

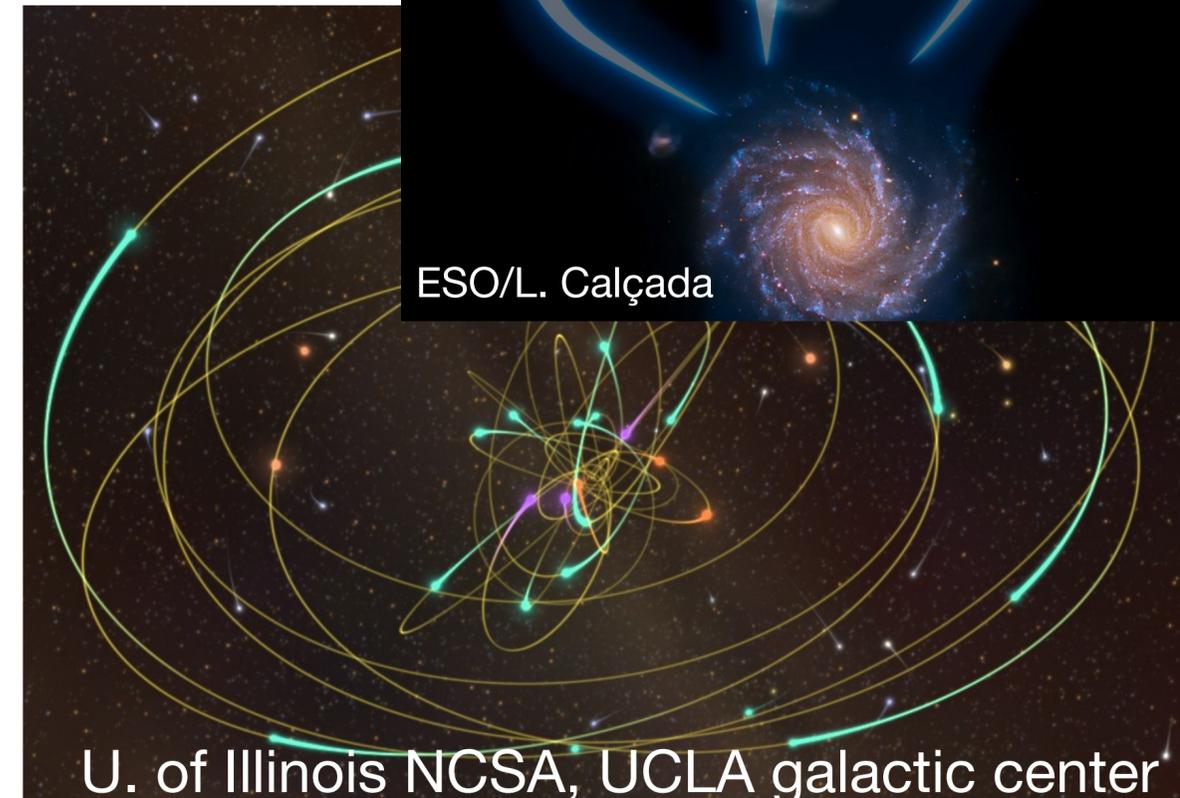
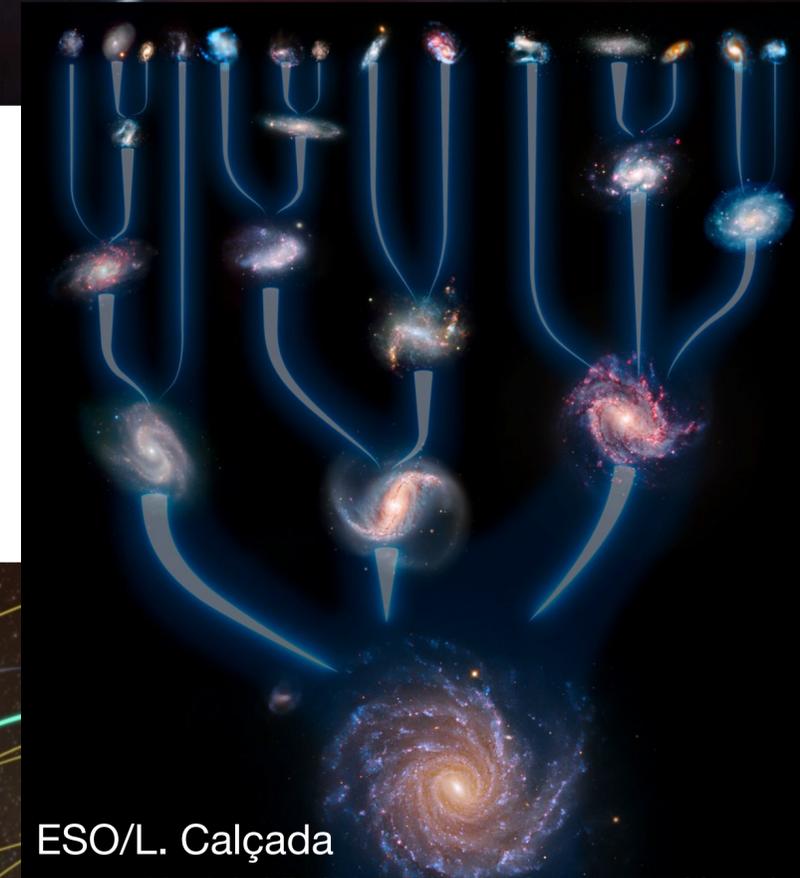
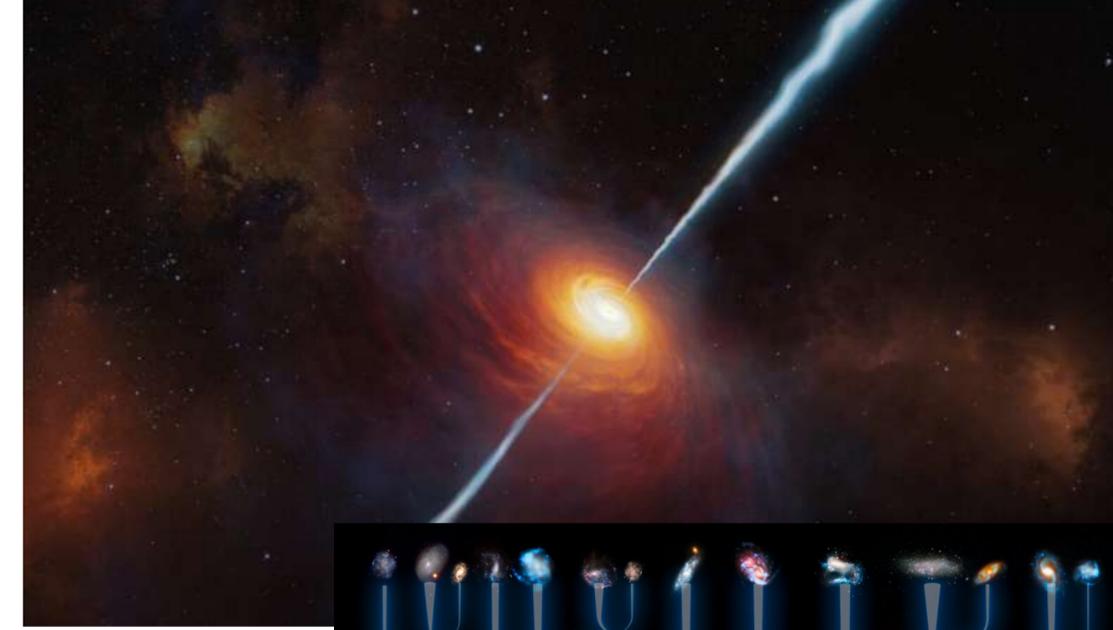
Tidal Disruption Events



Observing Timeline Presented by:
Brenna Mockler (Carnegie Observatories & UC Davis)
&
Erica Hammerstein (UC Berkeley)

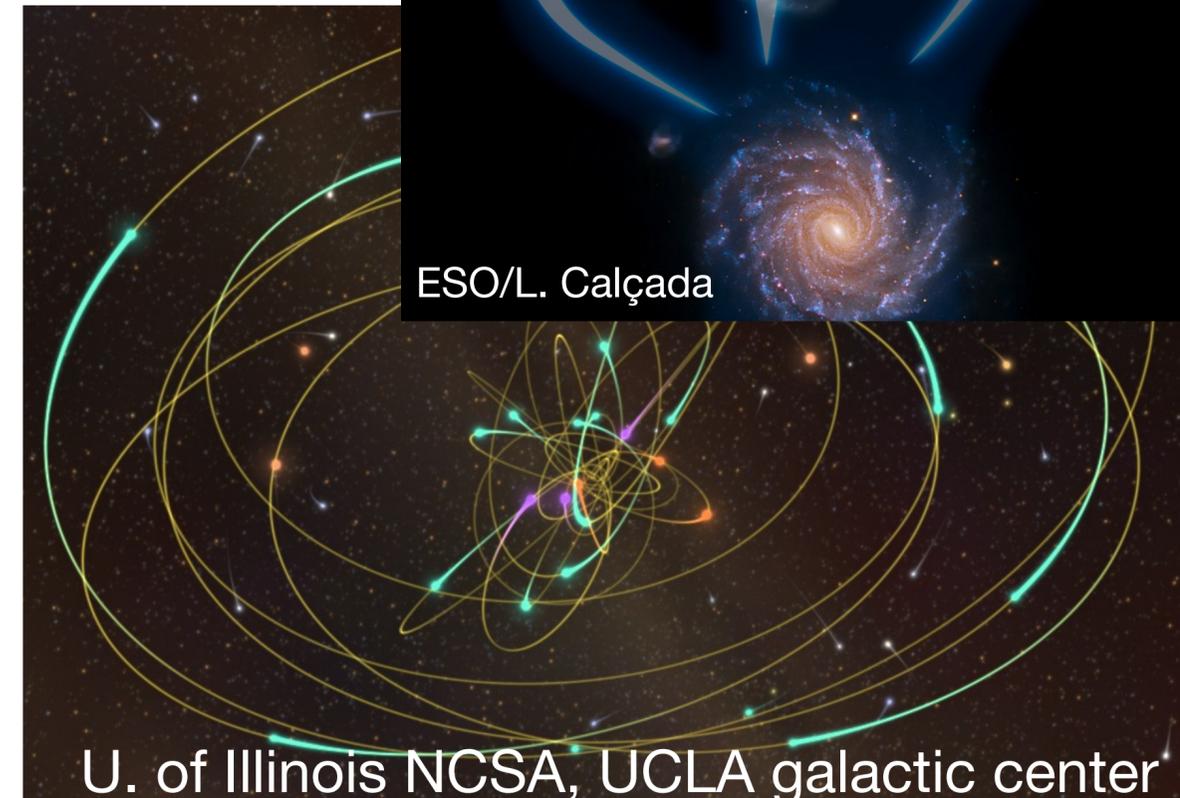
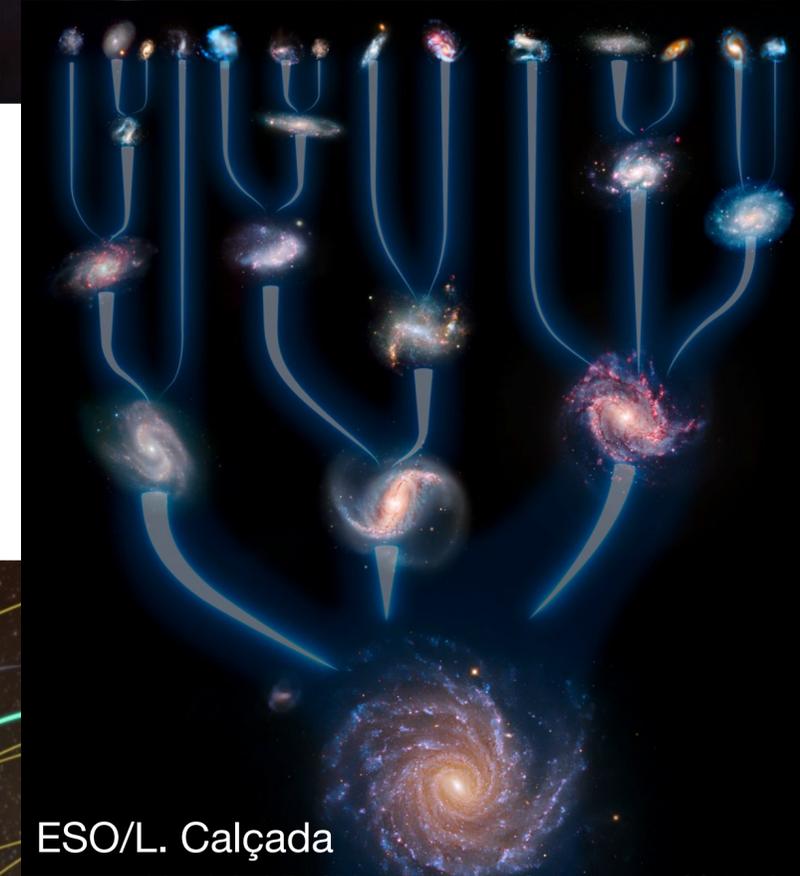
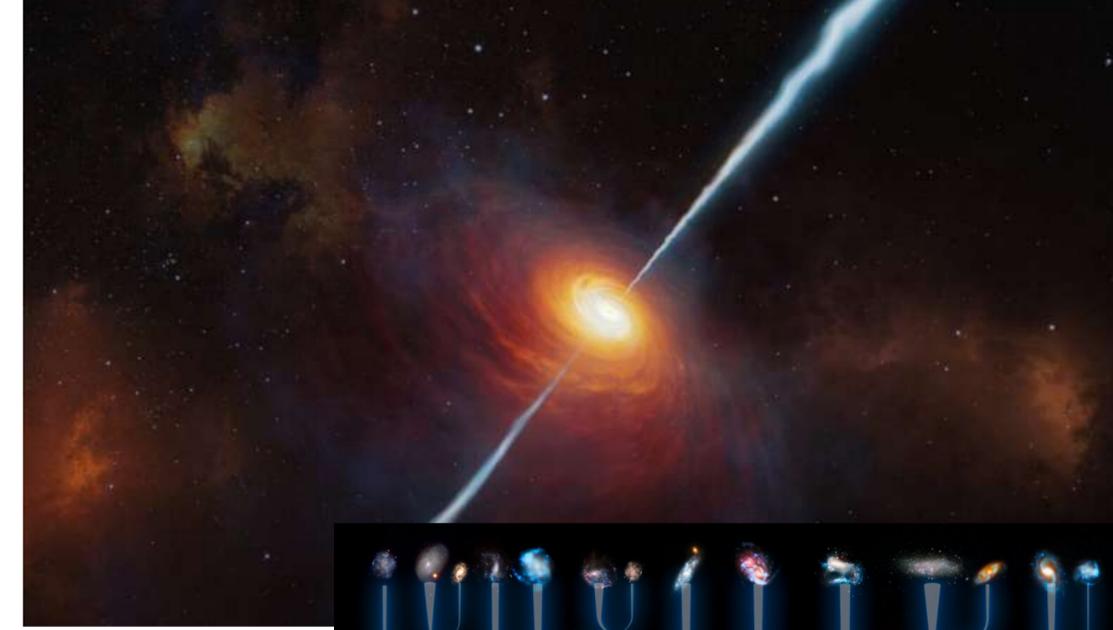
Motivation

- **Uncovering properties of quiescent MBHs**
- **Understanding MBH accretion across different scales**
- **Understanding MBH – host galaxy connection**
- **Constraining populations and dynamics of stars/compact objects in galactic nuclei**



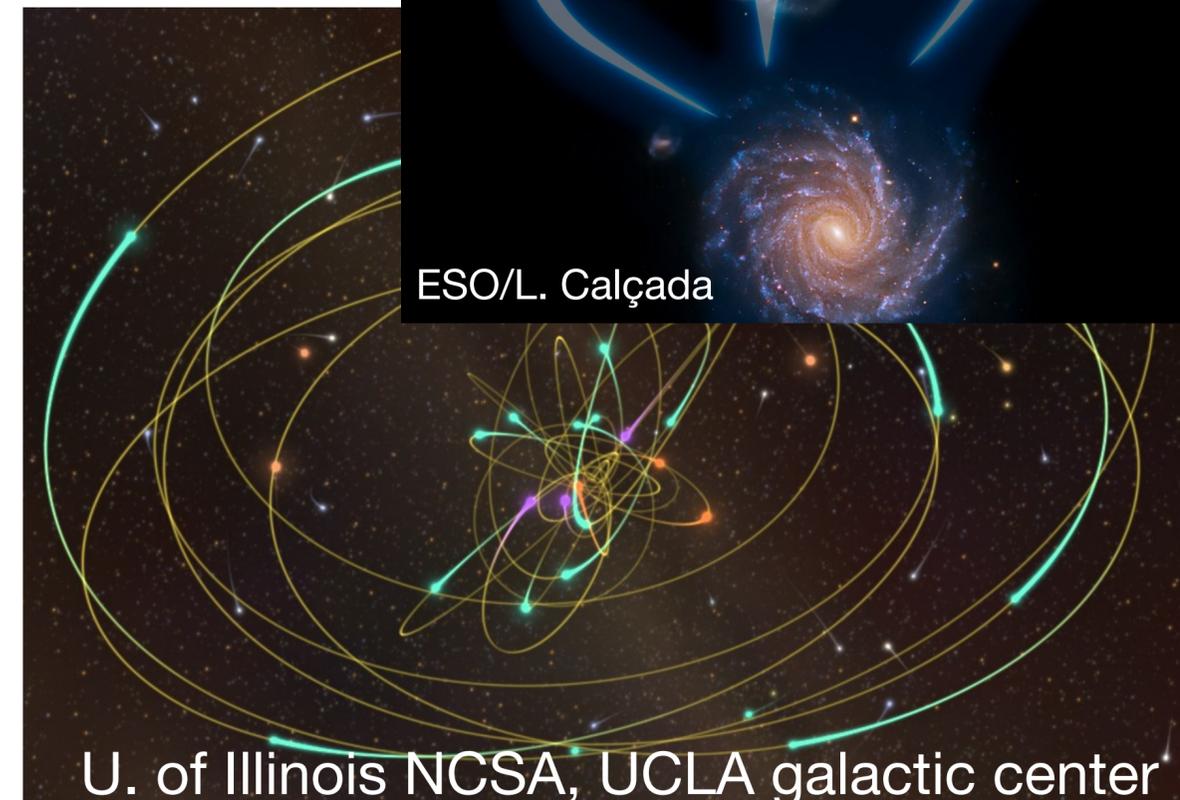
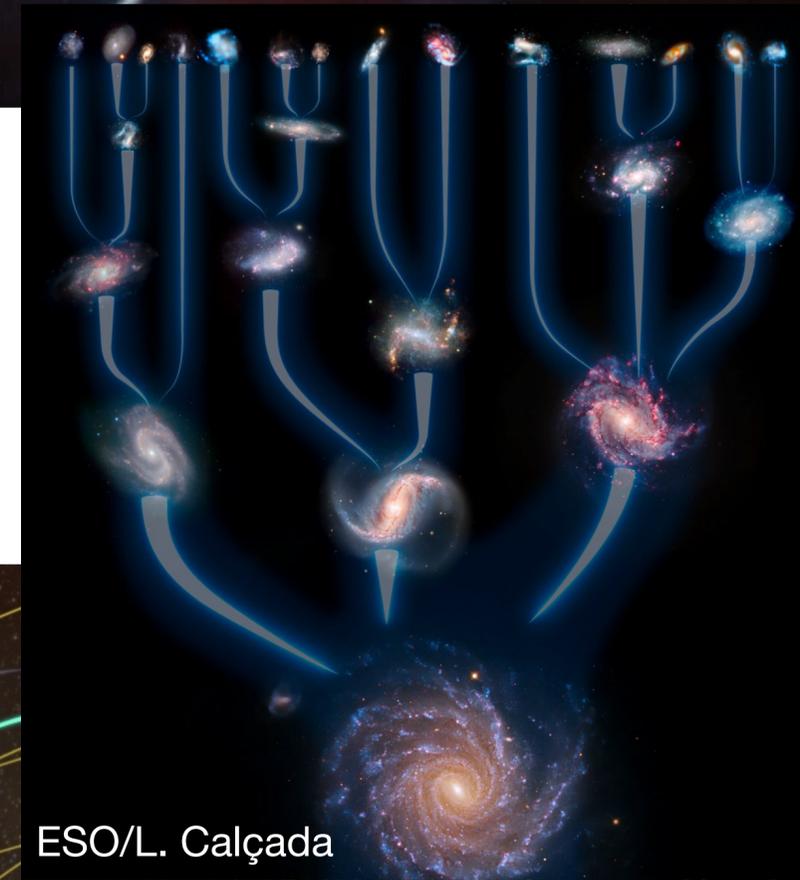
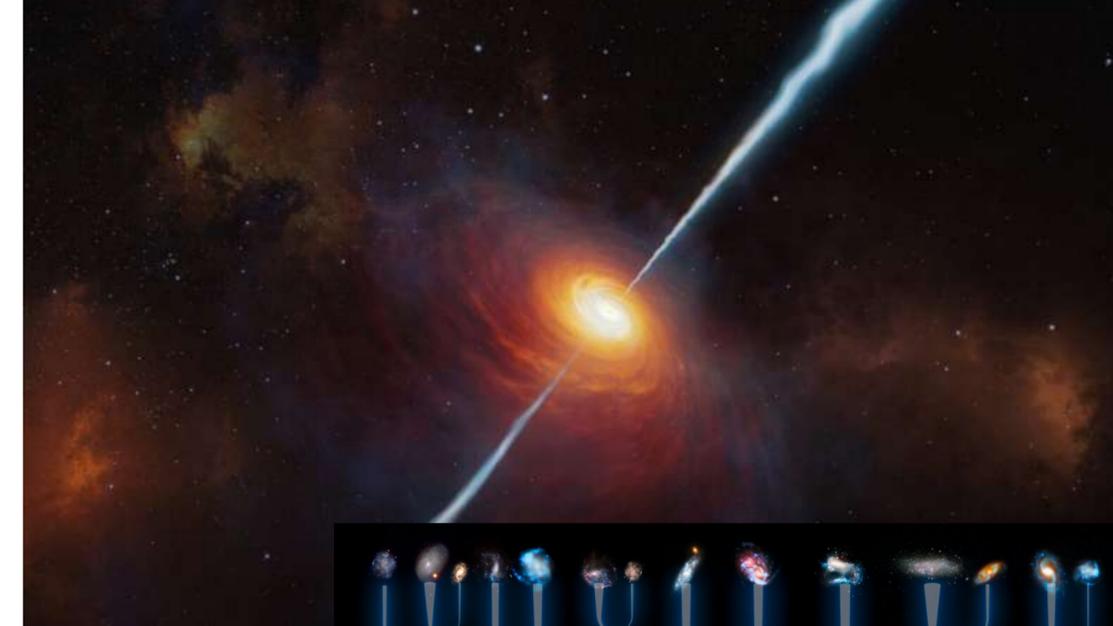
Motivation / Open Questions

