Multi-messenger signatures of delayed choked jets in tidal disruption events

Mainak Mukhopadhyay
Pennsylvania State University

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What are TDEs?

The shredding apart of a star when it comes close to a SMBH, due to its tidal forces

Disruption starts

↓

~ Half the debris is lost: Unbound orbit

~ Half the debris falls back: Bound orbit

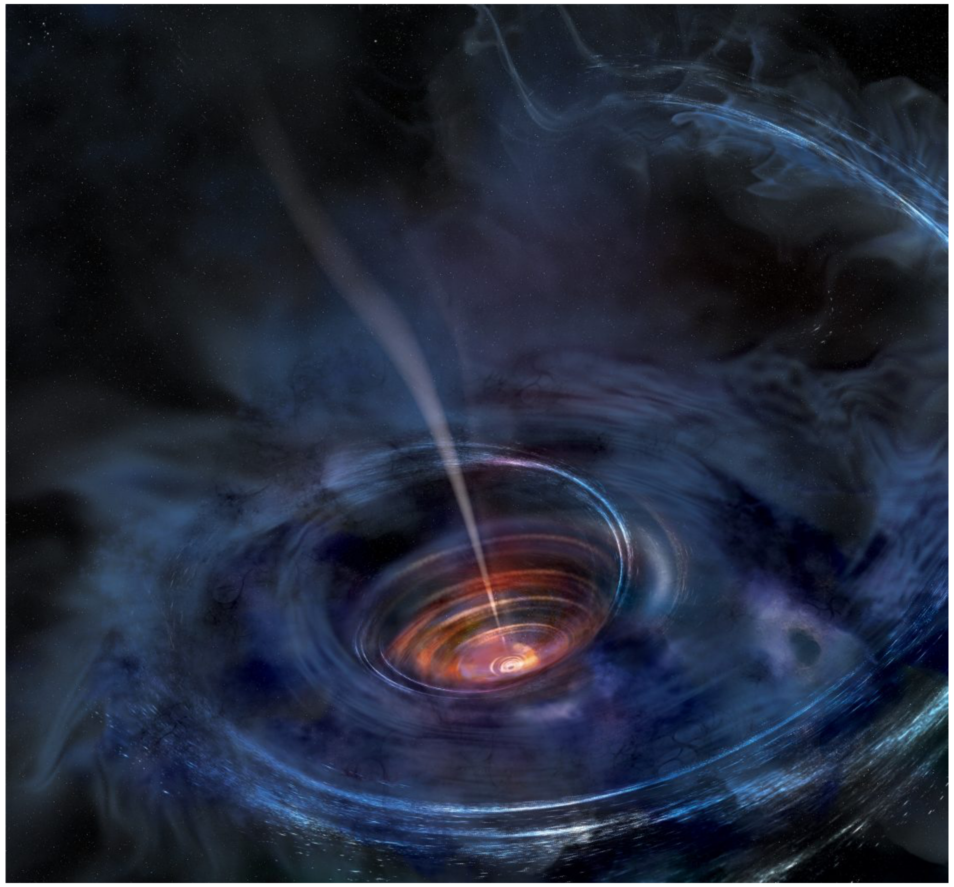
↓

Debris circularizes

↓

Part of the debris may form an accretion disk → Winds, Outflows, etc.

(Timescales are also uncertain)



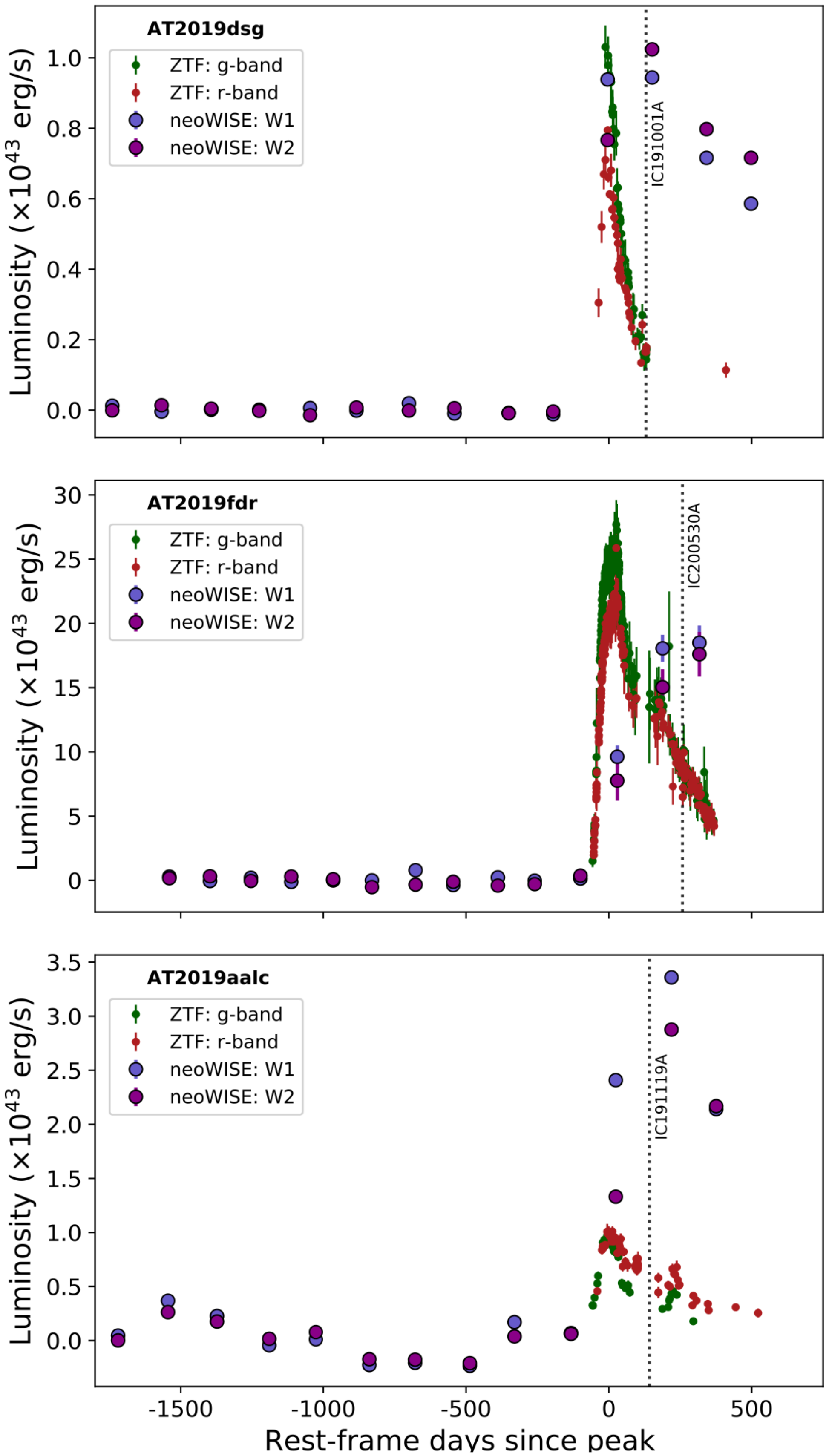
Credits: Aurore Simonnet/Press Image for Kara et al., 2016

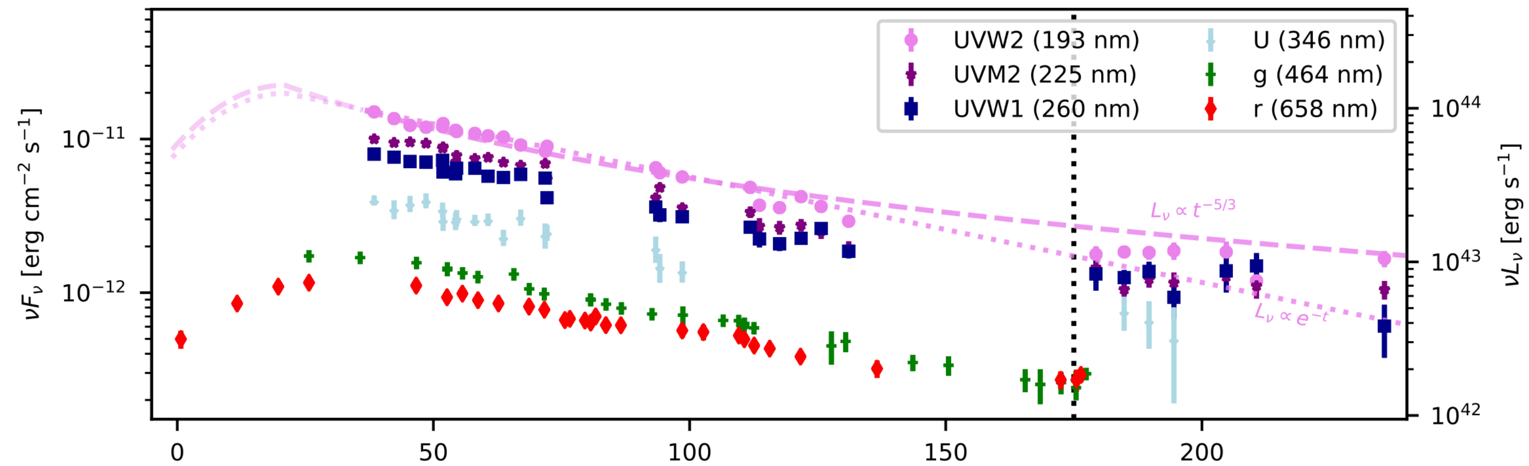
Based on: Multi-messenger signatures of delayed choked jets in tidal disruption events

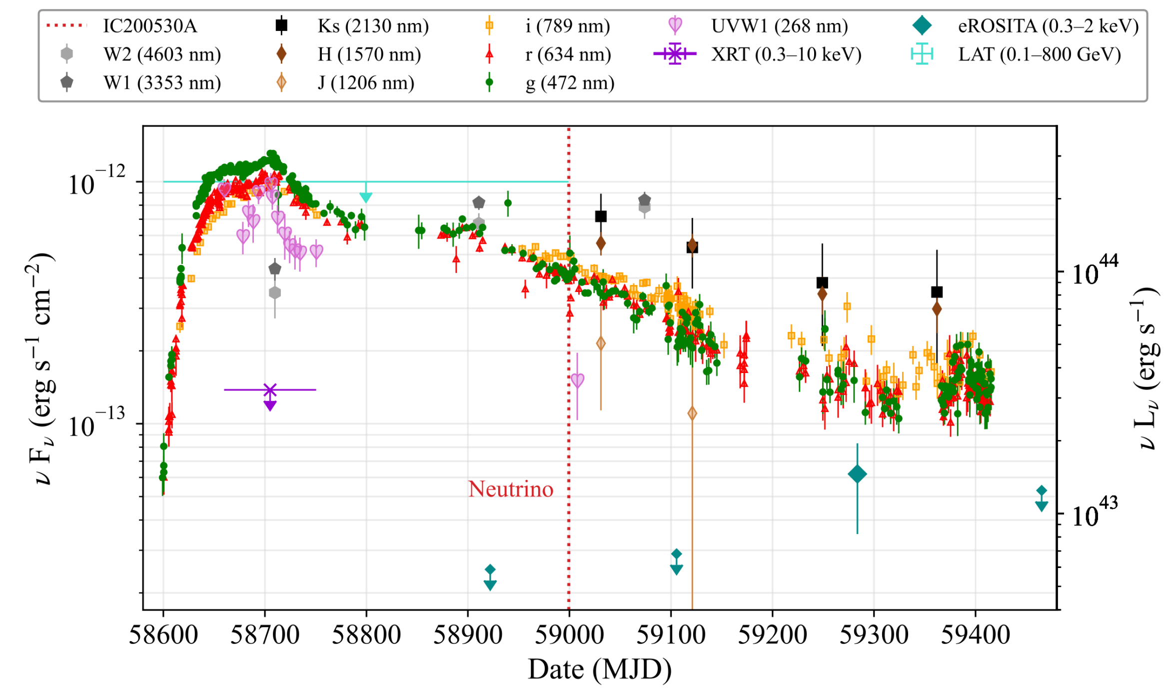
MM, M. Bhattacharya, K.Murase

(arXiv: 2309.02275).

