Image credit: DESY

Progress in understanding tidal disruption events …

… using observations

Gravi-Gamma-Nu - Oct 4, 2023

Sjoert van Velzen, Leiden Observatory

Key collaborators: Suvi Gezari, James Miller-Jones, Kate Alexander, Nicholas Stone, Robert Stein, Marek Kowalski, DJ Pasham, Andrew Mummery

Some (fundamental) questions

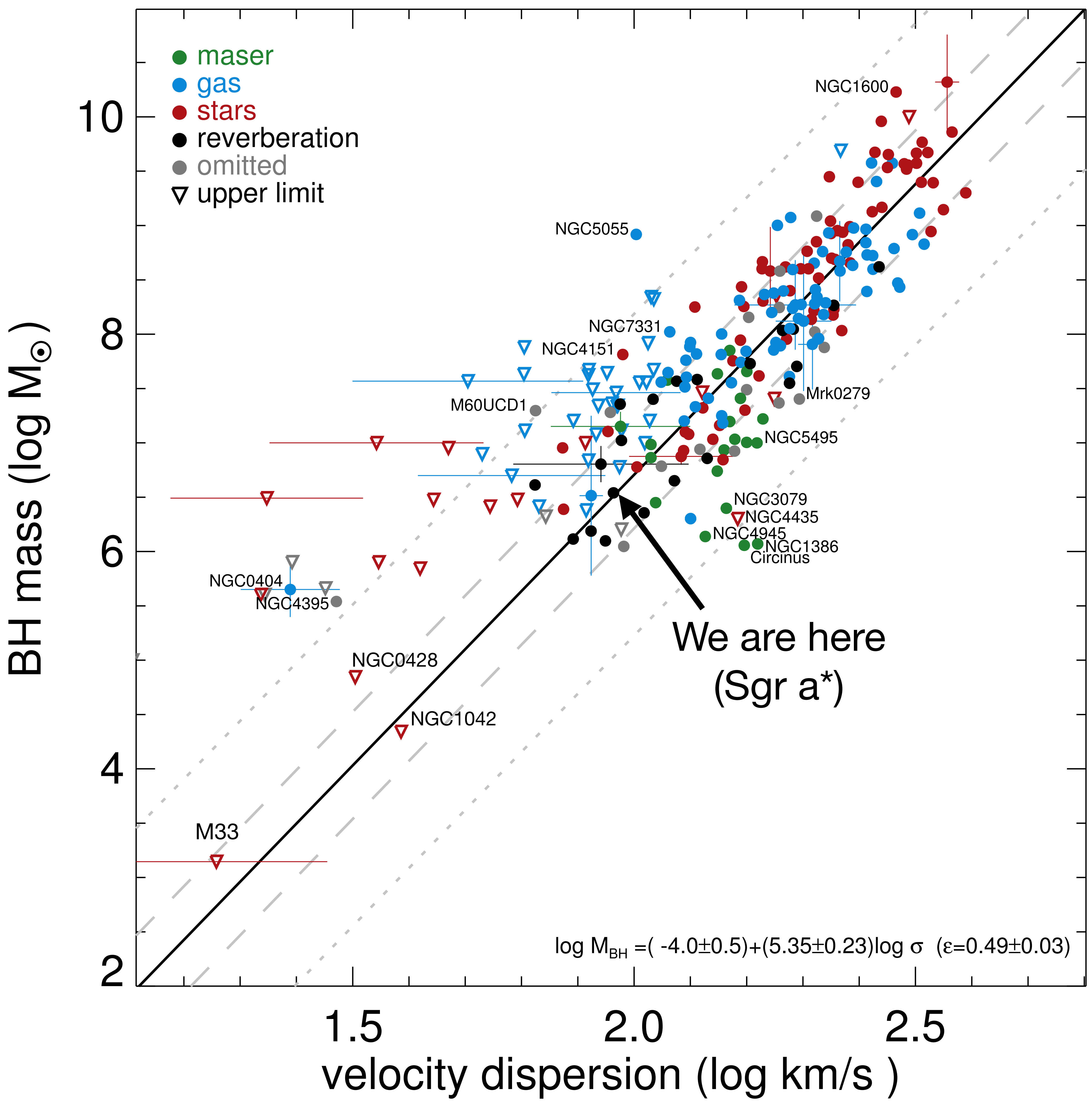
Are (most) black holes spinning?

Is accretion physics scale invariant?

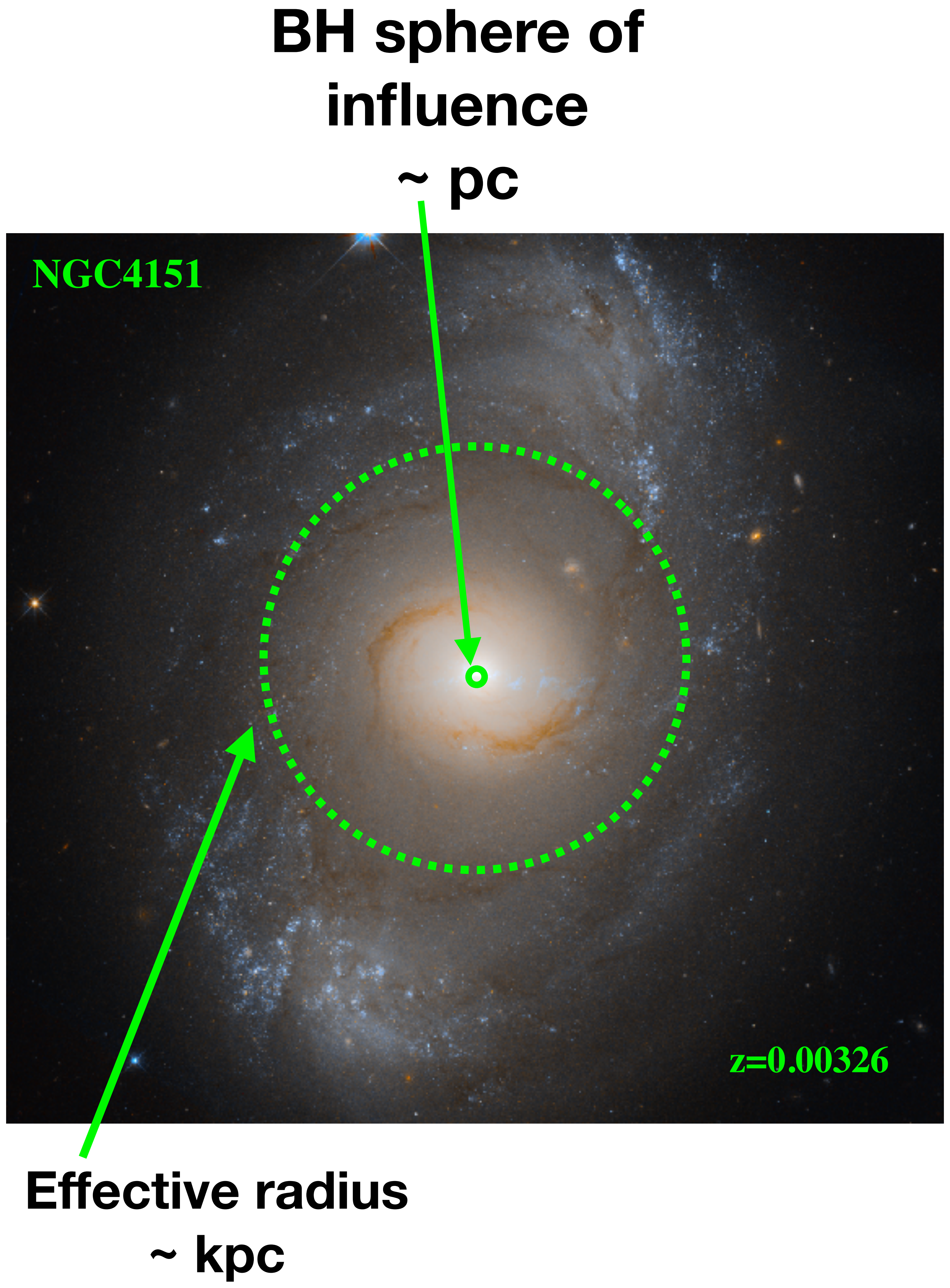
Black hole genesis in the early universe

Image credit: Wikimedia

Black hole mass measurements are challenging



van den Bosch (2016)



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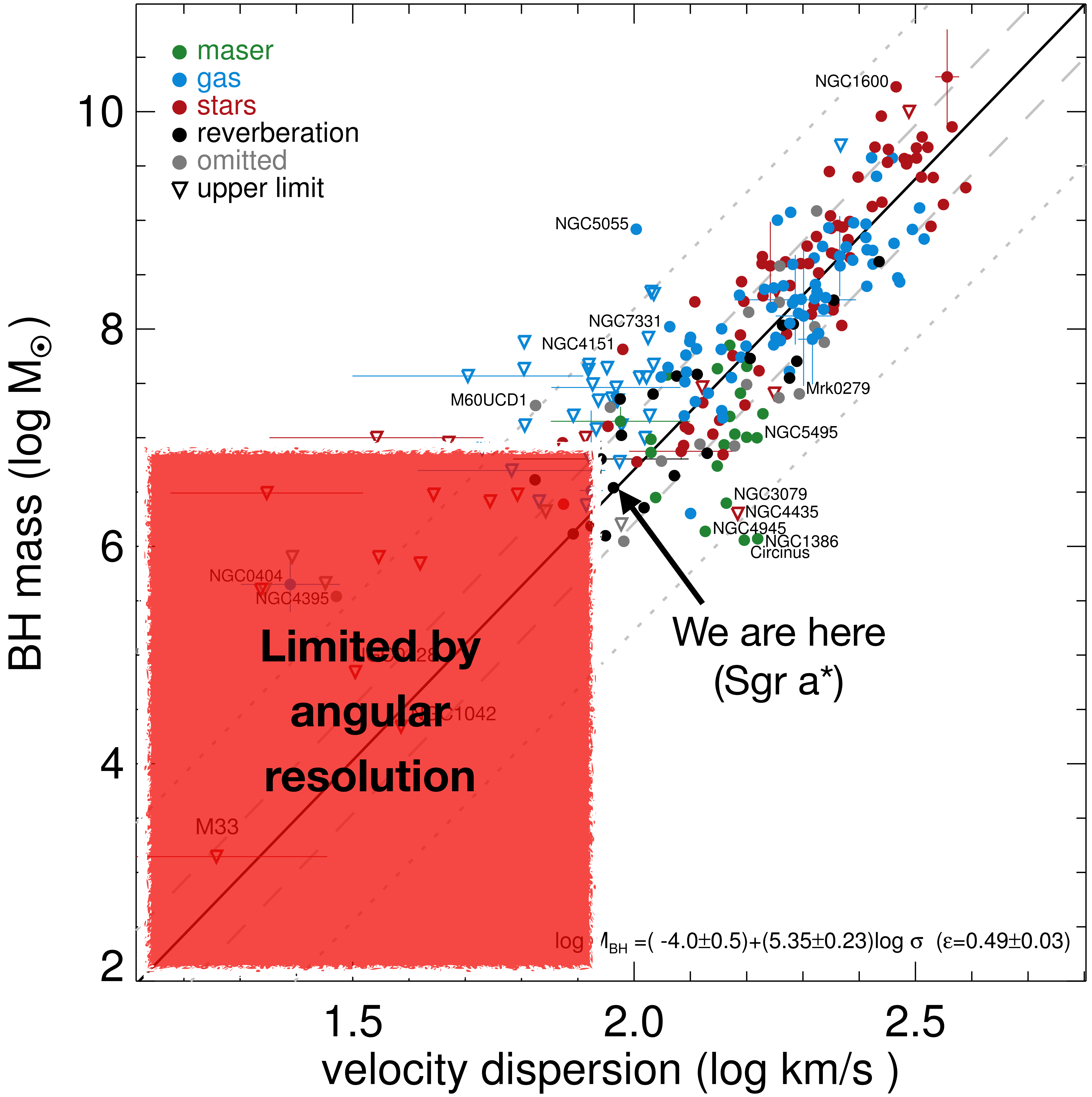
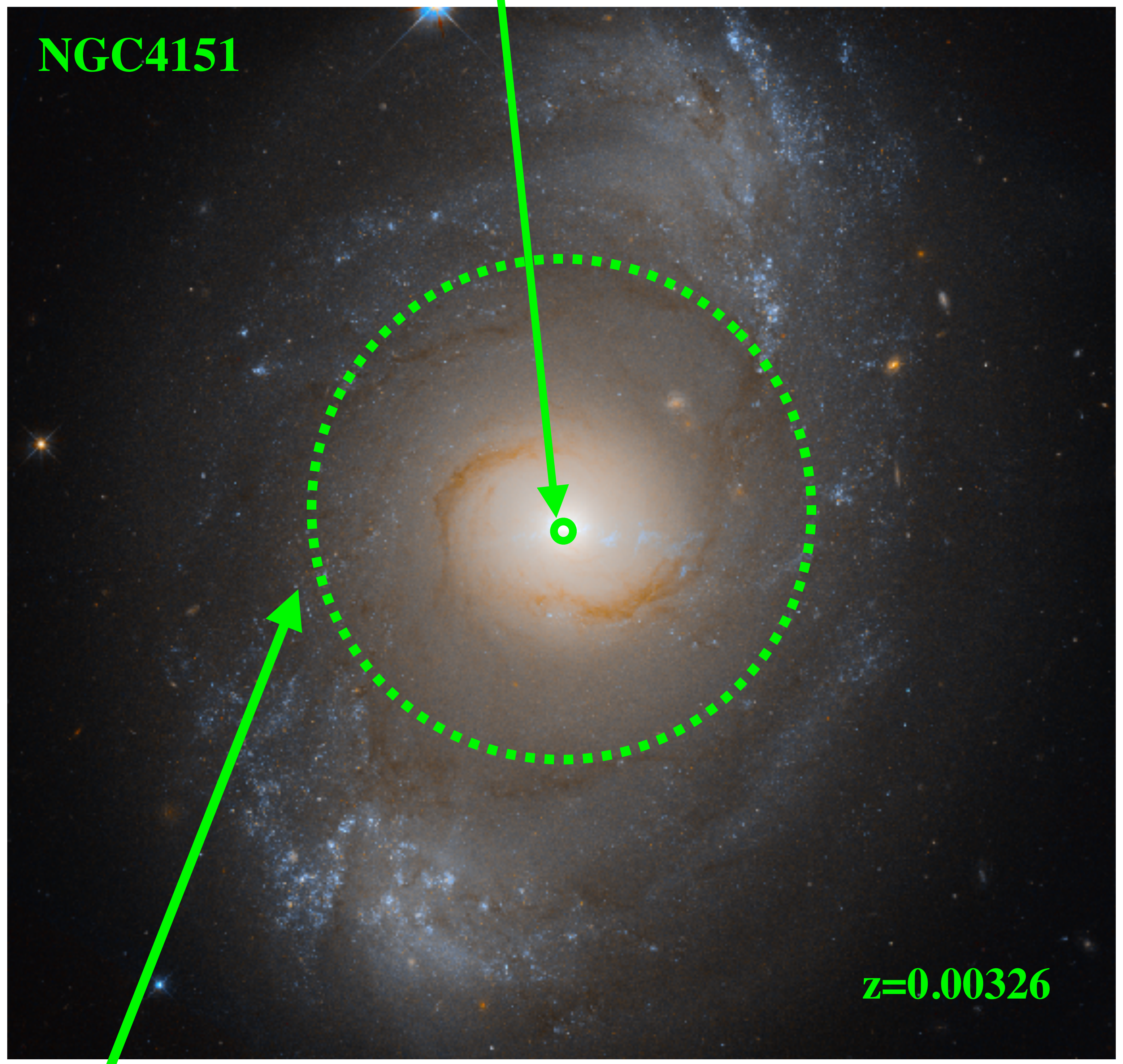


van den Bosch (2016)

BH sphere of influence ~ pc



Effective radius ~ kpc

Tidal disruption events (TDEs):
A new tool to study black holes in *quiescent* galaxies

Artis impression Image credit: NASA, van Velzen et al.
Simulation image: Guillochon et al.

Fundamental Questions

Are black holes spinning?

Is accretion physics scale invariant?

Black hole genesis in the early universe

TDE rate at high black hole mass

Radio + X-ray monitoring of TDEs

TDE rate in low-mass galaxies

Image credit: Wikimedia

Challenges

Are black holes spinning?

Large TDE samples

Is accretion physics scale invariant?

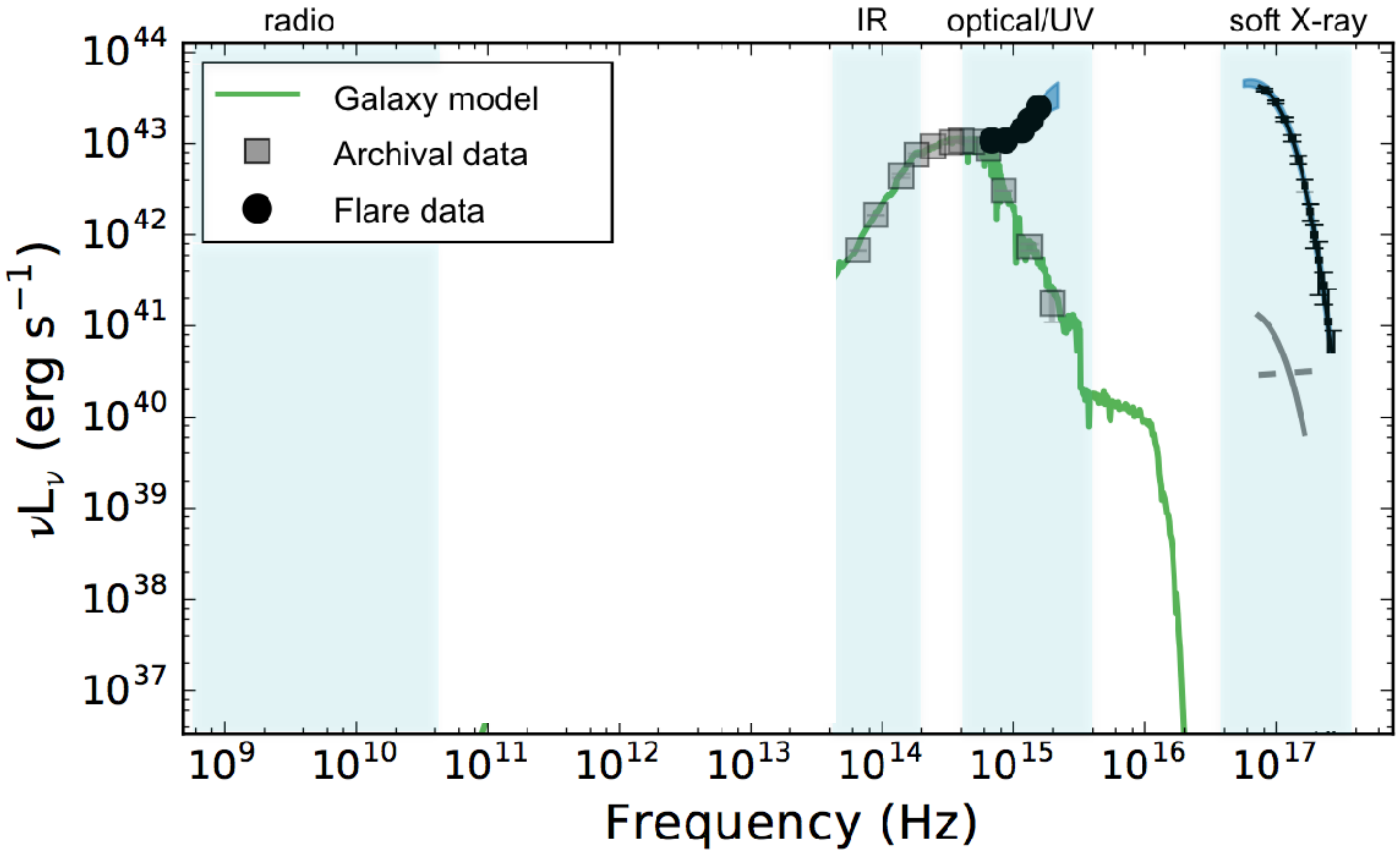
TDE Emission mechanism

Black hole genesis in the early universe

Emission mechanism + large samples

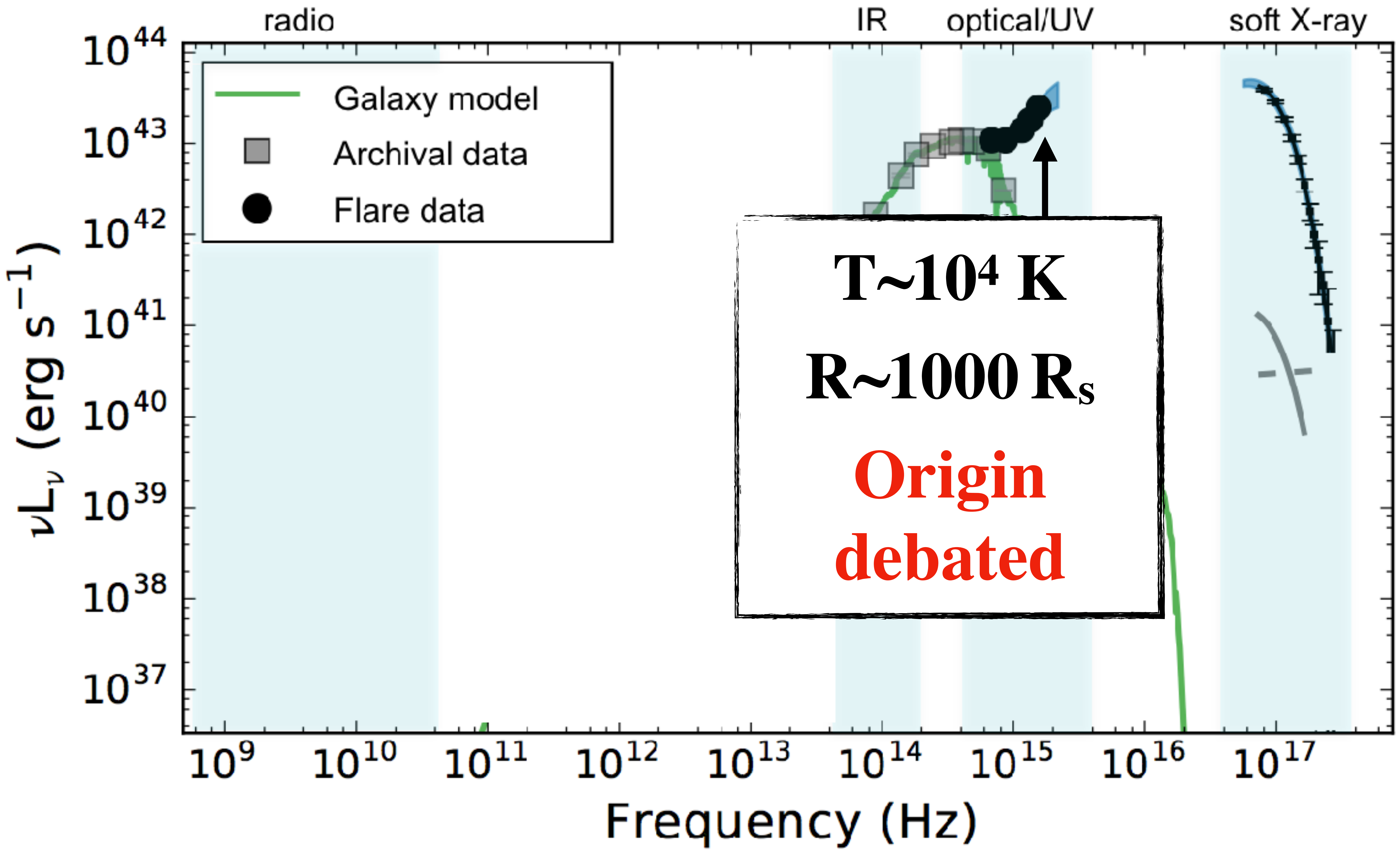
Image credit: Wikimedia

This talk: focus on thermal TDEs



van Velzen et al. (2016);
ASASSN-14li (Holoien et al. 2016)

