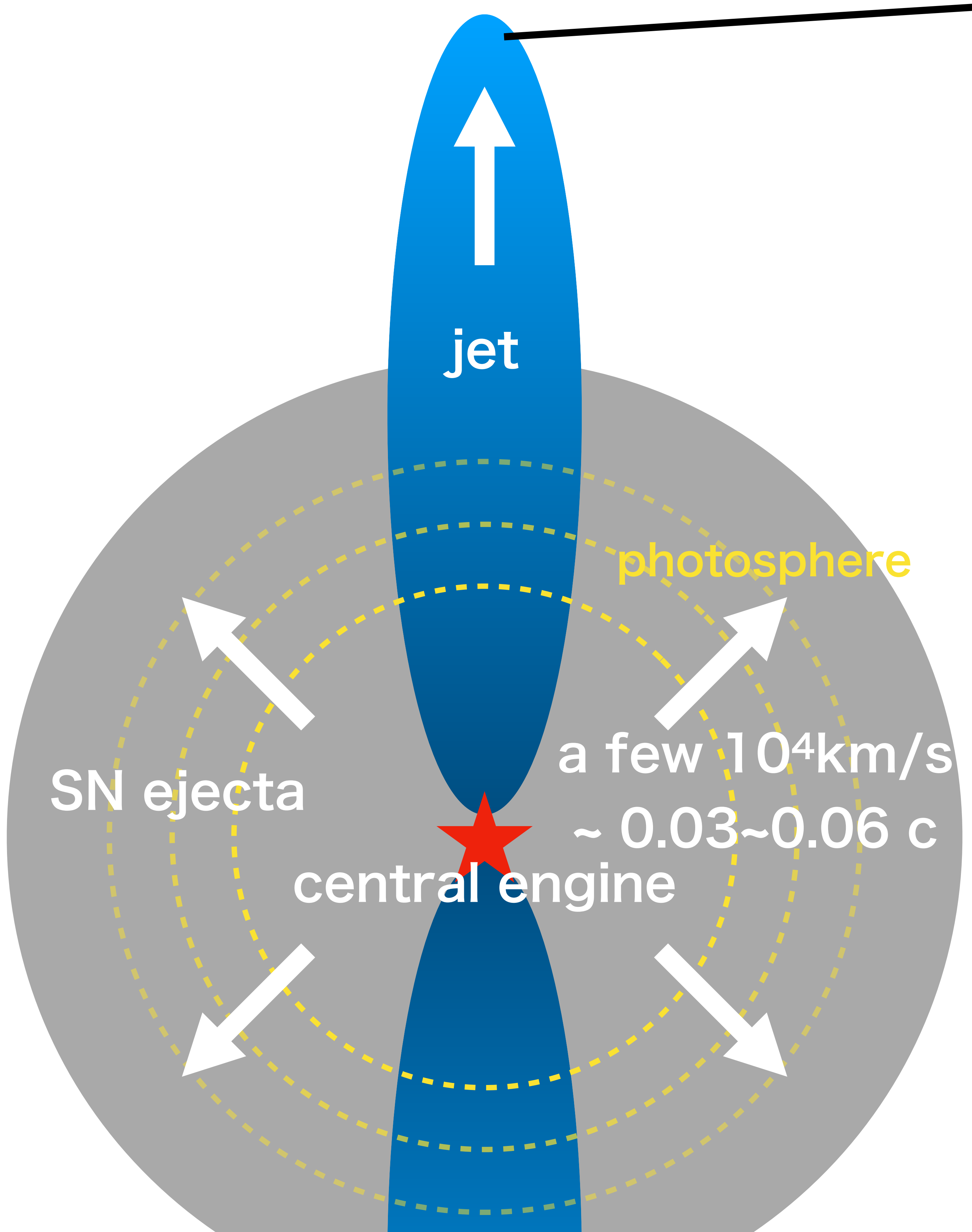
- multi-wavelength observations are essential
- prompt γ-ray detection
- afterglow from radio to TeV

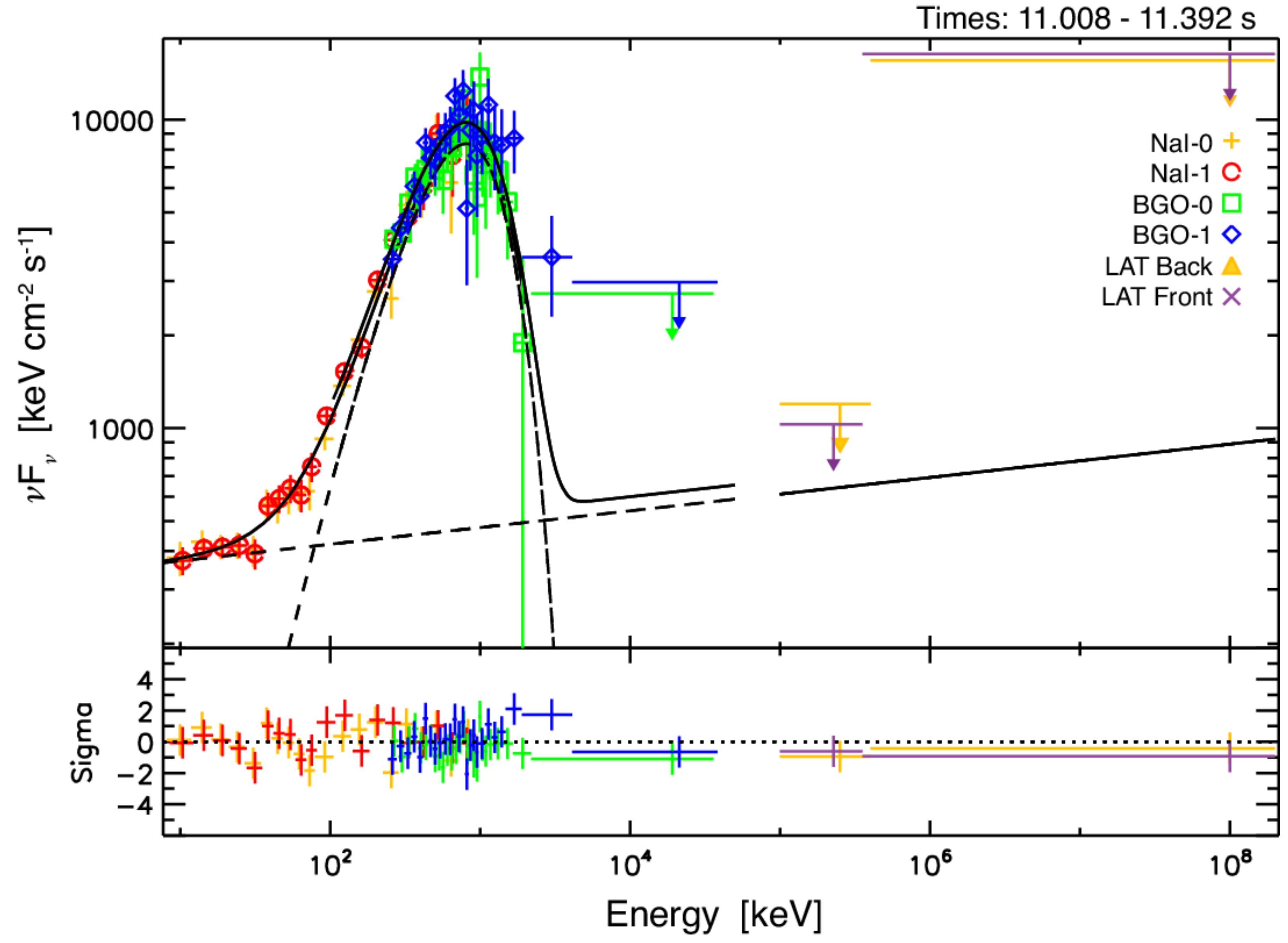




Prompt emission and its origin

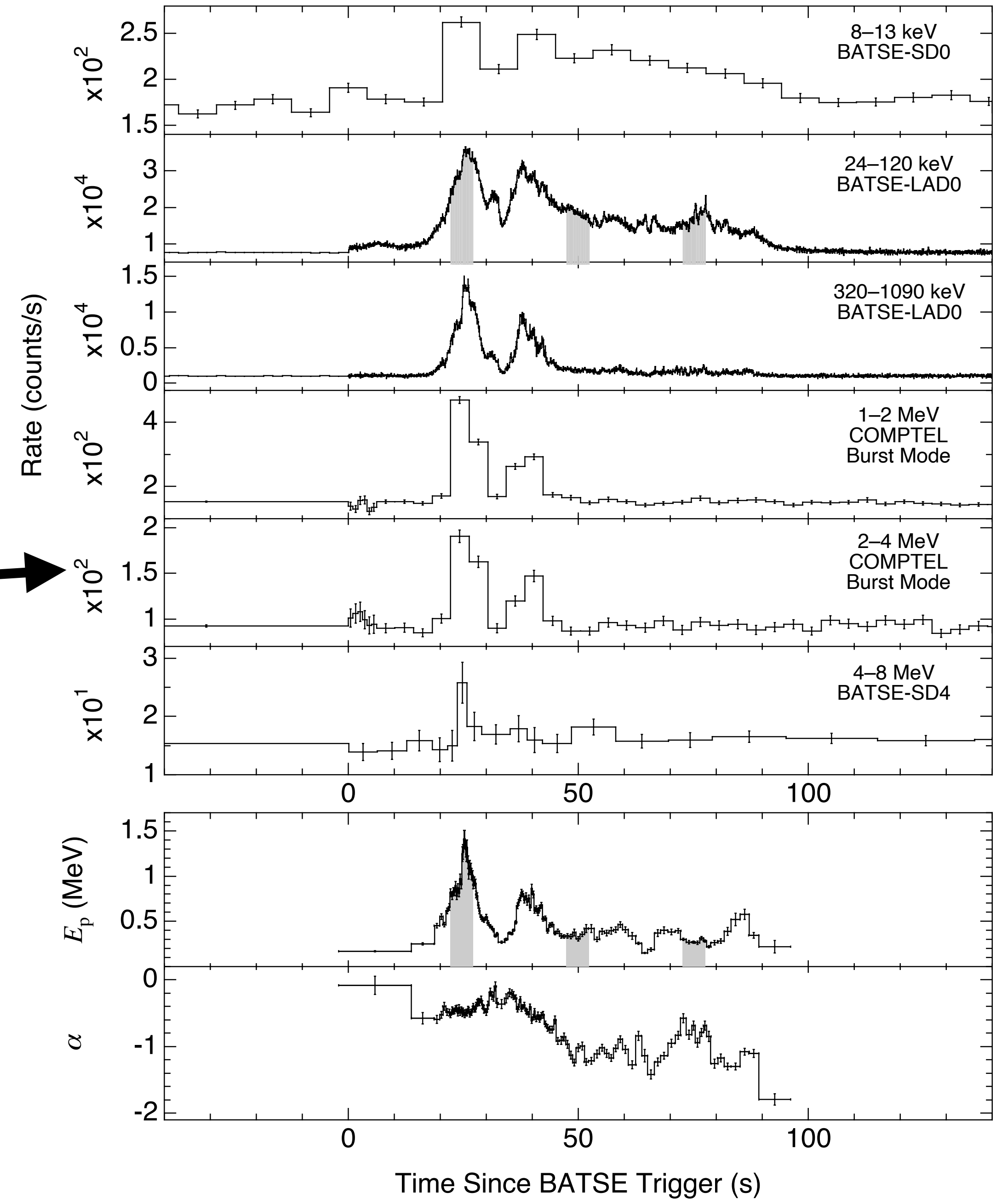
- still mysterious
- synchrotron? photospheric?
- energy dissipation mechanism: magnetic? internal shock?

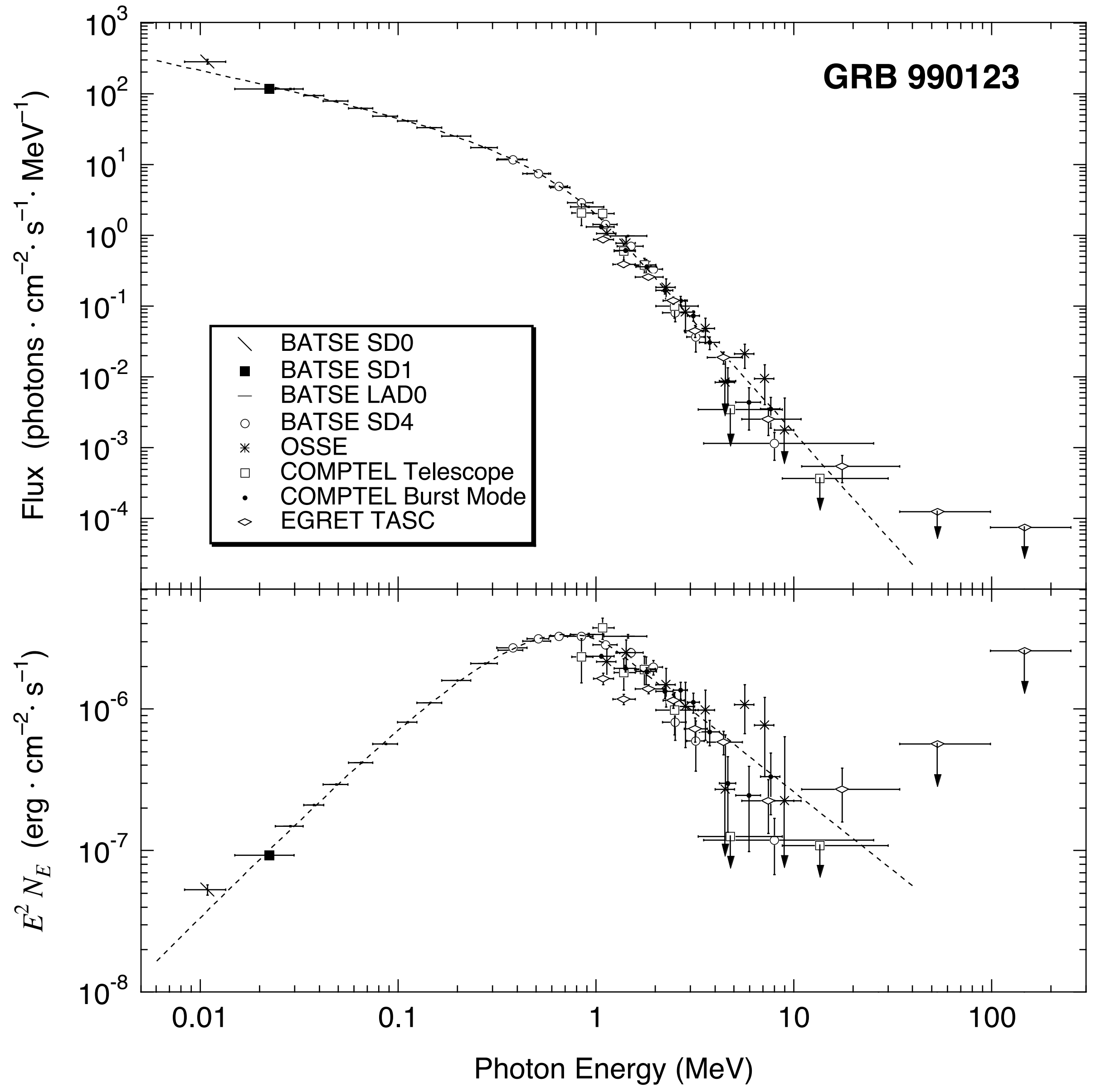




Ryde+(2010)

Prompt

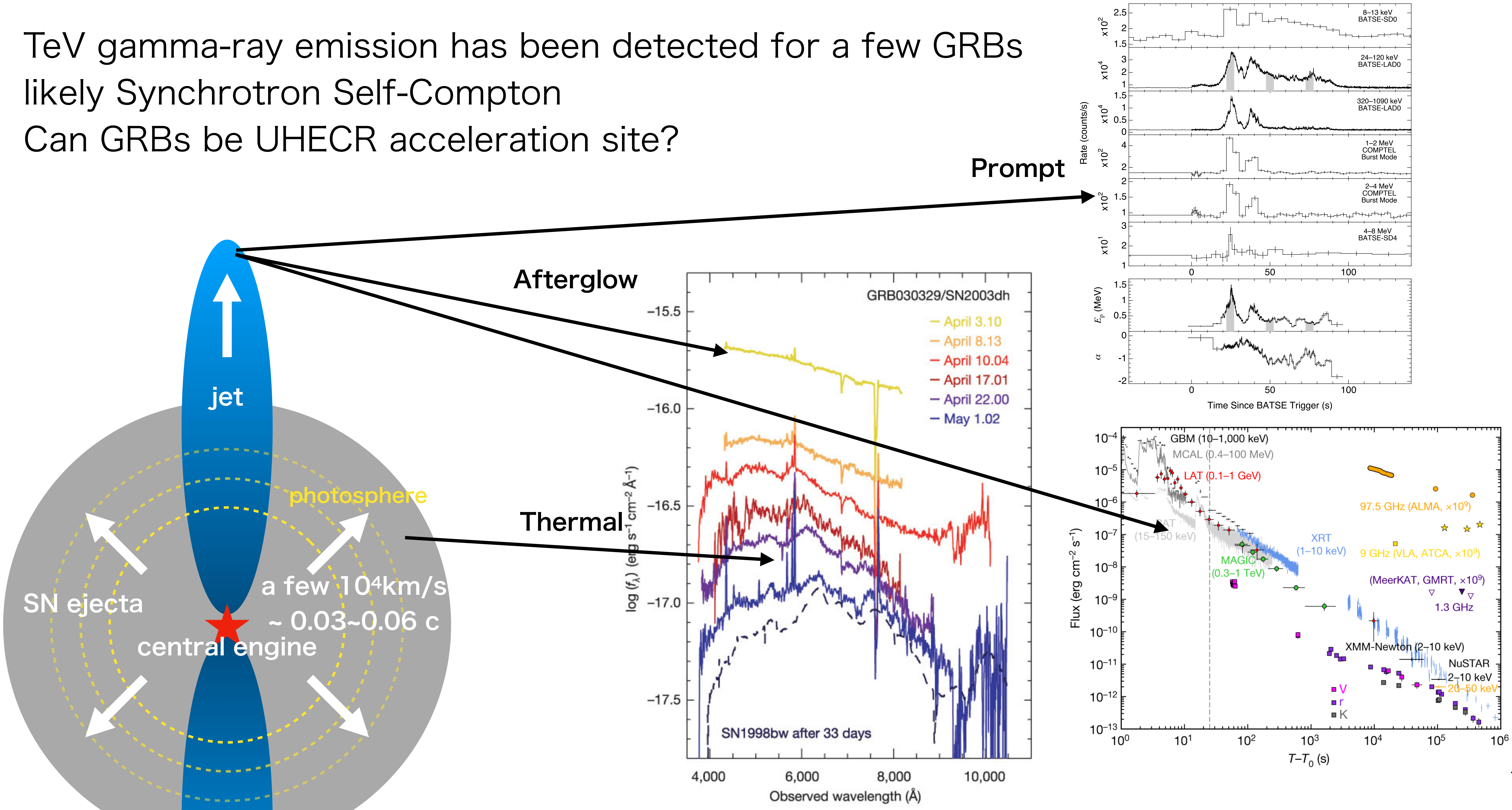




Briggs+ (1999)

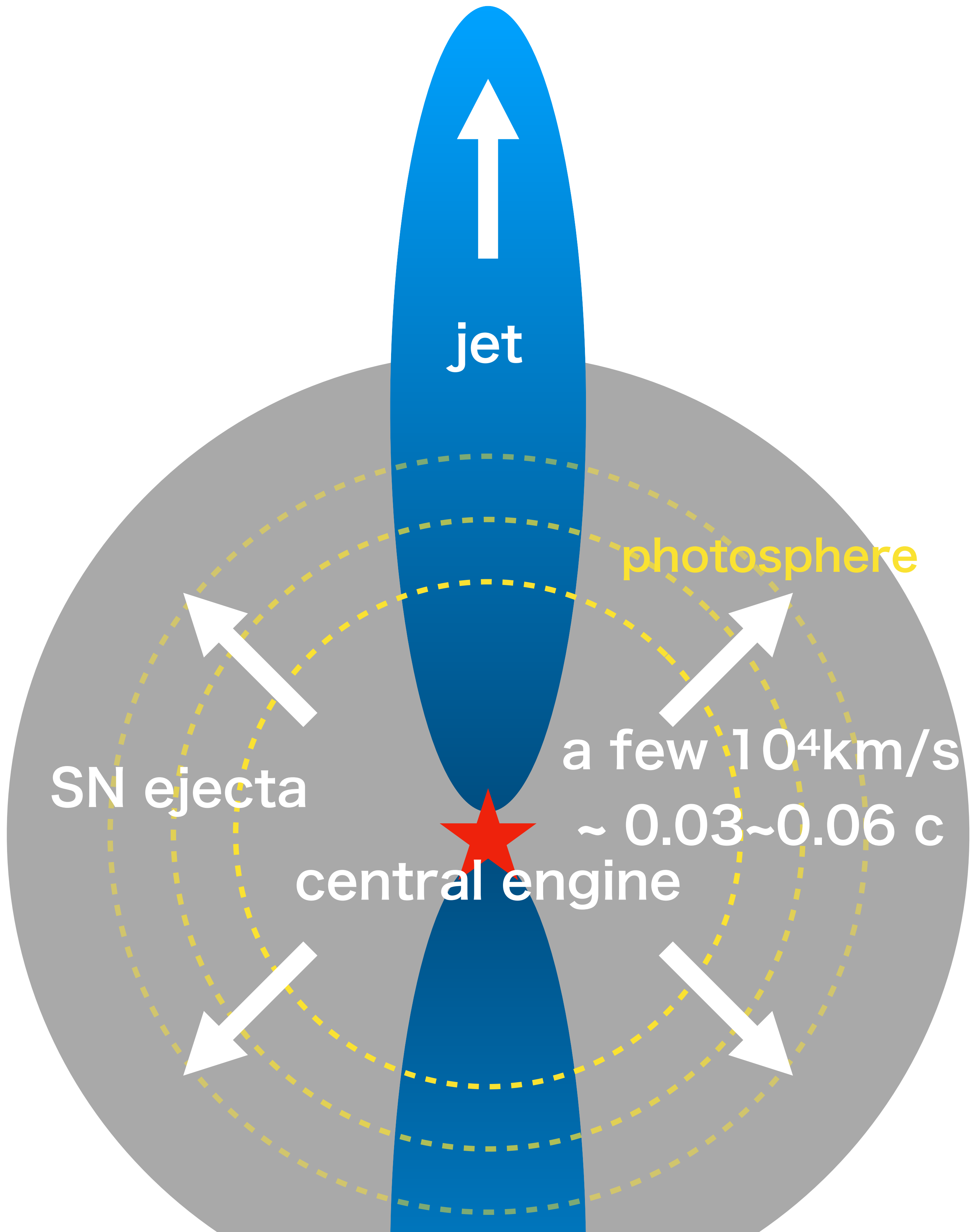
Particle acceleration in GRB jets

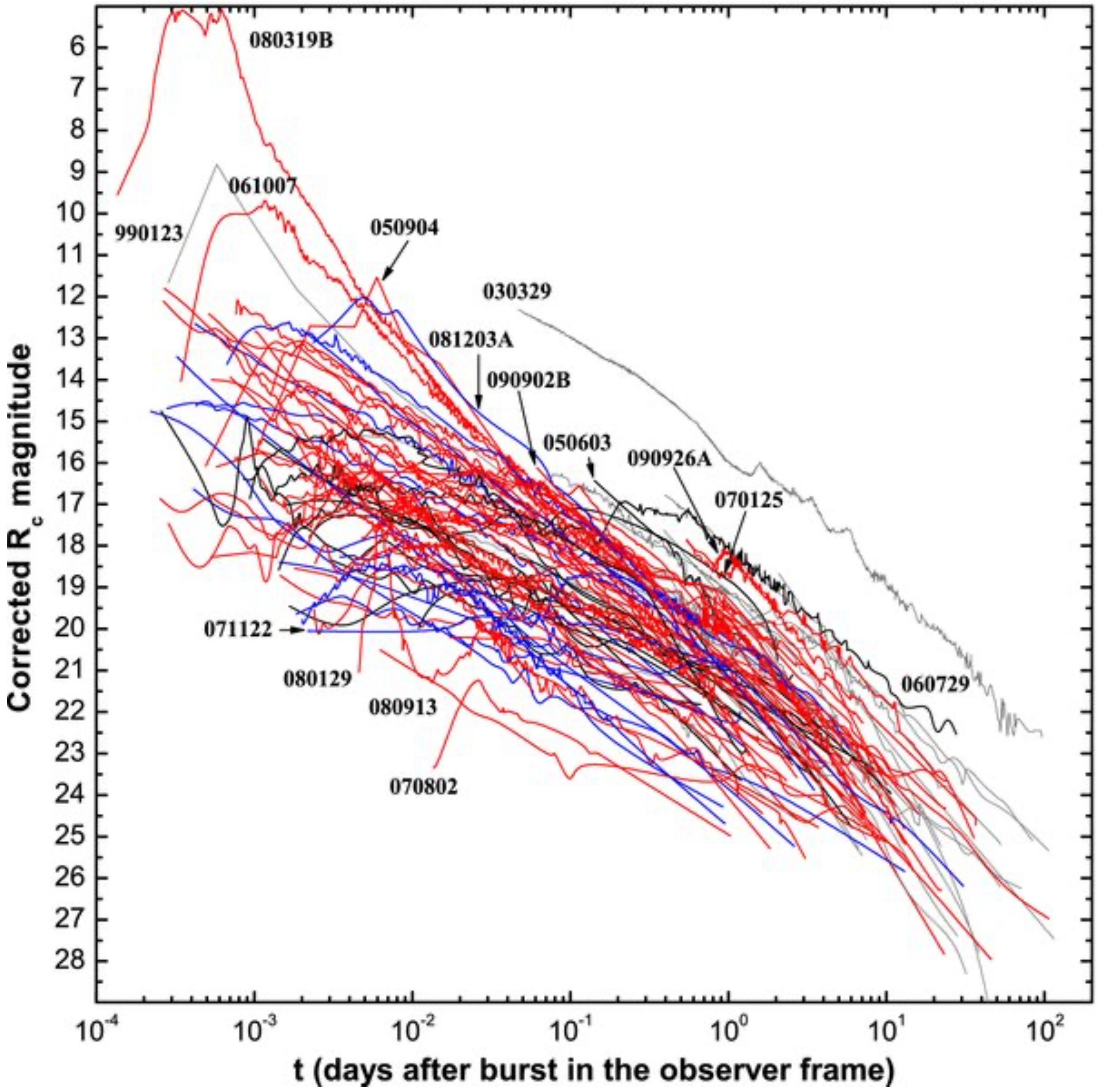
- TeV gamma-ray emission has been detected for a few GRBs
- likely Synchrotron Self-Compton
- Can GRBs be UHECR acceleration site?



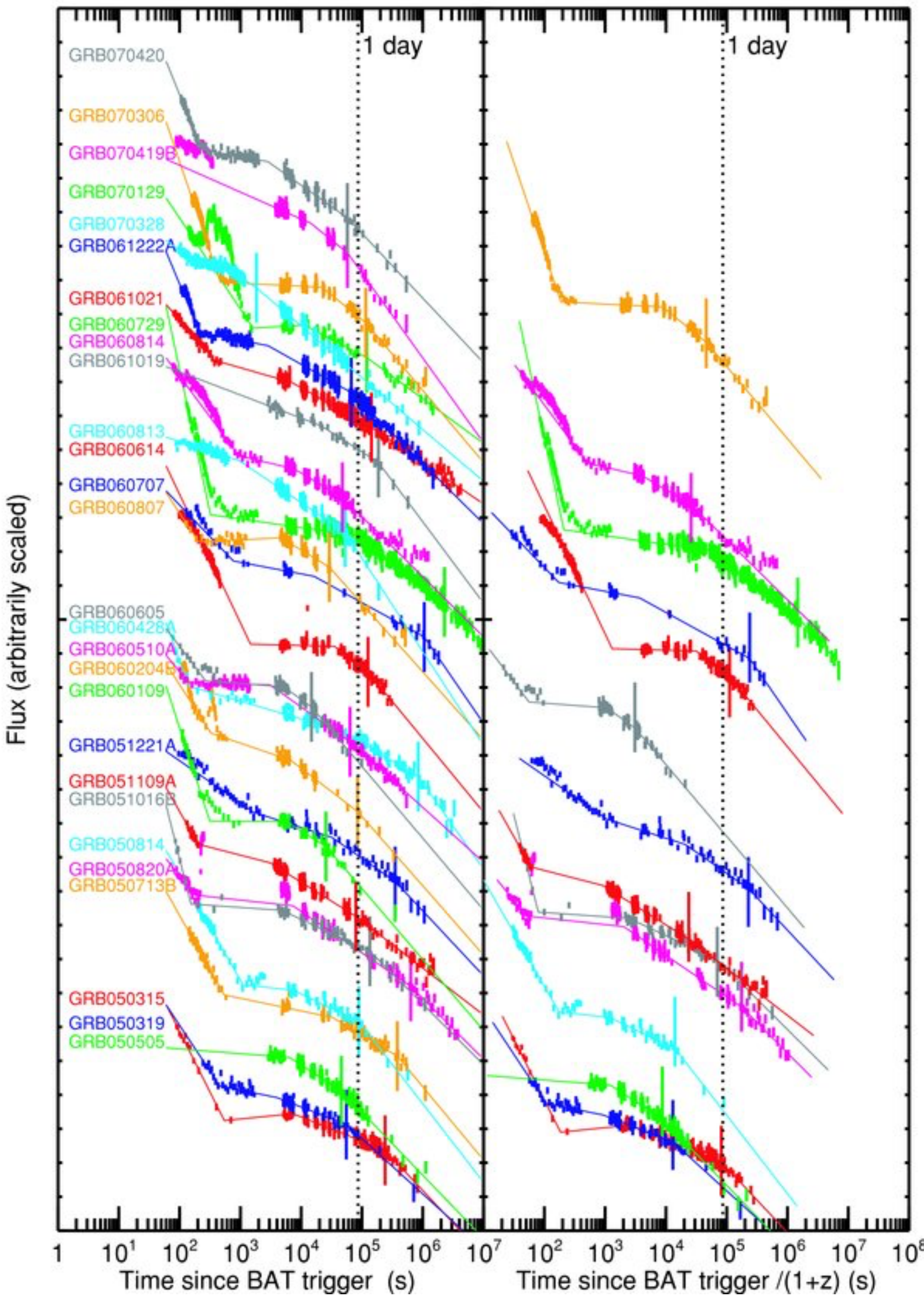
Plateau emission and its origin

- X-ray afterglow
- addition energy injection from the compact object?
- magnetar engine?





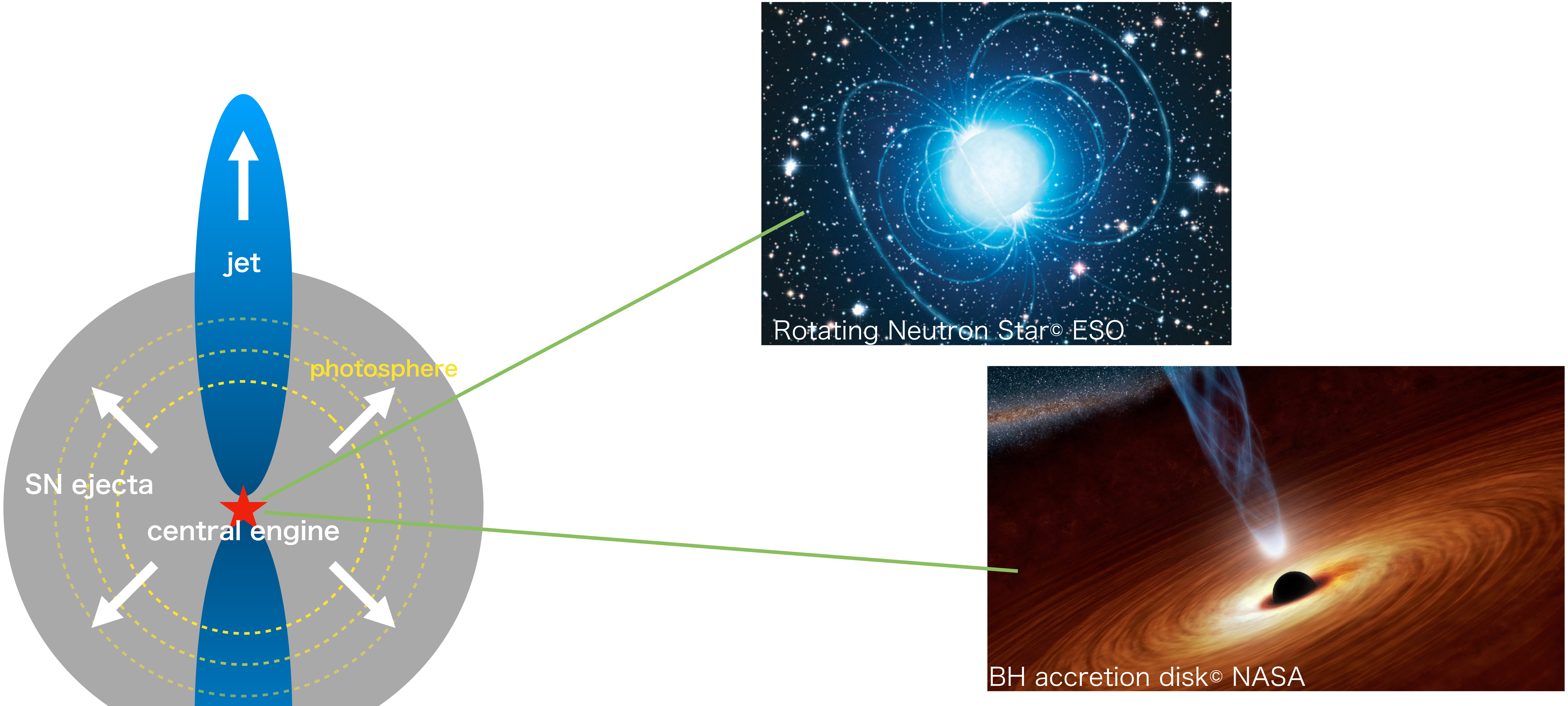
Optical afterglows, Kann+(2010)



GRB afterglows in X-rays, Racusin+(2009)

GRB engine: NS or BH formation?

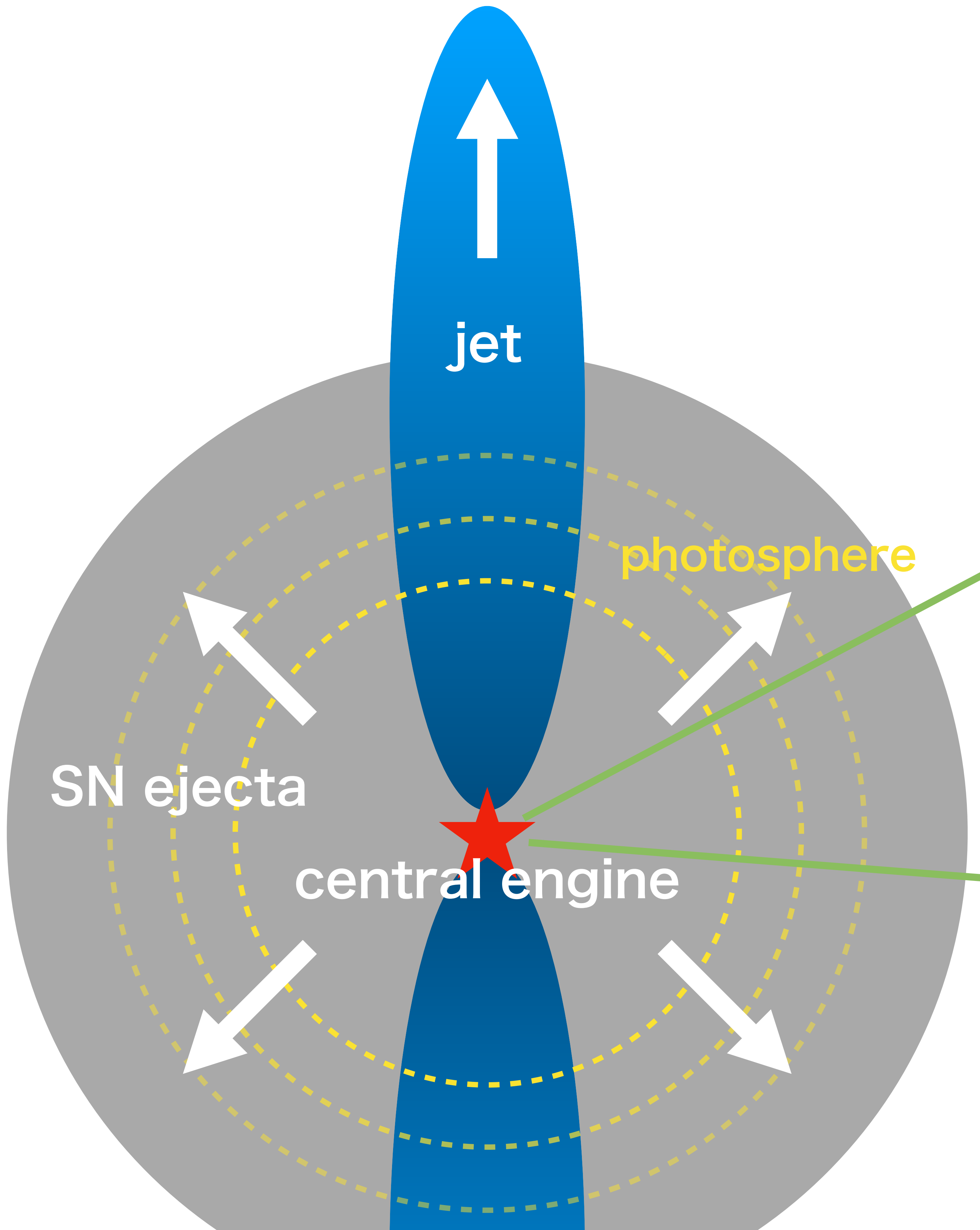
- neutron star formation: fast-rotating highly magnetized NS ? (e.g., Usov 1992)
- black hole formation: BH + accretion disk = collapsar ? (e.g., MacFadyen&Woosley 1999)

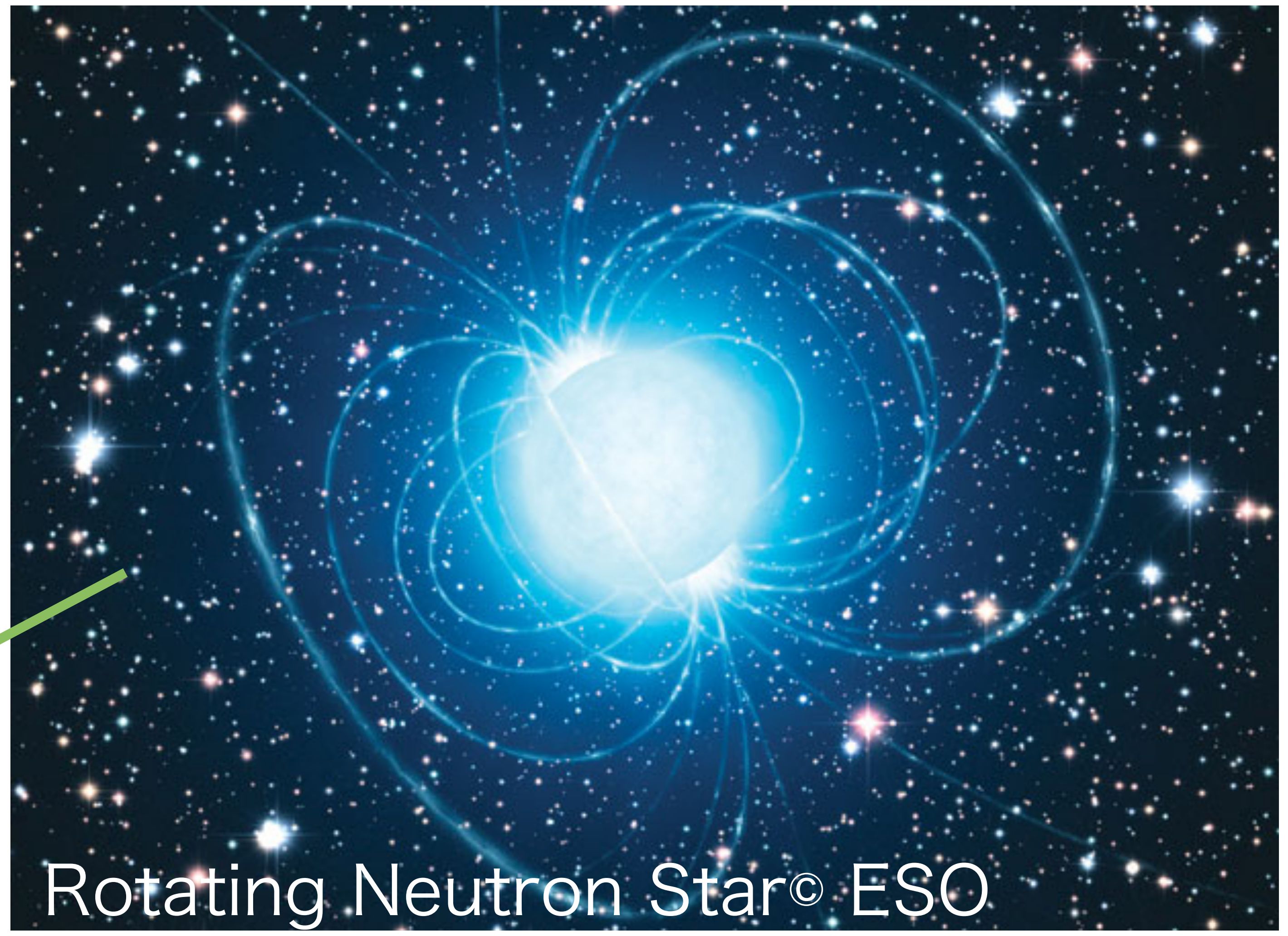


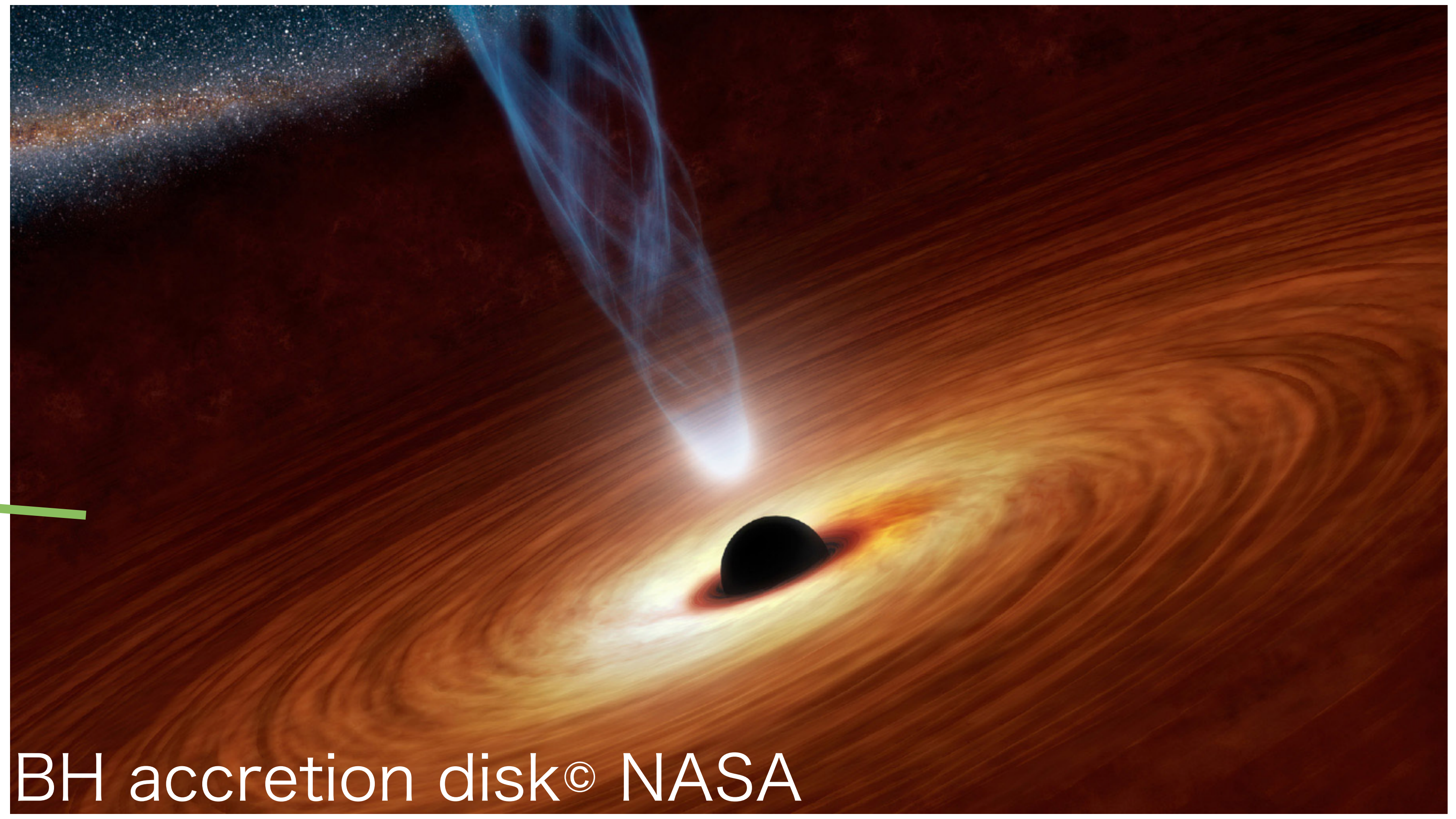
Rotating Neutron Star© ESO
BH accretion disk© NASA

GRB-SN connection and Ni problem

- How GRB jet and SN coexist in a collapsing massive star?
- ^{56}Ni production site?
- GRB jet itself is inefficient for ^{56}Ni production ↔ $0.1\text{-}0.4M_{sun}$ ^{56}Ni in observations

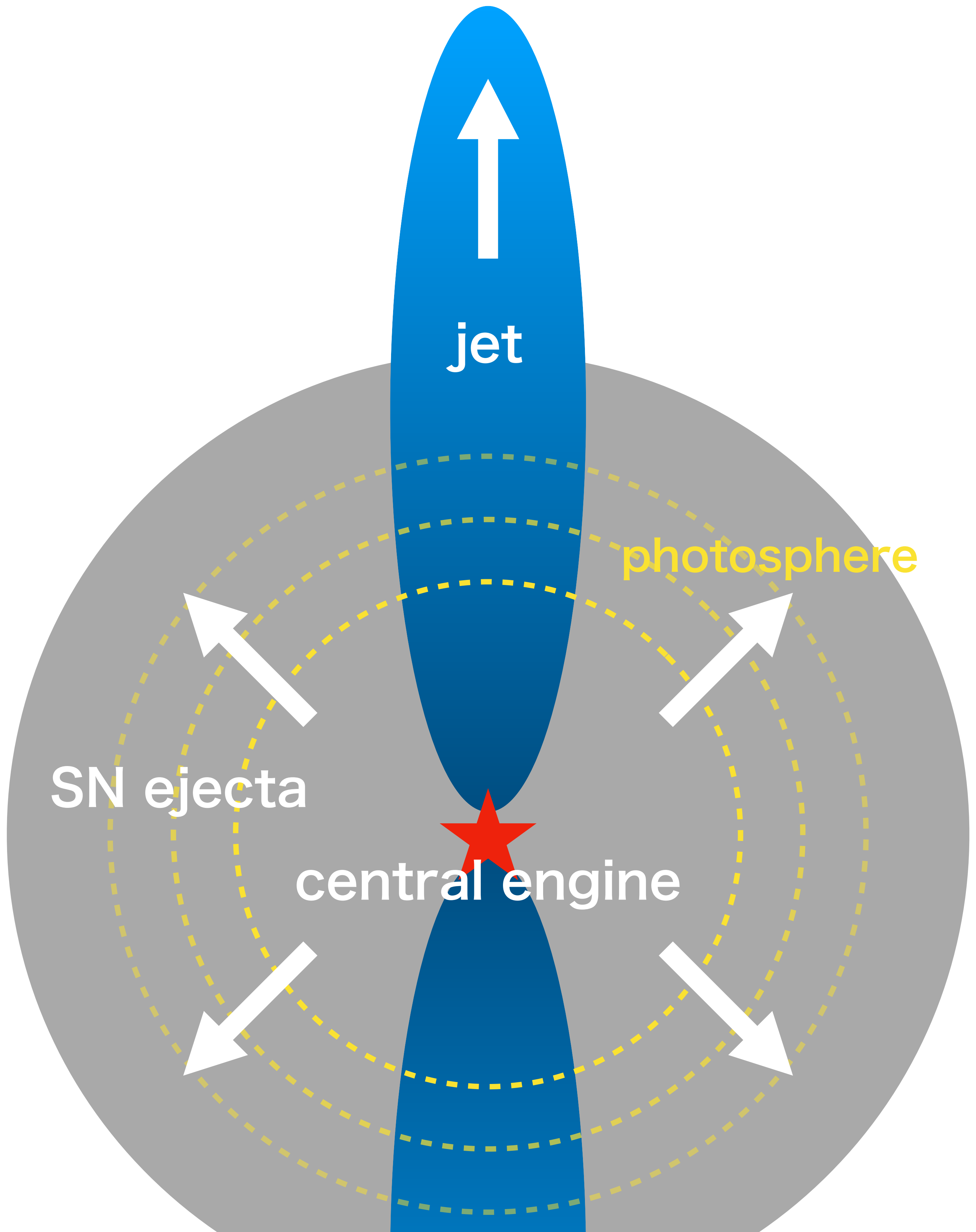


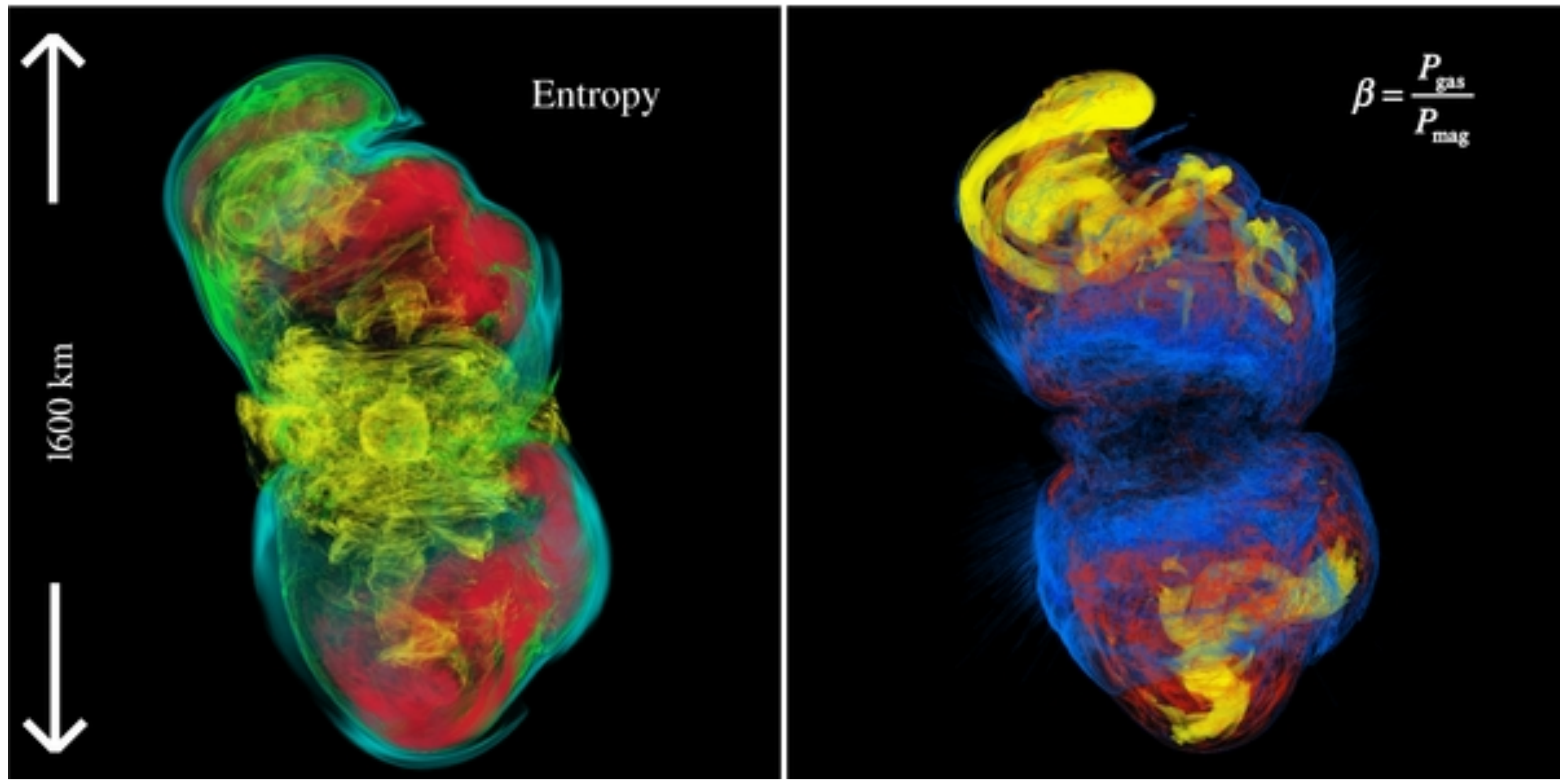

Rotating Neutron Star© ESO


BH accretion disk© NASA

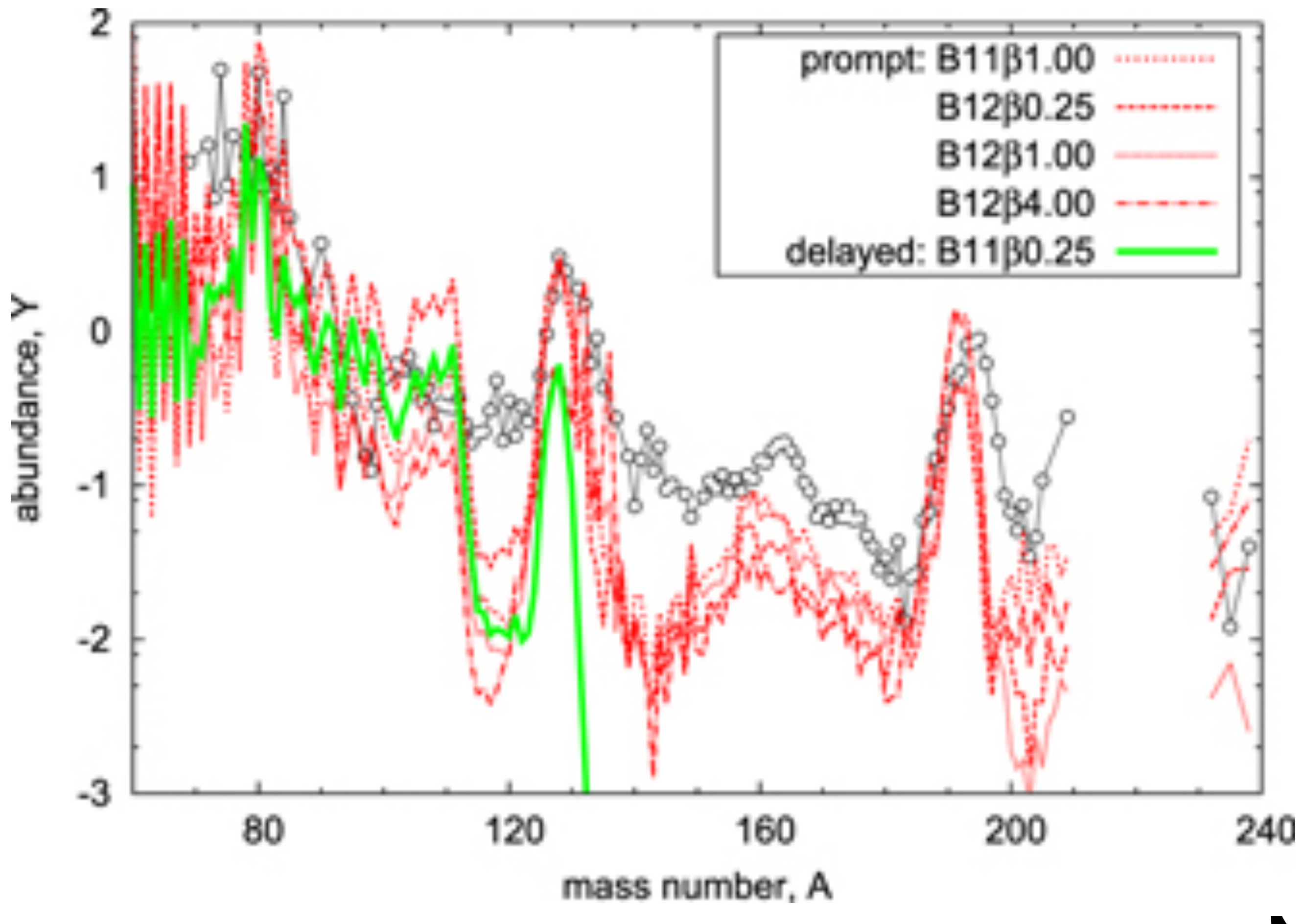
GRB-SNe as a *r*-process site?

- heavy element synthesis: a promising *r*-process site
- how the synthesized elements are ejected and distributed in SN?





