@Extreme Outflows in Astrophysical Transients
25 Aug. 2021

Probing Outflows in Tidal Disruption Events

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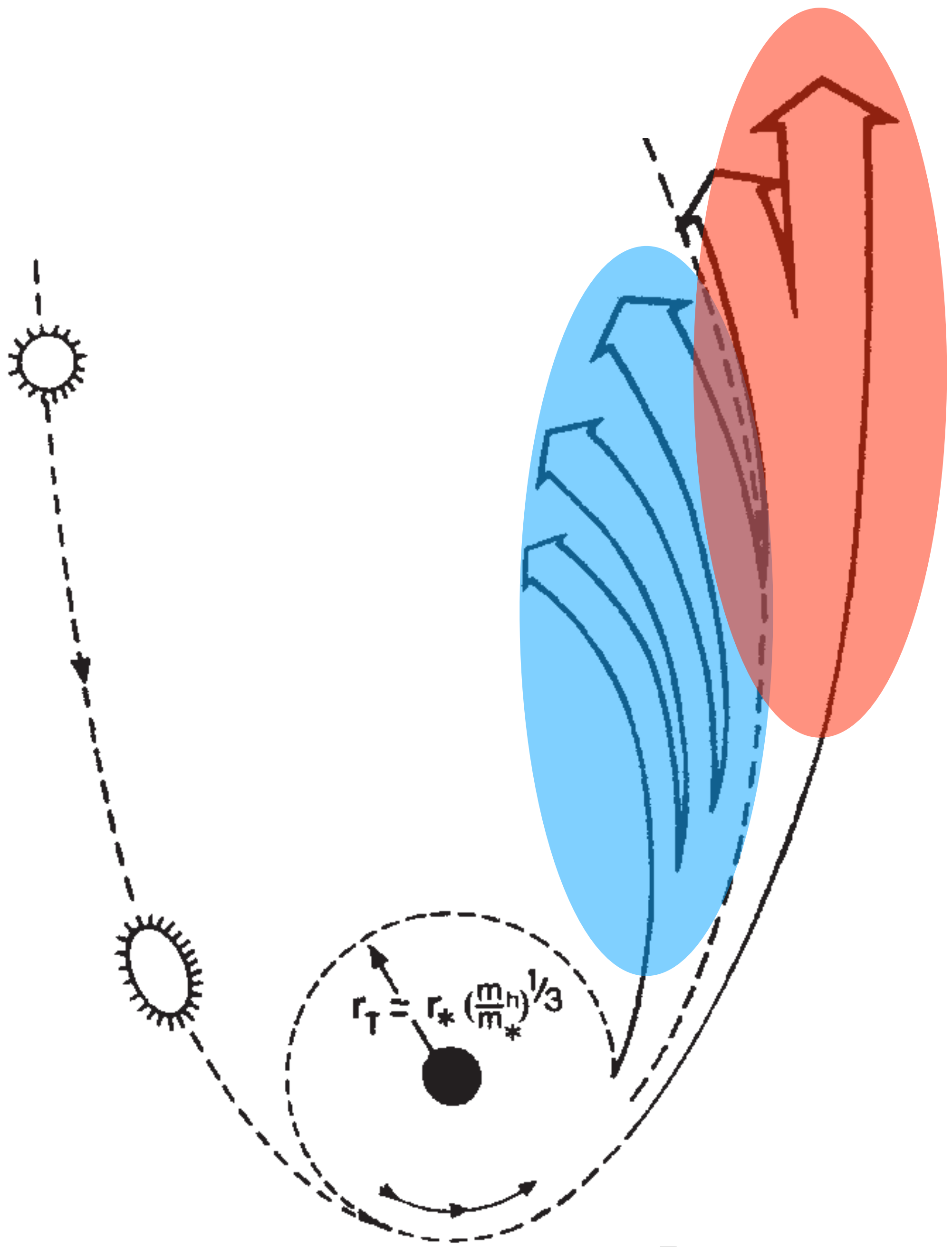
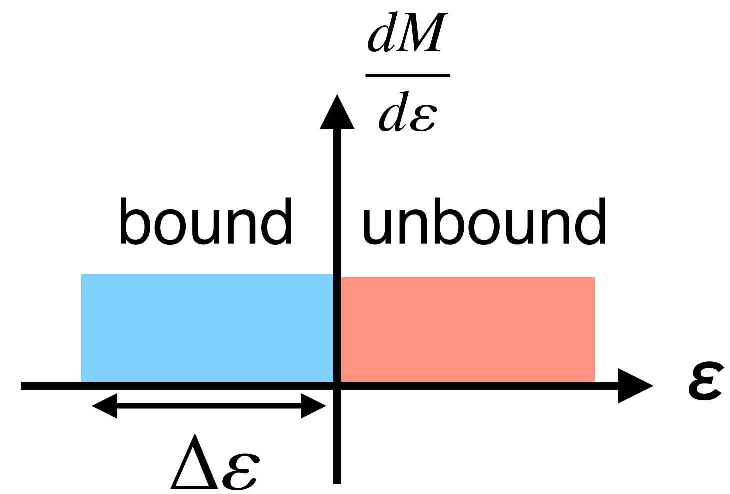
Optical constraint

Tidal Disruption Event



Rees88



$$\dot{M}_{\rm fb} \sim 10^2 \dot{M}_{\rm Edd} (t/40\,{\rm d})^{-5/3}$$

If a standard disk forms,

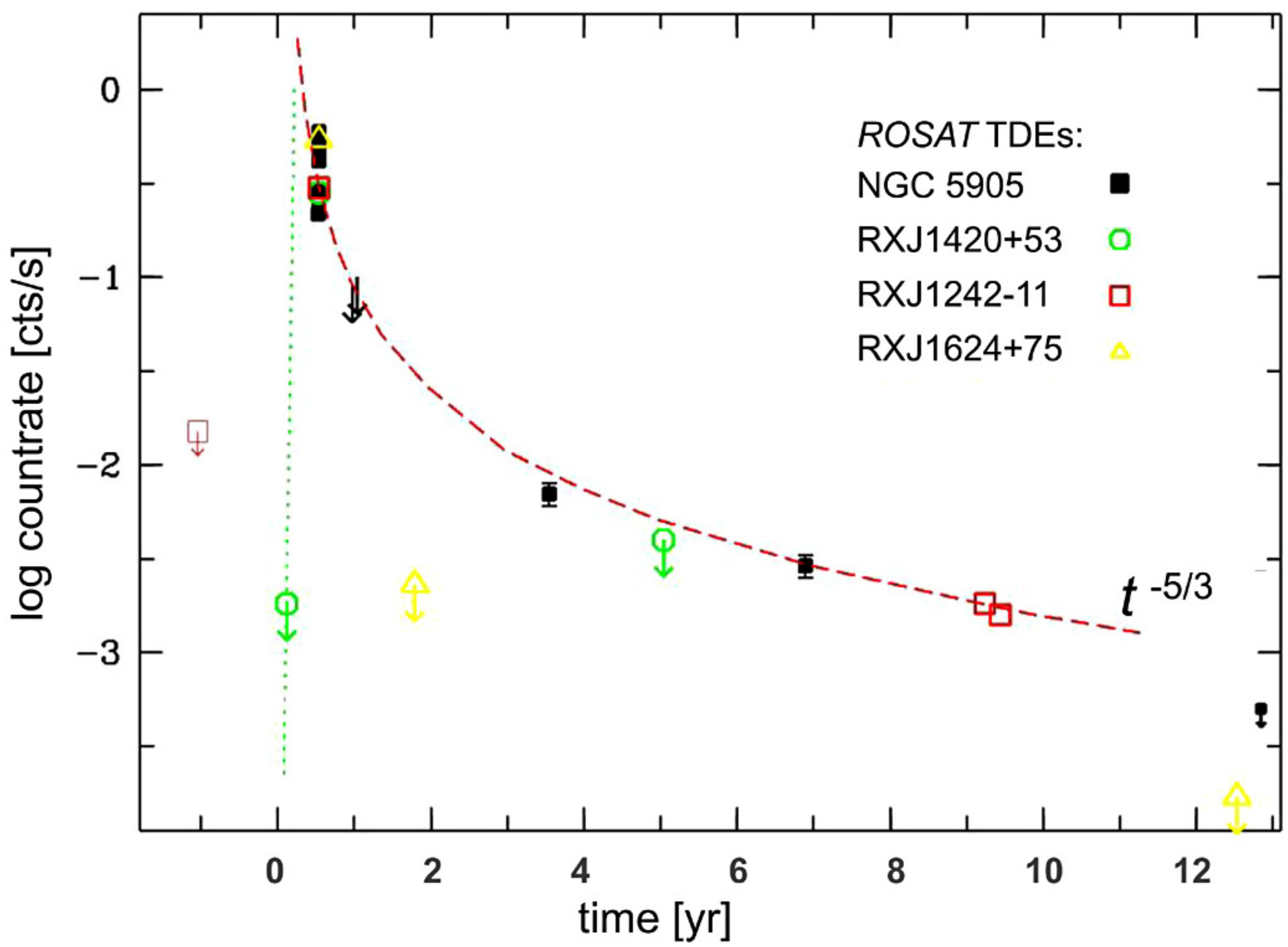
$$T \sim 10^{2-3}\,{\rm eV}$$

Expectation: soft X-rays flares

in galactic center with $\sim L_{\rm Edd}$ lasting $\sim$yr

X-ray TDEs (1990s~)

Komossa15



In galactic centers (not AGN)

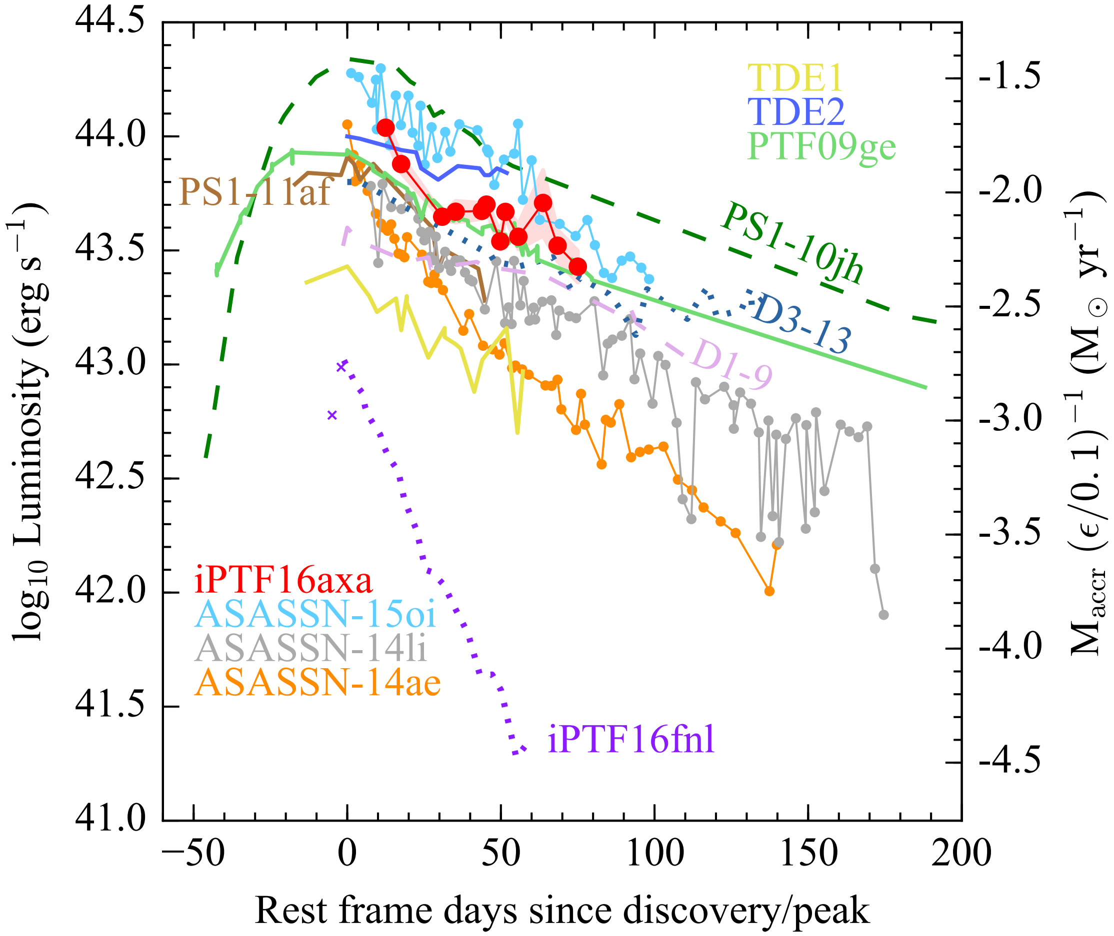
$$L_{\mathrm{X,peak}} \sim 10^{44} \mathrm{erg/s} \, (\sim L_{\mathrm{Edd}})$$

