初代星・初代銀河研究会2025 ＠AOSSA福井, 2025/12/1

潮汐破壊現象

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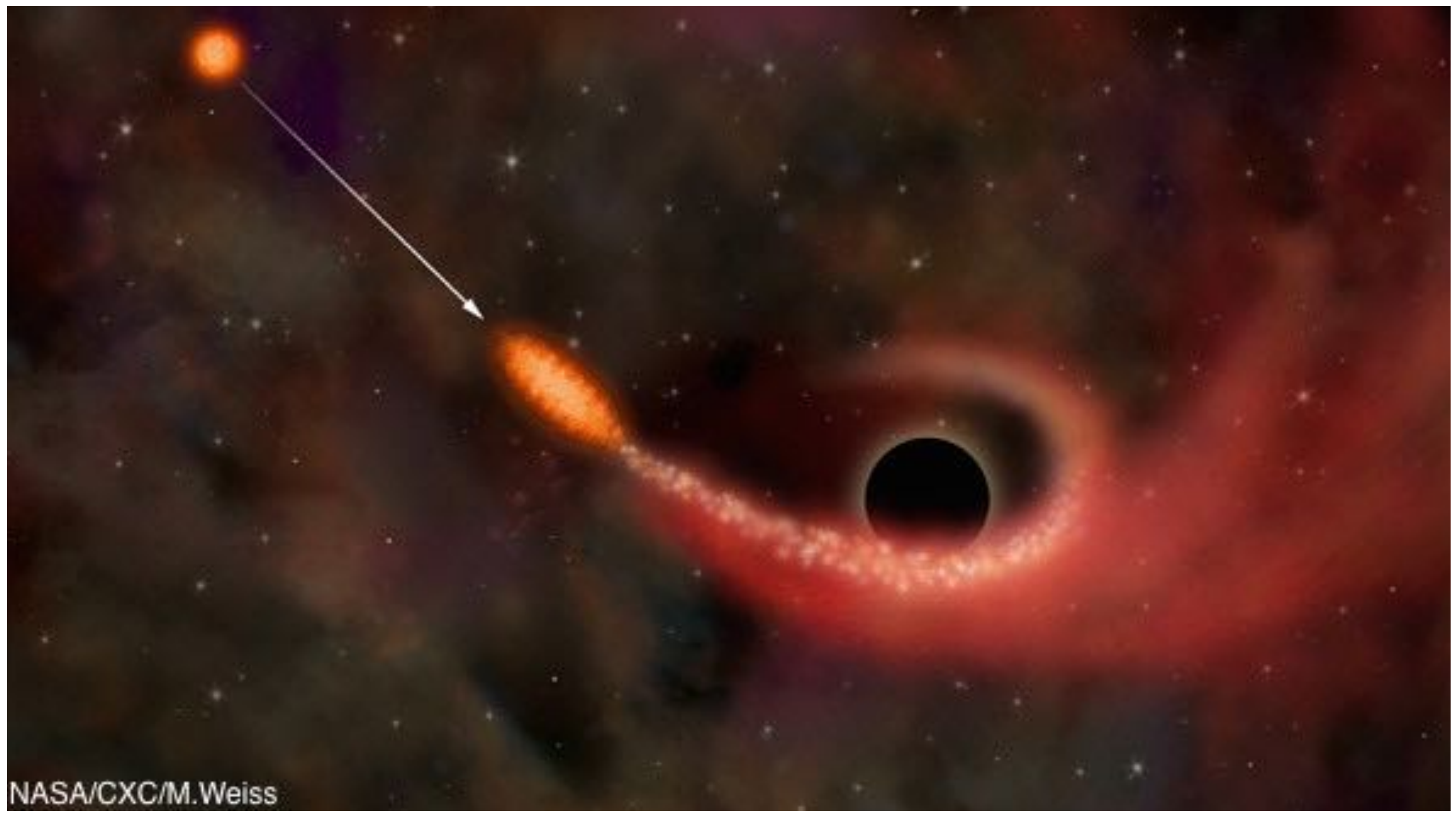
東京大学 理学系研究科 天文学専攻

Outline

1. Basics of Tidal Disruption Events
2. Recent Discovery & Progress
3. Radio Flares from TDEs

Tidal Disruption Events (TDEs)

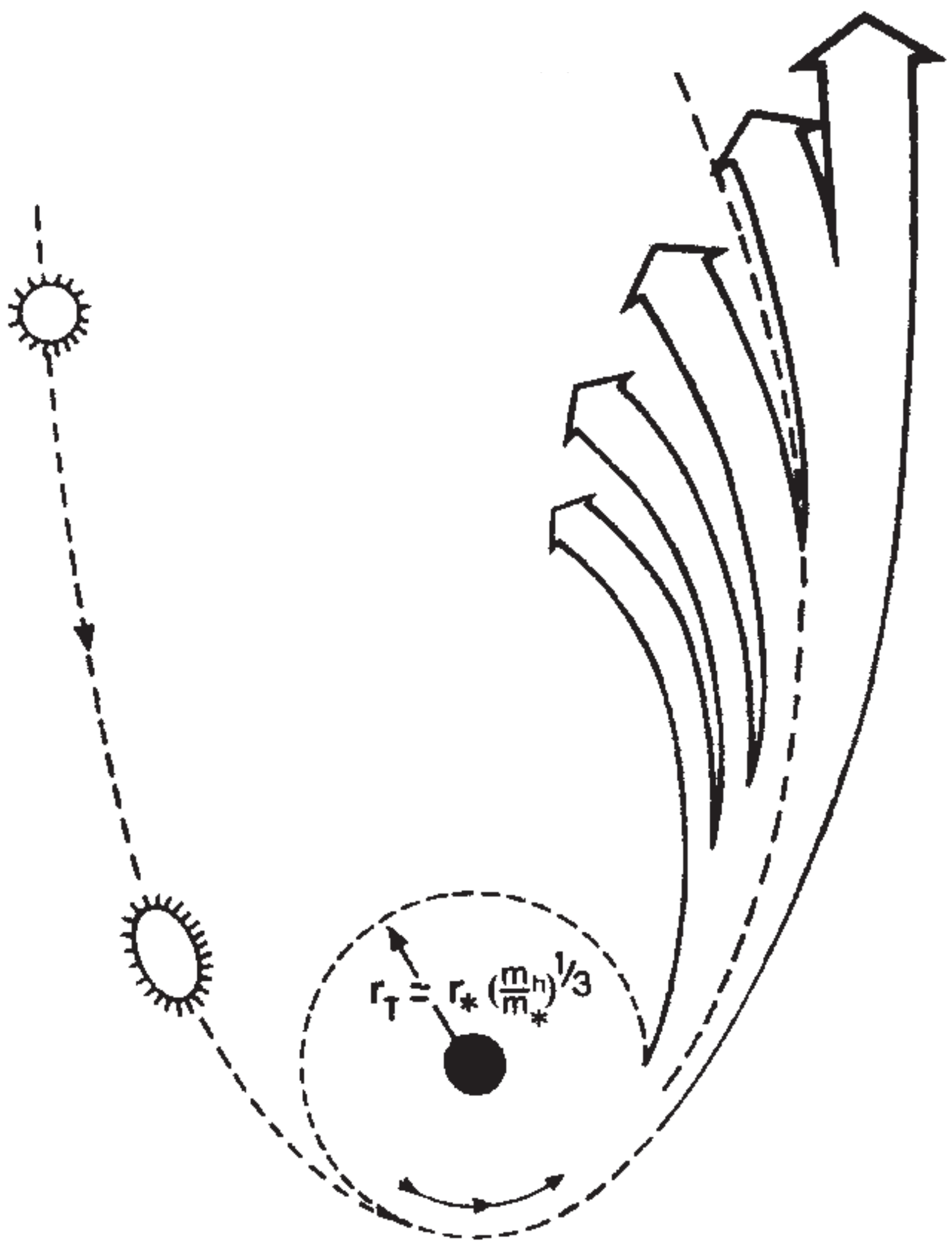


- Census of Supermassive Black Hole (SMBH) population
- Probe of environment around SMBHs (ISM&star cluster)
- Physics of Super Eddington accretion
- Relativistic jets

$$R_g = \frac{GM_\bullet}{c^2}$$

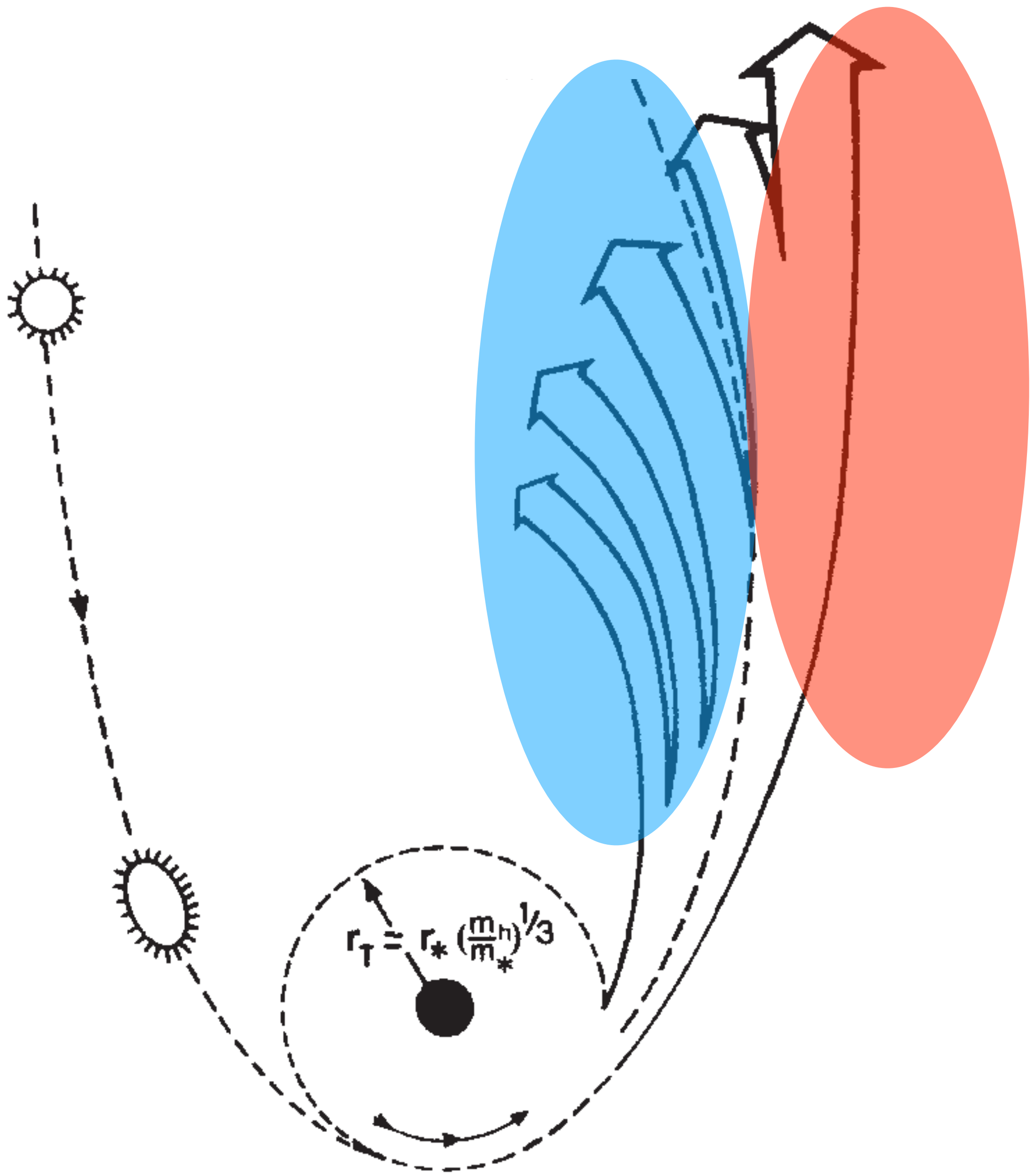
Basics of TDEs

$$R_T \equiv R_\star \left(\frac{M_\bullet}{M_\star}\right)^{1/3} \simeq 50R_g \, R_{\star,0} M_{\star,0}^{-1/3} M_{\bullet,6}^{-2/3}$$



Rees88,Phinney89

Basics of TDEs



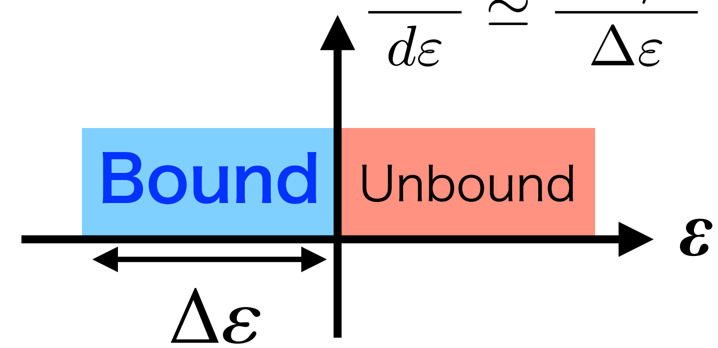
Rees88,Phinney89

$$R_{\rm T} \equiv R_\star \left(\frac{M_\bullet}{M_\star}\right)^{1/3} \simeq 50R_{\rm g}\, R_{\star,0} M_{\star,0}^{-1/3} M_{\bullet,6}^{-2/3}$$

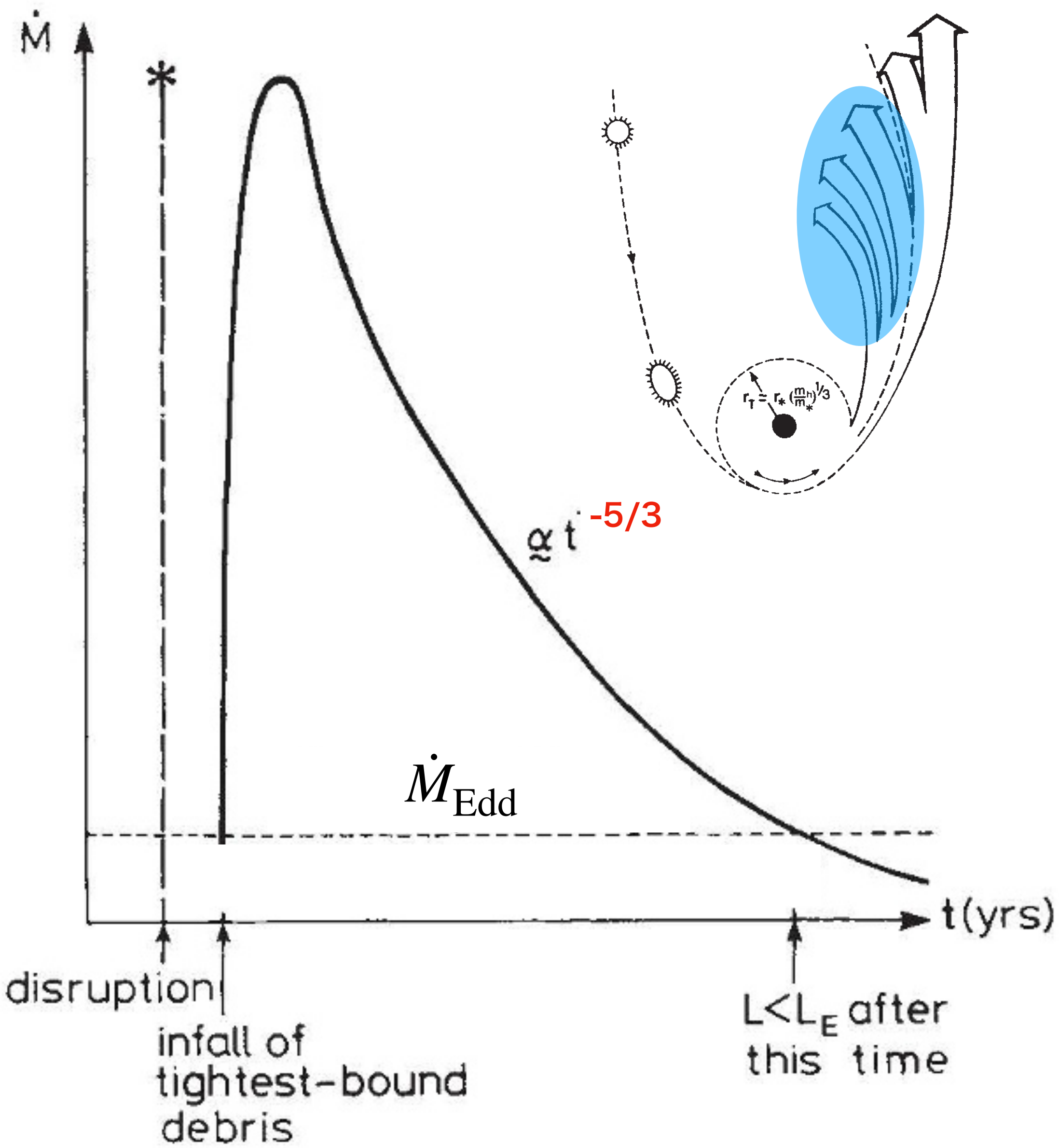
$$\Delta\varepsilon = \left(-\frac{GM_\bullet}{R_{\rm T}}\right) - \left(-\frac{GM_\bullet}{R_{\rm T} \pm R_\star}\right)$$

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

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



Basics of TDEs



Rees88,Phinney89

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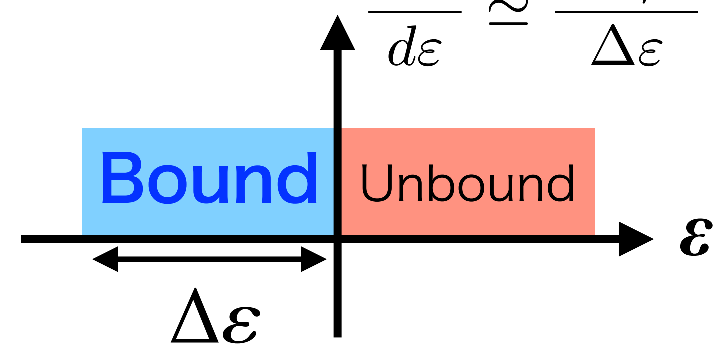


$$t = \frac{2\pi G M_\bullet}{(2|\varepsilon|)^{3/2}}$$

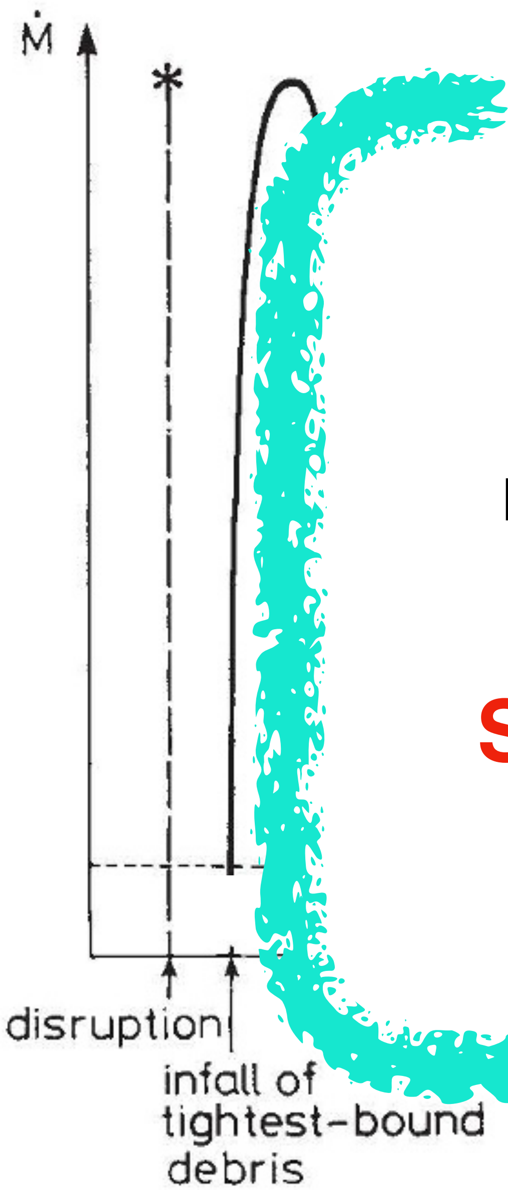
$$\dot{M}_{\rm fb} = \frac{dM}{d\varepsilon}\frac{d\varepsilon}{dt} = \dot{M}_{\rm peak}\left(\frac{t}{t_{\rm fb}}\right)^{-5/3}$$

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

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

Basics of TDEs

$$R_{\rm T} \equiv R_\star \left(\frac{M_\bullet}{M_\star}\right)^{1/3} \simeq 50R_{\rm g} \quad R_{\star,0}M_{\star,0}^{-1/3}M_{\bullet,6}^{-2/3}$$



Expectation

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

Soft X-ray/UV flares with ~$L_{\rm Edd}$ & ~yr @galactic nuclear region

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

nbound

ε

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

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

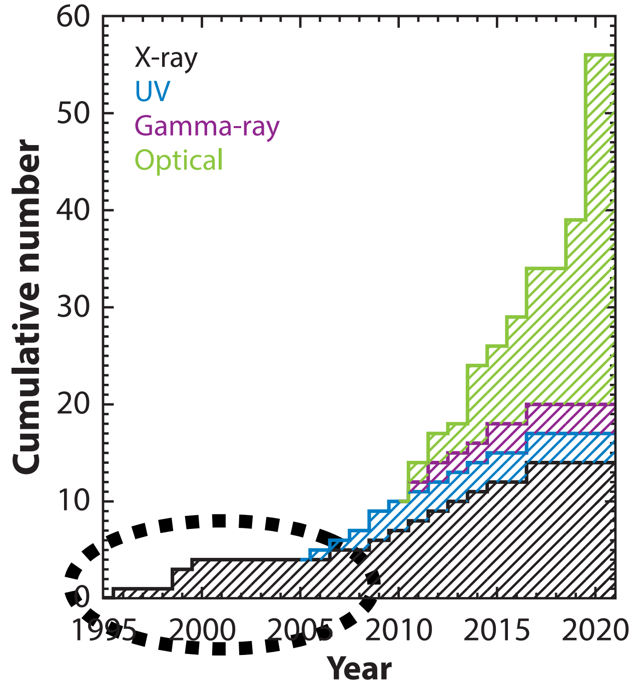
$$\dot{M}_{\rm peak} \simeq 100\dot{M}_{\rm Edd} \quad R_{\star,0}^{-3/2}M_{\star,0}^{2}M_{\bullet,6}^{-1/2}$$

Rees88,Phinney89

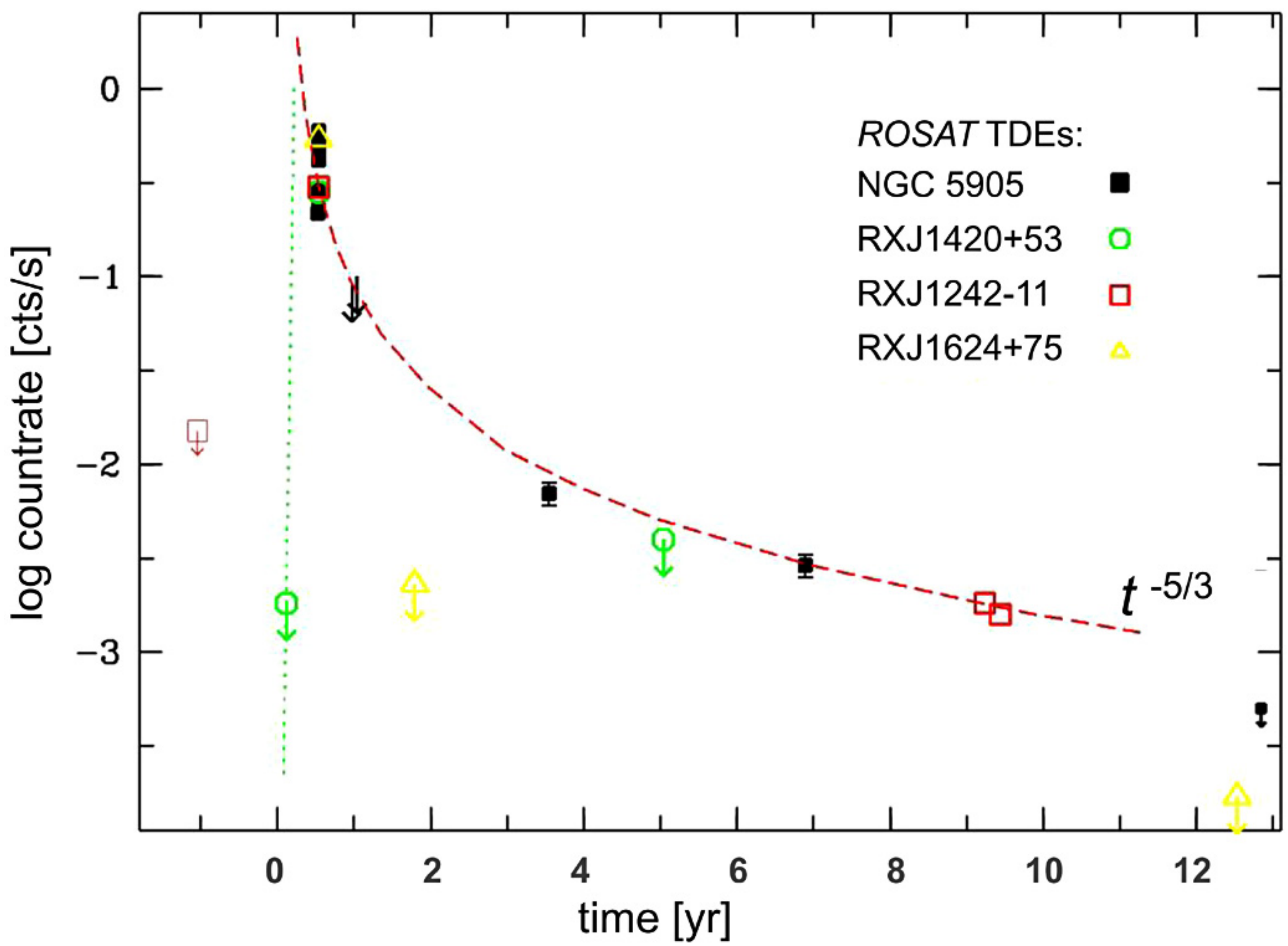
Observation: X-ray

X-ray TDEs (1990s~)

