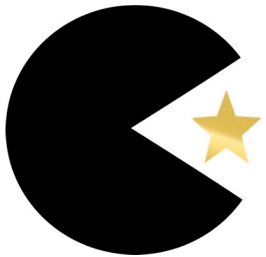
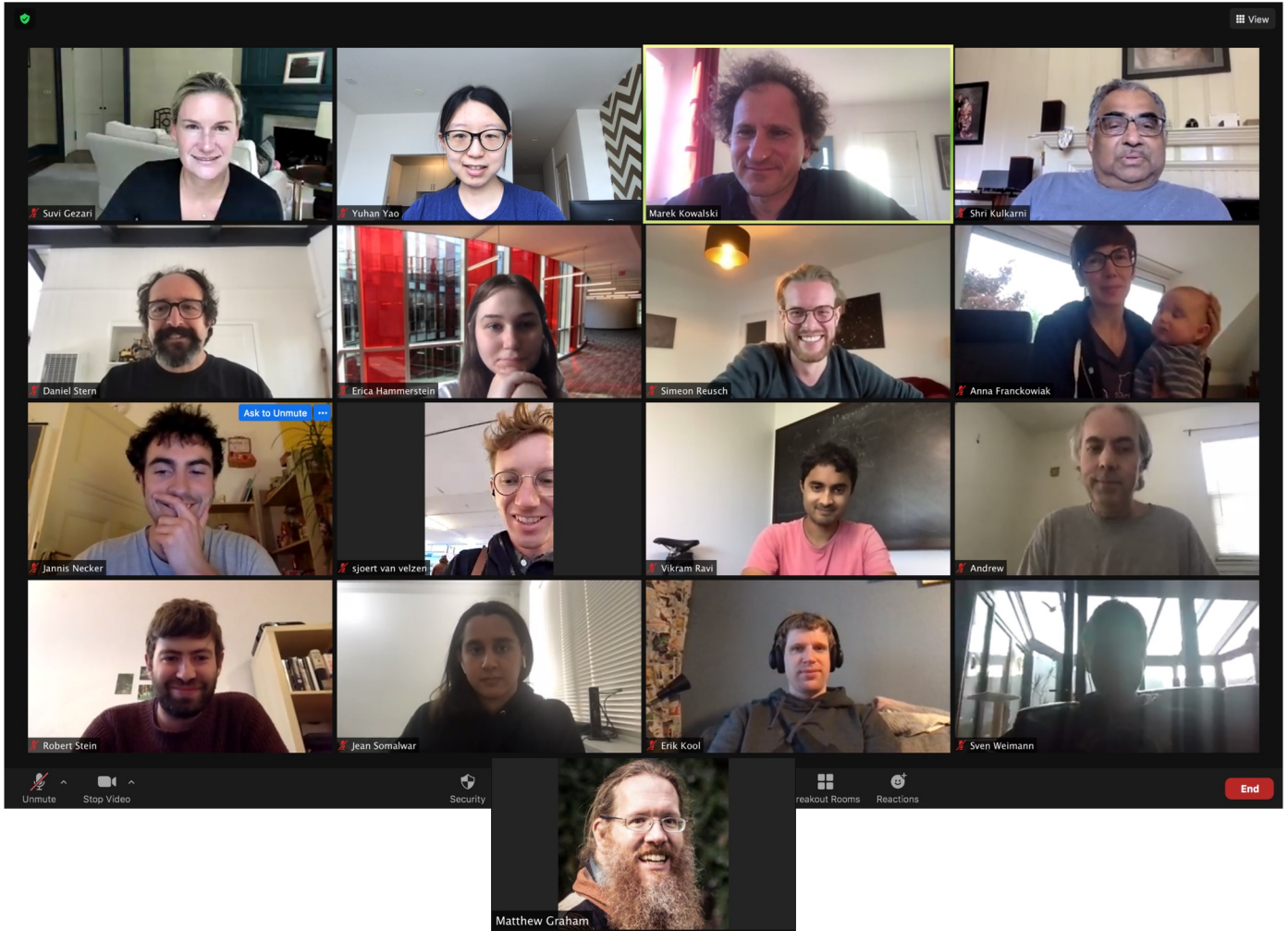
Nuclear Transient Science with ZTF

Matthew J. Graham (Caltech)
on behalf of the ZTFbh SWG



ZTFbh SWG


View
Suvi Gezari
Yuhan Yao
Marek Kowalski
Shri Kulkarni
Daniel Stern
Erica Hammerstein
Simeon Reusch
Anna Franckowiak
Ask to Unmute
Jannis Necker
sjoert van velzen
Vikram Ravi
Andrew
Robert Stein
Jean Somalwar
Erik Kool
Sven Weimann
Unmute
Stop Video
Security
reakout Rooms
Reactions
End
Matthew Graham

What are we doing?

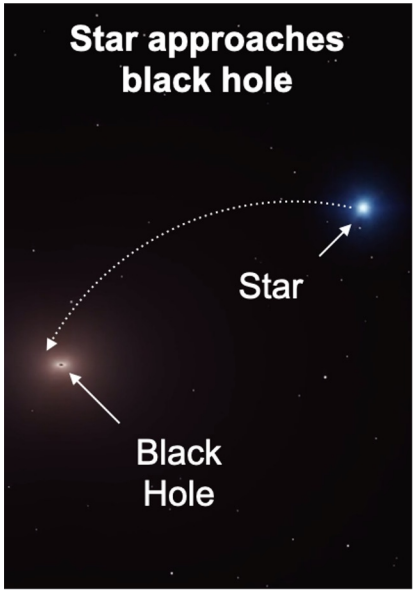
A systematic search and study of extragalactic nuclear transients!

- **Tidal disruption events**
- Other interests include variable AGN, changing-look quasars, and binary, recoiling, or intermediate mass black holes.

How are we conducting our search?

- Filtering of the ZTF alert stream:
  - Rise and fade timescales
  - Color and color evolution
- New for ZTF-II: boxes to more efficiently follow up all possible TDE candidates
- Systematic analysis of archival data

What is a TDE?



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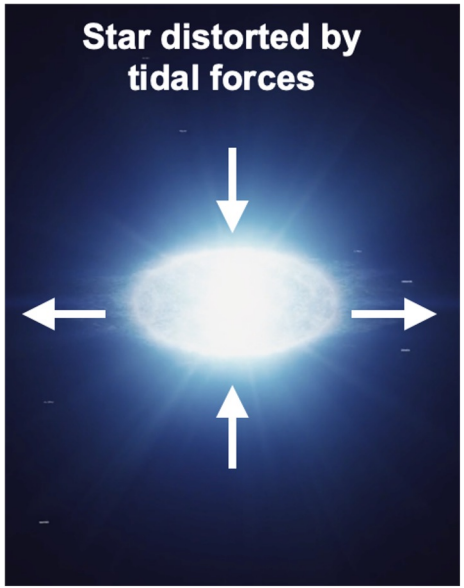

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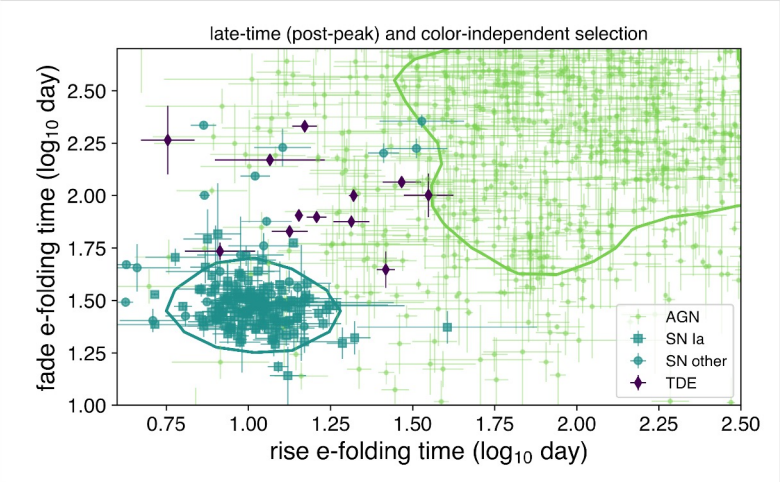
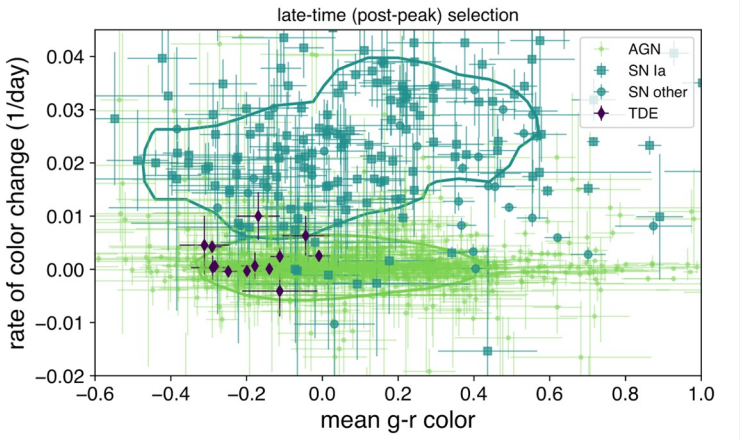
3