Magneto-rotational CCSN: Mösta+ (2014)



Nishimura, Takiwaki, &Thielemann (2015)

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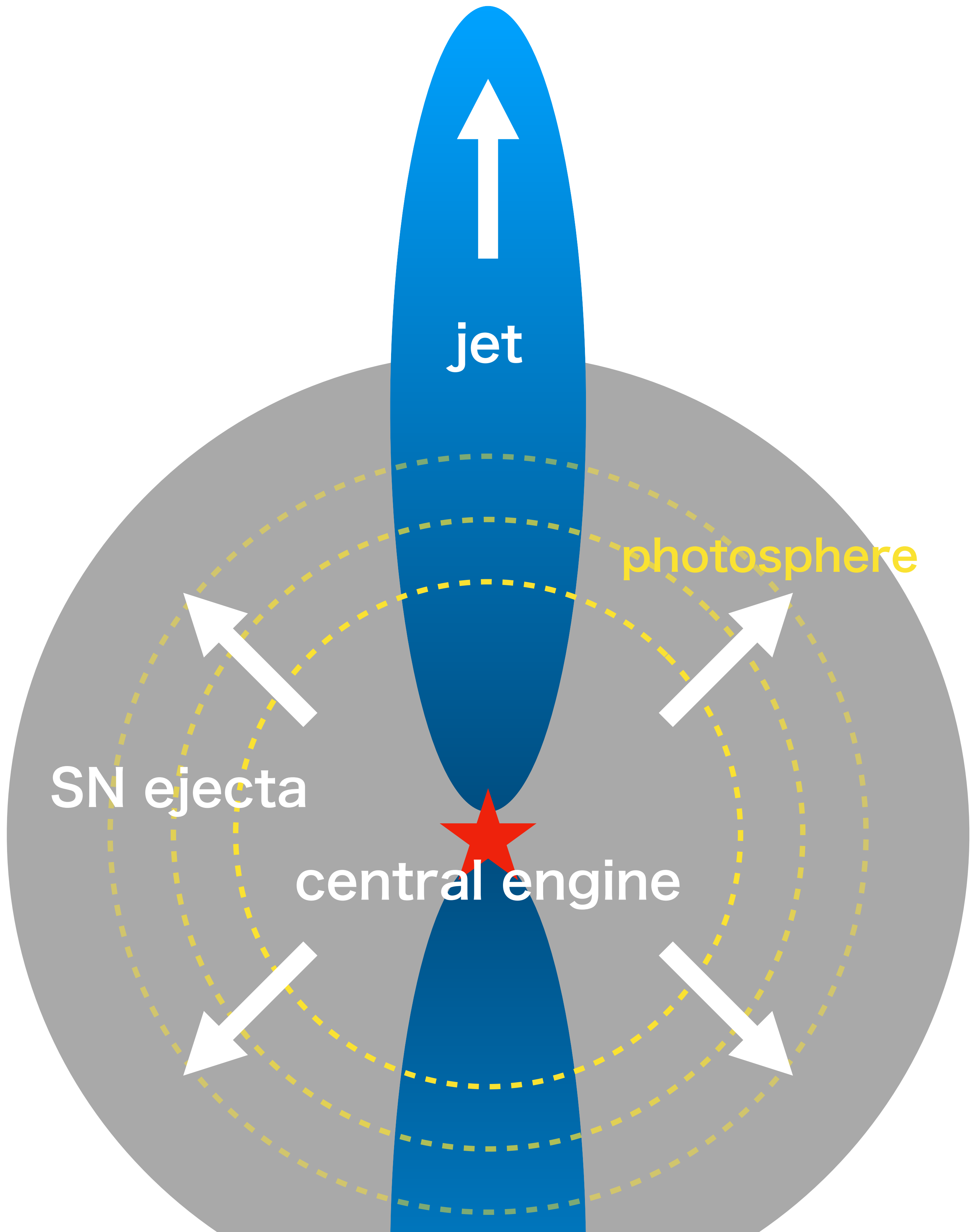
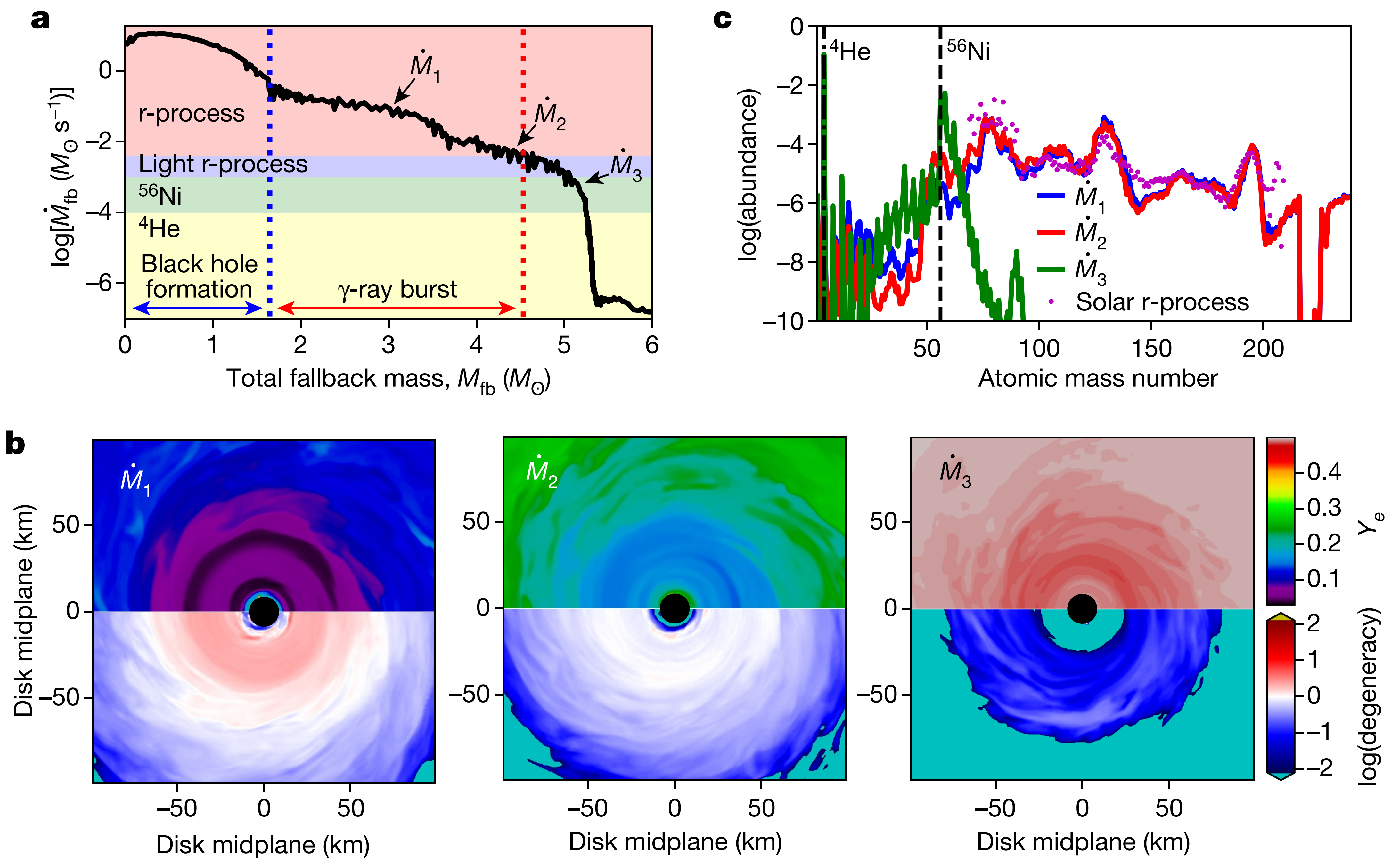


LETTER

https://doi.org/10.1038/s41586-019-1136-0

Collapsars as a major source of r-process elements

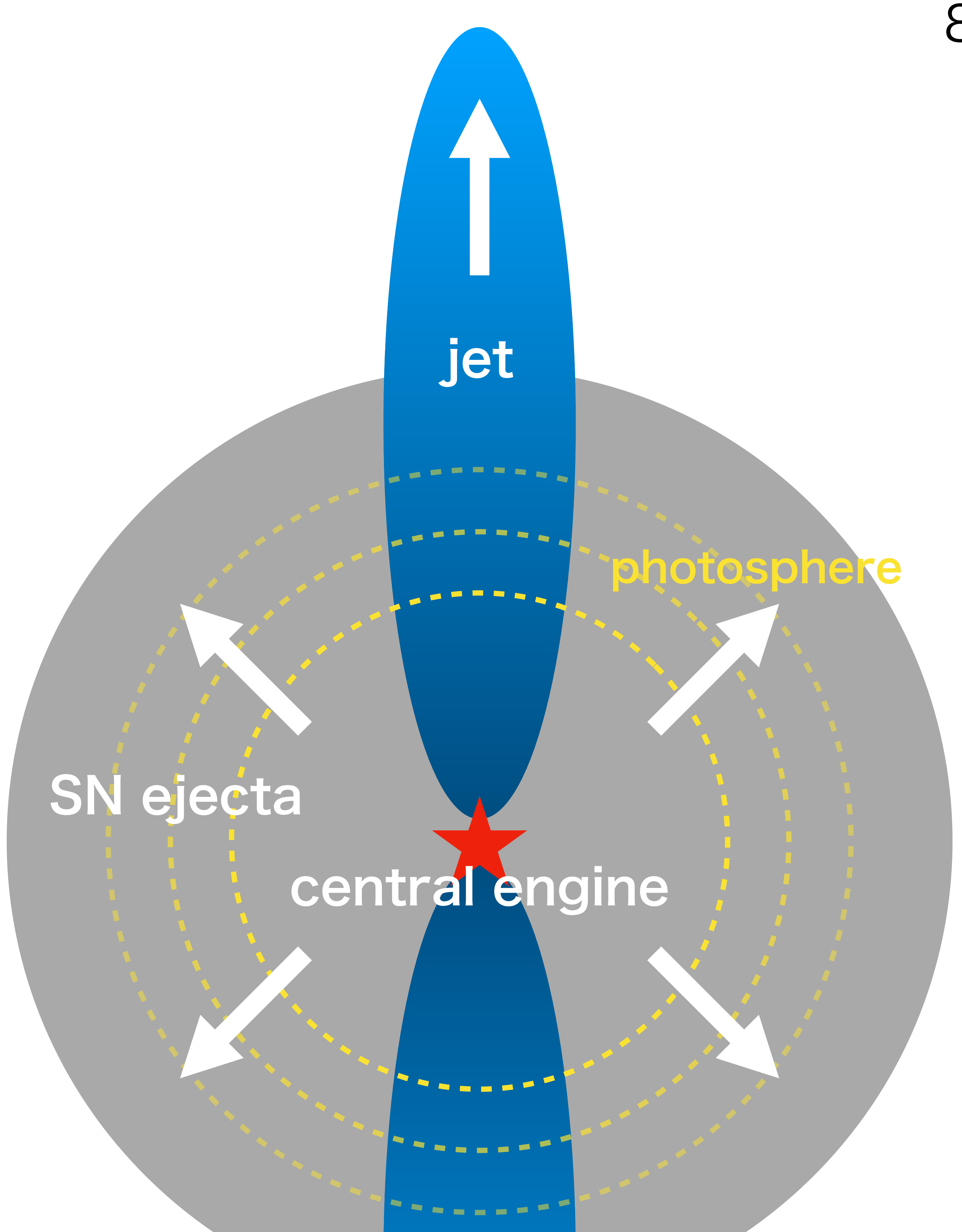
Daniel M. Siegel[1,2,3,4]*, Jennifer Barnes[1,2] & Brian D. Metzger[1,2]



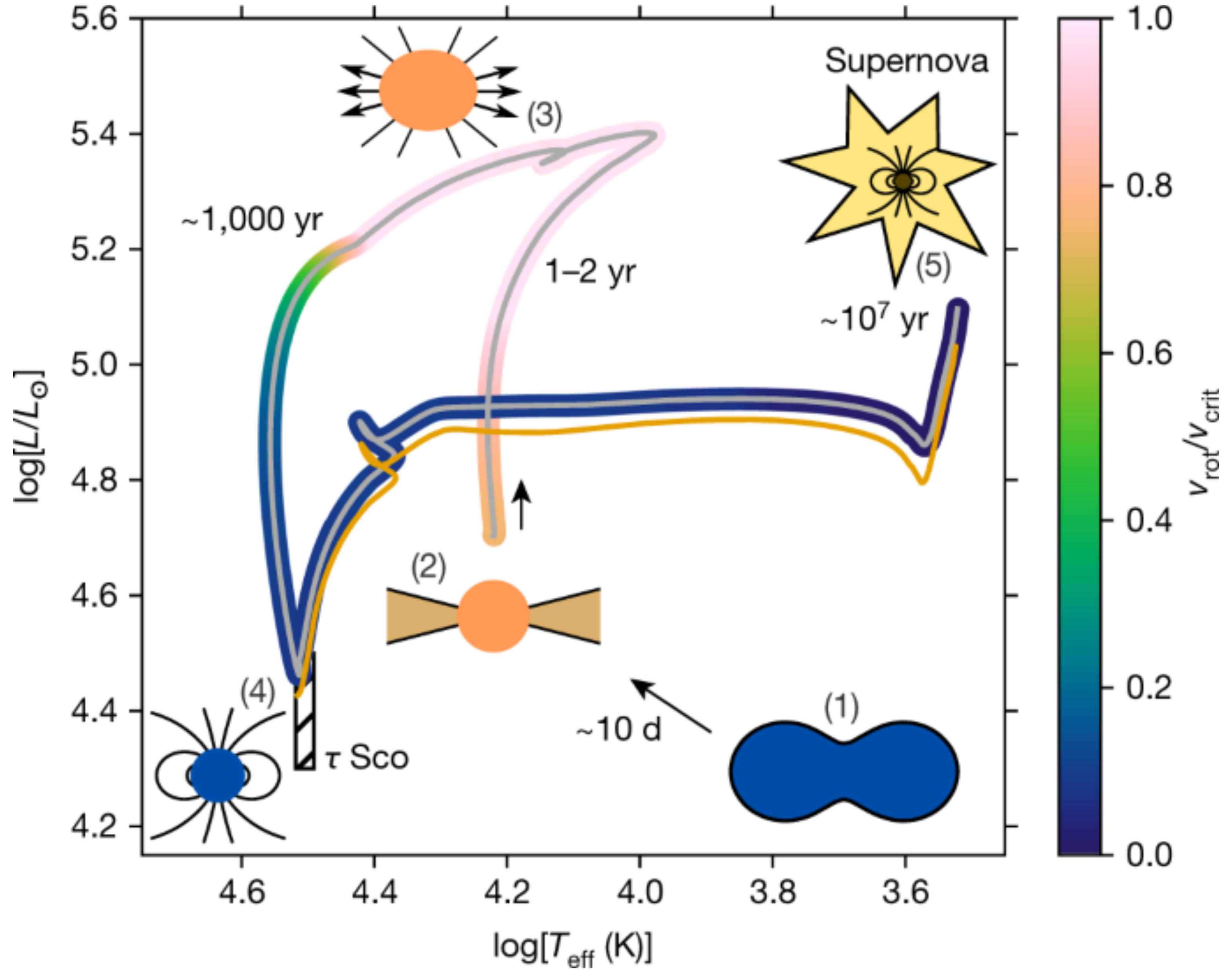
Siegel, Barnes, & Metzger (2019)

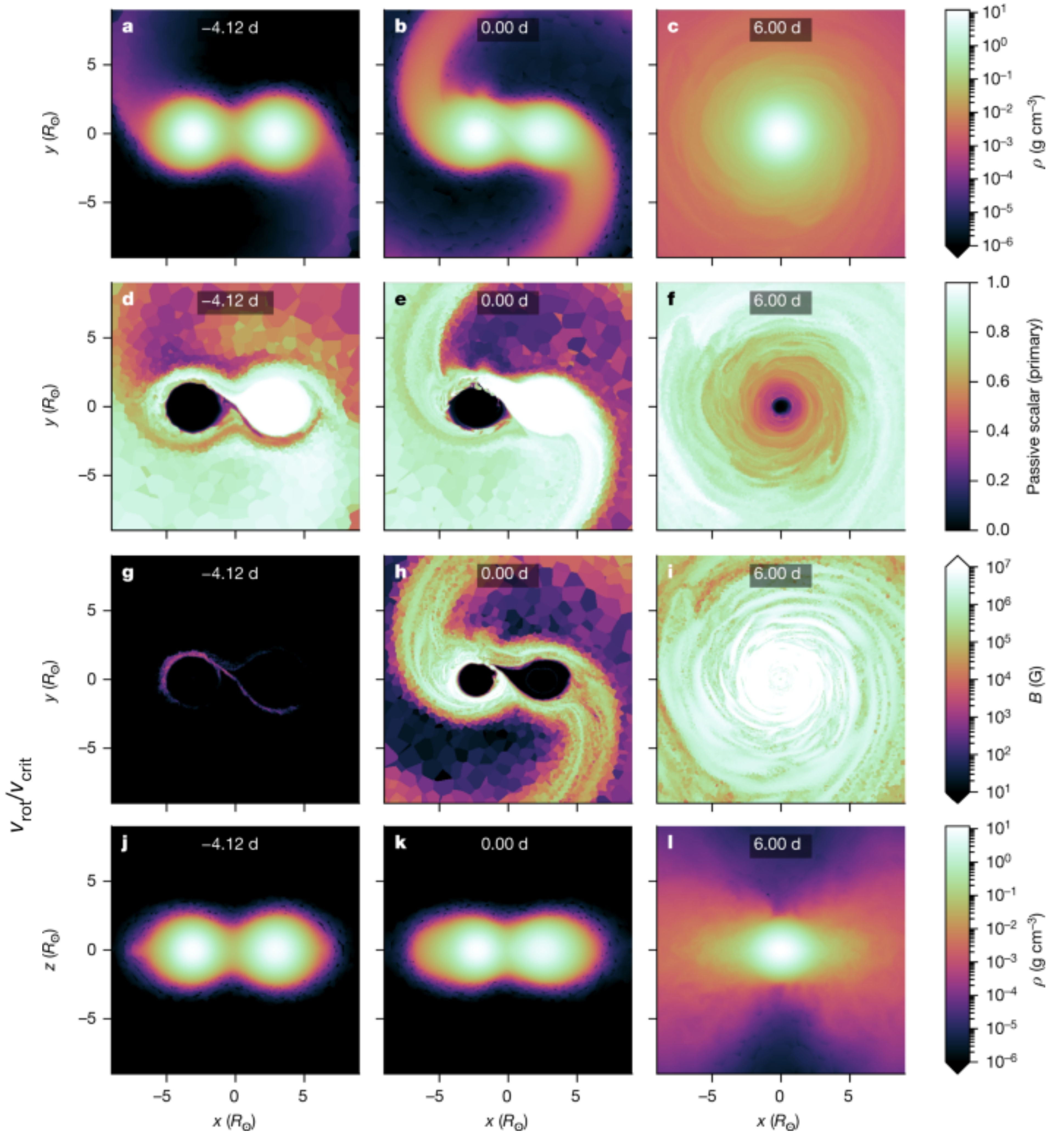
GRB progenitor and redshift evolution

- highly rotating CO star in low-metallicity enviroment
- mass-loss vs rotation → chemically homogeneous evolution?
- stellar merger?



$8M_{sun}$+$9M_{sun}$ stellar merger producing
a rotating massive star
Schneider+ (2019)

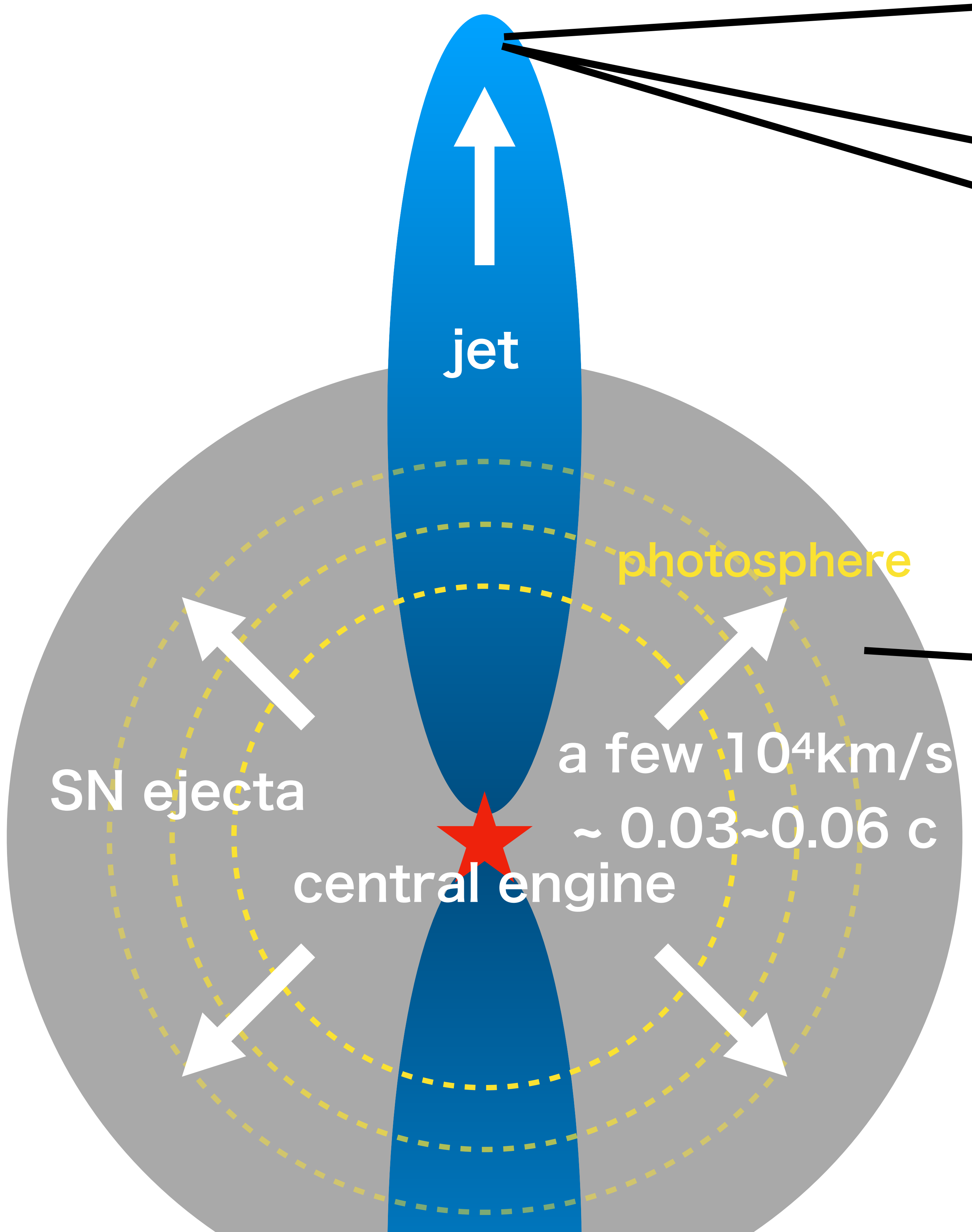




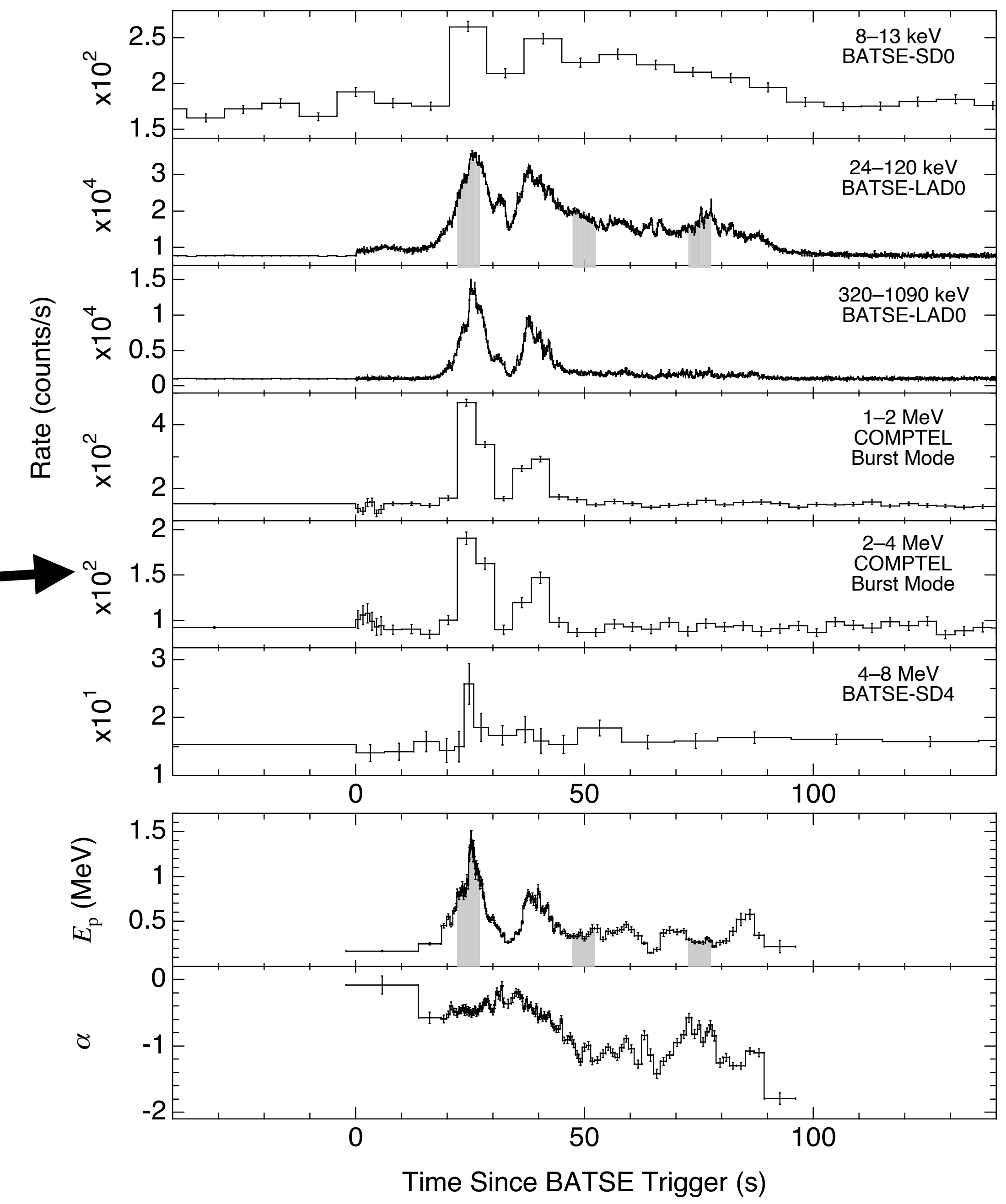
GRB jet unveiled by multi-wavelength observations

Gamma-ray bursts

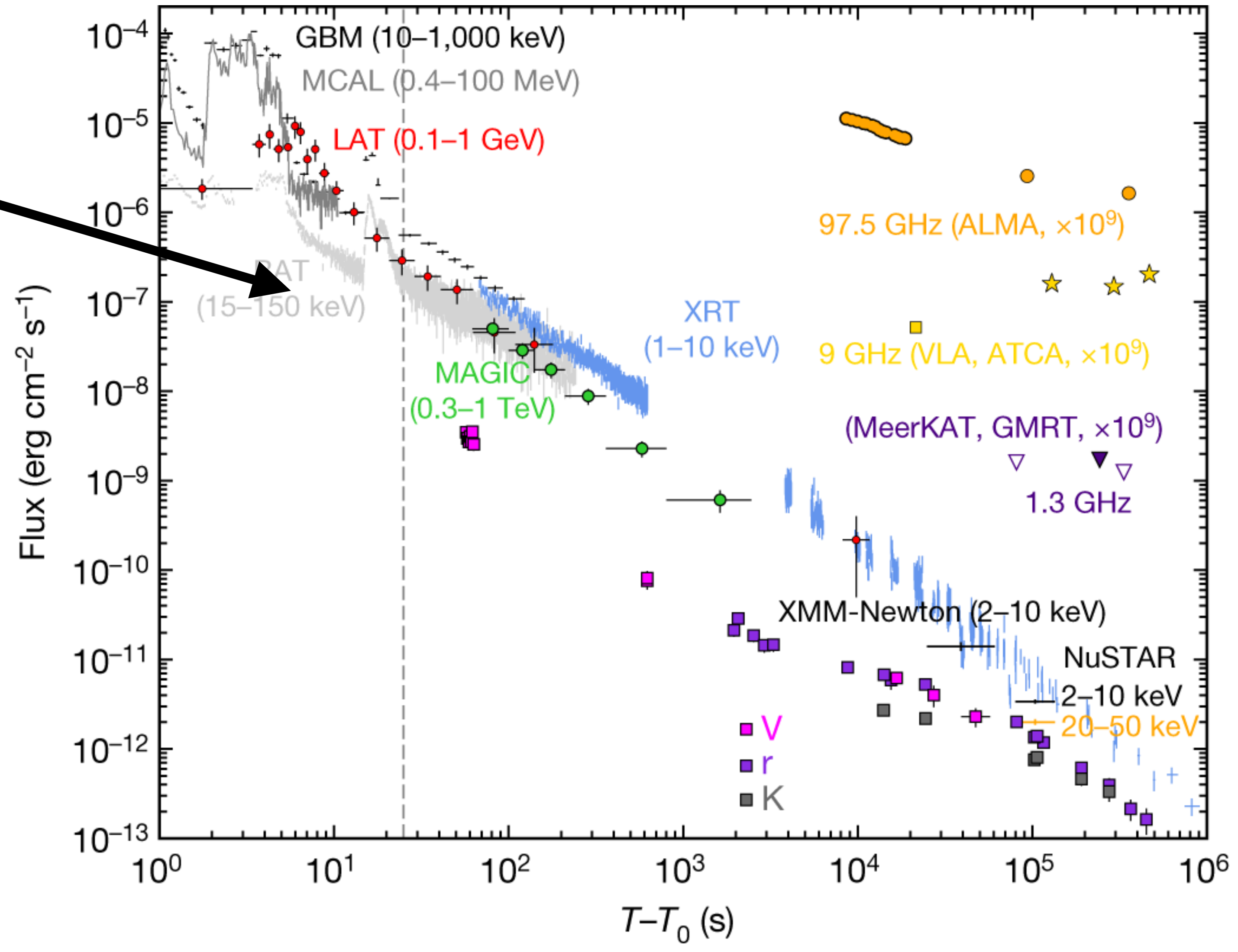
- multi-wavelength observations are essential
- prompt γ-ray detection
- afterglow from radio to TeV



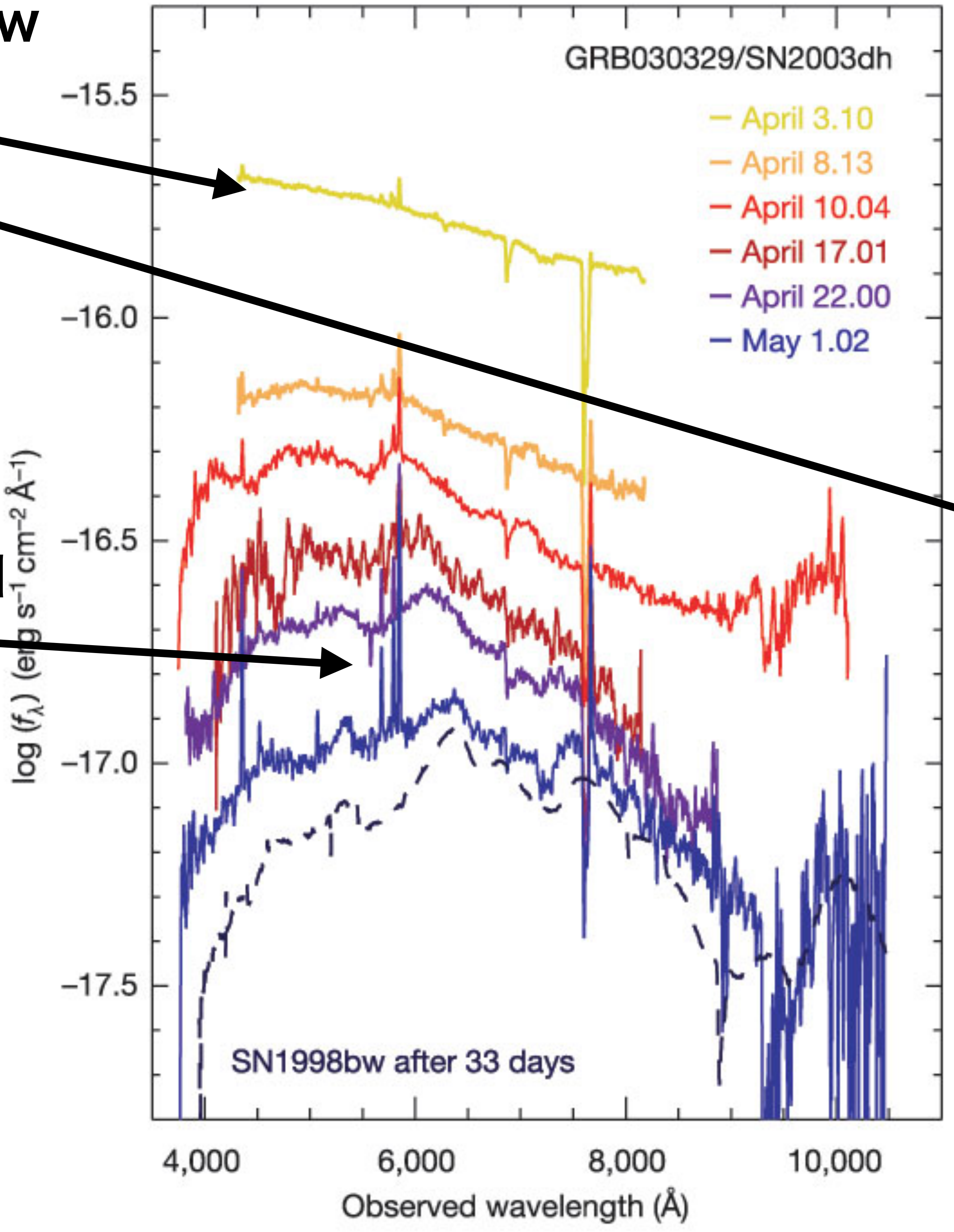
Prompt



Afterglow

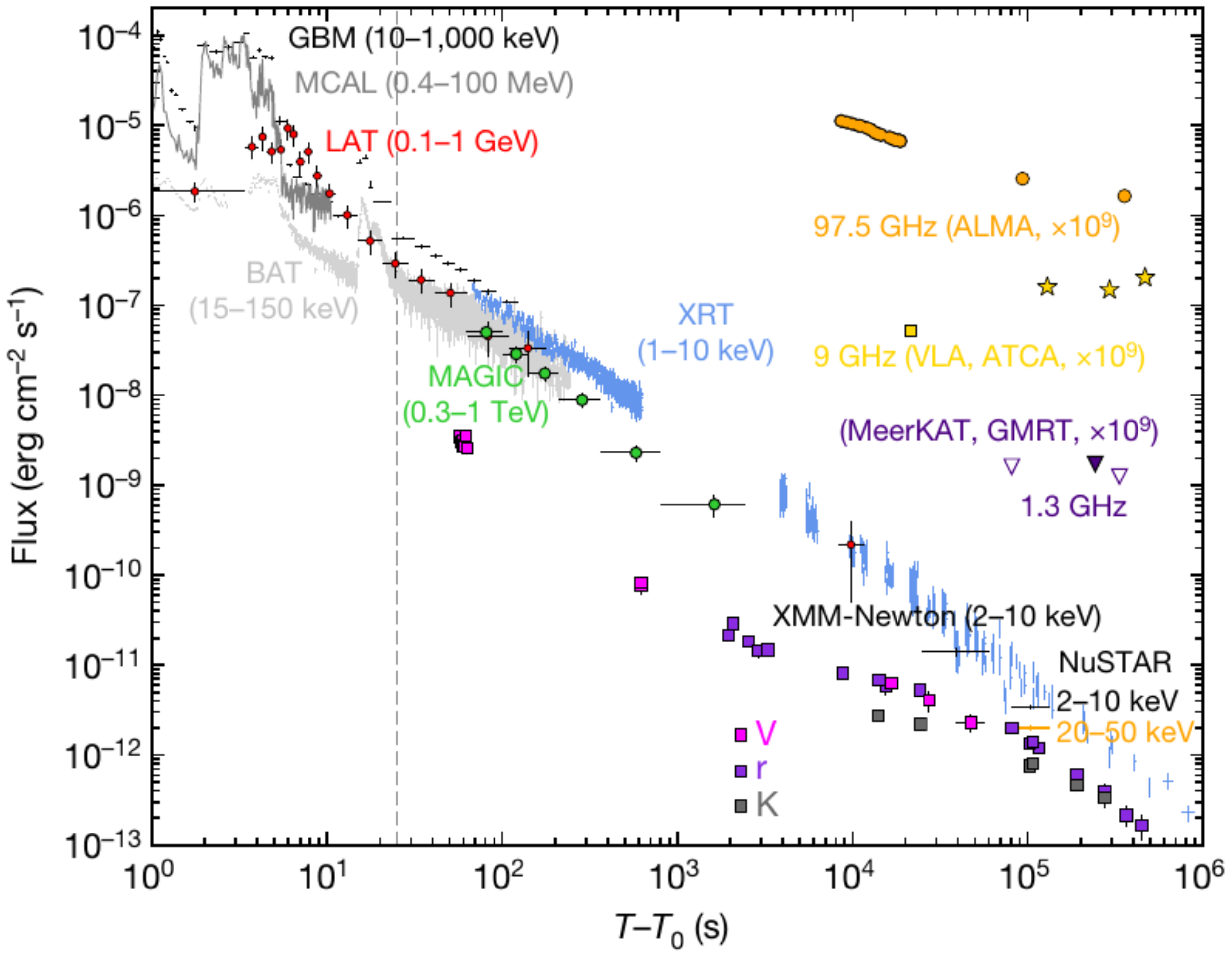


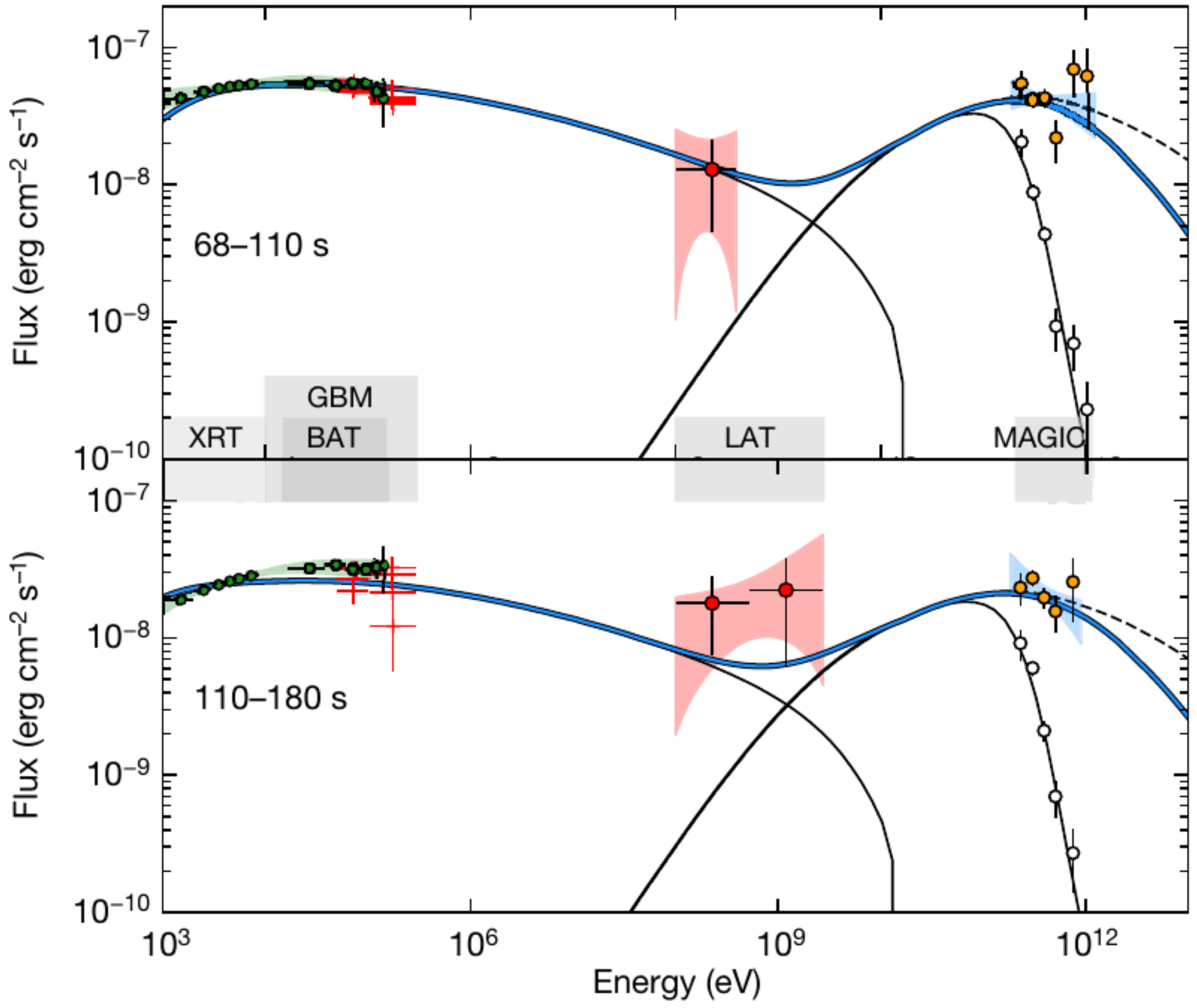
Thermal



(sub)TeV-detected GRBs

- GRB 190114C, 189726C, 190829A, ……
- likely Synchrotron Self-Compton
- GRB 190829A as an off-axis event?





Multi-wavelength light curves of GRB 190114C, Magic collaboration+(2019)

(sub)TeV-detected GRBs

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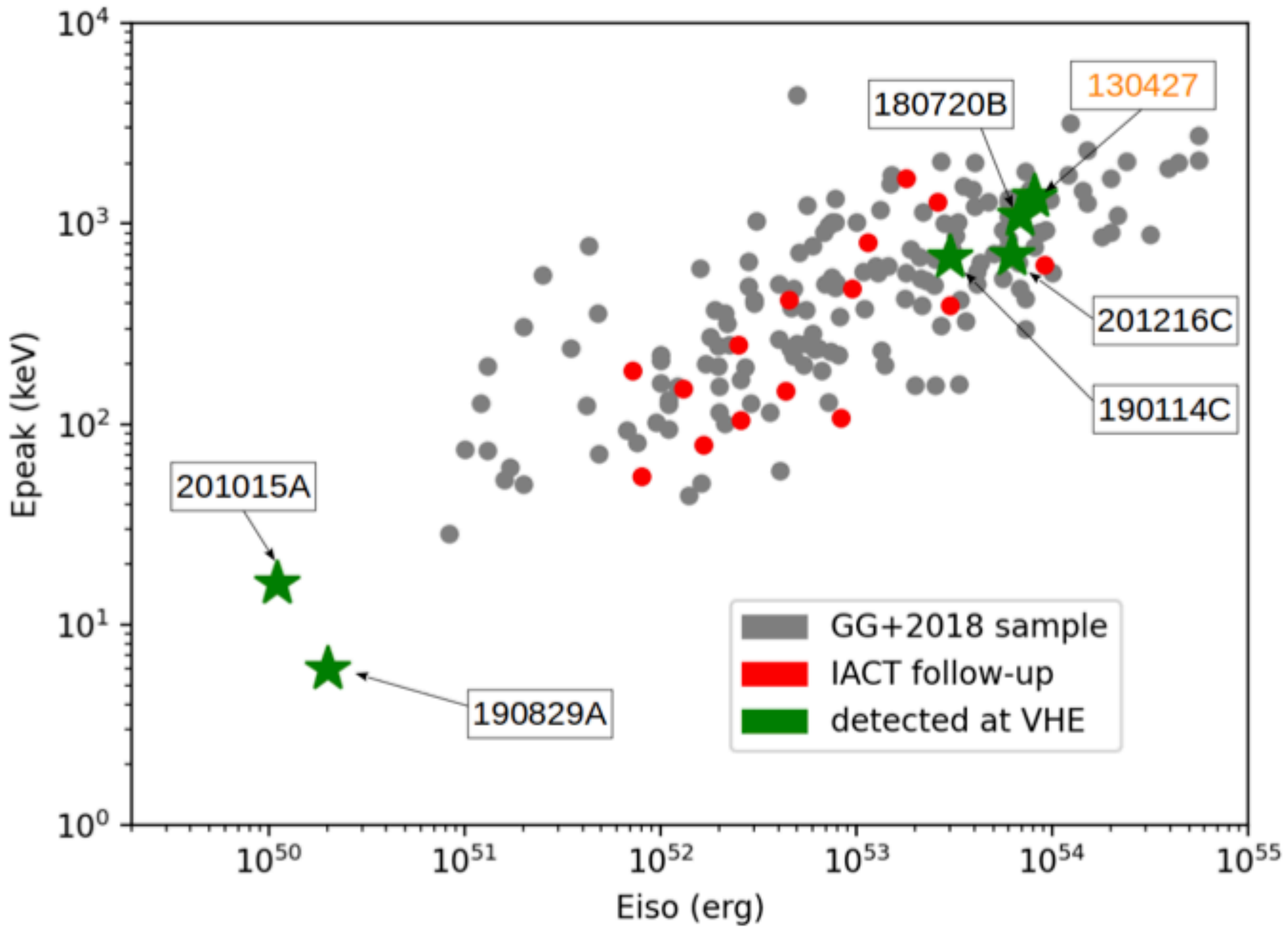
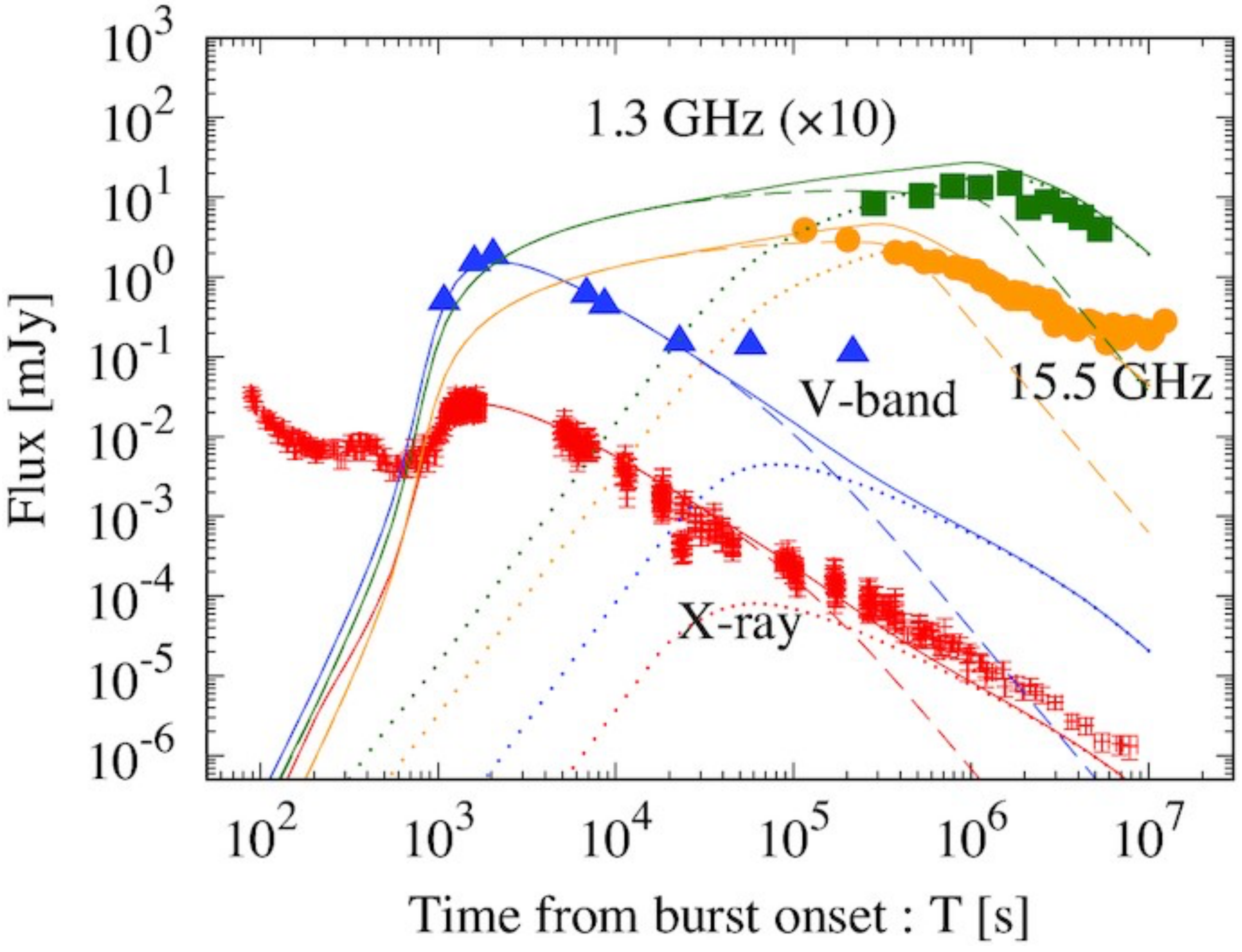
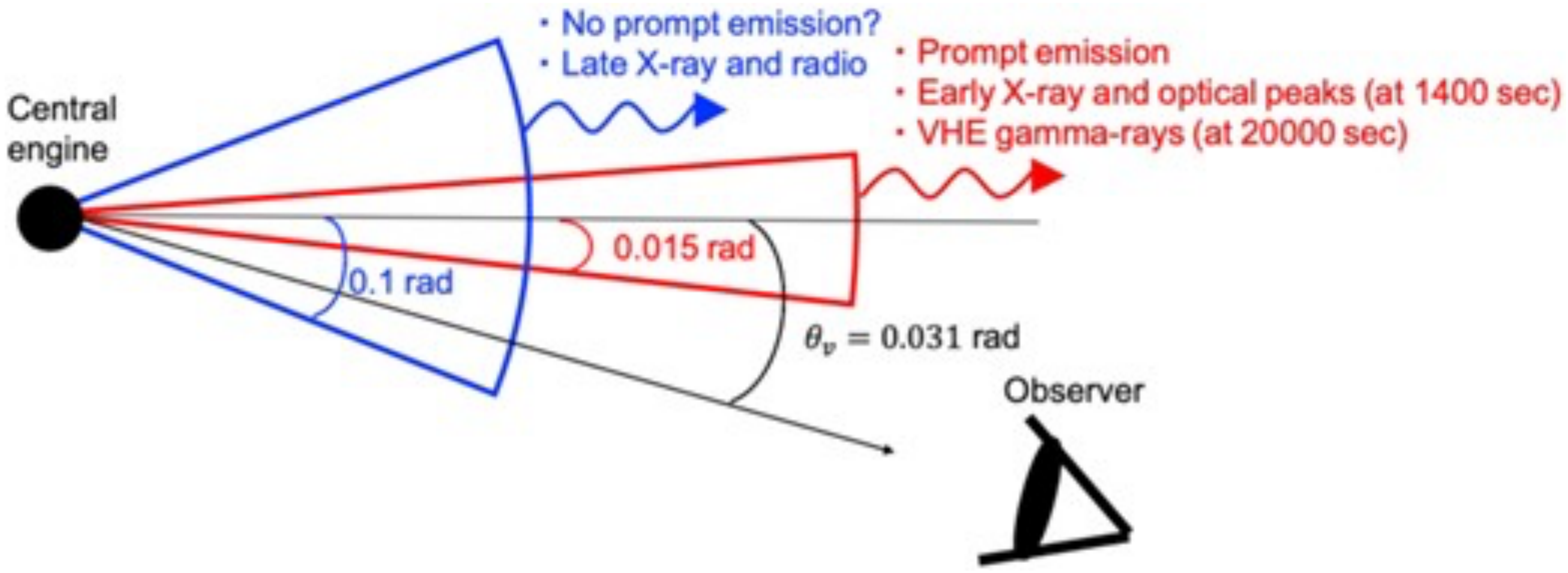
VHE GRBs. Carosi+(2021. arXiv:2108.04309)



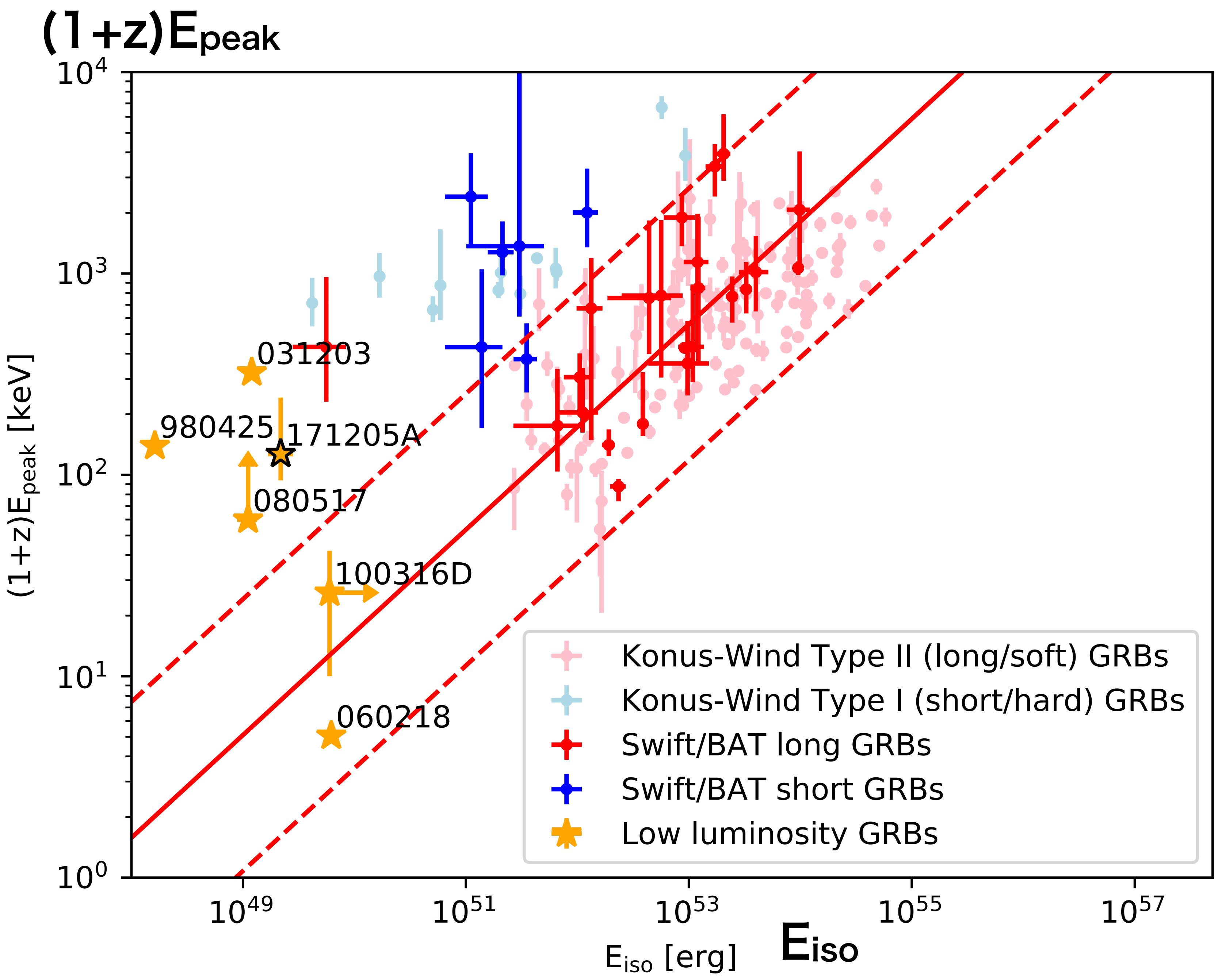




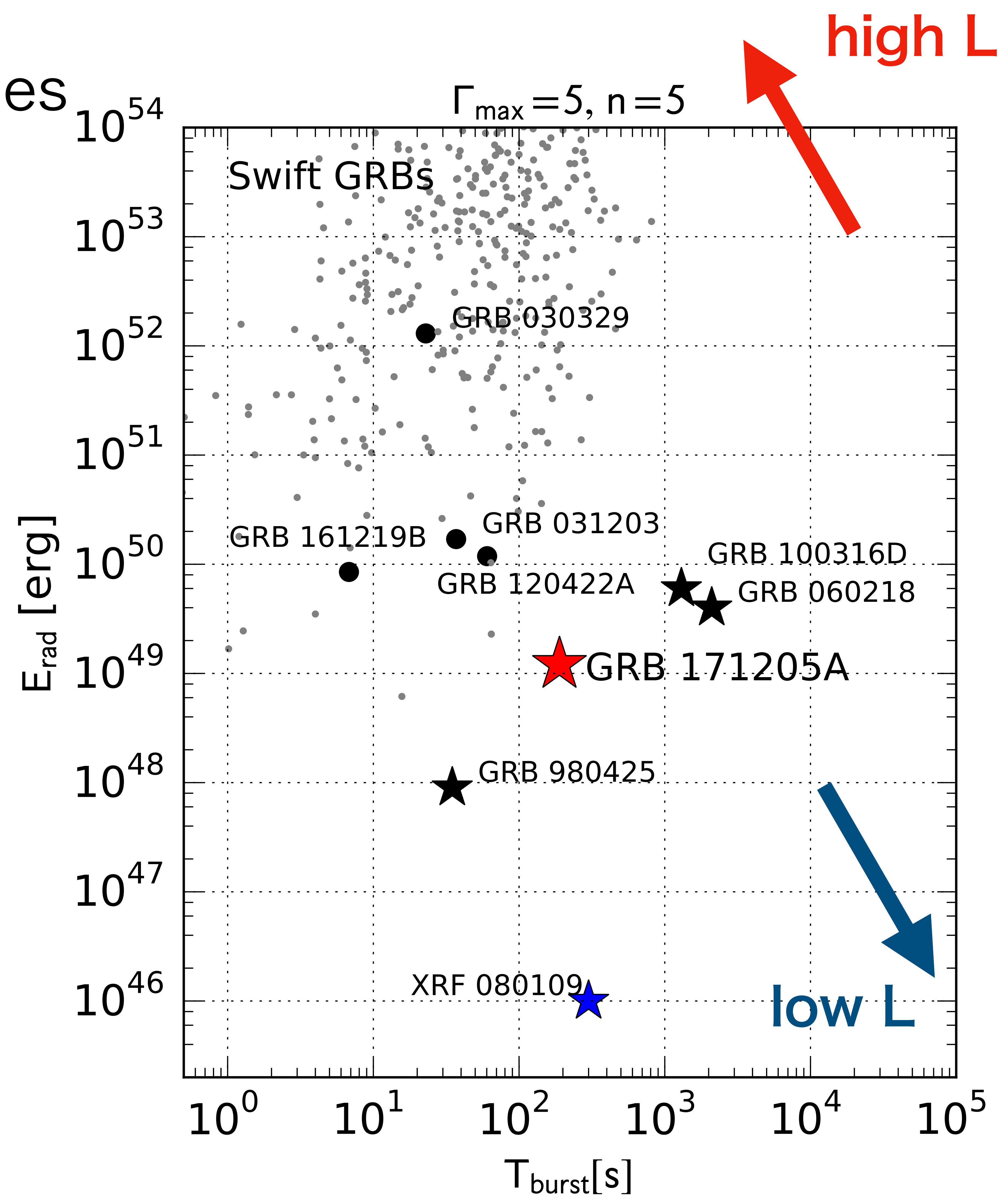
Multi-wavelength light curves modeling of GRB 190829A, Sato+(2021)

low-luminosity GRB as off-axis GRB?

