

Tidal disruptions and X-ray eruptions: stellar encounters with supermassive black holes

Matt Nicholl

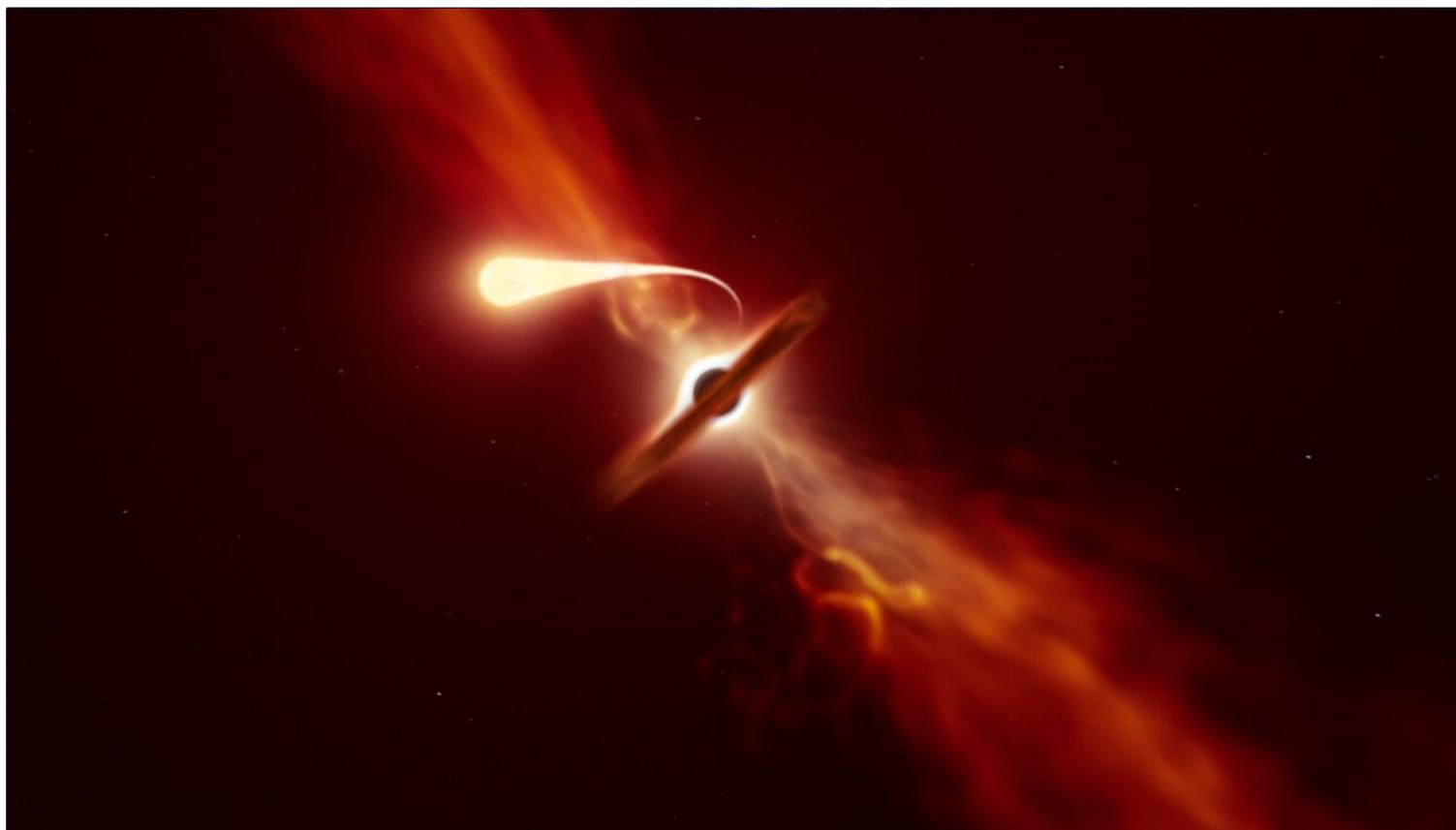
*With QUB / Oxford,
PESSTO, ZTF, 4MOST/TIDES,
M. Guolo, B. Mockler, A. Mummery,
DJ Pasham, S. Van Velzen...*



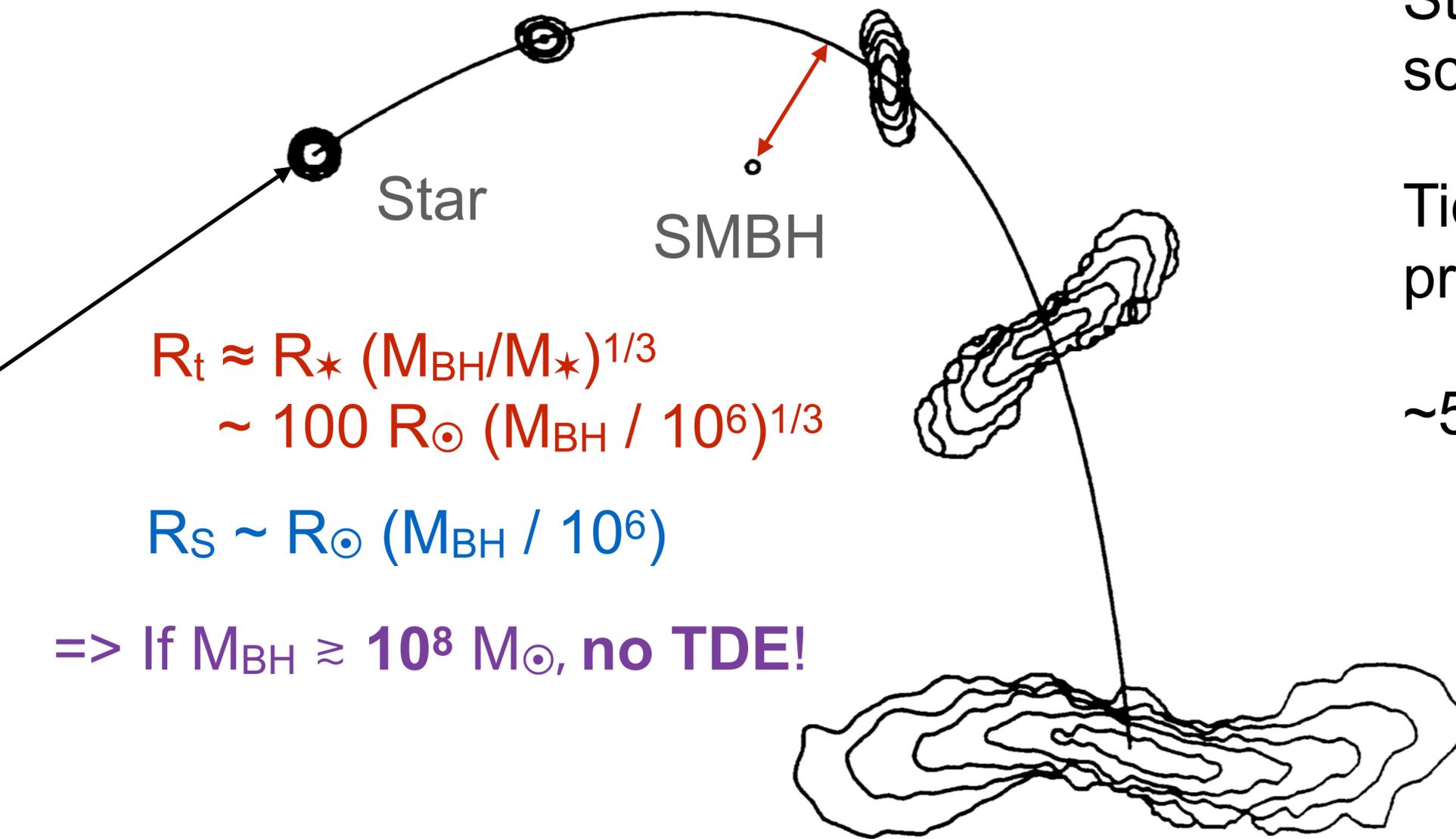
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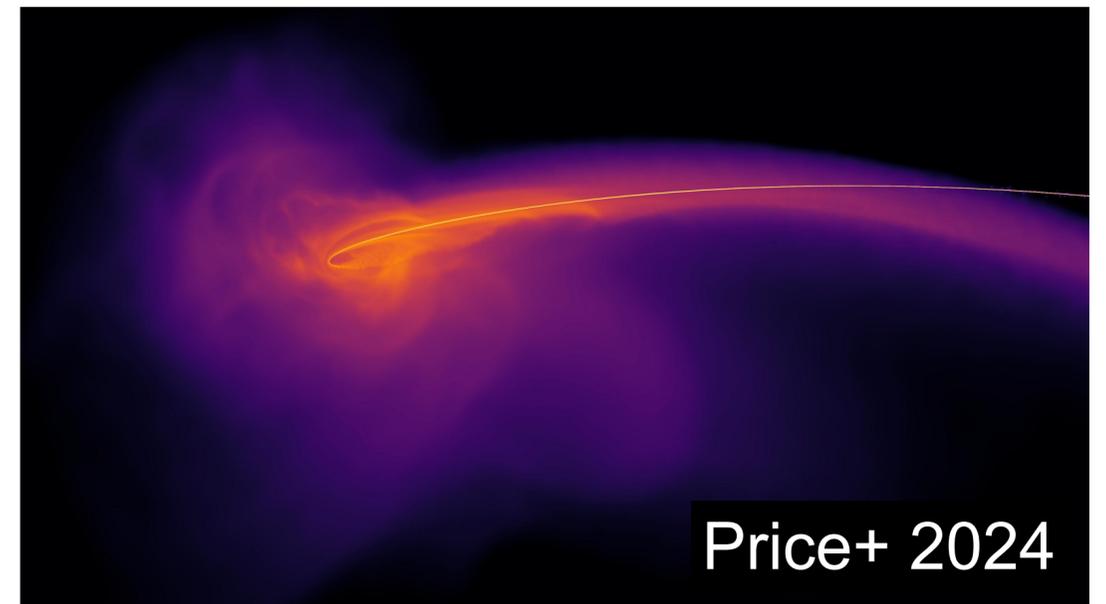
Tidal disruption events: dynamics



Star near SMBH sphere of influence scattered onto plunging orbit

Tidal forces at pericentre unbind star, produce thin stream

~50% of debris bound to SMBH



Evans & Kochanek 1999, Hills 1975, Rees 1988

Price+ 2024

TDEs: after disruption

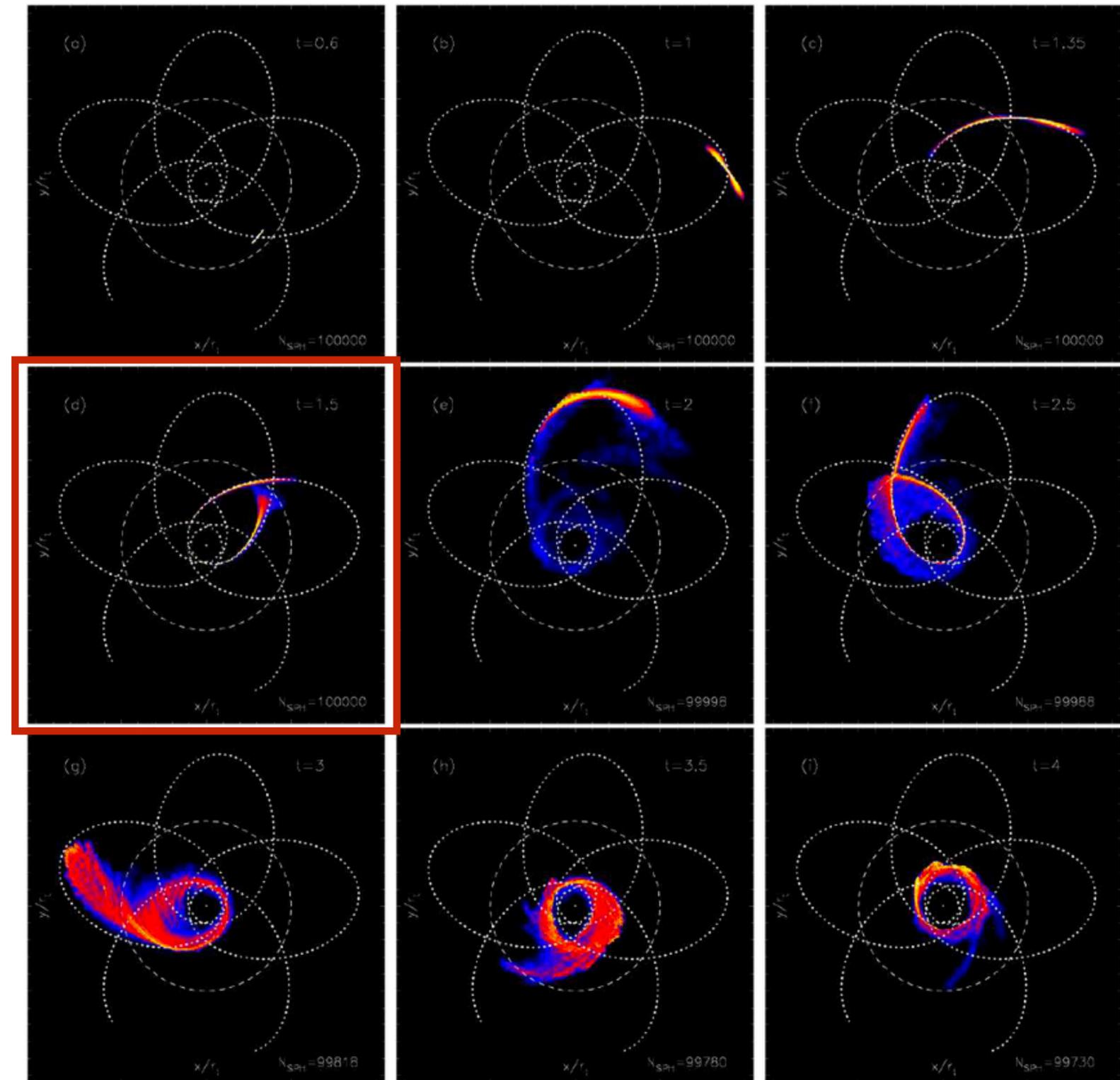
Bound debris returns to pericentre, at a rate $dM/dt \propto t^{-5/3}$

Initially highly super-Eddington

Self-intersection of stream due to apsidal precession (GR)

Shocks dissipate energy, circularise debris, form disk

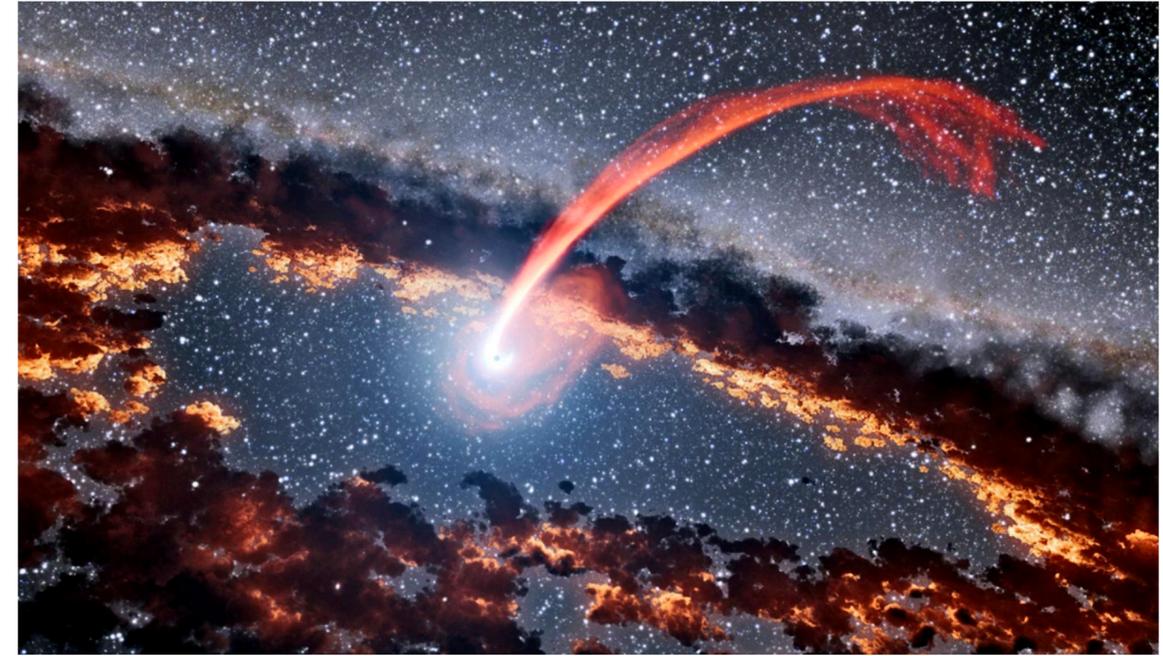
Somewhere* in this process, radiation is produced!



Hayasaki+ 2012



Why study TDEs?



Accretion physics from super-to-sub Eddington on convenient timescales

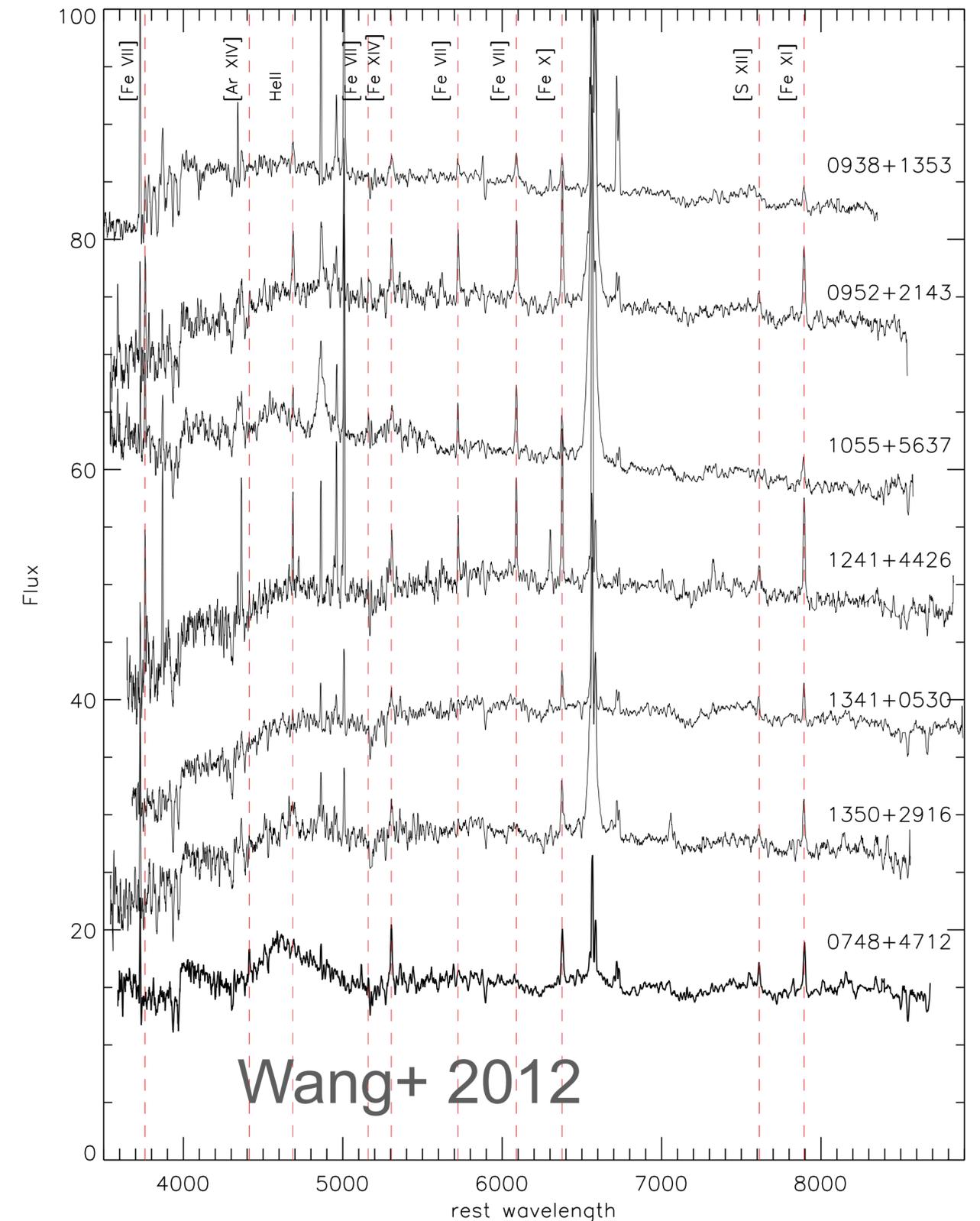
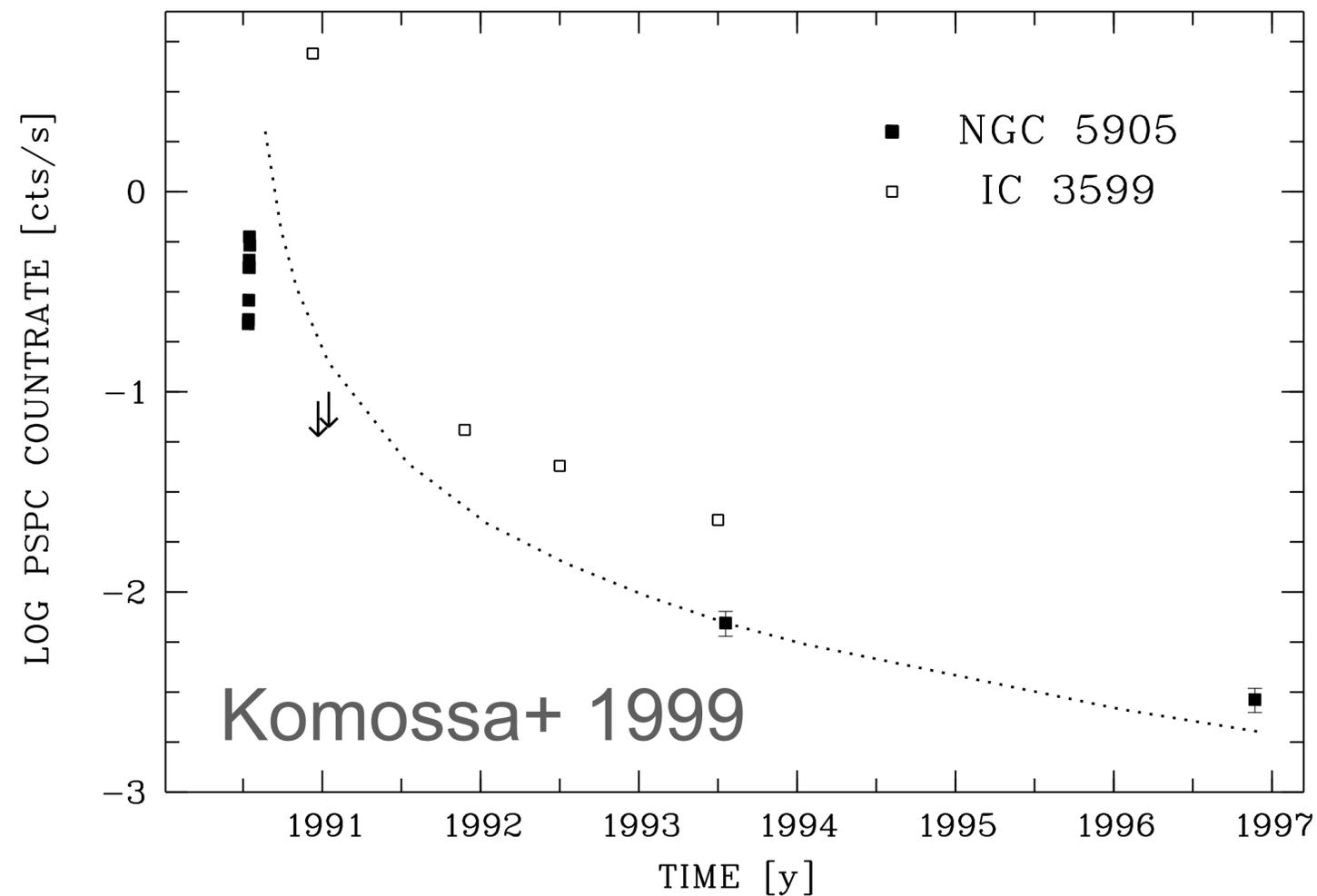
- May produce “clean” disks compared to messy AGN
- Multi-messenger astrophysics: emit from X-ray to radio, plus neutrinos (Stein+ 2021) and gravitational waves (Toscani+ 2022)

SMBH demographics, seeding and growth mechanisms

- Select for low mass SMBHs / IMBHs
- Probe central BH populations in otherwise dormant galaxies

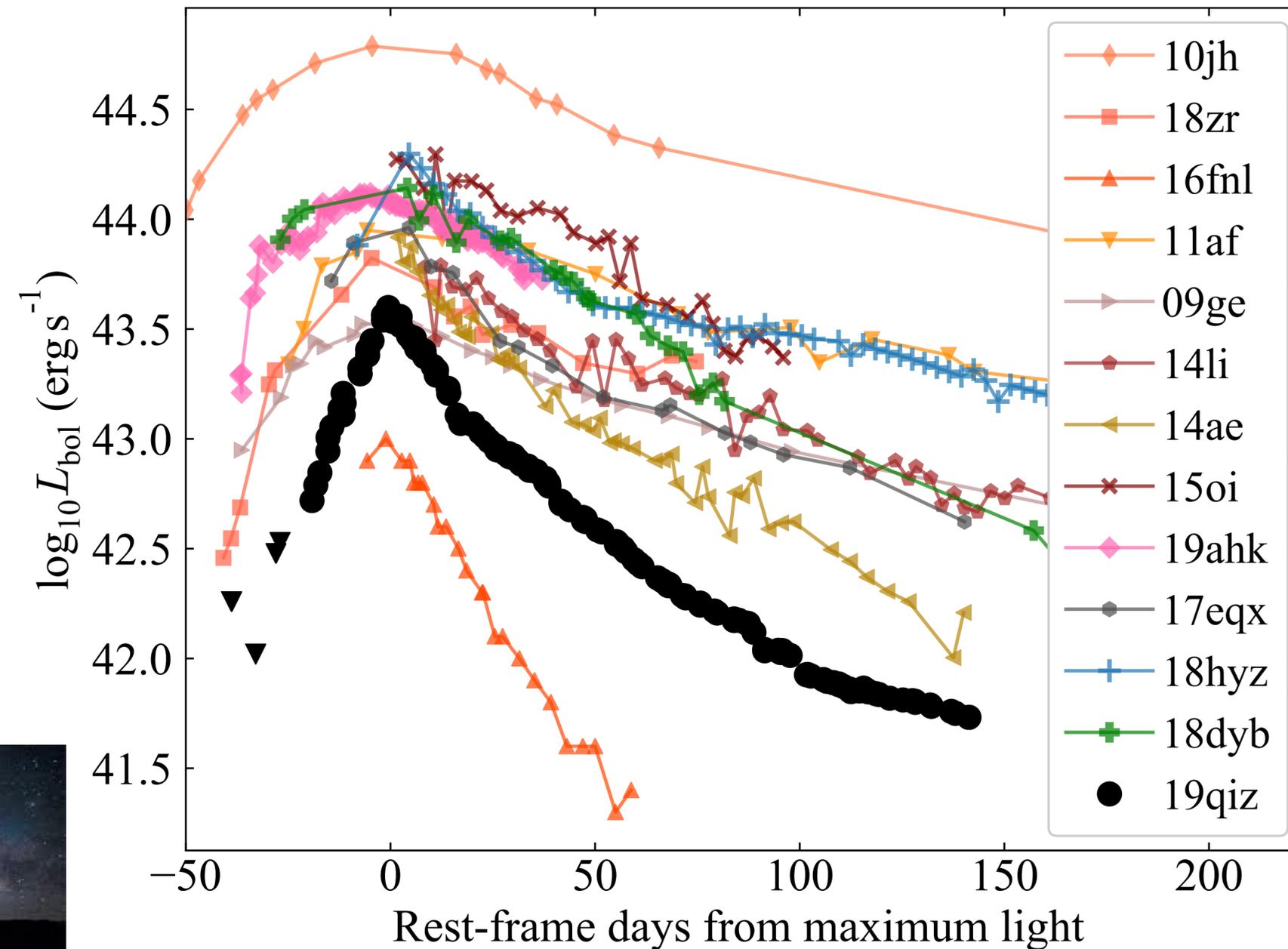
Observations: first candidates

- X-ray flares from cores of inactive galaxies
- Coronal emission lines in SDSS galaxies — light echoes of ionising radiation?

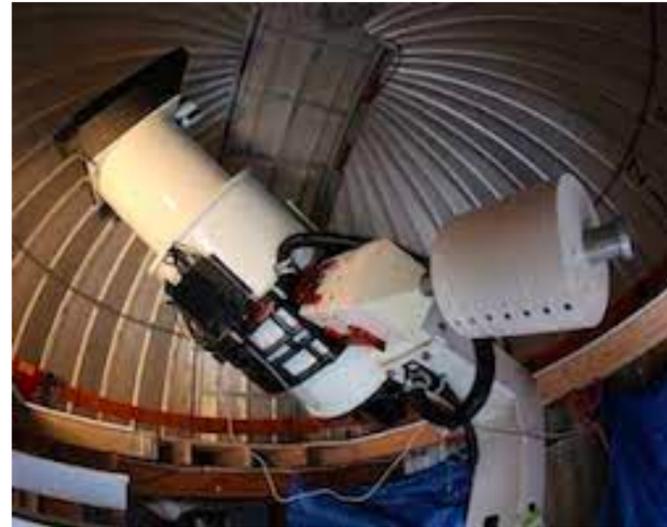


Observations: TDEs from wide-field surveys

Detection rate ≥ 10 per year, in galaxy nuclei



PanSTARRS



ATLAS



ASASSN



ZTF



GOTO

MN+ 2020

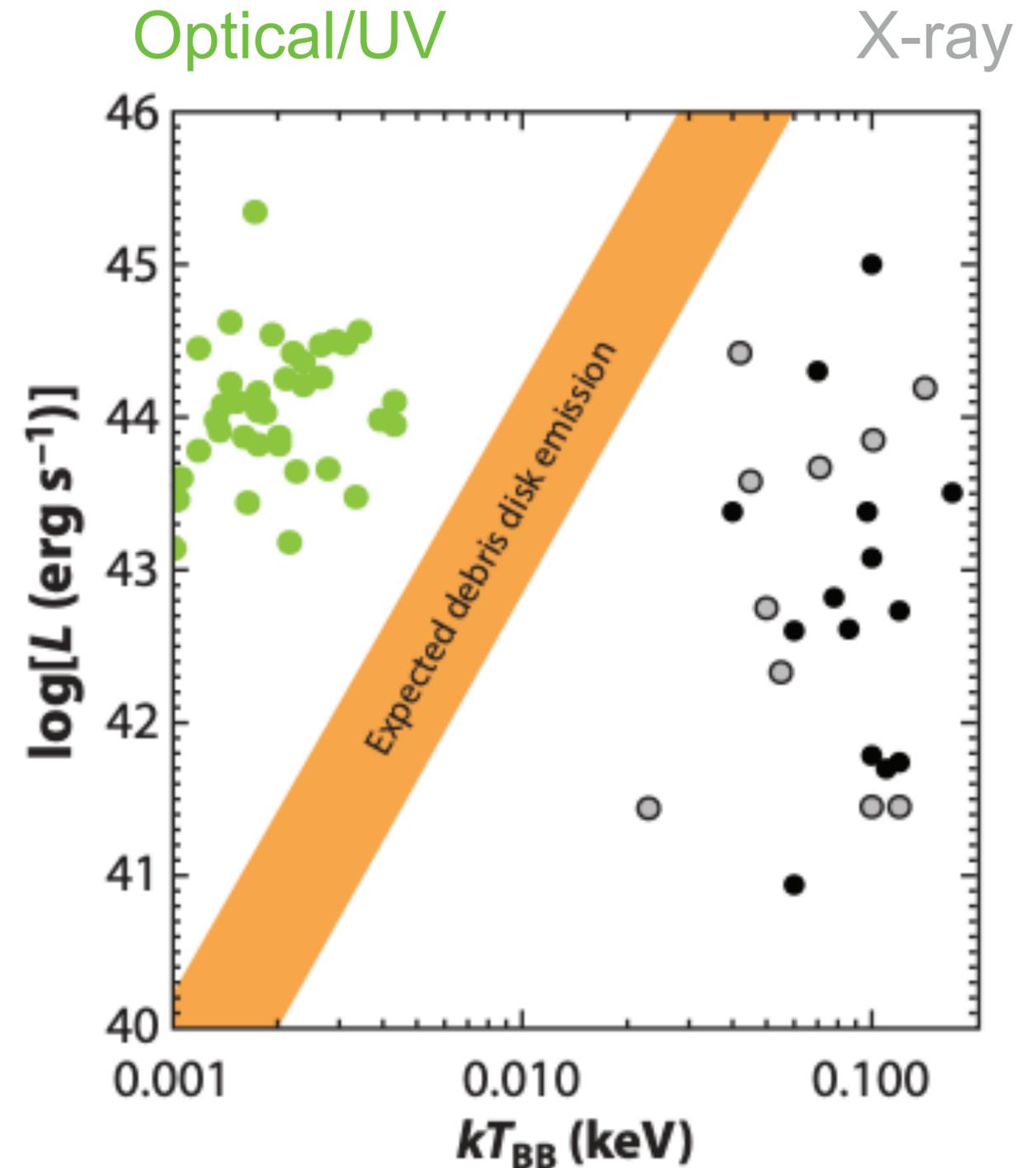
Optical vs X-ray TDEs

X-rays explained by accretion

But most **optical** TDEs are initially faint in X-rays, with very different effective T

What produces the early optical emission?

- Reprocessed accretion?
- Outflows?
- Shocks?
- At pericentre, stream crossing, disk formation...



