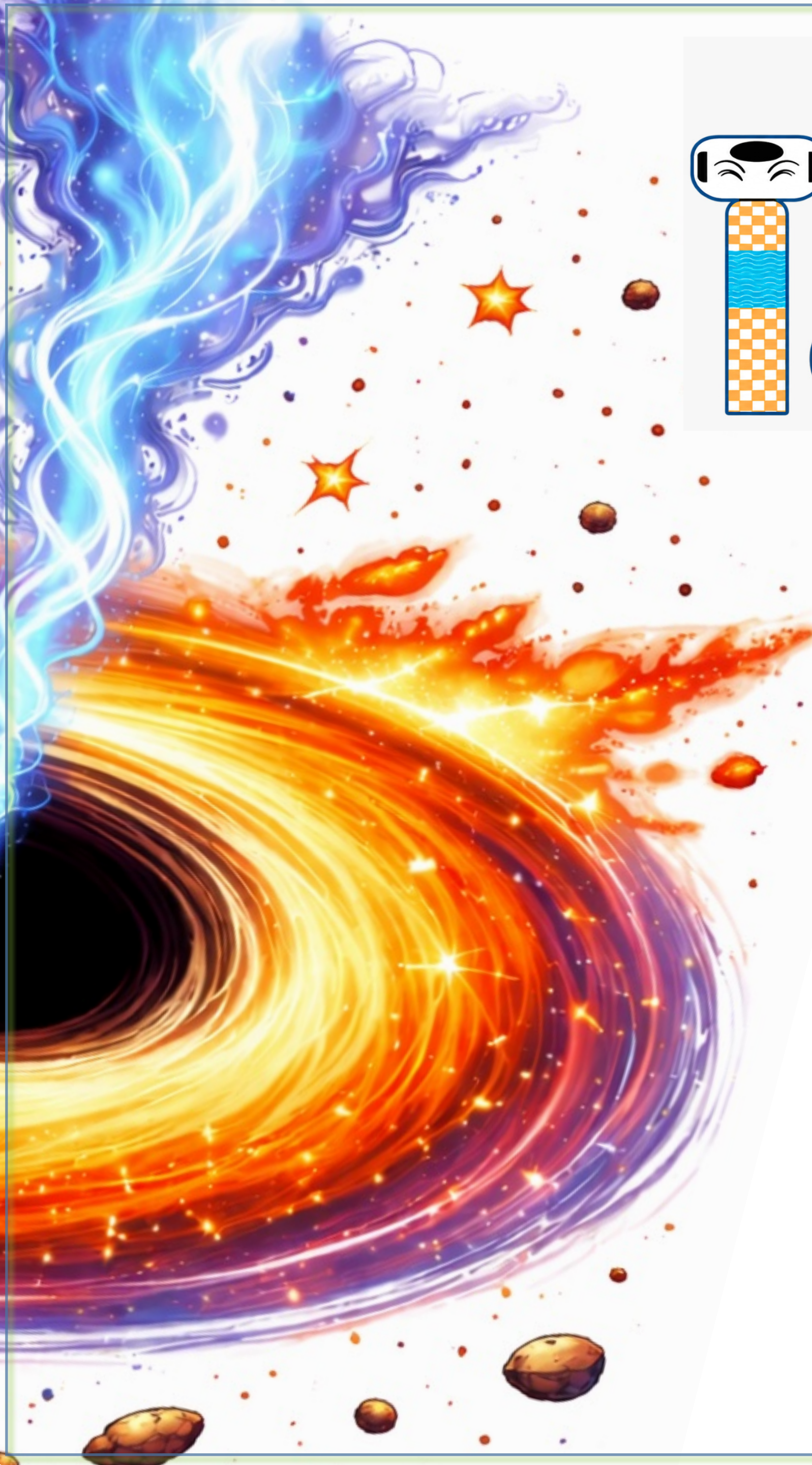




Hidden engines in core-collapse supernovae: multi-messenger signatures of choked jets

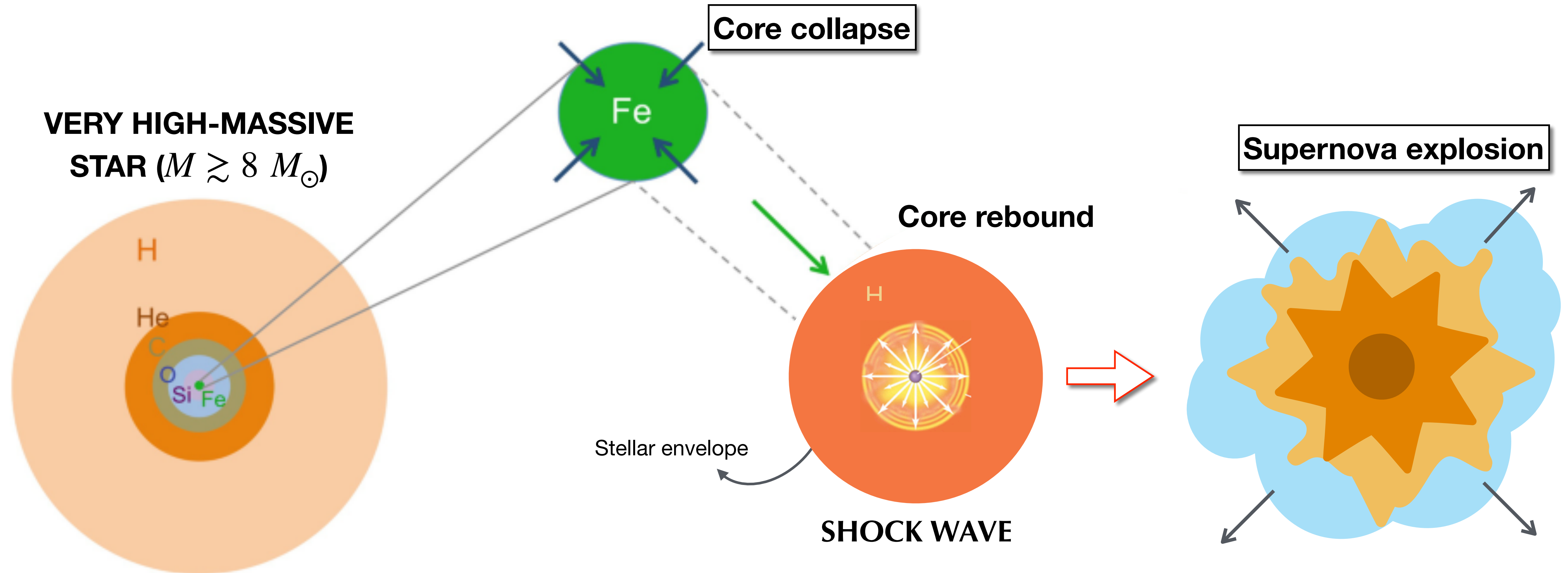
Angela Zegarelli

angela.zegarelli@astro.ruhr-uni-bochum.de

Outline

- * Core-collapse supernovae (CCSNe) and choked jets
- * Choked jets in the multi-messenger (MM) context
- * How to detect choked jets in MM astronomy?
- * Do choked jets produce neutrinos?

Core-collapse Supernovae (CCSNe)

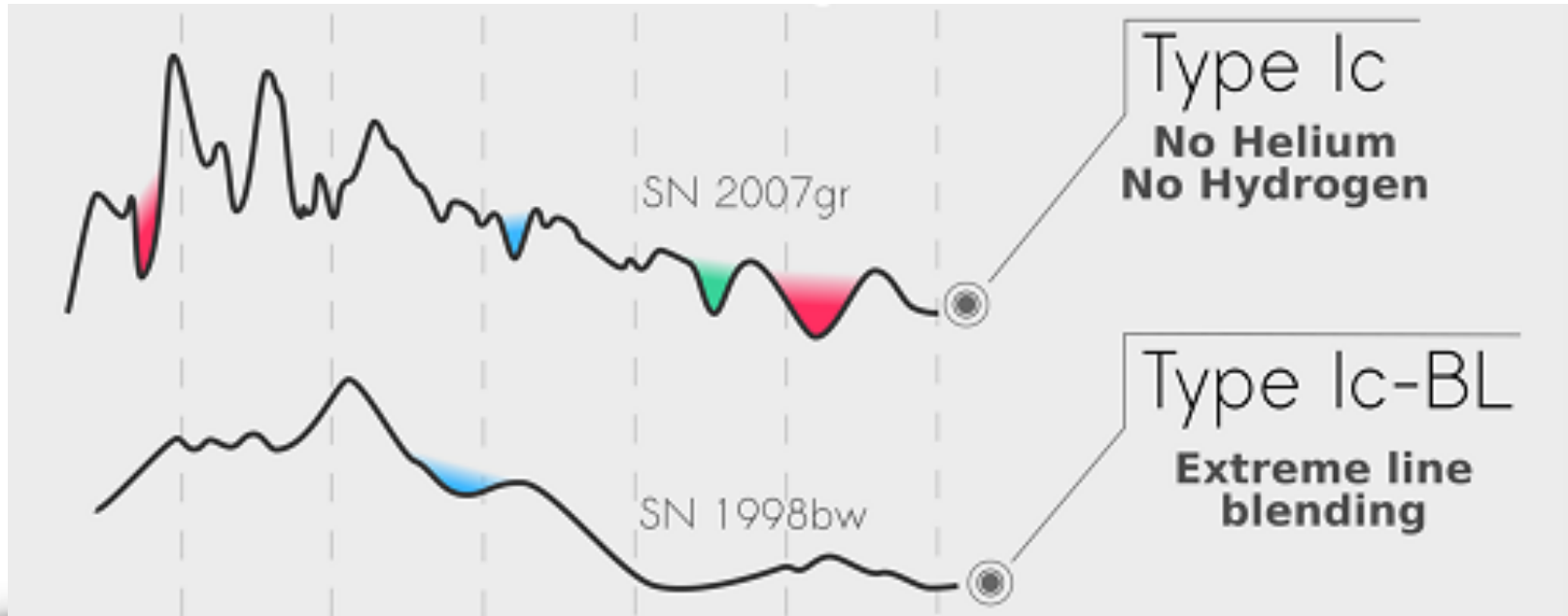


1. Atoms fuse to release energy to power the star, but eventually the star consumes all of its available fuel → **Gravity dominates**

2. Inward-falling material rebounds off the core, setting up an outward-going pressure wave

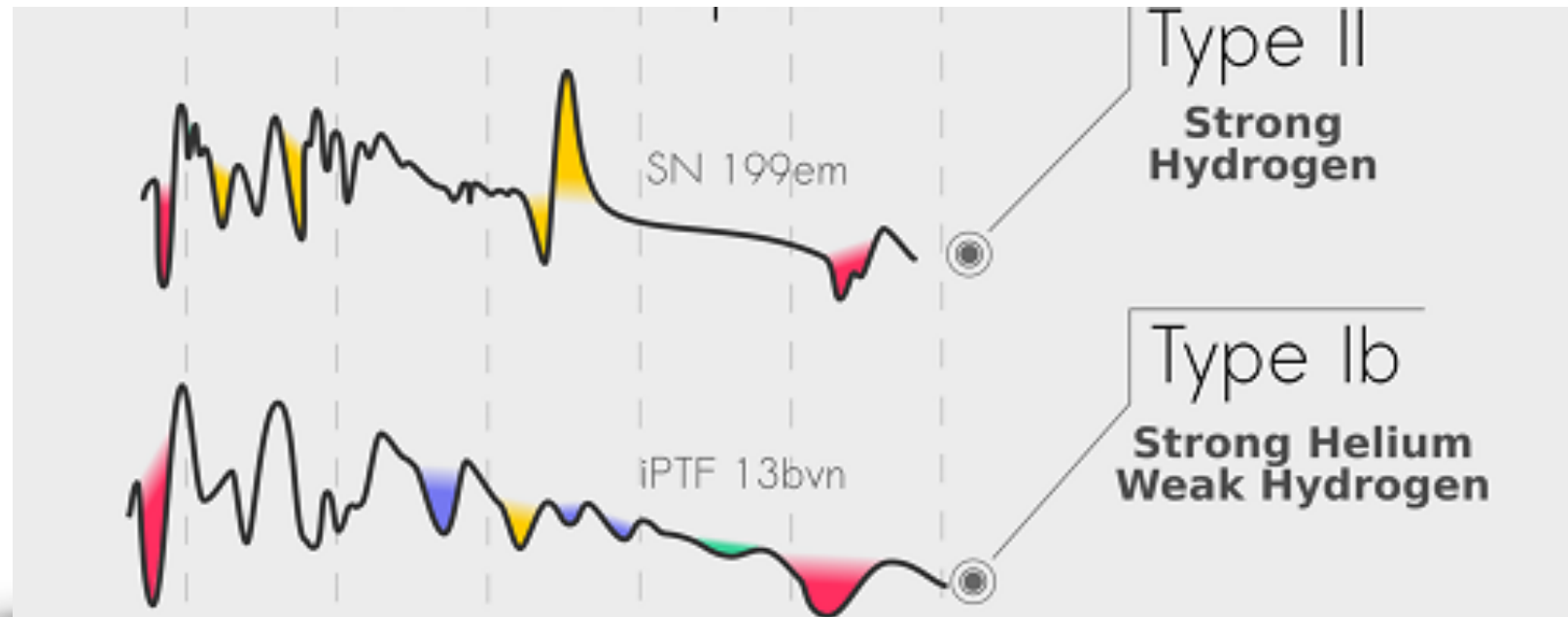
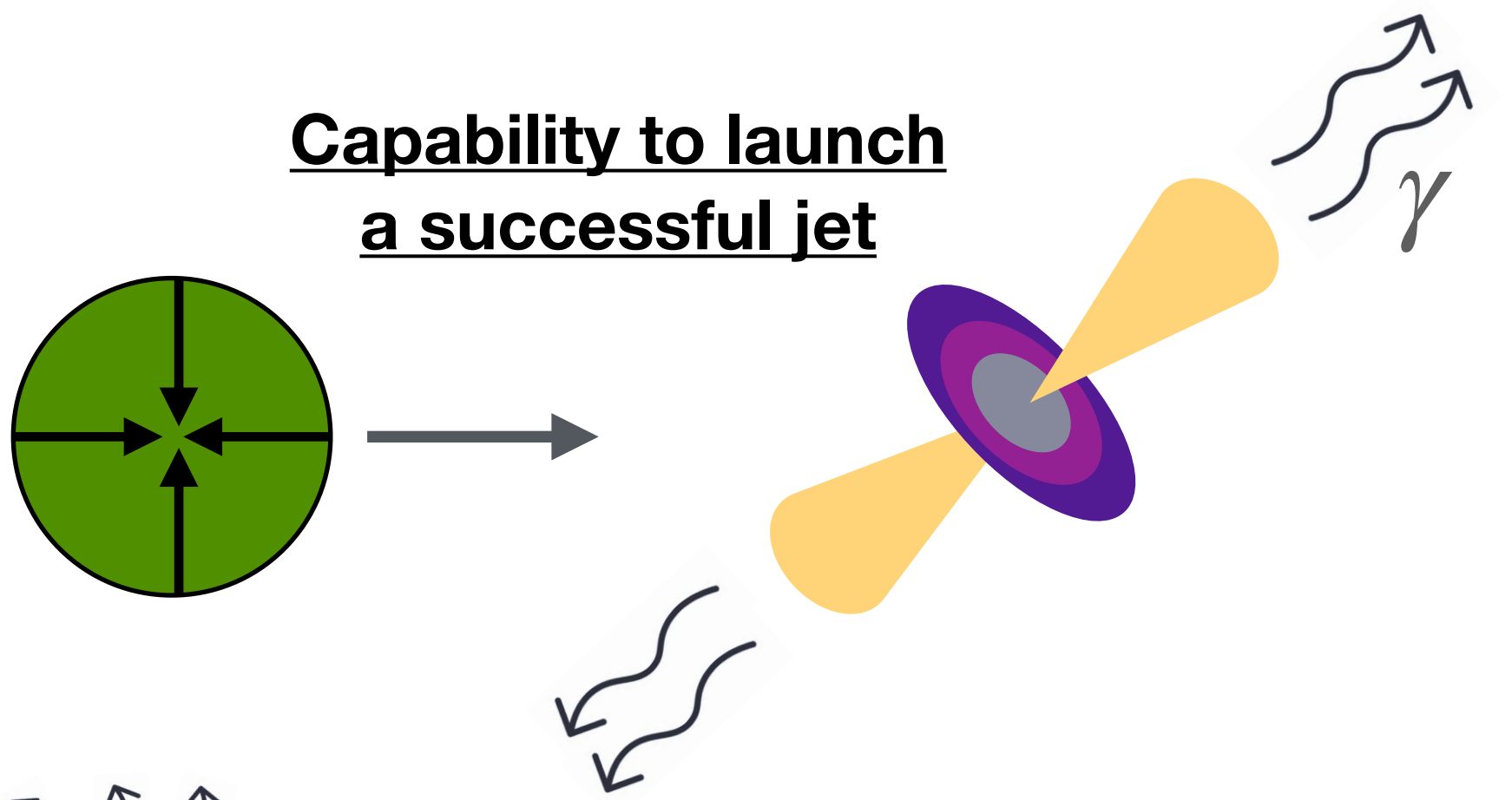
3. The shock wave moves outward through the star

CCSNe and connection with Gamma-Ray Bursts (GRBs)



Mostly associated to **standard long GRBs**, whose progenitors are **Wolf-Rayet (WR) stars**: very massive stars with strong winds blowing out most of the material of the stellar envelope

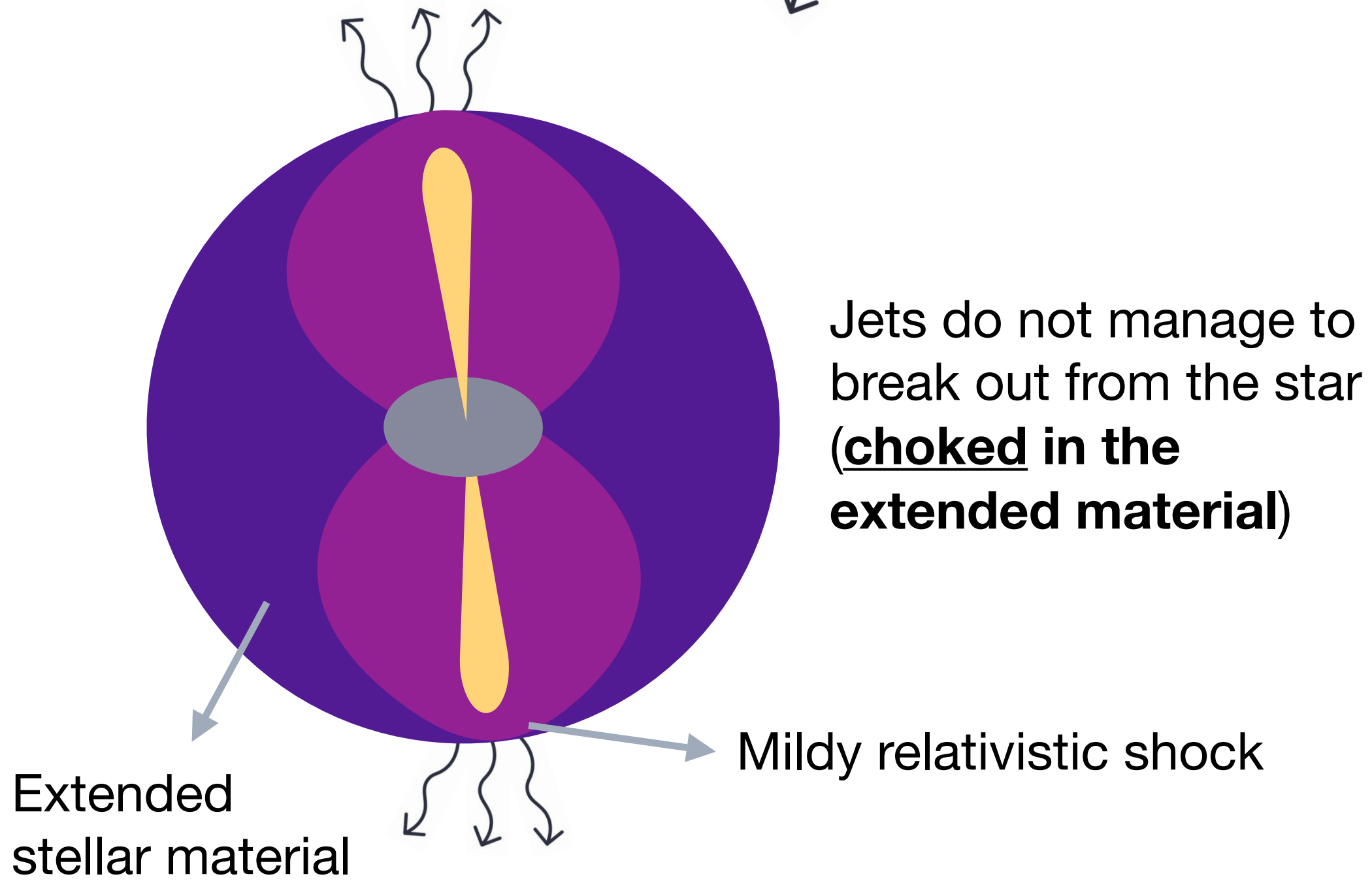
$L_{\gamma, \text{iso}}$ up to $\sim 10^{54} \text{ erg s}^{-1}$



A few associations with **low-luminous GRBs (//GRBs)**

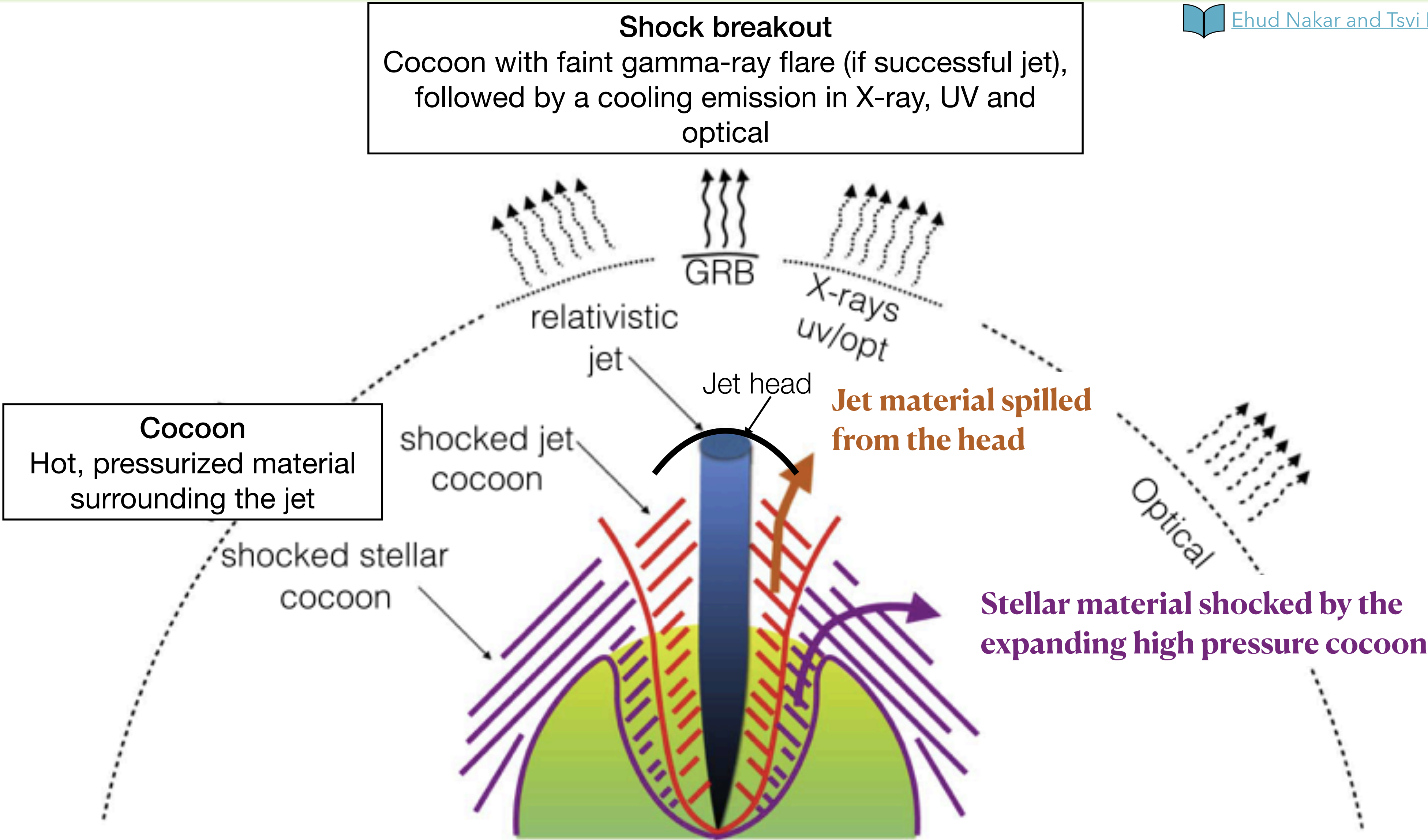
e.g., //GRB 060218 - SN 2006aj
Nakar 2015

$L_{\gamma, \text{iso}} < 10^{49} \text{ erg s}^{-1}$



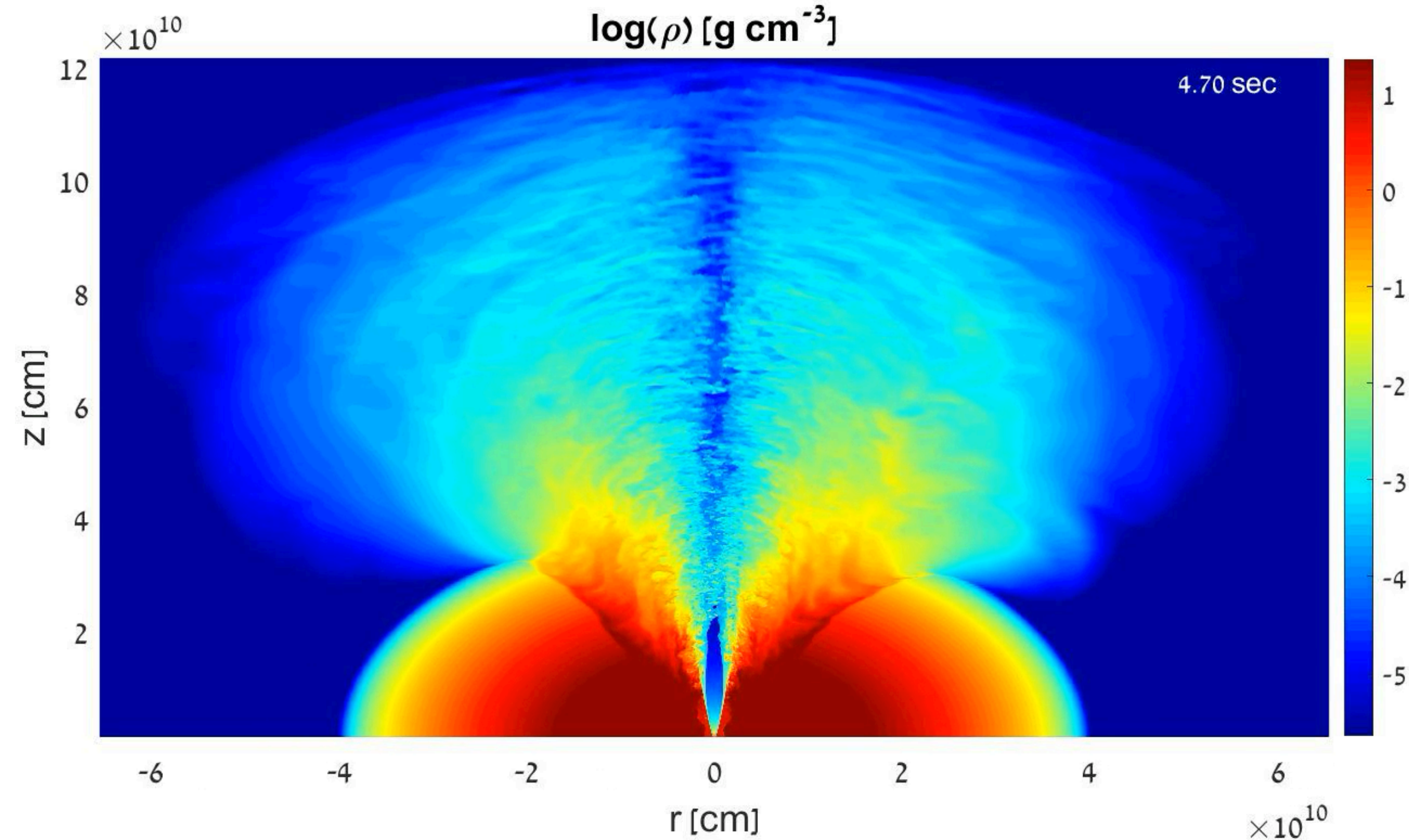
GRB cocoons in the *collapsar* model

 Ehud Nakar and Tsvi Piran 2017 ApJ **834** 28

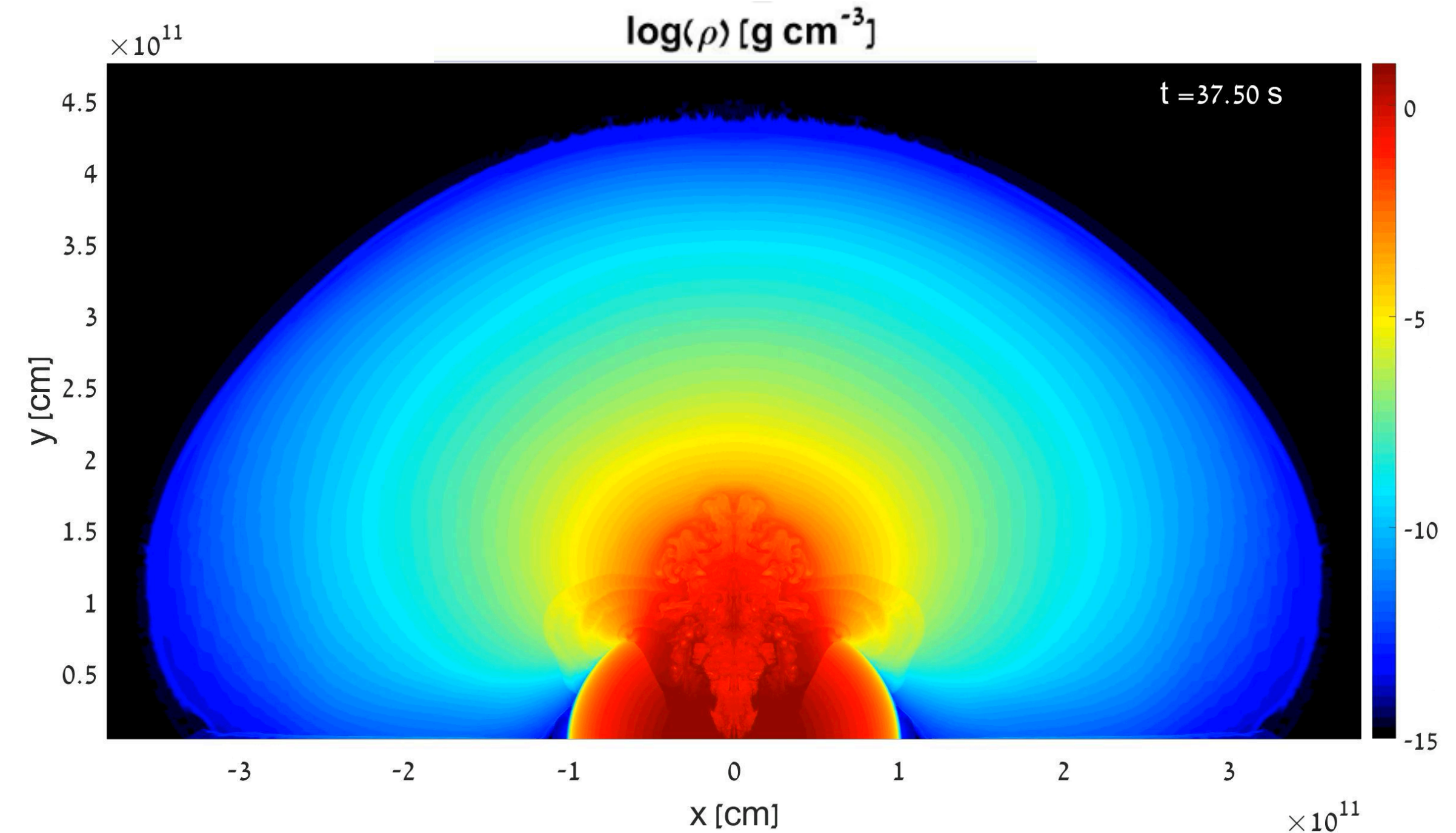


Cocoon emission in standard and choked GRB jets

Cocoon emission from long GRBs
(succesfull GRBs)



Choked jet with a cocoon breakout
Cocoon dominates the emission
quasi-isotropic, no beamed high-energy signal



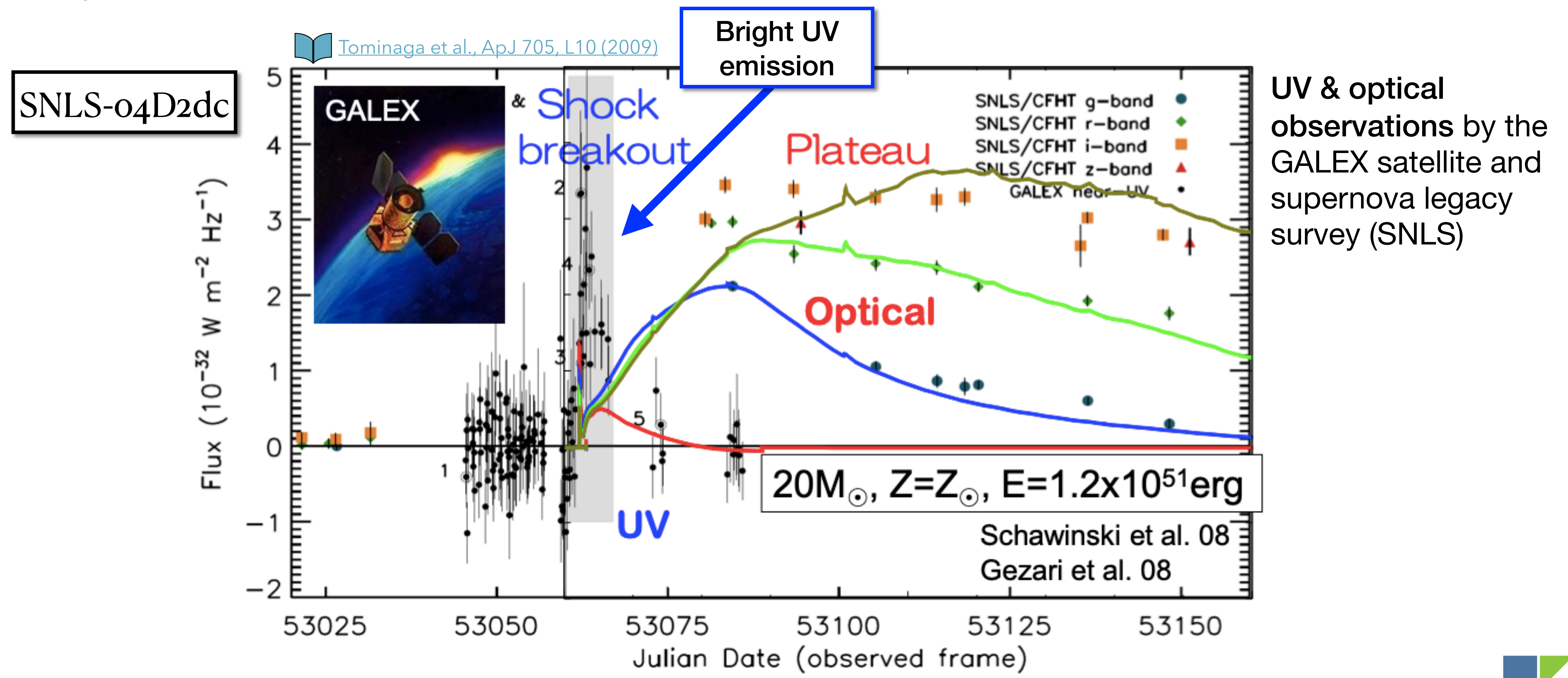
3D simulation with a jet launched from the core of a $4M_{\odot}$ Wolf Rayet star

Credits: Ore Gottlieb

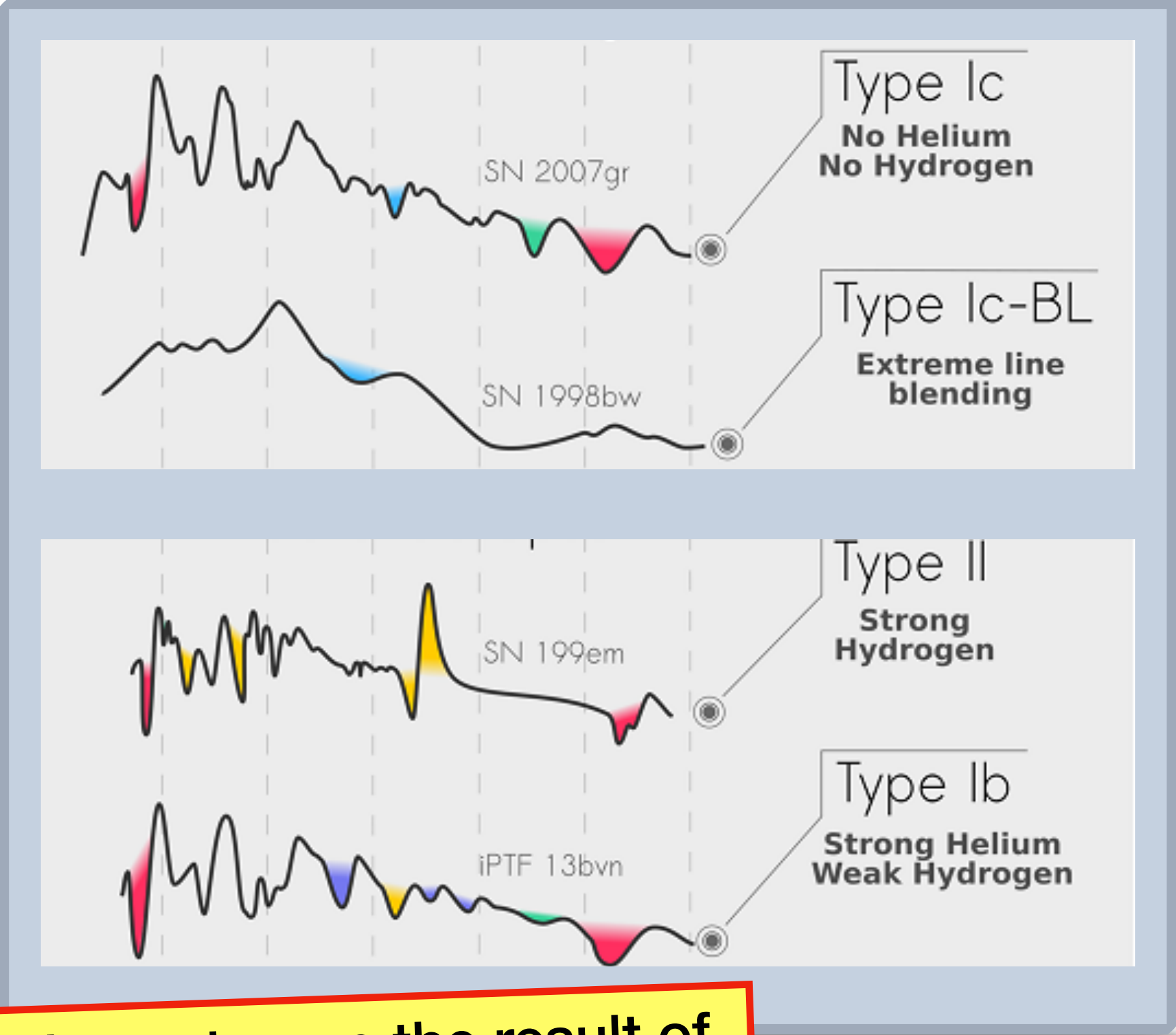
<https://www.oregottlieb.com/videos.html>

Example of a signature of SBO in SN light curve

2008 → First complete UV/optical light curves capturing the SBO of Type II Plateau SNe, named SNLS-04D2dc and SNLS-06D1jd



The formation of SN spectral lines

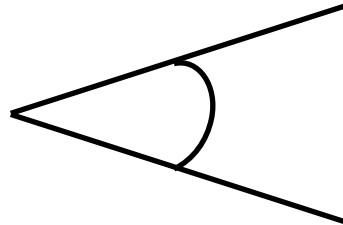


SN spectra are the result of this process occurring in different elements, each contributing its characteristic spectral features

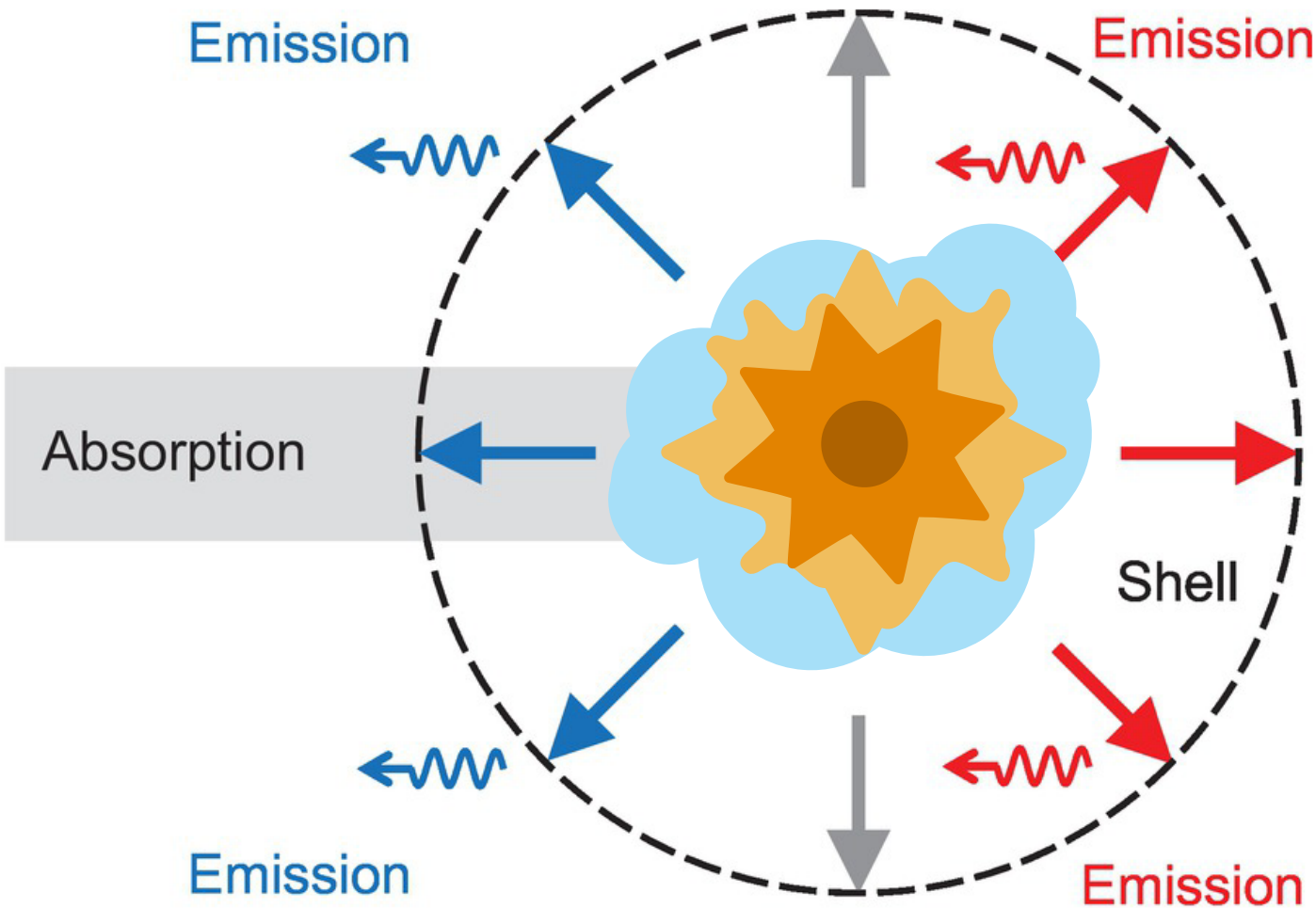
Ejecta velocity

$$v = c \frac{\Delta \lambda}{\lambda_0}$$

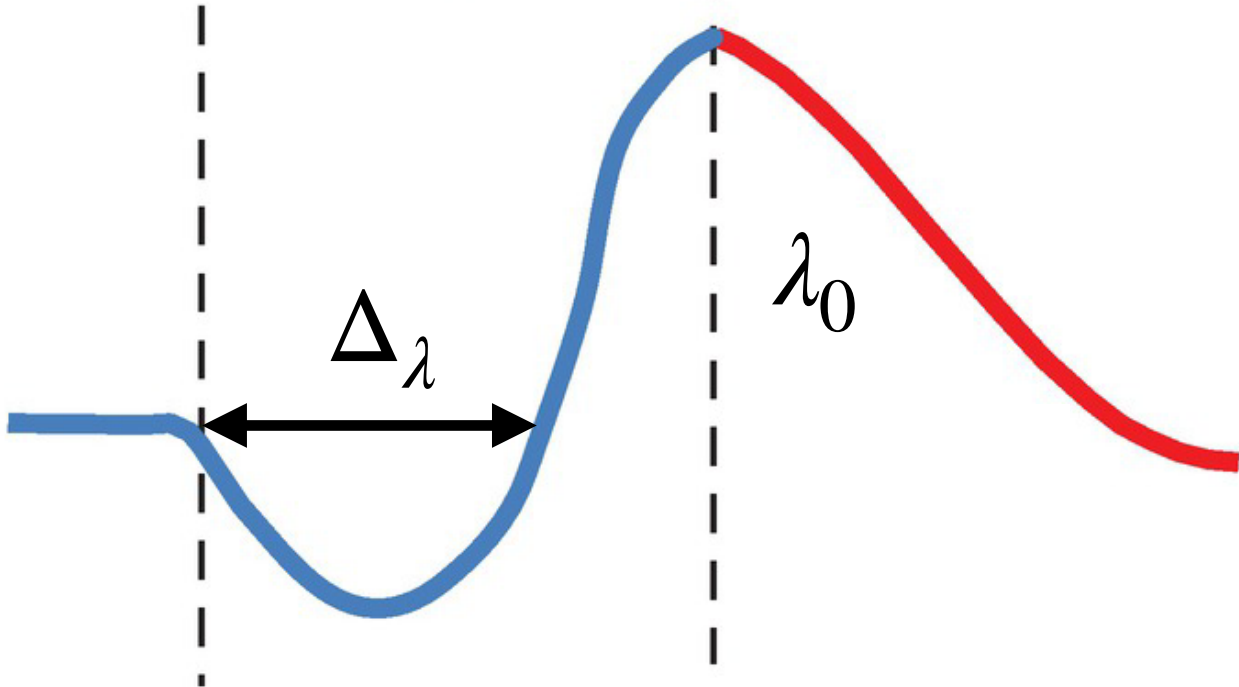
Observer



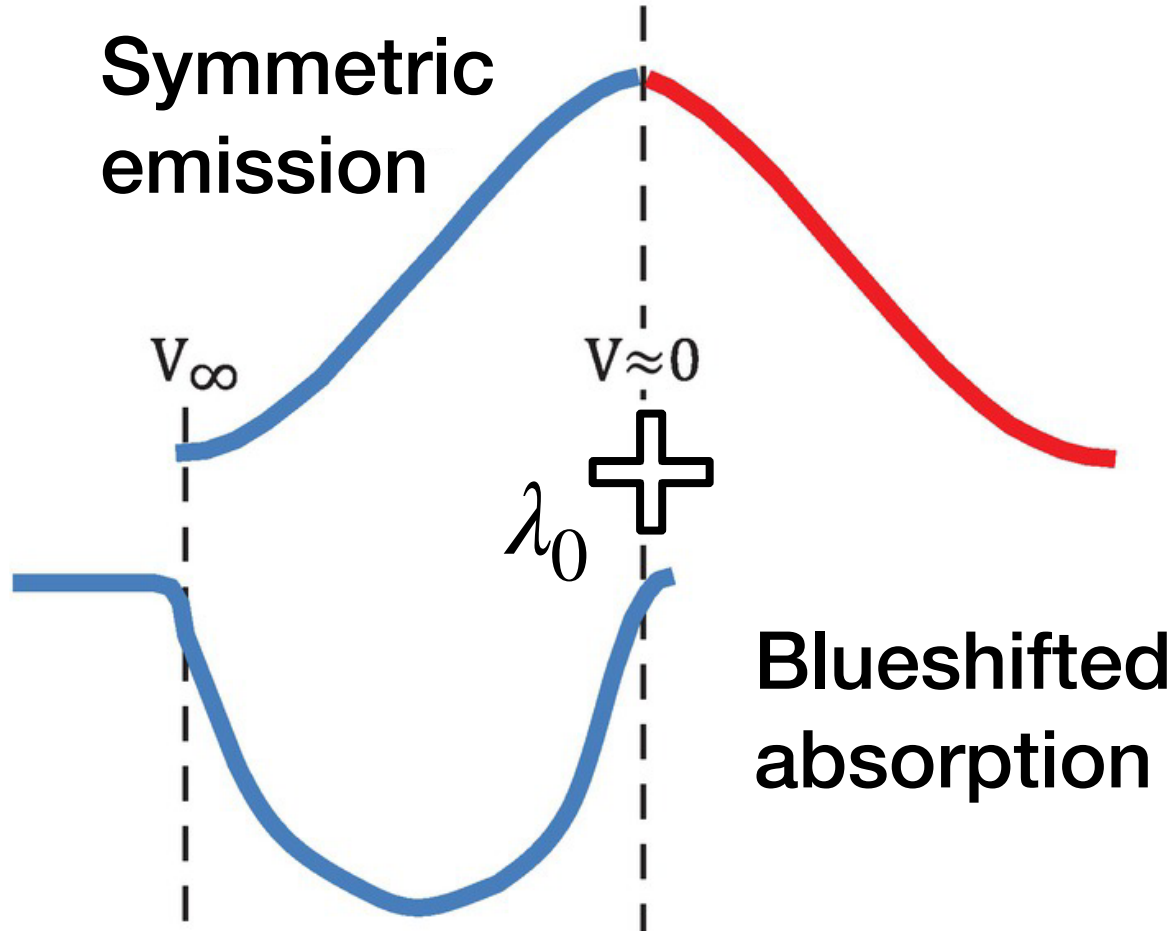
SN explosion
Spherical explosion



Resulting
P-Cygni profile



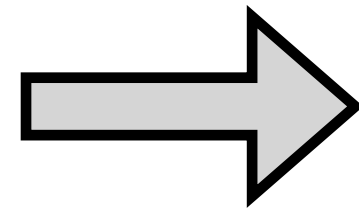
Symmetric
emission



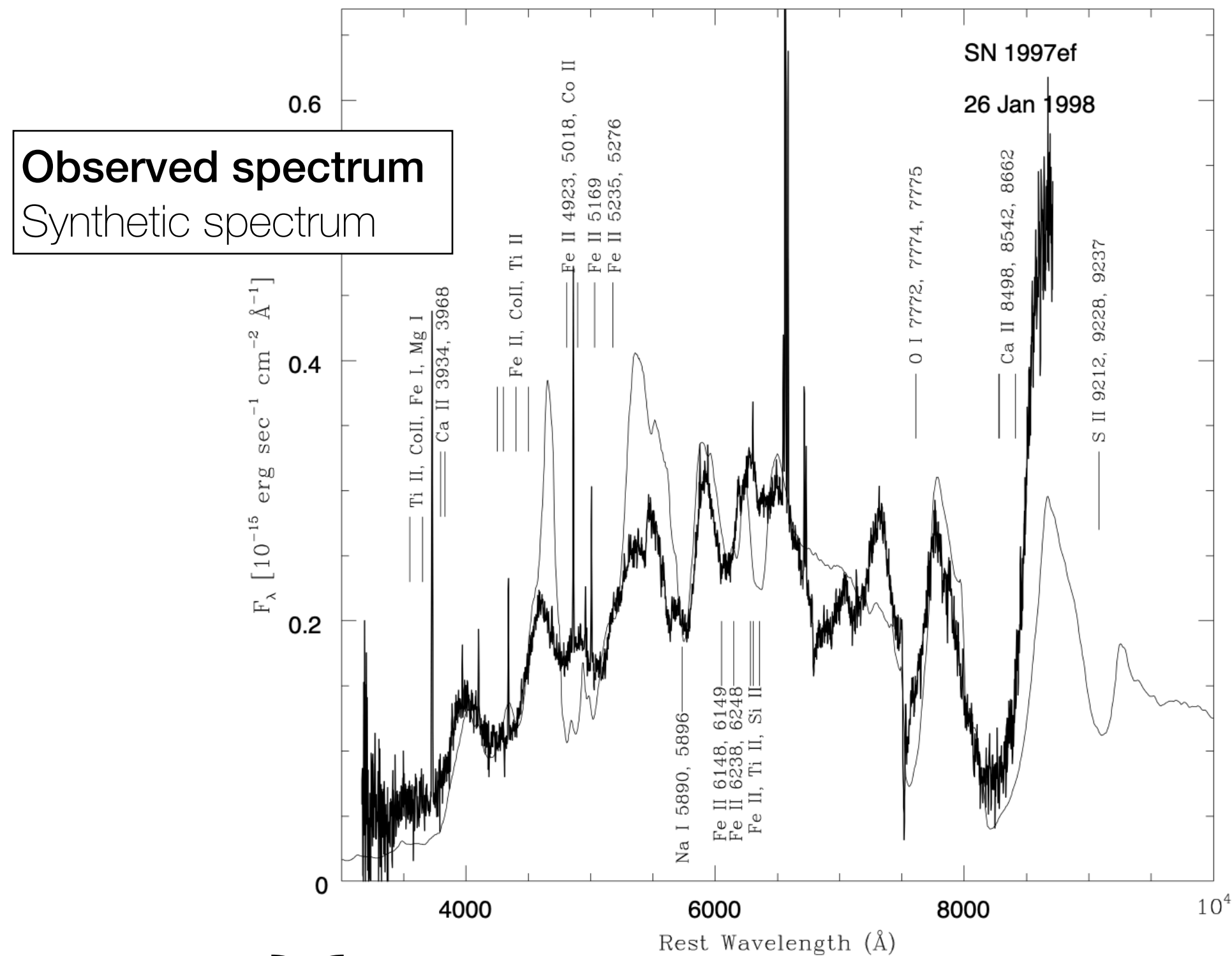
Energy-velocity distribution in SNe

Ejecta velocity

$$v = c \frac{\Delta\lambda}{\lambda_0}$$



Radiative transfer model
Comparison with
synthetic spectra at
different times

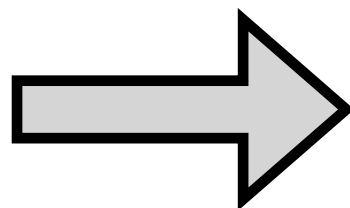


 [Mazzali, Iwamoto, Nomoto, ApJ 545 407-419 \(2020\)](#)

