Image credits: Stu Parker, Parkdale Observat

Extreme Nuclear Transients in the Multi-Messenger Era
Insights from Late Time + HST Observations of AT2021lwx aka "Scary Barbie"

Multi-Messenger Astrophysics in the Dynamic Universe
Yukawa Institute of Theoretical Physics (YITP) Workshop
Kyoto University
February 25, 2026

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In collaboration with Danny Milisavljevic, Raffaella Margutti, Ryan Chornock, Kate Alexander, David Sand, Dimitrios Giannios and many other wonderful collaborators!

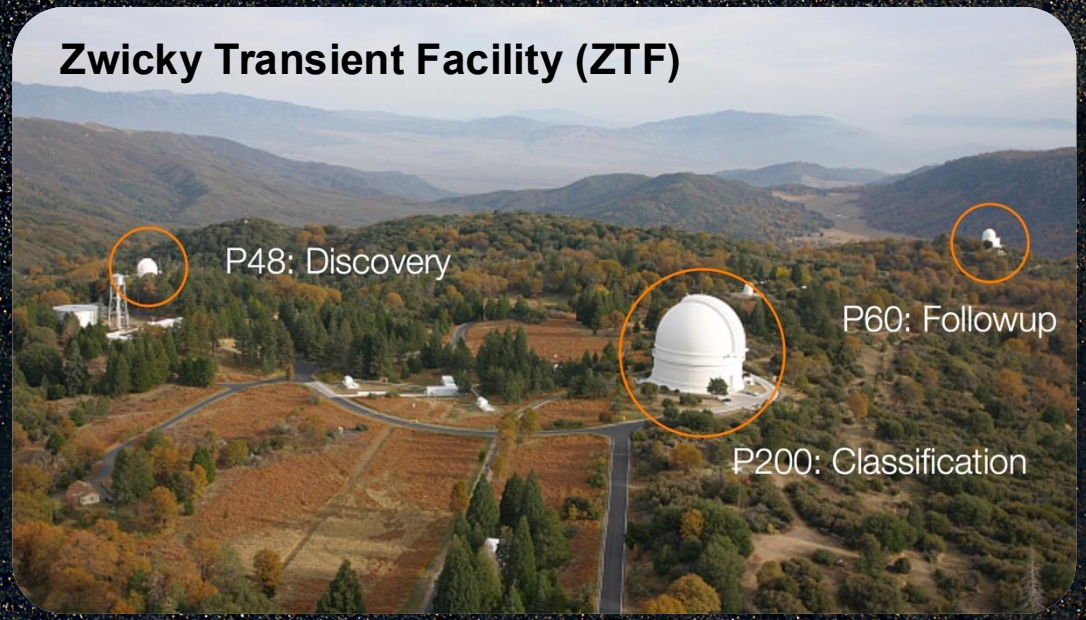
REFITT
Recommender Engine For Intelligent Transient Tracking

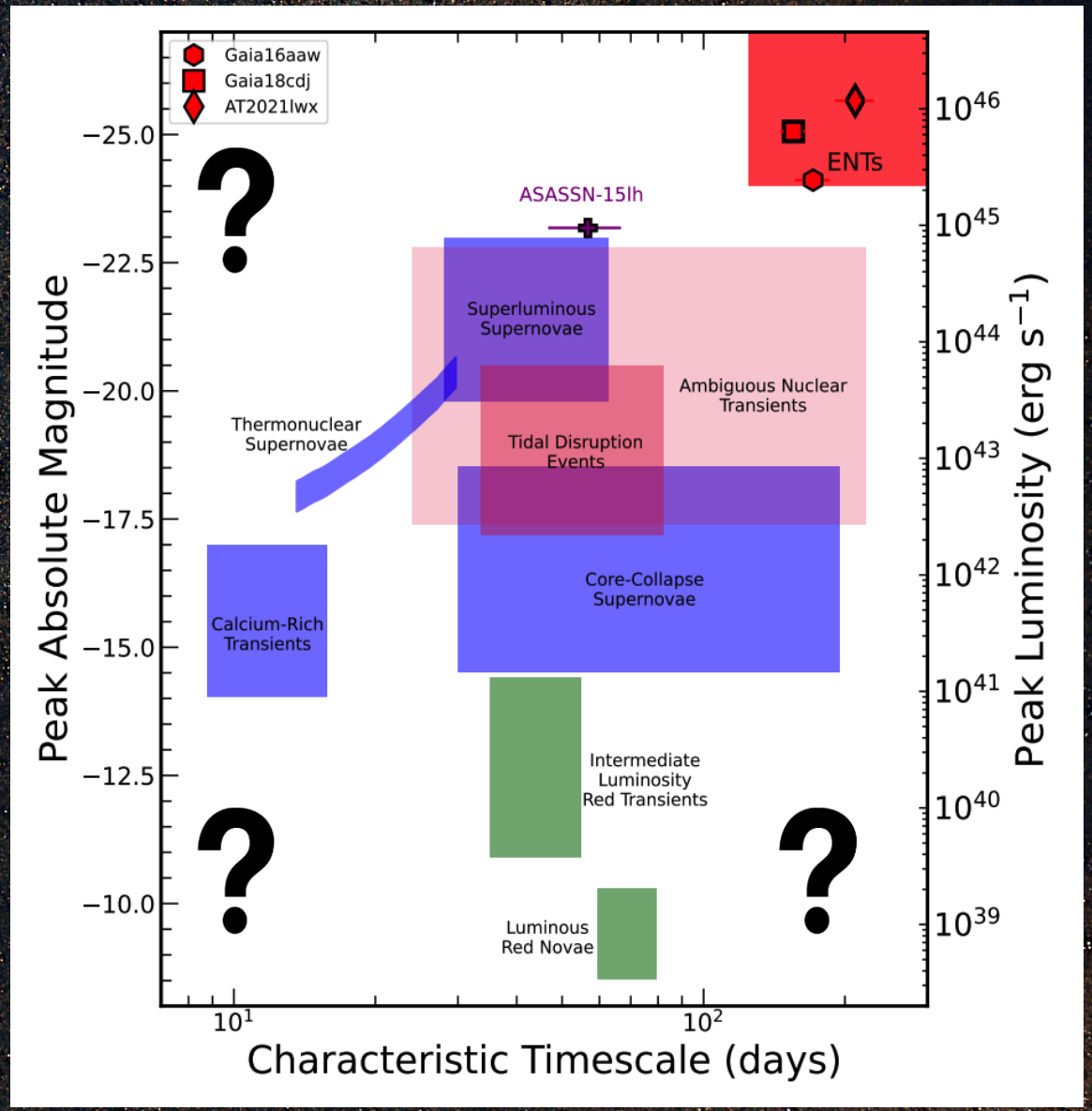
NASA | ESA hubble

YITP
YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

Untargeted All Sky Surveys and New Discoveries

We are in the LSST era!
Alerts already streaming / in the next 24 hours!!





Hinkle et. al 2025

Ambiguous Nuclear Transients (ANTs) from an observer's perspective!

(Trakhtenbrot et al. 2019; Ricci et al. 2020; Hinkle et al. 2022; Holoien et al. 2022; Yu et al. 2022, Wiseman et al. 2024)

Tidal Disruption Events (TDEs) see Kate's overview talk

Rees 1988; Evans & Kochanek 1989; Gezari et al. 2012; Brown et al. 2017; Gezari 2021)

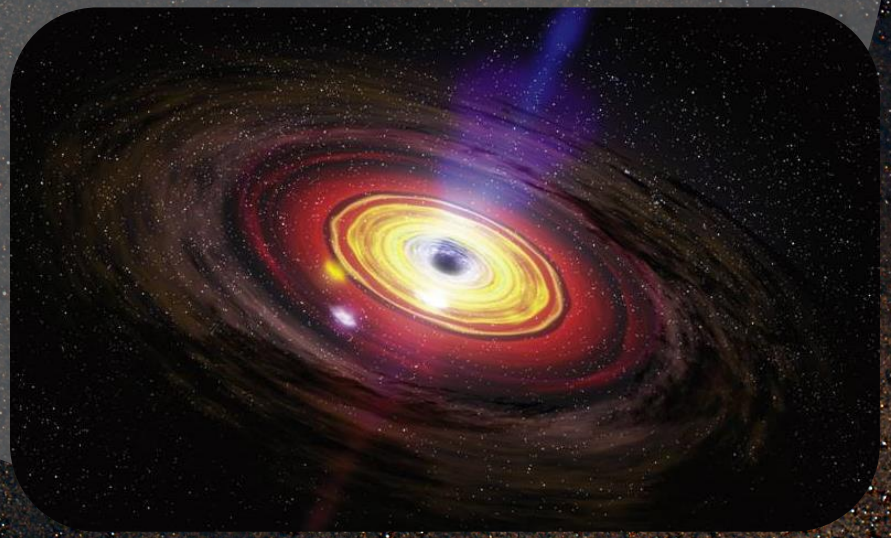
- UV/ Optical Blackbody
- Smooth Power Law ($t^{-5/3}$) Light Curve Evolution
- Broad H/He emission lines
- Soft X-ray Emission
- Radio emission after years

Ambiguous Nuclear Transients (ANTs)

Active Galactic Nuclei (AGNs)

Bianchi et al. 2005; Drake et al. 2011; Denney et al. 2014; Shappee et al. 2014; Frederick et al. 2021

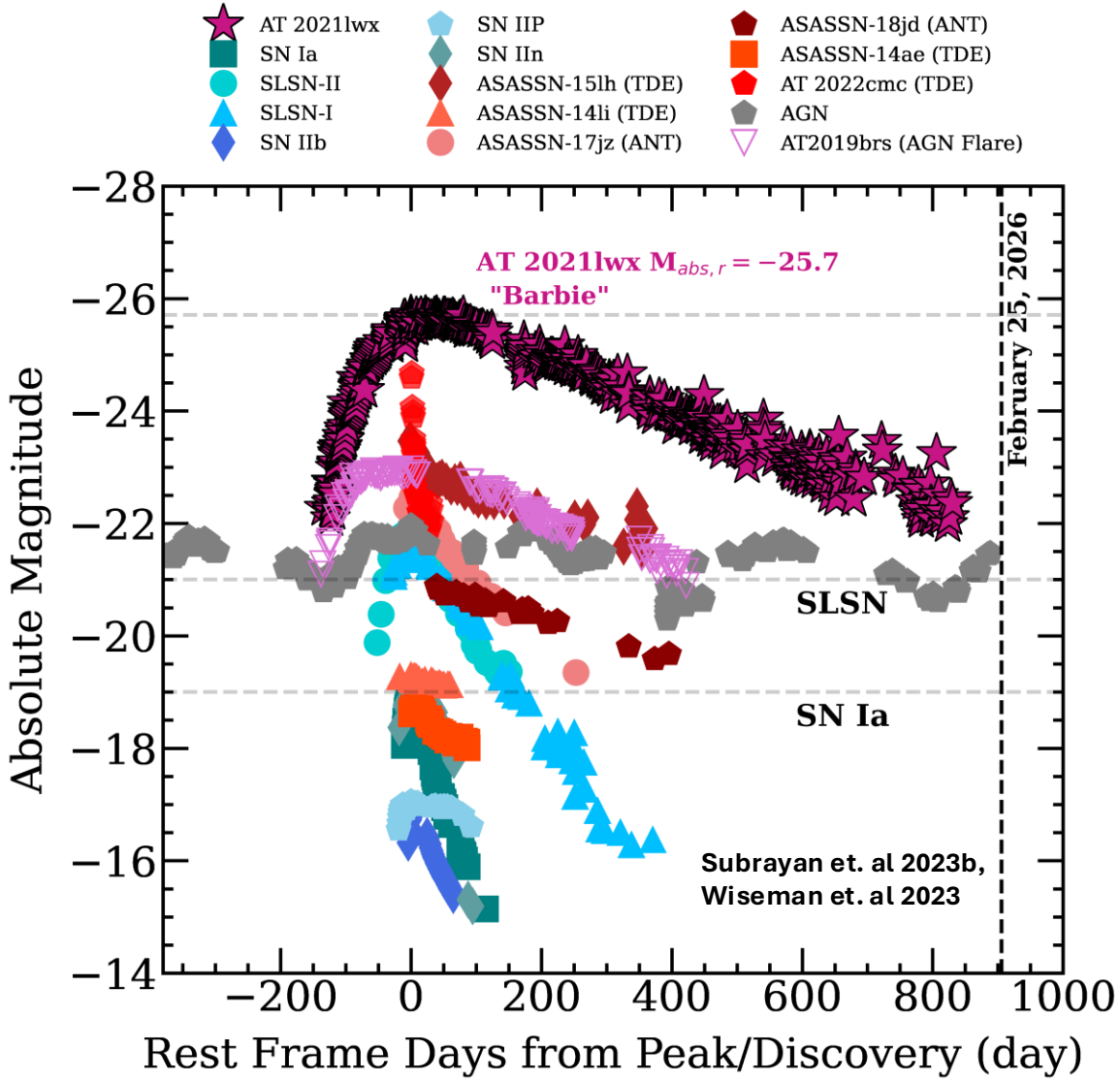
- UV/ Optical Blackbody
- Hallmark stochastic multi-wavelength variability in light curves
- Strong Narrow and Broad Emission Lines
- Hard X-ray Emission
- Most AGN's are radio loud

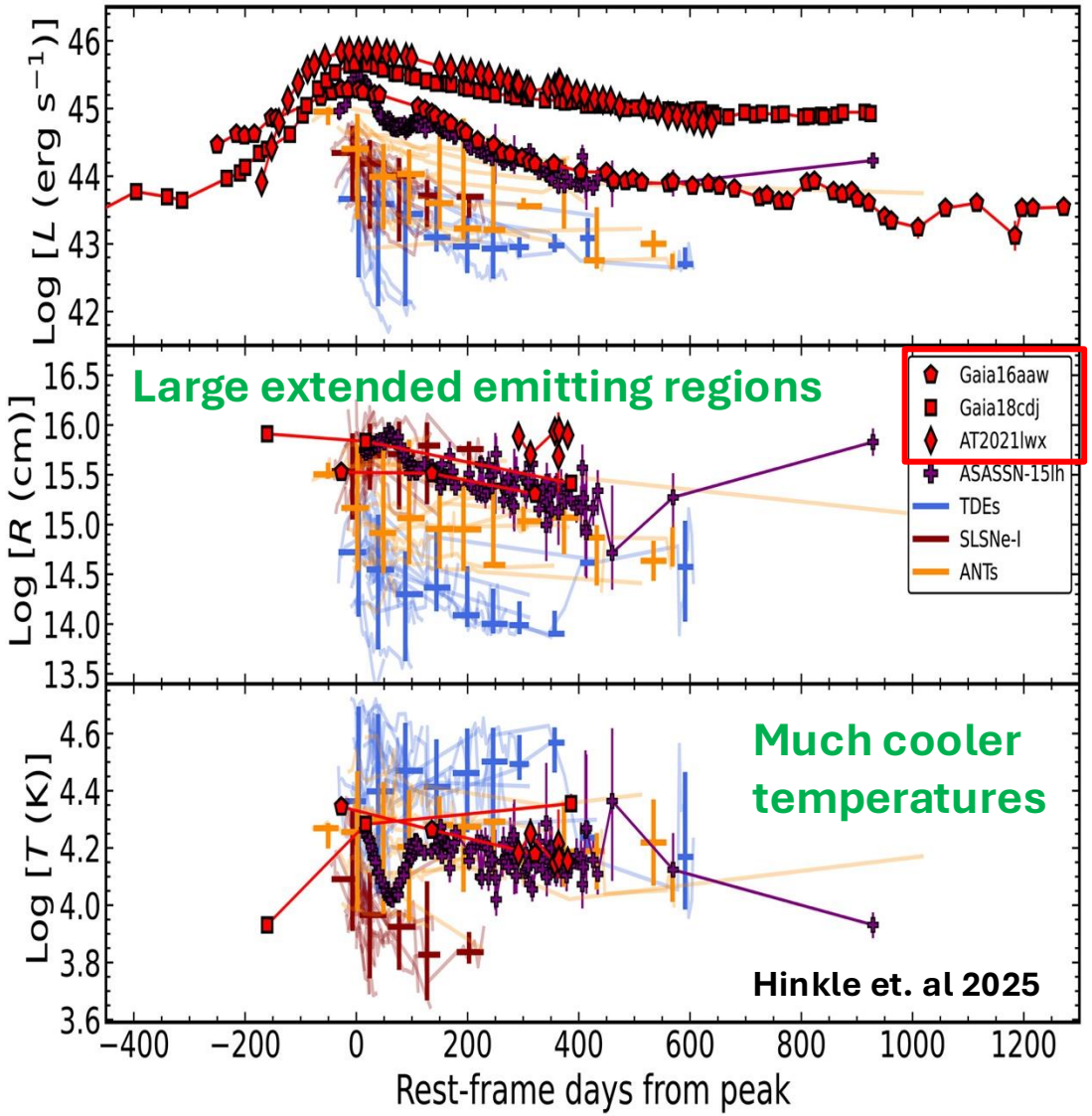


Slide idea adapted from https://www.youtube.com/watch?v=2zfzH0habSs

Extreme Nuclear Transients (ENTs) == Possible ANTs on steroids??!

