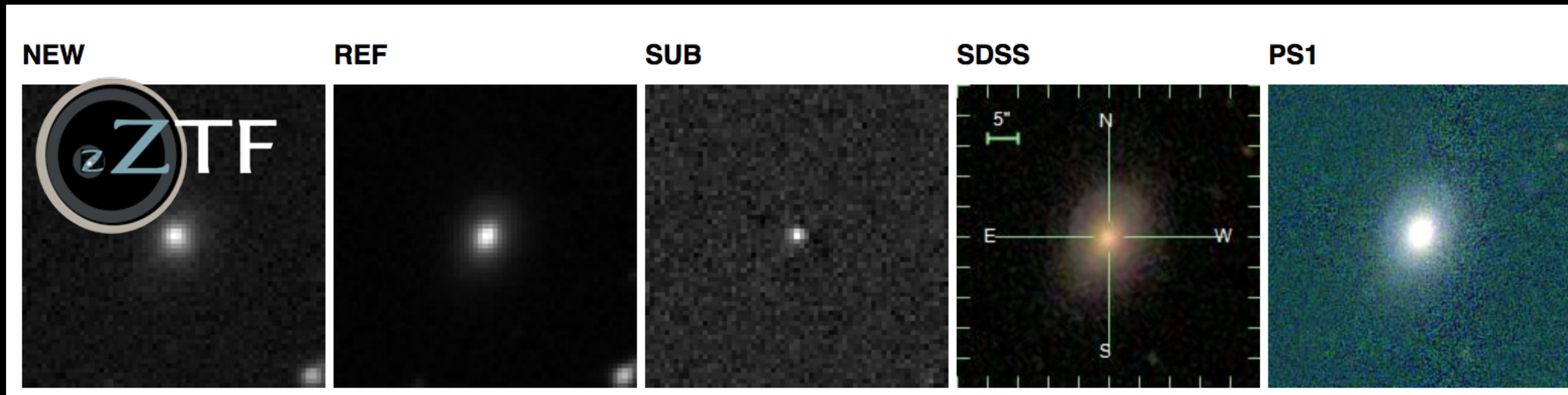

Entering New Era of Population Studies of Tidal Disruption Events

Suvi Gezari

STScI/JHU Colloquium

October 21, 2020

ANNUAL REVIEWS

Gezari 2021, ARA&A, Vol 59, in press

Tidal Disruption Events

Suvi Gezari,[1,2]

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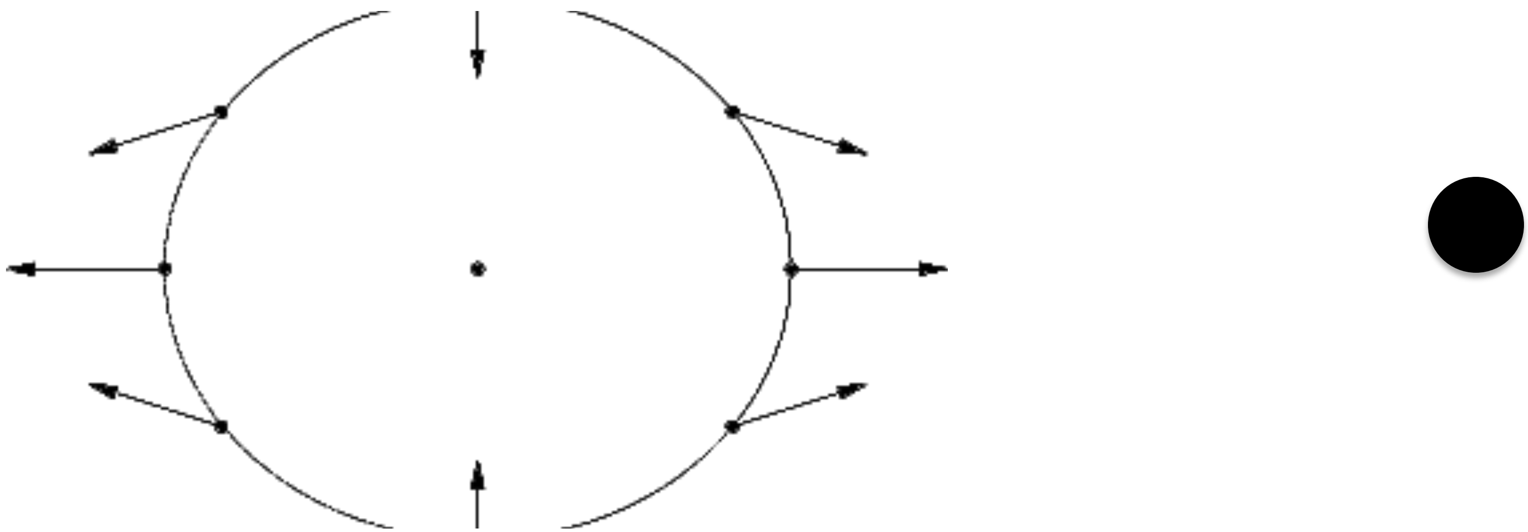
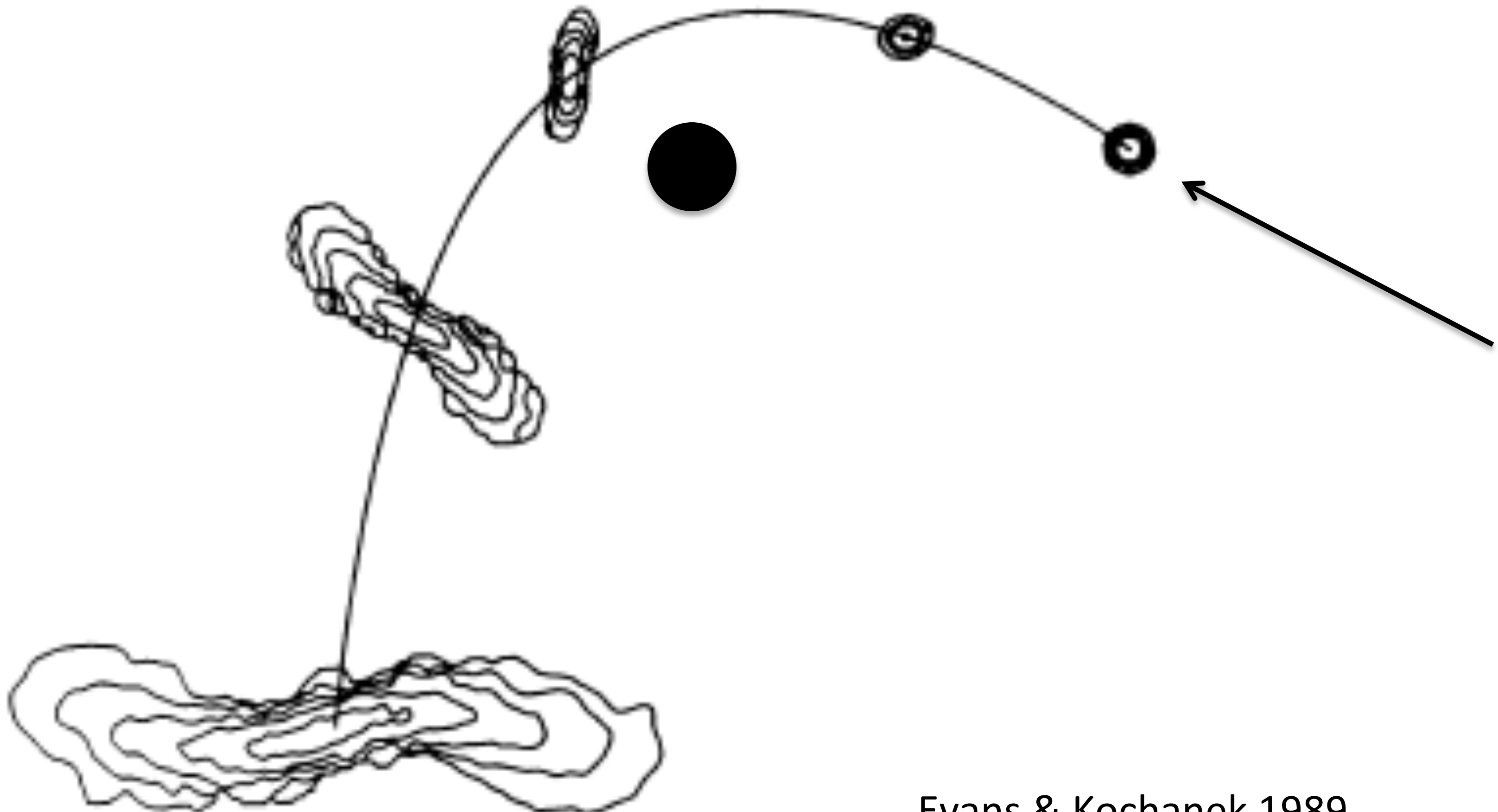
[2]Joint Space-Science Institute, University of Maryland, College Park, MD, 20742-2421

Tidal Forces



$$dF = (\frac{dF}{dr})dr = \frac{2GMm}{r^3}dr$$

What happens when a star ventures too close to a black hole?



Evans & Kochanek 1989

It gets ripped apart!

Tidal Disruption of a Star

The star is ripped apart when tidal forces overcome the self gravity of the star:

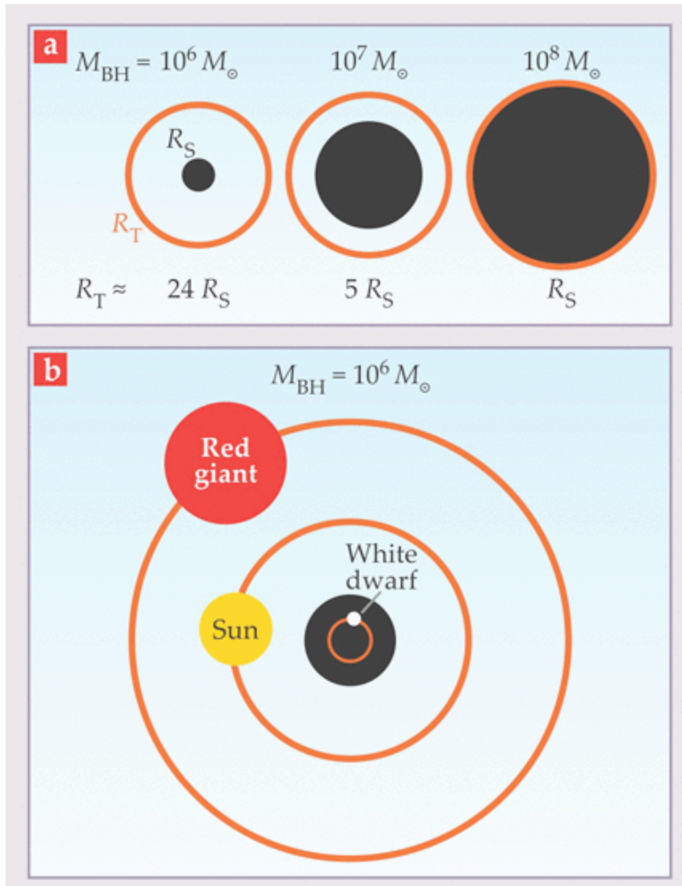
$$\frac{GM R_\star}{r^3} = \frac{Gm_\star}{R_\star^2}$$

Tidal Force　　　　Self-Gravity

$$r_\mathrm{T} \approx R_\star (M_\mathrm{BH}/m_\star)^{1/3}$$

Tidal Disruption Radius

How close do you have to get?

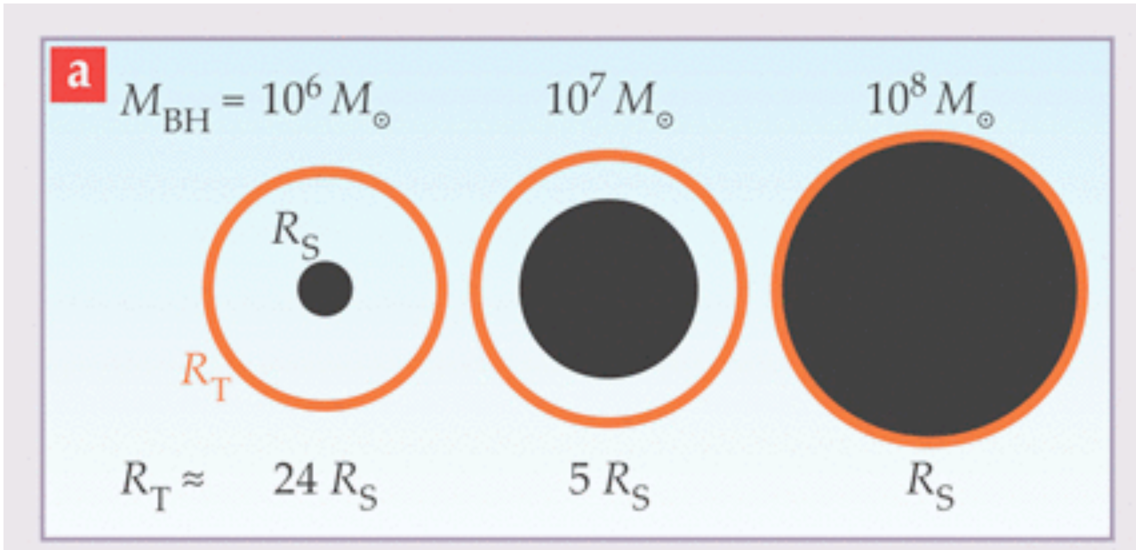


$r_S = 2GM_{BH}/c^2$

Event Horizon

It depends on the type of star and the mass of the black hole!

Only Observable for $M_{BH} < 10^8 M_{sun}$



Gezari 2014

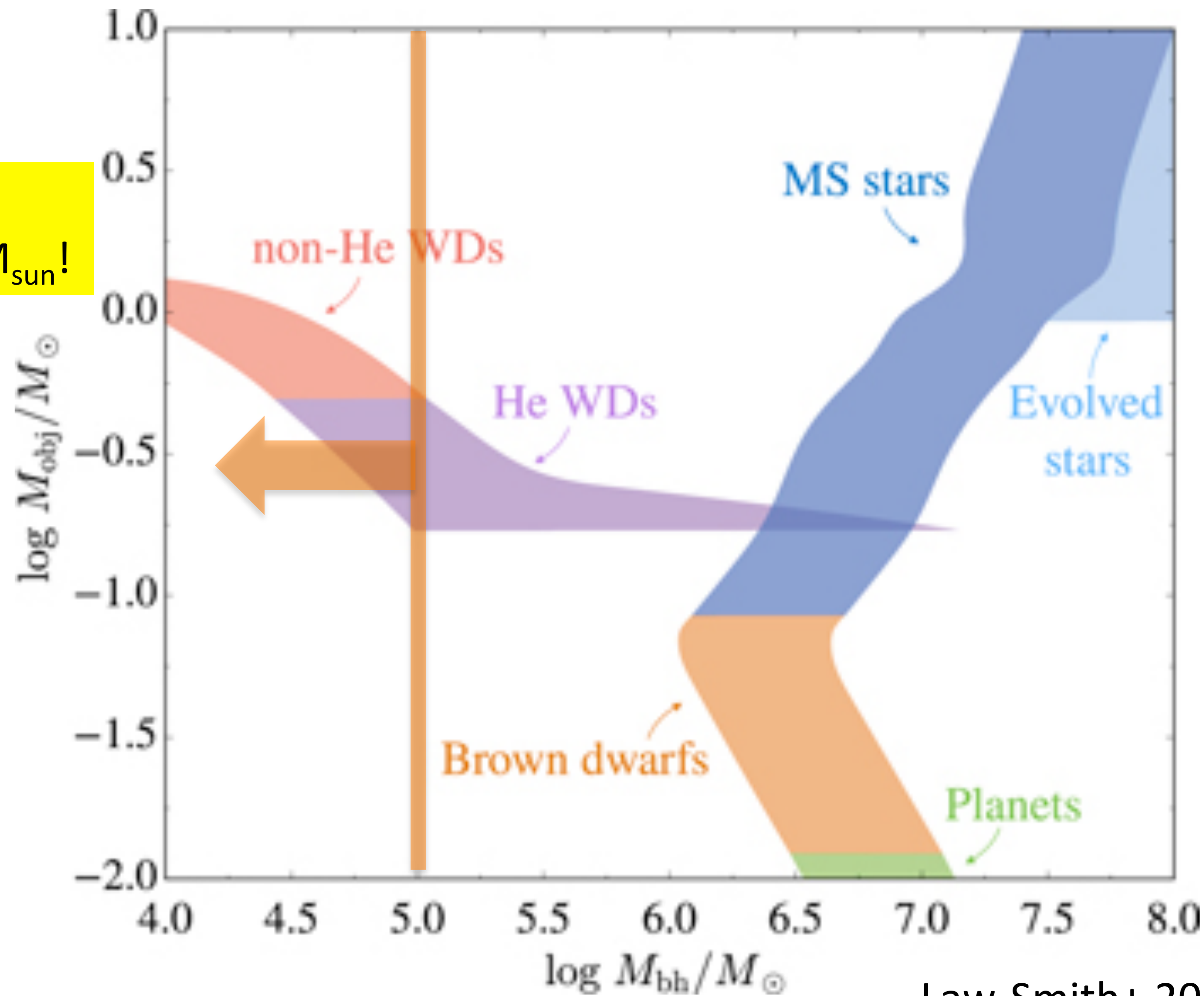
Maximum mass above which star will be swallowed whole ($R_T < R_S$):

$$M_{\rm max} \simeq \frac{c^3}{m_*^{1/2}}\left(\frac{R_*}{2G}\right)^{3/2} = 1.1\times 10^8 M_\odot \left(\frac{m_*}{M_\odot}\right)^{-1/2}\left(\frac{R_*}{R_\odot}\right)^{3/2}$$

For a spinning black hole, the event horizon shrinks, and M_{max} increases! (Belabodorov+ 1992, Kesden 2012)

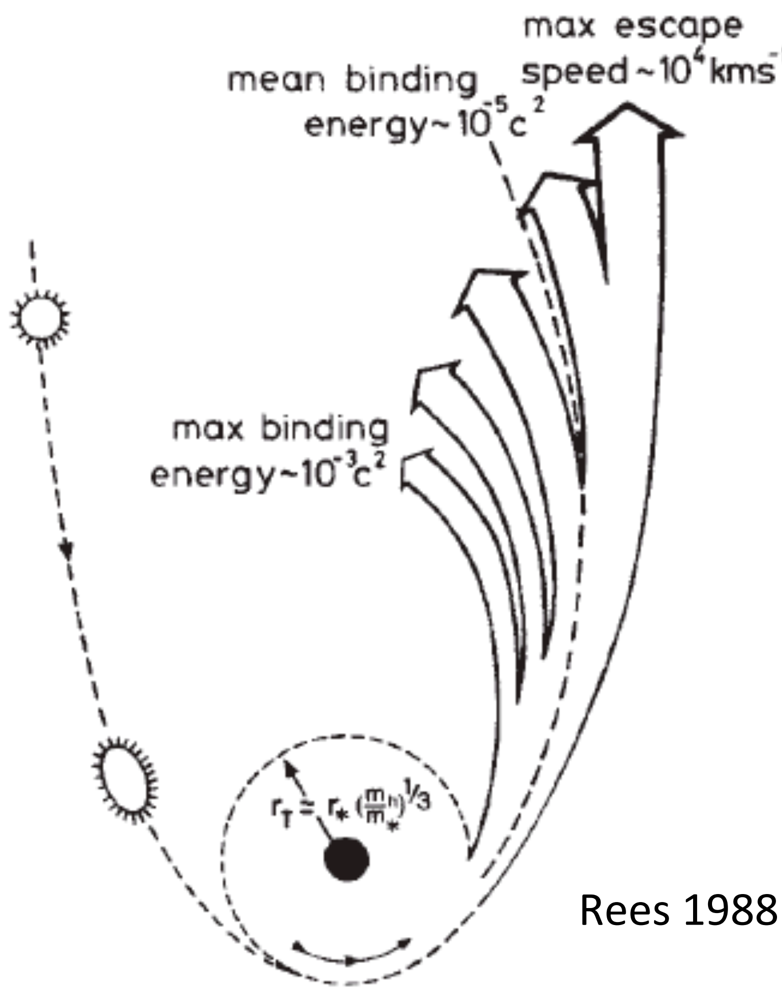
Max M_{BH} Depends on Stellar Type

For a C/O WD,
max $M_{BH}=10^5\ M_{sun}$!