- **Uncovering properties of quiescent MBHs**
 - How can we use TDE light curves and spectra to constrain **BH mass function**? As a fn of redshift/**over cosmic time**?
 - To constrain **BH spin**?
- **Understanding MBH accretion across different scales**
- **Understanding MBH – host galaxy connection**
- **Constraining populations and dynamics of stars/compact objects in galactic nuclei**



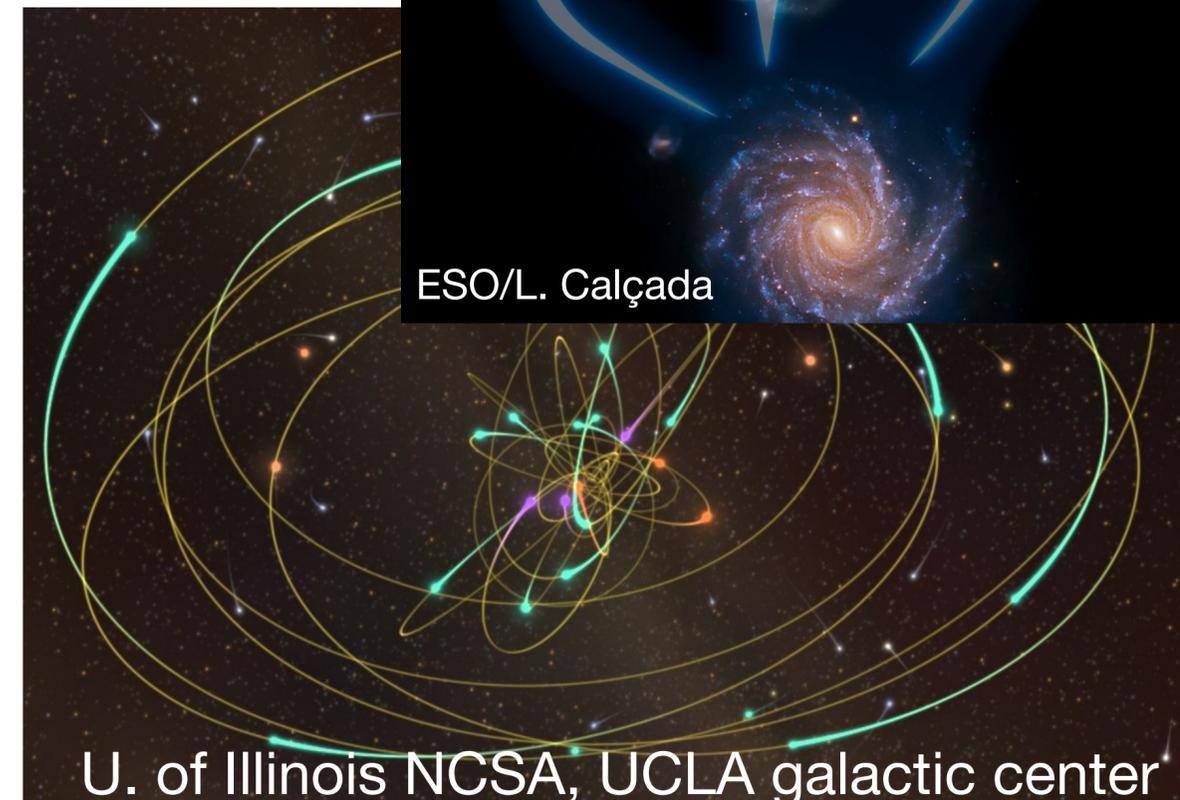
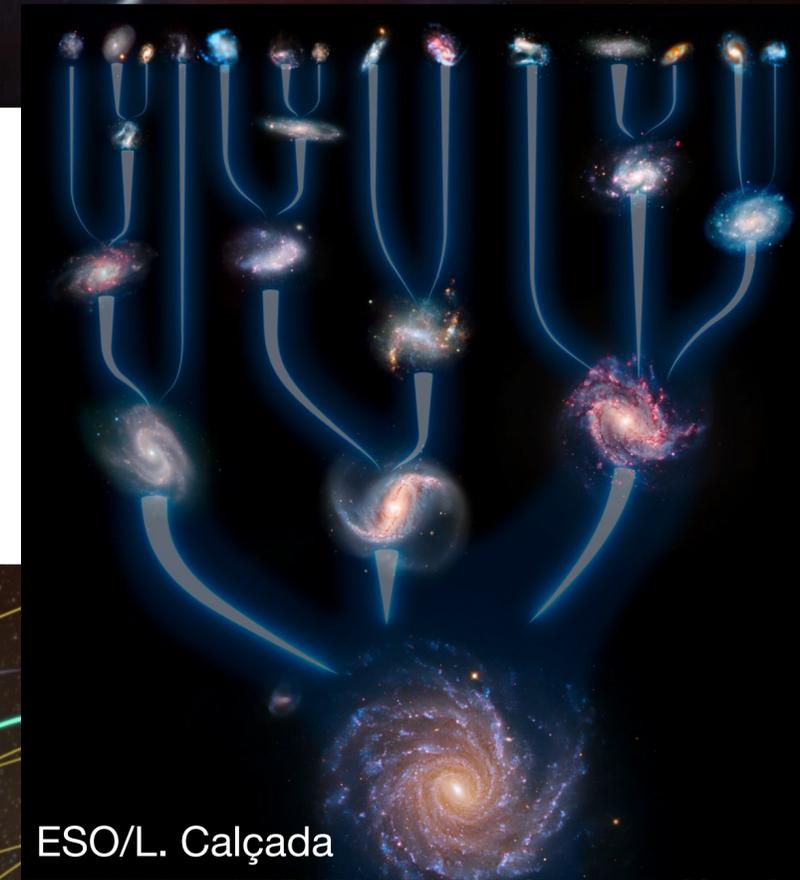
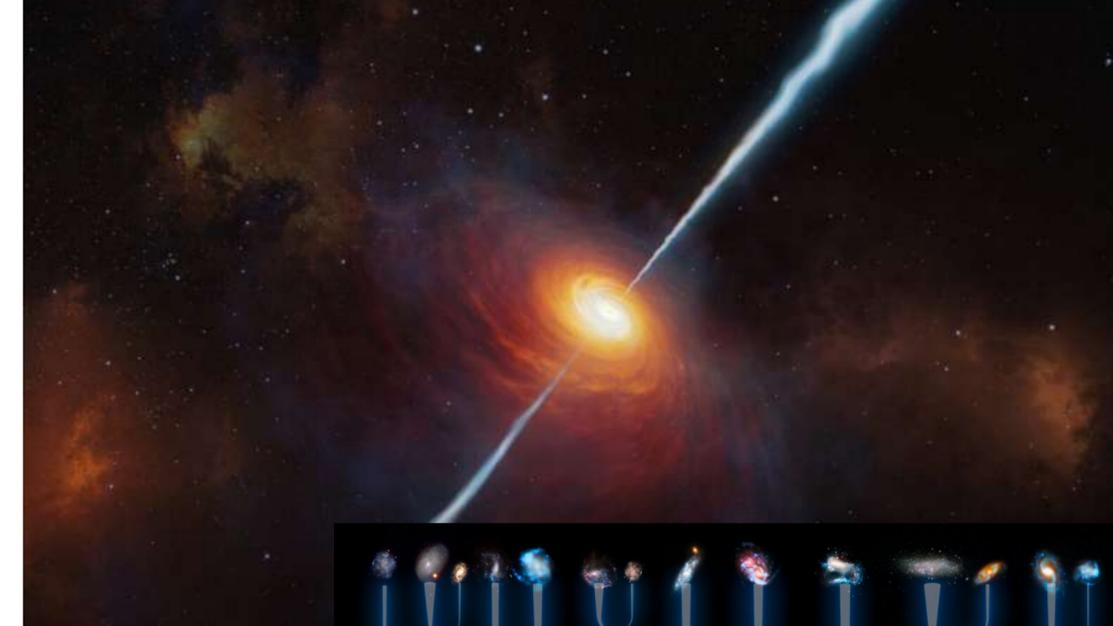
Motivation / Open Questions

- **Uncovering properties of quiescent MBHs**
 - How can we use TDE light curves and spectra to constrain **BH mass function**? As a fn of redshift/**over cosmic time**?
 - To constrain **BH spin**?
- **Understanding MBH accretion across different scales**
 - What is the timescale of disk formation?
 - How efficient is **super-Eddington** accretion?
 - When do **accretion state transitions** happen?
 - When do **outflows/jets** appear? How ubiquitous are they?
- **Understanding MBH – host galaxy connection**
- **Constraining populations and dynamics of stars/compact objects in galactic nuclei**



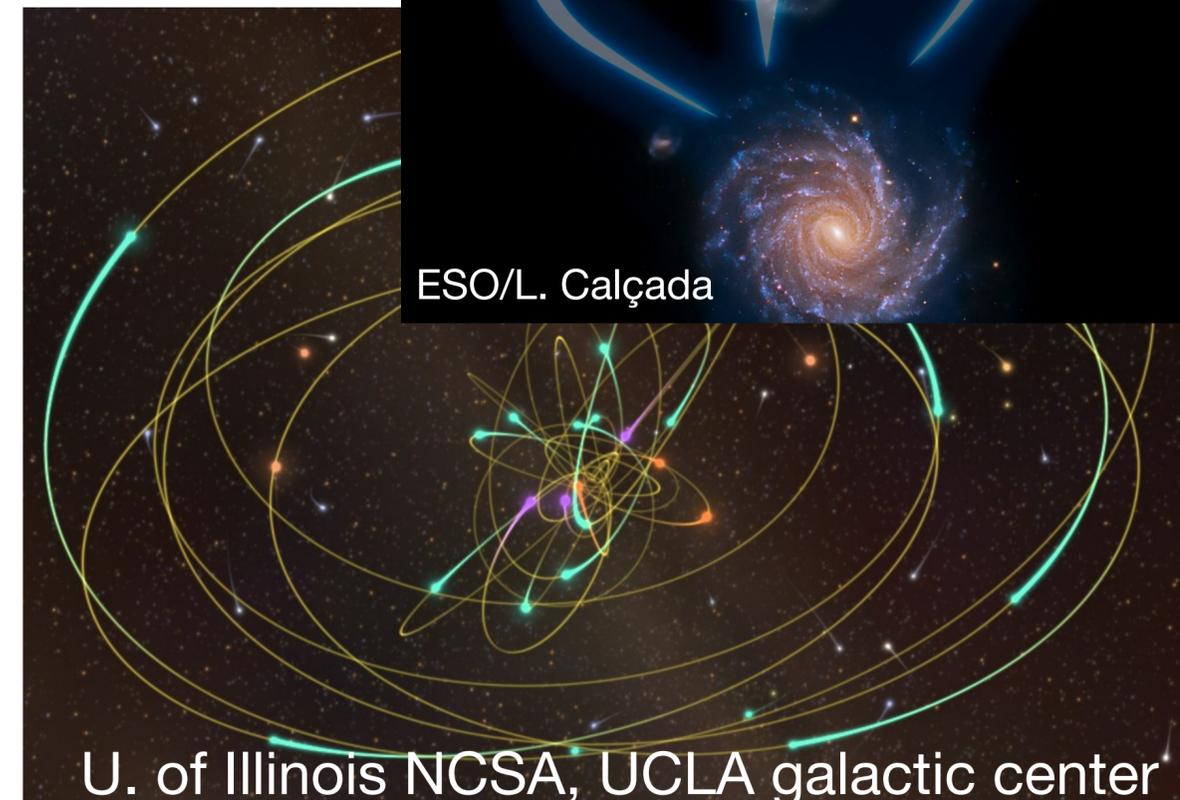
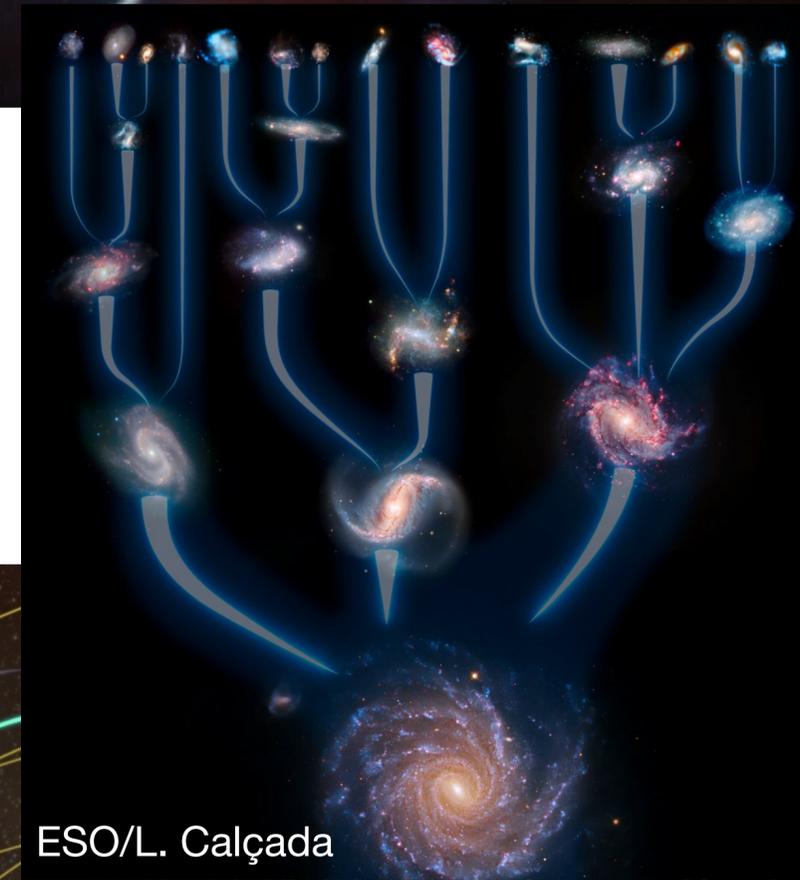
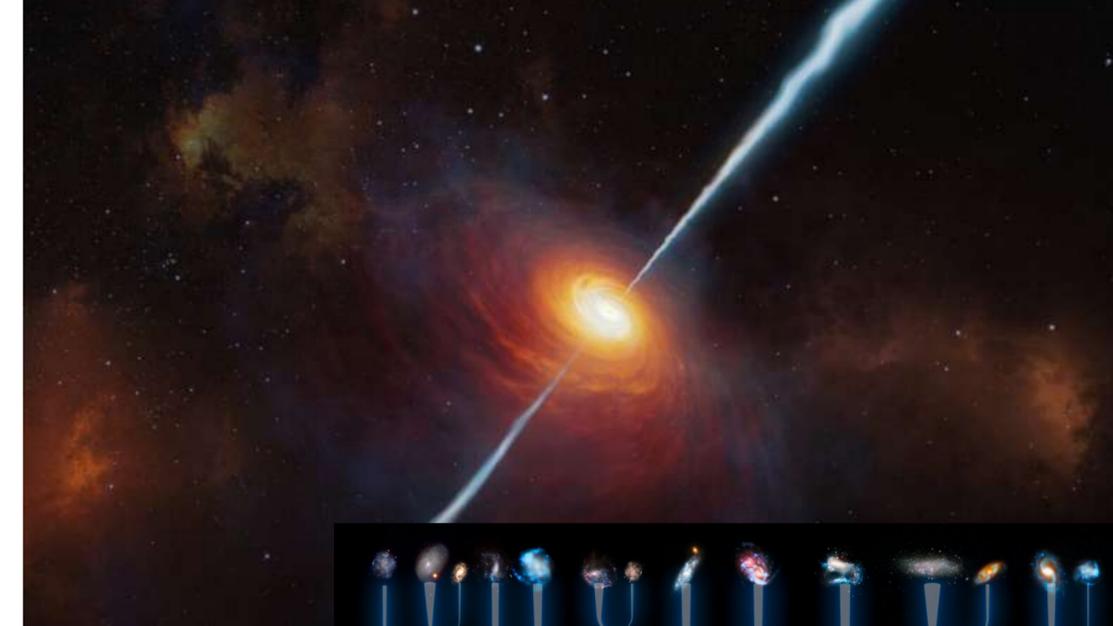
Motivation / Open Questions

- **Uncovering properties of quiescent MBHs**
 - How can we use TDE light curves and spectra to constrain **BH mass function**? As a fn of redshift/**over cosmic time**?
 - To constrain **BH spin**?
- **Understanding MBH accretion across different scales**
 - What is the timescale of disk formation?
 - How efficient is **super-Eddington** accretion?
 - When do **accretion state transitions** happen?
 - When do **outflows/jets** appear? How ubiquitous are they?
- **Understanding MBH – host galaxy connection**
 - How are TDE rates determined by **host galaxy evolution**?
 - What are the properties of TDE hosts?
- **Constraining populations and dynamics of stars/compact objects in galactic nuclei**