Part 1: Optical emission



van Velzen et al. (2016);
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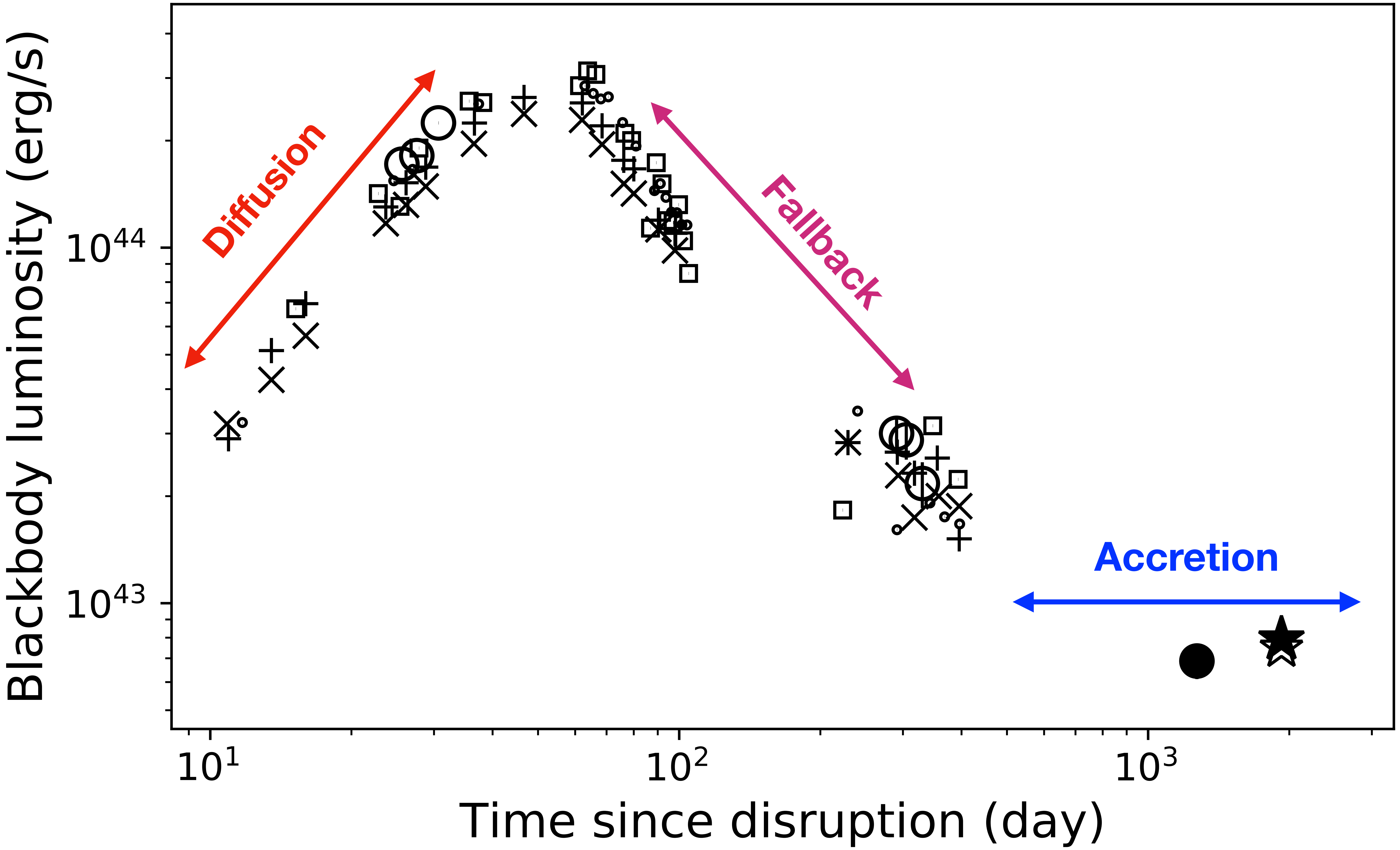
Summary of optical/UV emission

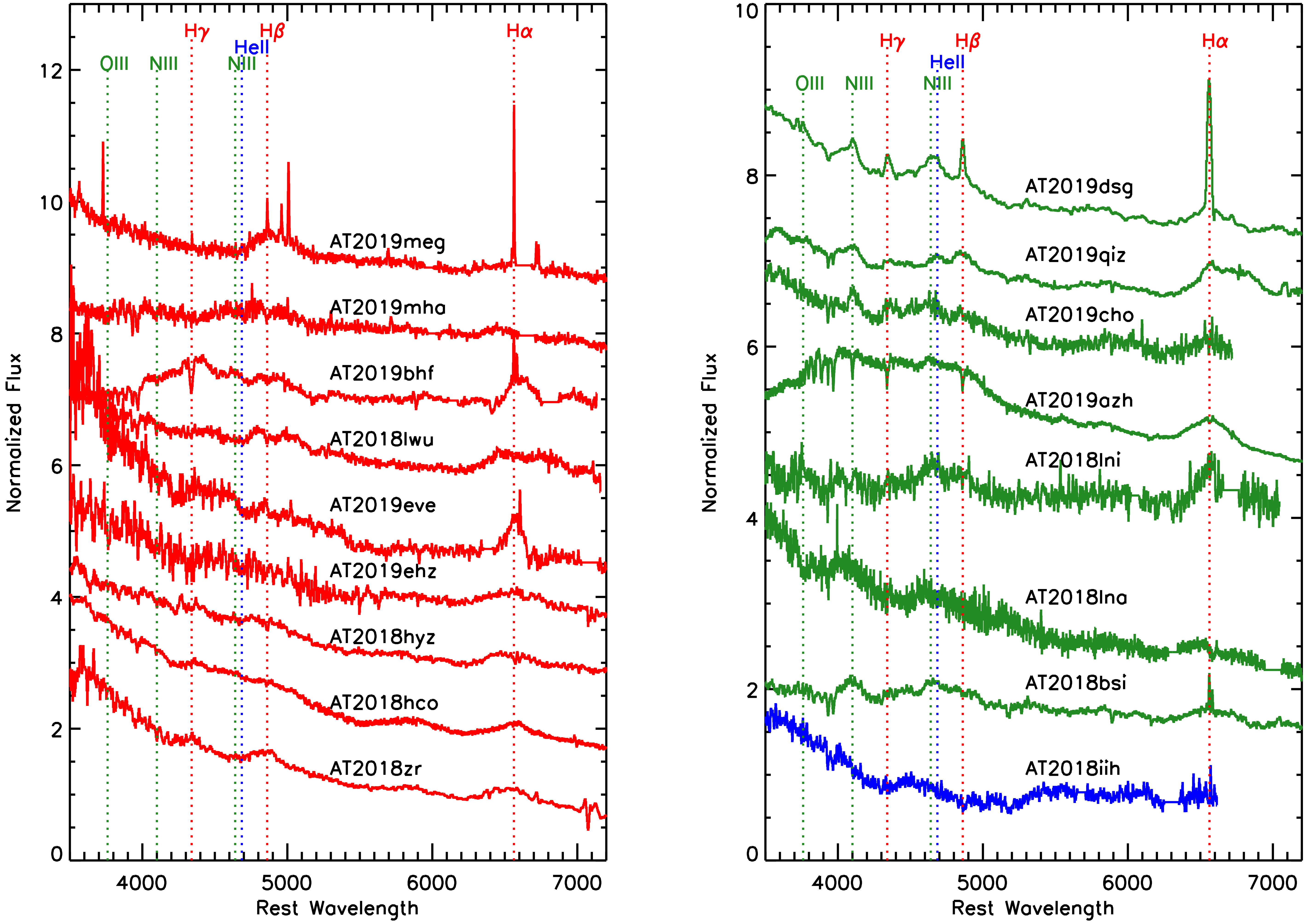


Information about:

- Density in photosphere
- BH mass
- BH mass, stellar mass

Data of PS-10jh Gezari et al. (2012, 2015); van Velzen et al. (2019)

Spectroscopic classification scheme established

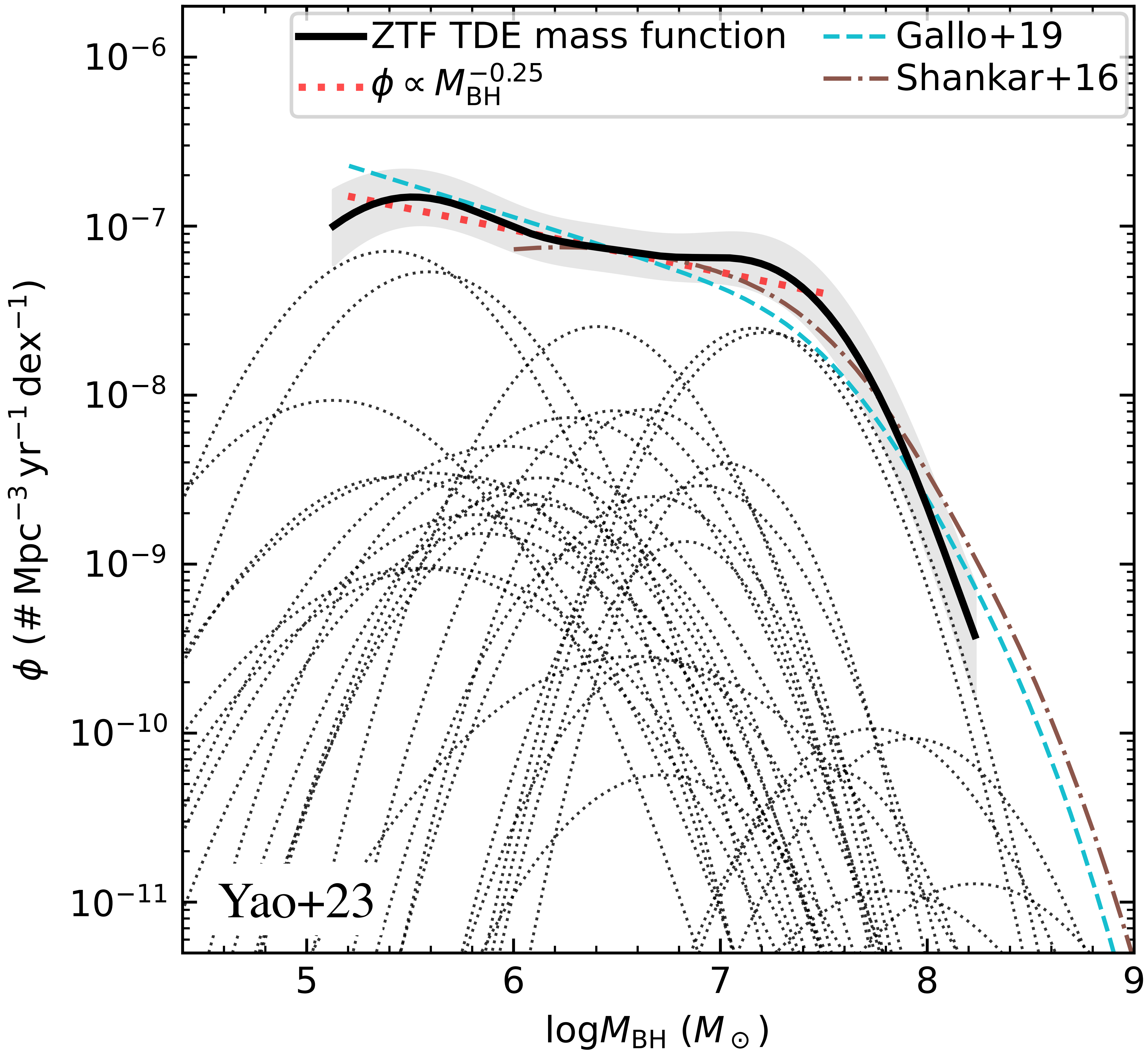


van Velzen et al. (2021)

- TDE-H
- TDE-H+He
  (often incl. Bowen lines)
- TDE-He
- Building on earlier work:
  Arcavi et al. (2014);
  Blagorodnova et al. (2018);
  Leloudas et al. (2019)
- Origin of emission lines is debated, line width due to electron scattering

Black hole mass function

- 33 ZTF TDEs (uniform sample)
- Assumption: BH mass from velocity dispersion
- Single power-law down to: $M_{\rm BH} \approx 10^{5.5} M_\odot$
  - Not enough data to detect a low-mass turnover



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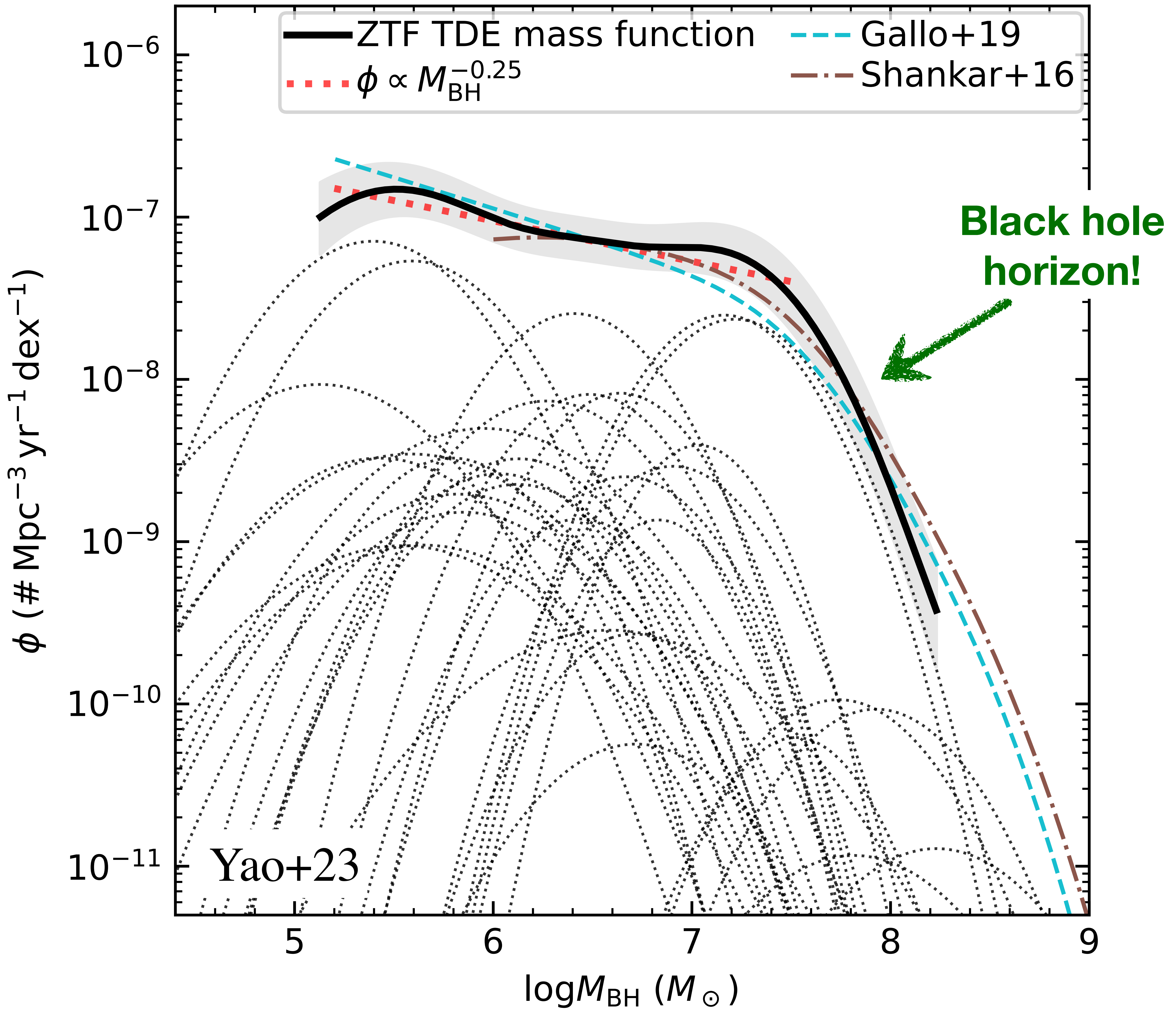


What’s new? Featureless spectra

- H+He class is most common
- **New class: featureless TDEs** (Hammerstein+22; Yao+23)
  - Very rare and high-mass host galaxies
- Helps to solve origin of emission lines?

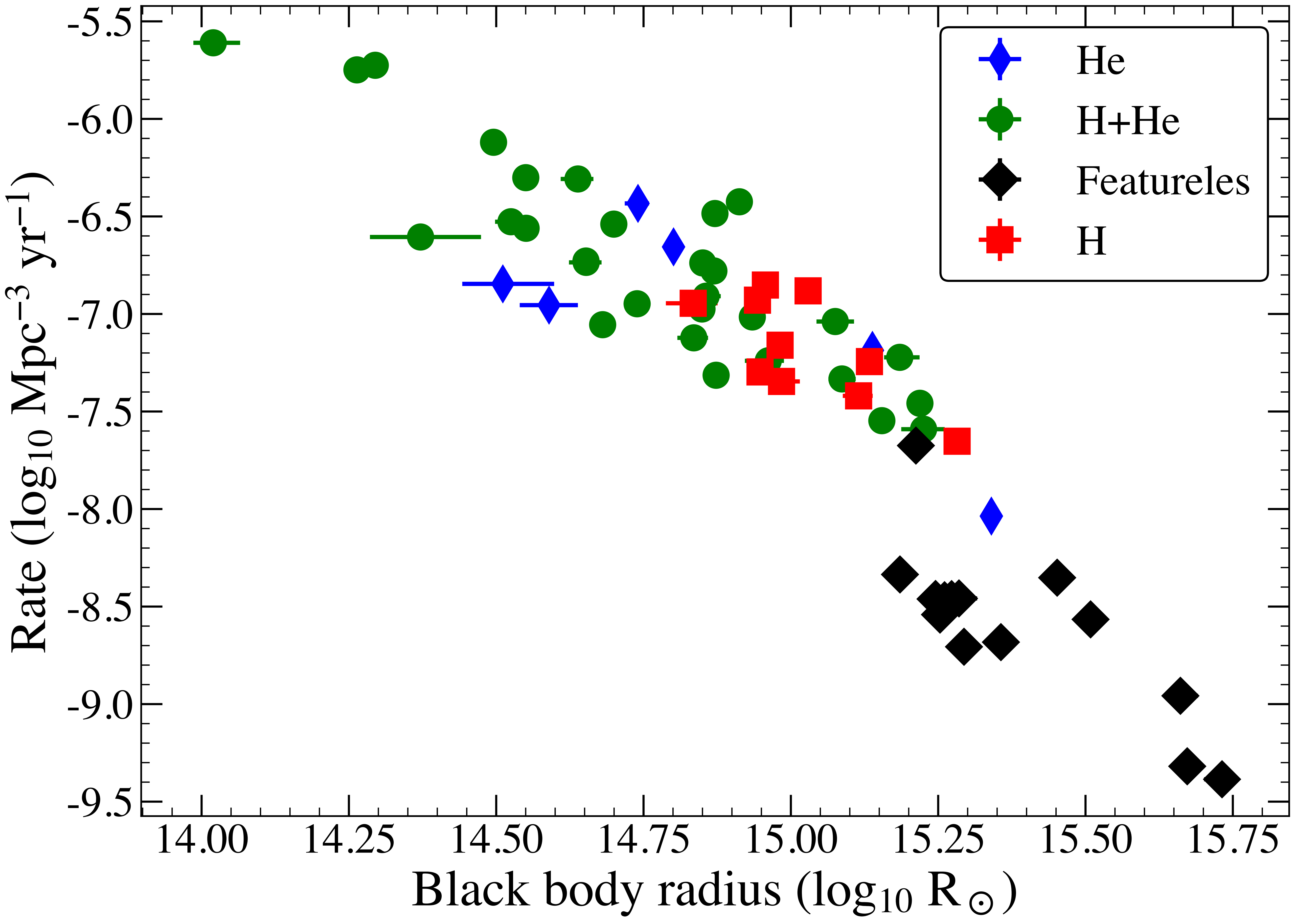
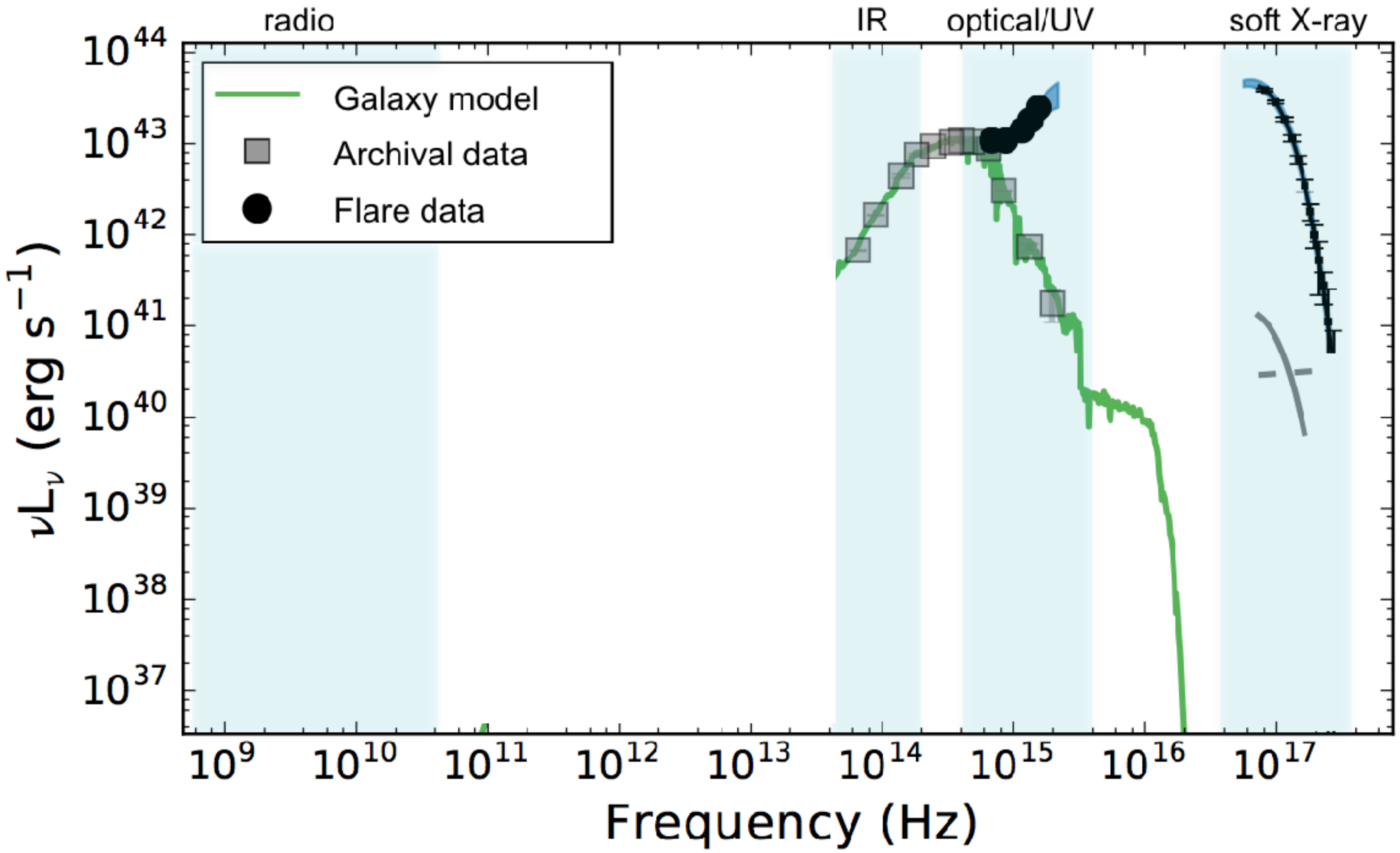


