高エネルギー現象で探る宇宙の多様性IV ＠柏 東京大学, 2024/11/12

潮汐破壊現象

ー最近の話題などー

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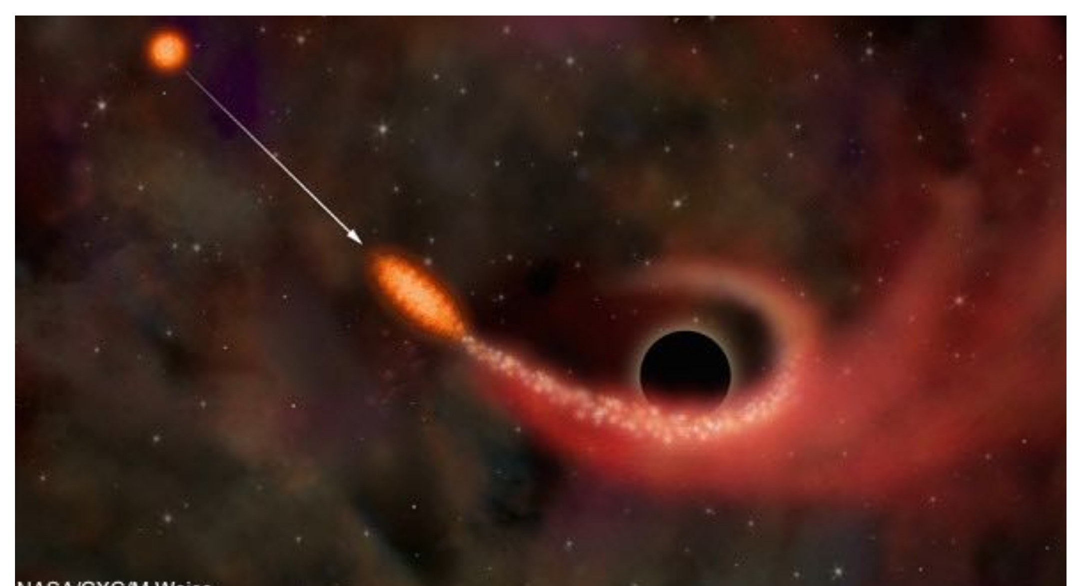
潮汐破壊現象
[**T**idal **D**isruption **E**vent]

- Census of SMBH population
- Physics of Super Eddington accretion
- Probe of environment of SMBHs (ISM, star cluster)
- Relativistic effects?

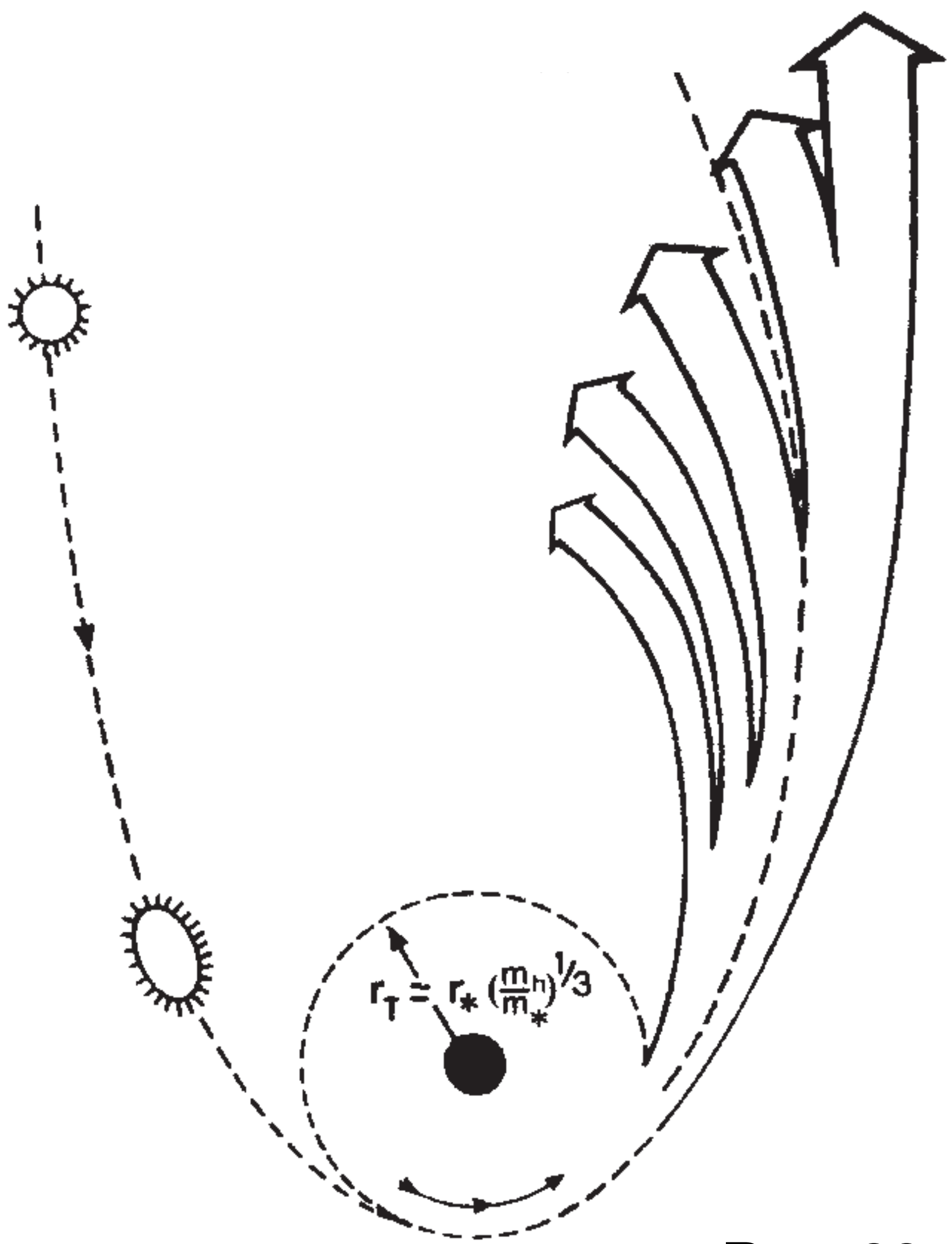


Outline

1. Basics
2. Optical&X-rays
3. Some recent topics
4. Radio

Basics of TDEs

$$R_{\rm T} \equiv R_\star \left(\frac{M_\bullet}{M_\star}\right)^{1/3} \simeq 20 R_{\rm S}\, R_{\star,0} M_{\star,0}^{-1/3} M_{\bullet,6}^{-2/3}$$



Rees88
Phinney89

Basics of TDEs

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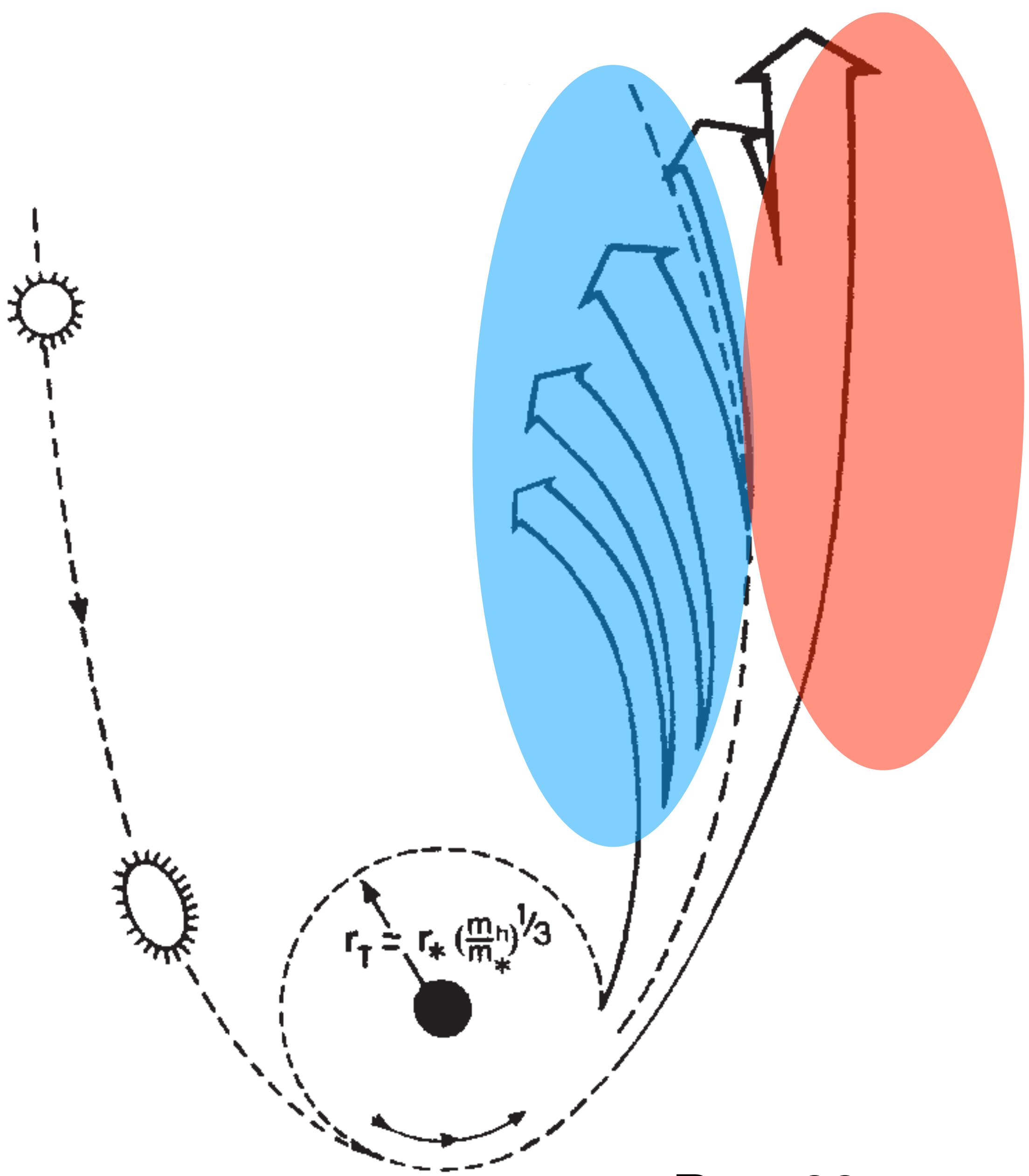
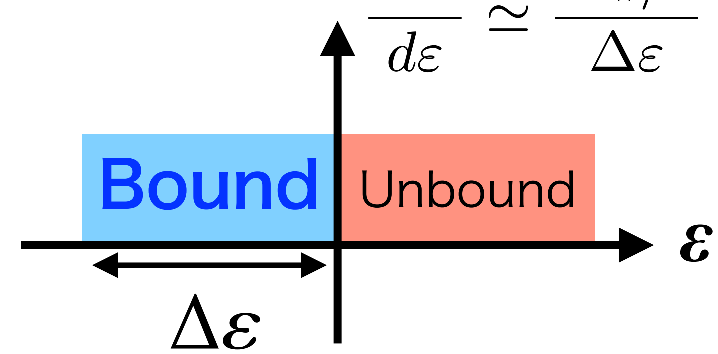


Rees88
Phinney89

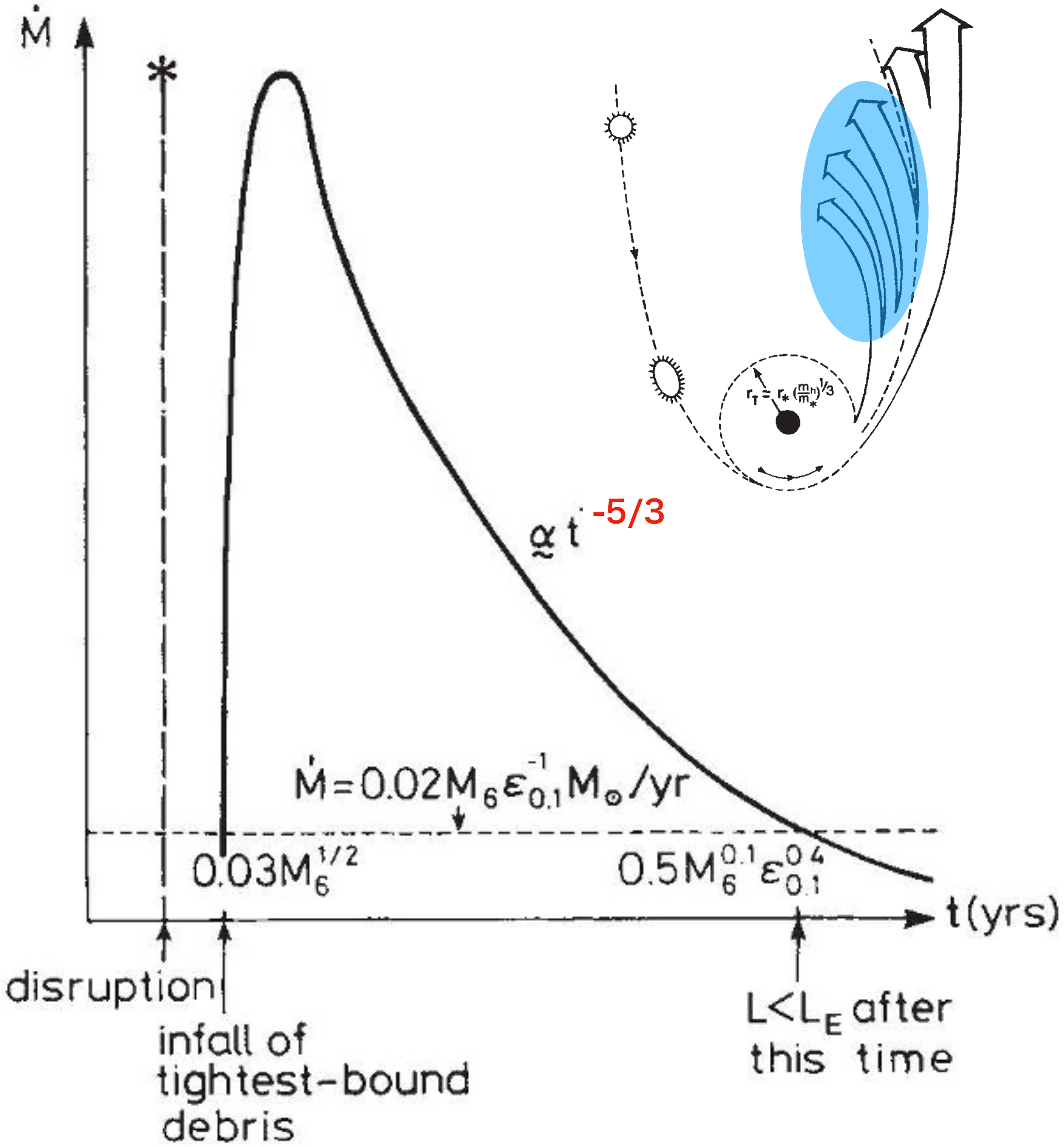
$$\Delta\varepsilon = \left(-\frac{GM_\bullet}{R_{\mathrm{T}}}\right) - \left(-\frac{GM_\bullet}{R_{\mathrm{T}} \pm R_\star}\right)$$

$$\simeq \pm \frac{GM_\bullet}{R_{\mathrm{T}}^2} R_\star$$

$$\frac{dM}{d\varepsilon} \simeq \frac{M_\star/2}{\Delta\varepsilon}$$



Basics of TDEs



Rees88
Phinney89

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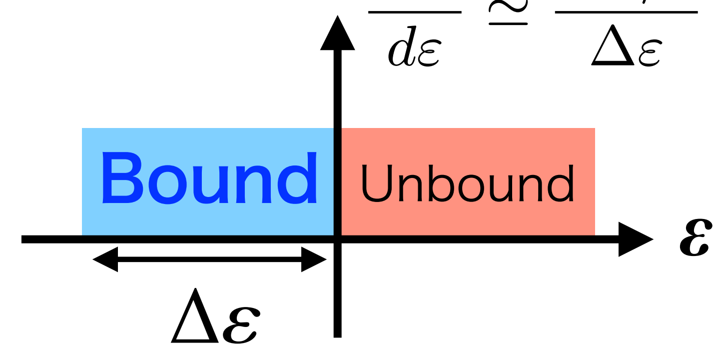

$$t = \frac{2\pi G M_\bullet}{(2|\varepsilon|)^{3/2}}$$

$$\dot{M}_{\rm fb} = \frac{dM}{d\varepsilon}\frac{d\varepsilon}{dt} = \dot{M}_{\rm peak}\left(\frac{t}{t_{\rm fb}}\right)^{\boxed{-5/3}}$$

$$t_{\rm fb} \simeq \boxed{40 \rm day}\; R_{\star,0}^{3/2} M_{\star,0}^{-1} M_{\bullet,6}^{1/2}$$

$$\dot{M}_{\rm peak} \simeq \boxed{100 \dot{M}_{\rm Edd}}\; R_{\star,0}^{-3/2} M_{\star,0}^{2} M_{\bullet,6}^{-1/2}$$

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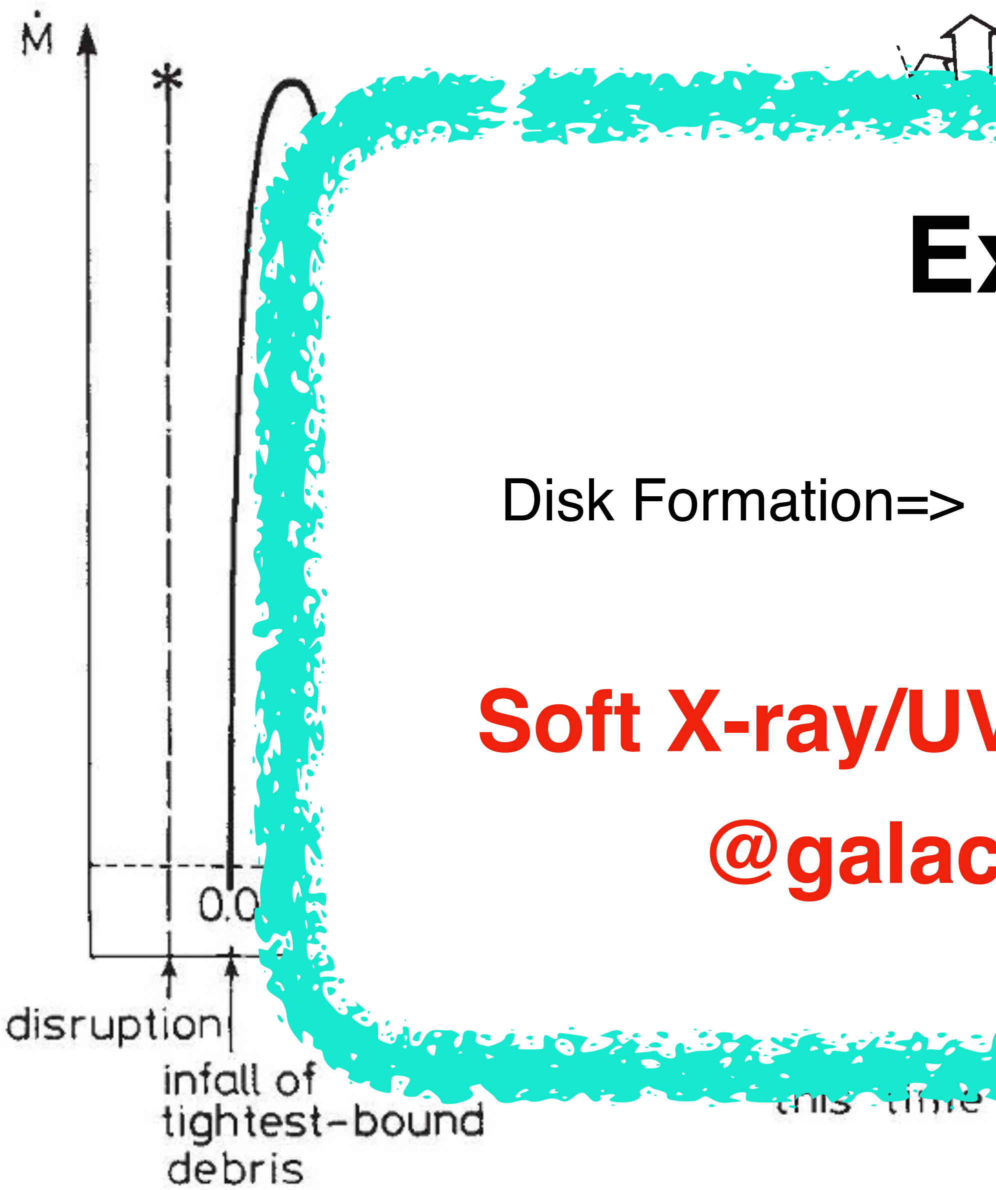


$$\frac{dM}{d\varepsilon} \simeq \frac{M_\star/2}{\Delta\varepsilon}$$

unbound

ε

Expectation

Disk Formation=> $T \simeq \boxed{400\mathrm{eV}} \left(\frac{t}{t_{\mathrm{fb}}}\right)^{-5/12} R_{\star,0}^{-3/8} M_{\star,0}^{1/2} M_{\bullet,6}^{-5/8}$

Soft X-ray/UV flares with ~L_{Edd} & ~yr

@galactic nuclear region

$$\left(\frac{t}{t_{\mathrm{fb}}}\right)^{\boxed{-5/3}}$$

$$t_{\mathrm{fb}} \simeq \boxed{40\mathrm{day}} \; R_{\star,0}^{3/2} M_{\star,0}^{-1} M_{\bullet,6}^{1/2}$$

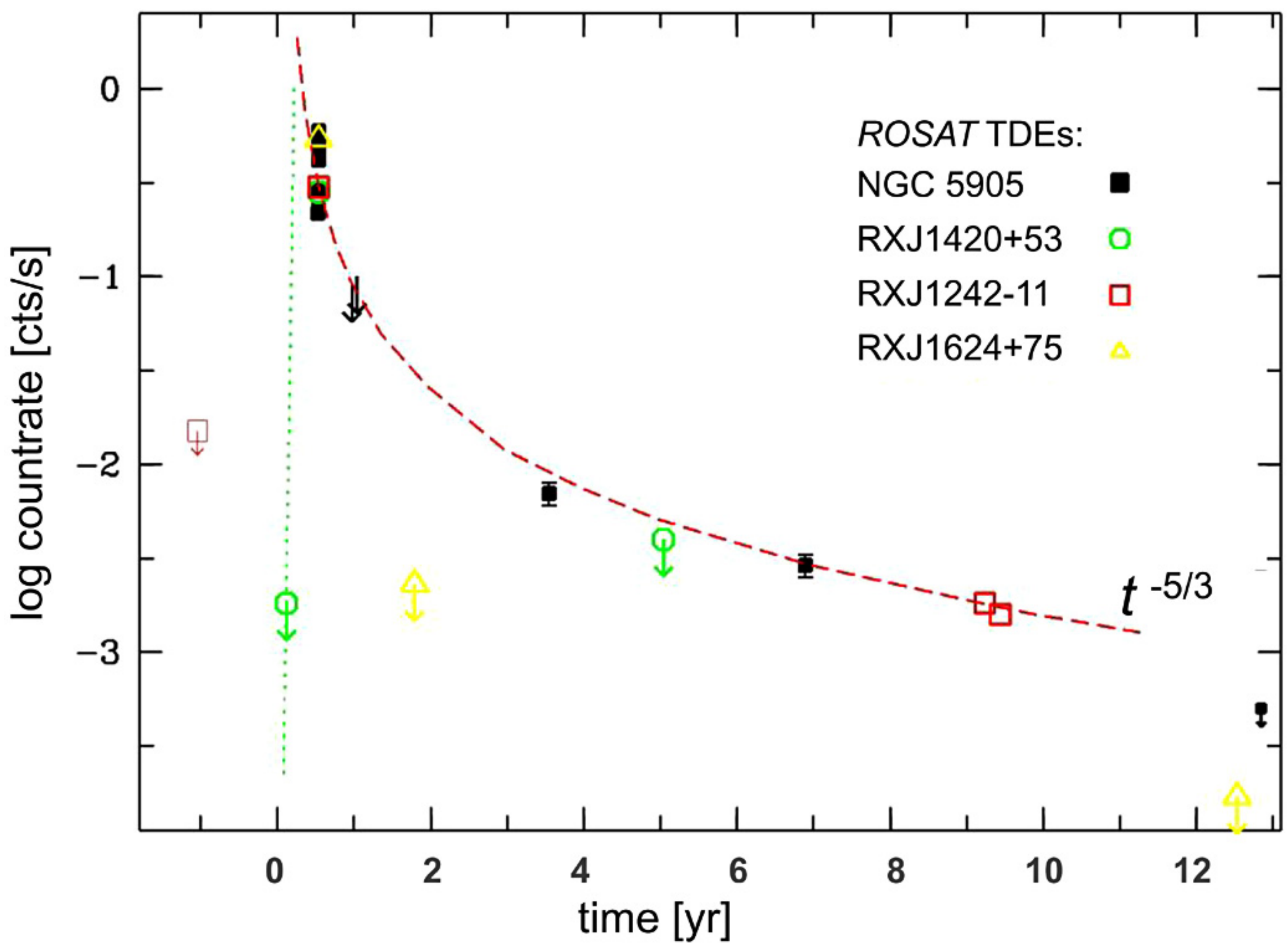
$$\dot{M}_{\mathrm{peak}} \simeq \boxed{100 \dot{M}_{\mathrm{Edd}}} \; R_{\star,0}^{-3/2} M_{\star,0}^{2} M_{\bullet,6}^{-1/2}$$

Rees88
Phinney89

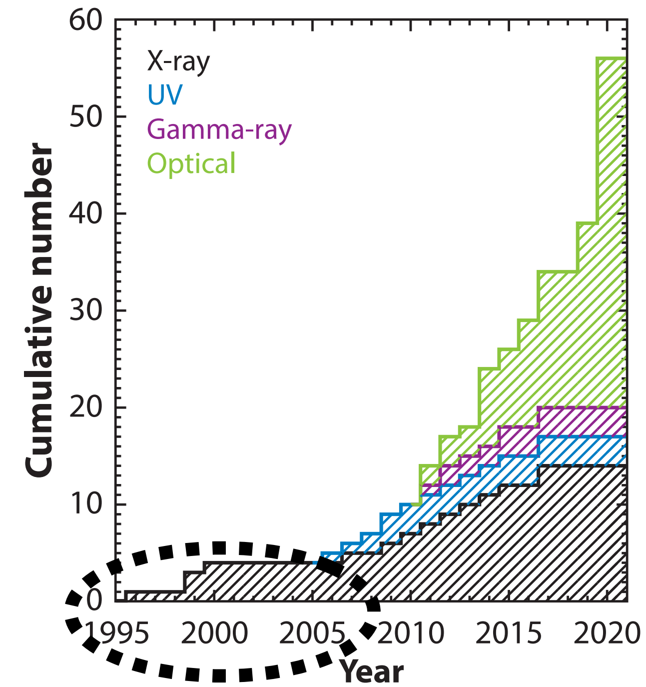
Observation: X-rays

X-ray TDEs (1990s~)

Komossa15



Gezari21



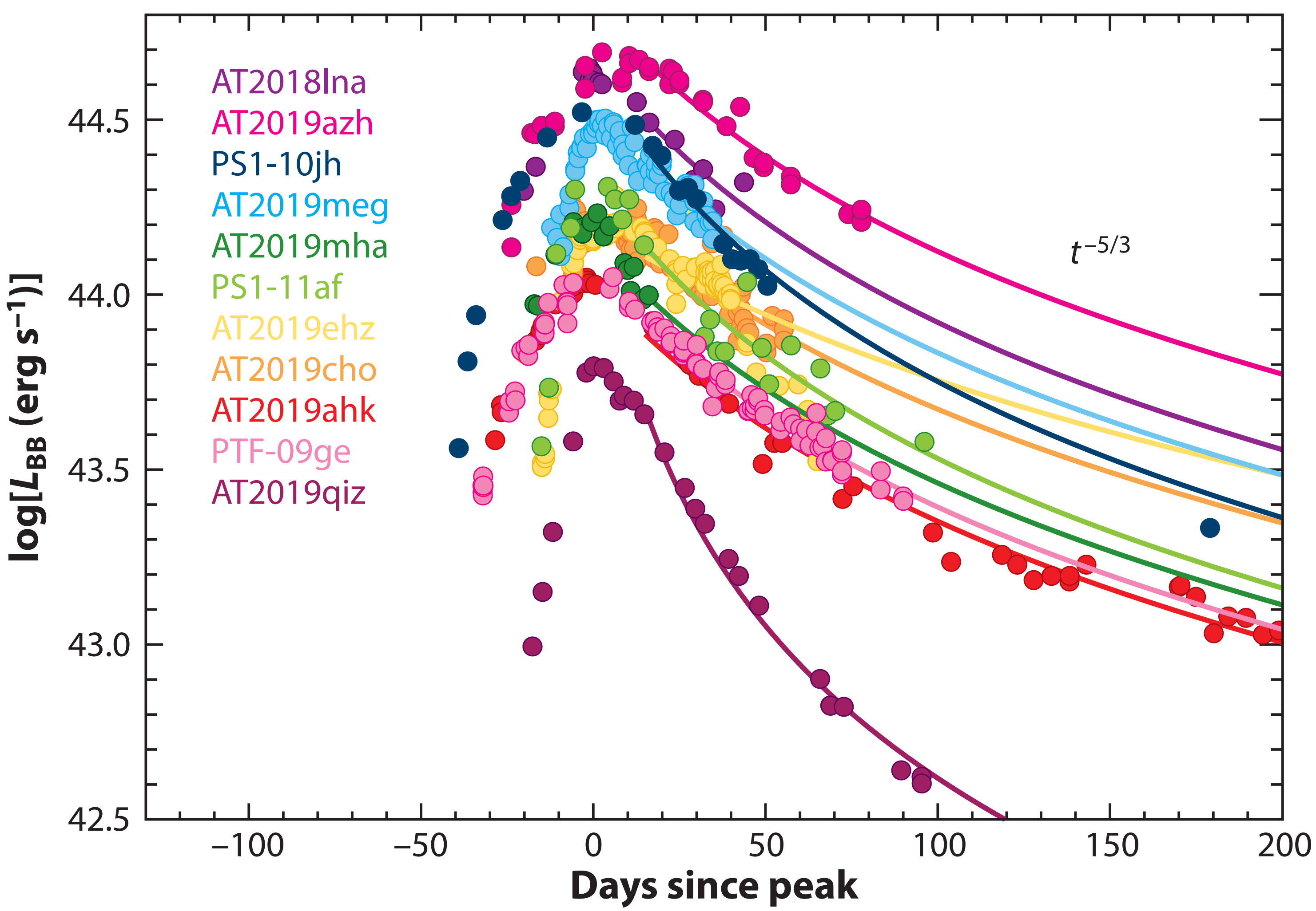
ROSAT all sky survey: 1990-91
20% of sky @0.1-2.4 keV

✓In galactic nuclear regions (not AGN)
✓Lx~10^{44} erg/s (~L_{Edd})
✓kT~0.1keV
✓L ~ $t^{-5/3}$

Observation: Optical

Optical TDEs (2010s~)

Gezari21



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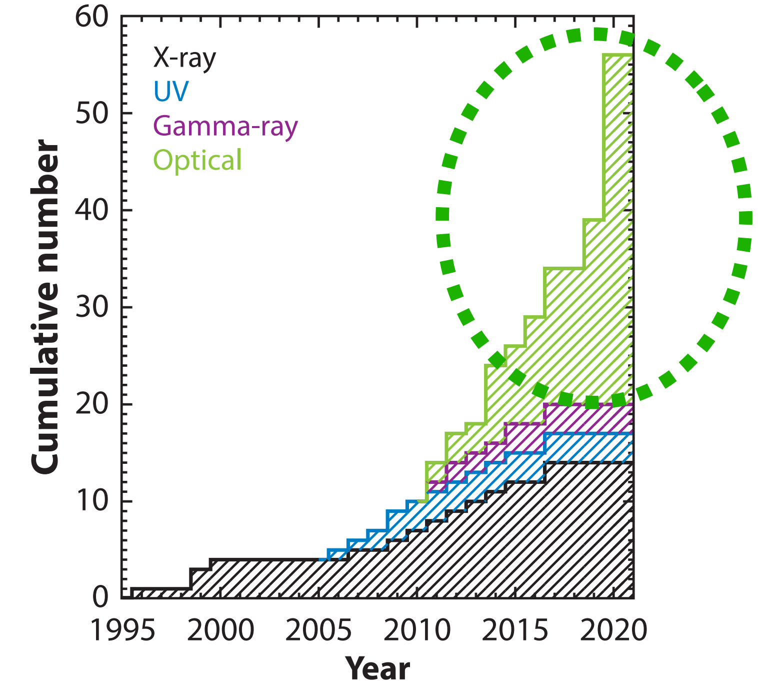


✓In galactic nuclear regions (not AGN)

✓Lx~10^{44} erg/s (~L_{Edd})