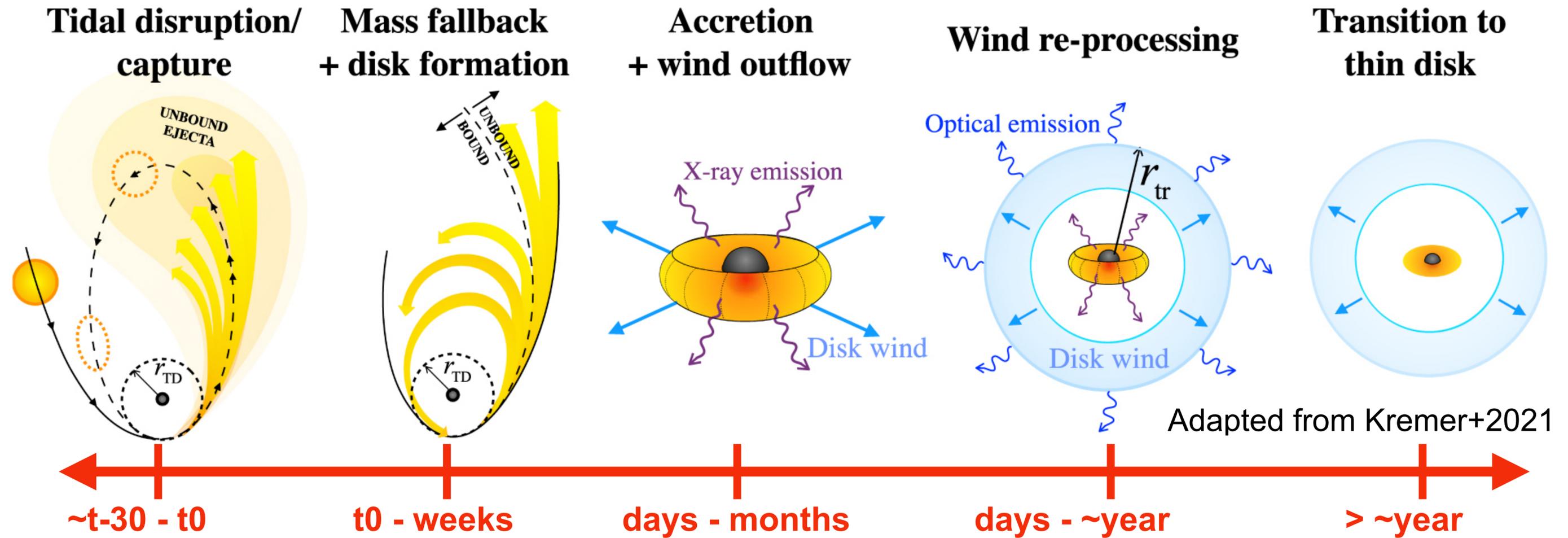
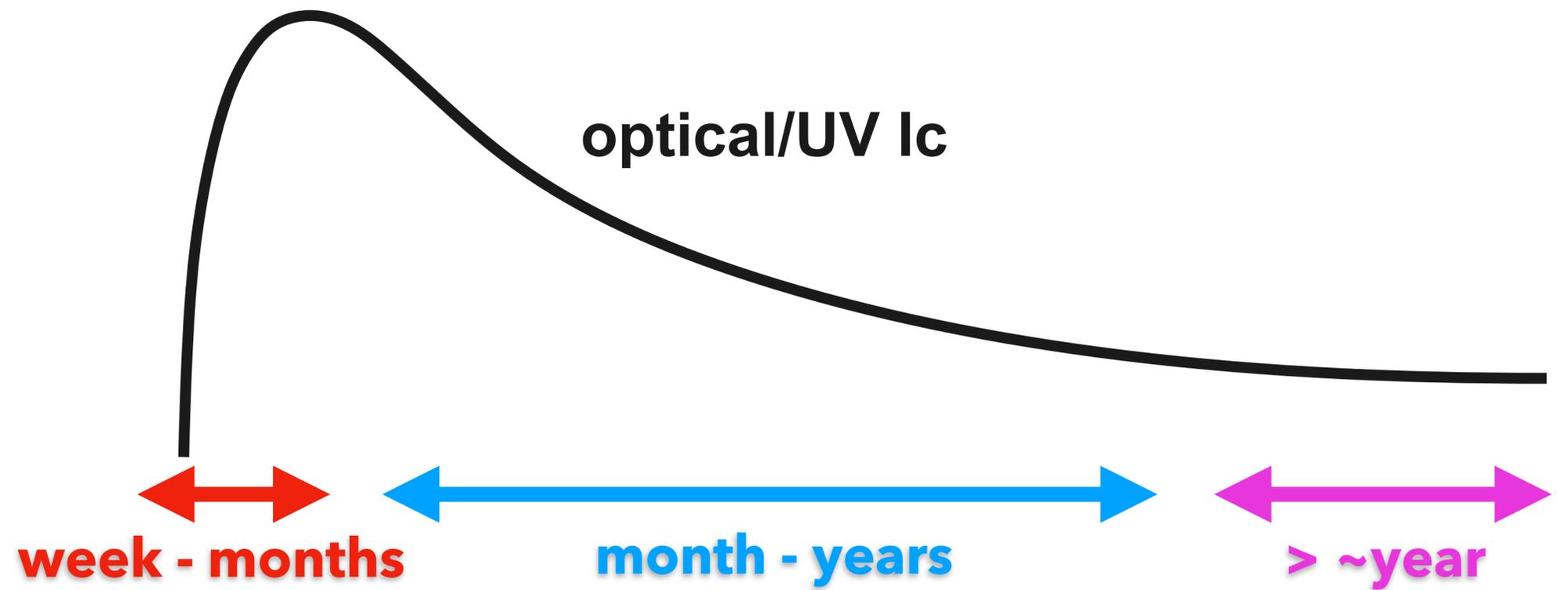
Motivation / Open Questions

- **Uncovering properties of quiescent MBHs**
 - How can we use TDE light curves and spectra to constrain **BH mass function**? As a fn of redshift/**over cosmic time**?
 - To constrain **BH spin**?
- **Understanding MBH accretion across different scales**
 - What is the timescale of disk formation?
 - How efficient is **super-Eddington** accretion?
 - When do **accretion state transitions** happen?
 - When do **outflows/jets** appear? How ubiquitous are they?
- **Understanding MBH – host galaxy connection**
 - How are TDE rates determined by **host galaxy evolution**?
 - What are the properties of TDE hosts?
- **Constraining populations and dynamics of stars/compact objects in galactic nuclei**
 - What are the **IMFs** in these **galactic nuclei**?
 - What are the density profile of the **stellar cusps**?



Timescales

- **Rise:** week - months
- **Decline:** month - years
- **Variability:** hours-days



Rates

- **Rates of optical TDEs:** currently **~60/year** (over typical redshift range $0.015 < z < 0.5$), **up to ~1000/year with Rubin/LSST** (though w/out dedicated spectral follow-up)
- **Rates of X-ray bright TDEs:** **~40% of optical** also detected in X-ray
- **Rates of jetted TDEs:** four confirmed, consistent with **~1% of TDEs** launching jets (most off-axis)

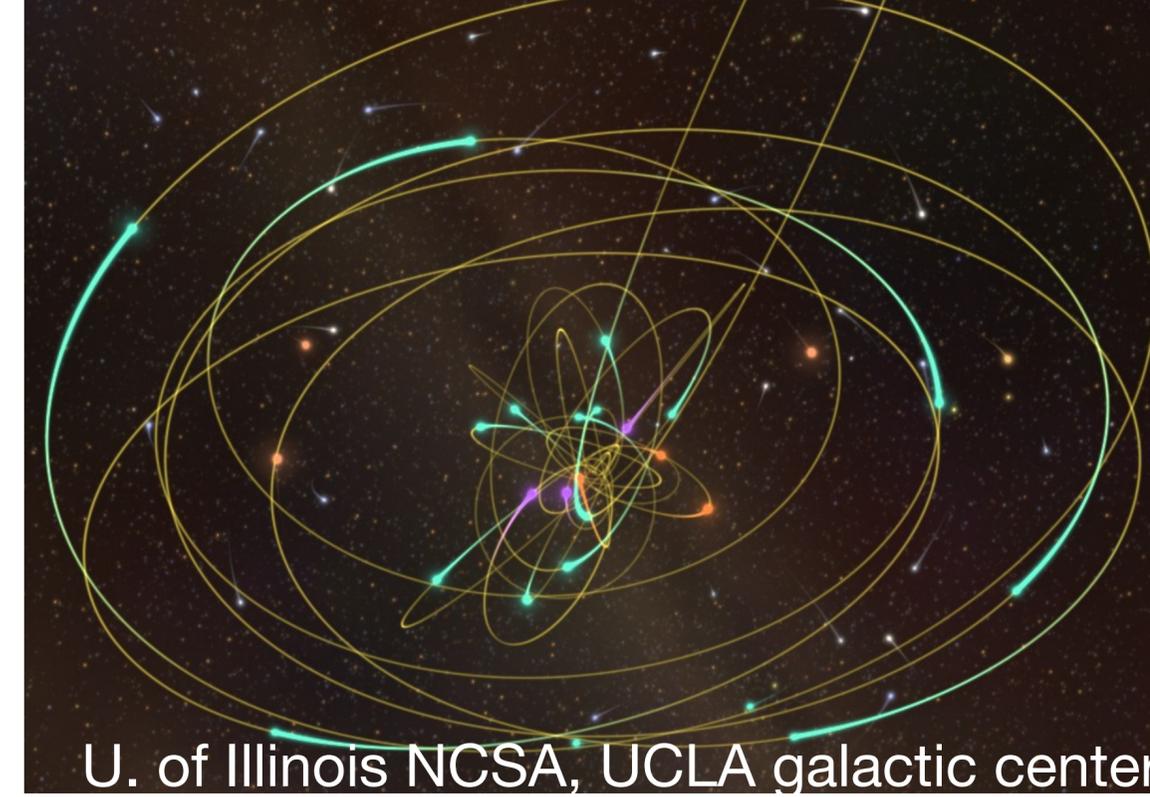
Suggested Triggering Criteria

- **Nearby TDE**

- Closer than nearest known event $z = 0.015$ (~65 Mpc)
- Rate $\sim 0.1/\text{year}$
- Detect early time emission produced during initial stream shocks and the accretion disk formation → **golden opportunity to watch SMBH form an accretion disk in real time**
- Detailed spectral analysis at multiple wavelengths --> constrain gas conditions and outflow velocities

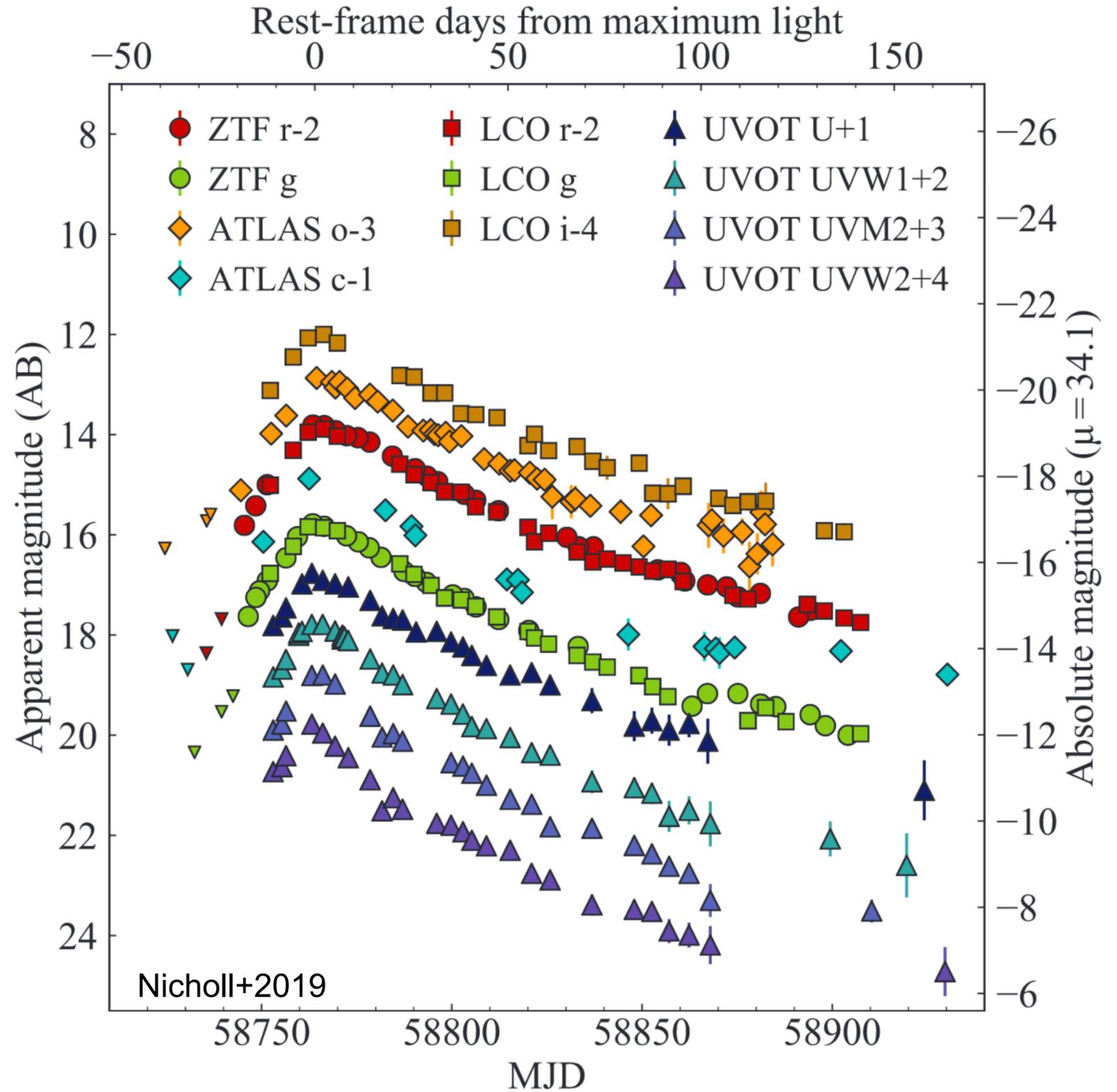
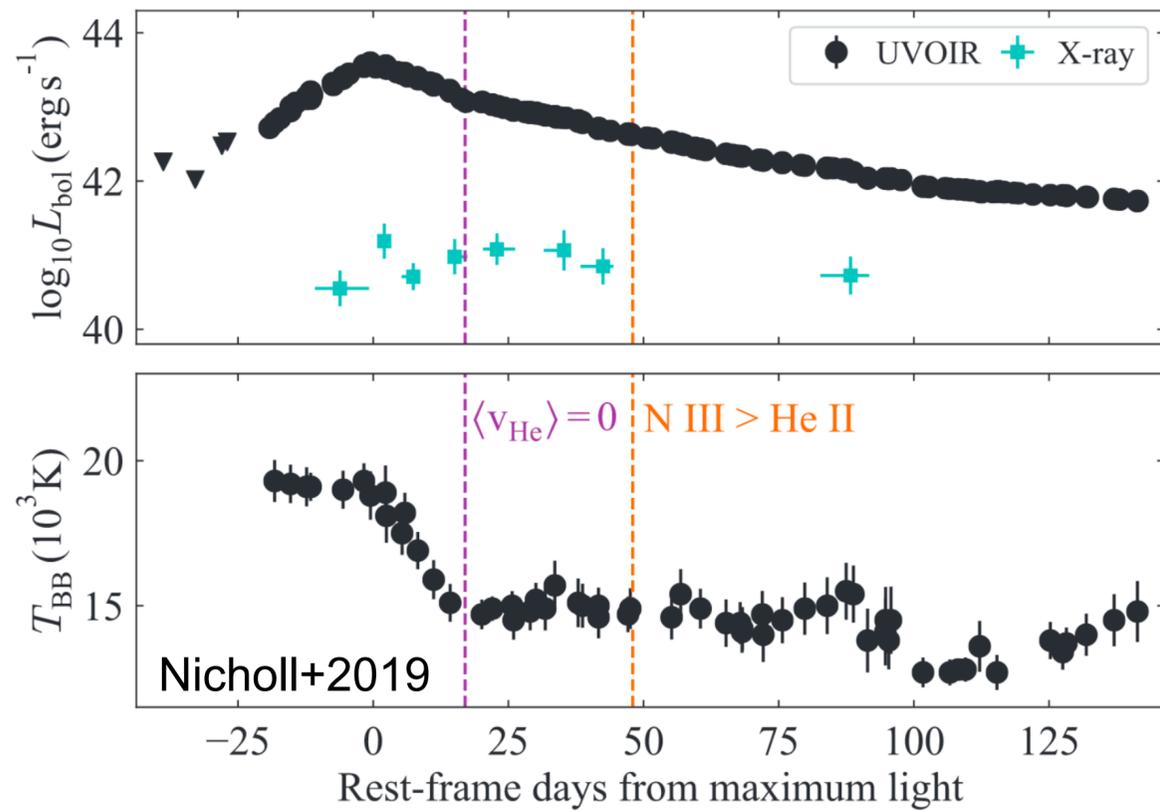
- **Jetted TDE**

- Rate (observed on-axis) $\sim 0.2/\text{year}$
- Jet formation in TDE (and in general) still poorly understood
- Jetted events with multi-wavelength emission allow better determination of when during optical TDE jet is launched



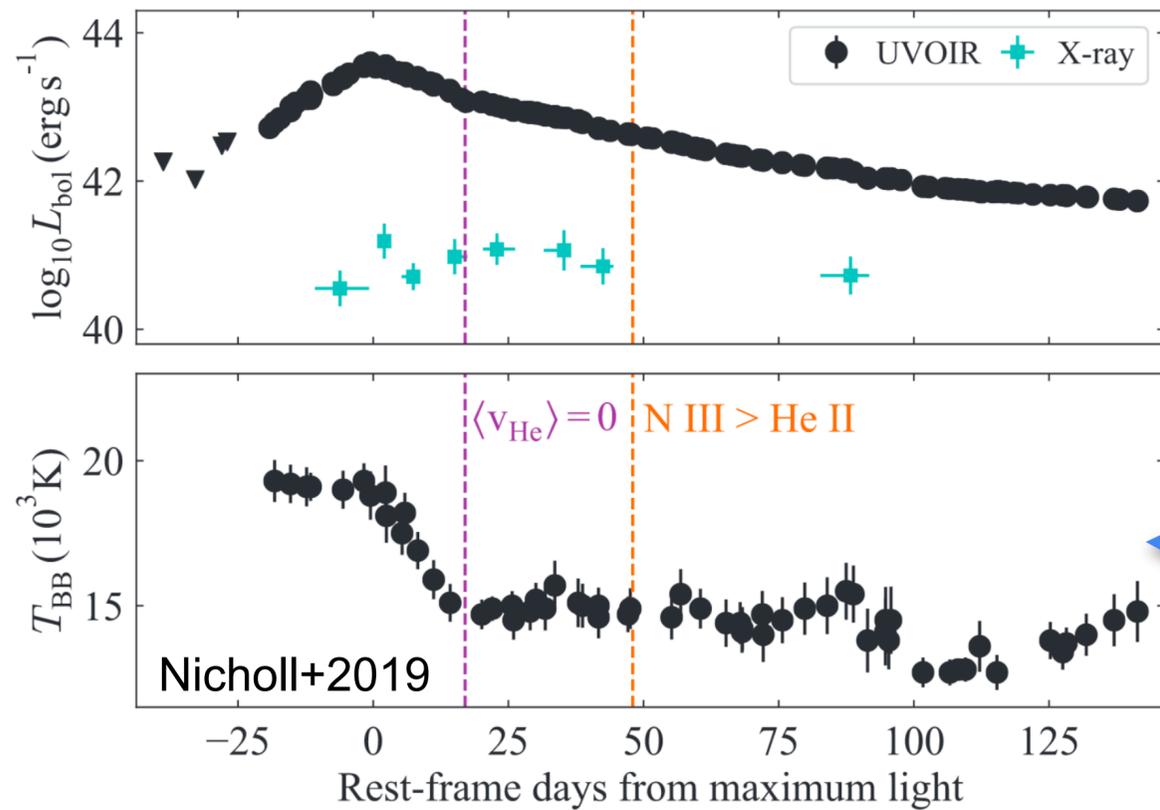
Exemplary events: Nearby TDE (AT2019qiz, 65 Mpc)

● Optical/UV light curve

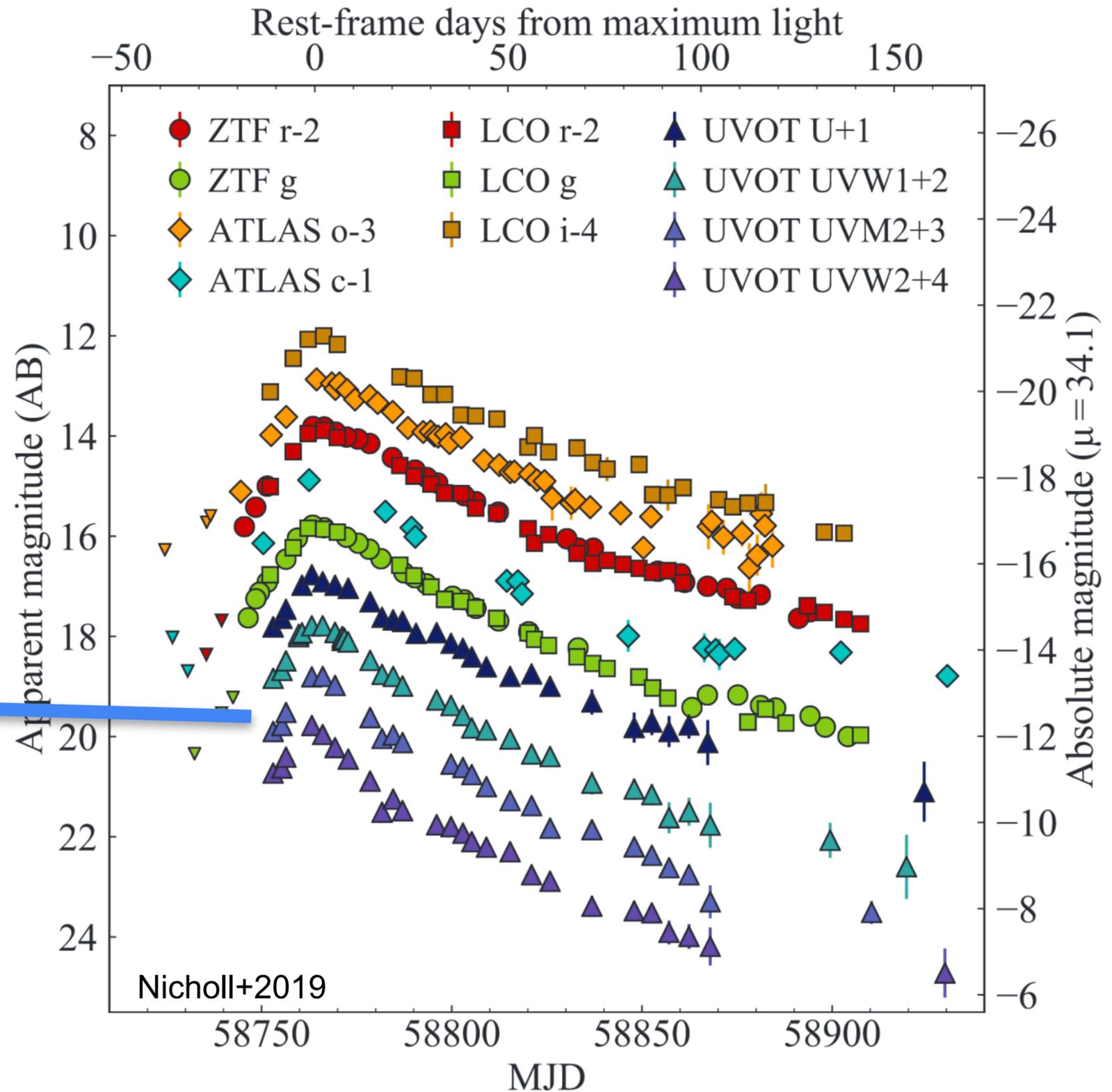


Exemplary events: Nearby TDE (AT2019qiz, 65 Mpc)