Figure based on van Velzen+21; updated with latest TDEs for this talk

Part 2: X-ray emission of thermal TDEs



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*however see: Steinberg & Stone (2022; arXiv:2206.10641)

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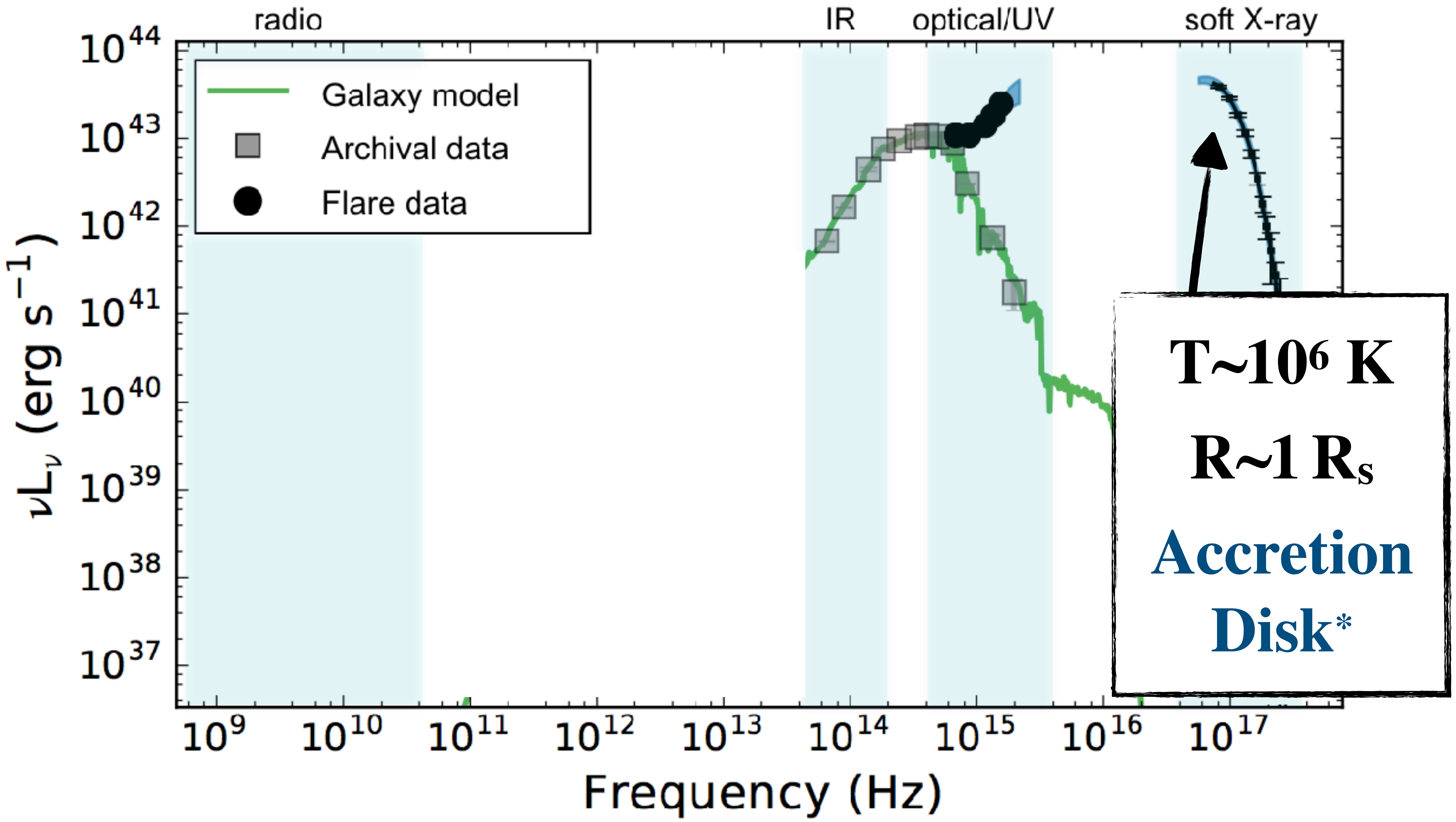

van Velzen et al. (Science, 2016);
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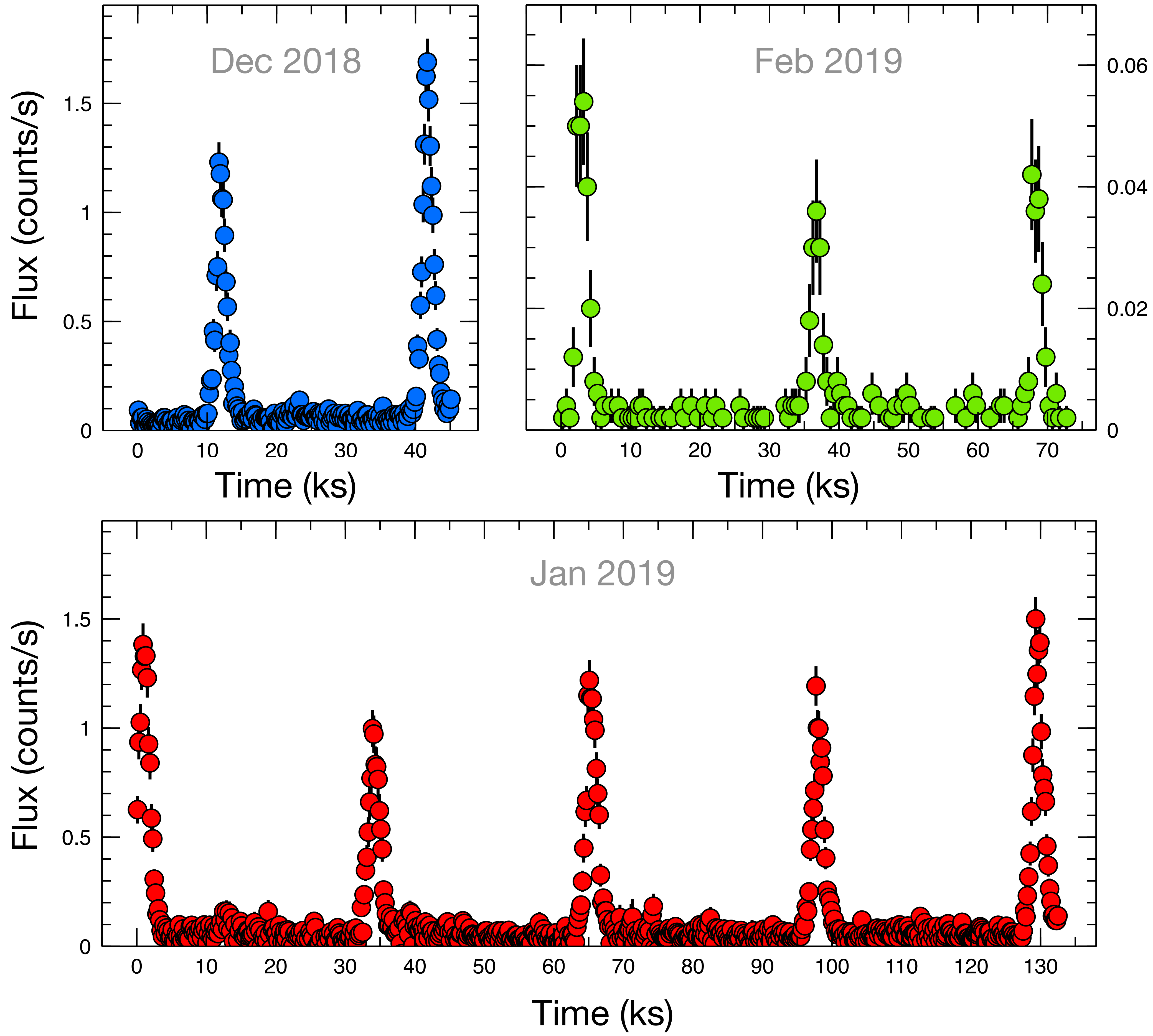
*however see: Steinberg & Stone (2022; arXiv:2206.10641)

What's new? X-ray QPEs!

Quasi Periodic Eruptions

- Serendipitously discovered in 2019 (Miniutti+19)
- Rapid X-ray flares, recurring on ~hours
- Similar host galaxies to TDEs (Wevers+21)
- To date, 6 published, 3 with a detected prior X-ray (candidate) TDE
  - Probability ~10^{-9} for chance association of TDEs and QPEs (Quintin+23)

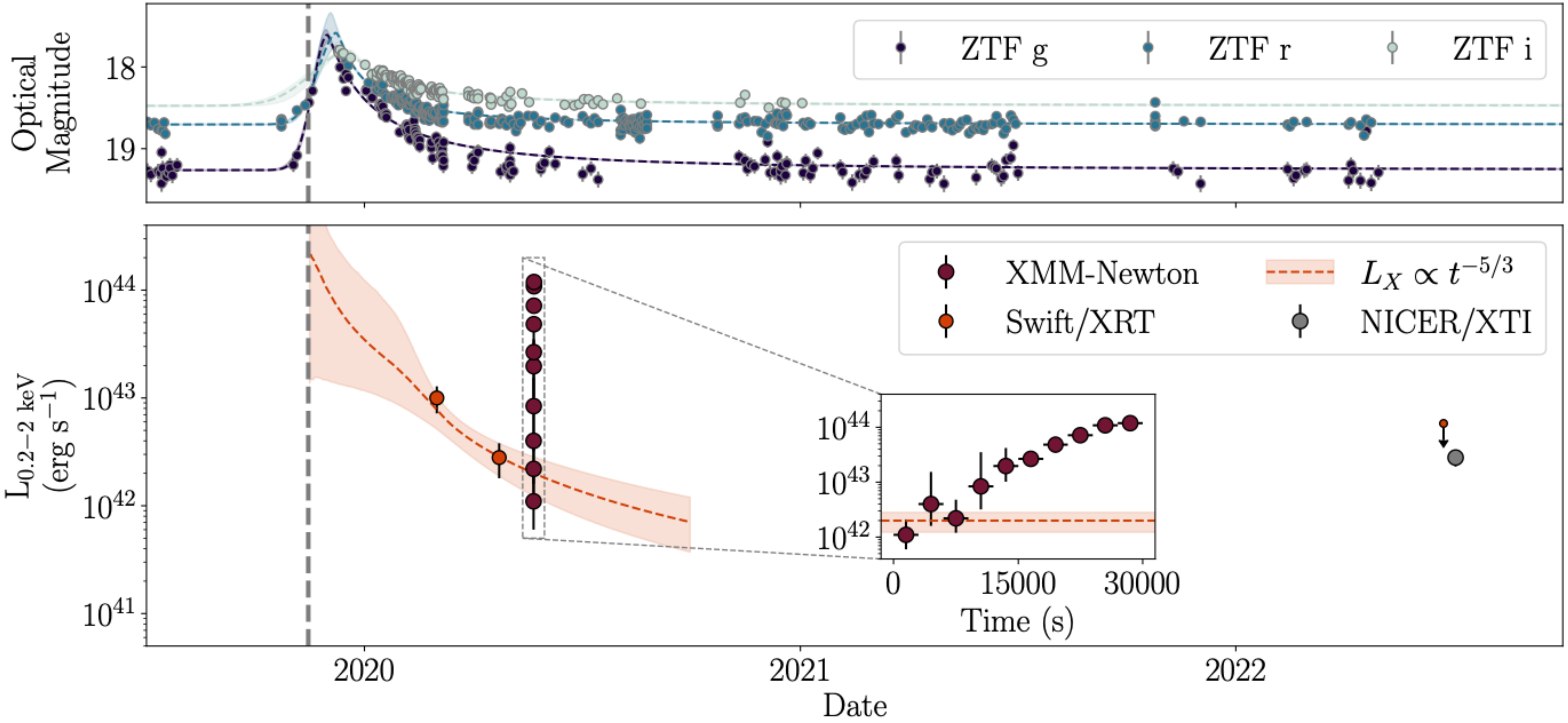


Miniutti+19

What's new? X-ray QPEs!

Quasi Periodic Eruptions

Quintin et al. "Tormund's return" (2023; arXiv:2306.00438)



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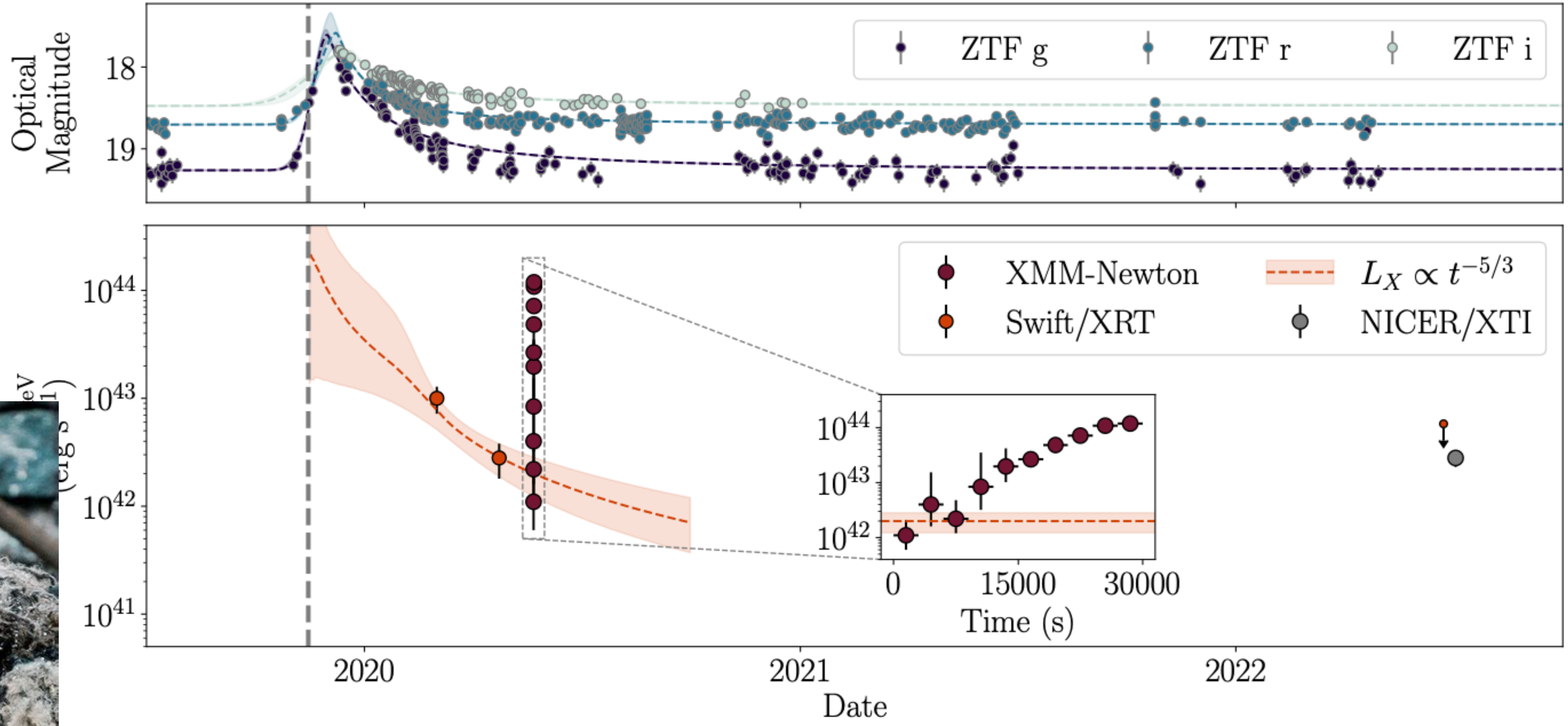
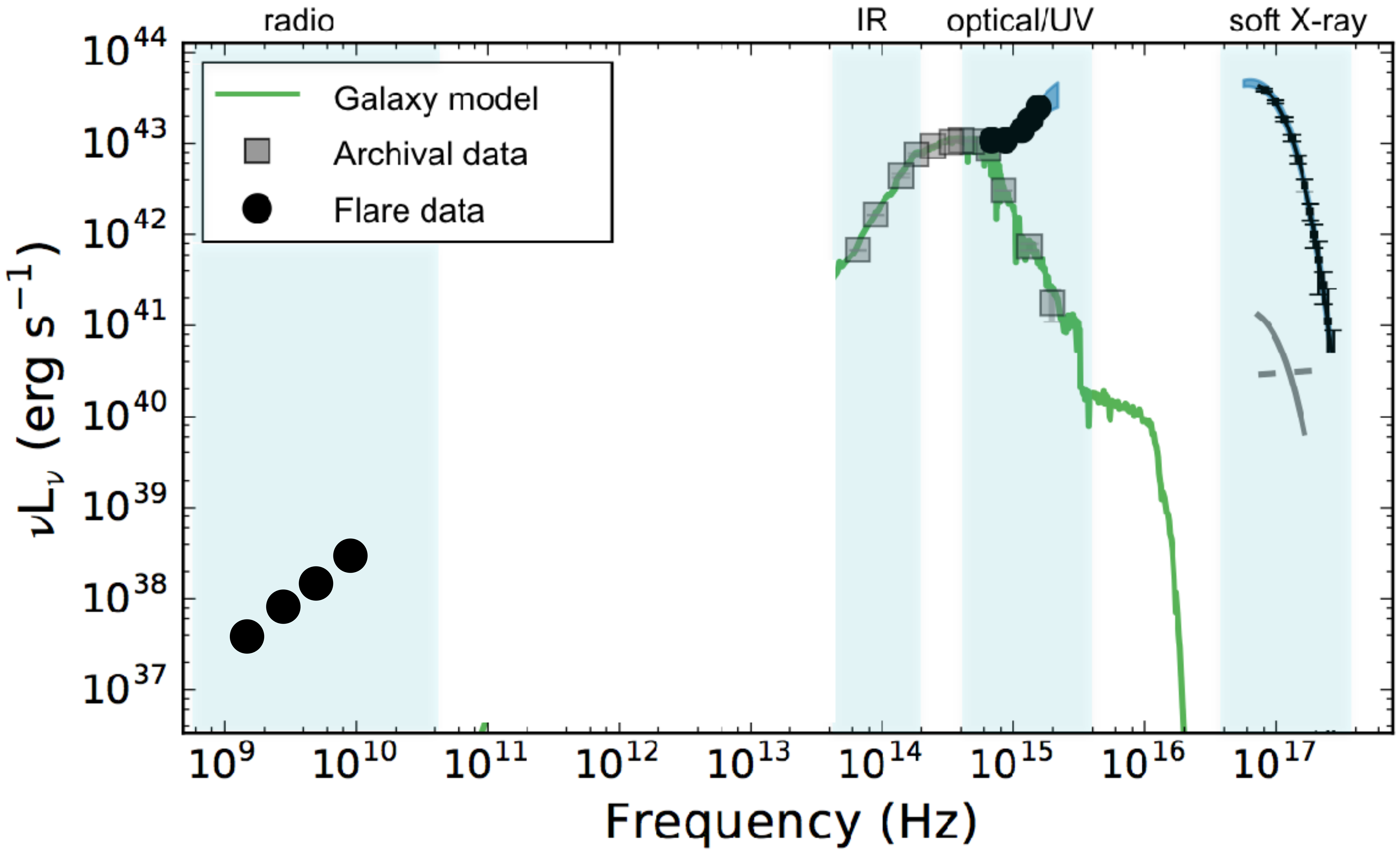