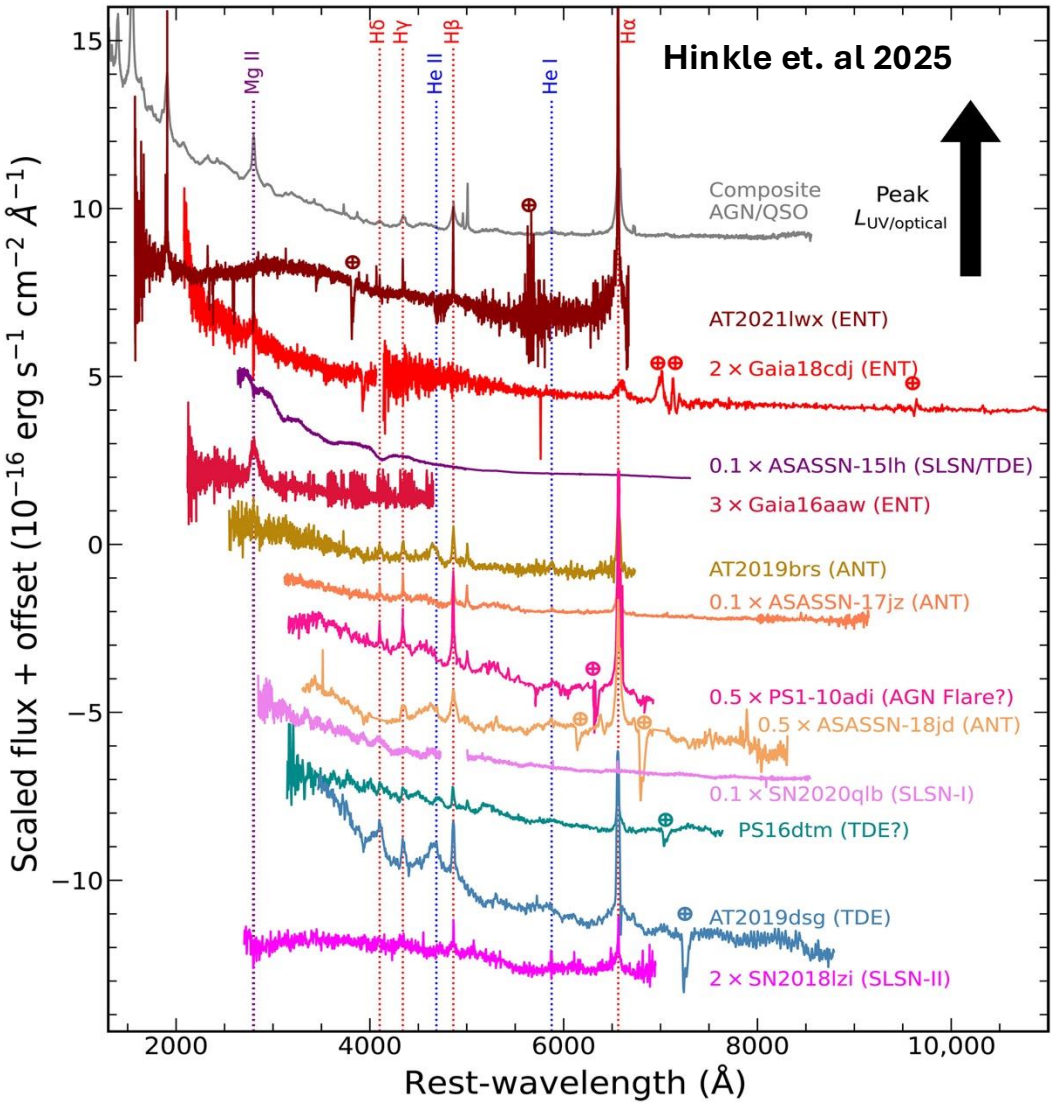
Extremely Luminous, Long-Lived, Energetic (> 10^{52} erg)

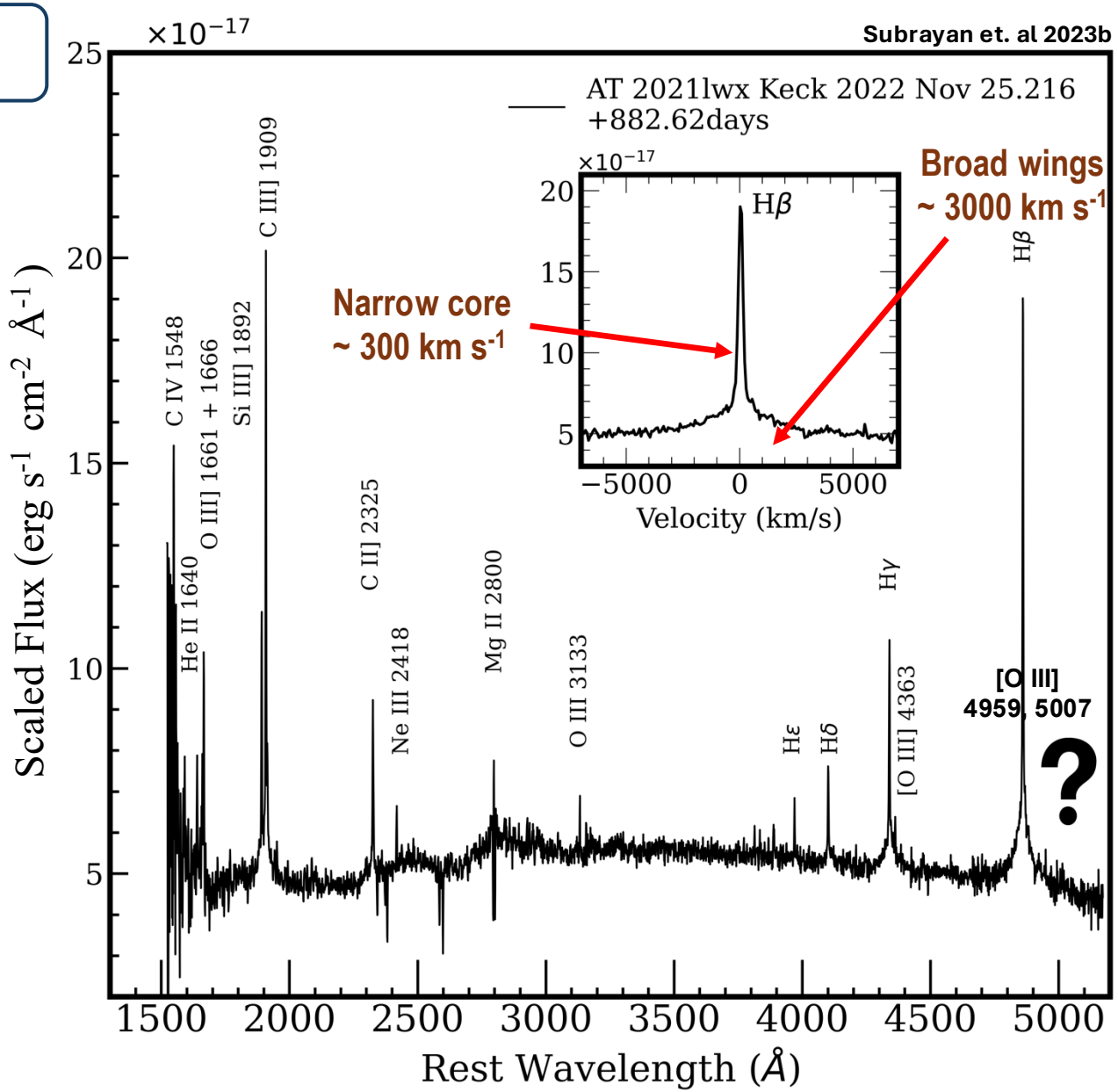




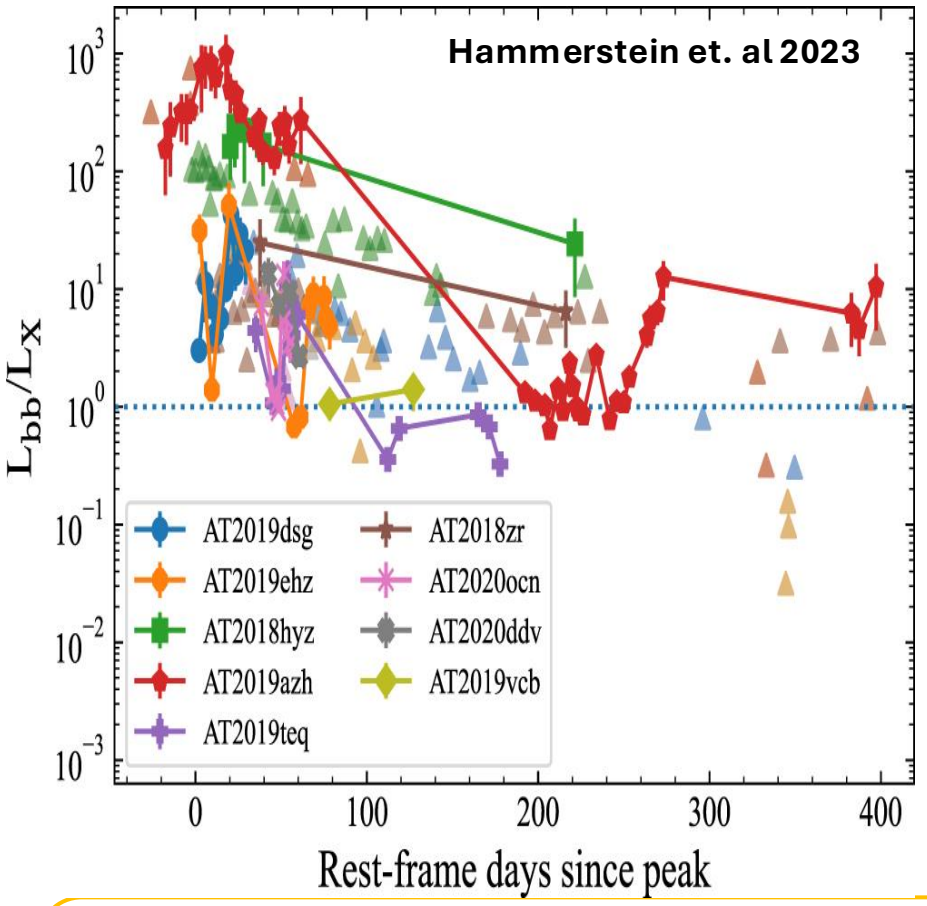
How do they look spectroscopically in the optical?

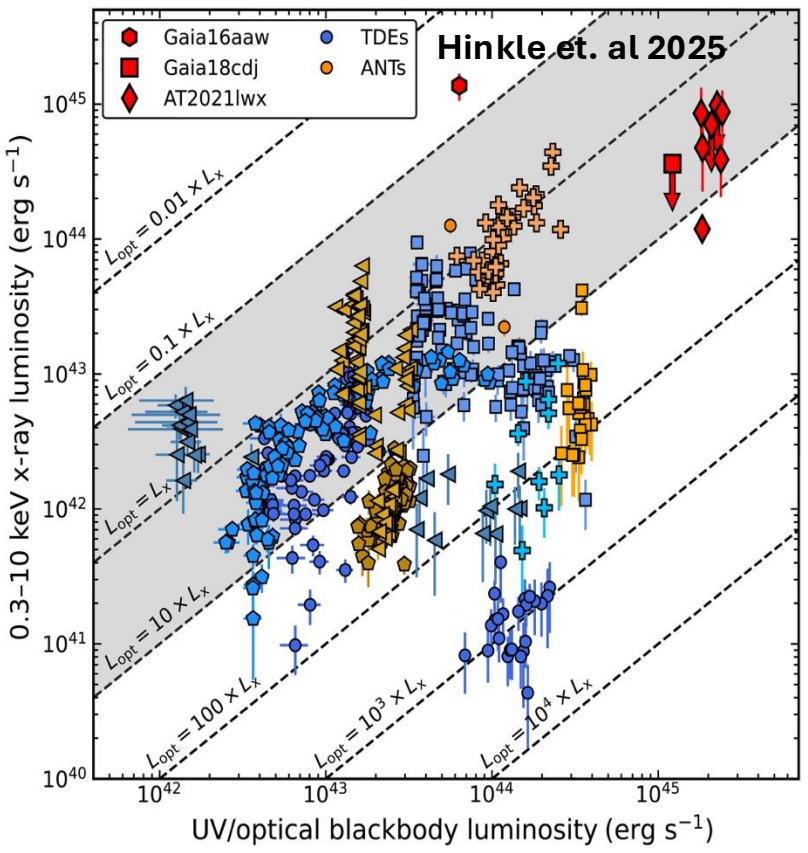
All ENTs show a strong blue continuum + H (Balmer series) + Mg II