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



D'Ellia+(2018)



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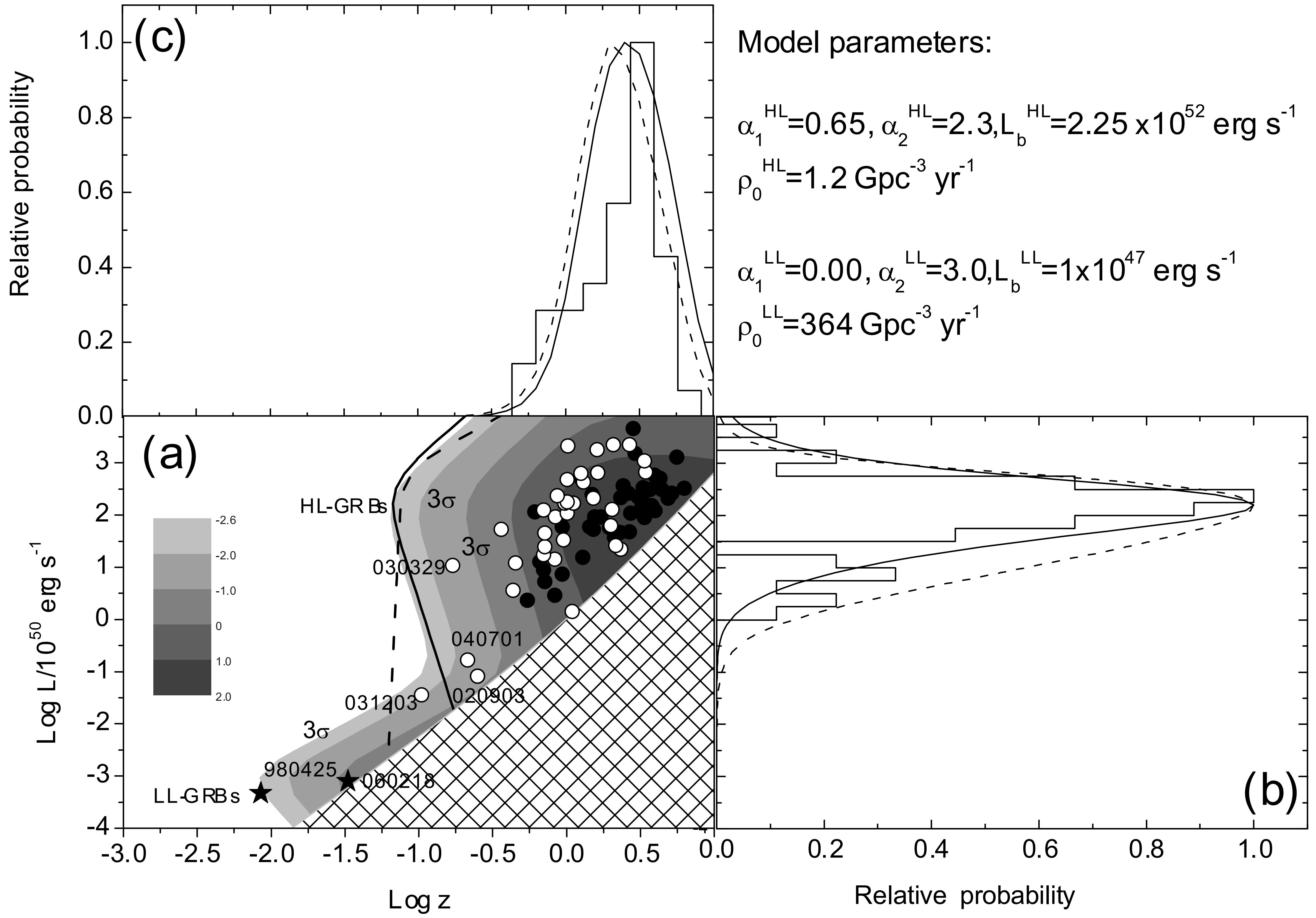

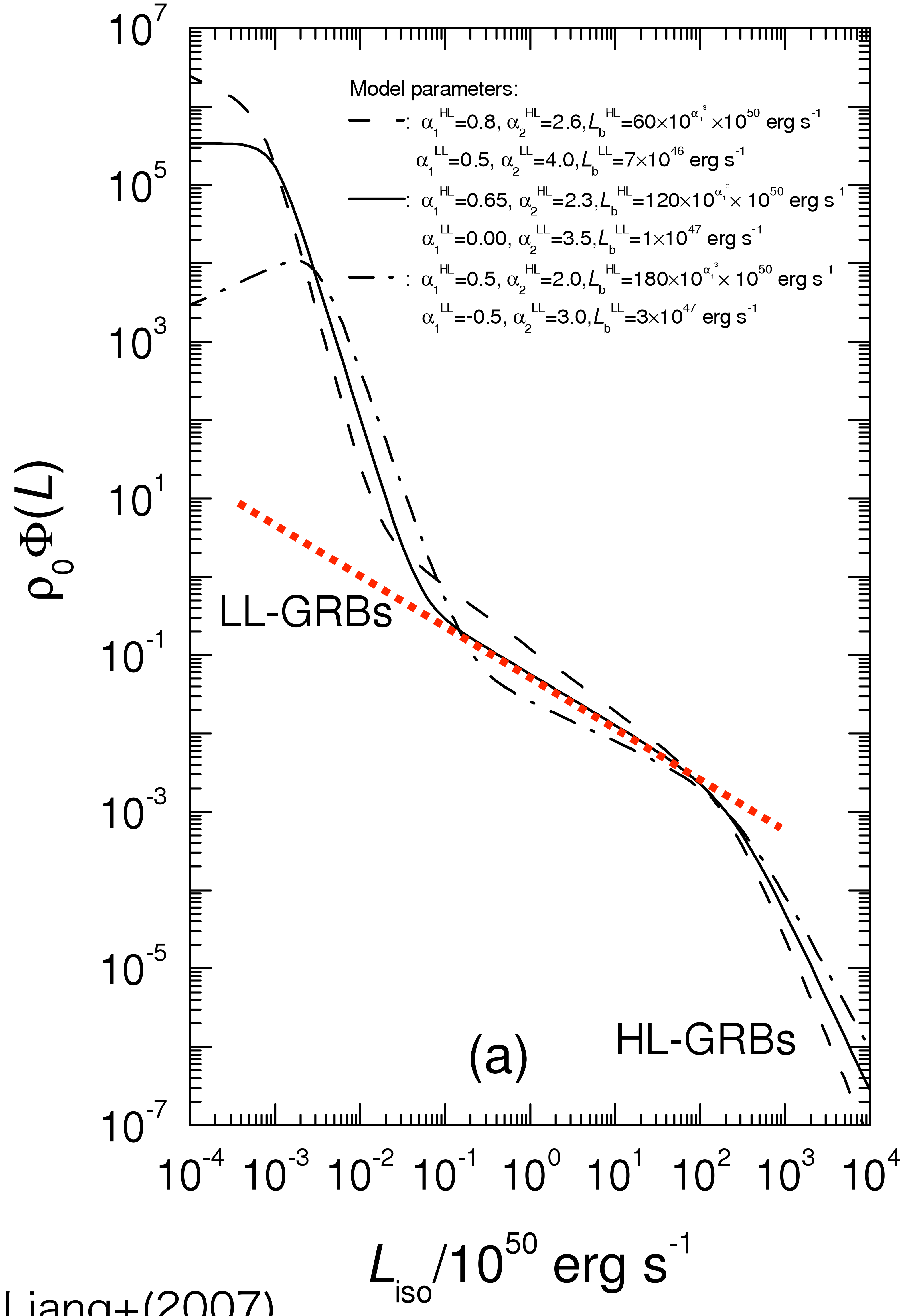

Liang+(2007)

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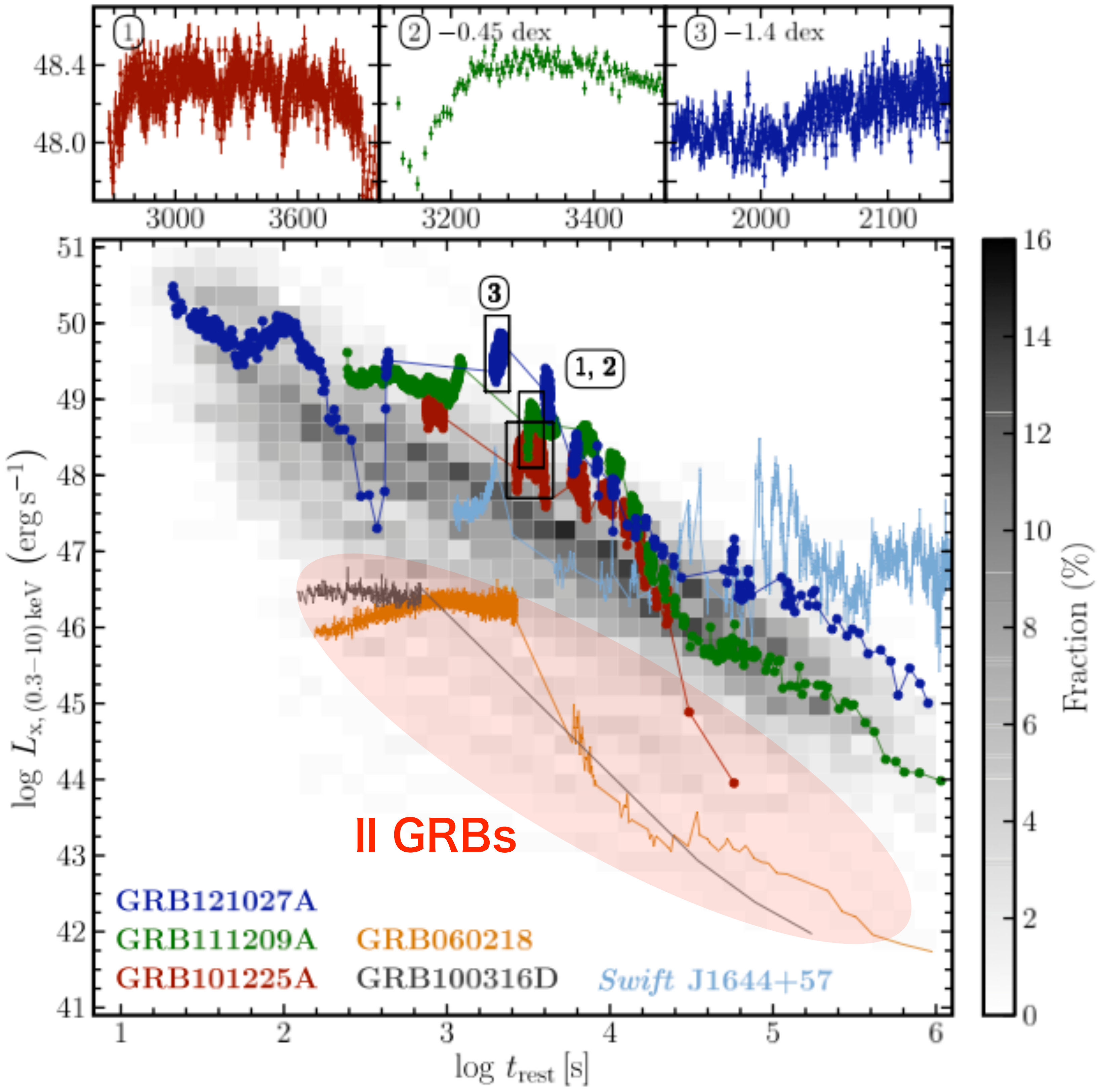
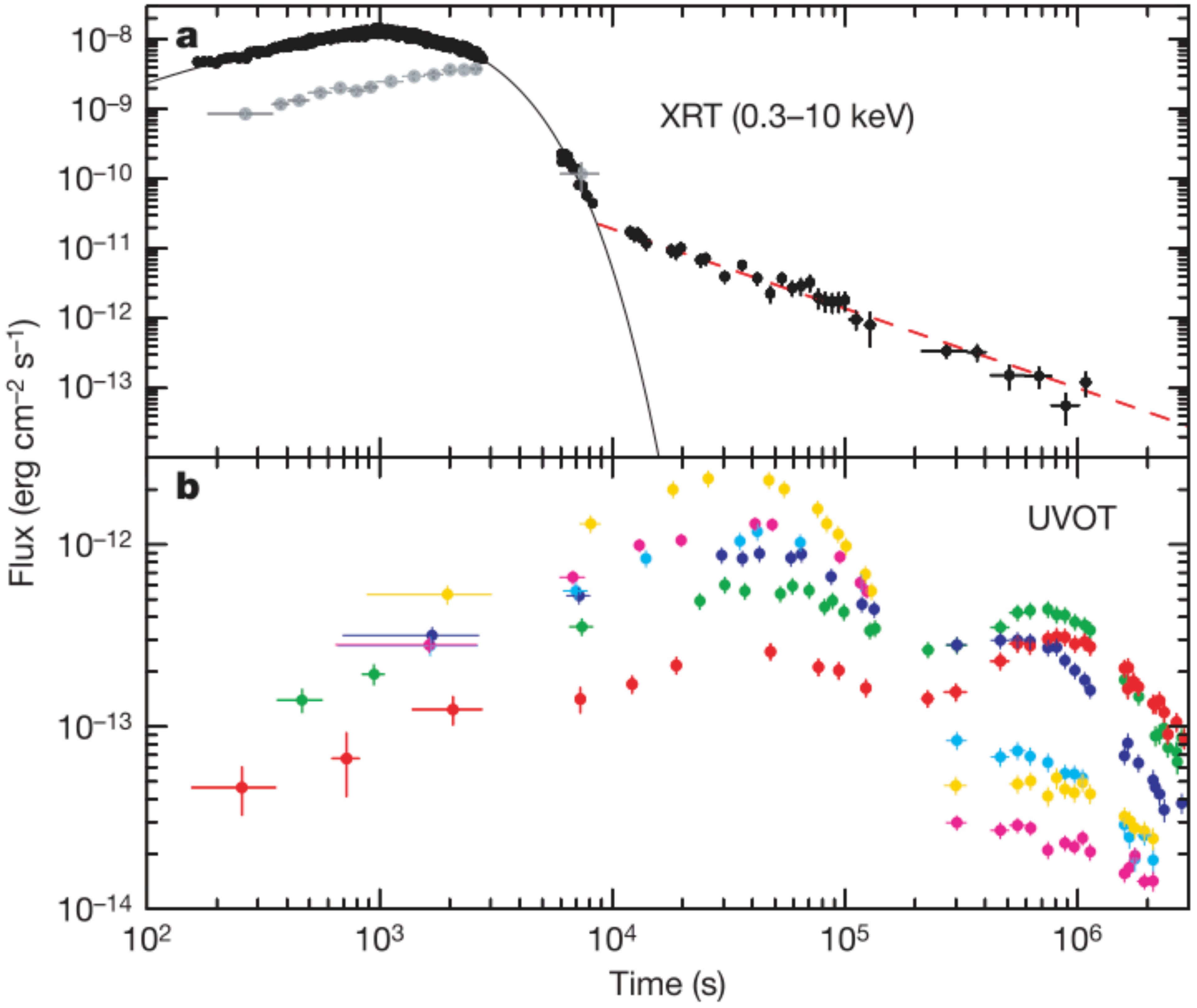


Levan+(2013)



Campana+(2006)

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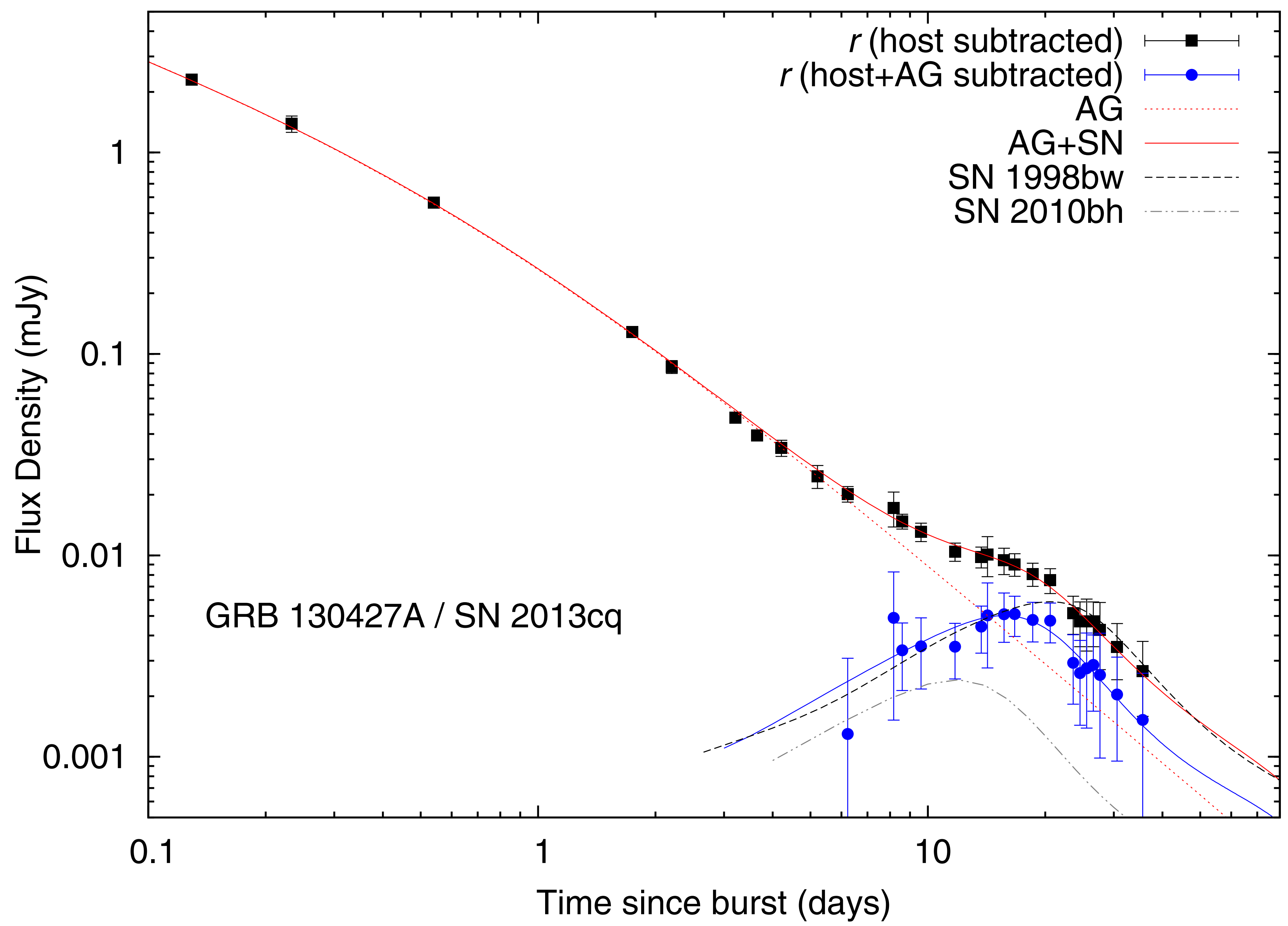
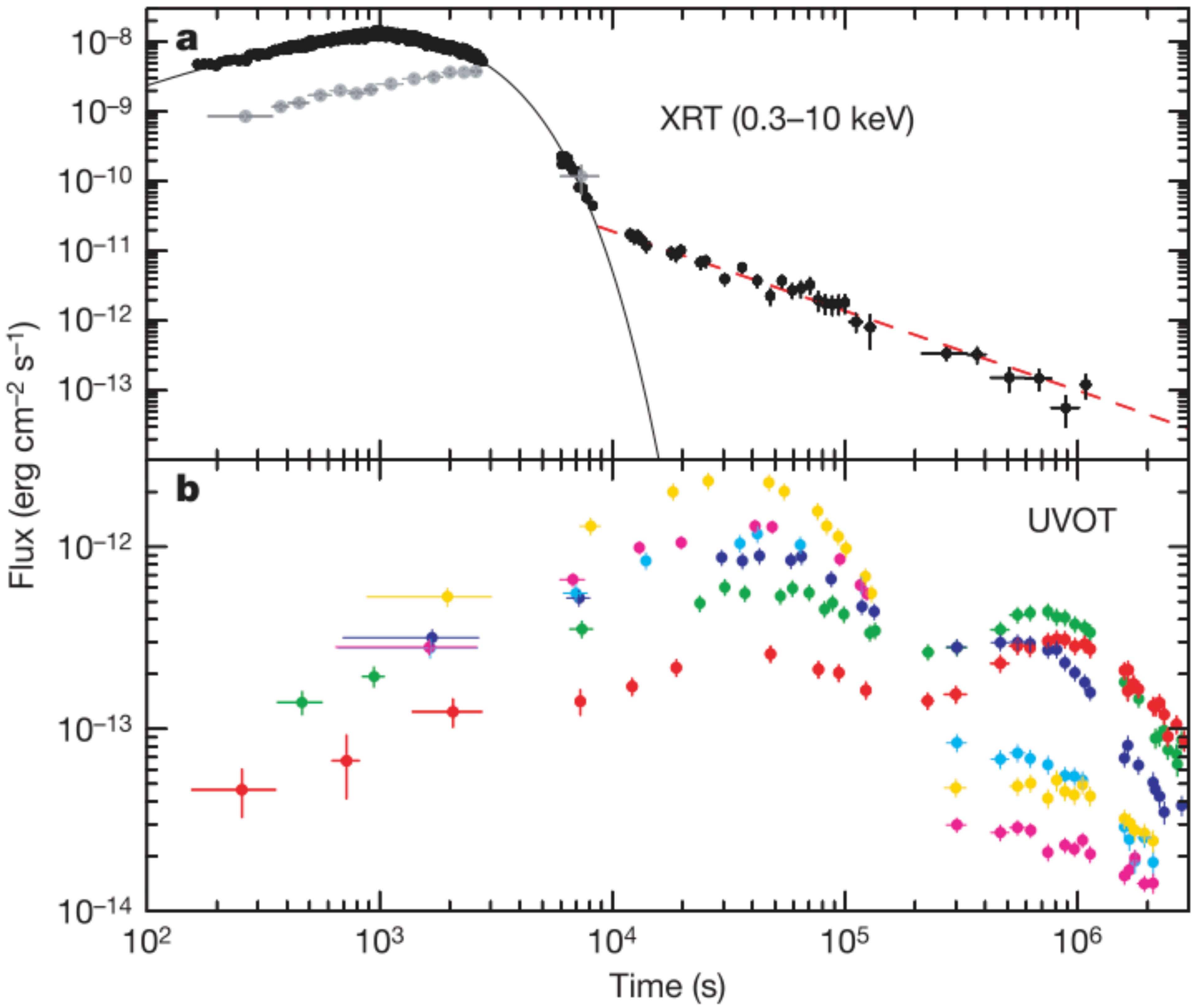


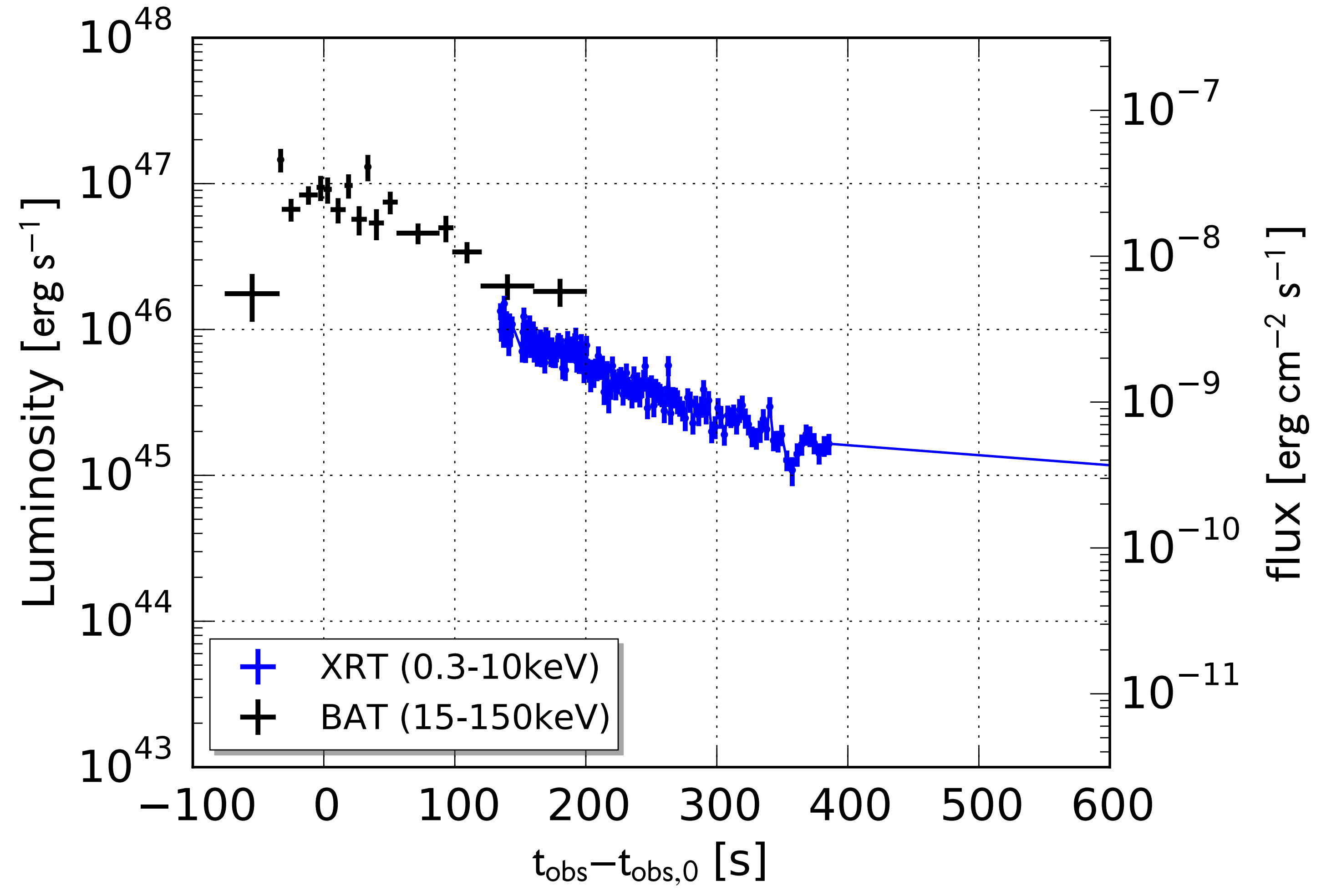
r-band light curve of GRB 130427A/SN 2013cq, Xu+(2013)

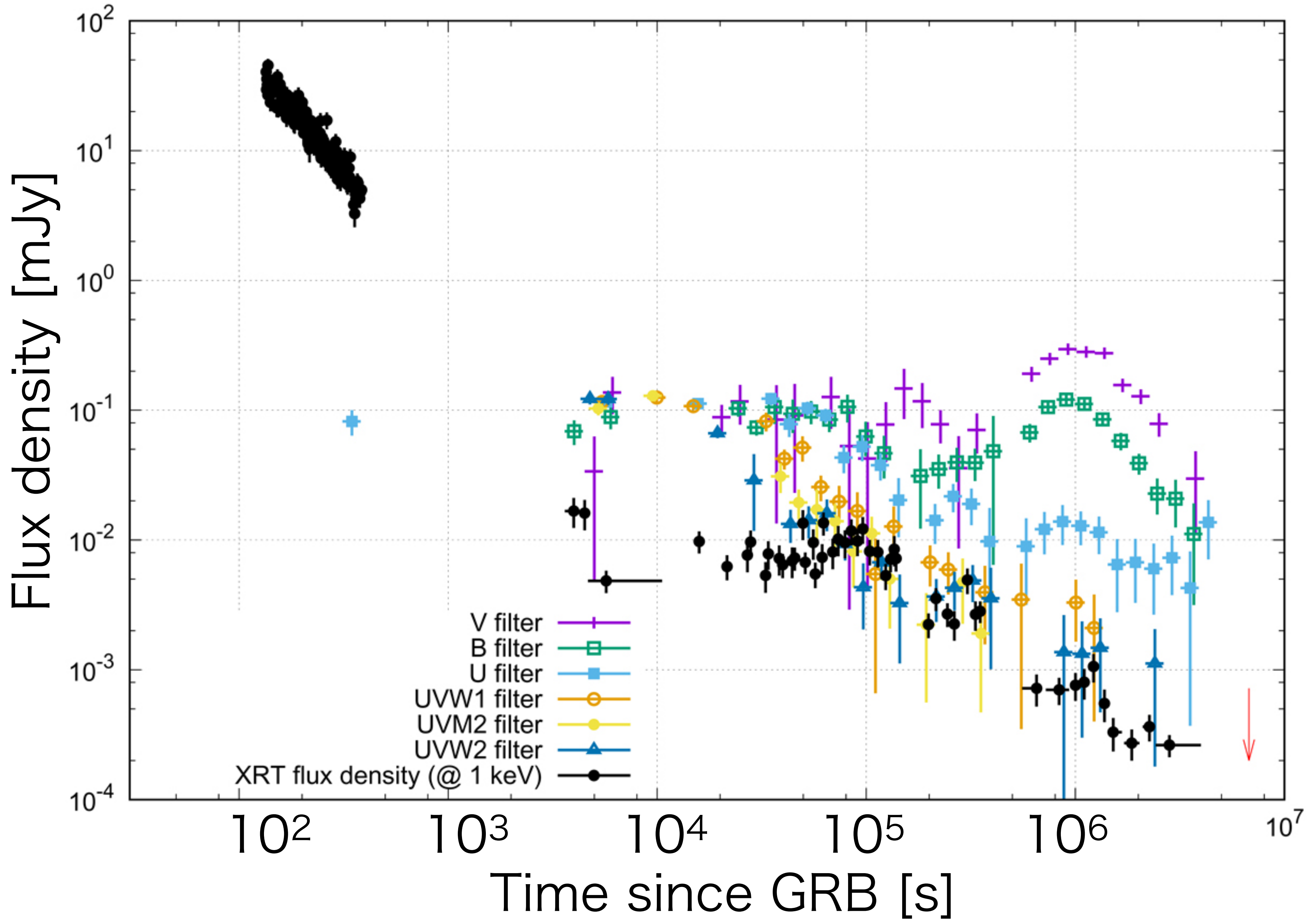


Campana+(2006)

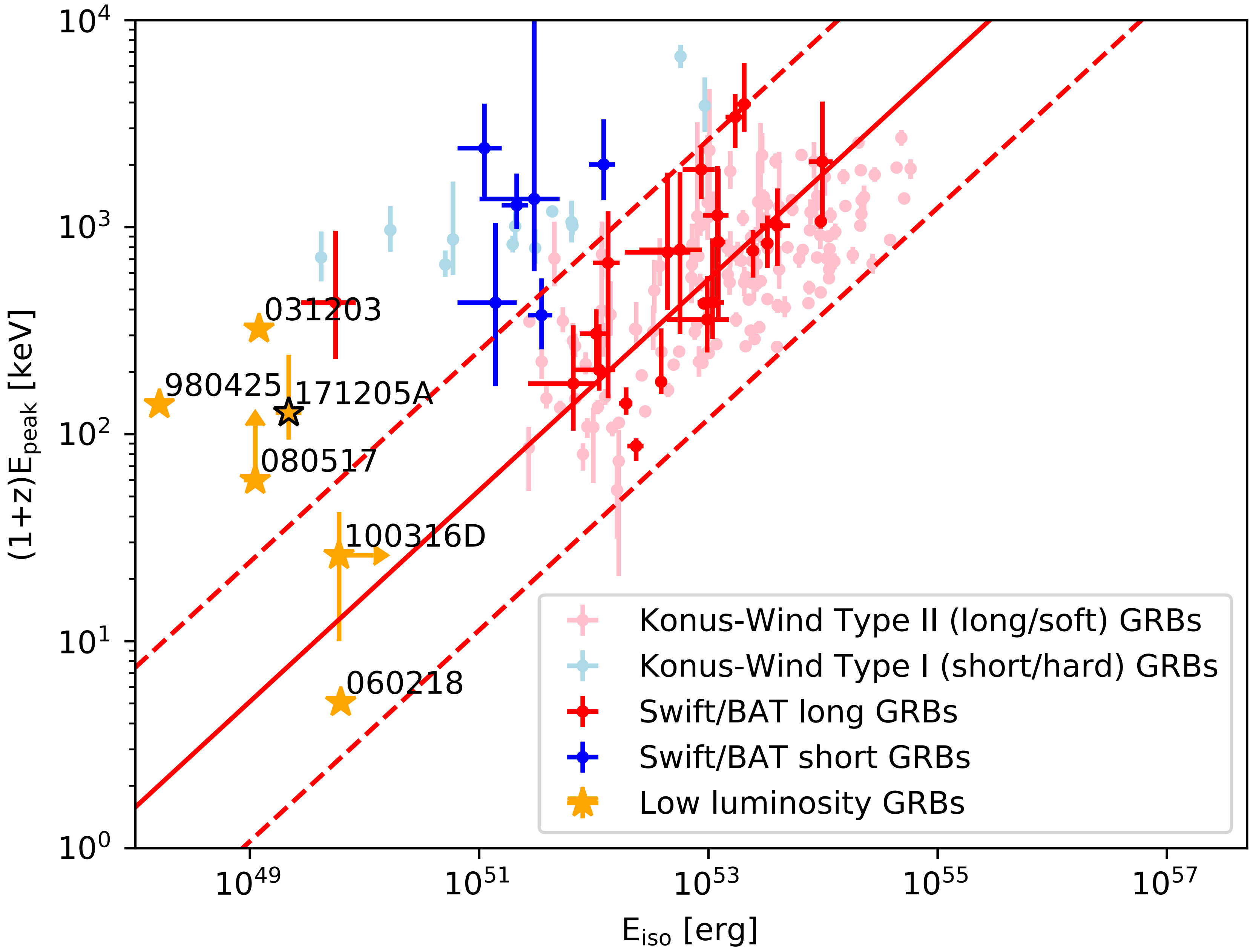
GRB 171205A: a GRB-SN in very early stage

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





(1+z)Epeak



Eiso

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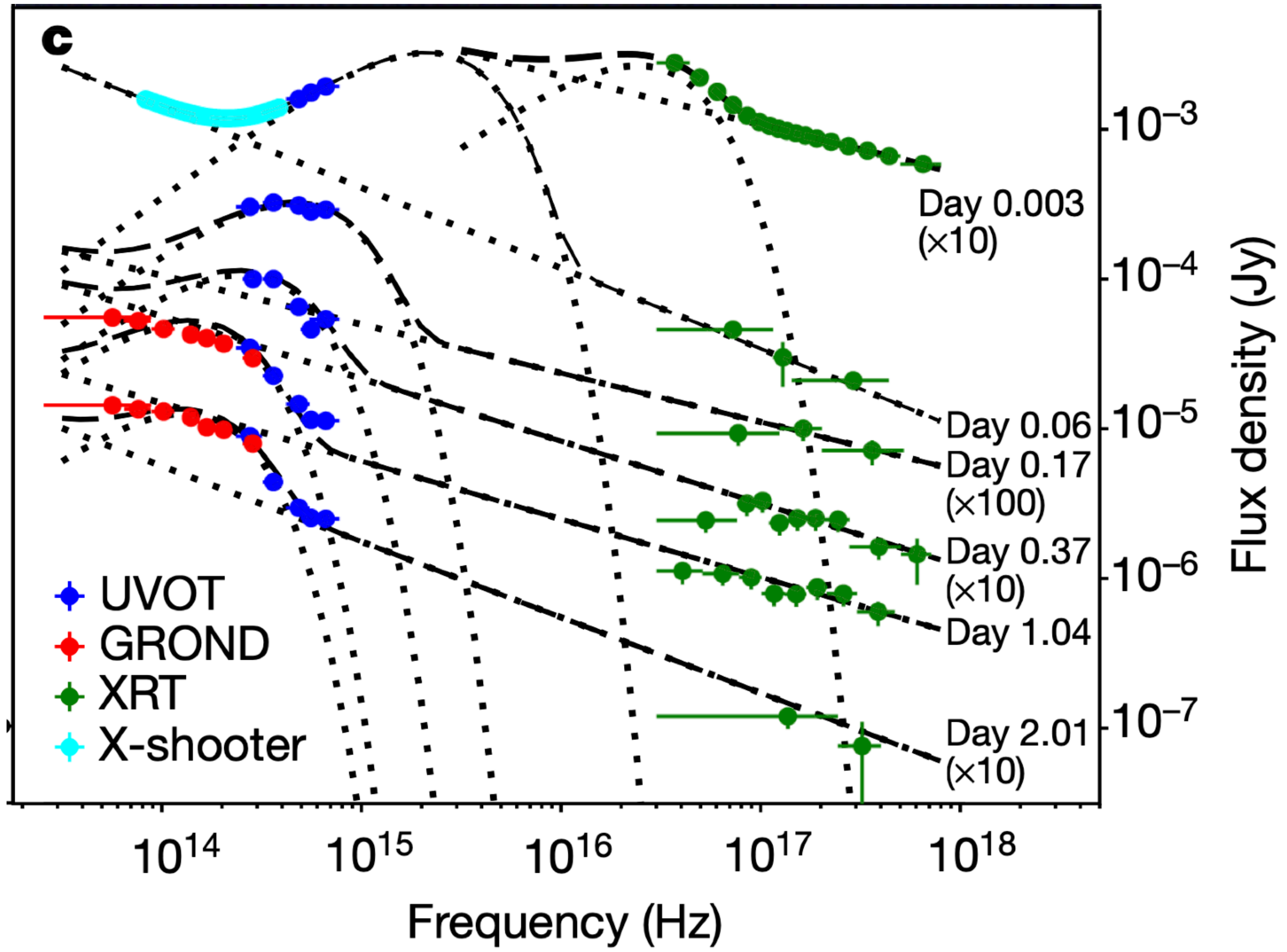

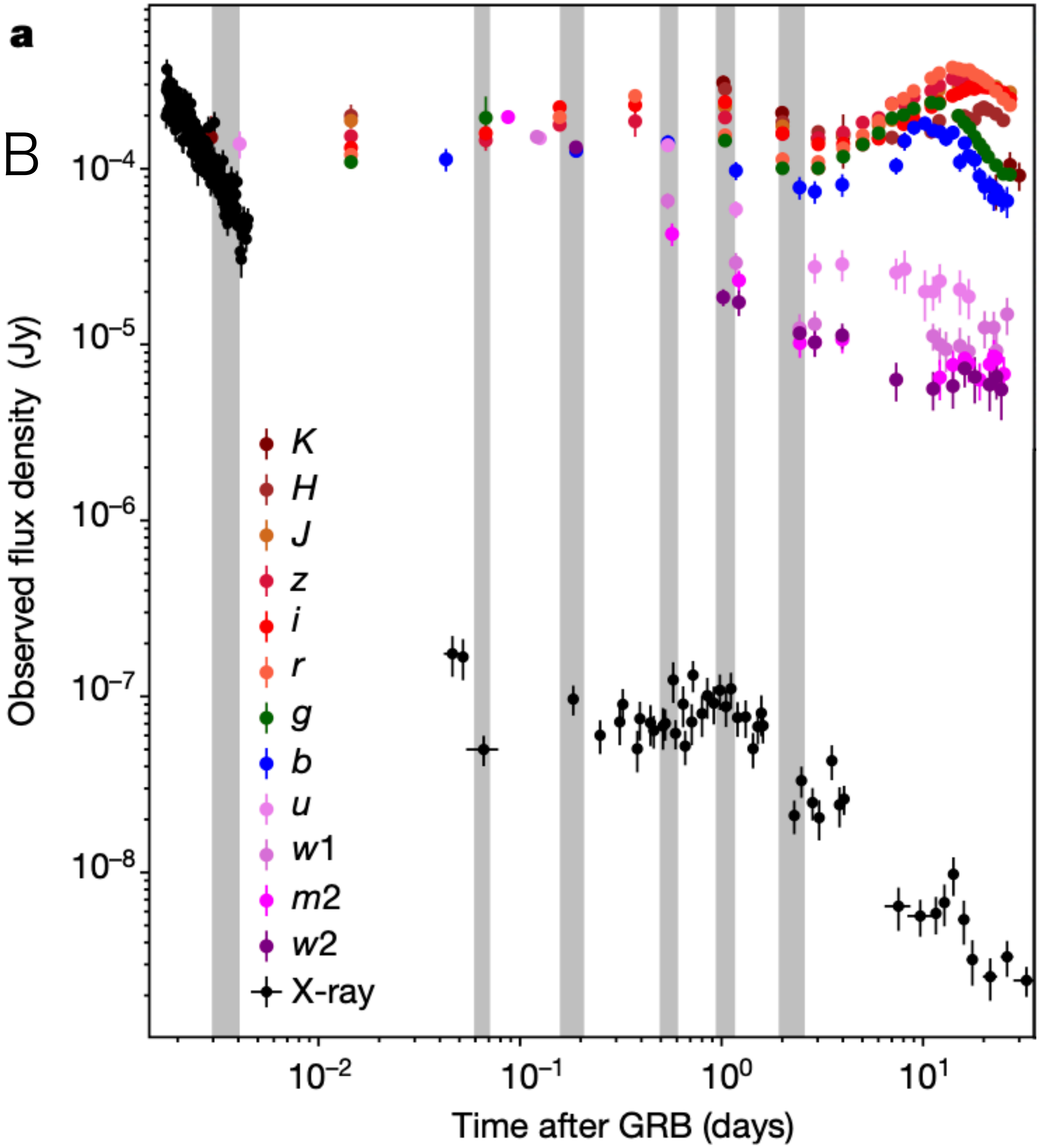

Izzo+ (2019, Nature) including K. Maeda & AS

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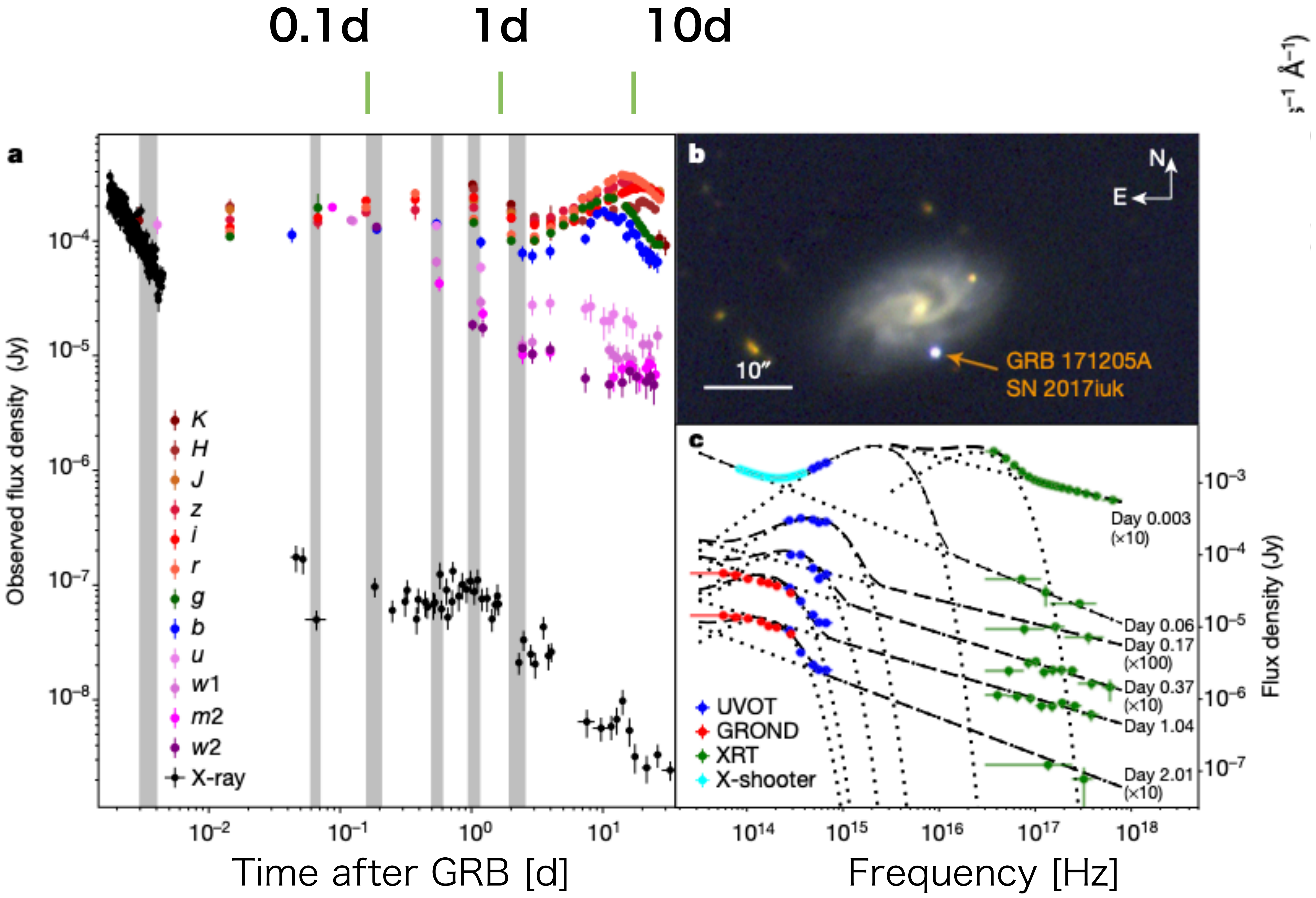

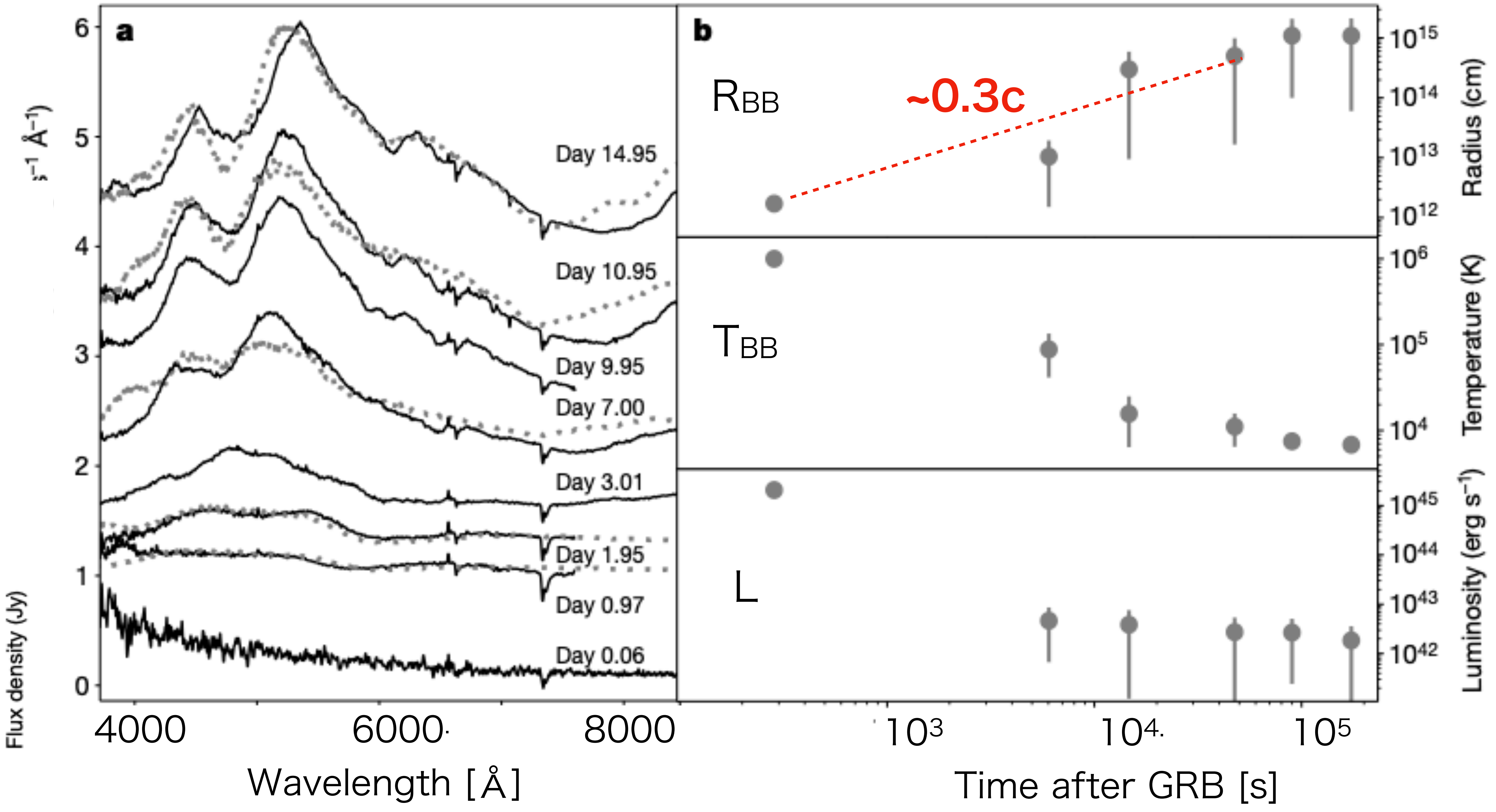

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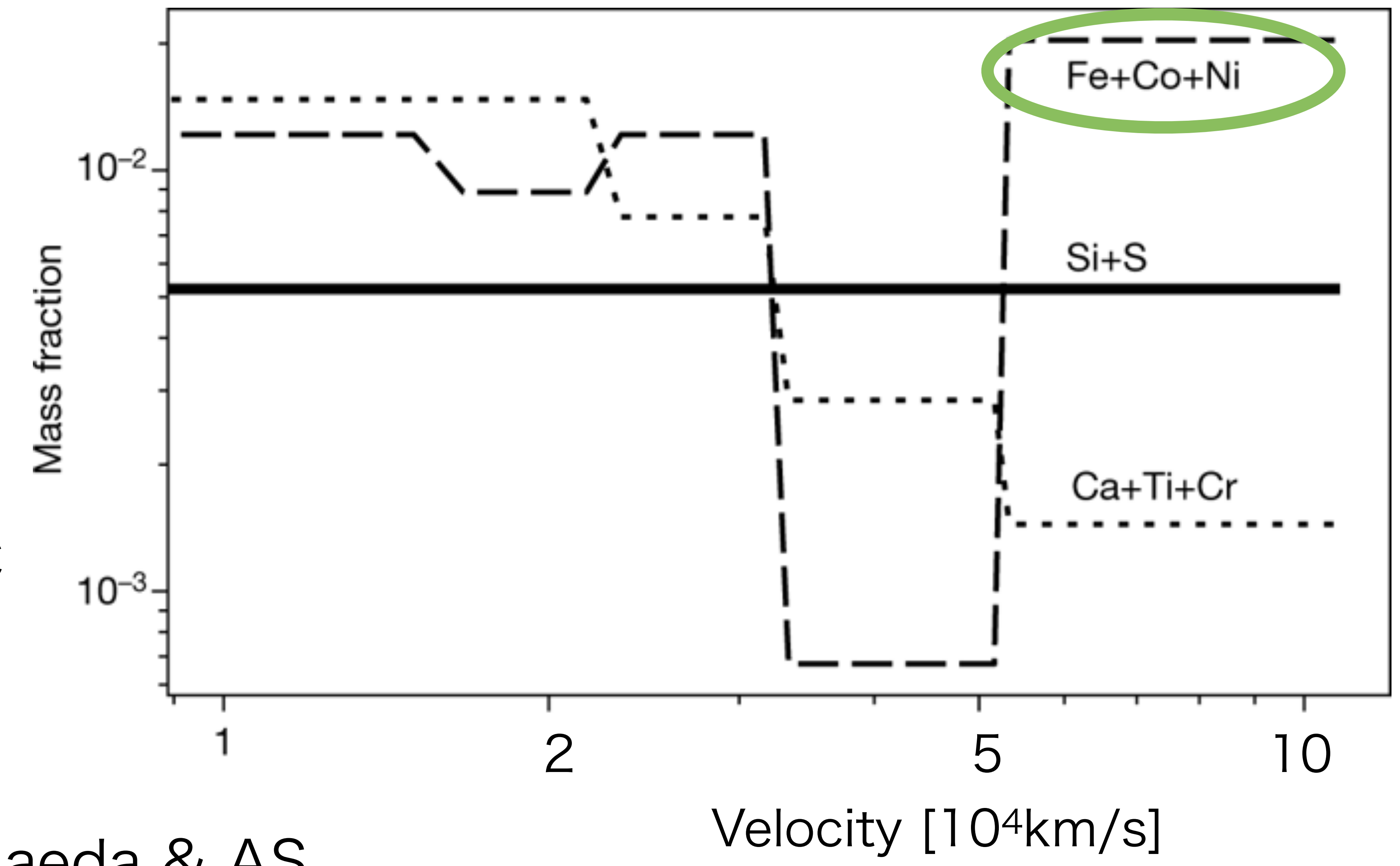
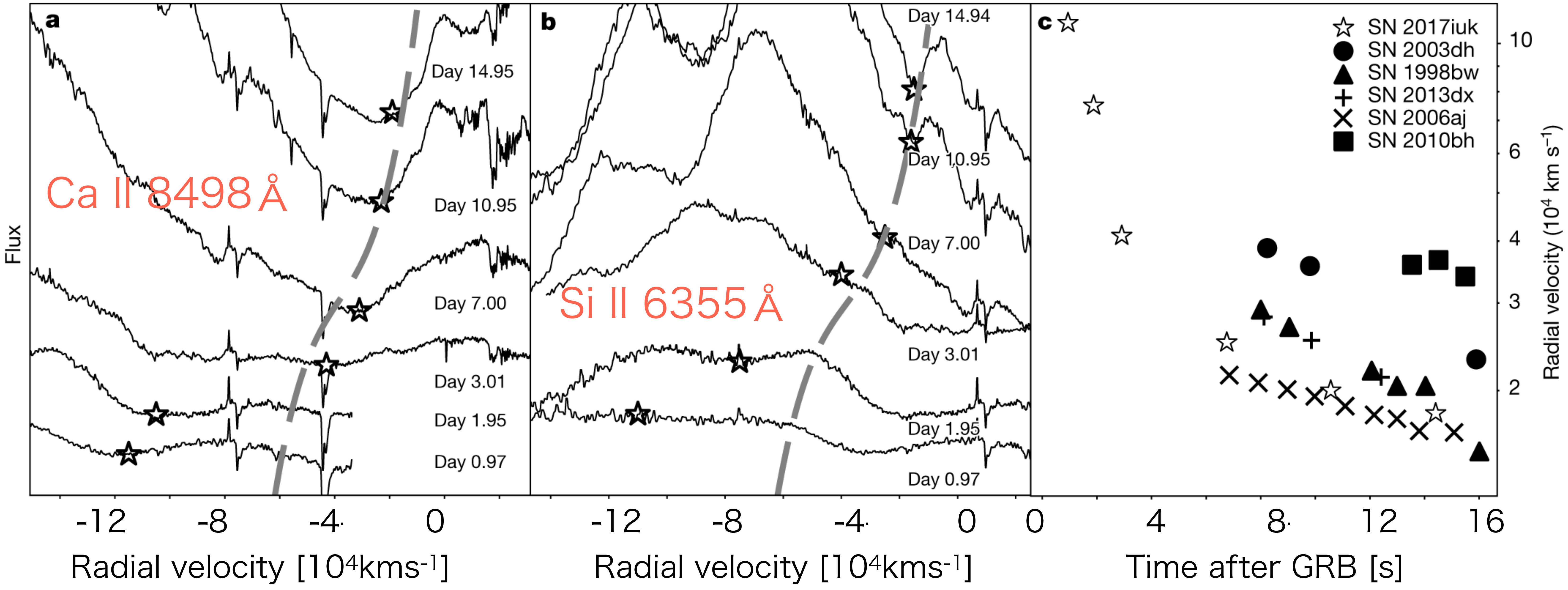
GRB 171205A: a GRB-SN in very early stage

- (low-luminosity) GRB 171205A/ SN 2017iuk at D=163Mpc
- optical spectroscopy as early as 0.06 days after GRB trigger
- blue-shifted absorption features with v=10^5km/s~0.3c
- Fe,Co,Ni well mixed into the fast component (X~0.01)
- density profile $\rho \propto v^{-6}$



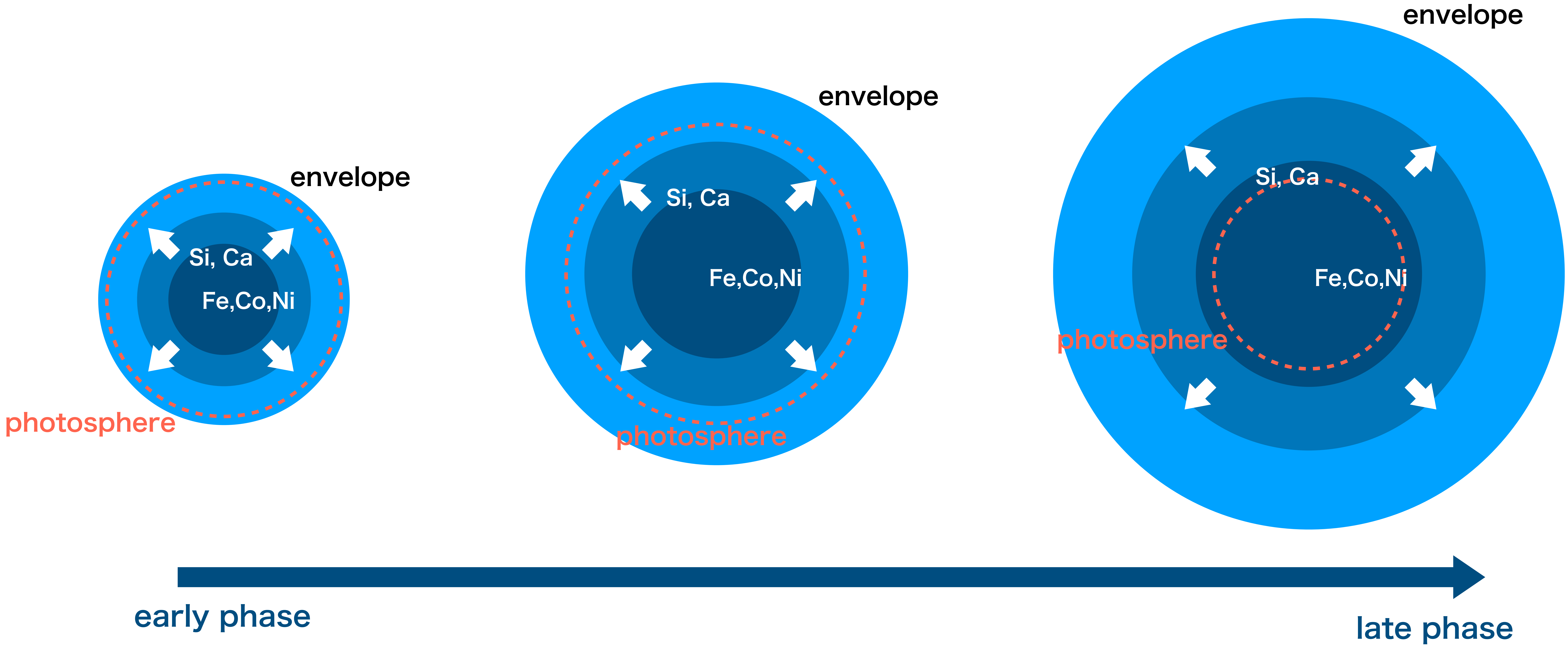
Izzo+ (2019, Nature) including K. Maeda & AS

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



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

- normal SNe reveal their inner layers gradually
- explosive nucleosynthesis products are found in late spectra.



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

- Maity&Chandra (2021)
- uGMRT observation at 250-1450 MHz
- $\rho_{csm}=Ar^{-2}$ with A = a few x 5×10^{11}g/cm
- Relatively fast radio LC at late epochs: off-axis jet contribution?