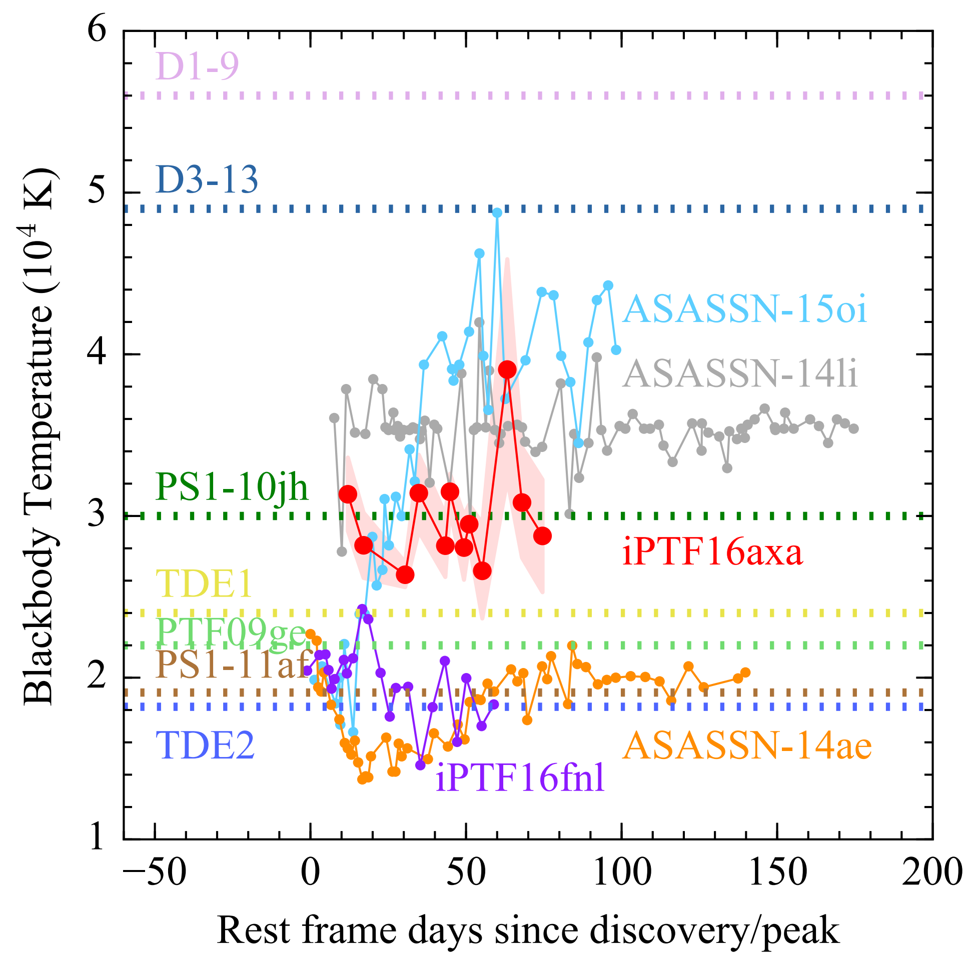
$$k_{\mathrm{B}} T \sim 0.1 \mathrm{keV}$$

$$L \propto t^{-5/3}$$

OPTICAL TDEs (2010s~)

Hung+17





Discovered by optical surveys

In galactic center (not AGN)

$L_{opt,peak} \sim 10^{44}$ erg/s, $t >\sim 100$ days

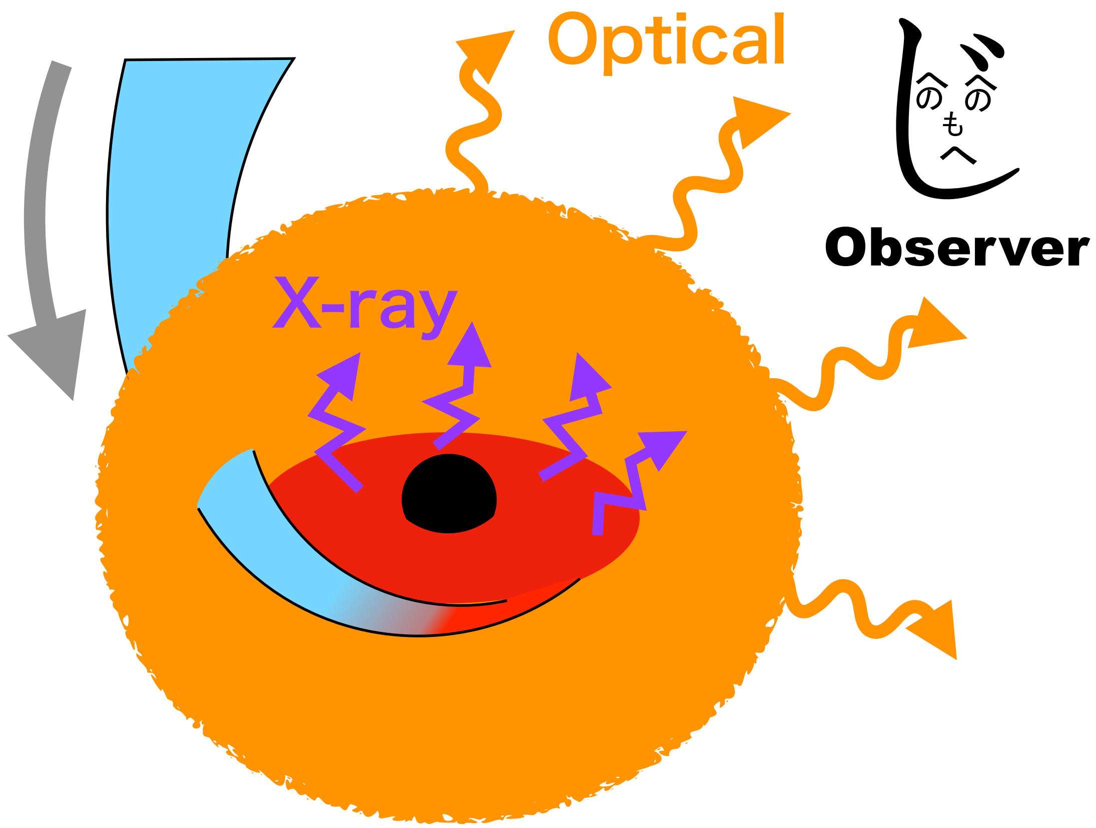
$T \sim 3\text{x}10^4$ K

Inconsistent with the classical picture

Models of optical TDEs

1) Reprocessed model

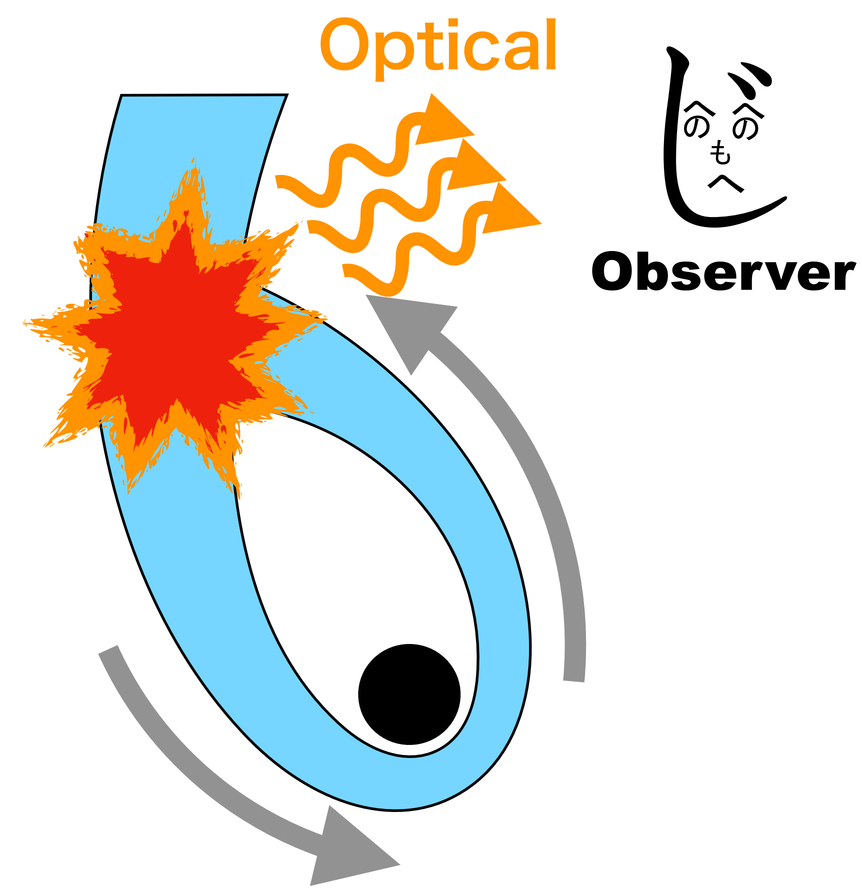
Loeb&Ulmer97,Metzger&Stone16,…



Debris forms a disk
=>The disk covered by envelope or disk-wind
=>X-rays from the disk are absorbed
and reprocessed to optical photons

2) Shock interaction model

Piran+15,Krolik+16,…



Debris ***does not*** form a disk
but collides with each other
=> optical emission from shocks

Models of optical TDEs

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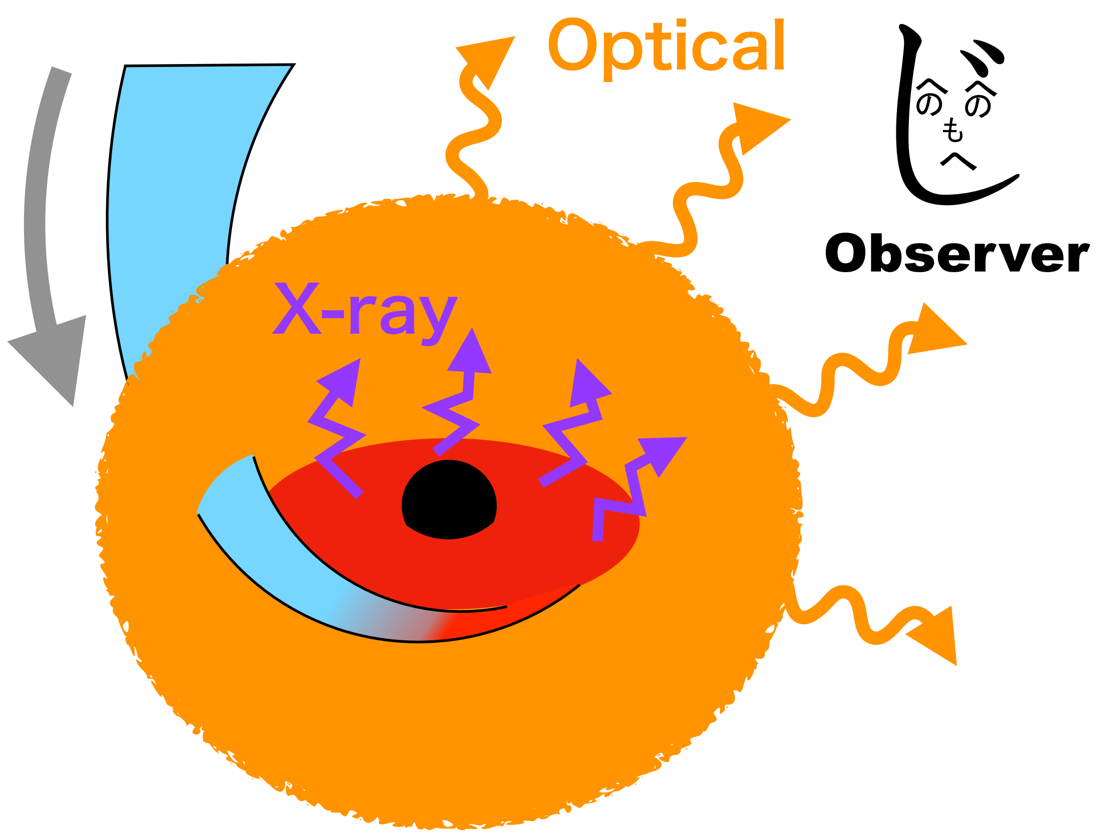

