UNIVERSITY OF OREGON

Tidal Disruption Events (TDEs): Progress, Open Questions, & Prospects

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Tidal Disruption Events (TDEs)

- A TDE occurs when a star goes too close to a supermassive black hole (SMBH), and is torn apart by tidal forces

Video credit: DESY

Tidal Disruption Events (TDEs)

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523

Tidal disruption of stars by black holes of 10^6–10^8 solar masses in nearby galaxies

Martin J. Rees

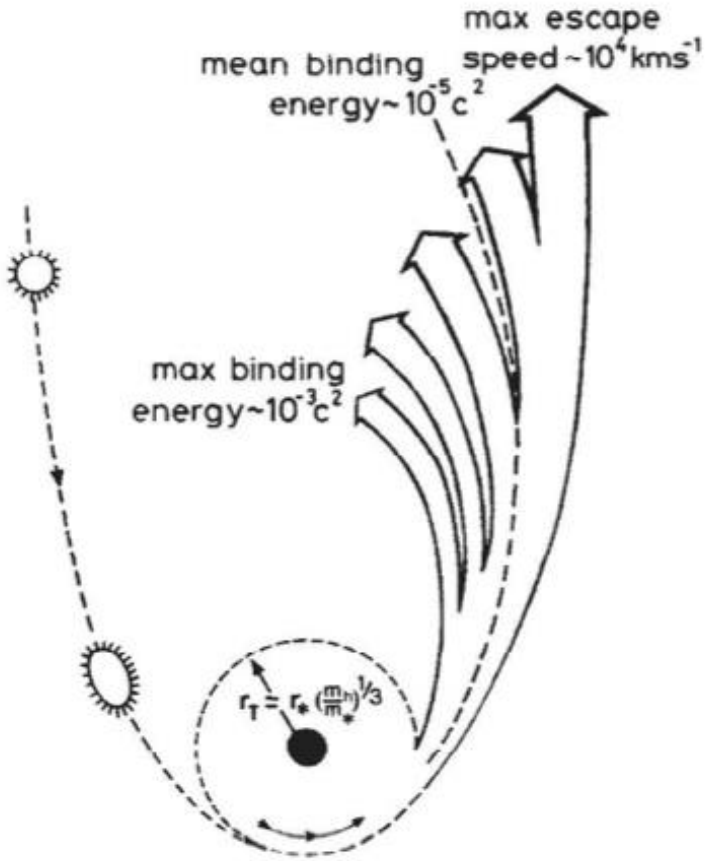
Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK

Stars in galactic nuclei can be captured or tidally disrupted by a central black hole. Some debris would be ejected at high speed; the remainder would be swallowed by the hole, causing a bright flare lasting at most a few years. Such phenomena are compatible with the presence of 10^6–10^8 $M_\odot$ holes in the nuclei of many nearby galaxies. Stellar disruption may have interesting consequences in our own Galactic Centre if a $\sim 10^6$ $M_\odot$ hole lurks there.

Rees (1988)

Open Questions about TDEs

- **What is the environment like around a black hole?** Particularly dormant ones?
- **What fundamental physics can we learn from TDE outflows?** Launching relativistic jets, time scales, potential multi-messenger probes…
- **What physical properties can we learn about the quiescent black hole population?** Spins, masses, EMRI rates, etc

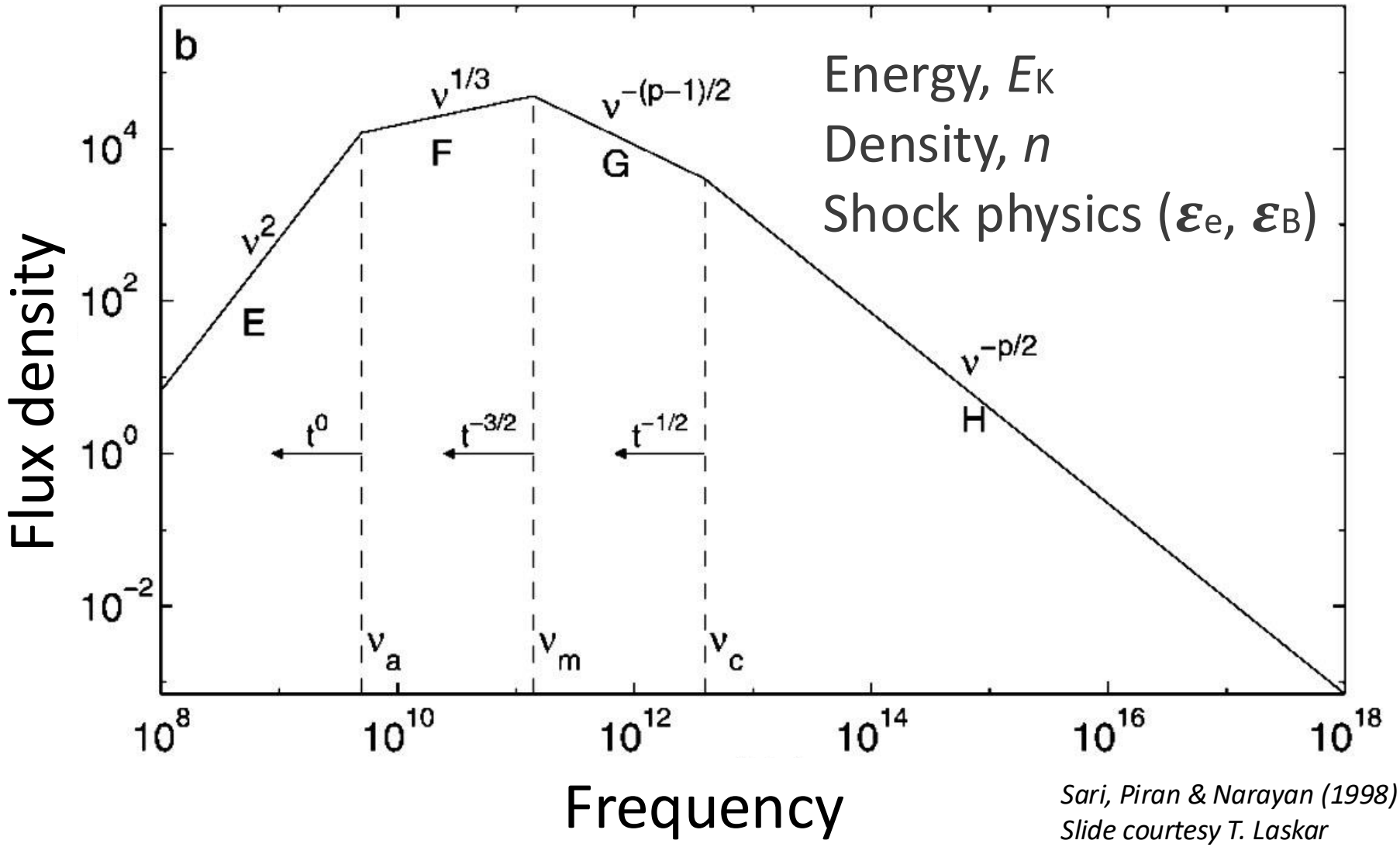


Rees, (1988)

How Radio Astronomy Works

- I use telescopes like the Very Large Array (VLA) in New Mexico to look for radio emission from transients
- We don't *actually* listen- the signals are too faint, and you'd only hear static
- Typically TDEs are first discovered by all-sky surveys (ASAS-SN, Zwicky, Rubin soon!), and we are following up on this emission (some in radio- see Anderson+19). ~100 TDEs known
- We are studying synchrotron emission- electrons spiraling in magnetic fields generated in the outflows

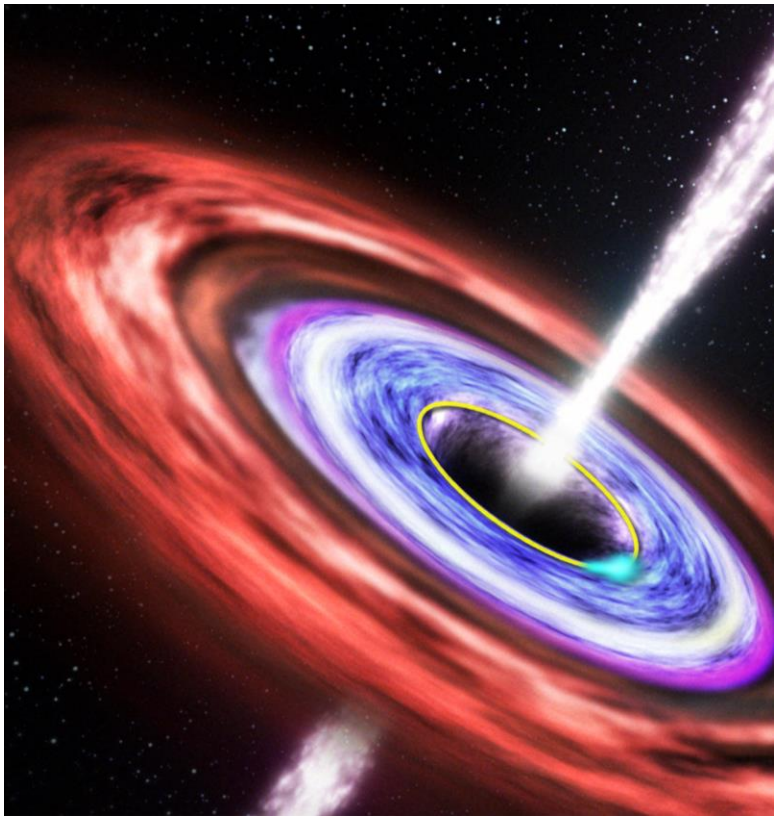
Outflows Generate Synchrotron Emission



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

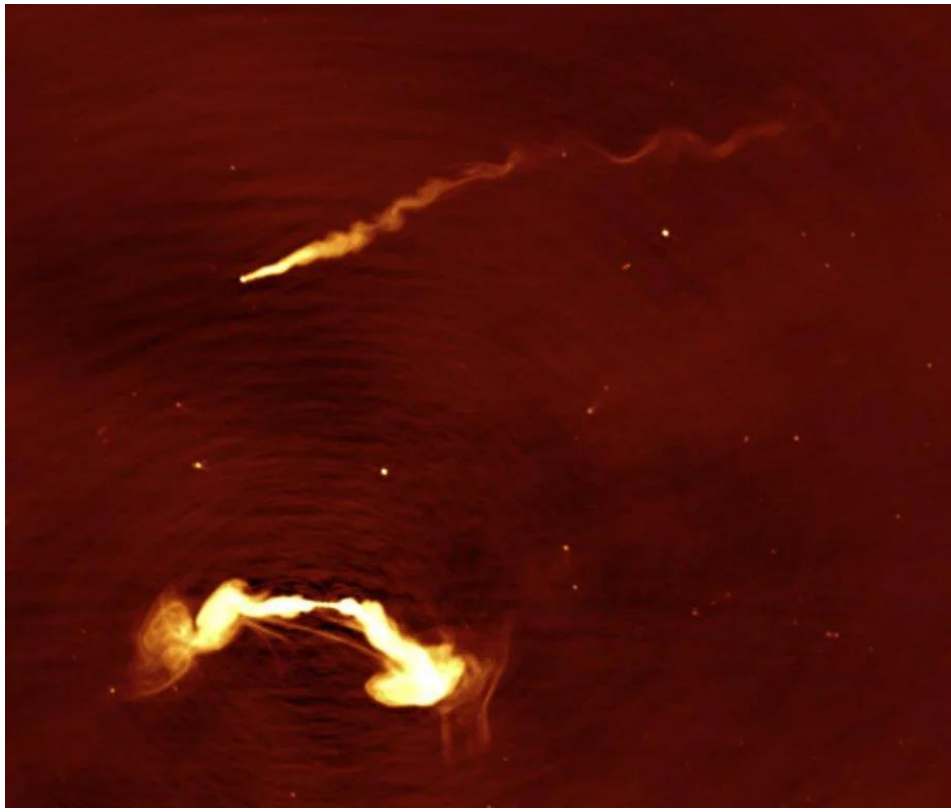
Introducing Swift J1644+57: A Relativistic TDE Outflow

- Sw1644+57 was first detected by the *Swift* satellite on March 28, 2011, z ~ 0.354
- Multi-frequency observations indicate the launch of an on-axis relativistic jet (Bloom+ 2011, Burrows+ 2011, Zauderer+ 2011)
- Best-studied case of a full on-axis tidal disruption event (TDE) to date!