Gezari21



Komossa15

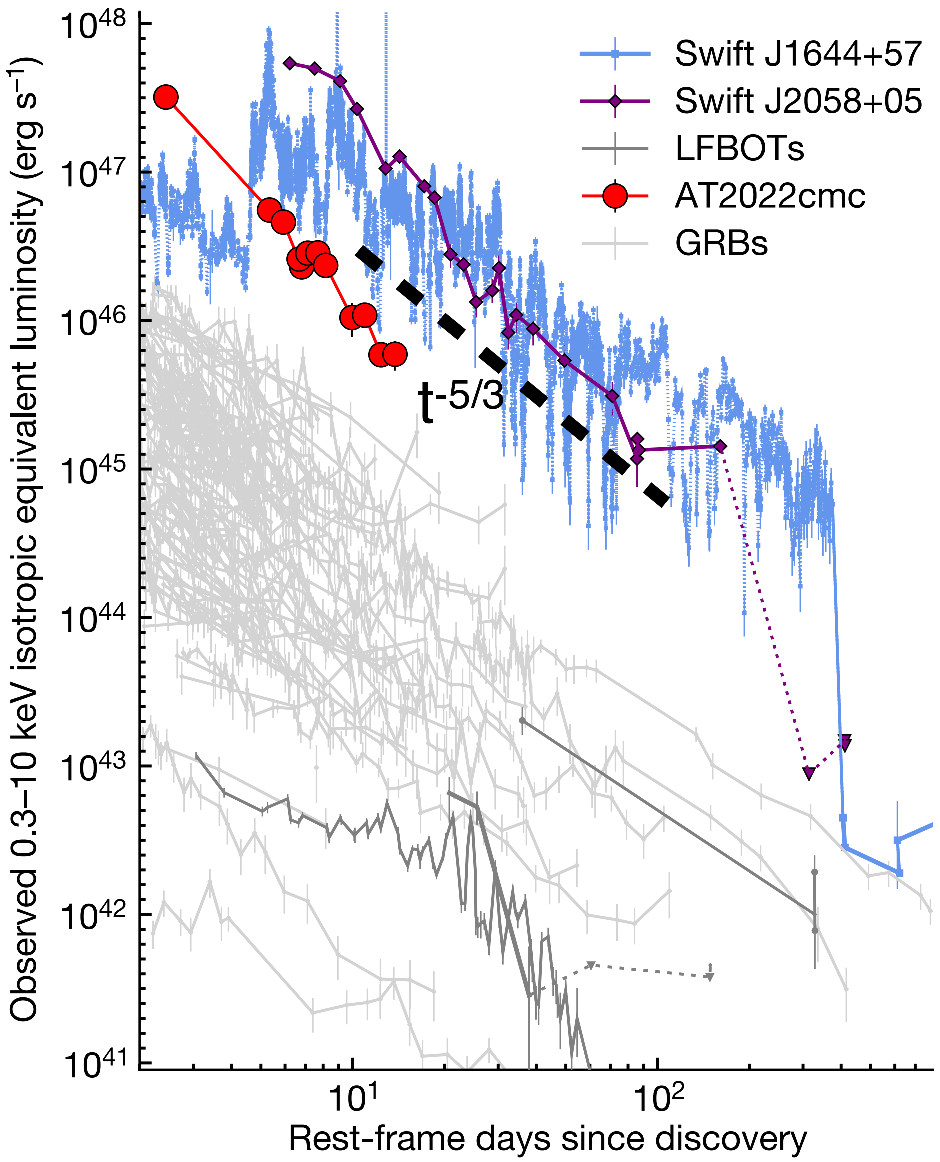


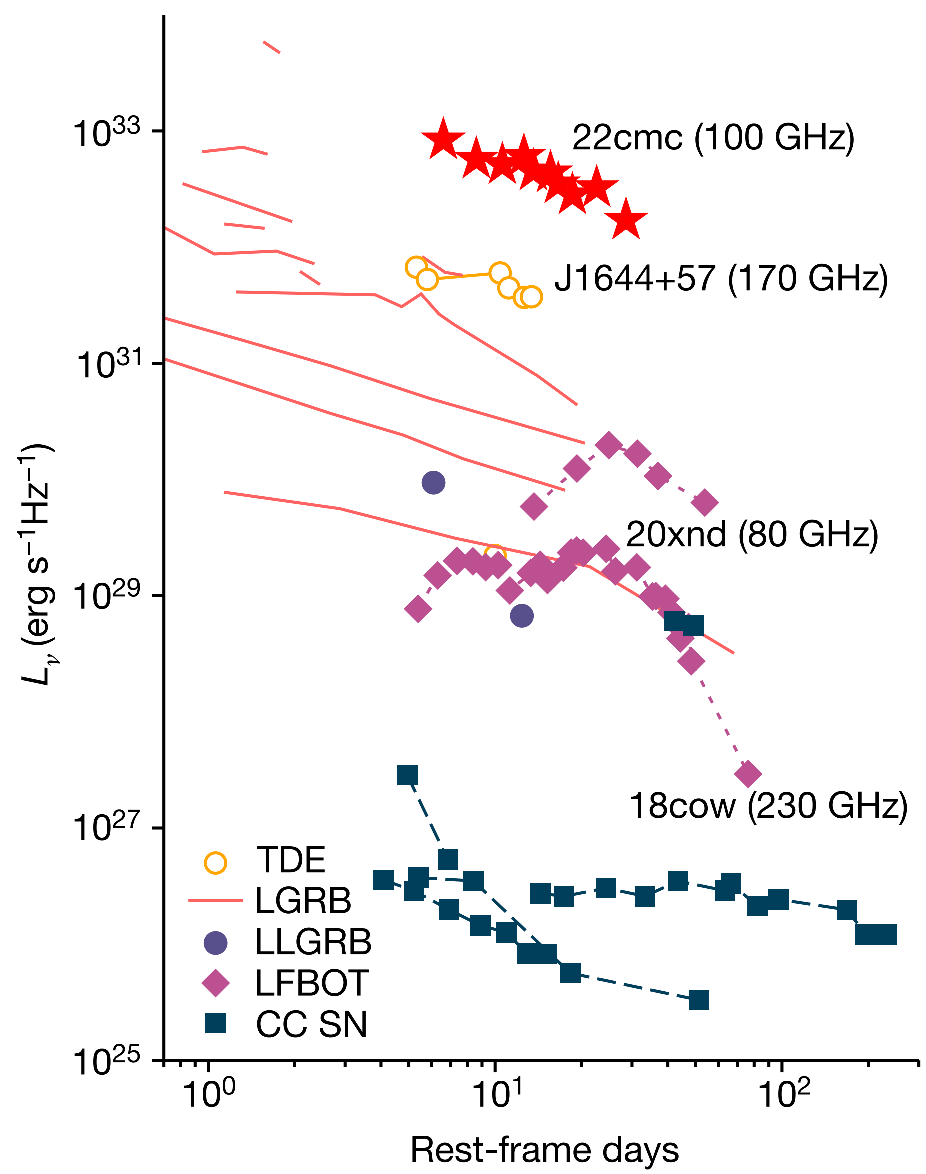
ROSAT all sky survey: 1990-91
20% of sky @0.1-2.4 keV

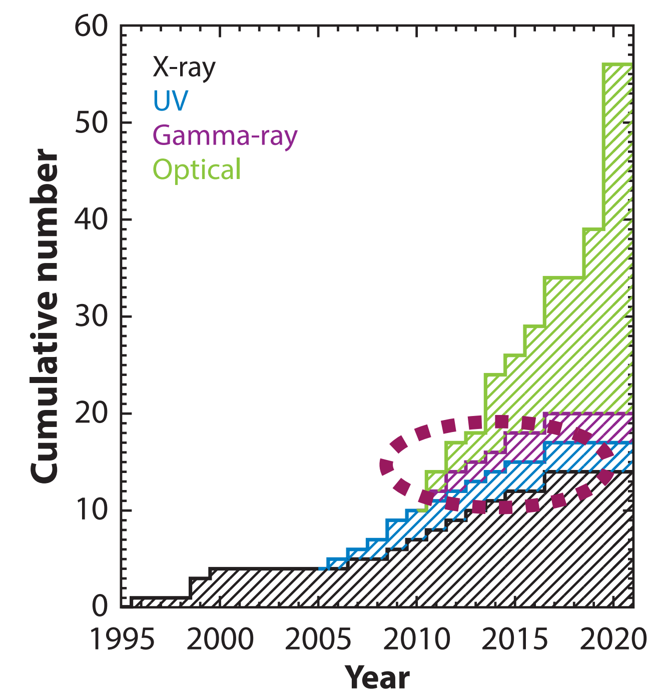
- ✓In galactic nuclear regions (not AGN)
- ✓$L_X \sim 10^{44}$ erg/s ($\sim L_{Edd}$)
- ✓kT~0.1keV
- ✓$L \sim t^{-5/3}$

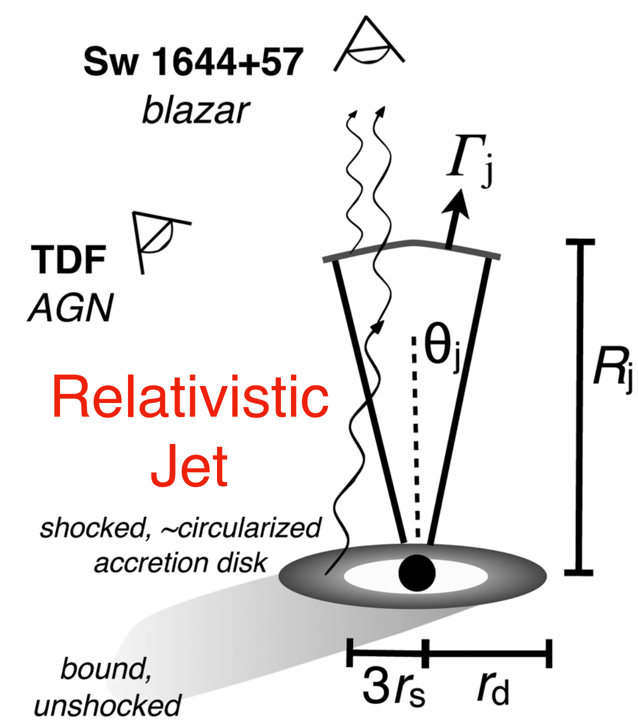
Observation: Gamma-ray

Bloom+11,Burrows+11,Andreoni+22



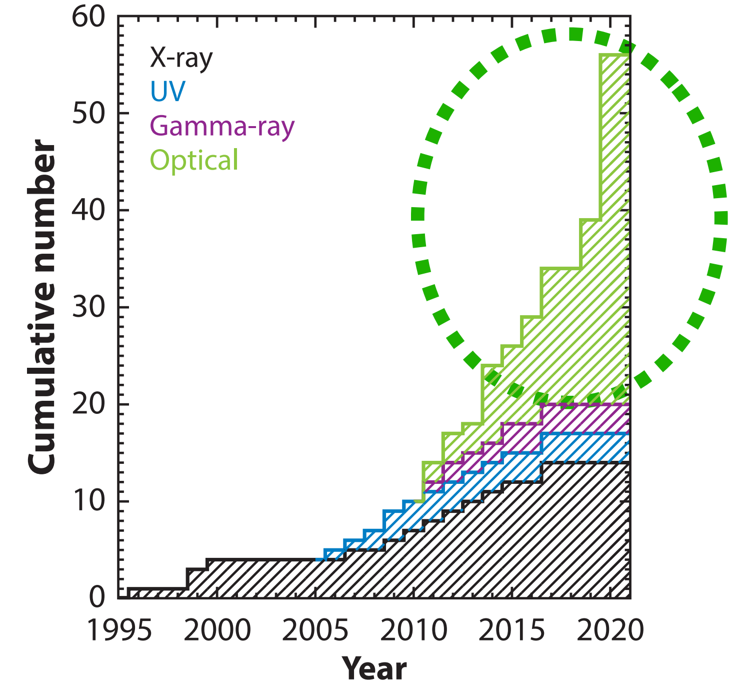






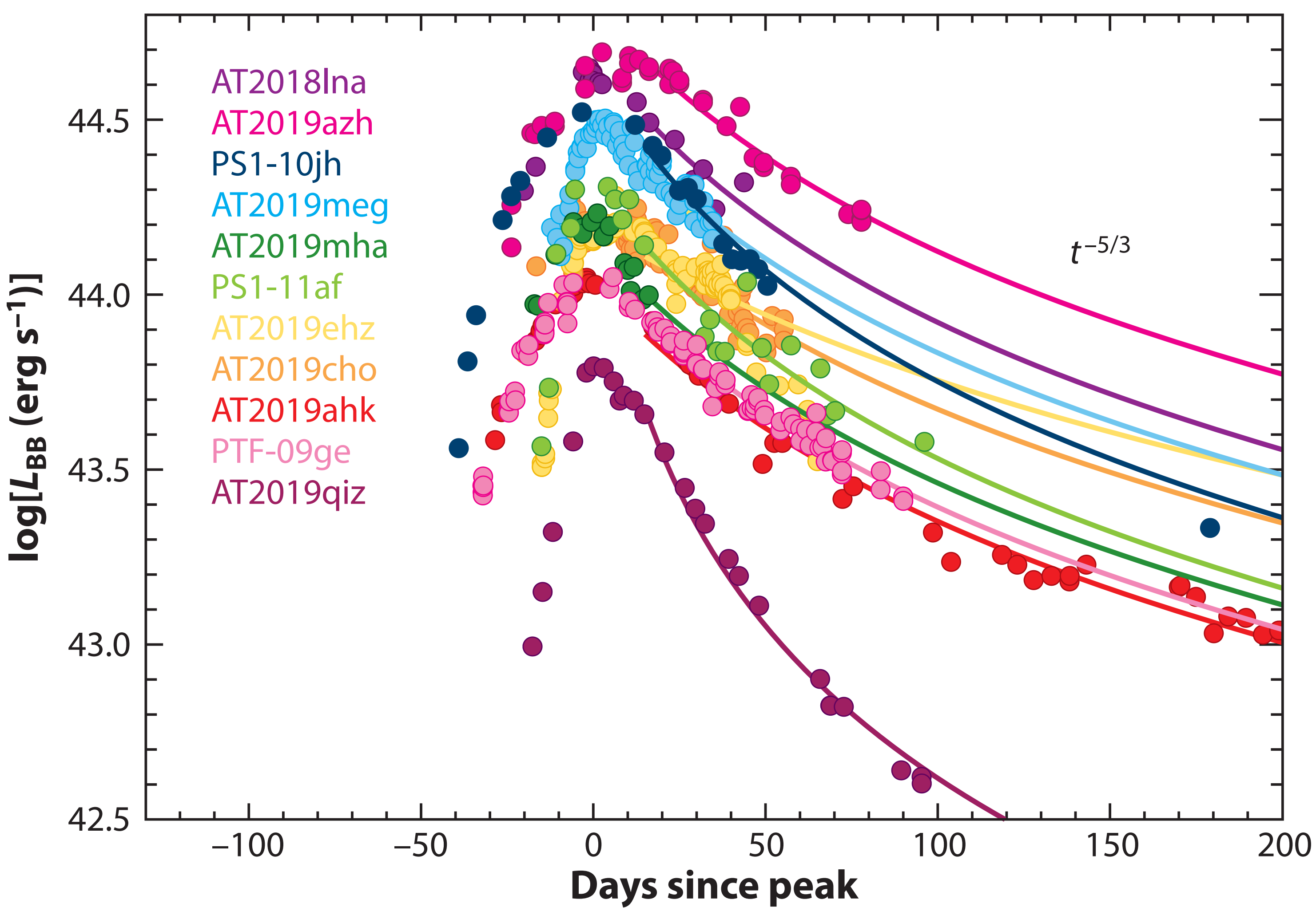
Observation: Optical

Gezari21



Optical TDEs (2010s~)

Gezari21



✓In galactic nuclear regions (not AGN)

✓$L_x \sim 10^{44}$ erg/s ($\sim L_{Edd}$)

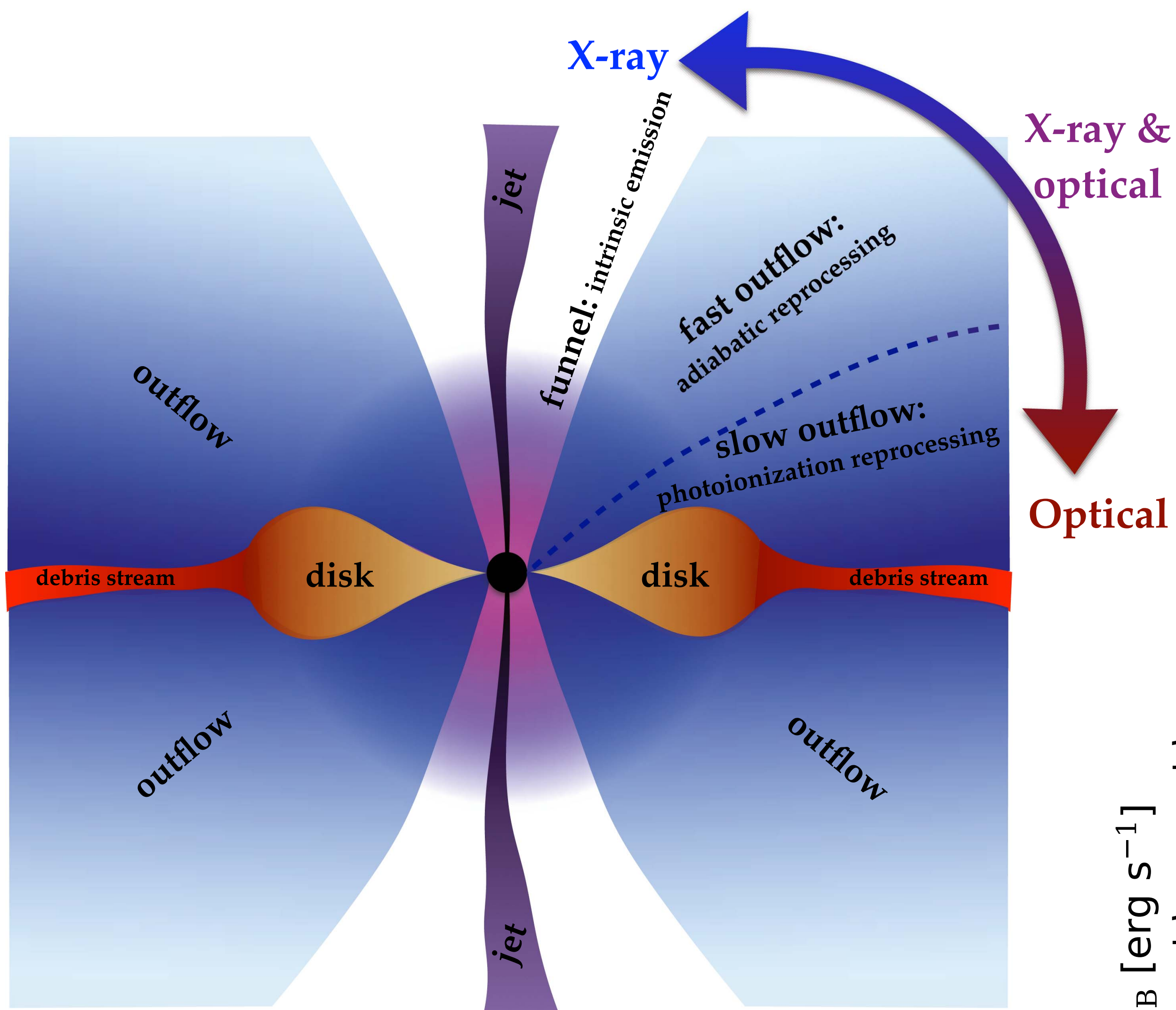
✓$T \sim 30000$K, $R_{bb} \sim 10^{15}$cm

✓$L \sim t^{-5/3}$

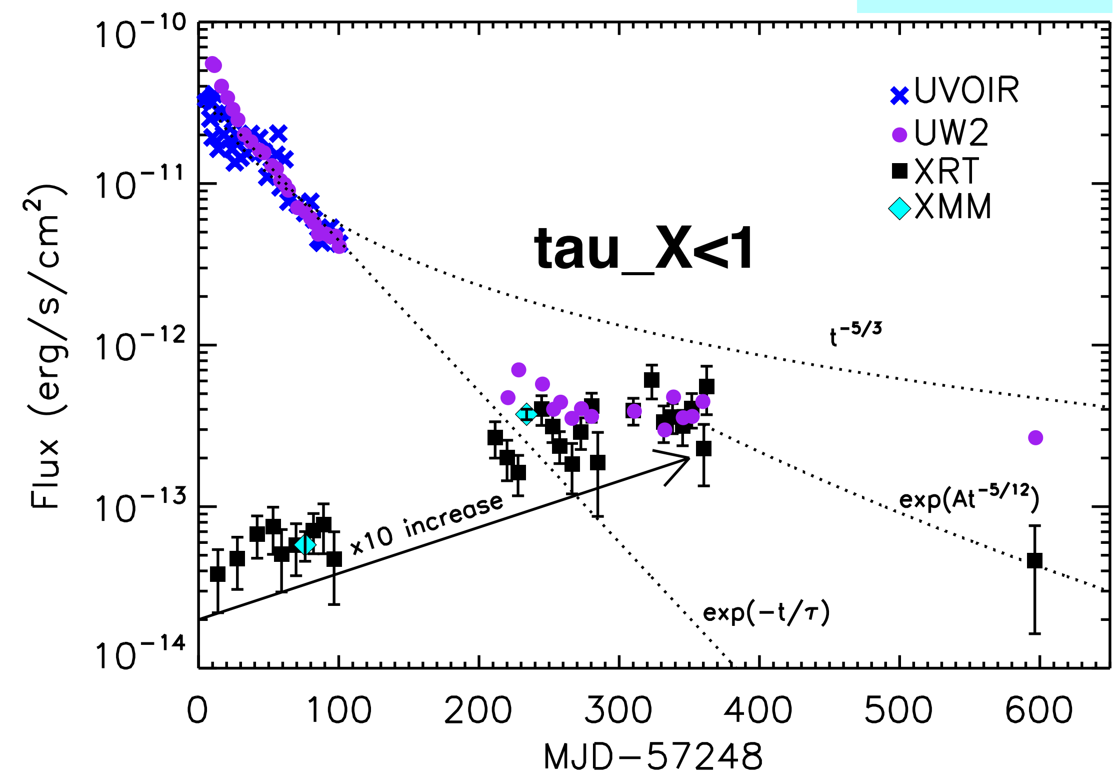
How to Produce Optical Emission?

Strubbe&Quataert09,Metzger&Stone16,Roth+16,Dai+18

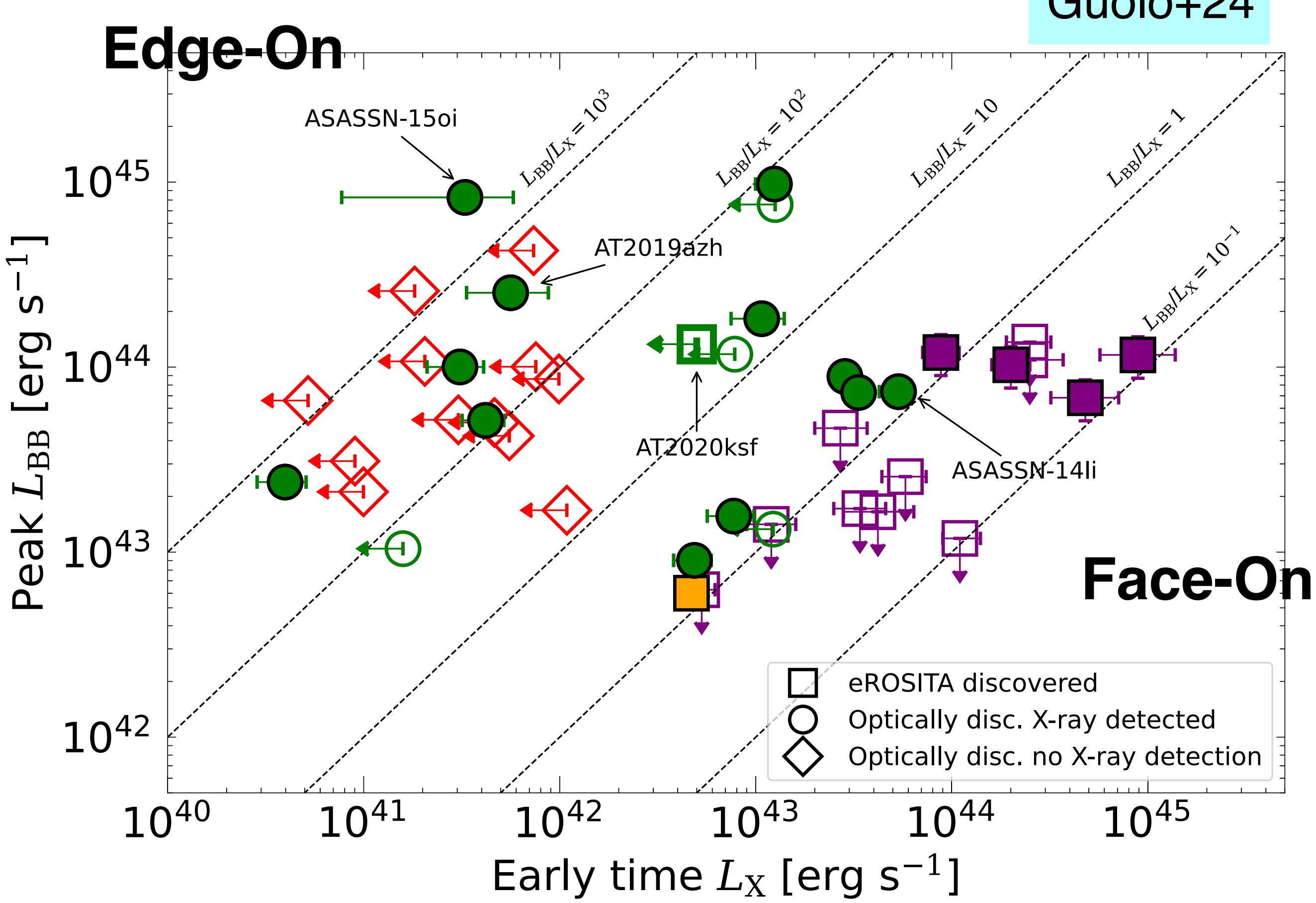
Reprocessing X-ray from Disk?



Gezari+17



Guolo+24

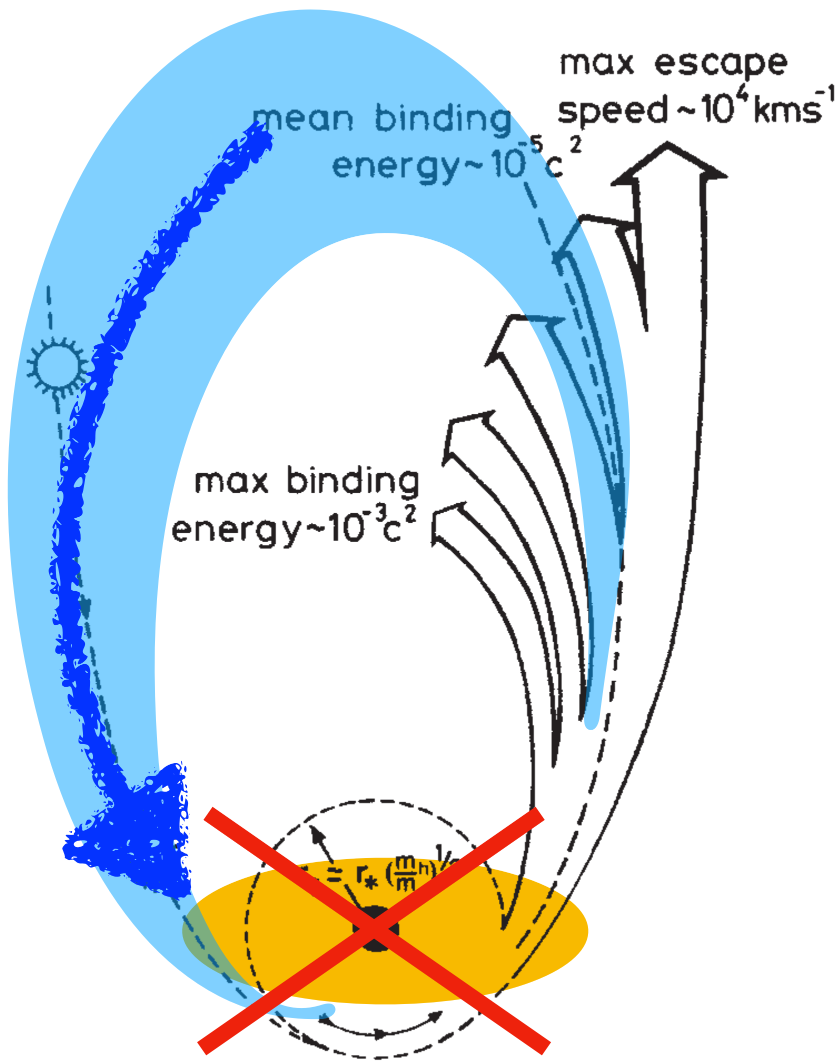


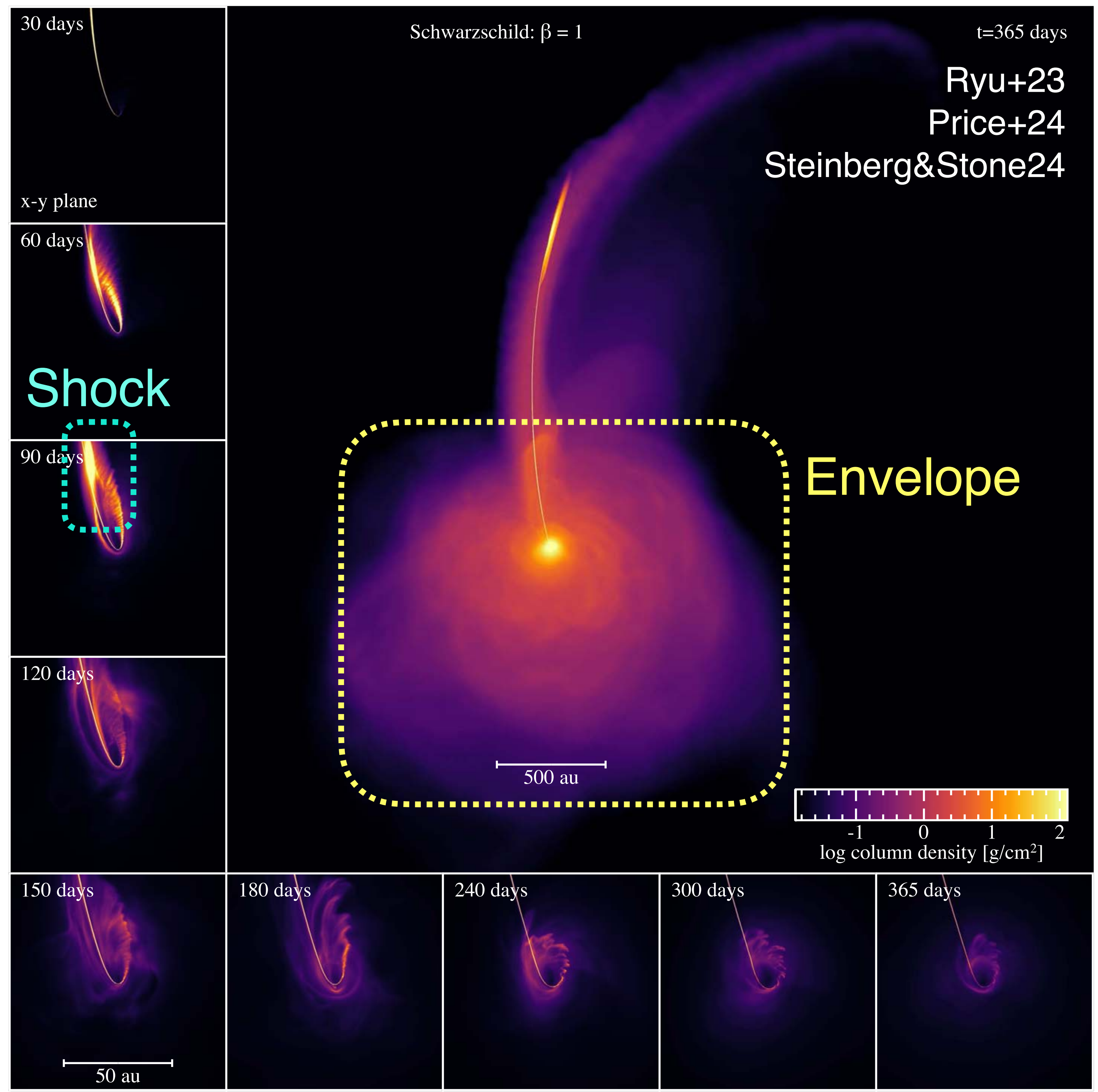
X-ray from Disk

=> Absorption by Outflow

=> Reprocessing to Optical

Slow Circularization?