Gezari 2021

How do we know these are TDEs? (i) spectra

Spectra distinct from SNe and AGN:

Hot, persistent thermal continuum (few $\times 10^4$ K)

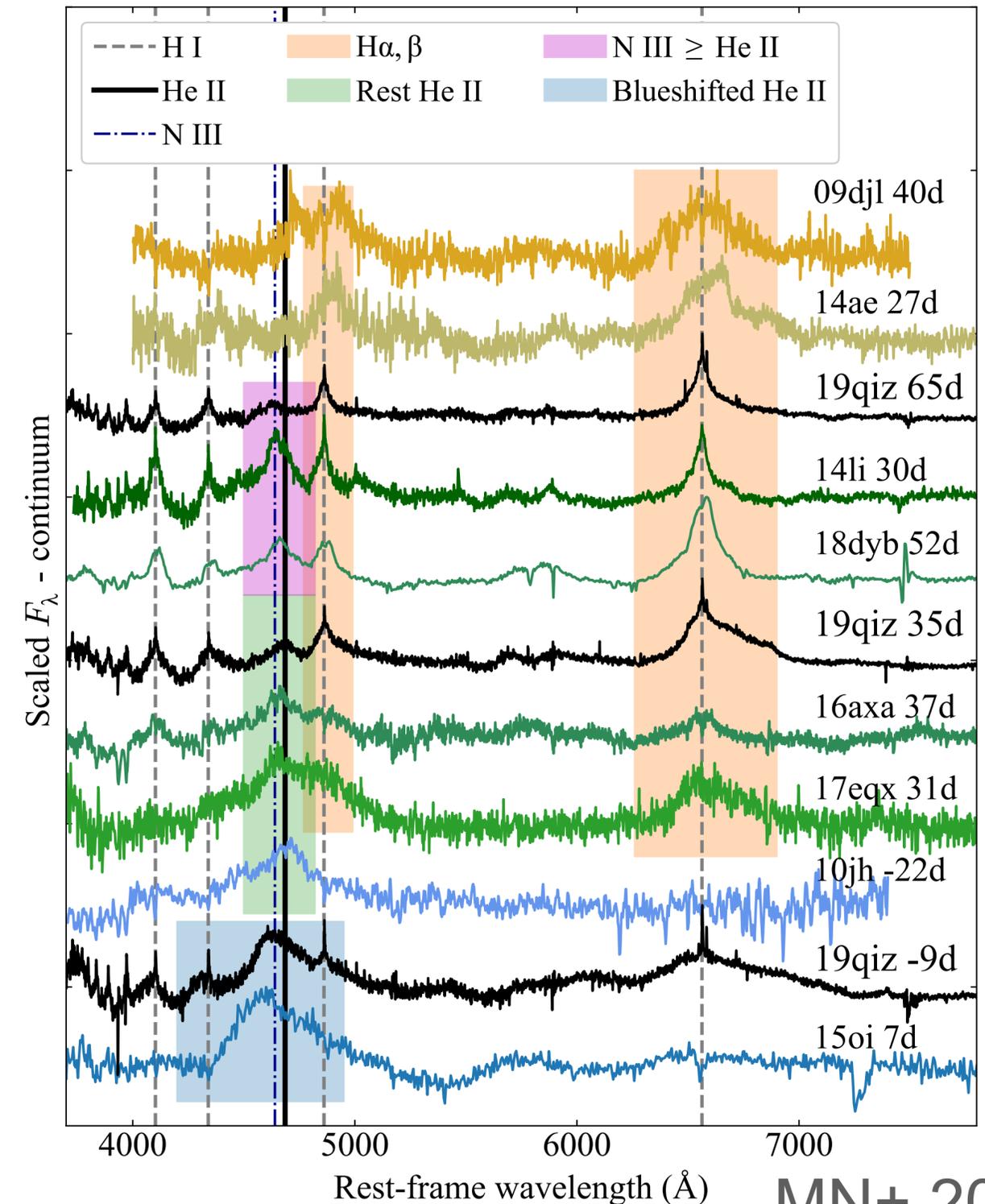
Broad, *shallow* emission lines (few $\times 1000$ km/s)

He II and N III:

- “Bowen fluorescence”
- Continuum photons >54 eV

Diverse line profiles:

- Some look like outflows, some like disks



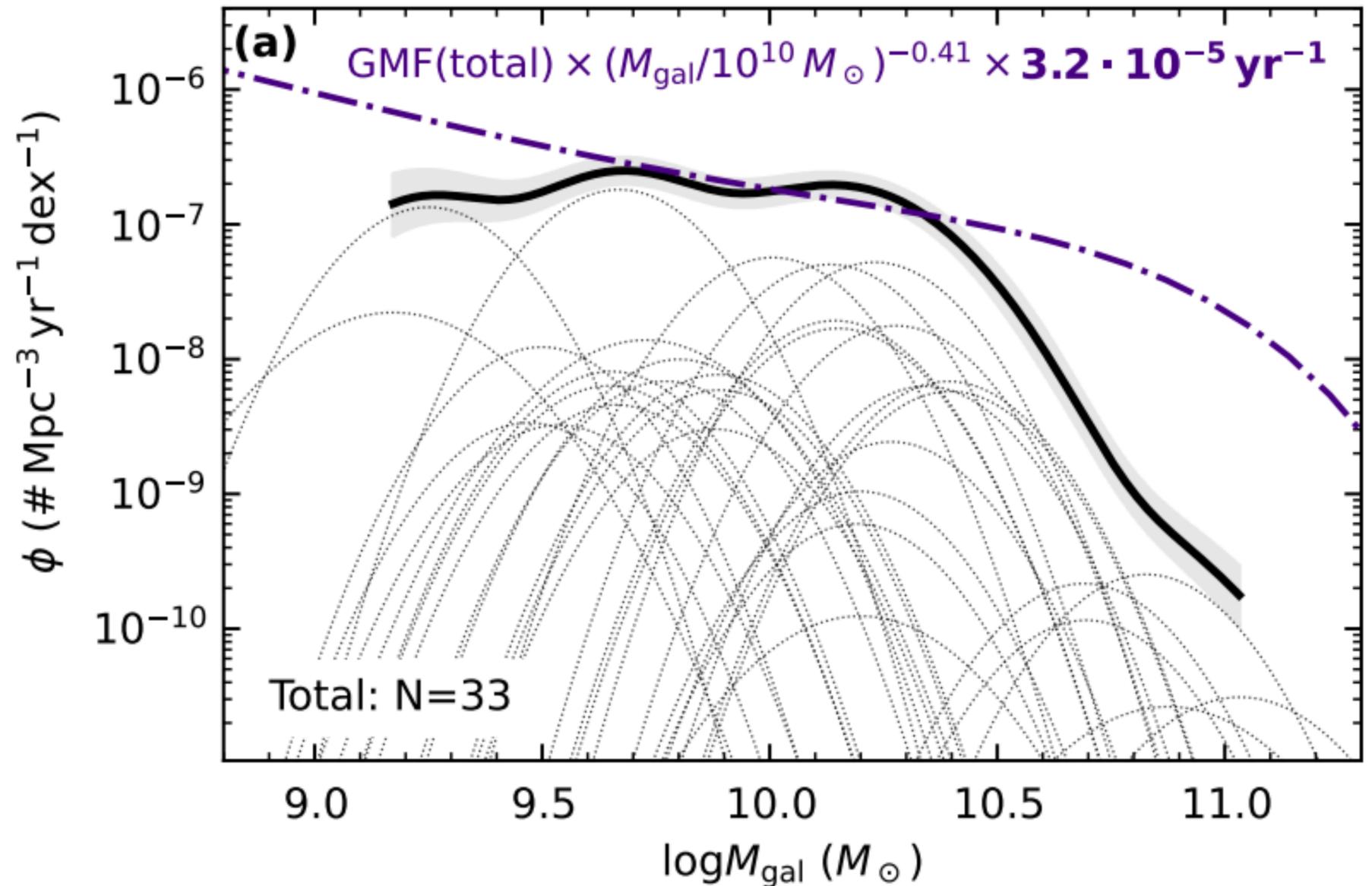
MN+ 2020

How do we know these are TDEs? (ii) hosts

These flares only occur up to a galaxy stellar mass $\sim 10^{10} M_{\odot}$

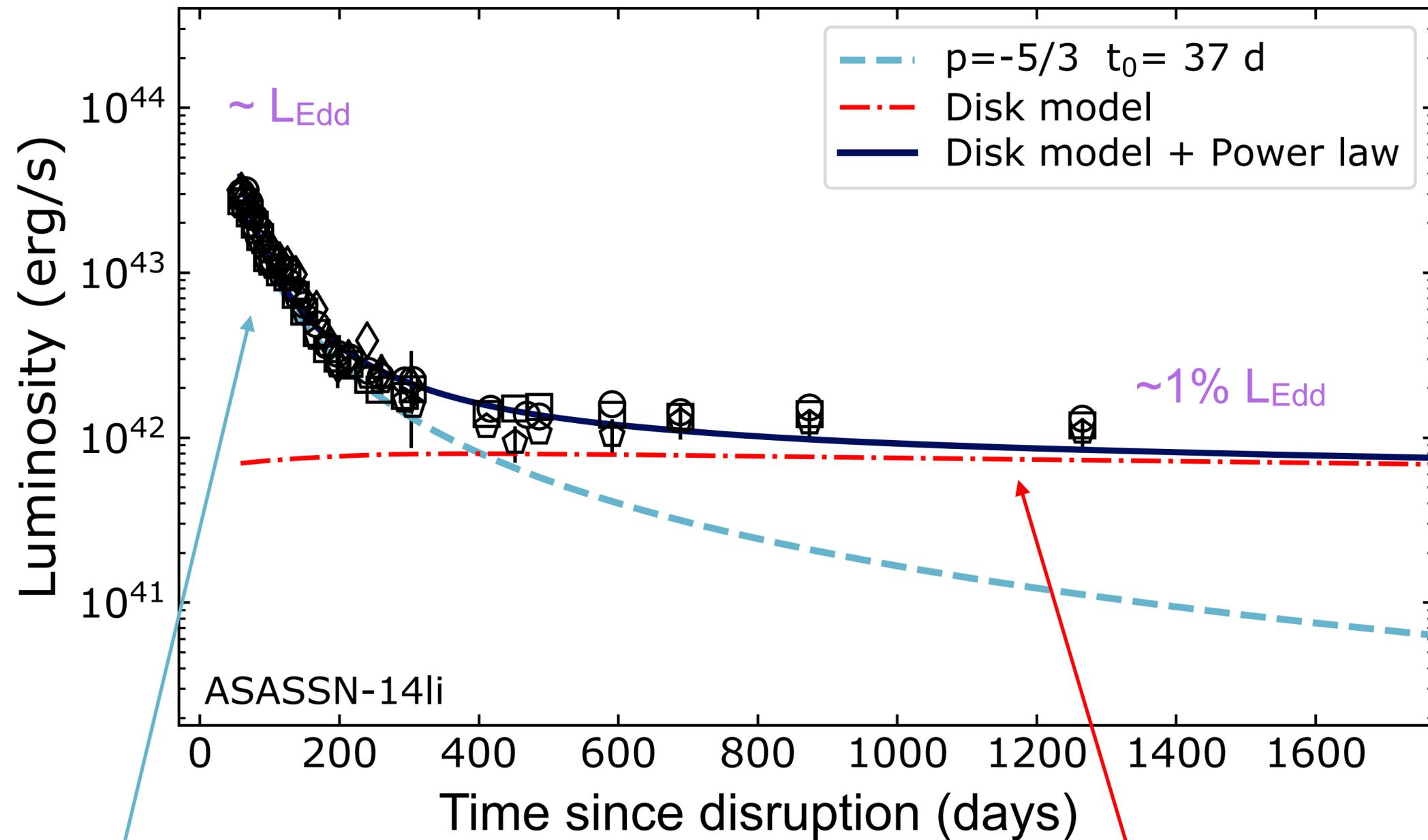
In more massive galaxies (more massive BHs), stars are swallowed whole!

Favour *post-starburst* galaxies with *high central densities*



Yao+ 2023

How do we know these are TDEs? (iii) late times



Van Velzen+ 2019,
Mummery+ 2024

Fallback accretion, shocks, disk formation, super Eddington: messy

Disk-mediated accretion: clean

BH demographics with TDEs

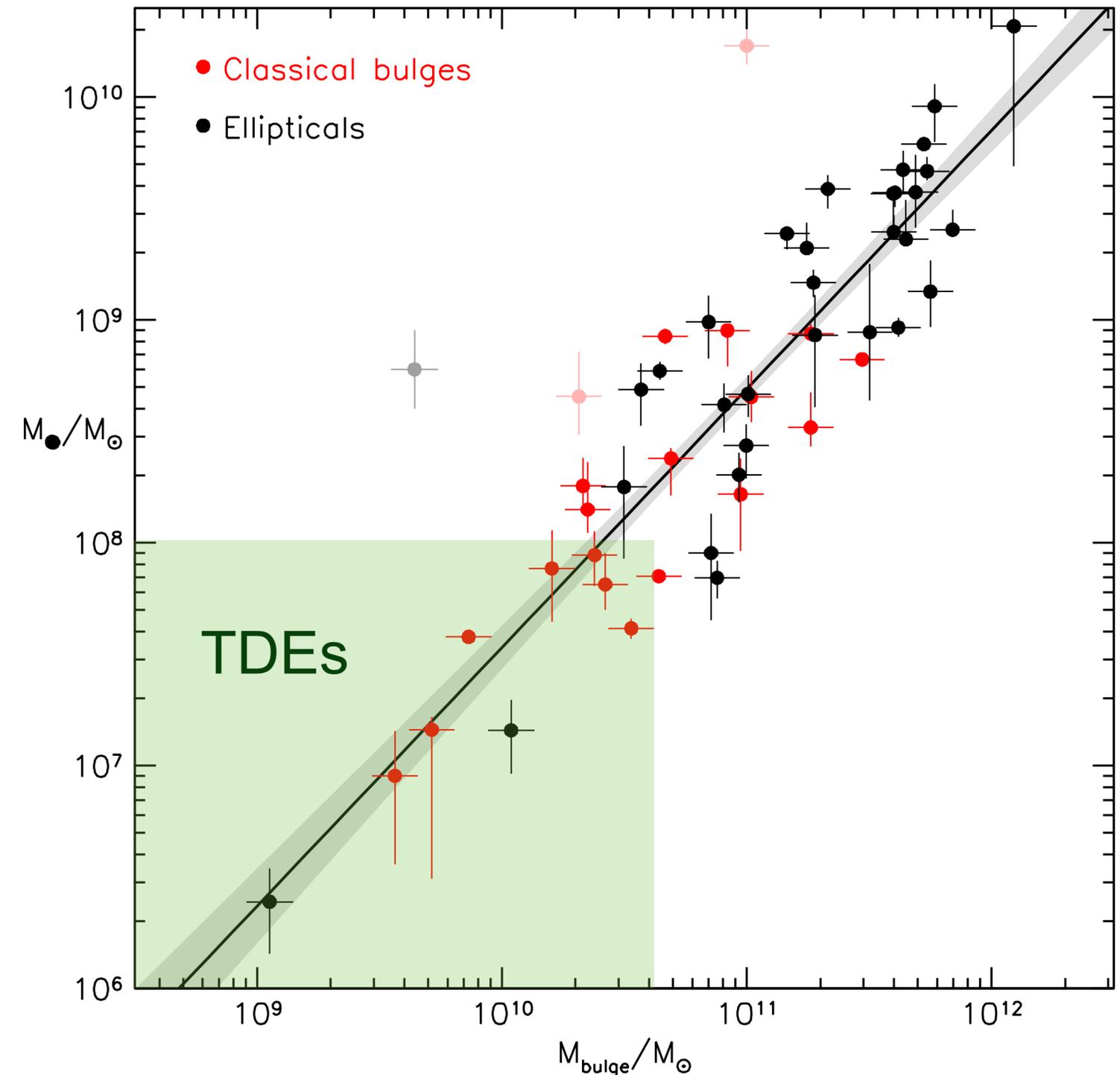
Kormendy & Ho 2013

Co-evolution: BH mass scales with galaxy mass / velocity dispersion

Dynamical mass measurements limited by angular resolution:

- Nearby galaxies (small sample)
- Need to resolve sphere of influence (easier for more massive BHs)

TDEs select for the missing MBHs!



First option

TDE alerts us to presence of MBH in galaxy

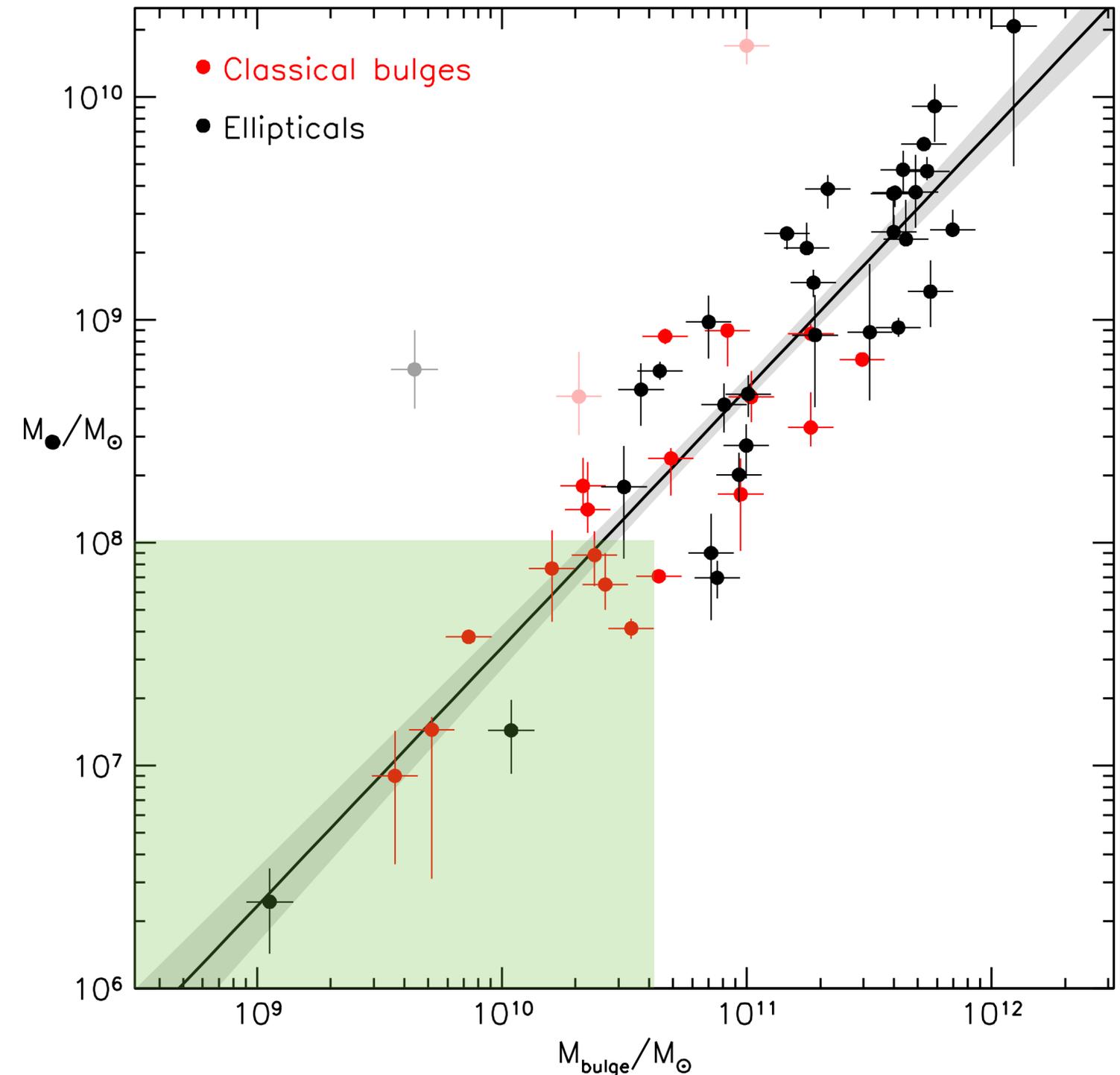
Galaxy properties well measured (LSST, 4MOST, DESI etc)

Use scaling relations to estimate BH mass

TDE rate per BH mass: find out the BH occupation fraction at low mass

- **Do all galaxies have SMBHs?**

Kormendy & Ho 2013



Better option

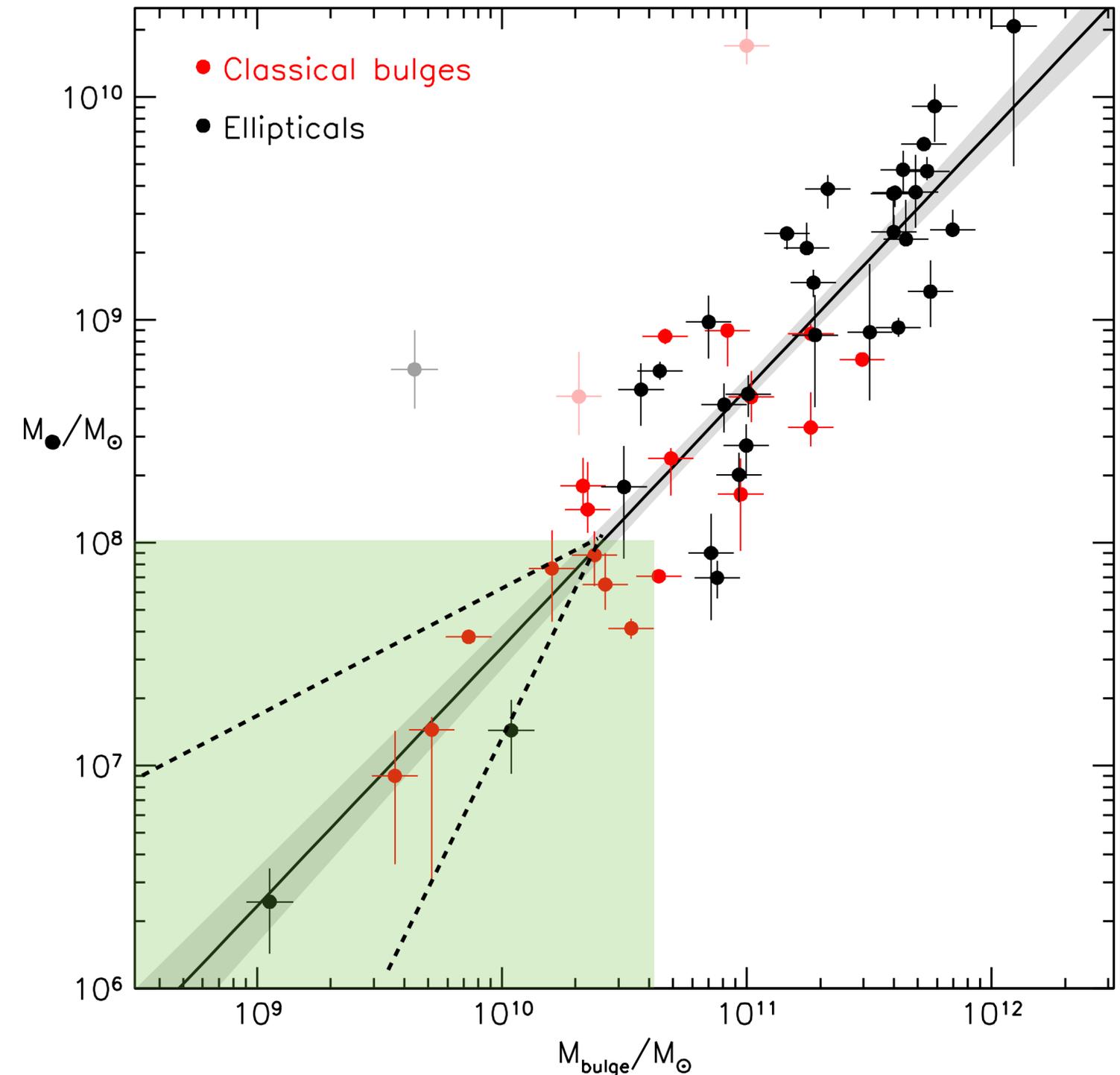
Use the TDE properties to *infer independently* the mass of the SMBH

Measure the *slope* of the BH vs galaxy properties at low BH mass

- **How are MBHs seeded and how do they grow?**

Limiting step: how well do TDEs encode BH mass?

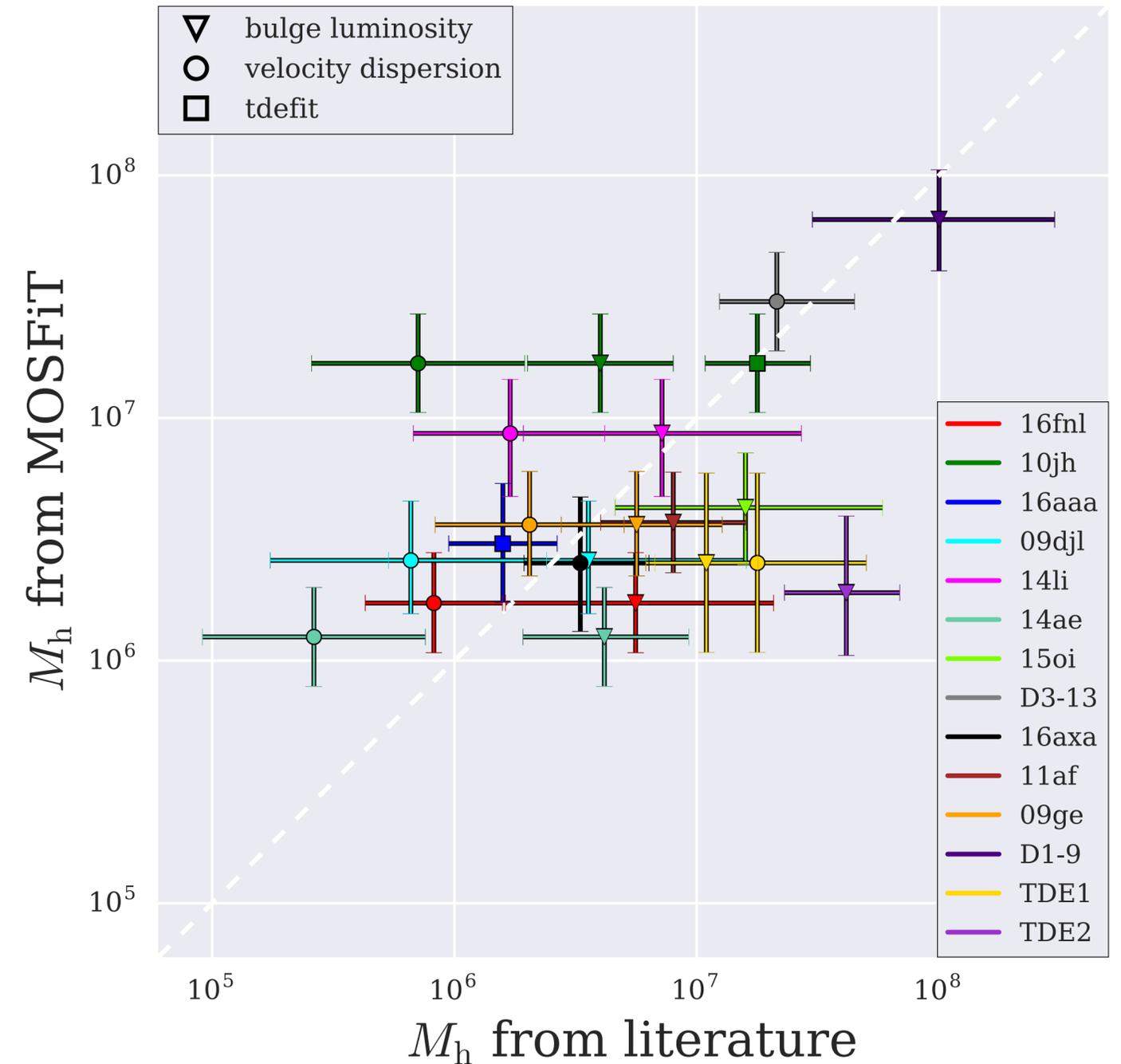
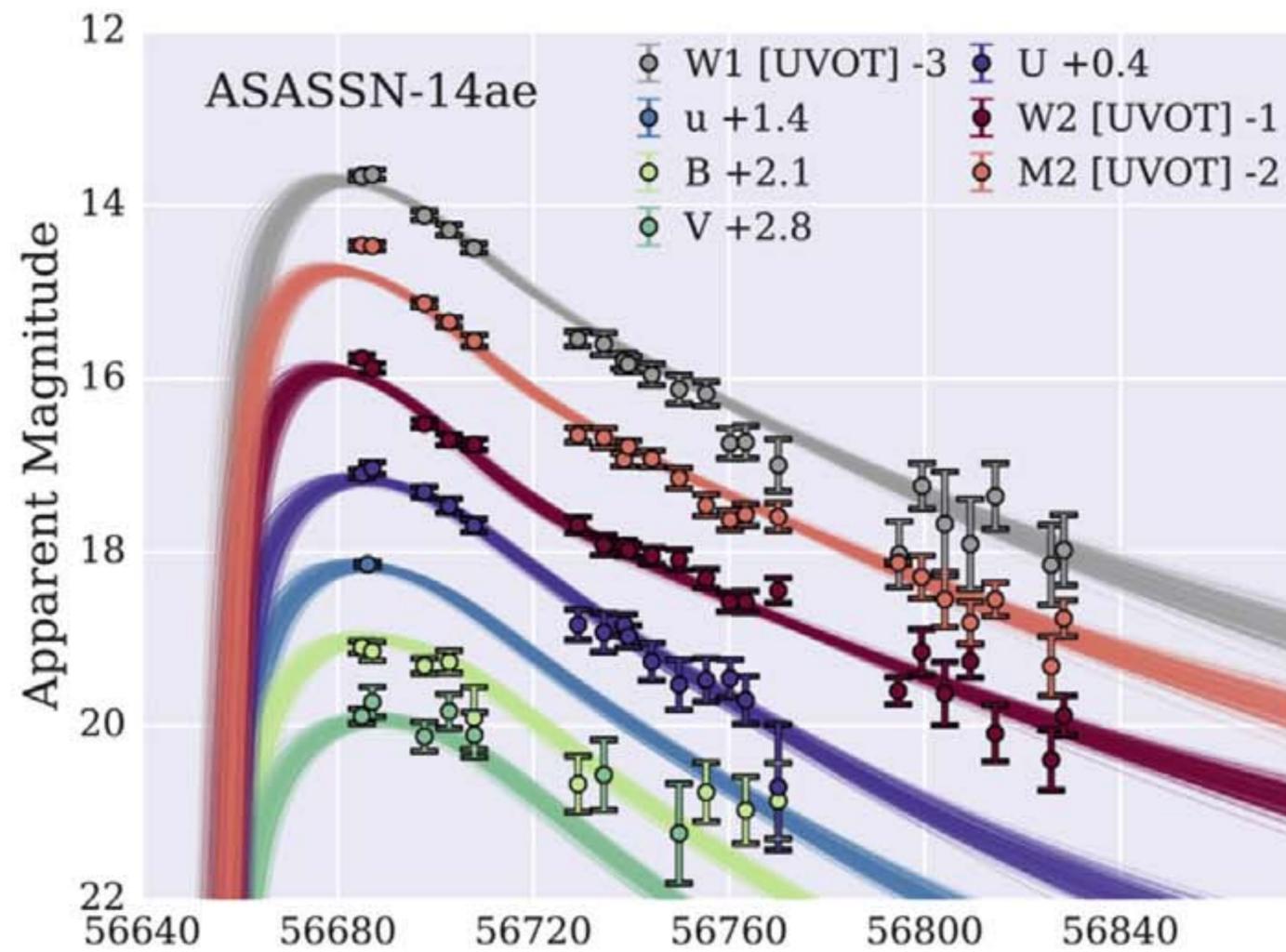
Kormendy & Ho 2013



Weighing BHs with TDEs: the peak emission

1. Assume luminosity tracks the fallback rate

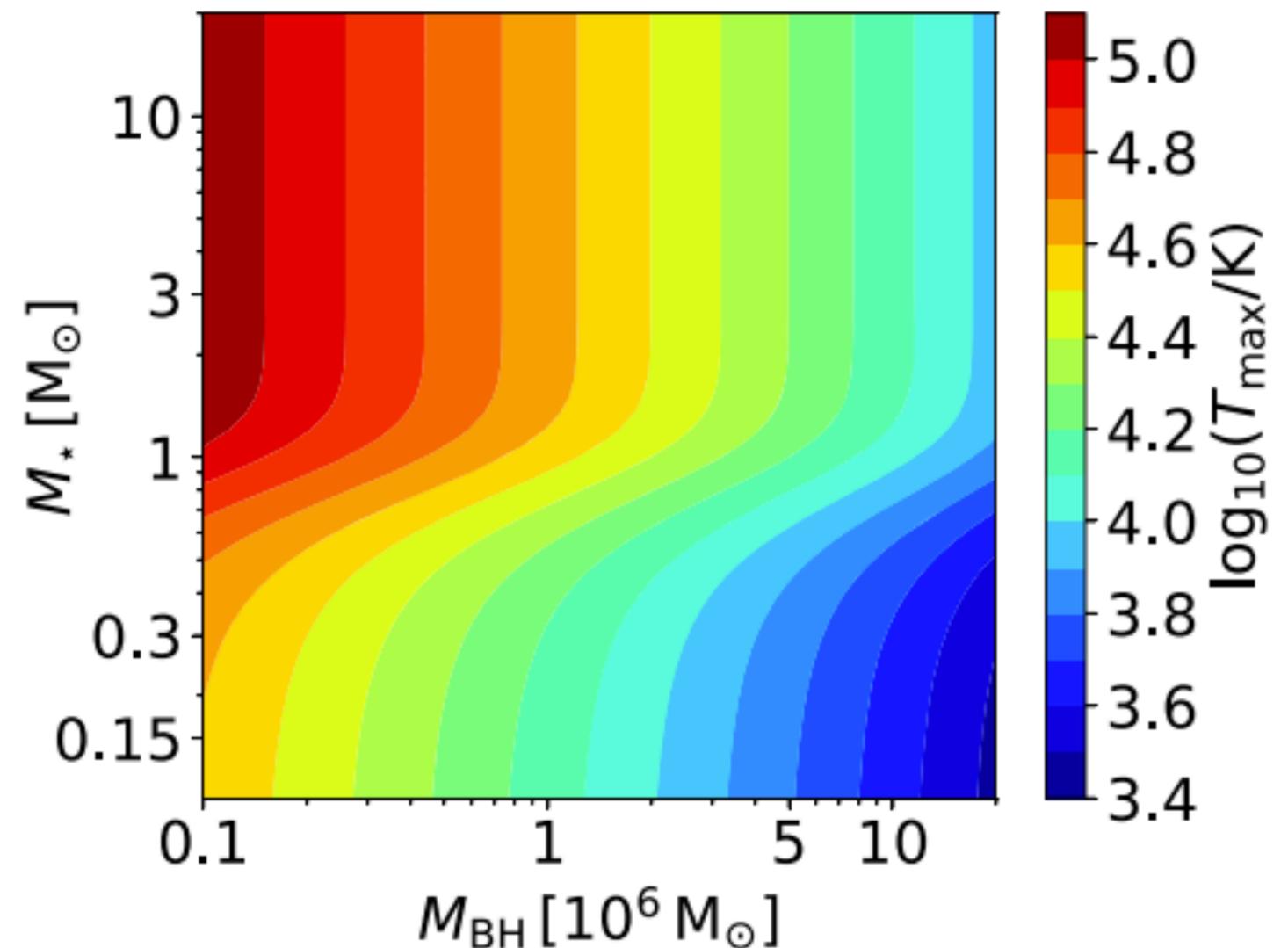
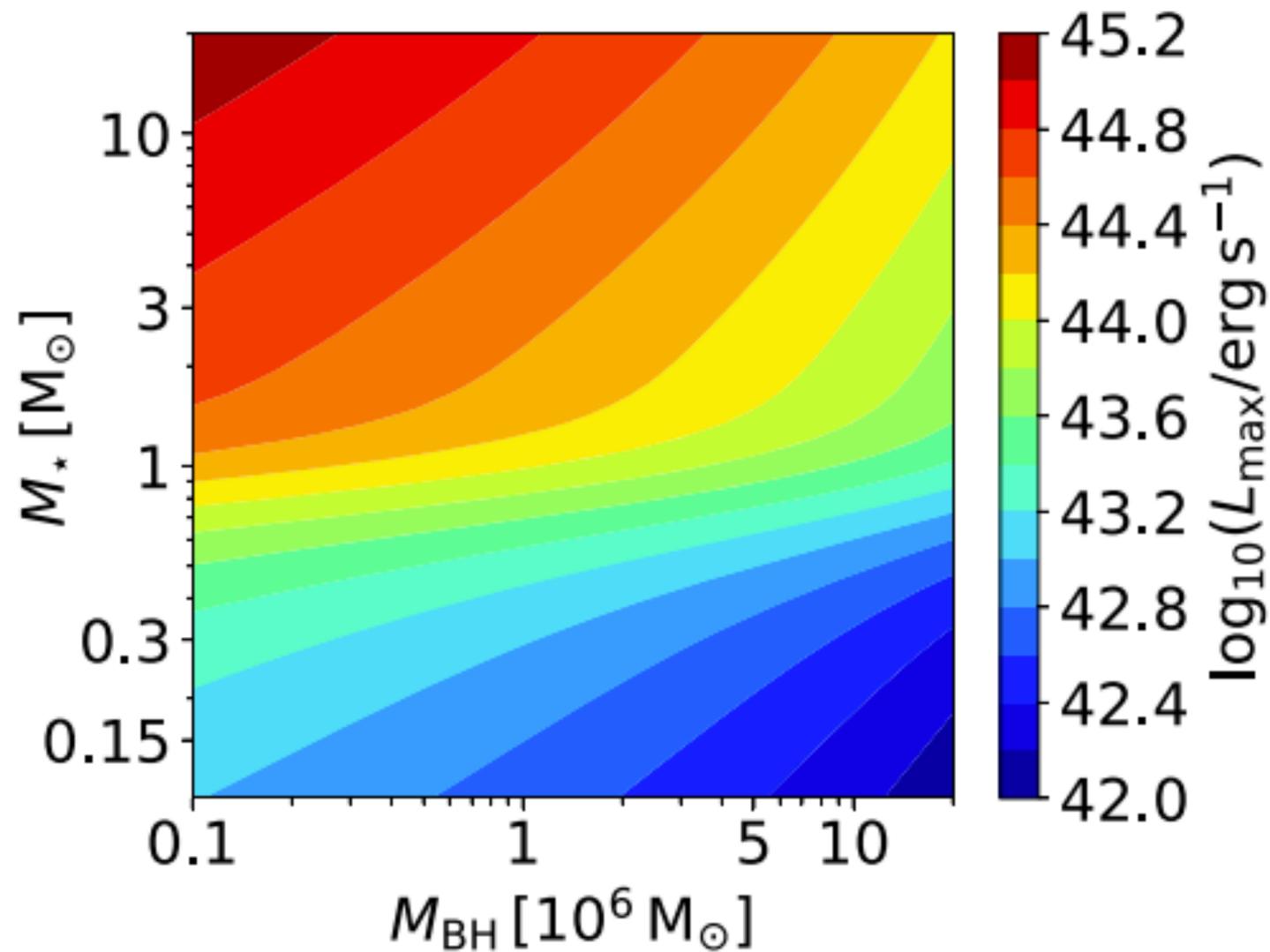
Mass fallback scales with M_{BH} (MOSFiT)