Observational aspects - Multi-messenger signatures (EM and ν)



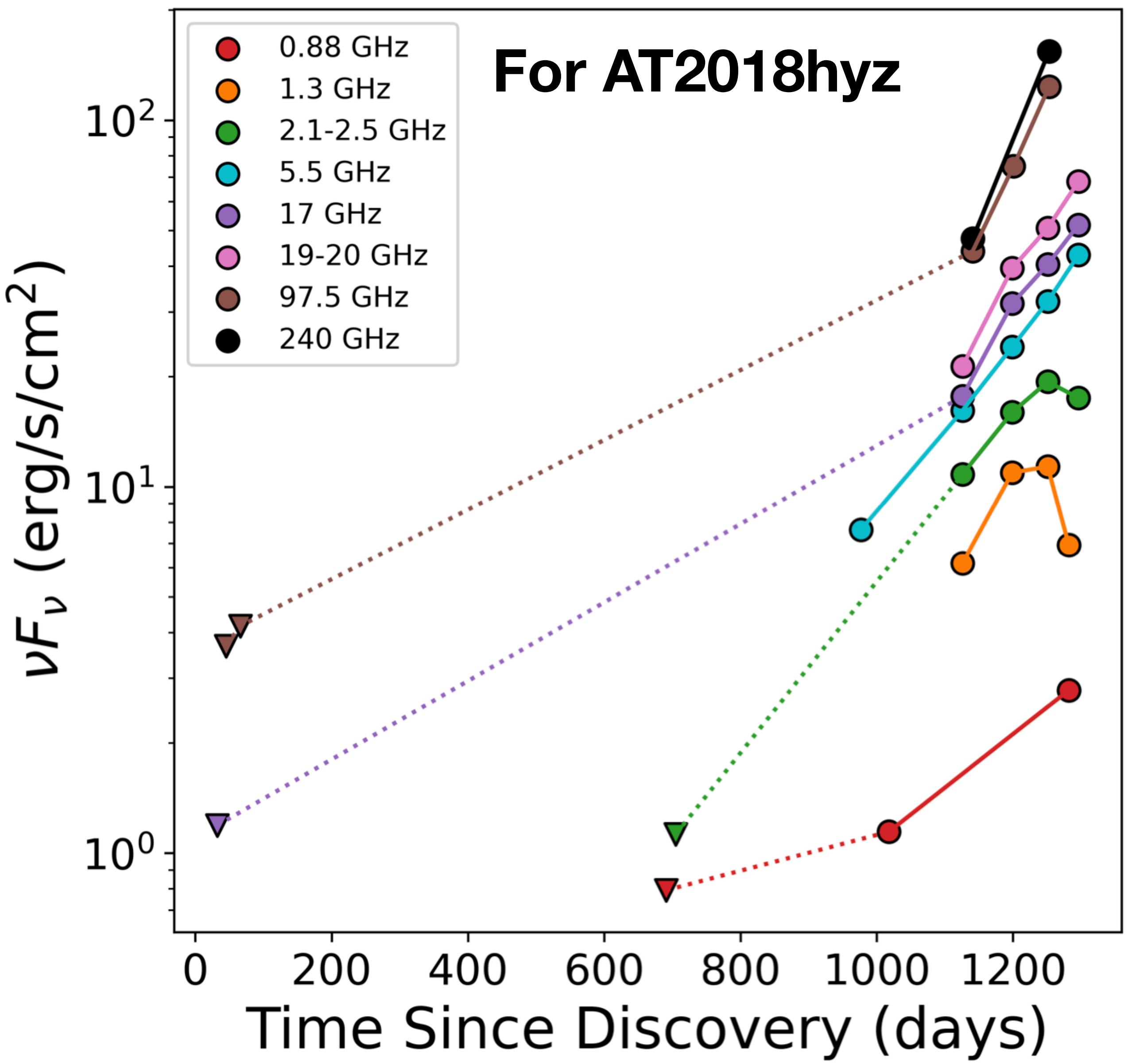




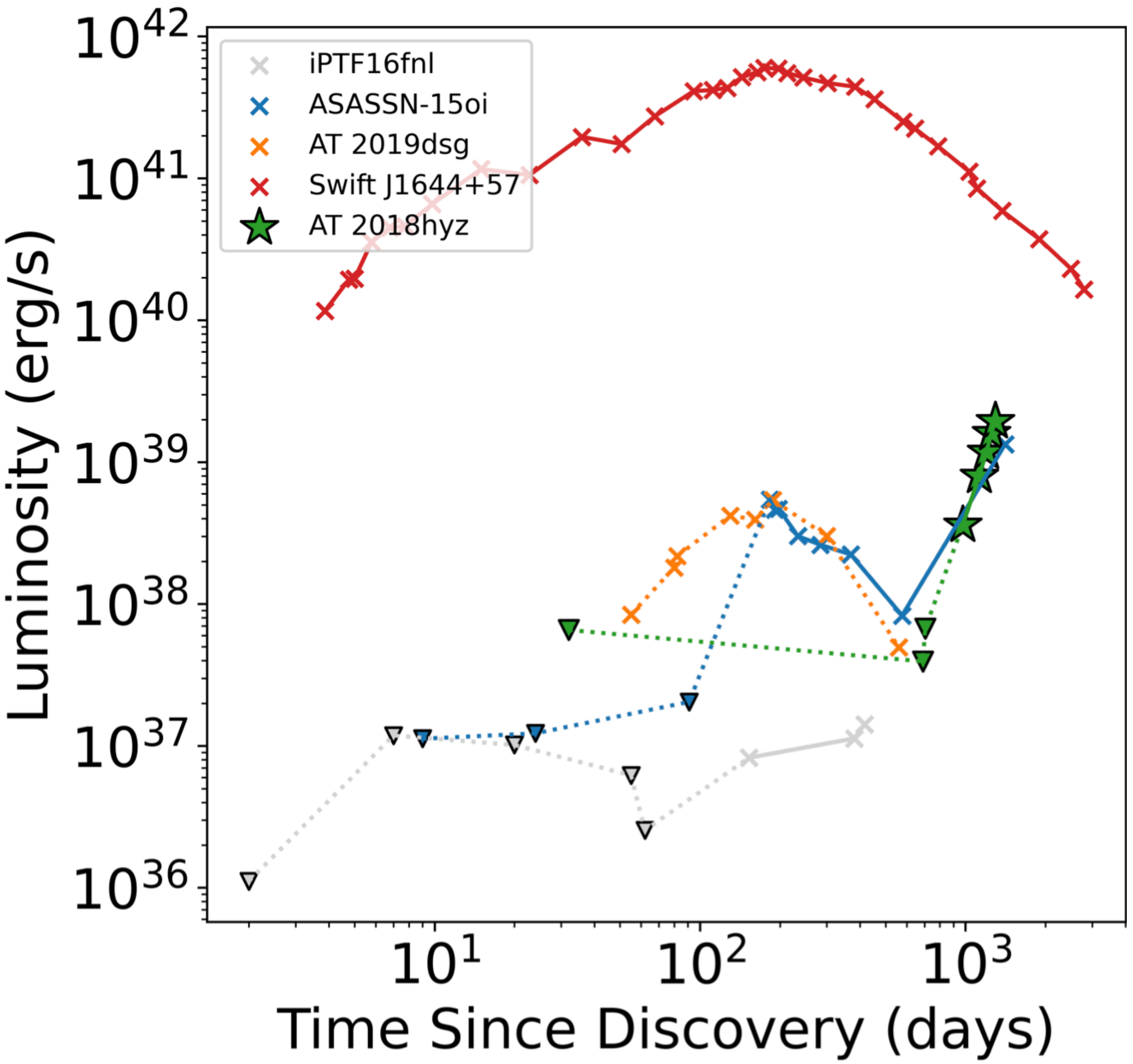
Flare name	Neutrino name	z	Δt days	Δd deg	X-ray temp. keV	*Fermi* limit erg/s/cm^2	M_{BH} $M_\odot$	f_{Edd}
AT2019dsg	IC191001A	0.051	150	1.3	0.07 ± 0.01	$10^{-11.7}$	$10^{6.7}$	3.1
AT2019fdr	IC200530A	0.267	393	1.7	0.06 ± 0.03	$10^{-12.0}$	$10^{7.1}$	0.5
AT2019aalc	IC191119A	0.036	148	1.9	0.17 ± 0.01	$10^{-11.2}$	$10^{7.2}$	0.6

Stein et.al. (2021), Nat. Astro.
Reusch et.al. (2022), PRL
Van Velzen et.al. (2021),

Observational aspects - Late time activity



Radio observations

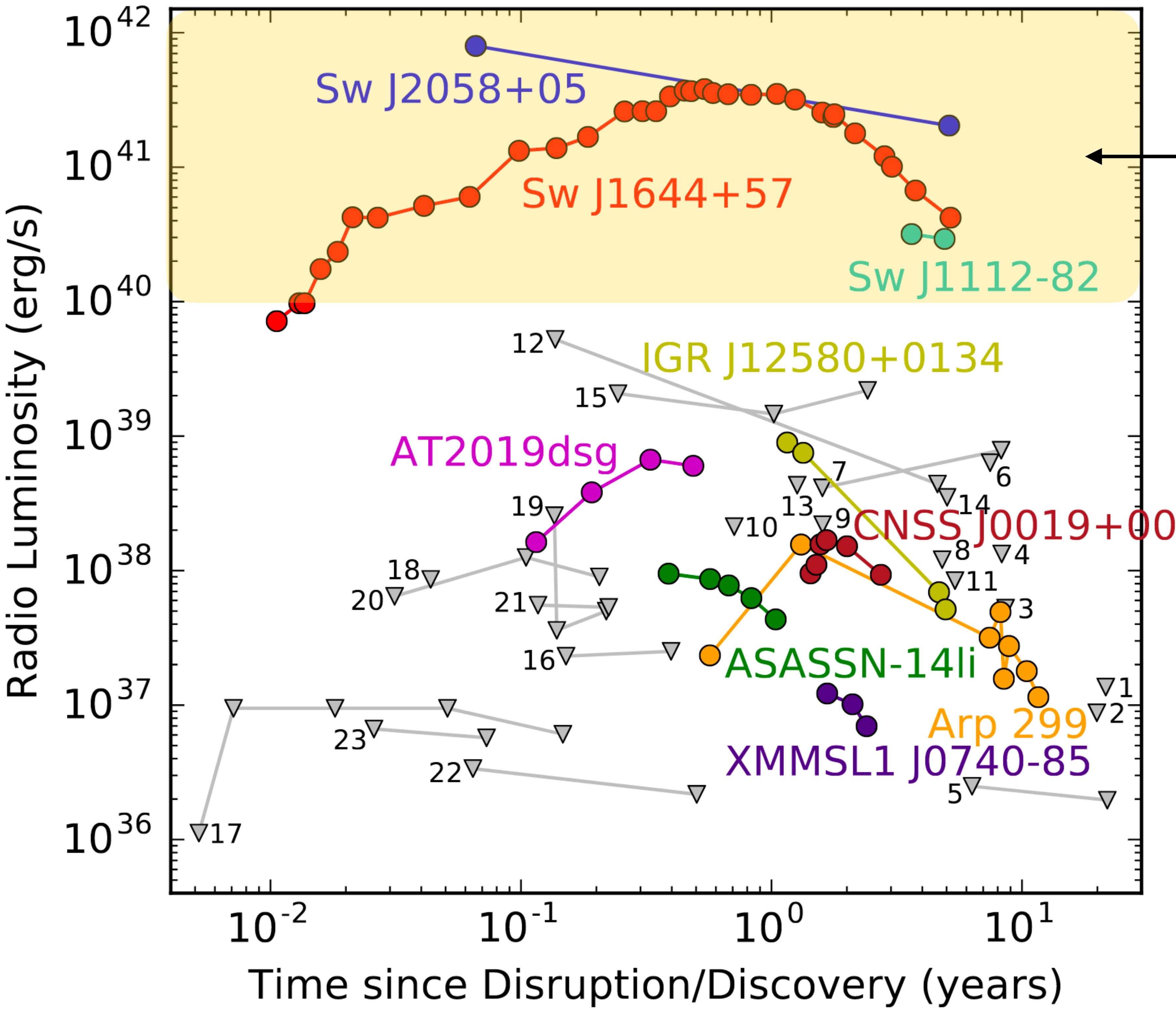


Radio luminosity comparisons

Delayed radio flares: Evidence for late time-activity

Cendes at.al. ApJ 938, (2022)