No Prompt Disk Formation!

- ✓ Shock Interaction
  - Piran+15,Ryu+18…
- ✓ BH envelope?
  - Metzger22,Krolik+24

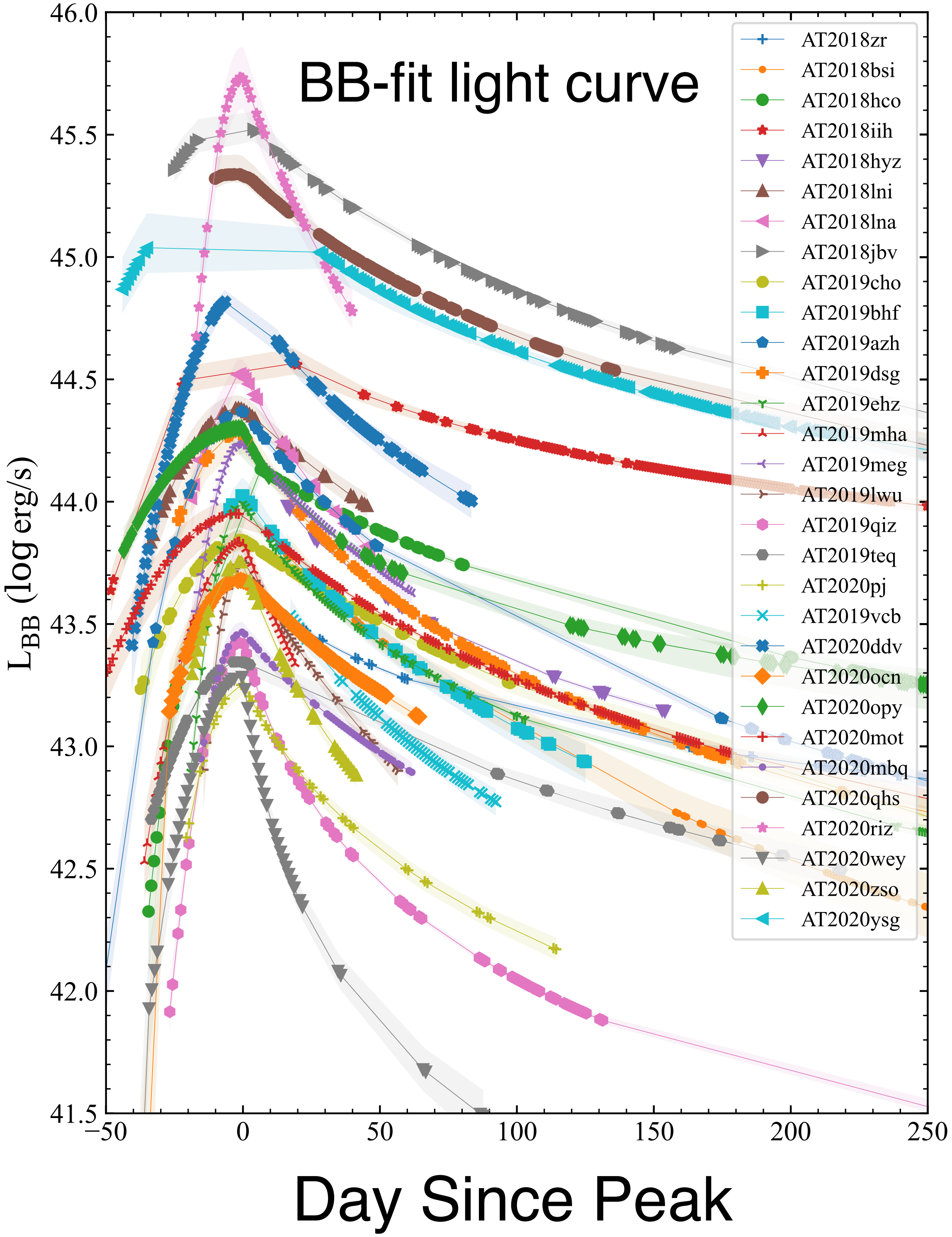
=>今後の課題

Outline

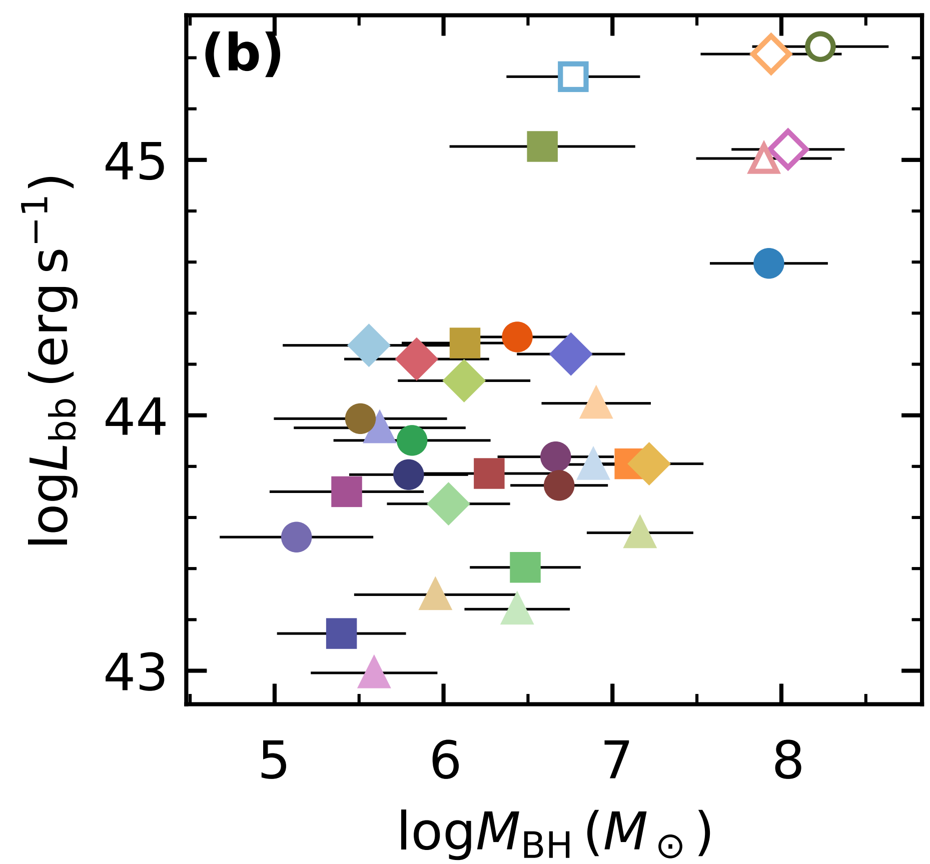
1. Basics of Tidal Disruption Events
2. **Recent Discovery & Progress**
3. Radio Flares from TDEs

More Optical TDEs: Population Study

Hammerstein+23



Yao+23



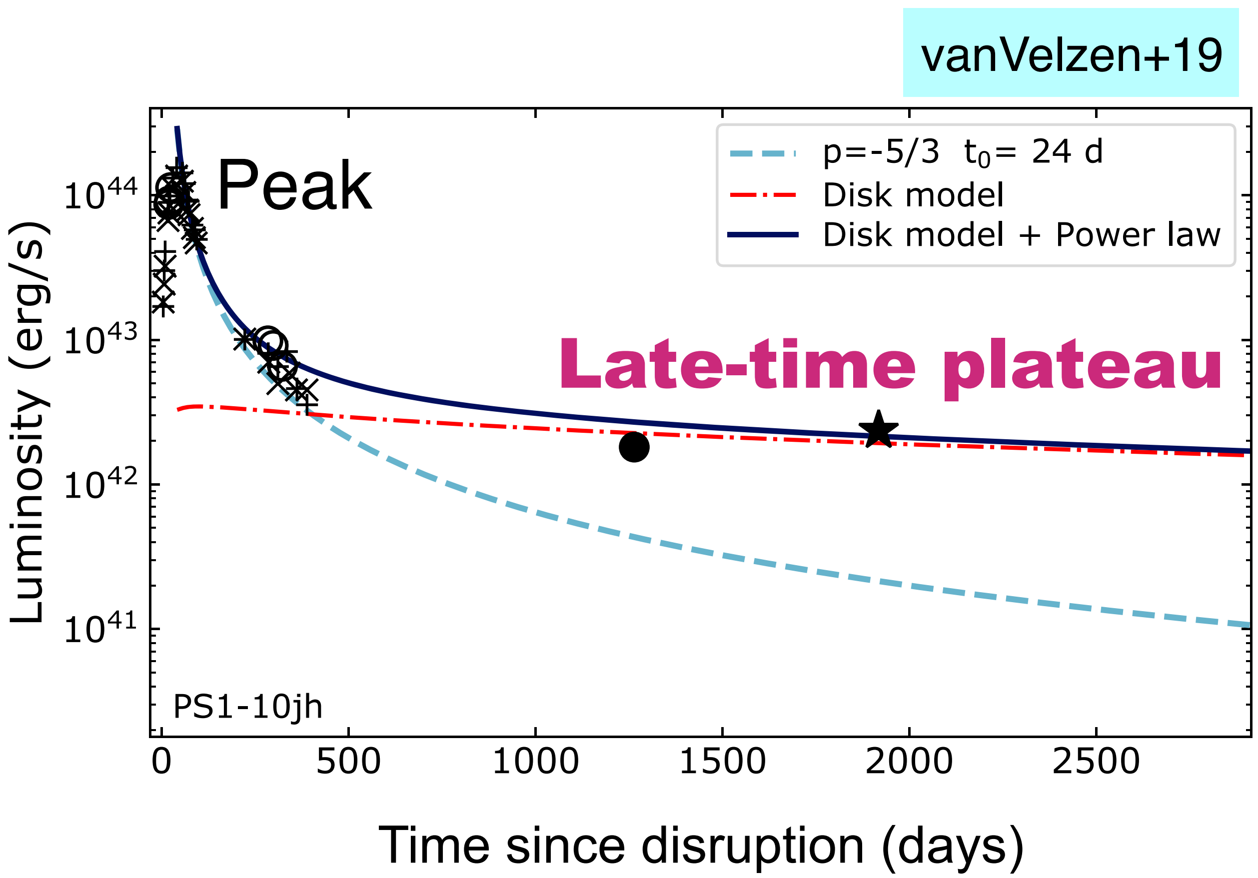
✓ Measuring σ of host

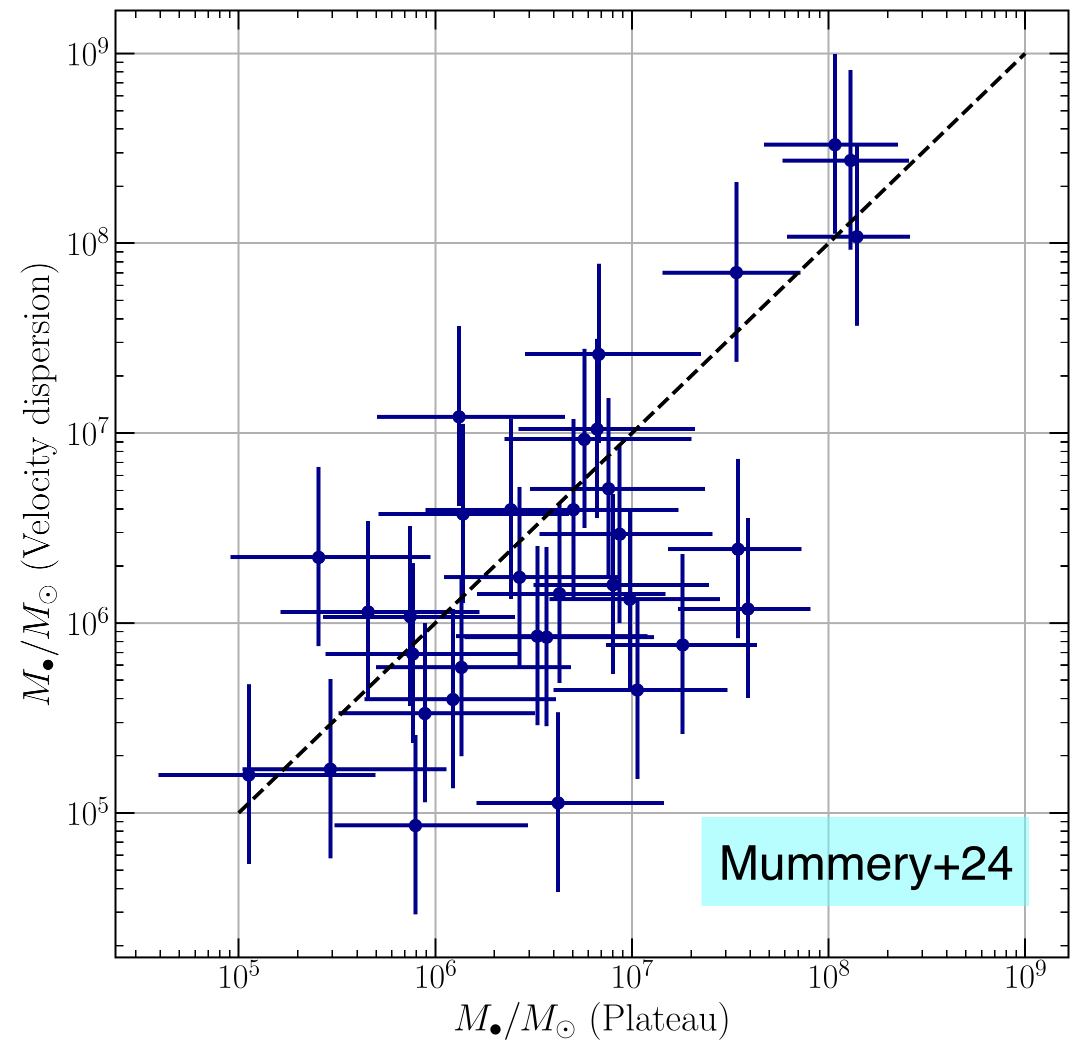
=> BH mass from M_{BH}-σ relation

✓ Possible correlations(?)

=> SMBH Census by TDEs(?)

Late-time Plateau: New Indicator?

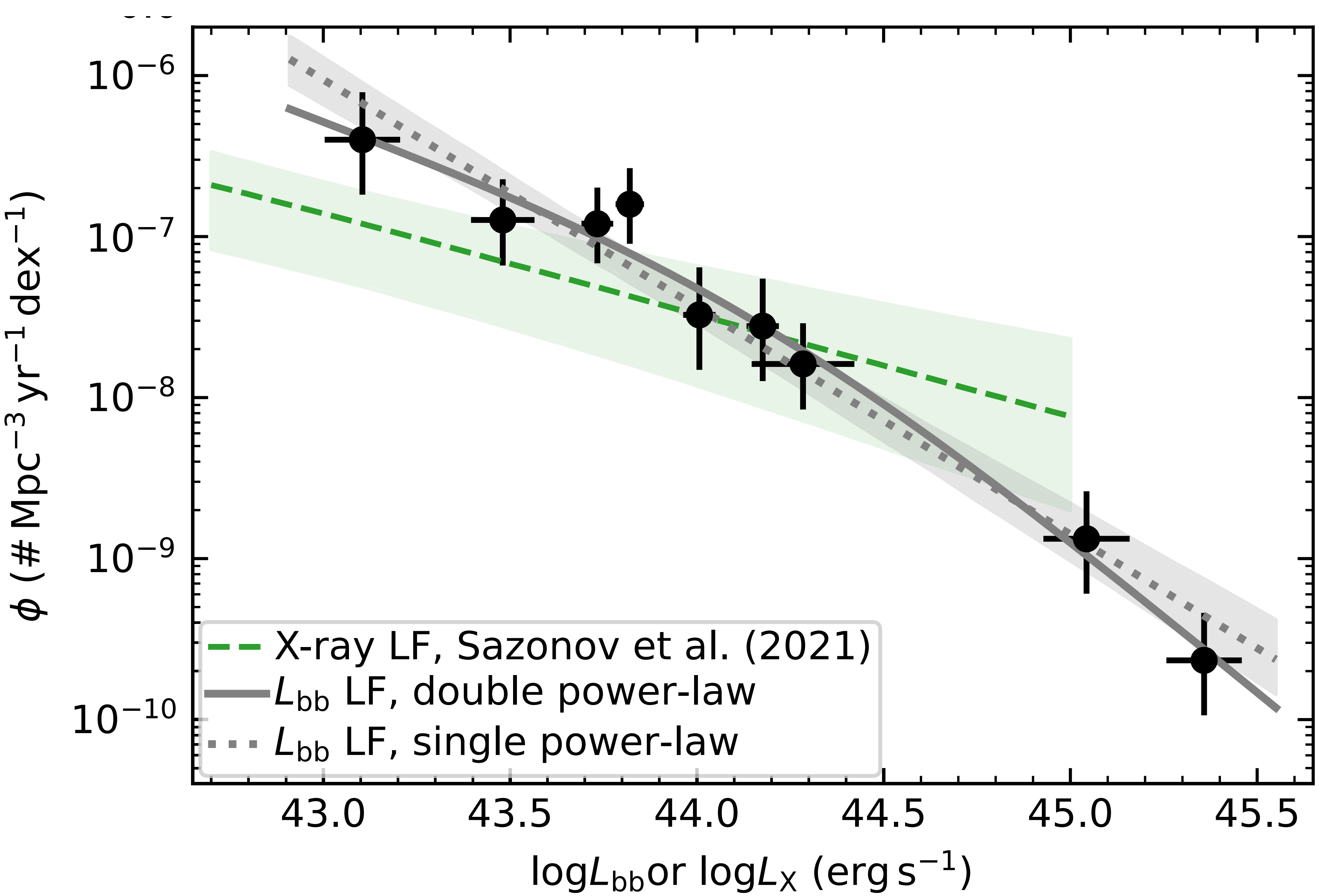




- ✓ Opt/UV light curves flatten at late time: “Plateau”
- ✓ Plateau is ubiquitous (~40/60 TDEs)
- ✓ Disk model predicts $L_{pl} \sim M_{BH}^{2/3}$ => More reliable estimate of M_{BH}?

Event rate

Yao+23



✓ Optical, X-ray, IR surveys give comparable event rate

✓ Rate ~ 1e-7/Mpc3/yr ~ 0.001x(SN rate)~**1e-5**/galaxy/yr

$$f_{\mathrm{lim}} \sim \frac{L}{4\pi d^2}$$

Prospects?

$$\dot{N} \sim \phi \times d^3 \sim \phi \left(\frac{L}{f_{\mathrm{limi}}}\right)^{3/2}$$

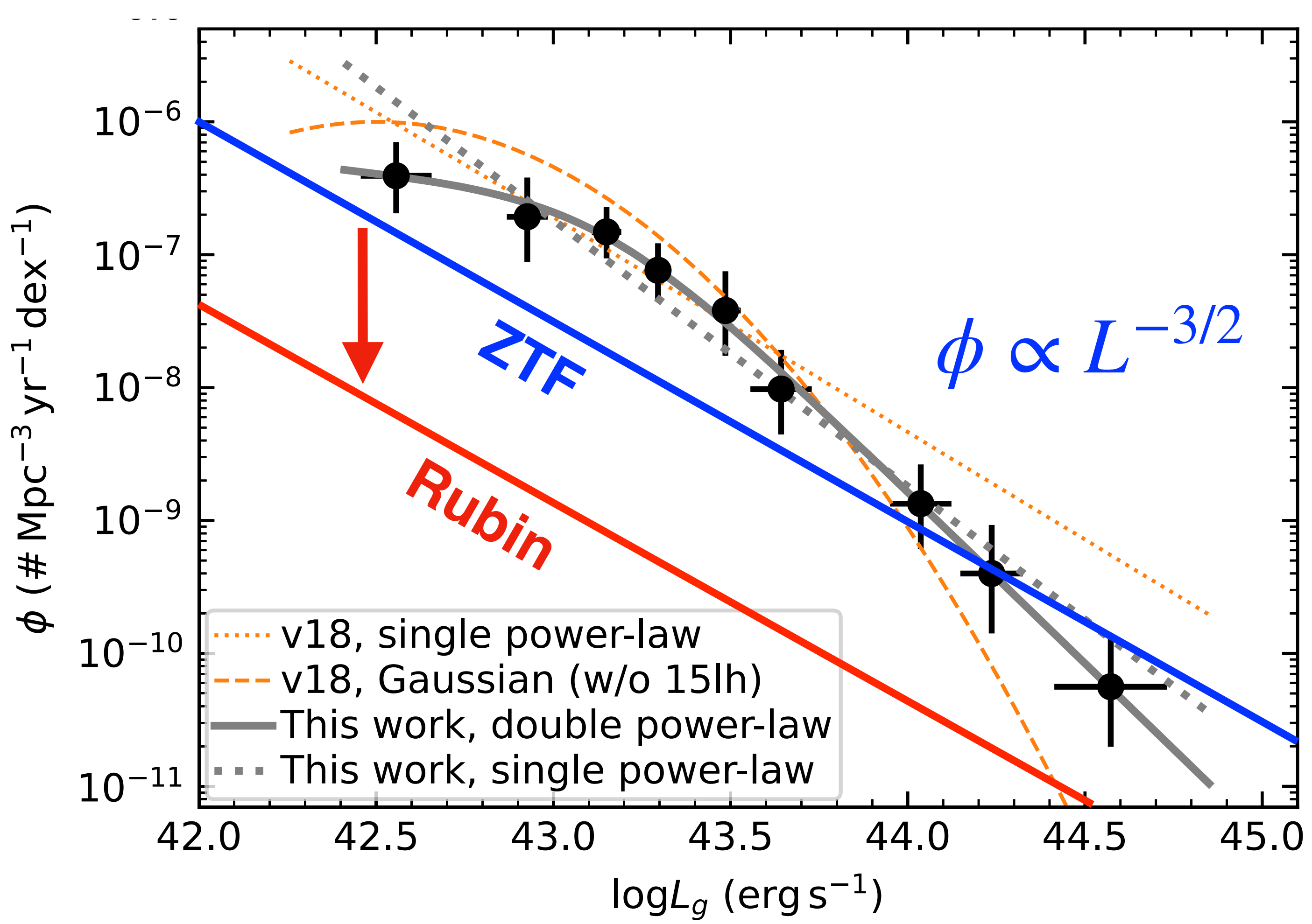
ZTF $f_{\mathrm{limit}} = 21\mathrm{mag}$

=> ~10 TDE/yr

Rubin $f_{\mathrm{limit}} = 24.5\mathrm{mag}$

=>f_limit x0.1, d x3, **N x 30**

Yao+23



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Yao+23

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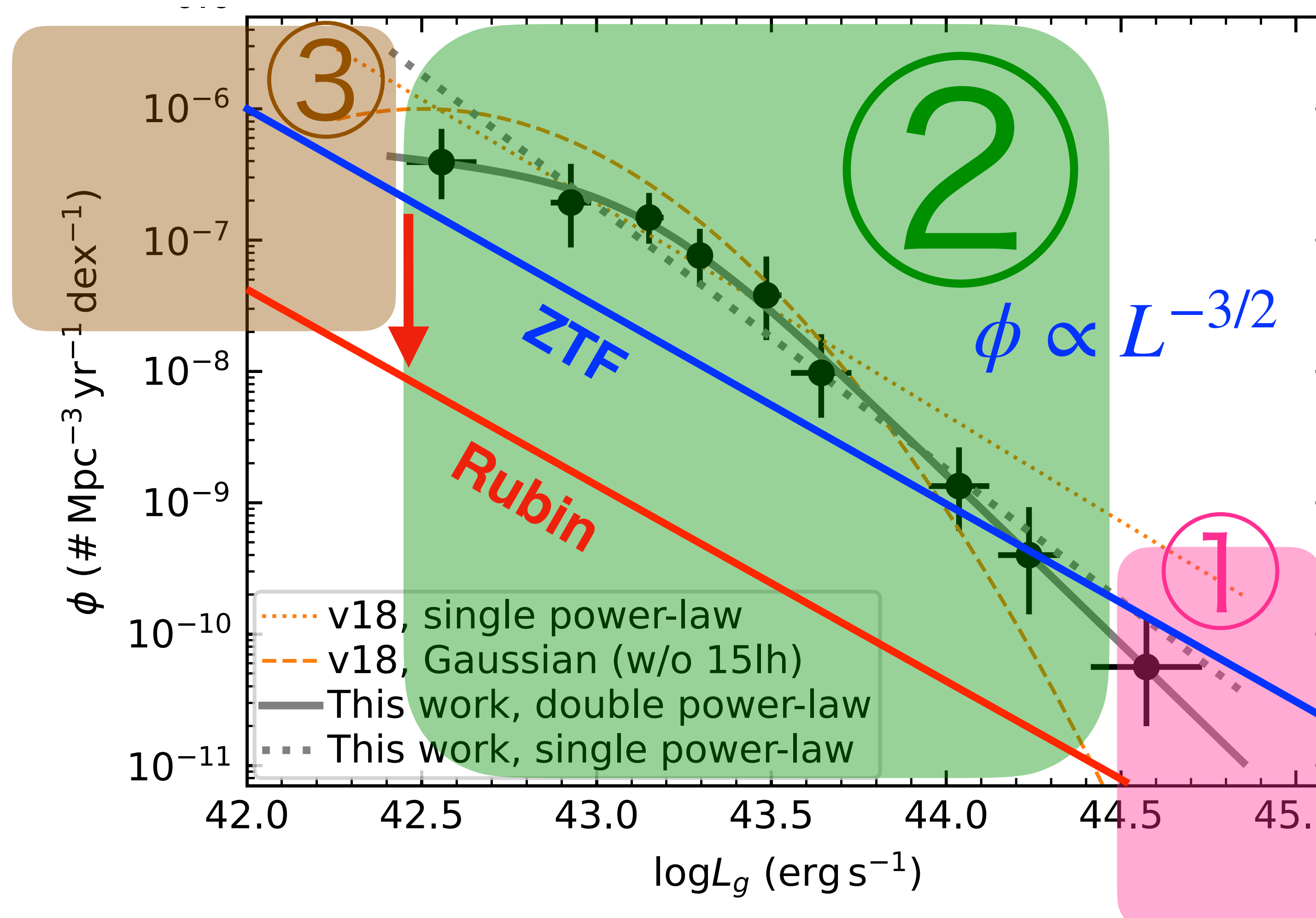
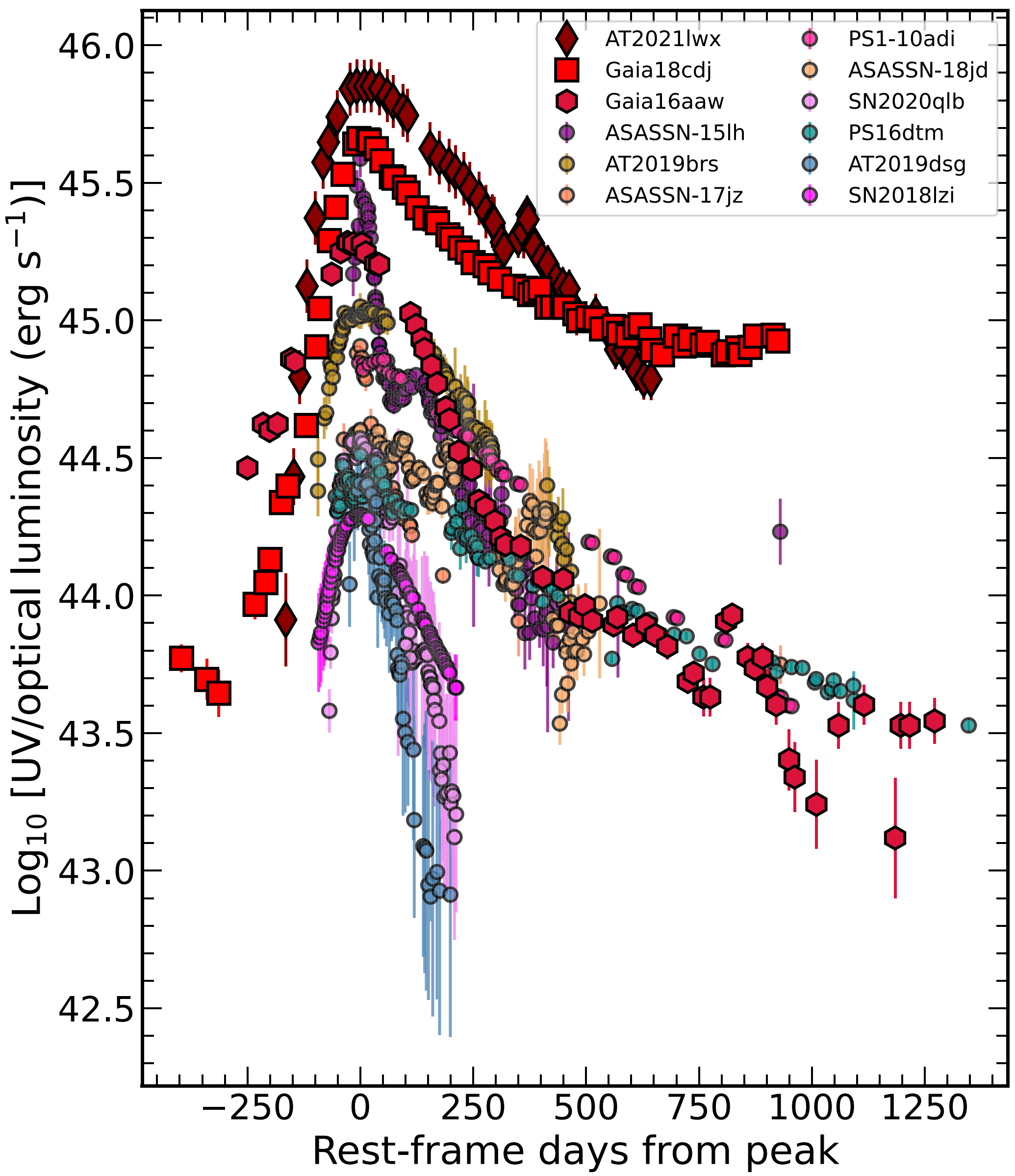


①**Bright-End** Objects => Extreme Nuclear Transients, Massive Star (Pop III) TDE?