● Optical/UV light curve



early UV shows evidence of temperature evolution

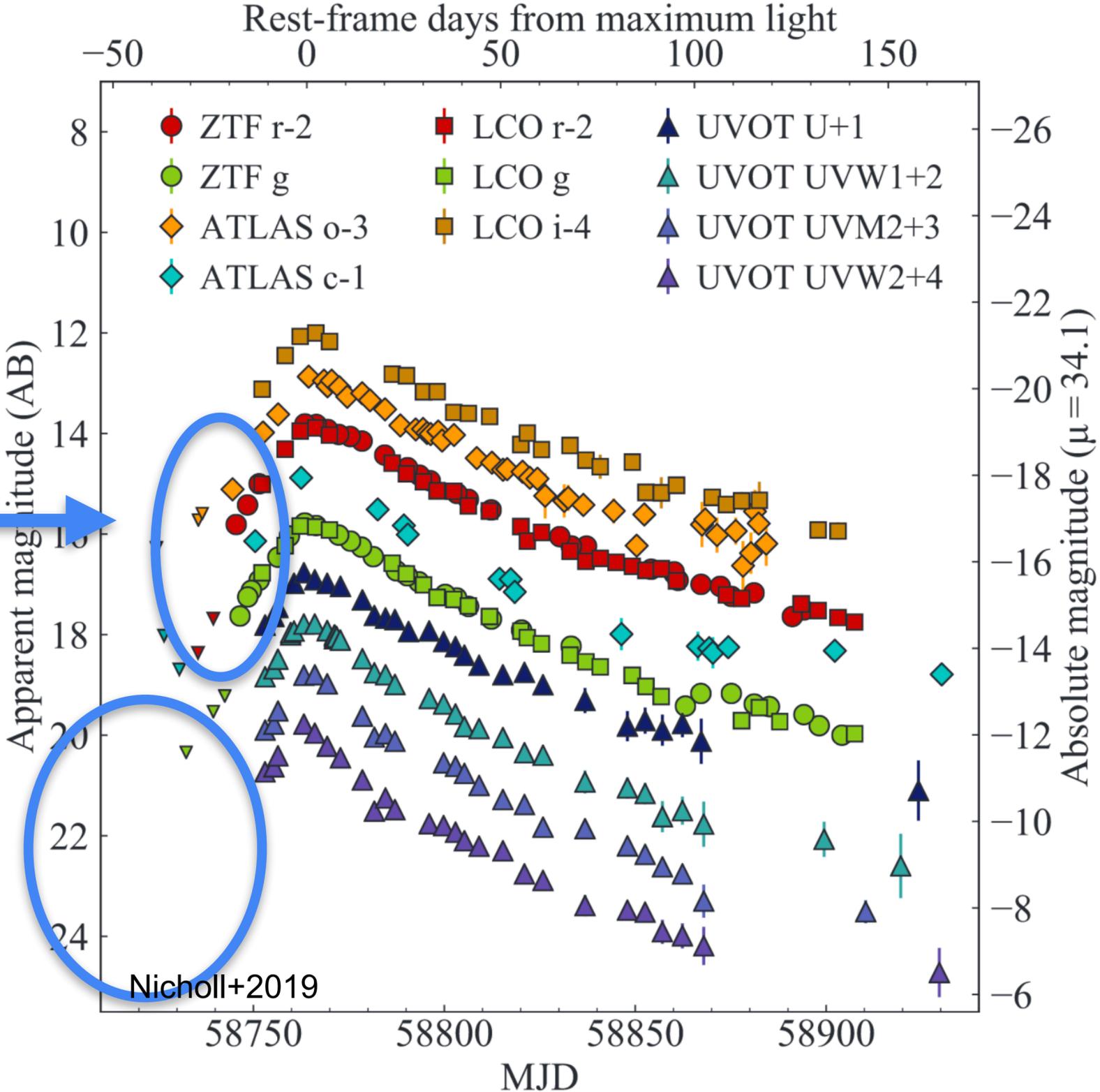


Exemplary events: Nearby TDE (AT2019qiz, 65 Mpc)

- Optical/UV light curve

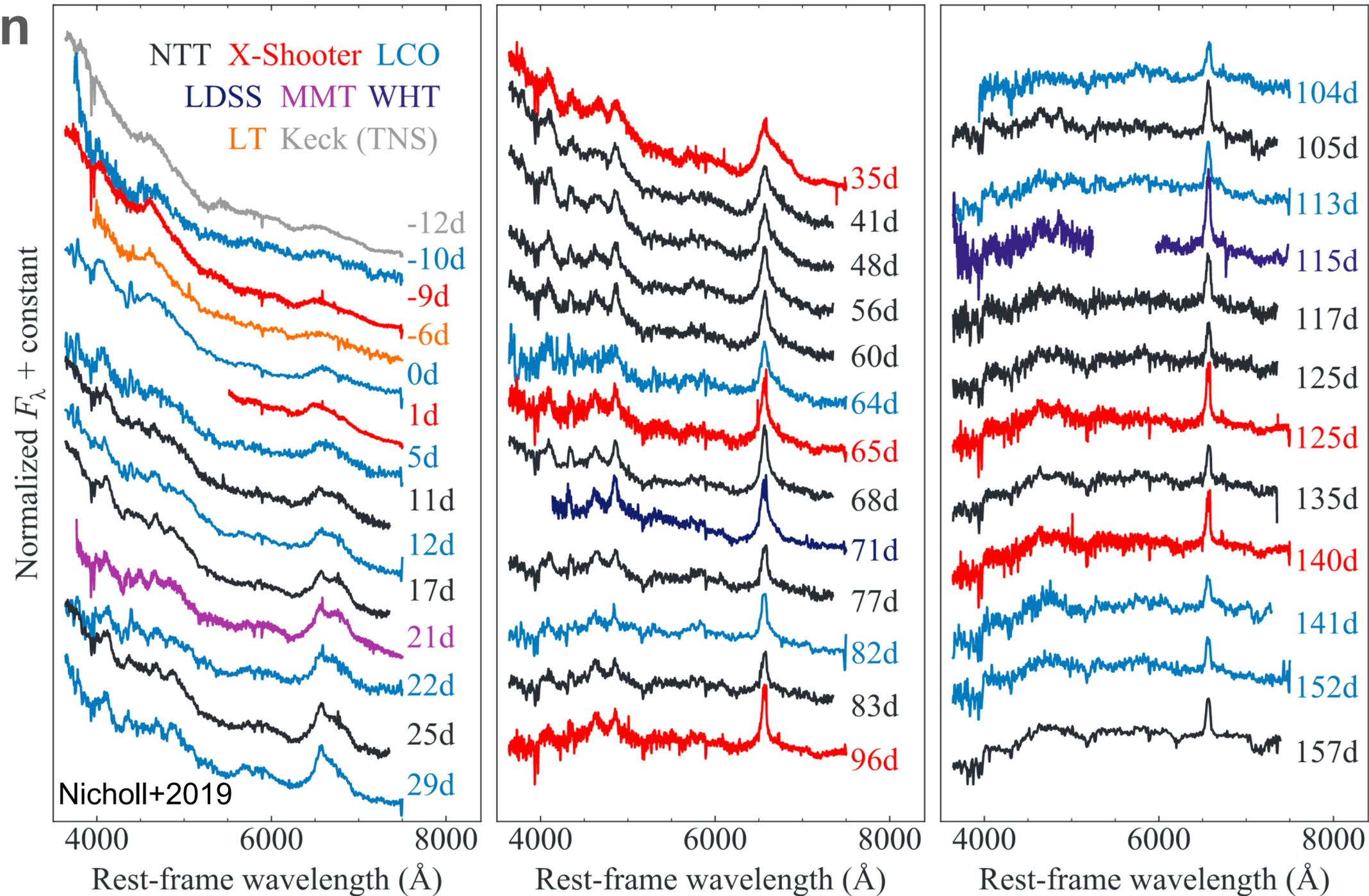
Would like limits on **~sub-day optical variability** to constrain **source variability/diffusion timescales**

Missing early time **UV?**



Exemplary events: **Nearby TDE** (AT2019qiz, 65 Mpc)

- **Optical spectral evolution**
- 39 epochs (!)

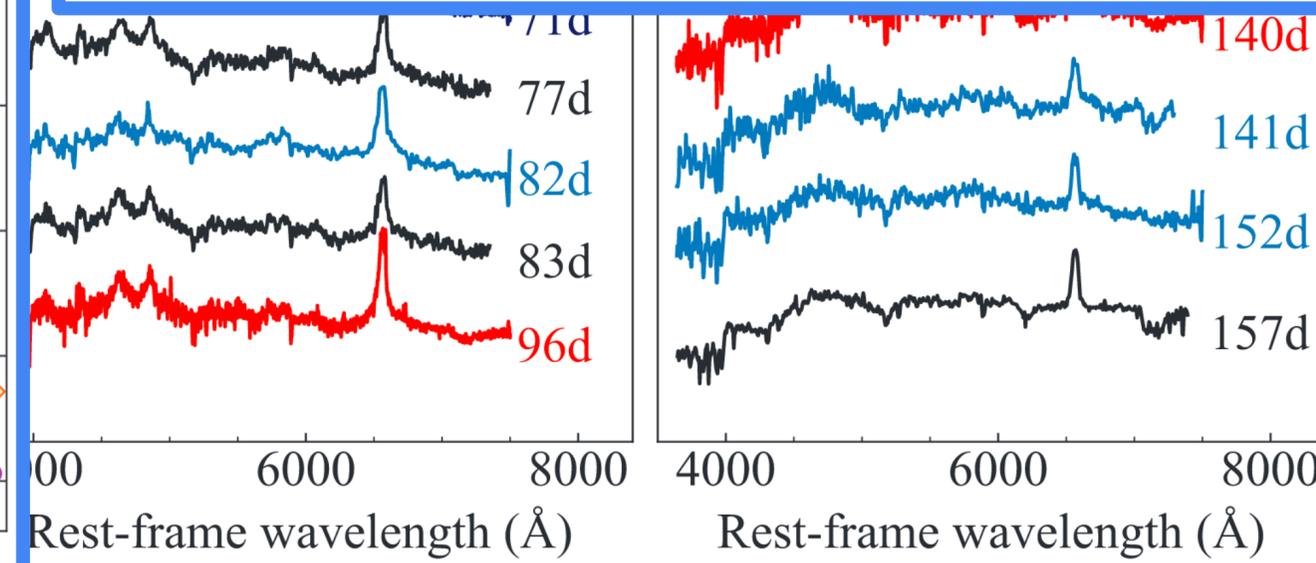
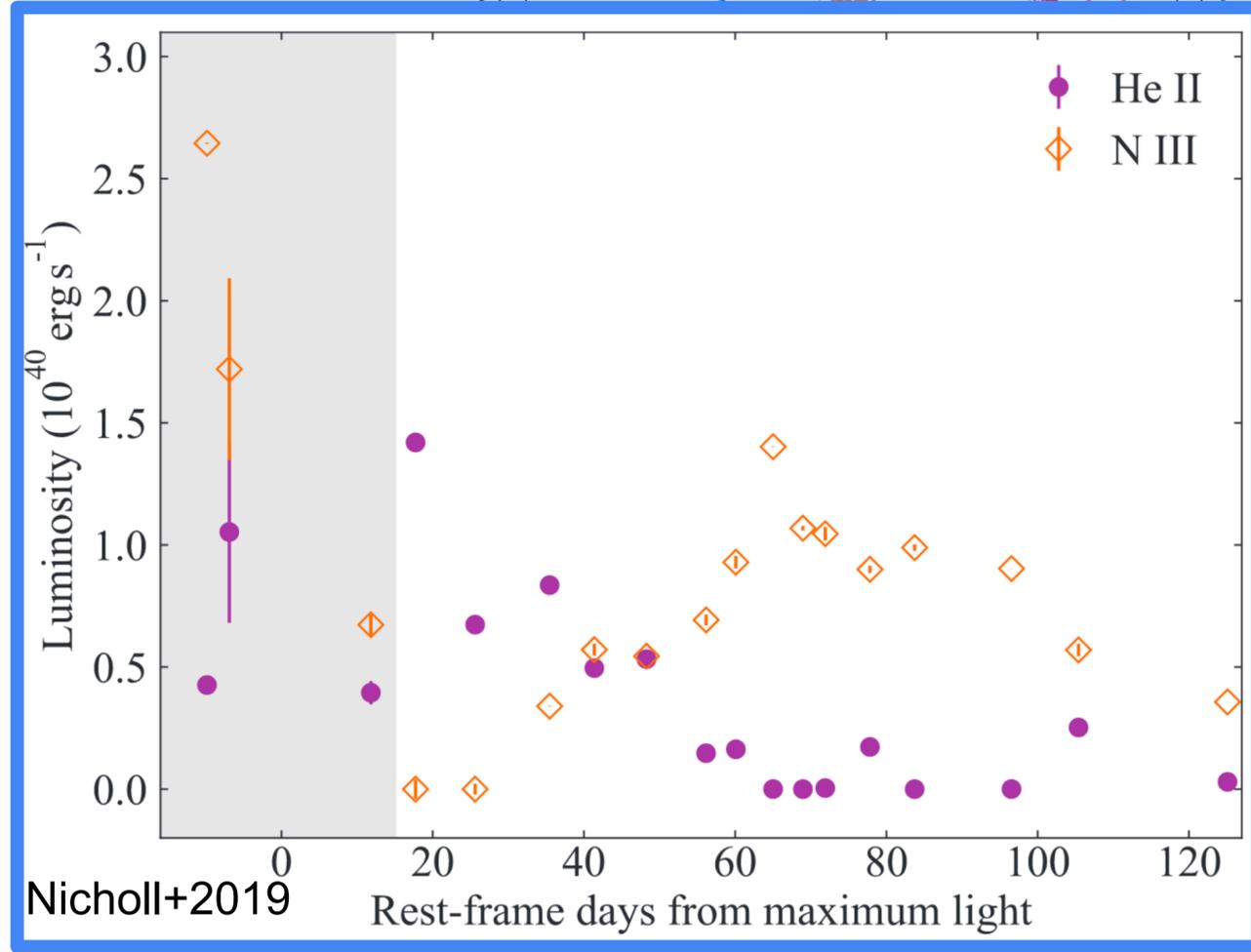
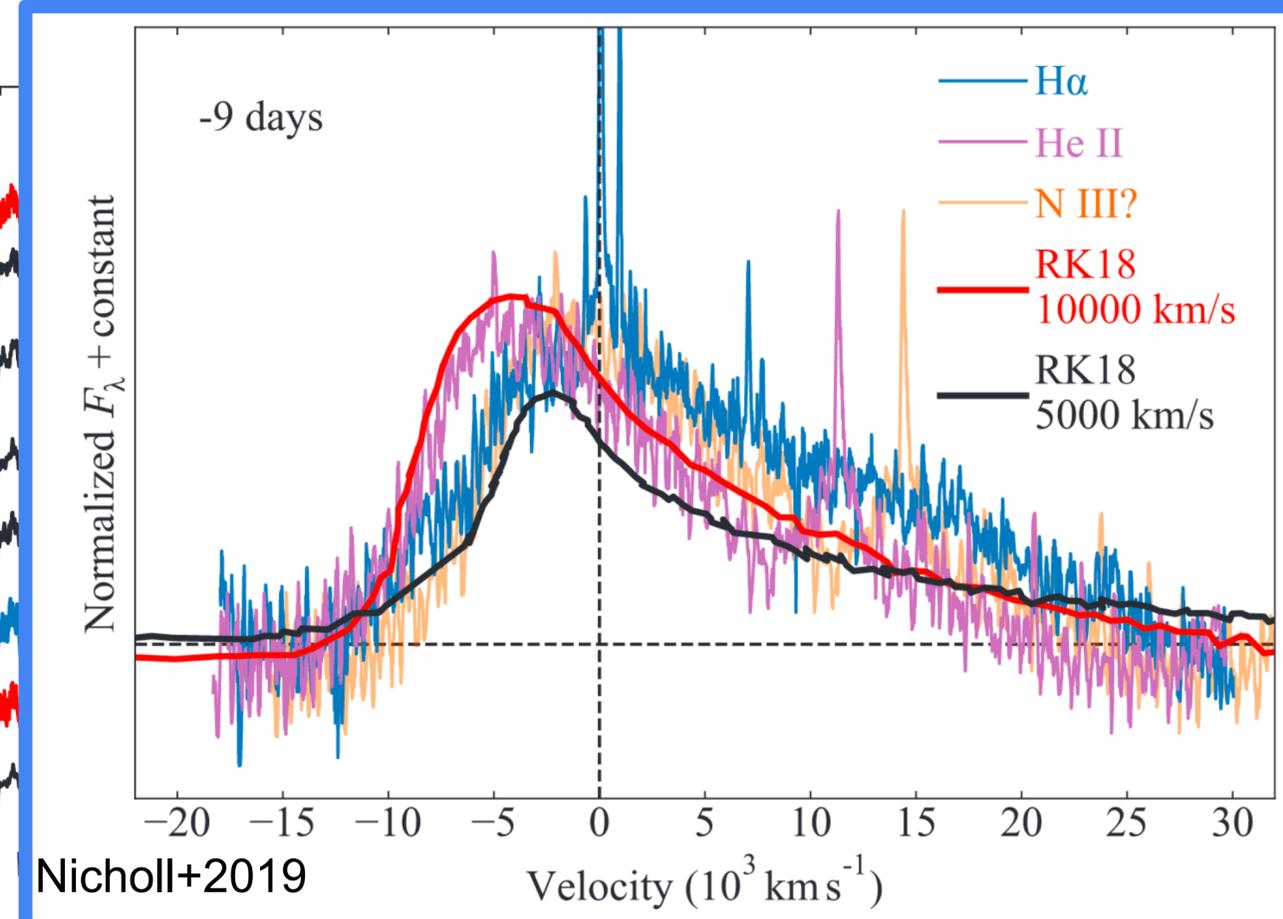
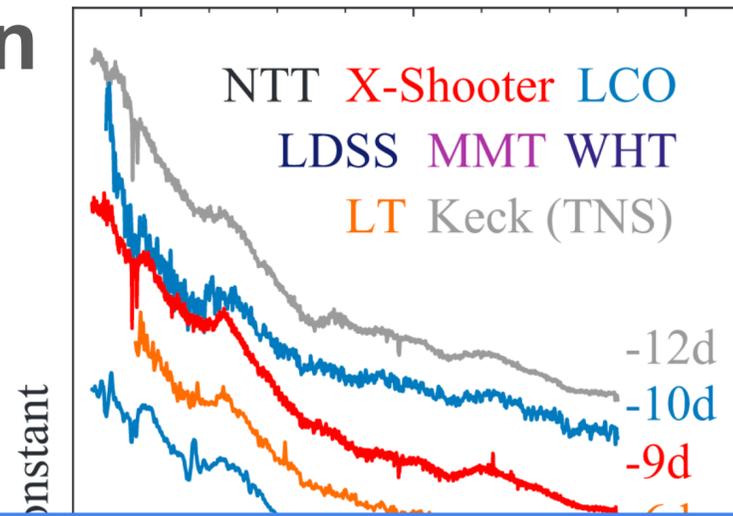


Exemplary events: Nearby TDE (AT2019qiz, 65 Mpc)

- **Optical spectral evolution**

- Blueshifted lines consistent with **outflow**

- Evolution of HeII/NIII also consistent with **expanding photosphere becoming optically thin**