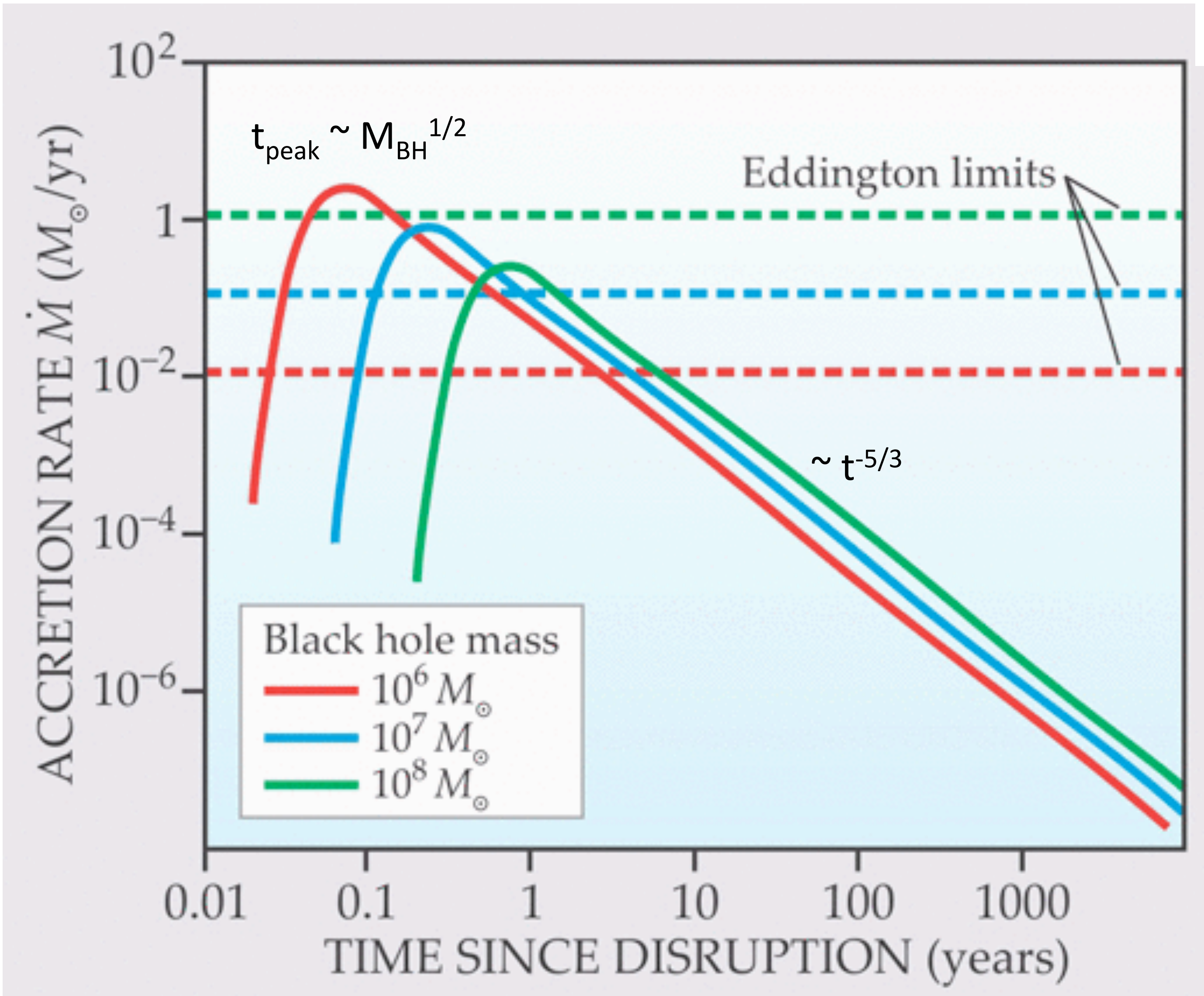
Law-Smith+ 2017

Tidal Disruption of a Star



Rees 1988

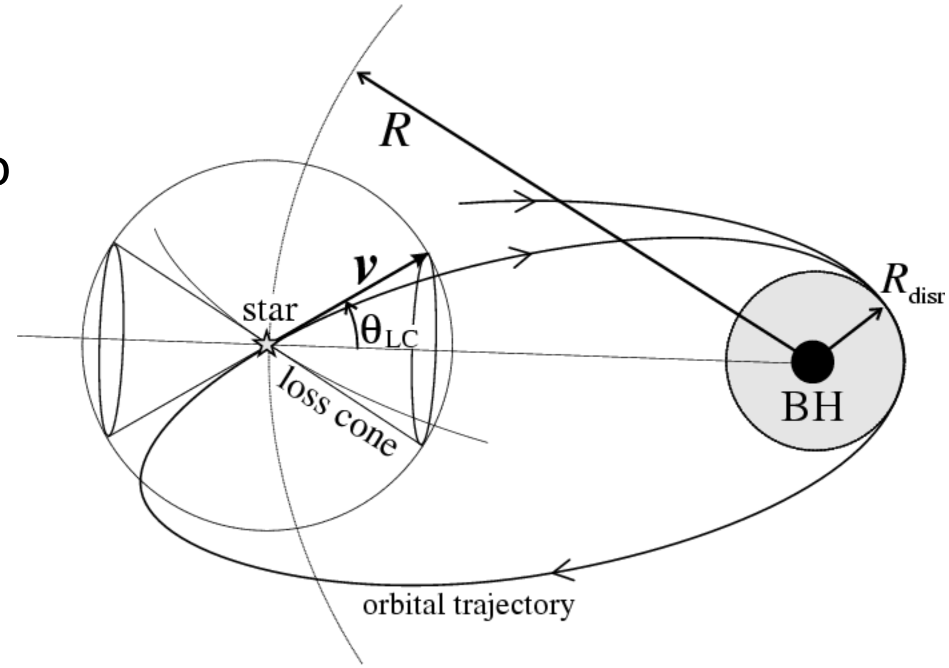
Probing Black Hole Mass



Gezari 2014, Adapted from De Colle+ 2012

Rate Determined by Dynamics

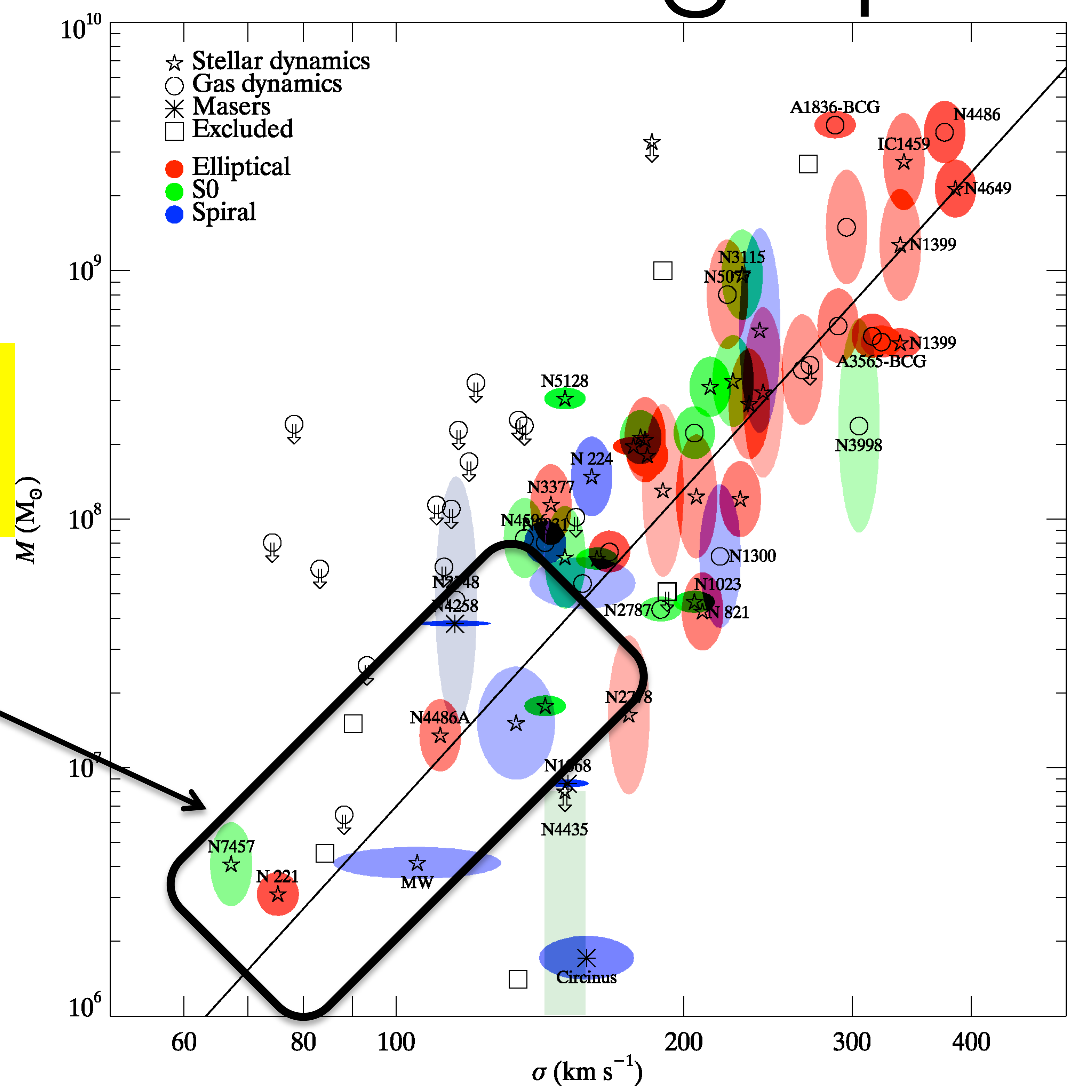
- The TDE rate is determined by the rate at which stars are diffused into the "radial loss cone":
  - $\theta_{LC} = 2GM_{BH}r_T/(v^2r^2)$
- The loss cone is repopulated by stellar encounters (angular-momentum diffusion) on the relaxation timescale.
- Dynamical models of galaxies predict a rate of 10^{-5} to 10^{-3} yr^{-1} (Magorrian & Tremaine 1999; Wang & Merritt 2004; Brockamp+ 2011).



Freitag + Bentz 2002

Probe of stellar density structure in galaxy nuclei.

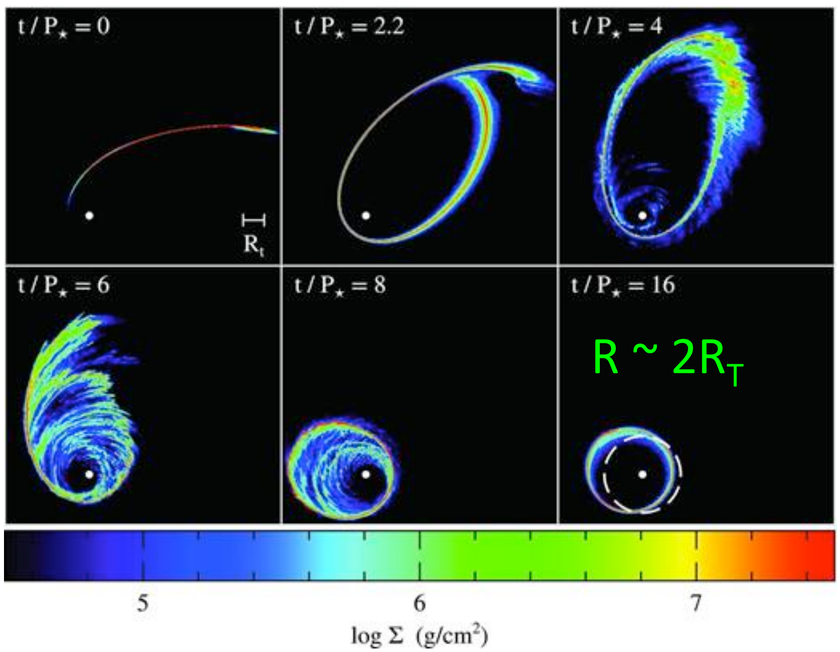
Probing SMBH Demographics



Probe BH mass range where even local scaling relations are poorly constrained.

Gultekin+ 2009

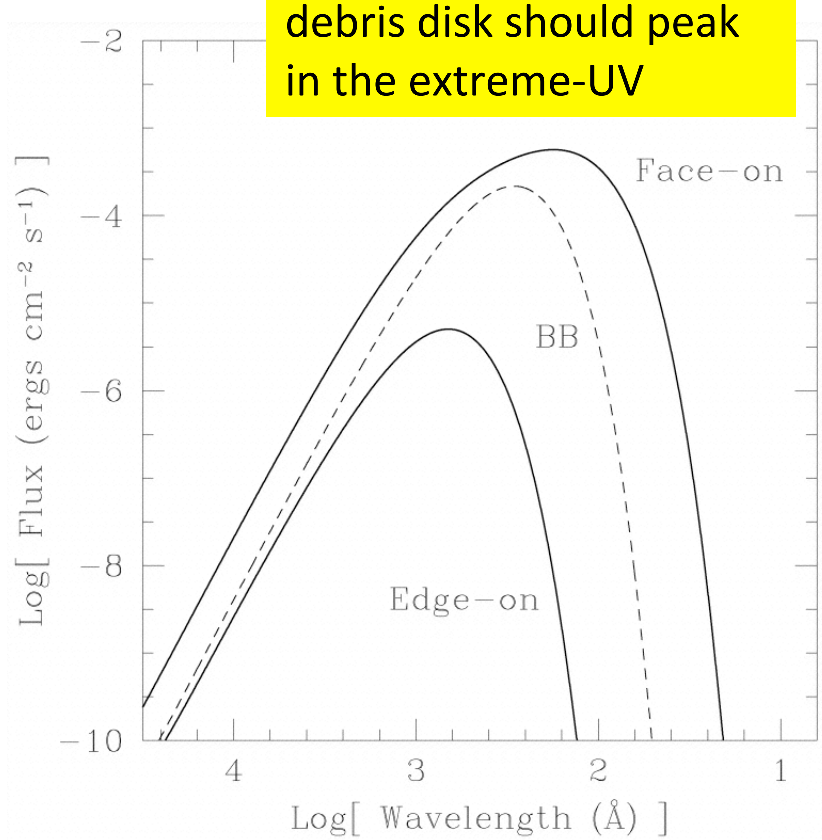
Classic Debris Disk



Debris streams intersect due to apsidal precession, shock, and circularize to form a disk.

Bonnerot+ 2016

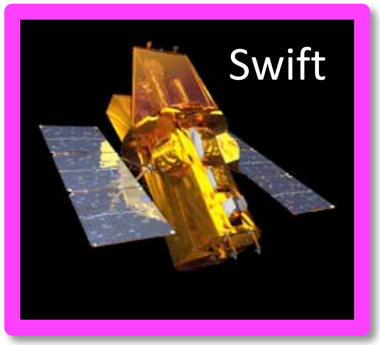
Thermal emission from debris disk should peak in the extreme-UV