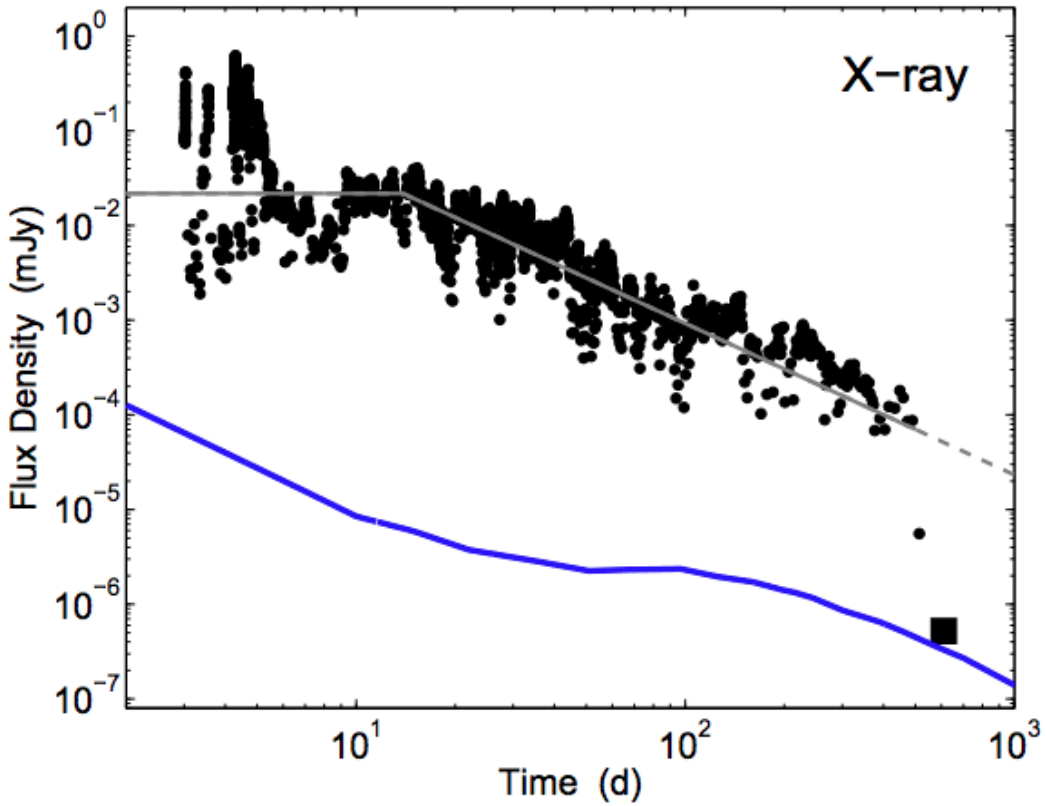
Relativistic Jets

- A relativistic jet is a powerful beam of radiation and particles, emitting from the SMBH near the speed of light
- How such jets are launched is not fully understood, thought to relate to conditions surrounding SMBH (spin, magnetic fields…)
- Consists of two jets a few degrees wide in angle, each jet can be <1 Mpc long!



Day ~500: Jet turns *Off*…

- In Swift J1644+57, we see initial variation, and slow decline in X-ray due to fallback of shredded material onto the black hole after initial disruption event
- At ~1.5 years, X-rays begin to decline abruptly, which is when the jet turns off!
- X-ray continues to fade (Cendes+2021A, Eftekhari+ 2018), now originates from the region of the forward shock (derived from radio emission)



Zauderer et al. (2013)

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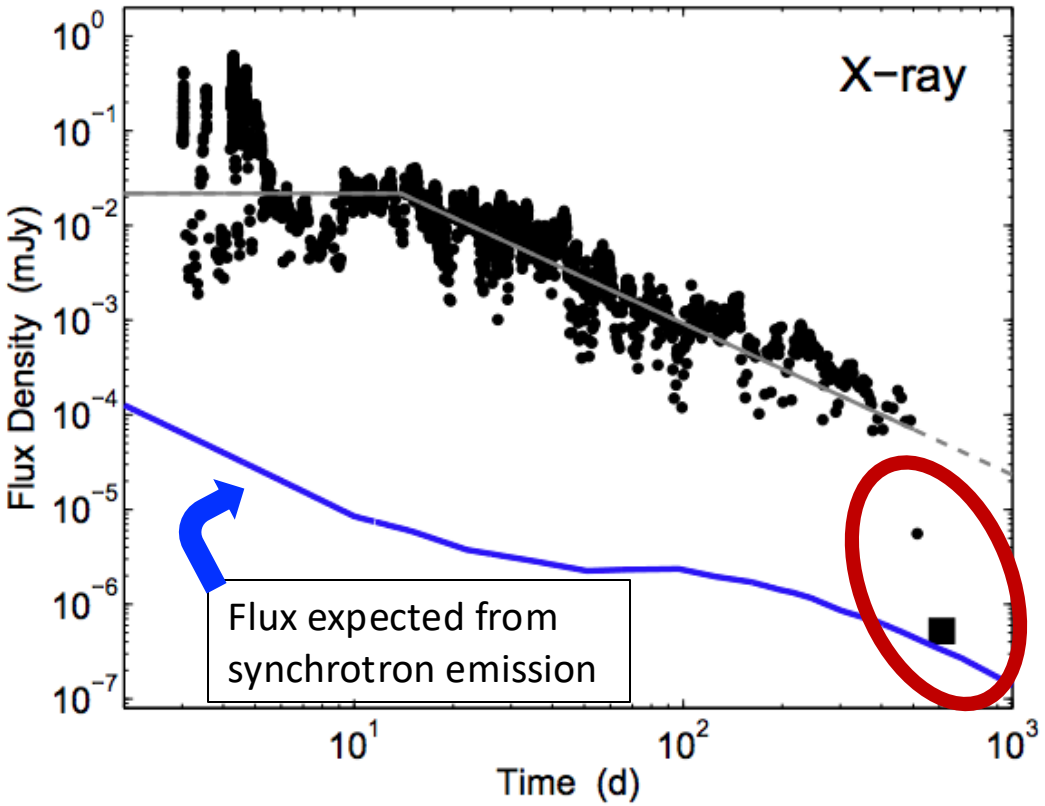
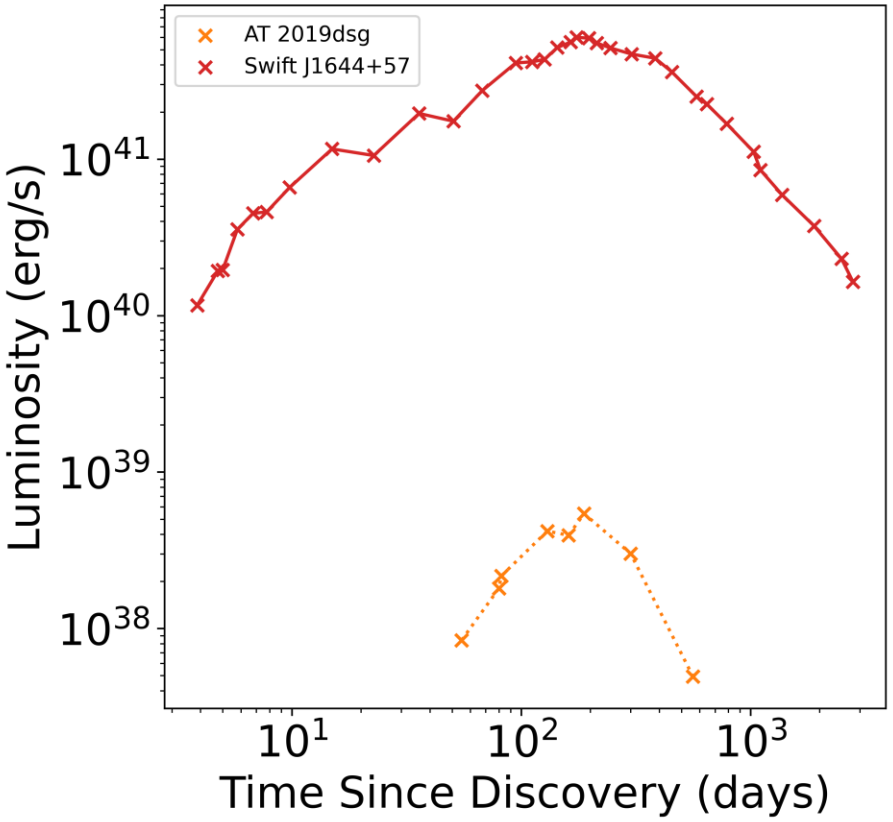


Zauderer et al. (2013)

Introducing AT2019dsg- A Non-Relativistic TDE

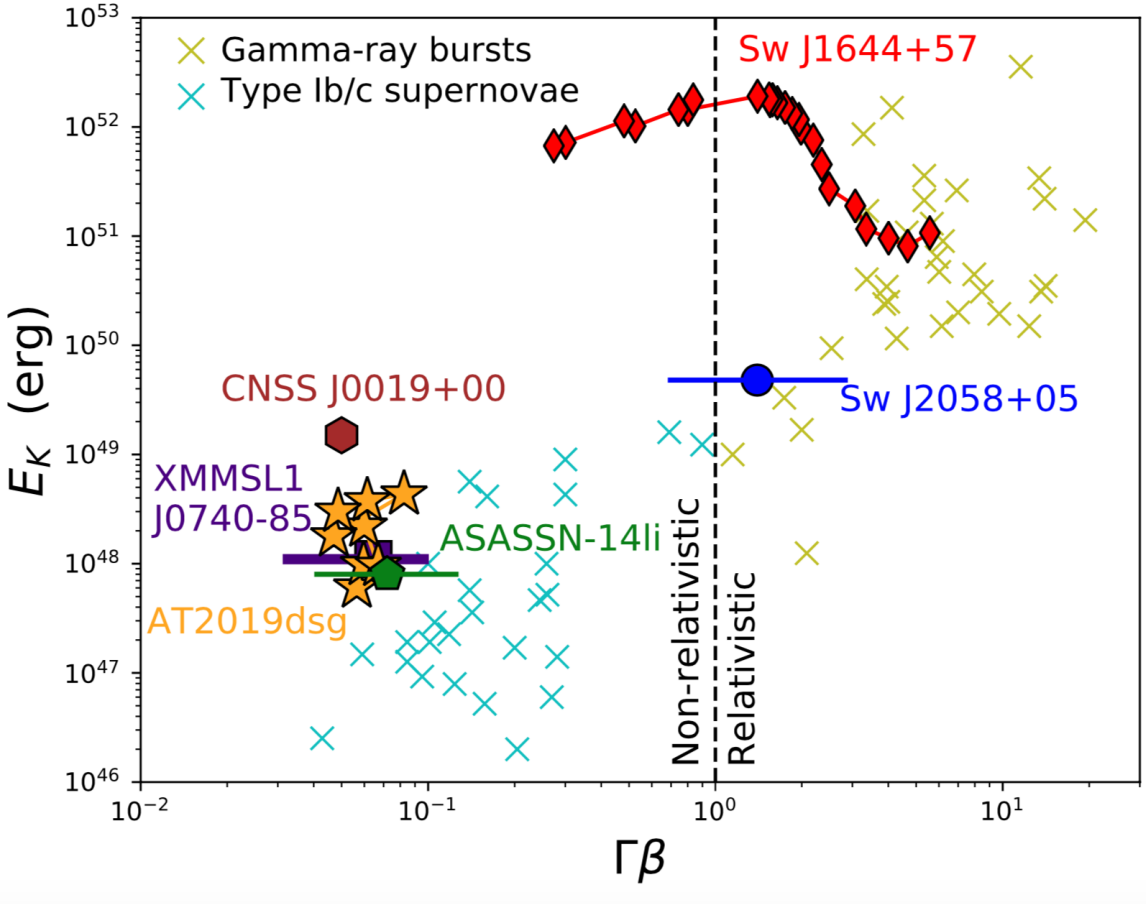
- ~99% of all TDEs appear to be non-relativistic, with AT2019dsg a classic example
- AT2019dsg was first detected April 9, 2019 by ZTF, z ~ 0.051 (~230 Mpc)
- A publication (Stein et al. 2021) argued for a neutrino association coincident with this TDE on Oct 1, 2019, mechanism still debated. Our analysis in Cendes et al. (2021B) cast doubt on this association