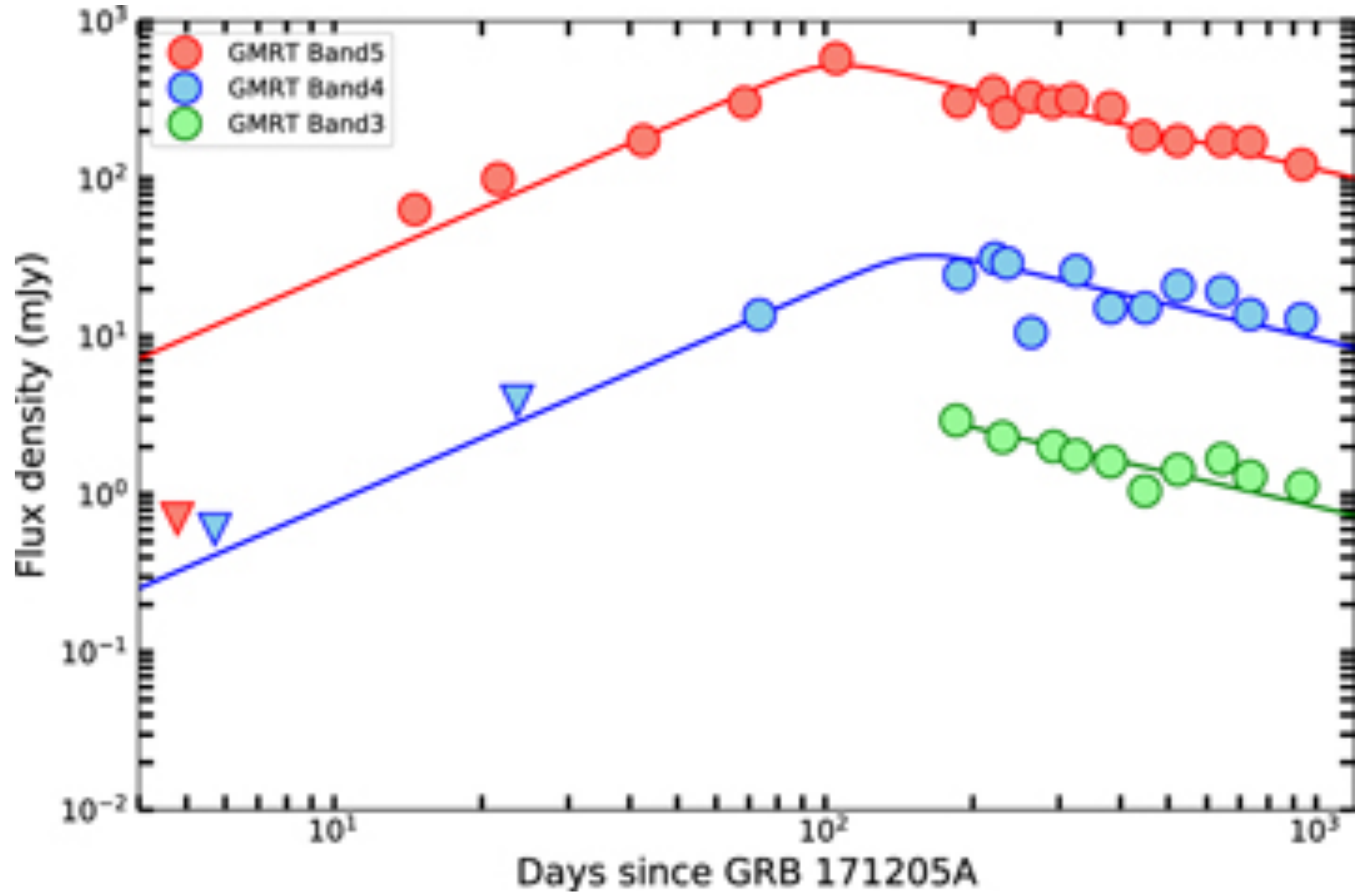


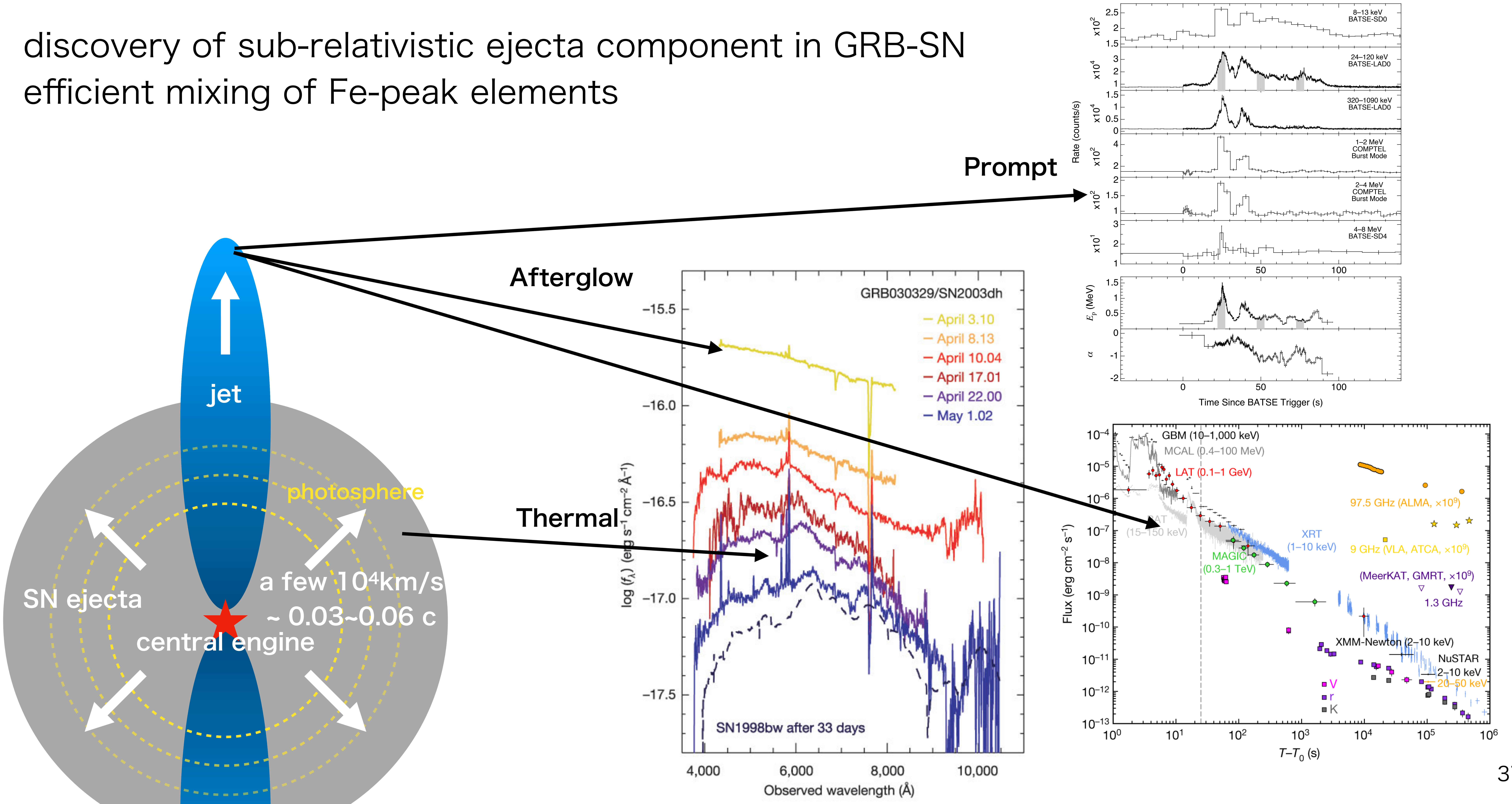
Table 2
Best-fit Parameters for the GRB 171205A uGMRT Data

Parameter	$\nu_a < \nu_m < \nu_c$		$\nu_m < \nu_a < \nu_c$				$\nu_a < \nu_c < \nu_m$			
	AG	SBO	AG		SBO		AG		SBO	
	$k = 2$	$k = 2$	$k = 2$	General k	$k = 2$	General k	$k = 2$	General k	$k = 2$	General k
A_*	$7.37^{+0.95}_{-0.80}$	$2.82^{+0.46}_{-0.39}$	$1.58^{+0.11}_{-0.75}$	$1.11^{+1.03}_{-0.54}$	$2.89^{+1.95}_{-1.26}$	$3.54^{+2.46}_{-1.55}$	$1.69^{+1.15}_{-0.51}$	$0.17^{+0.19}_{-0.09}$	$2.15^{+1.53}_{-0.78}$	$0.22^{+0.16}_{-0.11}$
η(η_{eff} for SBO)	$0.005^{+0.0004}_{-0.0004}$	$0.30^{+0.13}_{-0.12}$	$0.02^{+0.02}_{-0.01}$	$0.02^{+0.03}_{-0.02}$	$0.07^{+0.09}_{-0.05}$	$0.13^{+0.12}_{-0.07}$	$0.014^{+0.002}_{-0.002}$	$0.03^{+0.003}_{-0.003}$	$0.06^{+0.05}_{-0.03}$	$0.03^{+0.02}_{-0.01}$
ϵ_B	$0.94^{+0.05}_{-0.09}$	$0.70^{+0.20}_{-0.20}$	$0.21^{+0.24}_{-0.13}$	$0.11^{+0.17}_{-0.06}$	$0.03^{+0.03}_{-0.02}$	$0.01^{+0.01}_{-0.01}$	$0.17^{+0.14}_{-0.10}$	$0.02^{+0.01}_{-0.01}$	$0.08^{+0.09}_{-0.05}$	$0.01^{+0.01}_{-0.01}$
ϵ_e	$0.99^{+0.01}_{-0.02}$	$0.78^{+0.16}_{-0.23}$	$0.12^{+0.09}_{-0.06}$	$0.13^{+0.11}_{-0.07}$	$0.24^{+0.17}_{-0.11}$	$0.12^{+0.07}_{-0.06}$	…	…	…	…
p	$2.55^{+0.08}_{-0.06}$	$3.87^{+0.10}_{-0.19}$	$2.22^{+0.04}_{-0.04}$	$2.18^{+0.14}_{-0.09}$	$2.23^{+0.04}_{-0.05}$	$2.22^{+0.16}_{-0.13}$	…	…	…	…
k	…	…	…	$1.99^{+0.01}_{-0.02}$	…	$1.99^{+0.01}_{-0.01}$	…	$1.91^{+0.02}_{-0.01}$	…	$1.92^{+0.02}_{-0.02}$
s	…	$0.55^{+0.04}_{-0.04}$	…	…	$0.13^{+0.08}_{-0.07}$	$0.15^{+0.08}_{-0.08}$	…	…	$0.35^{+0.13}_{-0.16}$	$0.08^{+0.16}_{-0.18}$
	$\chi^2_\nu = 7.55$	$\chi^2_\nu = 2.58$	$\chi^2_\nu = 1.74$	$\chi^2_\nu = 1.80$	$\chi^2_\nu = 1.72$	$\chi^2_\nu = 1.78$	$\chi^2_\nu = 1.60$	$\chi^2_\nu = 1.52$	$\chi^2_\nu = 1.58$	$\chi^2_\nu = 1.57$

Note. Here AG is the standard isotropic afterglow model and SBO is the shock breakout model. In the case of fast cooling, the data are only in the regime of ν_a to ν_c (2 to 1/3 transition of spectra), for which we do not have p dependencies in temporal or spectral slopes. The only p dependency is in the expression of ν_a via that ratio of $G(p)$ parameter, which we have taken to be of order unity for $p \sim 2.1$. The ϵ_e dependency is also not there as ν_m is unconstrained.

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

- discovery of sub-relativistic ejecta component in GRB-SN
- efficient mixing of Fe-peak elements



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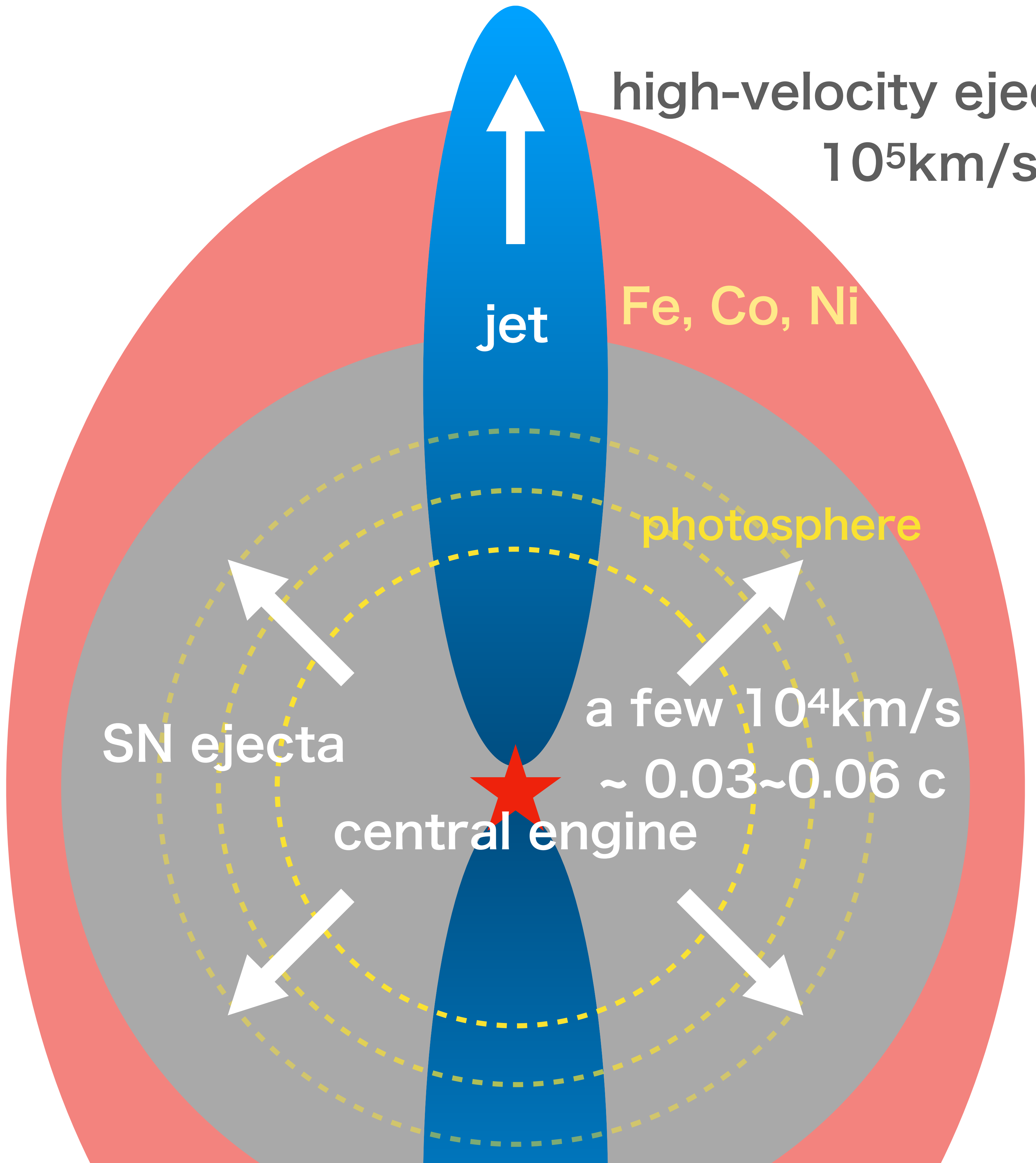
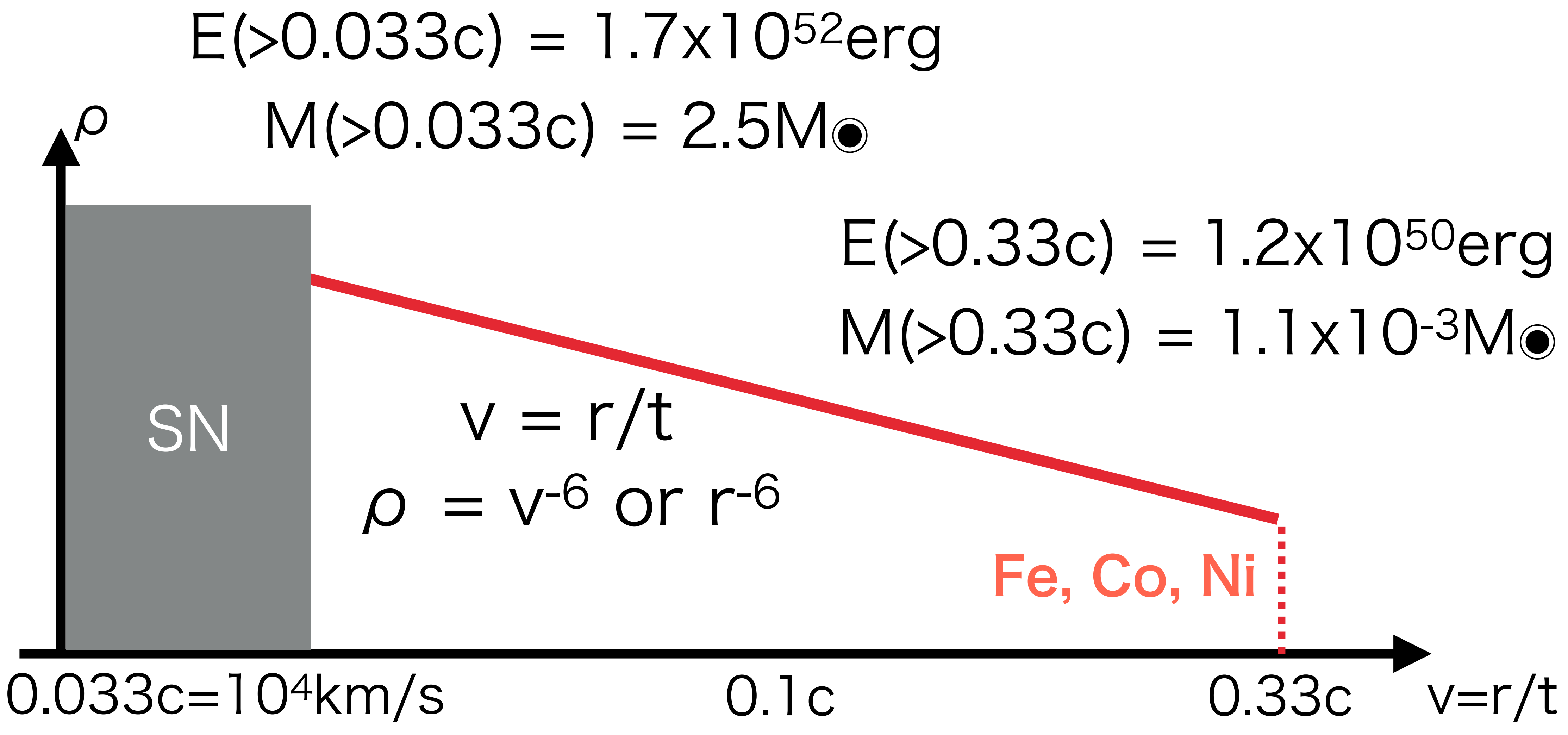
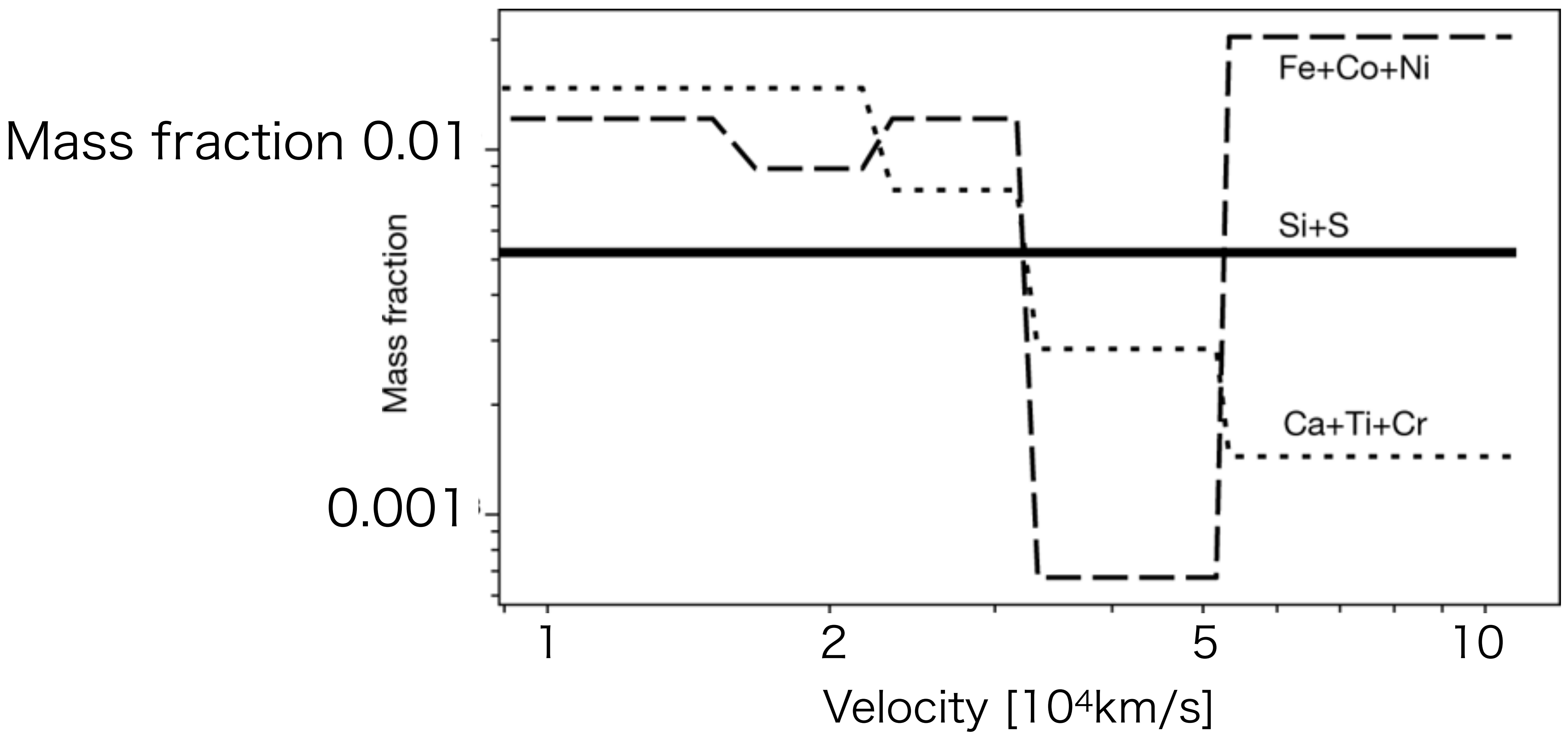
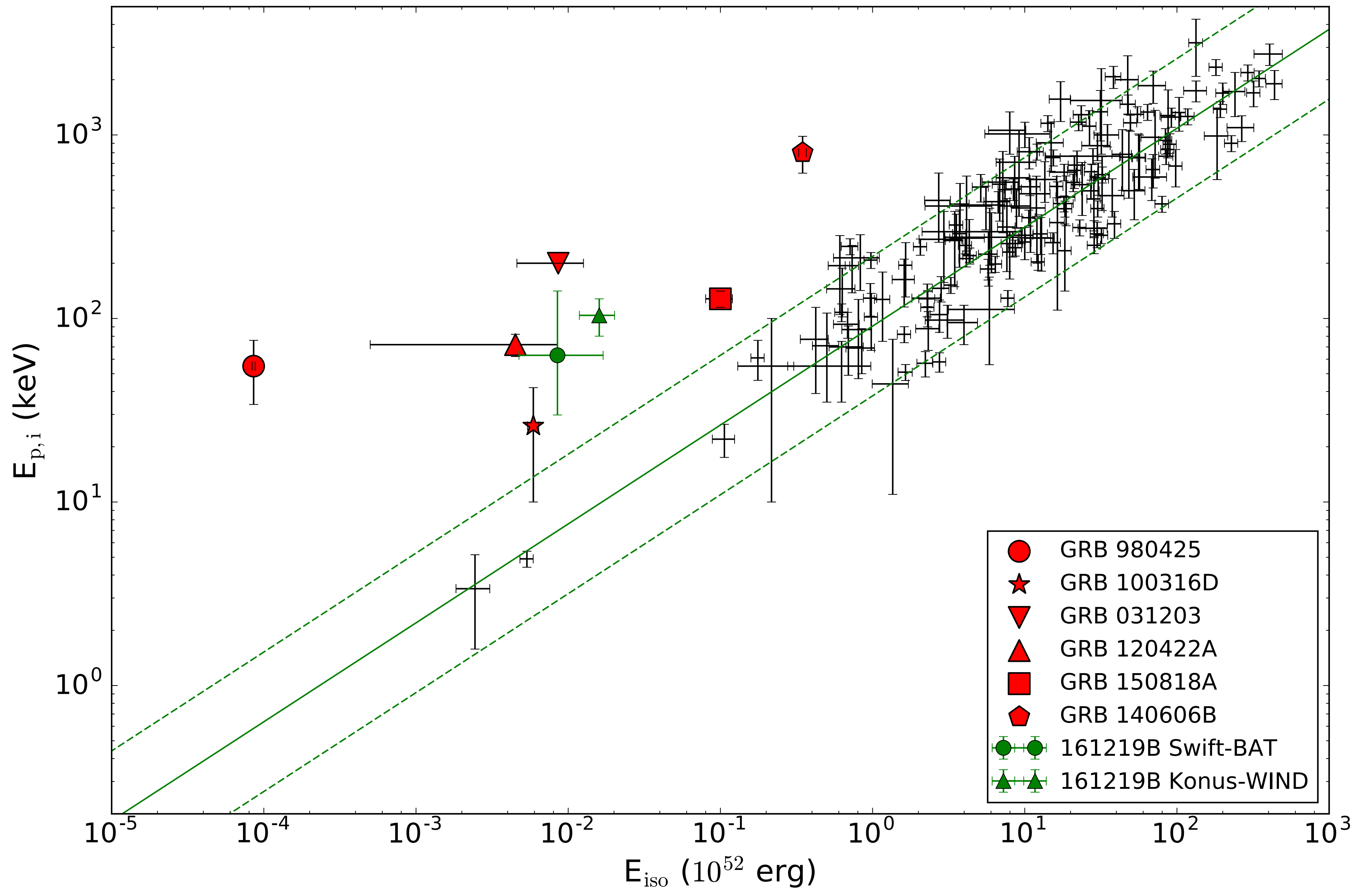


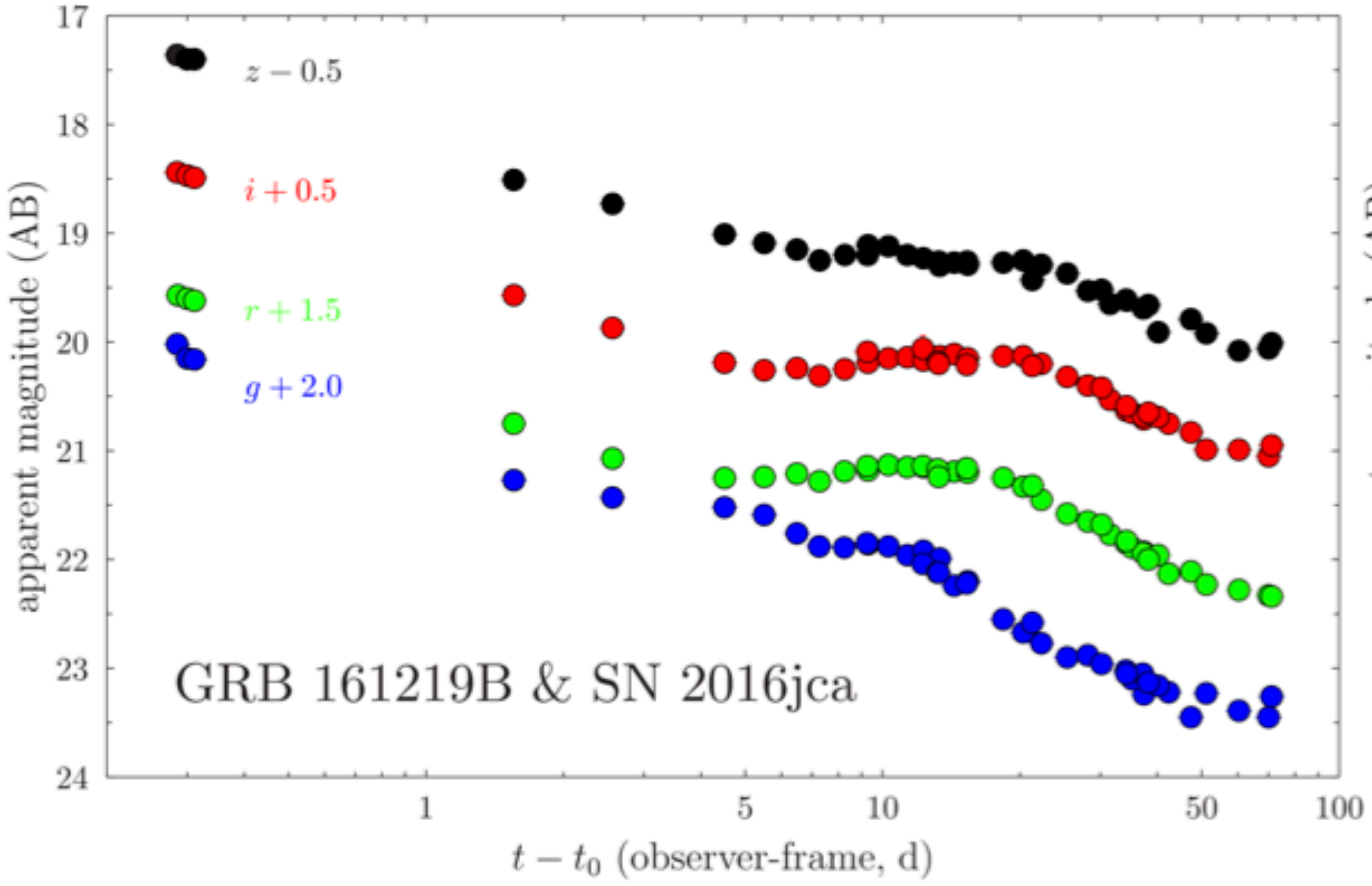


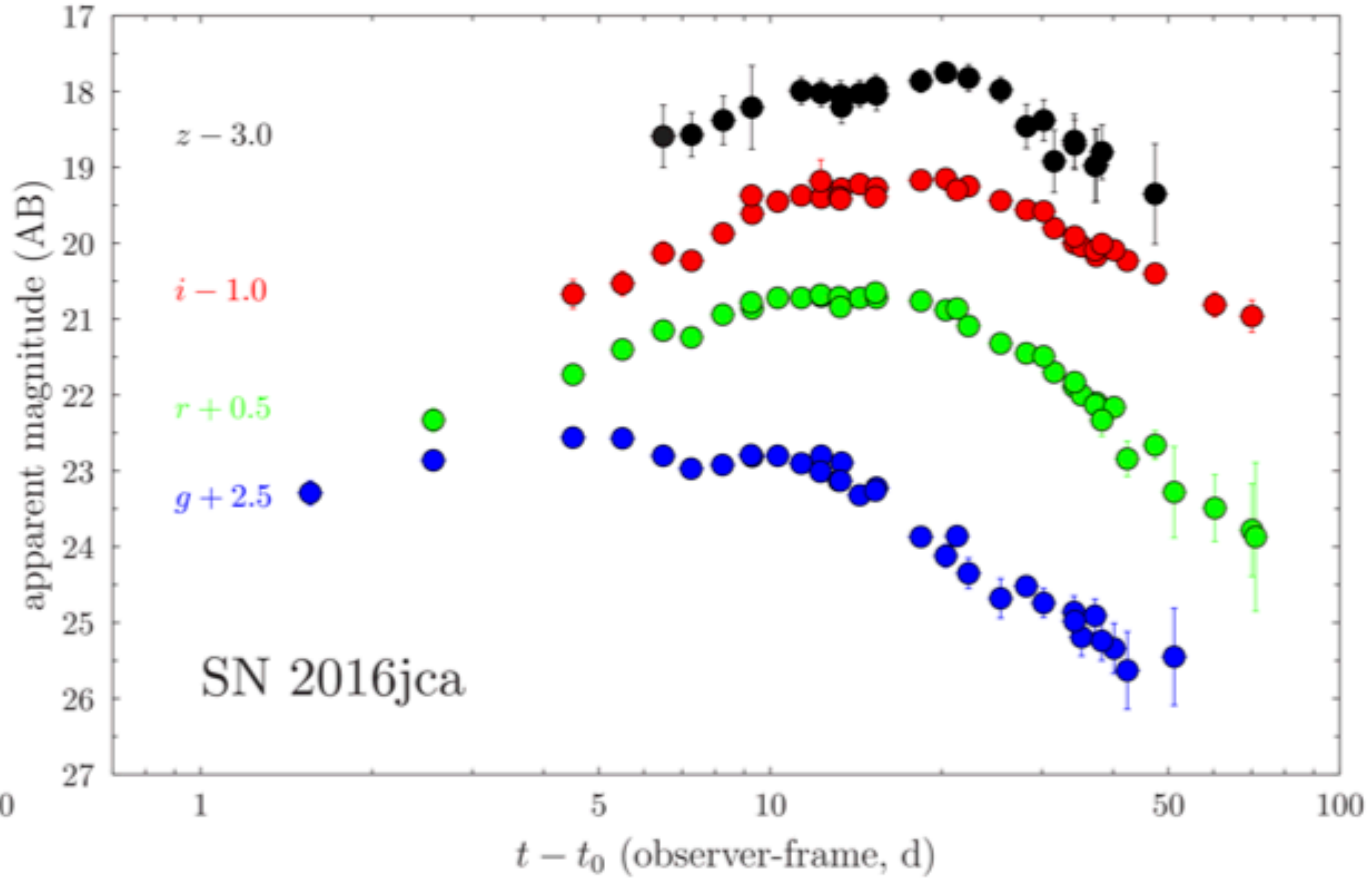


GRB 161219B: a GRB-SN in very early stage

- another example: GRB 161219B/ SN 2016jca
- D=700 [Mpc]
- T_{90}=6.9 [s]
- E_{iso} ~ 10^{50} [erg], E_{peak} ~ 60 [keV]
- low-luminosity GRB





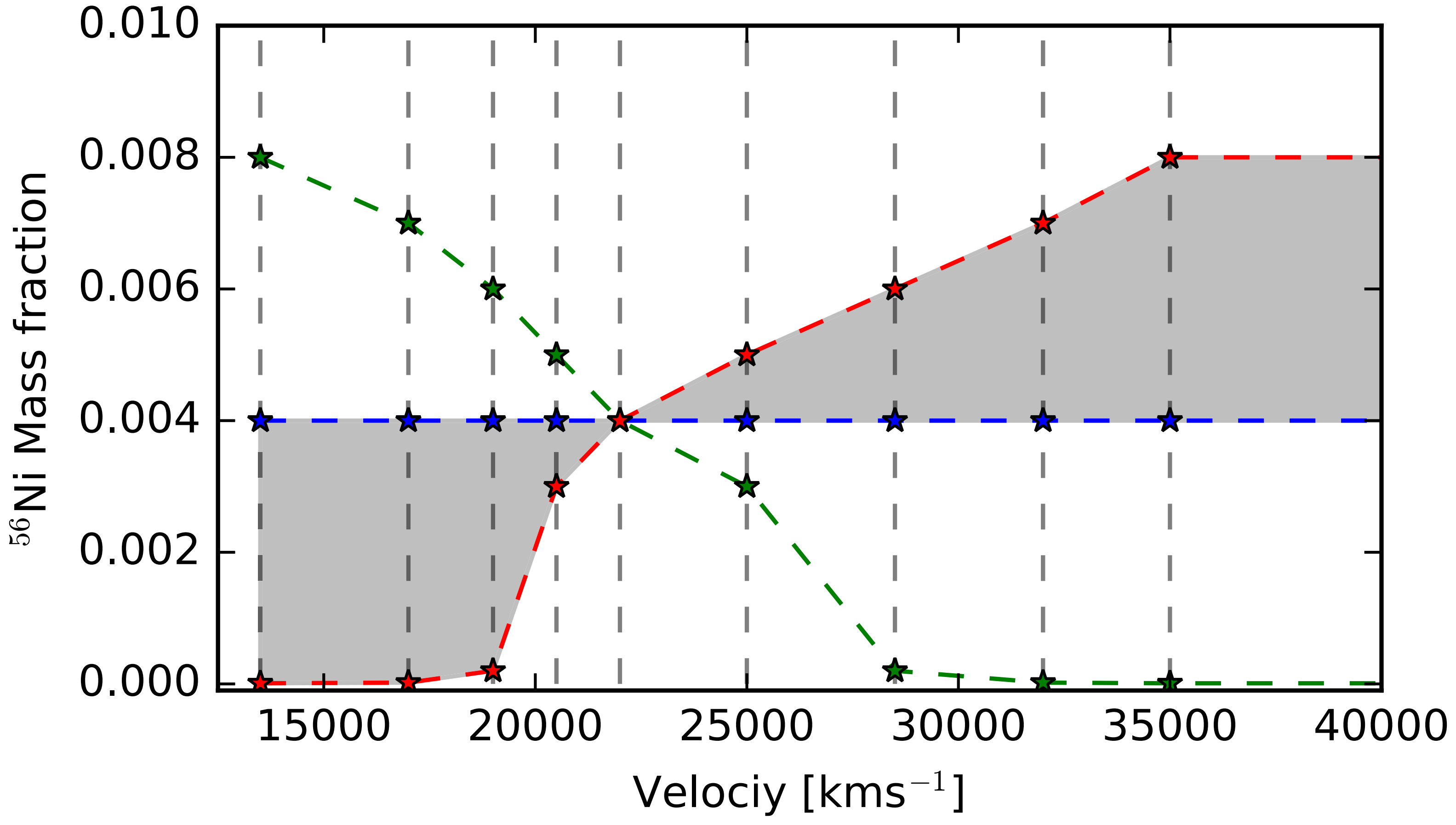


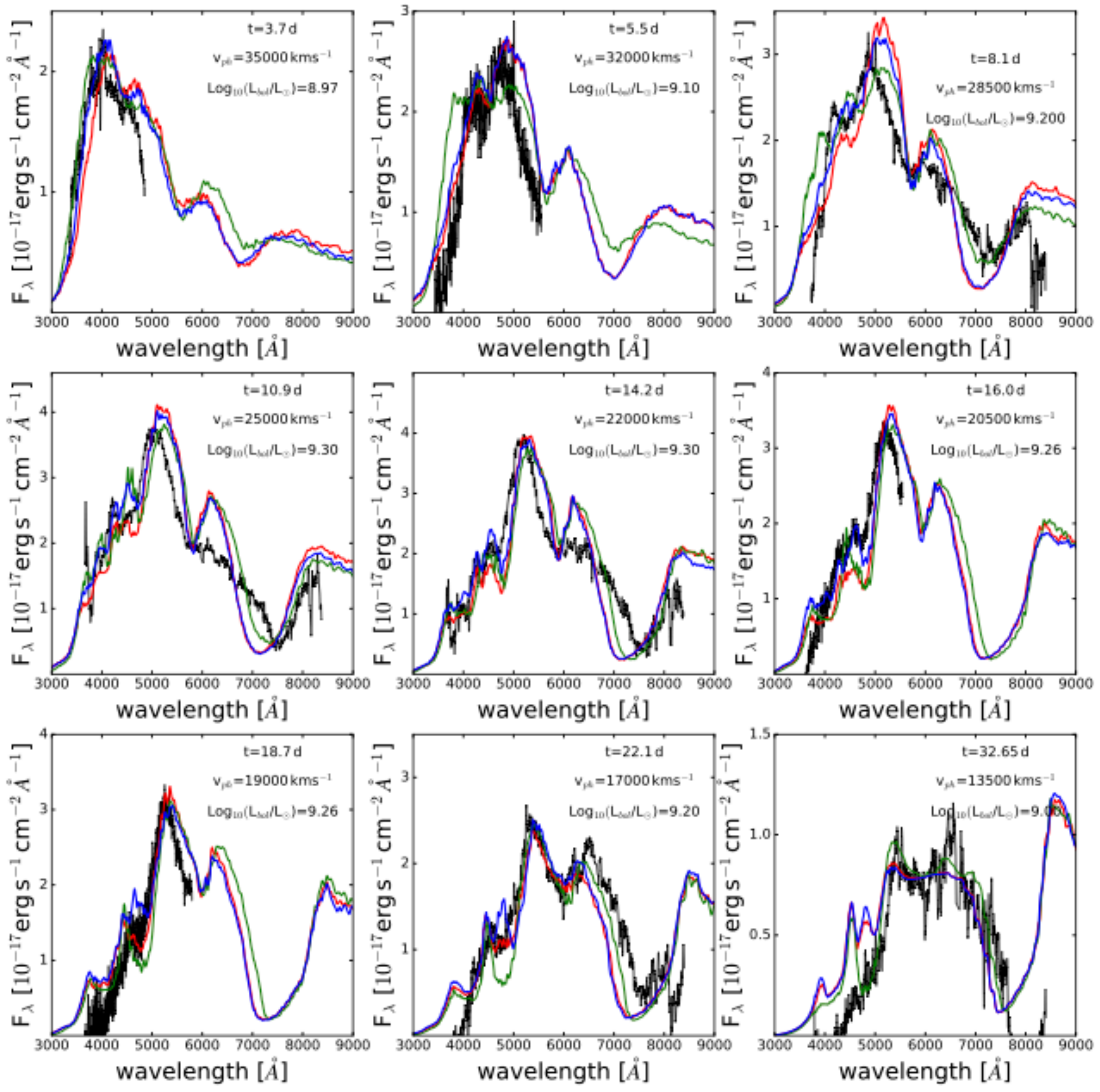
Cano+(2017)

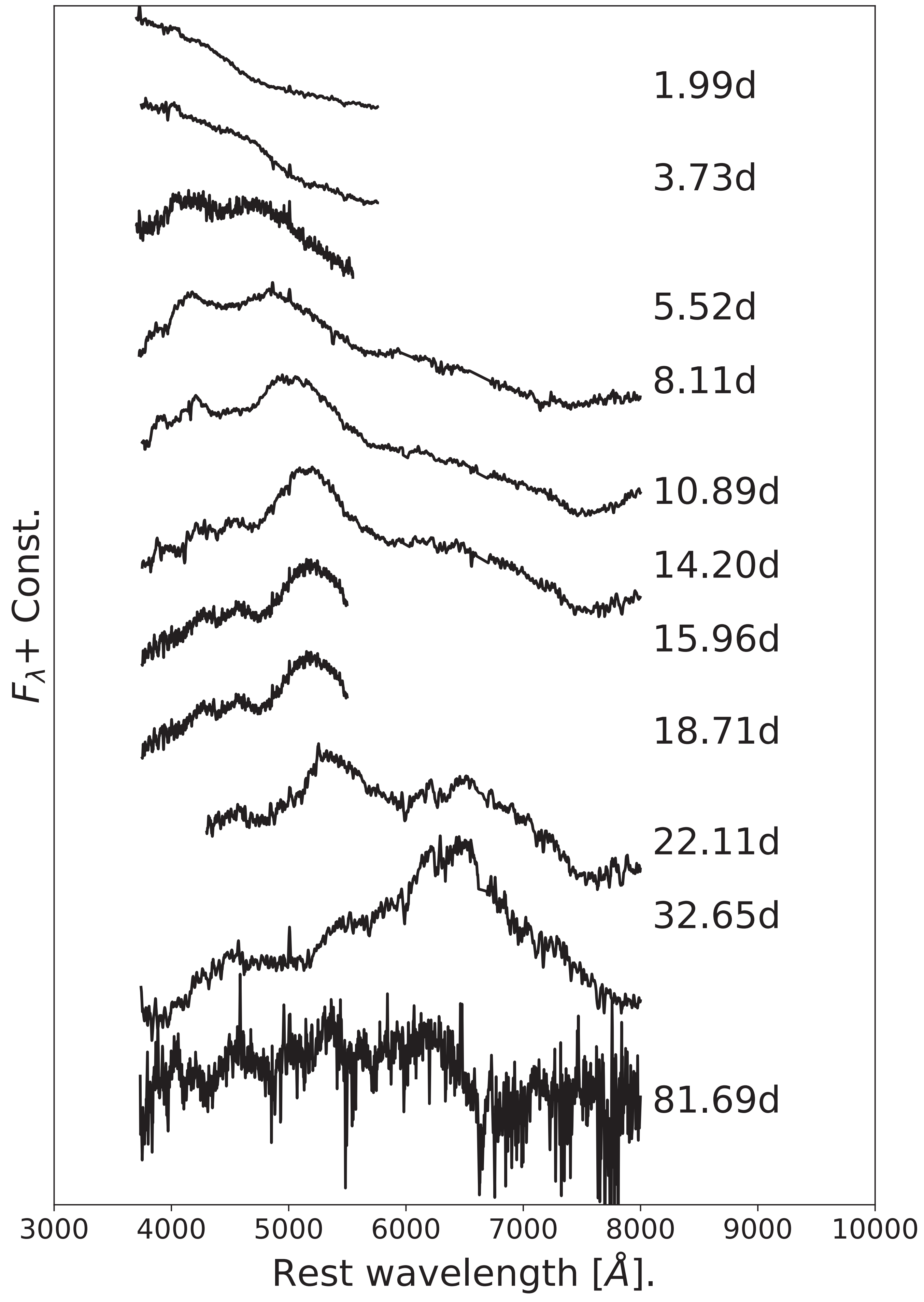
GRB 161219B: a GRB-SN in very early stage

- another example: GRB 161219B/ SN 2016jca
- red spectra: absorption at λ<5000Å
- efficient UV blocking by Ni and/or Co with v > 0.1c
- flat or increasing Ni abundance with increasing velocity

Ni abundance as a function of velocity



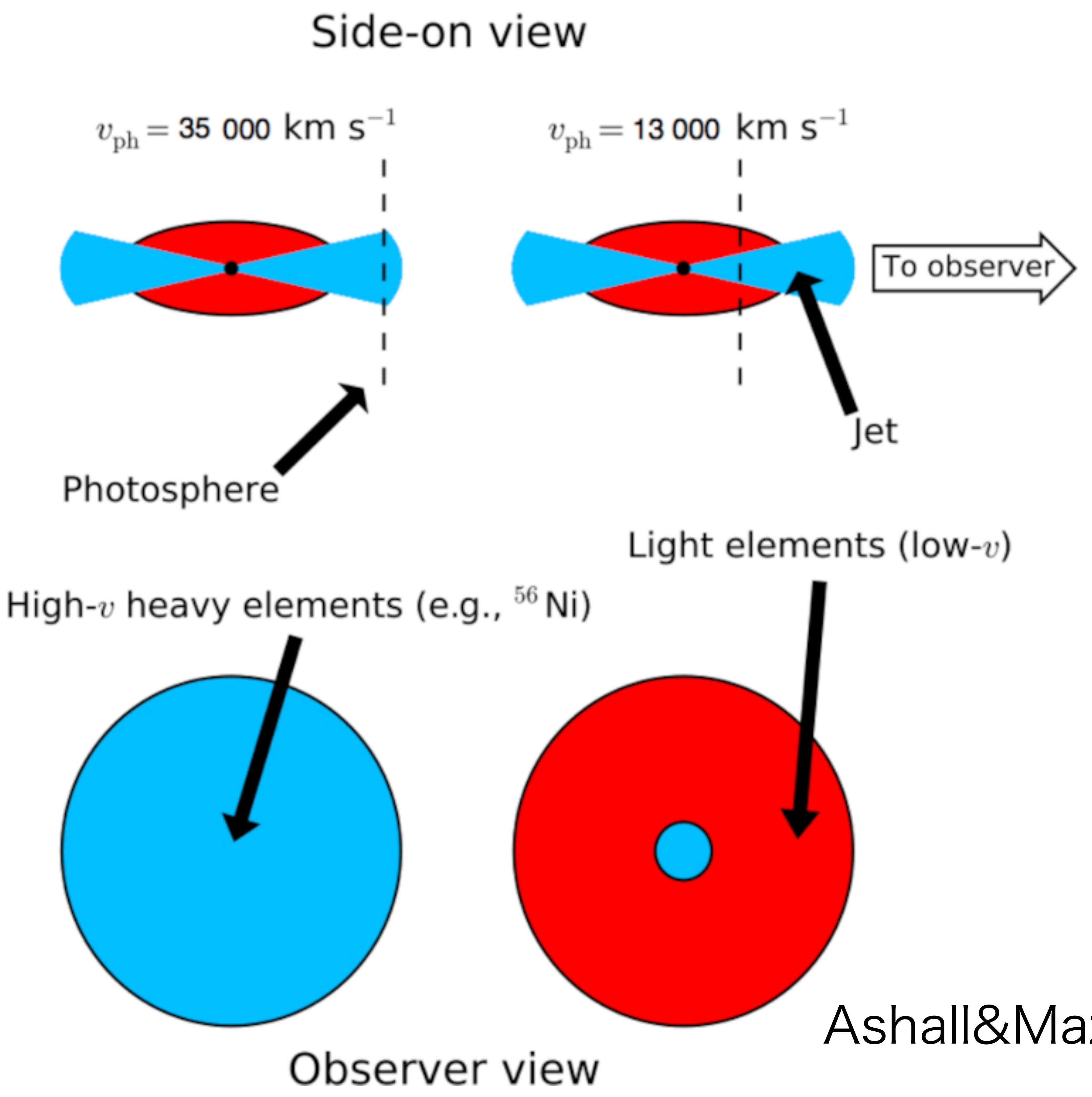




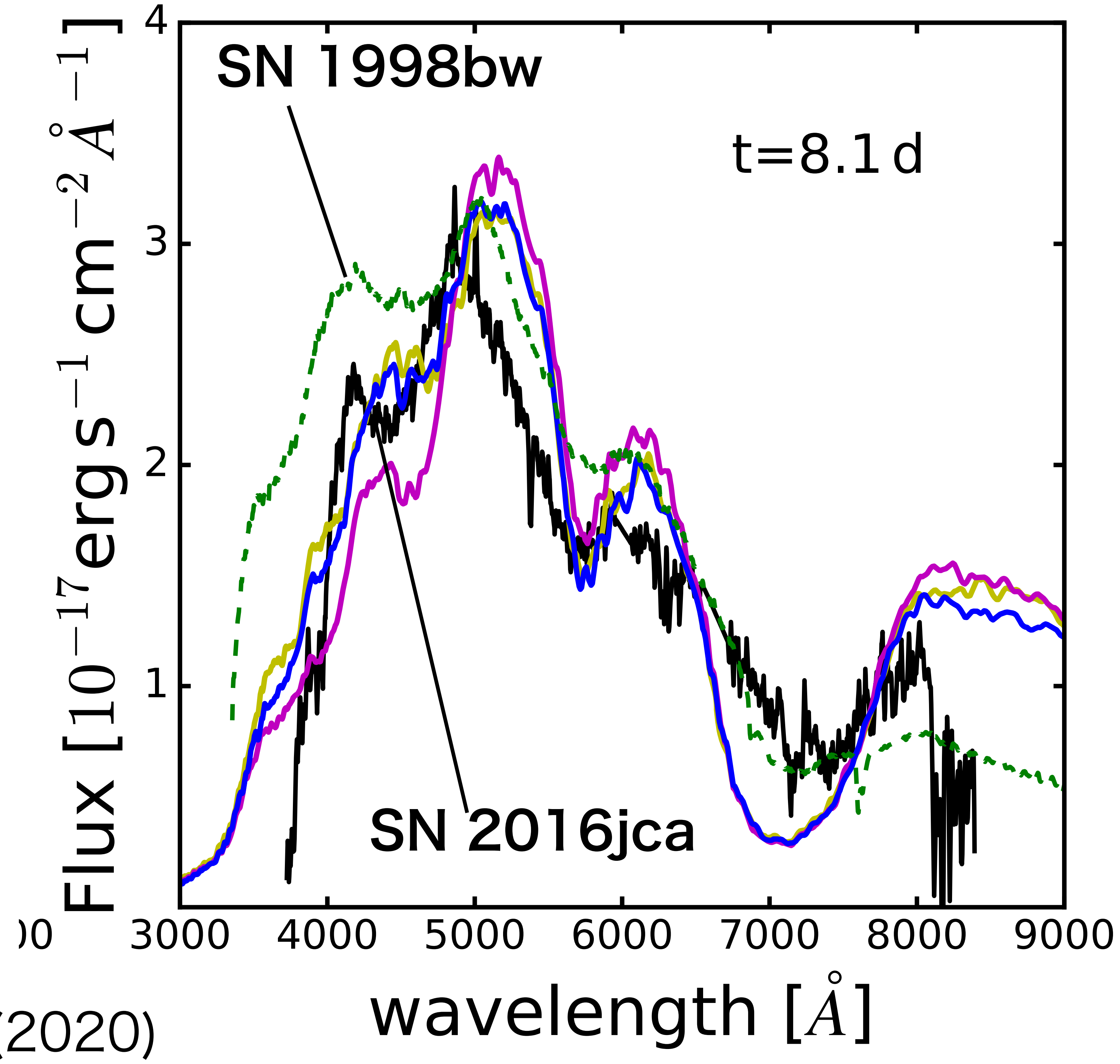
spectral evolution of GRB 161219B/ SN 2016jca: Ashall+ (2019)

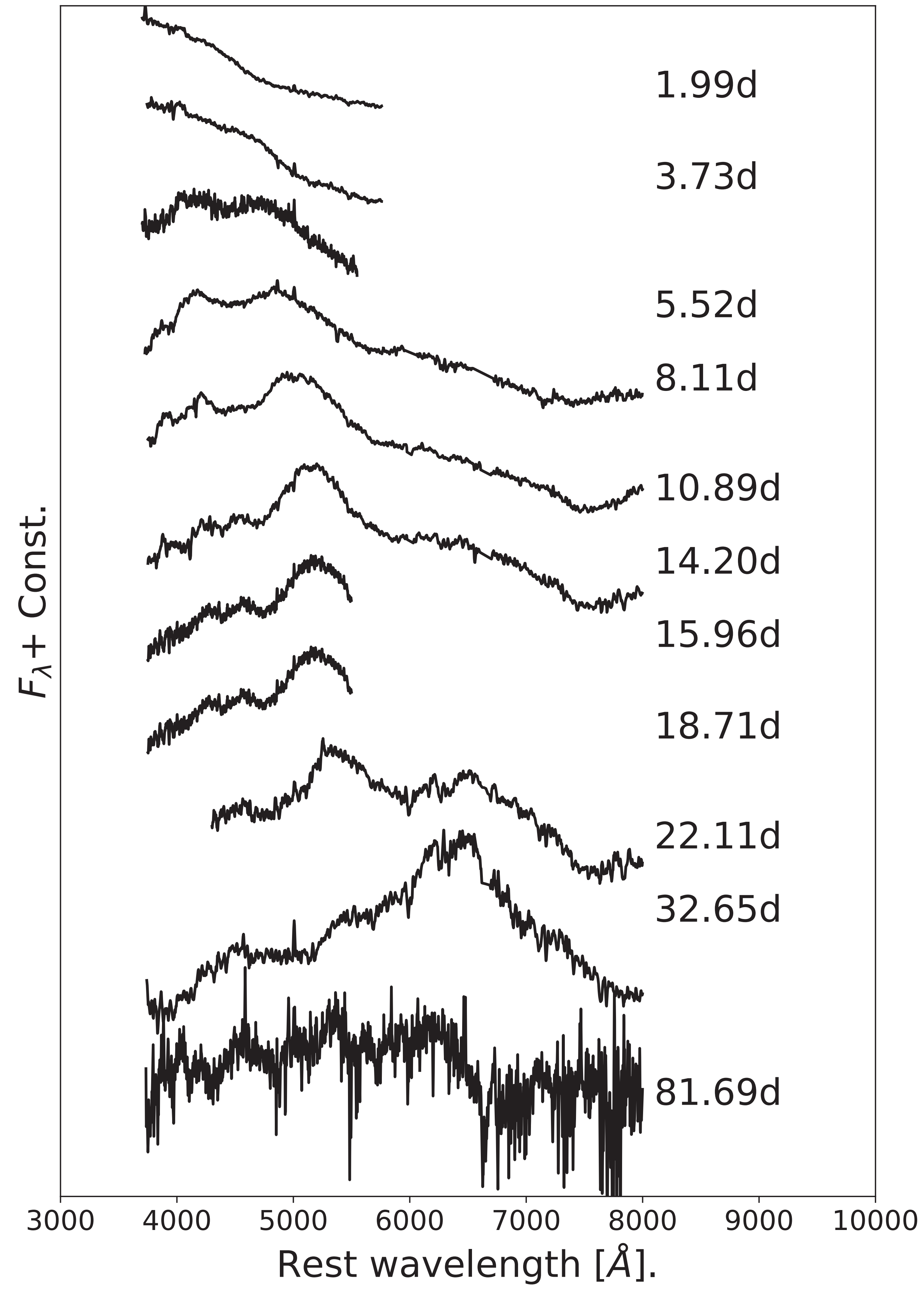
GRB 161219B: a GRB-SN in very early stage

- SN 2016jca vs SN 1998bw
- optical spectra at ~ 1 week
- less UV suppression for SN 1998bw than 2016jca
- variation in the mass-fraction of Fe-peak elements?



Ashall&Mazzali (2020)

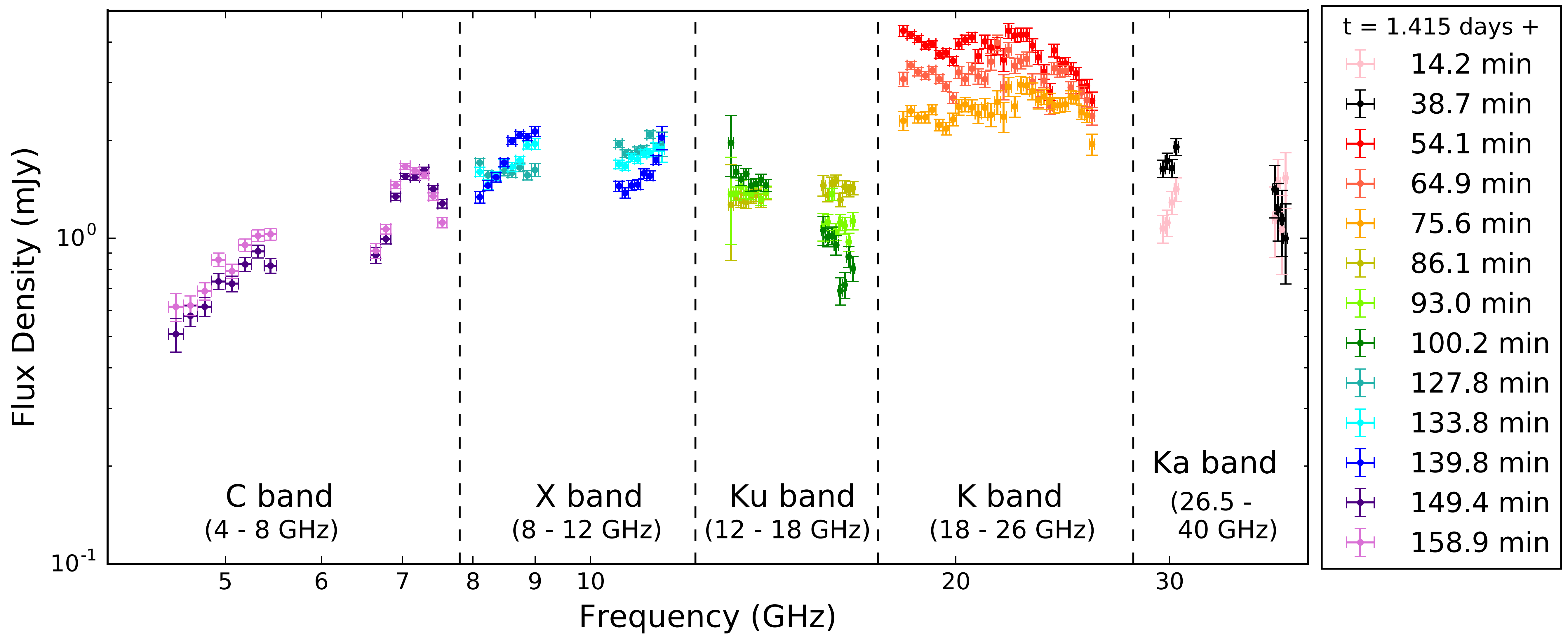


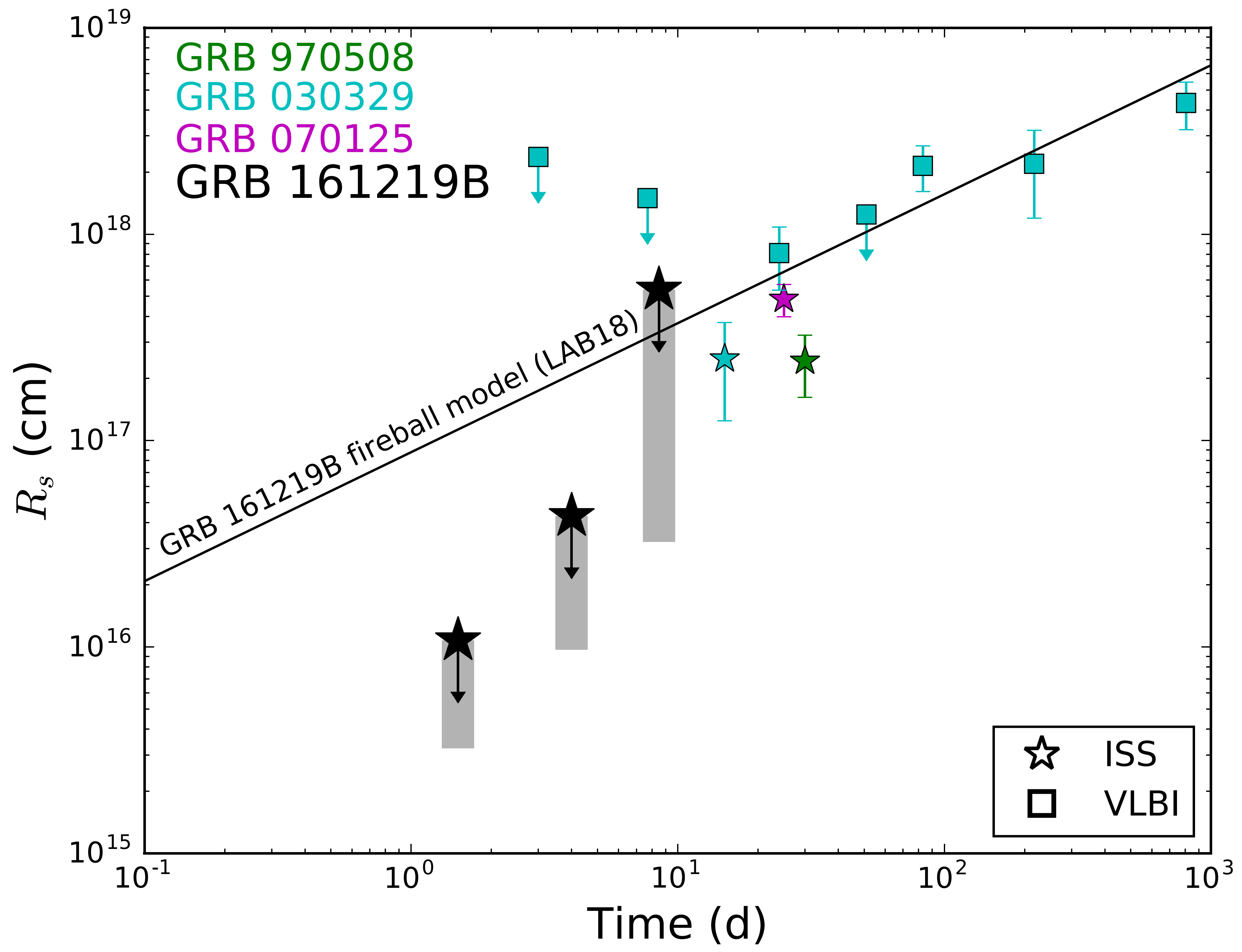


spectral evolution of GRB 161219B/ SN 2016jca: Ashall+ (2019)

GRB 161219B: a GRB-SN in very early stage

- reverse shock contribution in radio afterglow?
- radio interstellar scintillation (ISS)
- upper limits on the size of the (radio) emitting region
- deviation from the standard blast wave?
- what about a structure jet?