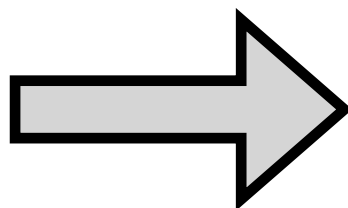
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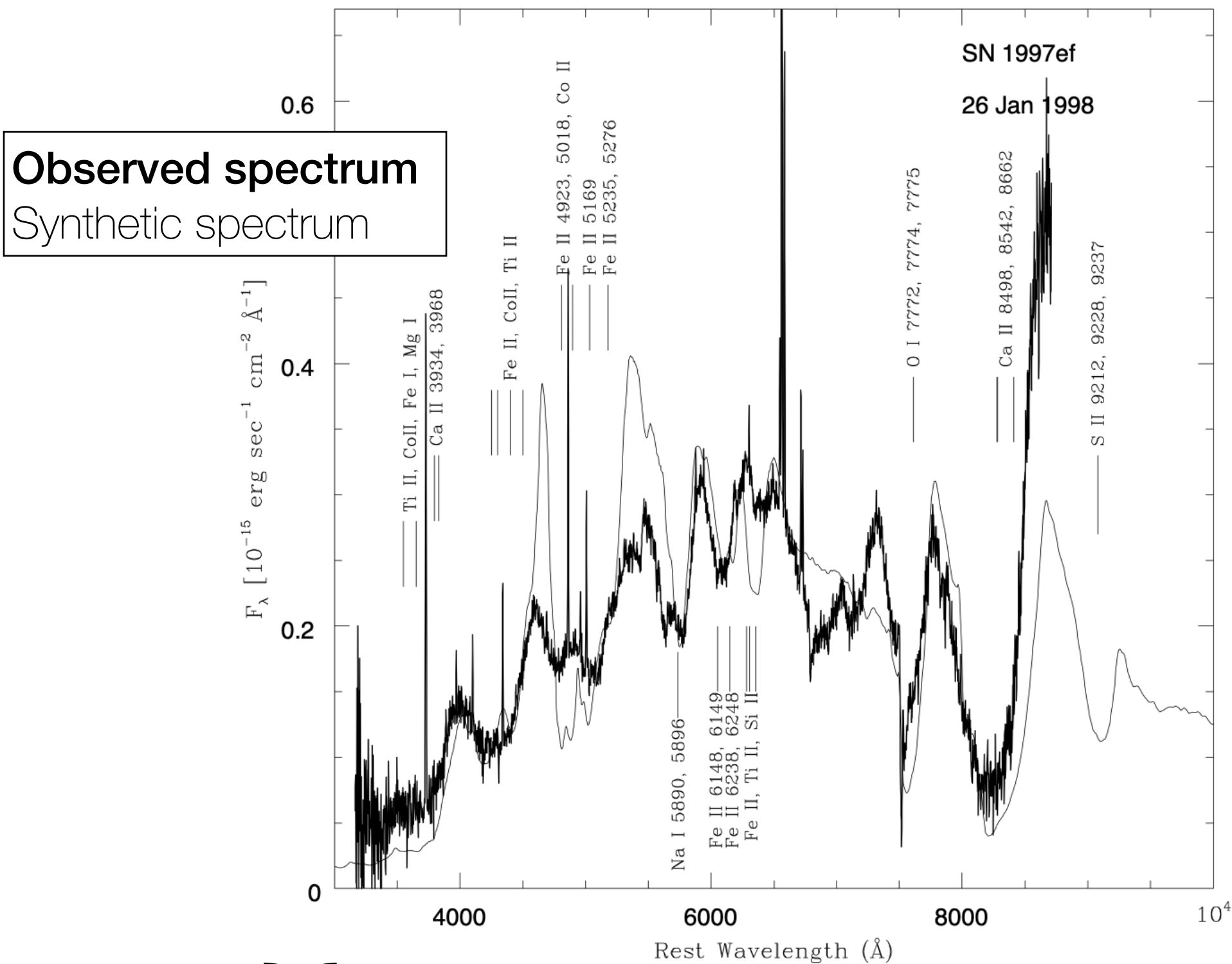
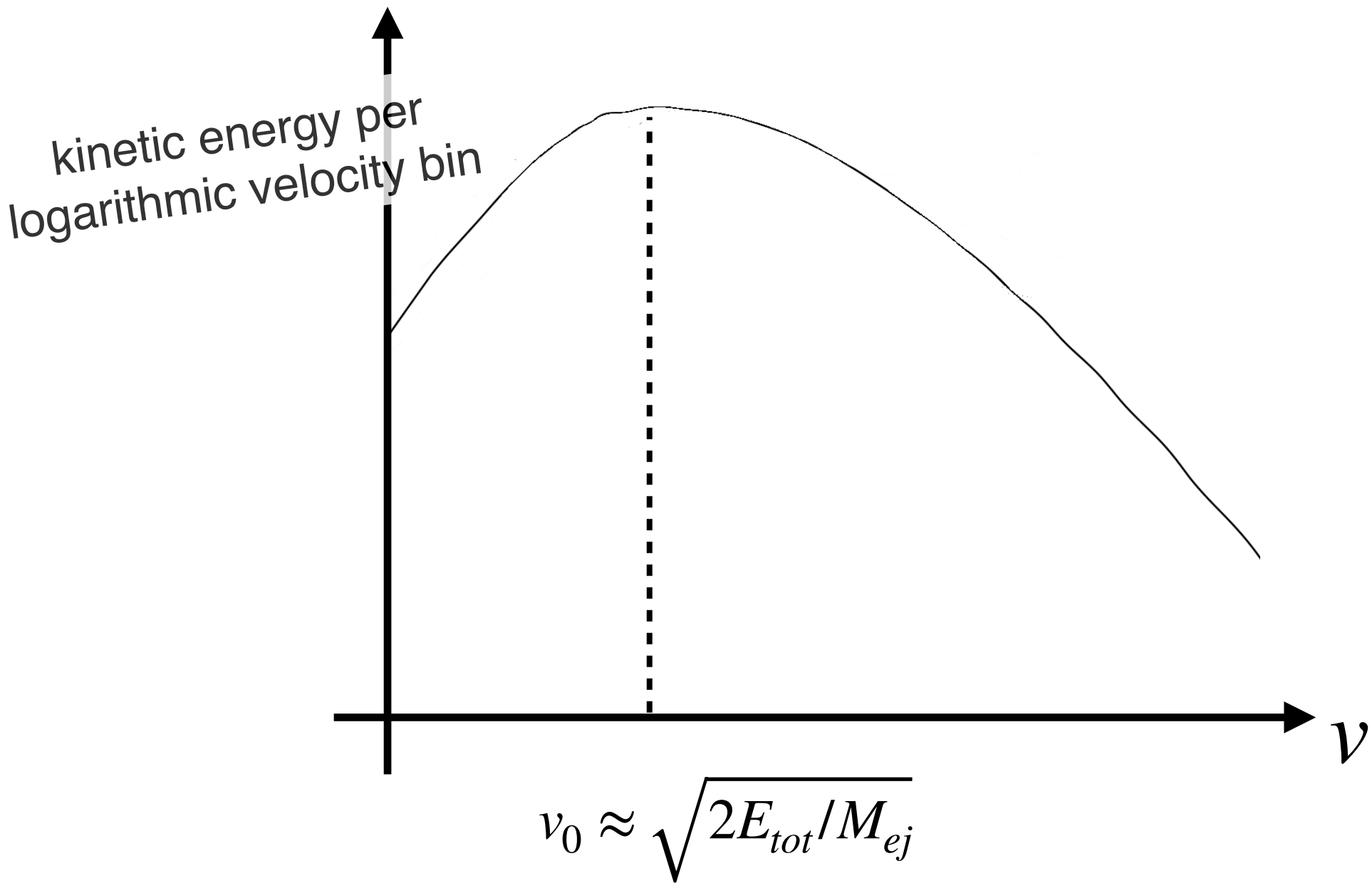
**Inferred
Energy - Velocity distribution**

$$\frac{dM}{dv} \rightarrow \frac{dE}{d \ln v}$$

Spherical explosion

Most of the mass is deposited close to v_0 , and progressively less and less mass is accelerated to higher velocities

 [Piran, Nakar, Mazzali, Pian, 2019 ApJ 871 25](#)
[Pais, Piran, Nakar, MNRAS 519, 1941-1954 \(2023\)](#)



 [Mazzali, Iwamoto, Nomoto, ApJ 545 407-419 \(2020\)](#)

Spectroscopical probe of relativistic jets

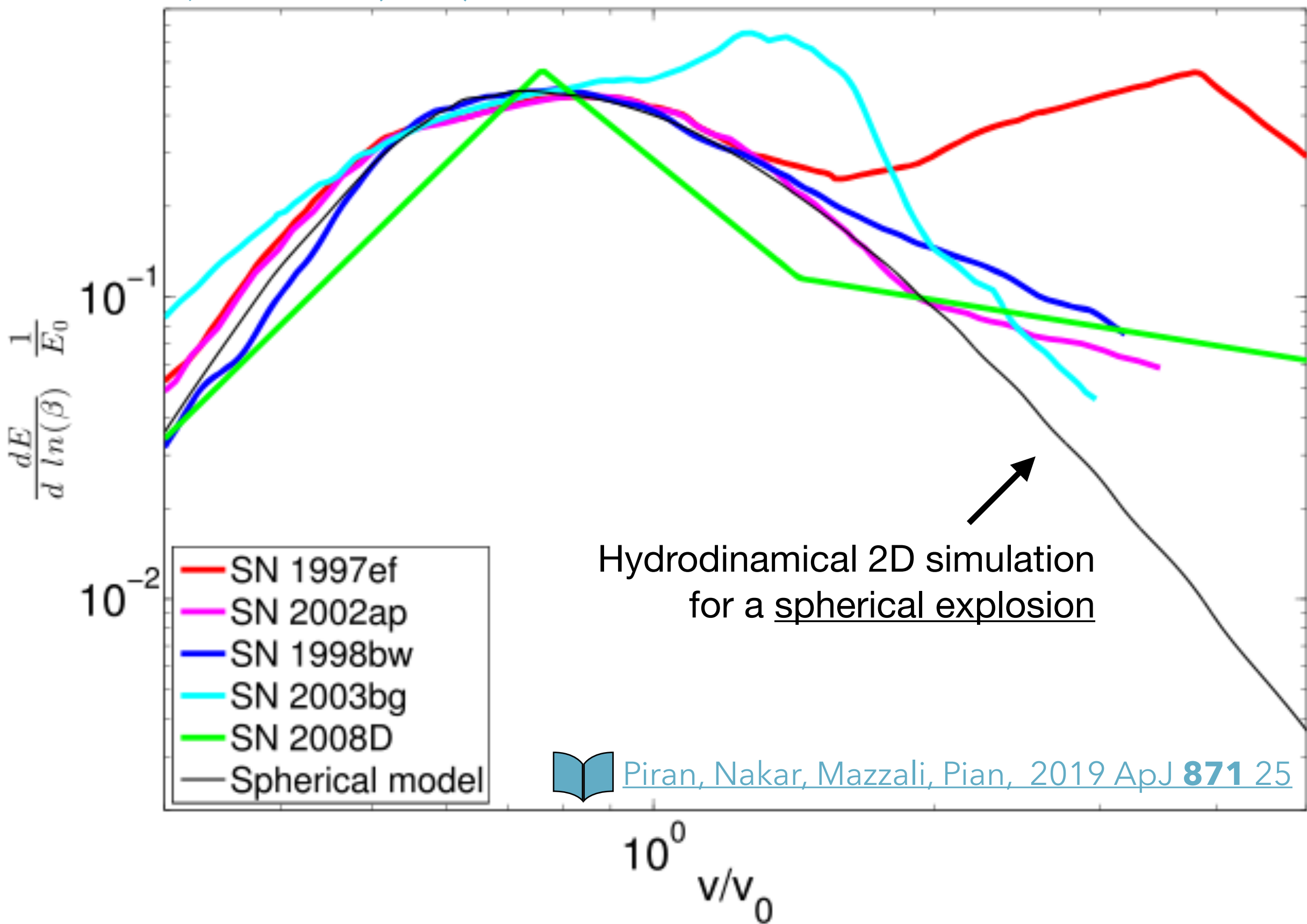
Probe of the presence of a relativistic jet
The explosion is jet-driven

The relativistic jet accelerates a small amount of stellar mass to high velocities along its narrow opening angle, contained within the wider cocoon opening angle

 [Pais, Piran, Nakar, MNRAS 519, 1941-1954 \(2023\)](#)

Excess of material at high velocity

SN	Type	Comments
1997ef (1)	Ic-BL	No GRB
1998bw (2)	Ic-BL	//GRB980425
2002ap (3)	Ic-BL	No GRB
2003bg (4)	IIb	No GRB
2008D (5)	Ib	X-ray burst
2016jca (6)	Ic-BL	GRB161219b



Spectroscopical probe of relativistic jets

Probe of the presence of a relativistic jet
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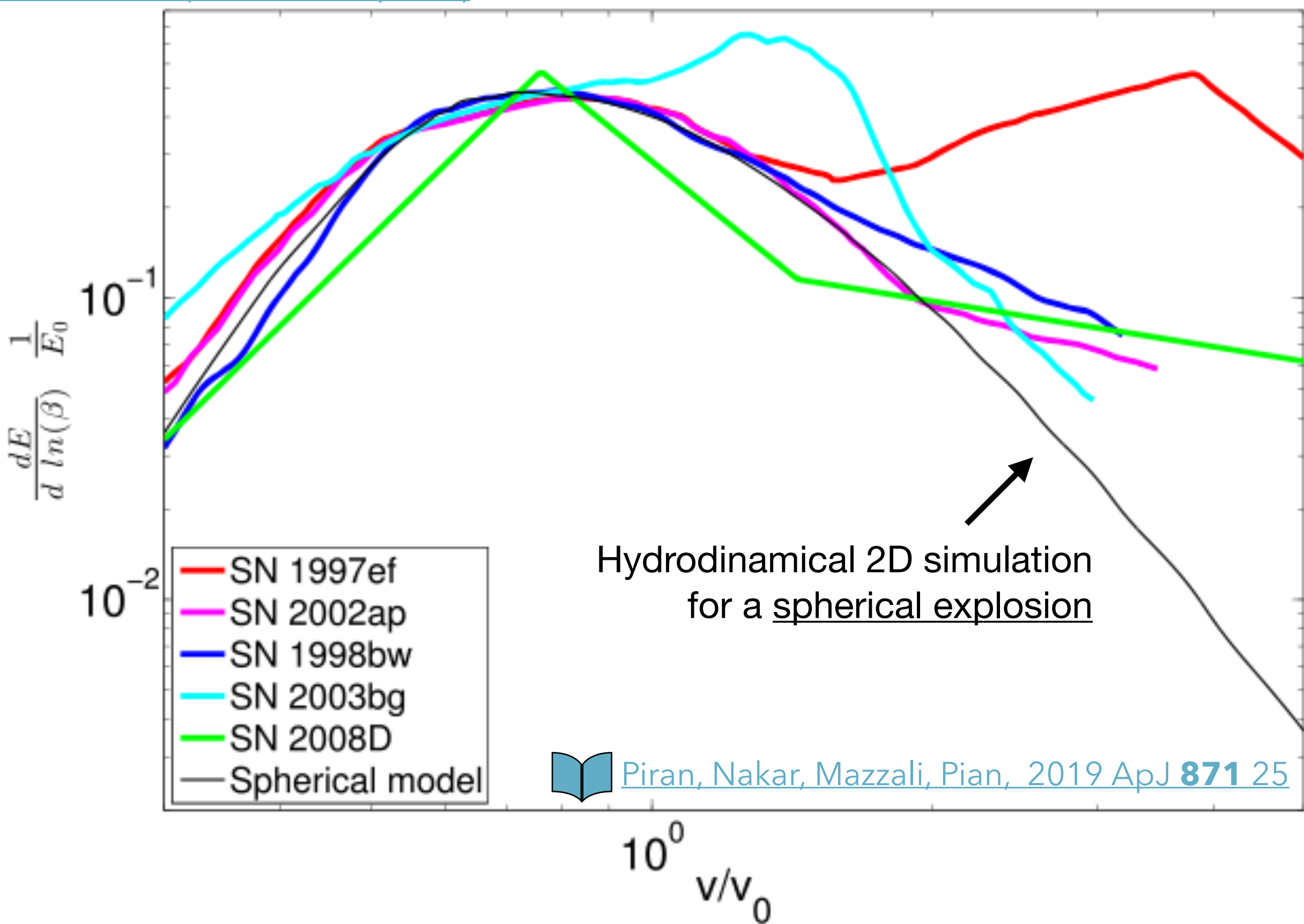
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Candidate choked jets



Observable signatures from cocoons in choked jets

By emission:

1. **Shock breakout** → **X-ray/UV** flash lasting hours
2. **Cooling emission** → **UV/optical** signal lasting *days*

Challenging to catch

Limited availability of rapid-response UV facilities

By spectroscopy:

- **Modified ejecta velocity profile** → jets can alter the SN ejecta dynamics, leaving signatures in the **velocity evolution of spectral lines**
- **Observational evidence** → a few CCSNe show signatures consistent with choked jets (*Type Ib, Ic-BL, IIb*)
- If those SNe are not associated with GRBs → *candidate choked jets*

Requires very early-time, high-quality spectroscopy

A few interesting perspectives ...

By emission:

1. **Shock breakout** → **X-ray/UV** flash lasting hours
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See Yuan Liu's
plenary talk on
Wednesday

Wide-field, high-cadence X-ray monitoring enables serendipitous detection (e.g., Einstein Probe - EP260321a/SN 2026gzf)

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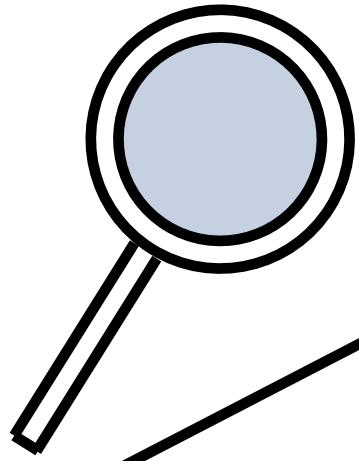
Rubin/LSST alerts enable rapid identification of young SNe ($\sim 10^7$ per night), but early-time spectroscopy follow-up capacity will be still limited

 [Addison et al., MNRAS 546, 2-21 \(2026\)](#)

What's the possibility of catching early UV/optical emission embedded in CCSNe? The case of BSGs and RSGs

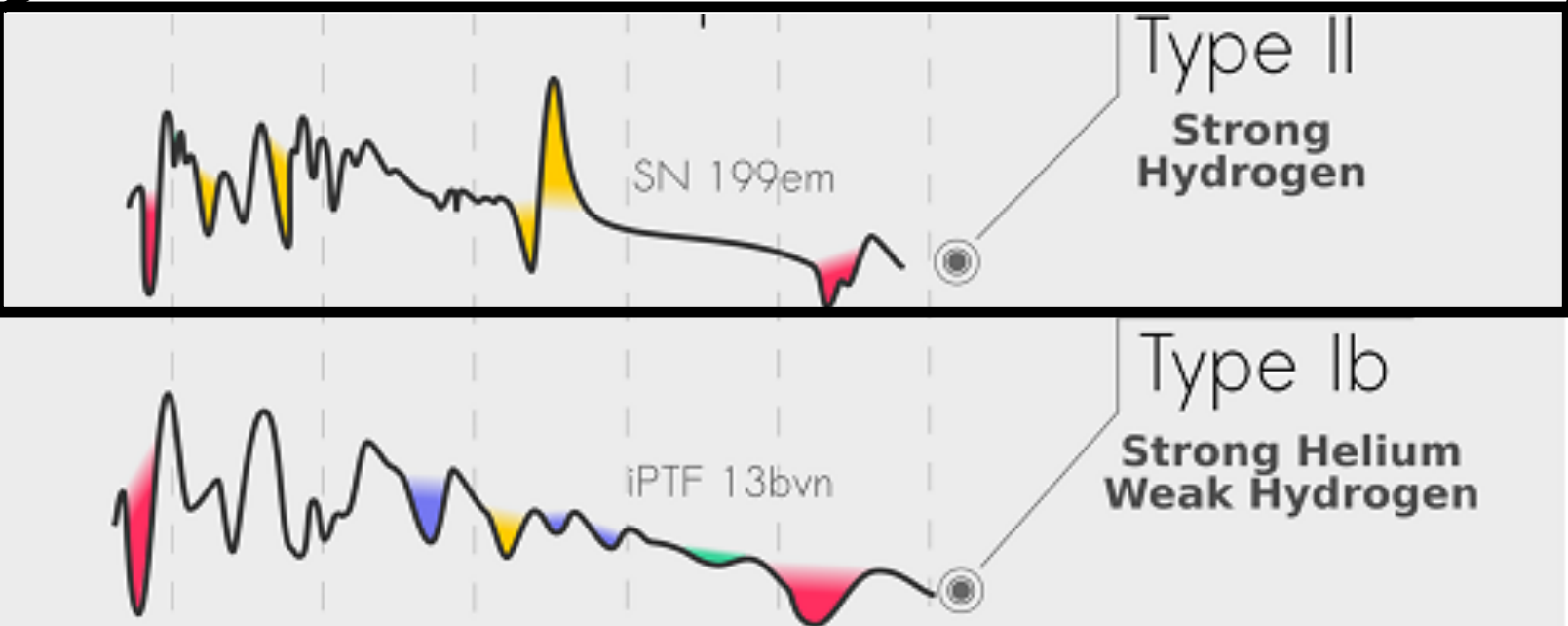
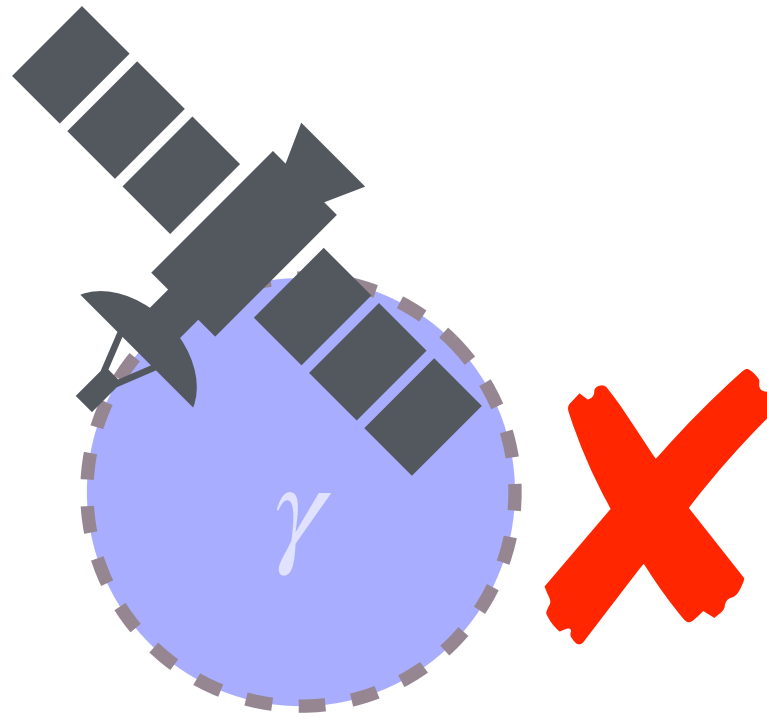
 A. Zegarelli, D. Guetta, S. Celli, S. Gagliardini, I. Di Palma, and I. Bartos, A&A, 690, A187 (2024)

Choked jets embedded in BSGs/RSGs



For very extended hydrogen-rich envelopes (extended massive stars as progenitors), the jet is expected to be **completely choked**

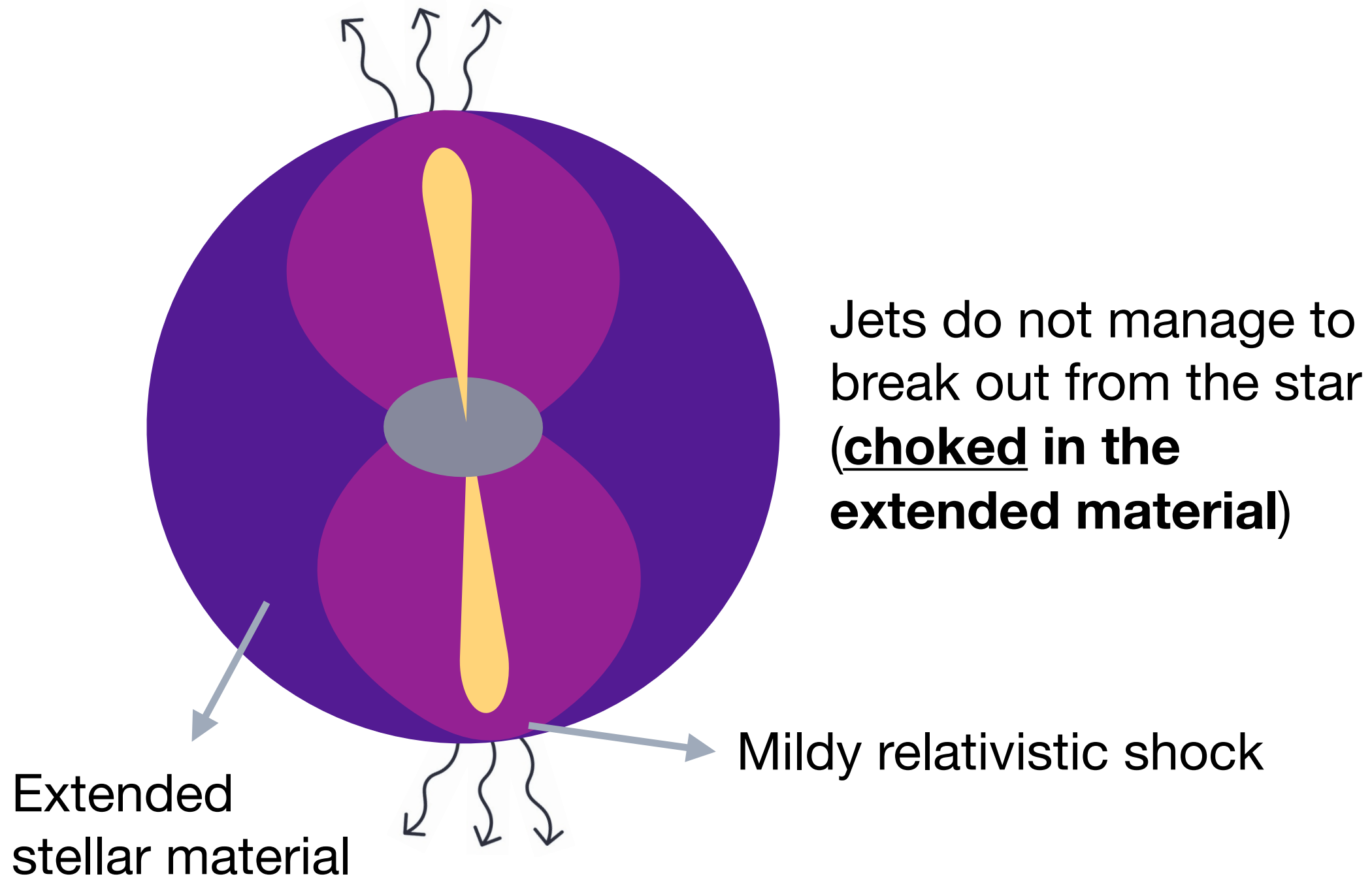
- Red Super Giants (RSGs)
- Blue Super Giants (BSGs),
i.e., underluminous SNe II
(e.g., SN 1987A) Arnett et al. 1989



A few associations with **low-luminous GRBs (//GRBs)**

e.g., //GRB 060218 - SN 2006aj
 Nakar 2015

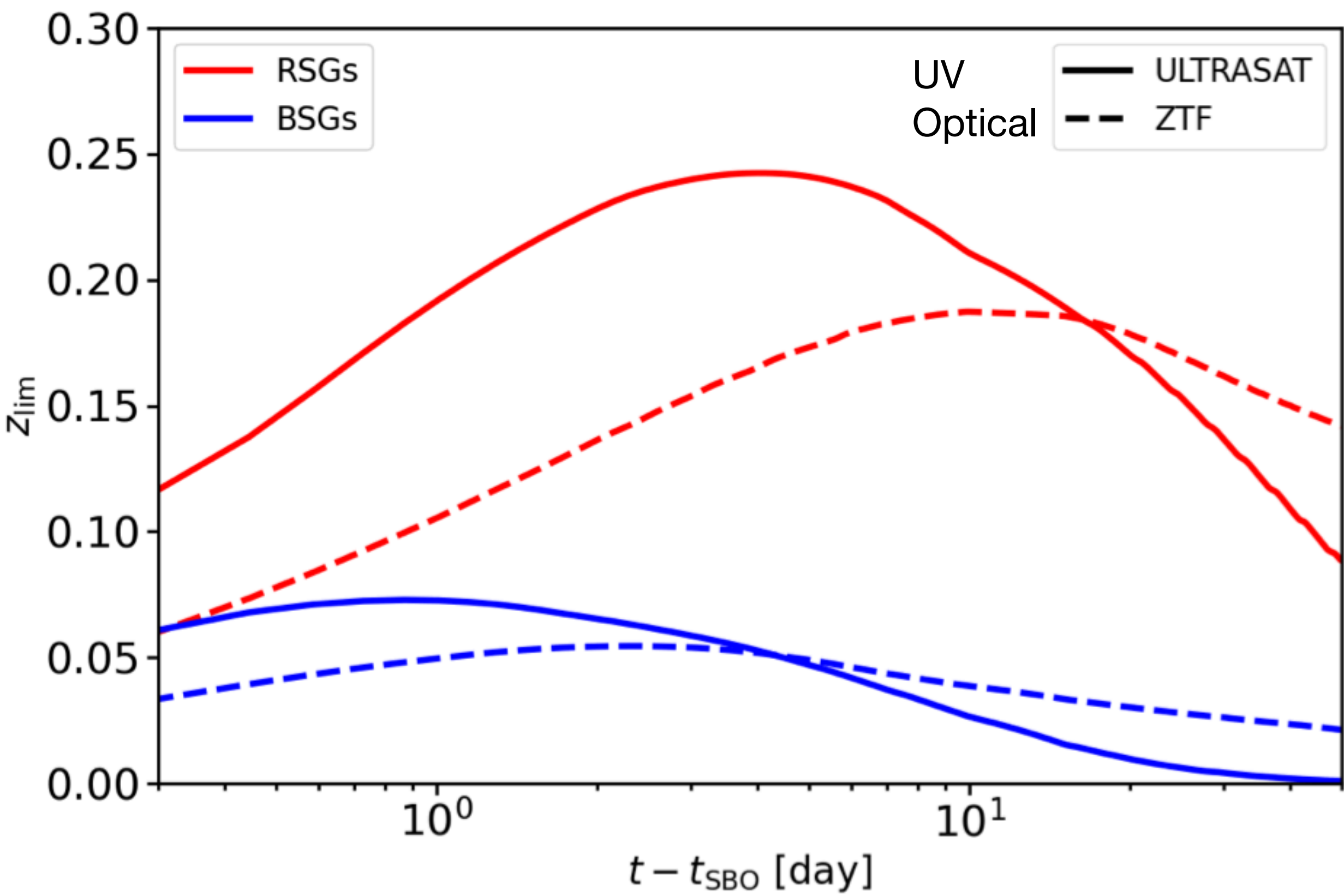
$$L_{\gamma, \text{iso}} < 10^{49} \text{ erg s}^{-1}$$



Max detectable redshift vs time after SBO

Model for early/UV optical emission from H-rich envelope CCSNe from  Waxman et al., ApJ 667, 351 (2007)
Rabinak & Waxman, ApJ 728, 63 (2011)

Time evolution of the emission compared with the limiting magnitude of each instrument at different distances



Results for peak of visibility in the emission

	z_{lim}	D_L [Mpc]	$t - t_{\text{SBO}}$ [days]
ULTRASAT	0.24	1200	4
ZTF	0.19	920	10

	z_{lim}	D_L [Mpc]	$t - t_{\text{SBO}}$ [days]
ULTRASAT	0.07	310	1
ZTF	0.05	220	4

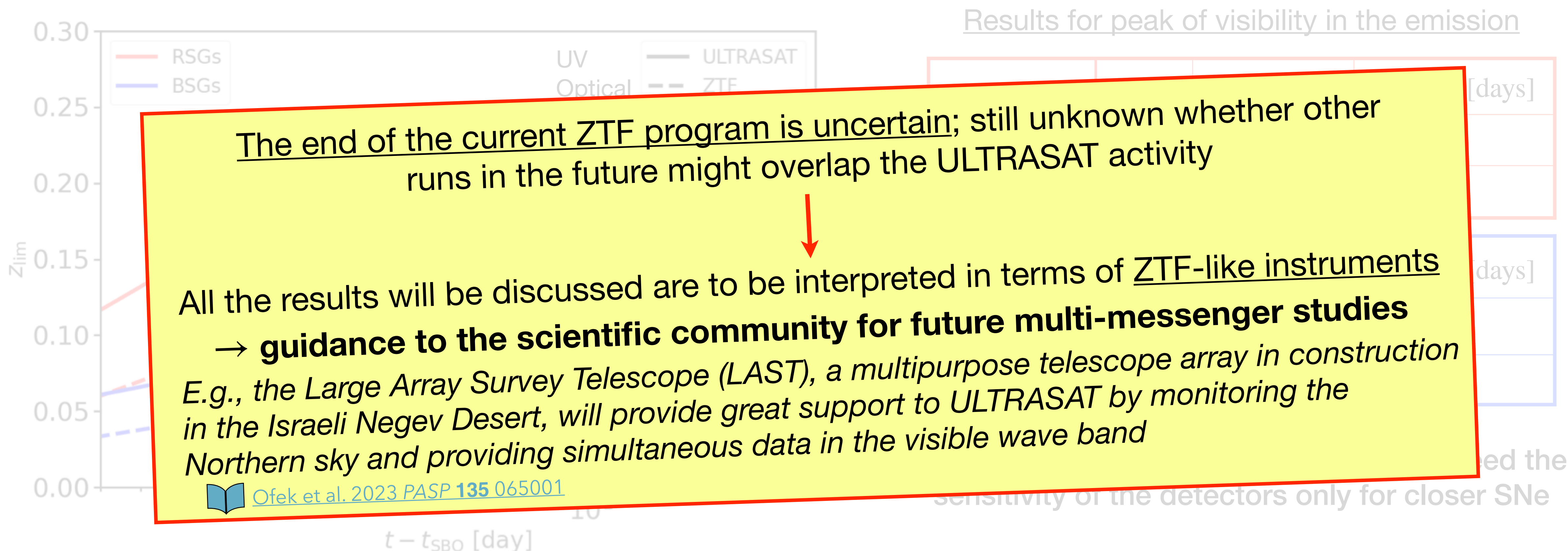
Previous and later emissions can still exceed the sensitivity of the detectors only for closer SNe

 A. Zegarelli, D. Guetta, S. Celli, S. Gagliardini, I. Di Palma, and I. Bartos, A&A, 690, A187 (2024)

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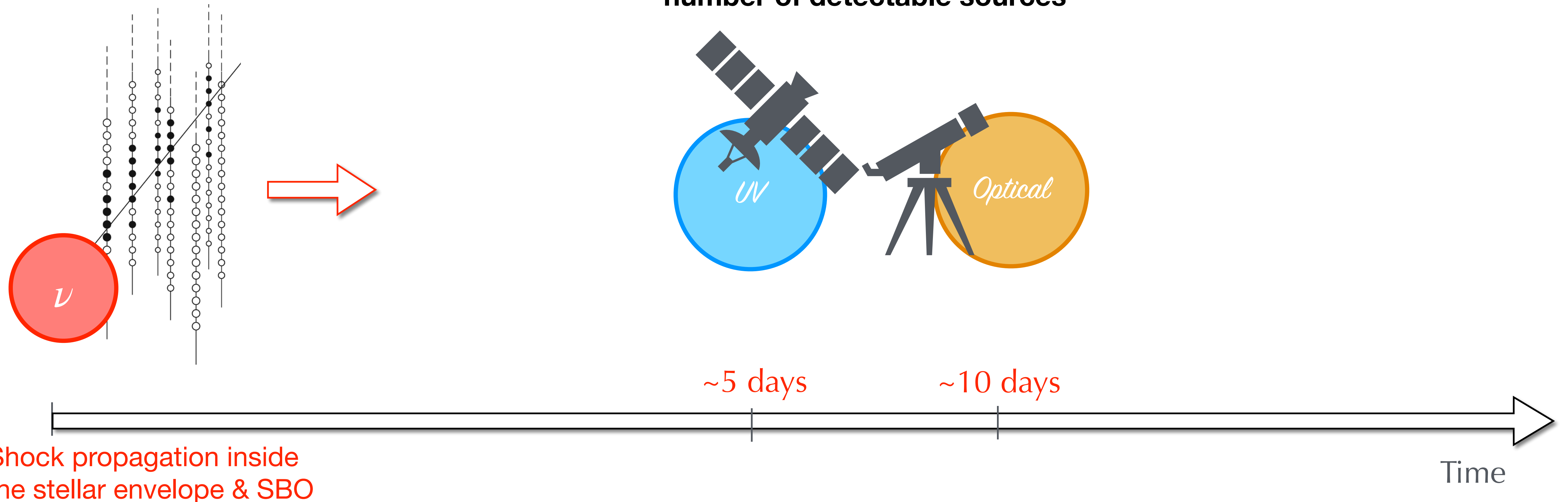


 A. Zegarelli, D. Guetta, S. Celli, S. Gagliardini, I. Di Palma, and I. Bartos, A&A, 690, A187 (2024)

High-energy ν - UV - optical follow-ups

1. **Neutrino alert** from Cherenkov-based high-energy neutrino telescopes (e.g., IceCube, KM3NeT)

2. ULTRASAT(ZTF-like telescopes) could point at the suggested direction in the sky within **~5(10) days** to search for possible EM counterparts **maximising the reachable sky volume and hence the number of detectable sources**



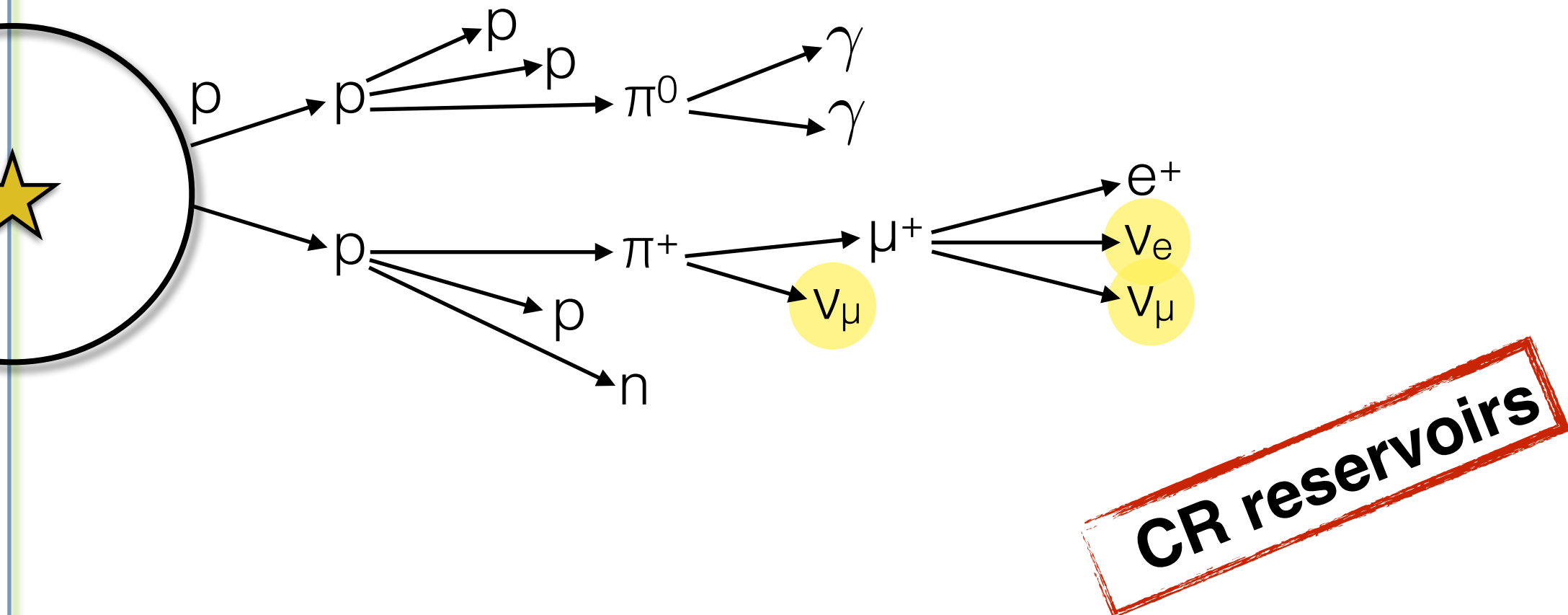
📖 A. Zegarelli, D. Guetta, S. Celli, S. Gagliardini, I. Di Palma, and I. Bartos, A&A, 690, A187 (2024)

Choked jets in the MM context

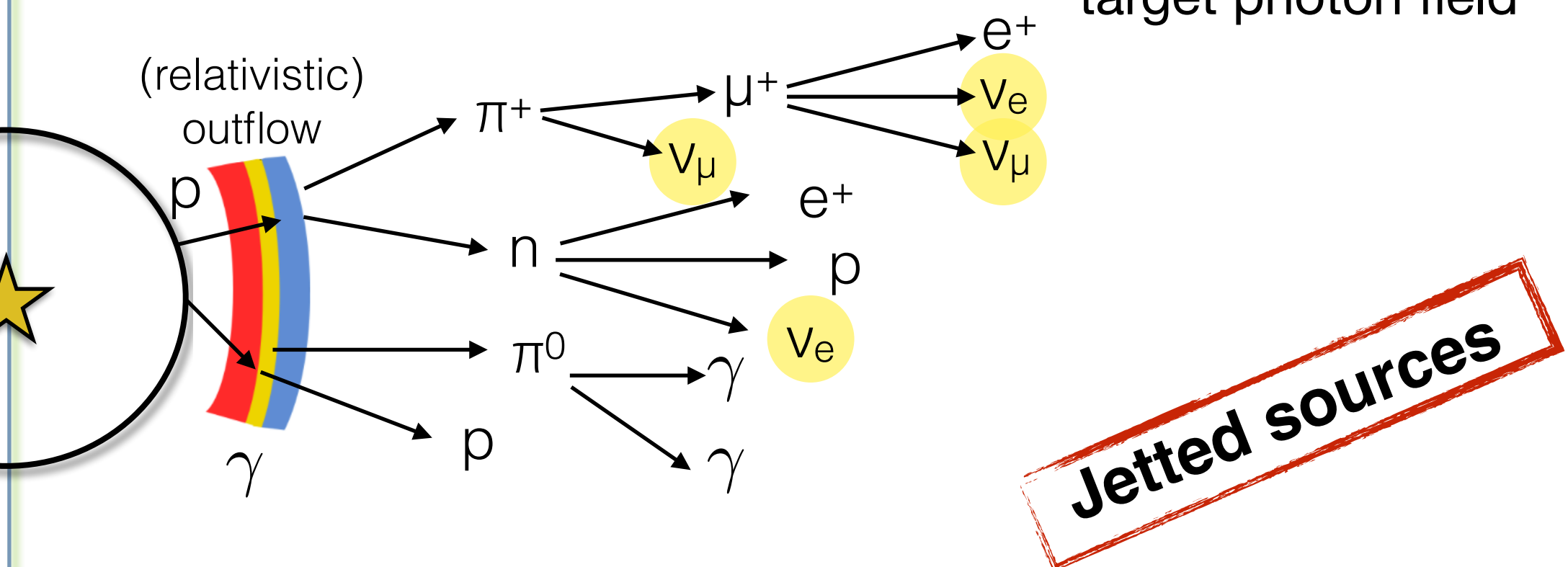
Why are they interesting for neutrino astronomy?