Cendes et al., (2021B) [arxiv: 2103.06299]

Energy/Velocity of TDEs

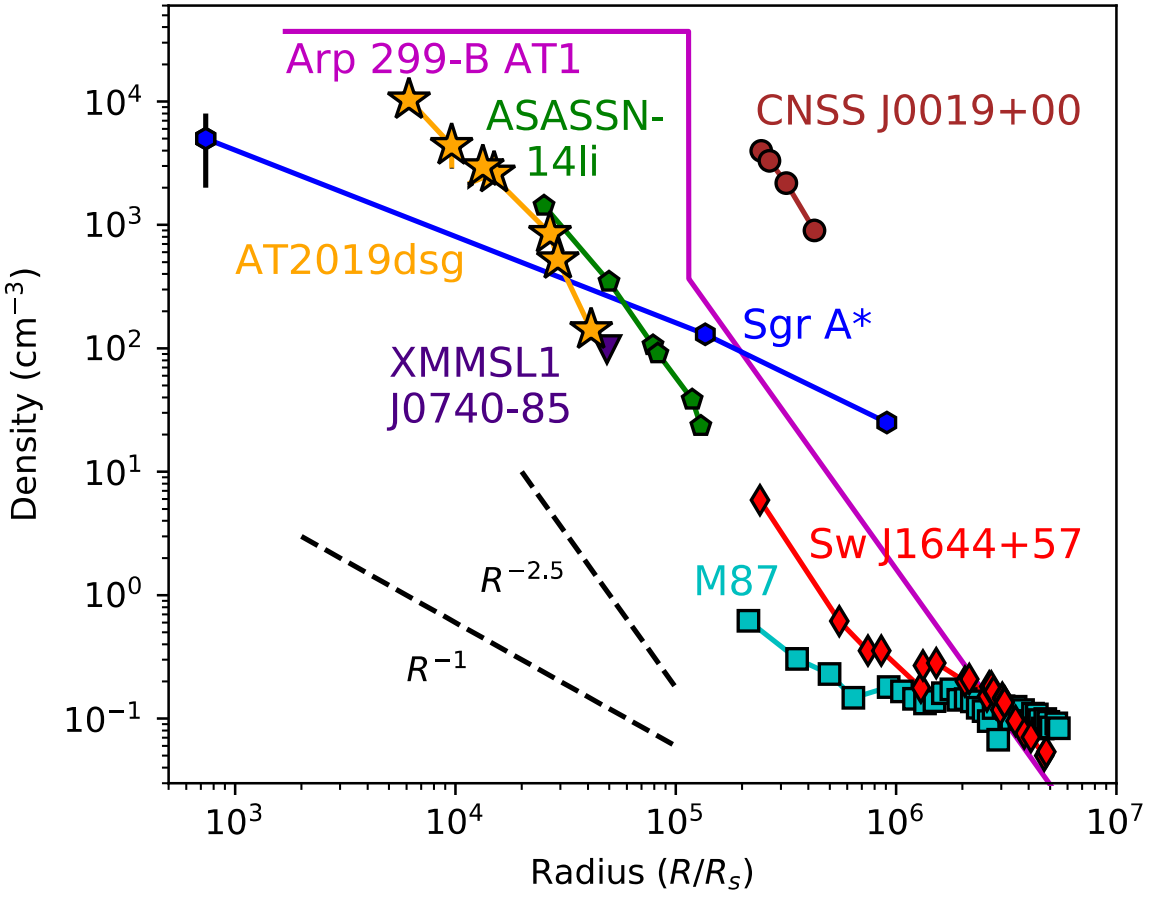
- There are two populations of TDEs emerging. One with relativistic properties similar to GRBs, one non-relativistic akin to typical SNe shocks



Cendes et al., (2021B) [arxiv: 2103.06299]

Density Surrounding TDEs

- Densities surrounding SMBH with TDEs are better sampled than for our own Milky Way!



Cendes et al., (2021B)
[arxiv: 2103.06299]

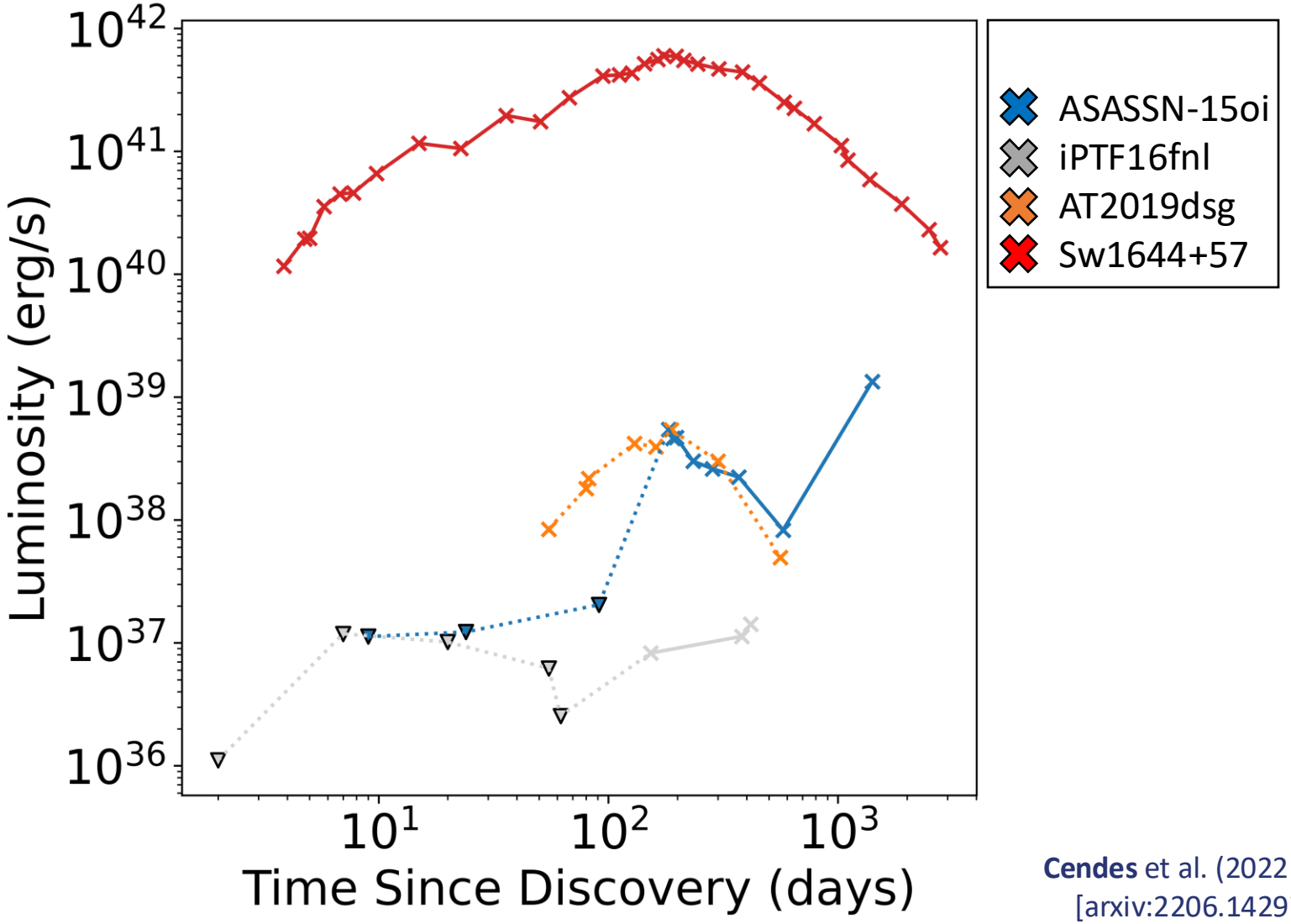
Late-Time Emission?

- Most radio TDE observations occur within the first 1-2 months. ~20% of TDEs are detected in radio during this time
- TTDEs- ASASSN-15oi (Horesh+2021), iPTF16fnl (Horesh+2021b)- became radio bright at >100 days. Is this common?
- To find out, we did a campaign with the VLA+MeerKAT of ~25 older (~2-3 years) optically selected TDEs with no prior radio emission…

Very Large Array (VLA), Socorro, NM

MeerKAT- Karoo desert, South Africa

An Unusual Discovery: AT2018hyz



Cendes et al. (2022B)
[arxiv:2206.14297]

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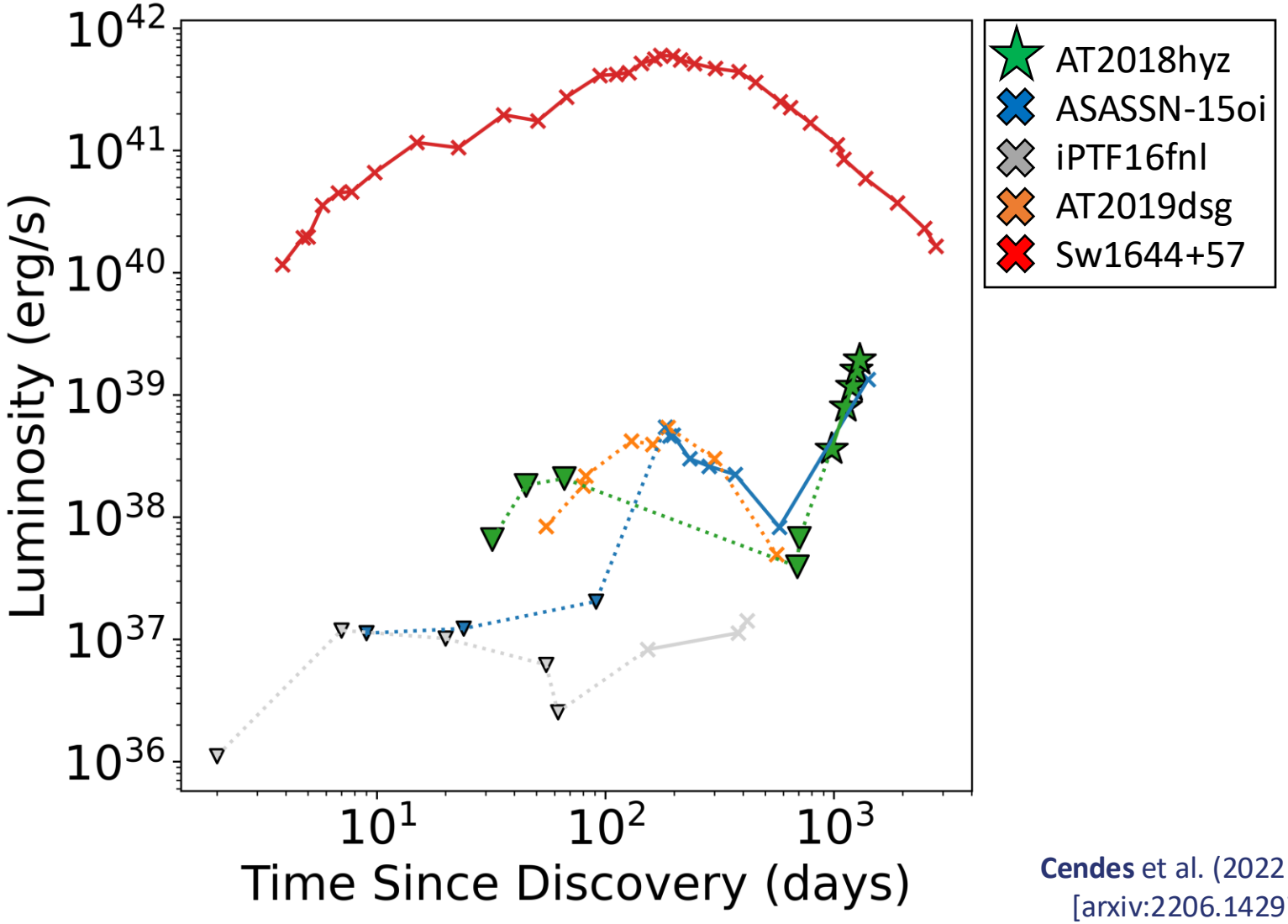