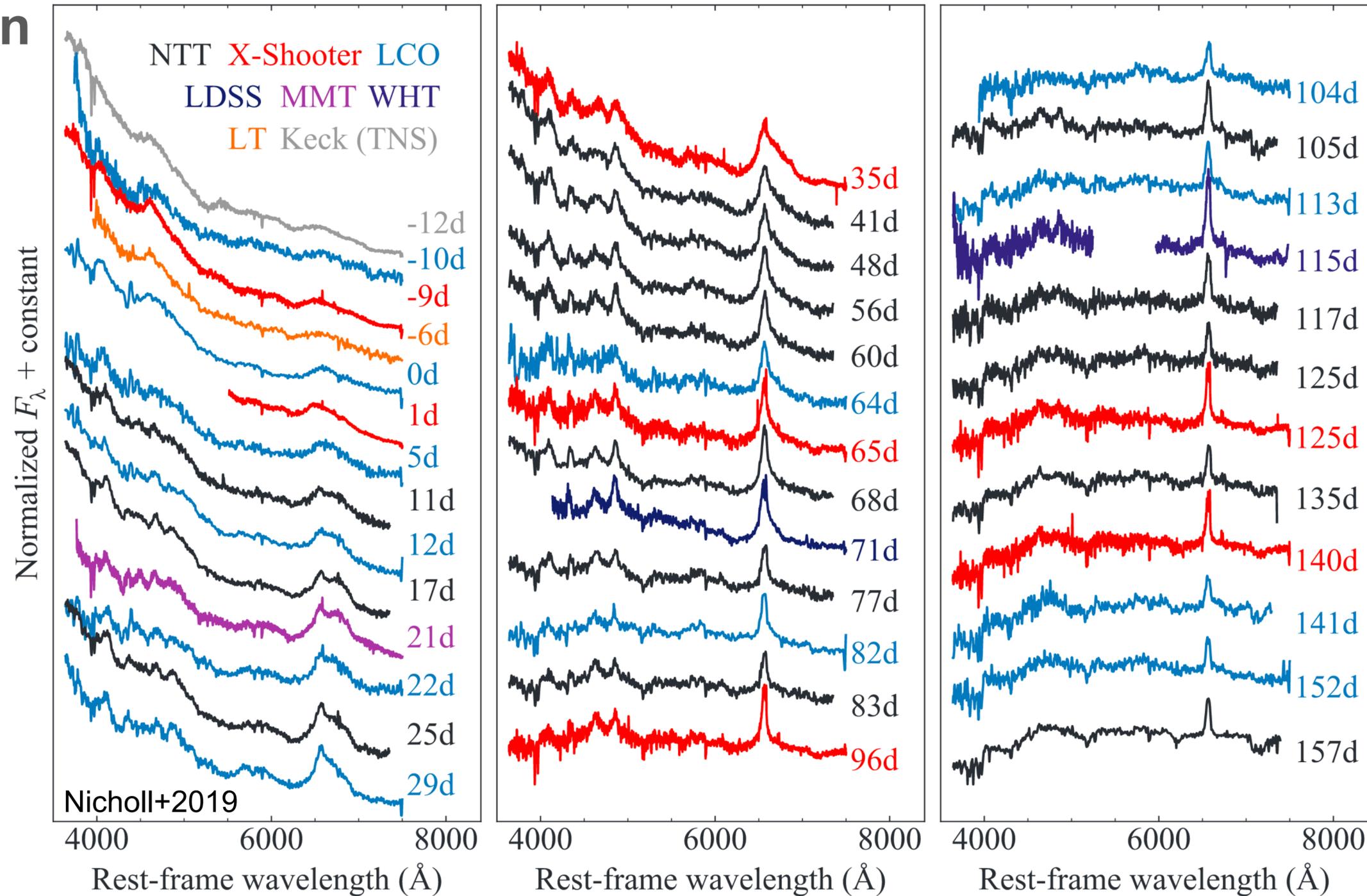
Exemplary events: **Nearby TDE** (AT2019qiz, 65 Mpc)

- **Optical spectral evolution**
- 39 epochs (!)

If observed closer to discovery (~ -20 days) would it have been featureless in optical?

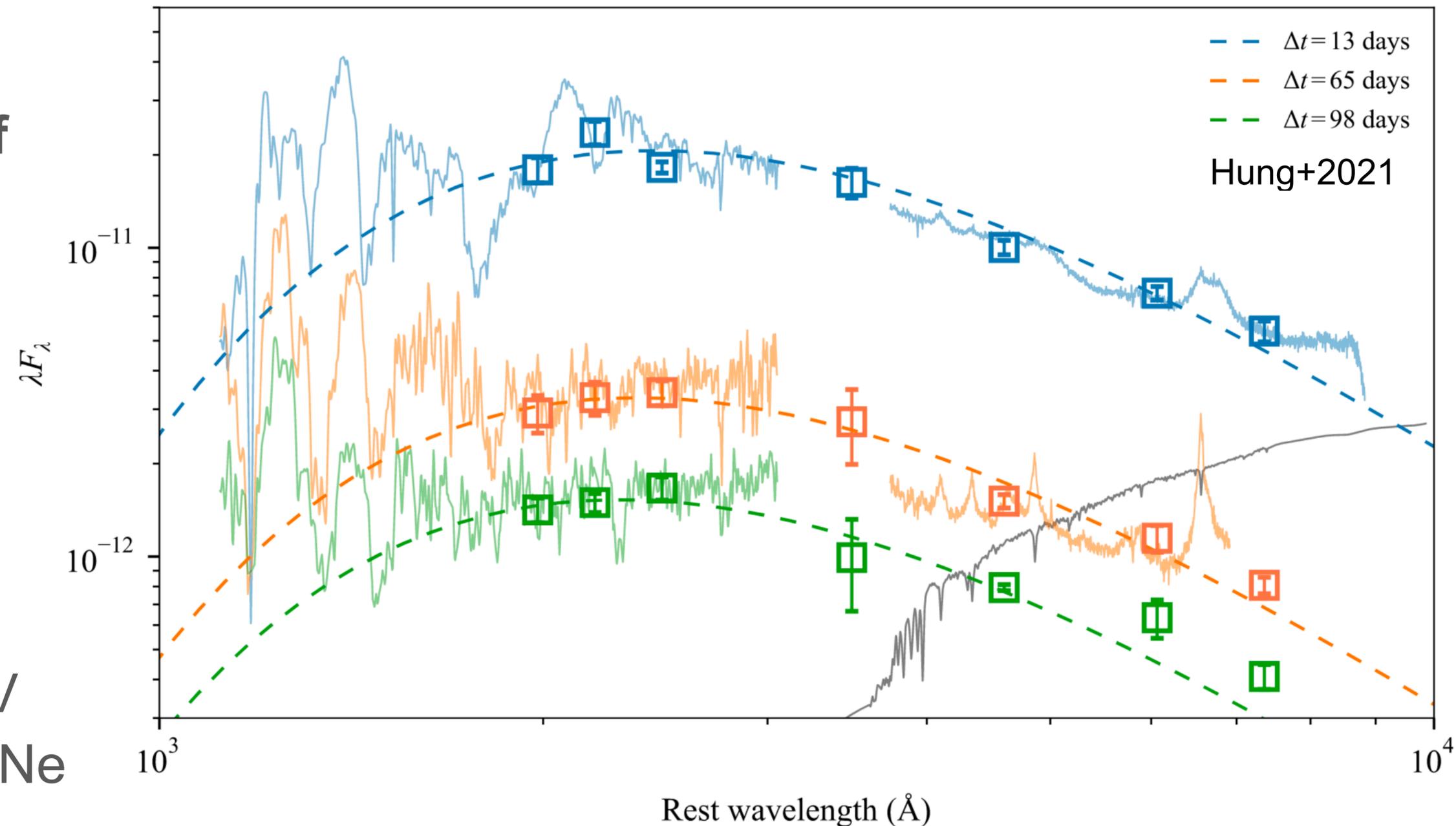


Probes **ionization state**, **X-ray/UV source luminosity**



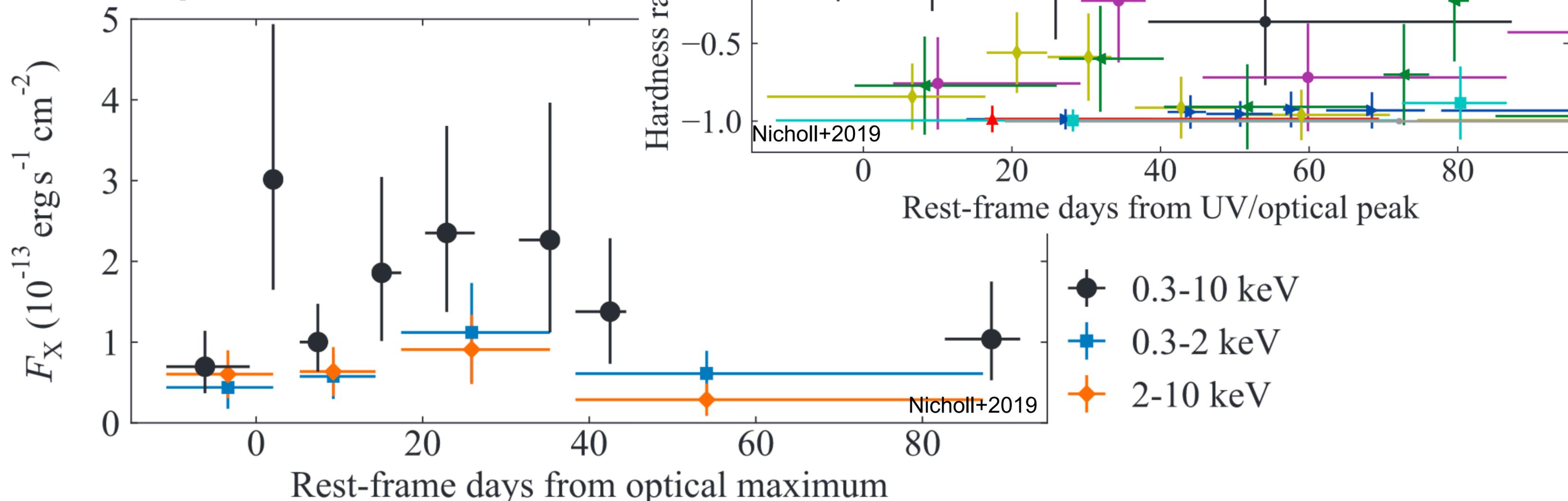
Exemplary events: **Nearby TDE (AT2019qiz, 65 Mpc)**

- **UV spectral evolution**
- **Earliest UV spectra of TDE** (though still post-peak)
- Spectral sequence shows **velocity evolution of outflow**
- Earliest spectra shows previously unseen NUV features similar to SLSNe
- Shows BB fitted to optical/NUV generally underpredicts FUV emission \rightarrow underpredicting **energetics**



Exemplary events: Nearby TDE (AT2019qiz, 65 Mpc)

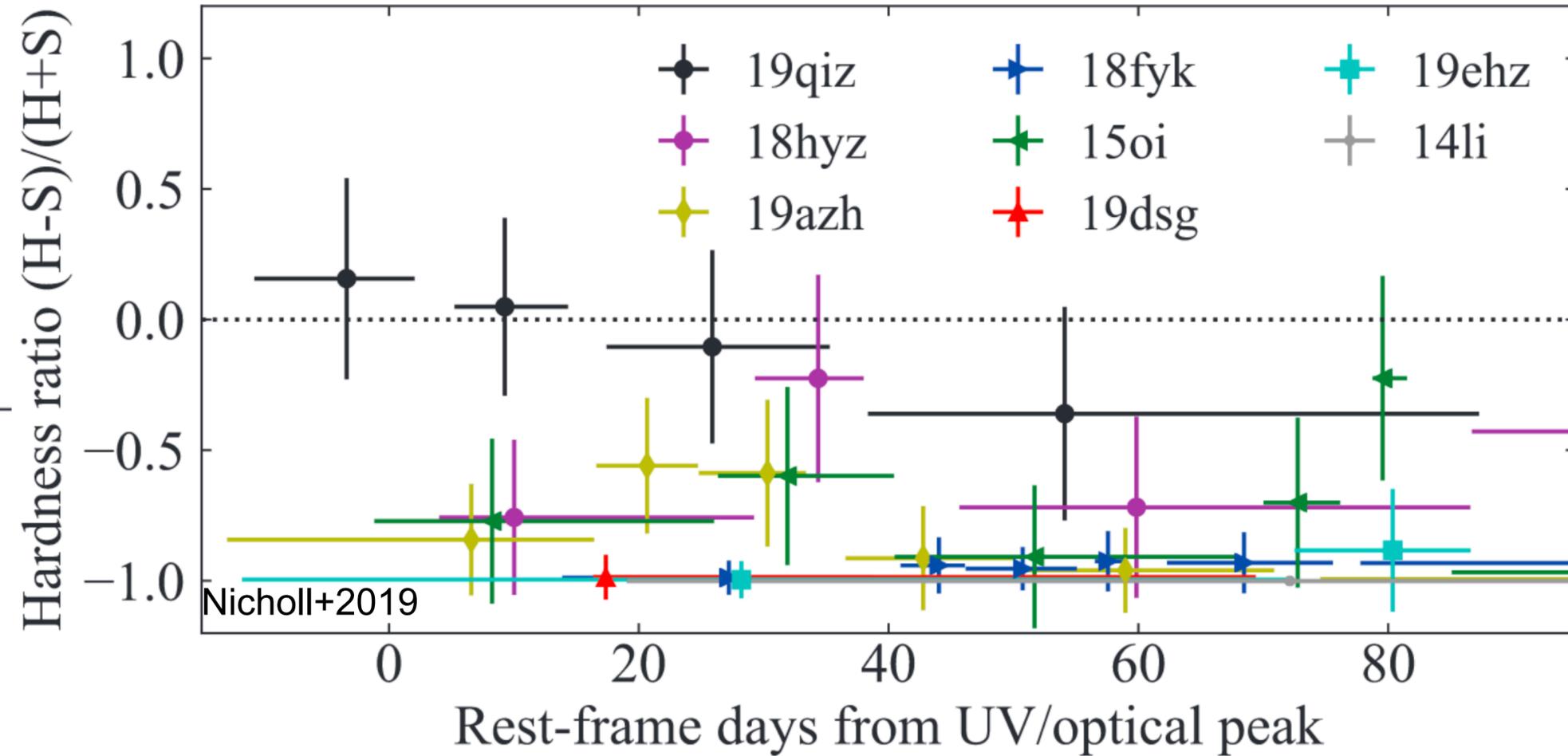
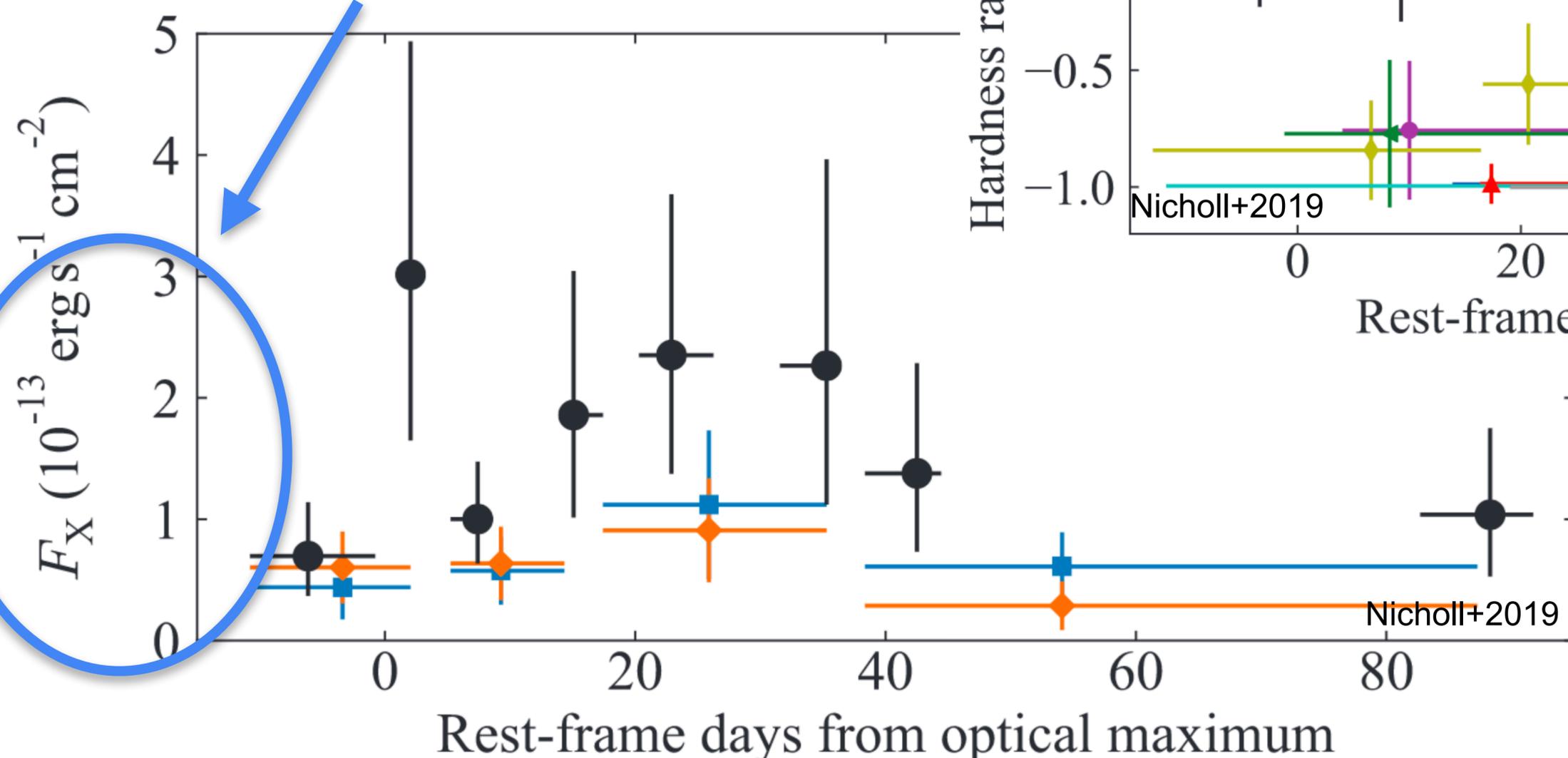
- **X-ray evolution**
- Evidence for harder x-ray emission pre-peak → **reprocessed disk?**



Exemplary events: Nearby TDE (AT2019qiz, 65 Mpc)

- X-ray evolution

First optical detection ~20 days before X-ray obs — Missing early time X-ray?

