# Out of left field: Searching for recoiling SMBHs and wandering IMBHs with the Zwicky Transient Facility and LSST

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# Outline

Previous work with ZTF:

- Gravitational wave recoil of SMBHs
- Outbursting LBVs
- ‘Hidden’ intermediate mass BHs

Future work with LSST:

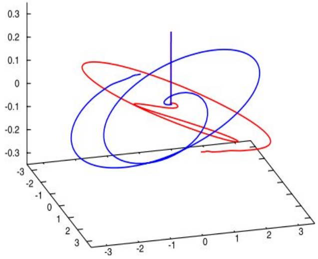
- A more sensitive search for IMBHs
- Variable high-z QSOs
- Strongly gravitationally lensed SNe
- Role of large spectroscopic surveys


# Gravitational wave recoil of SMBHs

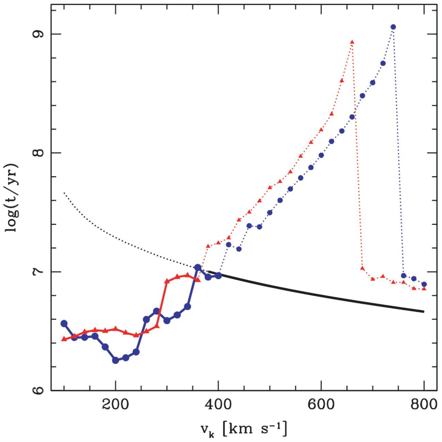
Constraining the spin ratios of SMBH mergers
Forward modeling of ZTF images
Nine recoiling SMBH candidates

# Supermassive black holes can be kicked out from their galaxy center

- Asymmetry in GW emission during **SMBH coalescence** gives momentum to the merged black hole.
- SMBH kicked up to ~**20 kpc** away from the galactic center at velocities up to **5000 km/s**.
- Broad line region carried away with the SMBH.
- BHs wander for $10^6$ - $10^9$ years.
- Effective time for off-center activity is $10^{6.2}$ - $10^7$ years for any kick velocity.



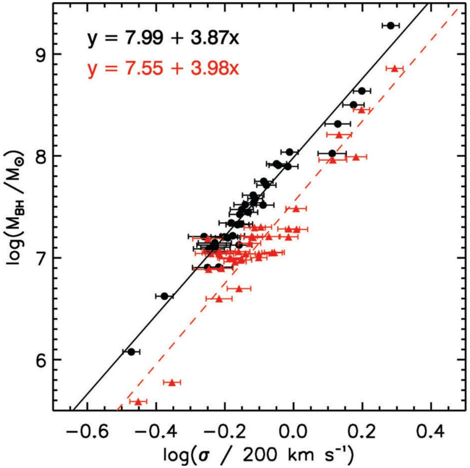
Campanelli et al. 2007



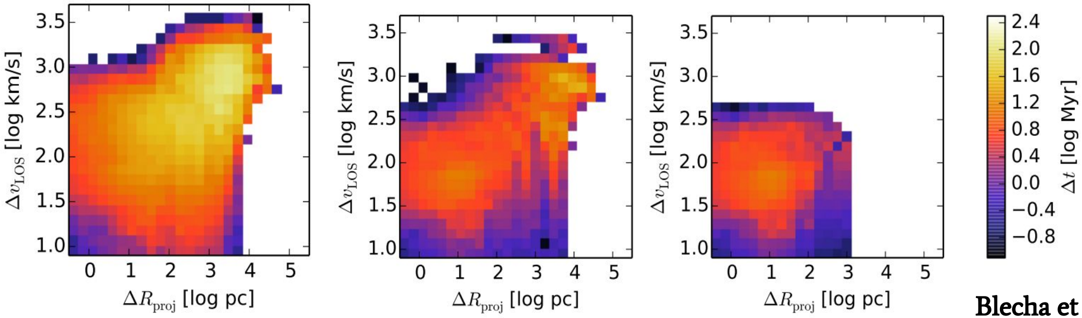

Blecha and Loeb 2008

# Recoiling SMBHs trace binary spin alignment

- Can study **efficiency of SMBH binary spin alignment** due to torques in the circumbinary gas disk and stellar interactions during inspiral.
- Can study **growth of SMBHs in the galaxy halo**, and the effect of recoil on the $M_{BH} - \sigma*$ relation.




**Blecha et al. 2011**

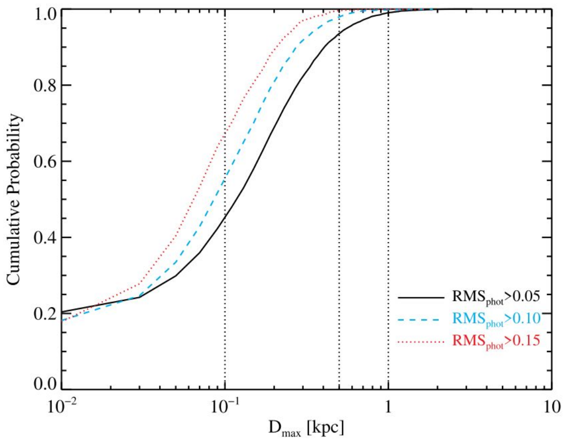



**Blecha et al. 2016**

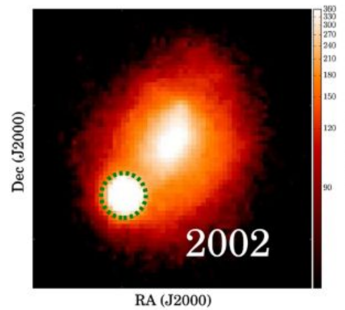
Randomly aligned spins　Mixture of spin scenarios　Perfectly aligned spins

# Visible recoiling SMBHs are rare

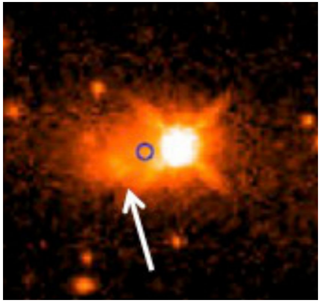
- ~20 candidates have been published to date.
- Detailed IFU, X-ray and radio analyses needed to rule out alternative explanations and AGN imposters.
- Off-nuclear AGN are not common: Gaia varstrometry shows that 99% of low z broad line AGN are within 1 kpc of the host, 90% within 500pc and 40% within 100 pc (Shen+ 2019).

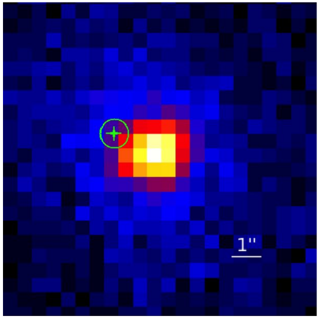



Shen et al. 2019




SDSS1133 (Koss et al. 2014)

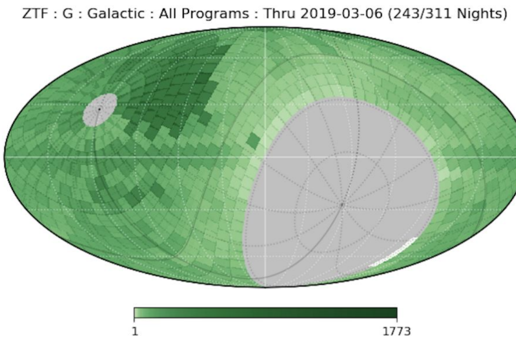


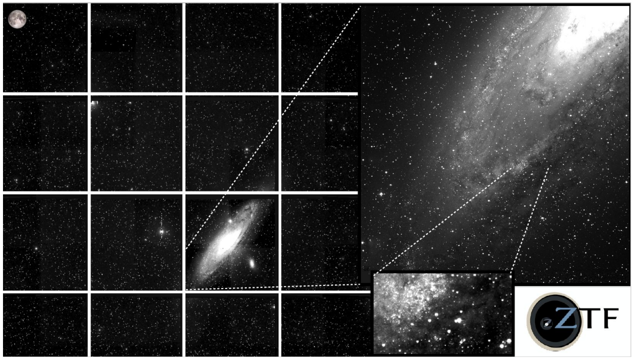


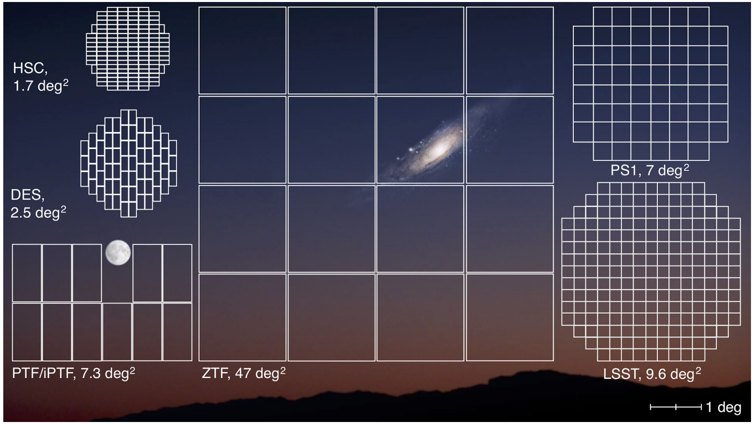

3C 186 (Chiaberge et al. 2017)

# The Zwicky Transient Facility

- Started in 2018 and Phase II is ongoing.
- 47 square degree FOV
- Mounted on the 48 inch Samuel Oschin Schmidt telescope at Palomar.
- ~20.5 mag in g, r and i band in a 30 second exposure.
- Average cadence once per 3 days.
- Covers declinations > -30 deg.



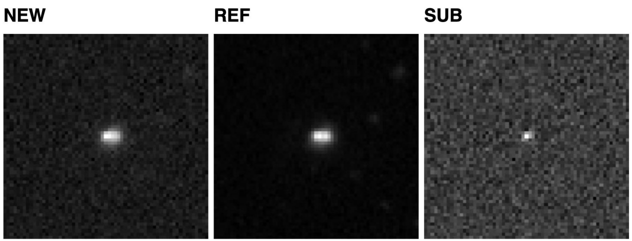
# ZTF difference imaging can find offset AGN

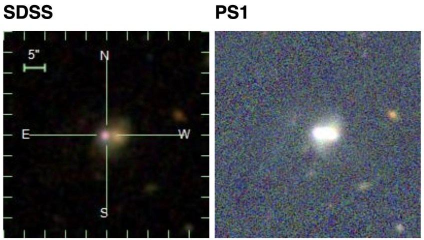
**Goal:** Search for transients with AGN-like variability which are spatially offset from their host galaxy.

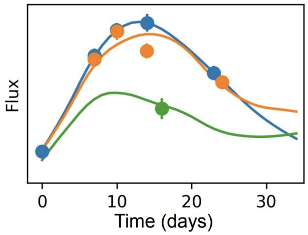
ZTF can:

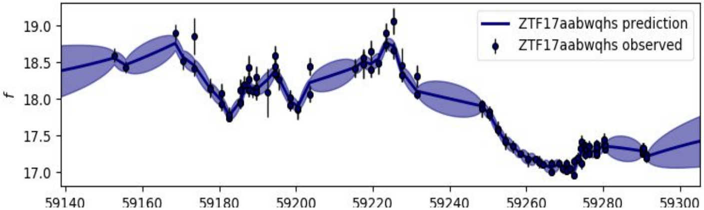
- **Find new AGN** by their variability.
- **Confirm** that AGN emission is from an **off-nuclear** source.
- Automatically identify offset sources during filtering.

Our ZTF filter used AGN catalogs and light curve modeling to find 5000 variable off-nuclear AGN candidates.



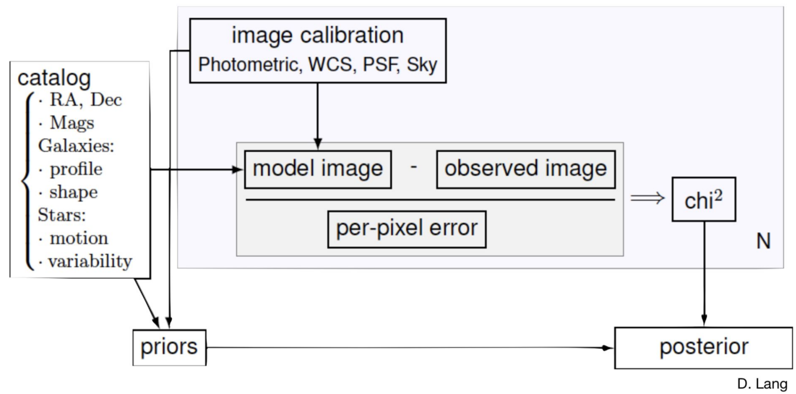



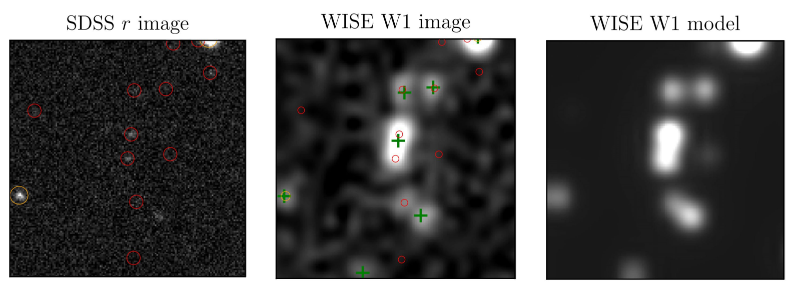



# Forward modeling with *The Tractor*

- Simultaneously models images with different pixel scales, limiting magnitude, bands etc.
- Models blended sources well.
- Tractor modelled the DECaLS, BASS, MzLS and WISE surveys to create galaxy photometry catalogs for DESI target selection.
- Rigorous approach to fitting the differing PSF and pixel sampling of the different imaging data.




Lang, Hogg and Schlegel (2016)

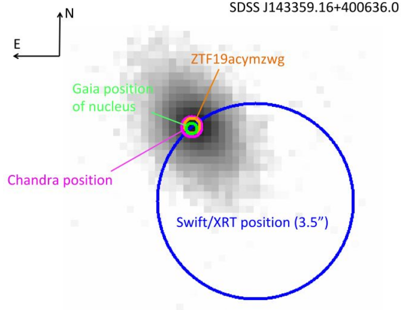

Dey et. al (2019)

# Forward modeling for transient astronomy

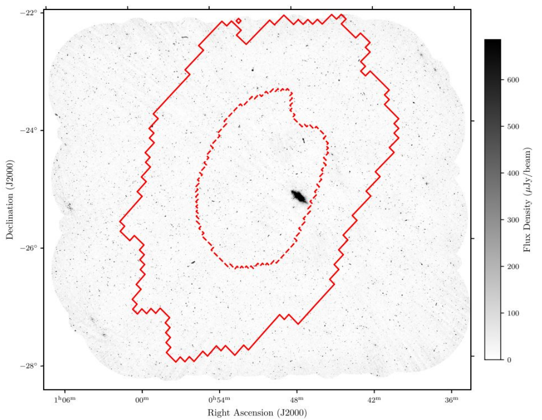
- We implemented a forward modeling pipeline for transients in the Palomar Transient Factory and ZTF.

- This was demonstrated for a range of applications on:

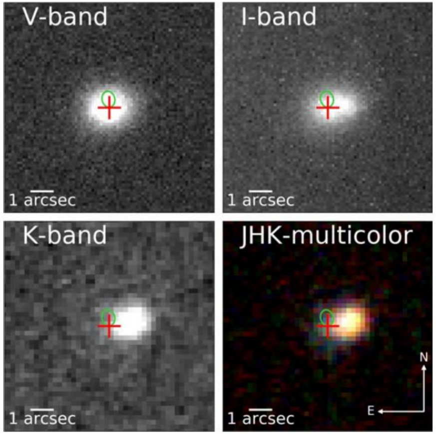
  - TDEs (Brightman et al. 2020)
  - FBOTs (Coppejans et al. 2020)
  - GW emitting mergers (Dobie et al. 2019; Andreoni et al. 2020)
  - Exoplanets (van Roestel et al. 2019).




