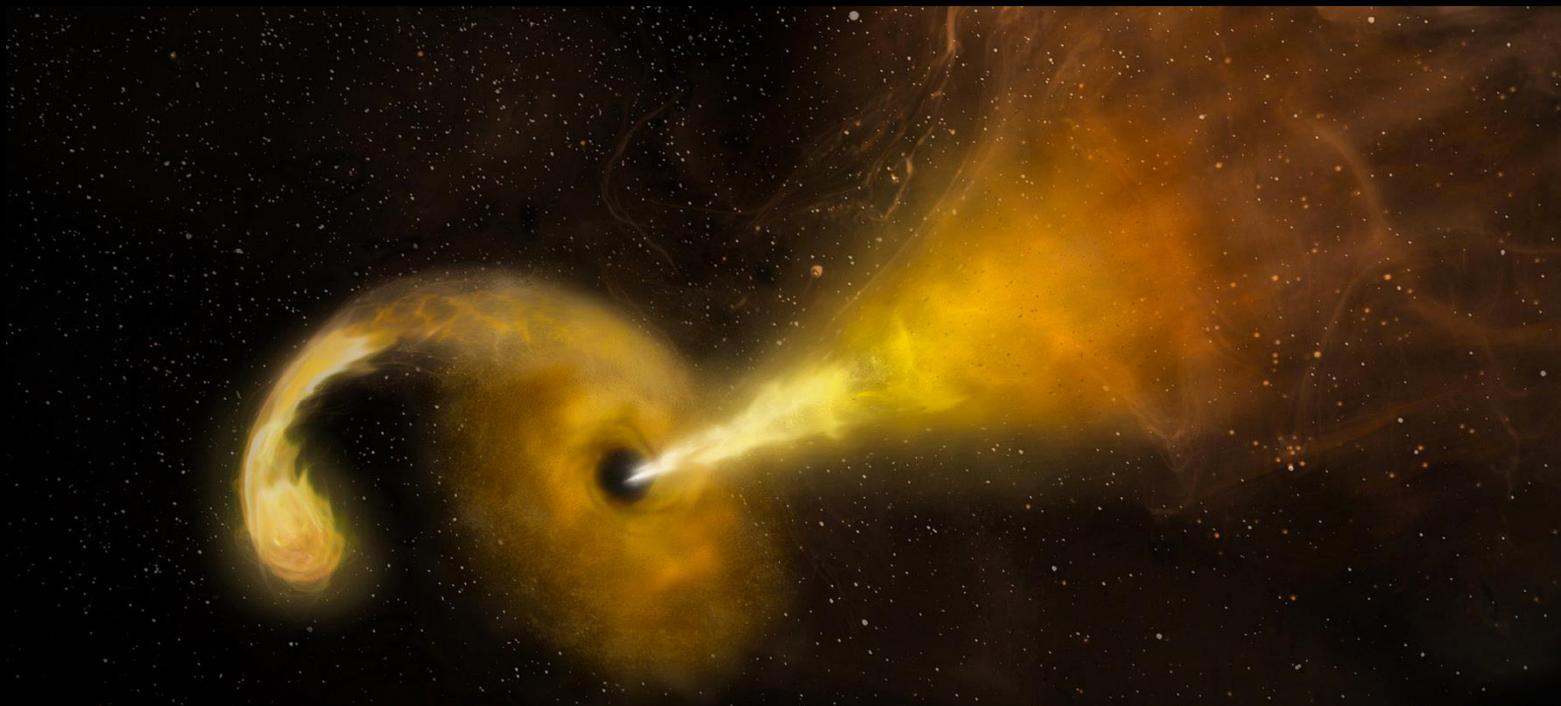


NEW SURPRISES FROM RADIO OBSERVATIONS OF TDE OUTFLOWS



NRAO/AUI/NSF/NASA

Kate D. Alexander
University of Arizona
February 24, 2026

Tidal Disruption Events (TDEs)

Star approaches
black hole

Stream-stream
collisions → shocks

Squeezing/
disruption of star
("spaghettification")

Interaction of
unbound gas
with ISM

Accretion phase

- Bright flare (hot gas)
- Jet formation (sometimes)
- Neutrinos? (Stein et al. 2021)

NASA/CXC/M. Weiss/Komossa et al. 2004



Tidal Disruption Events (TDEs)

But still many open questions:

- How efficiently can the stellar debris form an accretion disk?
 - What powers the early optical/UV emission? (Arcavi talk)
- Why are powerful relativistic jets so rare?
 - Can TDE jets produce neutrinos? (Langis, Lioudakis talks)
- What is the role of environment vs accretion state in the appearance of TDEs?
 - Diversity of spectral lines, X-ray light curves, radio evolution, IR echoes, QPEs...

Radio observations may provide clues! (This talk)

→ Neutrinos? (Stein et al. 2021)

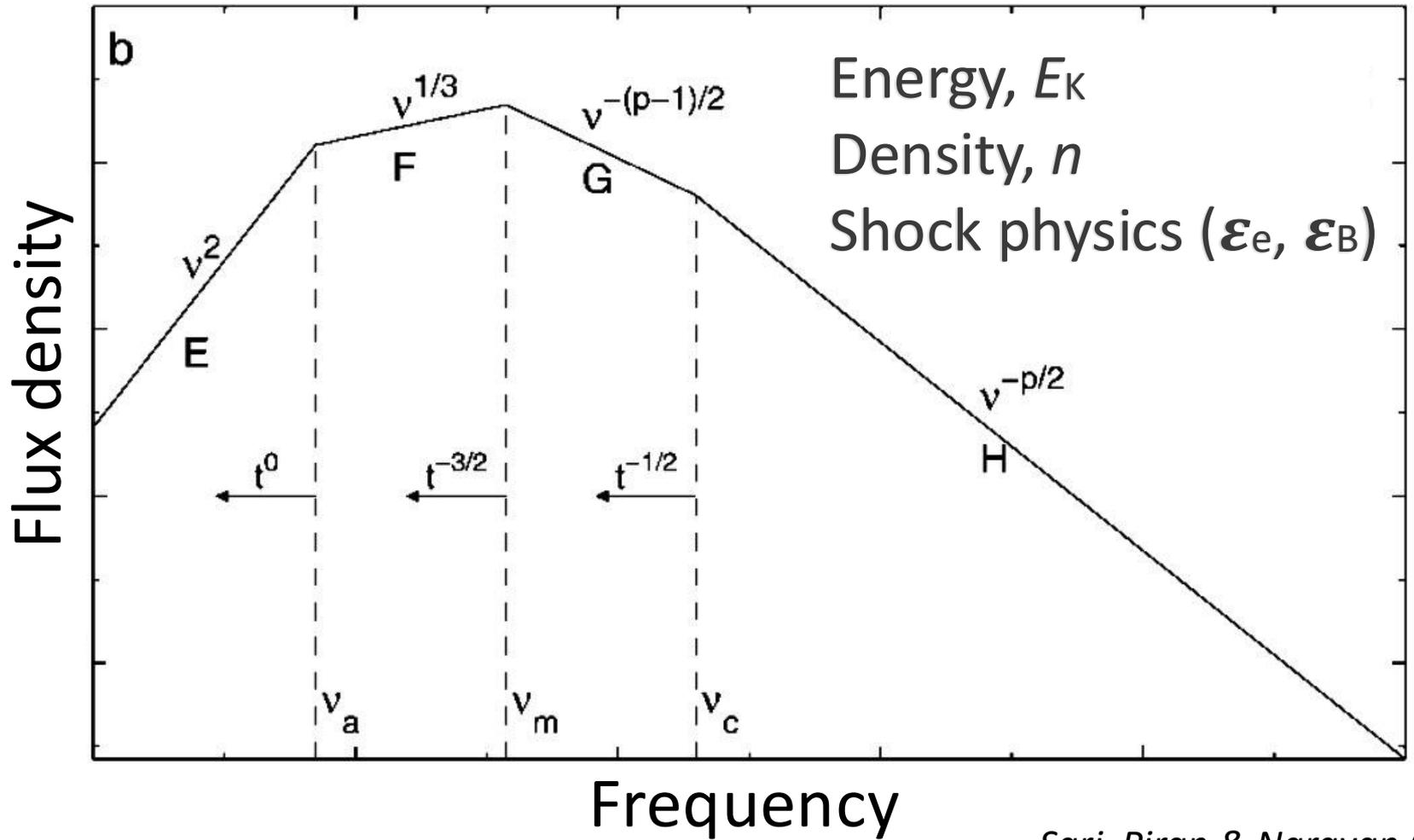
Radio observations probe mass ejection

Galaxy Hercules A



Hubble
Heritage

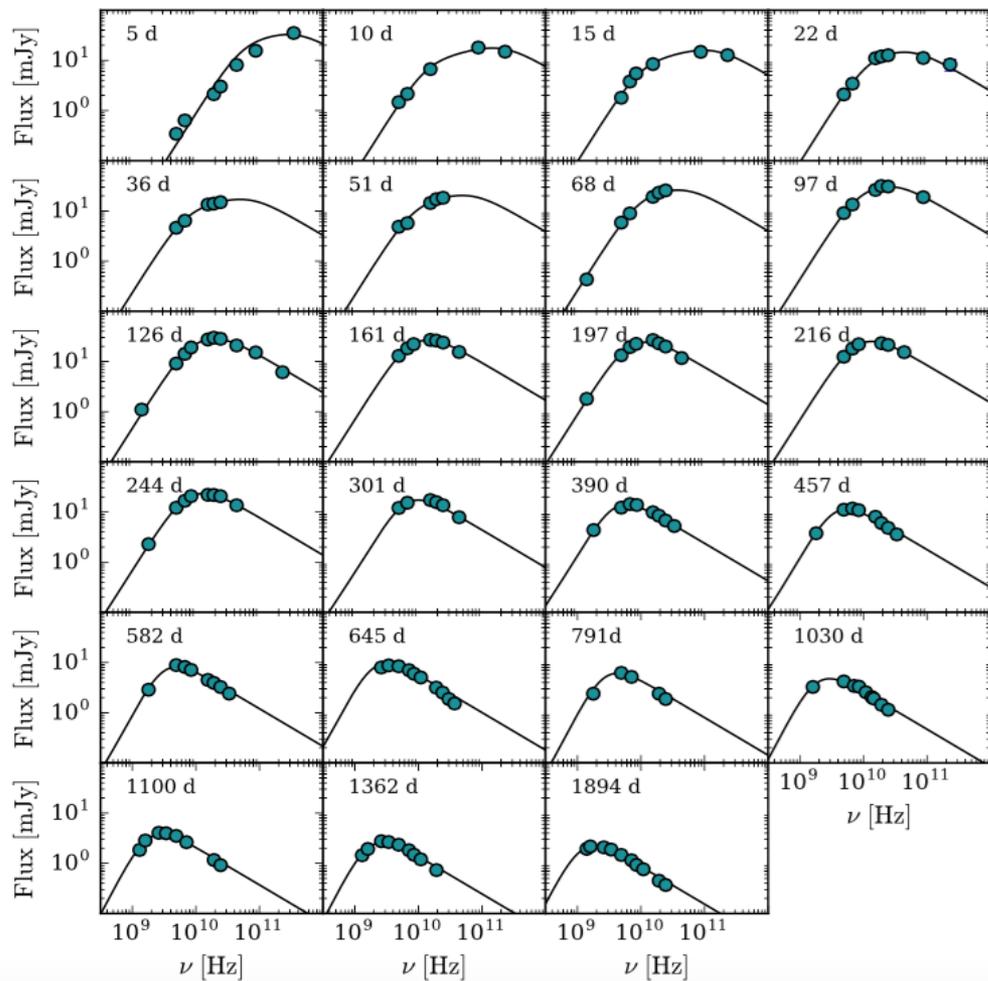
Shocks Generate Synchrotron Emission



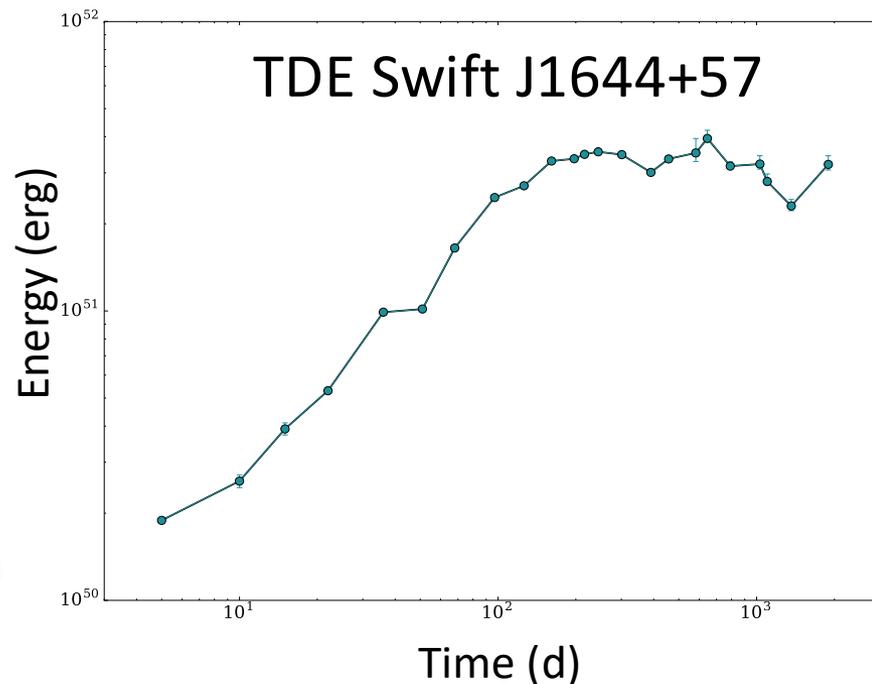
Sari, Piran & Narayan (1998)
Slide courtesy T. Laskar