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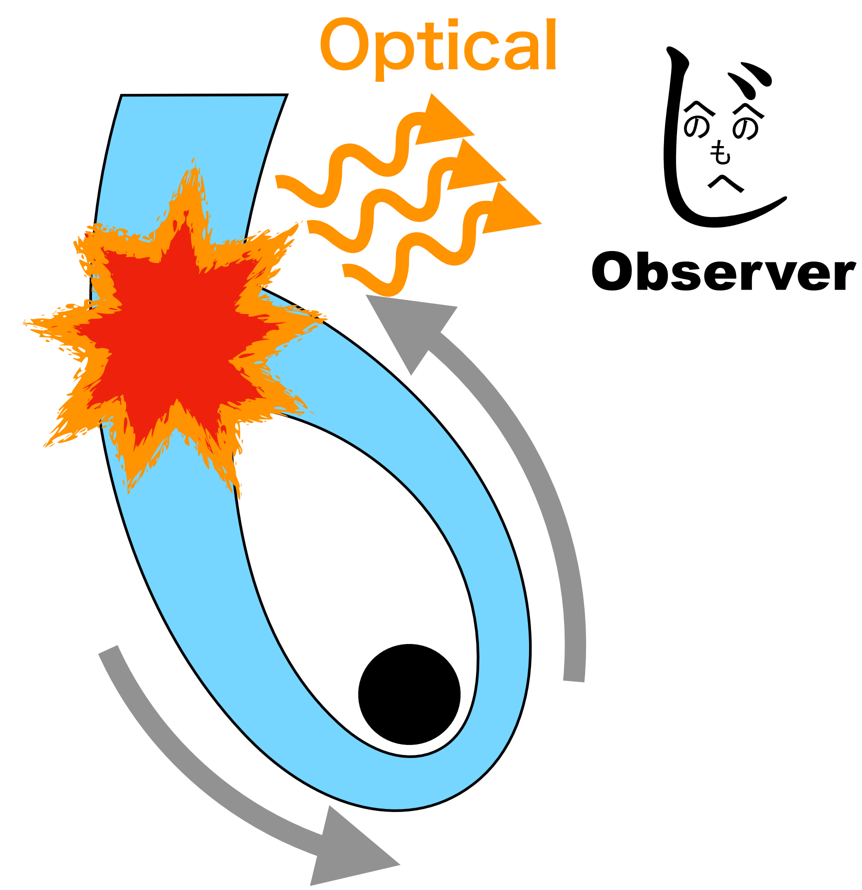

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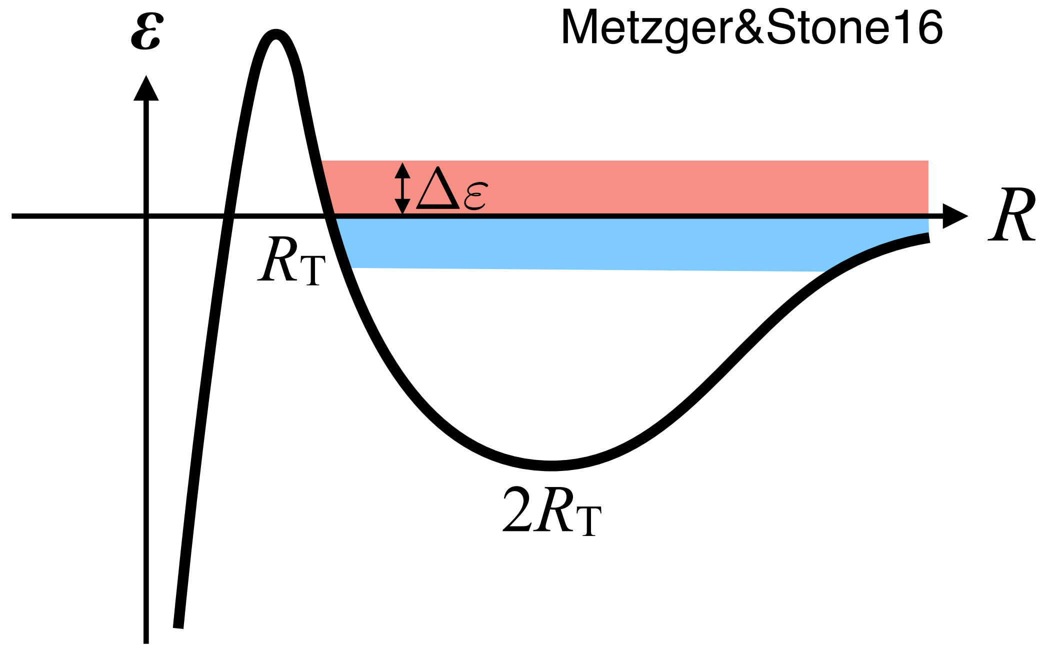
Reprocessed model



Energetics of disk formation @ $2R_T$

Debris energy:

$$E_{\rm debri} \simeq \Delta\varepsilon(M_*/2) \sim -10^{50}{\rm erg}$$

Binding energy @ $2R_T$:

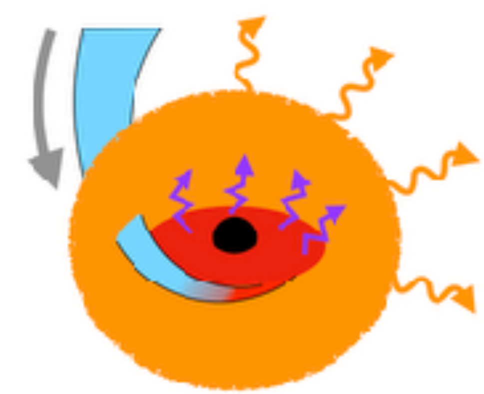
$$E_{\rm circ} \simeq \frac{GM_{\rm BH}(M_*/2)}{2R_{\rm T}} \sim -10^{52}{\rm erg} \iff E_{\rm opt} \sim 10^{51}{\rm erg}$$

Inverse energy crisis

=> Only a fraction $f_{\rm in} > 10^{-2}$ of debris forms a disk and other rest of debris is blown away as a wind

wind velocity $\frac{GM_{\rm BH}}{2R_{\rm T}}\dot{M}_{\rm acc} \simeq \frac{1}{2}\dot{M}_{\rm out}v^2$

$$v \simeq \sqrt{\frac{GM_{\rm BH}}{R_{\rm T}}\frac{f_{\rm in}}{1-f_{\rm in}}} \sim 10000\,{\rm km/s}\,f_{\rm in,-1}^{1/2}$$



Reprocessed model

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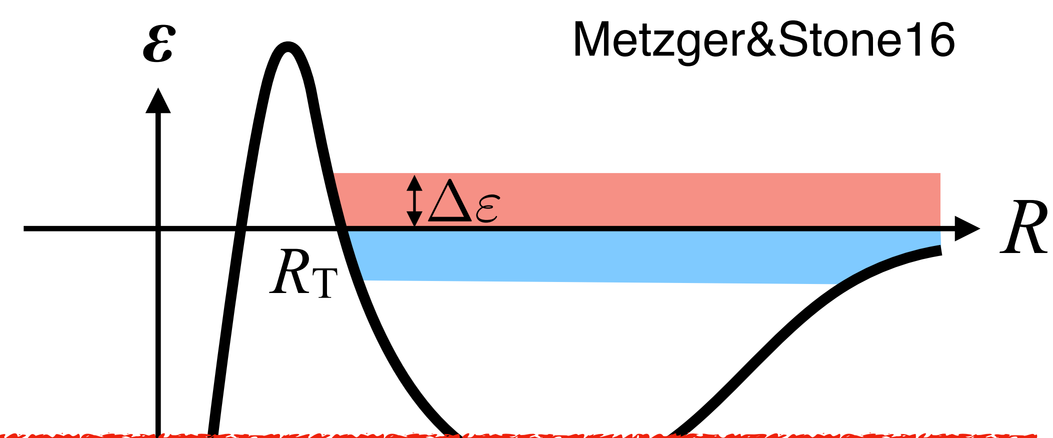

Check the consistency of reprocessed model with observations by estimating the ejected mass

and other rest of debris is blown away as a wind

wind velocity $\frac{GM_\mathrm{BH}}{2R_\mathrm{T}}\dot{M}_\mathrm{acc} \simeq \frac{1}{2}\dot{M}_\mathrm{out}v^2$

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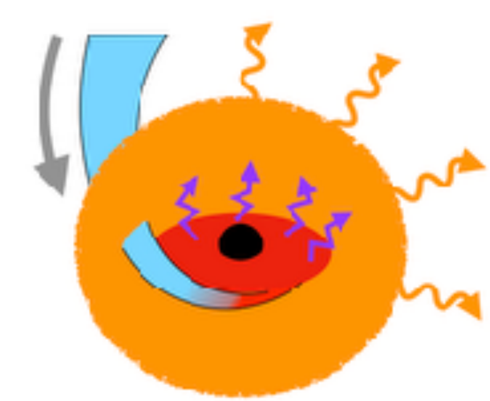


Our method

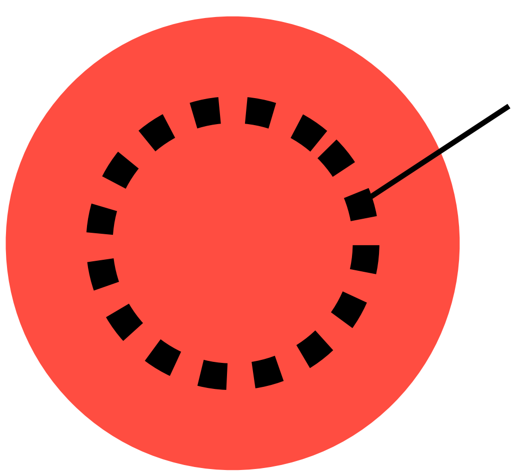
Estimate the condition
of optical emitting region from observation

Assumptions

1. Spherical ejecta
2. Thermal emission

Two radii

① Diffusion radius: R_d

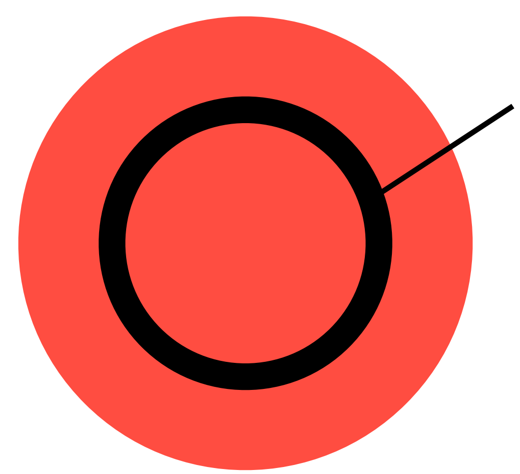


$\boldsymbol{\tau = c/v}$

(t_diff=t_dyn)

$$\tau(R_\mathrm{d}) \equiv \int_{R_\mathrm{d}}^{\infty} (\kappa_\mathrm{es} + \kappa_\mathrm{a})\rho dR$$