Jetted TDEs



Radio loud Jetted TDEs

Alexander et al (2020)

Motivations and physical model

Expanding spherical debris
$v_{\rm deb}$

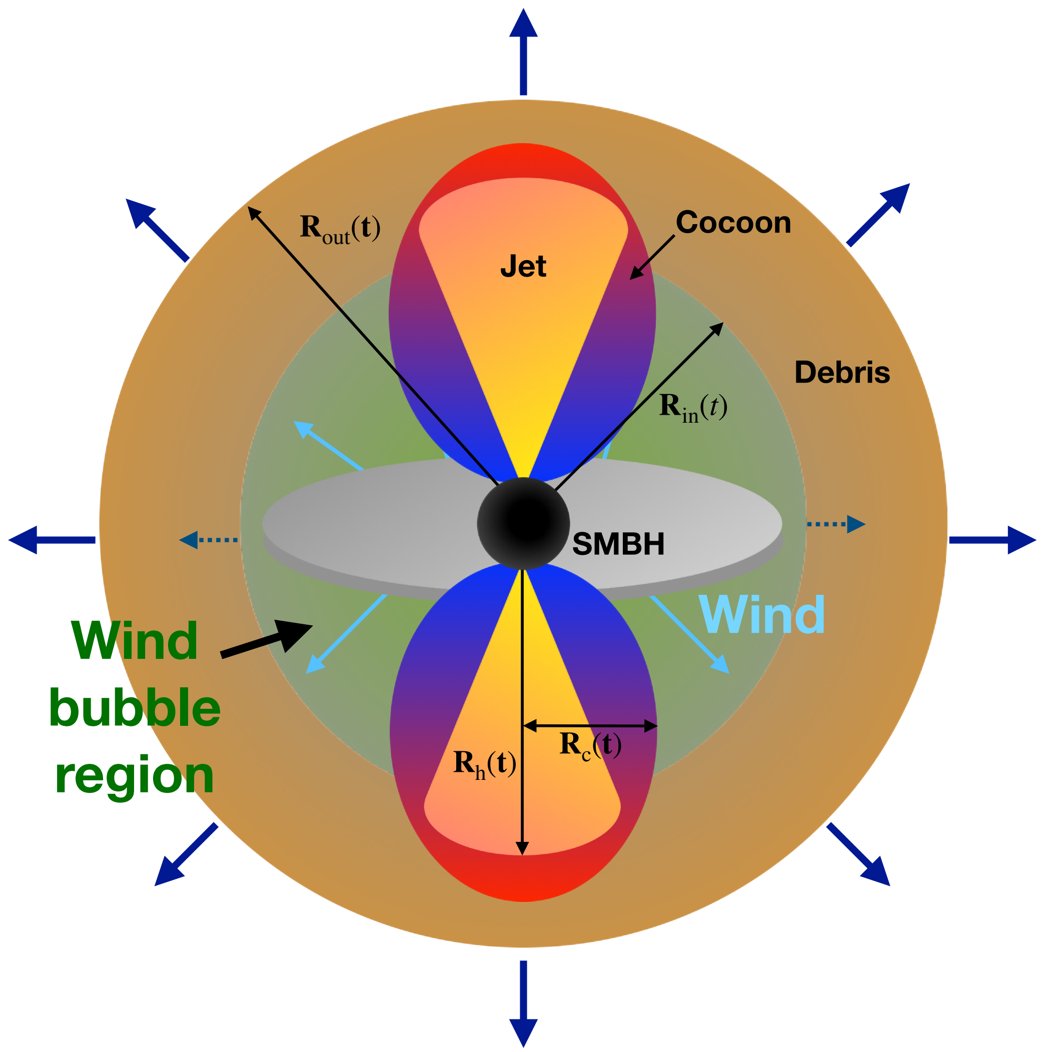
Observational evidence of late time activity → **Jetted TDEs** → **Delayed jet launching** → **Choked jets?**

Delayed radio flares

Radio loud TDEs

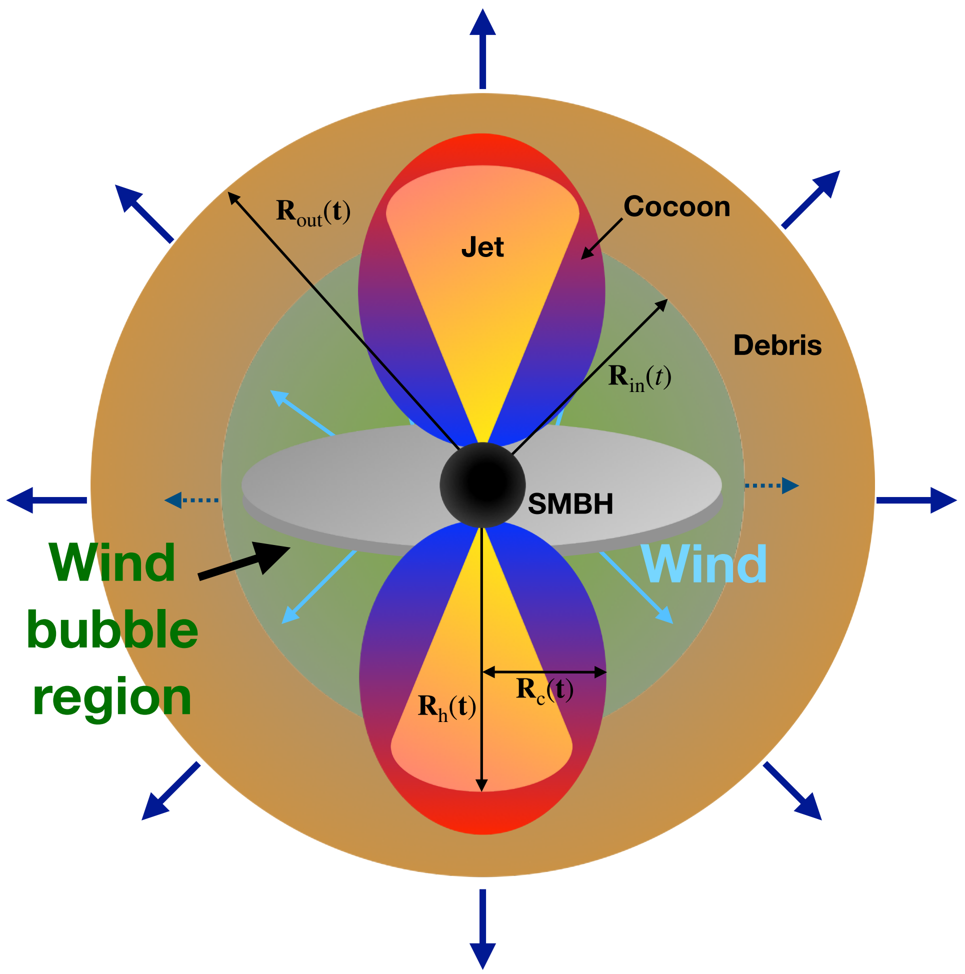
$t_{\rm lag}$

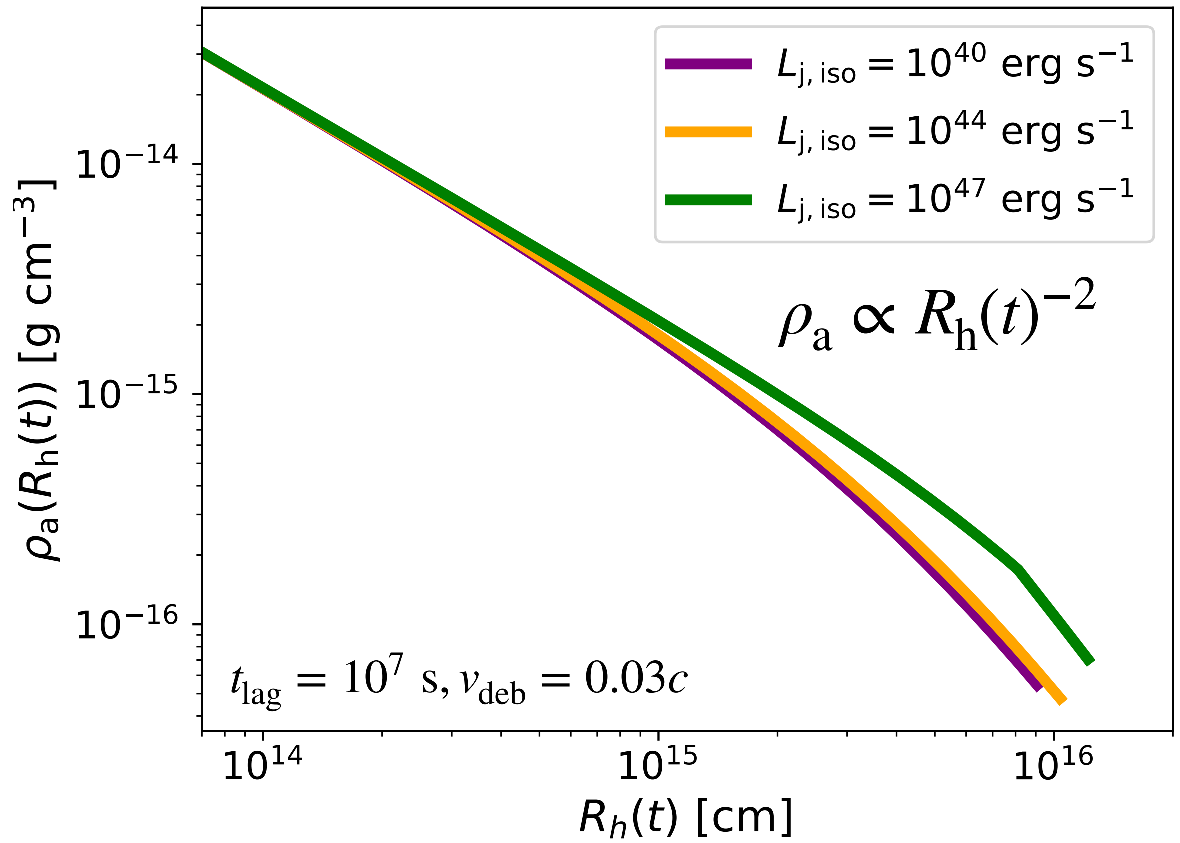
Neutrino arrivals ~ a few 100 days post optical peak