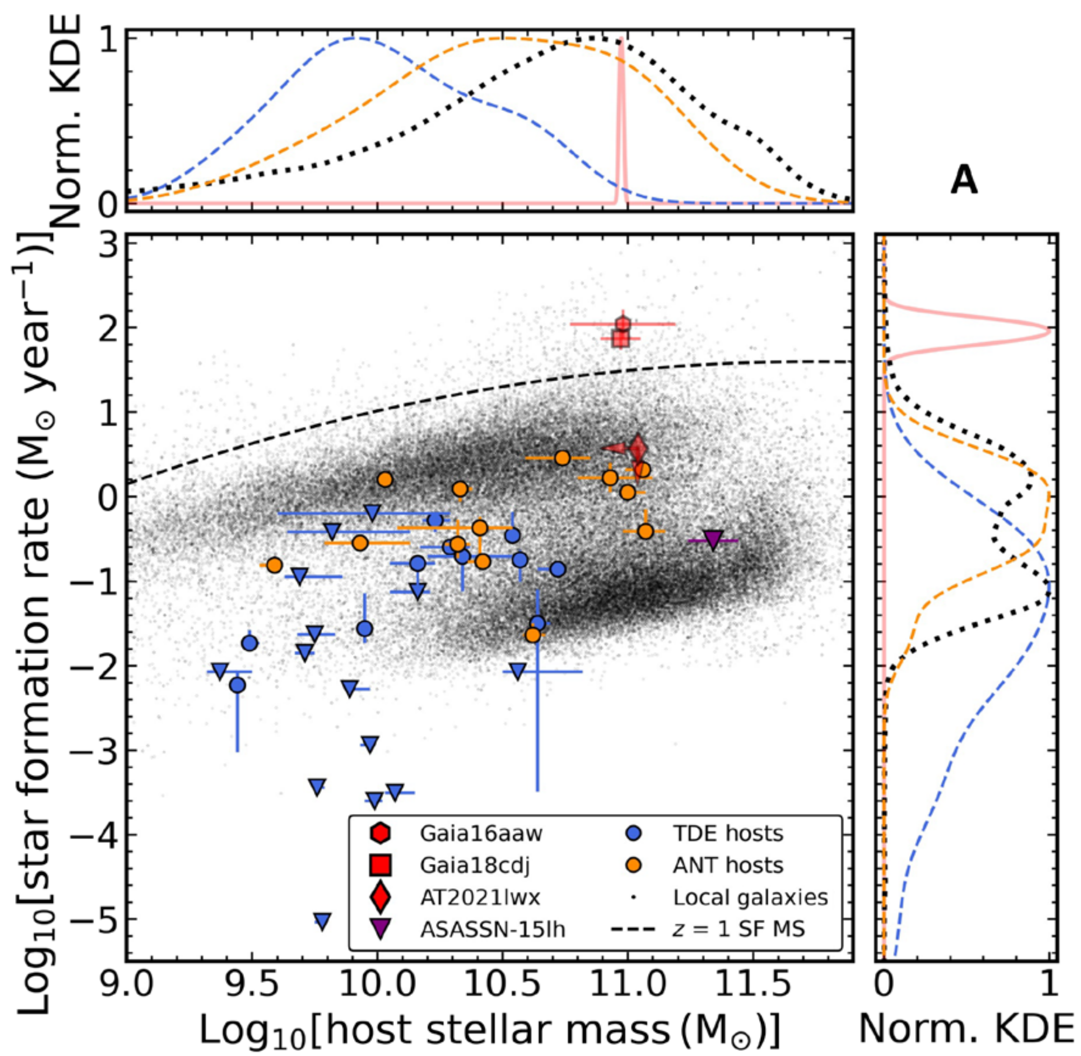
②**Many** Normal Objects => Peculiar events, e.g., Multi-peak events

③**Faint-End** Objects => Buried in host? Dwarf galaxy/Off-nuclear TDE (IMBH)

Extreme Nuclear Transient (ENT)



Subrayan+23,Wiseman+23,Hinkle+25,Graham+25



- ✓ Brightest Optical Transient, Very rare (>1e-3/yr/Gpc3)
- ✓ Happen in very peculiar galaxies (SFR>100Msun/yr)

=> Massive Star TDEs?

Pop III TDEs?

Karmen+25

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

$$\dot{M}_{\rm peak} \sim 100\dot{M}_{\rm Edd}$$

$$t_{\rm fb} \sim 40{\rm day}$$

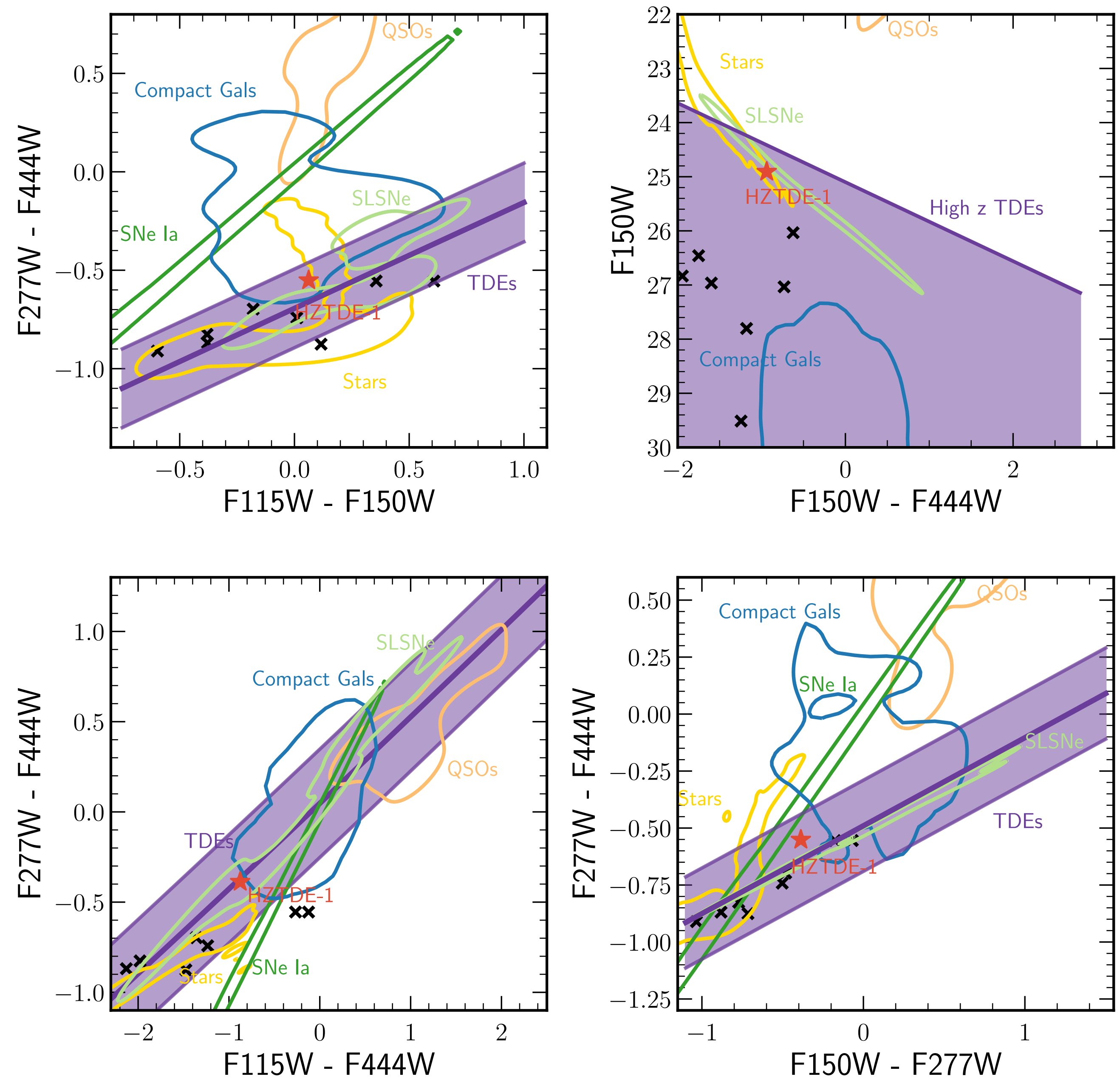
Massive Pop III (100Msun)

$\sim 10^6\dot{M}_{\rm Edd}$ $\sim 0.4{\rm day}$

- ✓ Maybe Bright TDE
- ✓ Event rate?

  ~ 1/Gpc3/yr

Karmen+25 but Inayoshi+24



- ✓ Selecting in Color diagrams
- ✓ One candidate at z~5, Mg~-21mag

$$f_{\rm lim} \sim \frac{L}{4\pi d^2}$$

Prospects?

Yao+23

$$\dot{N} \sim \phi \times d^3 \sim \phi \left(\frac{L}{f_{\rm limi}}\right)^{3/2}$$

ZTF $f_{\rm limit} = 21{\rm mag}$

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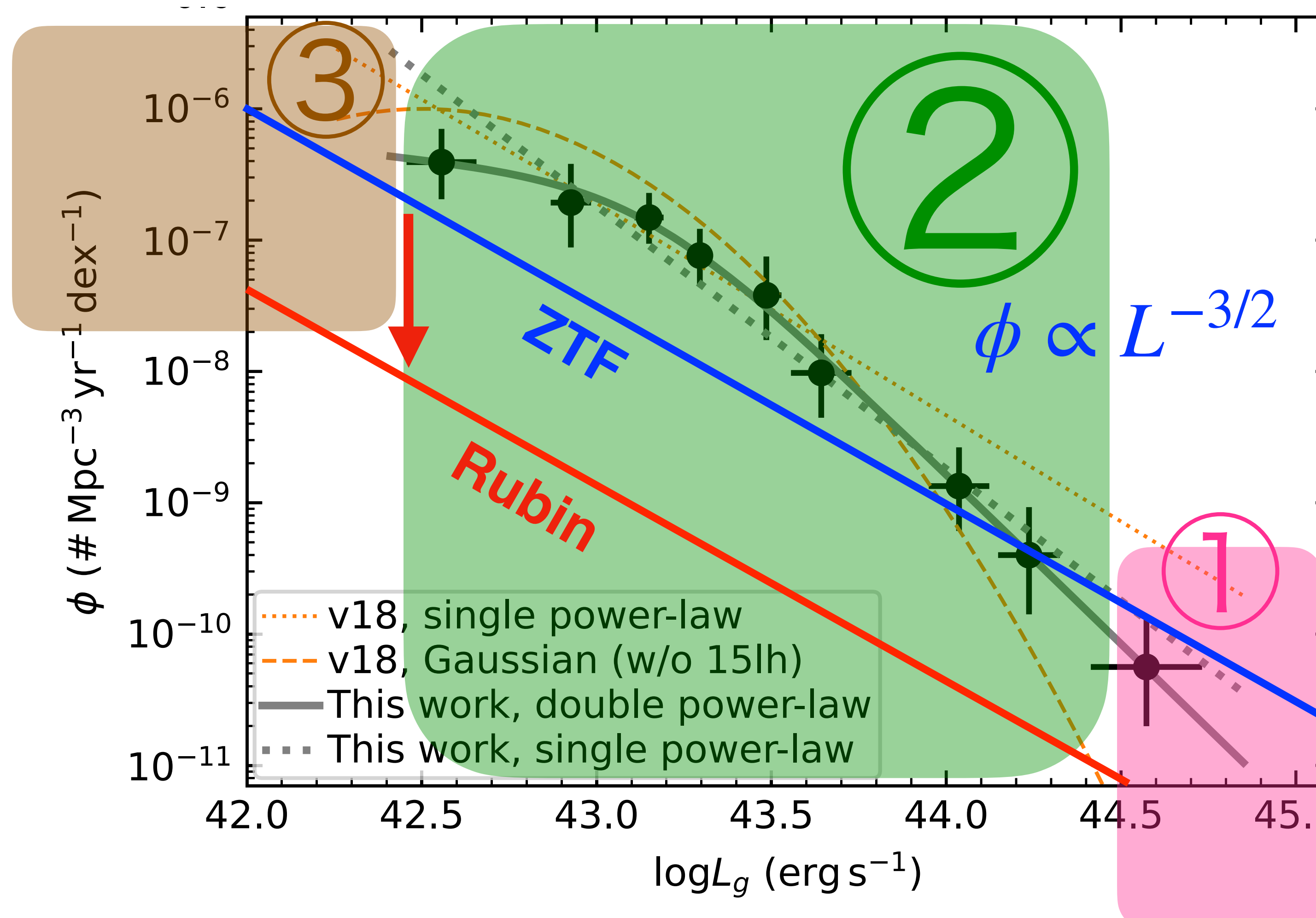
=>f_limit x10, d x3, **N x 30**



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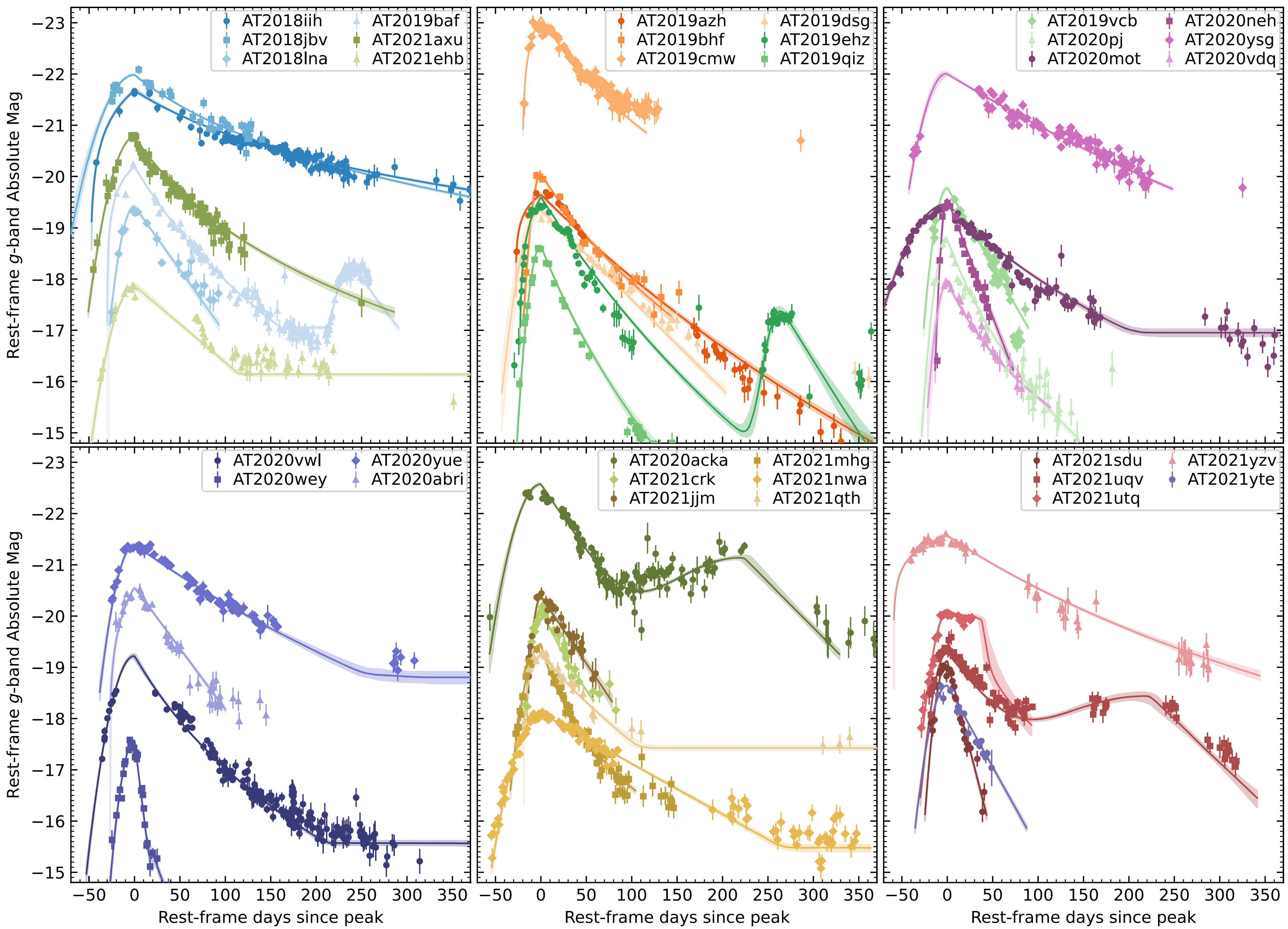
Yao+23