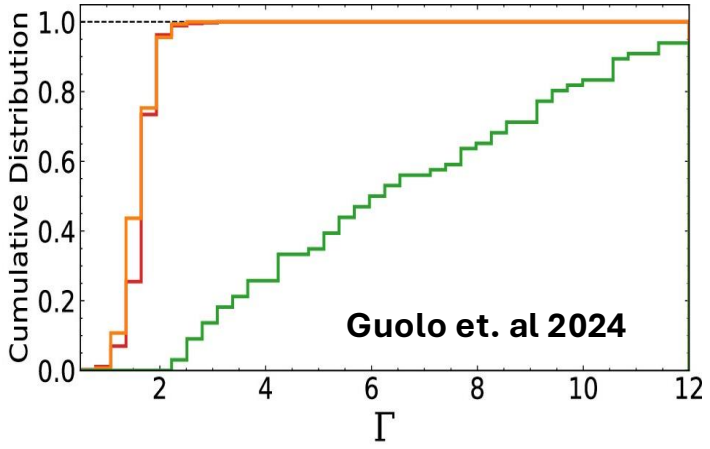


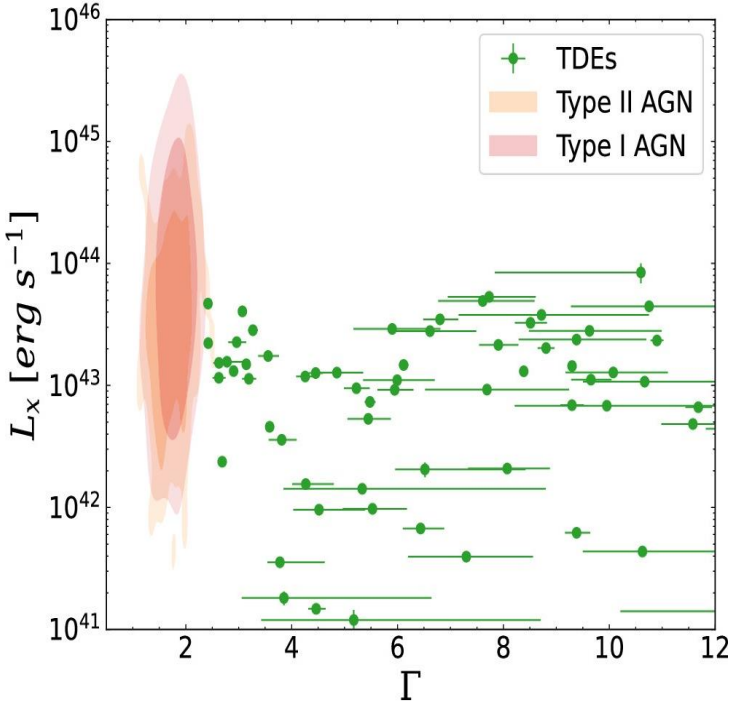


How luminous are ENTs in X-rays and Radio?



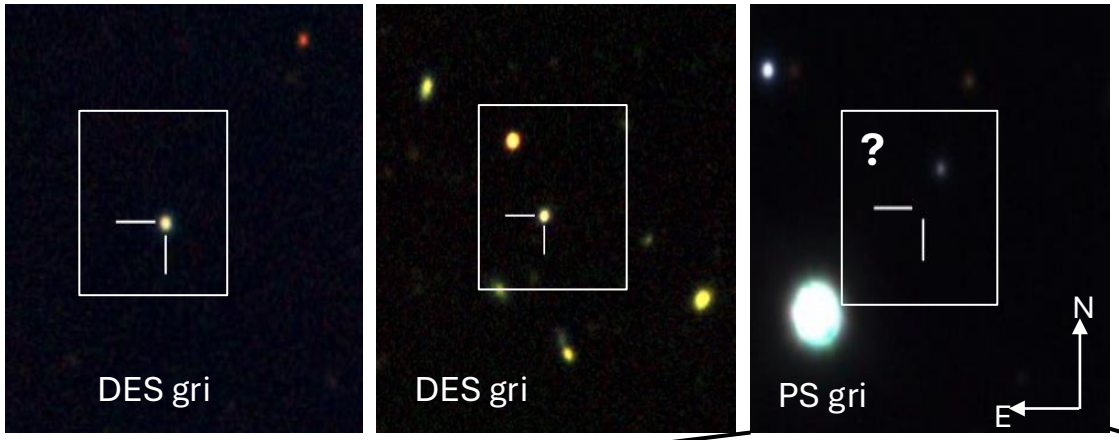




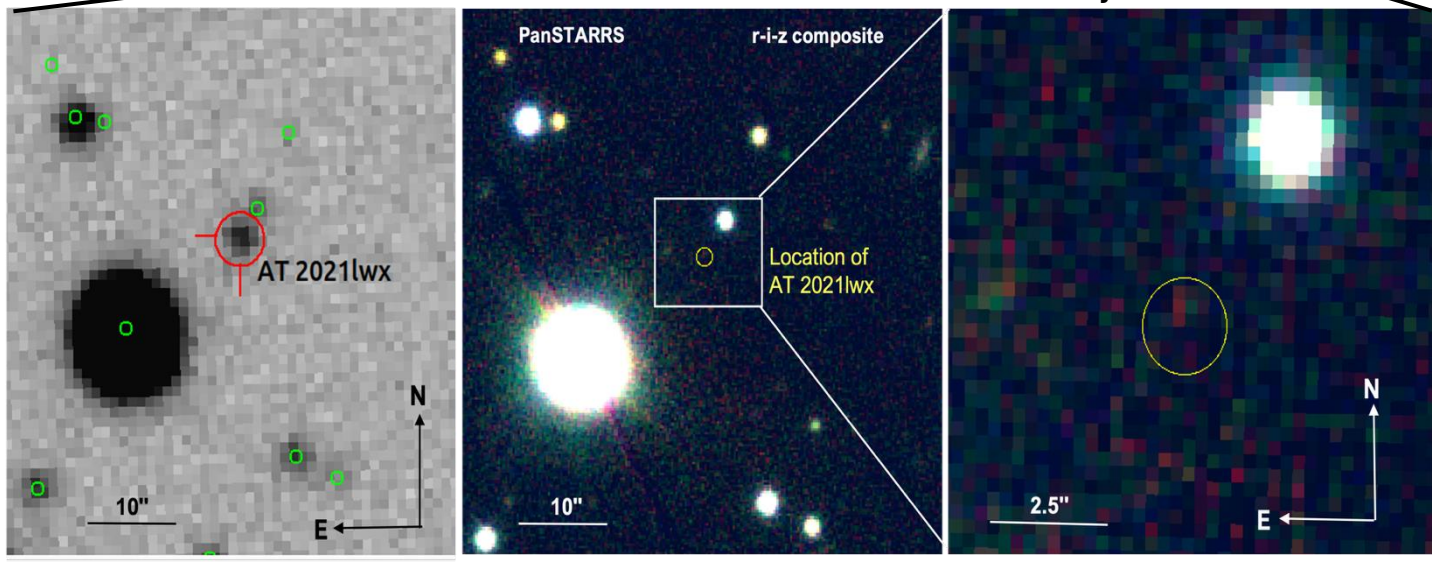


- ENTs are luminous in X-rays with harder photon index compared to TDEs and ANTs. X-ray emission more similar in behavior to AGNs.
- No detection in radio for AT 2021lwx. VLASS non-detection $F_\nu < 0.35$ mJy at ≈ 3 GHz. No jets detected yet!

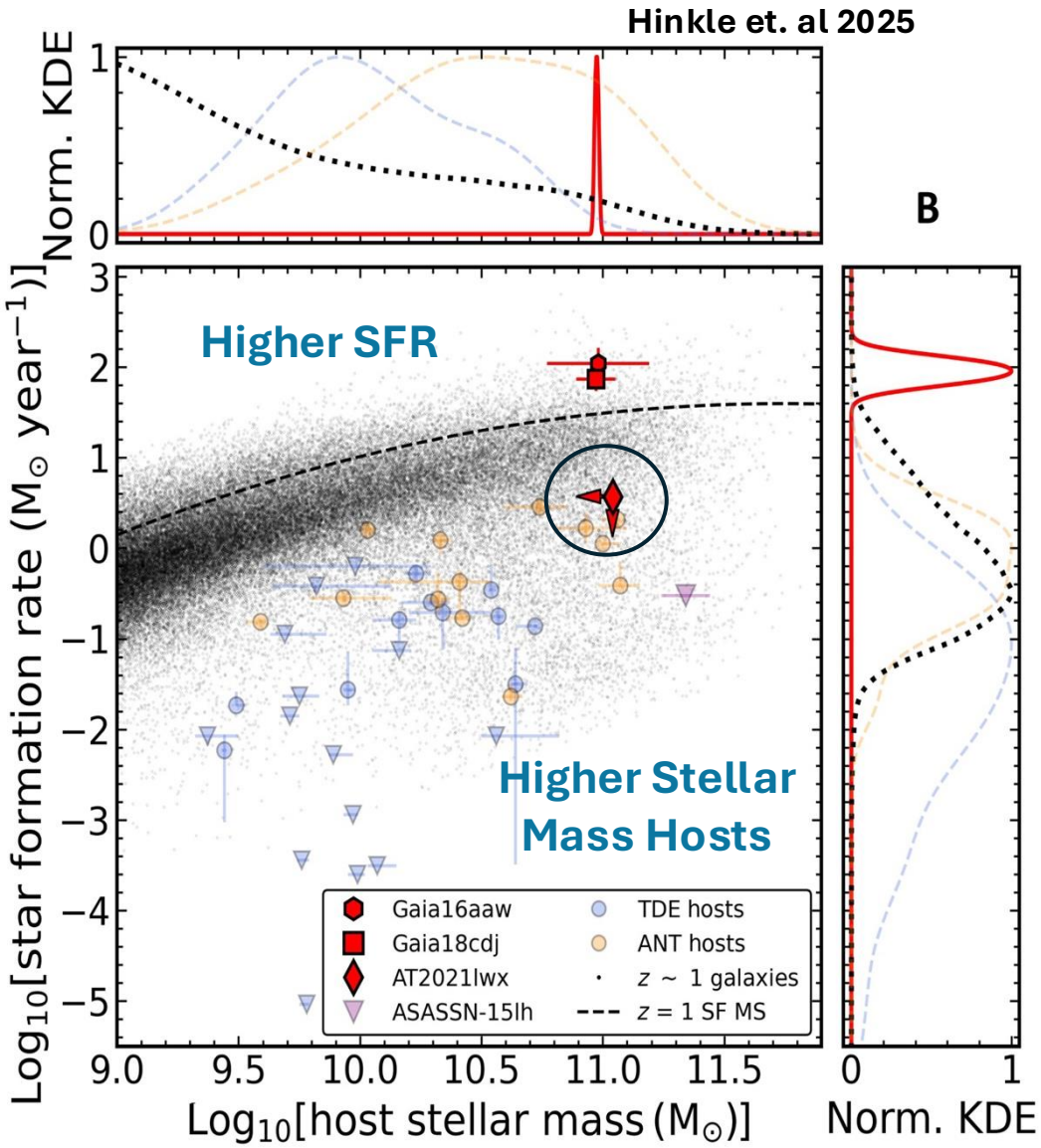
What do we know so far about ENT hosts and redshifts?
The story deepens for AT 2021lwx: No host detected conclusively yet



Subrayan et. al 2023b



Hinkle et. al 2025

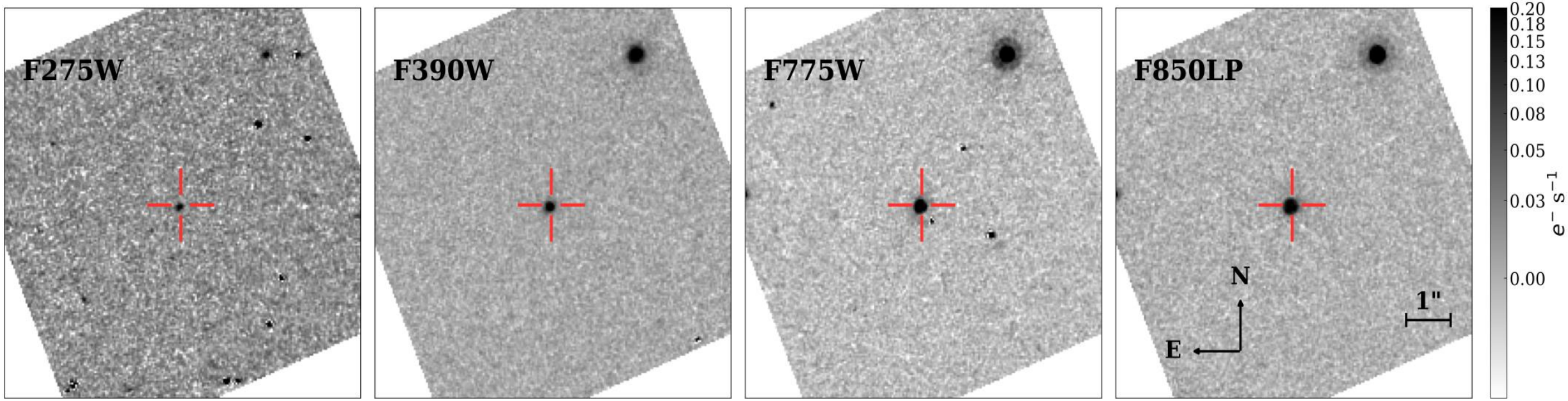


Hubble Space Telescope (HST) Observations of AT2021lwx
PI: Subrayan (ID:17748)

Goals of the HST program included:

- Immediately decipher any underlying host galaxy for AT2021lwx at z~1, which was intrinsically challenging with ground-based observations
- Understand the evolving SED of AT2021lwx
- For a TDE hypothesis interpretation, verify the location of AT2021lwx with respect to any host.
- Model the PSF + any Sersic profile to place quantitative limits of the host.

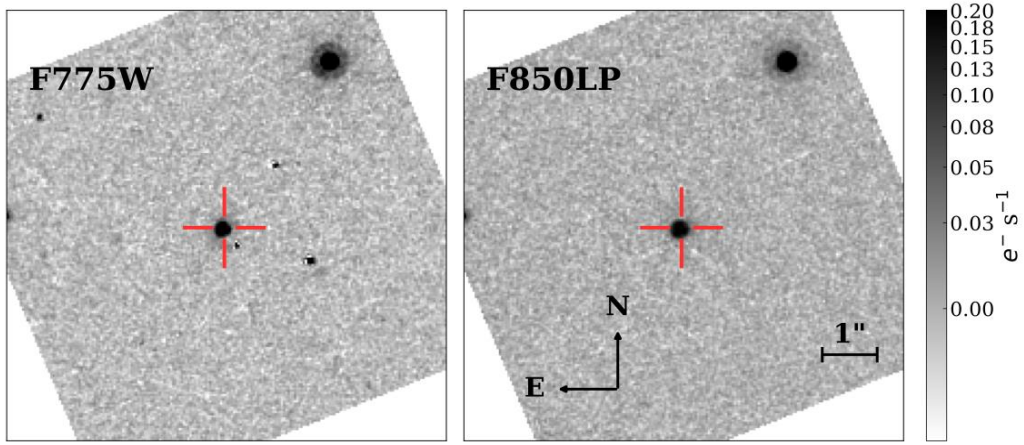
Subrayan et al. 2026 (in prep)



What do HST observations reveal so far?