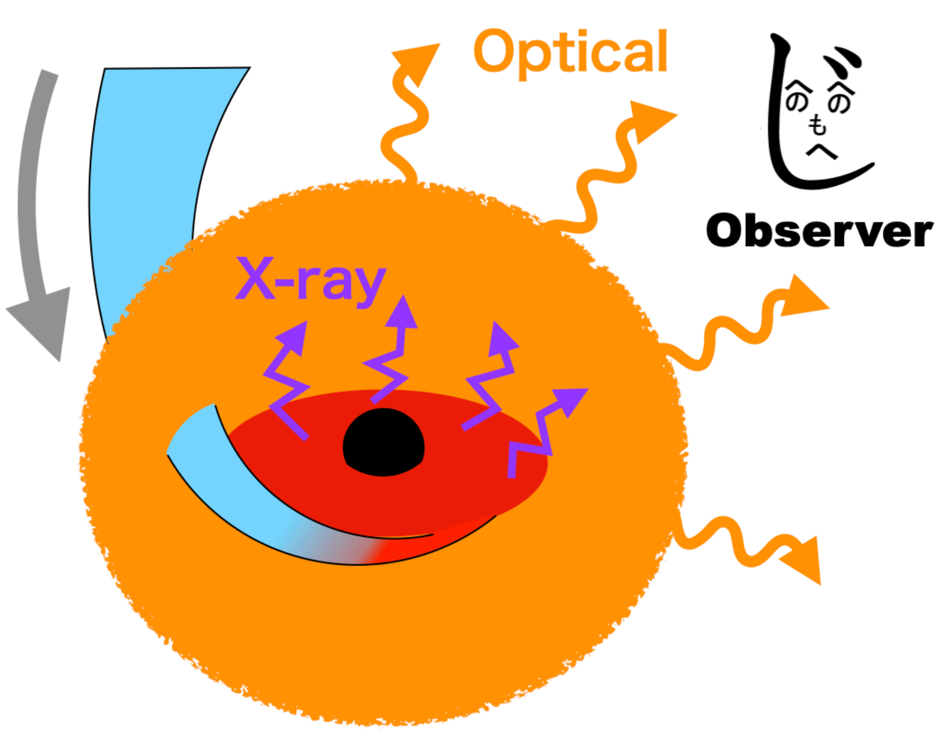
✓T~30000K, Rbb~10^{15}cm

✓L ~ $t^{-5/3}$

Models of optical TDEs

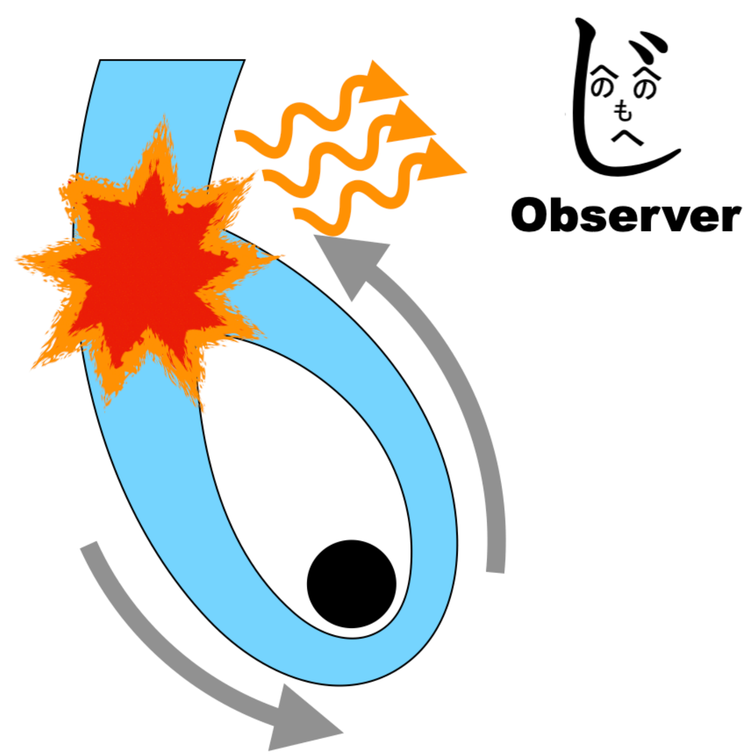
1) Reprocessing

Strubbe&Quataert09, Metzger&Stone16,Dai+18



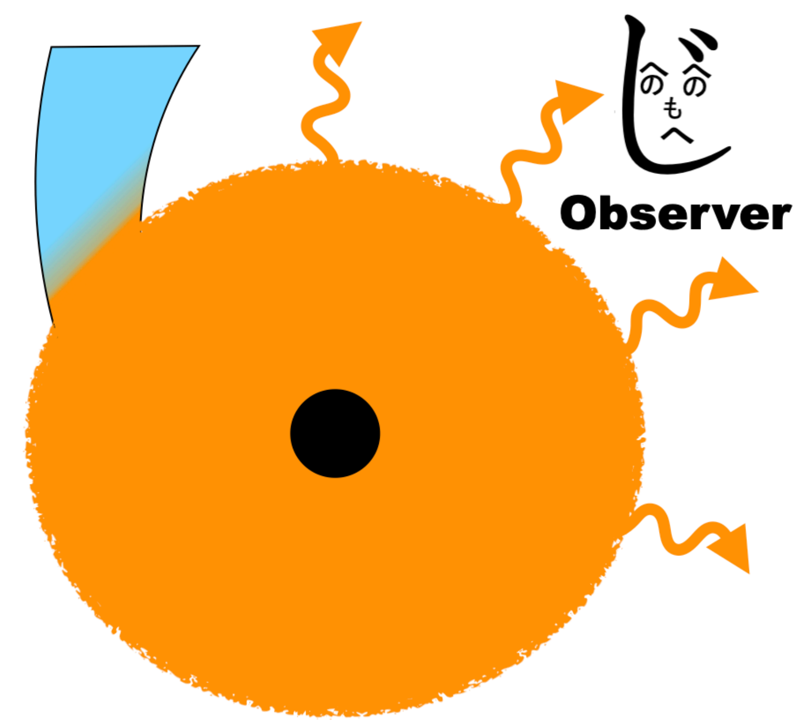
2) Shock interaction

Piran+15,Krolik+16,Ryu+20



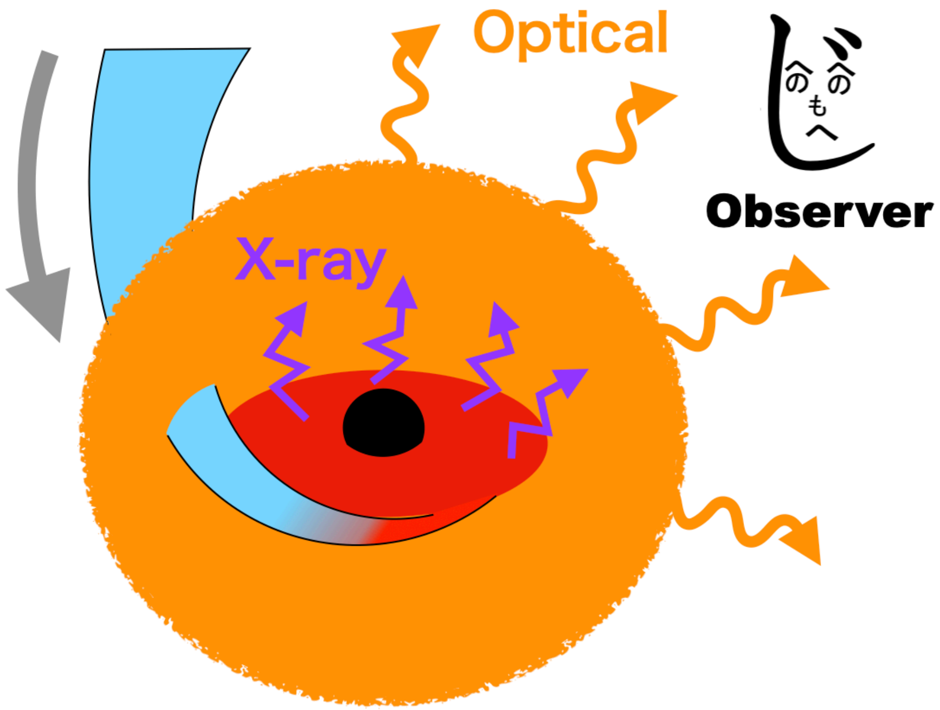
3) Cooling Envelope

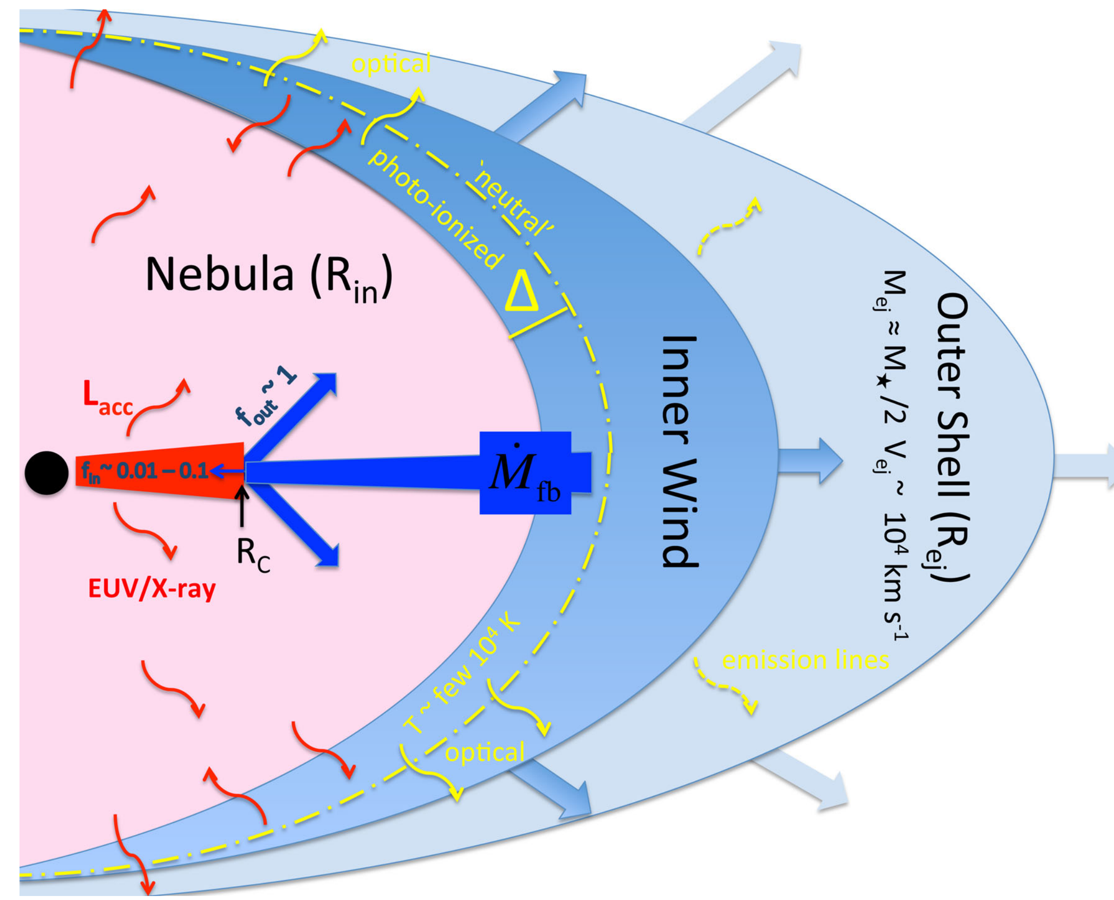
Loeb&Ulmer97,Metzger22



Strubbe&Quataert09,Metzger&Stone16,Dai+18

1)Reprocessing model



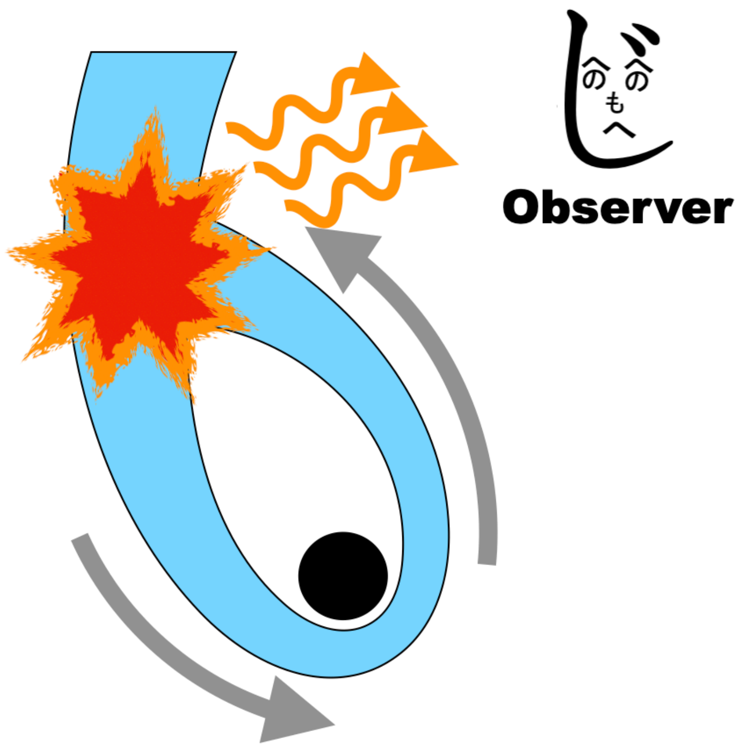


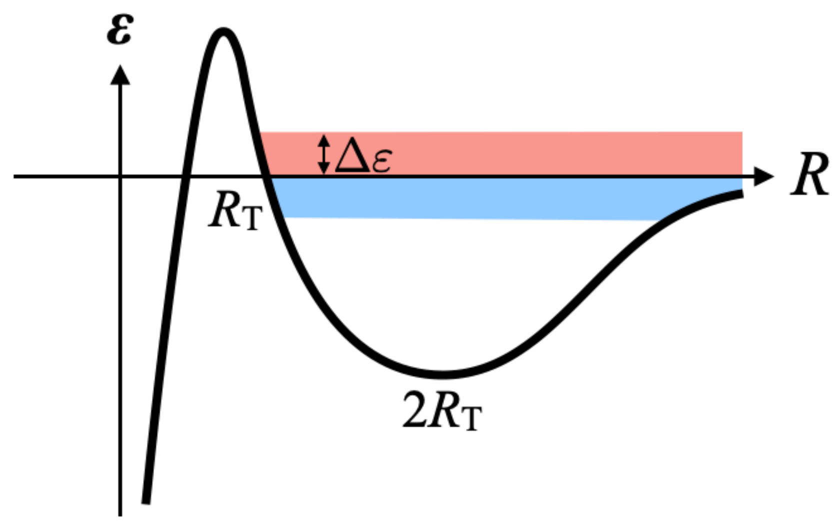
✓ Assumption: Rapid disk formation (“Circularization”)
✓ Disk is covered by opt. thick outflow or envelope.
✓ X-rays are absorbed and re-emitted in optical.

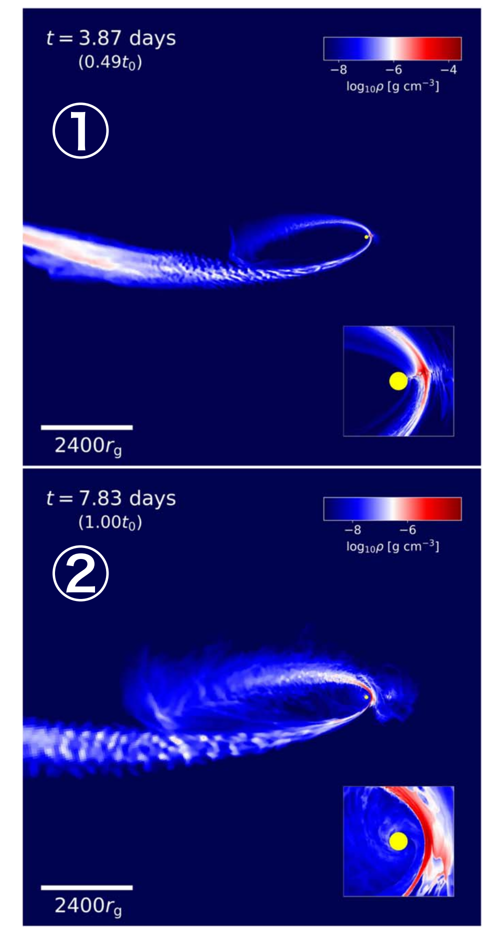
Piran+15,Krolik+16,Ryu+20

2)Shock interaction model

Ryu+23







✓ Assumption: Inefficient circularization

✓ Inverse energy problem:

E_{acc}~1e+53erg & E_{circ}~1e+52erg >> E_{opt}~1e+51erg

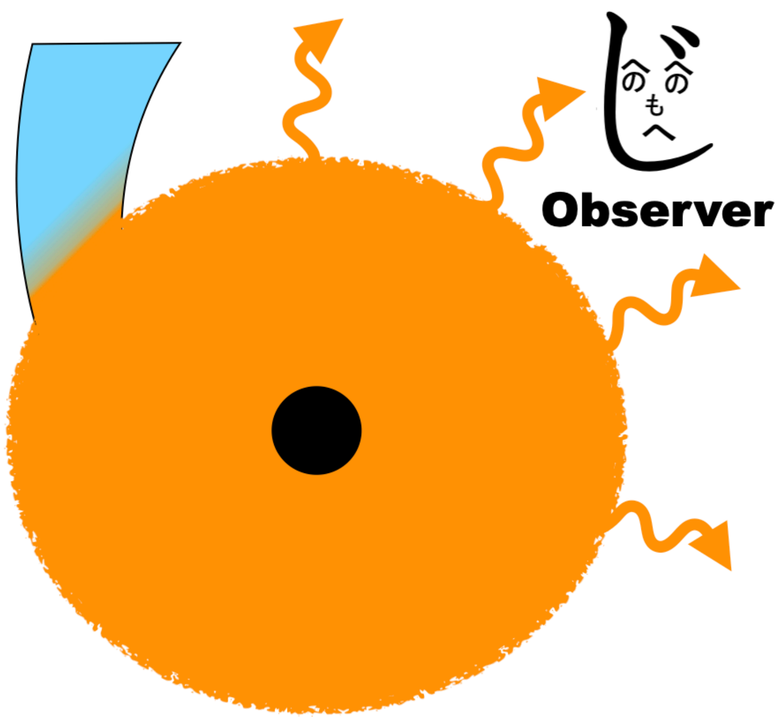
✓ Shock forms at ~ apocenter of bound debris.

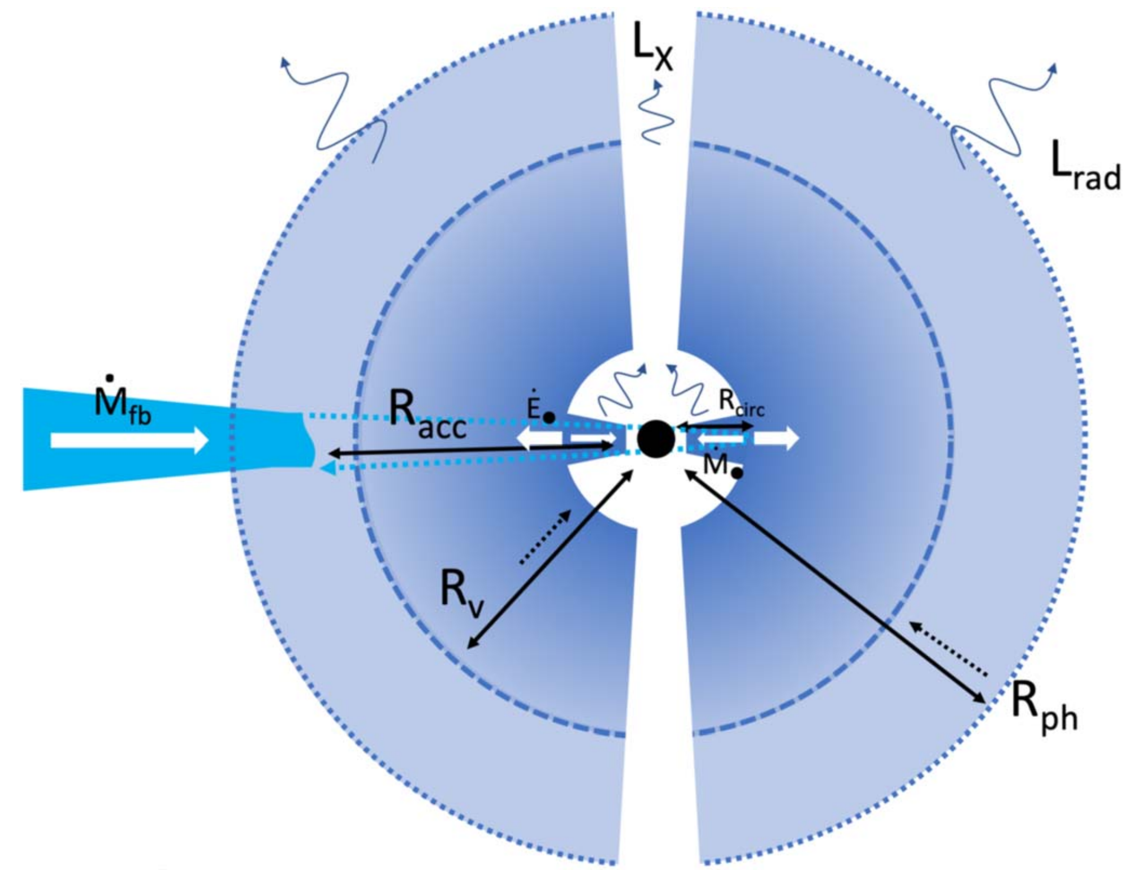
$$a_0 = \frac{GM_{\rm BH}}{\Delta E} = 6.5 \times 10^{14}\ {\rm cm}\ M_{\rm BH,6}^{2/3} M_\star^{2/9}$$

$$L_{\rm max} = \frac{GM_{\rm BH}\dot{M}_{\rm max}}{c_1 a_0} = 4.3 \times 10^{43}\ c_1^{-1} M_\star^{4/9} M_{\rm BH,6}^{-1/6}\ \Xi^{5/2}\ {\rm erg\ s^{-1}}.$$

Loeb&Ulmer97,Metzger22

3)Cooling envelope model





✓ Assumption: Inefficient circularization
✓ Debris virializes and forms an opt. thick envelope.
✓ Envelope cools over KH timescale with L_Edd.

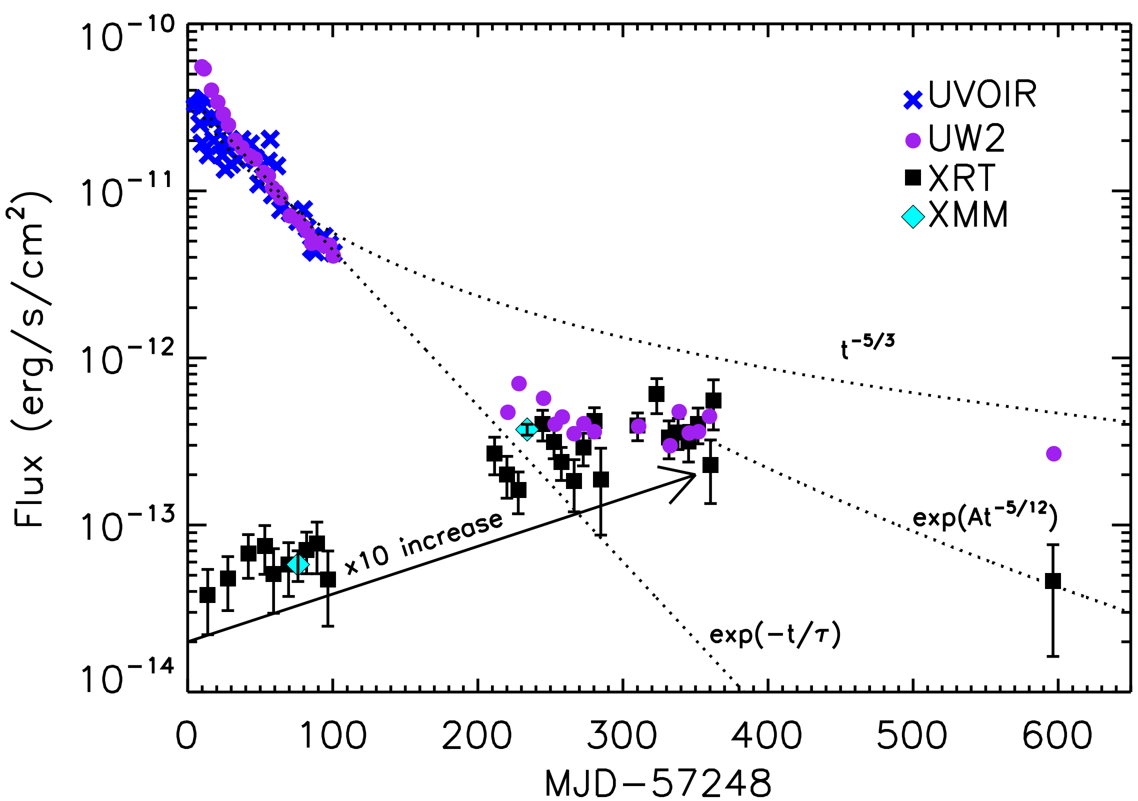
$$R_{v,0} \approx \frac{2R_\star}{5k}\left(\frac{M_\bullet}{M_\star}\right)^{2/3}\frac{M_e}{M_\star}$$
$$\approx 6.8 \times 10^{13}\,\mathrm{cm}\, m_\star^{2/15} M_{\bullet,6}^{2/3}\left(\frac{M_{e,0}}{0.2M_\star}\right),$$

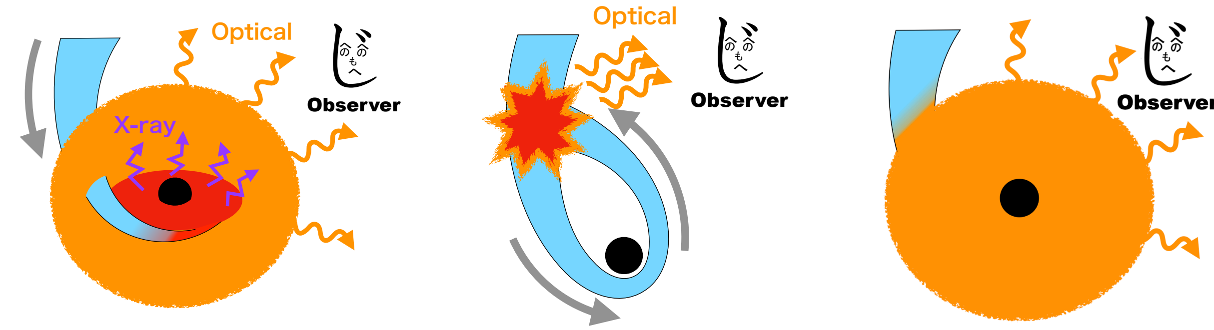
$$\frac{2GM_\bullet M_e}{5R_v^2}\frac{dR_v}{dt} = L_{\rm Edd}(M_\bullet).$$

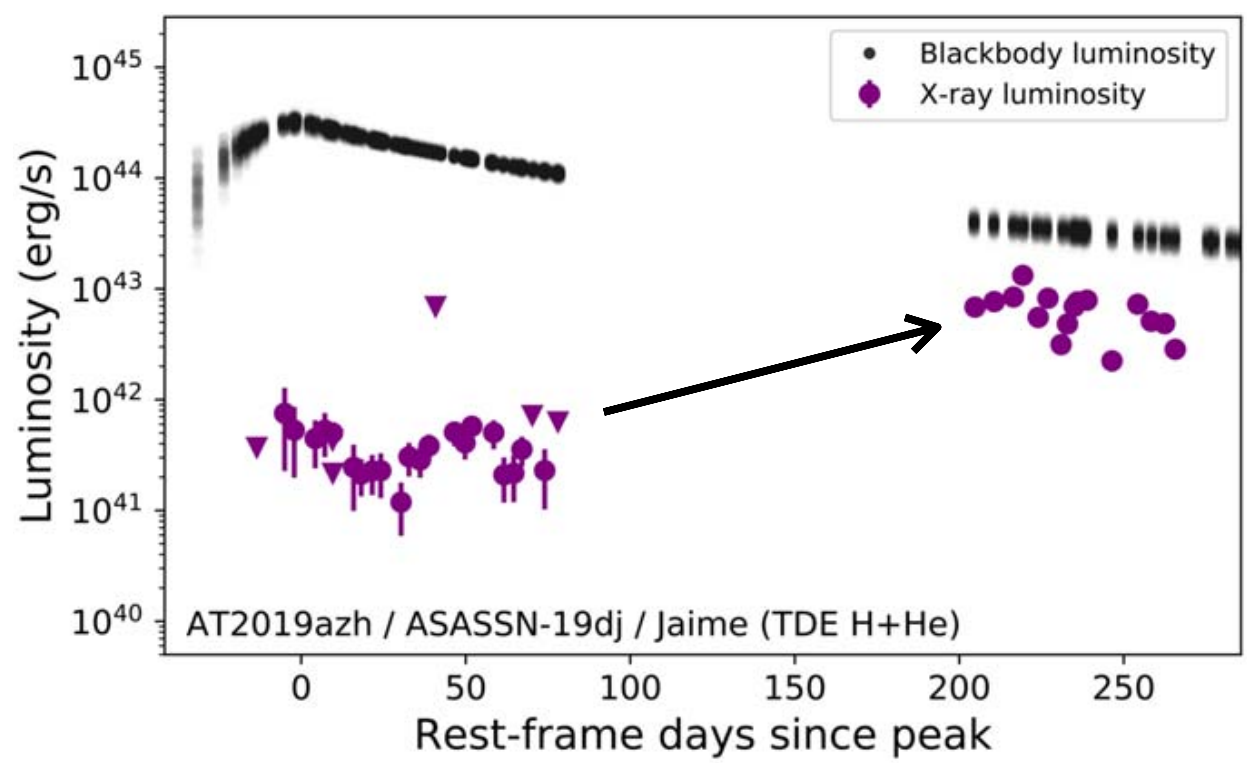
X-rays in opt. TDEs: Delayed brightening

ASASSN15oi

Gezari+17



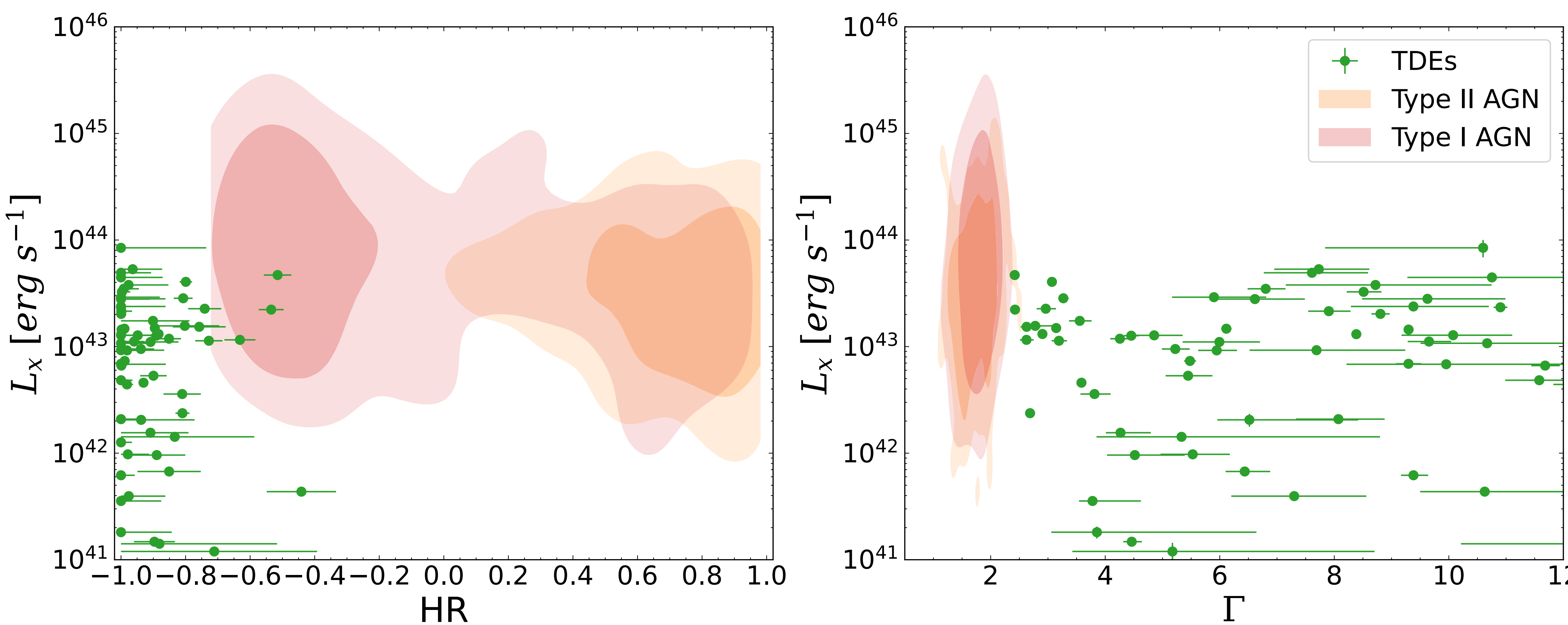




Shrink/evaporation of reprocessing materials/envelope?
Delayed accretion?

Guolo+24

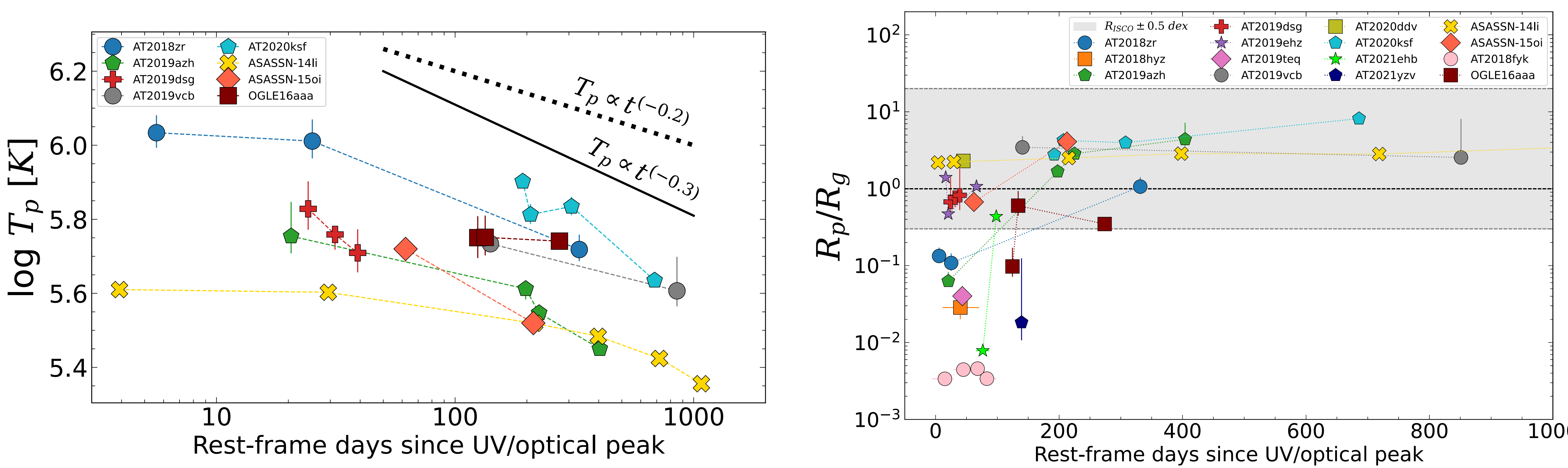
X-rays in opt. TDEs: Diverse behavior



✓ Soft spectrum, fitted by BB disk model (similar to ROSAT TDEs)
✓ 3/17 events shows soft-hard state transition
✓ T~ 3e+5-1e+6 K ~ 30-100eV, decreasing as time
✓ Some events have unphysical R(<<Rg): low-Lx, Blocked?
✓ Bright optical: Another emission component required

Guolo+24

X-rays in opt. TDEs: Diverse behavior



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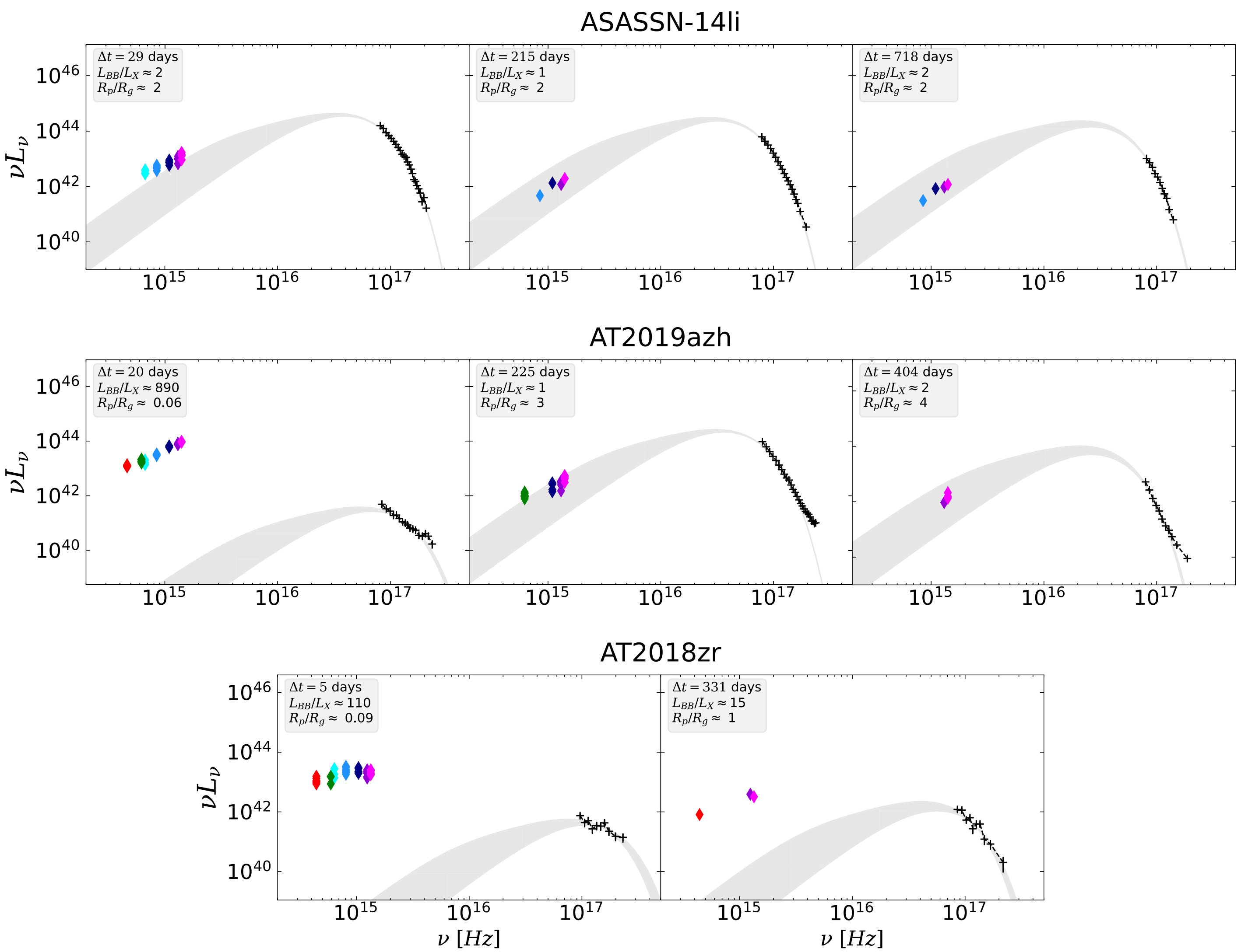
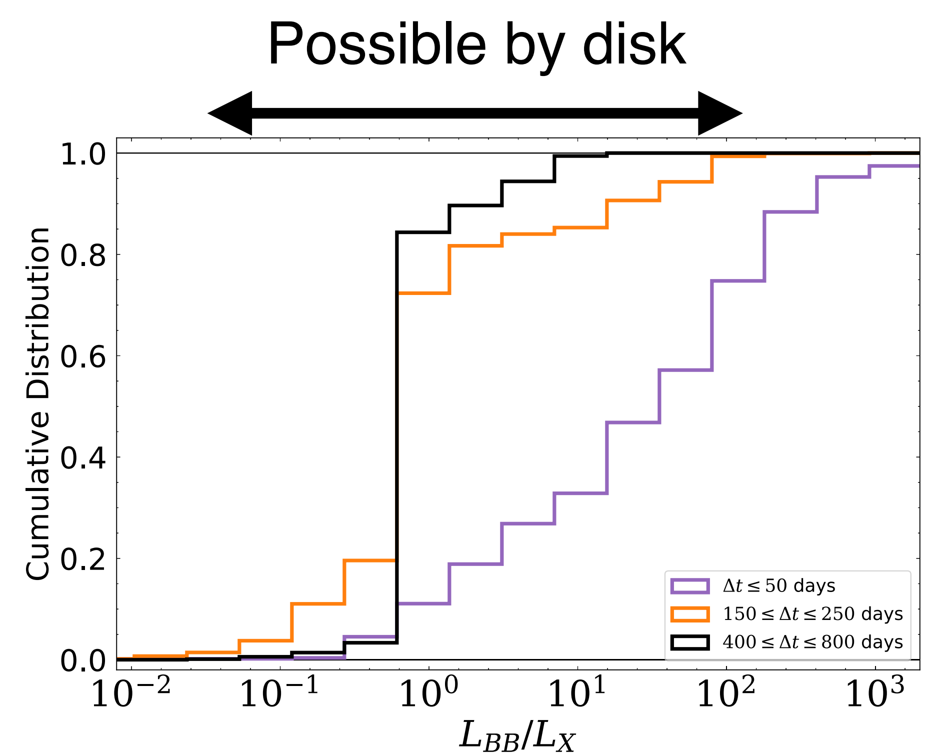
Guolo+24

X-rays in opt. TDEs: Diverse behavior





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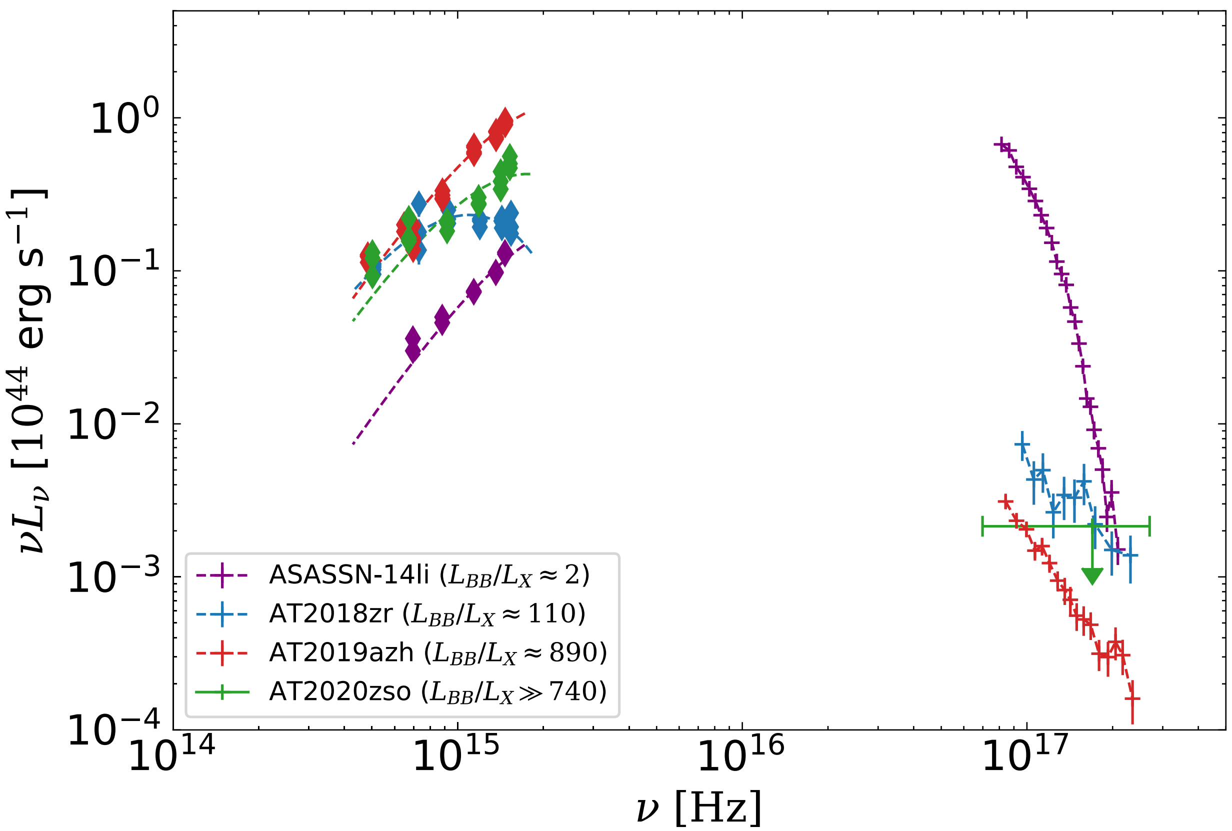
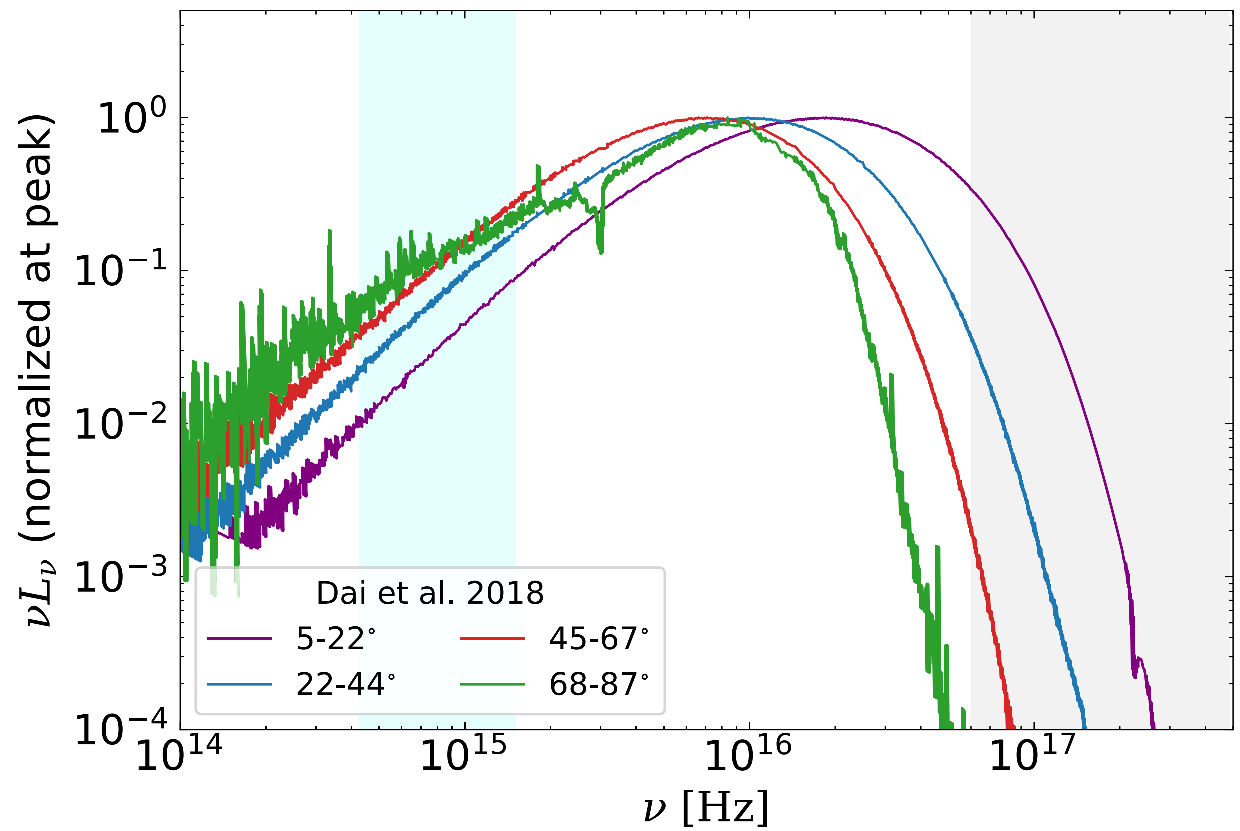
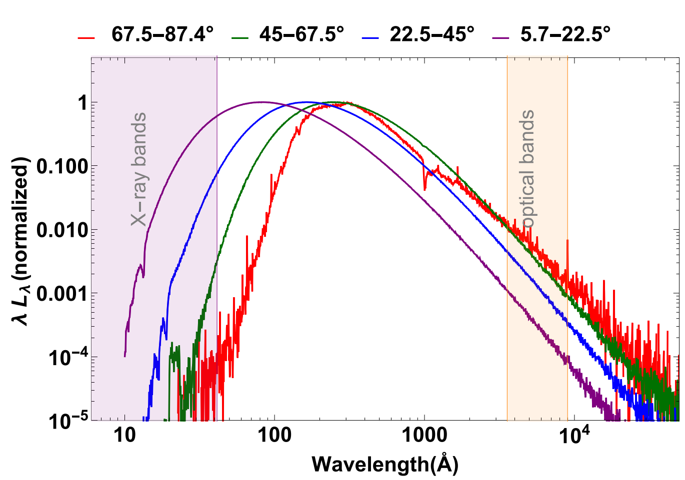
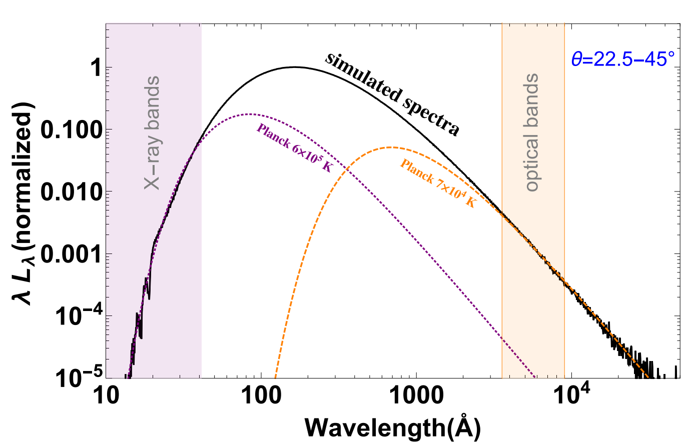
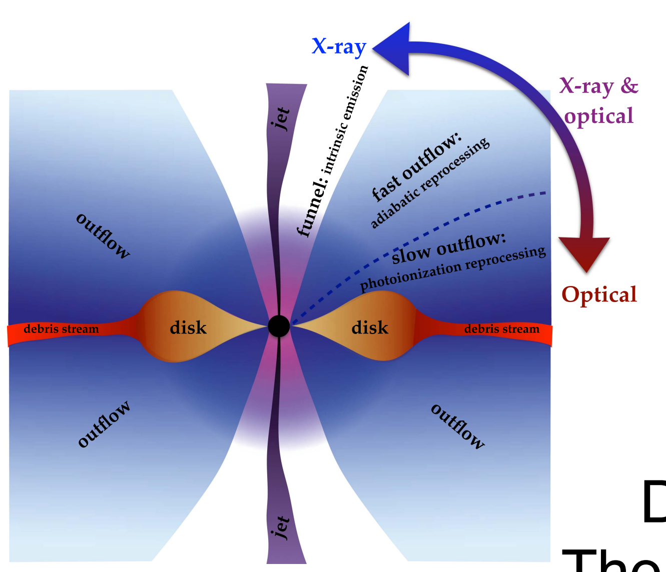
Reprocessing model: favored?