Diversity in optical light curve

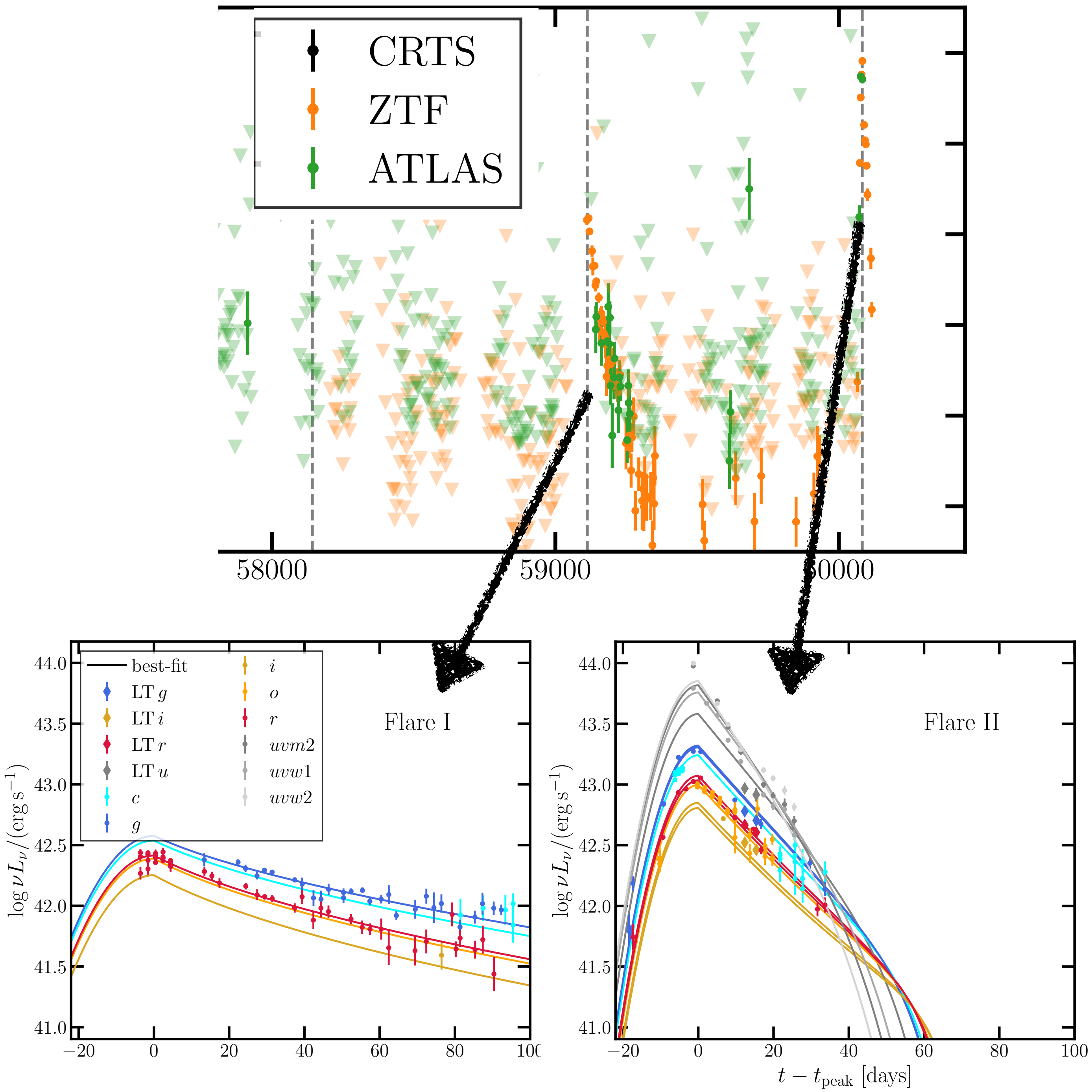


✓ 6/33 events show non-monotonic decline or double peak

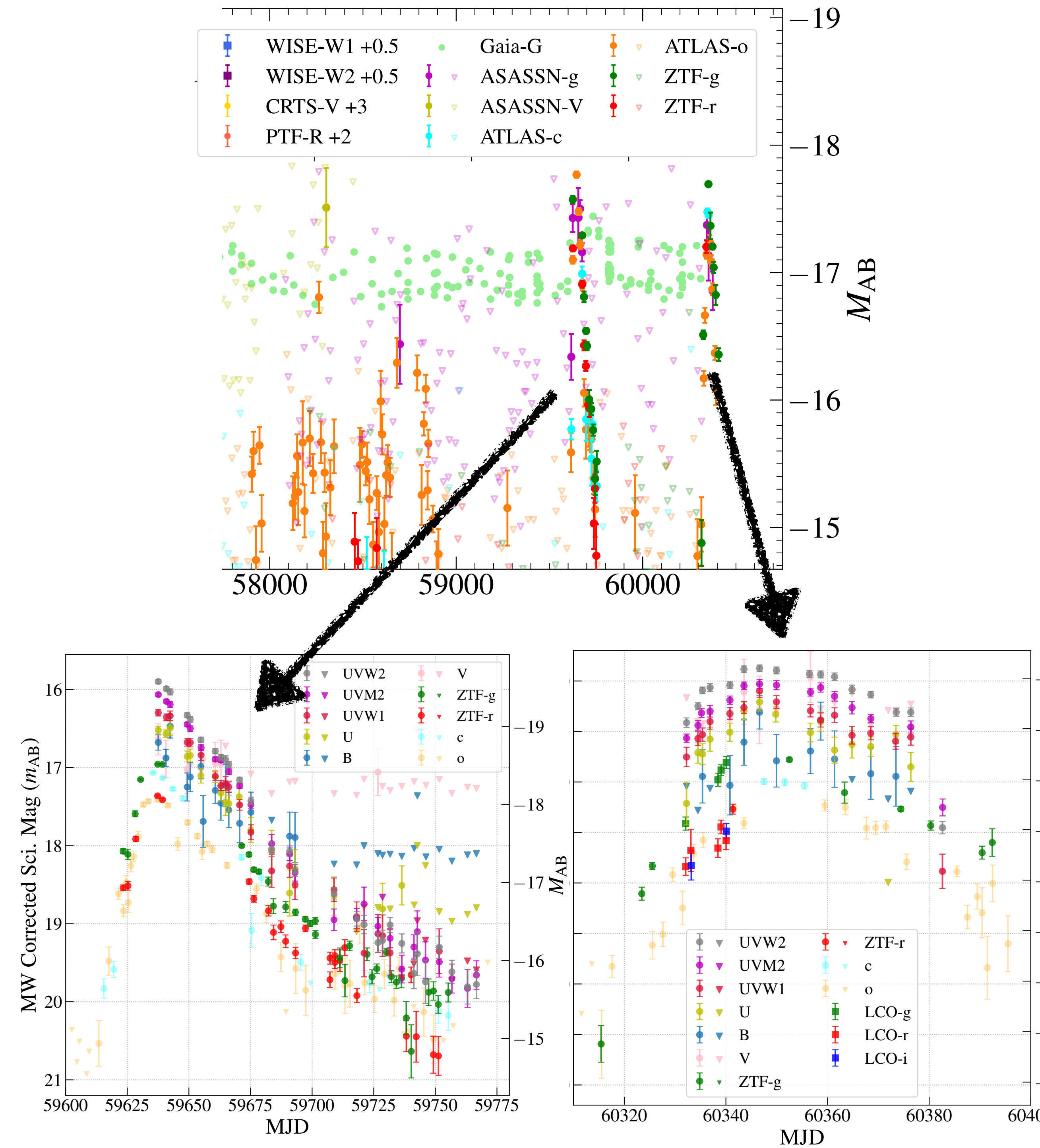
Somalwar+23,Lin+24,…

Multiple optical flares in galactic center

AT2020vdq

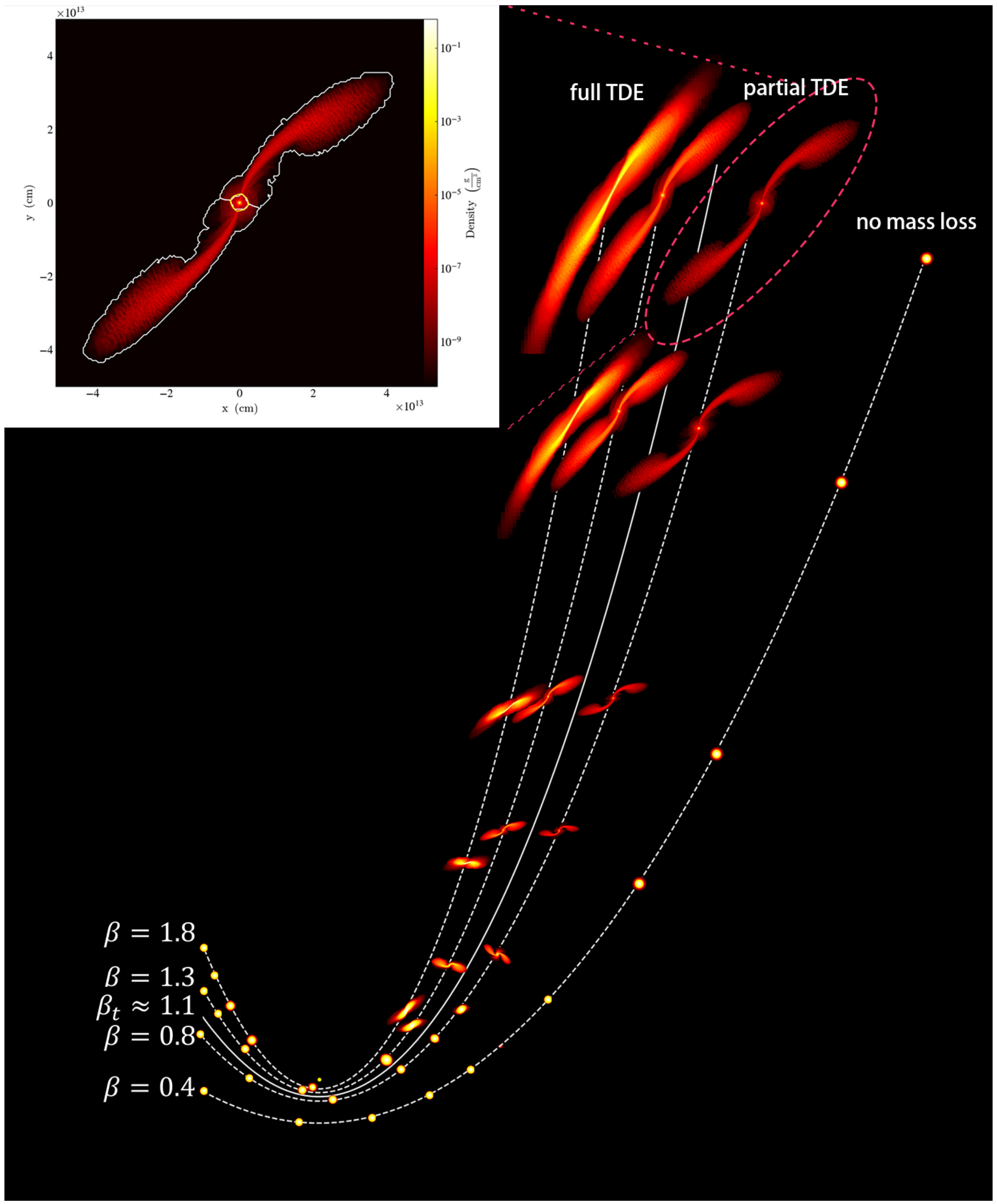


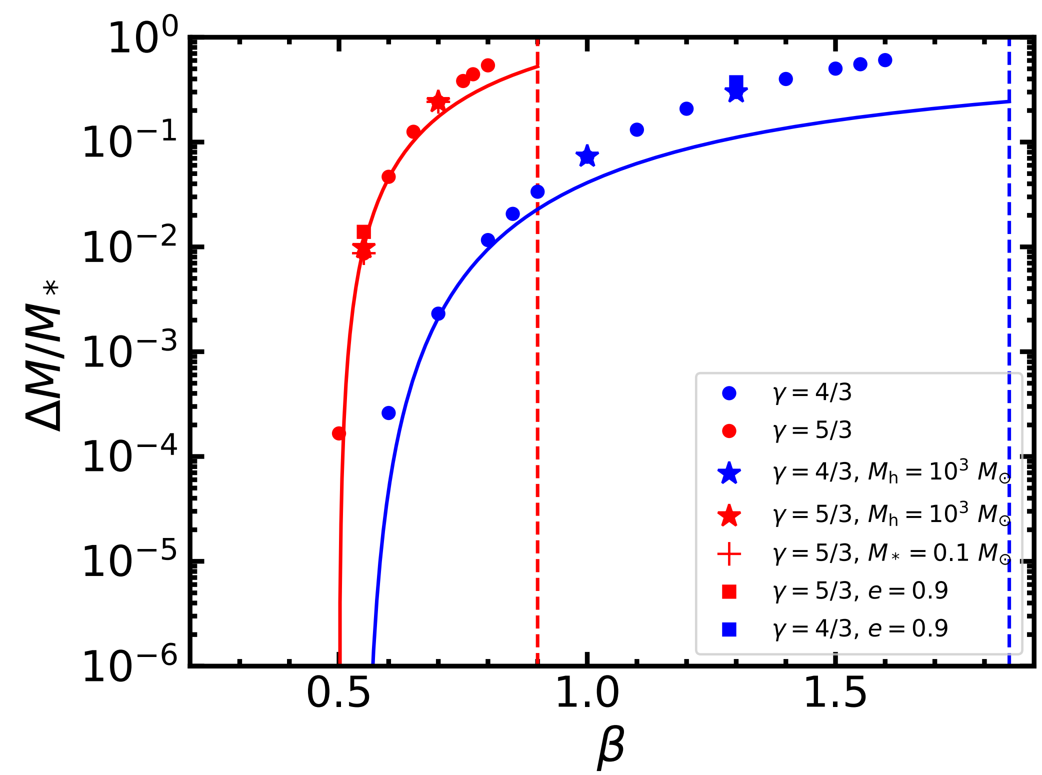
AT2022dbl



Chen+24

Multiple flares = Partial TDEs?

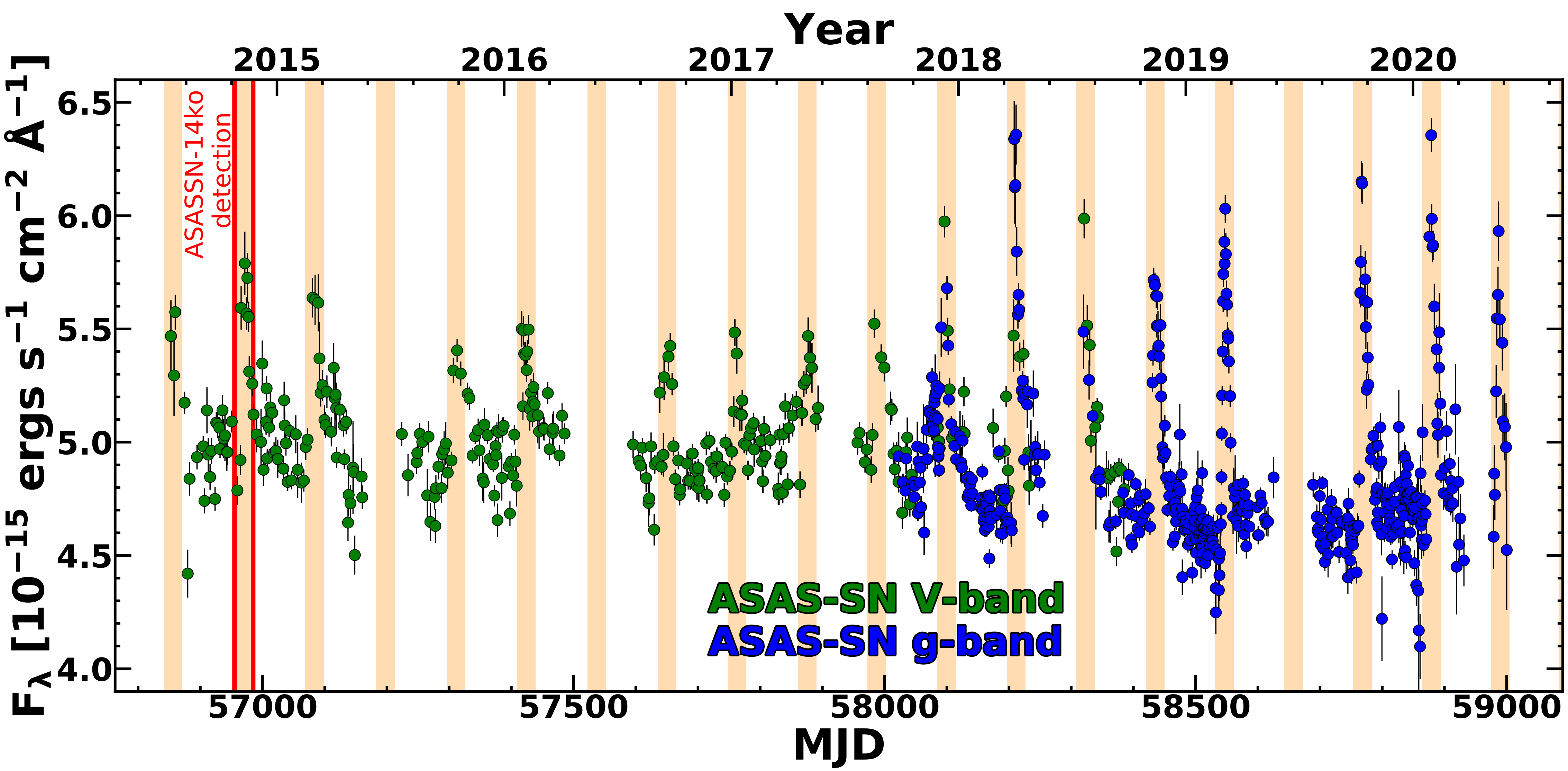




$$\beta \equiv \frac{R_{\rm T}}{R_{\rm p}}$$

Payne+21

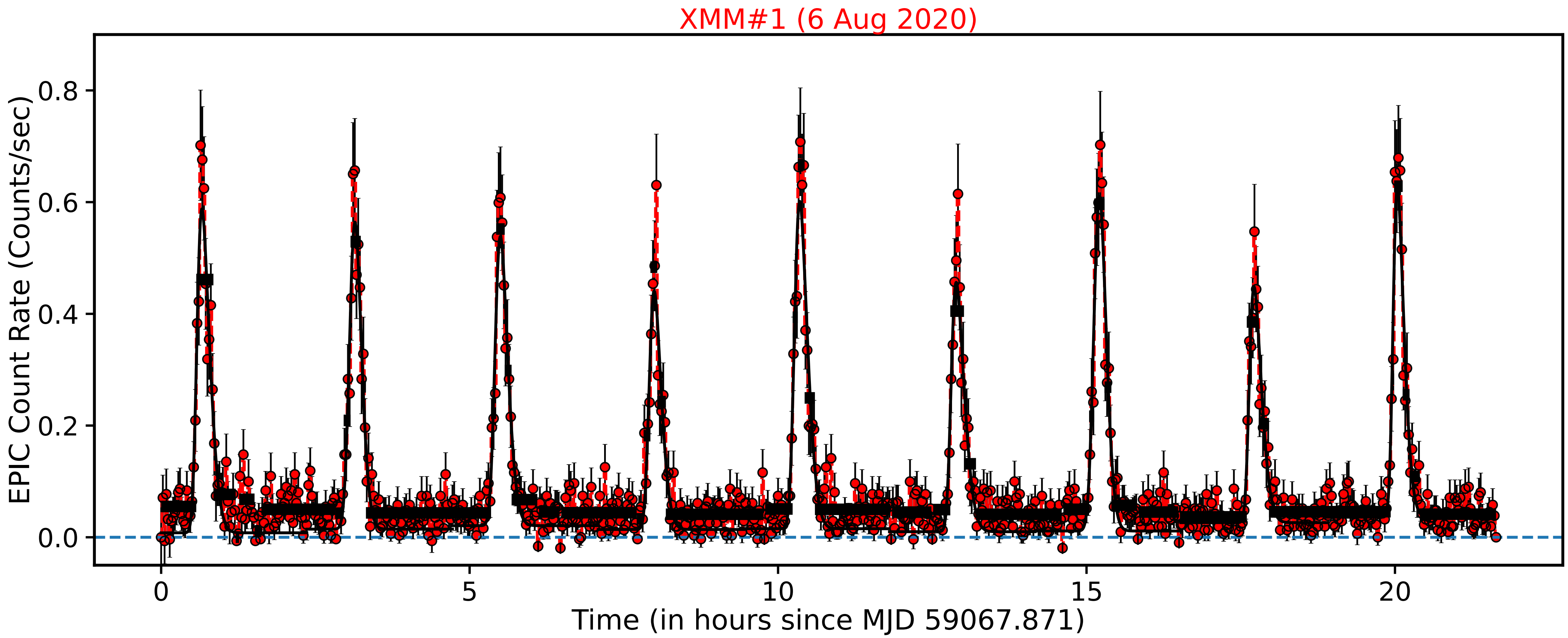
Multi-peak optical flare: ASASSN14ko



✓ 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

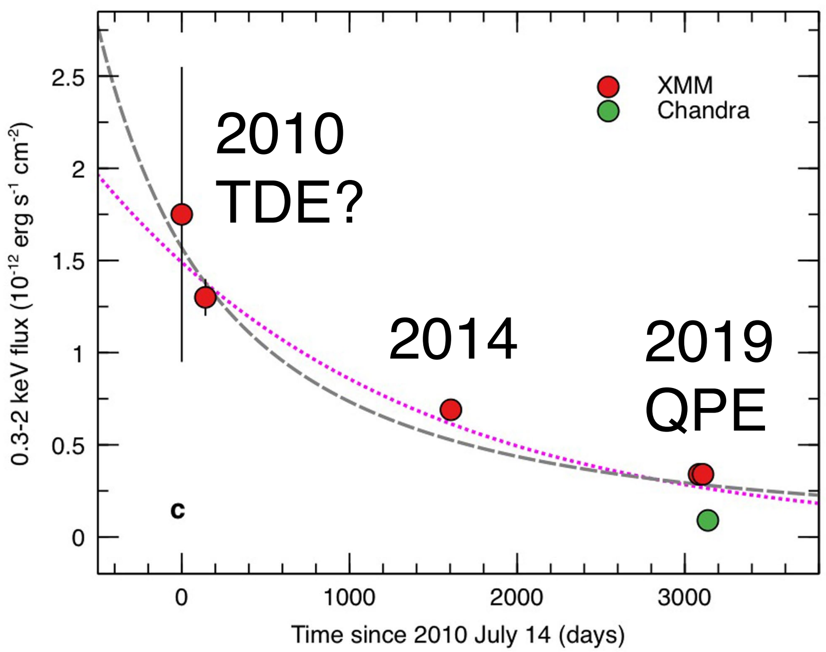


- ✓ ~5 systems
- ✓ Quasi-Periodic ~3-20 hrs, Duty cycle ~10%
- ✓ L~1e+42erg/s, kT~100eV
- ✓ Disk instability? **Star-disk interaction**?

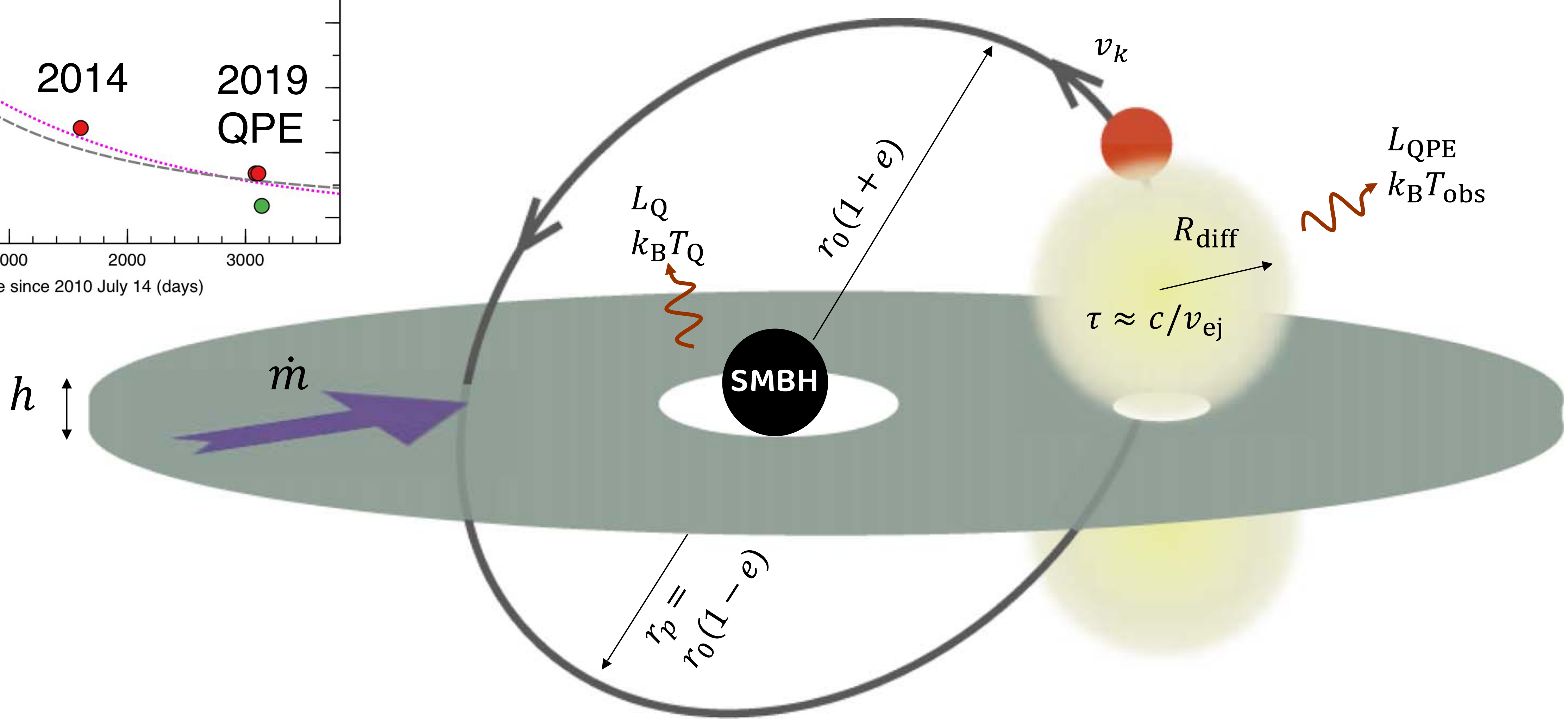
QPE = TDE + EMRI?

GSN069

Miniutti+19

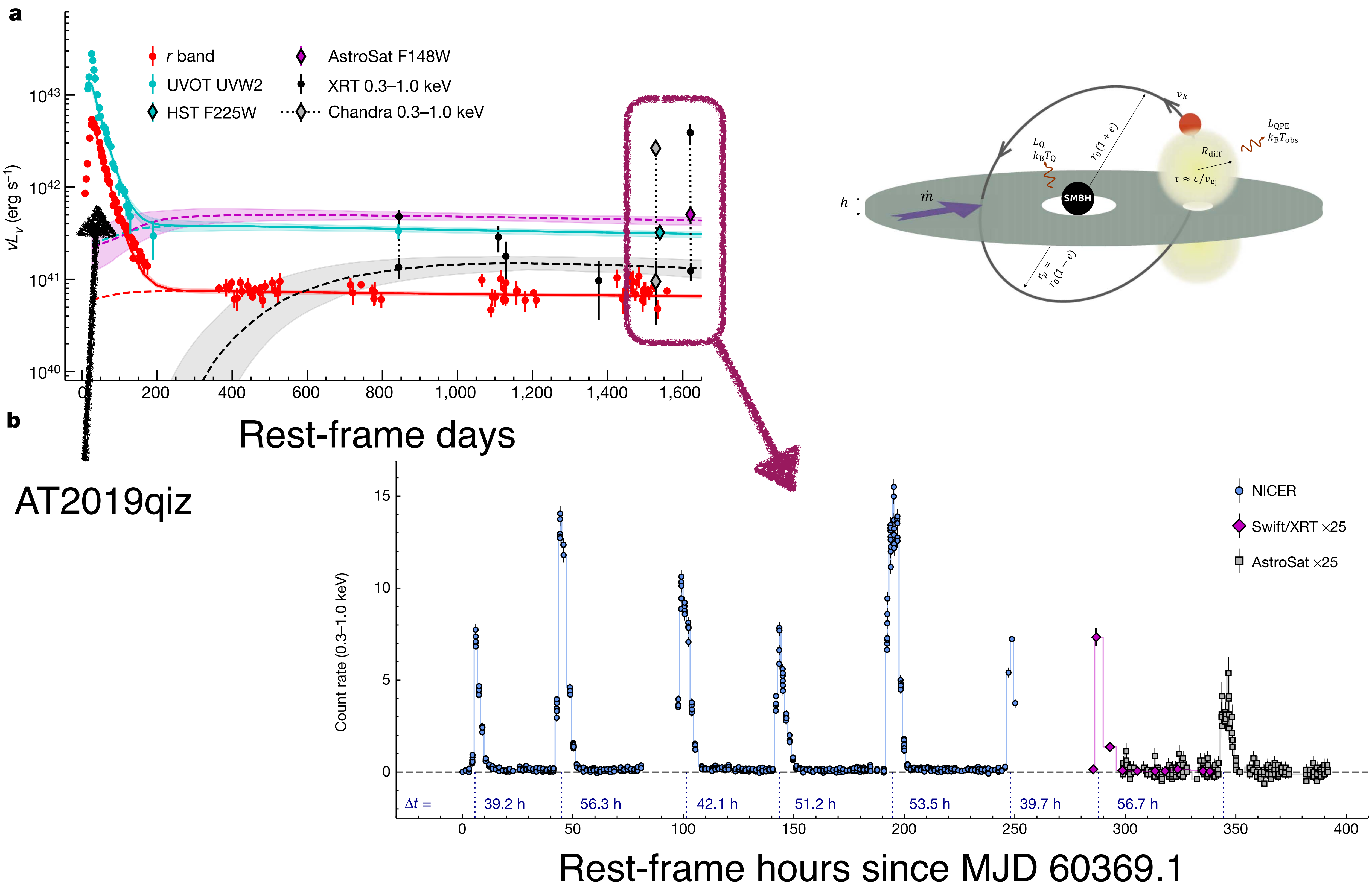


Linial&Metgzer23



Nicholl+24

Discovery of QPE after optical TDE



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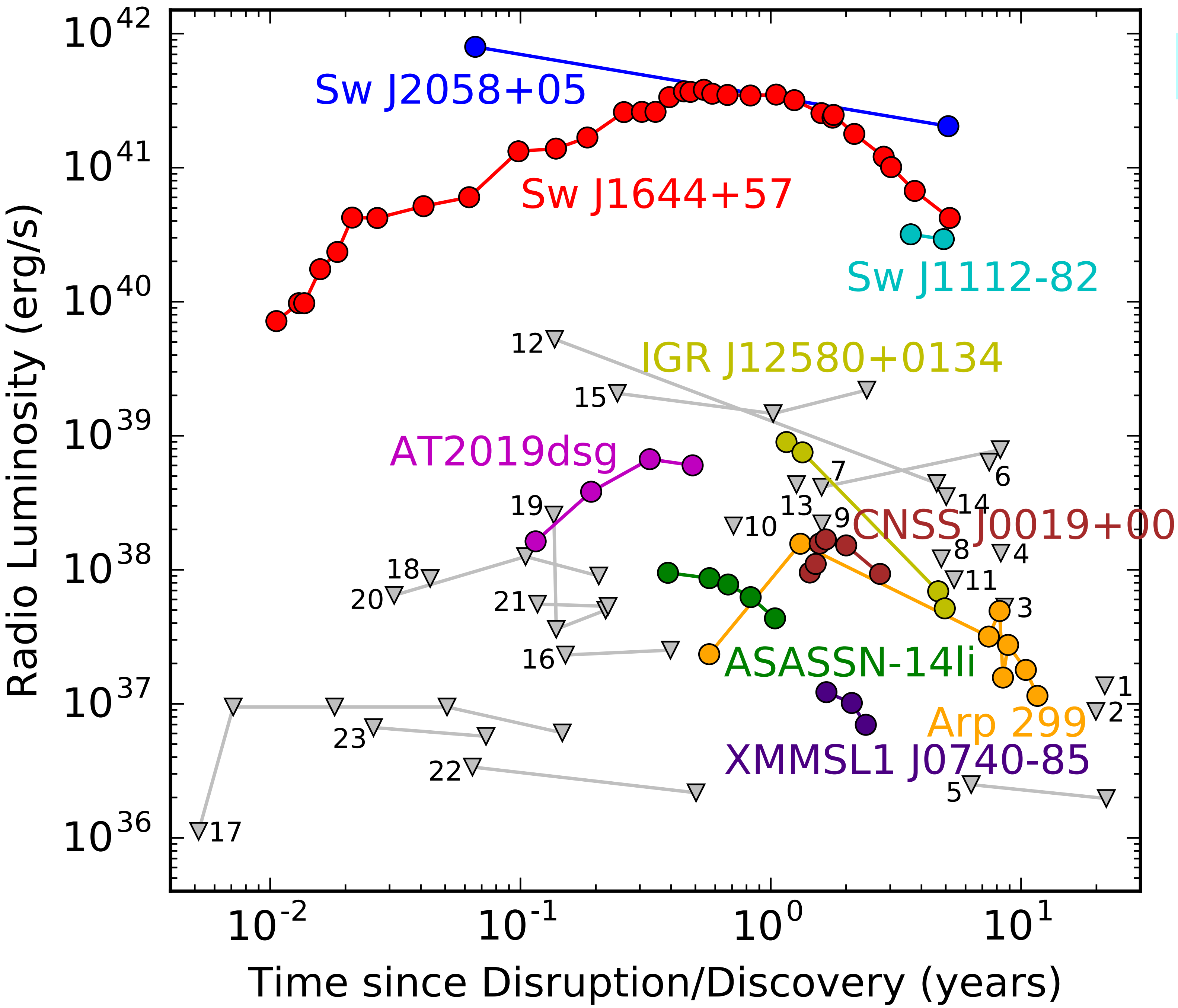
Radio Flare in TDEs



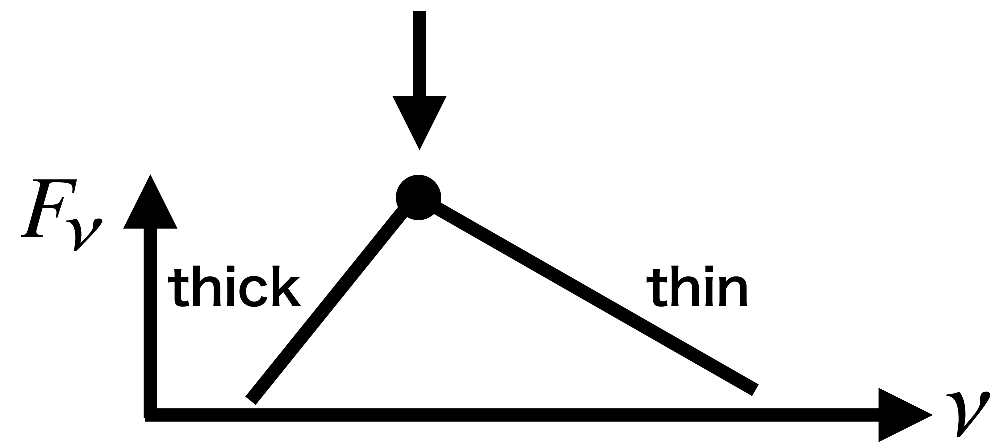
Alexander+20

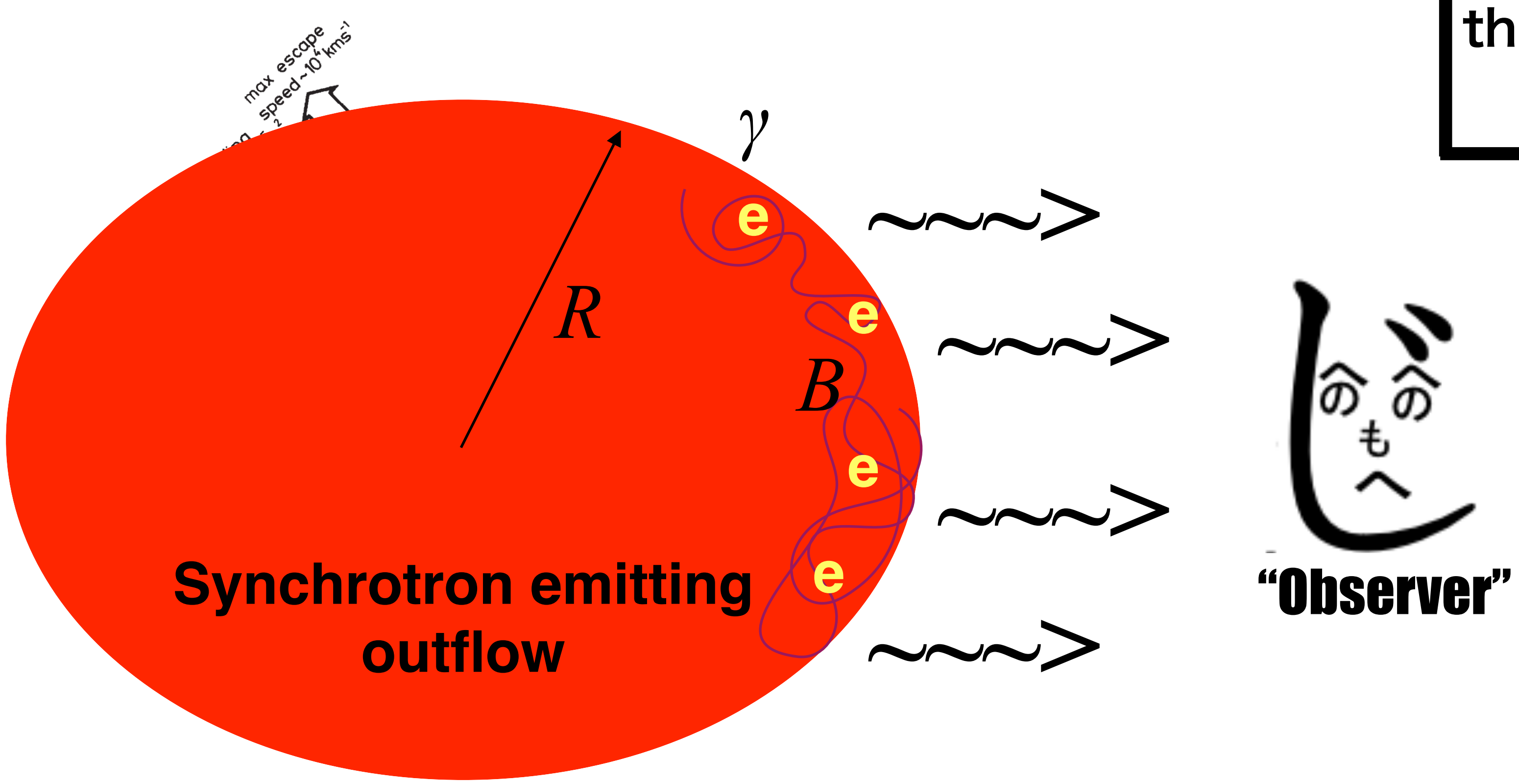
Synchrotron emission => Probe of Outflow + Environment