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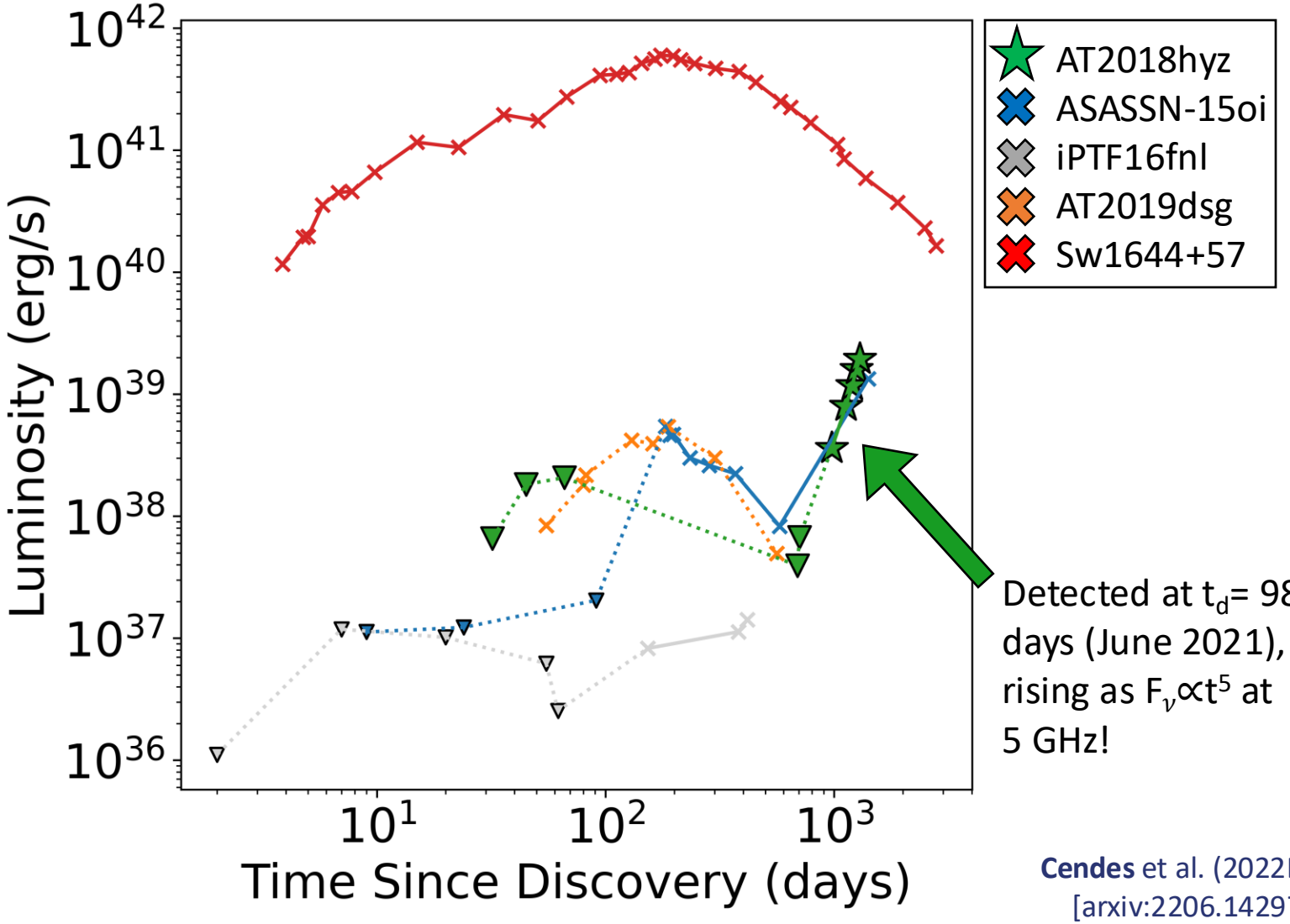

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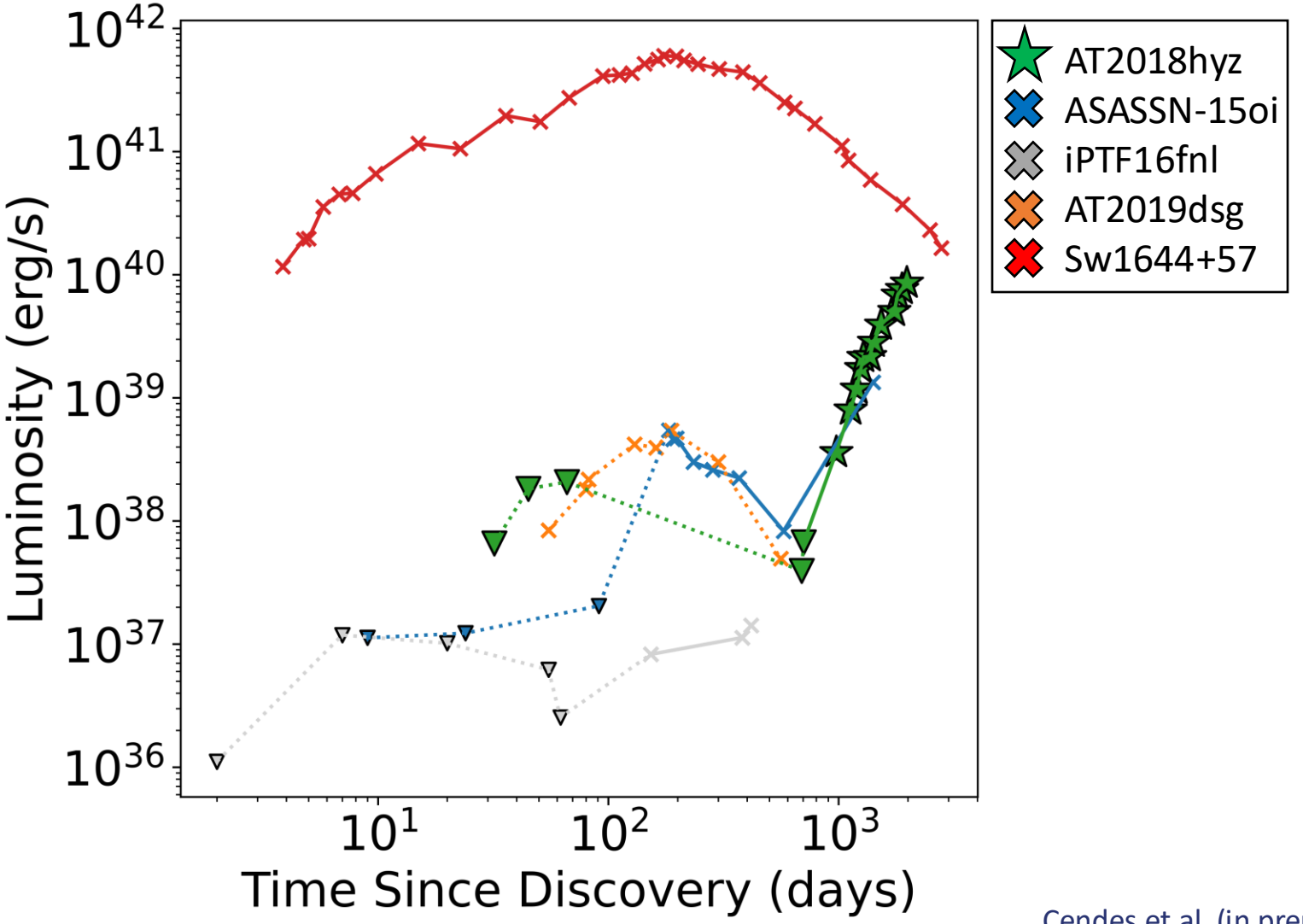
AT2018hyz Revisited



Cendes et al. (in prep)

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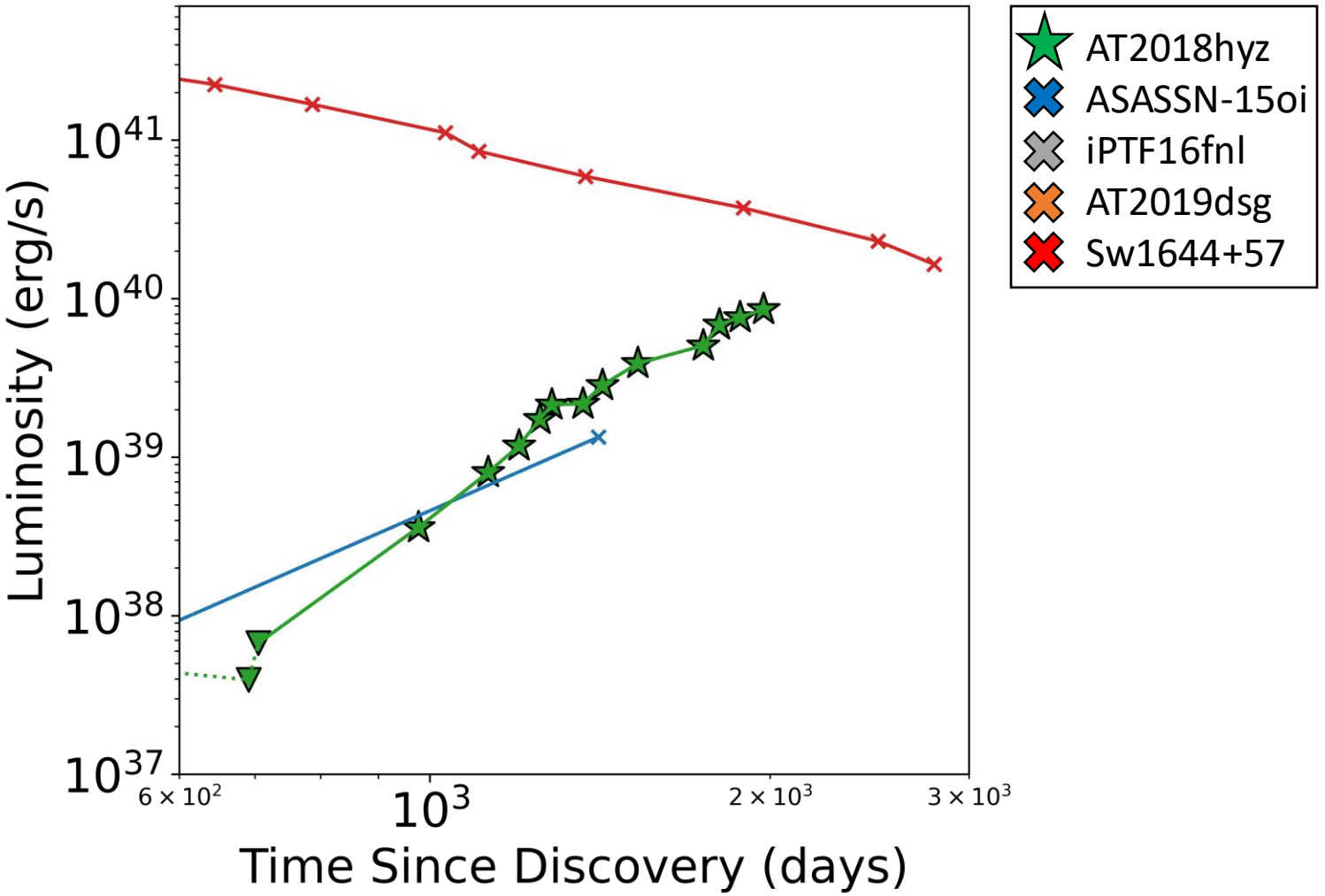