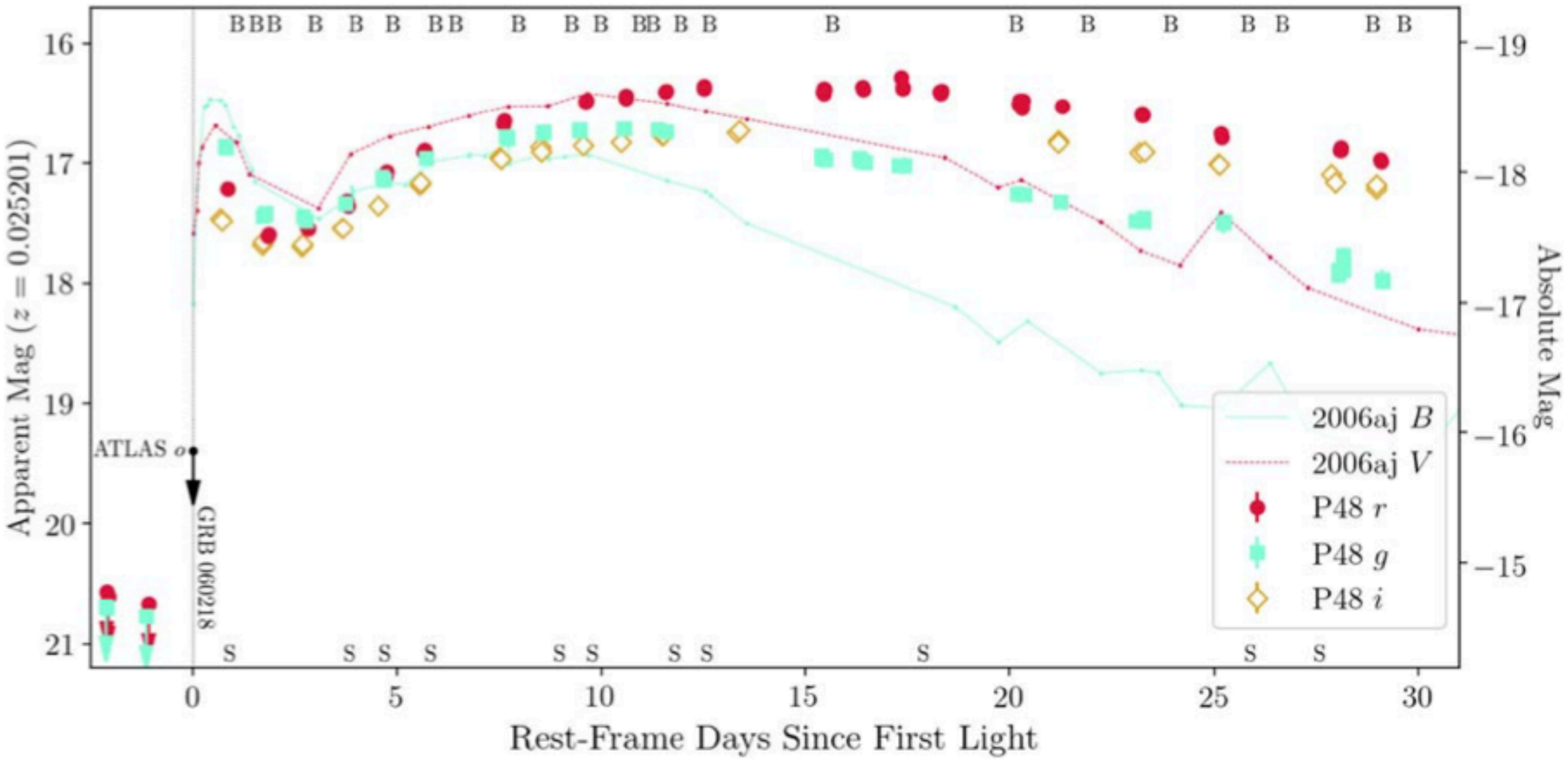




Emitting region constraints by ISS for GRB 161219B
Alexander+(2019)

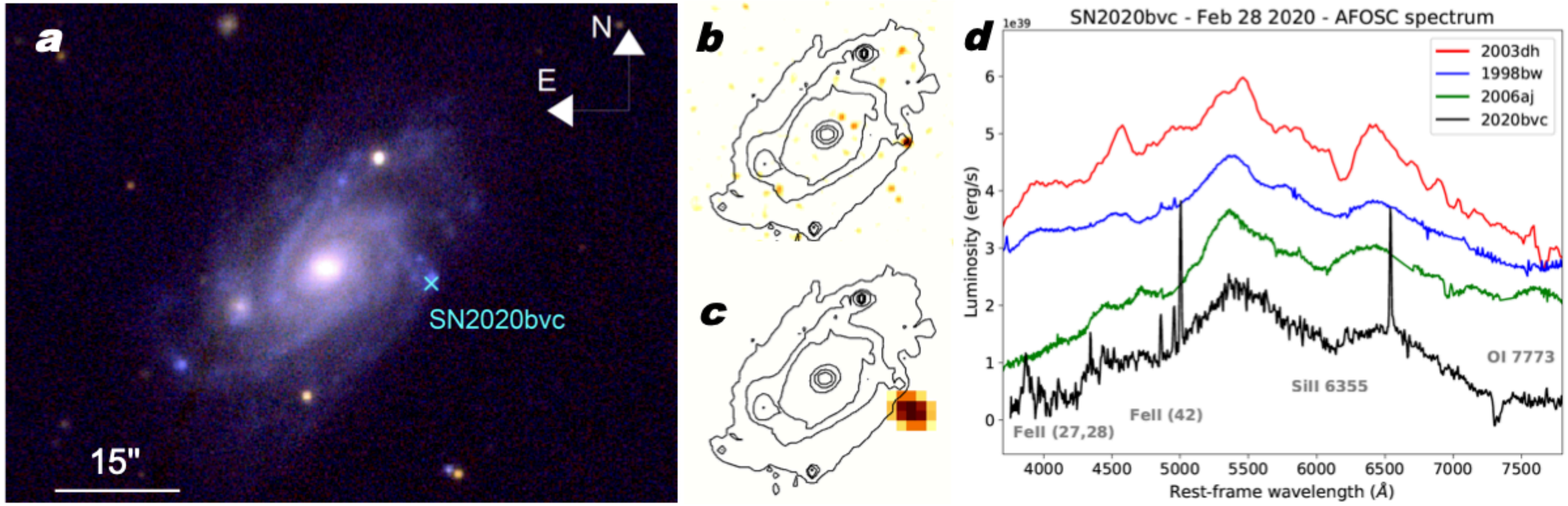
SN 2020bvc: an optically-selected off-axis GRB-SN?

- 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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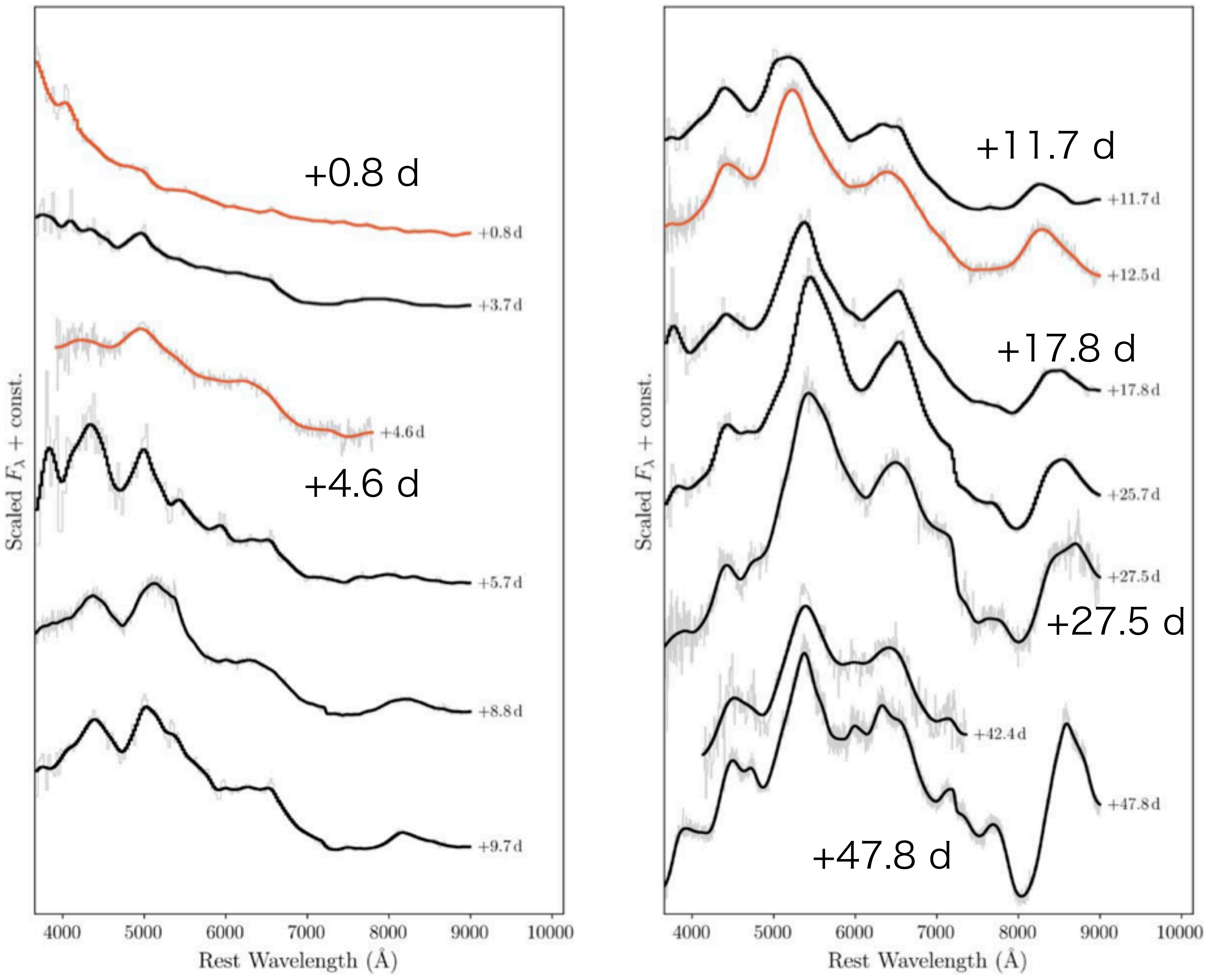
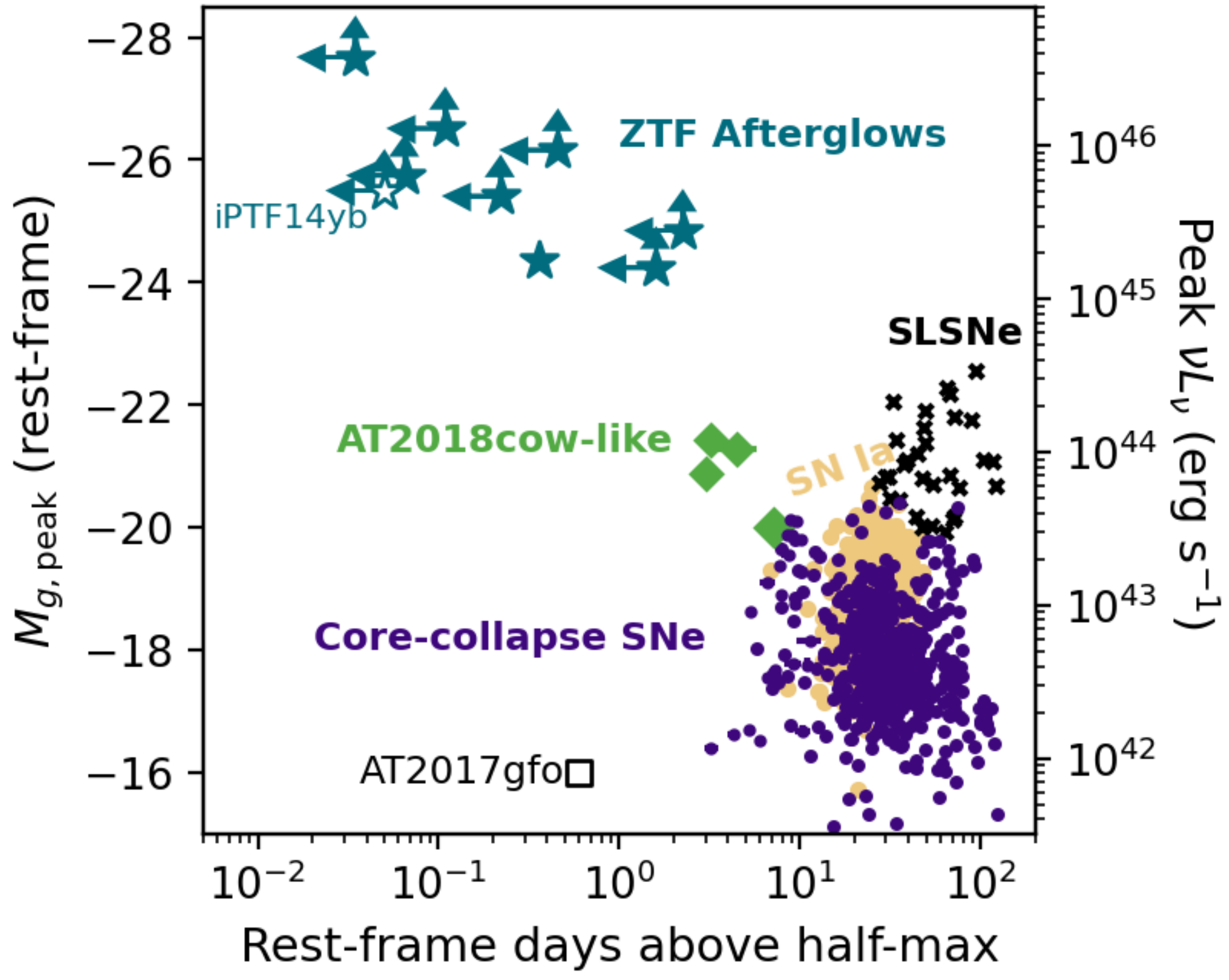
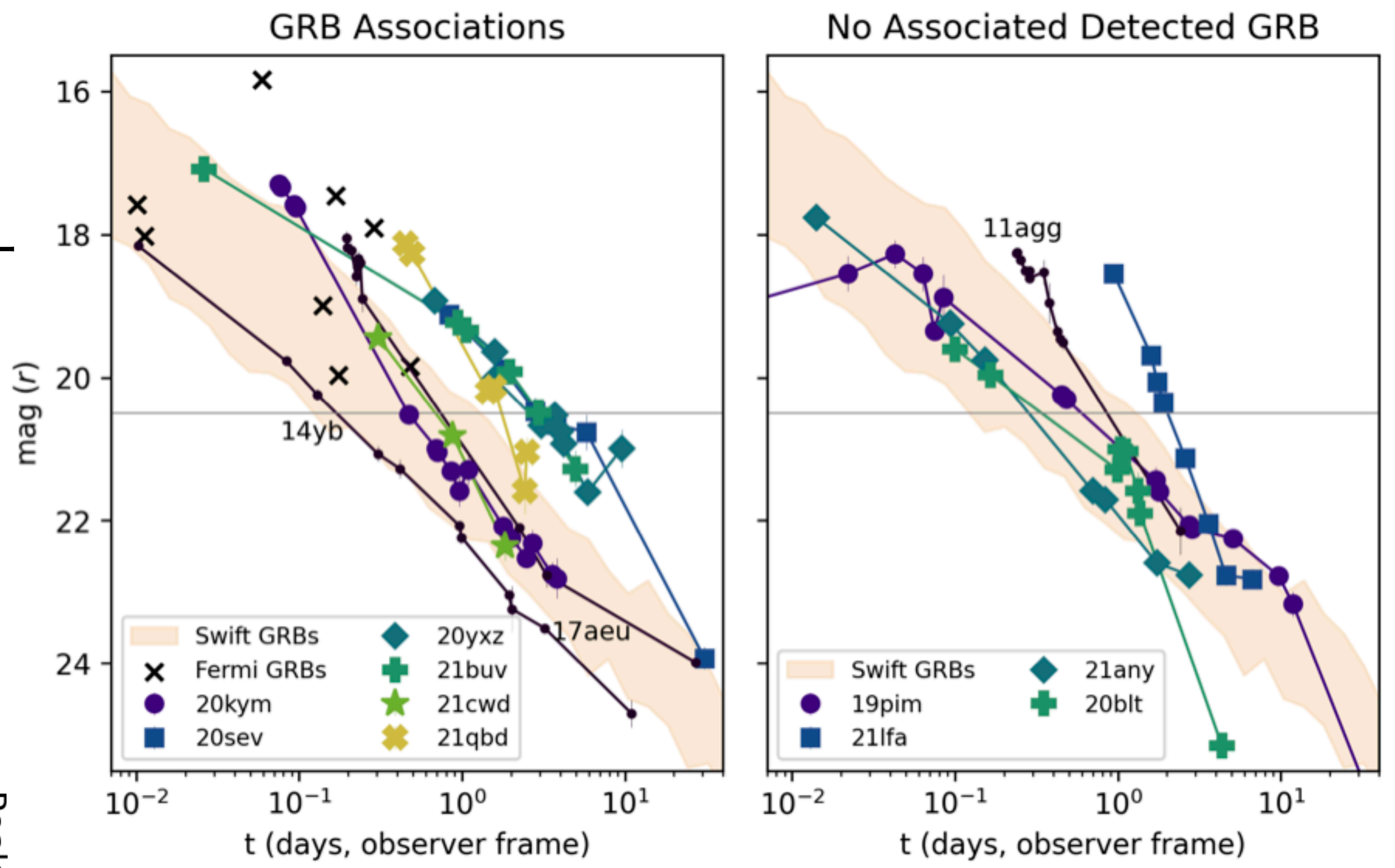


Off-axis optical afterglow candidates

- ZTF high-cadence survey
- afterglow-like transients: rapid decay, non-thermal SED
- 9 objects with redshift measurements
- 4 objects without GRB





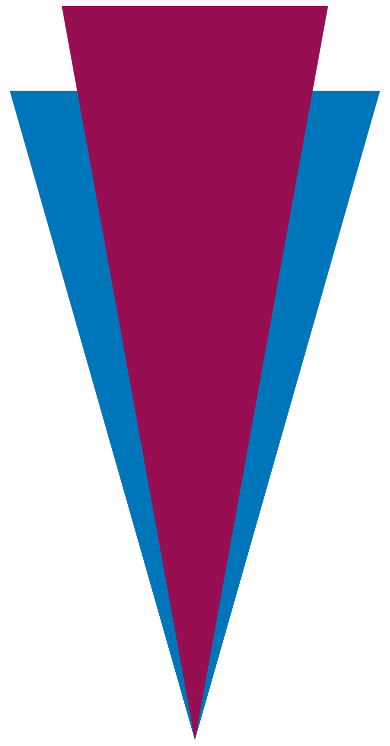
r-band light curves of ZTF afterglows, Ho+ (2022)

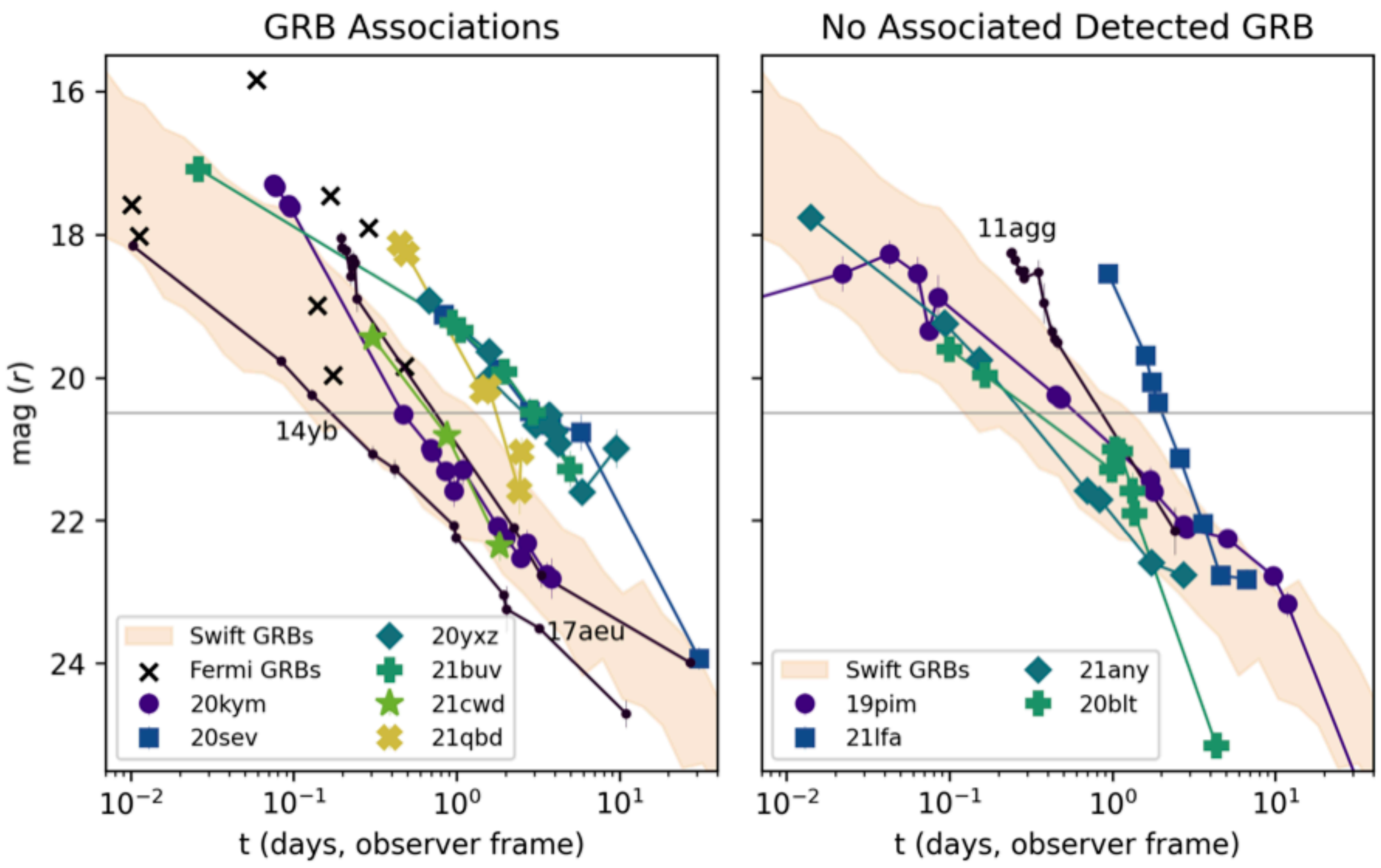
Off-axis optical afterglow candidates

- optical synchrotron emitting region is not so extended (assuming on-axis level luminosity)?
- not too many “dirty fireballs”
- $f_{b,\gamma} < 6 f_{b,opt}$ with 95% confidence
-

❌ $f_{b,\gamma} \ll f_{b,opt}$

✅ $f_{b,\gamma} \sim f_{b,opt}$





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- optical synchrotron emitting region is not so extended (assuming on-axis level luminosity)?
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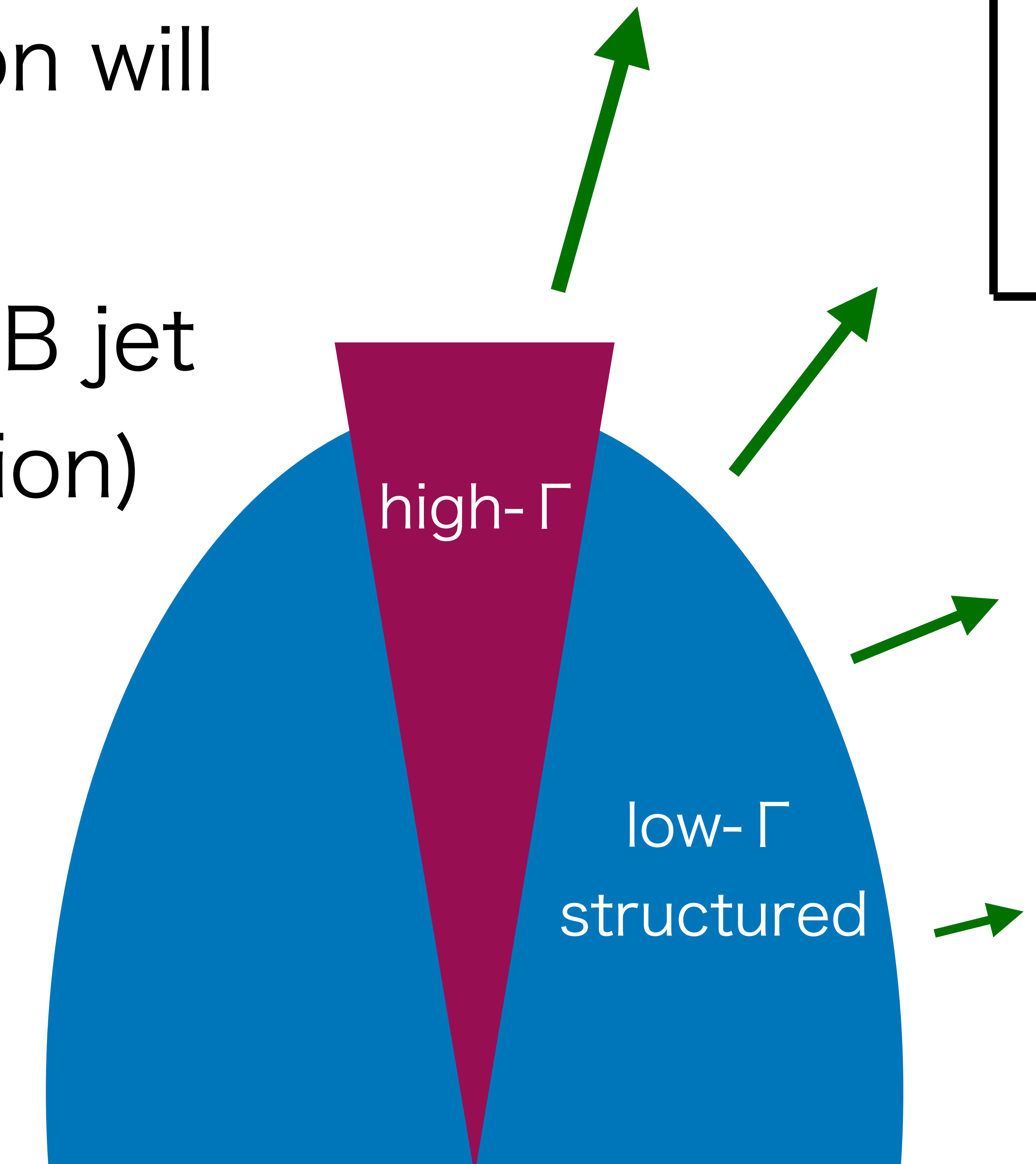
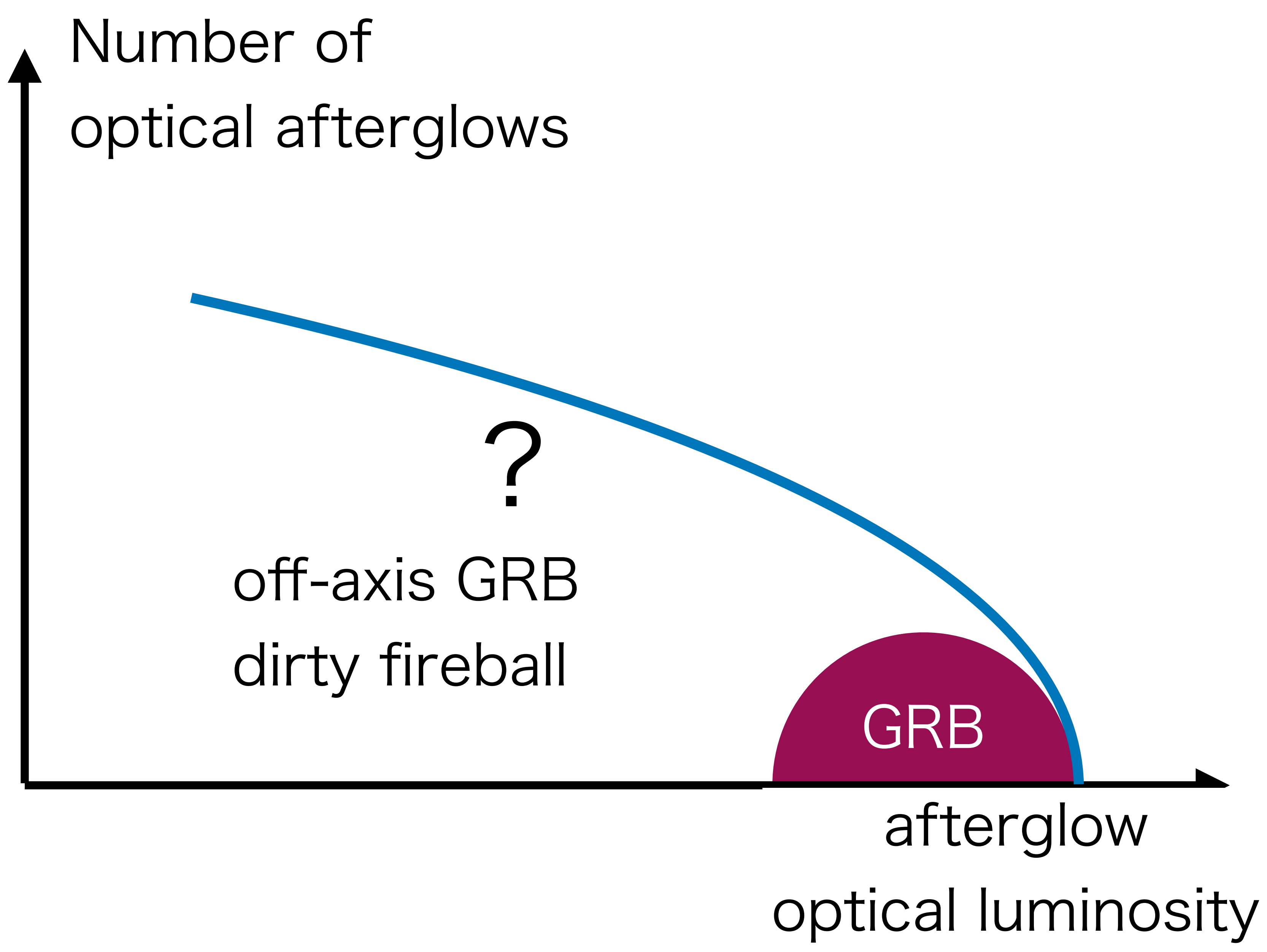
- $f_{b,\gamma} < 6 f_{b,opt}$ with 95% confidence
- optical afterglow luminosity function will be revealed in the future
- statistical inference of a typical GRB jet structure (angular energy distribution)





external and micro-physics parameters?

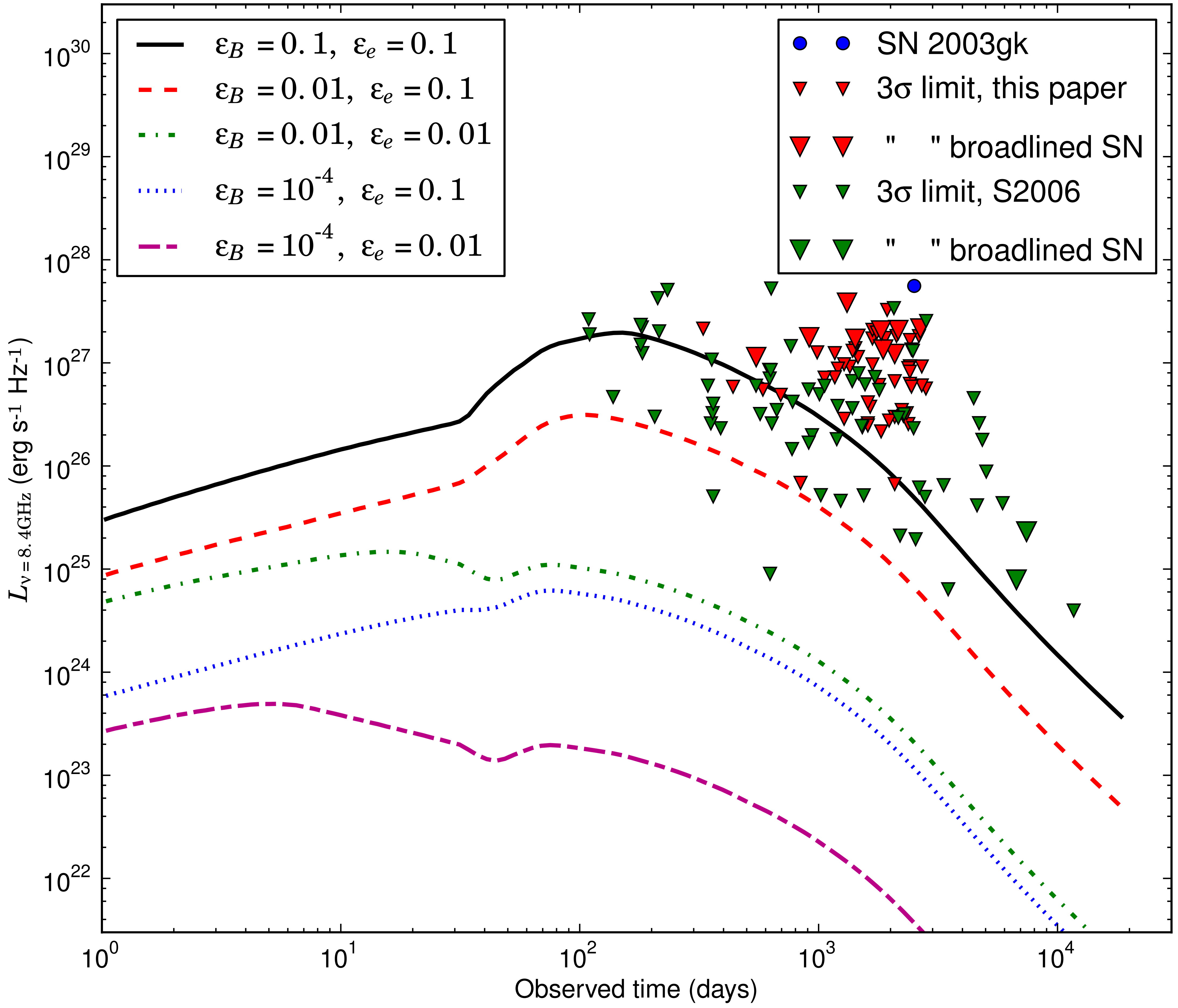
n_{ext}, ε_B, ε_e.

Off-axis radio afterglow constraints

- follow-up radio observations of stripped-envelop SNe (type Ib,Ic,Ic-BL)
- upper limits at 10-1000 days
- ruling out some off-axis jet models
- on-going and future radio surveys will do better (e.g., Karl G. Jansky Very Large Array Sky Survey; VLASS)

Model: $E_{k,iso}=10^{52}$ erg, $\theta_{obs}=90°$ off axis radio afterglow

Bietenholz+ (2014)



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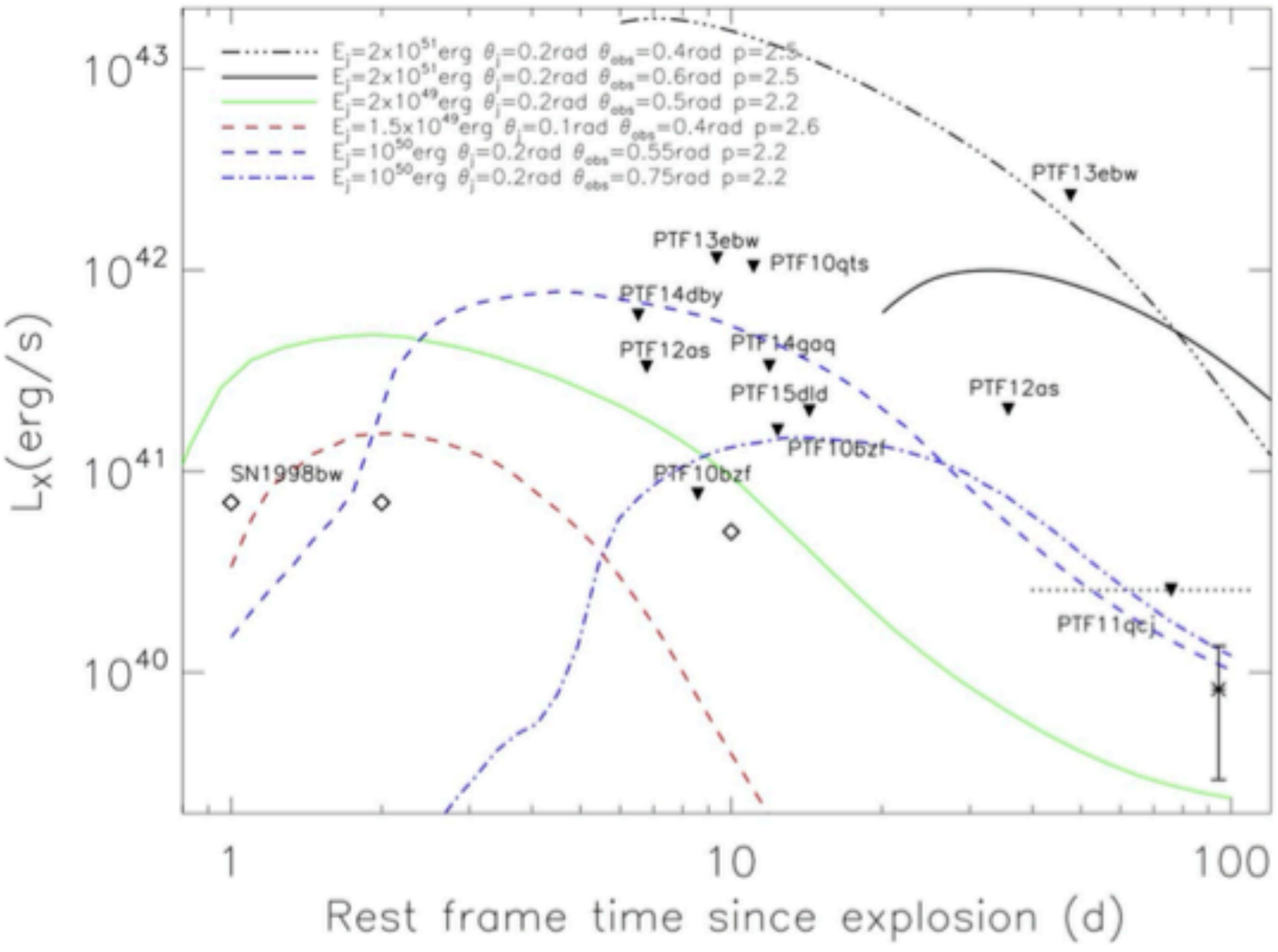
radio detections and upper limits for SNe Ic-BL in PTF sample
Corsi+ (2016)



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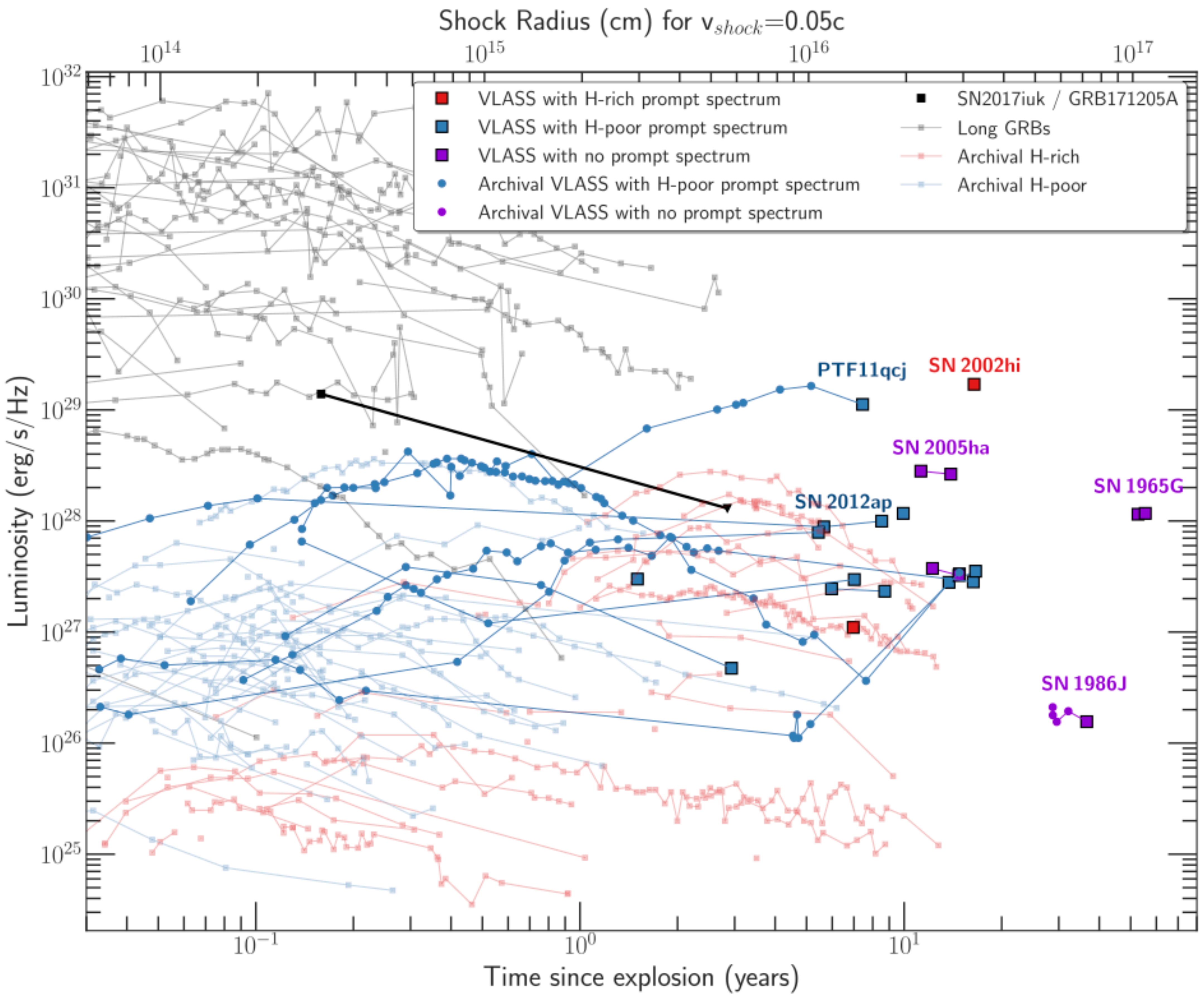
VLASS result for radio transients, Sroh+(2021)



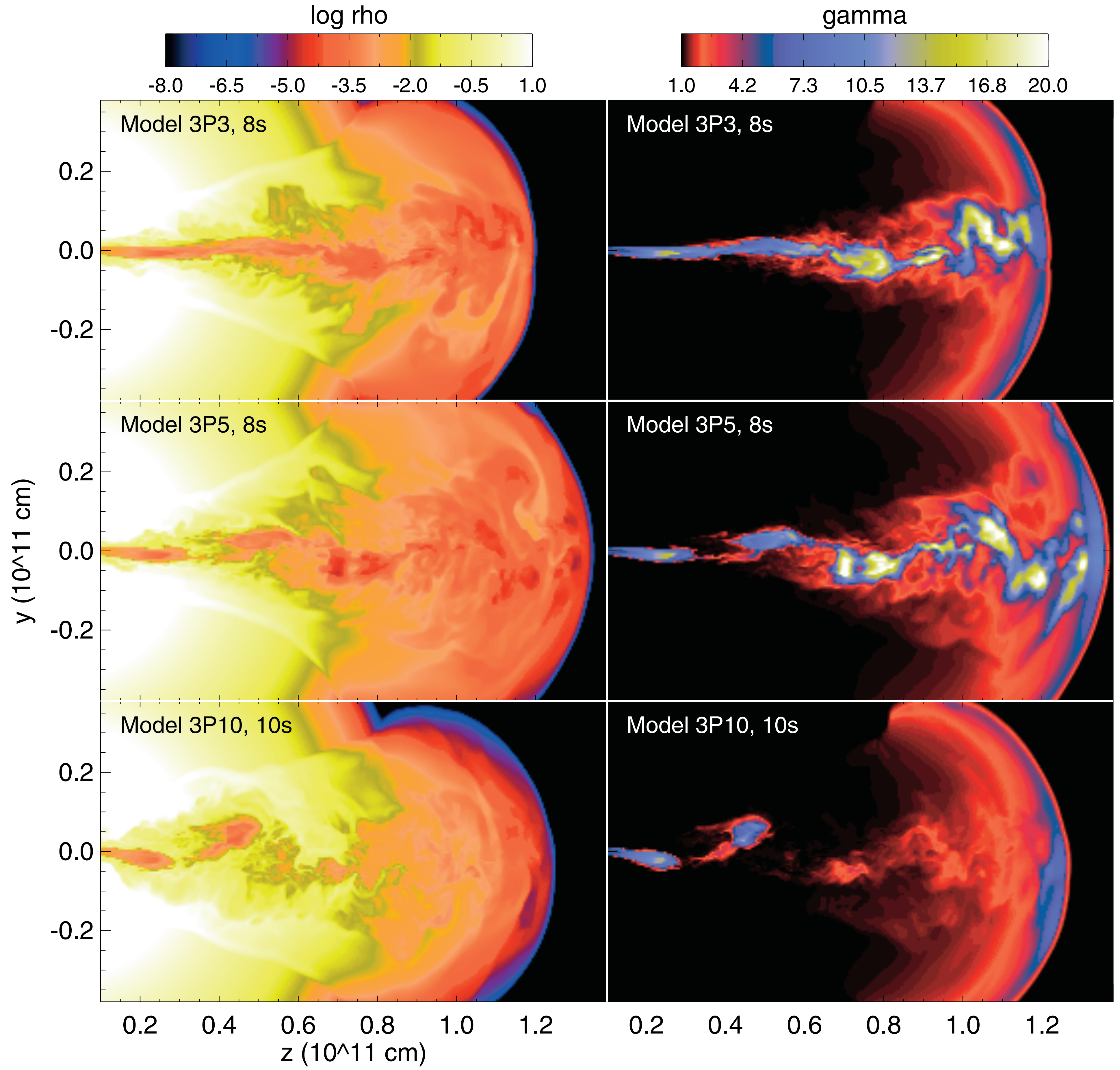
GRB jet revealed by numerical simulations

Phenomenological GRB jet simulation

- jet injection by hand
- multi-D hydro simulations since ~2000
- successful jet acceleration to $\Gamma>100$
- jet confinement in star
- jet breakout from the stellar surface
- cocoon formation

typically,

- jet power $L \sim 10^{50}$-10^{51} [erg/s]
- duration $t_{jet} \sim 10$-100 [s]
- initial Lorentz factor $\Gamma \sim 10$
- initial specific energy $e \sim 10$
- opening angle $\theta_{jet}=5°$-$10°$
- injection radius $r=10^8$-10^9 [cm]

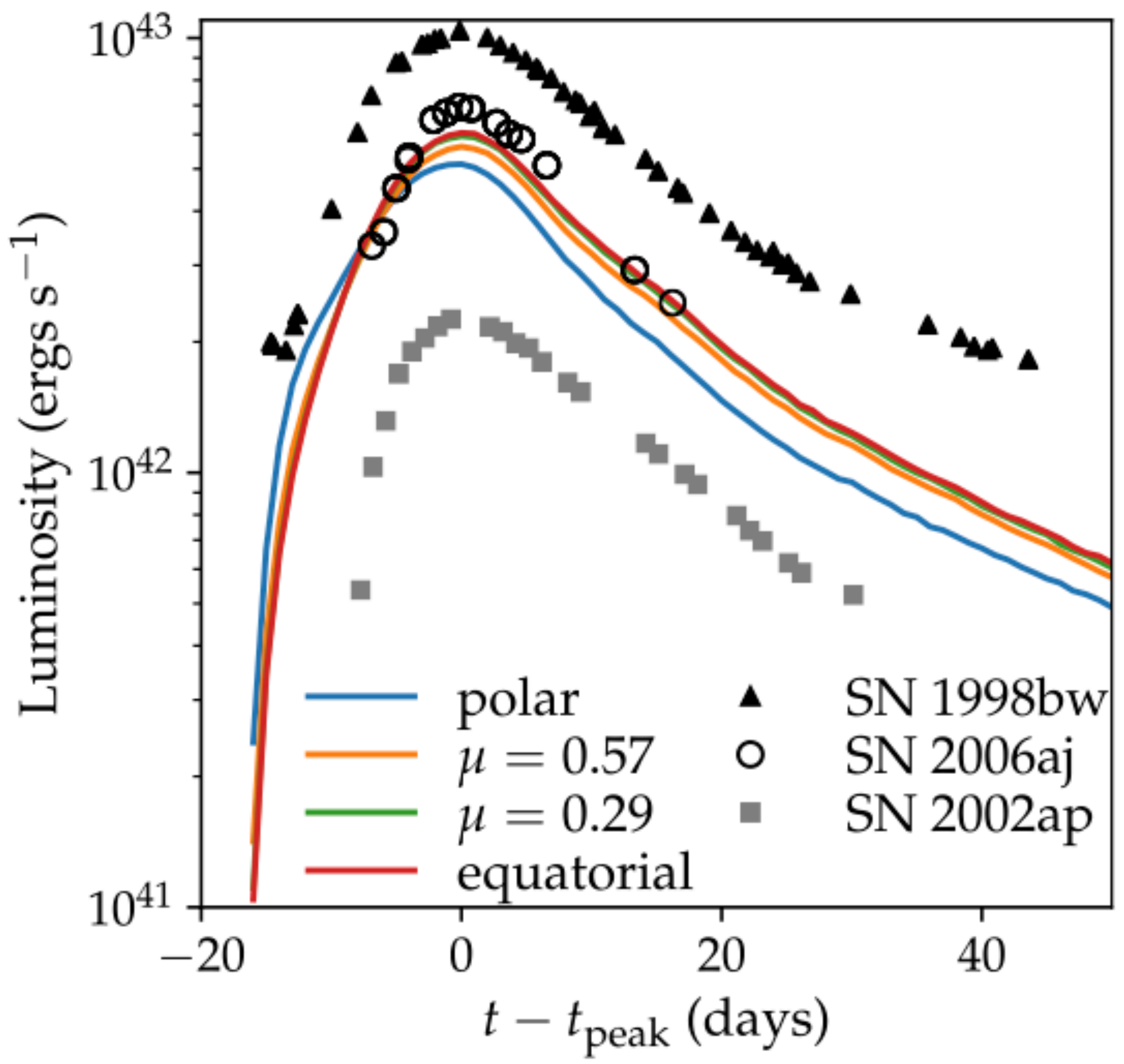


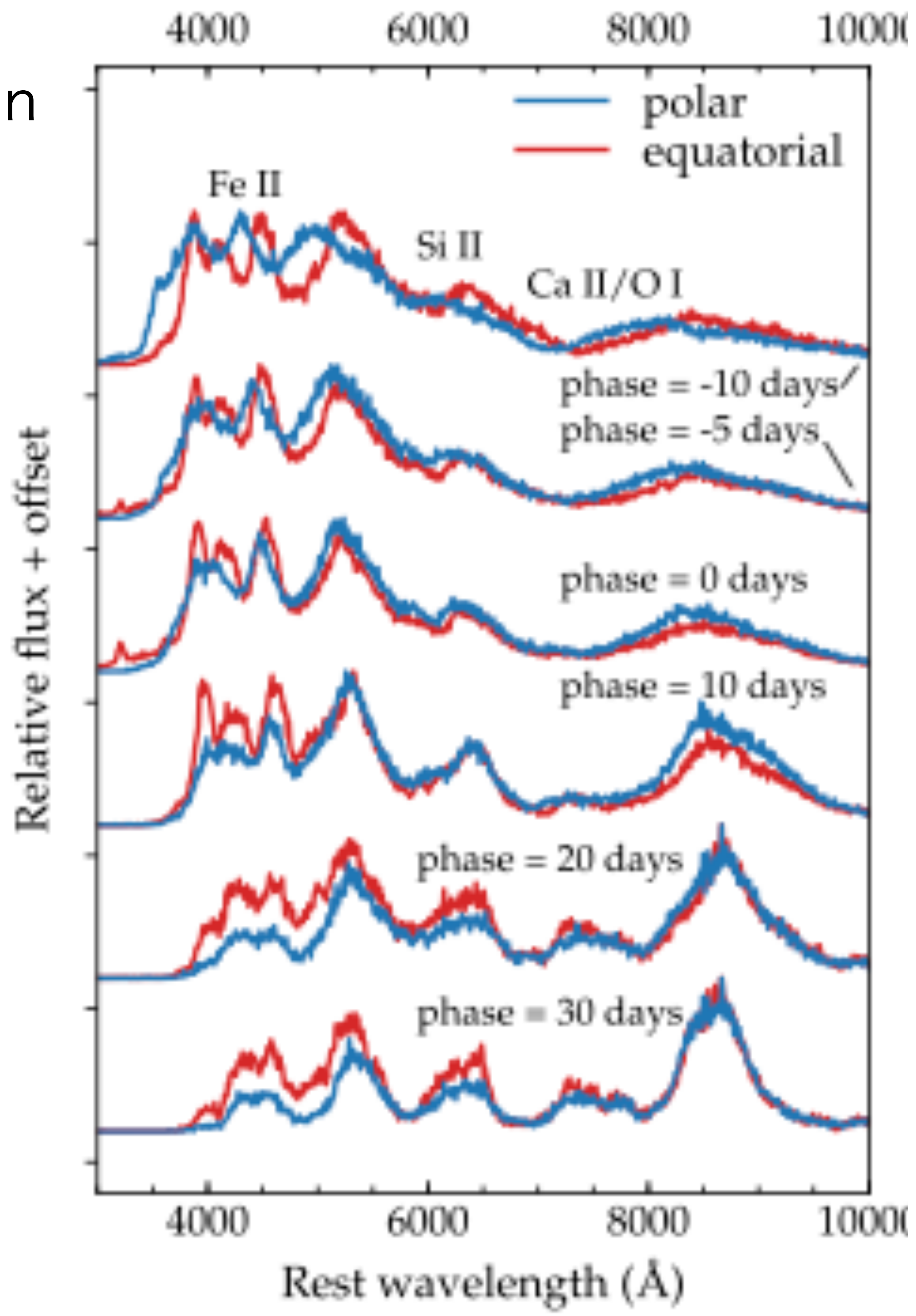
Zhang, Woosley, Heger (2004)