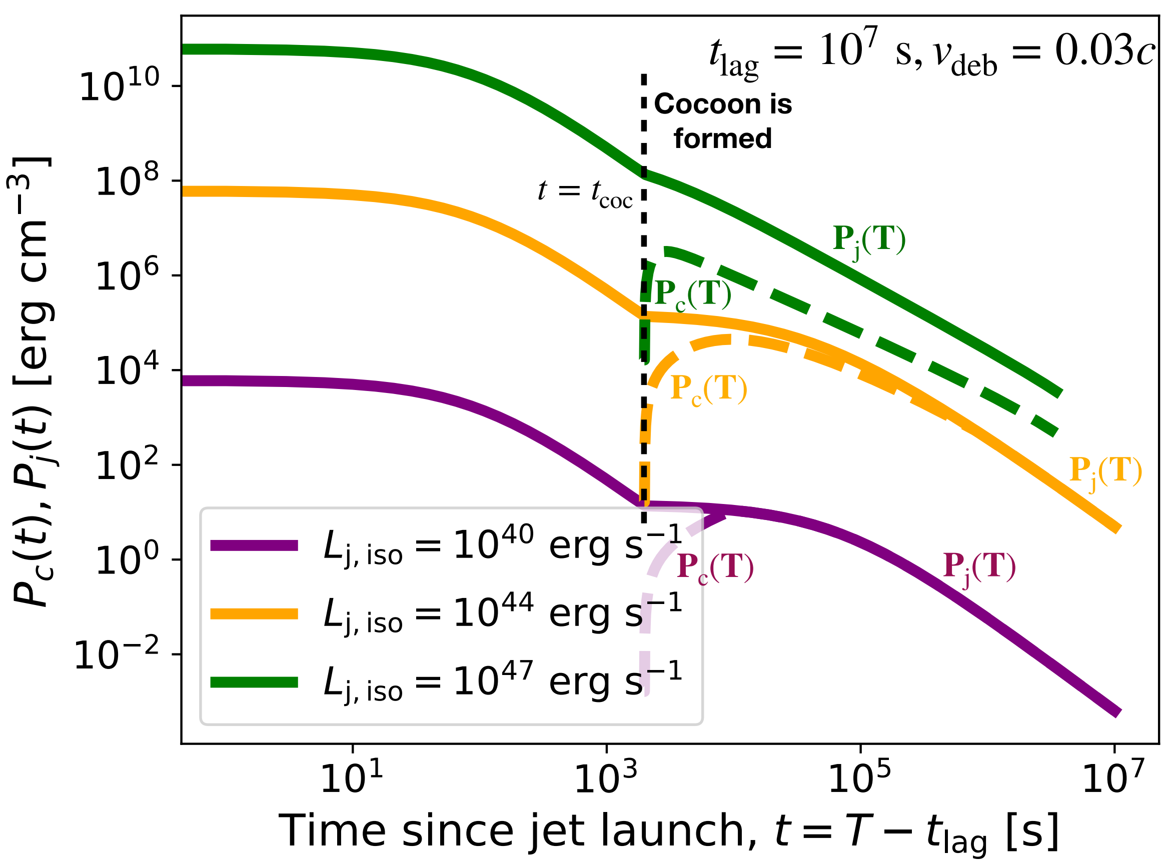


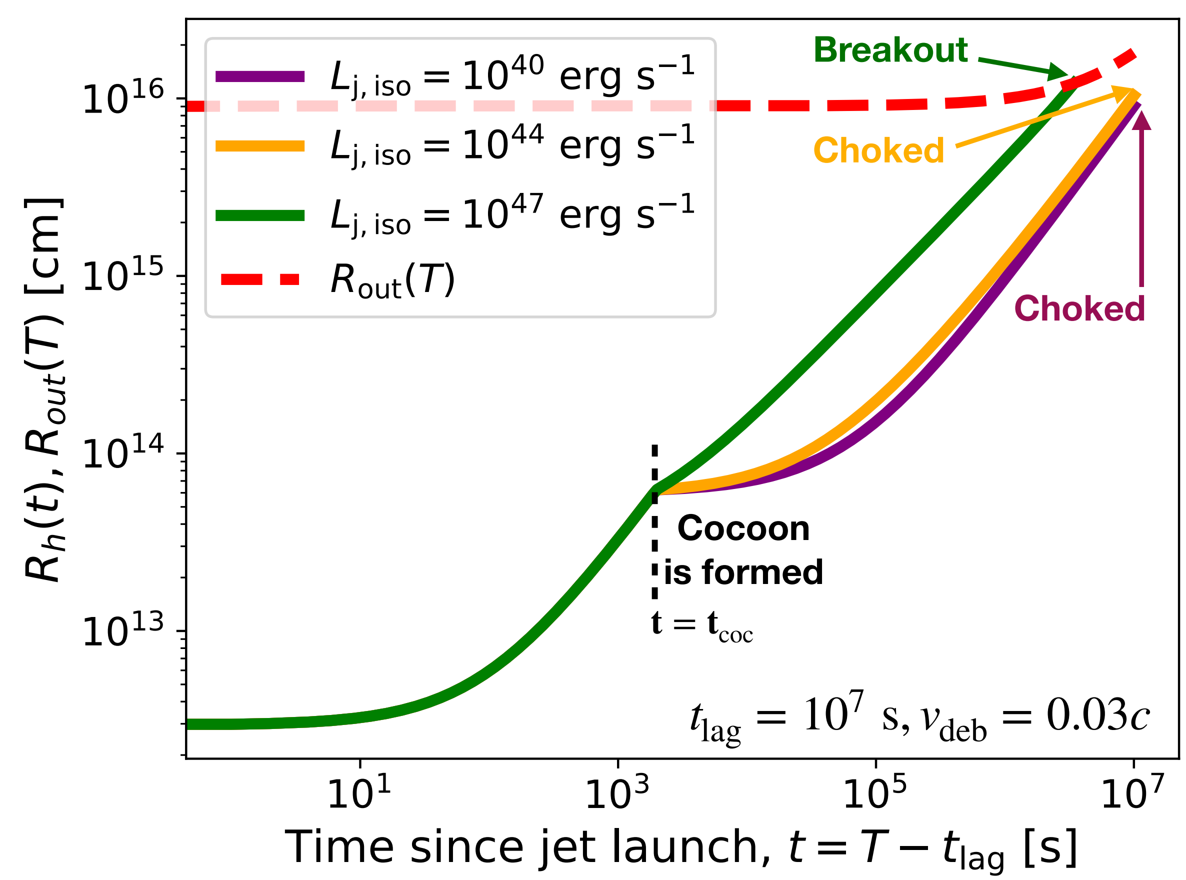
Multi-messenger signatures?
Explanations?
Implications?

Ambient medium density (ρ_a)









Results: Analytical estimate for choking

Choking criteria $R_{\rm h}(t_{\rm dur}) \leq R_{\rm out}(t_{\rm fin})$

$T = t_{\rm fin} = t_{\rm dur} + t_{\rm lag}$

Total evolution time

$$R_{\rm out} \simeq 1.8 \times 10^{16}\,{\rm cm} \left(\frac{\beta_{\rm deb}}{0.03}\right)\left(\frac{t_{\rm dur}}{10^7{\rm s}}\right)\left(\frac{\chi_{\rm lag}}{2}\right)$$

$$\chi_{\rm lag} = (1 + t_{\rm lag}/t_{\rm dur})$$

Assuming uncollimated jets

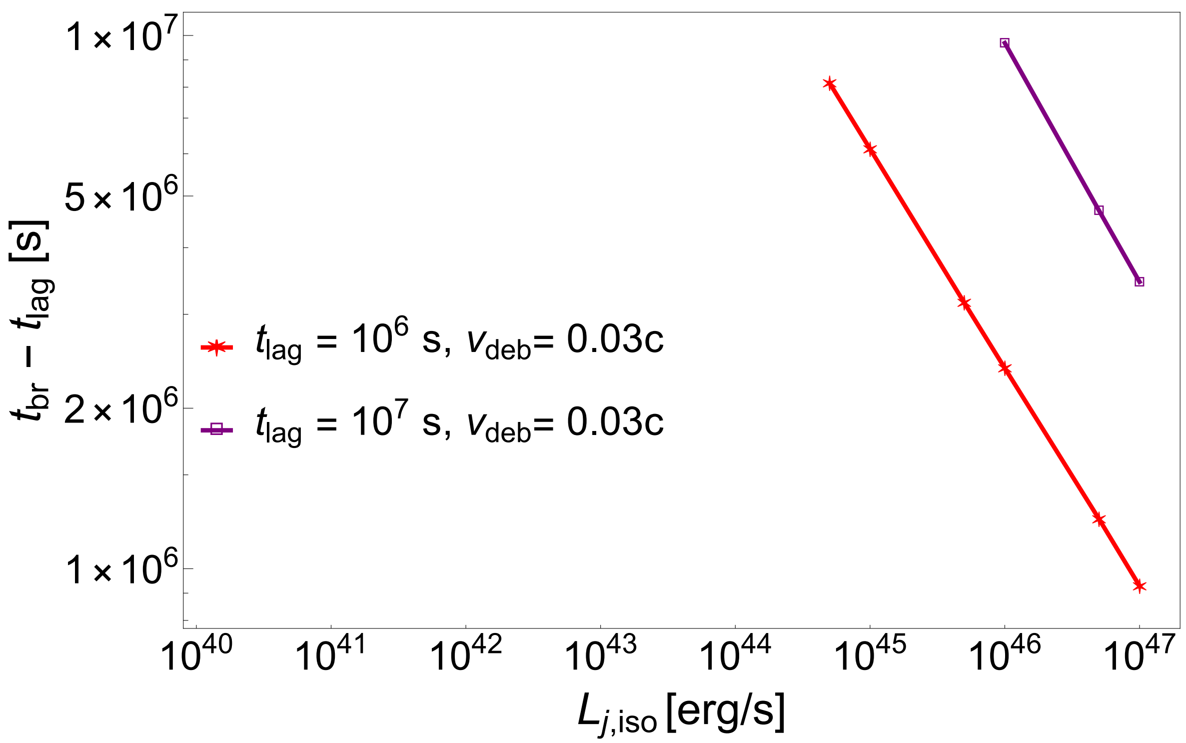
$$R_{\rm h} \simeq 5.6 \times 10^{15}\,{\rm cm} \left(\frac{N_s}{0.35}\right)^{5/3}\left(\frac{L_{\rm j,iso}}{10^{44}\,{\rm erg/s}}\right)^{1/3}\left(\frac{M_{\rm deb}}{0.5\,M_\odot}\right)^{-1/3}\left(\frac{\theta_0}{0.17}\right)^{-2/3}\left(\frac{\beta_{\rm deb}}{0.03}\right)^{1/3}\left(\frac{t_{\rm dur}}{10^7\,{\rm s}}\right)^{4/3}\left(\frac{\chi_{\rm lag}}{2}\right)^{1/3}$$

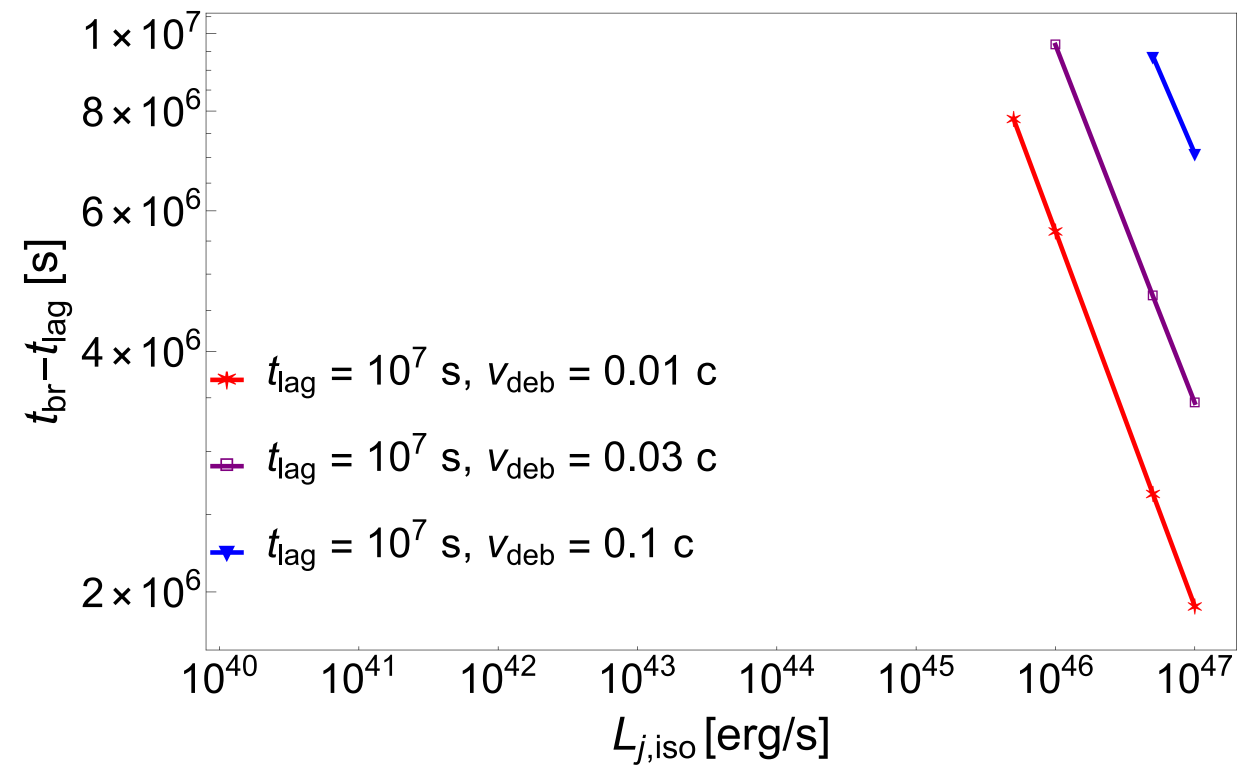
$$L_{\rm j,iso} \lesssim 3.2 \times 10^{45}\,{\rm erg/s} \left(\frac{N_s}{0.35}\right)^{-5}\left(\frac{M_{\rm deb}}{0.5M_\odot}\right)\left(\frac{\theta_0}{0.17}\right)^{2}\left(\frac{\beta_{\rm deb}}{0.03}\right)^{2}\left(\frac{t_{\rm dur}}{10^7\,{\rm s}}\right)^{-1}\left(\frac{\chi_{\rm lag}}{2}\right)^{2}$$