Neutrino production in hadronic sources

- **hadro-nuclear collisions** $p + p \longrightarrow N\pi + X$
target gas

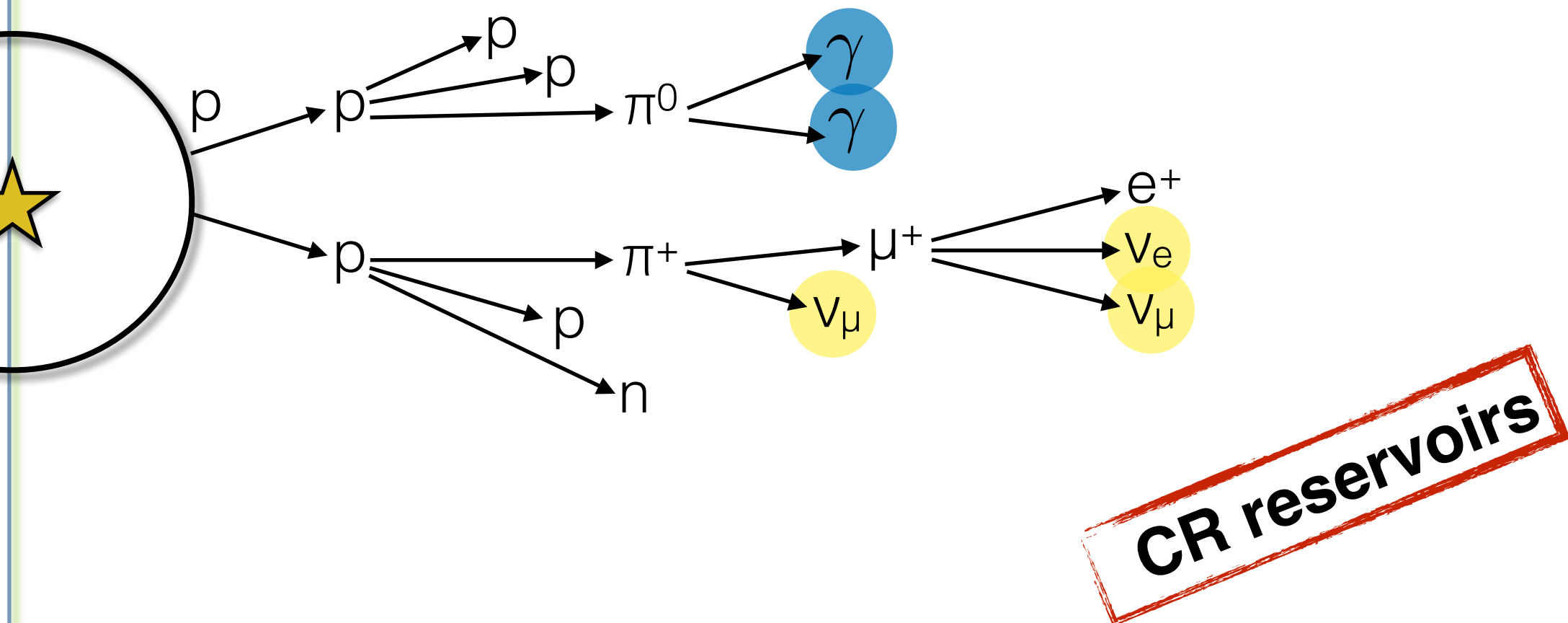


- **photo-hadronic collisions** $p + \gamma \longrightarrow N\pi + X$
target photon field



Neutrino production in hadronic sources

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target gas

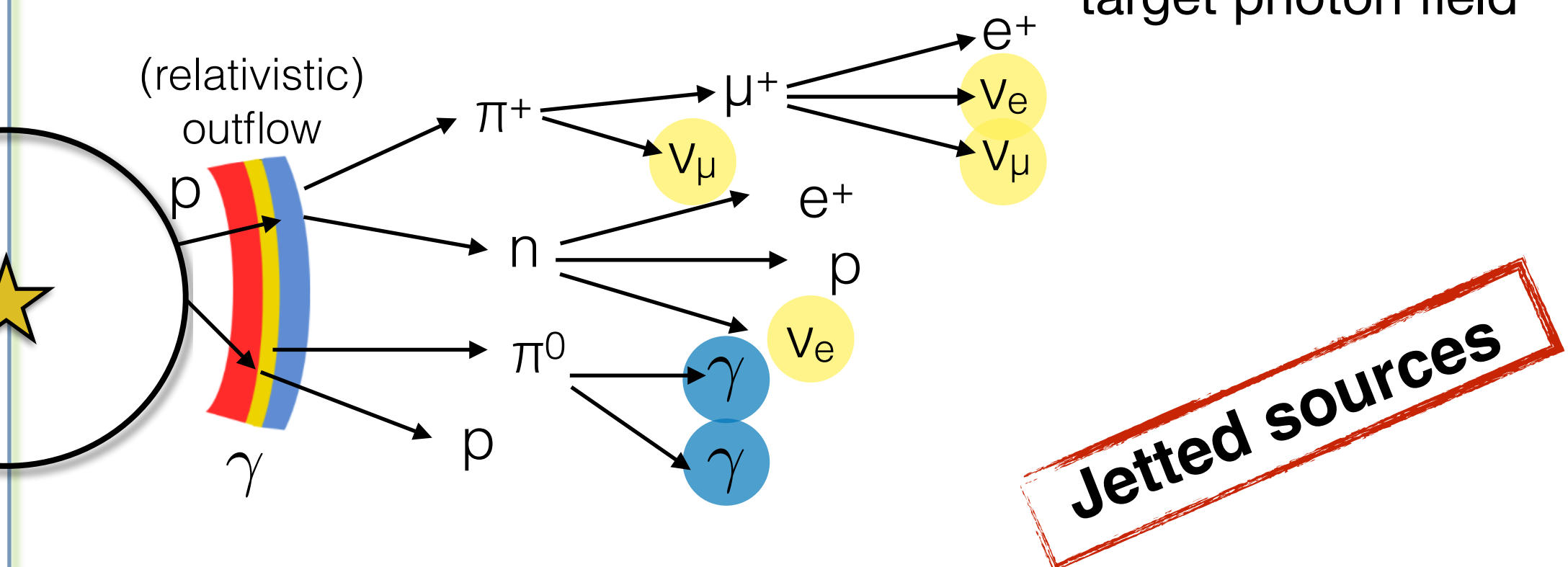


If the sources are transparent to gamma rays, the emitted γ-rays:

- escape the source
- Interact with EBL/CMB photons, initiating electromagnetic (EM) cascades
($\gamma_{\text{VHE}} + \gamma_{\text{EBL/CMB}} \rightarrow e^+e^- \rightarrow \text{EM cascades}$)
- contribute to the isotropic γ-ray background (IGRB) measured by Fermi-LAT

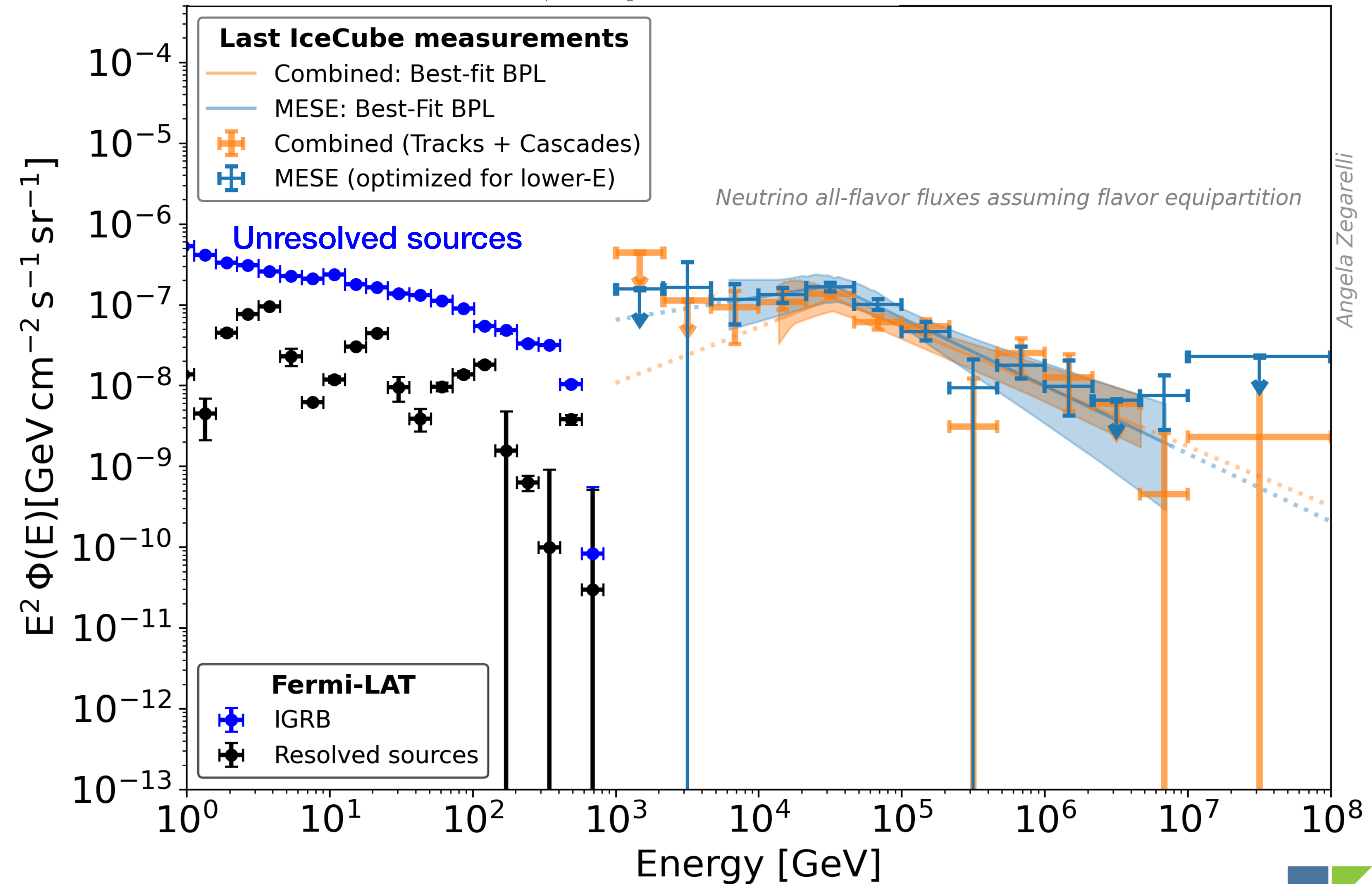
$$E_\nu^2 \Phi_\nu \sim E_\gamma^2 \Phi_\gamma$$

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IGRB vs High-Energy Neutrinos

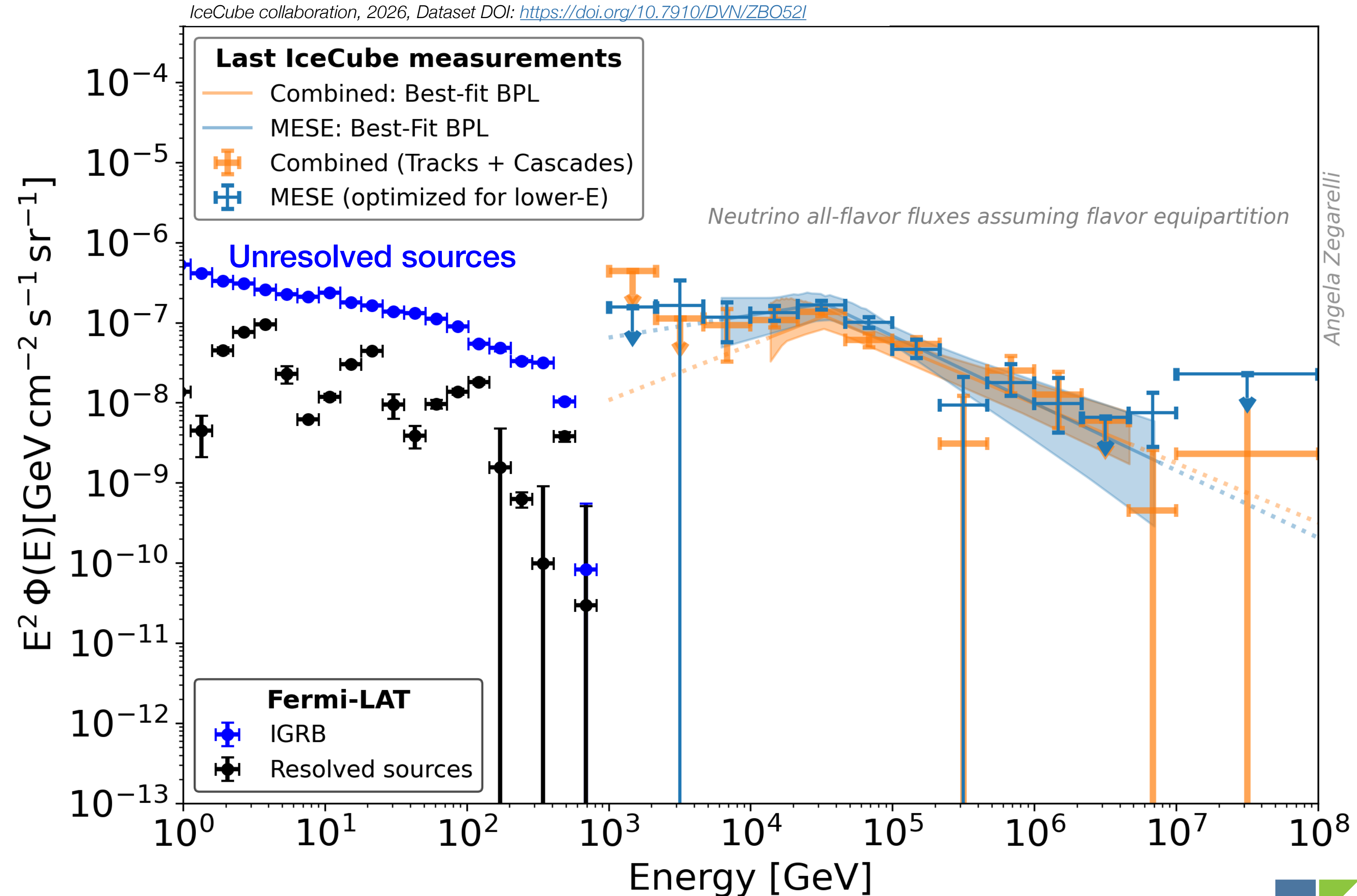
IceCube collaboration, 2026, Dataset DOI: <https://doi.org/10.7910/DVN/ZBO52/>



IGRB vs High-Energy Neutrinos

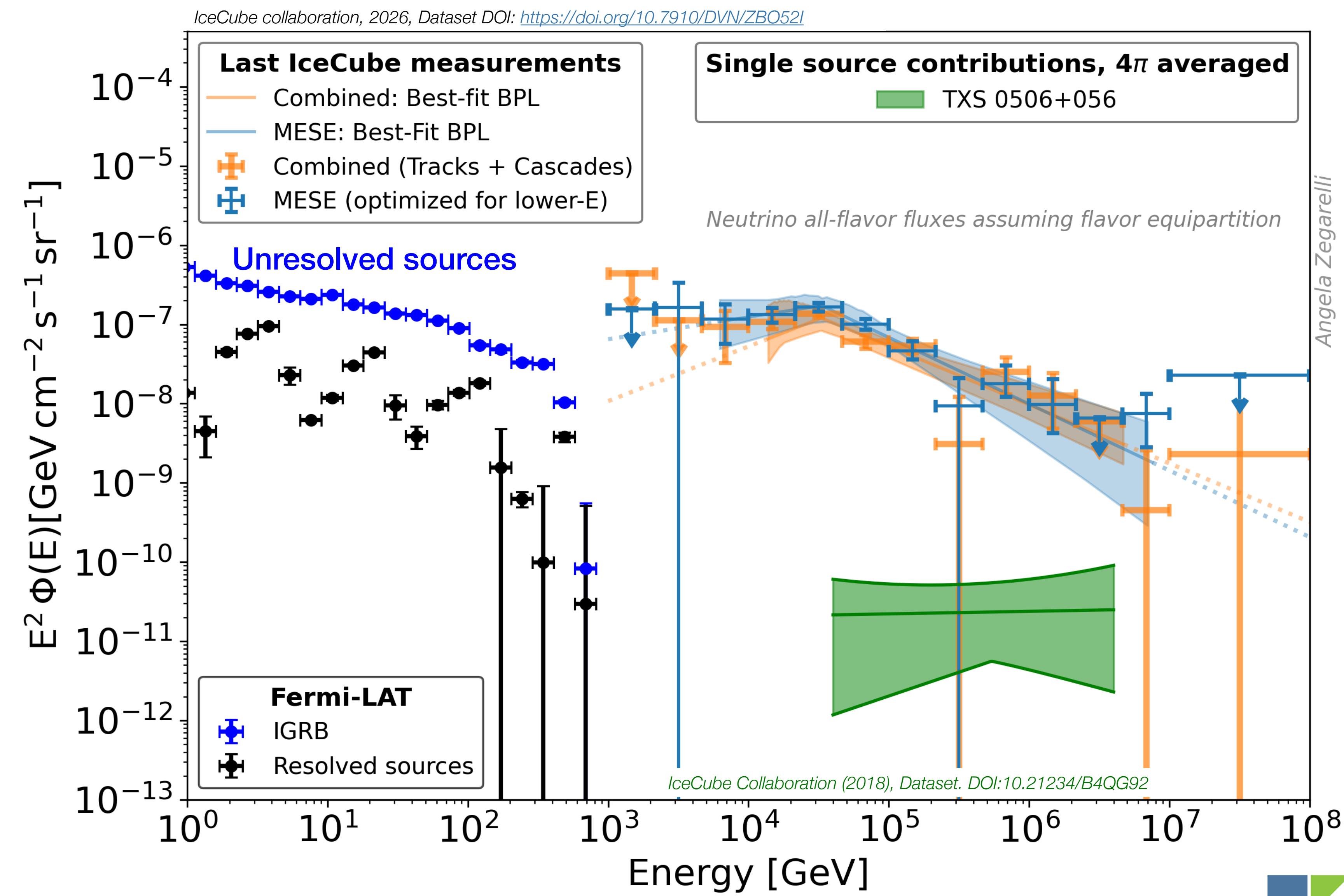
- The diffuse γ -ray background measured by Fermi-LAT is already largely explained by known source populations (e.g., *blazars alone account for at least 86% of the IGRB at energies > 50 GeV*)

 Ackermann et al. (2015)



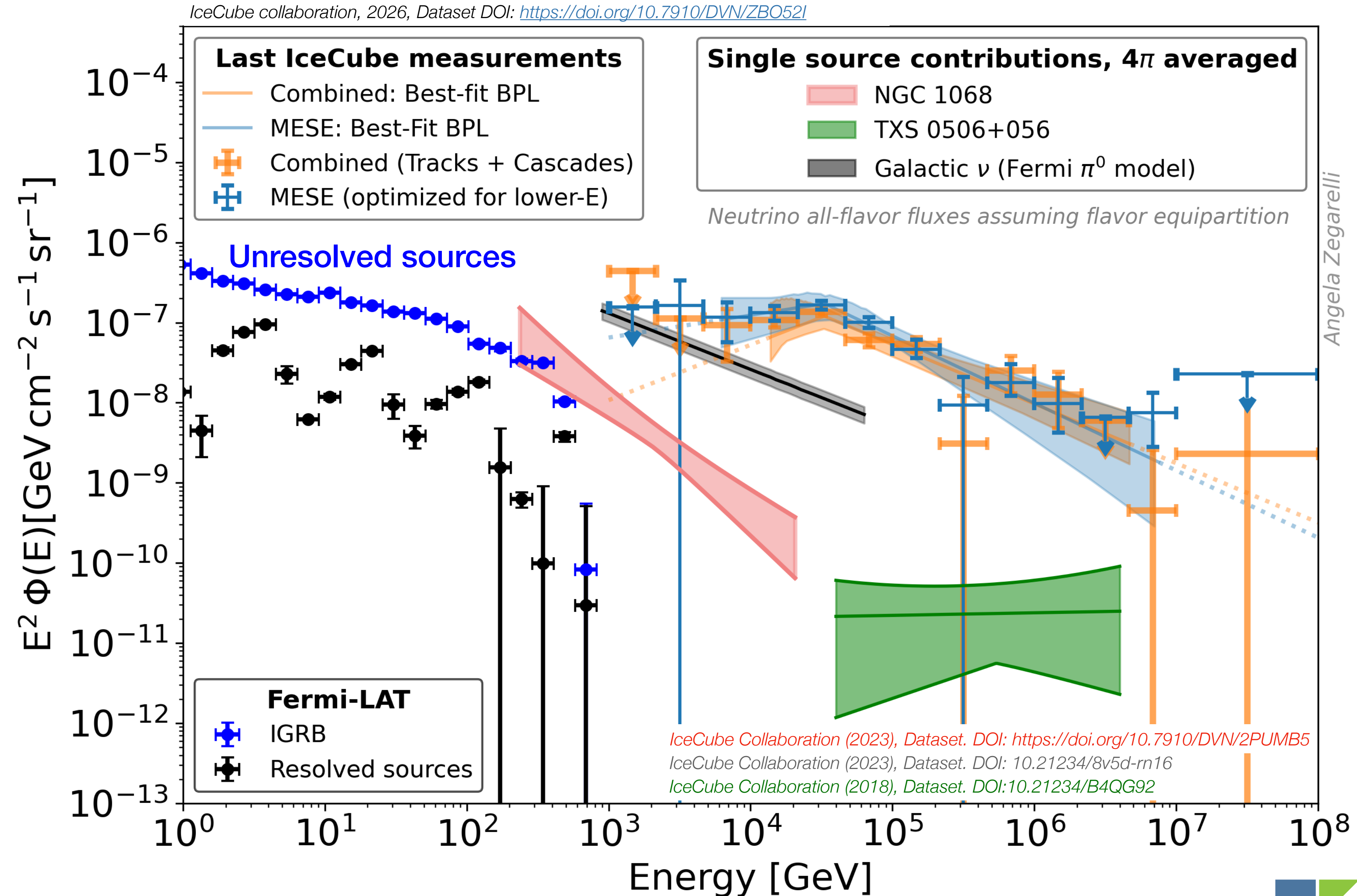
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- TXS 0506+056 is currently the only blazar associated (at $\sim 3.5\sigma$) to high-energy neutrinos (contribution to only a small contribution to the ν flux)
- Including the neutrino flux from the Milky Way and from the steady source NGC 1068, most of the diffuse ν flux remains unexplained



IGRB vs High-Energy Neutrinos

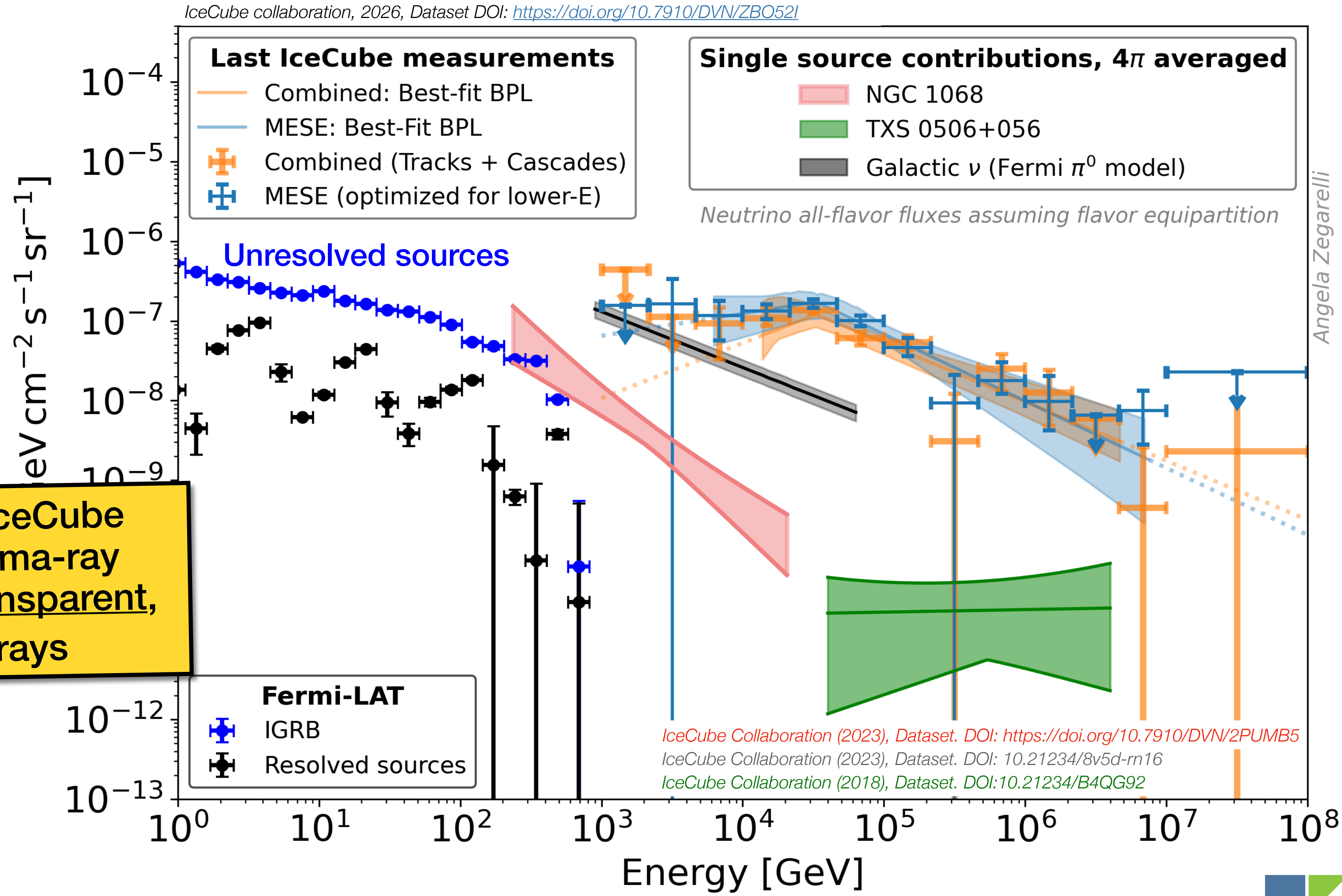
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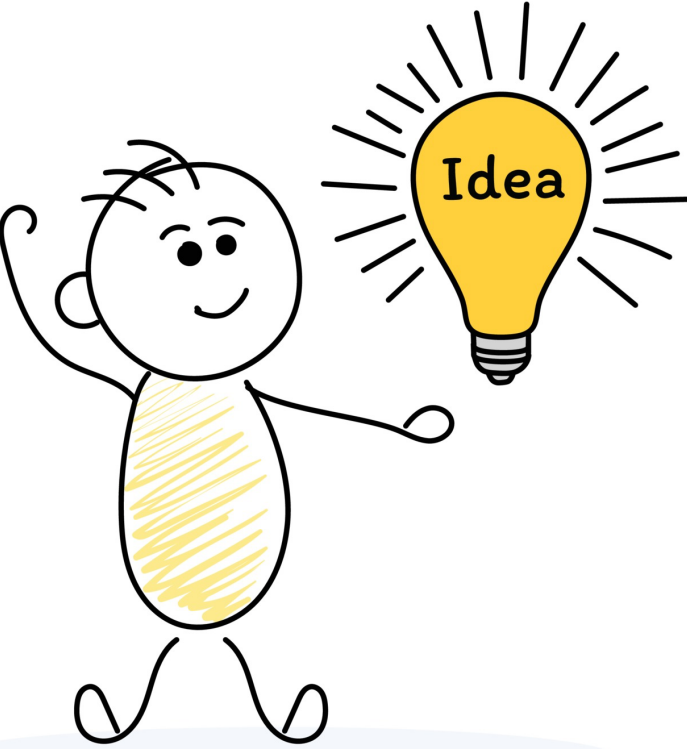
- TXS 0506+056 is currently the only blazar associated (at $\gtrsim 3\sigma$) to a high-energy neutrino

If the same sources produce IceCube neutrinos and the diffuse gamma-ray background, and they are all transparent, they would overproduce γ rays

steady source NGC 1068, most of the diffuse ν flux remains unexplained



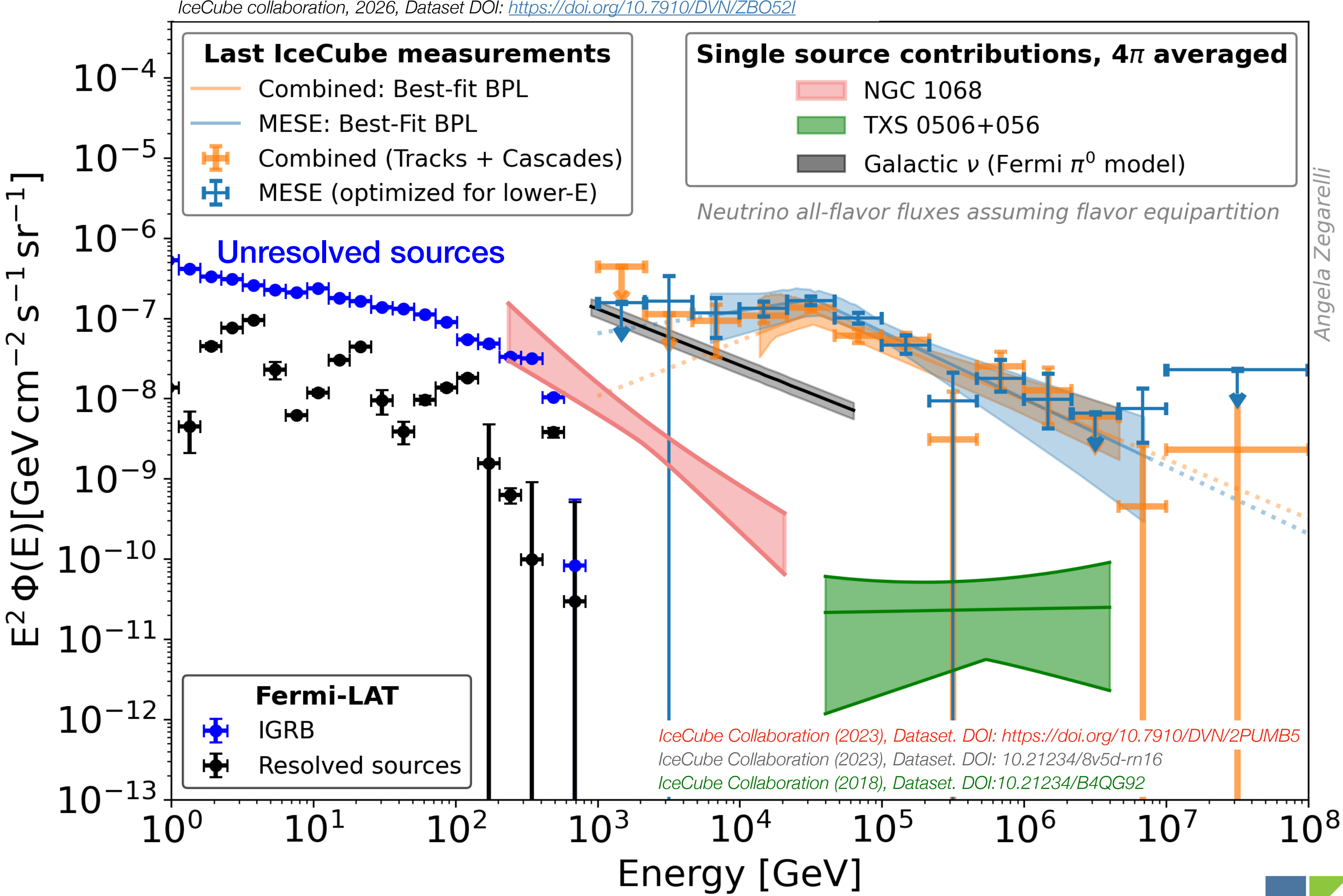
Choked jets as possible ν sources



Hidden sources to γ rays

Bartos et al. 2012
Murase & Ioka 2013
He et al. 2018
Senno et al. 2018
Emaili & Murase 2018
Fasano et al. 2021
Chang et al. 2022

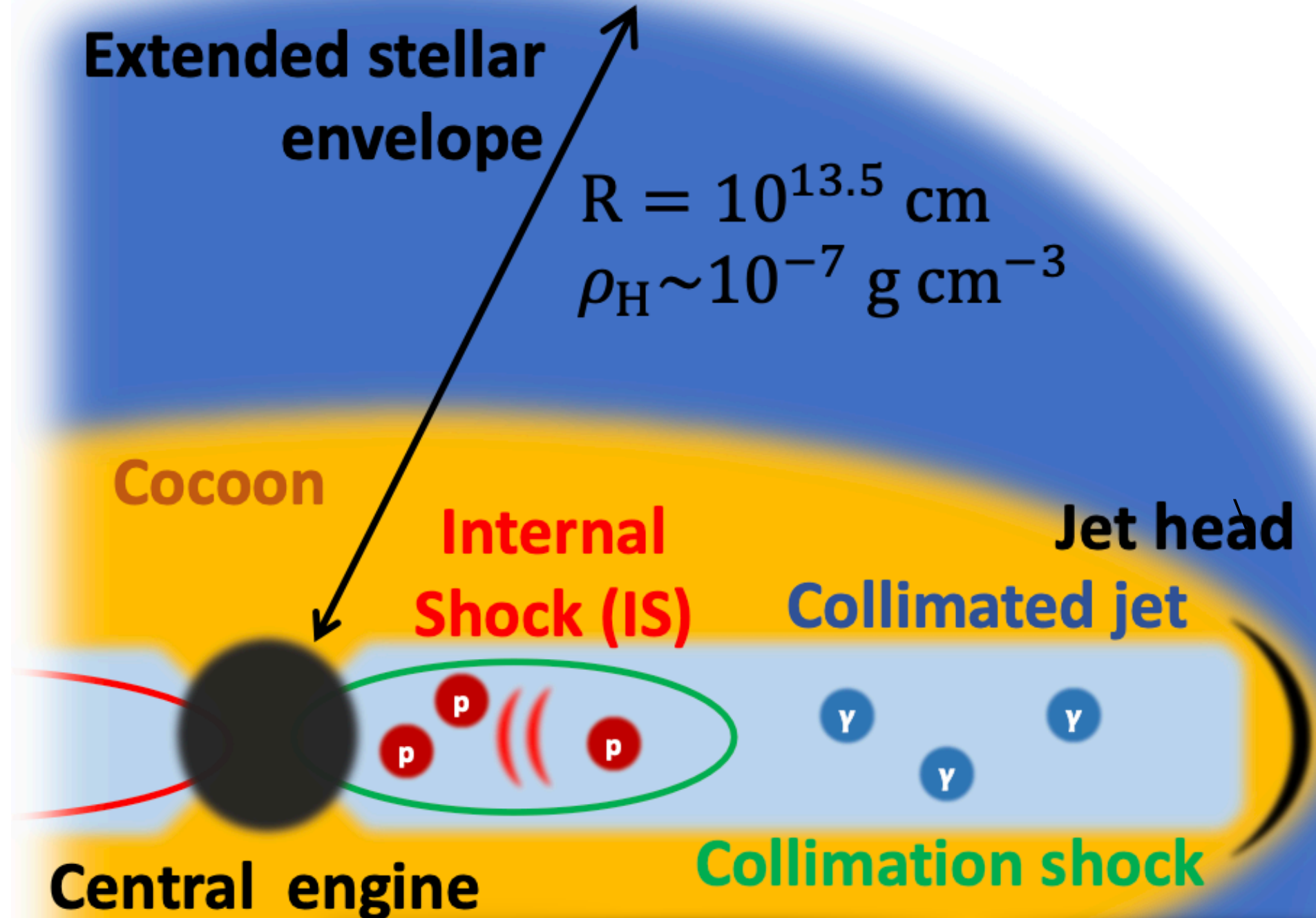
Choked jets / hidden sources avoid the tension between neutrino and Fermi data (we cannot observe corresponding γ rays)



Do choked jets produce neutrinos?

 M. Fasano, S. Celli, D. Guetta, A. Capone, A. Zegarelli, I. Di Palma, JCAP09 (2021) 044

Neutrinos from choked jets embedded in RSGs



- RSG progenitor, particle acceleration at internal shocks in the pre-collimated jet
- Based on analytic treatments of the jet–cocoon interaction Murase et al. (2013)
- $p\gamma$ interactions simulated inside a choked GRB jet through a detailed Monte Carlo code

$$p + \gamma \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases} \rightarrow \begin{cases} \pi^0 \rightarrow \gamma + \gamma \\ n \rightarrow p + e^- + \bar{\nu}_e \\ \pi^+ \rightarrow \mu^+ + \nu_\mu \\ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \end{cases}$$

CRs mainly interact with photons escaping back from the collimated jet

Accelerated protons:

$$\frac{dN_p}{dE_p} \propto E_p^{-2}$$

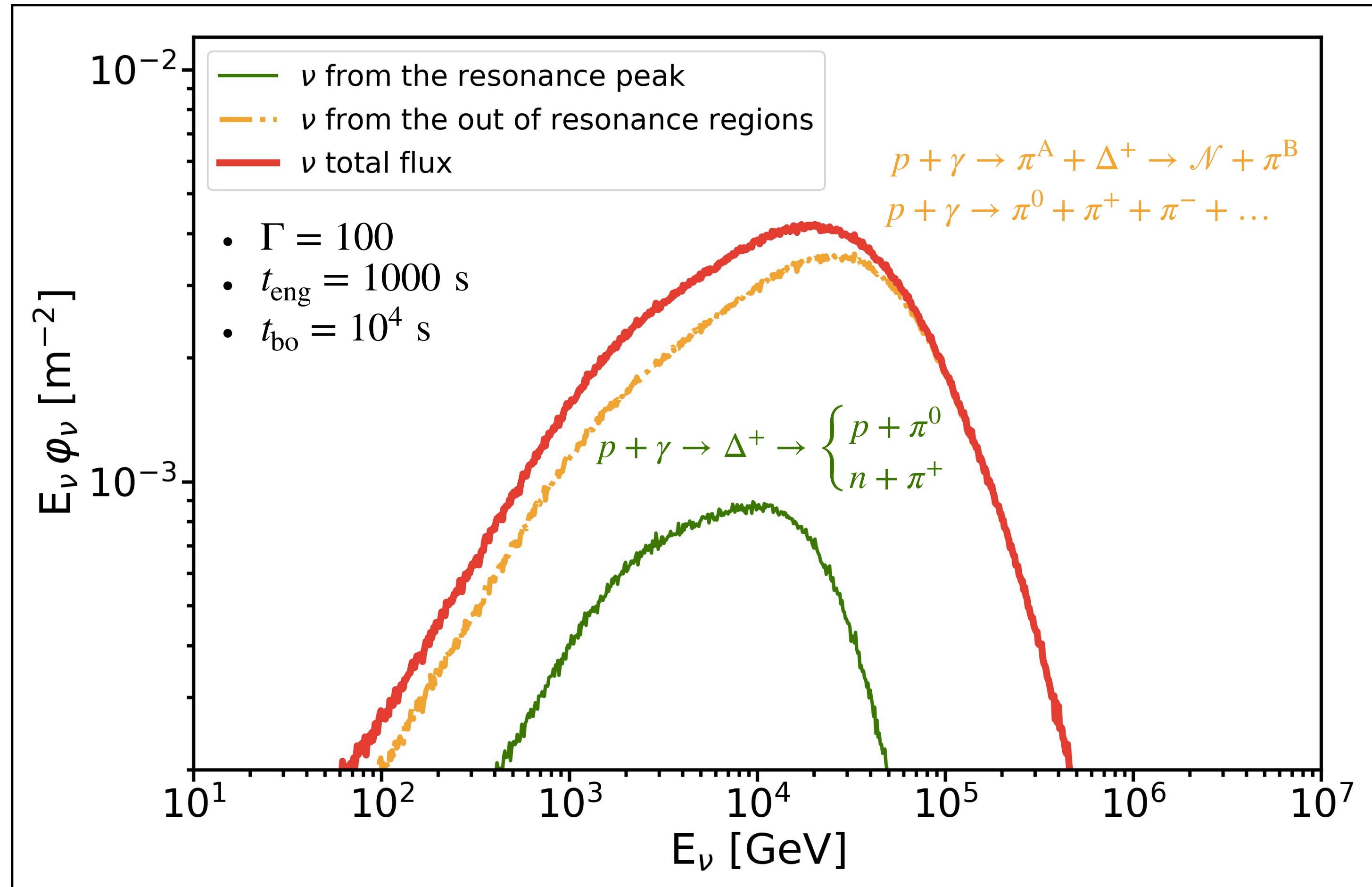
Target photons:

$$\frac{dN_\gamma}{dE_\gamma} = \frac{8}{19(kT_\gamma)^3} \frac{E_\gamma^2}{e^{\frac{E_\gamma}{kT_\gamma}} - 1}$$

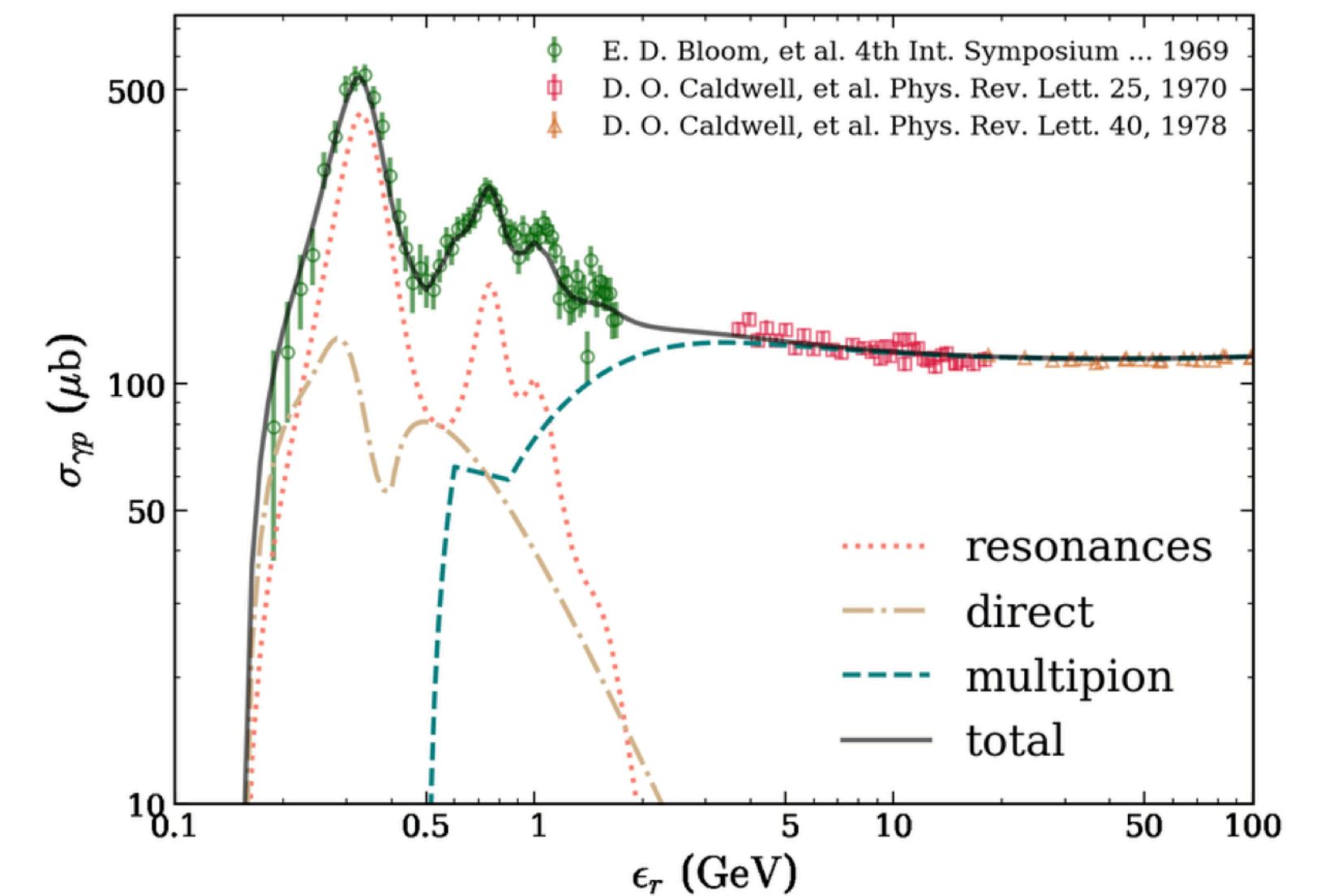
M. Fasano, S. Celli, D. Guetta, A. Capone, A. Zegarelli, I. Di Palma, JCAP09 (2021) 044

