Searching for recoiling black holes with the Zwicky Transient Facility

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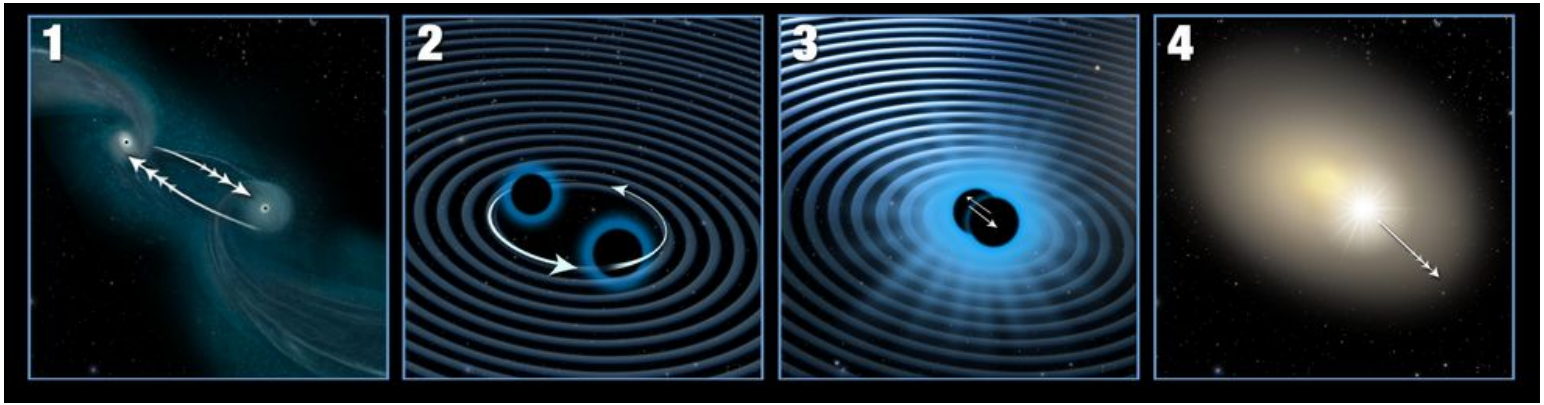
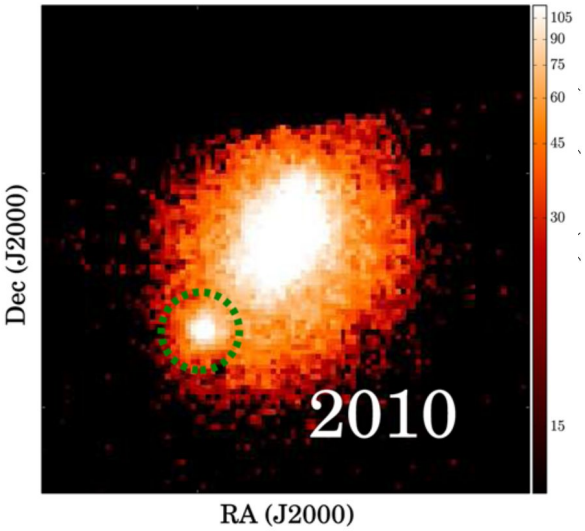
Black hole merger remnants can be ejected

- Asymmetry in masses or spins of two coalescing SMBHs → recoil kick for merged BH.
- Can be observed as an AGN up to 10 kpc away from the galactic center.
- Can use to study efficiency of black hole spin alignment.
- Can study unique BH/galaxy co-evolution.

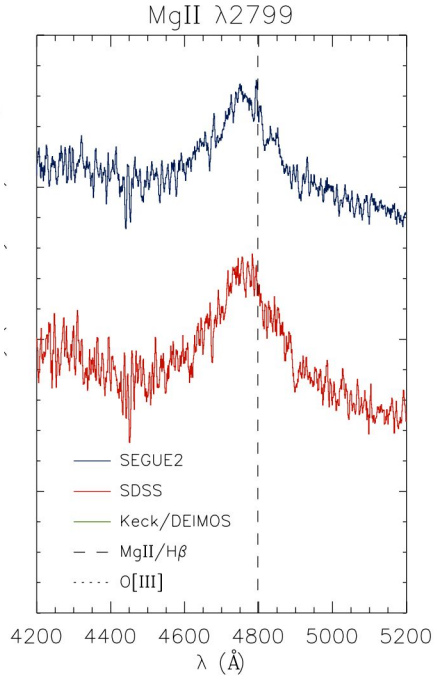


Spectral and imaging signatures of BH recoil

- **Spatial offset:** Relative to photometric centre of galaxy.
- **Velocity offset:** Quasar broadline region offset relative to narrow line region and host galaxy. **<200km/s** for non-spinning to **>1000km/s** for spinning.
- 13 candidates have been published but none have been confirmed.



Koss et al 2014



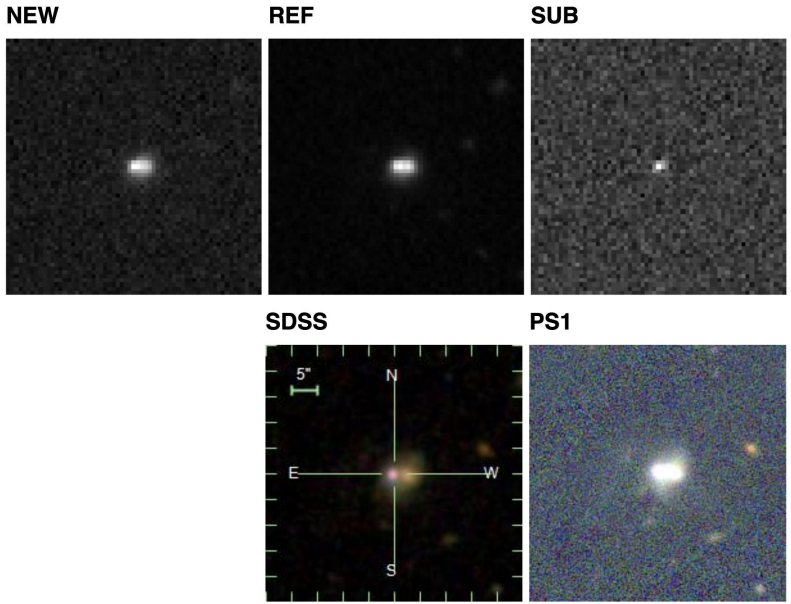
Steinhardt et al 2012

ZTF difference imaging can find offset AGN

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

ZTF is useful because it can:

