# Black hole demographics from variable and transient phenomena

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# Open questions related to supermassive black holes

- How do supermassive black holes form?
- Do intermediate-mass black holes exist?
- What is the nature of changing state AGN?

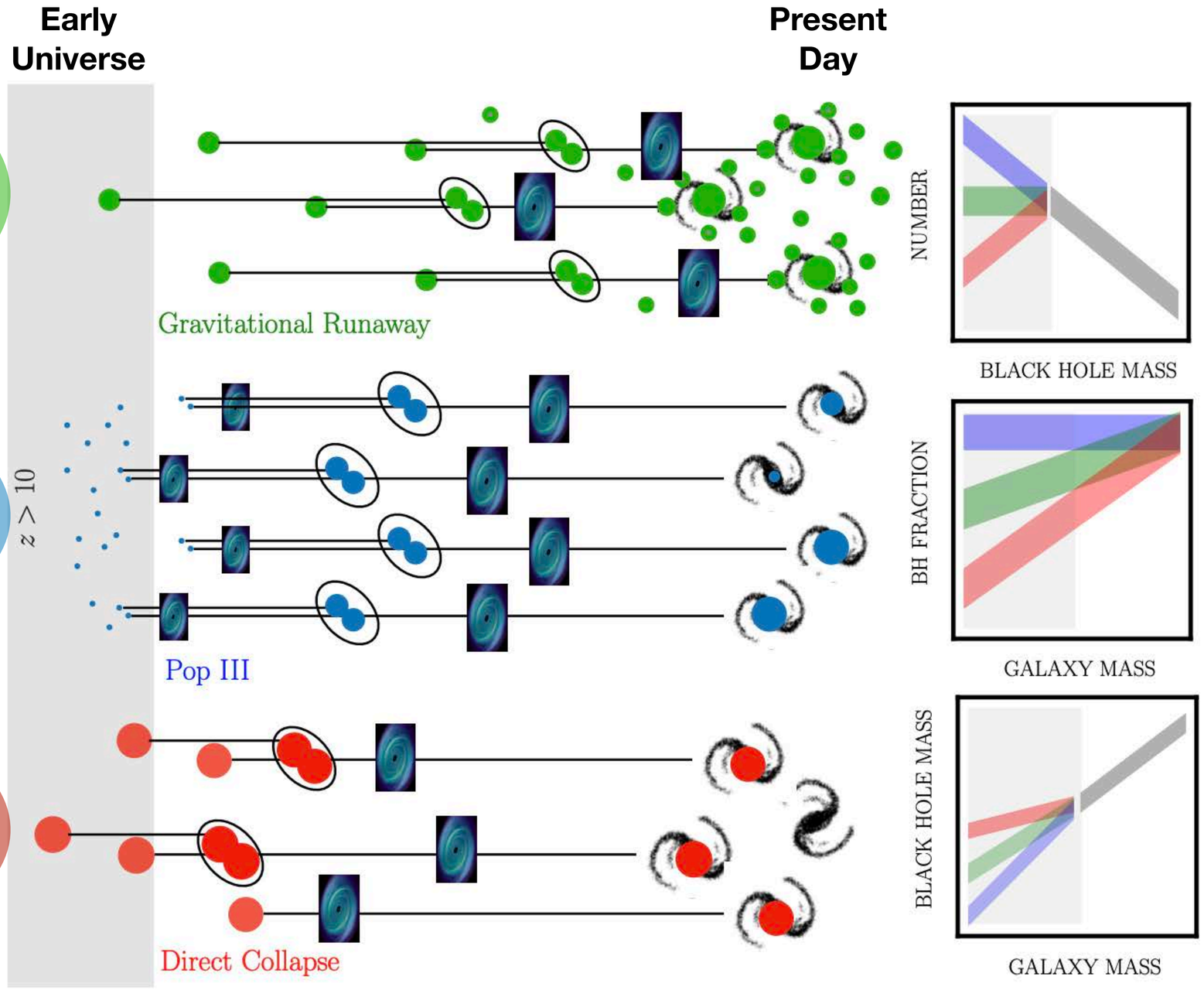
**Variability and transients can help!**

# Intermediate mass black holes and the black hole occupation fraction

BHs form through dynamical processes in star clusters

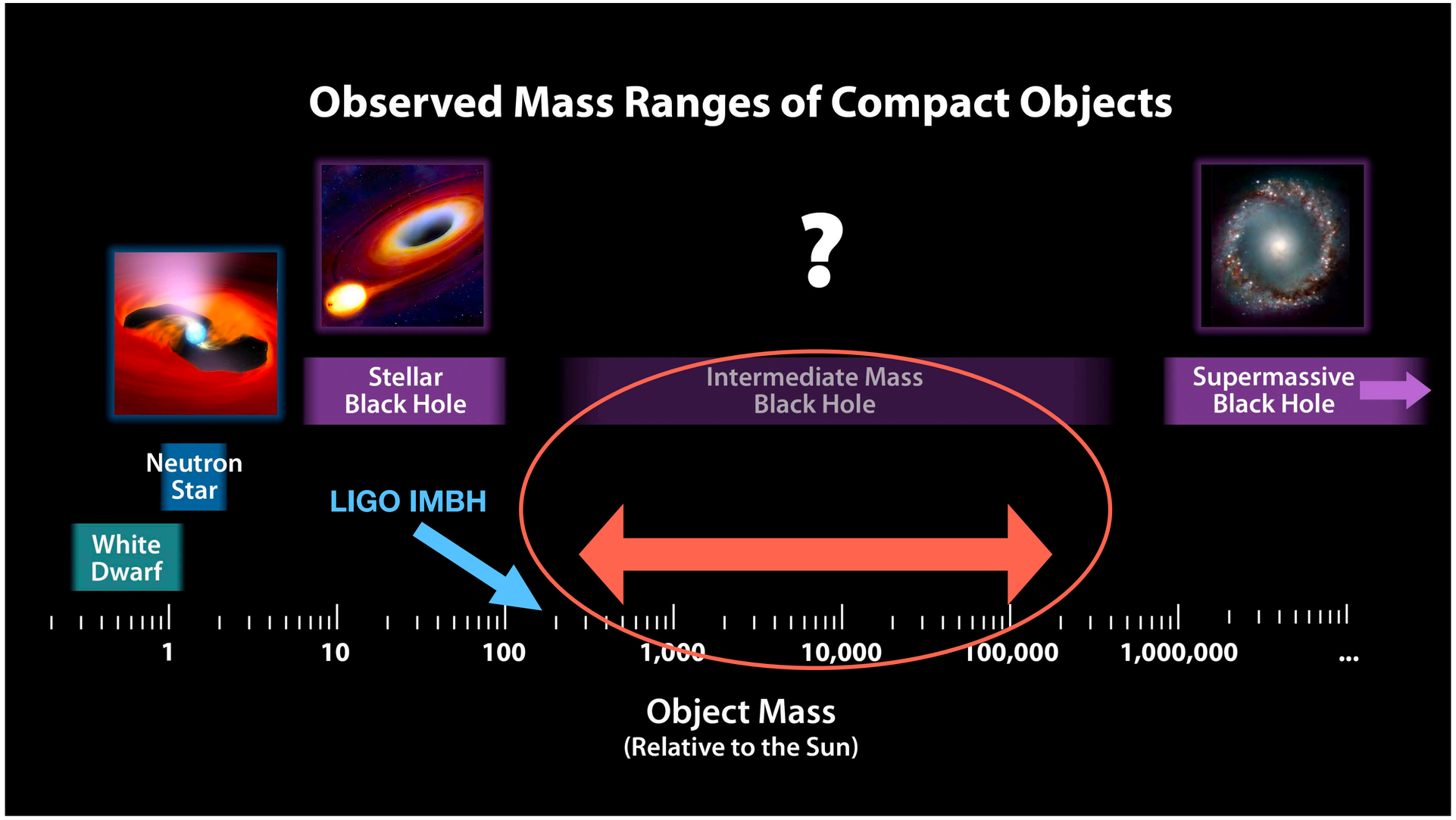
BHs form when massive stars in the early universe die

BHs form when large gas clouds collapse




Greene et al. 2020

# Black holes in dwarf galaxies might be intermediate-mass black holes



# Finding active BHs in low-mass galaxies with variability

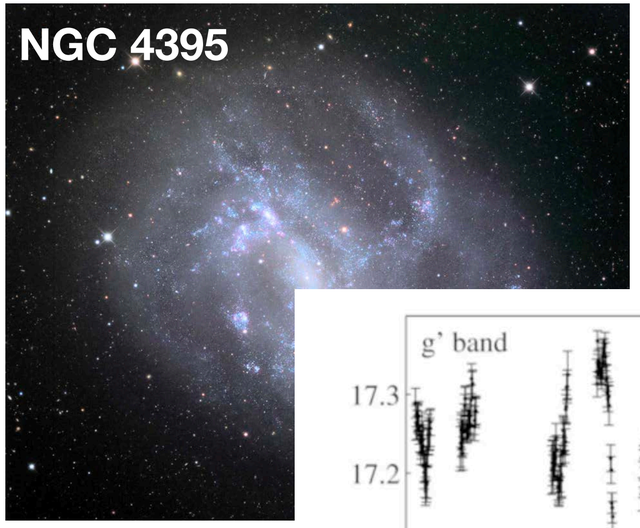
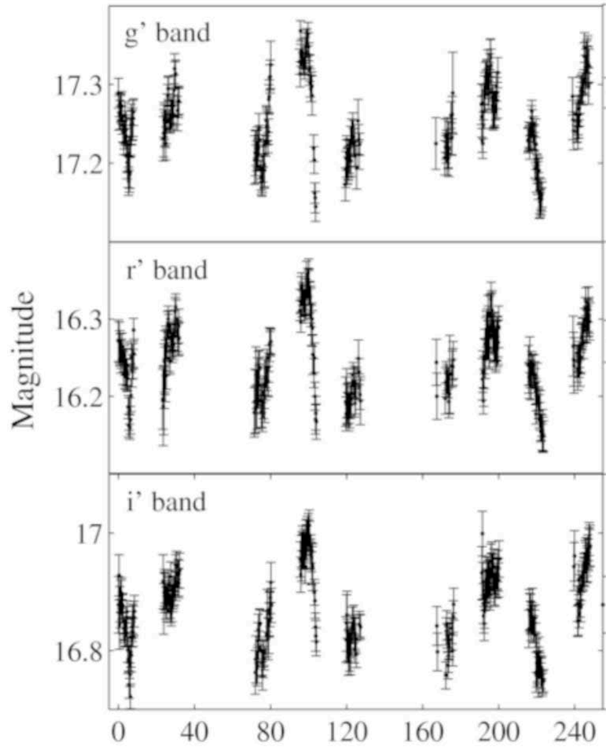