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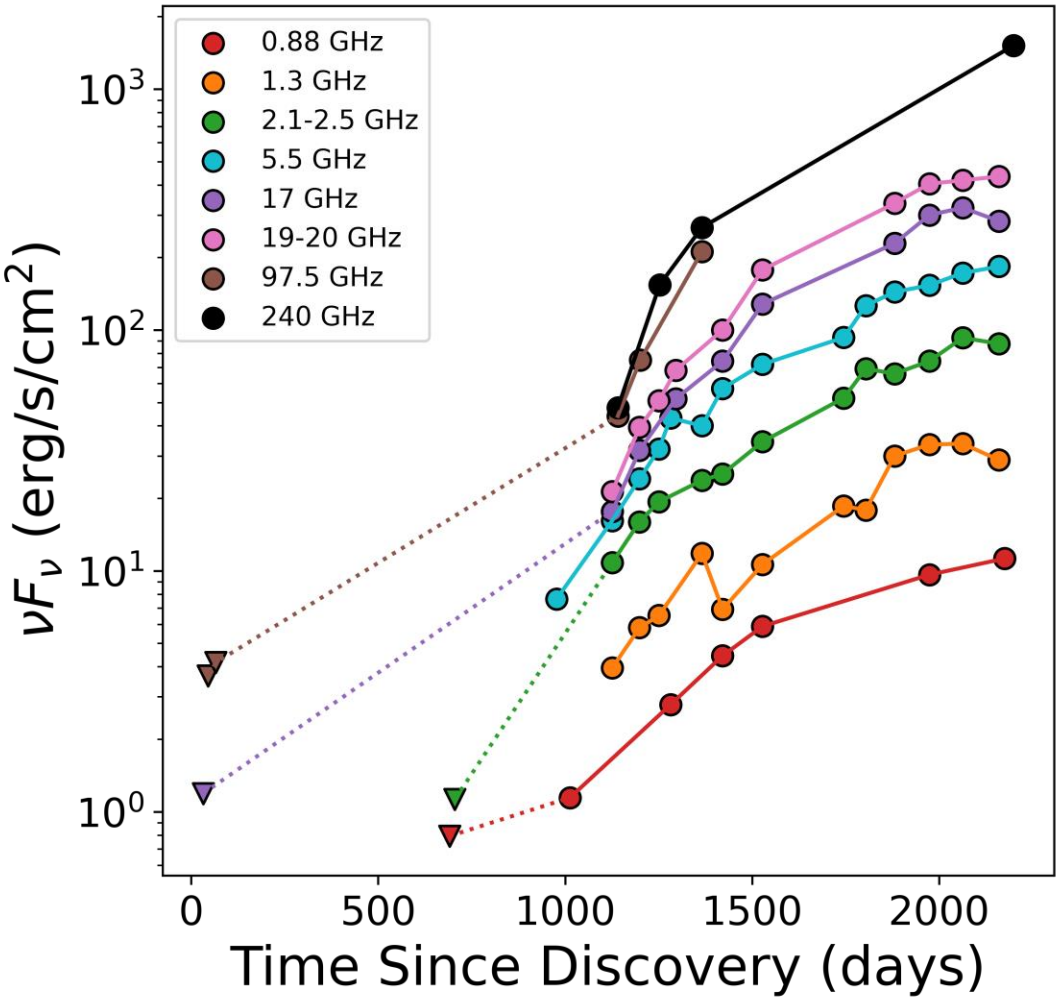
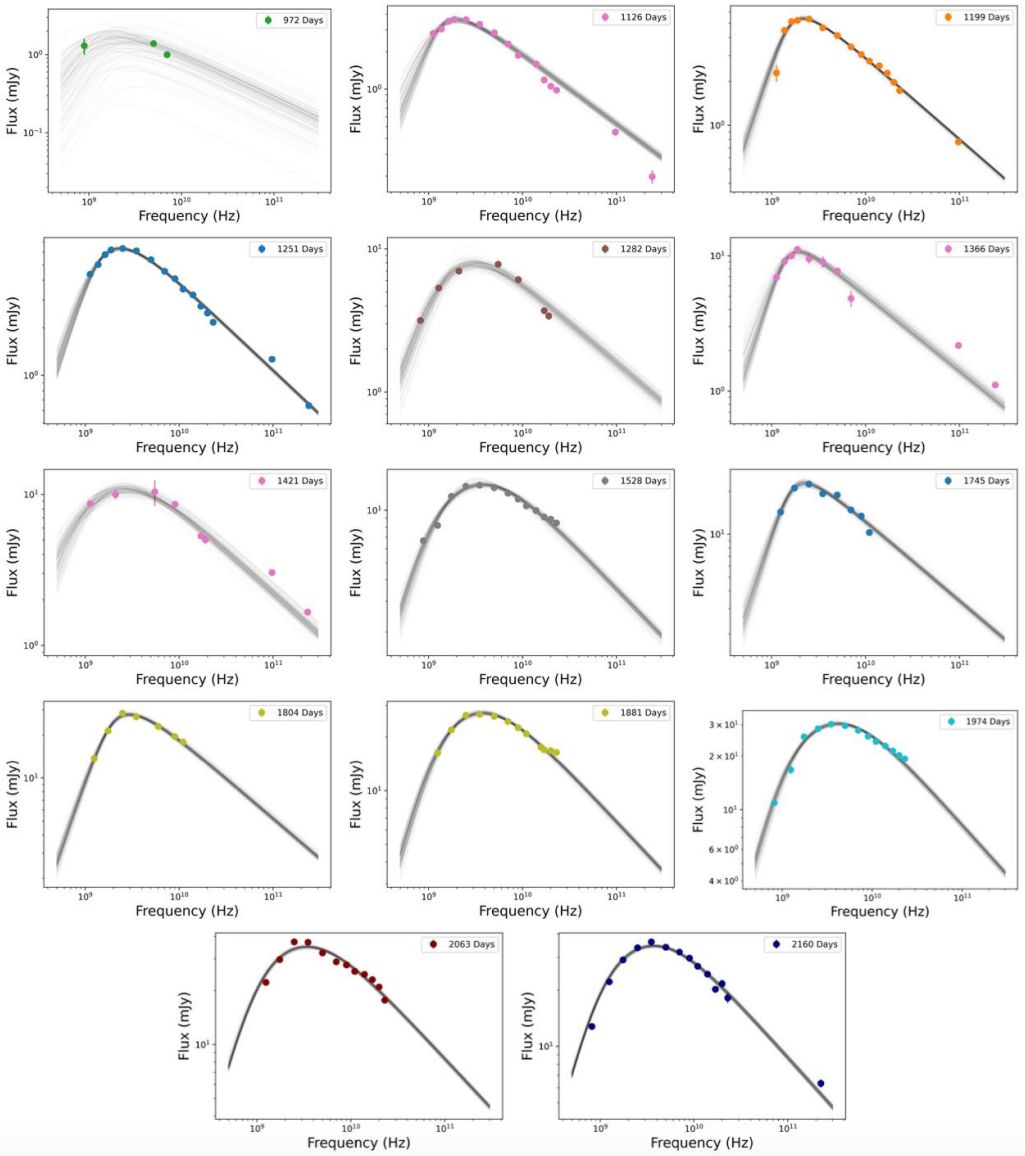


Cendes et al. (in prep)

Many, Many SEDs and Models

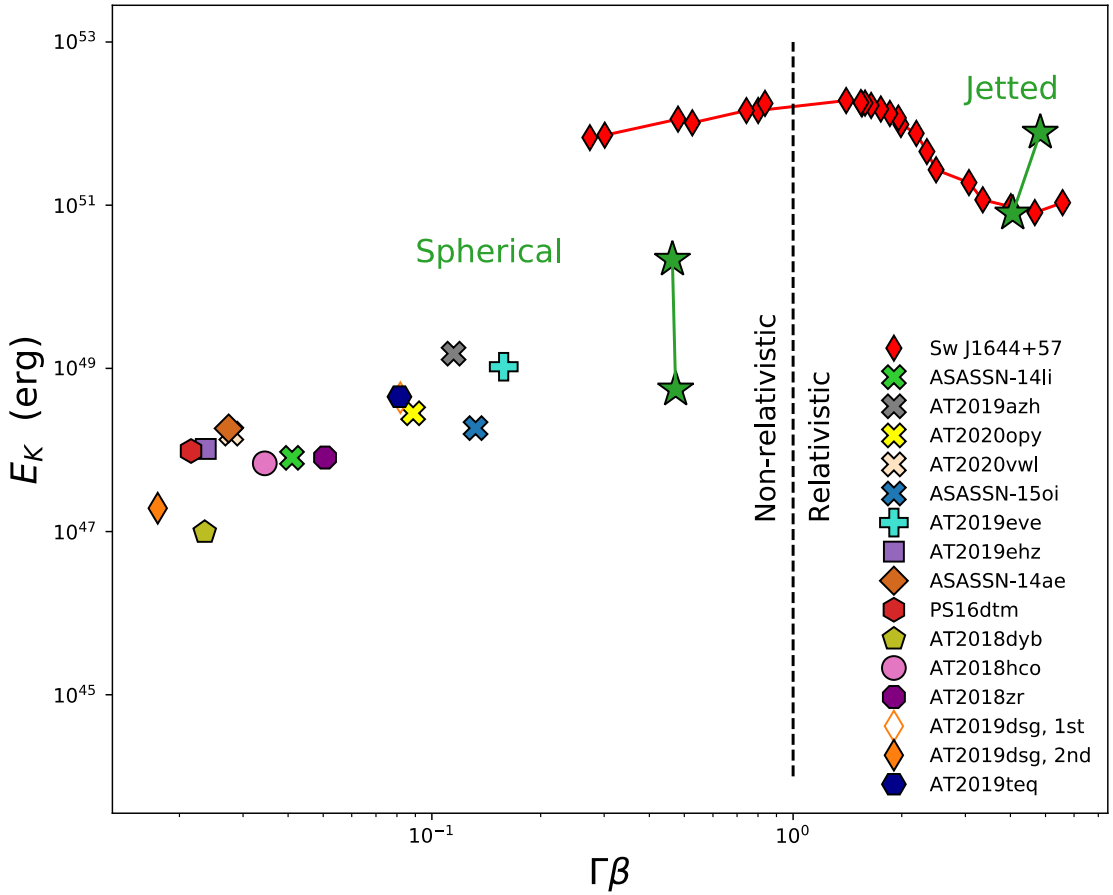
- Peak flux keeps rising, but peak frequency remains remarkably steady at a ~few GHz. We also see $\nu_m \approx 10$ GHz.
- Spherical outflow model suggests $t_d \approx 620$ days post-disruption
- However, new models (Matsumoto+23, Sfaradi+24) suggest that AT2018hyz could be an off-axis jet over a delayed semi-relativistic outflow. What does the data show?