Part 3: radio emission of thermal TDEs



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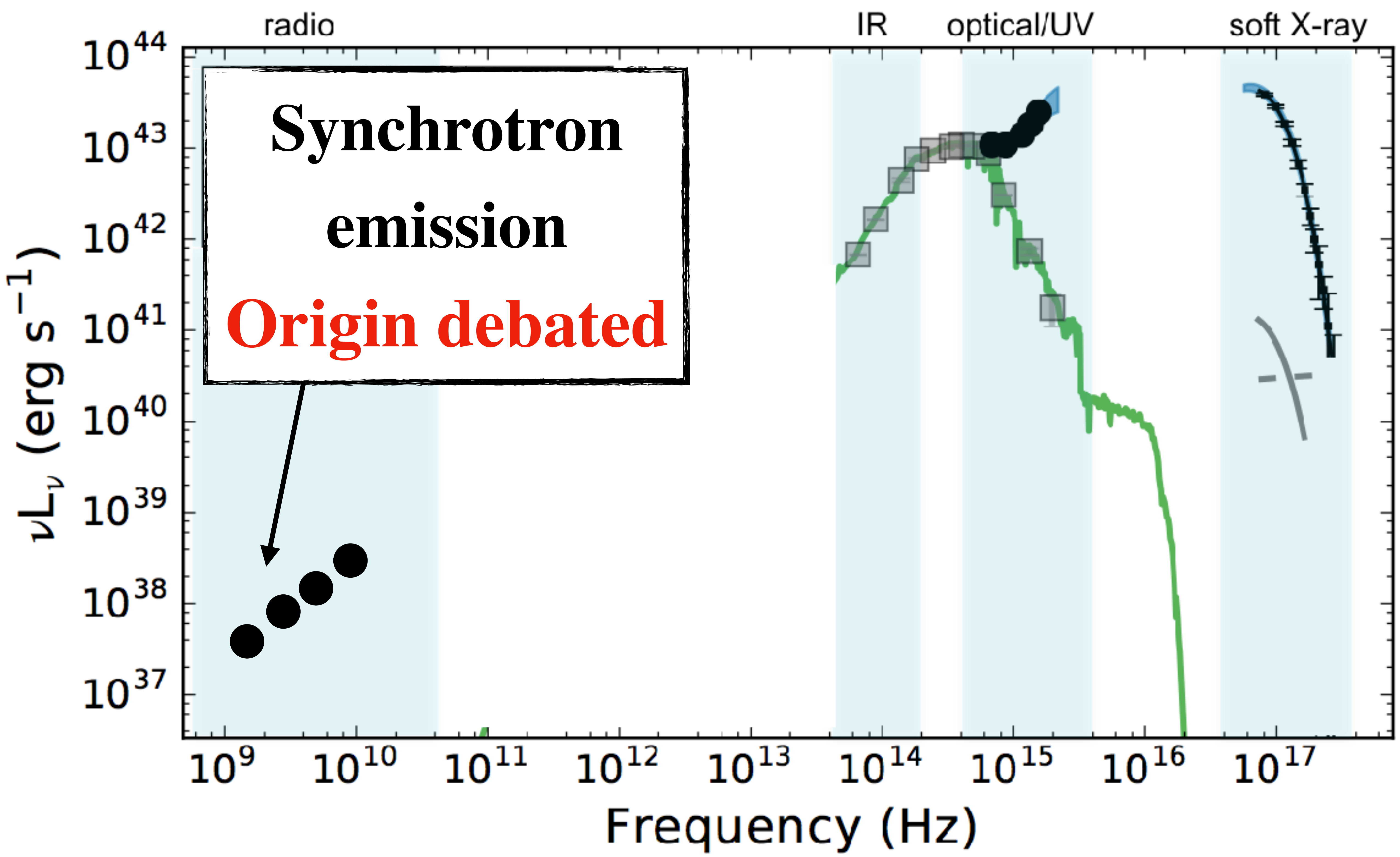
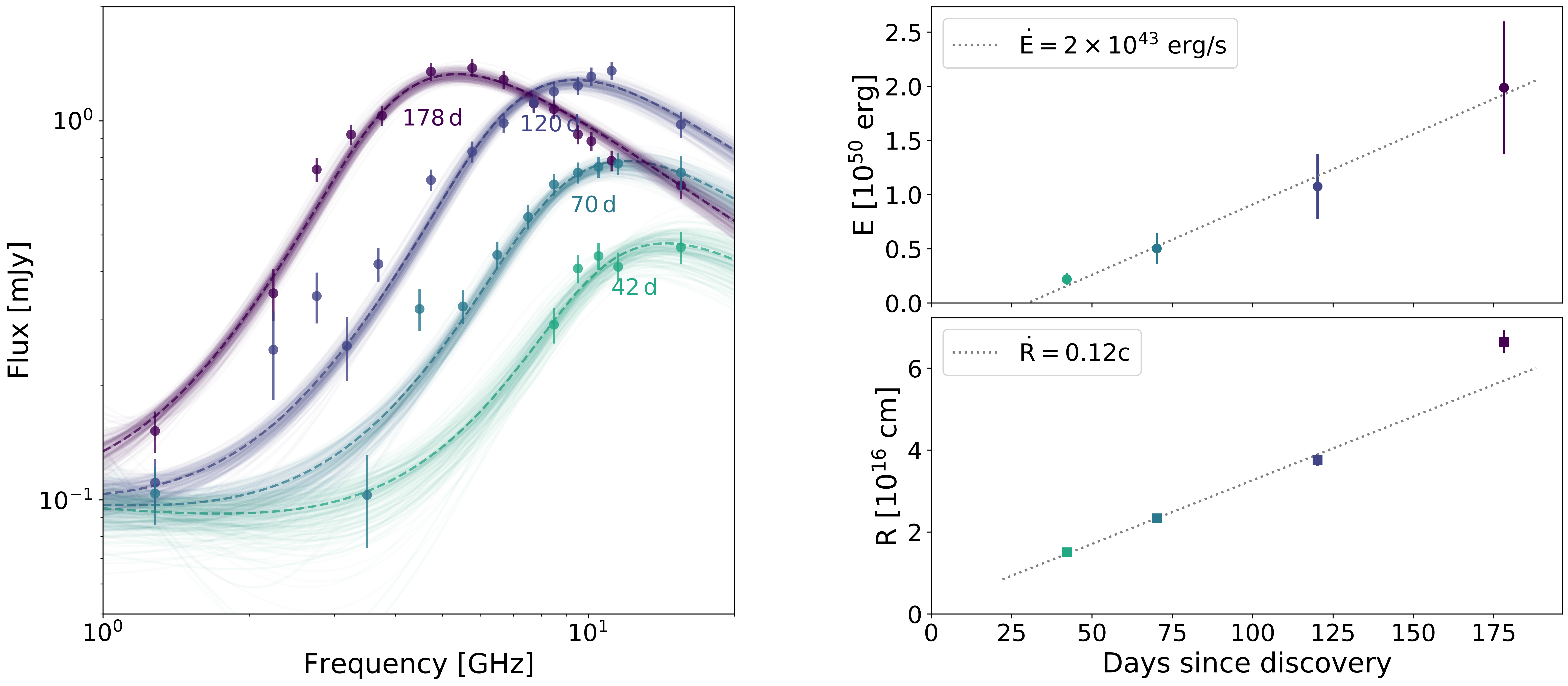


Single-zone synchrotron emission

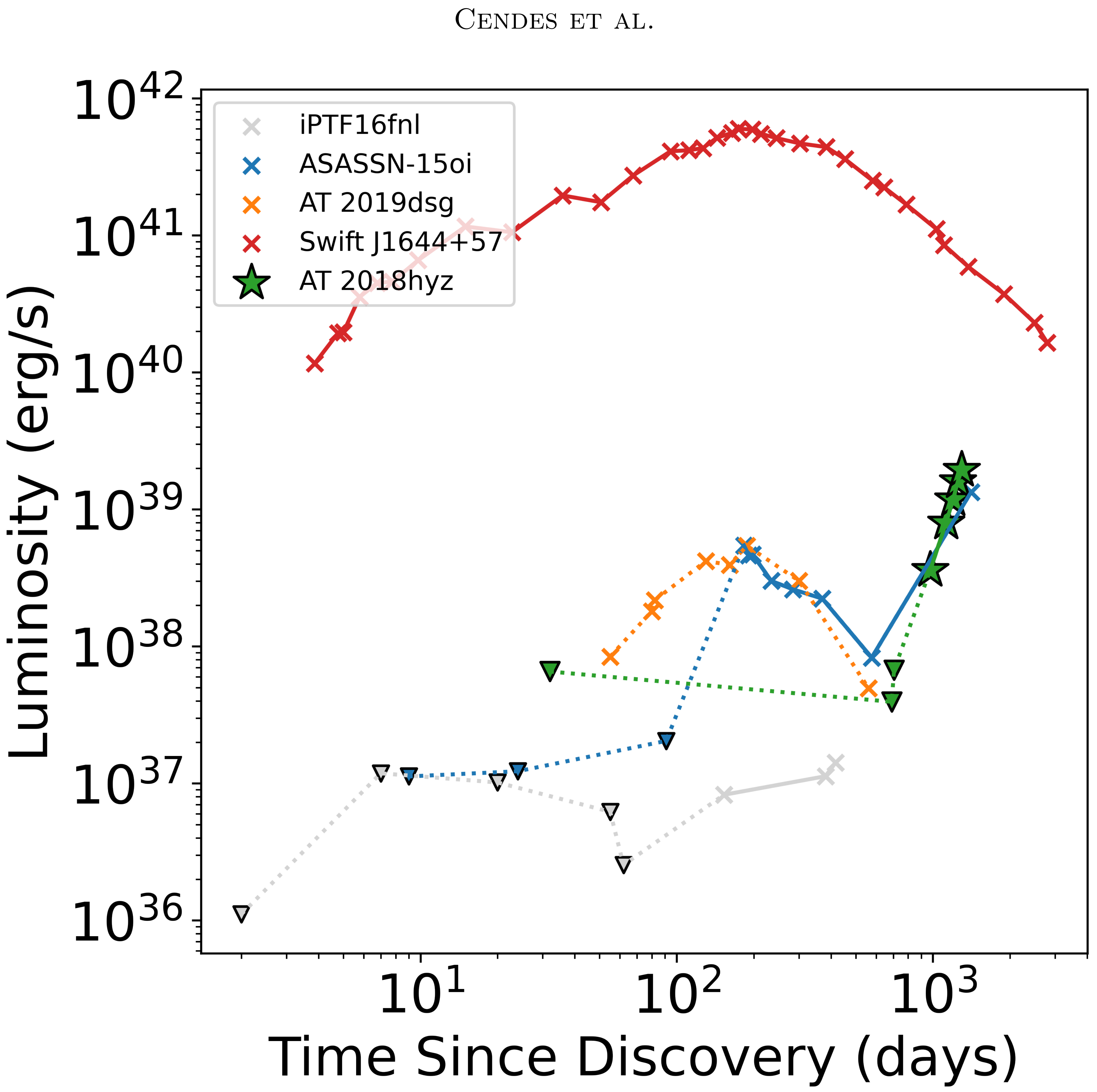
The “typical” case: outflows with 0.1c



AT2019dsg: Stein, van Velzen et al. (2021)

see Alexander, van Velzen et al. (2021) for a review

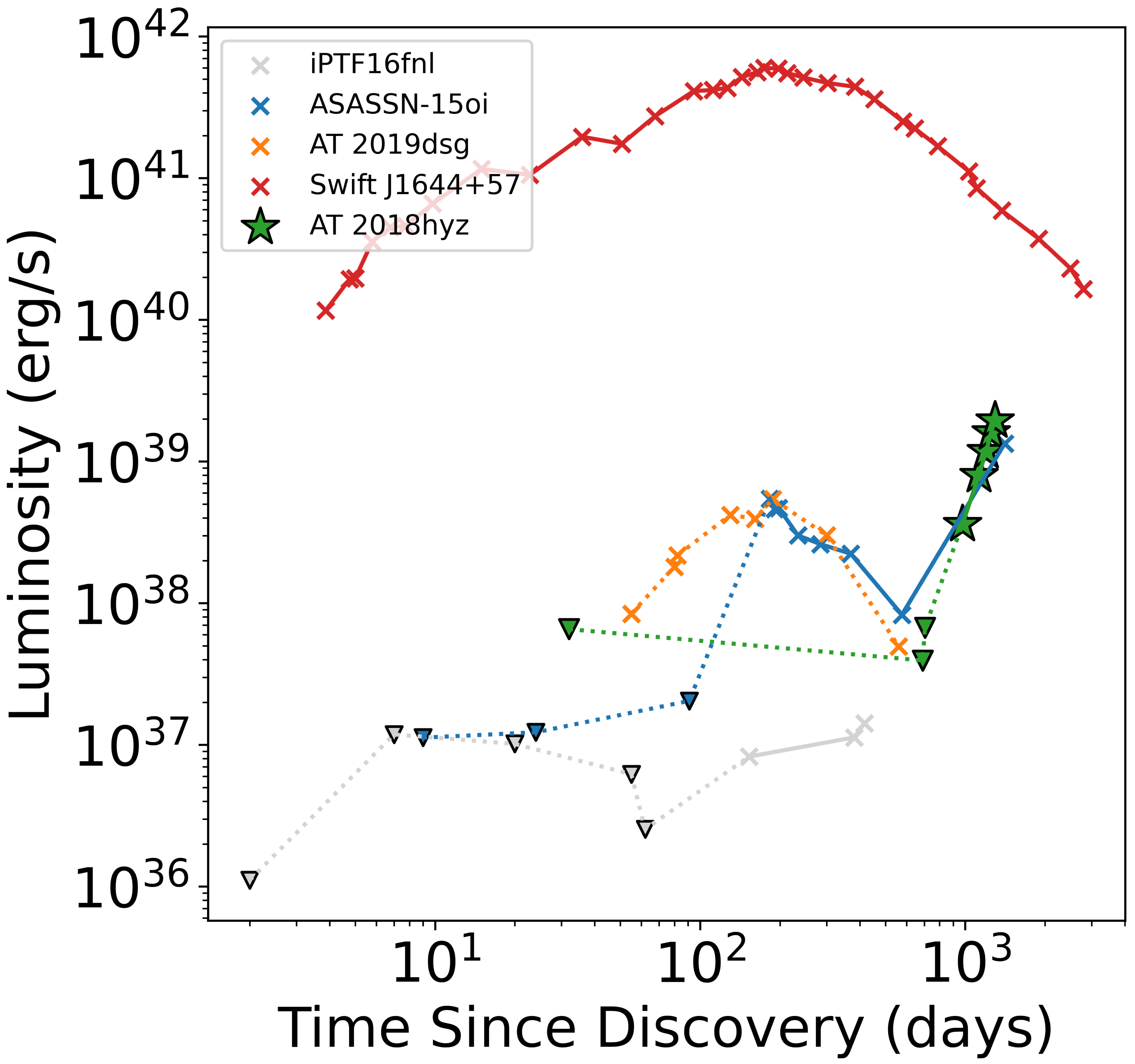
What's new? Late-time radio flares



What's new? Late-time radio flares

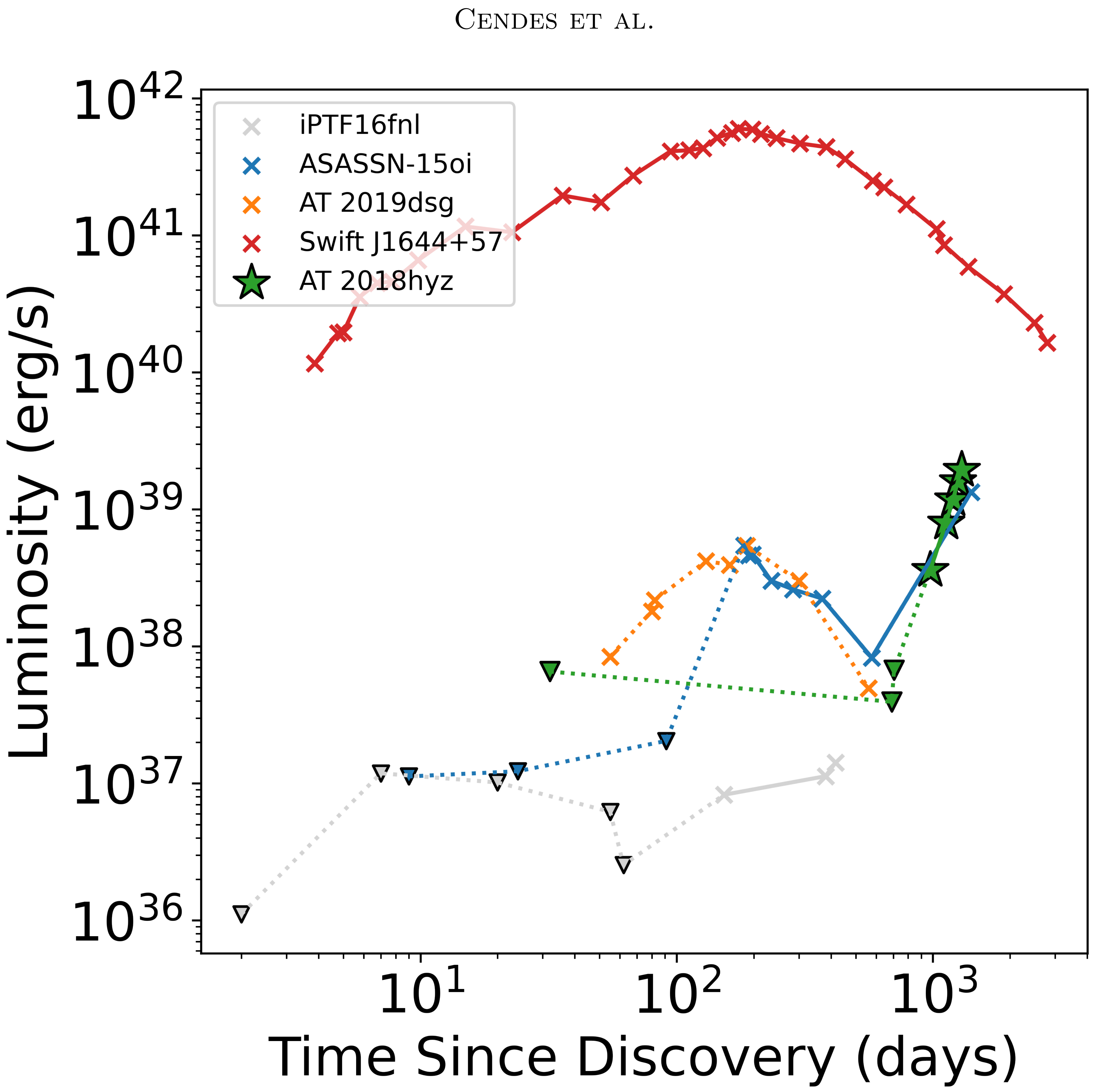
- Late-time radio flares
  (Horesh+21; Cendes+22)
  - Late-time accretion?
  - State change of accretion disk!

Cendes et al.

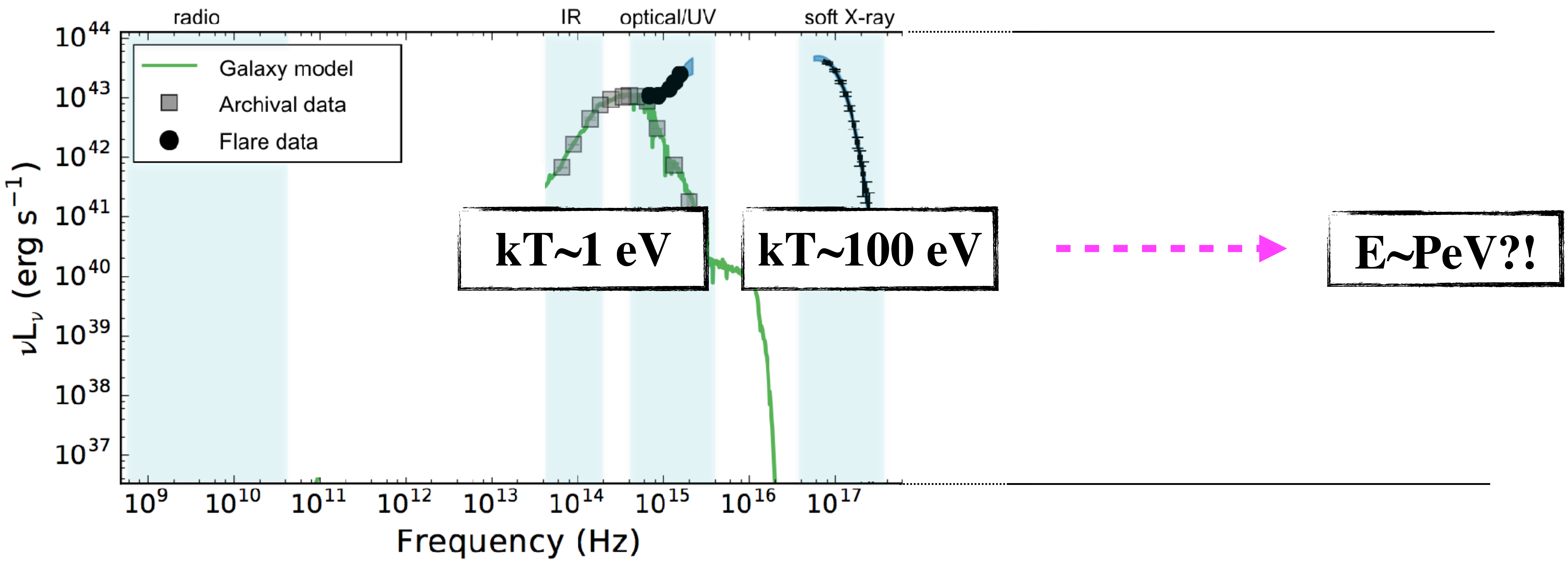


What's new? Late-time radio flares

- Late-time radio flares
  (Horesh+21; Cendes+22)
  - Late-time accretion?
  - State change of accretion disk!
- Rapid spectral changes
  (in AT2019azh; Goodwin+22)
  - Inhomogenous medium?
  - Jet geometry!

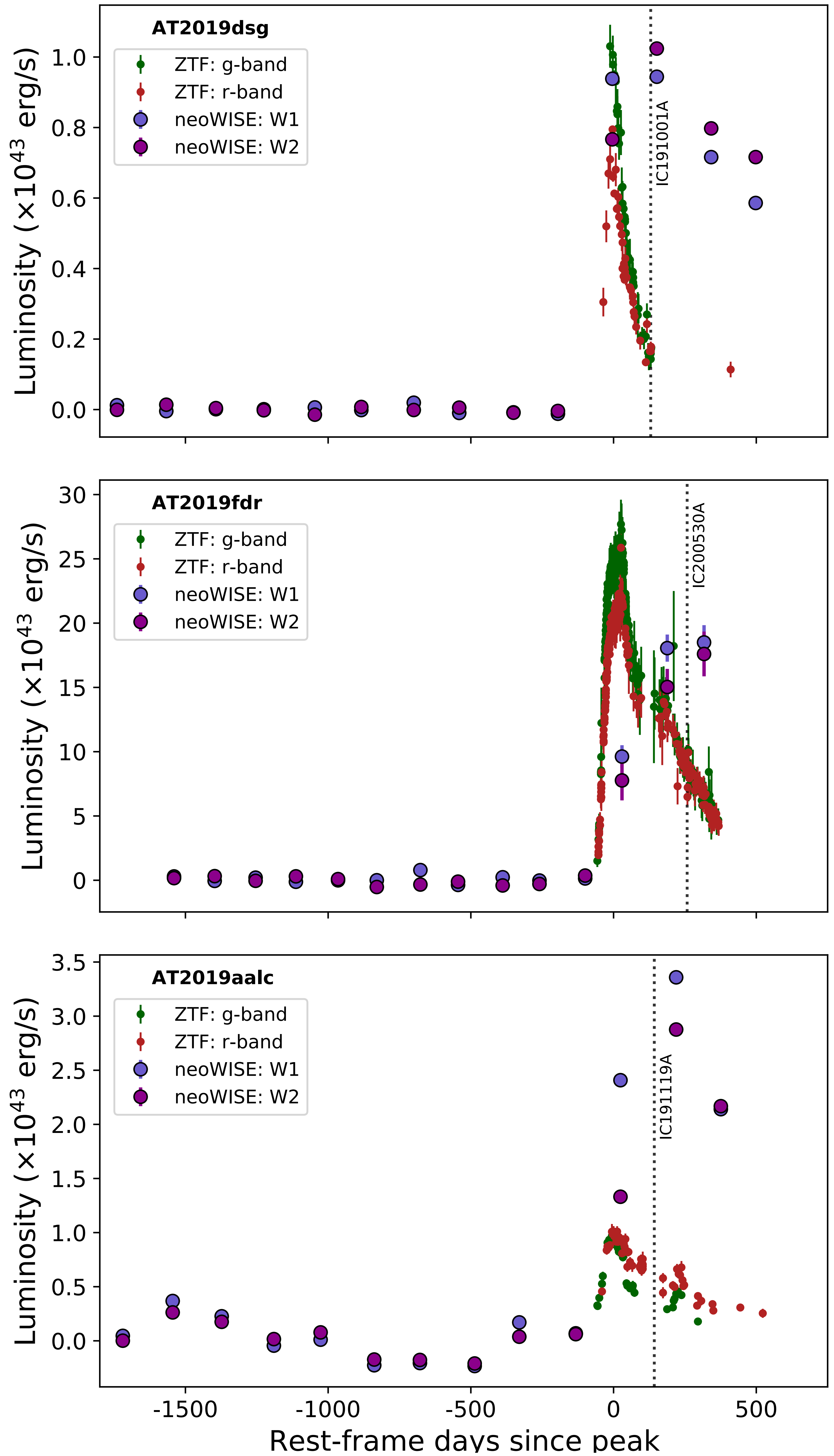


Part 4: Multi-messenger



Three black hole transients with a high-energy neutrino counterpart

- 3.6 sigma significance (based on dust echoes)



Stein+21; van Velzen+23 (arXiv:2111.09391)