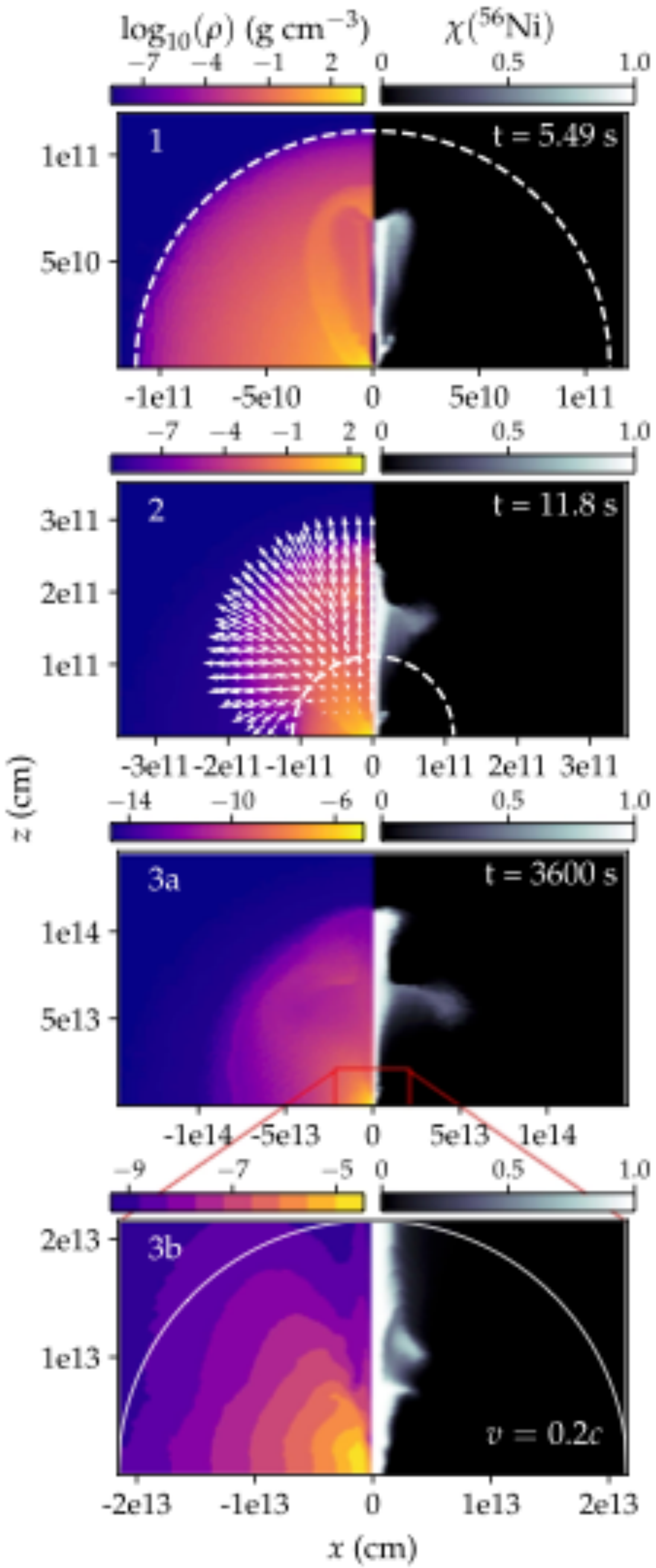
GRB-SN connection

- Barnes et al. (2018): GRB jet simulation coupled with post-process nucleosynthesis, light curve and spectral calculations
- exponentially decaying jet injection → ^{56}Ni
- E_{eng}=1.8x10^{52}[erg], t_{eng}=1.1 [s], M_{Ni}=0.24M_{sun}

$$L_{\rm eng}(t) = \frac{E_{\rm eng}}{t_{\rm eng}} \times \exp[-t/t_{\rm eng}].$$







Barnes+ (2018)

GRB-SN connection

- Grimmett et al. (2021): phenomenological jet engine + post-process nucleosynthesis
- rotating CO star (25,30M_{sun})
- “parametrized, but physically motivated” jet model
- E_{exp}>10^{52}erg, M_{Ni}=0.05 - 0.45 M_{sun}

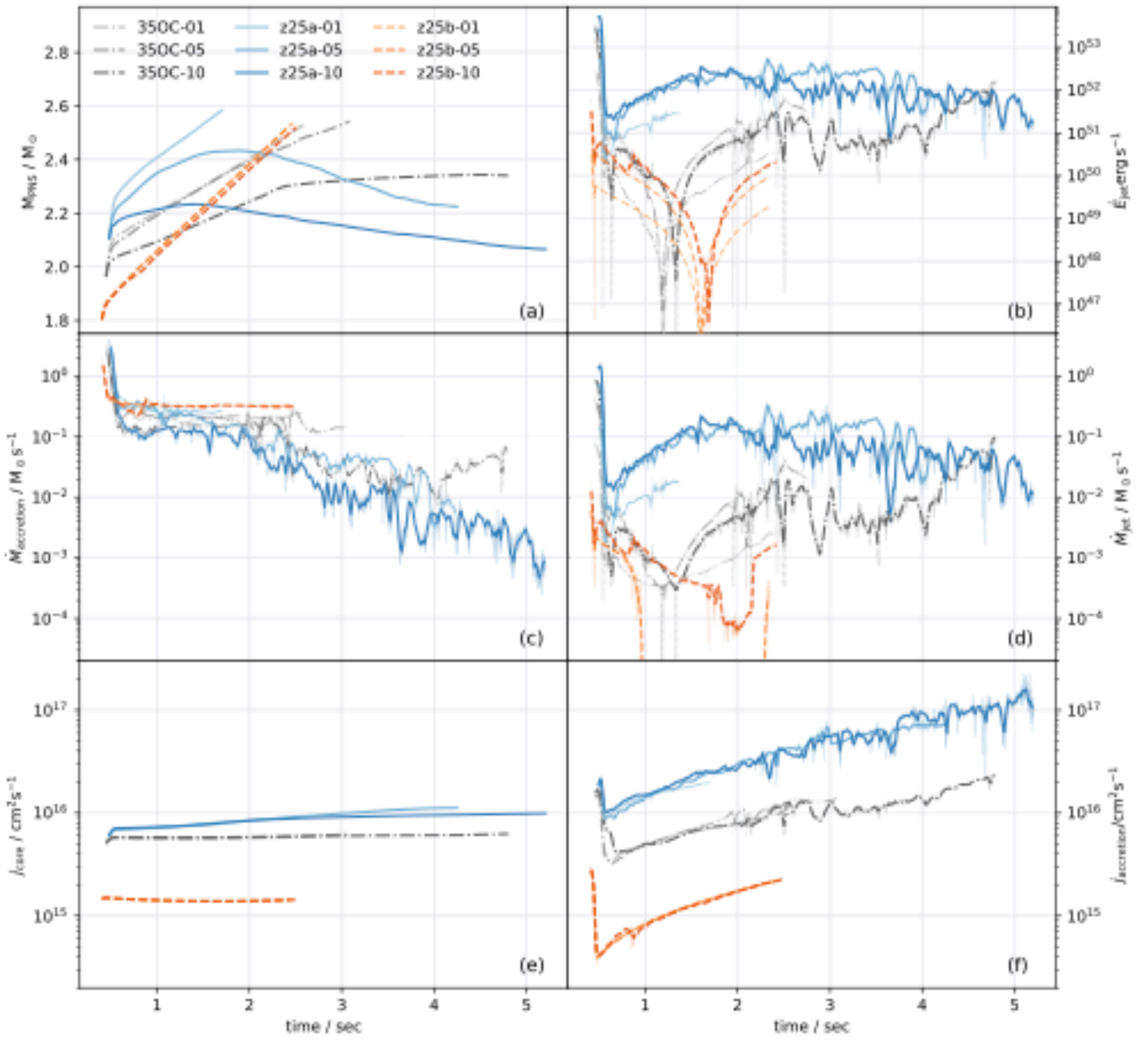
$$\dot{E}_{\rm rot,acc} = \dot{M}\frac{j^2}{4/5\,R^2}, \qquad (1)$$

$$\dot{E}_{\rm rot,PNS} = \frac{\rm d}{{\rm d}t}\left(\frac{J^2}{2I}\right) = \frac{\rm d}{{\rm d}t}\left(\frac{J^2}{4/5MR^2}\right) = \frac{5}{4R^2}\left(\frac{2\dot{J}J}{M} - \frac{\dot{M}J^2}{M^2}\right)$$

$$= \frac{5\left(2\dot{M}\,j\,j_{\rm PNS} - \dot{M}\,j_{\rm PNS}^2\right)}{4R^2} = \frac{5\dot{M}\left(2\,j\,j_{\rm PNS} - j_{\rm PNS}^2\right)}{4R^2}, \qquad (2)$$

$$\dot{E}_{\rm free} = \frac{5\dot{M}\left(j^2 - 2\,j\,j_{\rm PNS} + j_{\rm PNS}^2\right)}{4R^2} = \frac{5\dot{M}\left(j - j_{\rm PNS}\right)^2}{4R^2}. \qquad (3)$$

$$\dot{E}_{\rm jet} = \epsilon\dot{E}_{\rm free} = \frac{5\epsilon\dot{M}\left(j - j_{\rm PNS}\right)^2}{4R^2}. \qquad (4)$$



Grimmett+ (2021)

GRB-SN connection

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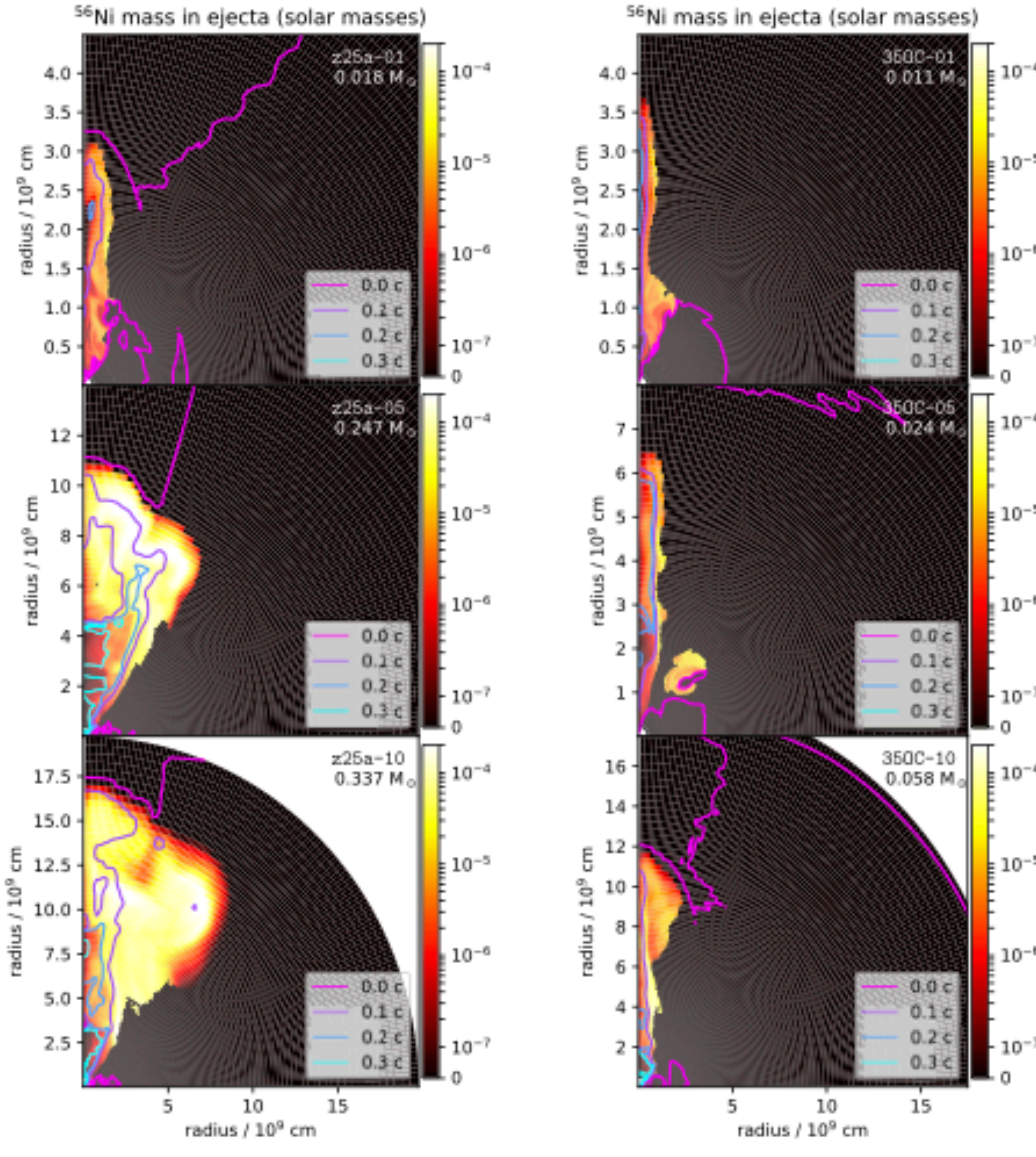


(a) Models z25a. (b) Models 350C.

(Off-axis) Afterglow modeling

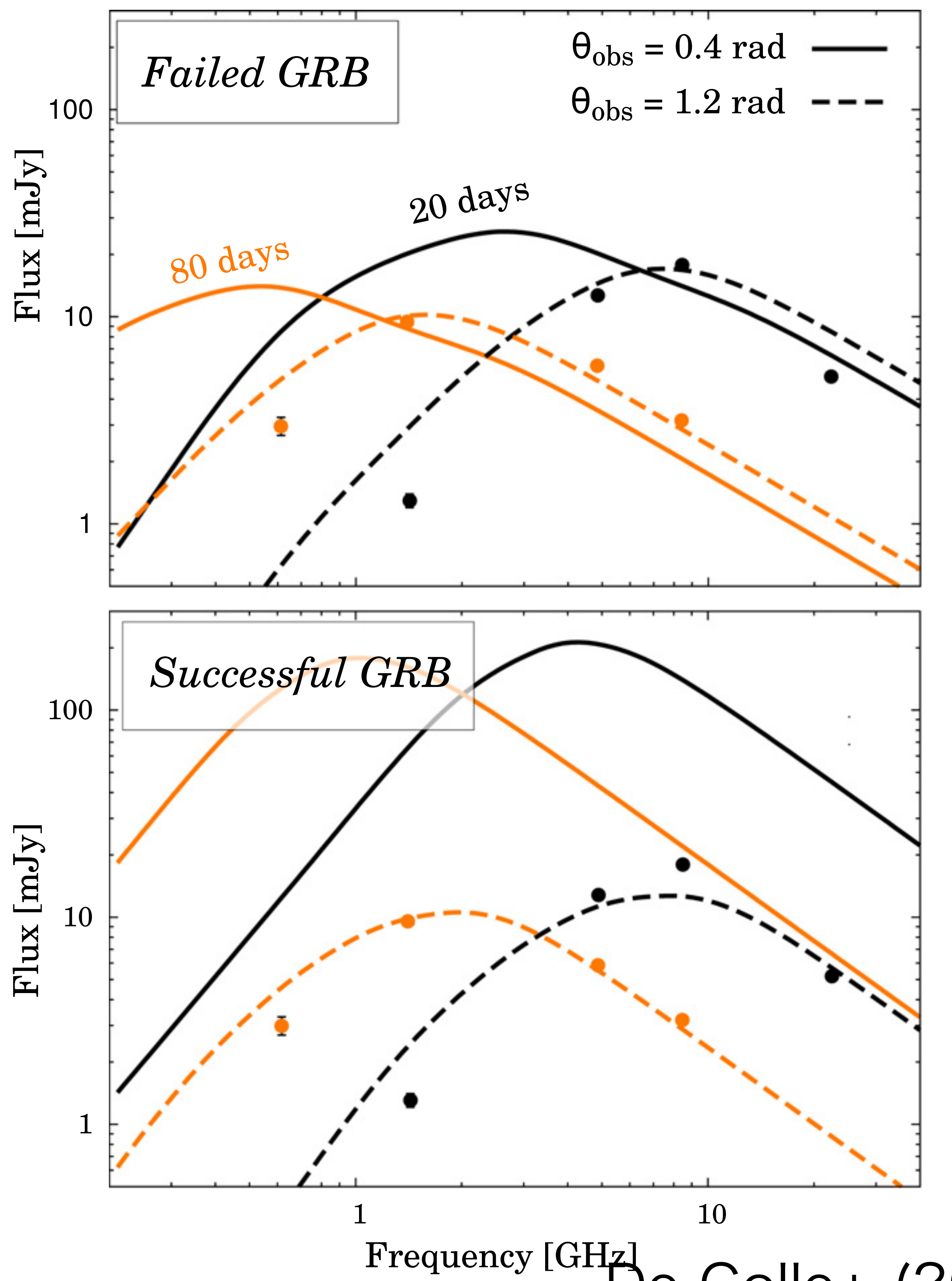
- De Colle et al. (2018): phenomenological jet engine
- post-process synchrotron emission modeling: $e_{acc} = \varepsilon_e \times e_{ps}$
- radio light curve consistent with some HNe

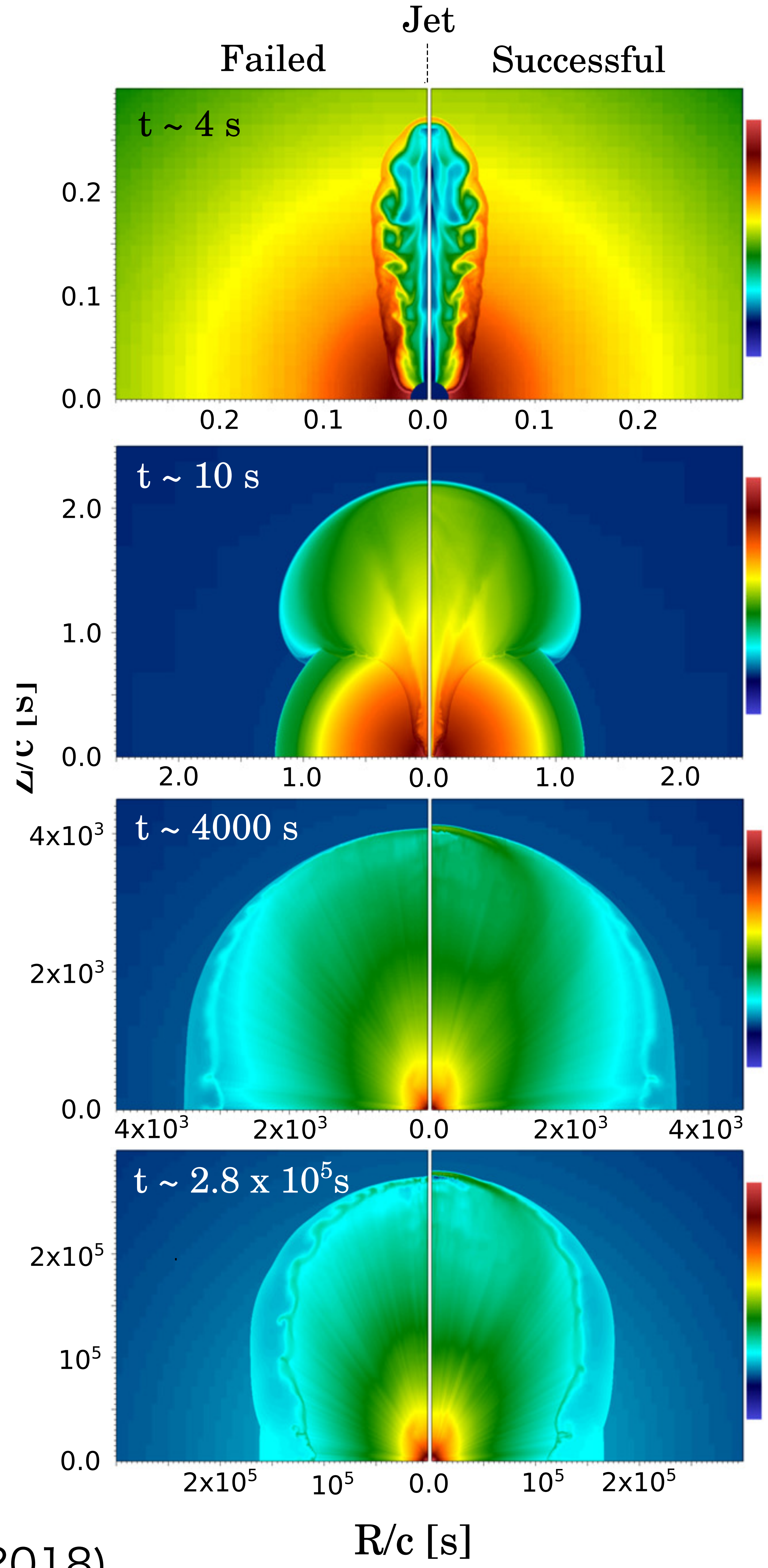
$$I_{\nu'} = \frac{j_{\nu'}}{\alpha_{\nu'}}(1 - e^{-\tau_{\nu'}}),$$

$$j_{\nu'} = 0.88 \frac{64 q_e^3}{27\pi m_e c^2} \frac{(p-1)}{3p-1} \frac{\xi_e n_{ps} B_{ps}}{\gamma^2 (1-\beta_\parallel)^2} \times \begin{cases} (\nu'/\nu_m)^{1/3} & \nu' \leqslant \nu_m \\ (\nu'/\nu_m)^{(1-p)/2} & \nu' > \nu_m \end{cases}$$

$$\alpha_{\nu'} = \frac{\sqrt{3} q_e^3 (p-1)(p+2)}{16\pi m_e^2 c^2} \frac{\xi_e n_{ps} B_{ps} \gamma (1-\beta_\parallel)}{\gamma_m \nu'^{,2}} \times \begin{cases} (\nu'/\nu_m)^{1/3} & \nu' \leqslant \nu_m \\ (\nu'/\nu_m)^{-p/2} & \nu' > \nu_m \end{cases}$$

$$\nu_m = \frac{3 q_e \gamma_m^2 B}{4\pi m_e c}, \qquad \beta_\parallel = \beta \cos\theta.$$





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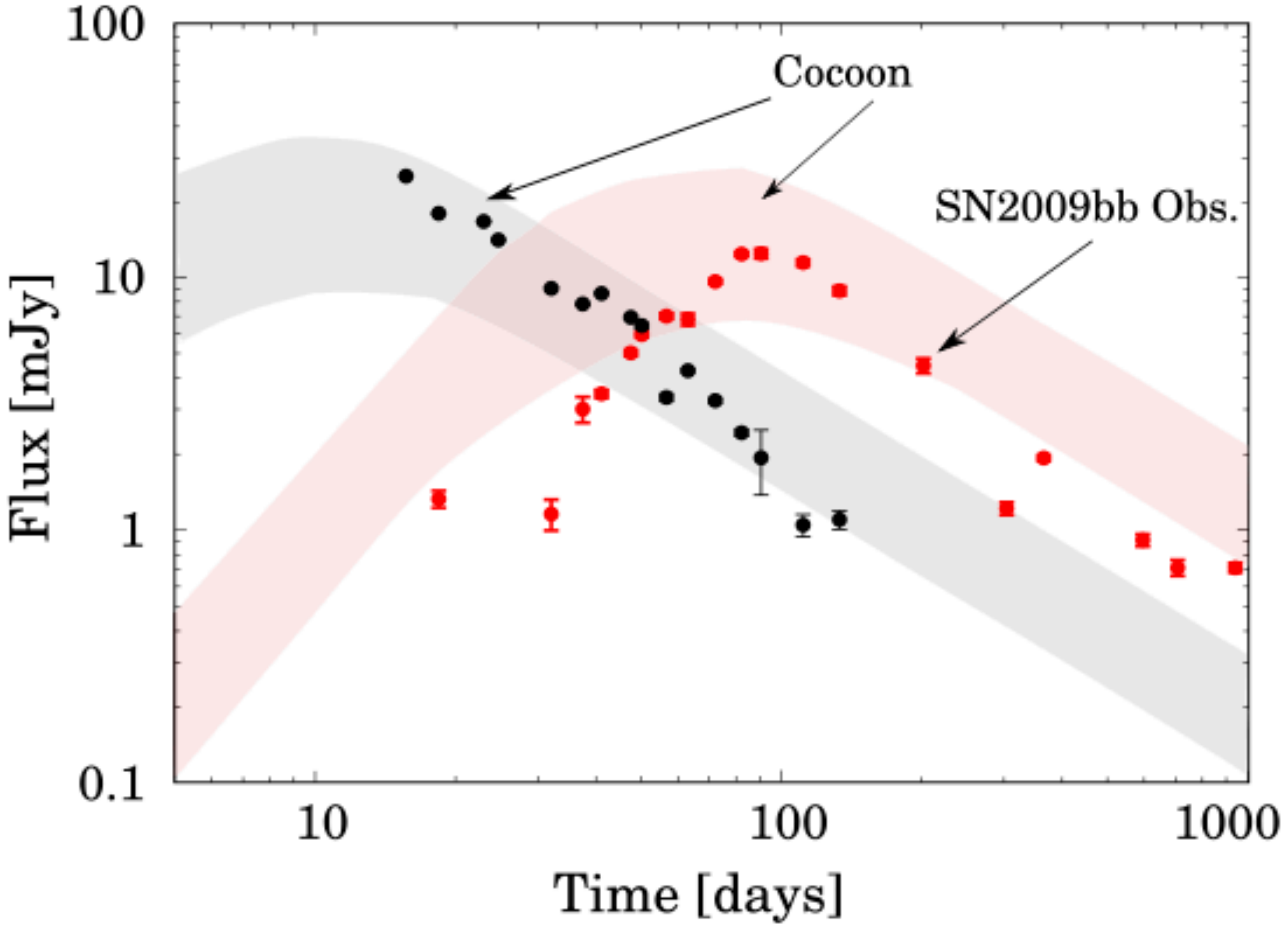

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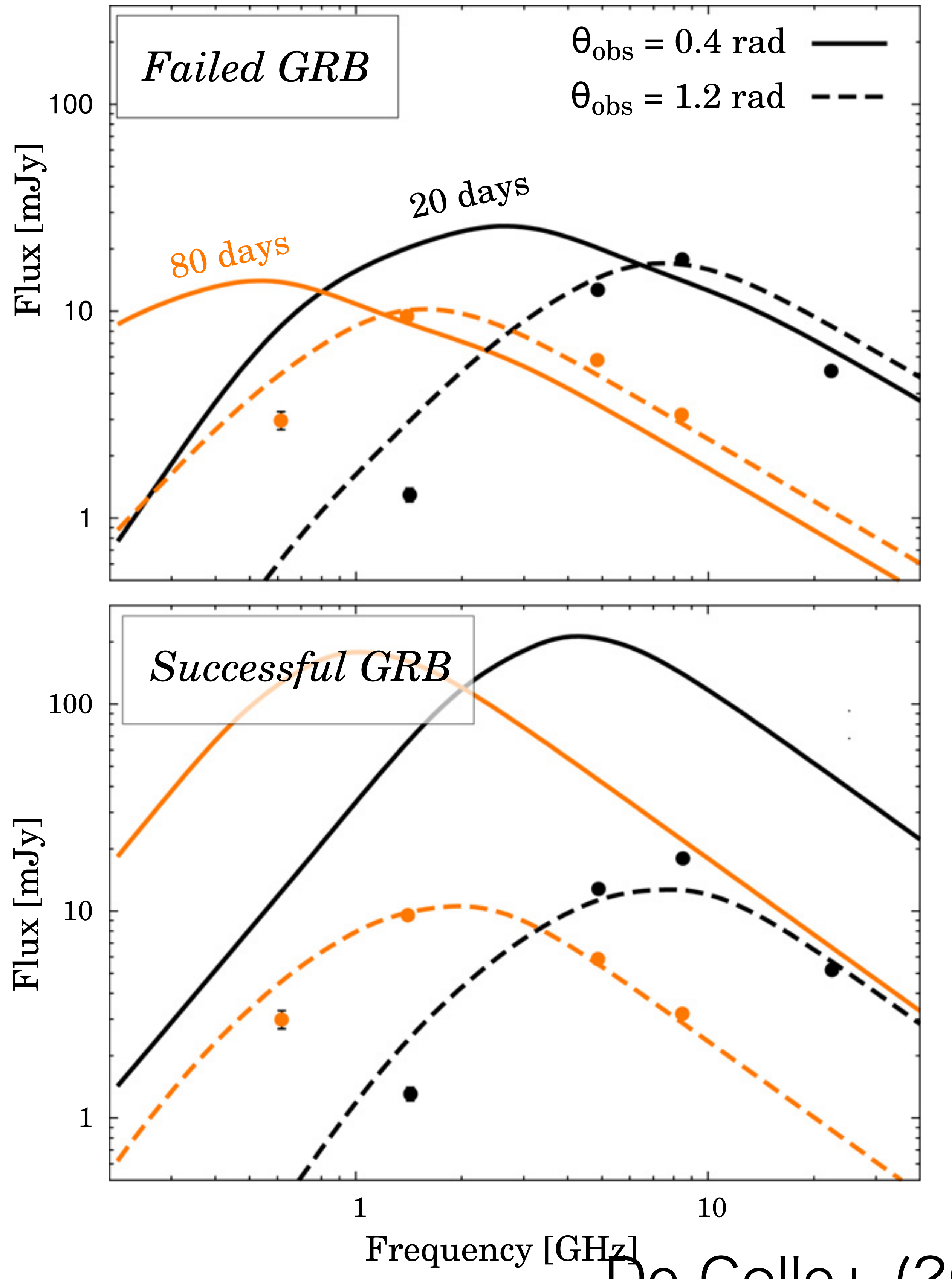
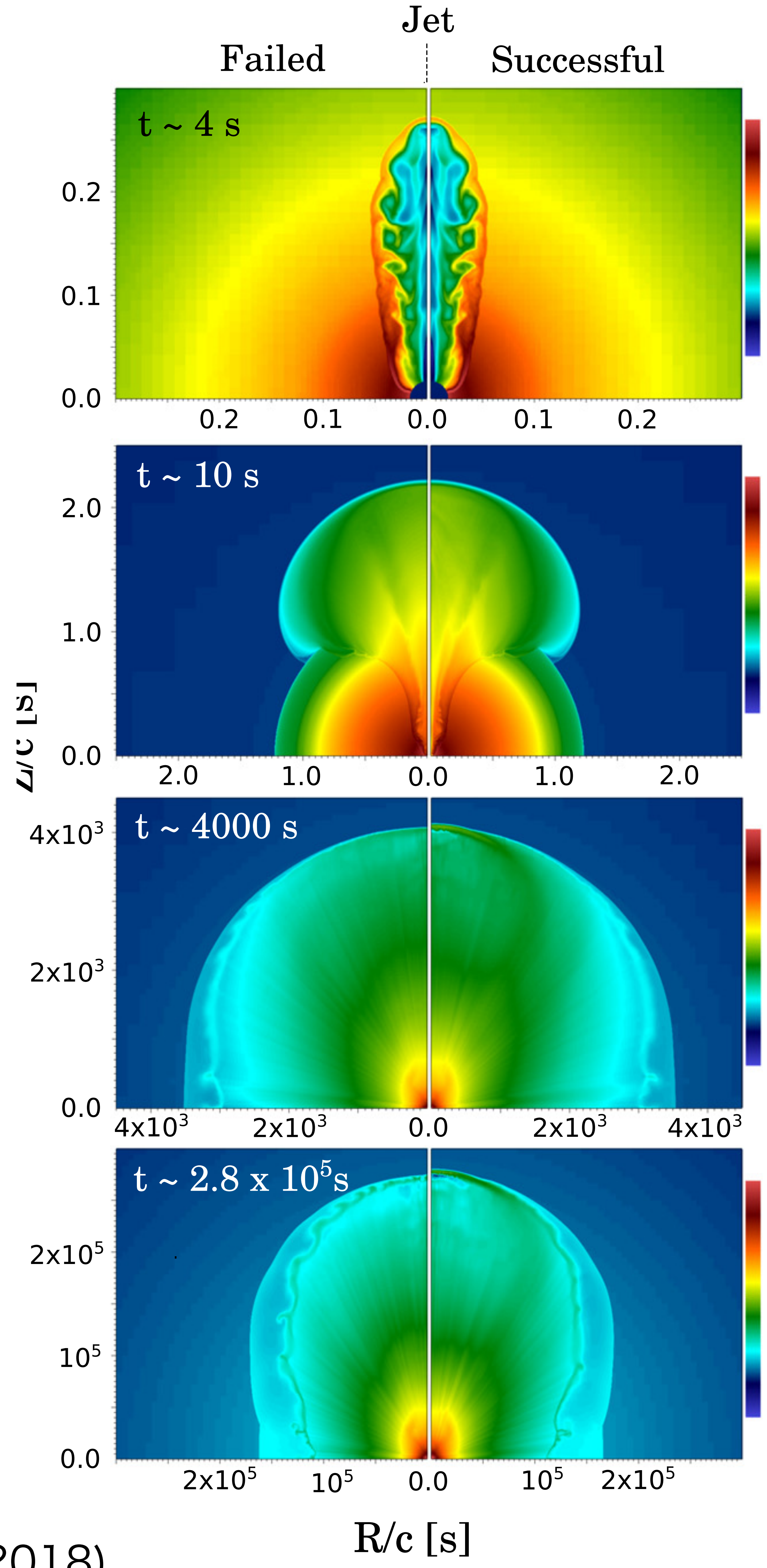


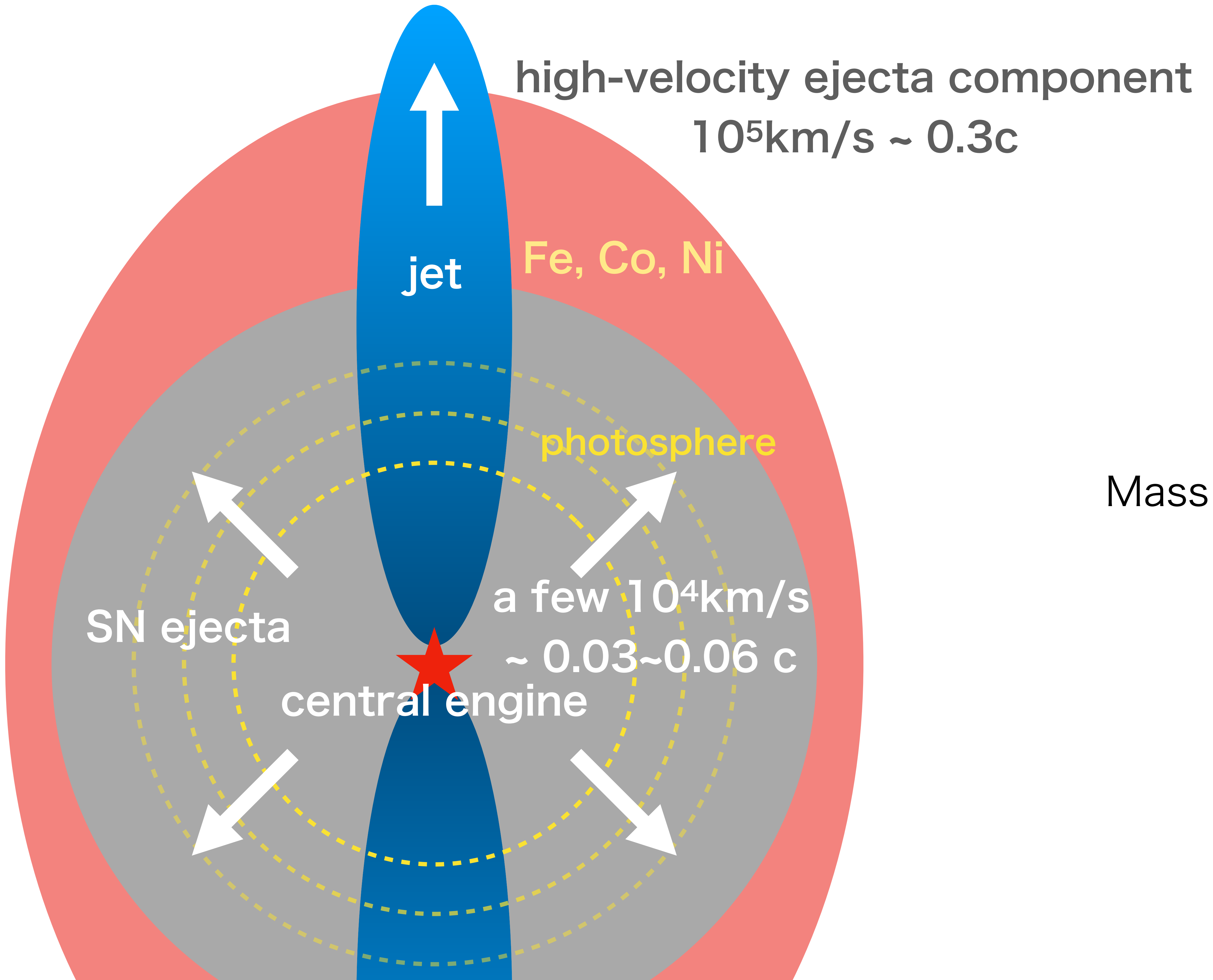


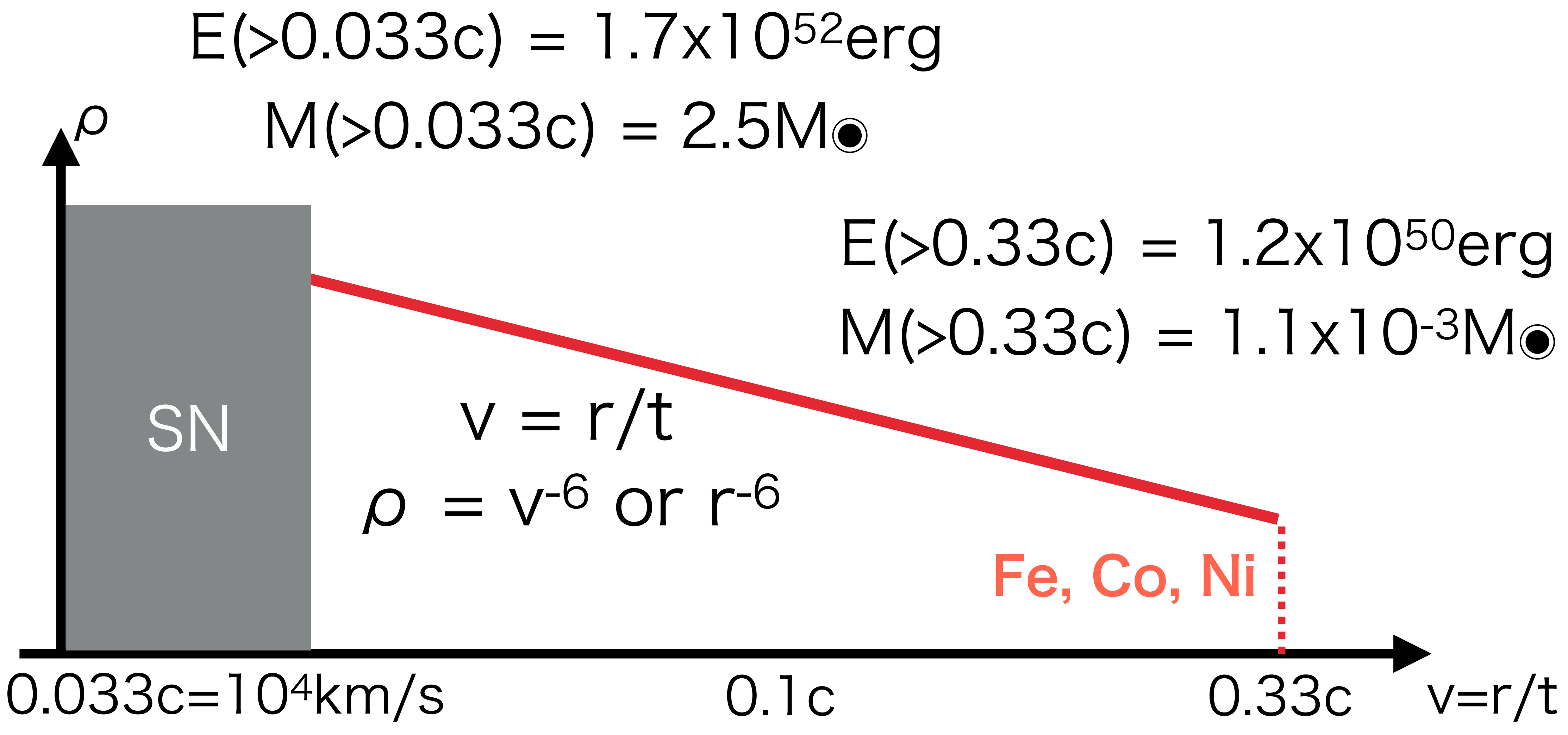
De Colle+ (2018)

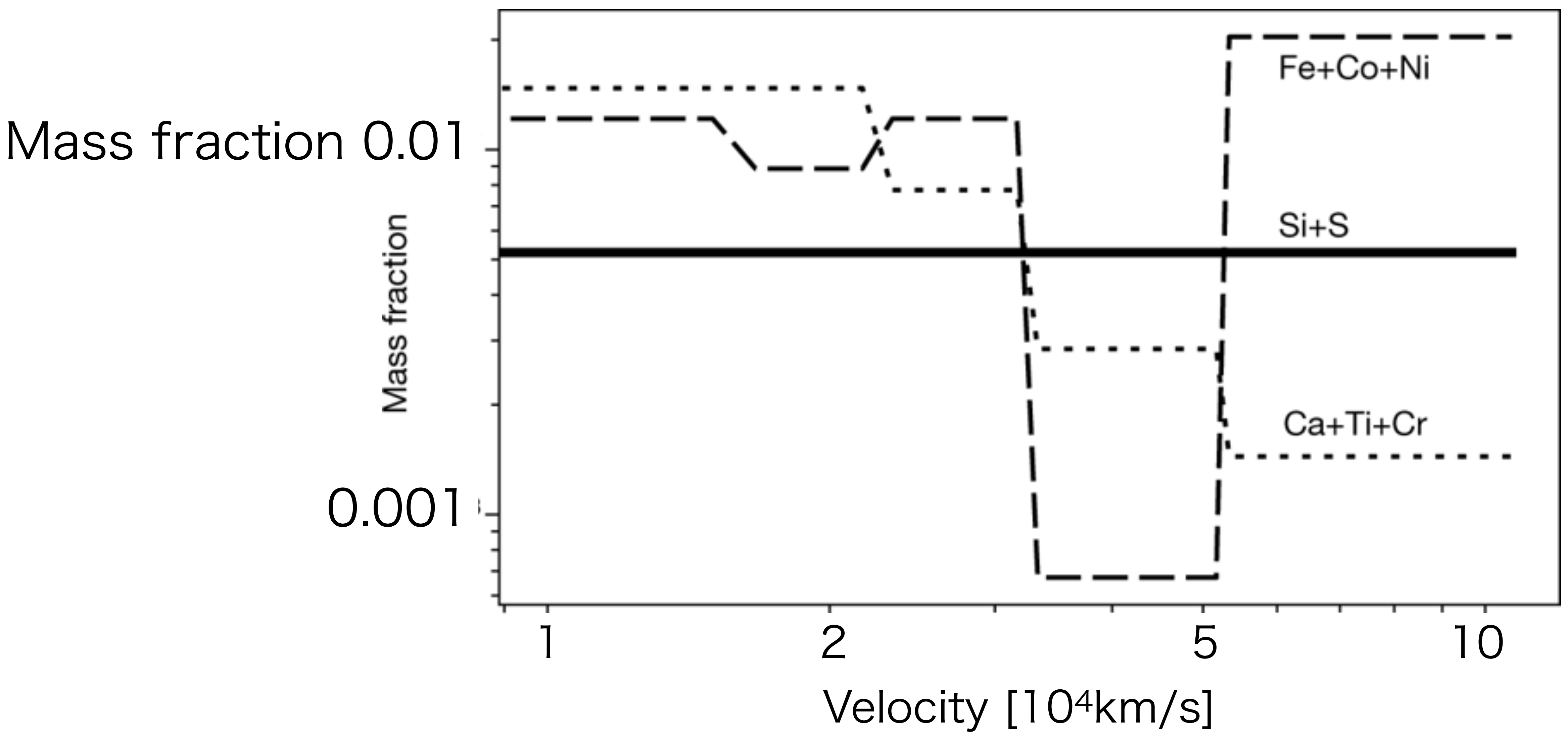
Our study on early emission from GRB-SNe

Recent progress : very early observations of GRB-SNe

- discovery of sub-relativistic ejecta component in GRB-SN
- efficient mixing of Fe-peak elements







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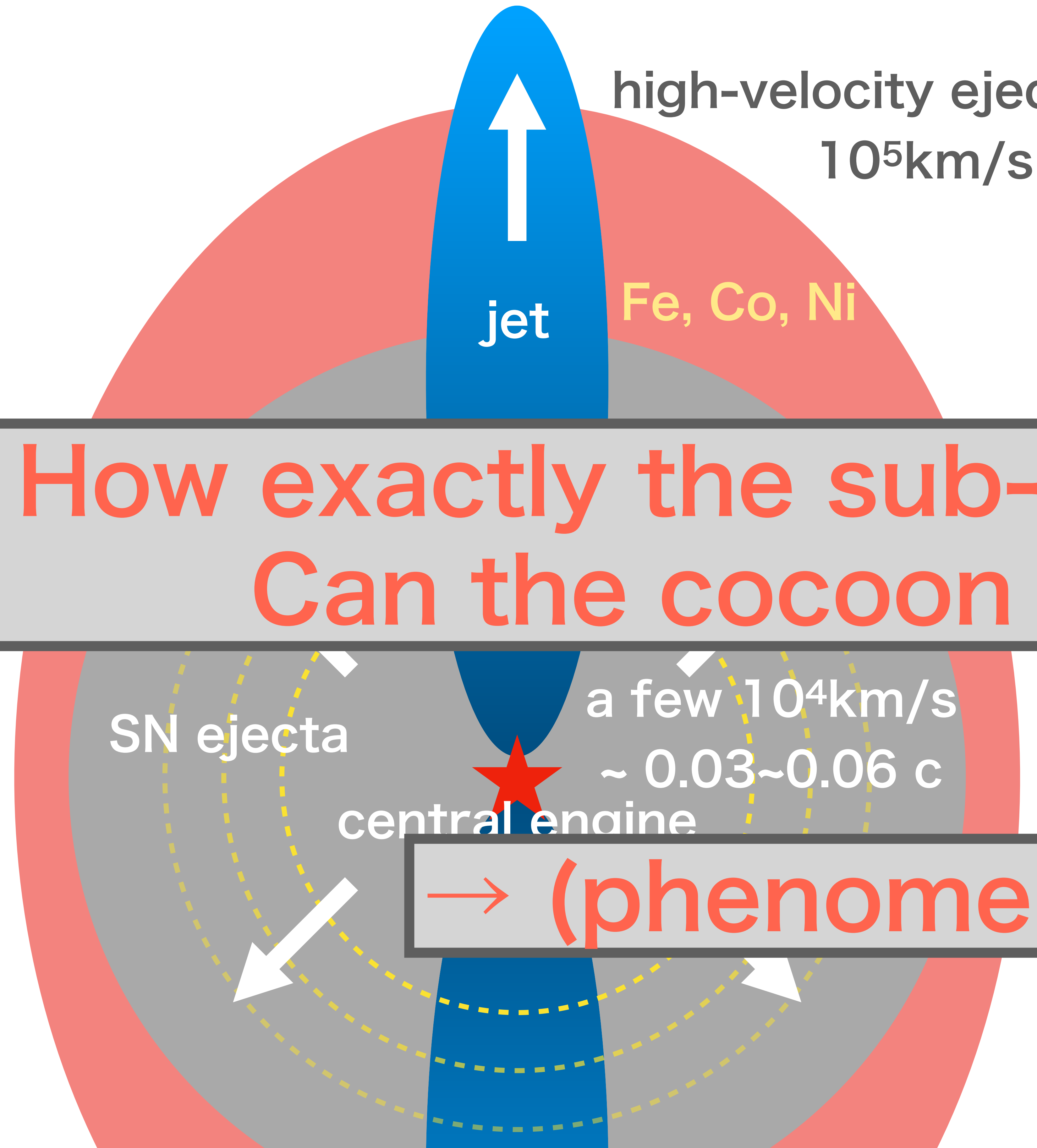
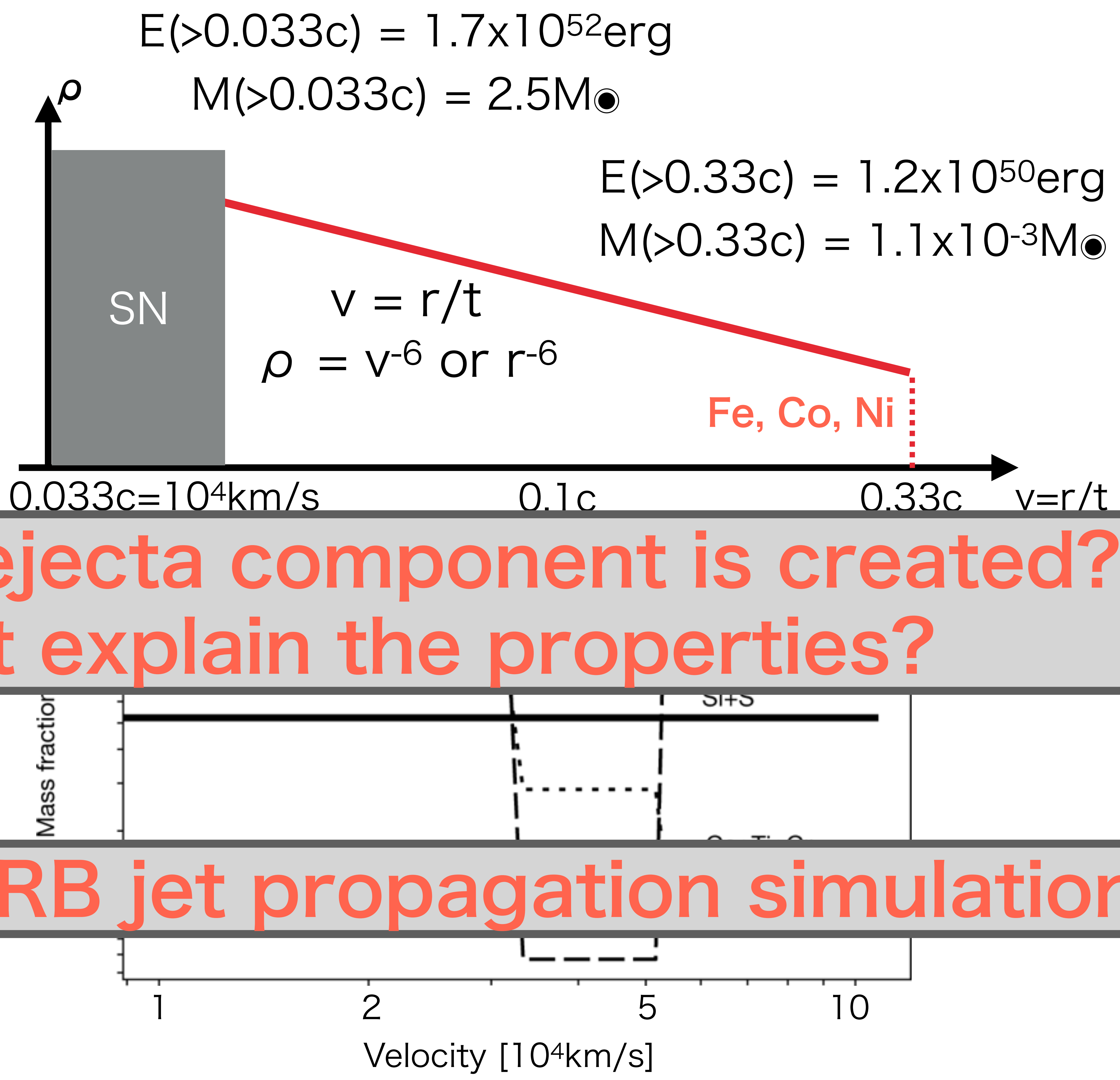




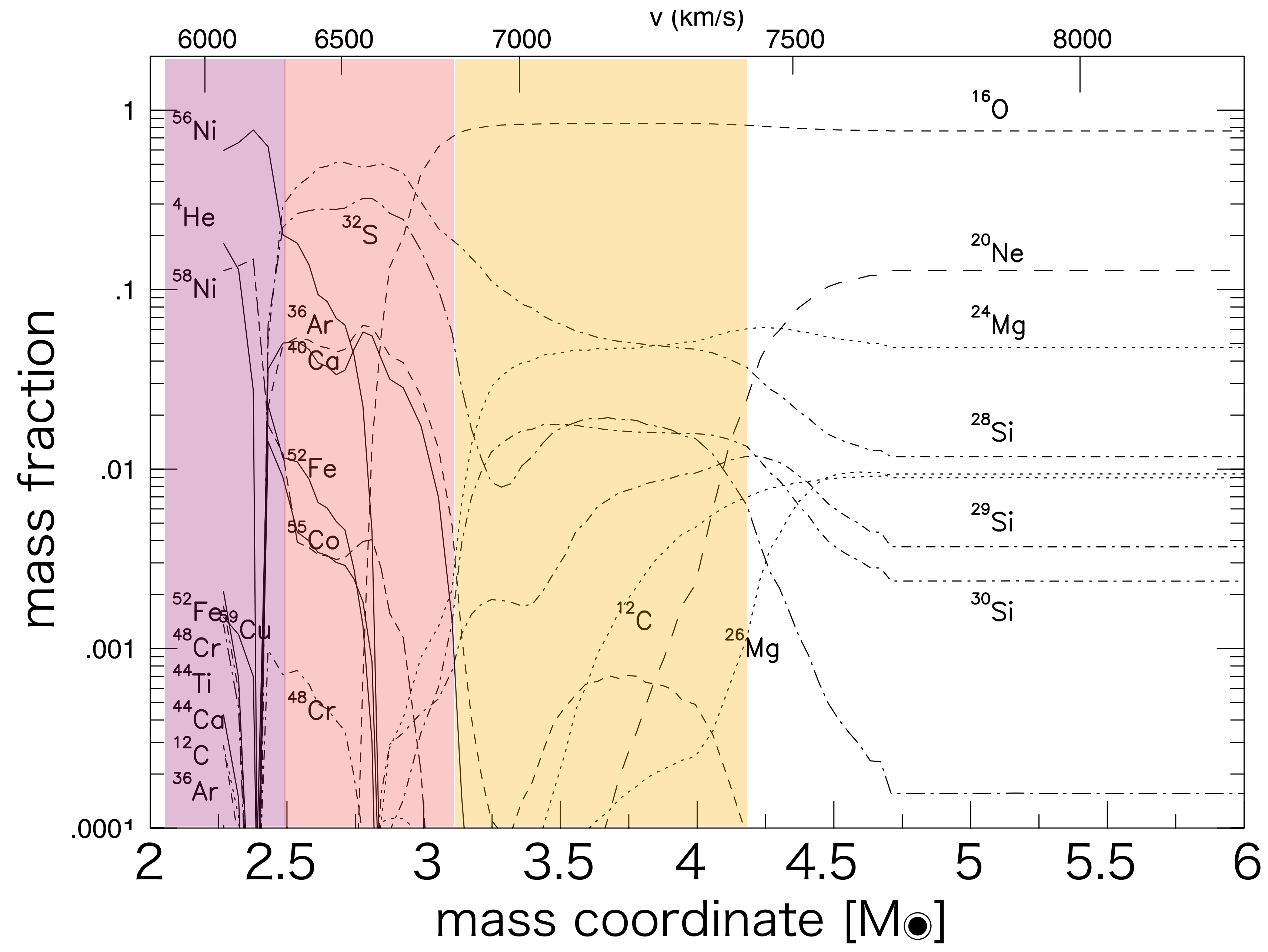
How exactly the sub-relativistic ejecta component is created?
Can the cocoon of a GRB jet explain the properties?

→ (phenomenological) GRB jet propagation simulation.

