Transient Phenomena and Physical Processes Around Supermassive Black Holes
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Late-time Radio Emission in Tidal Disruption Events

Tatsuya Matsumoto

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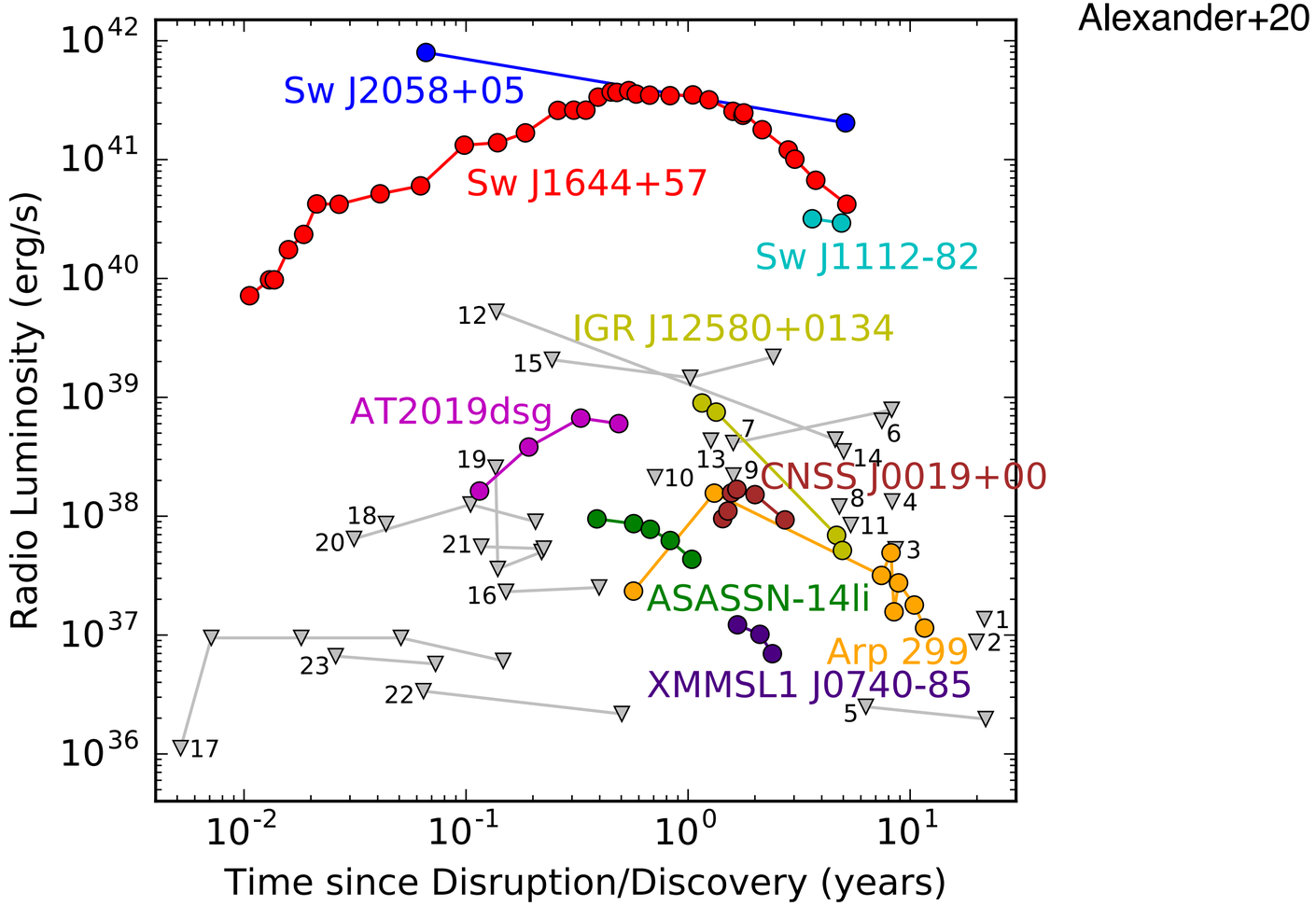
Radio emission in TDEs

Alexander+20



Synchrotron emission => Probe of Outflow + Environment

Radio emission in TDEs

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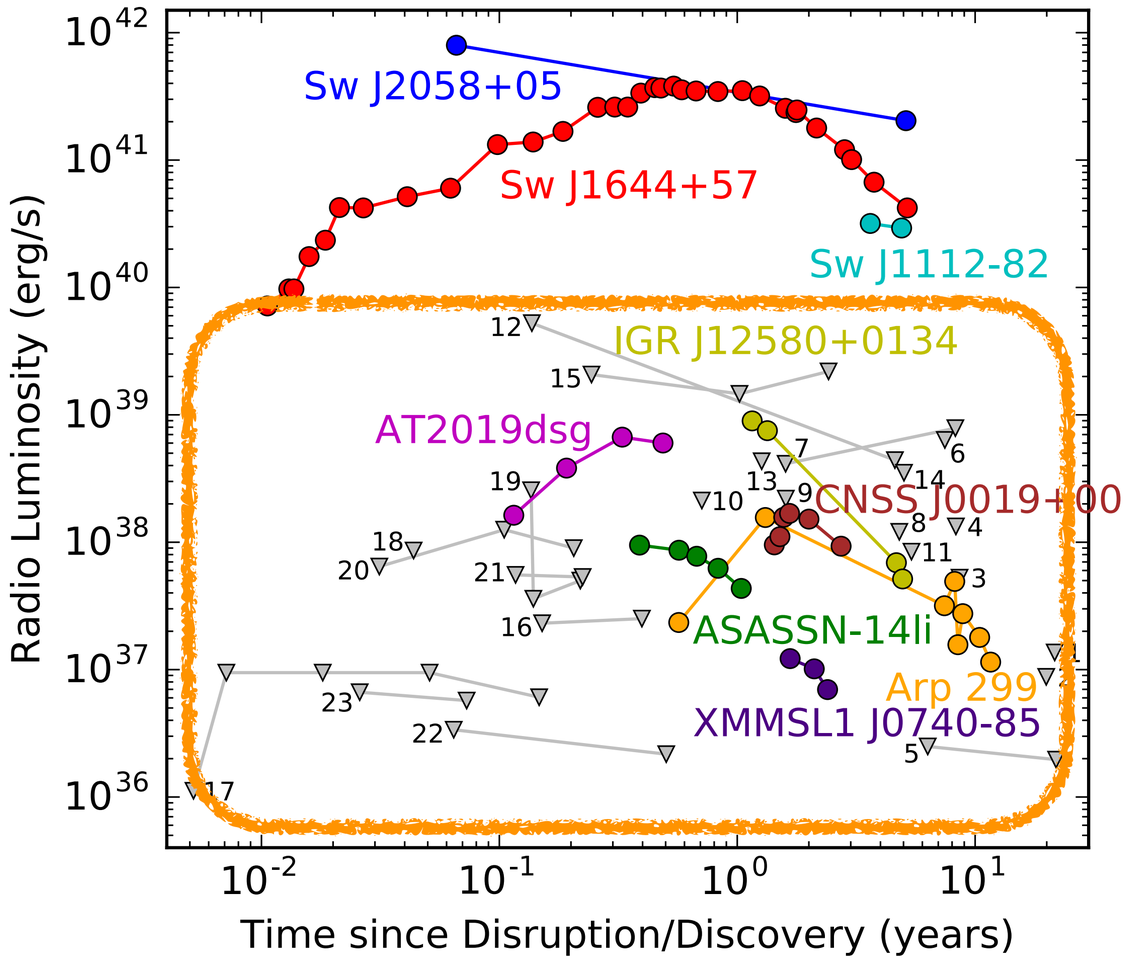
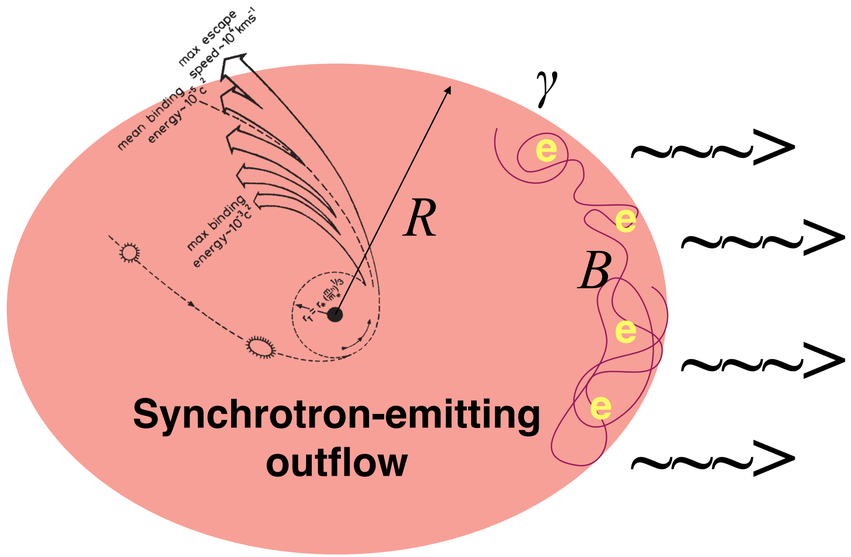
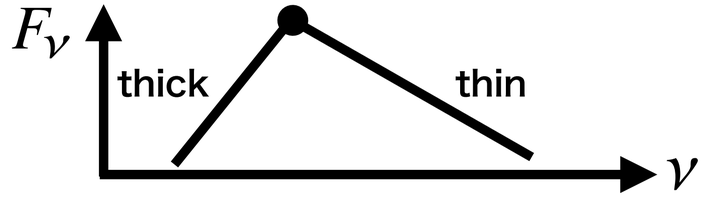


Synchrotron emission => Probe of Outflow + Environment

Chevalier98,Barniol-Duran+13

Radio in TDEs: Equipartition analysis



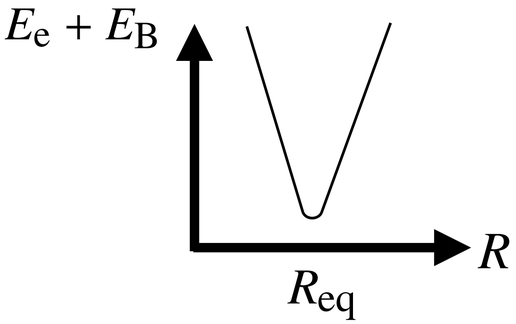


$$\nu_p \sim \gamma^2 \frac{eB}{m_e c} \propto \gamma^2 B$$

$$F_\nu \sim N \frac{\sigma_T c \gamma^2 B^2}{\nu_p d^2} \propto NB$$

$$F_\nu \sim \frac{m_e c^2 \gamma}{c^2} \frac{R^2}{d^2} \propto \gamma R^2$$

=> Total Energy: $E_{\rm tot} \sim B^2 R^3 + N m_e c^2 \gamma \sim R^{11} + R^{-6}$