Mockler+ 2019, following Guillochon+ 2014

Weighing BHs with TDEs: the peak emission

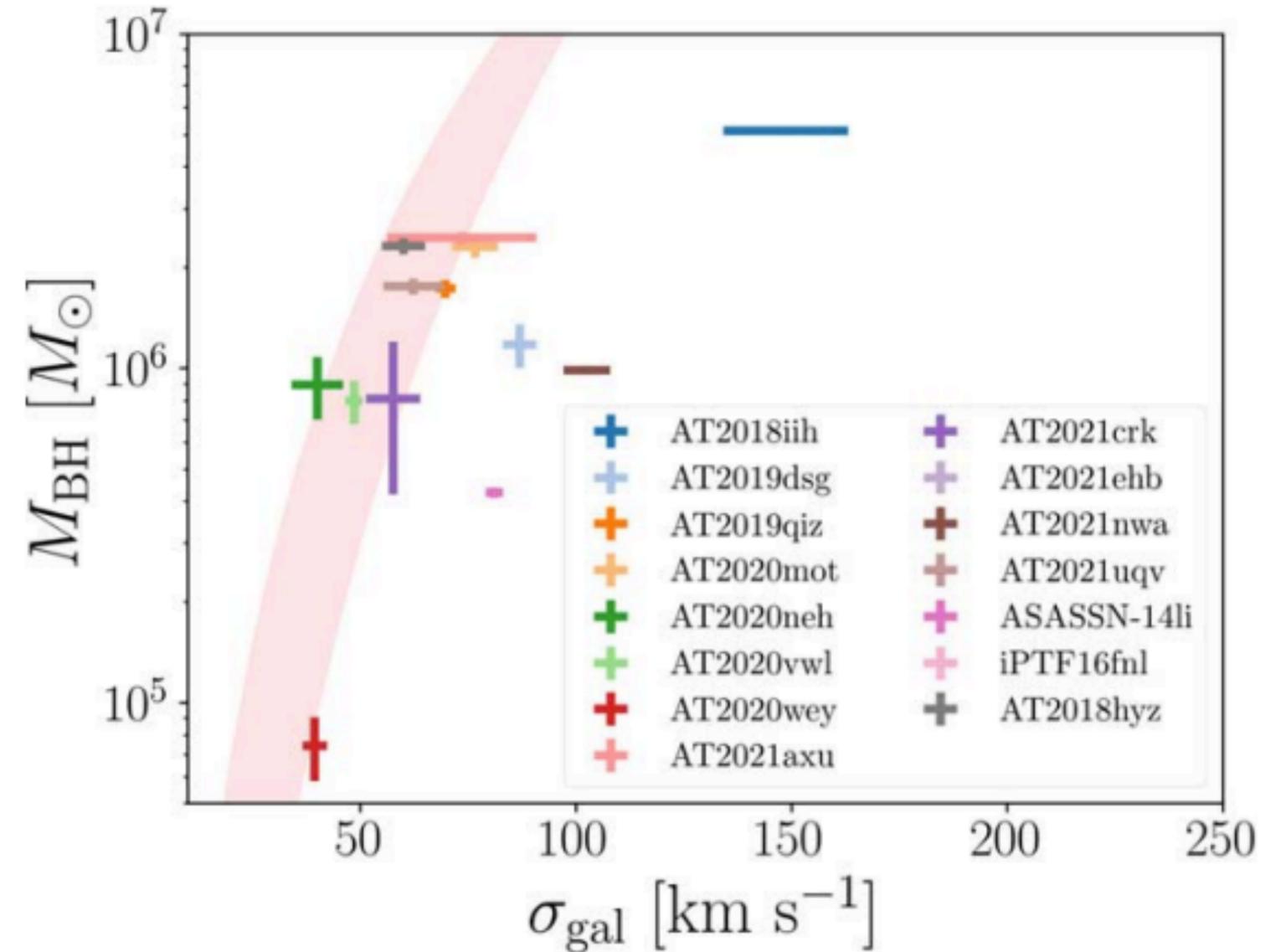
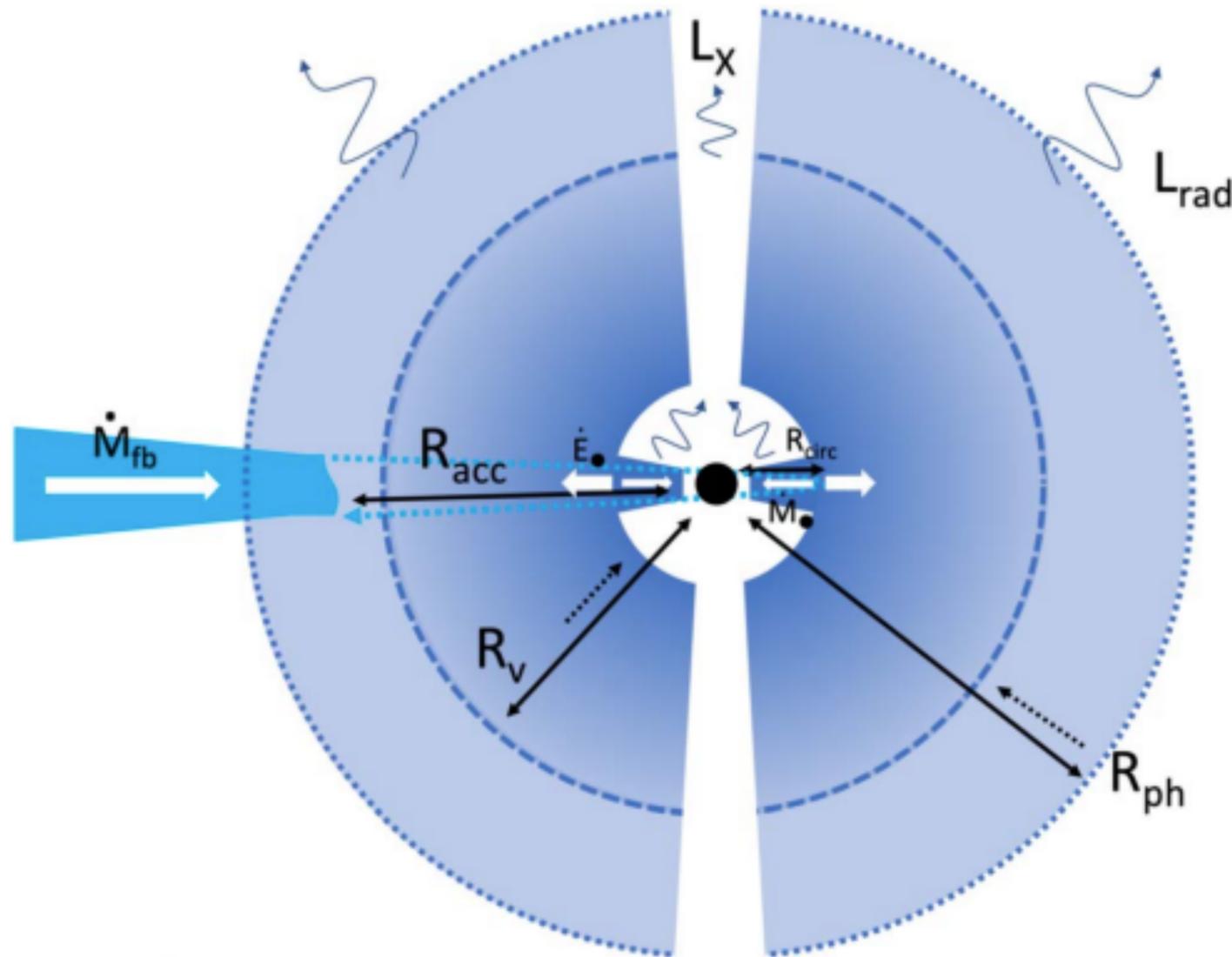
2. Assume luminosity from stream self-crossing shocks (TDEmass)



Ryu+ 2020

Weighing BHs with TDEs: the peak emission

3. Assume debris promptly forms a disk and pressure-supported cooling envelope



Metzger 2022, Sarin & Metzger 2024 (Redback)

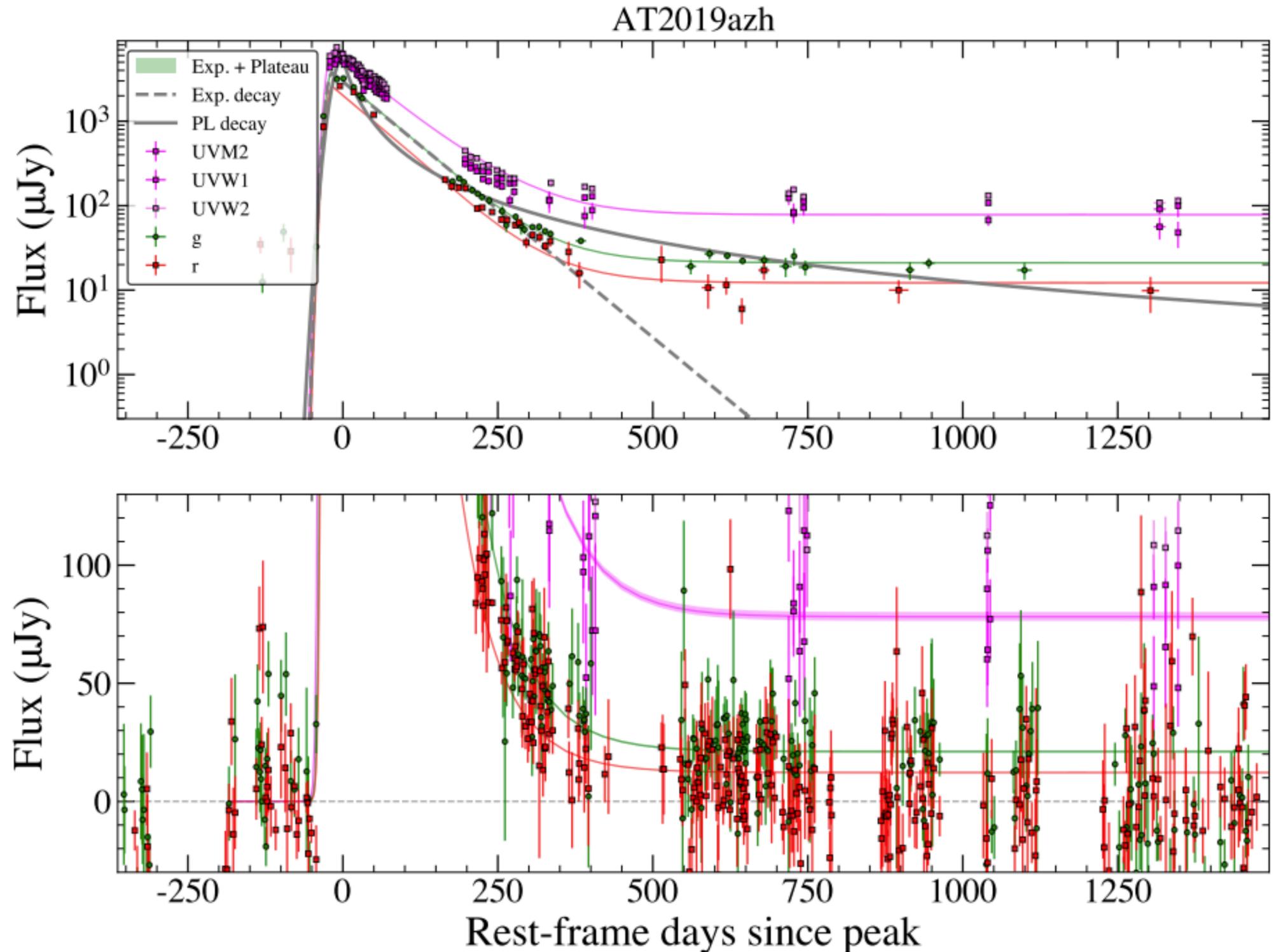
Weighing BHs with TDEs: the late emission

Physics of the peak is not well known

But late emission known to come from accretion disk

Well detected for all nearby TDEs

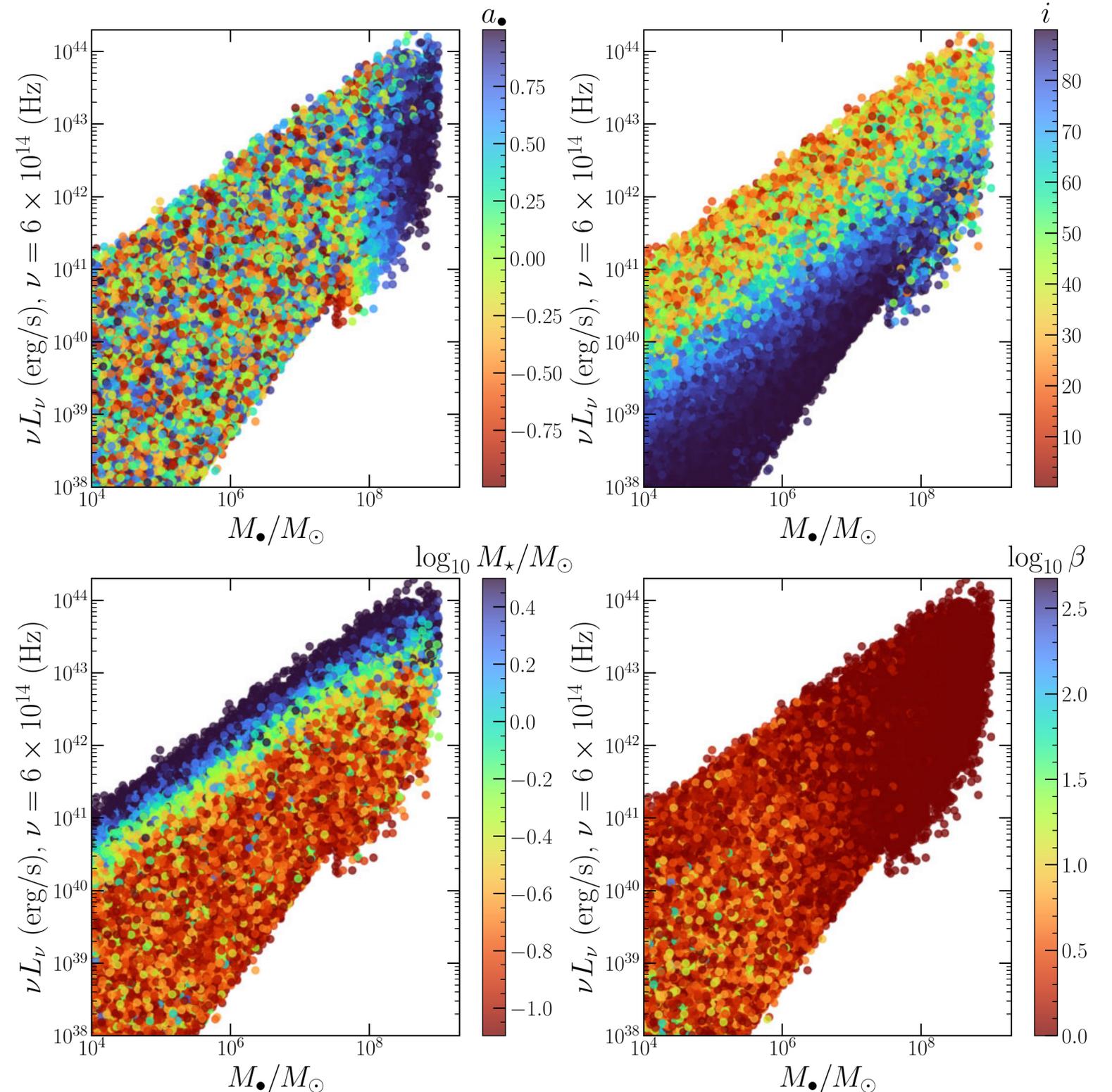
Mummery+ 2024



Weighing BHs with TDEs: the late emission

Viscously-spreading relativistic thin disk model reproduces plateau luminosity

Simulations match analytic theory:
 $L \propto M_{\text{BH}}^{2/3}$



Mummery+ 2024

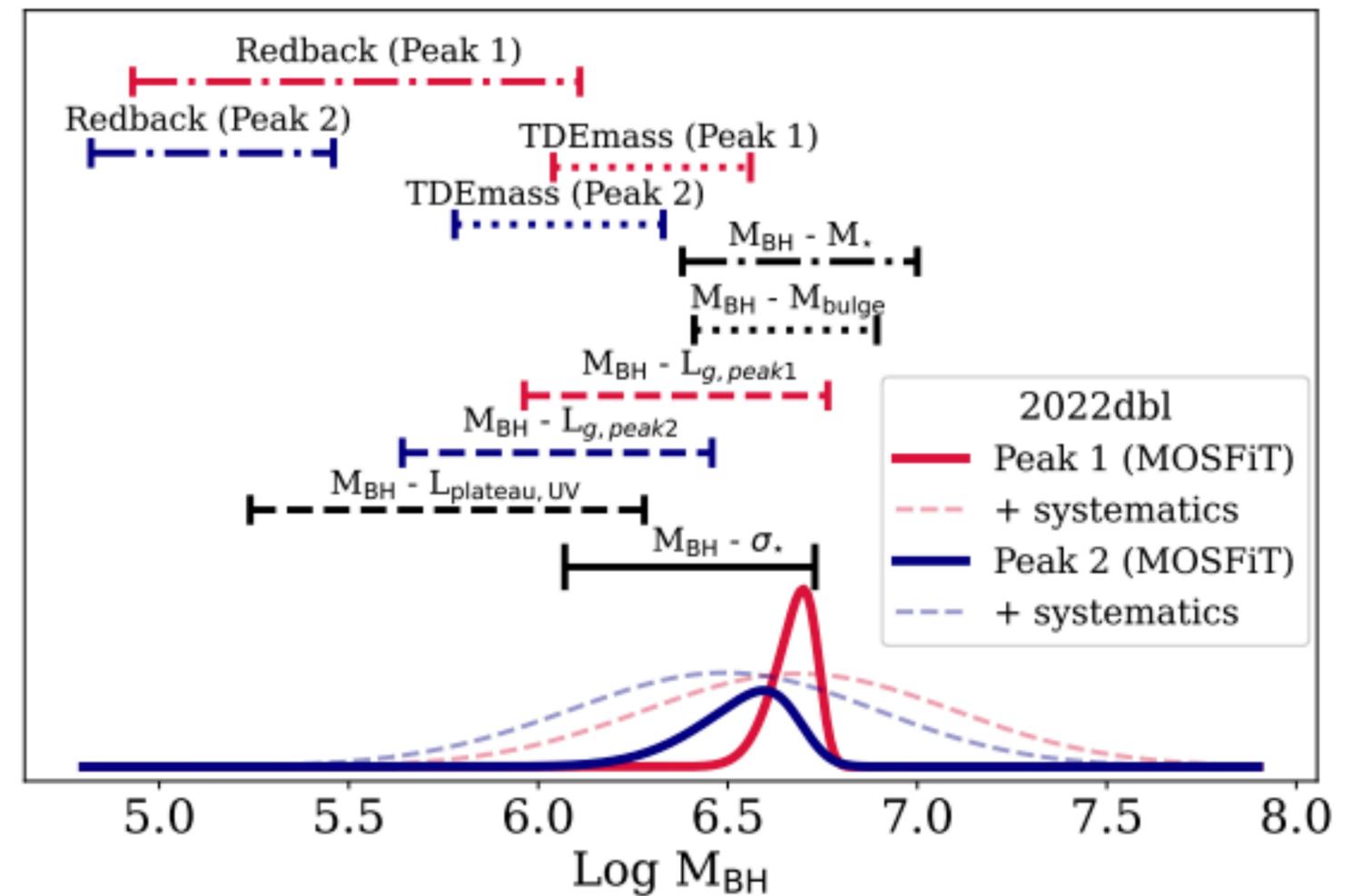
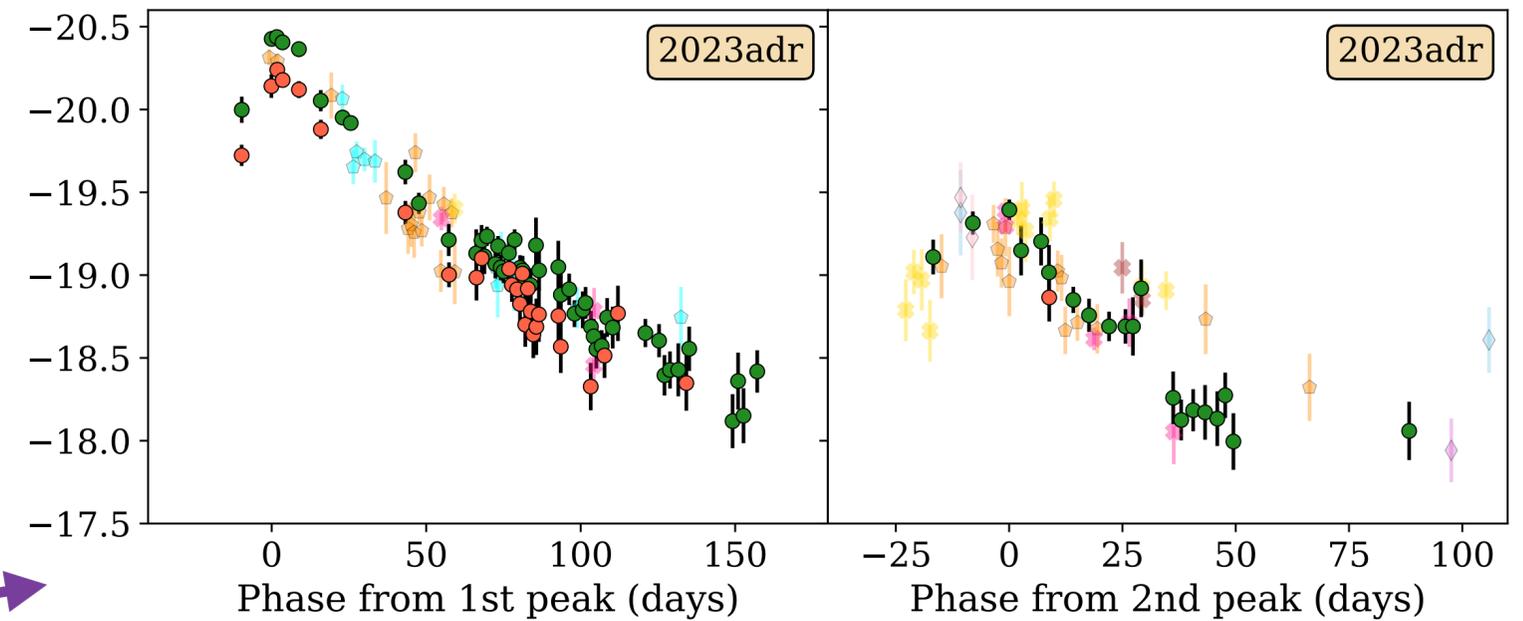
Test one

Some TDEs repeat: partially disrupted star returns to pericentre

- 2 known (Somalwar+, Lin+, Makygianni+), **1 new!**

Do we get same SMBH mass from modelling both TDE flares?

- Answer: mostly (but with large errors)



Charlotte
Angus

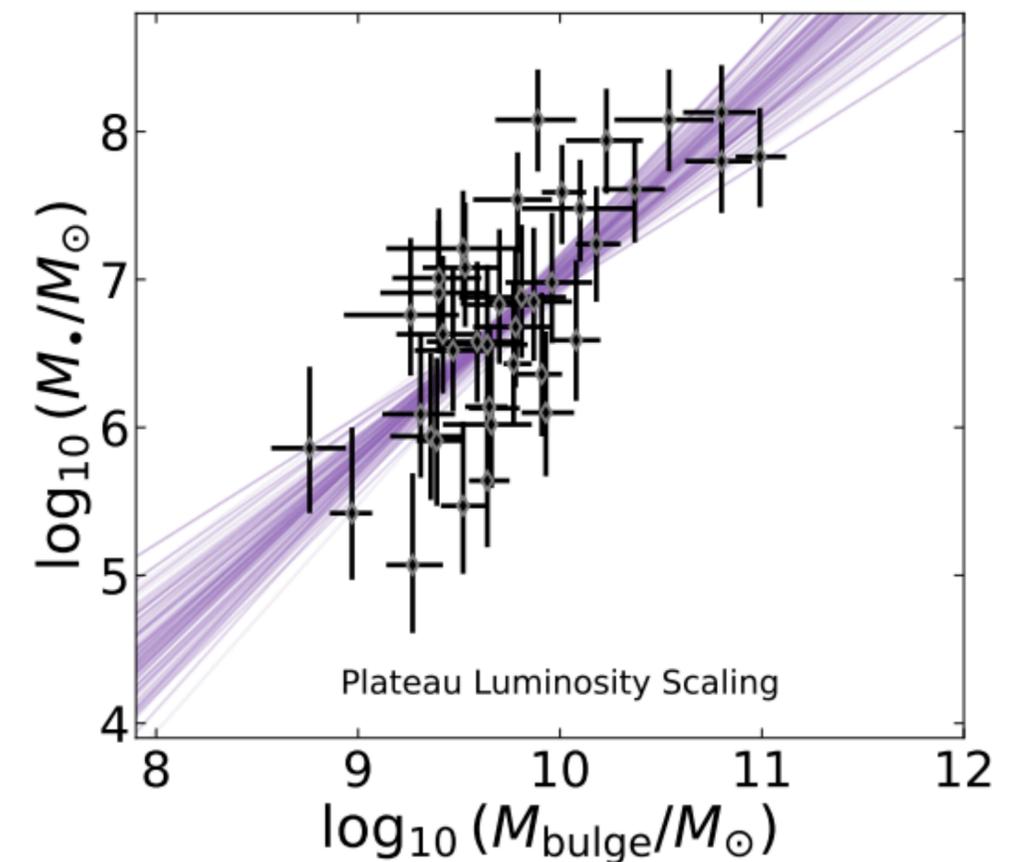
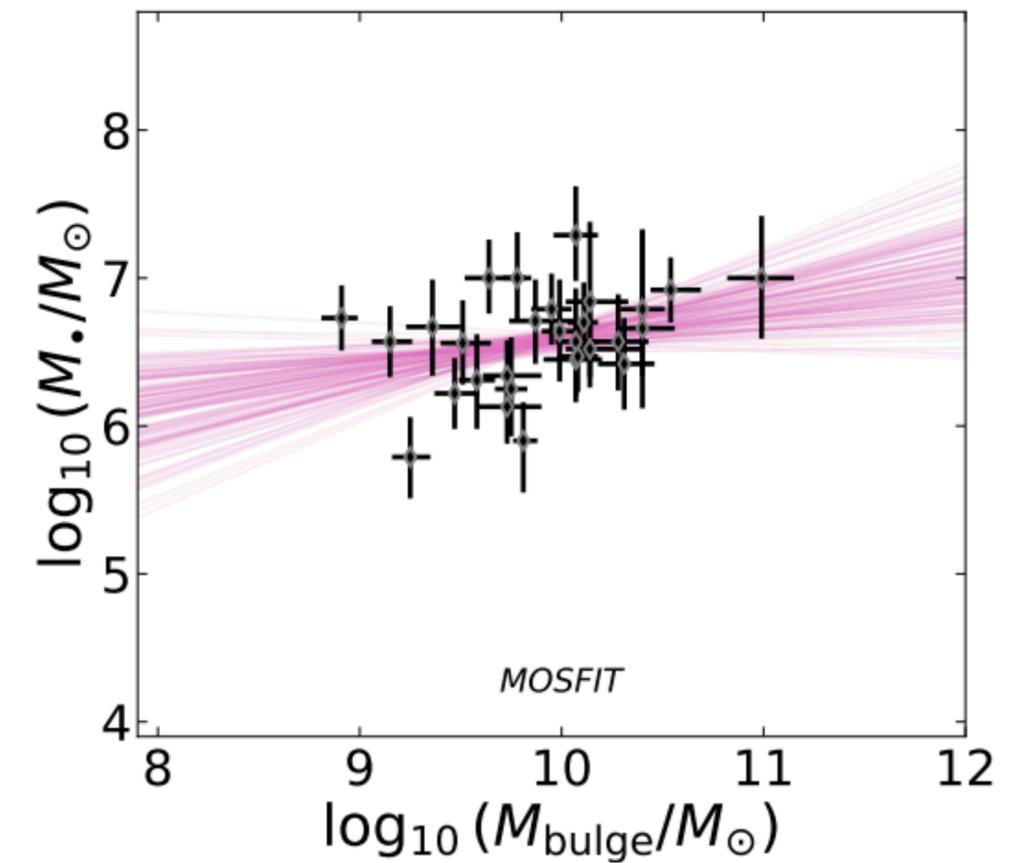
Angus+ 2026

Test two

Do mass measurements reproduce co-evolution?