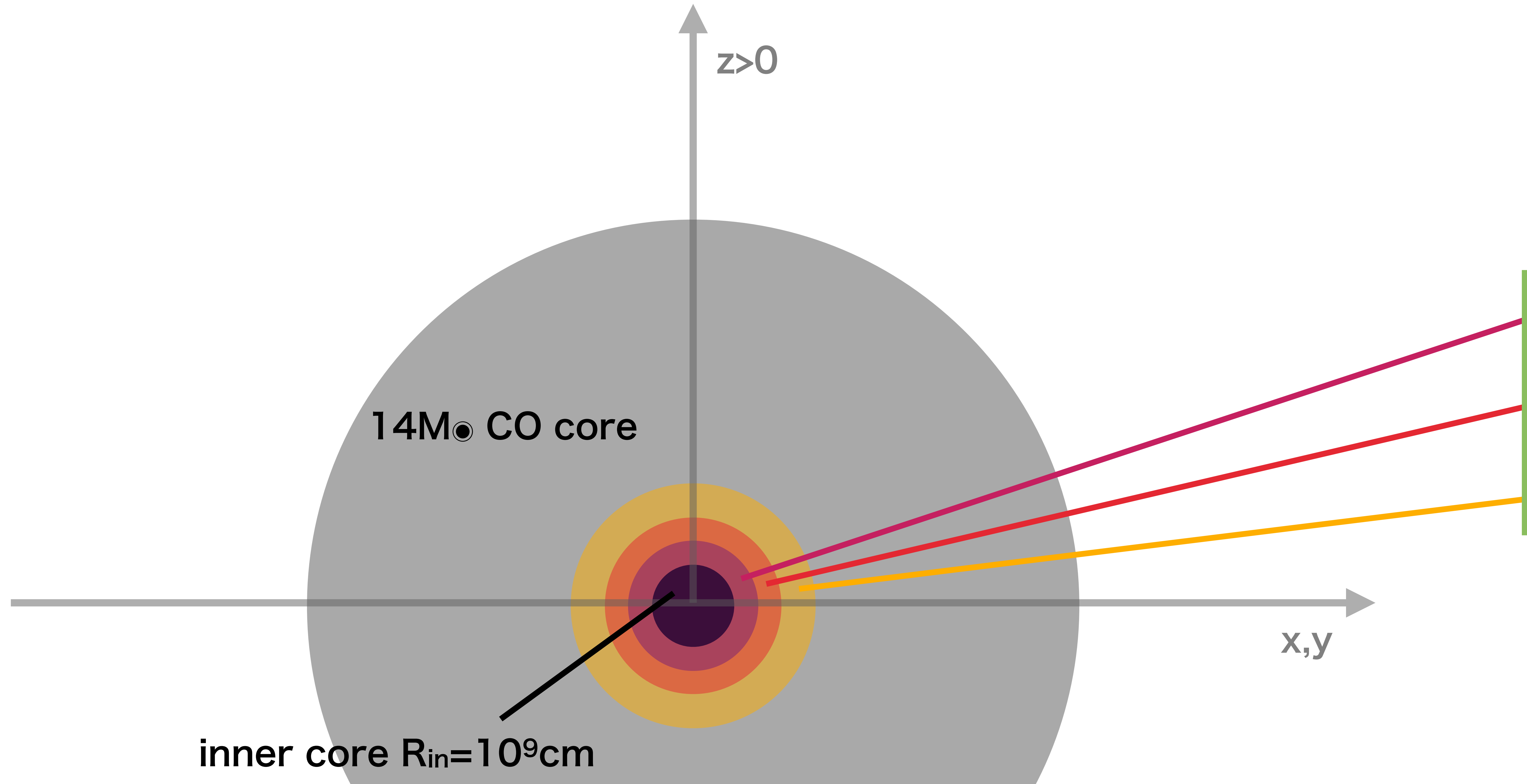
GRB jet simulation: setups

computation by using ATERUI II at CfCA

- 3D special relativistic hydrodynamic simulation in (x,y,z)
- 14 M⊙ CO core (16TI; Woosley&Heger 2006)
- chemical composition: hypernova-like (e.g., Iwamoto+ 2000)
- thermal bomb (5×10^{51} erg, $R_{in}=10^9$cm)
- relativistic jet (5×10^{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⊙
- Layer 2: incomplete Si burning, 0.6M⊙
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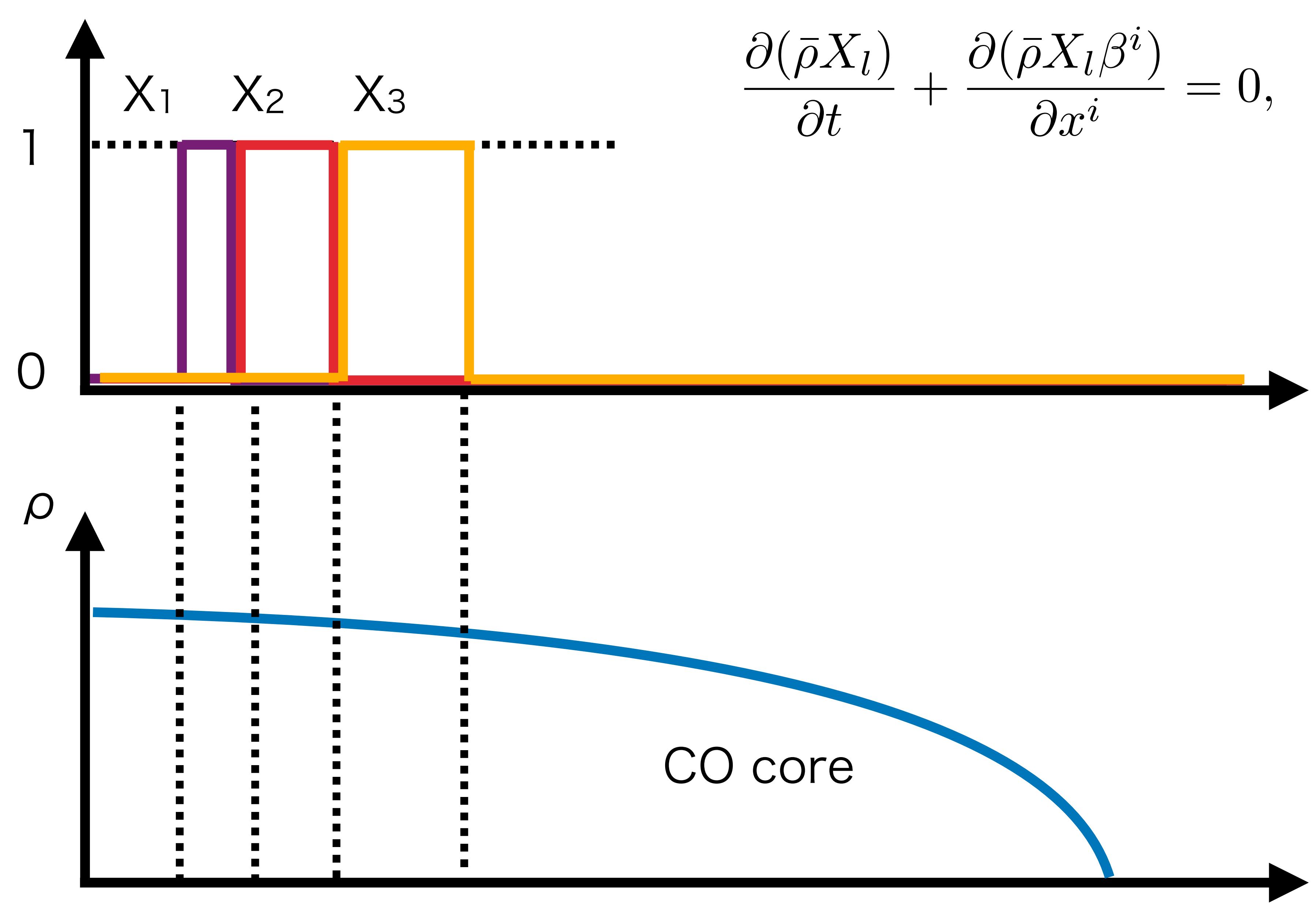
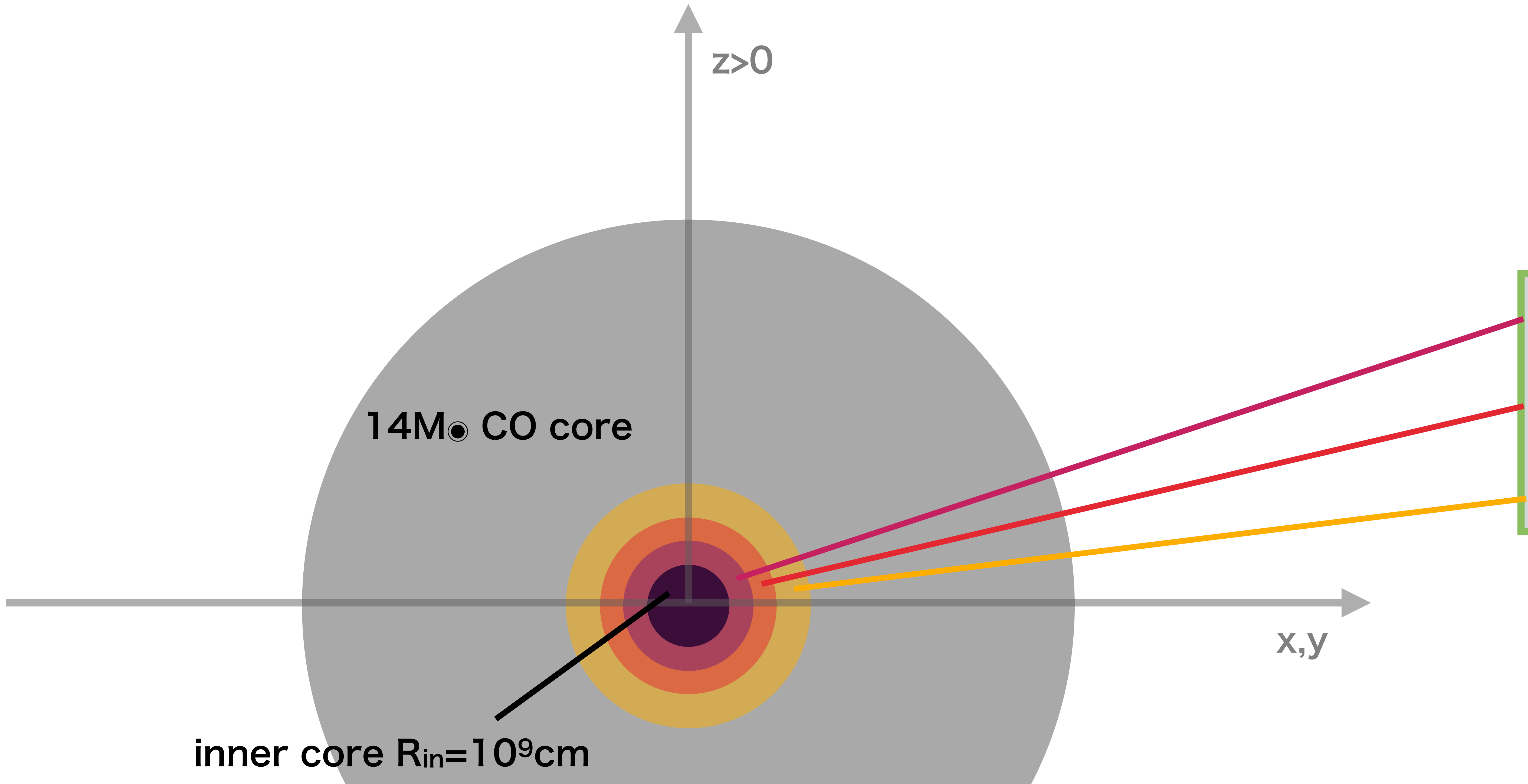
SR hydro eqs. +

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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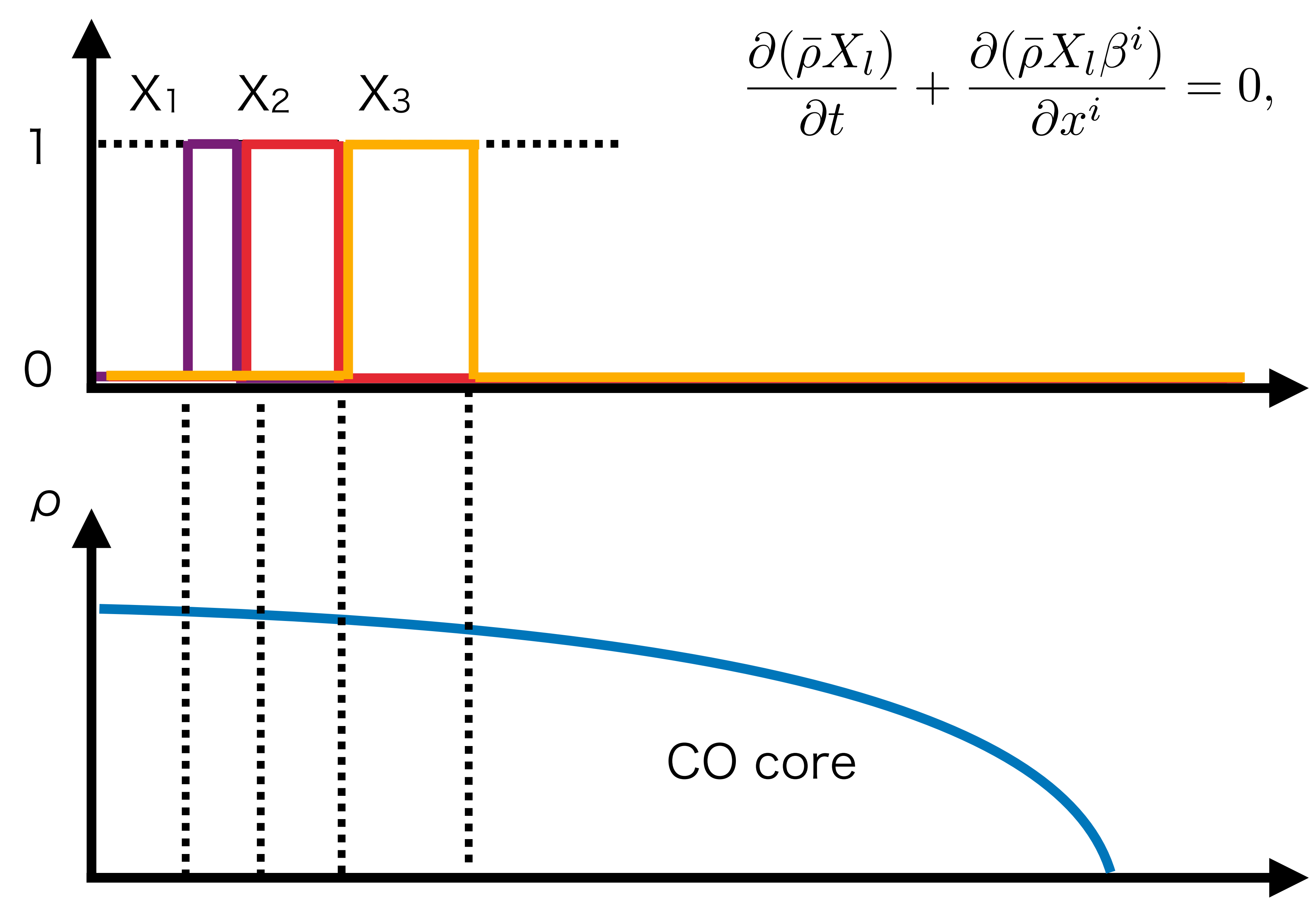

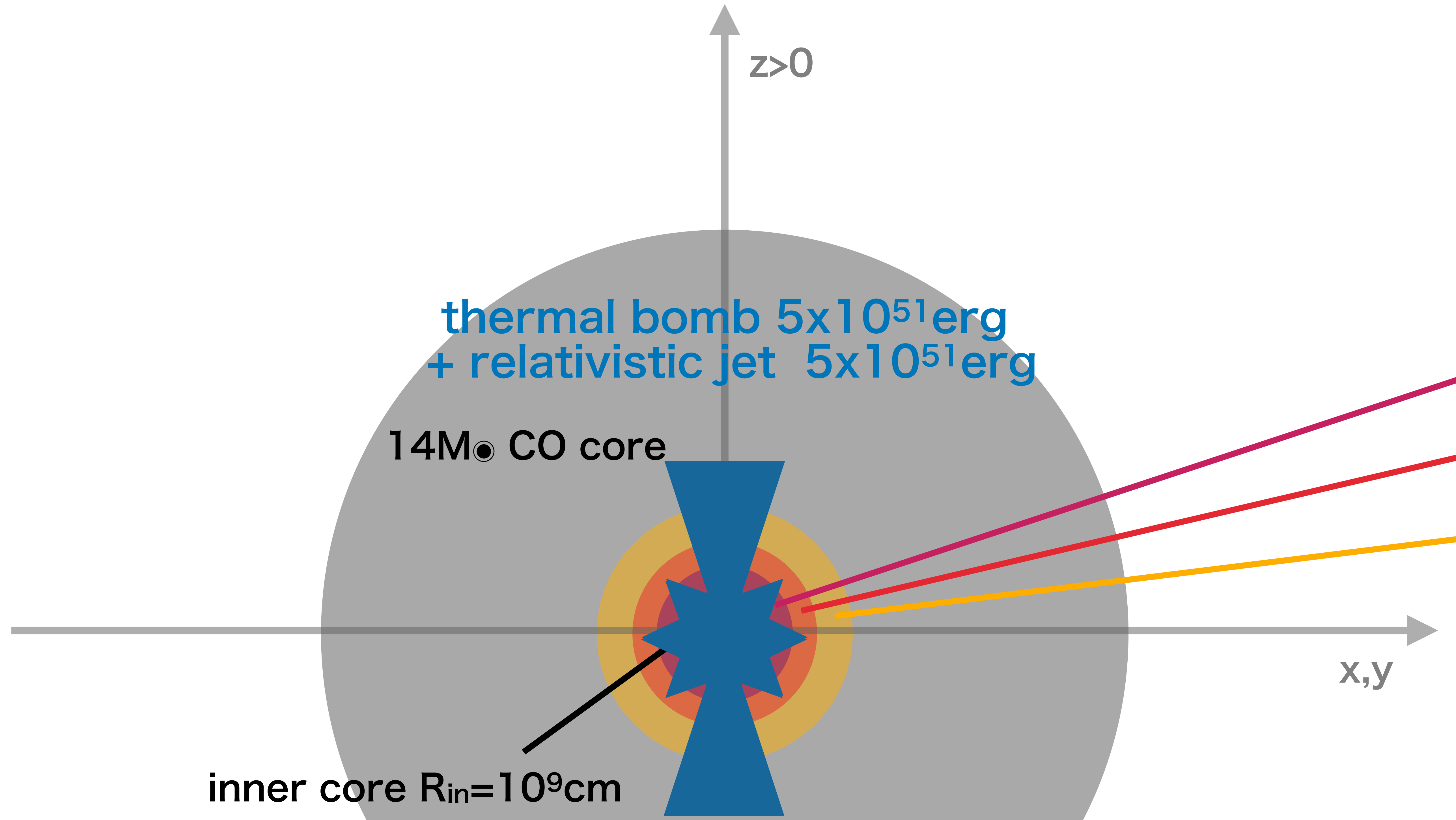

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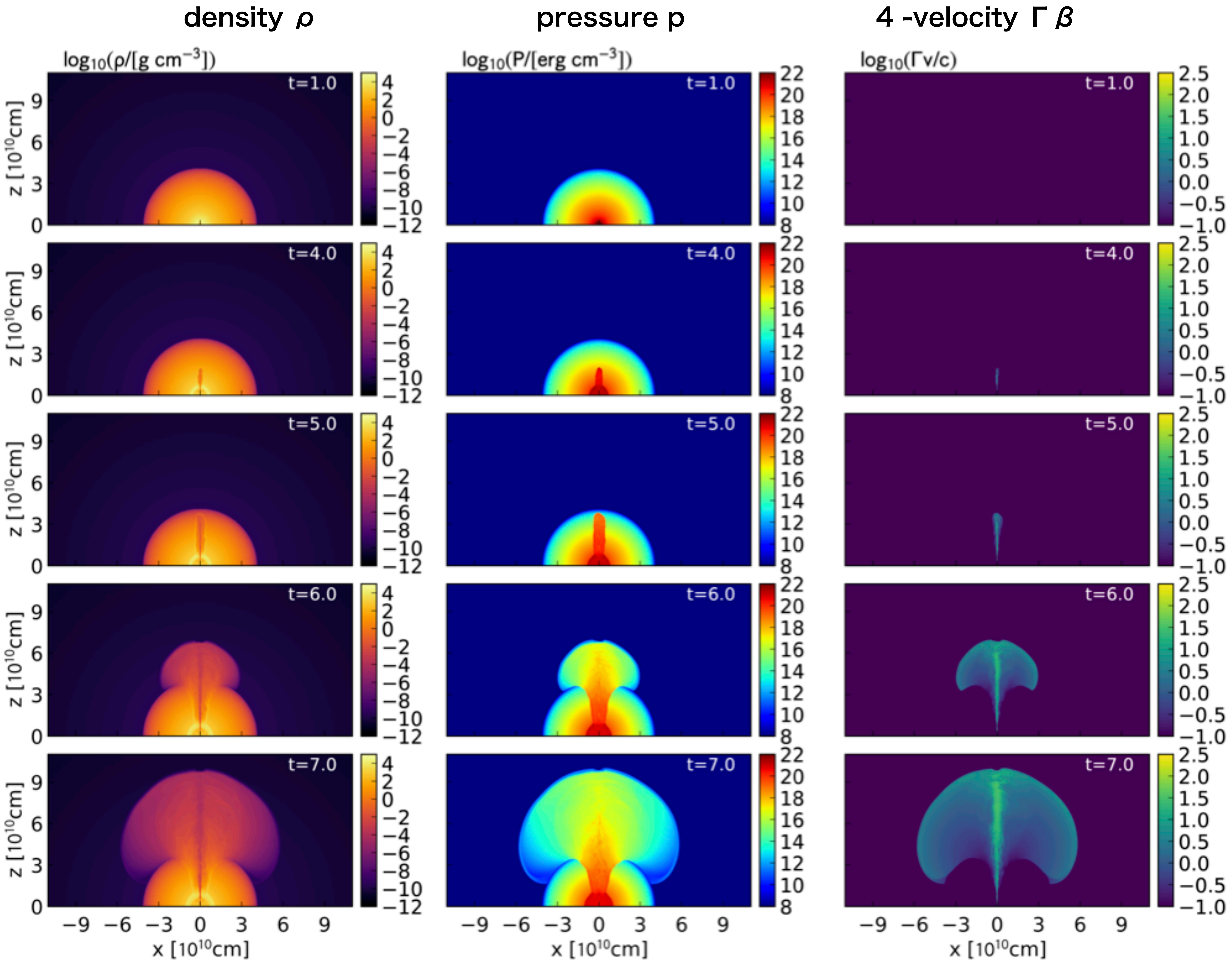
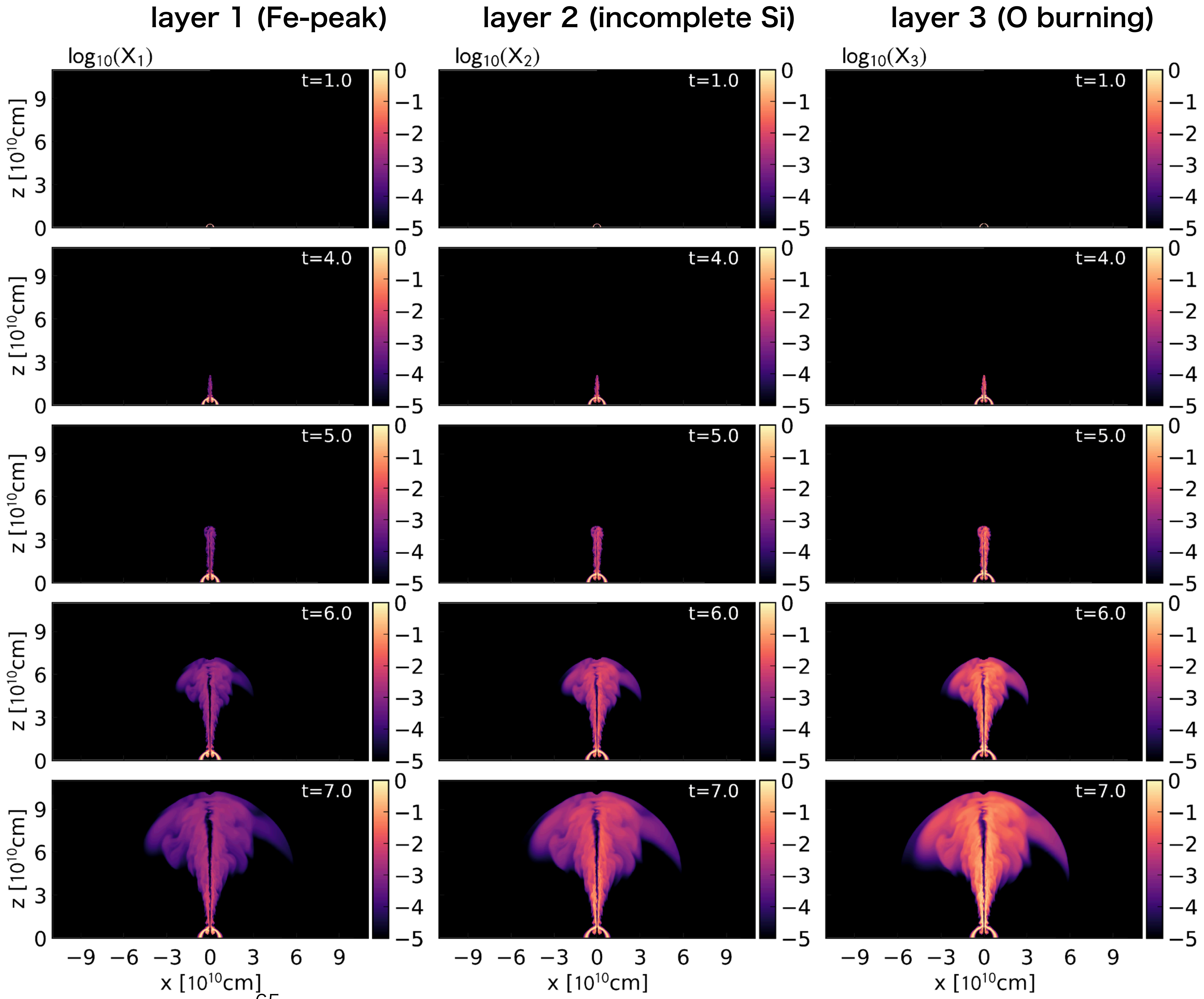
GRB jet simulation: dynamics

- meridional slice (x-z plane)
- spatial distributions of density, pressure, and 4-velocity
- jet breakout at t=5 [s]
- cocoon expansion after the jet breakout
- almost free expansion t>20 [s]
- terminal Lorentz factor~100



GRB jet simulation: chemical element

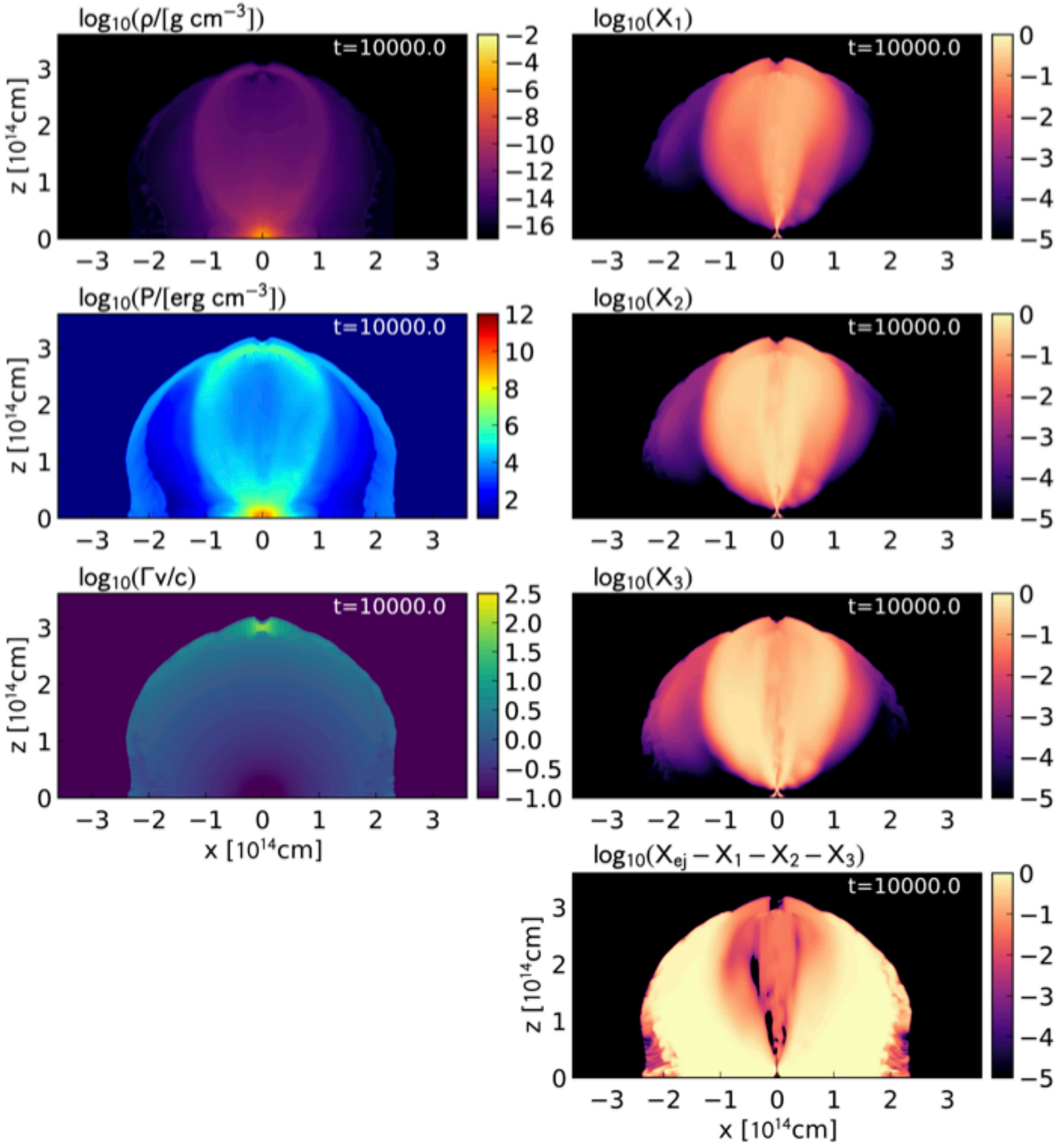
- meridional slice (x-z plane)
- mass fraction distribution of layer 1, 2, and 3
- GRB jet dredging up inner material
- almost similar distributions for layer 1, 2, and 3



GRB jet simulation: chemical element

- meridional slice (x-z plane)
- mass fraction distribution of layer 1, 2, and 3
- GRB jet dredging up inner material
- almost similar distributions for layer 1, 2, and 3
- finally, X_1~0.01-0.1 (layer 1) around the jet axis

t=10^4 sec after jet injection



Layer 1: Fe-peak

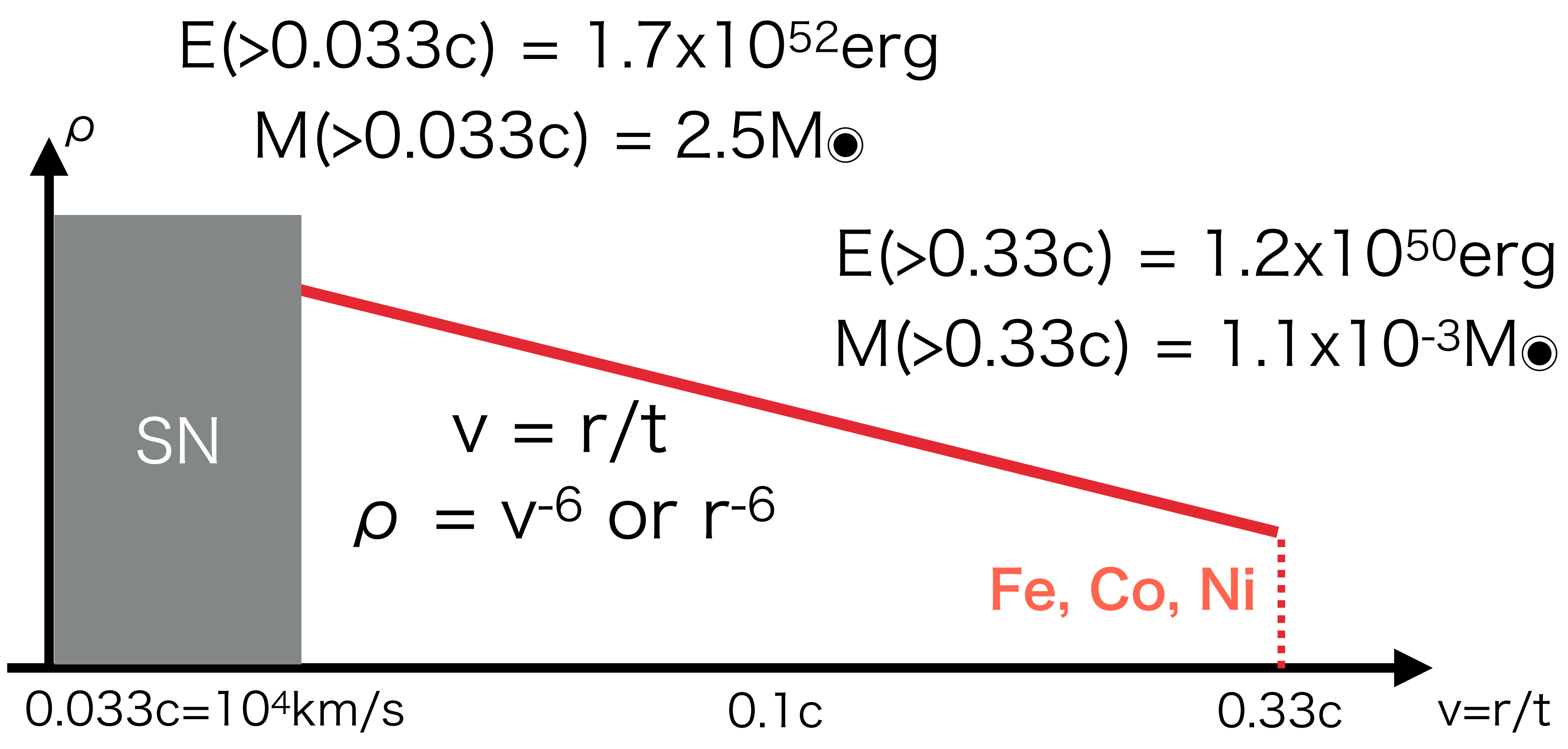
Layer 2: incomplete Si burning

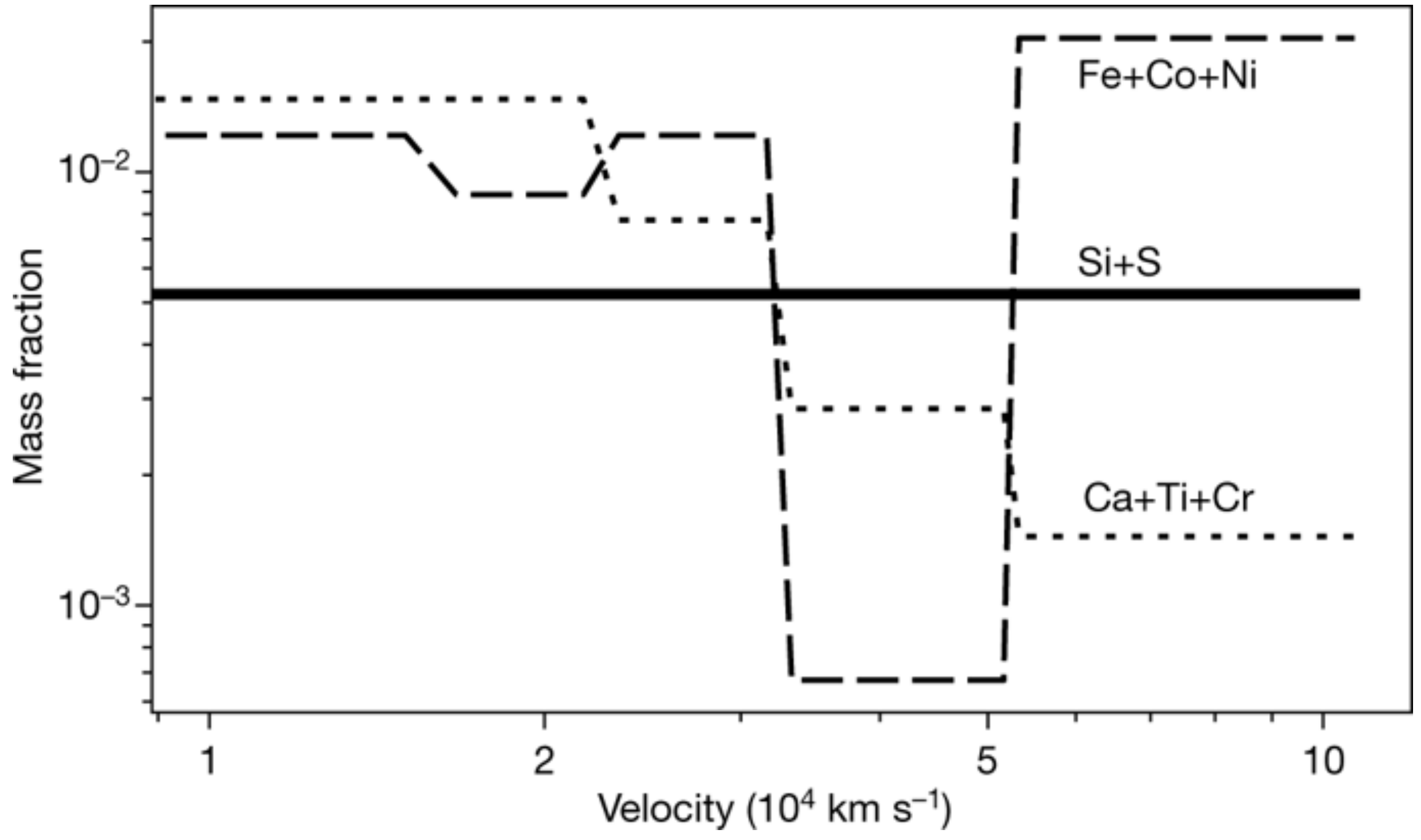
Layer3: O burning

Unburned ejecta

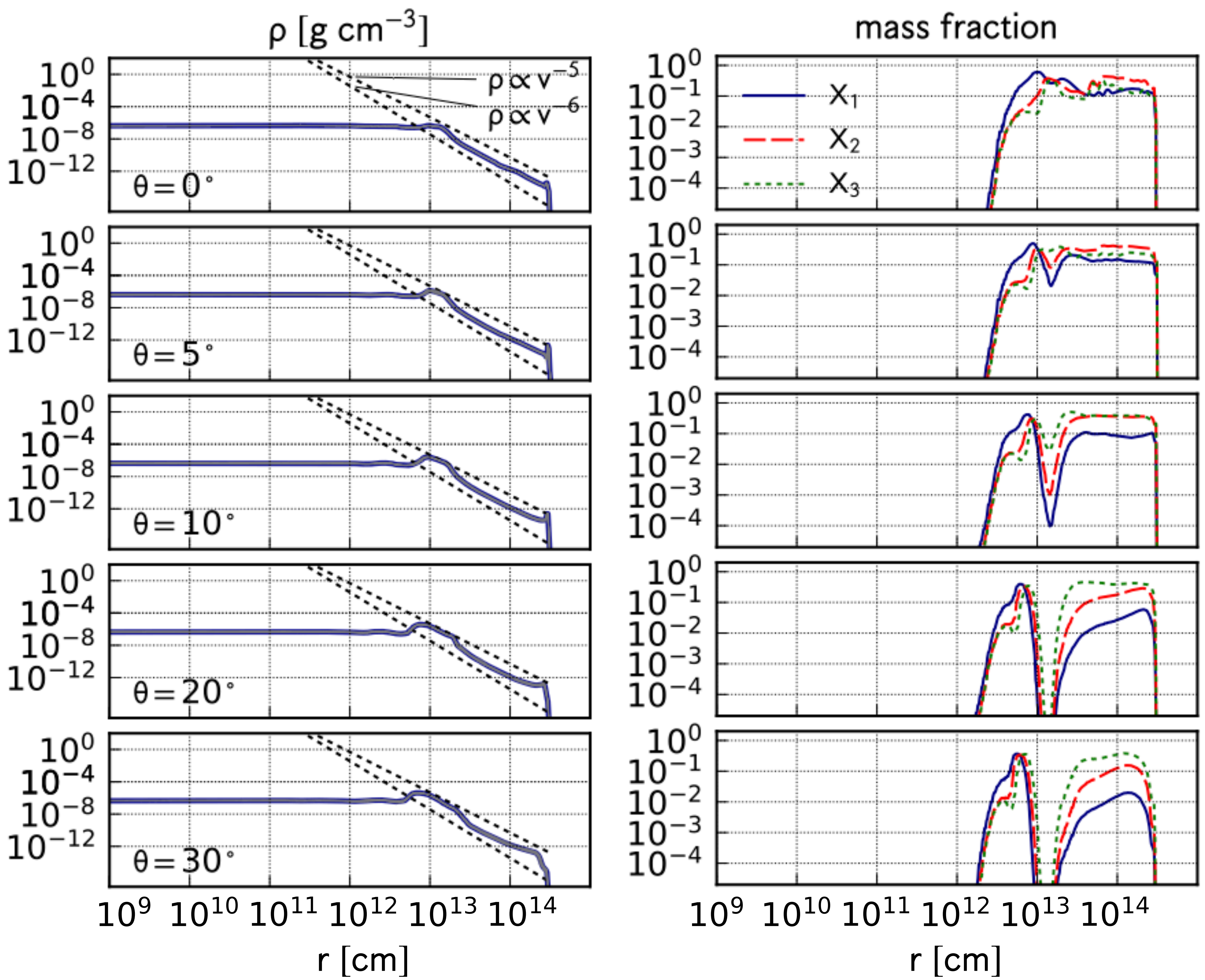
GRB jet simulation: radial profiles

- comparison with the fast ejecta component of GRB 171205A/SN 2017iuk



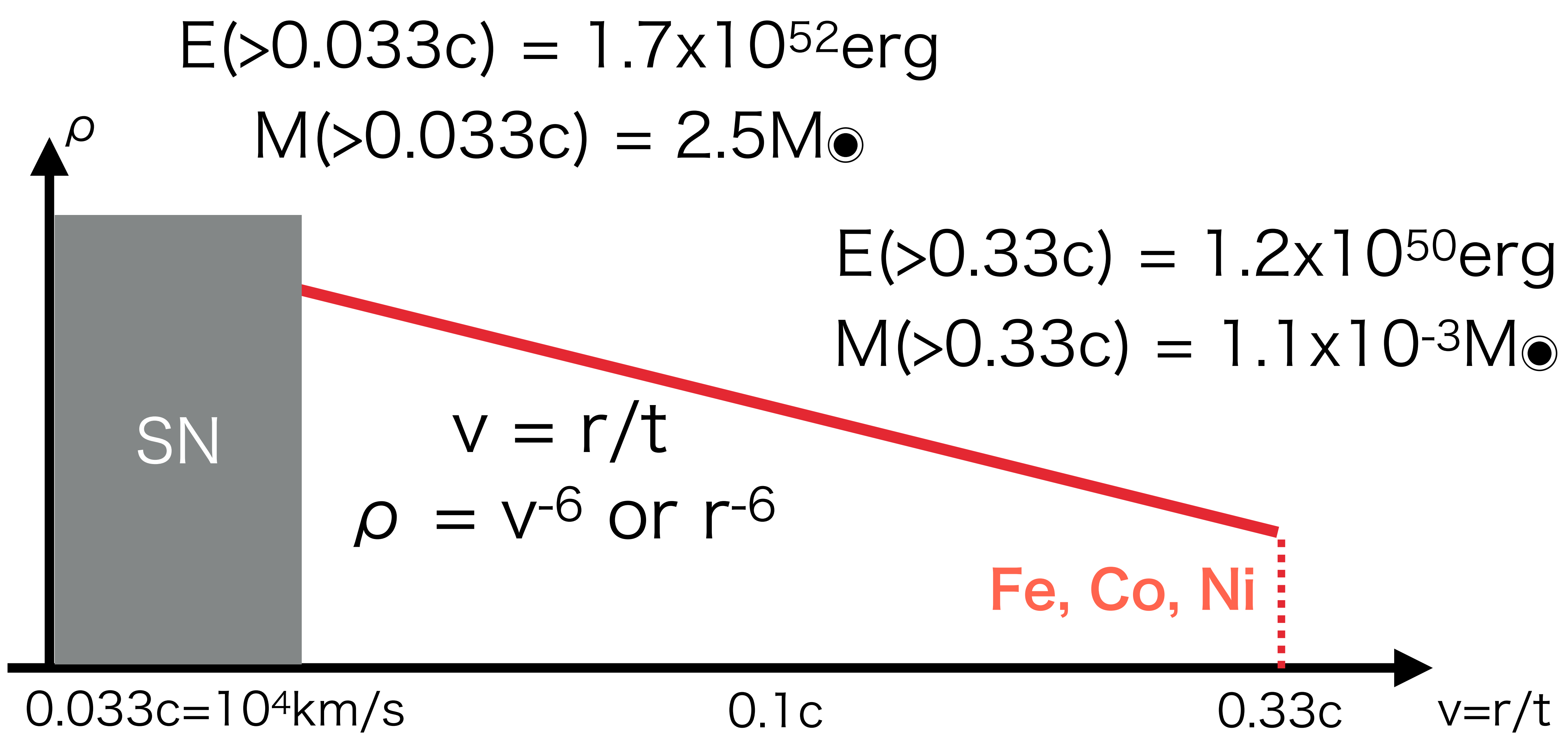


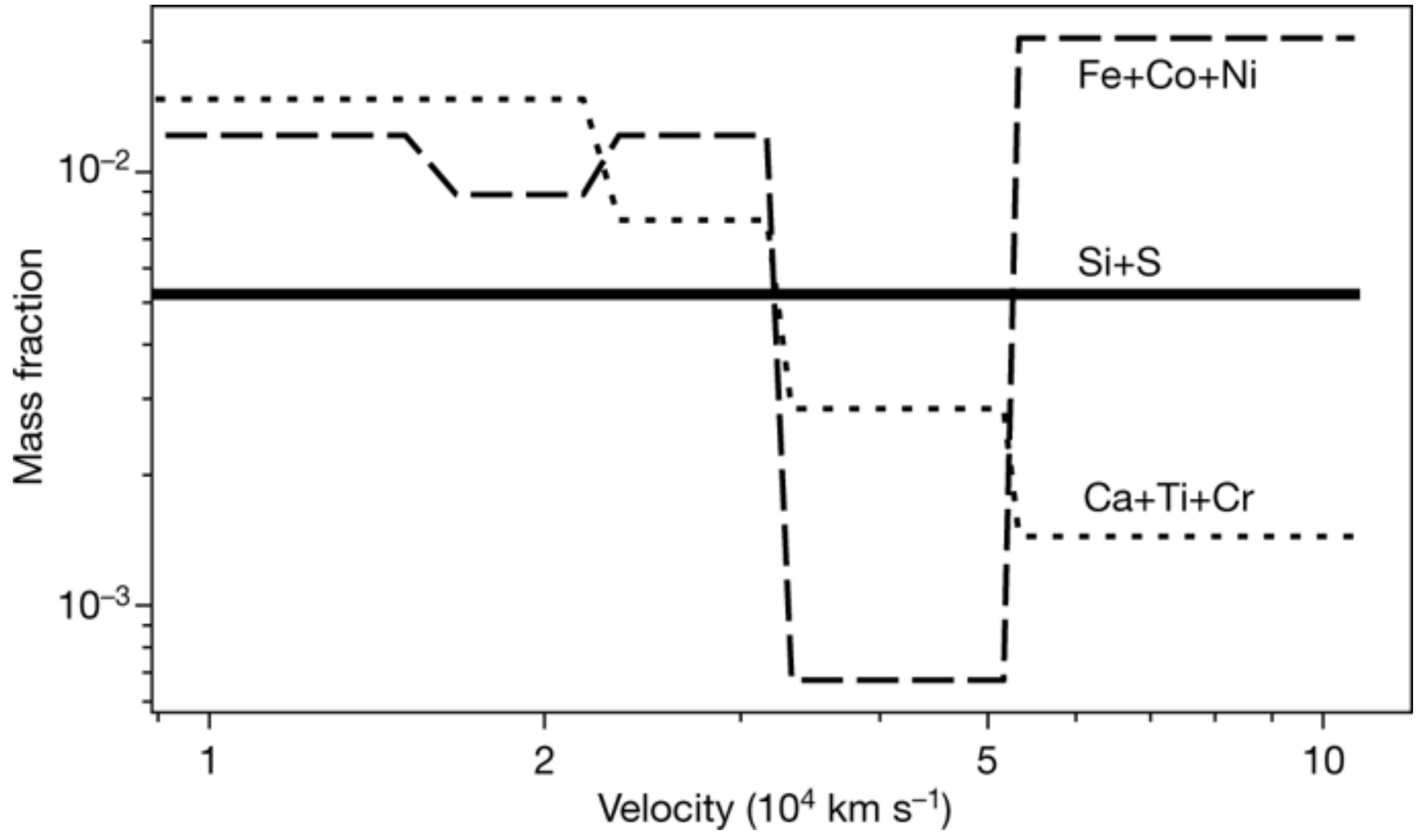
radial profiles (t=10^4 s, θ<30 deg)

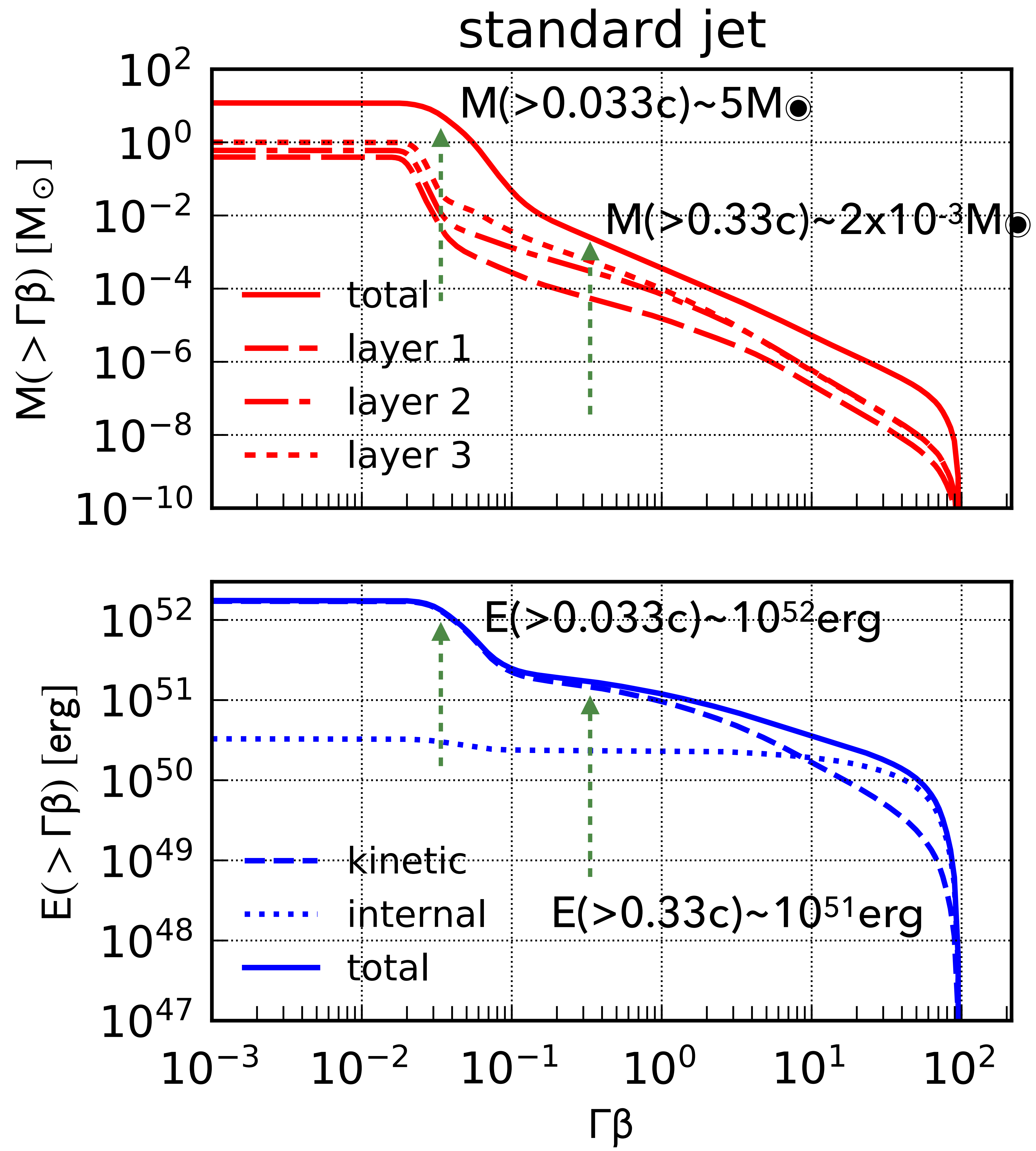


GRB jet simulation: radial profiles

- mass and energy spectra (mass and energy in ejecta faster than $\Gamma\beta$)







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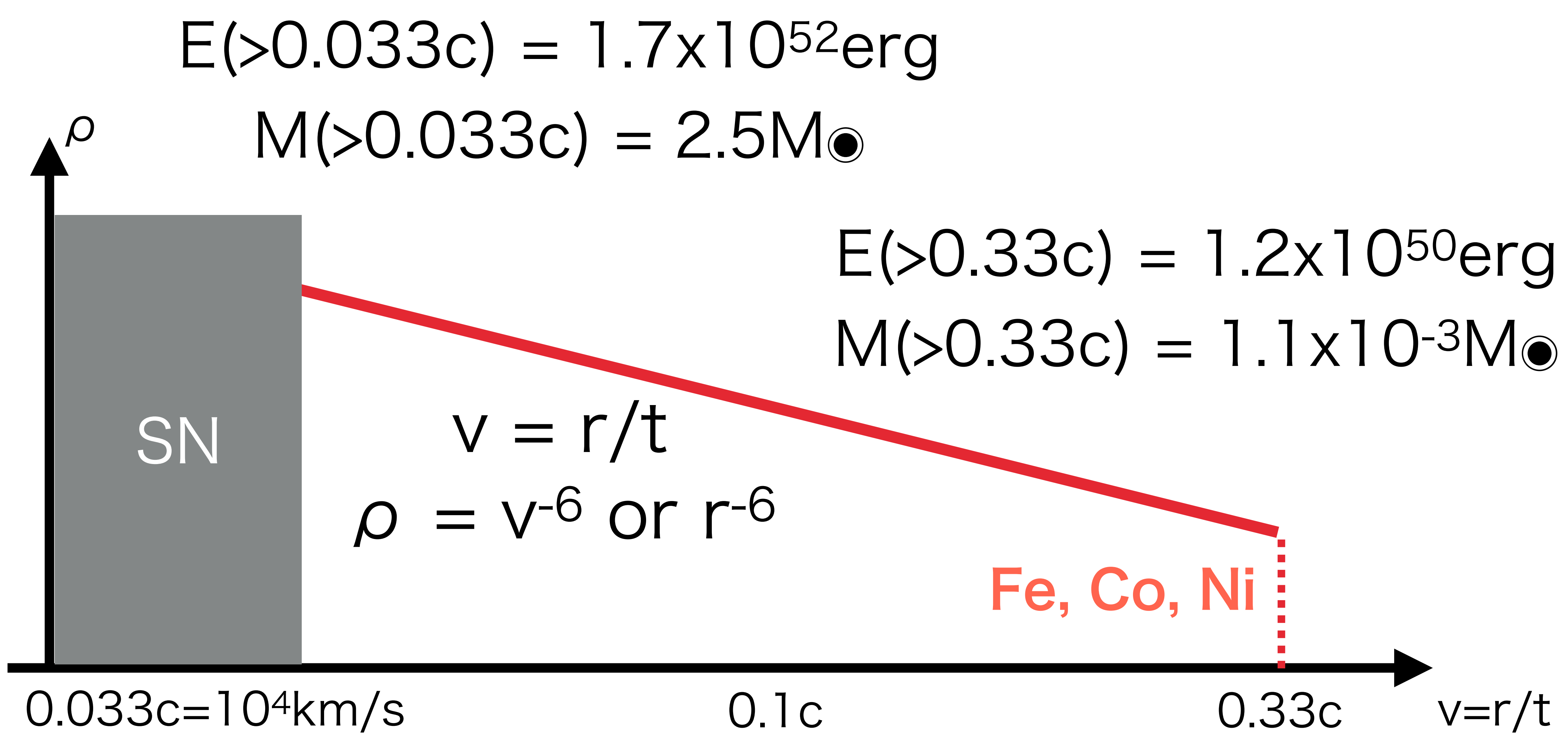
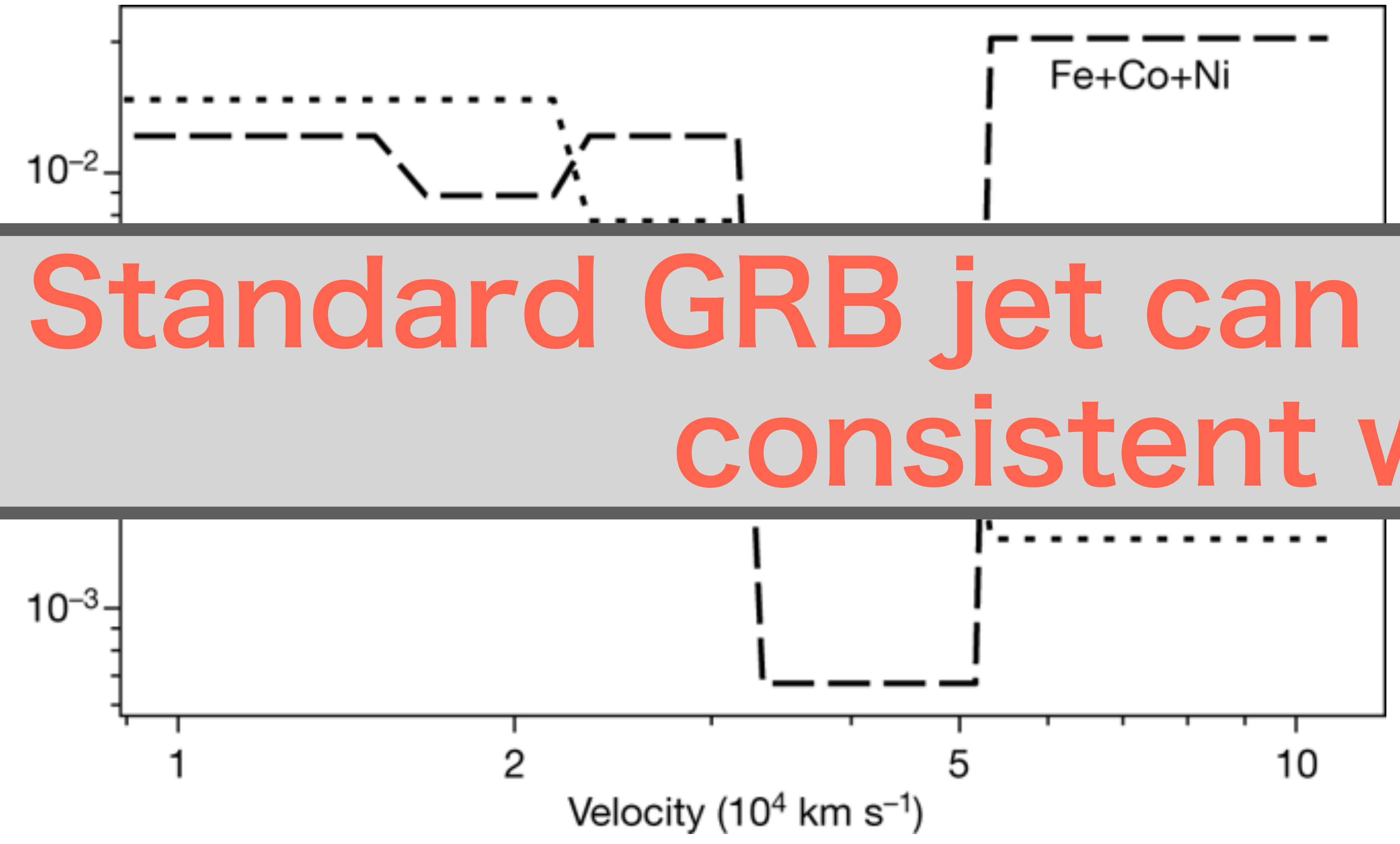
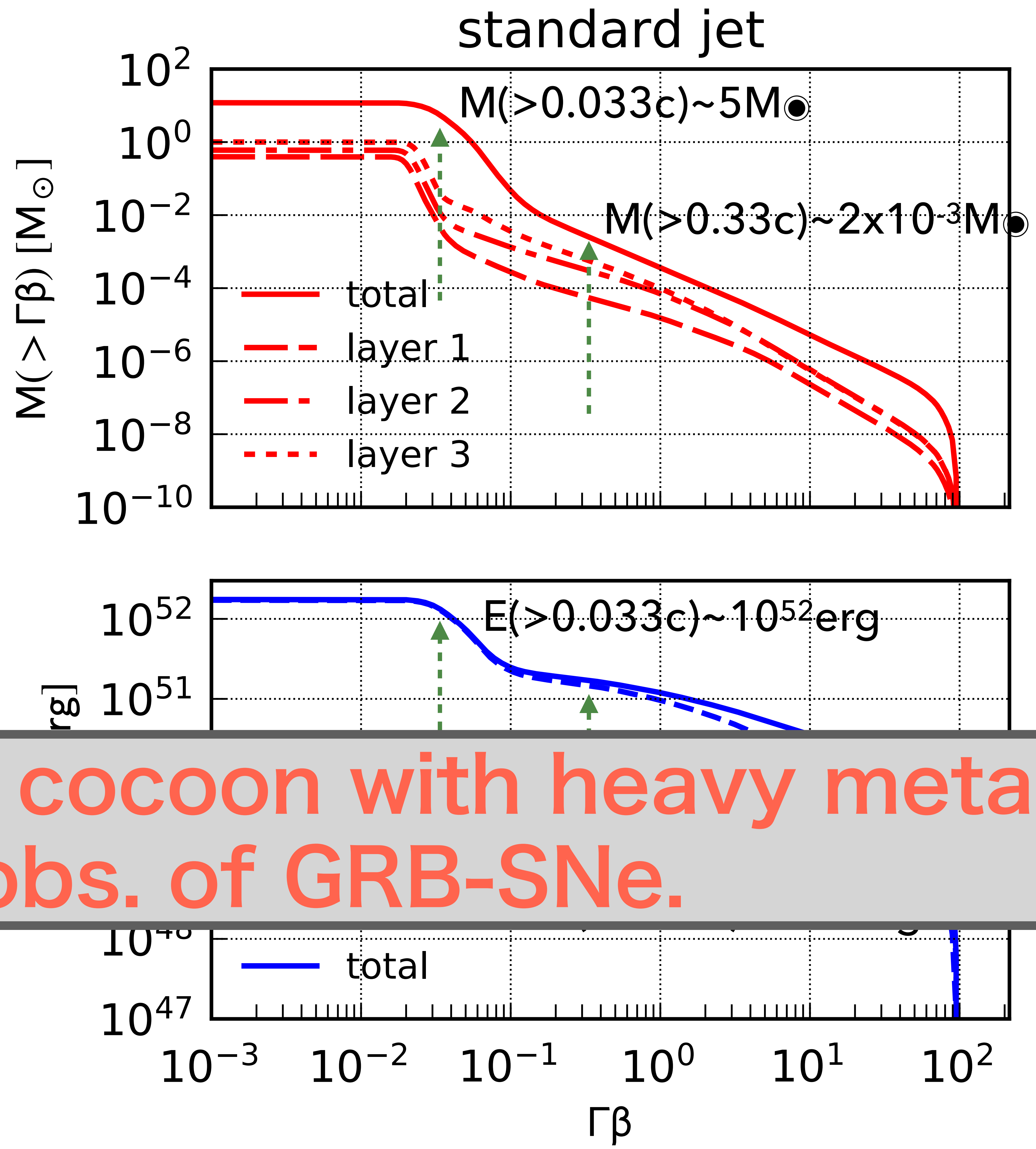


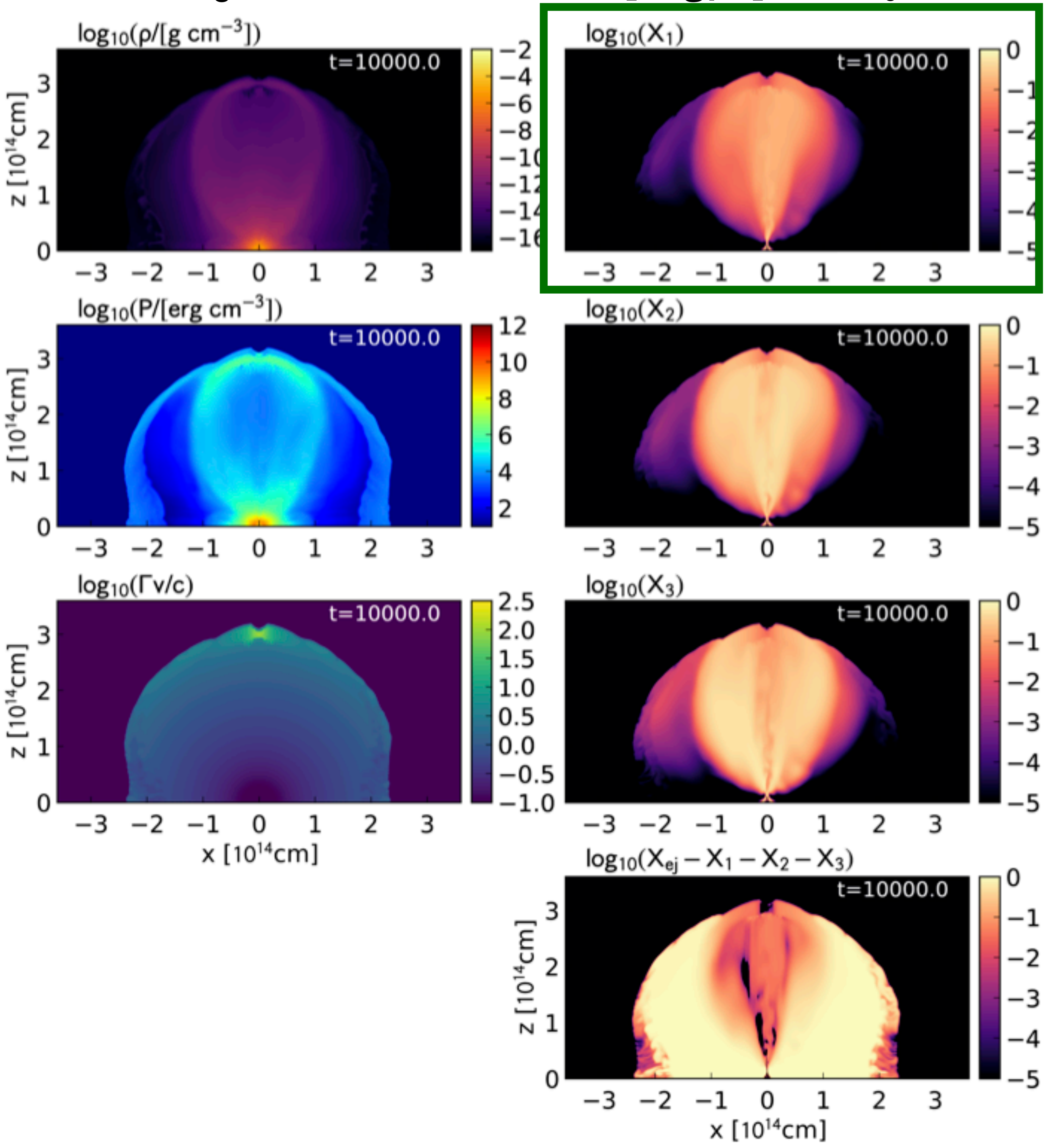




Standard GRB jet can enrich the cocoon with heavy metals, consistent with early obs. of GRB-SNe.