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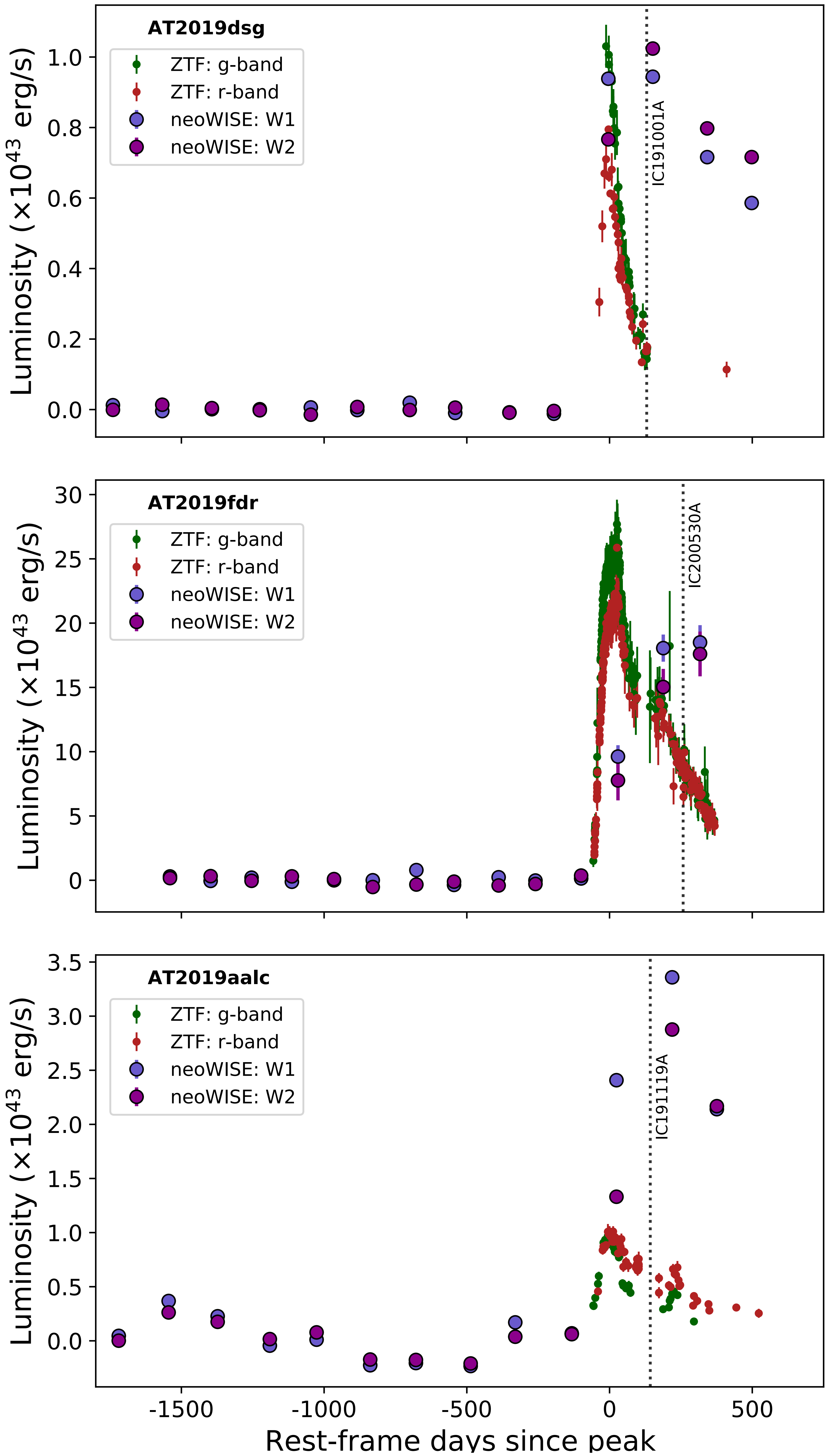

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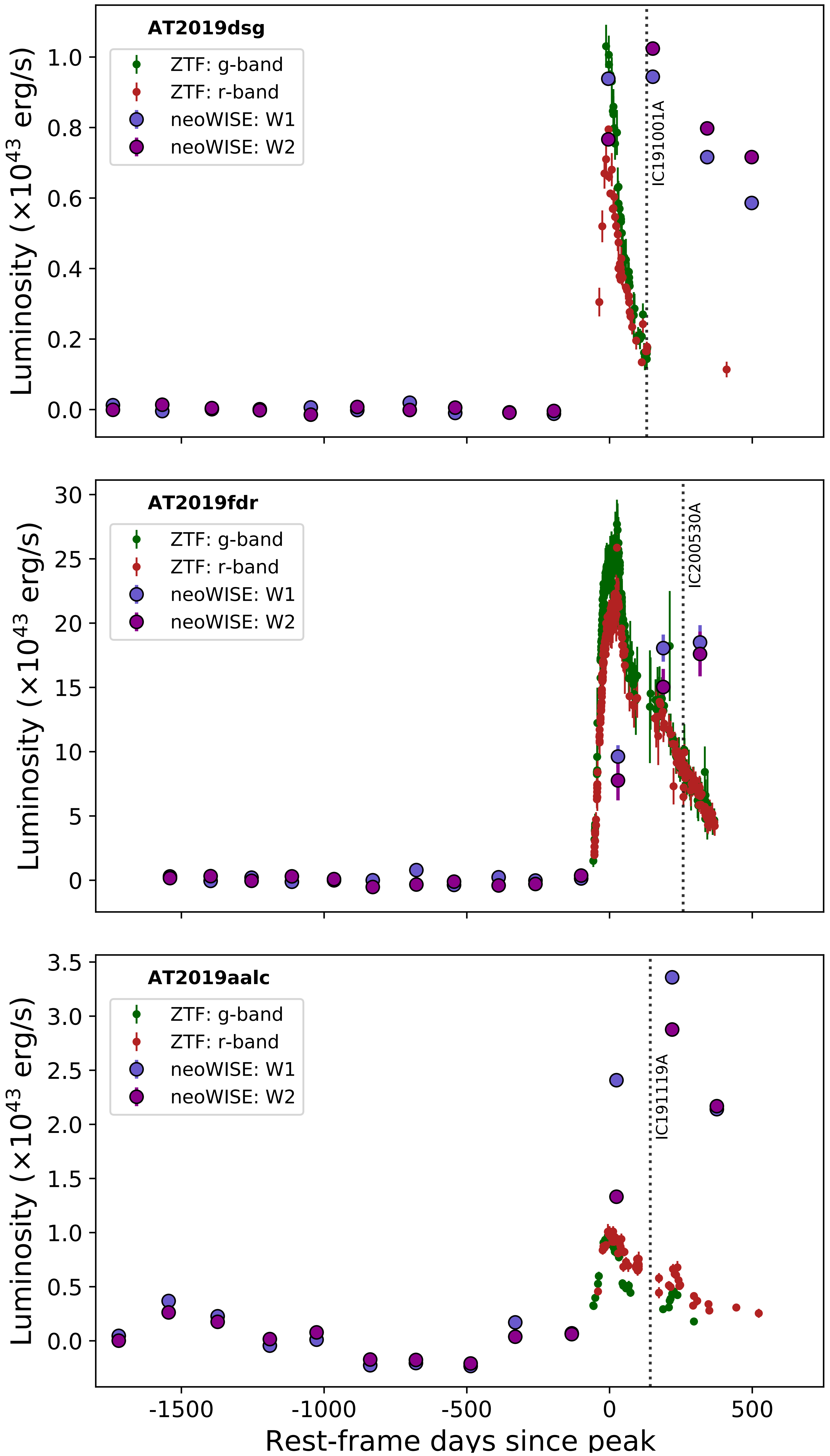

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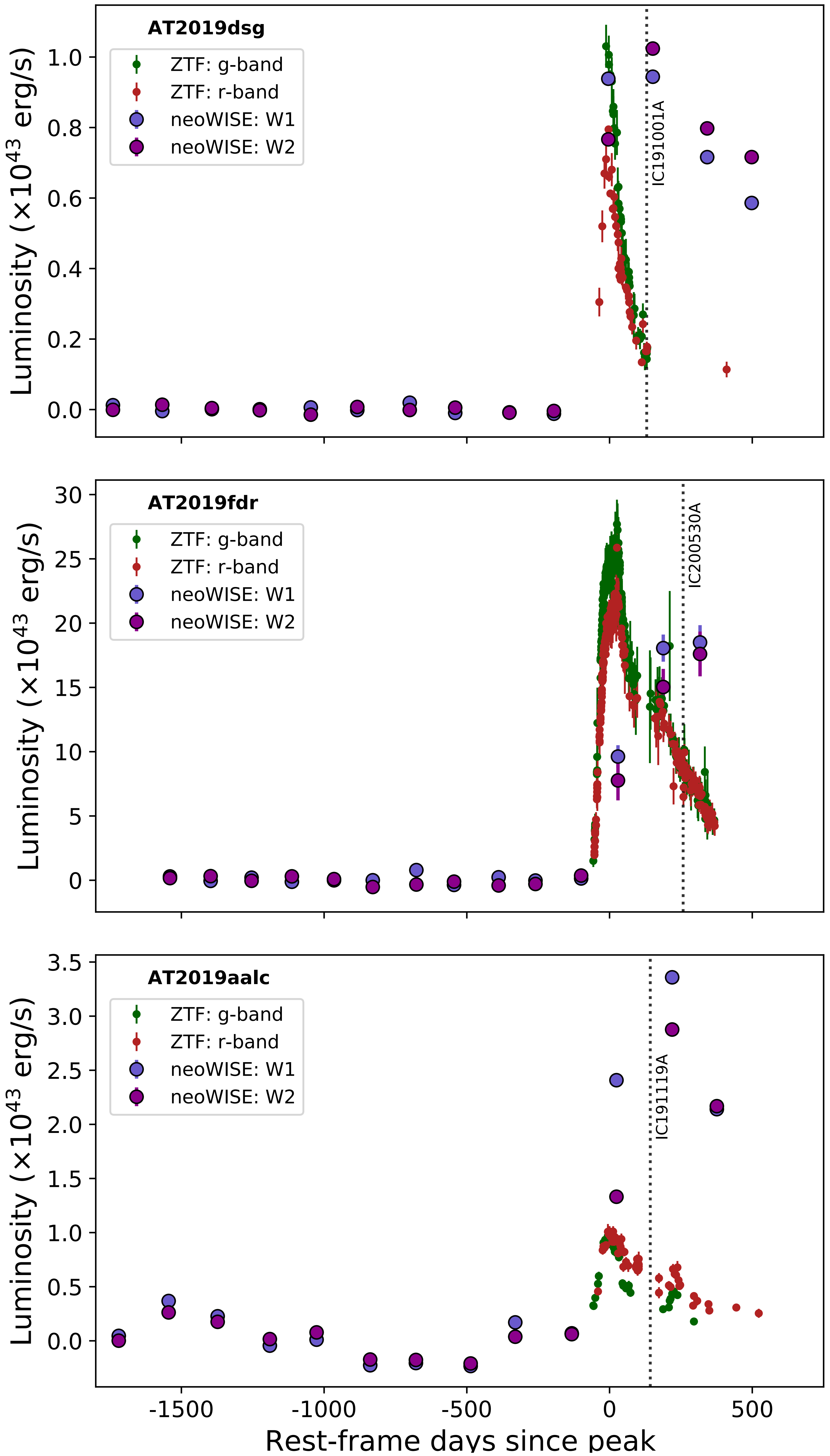

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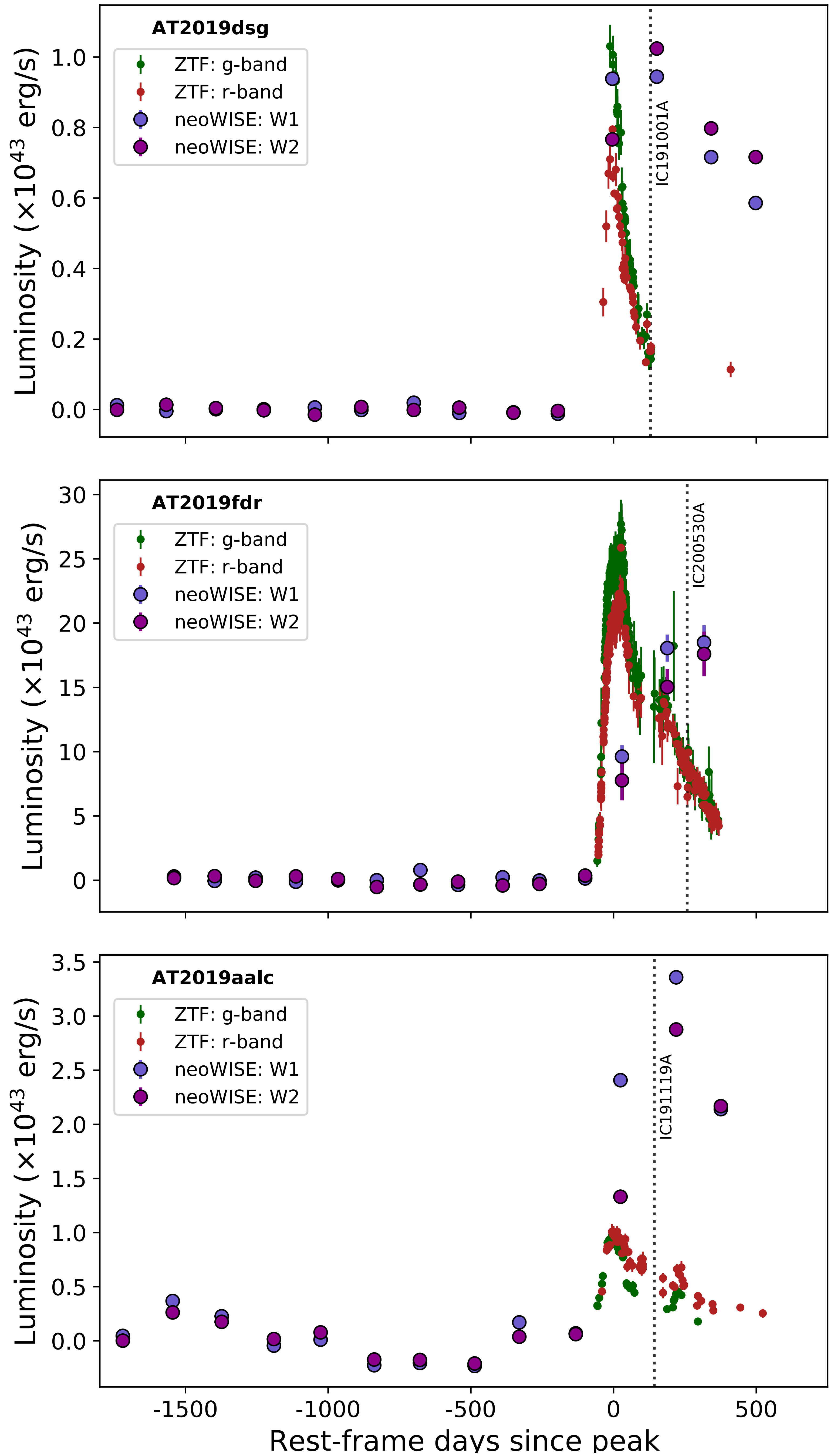

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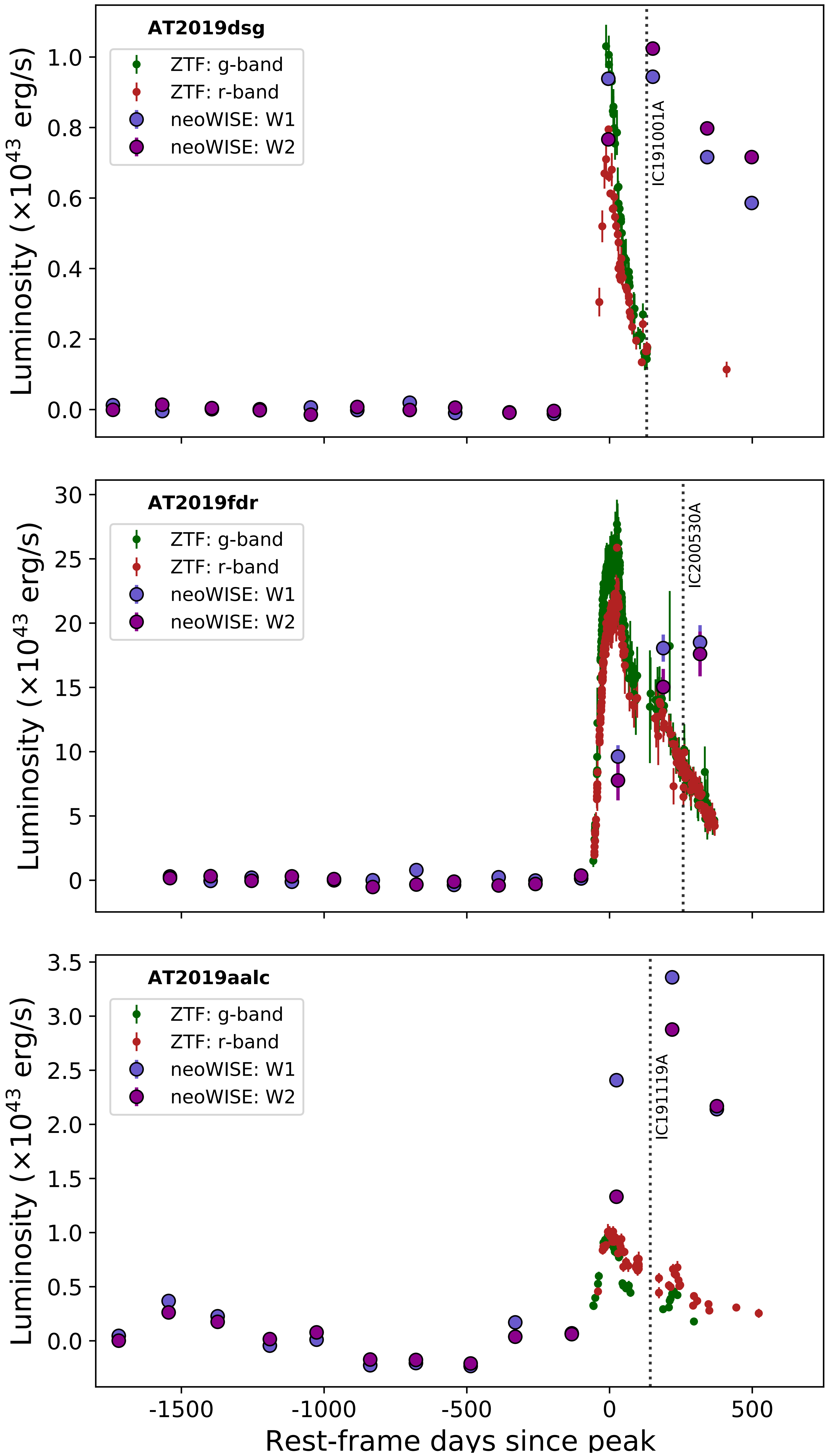

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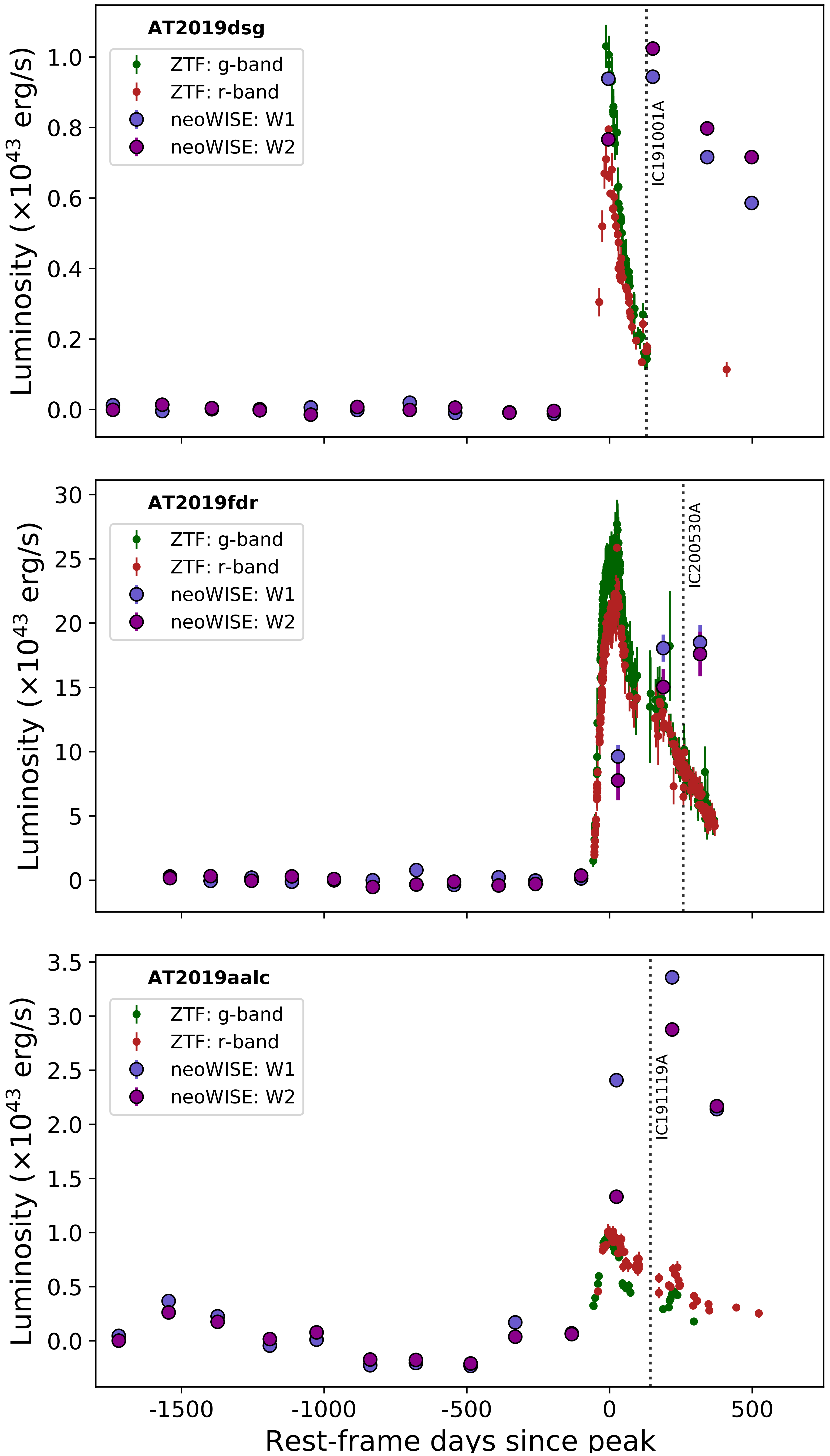
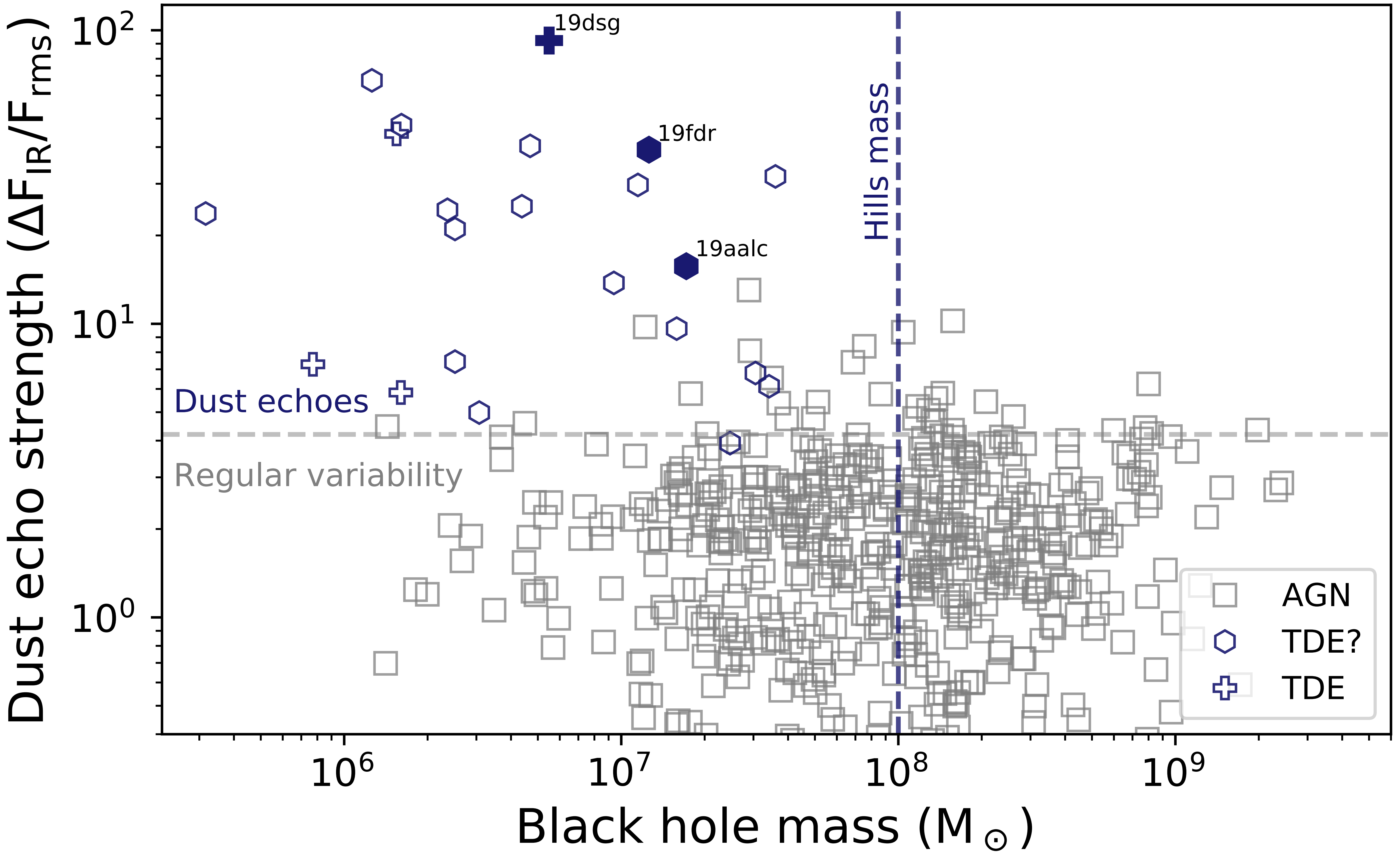
  - Detected in X-ray, with soft spectra (very uncommon for AGN)
- Connection with NGC 1068?