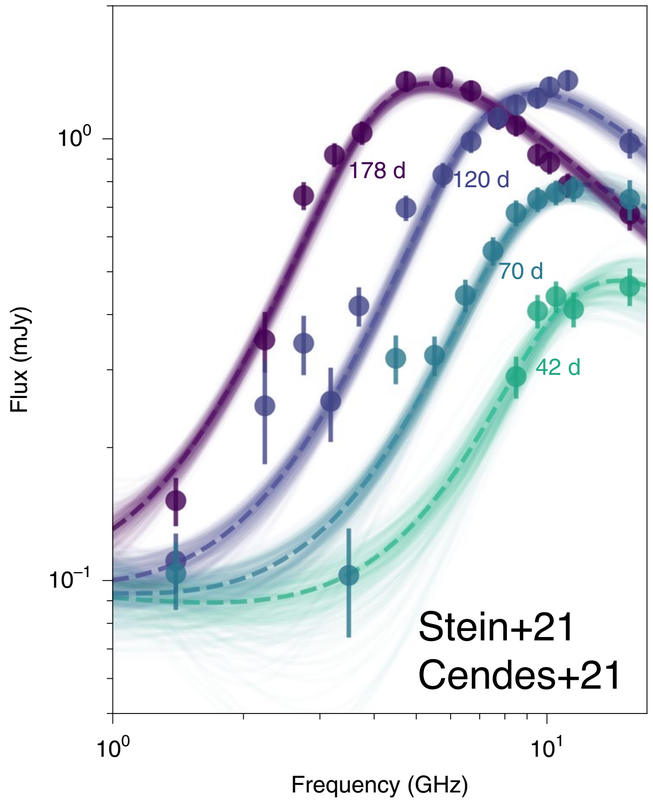
R should be $\sim R_{\rm eq}$

=> Estimation of other quantities

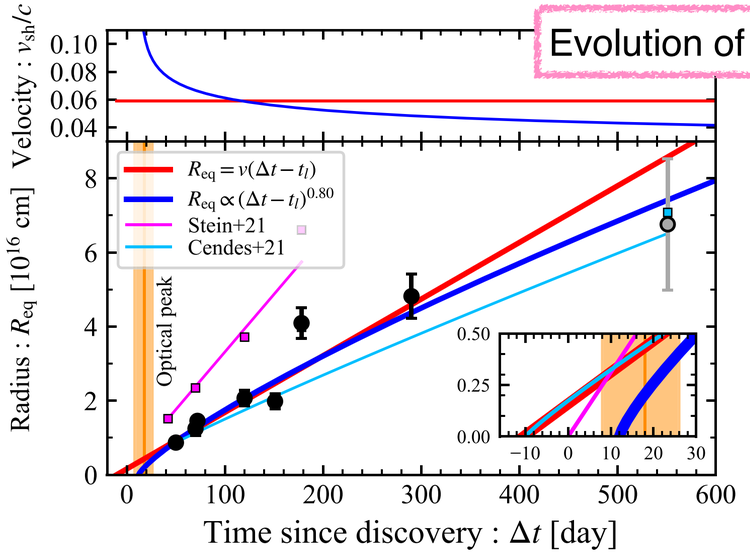
Chevalier98,Barniol-Duran+13

Radio in TDEs: Equipartition analysis

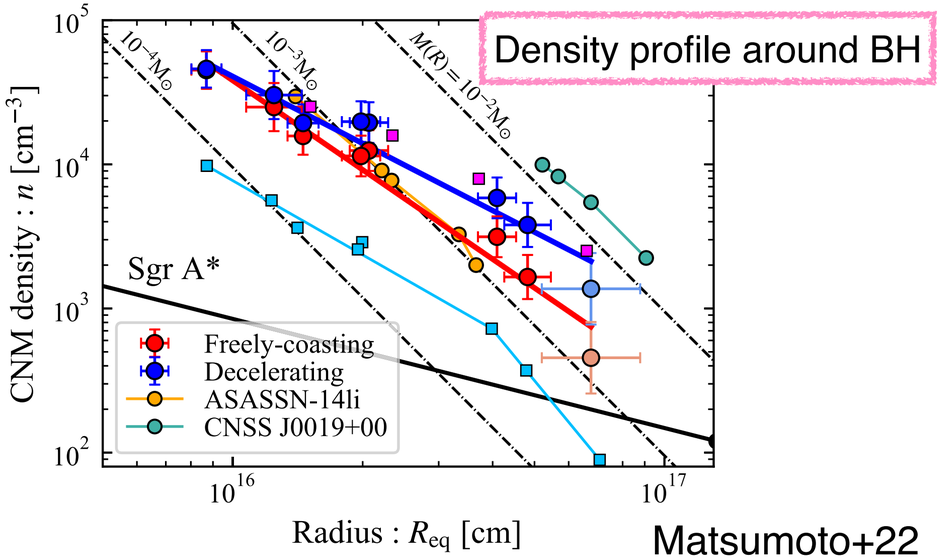
AT2019dsg



Evolution of Outflow



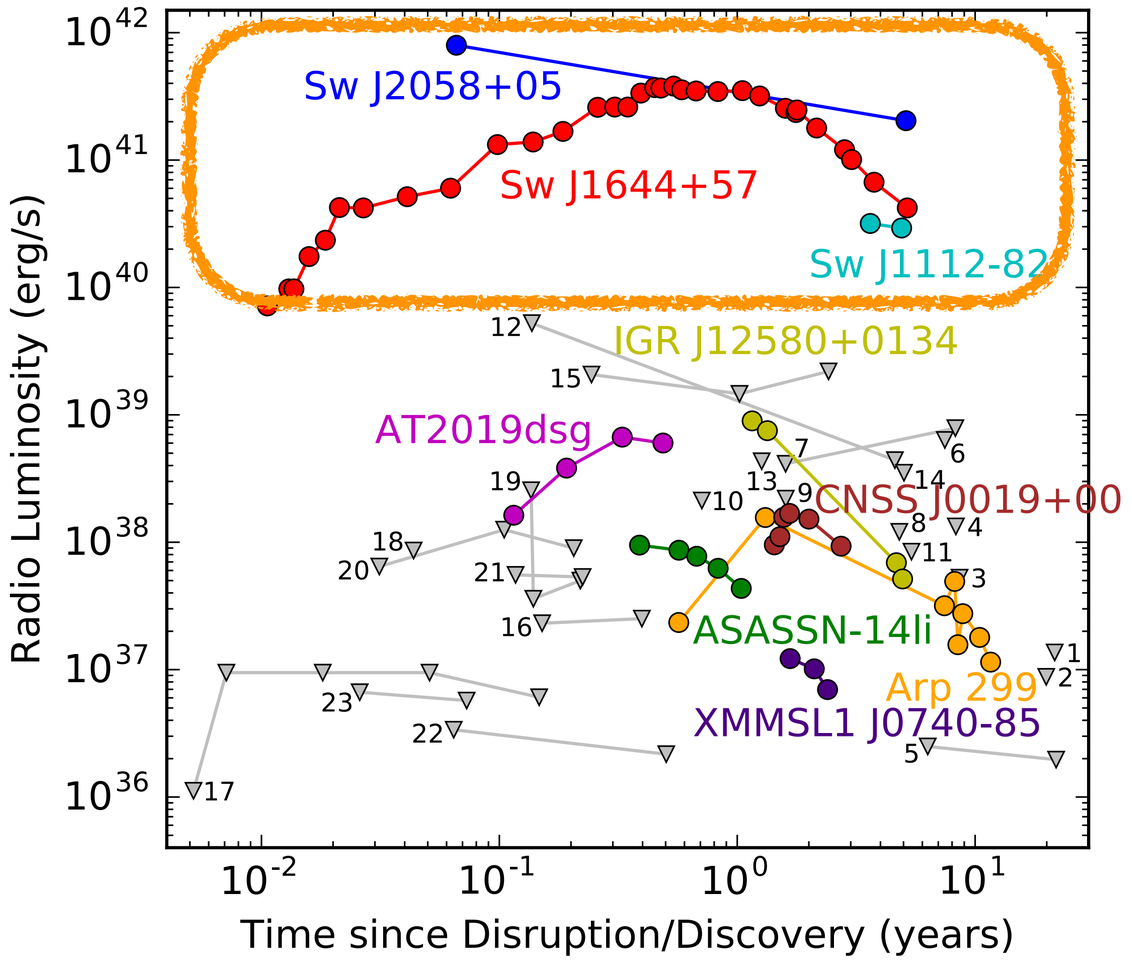
Density profile around BH



Matsumoto+22

Radio emission in TDEs

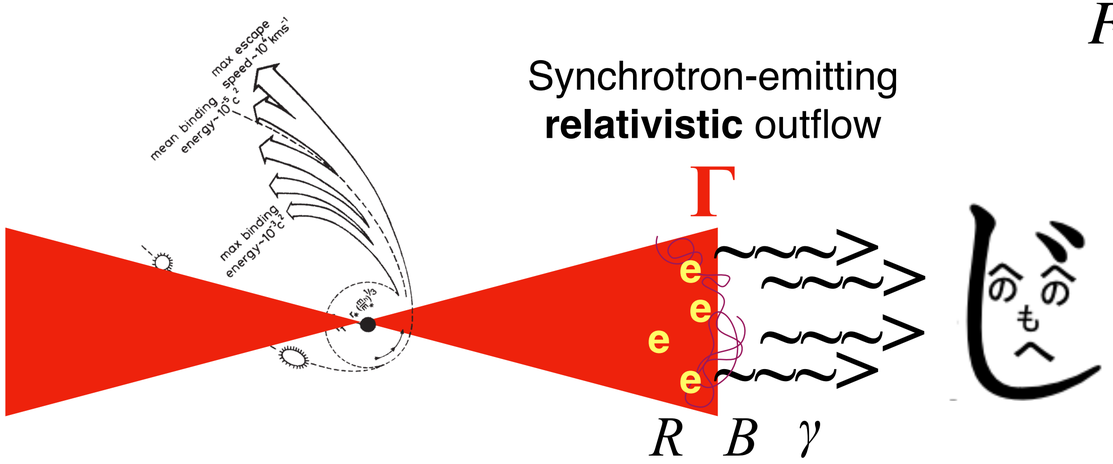
Alexander+20



Synchrotron emission => Probe of Outflow + Environment

Chevalier98,Barniol-Duran+13

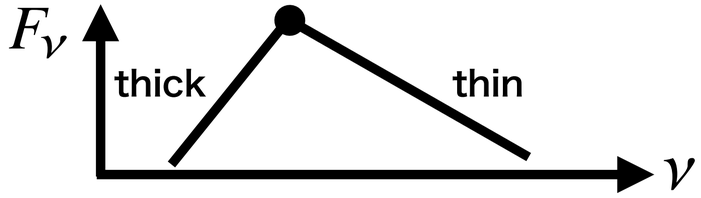
Radio in TDEs: Relativistic equipartition analysis



Synchrotron-emitting
relativistic outflow

Γ

$R \quad B \quad \gamma$



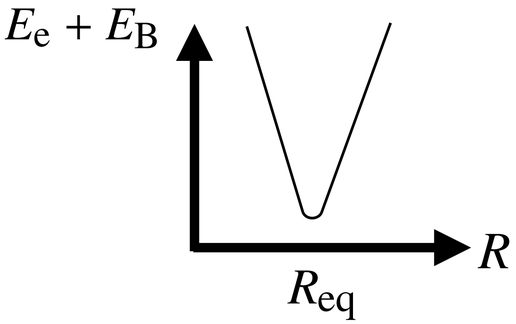
$$\nu_p \sim \gamma^2 \frac{eB}{m_e c} \propto \gamma^2 B \boldsymbol{\Gamma}$$

$$F_\nu \sim N \frac{\sigma_T c \gamma^2 B^2}{\nu_p d^2} \propto N B \boldsymbol{\Gamma^3}$$

$$F_\nu \sim \frac{m_e c^2 \gamma}{c^2} \frac{R^2}{d^2} \propto \gamma R^2 \boldsymbol{\Gamma}$$

$$\boxed{R \sim c\Gamma^2 t}$$

=> Total Energy: $E_{\rm tot} \sim B^2 R^3 + N m_e c^2 \gamma \sim R^{11} + R^{-6}$

