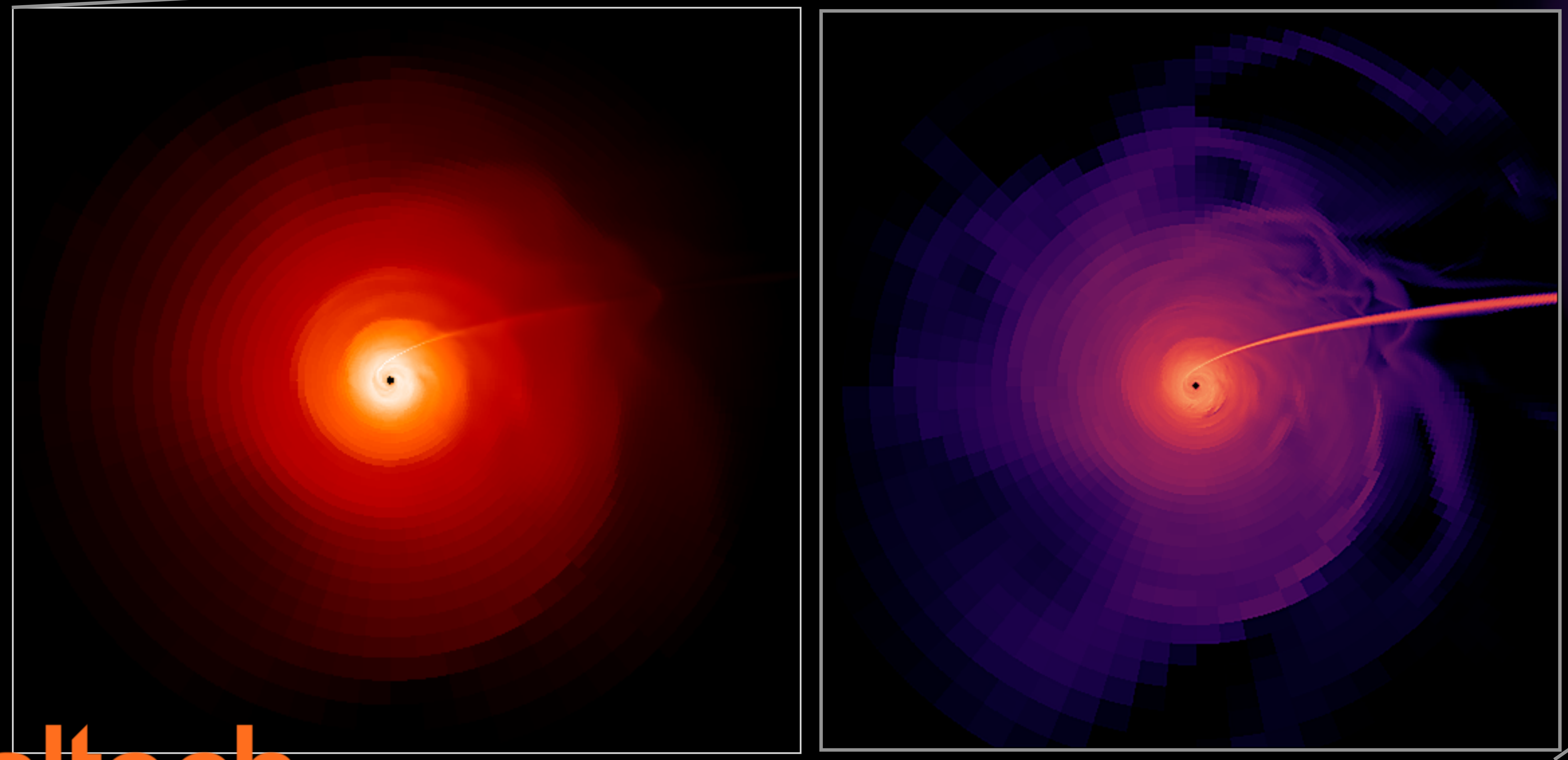
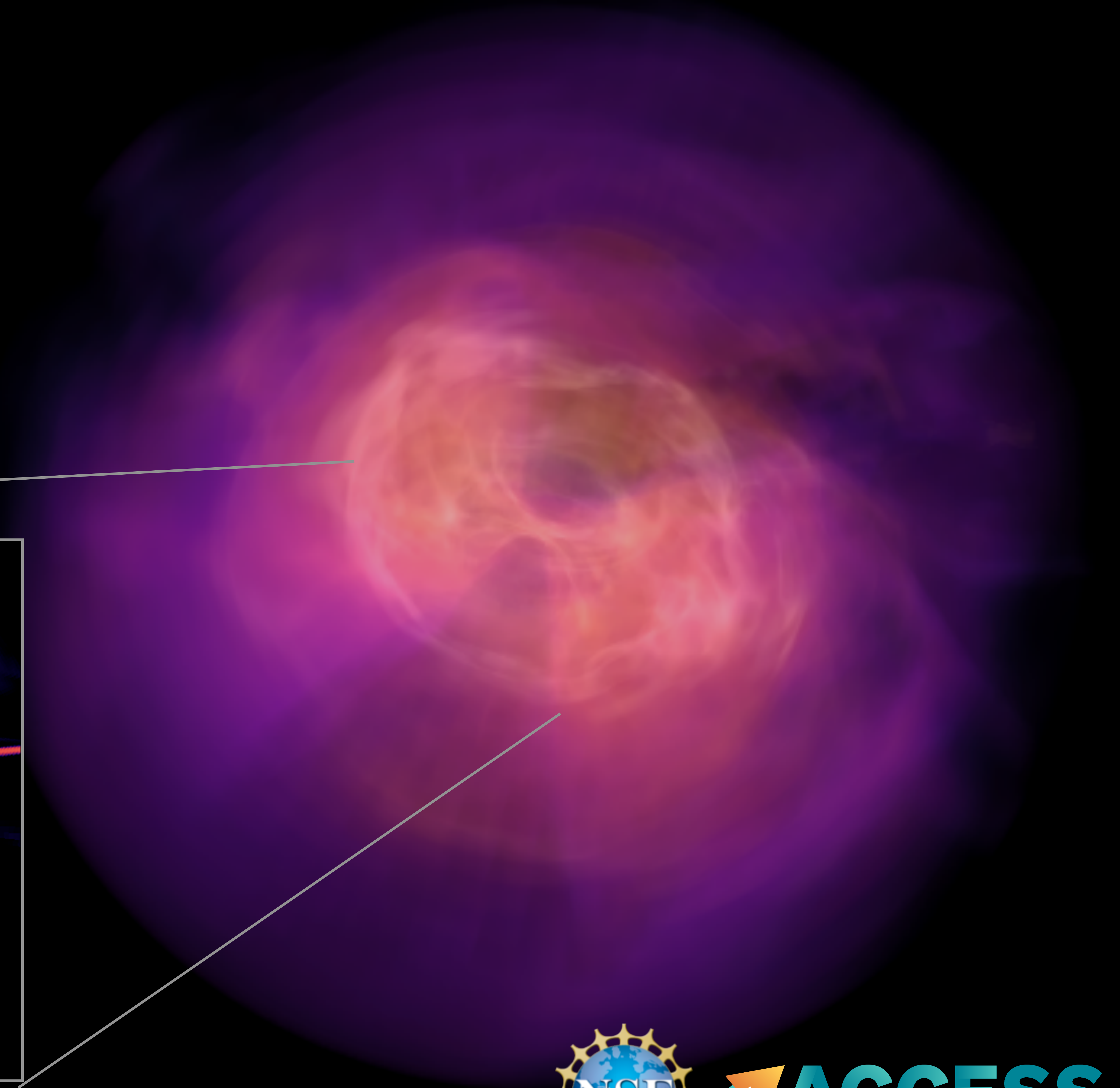
Tidal Disruption Events

Xiaoshan Huang

With Maria Renee Meza, Sol-bin Hazel Yun, Yuhan Yao, Brenna Mockler, Shane W. Davis, Yan-fei Jiang

Oct 29, TDAMM, Huntsville





Caltech

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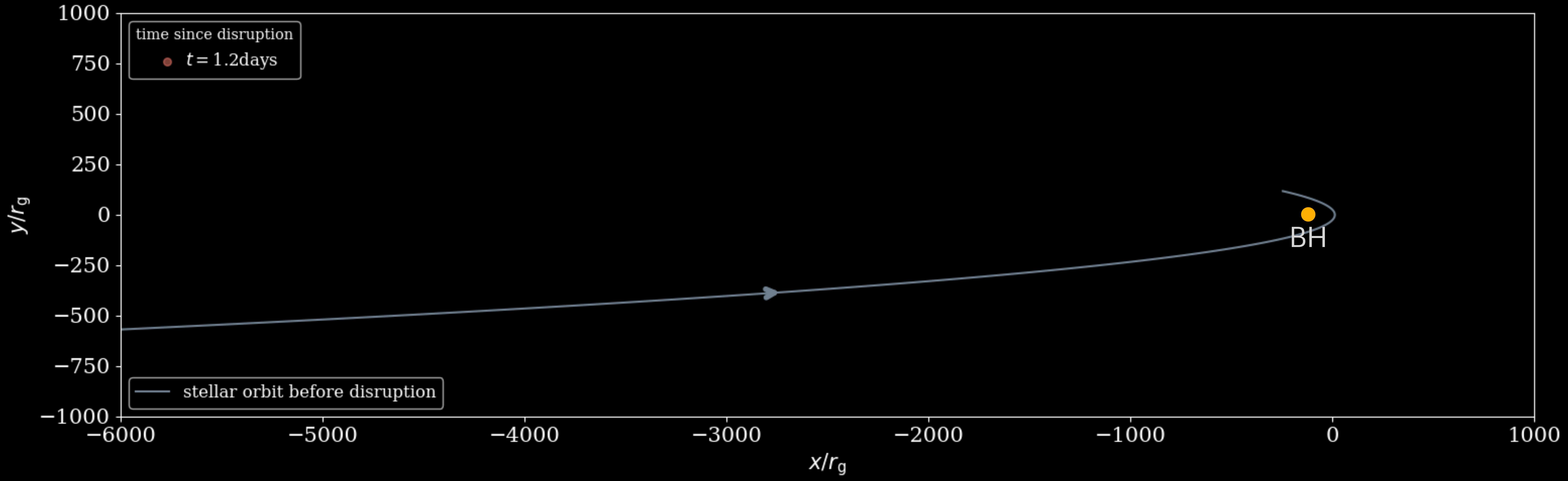
Tidal Disruption Events

- Transient feeding of black hole

Star on parabolic orbit gets close to BH, pericenter~tidal radius

Star is **tidally disrupted** around pericenter of orbit, debris from elongated stream



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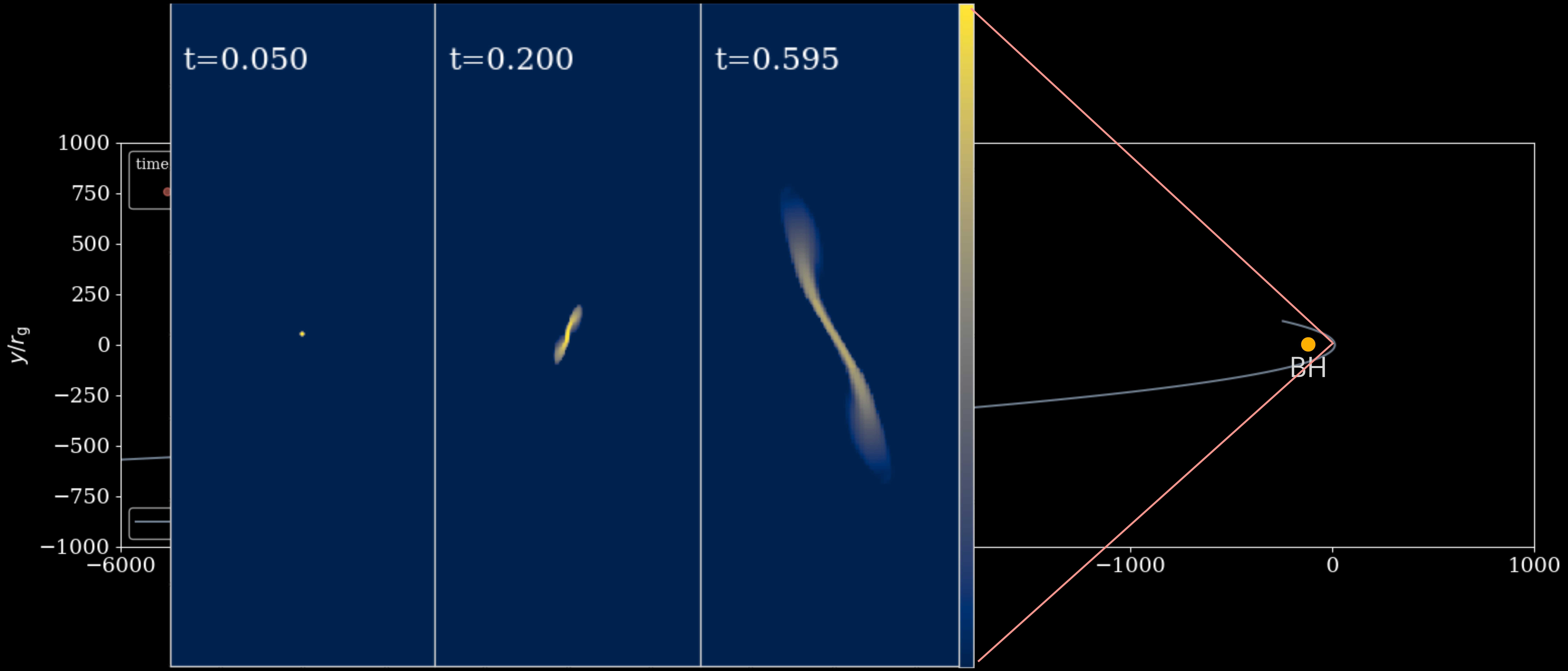

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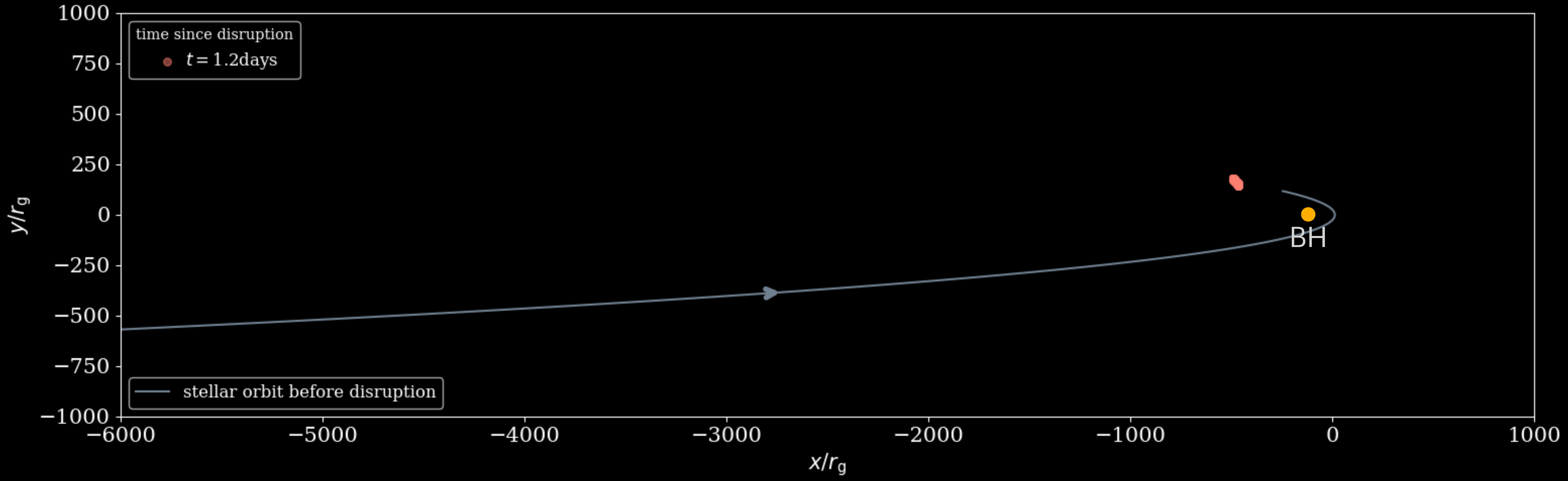
Quiescent black hole is activated, likely **super-Eddington accretion**



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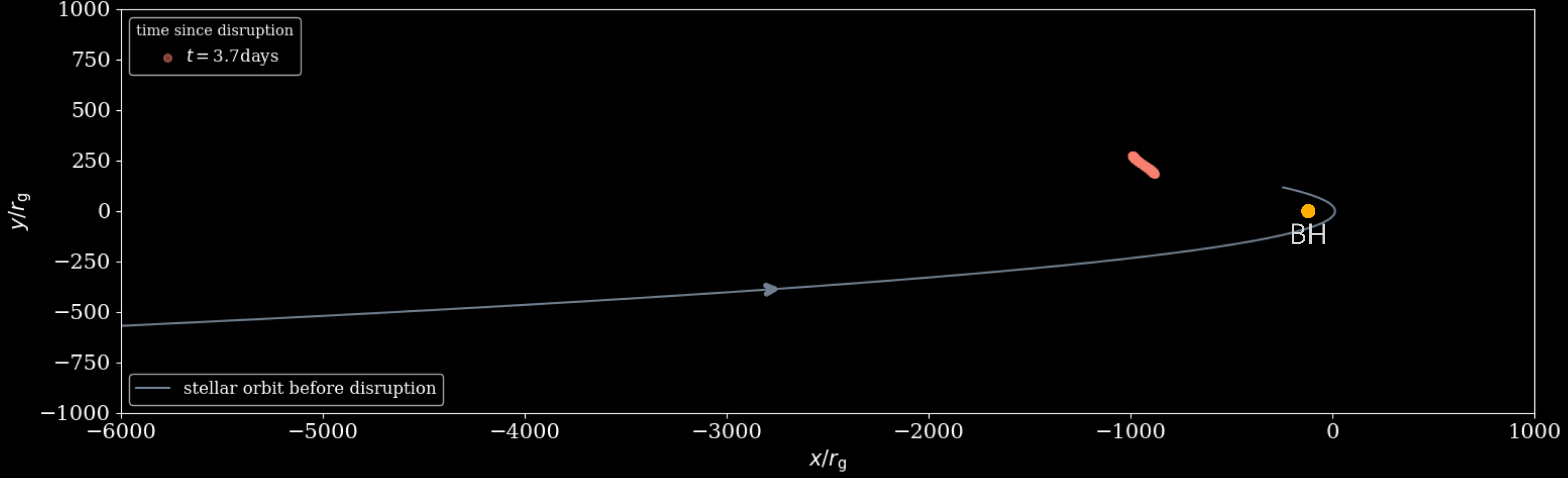

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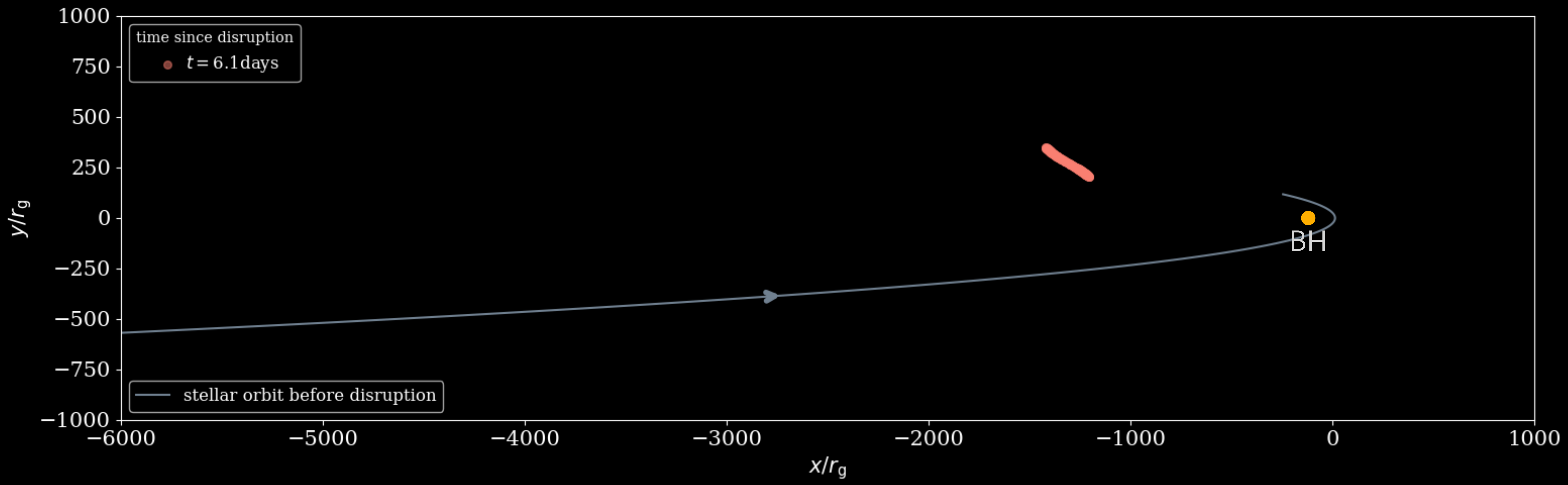

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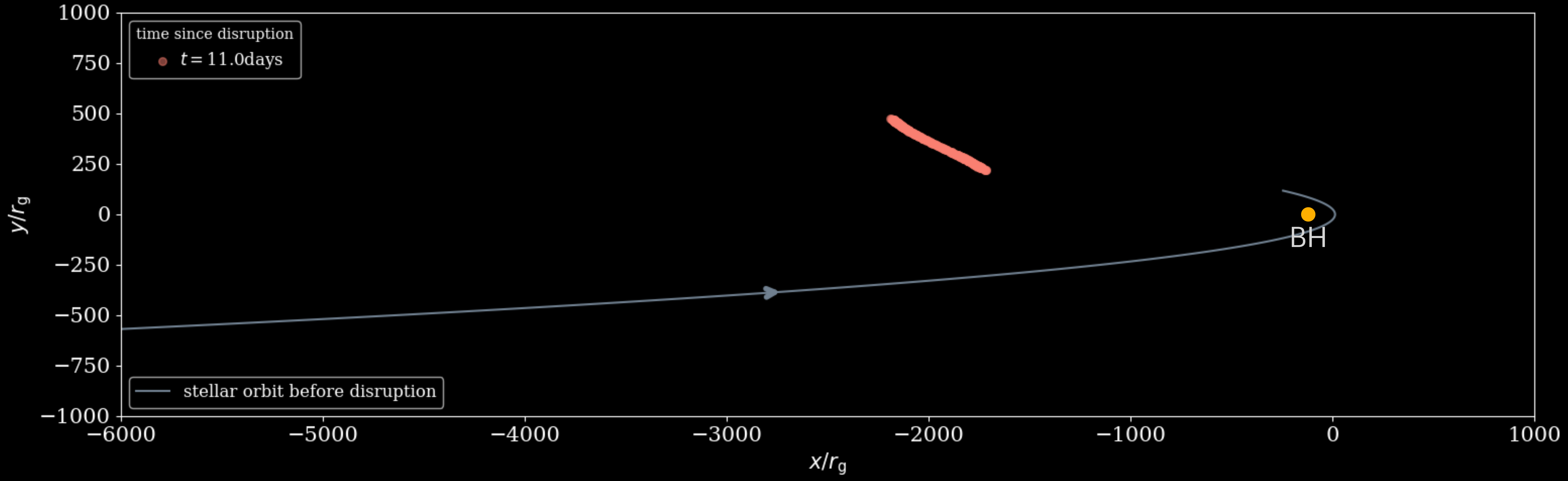

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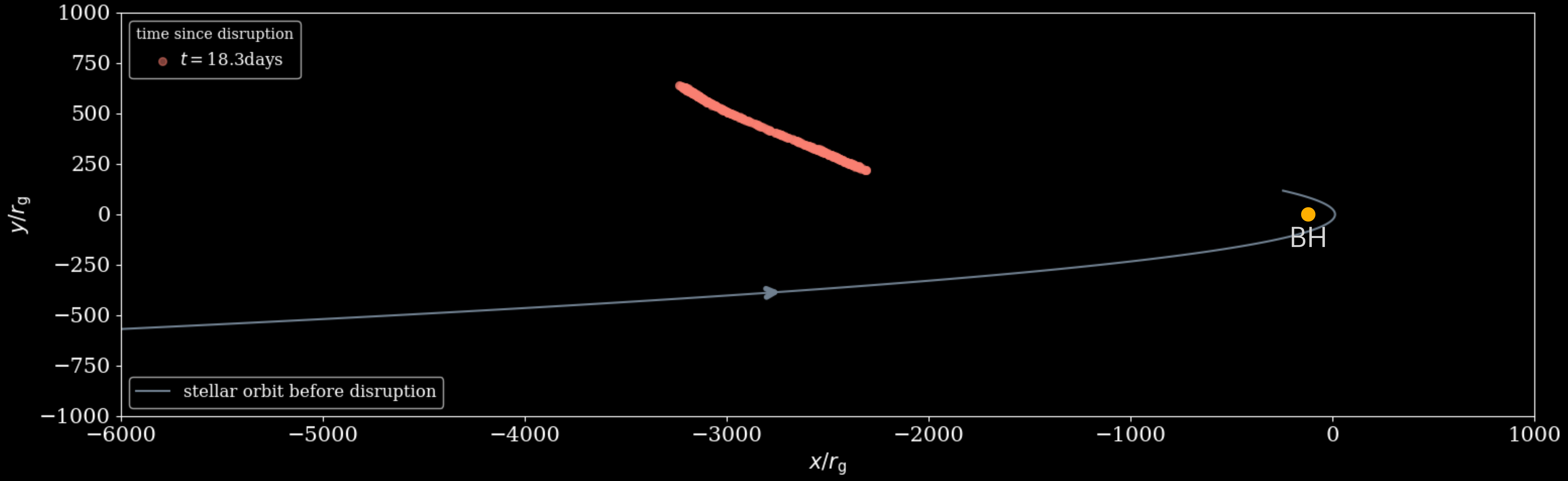

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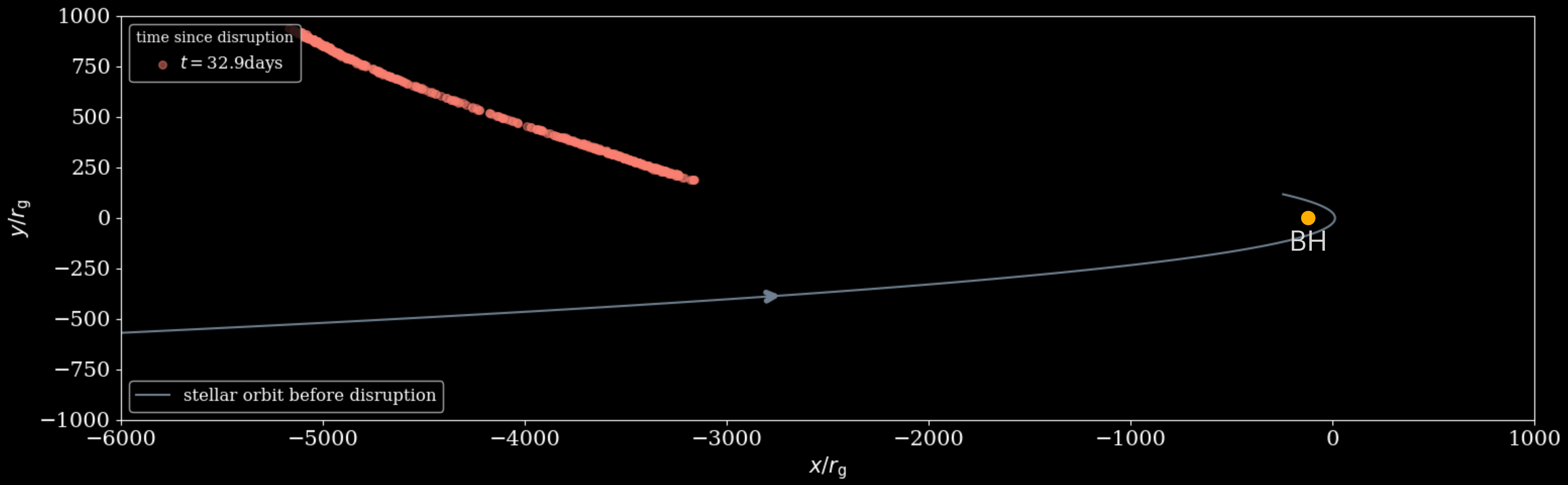

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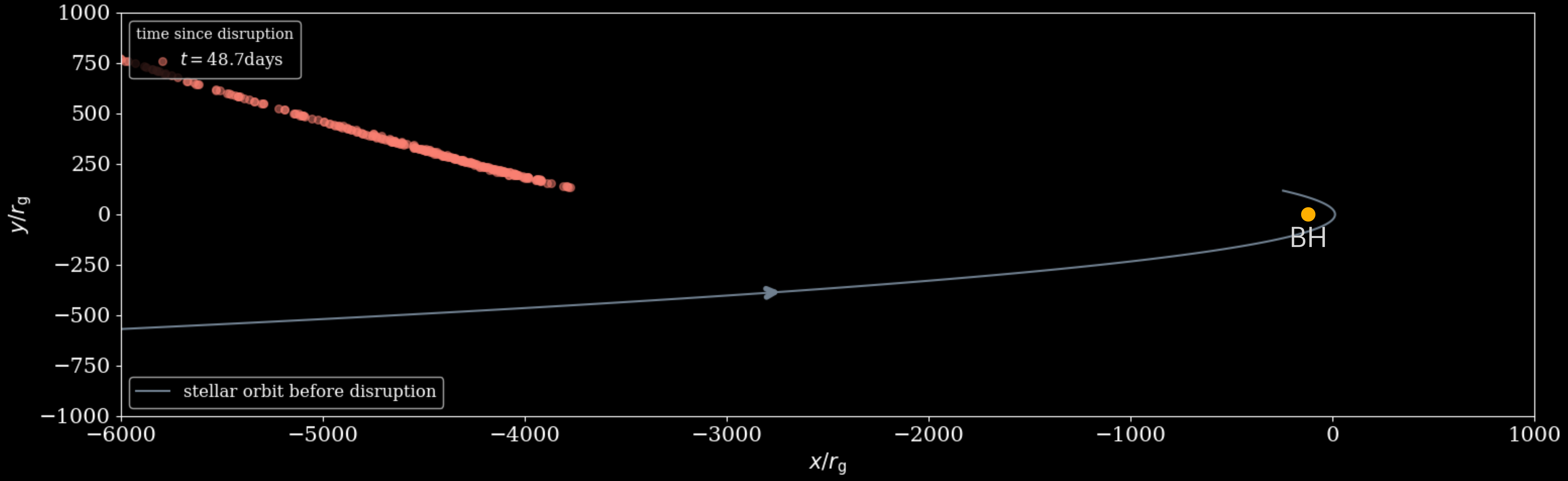

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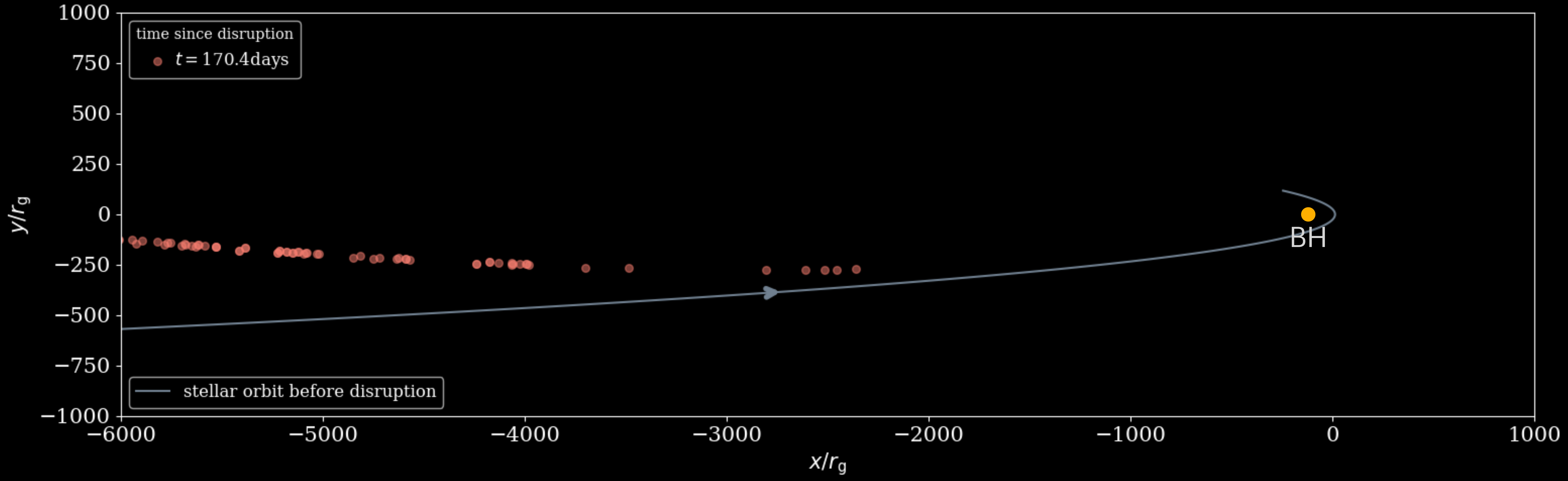