Fairly good estimates

Results: Analytical estimate for choking

$$L_{\rm j,iso} \lesssim 3.2 \times 10^{45}\,{\rm erg/s}\left(\frac{N_s}{0.35}\right)^{-5}\left(\frac{M_{\rm deb}}{0.5M_\odot}\right)\left(\frac{\theta_0}{0.17}\right)^2\left(\frac{\beta_{\rm deb}}{0.03}\right)^2\left(\frac{t_{\rm dur}}{10^7\,{\rm s}}\right)^{-1}\left(\frac{\chi_{\rm lag}}{2}\right)^2$$





$t_{\rm lag}$: ↑

The debris has more time to expand

Jets require higher luminosity to breakout

$v_{\rm deb}$: ↑

The debris expands with a higher velocity: extends to larger radii

Jets require higher luminosity to breakout

Electromagnetic (EM) and Neutrino Signatures

Signatures from delayed choked jets

Particle acceleration within jets:
- UHECRs
- High-energy neutrinos
- EM signatures

Jet-head

Relativistic (Initially) → Sub-relativistic

Interactions with the debris: cocoon

Deceleration

↓

Shocked regions → Forward shock / Reverse shock

↓

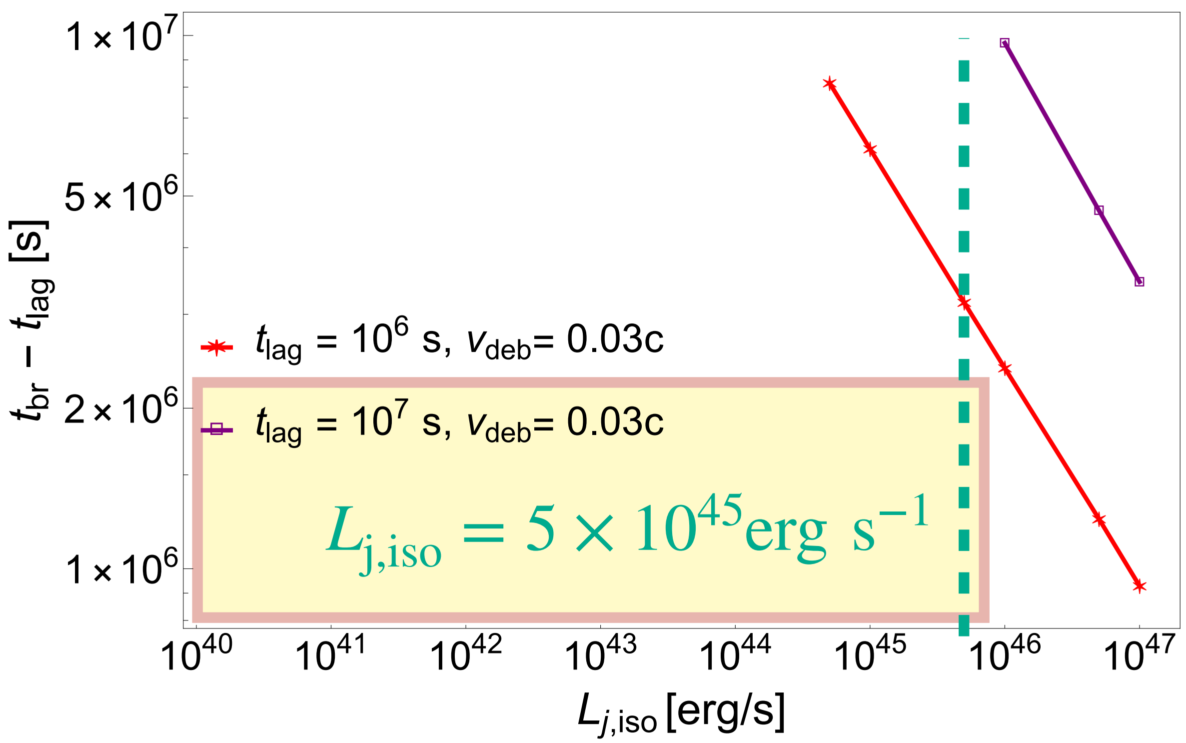
Relativistic electrons are accelerated

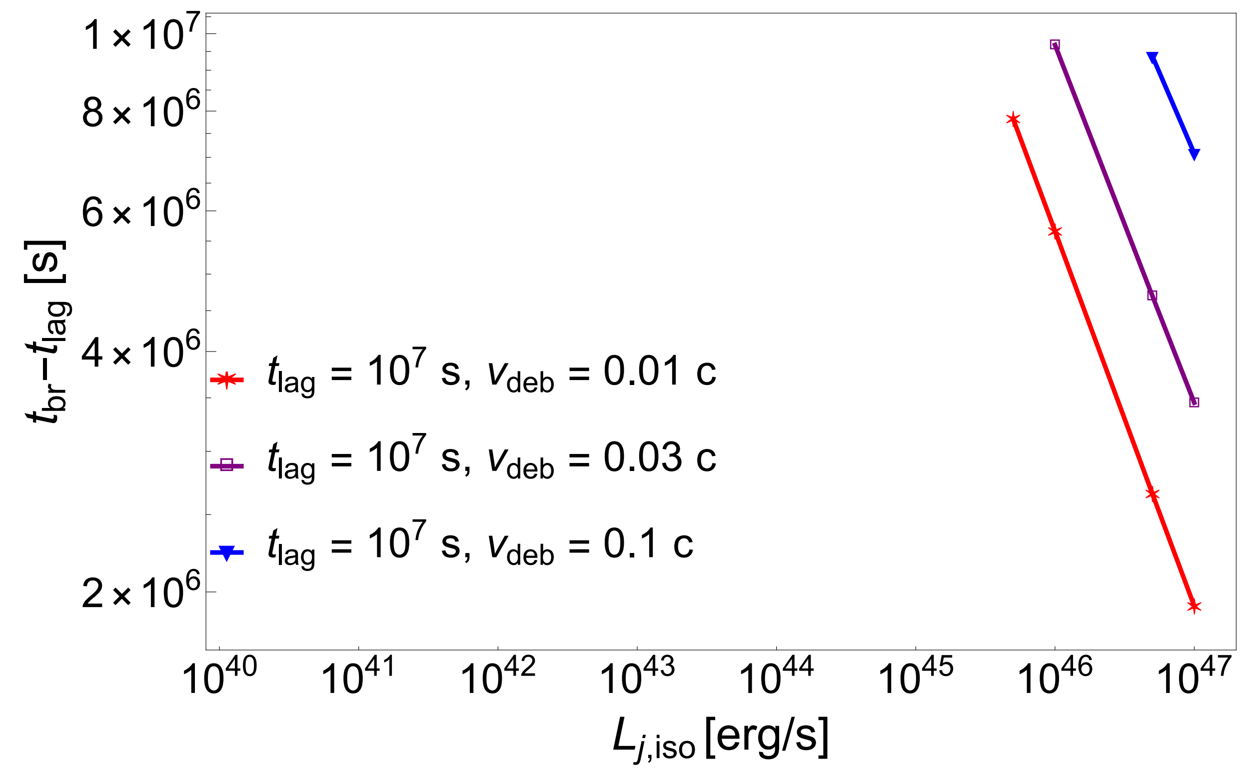
↓

Cool due to radiative losses:
Synchrotron, inverse Compton,….

Results: Analytical estimate for choking

$$L_{\rm j,iso} \lesssim 3.2\times10^{45}\,{\rm erg/s}\left(\frac{N_s}{0.35}\right)^{-5}\left(\frac{M_{\rm deb}}{0.5M_\odot}\right)\left(\frac{\theta_0}{0.17}\right)^{2}\left(\frac{\beta_{\rm deb}}{0.03}\right)^{2}\left(\frac{t_{\rm dur}}{10^7\,{\rm s}}\right)^{-1}\left(\frac{\chi_{\rm lag}}{2}\right)^{2}$$

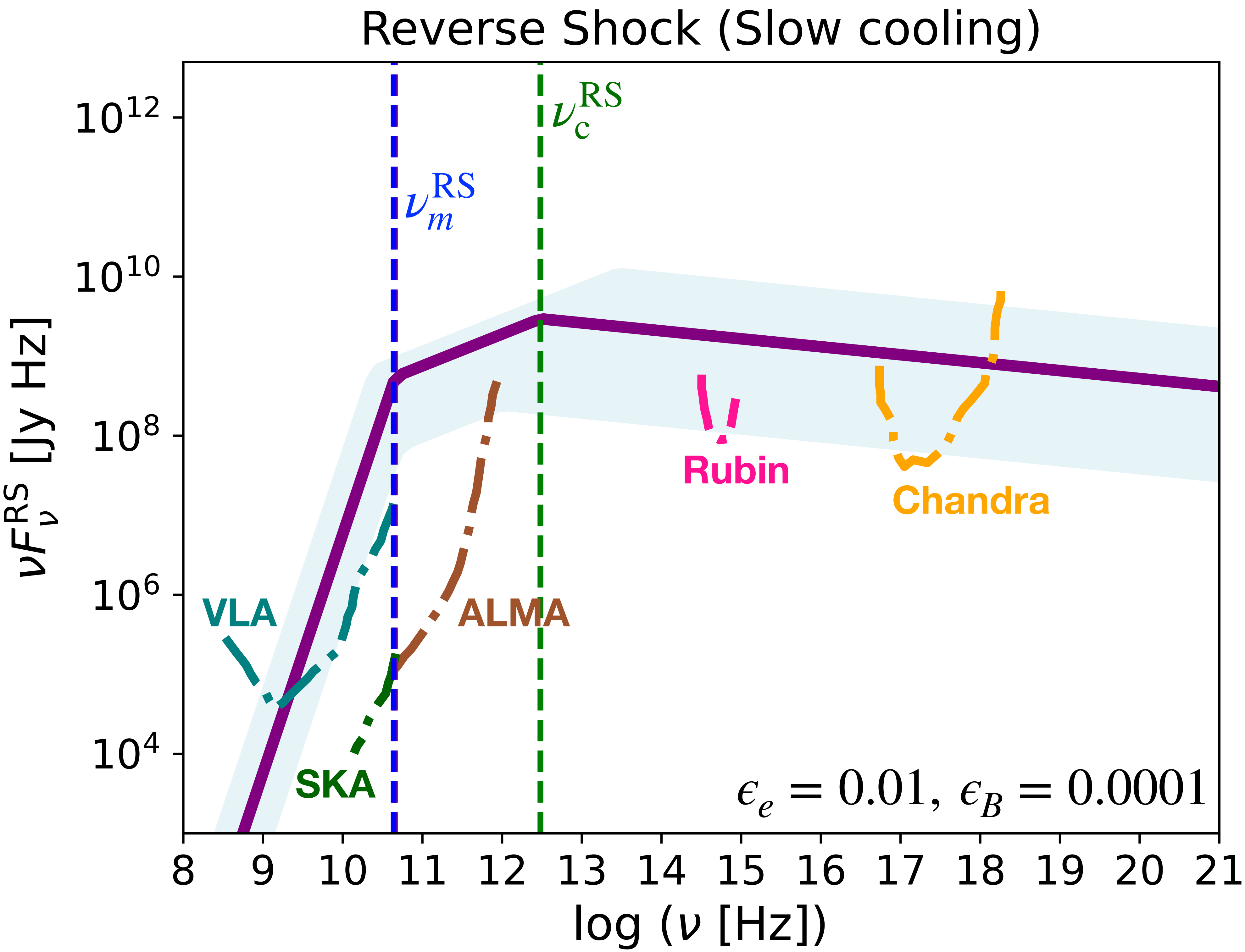




EM Signatures: Reverse Shock - Slow Cooling (z = 0.05)

$$F^{\rm RS}_{\rm syn,max} \simeq 37\ {\rm mJy}\ (f_e/0.48) n^{\rm RS}_{2.53} R^3_{\rm h,16.21} \Gamma^{\rm RS}_{0.70} B^{\rm RS} (1+z) d^{-2}_{L,26.82}$$