② Color radius: R_c



$\boldsymbol{\tau_\mathrm{eff} = 1}$

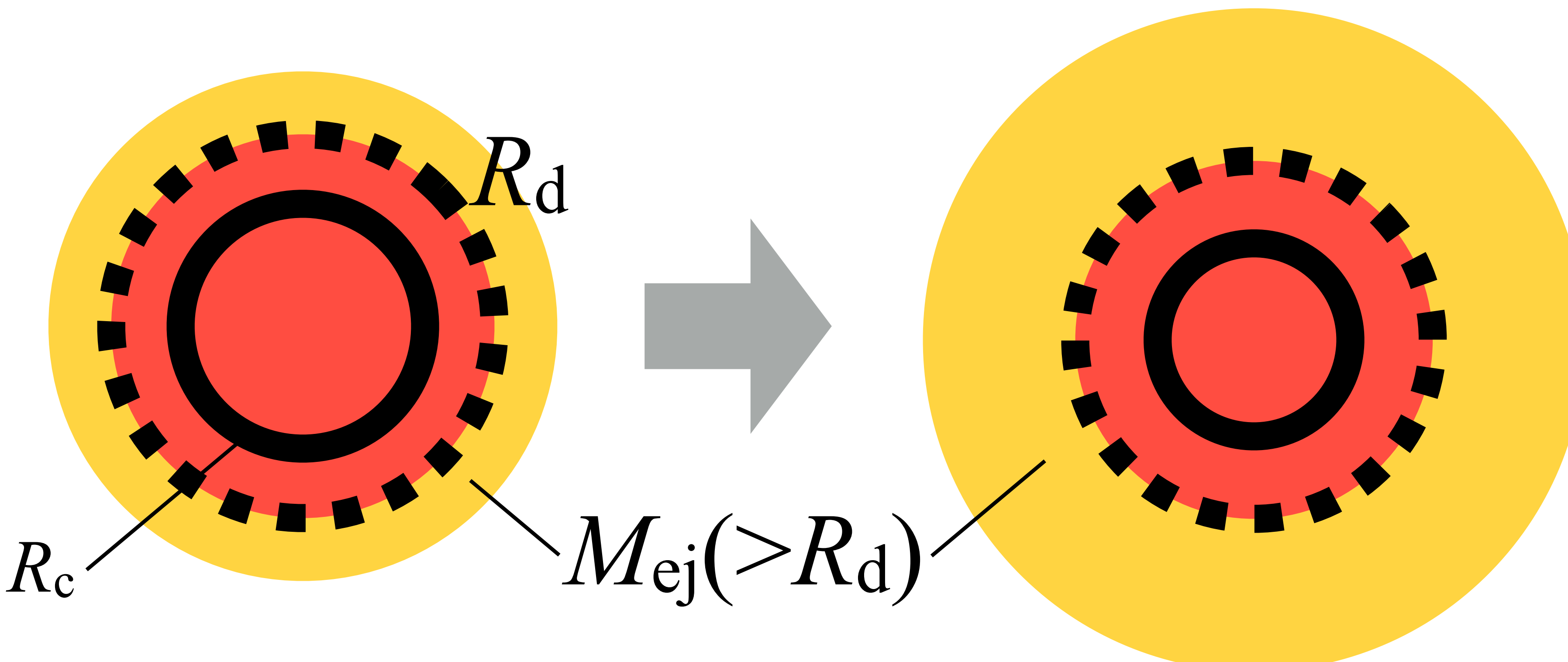
(Last photon absorption)

$$\tau_\mathrm{eff}(R_\mathrm{c}) \equiv \int_{R_\mathrm{c}}^{\infty} \sqrt{\kappa_\mathrm{a}(\kappa_\mathrm{es} + \kappa_\mathrm{a})}\rho dR$$

See Rybicki&Lightman

See also
Shen+15,Piro&Lu20,Uno&Maeda20

Case 1. $R_c < R_d$



Diffusion approximation @ R_d

$$L = -\frac{4\pi R^2 ac}{3\kappa_{es}\rho}\frac{dT^4}{dR} \simeq \frac{4\pi R_d ac T^4}{3\kappa_{es}\rho_d}$$

Def of tau

$$\tau(R_d) \simeq \kappa_{es}\rho_d R_d = \frac{c}{v_d}$$

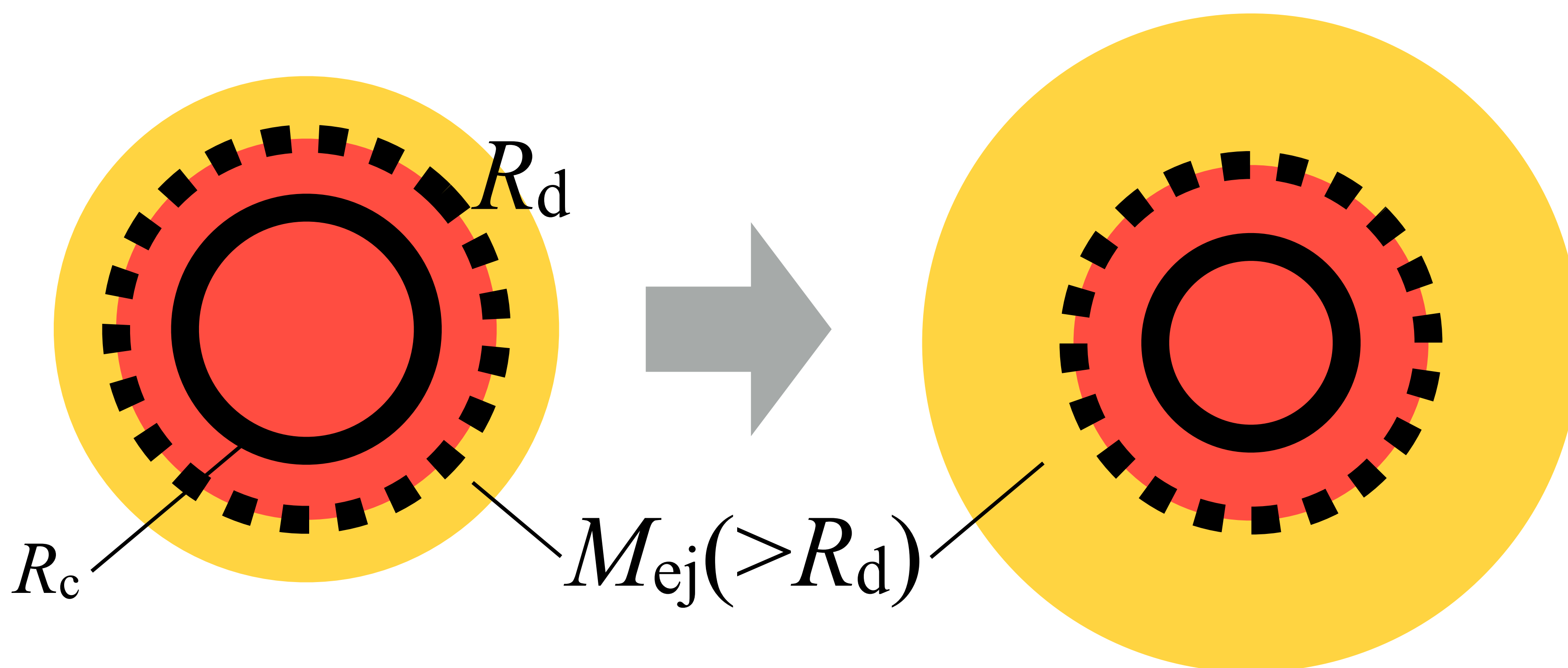
$\Rightarrow$

$\rho_d(L, T, v_d)$

$R_d(L, T, v_d)$

See also
Shen+15,Piro&Lu20,Uno&Maeda20

Case 1. $R_c < R_d$



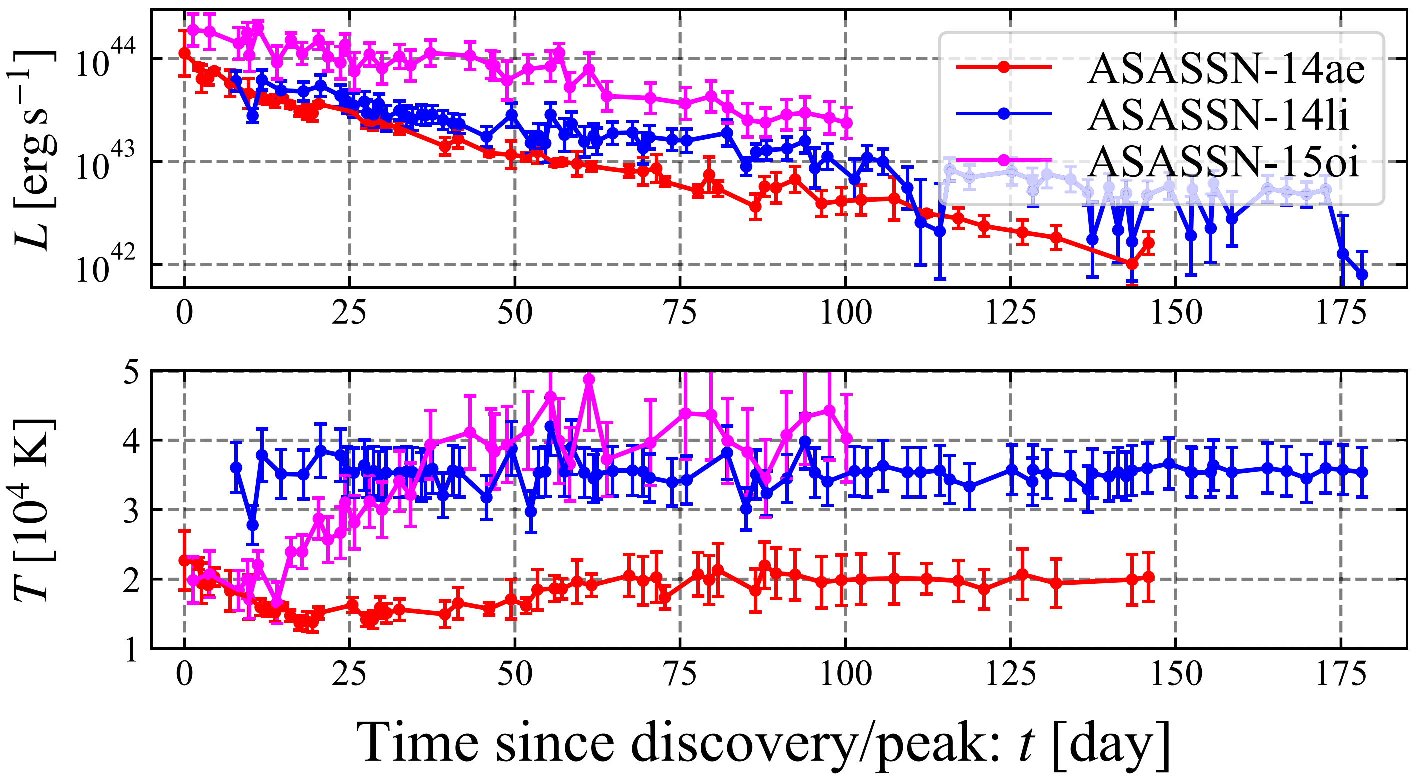
$L(\rho_d, R_d, T)$
$\tau(\rho_d, R_d) = v_d/c$
@ R_d