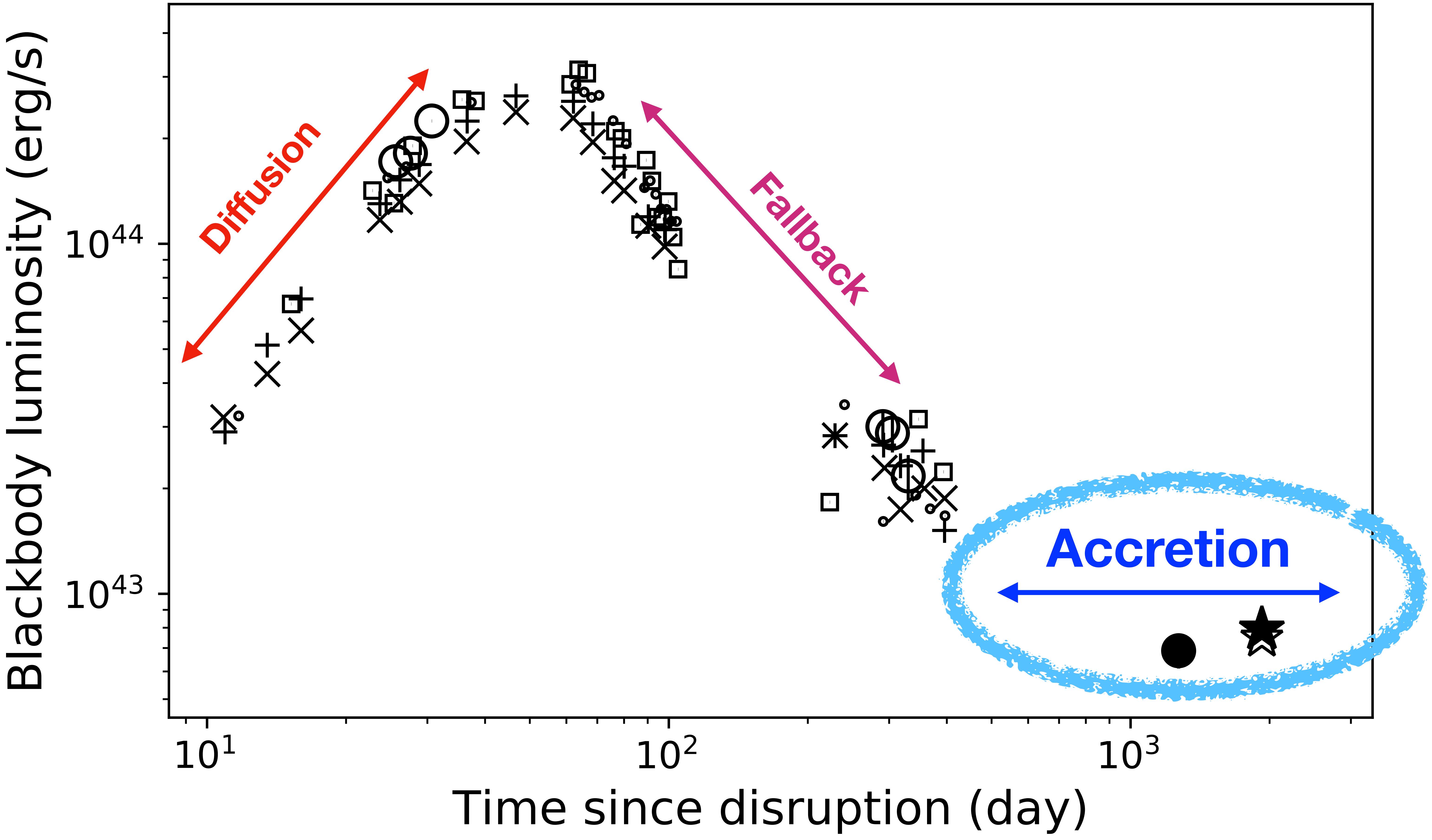
Stein+21; van Velzen+23 (arXiv:2111.09391)

Most nuclear transients are not TDEs

- Many "extreme" SMBH flares of unknown origin (e.g. Hinkle+22)
  - Fast and high amplitude (e.g., Graham+17; Frederick+20)
- (Recurring) TDEs in AGN?
  - Would require a significant TDE rate enhancement
- Link with neutrinos suggests a special state of the accretion disk?



Recap: summary of optical/UV emission



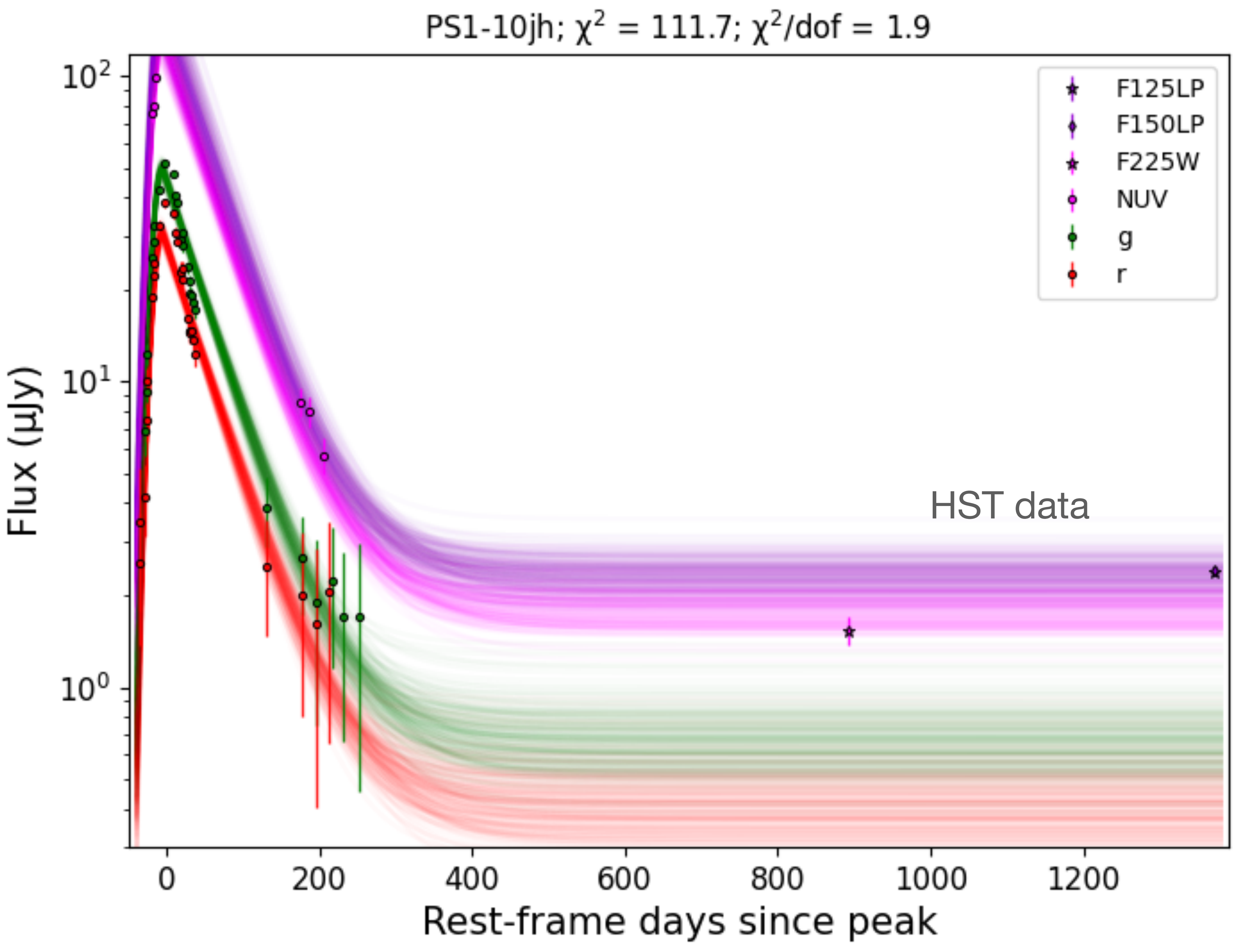
Information about:

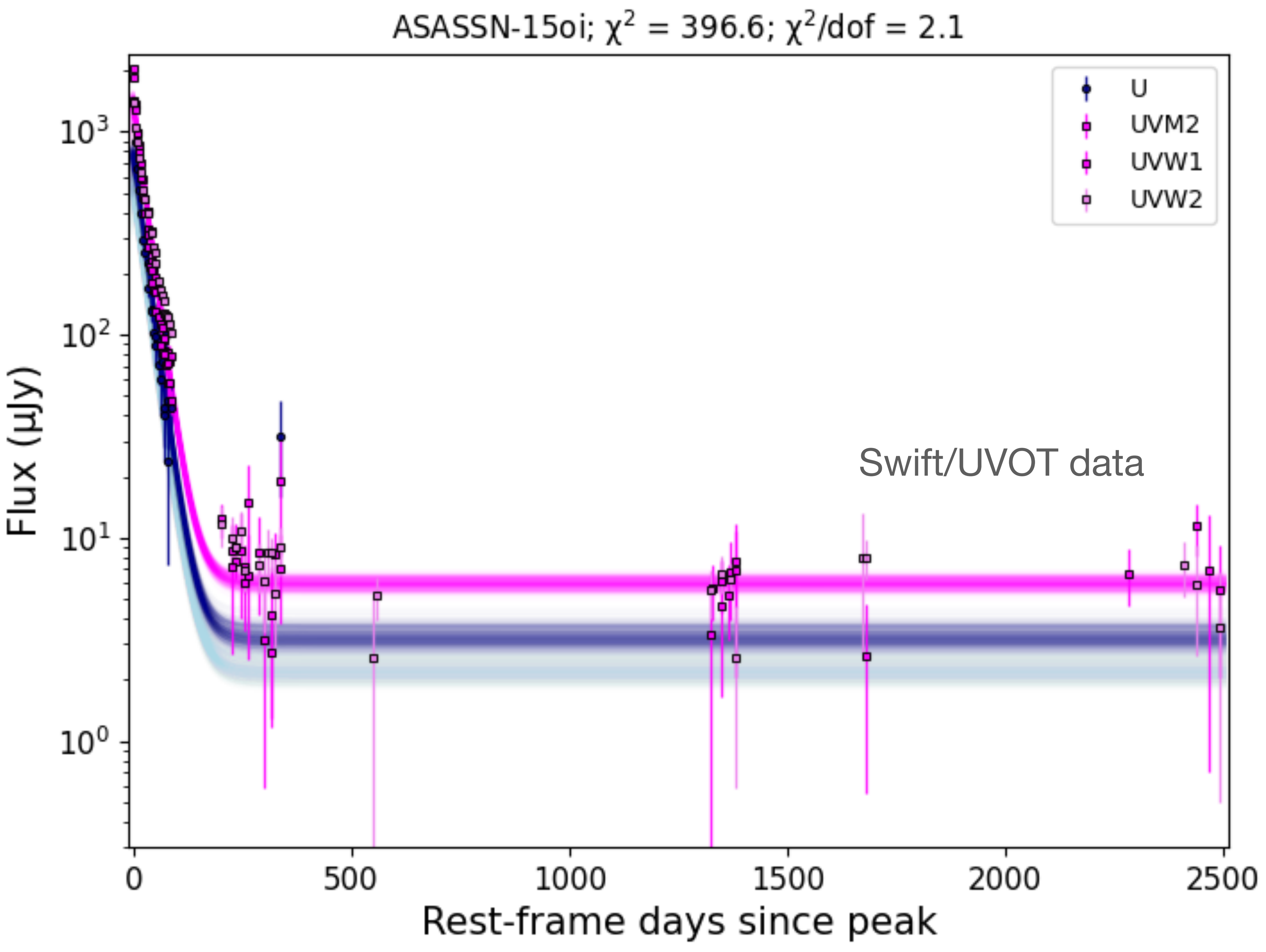
- Density in photosphere
- BH mass
- BH mass, stellar mass

Data of PS-10jh Gezari et al. (2012, 2015); van Velzen et al. (2019)

Let’s find all the plateaus

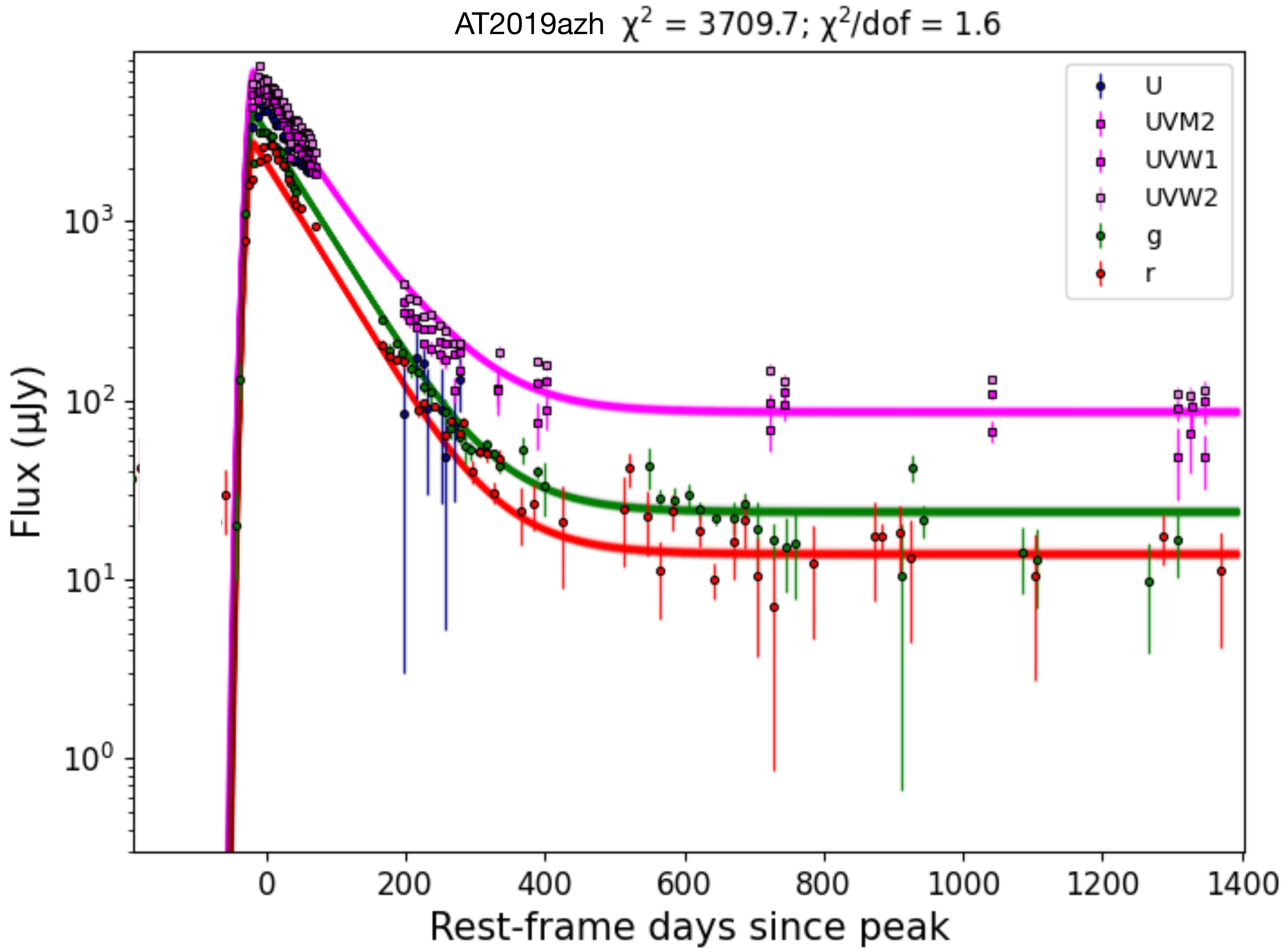
Classical approach: late-time UV observations





Let’s find all the plateaus

Breakthrough with optical photometry (ZTF)