**Brightman, Ward et al. (2020)**




**Dobie et al. (2019)**




**Coppejans et al. (2020)**

# Results from *Tractor* modeling of ZTF AGN

- In our sample of **~5000 optically variable ZTF AGN**, we confirmed **251 offset AGN**.
- **9 were recoiling SMBH candidates**
- **52 were AGN in mergers**.
- One new dual AGN spectroscopically confirmed.

THE ASTROPHYSICAL JOURNAL

AGNs on the Move: A Search for Off-nuclear AGNs from Recoiling Supermassive Black Holes and Ongoing Galaxy Mergers with the Zwicky Transient Facility

Charlotte Ward[1], Suvi Gezari[1,2], Sara Frederick[1], Erica Hammerstein[1], Peter Nugent[3,4], Sjoert van Velzen[1,5], Andrew Drake[6], Abigail García-Pérez[7], Immaculate Oyoo[8], Eric C. Bellm[9] + Show full author list

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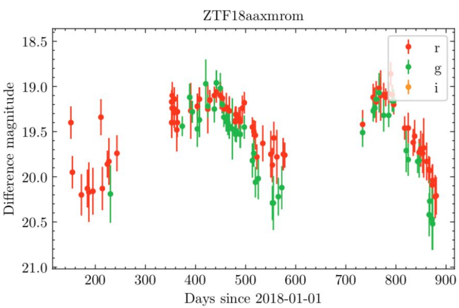
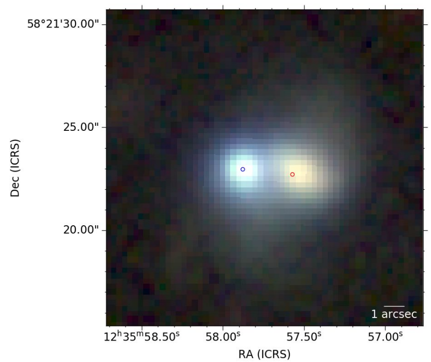
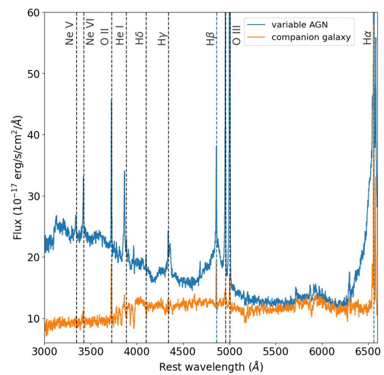
**Citation** Charlotte Ward *et al* 2021 *ApJ* **913** 102



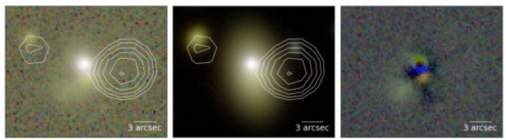



# 9 recoiling SMBH candidates

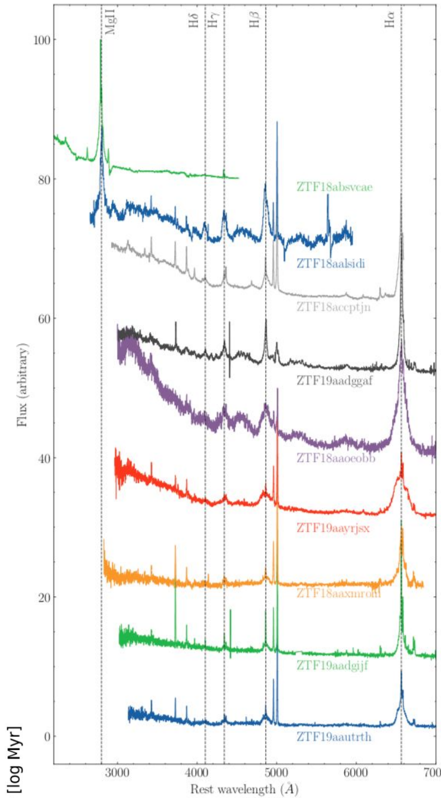
- 9 recoil candidates with a variable point source associated with a disturbed host galaxy.
- 7 had X-ray detections and 4 had radio detections.
- The large (2-22 kpc) spatial offsets only possible when SMBH binary spins are misaligned.

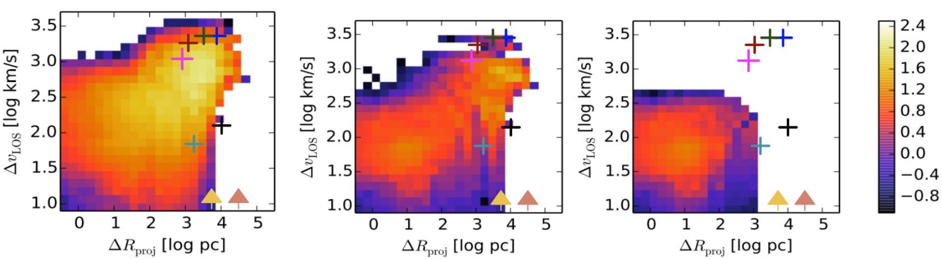
(a) ZTF19aautrth



(c) ZTF18aaxmrom

(e) ZTF18aalsidi




Ward *et al.* (2021a)

# Accretion disk and radio jet morphologies

- 5 were ‘double-peaked emitters’ - a higher fraction than the 16% observed for variable ZTF AGN overall.
- Radio analysis of ZTF18aaxmrom by Gabányi et al. (2021) confirmed radio point source coincident with AGN and jets consistent with inclination found from accretion disk modeling.
- Lobe size indicated formation of jets ~ 3 $\times 10^5$ yrs ago, consistent with predicted time since recoil.

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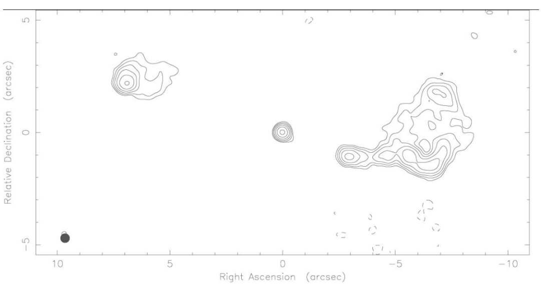
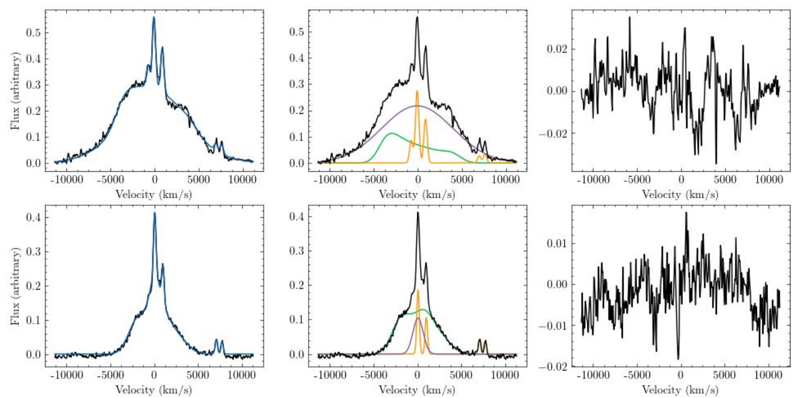


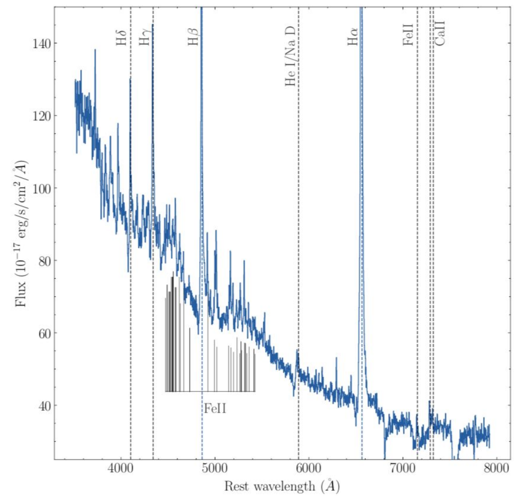

**Gabányi *et al.* (2021)**



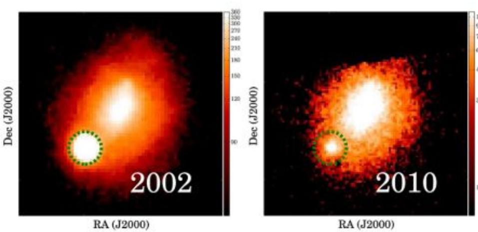

**Ward *et al.* (2021a)**

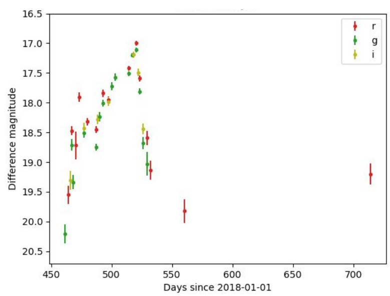
# Rebrightening of SDSS1133

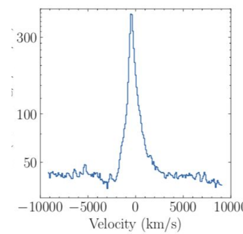
- History of variability since 1950 (Koss et al. 2014). It flared in 2001 and faded for 12 years.
- ~3 magnitude flare in ZTF in 2019 ruled out SNIIn for origin of 2001 flare.
- Blueshifted absorption features at 2000-8000 km/s, broad Balmer, Na D, He I, Ca II and Fe group lines returned.
- Spectroscopic features suggest a non-terminal supersonic LBV outburst in a dusty circumstellar environment.



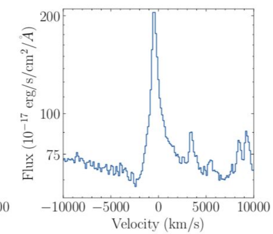

Complete spectrum




Hα broad line region.




Hβ broad line region.

**Ward *et al.* (2021a)**

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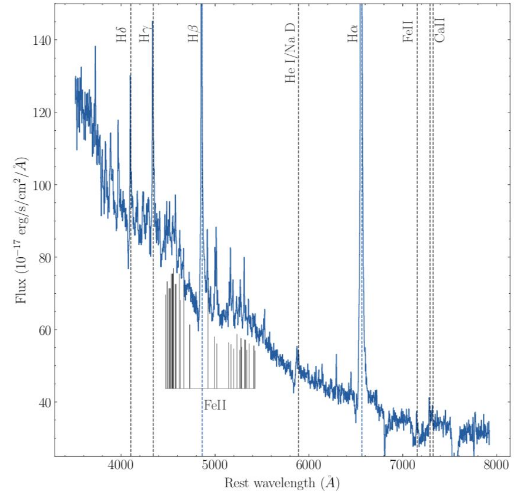
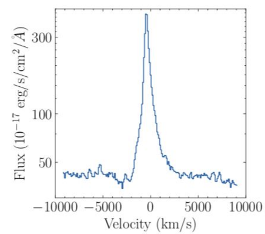



Complete spectrum

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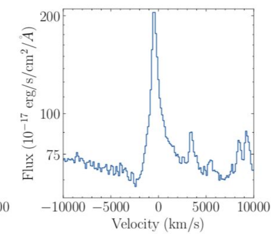


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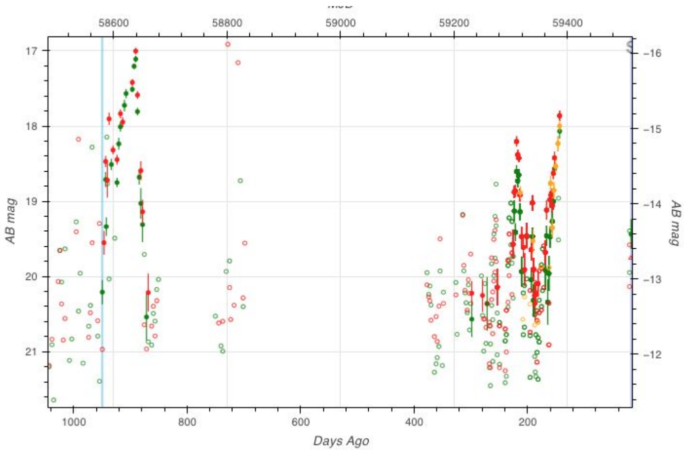


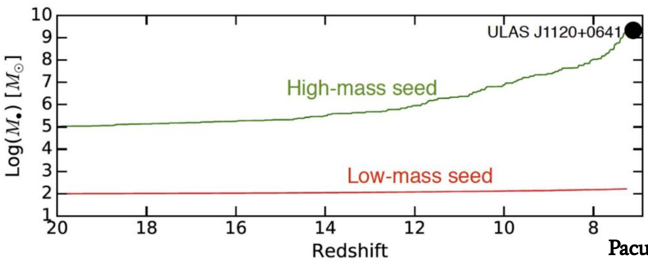

**Ward *et al.* (2021a)**

# Intermediate mass black holes

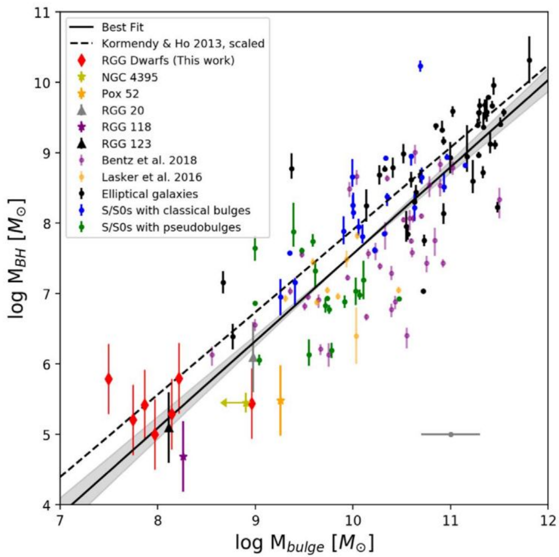
Motivations: Constraining BH seed formation mechanisms
Challenges: Low accretion rates and hard SEDs
Results: 200 new IMBH candidates from ZTF and WISE

# Intermediate mass black holes (IMBHs) are useful analogs to black hole seeds

- Hard to observe black hole seeds because of merger-driven growth.
- We can instead look at local black holes with masses $100 < M_{BH} < 10^6 M_\odot$
- Low accretion rates make them the best proxies for BH seeds.
- Primarily reside in dwarf galaxies with stellar masses of $M_* < 3 \times 10^9 M_\odot$