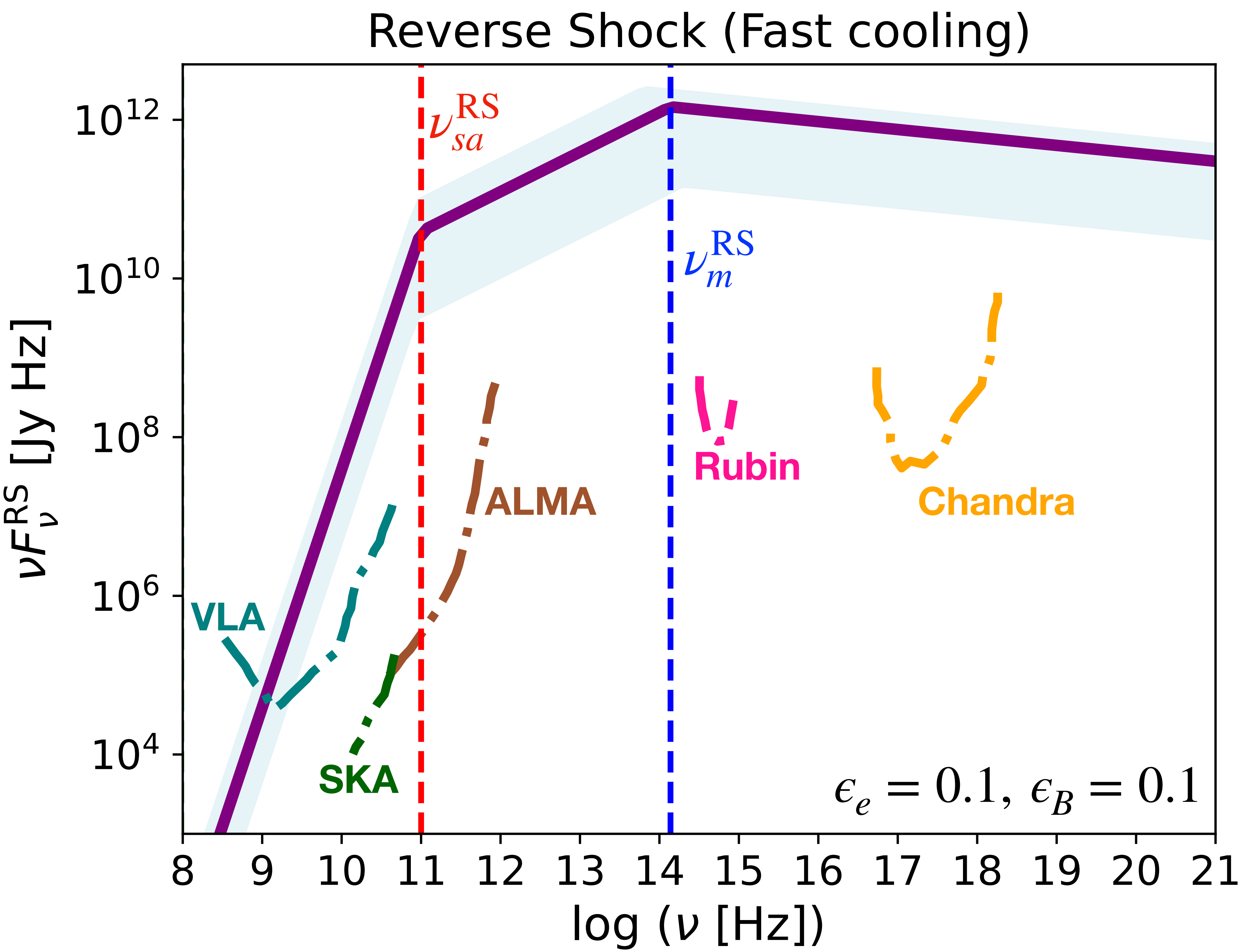
$$B^{\rm RS} \simeq 0.32\,{\rm G}$$



EM Signatures: Reverse Shock - Fast Cooling (z = 0.05)

$$F^{\rm RS}_{\rm syn,max} \simeq 37~{\rm mJy}~(f_e/0.48) n^{\rm RS}_{2.53} R^3_{\rm h,16.21} \Gamma^{\rm RS}_{0.70} B^{\rm RS} (1+z) d^{-2}_{L,26.82}$$

$$B^{\rm RS} \simeq 10.25\,{\rm G}$$

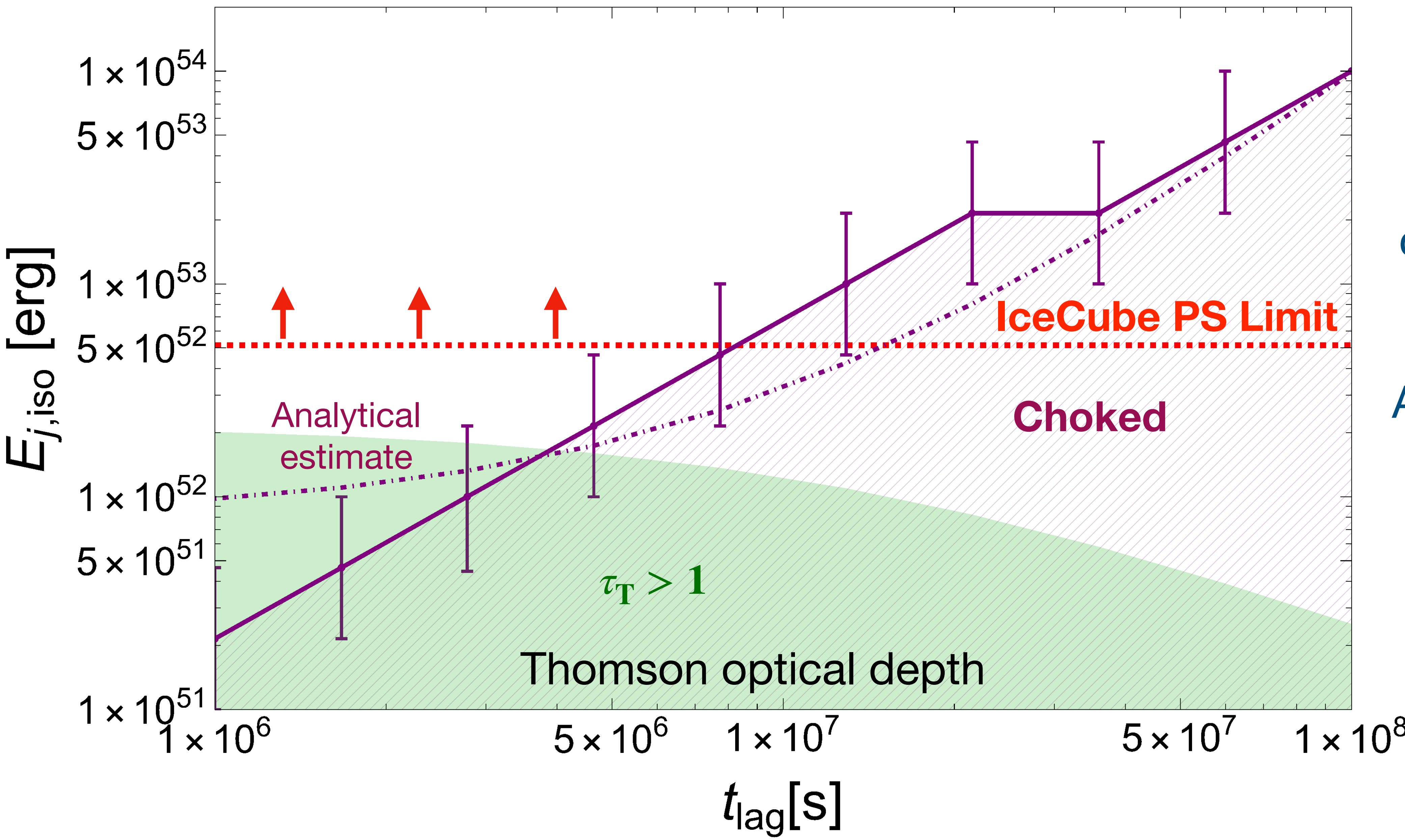


Neutrino Signatures: Choked jets ($t_{lag} = 10^7$ s, $z = 0.05$)

AT2019dsg

What is the energy budget required for the jet to produce 1 neutrino event given the IceCube point source (PS) limit

$E_\nu = 1\,\%$ of E_j



Can explain the coincident neutrino observations

Also for AT2019aalc

AT2019fdr is still challenging

Takeaways

Late time activity associated with the SMBH from observations:

- Delayed radio flares
- Coinicident neutrino detections: arrival after ~ 150 days, ~ 393 days, and 148 days post the optical peaks for AT2019dsg, AT2019fdr and AT2019aalc, respectively

Possibility of choked delayed jets

- Spherical debris envelope surrounding the SMBH, expanding outwards possibly driven by wind.
- Jet-cocoon interactions: collimation and choking - Higher delay times and debris velocities help with choking

Electromagnetic signatures

- Synchrotron radiation from delayed choked jets: Reverse shock: slow and fast cooling cases
- Optical and X-ray observatories: good prospects, radio observations seem likely as well.

Neutrino signatures

- Can explain the coincident observations by IceCube - AT2019dsg and AT2019aalc with this scenario of choked delayed jets.

Multi-messenger opportunities to understand the complicated dynamics of TDEs with next-gen detetectors

Possibilities with next generation neutrino experiments: IceCube-Gen2, KM3NeT and EM observatories
(See talk by C.Yuan!)

Thank You!

Backup

What are TDEs?

The shredding apart of a star when it comes close to a SMBH, due to its tidal forces

Disruption starts

↓

~ Half the debris is lost: Unbound orbit

~ Half the debris falls back: Bound orbit

↓

Debris circularizes

↓

Part of the debris may form an accretion disk → Winds, Outflows, etc.

(Timescales are also uncertain)

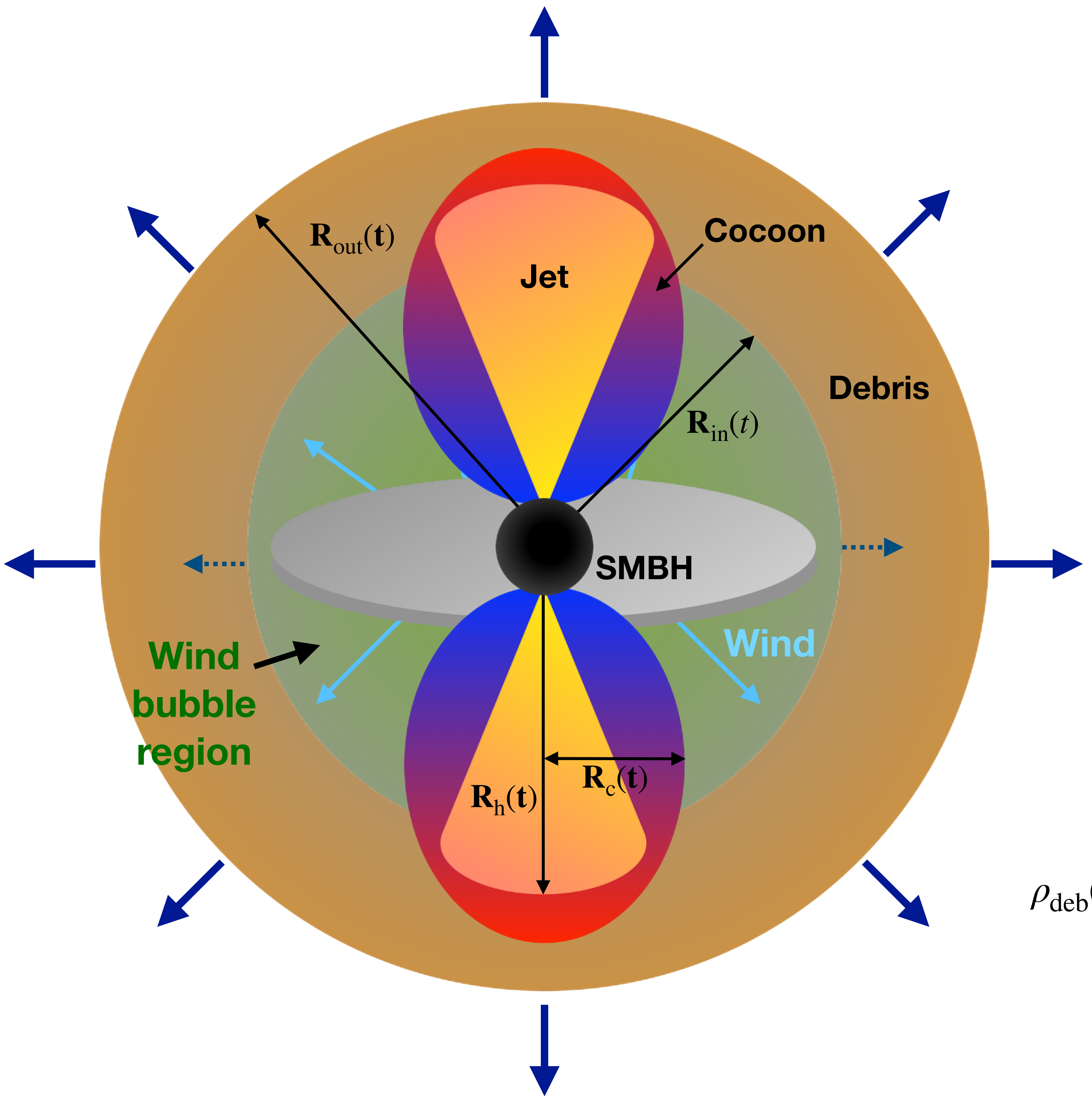
Tidal disruption radius: $\mathbf{R_T = R_* \frac{M_{BH}}{M_*}}$