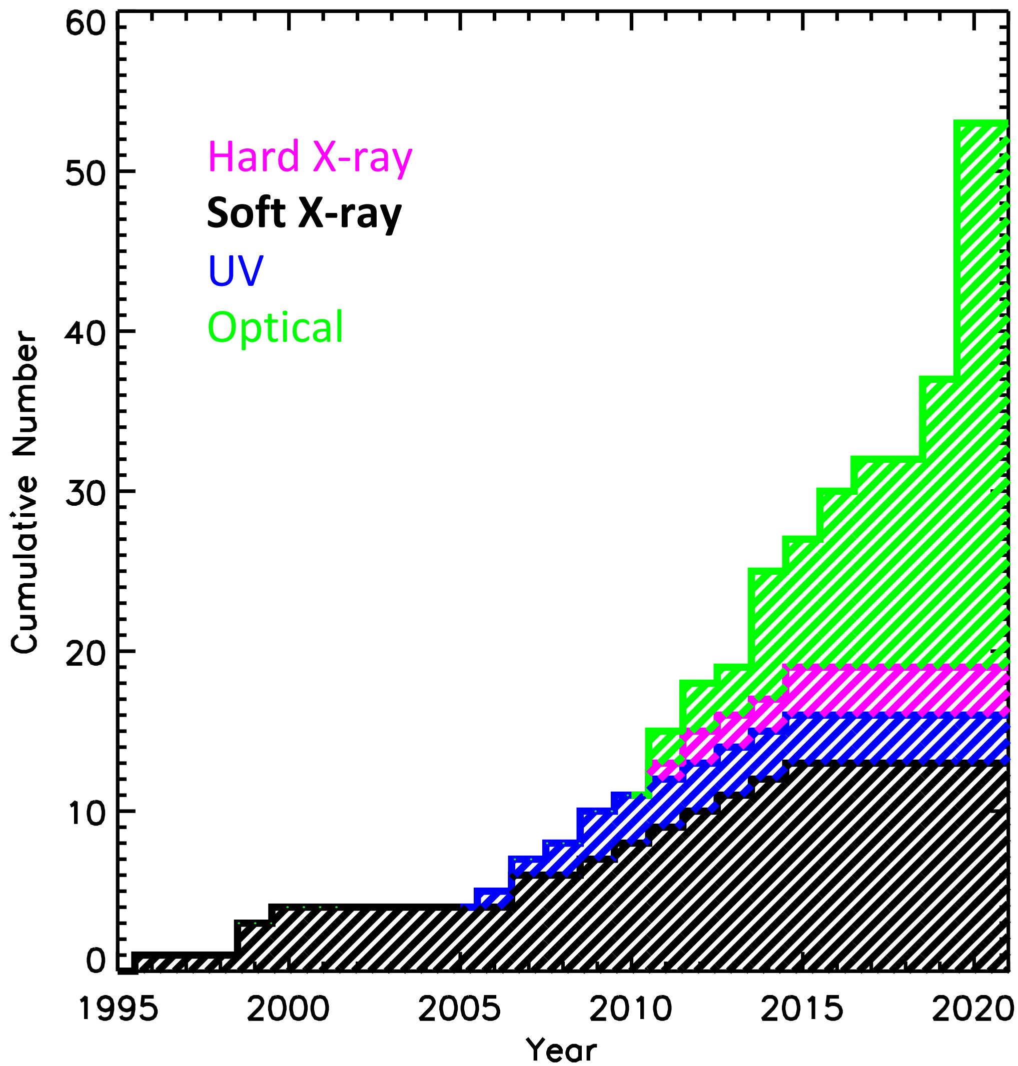


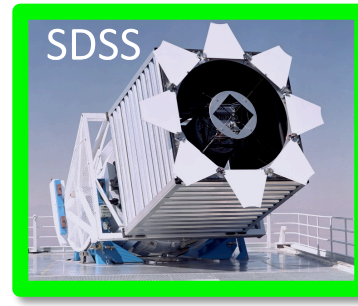
Ulmer 1999

$T_{eff}(R_T) \sim 10^5$ K

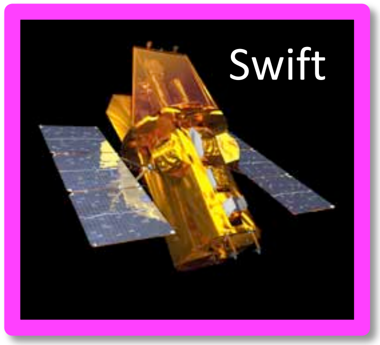
Multi-λ Searches

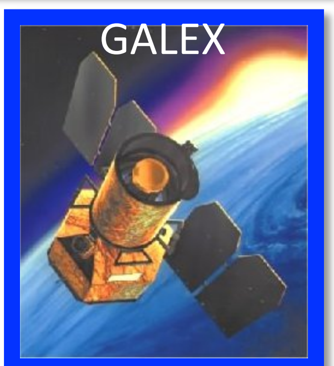


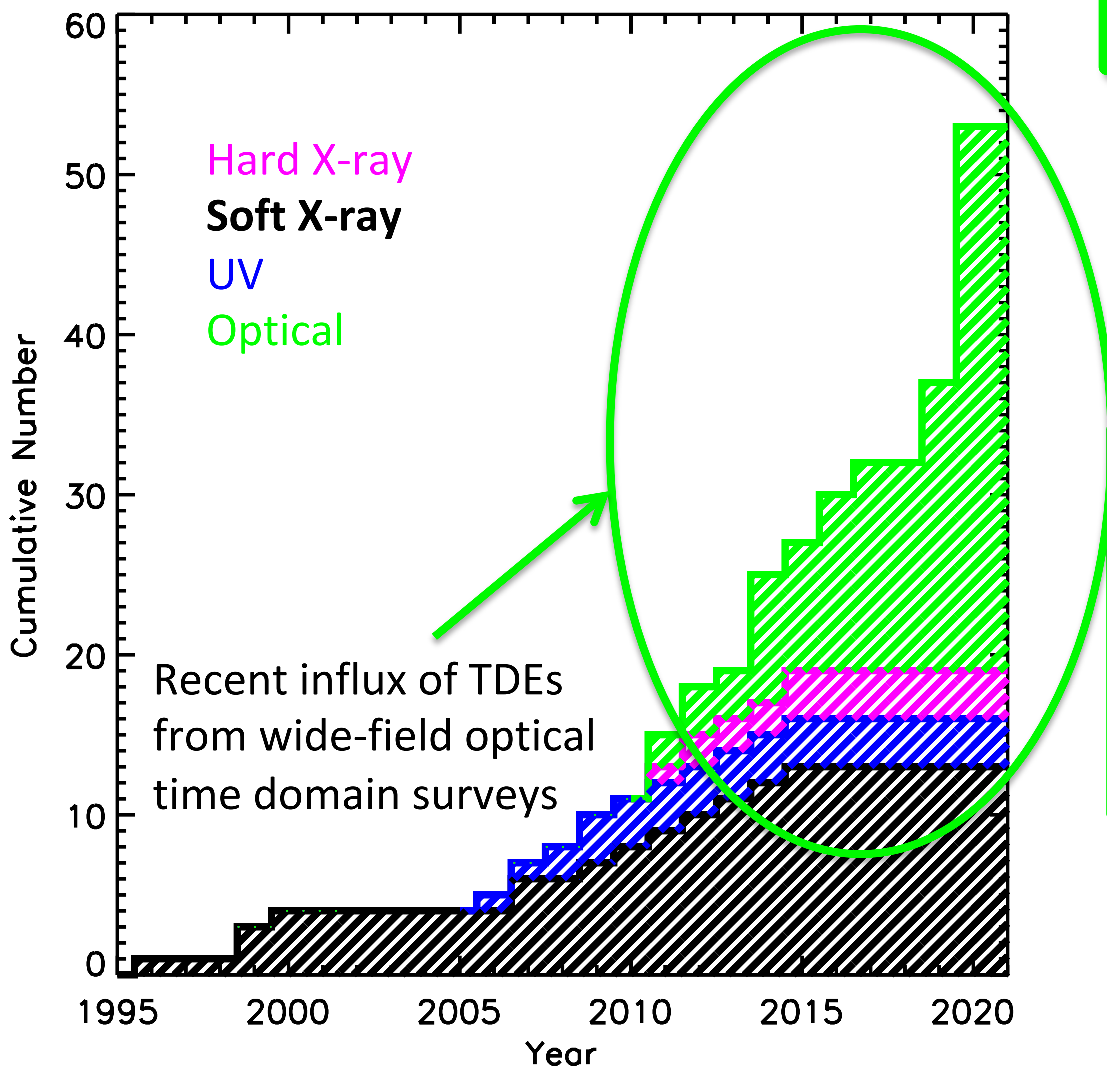


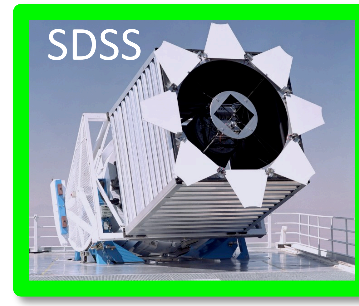


Multi-λ Searches

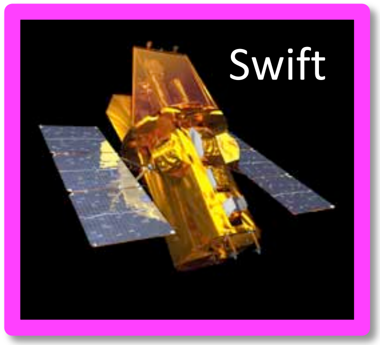


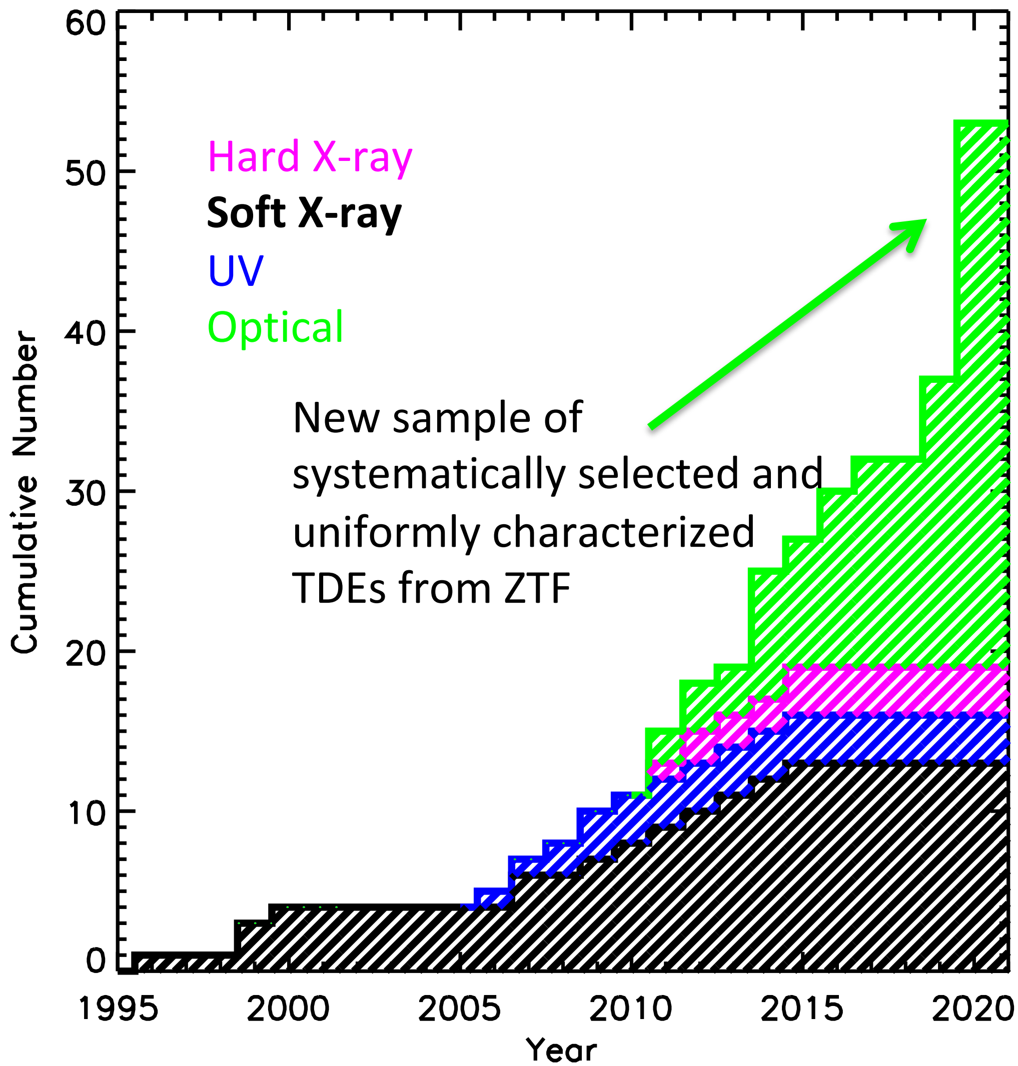


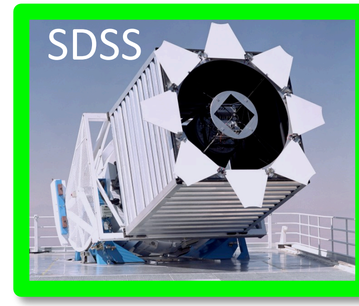




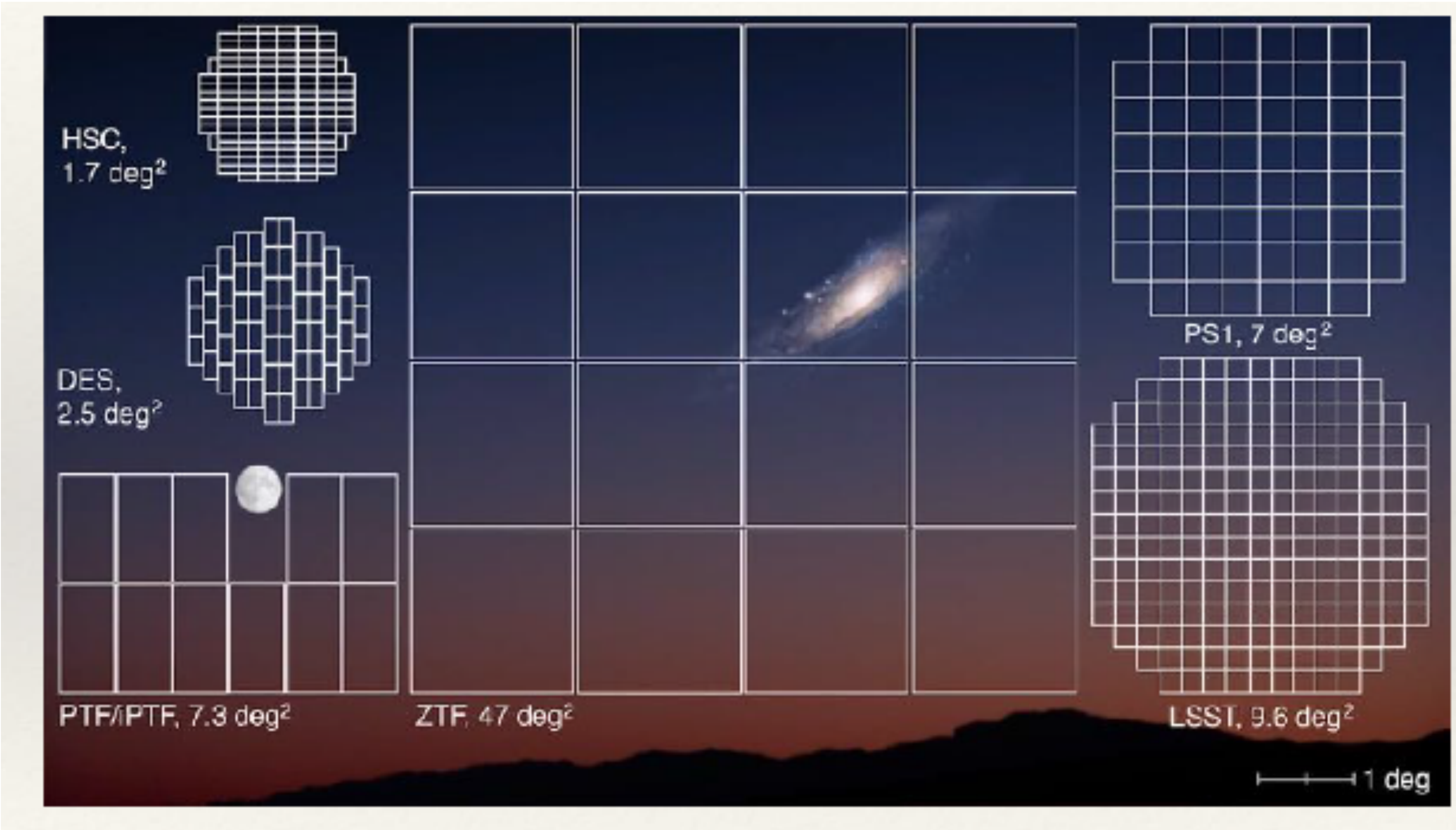
Multi-λ Searches





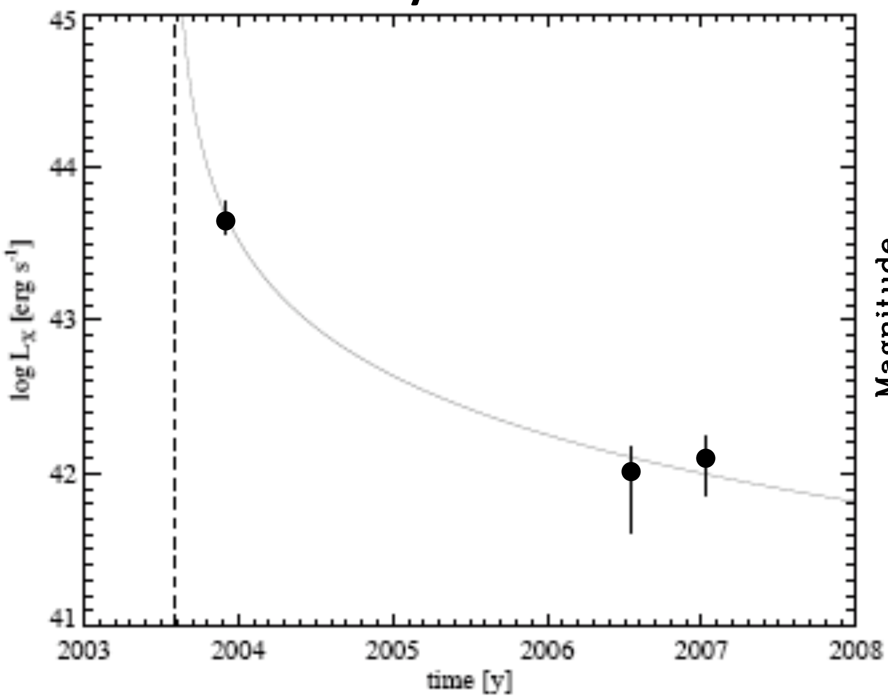


The Golden Age of Wide-Field Optical Surveys



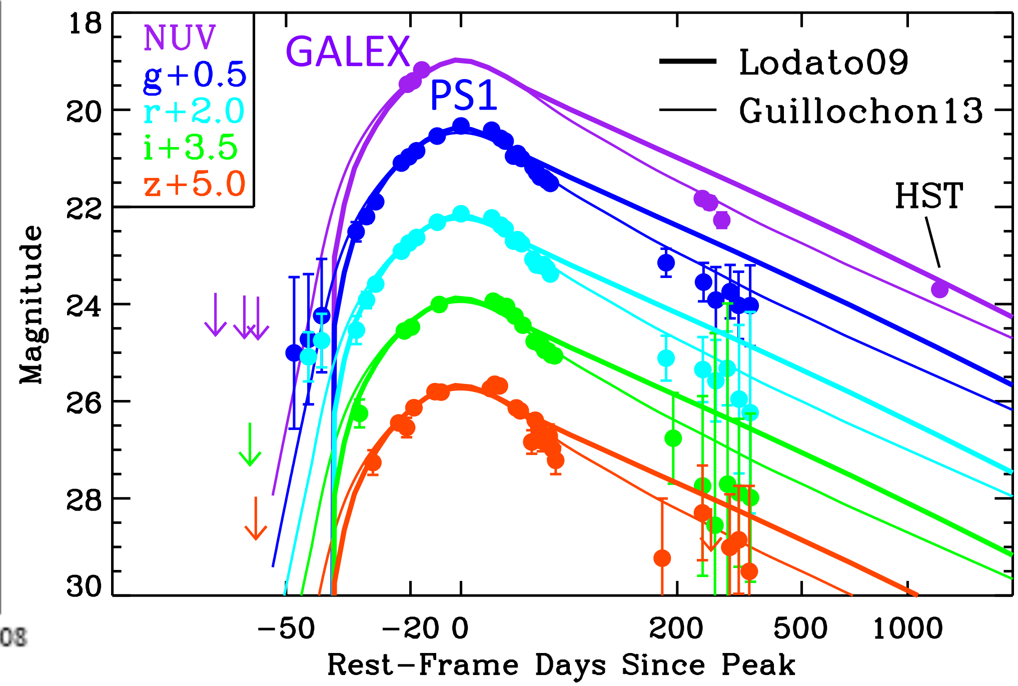
We've Come a Long Way…

X-ray Searches…



Esquej+ 2008

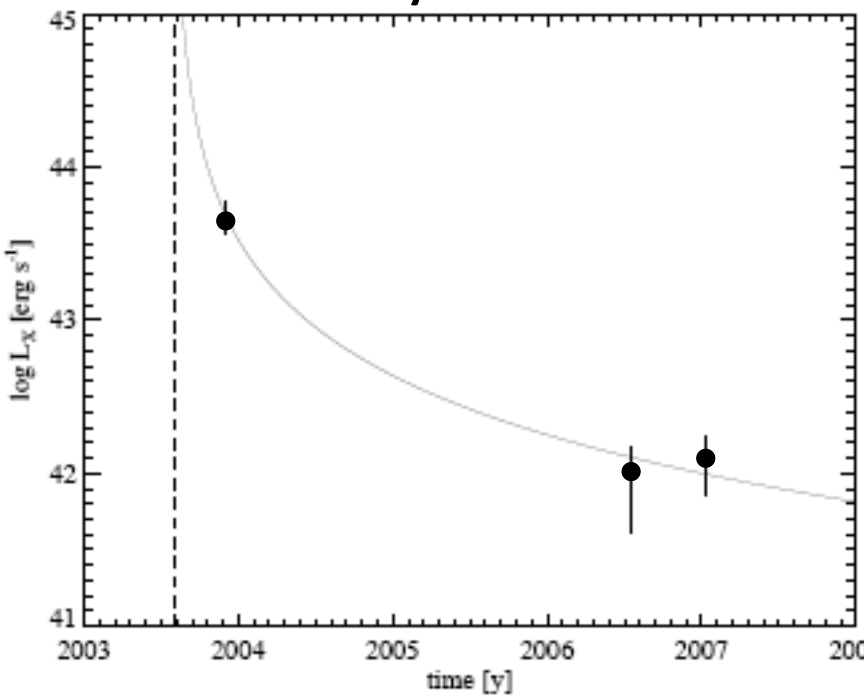
Optical Searches…



PS1-10jh: Gezari+ 2012, 2015

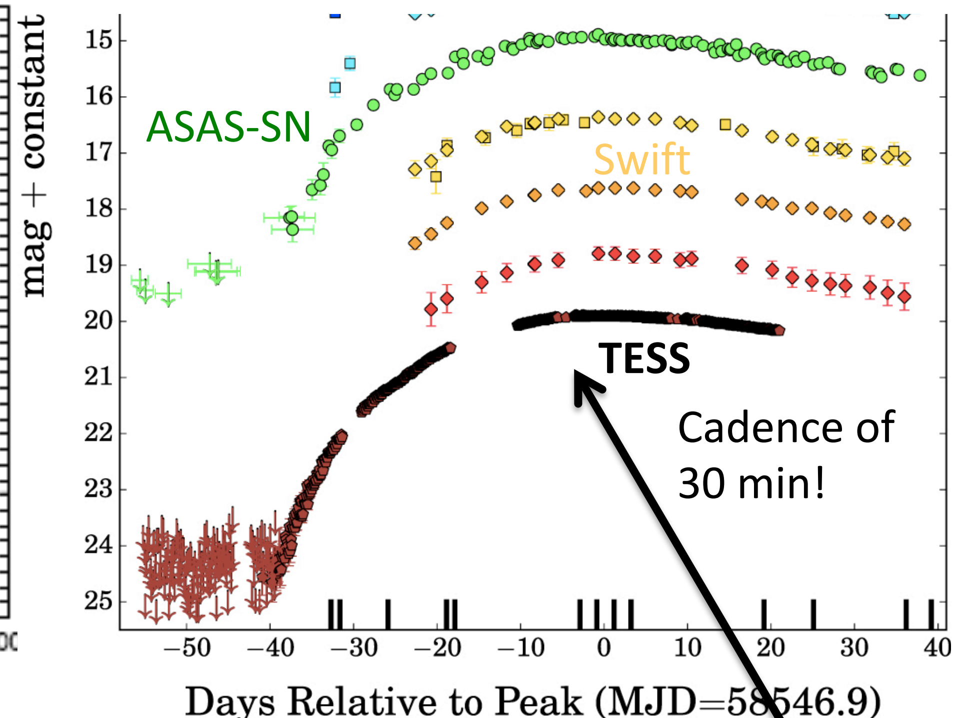
We've Come a Long Way…

X-ray Searches…



Esquej+ 2008

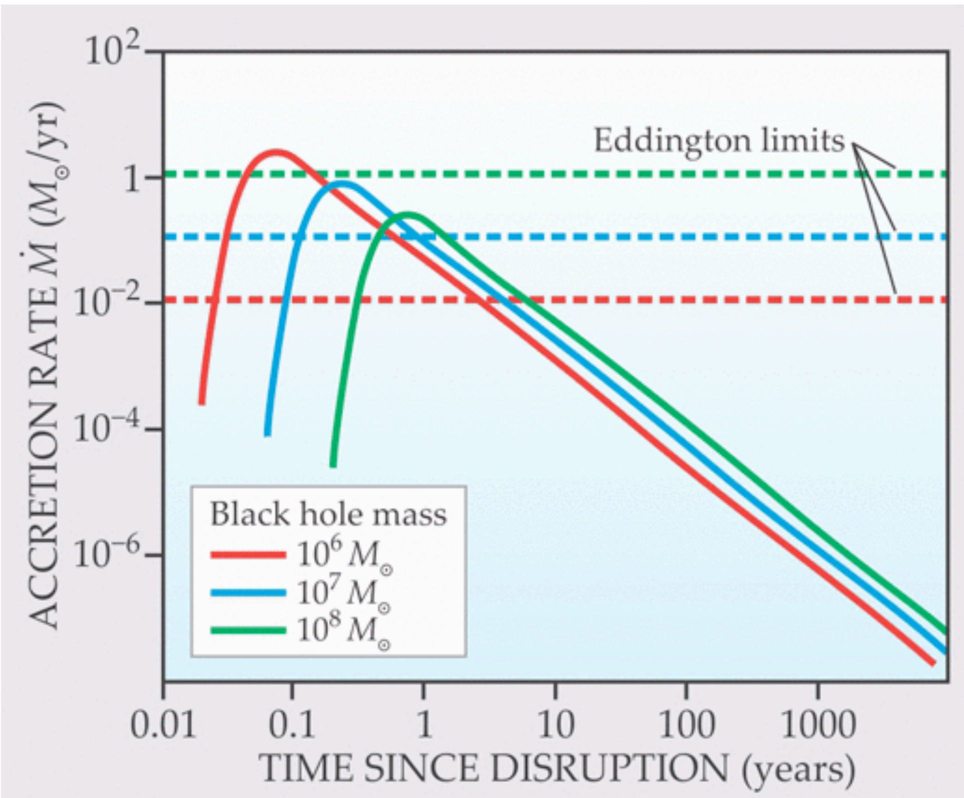
Optical Searches…



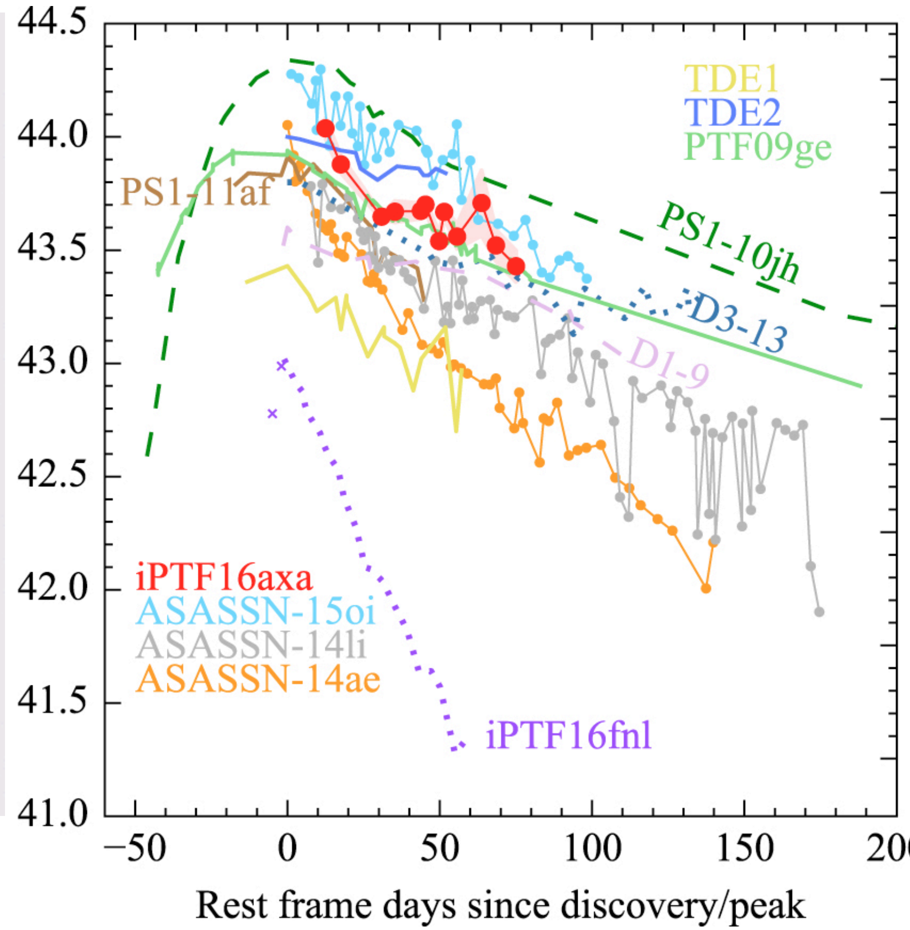
ASASSN-19bt: Holoien+ 2019

Some Basic Predictions Have Held True…

Theory



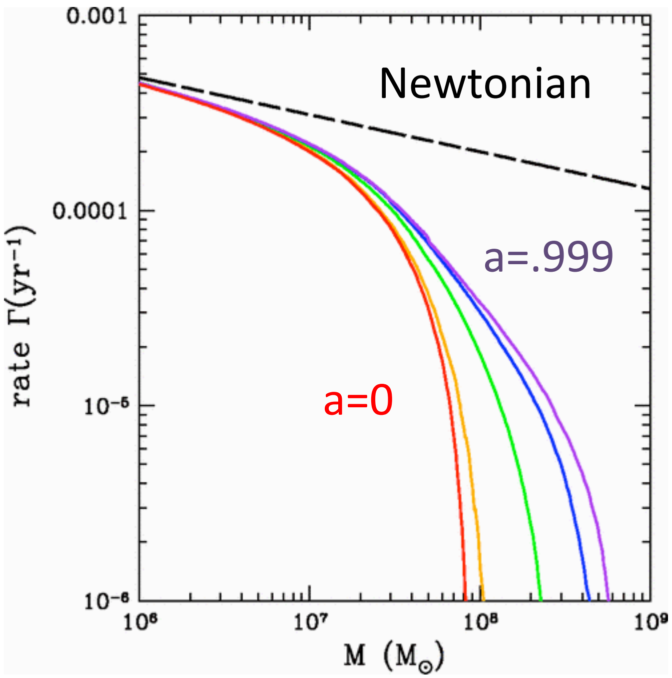
Observations



Hung, Gezari+ 2017

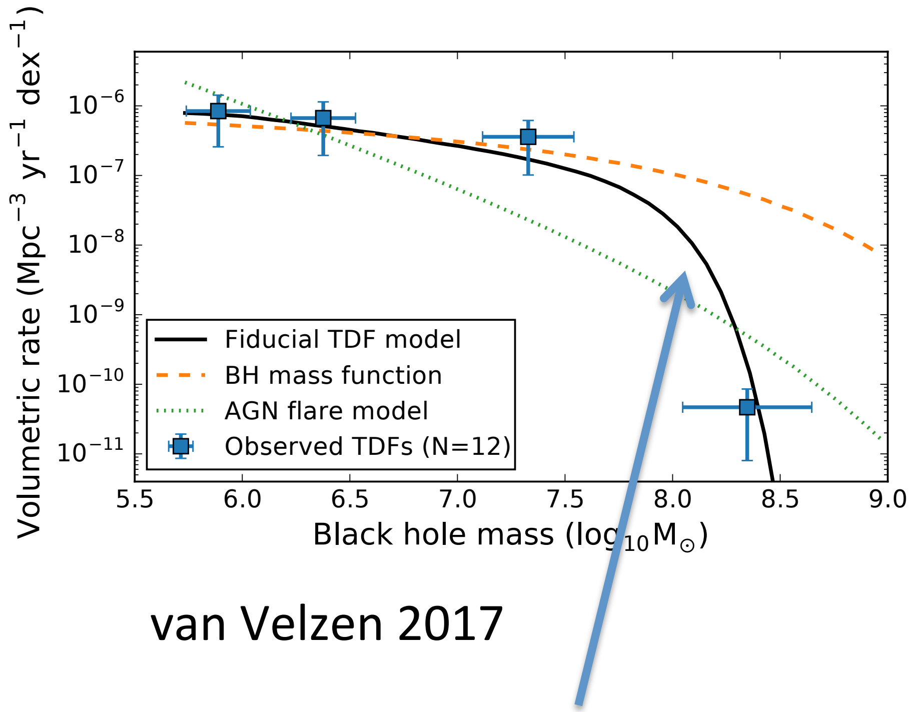
Maximum M_{BH} for Disruption

Theory



Kesden 2012

Observations

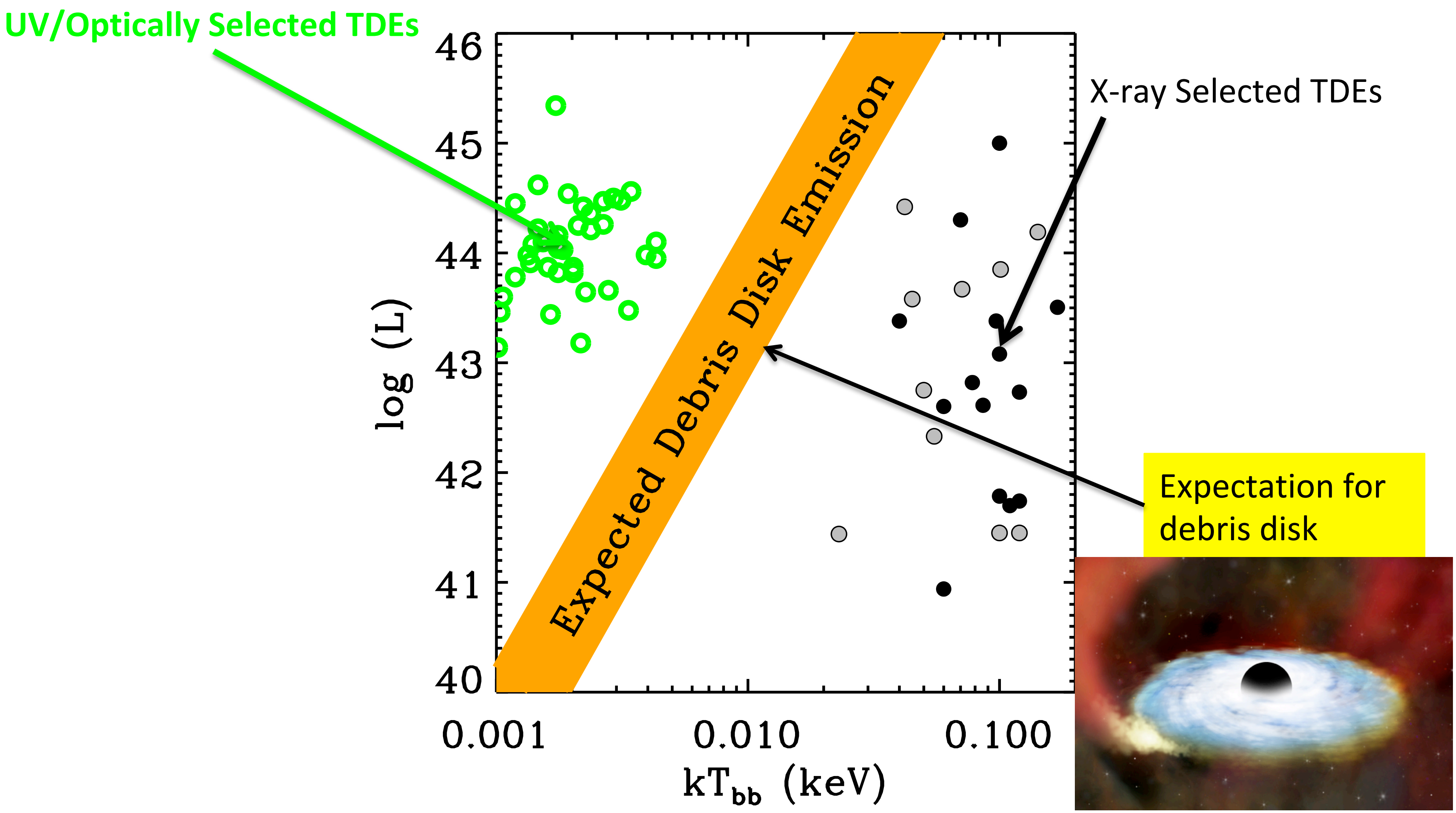


van Velzen 2017

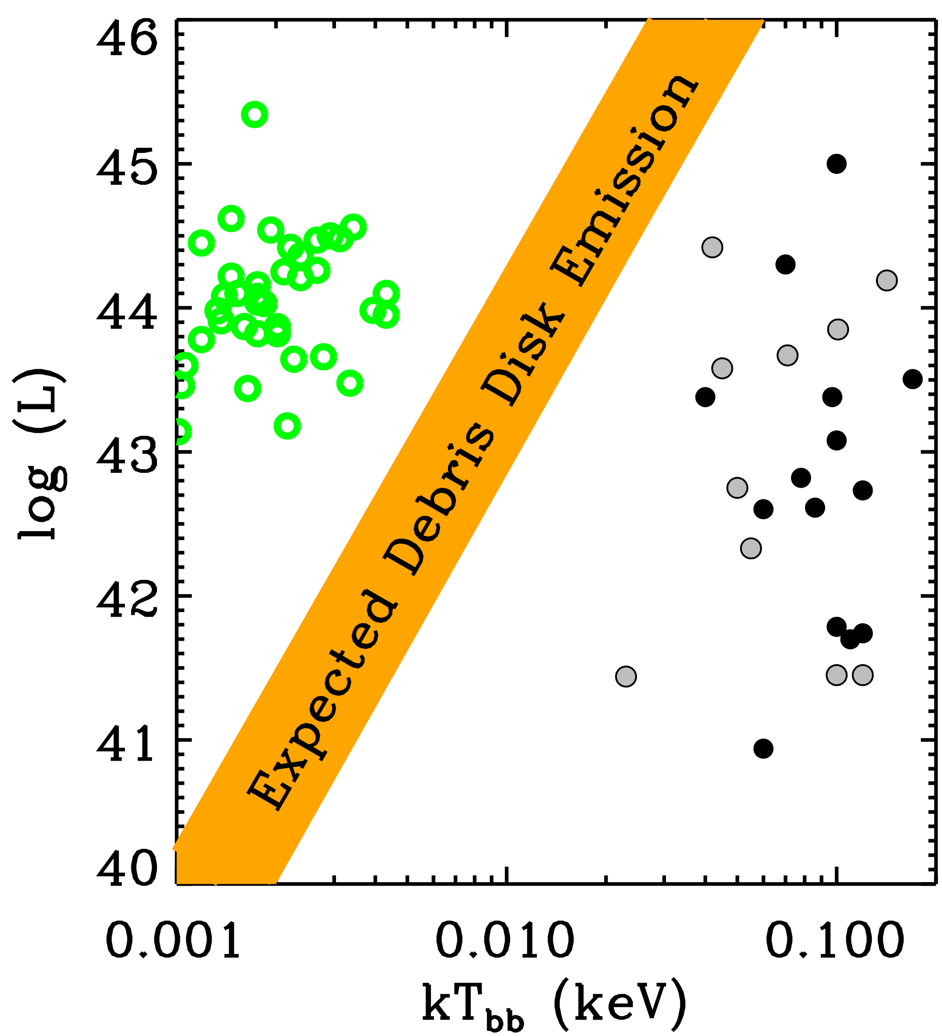
Evidence for suppression of the observed TDE rate above 10^8 M_{sun} due to direct capture by event horizon