Cendes et al. (in prep)

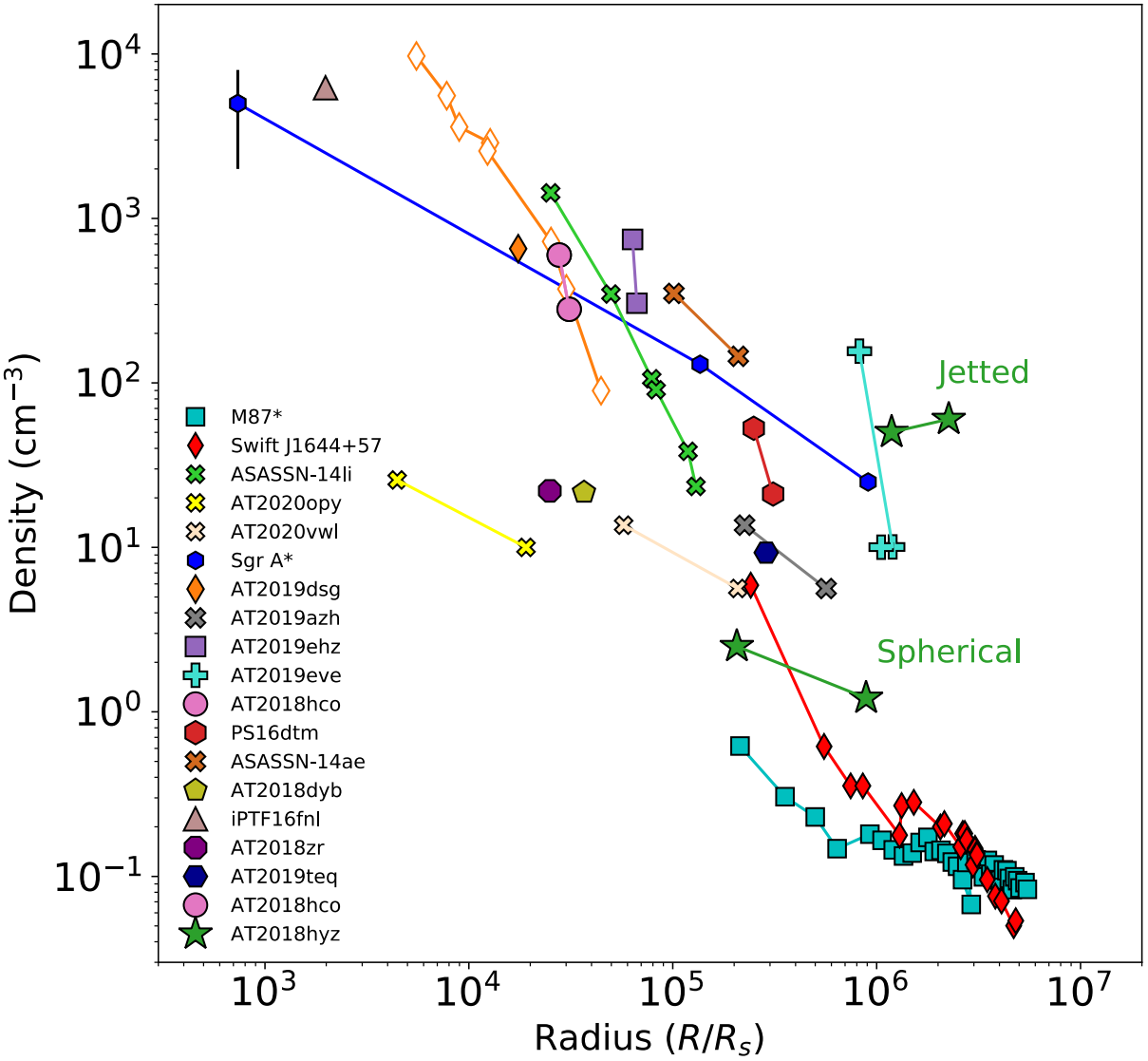
Energy/Velocity of the Outflow

- Assuming a 90 degree get, AT2018hyz's energy and velocity is consistent with Sw1644+57
- If a spherical outflow, it's the highest velocity one ever observed



Cendes et al. (in prep)

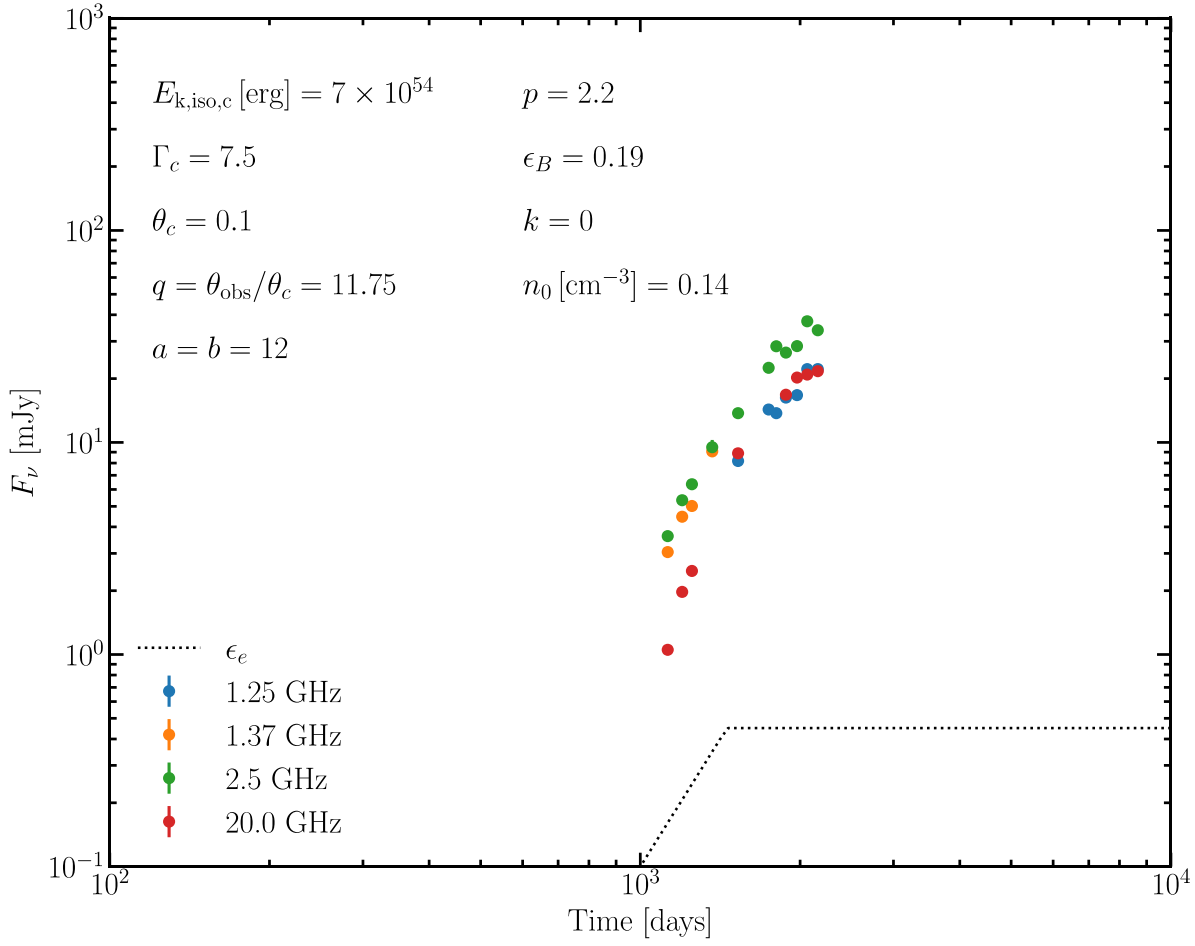
Density Profile



Cendes et al. (in prep)

An Off-Axis Structured Jet?

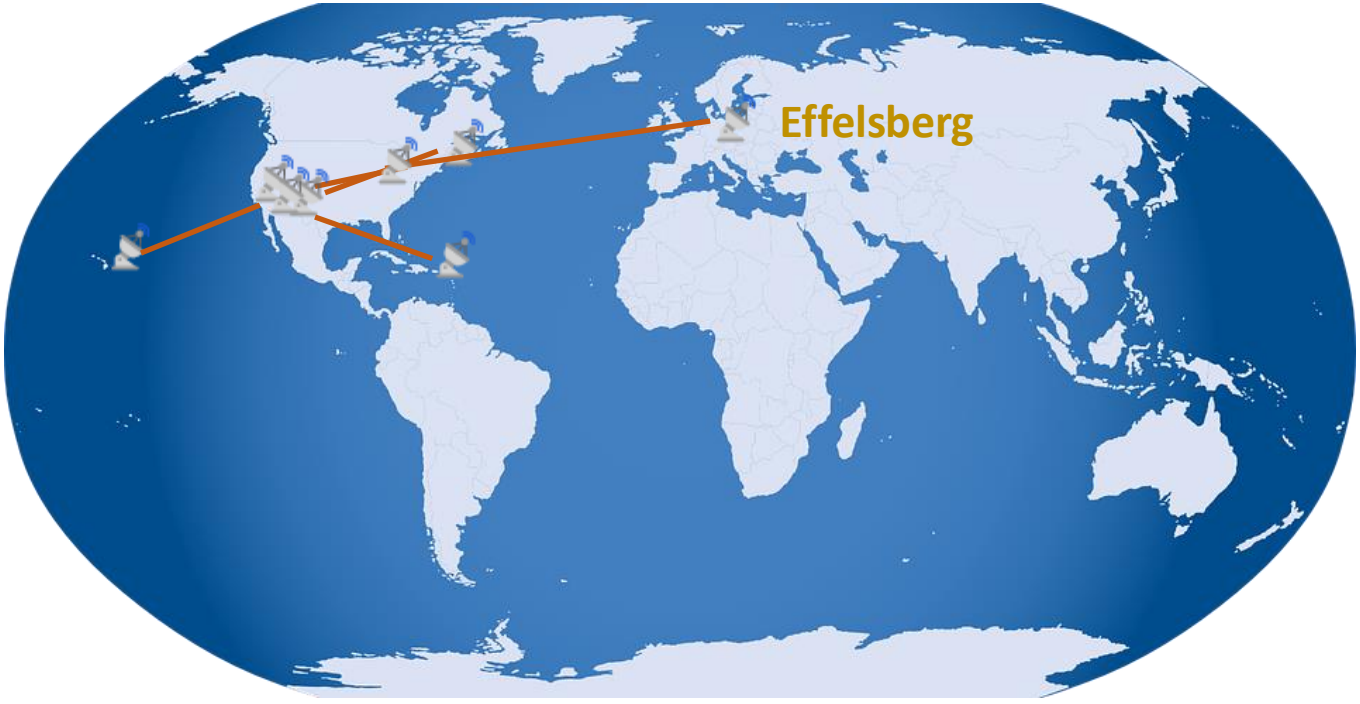
- Can also consider an off-axis top hat jet with steep gradients (ie Gill+18, Beniamini+20,22)
- Also consistent w very off-axis jet, predicts rise until t_d~3000 days



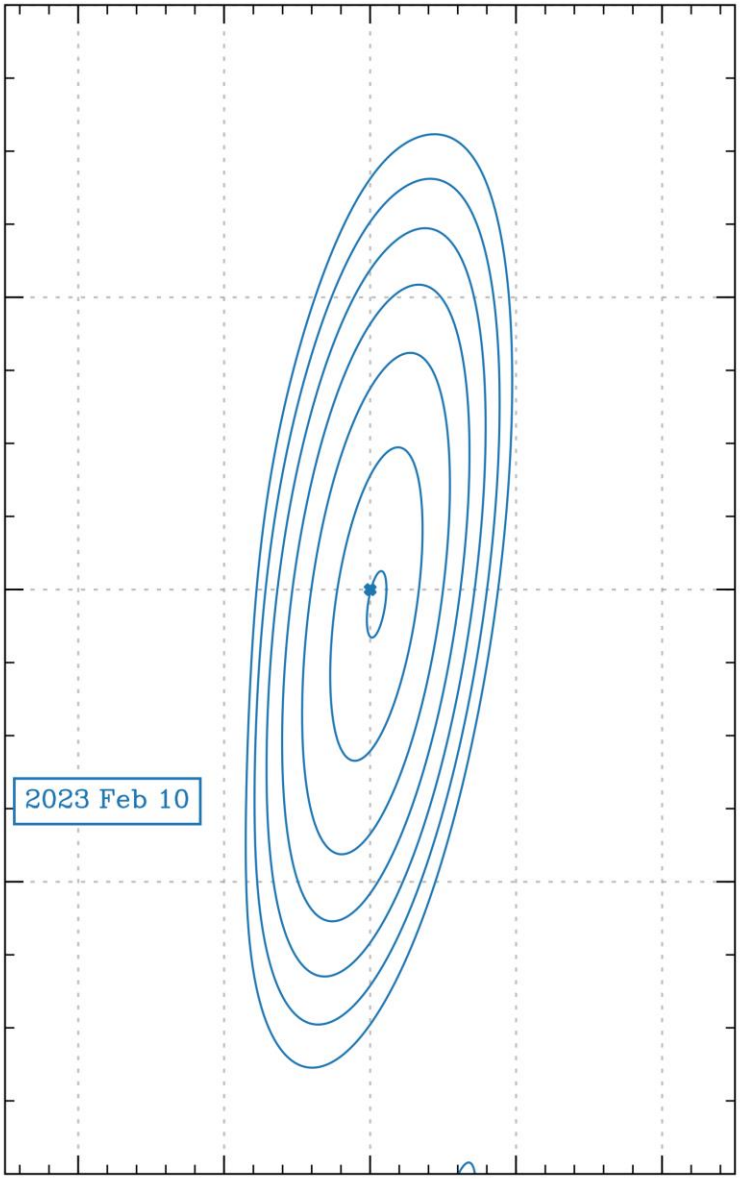
Cendes et al. (in prep)

Next Steps: VLBI!