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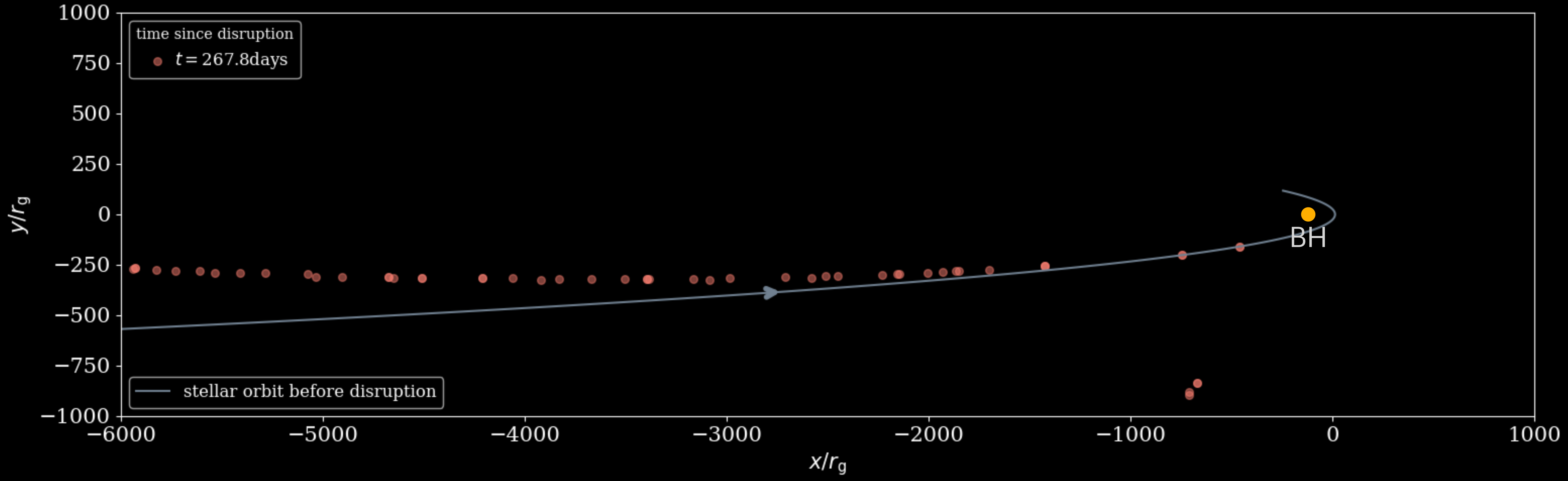
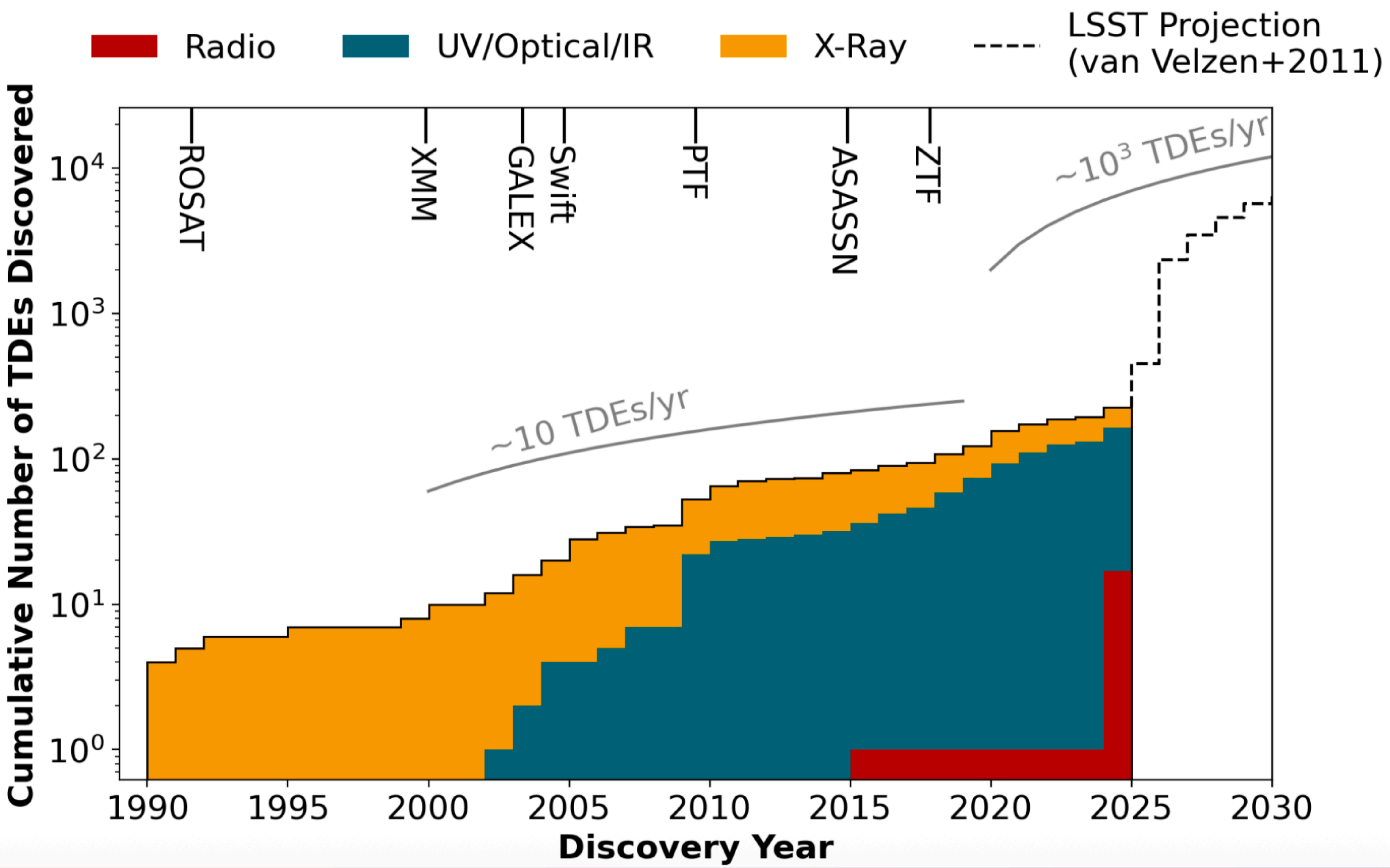


Tidal Disruption Events

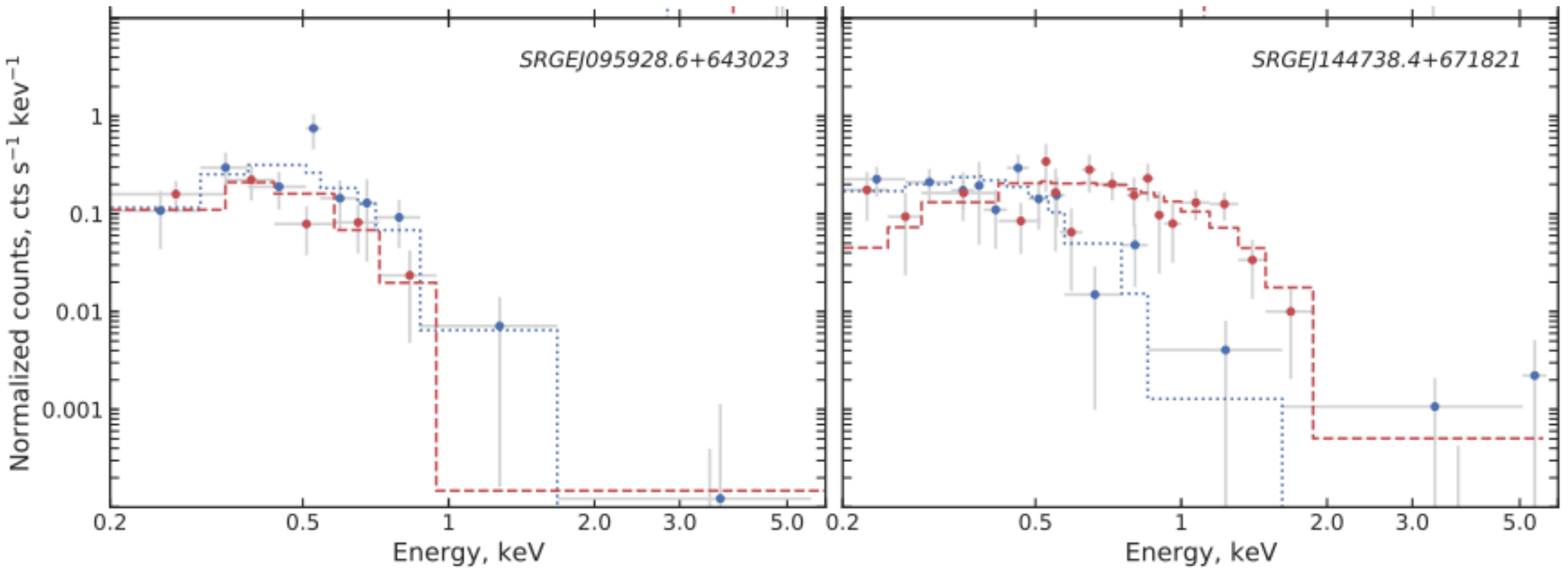
A Fast-evolving Field!



(Franz, Alexander et al 2025)

Multi-band Emitters

At first, we thought they're in (soft) X-ray, $k_B T_{\rm eff} \sim k_B \left(\frac{3GM_{\rm BH}\dot{M}}{8\pi\sigma R_{\rm ISCO}^3}\right)^{1/4} \approx 100\,{\rm eV} \left(\frac{\dot{\rm M}}{\dot{\rm M}_{\rm Edd}}\right)^{1/4} \left(\frac{\rm M_{BH}}{10^6 {\rm M}_\odot}\right)^{-1/4}$



(Sazonov et al 2021)

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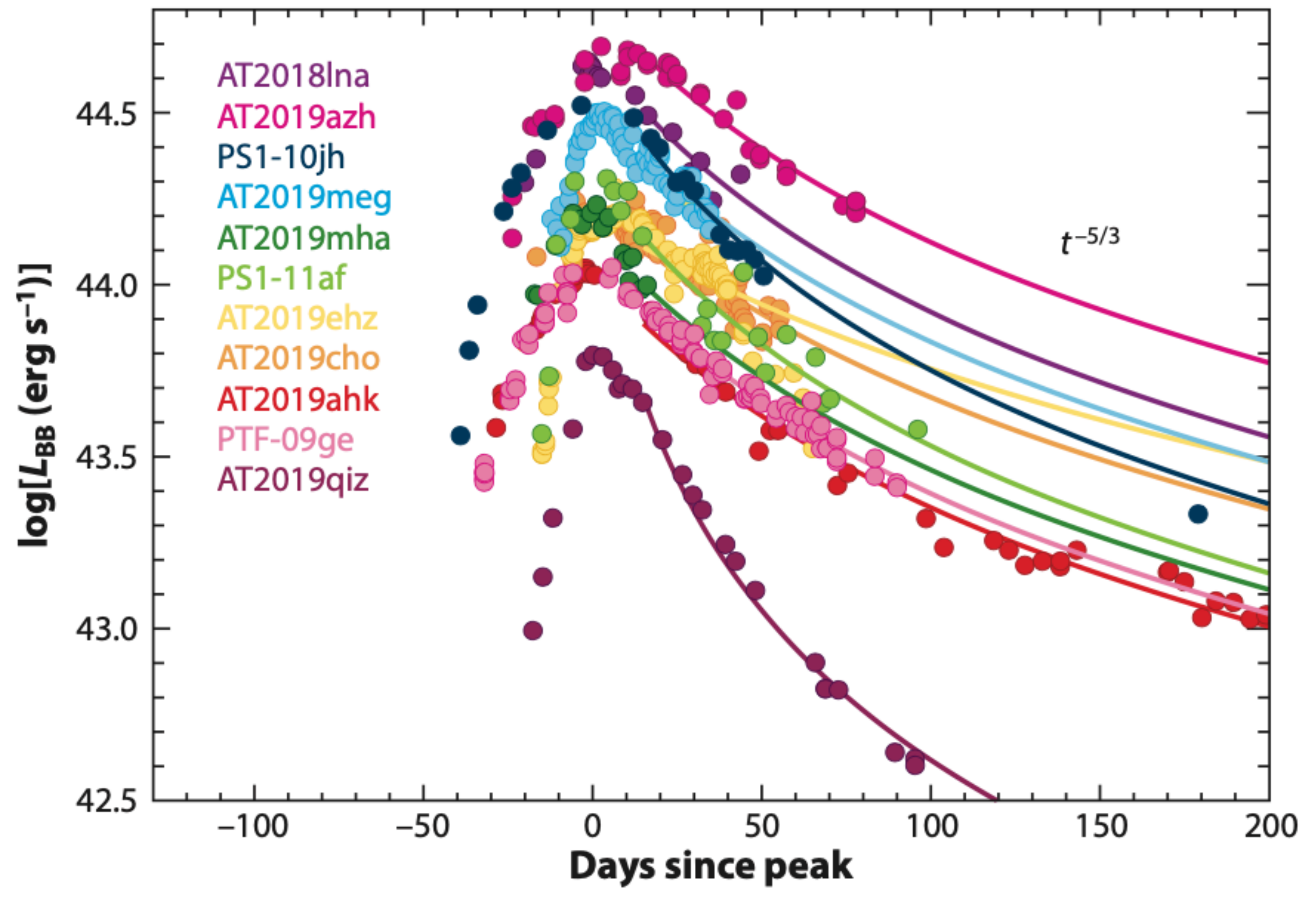

Photometry: smooth rise, t^-5/3 decay

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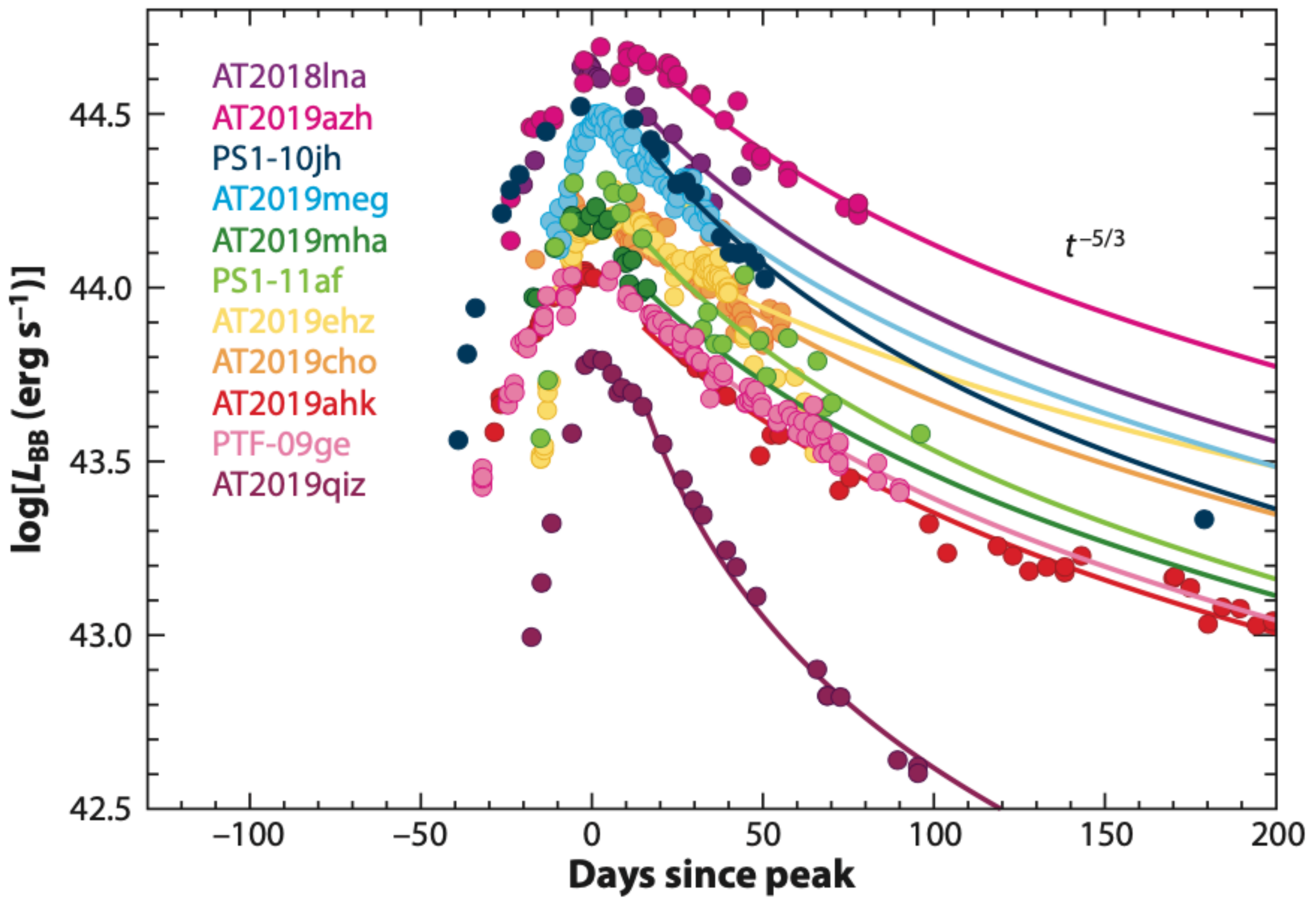

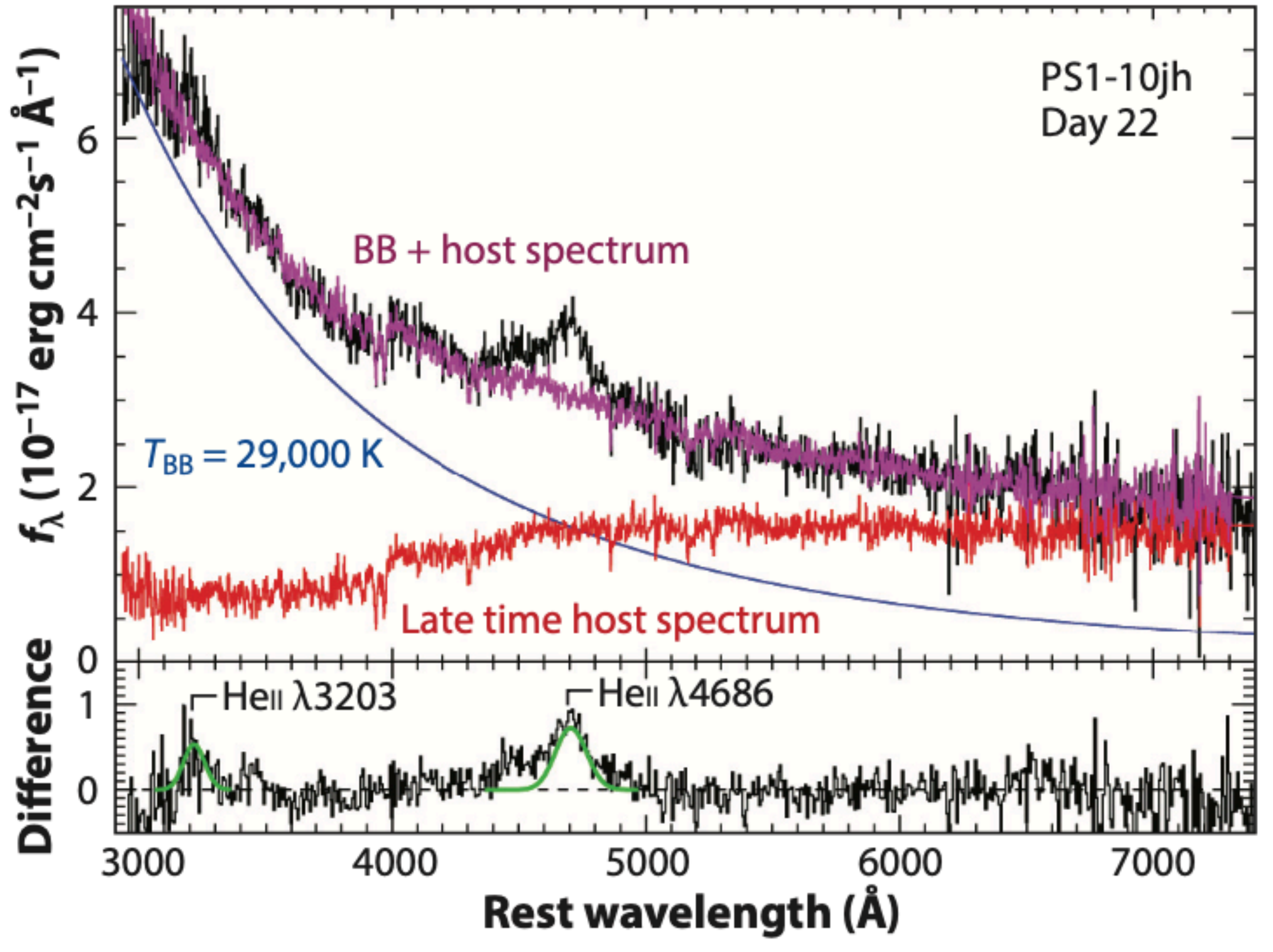

(Gerazi et al 2021)

Photometry: smooth rise, t^-5/3 decay
Spectroscopy: continuum + emission lines, low photosphere temperature, larger photosphere size

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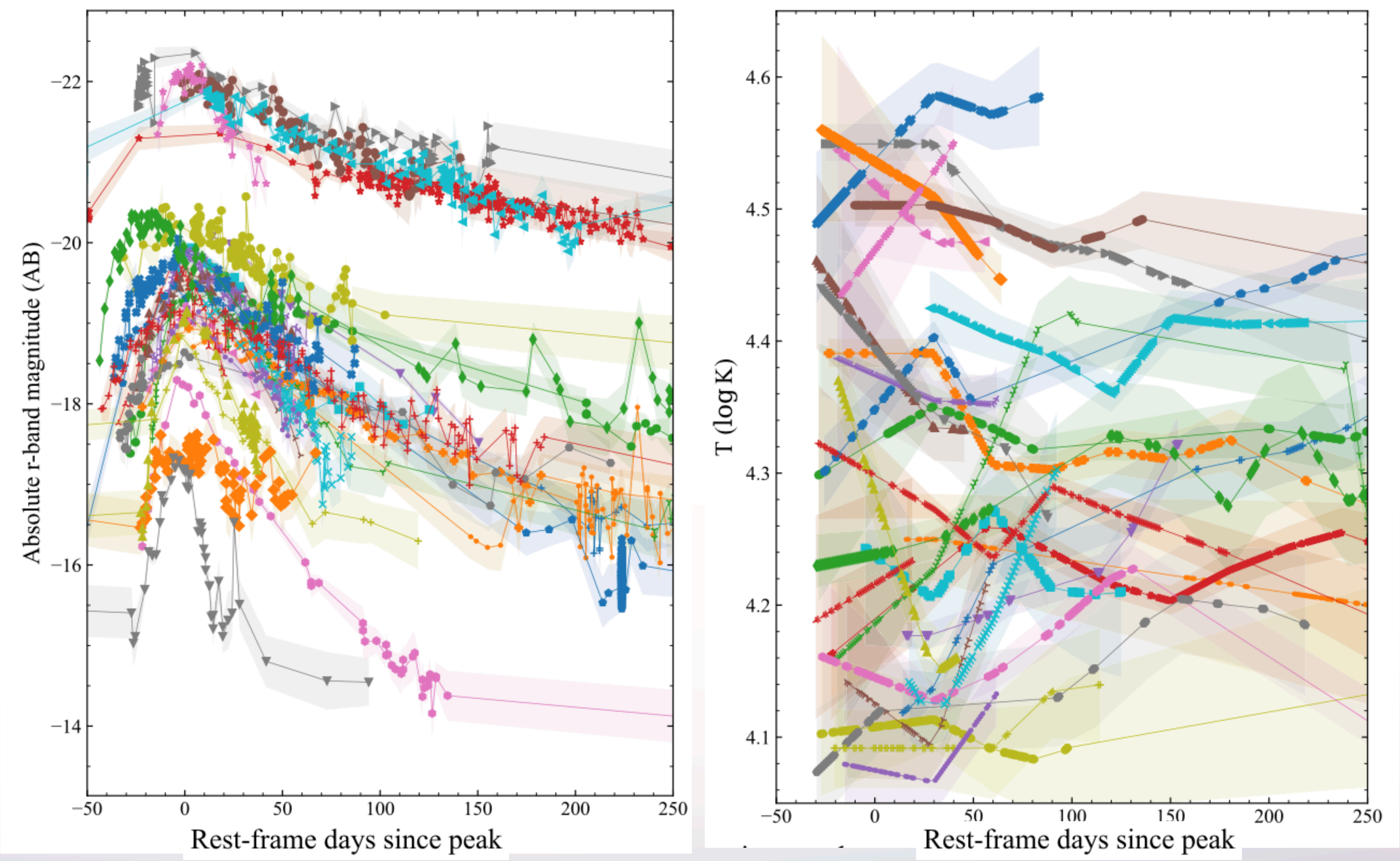

(Hammerstein et al 2023)

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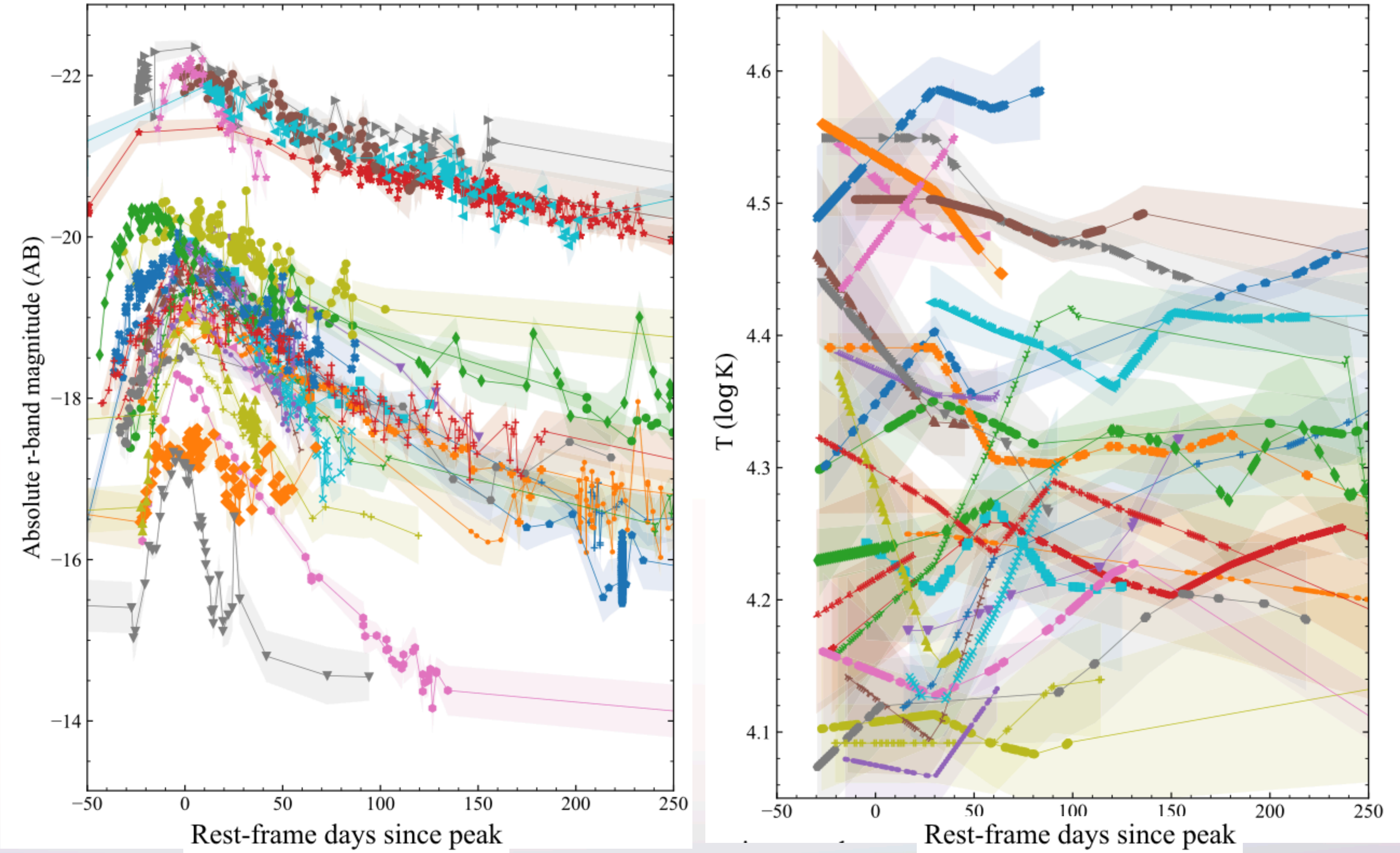
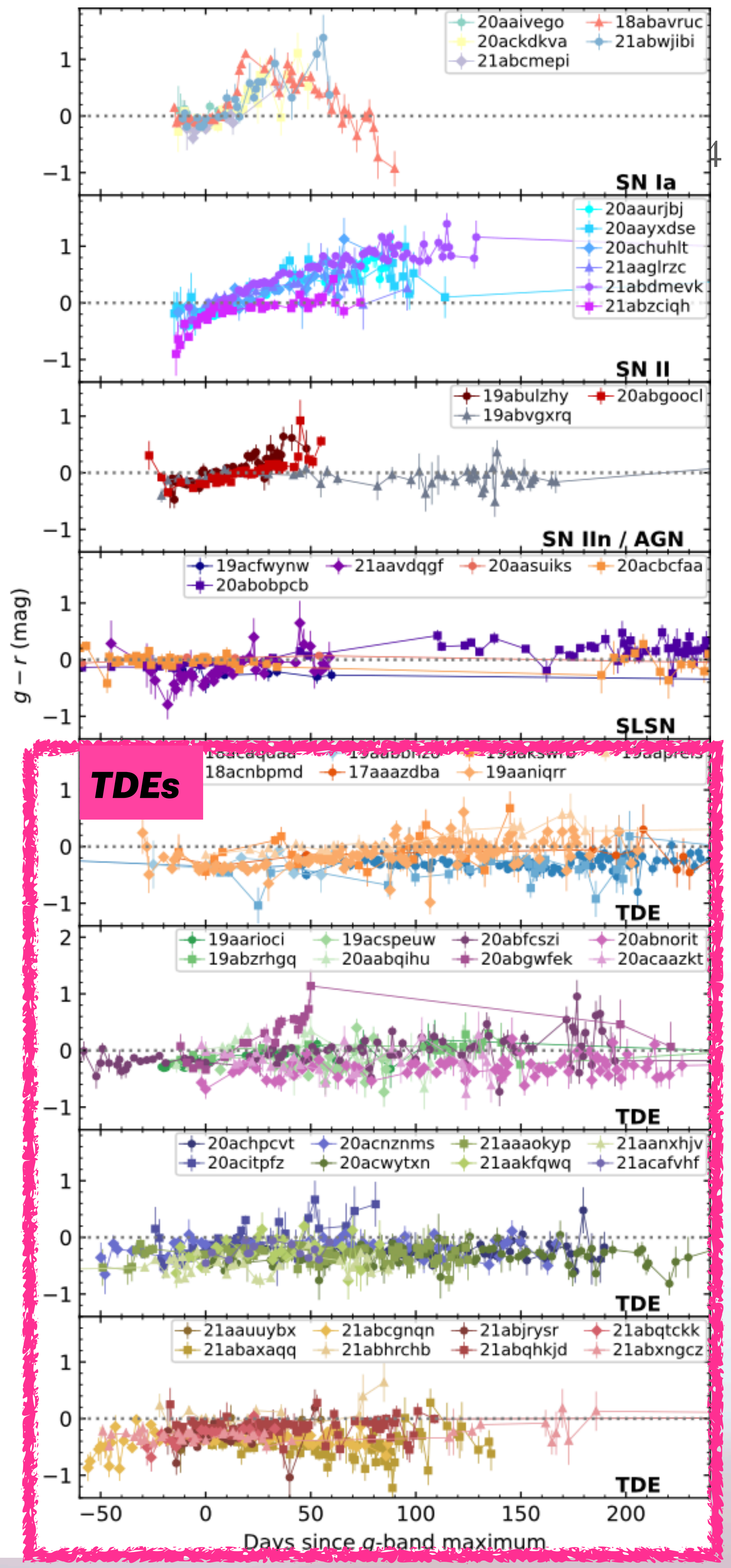


(Hammerstein et al 2023)

"Color": g-r magnitude



(Yao et al 2023)

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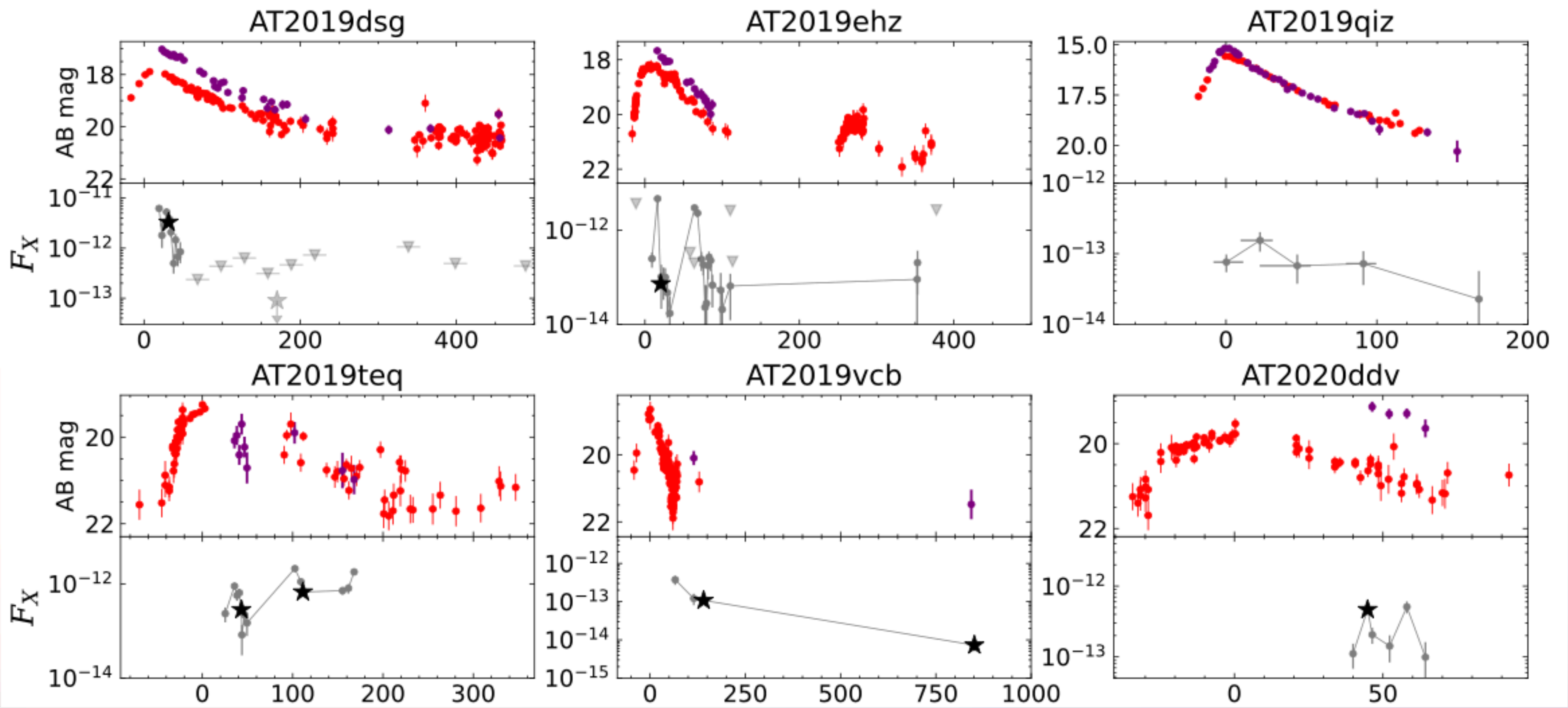
Multi-band emission source, X-ray to optical ratio show diverse evolution



(Guolo et al 2023)