- Optical peak: not really (so far)
- Need to keep refining theory of early optical emission
- Plateau: yes!
- Plateau-based masses strongly correlated with galaxy properties
- Slope consistent with expectations

Guolo+ 2025



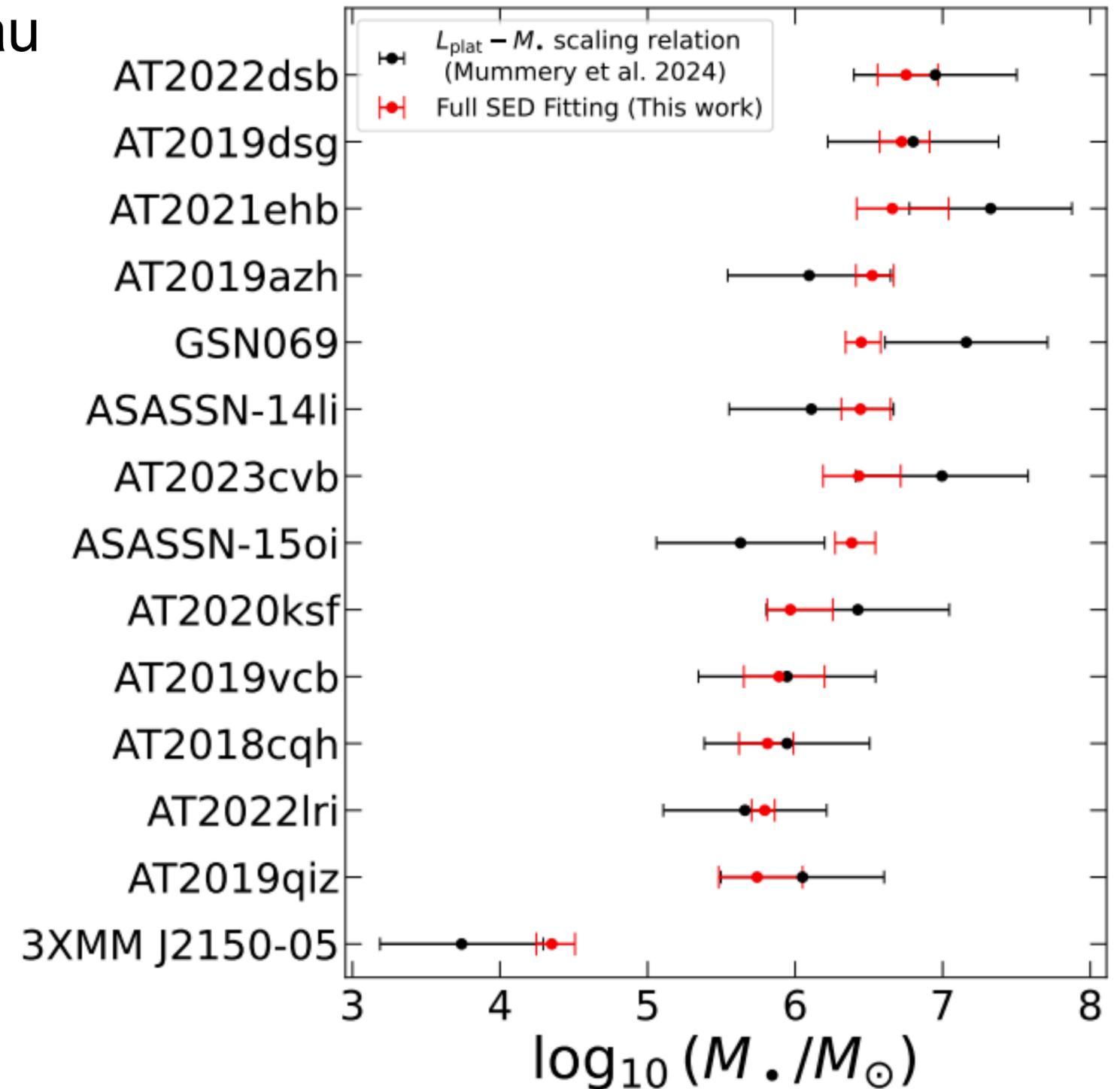
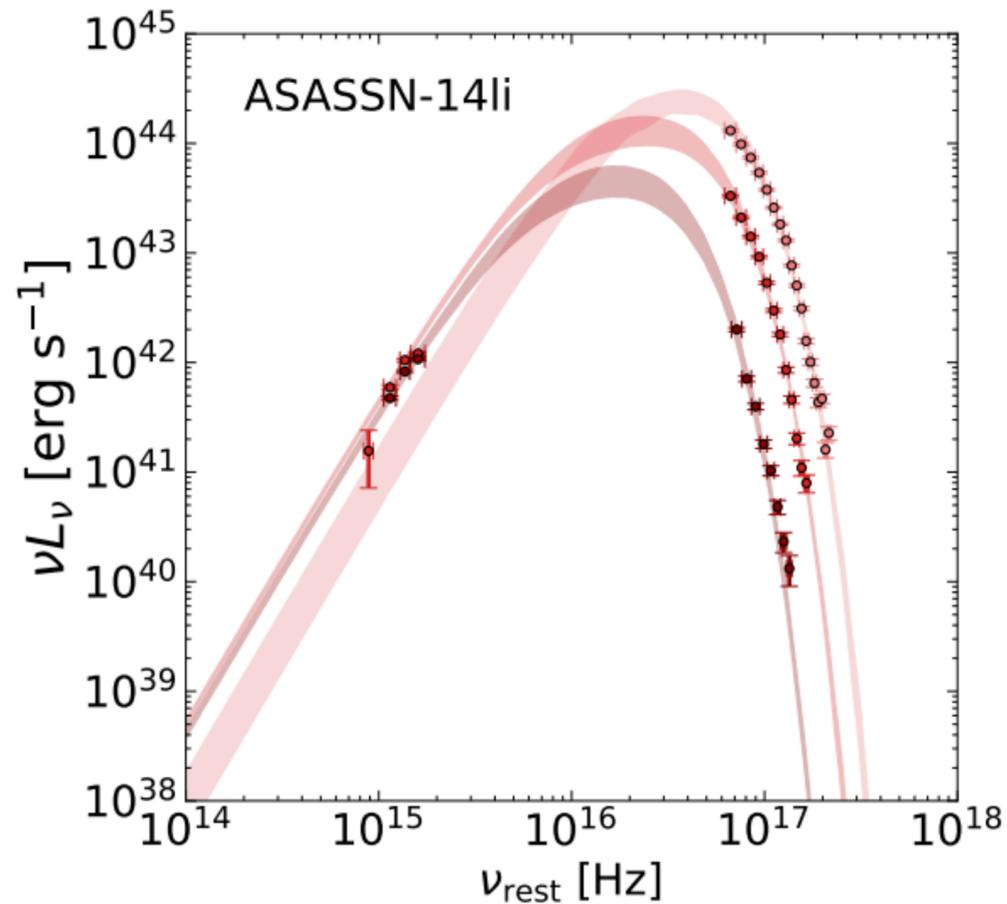
The gold standard

Guolo+ 2025

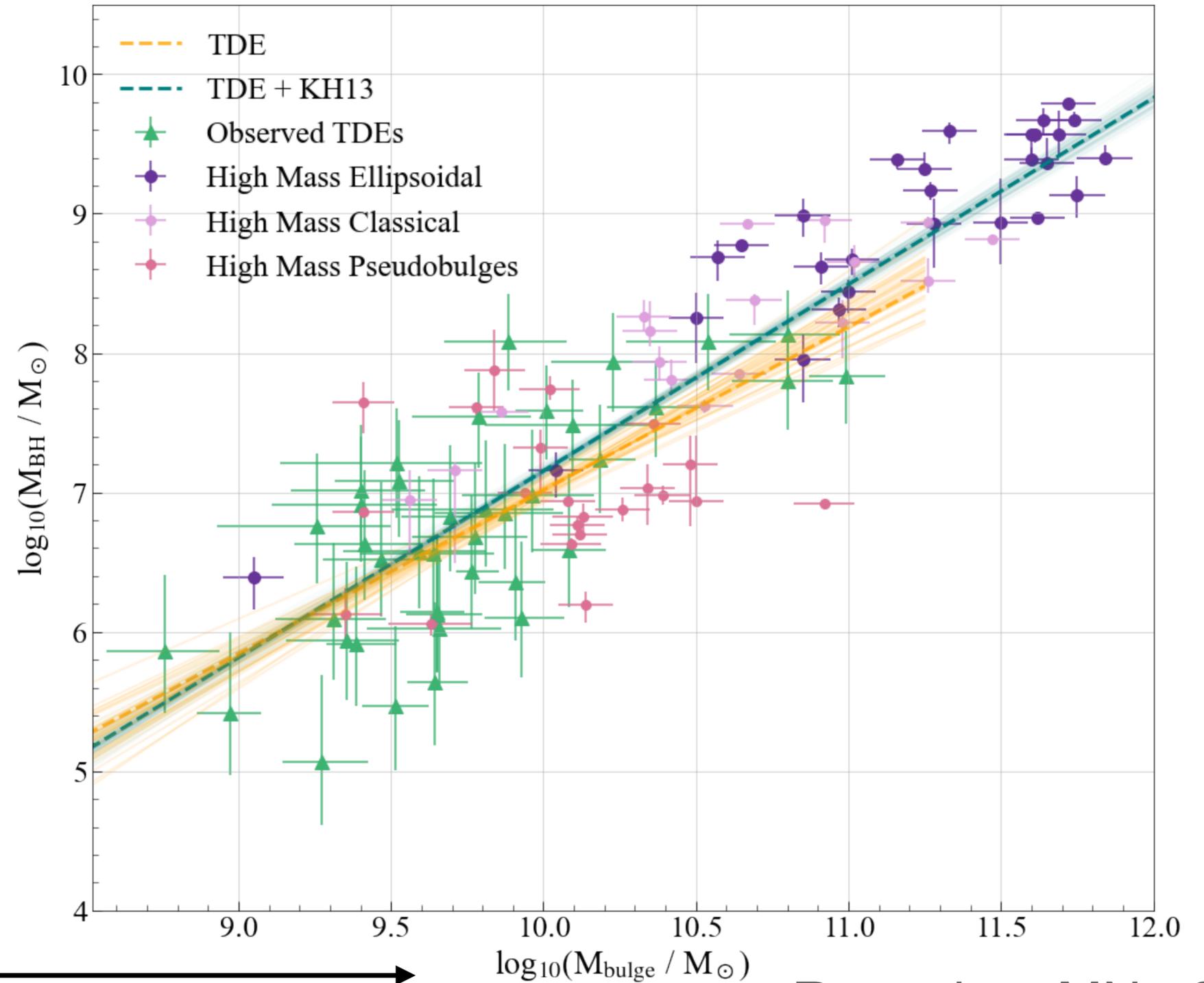
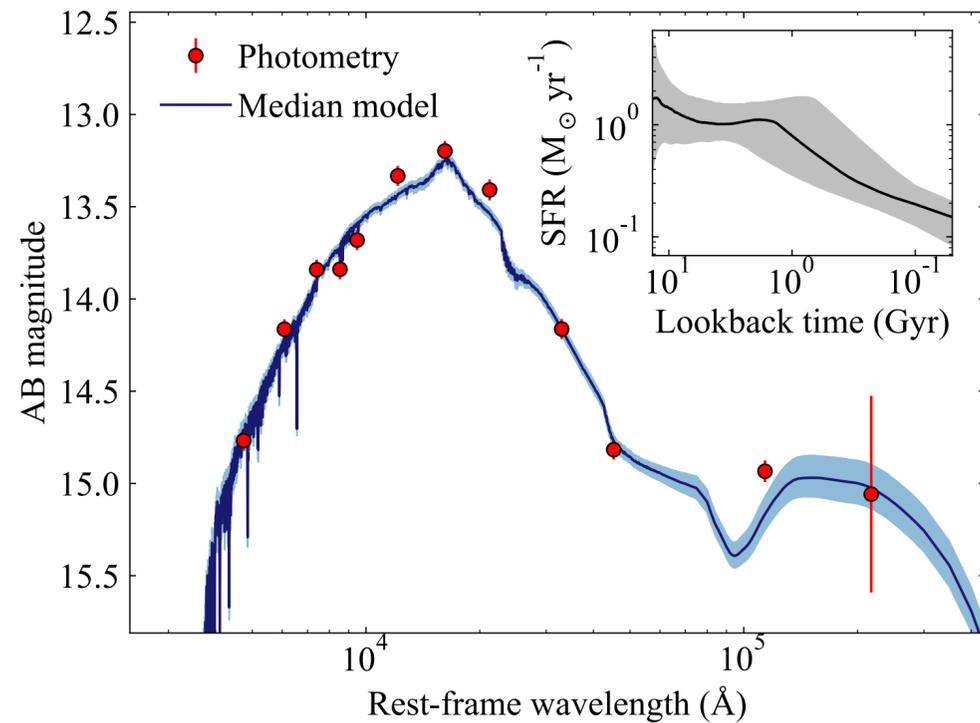
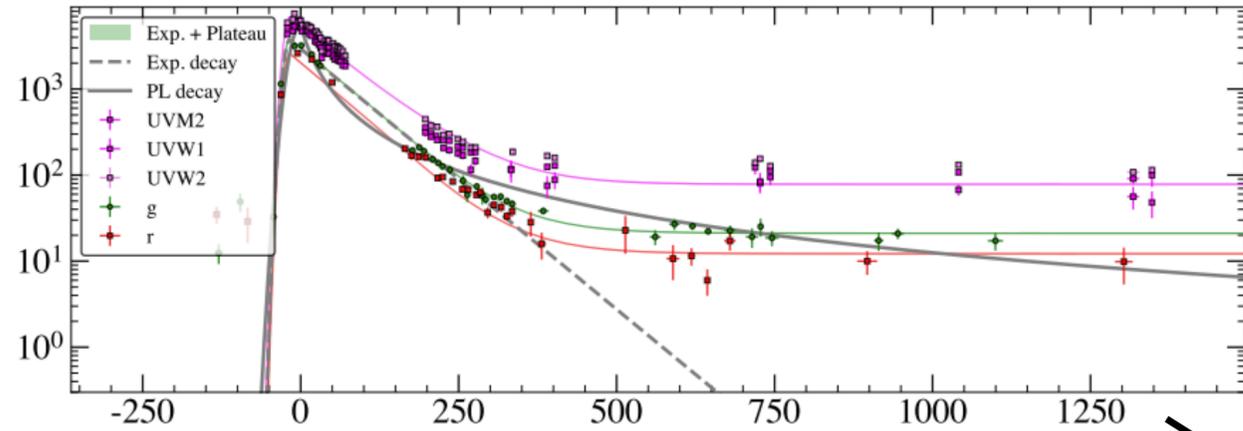
Full accretion disk fit: (early) X-rays + plateau

Time dependent SED

Masses to ~ 0.2 dex and reproduce co-evolution



SMBH and galaxy evolution with TDEs

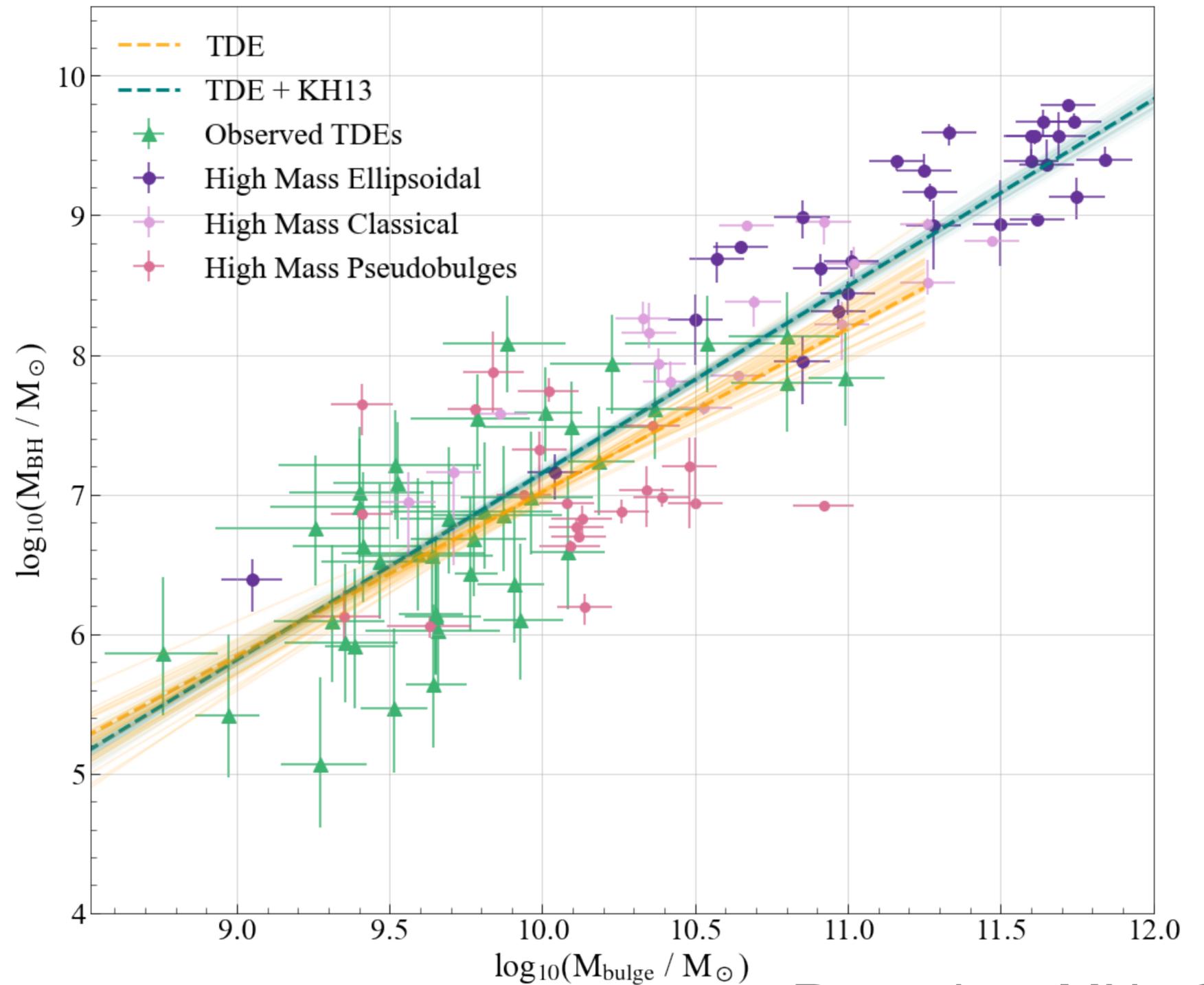


Ramsden, MN+ 2025

SMBH and galaxy evolution with TDEs

With 40 TDEs + high-mass sample:

	α	β	ϵ_0
TDE+KH13	$0.310^{+0.010}_{-0.010}$	$1.340^{+0.030}_{-0.030}$	0.45
KH13	$0.490^{+0.060}_{-0.050}$	$1.160^{+0.080}_{-0.080}$	0.29
MM13	$0.290^{+0.003}_{-0.003}$	$1.050^{+0.110}_{-0.110}$	0.34



Paige
Ramsden

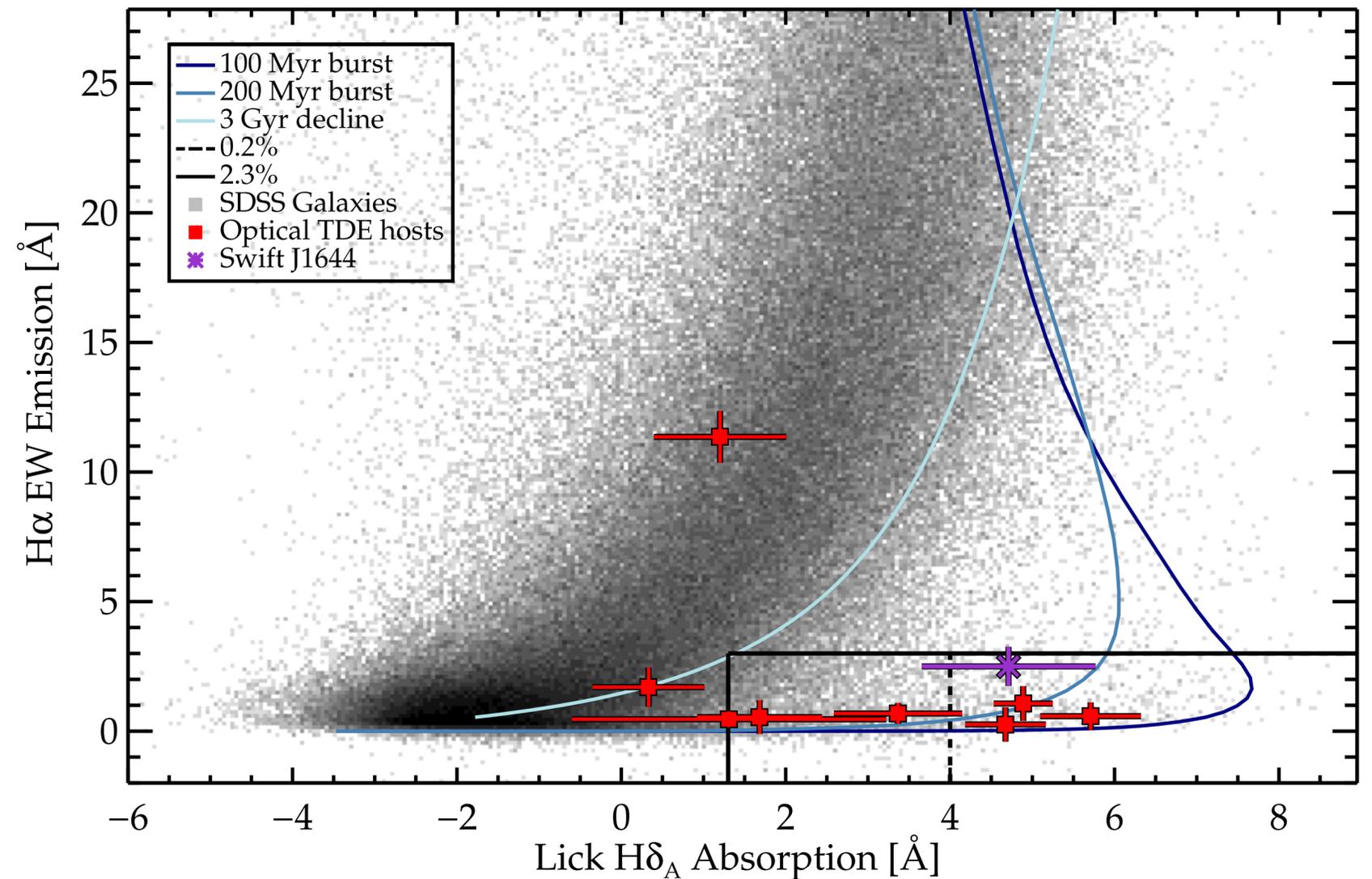
Ramsden, MN+ 2025

SMBH and galaxy evolution with TDEs

Up to 1/3 of TDEs occur in post-starburst galaxies

Around 30 times more common than expected!

- Recent mergers: binary SMBH or disrupted density profiles?
- Nuclear starbursts?
- TDEs cause the quenching?



French+ 2016

SMBH and galaxy evolution with TDEs

Where do quenched hosts live on TDE scaling relations?

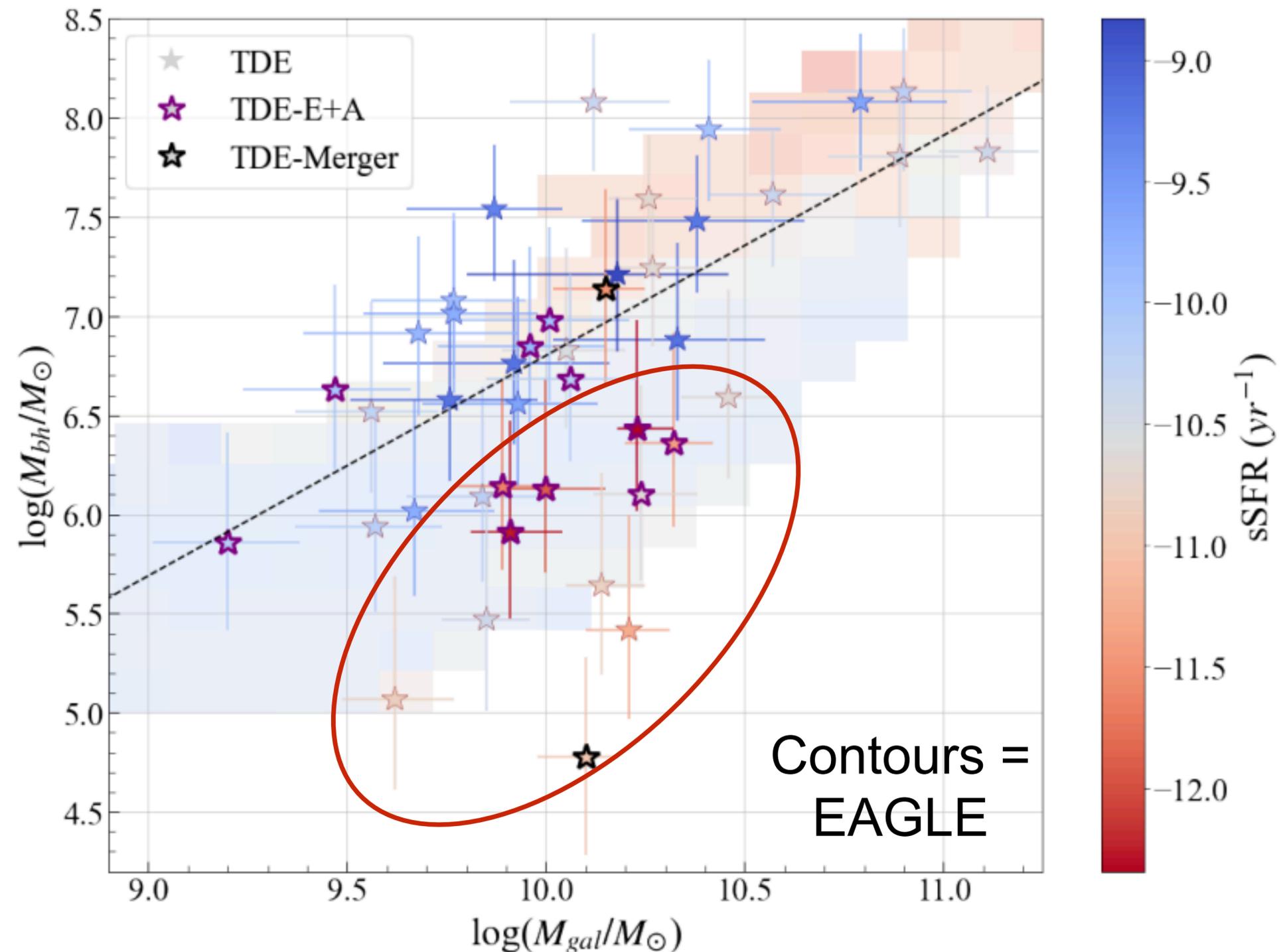
Systematically at low BH mass!

- Very surprising result!

In simulations, AGN feedback shuts off SF at *high* BH mass

Hypothesis: mergers remove gas, shut off both star-formation and BH growth

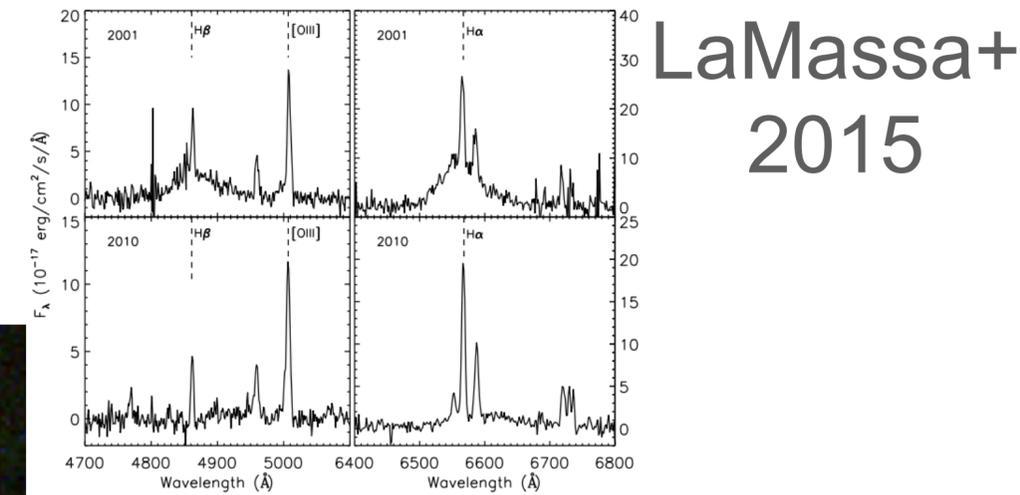
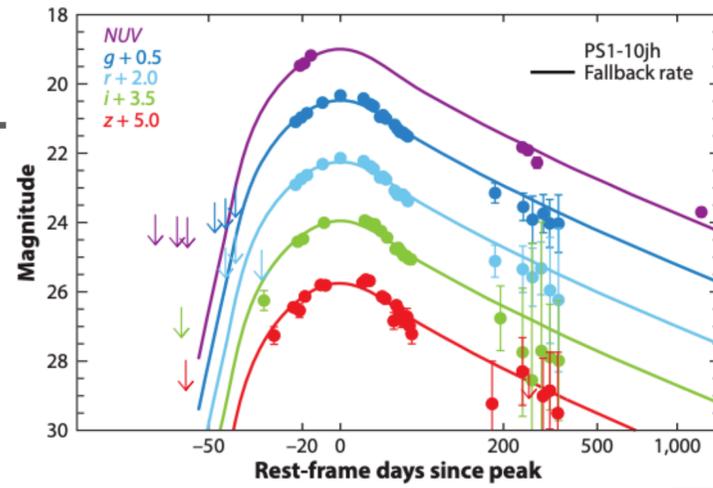
Do these mergers enhance the TDE rate?



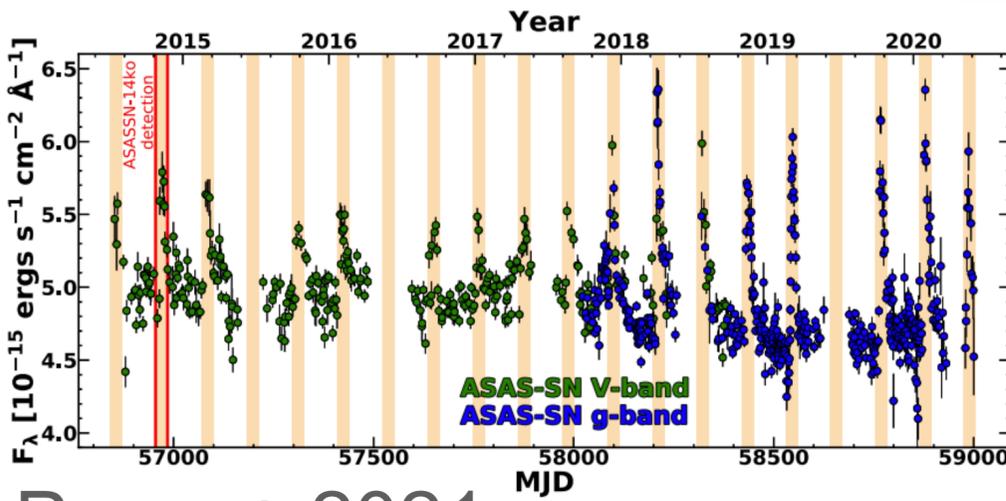
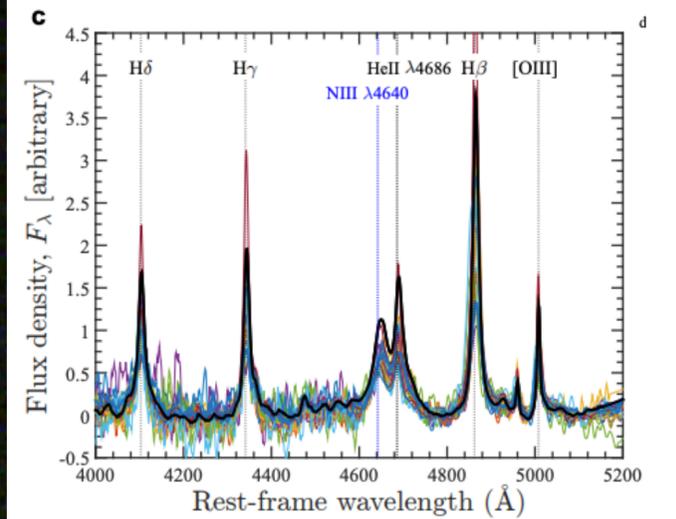
Ramsden, McGee, MN 2026

The SMBH transient zoo

Gezari+
2012

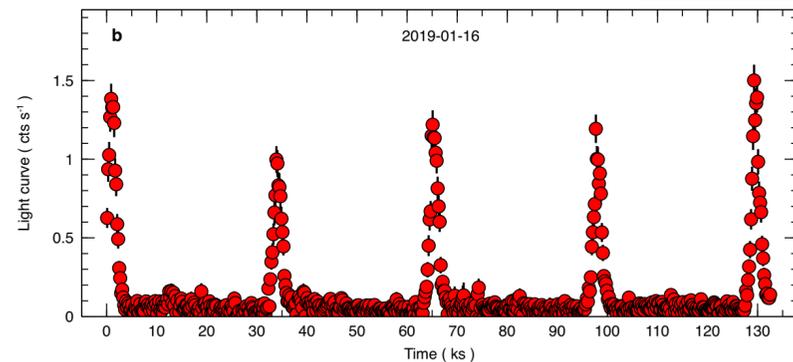


Trakhtenbrot+2019

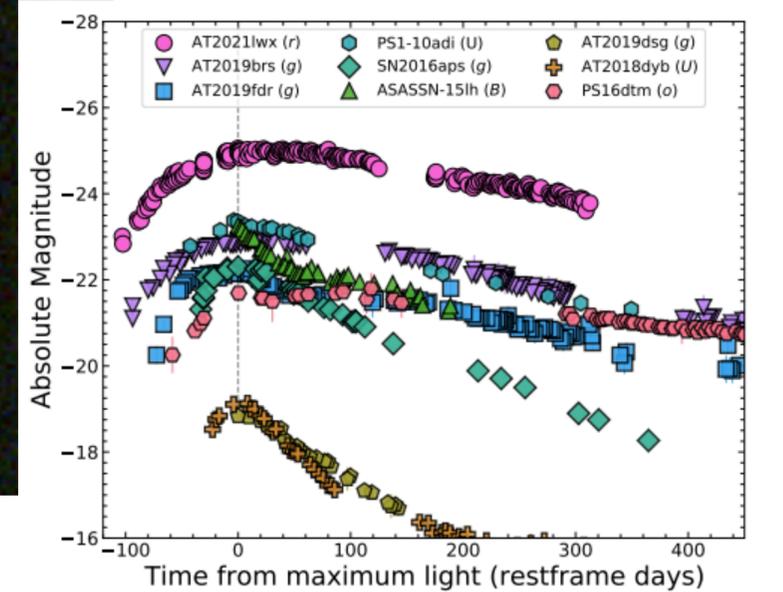
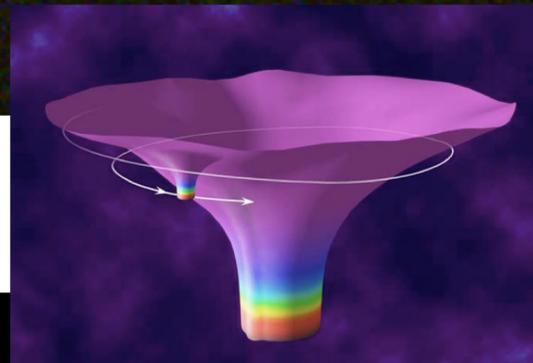
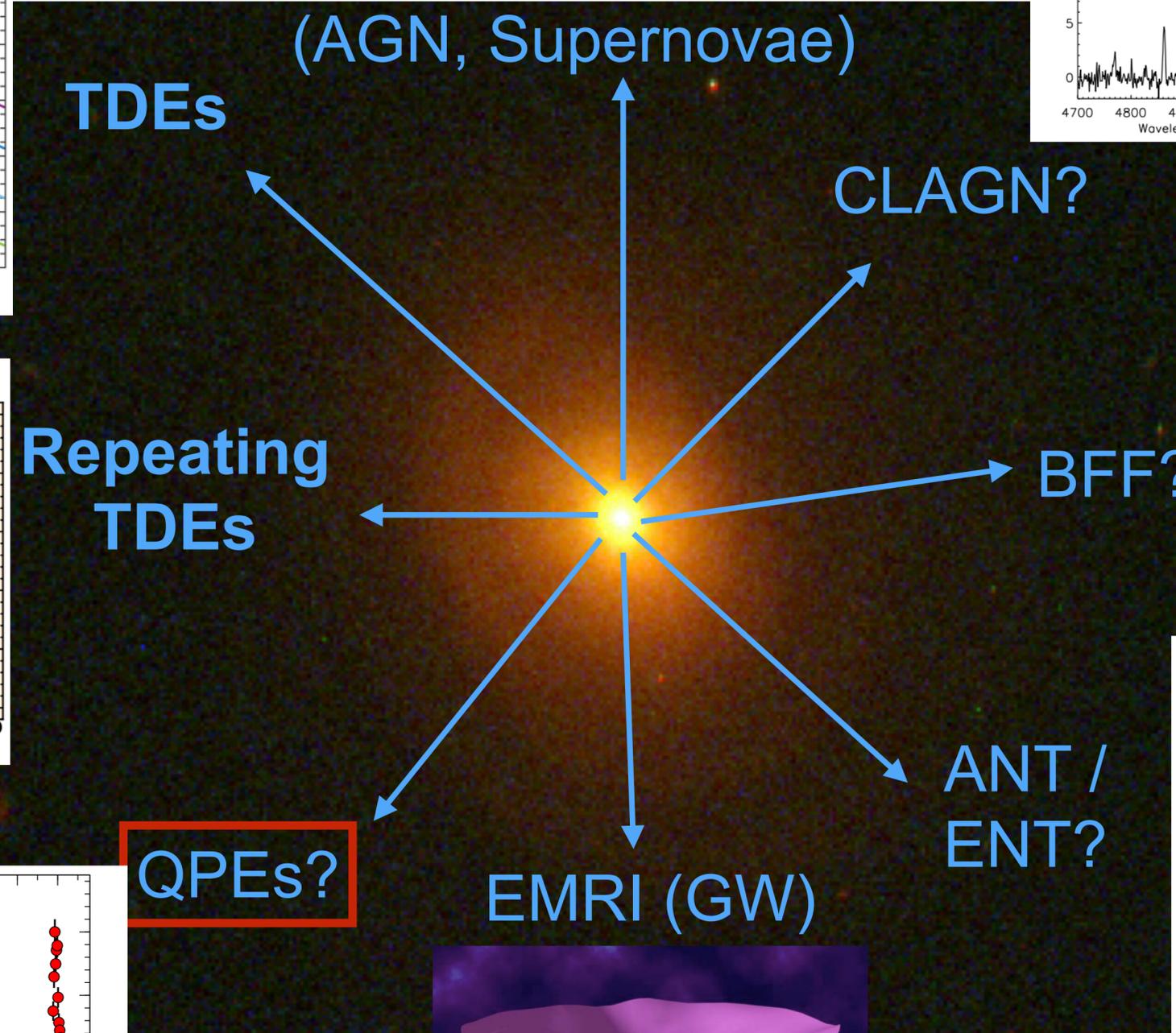