Image credit: Mt. Le

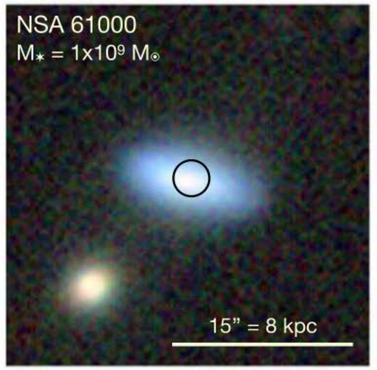


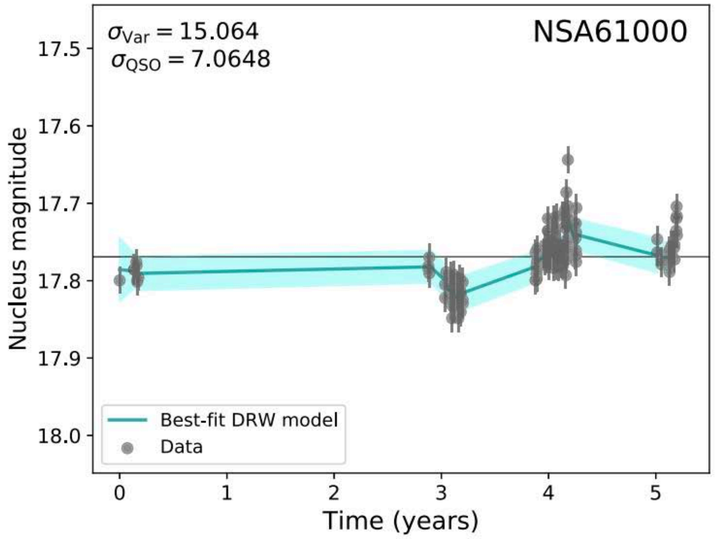

Edri et al. 2012

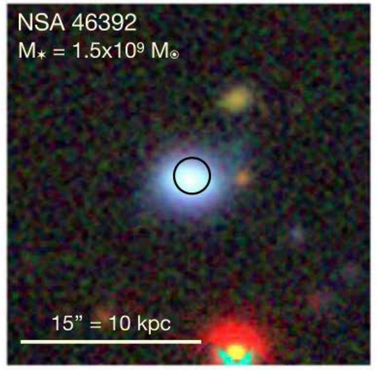
- The low-mass end of the black hole occupation fraction is not well constrained
- Black holes in dwarf galaxies are difficult to find due to small gravitational sphere of influence
- They are also difficult to detect as AGN because of relatively low luminosity and selection biases
- Variability and tidal disruption events can help find black holes in dwarf galaxies and measure their masses

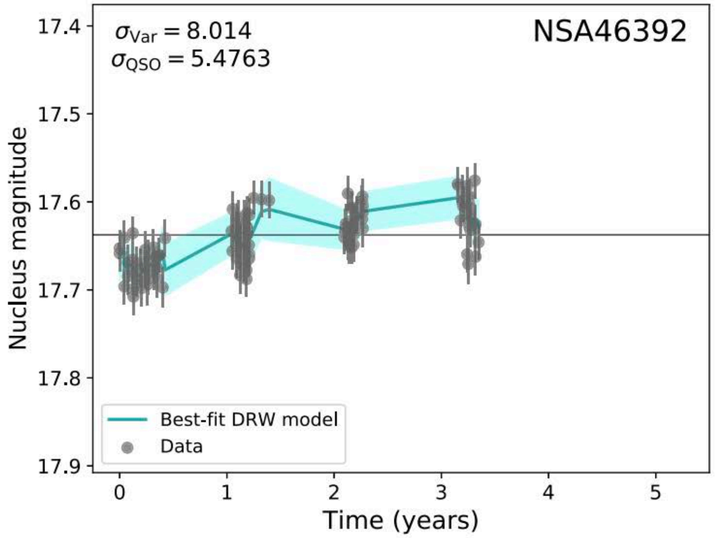
# Optical photometric variability can find AGN in dwarf galaxies

- In Baldassare et al. 2020, we constructed light curves for 35,000 low-mass galaxies in Palomar Transient Factory data
- We found 237 variable AGN with masses between $10^7$ and $10^{10}$ solar masses
- No change in fraction of variable AGN down to $10^9$ solar masses

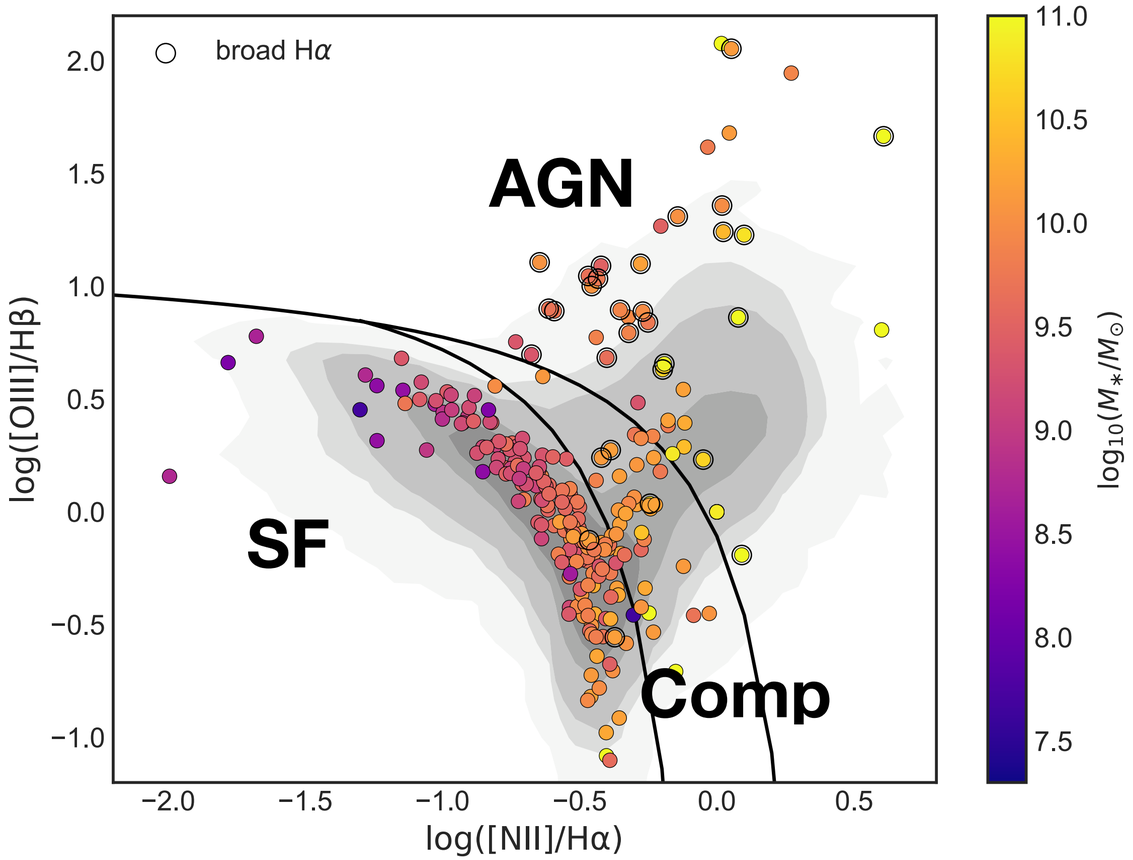


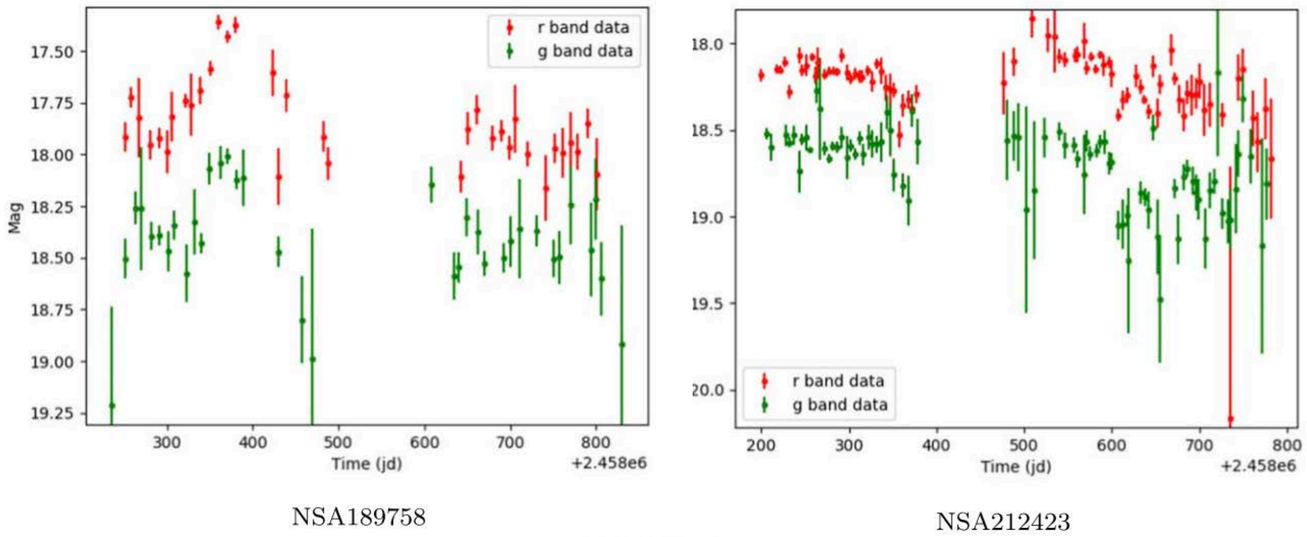
# Most variable AGN in dwarf galaxies are not classified as AGN by optical spectroscopy