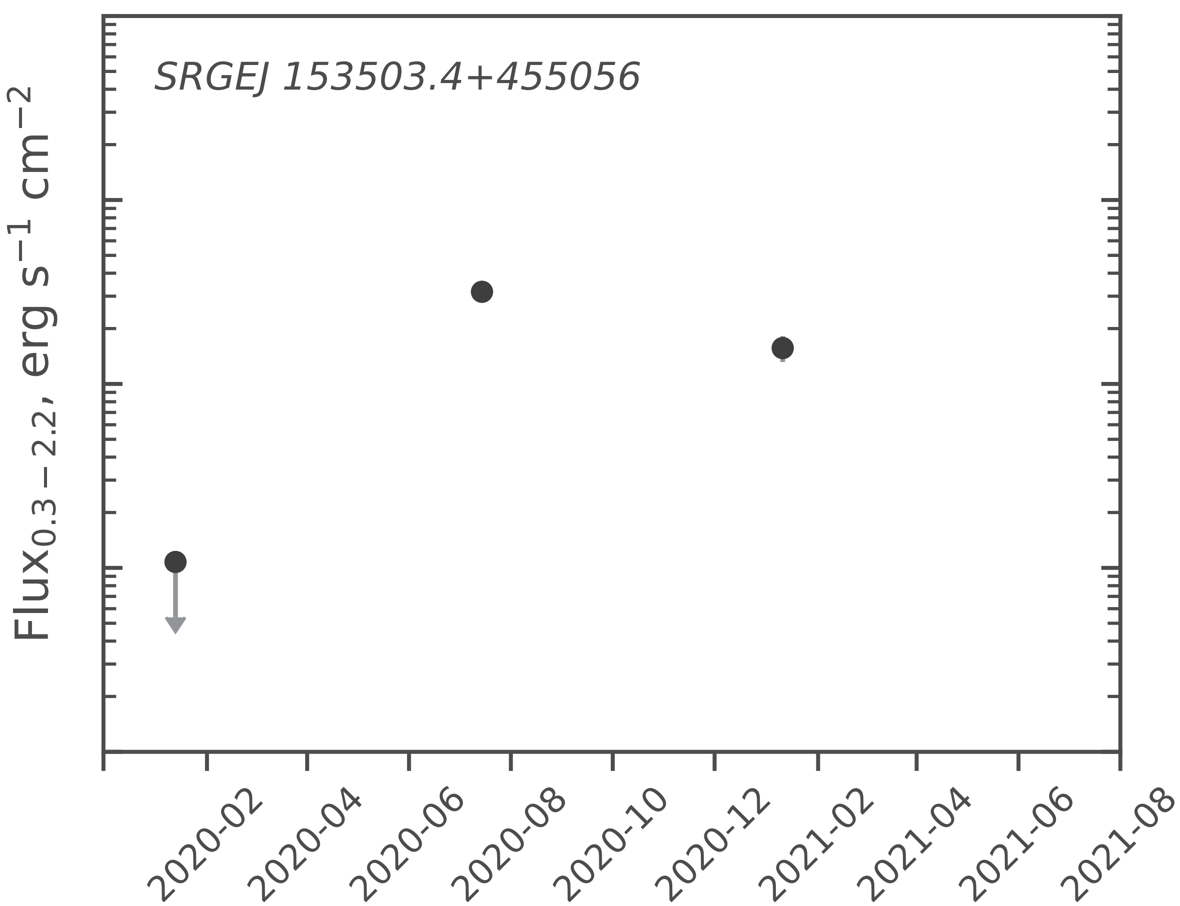


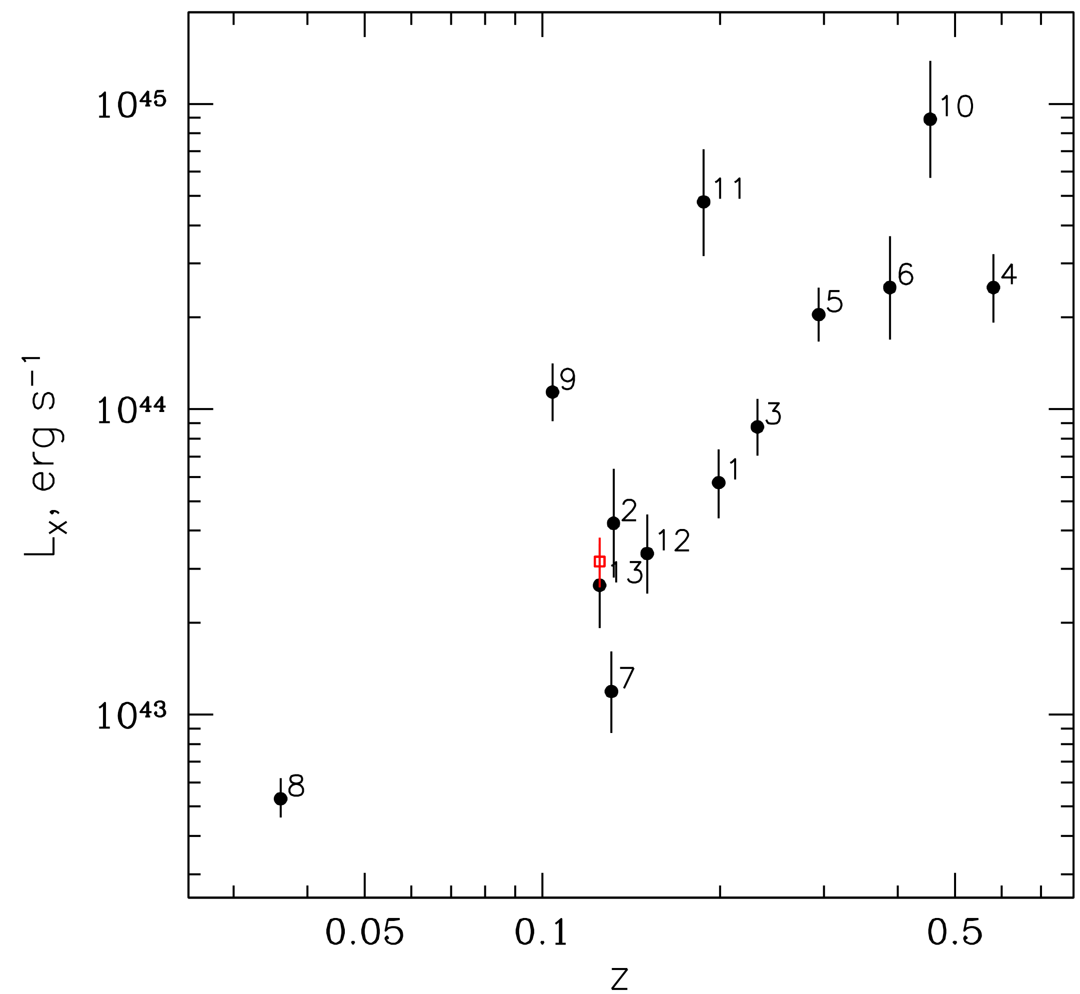


Dai+18
Thomsen+22

Sazonov+21

More X-ray TDEs by eROSITA





- ✓ Maybe the same population observed by ROSAT
- ✓ 13TDEs up to z~0.5, cadence~0.5yr, consistent with $t^{-5/3}$
- ✓ Spectrum: Consistent with single pl (Γ~3-7) or BB (T~100-300eV)
- ✓ 3/13 events show opt. counterpart

Unified Picture?

Guolo+23

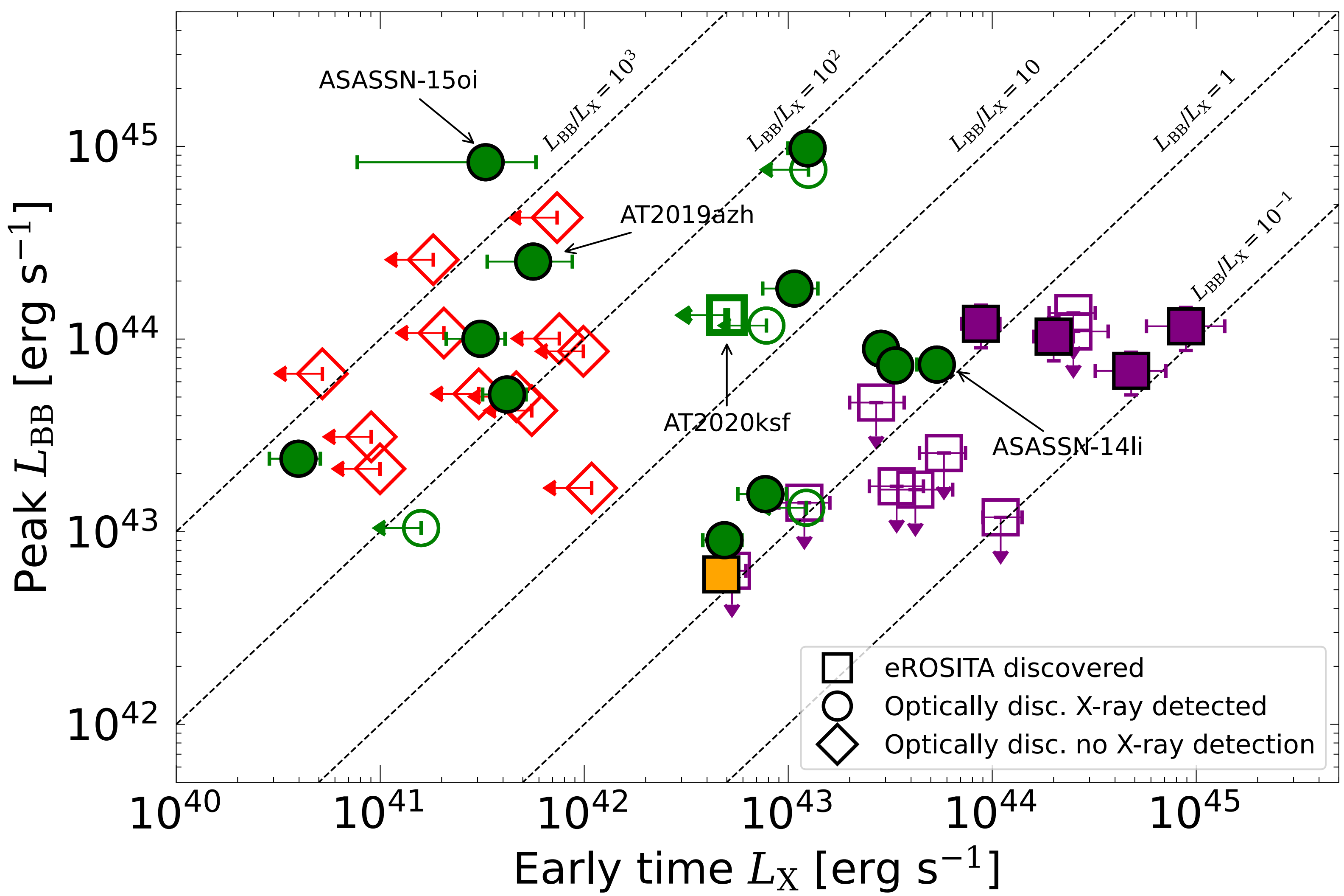
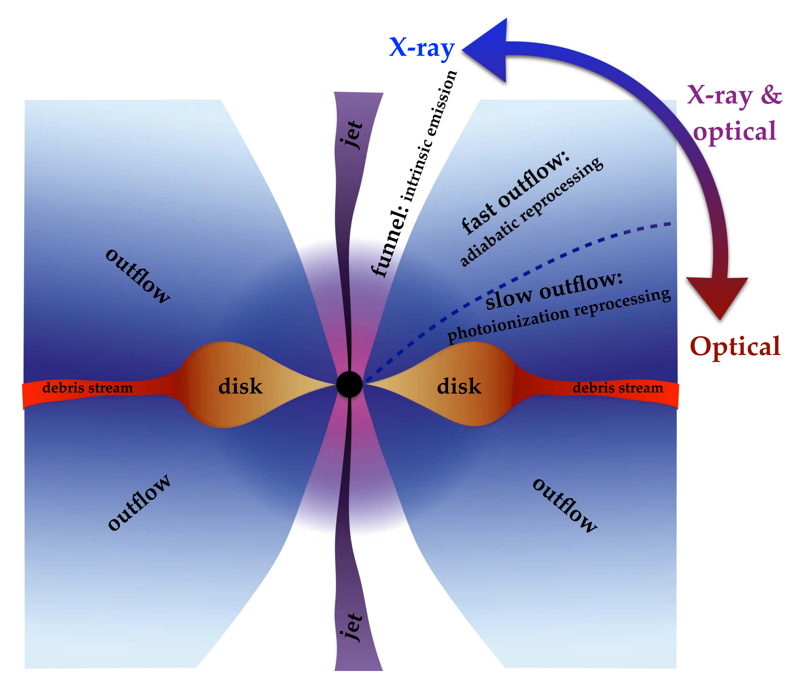
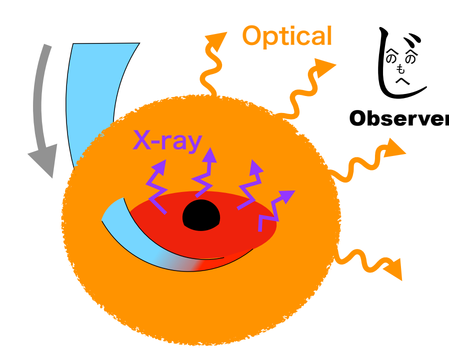


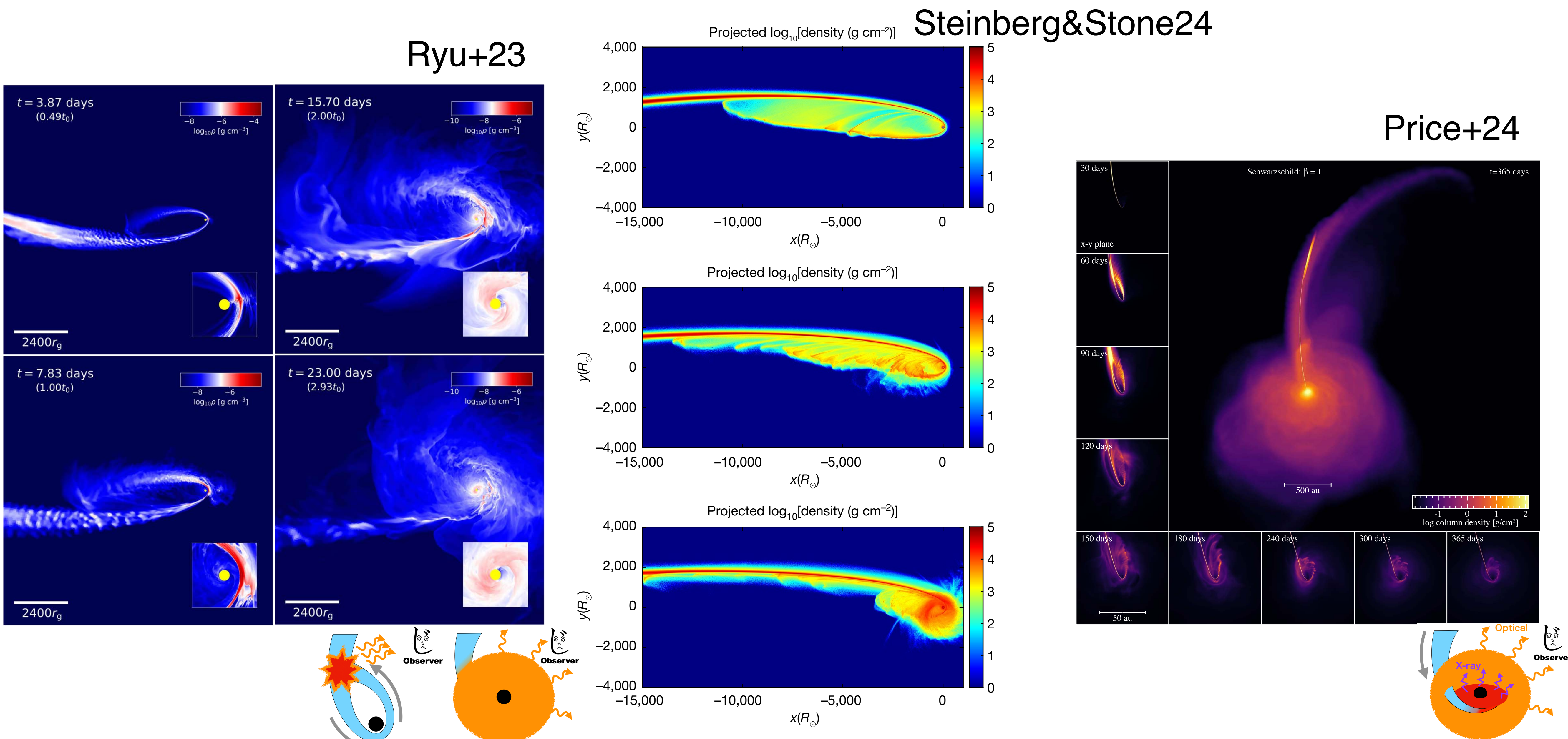
Figure 20. Distribution of peak L_{BB} × early time L_X for different TDE populations. Squares show *SRG*/eROSITA (X-ray) discovered sources, circles show optically discovered X-ray detected, while diamonds show optically discovered with no X-ray detection. Filled markers represent detections in both UV/optical and X-rays (early times), while hollow symbols represent upper limits in one of the two wavelength bands, where the arrows represent their 3σ upper limit. The colors are the same as in Fig. 19.

Dai+18





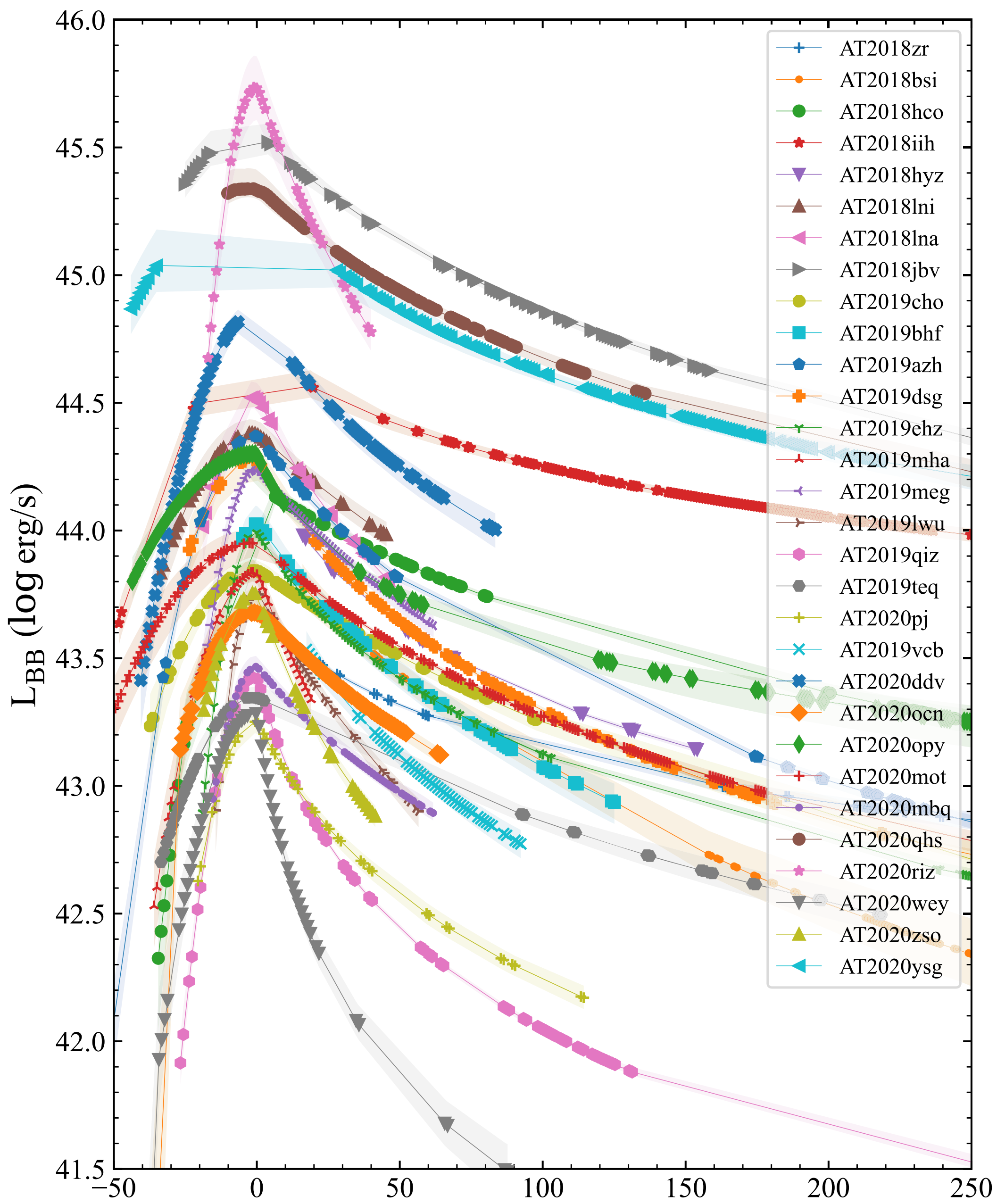
Insights from simulations



✓ Compact accretion disk does not form promptly (circularization is slow)
✓ Two shock structures appear: (weak) nozzle shock, “apocenter” shock
✓ ~ a few t_fb, a large-scale envelope appears

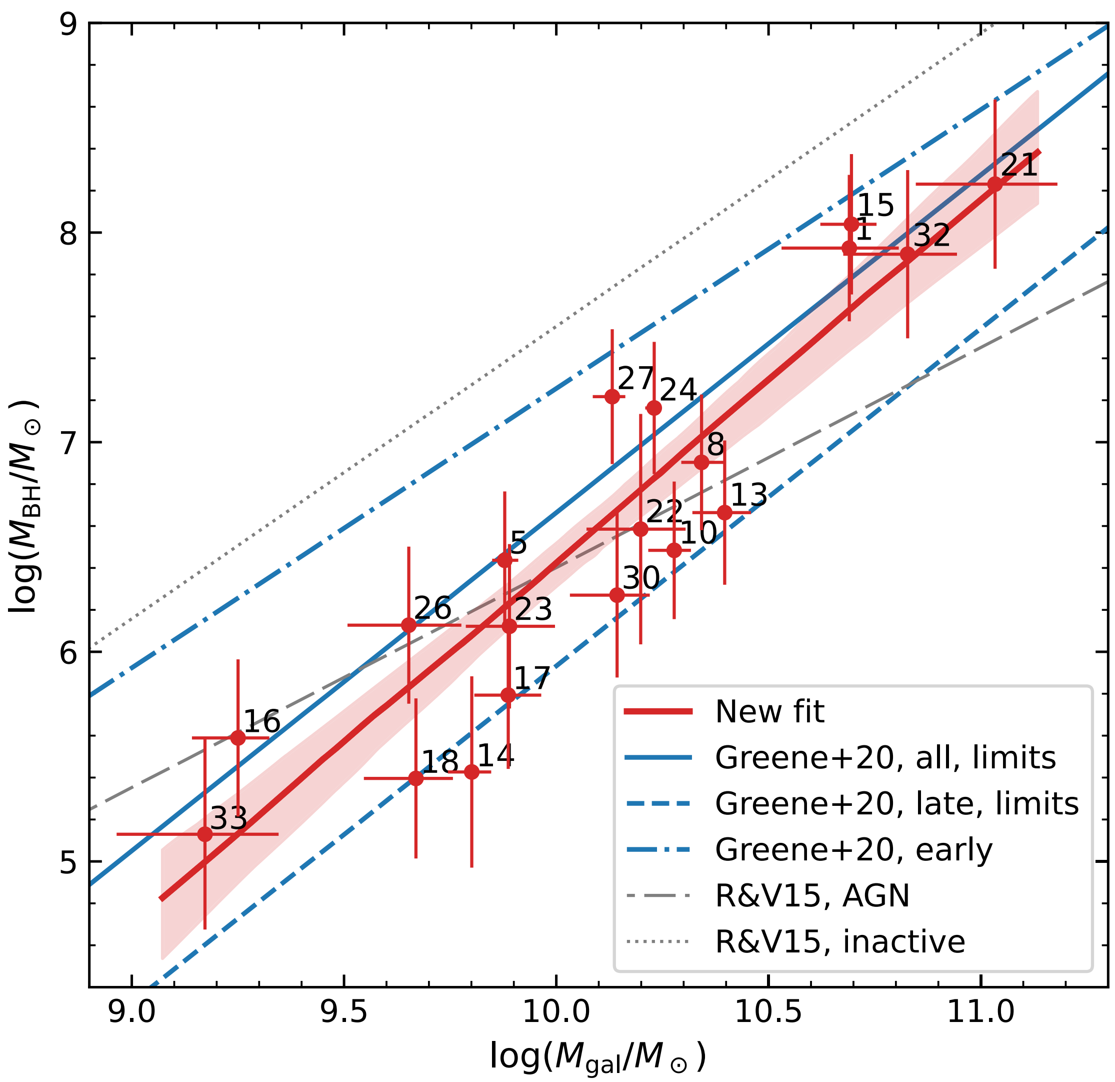
Krolik+24

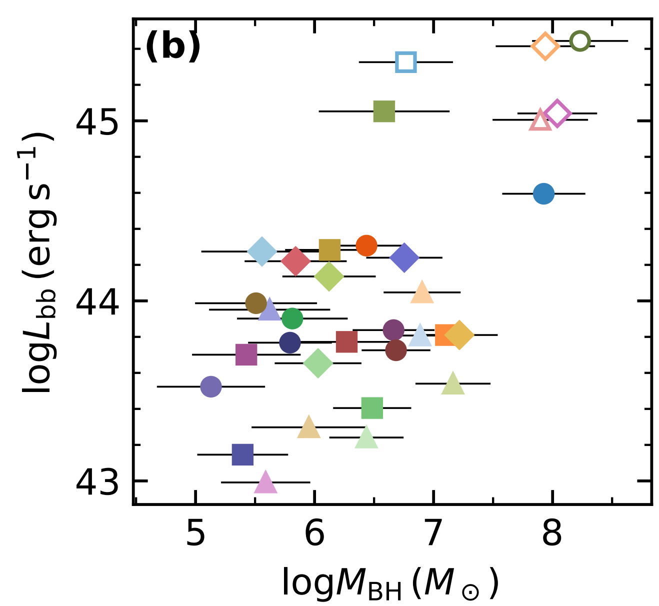
More Optical TDEs: Population study

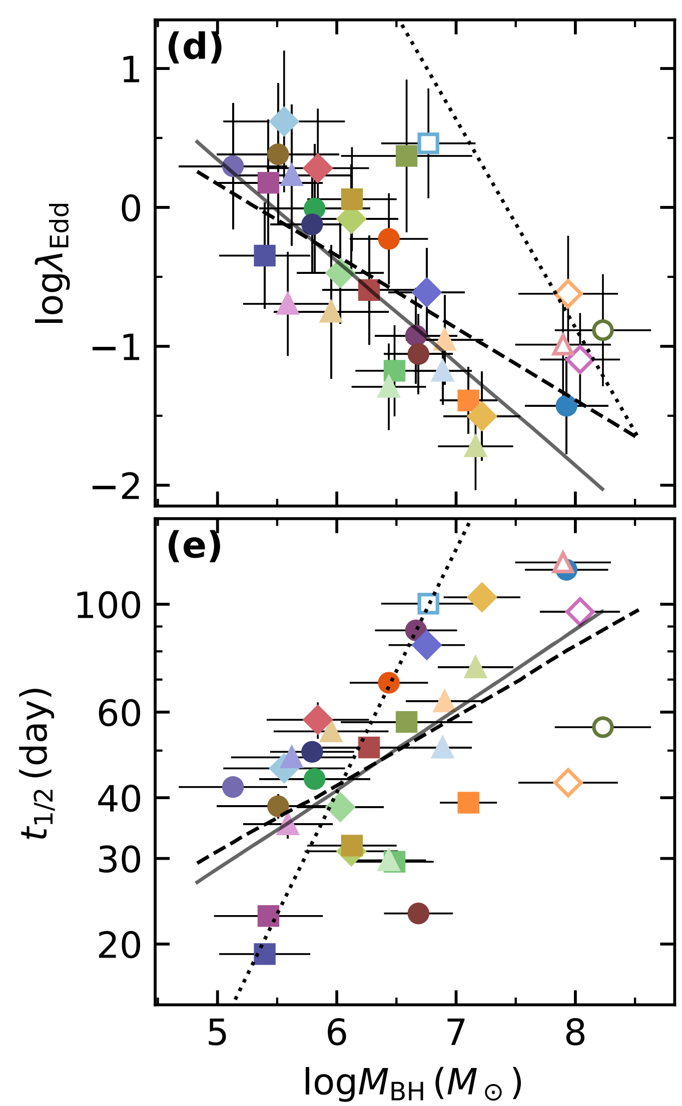


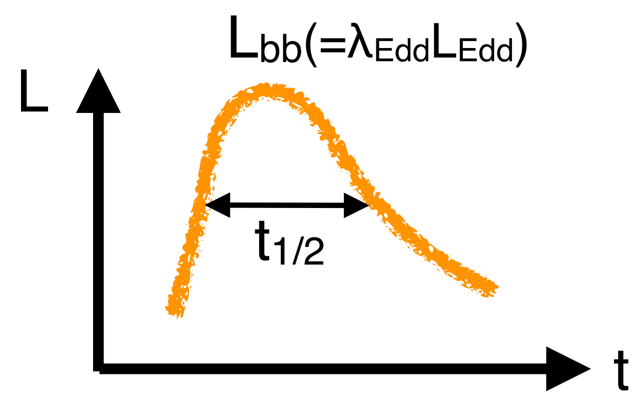
Yao+23

TDE Demographics: BH mass







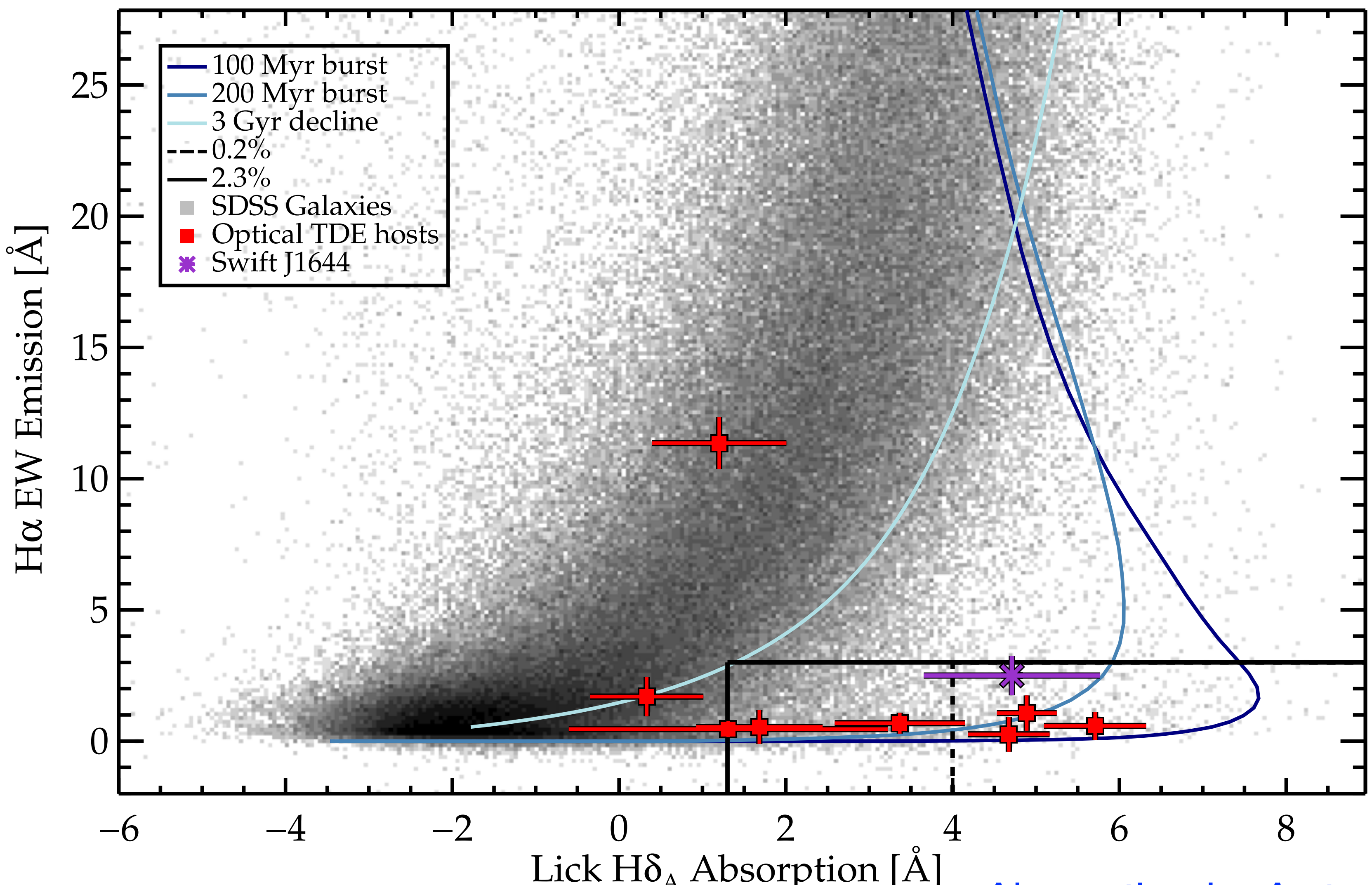


✓ Measuring σ in host => BH mass from M_{BH}-σ relation

✓ Possible correlations

French+16

Host: E+A (post-starburst) galaxy



:Emission
by ionized gas
=>Abundance
of O&B stars

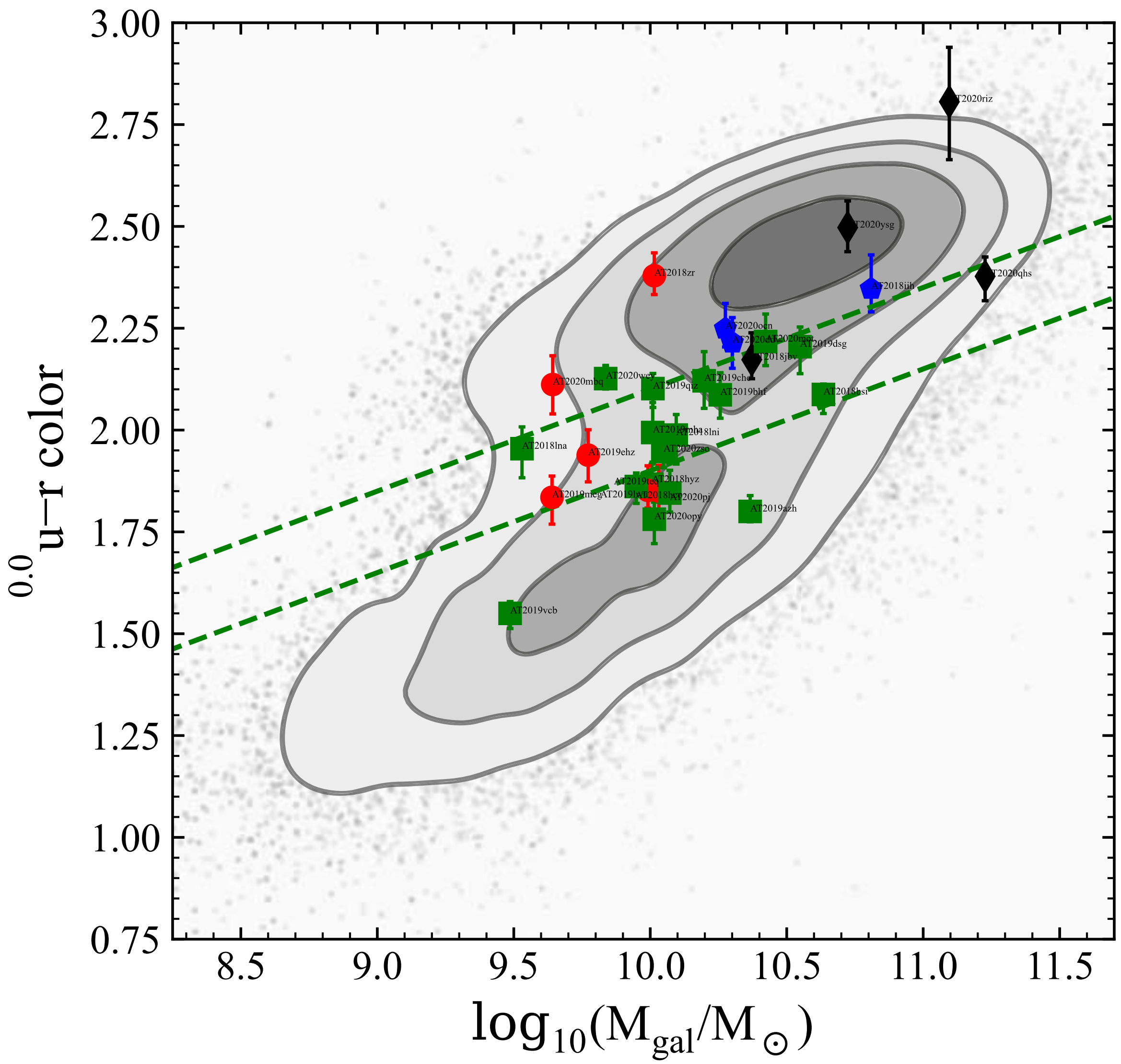
:Absorption by A stars
=>Abundance of A stars

✓ Optical TDEs prefer E+A galaxy (Starburst in past ~Gyr)

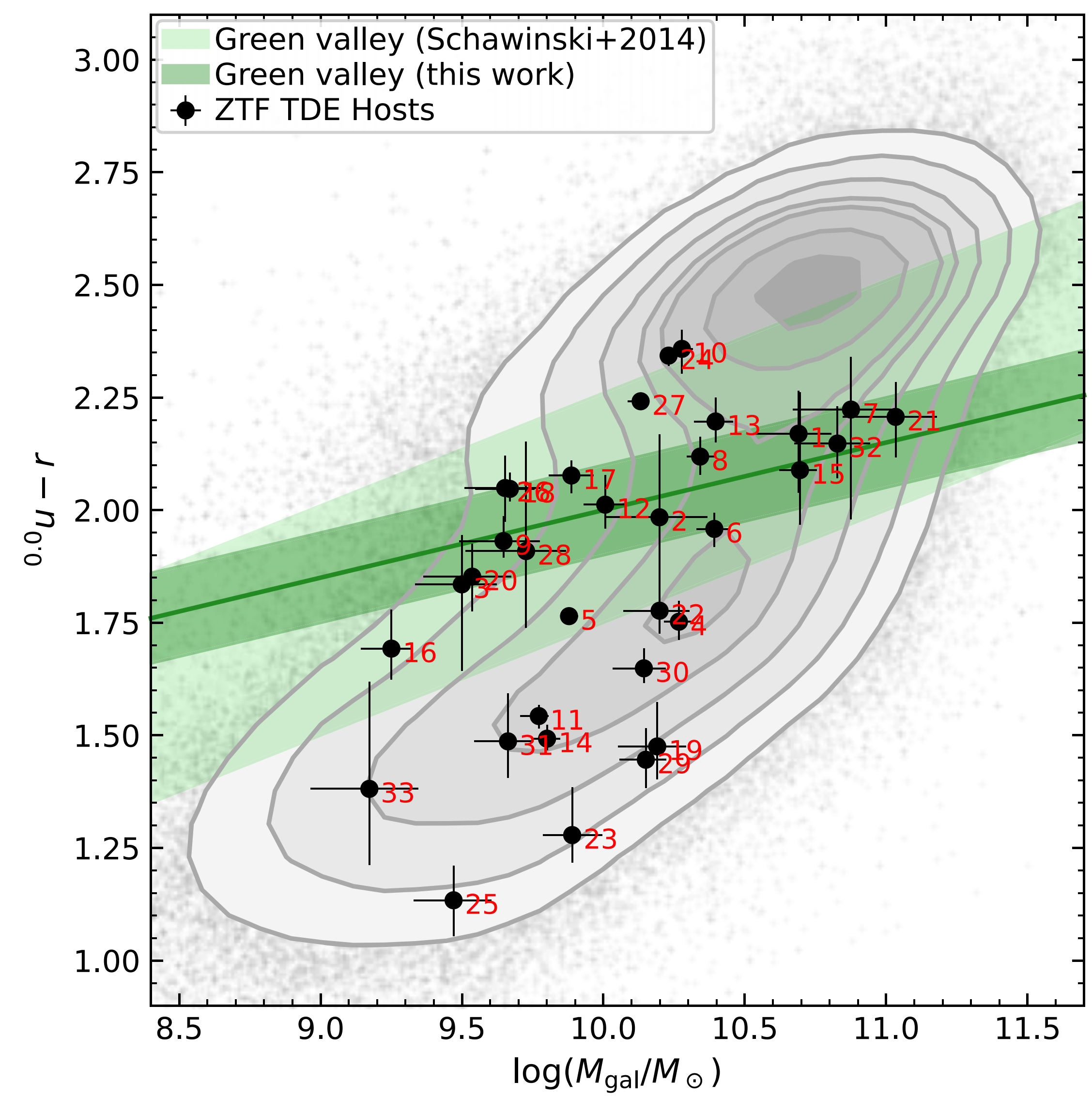
✓ E+A: ~0.1% in SDSS sample=>x30-200 over-represented