4

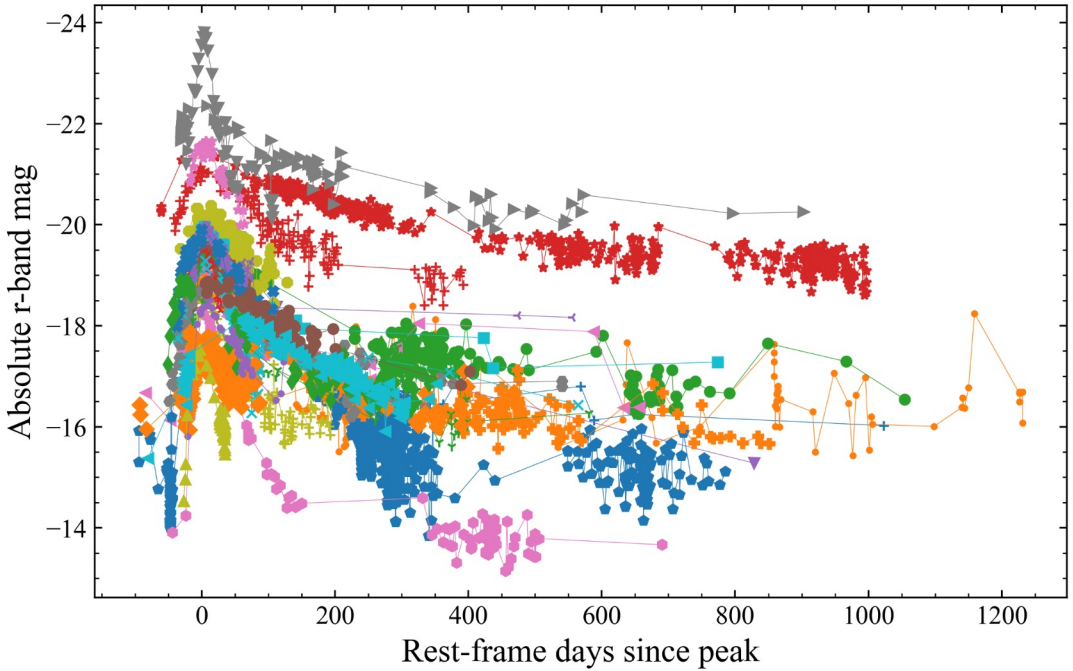
Photometric selection





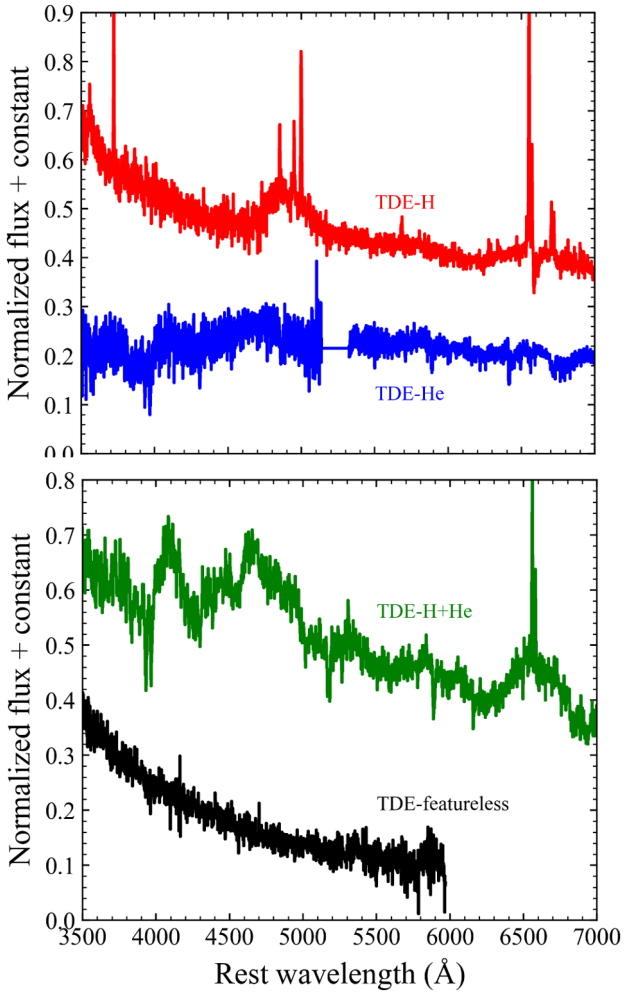
TDEs from ZTF-I and II

- 30 TDEs from ZTF-I (van Velzen+ 2021, Hammerstein+ 2021, Hammerstein+ 2022)
  - 4 spectroscopic classes of TDEs
- ~50 TDEs from ZTF-II
  - Expanding new TDE-featureless class
  - Single object papers: Yao+ 2022



Spectroscopic classification

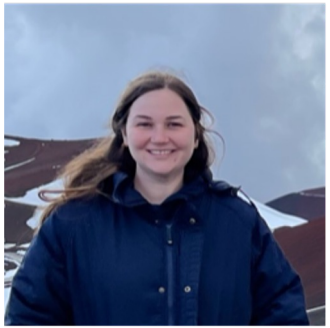
- TDE-H: 6 + ~3
- TDE-He: 3 + ~1
- TDE-H+He: 17 + ~12
- TDE-featureless (new!): 4 + ~7
- (many more with uncertain classifications)
- See Hammerstein et al. 2022 for more!



Ongoing Projects

Hosts, Rates, Synergy, Jets and MMA

TDE Hosts

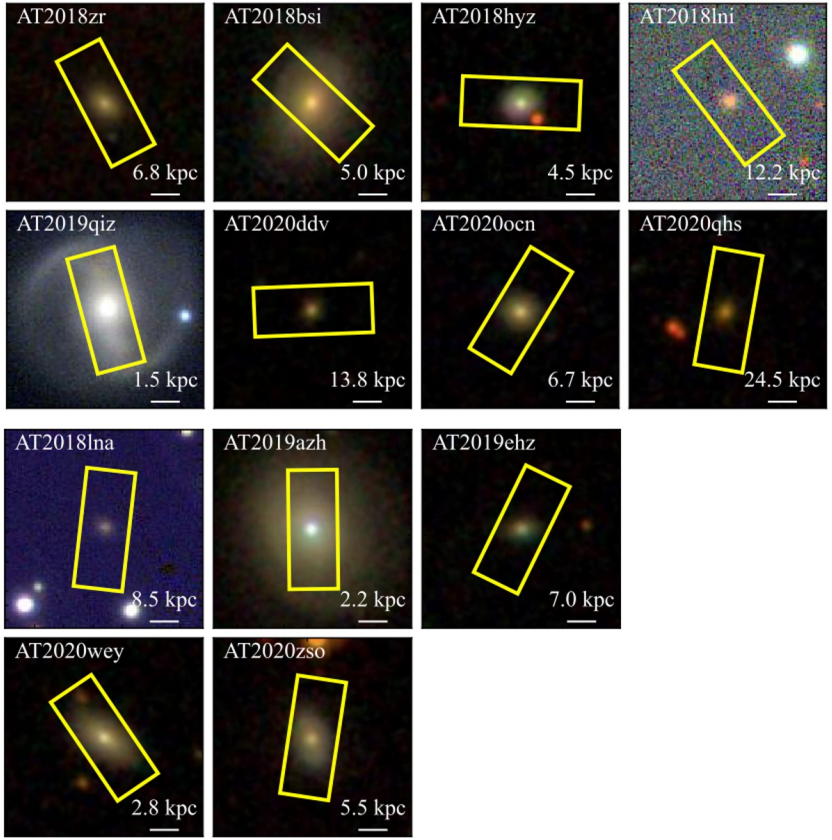


Erica Hammerstein
University of Maryland

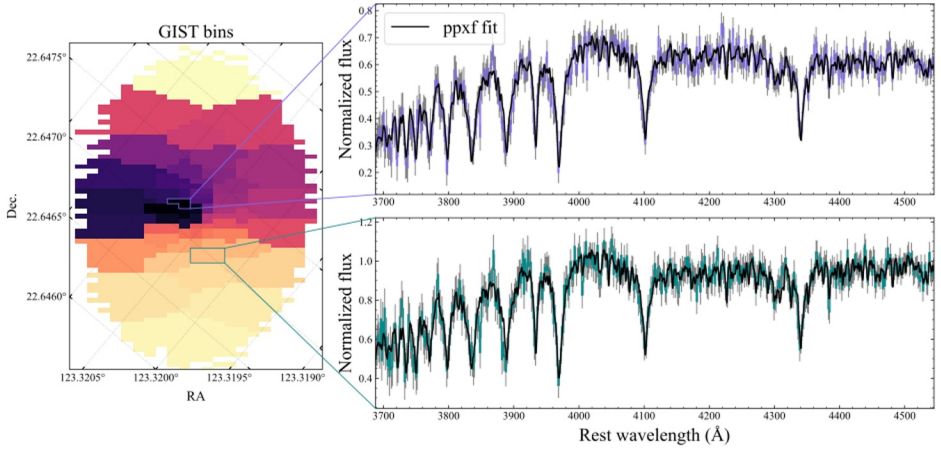
Keck KCWI IFU observations of ZTF TDE host galaxies