Baldassare et al. 2020a

# Similar results have been found in other data sets

**ZTF data**

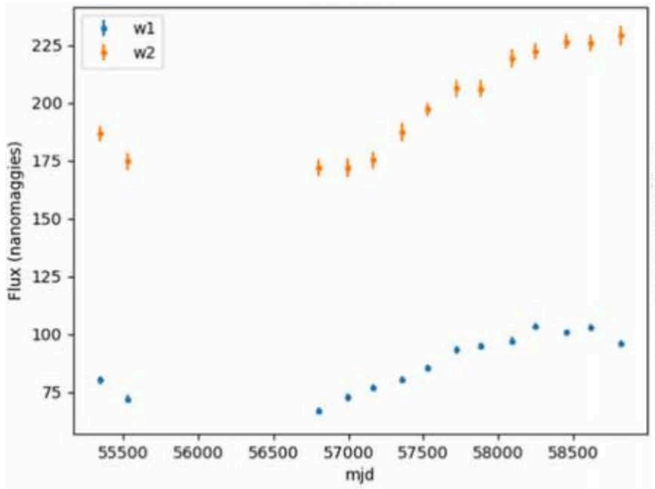



NSA189758

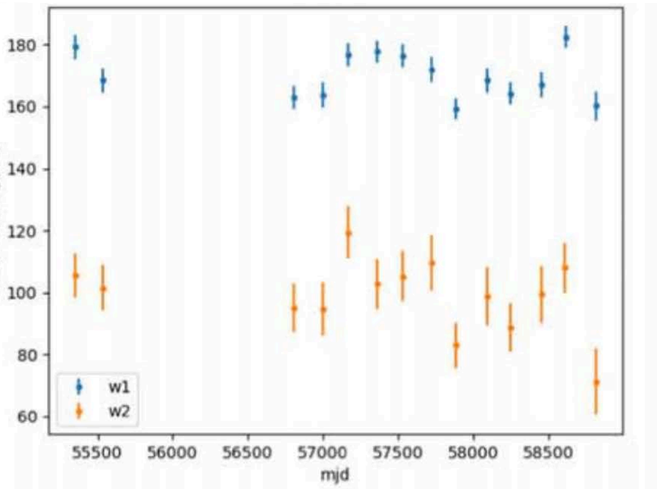



NSA212423

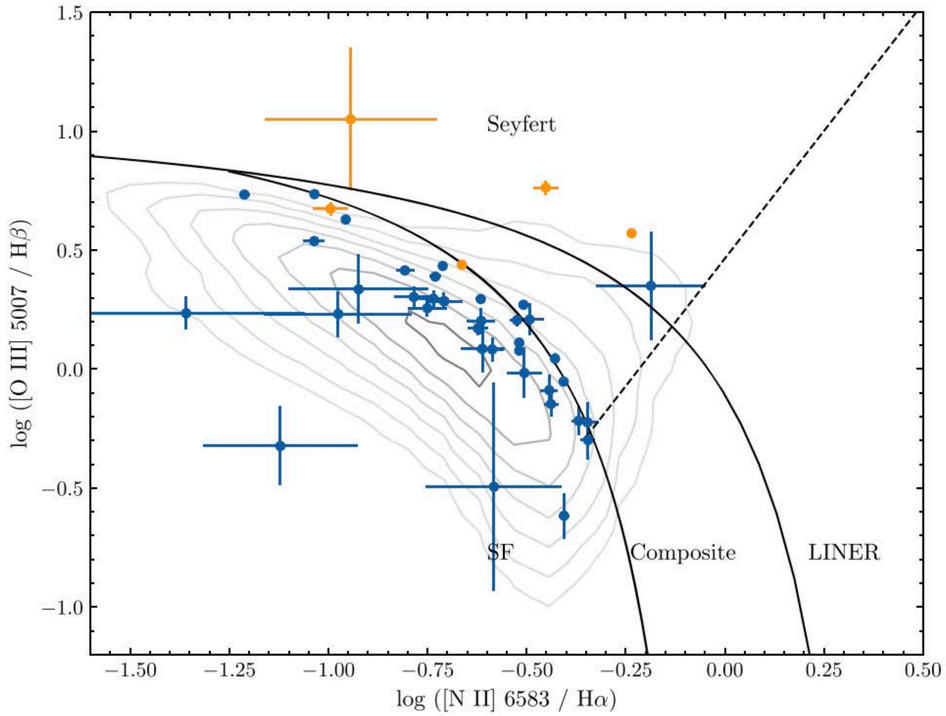
**WISE data**




NSA612283




NSA3045

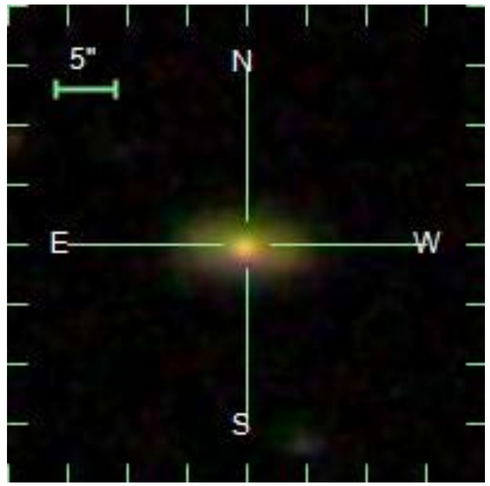


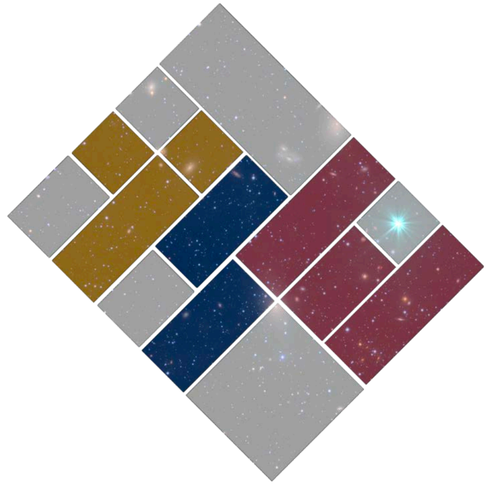

AGN candidates

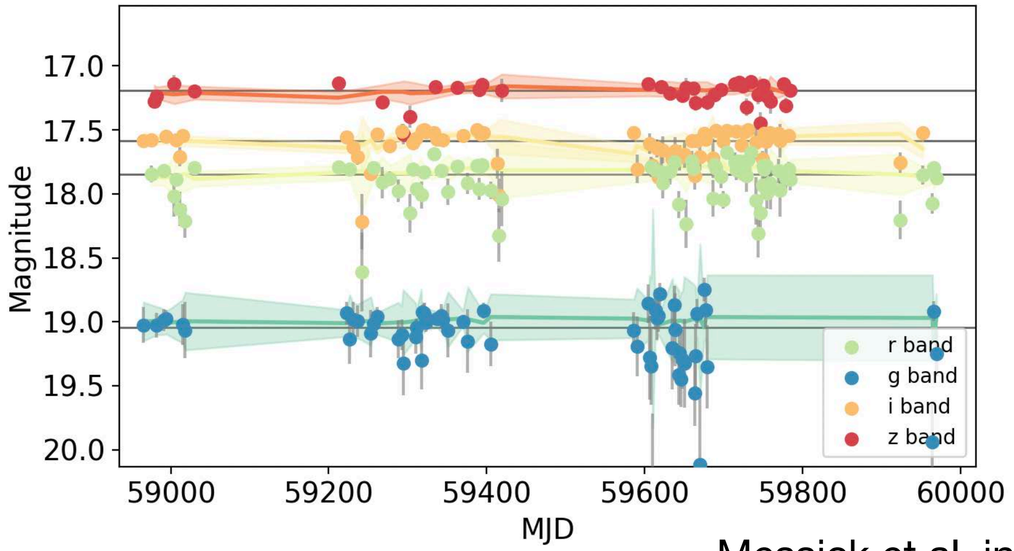
Ward et al. 2022

# Searching for dwarf galaxies with AGN in YSE

- Young Supernova Experiment is a time domain survey with the Pan-STARRs telescopes
- 3 day cadence in griz (and now y!) bands
- Depth of 21.5 mag in gri, 20.5 mag in z
- Using YSE to search for variable AGN in dwarf galaxies