2011: Synchrotron Emission from a TDE jet

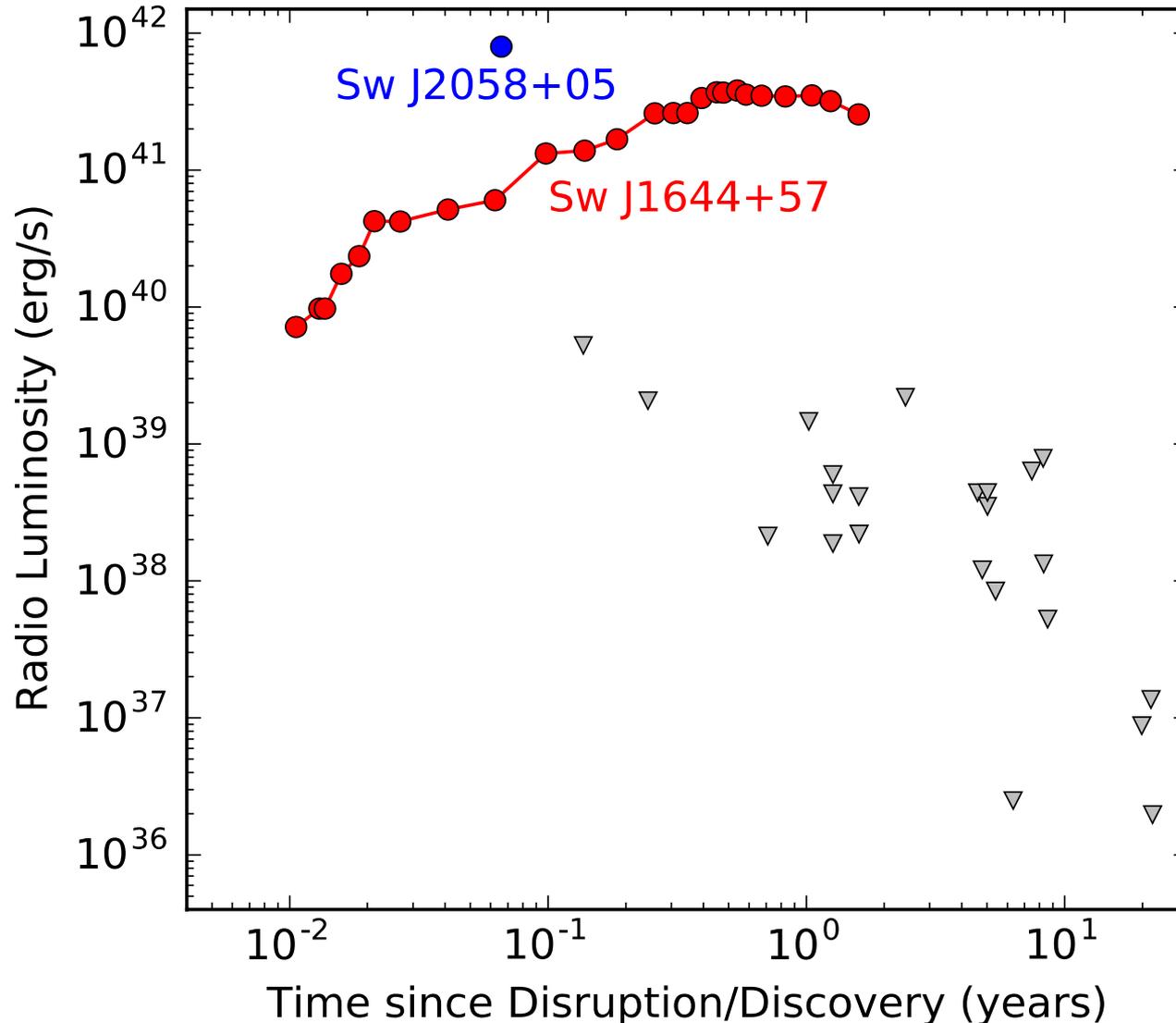


Eftekhari et al. (2018)



Eftekhari et al. (2018)

TDE Radio Observations (2014)

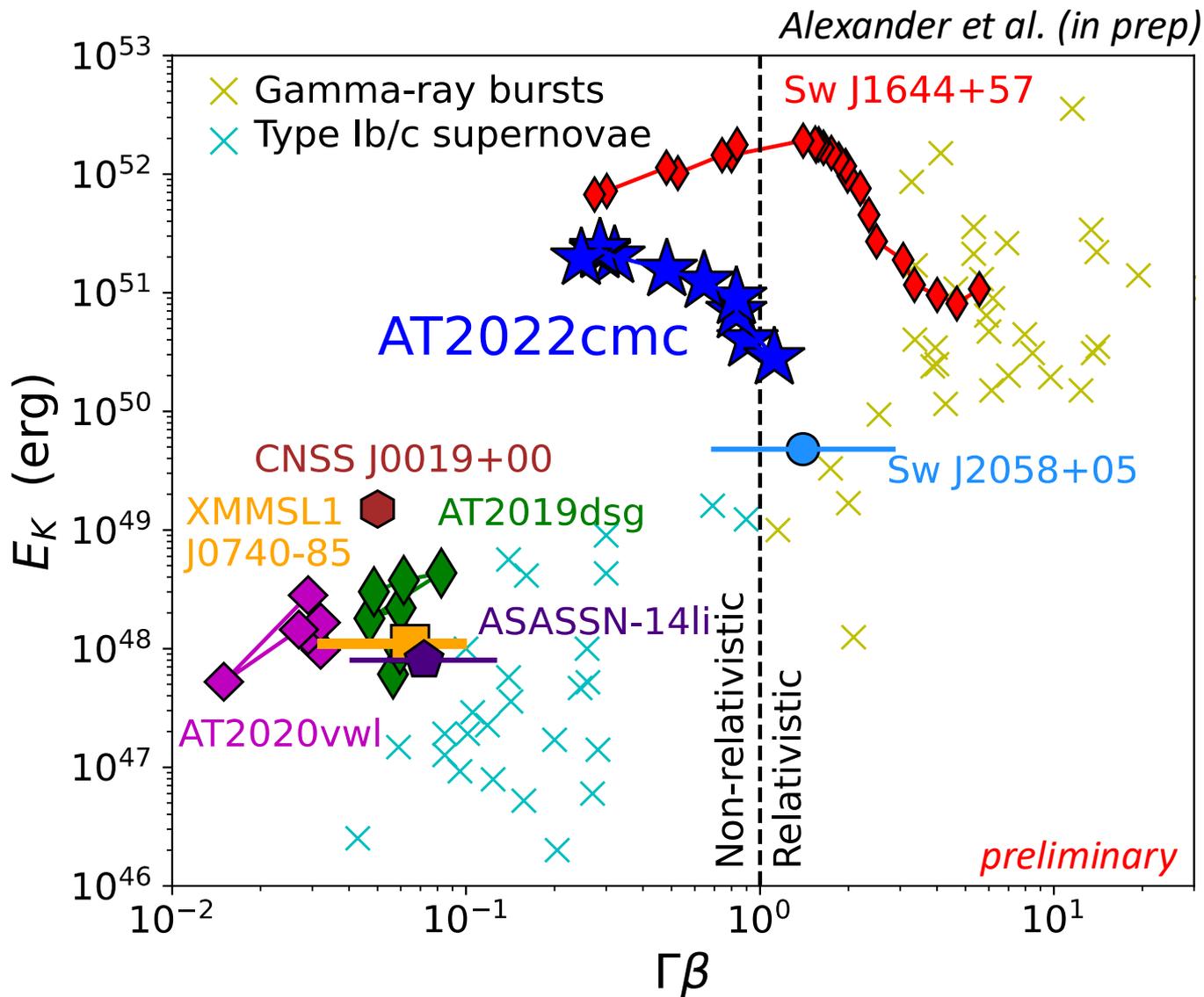


A few TDEs produce luminous radio jets, likely powered by a high (super-Eddington) accretion rate onto the SMBH.

- Where are the off-axis jets?
- What makes (powerful) jets so rare?