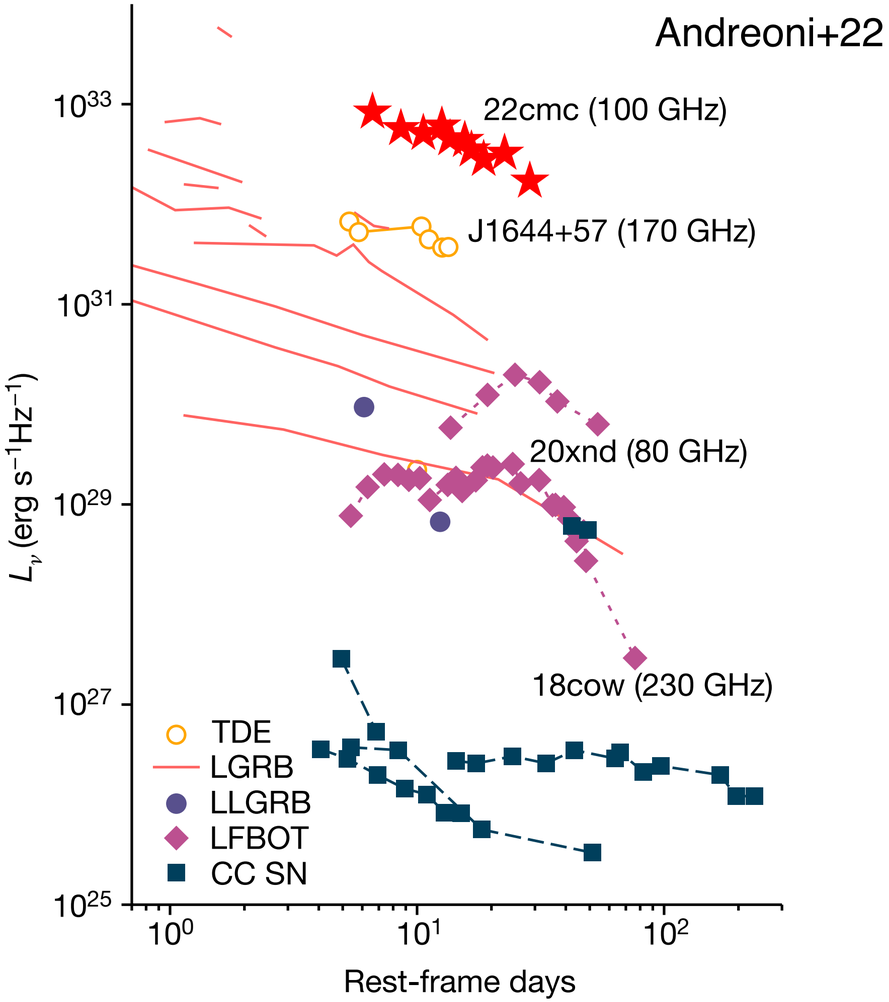


R should be $\sim R_{\rm eq}$

=> Estimation of other quantities

Chevalier98,Barniol-Duran+13

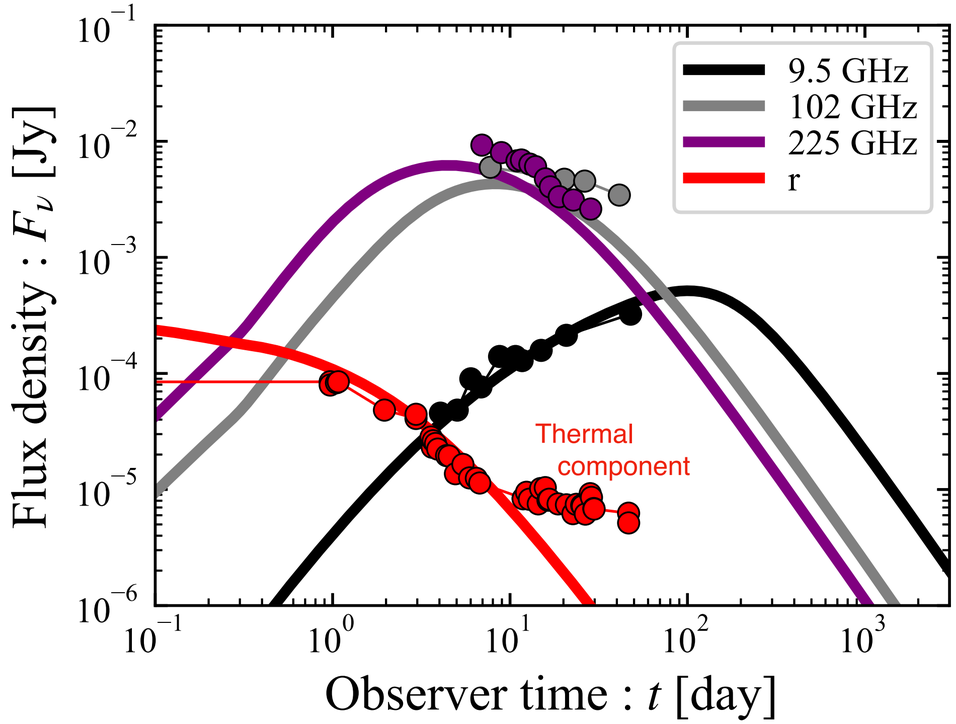
Radio in TDEs: Relativistic equipartition analysis



Γ~2-3 (Relativistic source!)

$E_{\rm j,iso}$~1e+53 erg

Detailed modeling
(as GRB afterglow, Sari+98)



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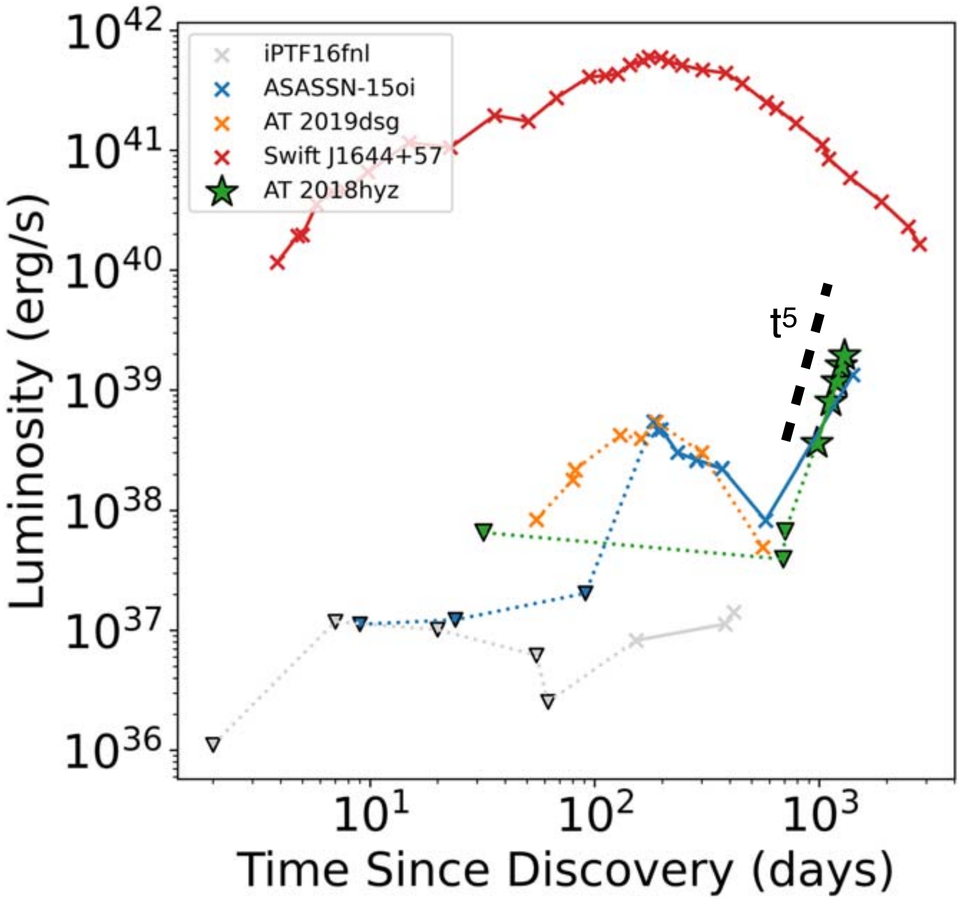
Late-time radio flares

Cendes+22,Horesh+21,Sfaradi+24



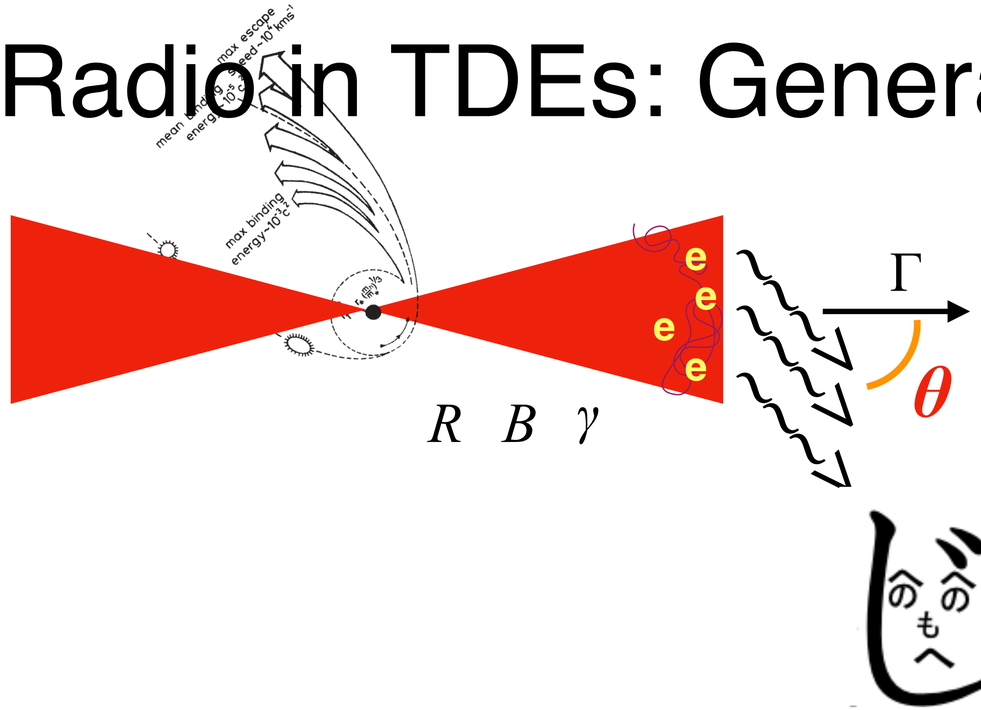
- Radio flare ~ 1000days after optical discovery
- Flux increases as t^5
- Origin?

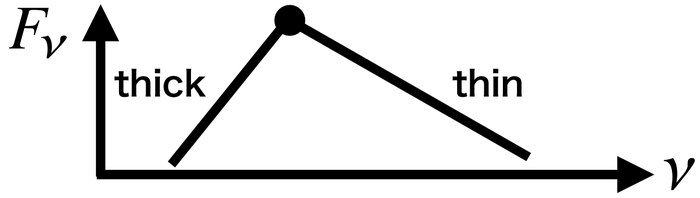
  Delayed disk formation?

  Off-axis jet?