Surprises Along the Way

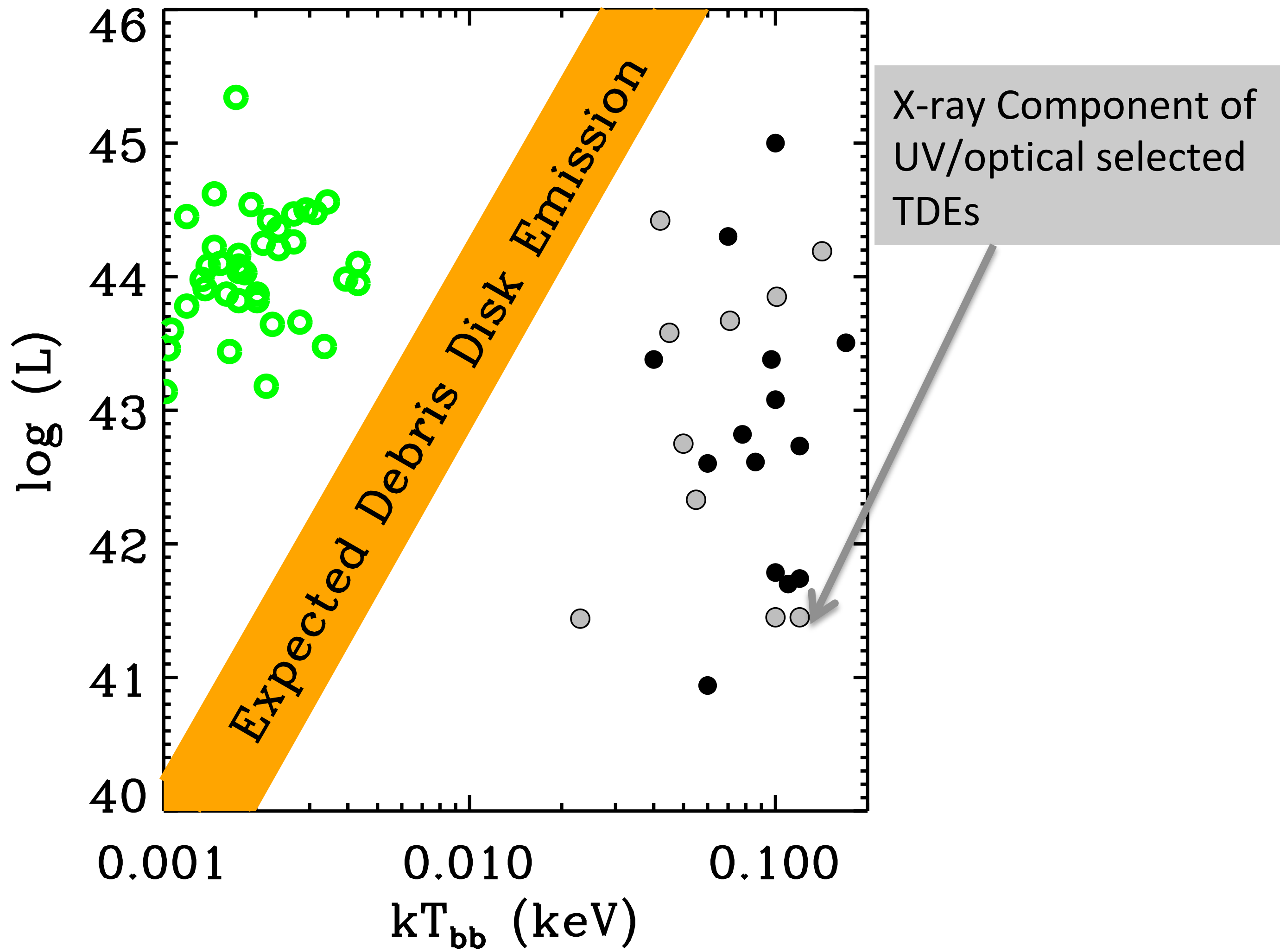
Surprise: Dichotomy of T_{BB}



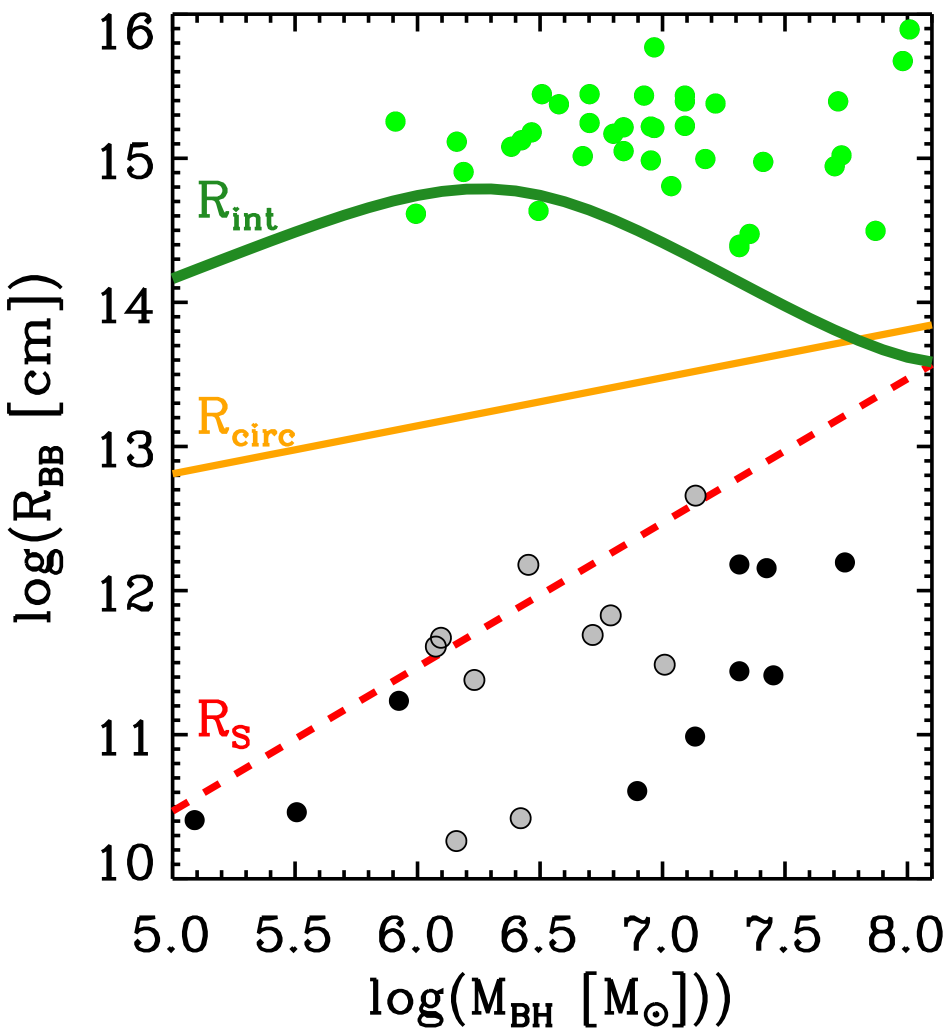
Two Populations?



Two Components?



Surprise: Large Radii



R_{int}: radius of intersection of debris streams near apocenter

R_{circ}: circularization radius (2x R_T)

R_S: Schwarzschild radius

Gezari 2021

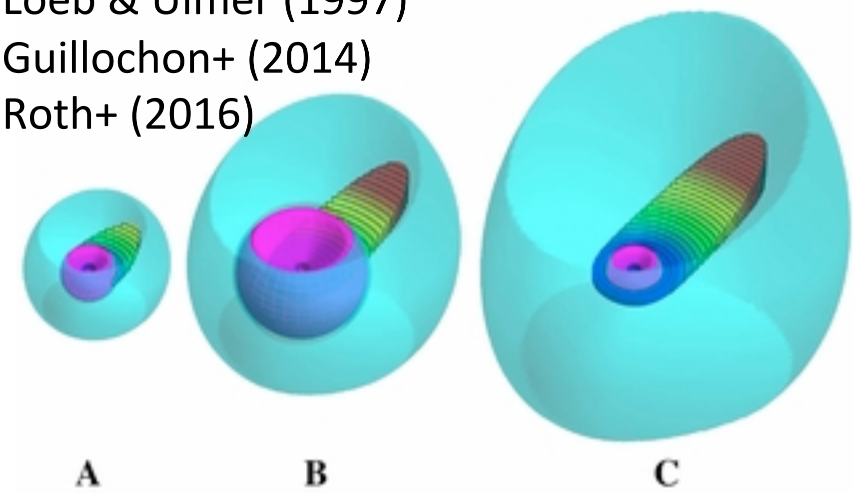
How to Get Large Radii

Reprocessing Envelope

Loeb & Ulmer (1997)

Guillochon+ (2014)

Roth+ (2016)



Guillochon+ 2014

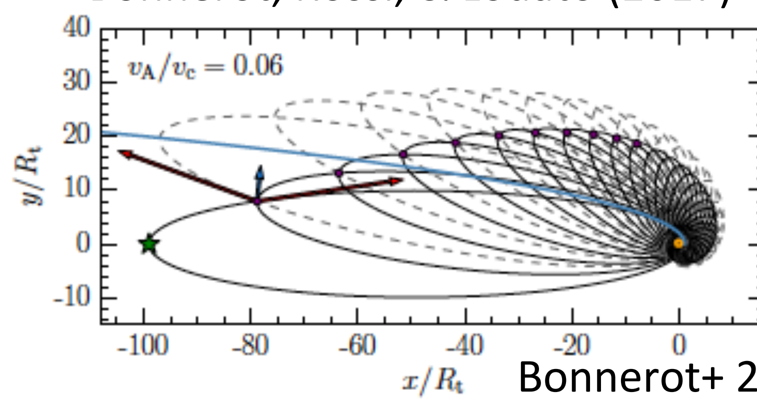
Circularization of Debris

Piran+ (2015)

Jiang,Guillochon, & Loeb (2016)

Svirski, Piran, & Krolik (2017)

Bonnerot, Rossi, & Lodato (2017)

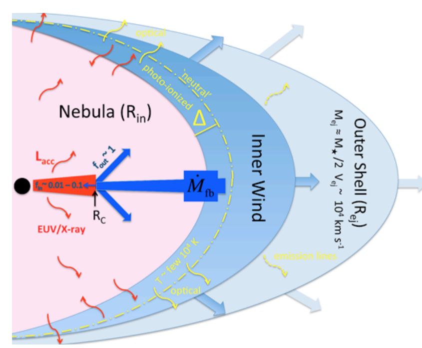


Bonnerot+ 2017

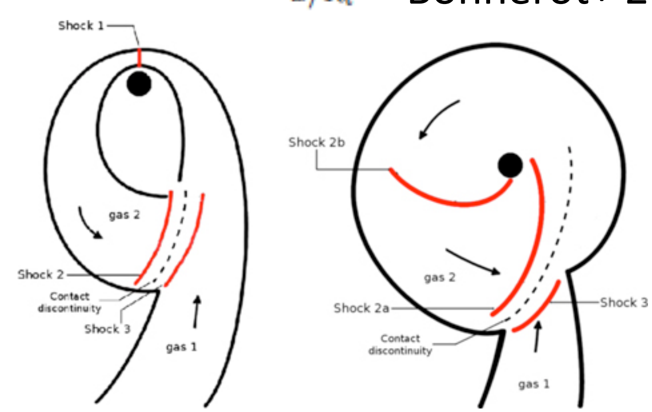
Radiatively Driven Wind

Miller (2015)

Metzger & Stone (2016)

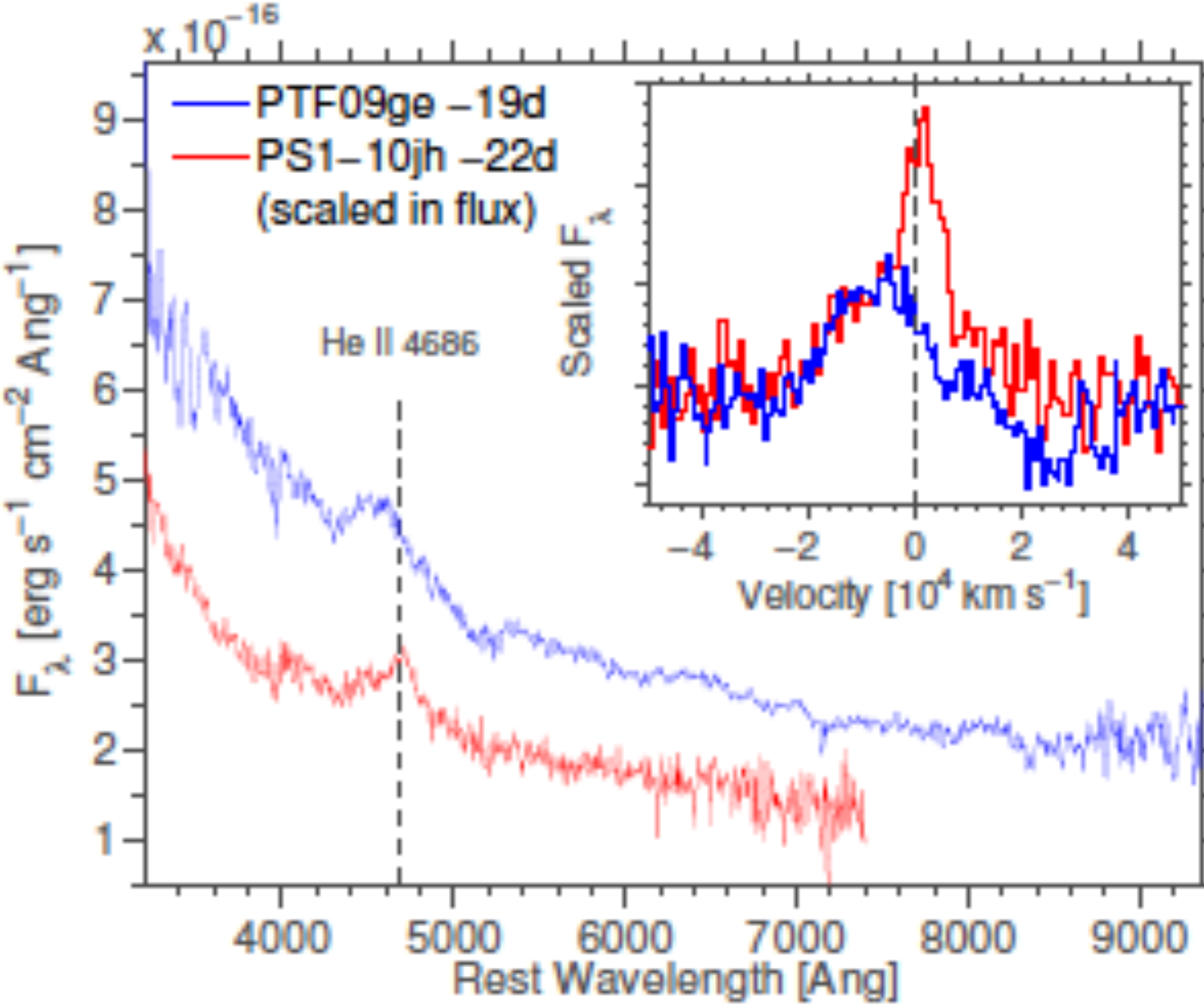


Metzger & Stone 2016



Piran+ 2015

Surprise: First TDE Spectra
Blue continuum, broad He II lines, and no H!



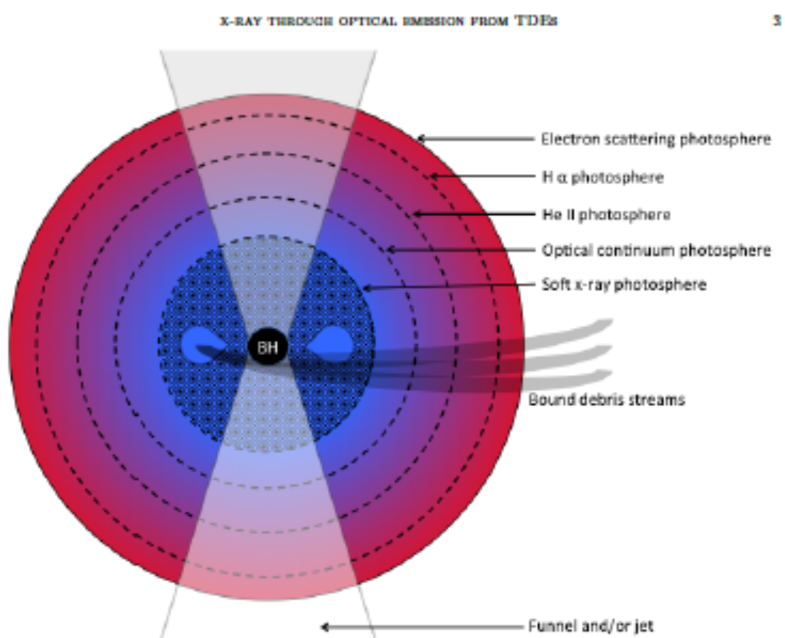
Can put strong constraints on Hα.

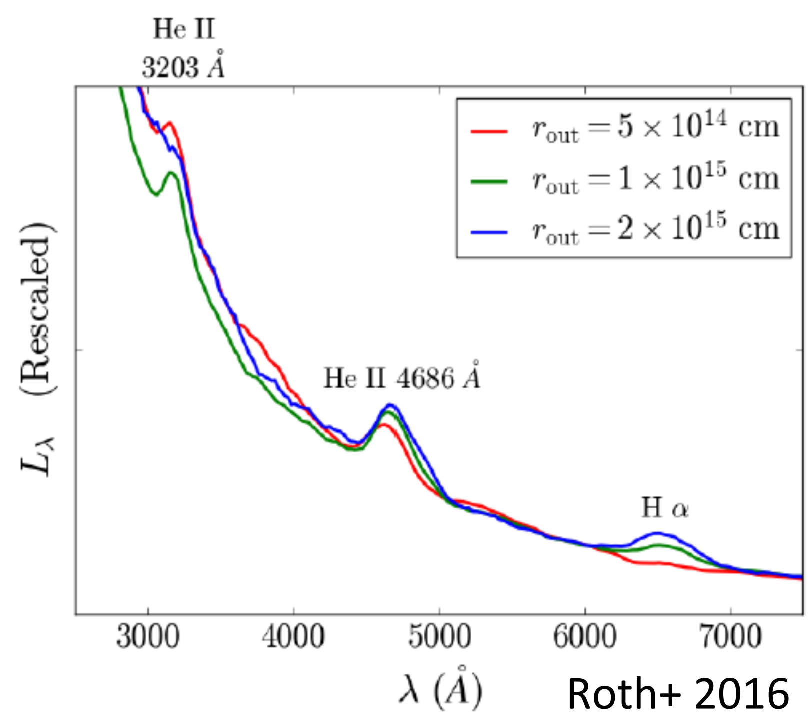
He II/Hα > 5

Gezari+ 2012, Arcavi+ 2014

How To Get High He-to-Hα Ratios

Reprocessing Envelope





Roth+ 2016

Chemical Composition of the Star

Gezari+ (2012)

Strubbe & Murray (2015)

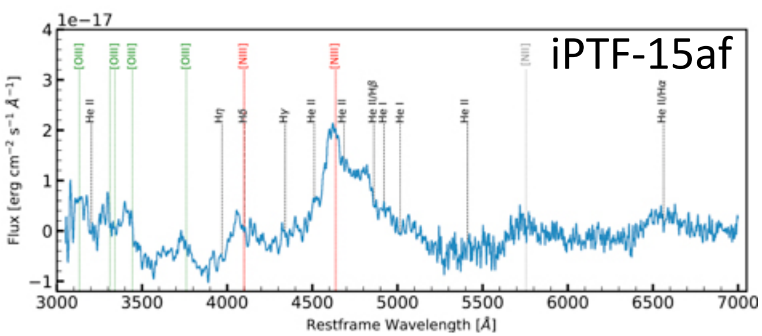
Kochanek (2016)

Law-Smith+ (2017)

Now 3 Spectral Types!

Bowen fluorescence lines require extreme-UV photons (λ< 228 A) to photoionize He II 4686, and trigger the Bowen mechanism via resonance with the O III and NIII line transitions.

In TDEs with very broad lines, the NIII+He II feature is blended.