Host: Green valley galaxy

Hammerstein+23



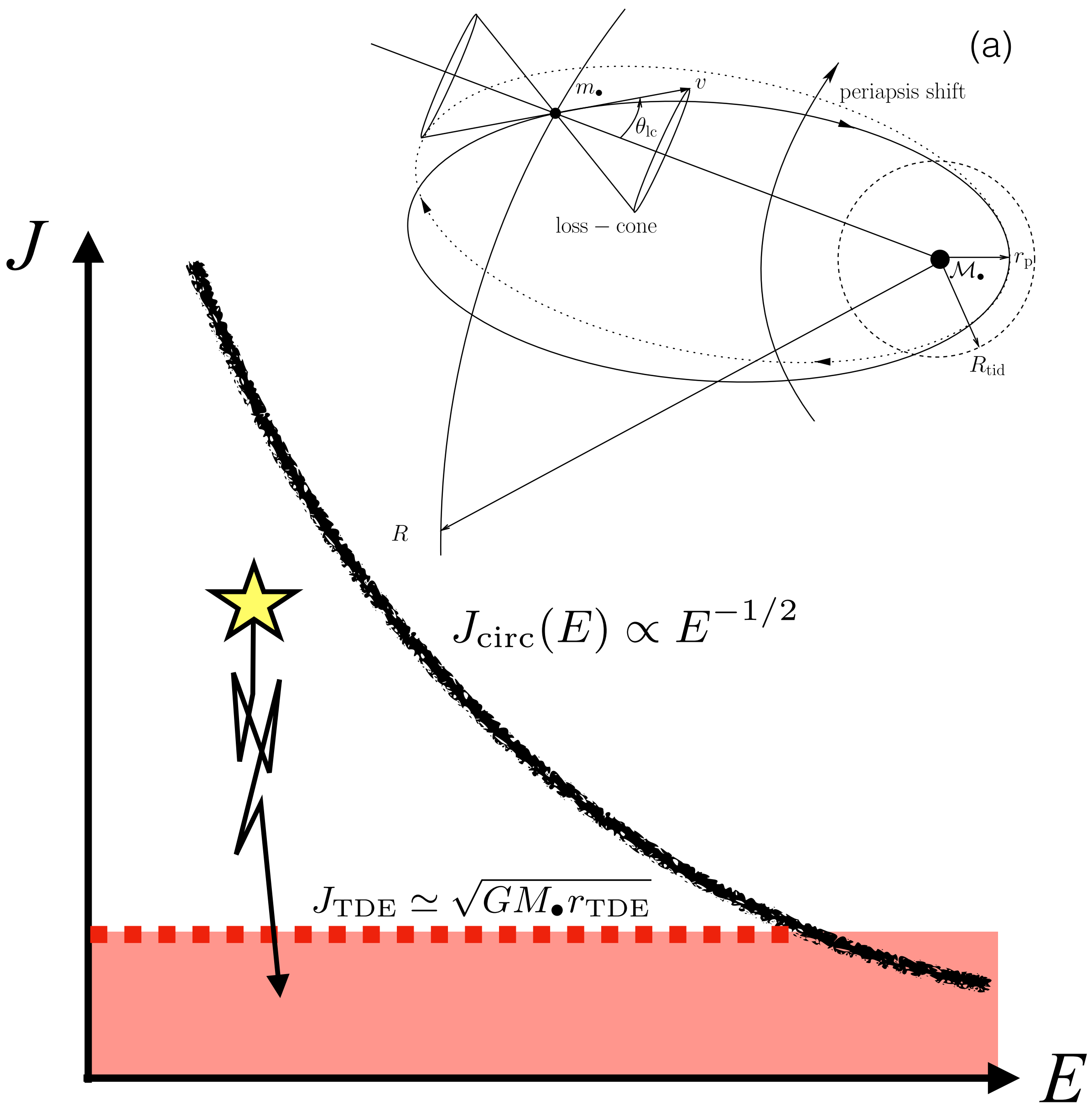
Yao+23



✓ Optical TDEs prefer <u>green-valley galaxy</u>

: Transition from blue star forming to passive red galaxies

Event rate: Theory



Note: E>0 is bound orbit

$$T_{\rm rel} \sim \frac{P_{\rm orb}}{N_\star}\left(\frac{M_\bullet}{M_\star}\right)^2 \sim 10^{10}{\rm yr} M_{\bullet,6}^{2}\sigma_{\rm h,7}^{-3}$$

$$\sigma_{\rm h}^2 \sim \frac{GM_\bullet}{r_{\rm inf}}$$

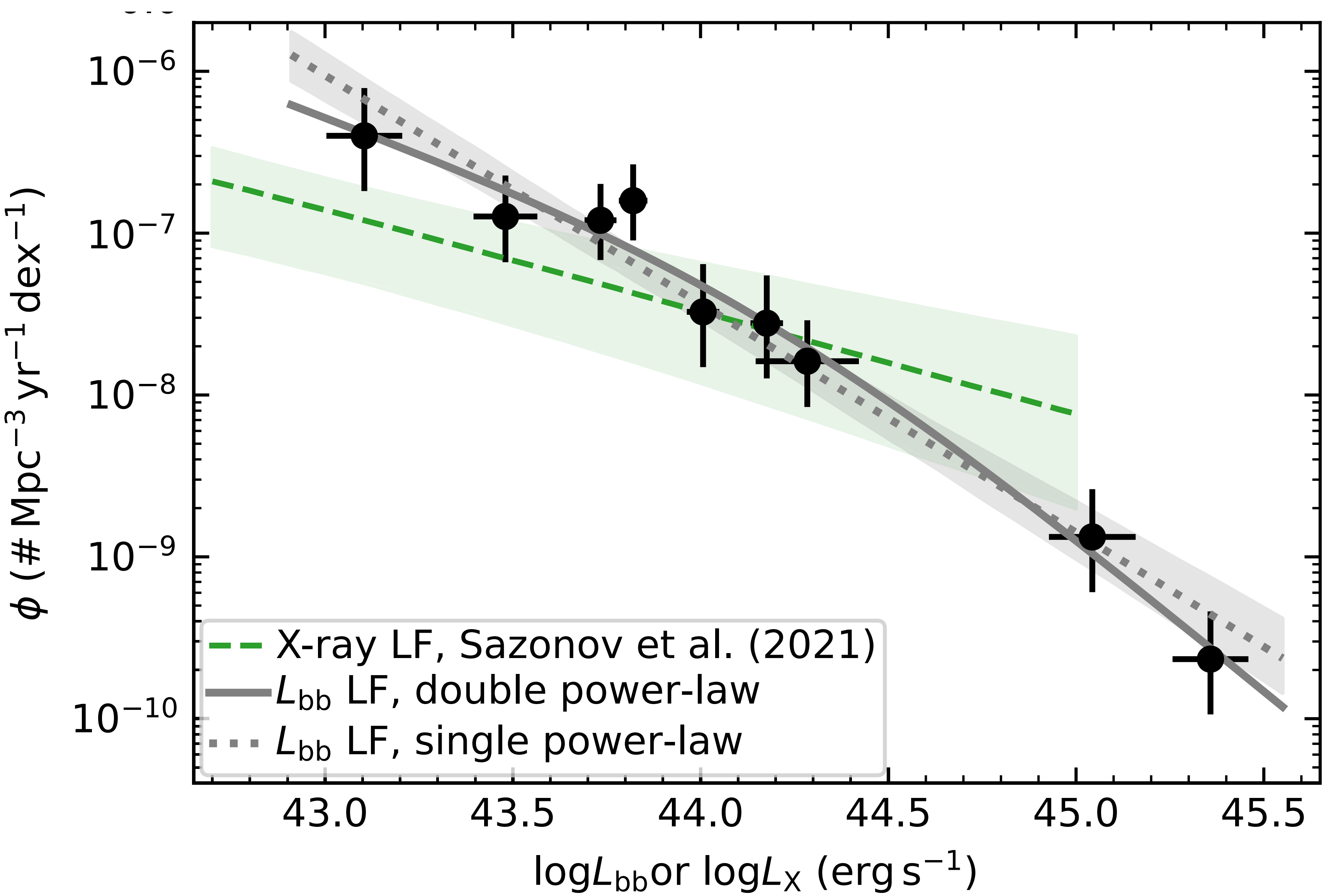
$$\mathcal{R}_{\rm TDE} \sim \frac{N_\star}{T_{\rm rel}}$$

$$\sim \frac{\sigma_{\rm h}^3}{GM_\bullet} \sim 10^{-4}{\rm yr}^{-1} M_{\bullet,6}^{-0.25}$$

$$M_\bullet \propto \sigma_{\rm h}^4$$

Linial&Sari23
But see e.g., Magorrian&Tremaine99,
Wang&Merritt04,Stone&Metzger16…

Event rate: Observation

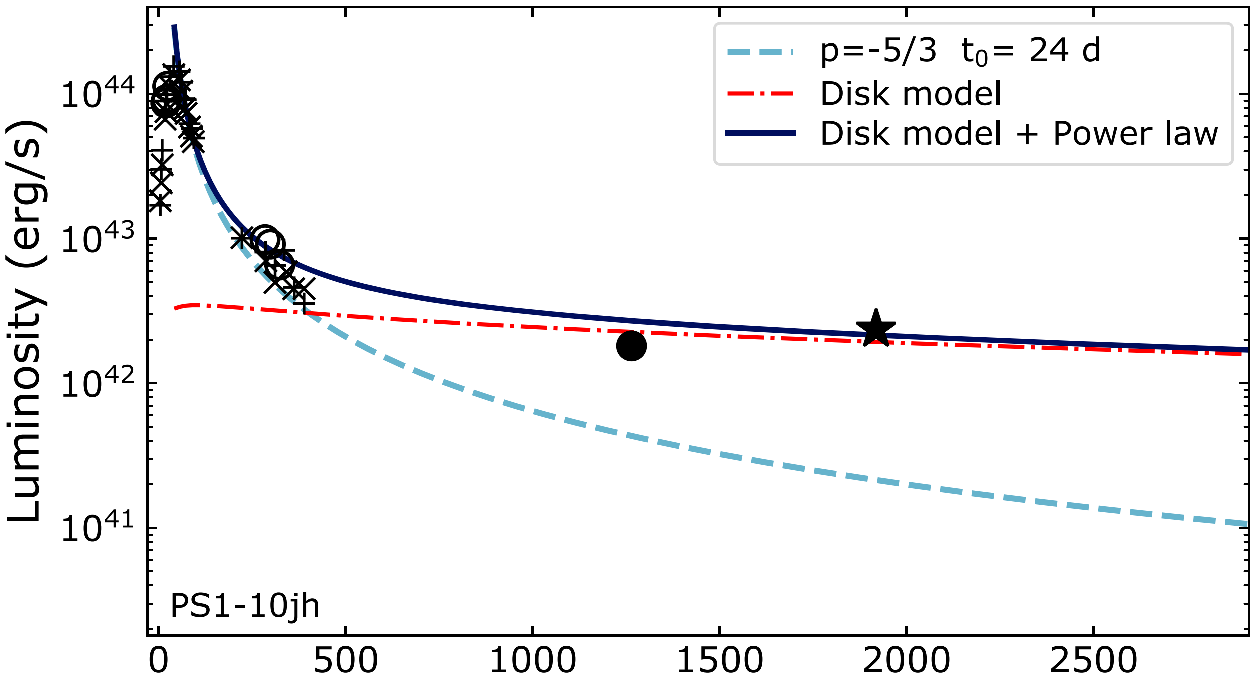


Yao+23

✓ Consistent between optical & X-ray TDEs

✓ Rate ~ 1e-7/Mpc3/yr ~ 0.001x(SN rate)~**1e-5**/galaxy/yr vanVelzen+19,Mummery+24

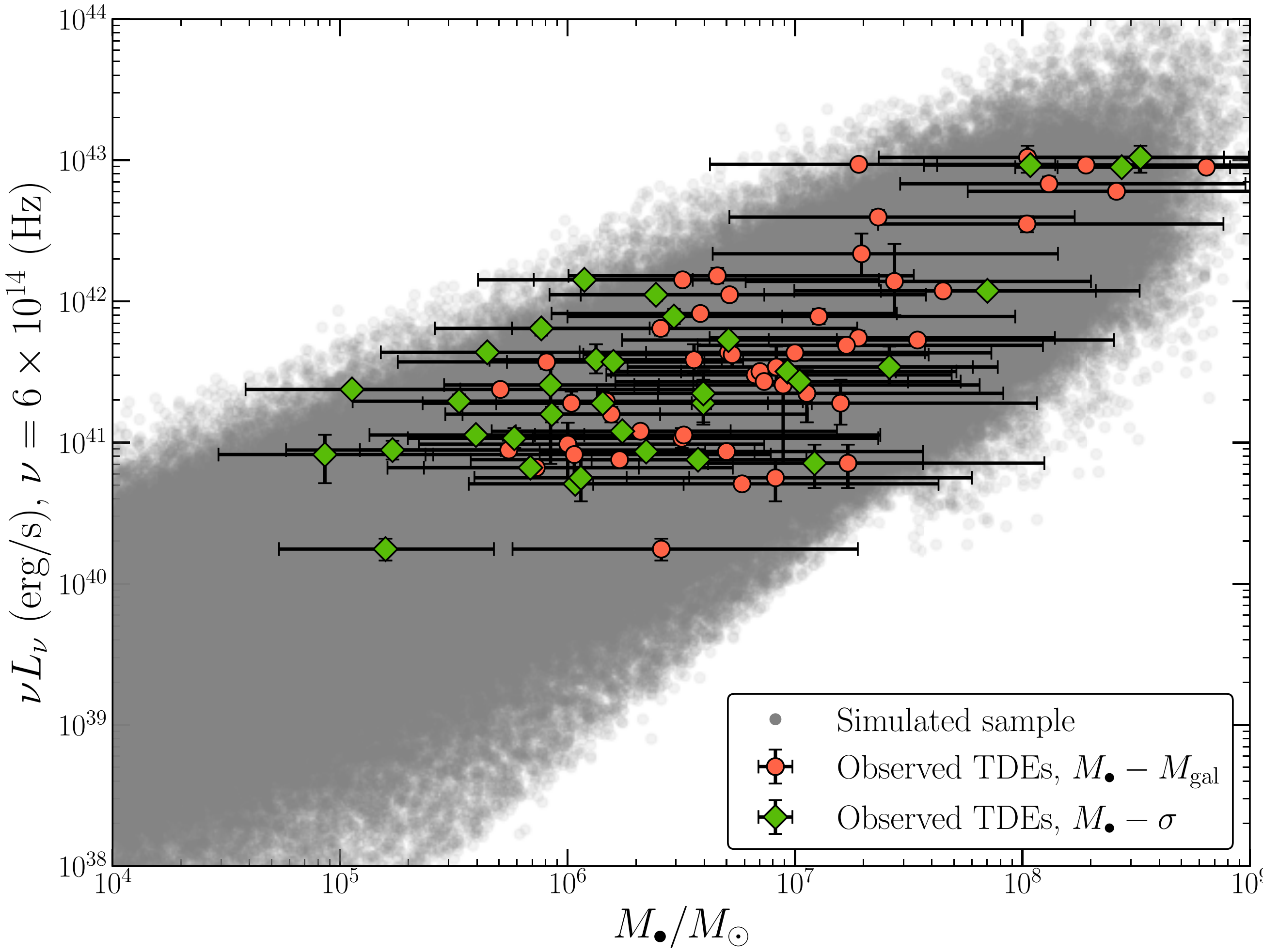
Late-time plateau: New indicator?

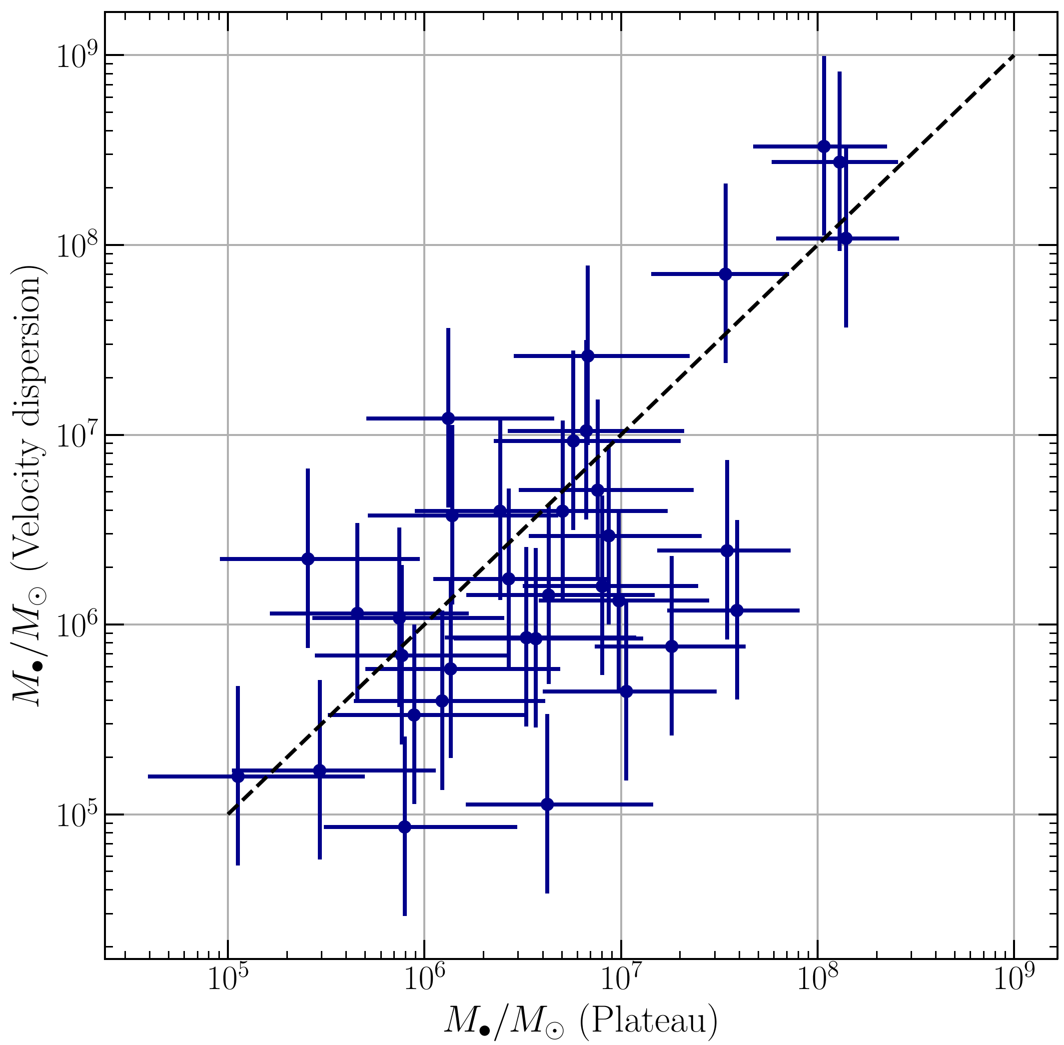


✓ TDE light curve settles into plateau phase at late time
✓ Plateau is ubiquitous
✓ Disk model predicts relation: $L_{pl} \propto M_{BH}^{2/3}$

Mummery+24

Late-time plateau: New indicator?





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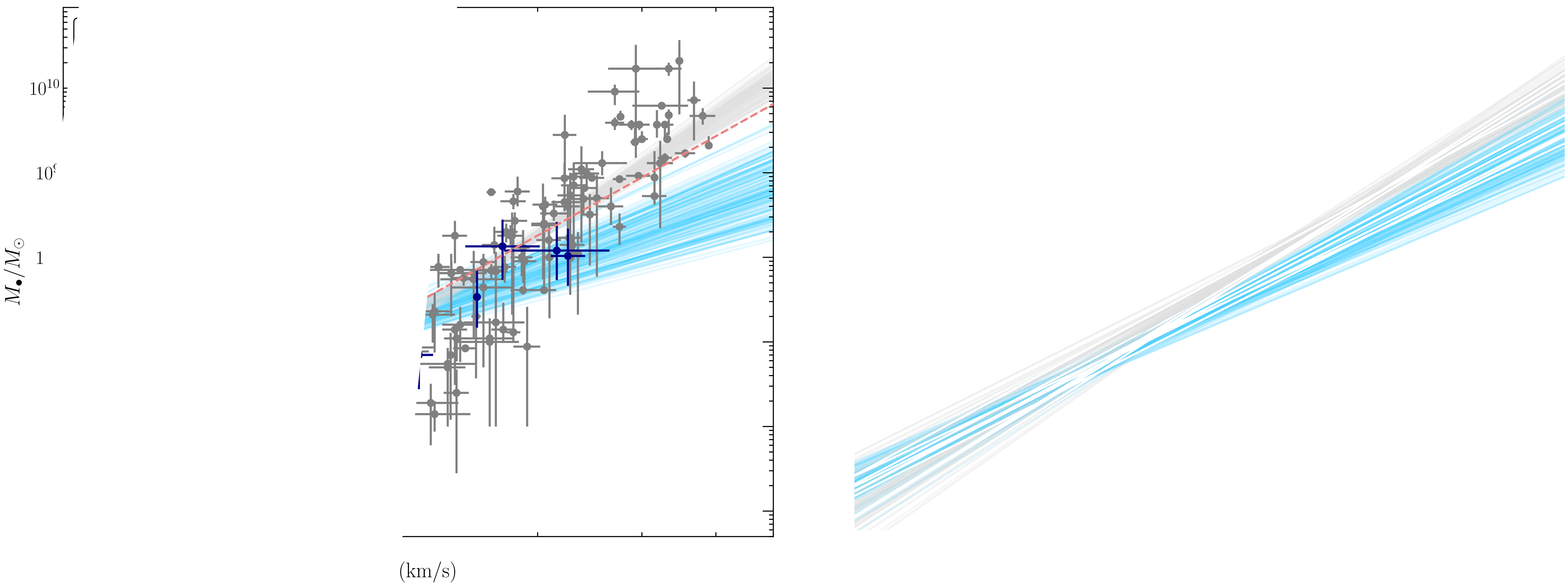
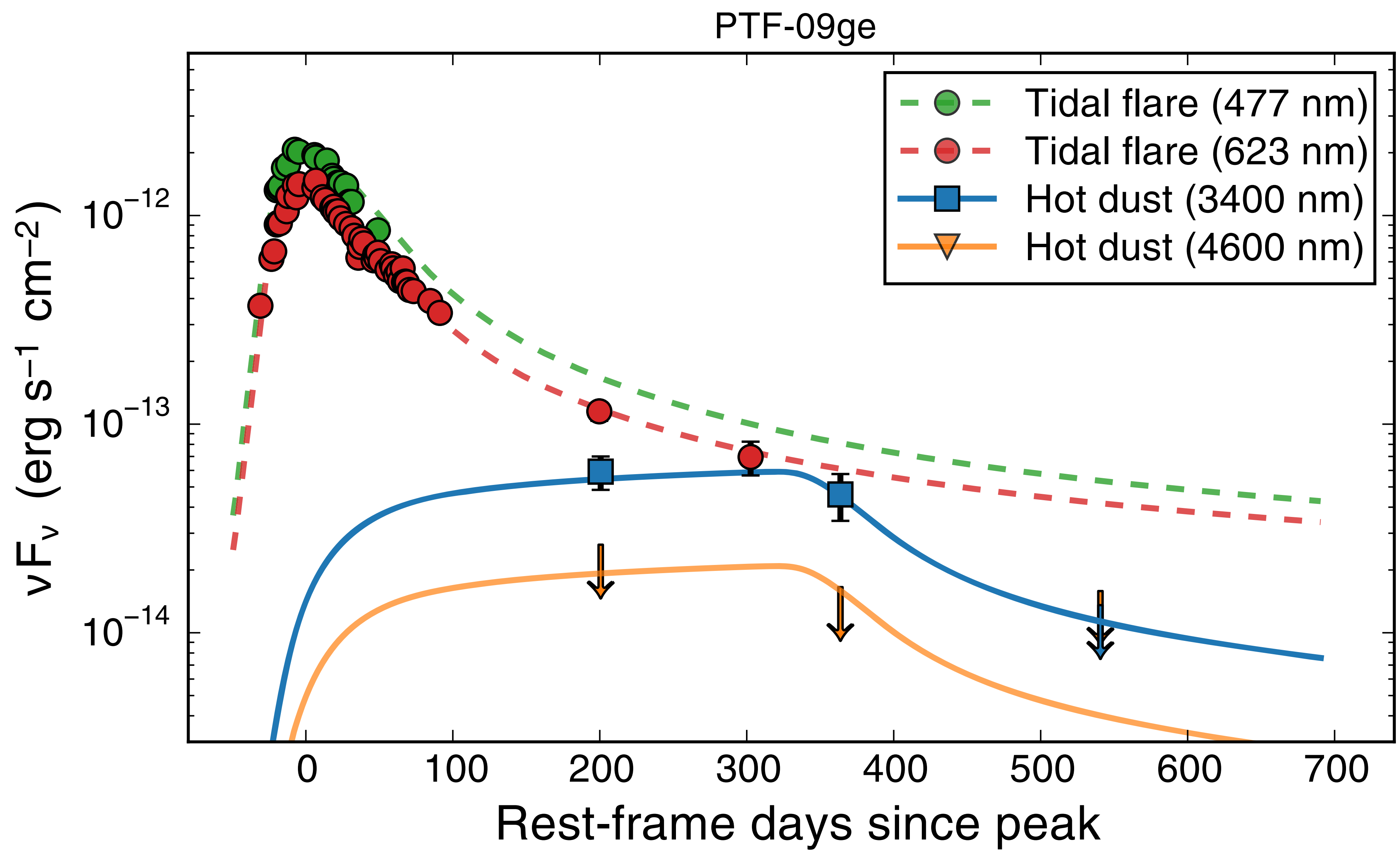
Mummery+24



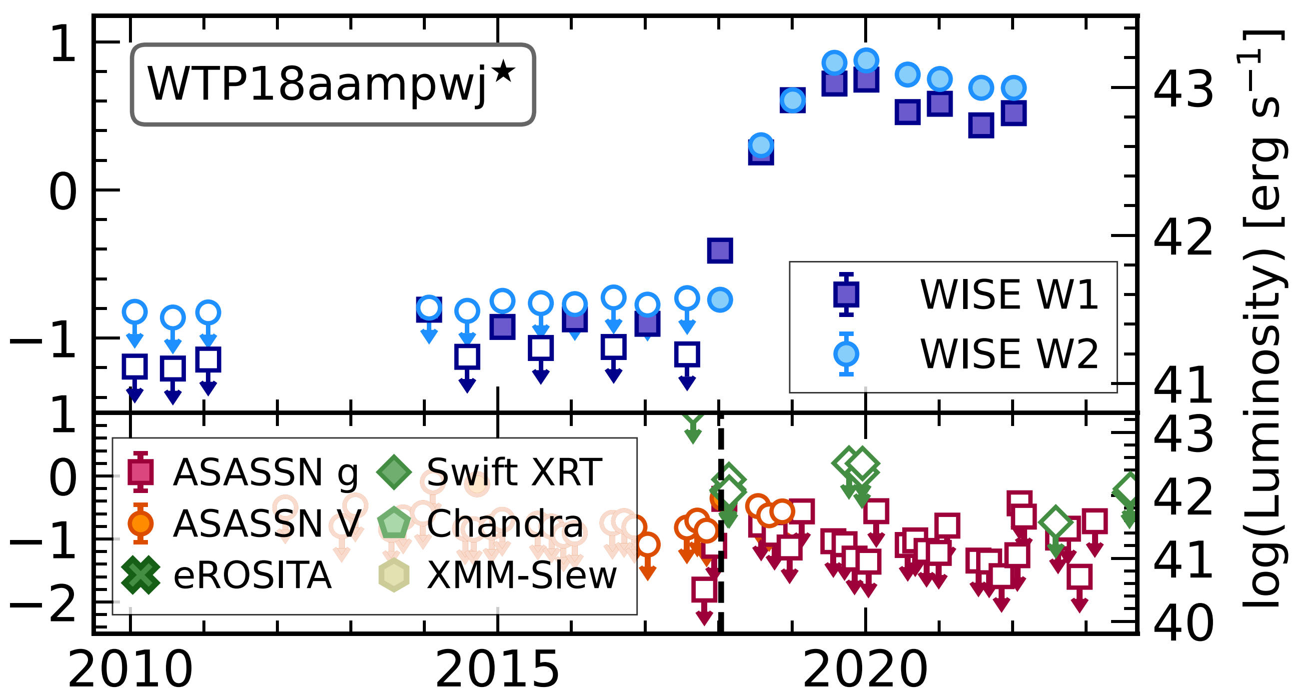
✓ TDE light curve settles into plateau phase at late time
✓ Plateau is ubiquitous
✓ Disk model predicts relation: $L_{pl} \propto M_{BH}^{2/3}$

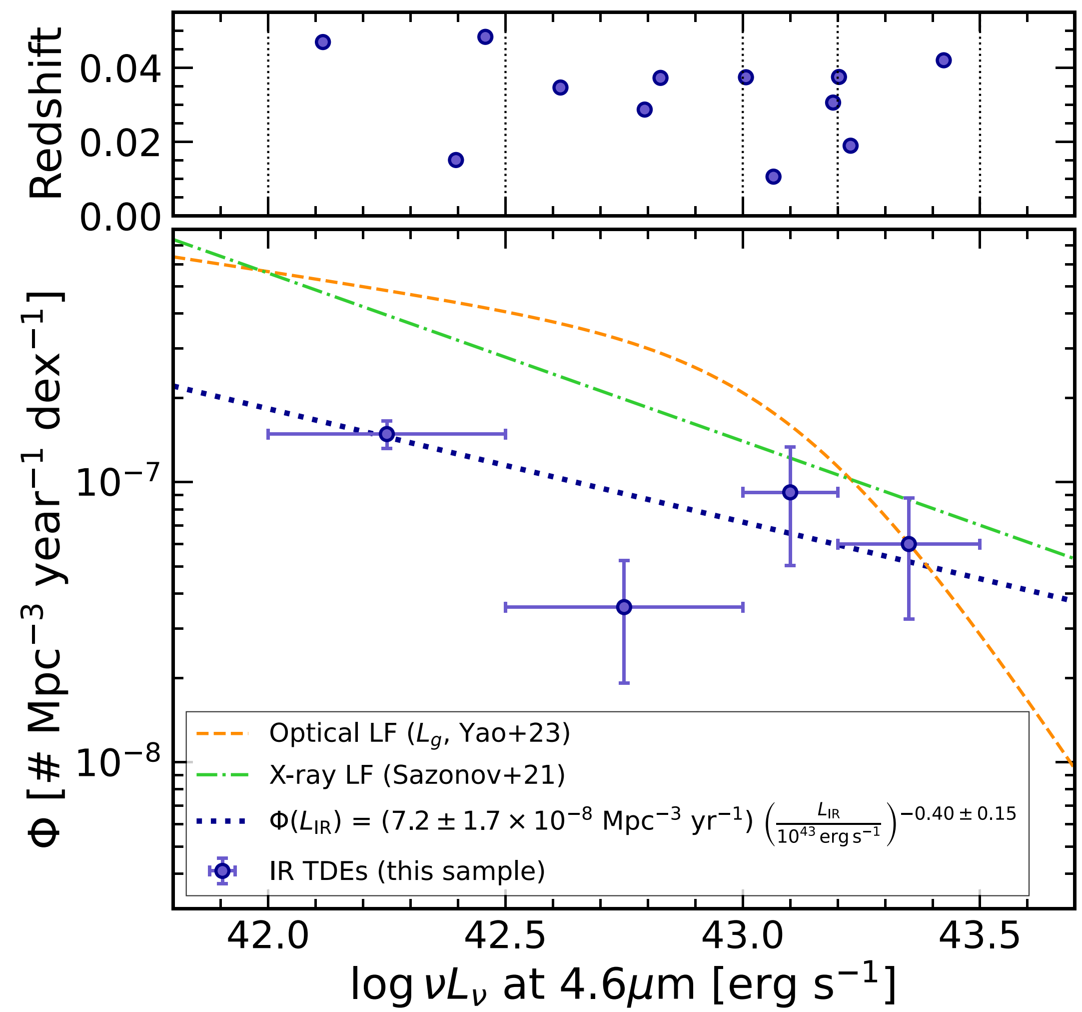
Infrared (IR) echo



✓ Opt.&UV absorbed and re-emitted in IR by dust
✓ L_{IR}/L_{opt}~0.01: Covering fraction of dust shell

IR Flare: Dust-obscured TDEs

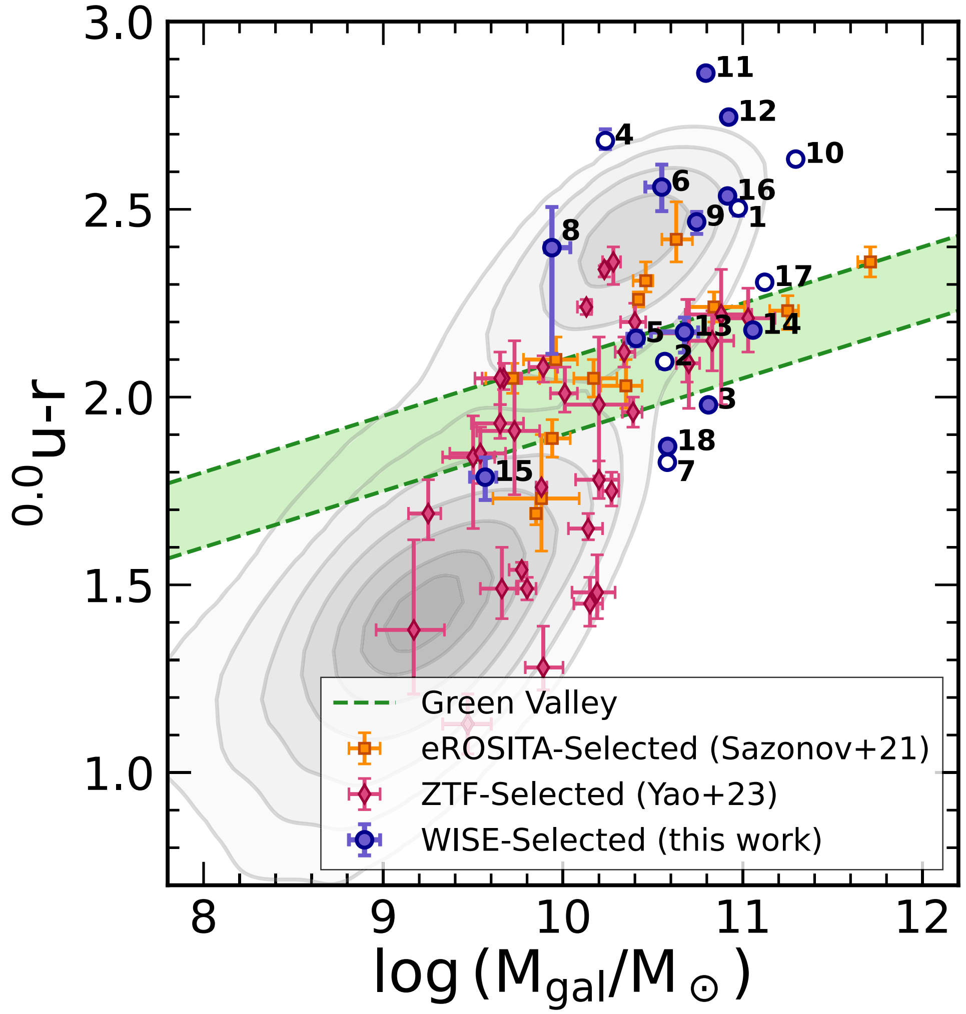


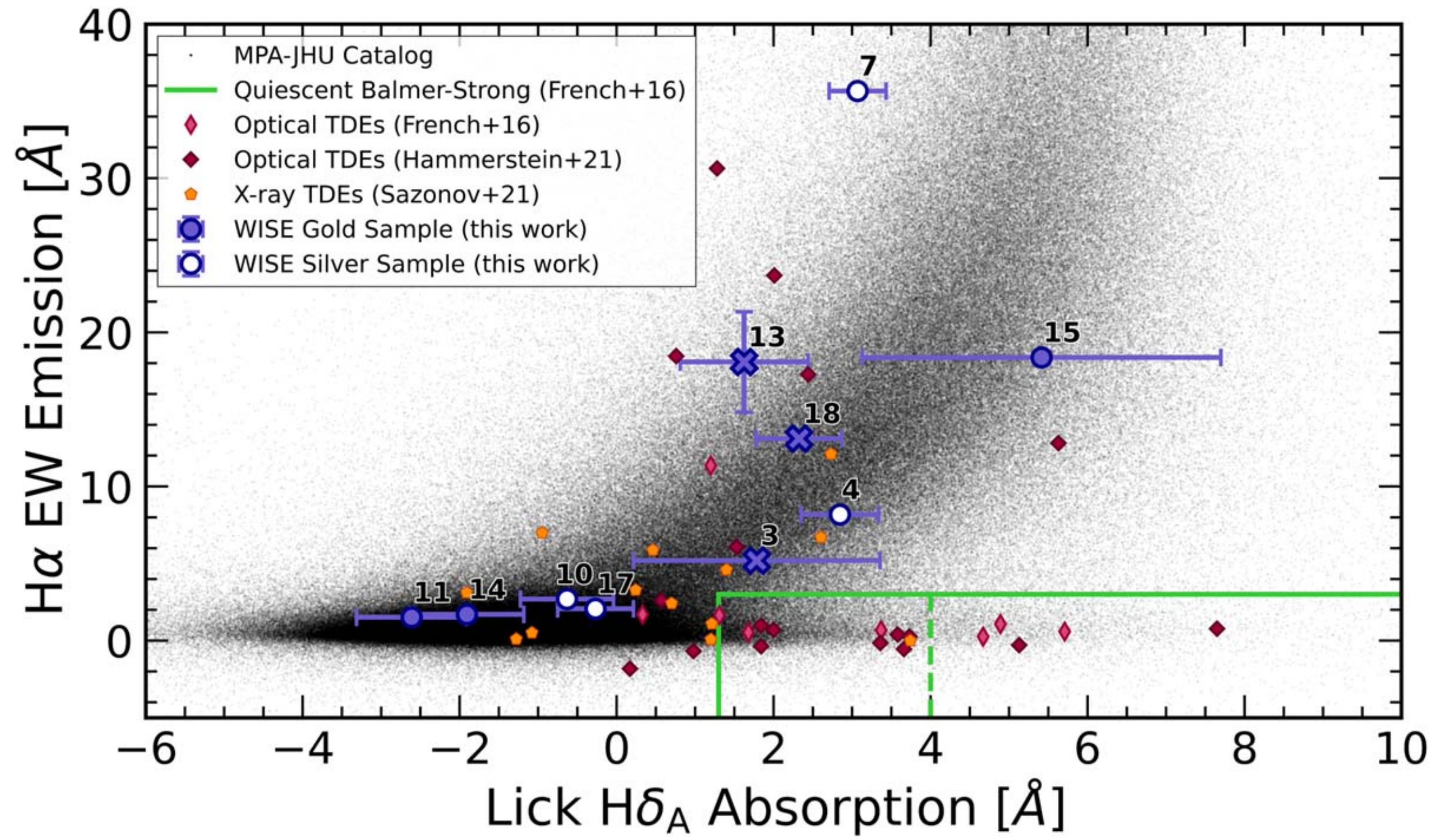


- ✓ 18 Flares within 200Mpc from WISE survey
- ✓ L~$10^{42\text{-}43}$erg/s => Erad~$10^{50\text{-}52}$erg
- ✓ R~0.1pc, Covering fraction~1
- ✓ Rate:~1e-7/Mpc3/yr~Opt.&X-ray => Opt.+X+IR ~ 1.e-6/Mpc3/yr