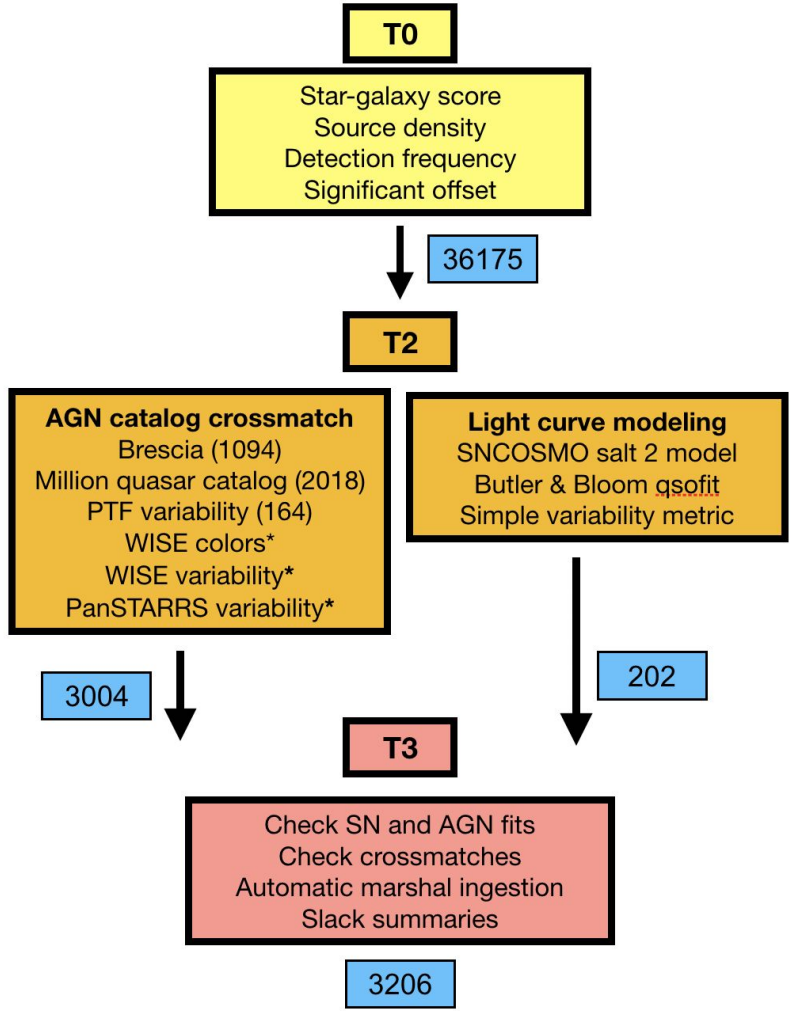
- Find new AGN by their variability.
- Confirm that AGN emission is from an off-nuclear source.
- Automatically identify offset sources during filtering.
- Pinpoint transient coordinates for galaxy asymmetry tests.



AMPEL filtering

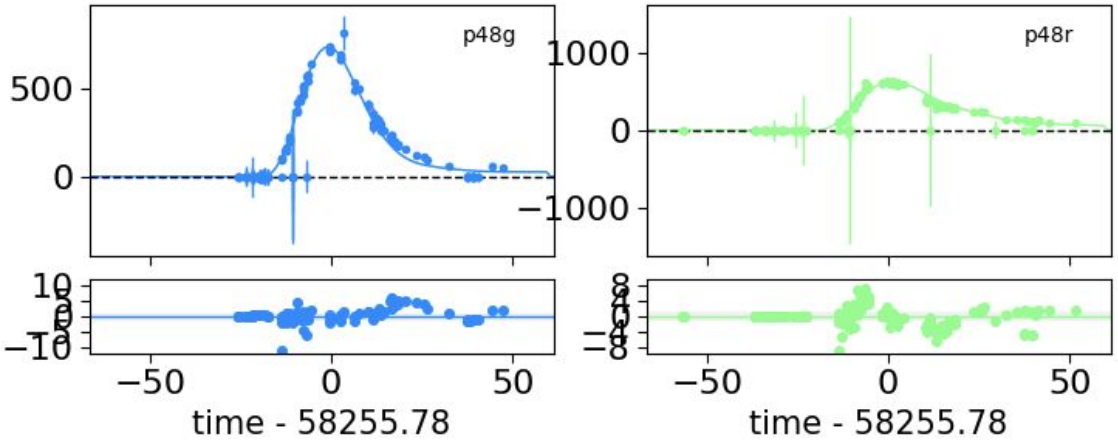
Why we use AMPEL:

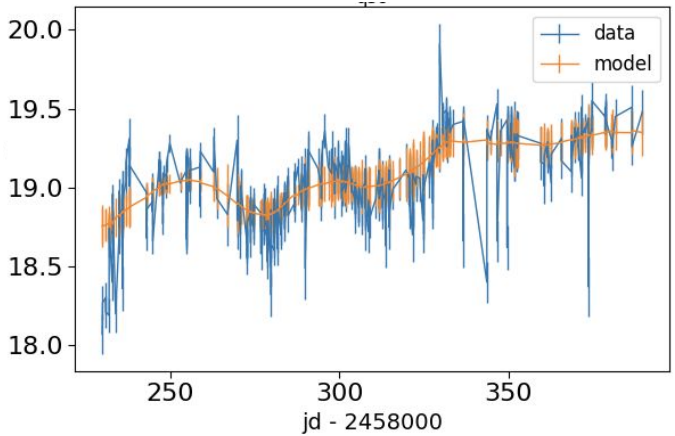
- Can add new catalogs with extcats or catsHTM.
- Can apply our python fitting modules.
- Can retroactively run AMPEL on all transients as we improve the filter.
- Get easy statistics on all transients passing t0.
- Automatic marshal ingestion and daily Slack summaries.