Pacucci et al. 2017b

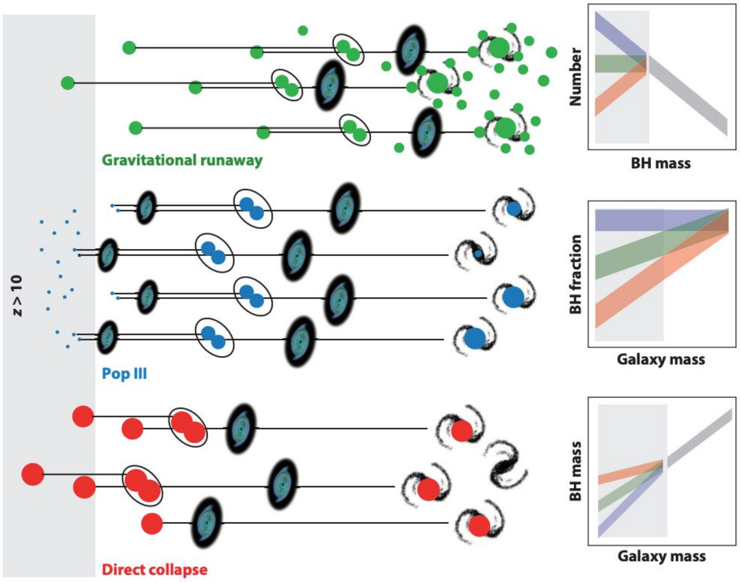



Schutte et al. 2019

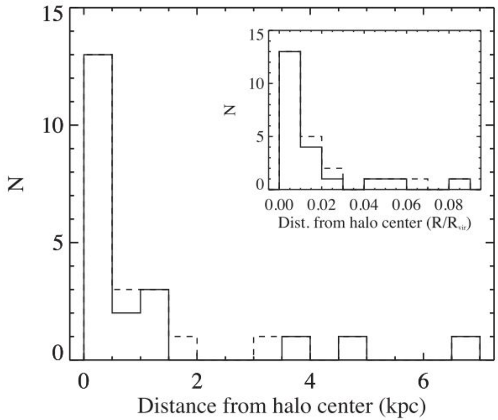
# Observable consequences of different BH seeding channels

Formation mechanism of early BH seeds can be traced by:

- BH occupation fraction
- BH mass function
- BH-galaxy scaling relations
- Wandering fraction



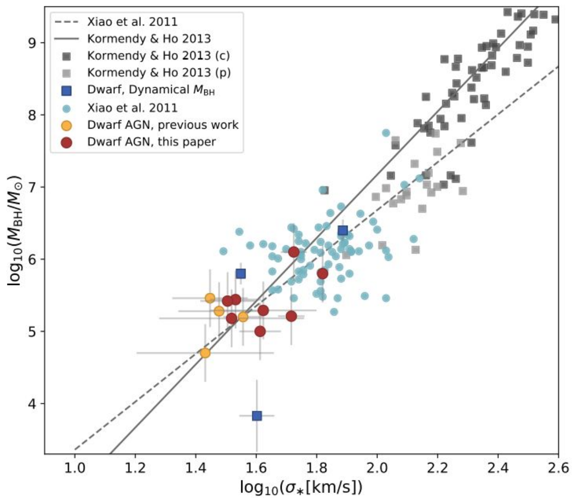

Greene et al. 2020



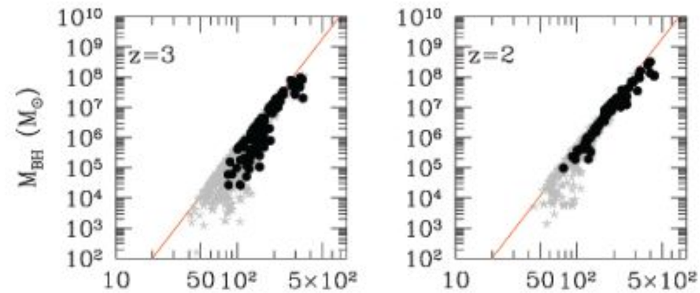

Bellovary et al. 2019

# Effect of seeding channel on $M_{BH}$-$\sigma_*$ relation

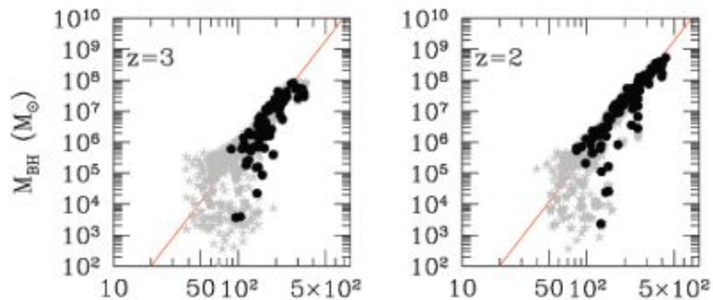
- Pop III stars will produce undermassive black holes while direct collapse mechanisms will produce large scatter in the $M_{BH}$–$\sigma_*$ relation.
- Only 15 low mass BHs have reliably measured stellar dispersion velocities and masses to be placed on the $M_{BH}$–$\sigma_*$ relation:




Baldassare et al. 2020




Pop III stars

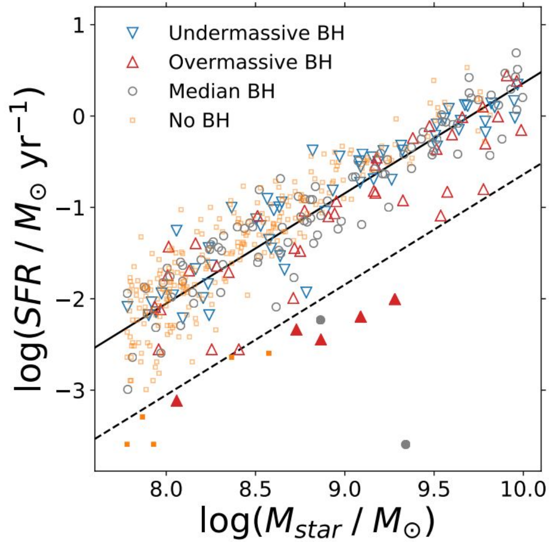



Direct collapse

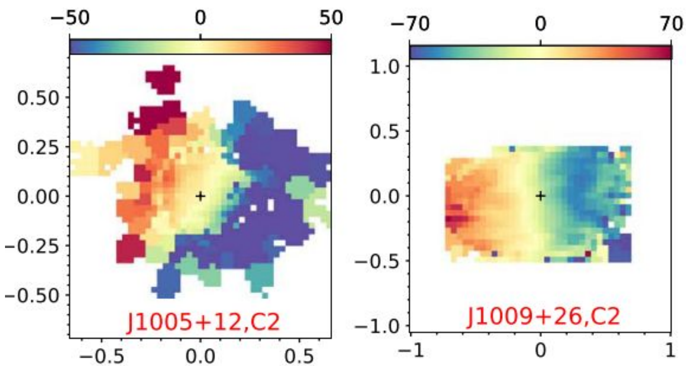
Volonteri & Natarajan 2009

# Can AGN in dwarf galaxies quench star formation?

- Dwarf galaxies without active star formation are rare.
- Are neighbouring galaxies the cause of SF quenching in dwarf galaxies? Do only overmassive BHs drive feedback?
- How often do dwarf galaxies have high velocity outflows?



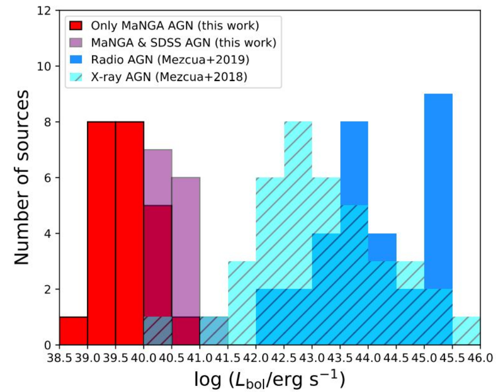

Sharma et al. 2019



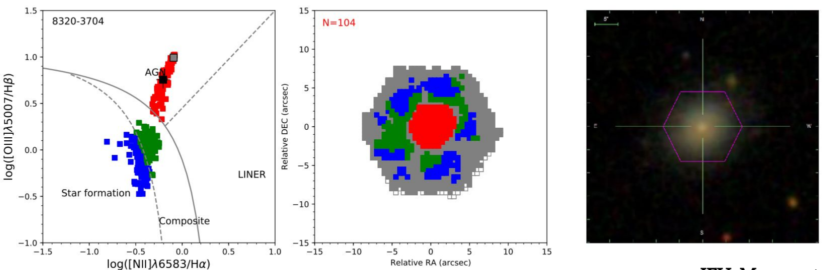

Liu et al. 2020

# Multi-wavelength search strategies

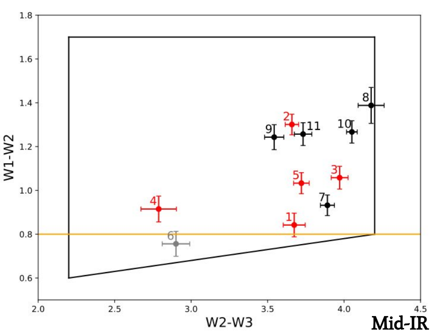
- Spectroscopic/IFU observations
- Radio and X-ray emission
- Long and short timescale optical variability
- Mid-IR color selection and variability



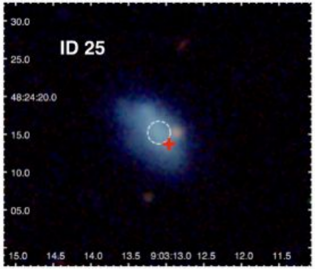

X-rays vs IFU: Mezcua et al. 2020



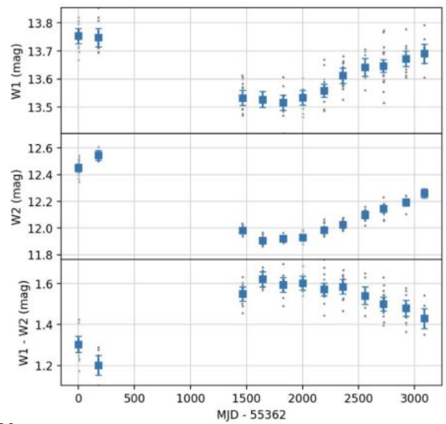

IFU: Mezcua et al. 2020




Mid-IR color: Latimer+ 2021



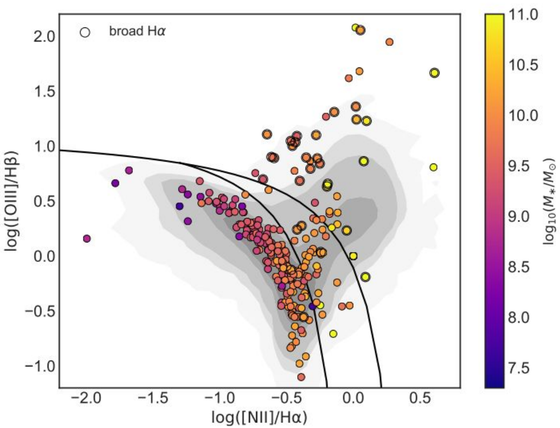

Radio: Reines+ 2020



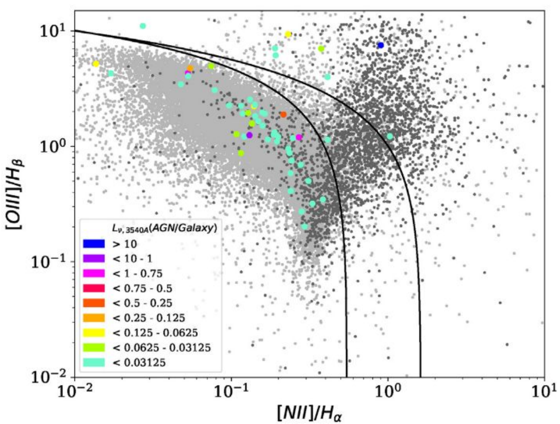

Mid-IR variability: Secrest et al. 2020

# Most low mass AGN are missed by traditional spectroscopic diagnostics

- Photoionization from stars can dilute AGN emission lines.
- Gas and dust can obscure central engine.
- Lower BH mass hardens SED of accretion disk,  reducing emission line ratios (Cann et al. 2019).
- Only 10% of optically variable AGN and 15% of X-ray selected AGN in dwarf galaxies from PTF have AGN or composite line emission ratios (Baldassare et al. 2020, Birchall+ 2020).



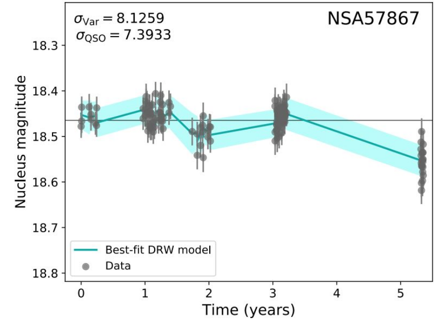

Baldassare et al. 2020



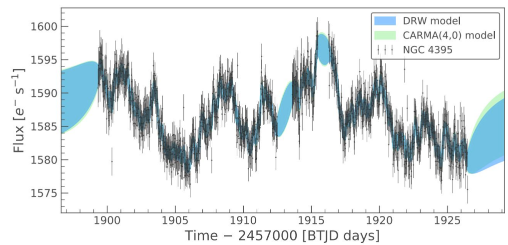

Birchall et al. 2020

# Long and short timescale optical variability

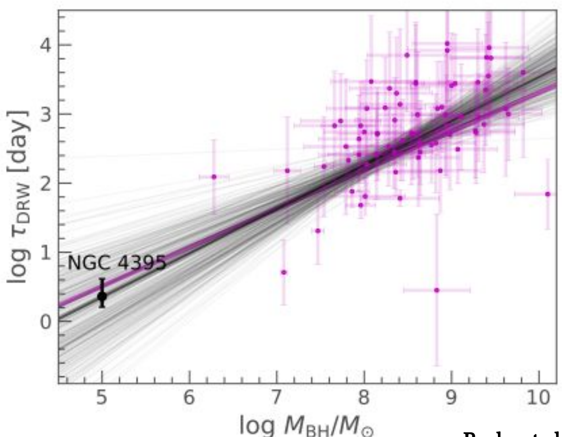
- SDSS, PTF, ZTF and DES studies have found AGN in dwarf galaxies with variability on month to year long timescales.
- TESS and HiTS have found AGN variability on hourly timescales.



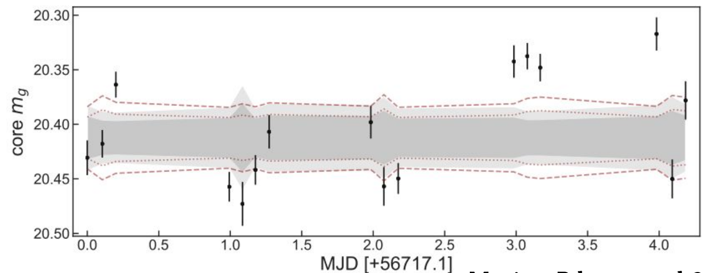

Baldassare et al. 2020




Burke et al. 2020



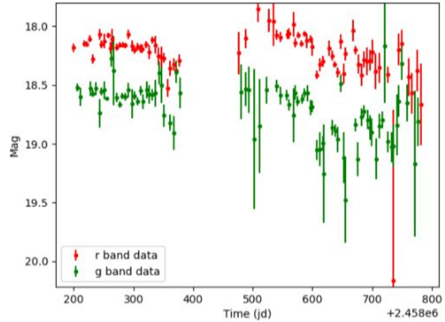

Burke et al. 2020




Martinez-Palomera et al. 2020

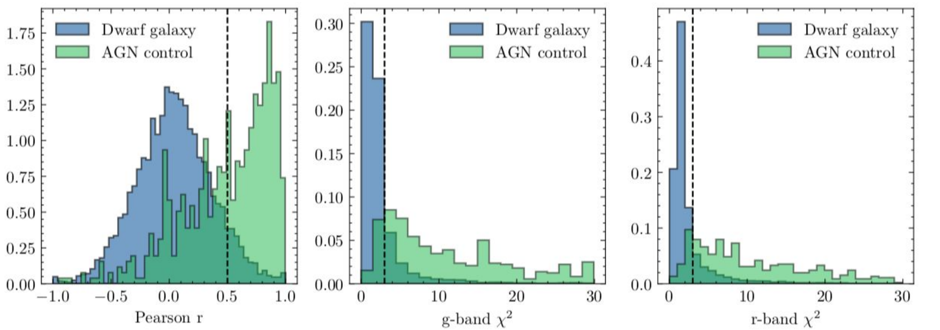
# A search for optically variable IMBHs with ZTF

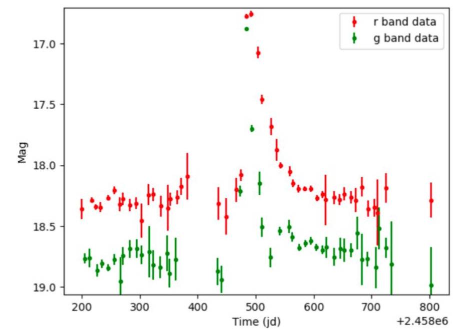
- Produced custom forced photometry with deep reference images for 26,000 dwarf galaxies in ZTF.
- Applied correlation and variance statistics to find 44 optically variable AGN (0.17 ± 0.03%).
- Rate of nuclear SNe in dwarf galaxies of 0.05 ± 0.01% $\text{year}^{-1}$ with 29% being SNII.