Masterson+24

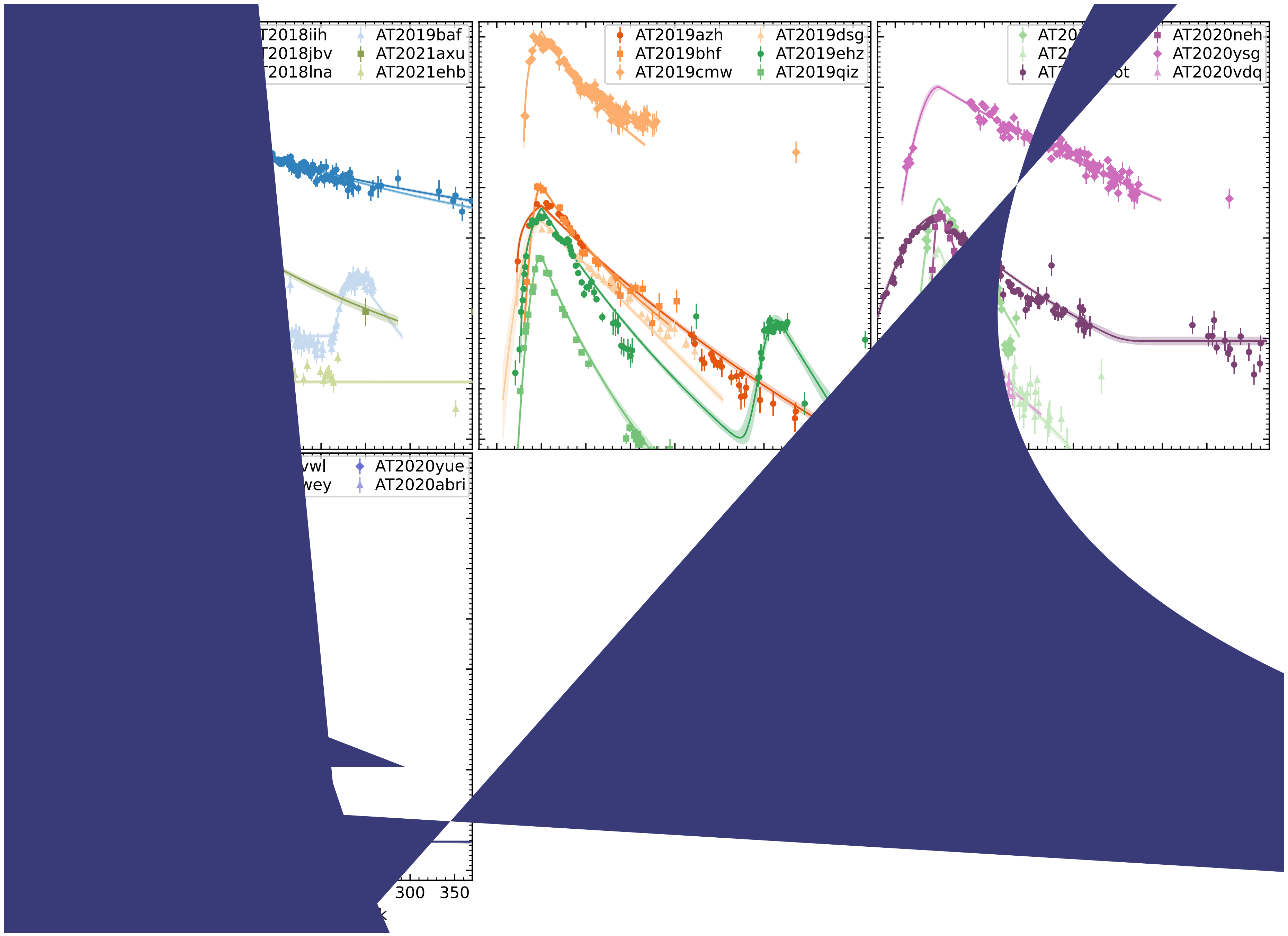
IR Flare: Host galaxy





✓ Not in green valley & Not E+A galaxy
✓ Most hosts are spiral (star-forming) galaxy

Diversity in optical light curve

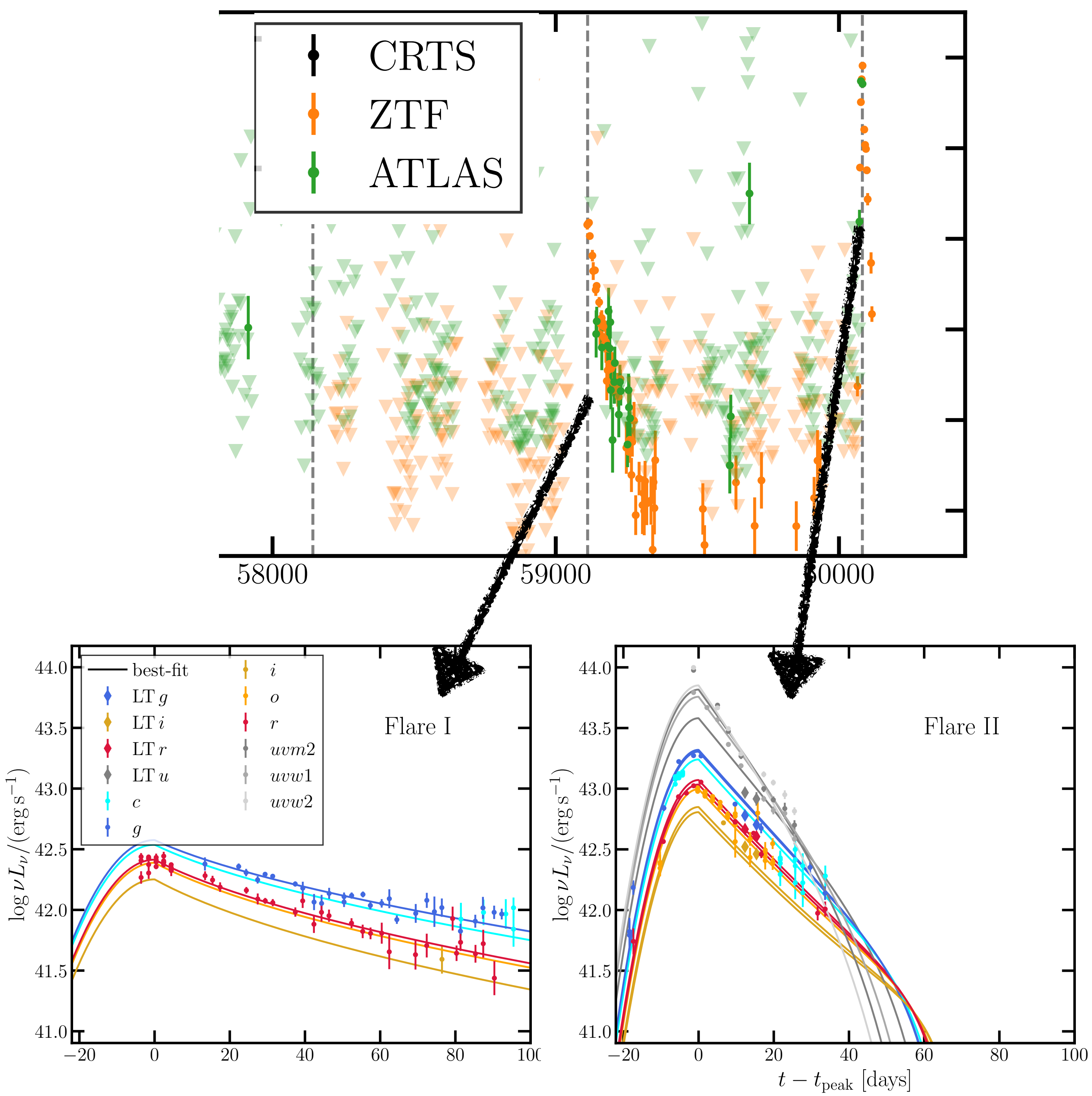


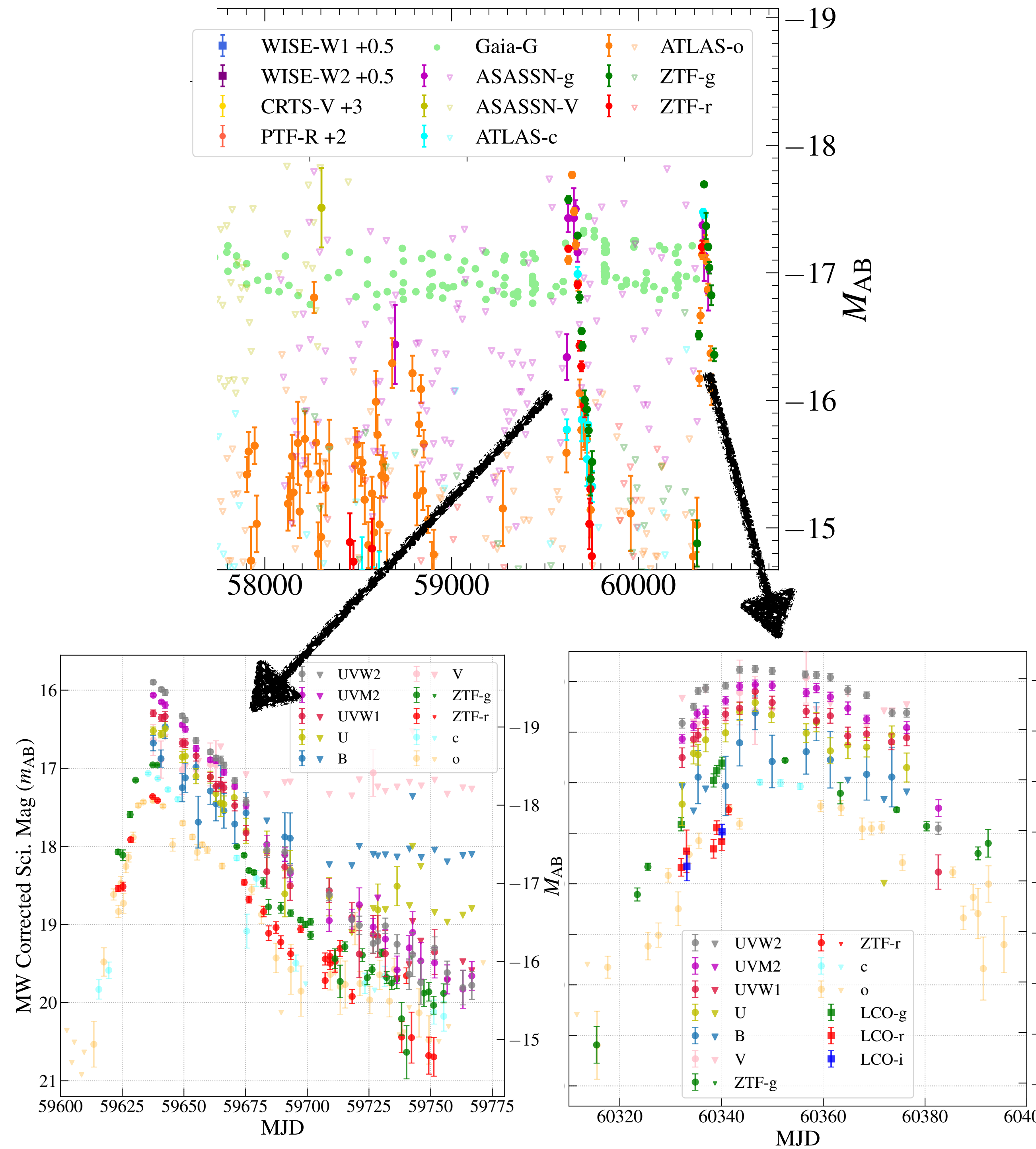
Somalwar+23,Lin+24,…

Multiple optical flares in galactic center

AT2020vdq

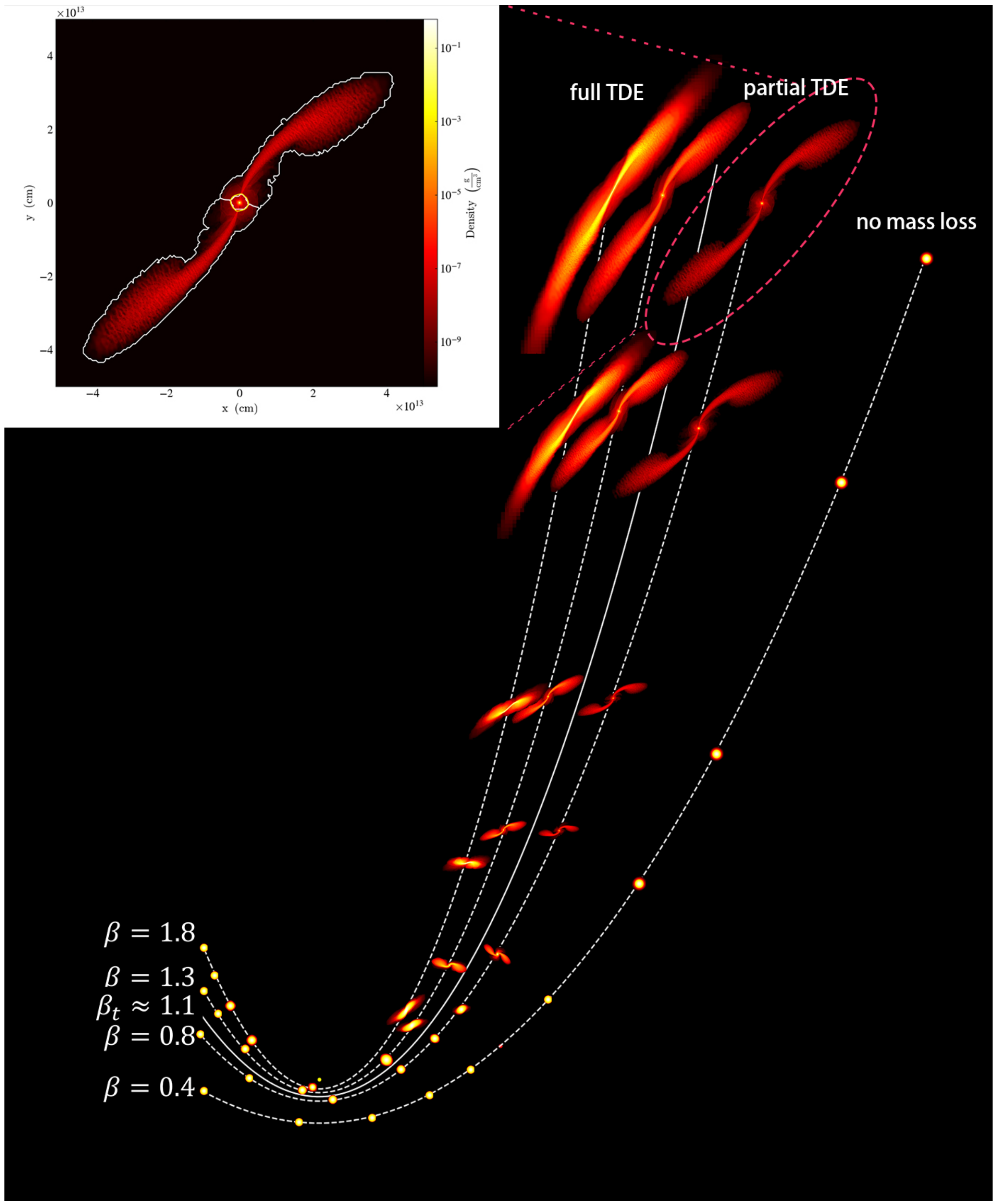
AT2022dbl

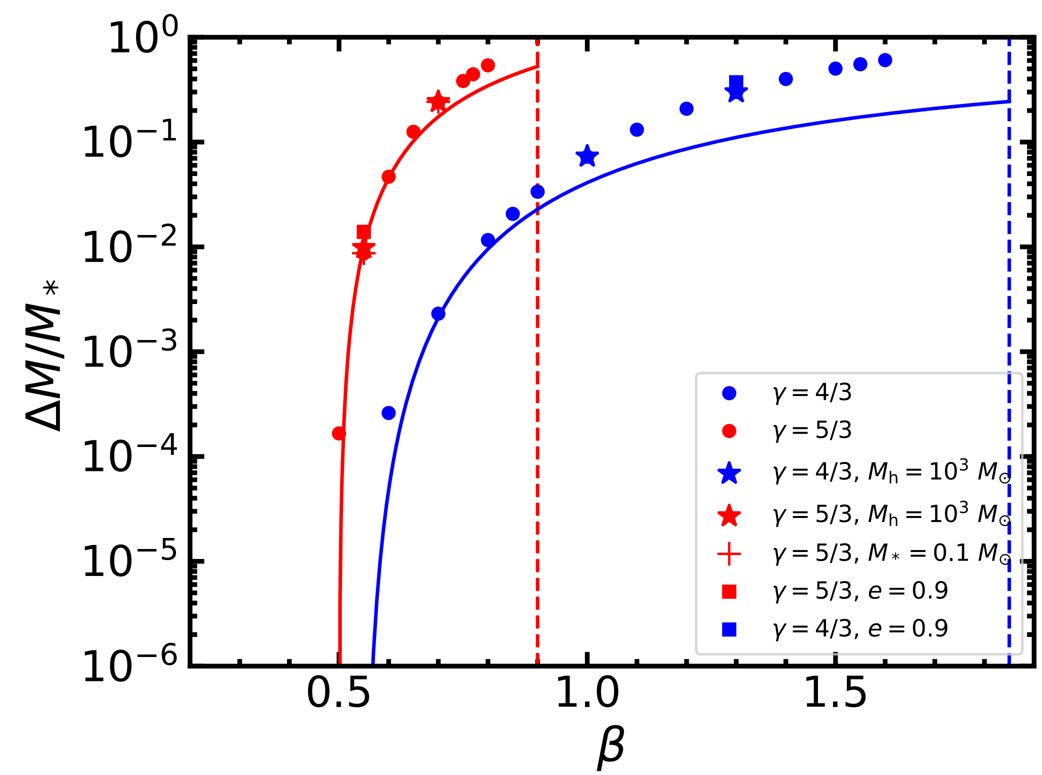




Chen+24

Multiple flares = Partial TDEs?

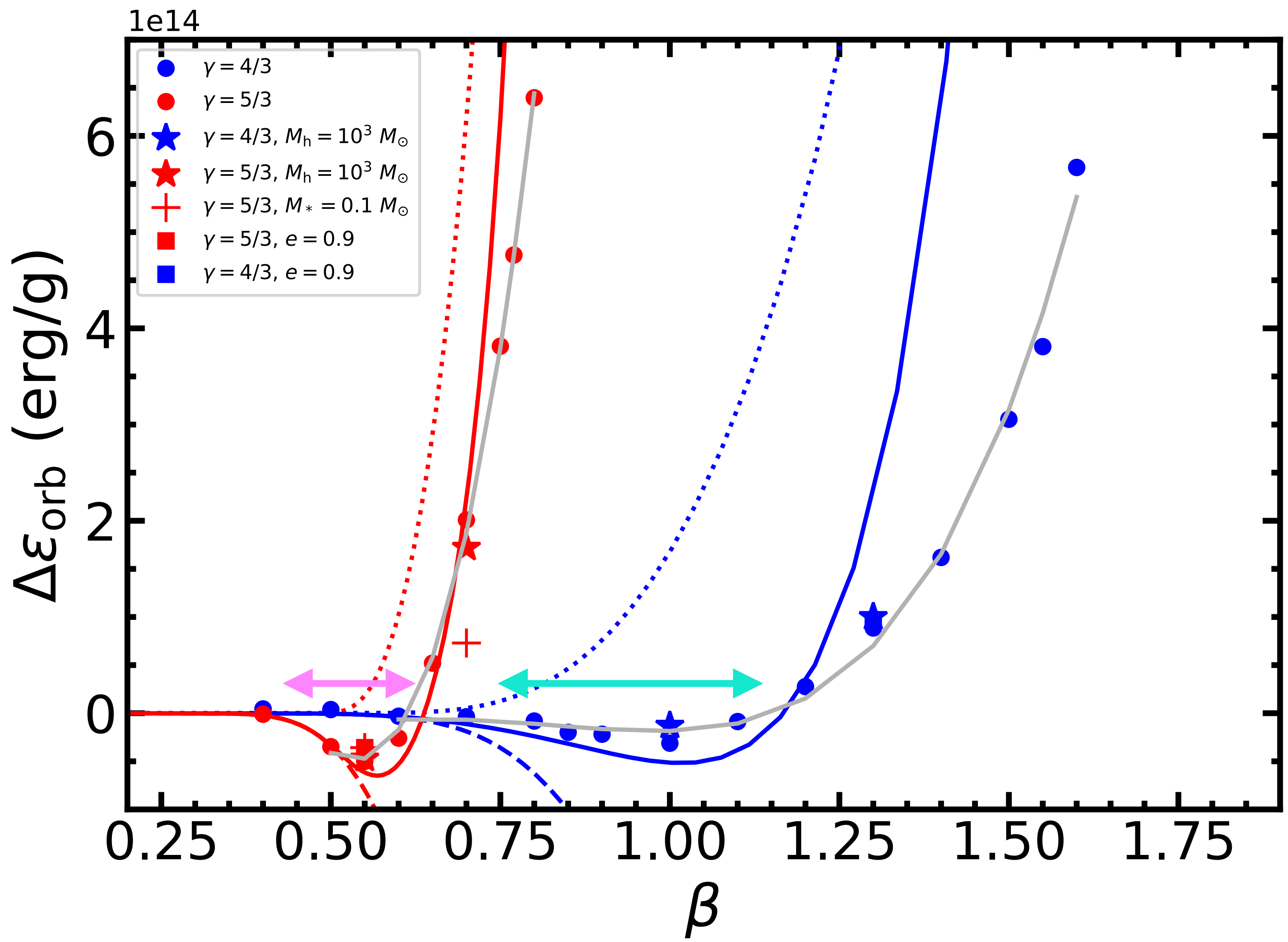




$$\beta \equiv \frac{R_T}{R_p}$$

Chen+24,Broggi+24

Multiple flares = Partial TDEs?



<u>Effects of pTDE</u>

1. (Asymmetric) mass loss

$$\Delta\varepsilon \sim \frac{GM_\star}{R_\star}\left(\frac{\Delta m}{M_\star}\right)\beta^3$$

:Unbound

2. Stellar oscillation

$$\Delta\varepsilon \sim -\frac{GM_\star}{R_\star}\beta^6$$

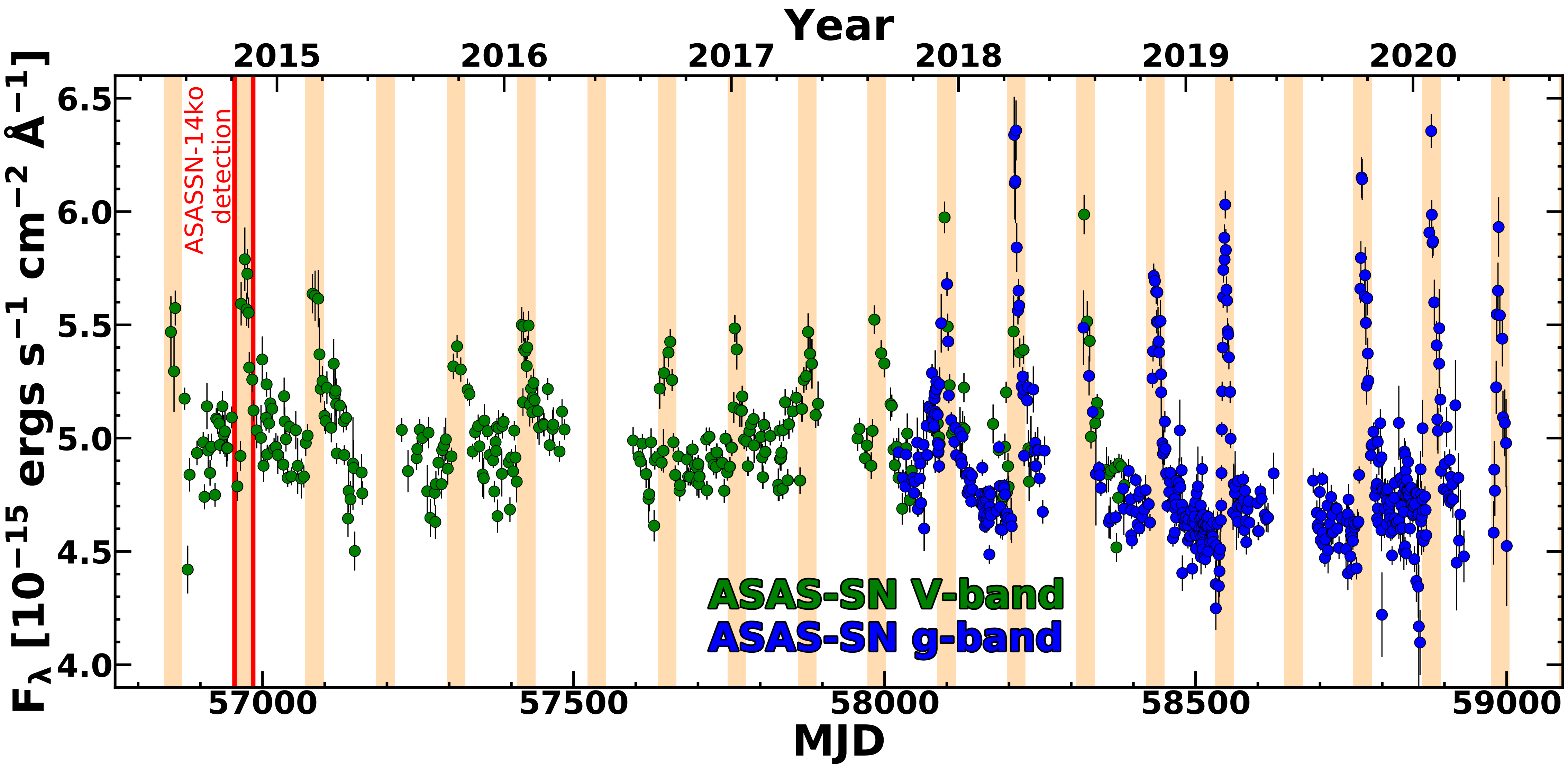
:Bound

✓ To produce 2nd flare, Δε<0 (Bound remnant).
✓ => Narrow range of β is allowed (Mass loss v.s. Oscillation).
✓ => E~MΔε~1e+47erg <=> P~**1e+7 day**$(E/10^{47}\mathrm{erg})^{-3/2}$

Extremely difficult to have P~100-1000days remnant…

Payne+21

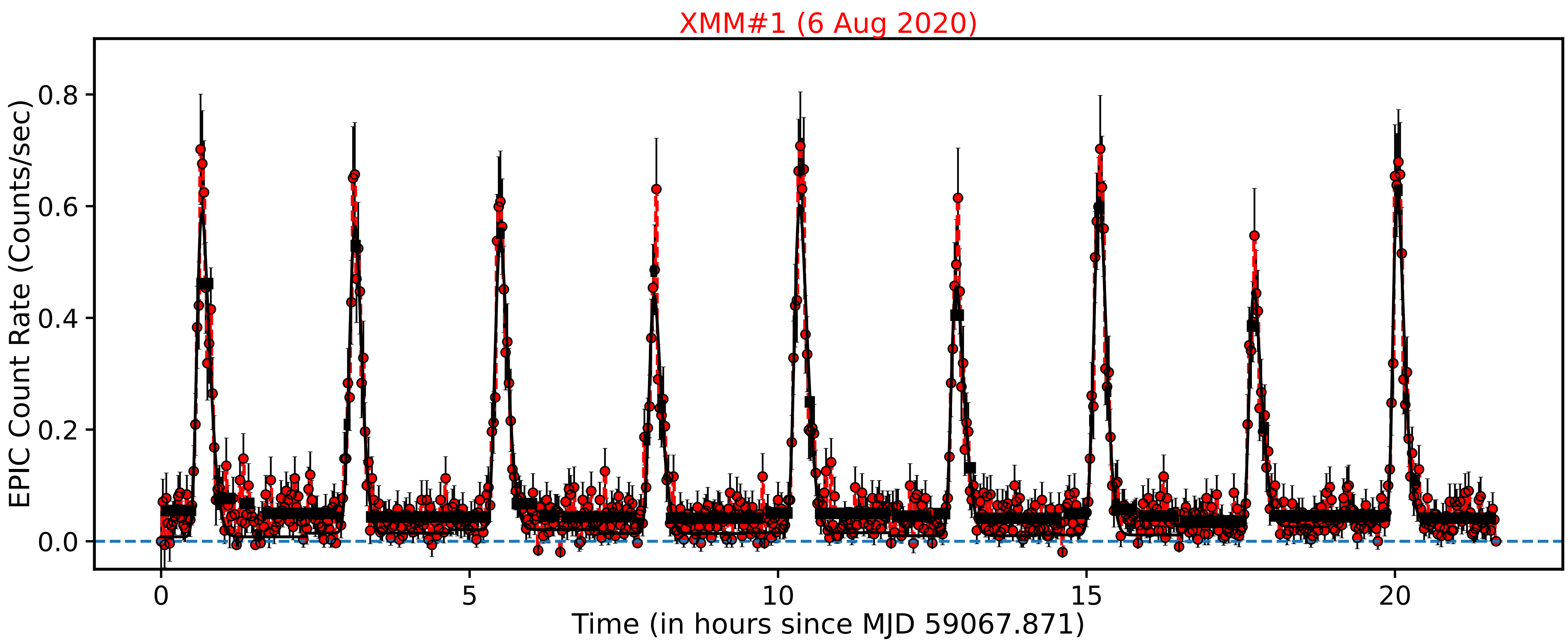
Multi-peak optical flare: ASASSN14ko



- ✓ More than 20 peaks with P-115days
- ✓ L~1e+44erg/s, t~10days => E~1e+50erg per flare
- ✓ Persistent emission L_X~1e+43erg/s => AGN disk?
- ✓ Disk instability? Star-disk interaction?

Multiple X-ray flare
:Quasi-Periodic Eruption (QPEs)

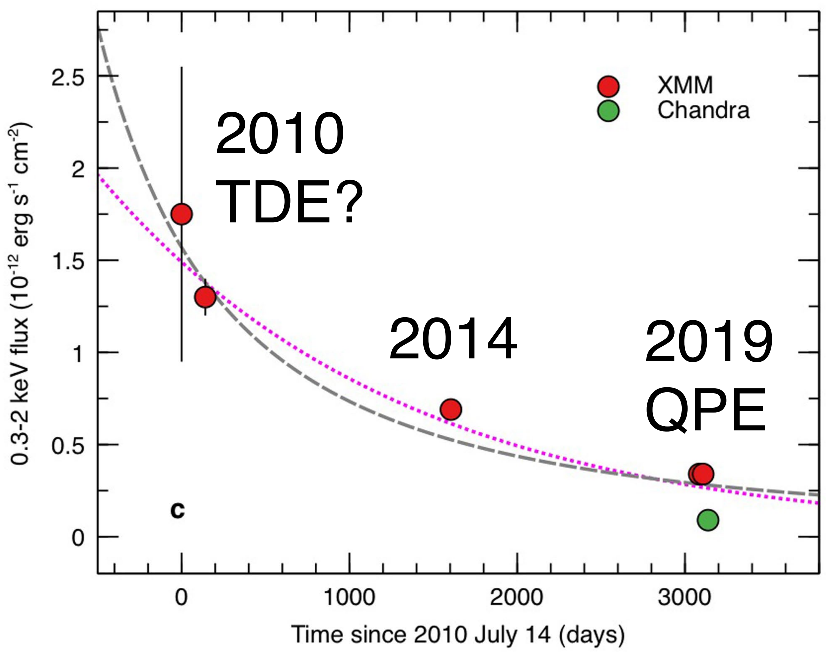
Pasham+24

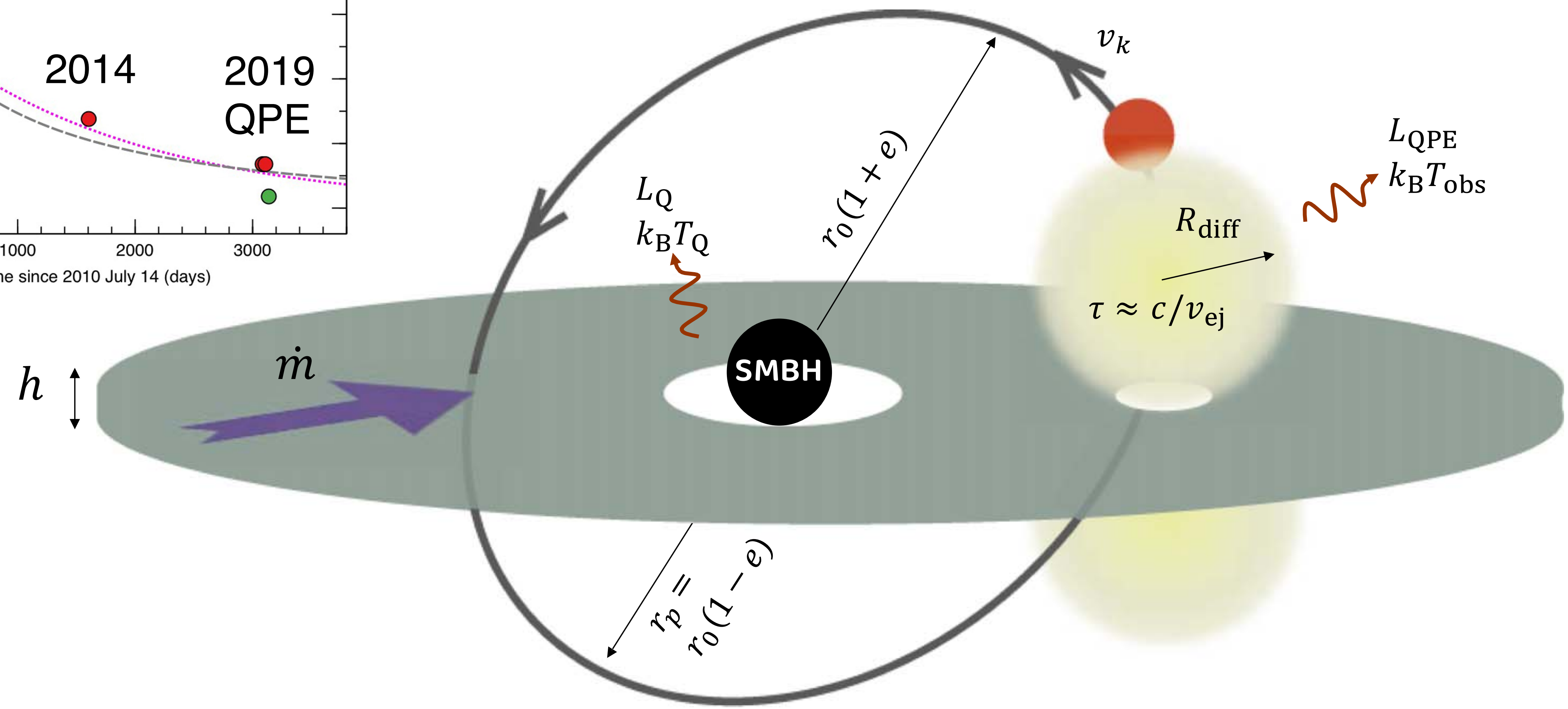


- ✓ ~5 systems
- ✓ Quasi-Periodic ~3-20 hrs, Duty cycle ~10%
- ✓ L~1e+42erg/s, kT~100eV
- ✓ Disk instability? **Star-disk interaction**?

QPE = TDE + EMRI?

GSN069 Miniutti+19



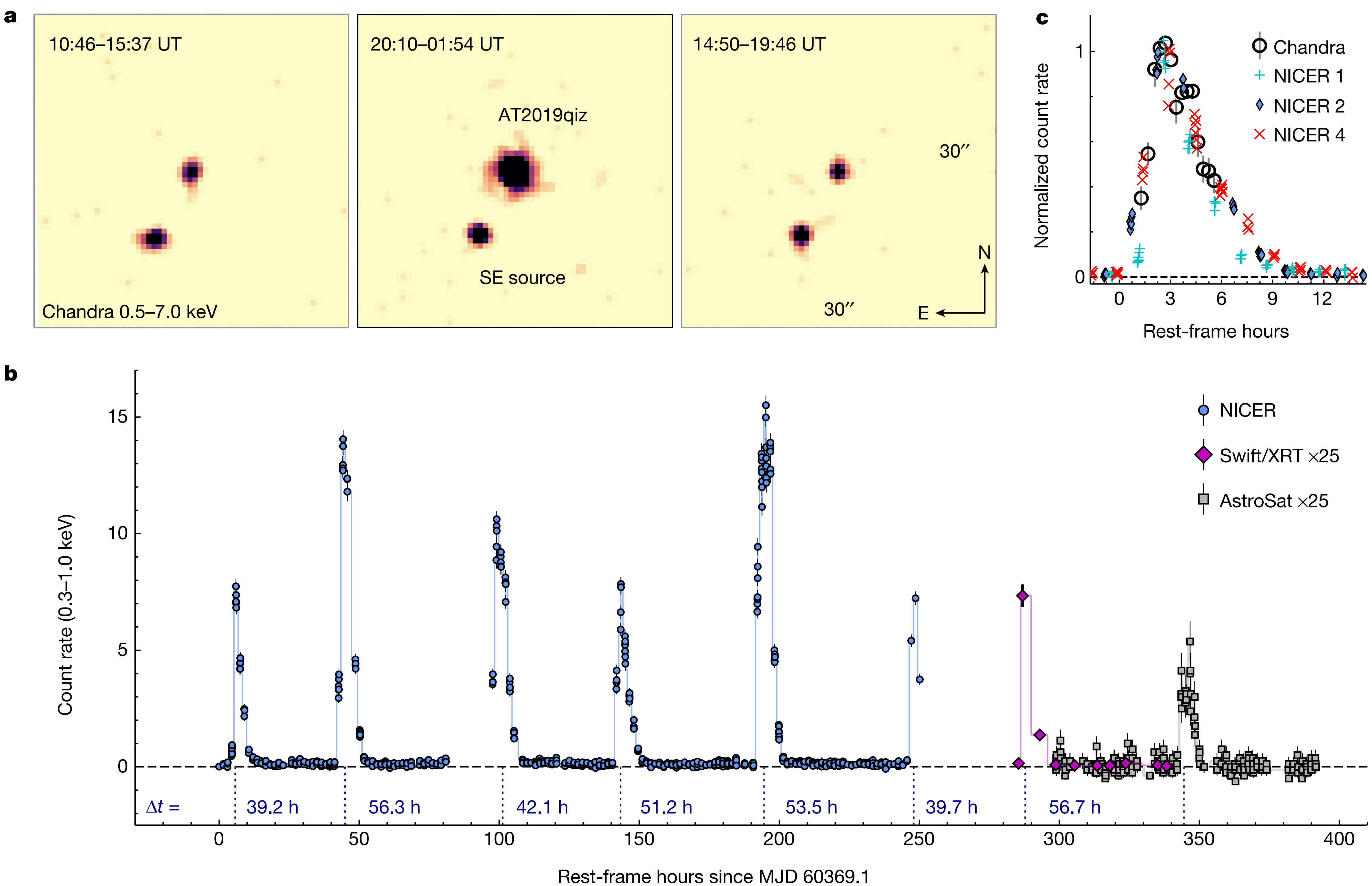


Linial&Metzger23

Nicholl+24

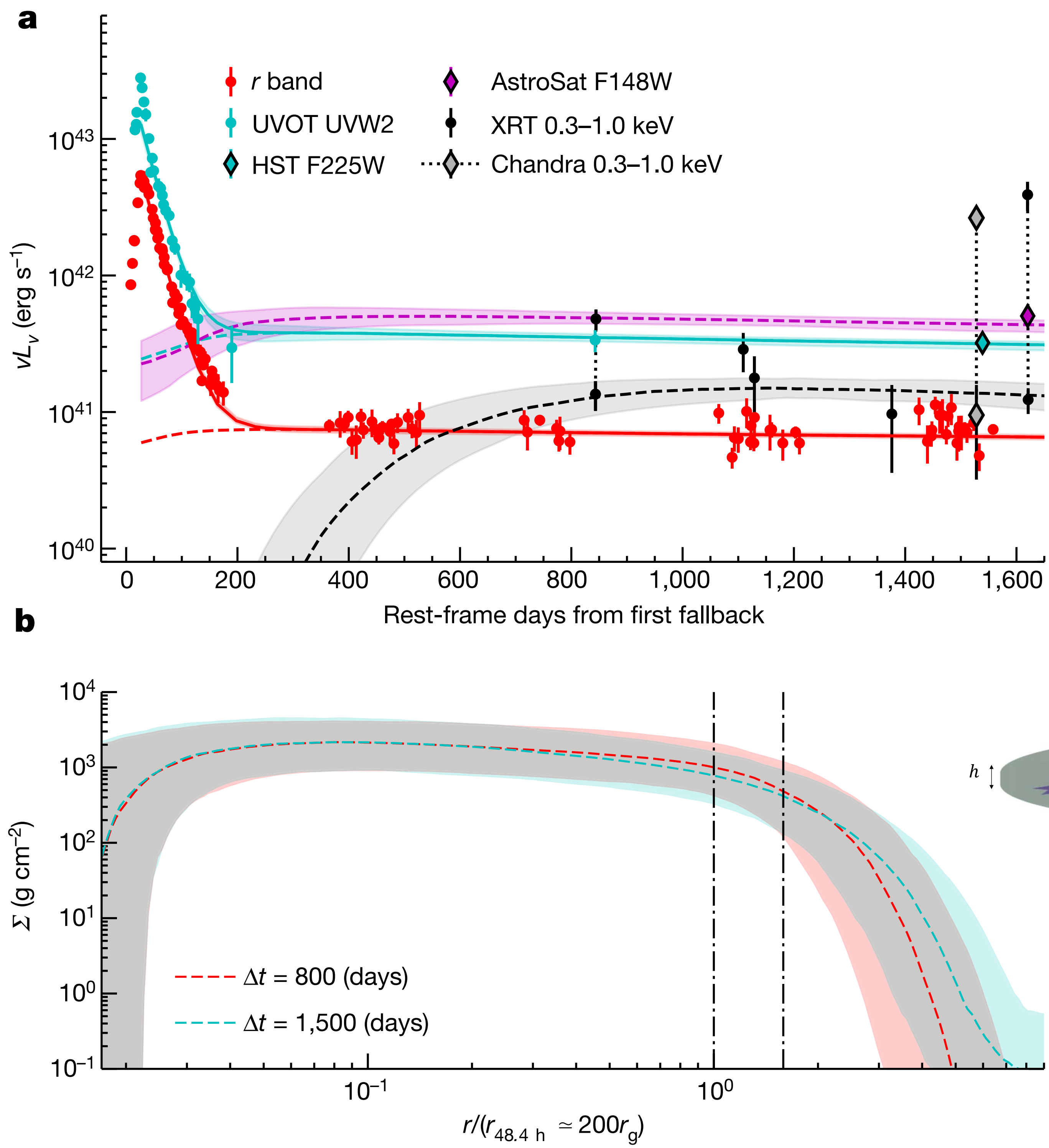
Discovery of QPE after optical TDE

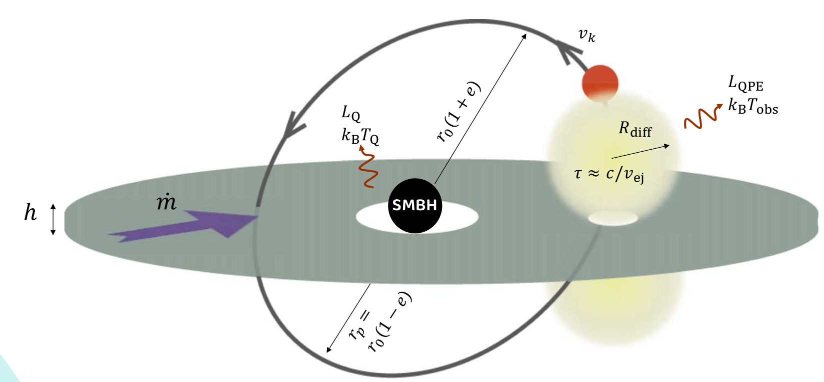
AT2019qiz: Nearby optical TDE (65Mpc)