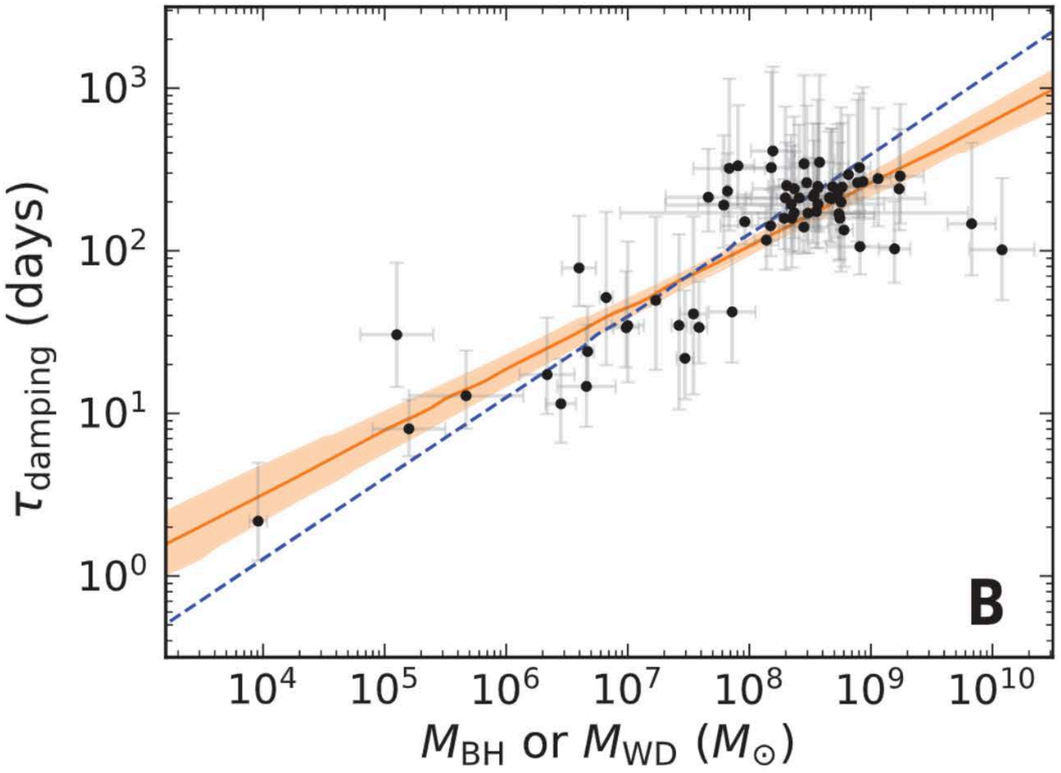





Messick et al. in prep

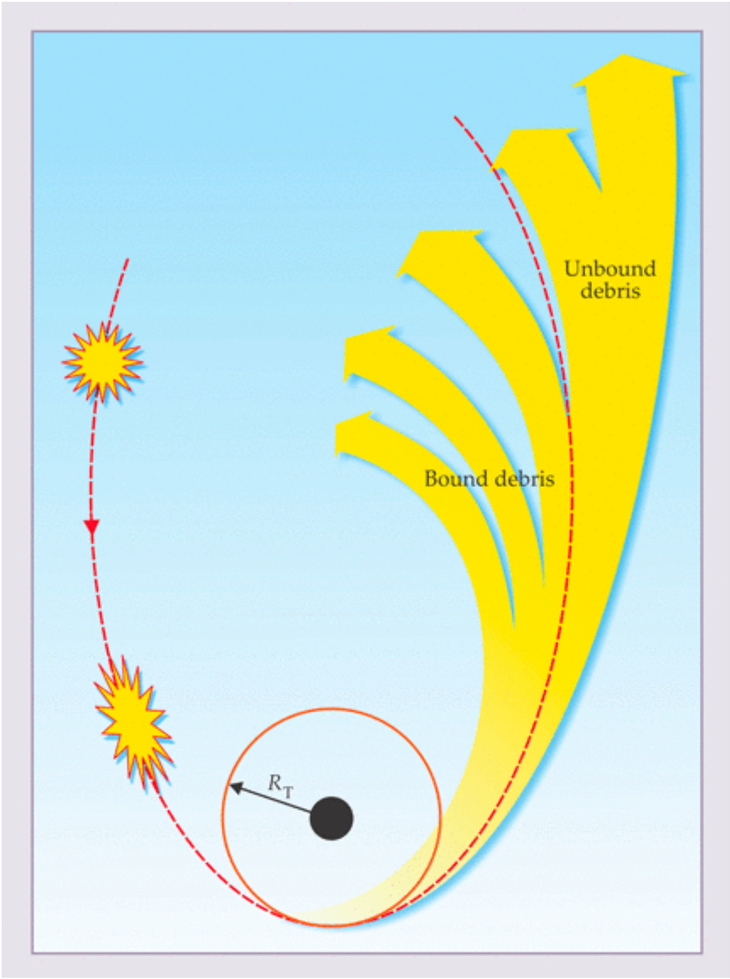
# Black hole masses from variability timescales




Burke et al. 2021

- Burke et al. 2021 finds a relationship between BH mass and variability timescale spanning many orders of magnitude
- Extends into the dwarf galaxy regime (and possibly beyond)
- At the low-mass end, requires high cadence observations since damping timescale is on the order of 1-10 days.

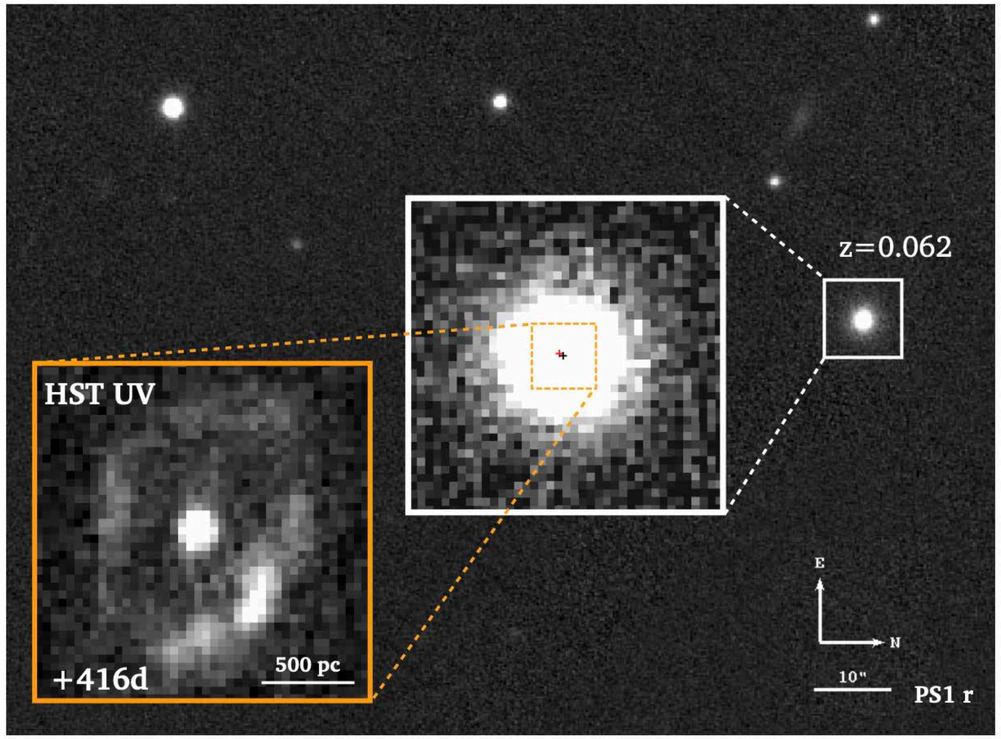
# Tidal disruption events are also extremely important for probing the low-mass end of the BH occupation fraction

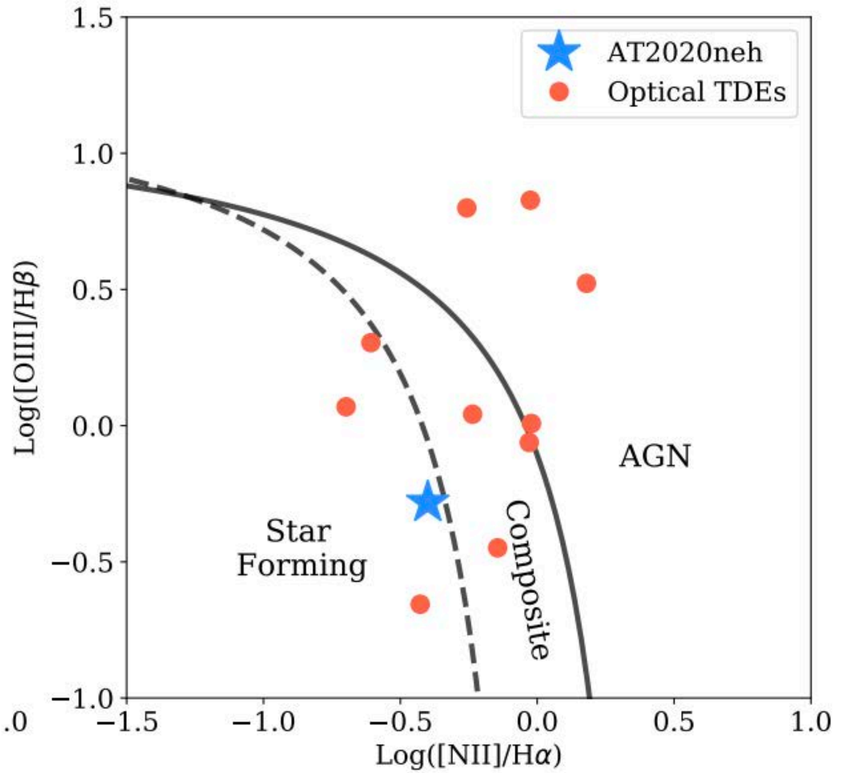



Gezari, Physics Today

- Tidal disruption events can reveal black holes in otherwise quiescent galaxies
- Light curve modeling provides an estimate of the black hole mass (Mockler et al. 2019)
- Rise time theoretically proportional to black hole mass

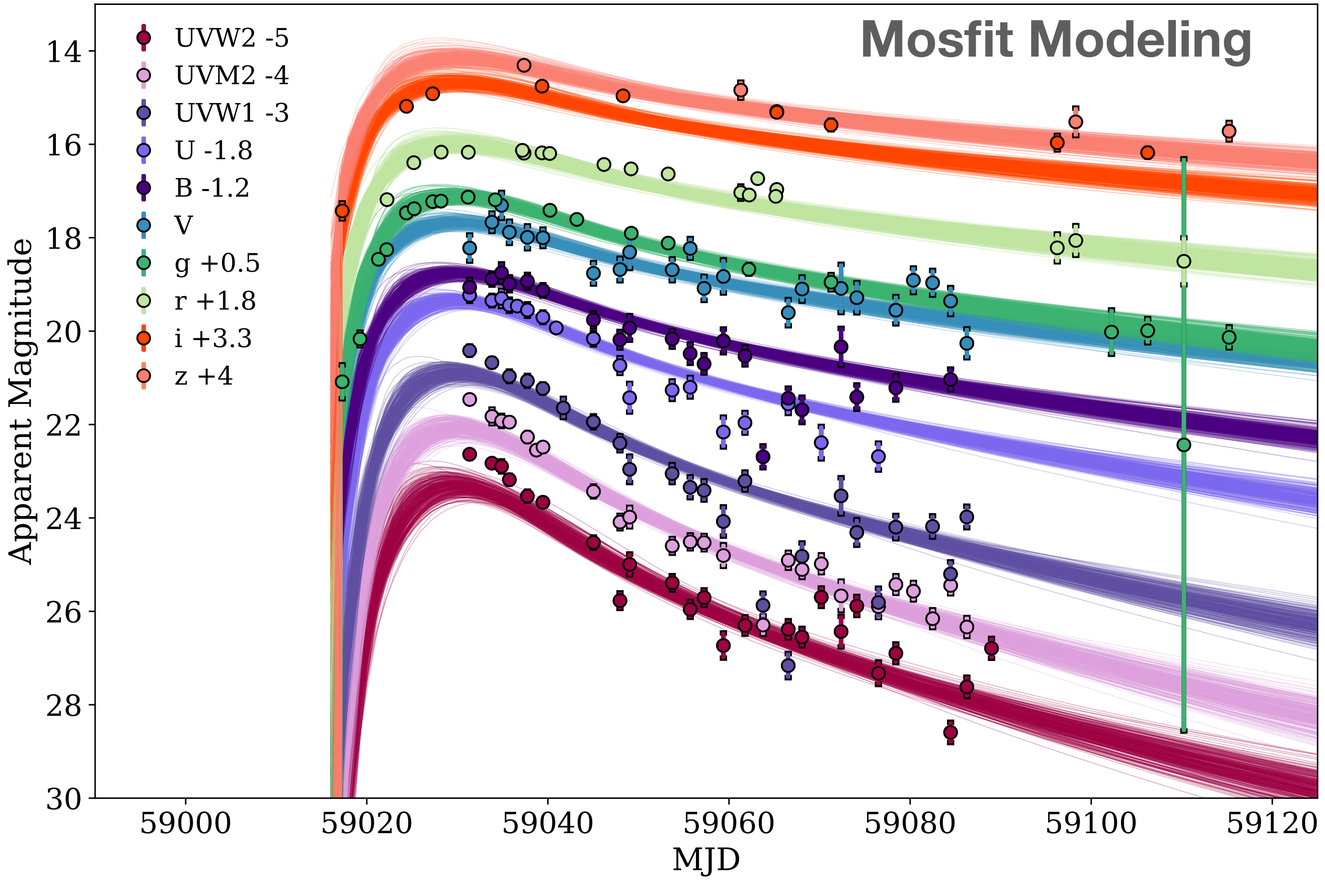
# AT 2020neh: tidal disruption event in a dwarf galaxy