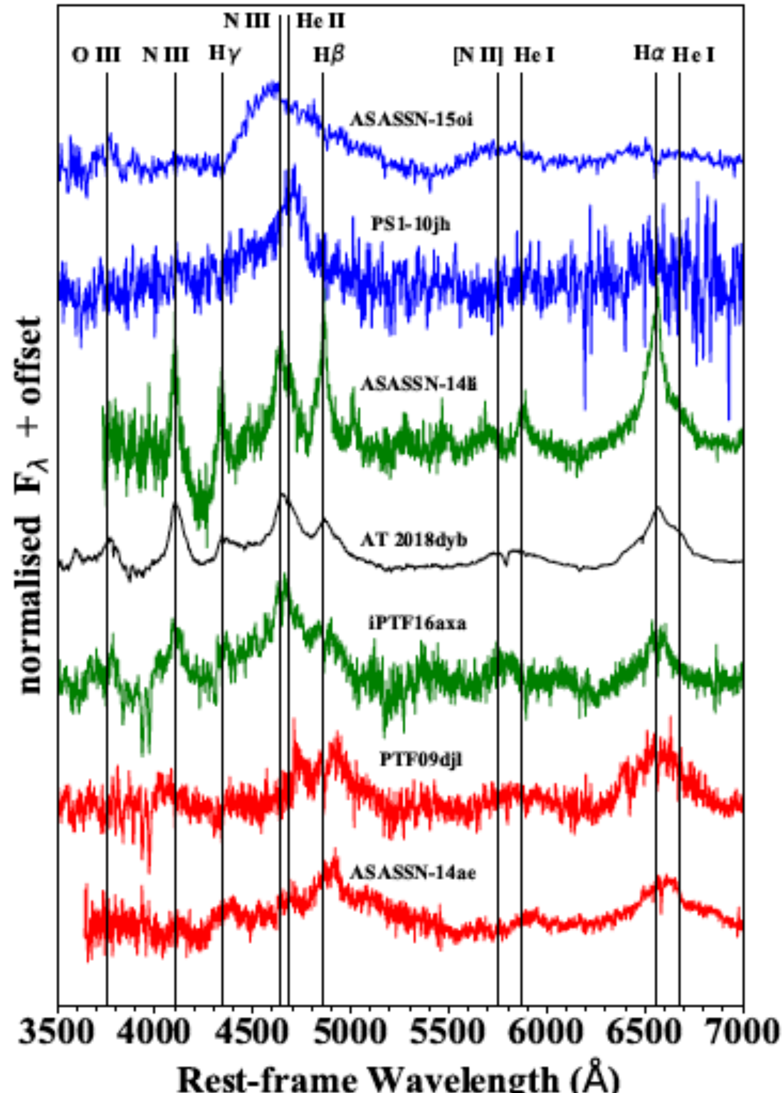


Blagorodnova et al. 2018

TDE-He

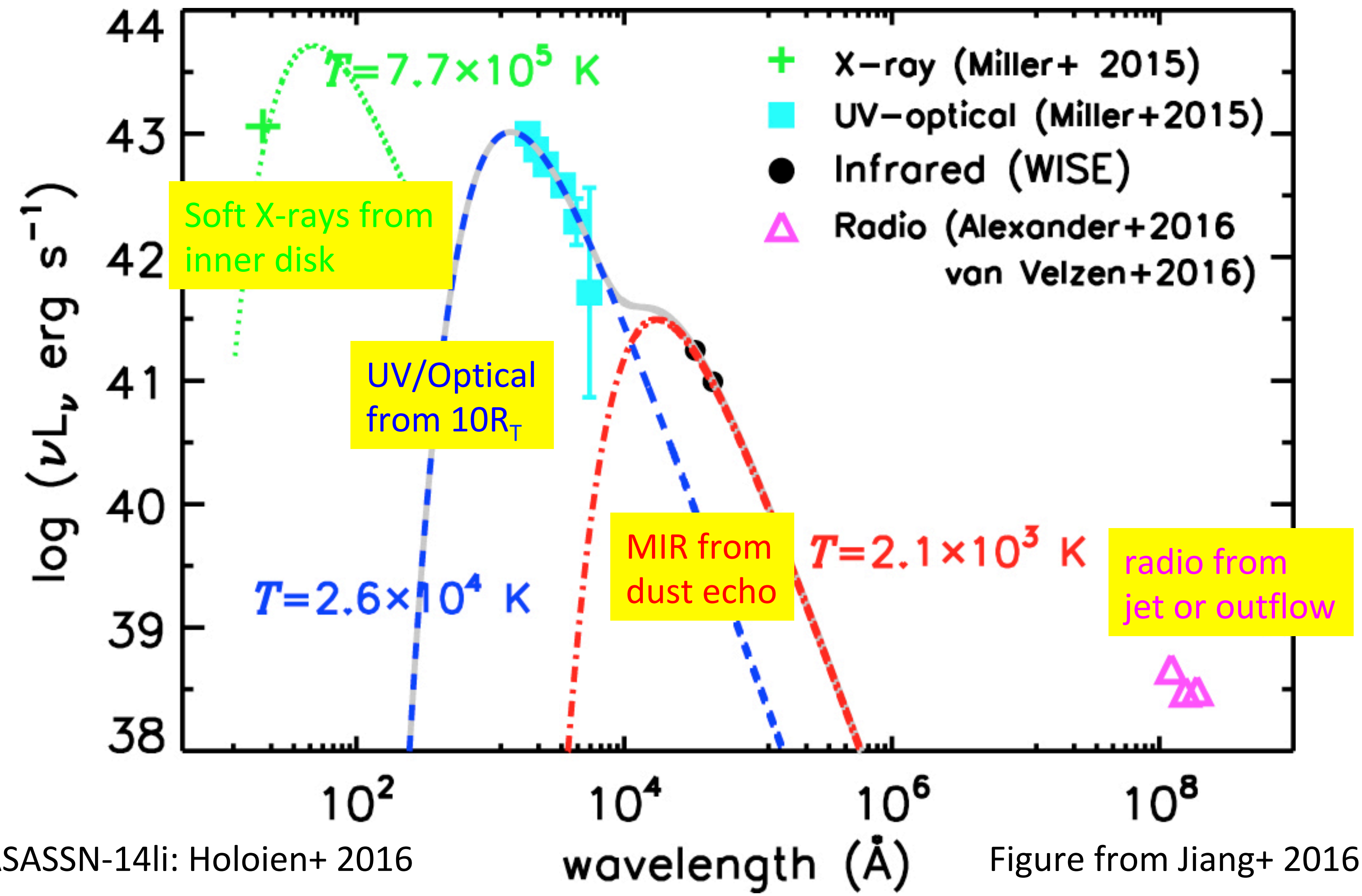
TDE-H+He

TDE-H



Leloudas et al. 2019

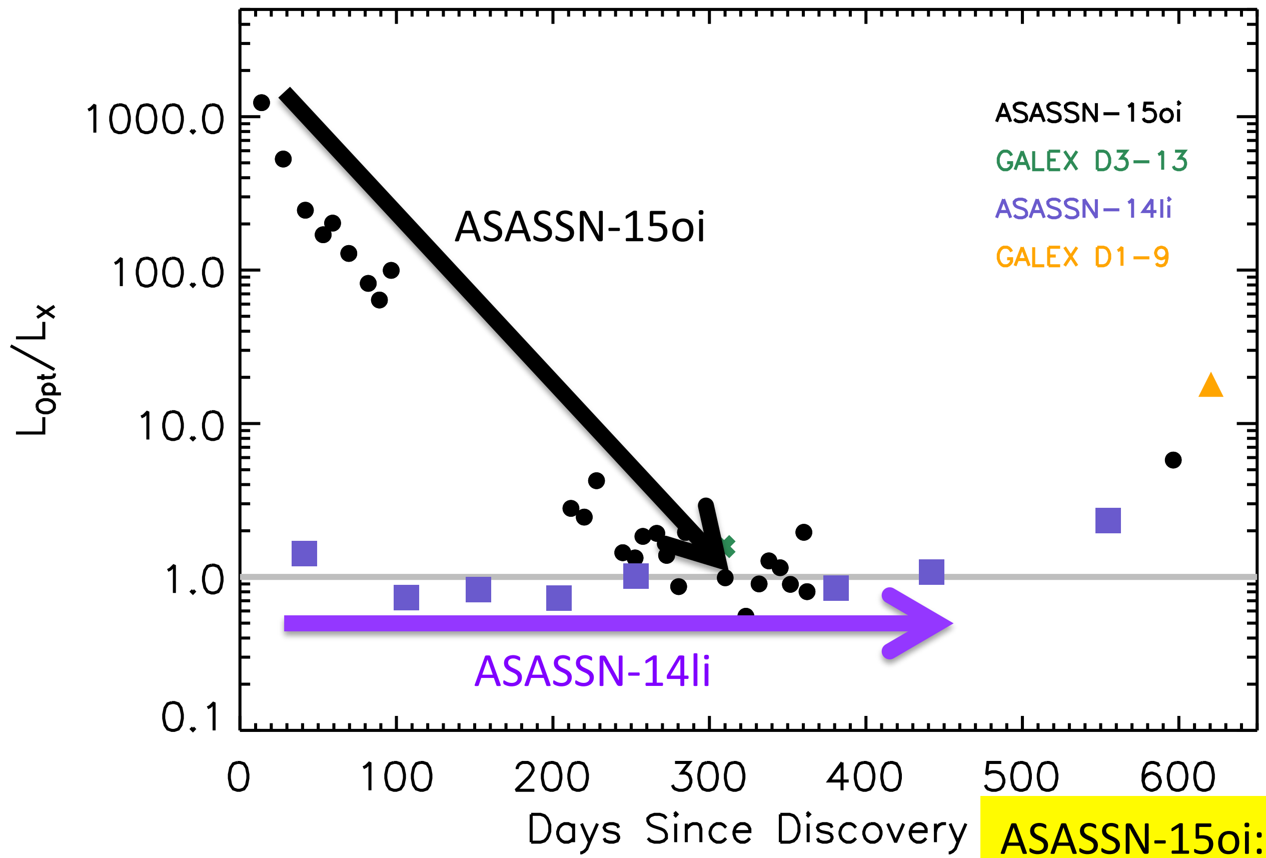
Multi-λ Emitters



ASASSN-14li: Holoien+ 2016

Figure from Jiang+ 2016

Surprise: Strong Evolution in L_{Opt}/L_X



ASASSN-14li: soft X-ray component (kT_{BB} ~ 50 eV) monitored by Swift to have a constant L_{opt}/L_X~1.

Holoien+ 2016, Brown+ 2017

ASASSN-15oi: Swift and XMM observed x10 brightening of soft X-rays on the timescale of 1 yr, with little change in spectral shape (kT_{BB} ~ 45 eV).

Gezari, Cenko & Arcavi (2017)

Accretion Timescales

The characteristic timescale for a TDE is set by the orbital period of the most tightly bound debris, known as the fallback time ($t_{\rm fb}$), which for a solar-type star is:

$$t_{\rm fb} = 41 \text{ d } M_6^{1/2}.$$

The circularization timescale ($t_{\rm circ}$) driven by relativistic apisidal precession of the debris streams depends on the black hole mass as

$$t_{\rm circ} = 8.3 t_{\rm fb} \, M_6^{-5/3} \beta^{-3}$$

where $\beta = R_{\rm T}/R_{\rm p}$ Bonnerot et al. (2016). Meanwhile, the viscous inflow time scale for a standard α-disk model (Shakura & Sunyaev 1973) is

$$t_{\rm visc} = \alpha^{-1}(h/r)^{-2} P_{\rm out} \sim 0.1 t_{\rm fb}(\alpha/0.1)^{-1}(h/r)^{-2}$$

where α is the standard viscous parameter, h is the scale-height of the disk, and $P_{\rm out}$ is the orbital period of the outer edge of the disk.

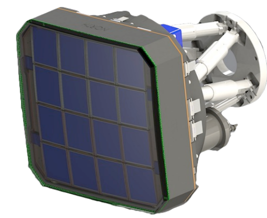
1 yr rise time of X-ray to peak is tantalizingly close to the circularization timescale of a 10^6 M_{sun} TDE!

Where do we go from here…

Where do we go from here…

More events…

The Zwicky Transient Facility (ZTF)



47 deg^2 field of view
600 Megapixel camera
10 sec readout time
Survey speed: 3750 deg^2/hour to 20.5 mag
g, R, i filters
PI: Shri Kulkarni (Caltech)

Started in March 2018

UMd is a member of the ZTF Partnership, along with:

ipac, Caltech, DESY, Los Alamos National Laboratory, Oskar Klein centre, UWM, מכון ויצמן למדע Weizmann Institute of Science, W, UST

NSF MSIP
Northern-Sky Survey
15,000 deg^2
3 day cadence, g+R
Public alert stream

ZTFbh: AGN and TDE SWG

+ =

SWG Motto: Leave no TDE behind!

UMd ZTFbh Members:

Sara Frederick, UMd (current grad student)
Charlotte Ward, UMd (current grad student)
Erica Hammerstein, UMd (current grad student)
Sjoert van Velzen, UMd/NYU → Leiden
Tiara Hung, UCSC (former grad student)
Brad Cenko, GSFC
Nathaniel Roth, UMd&GSFC (JSI Postdoc Fellow)

Sjoert van Velzen

Erica Hammerstein

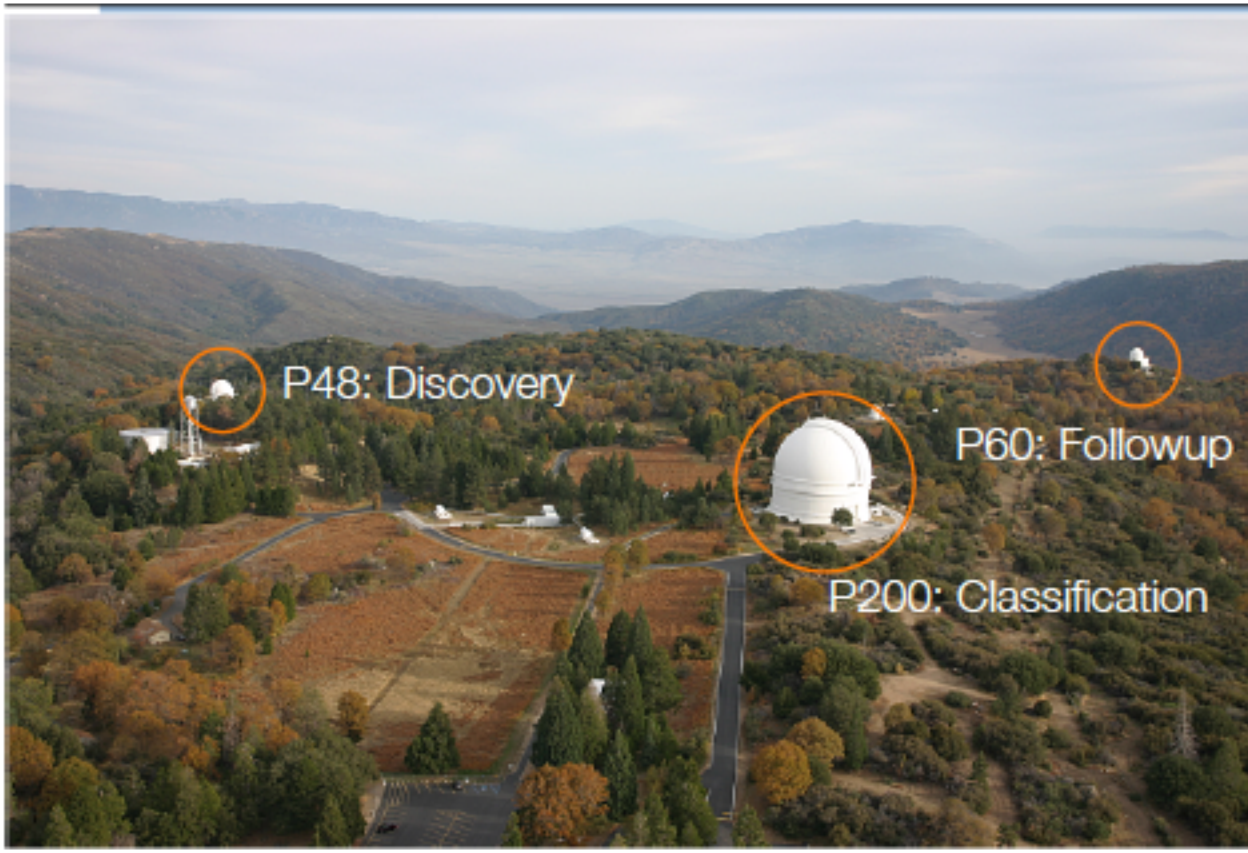
Sara Frederick

Charlotte Ward

Tiara Hung

Nathan Roth

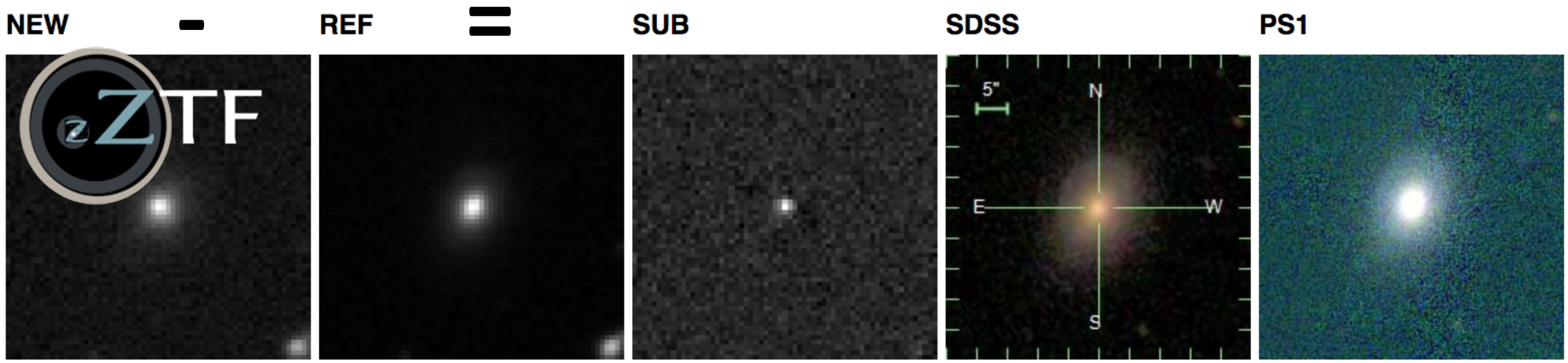
From Discovery to Classification



DCT (4.3m): LMI (imager), DeVeny (R~1000 spec), RIMAS (NIR imager and spec). *The only >4m facility with continuously available optical and NIR spectrographs.*

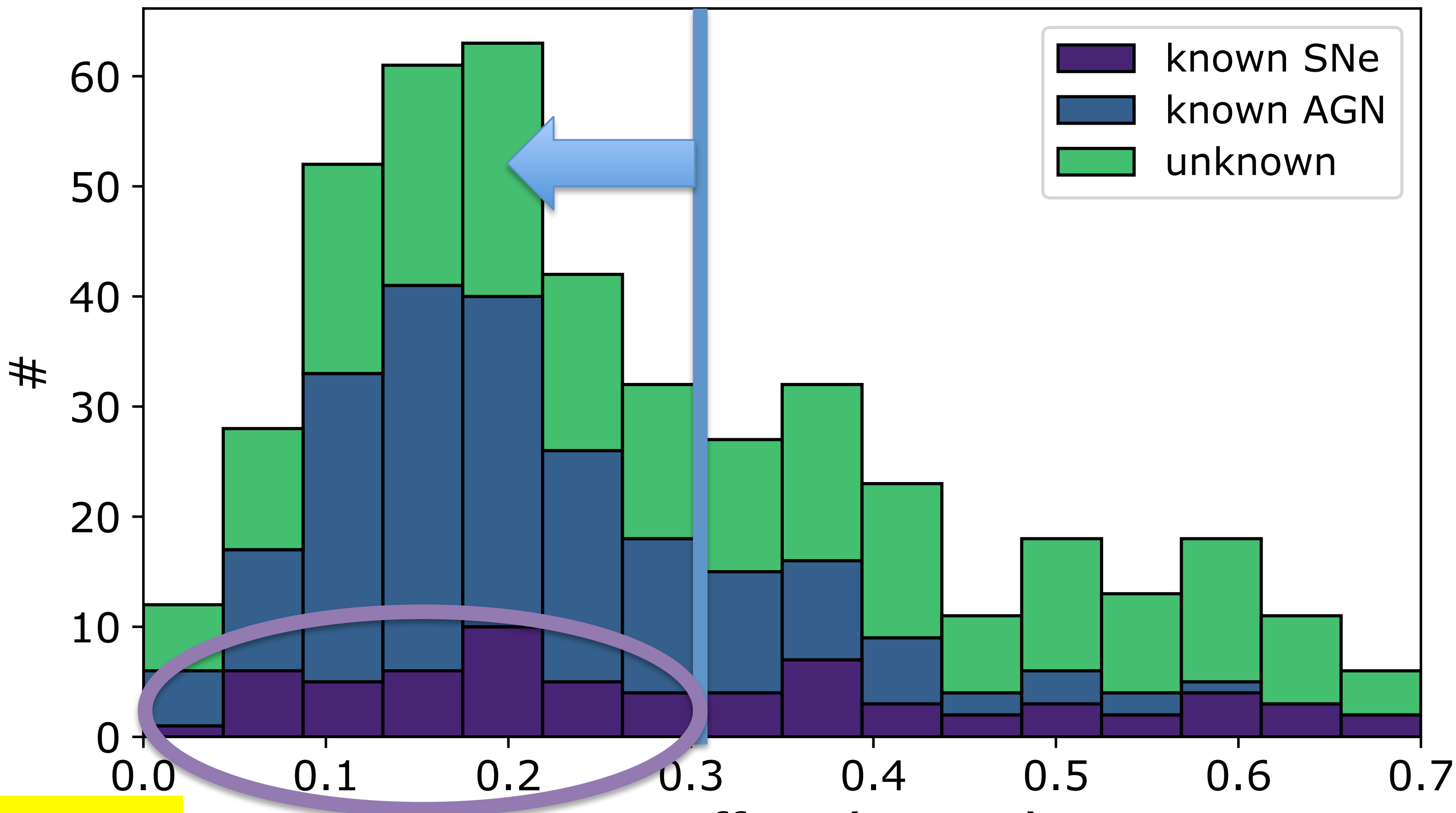
P48: Wide-field survey telescope in g,R, i with m_{lim} = 20.5 mag, 47 deg^2 FOV
P60: Dedicated SED Machine (R~100 spectrograph) for transients brighter than 19 mag
P200: DBSP (R~1000 spectrograph) for follow-up available in collaboration with Caltech.

We Use Image Differencing to Find Nuclear Transients...



...however, not every nuclear transient is associated with activity from the galaxy's central massive black hole!

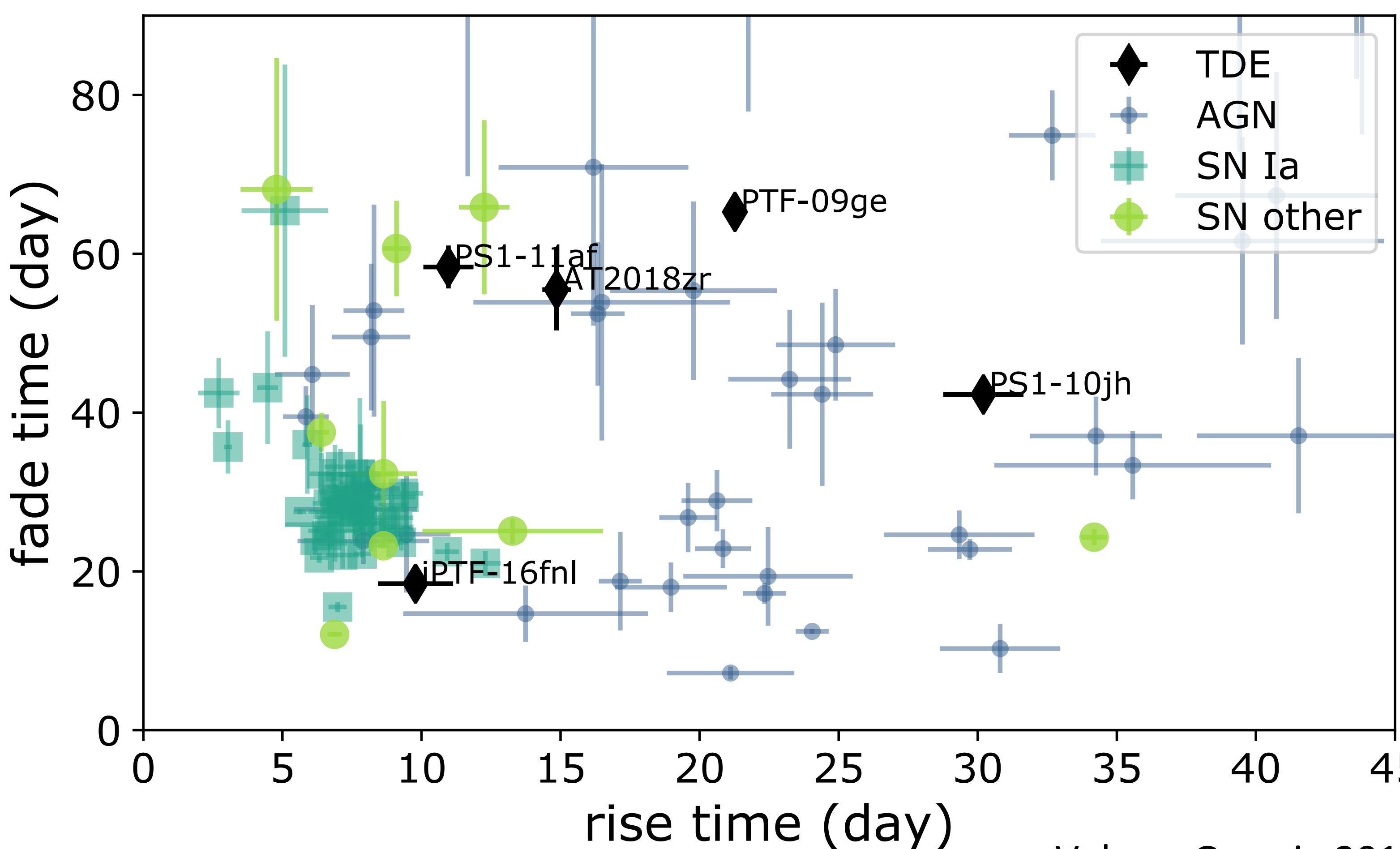
Nuclear Transients in ZTF



Must filter out nuclear SNe!