NSA212423

AGN



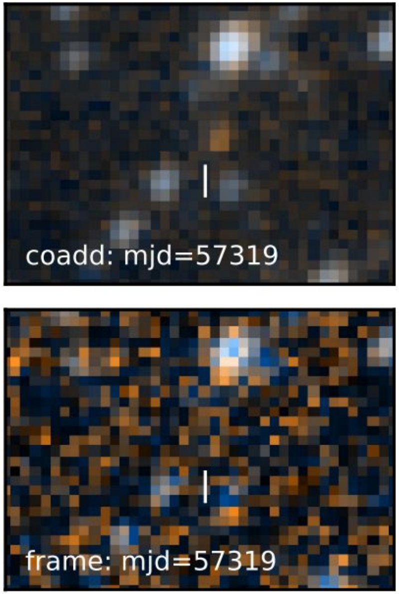




Supernova

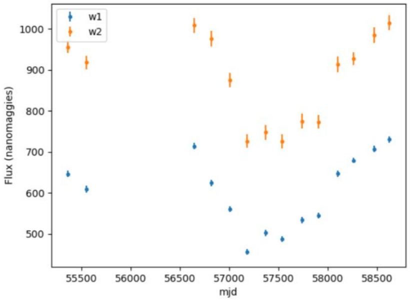
Ward et al. (2021b)

# A search for mid-IR variable IMBHs with WISE

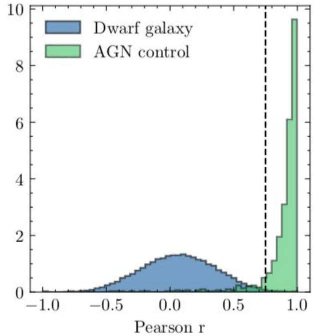
- A previous search for variable low mass AGN in WISE found only 2 (Secrest et al. 2020).
- Used Tractor forward modeled photometry of time-resolved WISE coadds (Meisner et al. 2018, Dey et al. 2019) of 80,000 dwarf galaxies for improved sensitivity.
- Applied correlation and variance statistics to find 158 mid-IR variable AGN ($0.20 \pm 0.02\%$).




Meisner et al. (2018)




NSA480677

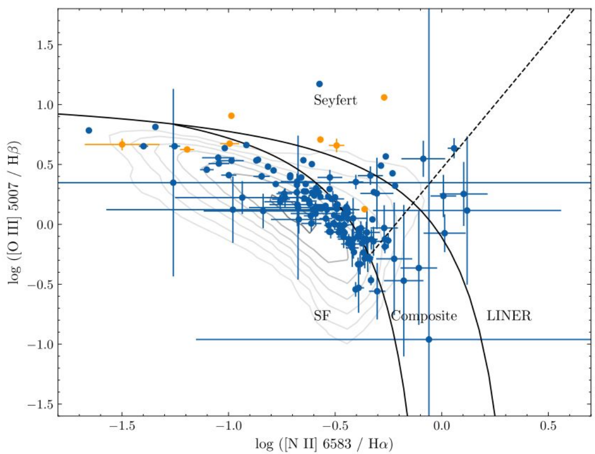



Ward et al. (2021b)

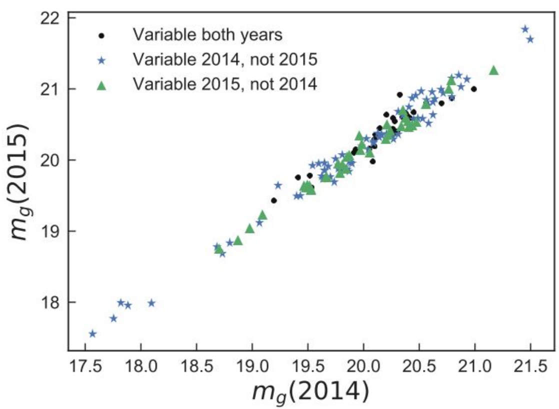
# 200 variable IMBH candidates

- Submitted to ApJ (**arXiv:2110.13098**).
- 81% of ZTF candidates and 69% of WISE candidates were not BPT AGN.
- Only 9 candidates were detected previously in radio, X-ray, and variability searches.
- Only 5 of 152 previously reported variability-selected AGN candidates from PTF were found - AGN accretion switching off at shorter timescales?


Ward et al. (2021b)



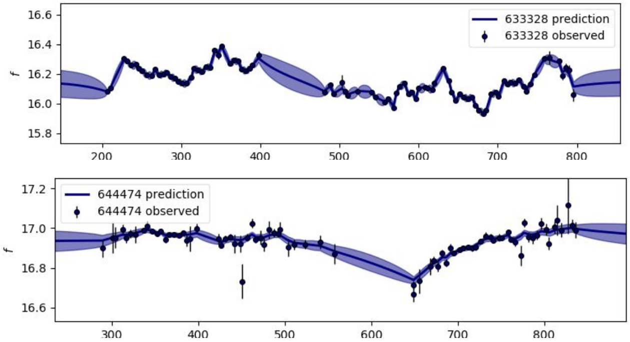

Ward et al. (2021b)

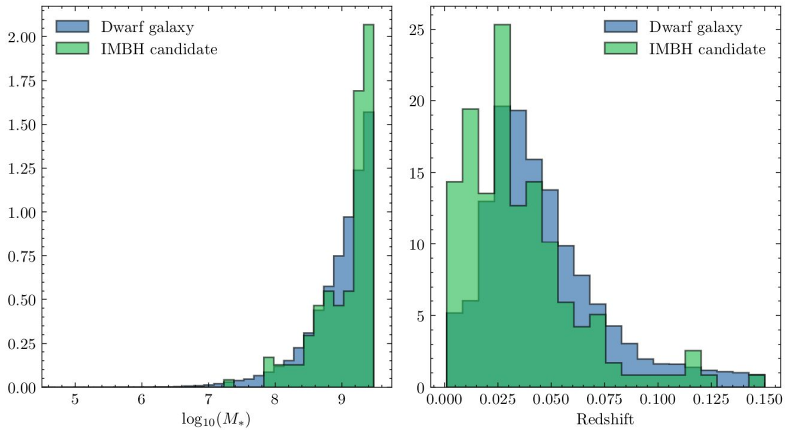



Martinez-Palomera et al. 2020

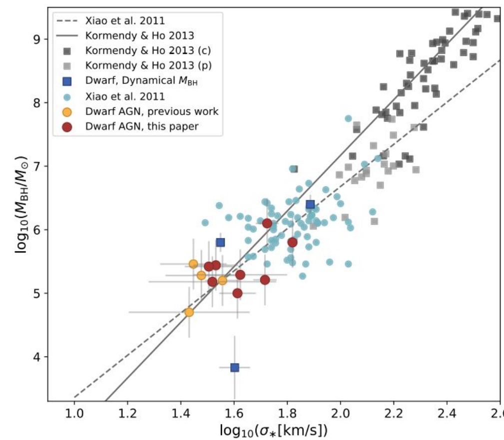
# Mass distribution of the IMBH candidates

- Virial BH masses were $10^5 M_\odot < M_{\mathrm{BH}} < 10^7 M_\odot$
- BH masses estimated from host galaxy mass occupied a similar range for the narrow line AGN.
- Variability timescales were shorter than SMBH AGN control sample, but still suggest AGN are overmassive for their hosts.




Ward et al. (2021b)



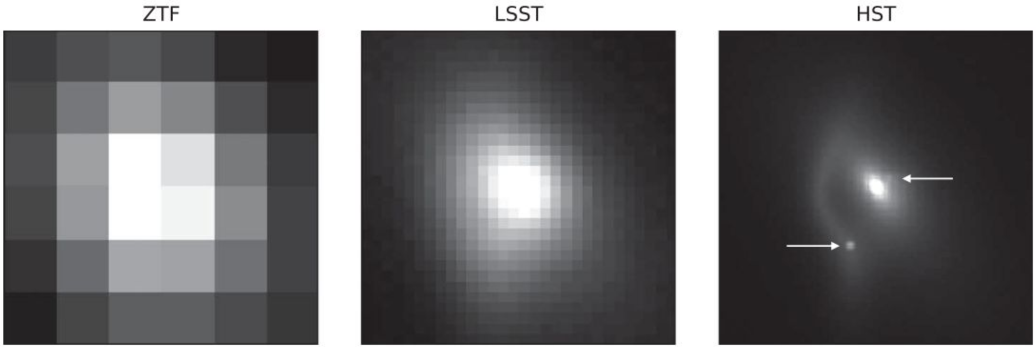

Baldassare et al. 2020

# Future work with LSST

A search for faint and wandering IMBHs
Variability studies of high-z quasars
Measuring time delays from strongly lensed SNe
Role of large spectroscopic surveys

# Looking to the future: Rubin and Roman

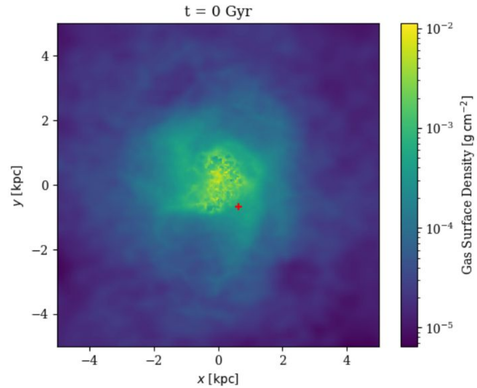
- ZTF has a single exposure limiting magnitude of g~21.5.
- LSST at Rubin observatory (beginning 2023) will have a single visit limiting magnitude of g~25.
- The Roman space telescope (launching in the mid-2020s) wide field imager has 1-hour WFI sensitivity of ~28 in most filters..
- These will provide a vastly more complete census of low accretion rate, off-nuclear BHs.


Goldstein et al. (2019)

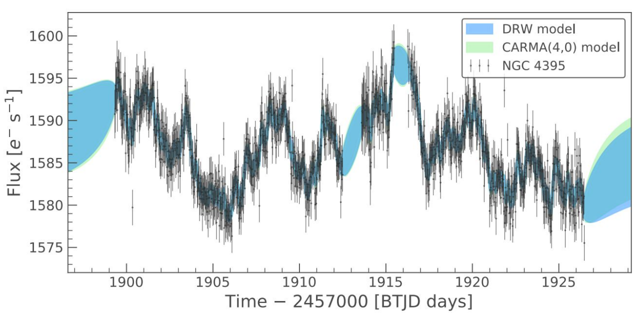
# Faint and off-nuclear IMBHs in LSST

- LSST will detect a much larger population of faint and low mass AGN than ZTF.
- Larger populations for spectroscopic follow-up will fill in the low mass end of scaling relations which inform BH seed models.
- Forward modeling of low accretion rate, off-nuclear IMBHs can test predictions about wandering fraction.



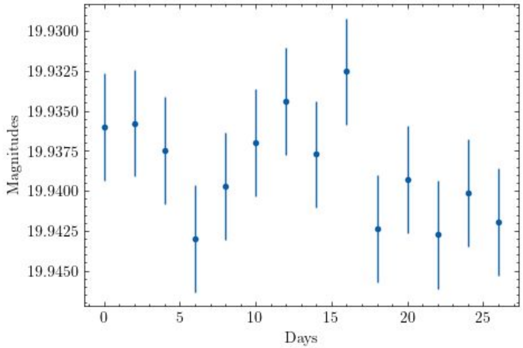

Bellovary et al. 2021

$10^5$M AGN in TESS



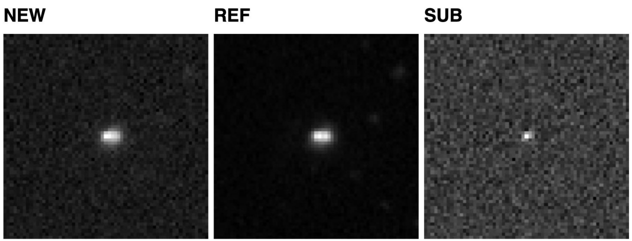

Burke et al. 2020

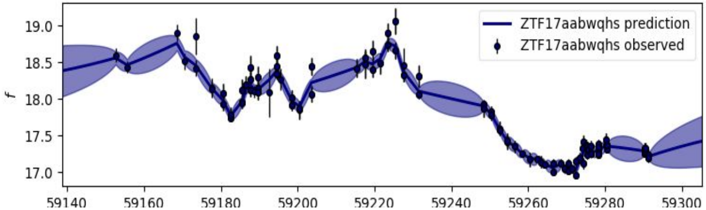
$10^5$M AGN in LSST

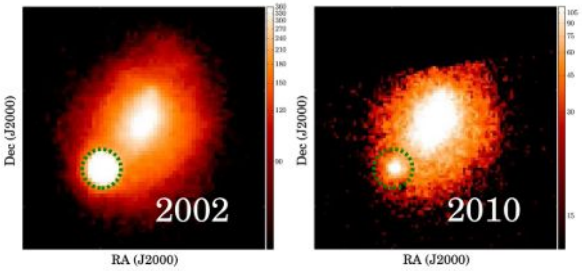


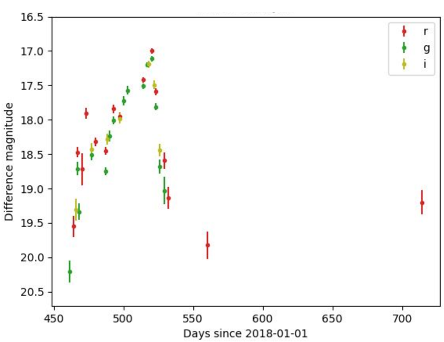
# Searches for off-nuclear variability

- Our ZTF filter used light curve modeling of off-nuclear transients to identify AGN and SNe.
- A search for off-nuclear transients in LSST will also yield SNIa, lensed QSOs and SNe, dual AGN/QSOs, LBVs in nearby galaxies...