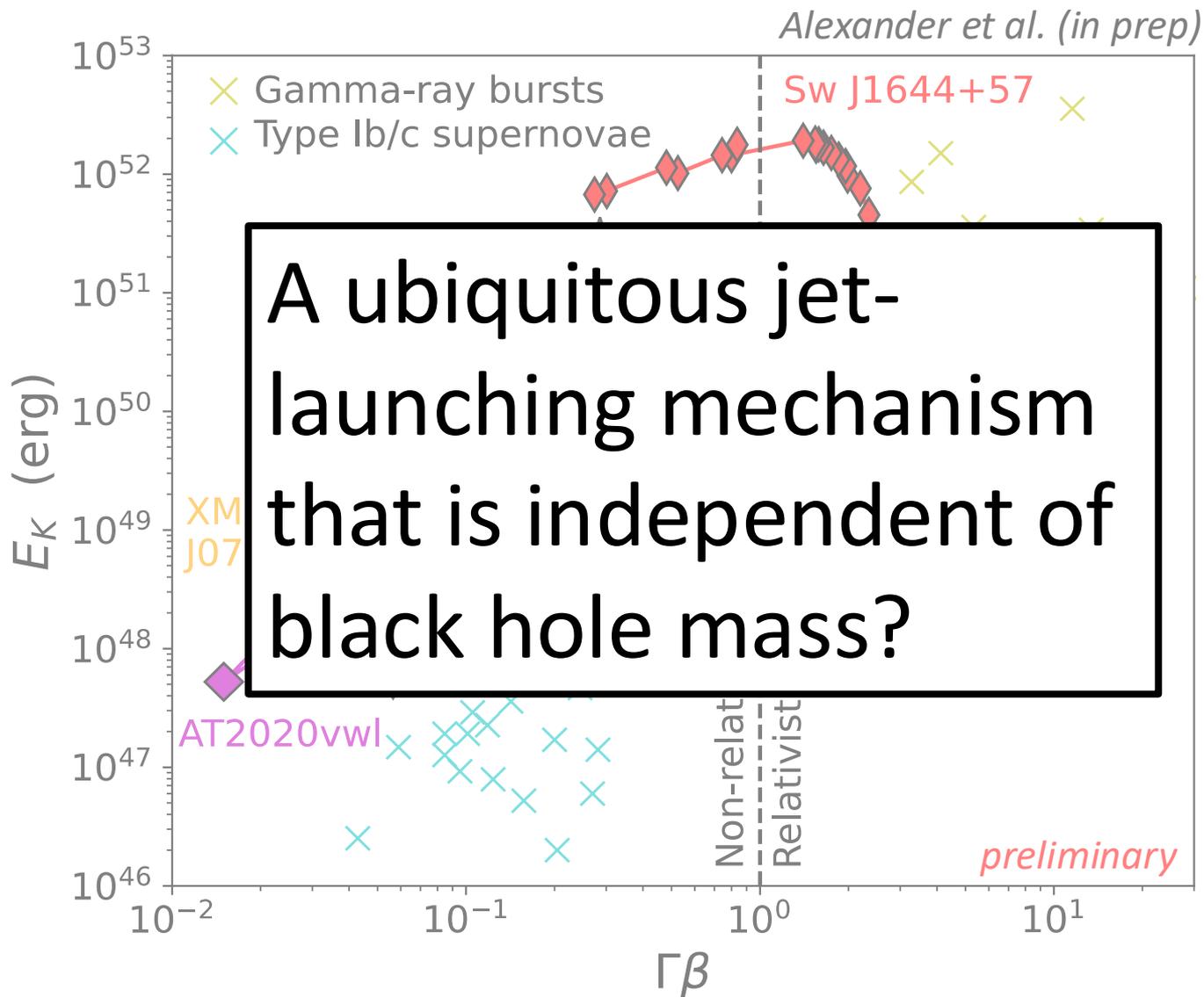


Why are jetted TDEs special? Energetics



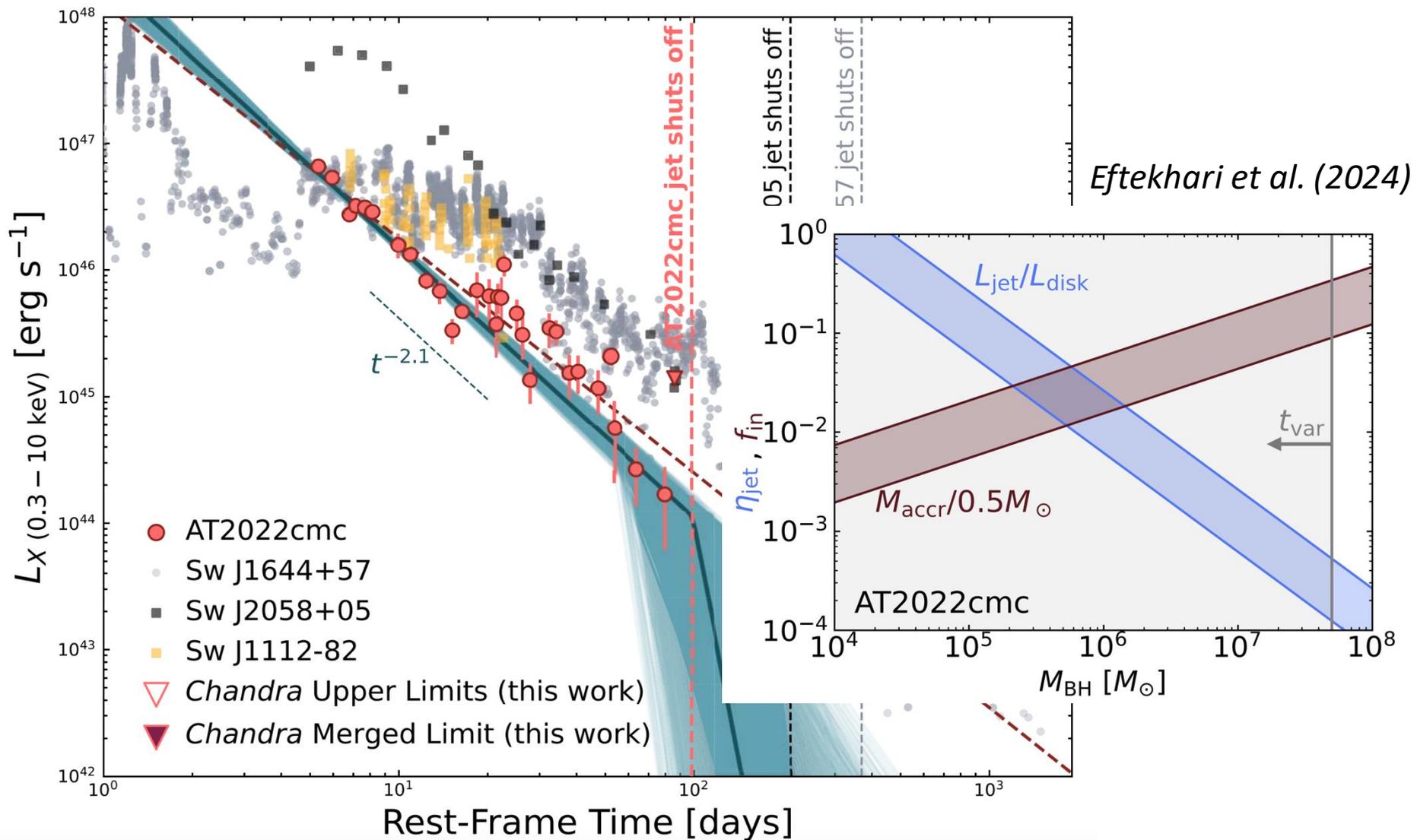


Why are jetted TDEs special? Energetics



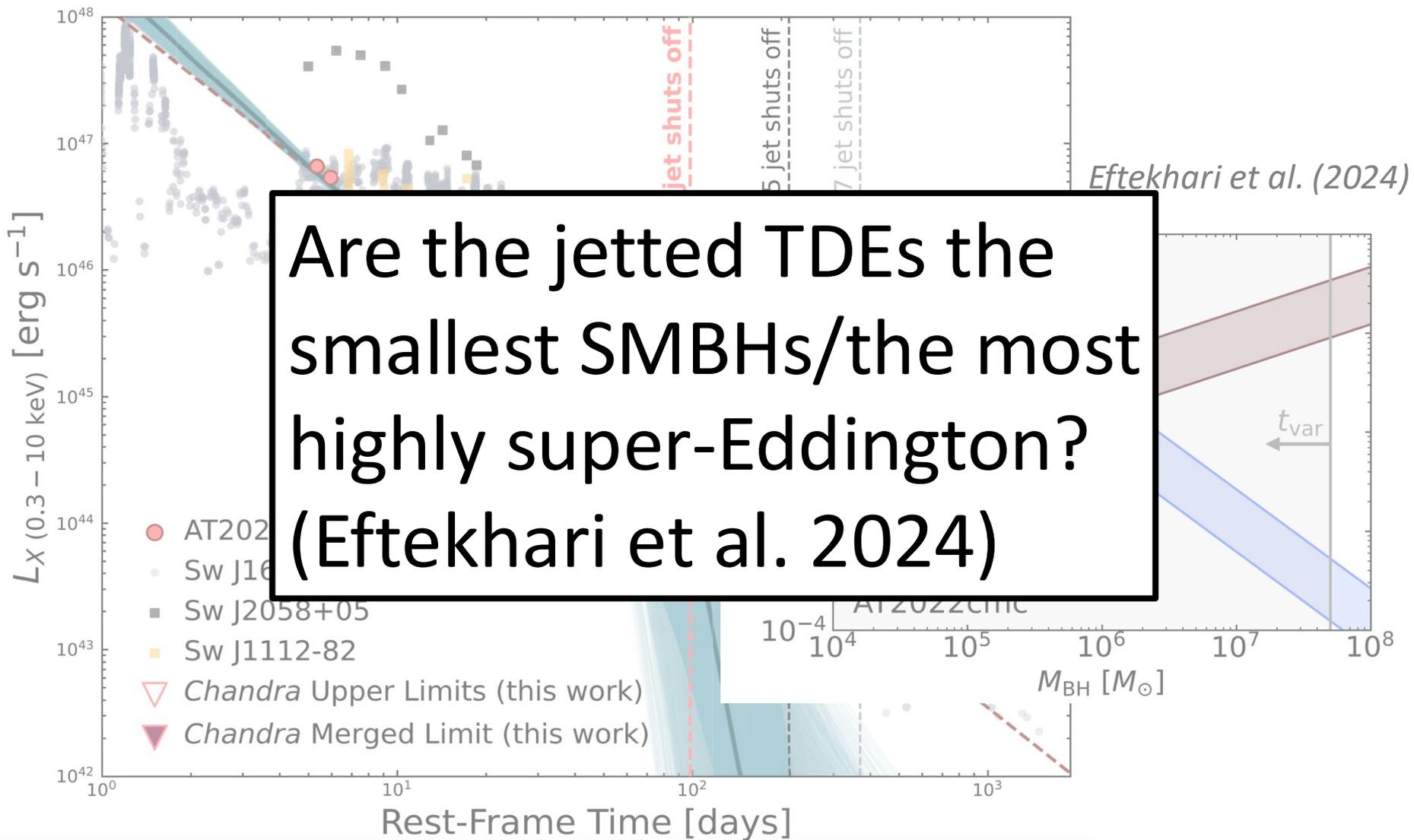


Why are jetted TDEs special? SMBH Mass





Why are jetted TDEs special? SMBH Mass

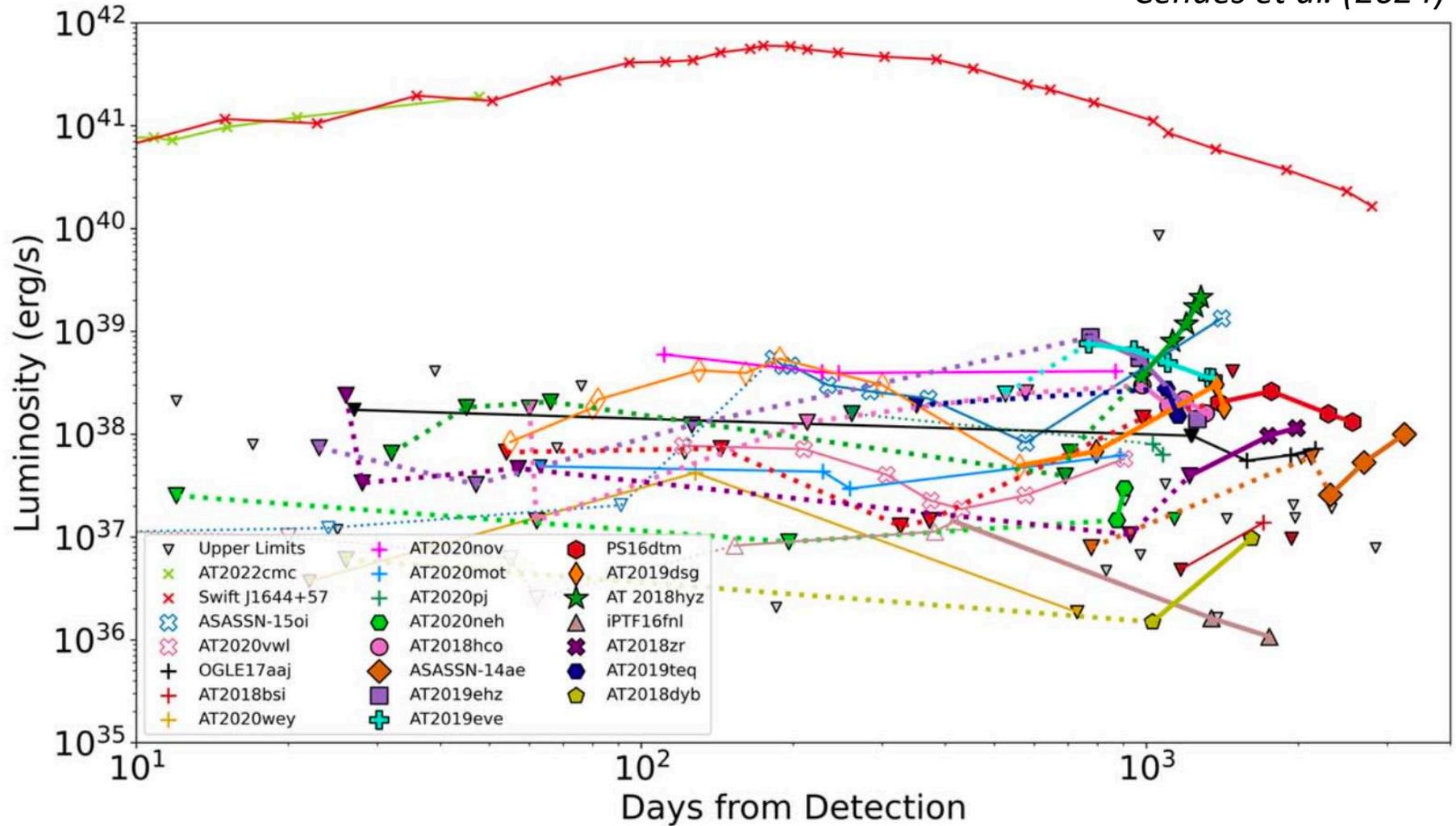


Are the jetted TDEs the smallest SMBHs/the most highly super-Eddington? (Eftekhari et al. 2024)



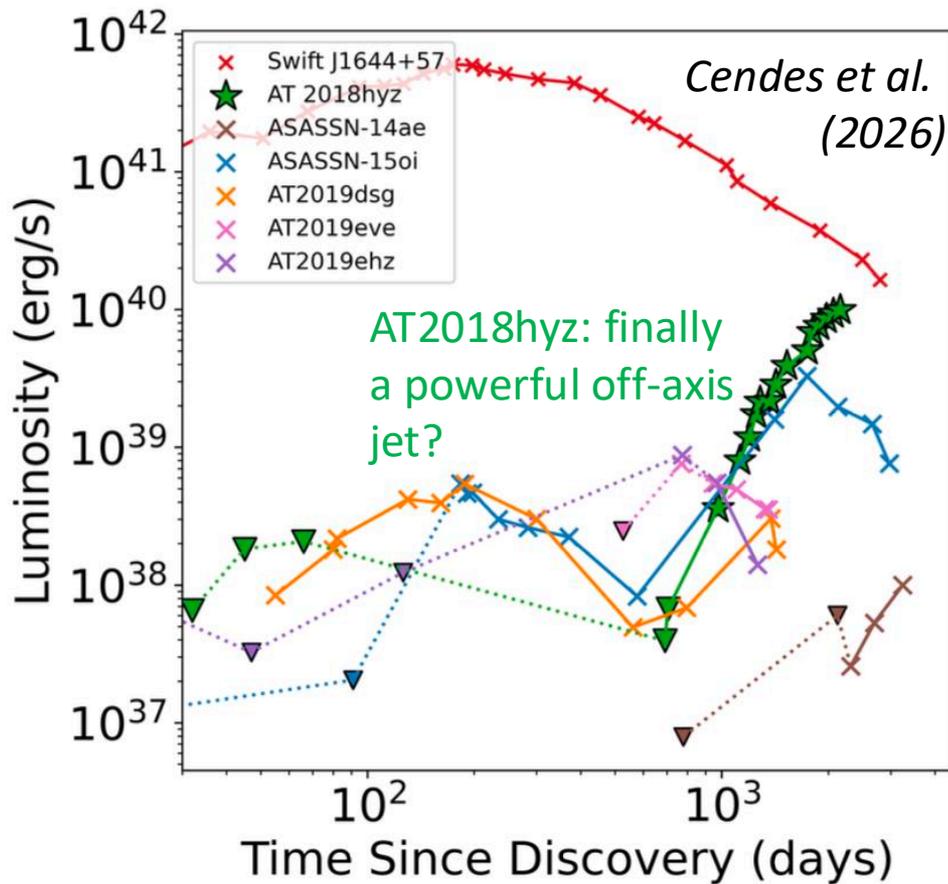
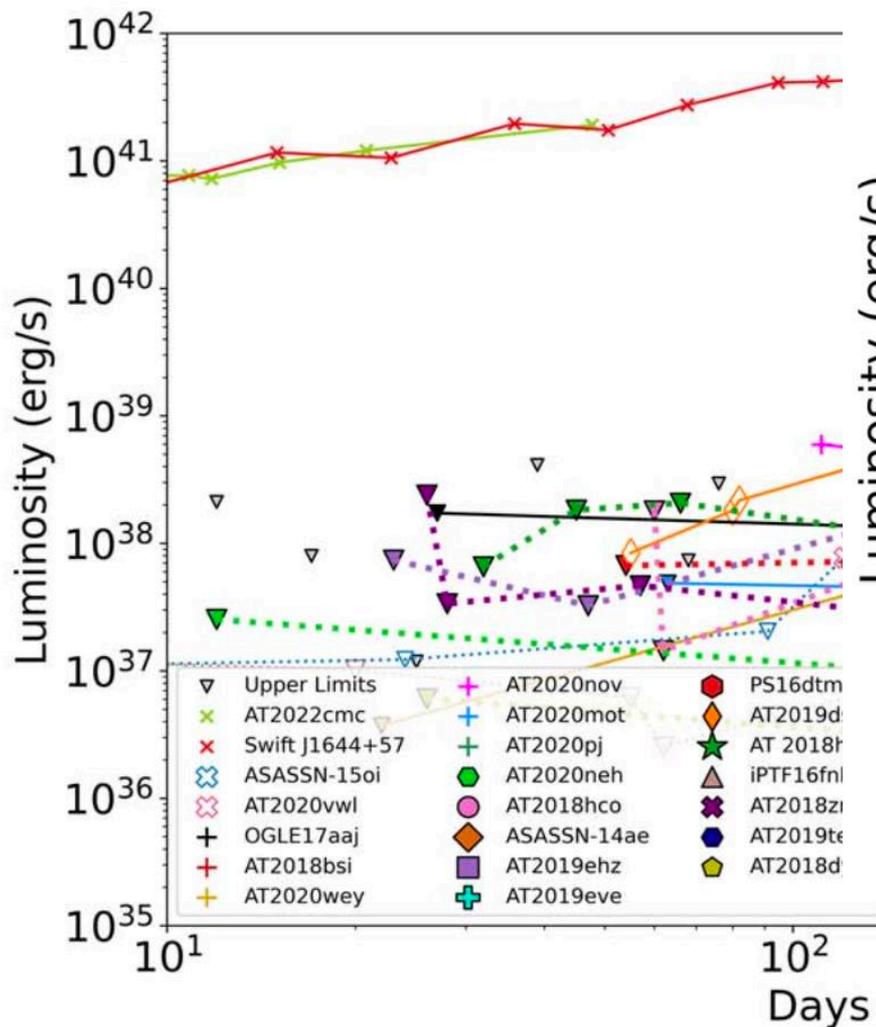
TDE Radio Observations (2024)

Cendes et al. (2024)





TDE Radio Observations (2024)



TDE Radio Observations (2024)

More data = more questions!

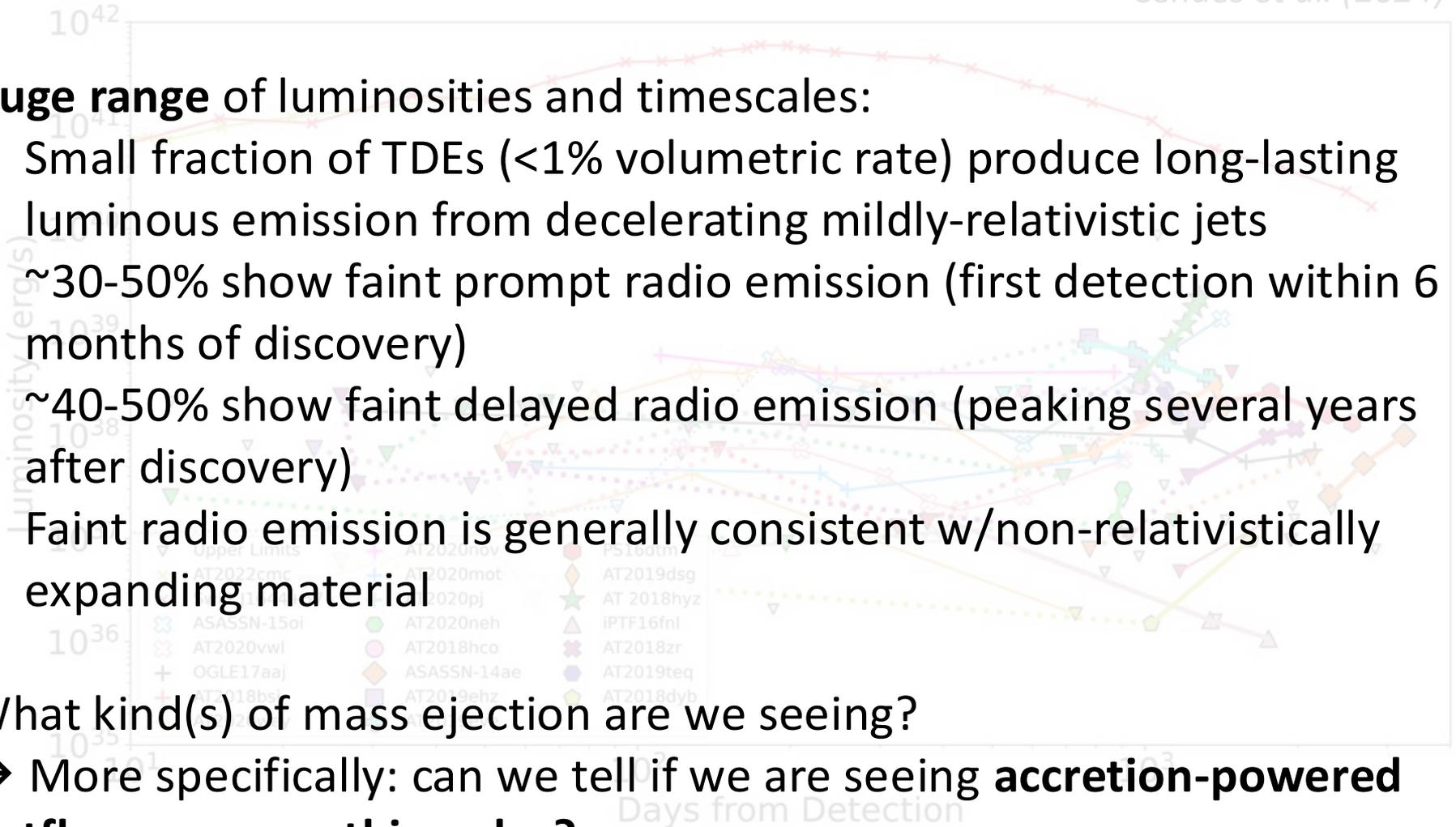
Cendes et al. (2024)

Huge range of luminosities and timescales:

- Small fraction of TDEs (<1% volumetric rate) produce long-lasting luminous emission from decelerating mildly-relativistic jets
- ~30-50% show faint prompt radio emission (first detection within 6 months of discovery)
- ~40-50% show faint delayed radio emission (peaking several years after discovery)
- Faint radio emission is generally consistent w/non-relativistically expanding material