Matsumoto&Piran23

Radio in TDEs: Generalized equipartition analysis





$$\Gamma \Rightarrow \delta = \frac{1}{\Gamma(1-\beta\cos\theta)}$$

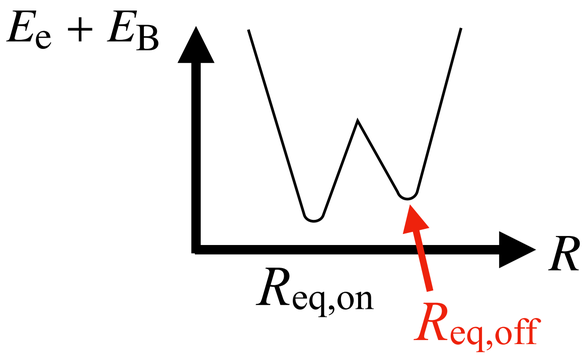
$$\nu_p \sim \gamma^2 \frac{eB}{m_e c} \propto \gamma^2 B\,\boldsymbol{\delta}$$

$$F_\nu \sim N \frac{\sigma_T c \gamma^2 B^2}{\nu_p d^2} \propto NB\,\boldsymbol{\delta^3}$$

$$F_\nu \sim \frac{m_e c^2 \gamma}{c^2}\frac{R^2}{d^2} \propto \gamma R^2\,\boldsymbol{\delta}$$

$$R \sim c\delta^2 t$$

=> Total Energy: $E_{\rm tot} \sim B^2 R^3 + N m_e c^2 \gamma \sim R^{11} + R^{-6}$



Two minimizing radii
corresponding to on/**off-axis**

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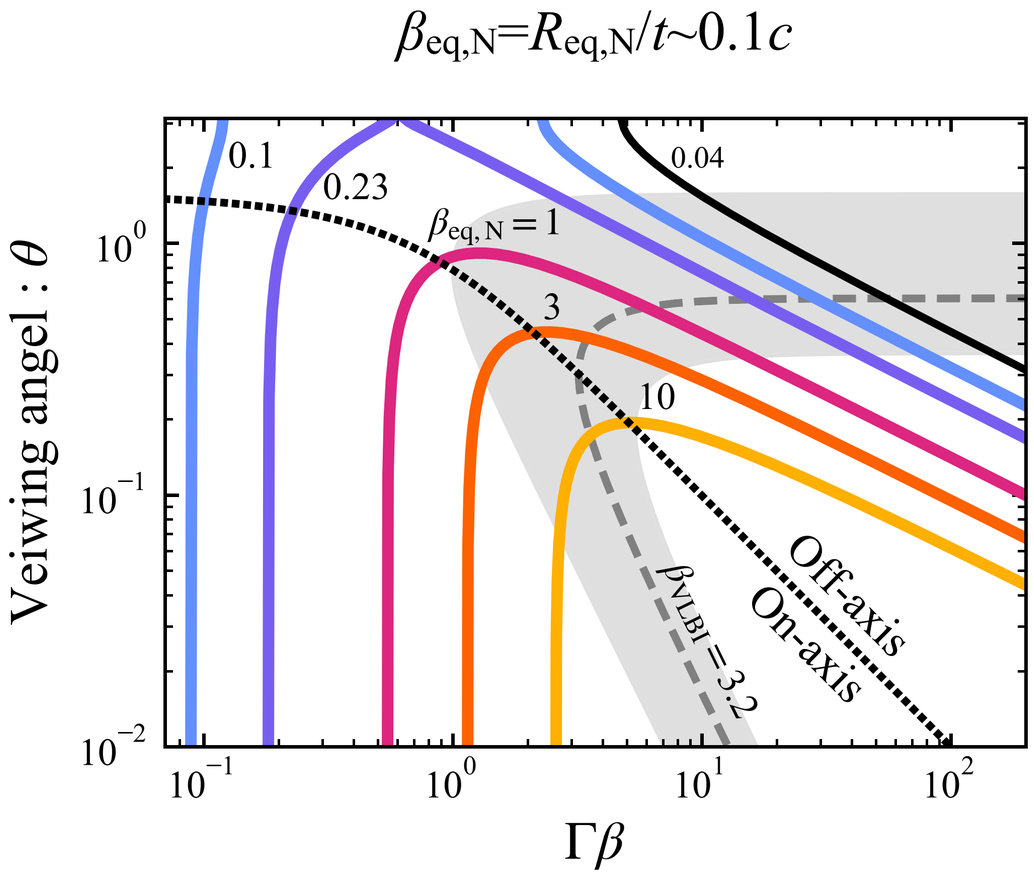
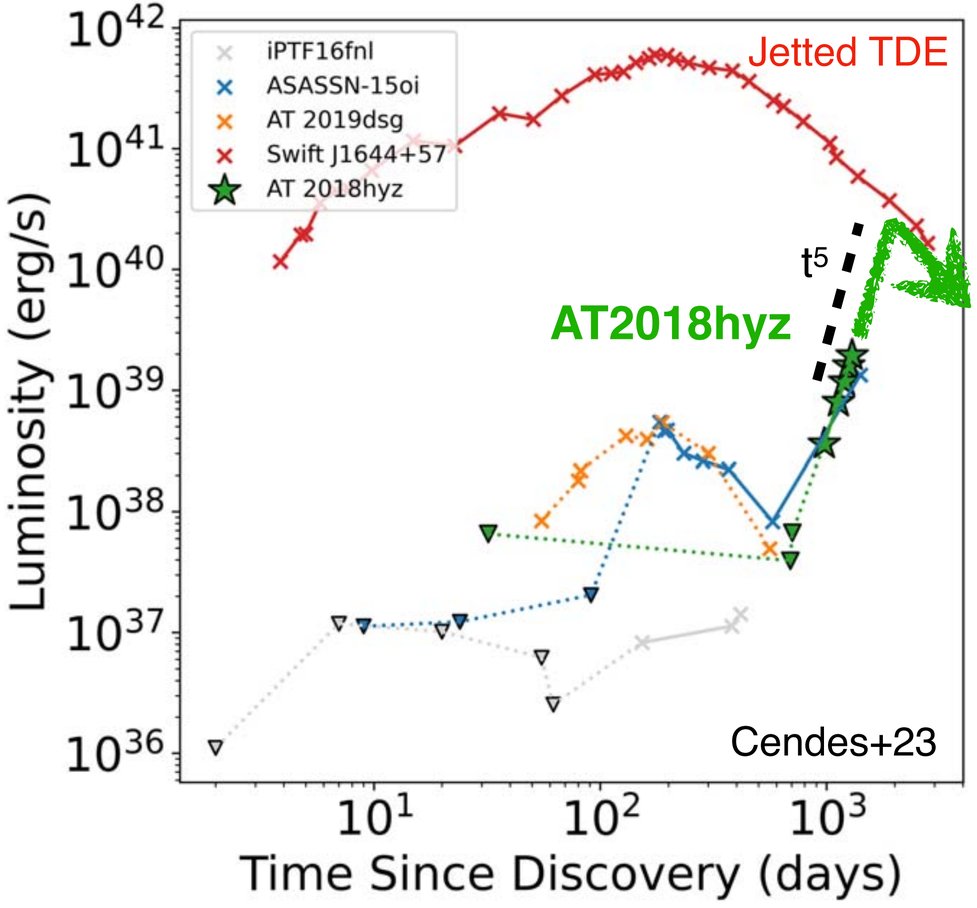
Late-time radio flare as off-axis jet