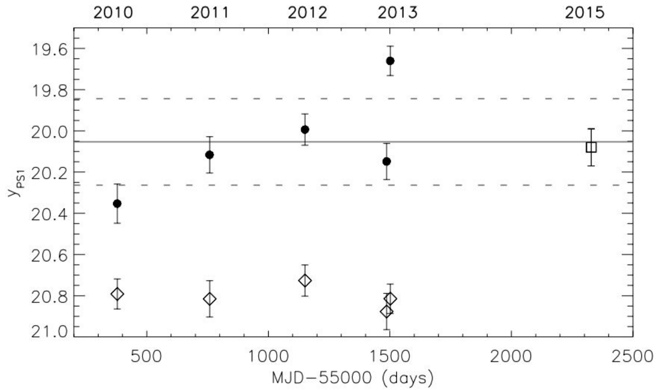



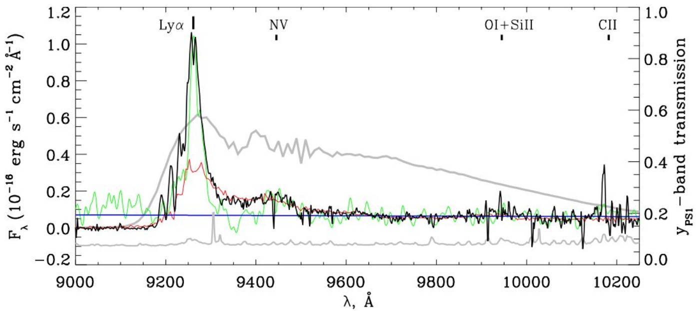



# Variable high-z quasars

- LSST can find variable high-z quasars such as PSO J006.1240 + 39.2219 at redshift z = 6.618.
- This QSO had variable Lyman-α emission on timescales of days and strength of line was comparable to local Narrow-Line Seyfert 1 galaxies.
- By 2017, only seven quasars found at z > 6.5.
- Beginning with catalog of AGN variability in LSST, use color and morphology cuts to find the variable high-z QSOs.

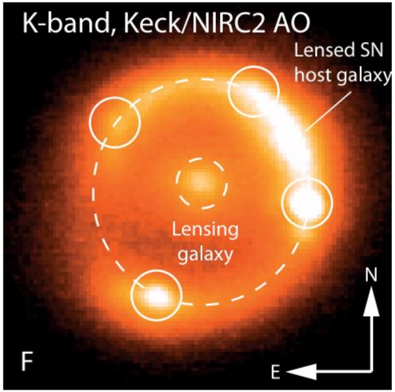


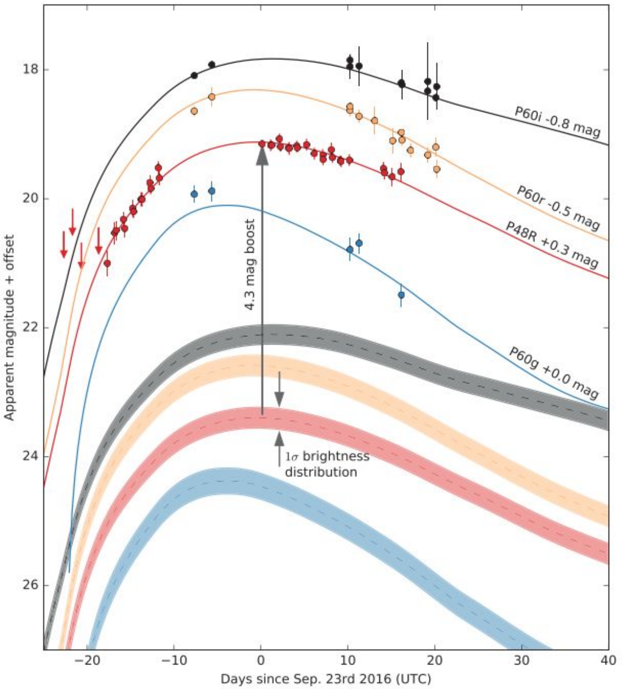




Koptelova et al. 2017

# Gravitationally lensed SNe

- Strong gravitational lensing of a SN by an intervening galaxy can produce multiple, highly magnified images of the SN.
- Time delays between the SN can be used to measure $H_0$.
- Measurement of distances from time delays can measure redshift vs distance for cosmography.
- Predictable light curves morphologies and easy extinction correction make SNIa ideal for time delay measurement.



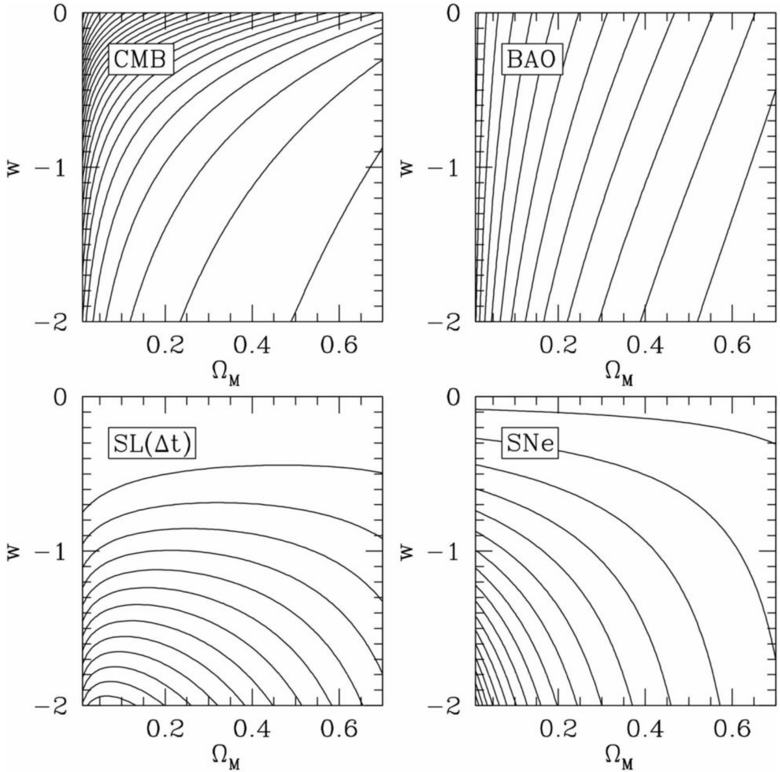




Goobar et al. 2017

# Why use lensed QSOs and SNe for distance measurements?

- Lensing is particularly sensitive to the dark energy equation of state parameter *w*.
- $f_{mod}$ must be minimized by careful measurements of image positions, delays and redshifts.

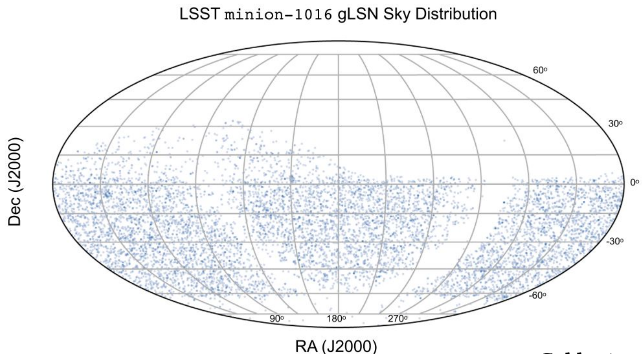
$$D \equiv \frac{D_{\mathrm{l}} D_{\mathrm{s}}}{D_{\mathrm{ls}}} = \frac{\Delta t_{\mathrm{obs}}}{f_{\mathrm{mod}}}$$

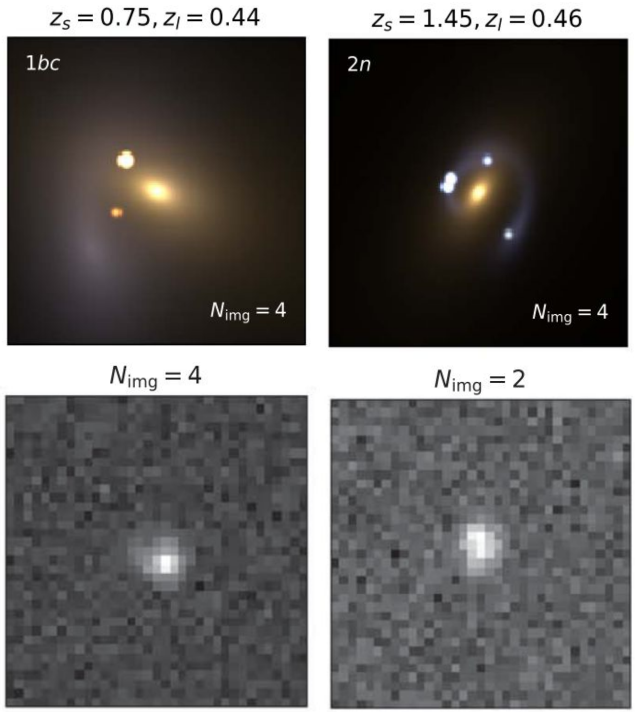



LSST Science Book

# The gLSNe population in LSST

- Can be found by searching for SNIa in elliptical galaxies with brightness and color evolution consistent with a redshift higher than the apparent host.
- Predicted to find 170 (50) gravitationally lensed SN (SNIa) per year.
- Will provide the first sample of SNIa large enough for robust measurement of $H_0$.



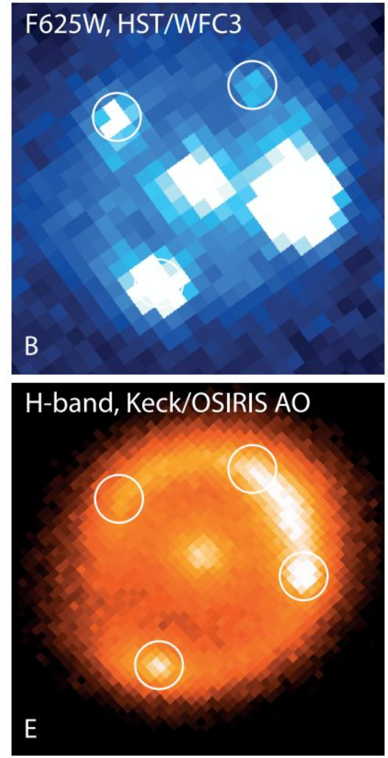

Goldstein et al. 2019

# *Tractor* modeling to measure gLSNe time delays

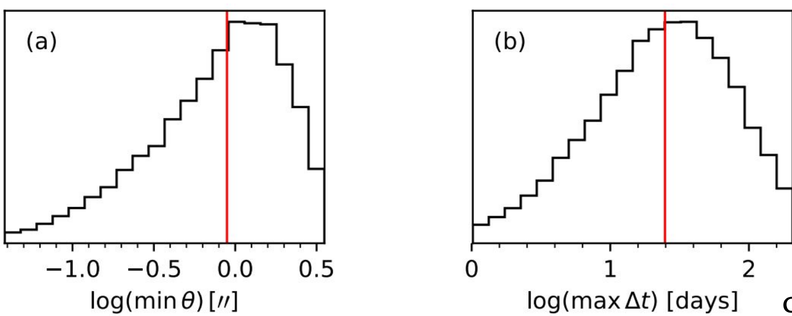
The median separation between doubly imaged gLSNe in LSST will be 0.6” and many will only be marginally resolved.

*Tractor* forward modeling will allow us to:

- Detect a larger population of gLSNe by improving sensitivity to marginally resolved images.
- Improve separation and time delay measurements.
- Remove contamination from AGN or transients in the lensing galaxy.
- Incorporate positional constraints from higher resolution imaging.



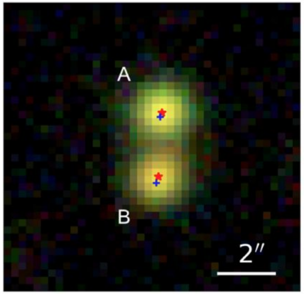

Goobar et al. 2017

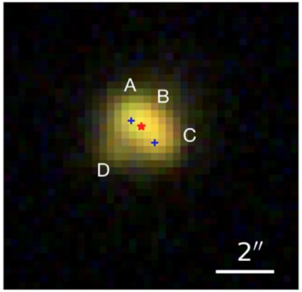


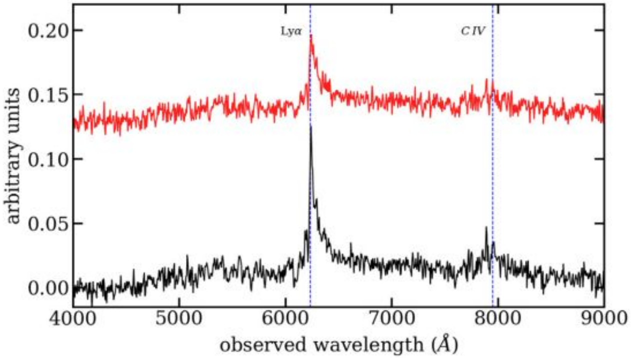

Goldstein et al. 2019

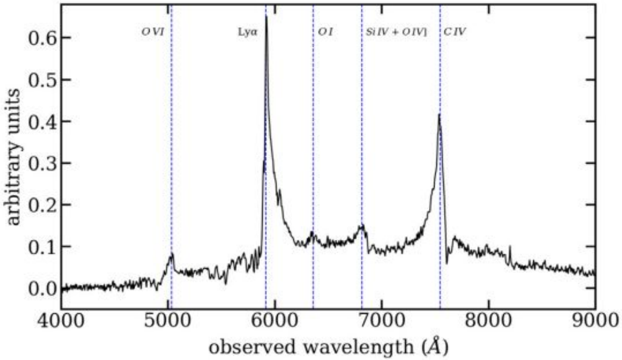
# Lensed high redshift QSOs

- Can search for lensed QSOs like two recently found at z = 4.130 and z = 3.866.
- LSST predicted to find 33 lensed QSOs at z ≥ 3.5 (25 doubles, 8 quads).
- So far, only 4 systems with z ≥ 4 and 10 systems with z ≥ 3.5 above the Gaia limit have been confirmed.



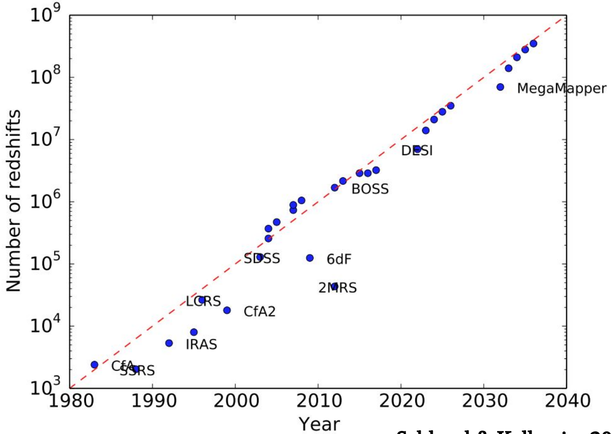

Desira et al. 2022

# The impact of large spectroscopic surveys

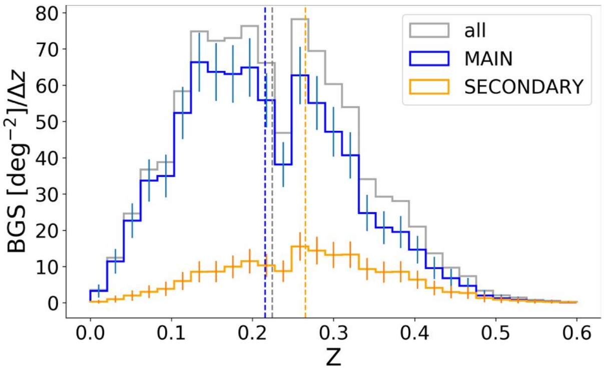
DESI and the proposed MegaMapper southern survey will:

- Improve redshift completeness of elliptical galaxy catalogs for discovery of gLSNe.
- Improve mass measurements of dwarf galaxies, providing larger galaxy samples for IMBH variability searches.
- Provide dwarf galaxy spectra for measurement of AGN virial masses and searches for short timescale changes in accretion states.

DECaLS imaging has already provided galaxy photometry which could be used to expand upon existing galaxy mass catalogs.




Schlegel & Kollmeier 2020




Ruiz-Macias et al. 2020

# LSST Timeline

Simulated images are currently available and allow for software testing in advance of on-sky data release in mid 2023.

**2022-2023**

- Spectroscopic follow-up ZTF IMBH candidates and measurement of wandering fraction with forward modeling.
- Prepare forward modeling pipeline and test astrometry and photometry for blended sources on simulated LSST images.