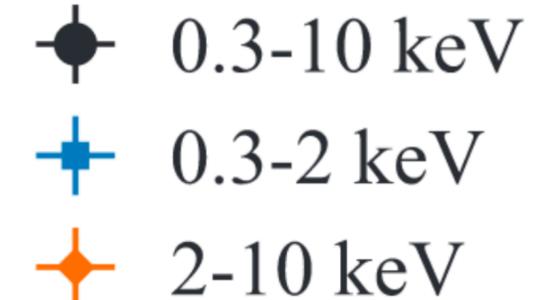
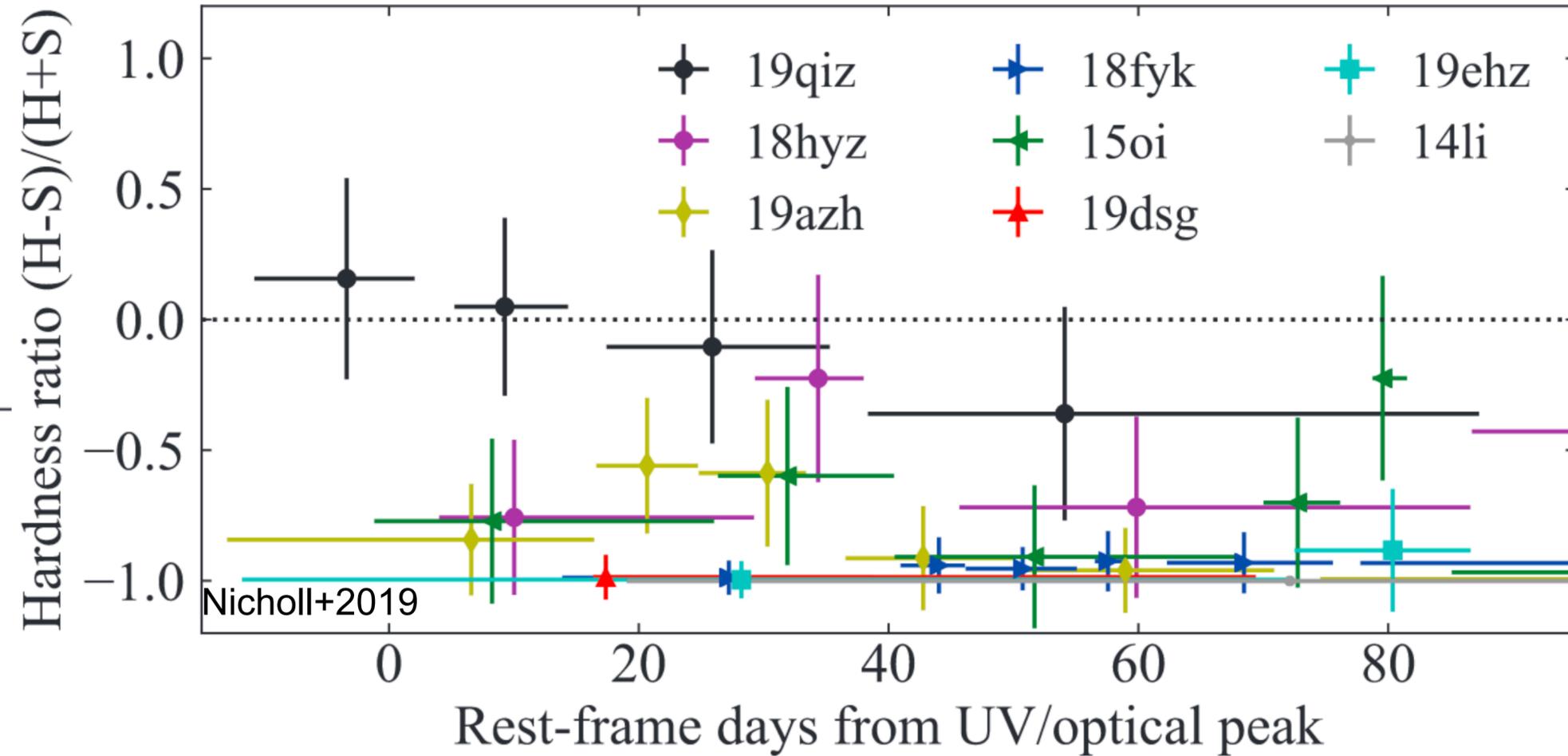
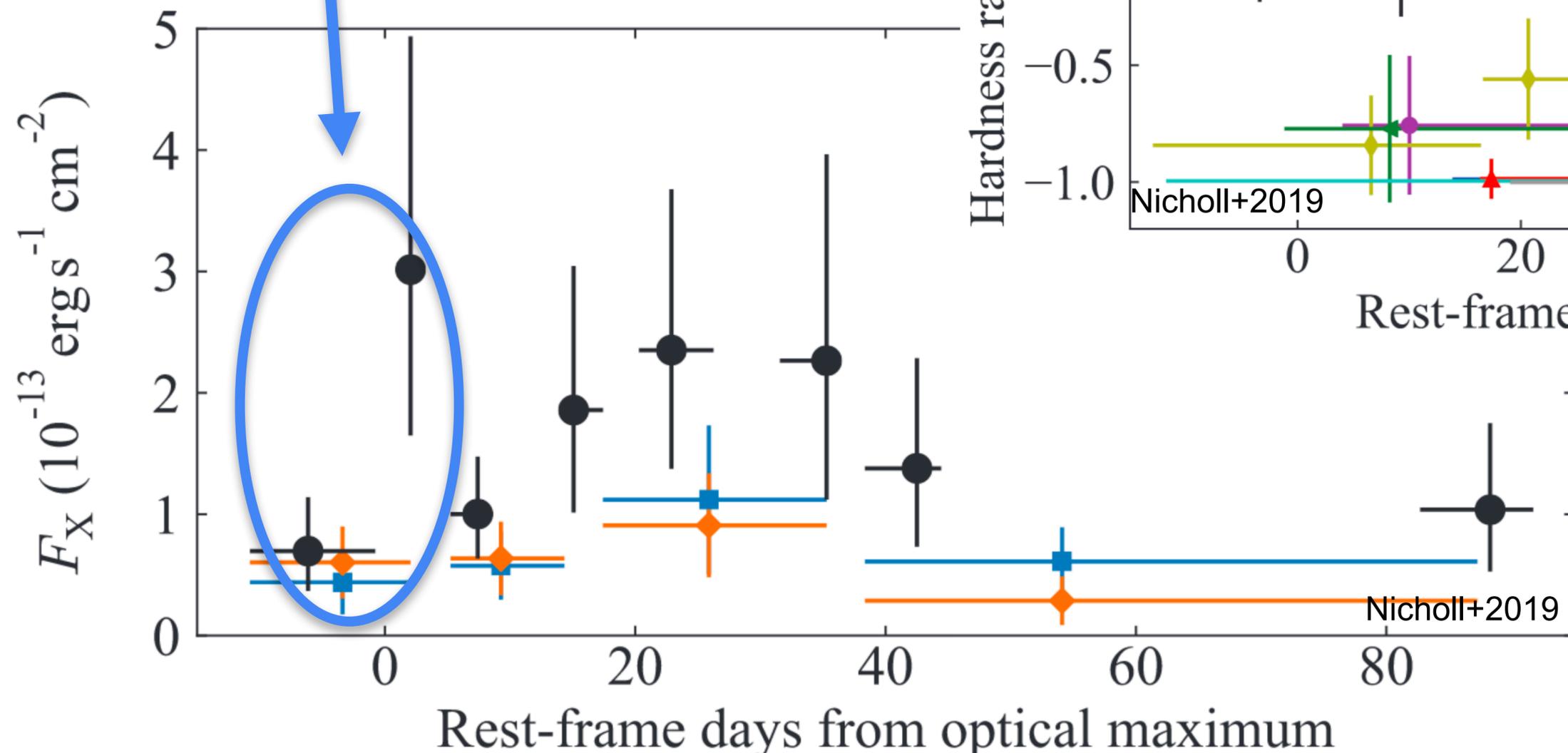


- 0.3-10 keV
- 0.3-2 keV
- ◆ 2-10 keV

Exemplary events: Nearby TDE (AT2019qiz, 65 Mpc)

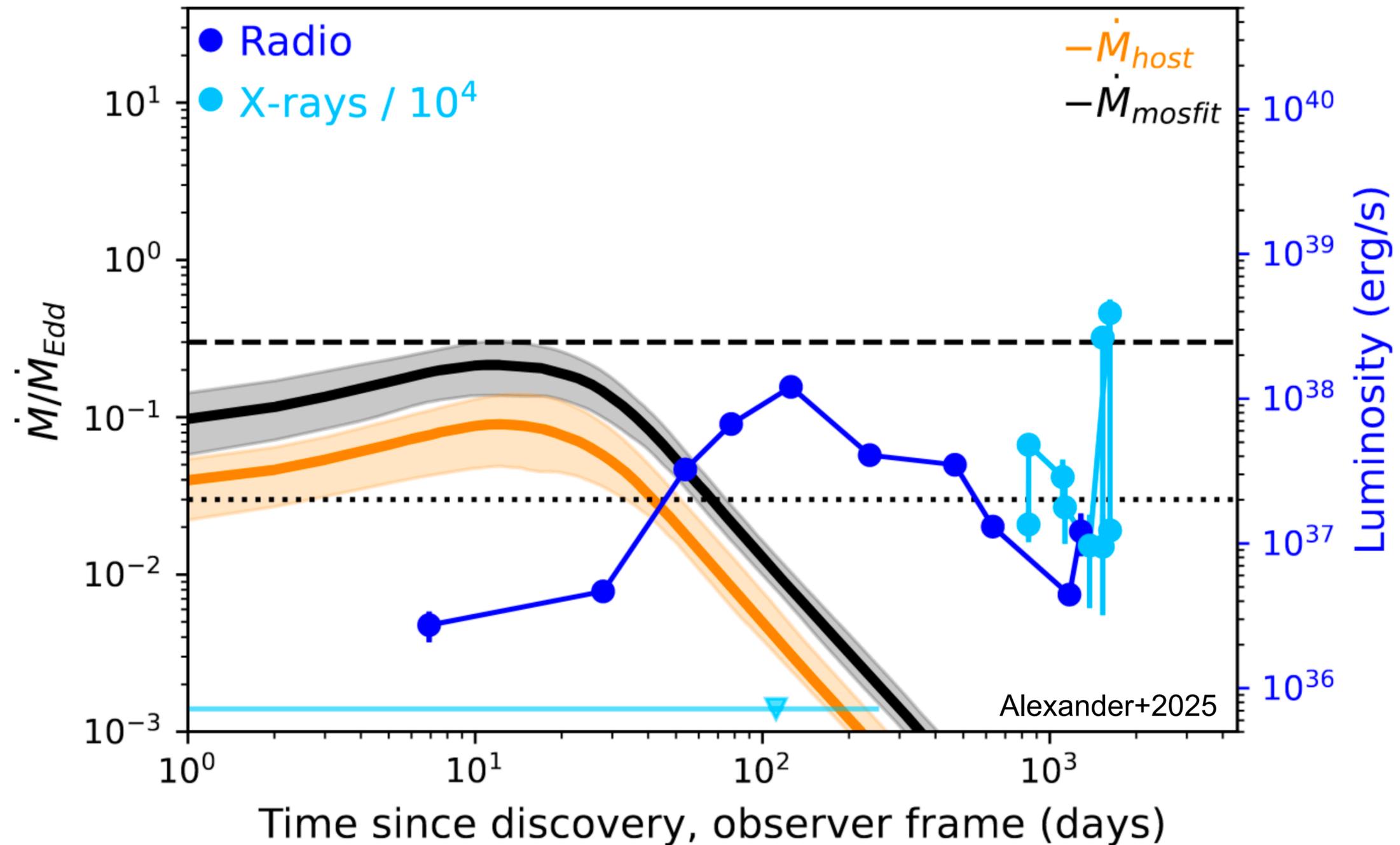
- X-ray evolution

~week between observations --> no probe of sub-day variability



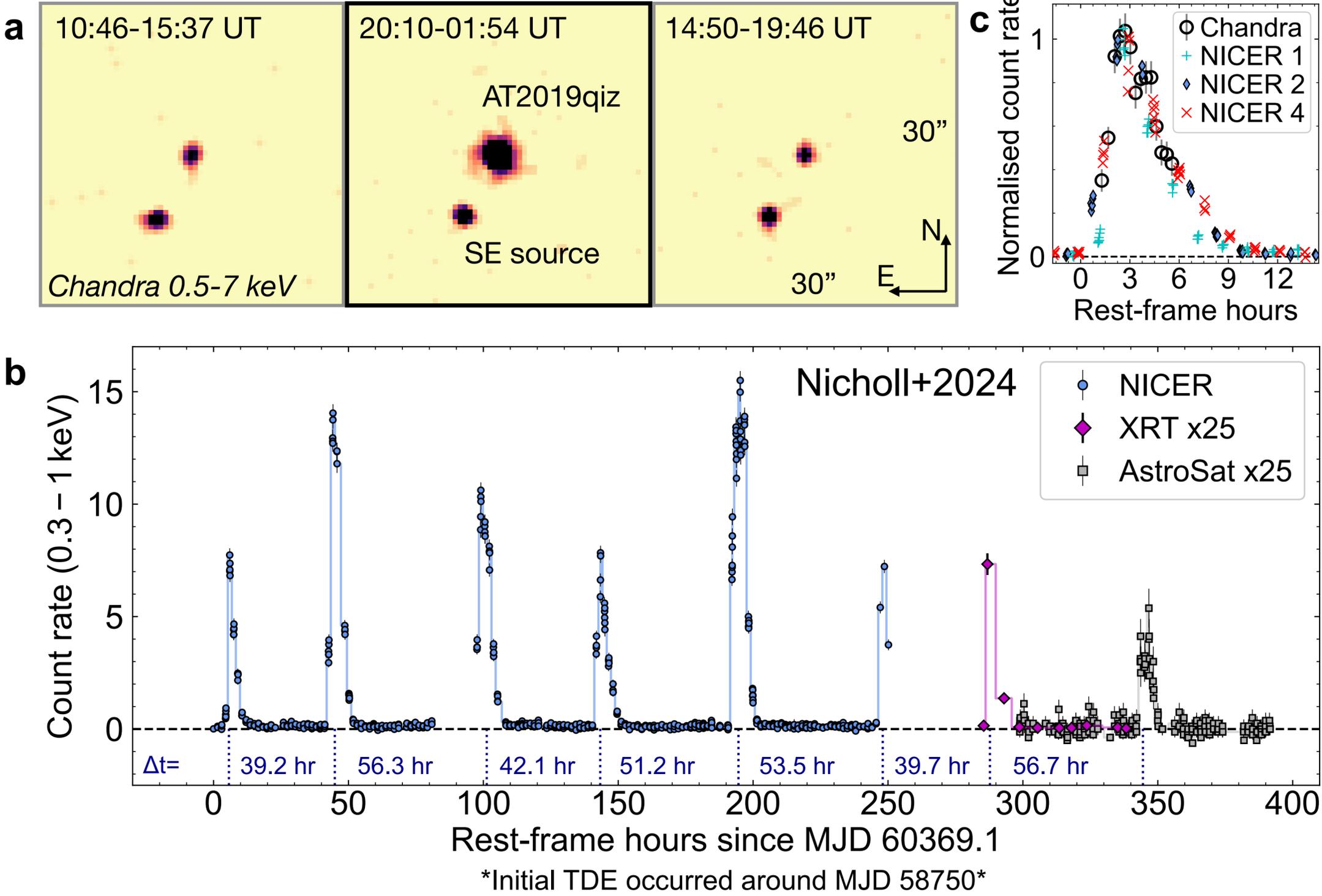
Exemplary events: Nearby TDE (AT2019qiz)

- Radio
- Earliest radio detection for a TDE --> 1 week after discovery, before peak of light curve
- evidence of outflows launched from circularization process?



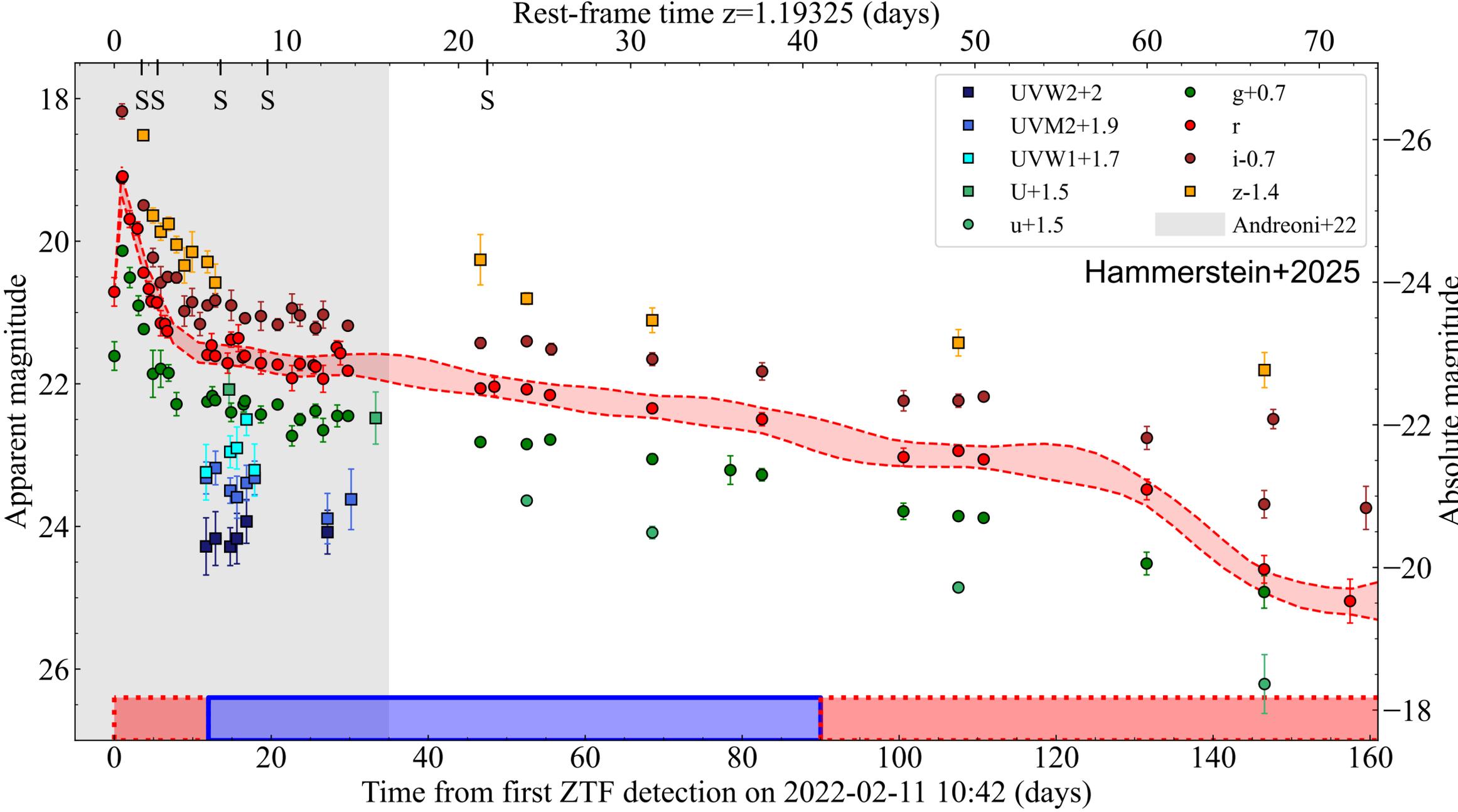
Exemplary events: Nearby TDE (AT2019qiz)

- First confirmed repeating **QPE** associated with a spectroscopically-confirmed TDE observed at peak brightness
- TDE disk constraints provide constraints on QPE models



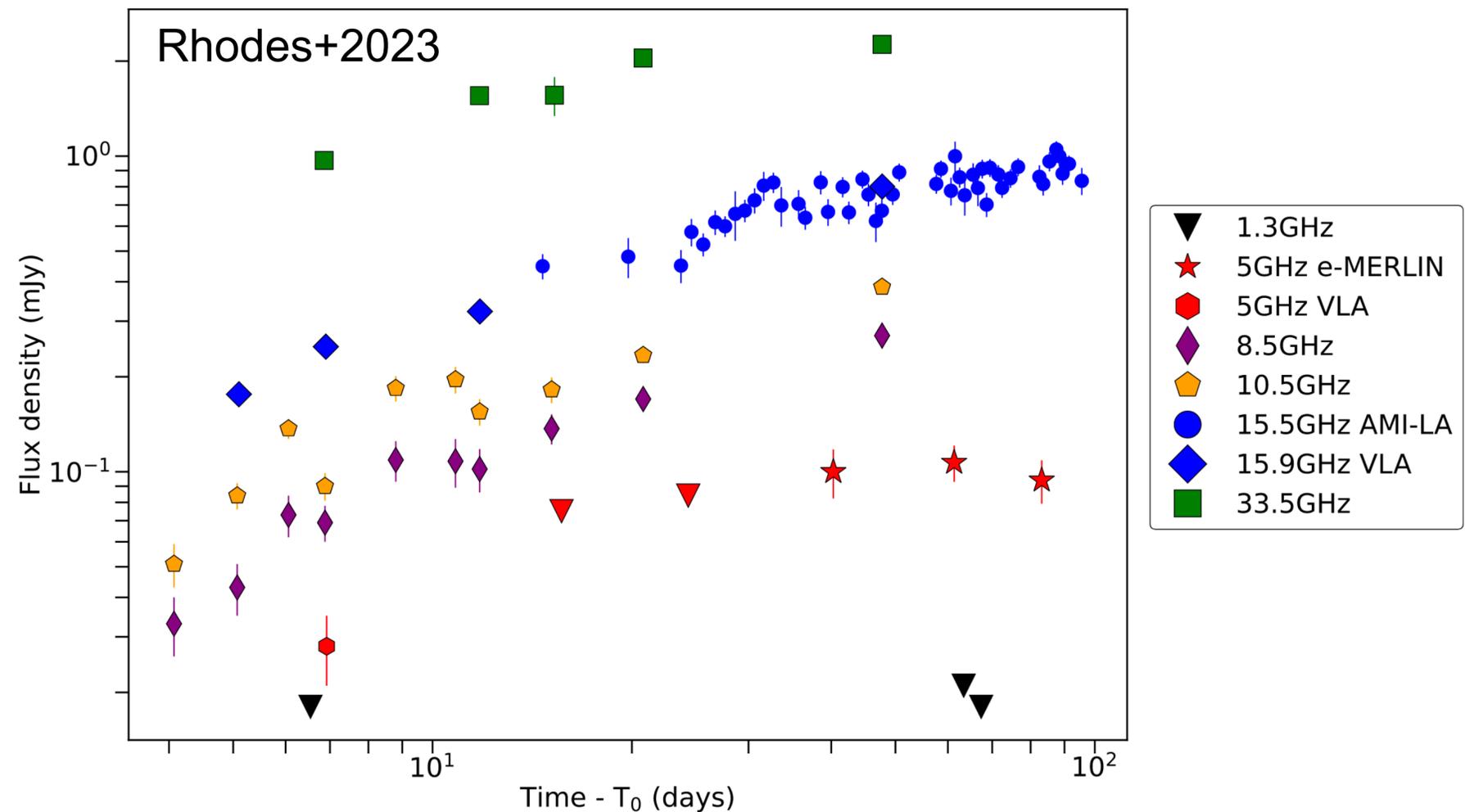
Exemplary events: Jetted TDE (AT2022cmc)

- Optical discovery with the Zwicky Transient Facility
- Discovery in optical surveys of particular interest in the Rubin era
- Multi-wavelength campaign from radio to X-ray
- Bright optical counterpart allowed this event to be placed in context of general TDE population