Fallback time: $\mathbf{t_{fb} = 2\pi\sqrt{a_{min}^3/(GM_{BH})}}$

Semi-major axis: $\mathbf{a_{min} \approx R_T^2/(2R_*)}$

Circularization radius: $\mathbf{R_{circ} = 2R_T}$

Physical Model



$$t_{coc} < t < t_{br} \text{ or } t_{coc} < t < t_{fin}$$

Static and contracting envelopes have been considered

Convention:

T : Time since TDE

t_{lag}: Time lag associated with the launching of the jet

t: Time since the launch of the jet

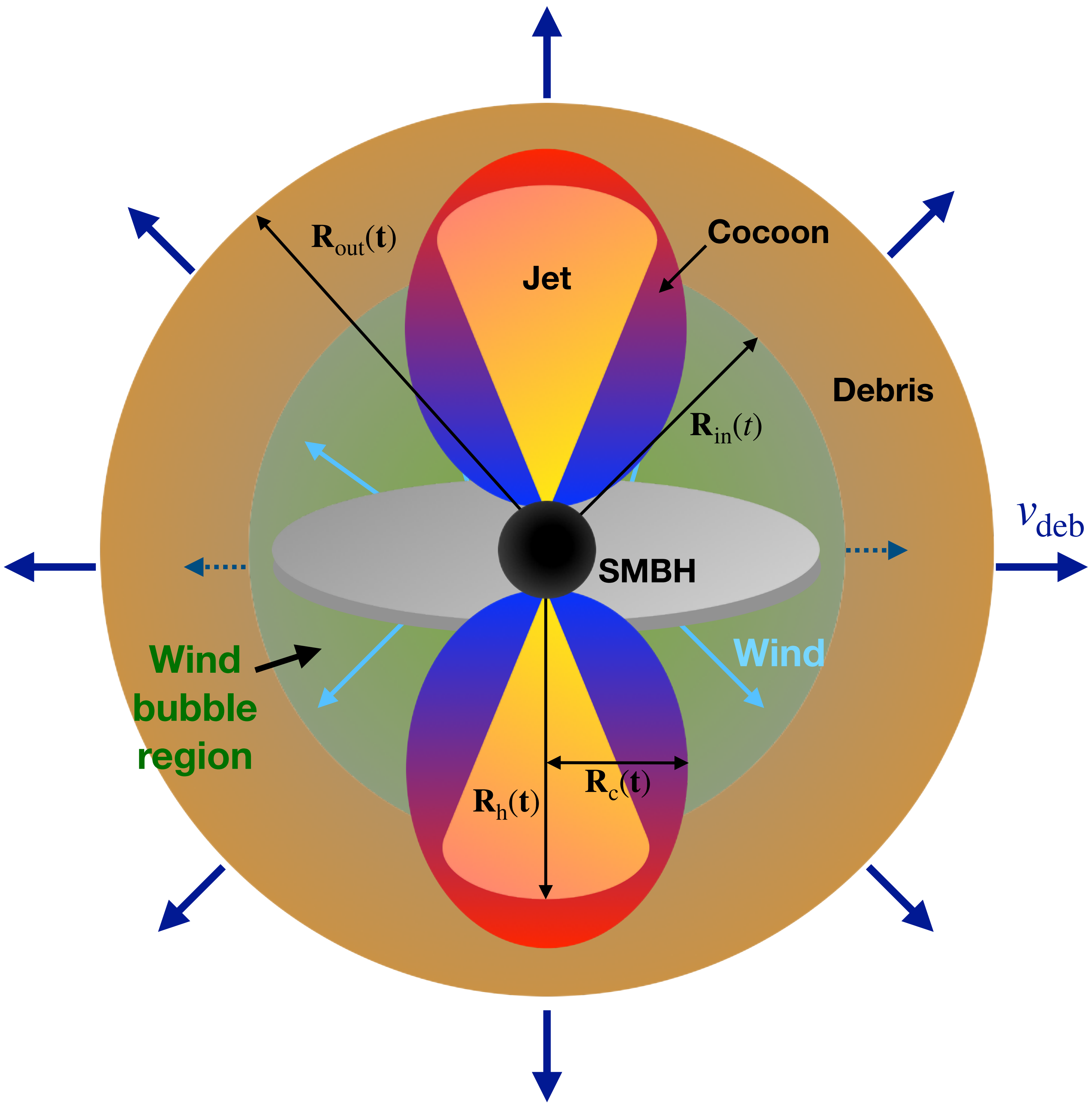
$$R_{out}(t) = v_{deb}t$$

$$R_{in}(t) = \begin{cases} R_{circ}, \ 0 < t \leq t_{fb}, \\ R_{circ}(t/t_{fb}), \ t > t_{fb} \end{cases}$$

$$\rho_{deb}(t, r) = \mathcal{N} \frac{M_{deb}}{4\pi R_{out}^3} \begin{cases} \left(r/R_{out}\right)^{-2}, r \geq R_{fb} \\ \left(R_{fb}/R_{out}\right)^{-2} \left(r/R_{fb}\right)^{-\delta}, r < R_{fb} \end{cases}$$

$$R_{fb} = \begin{cases} R_{in}(T=0), t < t_{fb} \\ R_{in}(T=0) + v_{deb}(T - t_{fb}), t \geq t_{fb} \end{cases}$$