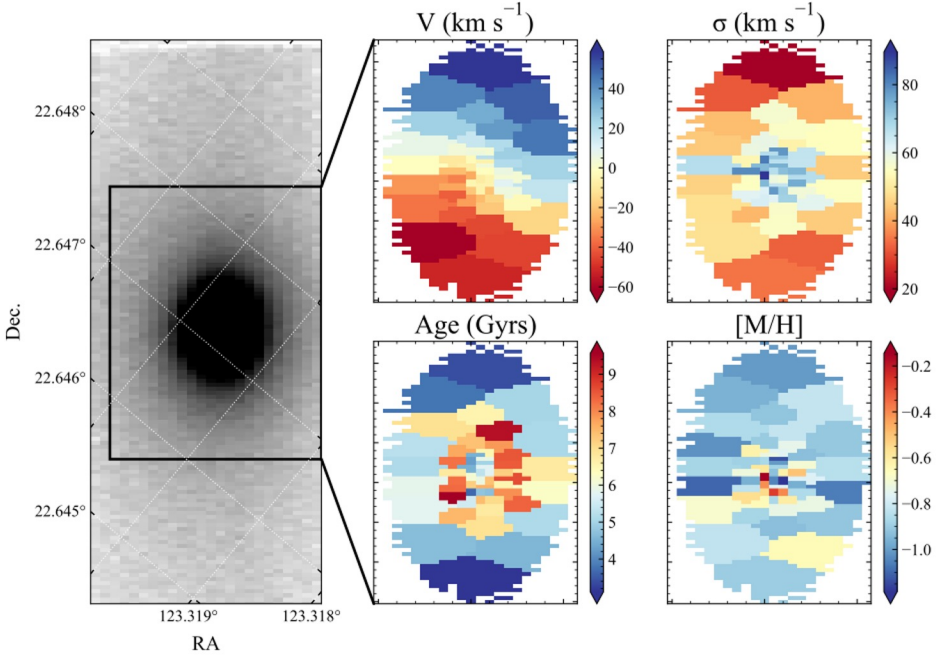
Goals:

1. **Understand the stellar populations and kinematic properties of TDE hosts – potentially explain their preference for "green" hosts**
2. Use the stellar velocity dispersion to infer the mass of the central black hole

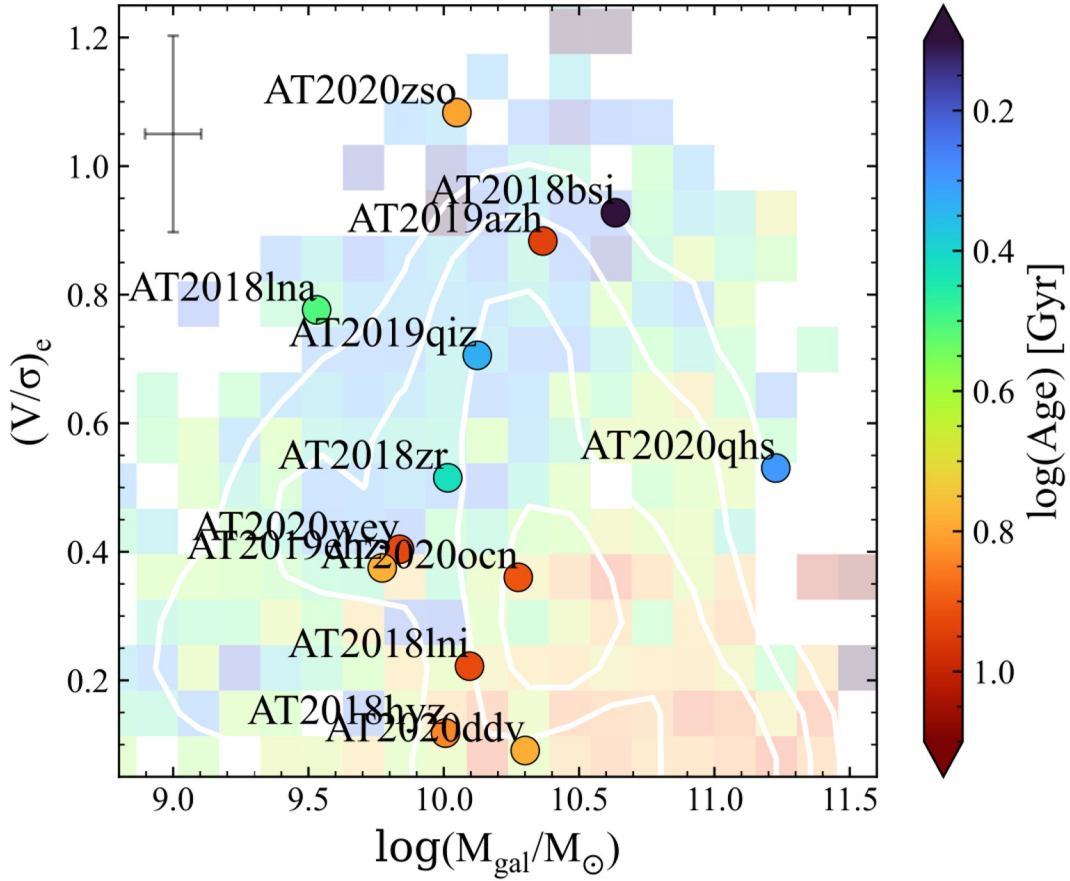


Fitting the KCWI spectra with the GIST pipeline



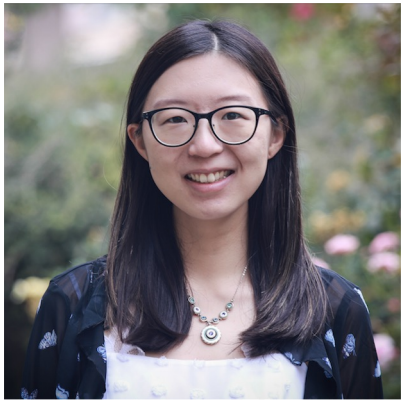


TDE host kinematics



- We examined the ratio of ordered to random stellar motion (V/σ), and find that TDE hosts are largely dominated by random stellar motions
- Correlation with host stellar population age may explain green color of TDE host galaxies