Automatic light curve modelling in AMPEL

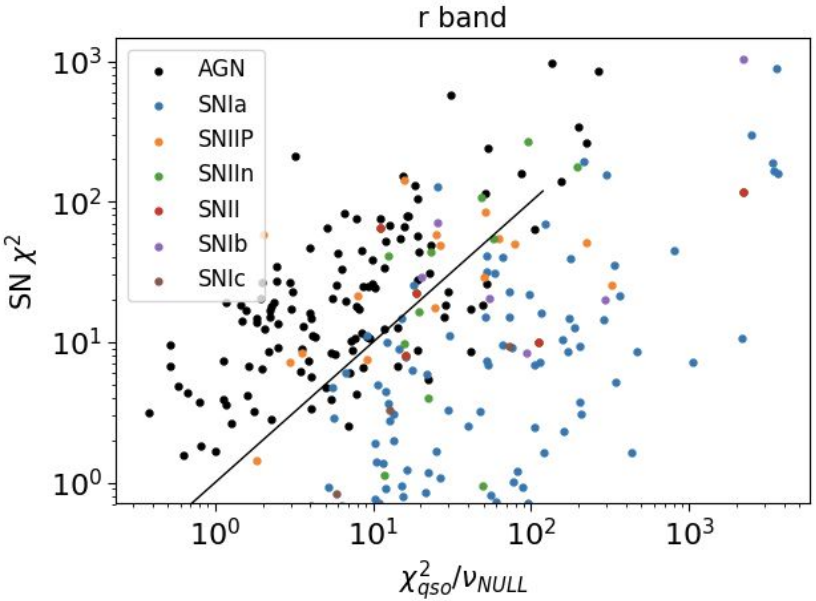
- Butler & Bloom (2011) qsofit python module finds best-fit random walk models.
- SNCOSMO salt 2 model automatically applied to light curves.
- Goodness of fit separates AGN and SN.

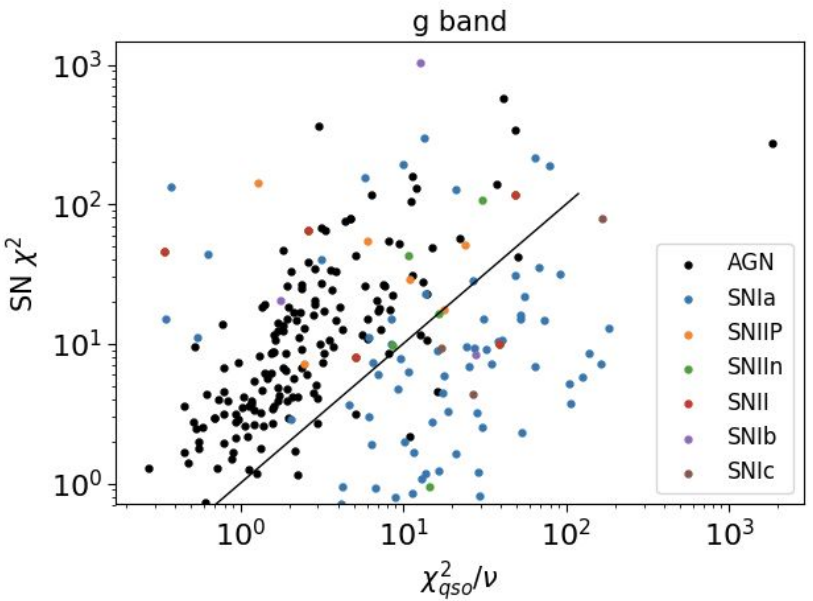




Light curve modeling separates AGN and SN

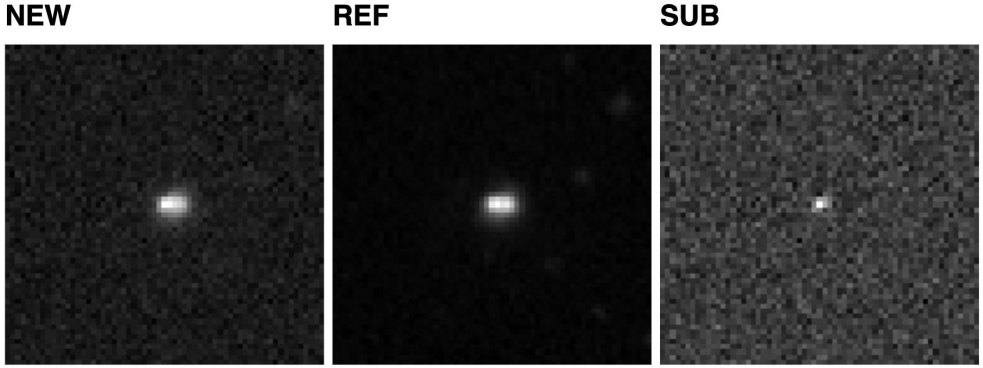
- Reject 81% of SNIa
- Keep 87% of AGN
- Only reject 30% of other SN types - for now.