Physical Model: Expanding spherical debris



$$R_h(t_{dur} = 0) = R_s = 2GM_{BH}/c^2$$

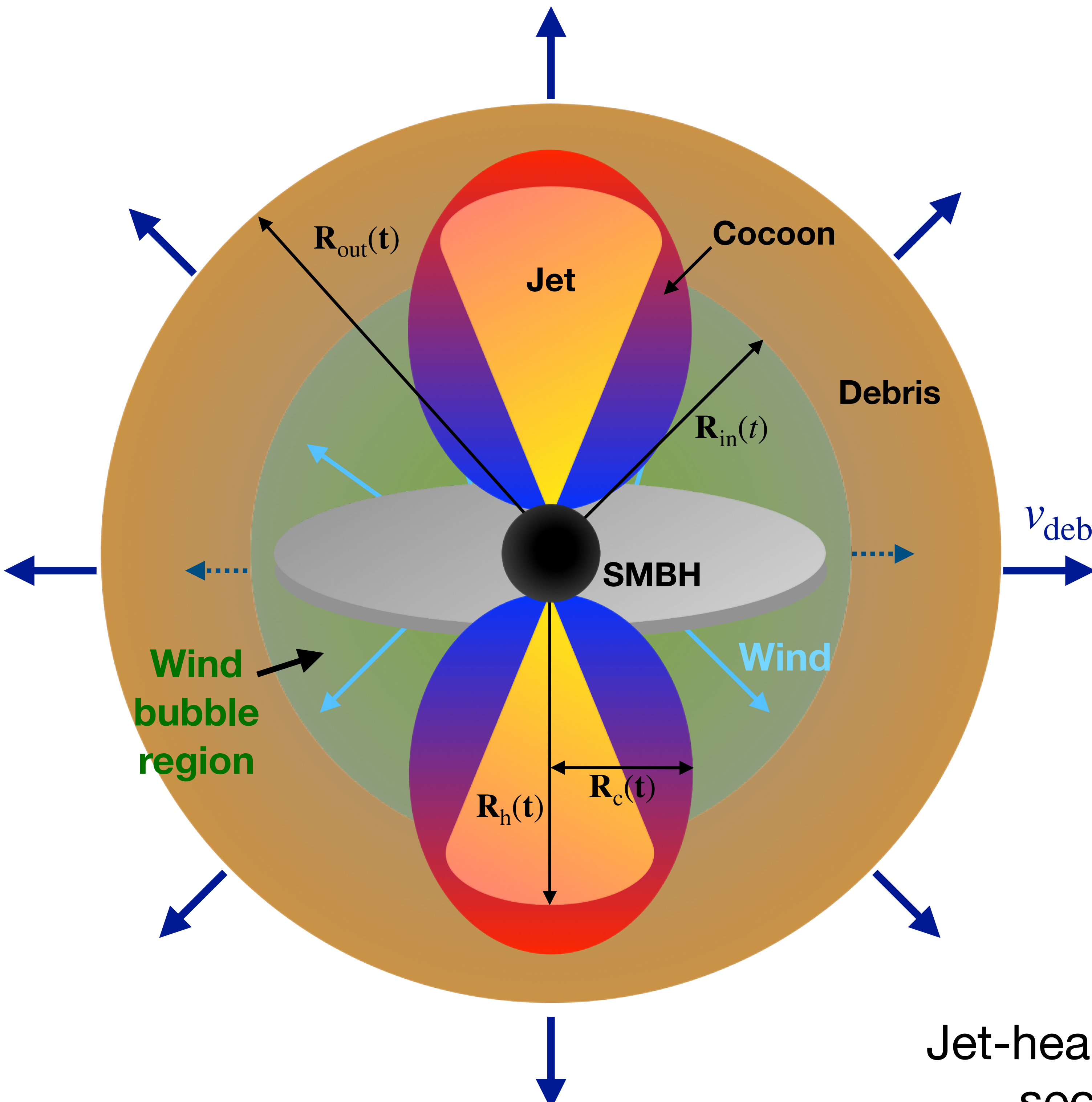
$$\dot{R}_h = c\beta_h$$

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

Ambient medium: surrounding medium of jet-head

$$\mathbf{t_{coc} < t < t_{br}} \text{ or } \mathbf{t_{coc} < t < t_{fin}}$$

Physical Model: Expanding spherical debris



$t_{coc} < t < t_{br}$ or $t_{coc} < t < t_{fin}$

$$R_h(t_{dur} = 0) = R_s = 2GM_{BH}/c^2$$

$$\dot{R}_h = c\beta_h$$

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

Ratio of energy density between jet and ambient medium

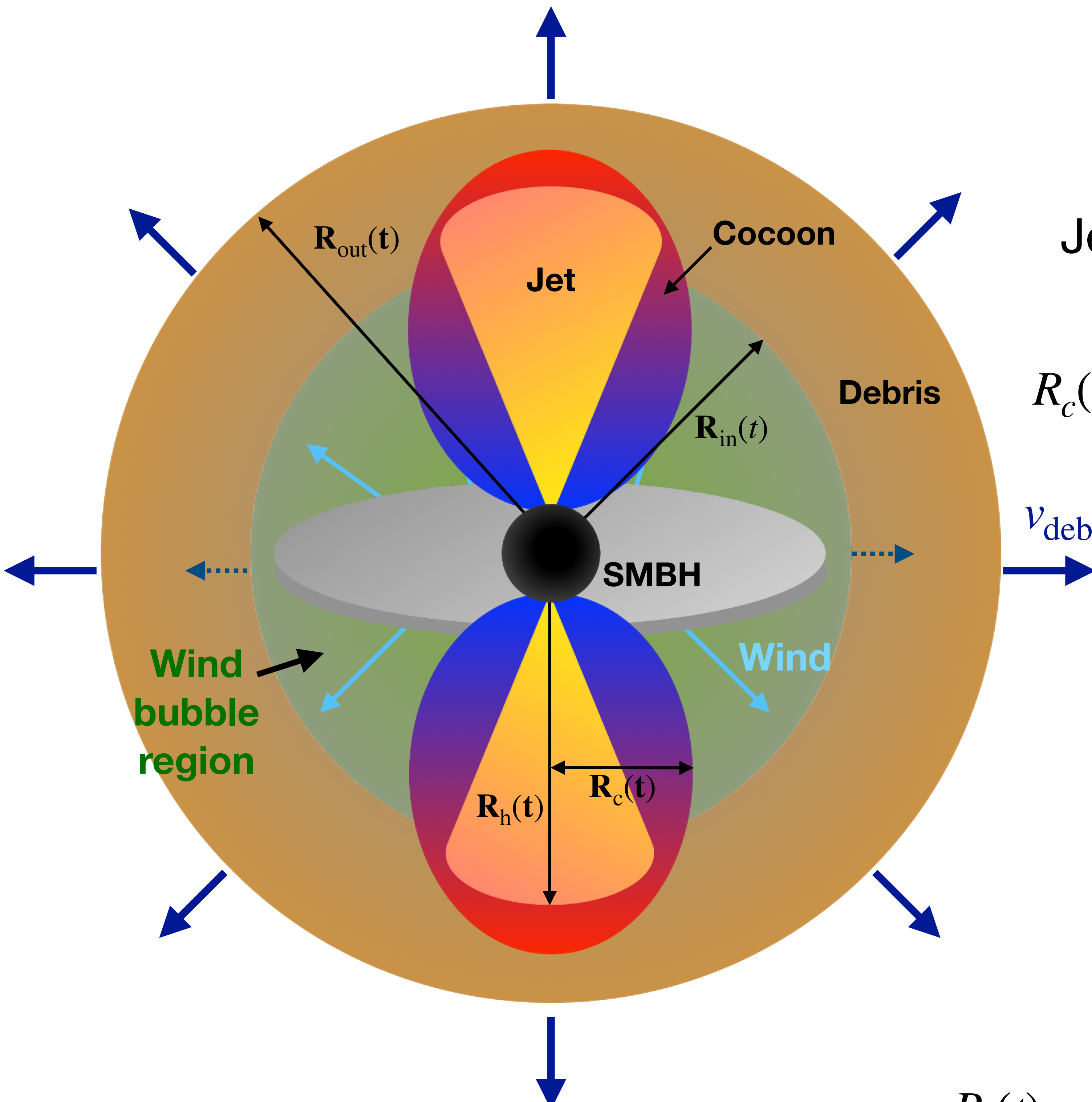
$$\tilde{L} = \frac{L_j}{\Sigma_j(t)\rho_a(t)c^3\Gamma_a^2}$$

Jet-head cross-section

$$\rho_a(t) = \rho_{deb}(t, r = R_h)$$

Density of ambient medium

Physical Model: Formation of cocoon and interaction



$t_{coc} < t < t_{br}$ or $t_{coc} < t < t_{fin}$

Jet head reaches the inner radius of the debris

$$R_c(t_{dur} = t_{coc}) = R_j(t_{dur} = t_{coc}) = R_h(t_{dur} = t_{coc})\theta_0$$

$$\dot{R}_c = c\beta_c$$

$$\beta_c \approx \frac{1}{c}\sqrt{\frac{P_c}{\rho_a(t)}} + \frac{R_c(t)}{R_{out}(t)}\frac{v_w}{c}$$

Cocoon pressure

$$P_c(t) = \frac{E_c}{3V_c} = \frac{\eta}{4\pi R_c(t)^2 R_h(t)} \int_{t_c}^{t} d\tilde{t}\; L_j(\tilde{t})\Big(1 - \beta_h(\tilde{t})\Big)$$

Electromagnetic (EM) signatures

$$\nu_\alpha^{\rm ES} = \frac{3}{4\pi}\frac{eB^{\rm ES}}{m_e c}\frac{\Gamma^{\rm ES}}{(1+z)}\left(\gamma_\alpha^{\rm ES}\right)^2$$

ES: External shock can be Forward or Reverse shock region

α: Can be injection frequency (m) or cooling frequency (c)

B: Magnetic field strength in the region

Γ: Bulk Lorentz factor in the shocked region

γ: Lorentz factor associated with the electrons

The absorption frequency $\nu_{\rm sa}$ is given by setting the synchrotron self-absorption optical depth to 1

$$B^{\rm ES} = \left[32\pi\epsilon_B \Gamma^{\rm ES}(\Gamma^{\rm ES} - 1) n^{\rm ES} m_p c^2\right]^{1/2}$$

↑ Fraction of electron energy converted to magnetic field energy

Electromagnetic (EM) signatures

$\nu_m > \nu_c$

Fast cooling

$$F_\nu^{\rm ES} = F_{\rm syn,max}^{\rm ES} \begin{cases} (\nu/\nu_{sa}^{\rm ES})^2 (\nu_{sa}^{\rm ES}/\nu_c^{\rm ES})^{1/3}, & \nu \leqslant \nu_{sa}^{\rm ES} \\ (\nu/\nu_c^{\rm ES})^{1/3}, & \nu_{sa}^{\rm ES} < \nu \leqslant \nu_c^{\rm ES} \\ (\nu/\nu_c^{\rm ES})^{-1/2}, & \nu_c^{\rm ES} < \nu \leqslant \nu_m^{\rm ES} \\ (\nu_m^{\rm ES}/\nu_c^{\rm ES})^{-1/2} (\nu/\nu_m^{\rm ES})^{-s/2}, & \nu_m^{\rm ES} < \nu \leqslant \nu_M^{\rm ES} \end{cases}$$

$\nu_c > \nu_m$

Slow cooling

$$F_\nu^{\rm ES} = F_{\rm syn,max}^{\rm ES} \begin{cases} (\nu/\nu_{sa}^{\rm ES})^2 (\nu_{sa}^{\rm ES}/\nu_m^{\rm ES})^{1/3}, & \nu \leqslant \nu_{sa}^{\rm ES} \\ (\nu/\nu_m^{\rm ES})^{1/3}, & \nu_{sa}^{\rm ES} < \nu \leqslant \nu_m^{\rm ES} \\ (\nu/\nu_m^{\rm ES})^{-(s-1)/2}, & \nu_m^{\rm ES} < \nu \leqslant \nu_c^{\rm ES} \\ (\nu/\nu_c^{\rm ES})^{-\frac{s}{2}} (\nu_c^{\rm ES}/\nu_m^{\rm ES})^{-\frac{(s-1)}{2}}, & \nu_c^{\rm ES} < \nu \leqslant \nu_M^{\rm ES} \end{cases}$$

In both cases the self-absorption frequency is the lowest

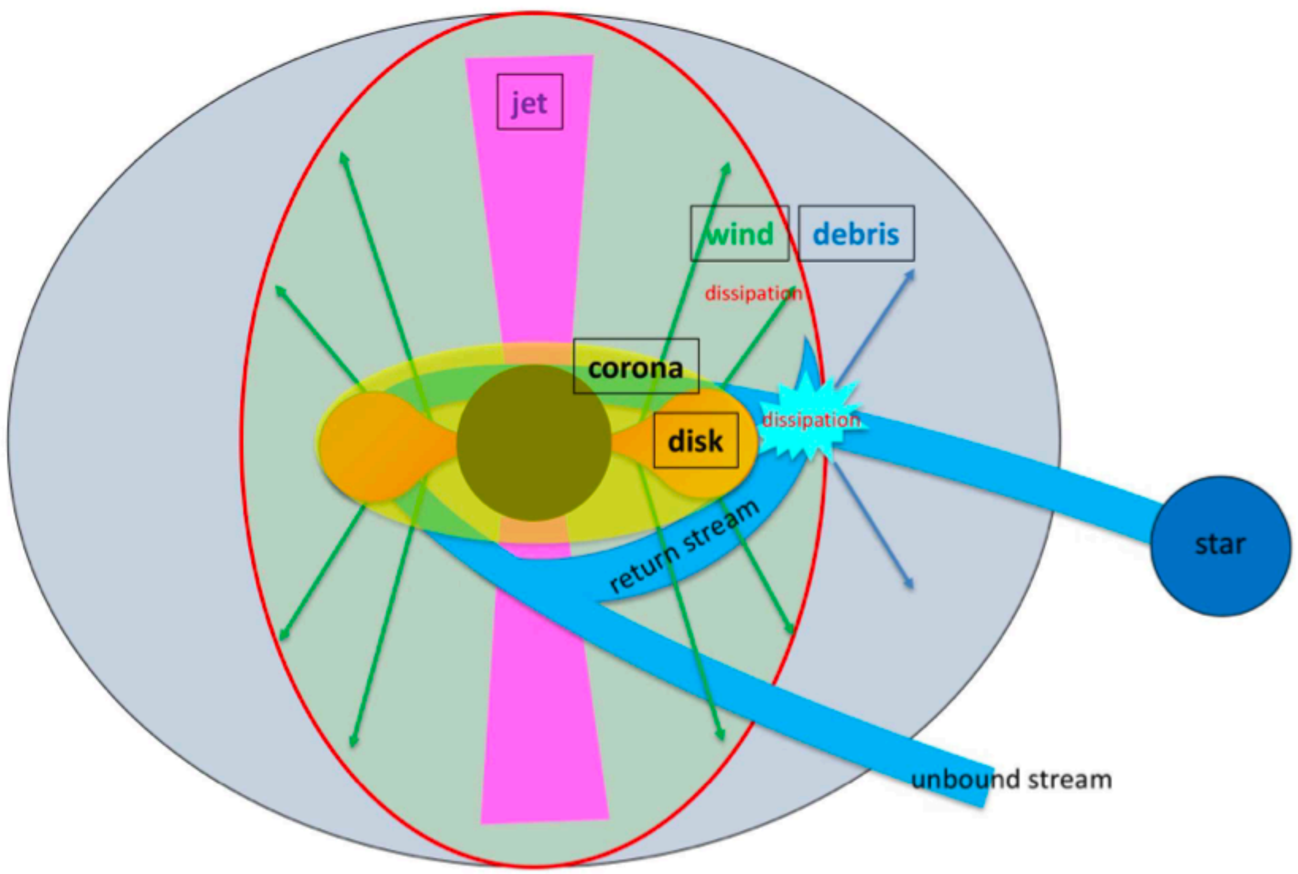
Fraction of accelerated electrons

$$F_{\rm syn,max}^{\rm ES} \approx 0.6 f_e n^{\rm ES} R_h^3 \Gamma^{\rm ES} e^3 B^{\rm ES} (1+z) / \left(\sqrt{3} m_e c^2 d_L^2\right)$$

Peak synchrotron flux

Particle number density

High energy neutrinos from TDEs



Murase et al (2020)

Successful/hidden jets
(Wang+16, Senno, Murase & Meszaros 17, Murase+ 20, Lunardini & Winter 17, 21)

Disk corona
(Murase+ 20)

RIAF disk
(Hayasaki & Yamazaki 19, Murase+ 20)

Hidden wind
(Murase+ 20, Wu+ 22, Winter & Lunardini 23)

- Powerful successful jets contradict with the absence of jet-induced afterglows
- Jets cannot be too powerful for jets to be “choked”

$$L_{\rm j,iso} \lesssim 1.5 \times 10^{44} {\rm erg\ s^{-1}} t_{\rm eng,6.5}^{-3} D_{\rm w,15.8} R_{\rm out,16}^{2} \theta_{\rm j,-1}^{2}$$

But this condition can be relaxed if jets are **delayed**

Murase et al. (2020)