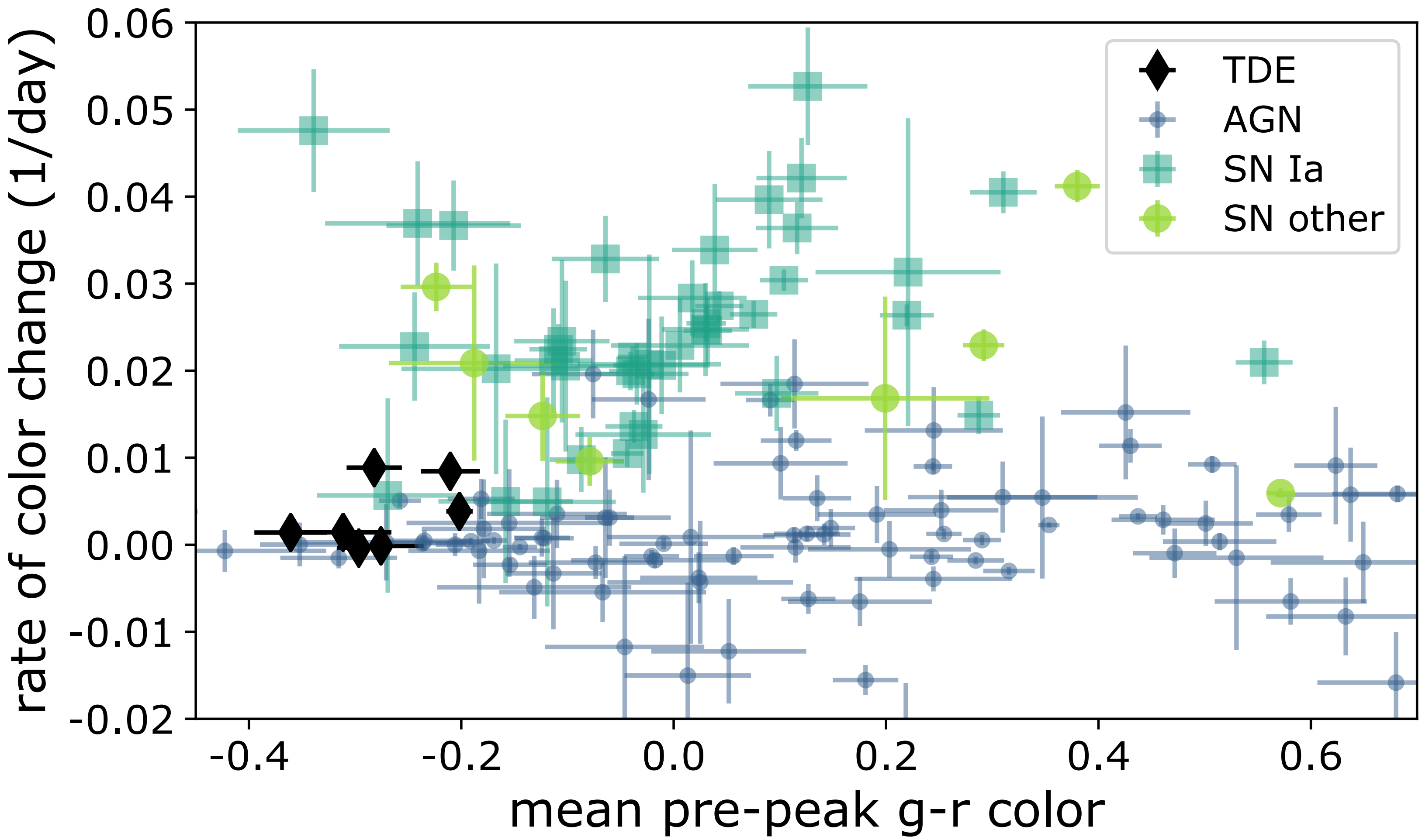
van Velzen, Gezari+ 2019

Filtering Out Pesky SNe



van Velzen, Gezari+ 2019

Filtering Out Pesky SNe



van Velzen, Gezari+ 2019

GROWTH
Global Relay of Observatories Watching Transients Happen

GOT Nicknames

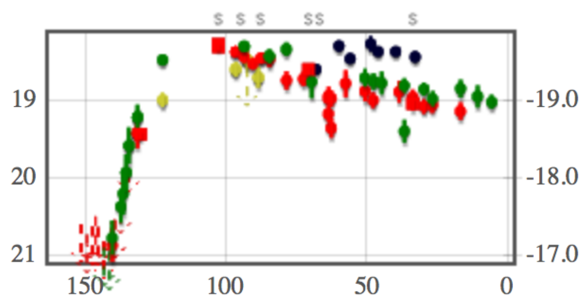
ZTF18abxftqm TDE

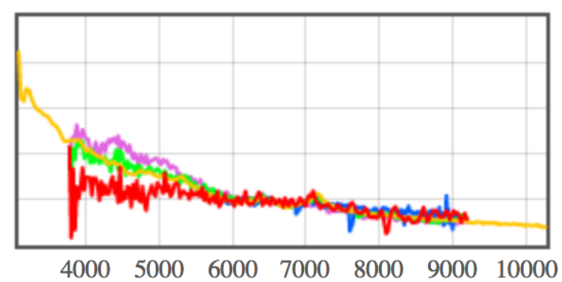
01:07:33.61 +23:28:34.
16.890057 +23.476219

OVERVIEW PHOTOMETRY SPECTROSCOPY OBSERVABILITY EXAMINE

Sansa

NEW REF SUB SDSS PS1





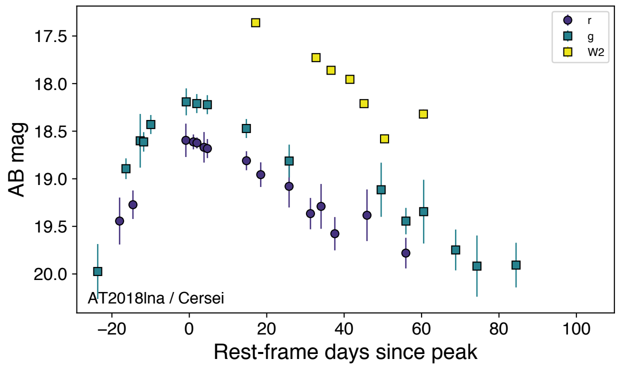
r = 19.1 (16.6 d) | Upload New Photometry

z = 0.088 | Upload New Spectroscopy
DM (approximate) = 38.00

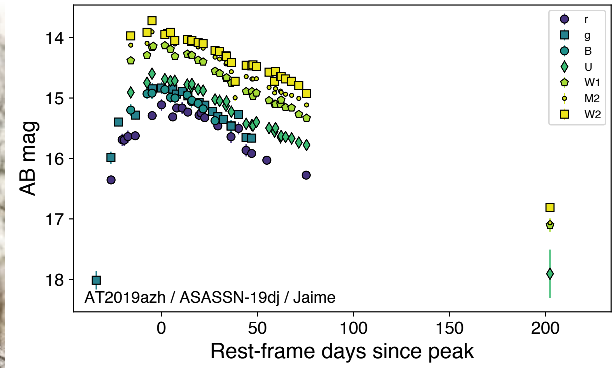

WINTER
IS
COMING

ZTF (g,r)+Swift (UV) Light Curve Examples

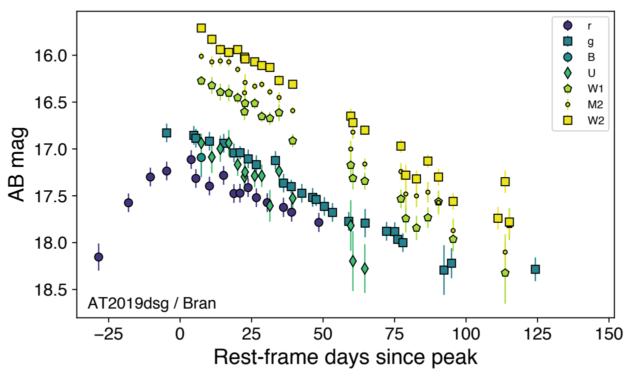
Cersei



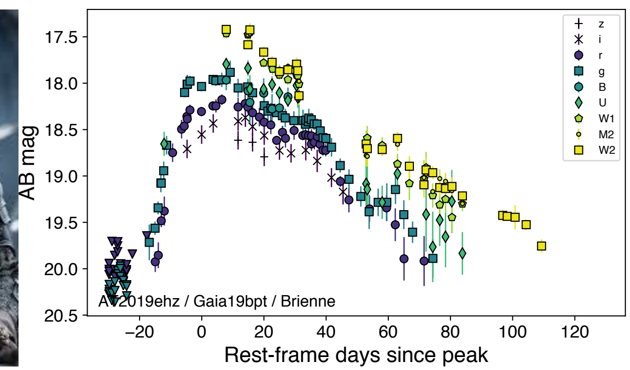
Jaime



Bran



Brienne

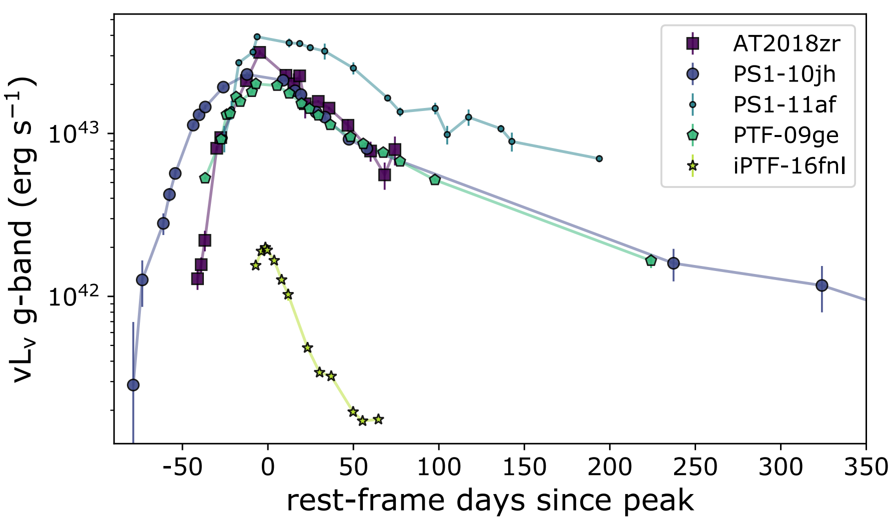


Note: some transients are detected by multiple surveys, so we use AT names from TNS.

van Velzen, Gezari+ 2020

ZTF Pre-Peak Light Curves

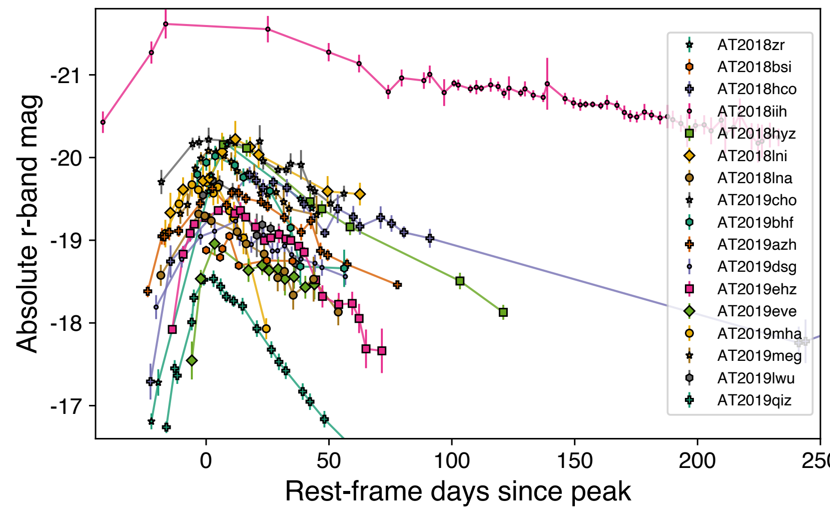
Before ZTF



van Velzen, Gezari, et al. 2018

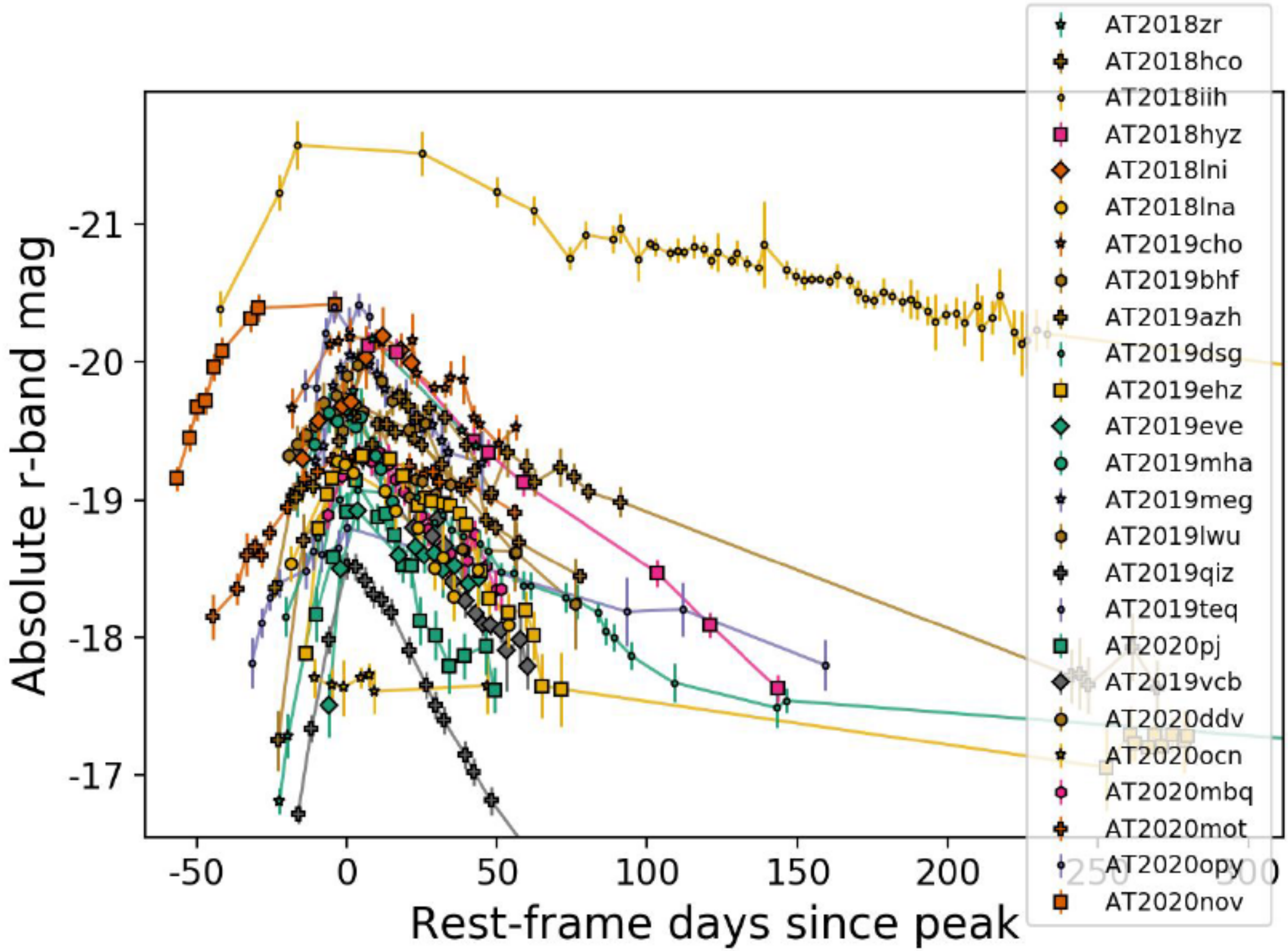
*AT2018zr, the first TDE detected by ZTF, was one of only 5 TDEs discovered **before** peak!*

After ZTF

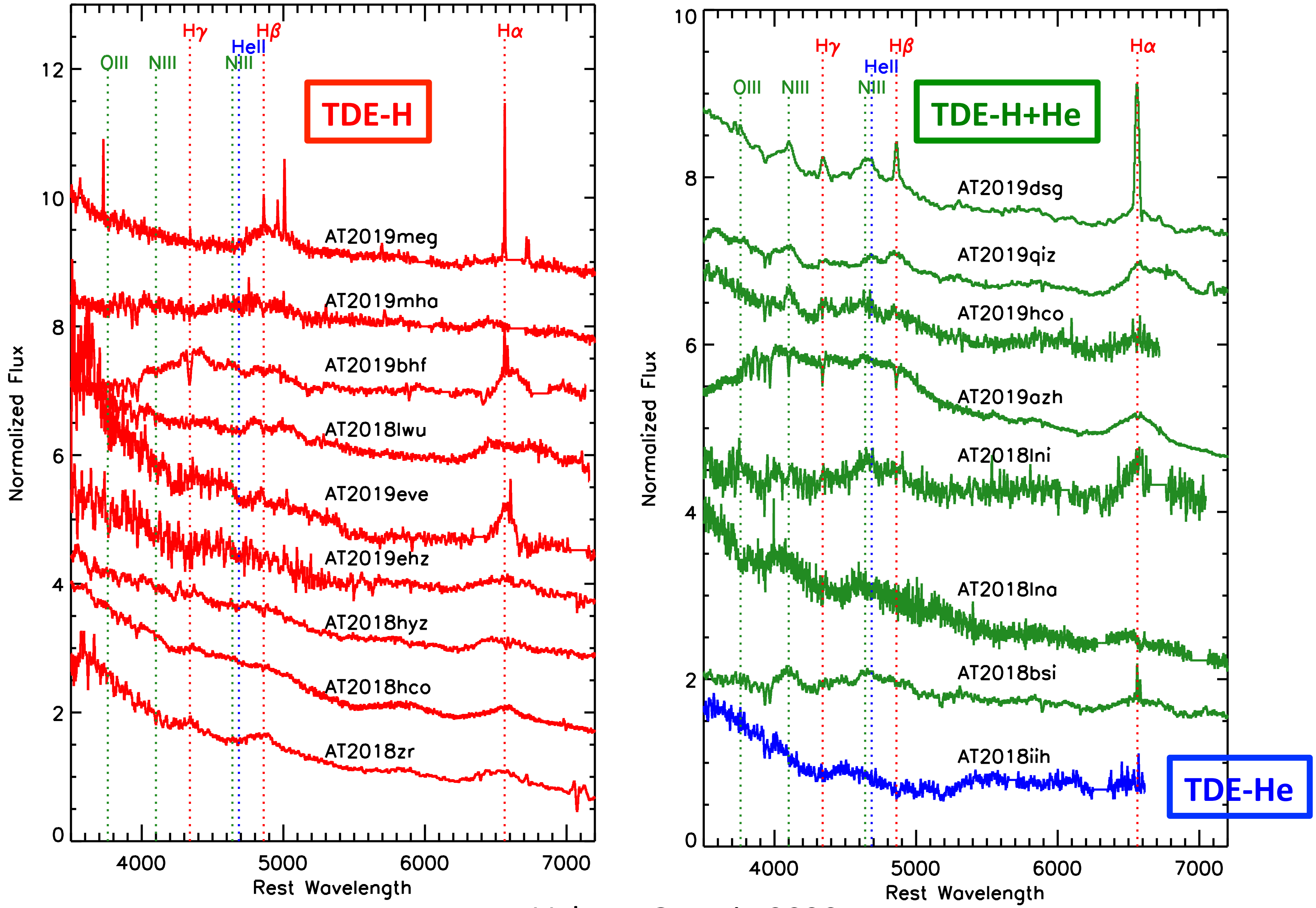


van Velzen, Gezari+ 2020

In the first 1.5yr of ZTF survey operations, we have detected 16 more!

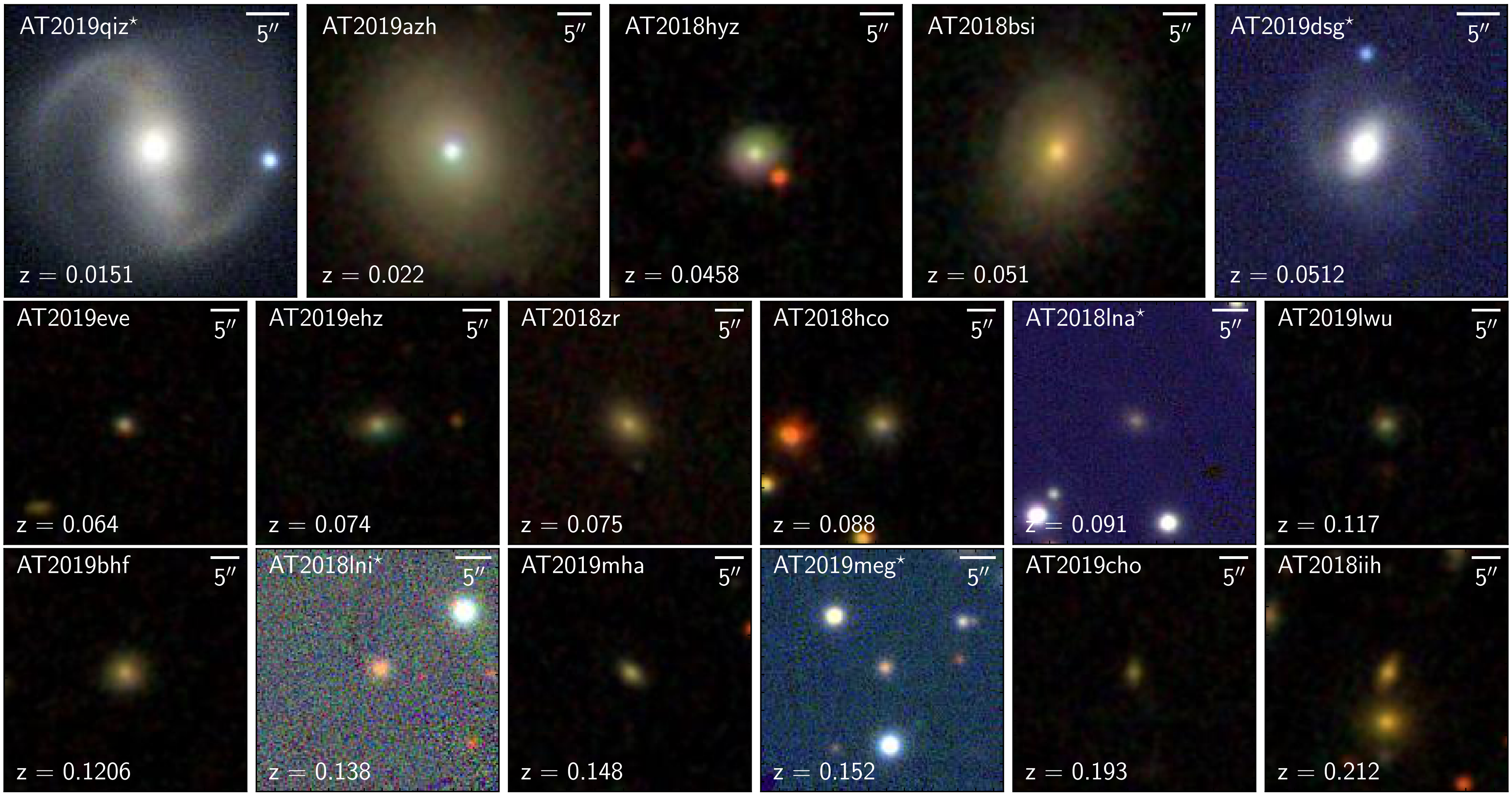

Absolute r-band mag
-21
-20
-19
-18
-17
-50
0
50
100
150
200
250
300
Rest-frame days since peak
AT2018zr
AT2018hco
AT2018iih
AT2018hyz
AT2018lni
AT2018lna
AT2019cho
AT2019bhf
AT2019azh
AT2019dsg
AT2019ehz
AT2019eve
AT2019mha
AT2019meg
AT2019lwu
AT2019qiz
AT2019teq
AT2020pj
AT2019vcb
AT2020ddv
AT2020ocn
AT2020mbq
AT2020mot
AT2020opy
AT2020nov