Angus et al. 2022 (Nature Astronomy)

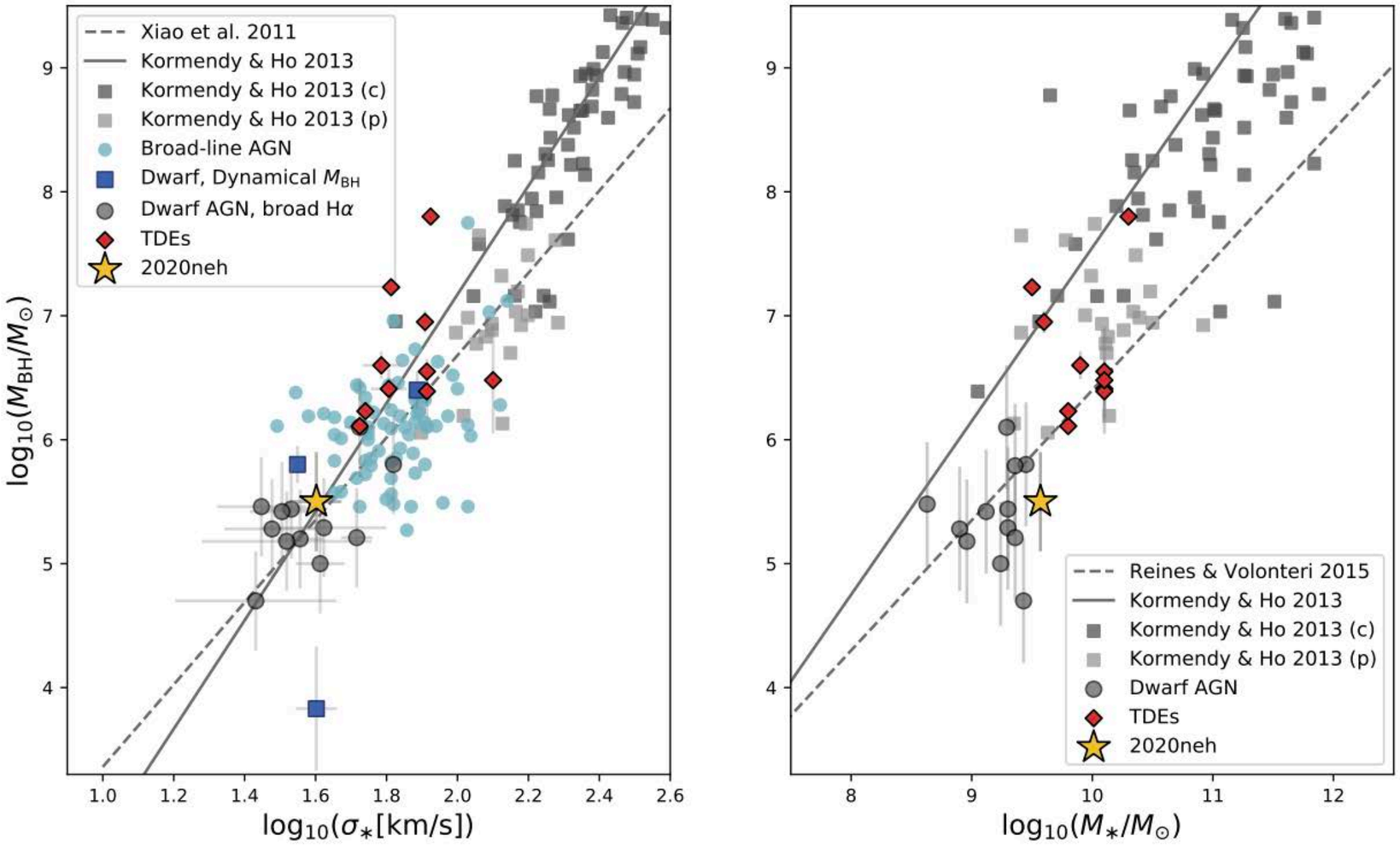
# AT 2020neh: tidal disruption event in a dwarf galaxy




We find that this BH is ~$10^5$ solar masses!

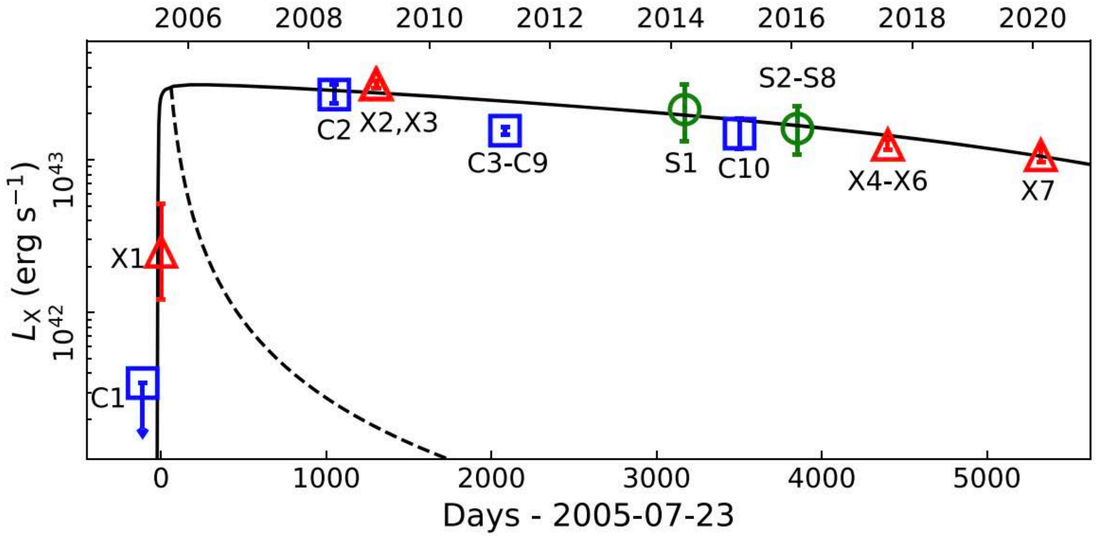
Angus et al. 2022 (Nature Astronomy)

# TDEs are a complementary BH mass estimation technique




Angus et al. 2022 (Nature Astronomy)

# Other IMBH candidates from tidal disruption events




**Irwin et al. 2010**

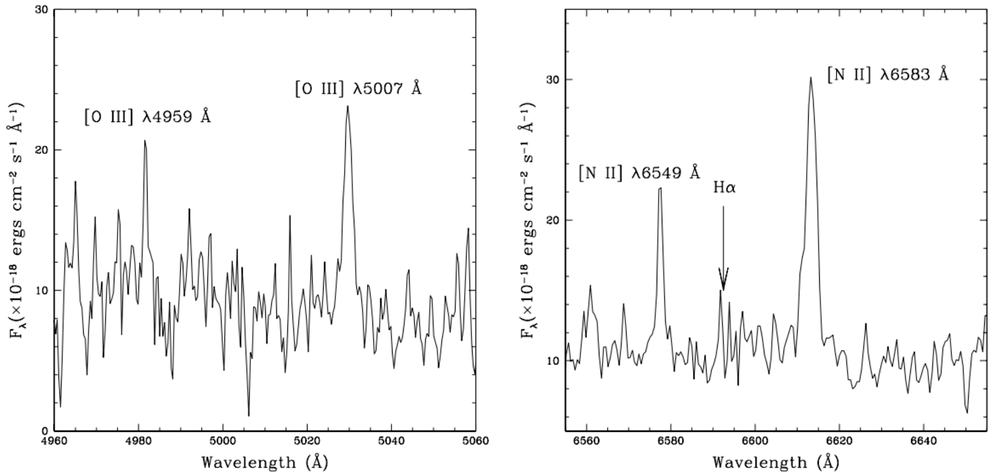
[OIII] and [NII] emission lines in a globular cluster with a bright X-ray source

Bright X-ray source, line widths, lack of hydrogen and helium suggest disruption of a white dwarf by an IMBH