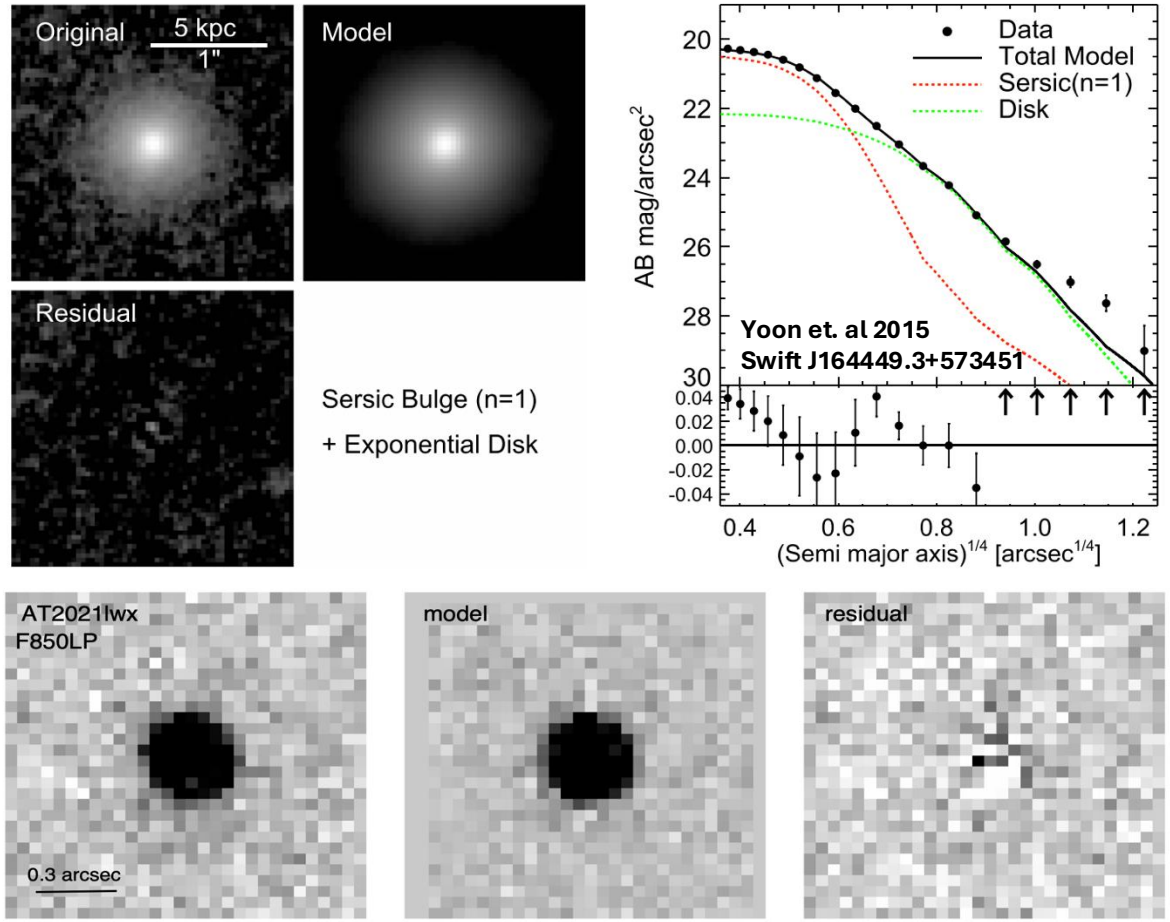
Subrayan et. al 2026 (in prep)

WORK IN PROGRESS



- **No surprises, AT 2021lwx is still very bright.**
- **The SED is clearly shifting to redder passbands motivating JWST follow-up.**
- We do not immediately see any significant underlying structure across all the bands. Need to place quantitative limits on this.
- Careful PSF modeling and motivation for future follow-up once the transient has faded.

GALFIT Modeling



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Subrayan et. al 2026 (in prep)

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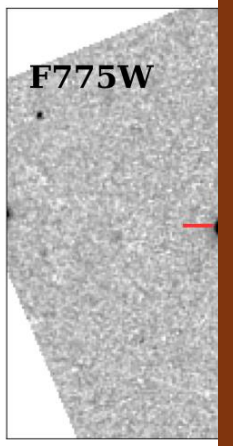
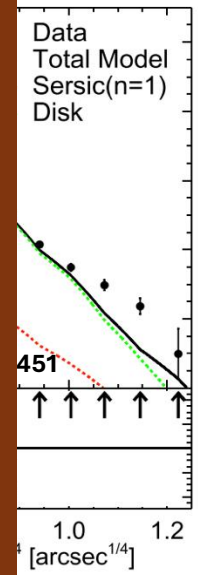


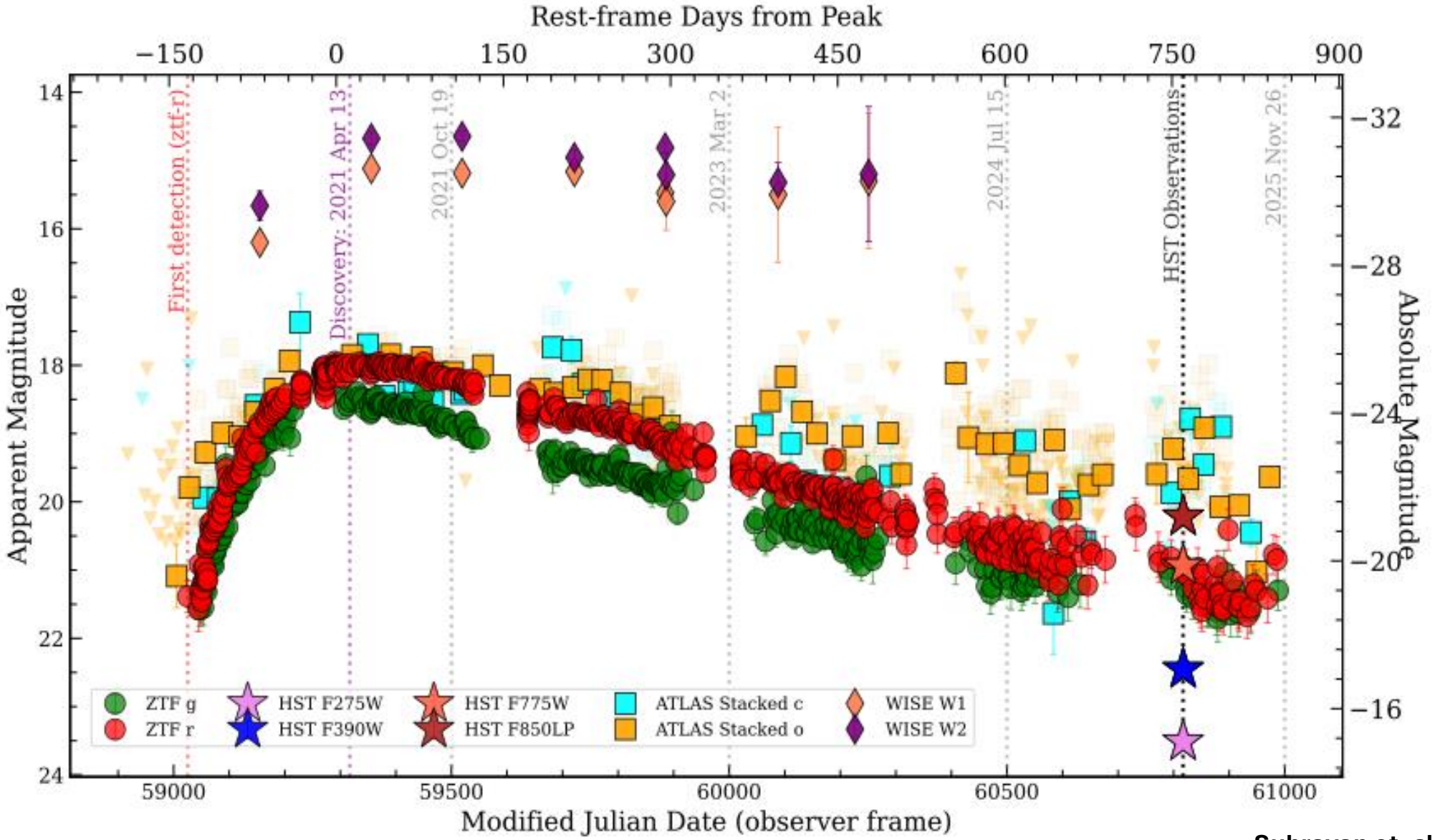
- No surp
- The SED
  motivati
- We do nc
  underlyir
  to place
- Careful P
  follow-up once the transient has faded.

The analysis will probe:

- **Structural parameters/ limits that can be placed on AT 2021lwx's host.**
- **Is the host a dwarf galaxy or heavily dust obscured?**
- **Is AT 2021lwx the first of an as-yet undiscovered population of ENTs in low-luminosity dust-obscured environments, or does it challenge our understanding of SMBH-galaxy co-evolution?**



Just a reminder, that AT2021lwx is still going strong!
Late time photometric and spectroscopic follow-up



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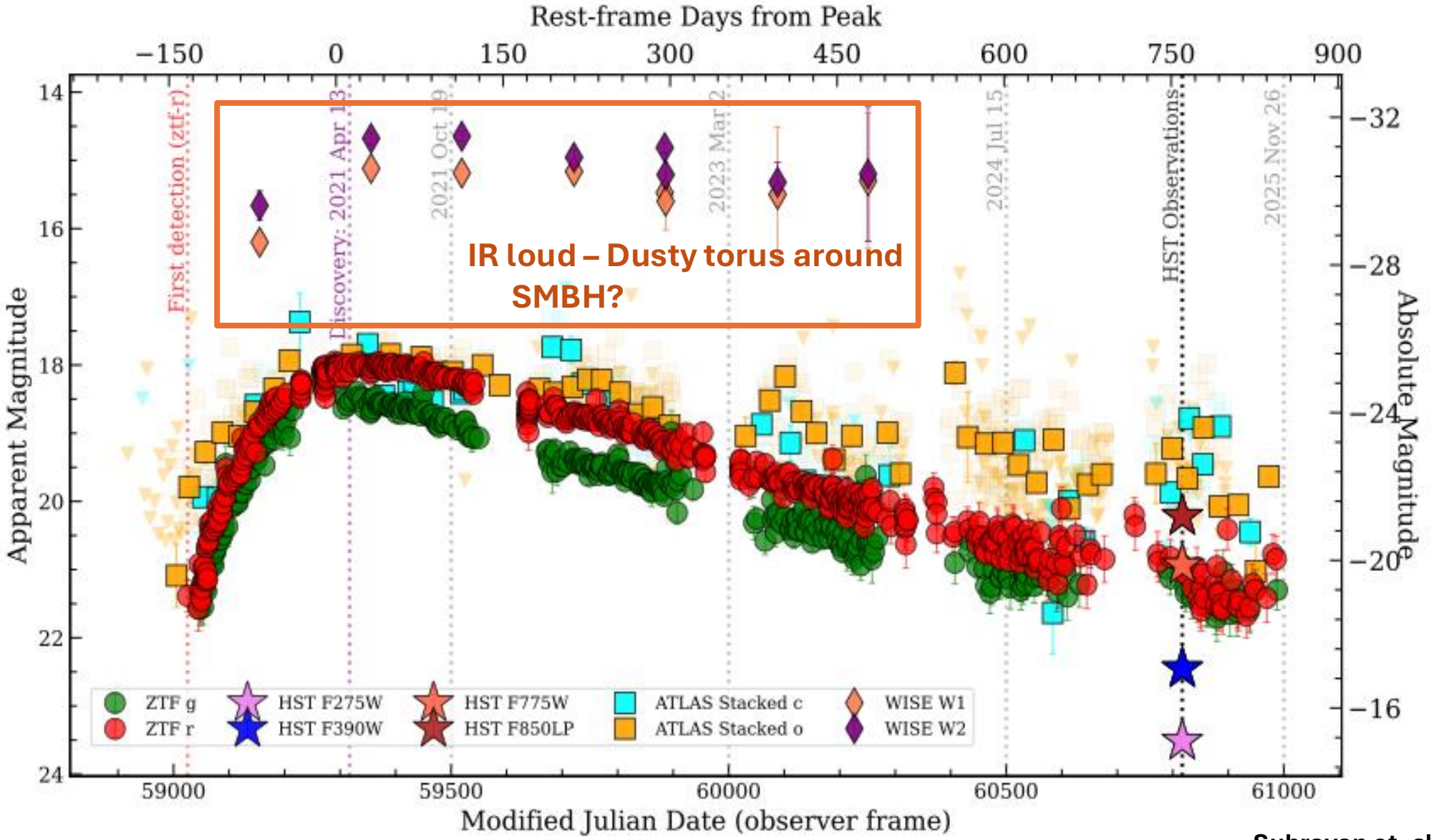
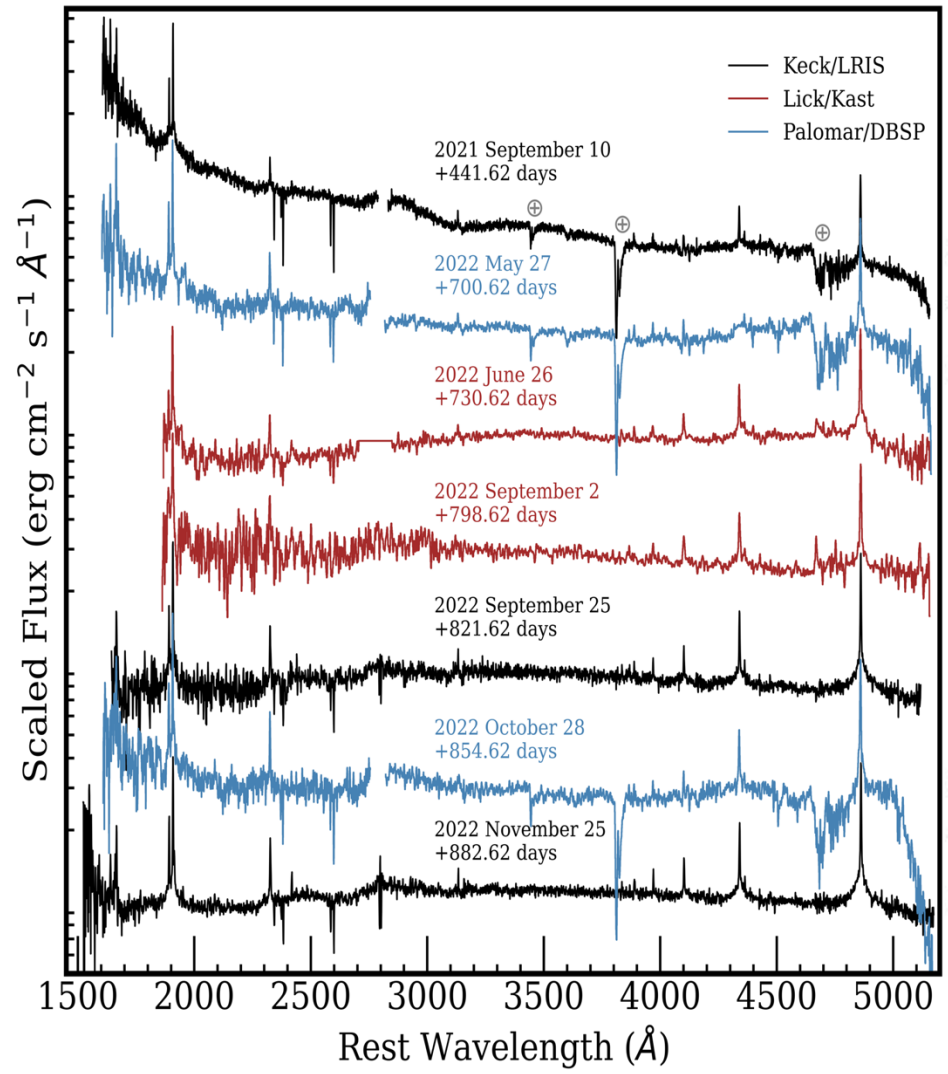
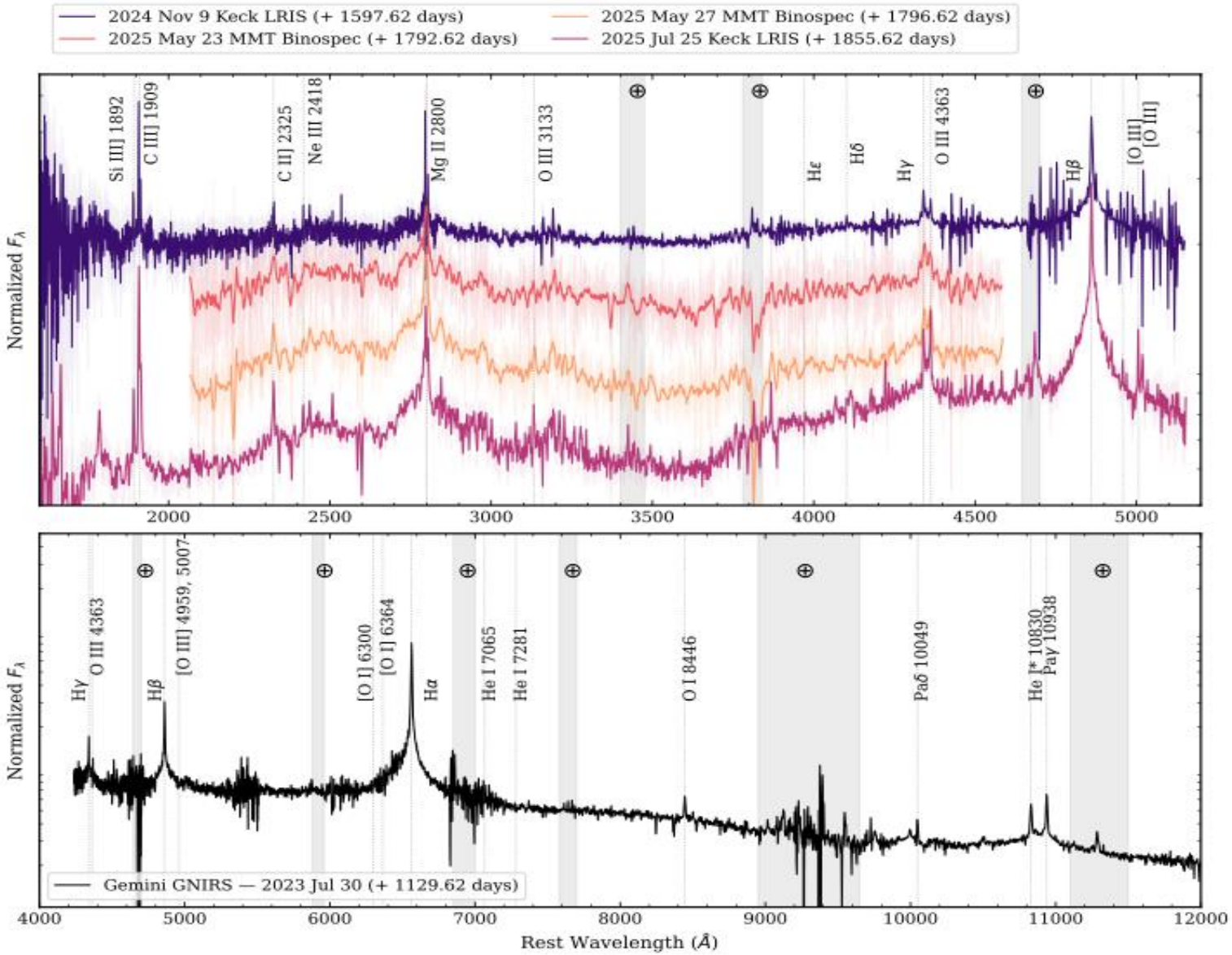