Neutrinos from choked jets embedded in RSGs

Neutrino flux observed at Earth from an individual source



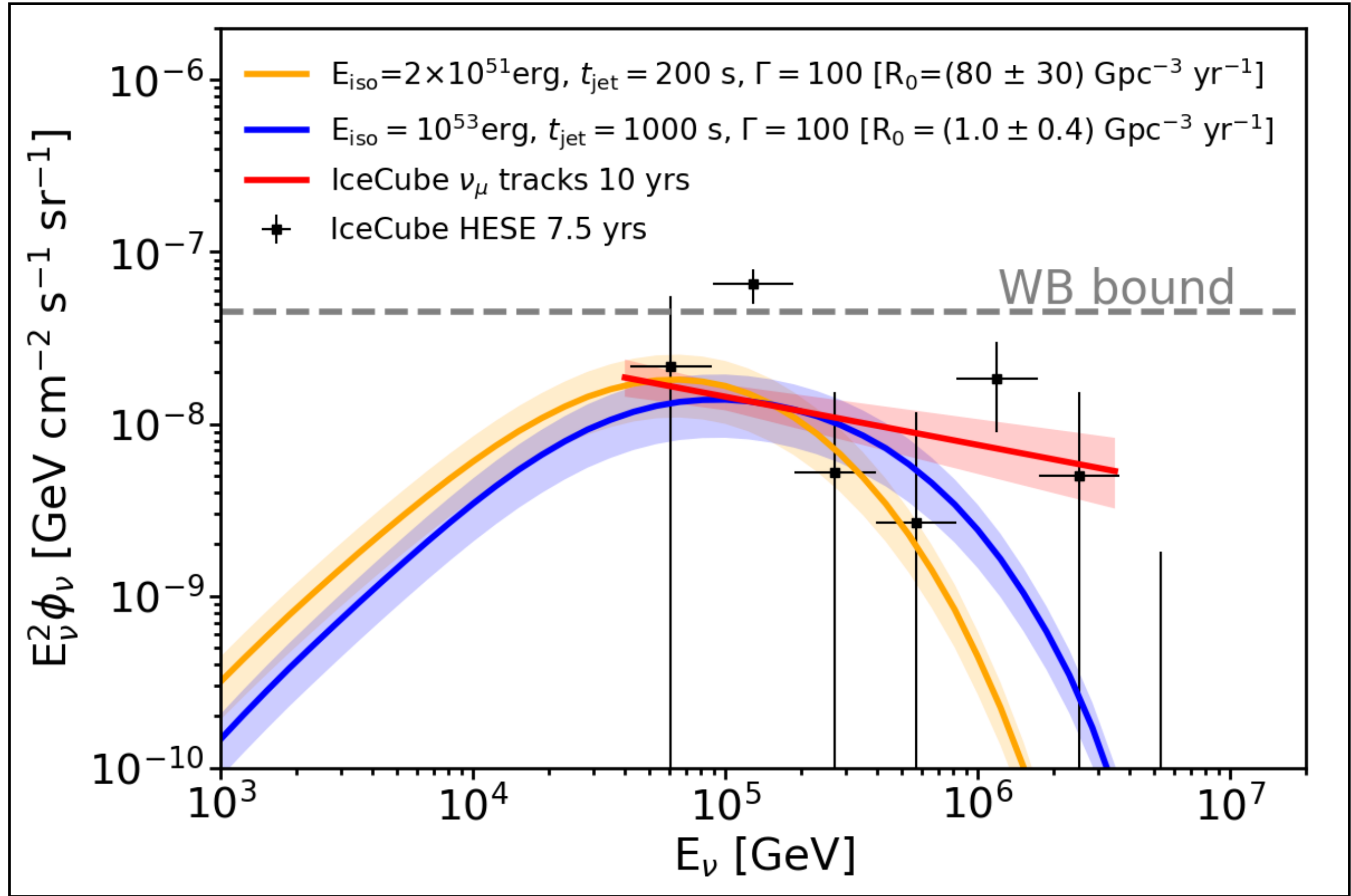
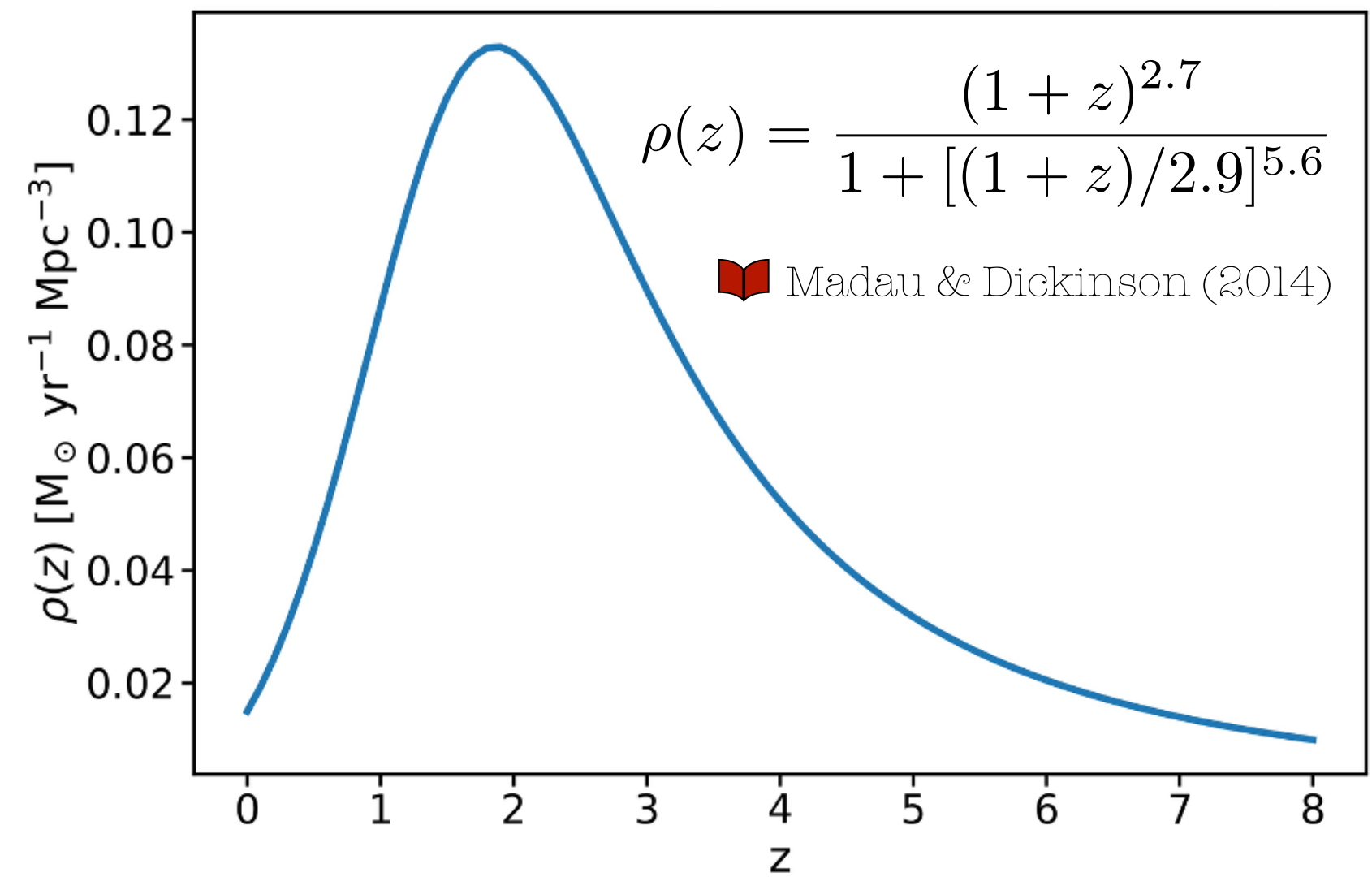
Both Δ^+ resonance, as well as the out-of-resonance region appears particularly crucial for neutrino production



M. Fasano, S. Celli, D. Guetta, A. Capone, A. Zegarelli, I. Di Palma, JCAP09 (2021) 044

Can choked jets reproduce diffuse ν observations?

$$E_{\nu_\mu}^{\text{obs}} \phi_{\nu_\mu}(E_{\nu_\mu}^{\text{obs}}) = \frac{c}{4\pi H_0} \int_0^8 E_{\nu_\mu} \frac{dN_{\nu_\mu}}{dE_{\nu_\mu}} ((1+z)E_{\nu_\mu}^{\text{obs}}) \frac{\frac{\Omega}{4\pi} R_0 \rho(z) dz}{(1+z) \sqrt{\Omega_\Lambda + \Omega_M (1+z)^3}}$$



Local rate of choked jets from RSGs as to reproduce 100% of IceCube observations

📖 M. Fasano, S. Celli, D. Guetta, A. Capone, A. Zegarelli, I. Di Palma, JCAP09 (2021) 044

What determines whether the jet actually chokes and accelerates particles efficiently? Need Radiation-Magnetohydrodynamics (RMHD) simulations

📖 M.Pais, A. Zegarelli, E. Peretti, S. Celli, in prep. (2026)

Breakout and choking conditions

Preliminary

📖 M.Pais, A. Zegarelli, E. Peretti, S. Celli, in prep. (2026)

1D hydrodynamic jet's equation of motion from 📖 Hamidani & Ioka (2021)

→ By integrating it and repeating this for different jet parameters:

Time for the jet to choke

(jet launching at $t = 0$)

When the jet tail catches the jet head

$$t_{\text{ch}} [\text{s}] \simeq 10 \left(\frac{t_{\text{eng}}}{10 \text{ s}} \right) + \begin{cases} 39 \left(\frac{t_{\text{eng}}}{10 \text{ s}} \right)^{1.27} \left(\frac{L_{\text{jet}}}{10^{51} \text{ erg s}^{-1}} \right)^{0.34} \left(\frac{\theta_{\text{jet}}}{5^\circ} \right)^{-1.41} & \text{(BSG)} \\ 60.3 \left(\frac{t_{\text{eng}}}{10 \text{ s}} \right)^{0.875} \left(\frac{L_{\text{jet}}}{10^{51} \text{ erg s}^{-1}} \right)^{0.205} \left(\frac{\theta_{\text{jet}}}{5^\circ} \right)^{-0.874} & \text{(RSG)} \end{cases}$$

Time of shock breakout

When the jet tail reaches the stellar radius

$$t_{\text{bo}} [\text{s}] \simeq \begin{cases} 116 \left(\frac{R_*}{50 R_\odot} \right) + 18 \left(\frac{L_{\text{jet}}}{10^{51} \text{ erg s}^{-1}} \right)^{-0.24} \left(\frac{\theta_{\text{jet}}}{5^\circ} \right)^{0.94} & \text{(BSG)} \\ 1160 \left(\frac{R_*}{500 R_\odot} \right) + 195 \left(\frac{L_{\text{jet}}}{10^{51} \text{ erg s}^{-1}} \right)^{-0.227} \left(\frac{\theta_{\text{jet}}}{5^\circ} \right)^{0.925} & \text{(RSG)} \end{cases}$$

Breakout and choking conditions

Preliminary

📖 M.Pais, A. Zegarelli, E. Peretti, S. Celli, *in prep.* (2026)

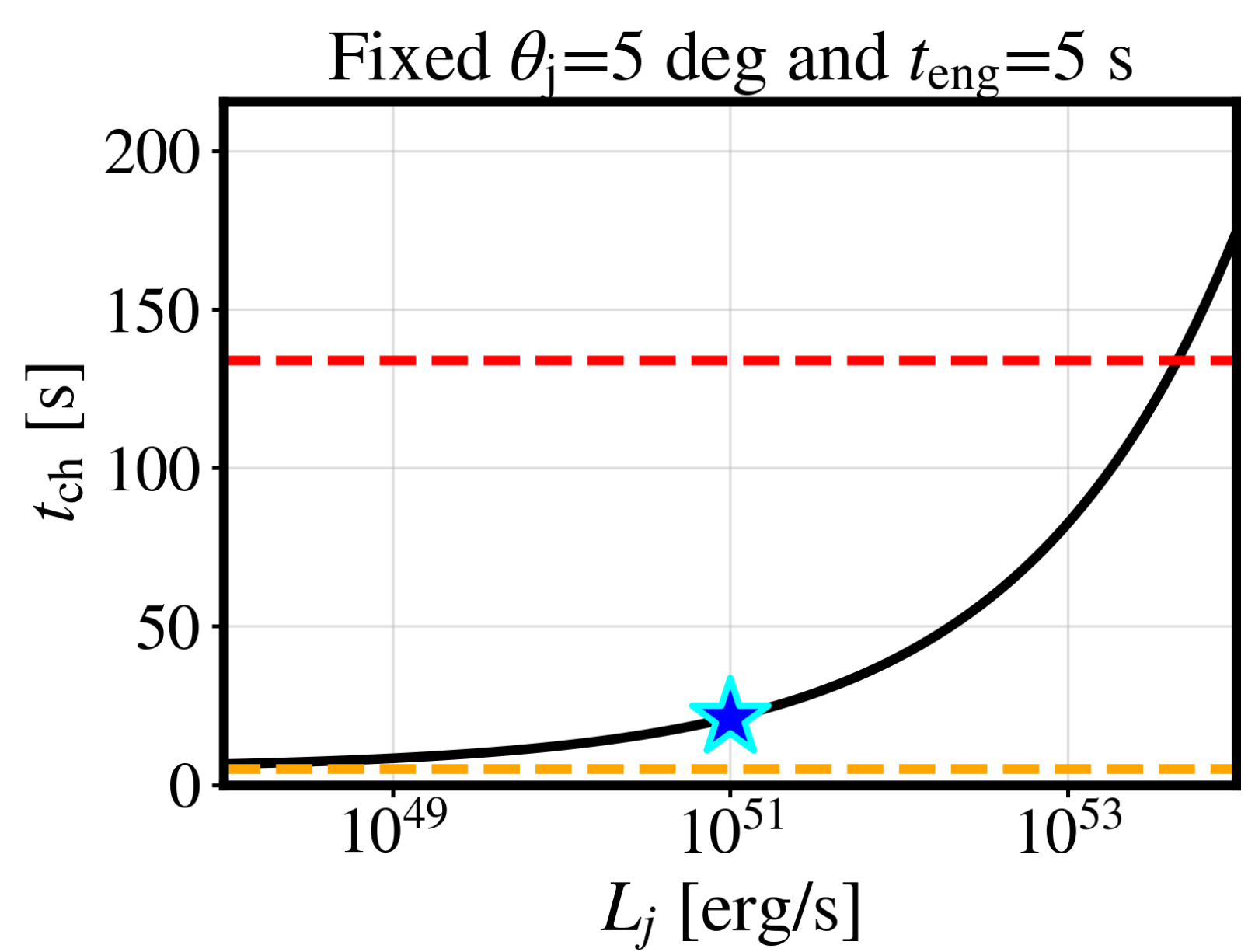
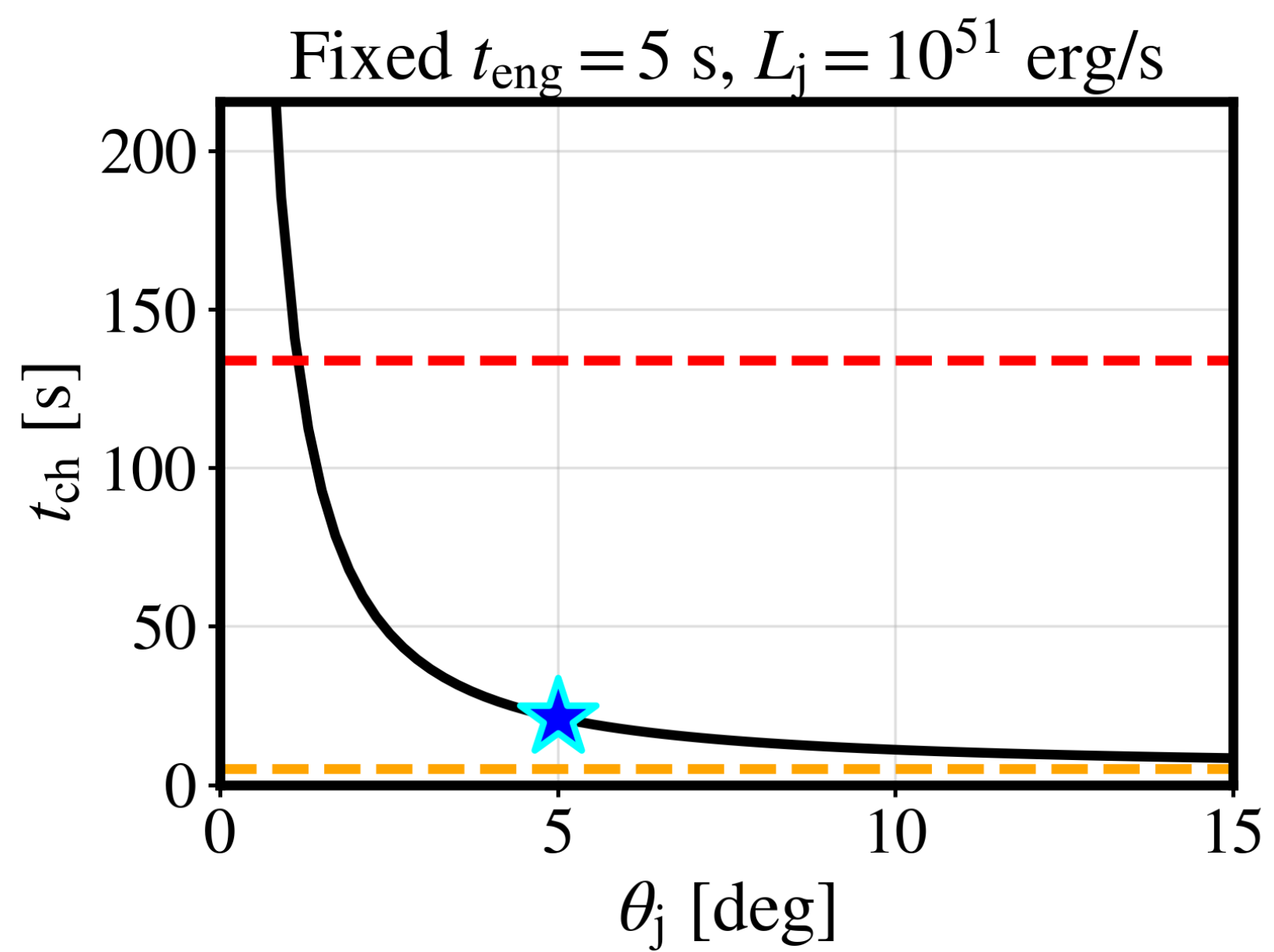
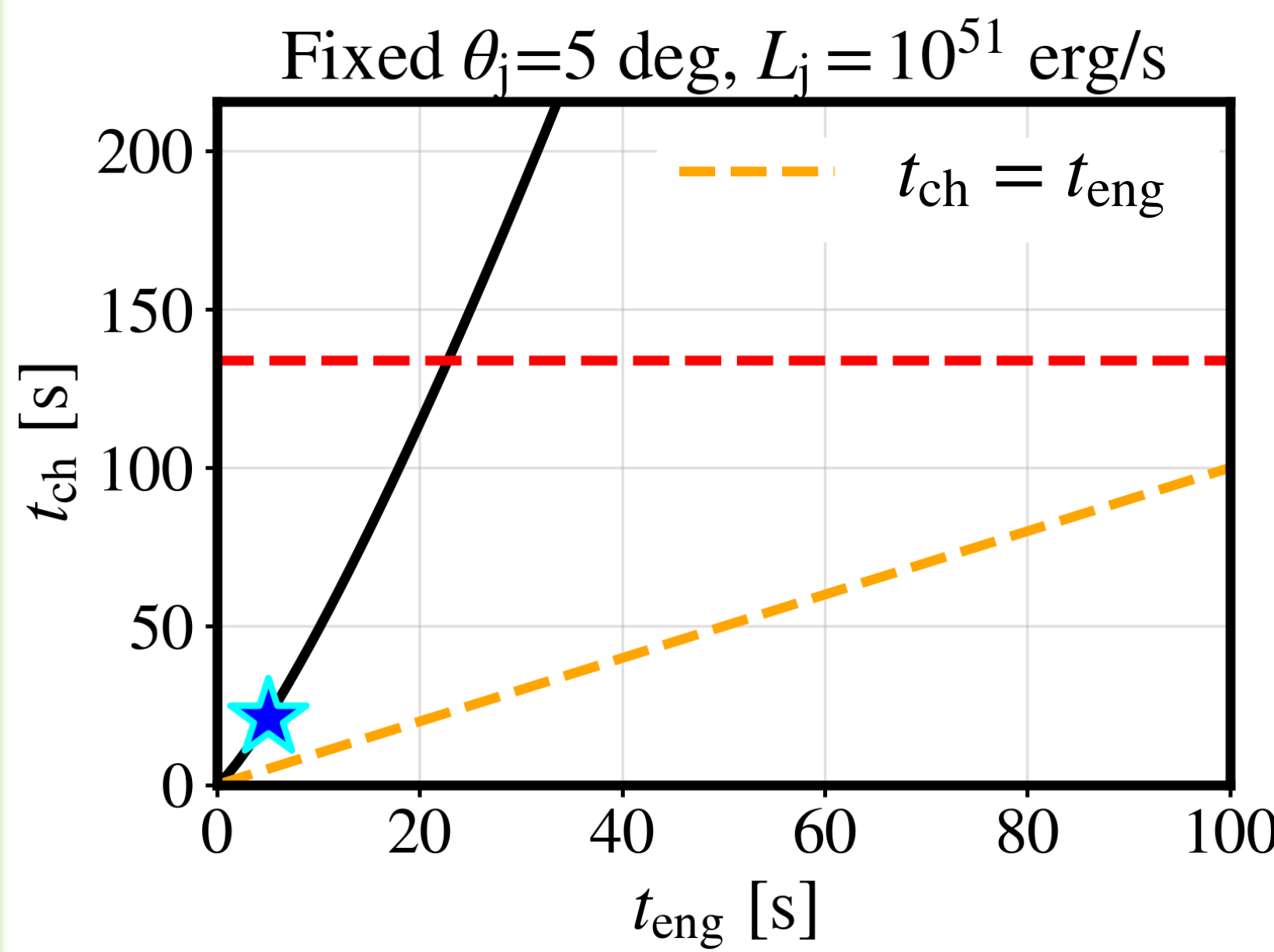


$R_* = 50 R_\odot$
 $L_j = 10^{51} \text{ erg/s}$
 $\theta_j = 5^\circ$
 $t_{\text{eng}} = 5 \text{ s}$

Choked!

$$t_{\text{ch}} < t_{\text{bo}}$$

★ $t_{\text{ch}}(t_{\text{eng}} = 5) = 21 \text{ s}$
 --- $t_{\text{bo}} = 134 \text{ s}$



Breakout and choking conditions

Preliminary

M.Pais, A. Zegarelli, E. Peretti, S. Celli, *in prep.* (2026)

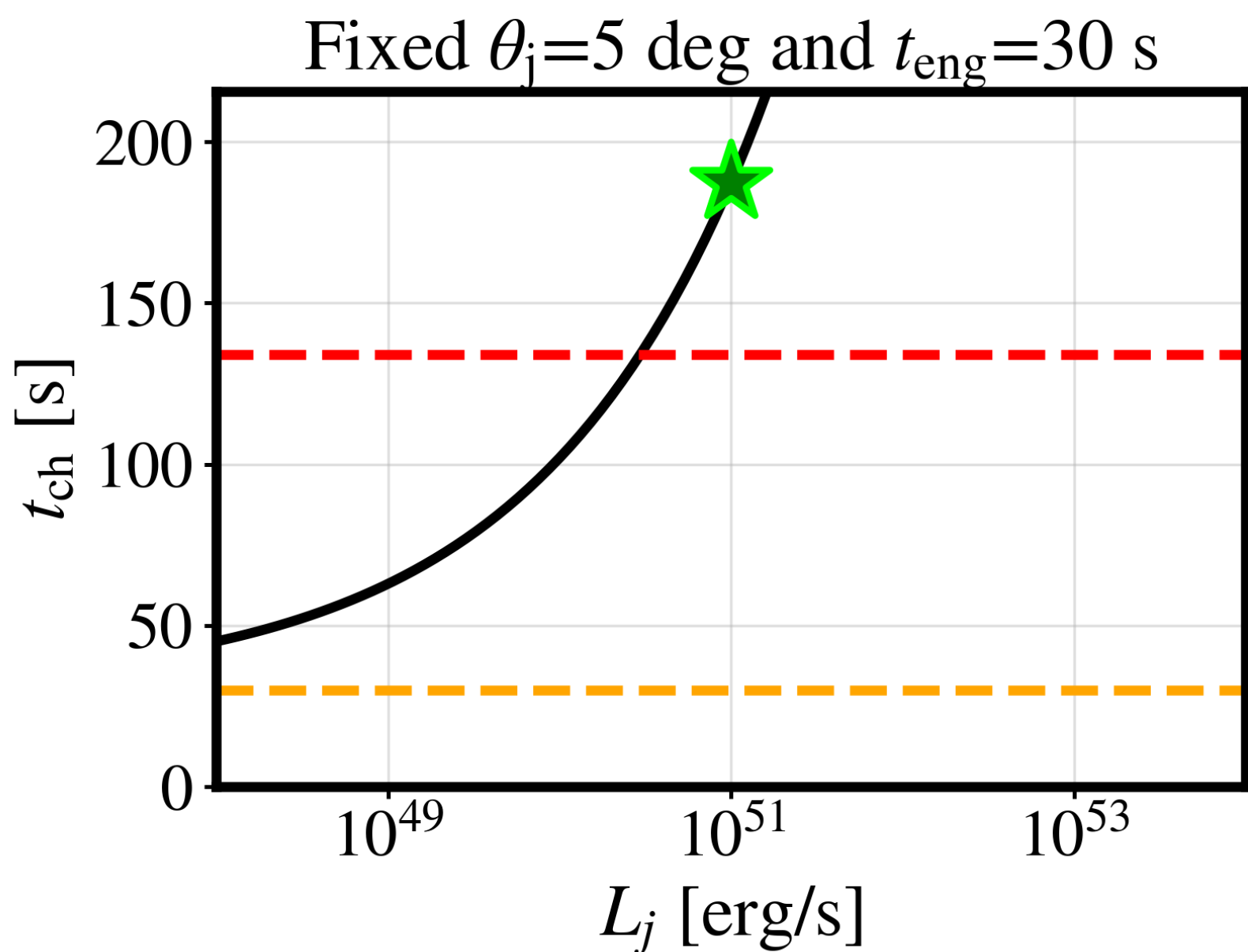
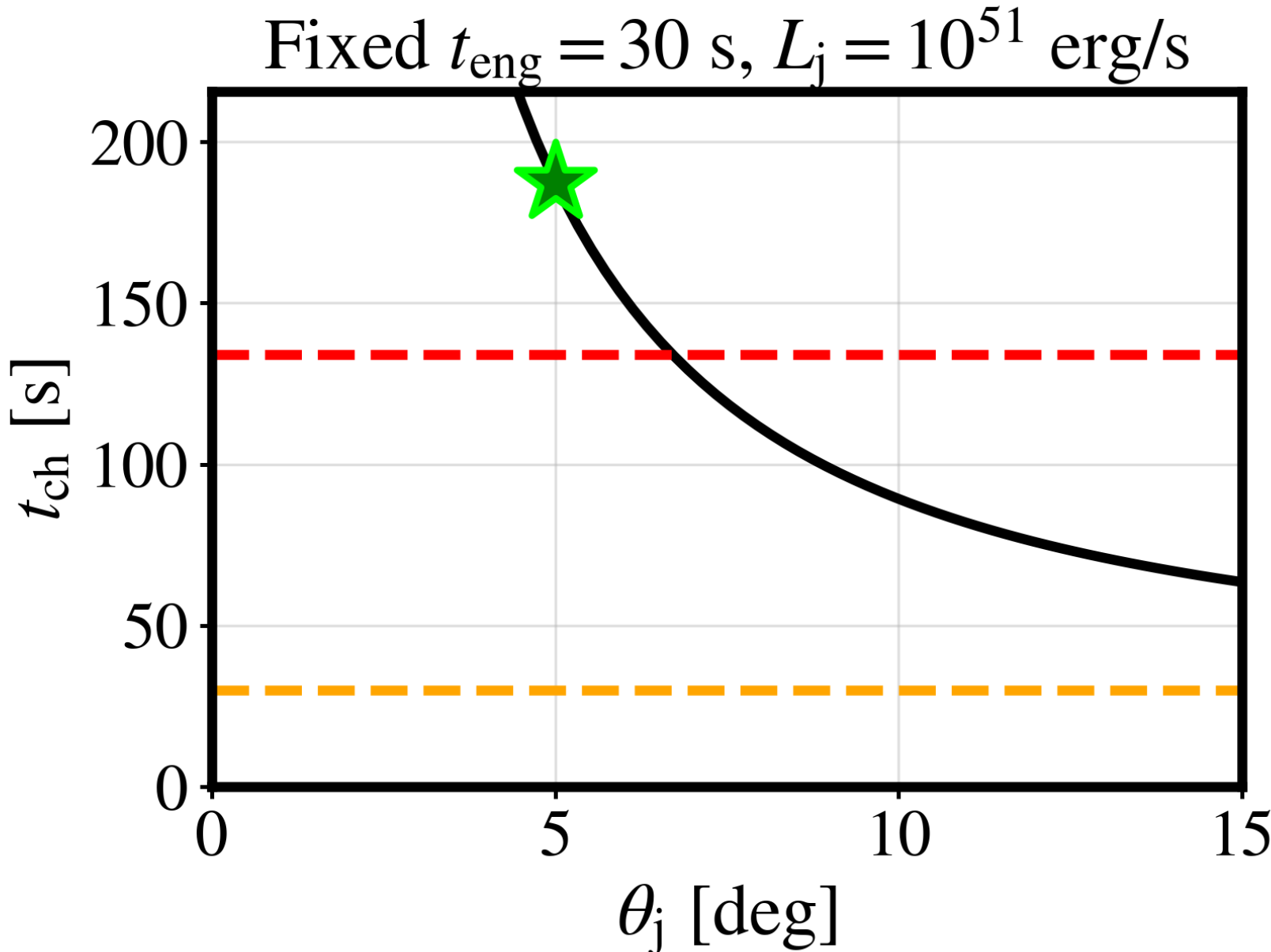
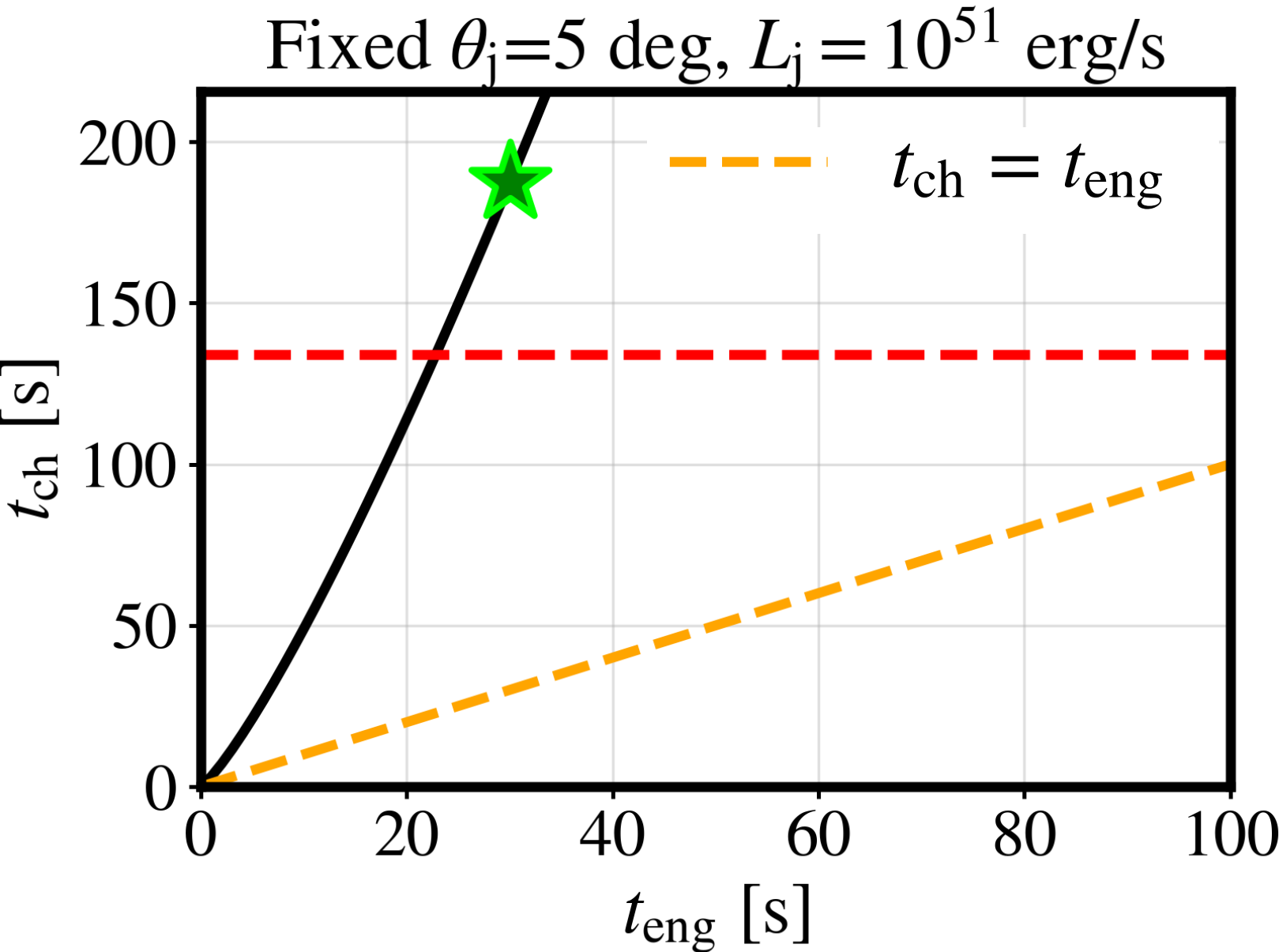


$R_* = 50 R_\odot$
 $L_j = 10^{51} \text{ erg/s}$
 $\theta_j = 5^\circ$
 $t_{\text{eng}} = 30 \text{ s}$

Successful

$t_{\text{ch}} > t_{\text{bo}}$

★ $t_{\text{ch}}(t_{\text{eng}} = 30) = 187 \text{ s}$
--- $t_{\text{bo}} = 134 \text{ s}$



Breakout and choking conditions

Preliminary

📖 M.Pais, A. Zegarelli, E. Peretti, S. Celli, *in prep.* (2026)



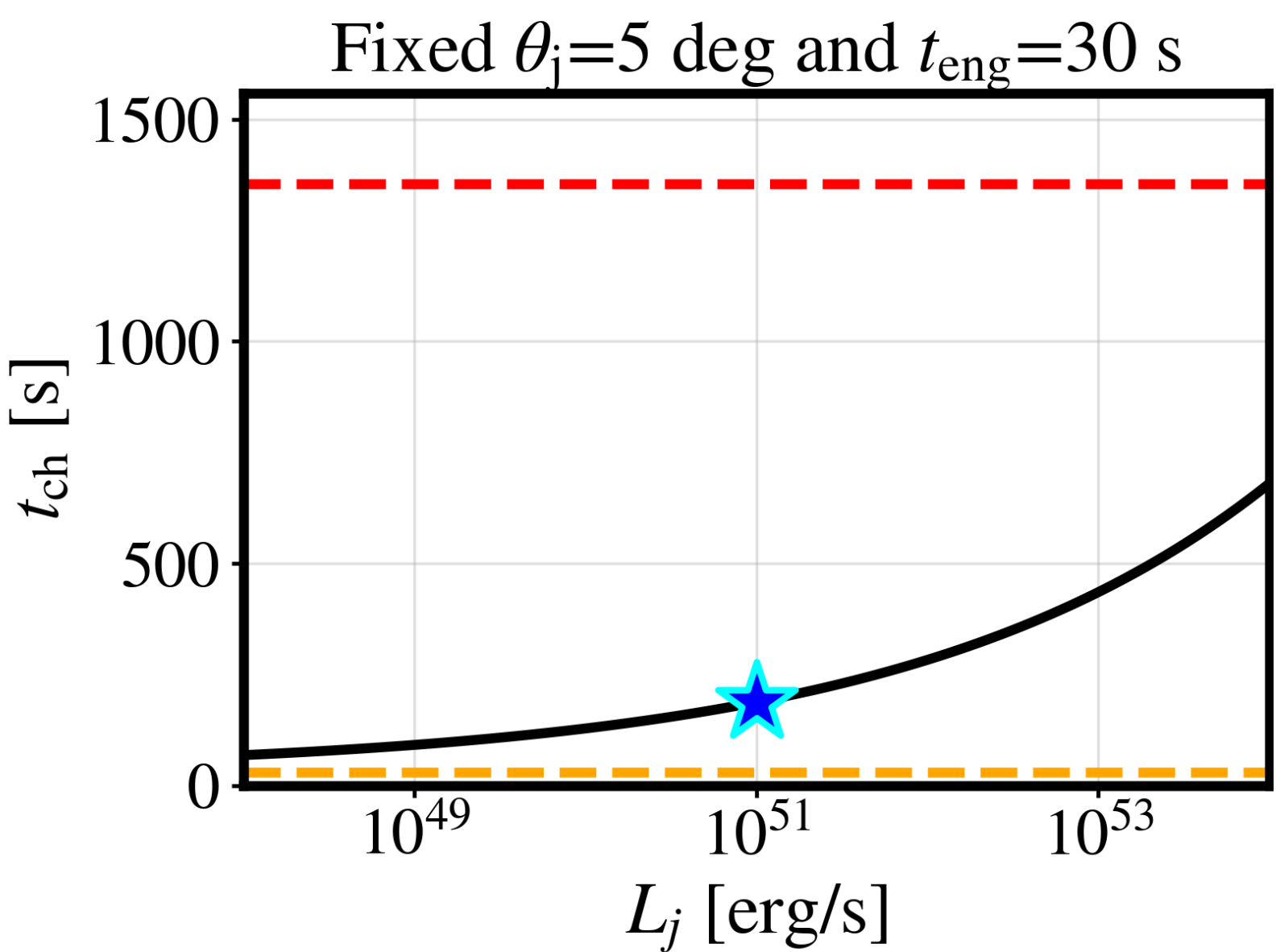
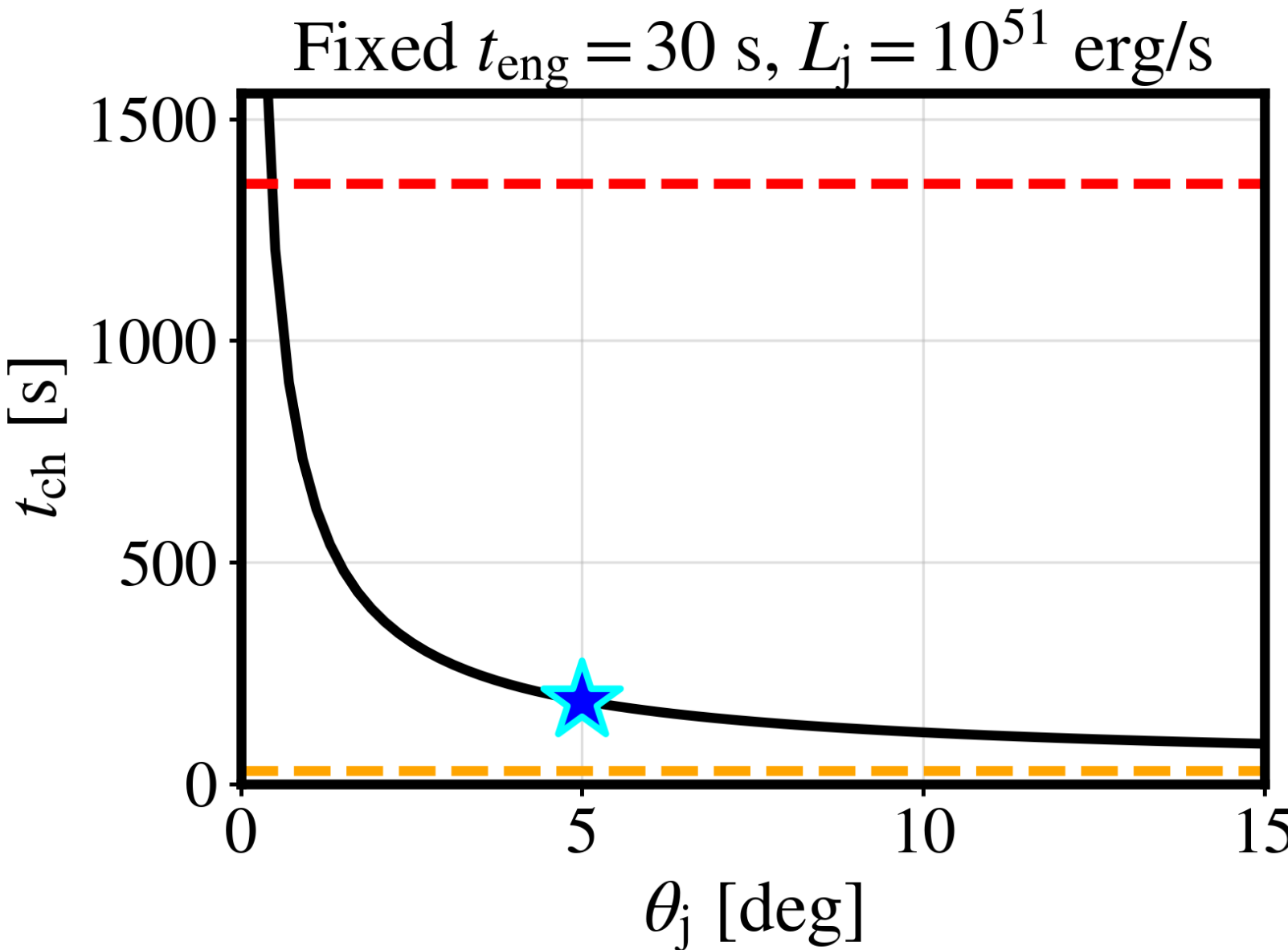
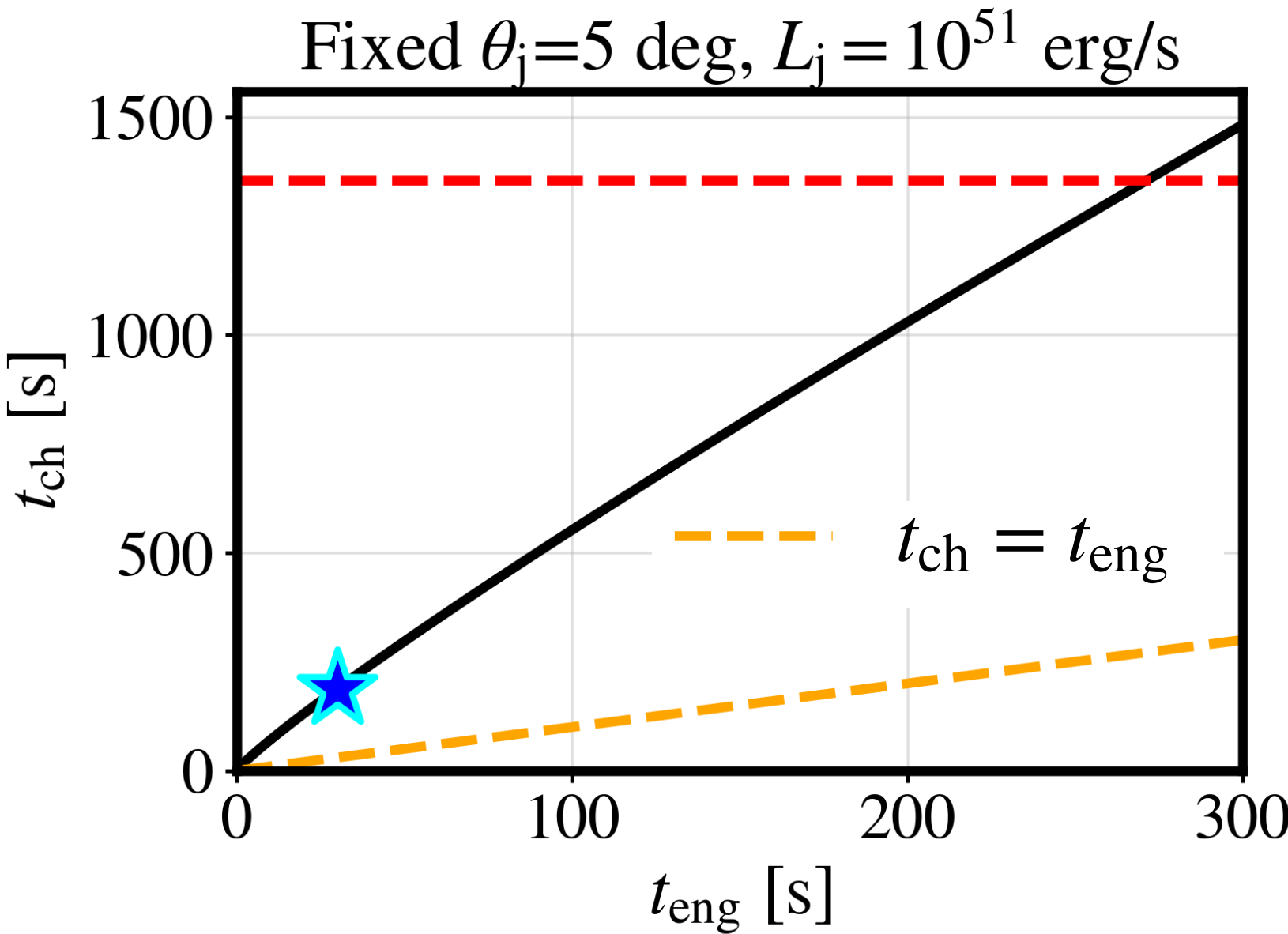
$R_* = 500 R_\odot$
 $L_j = 10^{51} \text{ erg/s}$
 $\theta_j = 5^\circ$
 $t_{\text{eng}} = 30 \text{ s}$

Choked!