**Lin et al. 2022**

Slow-evolving nuclear X-ray transient in a dwarf starburst galaxy

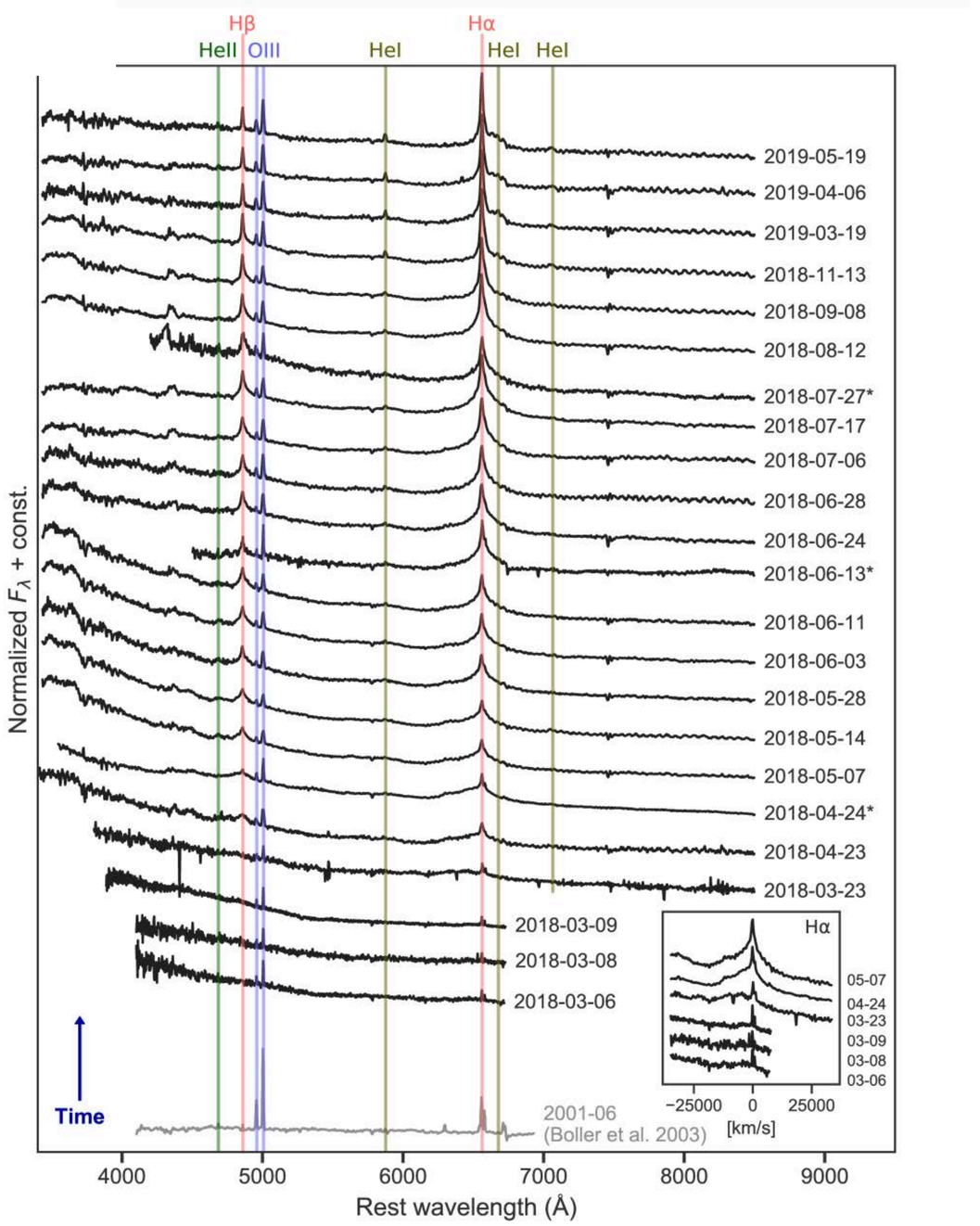
BH mass ~ 2x10$^5$ solar masses



# Diverse population of AGN revealed by variability

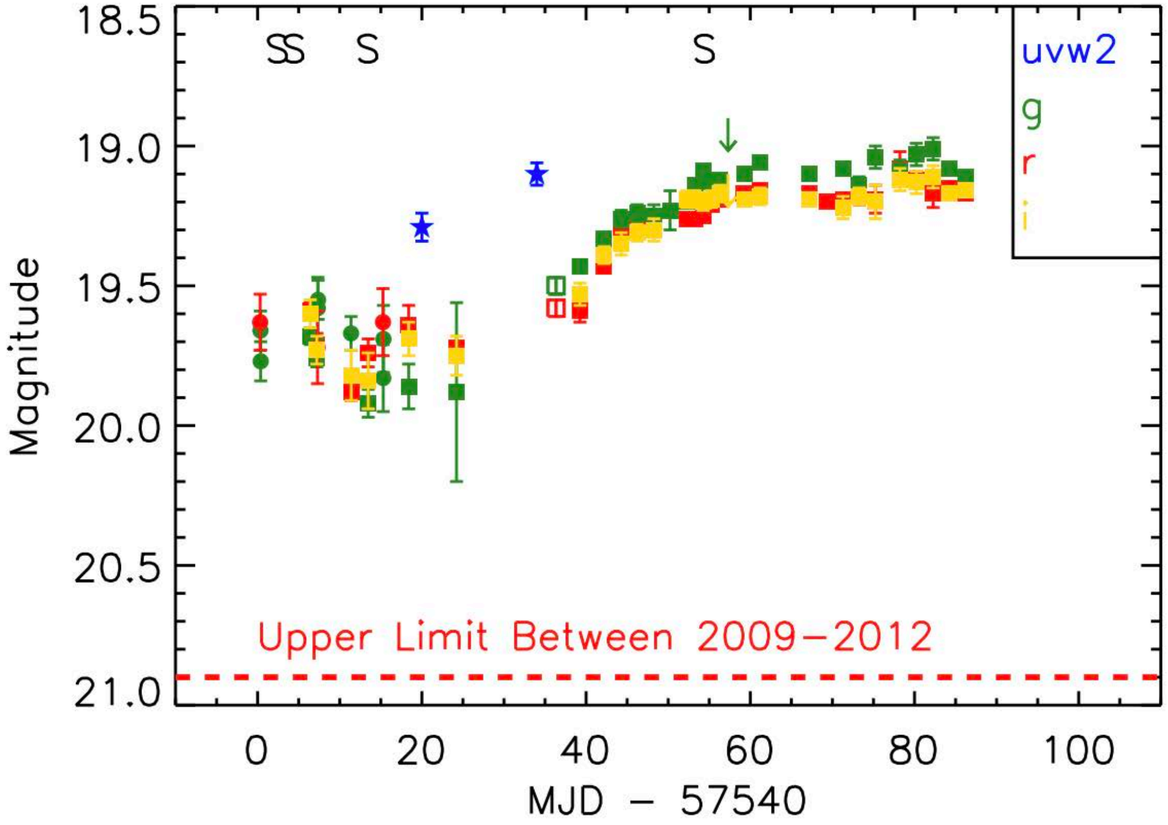
# Changing state AGNs

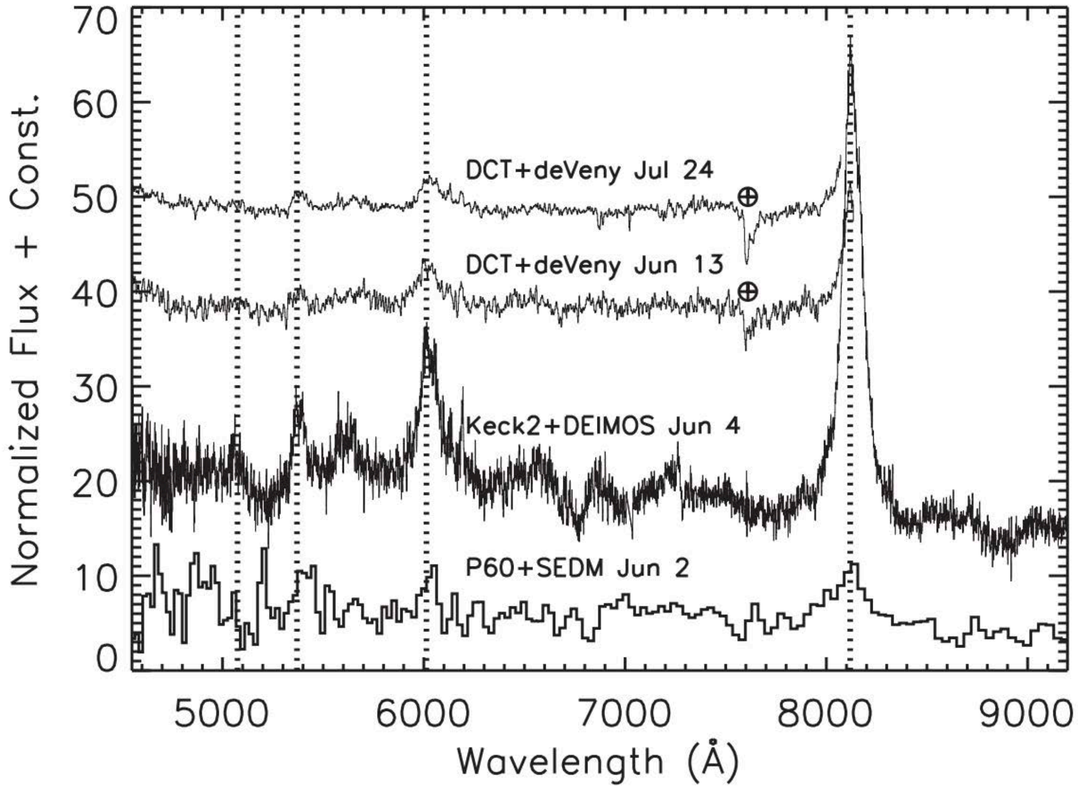
- Repeat spectroscopic observations have revealed a population of “changing state” AGN whose broad lines appear/disappear on years-long timescales
- The origin of the state changes is not well understood
- In order to constrain possible drivers, we need more observations of turn-off and turn-on AGN
  - Measure the rate of these events
  - Diversity of properties