Chevalier98,Barniol-Duran+13

Analysis of Radio Flares

$\tau = 1$ => ***R***

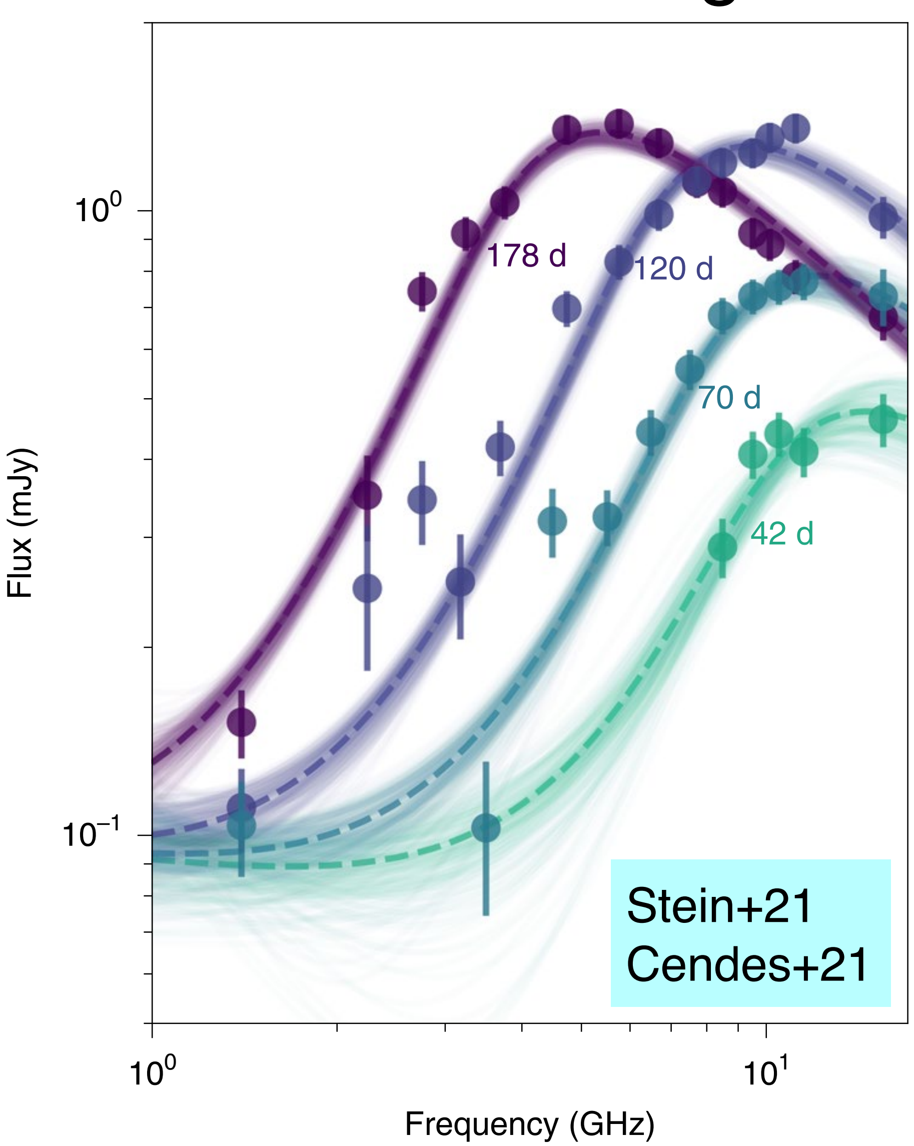


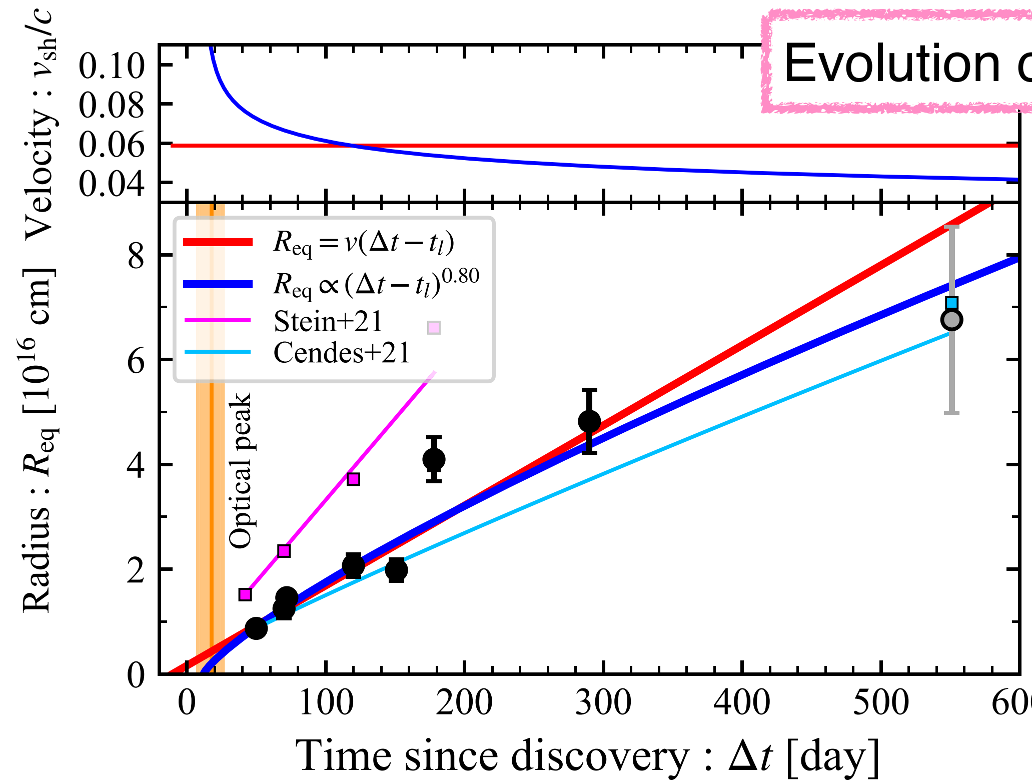


Chevalier98,Barniol-Duran+13

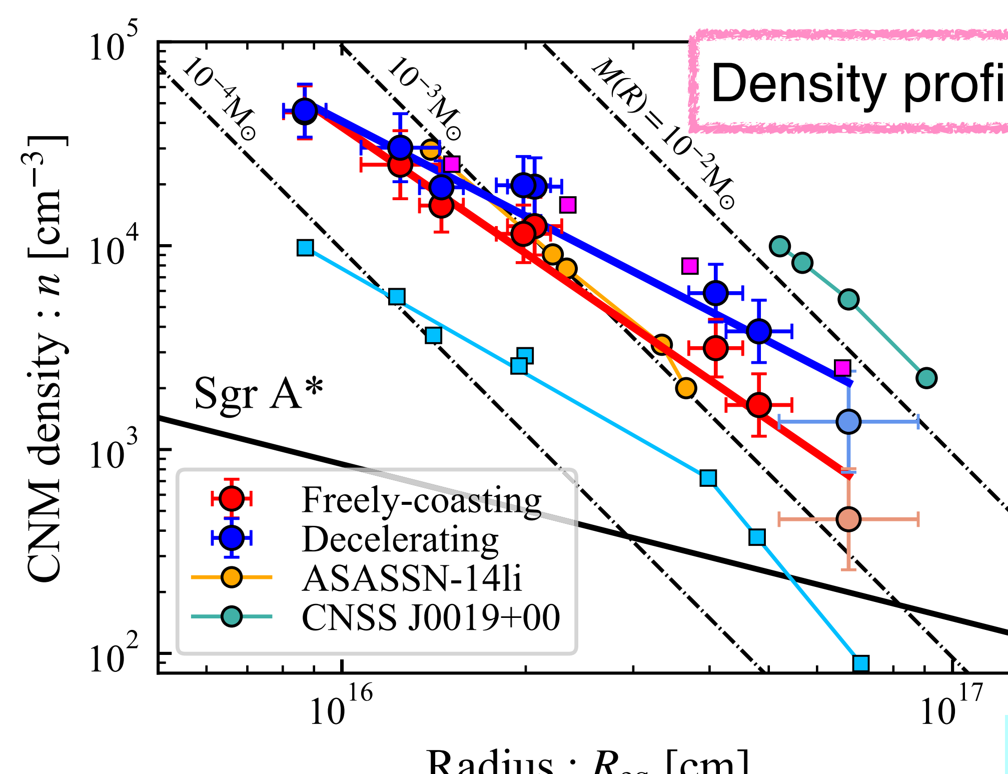
Analysis of Radio Flares

AT2019dsg





Evolution of Outflow

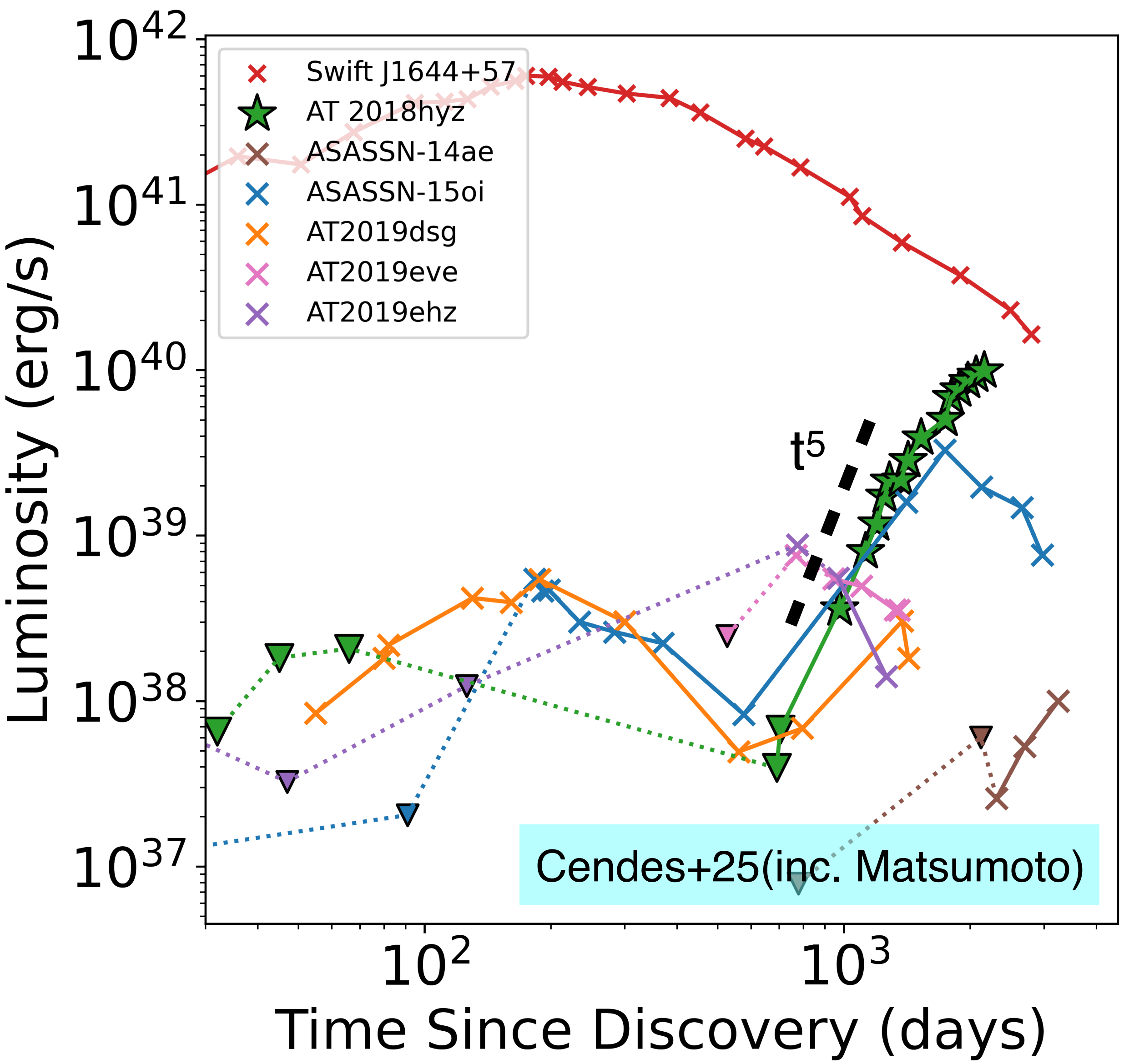


Density profile around BH

Matsumoto+22

Cendes+22,Horesh+21,Sfaradi+24,Cendes+25

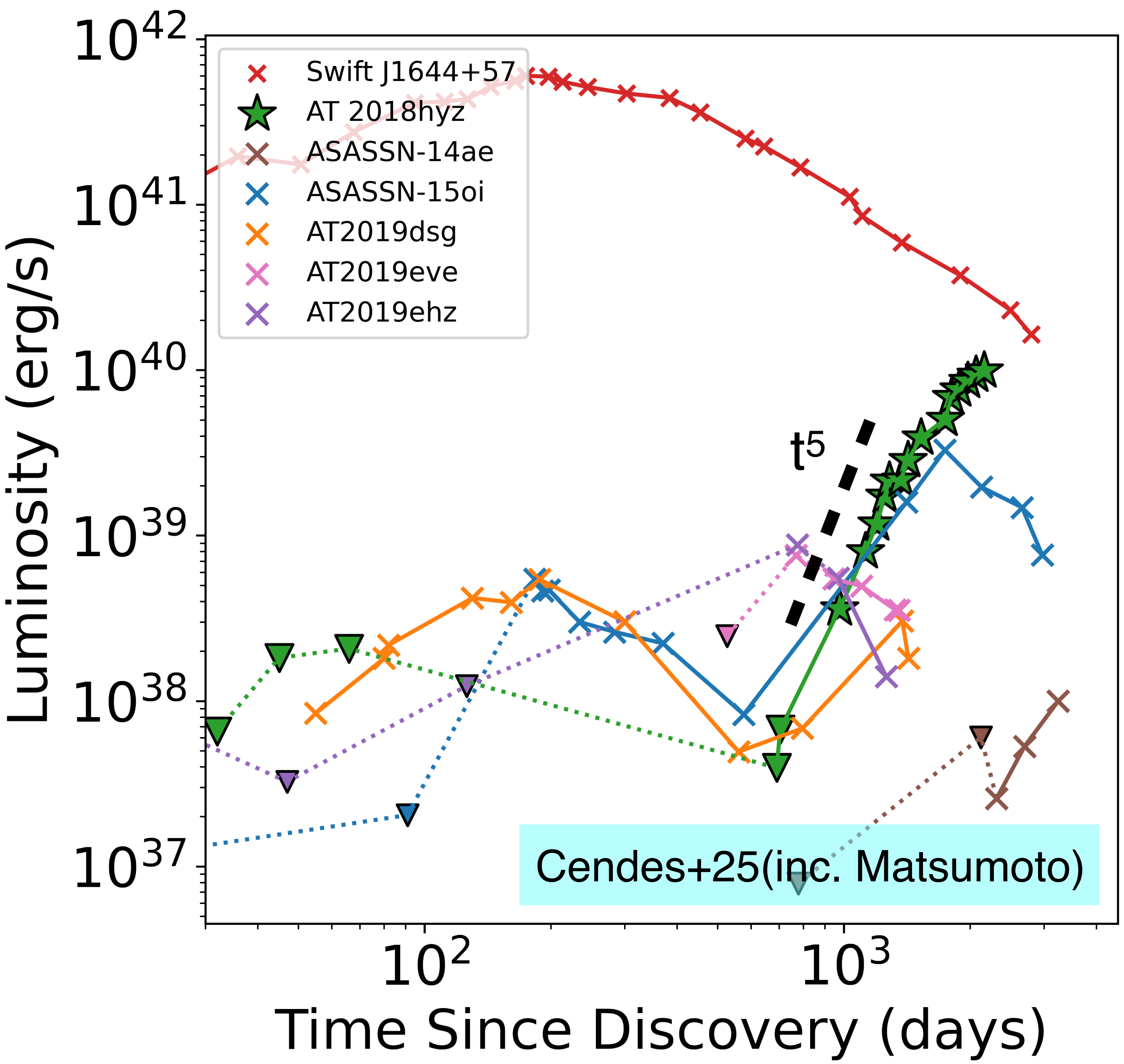
A Late-time Radio Flare: AT2018hyz



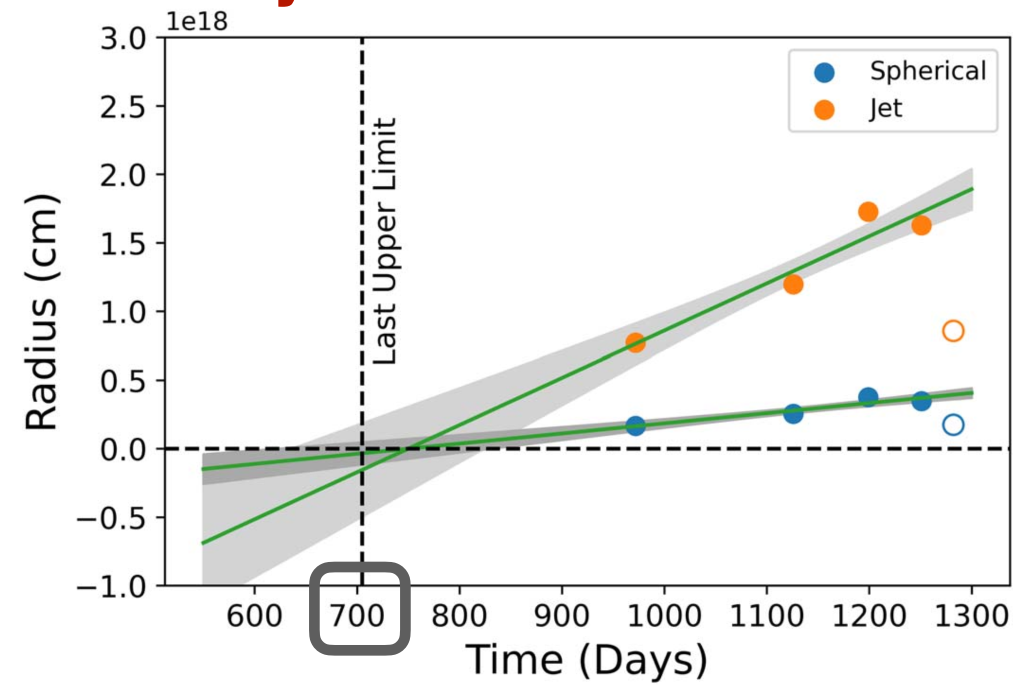
- Radio flare ~ **1000days** after discovery
- Flux increases as $\mathbf{t^5 \sim t^3}$

Cendes+22,Horesh+21,Sfaradi+24,Cendes+25

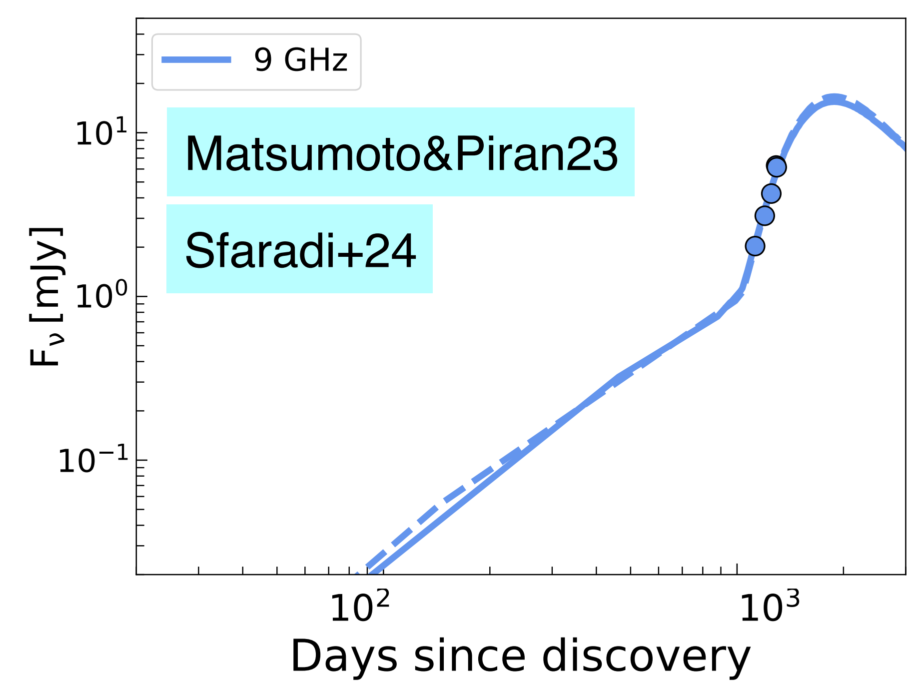
A Late-time Radio Flare: AT2018hyz



1. Delayed Newtonian Outflow?



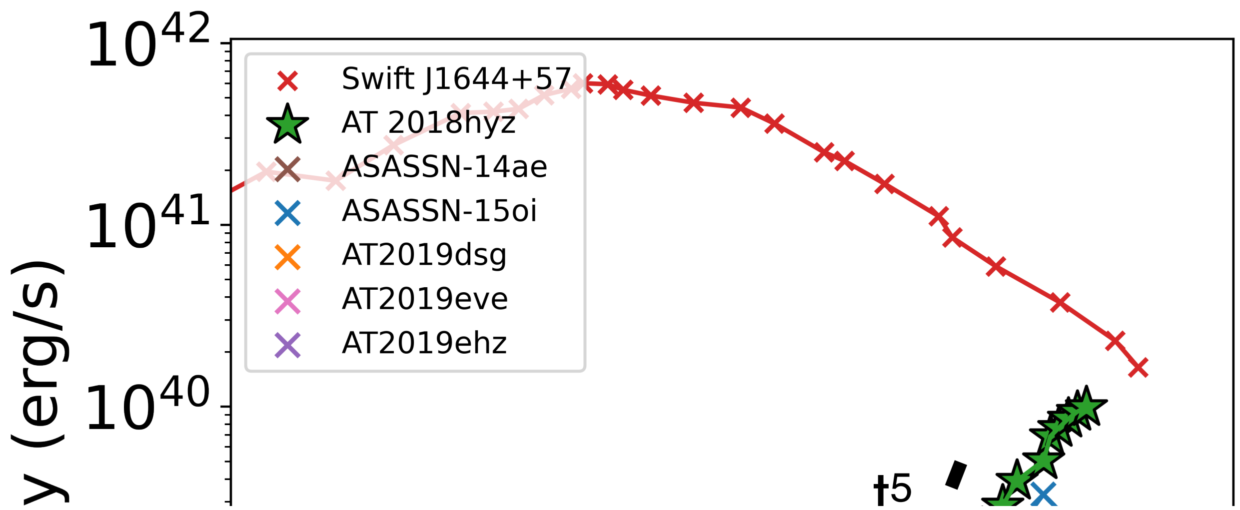
2. Off-axis Relativistic Jet?



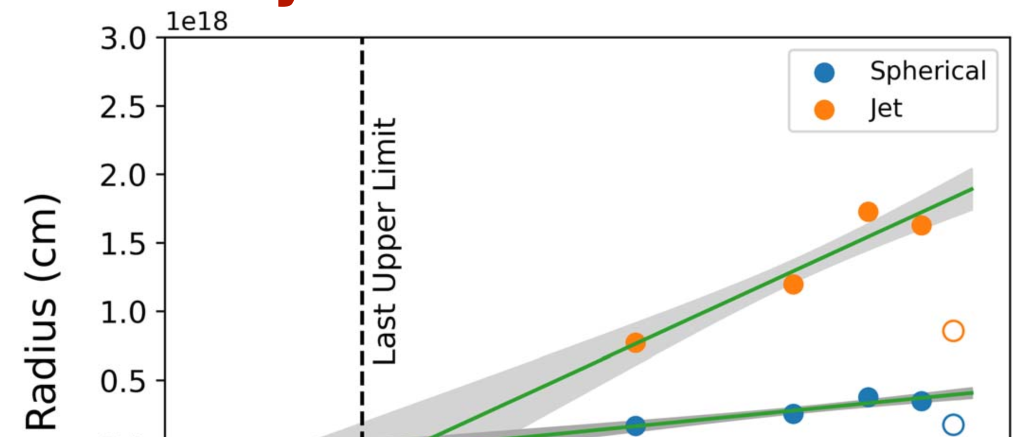
- Radio flare ~ **1000days** after discovery
- Flux increases as $\mathbf{t^5 \sim t^3}$

Cendes+22,Horesh+21,Sfaradi+24,Cendes+25

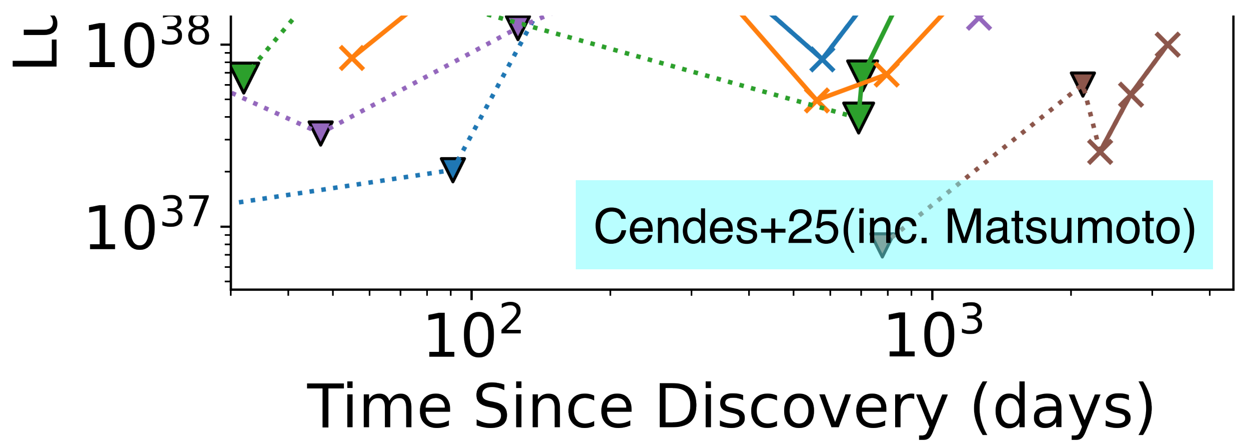
A Late-time Radio Flare: AT2018hyz



1. Delayed Newtonian Outflow?

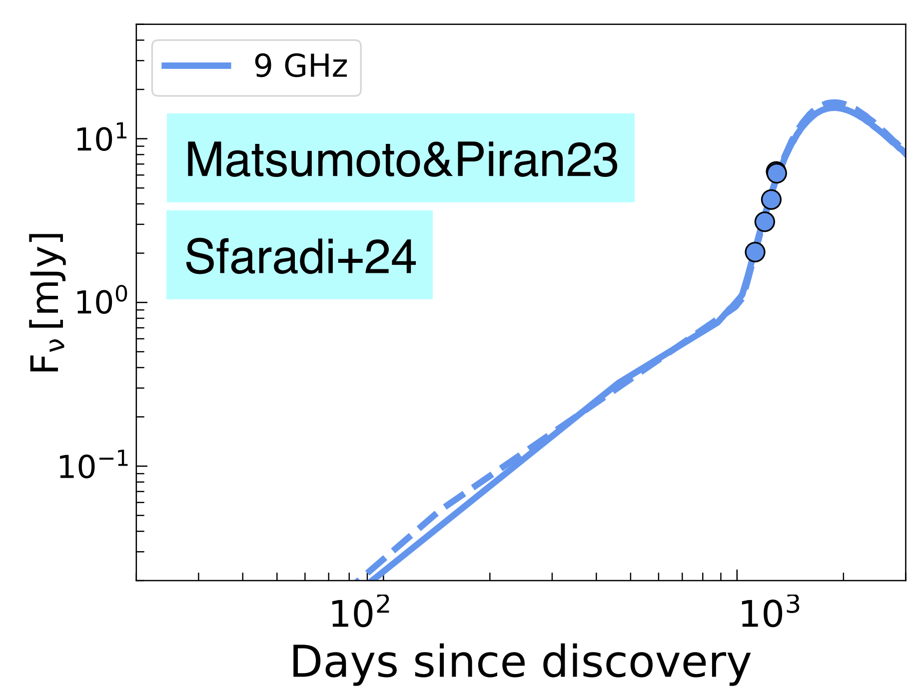


Can we break the degeneracy?