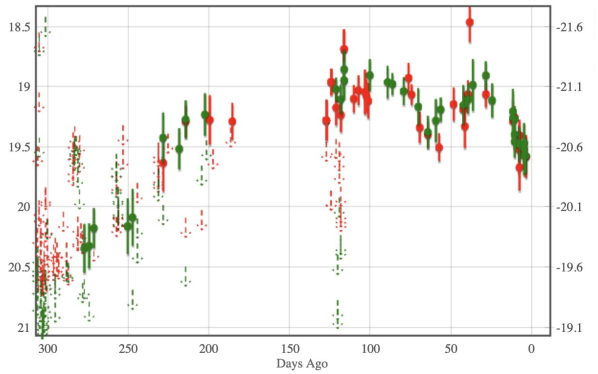


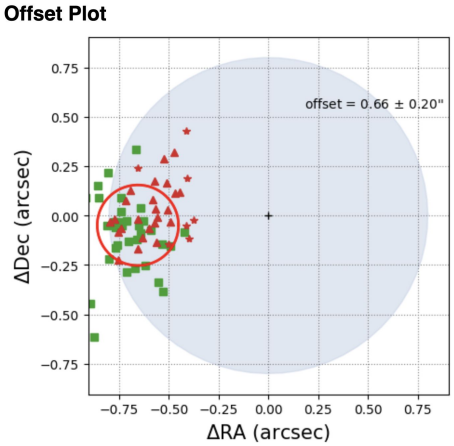


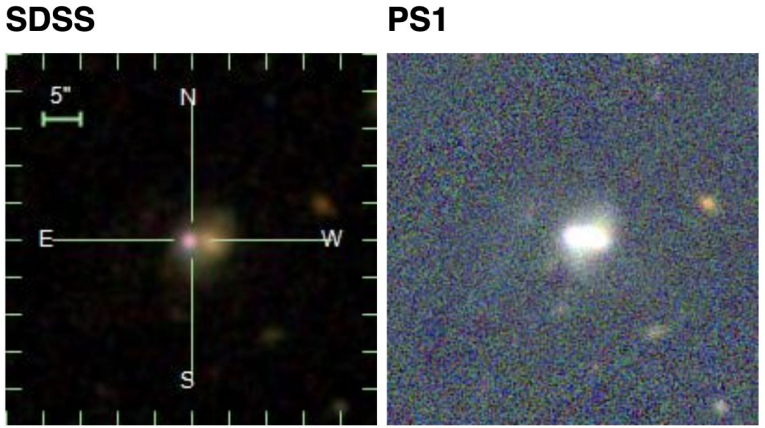
ZTF18aaxvmpg

- AGN-like transient is 0.66’’ from bright galaxy centre.
- Follow-up spectra from DCT will check for velocity offsets with host.



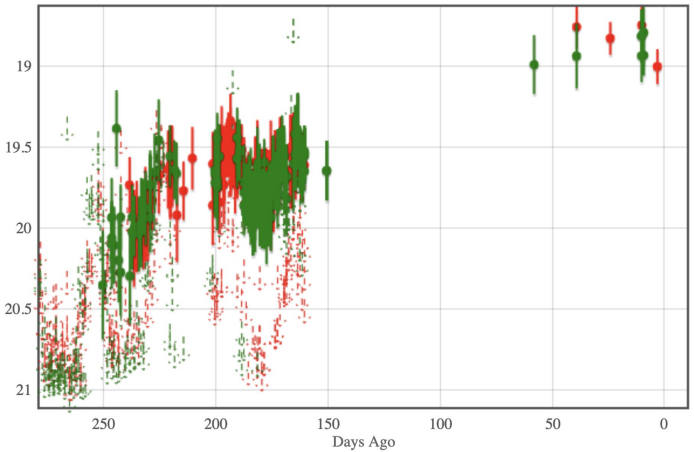


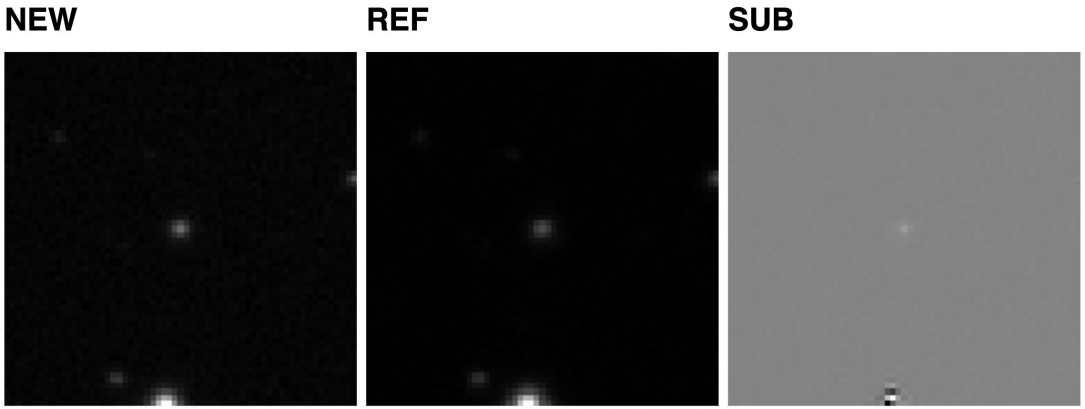


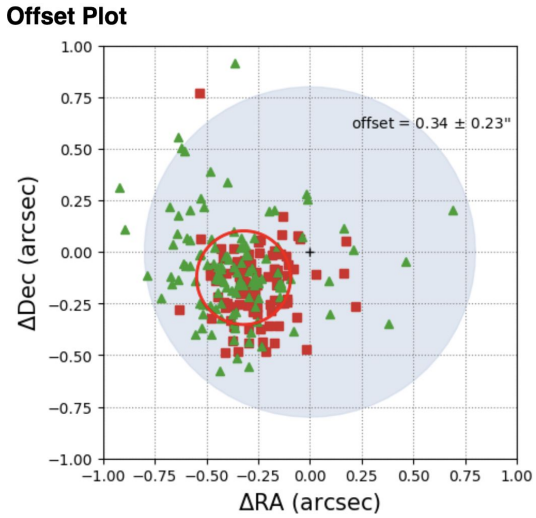


ZTF18aazkxlc

- Offset of 0.34”
- Broadline AGN
- Follow-up spectra from DCT will check for velocity offsets.