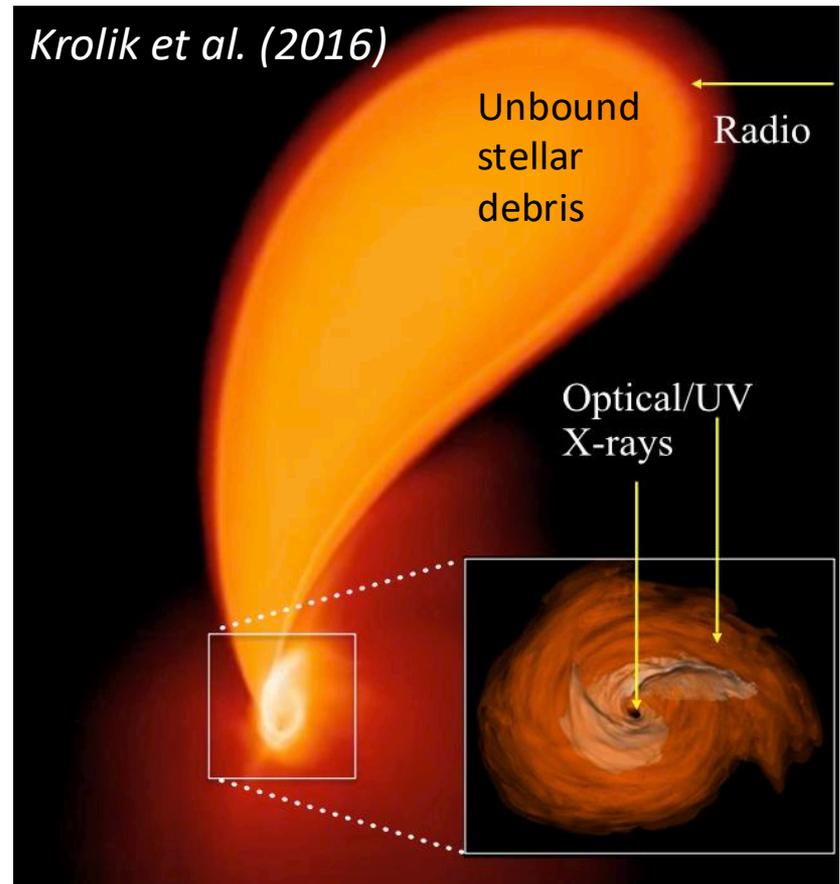
What kind(s) of mass ejection are we seeing?

→ More specifically: can we tell if we are seeing **accretion-powered outflows** or **something else**?





Many proposed models...



Accretion-powered jets and outflows? Stream-stream collisions? Collision-induced outflows (during debris circularization)? Shocks from the unbound stellar debris stream? Late emission from shock interaction w/density clumps?



Many proposed models...

How do we distinguish among these models?

Maybe timing of the radio emission?

- CIOs & unbound debris would need to have early launch dates (equipartition modeling)
- In accretion-based models, radio is correlated w/timing of specific accretion rates
- Environmental interactions should show random/broad onset of radio onset times, as they depend on the density distribution around the SMBH (maybe correlations w/other environmental probes?)
- Existing data often ambiguous...

Accretion
induced

stellar debris stream? Late emission from shock interaction w/density clumps?



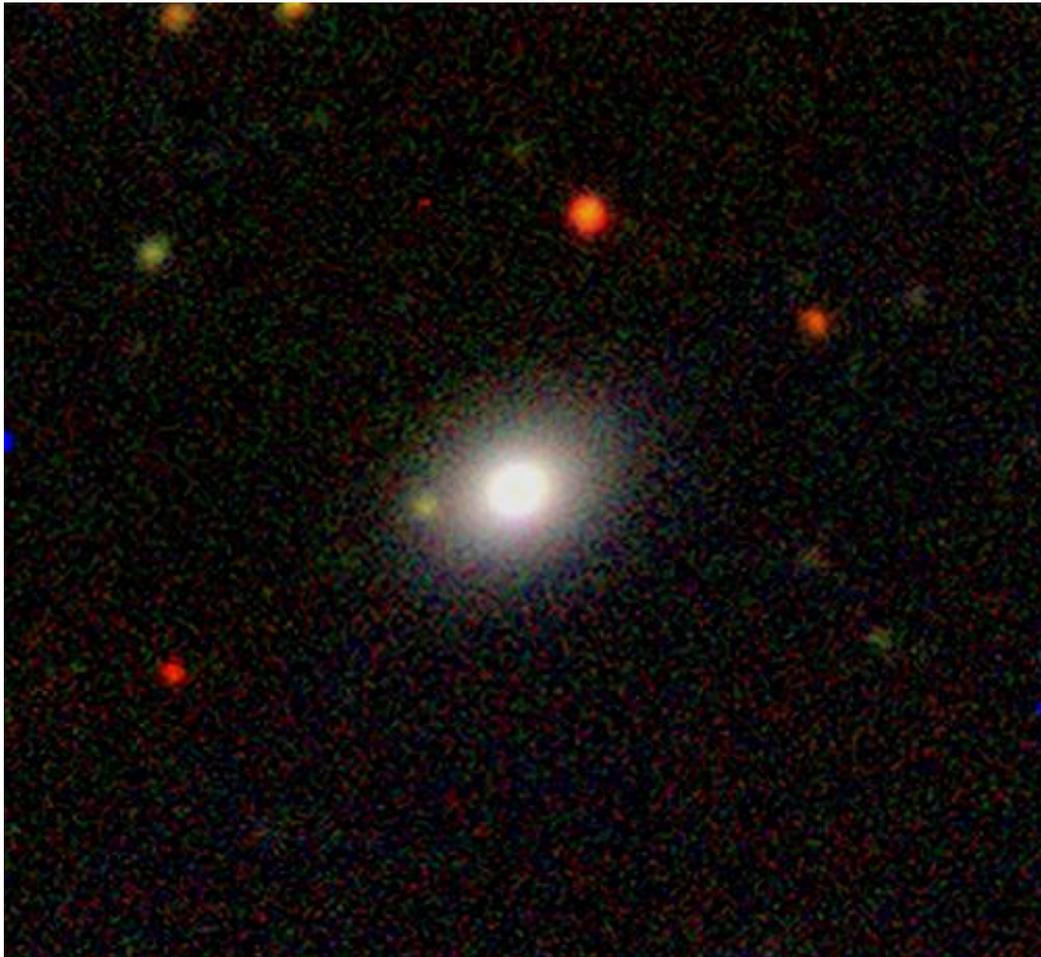
An example: the “typical” AT2020vwl

Discovered on 2020
October 10

Optical flare in the
nucleus of an inactive
galaxy (147 Mpc)

Classified as a TDE on
2020 December 21

Radio observations
began 2021 February
23

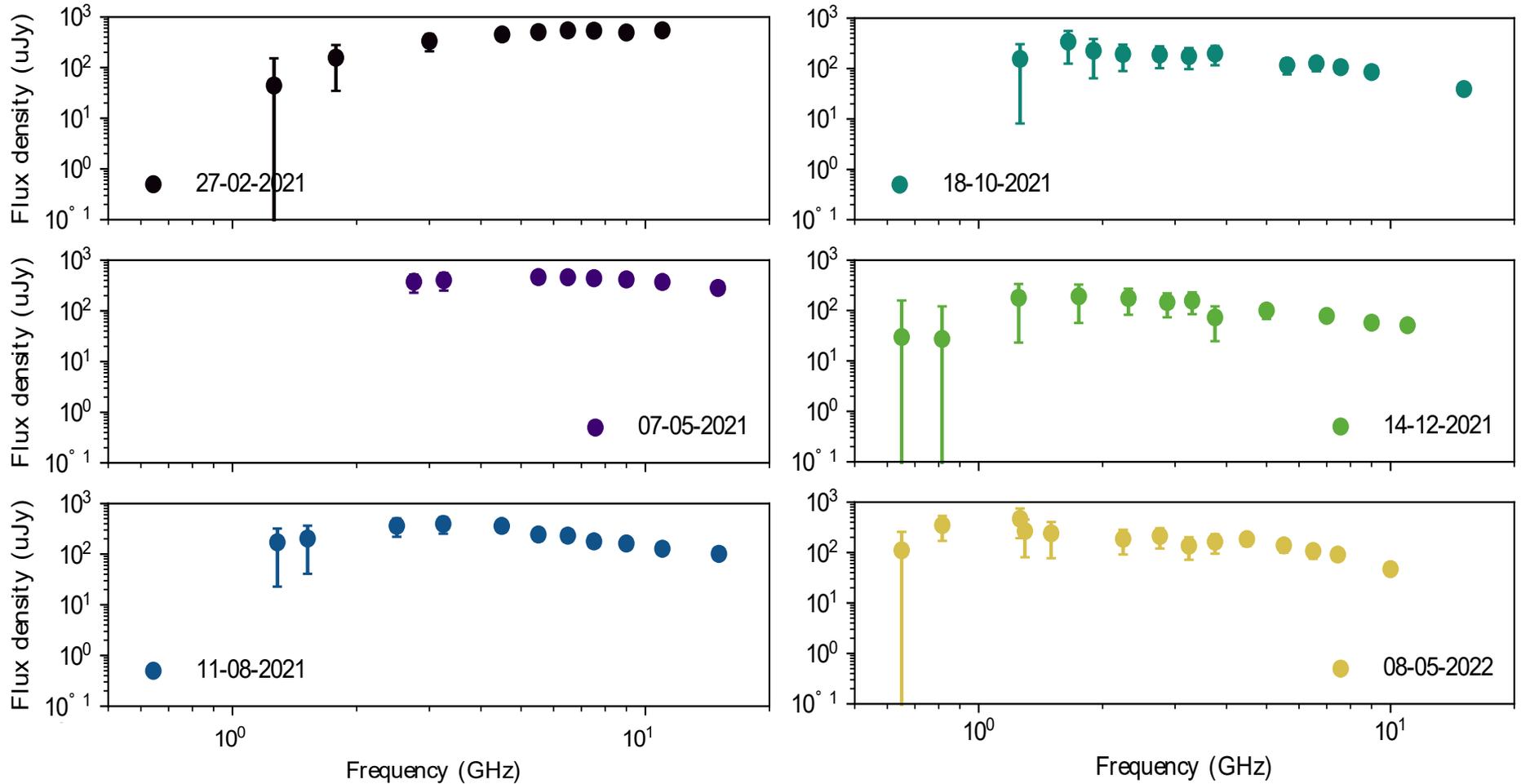


Goodwin, Alexander et al. (2023)



Radio monitoring of AT2020vwl

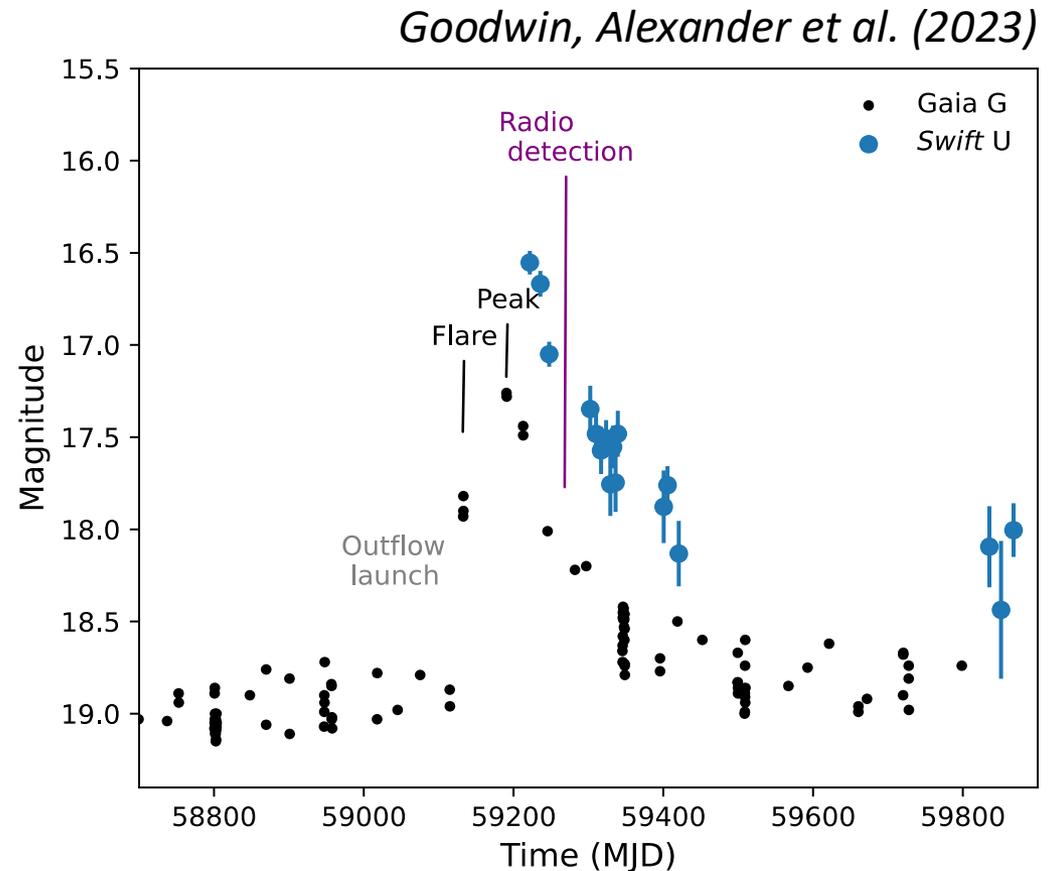
Goodwin, Alexander et al. (2023)



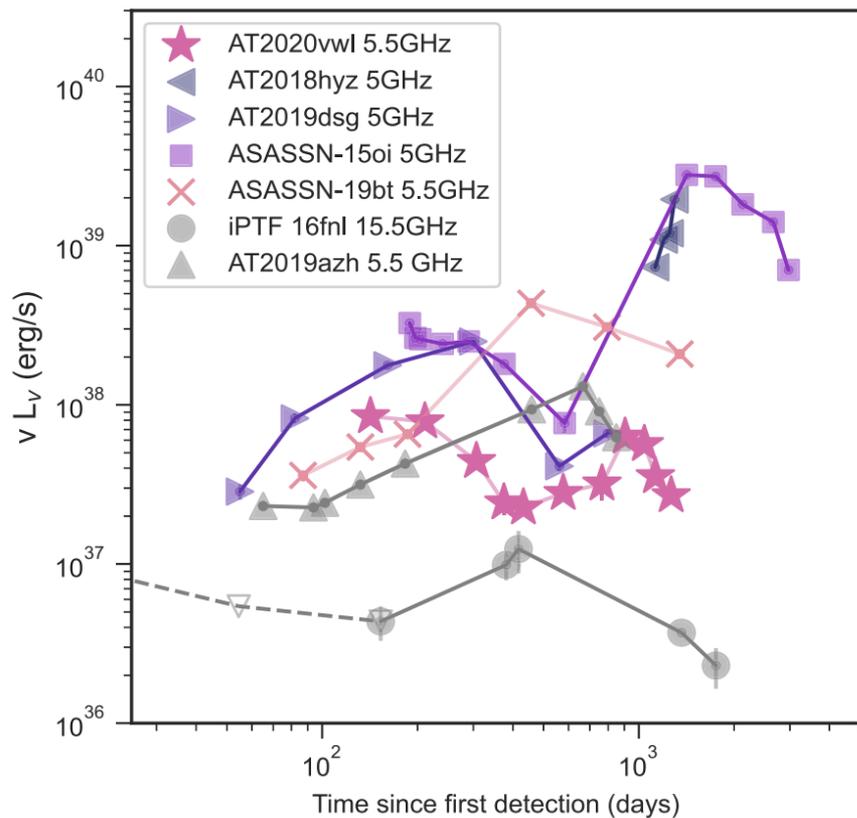
Radio observations reveal a non-relativistic outflow ($v \sim 0.03c$).