- AT2018hyz appeared inconsistent with off-axis jet- emission starts too late, rises too quickly- but some disagreement (see: Matsumoto+23, Sfaradi+23)
- We recently linked radio telescopes from the USA (VLBI) to Germany (Effelsberg) to try and resolve the outflow! Two observations so far, from Feb 2023 and Feb 2024, analysis led by PhD student Will Golay…



VLBI Results



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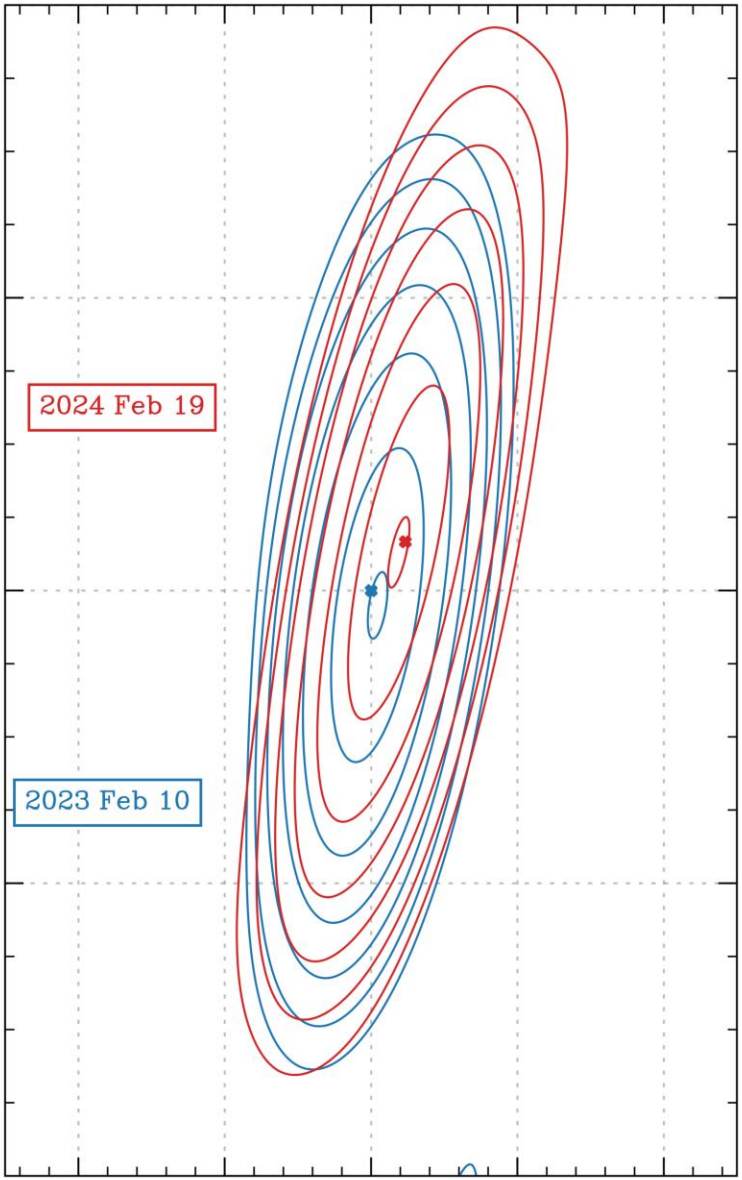
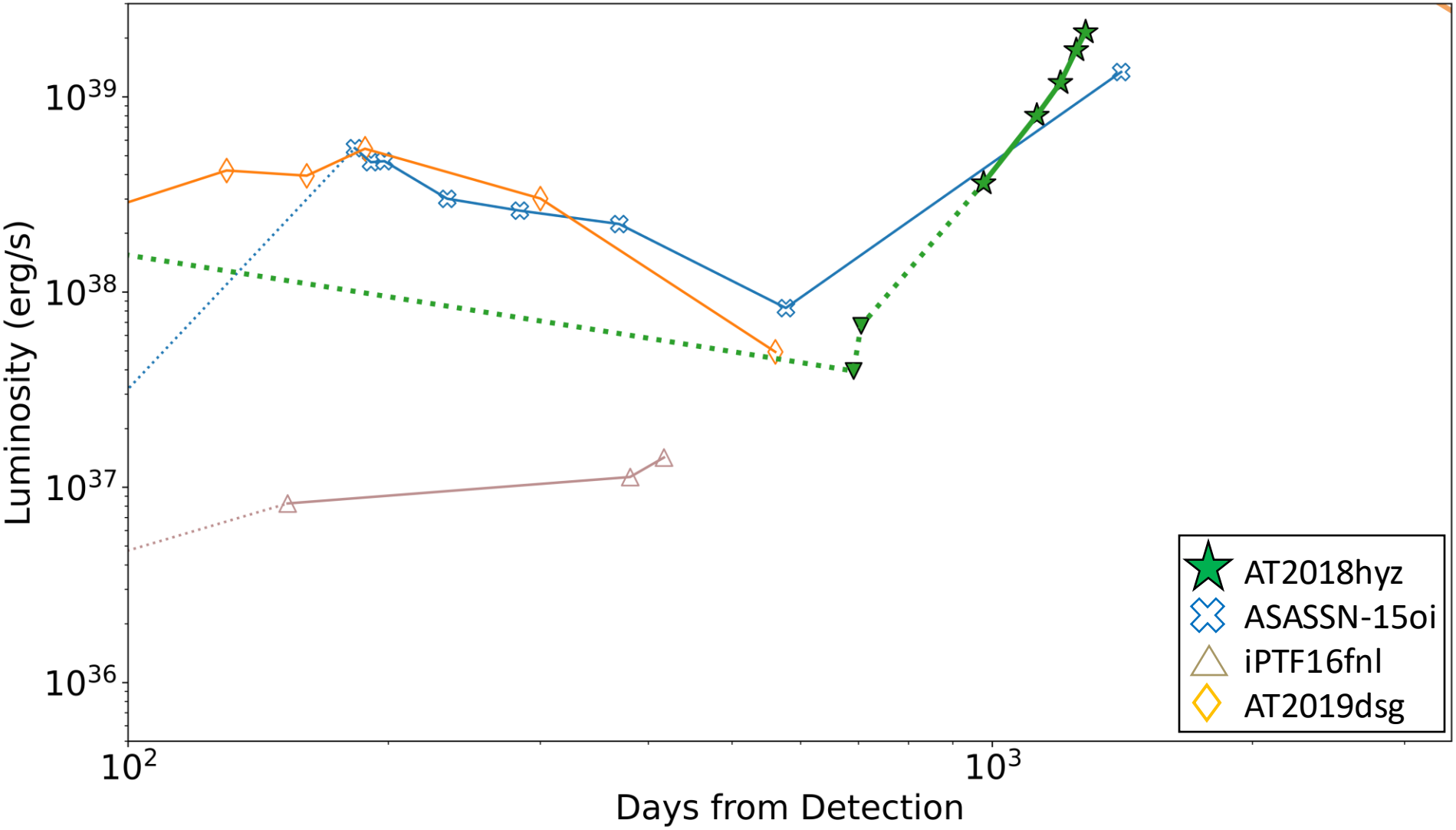


Looking Ahead: Other TDEs



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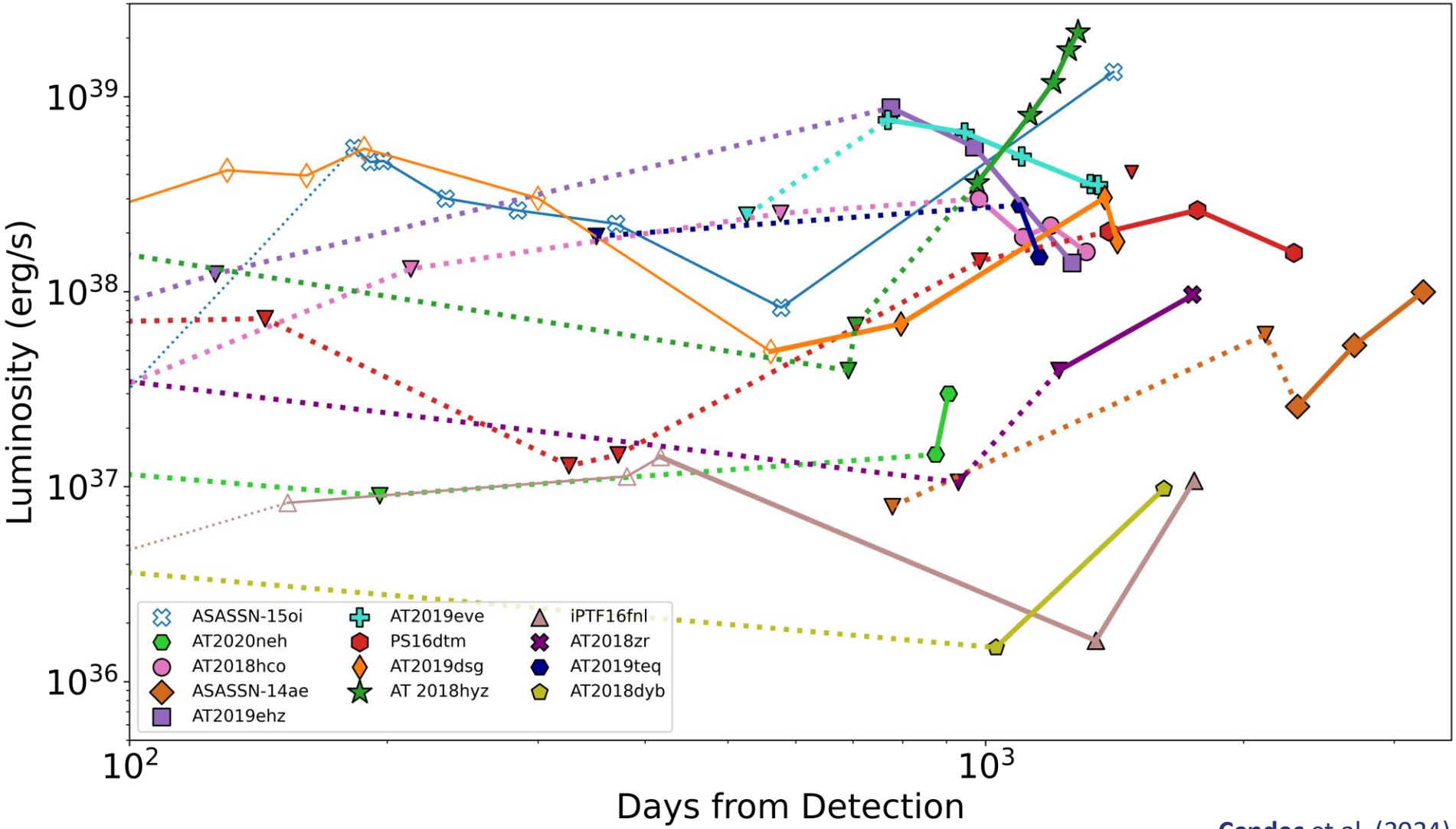
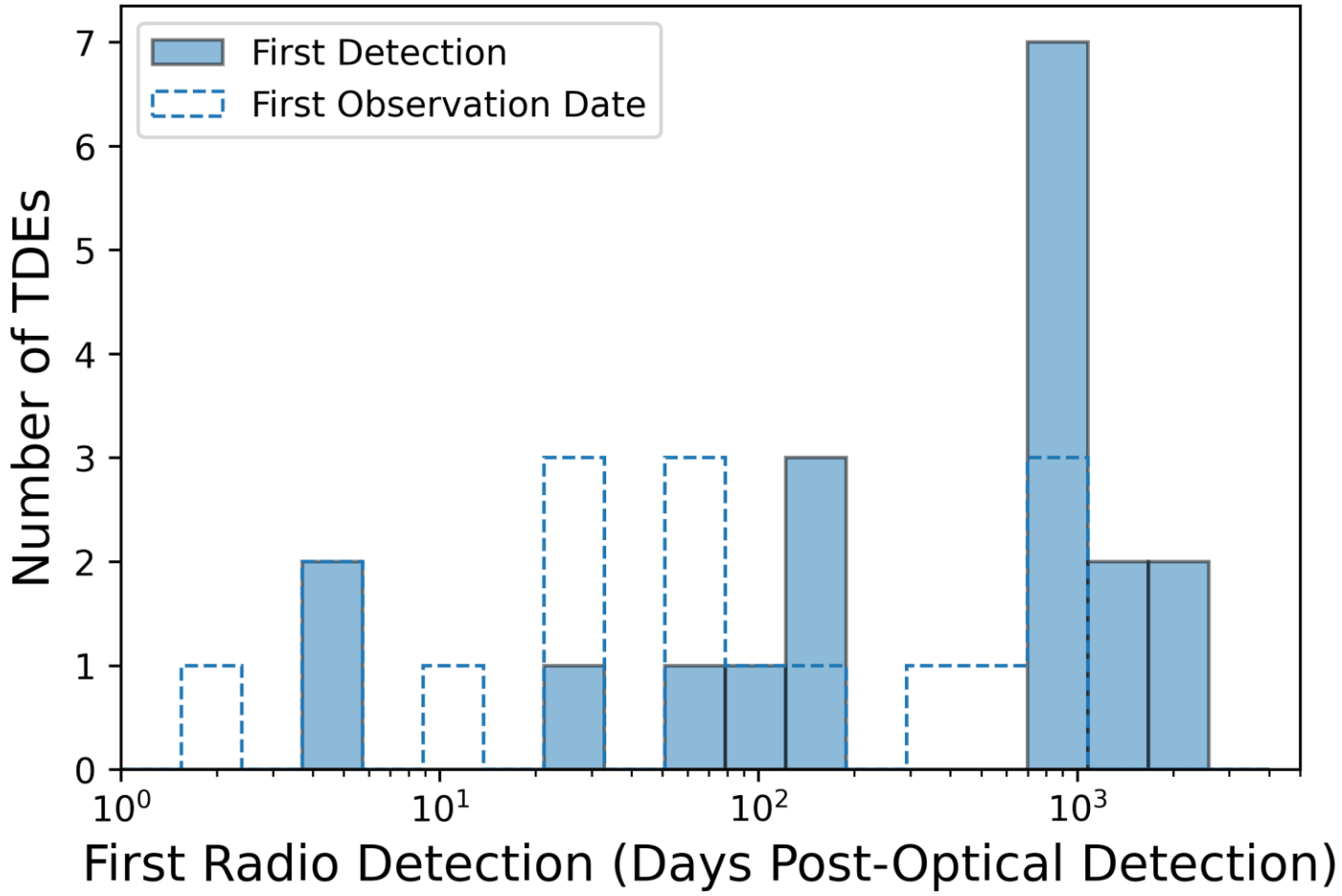