Nicholl+24

Discovery of QPE after optical TDE



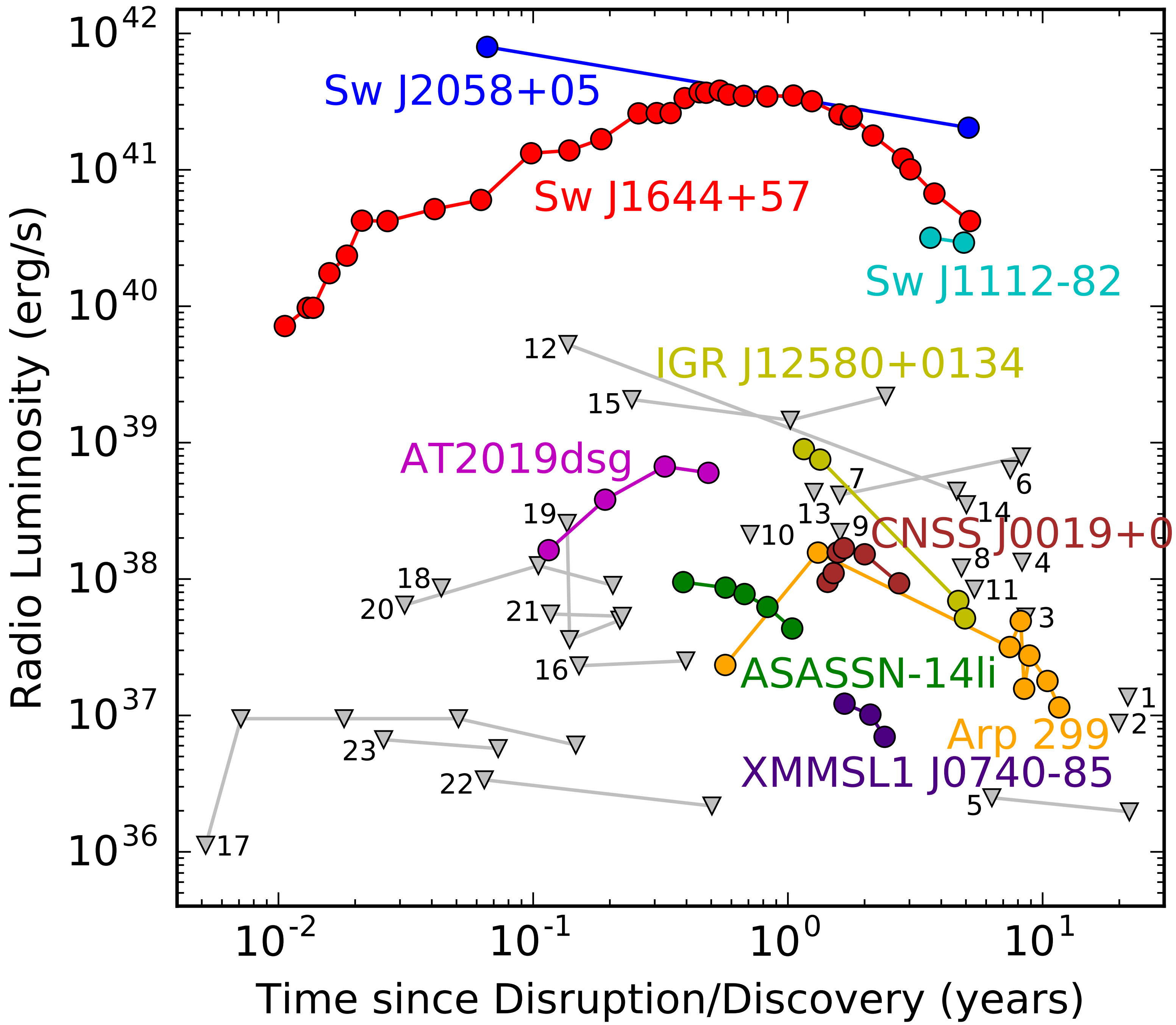


Outline

1. Basics
2. Optical&X-rays
3. Some recent topics
4. Radio

Radio emission in TDEs

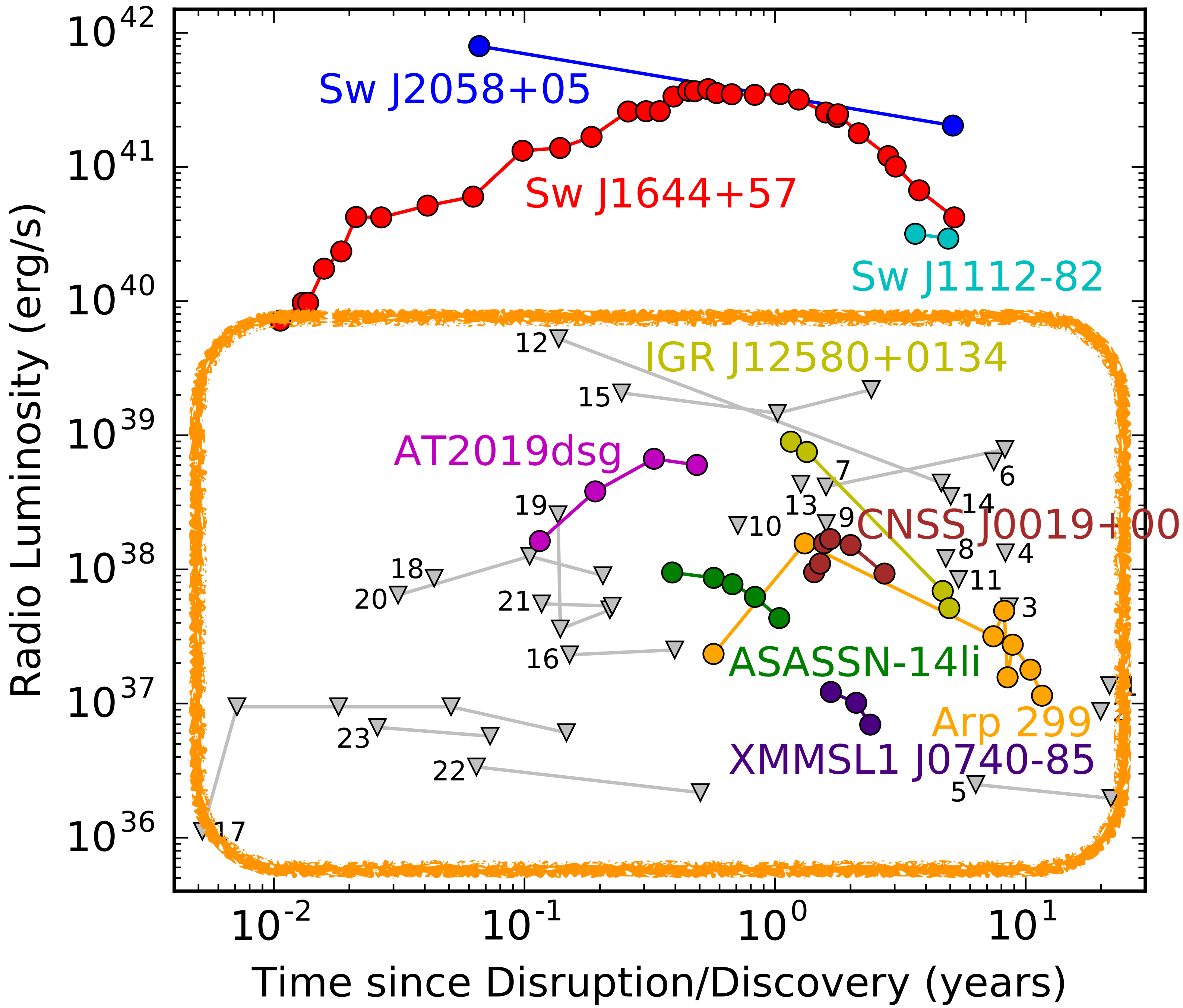
Alexander+20



Synchrotron emission => Probe of Outflow + Environment

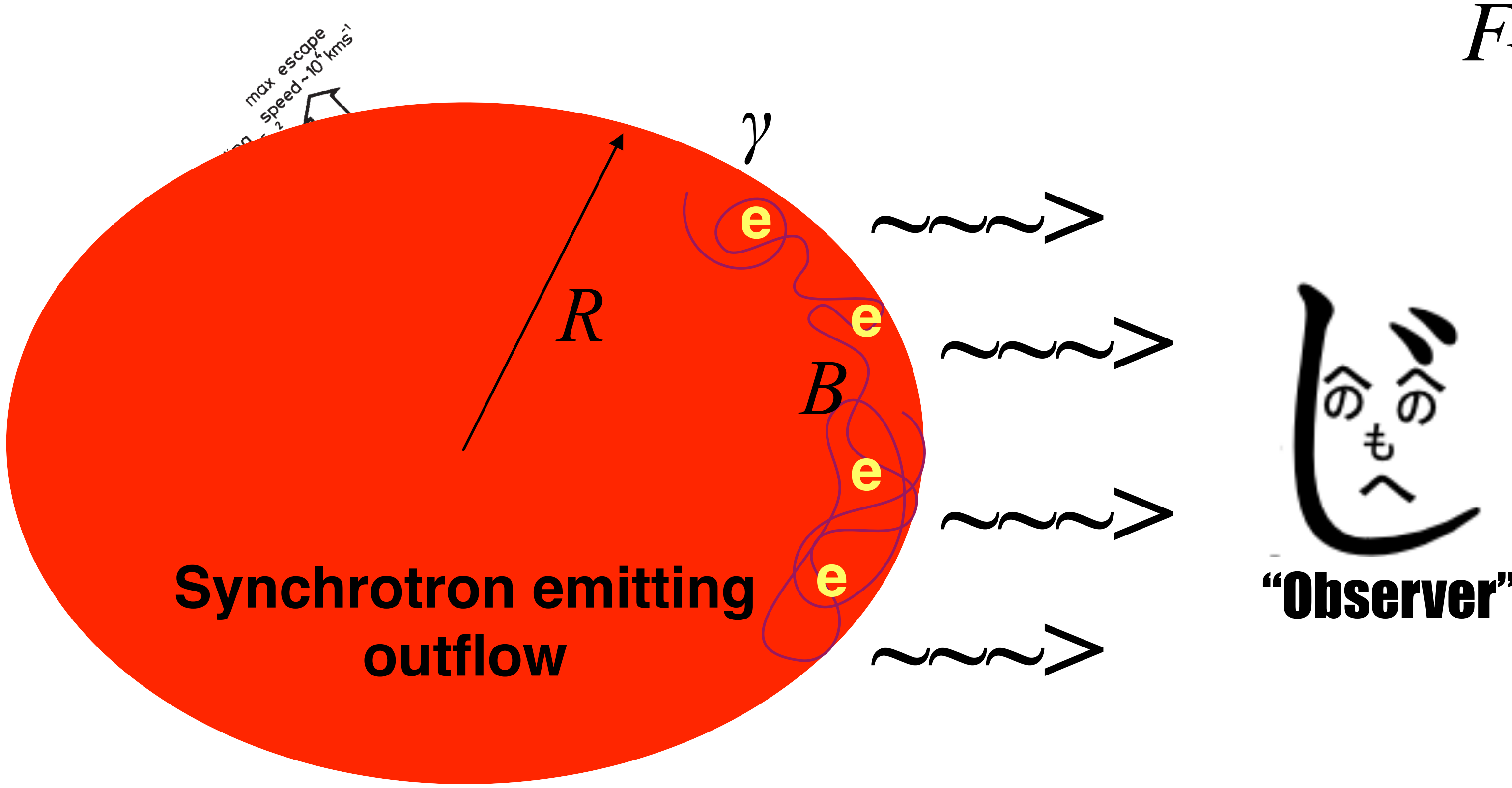
Radio emission in TDEs

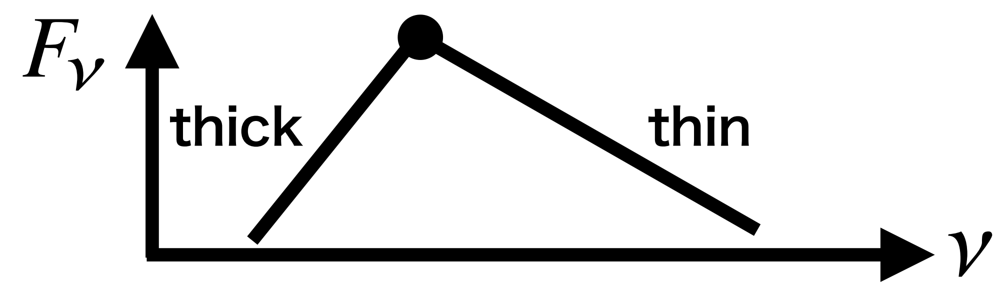
Alexander+20



Synchrotron emission => Probe of Outflow + Environment

Radio in TDEs: Equipartition analysis



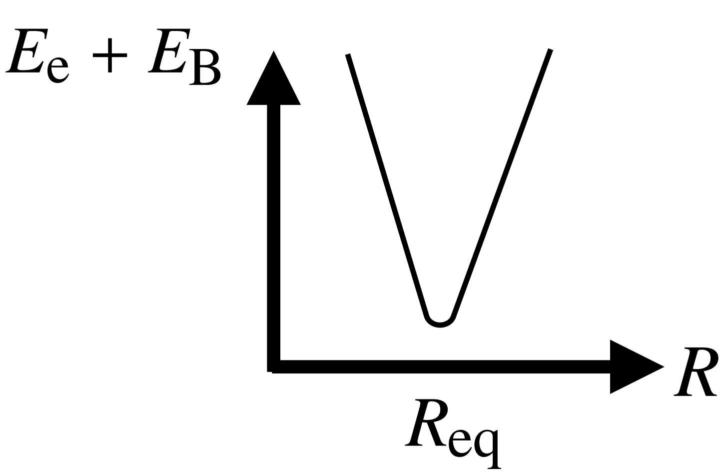


$$\nu_p \sim \gamma^2 \frac{eB}{m_e c} \propto \gamma^2 B$$

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

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

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



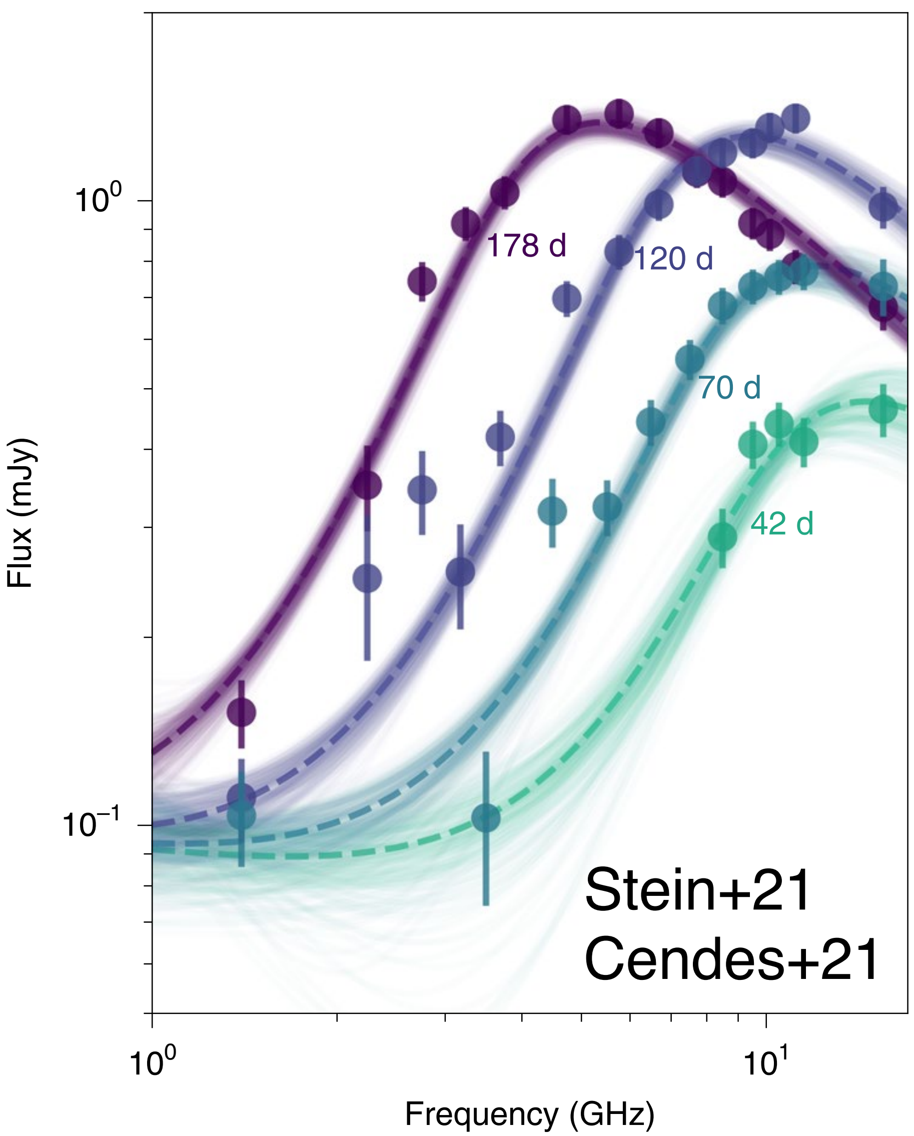
R should be $\sim R_{\rm eq}$

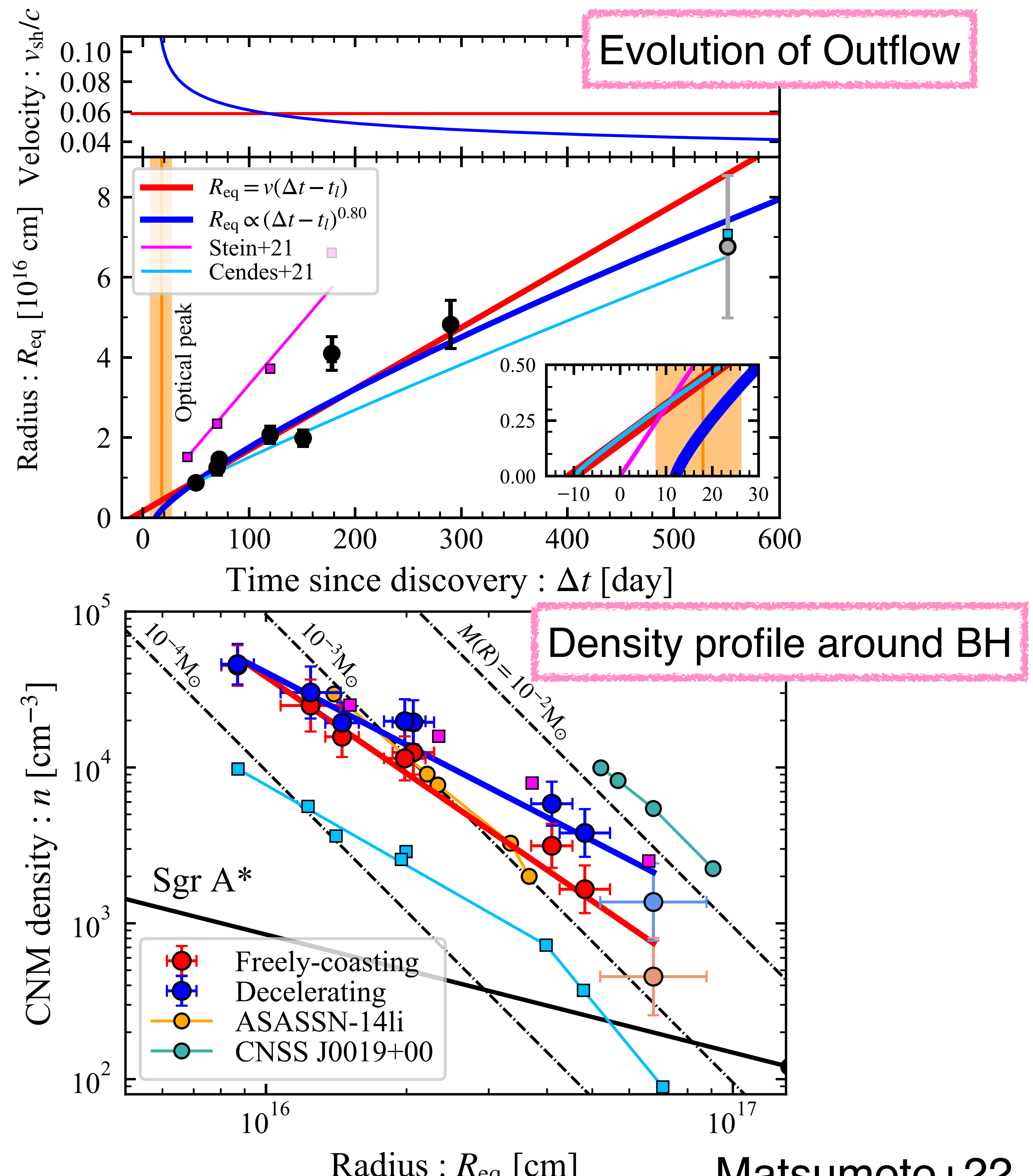
=> Estimation of other quantities

Chevalier98,Barniol-Duran+13

Radio in TDEs: Equipartition analysis

AT2019dsg

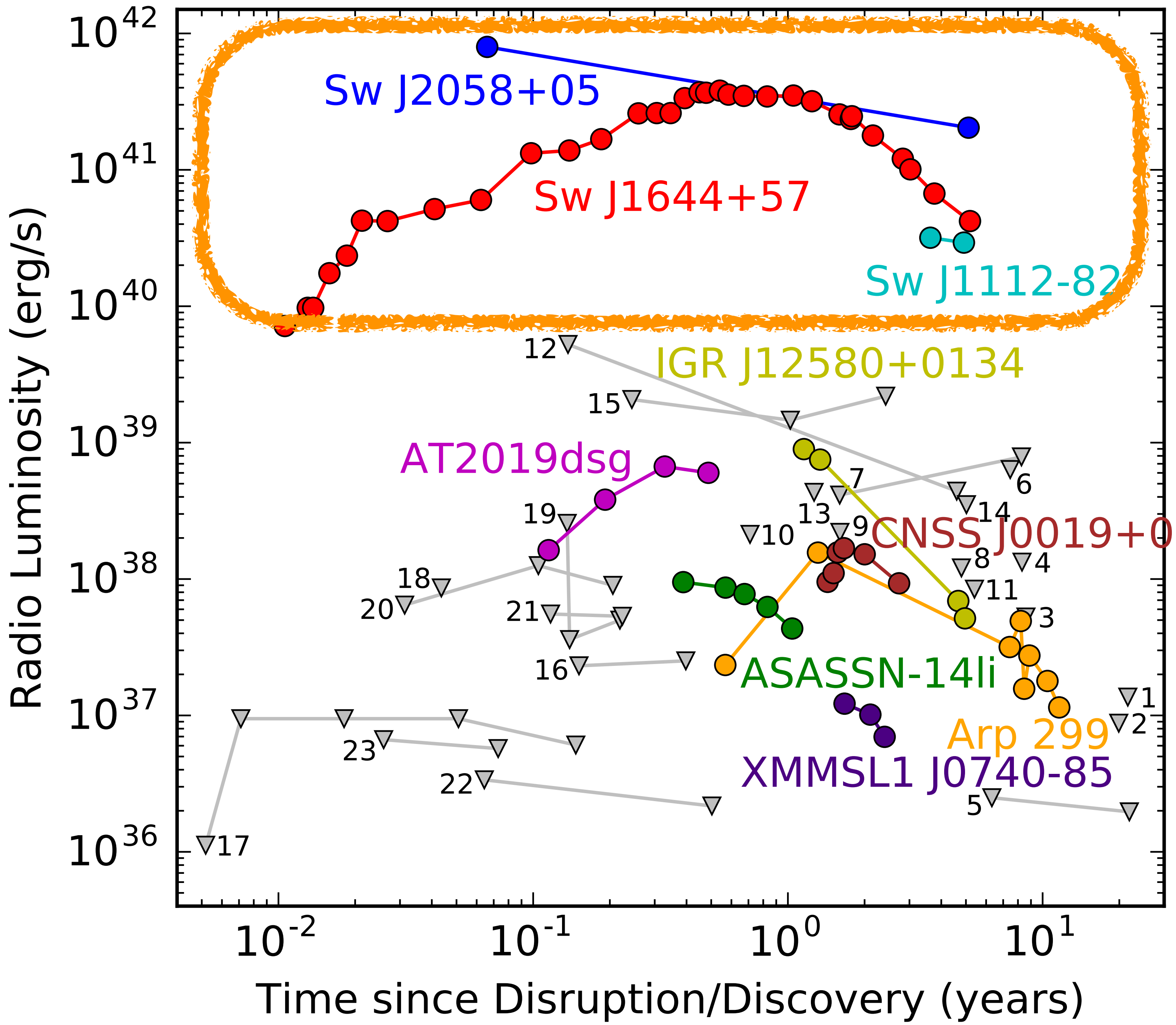




Matsumoto+22

Radio emission in TDEs

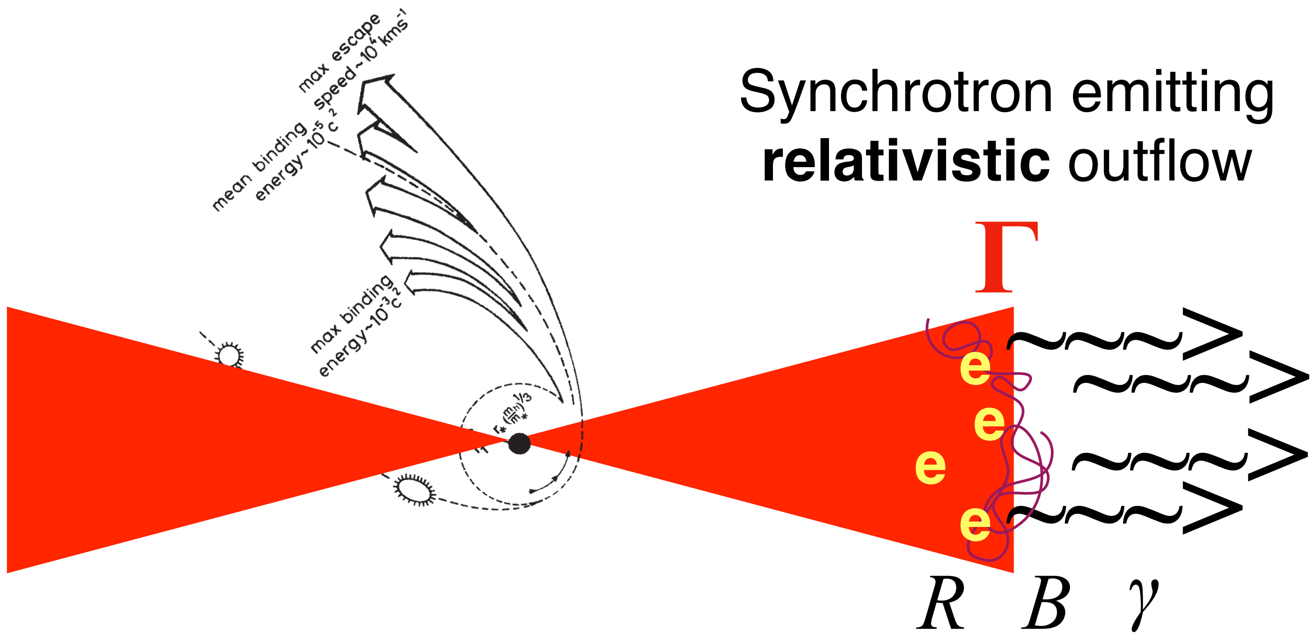
Alexander+20

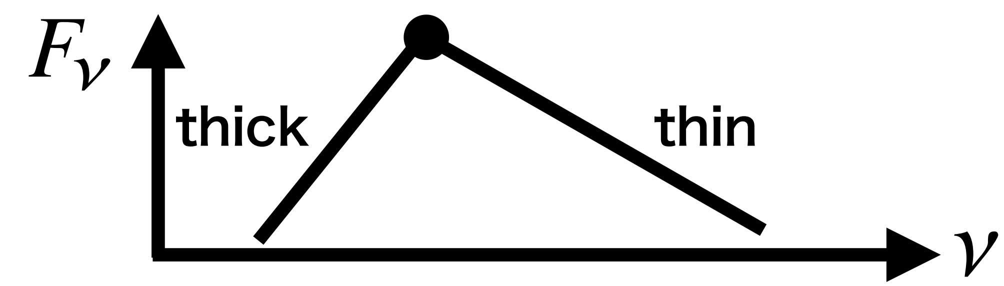


Synchrotron emission => Probe of Outflow + Environment

Radio in TDEs: Equipartition analysis

Synchrotron emitting
relativistic outflow





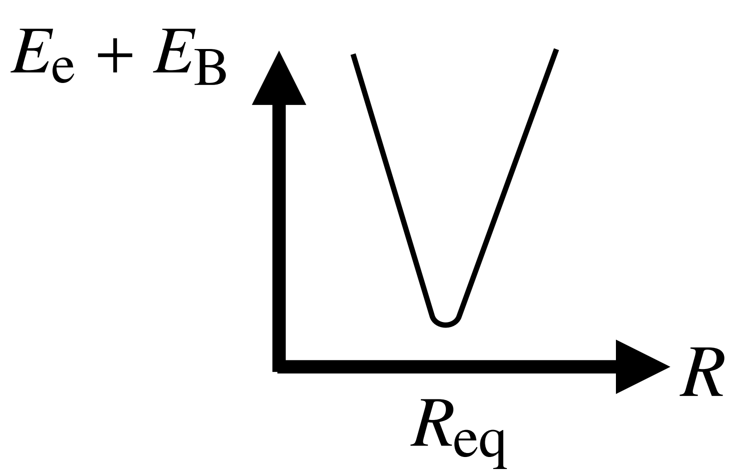
$$\nu_p \sim \gamma^2 \frac{eB}{m_e c} \propto \gamma^2 B\,\Gamma$$

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

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

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

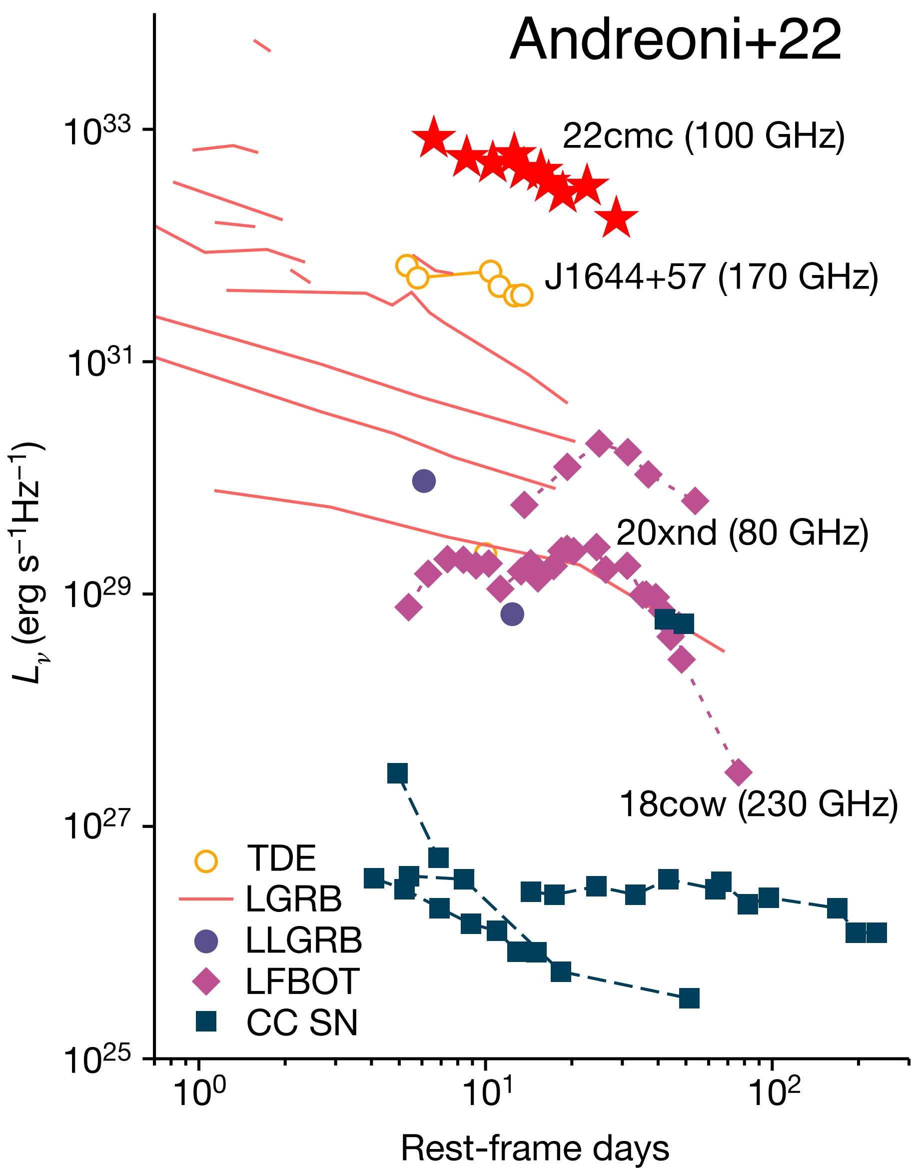
=> Total Energy: $E_{\rm tot} \sim B^2 R^3 + N m_e c^2 \gamma \sim R^{11} + R^{-6}$



R *should be* ~ $R_{\rm eq}$

=> Estimation of other quantities

Jetted TDEs: Radio analysis



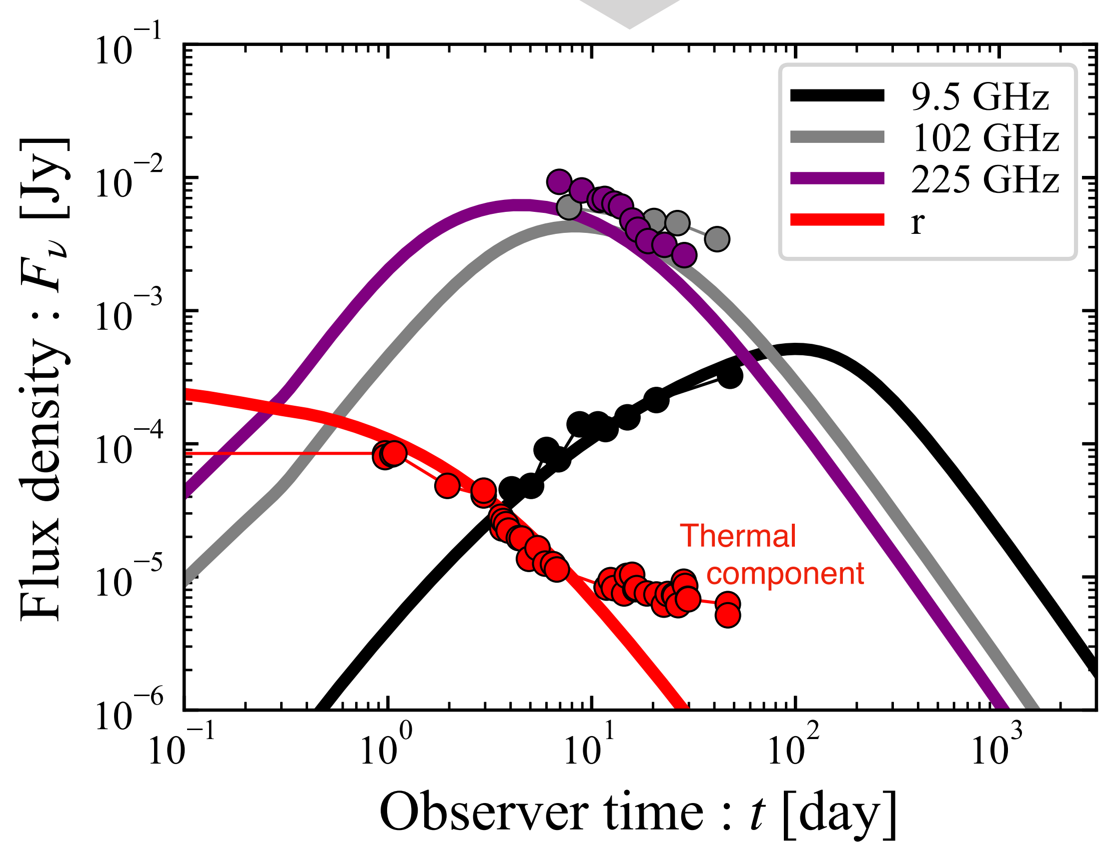
What can we learn?

Equipartition analysis

Γ~2-3 (Relativistic source!)