Subrayan et. al 2026 (in prep)

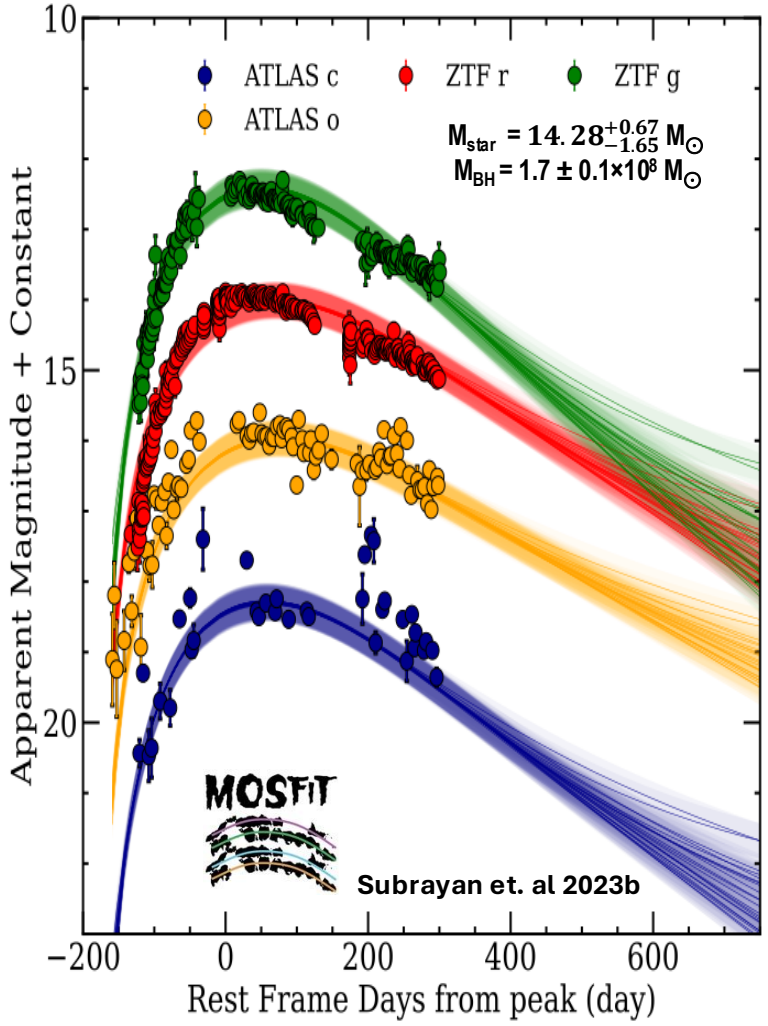
What do the early and late time spectroscopic data tell us? How have the lines evolved?

Subrayan et. al 2026 (in prep)

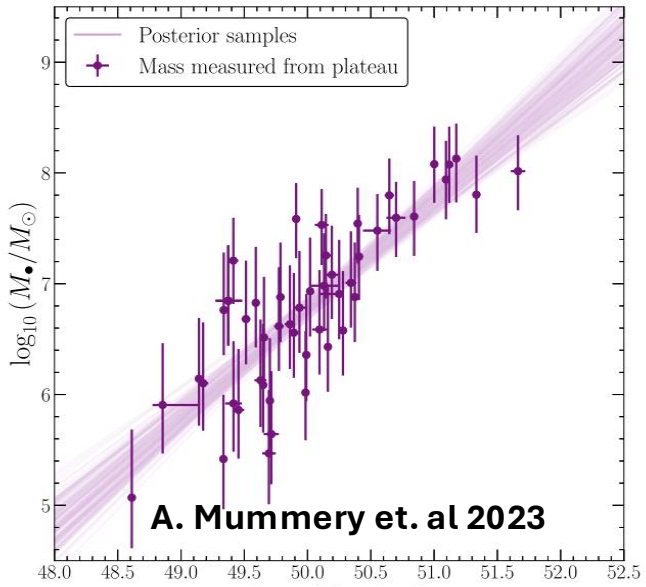


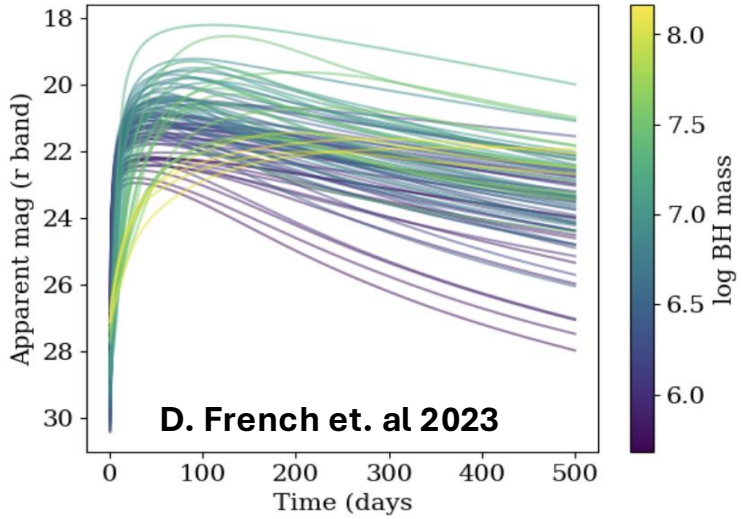


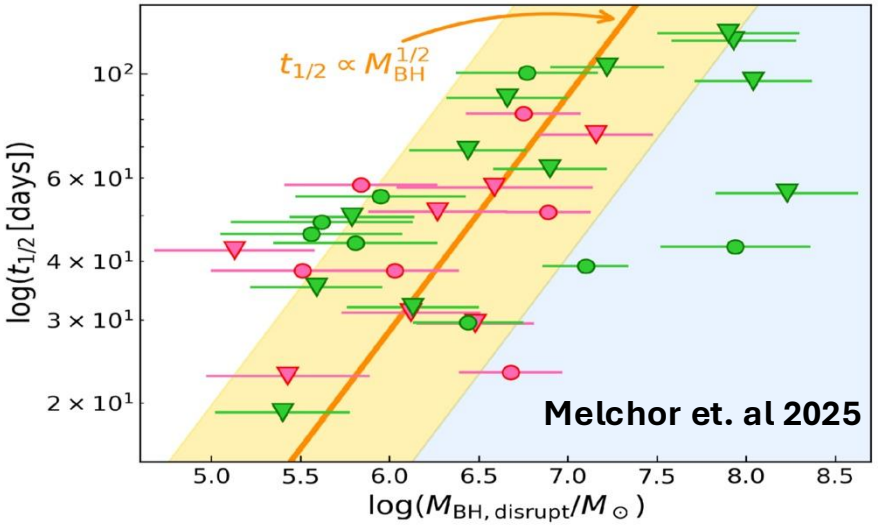
Possible Powering Mechanisms?
Disruptions from very massive stars/ gas clouds?

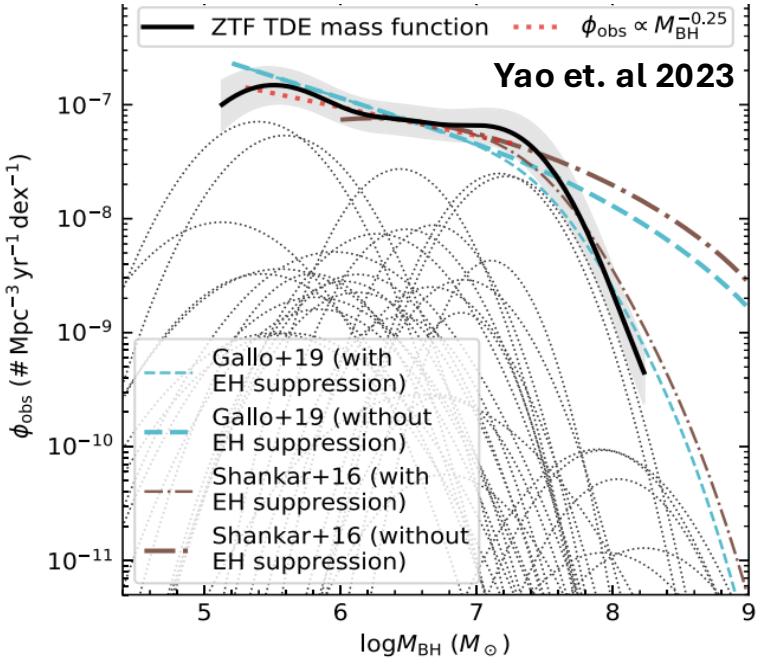


Disruption of a massive star > 10 solar mass.
Inferred a heavy SMBH, possibly spinning.