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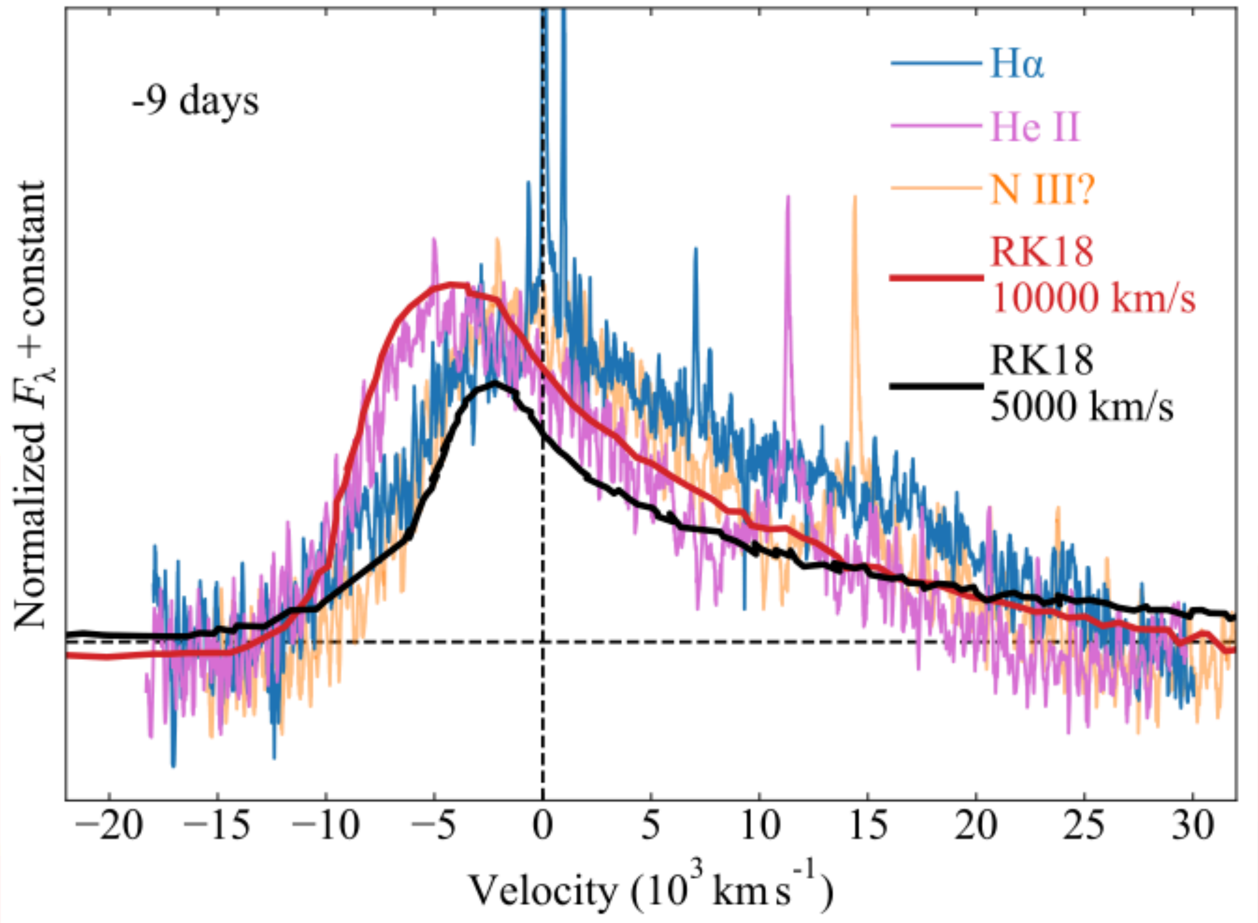
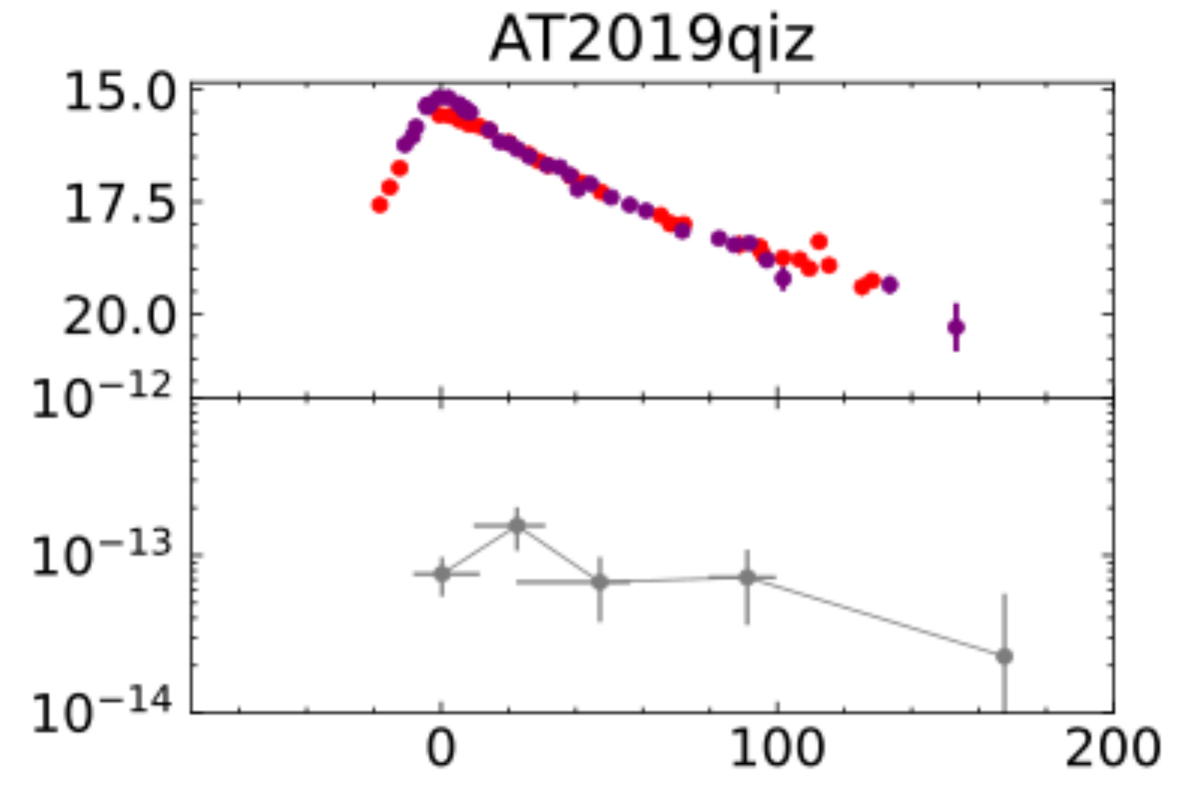
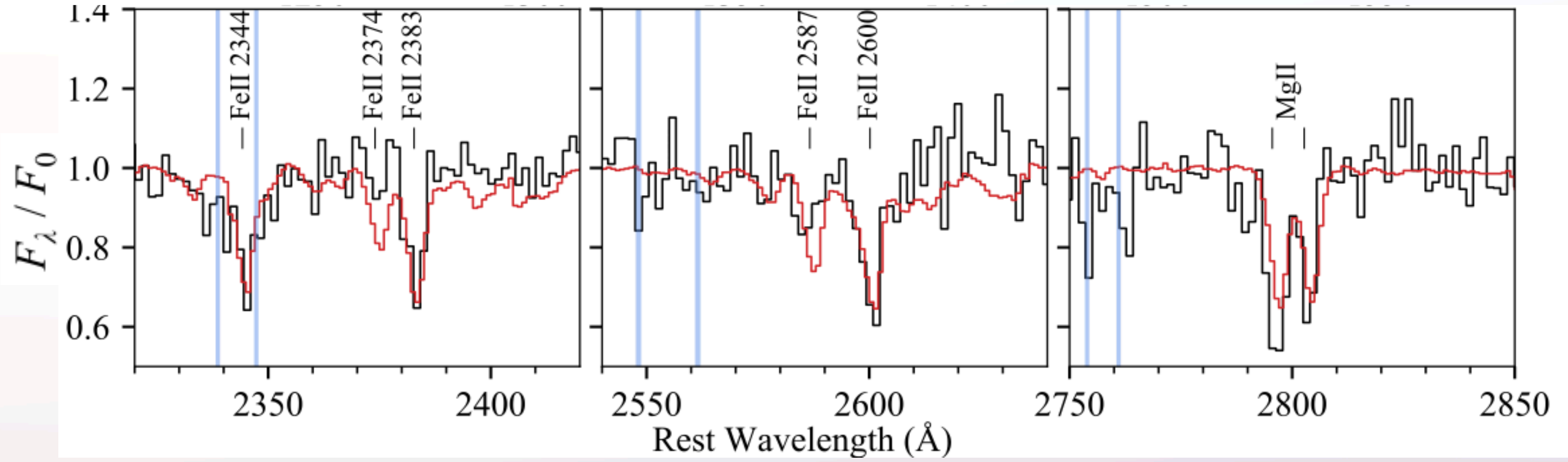
Rich dynamics revealed by spectroscopy analysis in nearby TDE AT2019qiz



(Nicholl et al 2020)

Transient blue-shifted emission lines suggest expanding outflow at -9days





(Hung et al 2021)

Low-ionization absorption lines (e.g. NV, SiII, CII...), first detection of Iron lines,

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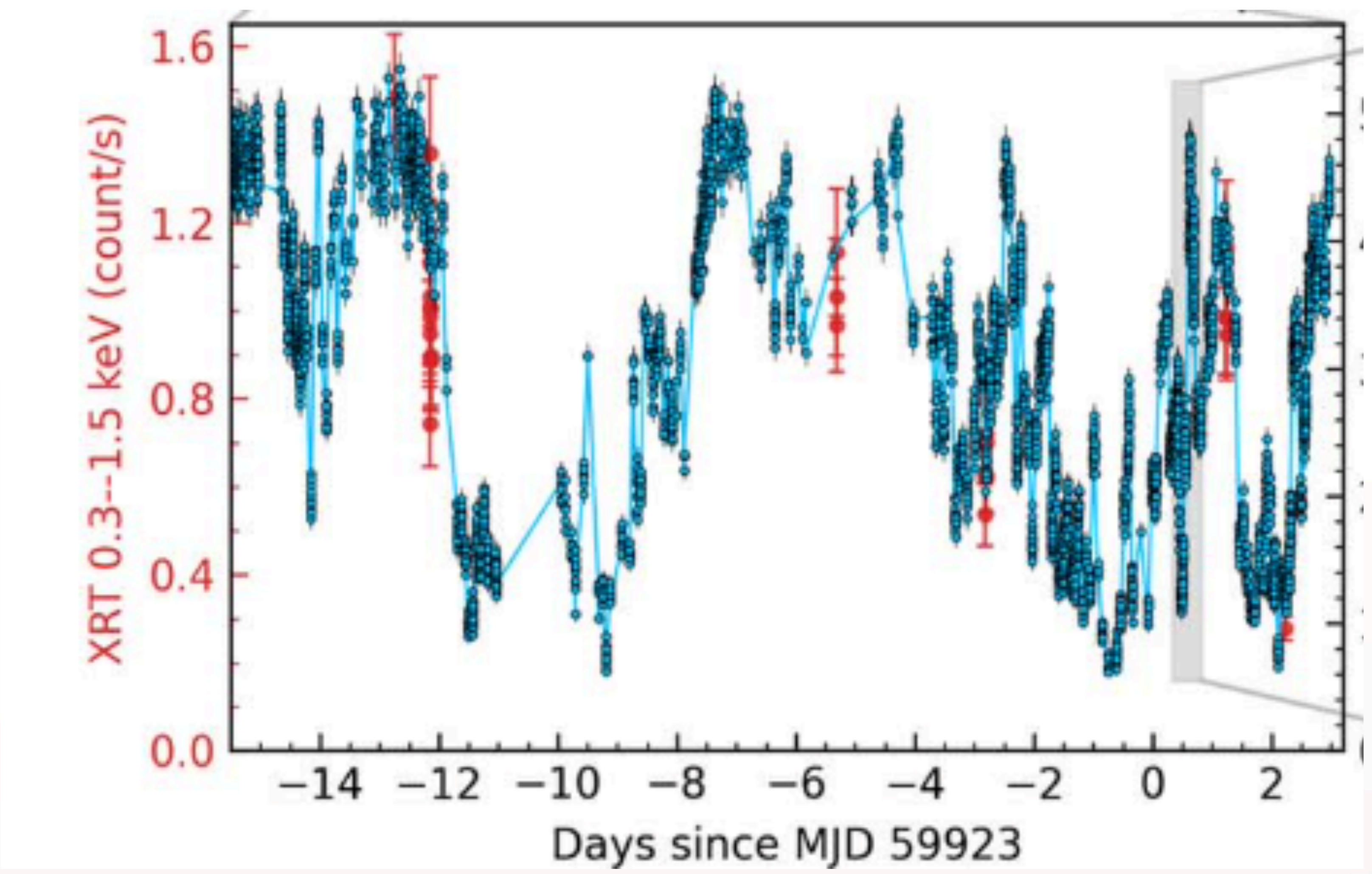
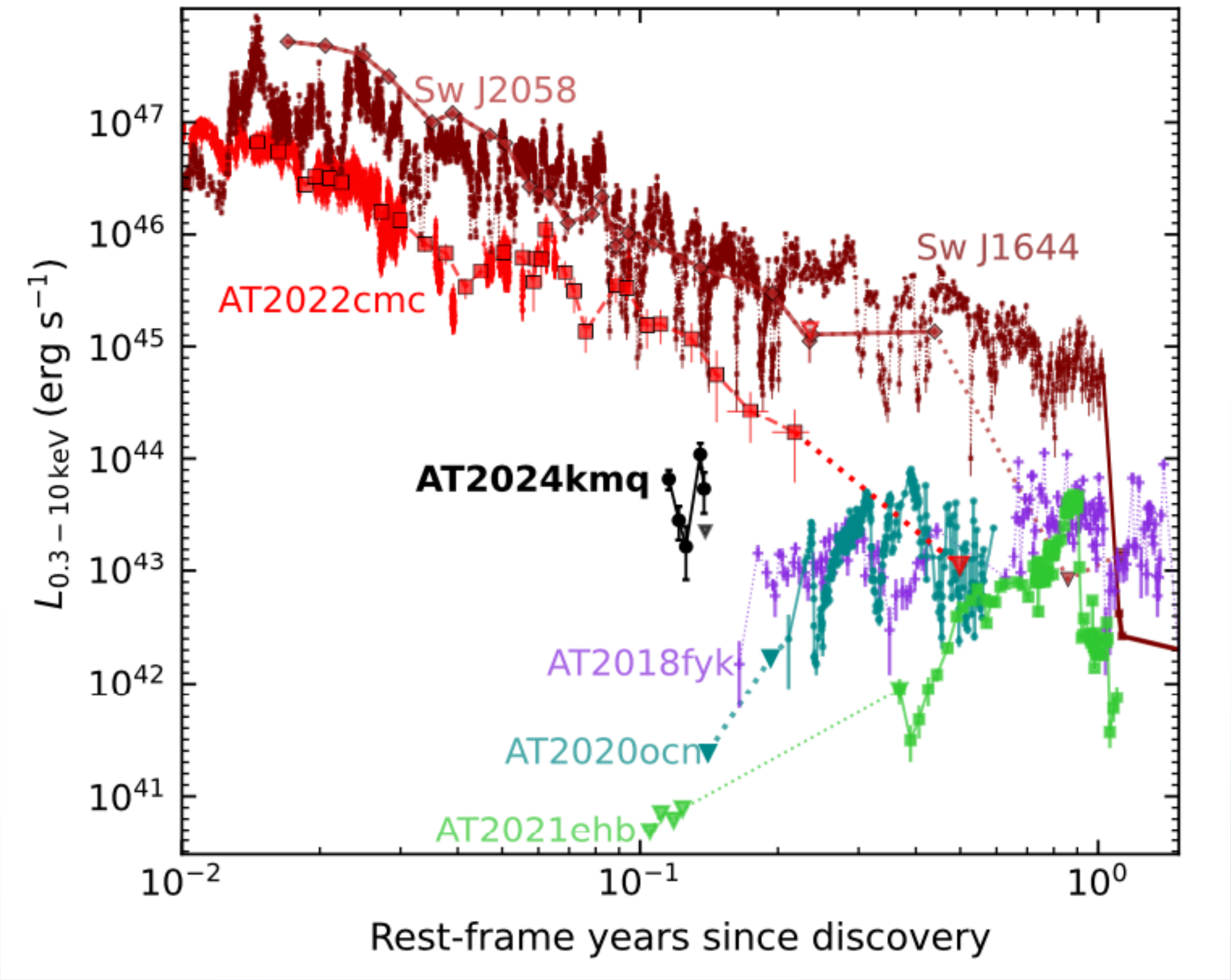
Diverse X-ray light curve in multi-band sources

Sub-day scale X-ray variability



(Yao et al 2024)



(Ho et al 2025)

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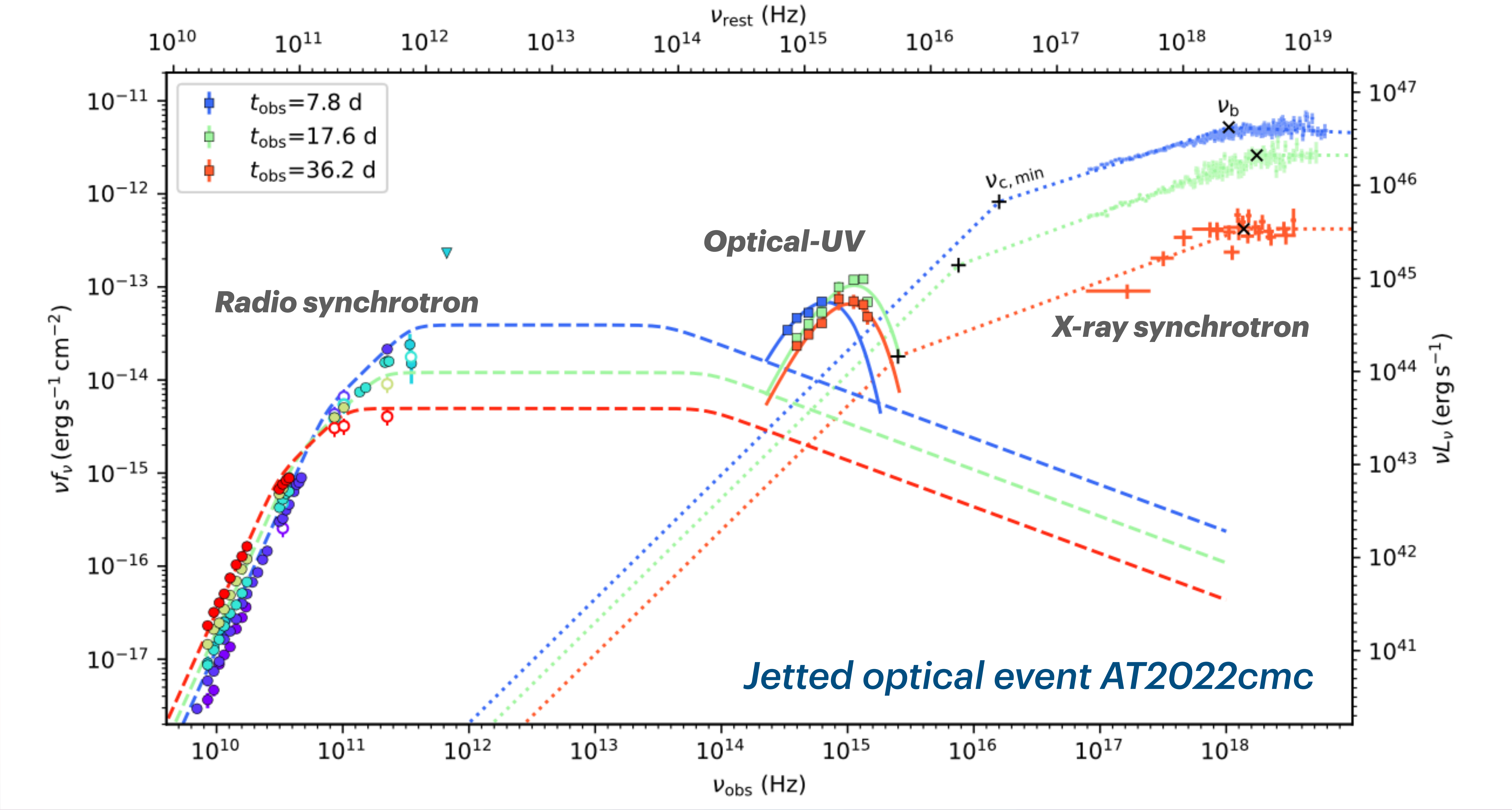

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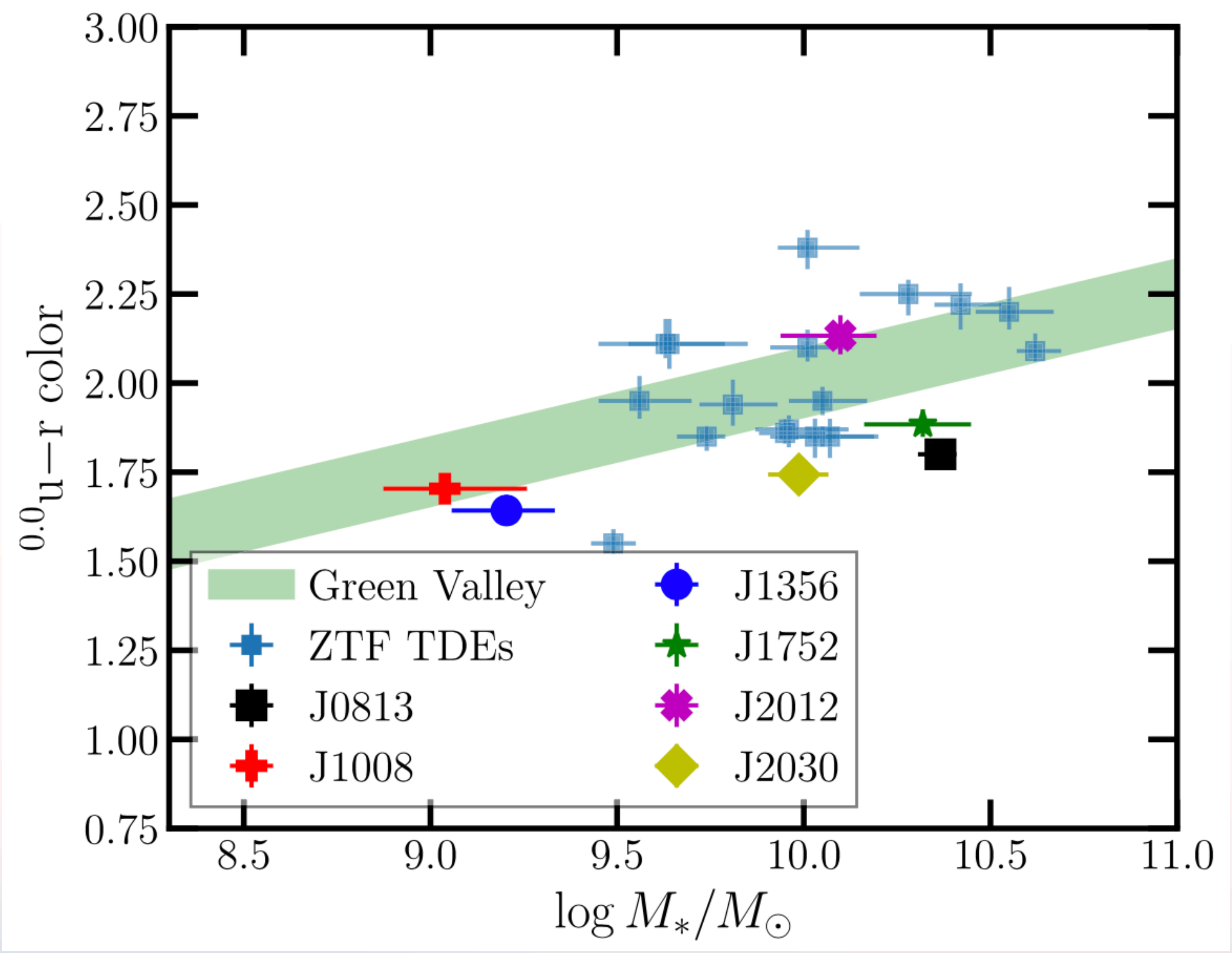
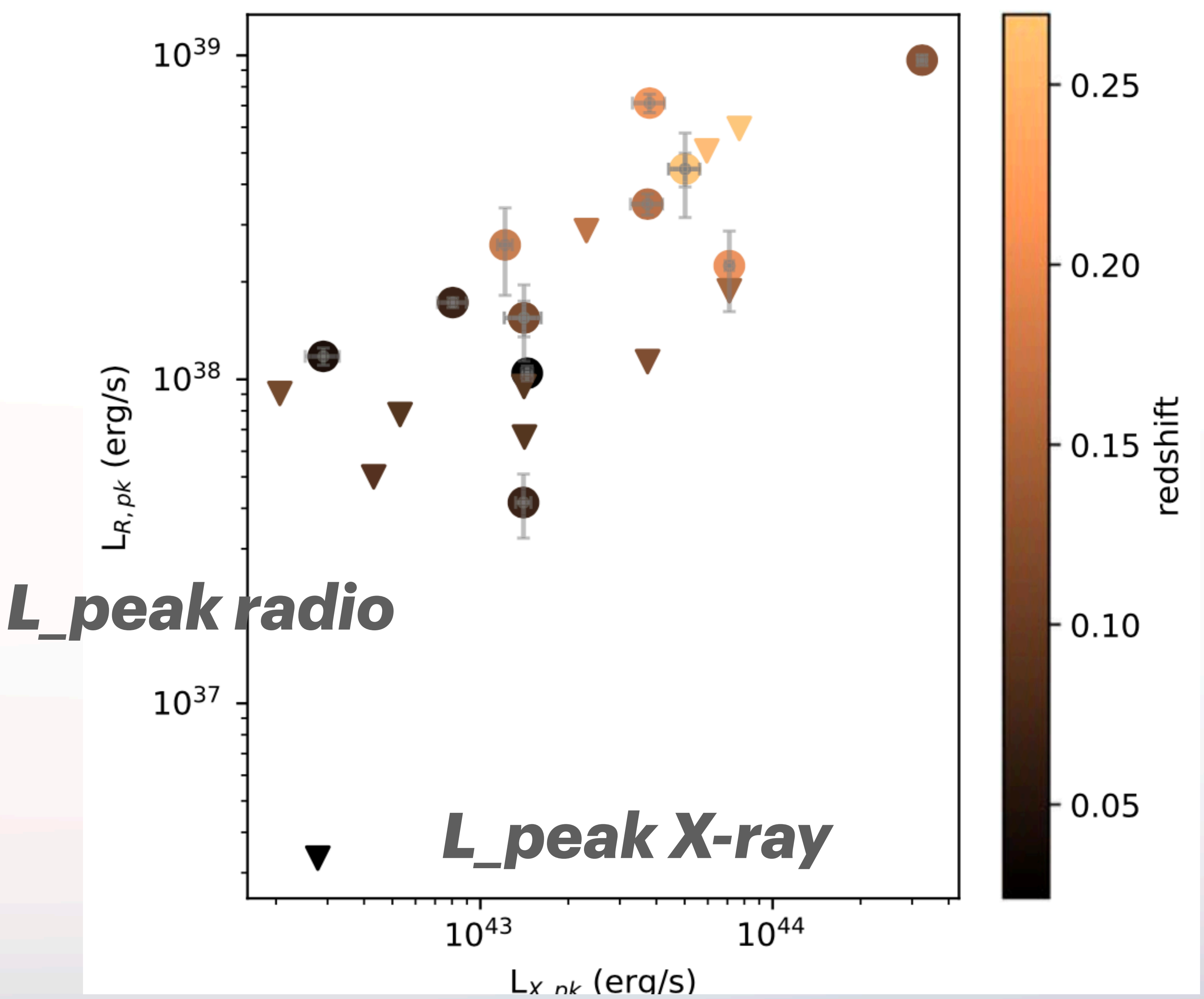
Late time radio emission are detected ~40% of TDEs

Radio TDEs host galaxies



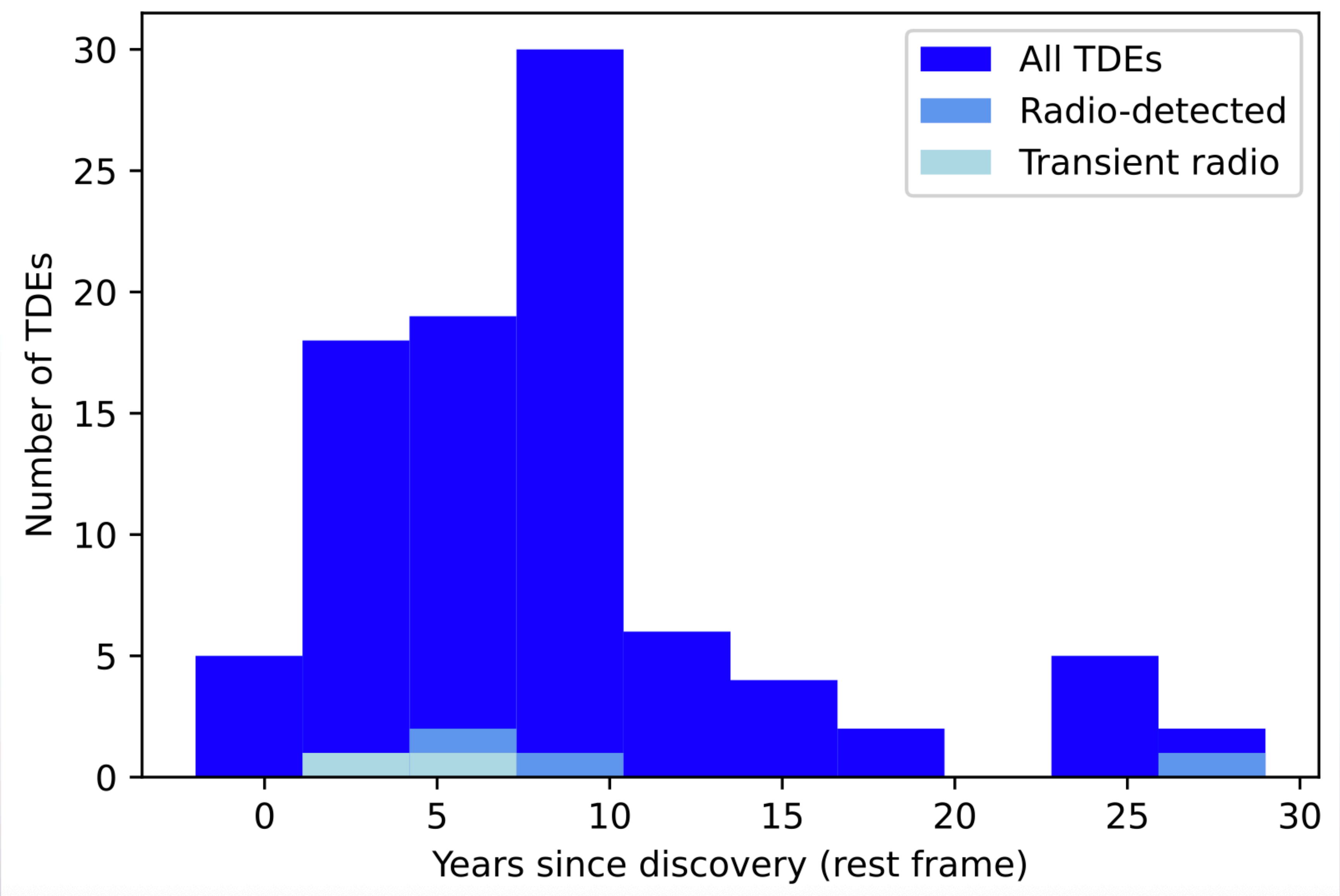
(Somalwar et al 2025)

Peak radio and X-ray luminosity



(Goodwind et al 2024)

Discover time



(Alexander et al 2025)

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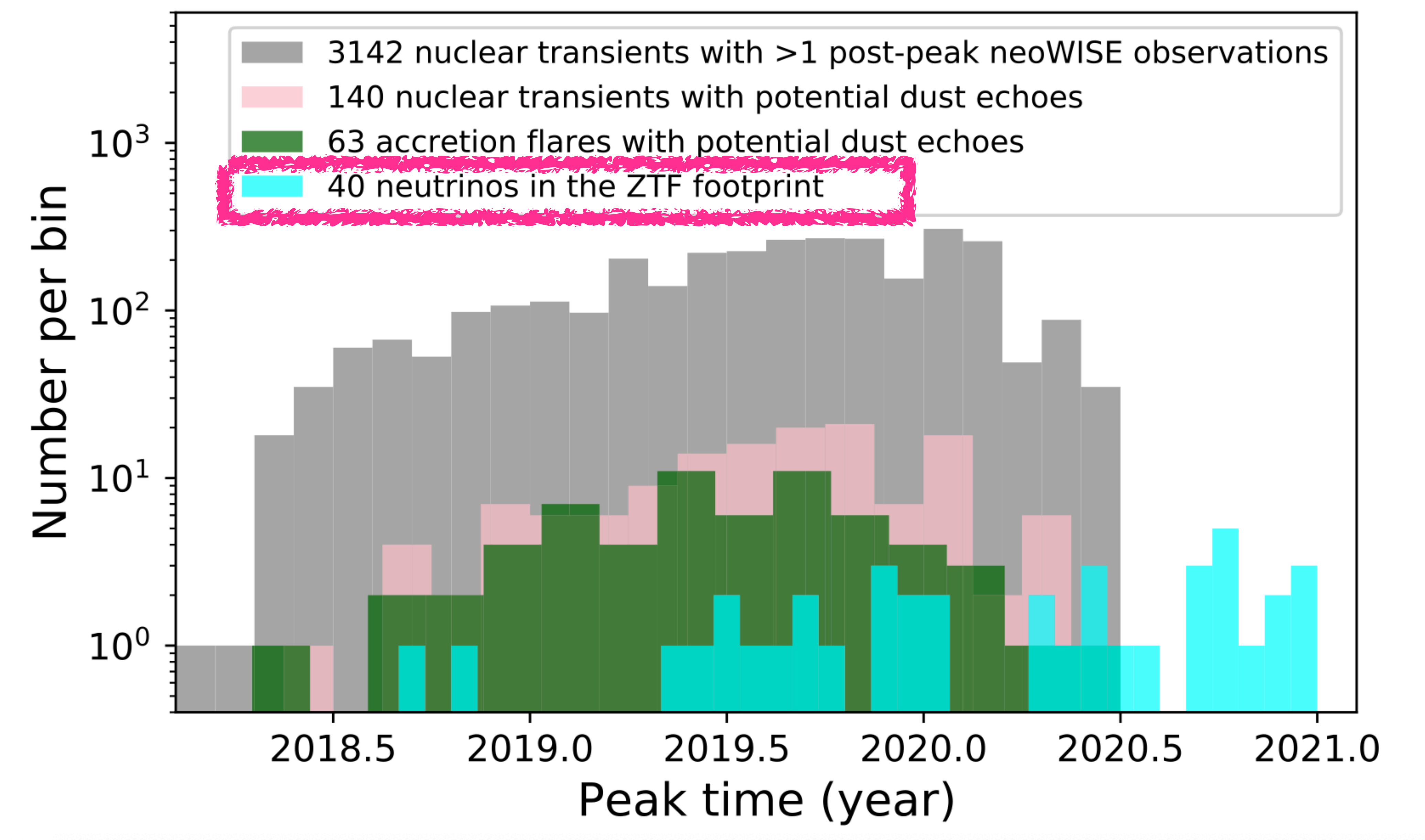
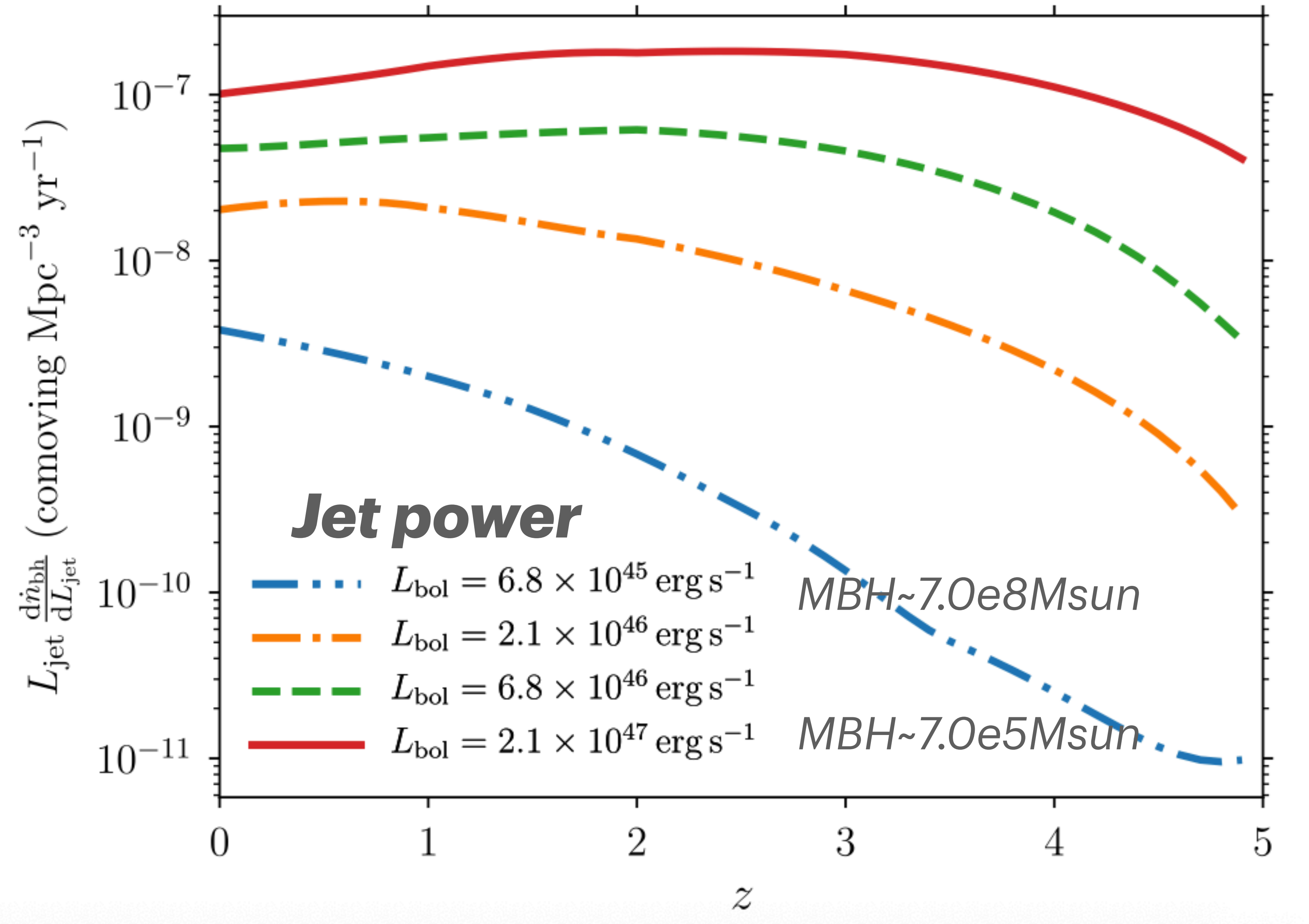
Even high energy neutrinos and UHECRs