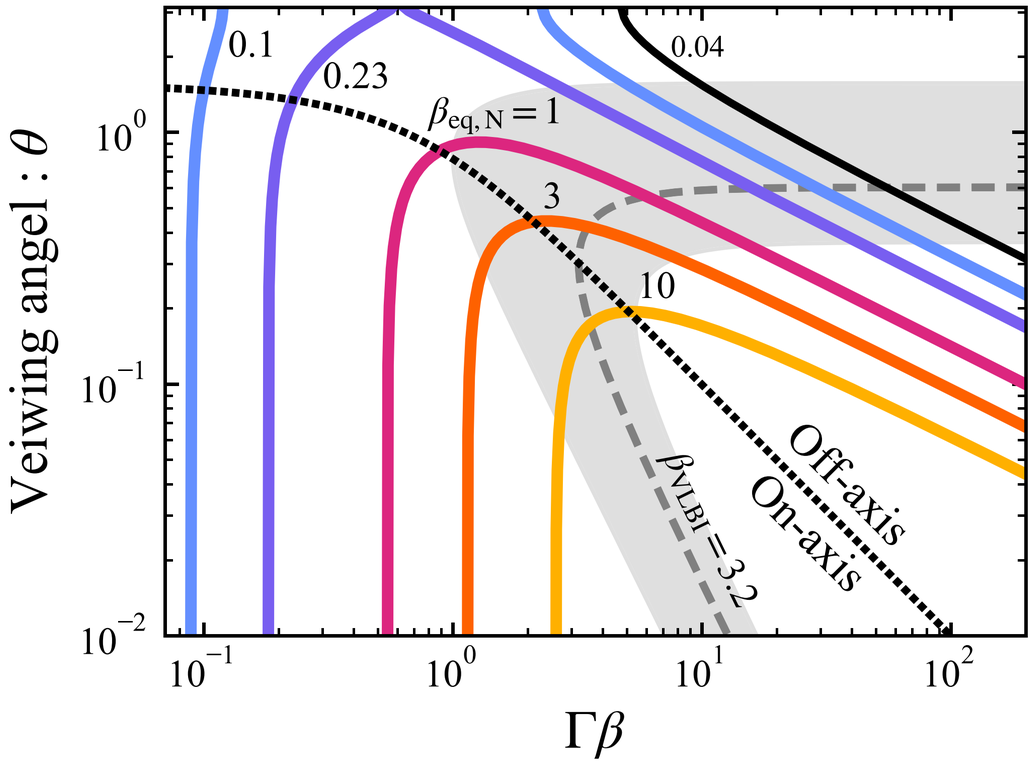




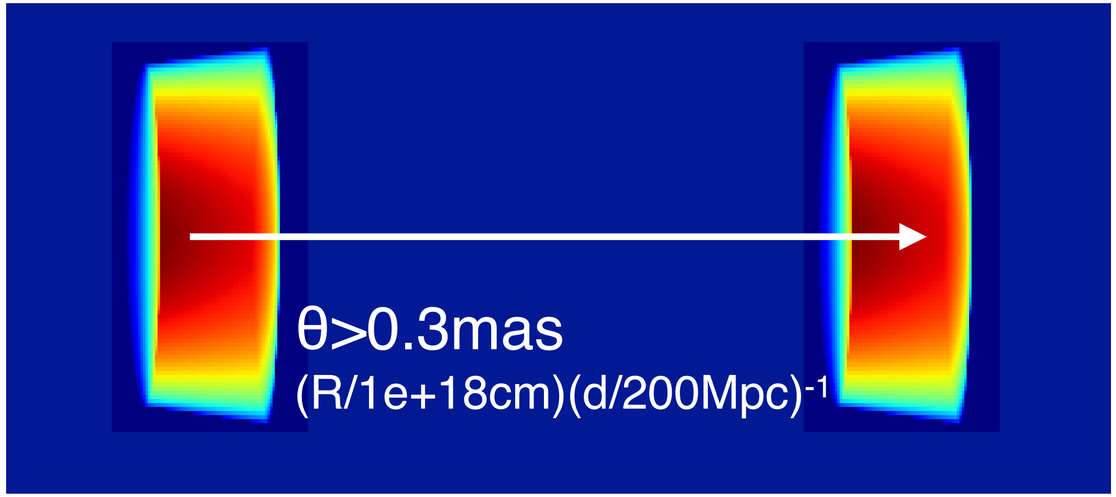
Matsumoto et al. in prep

VLBI diagnostics

$\beta_{\rm eq,N}=R_{\rm eq,N}/t\sim 0.1c$

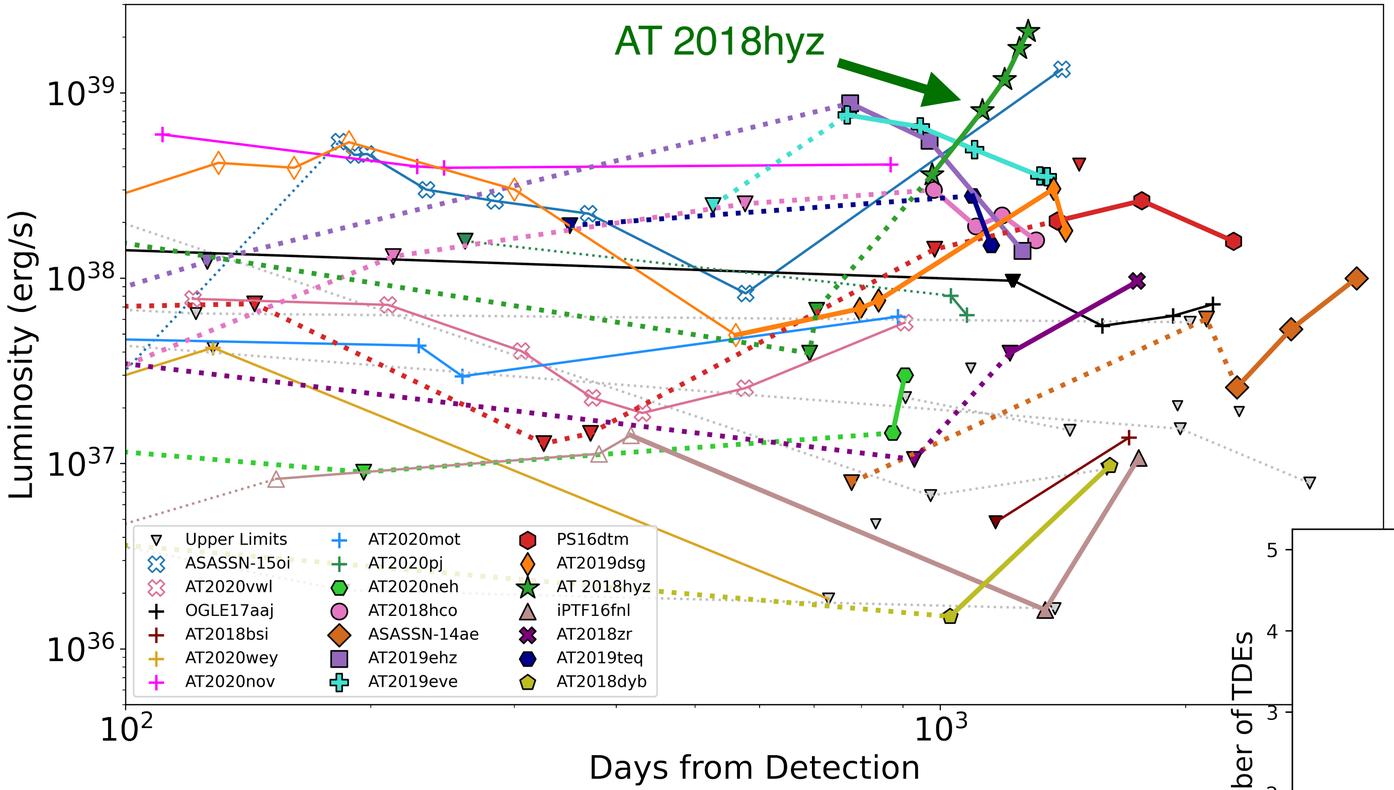


R>1.e+18cm (v/c)(t/yr)

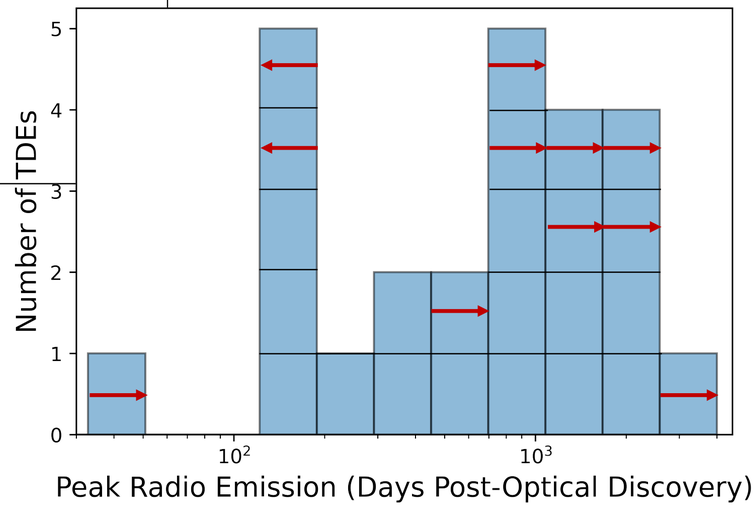


- Newtonian outflow (on-axis): ~0.1c
- Relativistic jet (off-axis): Γ~3

Ubiquitous late radio flare



Cendes+24



~40% of optical TDEs show
late (>1000days) radio flares!

=>Off-axis jet cannot produce all events

Event-rate consideration

$\mathcal{R}_{\rm opt} \sim \mathcal{R}_{\rm x} \sim 1000$ /Gpc^3/yr (~10^{-4} /galaxy/yr)

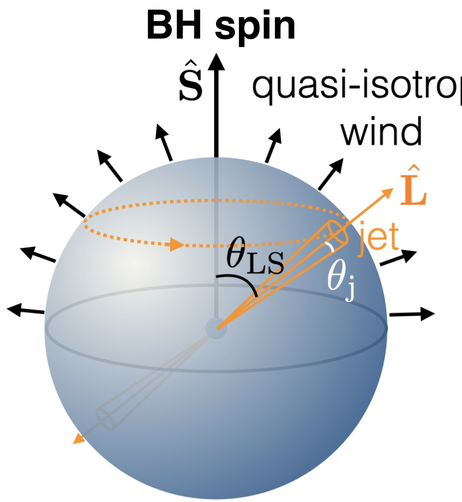
$\mathcal{R}_{\rm on\text{-}jet} \sim 0.01\text{-}0.1$ /Gpc^3/yr

Sazonov+21, Yao+23
Andreoni+22

Beaming: $f_{\rm b} \sim \theta^2 \sim 0.01$

$\mathcal{R}_{\rm off\text{-}jet} \sim 1\text{-}10$ /Gpc^3/yr

At most a few % of TDEs can have off-axis jet



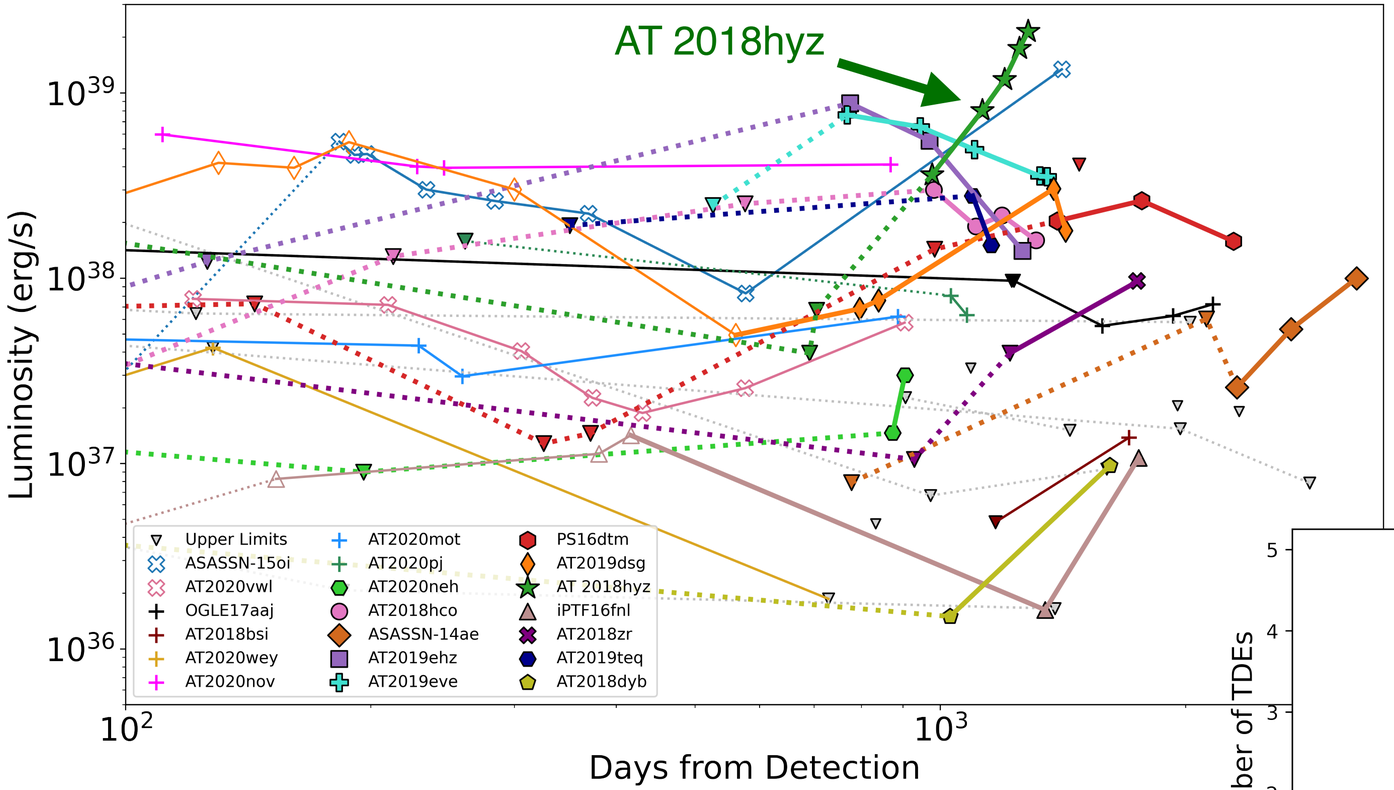
Jet breakout = **Double** alignment?

1. Observer's line of sight = jet axis : $f_{\rm b} \sim \theta_{\rm j}^2$
2. Stellar ang. mom. = BH spin : $f_{\rm LS} \sim \theta_{\rm LS}^2 \sim \theta_{\rm j}^2$

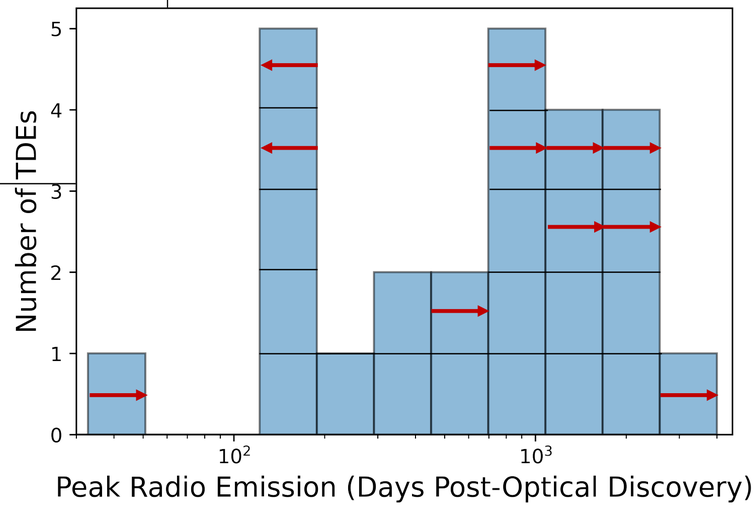
On-axis Successful Jet: $\mathcal{R}_{\rm on\text{-}jet}/\mathcal{R}_{\rm TDE} \sim \theta_{\rm j}^4 \sim \mathbf{10^{-4}}\,(\theta_{\rm j}/0.1)^4$