TDE Rates & Jet Physics



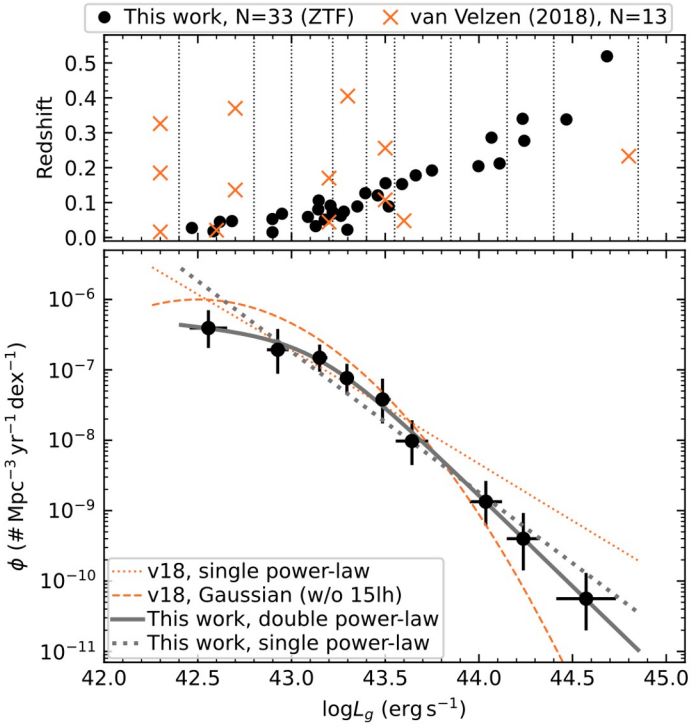
Yuhan Yao
Caltech → UC Berkeley

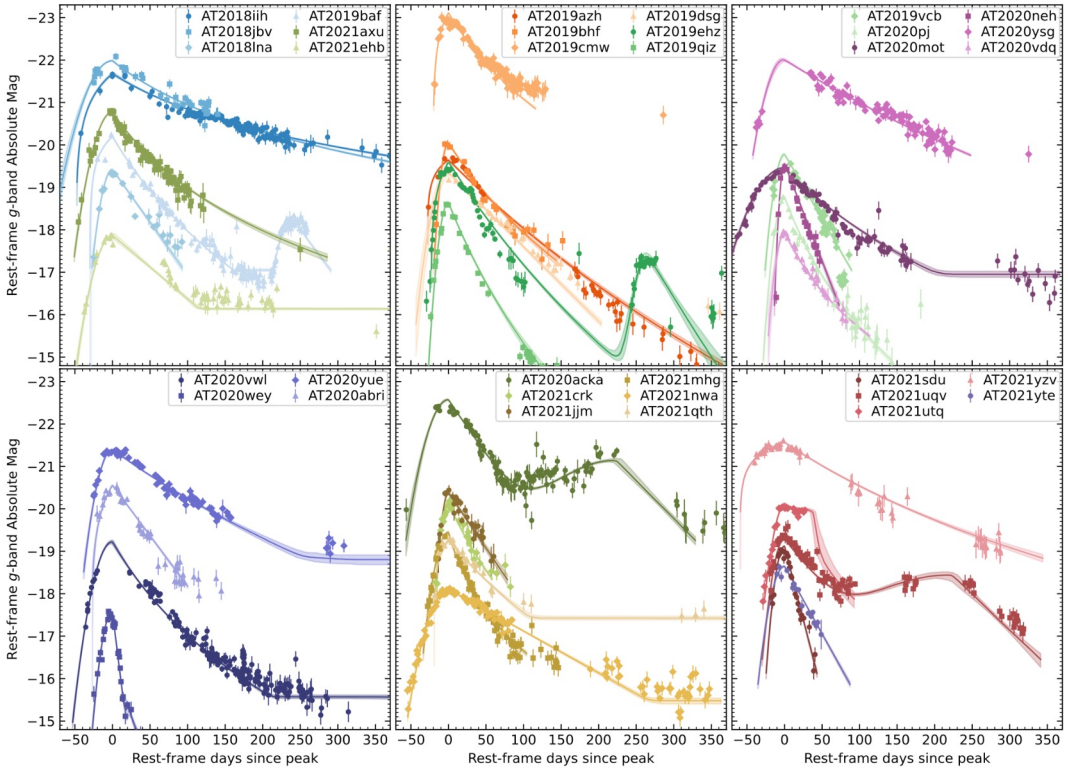
TDE Optical Luminosity Function with the ZTF

Yao+2023, arxiv 2303.06523

TDE Rates

A spectroscopically complete, flux-limited (g-band peak < 19) sample of 33 TDEs from three years of ZTF
Constructed with a clearly defined selection method + spectral coverage of almost all candidates





TDE Rates

Implications of the Local Black Hole Demographics

$$\phi_{\rm TDE}(M_{\rm BH}) \equiv \frac{dn_{\rm TDE}}{d\log M_{\rm BH}} = \dot{N}_0 \left(\frac{M_{\rm BH}}{10^6\,M_\odot}\right)^{\beta} \frac{dn_{\rm BH}}{d\log M_{\rm BH}}$$

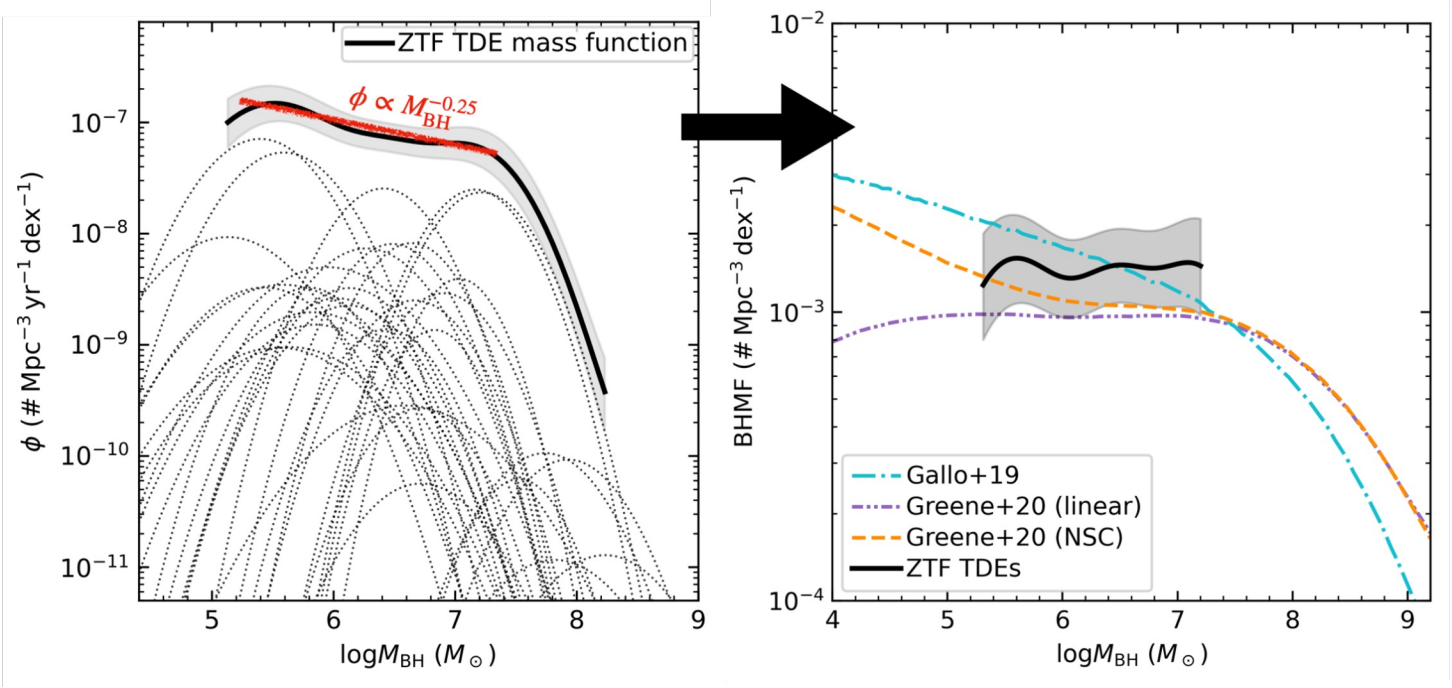
$\beta \approx -0.25$ see Wang+2004, Stone & Metzger 2016, Stone+2020

Normalization term (10^{-5} – 10^{-4} yr^{-1})

Two-body relaxation time scales with $M_{\rm BH}$

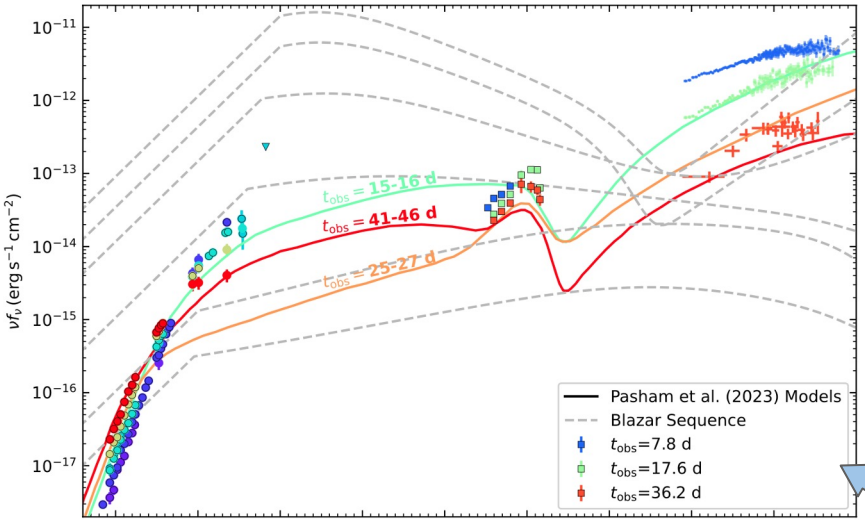
Black hole mass function (BHMF)