Payne+ 2021

Miniutti+
2019



Matt Nicholl



Wiseman+ 2023

Queen's University Belfast

Quasi-periodic eruptions

Short bursts of soft X-rays repeating every few hours

'Quasi'-periodic

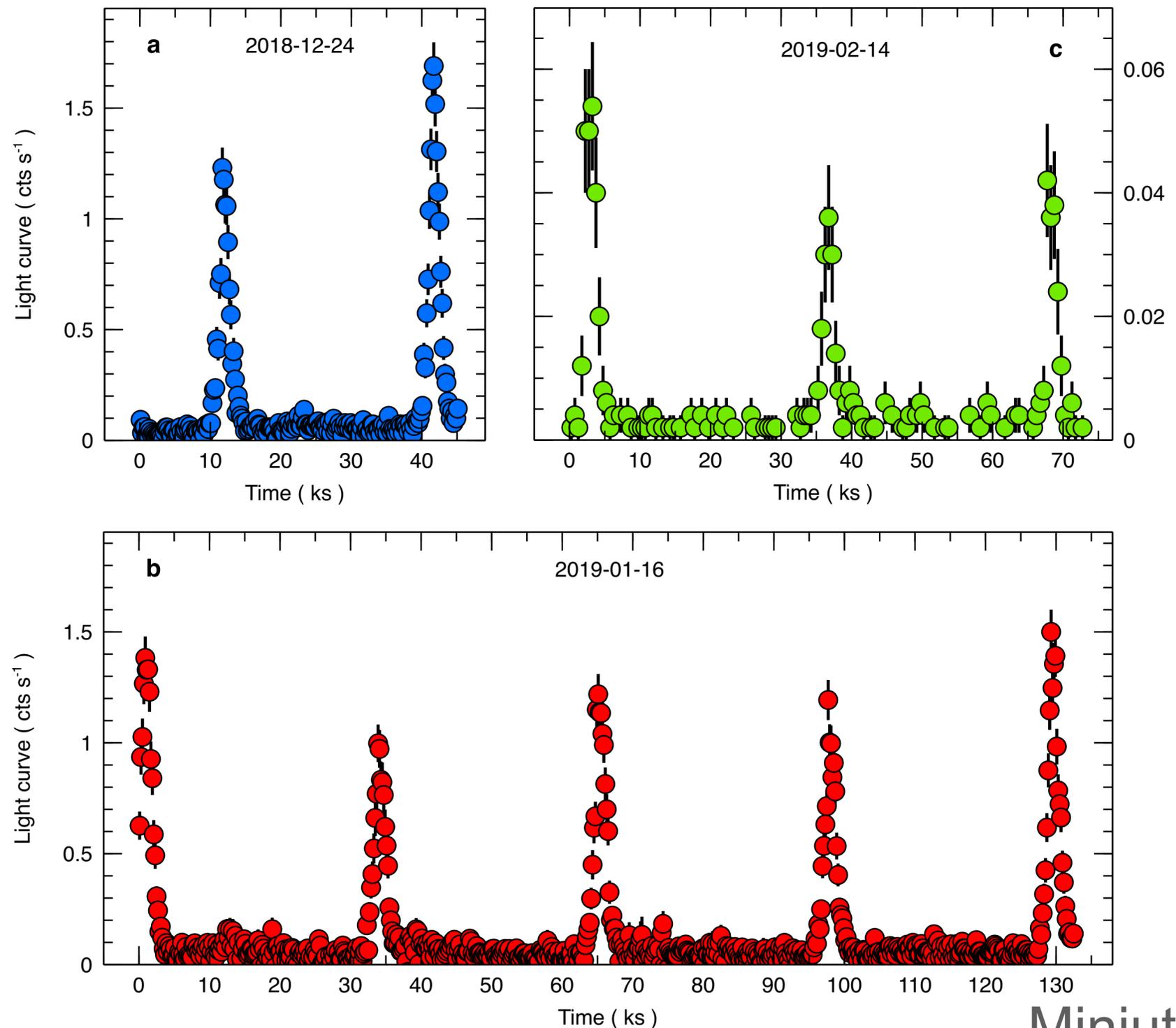
Consistent light curve shape

Persist for many years

~10 QPE sources now known, discovered by various X-ray missions

All in galaxy nuclei

GSN 069



Miniutti+ 2019

Flare properties

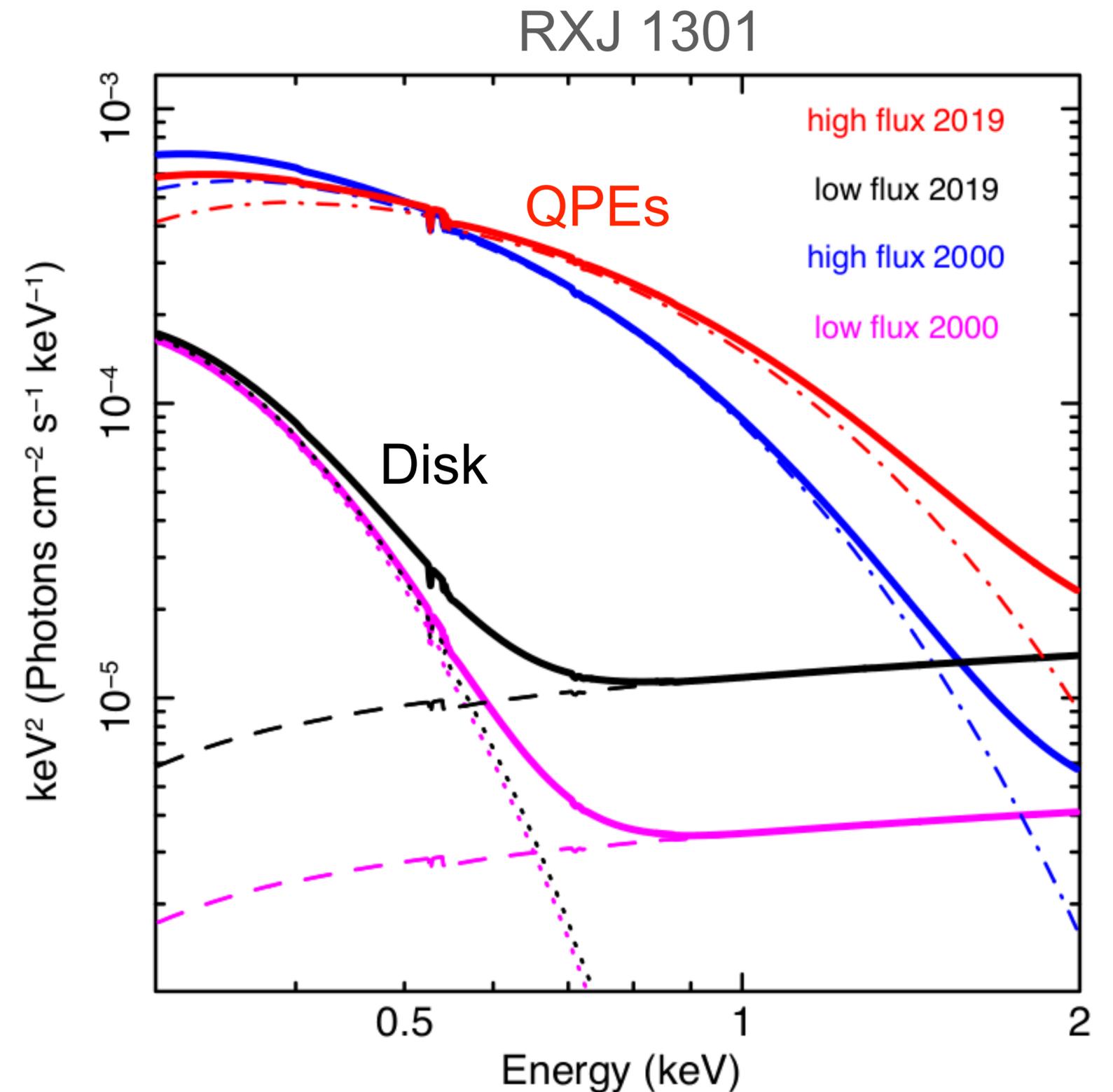
Peak luminosity $\sim 10^{42} - 10^{43}$ erg/s

Increase of 1-2 orders of magnitude

Eruption: single-temperature blackbody spectrum with $kT \sim 100$ eV

Quiescent phase: consistent with thermal accretion disk

Spectra, energetics and locations: must be from SMBHs / accretion disks



Giustini+ 2020

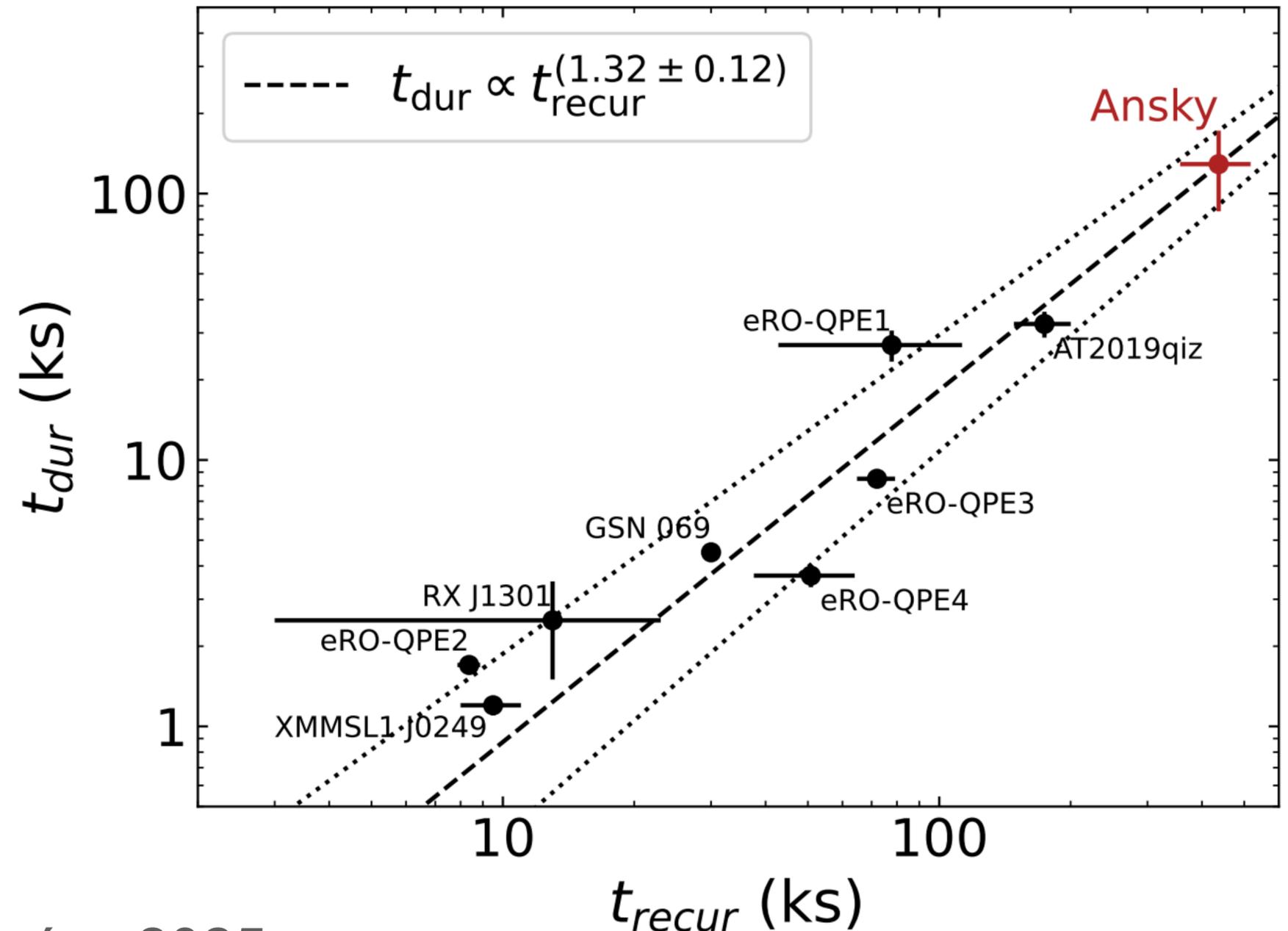
Population: durations and recurrence times

Recurrence times span ~few hours to ~few days

Flare durations from ~1 hour to ~1 day

Strongly correlated!

Duty cycle ~20%



Hernández-García+ 2025

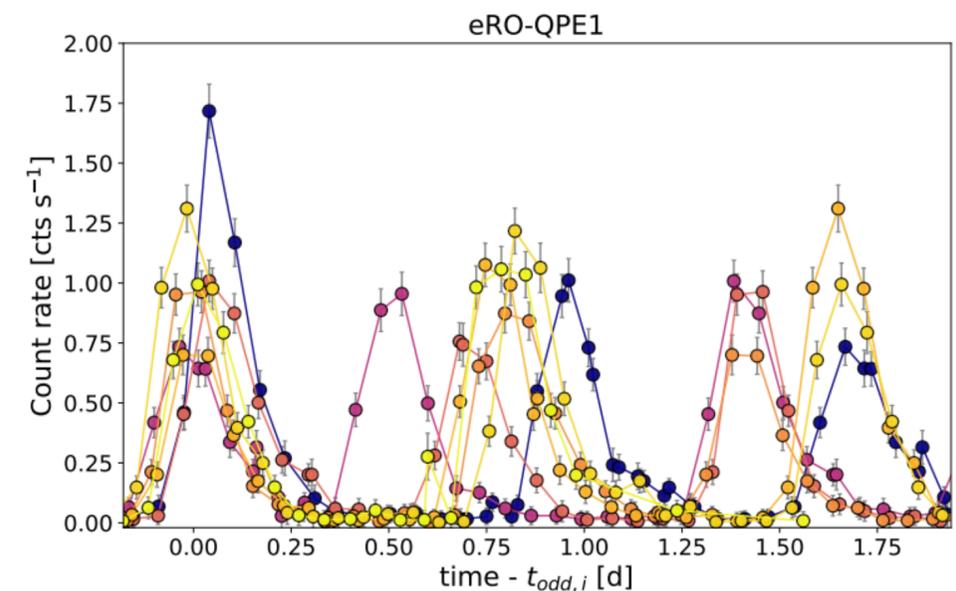
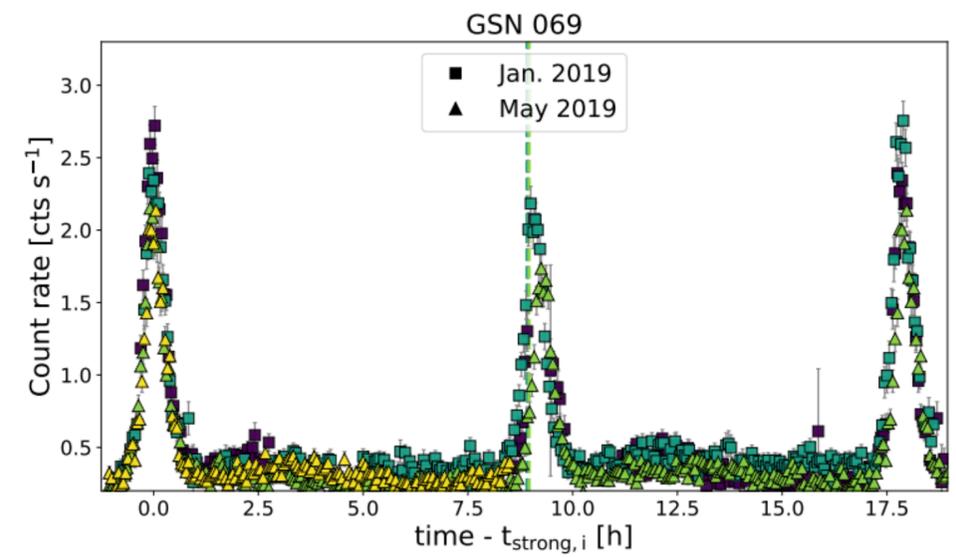
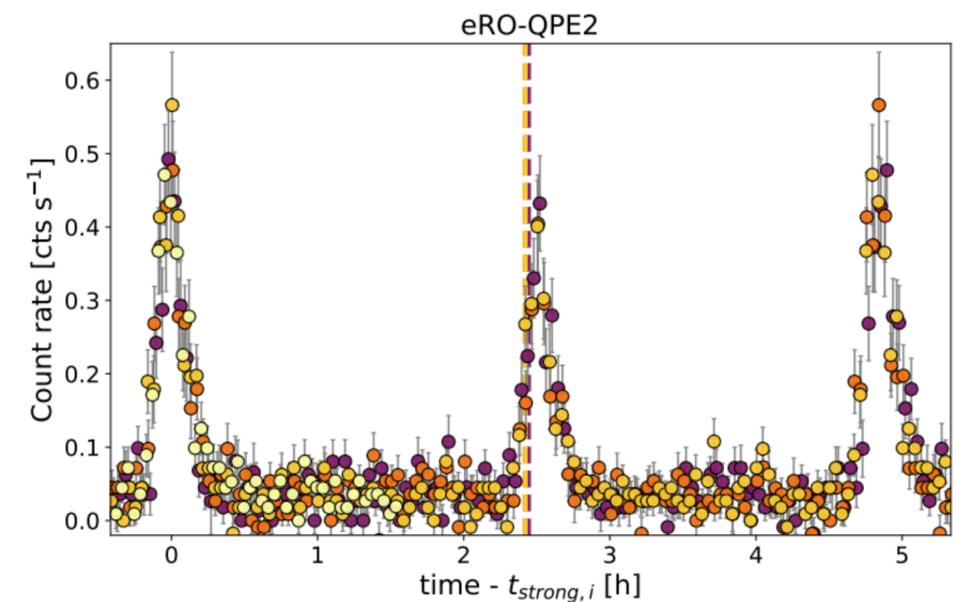
Phase-folded light curves

Some systems show alternating long/
short delay times and high/low
amplitudes

Others show very complex variation in
recurrence time!

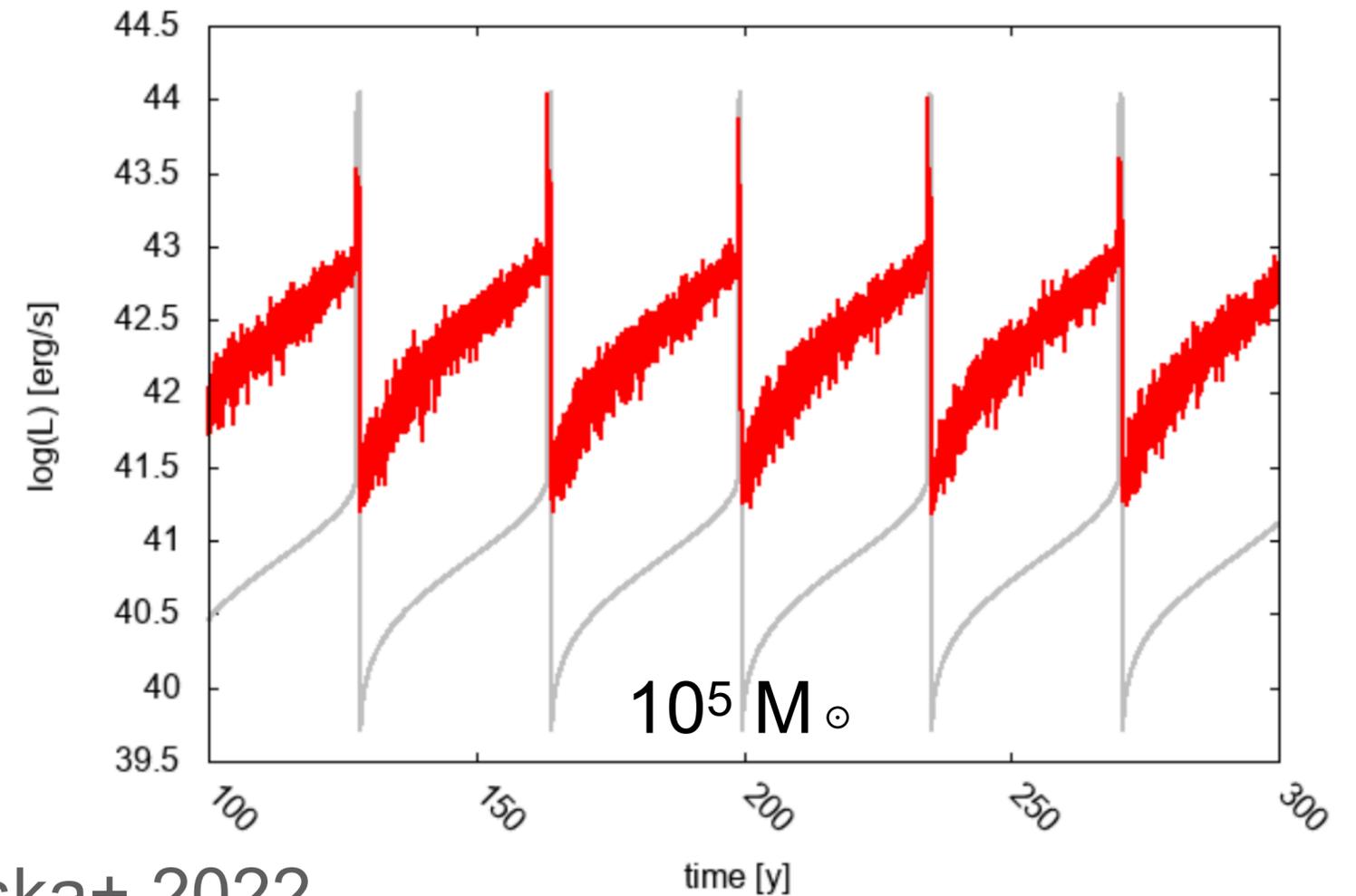
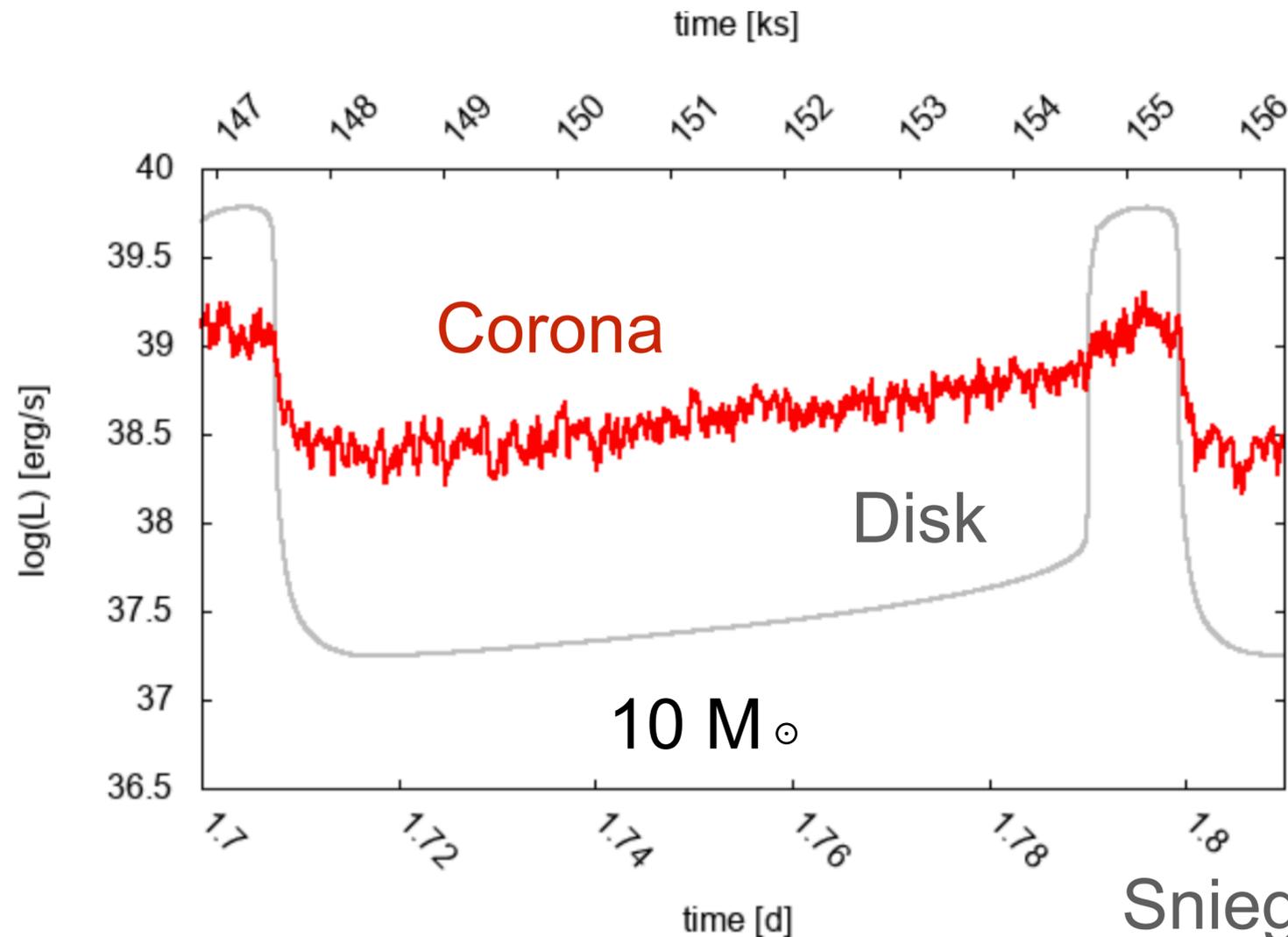
Average delay time can evolve on
timescales of \sim years

Arcodia+ 2022



Models for QPE emission: radiation pressure instability in the disk?

If $p_{\text{rad}} > p_{\text{gas}}$, small change in T leads to big change in heating rate \rightarrow runaway



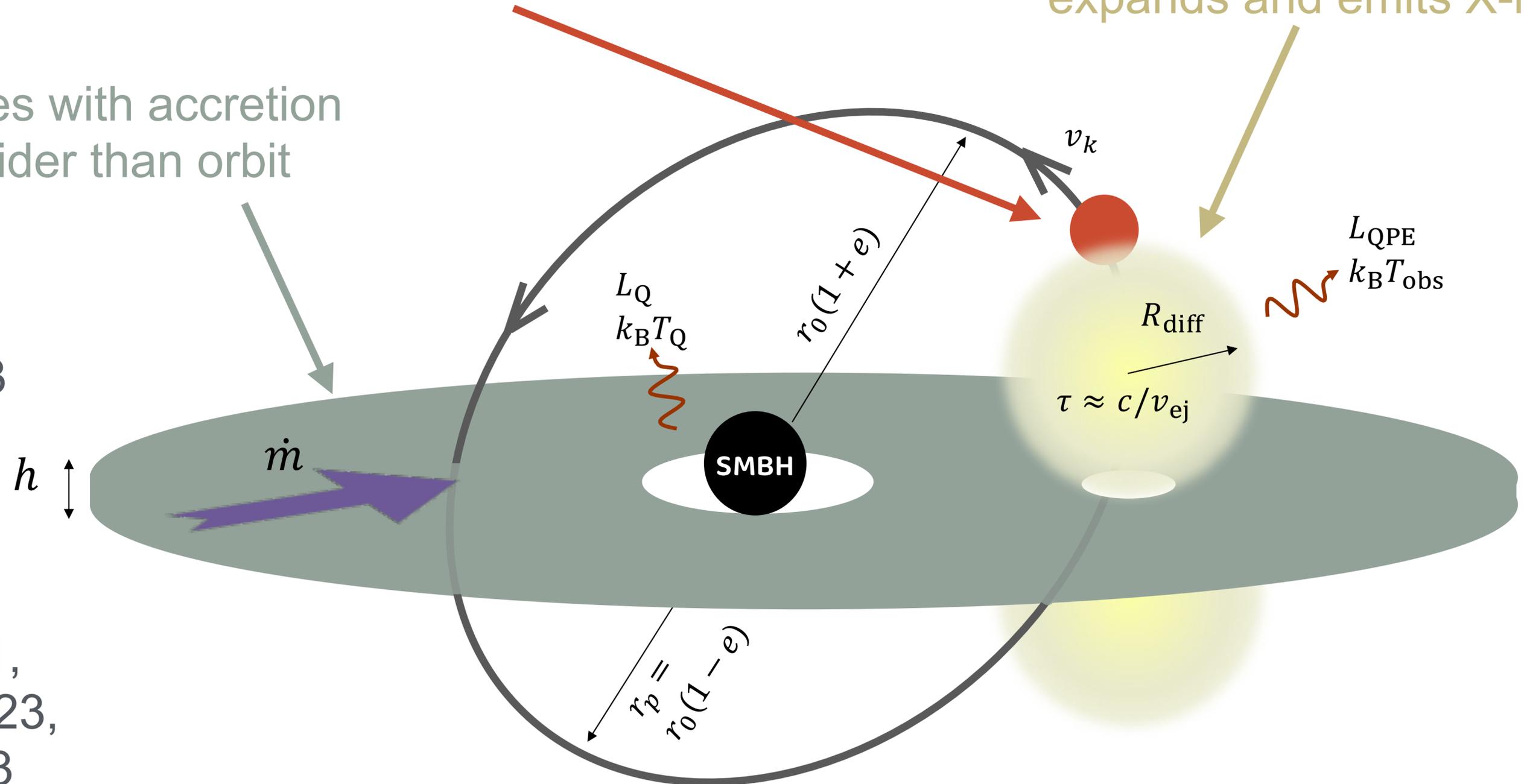
Sniegowska+ 2022

Close orbiter interacting with BH or disk?