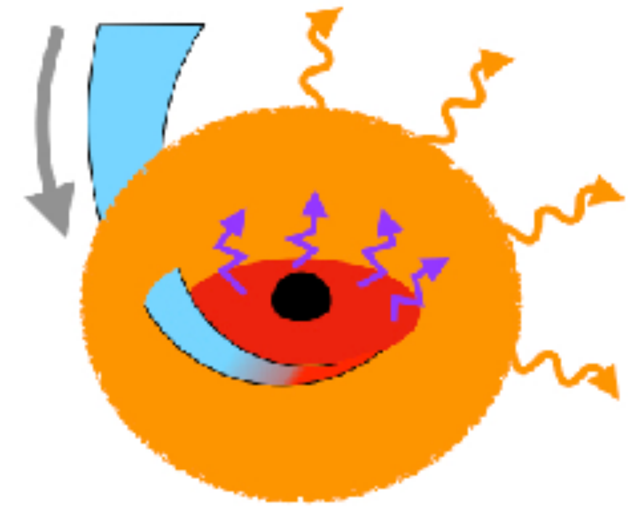
$\rho_d(L, T, v_d)$
$R_d(L, T, v_d)$

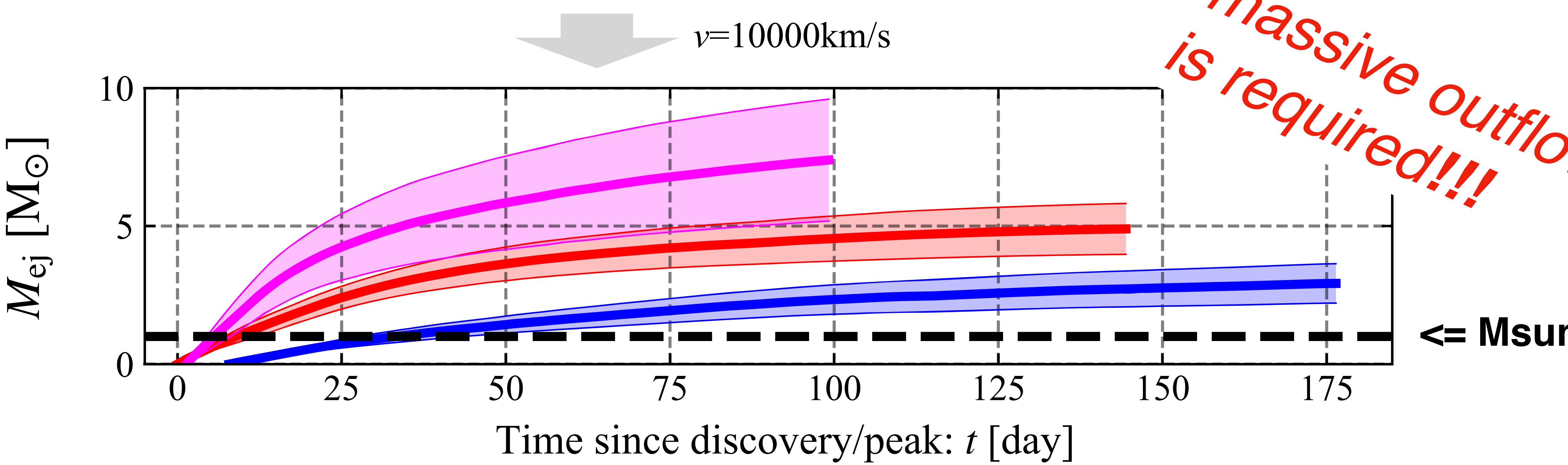
$\dot{M}_d \sim 4\pi R_d^2 \rho_d v_d$

$$M_{ej}(>R_d) = \int dt\, \dot{M}_d$$

Application to optical TDEs

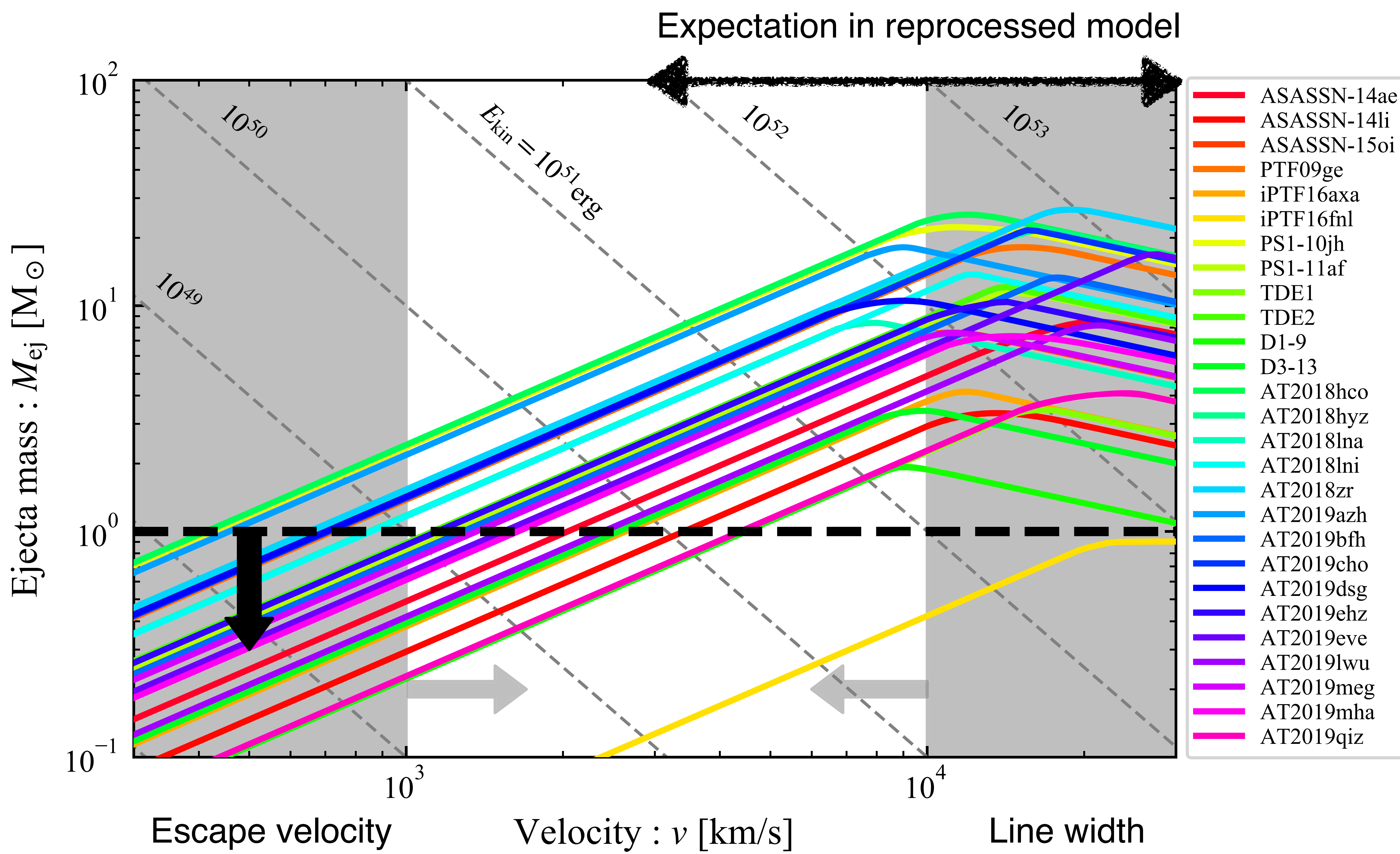






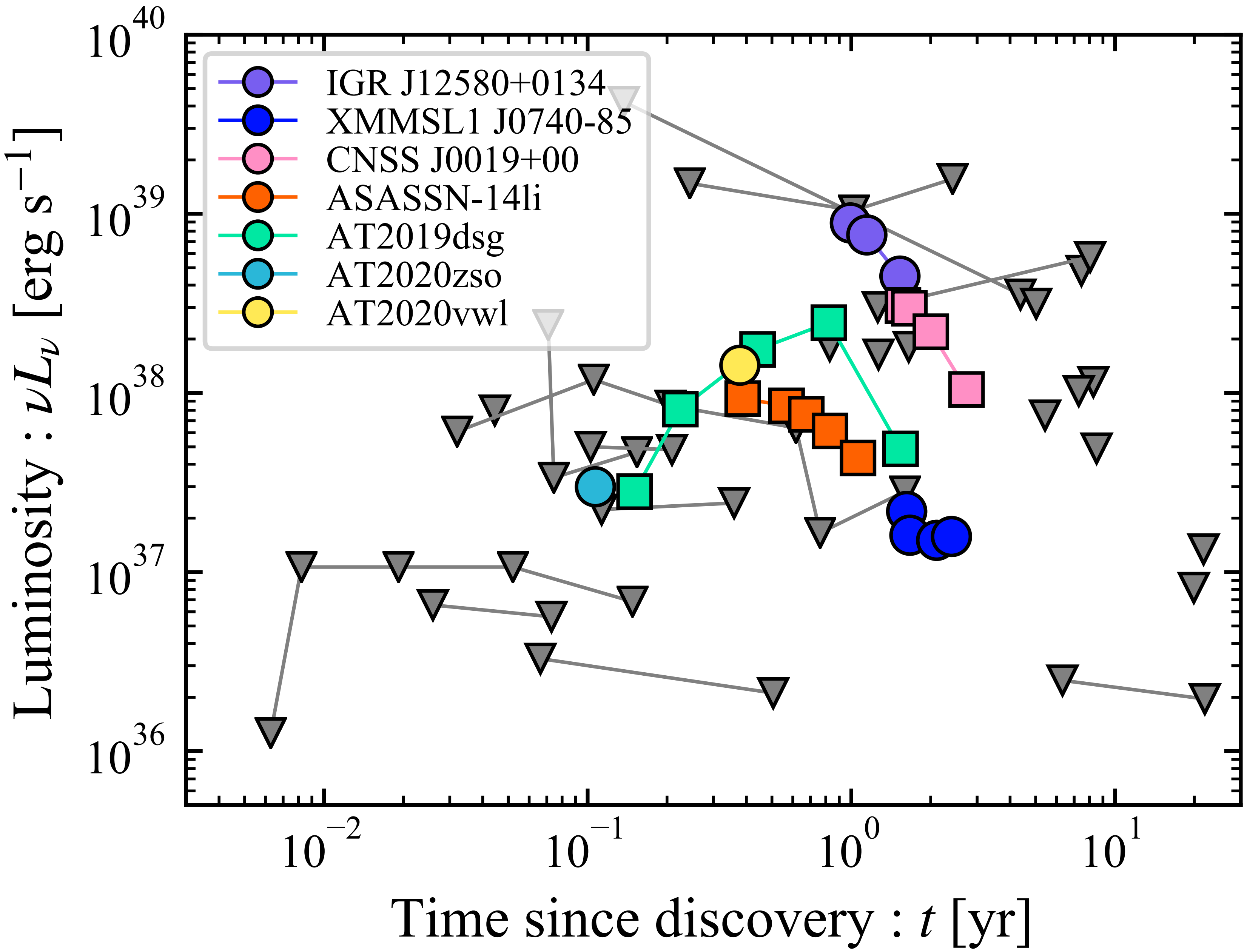
Too massive outflow is required!!!