What powered the outflow?

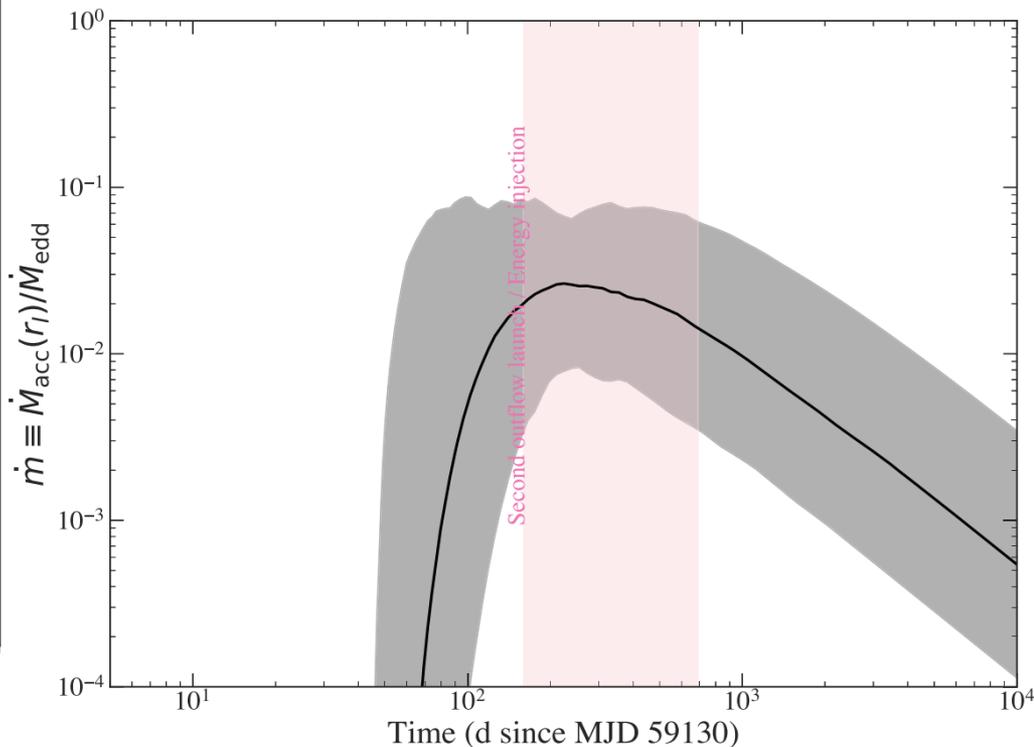
- Weak jets?
- Winds launched during a super-Eddington accretion phase?
- Shocks from the unbound stellar debris stream?
- **Stream-stream collisions?**



A second outflow from accretion?



Goodwin et al. (2025a)



- Disc modeling suggests that accretion rate peaks around the time that the second radio outflow is launched. Could also be energy injection into first outflow



What powers faint radio TDEs?

We need a **larger sample** of radio-detected TDEs, especially faint ones, to pin down the origin(s) of non-thermal emission. Multi-pronged approach:

i) Detailed studies of individual events

(e.g. Alexander et al. 2016; Hajela et al. 2025; Christy et al. 2026 *in press*)

ii) Systematic radio follow up of **all** nearby TDEs

(e.g. Cendes et al. 2024; Goodwin et al. 2025b; Christy et al. *in prep*)

iii) Multi-wavelength population studies

(e.g. Alexander et al. 2026 *in press*; Franz et al. 2026 *in press*; Goodwin & Mummery et al. 2026 *under review*)

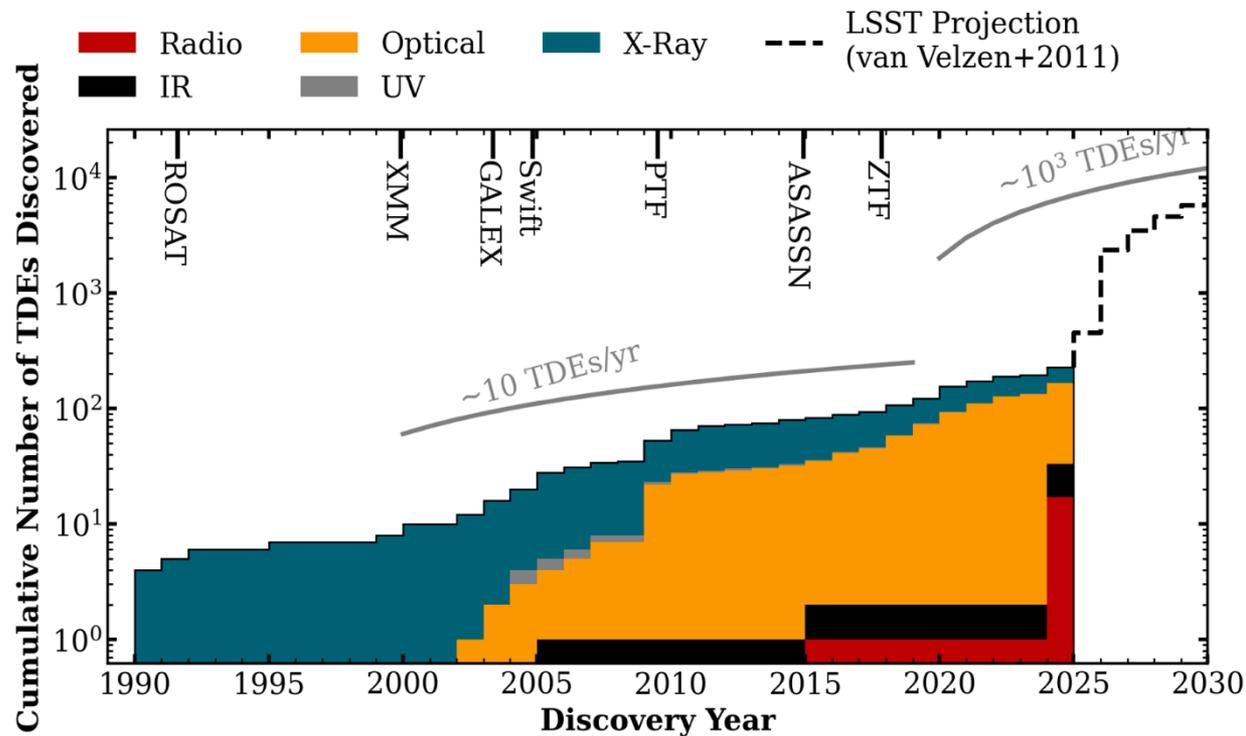
stellar debris stream?

The New Data-Rich Era is Here

We are making excellent progress on all three fronts:

- All sky surveys (e.g. ZTF) have found >100 TDEs, many of which are spectroscopically classified
- Rubin alerts are imminent (starting today!)
- Thousands of TDEs expected in the Rubin data stream

Franz et al. 2026 (*in press*)



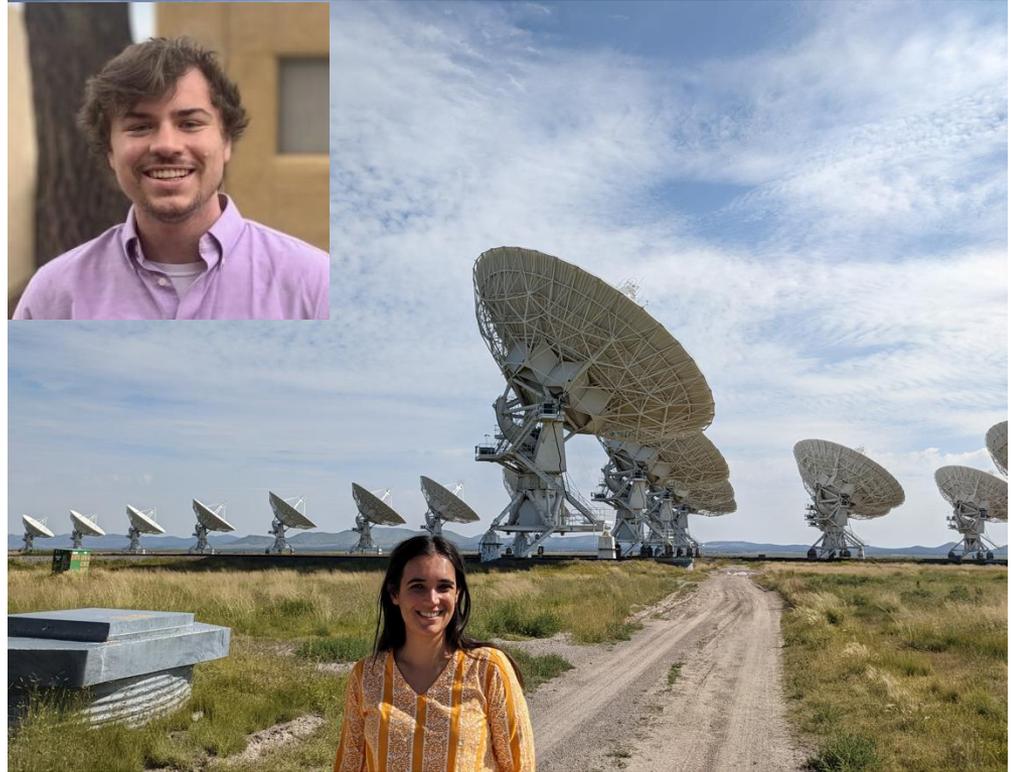


The New Data-Rich Era is Here

We are making excellent progress on all three fronts:

- Dedicated radio follow up campaigns at early times (VLA large program & others) and late times (e.g. Cendes et al. 2024)
- Mining of all-sky radio surveys (e.g. Anumarlapudi et al. 2024, Dykaar et al. 2024)

UA Ph.D. student Collin Christy



<https://as.arizona.edu/radiotdes/>

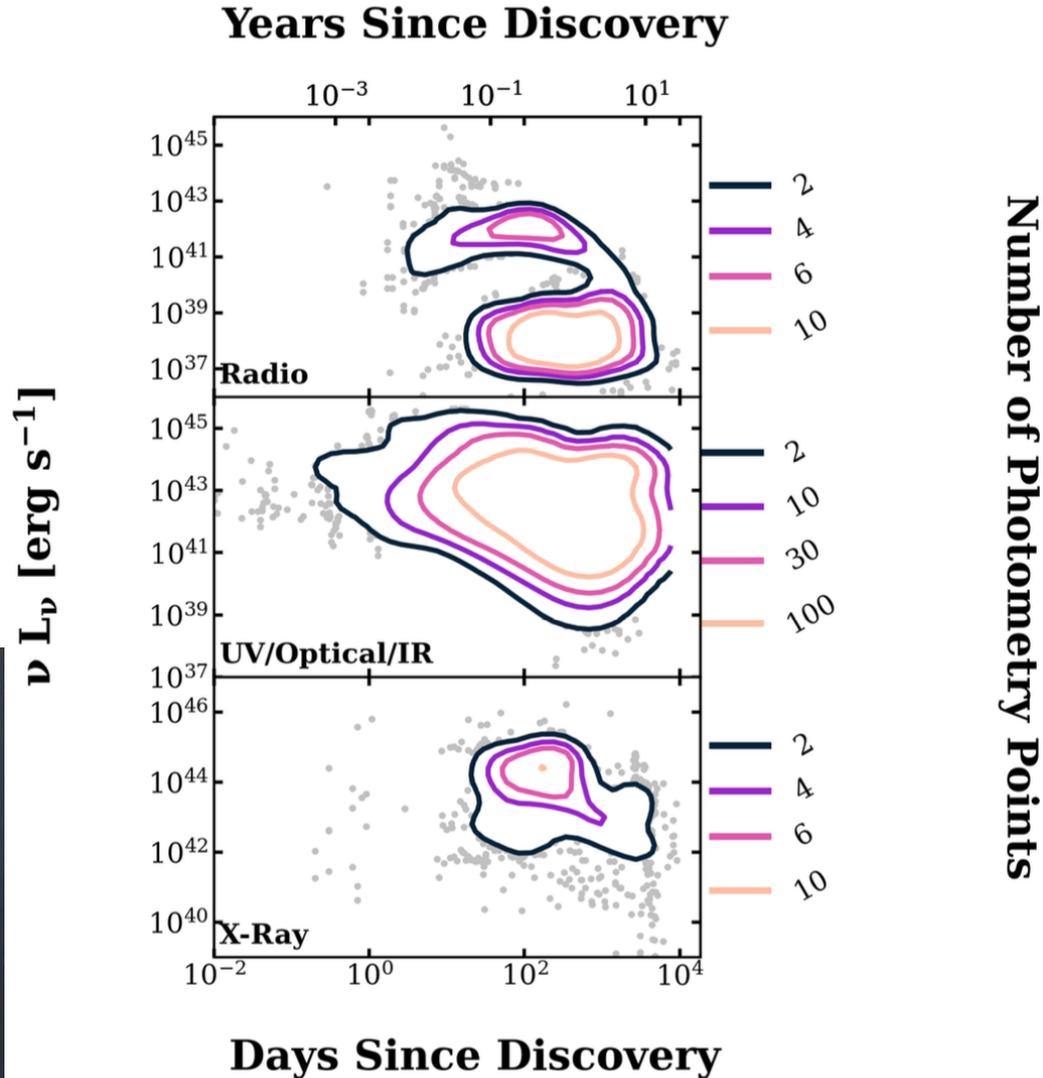
The New Data-Rich Era is Here

We are making excellent progress on all three fronts:

- New database tools to organize and model all this complex multi-wavelength data (e.g. OTTER; Franz et al. 2026 *in press*)



UA Ph.D. student
Noah Franz





The New Data-Rich Era is Here

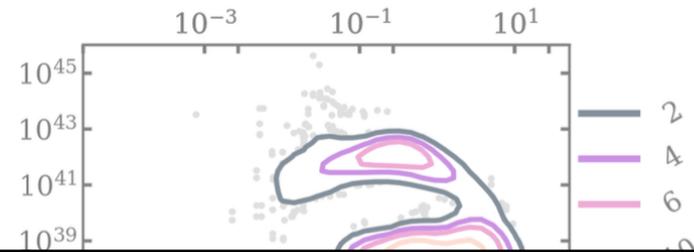
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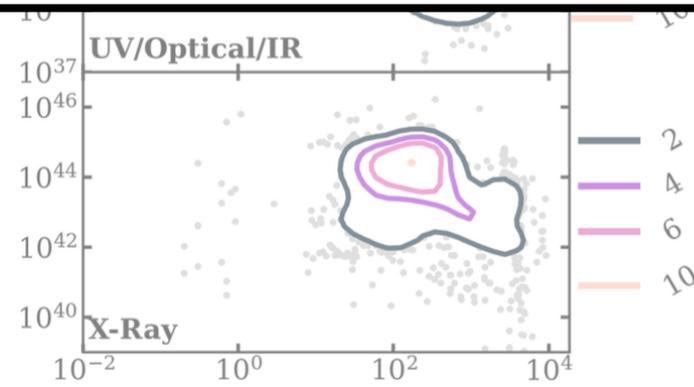
With all of this data, we can now start to test the accretion scenario(s) for TDE radio emission in a systematic way.