1. Star on hours-days orbit:
(captured by Hills mechanism?)

2. Collides with accretion
disk wider than orbit

3. Shocked disk material
expands and emits X-rays



Linial &
Metzger 2023

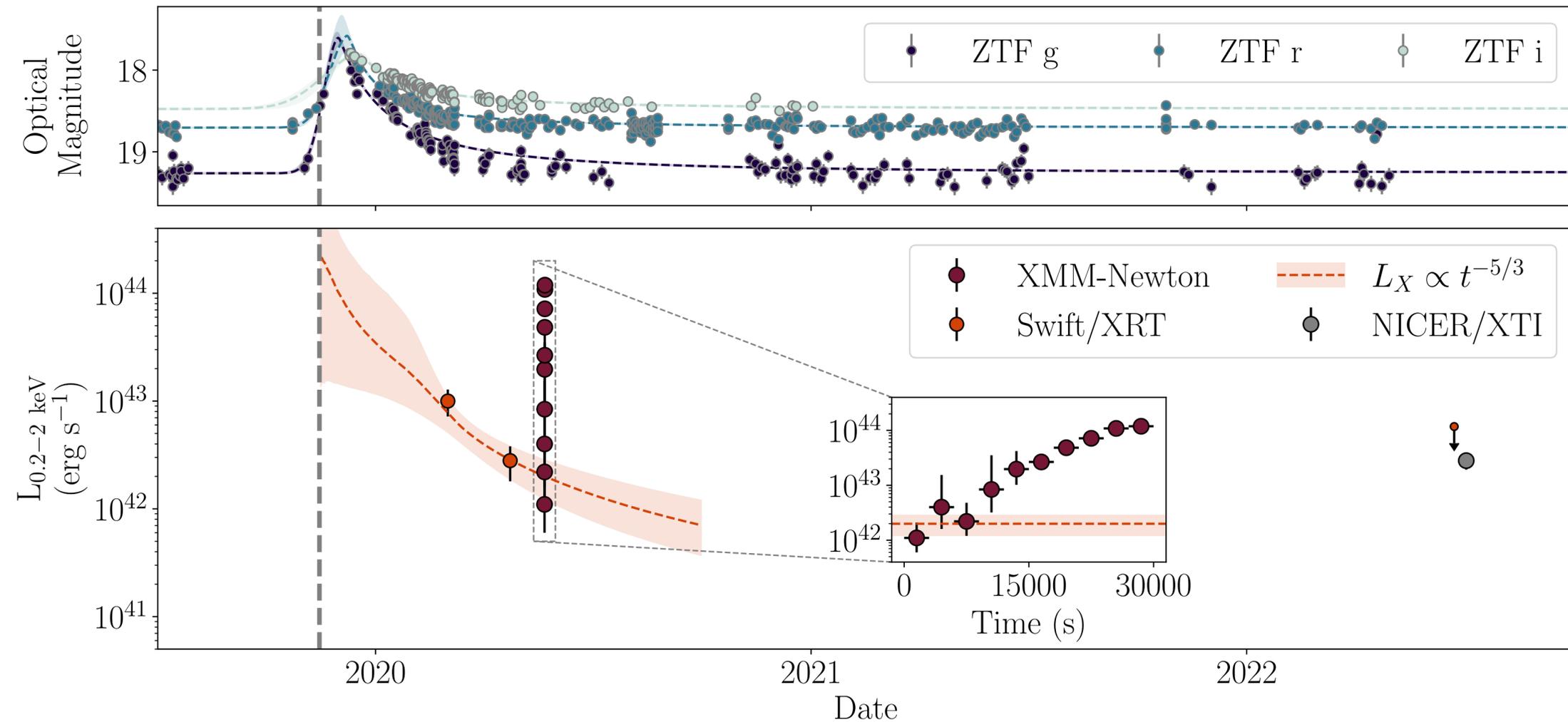
See also:
Dai+2010,
Xian+2021,
Sukova+2021,
Franchini+2023,
Tagawa+2023

Mounting evidence for QPE-TDE connection

Similar host galaxies
(eg Wevers+ 2024)

Several sources with
characteristics of both
classes (Shu+ 2018,
Chakraborty+ 2021,
Quintin+ 2023)

Theoretically, TDEs
provide fresh disks
(QPE collision models)
and a range of
Eddington ratios
(instability models)



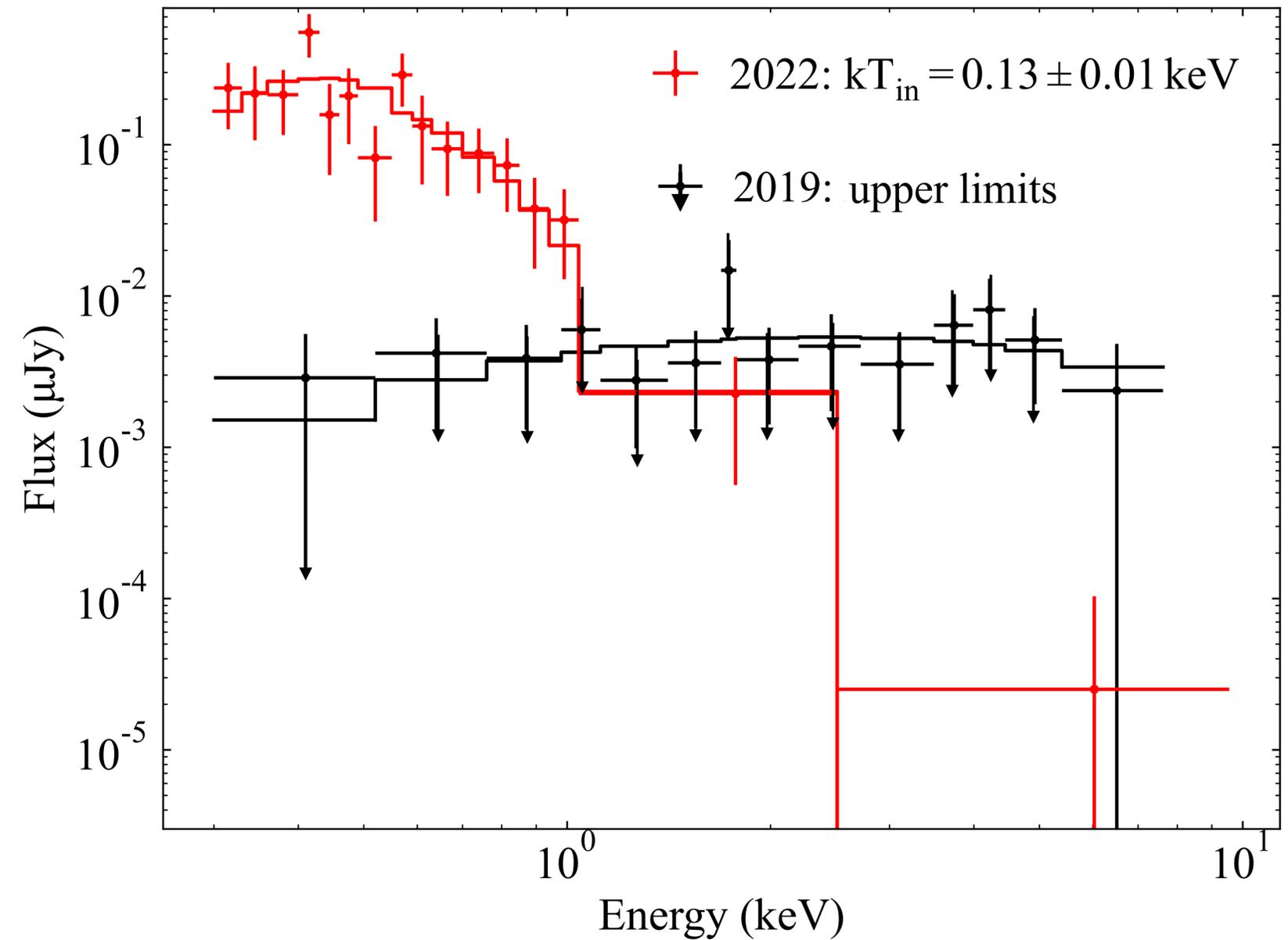
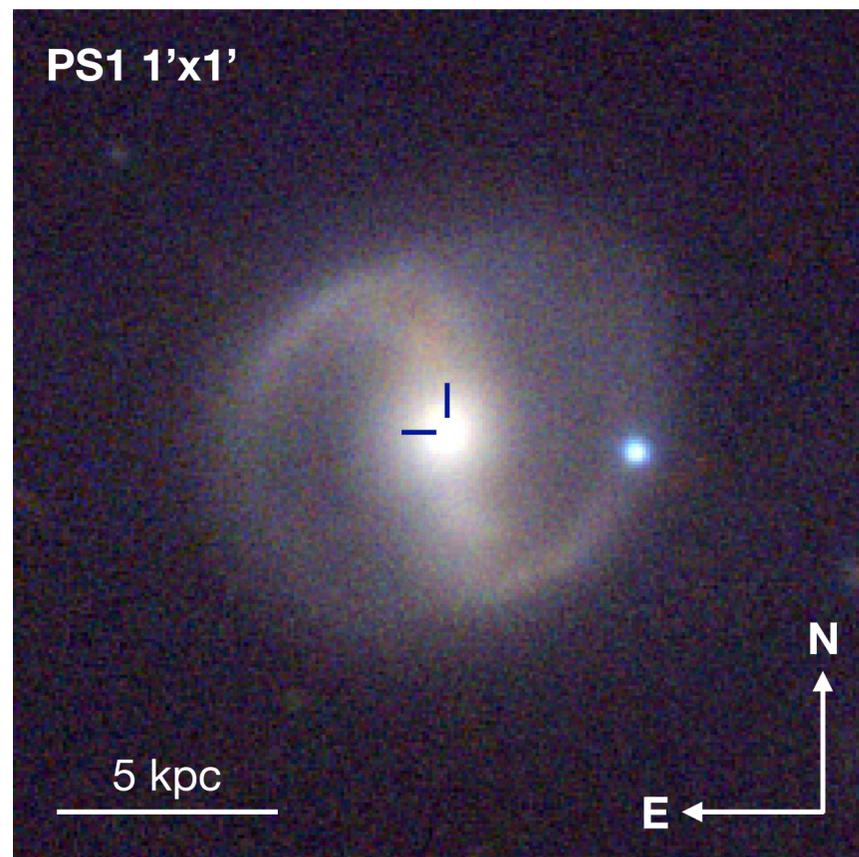
Quintin+ 2023

AT2019qiz: a very nearby TDE

65 Mpc, early discovery, exquisite follow-up

$M_{\text{BH}} \approx \text{few } 10^6 M_{\odot}$

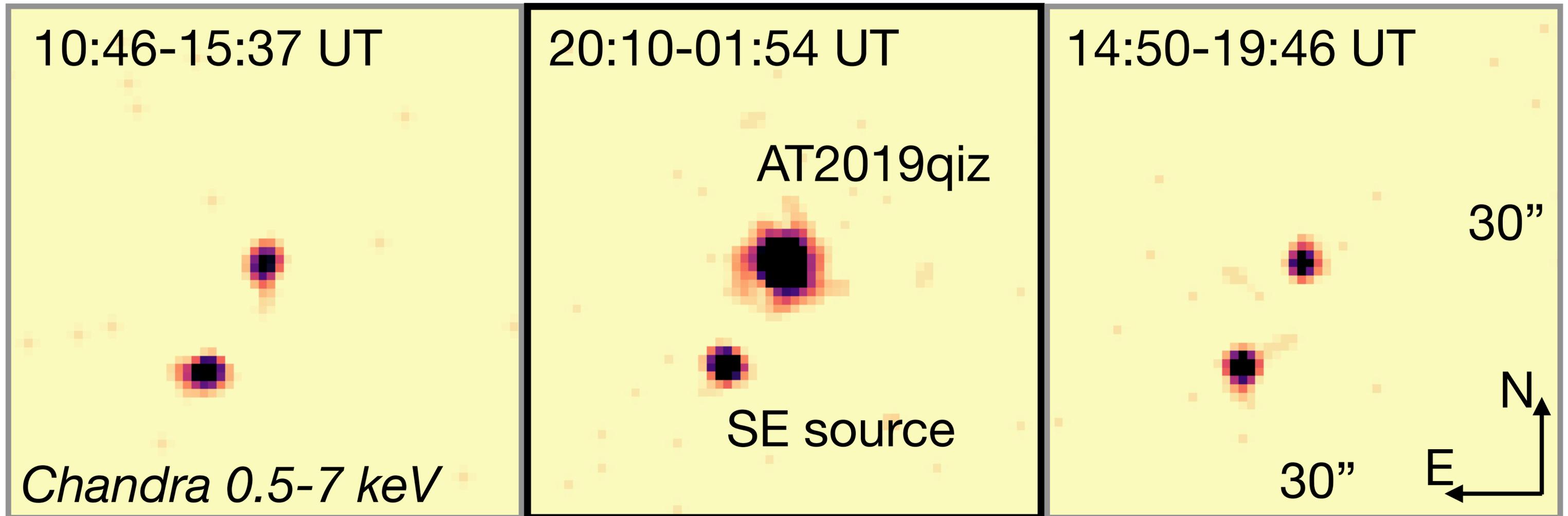
X-rays at ≈ 3 years: chance to study disk!



Short+ 2023

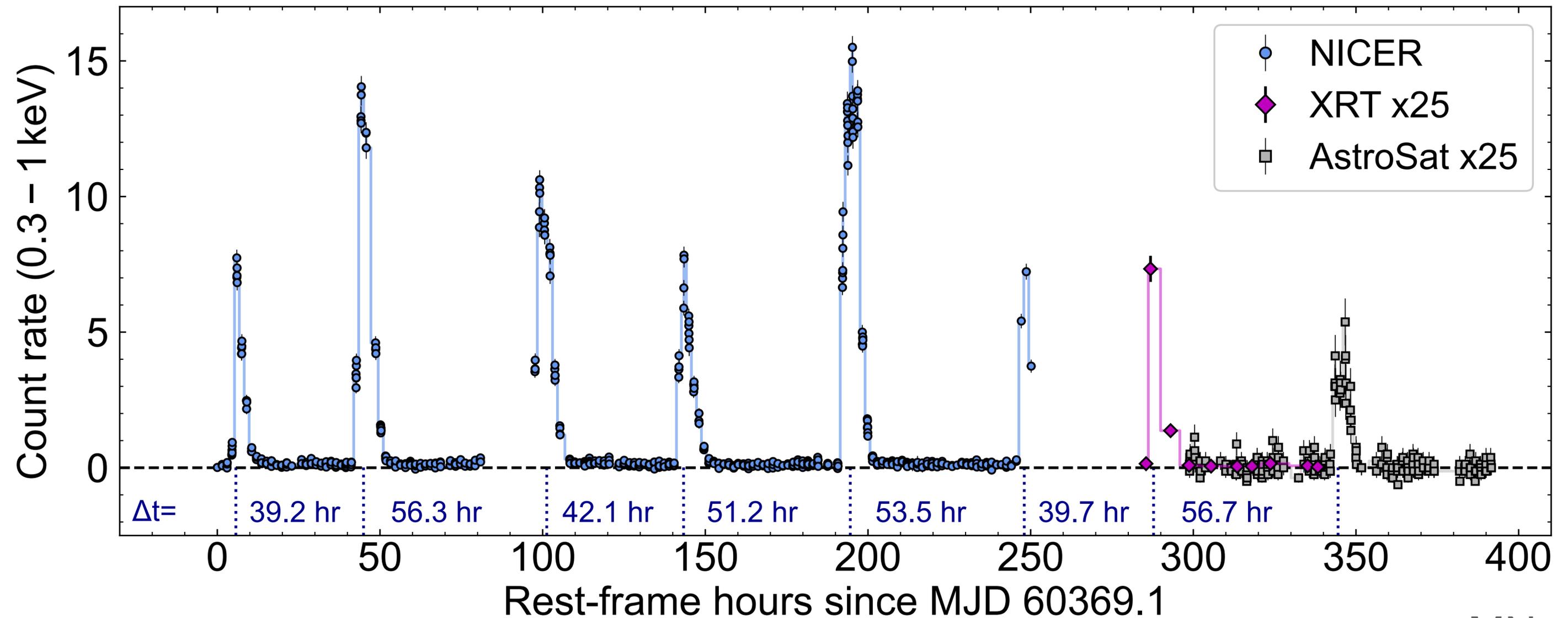
Chandra observation at +4 years

50 ks exposure (conveniently) split into three observations over 1.5 days



Nicholl+ 2024

Follow-up: QPEs!



MN+ 2024

All properties consistent with known QPE sample

Flare duration ~8-10 hours, average recurrence time ~48 hours

TDE-QPE link now definitive

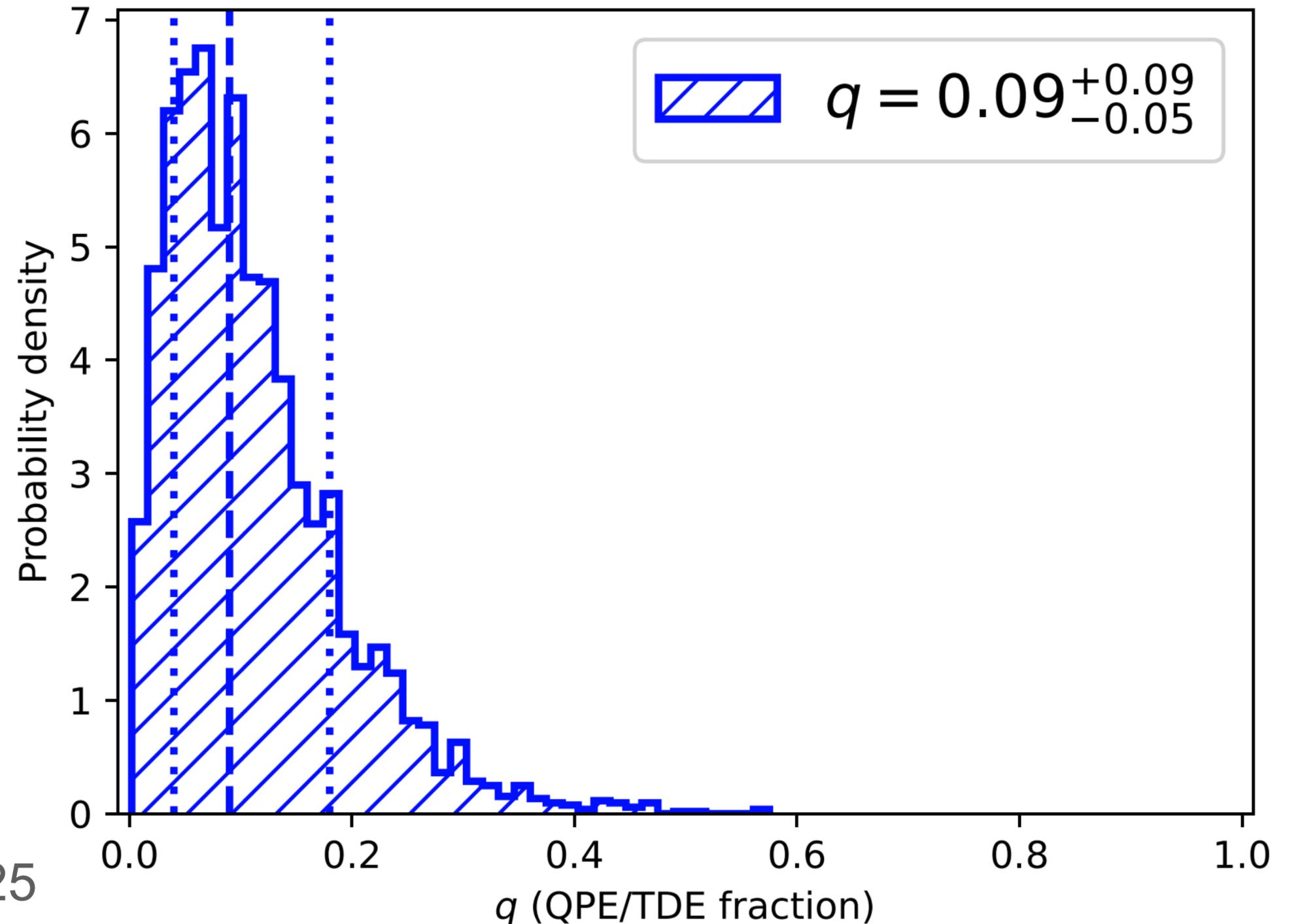
QPEs now seen in 3 confirmed TDEs

~10% of TDEs probably have QPEs

One 'turn-on' AGN also shows QPEs (Sánchez-Sáez+ 2024, Hernández-García+ 2025)

Chakraborty+ 2025

Posterior distribution of QPE/TDE fraction (q)



Coronal lines in TDEs and QPEs

Several (QPE+)TDEs show high-ionisation narrow iron lines

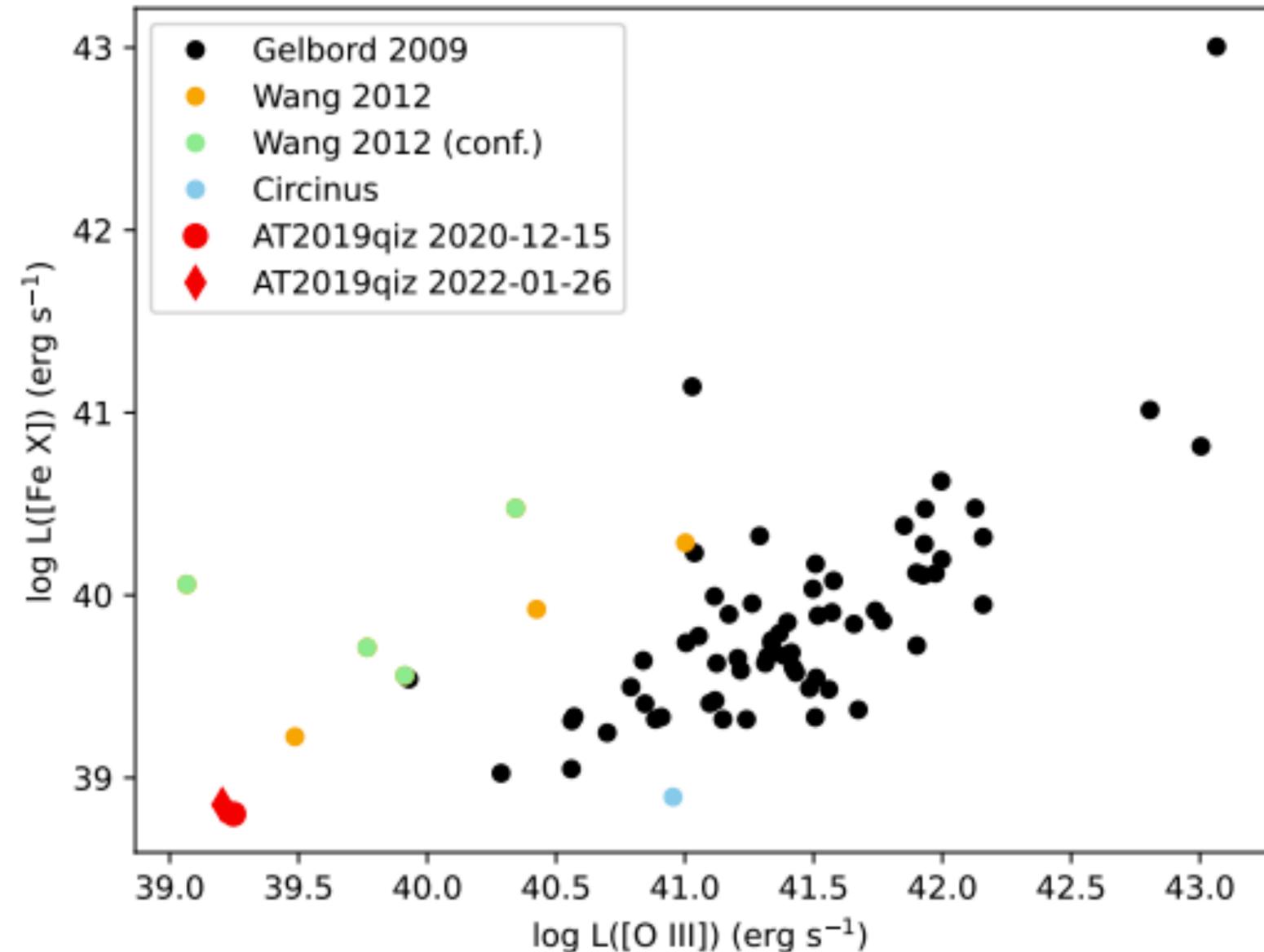
- [Fe VII] - [Fe XIV]

Line ratios similar to SDSS extreme coronal emitters!

- ECLEs are TDEs
(see also Onori+ 22, Clark+ 24...)

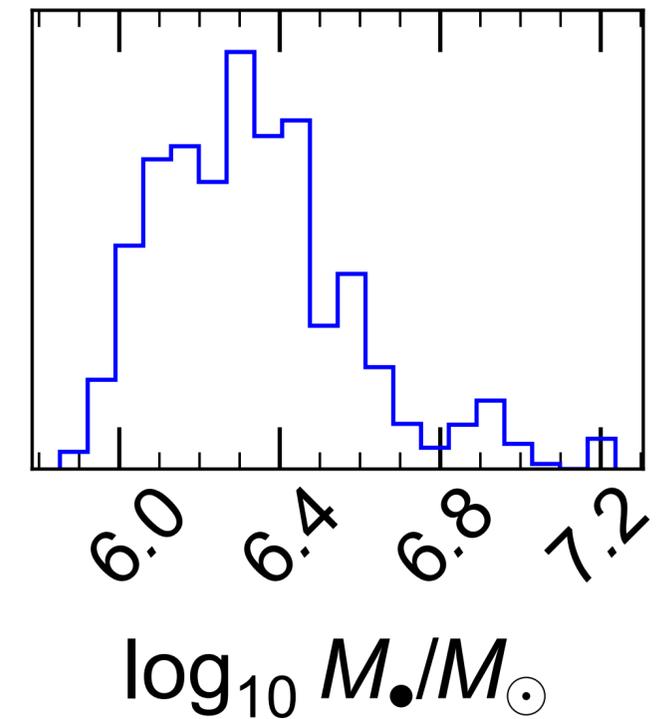
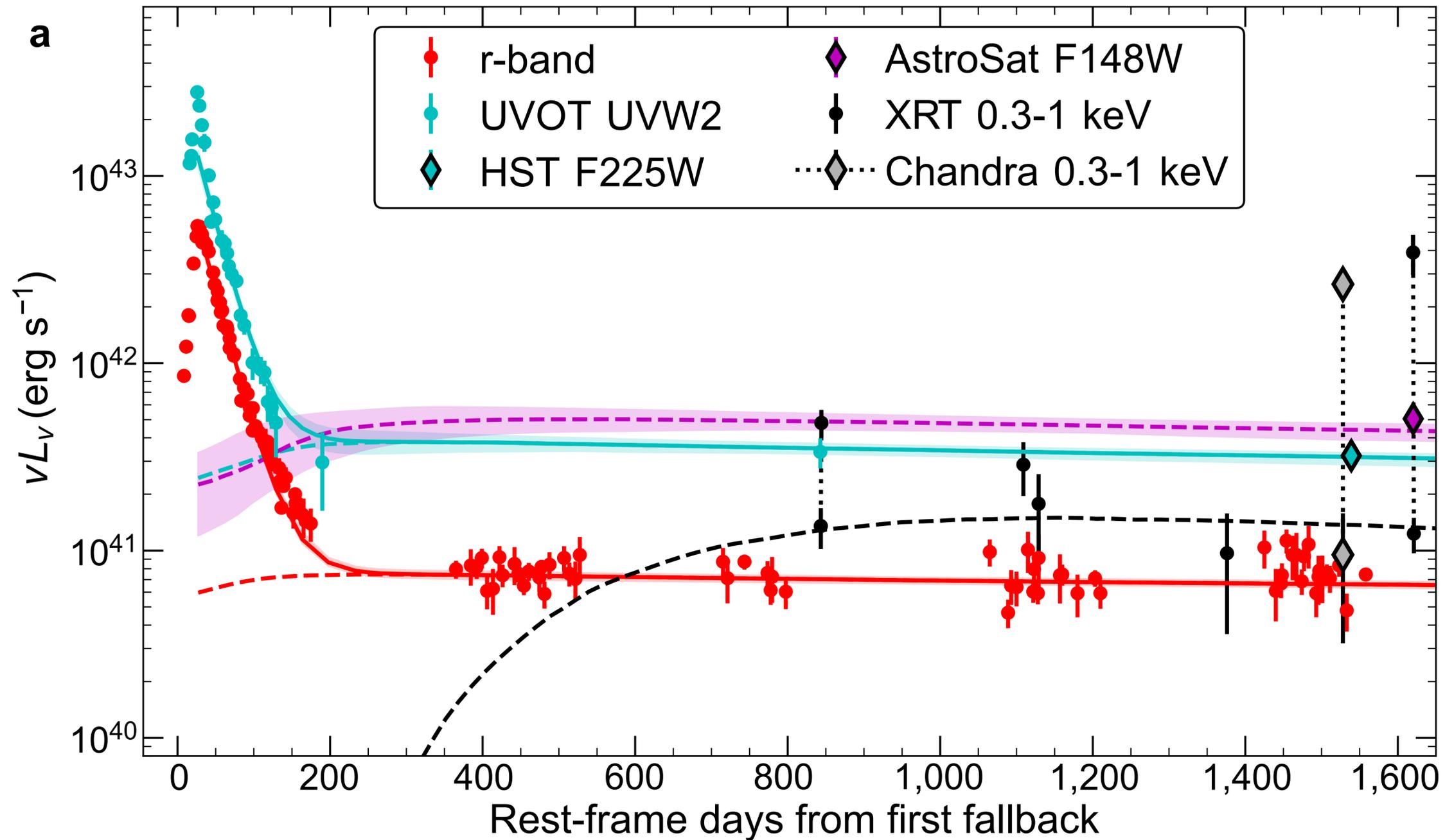
Disk (and QPEs?) ionise environment on ~pc scales

QPEs prefer gas-rich environments?



Short+ 2023

AT2019qiz: disk model and QPE mechanism



$$L/L_{\text{Edd}} \approx 0.04$$

MN+ 2024

QPEs from disk instabilities?

Kaur+ 2023 — explicit equations for instability timescales in TDE disks:

Radiation pressure instability:

$$t_{\text{qpe}} = t_{\nu}(R_{\text{st},o}) \simeq \boxed{2350 \text{ yr}} M_6^{4/3} \alpha_{-1}^{-2/3} \left(\frac{\dot{M}}{\dot{M}_{\text{Edd}}} \right)^{2/3} \quad \mathbf{X}$$

Magnetic pressure instability:

$$t_{\text{qpe}}^{\text{B}} = t_{\nu}(R_{\text{st},o}^{\text{B}}) \simeq \boxed{1.1 \text{ yr}} \frac{M_6^{44/37}}{p_0^{56/37} \alpha_{-1}^{30/37}} \left(\frac{\dot{M}}{\dot{M}_{\text{Edd}}} \right)^{38/37} \quad \mathbf{X}$$

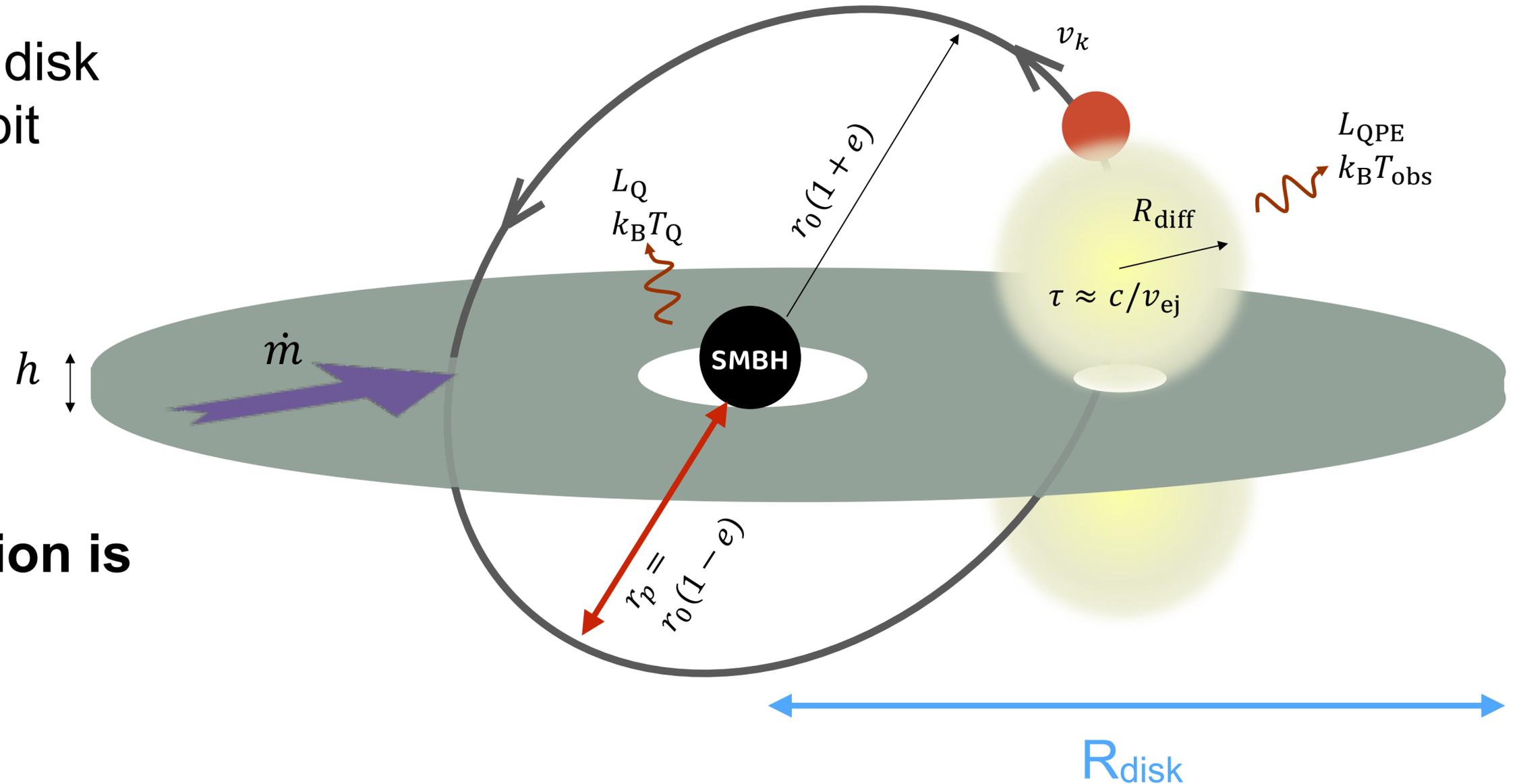
QPEs from star-disk collisions?

Orbit could intersect disk once or twice per orbit

In either case:

Fundamental condition for collision is

$$R_{\text{disk}} > R_p$$



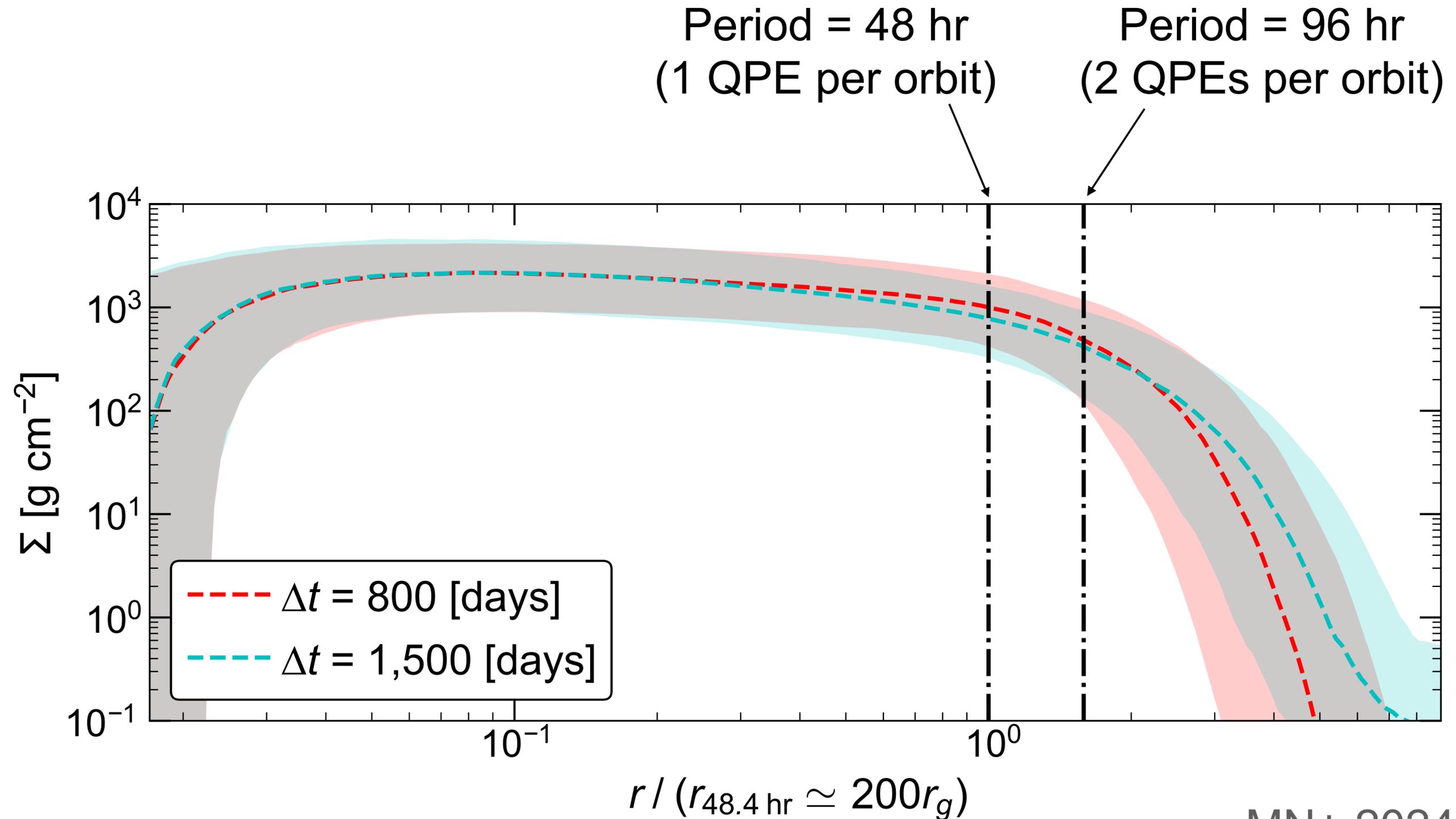
Linial & Metzger 2023

QPEs from star-disk collisions?