Lu, Matsumoto, Matzner 23, Teboul&Metzger 23

Ubiquitous late radio flare



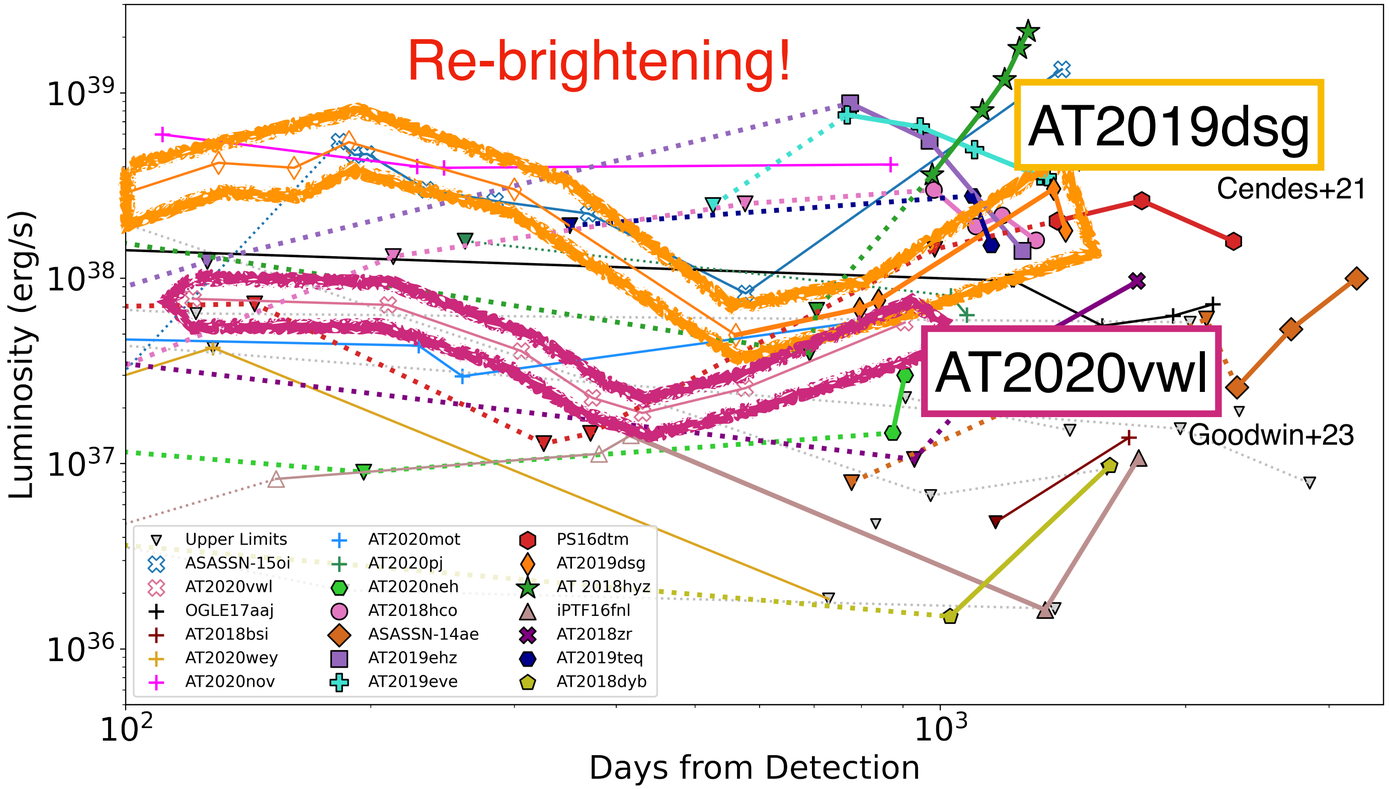
Cendes+24



~40% of optical TDEs show
late (>1000days) radio flares!

=>Off-axis jet cannot produce all events

Double-peak radio flares



Cendes+24

$$F_\nu \sim N \frac{\sigma_T c \gamma^2 B^2}{\nu_p d^2} \propto NB$$

$$N \sim nR^3$$

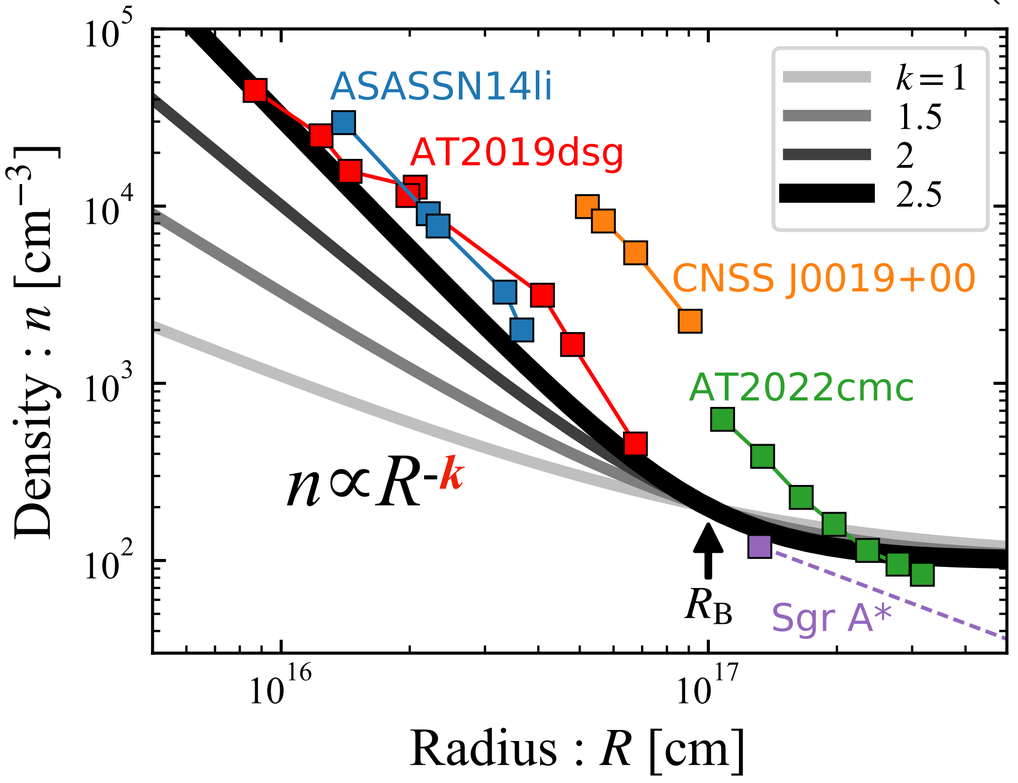
Late-time rise with **opt. thin** spectrum
=> Different mechanism from the 1st peak to make radio rise

(Most late flares show opt. thin spectrum)

Matsumoto&Piran 24

Outflow reaches Bondi radius

0.1c x 1000day ~ 1.e+17cm <=> $R_{\rm Bondi} \sim 10^{17}{\rm cm}\left(\frac{M_\bullet}{10^6 {\rm M}_\odot}\right)\left(\frac{T}{\rm keV}\right)^{-1}$



$n_{\rm ISM}$ (flat)

$F_\nu \sim N\frac{\sigma_T c \gamma^2 B^2}{\nu_p d^2} \propto NB$ $\quad N \sim nR^3 \propto R^{3-k}$

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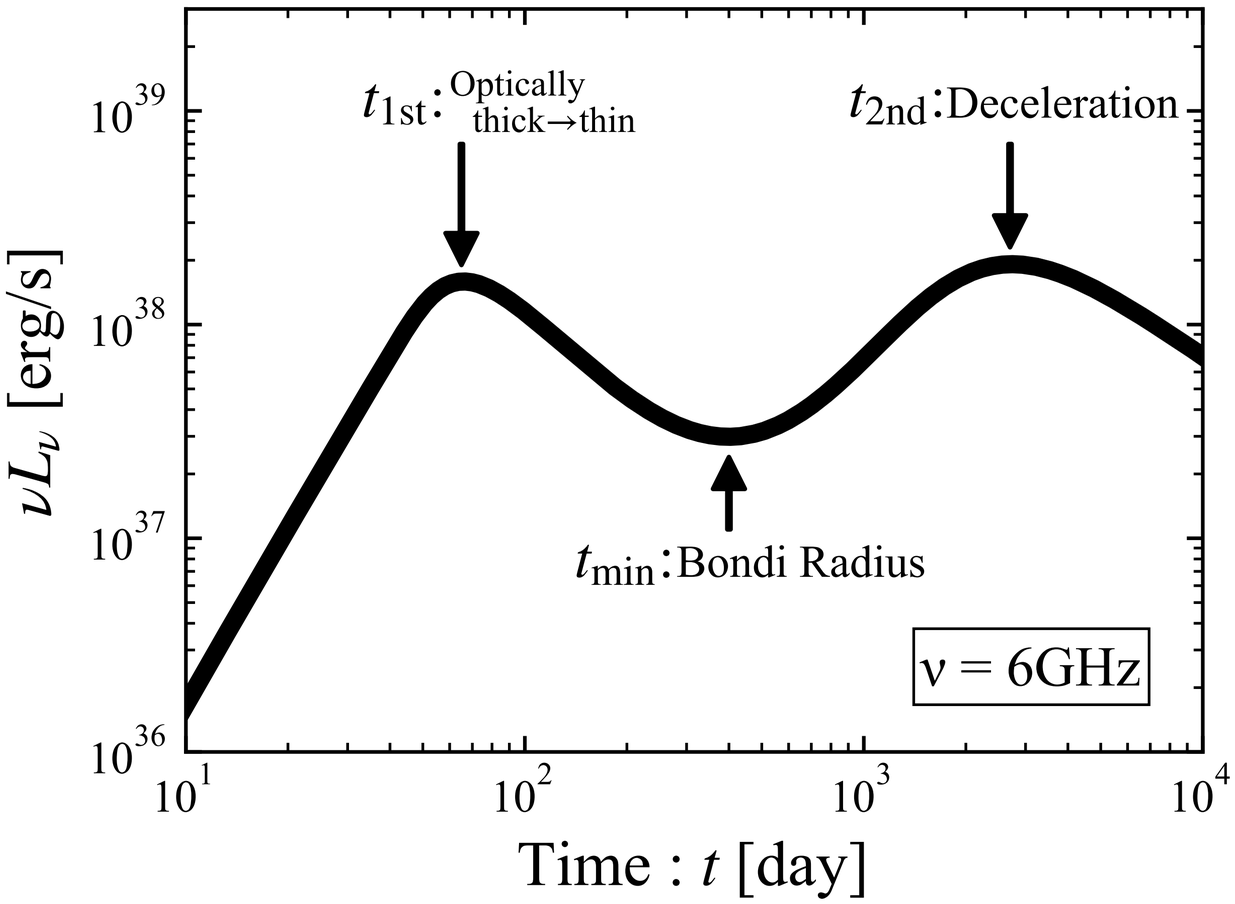
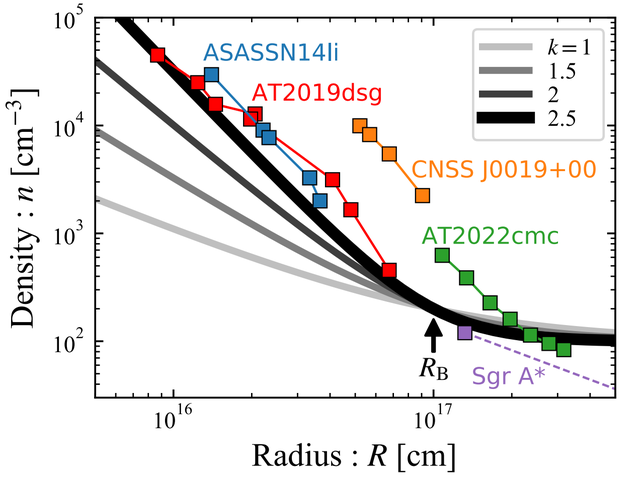
Light curve





Mej = 0.1Msun
v = 0.1c
p = 2.5
$\varepsilon_e = 0.1$, $\varepsilon_B = 0.01$
$n \propto R^{-2.5}$

Double peaks naturally arise!