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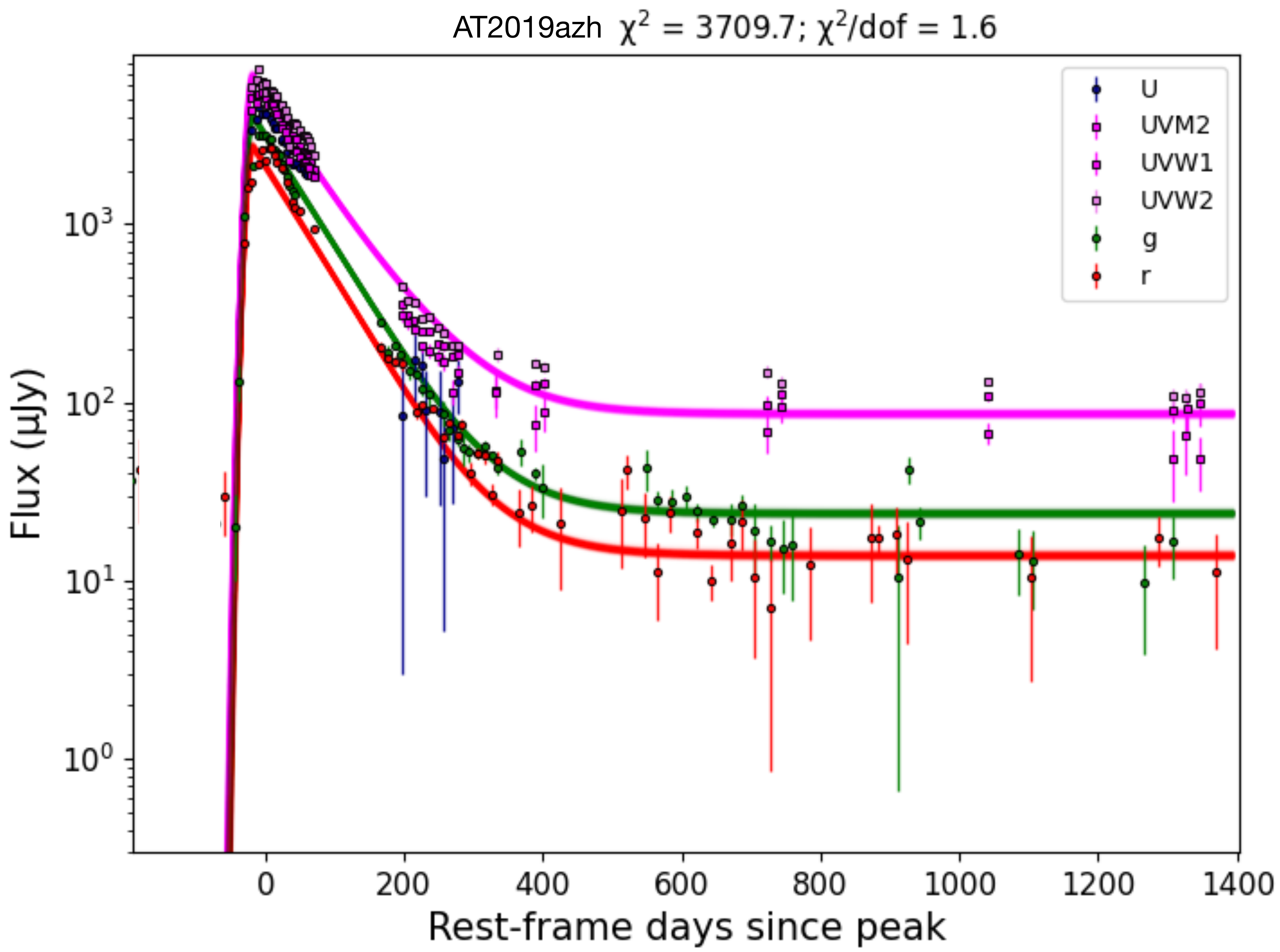
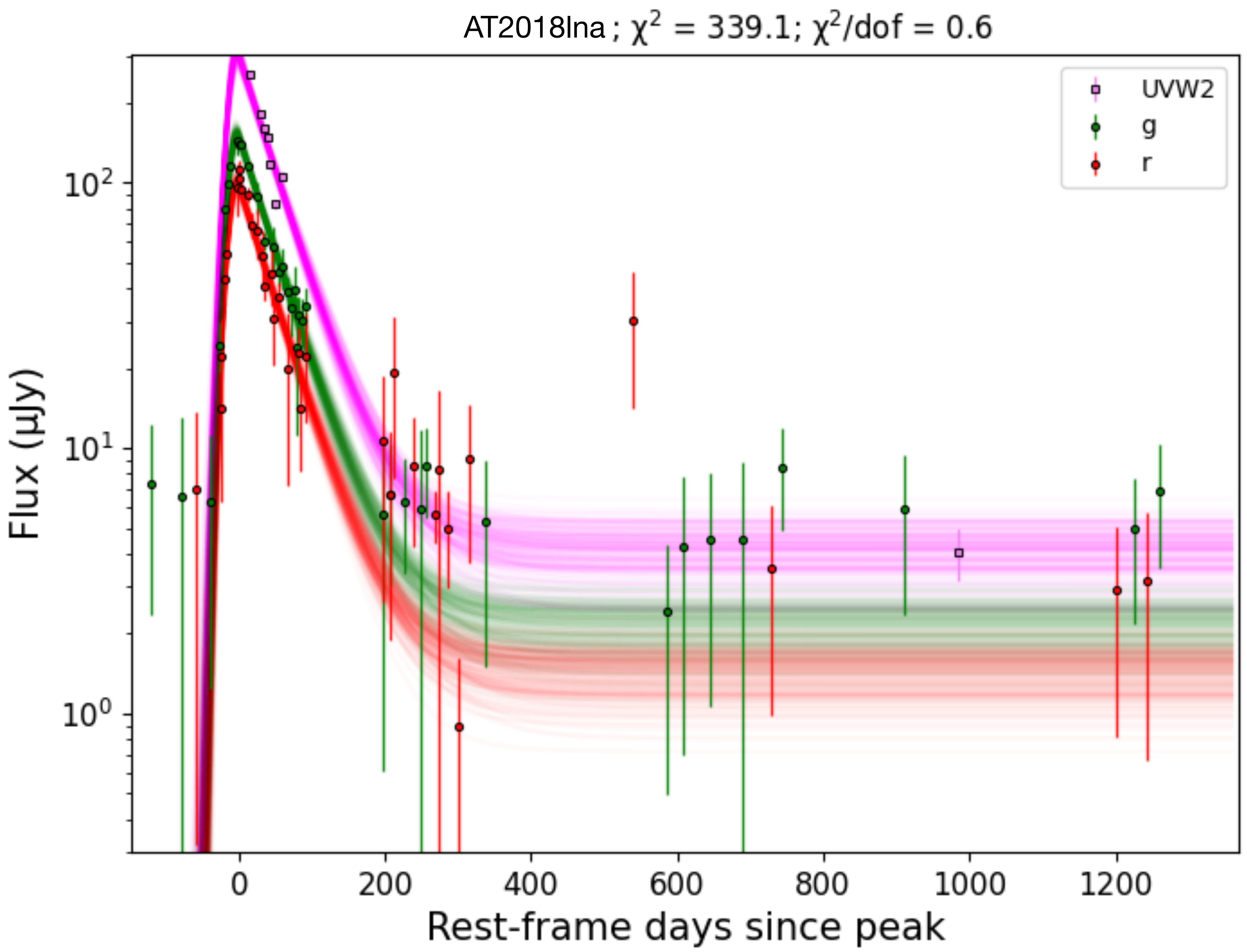
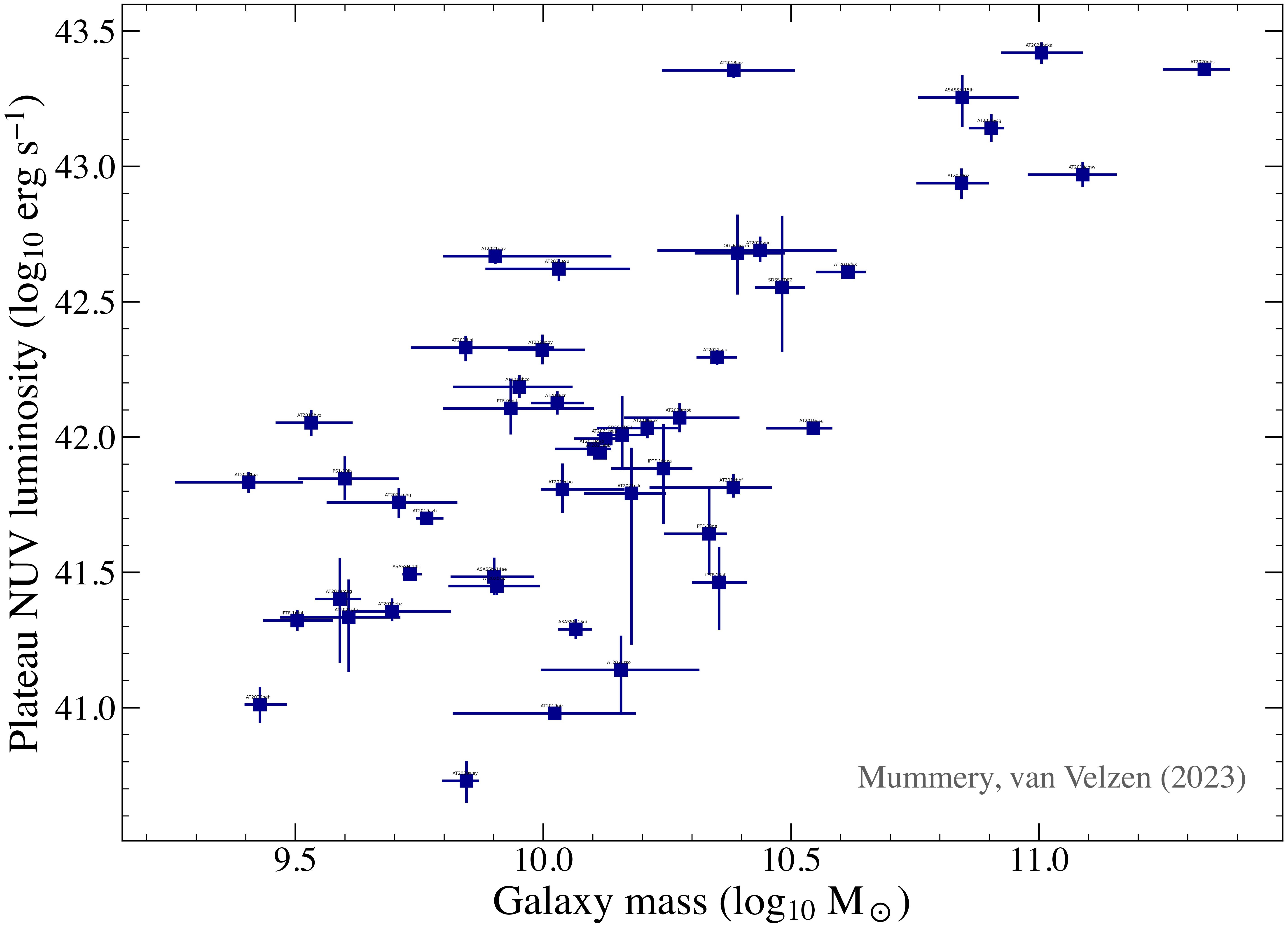




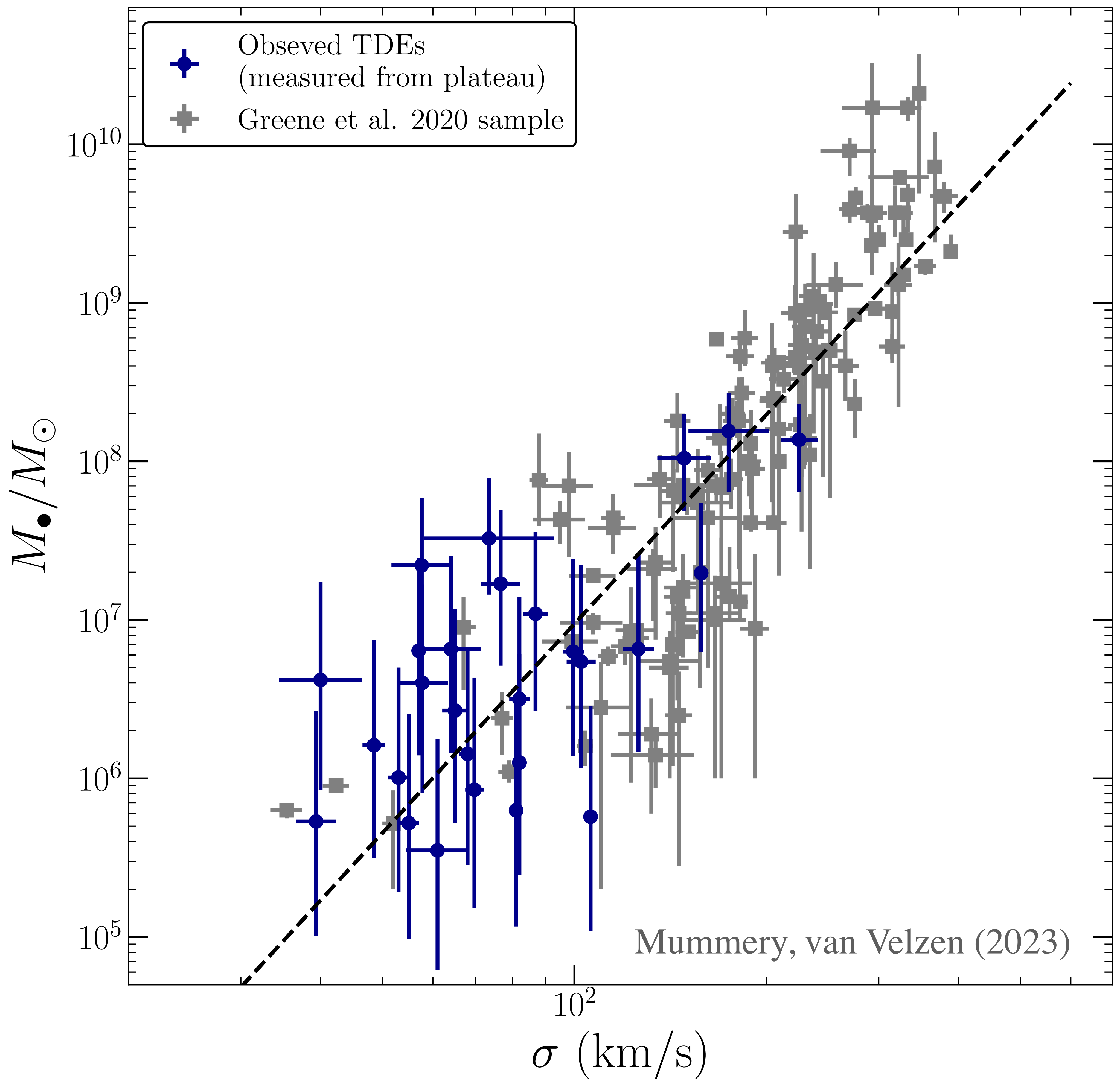
Plateau luminosity correlates with host galaxy mass

- Strongest correlation of all lightcurve properties
- Significance:
  $p = 2\ 10^{-6} \sim 5\sigma$
- 0.30 dex scatter in mass-direction
- Theory predicts plateau luminosity for a given black hole mass

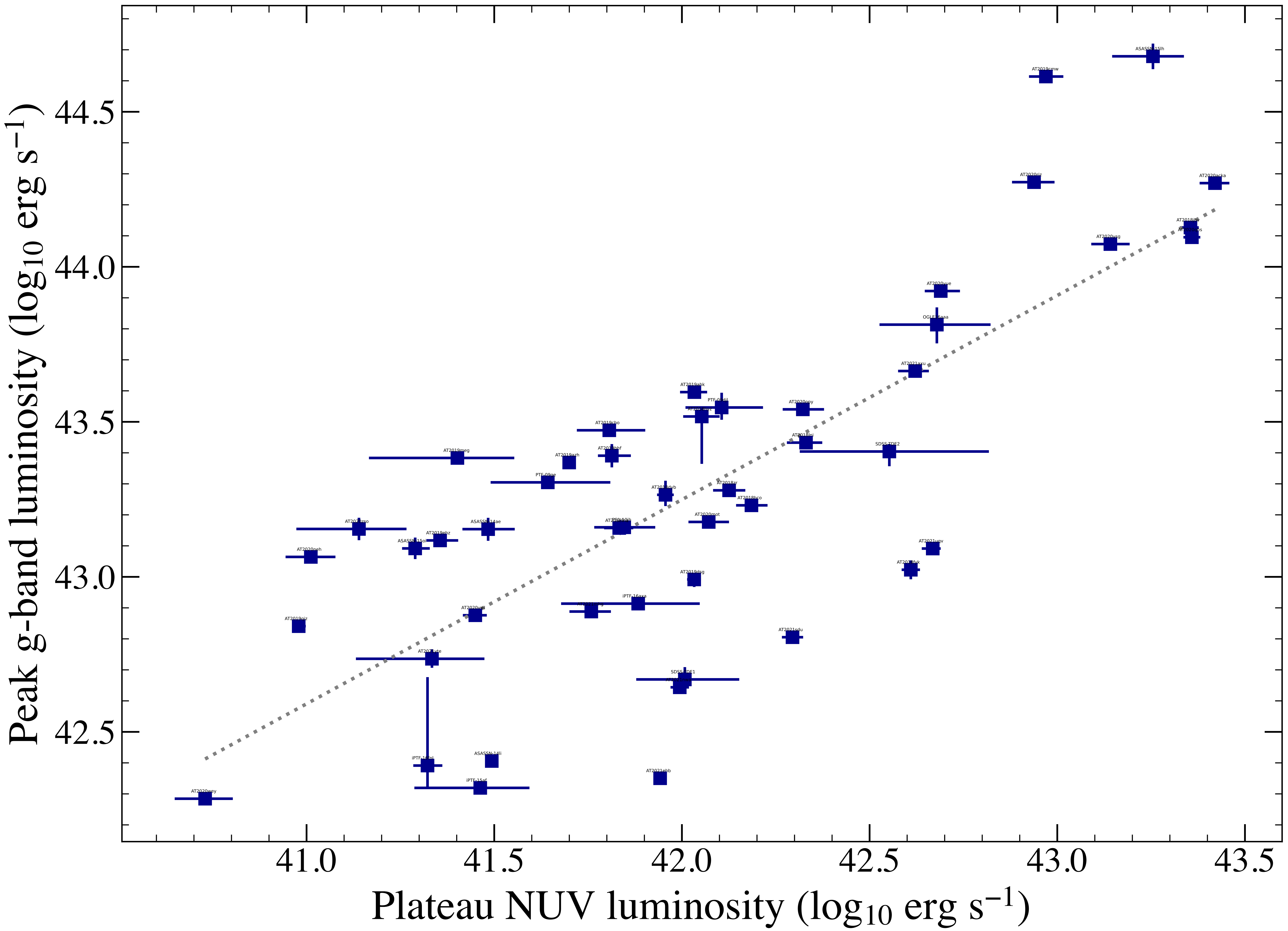


Extending the M-sigma relation

Excellent agreement

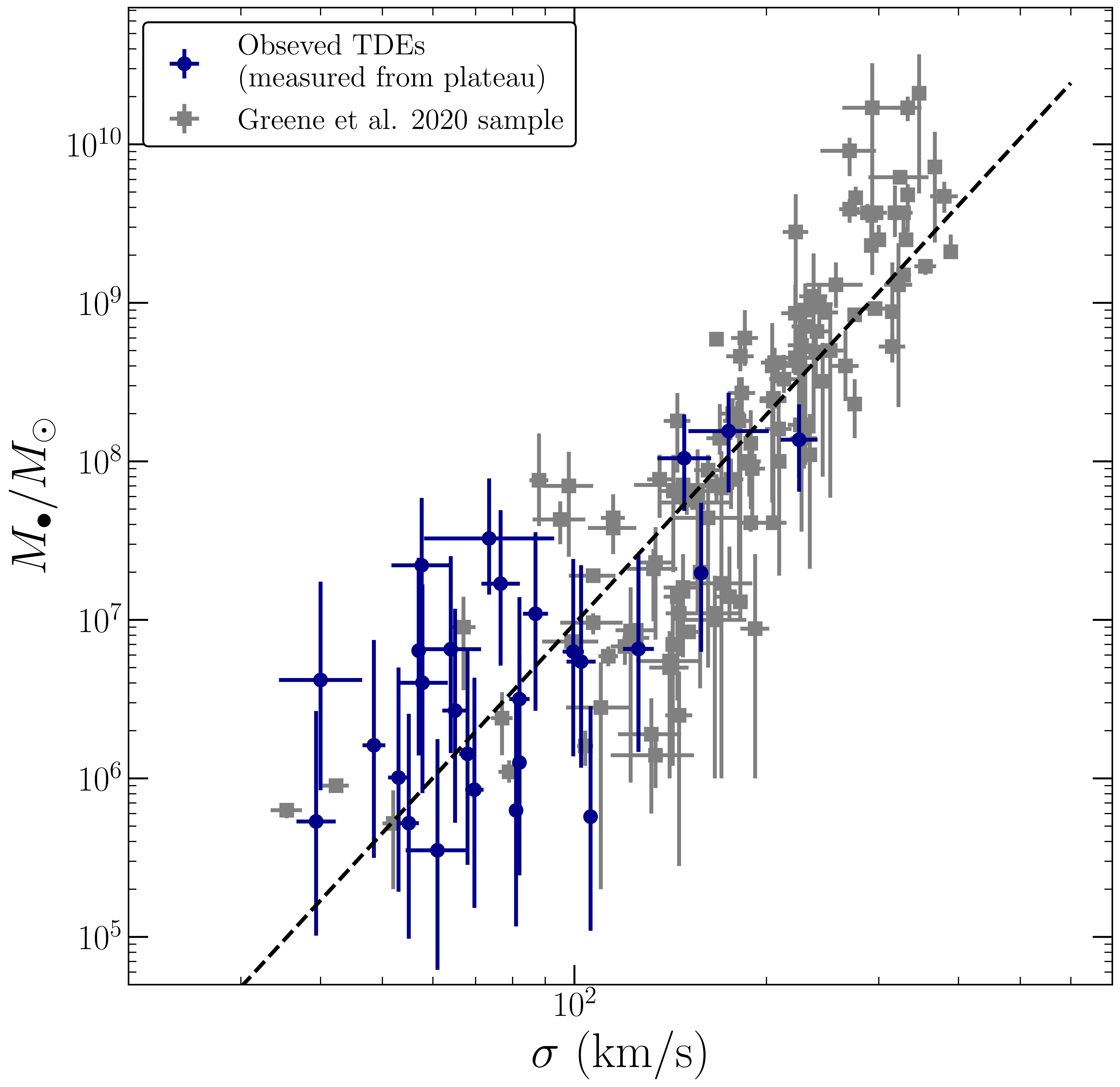


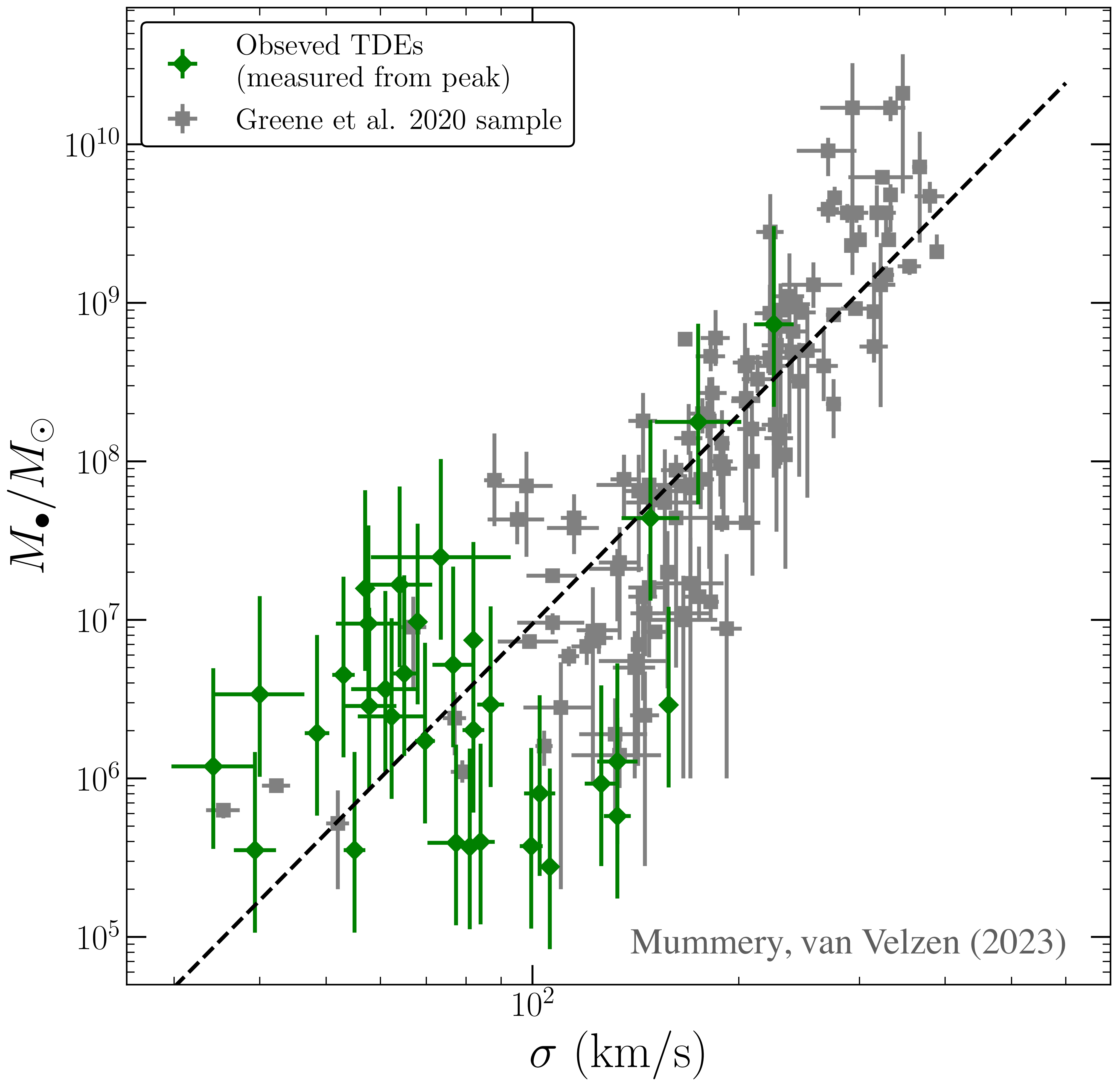
TDE peak luminosity correlates with plateau luminosity