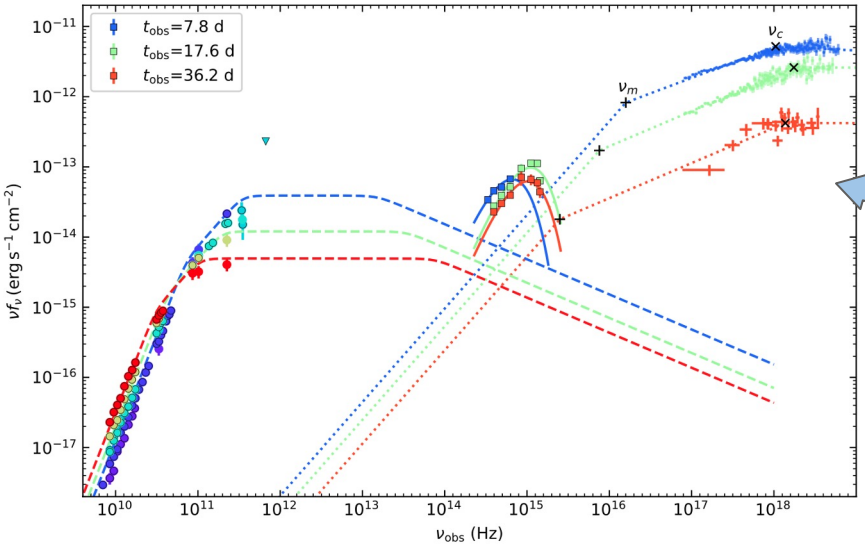
Yao+2023, arxiv 2303.06523



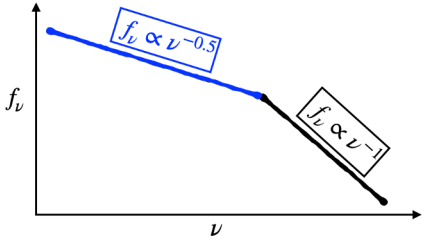
Jet Physics

Broadband SED Modeling of AT2022cmc





New data: ***NuSTAR*** observations, which reveal that the X-ray spectrum is a broken power-law



Top panel: models by **Pasham+2023**
X-ray and radio both come from jet front, X-ray is synchrotron self-Compton (SSC) of radio photons.
Problems: underpredict mm flux, no energy break in X-rays

Bottom panel: models by **Yao+2023**, in prep
X-ray: internal energy dissipation within the jet (synchrotron origin, bulk Lorentz factor ~ 30)
Radio: forward shock interacting with ambient medium (synchrotron origin bulk Lorentz factor ~3)
Supports the physical picture proposed in the ZTF discovery paper: **Andreoni, Coughlin+2022**

X-ray TDEs with Swift/XMM

Muryel Guolo
JHU

X-ray Properties of Optically Selected TDEs

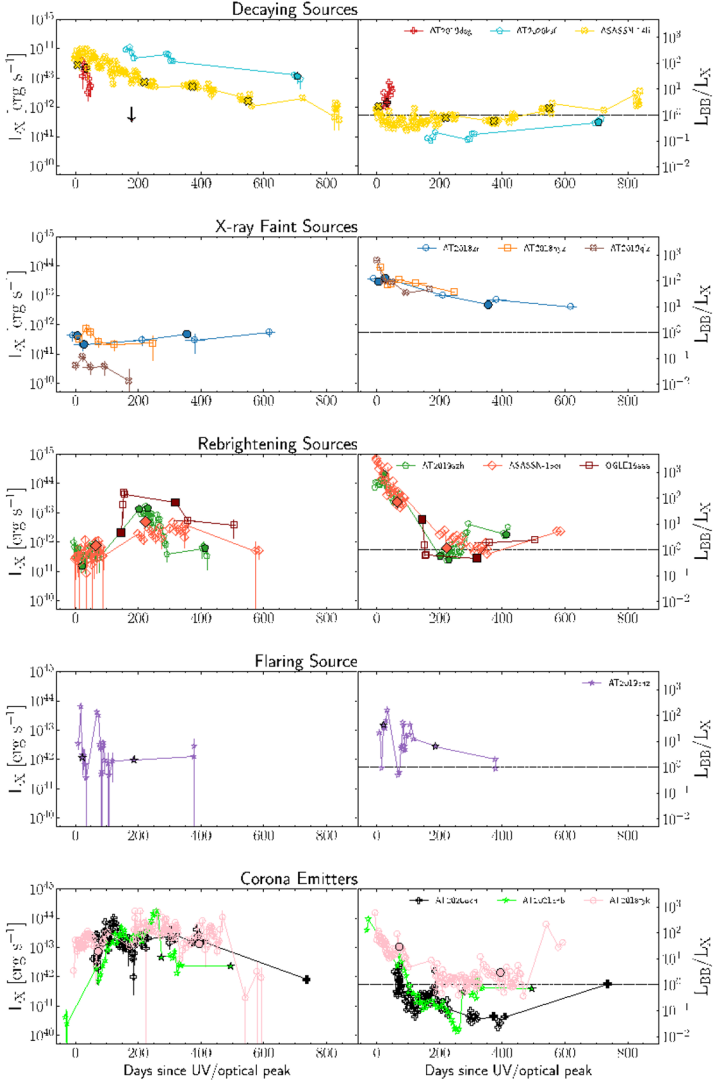
Sample of 16 ZTF TDEs observed with Swift (ZTF TDE group) and XMM-Newton (PI: Gezari). 8 ZTF TDEs detected as X-ray bright.

Multi-epoch (2-3) XMM-Newton spectra of the 8 X-ray bright TDEs from ZTF plus 4 from the archive are fitted with a multi-temperature disk model (**tdediscspec**) to get a characteristic temperature and radius with time.

Several TDEs show evidence in XMM-Newton spectrum for ultra-fast outflow absorption features below 1 keV.

Diverse range of X-ray behaviors: decaying sources, relatively X-ray faint sources, late-time brightening sources, flaring sources, and sources which develop a hard non-thermal “corona” component.

Guolo, Gezari, Yao et al. (in prep)



UV TDEs with LT

Matt Nicholl
Queen's University Belfast

Evan Ridley
University of Birmingham

TDEs with LT

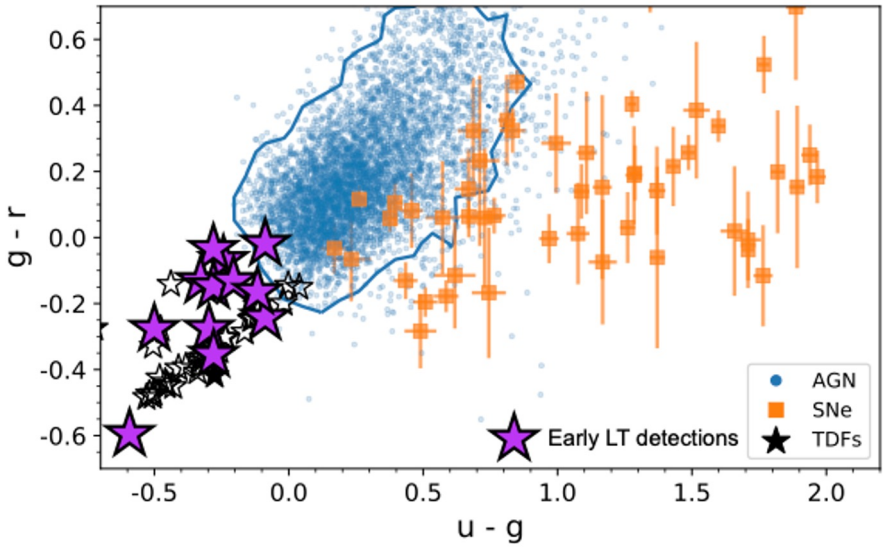
Overview

- Liverpool Telescope is a 2m, fully robotic telescope in La Palma
- Reaches *u* ~ 21 in 600s (S/N ~ 10)
- TDE group are running a program to classify and follow-up promising nuclear transients

TDEs with LT

Aims

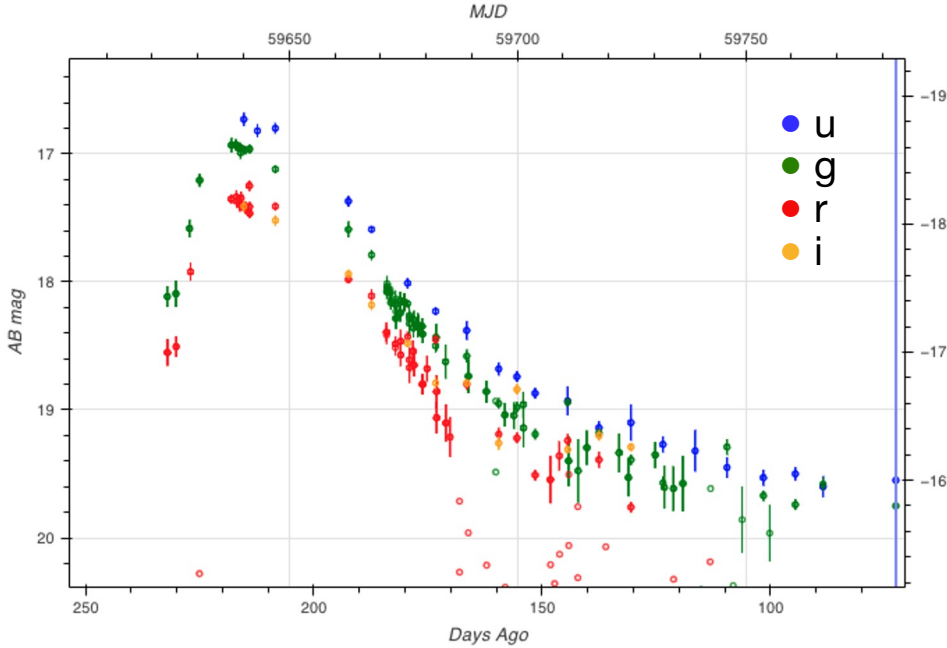
- For young, unclassified nuclear transients with g_{ZTF} - r_{ZTF} < 0:
  - Obtain *ugri* imaging with LT — TDEs jump out in *u-g*
  - Inform target selection for spectroscopy
  - Multicolour imaging allows pre-peak temperature measurement even before triggering *Swift*