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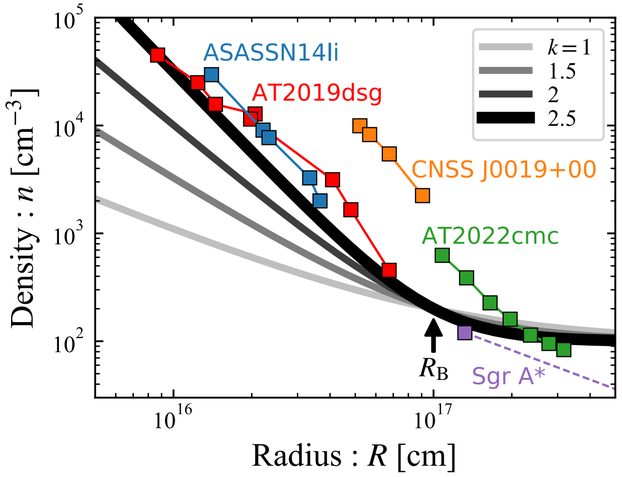
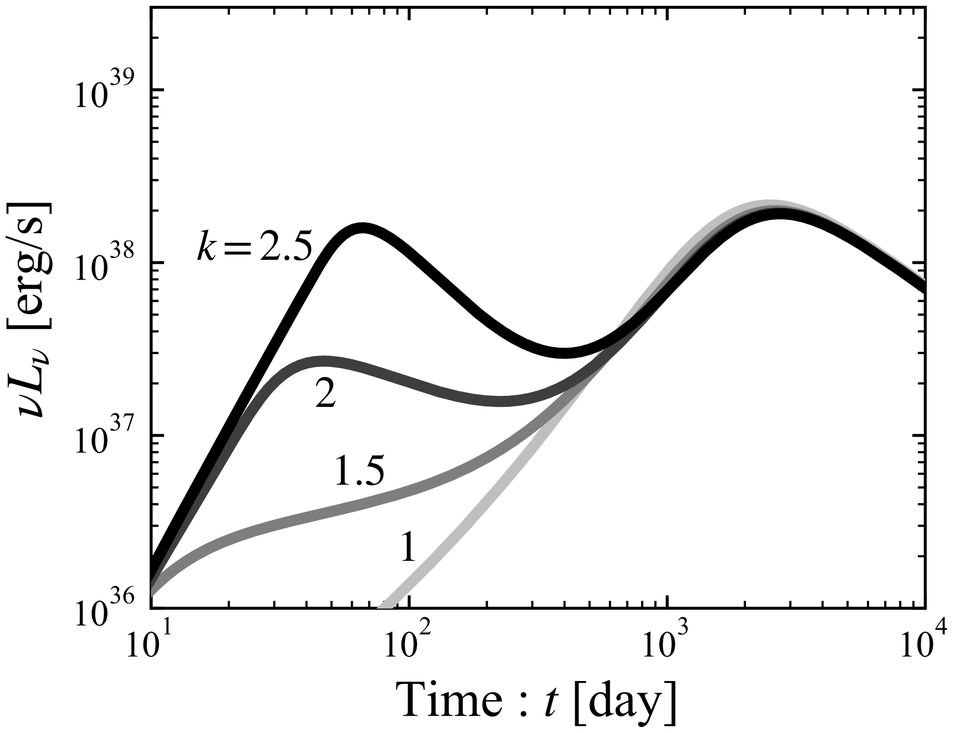
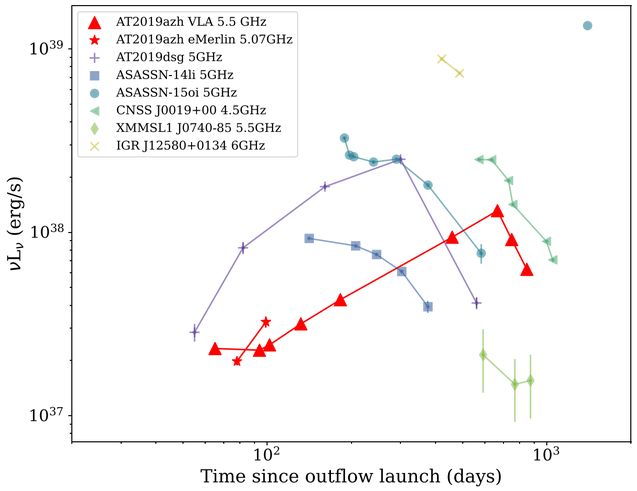
Parameter dependence



Slope of density profile



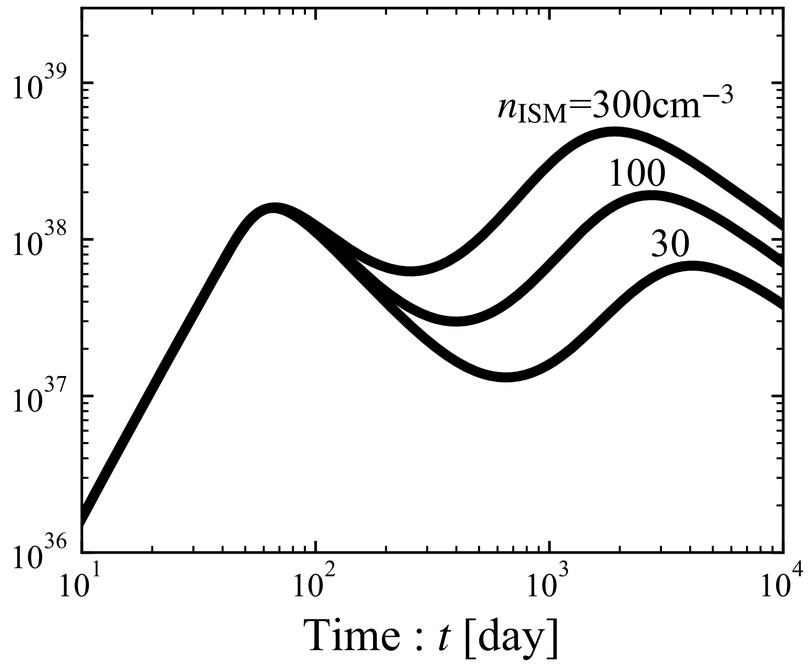
Goodwin+22,Sfaradi+22



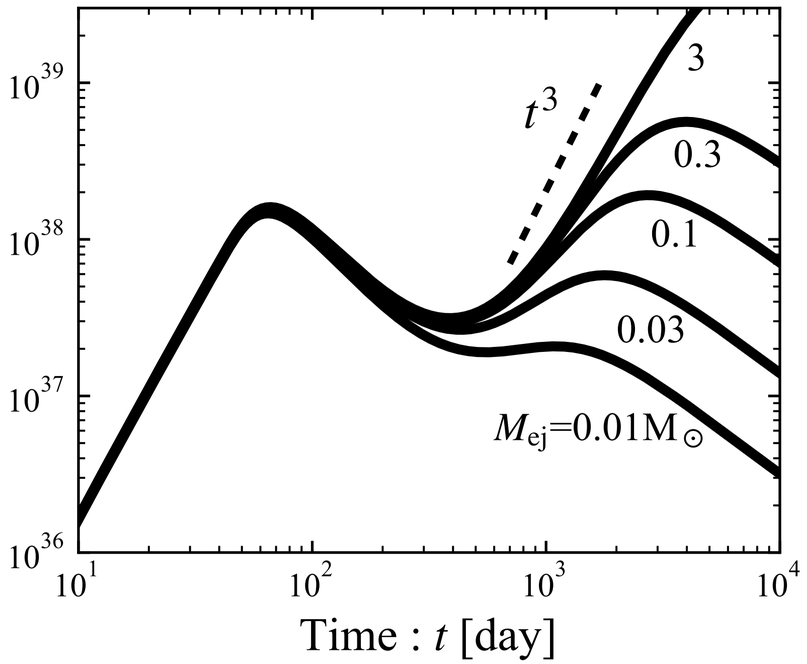
Profile for Bondi accretion can explain slow rise (AT2019azh?)

Parameter dependence

ISM density

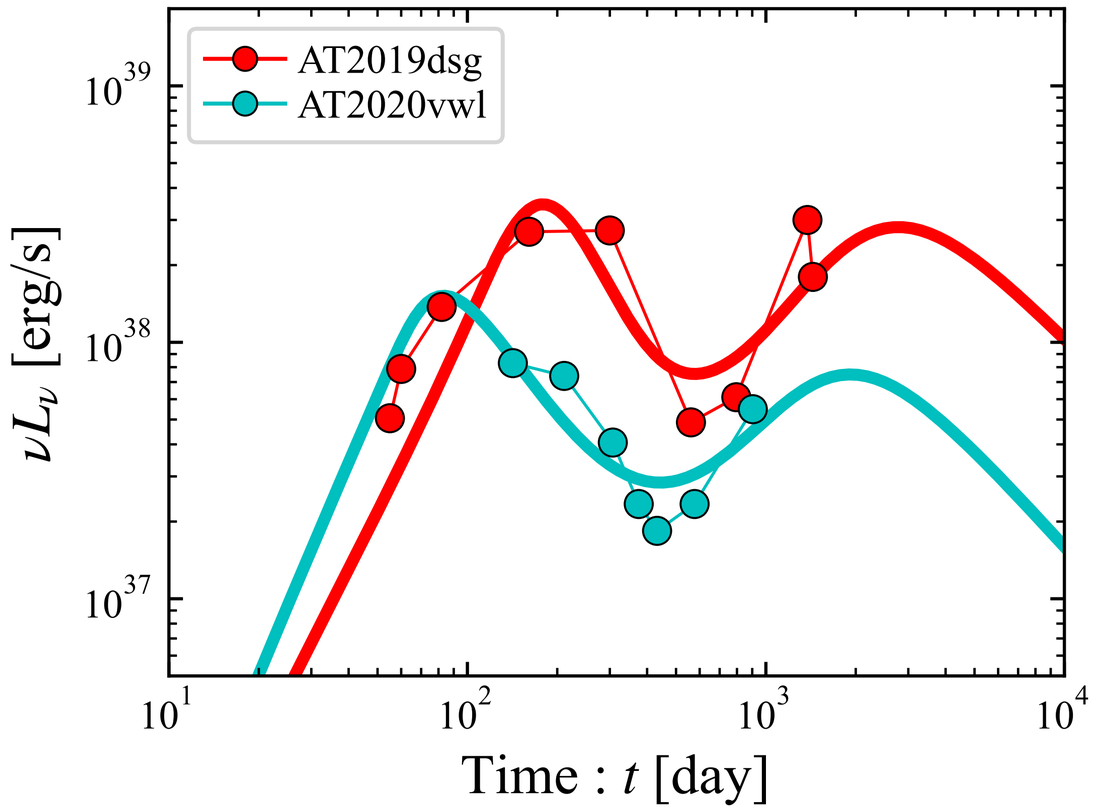


Ejecta mass

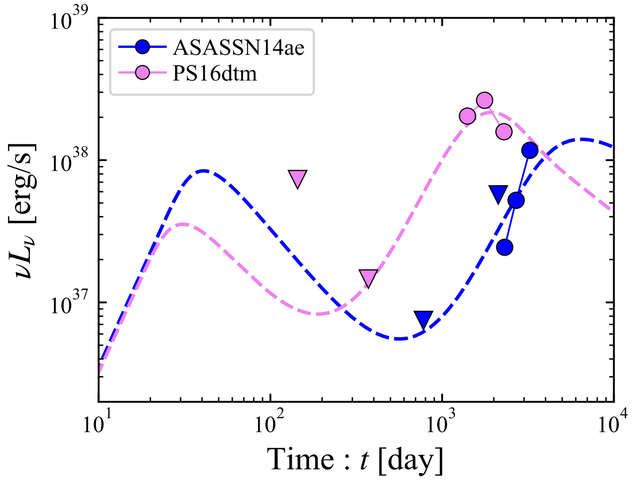


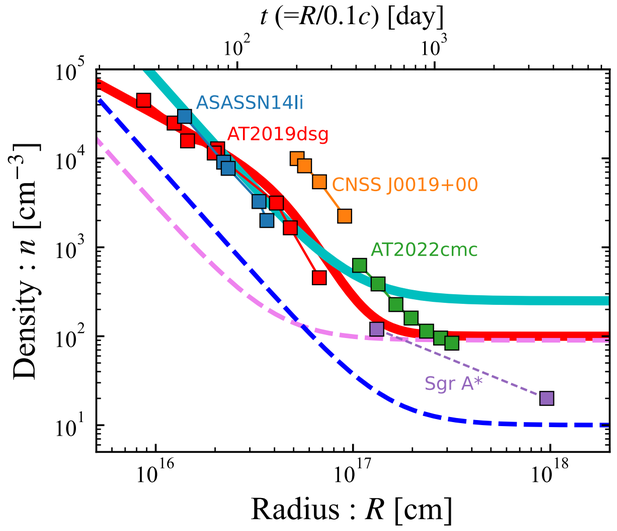
$$R_{\rm dec} \simeq \left(\frac{3M_{\rm ej}}{4\pi m_{\rm p} n_{\rm ISM}}\right)^{1/3} \simeq 6.6\times10^{17}\,{\rm cm}\, M_{\rm ej,-1}^{1/3} n_{\rm ISM,2}^{-1/3}\ ,$$