Other TDEs with various velocity



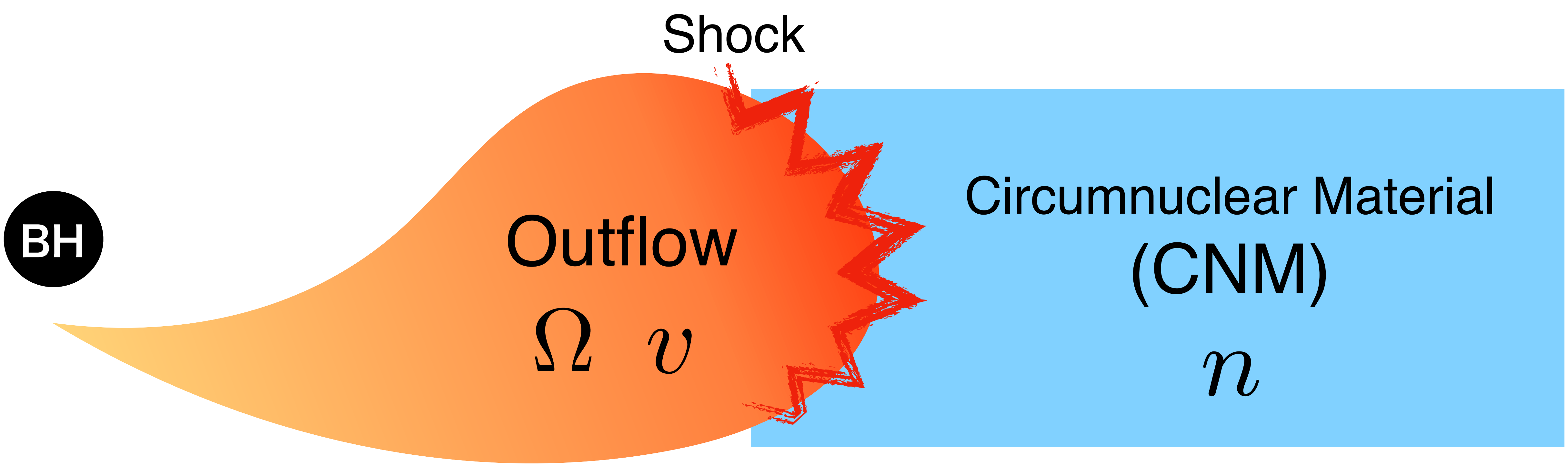
Radio constraint

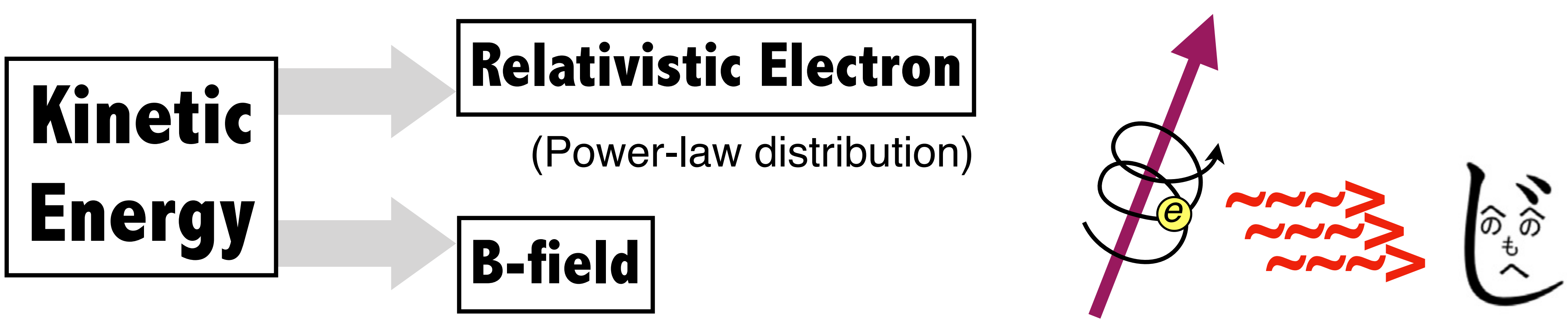
Radio: Observations



Radio by synchrotron emission: Outflow + surrounding materials

Radio: Synchrotron model



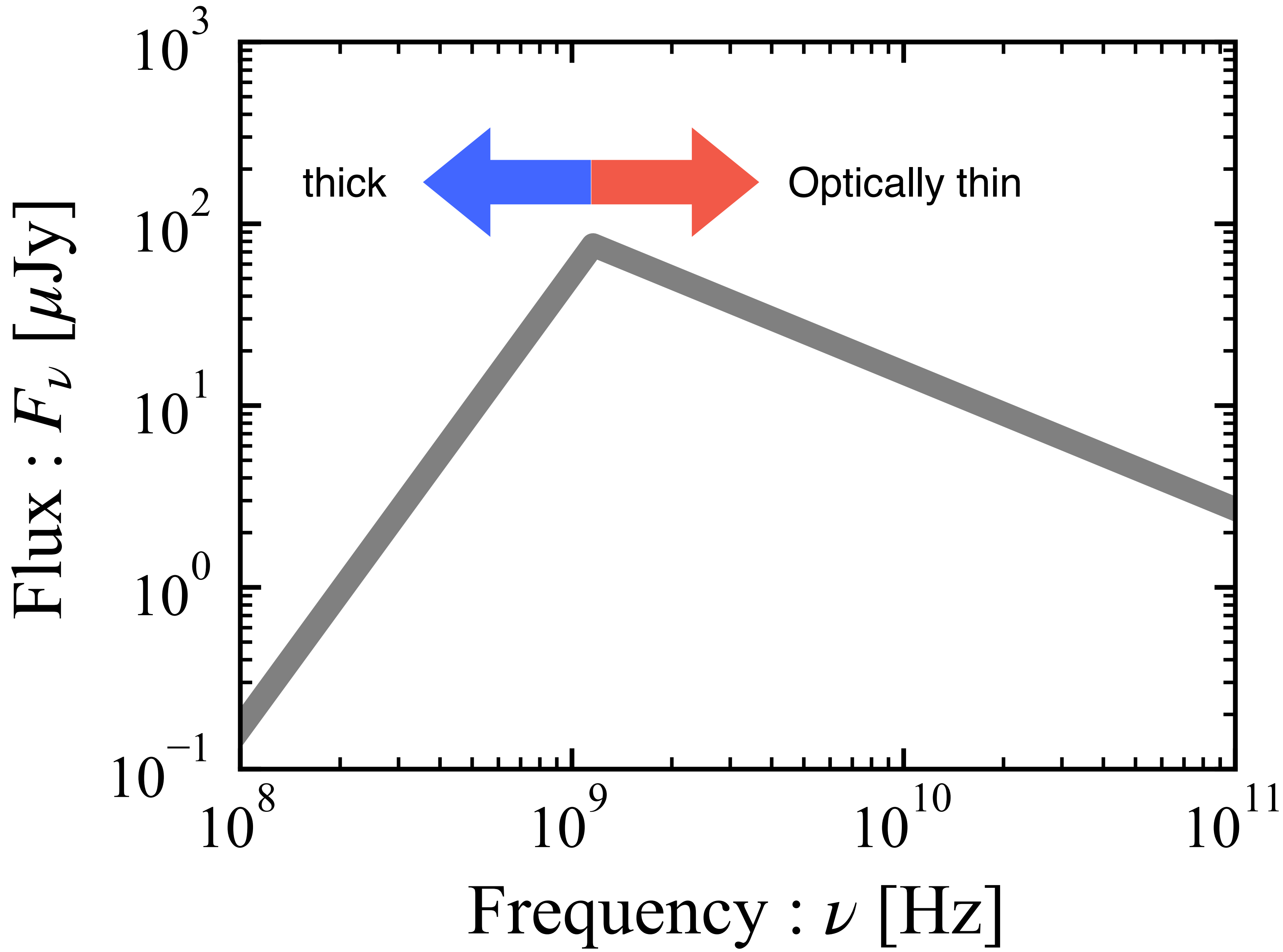


Radio emission: Probe of outflow & CNM

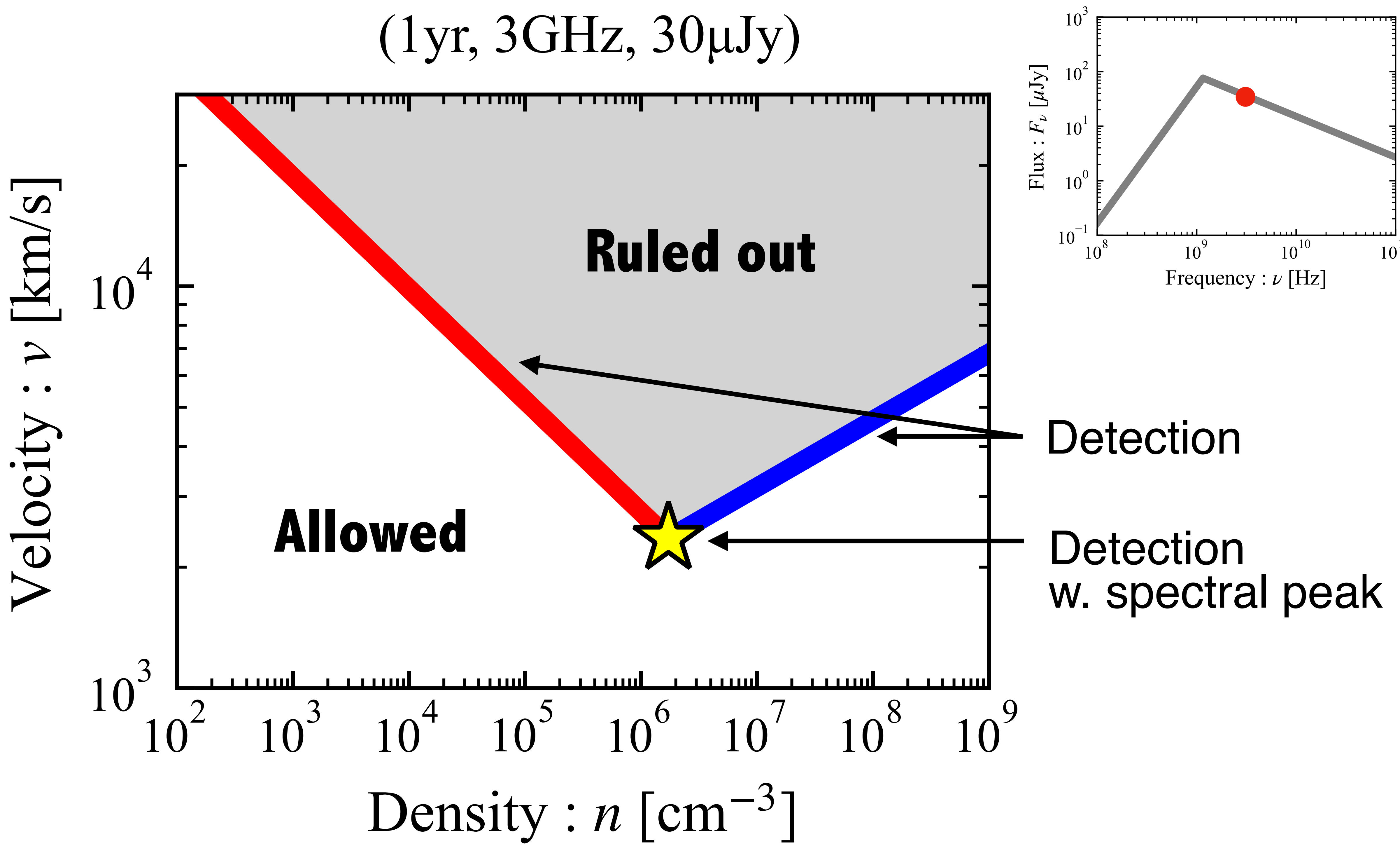
Radio: Synchrotron model

$$F_\nu(\Omega, v, n)$$

10000km/s, 10^4cm^{-3}
1yr ($R \simeq vt$)