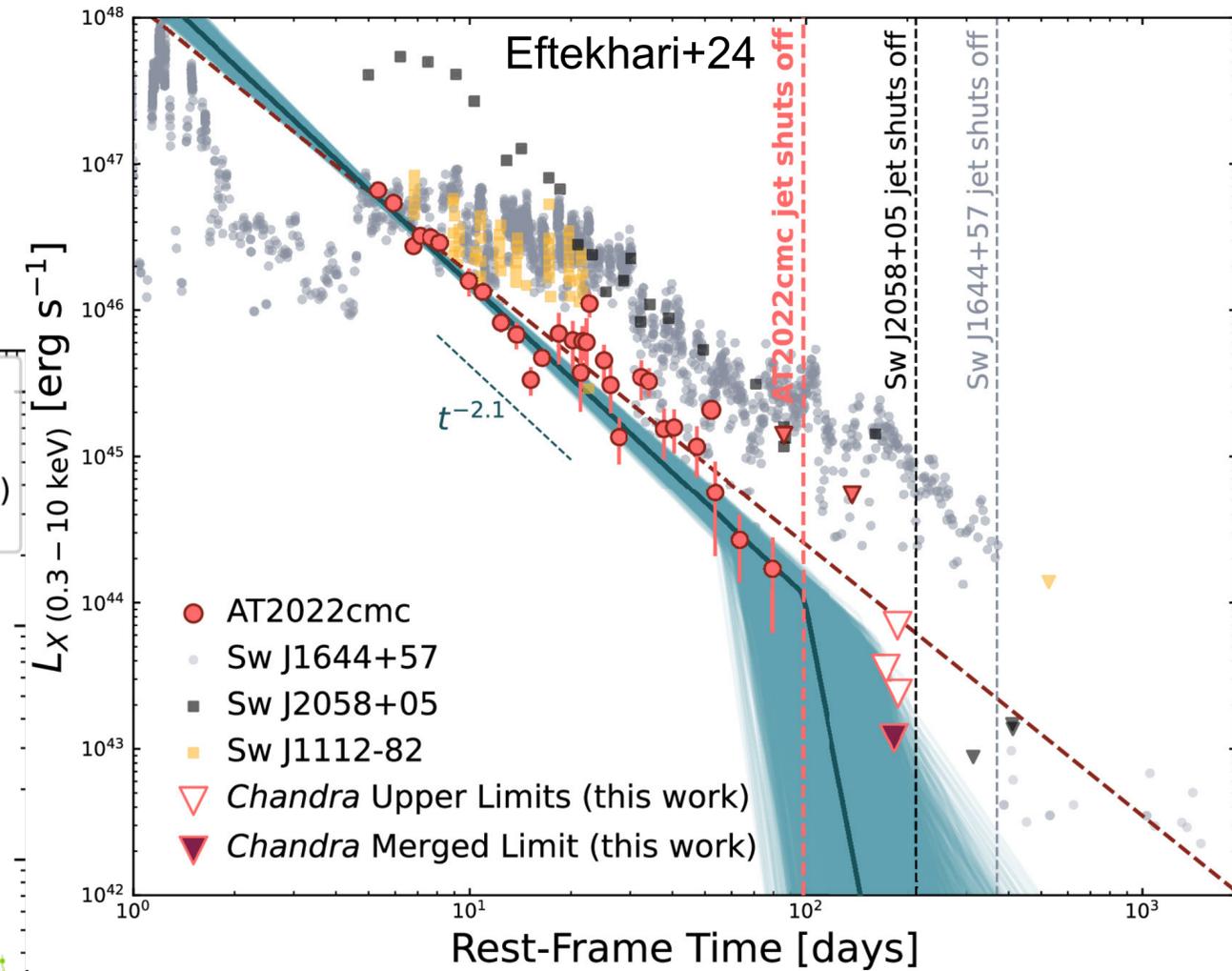
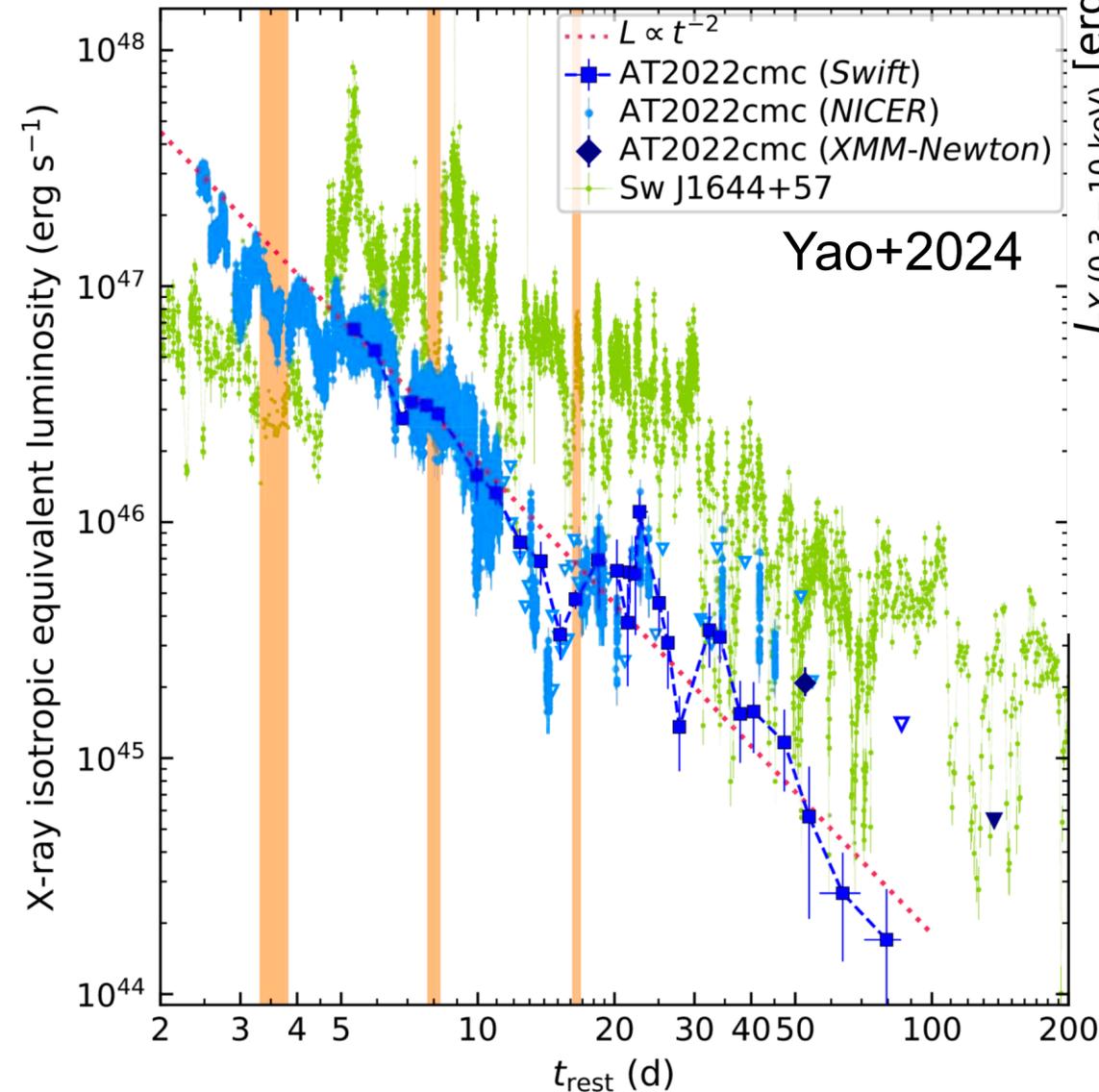
Exemplary events: **Jetted TDE (AT2022cmc)**

- Radio emission consistent with synchrotron emitting jet
- Multi-facility radio observations over the first 100 days
- Day timescale variability observed which provided conclusive evidence that the radio emission is from a relativistic jet

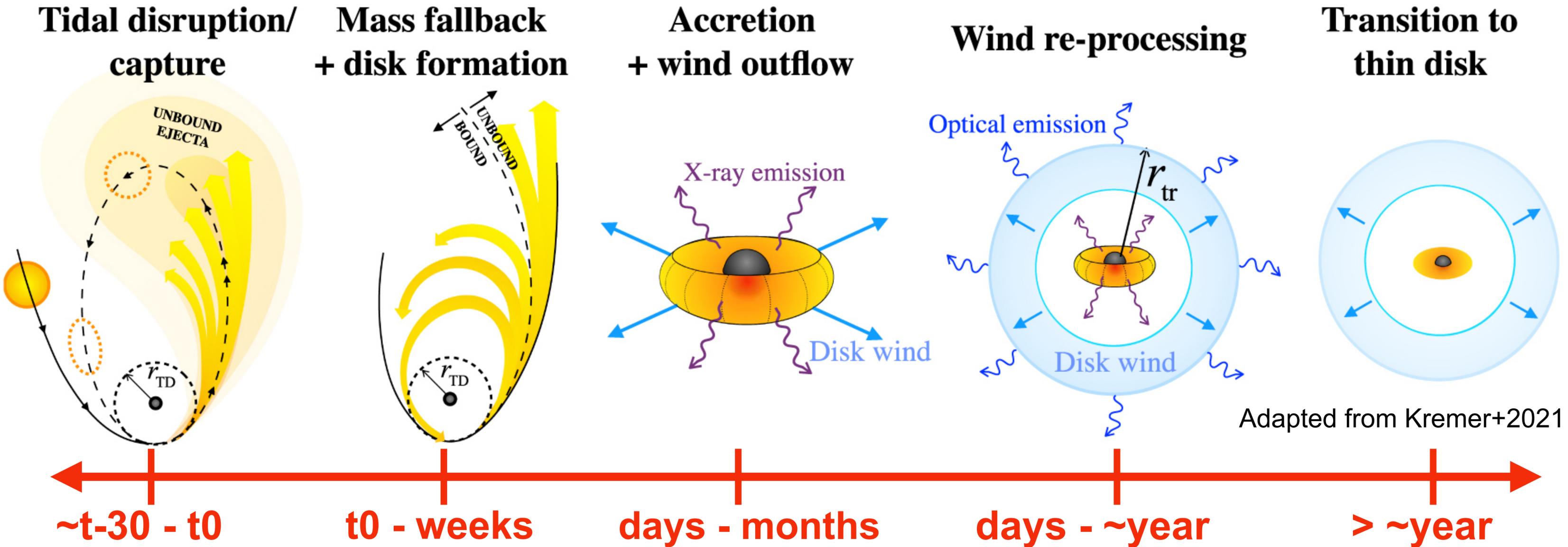


Exemplary events: Jetted TDE (AT2022cmc)

- X-ray light curve shows variability on short timescales
- Late-time monitoring finds X-ray shut-off at $t \sim 100$ d
- All jetted TDEs with well-sampled X-ray light curves have shown this shut off — interpreted as accretion state change and cessation of the jet
- Possible to use this to estimate BH mass



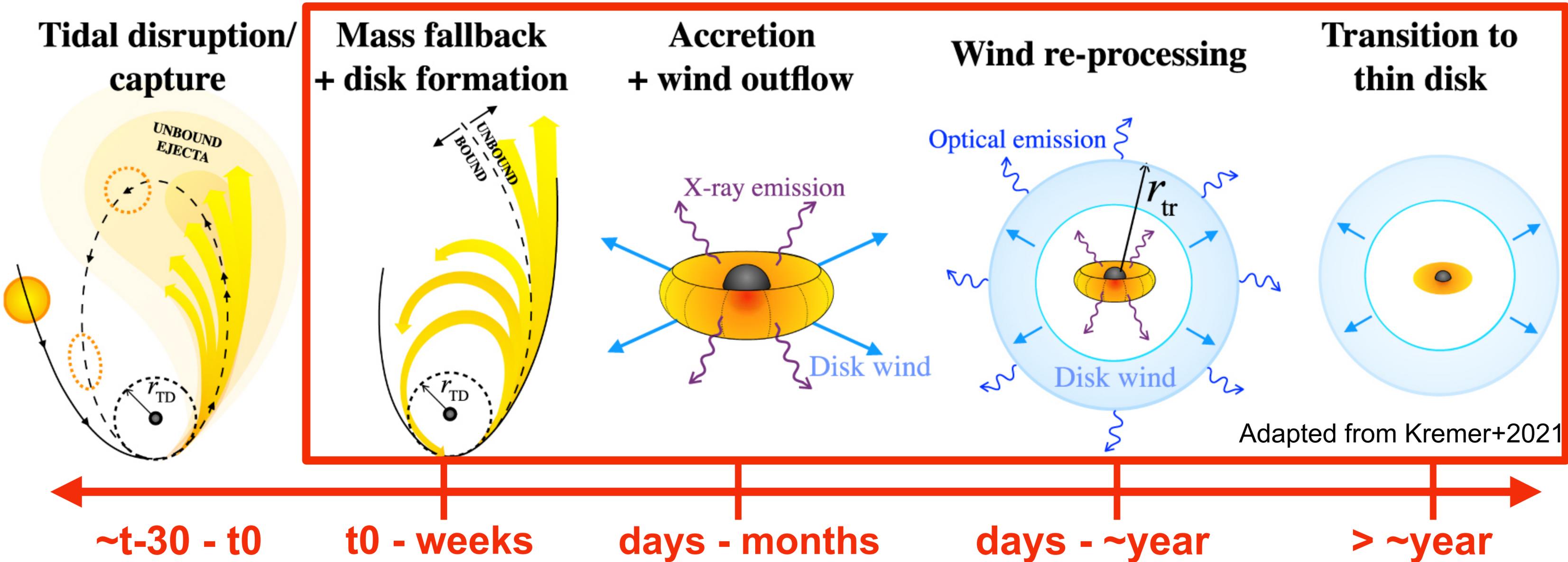
Observing Timeline



- Where t_0 is when we expect to detect first photons*

*pancake shock from initial disruption could potentially be observed for t_0 - weeks **very** nearby TDEs

Observing Timeline



- Where t_0 is when we expect to detect first photons*

*pancake shock from initial disruption could potentially be observed for $t_0 - \text{weeks}$ **very** nearby TDEs

Timeline: 0–48 hr

1. **Detection** with *Swift* or EP (X-rays) and/or discovery by ground-based optical sky surveys

2. **Swift**: UV photometry/X-ray:

Stream collisions/accretion disk at early times (before outflows obscure inner region),
constrain SED at early times

3. **Optical/ground based**:
variability, polarization, time of emergence of **optical lines**

4. **XMM**: X-ray spectrum:
Evidence of **winds**, X-ray spectra
constrain **disk properties**/**Mh**
constraints from disk

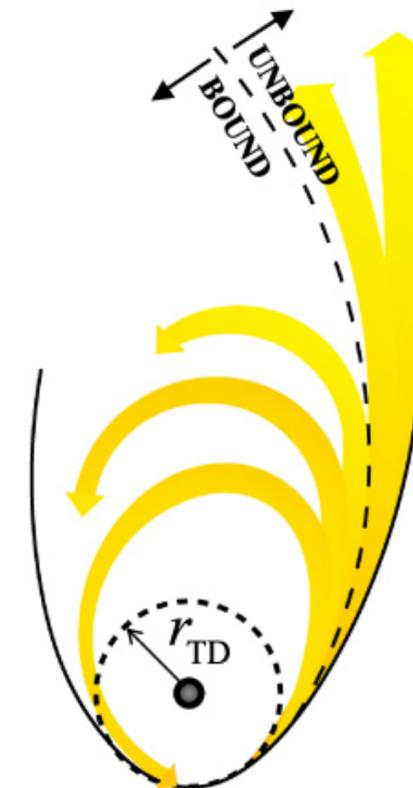
MBH accretion

MBH – host galaxy connection

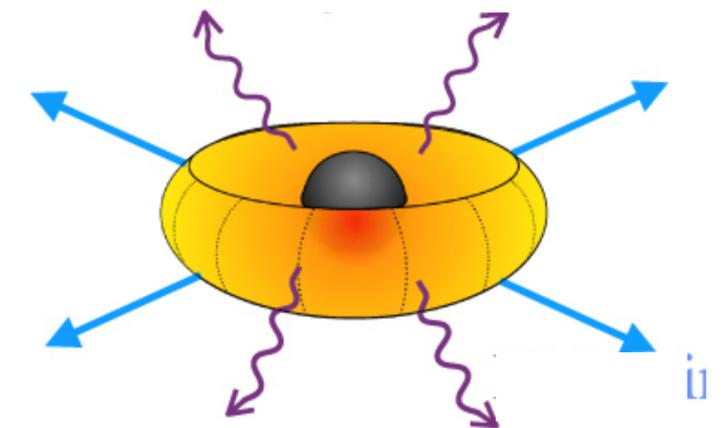
properties of quiescent MBHs

stars/compact object populations

**Mass fallback
+ disk formation**



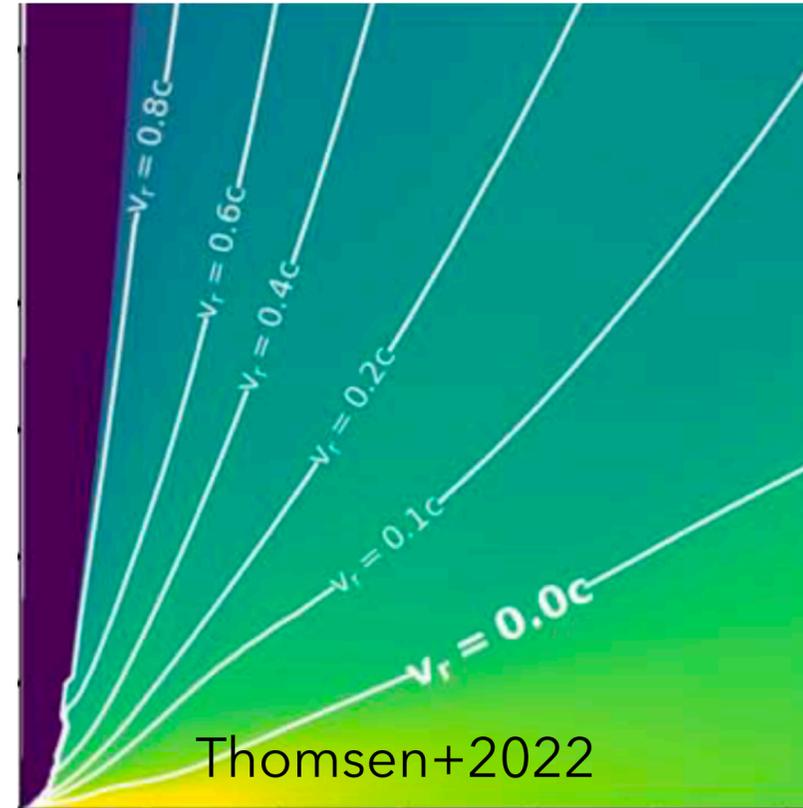
**Accretion
+ wind outflow**



Timeline: 0–48 hr

1. **Detection** with *Swift* or EP (X-rays) and/or discovery by ground-based optical sky surveys
2. **Swift**: UV photometry/X-ray: **Stream collisions/accretion disk** at early times (before outflows obscure inner region), **constrain SED** at early times
3. **Optical/ground based**: **variability, polarization**, time of emergence of **optical lines**
4. **XMM**: X-ray spectrum: Evidence of **winds**, X-ray spectra constrain **disk properties/Mh** **constraints from disk**

Disk

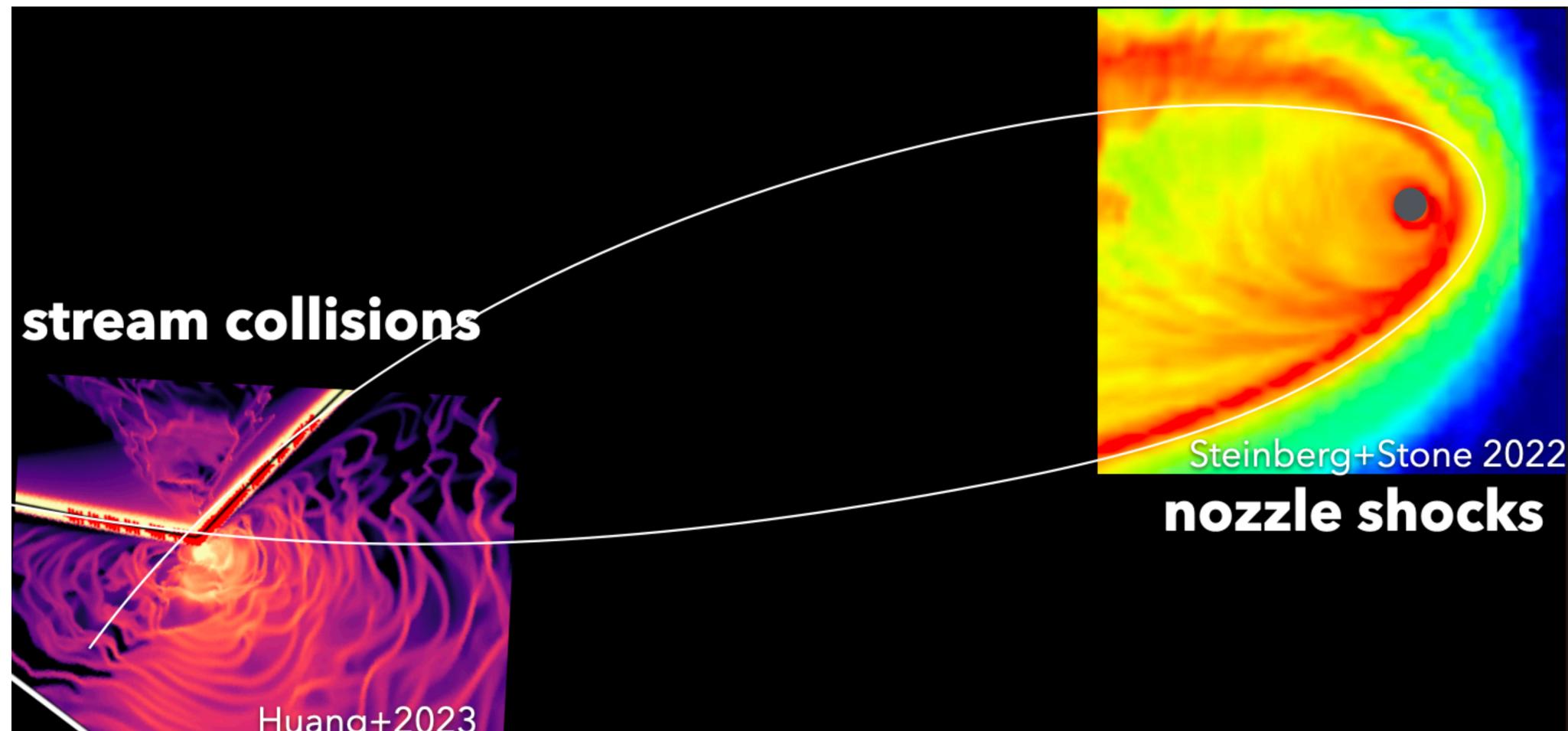


MBH accretion

MBH – host galaxy connection

properties of quiescent MBHs

stars/compact object populations



Timeline: **2 - 7 days** (light curve rise) & **weeks - year** (initial decline)