Comparison with observed events



Event	p	ε_e	ε_B	M_{ej} [$M_\odot$]	β_0
AT2019dsg	2.7	0.2	0.02	0.1	0.1
AT2020vwl	3	0.15	0.01	0.1	0.1
PS16dtm	2.1	0.13	0.01	0.04	0.08
ASASSN14ae	2.2	0.08	0.01	0.2	0.1





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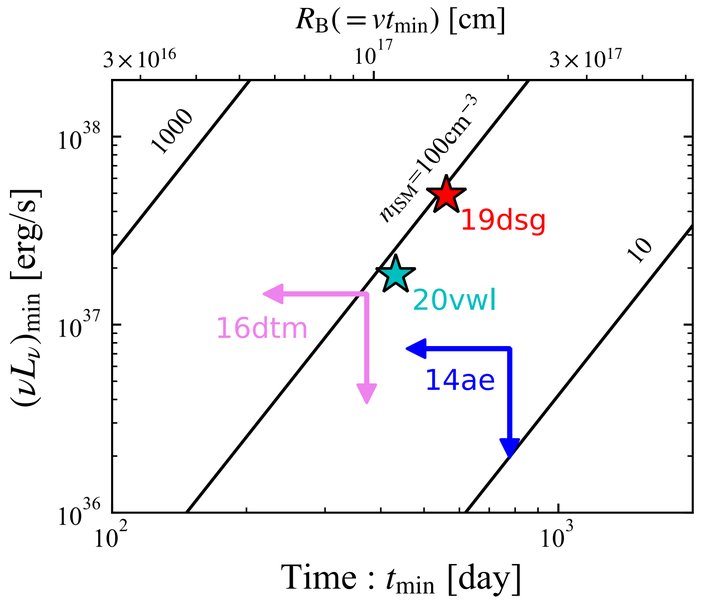
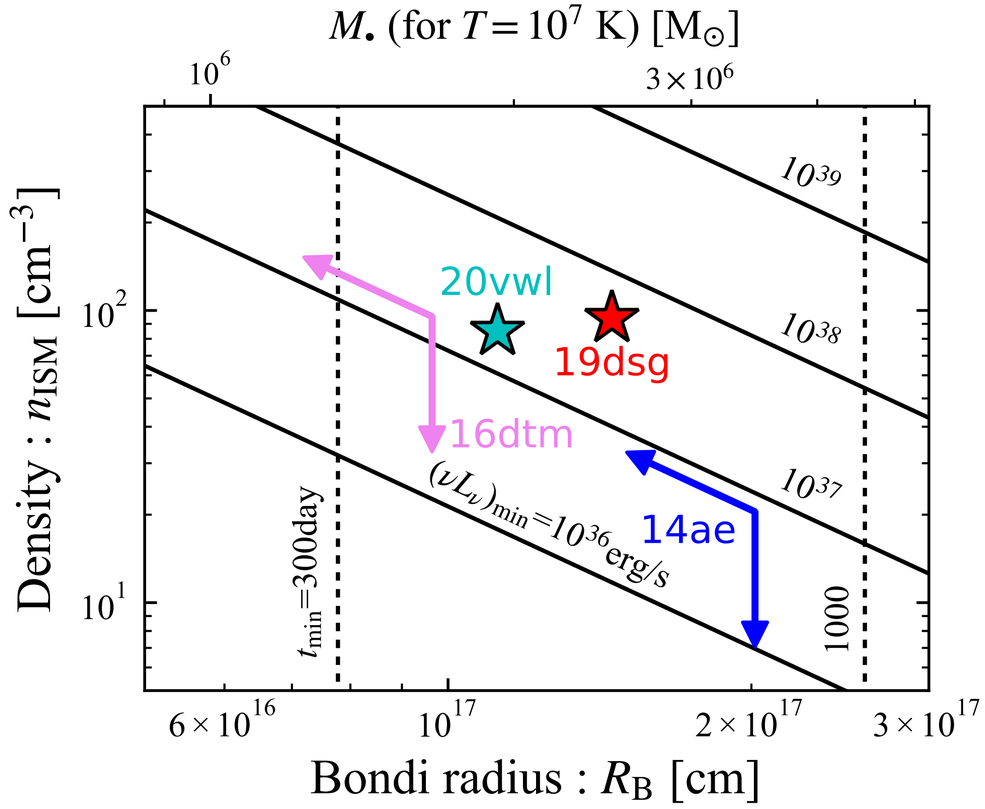
Minimum in light curve=>**BH mass**



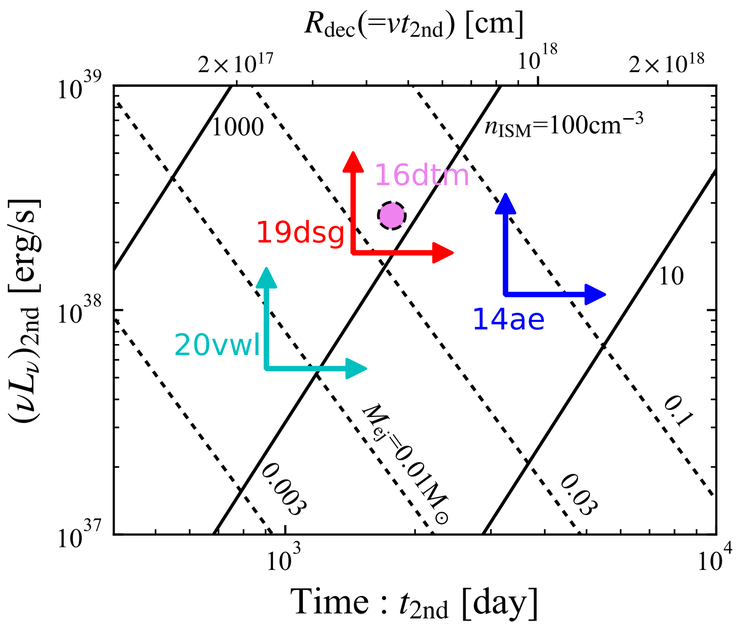


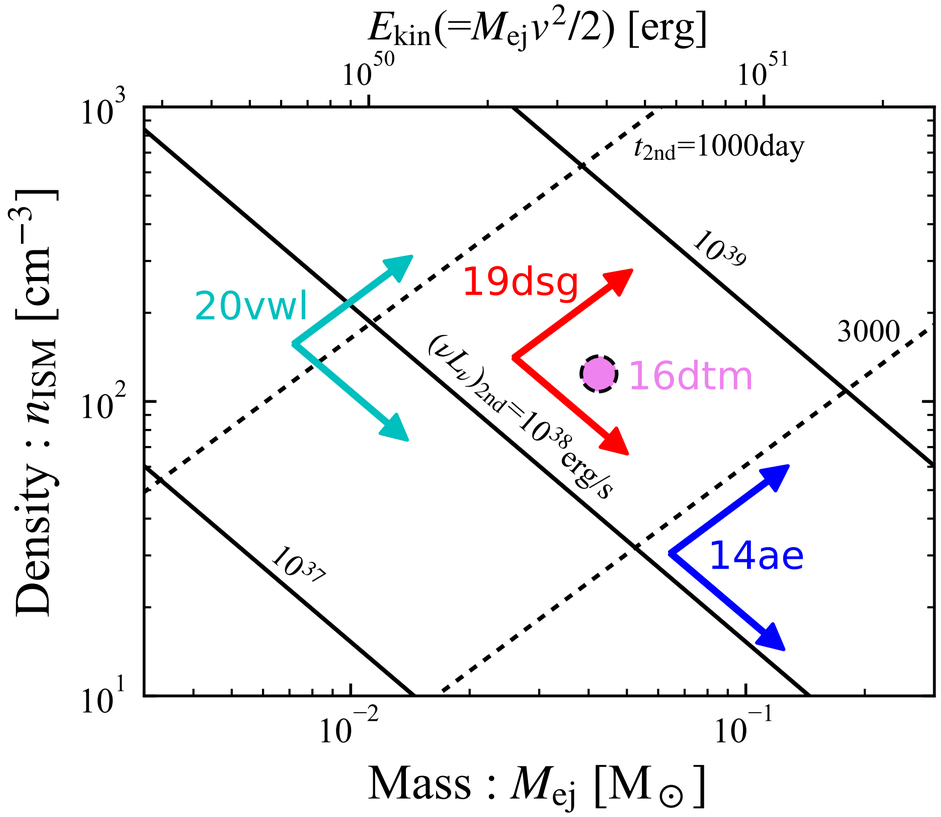
v = 0.1c, p = 2.5, $\varepsilon_{\rm e}$ = 0.1, $\varepsilon_{\rm B}$ = 0.01

$$n_{\rm ISM} \overset{p=2.5}{\simeq} 1.1\times10^{2}\,{\rm cm^{-3}}\,\bar{\varepsilon}_{\rm e,-1}^{-\frac{4}{p+5}}\varepsilon_{\rm B,-2}^{-\frac{p+1}{p+5}}\beta_{-1}^{-\frac{2(p+11)}{p+5}} \nu_{\rm 6GHz}^{\frac{2(p-3)}{p+5}}(\nu L_\nu)_{\rm min,37}^{\frac{4}{p+5}}\left(\frac{\Omega}{4\pi}\right)^{-\frac{4}{p+5}} t_{\rm min,300day}^{-\frac{12}{p+5}} f_{t_{\rm min}}^{\frac{12}{p+5}} f_{L_{\rm min},1}^{-\frac{4}{p+5}},$$

$$R_{\rm B} \simeq vt_{\rm min}/f_{t_{\rm min}} \simeq 7.8\times10^{16}\,{\rm cm}\,\beta_{-1}t_{\rm min,300day}f_{t_{\rm min}}^{-1}$$

2nd peak in light curve=>**outflow mass**





v = 0.1c, p = 2.5, $\varepsilon_{\rm e}$ = 0.1, $\varepsilon_{\rm B}$ = 0.01

$$n_{\rm ISM} \overset{p=2.5}{\simeq} 6.3\times10^{2}\,{\rm cm^{-3}}\,\bar{\varepsilon}_{\rm e,-1}^{-\frac{4}{p+5}}\varepsilon_{\rm B,-2}^{-\frac{p+1}{p+5}}\beta_{-1}^{-\frac{2(p+11)}{p+5}} \nu_{\rm 6GHz}^{\frac{2(p-3)}{p+5}}(\nu L_\nu)_{\rm 2nd,39}^{\frac{4}{p+5}}\left(\frac{\Omega}{4\pi}\right)^{-\frac{4}{p+5}} t_{\rm 2nd,1000day}^{-\frac{12}{p+5}}$$

$$M_{\rm ej} \overset{p=2.5}{\simeq} 3.9\times10^{-2}\,{\rm M_\odot}\,\bar{\varepsilon}_{\rm e,-1}^{-\frac{4}{p+5}}\varepsilon_{\rm B,-2}^{-\frac{p+1}{p+5}}\beta_{-1}^{-\frac{p-7}{p+5}} \nu_{\rm 6GHz}^{\frac{2(p-3)}{p+5}}(\nu L_\nu)_{\rm 2nd,39}^{\frac{4}{p+5}}\left(\frac{\Omega}{4\pi}\right)^{-\frac{4}{p+5}} t_{\rm 2nd,1000day}^{\frac{3(p+1)}{p+5}}$$

Summary

- Radio emission: Probe of outflows and environment.
- Late-time radio flares (>1000days):
  - The origin is unclear.
  - Rapidly rising events (AT2018hyz) => Off-axis jet?
  - Double-peak events (AT2019dsg & 2020vwl)

    =>Single outflow traveling into power-law+flat density profile can explain the observations.

    =>Estimation of BH mass, outflow mass/energy.

謝謝!