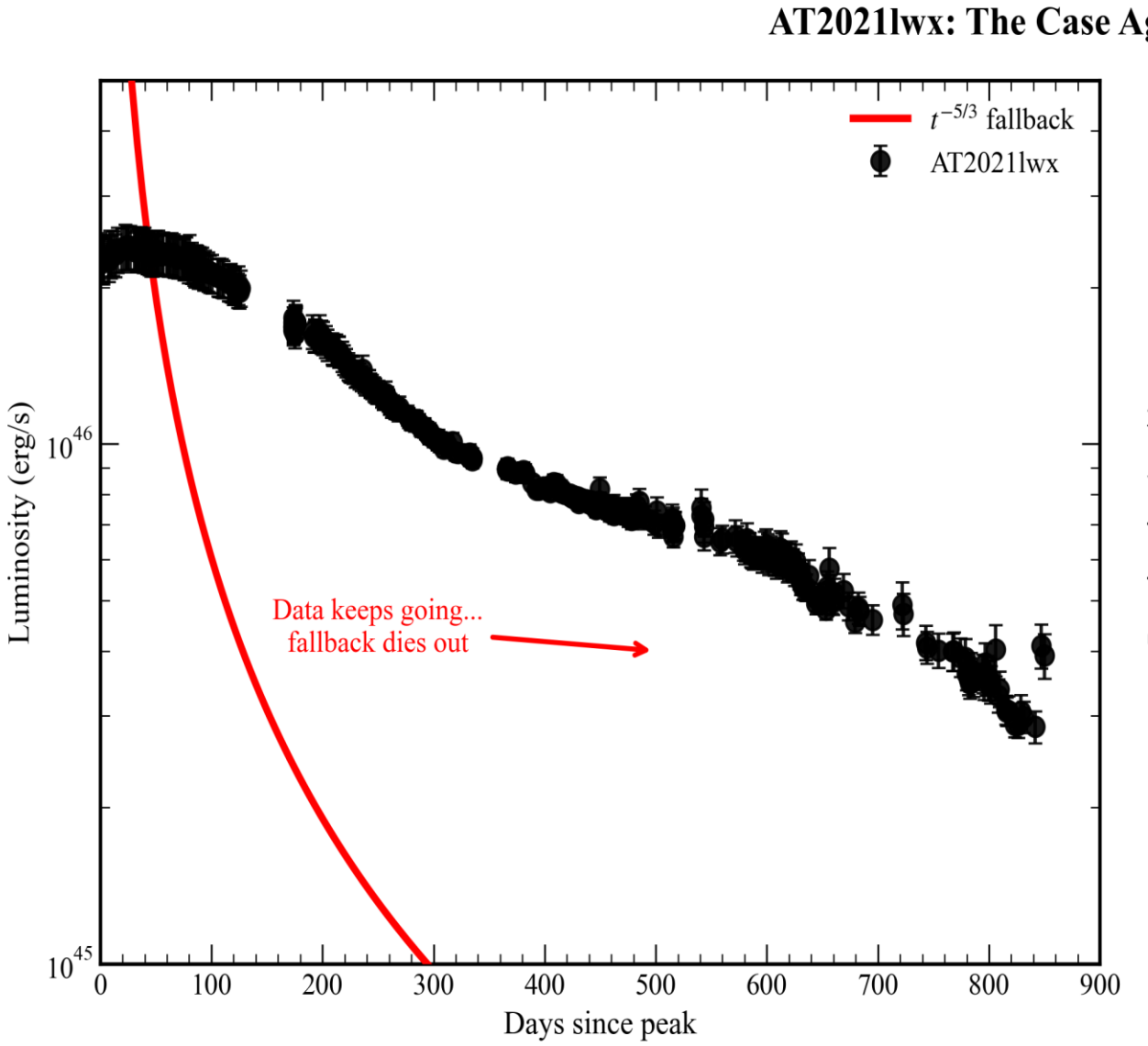




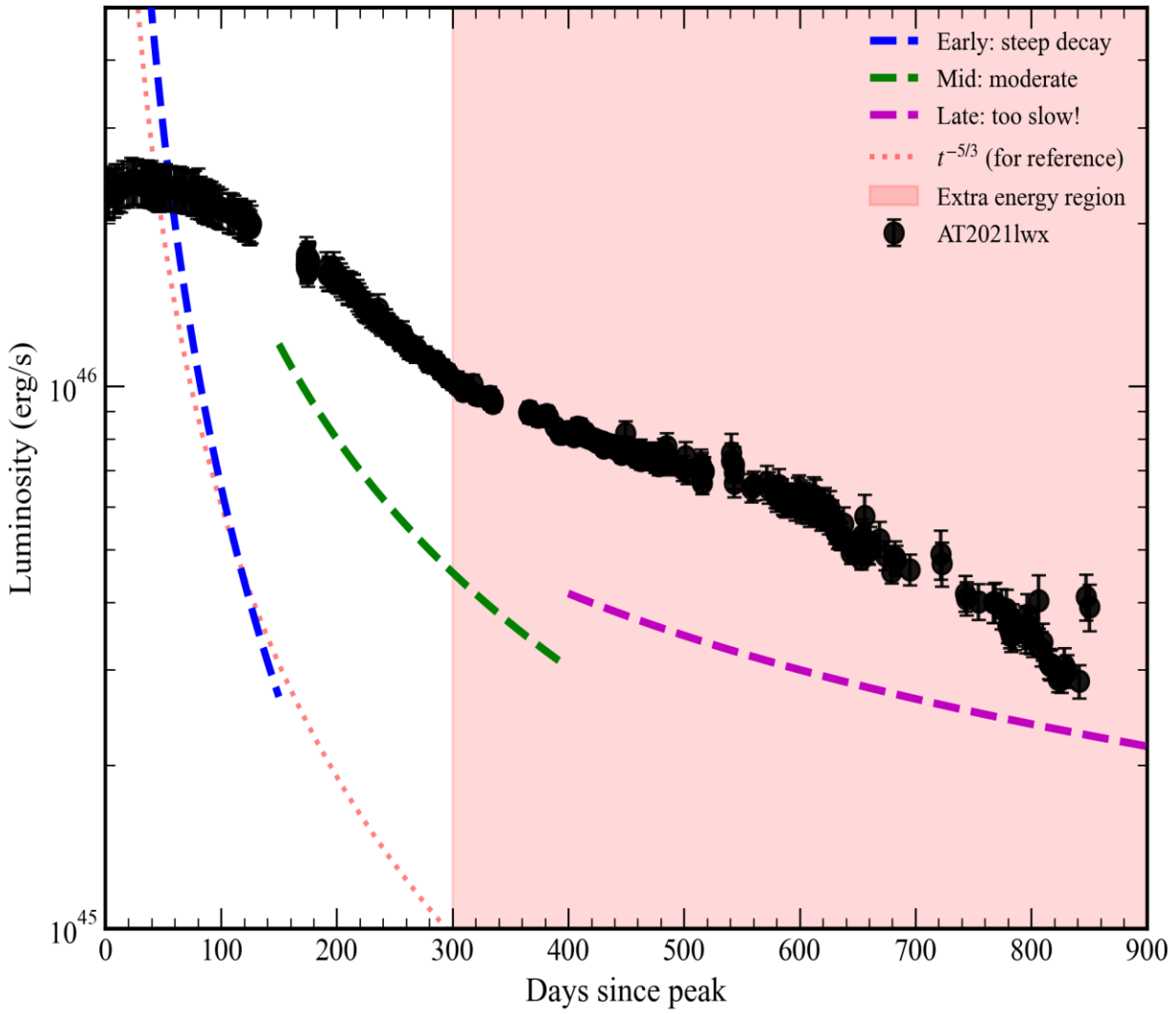




Additional powering mechanisms? Constant Energy Ingestion? CSM? Magnetar? Winds/Outflows?



Subrayan et al. 2026 (in prep)



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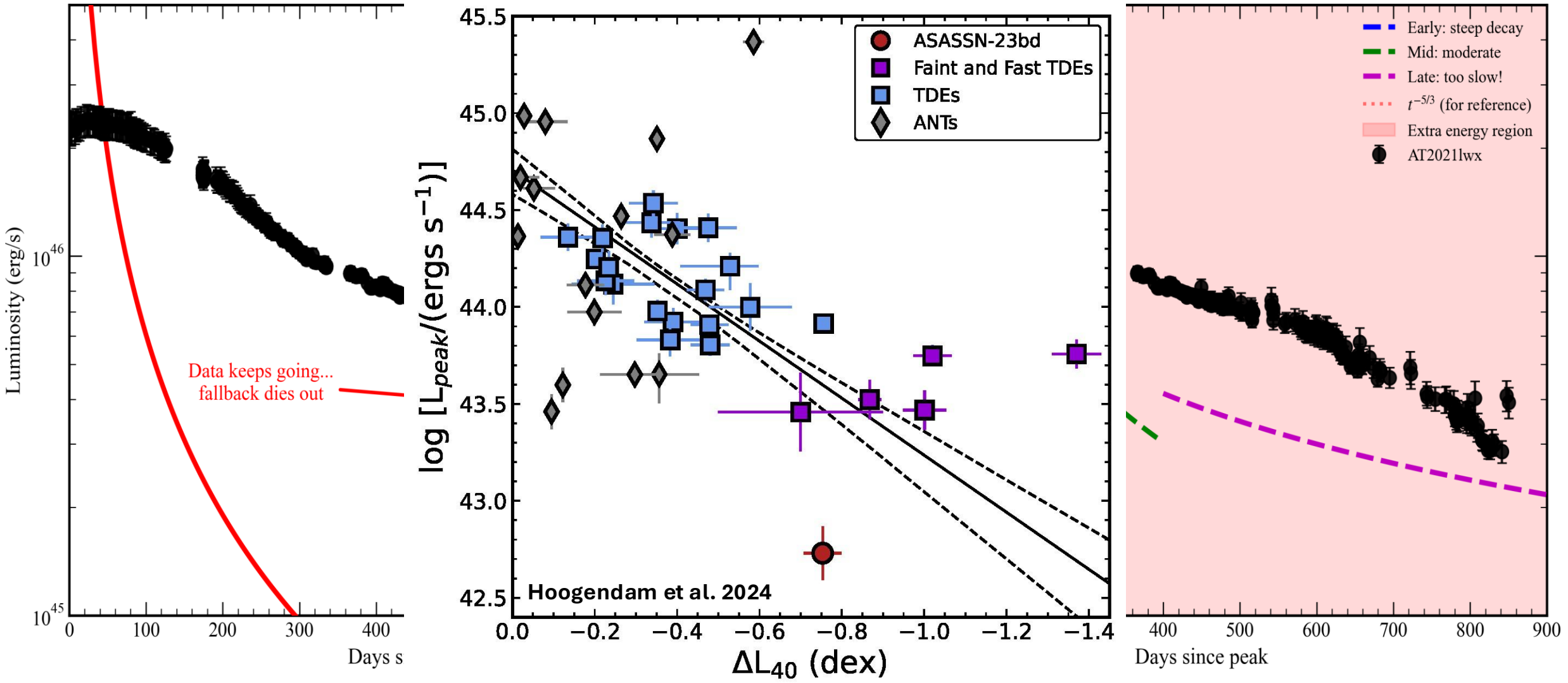
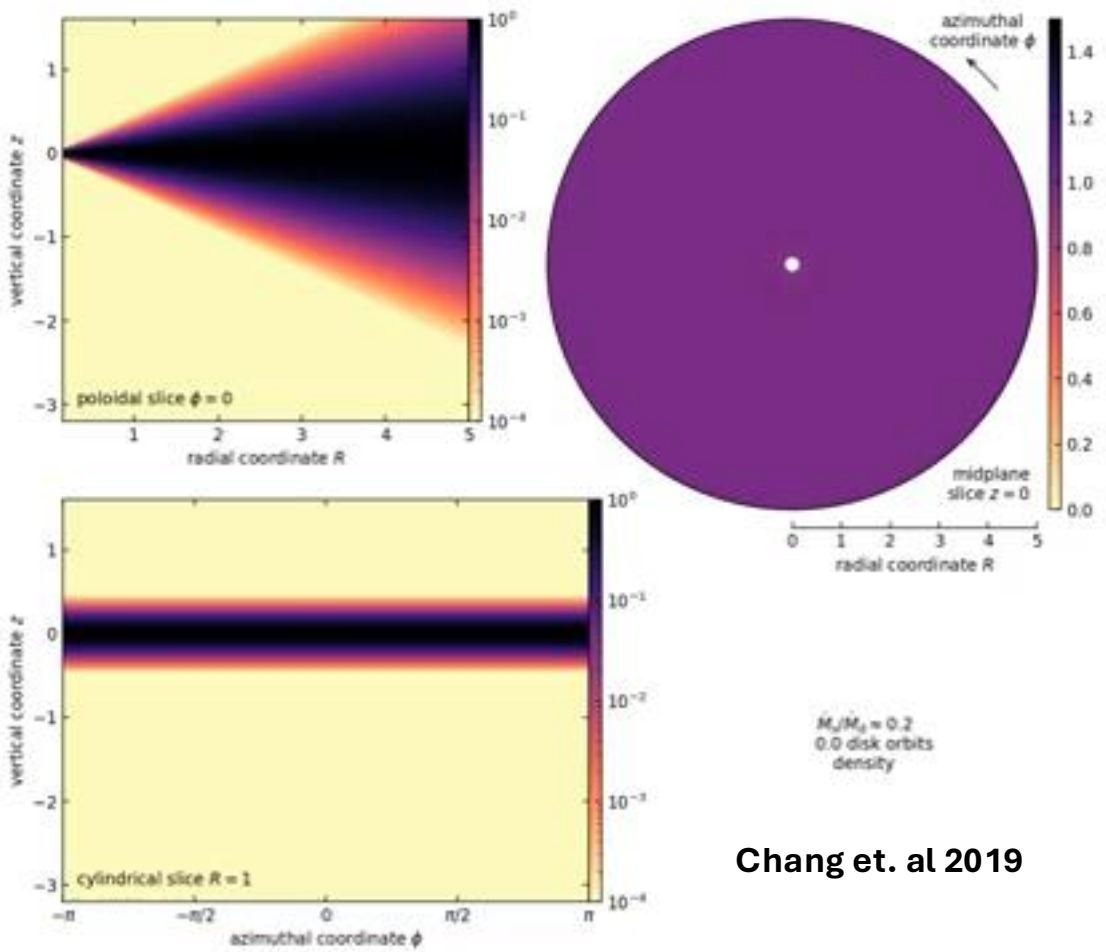
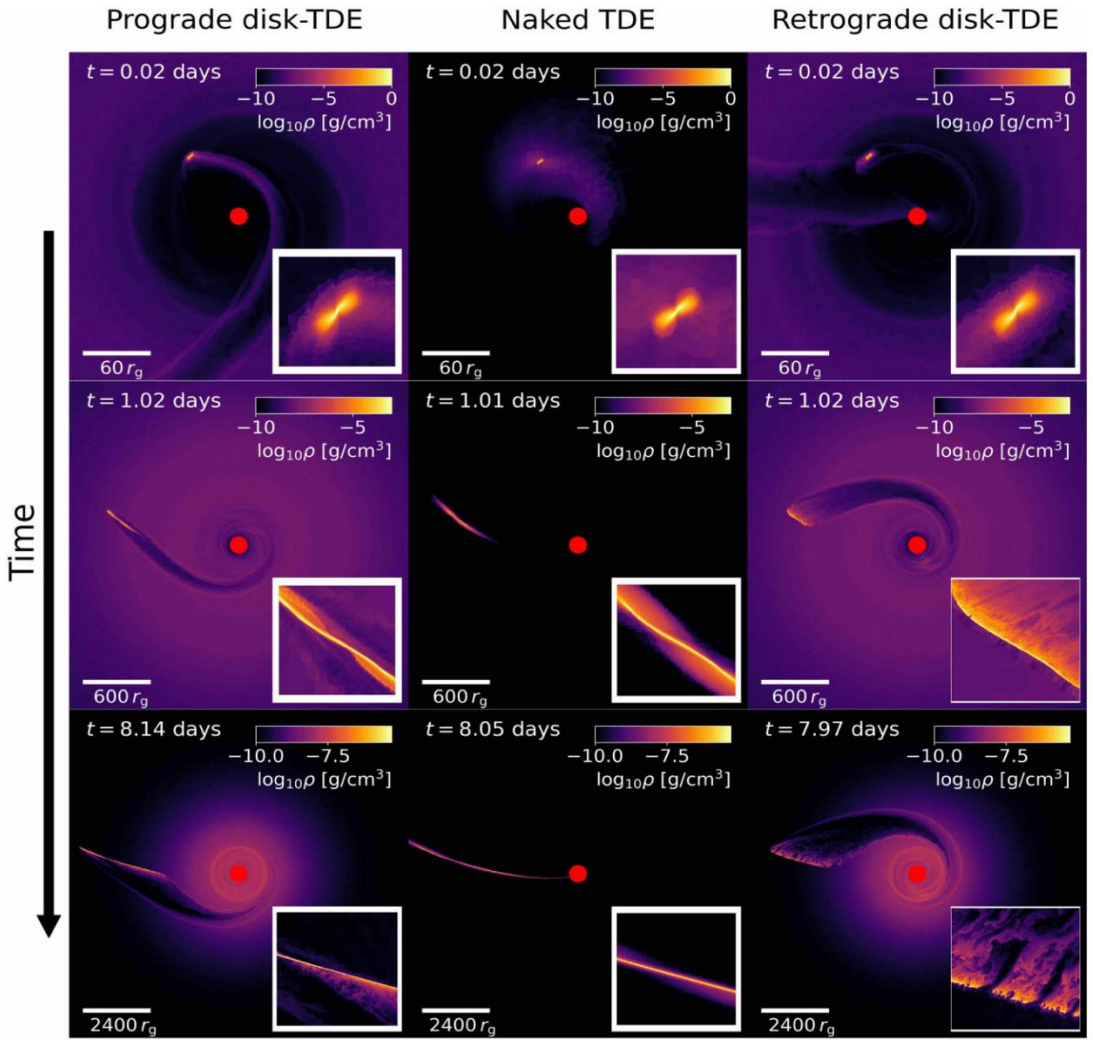


Super-massive Pop III/ Pop II stars (Cedric's Talk)? Quasi-stars? (Mitchell's Talk) TDE's in AGN (Itai's Talk)?