ZTF TDE Spectral Types

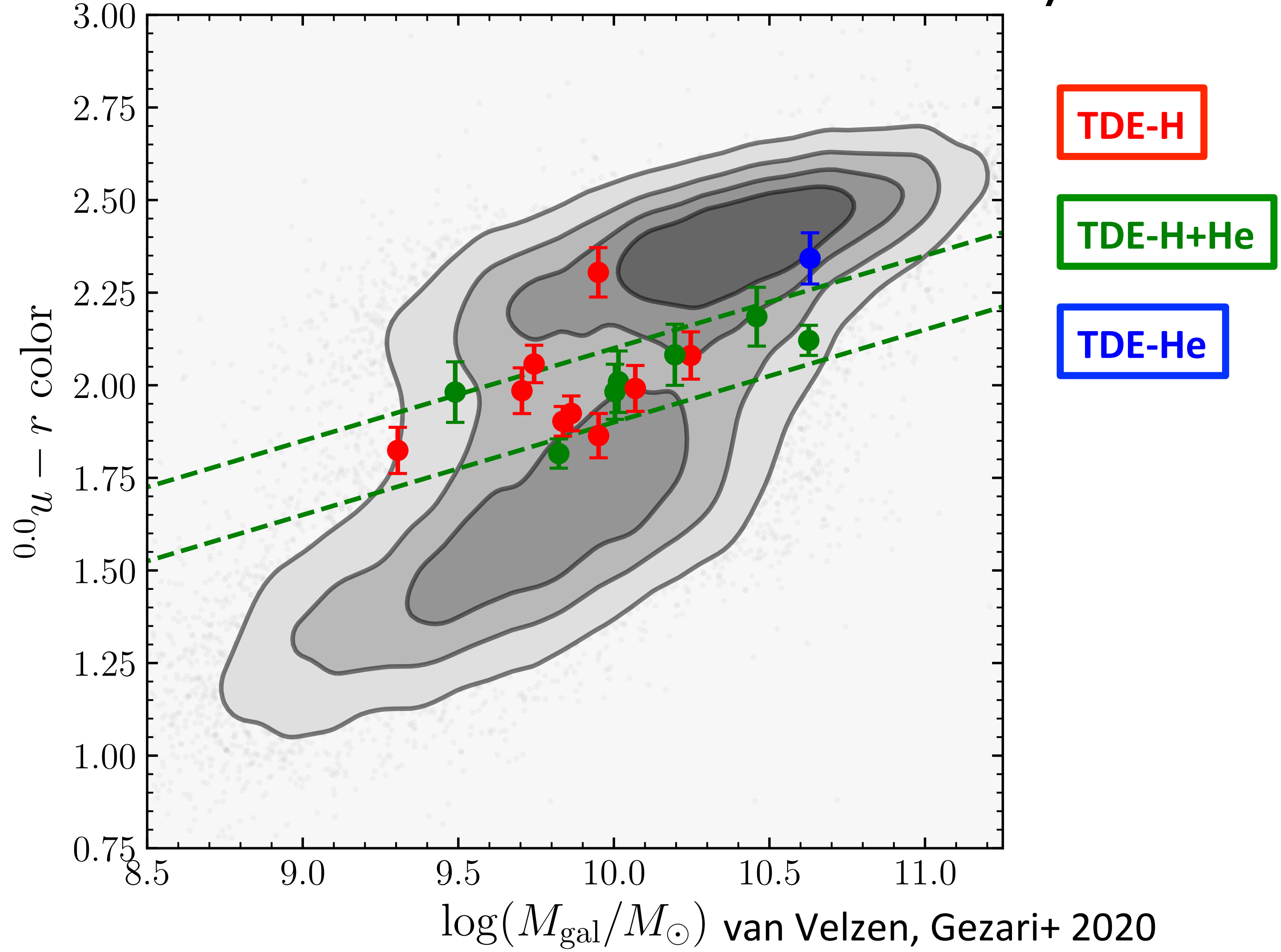


van Velzen, Gezari+ 2020

Host Galaxies



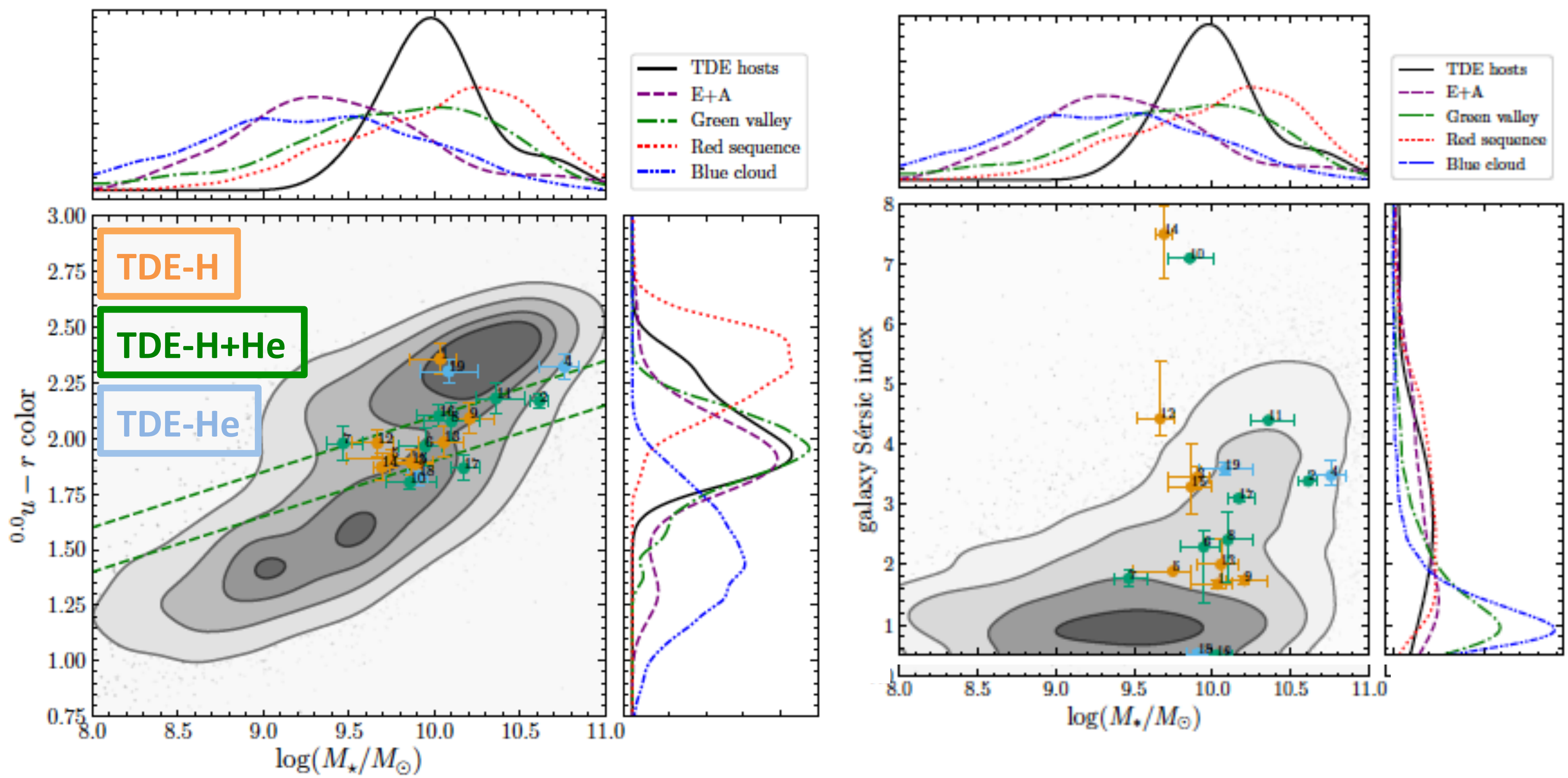
Red & Green, but few Blue Galaxy Hosts



van Velzen, Gezari+ 2020

Very few blue galaxy hosts, even though in the galaxy mass range, must galaxies are blue!

TDE Hosts are Green and Centrally **Concentrated**

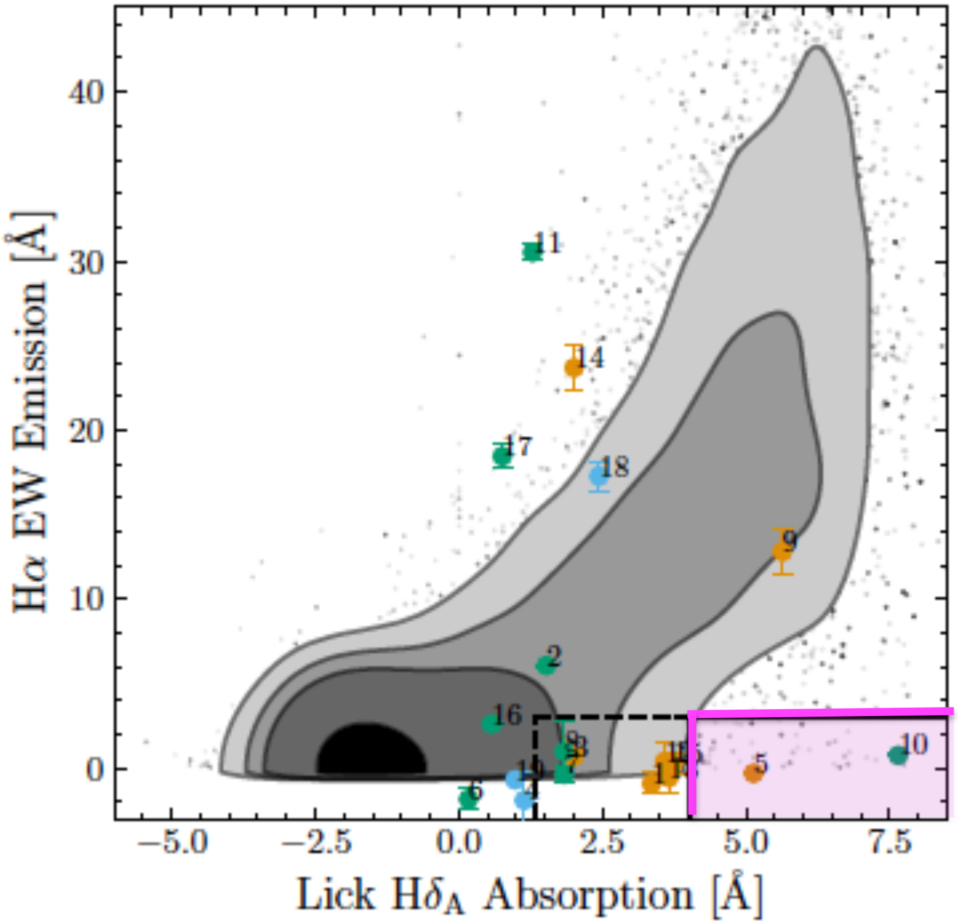


Hammerstein, Gezari+ 2020

TDE-H

TDE-H+He

TDE-He



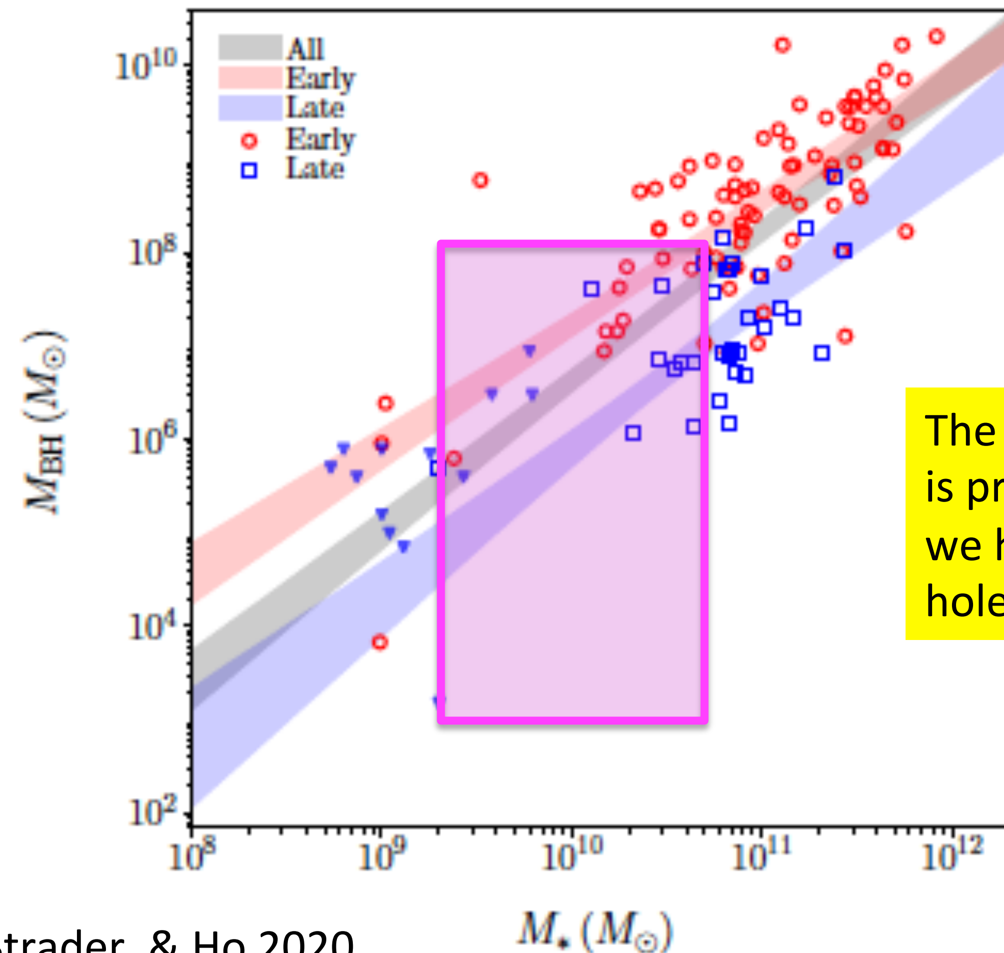
E+A galaxy overrepresentation disappears when you select for only green galaxies with n > 2

E+A galaxies

Table 2. E+A Overrepresentation

	Overall	Green Valley	$n_g > 2.0$	Green Valley + $n_g > 2.0$
Full Sample (sF16)	22×	7×	15×	3×
$9.47 \leq \log(M_\star/M_\odot) \leq 10.76$ (sF16)	29×	8×	29×	1×

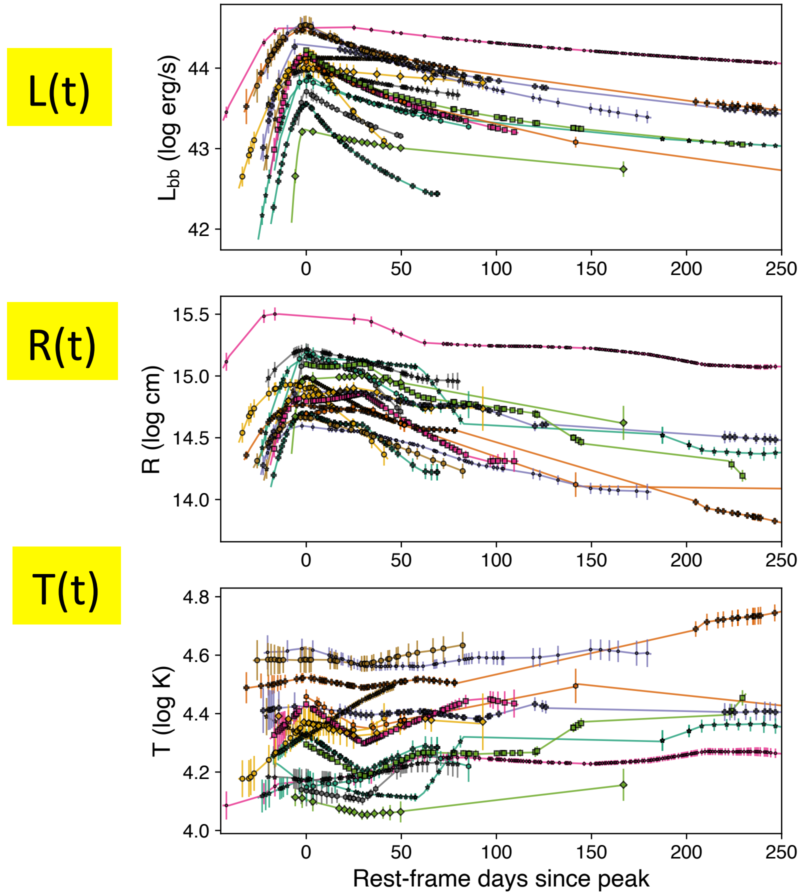
Low-Mass M_{BH}



Greene, Strader, & Ho 2020

The TDE host galaxy mass range is probing $M_{BH} < 10^8\ M_{sun}$, where we have few dynamical black hole mass measurements.

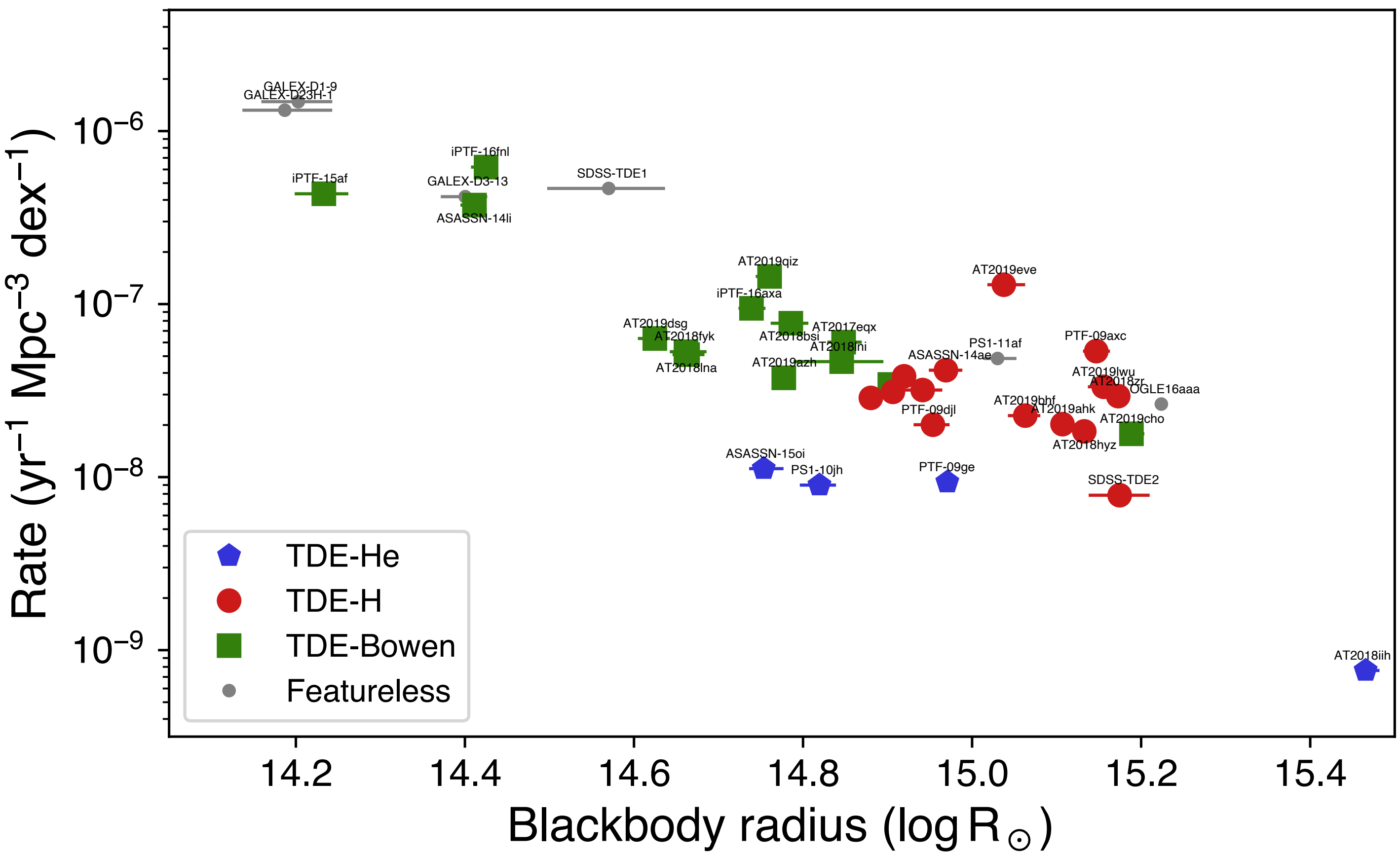
We are now entering an era of TDE population studies…



van Velzen, Gezari+ 2020

We apply a uniform analysis of **17 ZTF + 15 archival = 32 spectroscopically classified TDEs**, and search for **correlations** between flare properties, spectral class, and host galaxy mass.

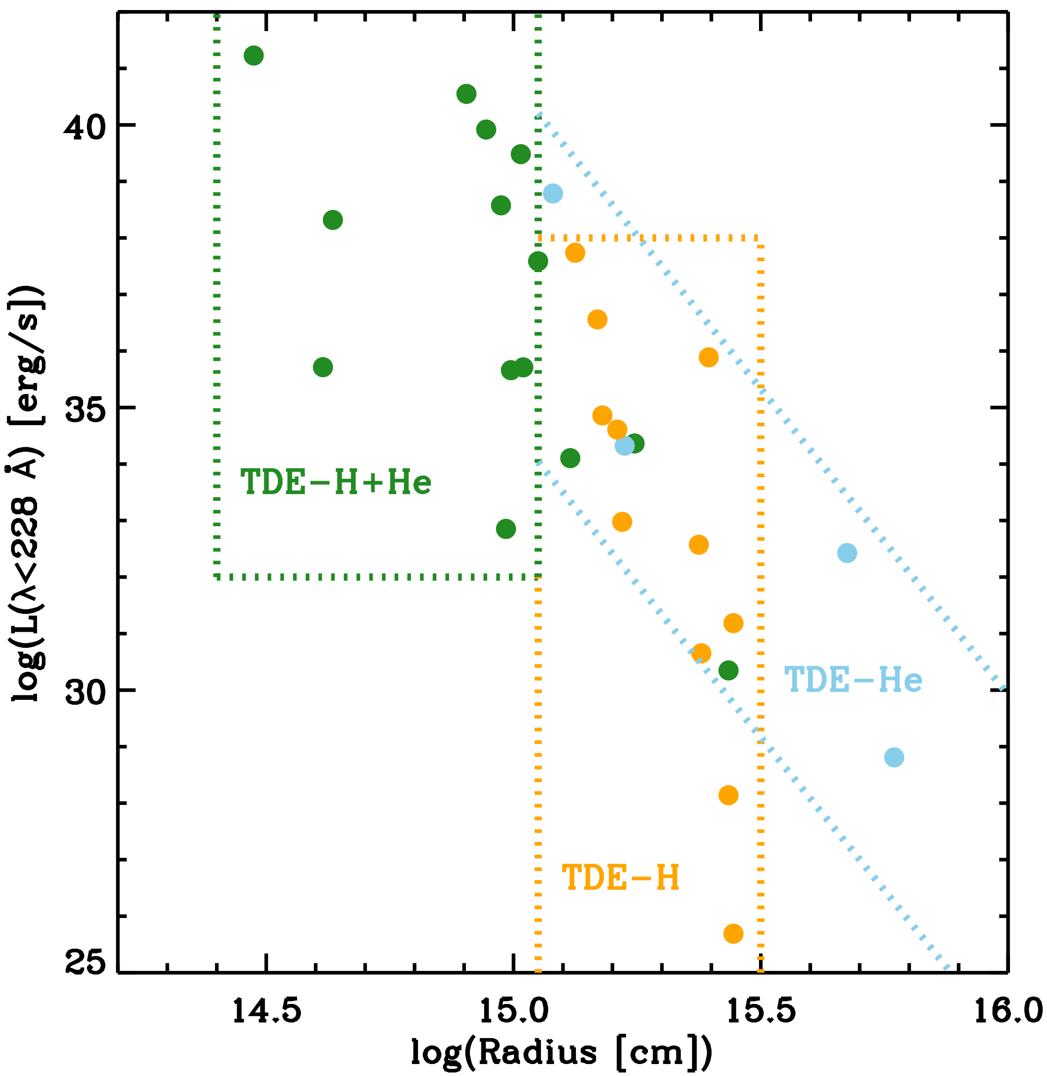
Separation of Spectral Types



TDE-Bowen class are the most common, perhaps indicating disruption of low-mass stars?
TDE-He class are the least common, perhaps indicating the disruption of rare He stars?