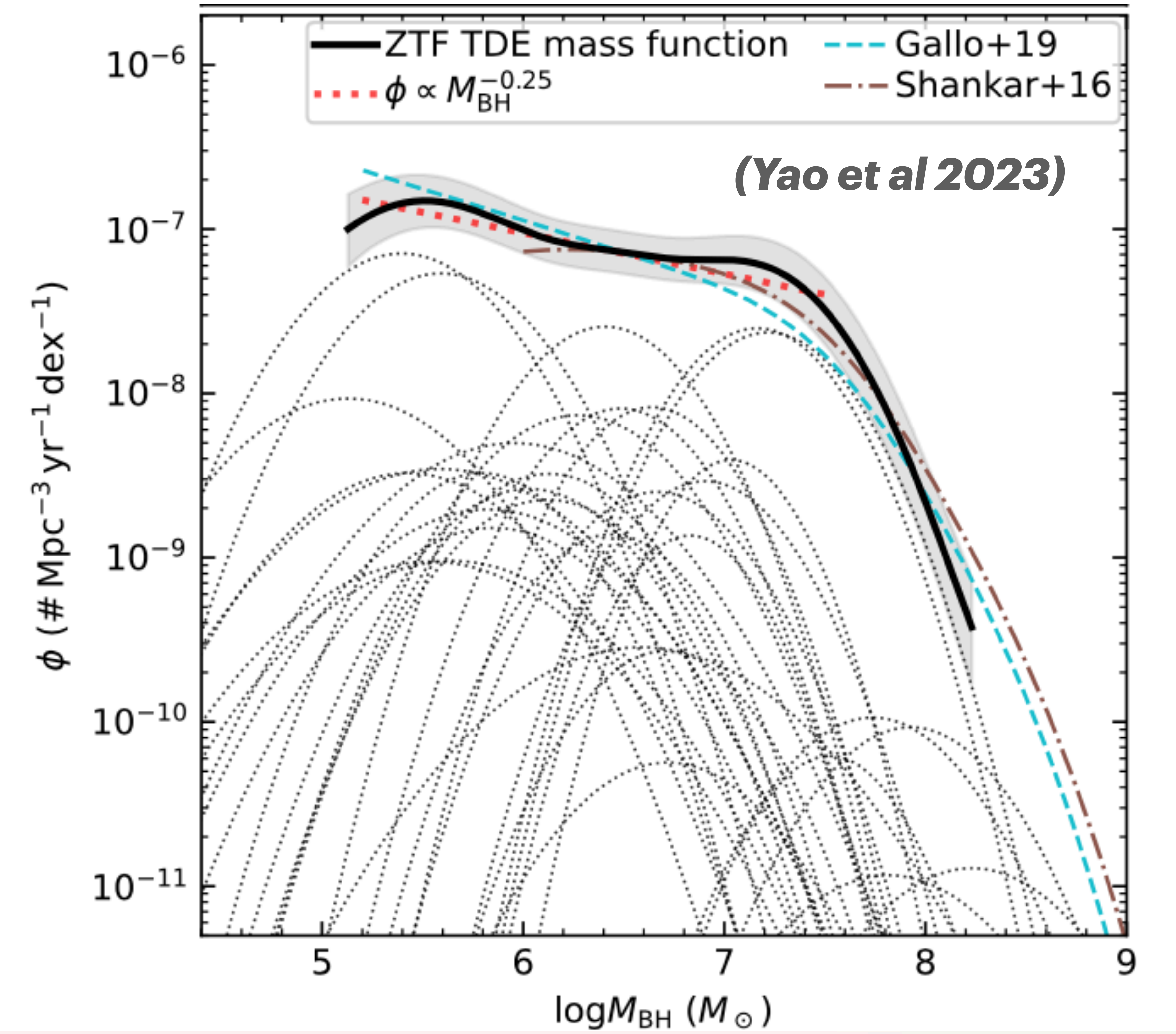
(Van Velzen , Stein+ 2025)



(Guepin, Kotera, Barausse+ 2018)

TDEs as Accretion Systems

- **Timescale** 1-3 years,
- $M_{\mathrm{BH}} \approx 10^{6-8} M_{\odot}$



From TDE host galaxies

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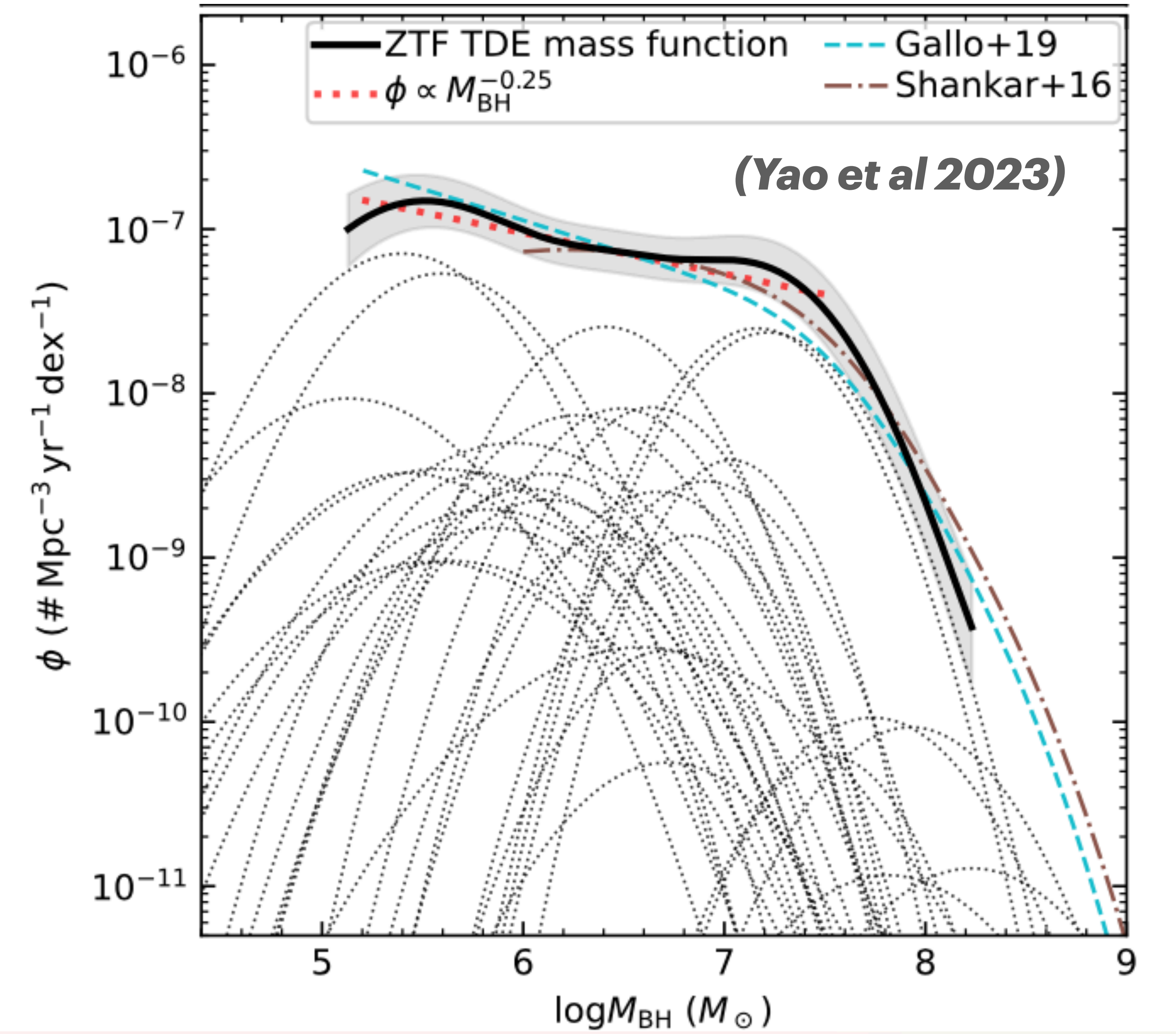

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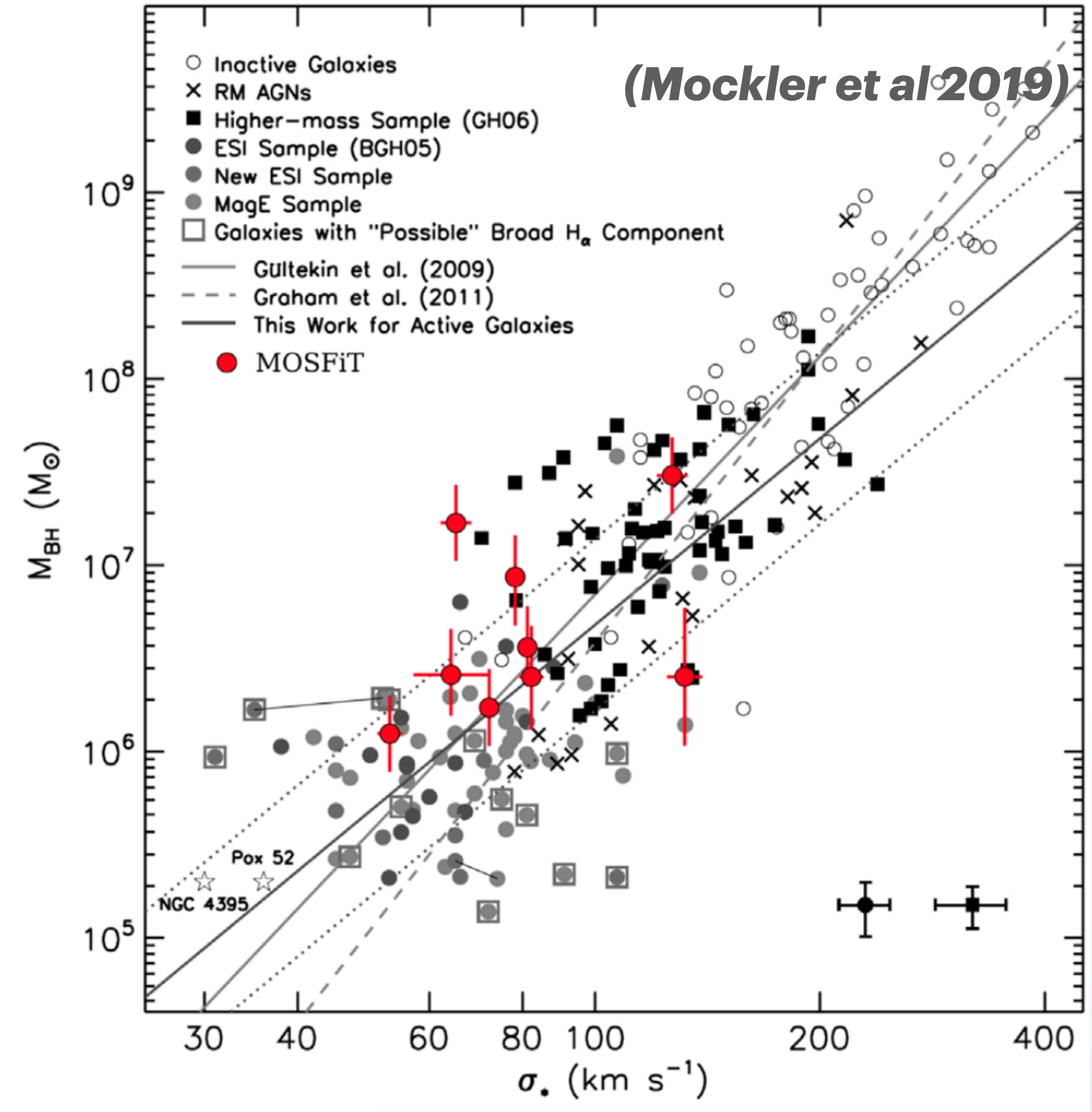
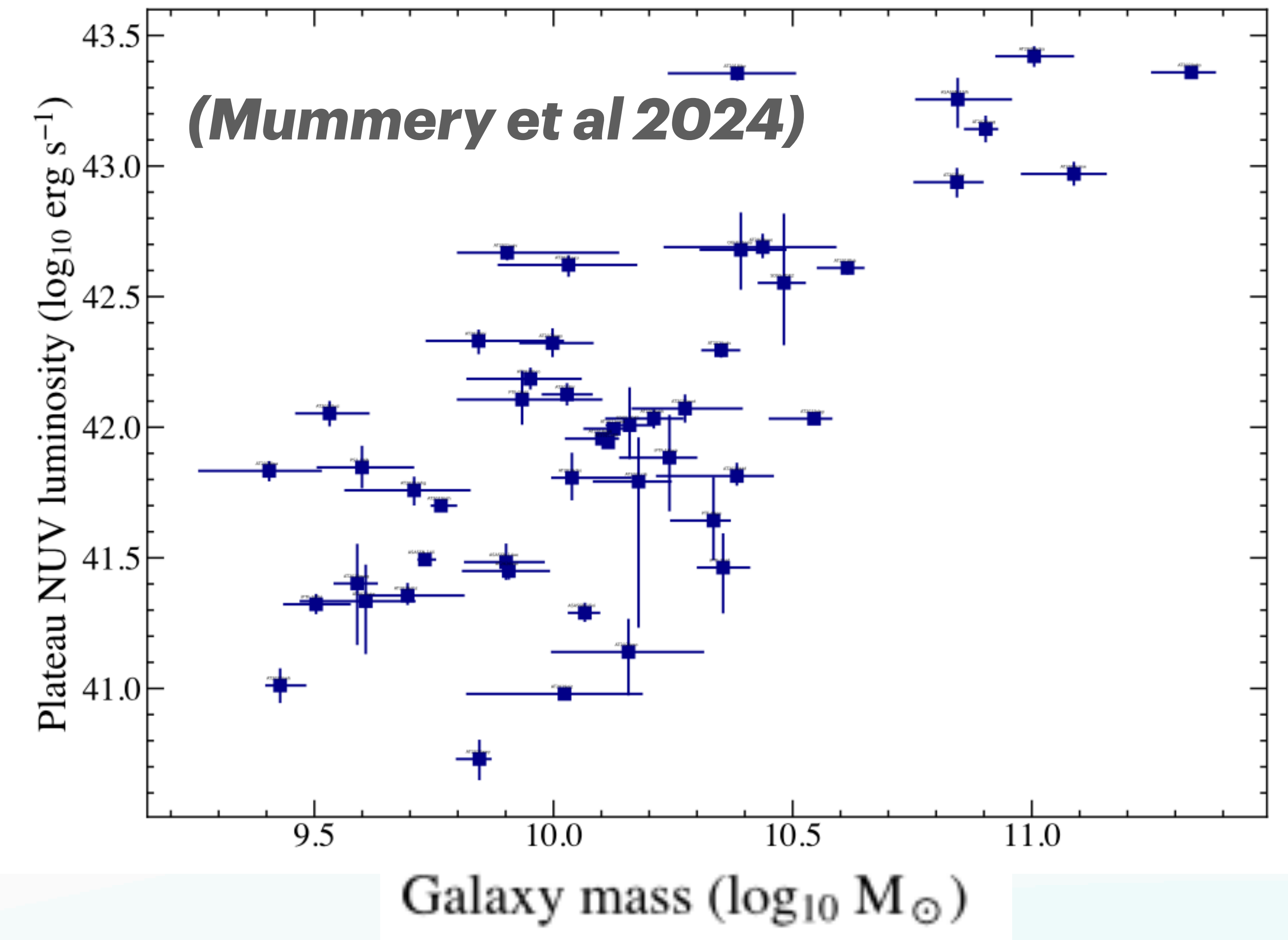


From TDE light curve + fallback modeling

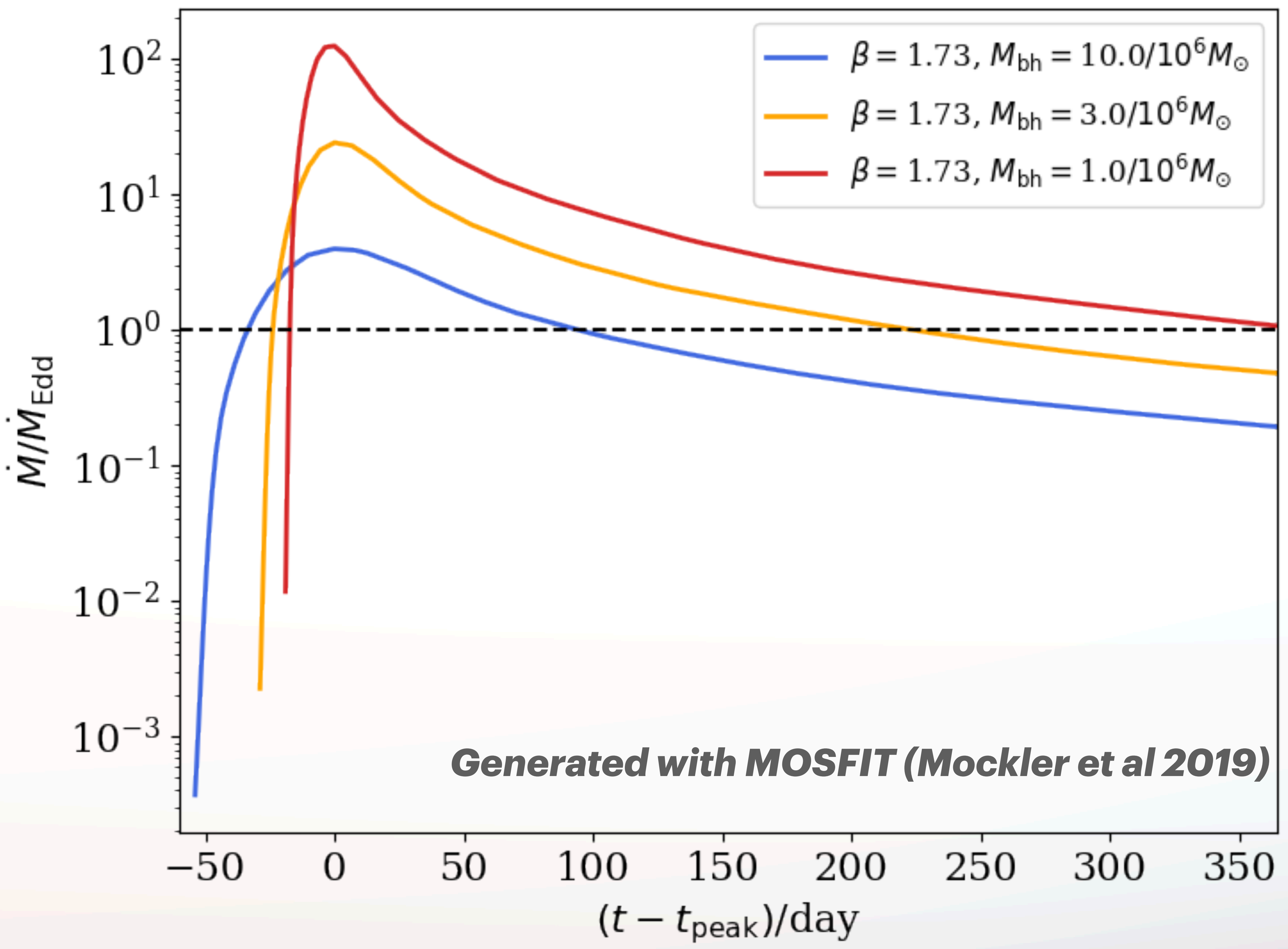


From UV plateau +disk modeling

TDEs as Accretion Systems

- **Super-Eddington feeding** -> super-Eddington accretion (?)

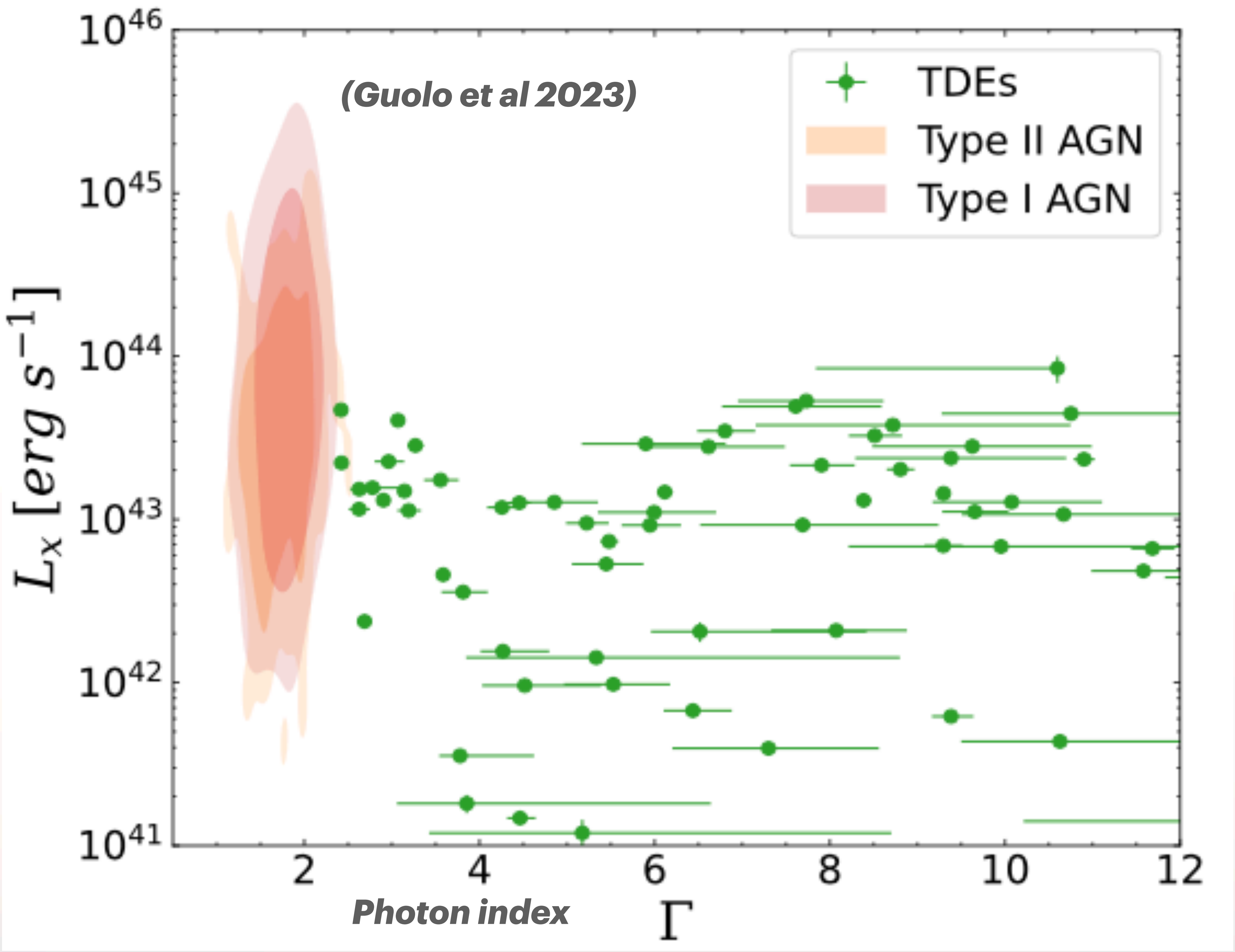
debris fallback rate
(Eddington)



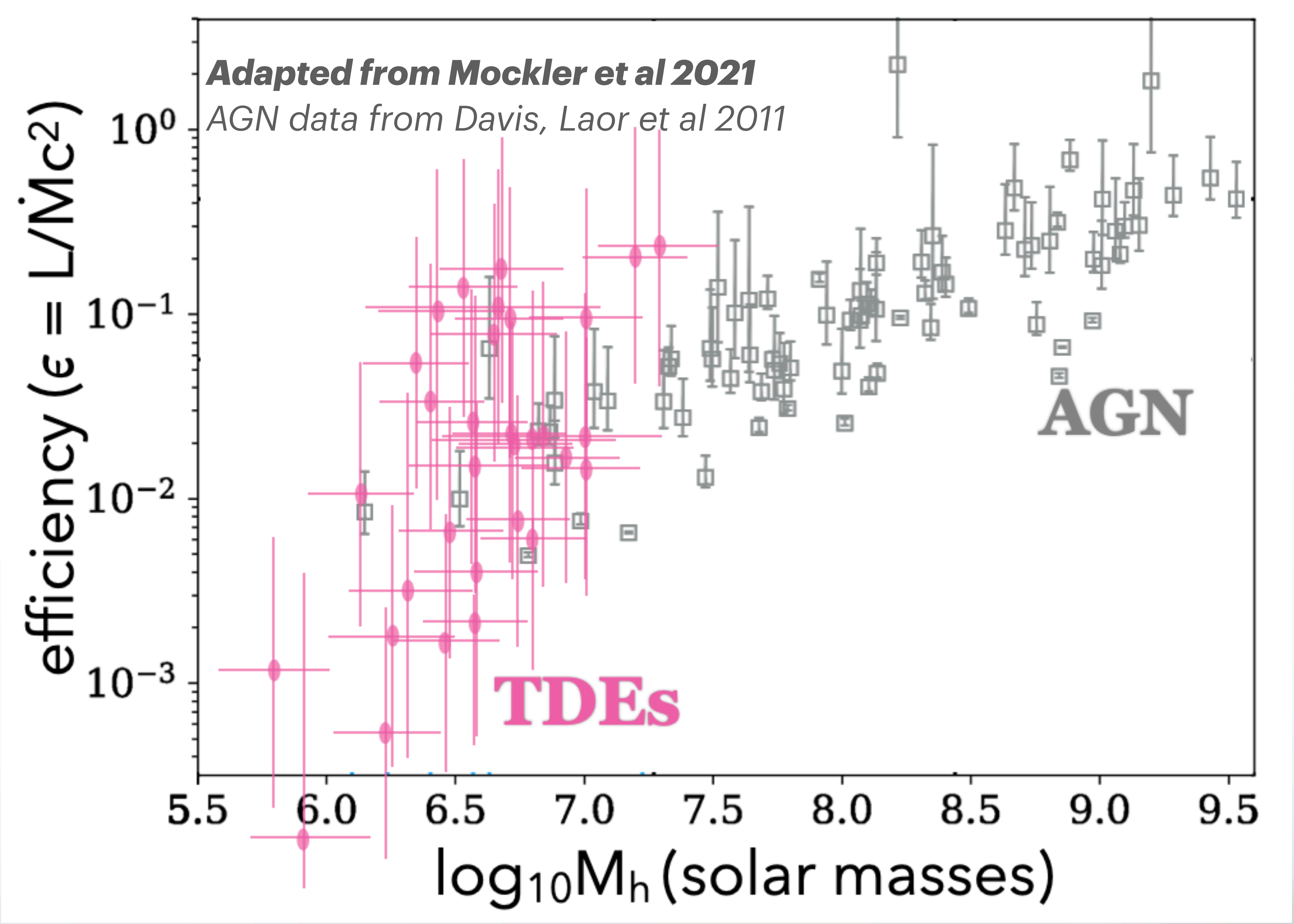
$10^6 M_\odot$ **BH**
$3 \times 10^6 M_\odot$ **BH**
$10^7 M_\odot$ **BH**

TDEs as Accretion Systems

- (Usually) **X-ray spectra is shallower than typical AGN system** -> multi-color disk BB ? thermal Compton?



- Estimated **radiation efficiency** of mass fallback rate show larger spread than typical AGN system



Interesting questions that are missed in this talk

- ***Frequent late-time radio detection***

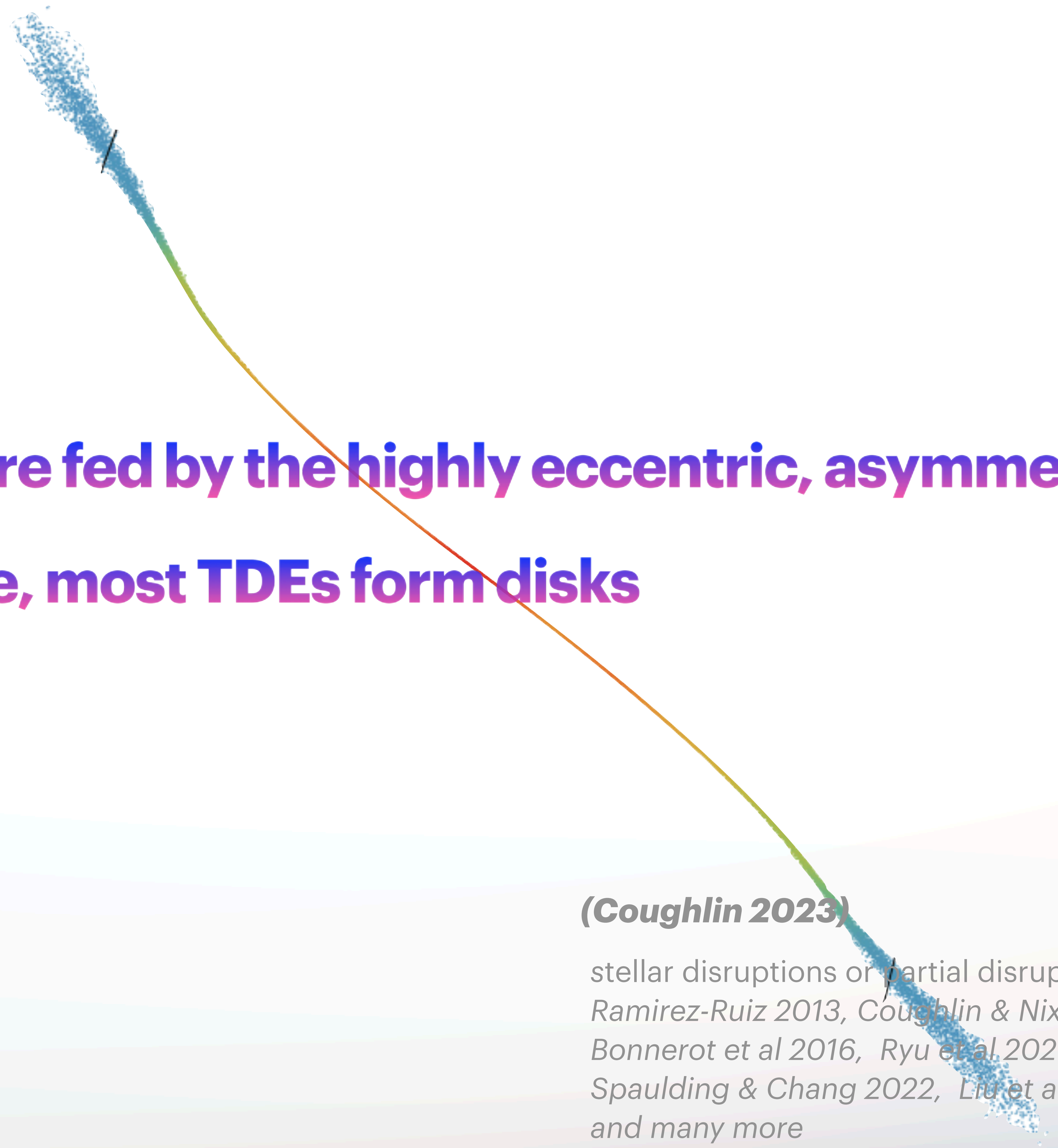
-> mass ejection is common is TDEs (how & when?)
-> jets are rare -> for those jetted events (what disk look like when they launch jet?)
-> simulation find hard to form magnetized disk (missing physics?)