$t_{\text{ch}} < t_{\text{bo}}$

★ $t_{\text{ch}}(t_{\text{eng}} = 30) = 187 \text{ s}$

--- $t_{\text{bo}} = 1355 \text{ s}$



Breakout and choking conditions

 M.Pais, A. Zegarelli, E. Peretti, S. Celli, *in prep.* (2026)



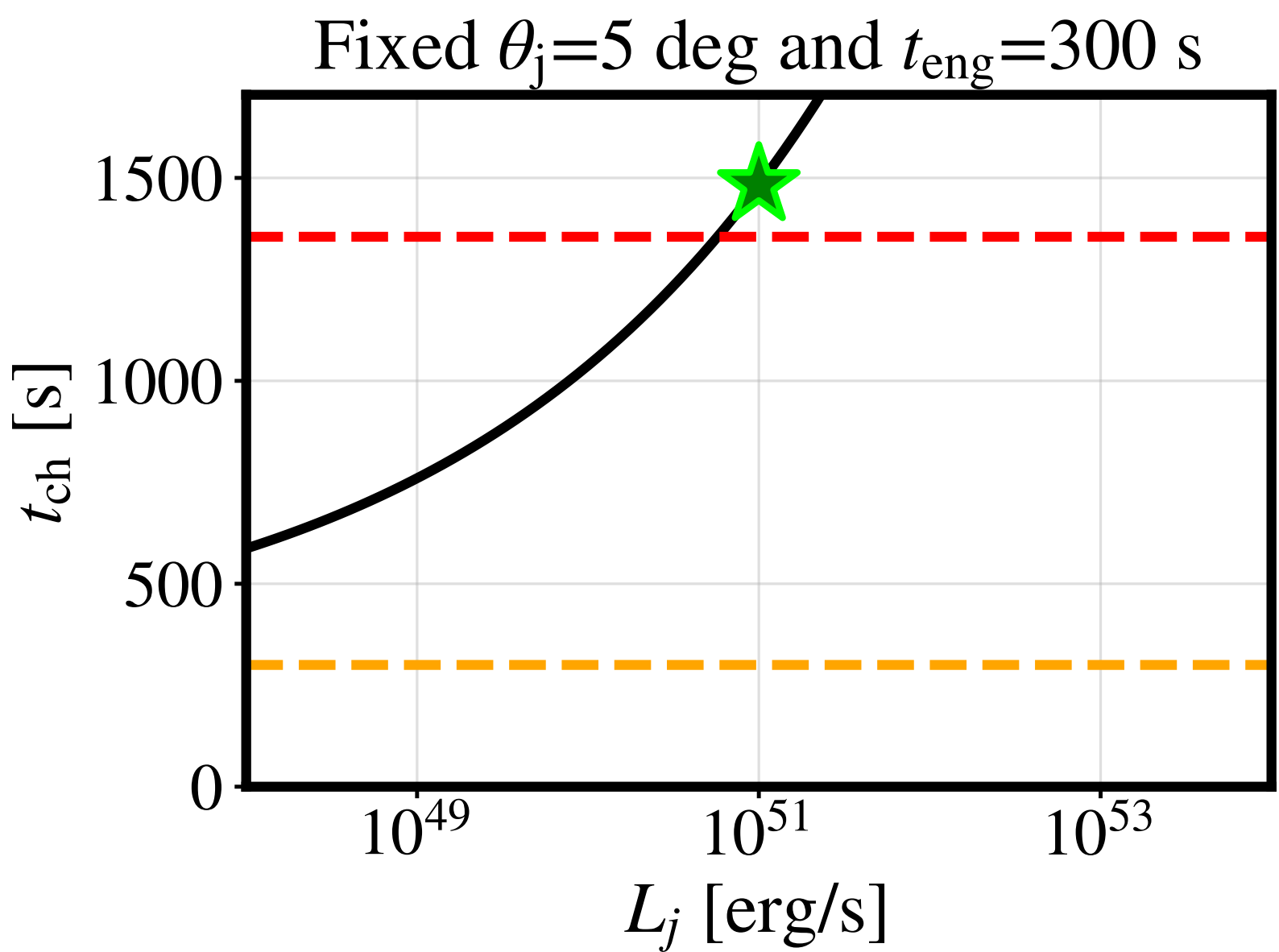
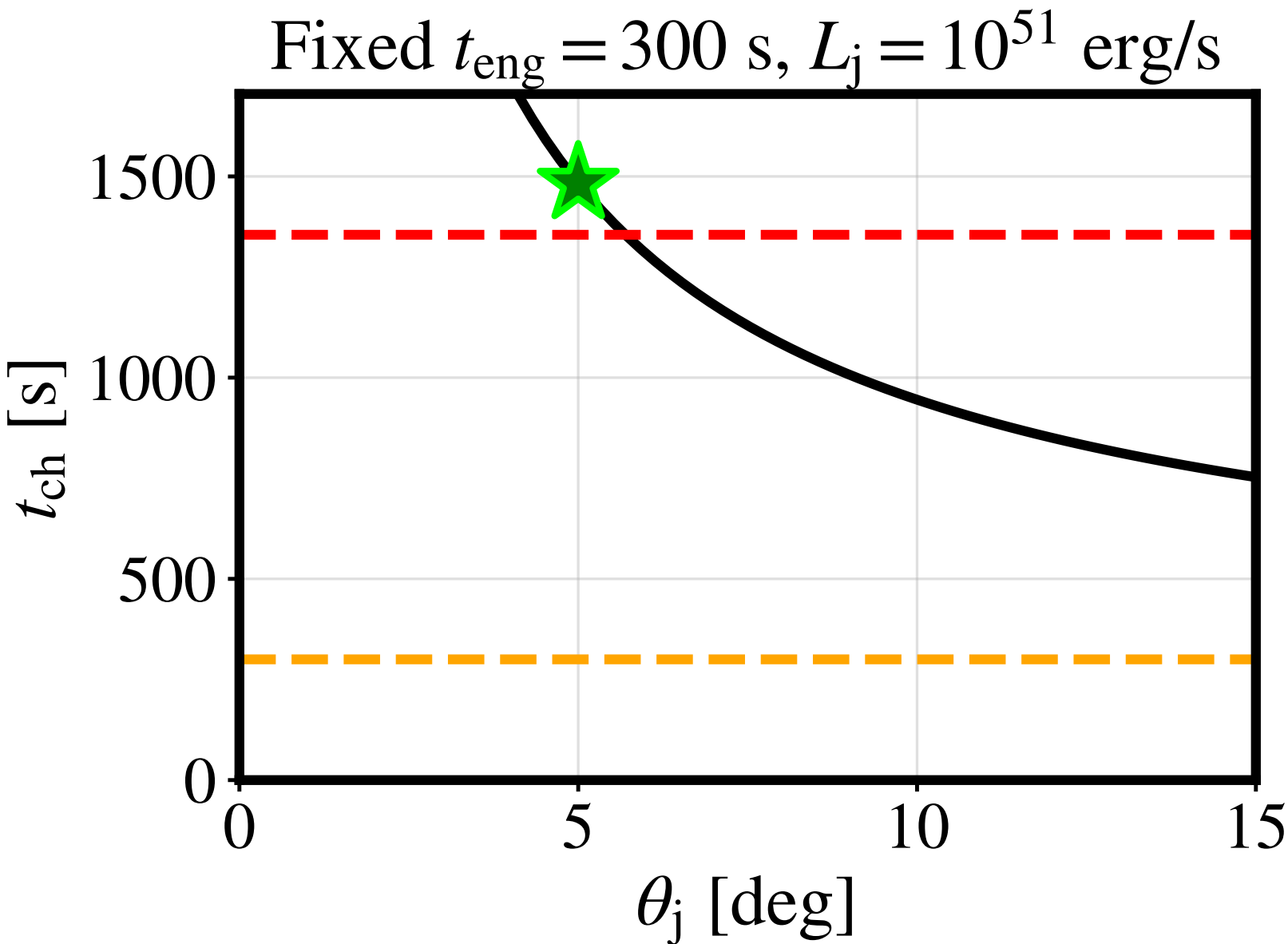
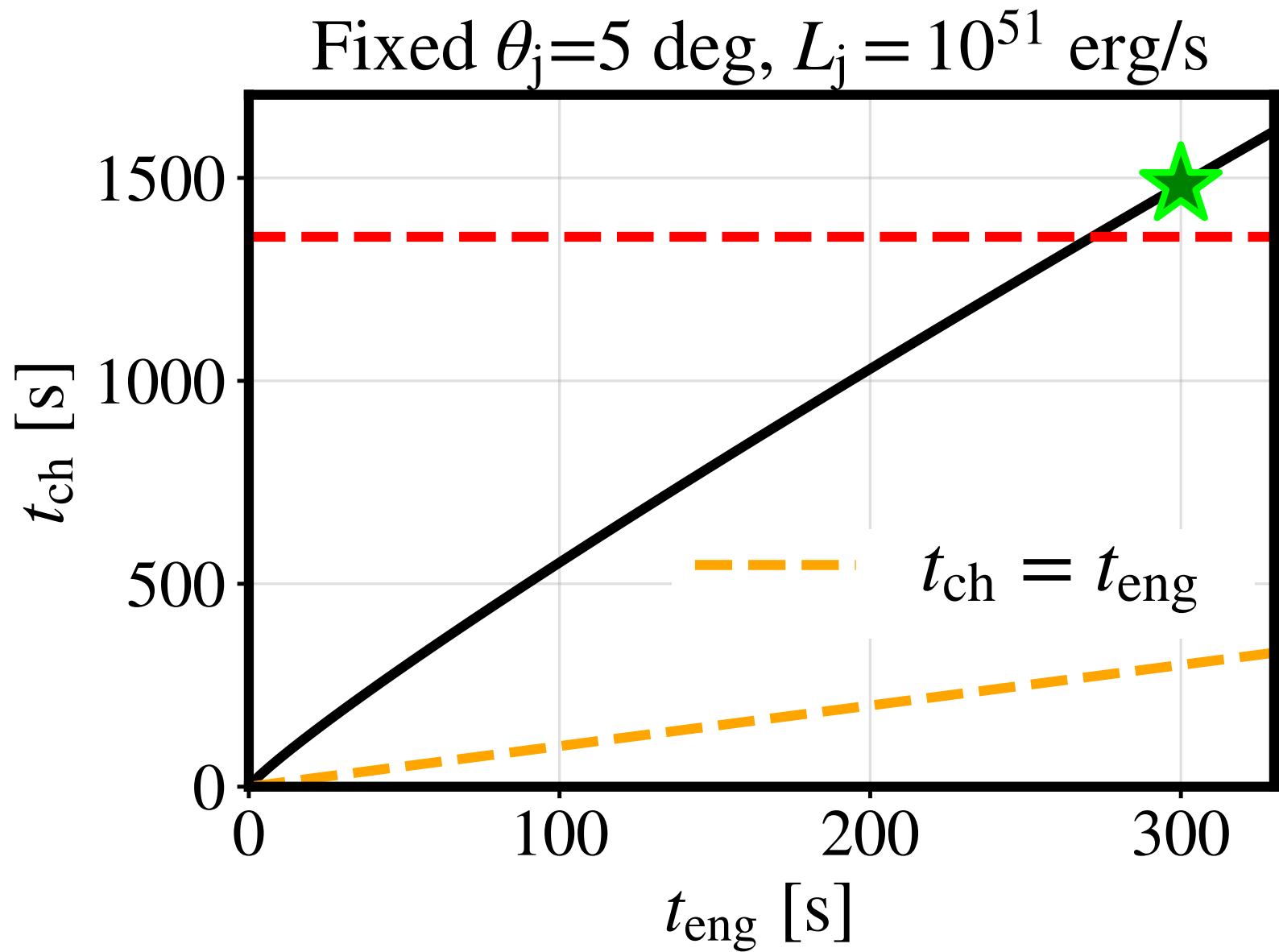
$R_* = 500\ R_\odot$
 $L_j = 10^{51}\ \text{erg/s}$
 $\theta_j = 5^\circ$
 $t_{\text{eng}} = 210\ \text{s}$

Successful

$t_{\text{ch}} > t_{\text{bo}}$

$t_{\text{ch}}(t_{\text{eng}} = 300) = 1482\ \text{s}$

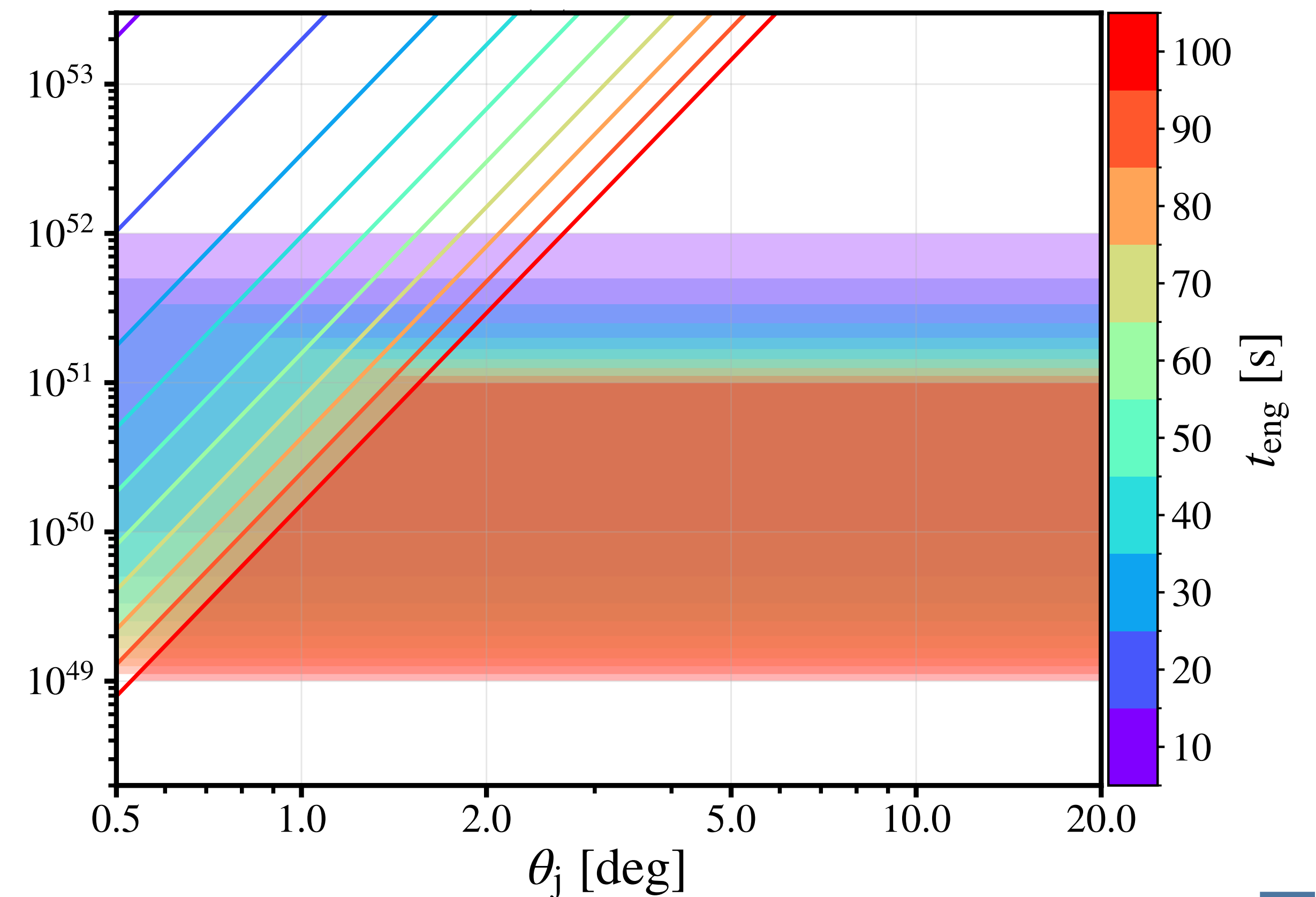
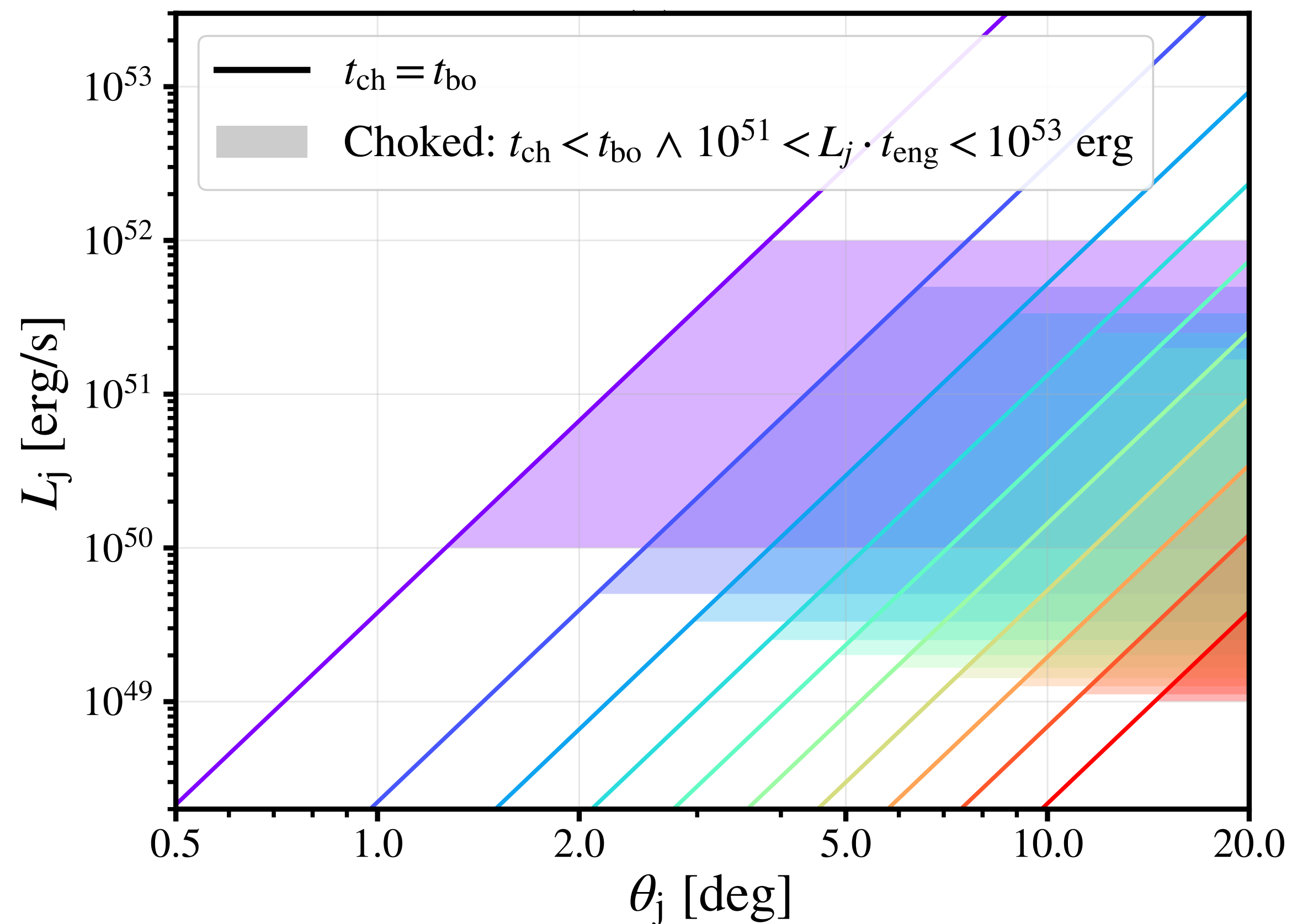
 $t_{\text{bo}} = 1355\ \text{s}$



Parameter space for choked jets

Preliminary

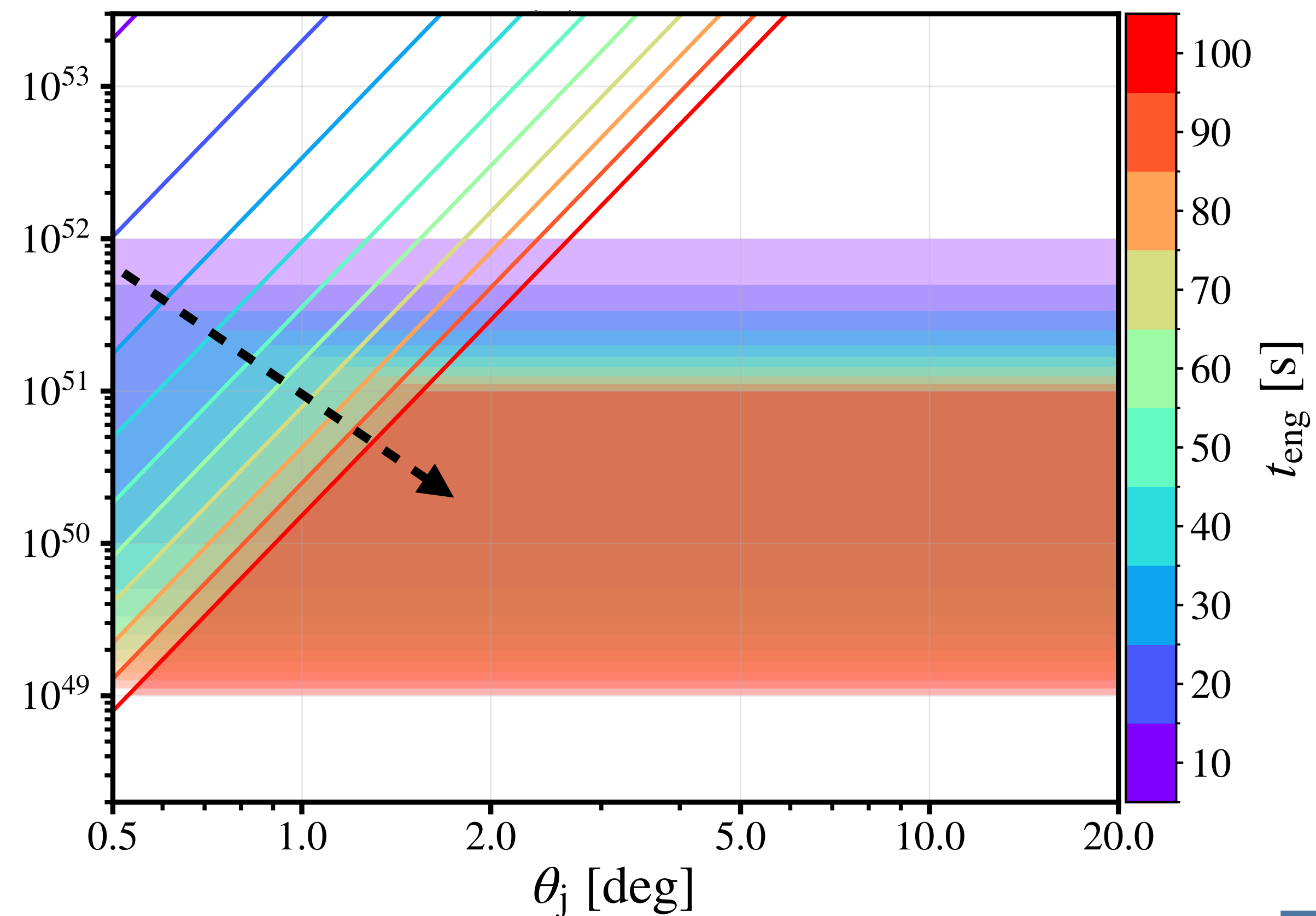
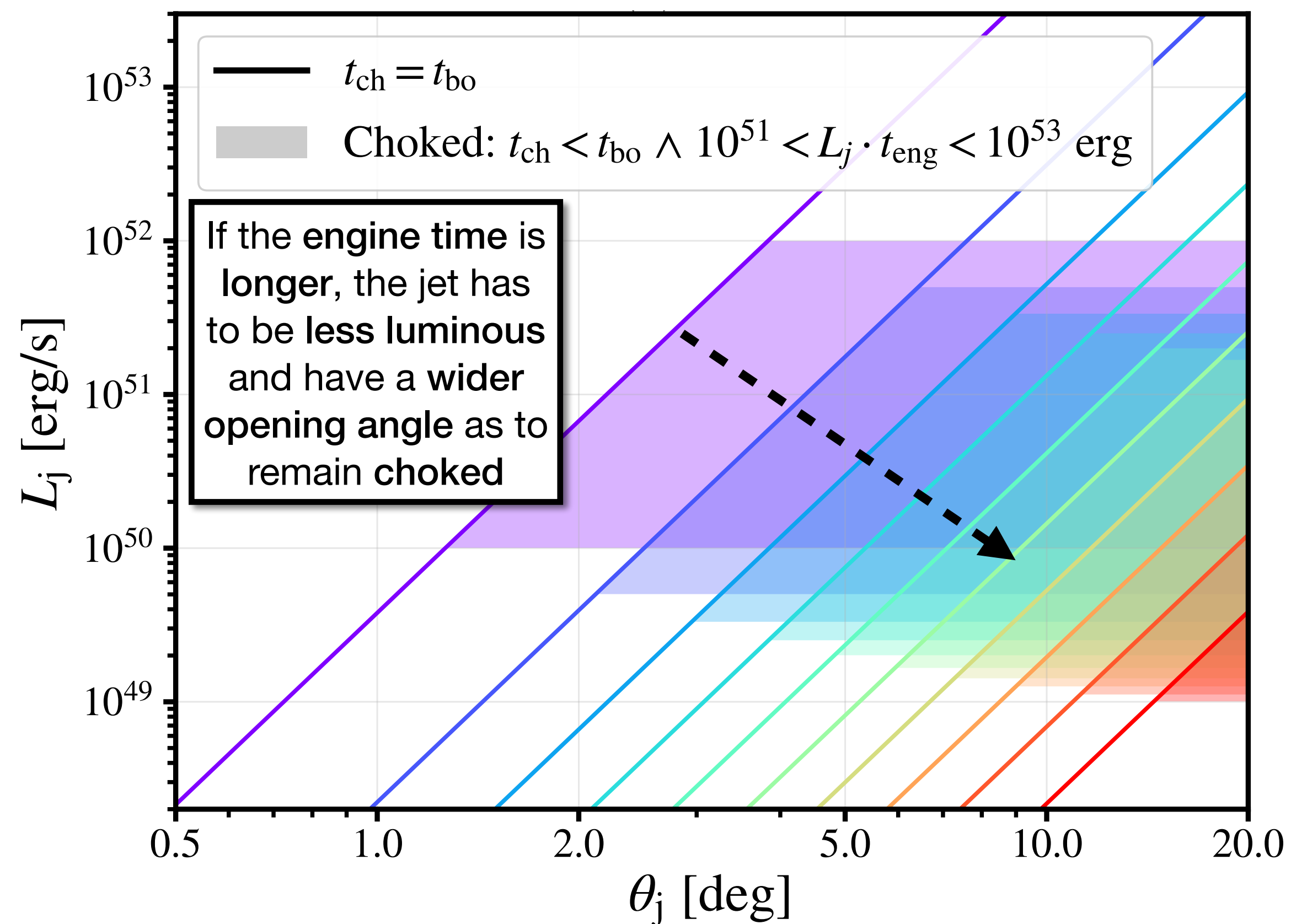
📖 M.Pais, A. Zegarelli, E. Peretti, S. Celli, *in prep.* (2026)



Parameter space for choked jets

Preliminary

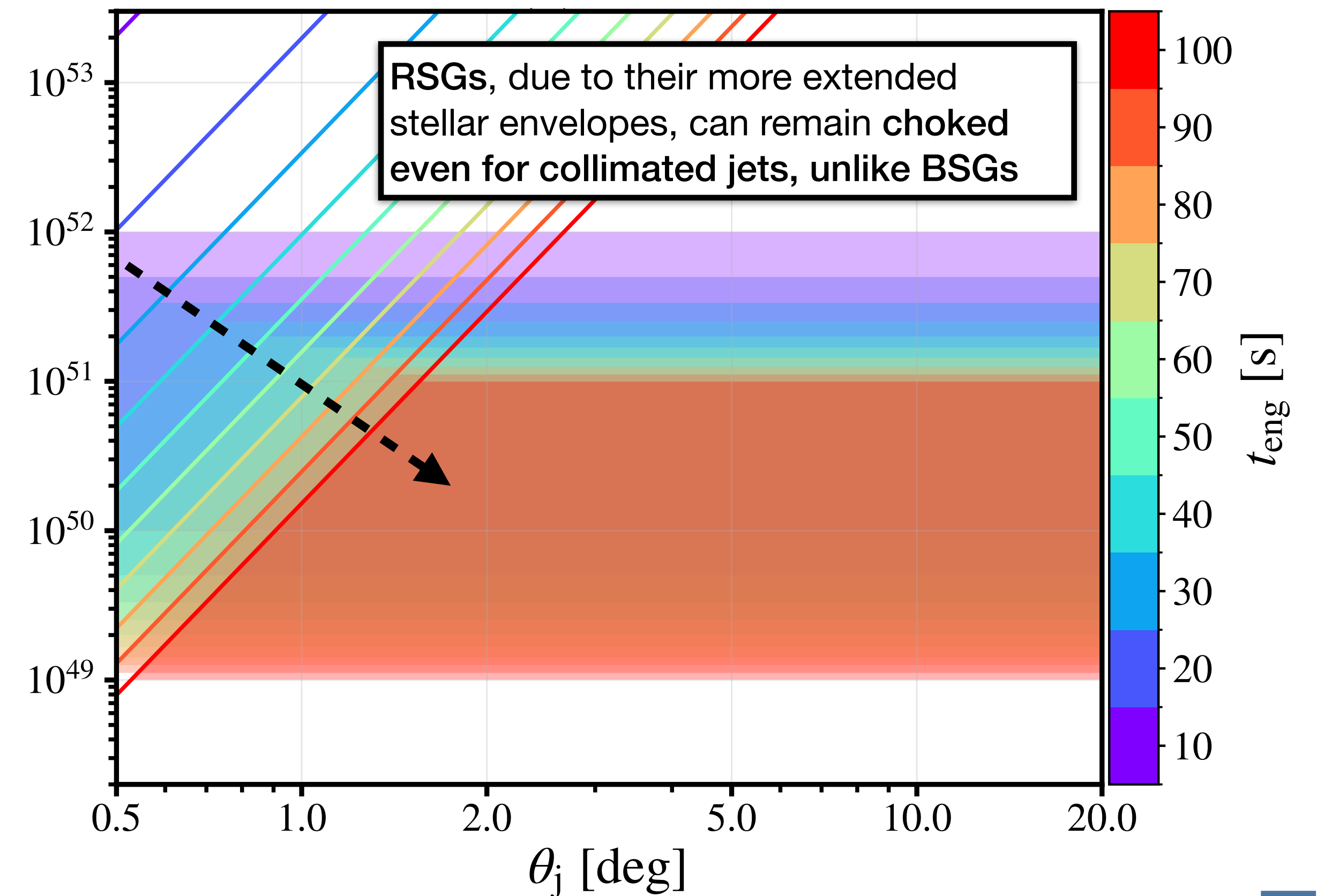
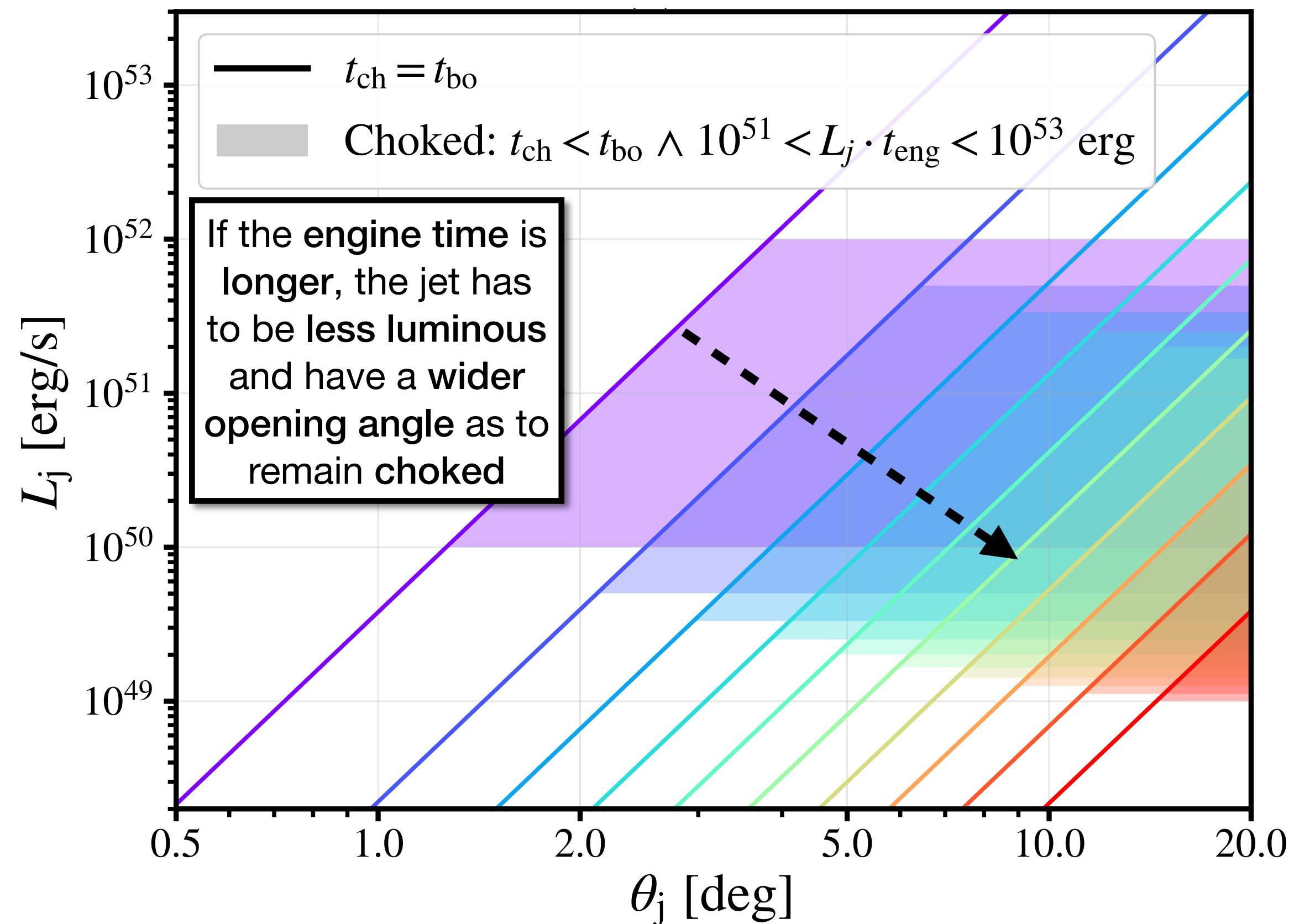
📖 M.Pais, A. Zegarelli, E. Peretti, S. Celli, *in prep.* (2026)



Parameter space for choked jets

Preliminary

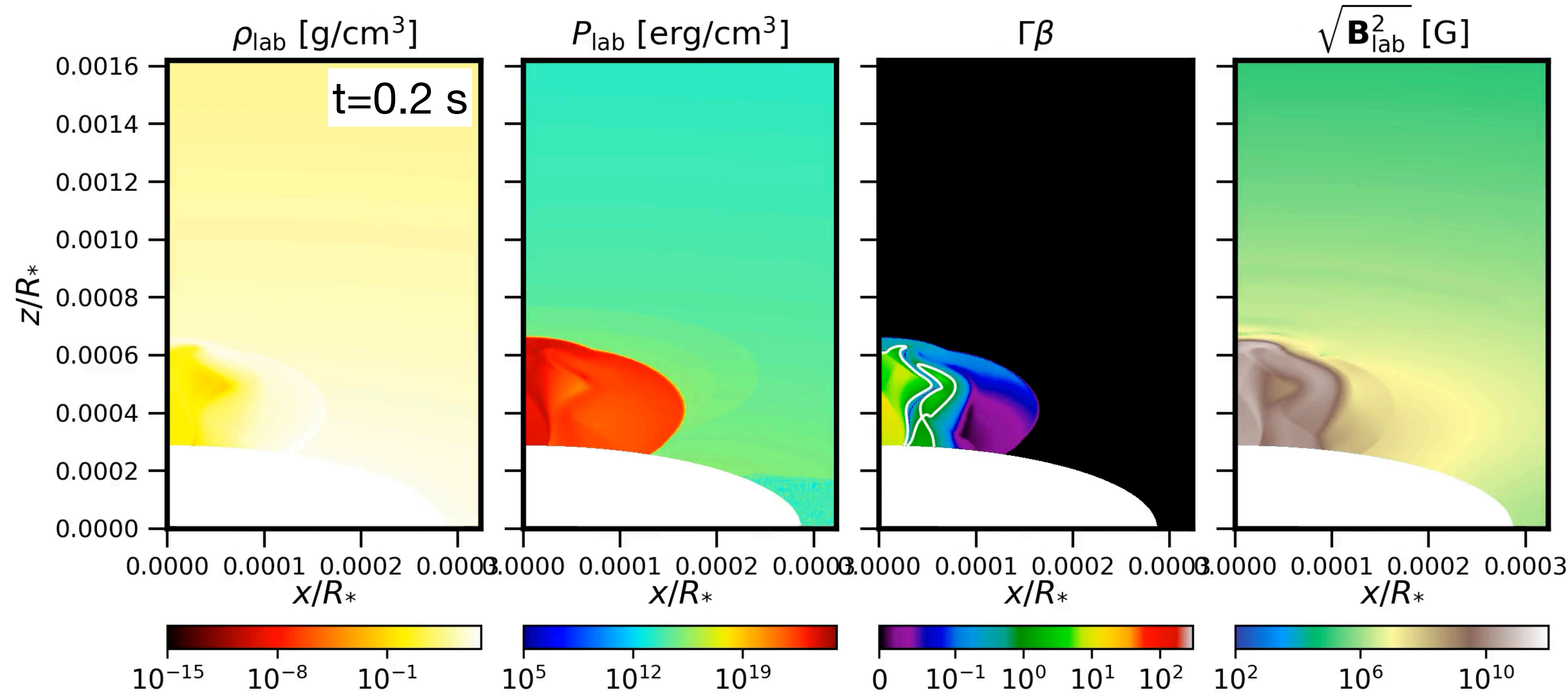
📖 M.Pais, A. Zegarelli, E. Peretti, S. Celli, *in prep.* (2026)



Simulation results: BSG ($t_{\text{eng}} = 5 \text{ s}$)

Preliminary

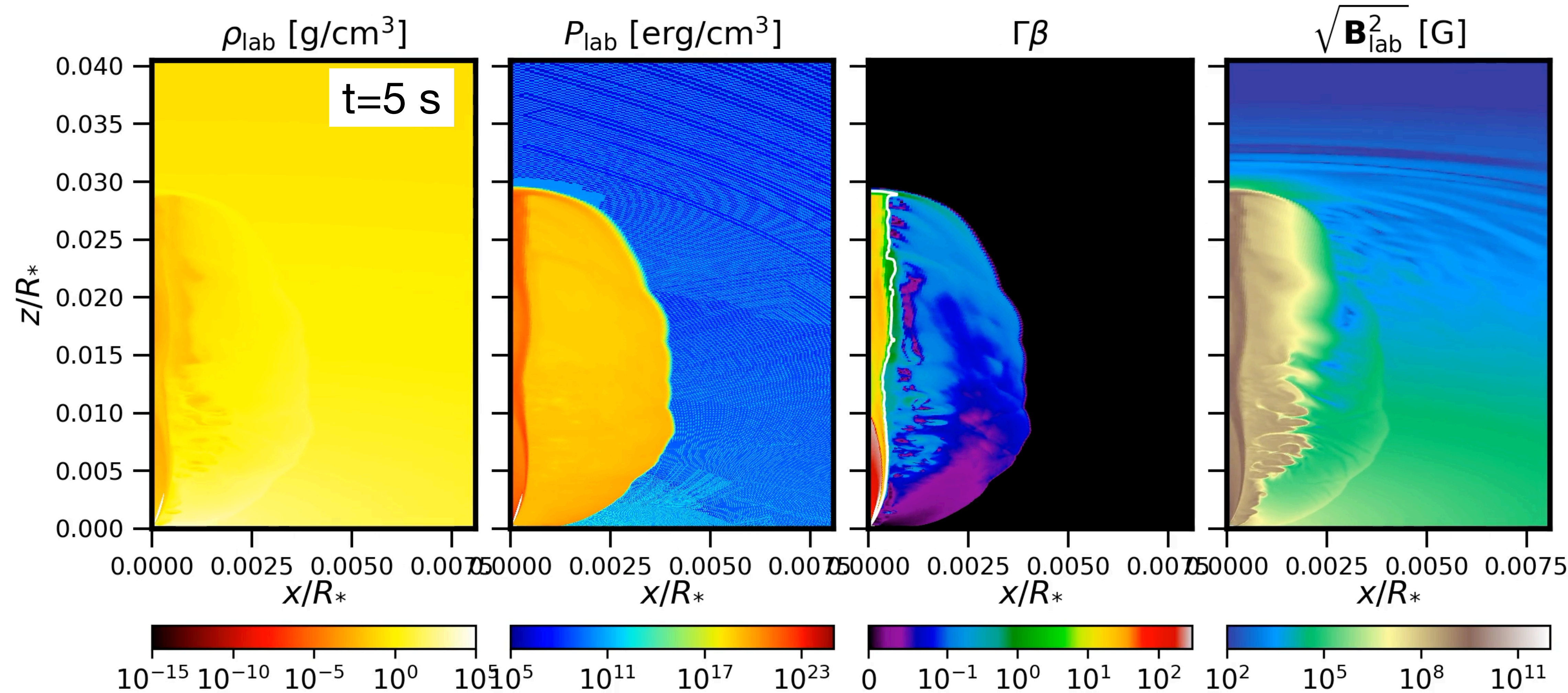
M.Pais, A. Zegarelli, E. Peretti, S. Celli, in prep. (2026)



Simulation results: BSG ($t_{\text{eng}} = 5 \text{ s}$)

Preliminary

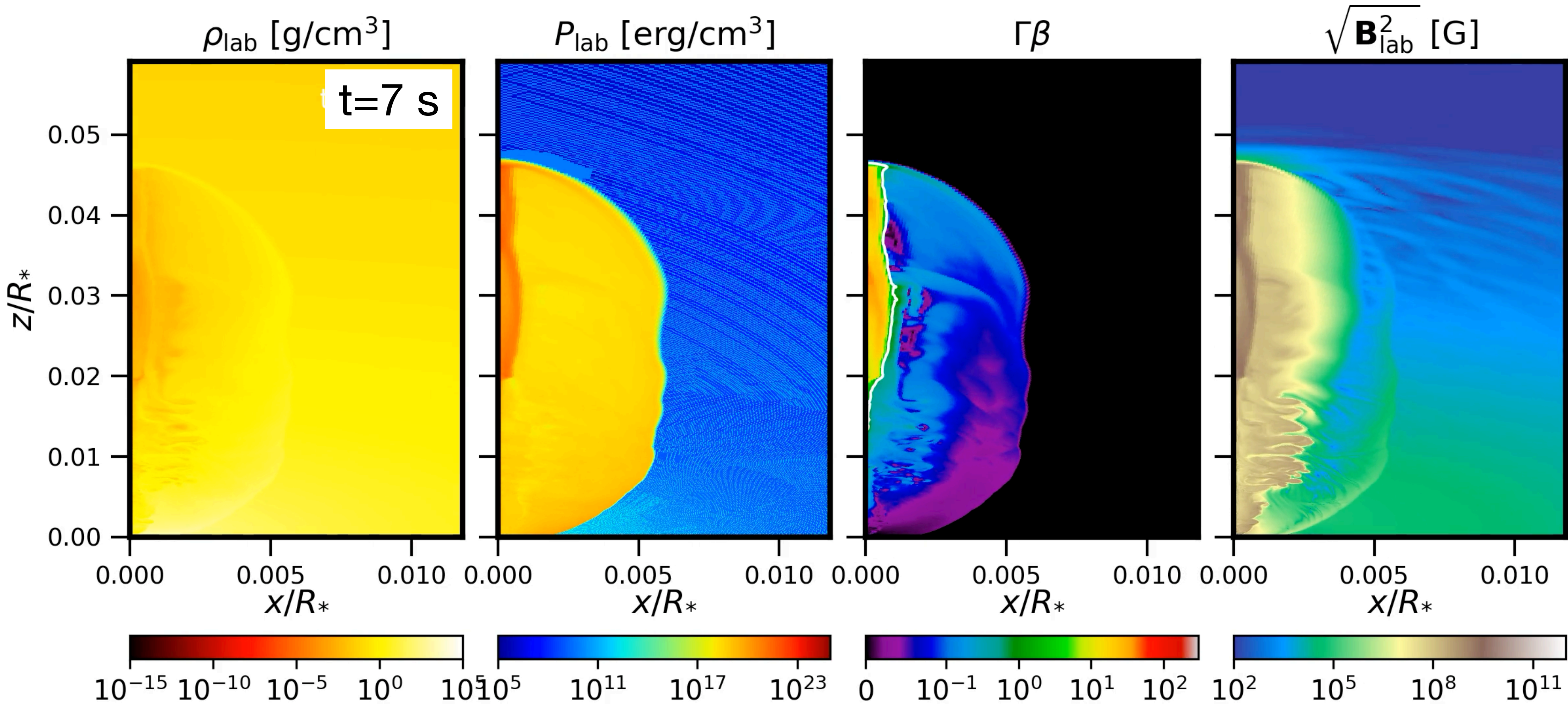
M.Pais, A. Zegarelli, E. Peretti, S. Celli, in prep. (2026)



Simulation results: BSG ($t_{\text{eng}} = 5 \text{ s}$)

Preliminary

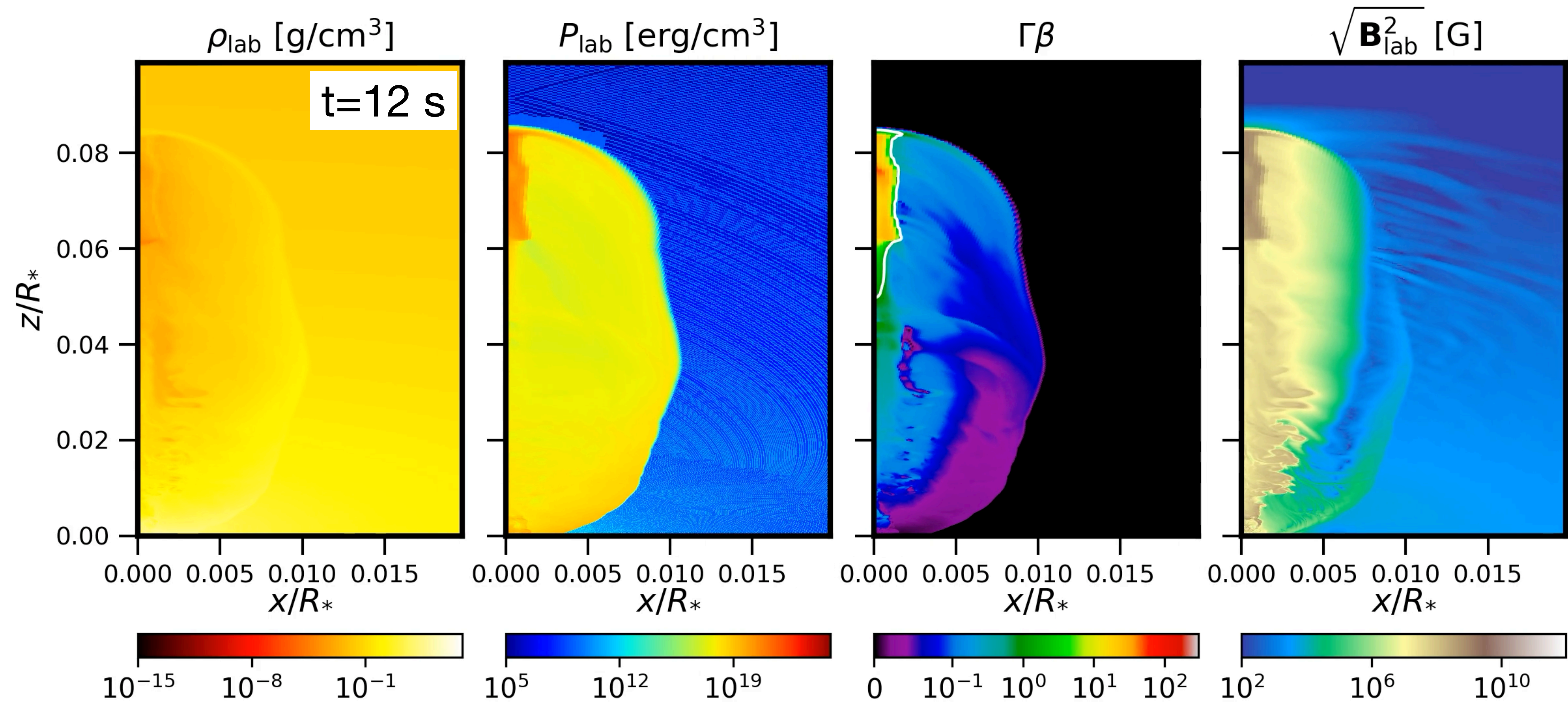
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Simulation results: BSG ($t_{\text{eng}} = 5 \text{ s}$)

Preliminary

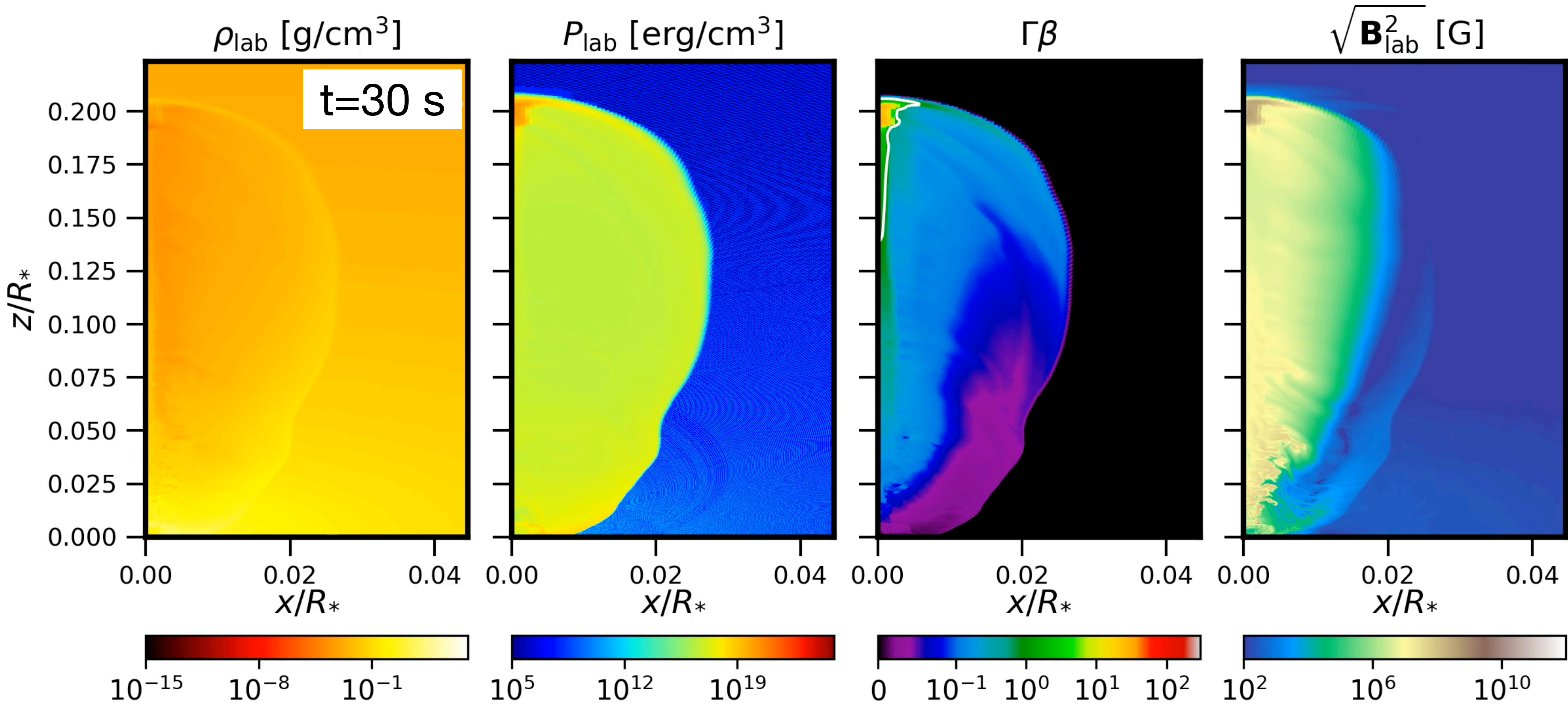
📖 M.Pais, A. Zegarelli, E. Peretti, S. Celli, *in prep.* (2026)