Ricci & Trakhtenbrot 2022

# Many turn-on changing state AGN are found through their photometric variability

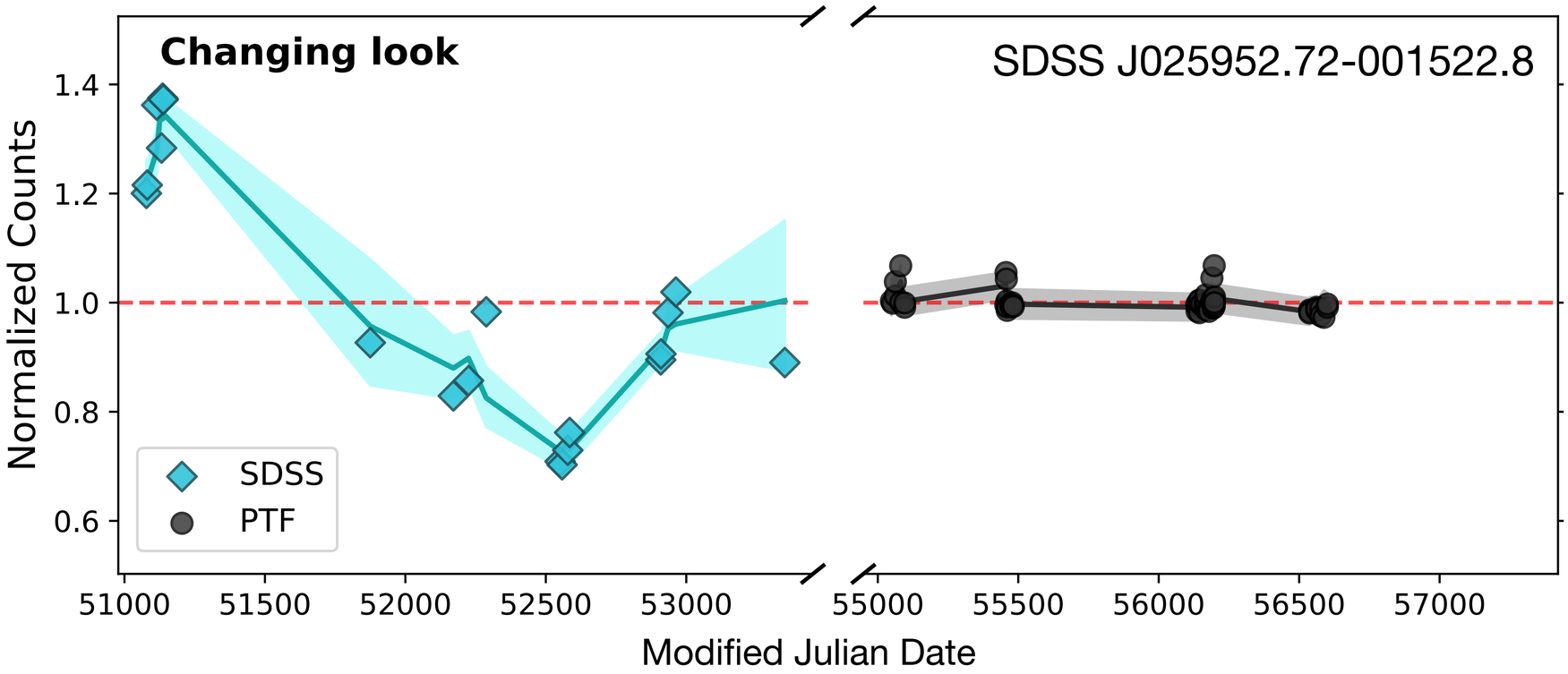



Gezari et al. 2017

# Changing state AGN from Stripe 82 and PTF

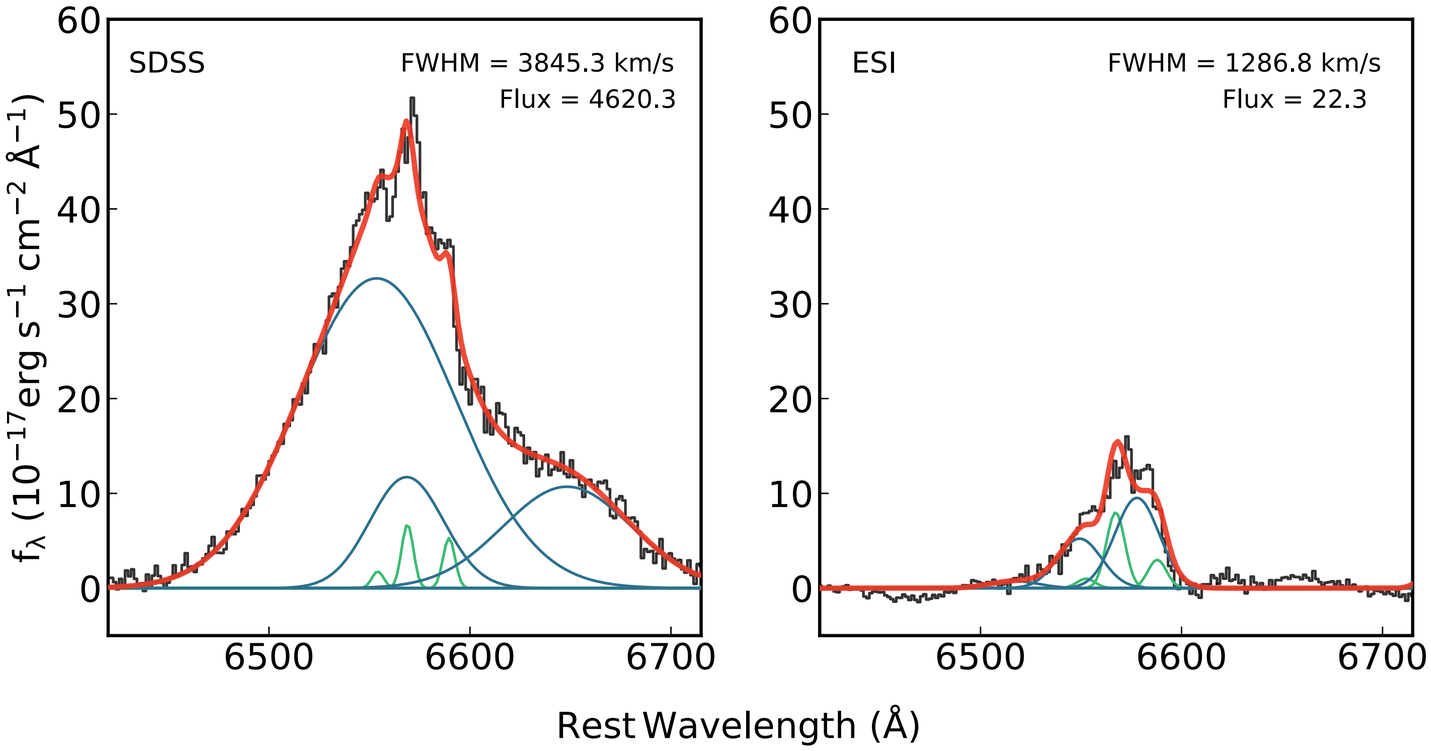
- Comparing light curves of broad line AGN in Stripe 82 (2000-2008) and PTF (2008-2017)
- Population of AGN that were variable in Stripe 82 and quiescent in PTF




Baldassare et al. in prep

# Follow-up spectroscopy show that these are changing-state AGNs

- 8/42 broad line AGN that were variable in Stripe 82 show no variability in PTF observations
- Took follow-up spectroscopy of four of these
- All four showed changing state behavior
- At least 4/42 variable broad line AGN underwent state change over 20 years




Baldassare et al. in prep

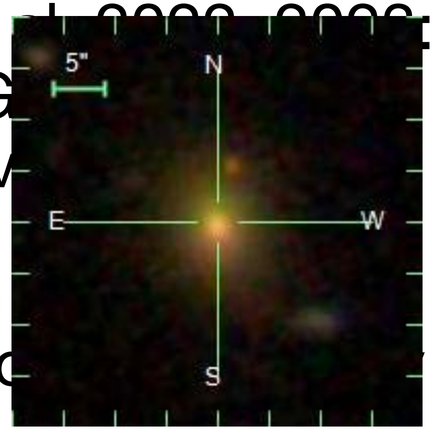
# Variability reveals AGN in unlikely places

- Wasleske et al. 2020, 2022: analysis of G… Domain Surv…

Old stellar population

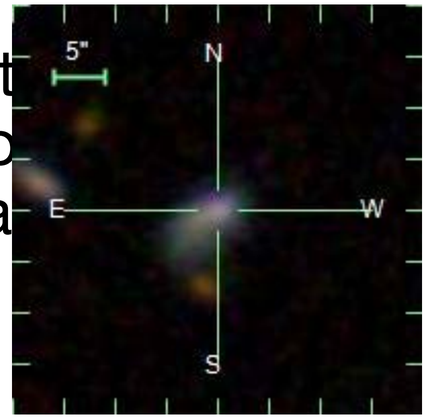
Bright X-ray source

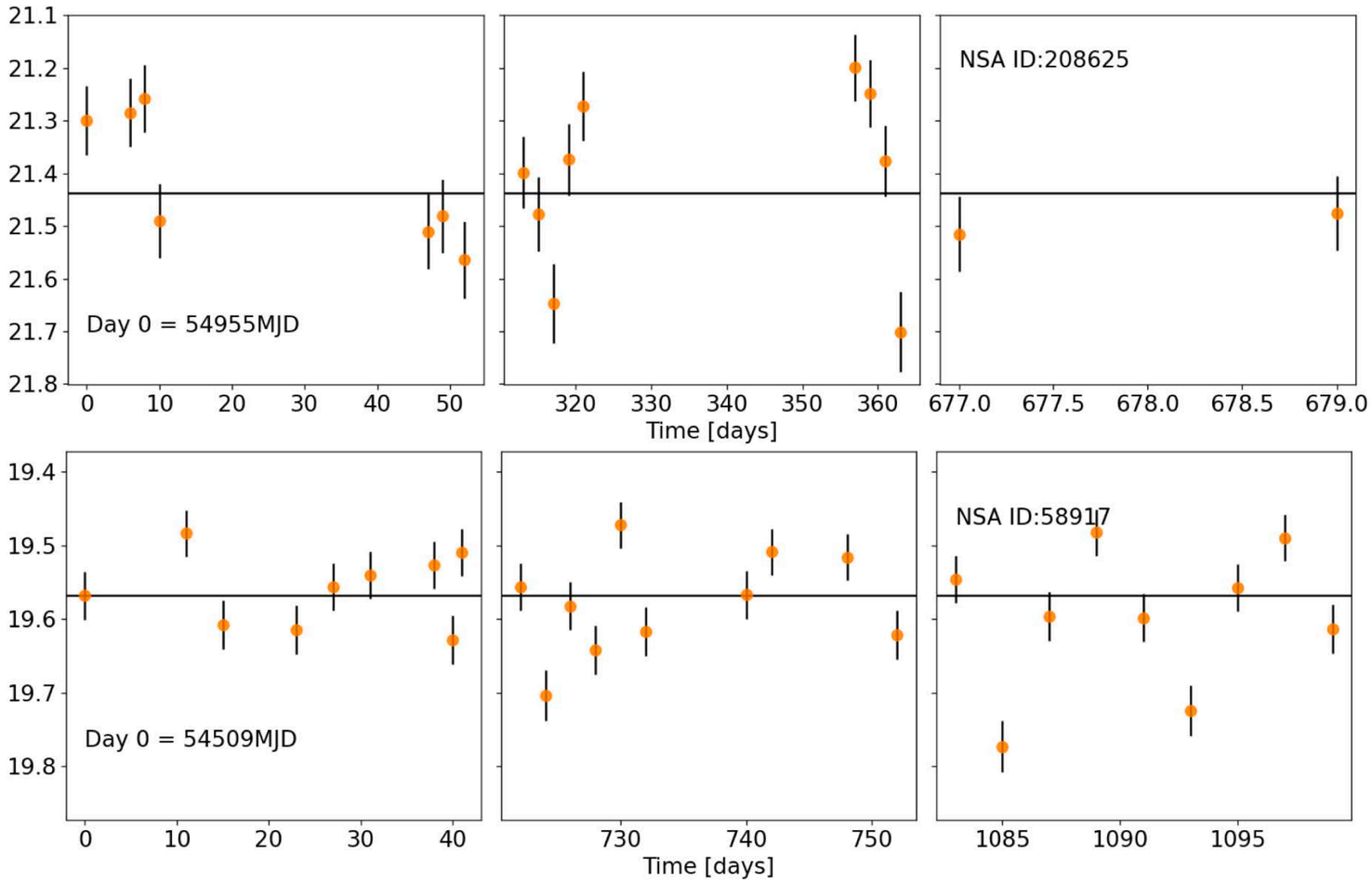
- Identified 48 … in a sample o… galaxies