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

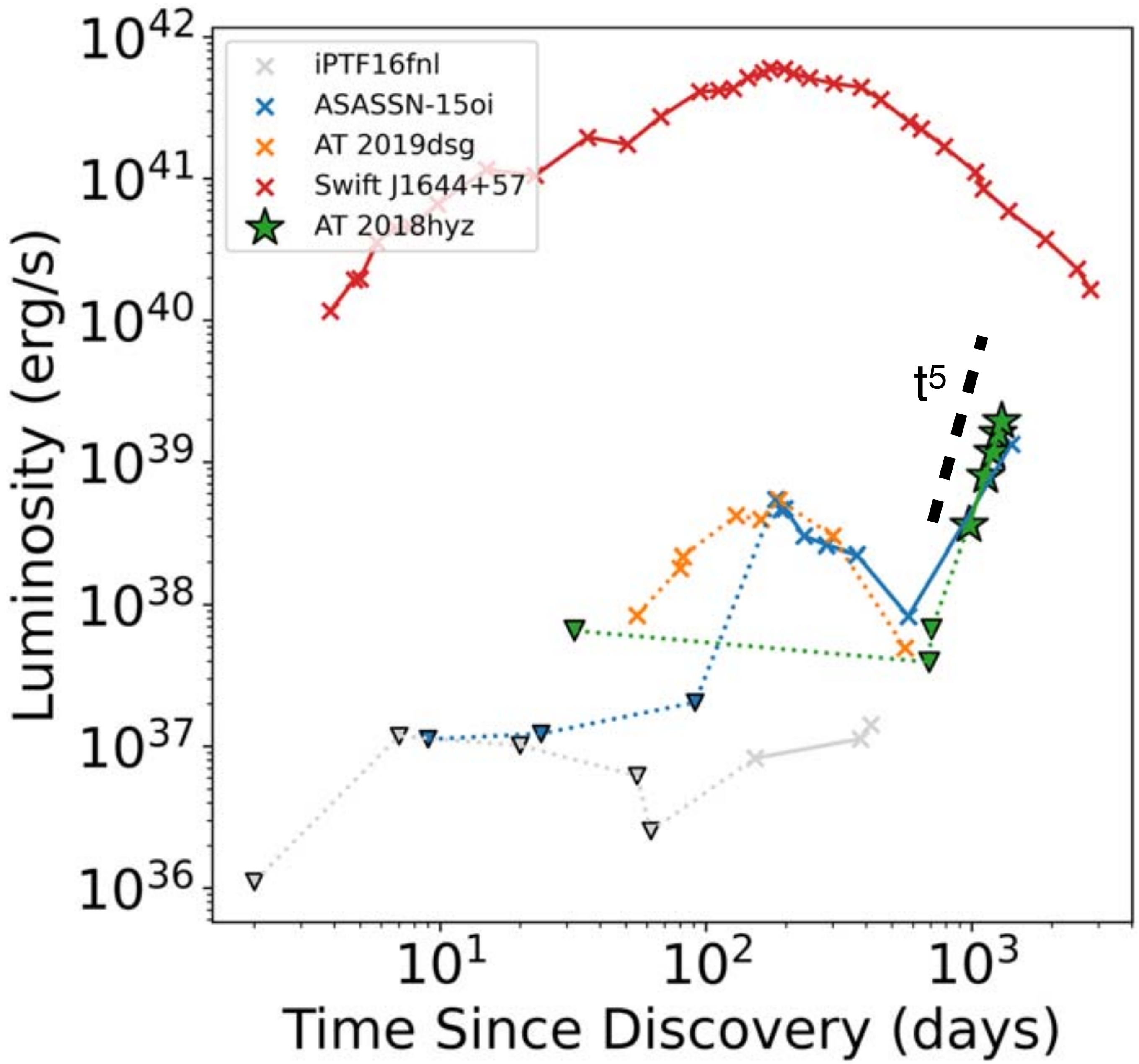
Detailed modeling
(as GRB afterglow)



Matsumoto&Metzger23

Late-time radio flares

Cendes+22,Horesh+21,Sfaradi+24



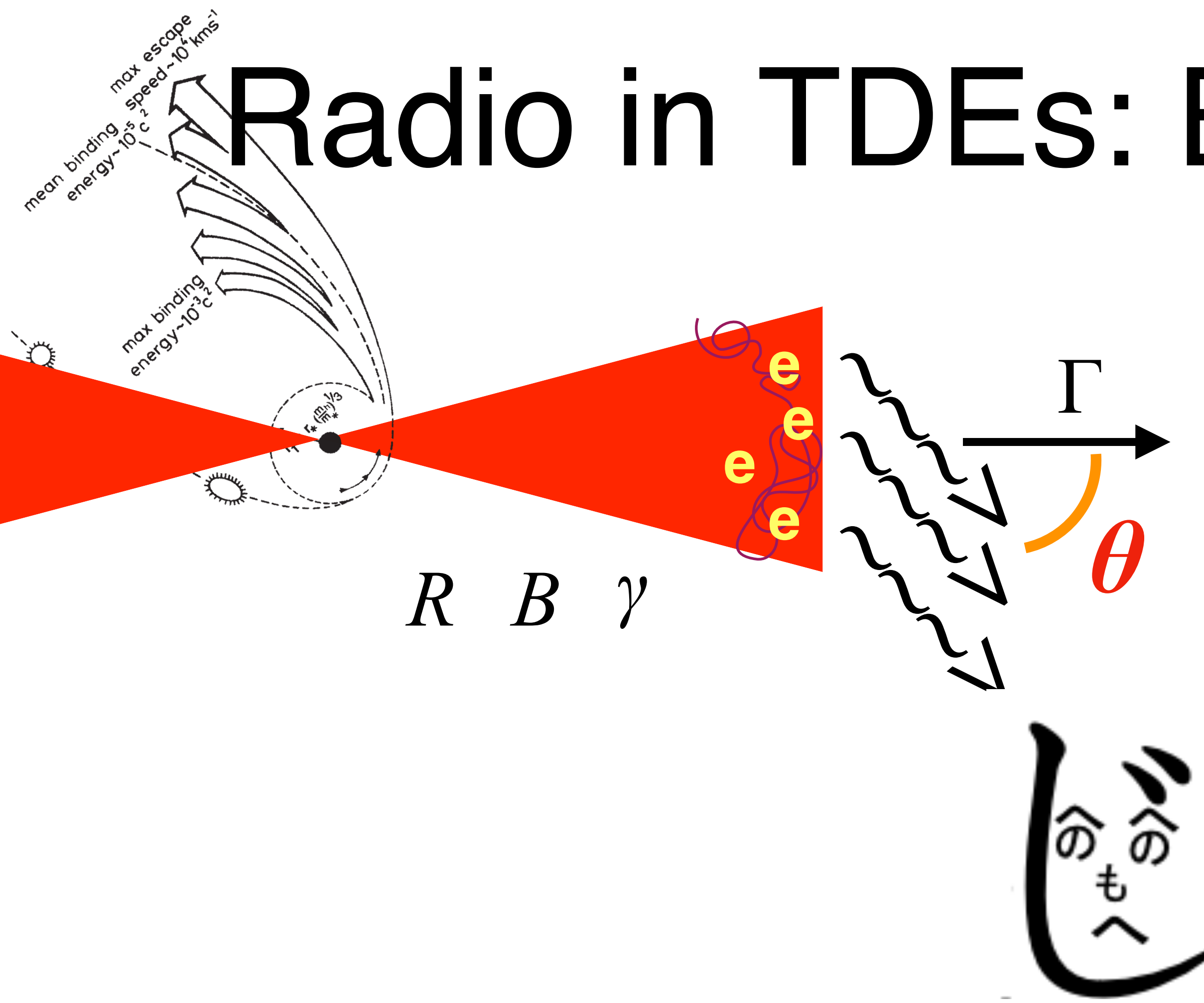
- Radio flare ~ 1000days after optical discovery
- Flux increases as t^5
- Origin?

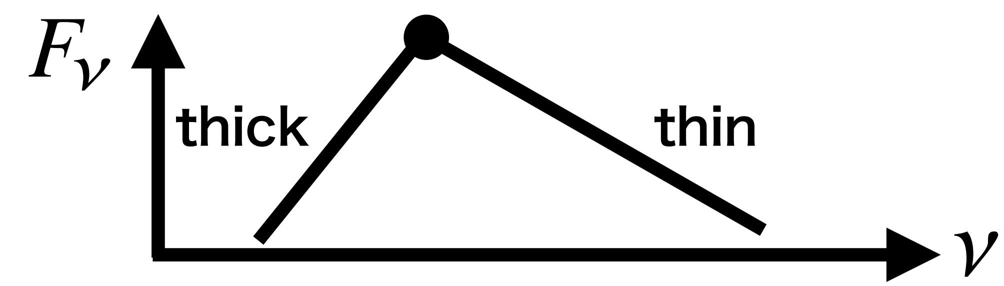
  Delayed disk formation?

  Off-axis jet?

Matsumoto&Piran23

Radio in TDEs: Equipartition analysis





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

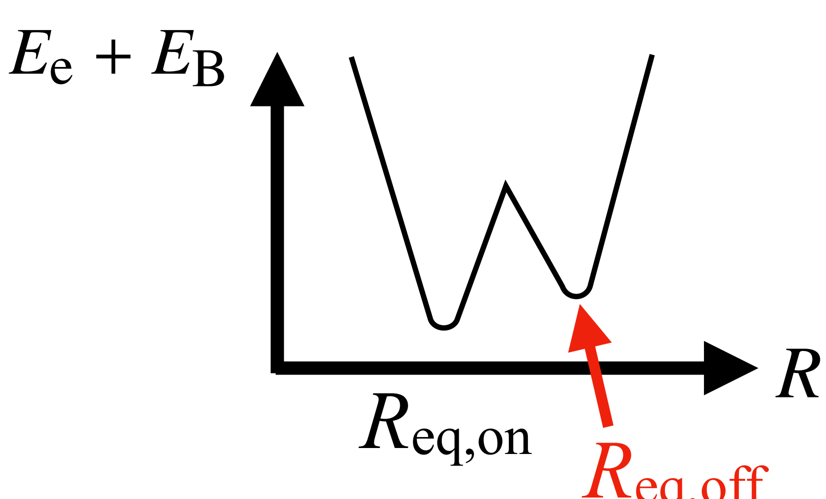
$$\nu_p \sim \gamma^2 \frac{eB}{m_e c} \propto \gamma^2 B\, \boldsymbol{\delta}$$

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

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

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

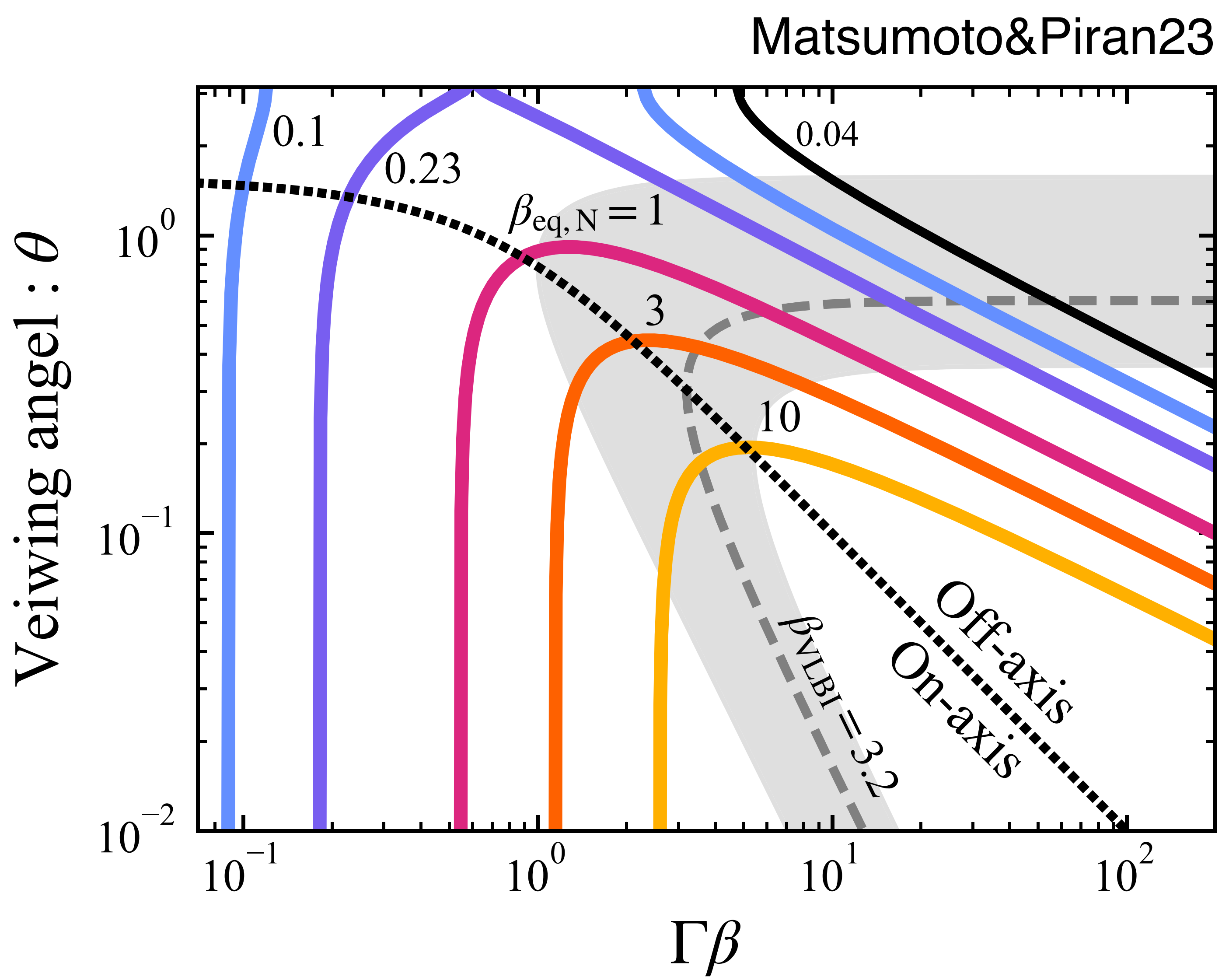
=> Total Energy: $E_{\rm tot} \sim B^2 R^3 + N m_e c^2 \gamma \sim R^{11} + R^{-6}$

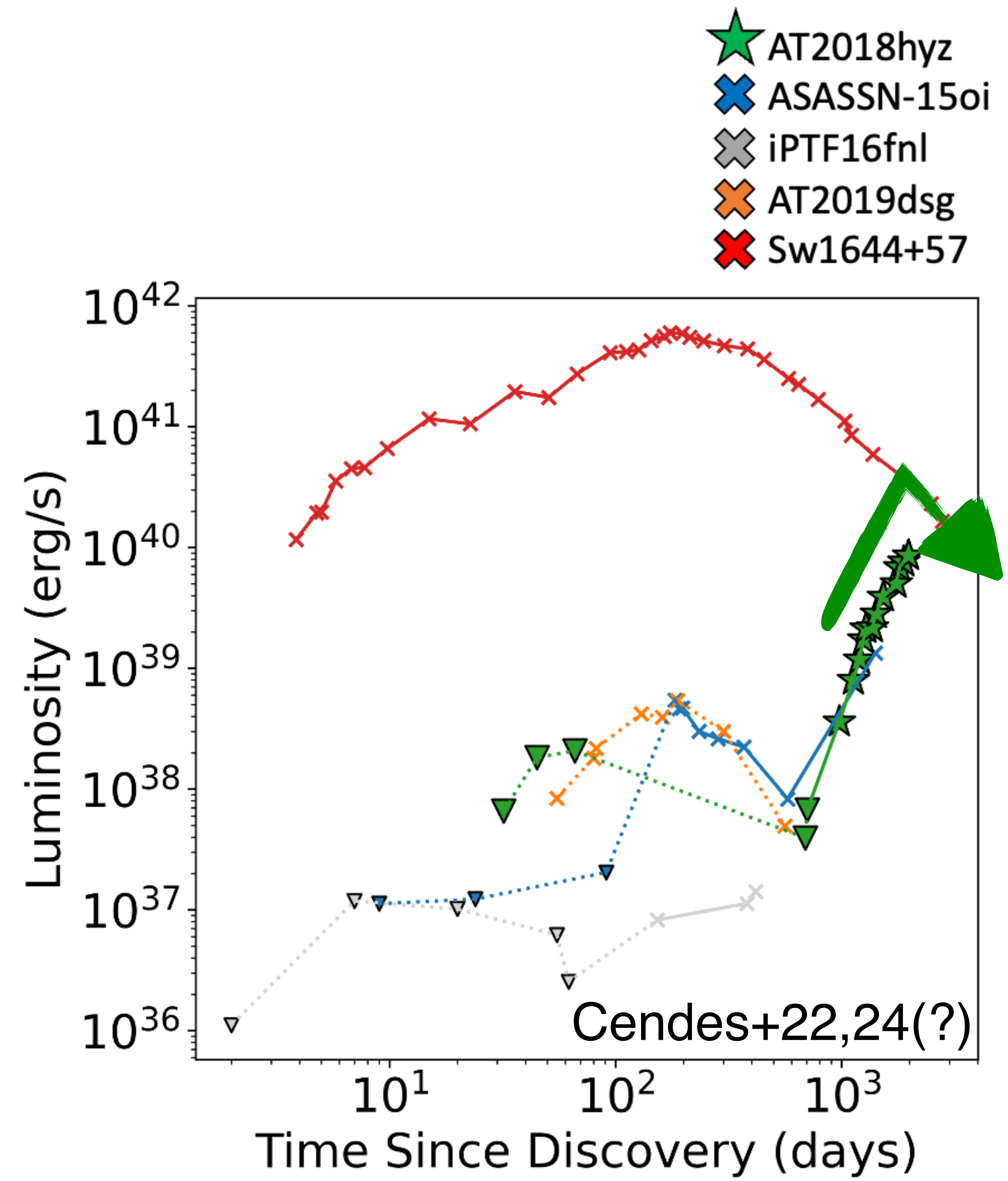


Two minimizing radii
corresponding to on/**off-axis**

Late-time radio flare as off-axis jet

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





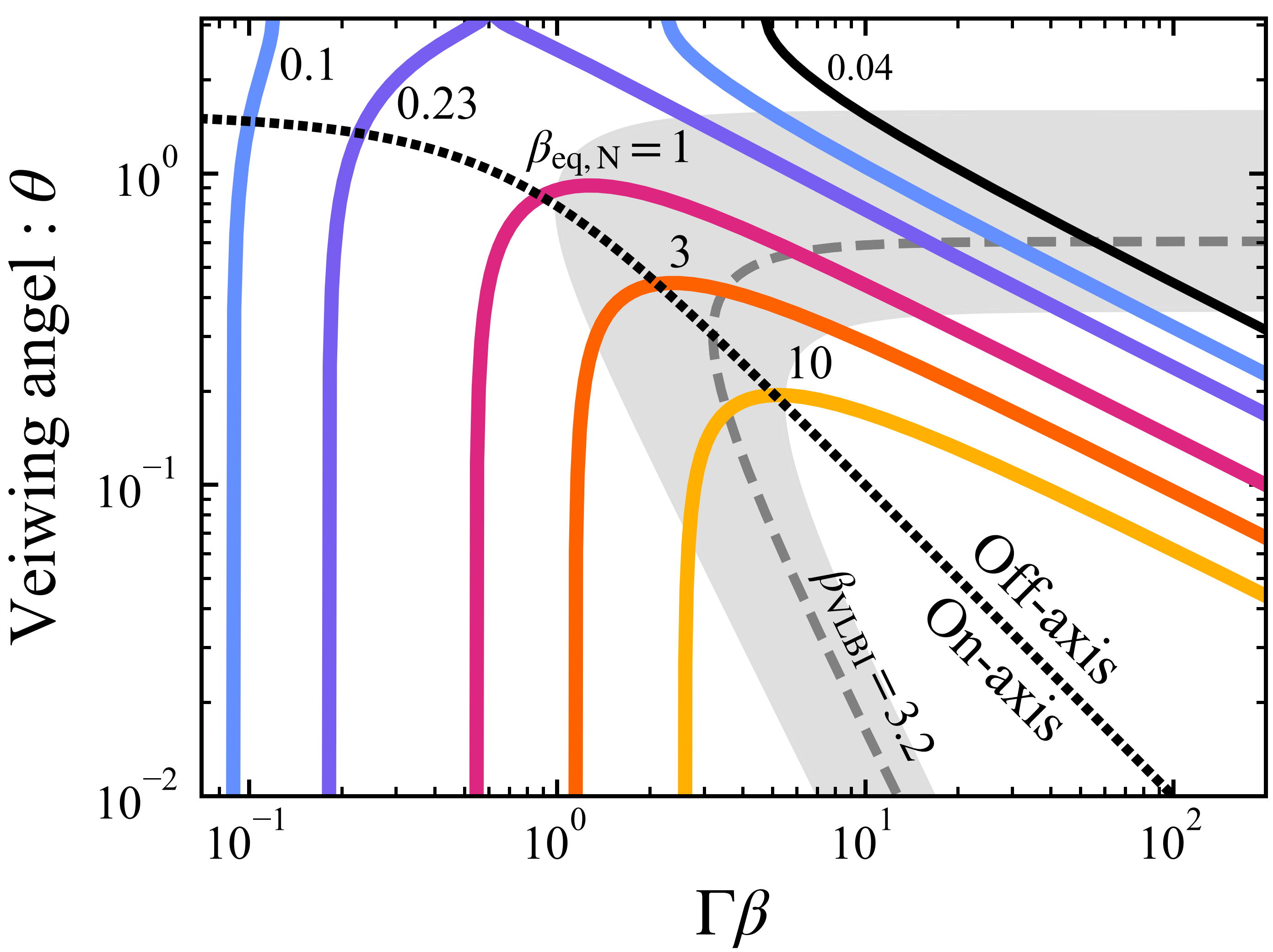
Matsumoto&Takahashi in prep.

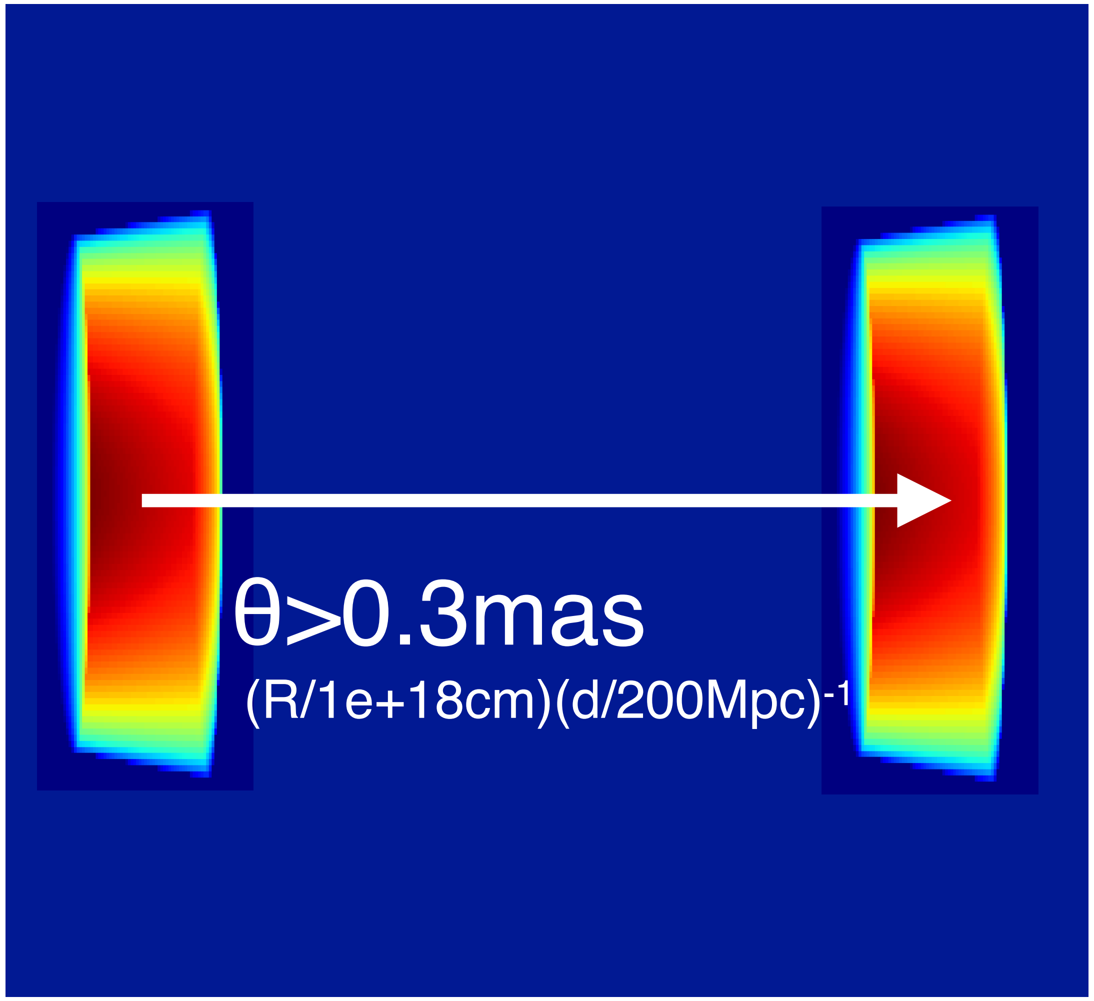
VLBI diagnostics

$\beta_{\mathrm{eq,N}}=R_{\mathrm{eq,N}}/t\sim0.1c$

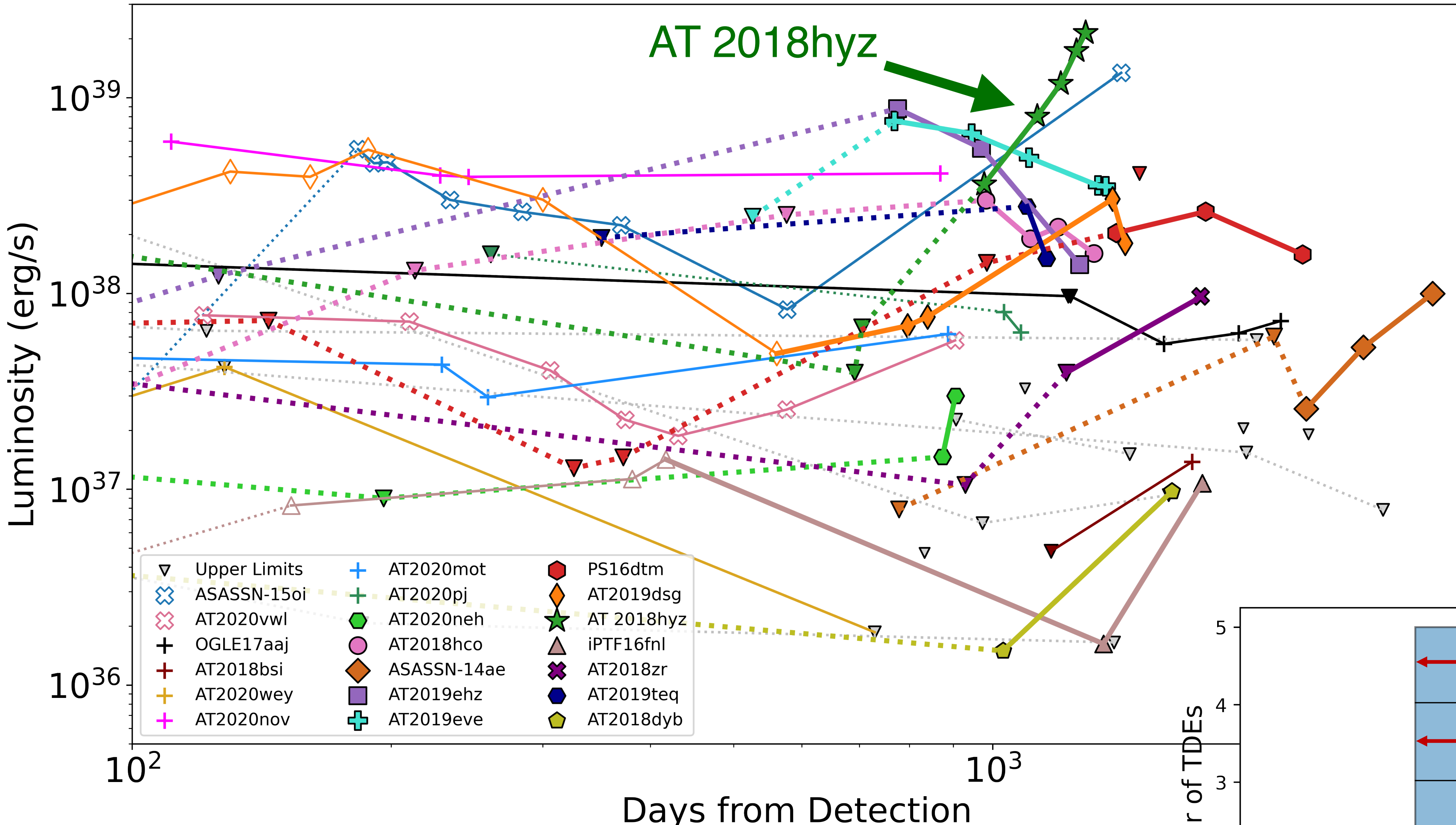
R>1.e+18cm (v/c)(t/yr)

Matsumoto&Piran23

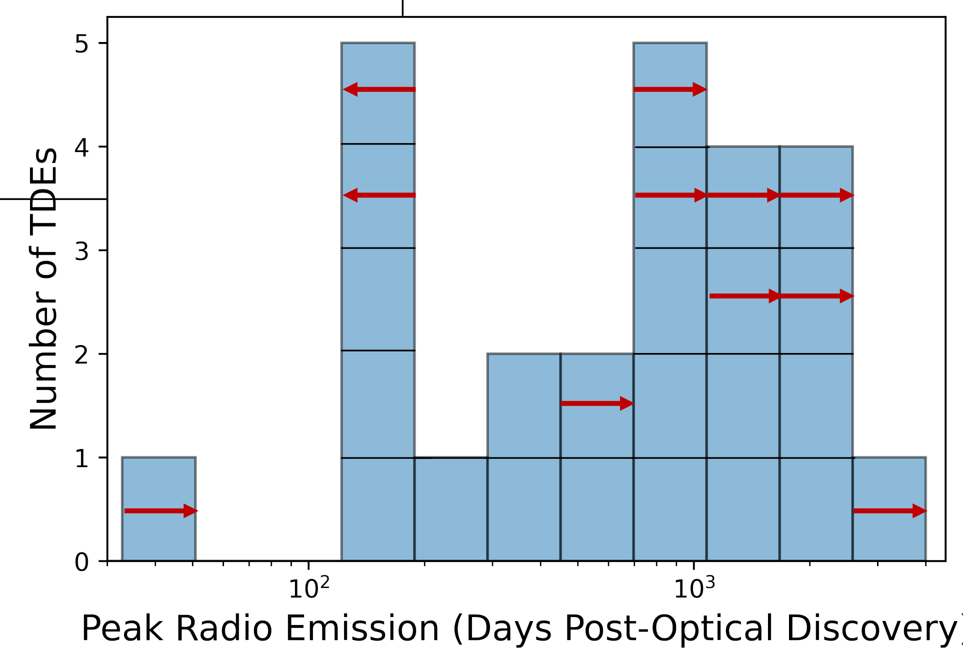




Ubiquitous late-time radio flare



Cendes+23



~40% of optical TDEs show
late (>1000days) radio flares!
=>Off-axis jet cannot produce all events

Event rate of jetted TDEs

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

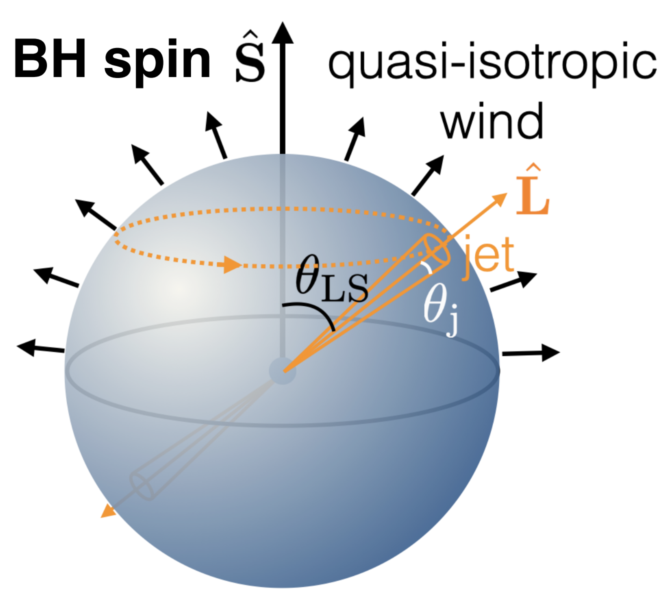
Sazonov+21,Yao+23
Andreoni+22

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

Beaming: $f_b \sim \theta^2 \sim 0.01$

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

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



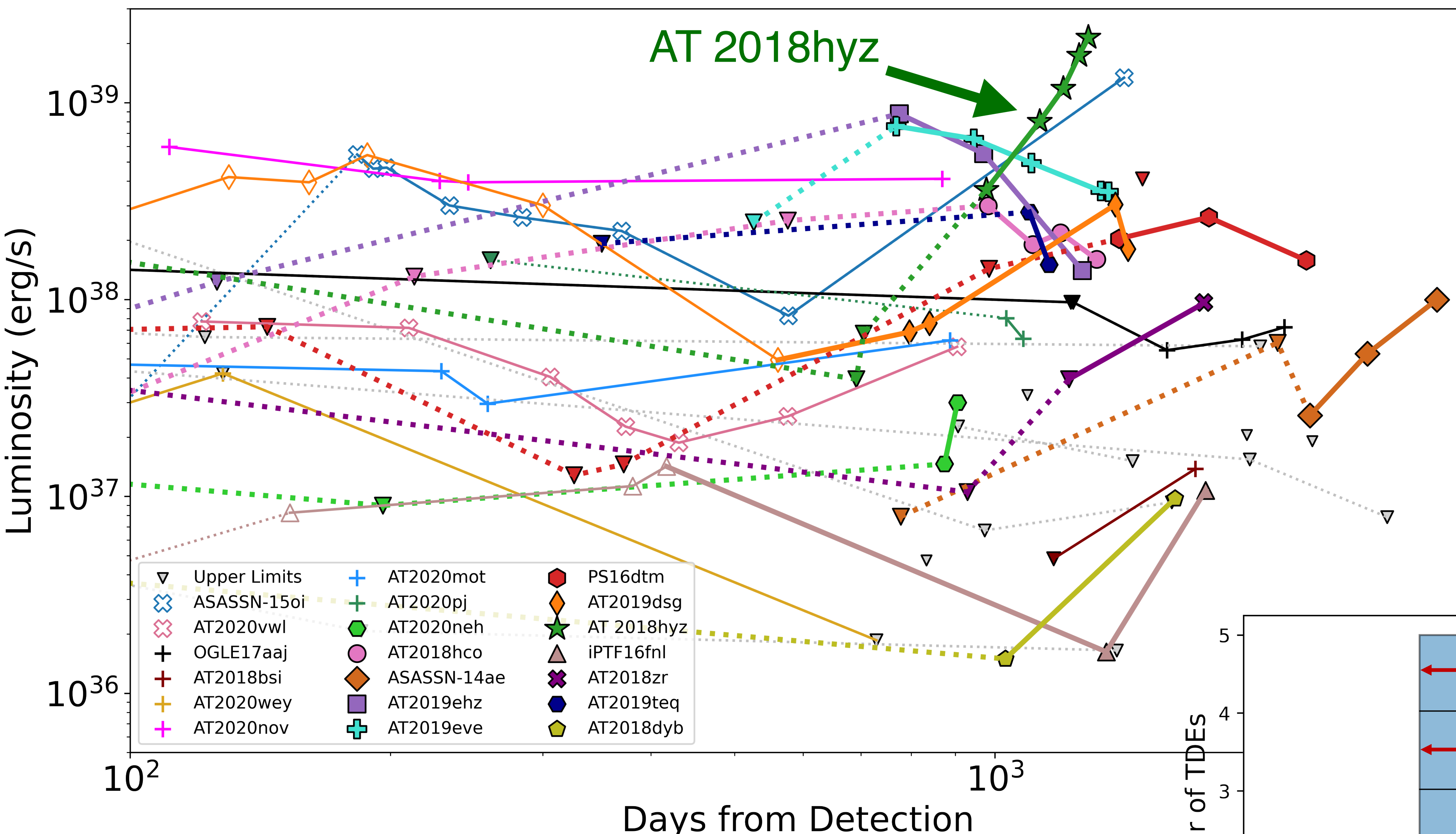
Jet breakout = **Double** alignment?

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

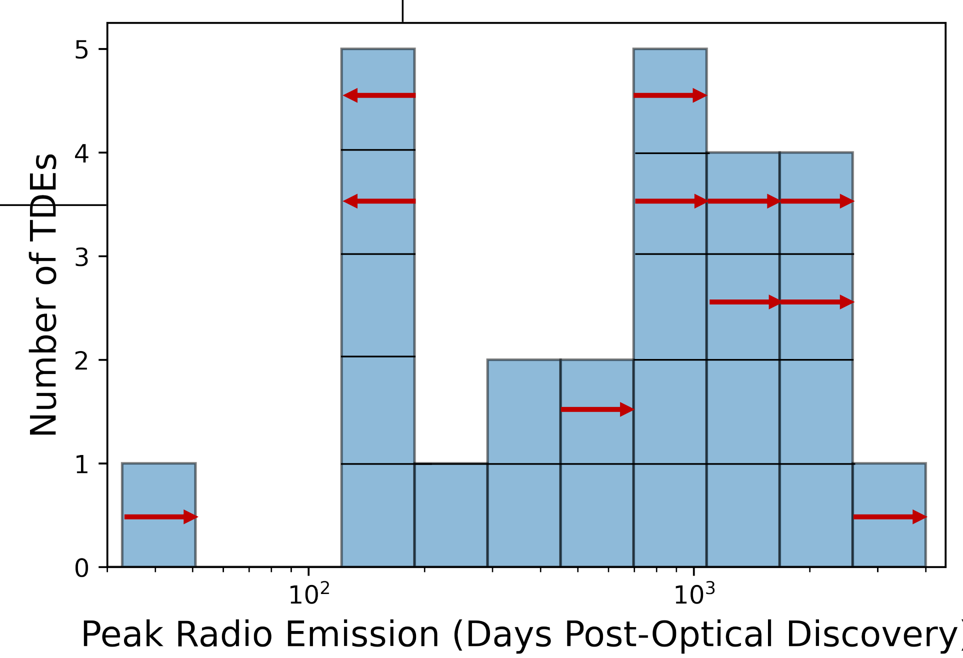
On-axis Successful Jet: $\mathcal{R}_{\rm on\text{-}jet}/\mathcal{R}_{\rm TDE} \sim \theta_j^4 \sim \mathbf{10^{-4}}\,(\theta_j/0.1)^4$

Lu,Matsumoto,Matzner23, Teboul&Metzger23

Ubiquitous late-time radio flare



Cendes+23



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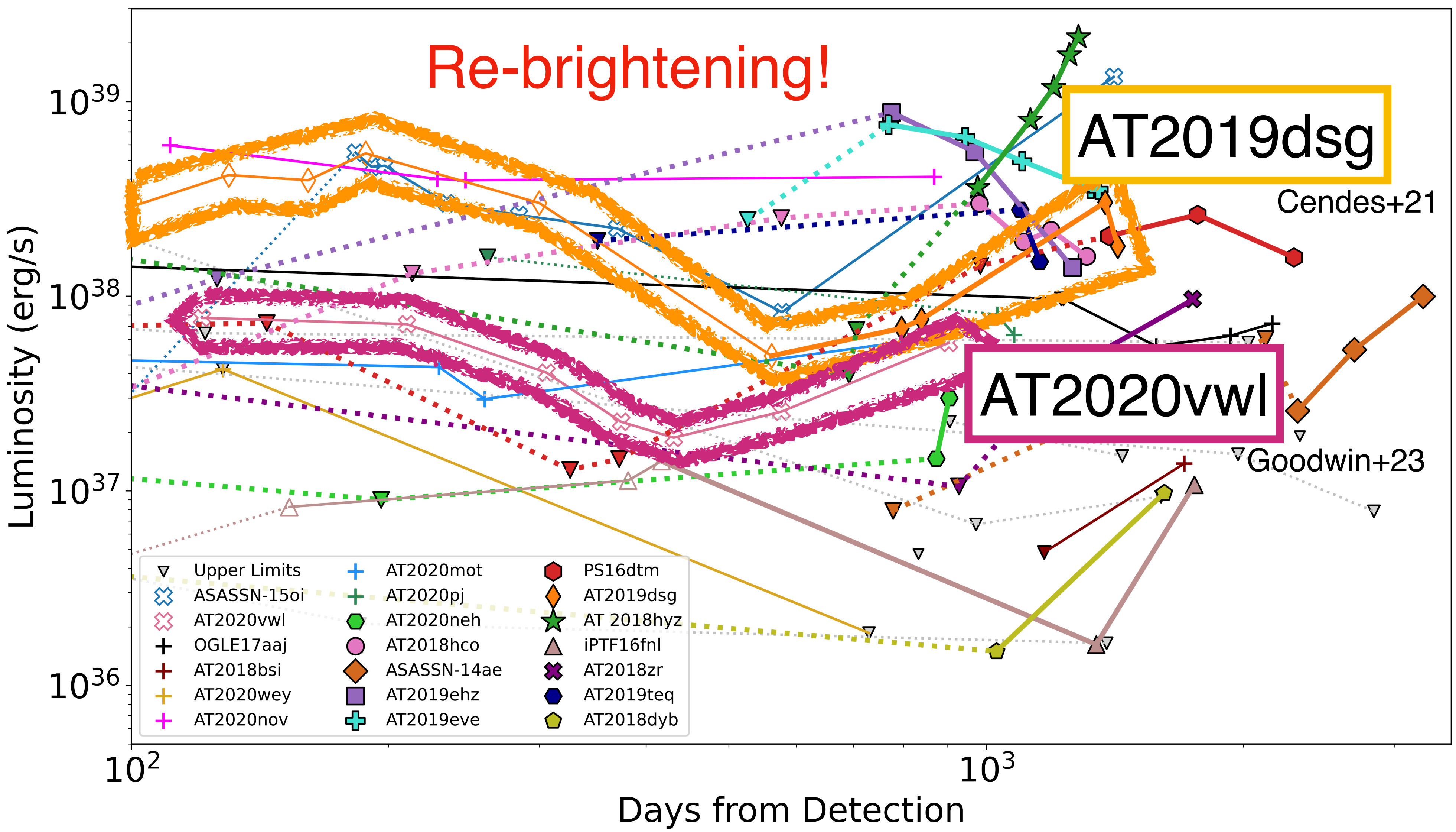
Double-peak radio flares