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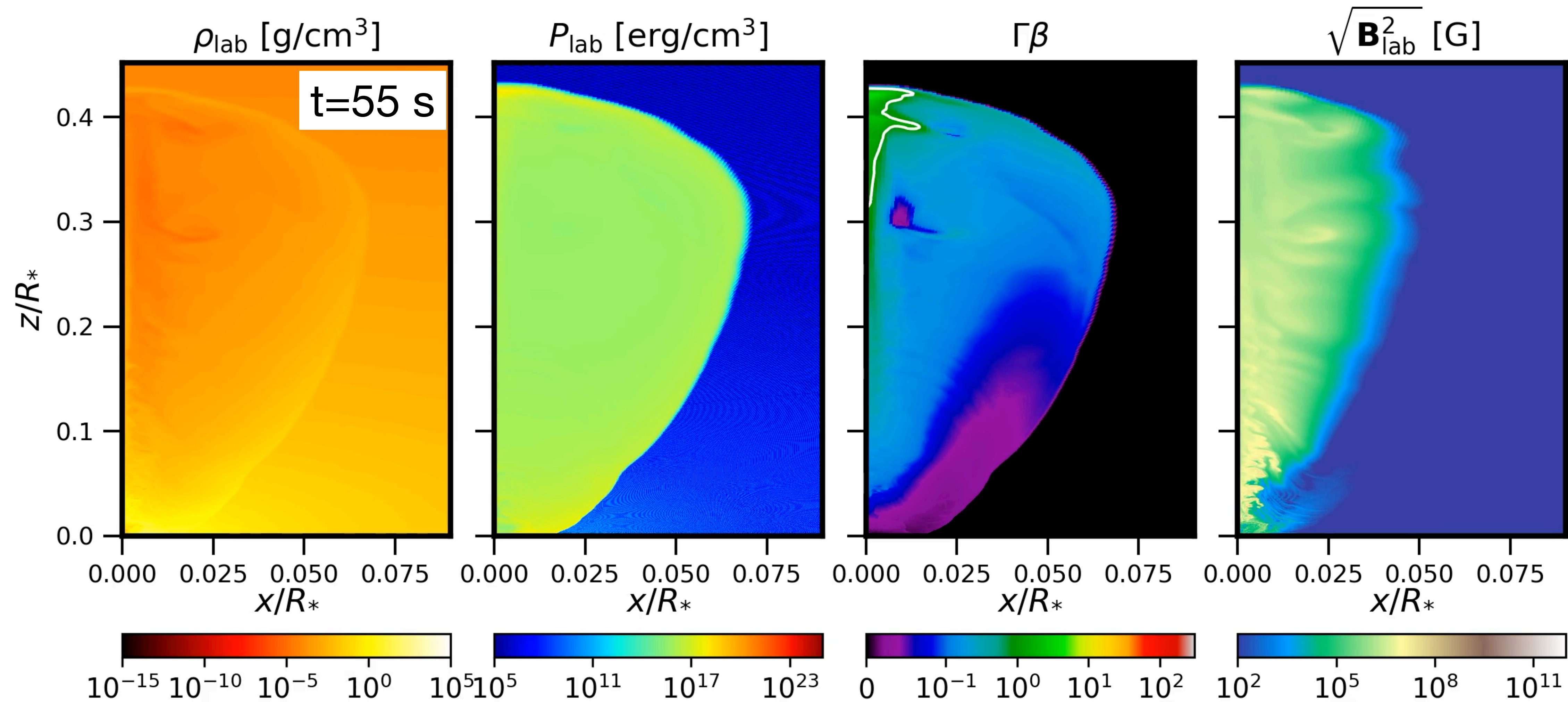
M.Pais, A. Zegarelli, E. Peretti, S. Celli, in prep. (2026)



Simulation results: BSG ($t_{\text{eng}} = 5 \text{ s}$)

Preliminary

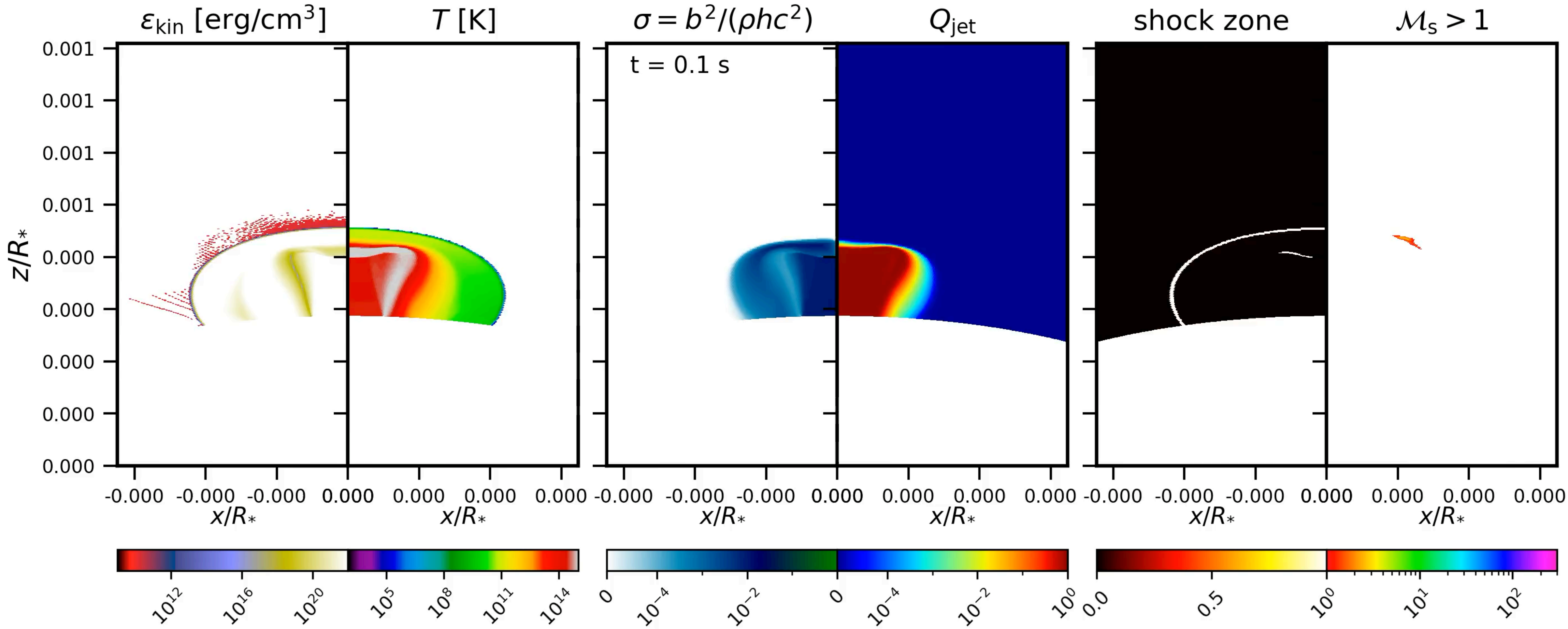
📖 M.Pais, A. Zegarelli, E. Peretti, S. Celli, *in prep.* (2026)



Identification of candidate acceleration sites: BSG

Preliminary

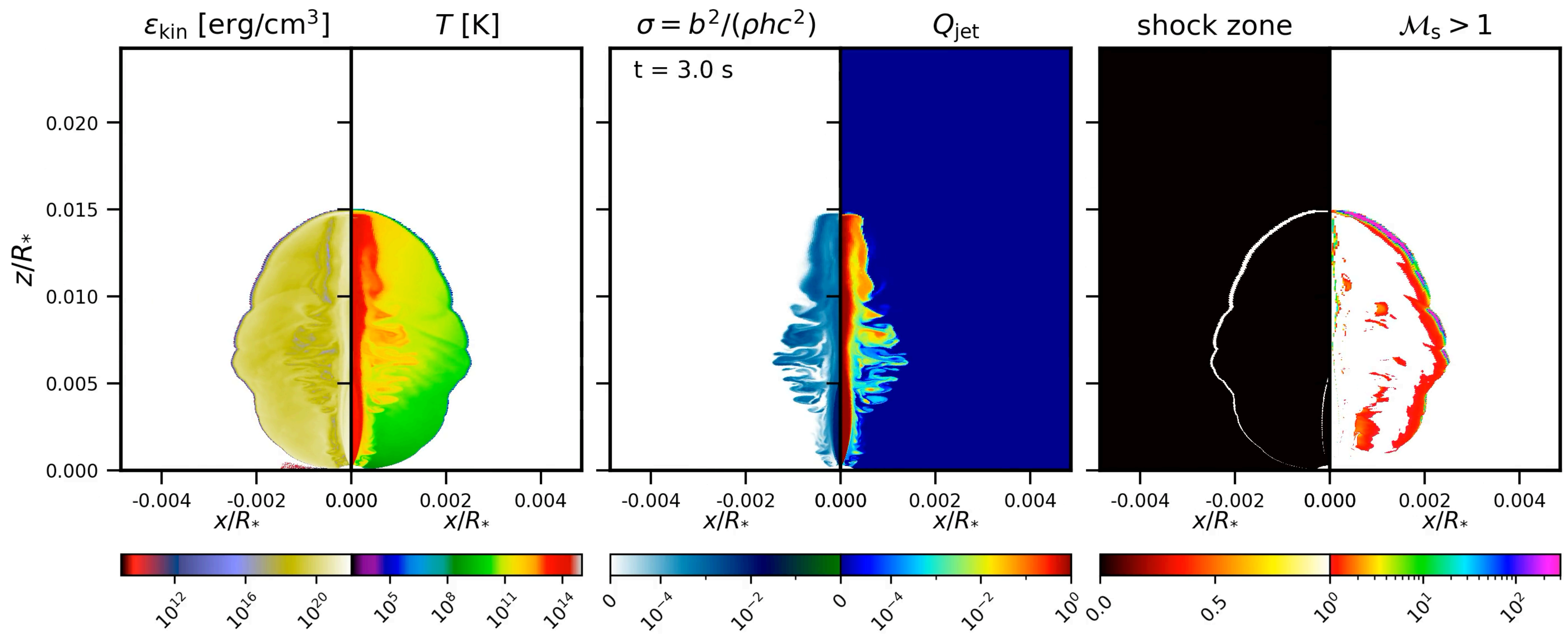
M.Pais, A. Zegarelli, E. Peretti, S. Celli, in prep. (2026)



Identification of candidate acceleration sites: BSG

Preliminary

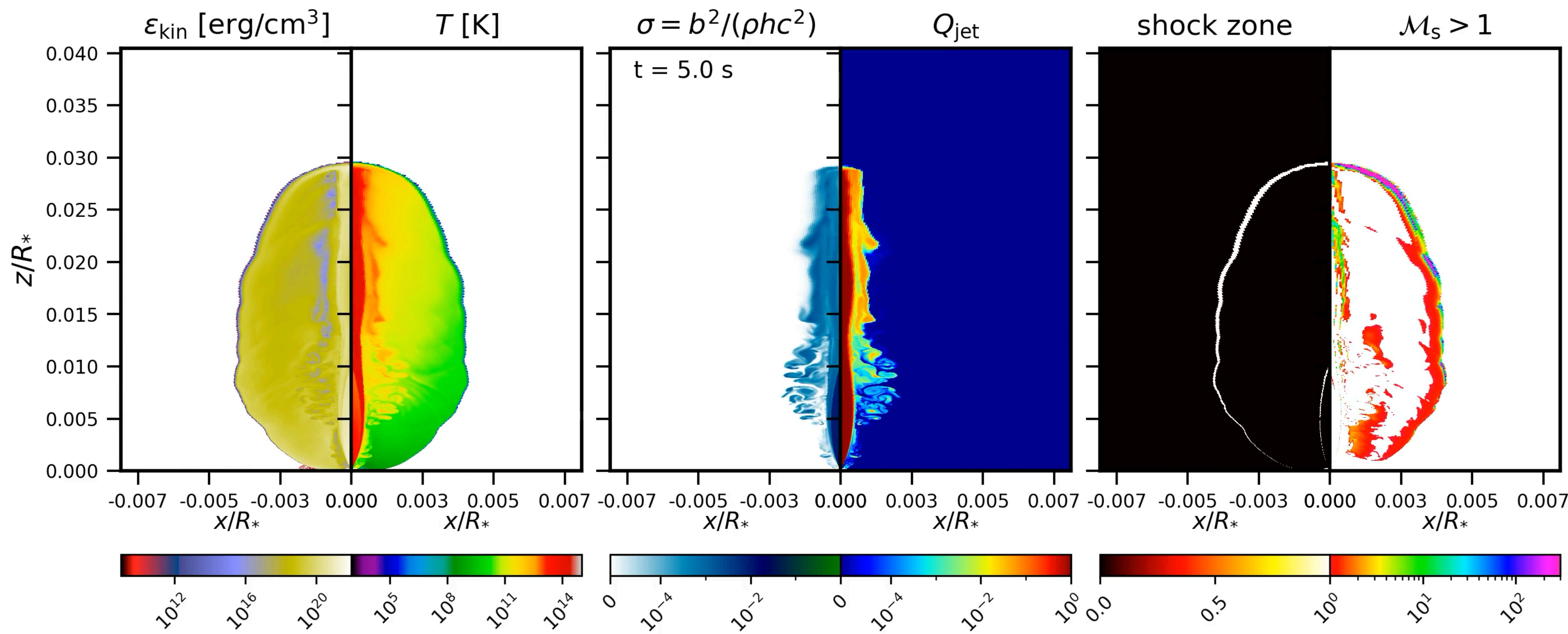
M.Pais, A. Zegarelli, E. Peretti, S. Celli, *in prep.* (2026)



Identification of candidate acceleration sites: BSG

Preliminary

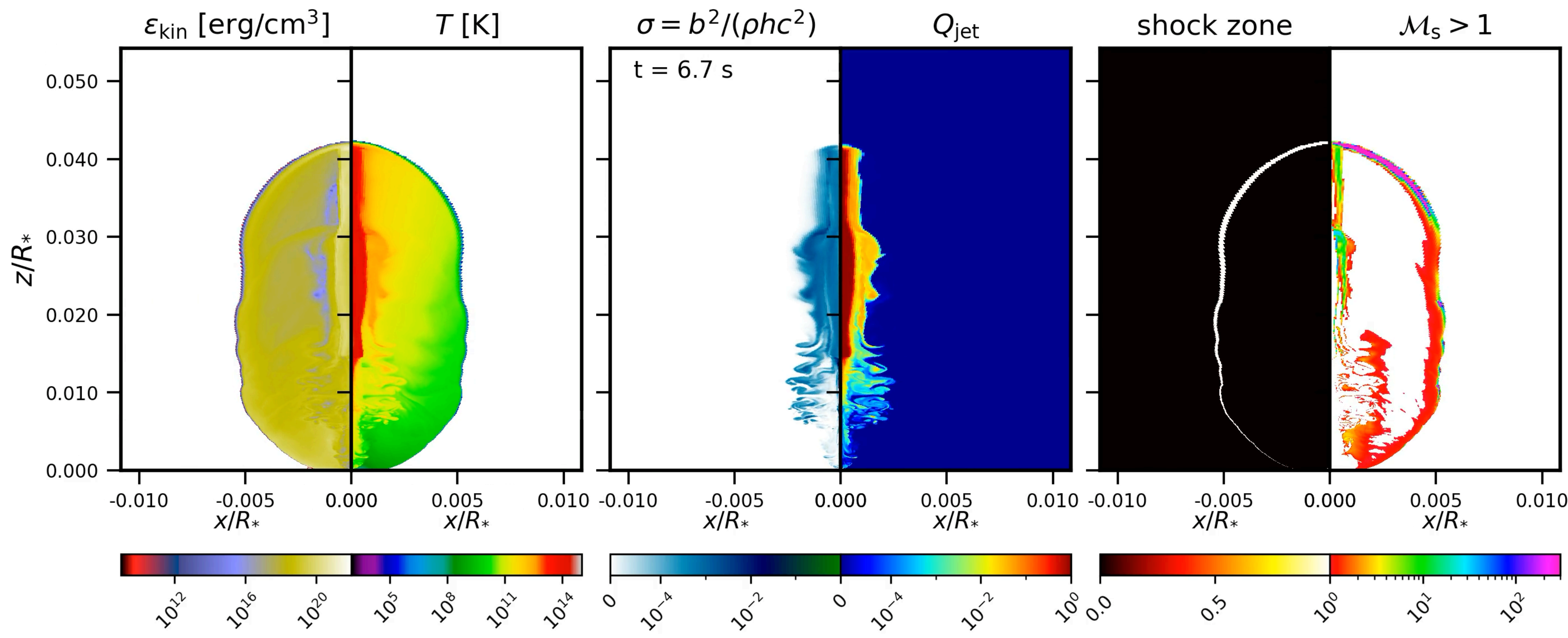
M.Pais, A. Zegarelli, E. Peretti, S. Celli, in prep. (2026)



Identification of candidate acceleration sites: BSG

Preliminary

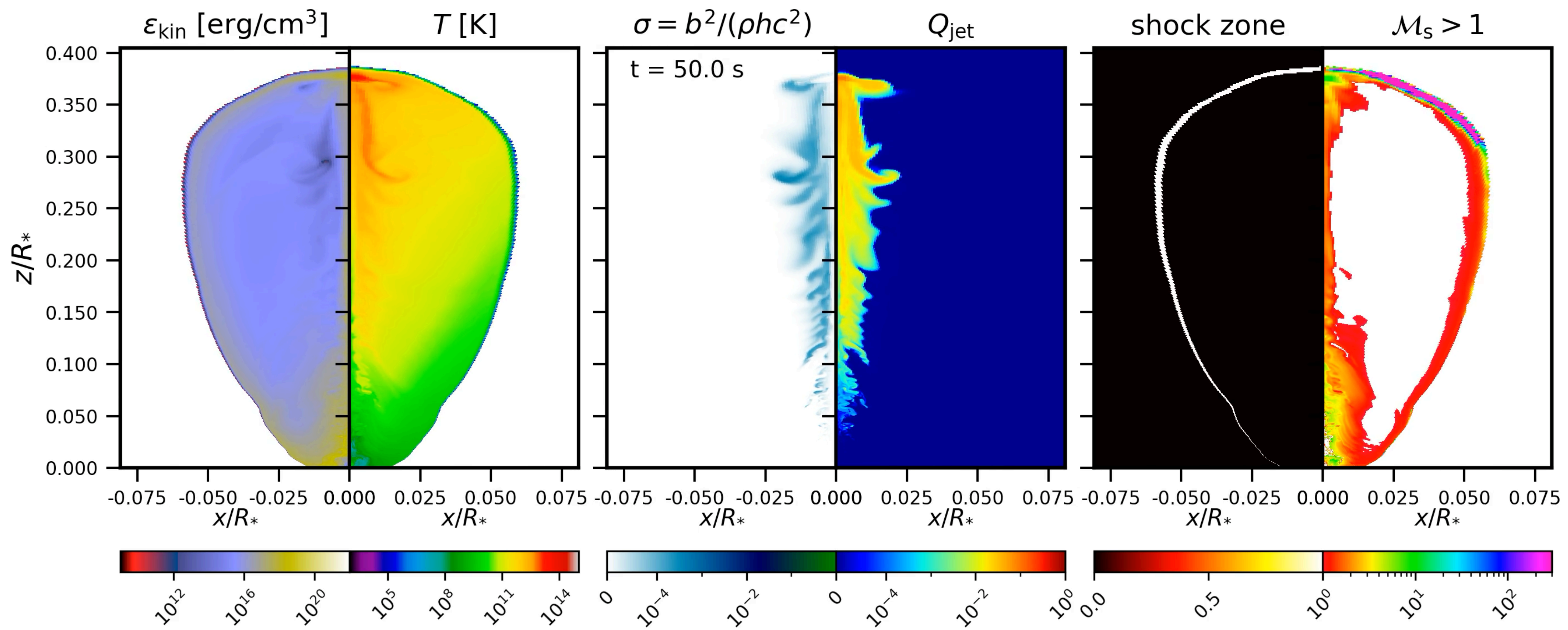
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Identification of candidate acceleration sites: BSG

Preliminary

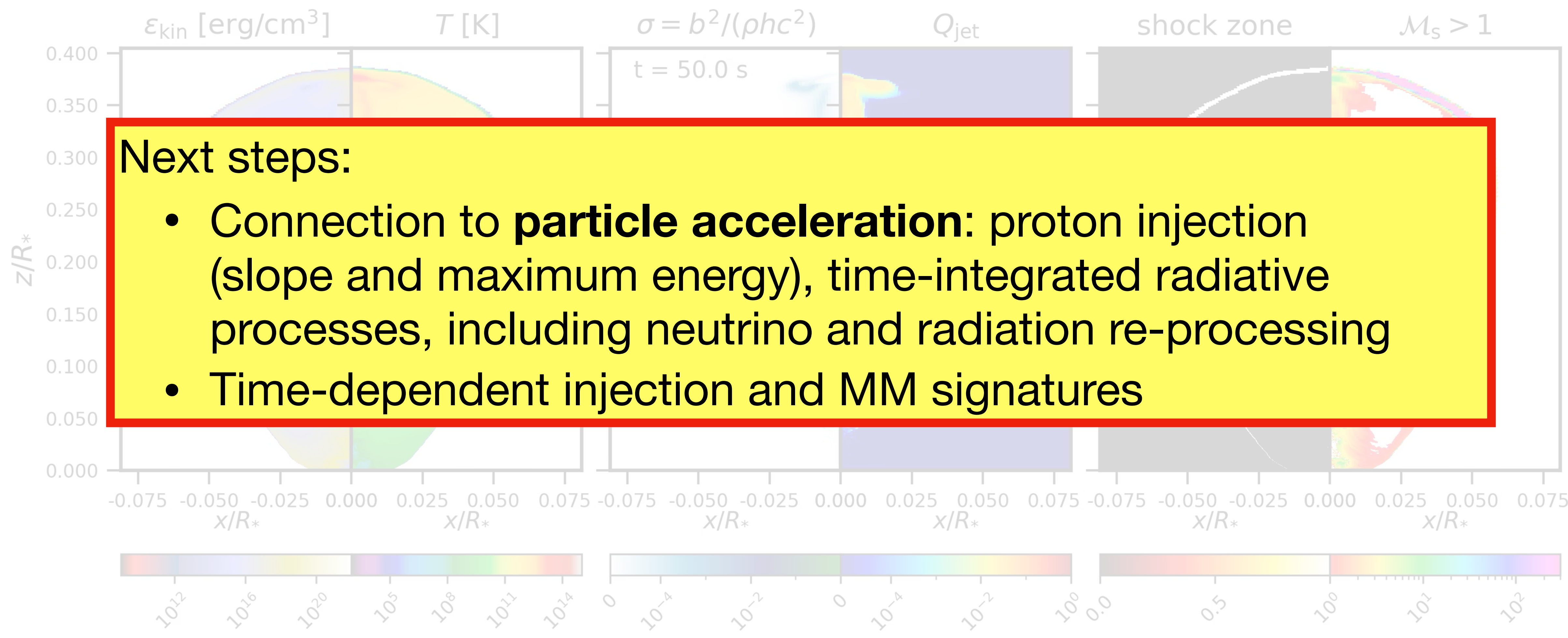
M.Pais, A. Zegarelli, E. Peretti, S. Celli, in prep. (2026)



Identification of candidate acceleration sites: BSG

Preliminary

M.Pais, A. Zegarelli, E. Peretti, S. Celli, in prep. (2026)



Take-home messages

- * Evidence of choked jets from CCSNe
- * γ -rays are trapped within the stellar envelope
 - The hidden engine can still leave observable EM signatures
 - X-ray shock breakout + UV/optical cooling emission + high-velocity ejecta signatures (spectral features)
- * If choked jets are efficient particle accelerators
 - Neutrinos, combined with EM signatures, provide a unique probe
- * We are entering the right observational era
 - e.g., Einstein Probe + ULTRASAT + Rubin + IceCube/KM3NeT can turn choked jets from a theoretical population into a searchable MM population
- * RMHD simulations are key to connecting the jet-cocoon physics to observables and to determining whether choked jets are efficient particle accelerators and neutrino sources → *First attempts of exploring RSG and BSG progenitors*

Stay tuned!



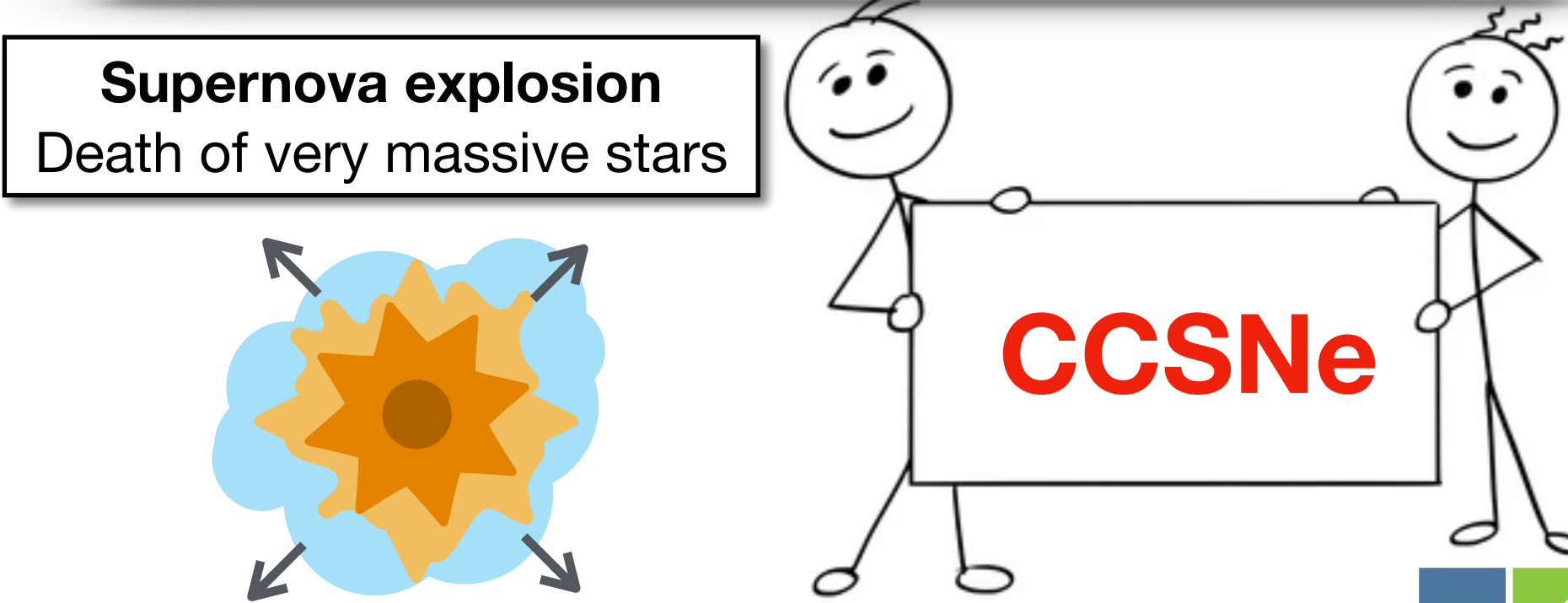
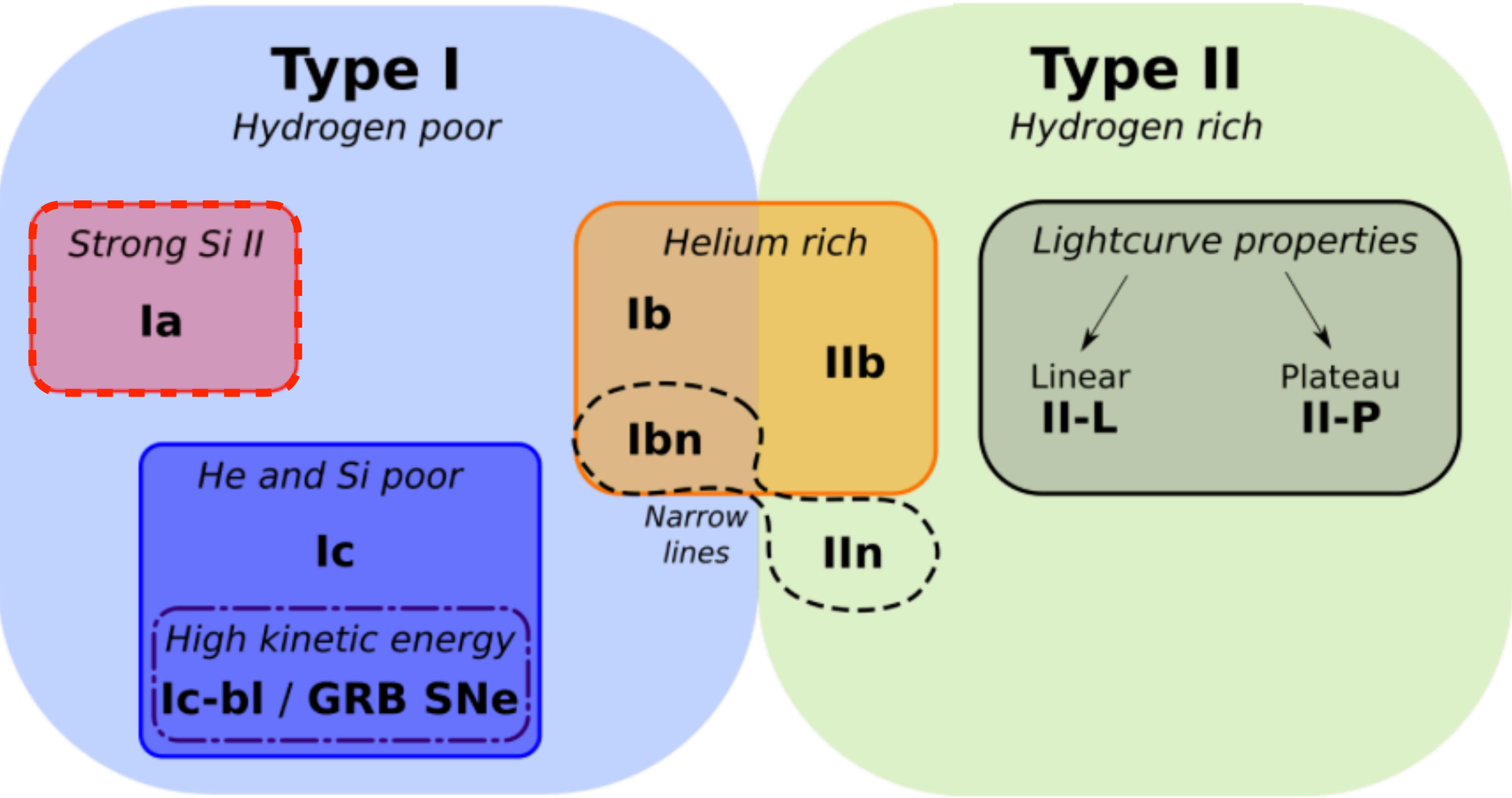
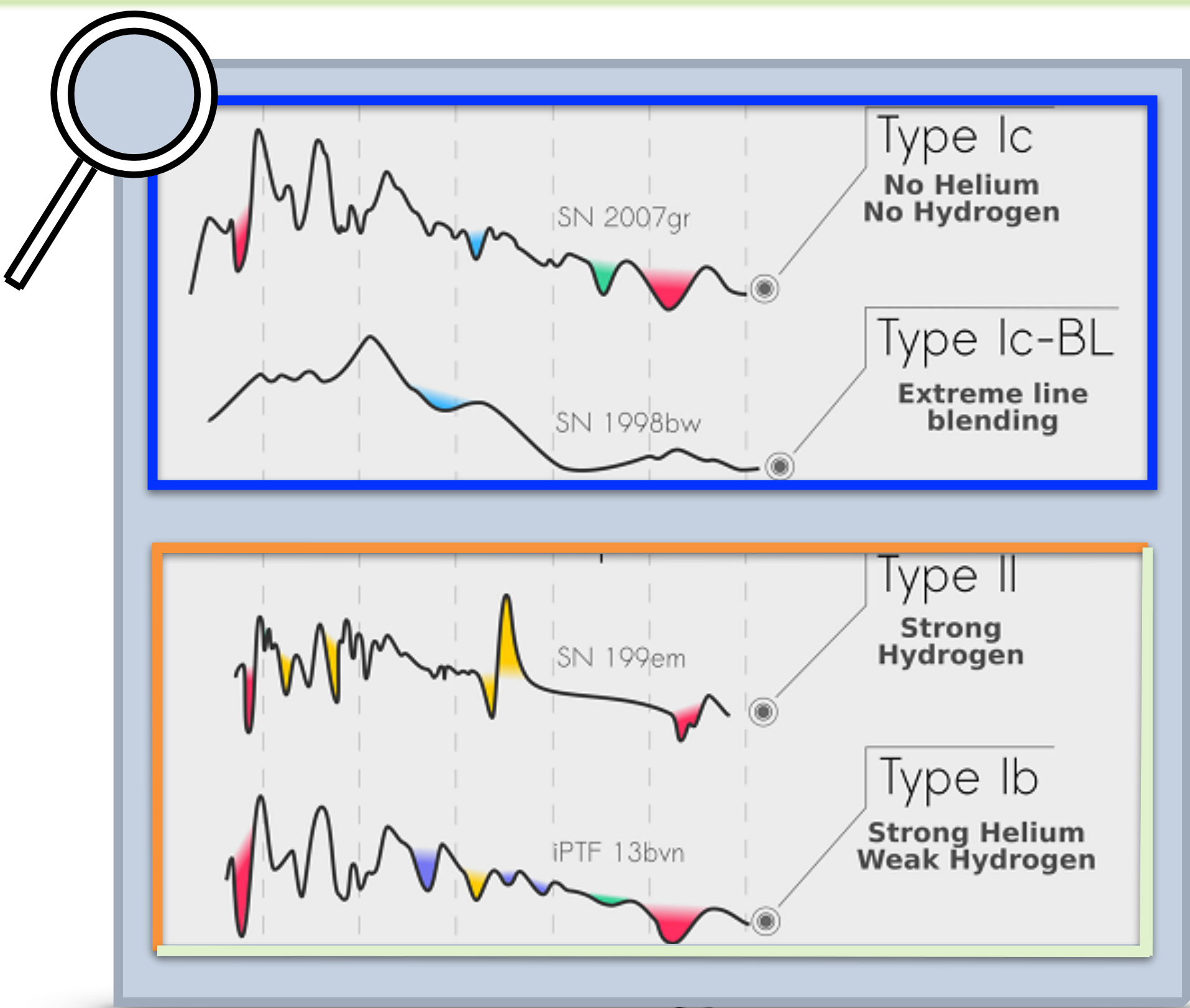
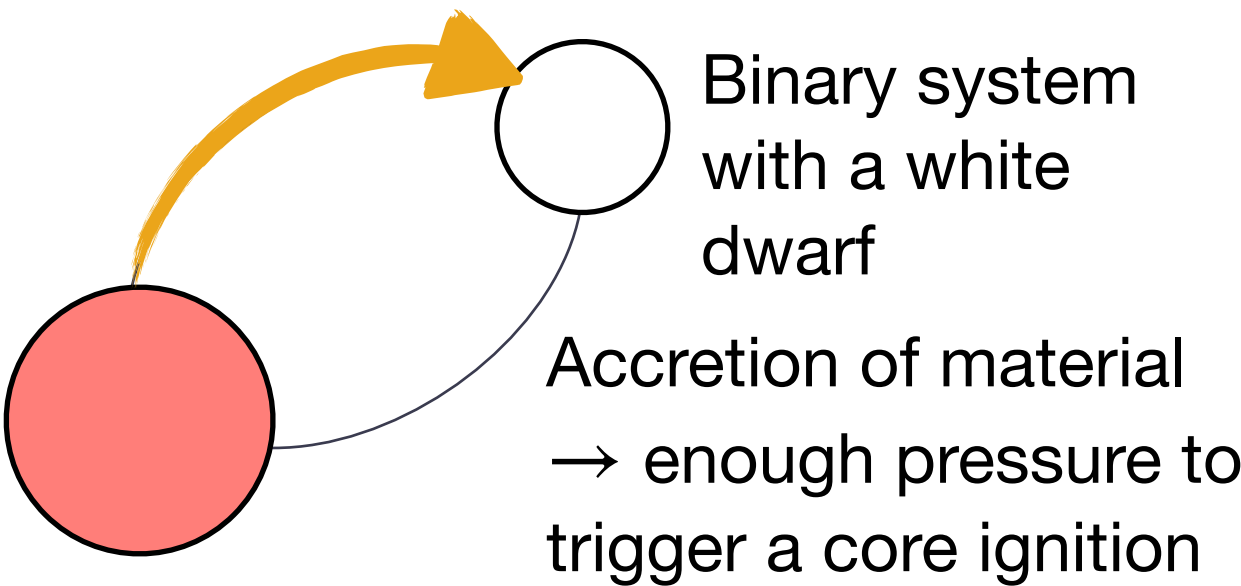
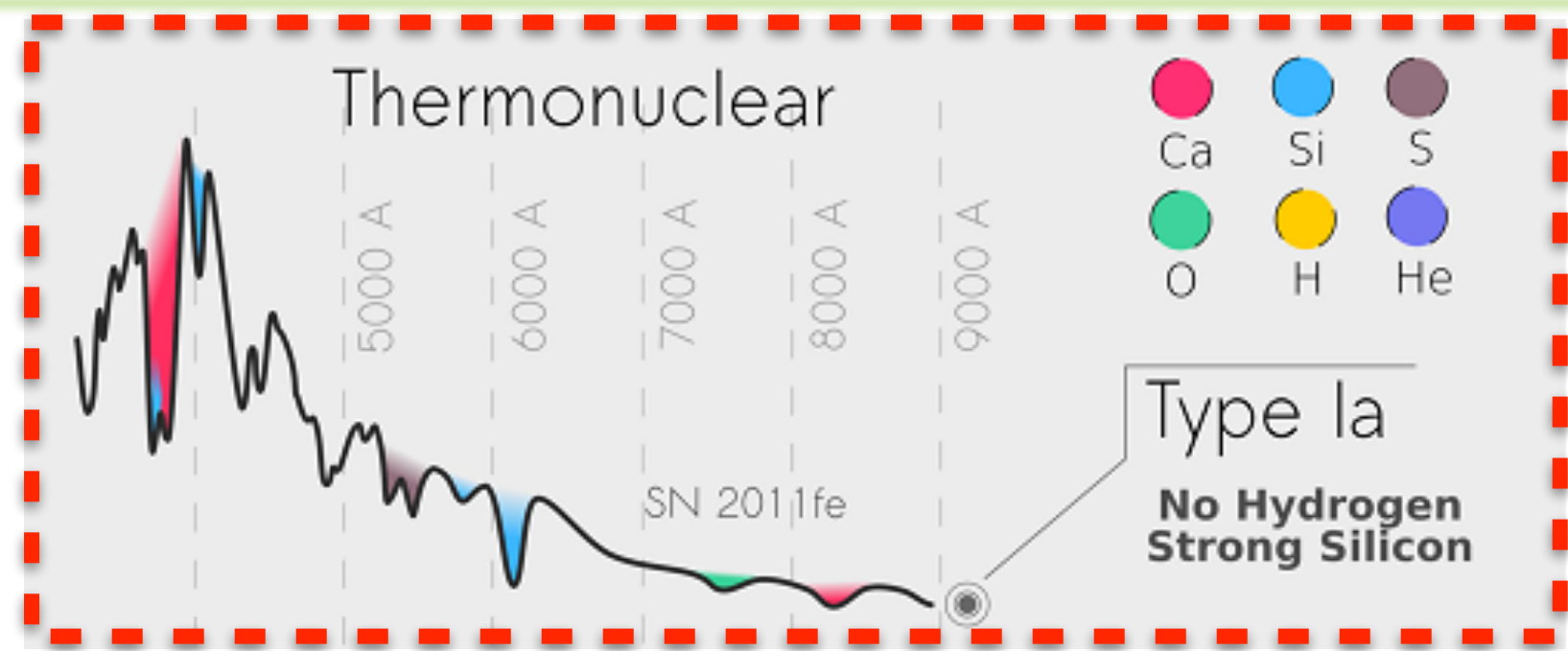


*Thank you for the
attention!*

ご清聴ありがとうございました

Backup

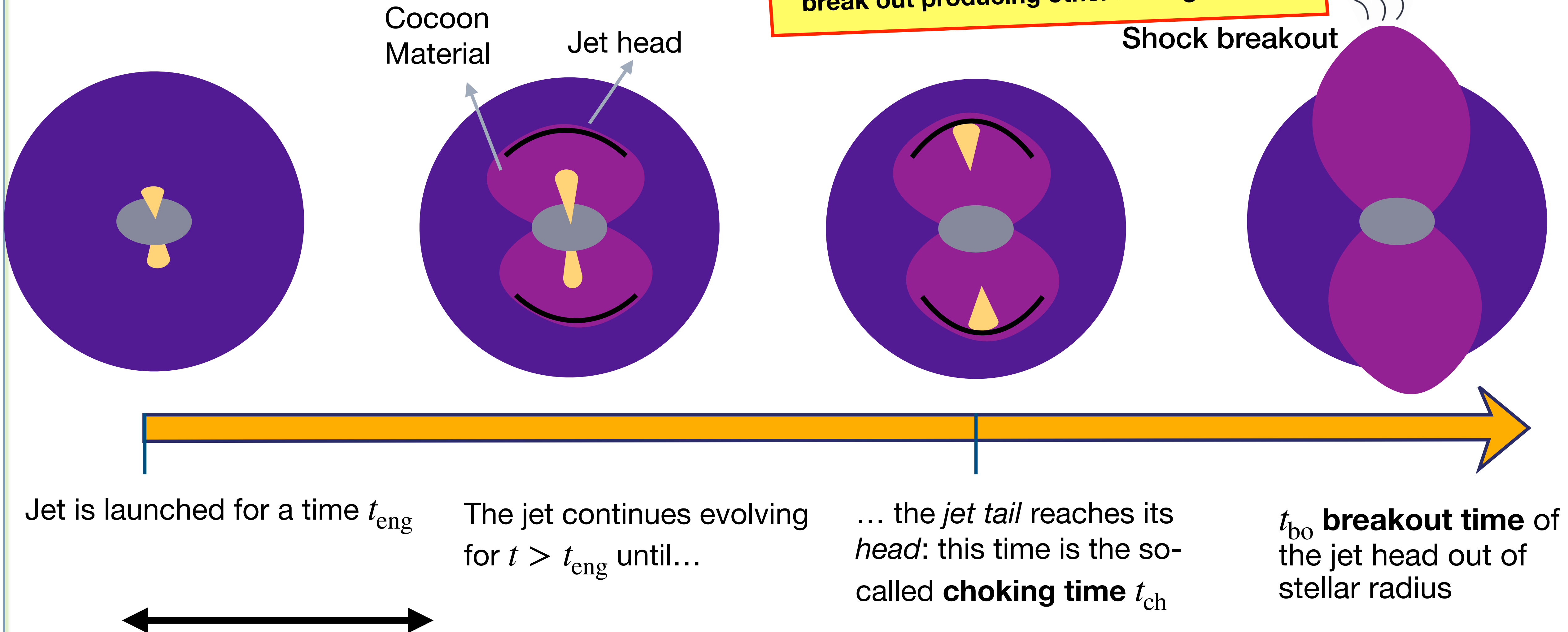
SNe classification



Dynamics of relativistic choked jets

!!!

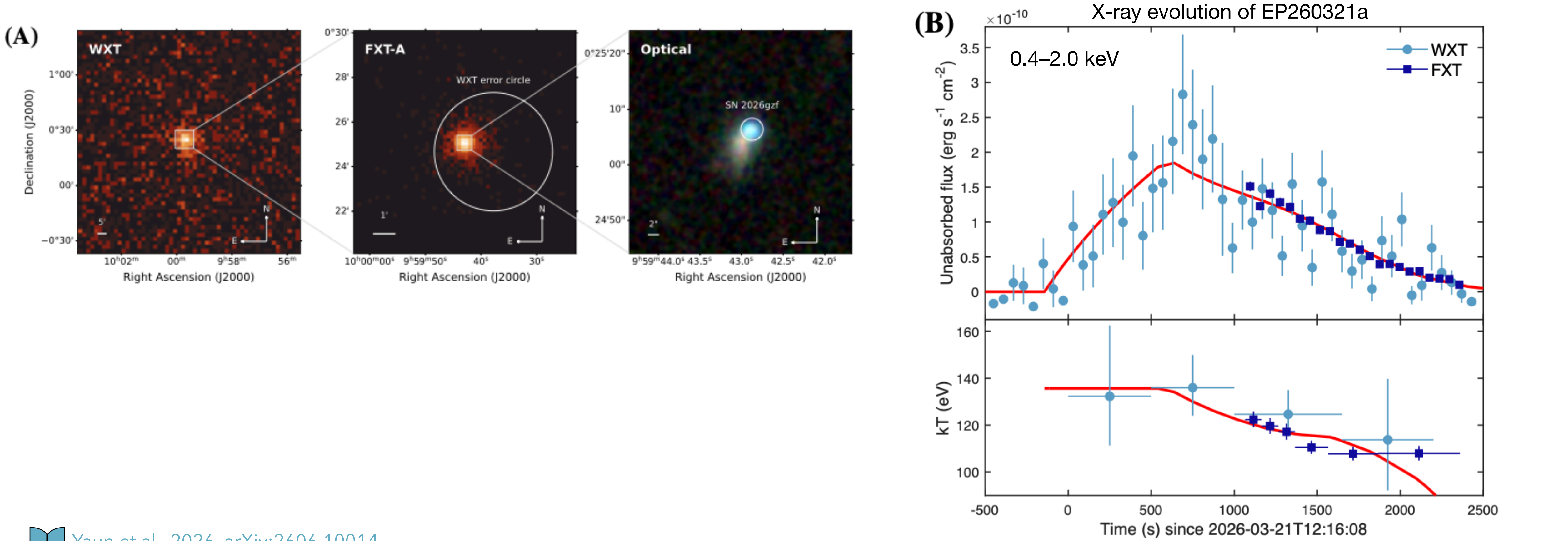
The jet is choked but ... the *cocoon* can still break out producing other EM signatures



A few interesting perspectives ...

A few months ago, *Einstein Probe* caught the second X-ray shock breakout in 20 years (EP260321a/SN 2026gzf), the faintest SBO associated with a Type Ic-BL SN, and no associated GRB (candidate choked jet) [Connor et al., 2026, ApJL 1006 L13](#)

The first one was SN2008D (Type Ib SN), which was associated with an X-ray burst detected by *Swift*.