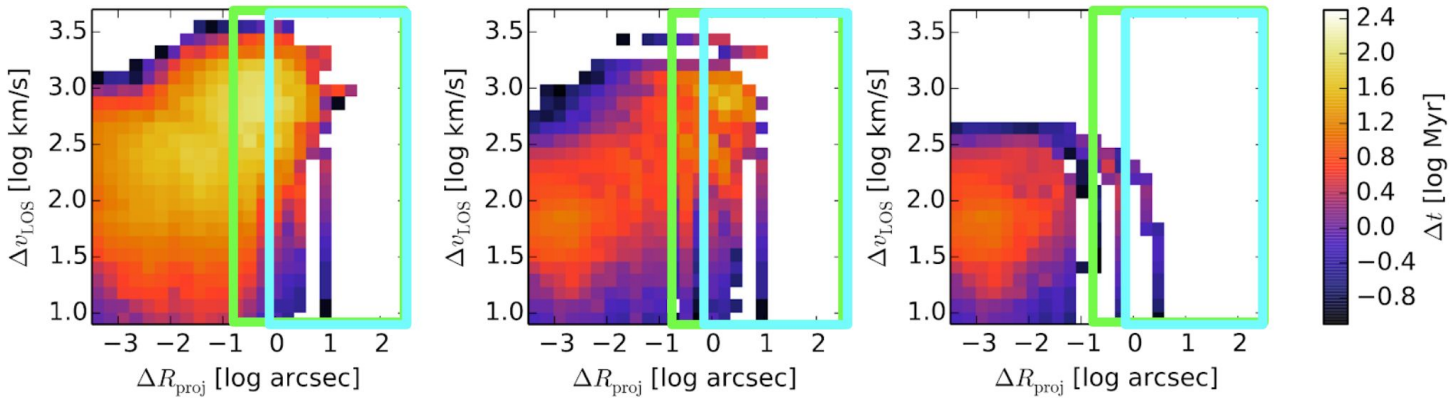






Small offsets and faint variability

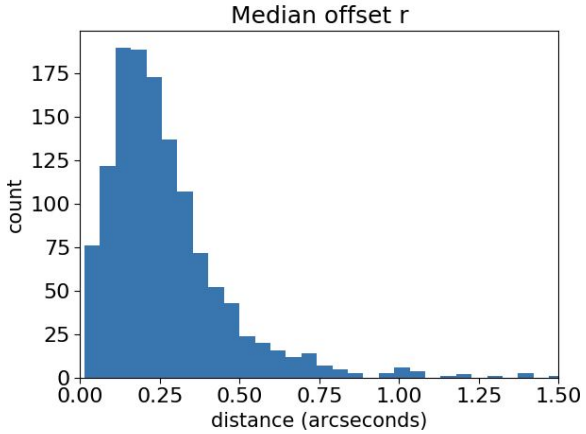
- If we could push offset sensitivity to 0.2’’ we will be sensitive to a much larger fraction of the simulated recoil population.
- If we can push photometry to find faint AGN, we will be able to detect more of the high offset population.

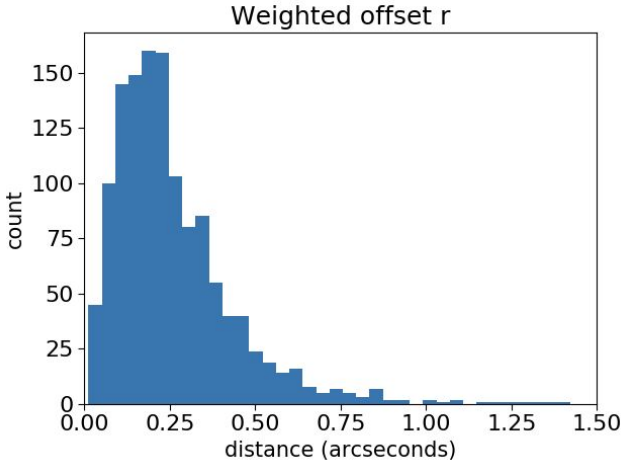


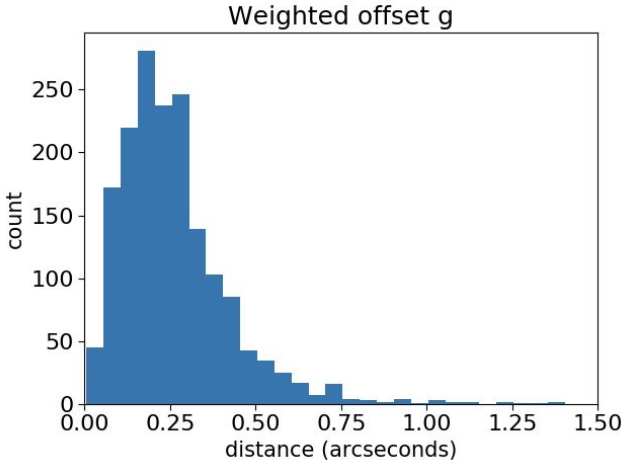
Blecha 2014

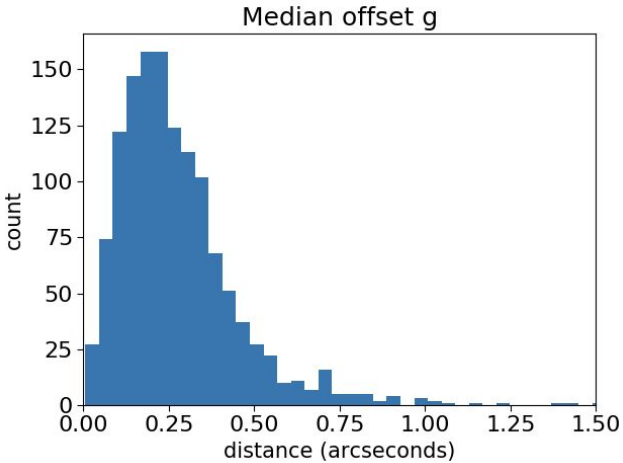
Offset sensitivity

- ZTF reference-transient offsets for known AGN can extend to 0.6’’.