- ***TDE are classified by emission lines***

-> line formation and evolution (need good radiation transfer modeling)
-> star's population and dynamics -> formation channel and host galactic environment (also exciting as Rubin and Roman finding higher z events)

- ***Peculiar events e.g. off-center TDEs, featureless TDEs, FBOTs (?)***

- ***Partial disruptions and repeating transients***



Initially, BHs are fed by the highly eccentric, asymmetric debris stream

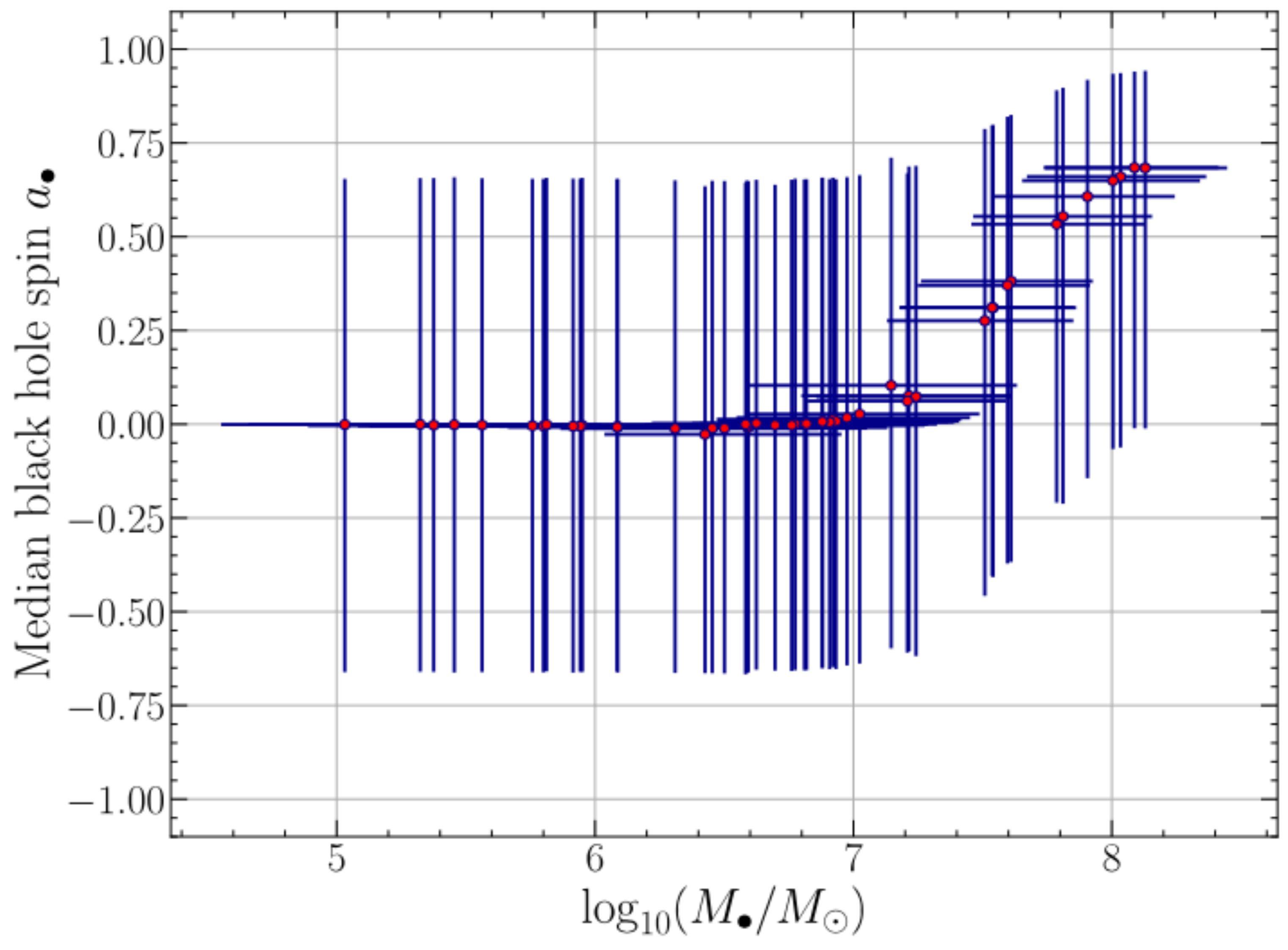
But in late time, most TDEs form disks

(Coughlin 2023)

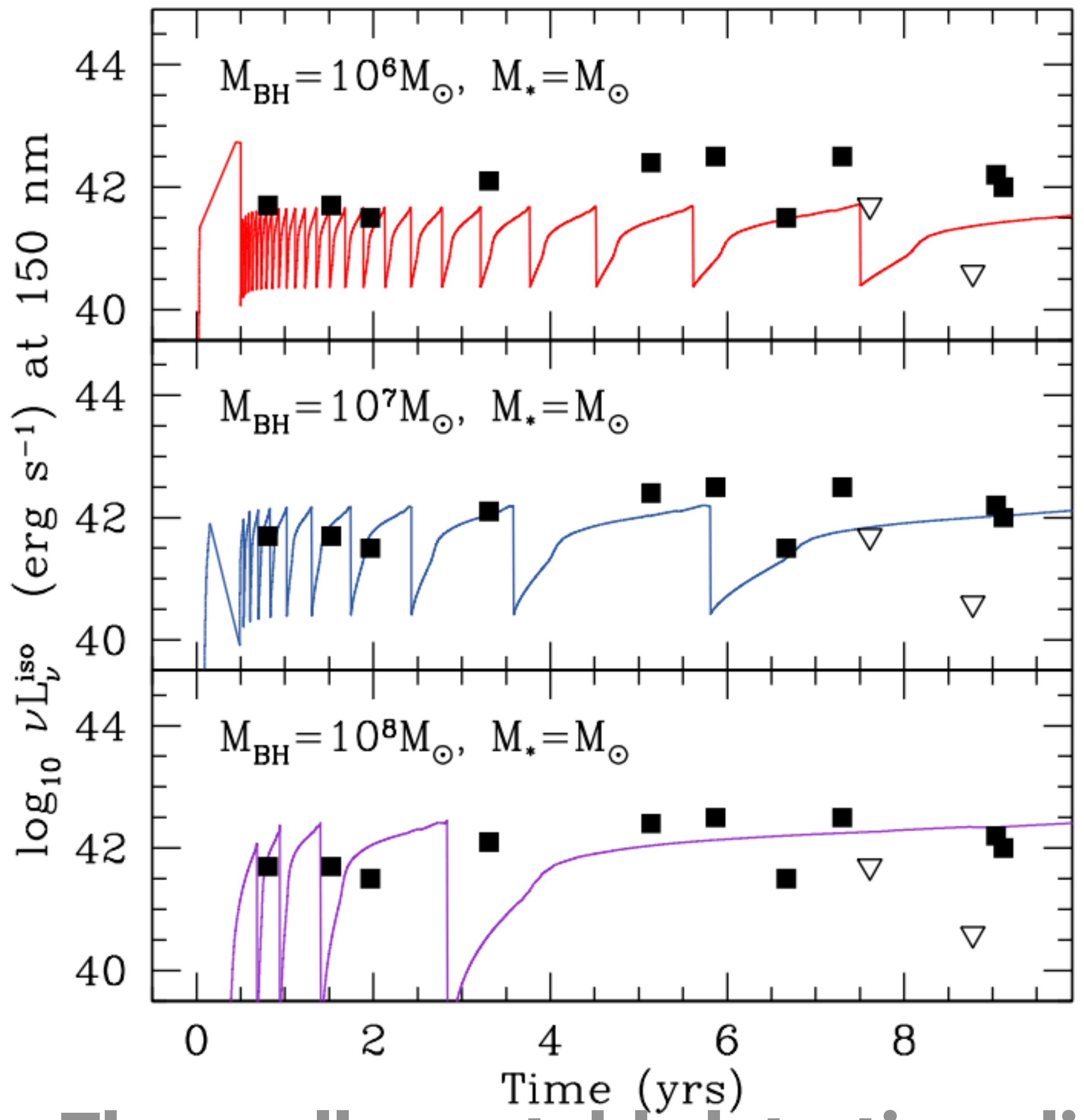
stellar disruptions or partial disruption also see e.g. *Guillochon & Ramirez-Ruiz 2013, Coughlin & Nixon2015, Coughlin et al 2016, Bonnerot et al 2016, Ryu et al 2020+, Nixon & Coughlin 2022, Spaulding & Chang 2022, Liu et al 2024, Abolmasov et al 2025 … and many more*

Most TDEs form Disks

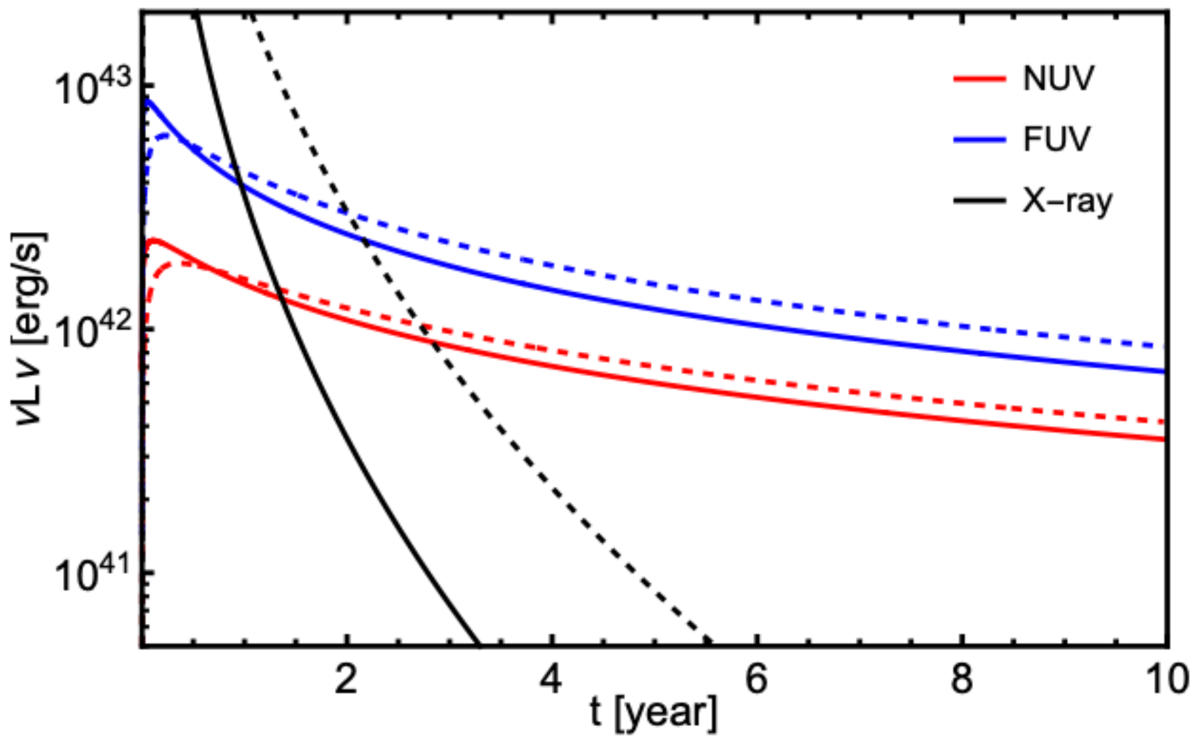
(Mummery et al 2024)



(Piro & Mockler 2025)



(Alush & Stone 2025)

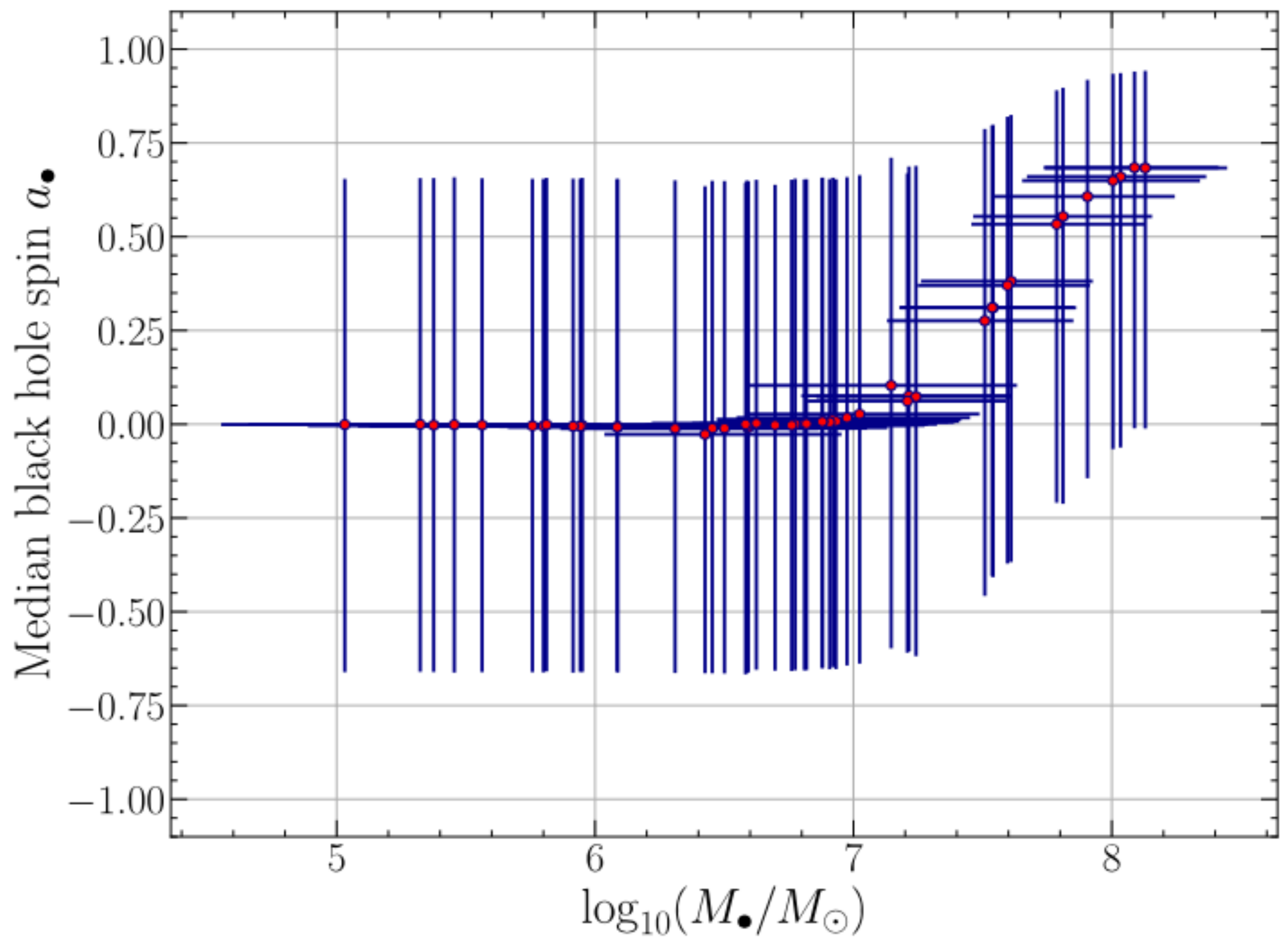


By modeling late-time UV and disk evolution, potentially we can constrain BH mass and spin

Thermally unstable late-time disks can undergo episodical outbursts, while prevailing Maxwell stress can stabilize disk

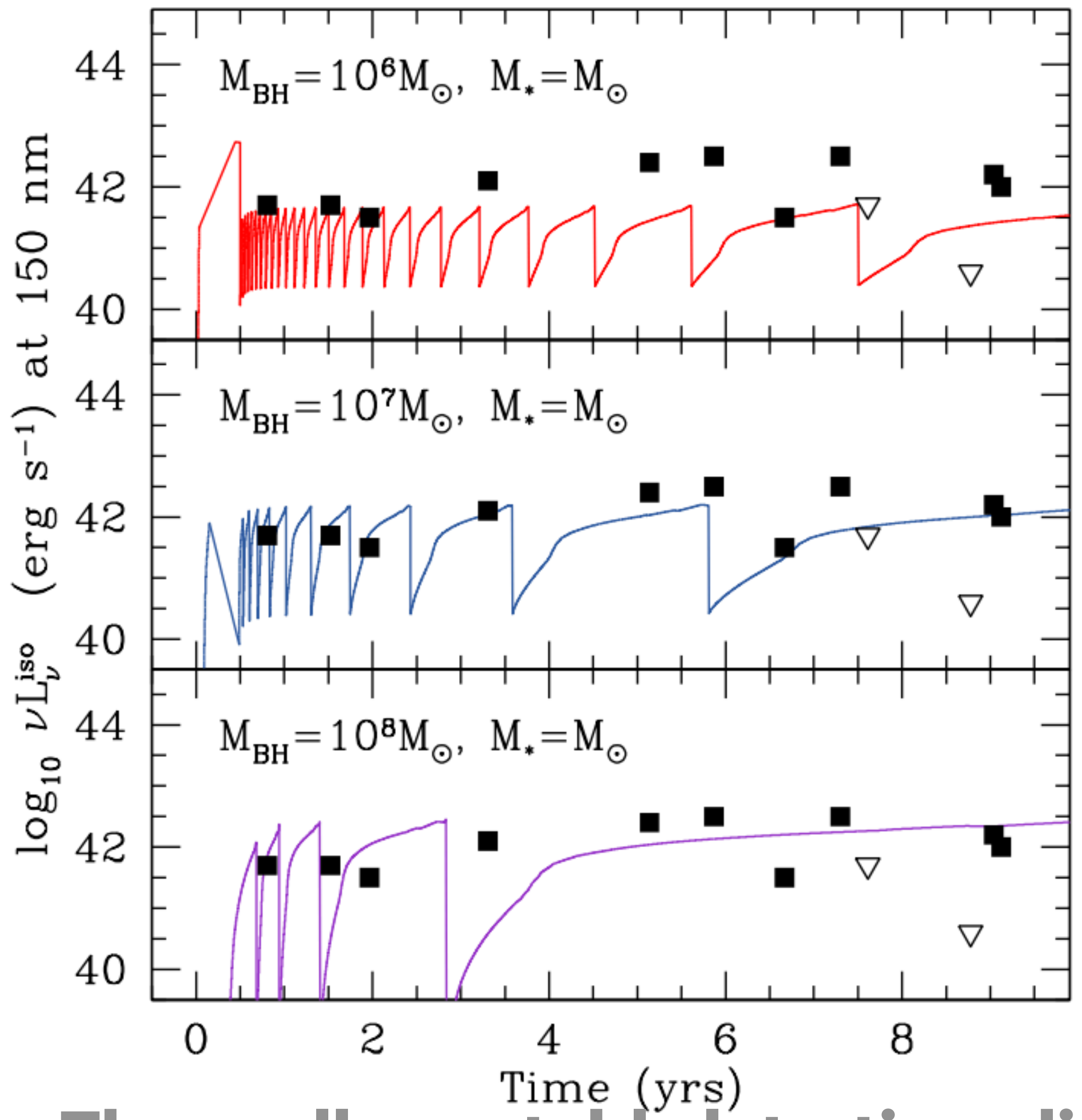
Most TDEs form Disks

(Mummery et al 2024)



By modeling late-time UV and disk evolution, potentially we can constrain BH mass and spin

(Piro & Mockler 2025)



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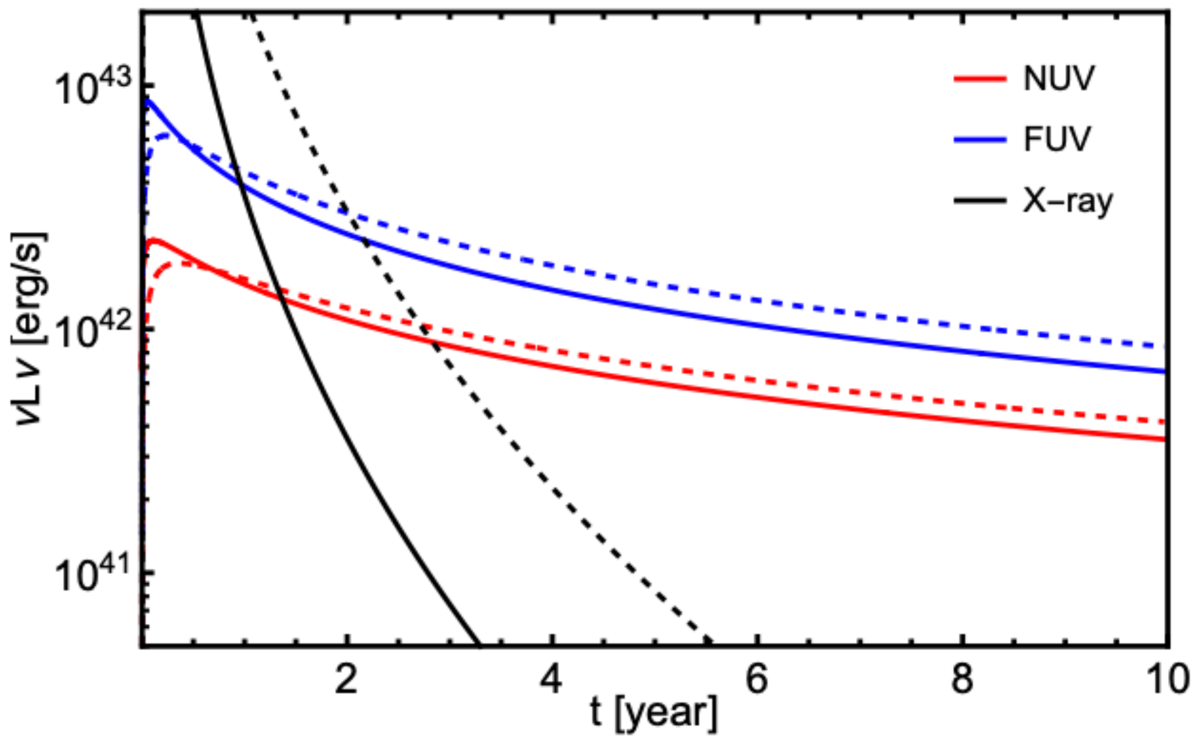

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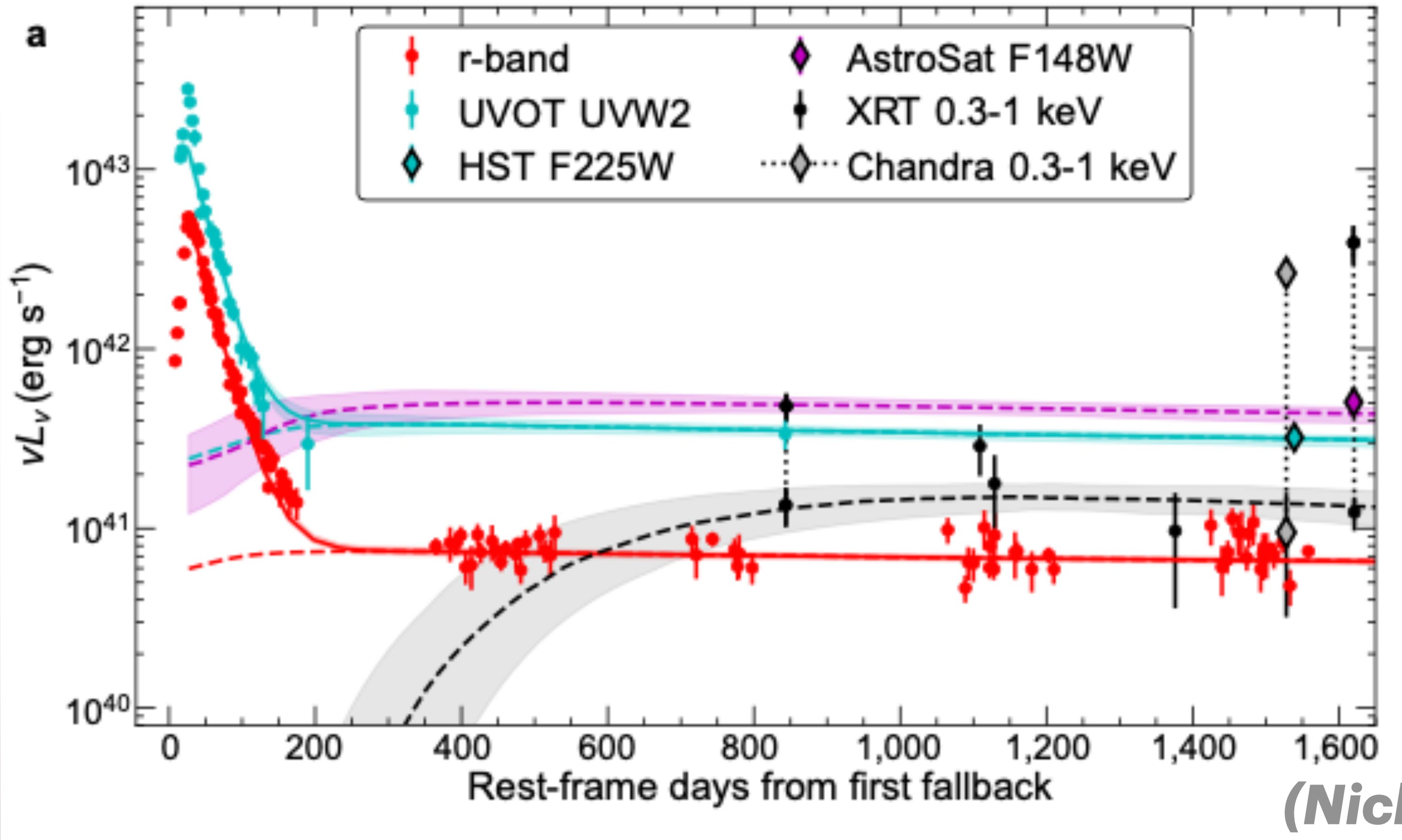
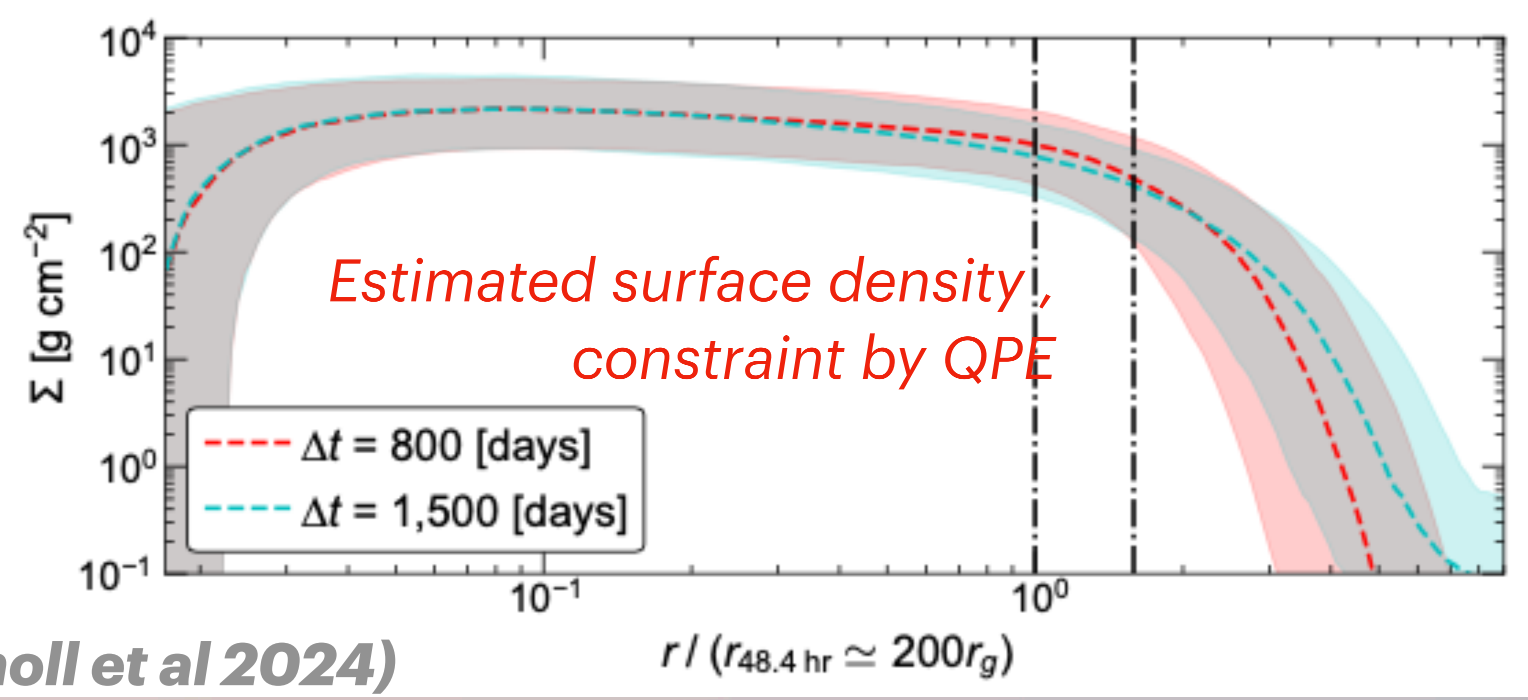
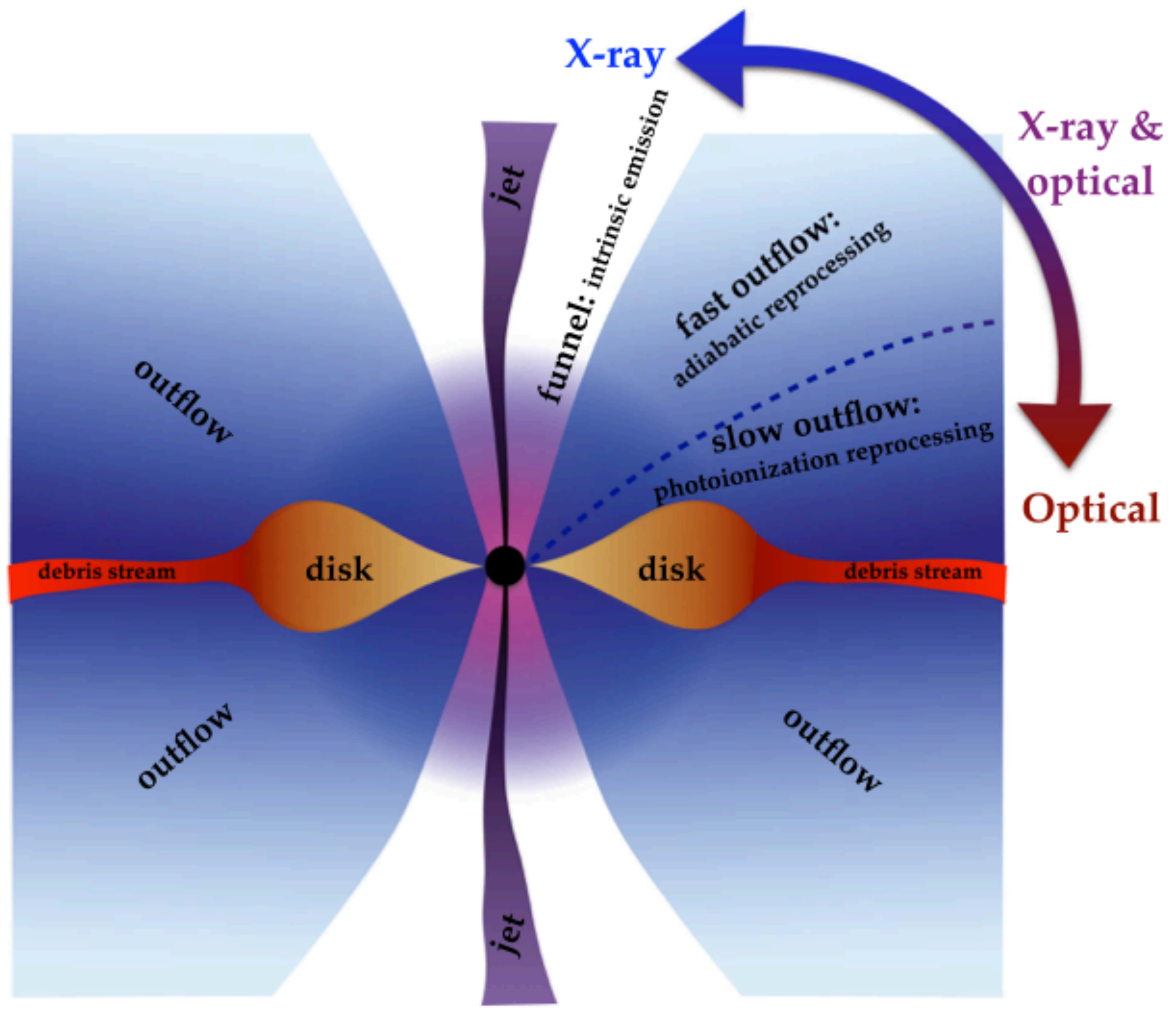


AT2019qiz provides an another channel (QPEs) to diagnostic late-time disk, even when it fades out from optical!



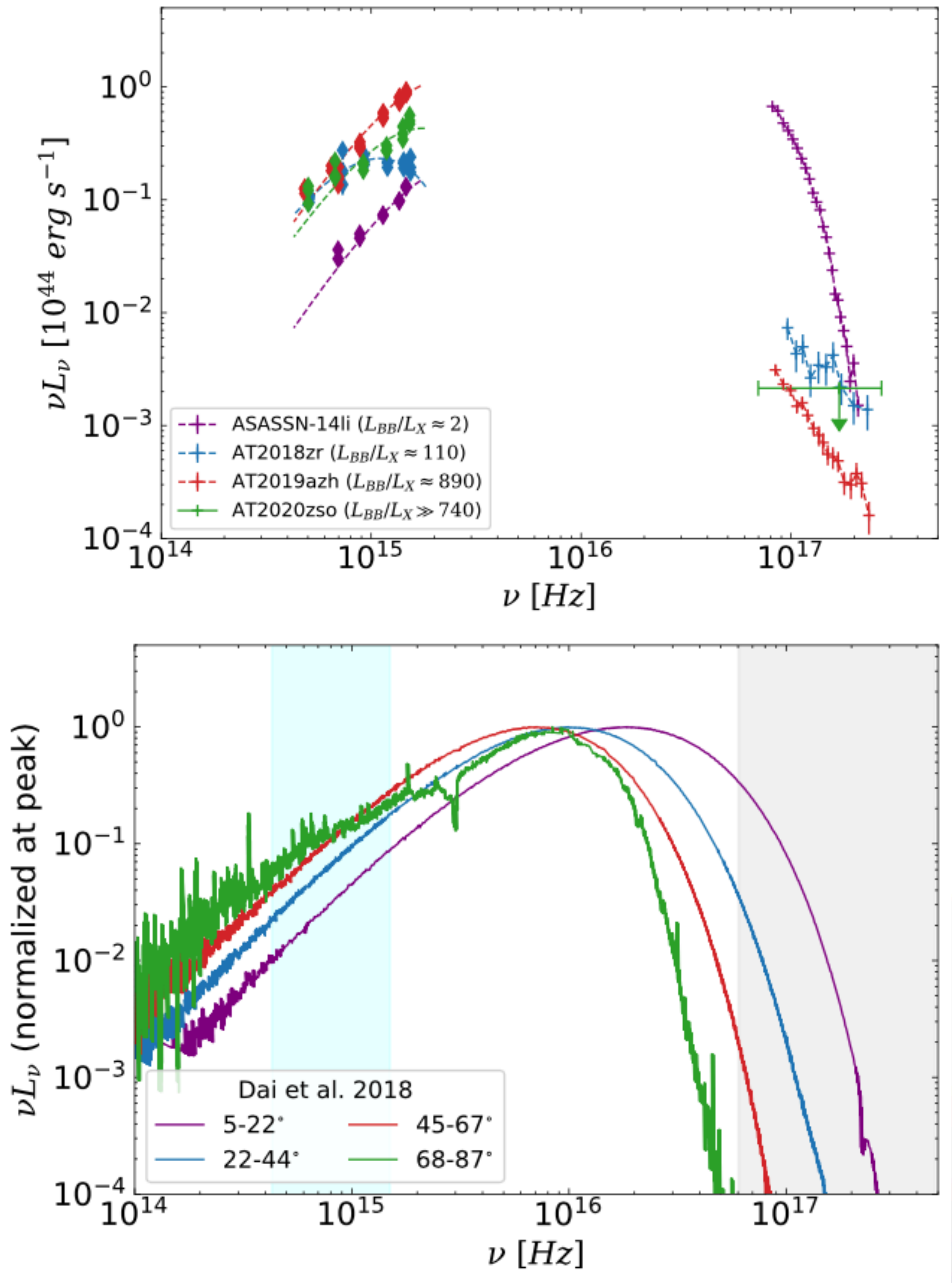
(Nicholl et al 2024)

Super-Eddington Disk Models X-to-optical Ratio

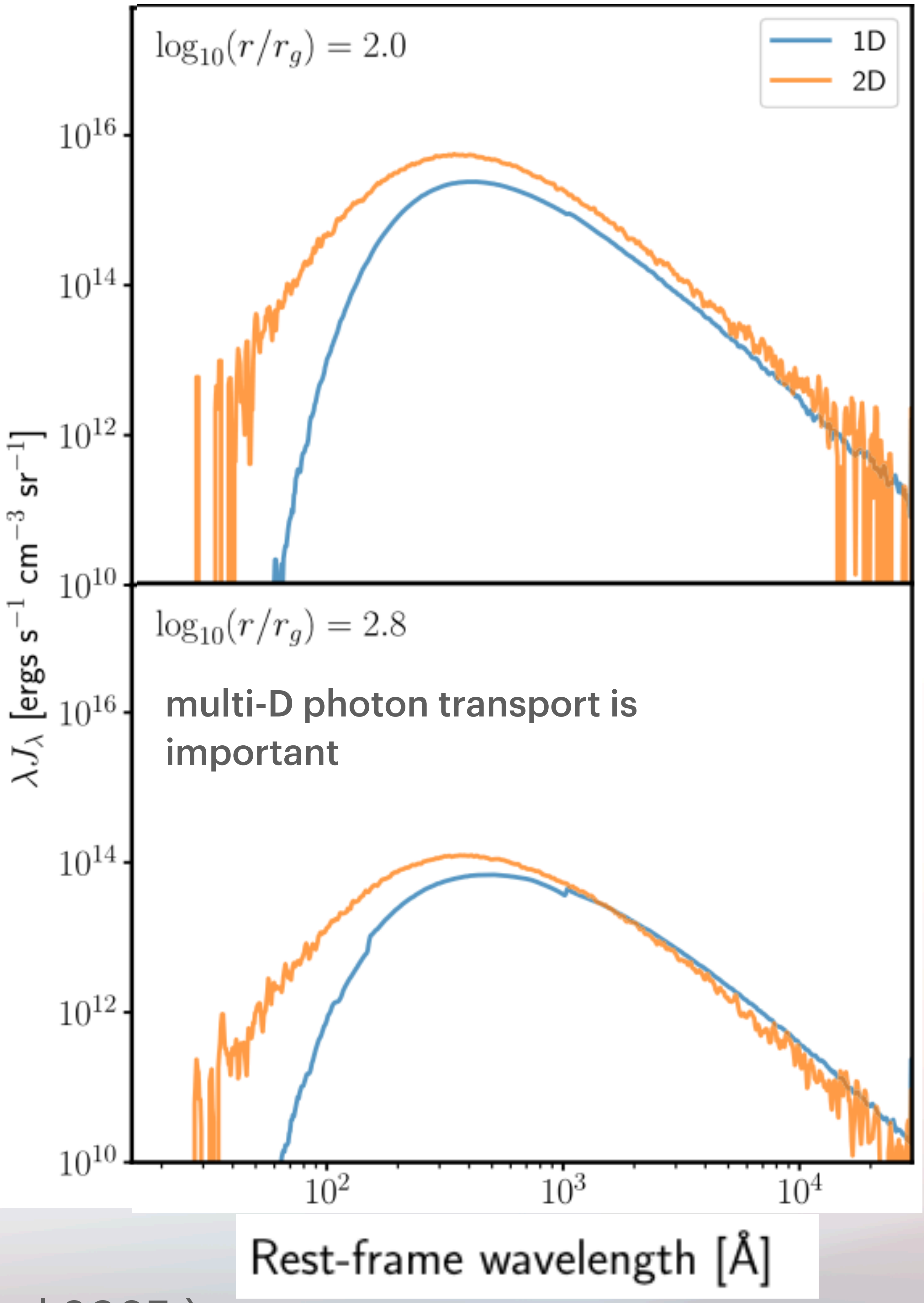


(Dai et al 2018)