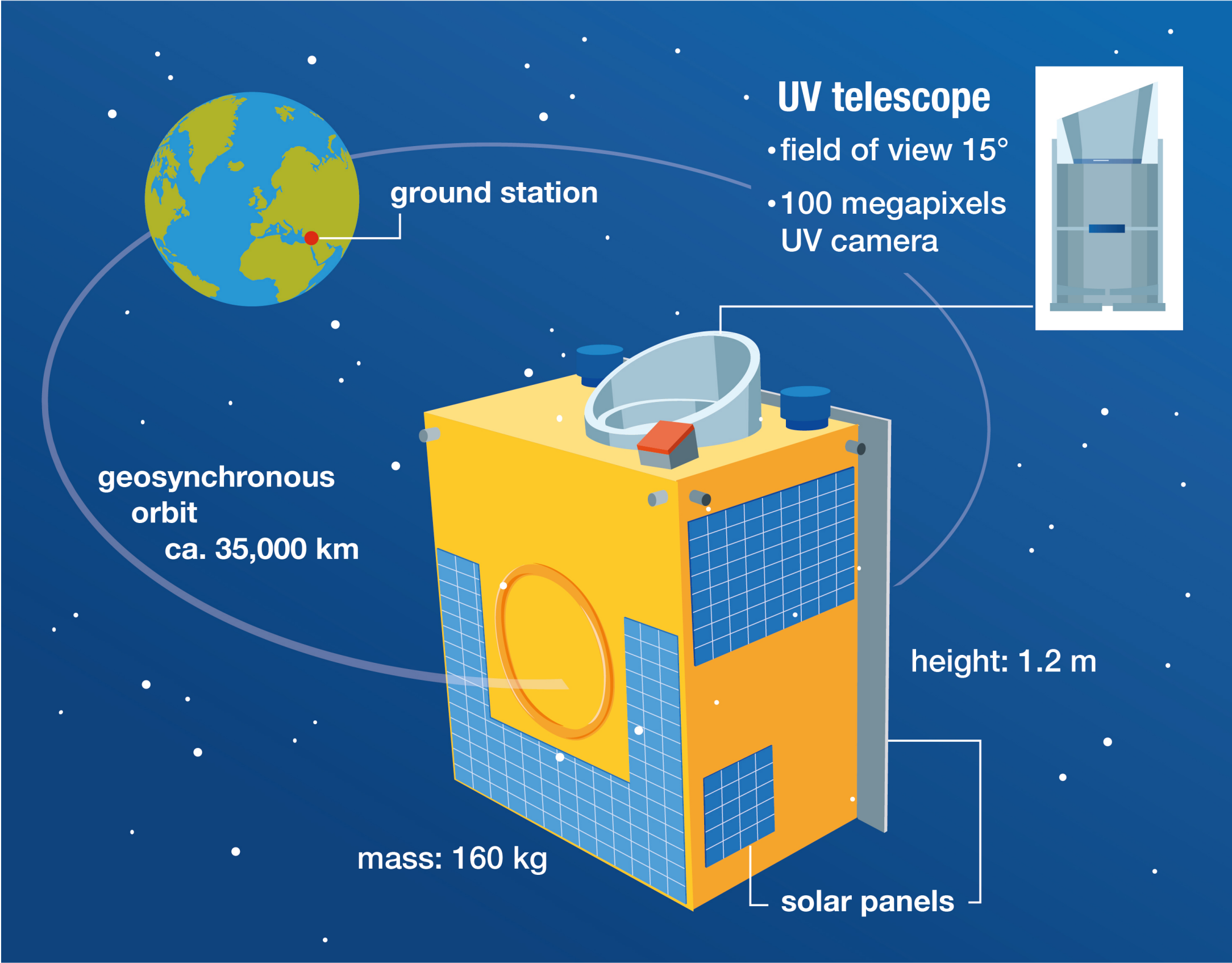


[Yaun et al., 2026, arXiv:2606.10014](#)

Ultraviolet Transient Astronomy Satellite



An eye in the UV sky with the **U**ltraviolet **T**ransient **A**stronomy **S**atellite (ULTRASAT)
Expected to be launched in 2028



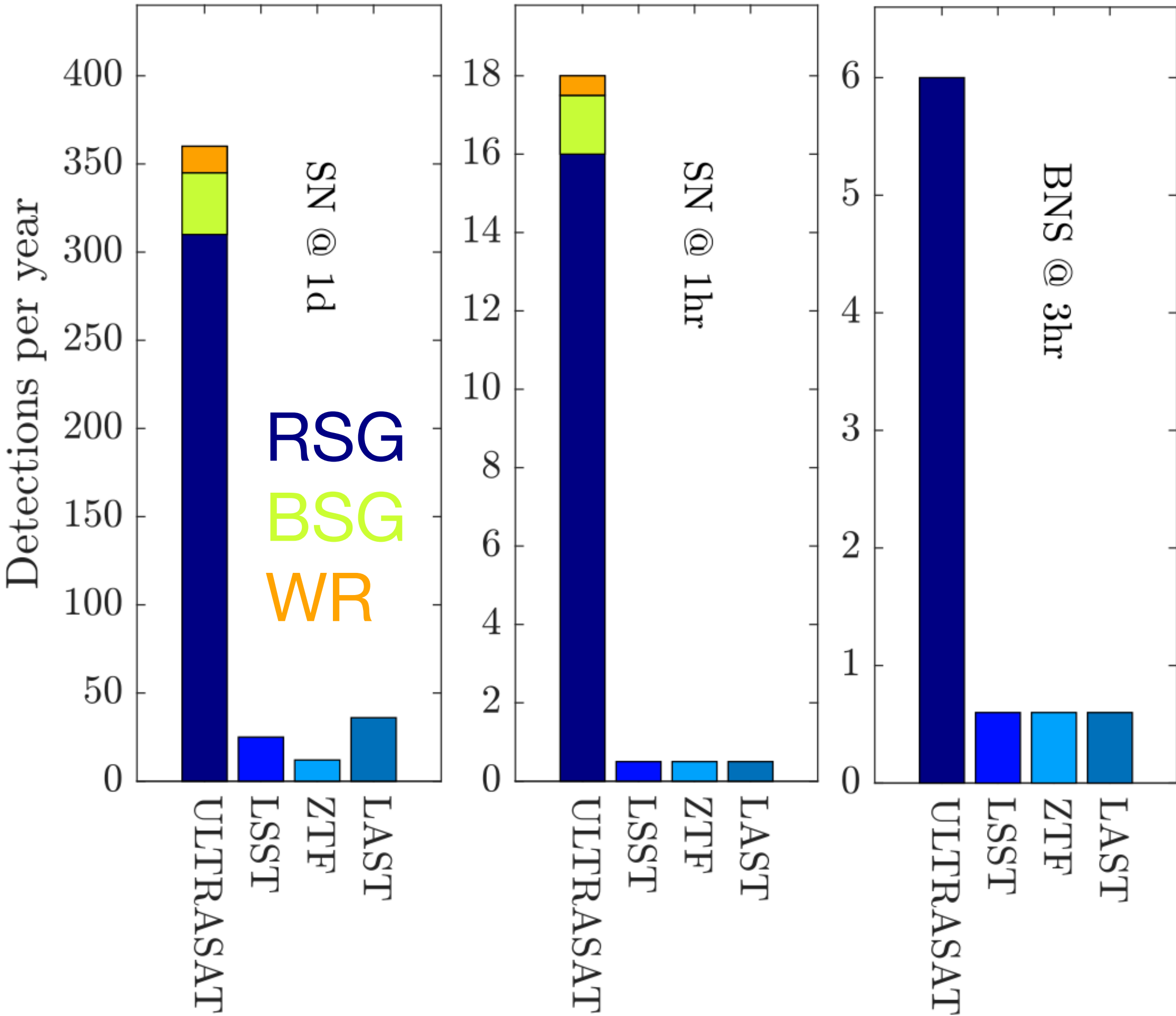
Source: Weizmann Institute of Science / DESY

ULTRASAT Key Properties		
Property	Value	Comments
Mission lifetime	3 years	Propellent for 6 years
Orbit	GEO	
Total FoV	204 deg ²	Unprecedented FoV
Operation waveband	230-290 nm	Near-UV band
Cadence	300 s	For the high cadence survey
Mean effective PSF	8.3"	In central 170 deg ² For T = 20,000 K blackbody source
Mean limiting magnitude (in 900s, 5σ)	22.4 ABmag	In central 170 deg ² For T = 20,000 K blackbody source

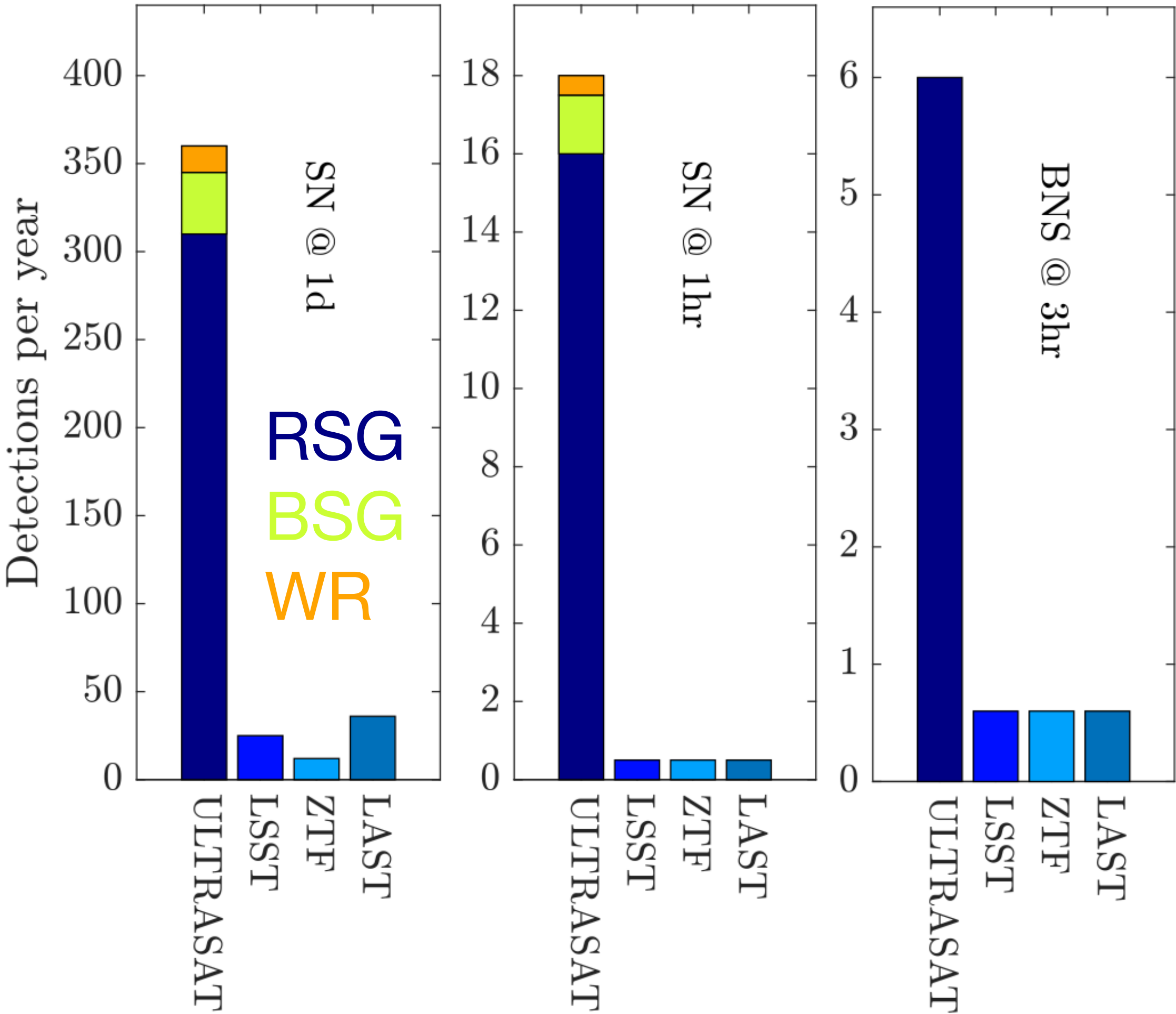
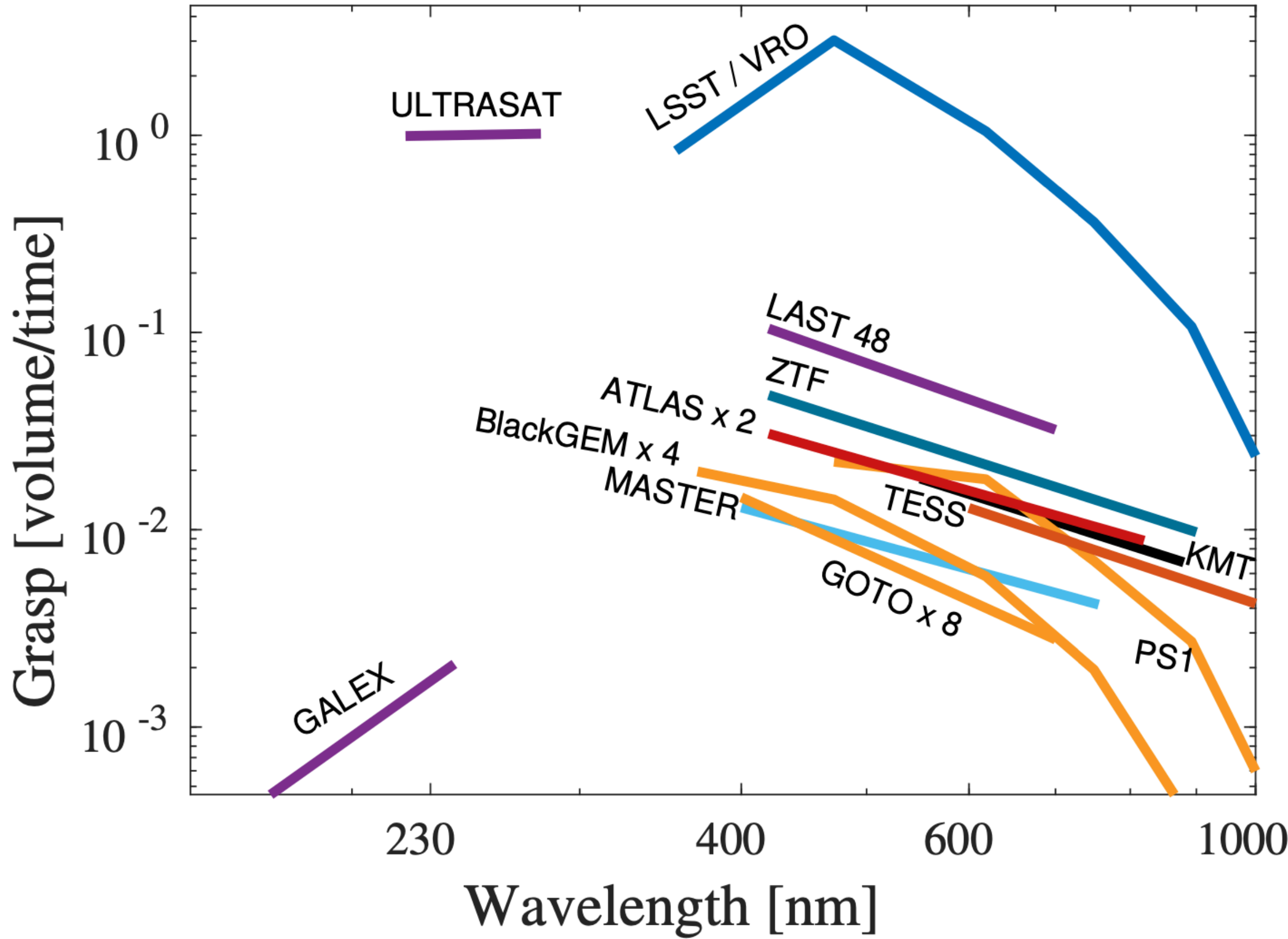
Ultraviolet Transient Astronomy Satellite



Source Type	# Events per 3 yr mission
Supernovae	
Shock break-out and Early (shock cooling) of core collapse SNe	> 40
Superluminous SNe	> 500
Type Ia SNe	> 250
	> 1000
Gamma Ray Bursts	
GRBs occurring in-field	~ 30
Orphan Afterglows	> 30

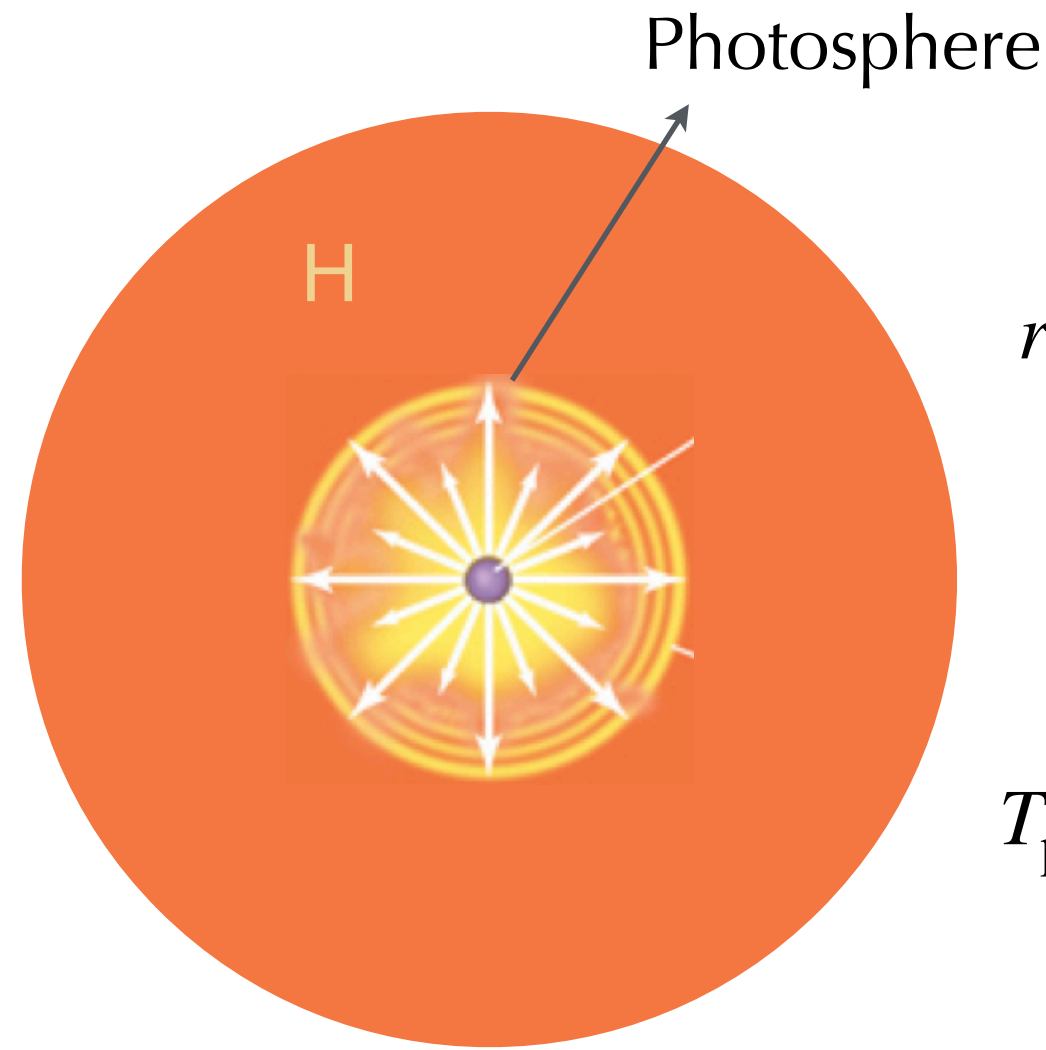


ULTRASAT vs other EM facilities



Early UV/optical emission from choked jets embedded in CCSNe

Model from  [Waxman et al., ApJ 667, 351 \(2007\), Rabinak & Waxman, ApJ 728, 63 \(2011\)](#)



$$r_{\text{ph}}(t) = \begin{cases} 3.3 \times 10^{14} f_{\rho}^{-0.062} \frac{E_{51}^{0.41} k_{0.34}^{0.093}}{(M_{\text{ej}}/M_{\odot})^{0.31}} t_5^{0.81} \text{ cm} & (n = 3/2) \\ 3.3 \times 10^{14} f_{\rho}^{-0.036} \frac{E_{51}^{0.39} k_{0.34}^{0.11}}{(M_{\text{ej}}/M_{\odot})^{0.28}} t_5^{0.78} \text{ cm} & (n = 3) \end{cases}$$

$$T_{\text{ph}}(t) = \begin{cases} 1.6 f_{\rho}^{-0.037} \frac{E_{51}^{0.027} R_{*,13}^{1/4}}{(M_{\text{ej}}/M_{\odot})^{0.054} k_{0.34}^{0.28}} t_5^{-0.45} \text{ eV} & (n = 3/2) \\ 1.6 f_{\rho}^{-0.022} \frac{E_{51}^{0.016} R_{*,13}^{1/4}}{(M_{\text{ej}}/M_{\odot})^{0.033} k_{0.34}^{0.27}} t_5^{-0.47} \text{ eV} & (n = 3) \end{cases}$$

R_* = progenitor radius

f_{ρ} = factor related to the average ejecta density (it varies linearly with mass of progenitors M)

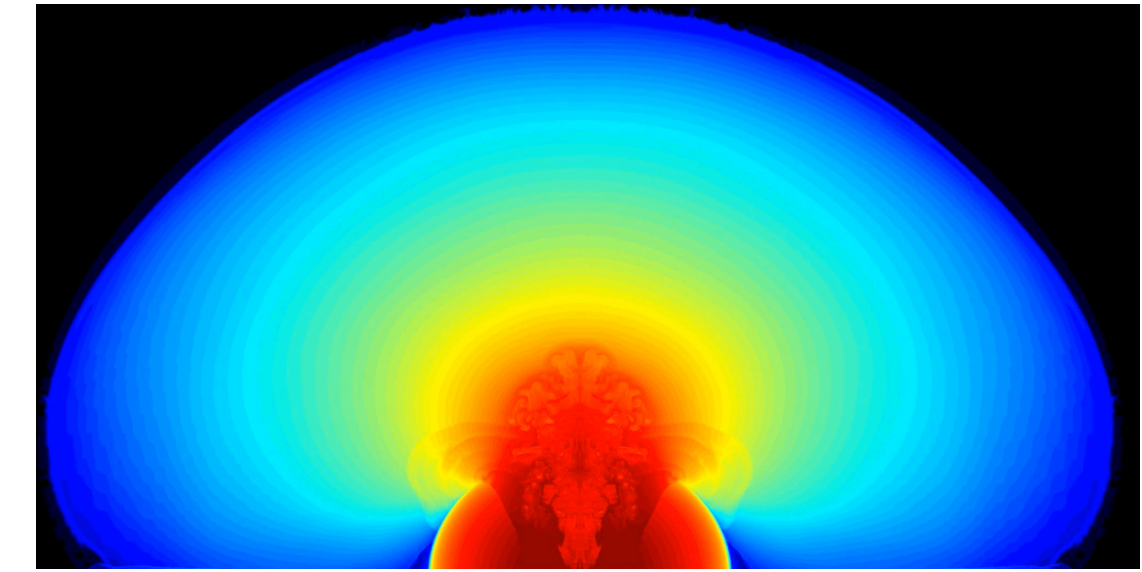
k = opacity of the stellar envelope in $\text{cm}^2 \text{ g}^{-1}$

$E = 10^{51} E_{51} \text{ erg}$ = released energy

$t = 10^5 t_5 \text{ s}$ = time from the shock breakout

$n = 3/2$ for convective envelopes (RSGs), and $n = 3$ for radiative envelopes (BSGs)

Model specific intensity observed in UV/optical



Black-Body radiation modified by **extinction**

$$f_{\lambda}(\lambda, t) = \left(\frac{r_{\text{ph}}}{D_L(z)} \right)^2 \sigma T_{\text{ph}}^4 \frac{T_{\text{col}}}{hc} g_{BB}(x) e^{-\tau_{\lambda}}$$

$$g_{BB}(x) = \frac{15}{\pi^4} \frac{x^5}{e^x - 1}$$

$$x = hc/\lambda T_{\text{col}}$$

$T_{\text{col}} \simeq 1.2 T_{\text{ph}}$ = color temperature, i.e., temperature at which a black body would emit radiation of the same color of a given source

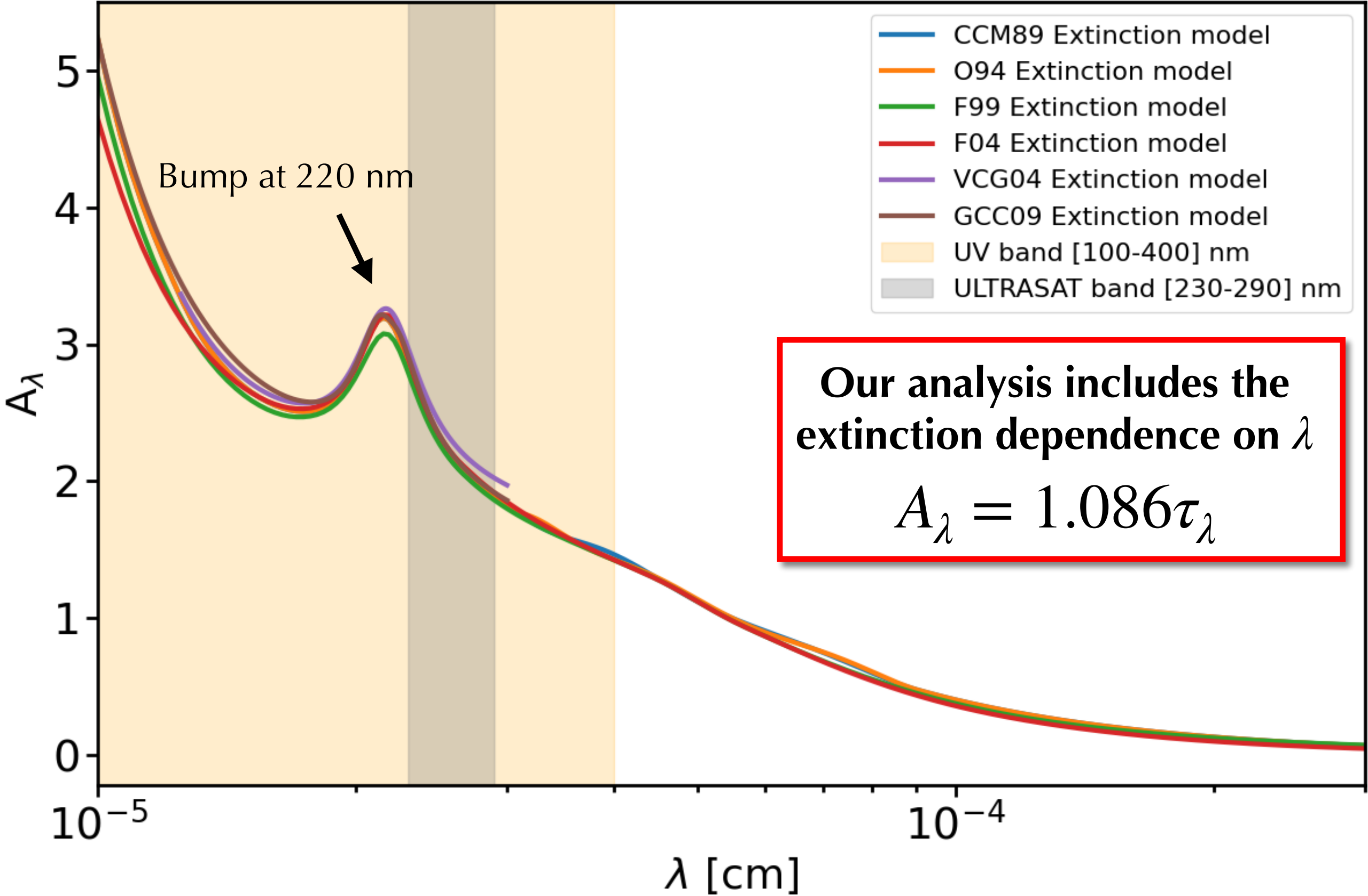
τ_{λ} = extinction optical depth at a given wavelength λ

 A. Zegarelli, D. Guetta, S. Celli, S. Gagliardini, I. Di Palma, and I. Bartos, A&A, 690, A187 (2024)

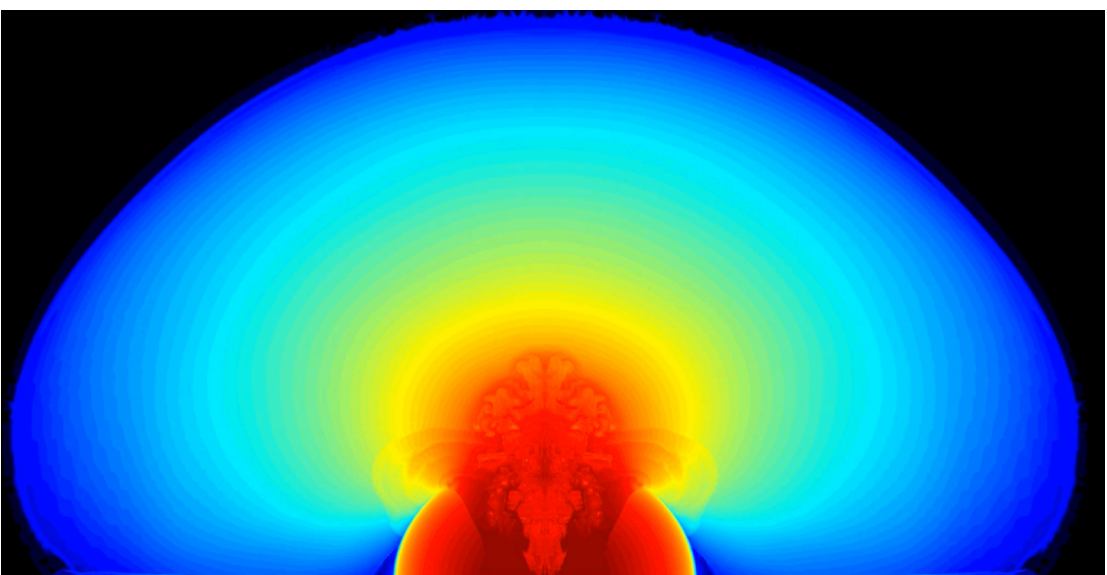
Early UV/optical emission from choked jets embedded in CCSNe

Model from  [Waxman et al., ApJ 667, 351 \(2007\)](#), [Rabinak & Waxman, ApJ 728, 63 \(2011\)](#)

The extinction is very pronounced at UV wavelengths



Model specific intensity observed in UV/optical



Black-Body radiation modified by extinction

$$f_\lambda(\lambda, t) = \left(\frac{r_{\text{ph}}}{D_L(z)} \right)^2 \sigma T_{\text{ph}}^4 \frac{T_{\text{col}}}{hc} g_{BB}(x) e^{-\tau_\lambda}$$

$$g_{BB}(x) = \frac{15}{\pi^4} \frac{x^5}{e^x - 1}$$
$$x = hc/\lambda T_{\text{col}}$$

$T_{\text{col}} \simeq 1.2 T_{\text{ph}}$ = color temperature, i.e., temperature at which a black body would emit radiation of the same color of a given source
 τ_λ = extinction optical depth at a given wavelength λ

 A. Zegarelli, D. Guetta, S. Celli, S. Gagliardini, I. Di Palma, and I. Bartos, A&A, 690, A187 (2024)

Dust extinction

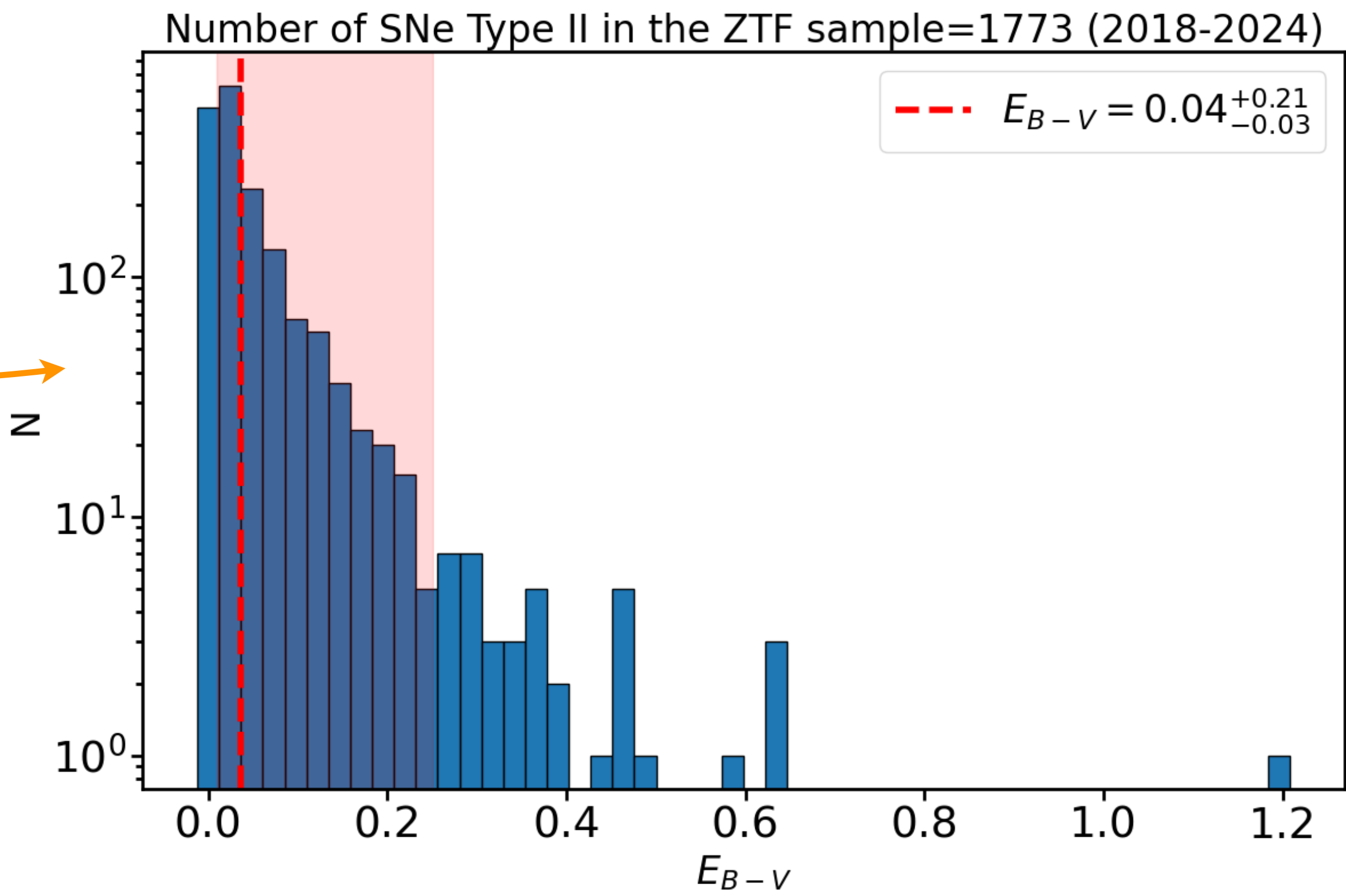
$$f_{\text{obs}}(\lambda) = f_{\lambda}(\lambda, t) = \left(\frac{r_{\text{ph}}}{D_L(z)} \right)^2 \sigma T_{\text{ph}}^4 \frac{T_{\text{col}}}{hc} g_{BB}(x) e^{-\tau_{\lambda}} = f_{\text{int}}(\lambda) e^{-\tau_{\lambda}}$$

$$f_{\text{obs}}(\lambda) = f_{\text{int}}(\lambda) e^{-\tau_{\lambda}} = f_{\text{int}}(\lambda) 10^{-0.4 A_{\lambda}}$$

Observed color excess
 $E_{B-V} = E_{B-V}^{\text{observed}} - E_{B-V}^{\text{intrinsic}}$

$$A_{\lambda} = 1.086 \tau_{\lambda} = \underbrace{k(\lambda)}_{\text{Reddening curve}} \underbrace{E_{B-V}}_{\text{Observed color excess}} = k(\lambda) \frac{A_V}{R_V}$$

We adopt the averaged dust extinction model from [Cardelli et al. \(1989\)](#) for diffuse interstellar medium in the Milky Way with $R_V = 3.1$



Distribution of Galactic extinction values for galaxies hosting Type II SNe detected by the Zwicky Transient Facility (ZTF)
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Cooling UV/optical signal after SBO in RSGs and BSGs



RSG



BSG

From SN II observations
 Ganot et al. 2022

$R_* = 722 R_\odot$
 $E = 1 \times 10^{51}$ erg
 $M_{\text{ej}} = 2.8 M_\odot$
 $f_\rho = 1.455$

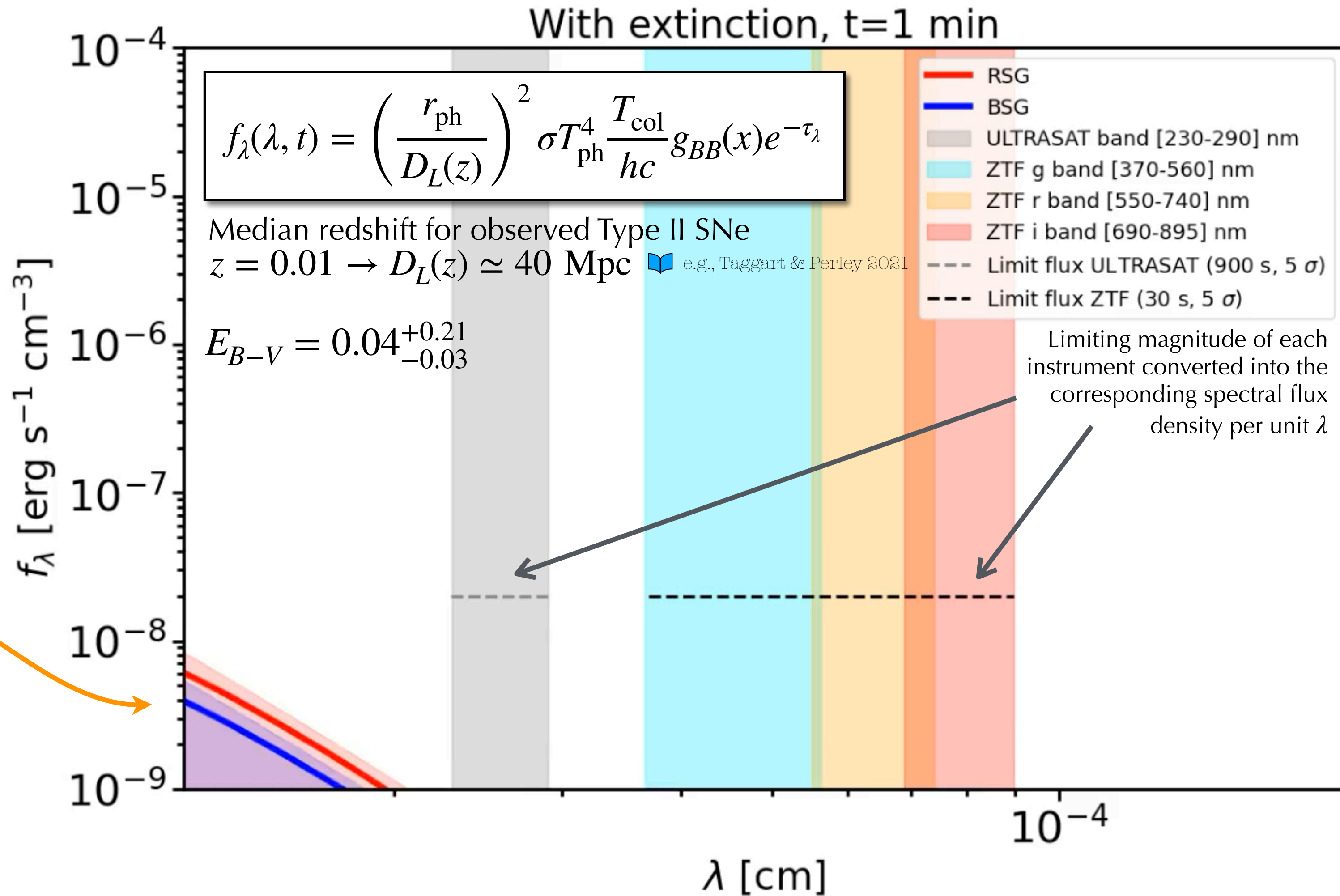
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Reddening curve

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A. Zegarelli, D. Guetta, S. Celli, S. Gagliardini, I. Di Palma, and I. Bartos, A&A, 690, A187 (2024)