Cendes et al. (2024)
[arxiv:2308.13595]

The New Radio TDE Landscape



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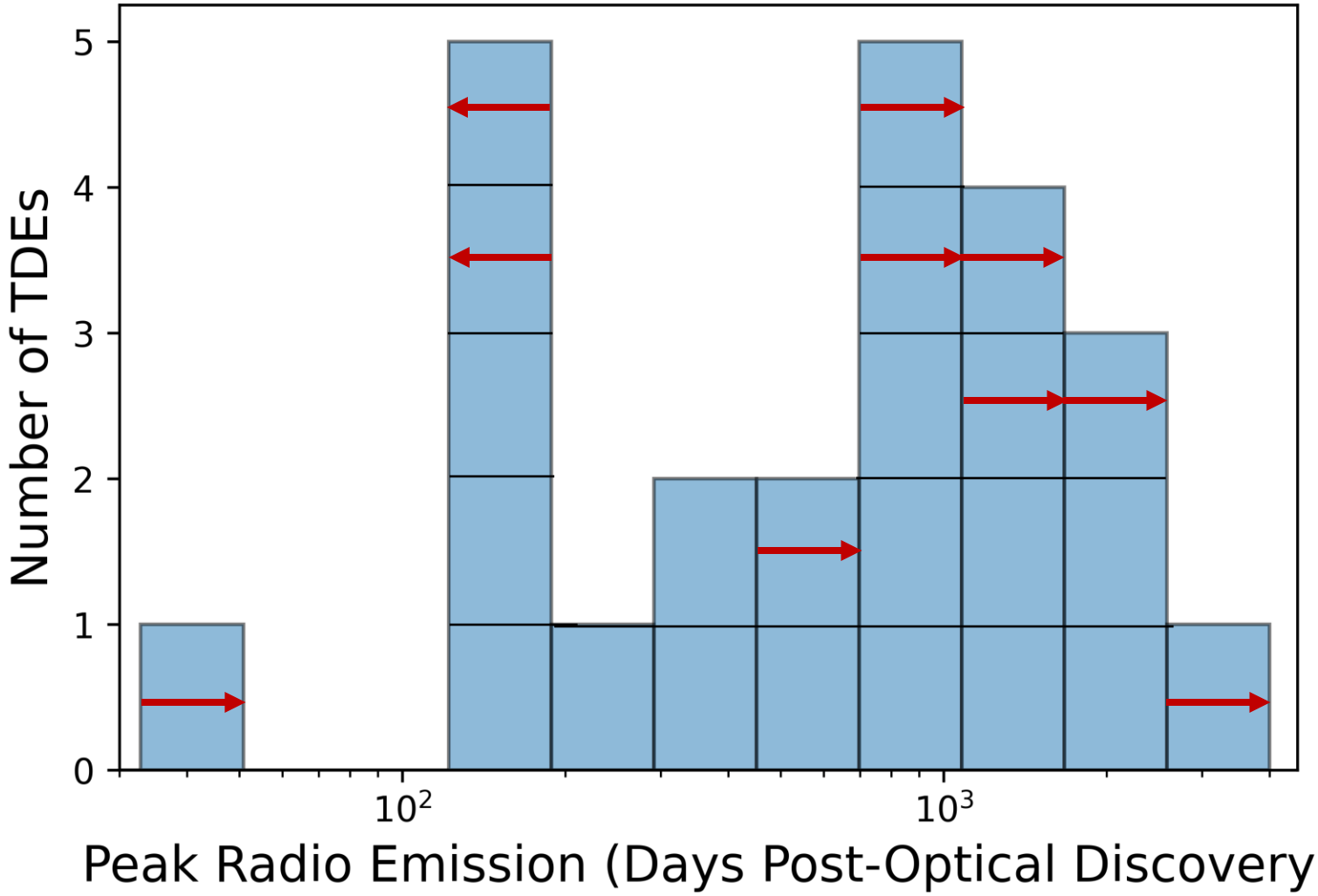

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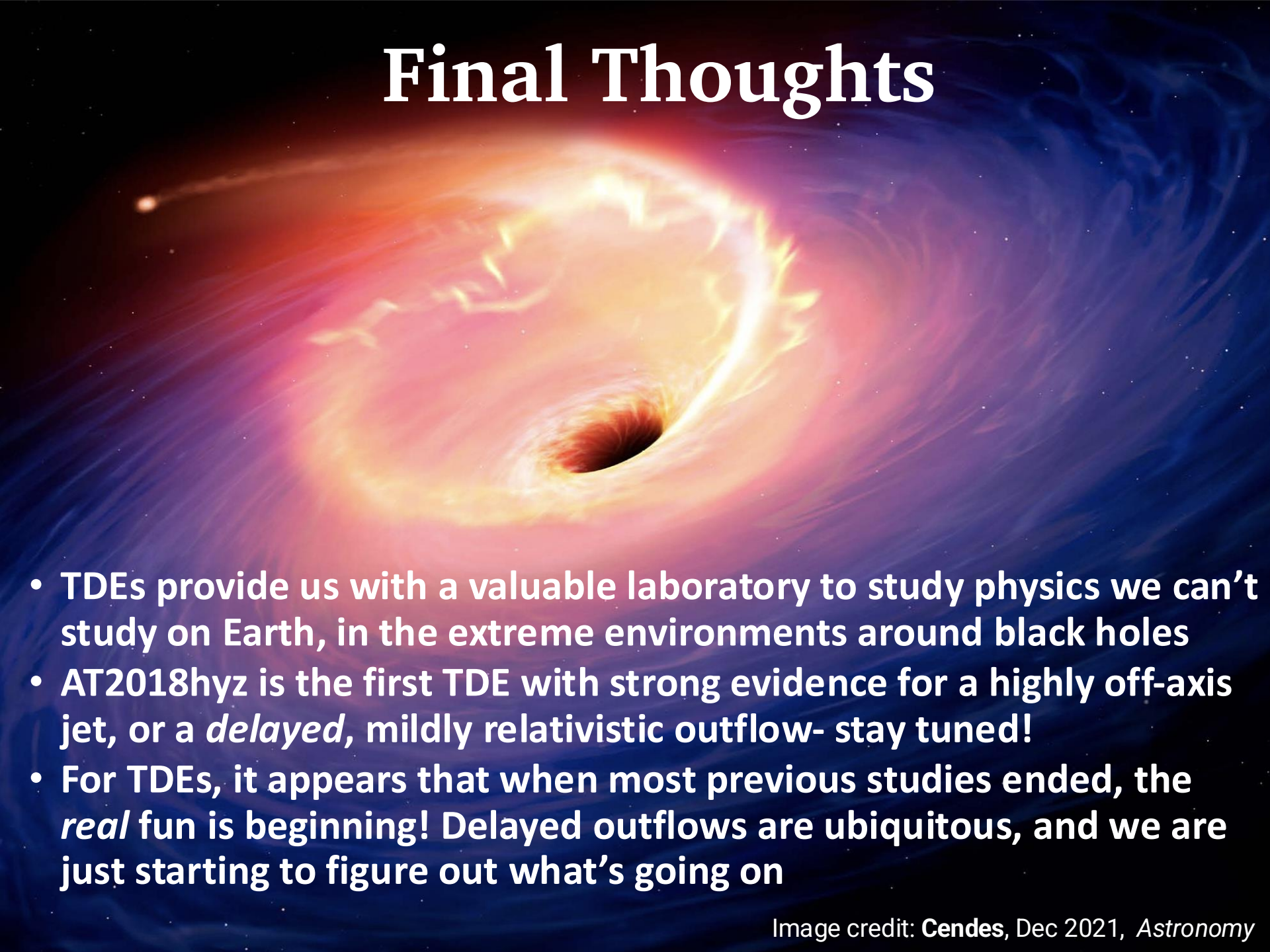
What is Going On?!

<u>What We Know:</u>

- $\lesssim$ 50% of our sample turns “on” in radio 2-6 years post-disruption, vs ~20-30% at early times (ie, the first few months post-disruption). Many are still rising! We also see a 2nd rise in TDEs w an initial radio outburst
- This is a population of (primarily) non-relativistic TDE outflows, which begin on ~years post-TDE time scales. We can rule out off-axis jets in most cases
- No clear markers with other wavelengths to ID which will turn “on.” Optical, X-ray data will be in companion paper! (Alexander et al., in prep)
- Interpretation is as-yet unclear. Delayed disk formation/ jets (Teboul+23)? Density (Matsumoto+24)? Multiple outflows (Goodwin+24)? Others?

Final Thoughts



- TDEs provide us with a valuable laboratory to study physics we can't study on Earth, in the extreme environments around black holes
- AT2018hyz is the first TDE with strong evidence for a highly off-axis jet, or a *delayed*, mildly relativistic outflow- stay tuned!
- For TDEs, it appears that when most previous studies ended, the *real* fun is beginning! Delayed outflows are ubiquitous, and we are just starting to figure out what's going on

Image credit: **Cendes**, Dec 2021, *Astronomy*