Years Since Discovery



Number of Photometry Points

UV/Optical/IR



Days Since Discovery



UA Ph.D. student
Noah Franz



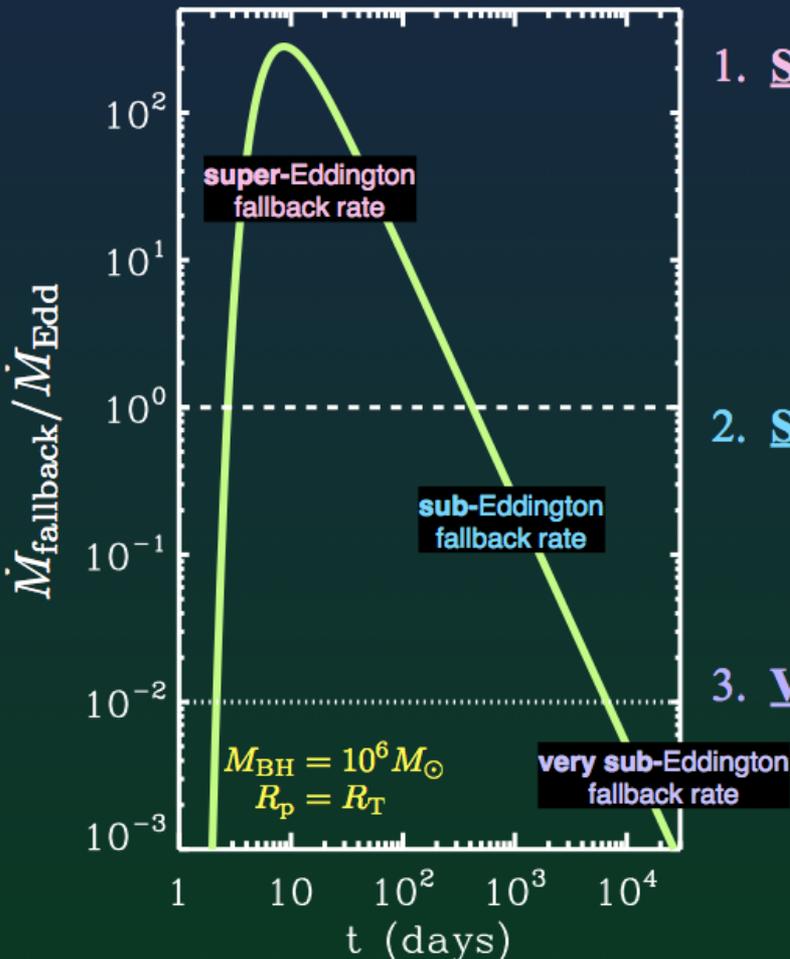
DL

TDEs as unique probes of accretion

Fallback & Observable Signatures

$$\dot{M}_{\text{fallback}} \sim \frac{M_*}{t_{\text{fallback}}} \left(\frac{t}{t_{\text{fallback}}} \right)^{-5/3}$$

As fallback rate declines with time,
3 Phases of Evolution:



1. **Super-Eddington fallback:** ~weeks - months

$$\dot{M}_{\text{fallback}} \gg \dot{M}_{\text{Edd}}$$

Physics is uncertain, but likely
advective disk + powerful outflows
(+ jet?)

2. **Sub-Eddington fallback:** ~months - year

$$\dot{M}_{\text{fallback}} \lesssim \dot{M}_{\text{Edd}}$$

Thin accretion disk

3. **Very Sub-Eddington fallback:** ~several yr - decades

$$\dot{M}_{\text{fallback}} \lesssim 10^{-2} \dot{M}_{\text{Edd}}$$

Radiatively inefficient flow:
hot disk + jet



TDEs are unique probes of accretion

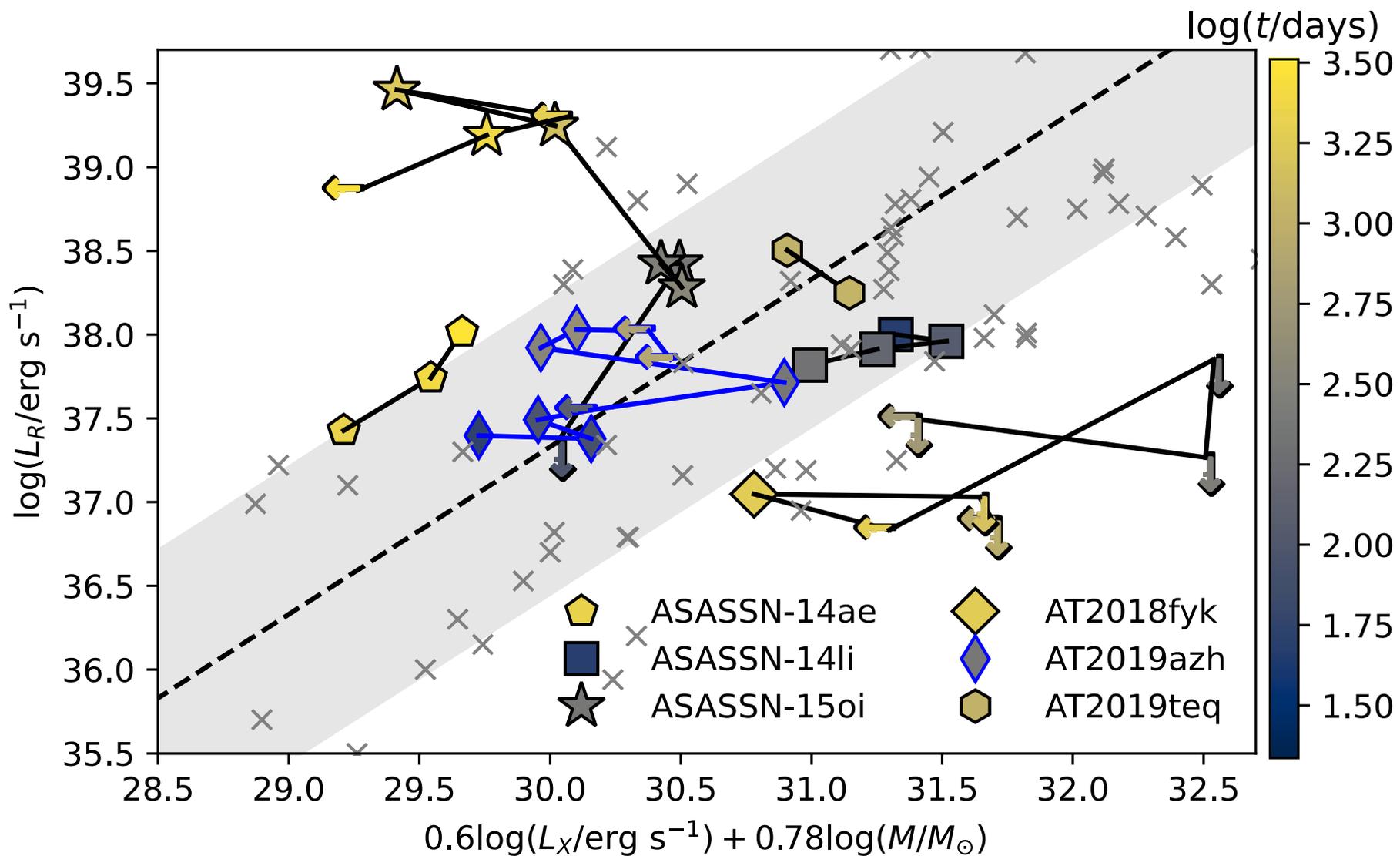
Note: This implicitly assumes that the accretion rate directly tracks the fallback rate – assumption made by some commonly-used codes (e.g. MOSFiT tends to fit low/zero viscous delays), but this is likely not the case, especially at late times after a disk forms! (Goodwin, Mummery talks)

- Need a prescription to map observables to accretion rate
- This is best done with **multi-wavelength** observations (i.e. optical/UV/X-ray)
- Goal is to test if radio emission is correlated with particular Eddington-normalized accretion rates



TDEs on the Fundamental Plane*

* Total X-ray flux used, not just hard X-rays

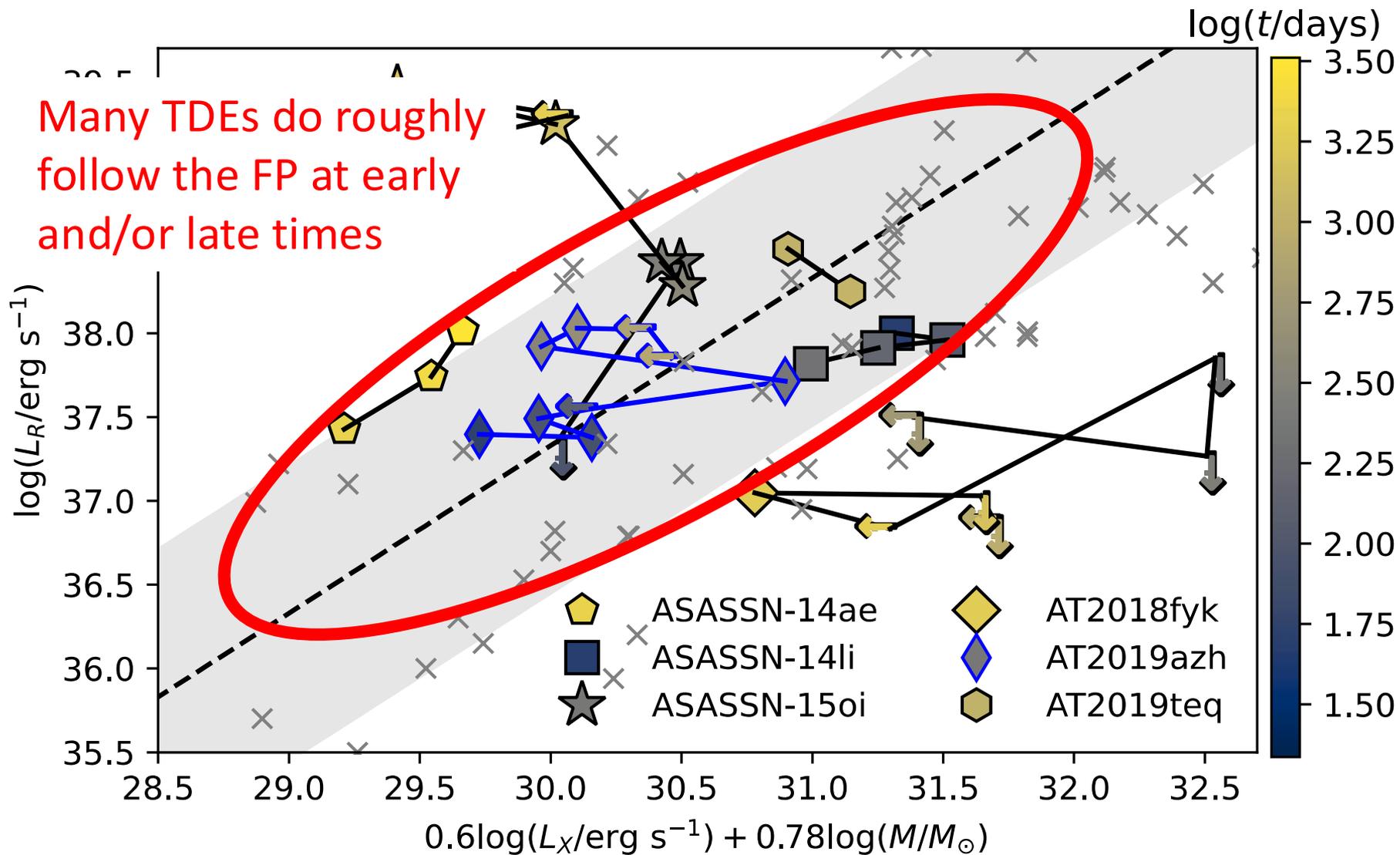


Alexander et al. 2026 (in press)



TDEs on the Fundamental Plane*

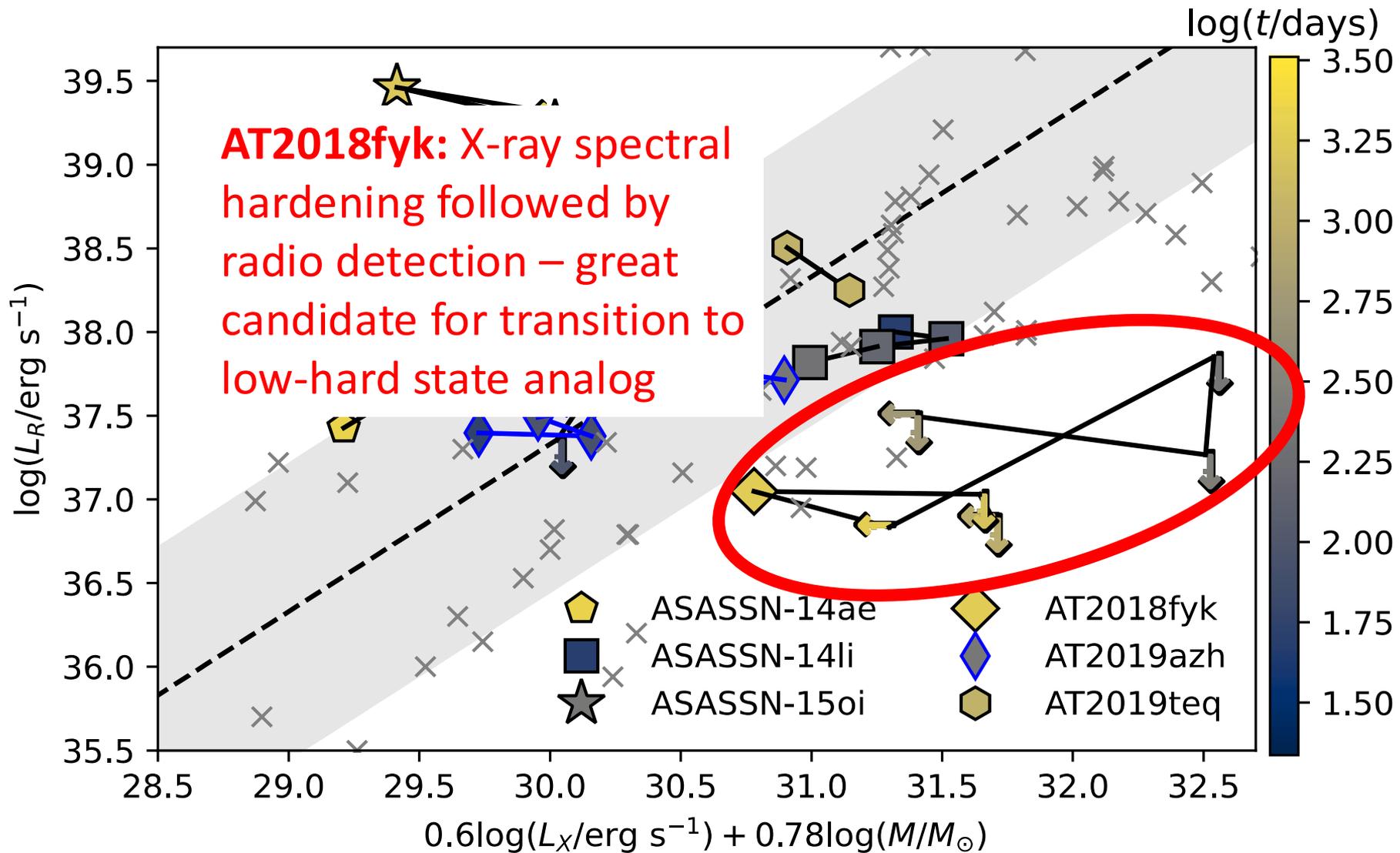
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Alexander et al. 2026 (in press)