**2023-2025:**

- Comprehensive search for variable IMBHs in dwarf galaxies in LSST, including off-nuclear sources.
- Search for variable high-z QSOs.
- Discover lensed SNe and QSOs for measurement of $H_0$ from time delays.

| Rubin Baseline Data Release Scenario | Jun 2021 | Jun 2022 | Jul-Sep 2023 | Apr-Sep 2024 | Feb-Jul 2025 |
|---|---|---|---|---|---|
| | DP0.1 | DP0.2 | DP1 | DP2 | DR1 |
| Data Product | DC2 Simulated Sky Survey | Reprocessed DC2 Survey | ComCam On-Sky Data | LSSTCam On-Sky Data | LSST First 6 Months Data |
| Raw Images | ☑ | ☑ | ☑ | ☑ | ☑ |
| DRP Processed Visit Images and Visit Catalogs | ☑ | ☑ | ☑ | ☑ | ☑ |
| DRP Coadded Images | ☑ | ☑ | ☑ | ☑ | ☑ |
| DRP Object and ForcedSource Catalogs | ☑ | ☑ | ☑ | ☑ | ☑ |
| DRP Difference Images and DIASources | ☐ | ☑ | ☑ | ☑ | ☑ |
| DRP ForcedSource Catalogs including DIA outputs | ☐ | ☑ | ☑ | ☑ | ☑ |
| PP Processed Visit Images | ☐ | ☐ | ☑ | ☑ | ☑ |
| PP Difference Images | ☐ | ☐ | ☑ | ☑ | ☑ |
| PP Catalogs (DIASources, DIAObjects, DIAForcedSources) | ☐ | ☐ | ☑ | ☑ | ☑ |
| PP Alerts (Canned) | ☐ | ☐ | ☑ | ☑ | ☑ |
| PP Alerts (Live, Brokered) | ☐ | ☐ | ☐ | ☑ | ☑ |
| PP SSP Catalogs | ☐ | ☐ | ☑ | ☑ | ☑ |
| DRP SSP Catalogs | ☐ | ☐ | ☐ | ☐ | ☑ |

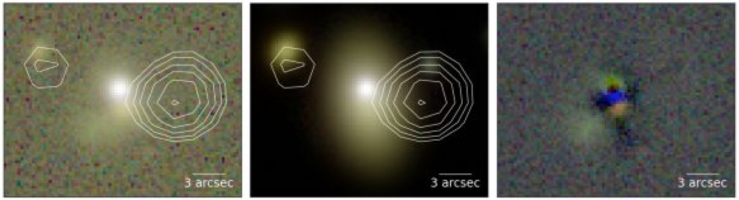
# Summary

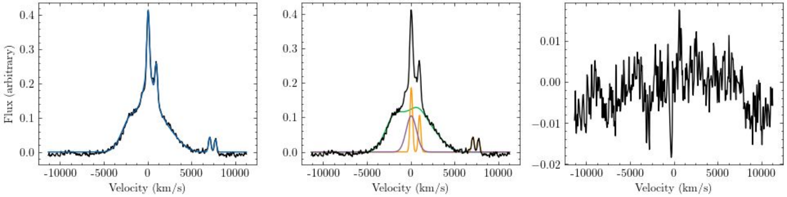
We used forward modeling techniques on ZTF and WISE data to find:

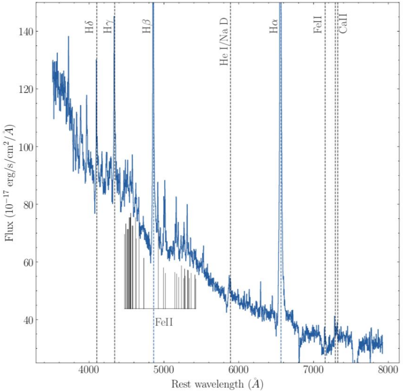
- 9 recoiling SMBH candidates which may originate from binaries with misaligned spins.
- Outbursts from an LBV in a dusty environment.
- 200 variability-selected IMBH candidates.

Future work will:

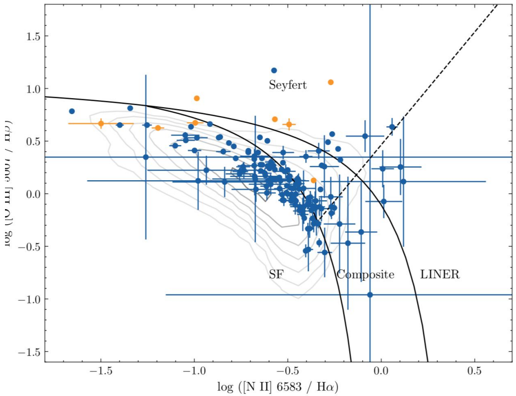
- Use LSST to search for off-nuclear and faint IMBHs.
- Use LSST to find variable high-z QSOs.
- Discover marginally resolved lensed SNe and QSOs and improve time delay measurements.



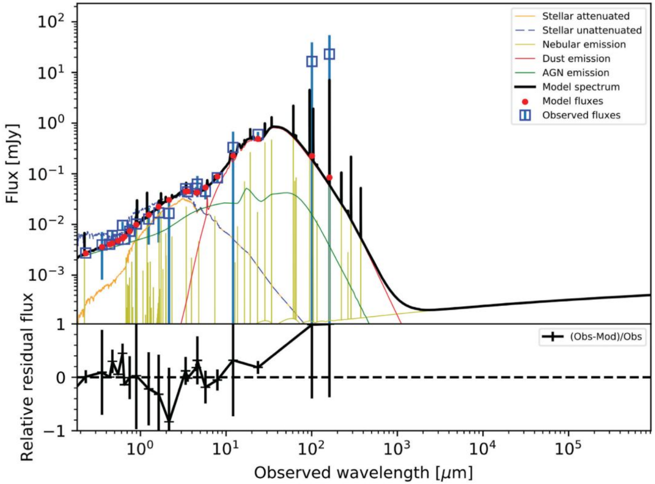




Complete spectrum



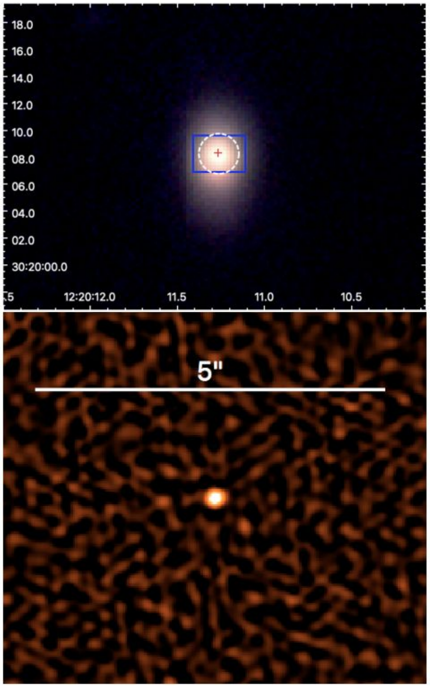
# Backup slides

# Accretion states of low mass AGN




Guo et al. 2020

$$M_{\bullet} \approx 10^{6.43}\text{–}10^{6.72}\,\mathrm{M}_{\odot}$$




$$M_{\mathrm{BH}} = 10^{4.9} M_{\odot}$$

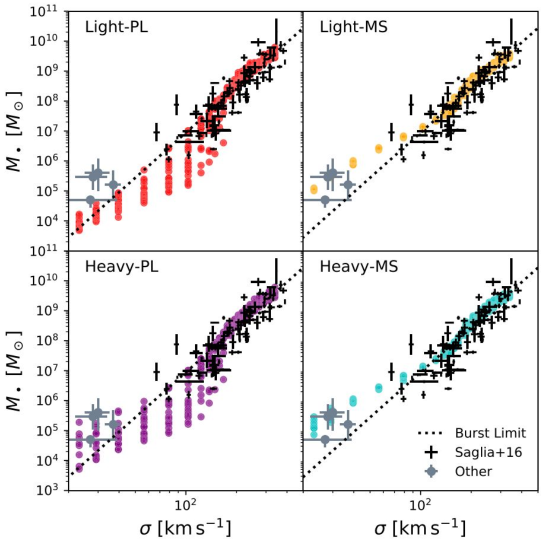
Molina et al. 2021a

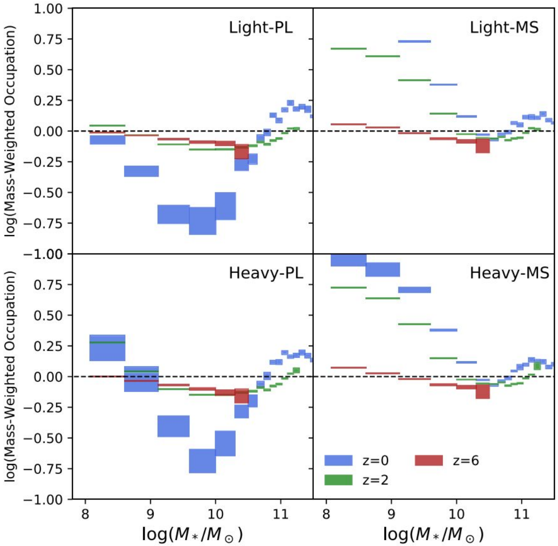
# Accretion prescriptions affect interpretation of black hole seed signatures

- Ricarte & Natarajan (2018) studied the effect of different accretion prescriptions and light vs heavy seeds on the predicted $M_{BH}$–$\sigma_*$ relation and occupation fraction.

- MS (main sequence) model - accretion related to SF rate. PL (power law) model: accretion set by universal Eddington ratio distribution tuned to produce local luminosity function.

- The low mass ends are dominated by uncertainties in the accretion prescription.




Ricarte & Natarajan (2018)

# Conditions for efficient accretion onto IMBHs

Two radial accretion regimes which depend on transition radius $R_T$

- Growth limited by radiative feedback $(r \gg R_T)$
- Growth limited by gas supply $(r \ll R_T)$

Small scale growth depends on transition radius compared to photon radius:

$$M_\bullet > 10^{-11}\left(\frac{n_\infty}{1\ \mathrm{cm}^{-3}}\right)^2 M_\odot$$

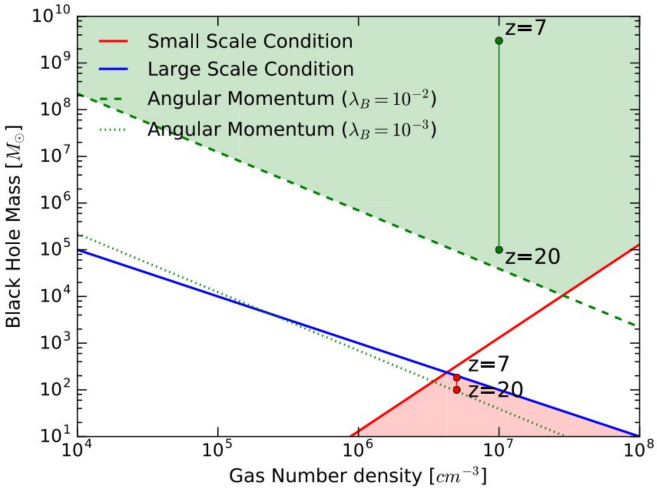
Large scale growth depends on density needed for rapid gas supply from Bondi radius to reach super Eddington rates:

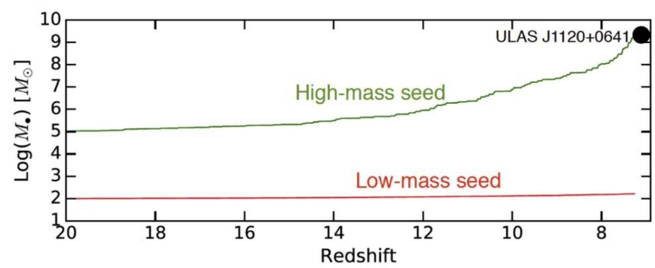
$$M_\bullet > 10^9\left(\frac{n_\infty}{1\ \mathrm{cm}^{-3}}\right)^{-1} M_\odot$$

Angular momentum barrier to be overcome by infalling gas (depends on Bondi radius $l_B$):

$$M_\bullet > 2.2 \times 10^{19}\left(\frac{n_\infty}{1\ \mathrm{cm}^{-3}}\right)^{-5/4} \lambda_B^3\, M_\odot$$

$$\lambda_B = \ell_B/(GMR_B)^{1/2}$$

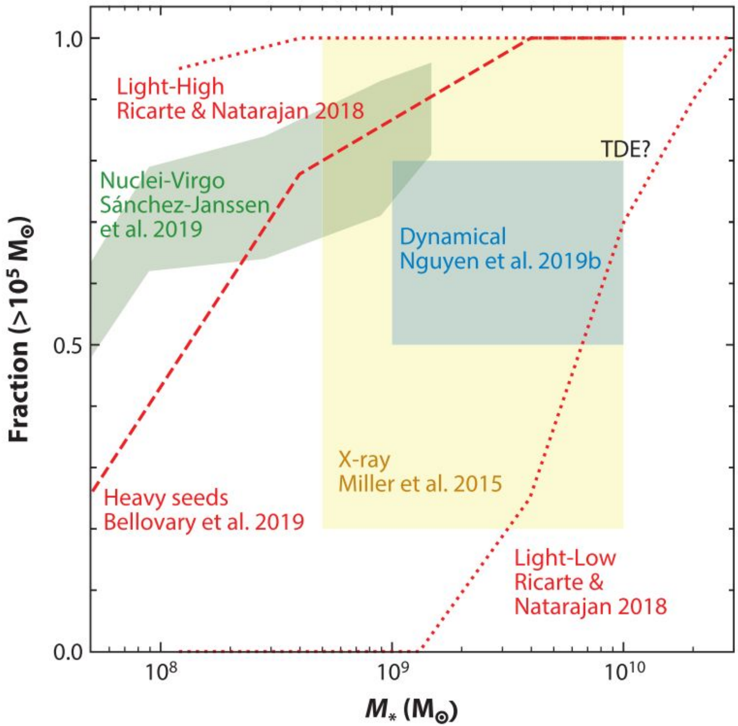



Pacucci+ 2017b

# Observational limits to BH occupation fraction

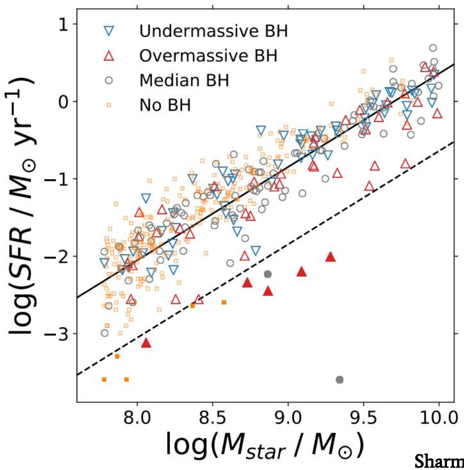
- Observational studies so far support >50% occupation fraction in low mass galaxies.
- Population III models with different accretion prescriptions span the full range (Ricarte & Natarajan 2018).
- Direct collapse seeds fall between the two light seed predictions.
- Observations could be consistent with either light or heavy seeds.