Cendes+23

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

$$N \sim nR^3$$

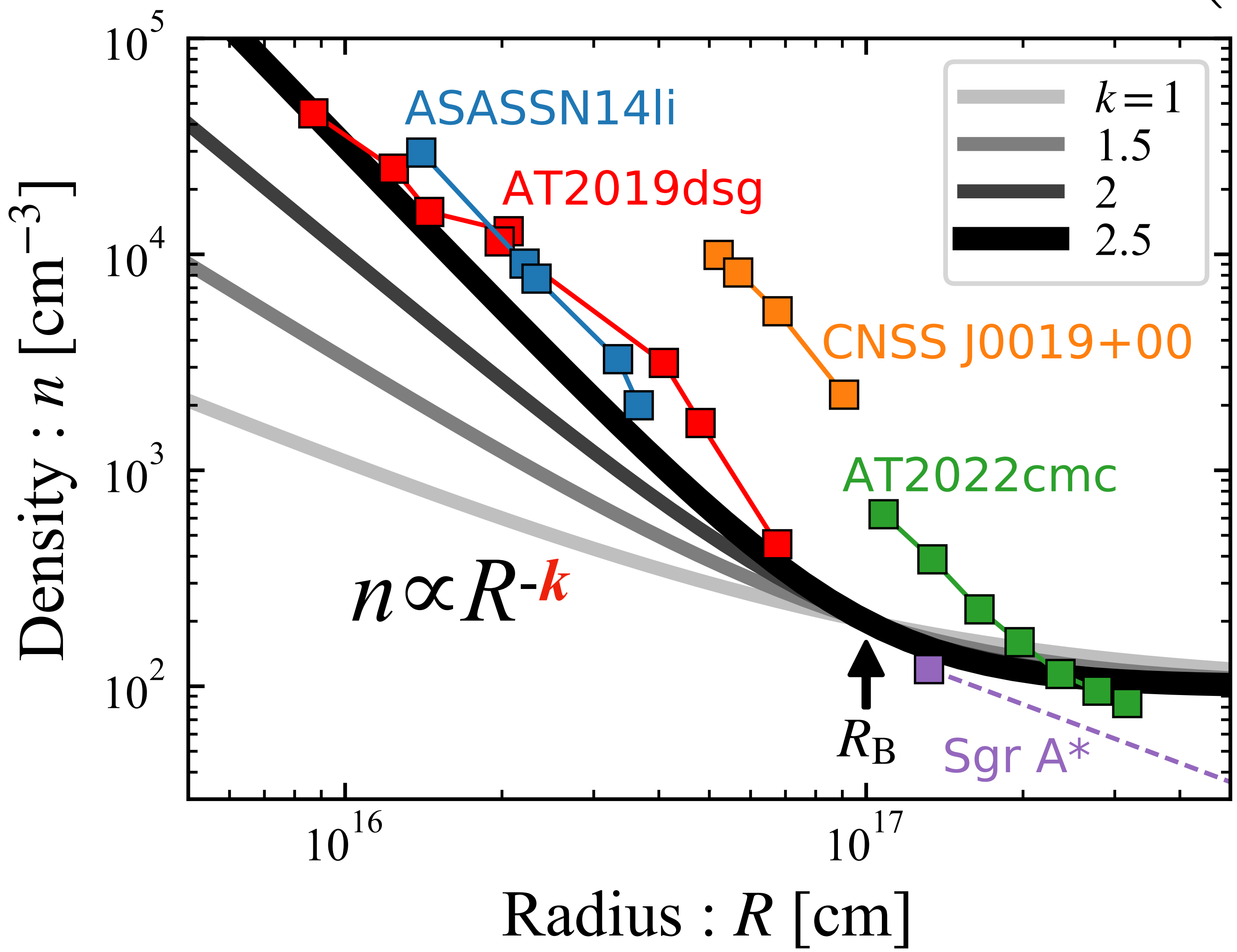
Late-time rise with **opt. thin** spectrum
=> Different mechanism from the 1st peak to make radio rise

(Most late flares show opt. thin spectrum)

Matsumoto&Piran24

Outflow reaches Bondi radius

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

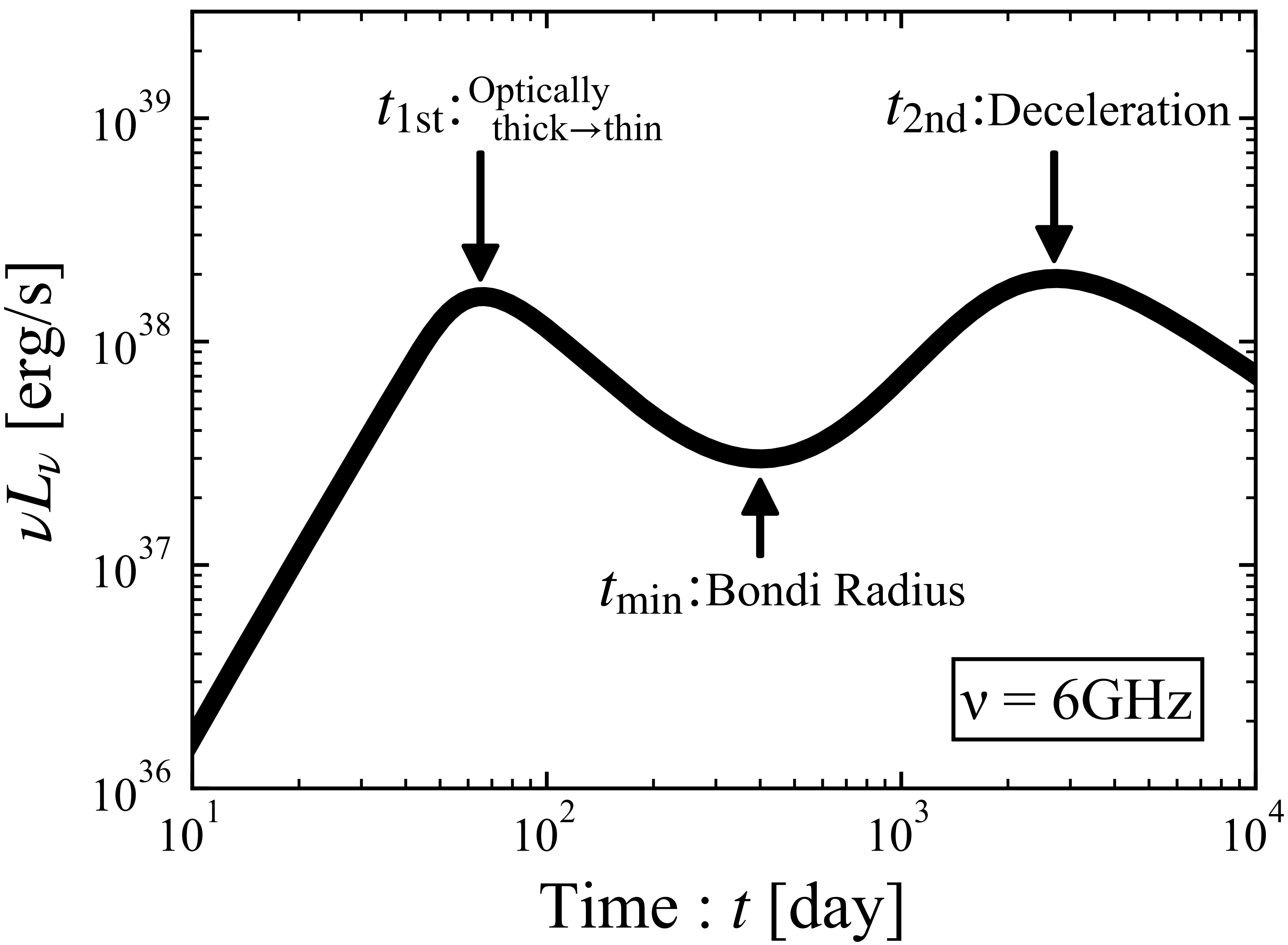


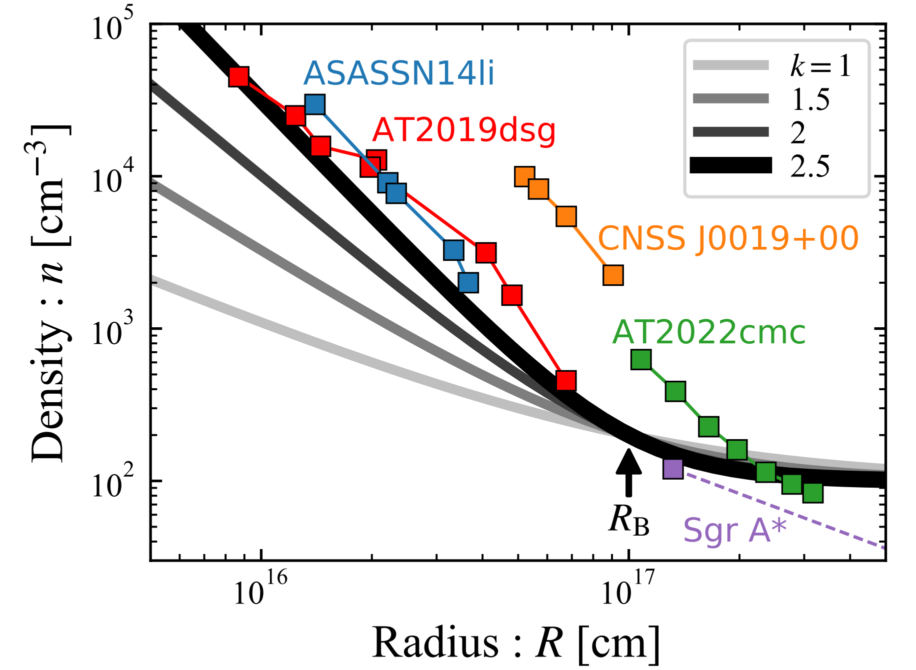
$n_{\rm ISM}$ (flat)

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

Matsumoto&Piran24

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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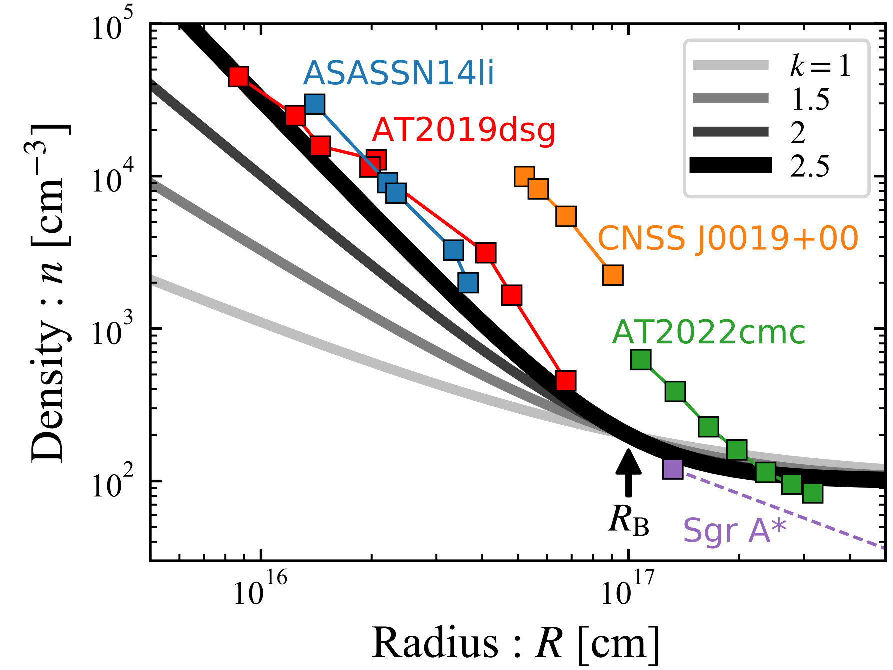
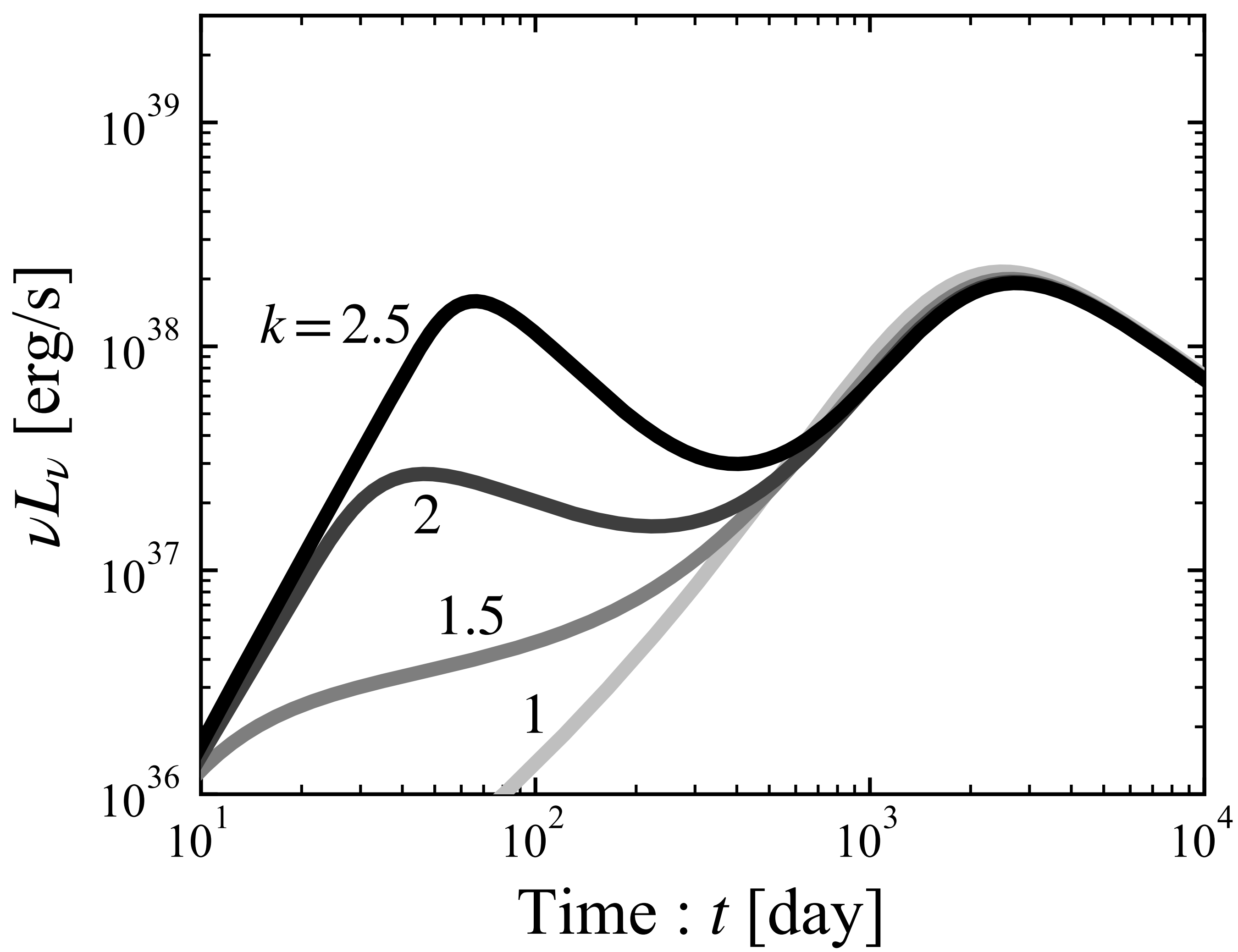
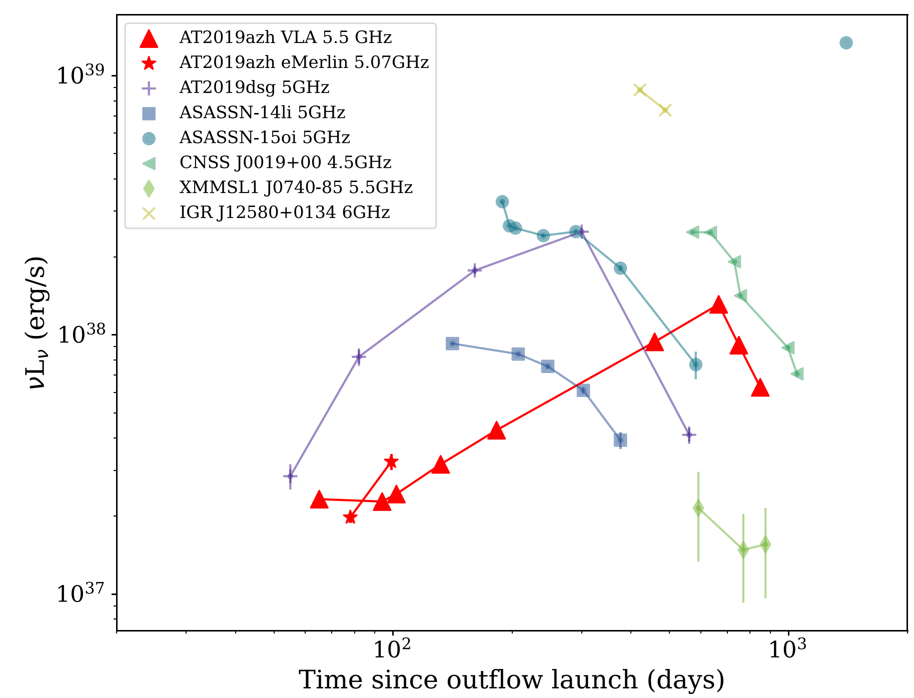
Parameter dependence



Slope of density profile



Goodwin+22,Sfaradi+22



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

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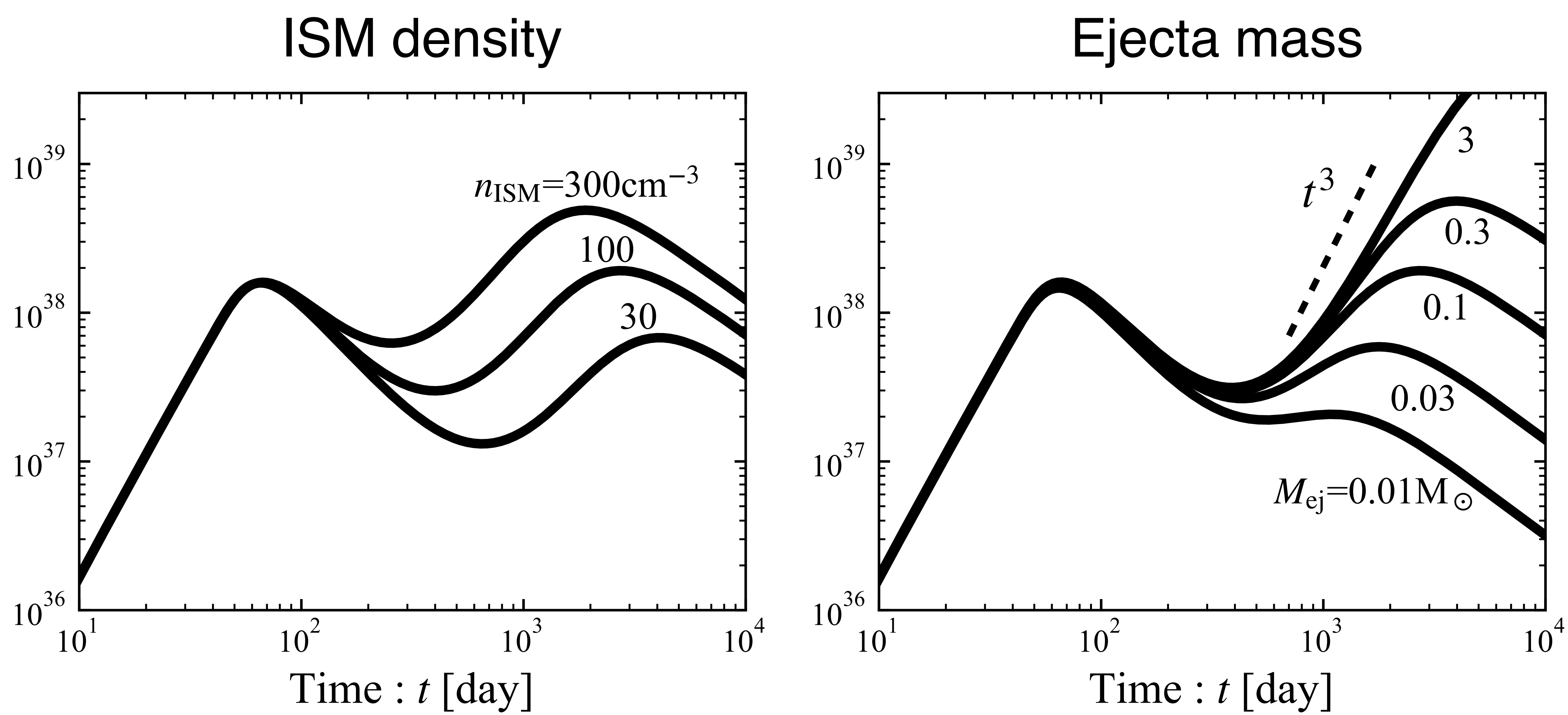
Parameter dependence



$$R_{\rm dec} \simeq \left(\frac{3M_{\rm ej}}{4\pi m_{\rm p} n_{\rm ISM}}\right)^{1/3} \simeq 6.6 \times 10^{17}\,{\rm cm}\, M_{\rm ej,-1}^{1/3} n_{\rm ISM,2}^{-1/3} \;,$$

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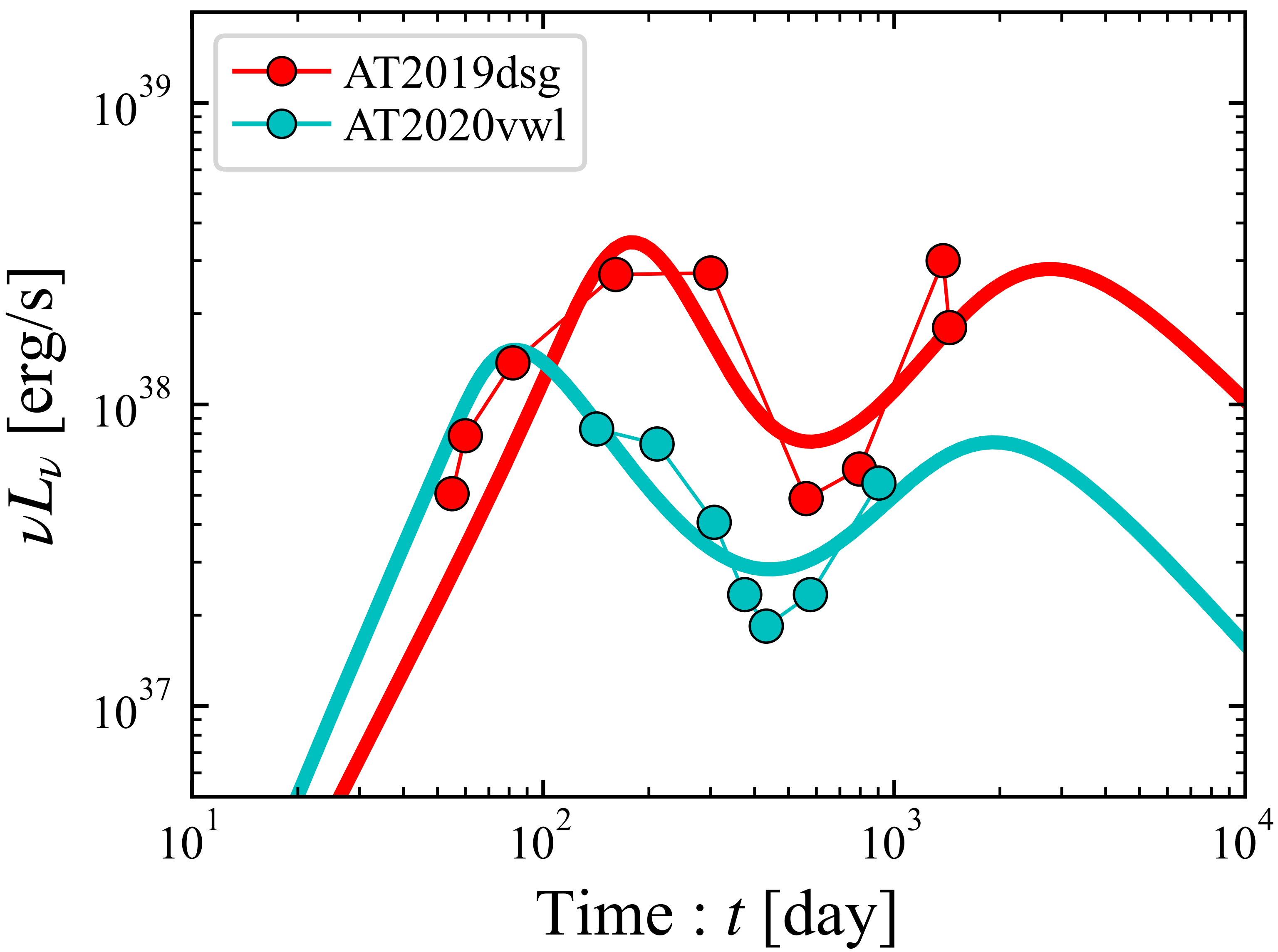
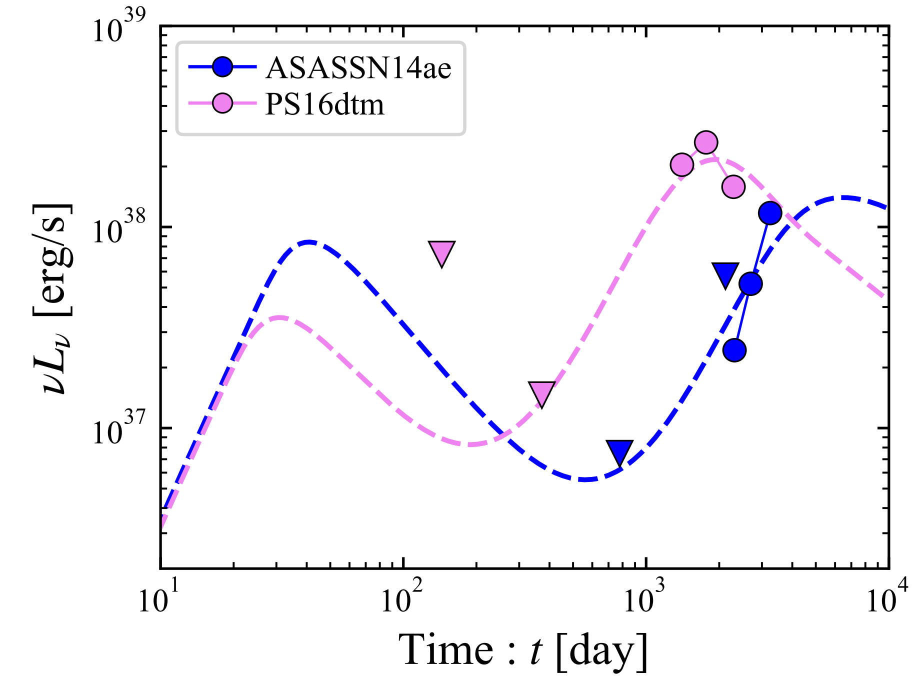
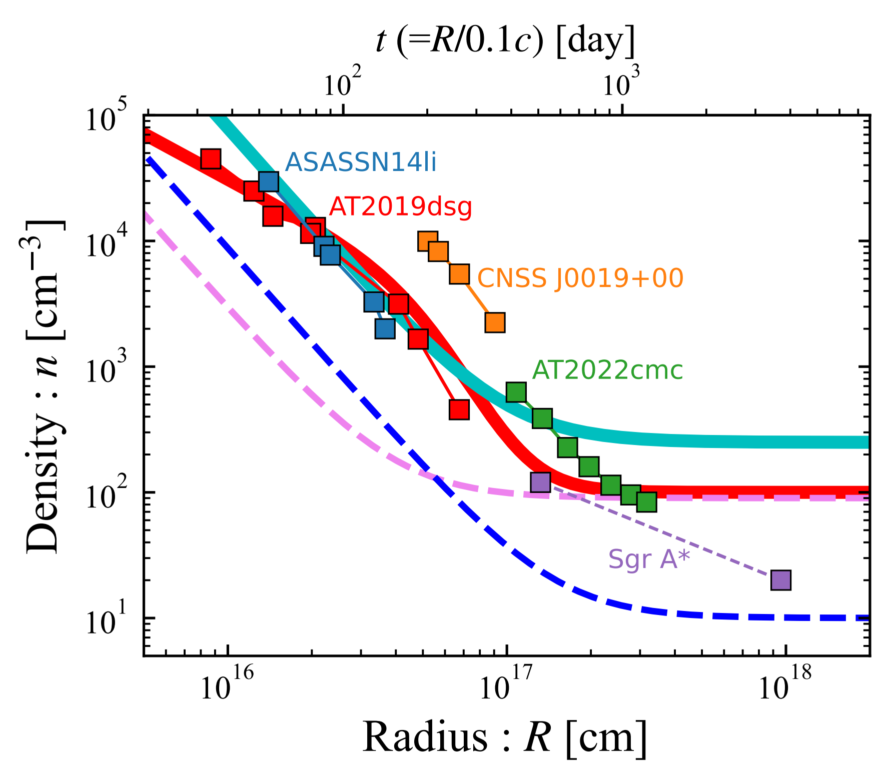
Comparison with observed events







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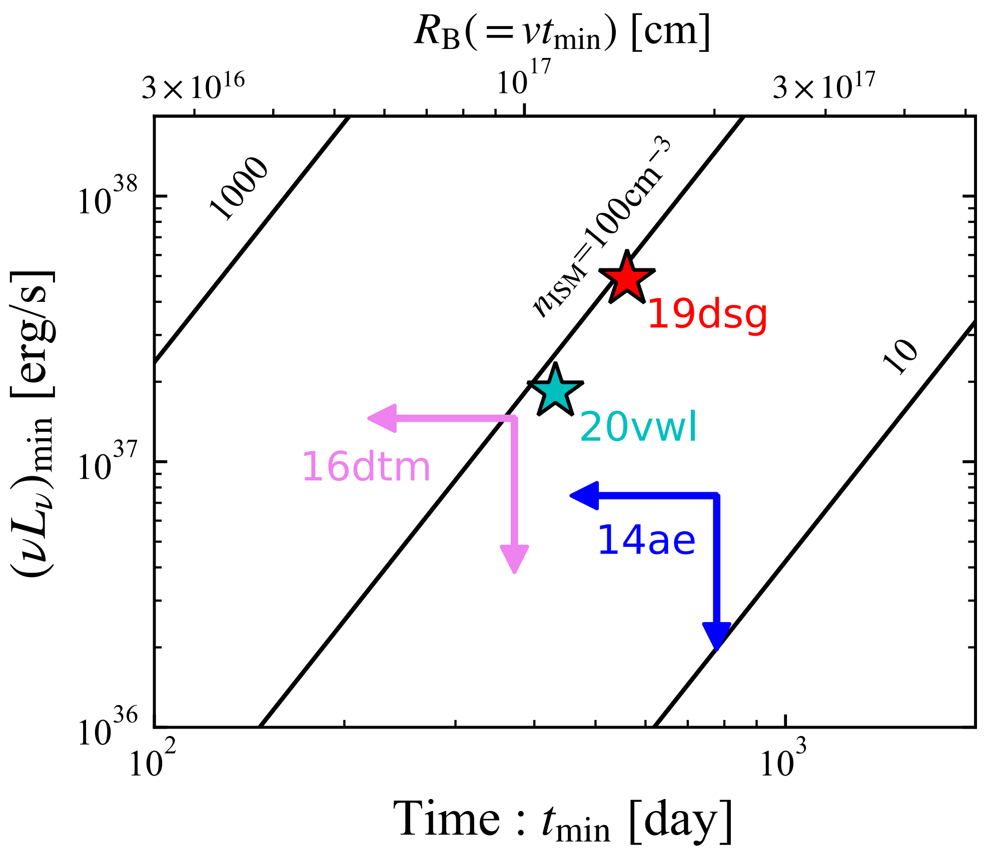
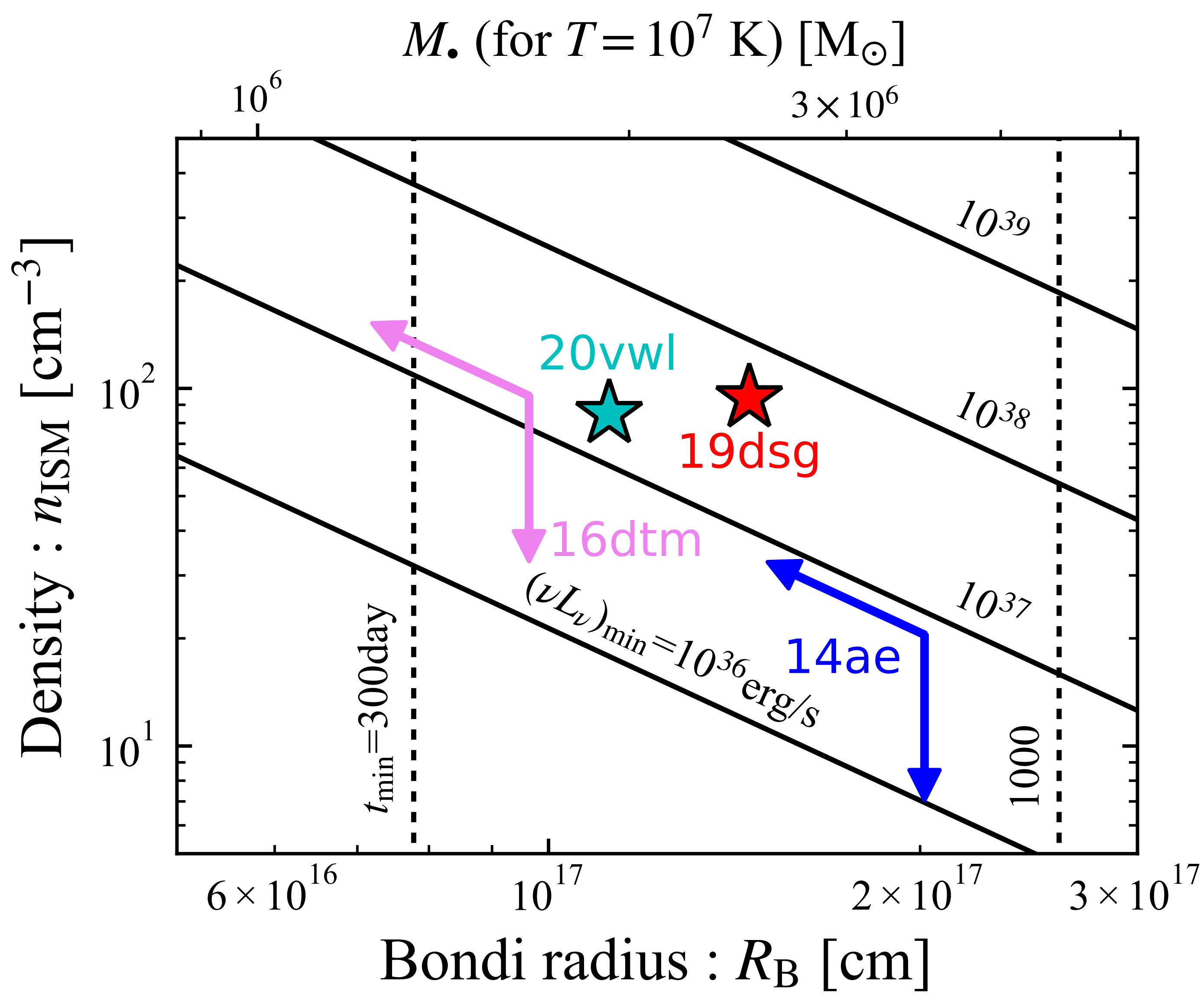
Minimum in light curve=>**BH mass**



$v = 0.1c$, $p = 2.5$, $\varepsilon_e = 0.1$, $\varepsilon_B = 0.01$



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

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

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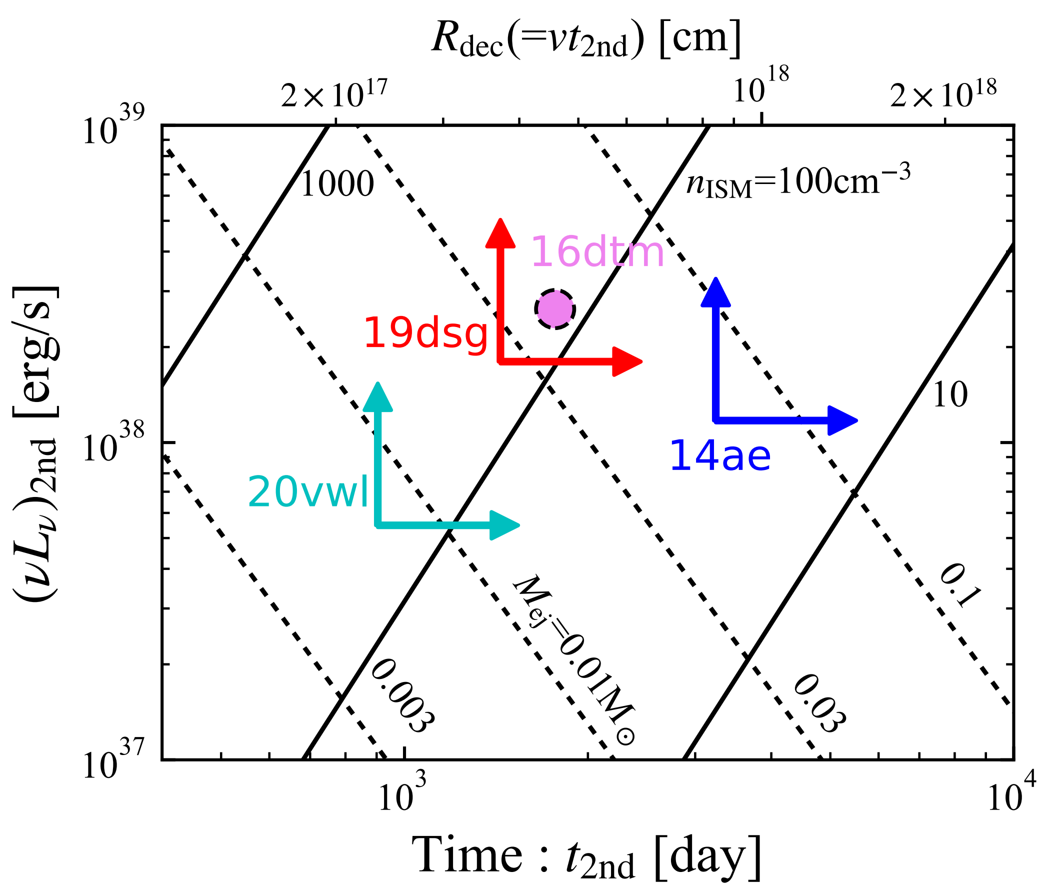
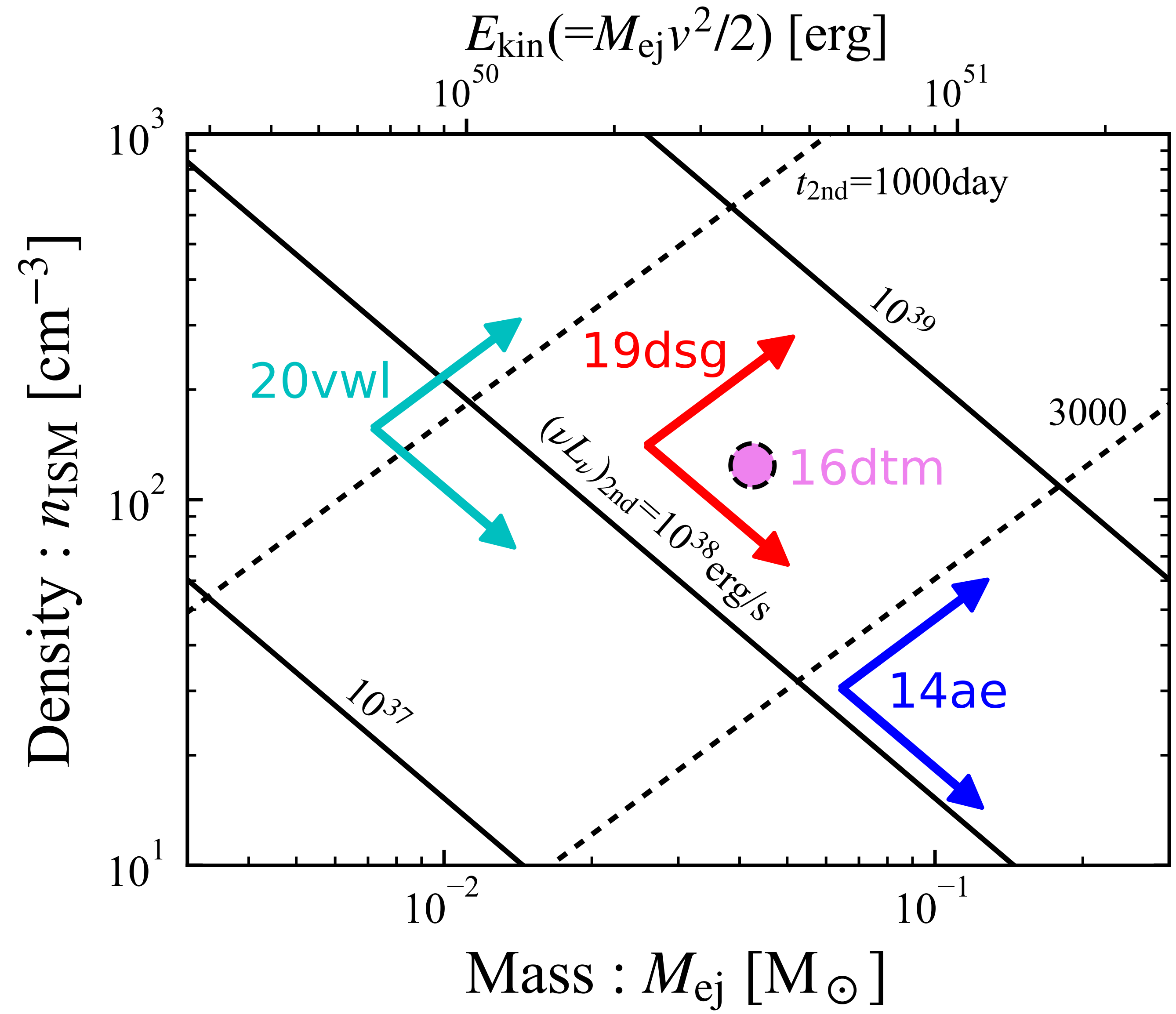
2nd peak in light curve=>**outflow mass**



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



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

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

Summary

- Tidal Disruption Events: Flares in galactic centers
- Optical & X-ray observations:
    - -Origin of optical emission is still not well understood.
    - -Reprocessing, shock, cooling envelope?
    - -But global simulations give insights.
    - -Population studies by observations will be promising
- Rate: 0.001-0.01 of supernovae
- Post star burst galaxy preference?
- Late time plateau, IR flares, Multi-peak events
- Radio: Probe of environment and outflow