TDEs with LT

Status

- Workflow operational since last summer
- Six new TDEs first identified by *u-g* colours
- 18 confirmed TDEs with active follow-up - weekly cadence
- Google spreadsheet to coordinate targets and triggering
- Program renewed for LT 2023A semester (Jan-July) - continuing to trigger



ZTF18aabdajx = AT2022dbl = Luke Skywalker

ZTF+LT light curve

Radio TDEs with VLASS

Jean Somalwar
Caltech

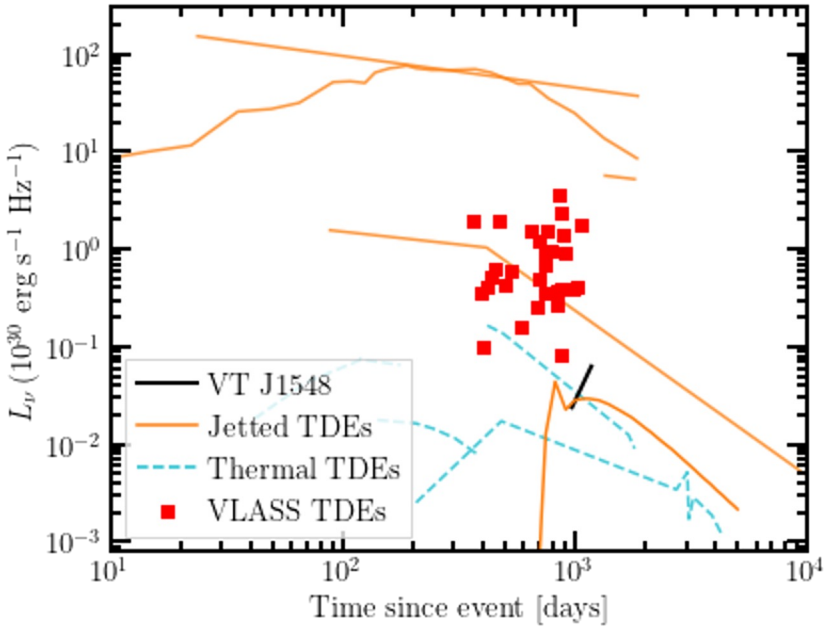
Tidal disruption events in VLASS

Our work: first *complete* radio-selected TDE sample.

VLASS: 3 GHz (almost) full sky radio survey with high angular resolution (~2.5”) and 0.2 mJy sensitivity, three epochs with cadence of ~a few years

Selection:

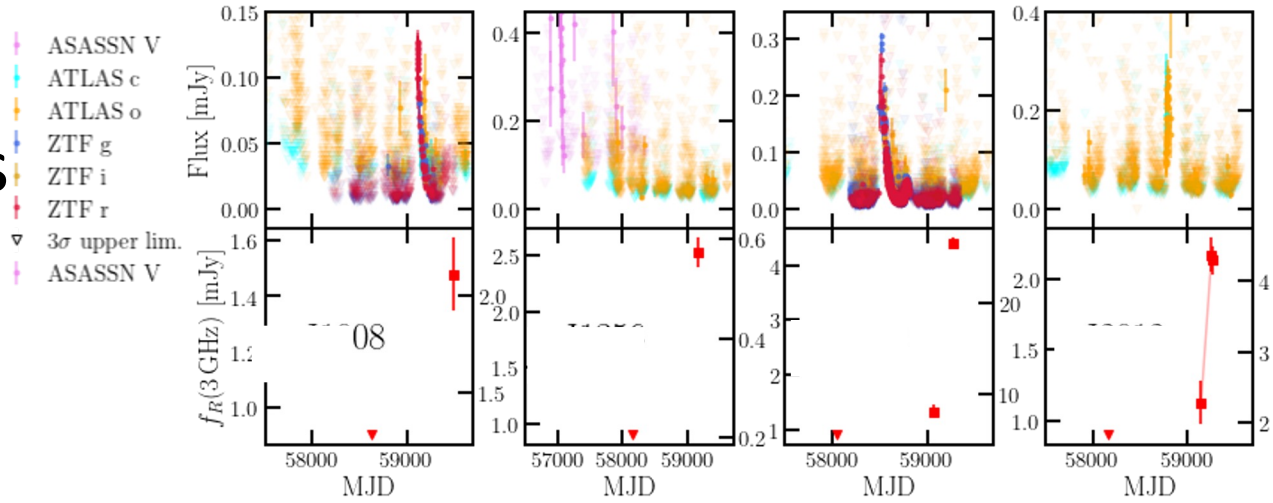
- radio transients in PanSTARRS galactic nuclei
- no past variability nor strong evidence for AGN activity
- relatively nearby (z < 0.25)
  (a 10^{38} erg s^{-1} source can be detected at 3σ to z ~ 0.055)

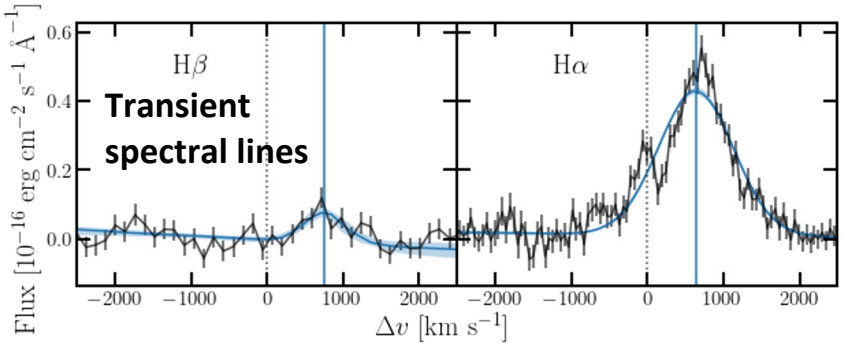


- ~140 *candidates* (unconfirmed TDEs) thus far
- Of those with optical spectra: **~30 with no strong AGN-like lines** (~1/3 of sample)
- **Six with optical counterparts in ZTF/ATLAS/ASASSN**

Highlights: optical+radio TDEs

(Somalwar+ in prep.)





One transient in a quiescent galaxy has long-lived transient Balmer lines that are redshifted ⟶ SMBH binary? Recoiling SMBH?

Six sources with optical counterparts

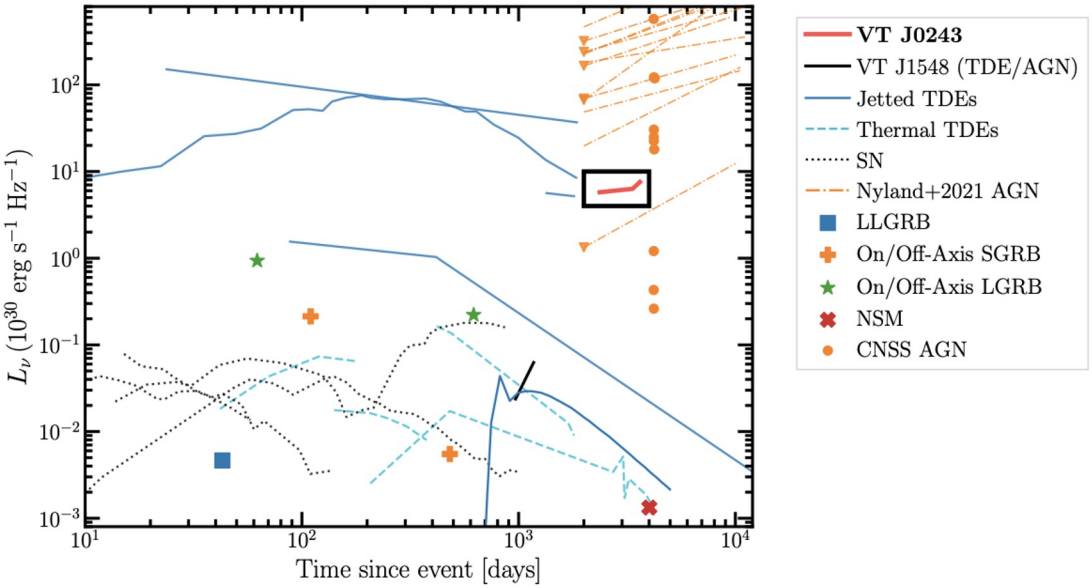
The multiwavelength properties and host galaxy properties of the VLASS selected TDEs are distinct from previous TDEs!