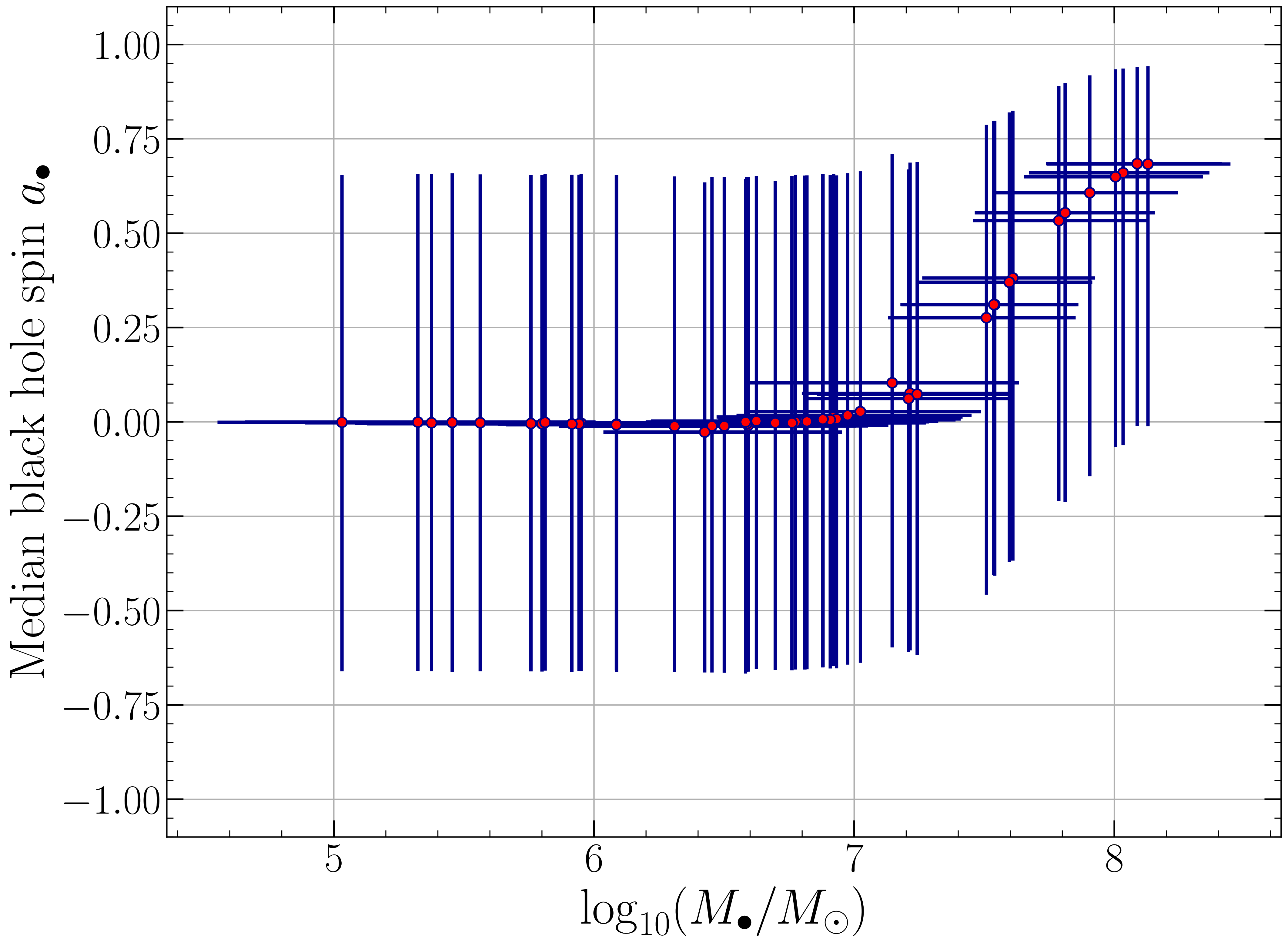
Extending the M-sigma relation

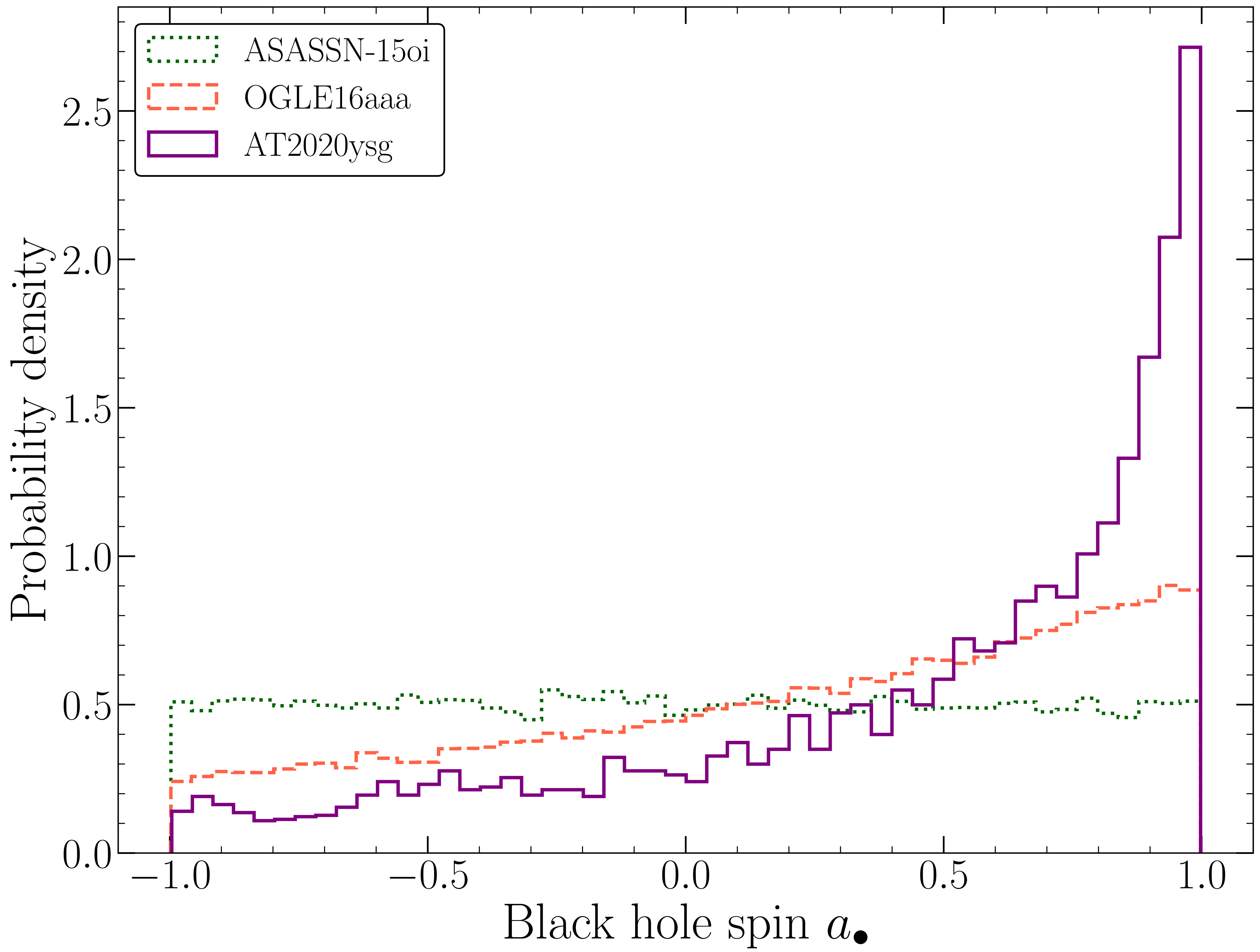
Using the peak luminosity





Spin constraints

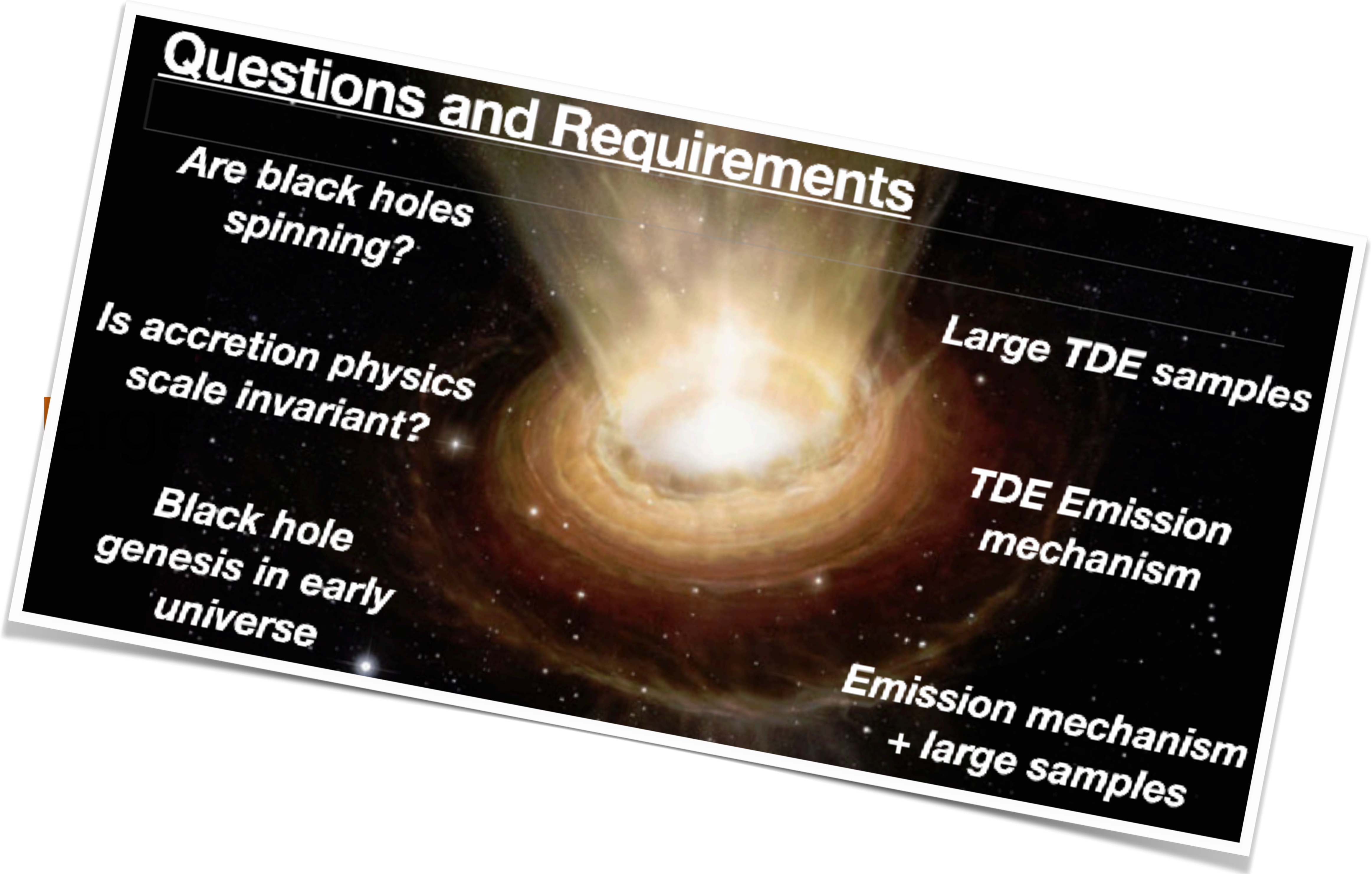




Mummery, van Velzen (2023)

Summary

Progress at all wavelengths



- ✳ **X-ray:** new discoveries (QPEs), samples (eROSITA)
- ✳ **Radio:** unexpected late-time flares
- ✳ **High-energy** neutrinos
- ✳ **Optical:** large samples
  - ✓ Almost 100 TDEs!
  - ✓ Clear correlations with host galaxy mass
  - ✓ Could soon resolve origin of optical emission
- ✳ Connection to AGN flares remains unclear

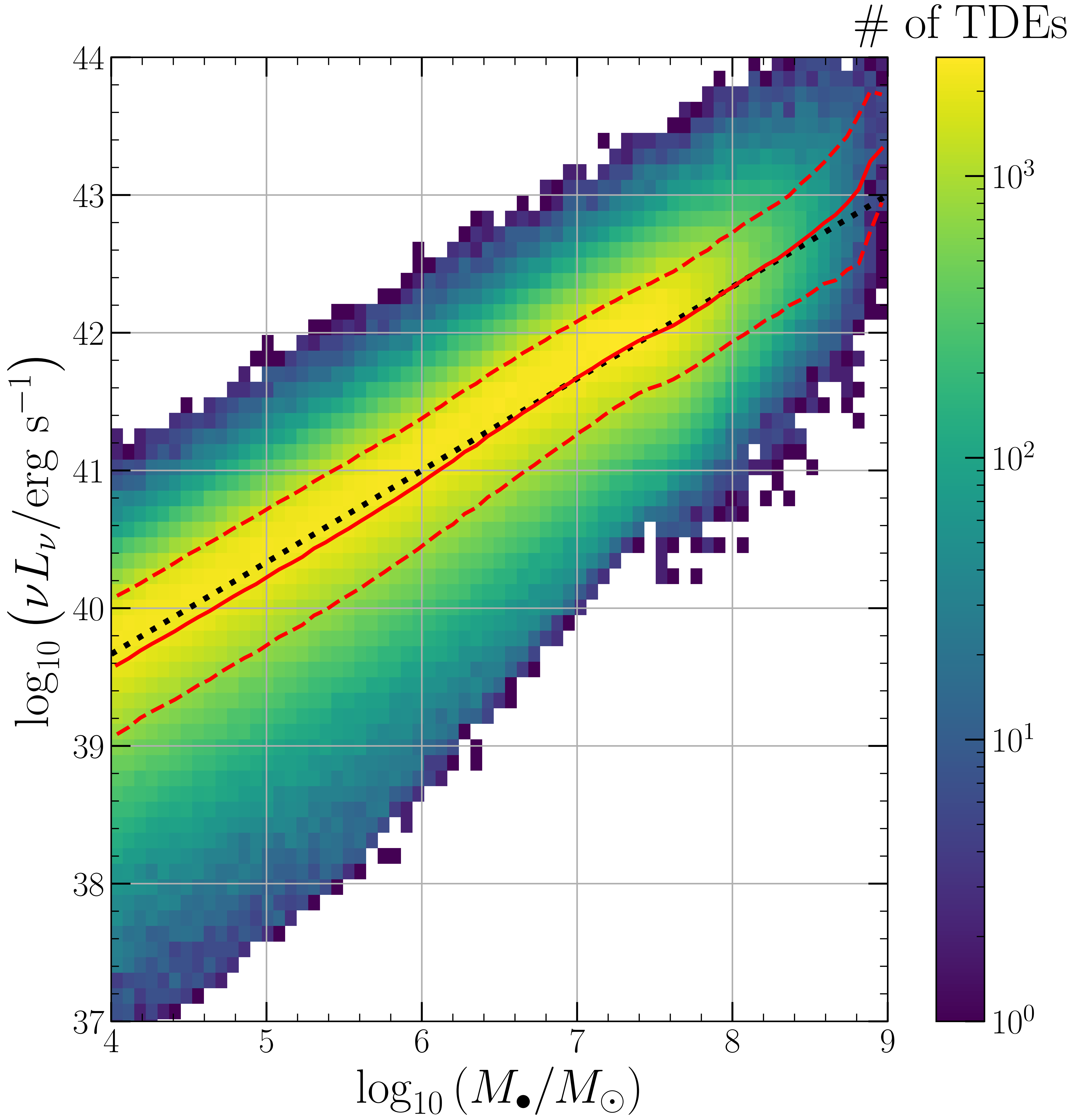
What is next?

What is next?

What is next?

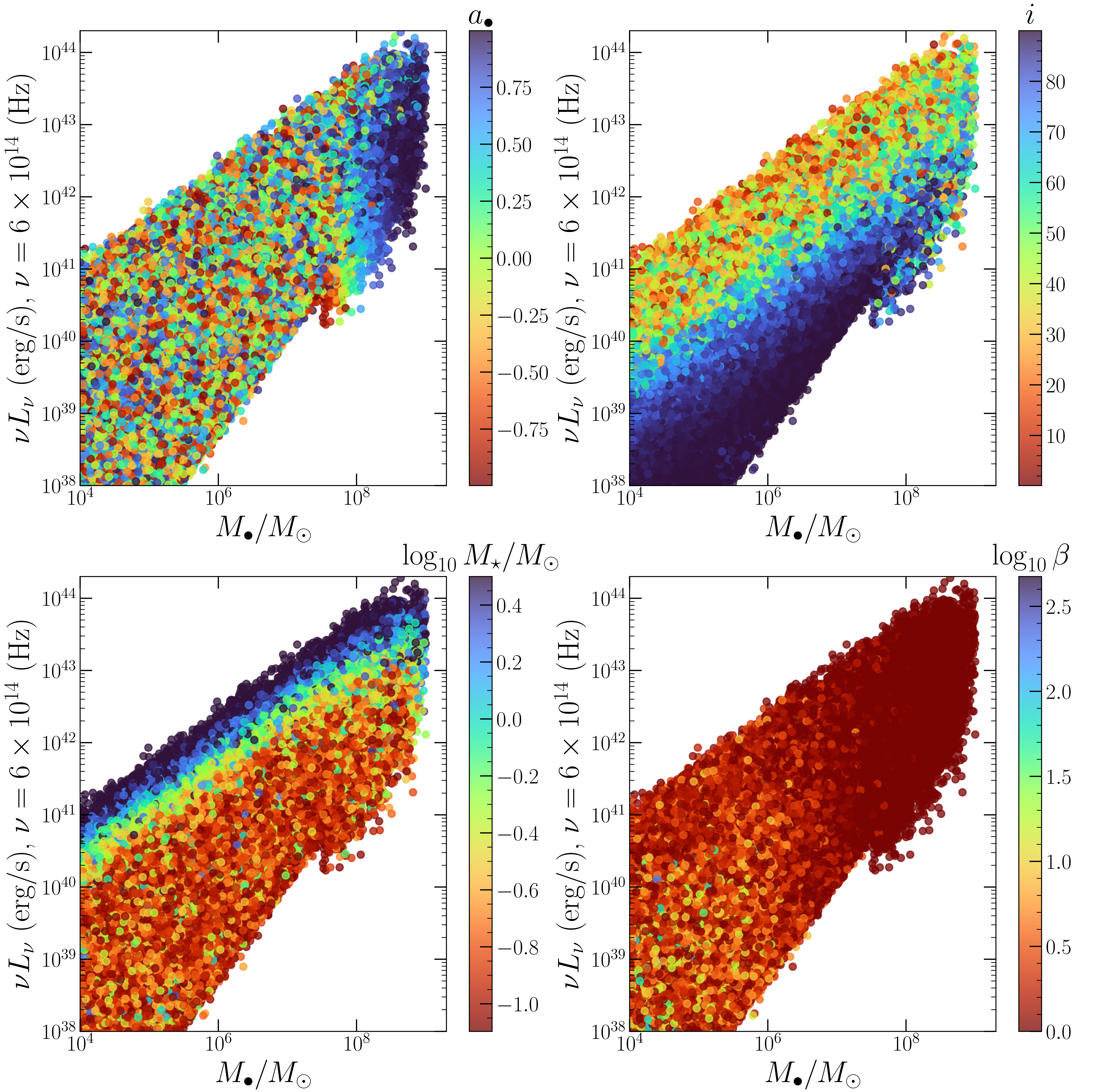
- More TDEs with **Rubin Observatory**: 10-1000 per year
- More neutrinos: KM3NET, IceCube (Gen2)
- More detections in (blind) radio surveys: VLASS, DSA-1000, ngVLA, SKA
- Optical/UV detections from space: Gaia, EUCLID, ULTRASAT, Roman
- More IR detections: ground based, JWST(!) and NEO surveyor

Disk model



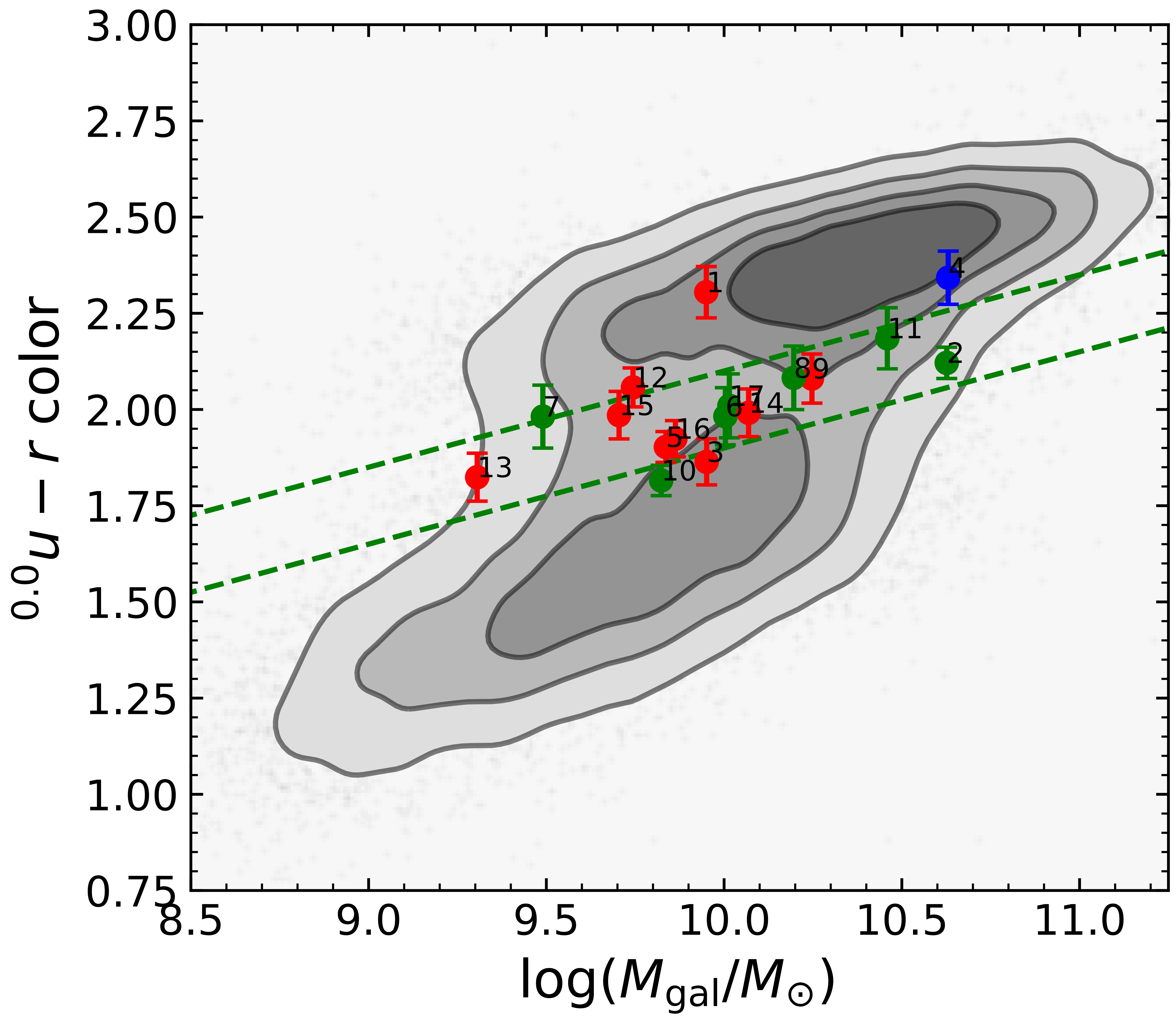
# of TDEs
$\log_{10}(\nu L_\nu/\mathrm{erg\ s^{-1}})$
$\log_{10}(M_\bullet/M_\odot)$
44
43
42
41
40
39
38
37
4
5
6
7
8
9
10^3
10^2
10^1
10^0

Disk model



Mummery, van Velzen (2023)

Host galaxies: preference for “green valley”



65% of TDEs in green valley compared to 10% of normal galaxies

Hammerstein et al. 2021

Similar to post-starburst preference

(Arcavi et al. 2014; French et al. 2016; Law-Smith et al. 2017; Graur et al. 2017)

Explaining the cosmic neutrino flux

Particle acceleration in a super-Eddington accretion disk

- Puzzling facts:
  - About 10% of HE neutrinos from TDE-like flares
  - Normal AGN outshine TDEs by 2 orders of magnitude
  - For common particle acceleration, AGN *should* dominate the neutrino sky

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    - Super-Eddington accretion: common for TDEs, uncommon for AGN
- Supporting evidence:
    - NGC 1068 (IceCube hotspot) is the nearest super-Eddington AGN (!)

AT2019fdr (TDE?): another large dust echo - Reusch et al (arXiv:2111.09390)