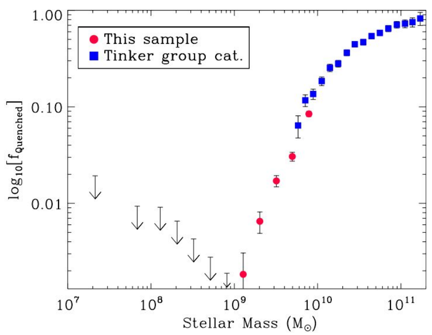

Greene+ 2020

# Can AGN in dwarf galaxies quench star formation?

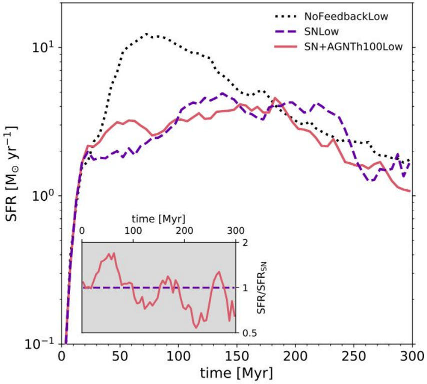
- Geha (2012) found that SDSS dwarf galaxies with no active SF were rare and more massive neighbouring galaxies were the cause of quenching (below).
- Dwarf galaxies in the Romulus25 cosmological hydrodynamical simulation with overmassive BHs had lower central stellar mass density, lower HI gas content and lower SF rates (Sharma+ 2019) --> overmassive BHs drive feedback and suppress SF (upper right).
- AREPO simulations of outflows in dwarf galaxies suggest that AGN outflows have a small effect on SF rates compared to supernovae (Koudmani+ 2019, bottom right).




Sharma+ 2019



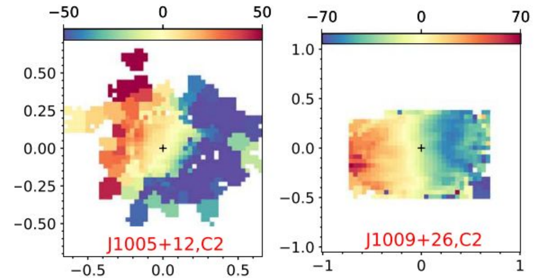

Geha+ 2012



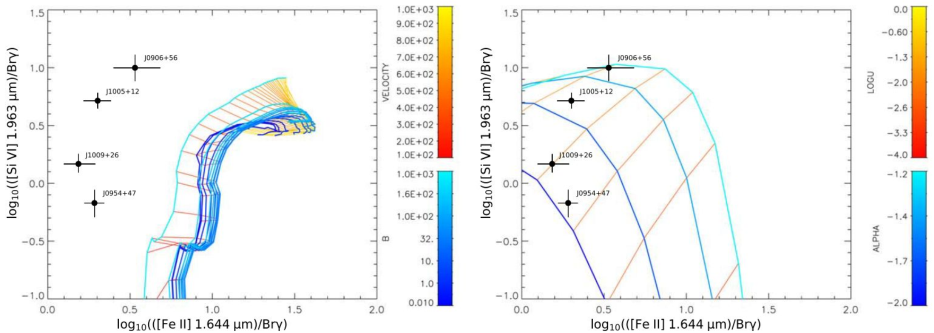

Koudmani+ 2019

# AGN outflows observed in dwarf galaxies

- GMOS IFU observations of 8 dwarf galaxies detected outflows in 7, with median velocity 240 km/s extending up to a few kpc (Liu+ 2020, right).
- The outflows were determined to be photoionized by AGN instead of shocks or young massive stars.
- Coronal line emission was detected from 5 of these objects and was also inconsistent with shocks (Bohn+ 2021, below).




Liu+ 2020

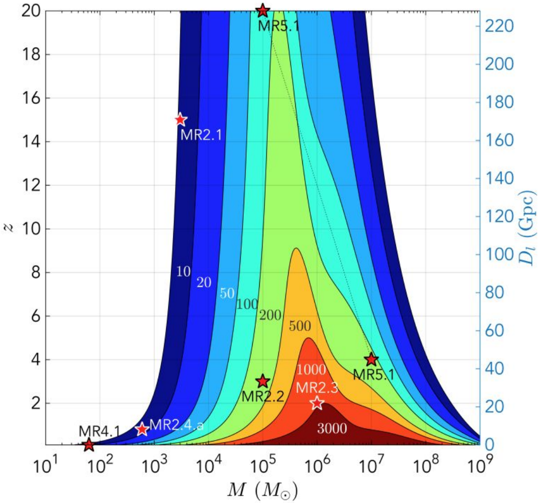



(a) (b)

Bohn+ 2021

# Other motivations to study IMBHs

- LISA can detect BH mergers from BHs with $10^4$-$10^5$ M out to z=20, with mass ratios 0.1-1
- Independent measurements of BH number densities will help to determine merger rates and interpret GW signals from LISA.
- IMBH studies can help us understand the impact of mini-quasars on early galaxy formation and reionization of the early Universe (Madau & Haardt 2015).




Danzmann+ 2017

# Classifying low mass AGN with the BPT diagram

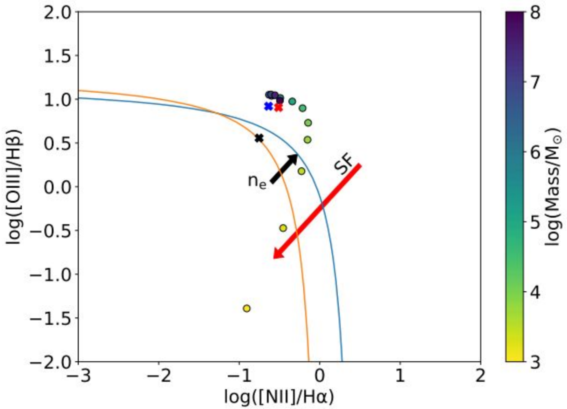
- Photoionization from stars can dilute AGN emission lines and gas and dust can obscure central engine.

- Lower BH mass hardens SED of accretion disk, extending partially ionized zone and reducing emission line ratios (Cann+2019).

$$T = 6.3 \times 10^5 \left(\frac{\dot{m}}{\dot{m}_{\rm Edd}}\right)^{1/4} \left(\frac{M_{\rm BH}}{10^8 M_\odot}\right)^{-1/4} \left(\frac{R}{R_s}\right)^{-3/4} \mathrm{K}$$

- Some ionization states of O shift from $O^+$ and $O^{2+}$ to higher states.

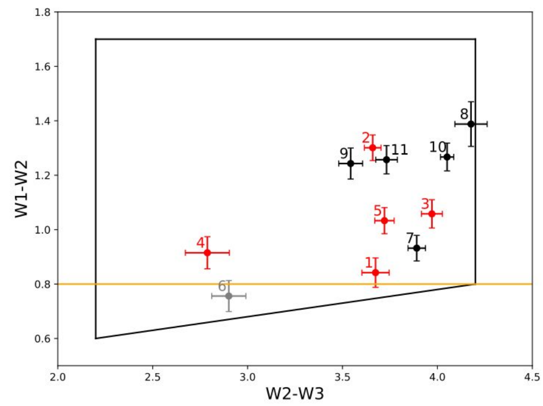
- As BH mass decreases, enhanced X-ray emission from accretion disk penetrates further into the cloud, producing an extended partially ionized zone with $H^+$ but not $O^{2+}$ being produced.

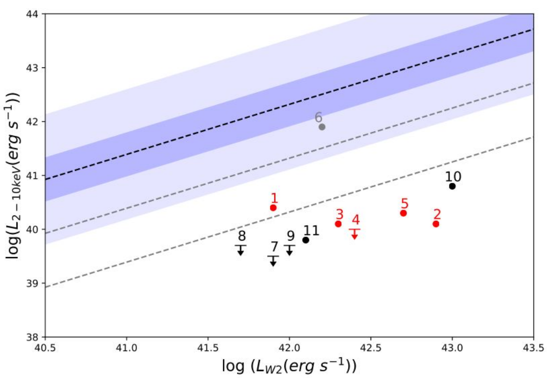


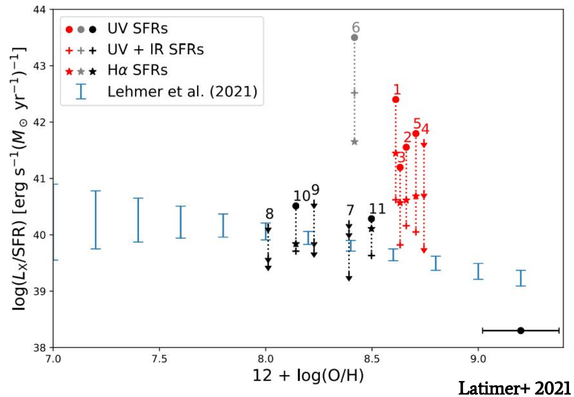

Cann+ 2019

# Using mid-IR colors to find AGN in dwarf galaxies

- Dwarf galaxies can have red mid-IR colors due to young starbursts in low metallicity environments instead of AGN activity.
- Latimer (2021) observed 11 dwarf galaxies with WISE mid-IR AGN colors (upper right) with Chandra.
- They found that 5 of 6 galaxies classified as AGN in the BPT diagram (red) had X-ray point sources consistent with AGN (bottom right).
- Only 2 with SF optical colors were detected in X-rays but at a level consistent with X-ray binaries.
- The X-ray emission from all 11 was lower than expected based on scaling relations (below).



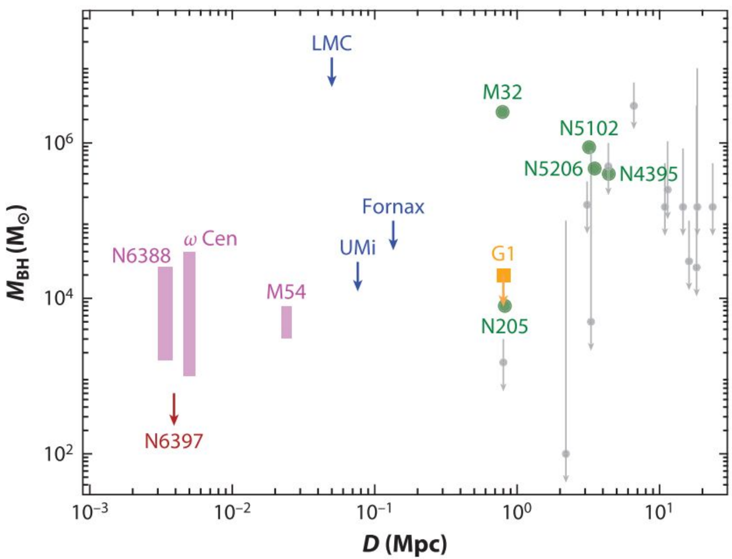




Latimer+ 2021

# Dynamical searches for IMBHs

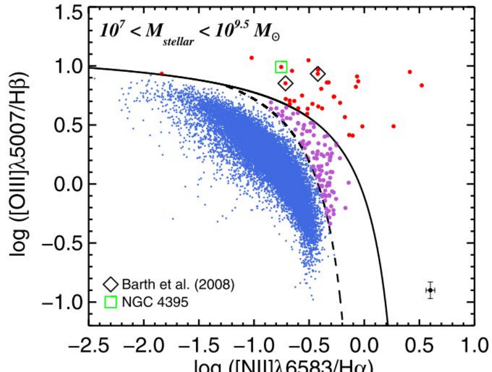
- Dynamical measurements for 10 nucleated $10^9$-$10^{10}$ M galaxies within ~4Mpc of the Sun are shown right.
- There is indirect evidence of an IMBH in the LMC from a hypervelocity star, but there is disagreement on the location of the LMC center.
- Small residual proper motion of Sgr A* perpendicular to plane of galaxy indicate that no dark object larger than $10^4$M is permitted within $10^3$-$10^5$ AU from Sgr A*.
- wCen: isotropic modeling of radial velocity dispersion and surface brightness profiles suggest presence of $5\text{x}10^4$M IMBH, but velocity dispersion signature was not found in proper motions of central stars.



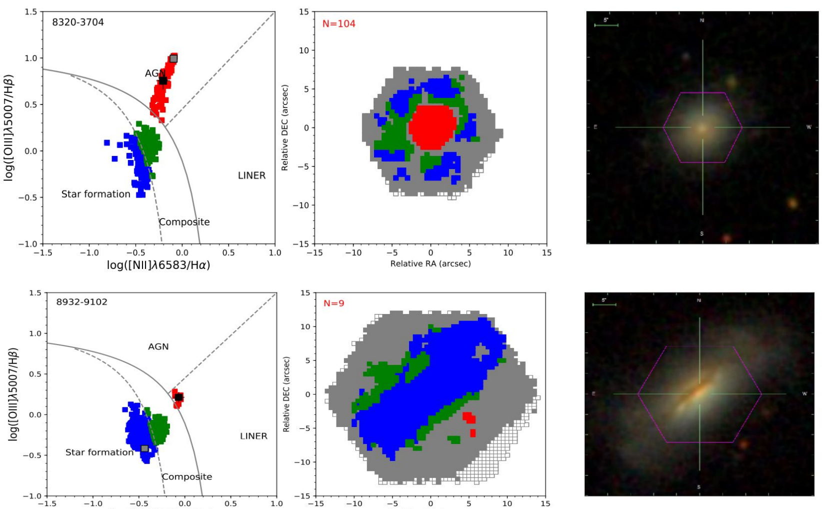

Greene+ 2020

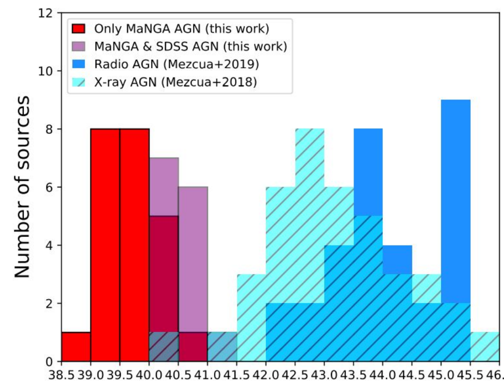
# Spectroscopic searches for AGN in dwarf galaxies

- 152 found by optical emission line diagnostics in a sample of 25,000 dwarf galaxies (Reines+ 2013).
- MaNGA integral field unit spectroscopy used to spatially resolve AGN emission lines from 37 dwarf galaxies (Mezcua & Sanchez 2020). An AGN with broad lines has estimated mass of $M_{\mathrm{BH}} = 5.07\ \mathrm{M}_{\odot}$
- One off-nuclear source may be a wandering IMBH!




Reines+ 2013

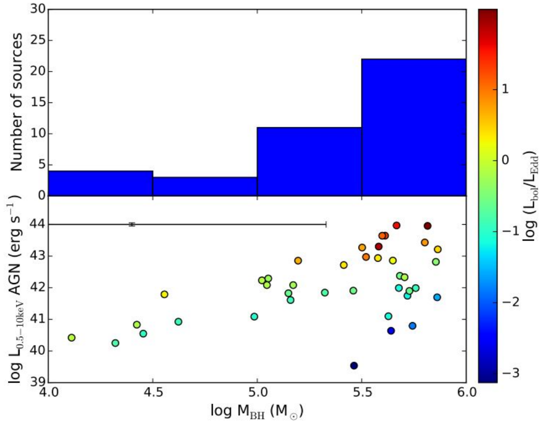


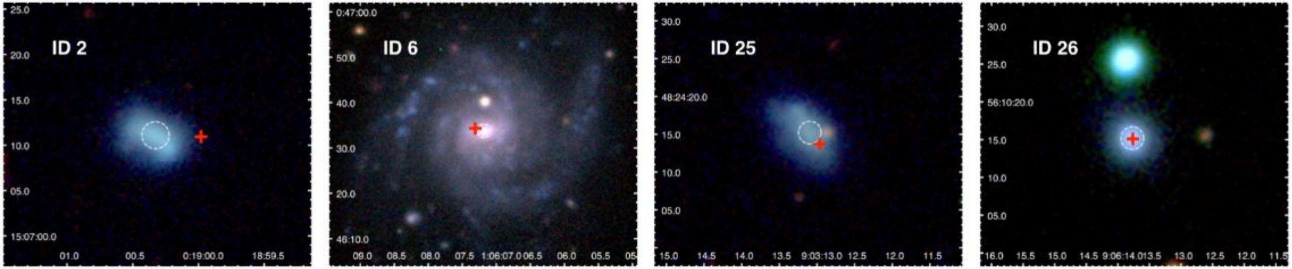

Mezcua+ 2020

# X-ray and radio searches for IMBHs

- 40 AGN found in dwarf galaxies via X-ray emission in Chandra (Mezcua+ 2018). They found an AGN fraction of 0.4% and this decreased for smaller X-ray luminosities and smaller stellar masses.
- VLA observations of 111 dwarf galaxies previously detected in FIRST found that 13 were detectable at 8-12 GHz and the majority were spatially offset from the host nucleus (Reines 2020).