A jetted TDE in VLASS vs NVSS

In a search for radio transients between VLASS and the NVSS survey, we identified an extraordinarily bright and long-lived TDE candidate, VT J0243 (Somalwar+2022)

NVSS: 1.4 GHz survey, δ>-40°

- Long live (>3 years) 10^{40} erg s^{-1} radio flare that is still rising.
- Radio SED is consistent with an expanding jet
- Possible optical flare in PanSTARRS
- Transient soft X-ray emission



AGN counterparts to GWs

Matthew Graham
Caltech

The big search for O3 EM AGN counterparts

- An AGN accretion disk is a viable location for a stellar mass BH-BH merger, particularly massive (multi-generational) components - baryon-rich high density environment means an EM counterpart must occur
- A viable emission mechanism involving Blandford – Znajek jet - observational signature different from NS-compact mergers but ideal for regular ZTF monitoring
- 83 BBH mergers in LIGO O3: we find 7 candidate flares, all with $M > 60\ M_{\odot}$
- Detailed consideration on false positives particularly intrinsic AGN activity
- The numbers are in line with expectation
- LIGO O4 campaign (prompt good skymaps and masses) and potential H_0 measurement

Baratheons

Matthew Graham
Caltech

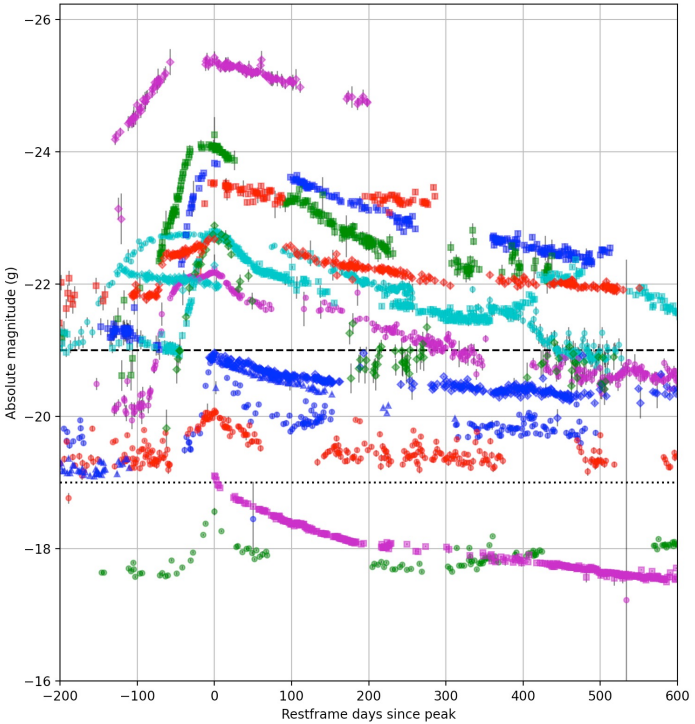
What are Baratheons?

- ”The most energetic and luminous transients ever observed”
- “Extreme extension of known scenarios of black hole accretion”

- Could be extreme TDEs – 15 $M_\odot$ with $10^{8.1}$ $M_\odot$ or accretion of giant molecular cloud

- Recovering – retrograde TDE with infilling cavity?

- Repeater – EMRIs?



ML Classification of TDEs

Robert Stein
Caltech

Simeon Reusch
DESY

ZTF: The director's cut

Goal of ongoing study

Systematize and expand search for (candidate) TDEs + dust echoes: characterize and classify ZTF nuclear transients (and check for IR counterpart)

Parameter	Value
sgscore	< 0.4
Gaia sgscore	< 0.5
diffmag (at least once)	< 20 mag
rb (at least once)	> 0.3
min galactic latitude	> 5 deg
mindet / band	>= 3
dist to ref	< 0.5 arcsec

Rerun of live TDE filter with AMPEL

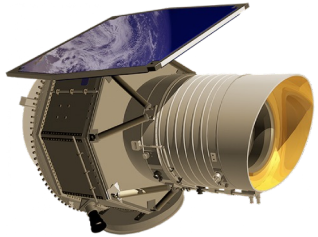
Filter rerun and forced photometry

Obtained 3.5 years worth of data

11687 transients survive

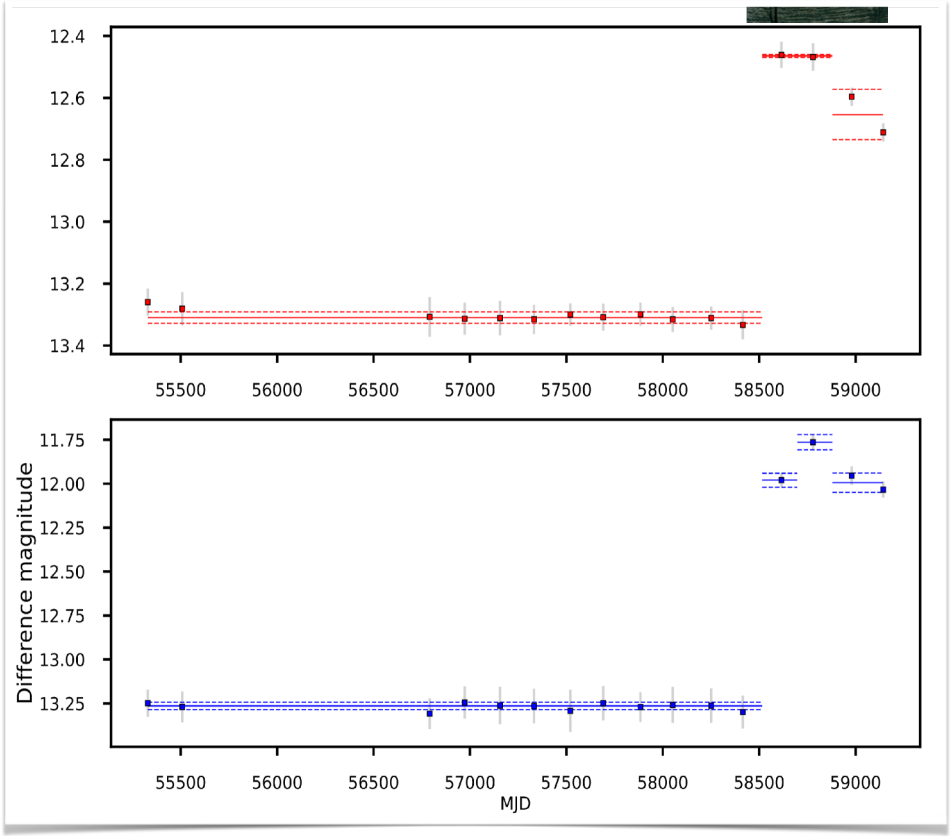
Obtained forced photometry
for full sample with **fpbot**

98% have a WISE
counterpart



Analyzed with Bayesian
block framework

~ 16% have a prominent peak



Result: A multivariate TDE classifier

Goal: Classify the full nuclear sample

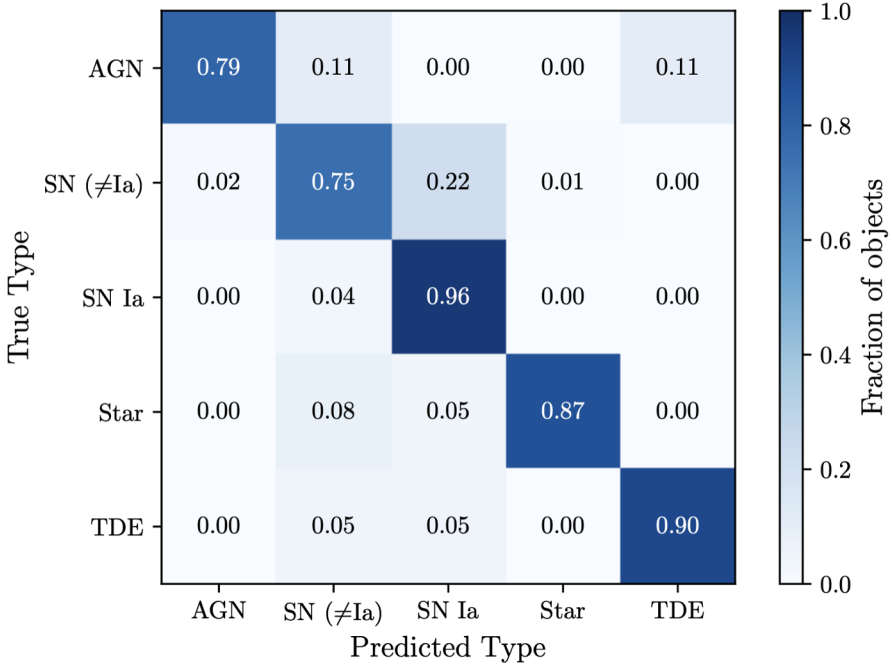
Feature extraction

- TDE fits (rise, decay, temperature, …)
- SALT fit
- Core dist
- WISE colors
- …

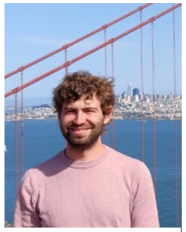
Look for oddballs

Sample paper in prep.