Radio: Synchrotron model

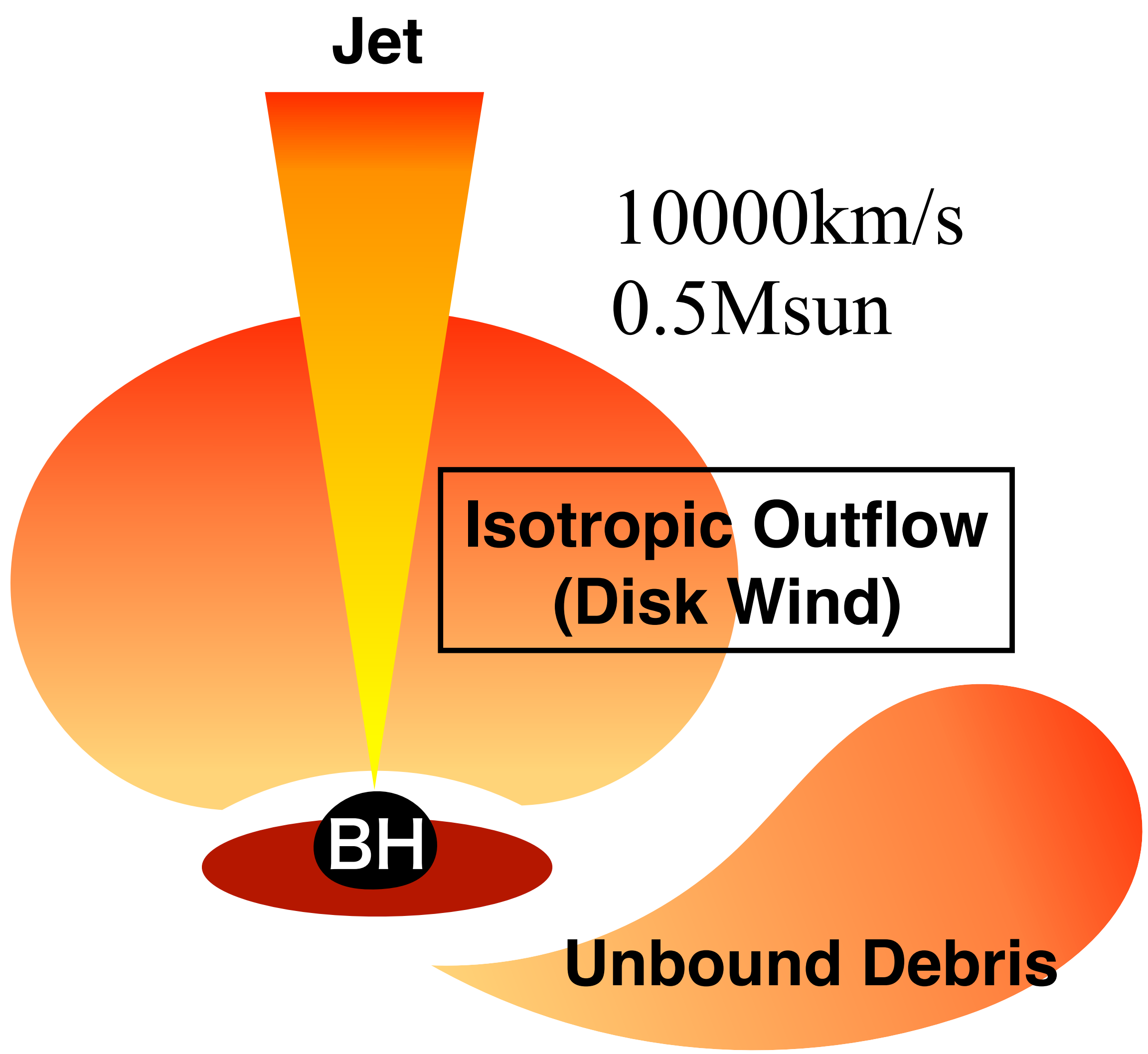


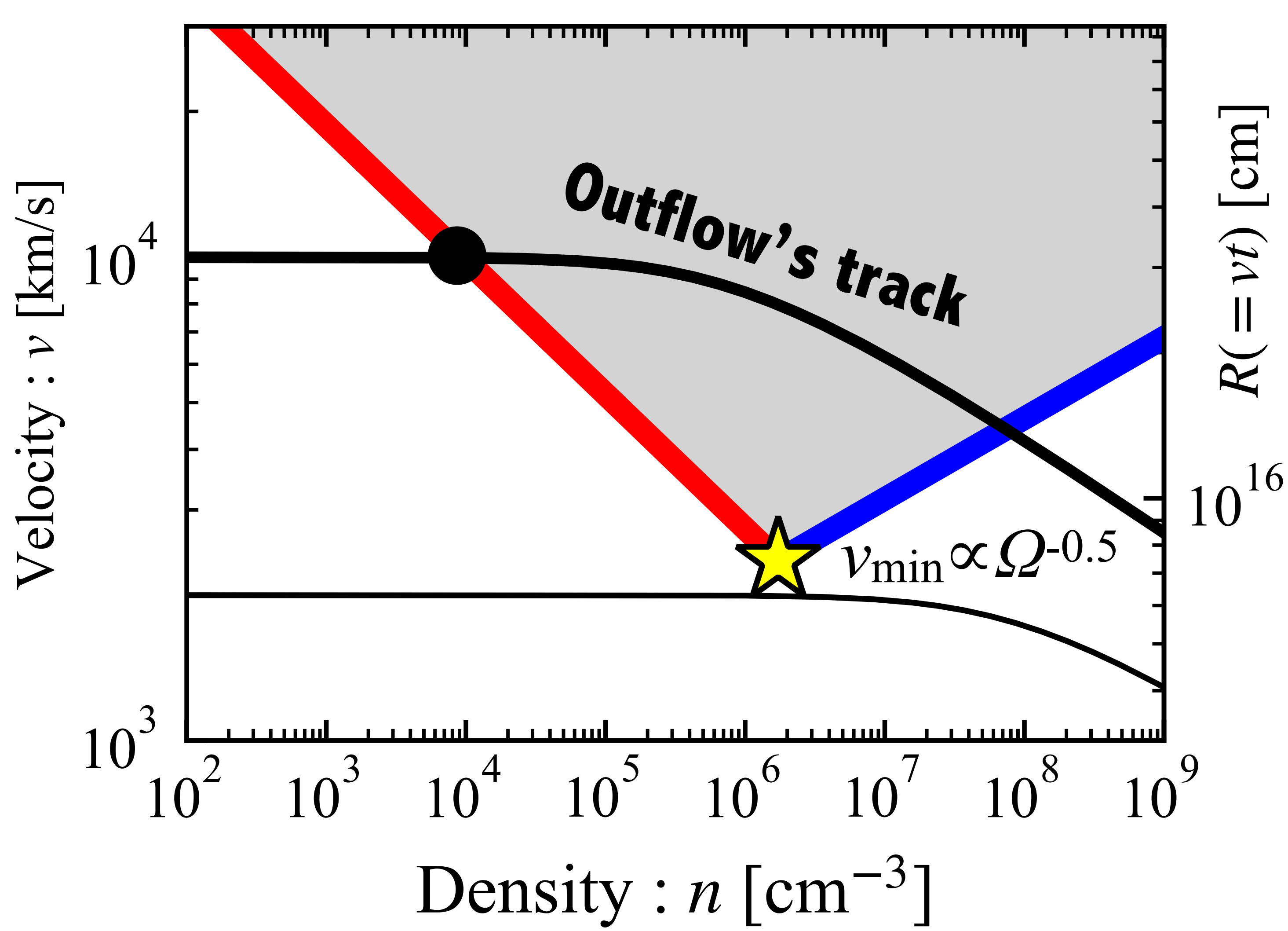
Where is an outflow's parameter located in this space?