(Guolo et al 2023)

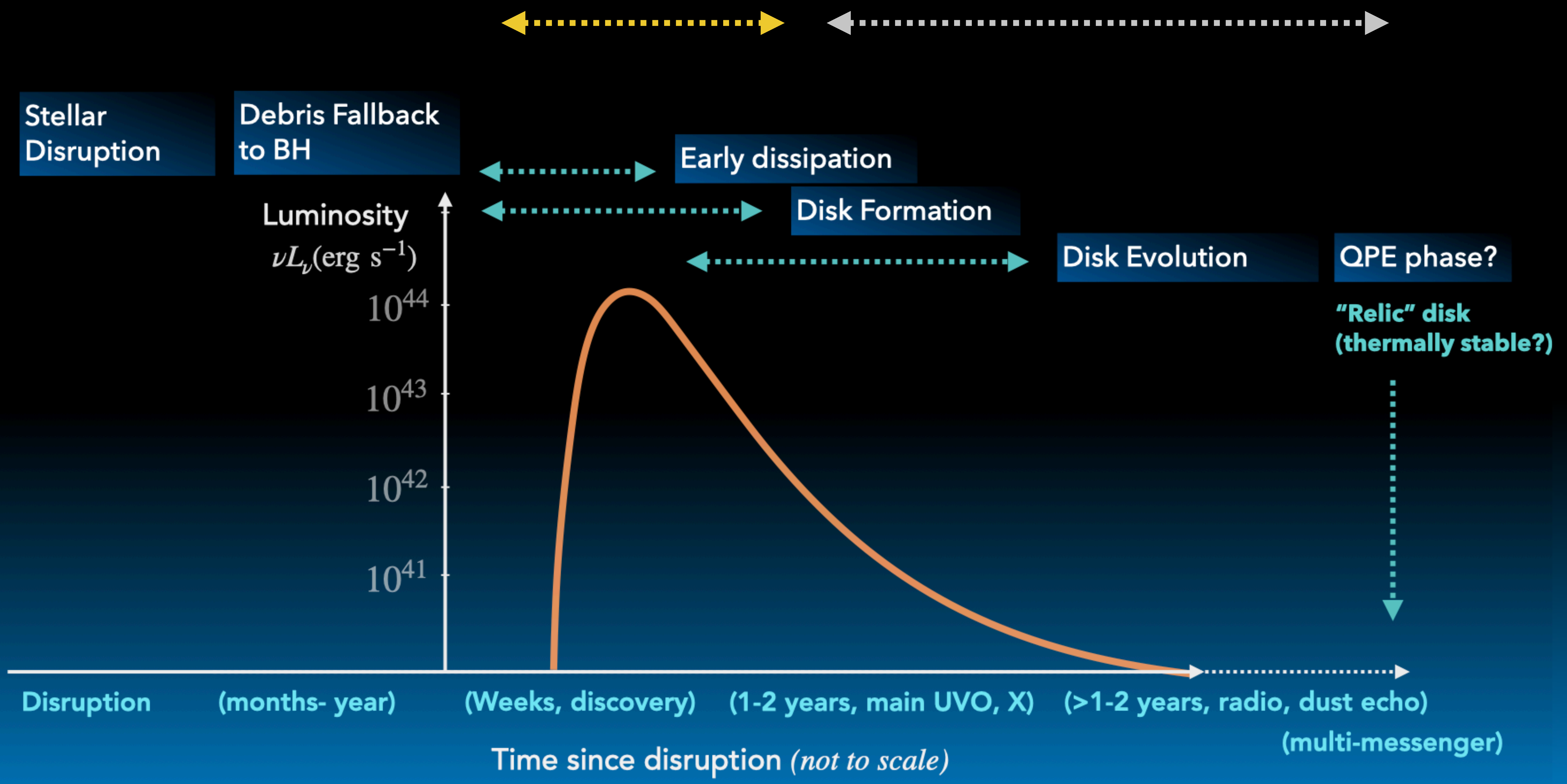


(Parkinson et al 2025)



(See also: Thomsen et al 2022, Qiao et al 2025)

From Debris Stream to Super-Eddington Disk



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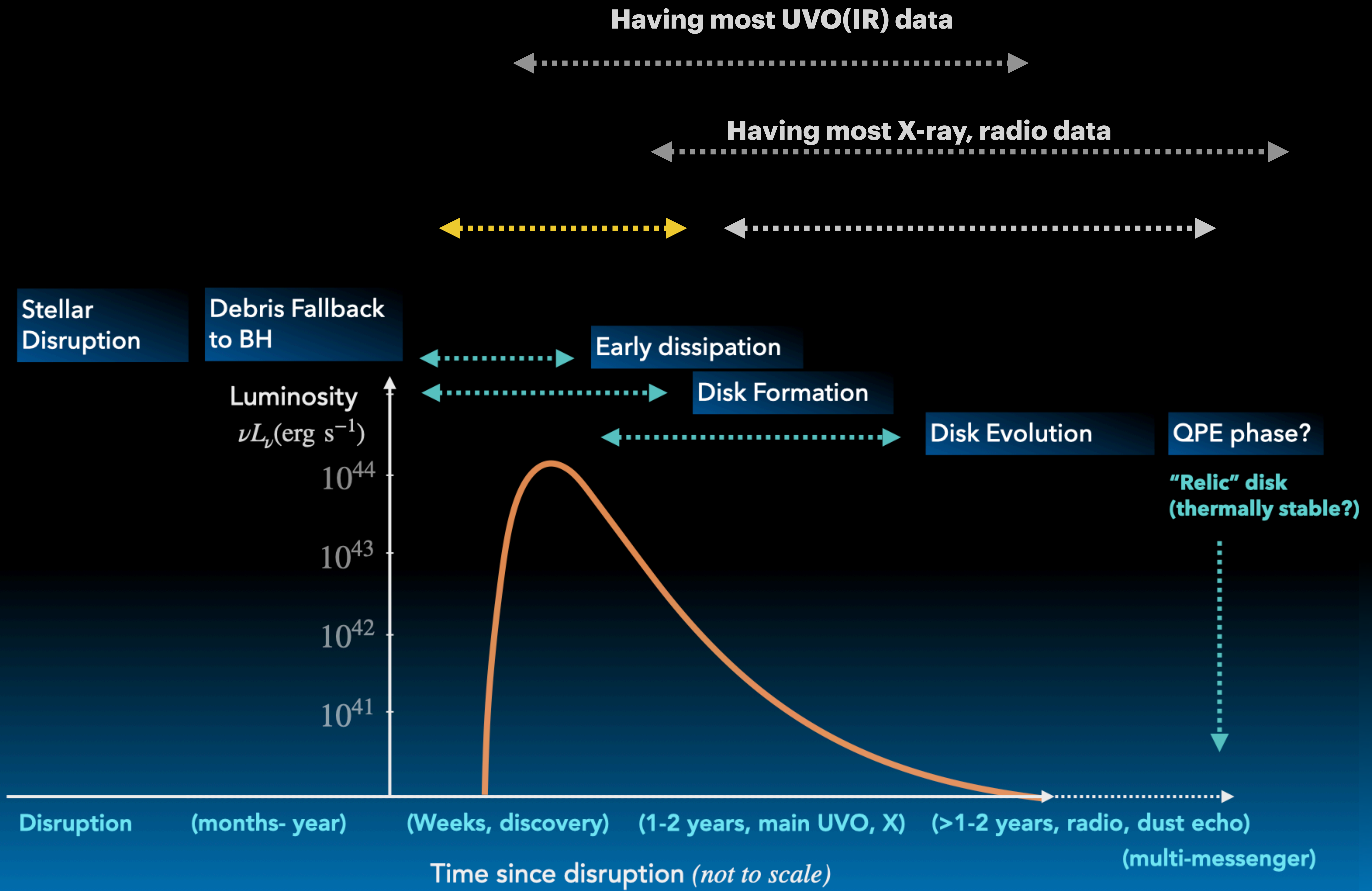
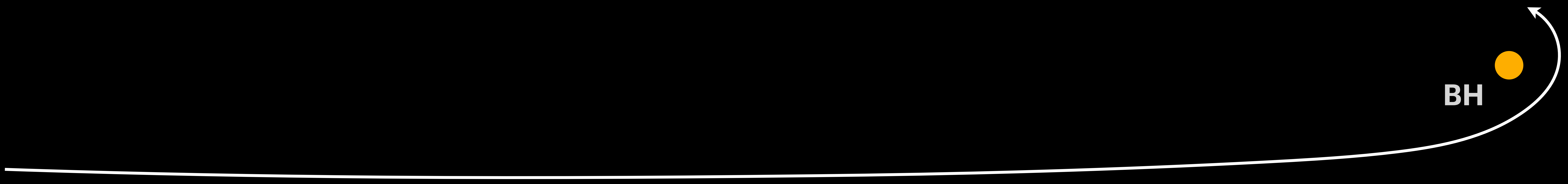


Early Dissipation Processes

Shock from compressed star
Nozzle shock
Debris recombination
Stream self-intersection
Stream-disk shock
...



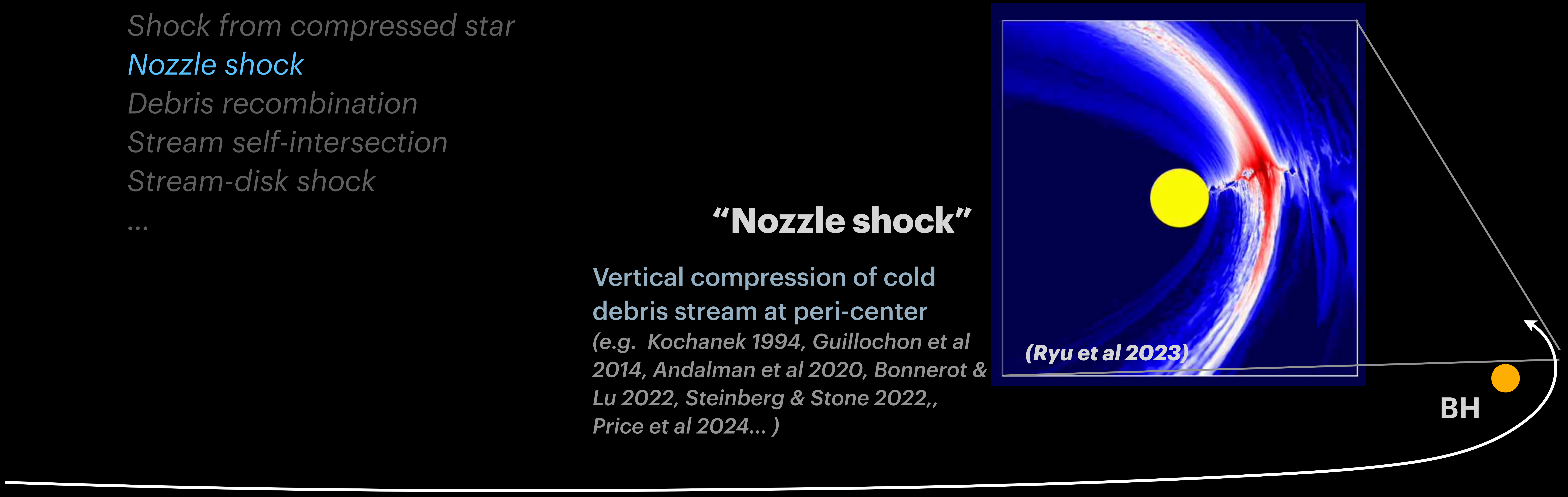
Bound debris fallback to black hole

Early Dissipation Processes

Shock from compressed star
Nozzle shock
Debris recombination
Stream self-intersection
Stream-disk shock
…

"Nozzle shock"

Vertical compression of cold debris stream at peri-center
(e.g. Kochanek 1994, Guillochon et al 2014, Andalman et al 2020, Bonnerot & Lu 2022, Steinberg & Stone 2022,, Price et al 2024…)



Early Dissipation Processes

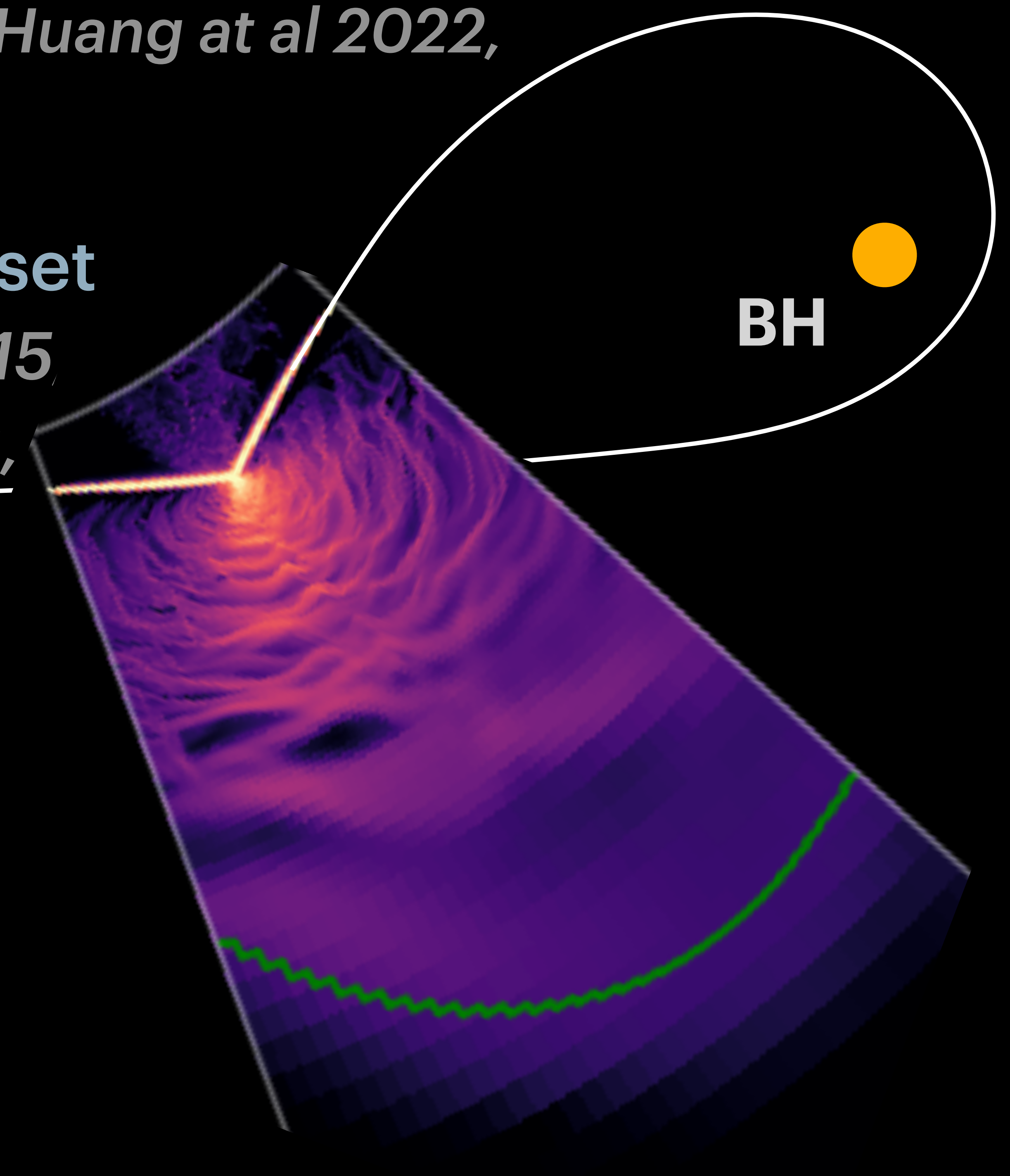
Shock from compressed star
Nozzle shock
Debris recombination
Stream self-intersection
Stream-disk shock
…

"Stream self-intersection"

Apsidal precession leads to debris stream self-intersection after peri center passage
(e.g. Dai et al 2015, Piran et al 2015, Shiokawa et al 2015, Jiang et al 2016, Lu & Bonnerot 2020, Huang at al 2022, Andalman et al 2022…)

BH spin will introduce vertical offset
(e.g. Guillochon & Ramirez-Ruiz 2015, Hayasaki et al 2016, Jiang et al 2016, Jankoviet et al 2023)

Bound debris fallback to black hole



(Huang et al 2023)

Early Dissipation Processes

Shock from compressed star
Nozzle shock
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Stream self-intersection
Stream-disk shock
...

"Stream self-intersection"

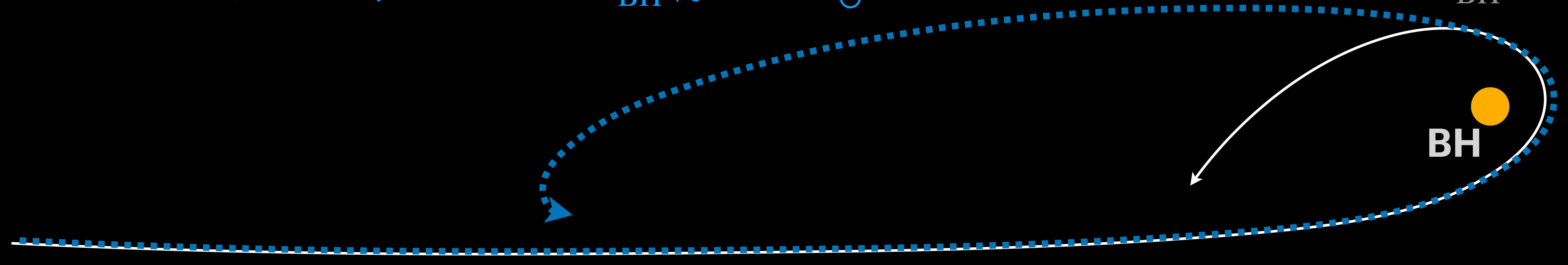
Apsidal precession is sensitive to BH mass

$\sim 10^{2-3} r_\mathrm{g}$

(Weaker precession, $M_\mathrm{BH} \lesssim 10^{6.5} M_\odot$)

$\lesssim 10^{2} r_\mathrm{g}$

(Stronger precession $M_\mathrm{BH} \sim 10^{6.5-8} M_\odot$)



Early Dissipation Processes

Shock from compressed star
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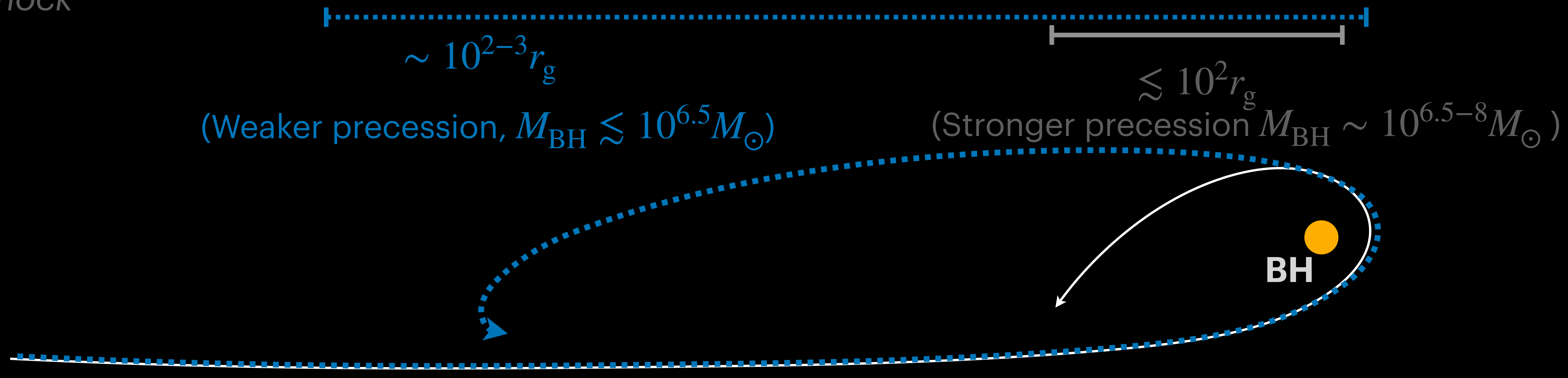
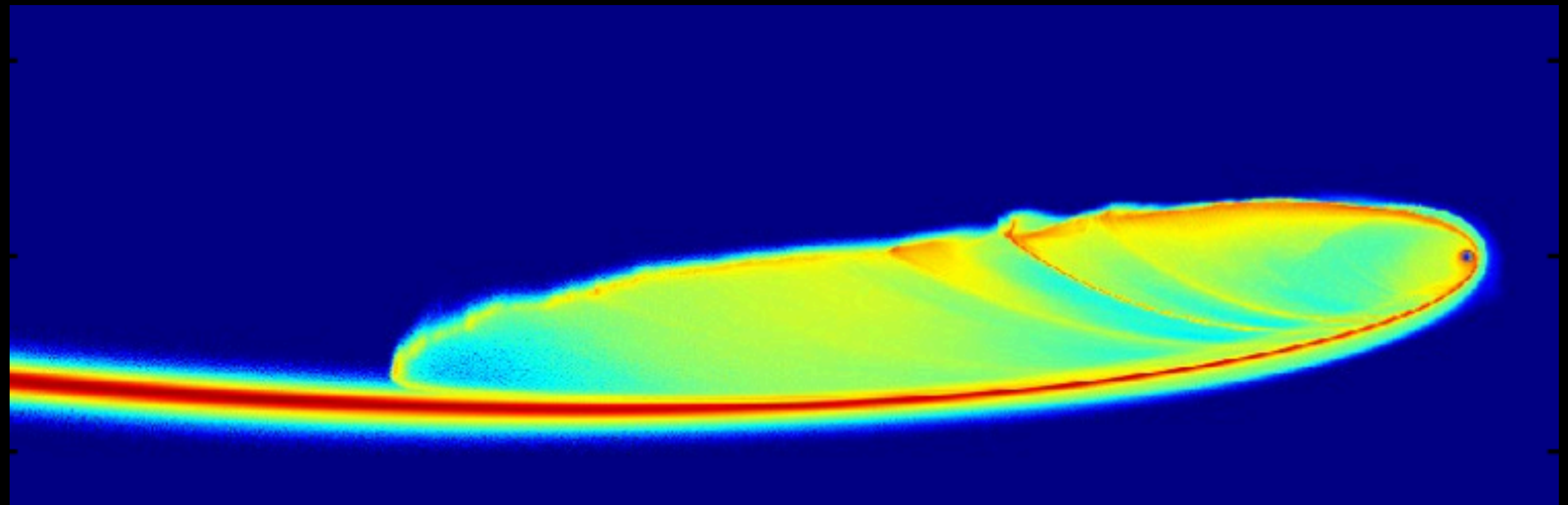


"Apocenter shock"

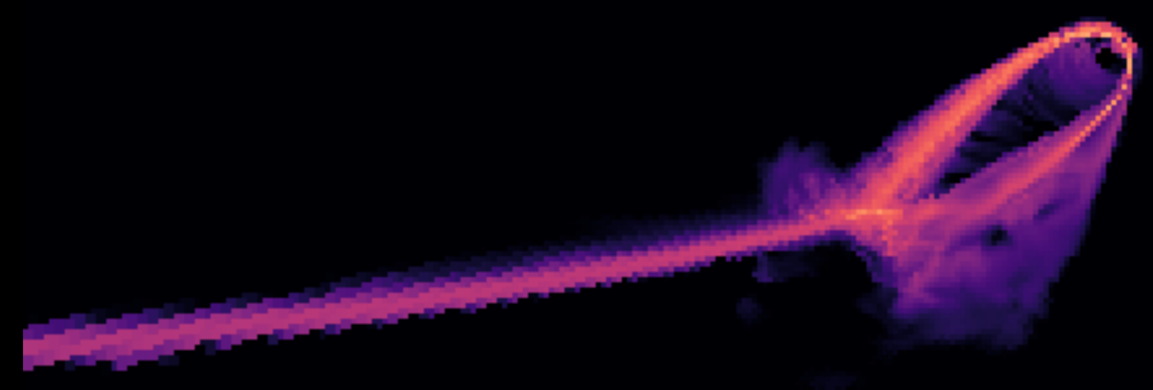
Piran et al 2015, Shiokawa et al 2015, Ryu et al 2023, Price et al 2024…



(Steinberg & Stone 2022)

"Stream-stream collision"

Dai et al 2015, Jiang et al 2016, Bonnerot et al 2021, Andalman et al 2020, Meza et al 2025…



(Huang et al** in prep**)

Early Dissipation Processes

Shock from compressed star
Nozzle shock
Debris recombination
Stream self-intersection
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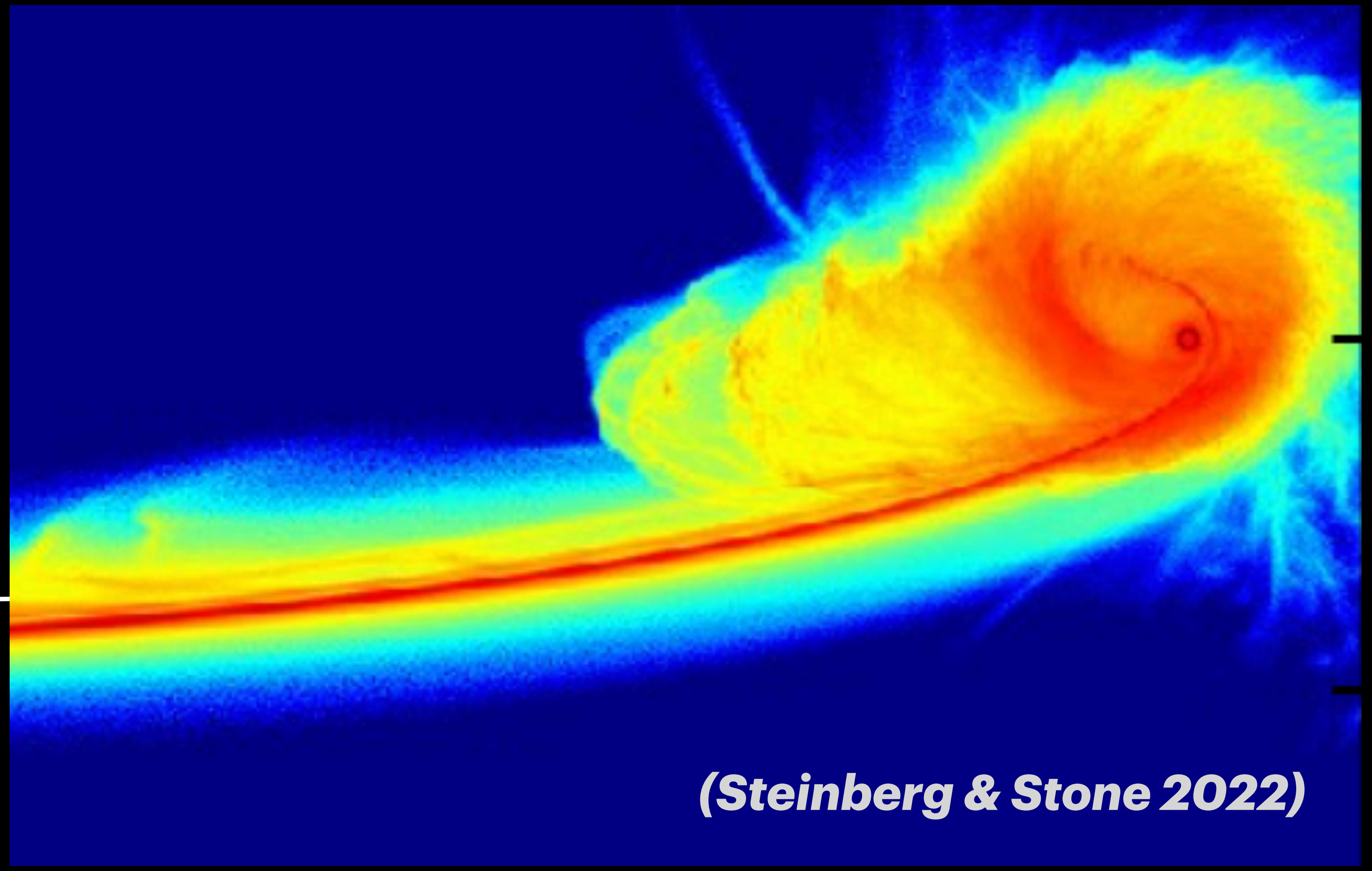


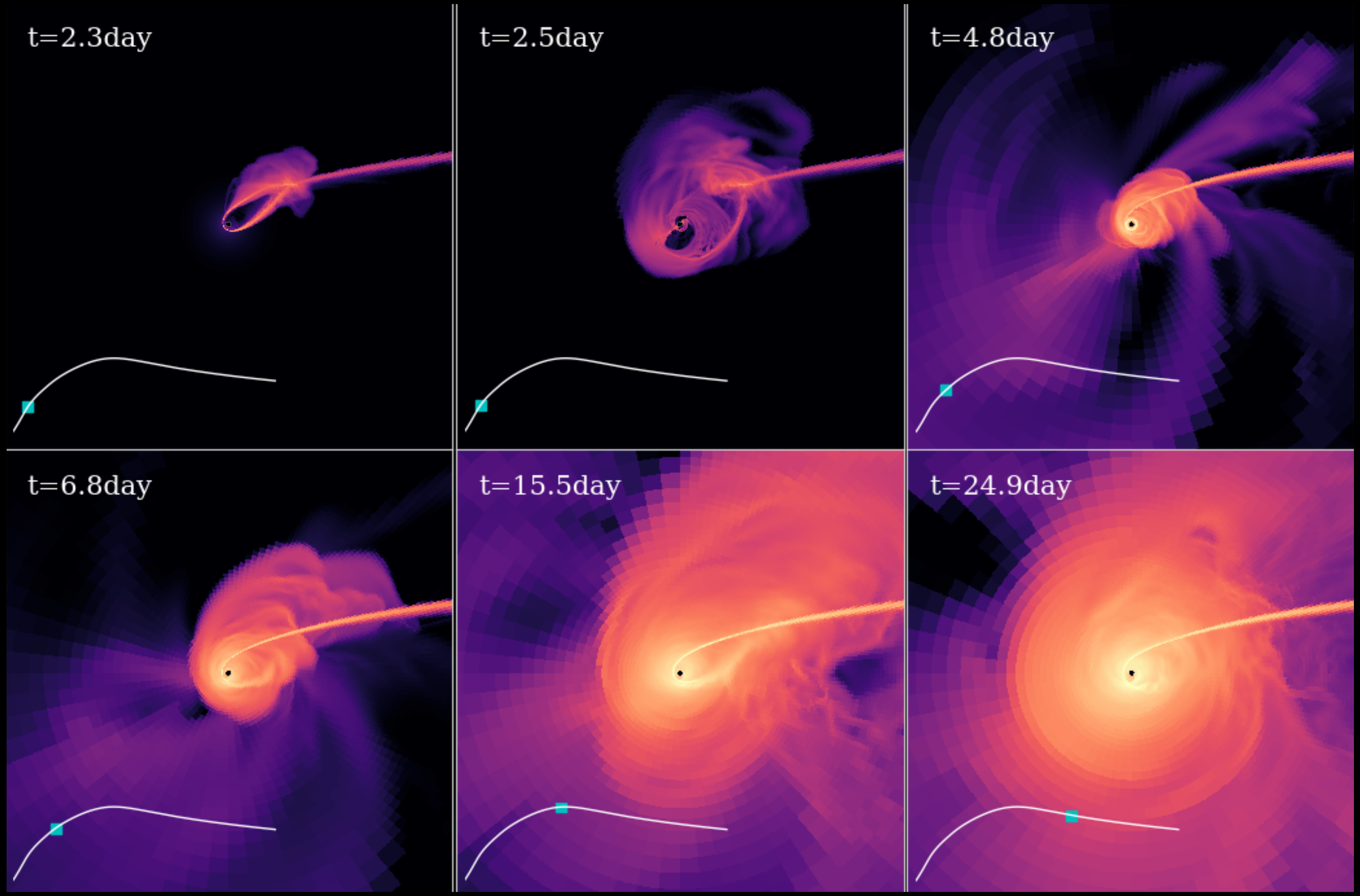
"Stream-Disk Shock"

The debris stream pierces through the circularizing disk, until small-scale instabilities dissolves the stream near circularization radius
(e.g. Andalman et al 2020, Steinberg & Stone 2022, Curd et al 2023, Huang et al 2024...)

Transition to Super-Eddington Disk

Low Angular Momentum Accretion Flow

Viralized Spherical Structure? (Stubble & Quateart 2016, Metzger 2022, Price et al 2024...)
Zero-Bernouii Number Accretion Flow? (Coughlin et al 2014, Wu et al 2018, Eyles2022 et al...)