Model gives
disk density
profile

Disk is big
enough to
intersect any
orbit
matching
QPE period!

Necessary
(but not
sufficient)
condition



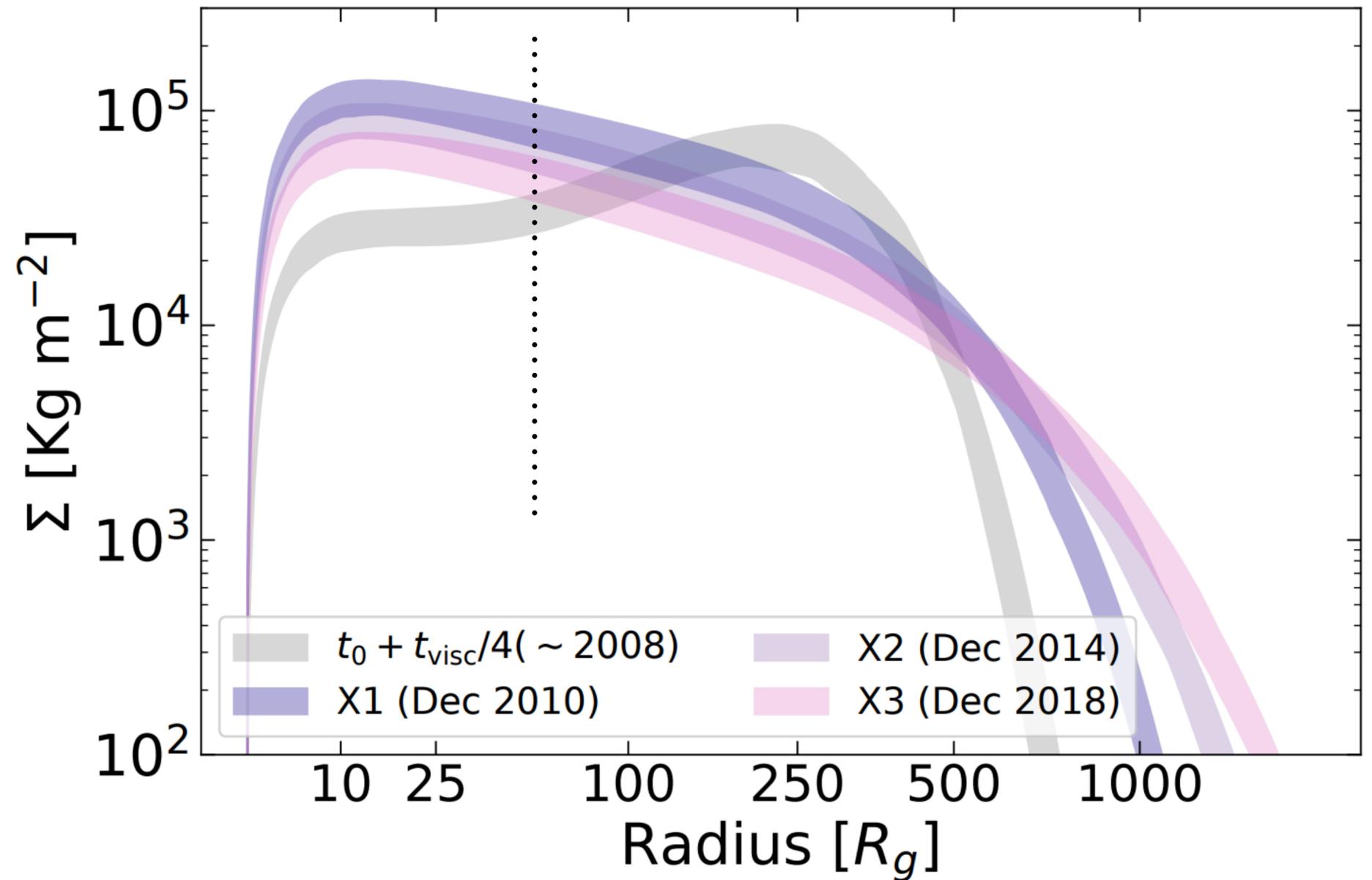
MN+ 2024

Disk model applied to previous QPEs

All other QPEs with disk measurements also show sufficiently extended disk

But GSN 069 disk was similar size in 2014

- No QPEs then!



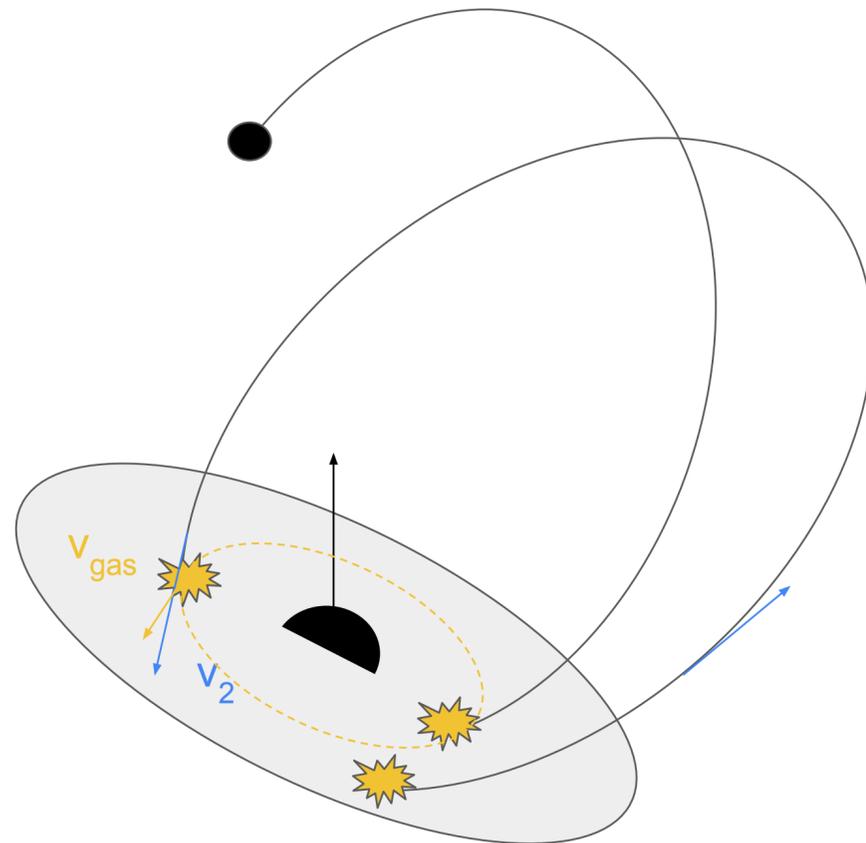
Guolo+ 2025

Challenges: QPE timing

Orbiter model gives a 'simple' clock, but most QPEs show complex timing

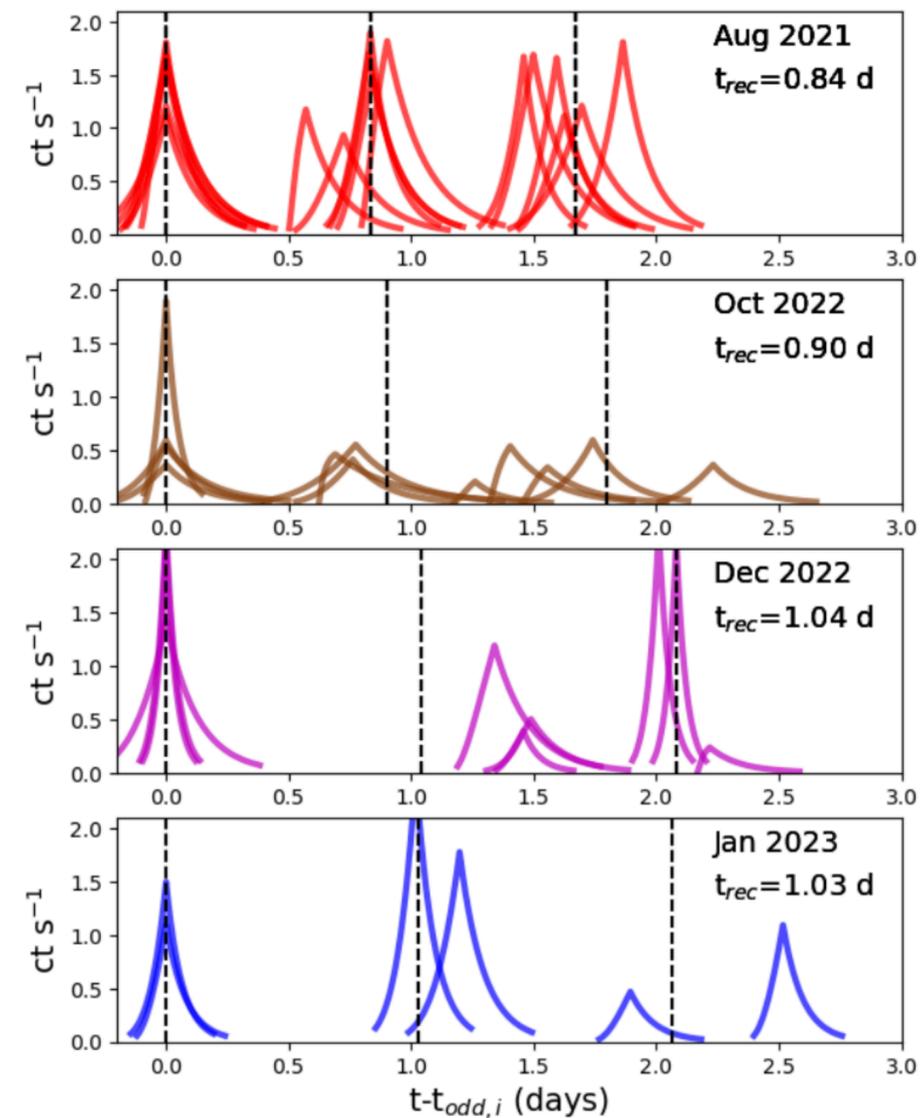
Can this be explained by precession of orbit and/or disk?

Franchini+ 2023

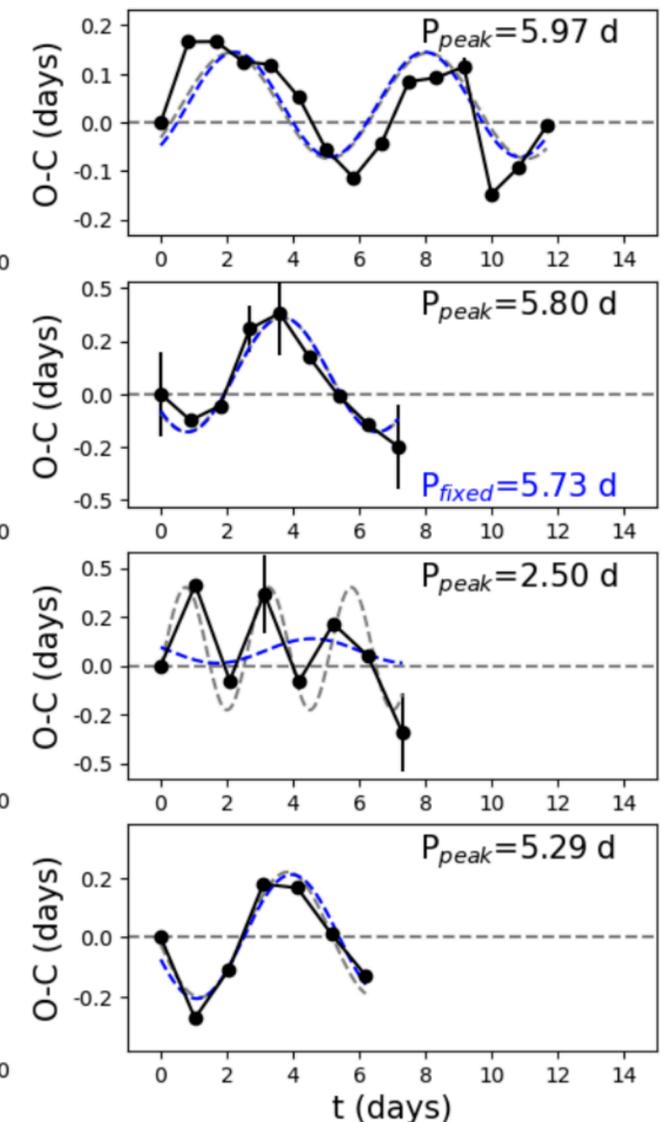


Chakraborty+ 2024

Overplotted even/odd QPEs



O-C timing residuals



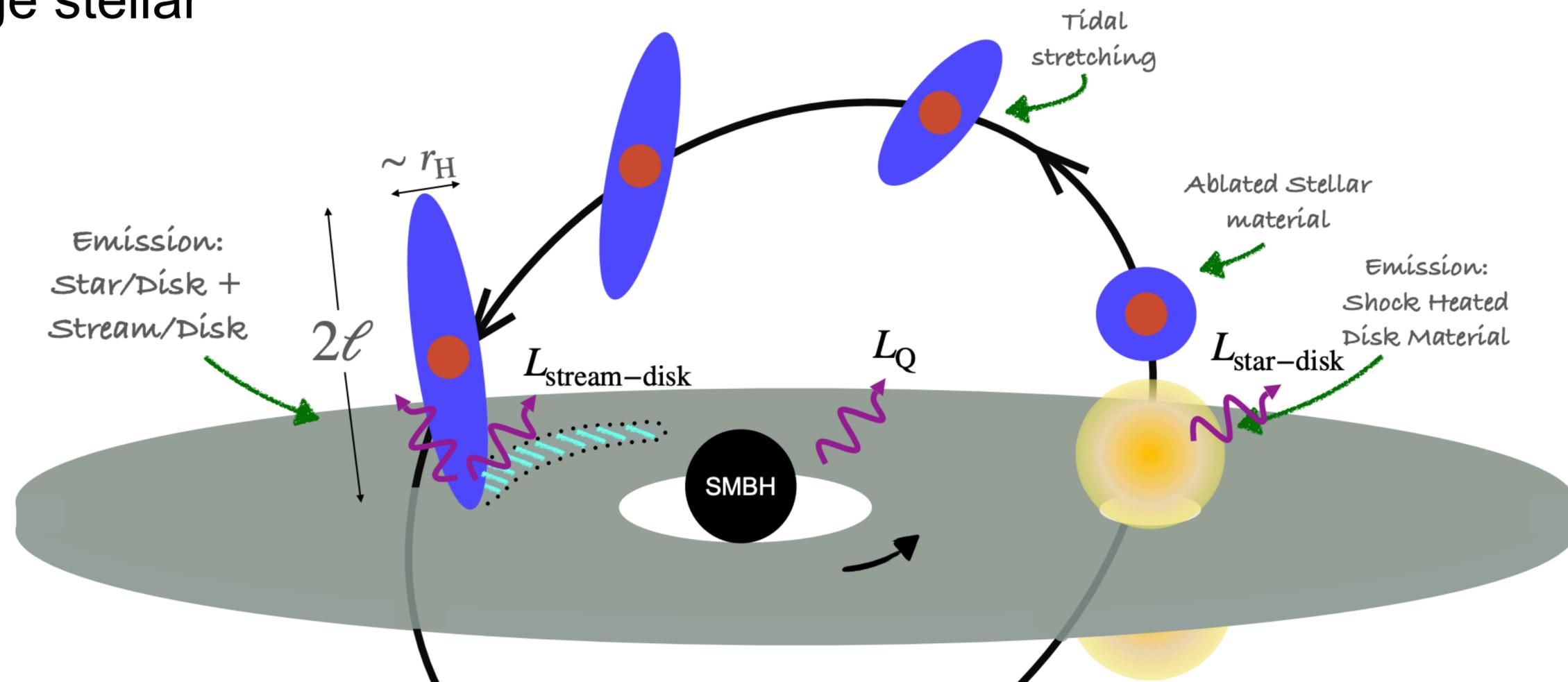
Challenges: dynamics and energetics

The most energetic (long period) QPEs are difficult to reproduce with impacts from Sun-like body

Repeat collisions change stellar structure?

Gas dynamics also affect QPE timing?

Linial+ 2025



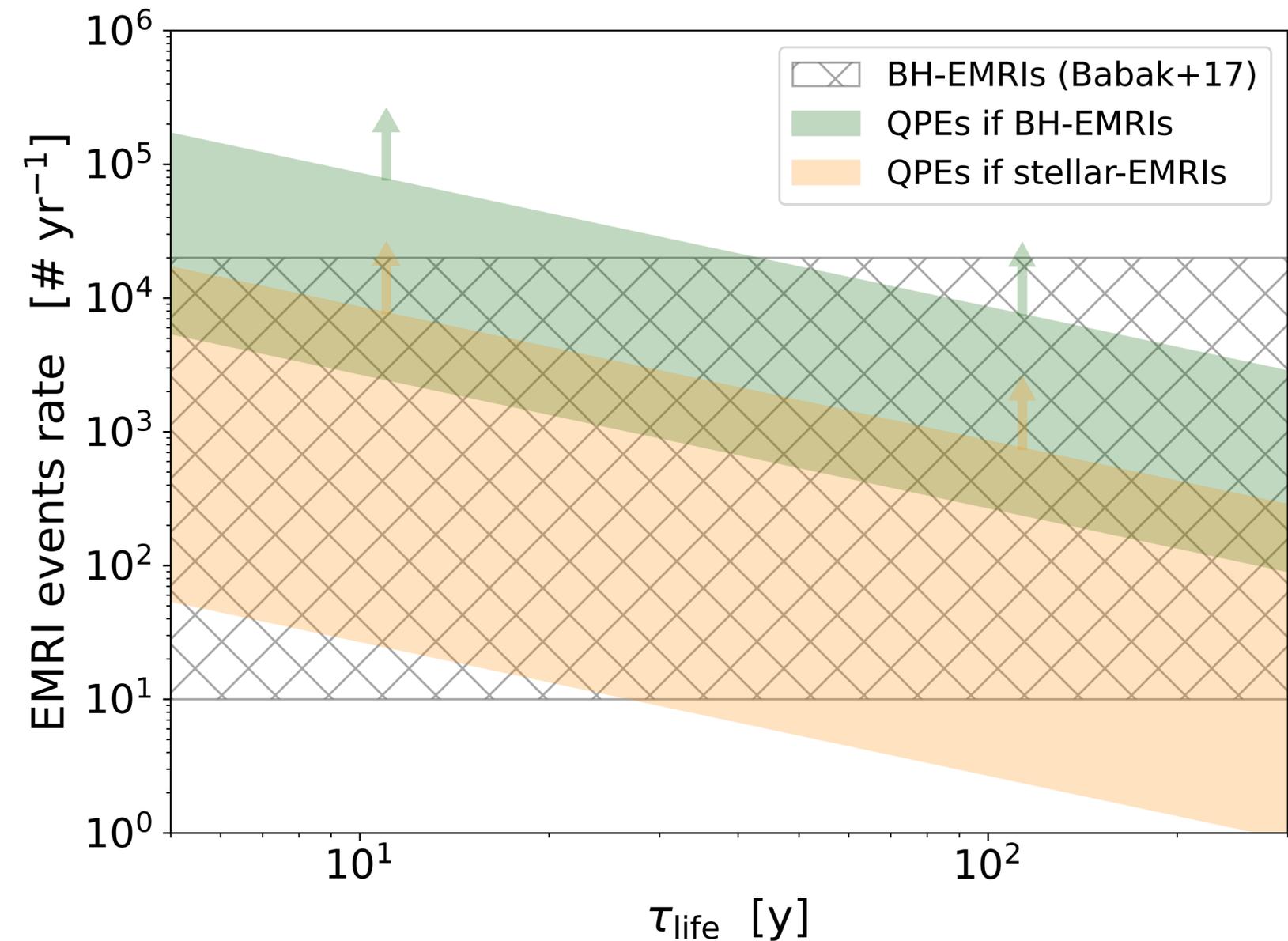
The rate of extreme mass ratio inspirals

If orbiter model is correct:

- QPEs probe dynamics of galaxies on \sim AU scales

EMRIs: merger of stellar-mass compact objects with SMBHs

- QPE:TDE ratio + disk sizes constrains the EMRI formation rate



Arcodia+ 2024b

The future (i): early detection

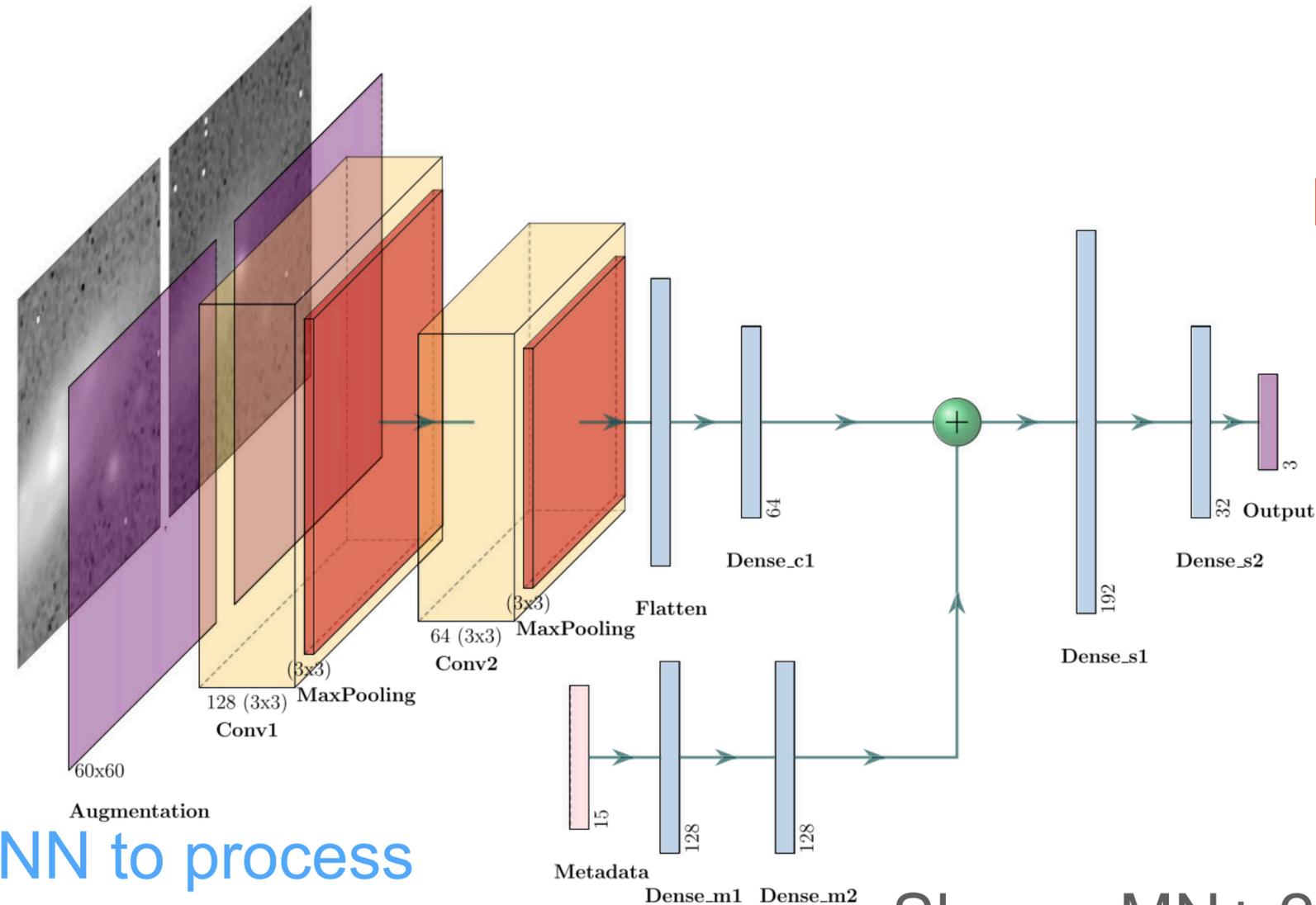
Xinyue
Sheng



Early detection → early spectra → physics of optical peak

NEEDLE trained to find TDEs using ZTF data (pre-peak only!)

CNN to process
discovery images



Layers combined,
softmax layer
provides class
probabilities

Fully connected DNN to process
light curve and catalog features

Follow-up with
spectra: SoXS++

Sheng, MN+ 2024

Now streaming *live* on UK Lasair alert broker!



- Filters ⓘ
- Watchlists ⓘ
- Watchmaps ⓘ
- Annotators ⓘ**
- Status >
- Quick Start
- About ⓘ
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- Contact ⓘ

Public Gallery

Annotators submitted to the public gallery by the Lasair Team or other Lasair users.

Search table...

Topic	Owner	Description	Count
alerce_lc	Admin Admin	The ALeRCE light cu ... more	393,989
alerce_stamp	Admin Admin	The Alerce Stamp CI ... more	19,339
BBBobjects	Admin Admin	Interesting fast risers found by the BazinBlackBody (BBB) me ... more	758
fastfinder	Michael Fulton	Fastfinder is an early-time, fast transient alerting system ... more	20,990
Fink	Admin Admin	Fink is a LSST Community ... more	40,581
NEEDLE	 NEEDLE	NEEDLE is a novel hybrid classifier to select for two rare c ... more	8,984
slowSN	Philip Wiseman	Mining Lasair for other examples of AT2021lwx also known as ... more	7
test	Roy Williams	Testing	11

100 rows per page Showing 1 to 8 of 8 rows

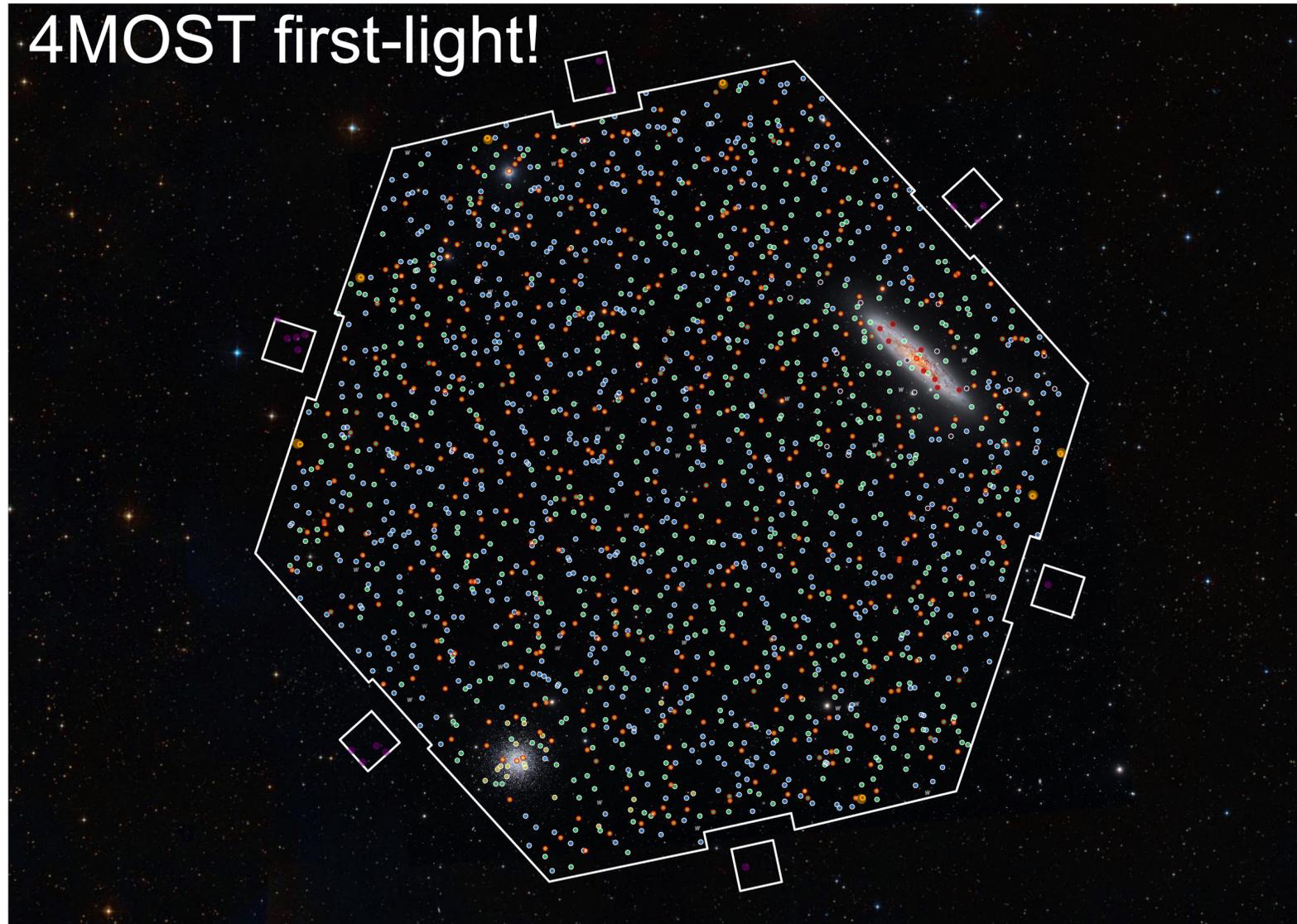
Correctly predicted classification for 10 TDEs from Aug '24 to July '25

Almost half of the total discovered!

Future targets from LSST and LS4

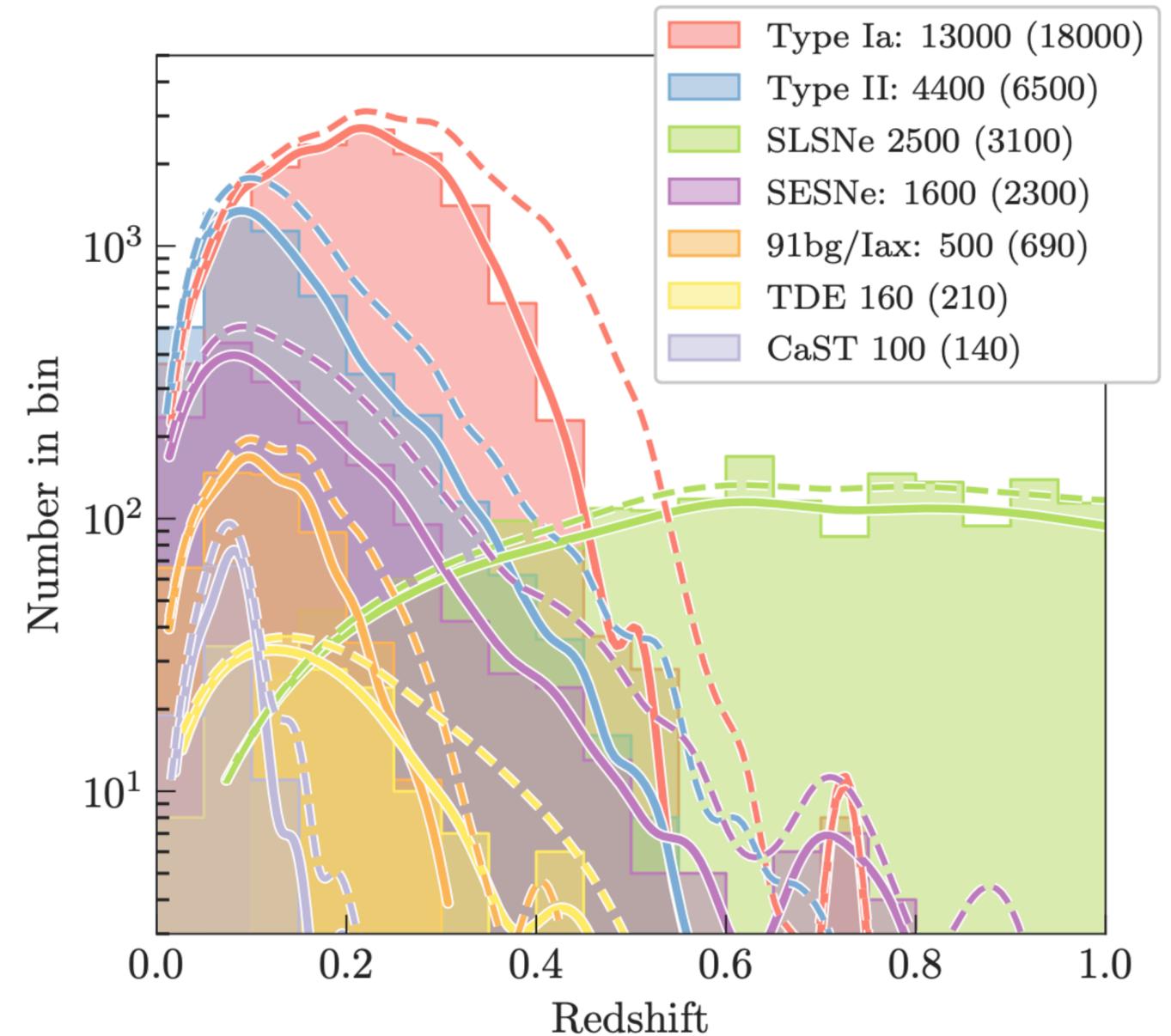
See also **FLEET** and **tdescore**

The future (ii): LSST + 4MOST / TiDES



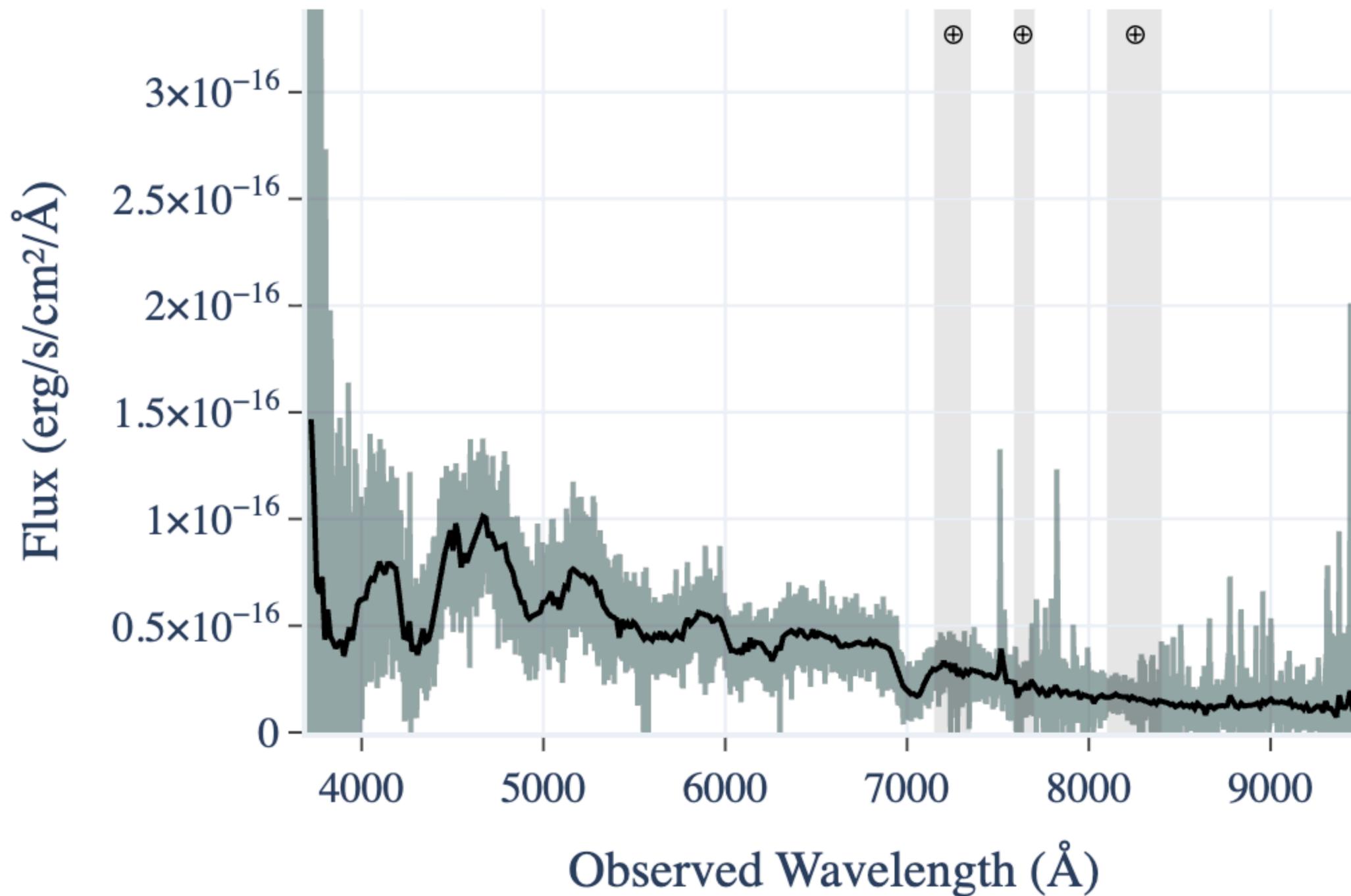
Credit: AIP/Background: Harshwardhan Pathak/Telescope Live

Unbiased sample of ~200 TDEs!