Cendes+25(inc. Matsumoto)

2. Off-axis Relativistic Jet?



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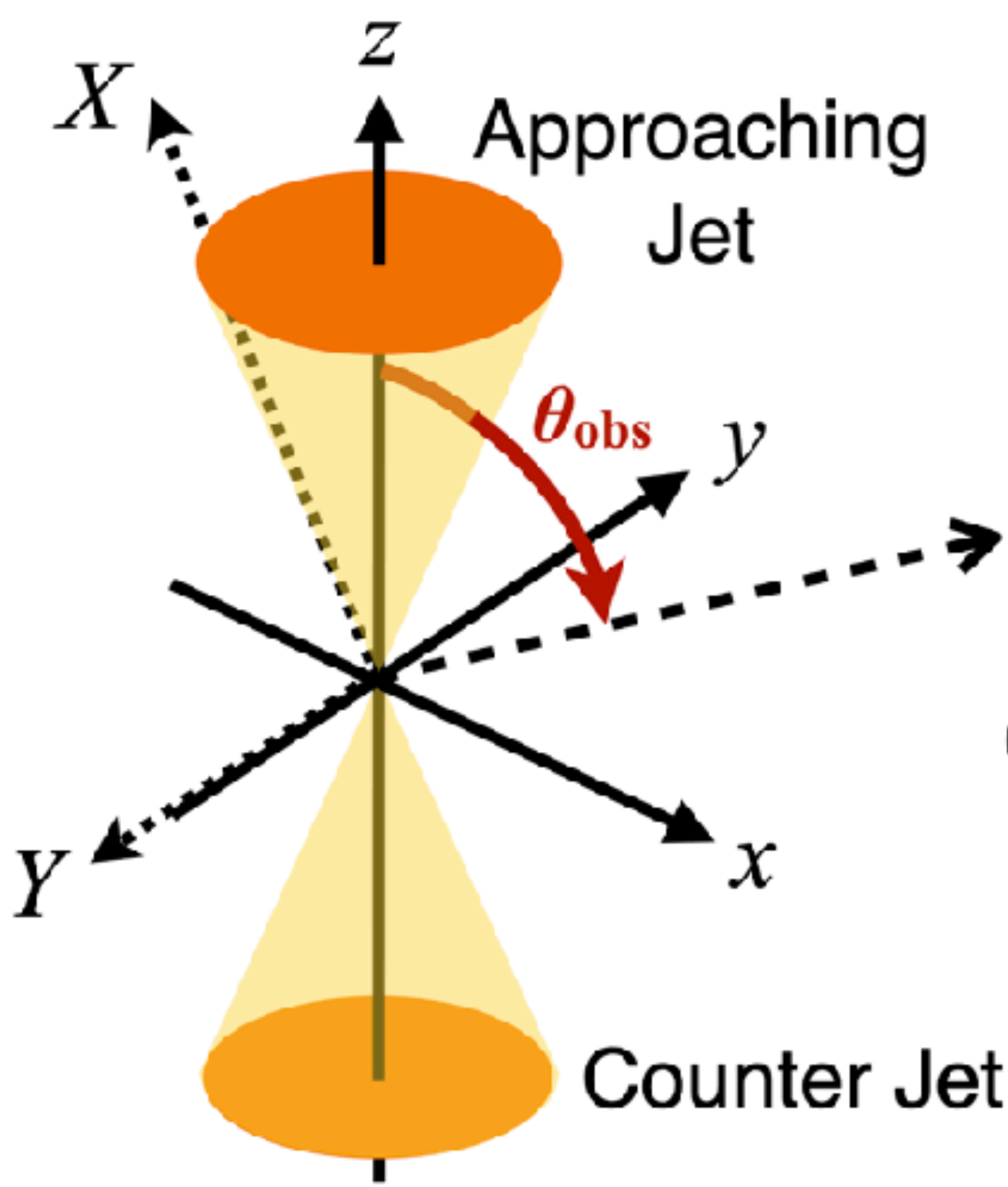
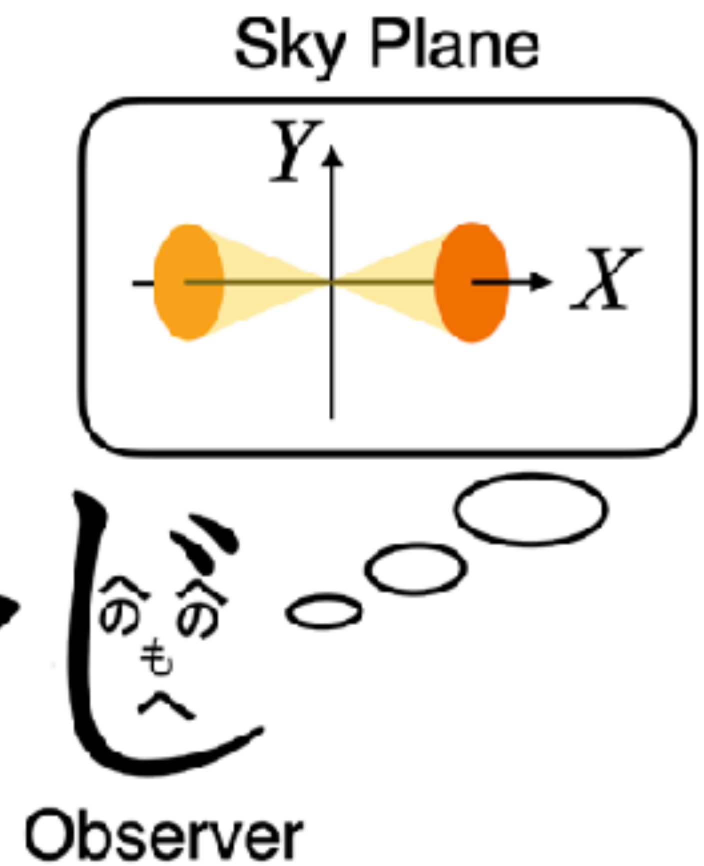
Sfaradi+24

- Radio flare ~ **1000days** after discovery
- Flux increases as **t⁵**

Diagnostic: **Radio Image** by VLBI

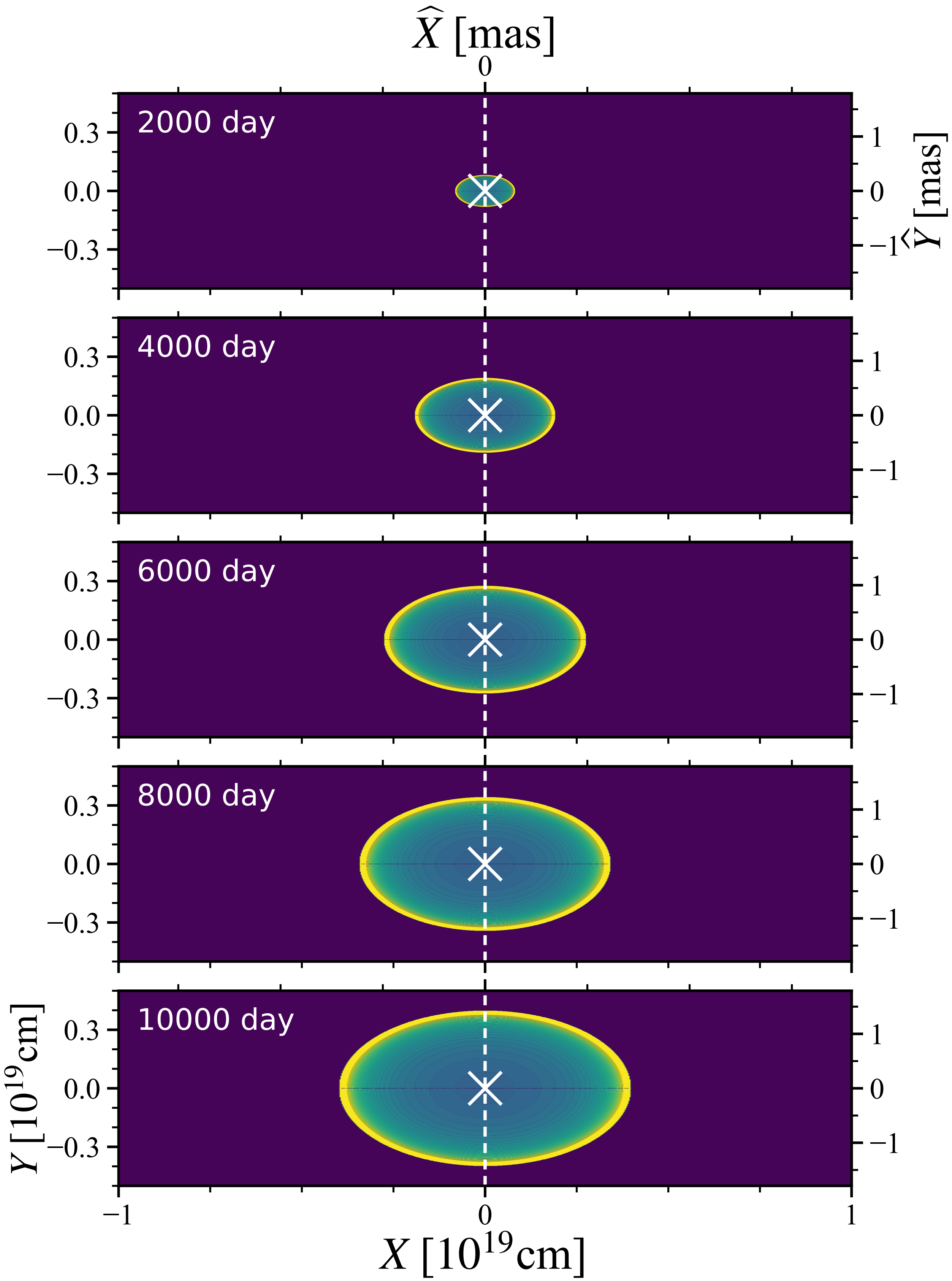




$$F_{\nu_{\rm obs}} = \frac{(1+z)}{D_{\rm L}^2} \int \delta_{\rm D}^2 j'_{\nu'} \left(\frac{1-e^{-\tau_\nu}}{\tau_\nu} \right) dV$$

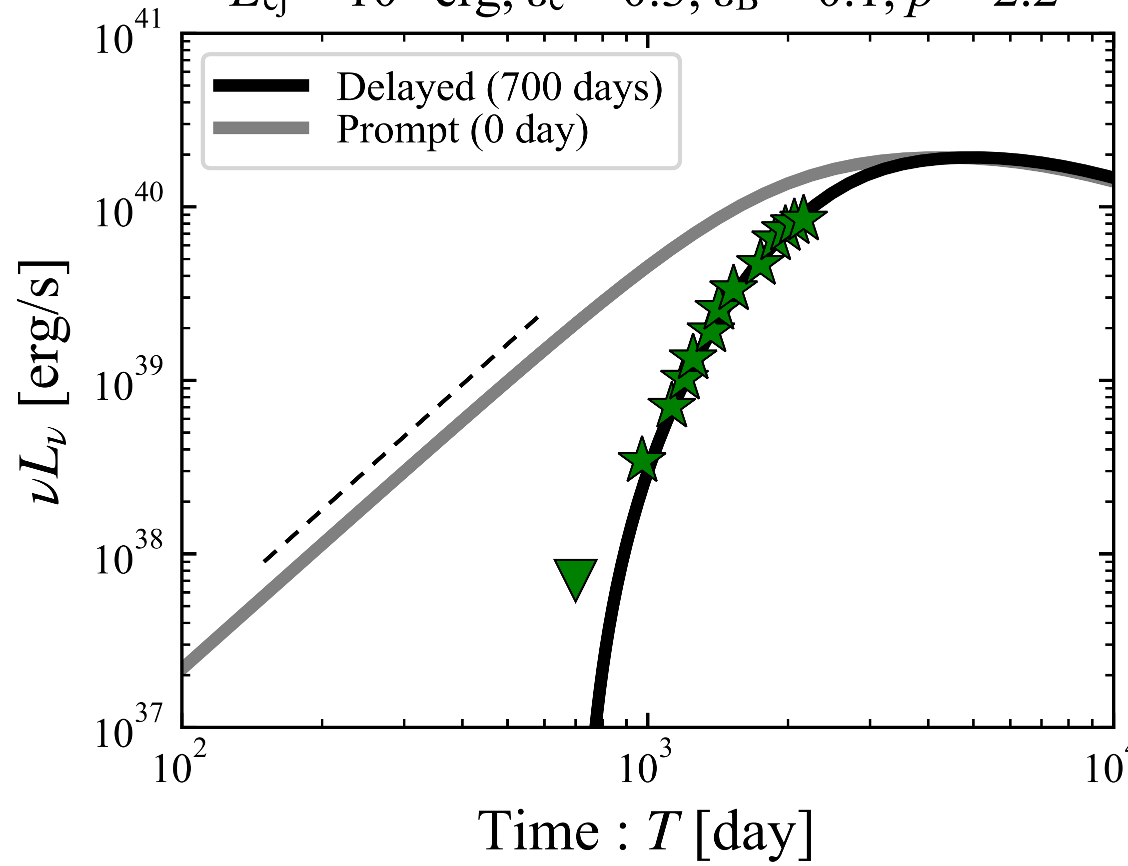
Matsumoto in prep.

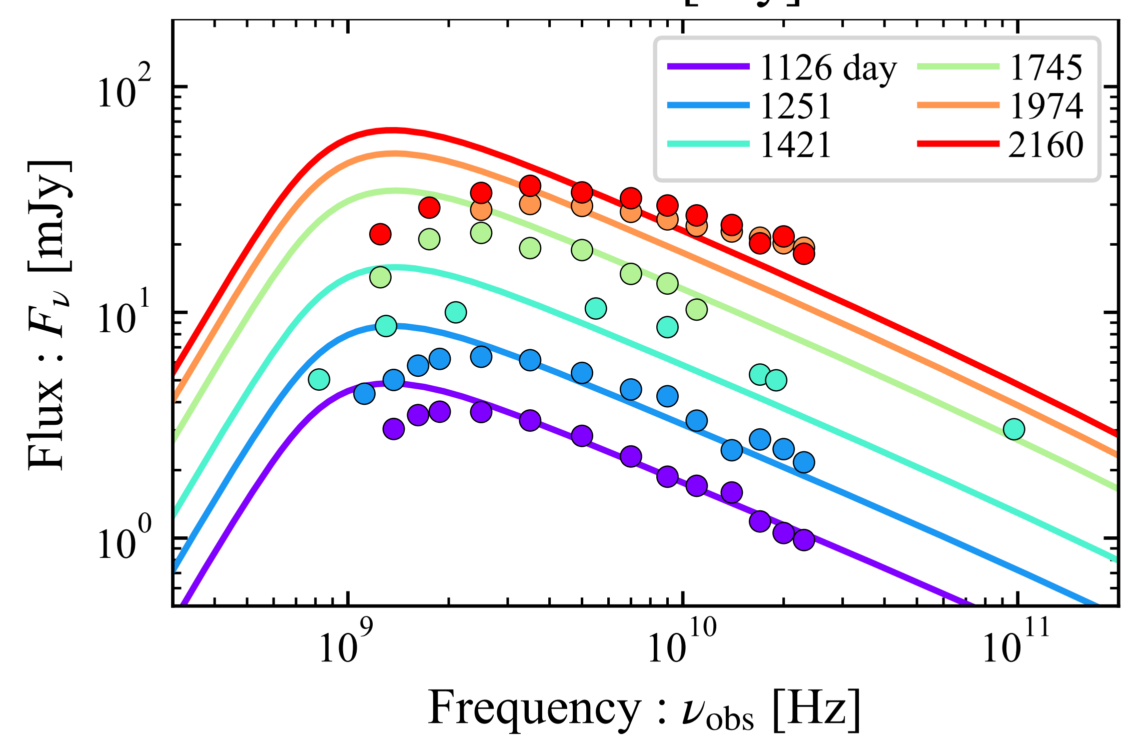
Radio Image: Newtonian Outflow



$v = 0.25c$, $n \sim 10\mathrm{cm}^{-3}$

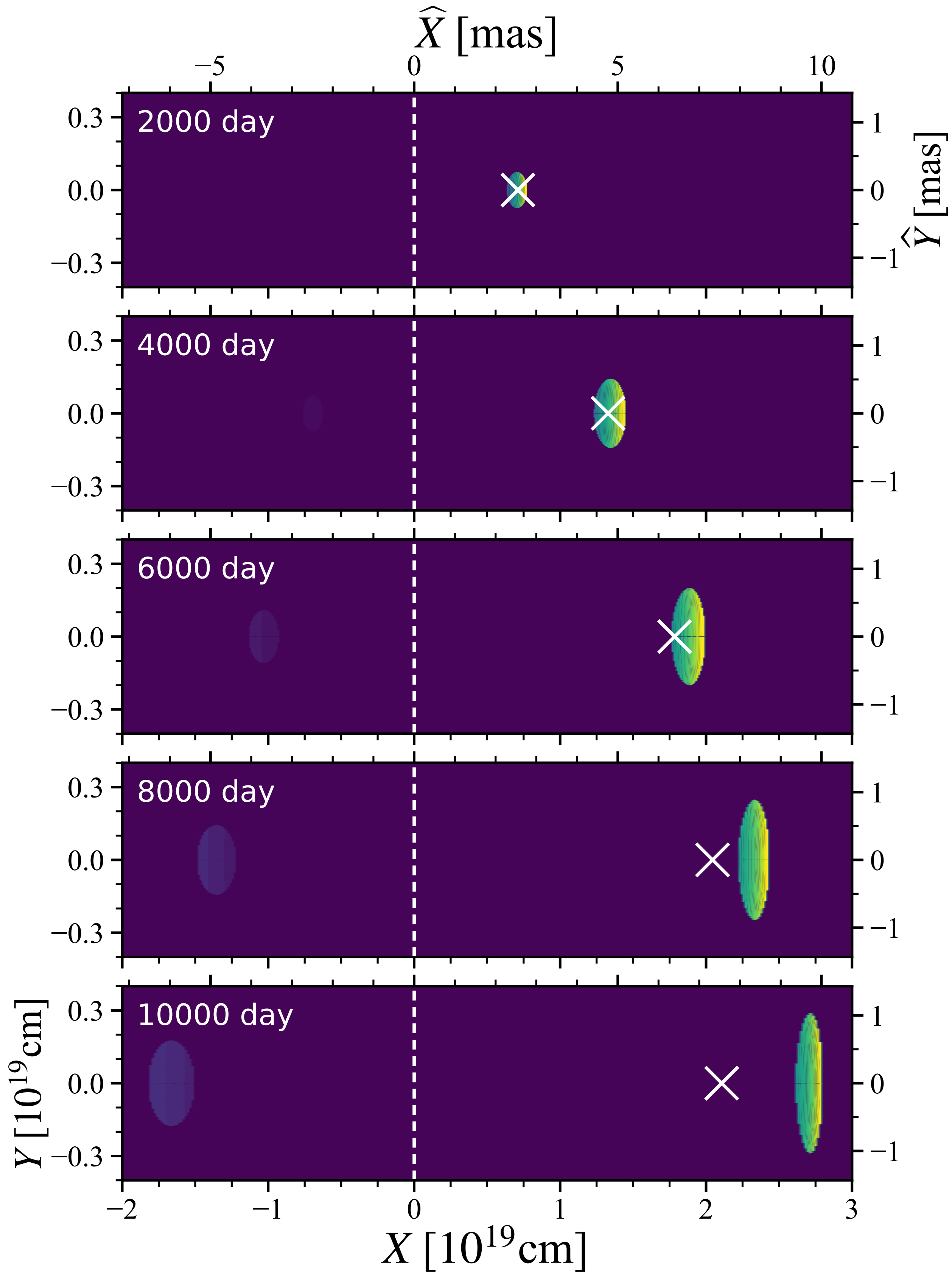
$E_{\rm ej} = 10^{52}$erg, $\varepsilon_{\rm e} = 0.3$, $\varepsilon_{\rm B} = 0.1$, $p = 2.2$

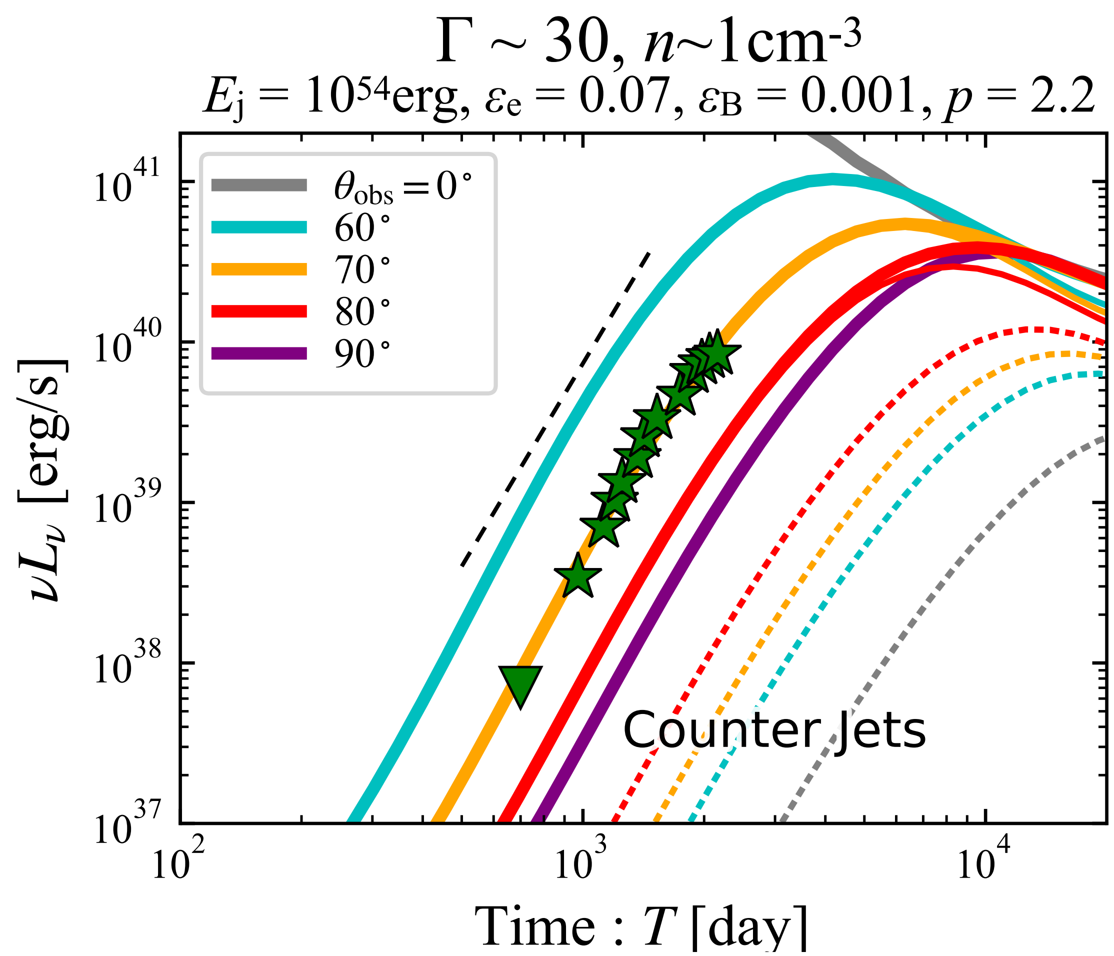


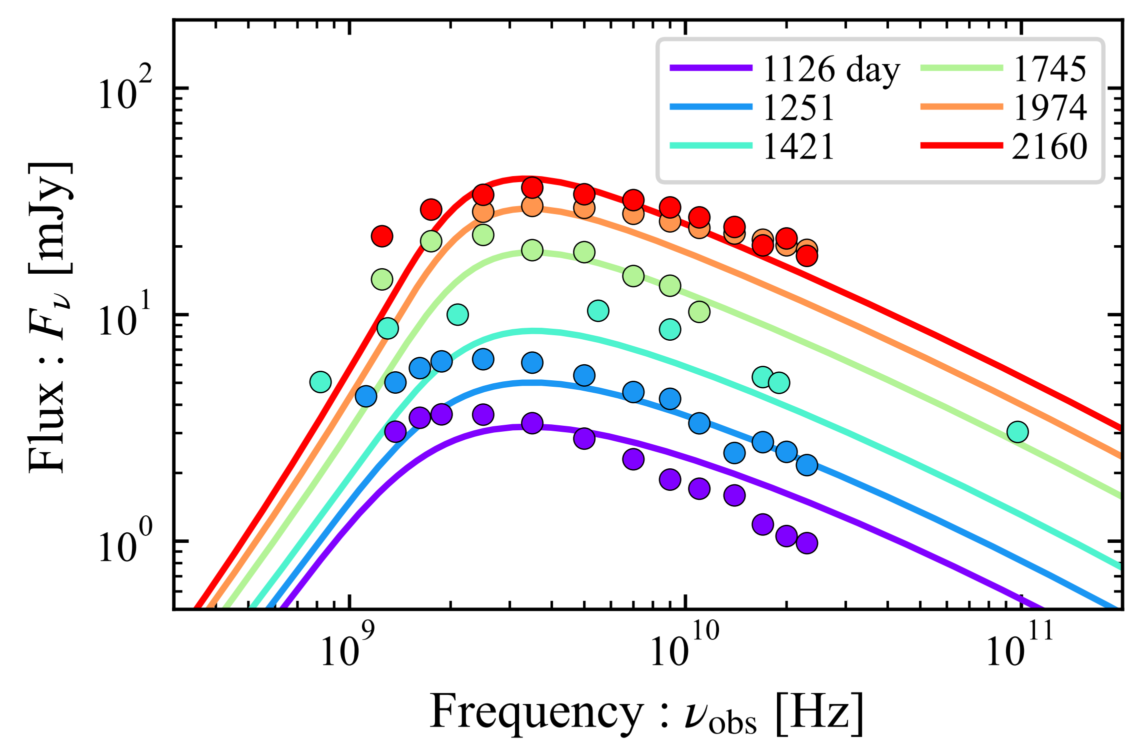


Matsumoto in prep.