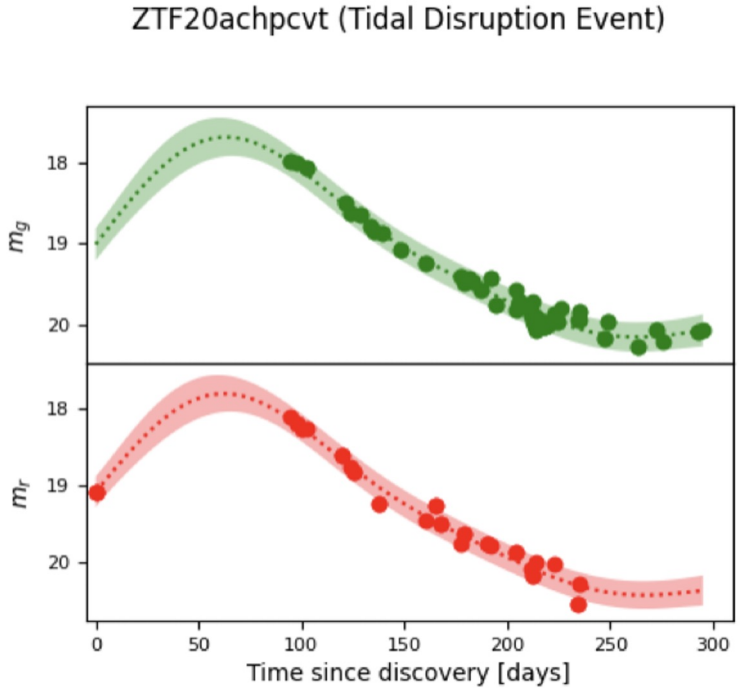
Classifier trained on noisified BTS light curves (prelim)



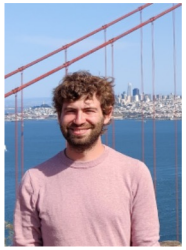
Complementary Gaussian Process Analysis



- Start with same ~12000 nuclear transients from Ampel filter
- Lightcurve analysis with gaussian process
- Extract rise/fade/colour etc
- Crossmatch to WISE/PS1
- Select classifications from Fritz for labelling

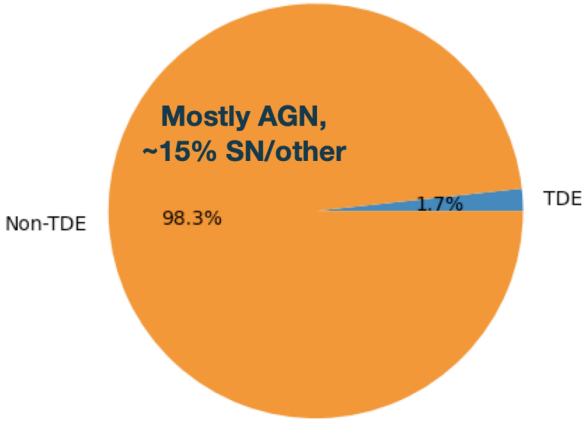


“Tdescore”: A binary classifier…



~3000 classified transients,

>98% are non-TDE

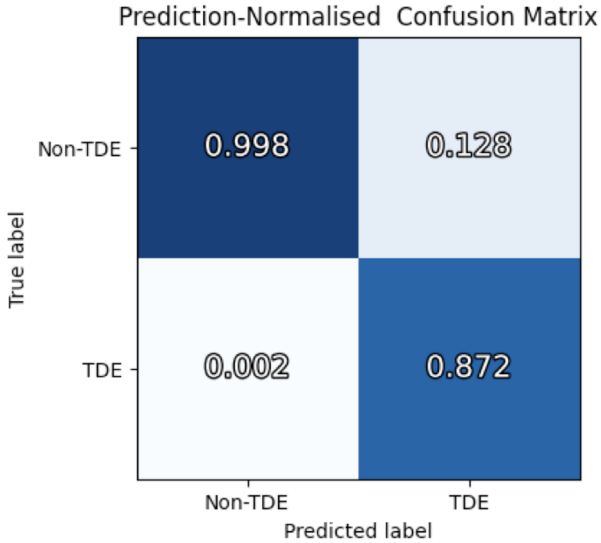


Balanced training with SMOTE

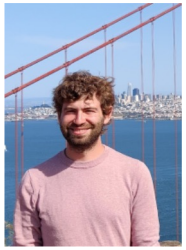
Paper draft in prep.

Rejects non-TDEs with >99.8% efficiency

Yields very pure (>85%) sample of TDEs

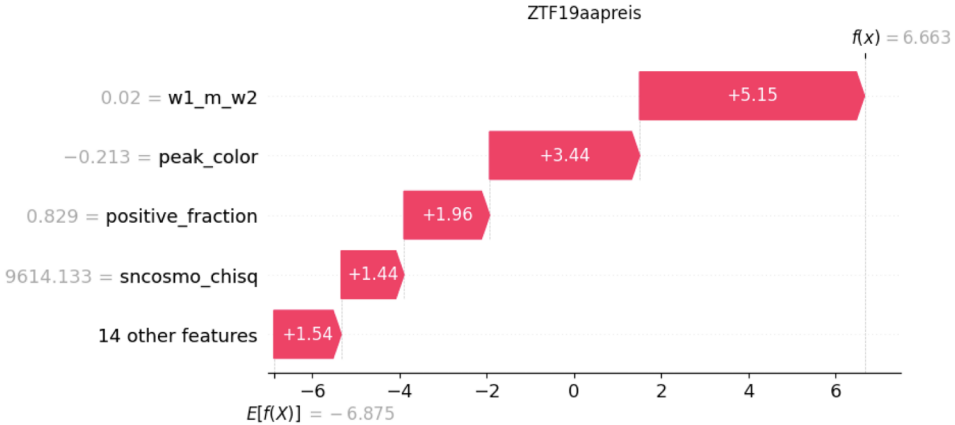


…Which is NOT a black box!



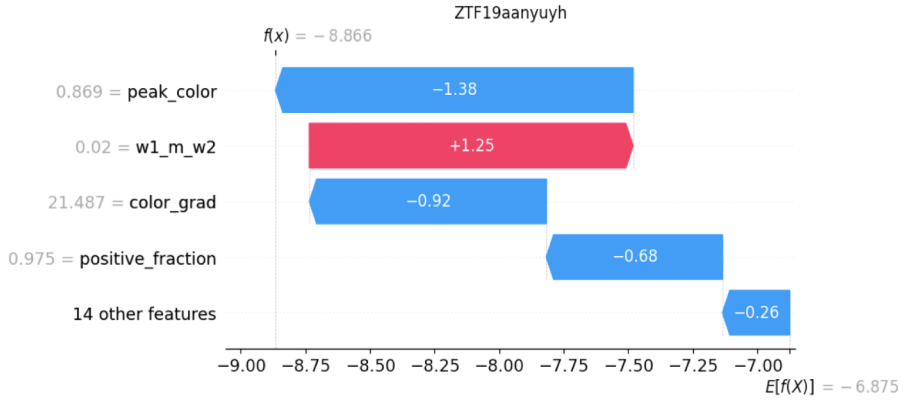
Real TDE gets high score

(Due to e.g non-AGN WISE colour, peak colour…)



Real SNIa gets low score

(due to colour at peak, cooling …, and despite non-AGN WISE colour)



Summary

Summary

ZTF AGN/TDE working group is producing a lot of great science!

- TDE studies with ZTF remain ongoing. “Systematic selection” is done, now completing “hosts” and “rates”. By the end of ZTF-II, I am optimistic that we will have fully characterised “vanilla” optical TDEs.
- There is a lot of momentum towards TDE synergy studies, spanning the electromagnetic spectrum. ZTF remains the essential anchor survey here.
- More momentum to exploit ZTF Nuclear Sample for ML classification, as a template for Rubin and other surveys
- And we’re doing some stuff with AGN

Backup