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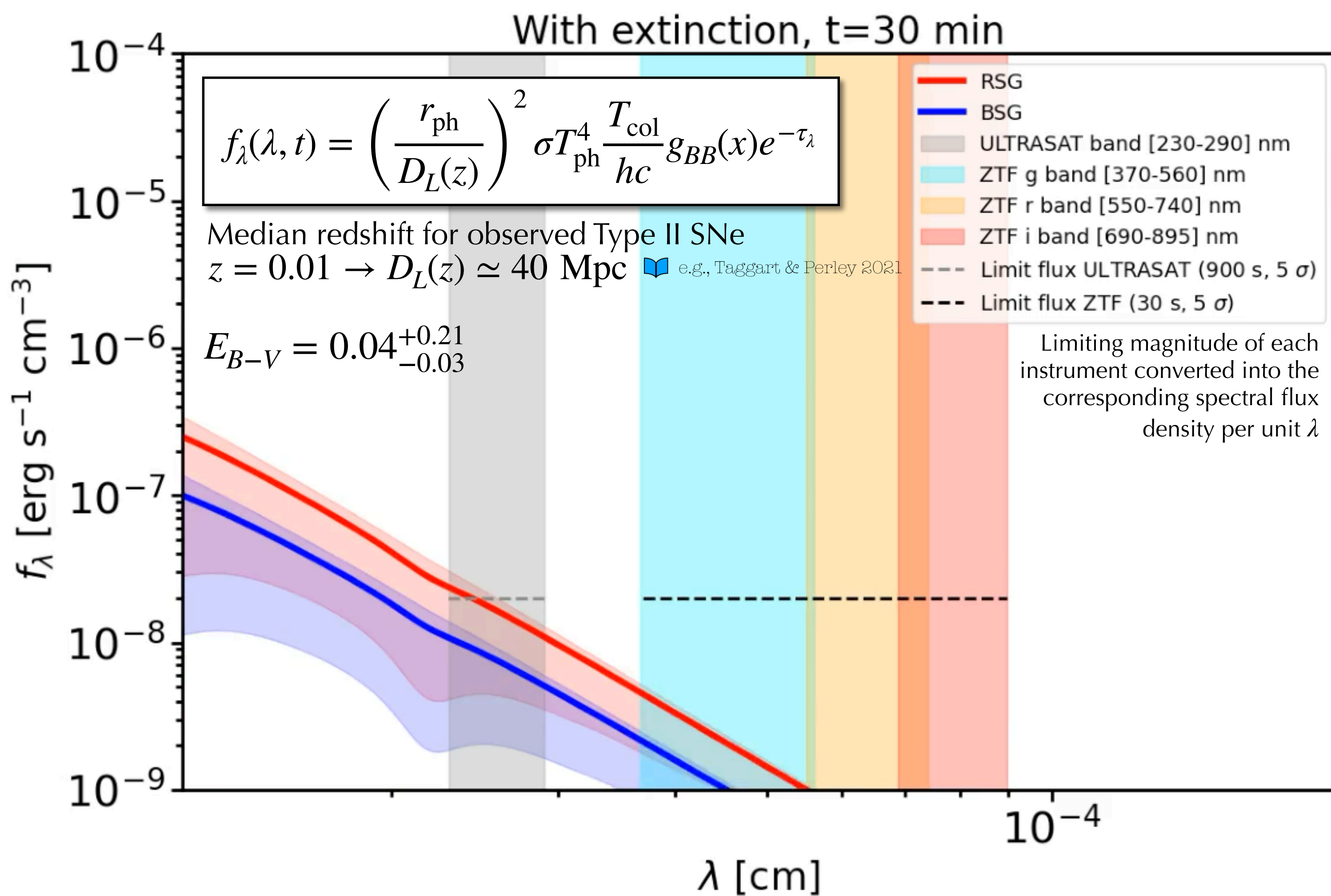
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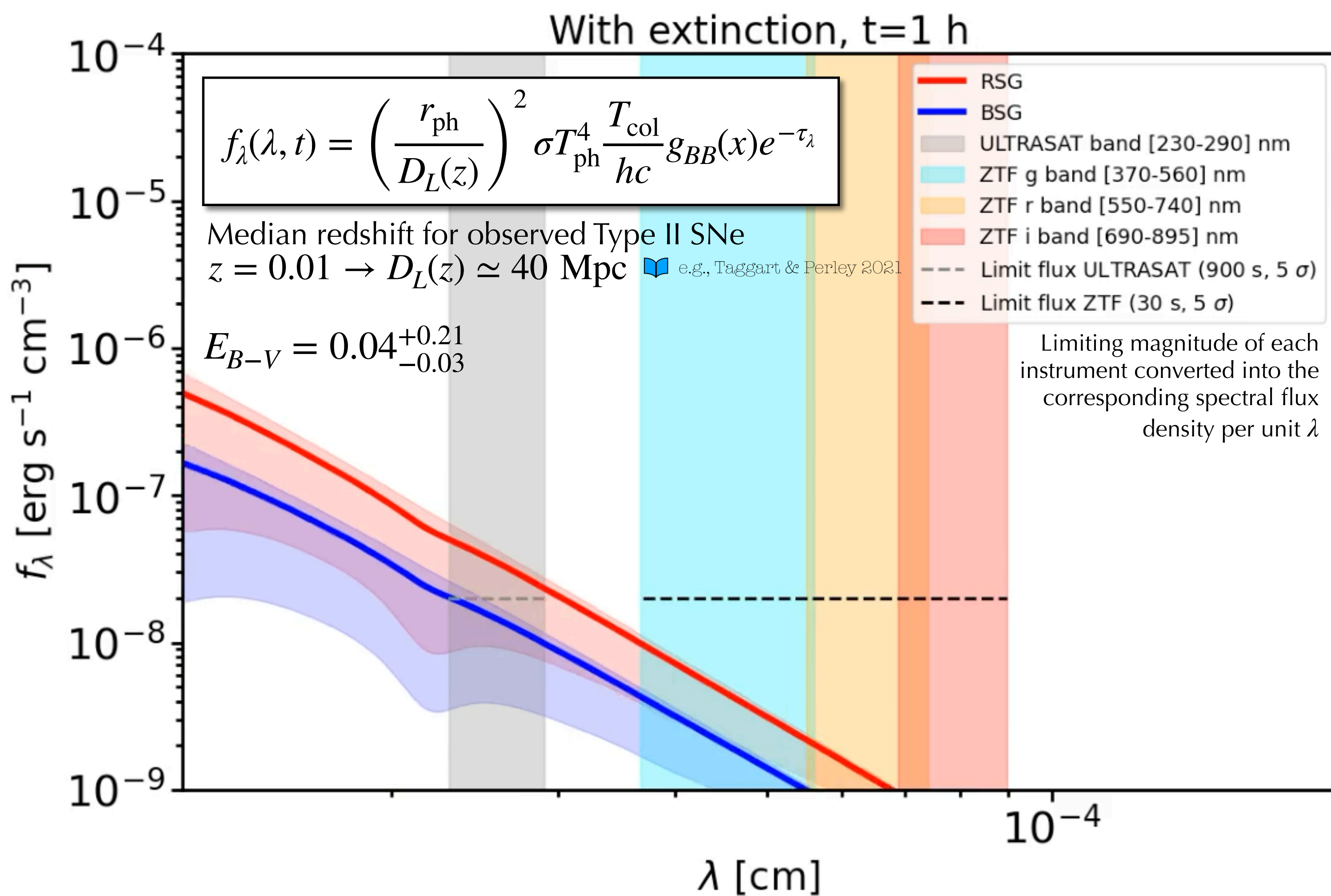
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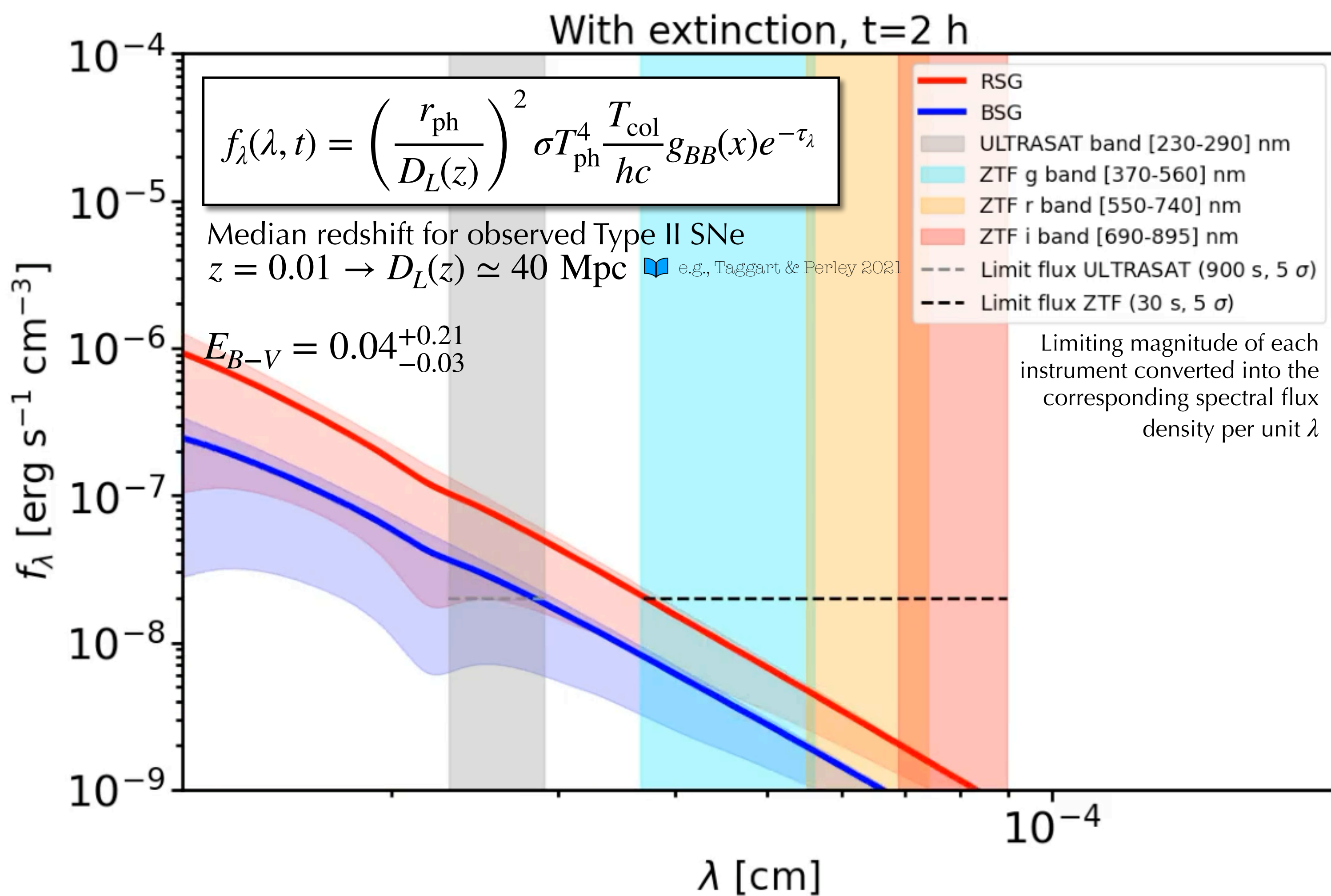
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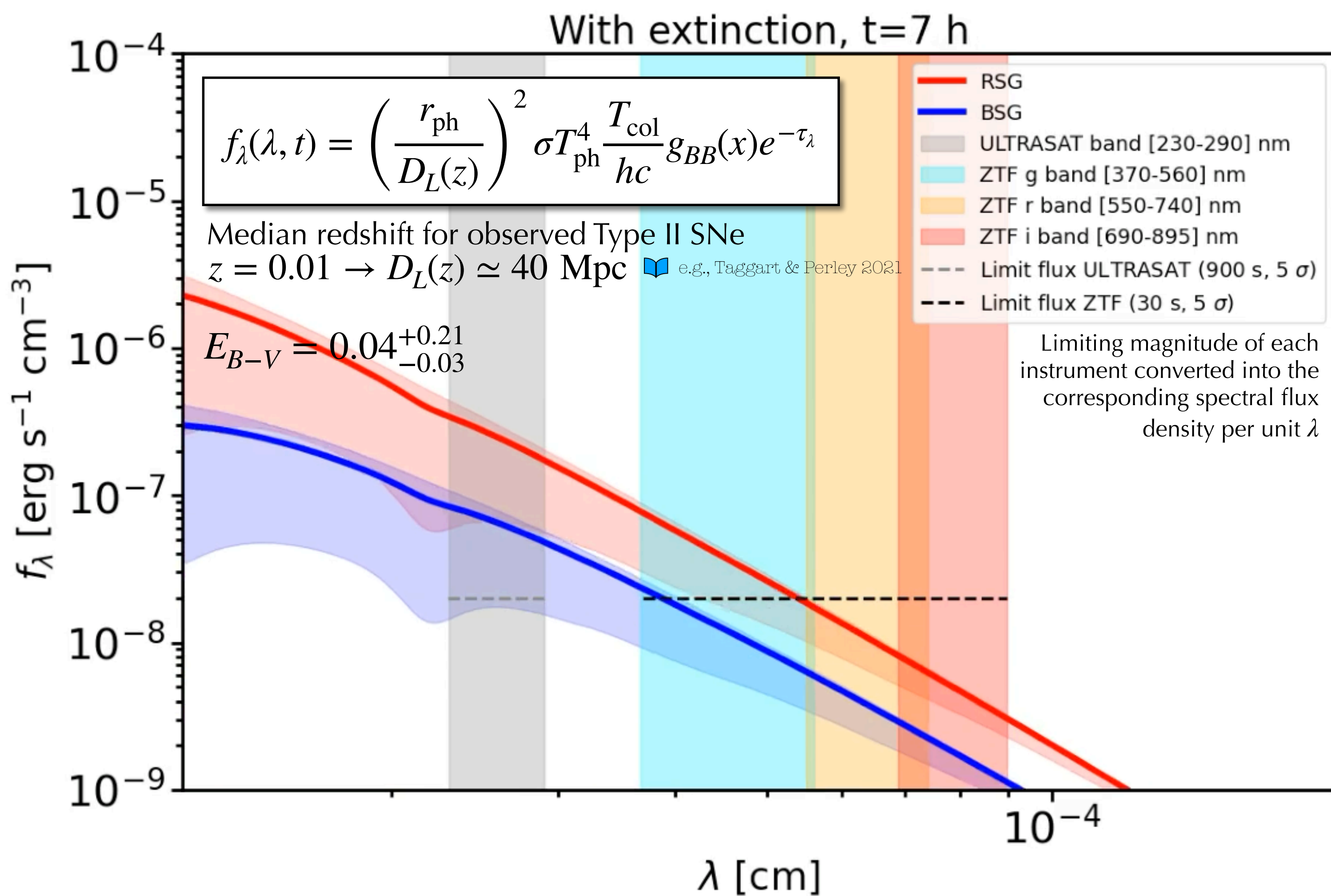
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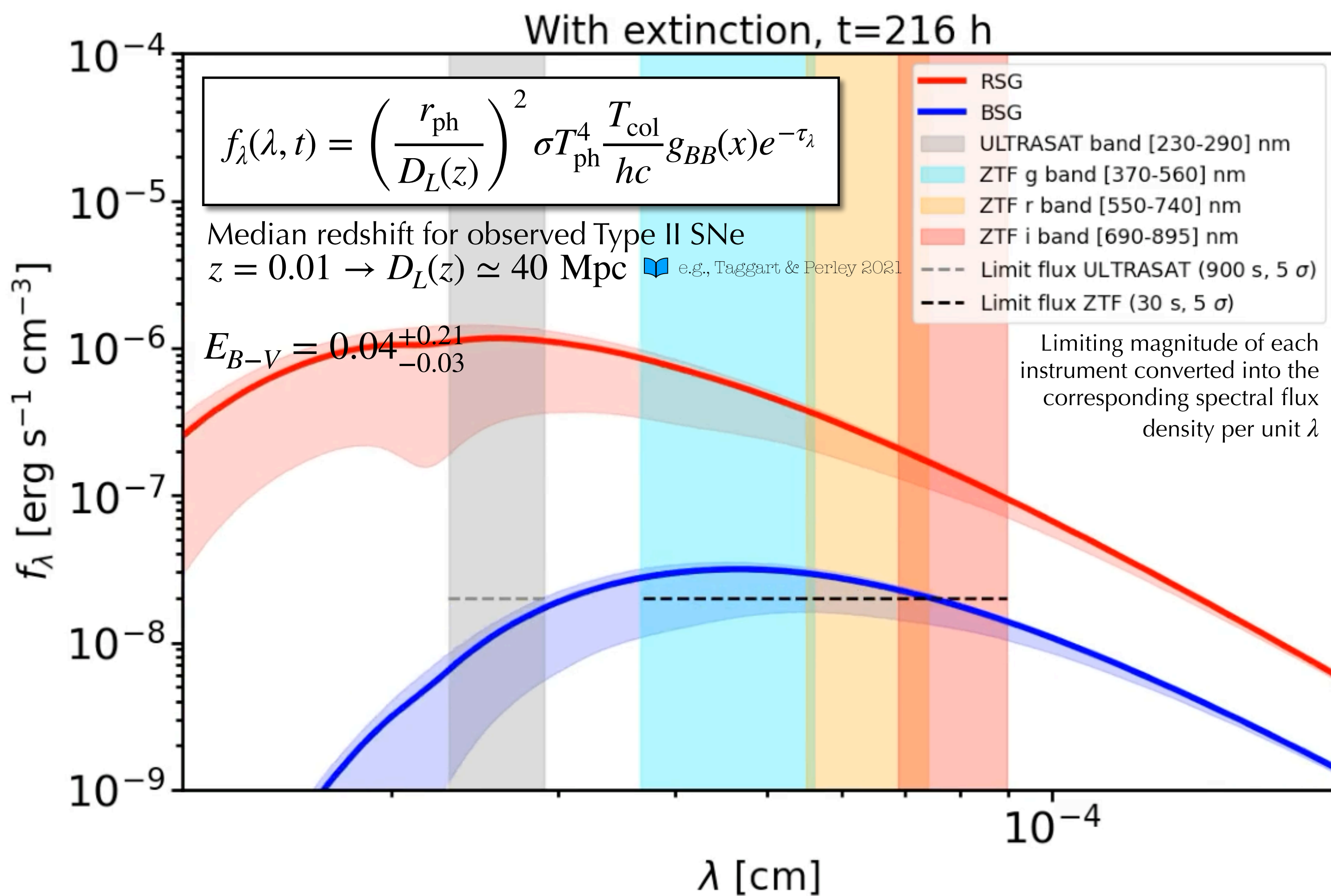
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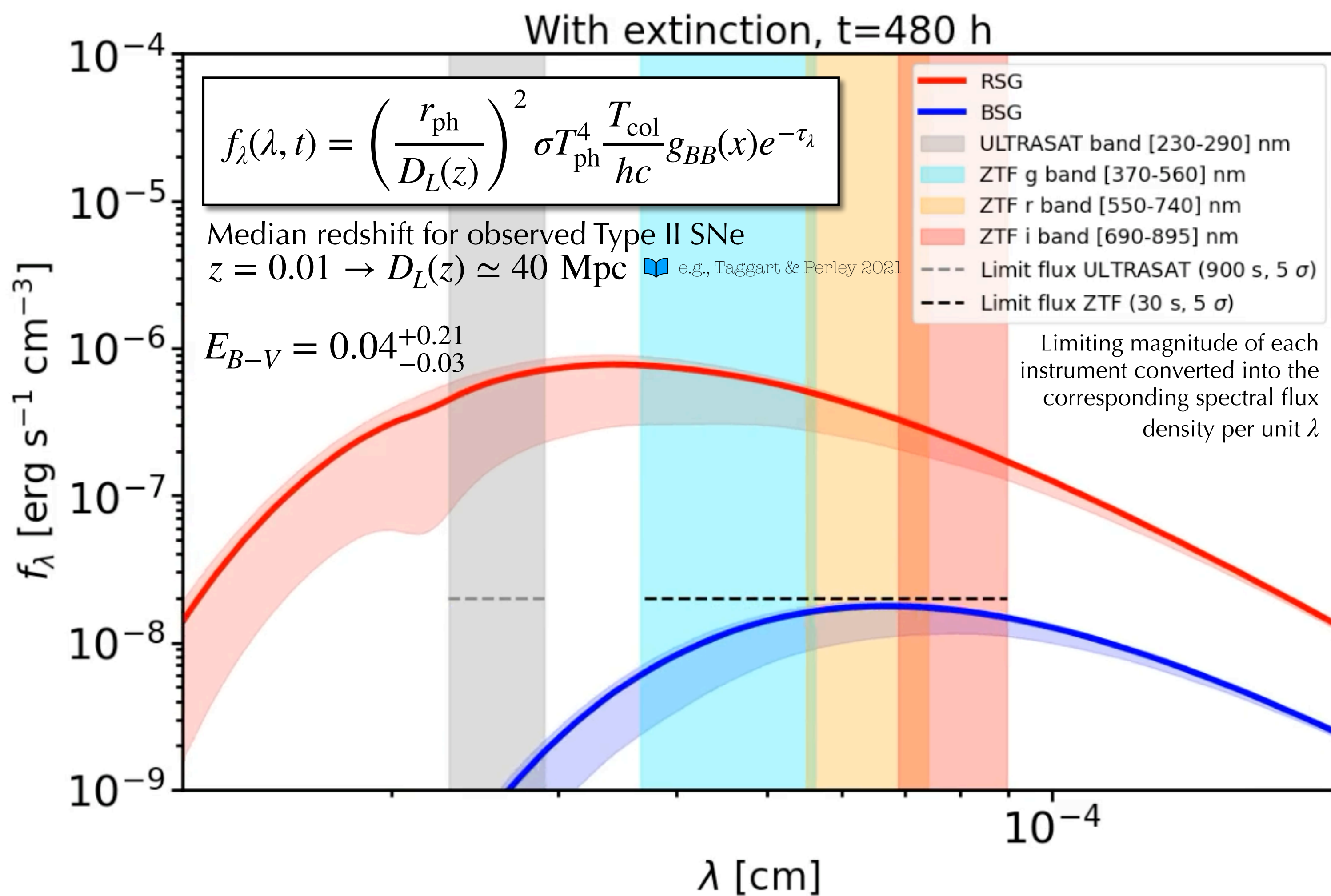
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A. Zegarelli, D. Guetta, S. Celli, S. Gagliardini, I. Di Palma, and I. Bartos, A&A, 690, A187 (2024)

Computation of rate of events

$$\forall t \rightarrow \dot{N} = \underbrace{\int d\Omega}_{\text{Telescope FoV}} \int_0^{z_{\text{lim}}} \frac{dN(z)}{dz} dz = \int d\Omega \int_0^{z_{\text{lim}}} \underbrace{\frac{R(z)}{1+z}}_{\text{Comoving rate of sources}} \underbrace{\frac{dV(z)}{dz}}_{\text{Differential comoving volume}} dz$$
$$R(z) = R_0 \frac{(1+z)^{2.7}}{1 + \left(\frac{1+z}{2.9}\right)^{5.6}}$$

Telescope FoV

This factor accounts for the cosmological time dilation of the observed rate

Differential comoving volume

Comoving rate of sources

The redshift dependence follows the star formation rate
Madau & Dickinson 2014

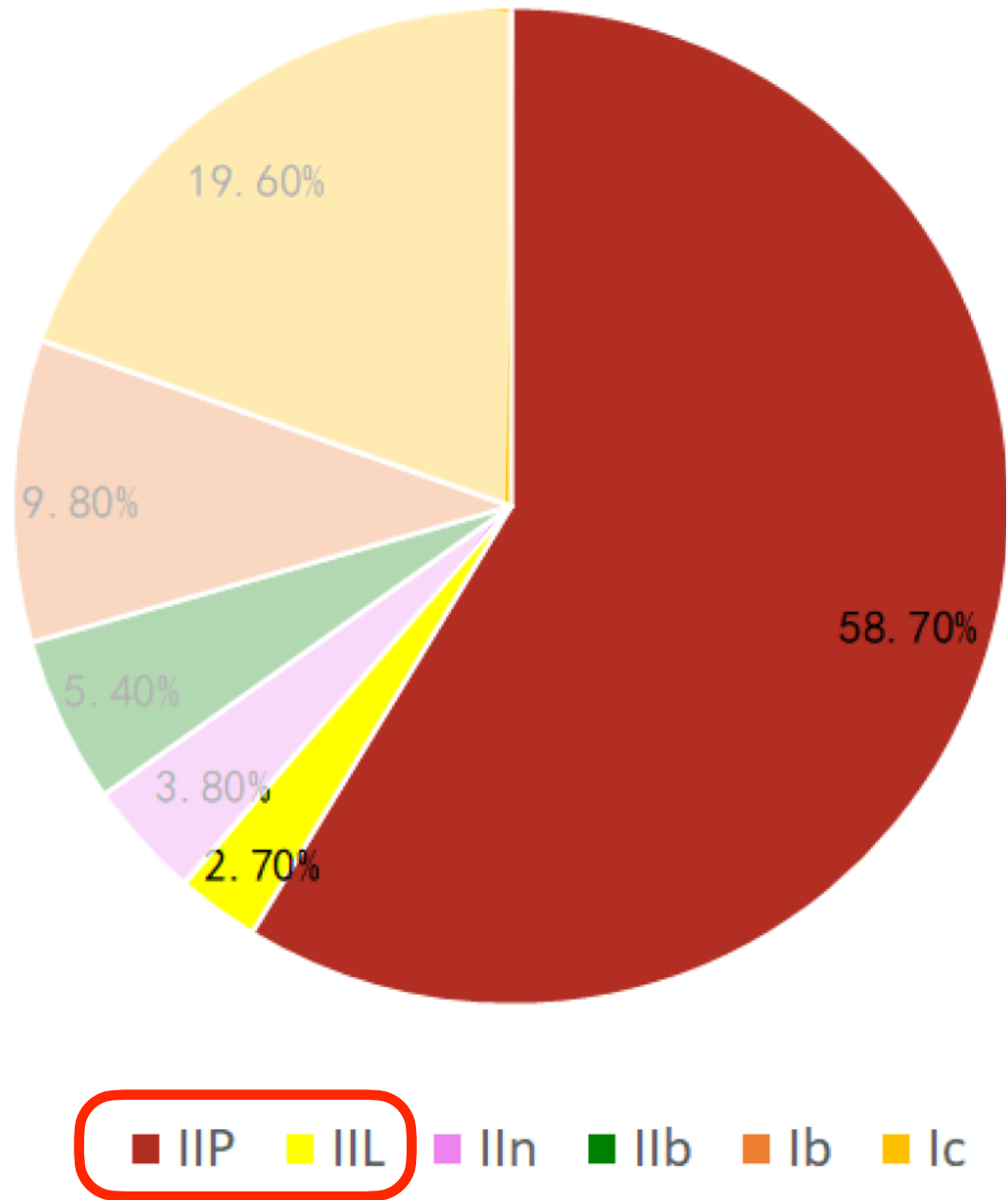
- Local rate R_0 of Type II SNe with no interaction with CSM taken as 60% of the total rate of Type II SNe $\rightarrow R_0 = 1.1 \times 10^{-5} \text{ Mpc}^{-3} \text{ yr}^{-1}$ [Li et al. 2011, Lin et al. 2023](#)
- On average, ratio between BSG and RSG stars in our Galaxy $\simeq 3$ [Eggenberger et al. 2002](#)



$$R_0 = 1.1 \times 10^{-5} \text{ Mpc}^{-3} \text{ yr}^{-1}$$



$$R_0 = 2.5 \times 10^{-5} \text{ Mpc}^{-3} \text{ yr}^{-1}$$



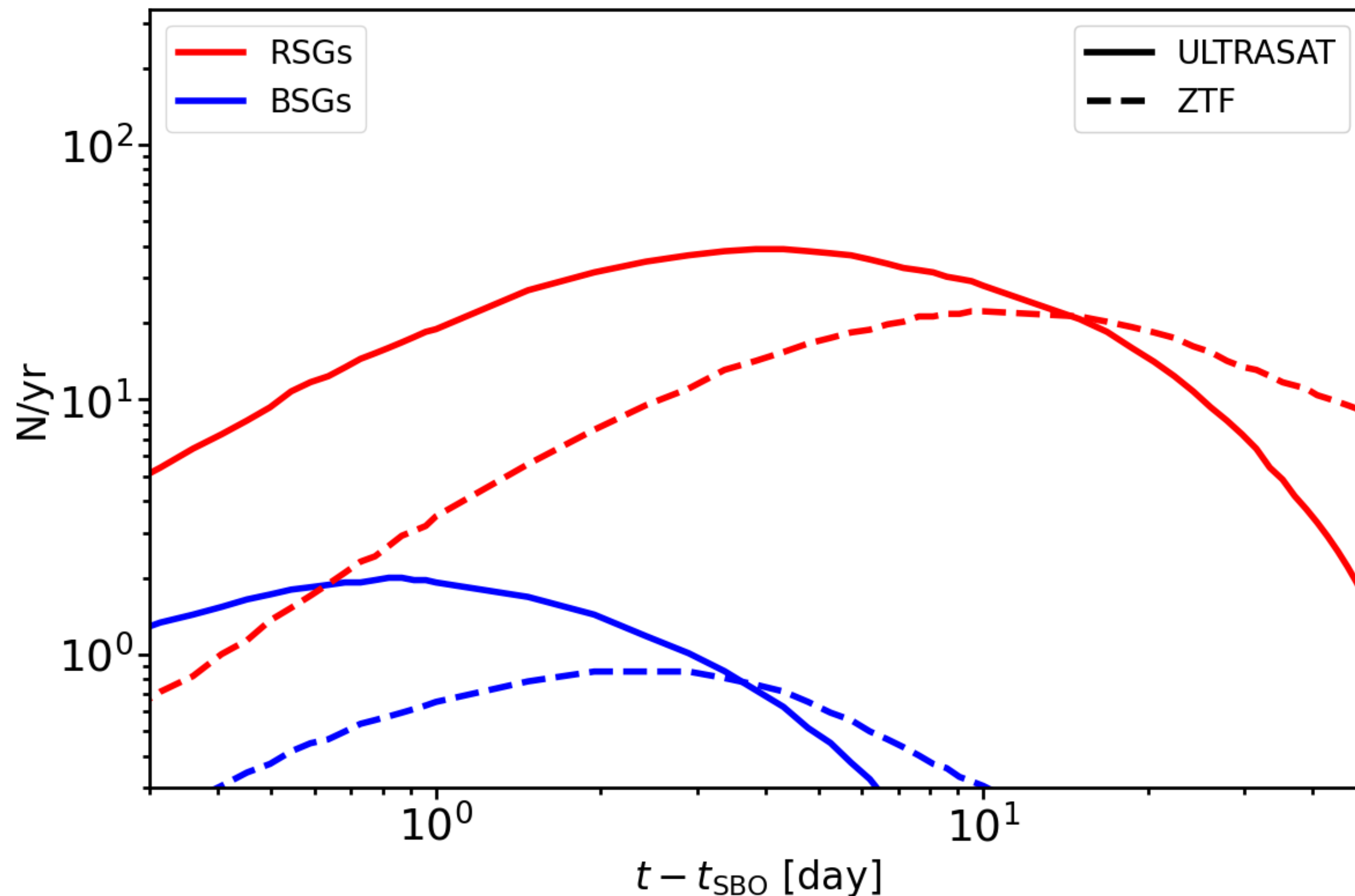
[A. Zegarelli, D. Guetta, S. Celli, S. Gagliardini, I. Di Palma, and I. Bartos, A&A, 690, A187 \(2024\)](#)

Computation of rate of events

Observation times in 1 hour:

ULTRASAT $\rightarrow 4 \times 900$ s, each covering FoV = 204 sqdeg

ZTF $\rightarrow 3750$ sqdeg + correction by instrument's duty cycle (e.g., it can operate only nightly and in good weather conditions)

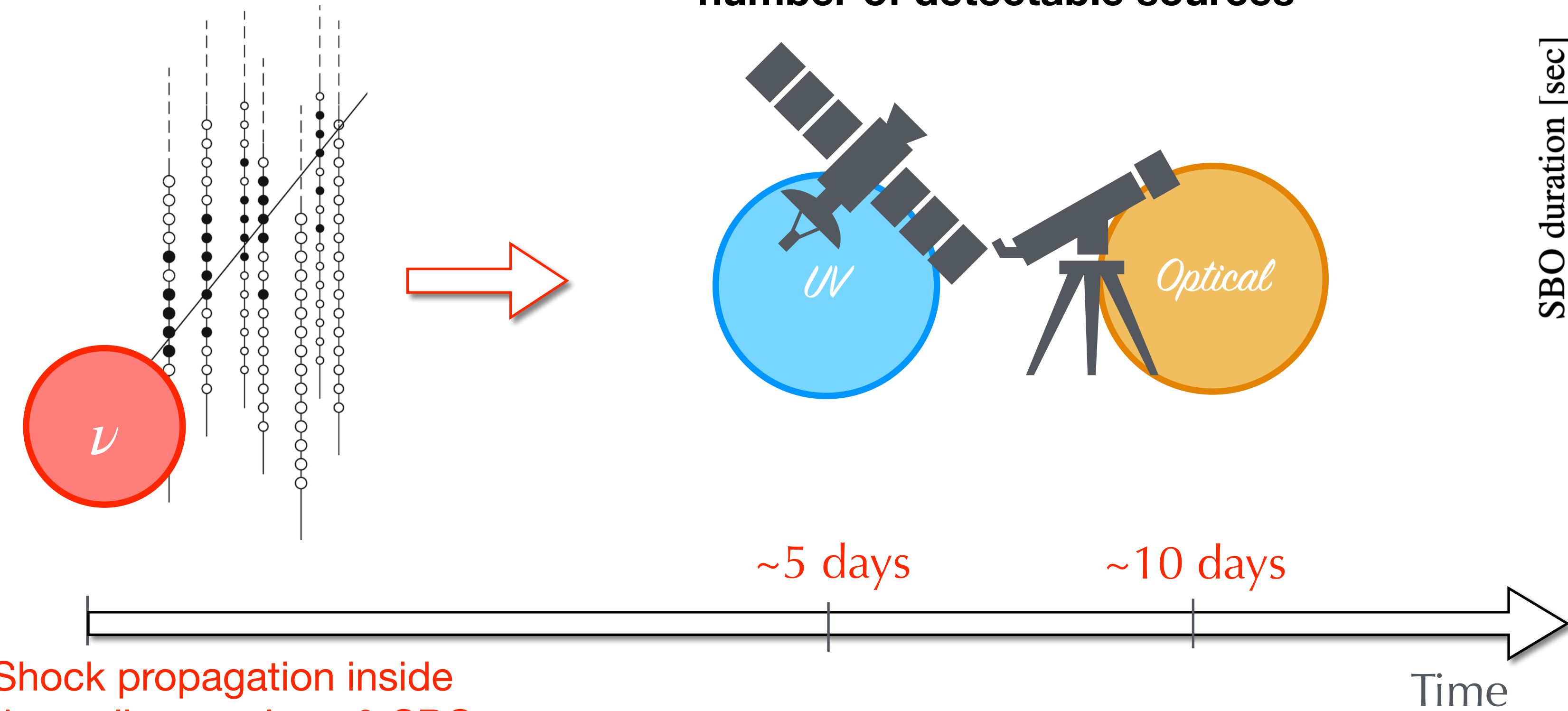


- Around **60% of Type II SNe from RSGs** can be accompanied also by an **optical detection** by ZTF, if it catches optical emission within around 10 days after the SBO (namely, **1 week after the UV detection**)
- **One source out of the three** detectable by **ULTRASAT** in one year for **Type II SNe from BSGs** may be associated with **optical measurements with ZTF**

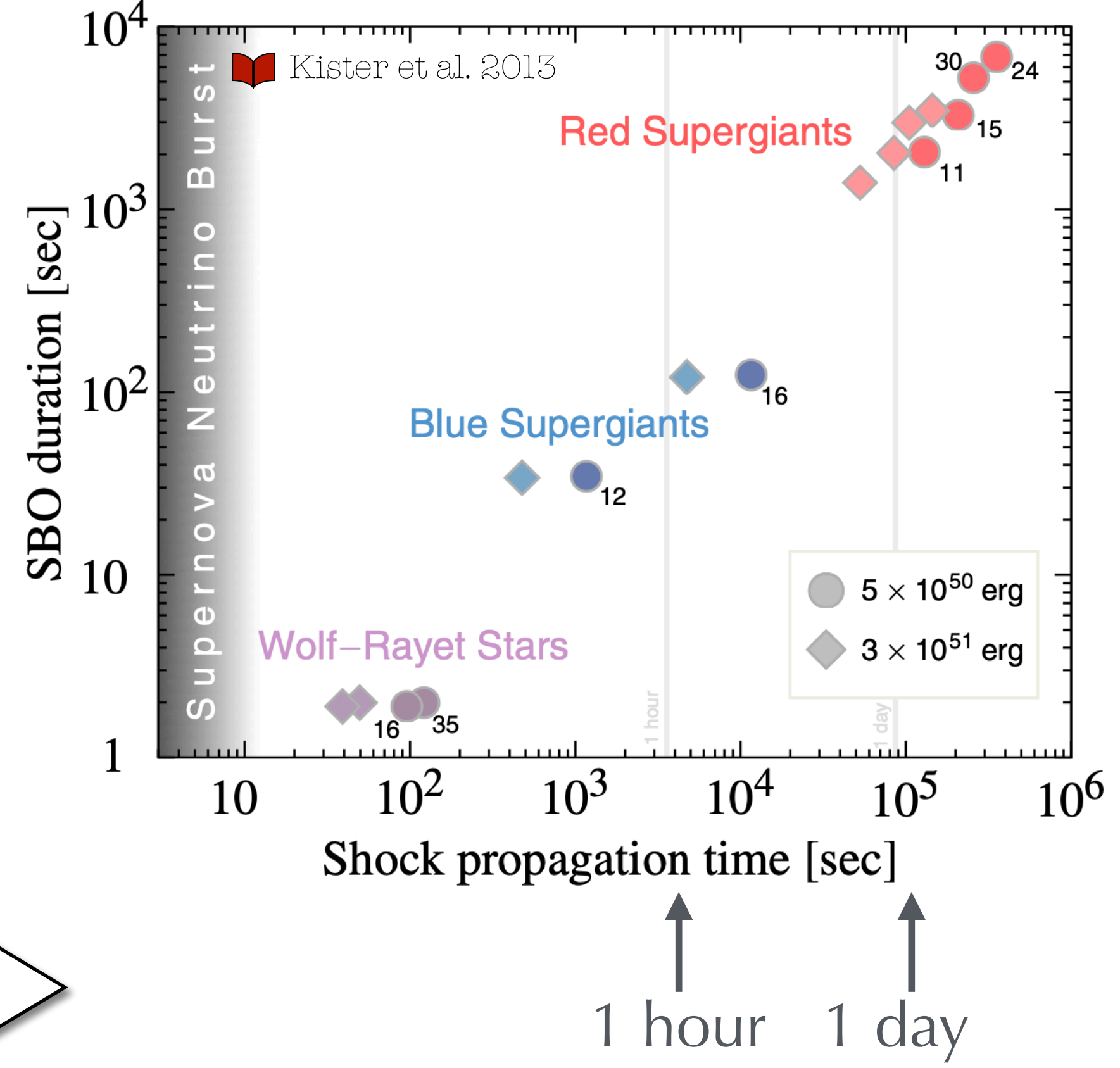
📖 A. Zegarelli, D. Guetta, S. Celli, S. Gagliardini, I. Di Palma, and I. Bartos, A&A, 690, A187 (2024)

High-energy ν - UV - optical follow-ups

1. **Neutrino alert** from Cherenkov-based high-energy neutrino telescopes (e.g., IceCube, KM3NeT)
2. ULTRASAT(ZTF-like telescopes) could point at the suggested direction in the sky within **~4(10) days** to search for possible EM counterparts **maximising the reachable sky volume and hence the number of detectable sources**



Shock propagation time inside the stellar envelope



📖 A. Zegarelli, D. Guetta, S. Celli, S. Gagliardini, I. Di Palma, and I. Bartos, A&A, 690, A187 (2024)



Simulation setup

Preliminary

📖 M.Pais, A. Zegarelli, E. Peretti, S. Celli, in prep. (2026)

- 2.5D spherical RMHD simulations performed with the PLUTO code (v4.4.3) 📖 Mignone et al., 2007
- Jet launch at $r_j = 10^4$ km, neglecting the accretion onto a central BH at the core (by-hand jet)
- Jet injected through a narrow nozzle
- Density profile for the stellar atmosphere:

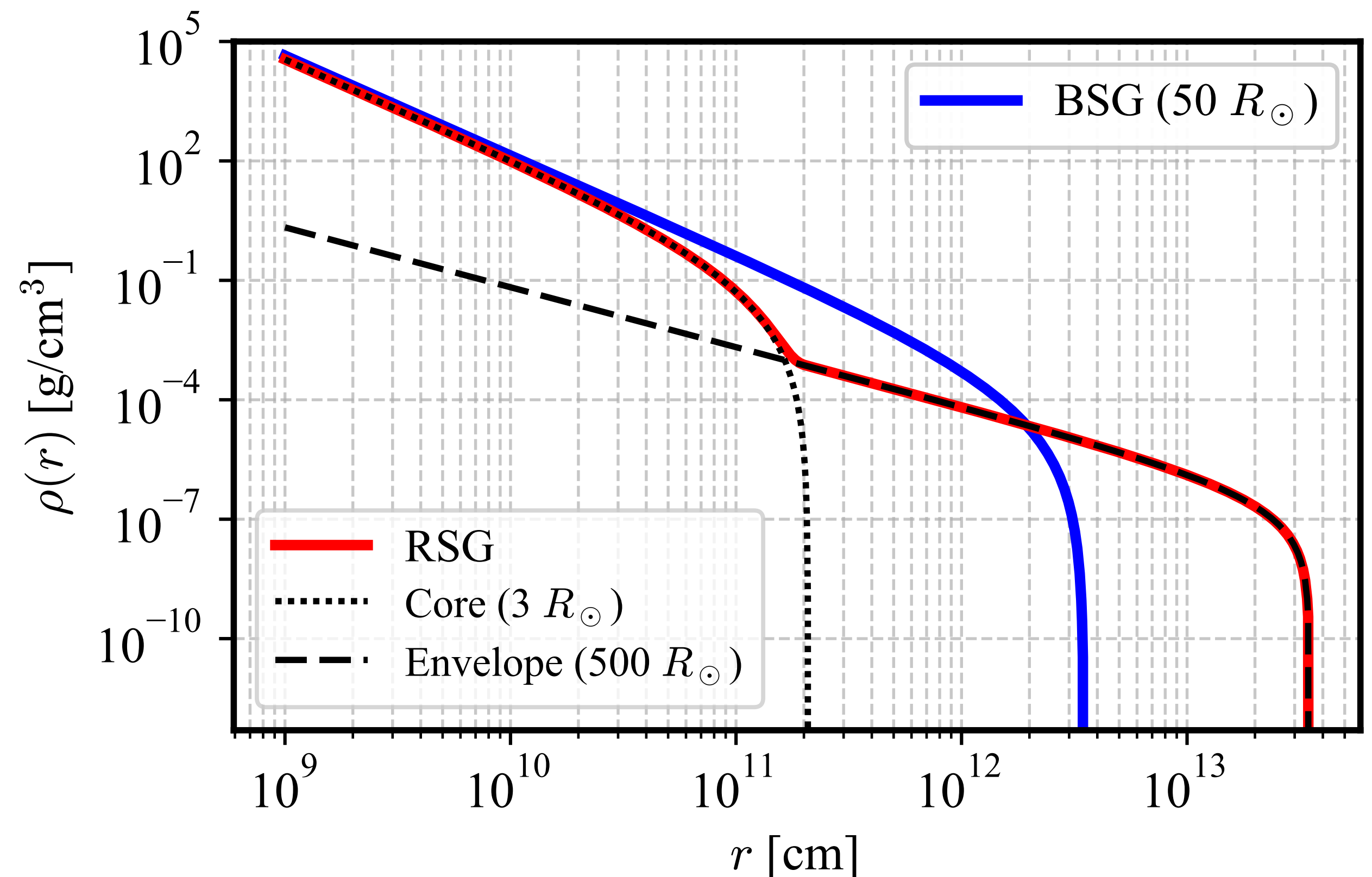
$$\rho(r) = \rho_0 \left(\frac{r}{R_*} \right)^{-\alpha} \left(1 - \frac{r}{R_*} \right)^n$$

For BSG, one polytrope with $\alpha = 2.5$ and $n = 3$

Wongwathanarat et al. 2017

For RSGs, we consider the sum of two polytropes, one for the core ($\alpha = 2.5, n = 3$) and one for the extended envelope ($\alpha = 1.5, n = 1.5$)

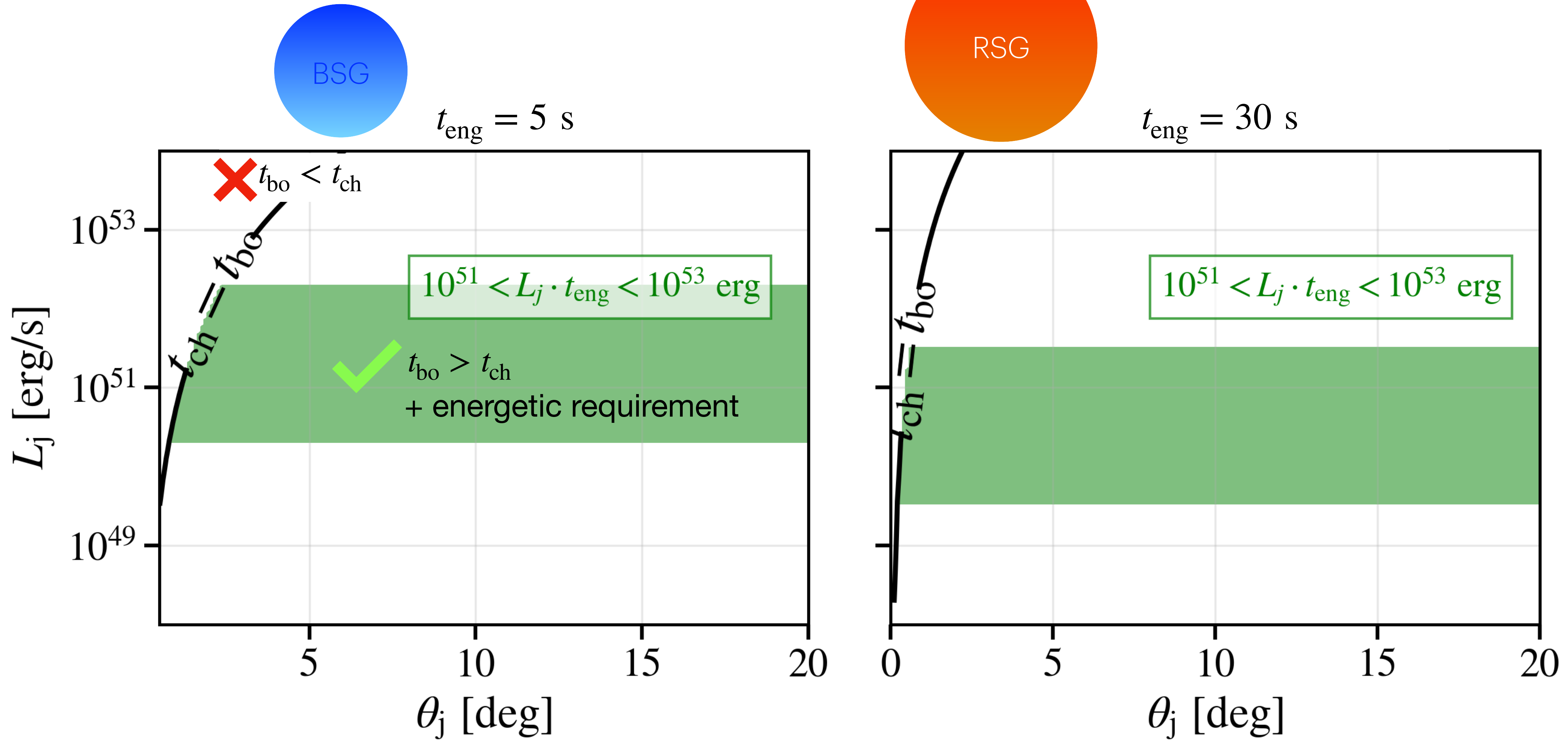
📖 Nakar & Piro 2014
Matzner & McKee 1999
Rabinak & Waxman 2011



Parameter space for choked jets

Preliminary

📖 M.Pais, A. Zegarelli, E. Peretti, S. Celli, *in prep.* (2026)



Possible acceleration sites in the simulation

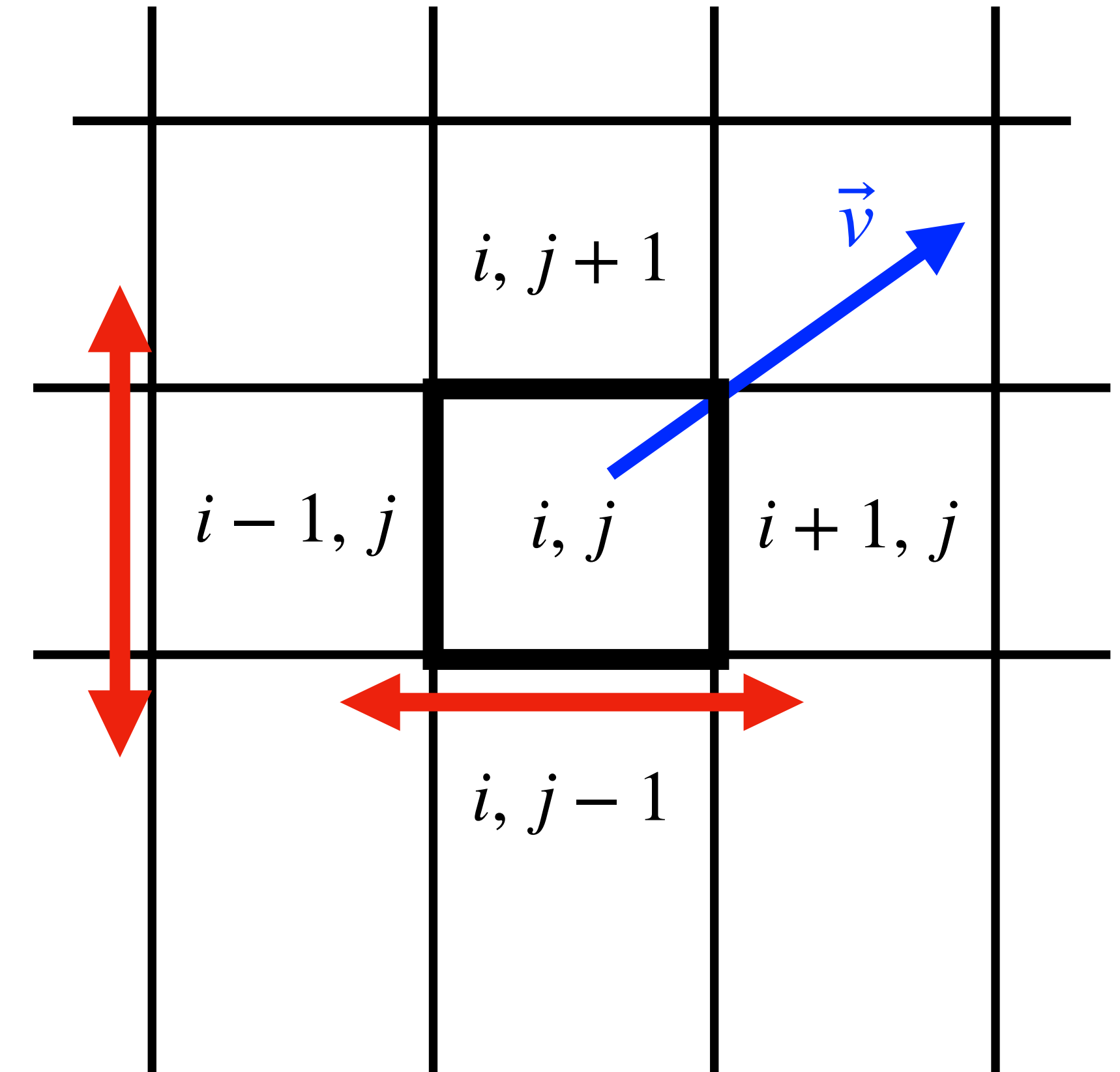
Preliminary

📖 M.Pais, A. Zegarelli, E. Peretti, S. Celli, *in prep.* (2026)

In order to identify the spatial regions for **particle acceleration**, we implemented the following algorithm for **shock identification** for each cell in the grid:

1. Converging flows *from the velocity field*
($\nabla \cdot \vec{v} < 0$) $\rightarrow$ compression and density increase
2. Pressure jump between adjacent cells
3. Alignment of temperature and density gradients
($\nabla T \cdot \nabla \rho > 0$, to filter spurious shocks)
4. Strongest shocks in the jet material
(identified via the Mach number)

The flow quantities are discretized on a rectangular computational grid enclosed by a boundary



Gradients from neighbouring cells

Breakout and choking conditions

Hamidani & Ioka (2021)

We can solve numerically with a 4th-order Runge-Kutta

$$\beta_h = \frac{\beta_j - \beta_a}{1 + \tilde{L}^{-1/2}} + \beta_a,$$

jet head speed

$$V_c = \frac{2\pi}{3} r_c^2(t) r_h(t)$$

cocoon volume

$$\Sigma_j(t) = \begin{cases} \pi r_h^2(t) \theta_0^2 & \text{if } r_h(t) < \hat{z}/2 \text{ (uncollimated jet),} \\ \pi r_h^2(t) \theta_j^2(t) & \text{if } r_h(t) > \hat{z}/2 \text{ (collimated jet),} \end{cases}$$

jet head cross section

The equations describing the jet-cocoon

$$\frac{dr_c(t)}{dt} = c\beta_{\perp},$$

cocoon lateral speed

$$\beta_{\perp} = \sqrt{\frac{P_c}{\rho_a(r_h/2, t) c^2}} + \left[\frac{r_c(t)}{r_m(t)} \right] \frac{v_m}{c},$$

jet lateral speed

$$P_c = \frac{E_i}{3 V_c} = \eta \frac{L_j (1 - \langle \beta_h \rangle) (t - t_0)}{2\pi r_c^2(t) r_h(t)},$$

cocoon pressure

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

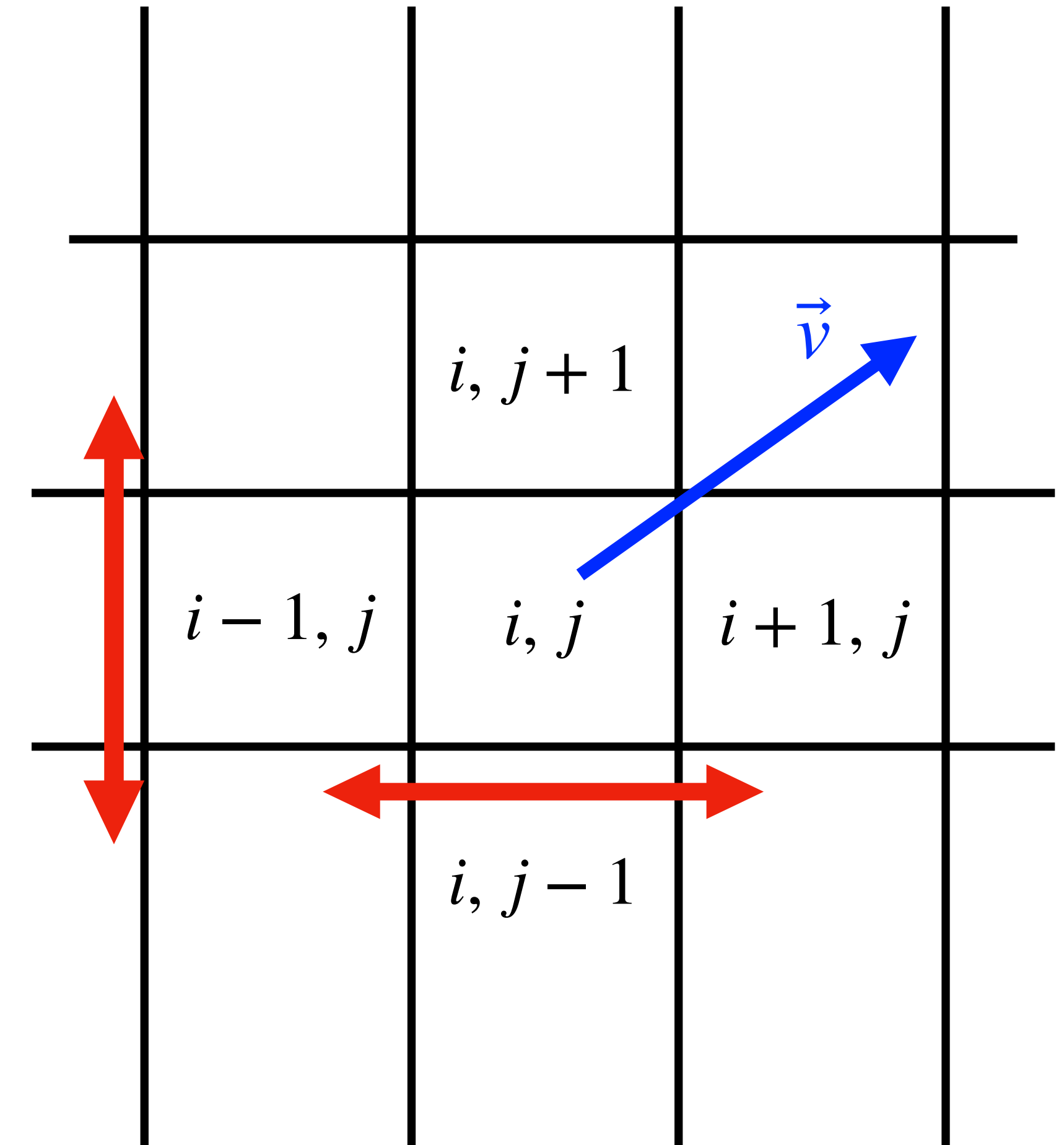
Shock regions in the simulation

Preliminary

📖 M.Pais, S. Celli, E. Peretti, A. Zegarelli, in prep. (2026)

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1. converging flows ($\nabla \cdot \vec{v} < 0$) $\rightarrow$ compression and density increase
2. Pressure jump between adjacent cells
 $|\nabla P| / \vec{P}_{\min,t} \cdot \Delta \vec{x} \geq \epsilon_{\text{thresh}}$
3. Alignment of temperature and density gradients (to filter spurious shocks)
 $\nabla T \cdot \nabla \rho > 0$
4. Strongest shocks in the jet material through the Mach number $\mathcal{M} = \frac{v_{\text{shock}}}{v_{\text{sound}}}$



The flow quantities are discretized on a rectangular computational grid enclosed by a boundary

Radiation from choked jets: planned pipeline

Preliminary

RMHD simulation

Post-processing

1. **Particle injection** in the identified shock regions with energy density proportional to a fraction of the kinetic energy density of each cell;
2. Post-processing run of AM3 to produce **radiation output** using the physical plasma properties in the cell (thermal and magnetic by PLUTO);
3. The method is looped all over the entire domain for each flagged cell;
4. Cumulative, time and observer-dependent, multi-wavelength (photons and neutrinos) emission is then calculated at the each snapshot.

PLUTO snap (i)

gives input data for

AM3 radiation (i)

evolves for 0.1 s and generates

evolves for 0.1 s and gives pre-existing particles to

PLUTO snap ($i+1$)

gives input data for

AM3 radiation ($i+1$)

evolves for 0.1 s and generates

evolves for 0.1 s and gives pre-existing particles to

PLUTO snap ($i+2$)

gives input data for

AM3 radiation ($i+2$)