Weak jet fails to produce metal-rich cocoon

Standard jet with L=2.5x10^{50}[erg/s] and t_{jet}=20 sec



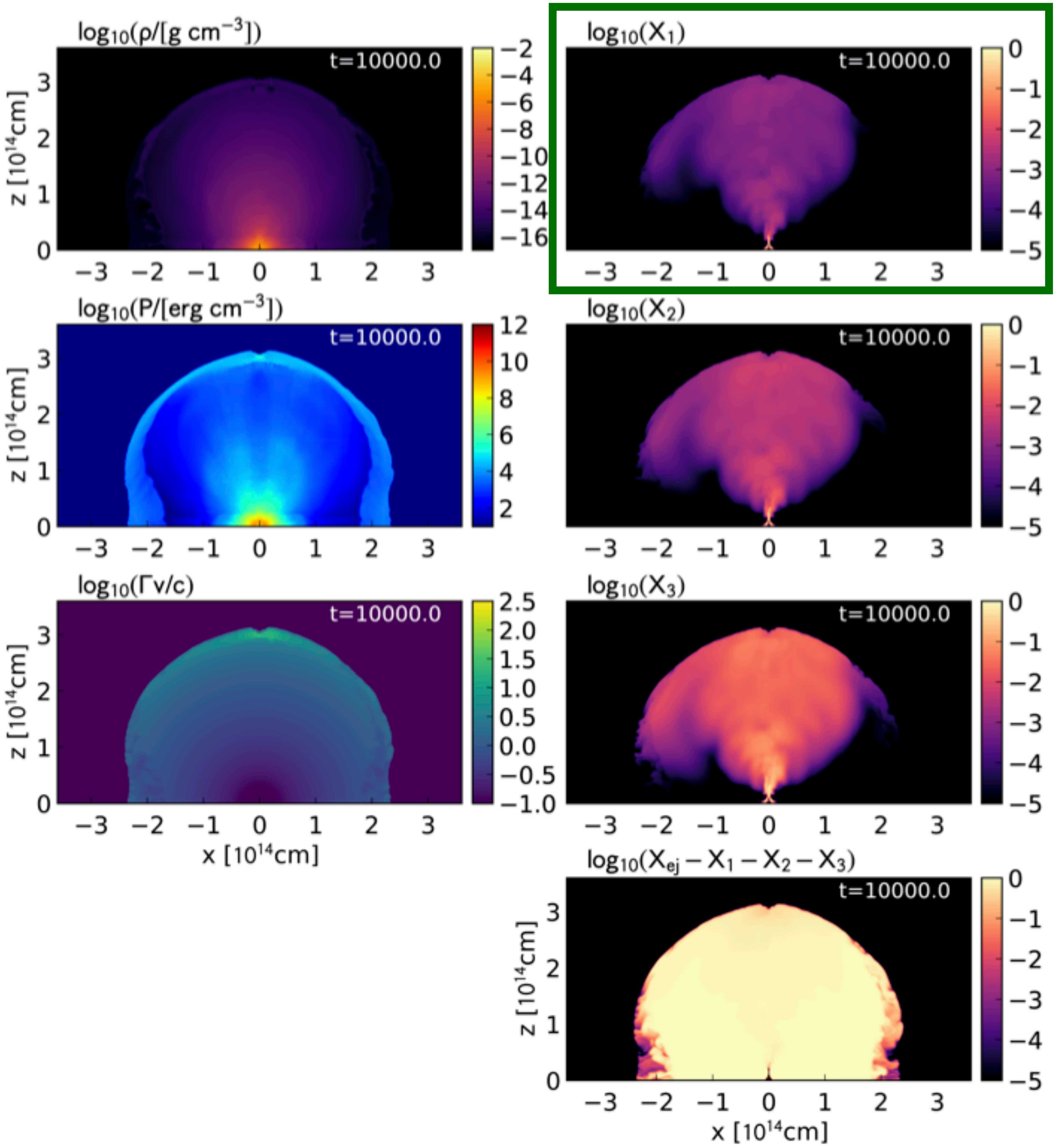
Fe-peak

incomplete Si burning

O burning

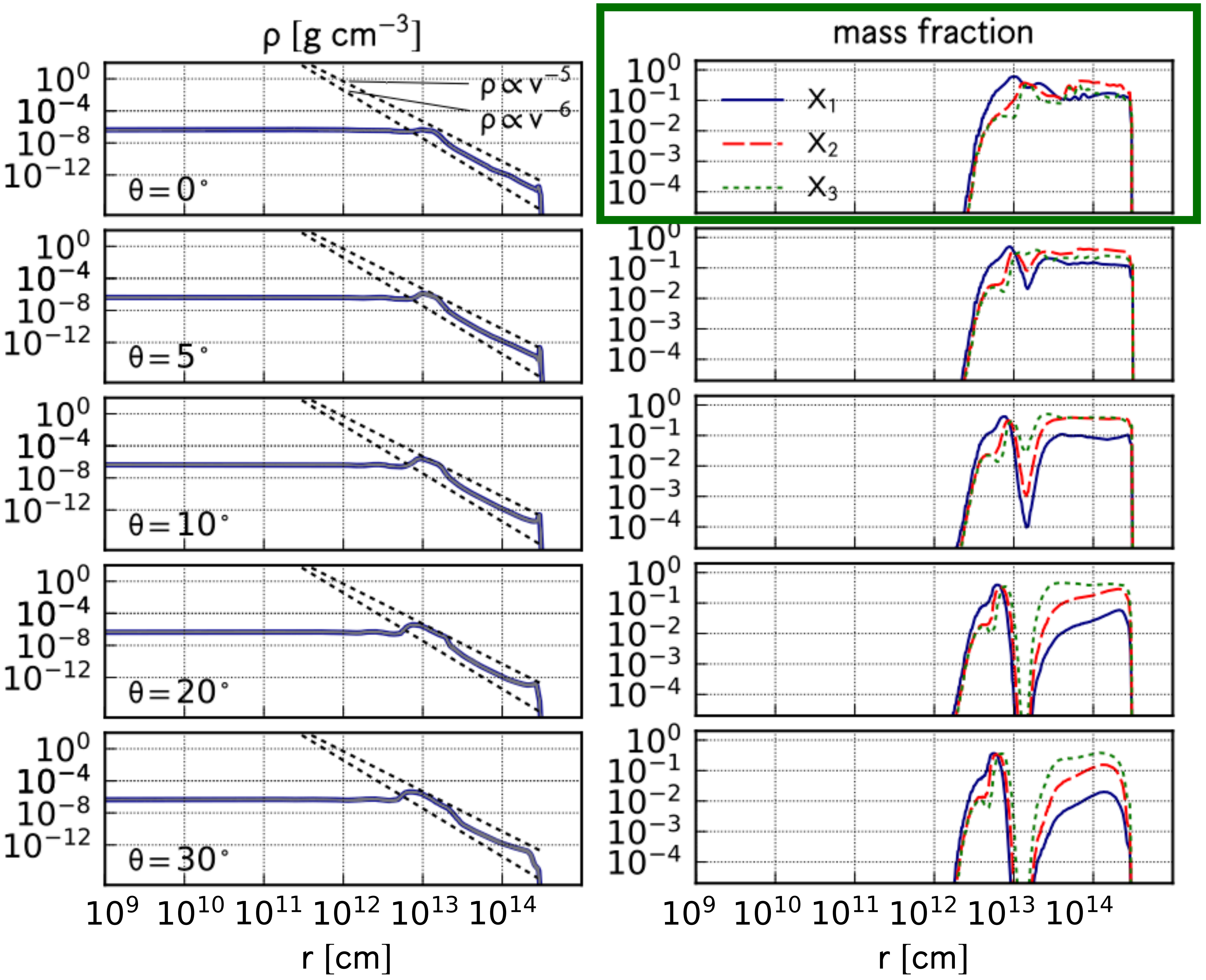
Unburned ejecta

Weak jet with L=2.5x10^{50}[erg/s] and t_{jet}=4 sec



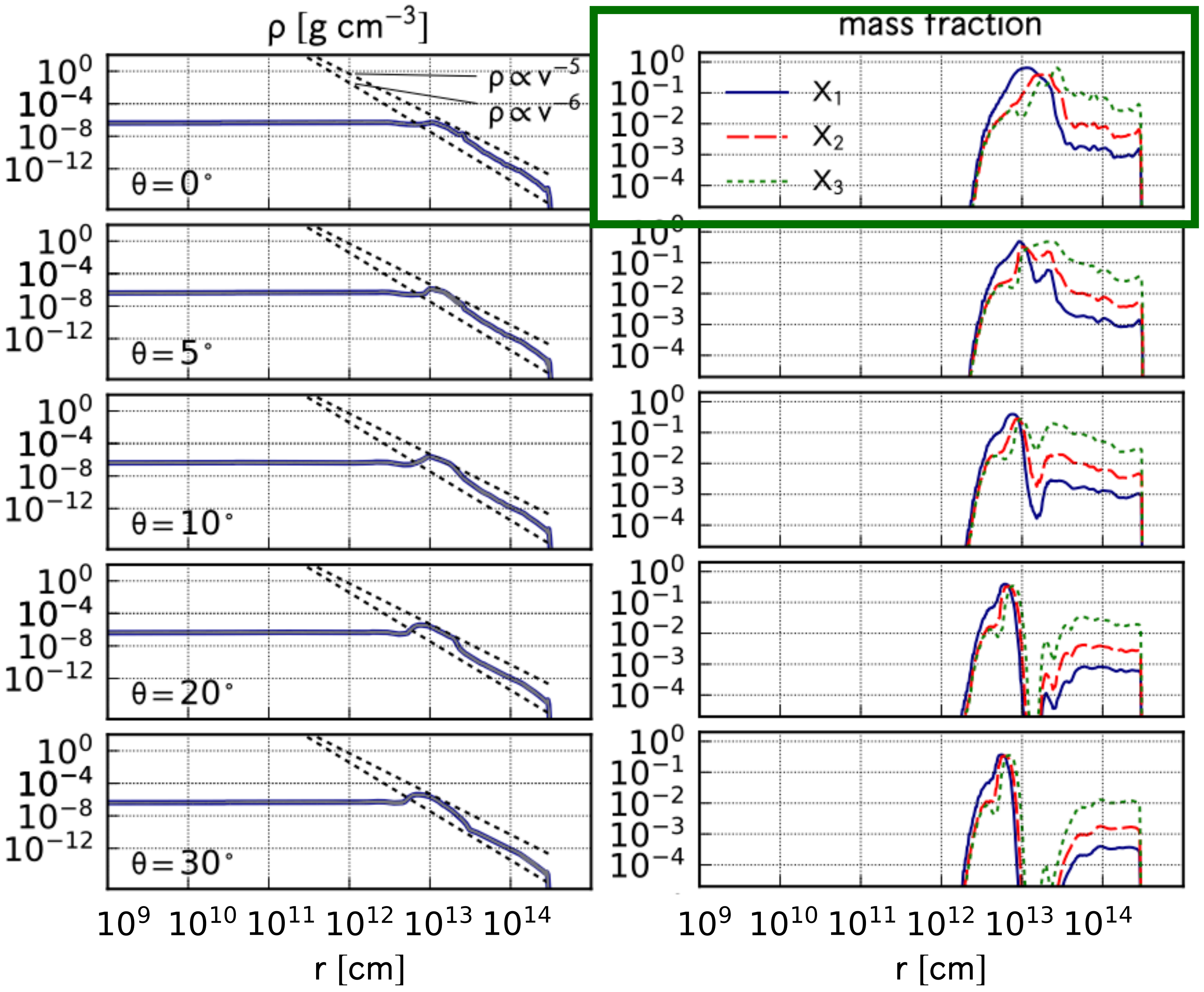
Weak jet fails to produce metal-rich cocoon

Standard jet with $L=2.5\times10^{50}$[erg/s] and t_{jet}=20 sec



as much as 10% Fe-peak elements along jet

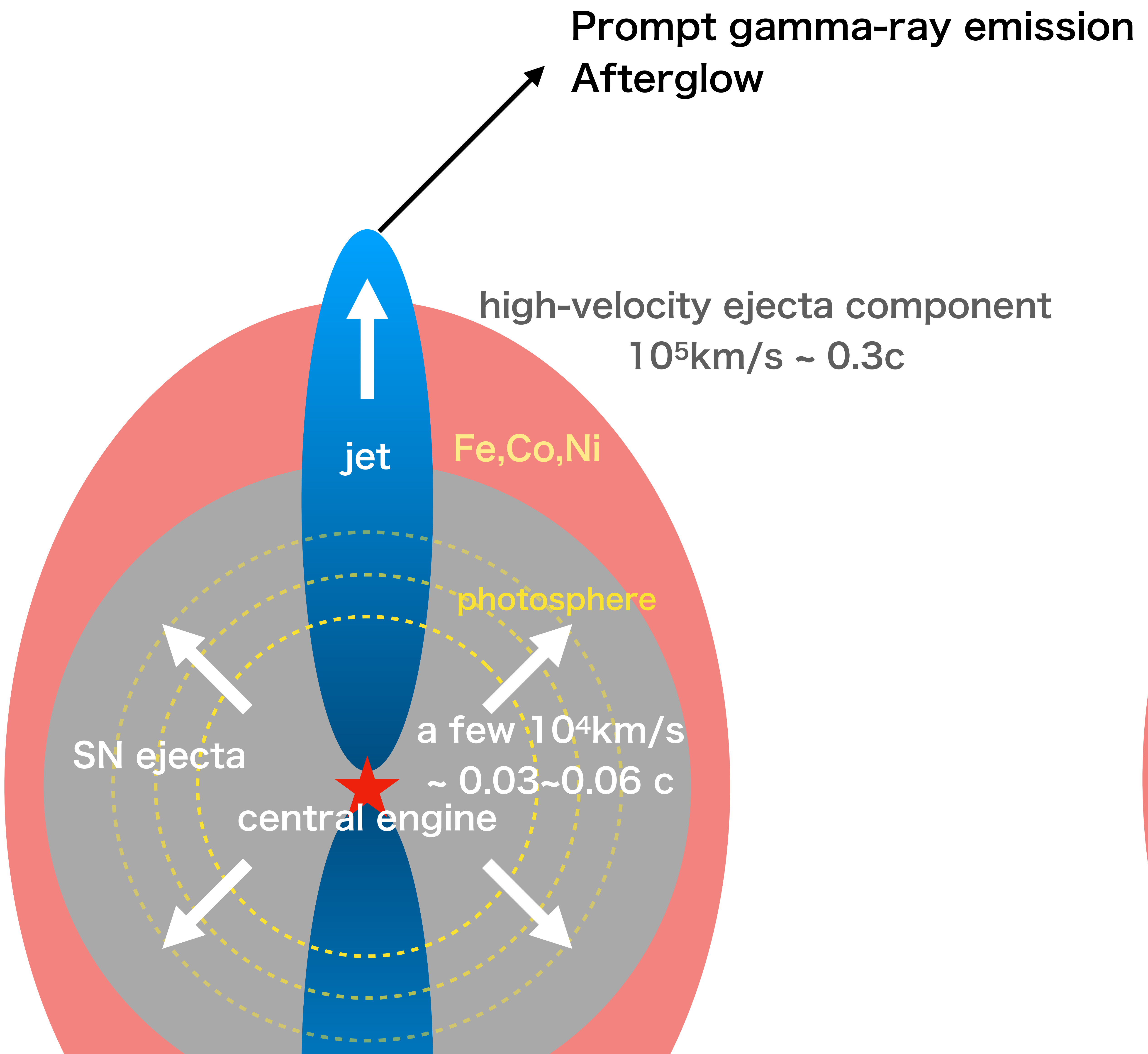
Weak jet with $L=2.5\times10^{50}$[erg/s] and t_{jet}=4 sec



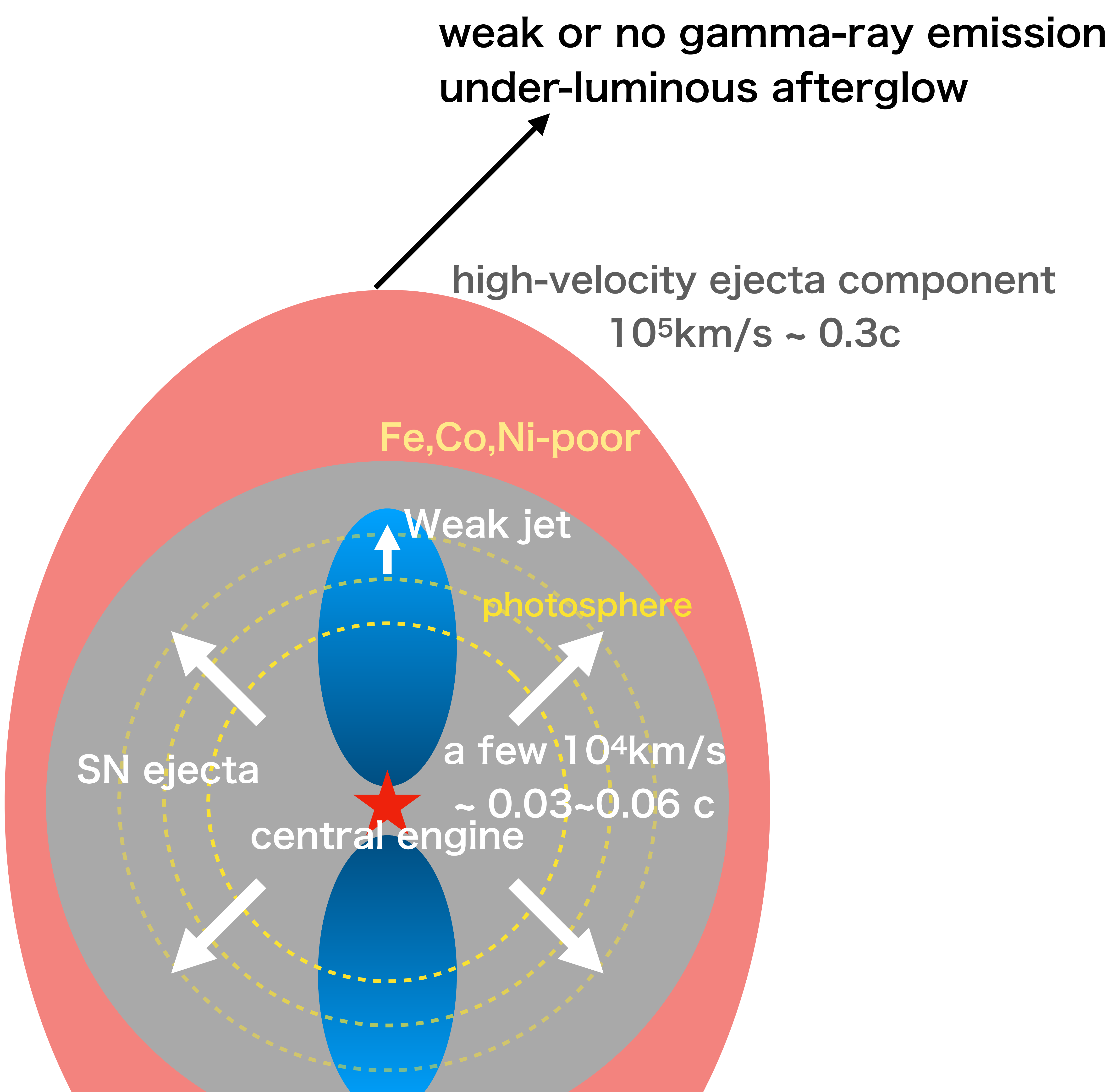
as much as 0.1% Fe-peak elements along jet

Weak jet fails to produce metal-rich cocoon

Standard jet with $L=2.5\times10^{50}$[erg/s] and $t_{jet}=20$ sec

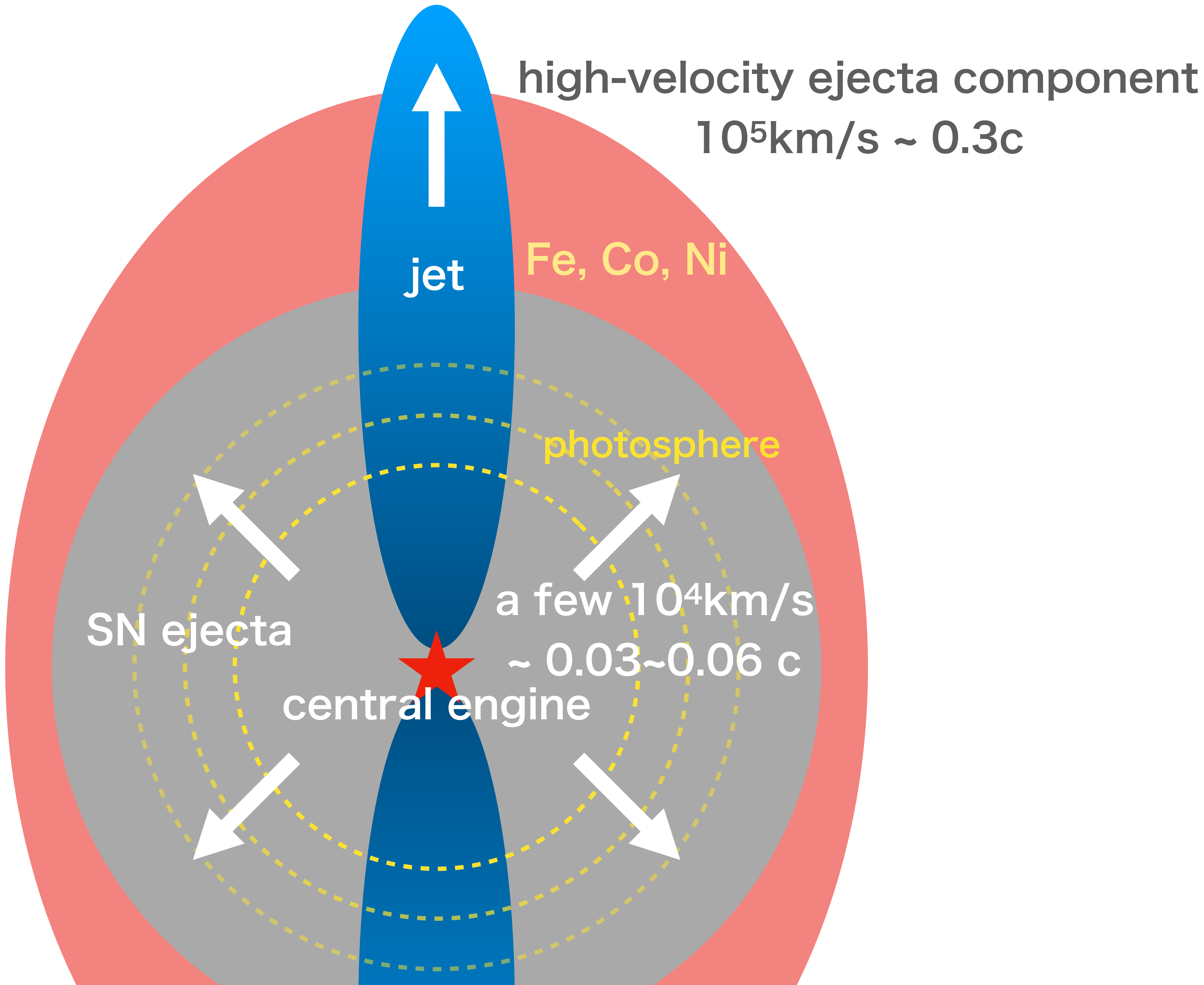


Weak jet with $L=2.5\times10^{50}$[erg/s] and $t_{jet}=4$ sec



Summary: GRB-SNe revealed by early thermal emission

- central engine: magnetar (NS) or collapsar (BH) ?
- jet mechanism?



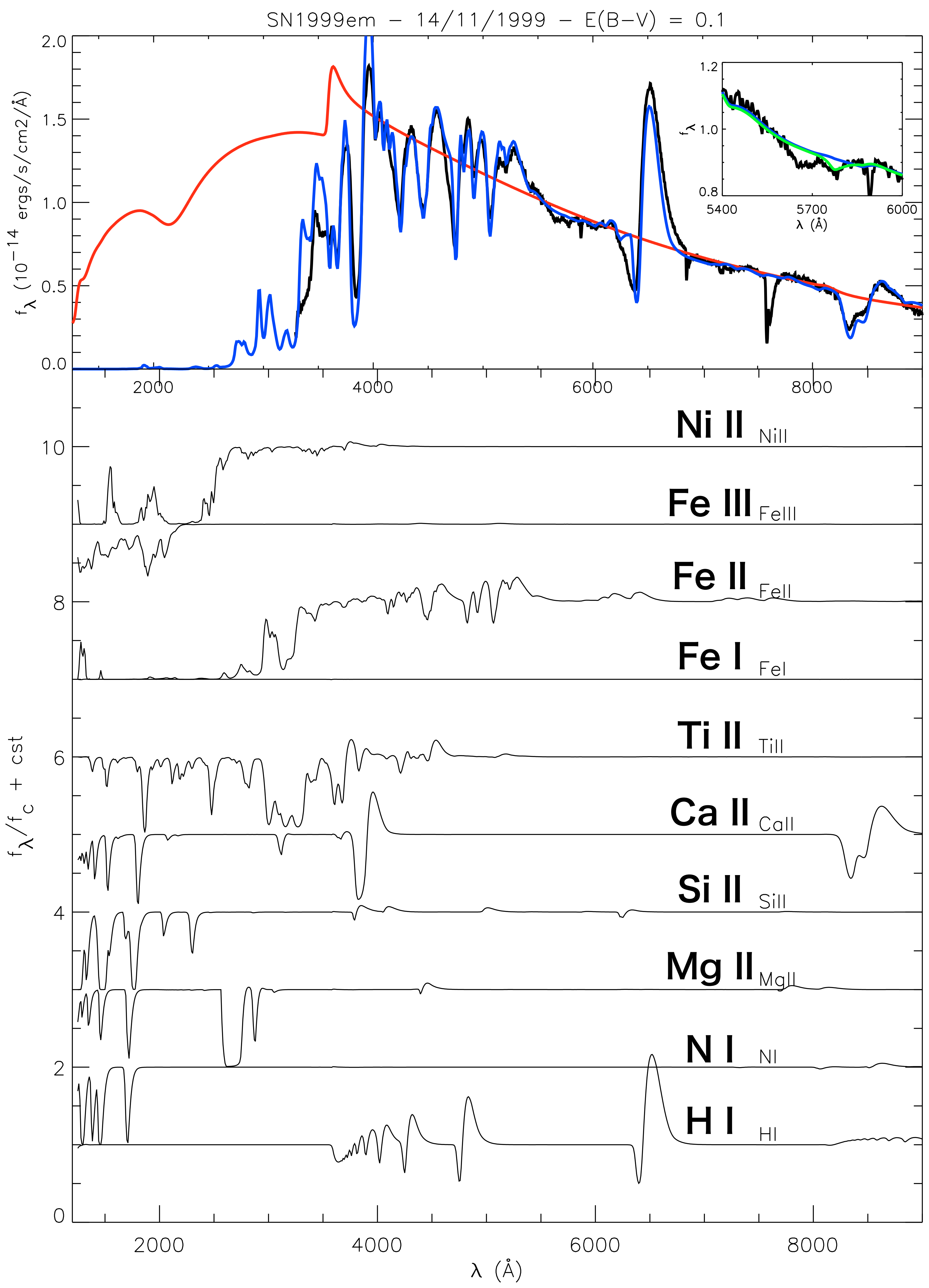
- very early obs. of GRB-SNe revealed the high-velocity component preceding SN.
- a GRB cocoon explains the properties of the high-velocity component without serious difficulty
- an important opportunity to know **how much mass and energy are loaded on the cocoon** and **the nucleosynthesis around the central-engine**

Backup slides

Supernova explosions: light curves and spectra

- Tow major energy sources for optical emission:
  - ➡ thermal energy deposited by the explosion itself
  - ➡ radioactive decay ($^{56}Ni \rightarrow ^{56}Co \rightarrow ^{56}Fe$)

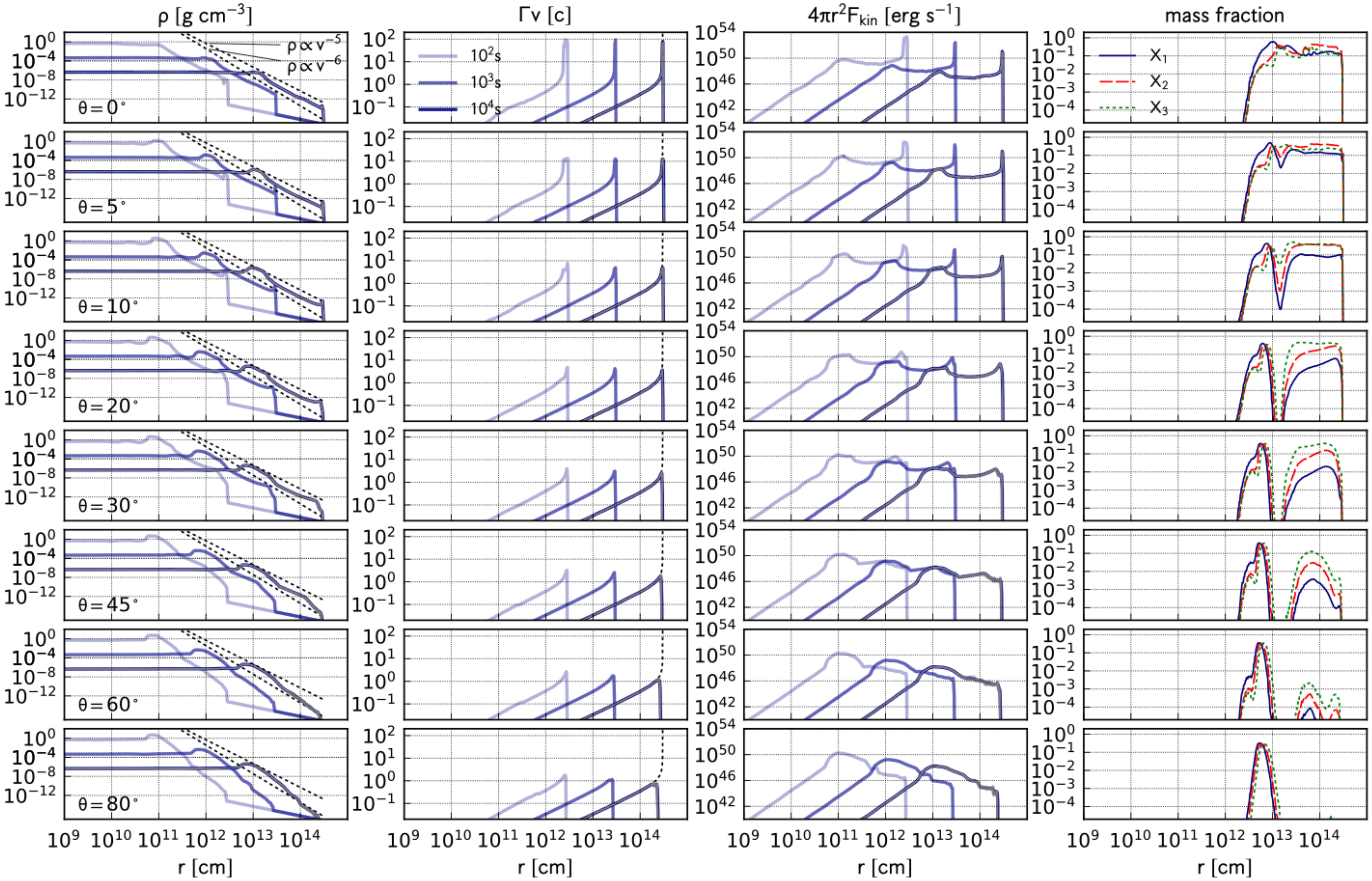
- emitting radius: 10^9cm/s x 10-100 days ~ $10^{15\text{-}16}$cm
- radioactive tail ^{56}Ni mass
- diffusion time scale $\sim(\kappa M_{ej}/cv)^{1/2} \propto M_{ej}^{3/4} E^{-1/4}$
- spectral shape → BB temperature
- absorption lines → velocity, composition



synthetic spectra of H-rich CCSNe
Dessart&Hillier (2005)

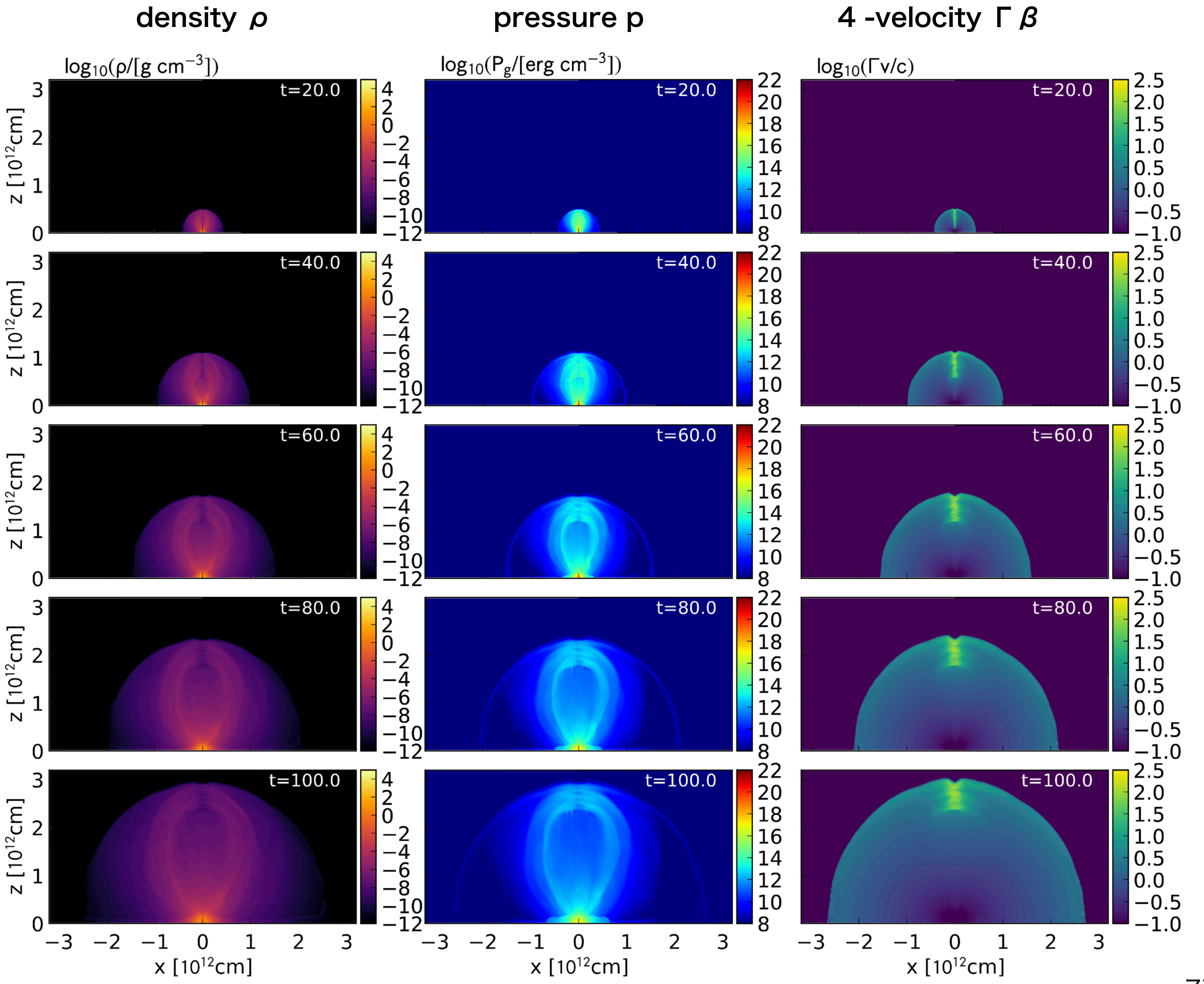
GRB jet simulation: radial profiles

ϕ-averaged radial profiles along different θ at t=10^4 s



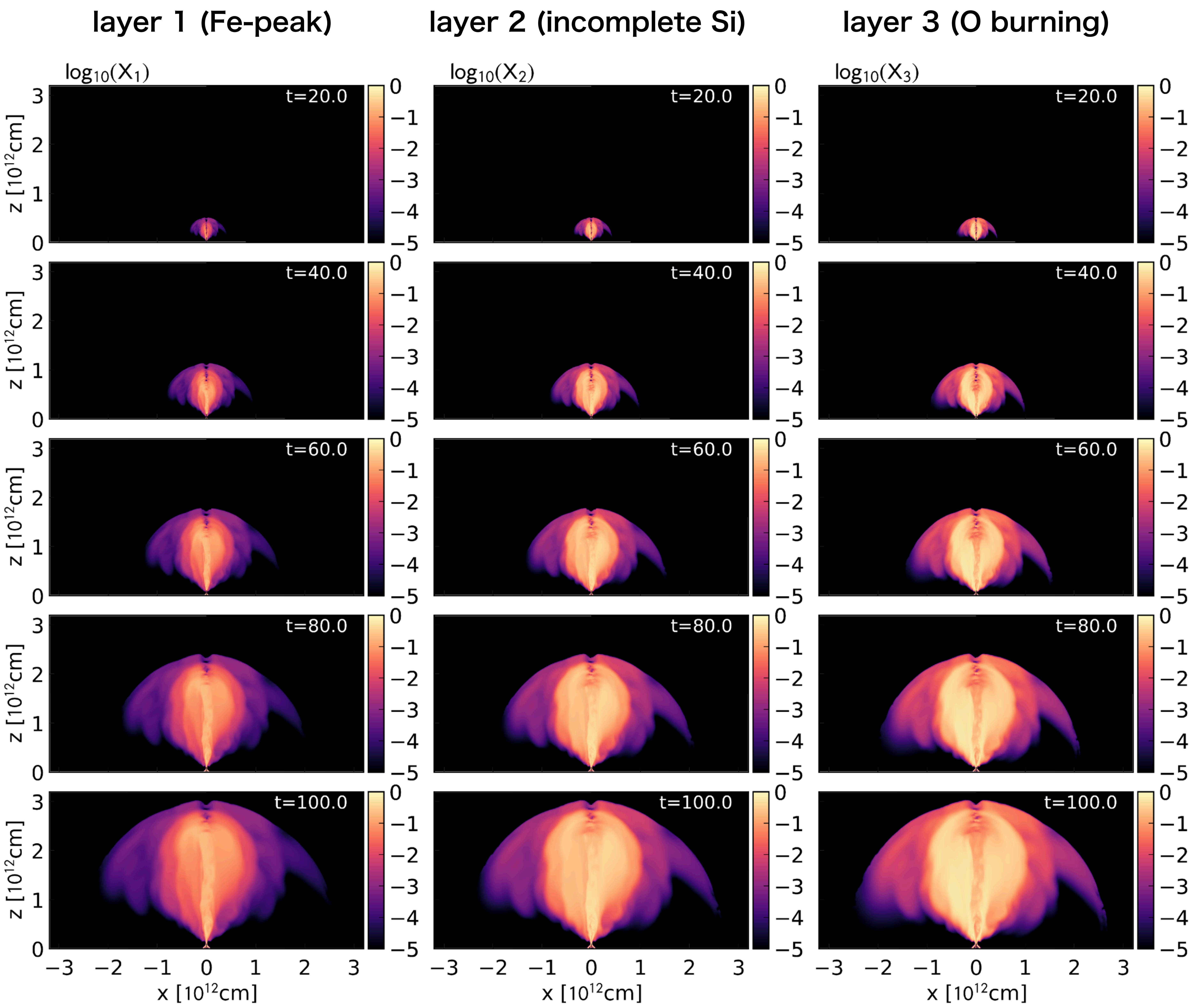
GRB jet simulation: dynamics

- meridional slice (x-z plane)
- spatial distributions of density, pressure, and 4-velocity
- jet breakout at t=5 [s]
- cocoon expansion after the jet breakout
- almost free expansion t>20 [s]
- terminal Lorentz factor~100



GRB jet simulation: chemical elements

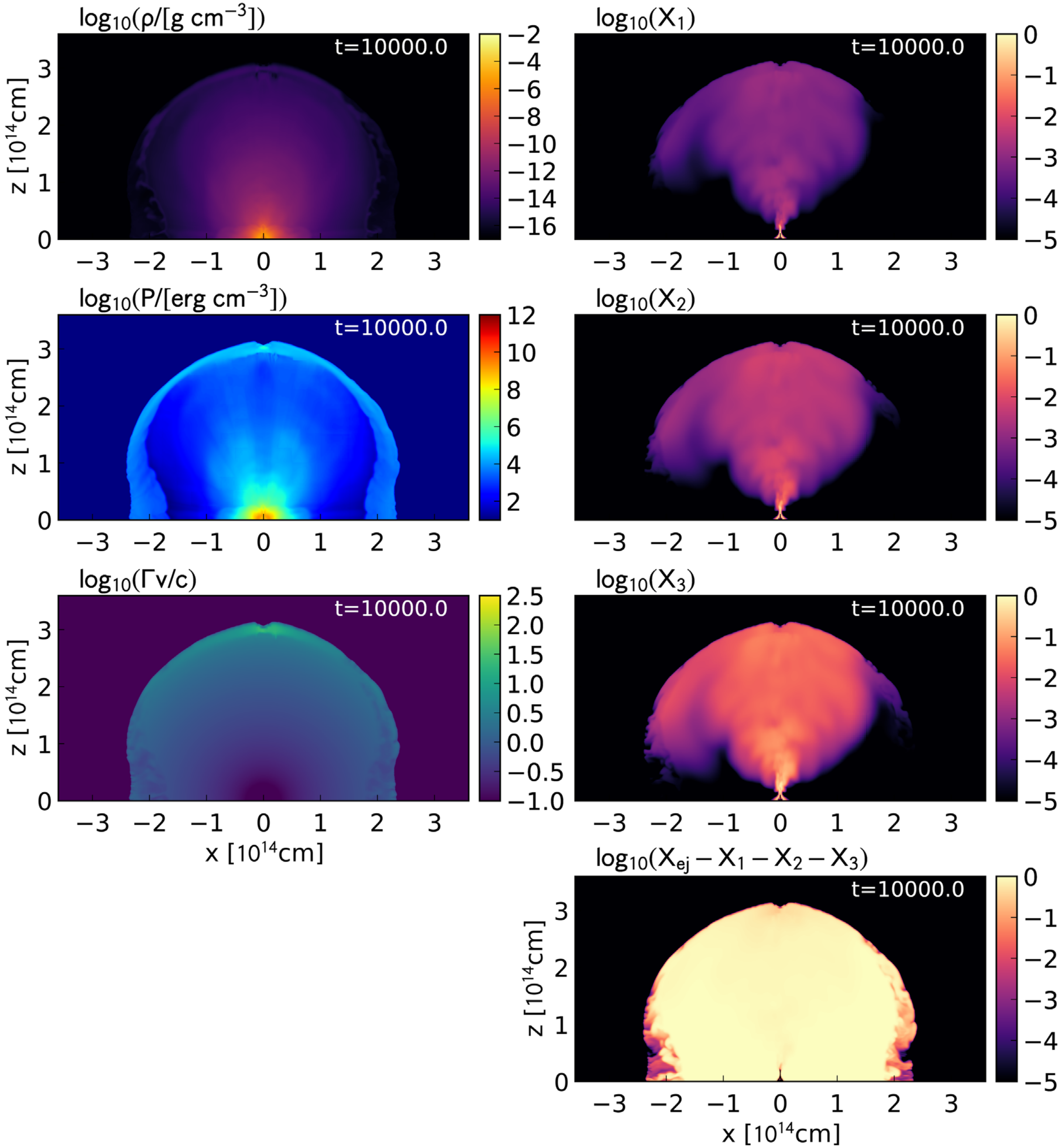
- meridional slice (x-z plane)
- mass fraction distribution of layer 1, 2, and 3
- GRB jet dredging up inner material
- almost similar distributions for layer 1, 2, and 3
- finally, X_1~0.01-0.1 (layer 1) around the jet axis



Failed jet case

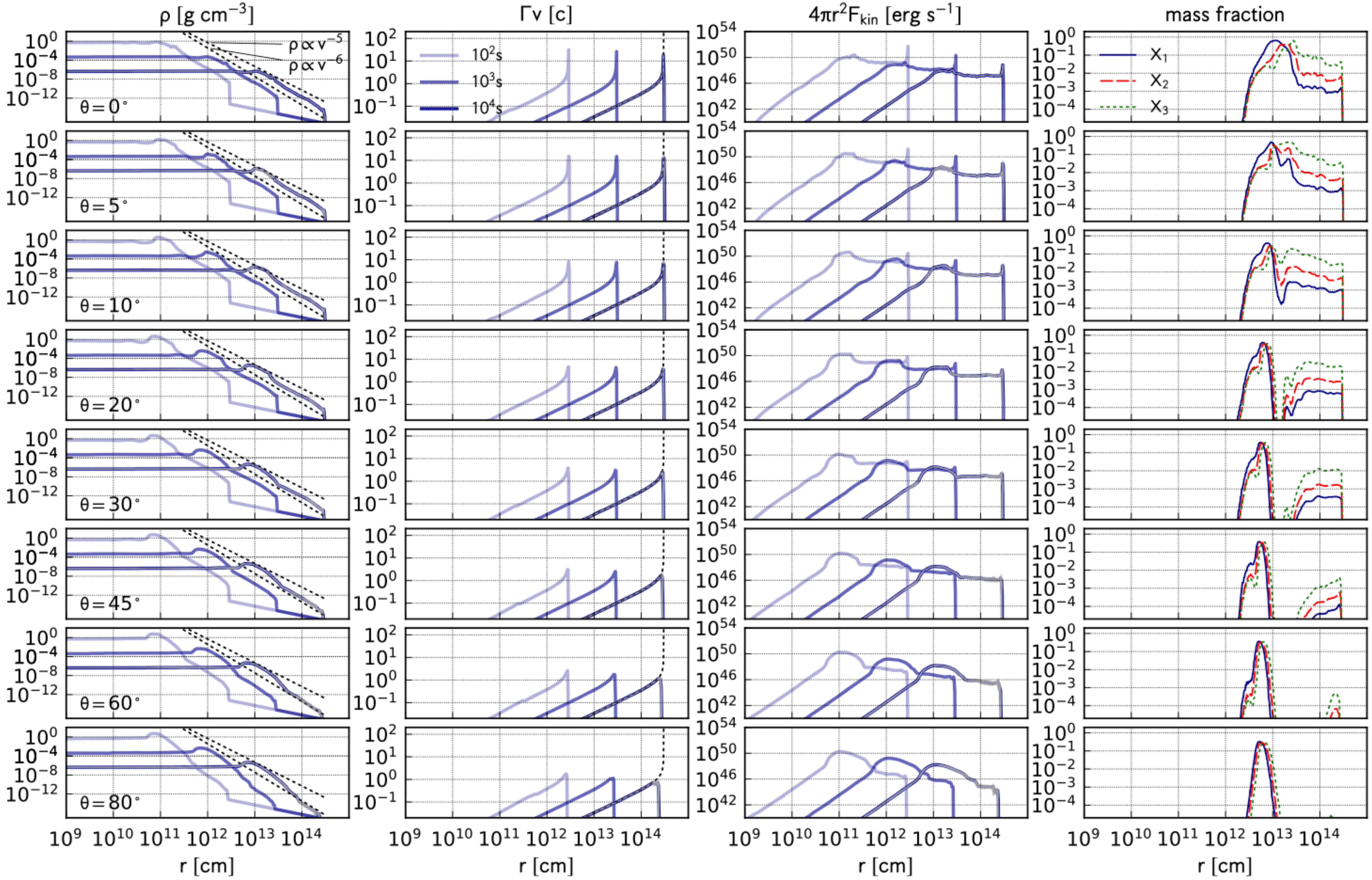
- meridional slice (x-z plane)
- mass fraction distribution of layer 1, 2, and 3
- GRB jet dredging up inner material
- almost similar distributions for layer 1, 2, and 3
- less efficient jet-induced mixing

Weak jet with $L=2.5\times10^{50}$[erg/s] and $t_{jet}=4$ sec



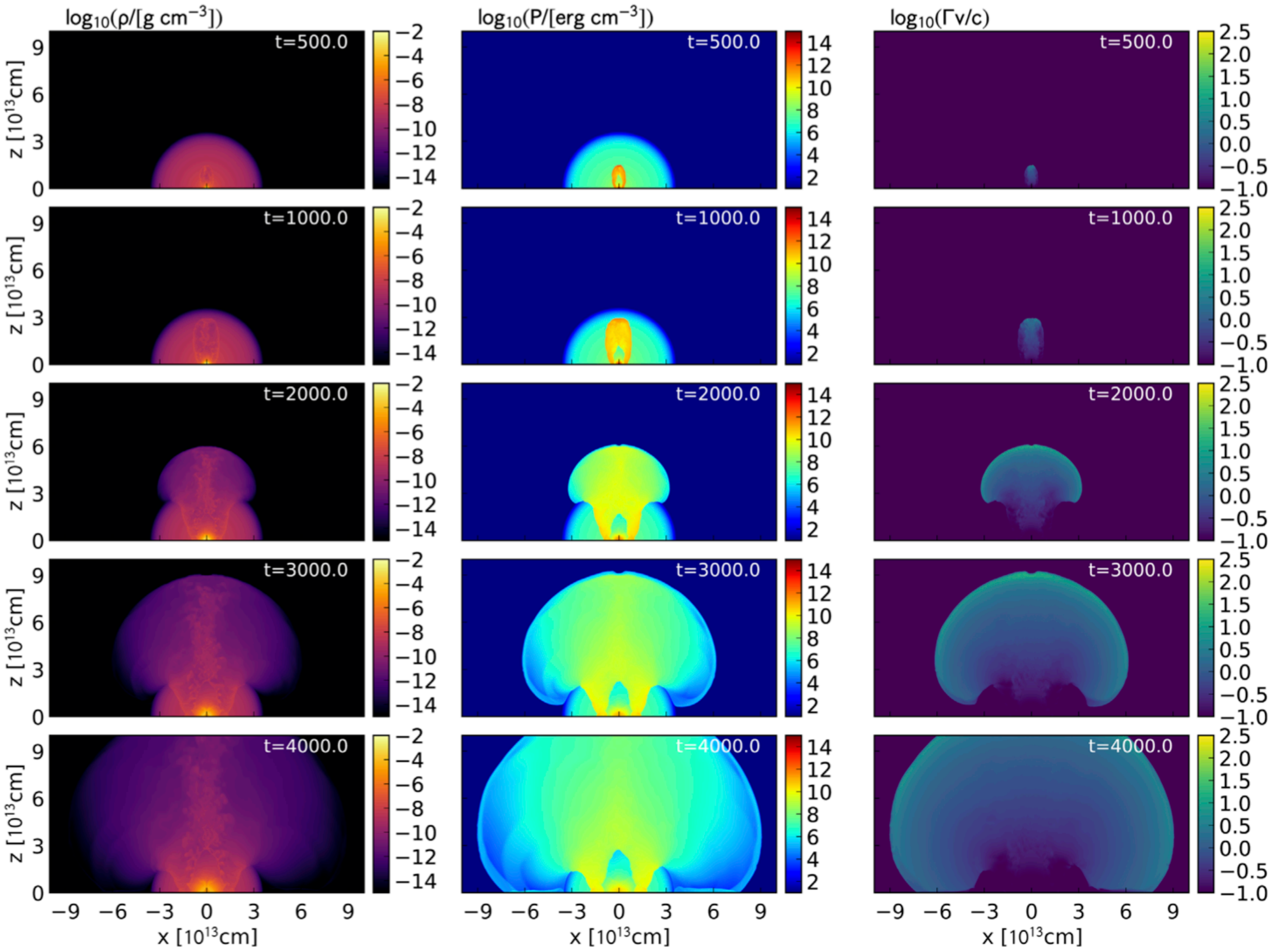
Failed jet case

Weak jet with L=2.5x10^{50}[erg/s] and t_{jet}=4 sec



Jet-CSM interaction

- 0.1M☉ CSM surrounding the progenitor
- the massive CSM stops the jet propagation -> jet energy dissipation at a large radius.
- relativistic shock breakout from the CSM
- origin of low-luminosity GRBs?



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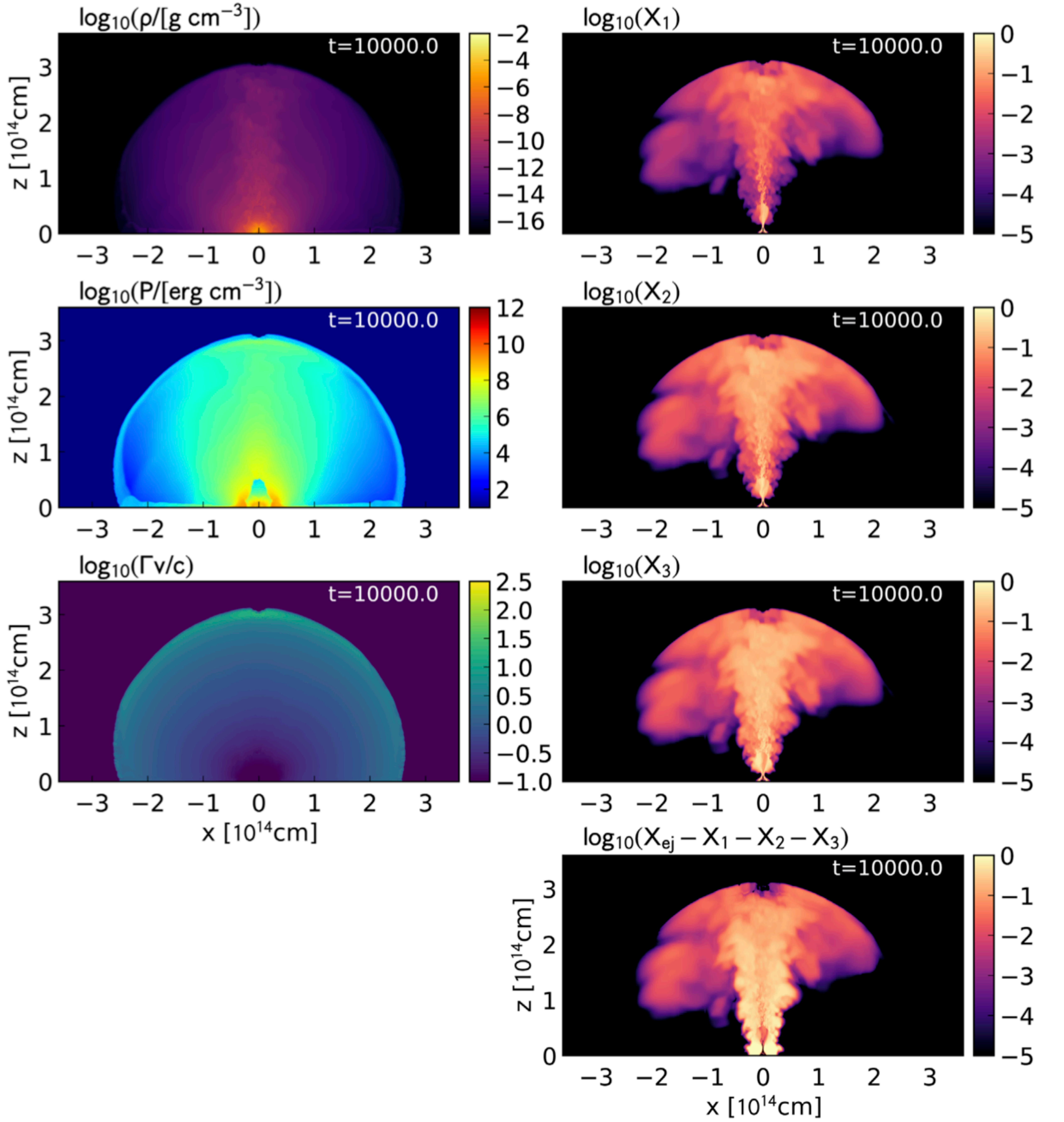

Jet-CSM interaction