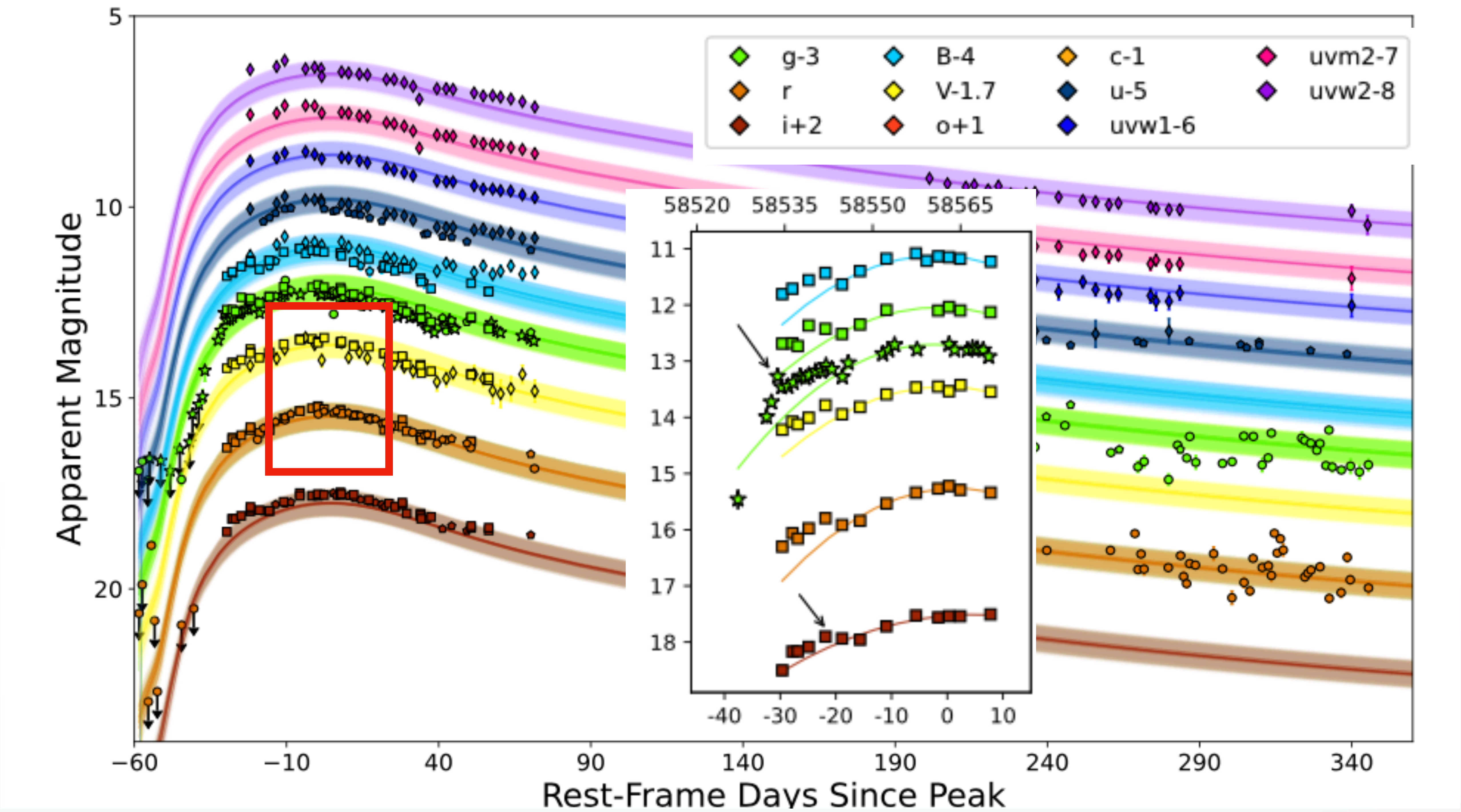


(Huang et al *in prep*)

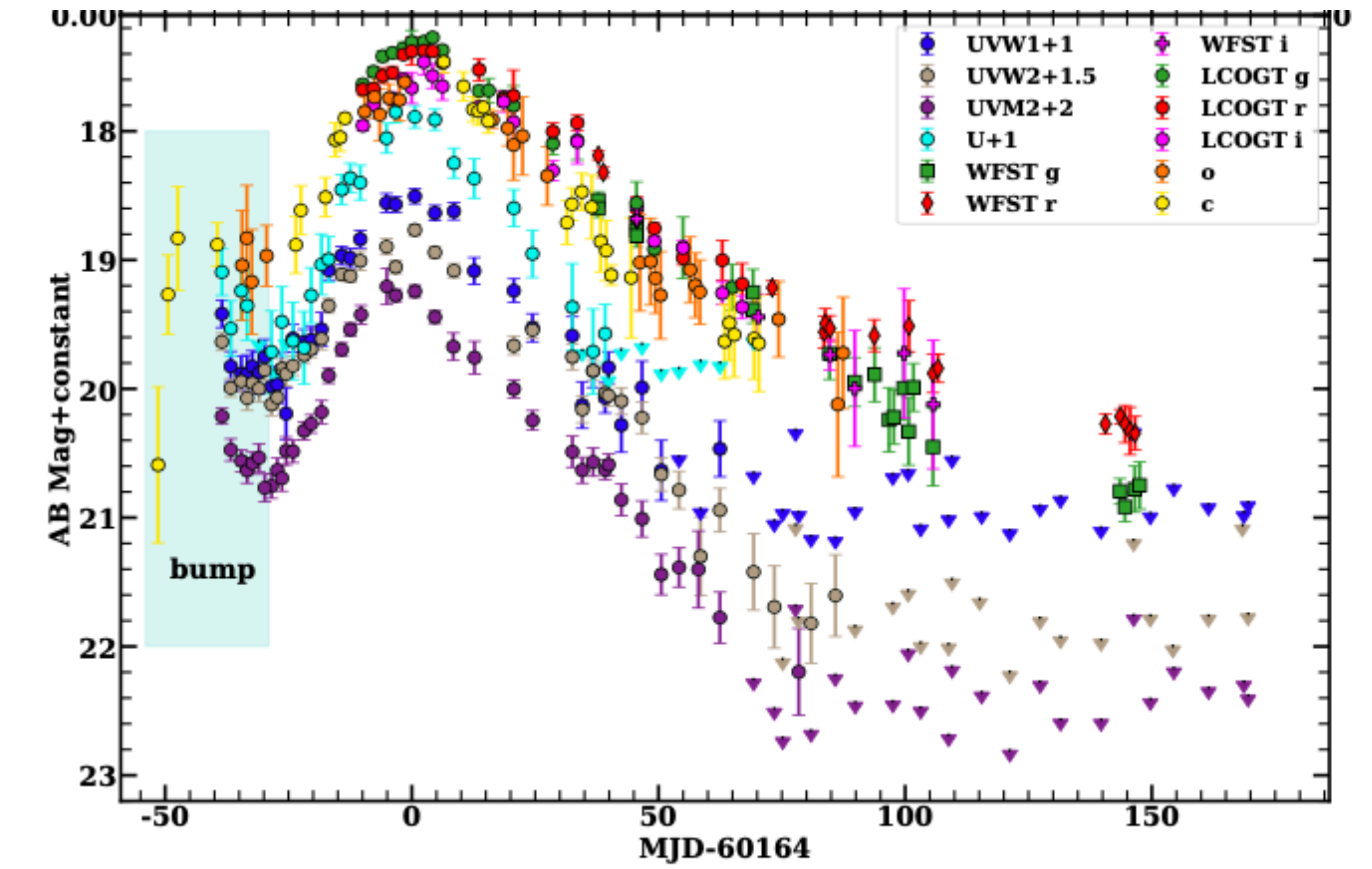
Pre-peak color evolution / precursors

"Optical bump"

AT2019azh (*Faris et al 2024*)



AT2023lli (*Huang et al 2024*)

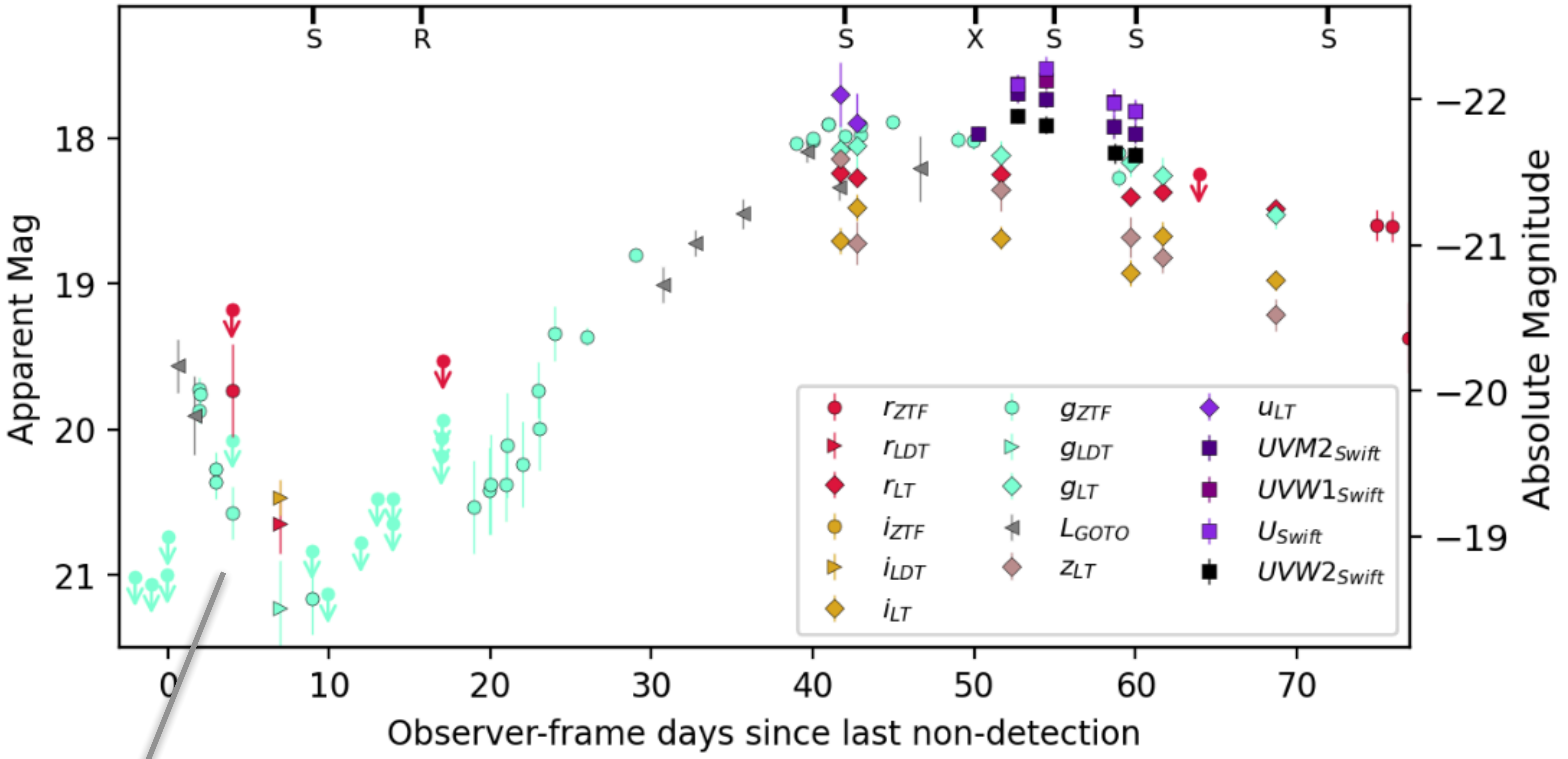


(Pinto et al 2015)

Pre-peak color evolution / precursors

Red "Precursor" **AT2024kmq *(Ho et al 2025)***

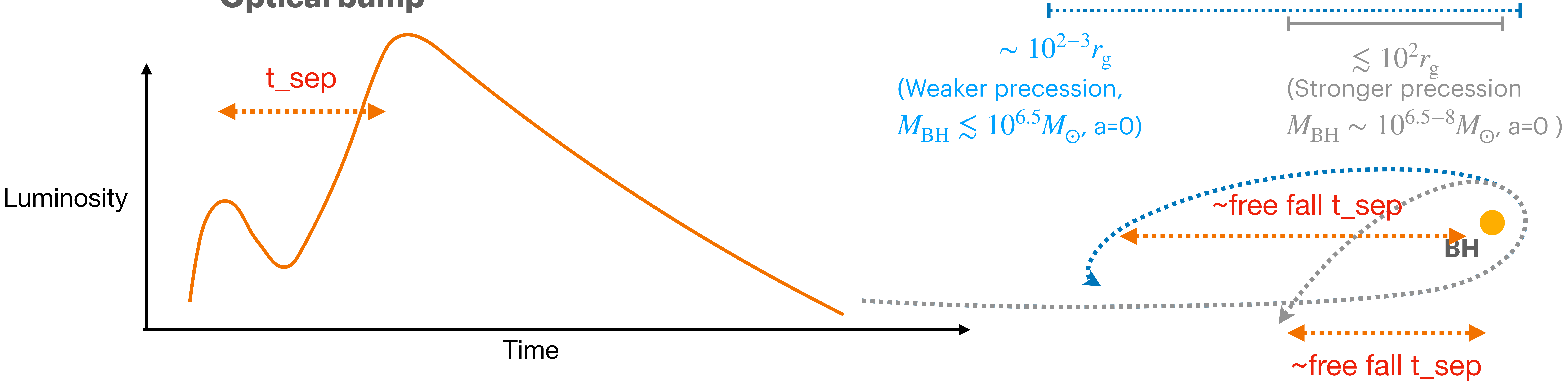
Likely high mass black hole: $M_{\rm BH} \sim 10^8 M_\odot$



Off axis jet?
Stream self-intersection?

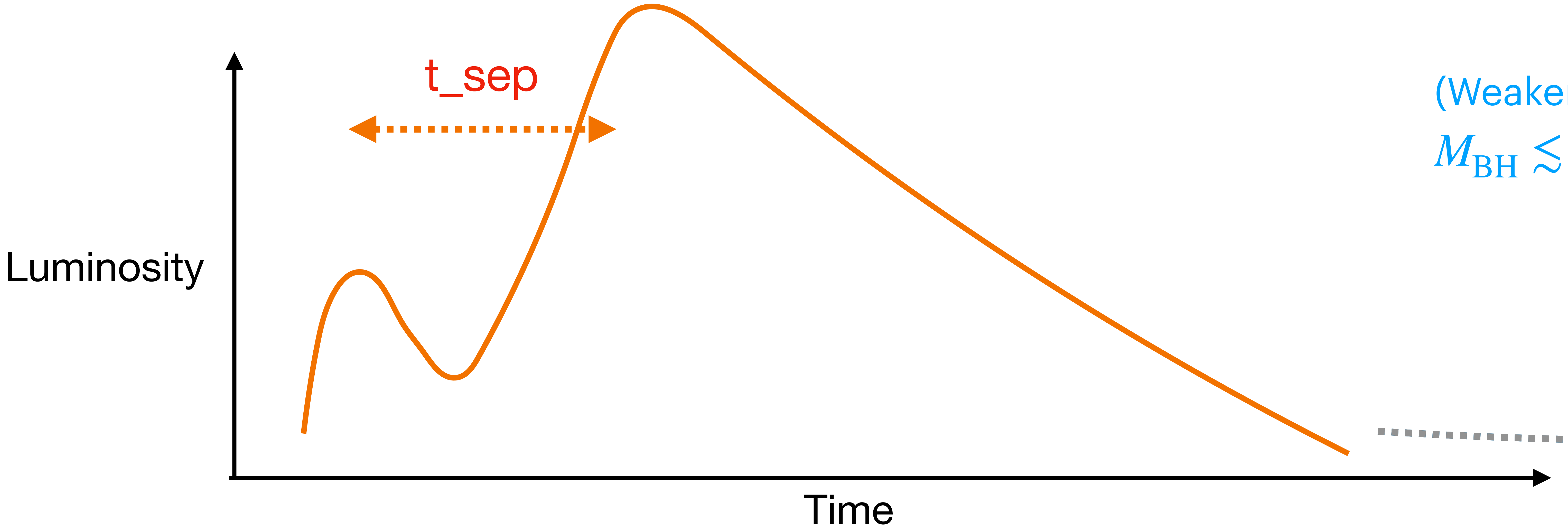
Pre-peak color evolution / precursors

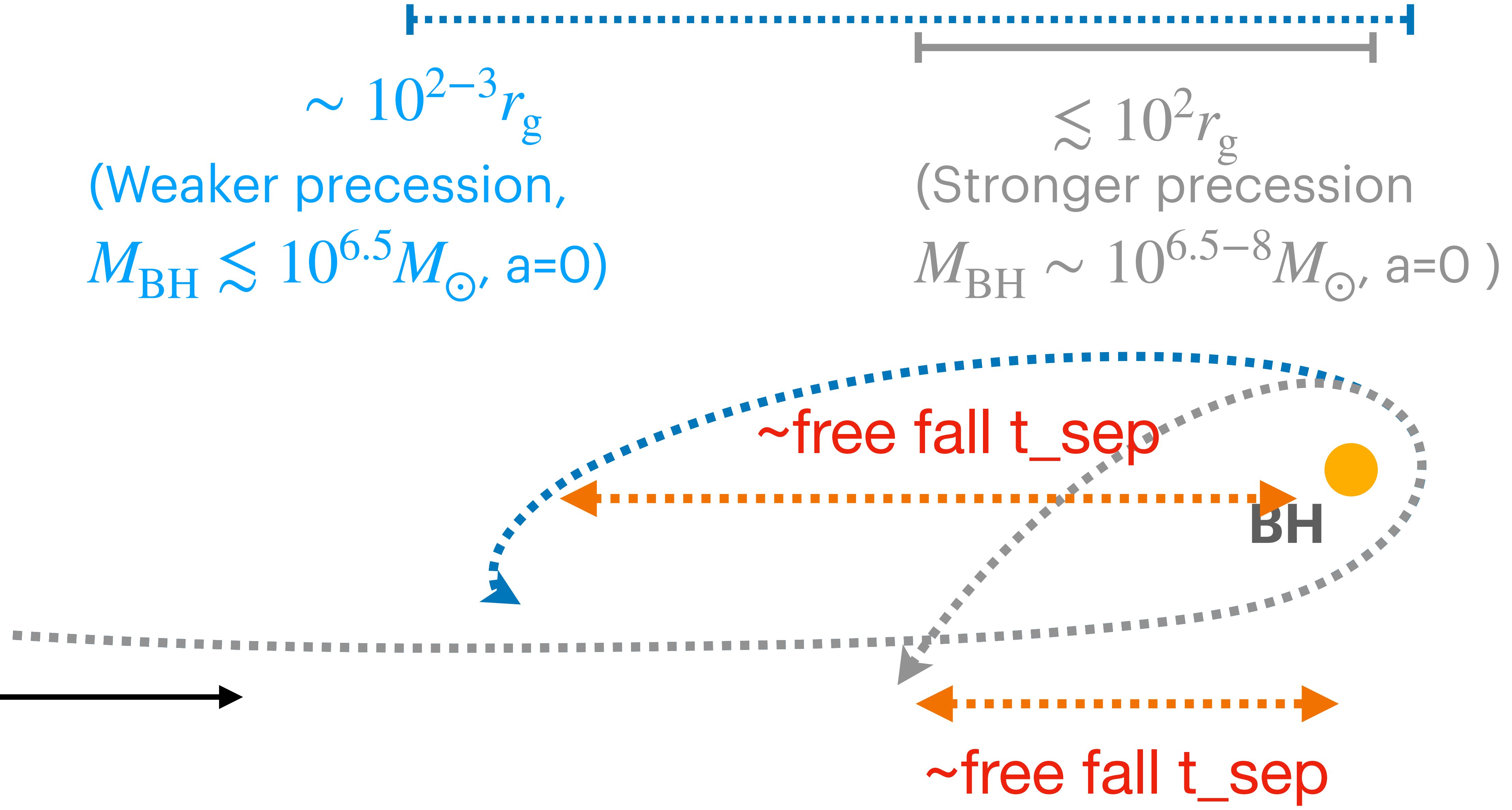
"Optical bump"

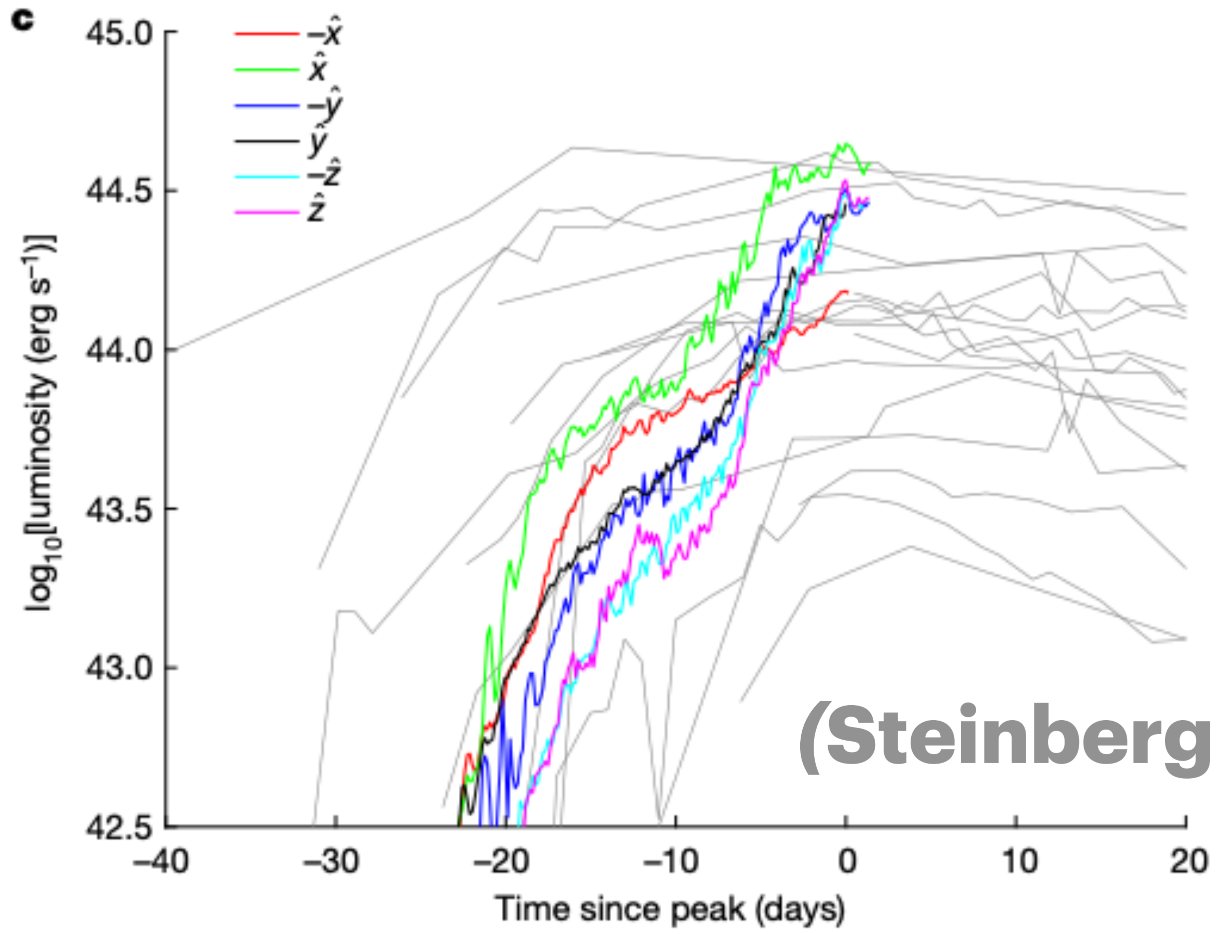


Pre-peak color evolution / precursors

"Optical bump"



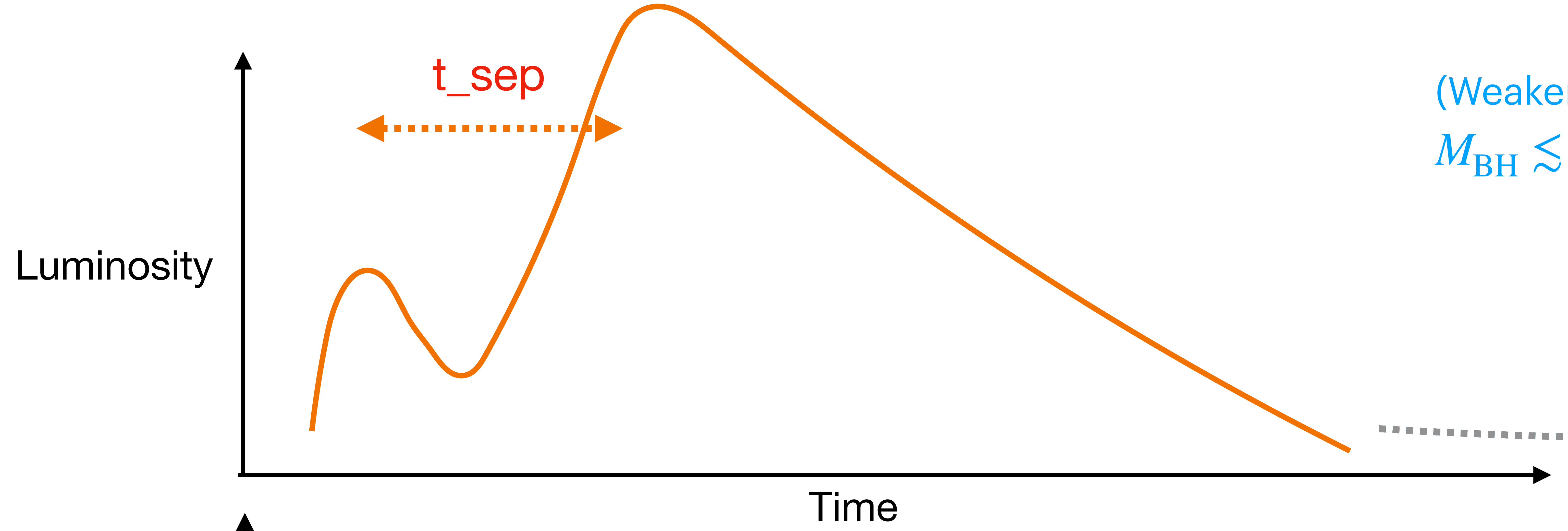


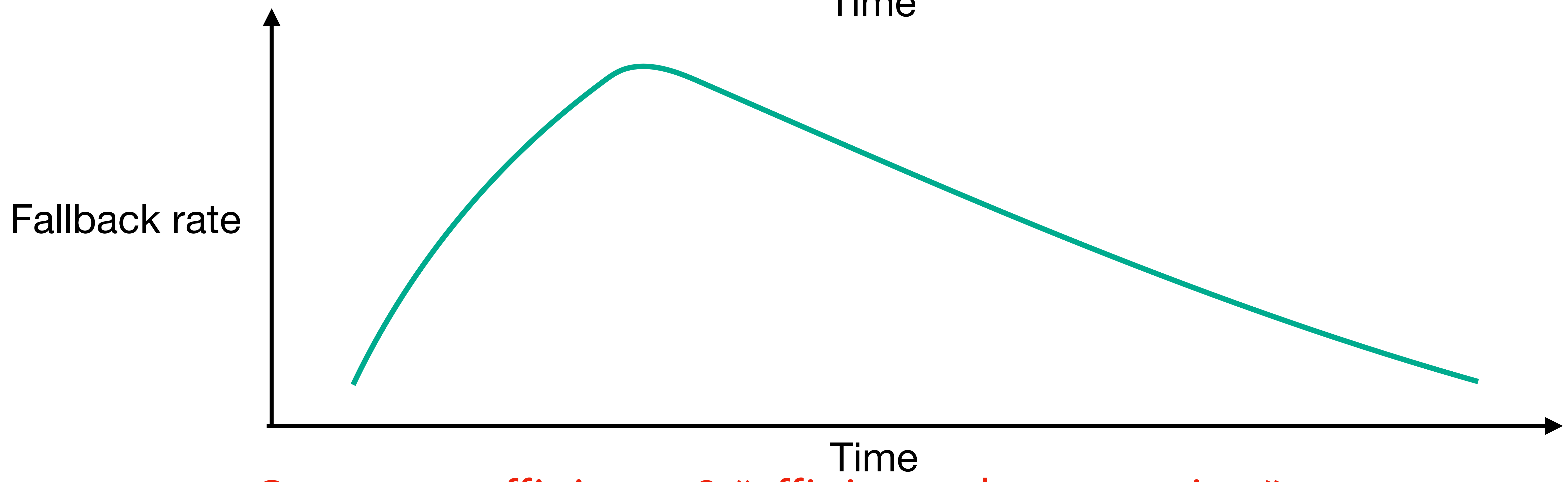


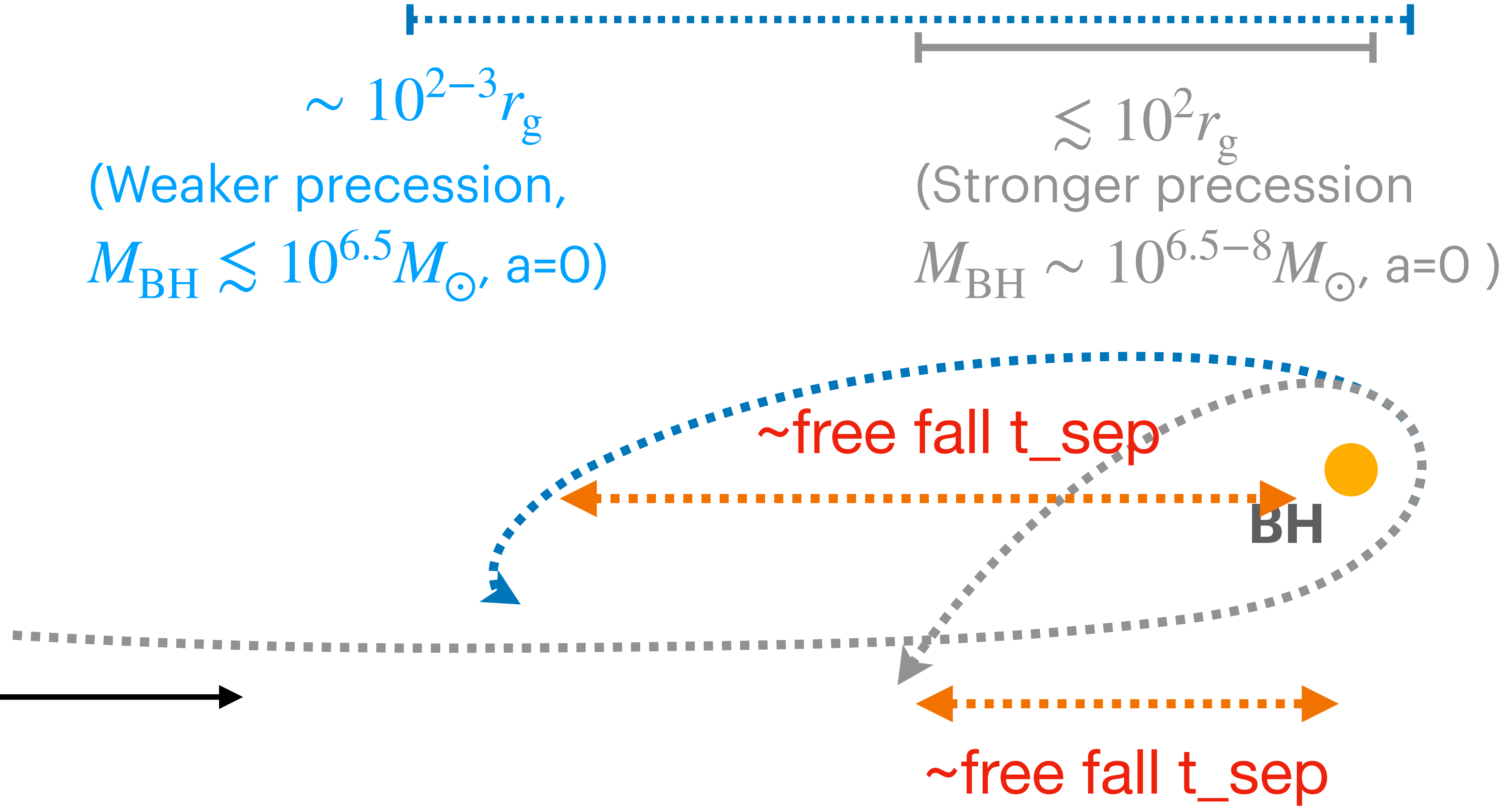
(Steinberg & Stone 2022)

Pre-peak color evolution / precursors

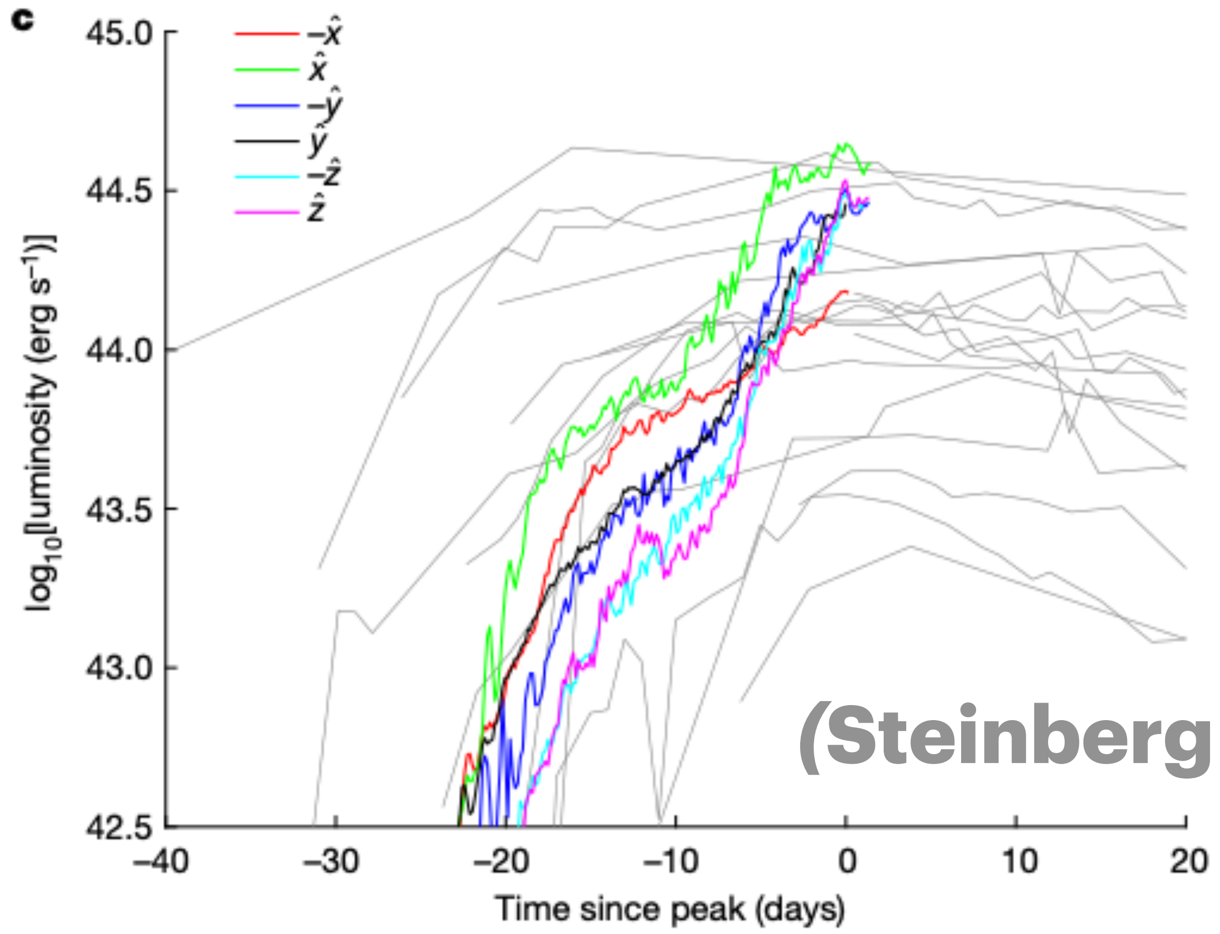
"Optical bump"







Compare efficiency? "efficiency by accretion" $\eta_{acc} \sim L/\dot{M}c^2$, "efficiency by shock" $\eta_{shock} \sim L/\dot{M}v^2$