MBH accretion

MBH – host galaxy connection

properties of quiescent MBHs

stars/compact object populations

1. **Swift**: UV photometry/X-ray

a. **Constraints on disk energetics**

2. **Ground-based observatories**: Optical

a. **Constrain peak timescale to connect to fallback timescale & M_h**

b. **Polarization** \rightarrow stream collisions (more asymmetric) or disk winds?

c. **Optical variability** (compared to X-ray/UV)

d. **Outflow properties** from optical line shapes

a. **Gas conditions** from line widths and ratios/ constraints on amount of **mass bound to BH**

4. **XMM-Newton**: X-ray spectra

a. Evidence of **outflows from blueshifted absorption lines**

b. X-ray spectra constrain **disk properties/ M_h constraints** from continuum fitting of BB to disk model

5. **HST**: UV spectra

a. UV spectra constrain presence of **outflows through broad absorption lines**

b. **Composition constraints** on star at early times from UV line ratios

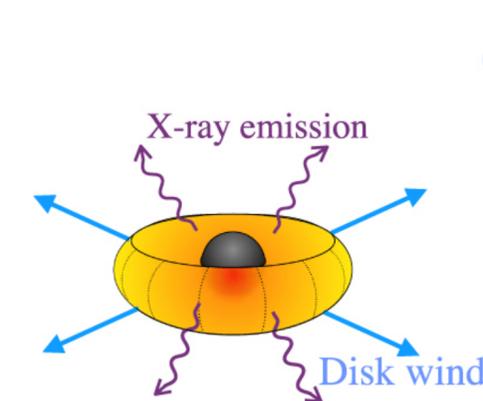
6. **Radio** (NOEMA/ALMA/SMA, VLA/MeerKAT/ATCA)

a. Constrain the presence of **jet/outflows** (look for synchrotron emission)/**spin constraints** from jet power

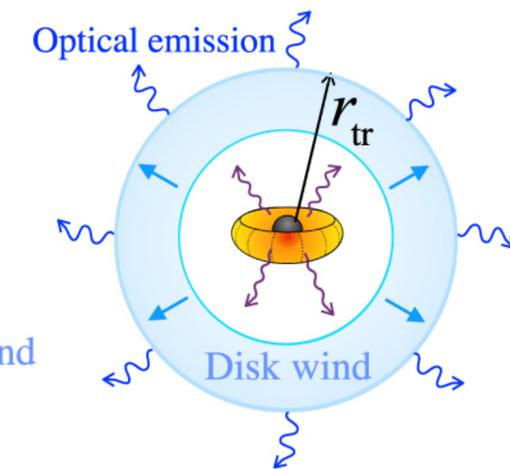
Mass fallback + disk formation



Accretion + wind outflow

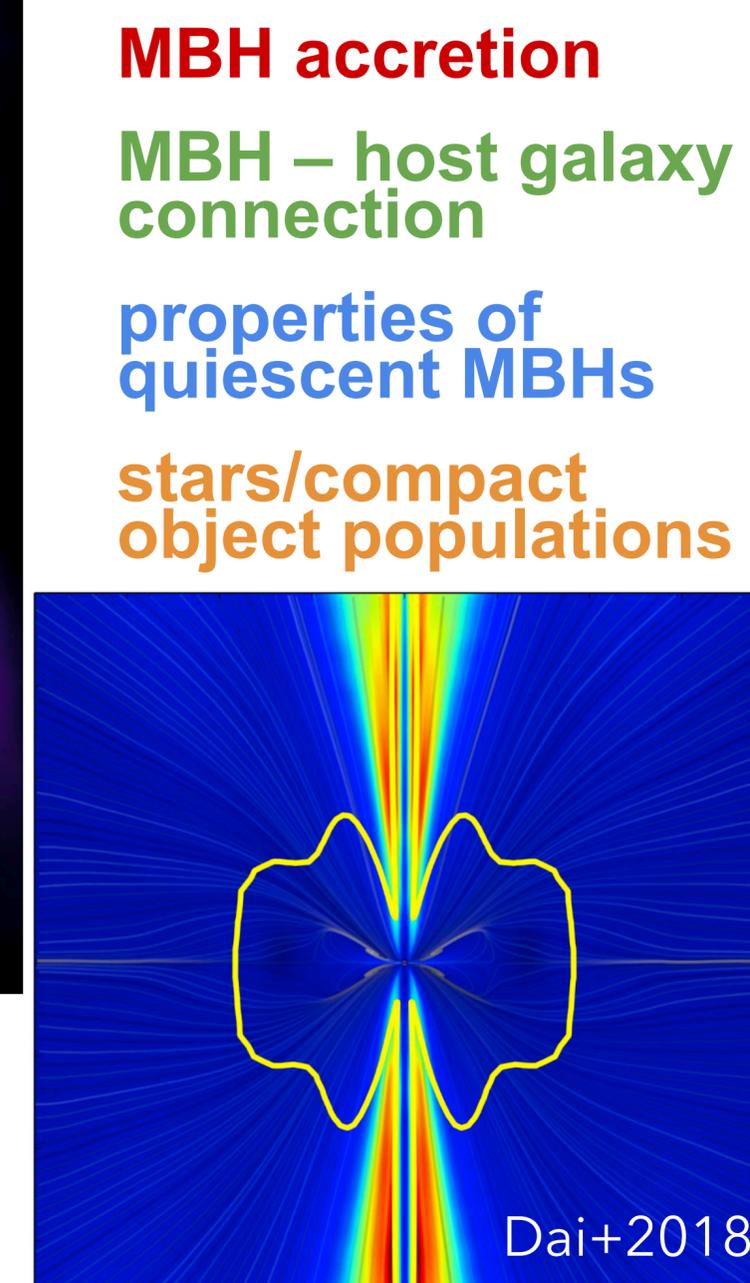
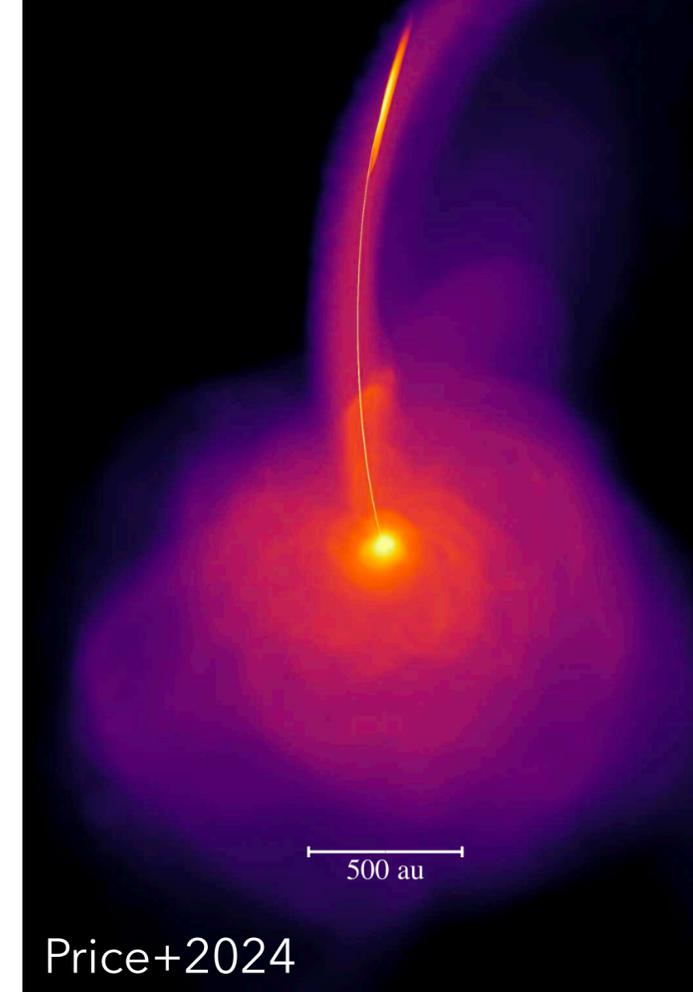


Wind re-processing



Timeline: **2 - 7 days** (light curve rise)
& **weeks - year** (initial decline)

1. **Swift**: UV photometry/X-ray
 - a. Constraints on disk energetics
2. **Ground-based observatories**: Optical
 - a. Constrain peak timescale to connect to fallback timescale & M_h
 - b. **Polarization** \rightarrow stream collisions (more asymmetric) or disk winds?
 - c. Optical **variability** (compared to X-ray/UV)
 - d. **Outflow properties** from optical line shapes
 - a. **Gas conditions** from line widths and ratios/ constraints on amount of mass bound to BH
4. **XMM-Newton**: X-ray spectra
 - a. Evidence of **outflows from blueshifted absorption lines**
 - b. X-ray spectra constrain **disk properties/ M_h constraints** from continuum fitting of BB to disk model
5. **HST**: UV spectra
 - a. UV spectra constrain presence of **outflows through broad absorption lines**
 - b. **Composition constraints** on star at early times from UV line ratios
6. **Radio** (NOEMA/ALMA/SMA, VLA/MeerKAT/ATCA)
 - a. Constrain the presence of **jet/outflows** (look for synchrotron emission)/**spin constraints** from jet power



Timeline: \sim year (decline/late time plateau)

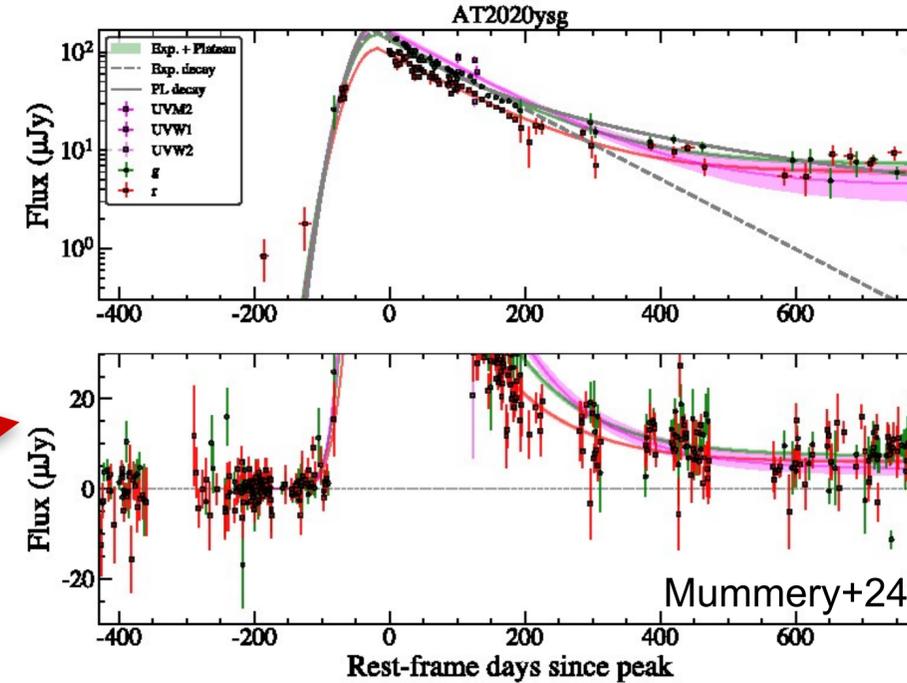
MBH accretion

MBH – host galaxy connection

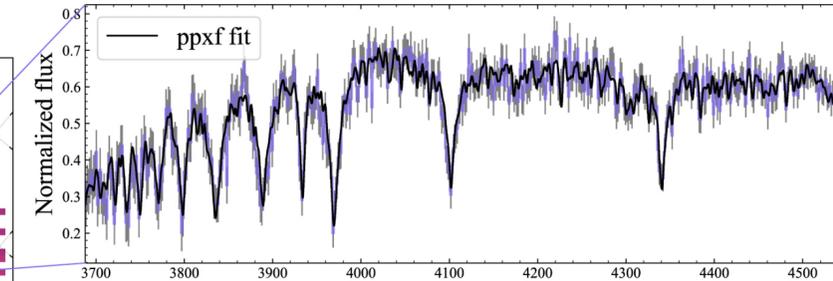
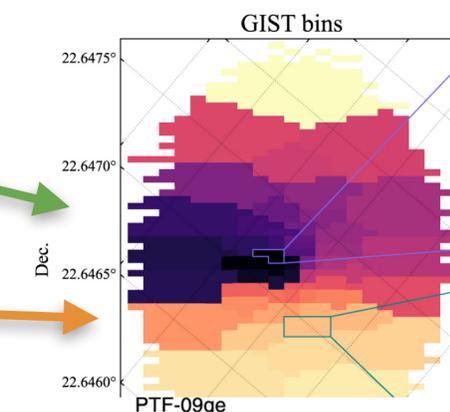
properties of quiescent MBHs

stars/compact object populations

- **Swift, X-ray observatories, HST, optical spectroscopy/photometry**
- **UV photometry**
 - How much energy released in optical/UV?
 - Long term disk evolution/BH mass from disk
- **Trigger host galaxy observations regardless of previous observations**

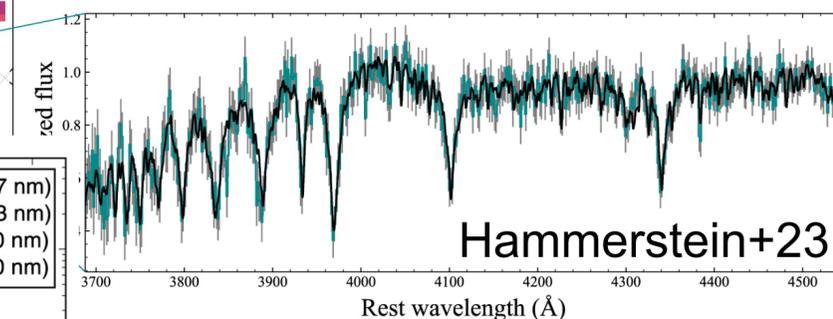


- High resolution optical spectroscopy to get **BH mass from stellar kinematics**
- HST imaging for high resolution host galaxy studies (**structure/morphology** and **stellar populations**)



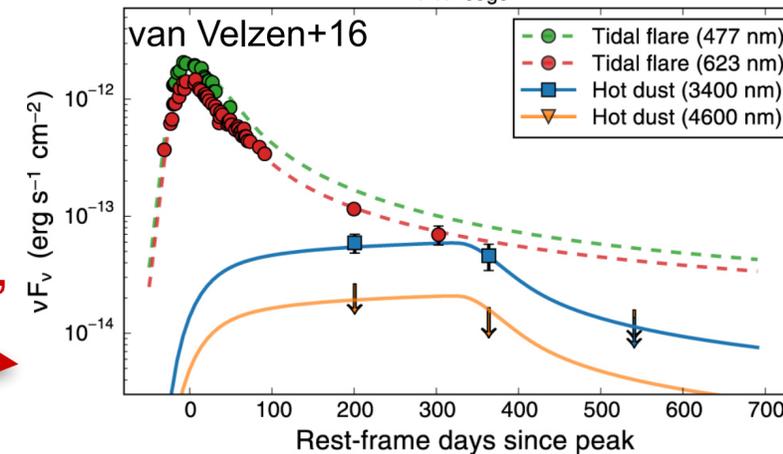
- **X-ray monitoring** regardless of prior detections

- Look for QPEs (**probes accretion, stellar populations**)
- **Evidence of disk formation**



- **IR**

- How much dust reprocessed energy? – constraint on FUV, expected peak of SED



Open Questions/ Under-explored parameter space

MBH accretion

MBH – host galaxy connection

properties of quiescent MBHs

stars/compact object populations

- **Pre-peak X-ray**

- **existence of a disk** is best probed in soft ($\sim 0.1-5$ KeV) X-rays,
- **Constraints on M_h , spin** from disk best probed by X-ray spectra

- **Short cadence X-ray follow-up at earliest times & late times**

- Early time X-ray variability data could be used to **study stream shocks, disk formation, disk stability**.
- Late-time X-ray variability studies have shown **QPEs** prefer TDE host galaxies (e.g. Chakraborty et al. 2025) --> potential connections to EMRI candidates, disk instability timescales

- **Pre-peak UV photometry**

- critical for constraining **pre-peak temperature evolution** to help differentiate between most likely **emission models**. Some indications temperatures may be higher pre-peak/that UV may peak before optical, but limited number of events with pre-peak UV data mean it has been difficult to do a population study. **This will also provide better constraints on the bolometric luminosity.**

Open Questions/ Under-explored parameter space

- **UV spectra — both pre & post-peak**

- Improved energetics, temperature evolution

- **UV line ratios constrain composition** of the disrupted star (similar to AGN studies)

- **UV broad absorption lines indicate presence and velocity of outflows** --> existence (or lack) of outflows may point to different mechanisms for the origin of optical emission.

- Early time optical lines less prominent --> concurrent **UV spectra probe** if this is due to **ionization state**, improving our understanding of formation of spectra

MBH accretion

MBH – host galaxy connection

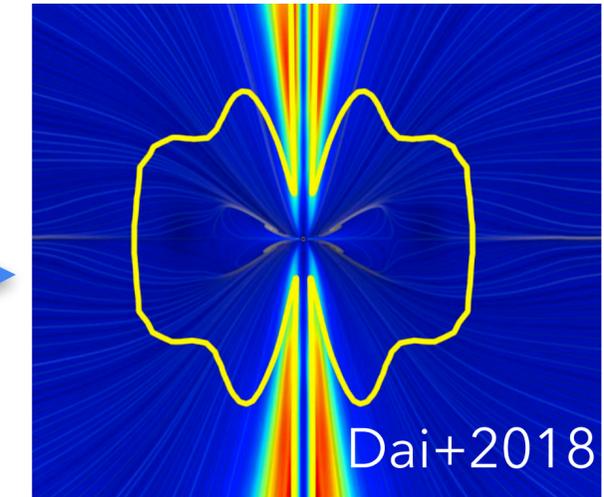
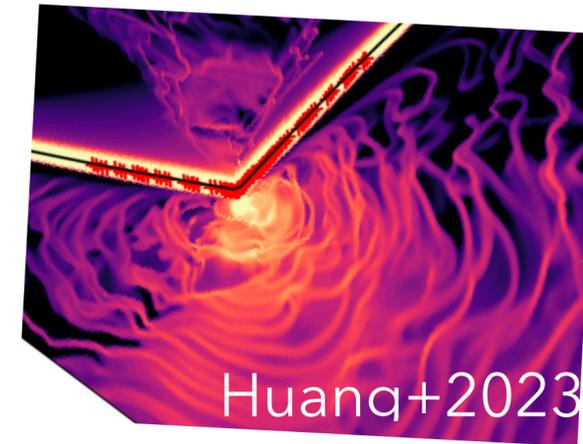
properties of quiescent MBHs

stars/compact object populations

Open Questions/ Under-explored parameter space

- **Pre- and post- peak polarization measurements**

- Constraining polarization at early and late times will help **constrain the emission mechanism and disk formation timescale** --> at early times, gas around BH likely comes from stream collision and stream-disk shock driven outflows which are more asymmetric than a puffy super-eddington disk.



- **Radio follow-up over initial optical light curve**

- Early time detections (& upper limits!) determine **when outflows are launched** as well as how many outflows are launched. Provides information on **disk formation** (shock-driven outflows) **and evolution** (state change or instability-driven outflows).

MBH accretion

MBH – host galaxy connection

properties of quiescent MBHs

stars/compact object populations