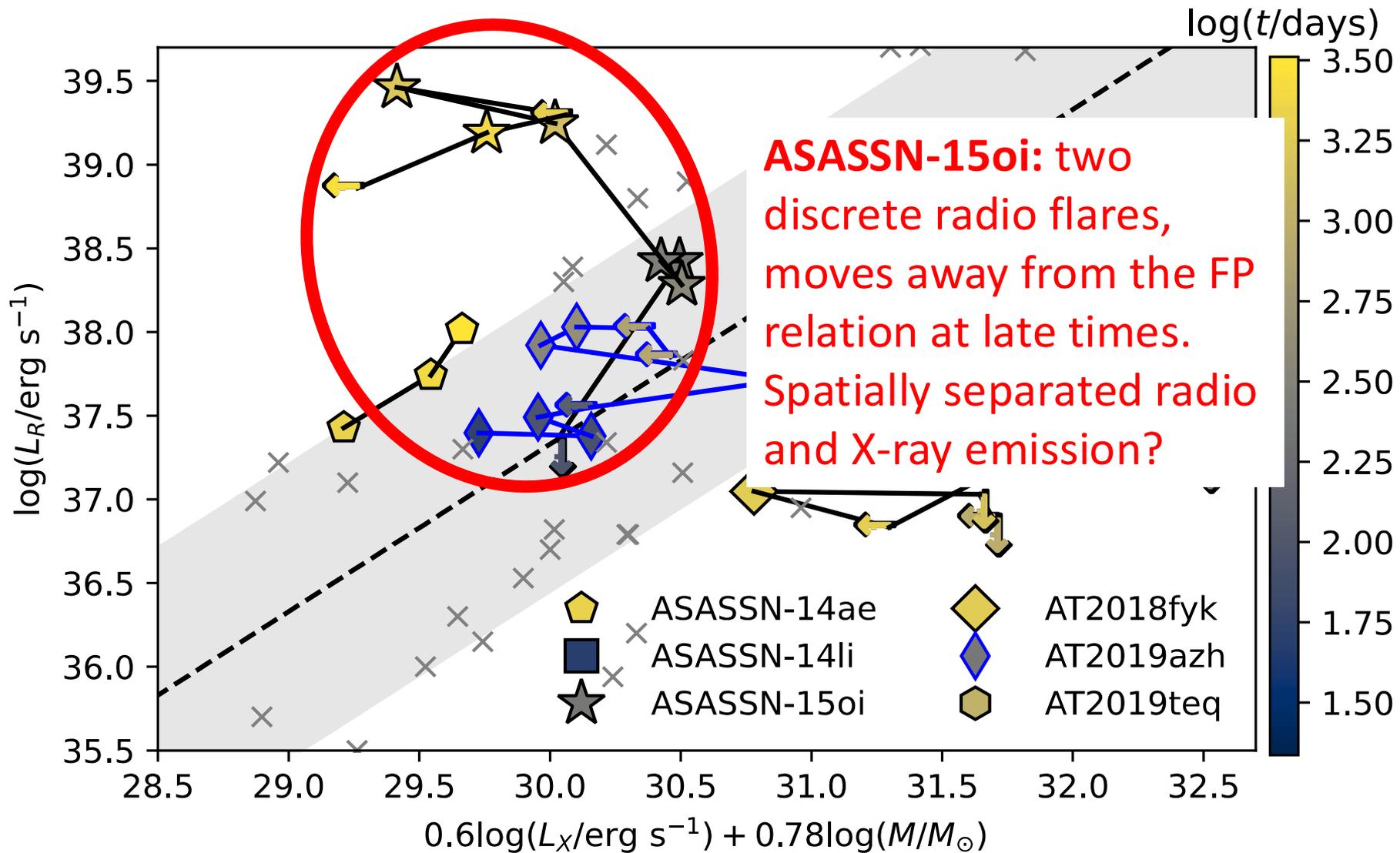
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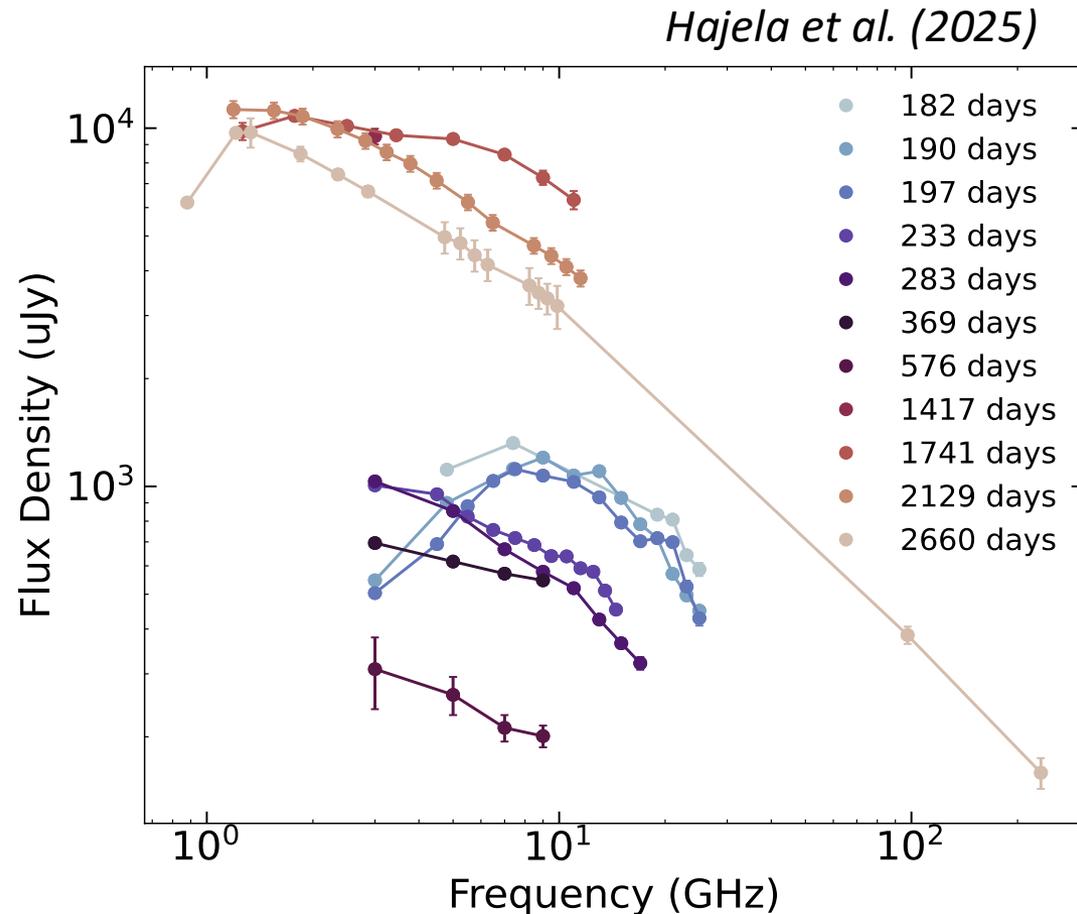




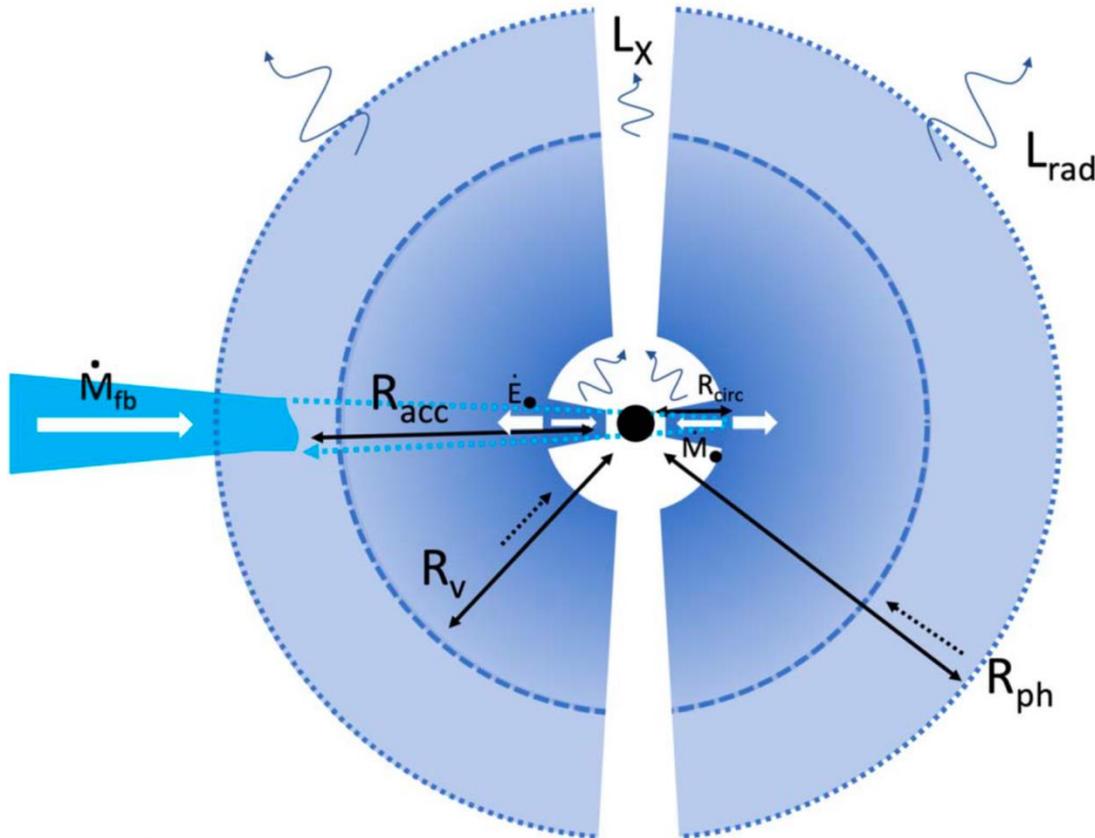
ASASSN-15oi: a tale of two outflows



- Two radio flares: first ~182 days, second ~1400 days
- Multi-frequency radio observations show that the second flare is more energetic, possibly expanding faster!
- Excellent multi-wavelength dataset to put radio in context



Origin of the radio outflows

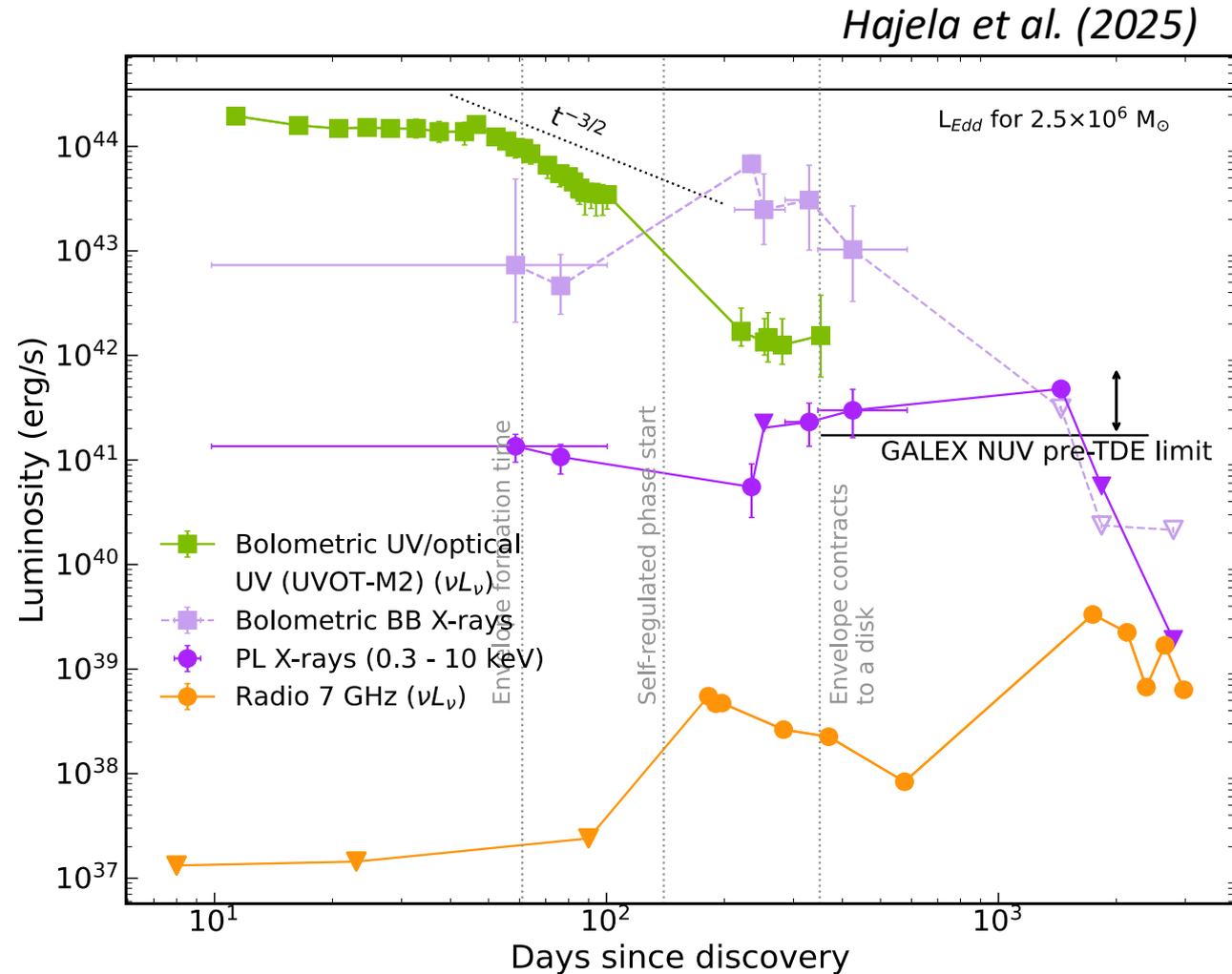


Metzger (2022)

- Cooling envelope model (Metzger 2022) seems to fit this TDE well:
 - Stellar debris stream rapidly circularizes, but material is not able to accrete promptly
 - Instead, a quasi-spherical pressure-supported debris envelope forms
 - The envelope cools and shrinks as \dot{M}_{fb} drops, eventually allowing the accretion rate to rise (after \sim several 100 days)
 - High accretion rates may power outflows

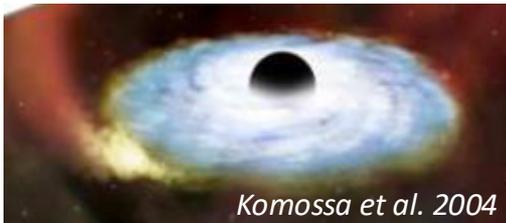
Origin of the radio outflows

- In this model, the X-ray light curve is an approximate tracer of the accretion rate
- Can compare radio and X-ray timing to gain insight into possible origins of radio flares