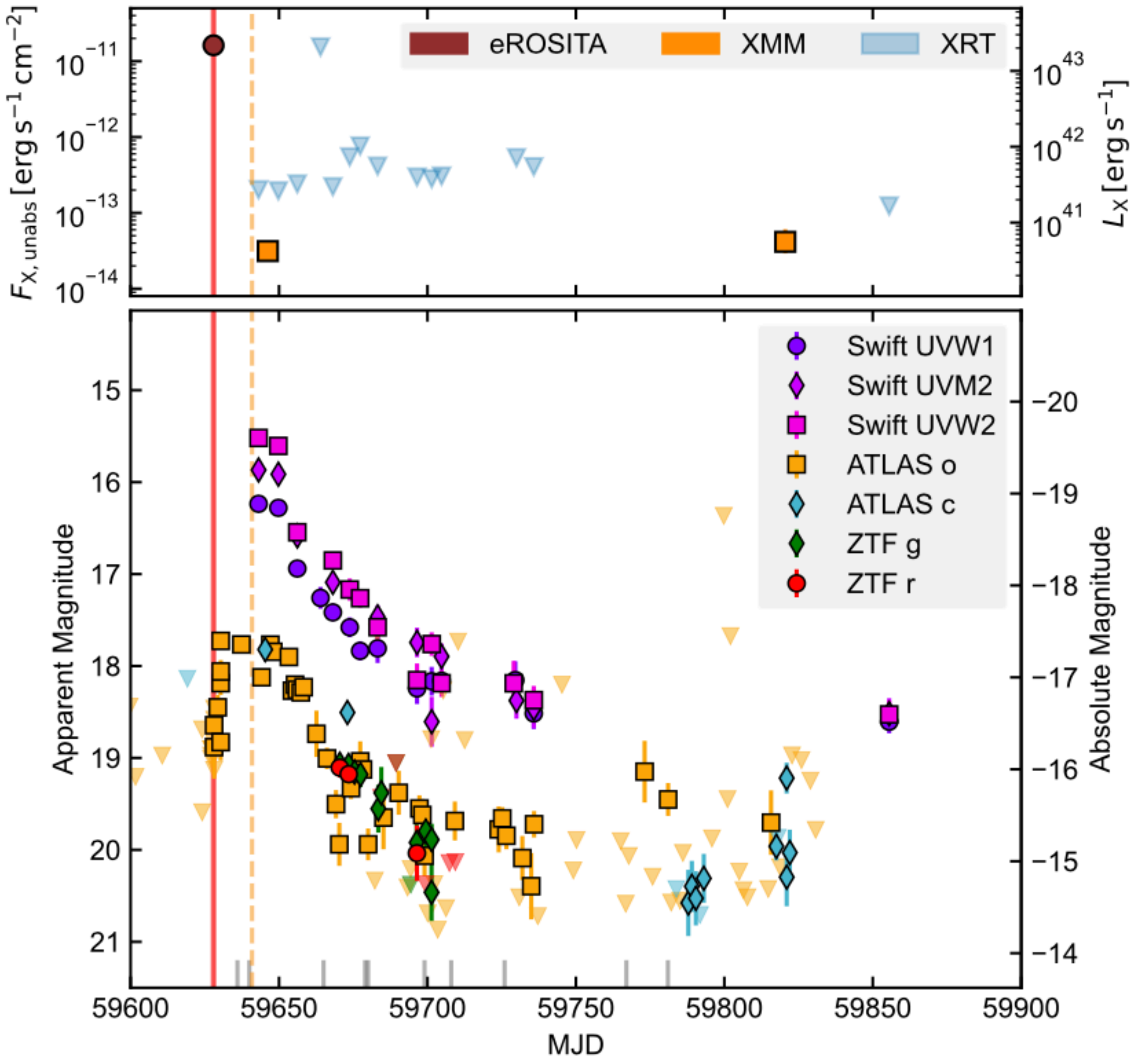


(Steinberg & Stone 2022)

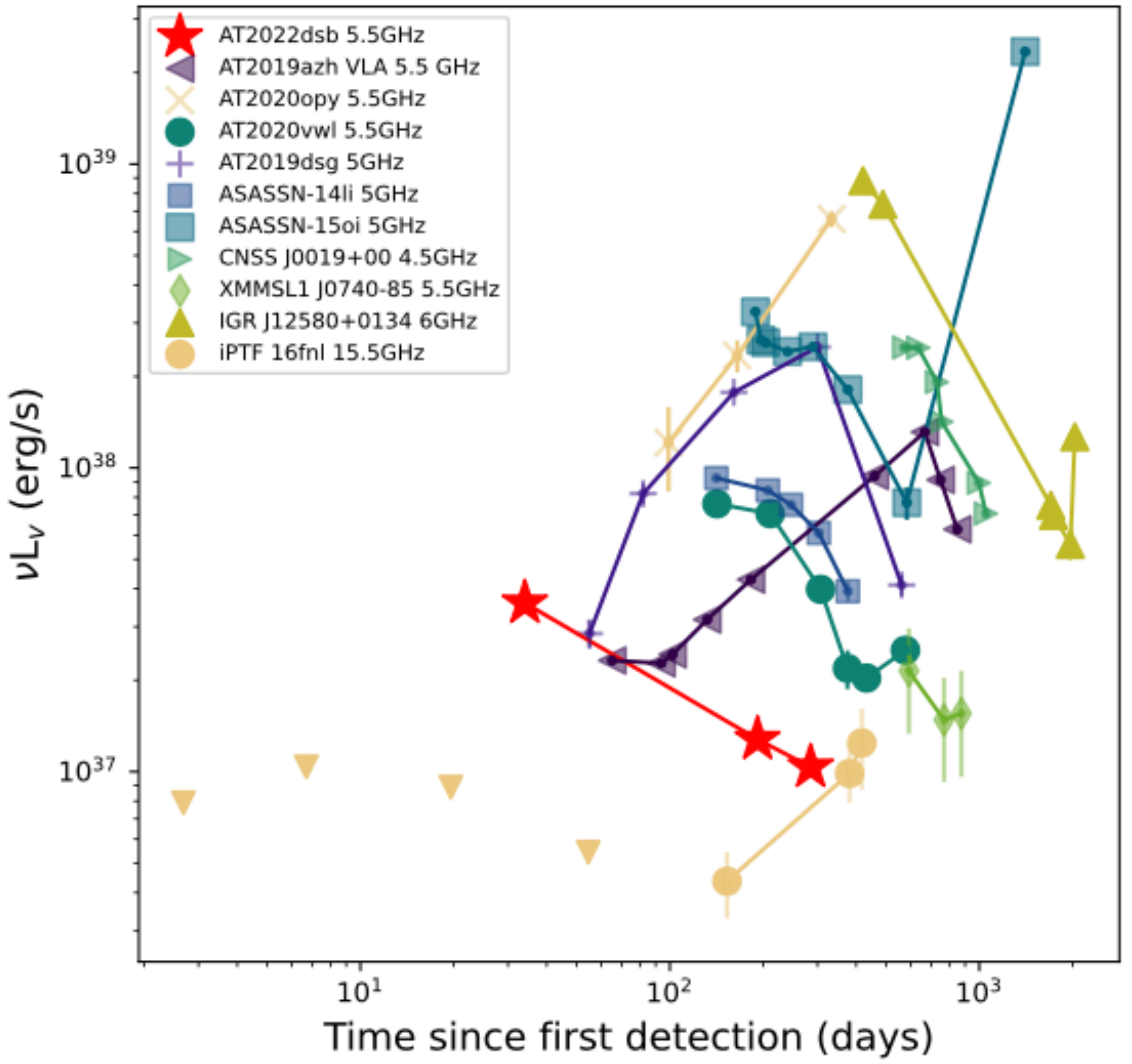
Pre-peak color evolution / precursors

Early (Pre-peak) X-ray   AT2022dsb *(Malyali et al 2023)*

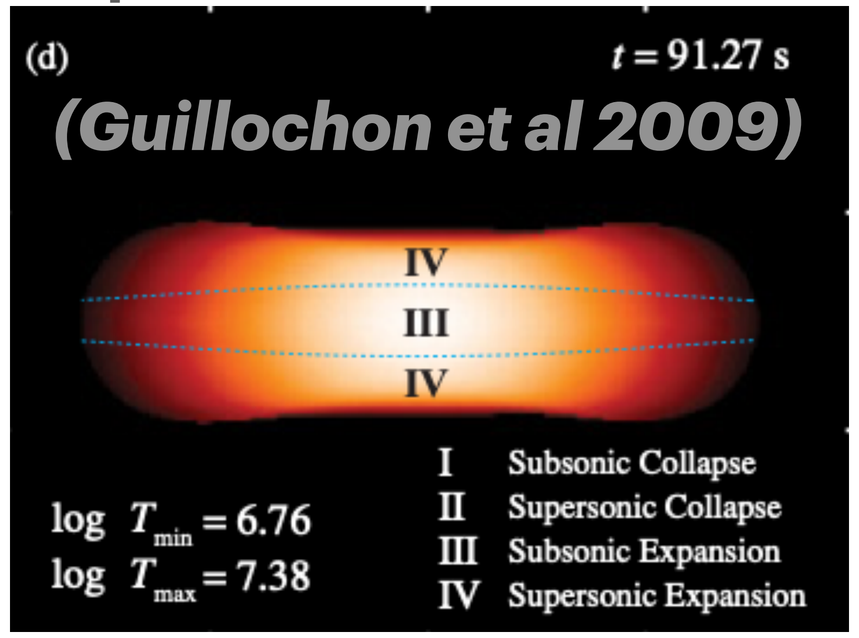
Pre-peak Lx~1.0e43erg/s, "faint and fast" Optical-UV LC



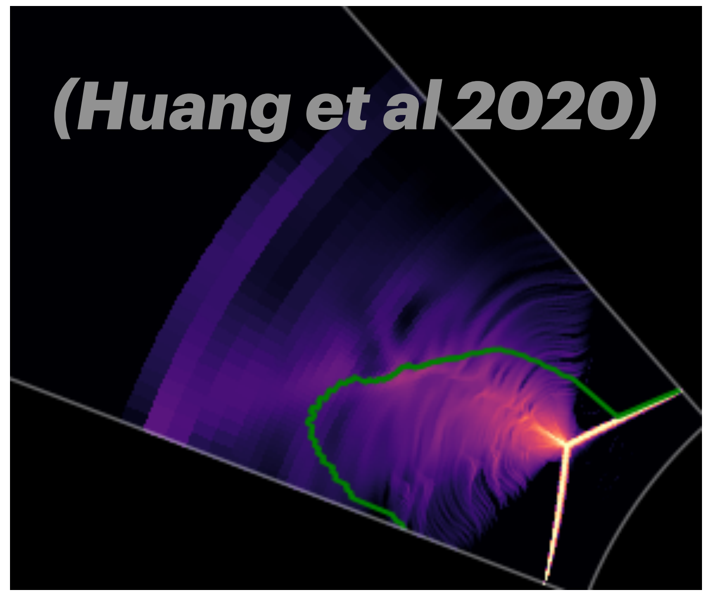
With a relatively early radio flare



Shock BO from the tidally compressed star?

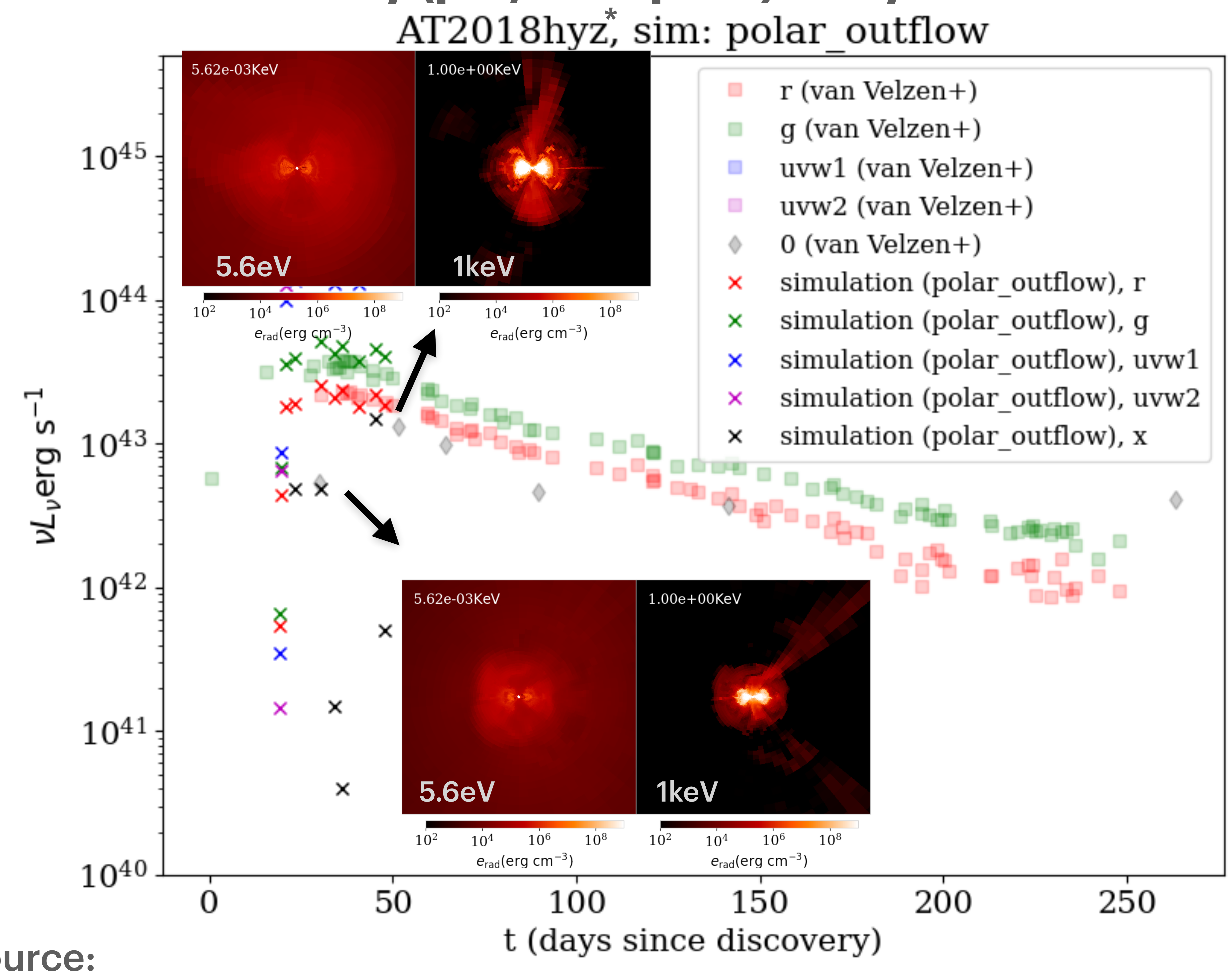


Sub-Edd fallback ->slow/ incomplete reprocessing?



Pre-peak color evolution / precursors

Early (pre/near-peak) X-ray: simulation



(Huang et al *in prep*)

Generated with ***OTTER*** (Franz et al 2025)

Multi-group 3D simulations *(changed luminosity normalization)*

X-ray != Disk
Simulations also find in early time before disk disk form, shocks + varying photosphere are sufficient to produce X-ray variabilities

* for this particular source:
Increasing radio: Cendes+ 2025
Possible UHECR: Piran+ 2023

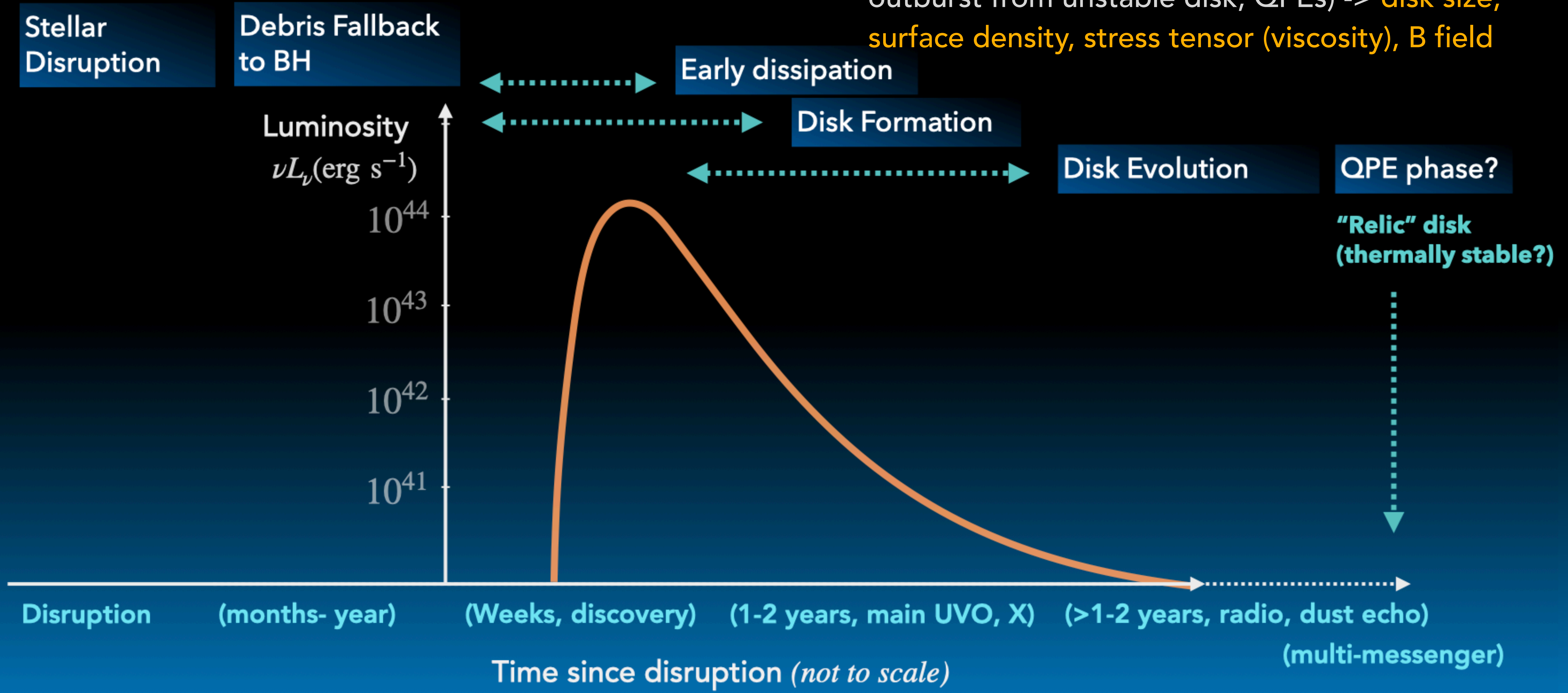
Summary: Decoding TDE Evolution

Unique BH Feeding in TDEs

- Precursors -> direct diagnostic of GR precession (apsidal & Lense-Thirring)
- Disruption processes -> further constrain BH mass, possibly break degeneracy of spin and mass.
- Pre-peak color evolution -> reprocess layer formation (pre-peak cooling or invariable/heating -> slow/rapid build optical-depth build up) -> mechanisms to damp eccentricity and form disk?

Disk Dominated Emission

- Develop disk spectral and light curve model -> BH mass and possibly spin
- Combine with radio that tracks mass ejection -> mass budget in TDE (how much accreted/ejected?) disk mass and angular momentum content
- For jetted TDE, what is disk structure when the jet is launched?
- Combine with other transients (e.g. episodical outburst from unstable disk, QPEs) -> disk size, surface density, stress tensor (viscosity), B field



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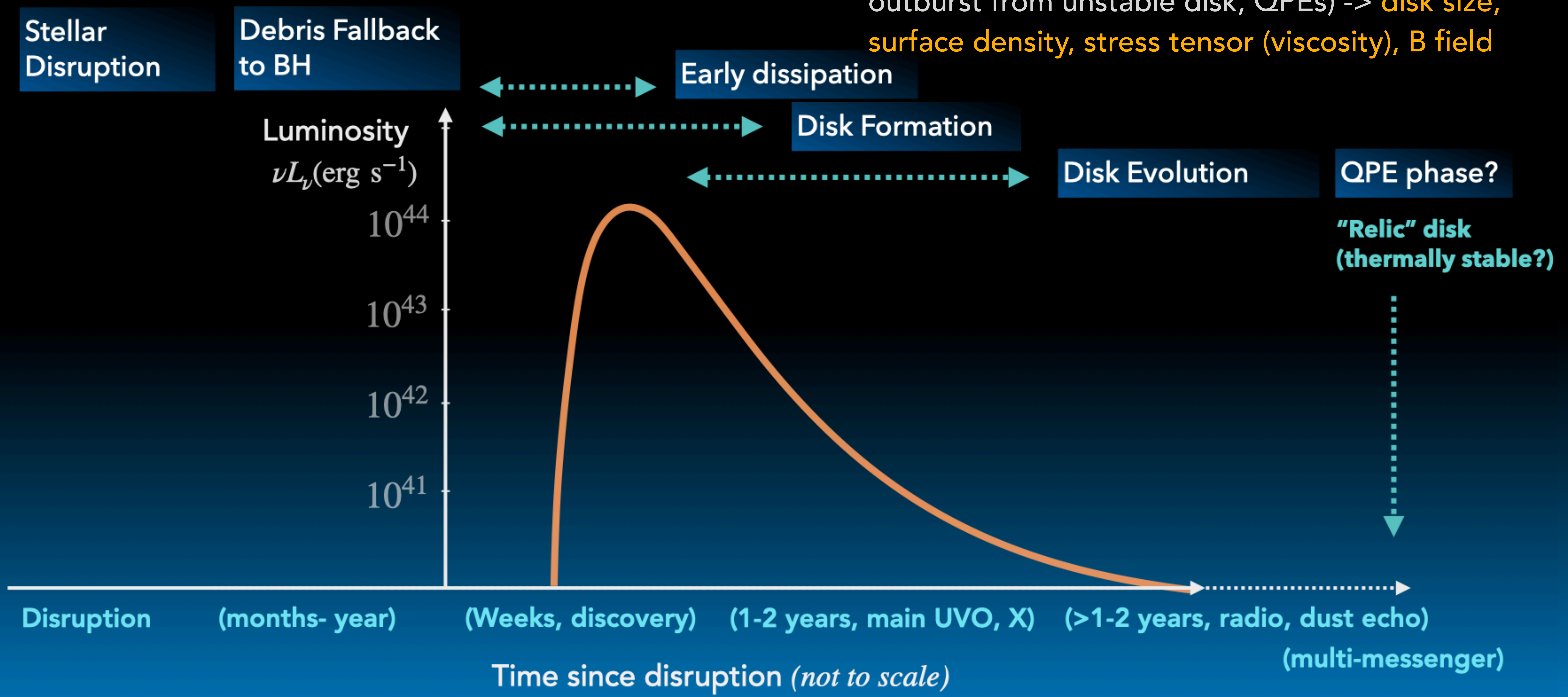

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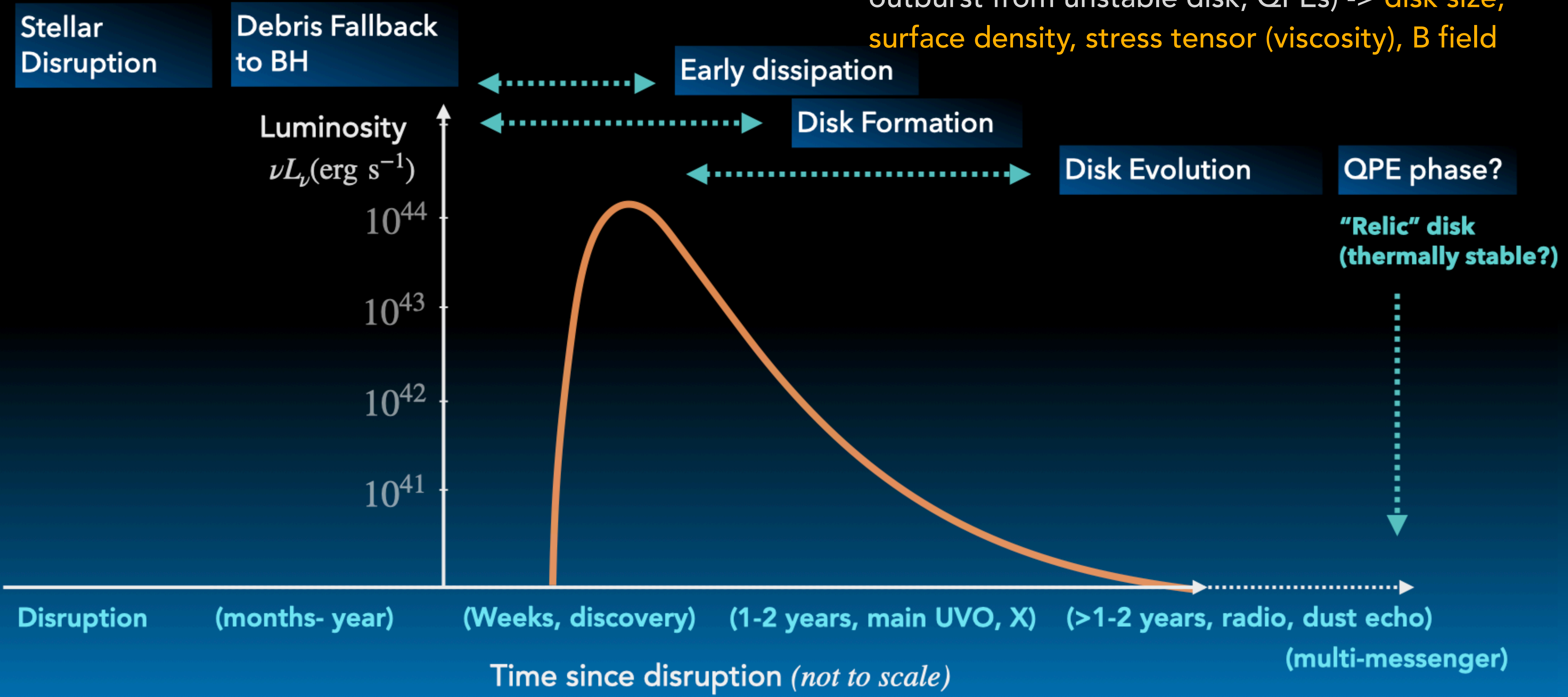

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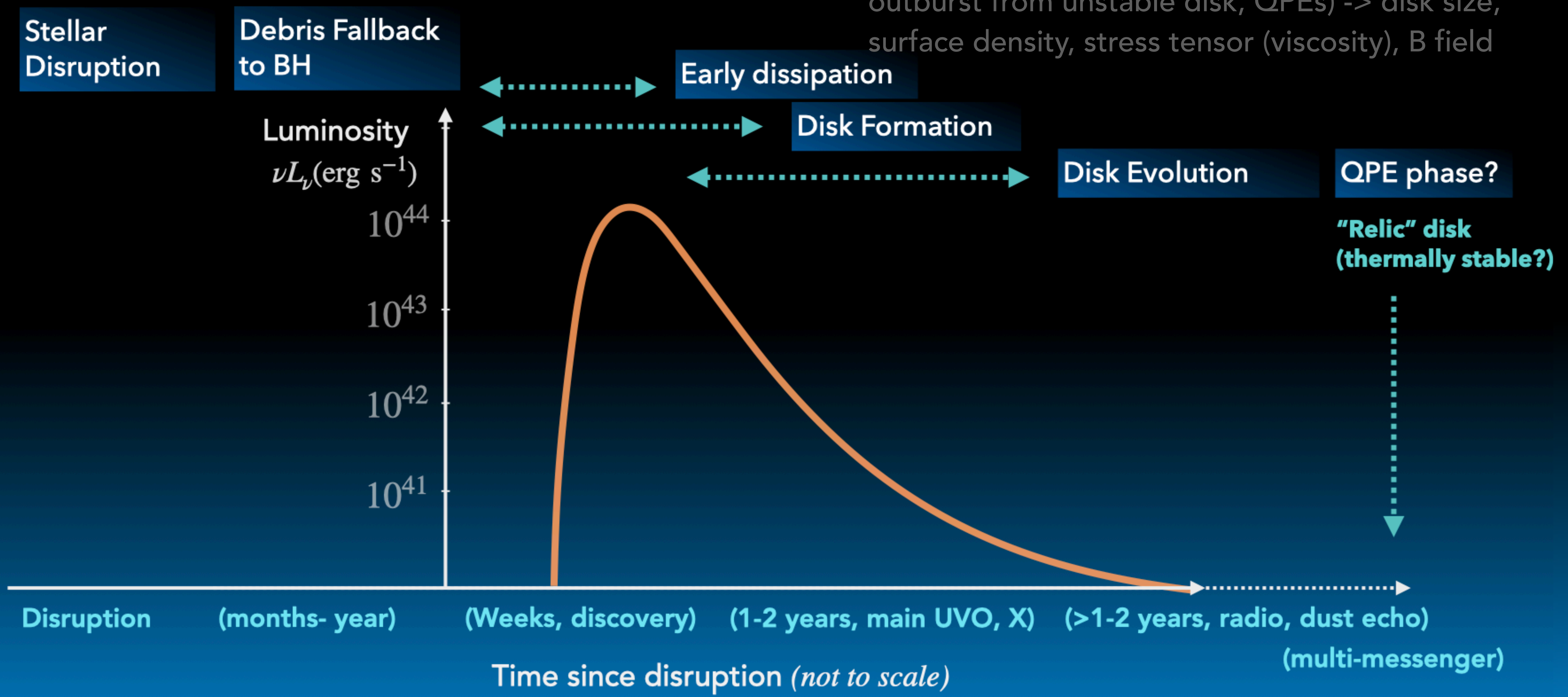

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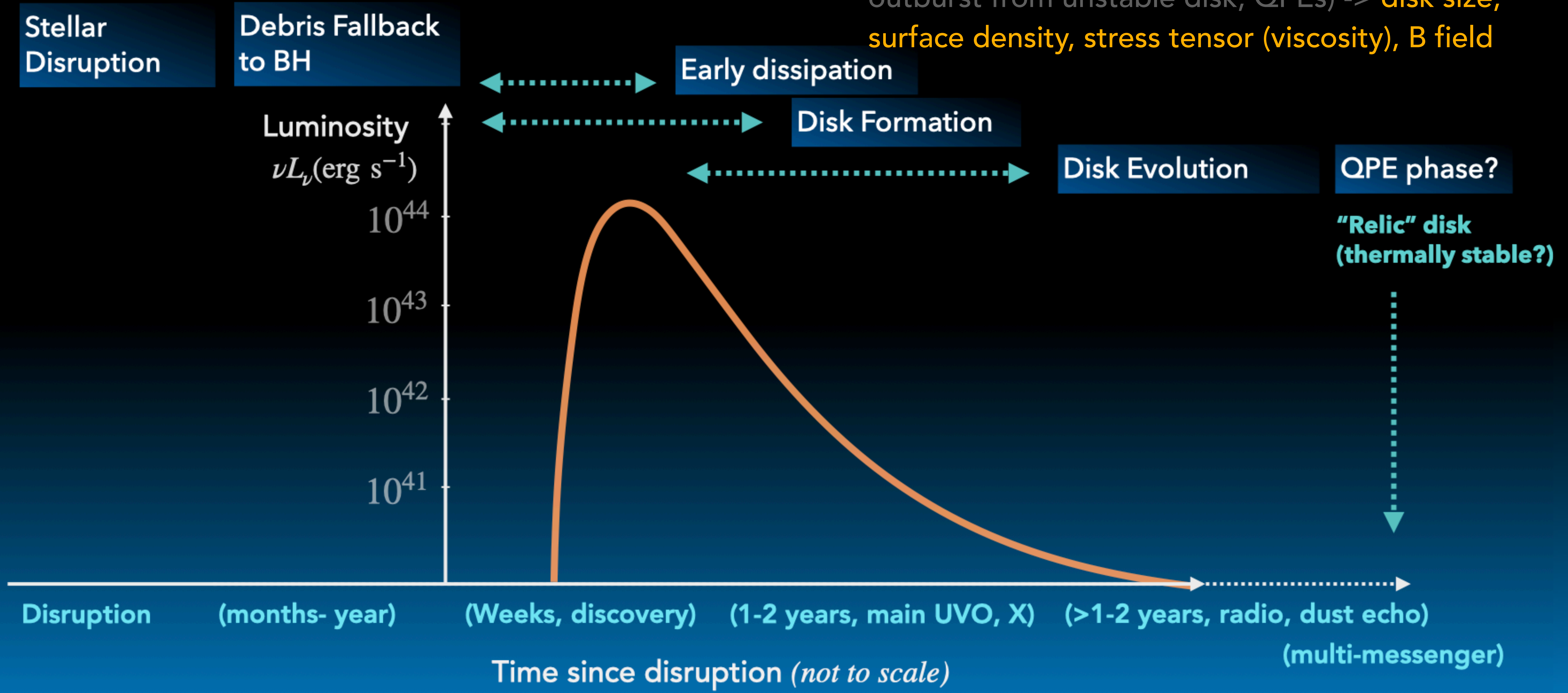

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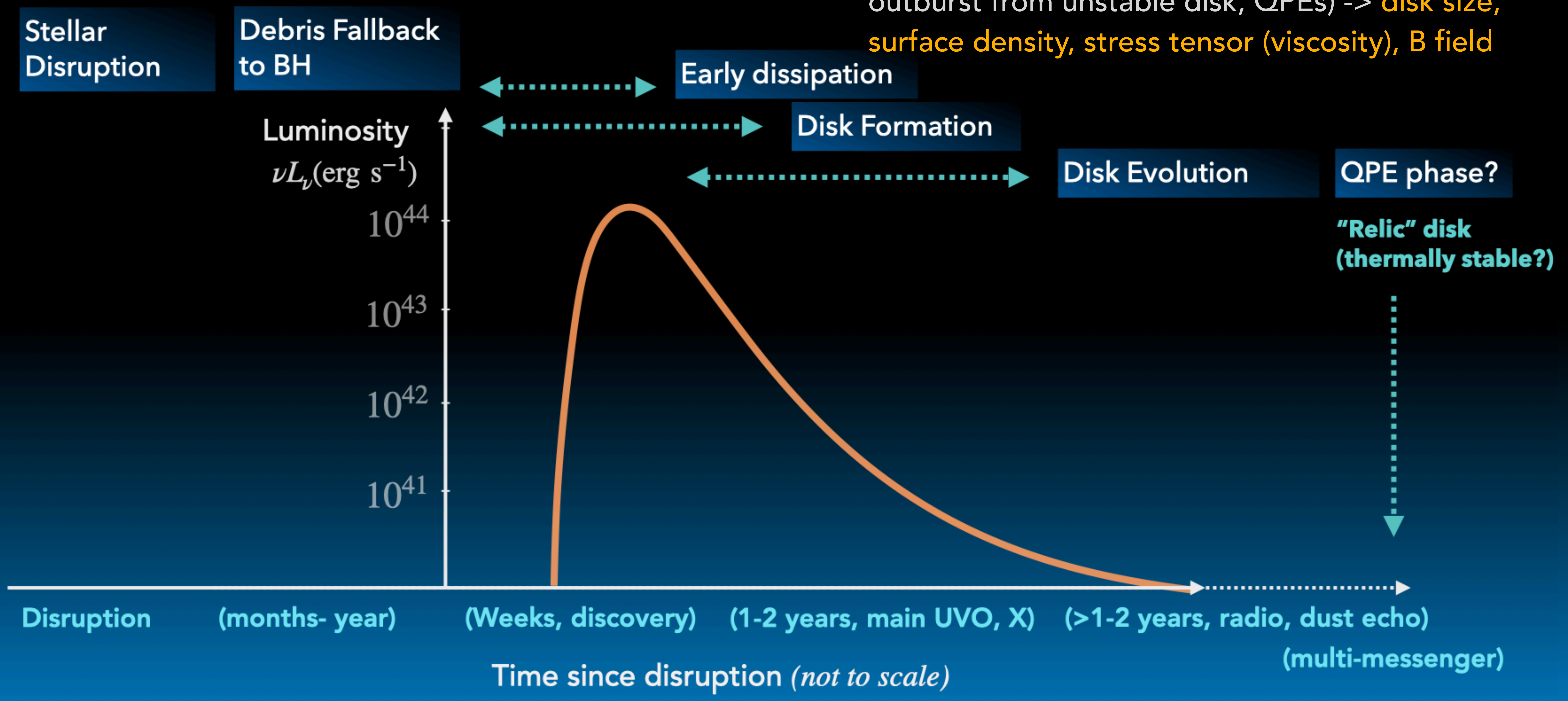

An example question