Outflow model

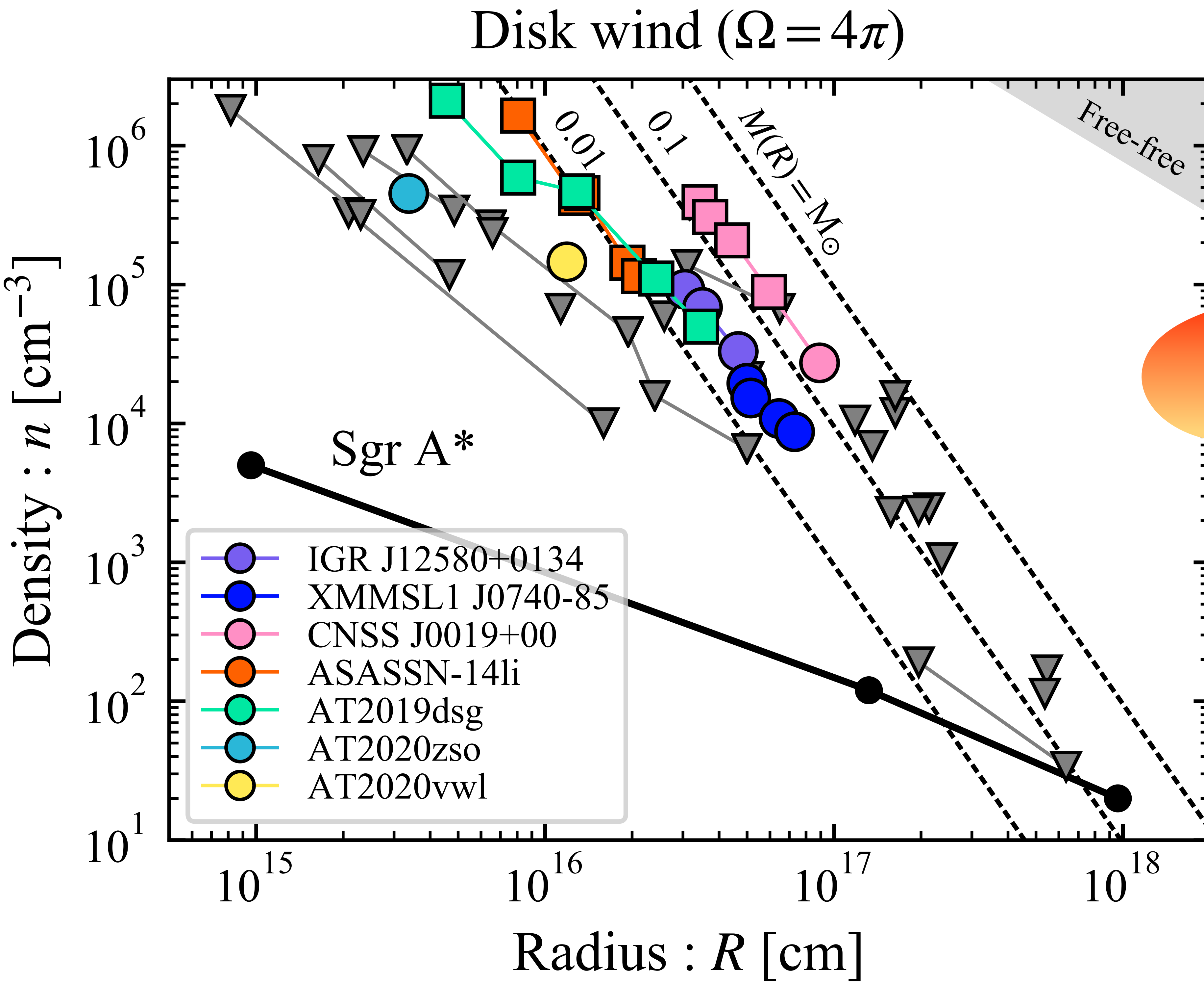
$$E_{\rm kin}=[M_{\rm ej}+M(R)]v^2/2$$

$$M(R)=\Omega m_{\rm p} n R^3$$

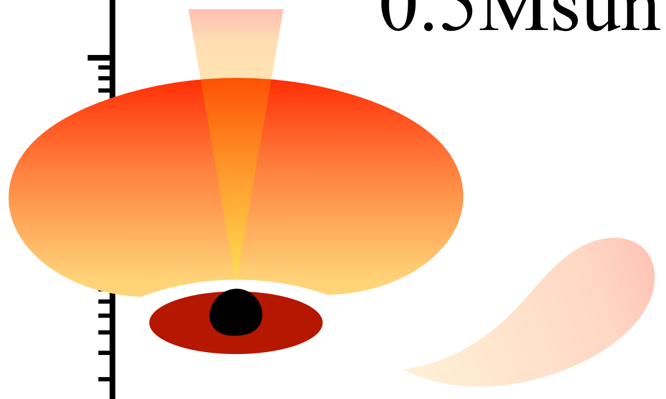




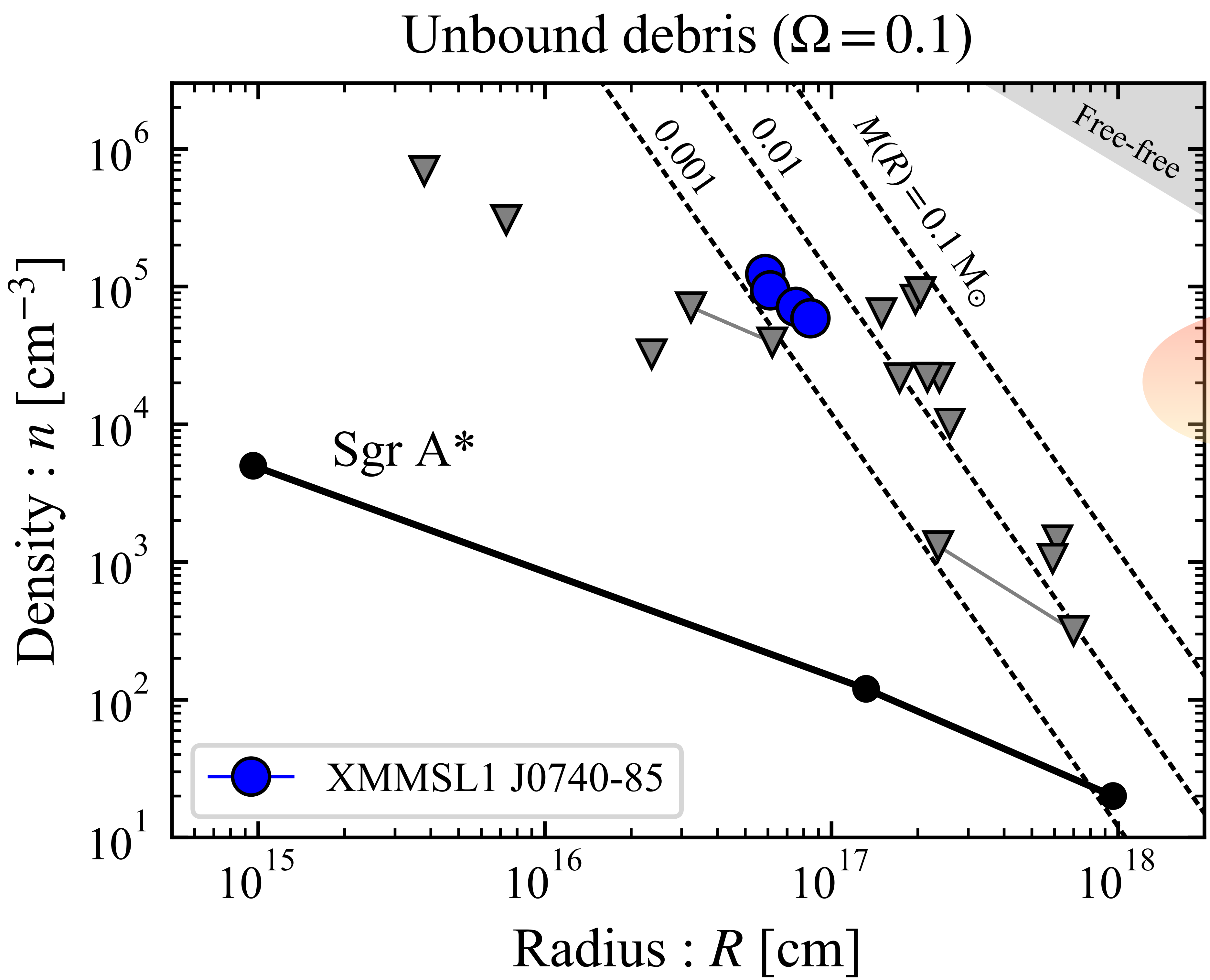
Isotropic Outflow (Disk Wind)

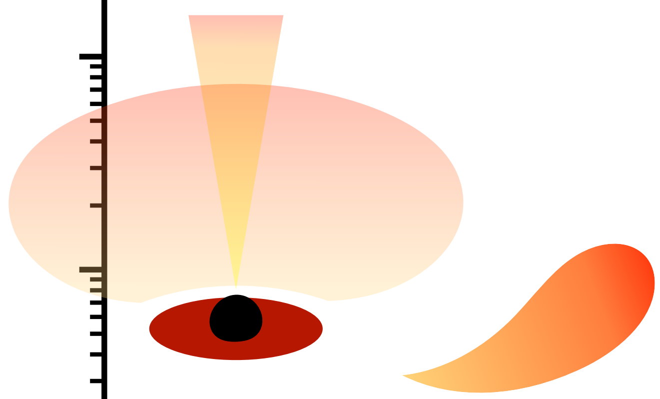


10000km/s
0.5Msun



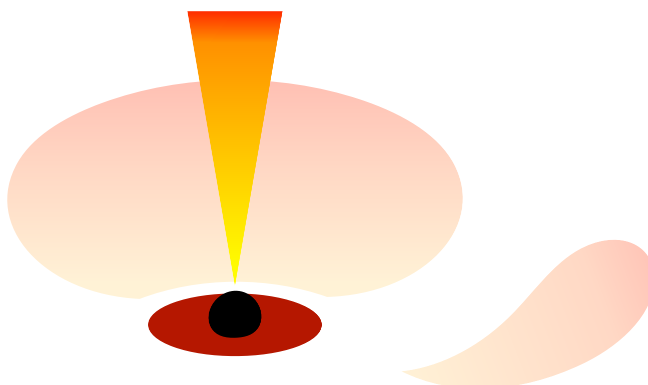
Unbound Debris





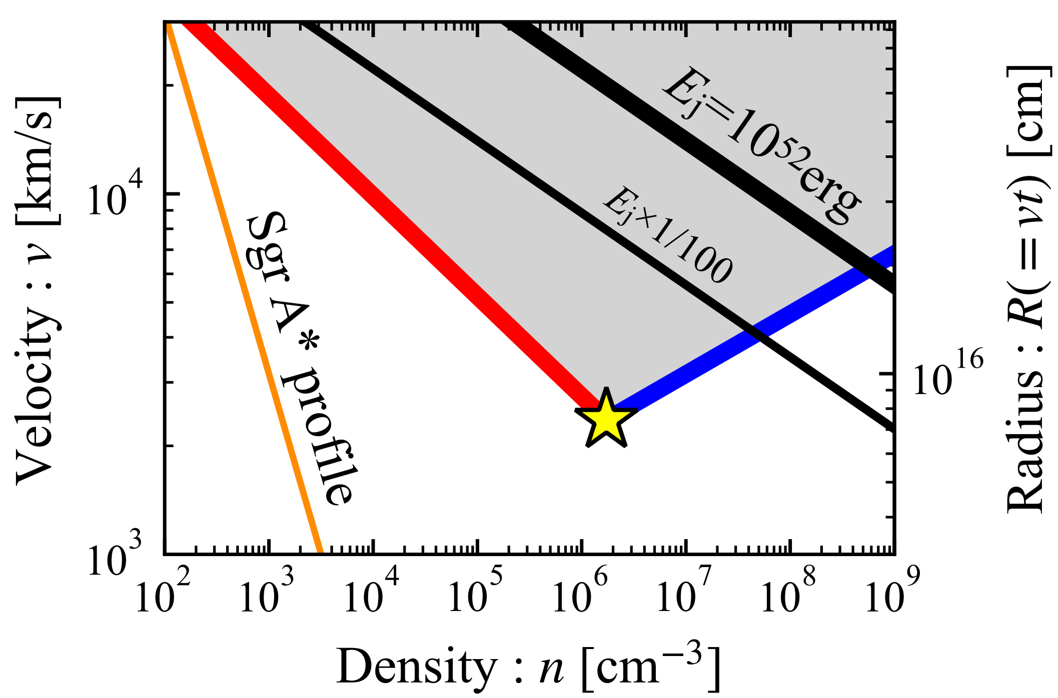
~10000km/s
0.5Msun

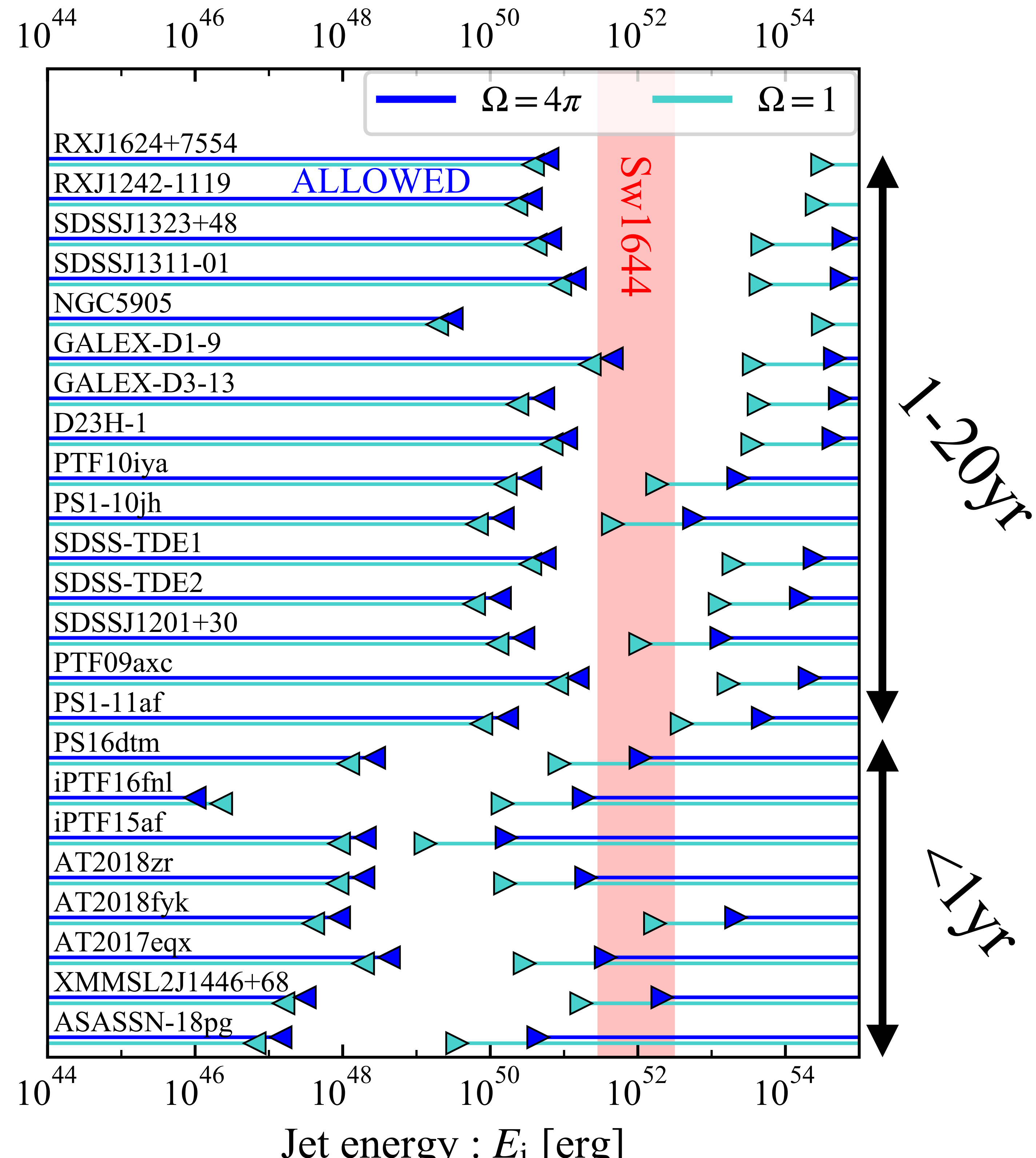
Relativistic Jets



$$E_j = [M_{ej} + M(R)]v^2/2$$

$$M(R) = \Omega m_p R^3$$





Summary

Optical

- We found TDE ejecta mass more than 3-10 Msun for velocity of ~10000km/s.
- This is unreasonable for TDEs whose typical ejecta mass should be < Msun.
- Reprocessed emission model is unlikely unless the reprocessing material is (marginally) bounded to BHs.

Radio

- Given an outflow model, we can constrain the density.
- Disk wind: Possible radio source. Not all TDEs launch winds or CNM profiles vary among galaxies.
- Unbound debris: Difficult to reproduce observations due to small Ω, Radio TDEs are deep penetration events ($\Omega \sim 1$)?
- Jet: Upper limits constrain jet energy and Sw1644 like energetic jet is rare. We still need late time followups.