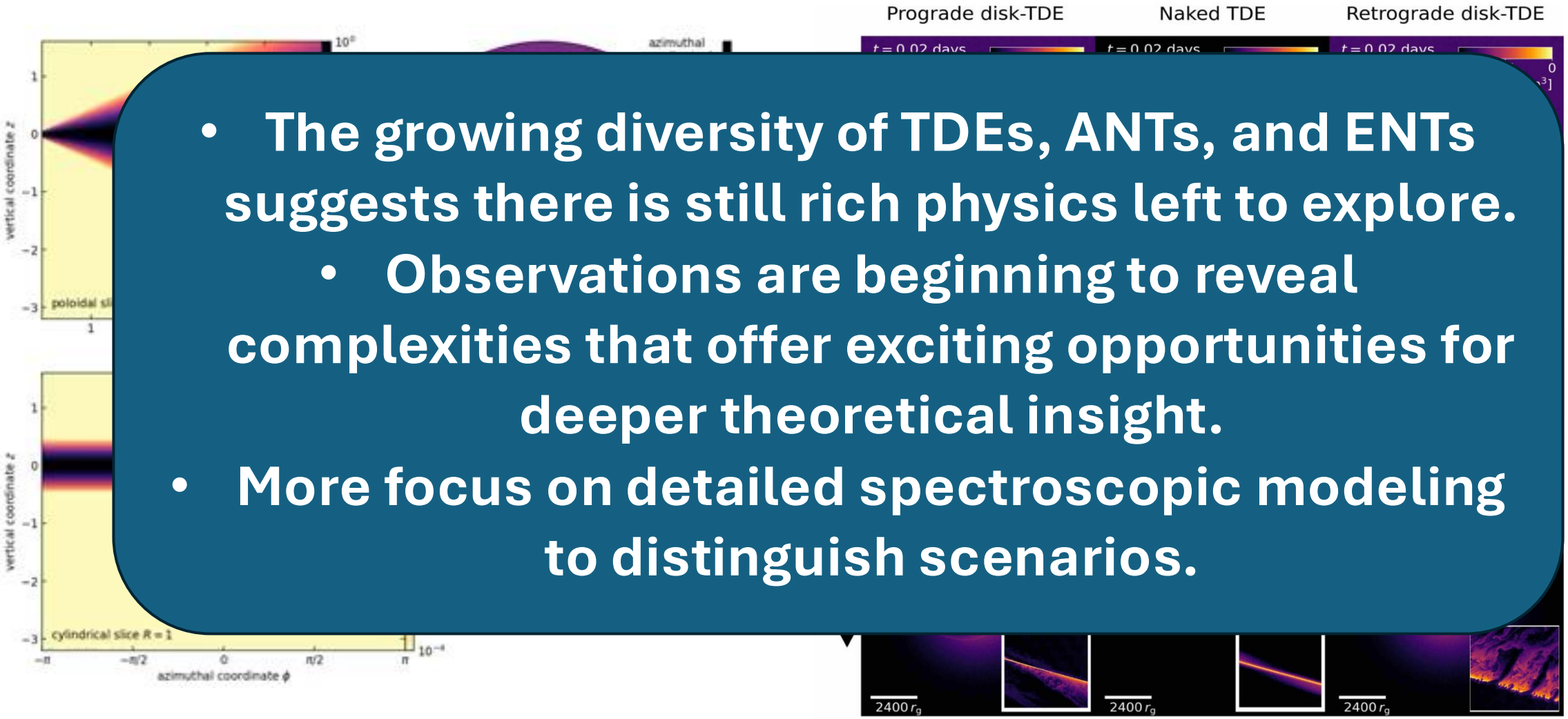


Chang et. al 2019



Ryu et al. 2024

Super-massive Pop III/ Pop II stars (Cedric's Talk)?
Quasi-stars? (Mitchell's Talk) TDE's in AGN (Itai's Talk)?



- The growing diversity of TDEs, ANTs, and ENTs suggests there is still rich physics left to explore.
- Observations are beginning to reveal complexities that offer exciting opportunities for deeper theoretical insight.
- More focus on detailed spectroscopic modeling to distinguish scenarios.

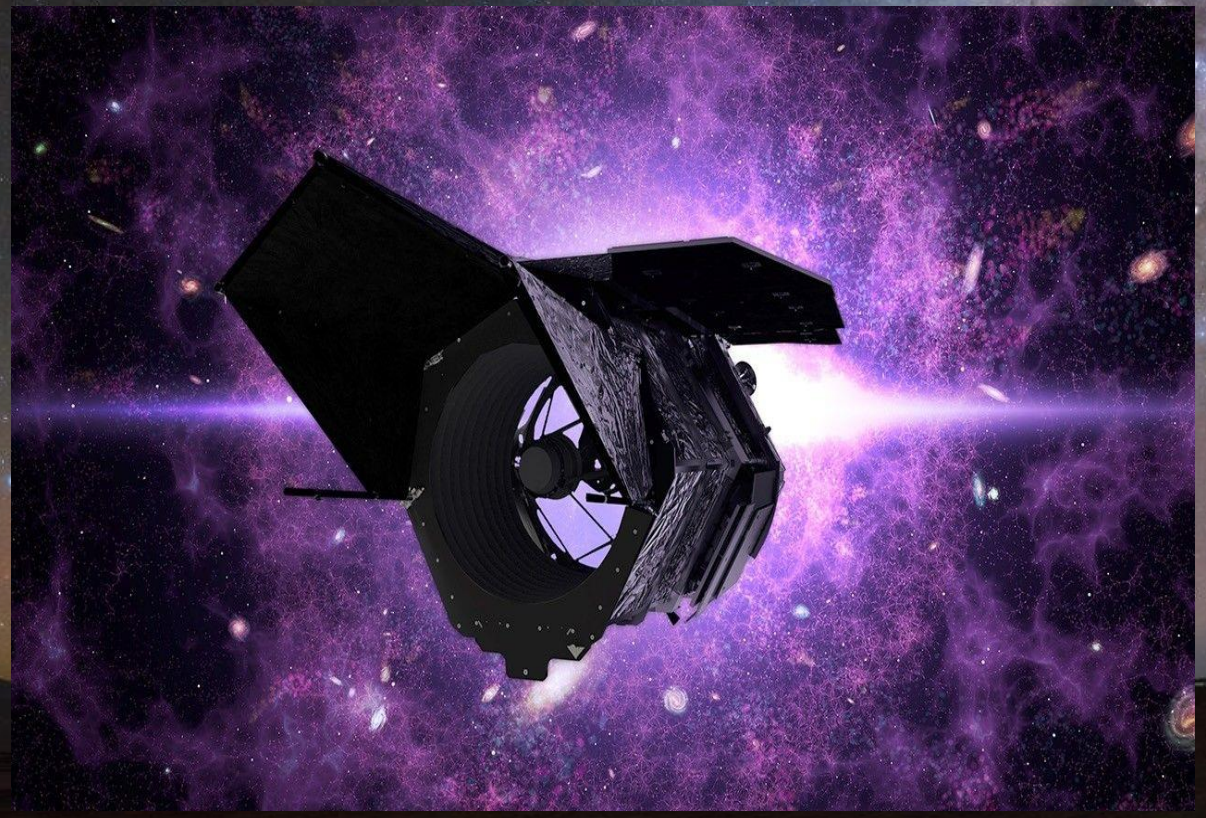
Ryu et al. 2024

ENTs are excellent laboratories to decode extreme accretion physics, understand black hole growth in action, map dormant SMBH at high redshifts and explore how nuclear activity may shape galaxy evolution.

Open Questions:

1. What powers the extreme luminosities in ENTs that can give a coherent picture that can explain the current observations?
2. Do we understand the implications ENTs could probe about galaxy assembly and co-evolution of SMBH and host galaxies at lower redshifts? Are SMBH heavy for their host galaxies?
3. Will there be delayed radio emissions from ENTs and if so, how can we model/predict their timing?

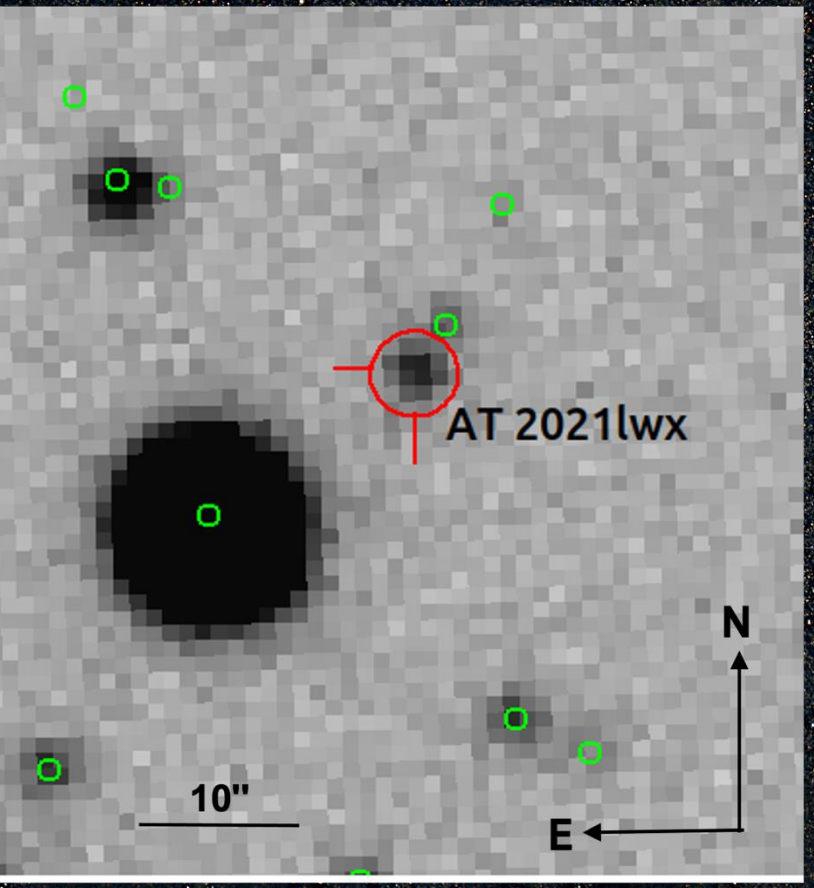
Exciting times for Time-Domain Astronomy!
We are already in the Big Data Era!
Thank you!