Frohmaier+ 2025

The future (ii): LSST + 4MOST / TiDES



Last week:
The first SN spectrum
from 4MOST!

The future (iii): Photometric classification



Dylan Magill

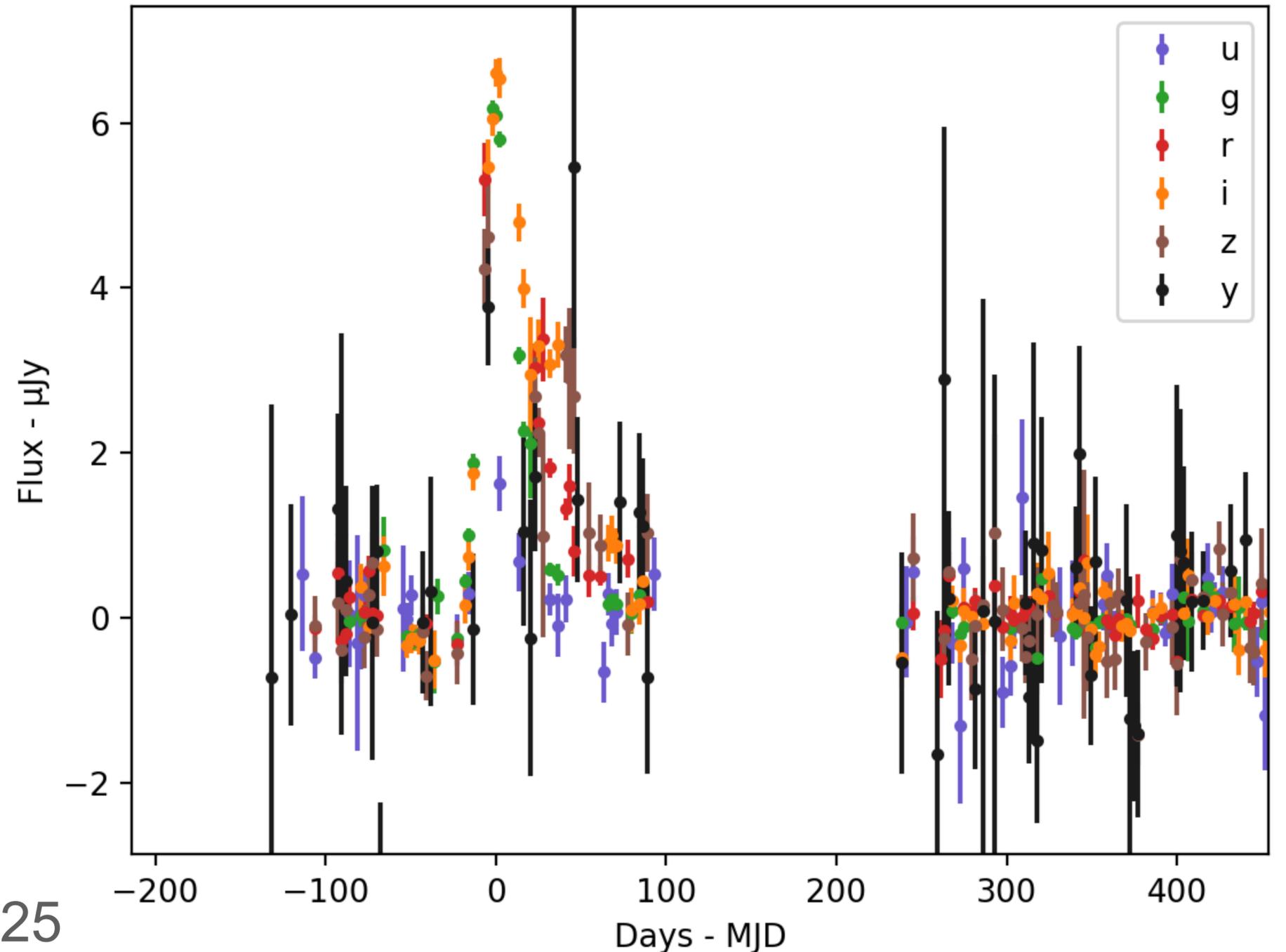
LSST expected to detect ~few thousand TDEs!

Most will never get a spectrum

Need to classify these with photometry only

Need a training set for ML models and to evaluate biases

Use ZTF data to simulate 10,000 TDEs+AGN+SNe *as they would appear in LSST*



Magill, MN+ 2025

Data challenge hosted on Kaggle



Participation

2,389 Entrants
989 Participants
893 Teams
13,064 Submissions



#	△	Team	Members	Score
1	▲ 3	John Titor		0.6824
2	▼ 1	Suxing's Astronomer		0.6762
3	▼ 1	Sigrid Nissen		0.6758

Analysis of results and lessons coming soon!

with Vysakh Anilkumar and Sjoert van Velzen

Summary: TDEs from Rubin 🙌

NEEDLE + SoXS	Early triggering, high quality spectral time-series, physics of the optical peak	~few 10
TIDES	Unbiased spectroscopic sample, BH demographics	~200
Photometric	Large samples, rates and energetics	~10 ³

Conclusions

TDEs and QPEs are excellent probes of galaxy dynamics, accretion physics, SMBH growth

Direct connection between the two classes, with $\sim 10\%$ of TDEs followed by QPEs

Many open questions in physical mechanisms behind these events!

Unusual host galaxies suggest these sources may trace recent mergers

Rubin will be revolutionary in this field, if we can combine large spectroscopic and photometric samples with targeted follow-up of nearby events

Bonus: stellar-mass TDEs?

AT2022aedm

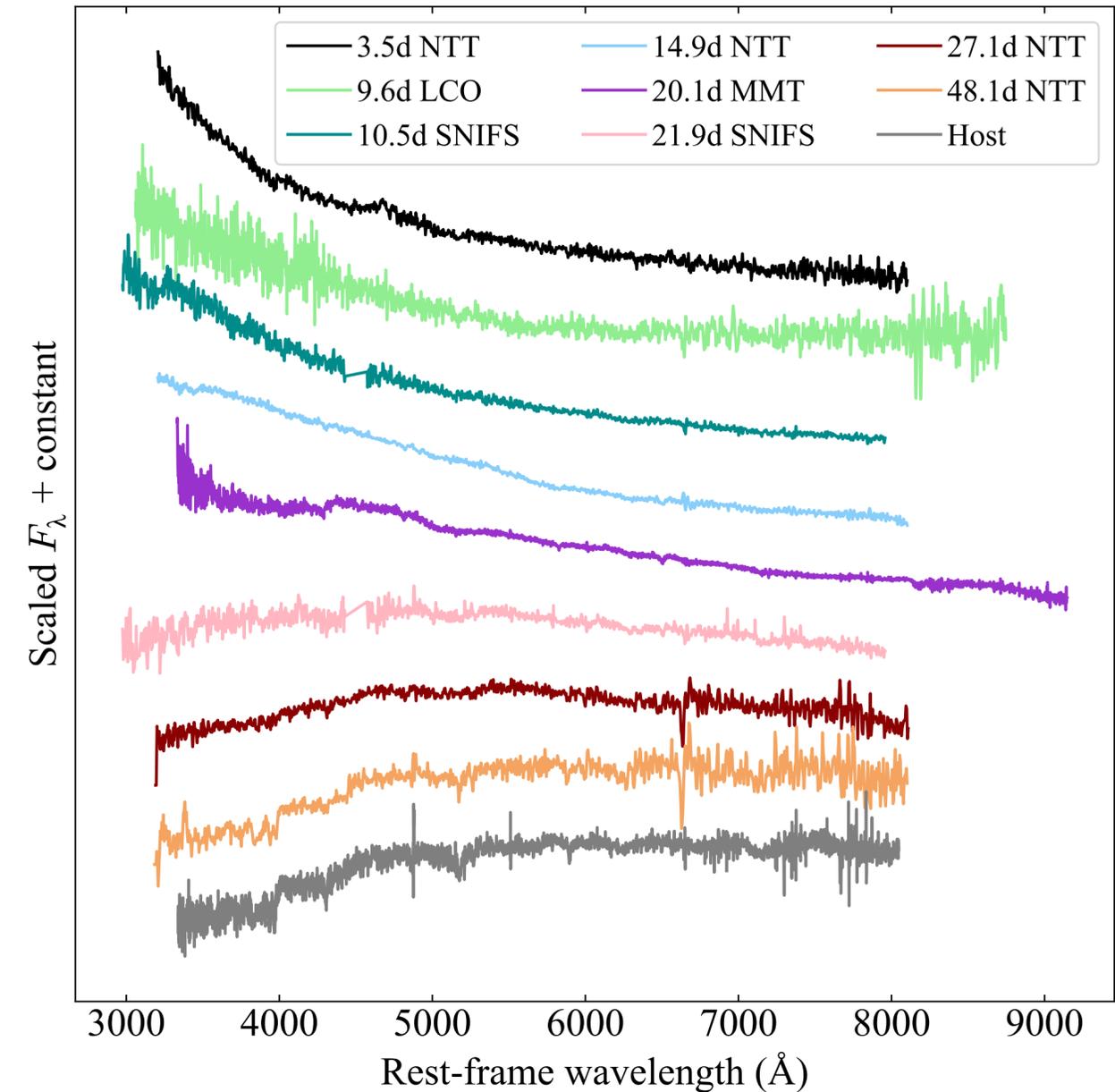
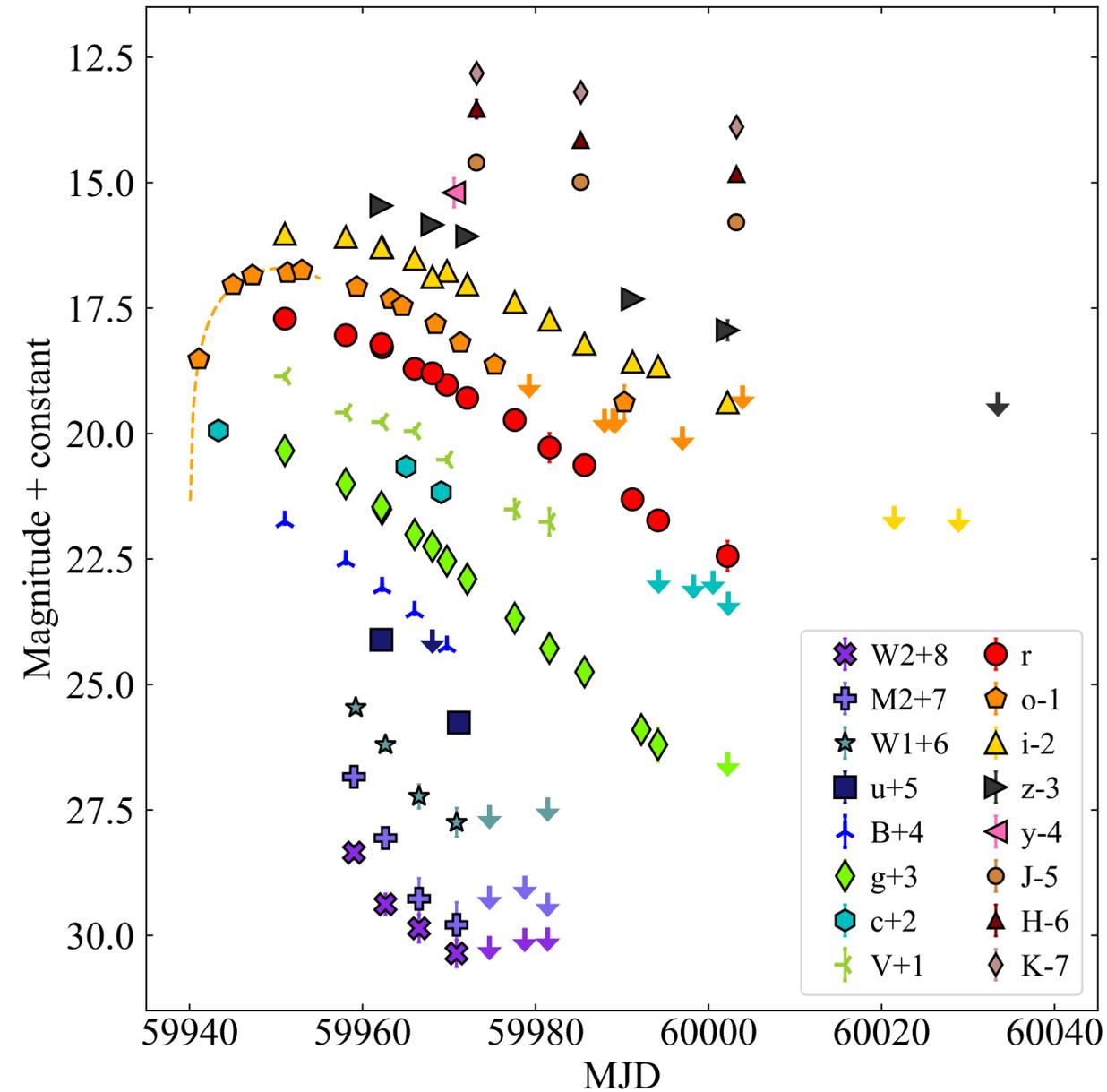
Discovered by
ATLAS

Rises in ~1 week

Peak at -22 mag

Fades *and cools*
rapidly

Early spectrum
shows broad
He II



MN+ 2023

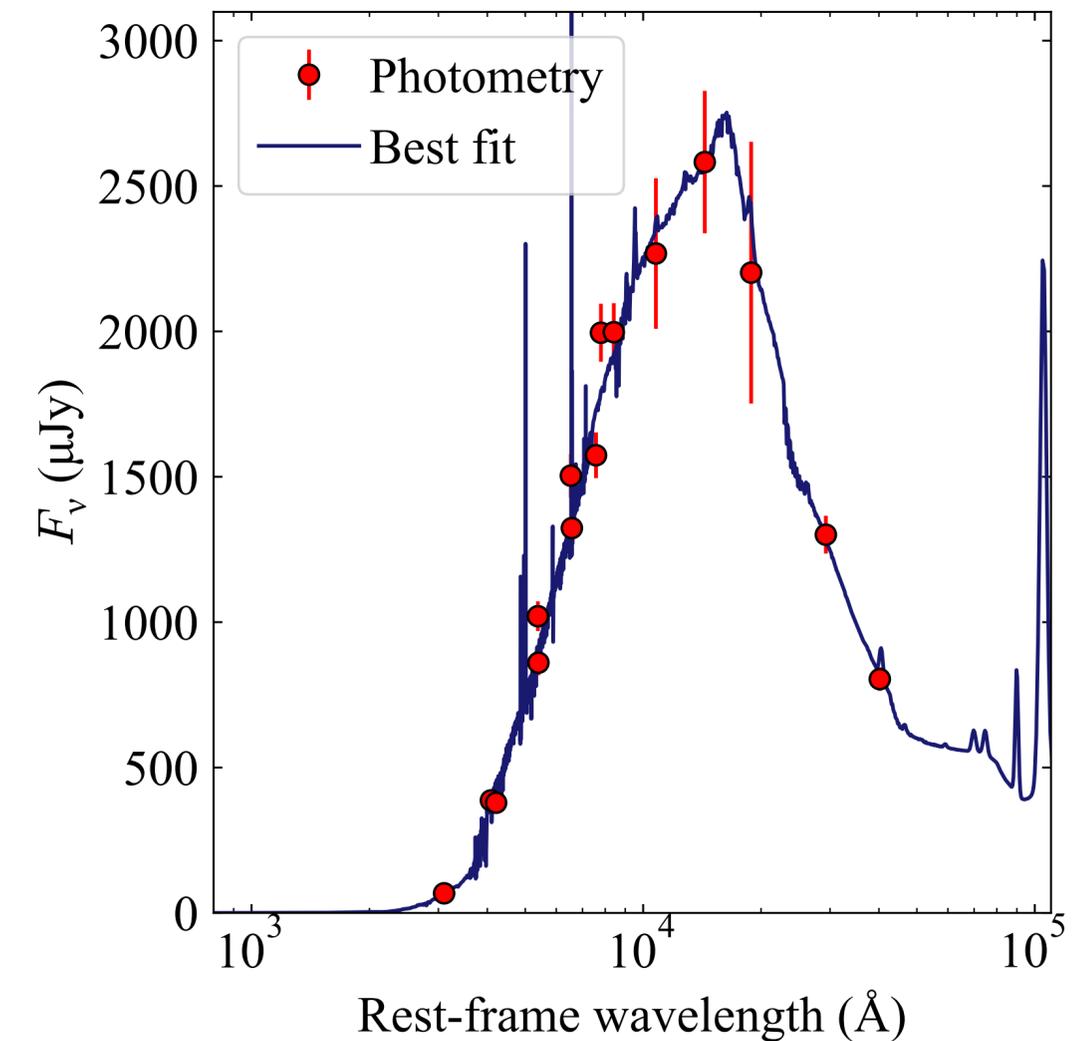
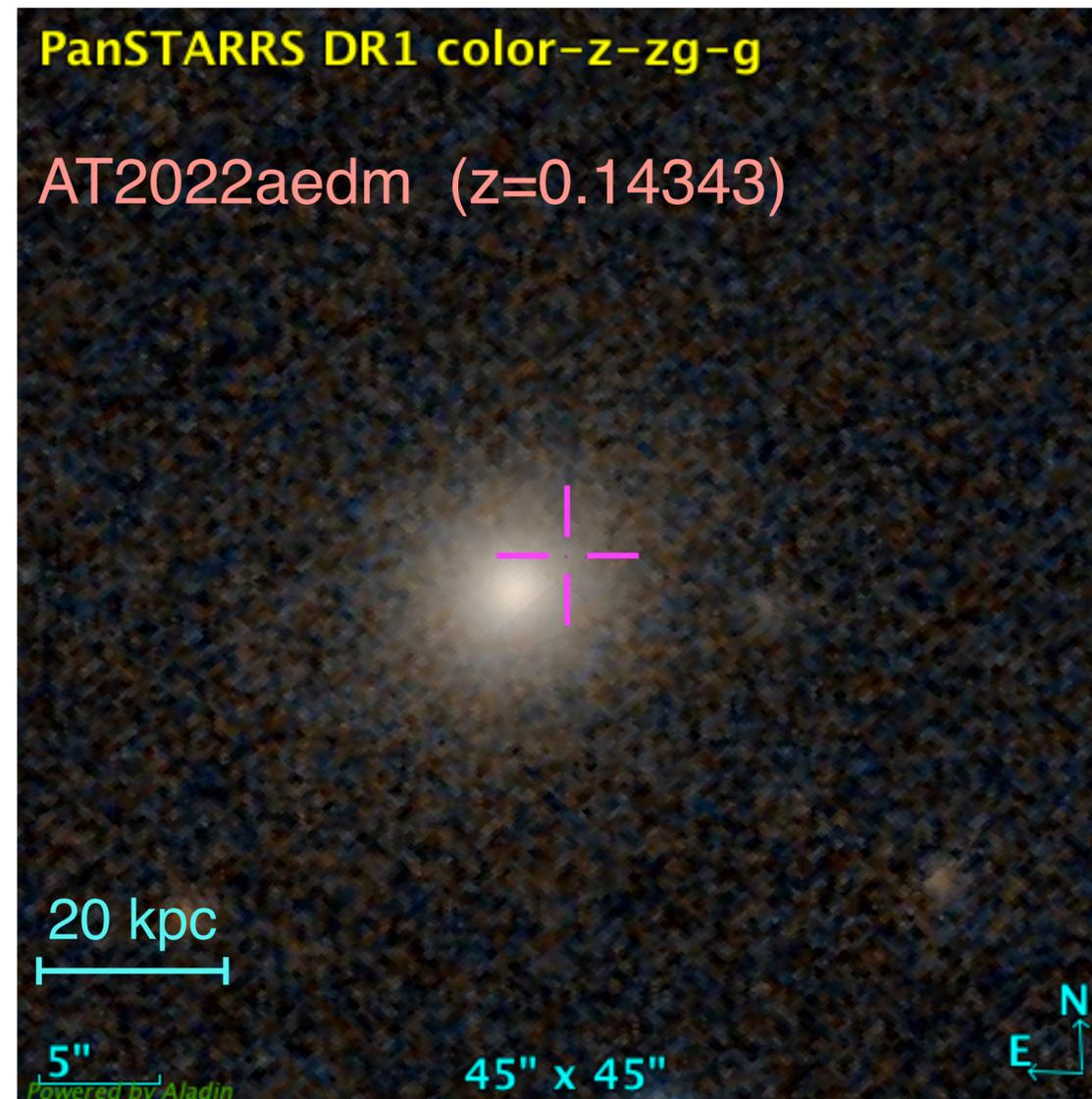
What is the origin?

Galaxy completely red and dead

- Challenging for any massive star progenitor

Transient NOT in the nucleus

- Not a conventional TDE

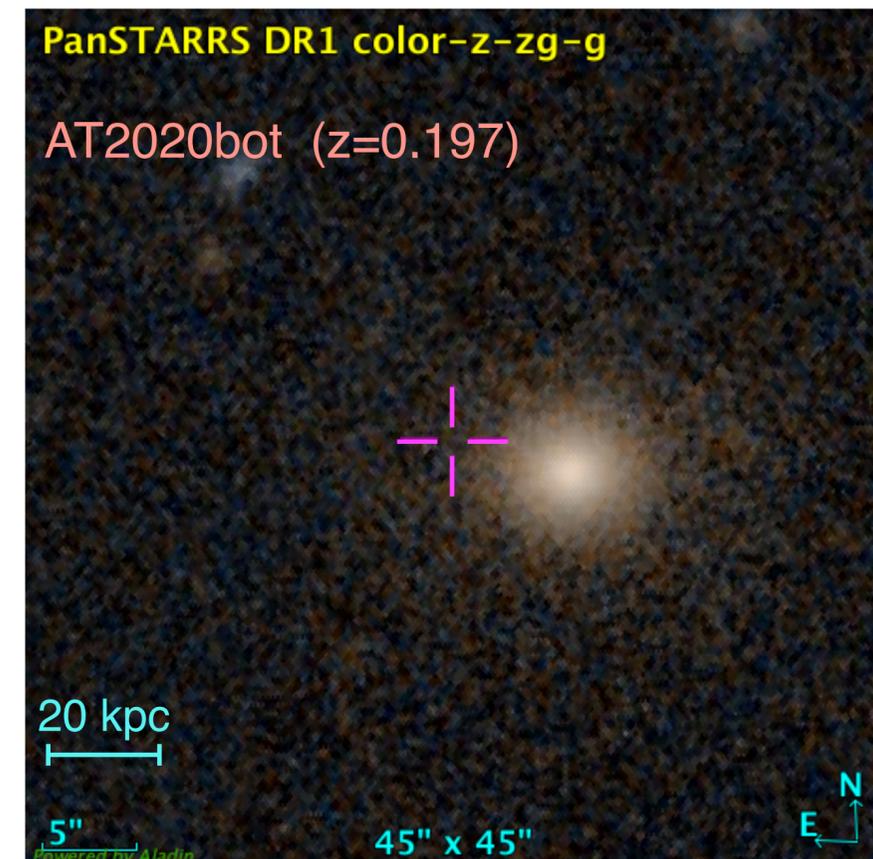
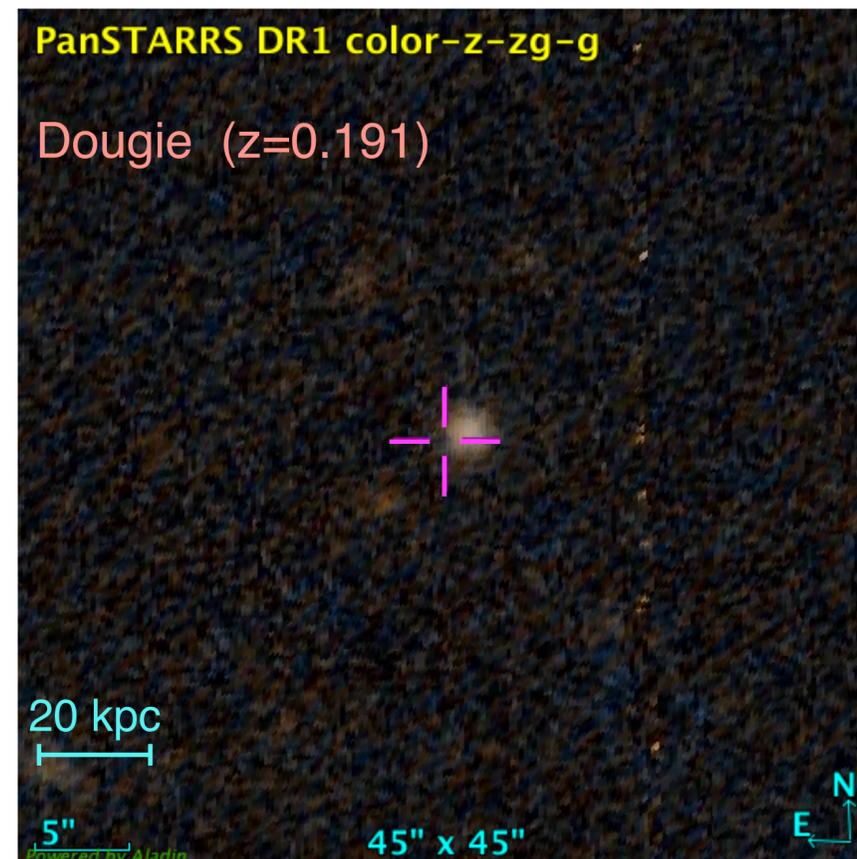
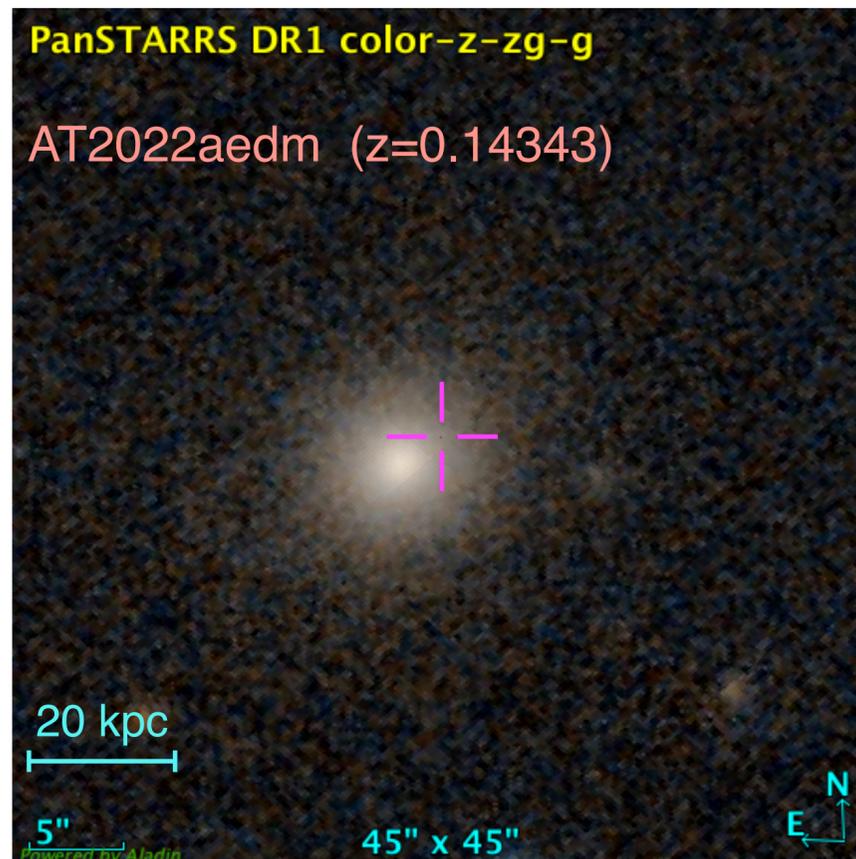


Two other sources with similar properties

New class of “luminous fast cooling” (LFC) transients

All in outskirts of elliptical galaxies!

Rate ~ 1 per Gpc^3 per yr, consistent with stellar-mass BH TDEs in globular clusters

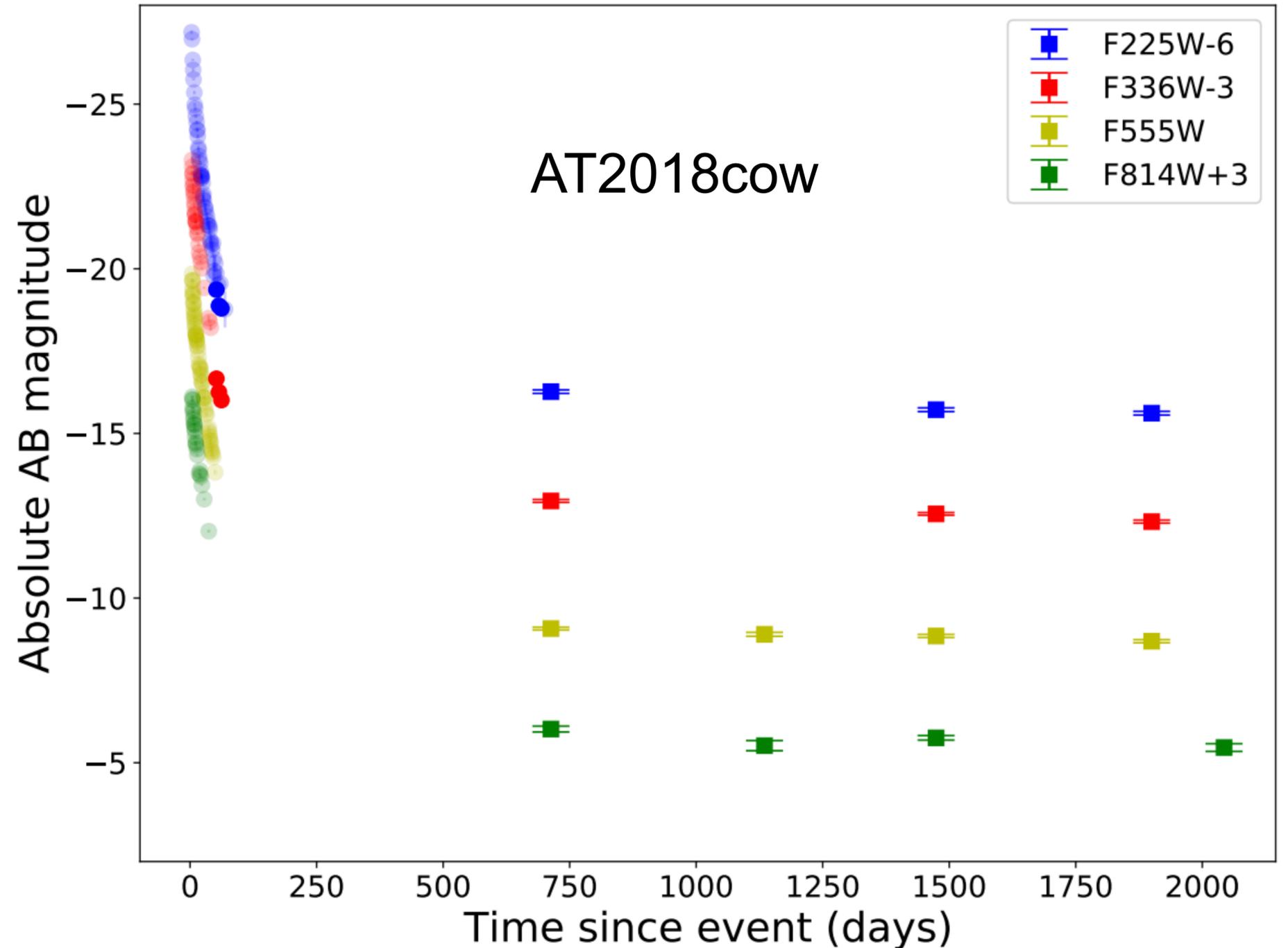


Hypothesis?

“Classical” TDES
→ SMBHs

LFBOTs (eg AT2018cow)
→ IMBHs

LFCs (eg AT2022aedm)
→ stellar BHs



Inkenhaag+ 2025