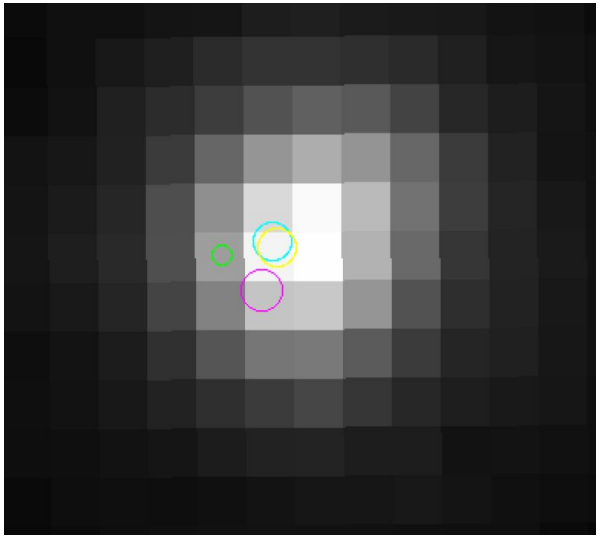


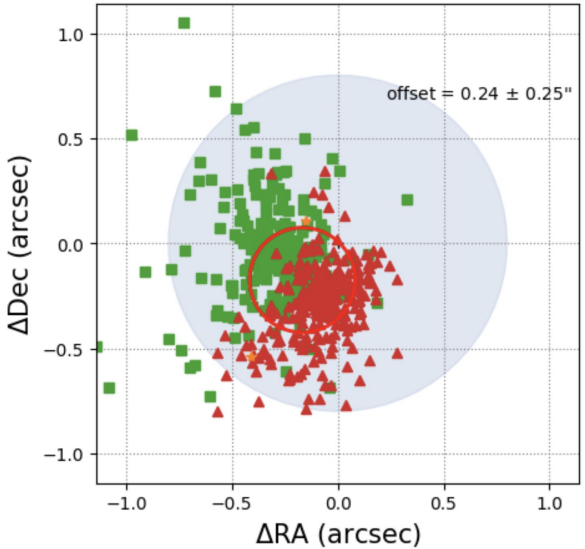


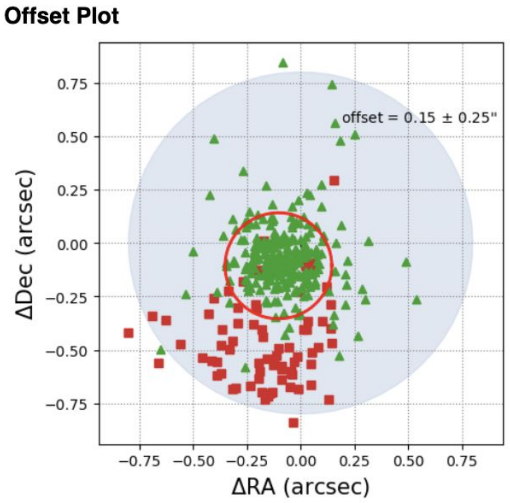


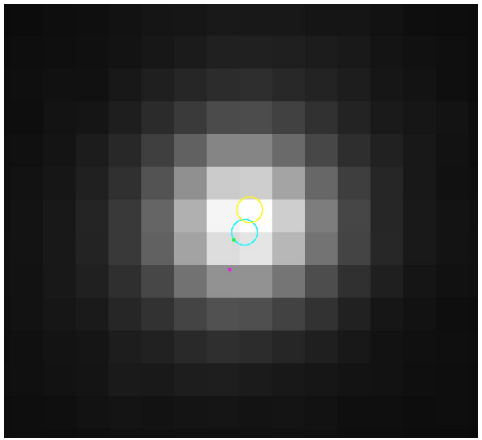
Offset sensitivity

- We see many cases with inconsistent g and r band transient positions.