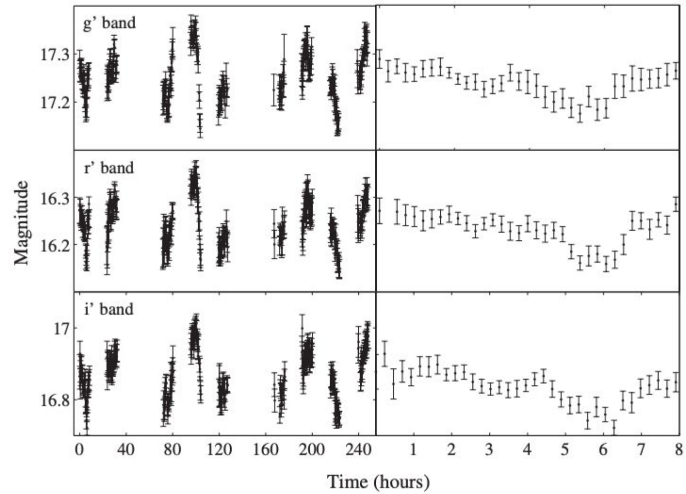

Mezcua+ 2018



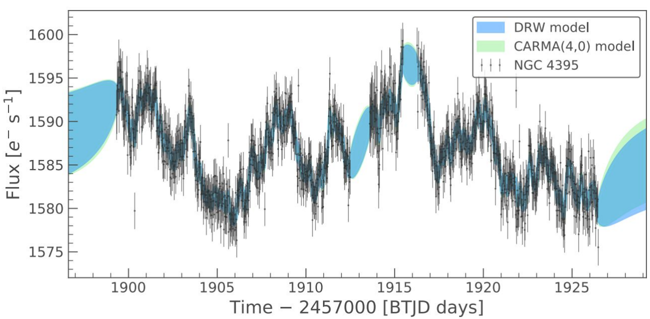

Reines+ 2020

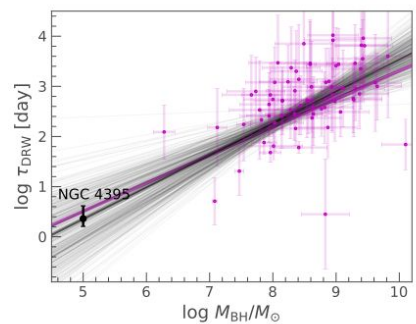
# Short term optical variability from IMBHs

- For NGC4395, with mass $\sim 10^5\ \mathrm{M}_\odot$ and radius $R \sim 5 \times 10^2$ one would predict 0.3 hour variability based on accretion disk size (Martinez-Palomera+ 2020).
- This timescale of variability was observed by Edri+ (2012).
- Burke+ (2020) used TESS to make a month long, 30 minute cadence light curve and found the damping timescale to be ~2.3 days.
- This was a good extrapolation of the damping timescale - BH mass relation measured for heavier BHs.




Edri+ 2012

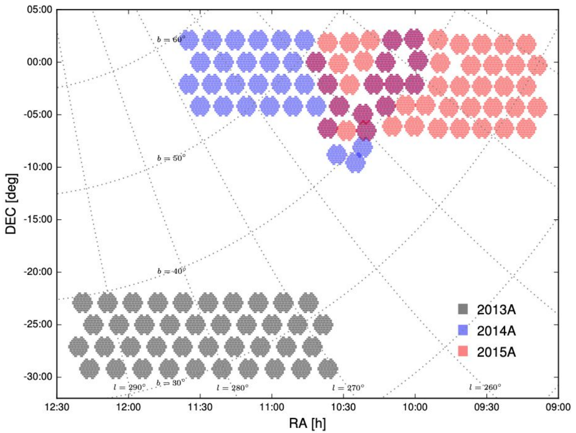


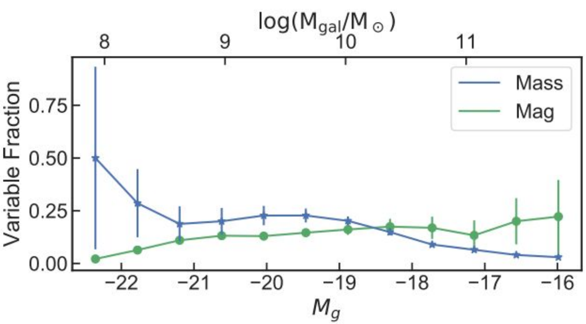

Burke+ 2020

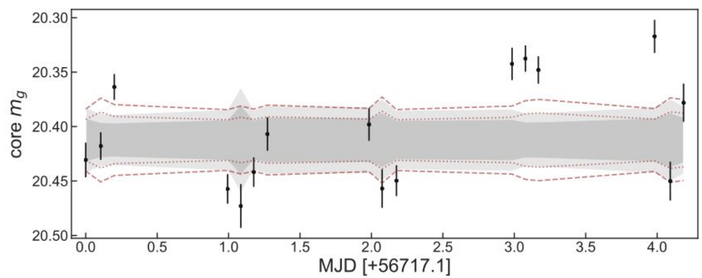
# Short term optical variability searches

- The HiTS survey undertook 3 week-long campaigns with 2 hour cadence DECam observations, with typical g band limiting magnitude of 24.3.
- Martinez-Palomera+ (2020) looked for hourly, small amplitude optical variability using the excess variance statistic to find real variability then required amplitude changes < 0.1.
- 500 galaxies with were variable - a 4% variability fraction.
- 30% were in galaxies of masses < $10^{10} M_{\odot}$




Forster+ 2016

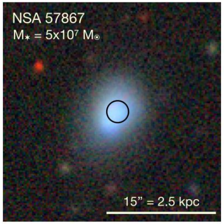


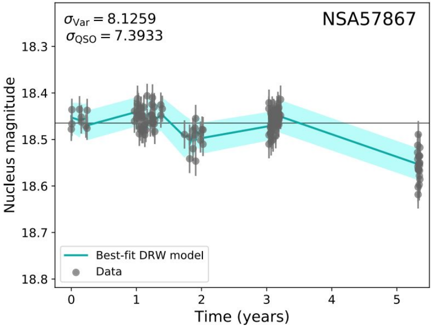



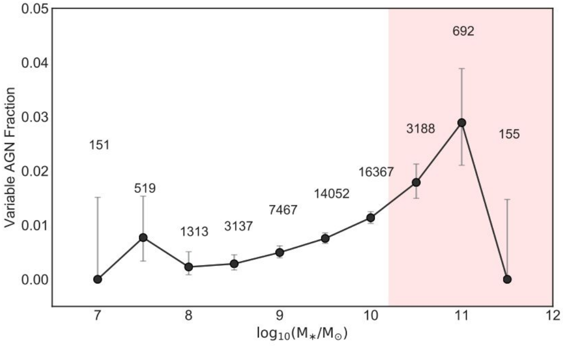

Martinez-Palomera+ 2020

# Long term optical variability searches

- Two papers looked for long term optical variability in g band imaging data from SDSS Stripe 82 (limiting mag ~20) and the Palomar Transient Factory (limiting mag ~ 20.5).
- They fit the light curves with damped random walk models to find AGN.
- They found 135 AGN in dwarf galaxies via optical variability in SDSS (Baldassare+ 2018) and 244 in PTF (Baldassare+ 2020).
- The variable fraction was 0.25% for the full sample, but increased to 1% for light curves with >2 year baselines.
- The variable fraction was constant down to 10^9 M after correcting for nucleus magnitude.



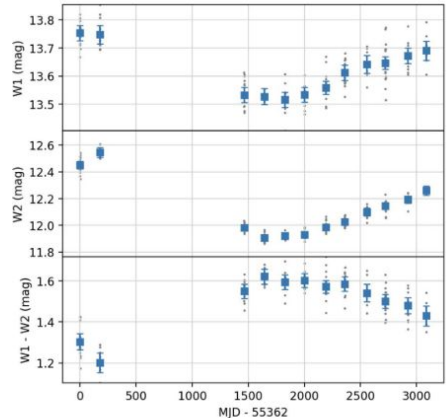



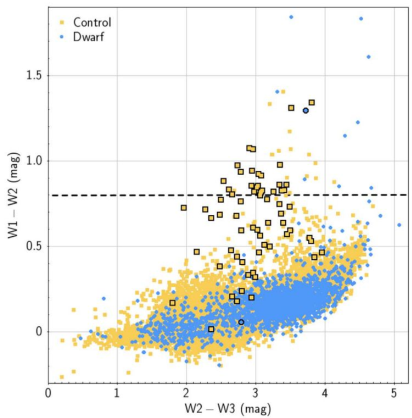

**Baldassare+ 2020**

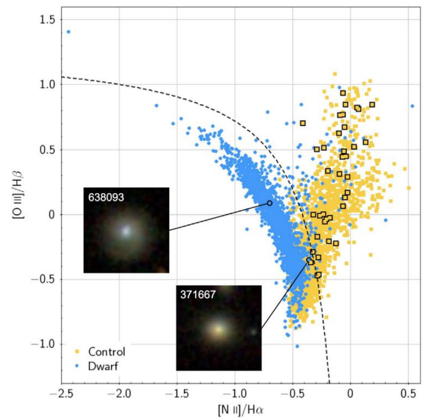
# Mid-IR variability searches

- In a search for variable AGN in dwarf galaxies with the WISE survey, Secrest+2020 found only 2 of 2197 dwarf galaxies were variable in the mid-IR.
- This was a factor of 10 less frequent than massive galaxies showing mid-IR activity.
- The 0.09% of dwarf galaxies with mid-IR variability was comparable to the fraction showing optical variability found by Baldassare+ (2018).
- One variable IMBH candidate was optically SF in the BPT diagram but had AGN WISE colours, while the other was almost optically AGN but had SF WISE colors.




Secrest+ 2020



# AMPEL filtering

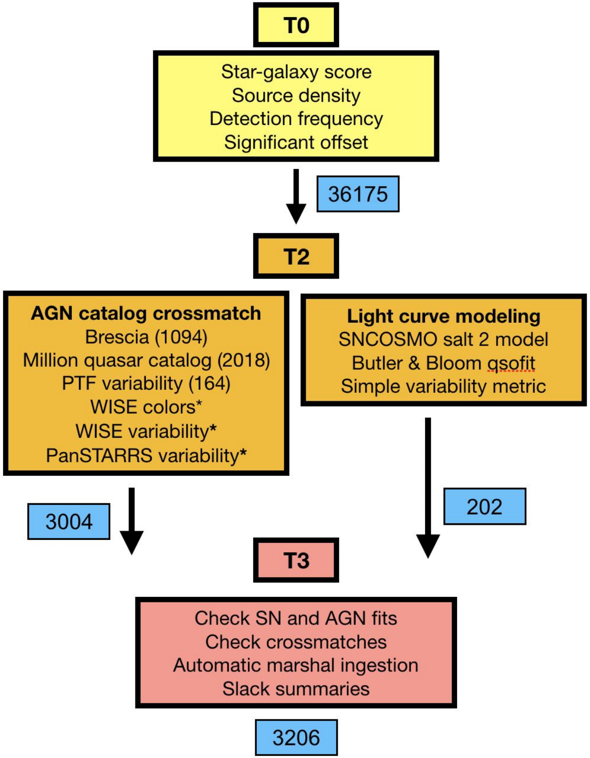
Alert Management, Photometry and Evaluation of Lightcurves!

**T0: Find real transients near galaxies**

- Remove incorrect subtractions, moving sources and stars.
- Search for transient-host offsets.

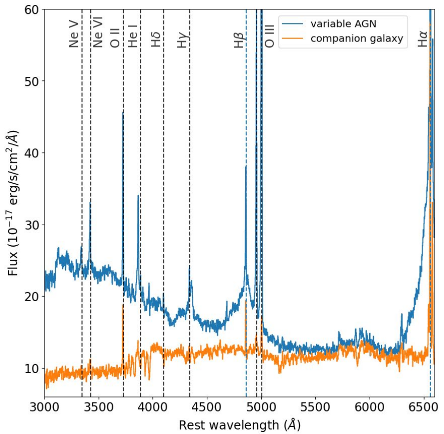
**T2: Remove supernovae**

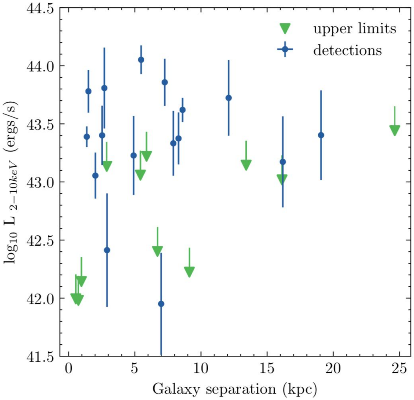
- Crossmatch to AGN catalogs.
- Fit light curves with AGN stochastic variability (Butler & Bloom (2011) ensemble structure function model ) and supernova model (SNCOSMO)

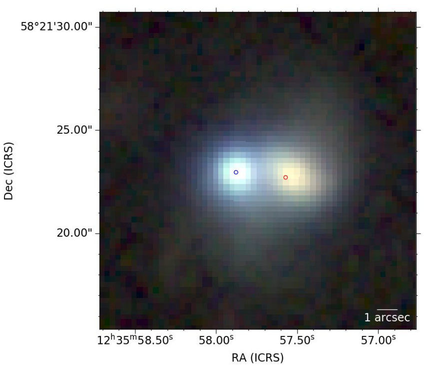


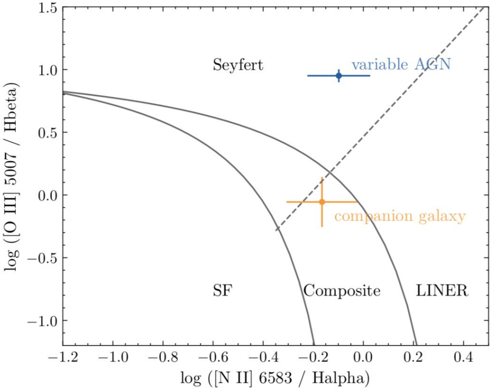
# 52 AGN in galaxy mergers

- 52 AGN were in ongoing galaxy mergers.
- 14/15 AGN with SDSS spectra of both galaxies were single offset AGN. Another was a dual AGN.
- We discovered a new dual AGN upon spectroscopic follow-up of ZTF18aaxvmpg.
- No correlation between X-ray luminosity and separation was found at these separations.
- A useful sample to study merger activated accretion.



# Tractor for ZTF transients

- Can model ZTF, PTF, PanSTARRS and DECam images.
- Models for transients:

  - Point source
  - Exponential galaxy + point source
  - De Vaucouleurs galaxy + point source
  - Composite galaxy + point source
  - Any galaxy model + 2 point sources.

- Galaxy shape/position parameters fixed across multiple bands and epochs.
- Flux of point source can vary across epochs.