Origin of the radio outflows

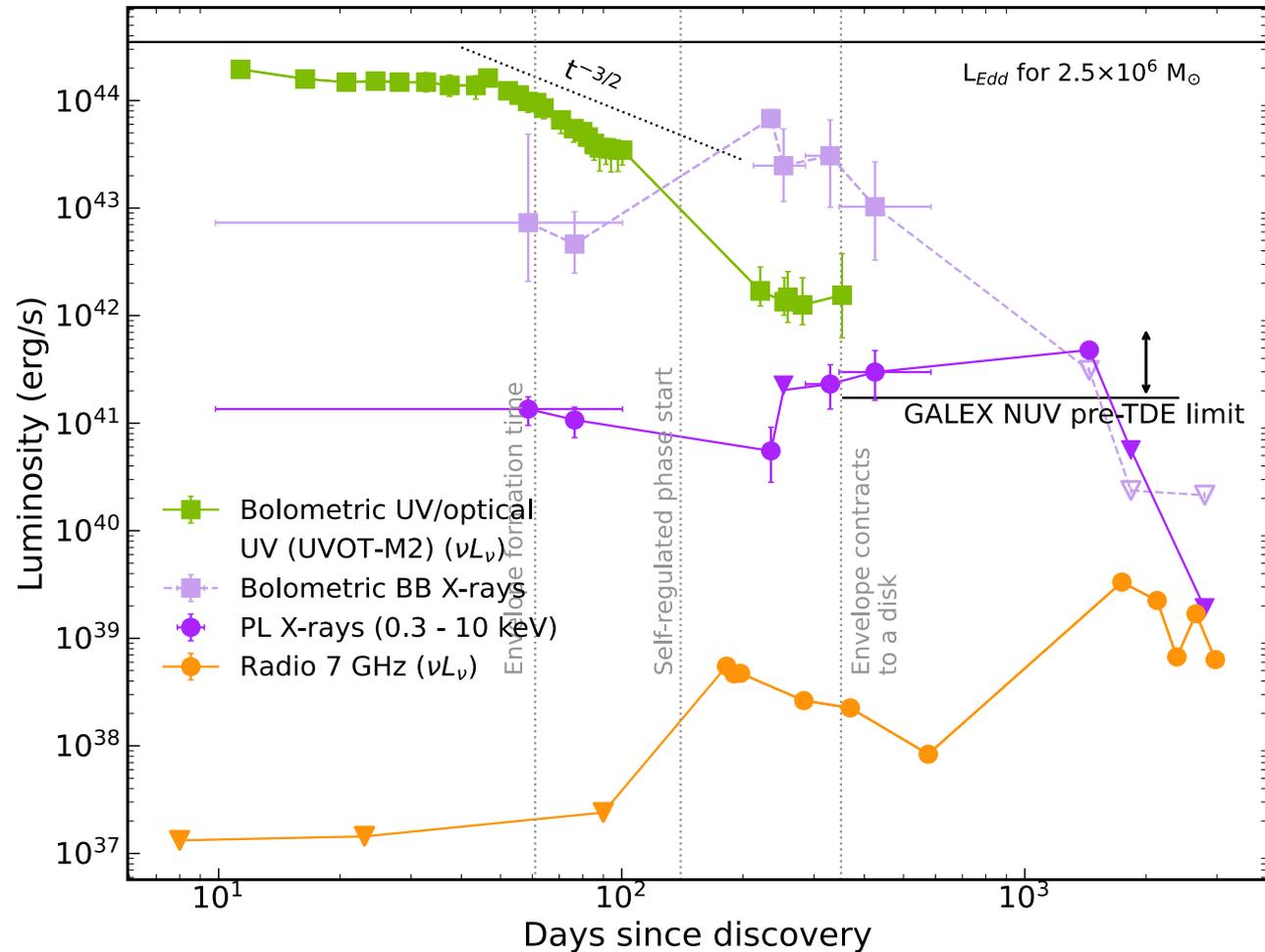
- First radio flare: predates rise in X-ray emission → related to circularization?



- Second radio flare: decelerated jet launched at peak accretion time?



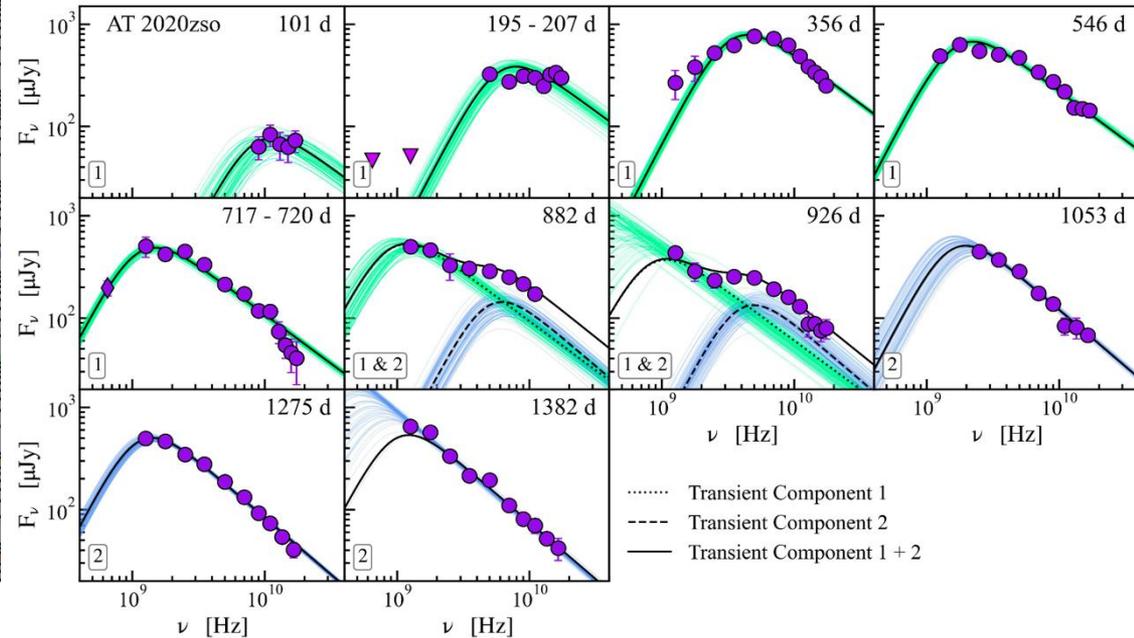
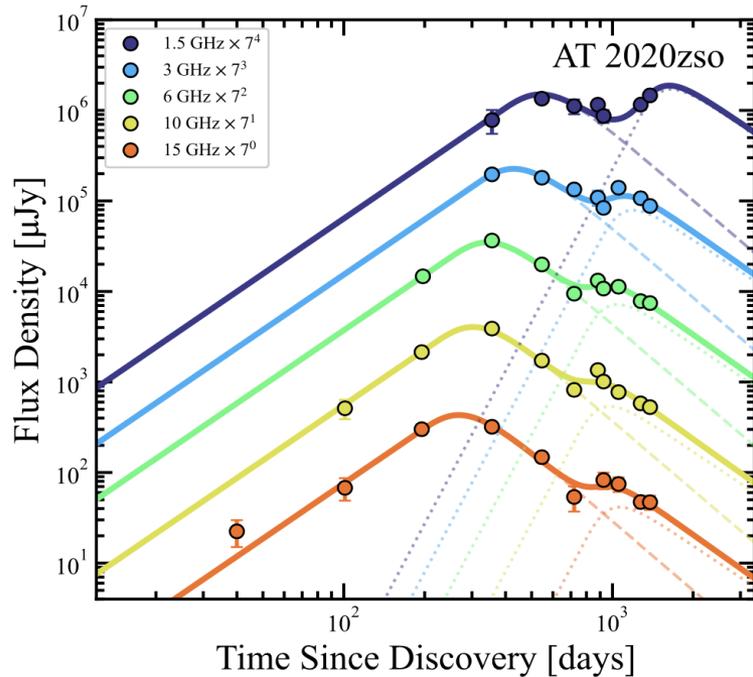
Hajela et al. (2025)





AT2020zso: 2 accretion-driven outflows?

Christy et al. (2026, in press)



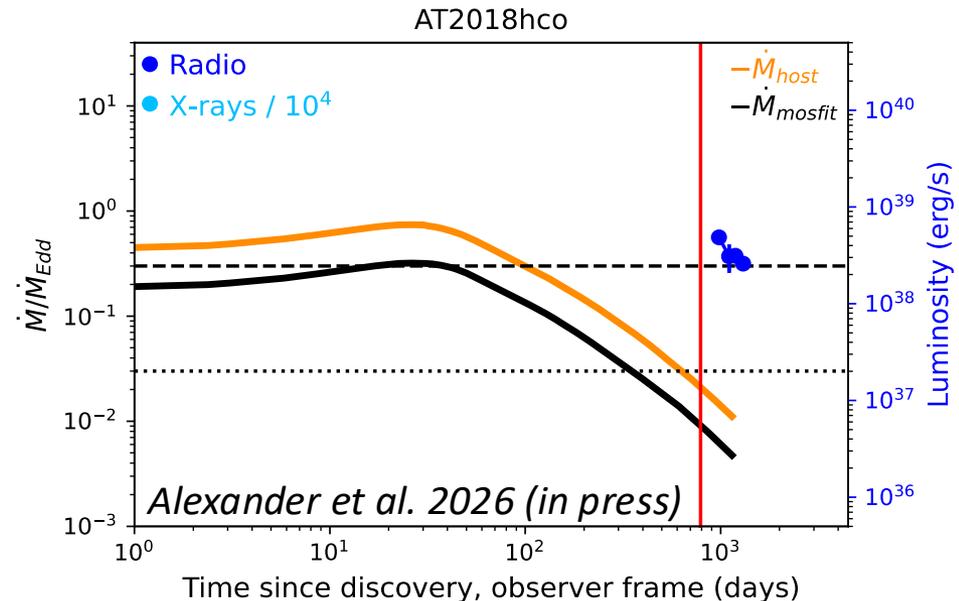
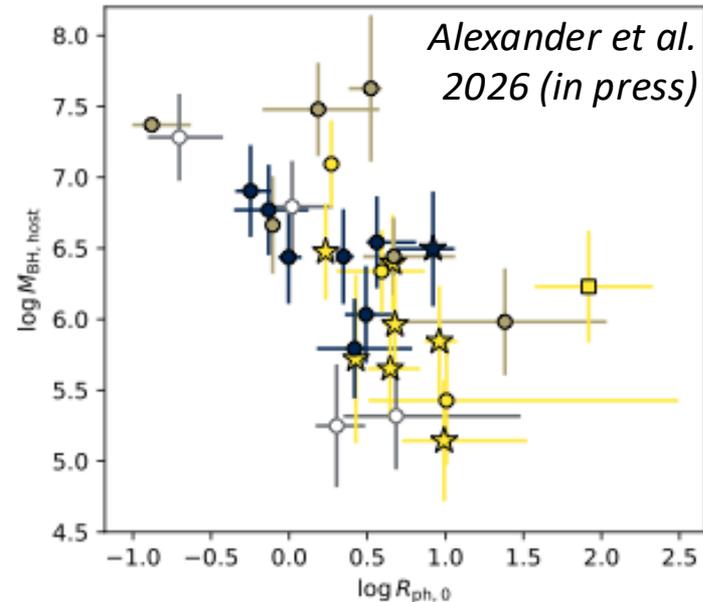
- Radio flares are both temporally AND spectrally resolved! Suggests two distinct emitting regions
- Could correspond to outflows launched during high and very low accretion states respectively

Multi-wavelength population insights

TDEs with delayed radio emission also show **delayed or absent He lines** ($p=0.002$) – Alexander et al. 2026 (*in press*)

Modeling the UVOIR light curves with MOSFiT:

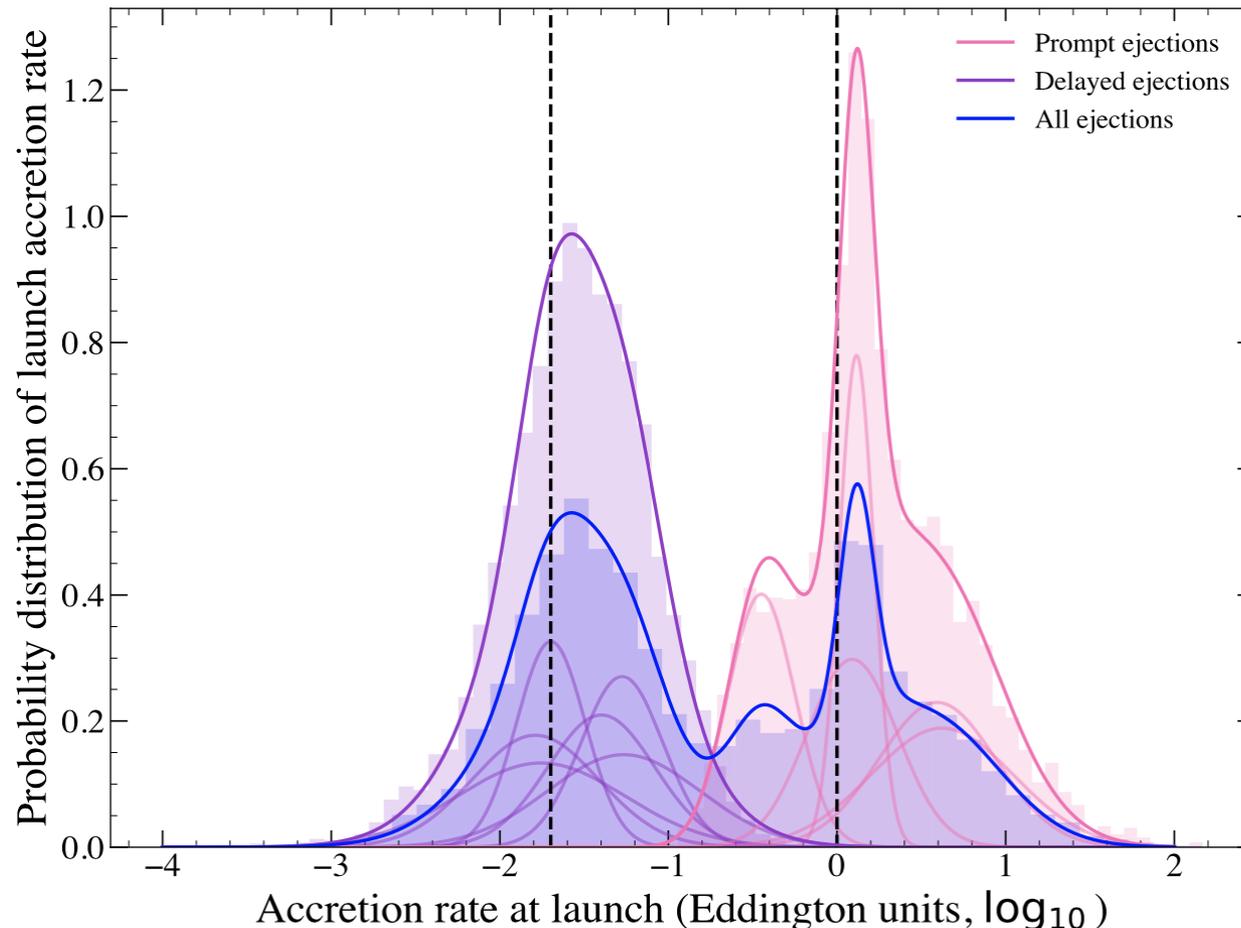
- TDEs w/delayed radio have larger R_{phot} ($p=0.026$).



- accretion state changes sometimes correlated with delayed radio launch (other times radio appears a few hundred days later than MOSFiT prediction)

Multi-wavelength population insights

Using a disc model (FitTeD) instead – does seem to show a correlation with specific accretion rates! (Mummery, Goodwin talks; Goodwin & Mummery *under review*)





Summary

- Radio observations probe mass ejection in TDEs.
 - Powerful relativistic jets are rare, non-relativistic outflows are more common.
 - Delayed emission likely accretion-powered, early emission may also be accretion-powered, or may be related to circularization or unbound debris.
 - Progress requires multi-wavelength analysis.
- New data/technology is driving the field.
 - Optical wide-field surveys discovering 10s of TDEs per year, soon to be 100s or 1000s (Rubin Observatory)
 - **VLA Large Program**: characterize local X-ray and optically-selected TDEs. Complementary to blind searches in radio surveys.
- More surprises are inevitable! Stay tuned.