Radio Image: Relativistic Jet

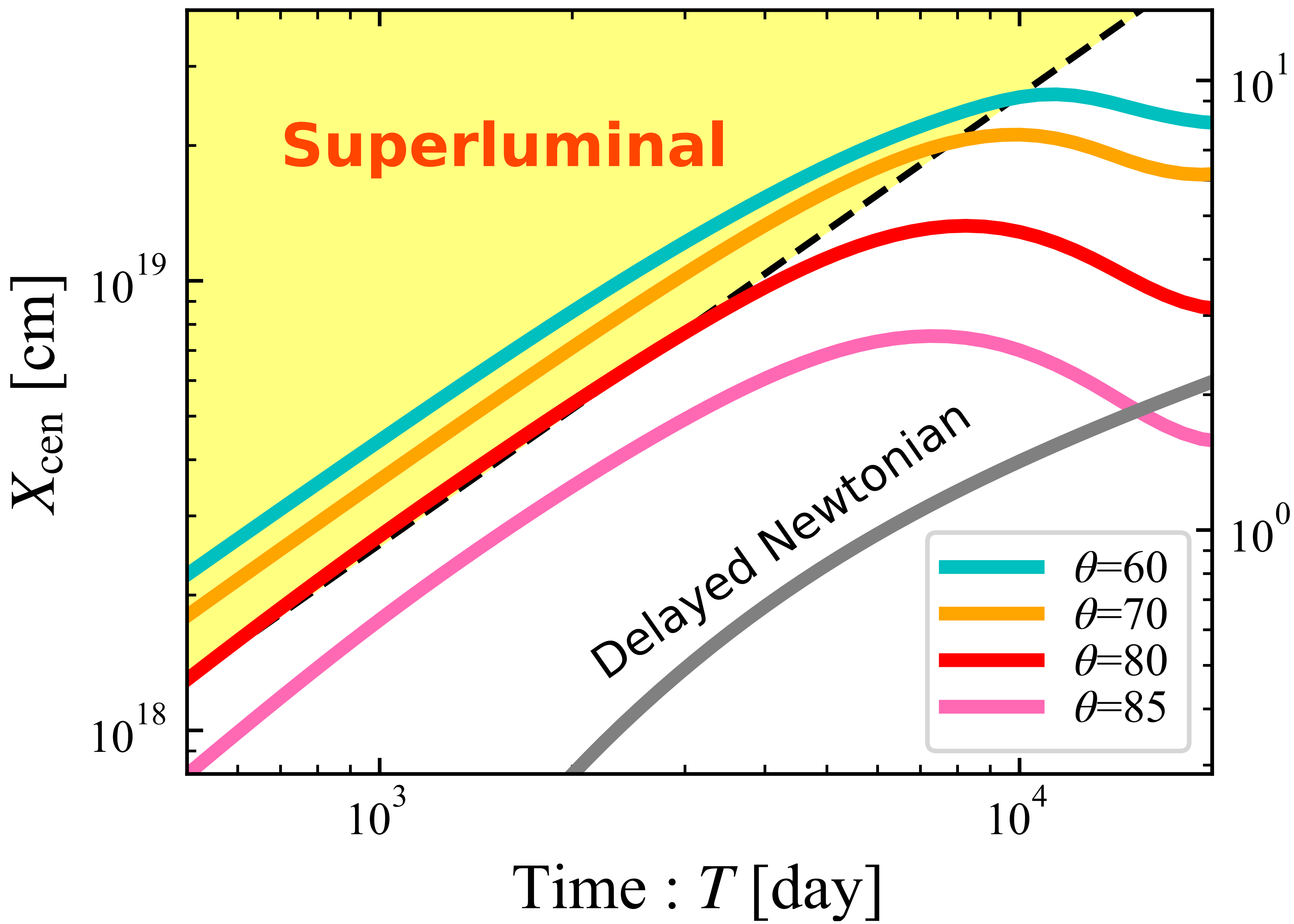


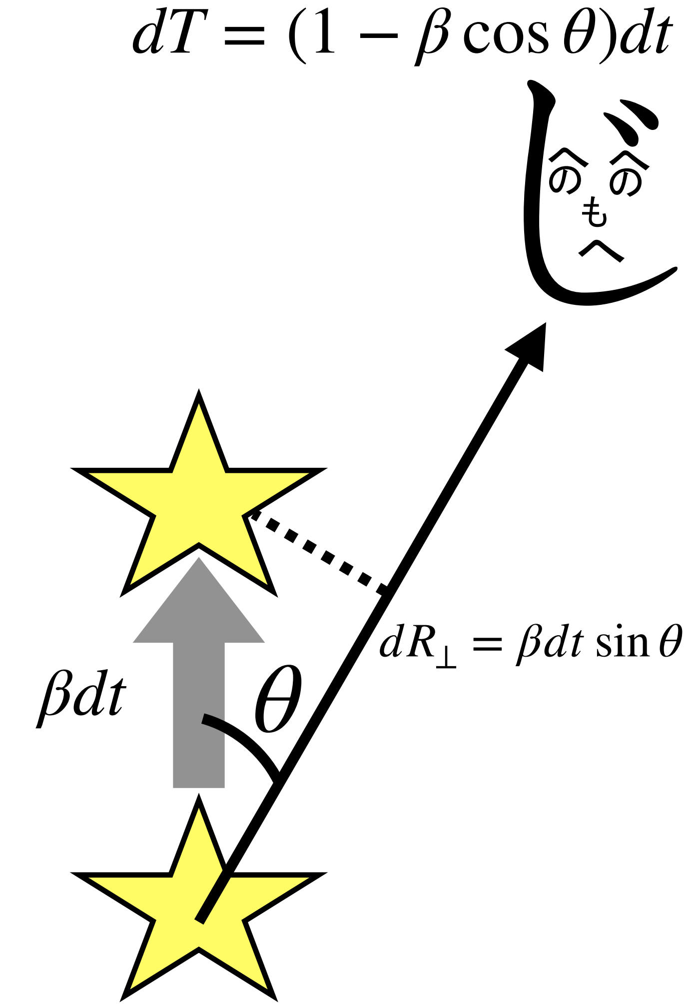




Matsumoto in prep.

Motion of Emission Centroid

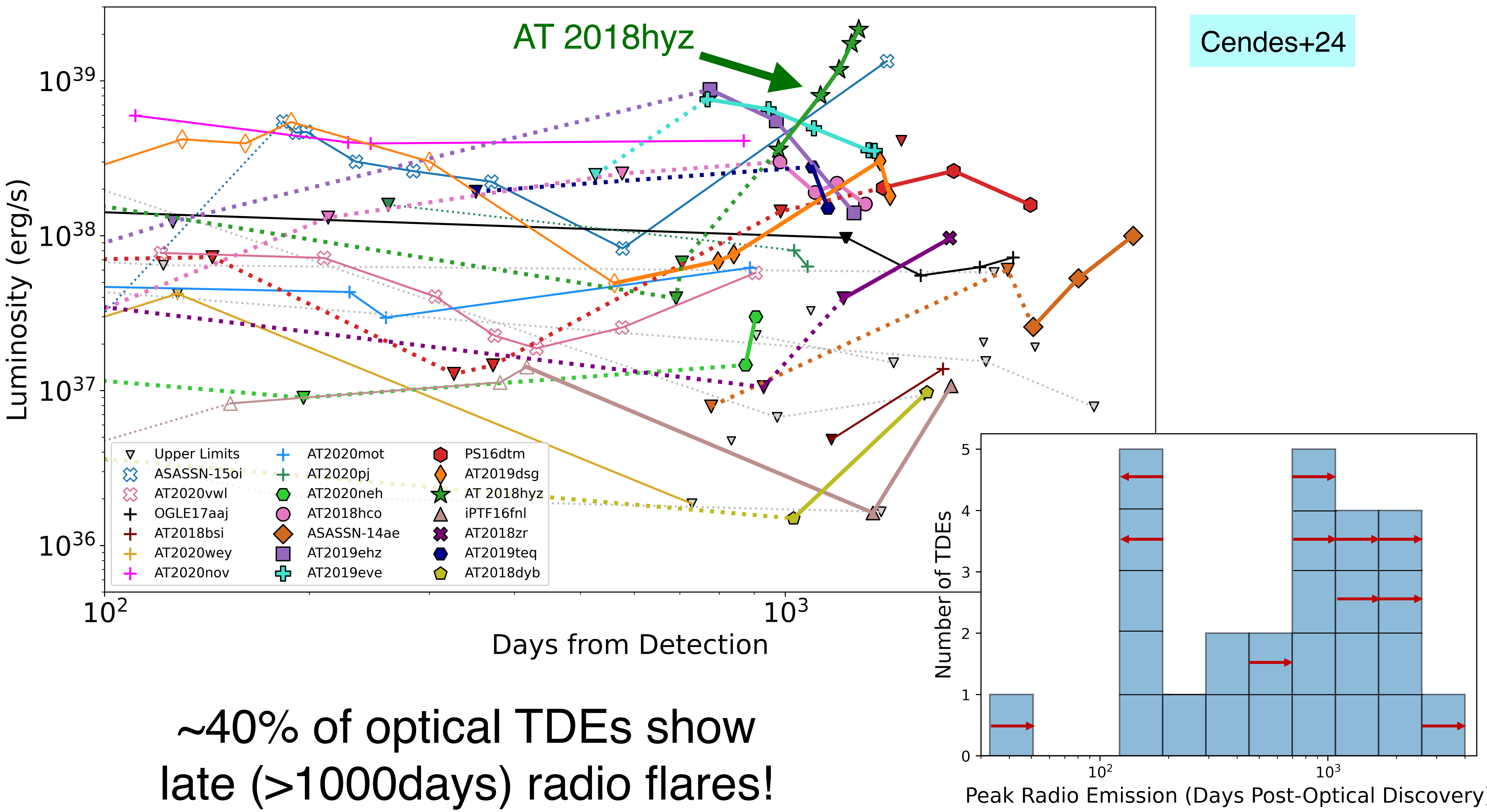




$$\beta_{\rm app} = \frac{\beta\sin\theta}{1 - \beta\cos\theta}$$

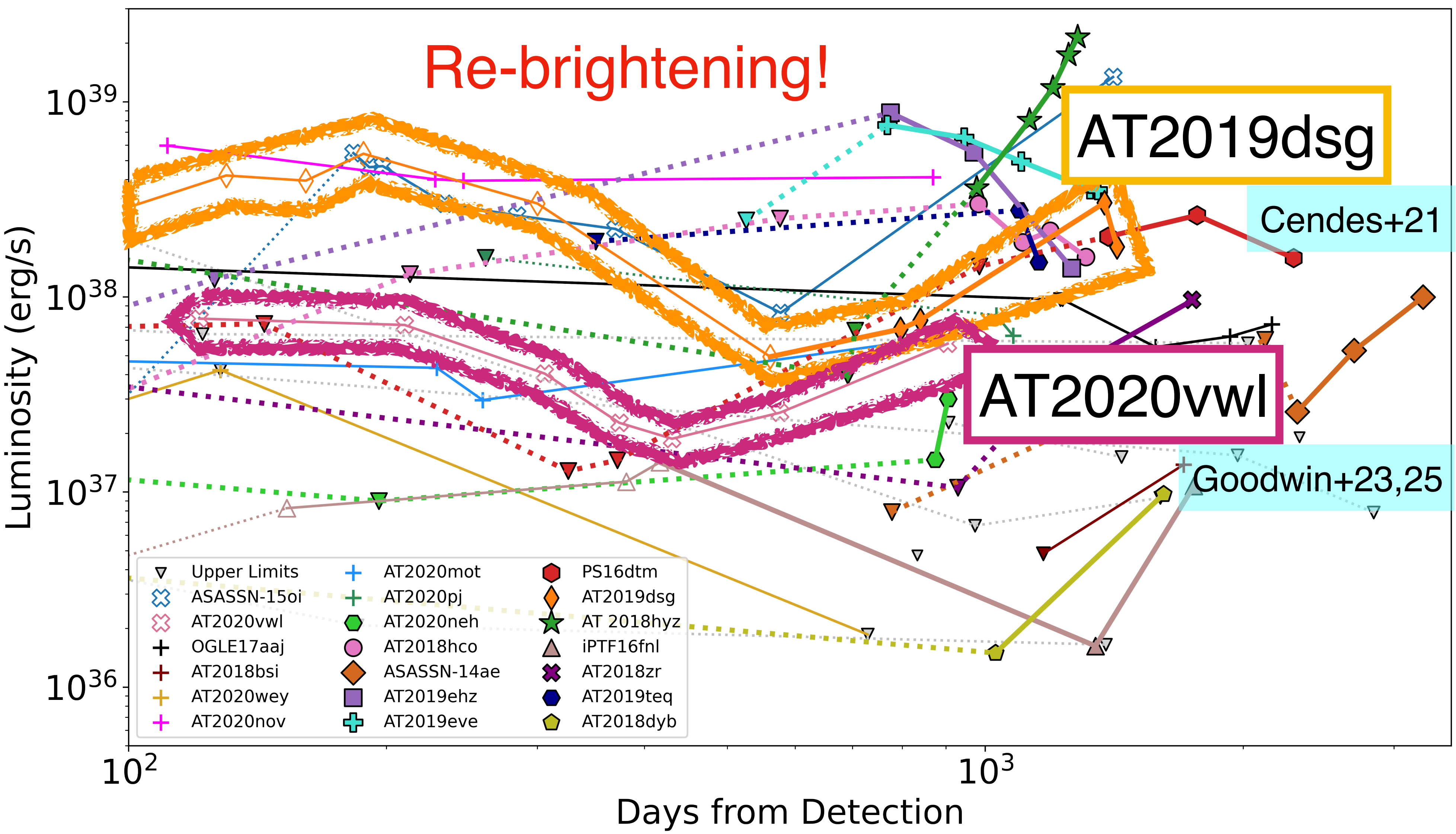
Superluminal Motion will be
A smoking gun of the off-axis jet scenario.

Late-time Flares Are **Ubiquitous**



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

Late-time Flares Are **Ubiquitous**



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

$$N \sim nR^3$$

Late-time rise with **opt. thin** spectrum

=> Different mechanism from the 1st peak to make radio rise

(Most late flares show opt. thin spectrum)

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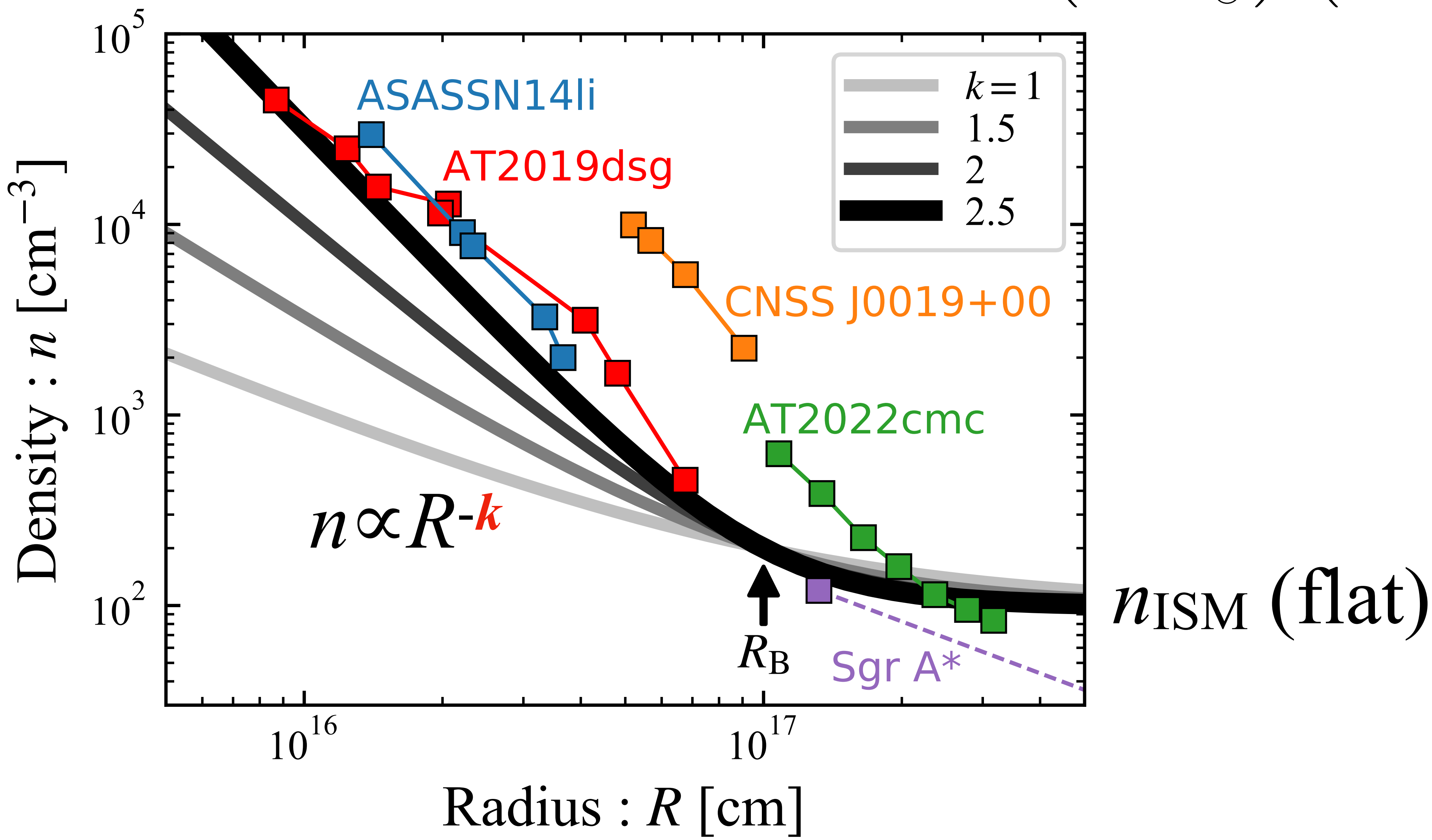
Outflow reaches Bondi Radius

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



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

$$N \sim nR^3 \propto R^{3-k}$$

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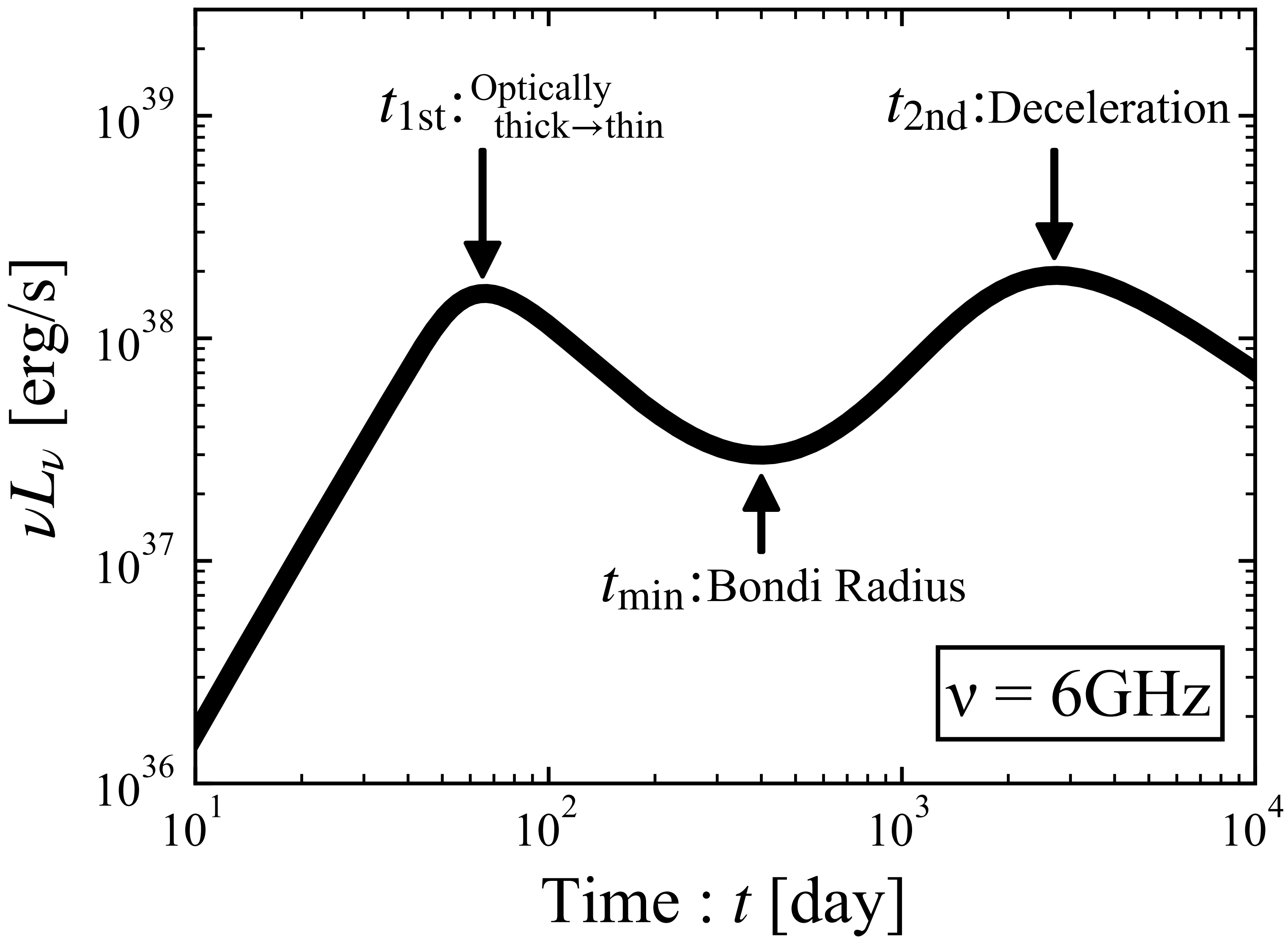
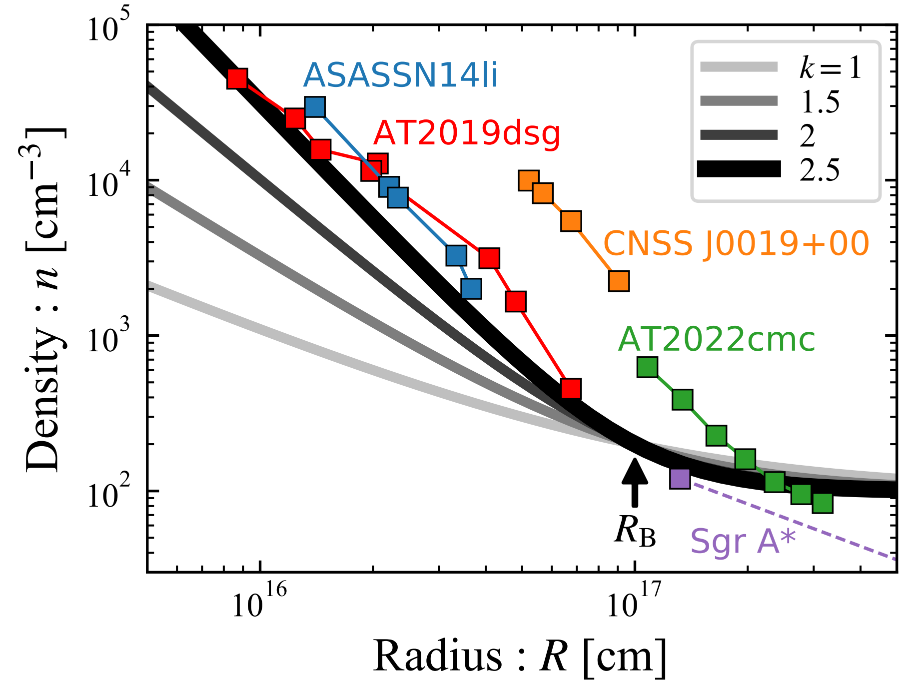
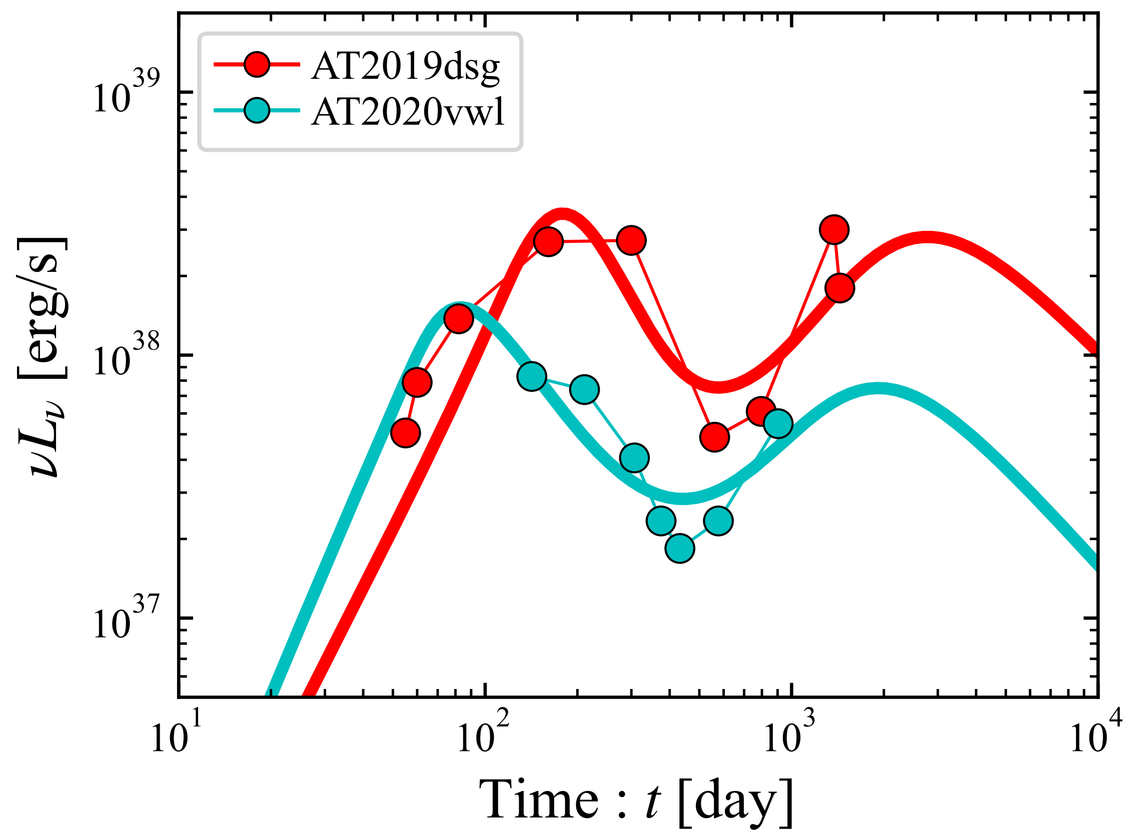
Light Curve







Double peaks naturally appear!

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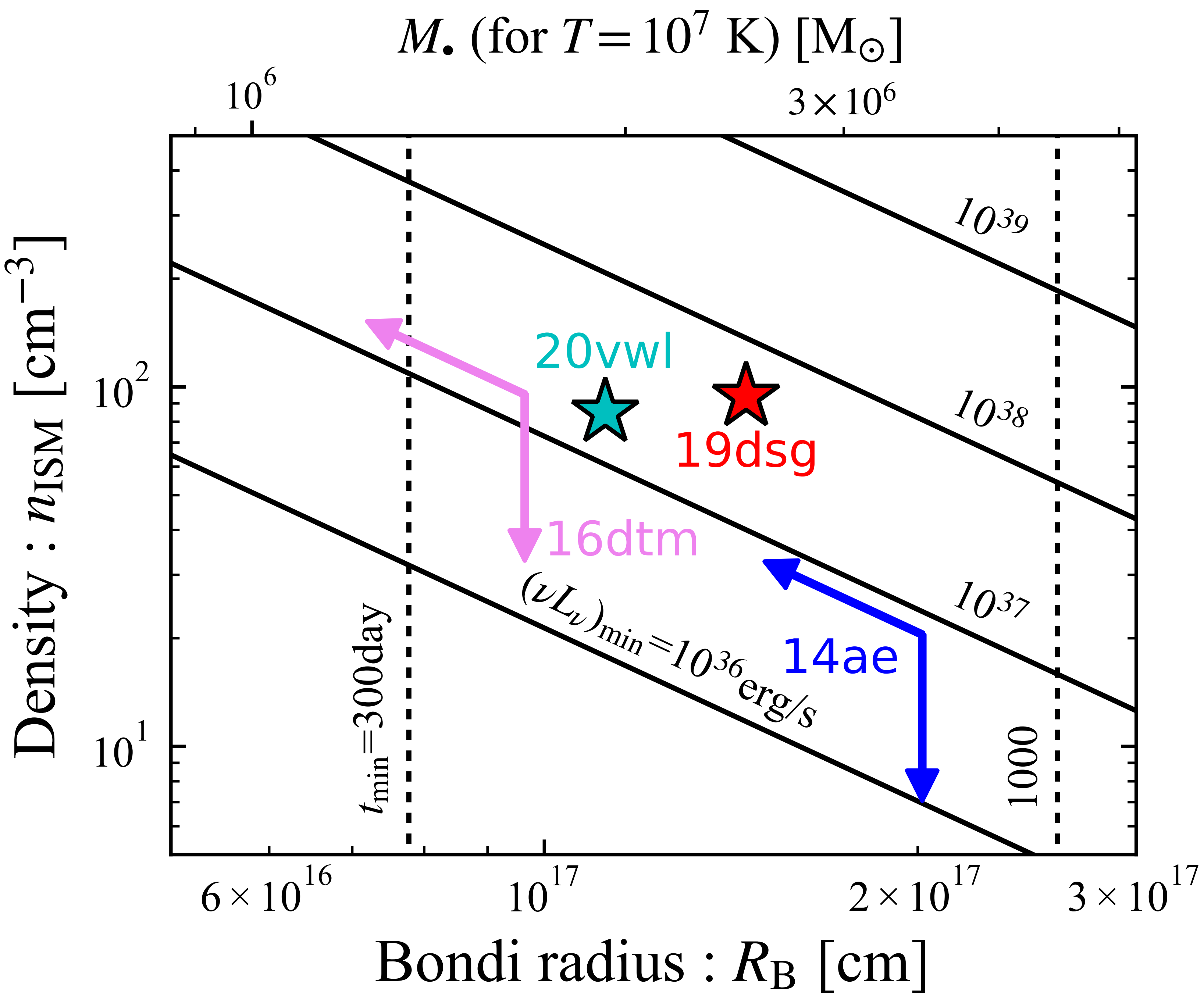
Minimum in Light Curve=>**BH mass**



BH mass may be estimated only by radio flares.

Summary

- Tidal Disruption Events: Flares in galactic centers
- Optical & X-ray observations:

  -Origin of optical emission is still not well understood.

  -Reprocessing, shock interaction, or another mechanism?

  -Global simulations are necessary.

  -Population studies by observations will be promising
- Recent Progress: Population Study

  -Potential Correlation between Observables and Mbh?

  -Event rate: 0.001-0.01 of Supernovae

  -Bright events, Multiple-peak objects
- Radio: Probe of environment and outflow