- Some in syst… old stellar po… some in dwa…

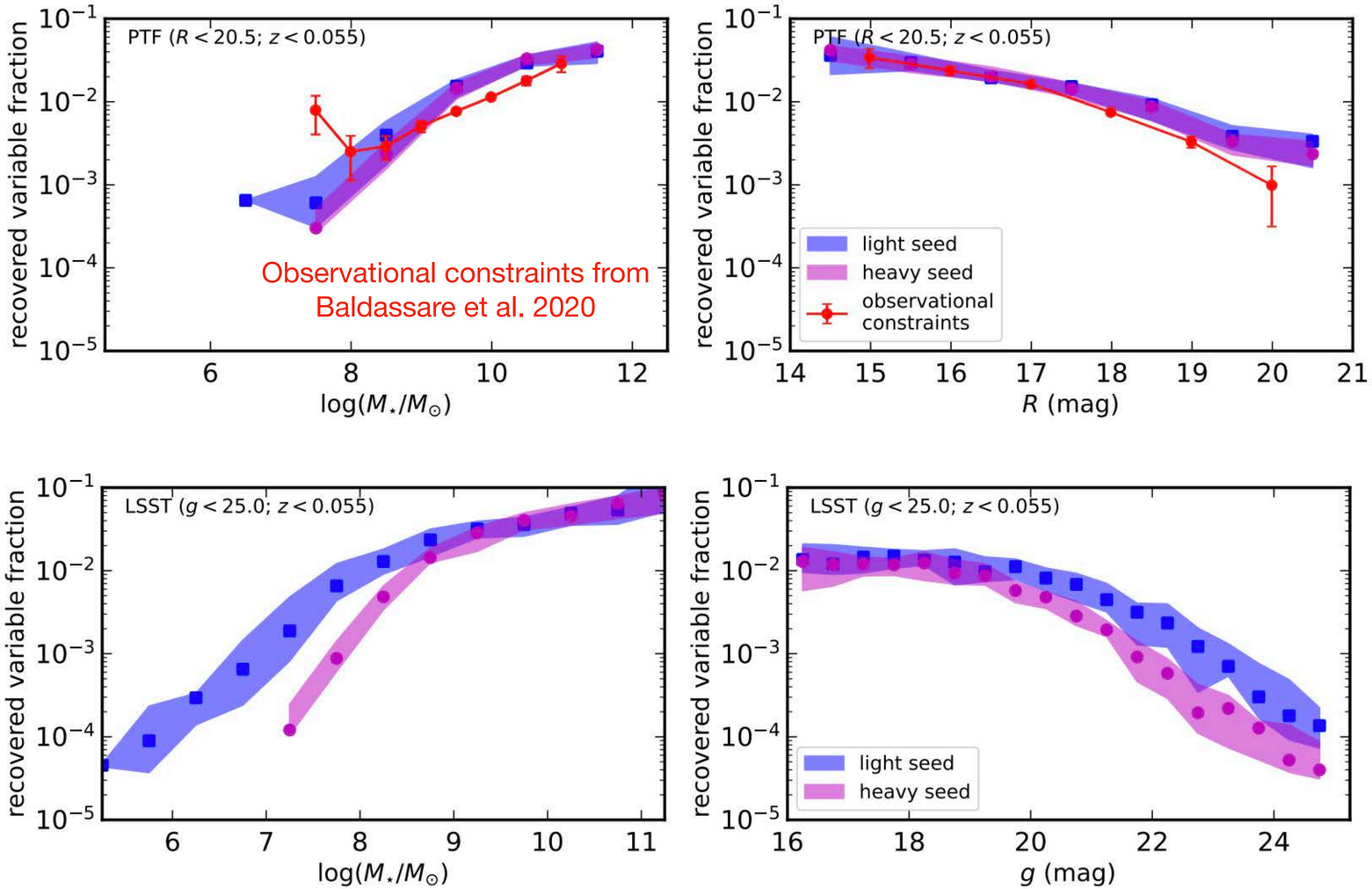
Dwarf galaxy!



# Future prospects

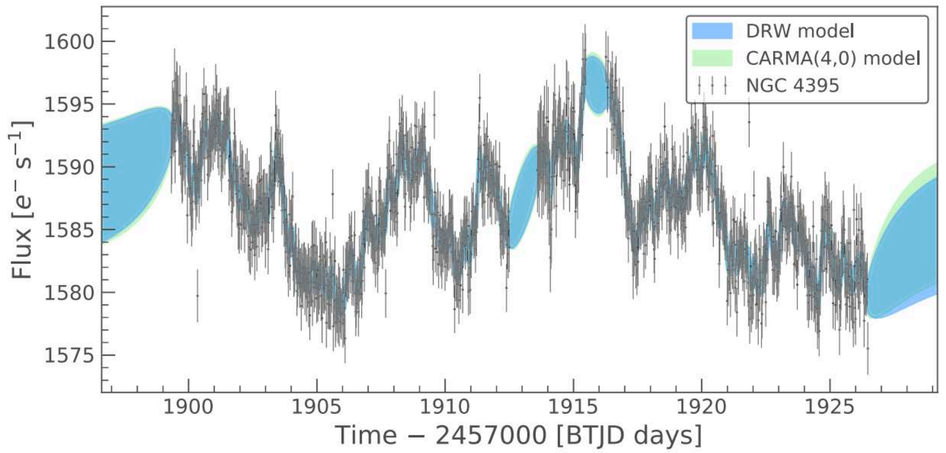
# Rubin Observatory should be able to distinguish between light and heavy seed models




Burke et al. 2022

# Future prospects and challenges

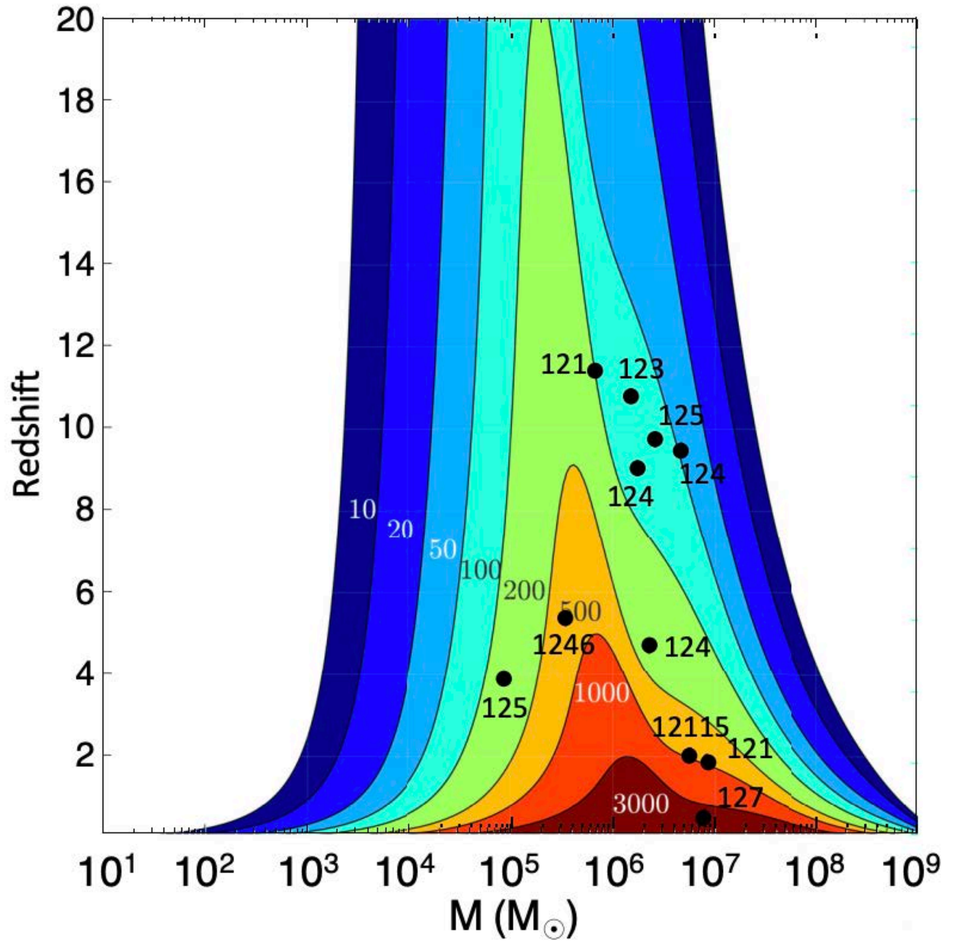
- Population of variable AGN in dwarf galaxies found with Vera Rubin Observatory can distinguish between BH seed formation models
- Need **deep, high cadence** observations to constrain BH masses in dwarf galaxies with variability
- We are discovering increasing numbers of TDEs, which should lead to more BH mass measurements in dwarf galaxies (including IMBHs!)




**TESS light curve of NGC 4395 (Burke et al. 2020)**

# LISA will be perfect for detecting IMBHs

- LIGO is already pushing on the IMBH regime from the low-mass end
- LISA will be able to detect IMBH mergers out to high redshift to reveal the merger histories of black holes




Bellovary et al. 2018

# Take aways

- Variability and transients are key for filling in an important part of black hole mass parameter space
- Variability can find interesting populations of black holes that are missed by other AGN selection techniques
- Deep, high-cadence observations will be needed to estimate BH masses in dwarf galaxies
- **Important to create light curves for “normal” galaxies, facilitate searches for variables and transients in extended sources**