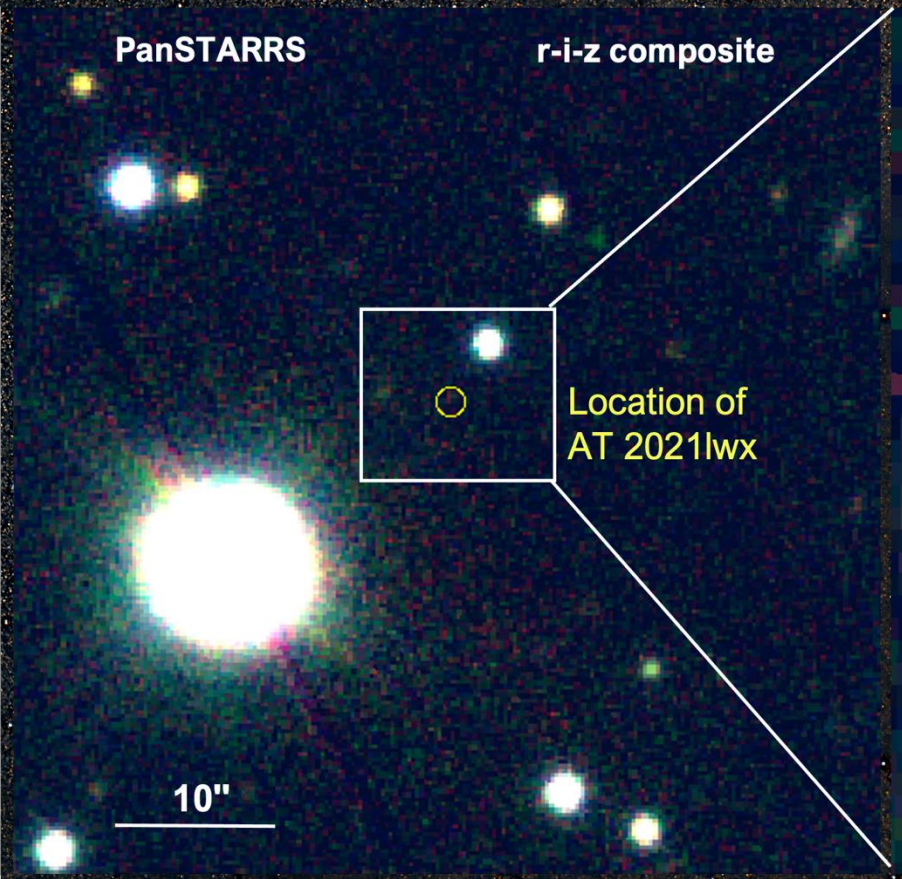


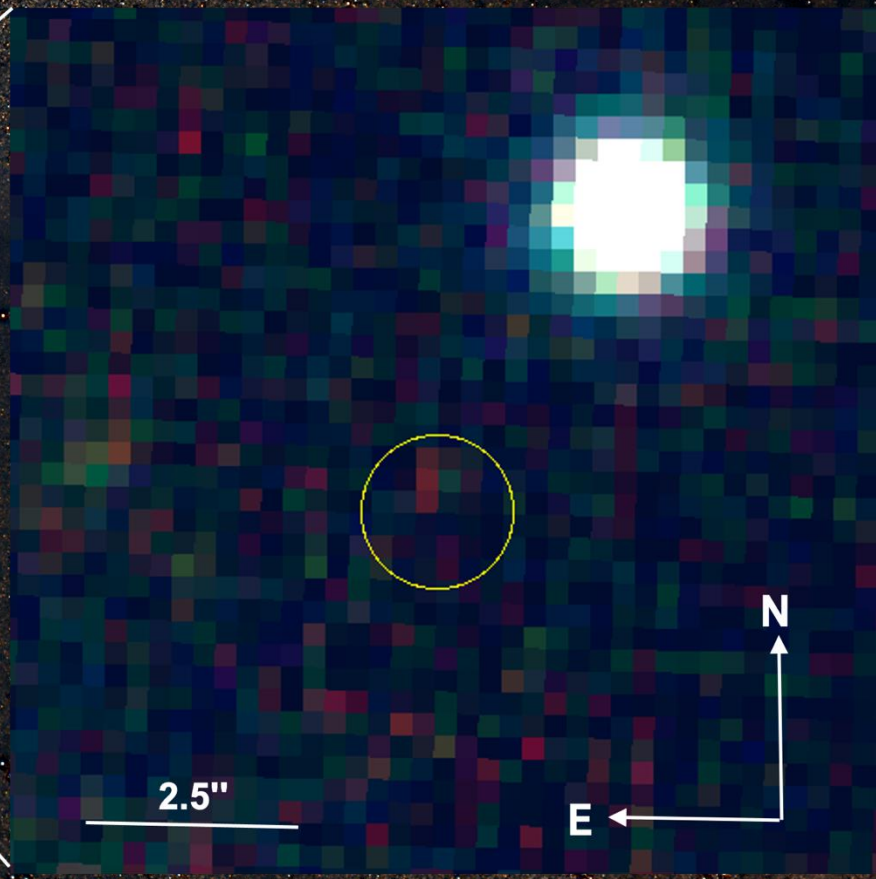
Extra Slides/ Backup Slides

Uniqueness of AT2021lwx (ZTF20abrbeie) + Future Follow Up

No host galaxy detected yet + the most luminous ANT among the sample



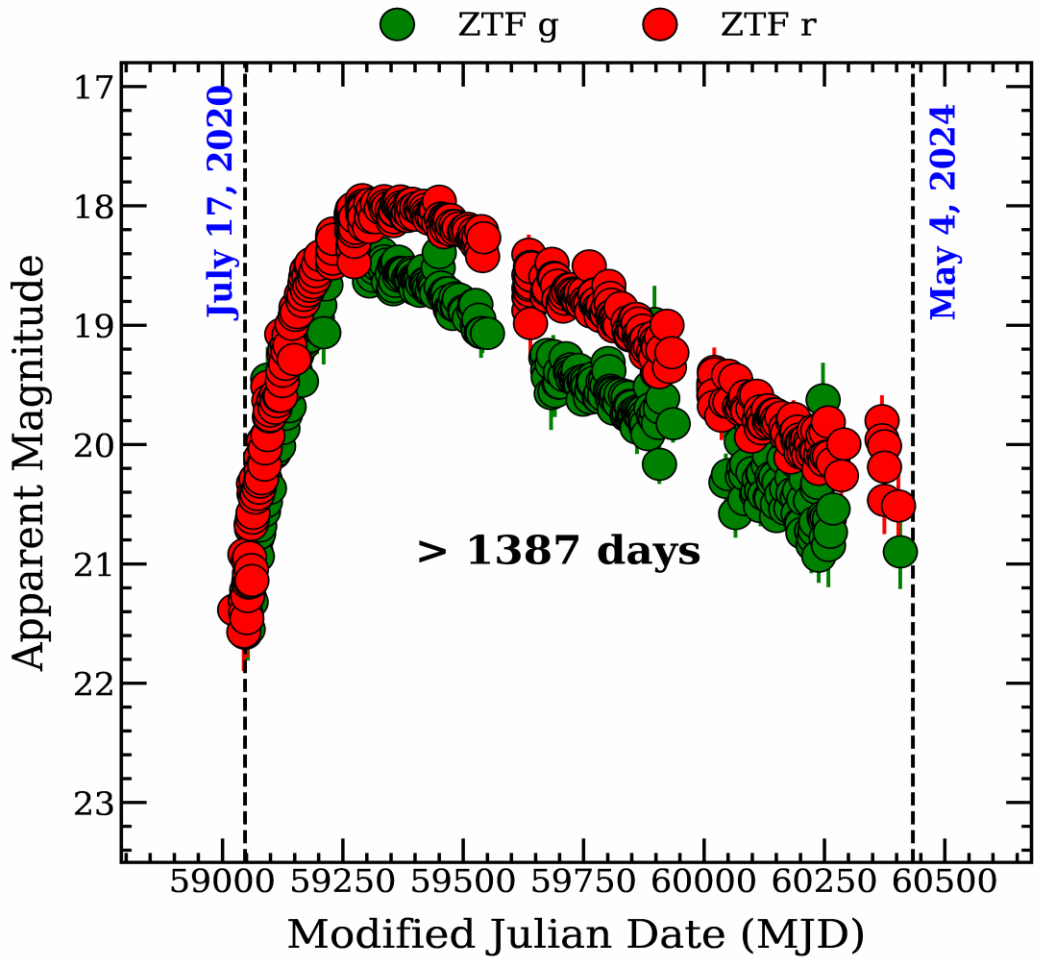


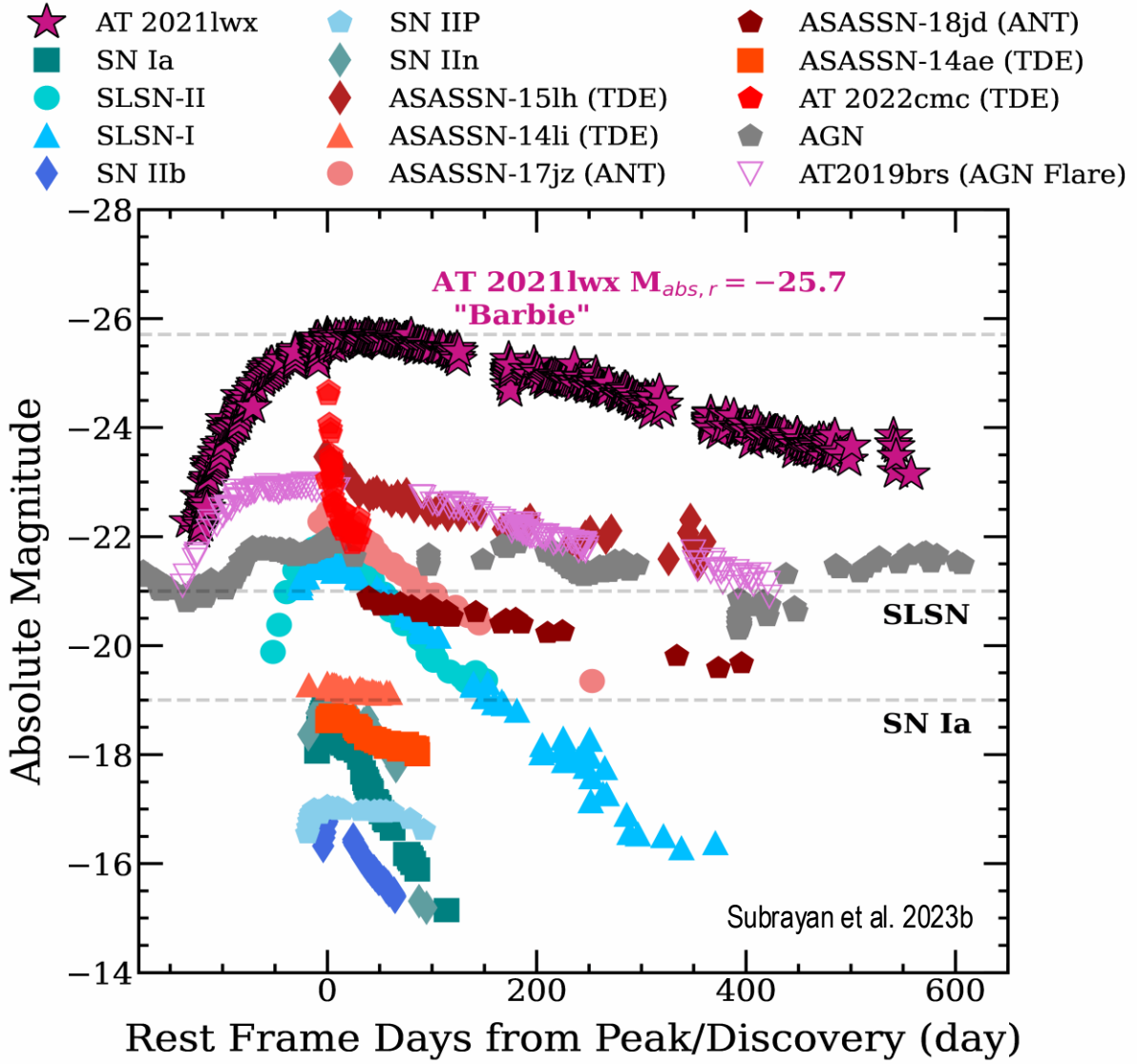


REFITT
Recommender Engine For Intelligent Transient Tracking

ANTs have luminous, extremely slowly declining long-lived smooth light curves Photometrically like TDEs

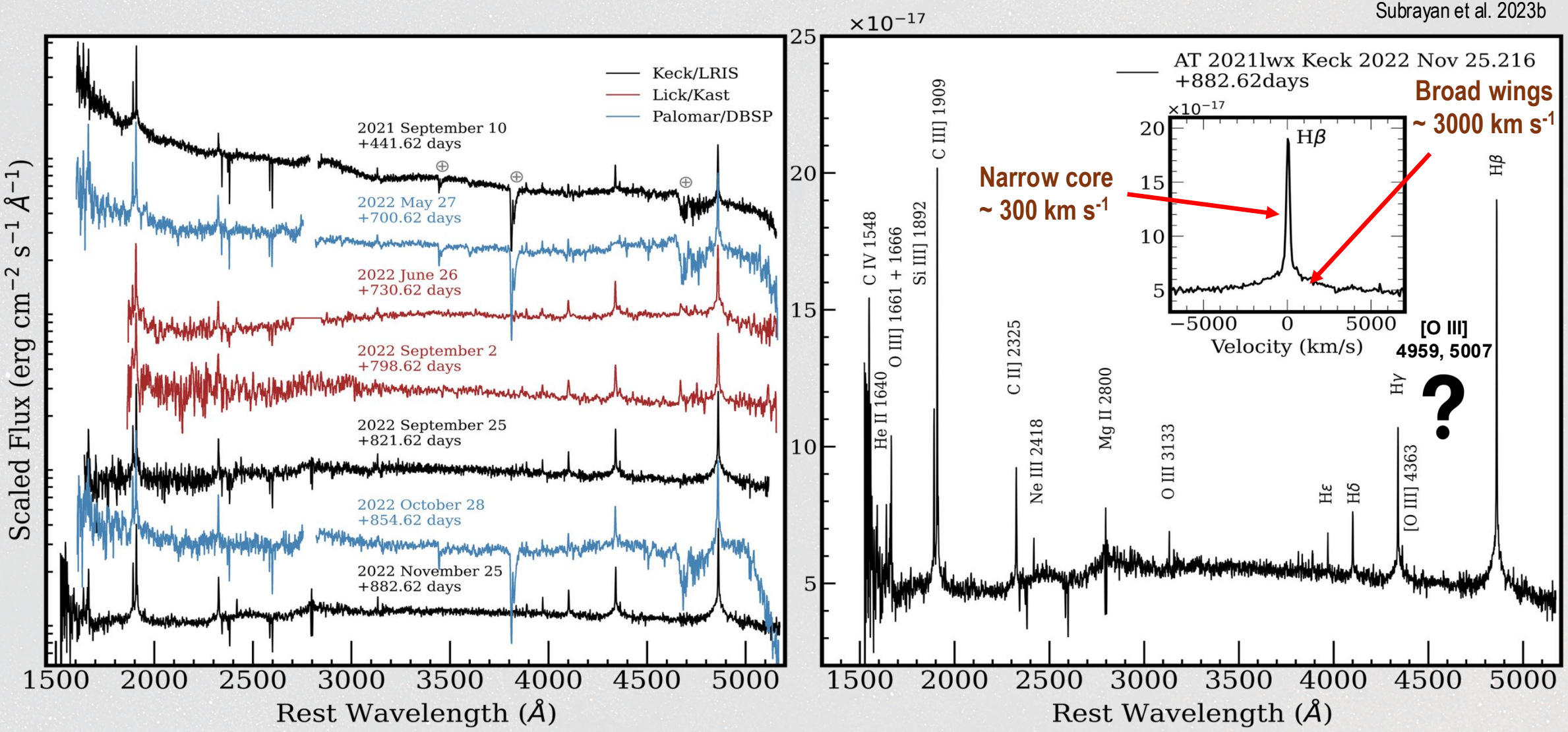
AT 2021lwx aka ZTF20abrbeie aka "Scary Barbie"
(Extreme Nuclear Transient)
log L_{peak} = 45.7 erg s^{-1} and $E_{radiated}$ > 10^{53} erg





AT2021lwx showed strong narrow cores and broad emission lines early on
Spectroscopically very much like AGNs

Subrayan et al. 2023b



Discussion on Physical Mechanisms and Rate Calculations

TDEs, CLAGNs or something else?

- Extreme instability in an existing accretion disk ?
  - ➢ Requires an already existing disk
  - ➢ Problem: Dynamical timescales of classical accretion disk much longer (>70 years) than rise times of ANTs (~month)

- TDE in an accretion disk ?
  - ➢ Predictions of these are sparse and many possible outcomes. Need to explore!

- TDE of a massive star?
  - ➢ Disruptions of intermediate mass or massive stars > $5M_{\odot}$. Current theoretical models do not handle this, mostly geared towards canonical TDE's ~ 1 $M_{\odot}$.

- TDE of GMC?
  - ➢ Arguments for the size ~ pc scale GMC to match with the timescales of ANTs

Volumetric Rate Calculations

ANT Rate: $\gtrsim 3\times10^{-11}$ Mpc^{-1} yr^{-1}

- Considering 6 ANTs in the photometric sample, sky area of the public survey to be 15,000 deg^2 and 4.7 yr for survey baseline.

Massive Star TDE Rate:

- $\sim 10^{-13}$ Mpc^{-1} yr^{-1} from > 10 $M_{\odot}$ (based on IMF arguments and lifetimes of massive stars)
- $\gtrsim 3\times10^{-11}$ Mpc^{-1} yr^{-1} is more consistent with 0.1 – 10 $M_{\odot}$

Powering Mechanisms? Disruptions from very massive stars/ gas clouds? Super-massive stars (Cedric's Talk)? Quasi-stars? (Mitchell's Talk) TDE's in AGN?