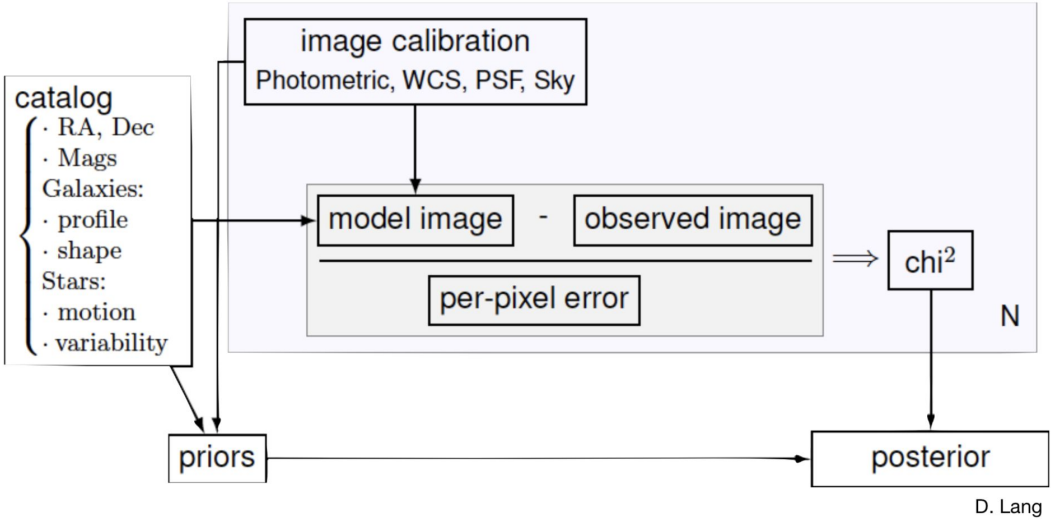


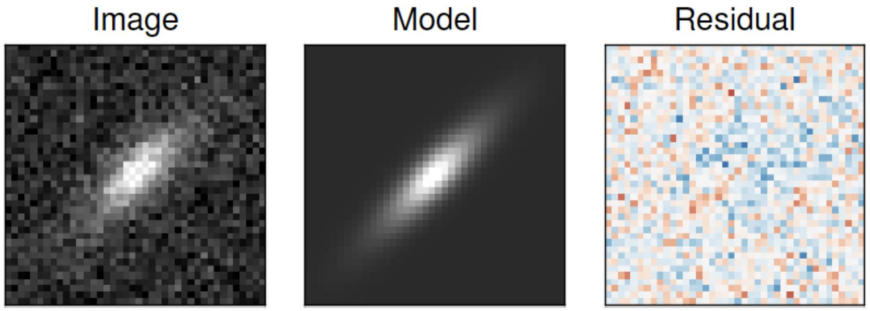




Tractor forward modelling

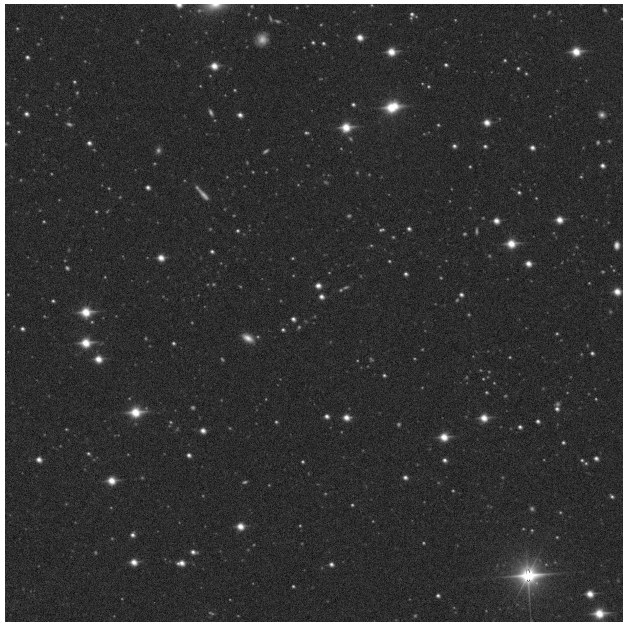
- Parametrize sky model, PSF model, catalog information.
- Can model multiple exposures, and images from different telescopes, bands etc.
- Avoids deblending.
- Allows us to refit calibration parameters.



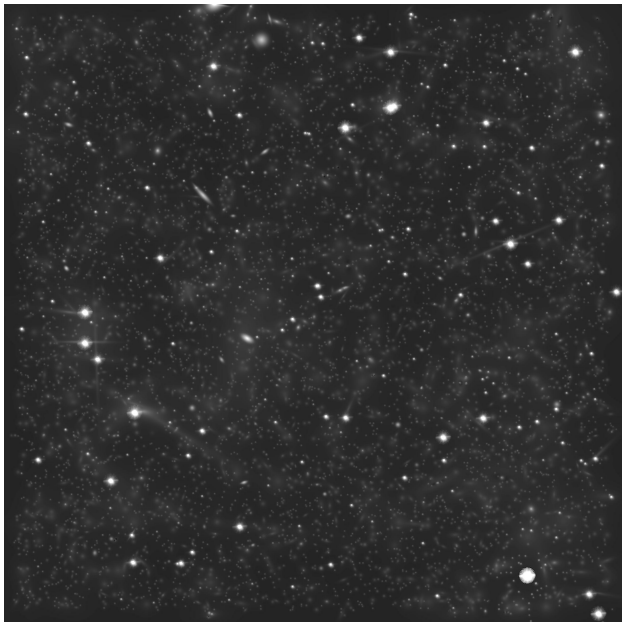


Tractor can model whole ZTF images

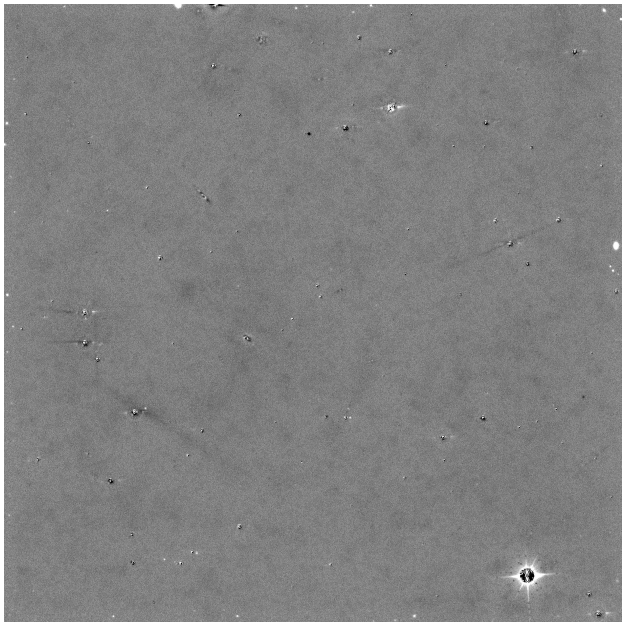
ZTF image



Tractor Model



Residuals

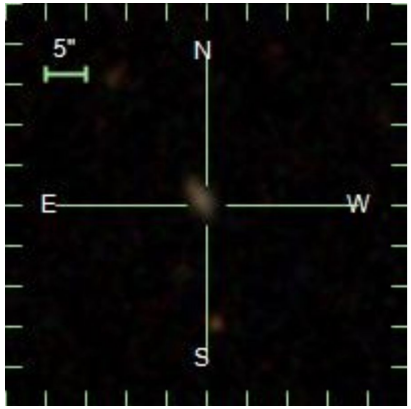


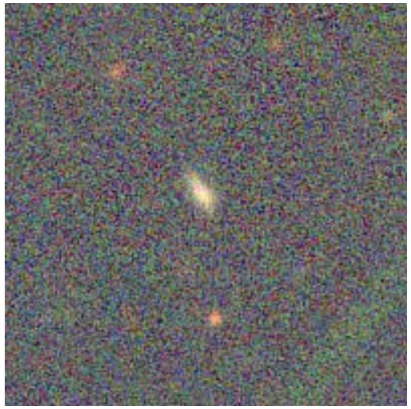
Tractor can model point sources within galaxies

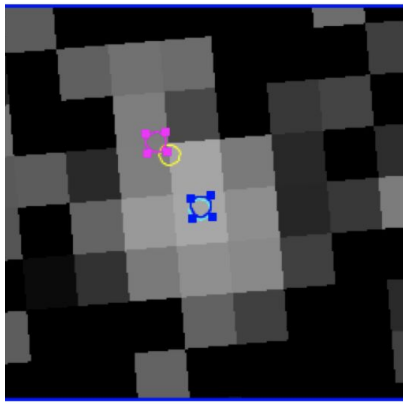
New models available:

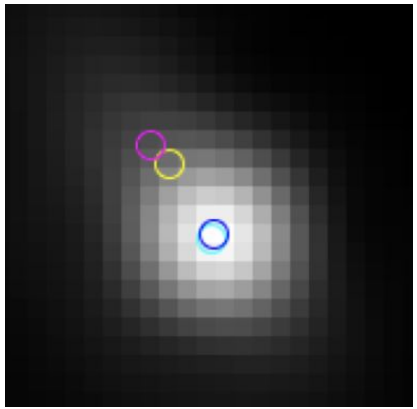
- Exponential galaxy + point source
- DeVancouleurs galaxy + point source
- Composite galaxy + point source

We can add new models for other interesting systems (e.g. AGN + another transient).







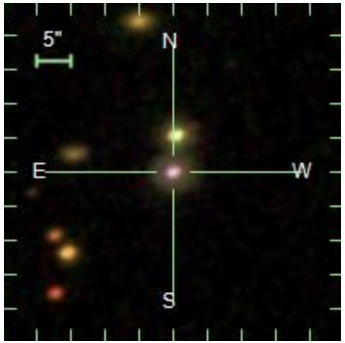


Tractor can model sources using different surveys

ZTF science images

DECaLS

SDSS*



PanSTARRS*

2MASS catalog

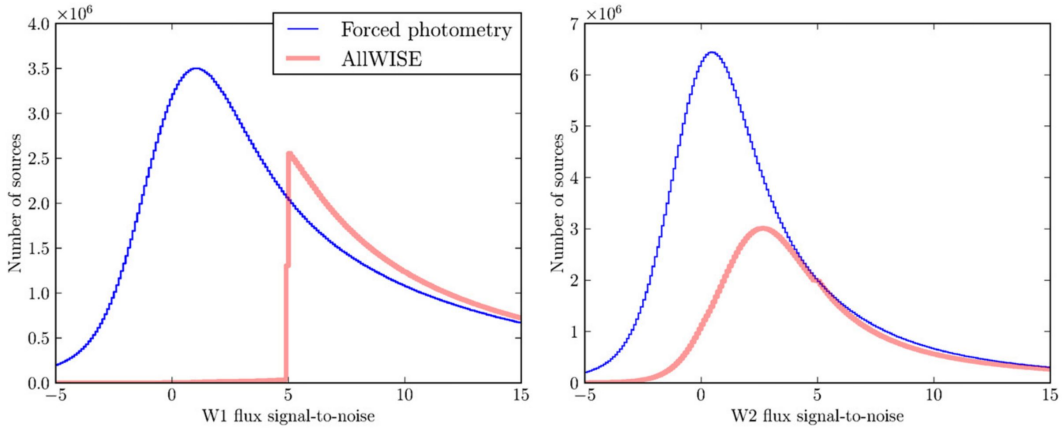
WISE catalog

Gaia catalog

Tractor model

Tractor can do forced photometry of transients

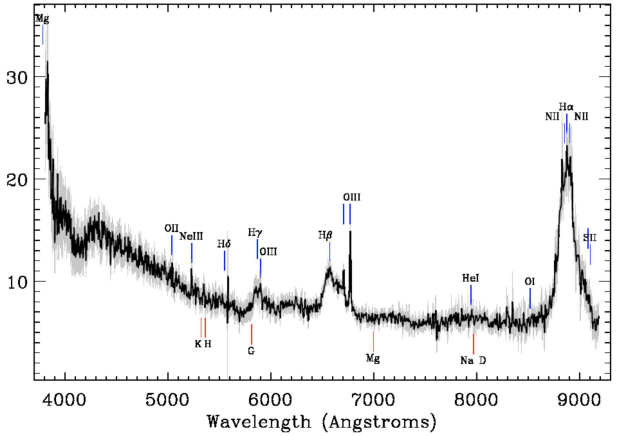
- Tractor was used for forced WISE photometry by Lang, Hogg and Schlegel (2016).
- Best fit position from Tractor modelling can be used to produce light curves for transients.
- We can measure low level variability.
- We can produce light curves from data across surveys.

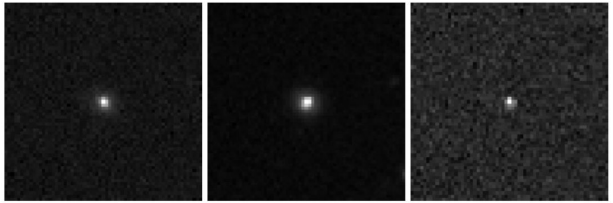


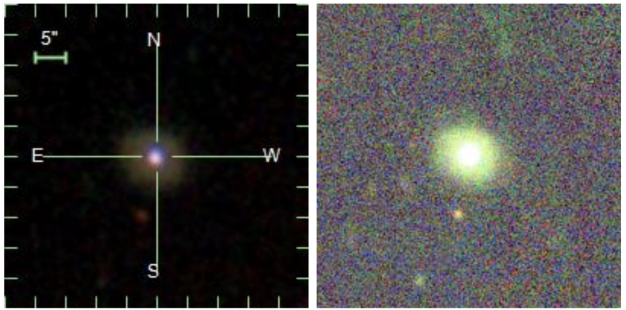
Lang, Hogg and Schlegel (2016)

Summary and next steps

- We have found AGN with real spatial offsets which are soon to have spectral follow-up.
- We have found AGN with offset broad lines but only tentative spatial offsets.
- We will continue to find large offset candidates with AMPEL for spectral follow-up.
- We will tractorize all ZTF AGN to model their positions in better detail and find small offset candidates.







Backup slides

Astrometry testing with simulations

- Galsim was used to to simulate point sources within real galaxies.
- Tractor astrometry was tested for a range of PSF fwhms, PSF shapes, S/N ratios, galaxy-point source offsets.