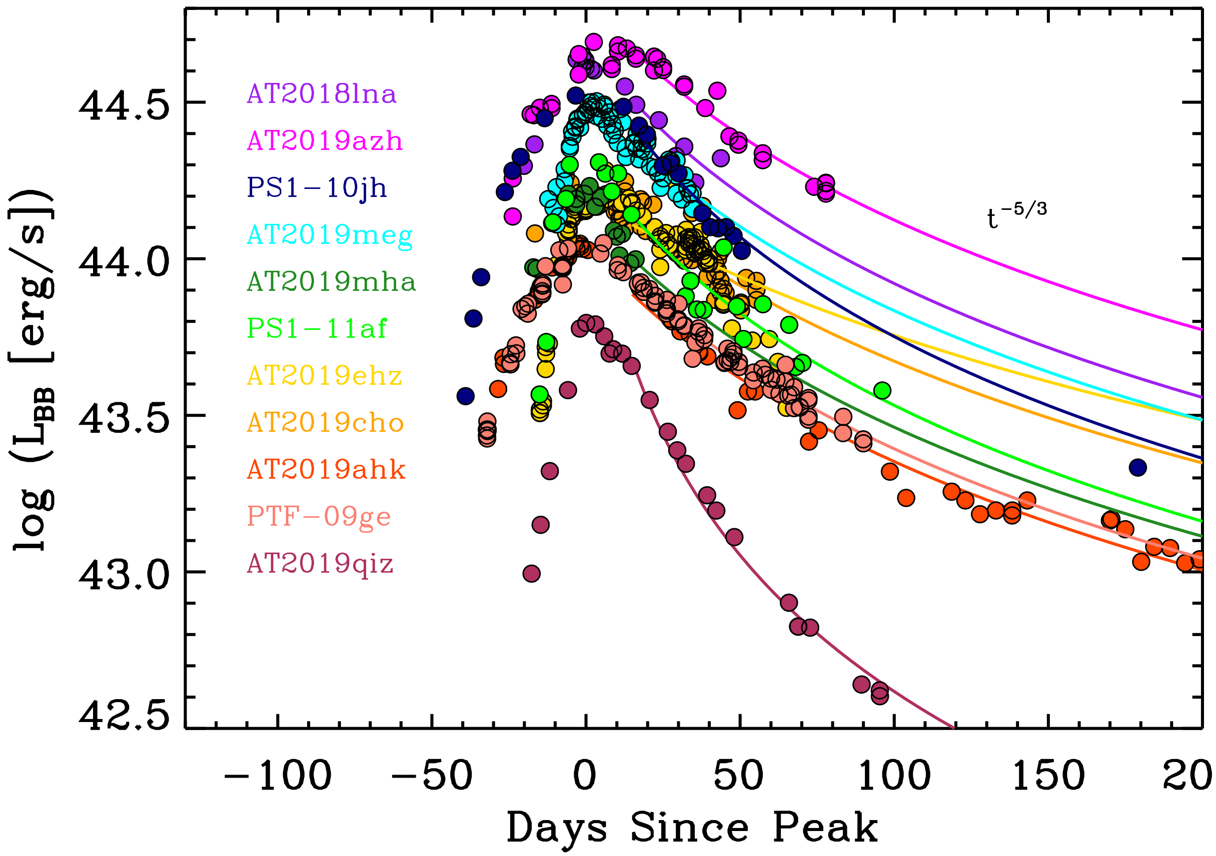
van Velzen, Gezari+ 2020

Separation of Spectral Types



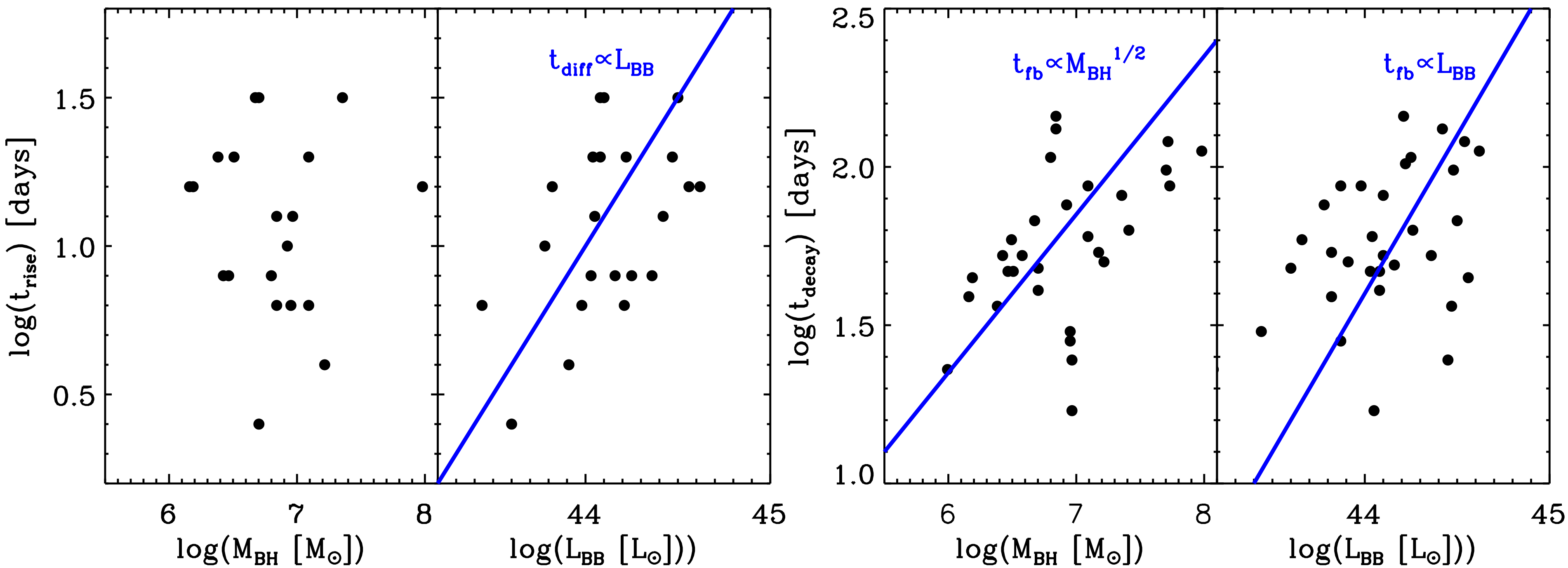
Gezari 2021

Well-Sampled Pre-Peak Light Curves, $t^{-5/3}$ Power-Law Decline



Gezari 2021

Decay Scales with $M_{BH}^{1/2}$, Rise Time Does Not!



Rise time appears to scale with L, as would be expected for radiative diffusion timescale.

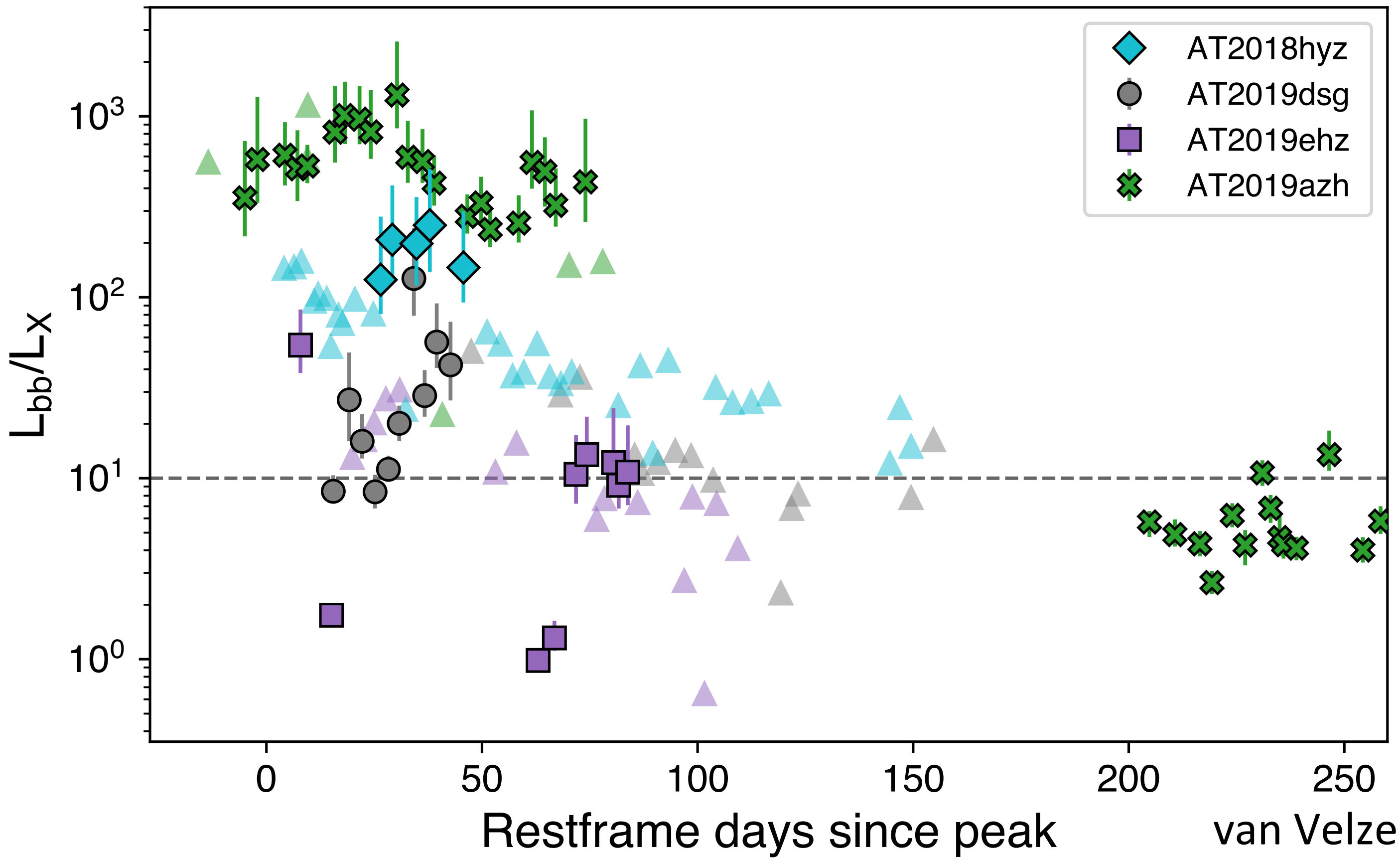
$$t_{\rm diff} \propto \rho R^2 \propto M/R \propto L/R$$

Decay time appears to scale with $M_{BH}^{1/2}$, as would be expected for fallback rate.

$$t_{\rm fb} \propto R_\star^{3/2} M_\star^{-1} M_{\rm BH}^{1/2}$$

Gezari 2021

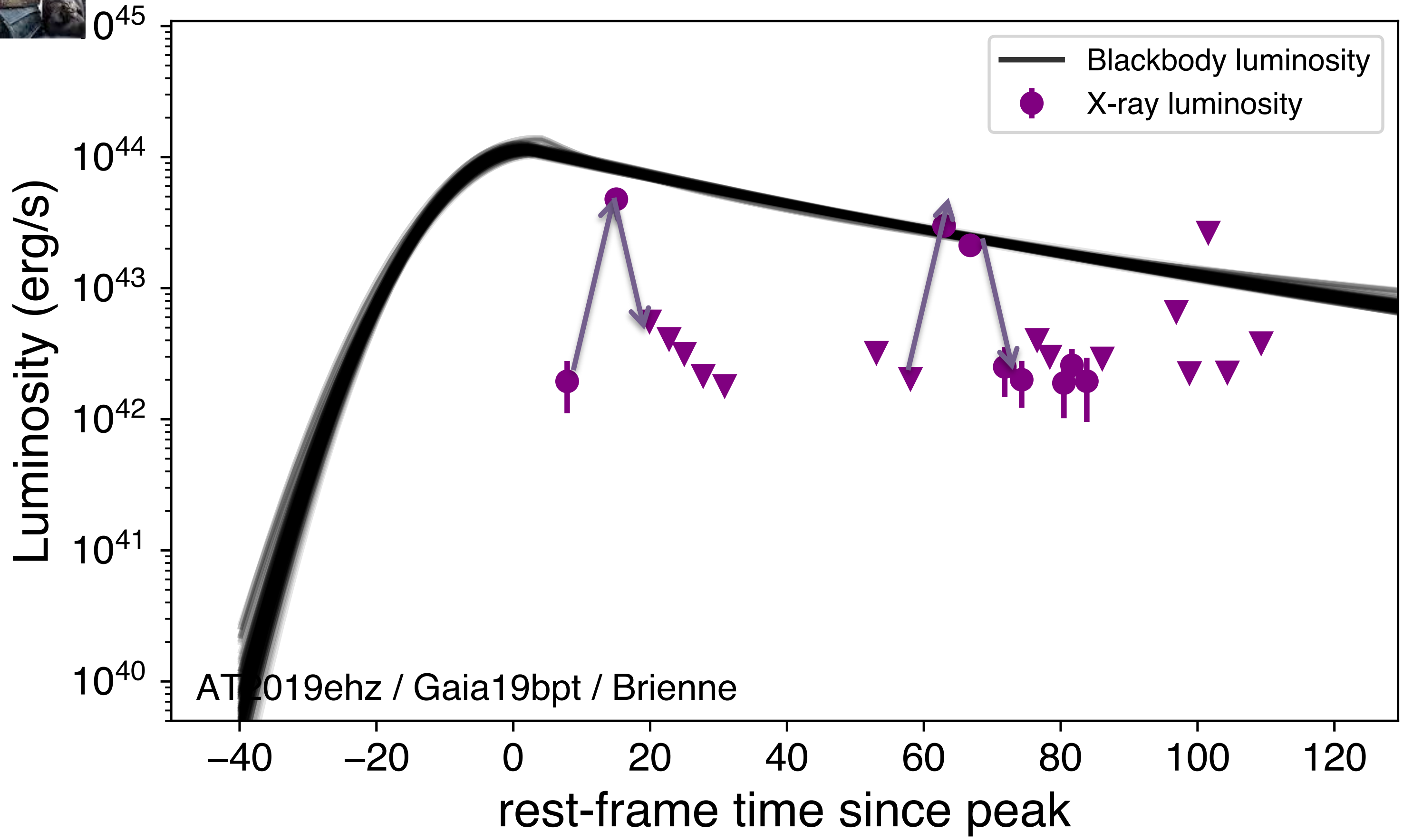
New Landscape of Optical+X-ray TDEs



van Velzen, Gezari+ 2020

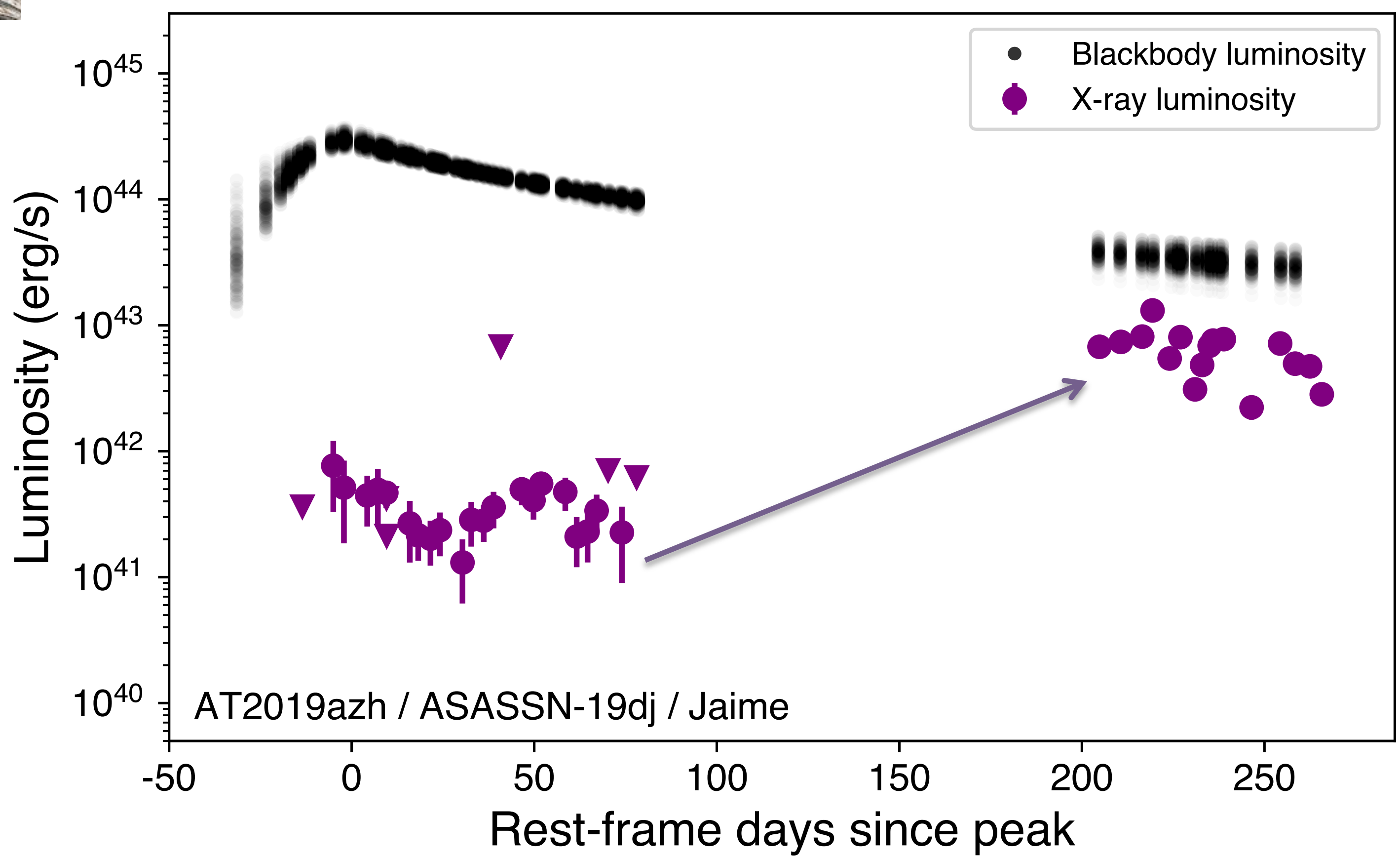
In the first 1.5yr of ZTF survey operations, we now have detected 4 more TDEs in the soft X-rays, and with dramatic variability caught by Swift monitoring!

Brienne: Rapid Flaring



van Velzen, Gezari+ 2020

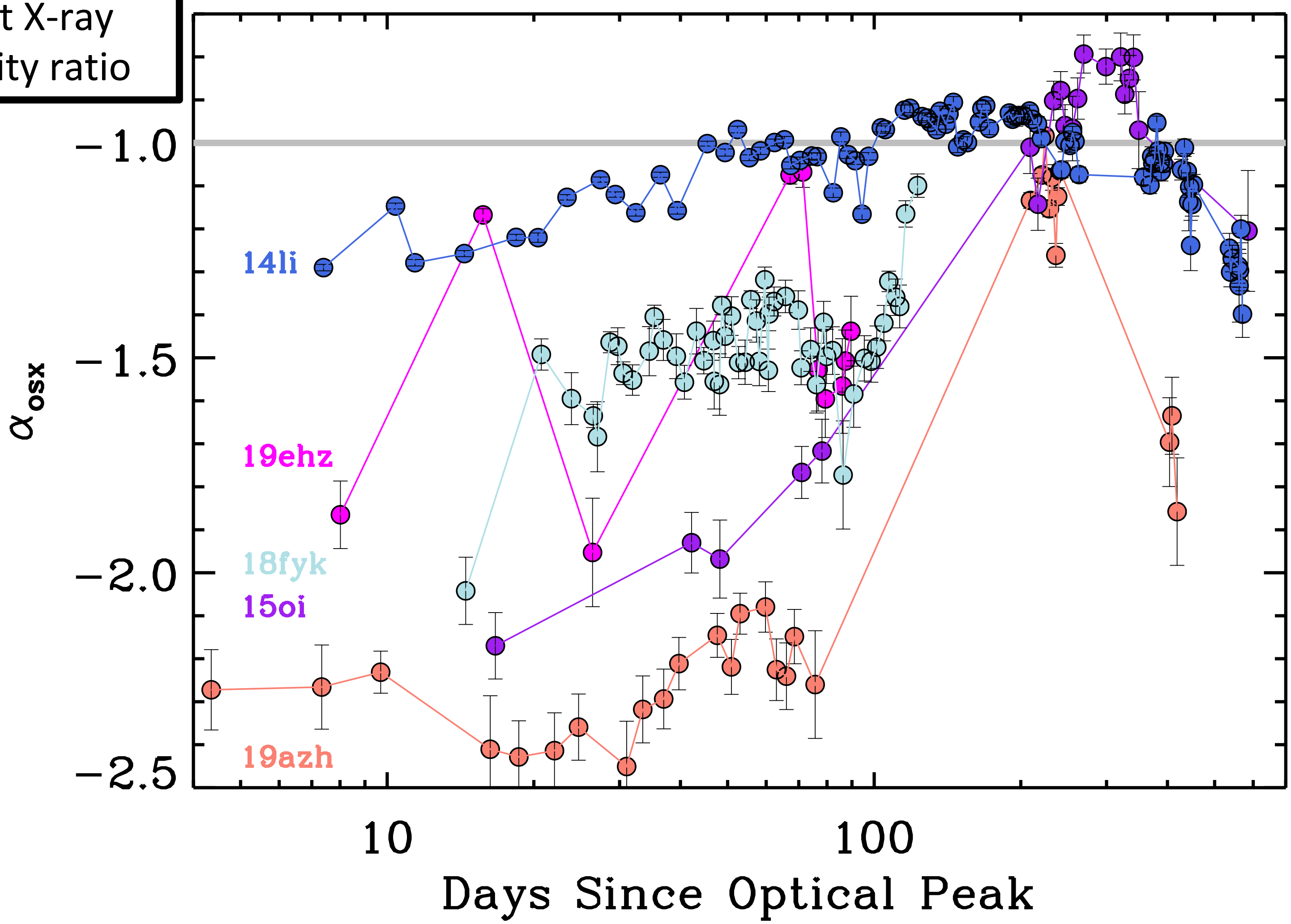
Jaime: Late-time Brightening



van Velzen, Gezari+ 2020

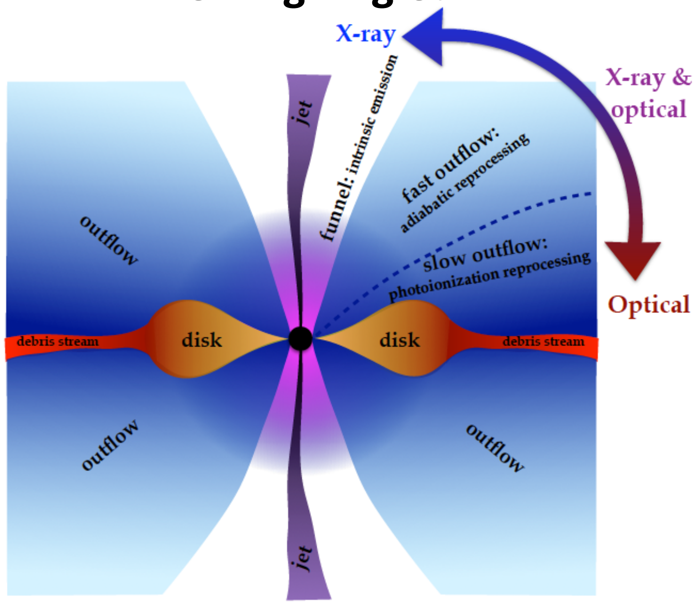
Dramatic X-ray Variability

UV to soft X-ray flux density ratio



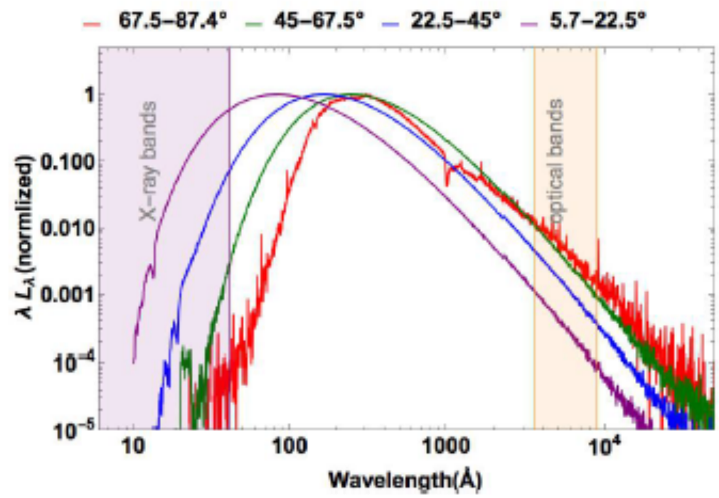
What is driving dramatic soft X-ray evolution?

Viewing Angle?



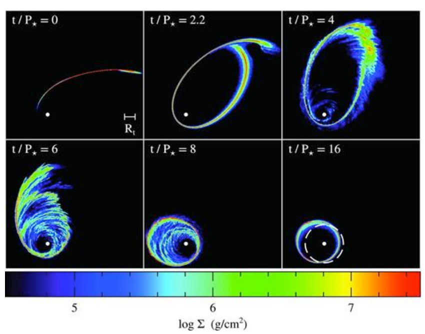
Dai et al. 2018

Reprocessing?



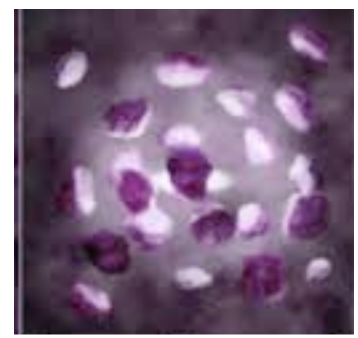
Dai et al. 2018

Circularization Delay?



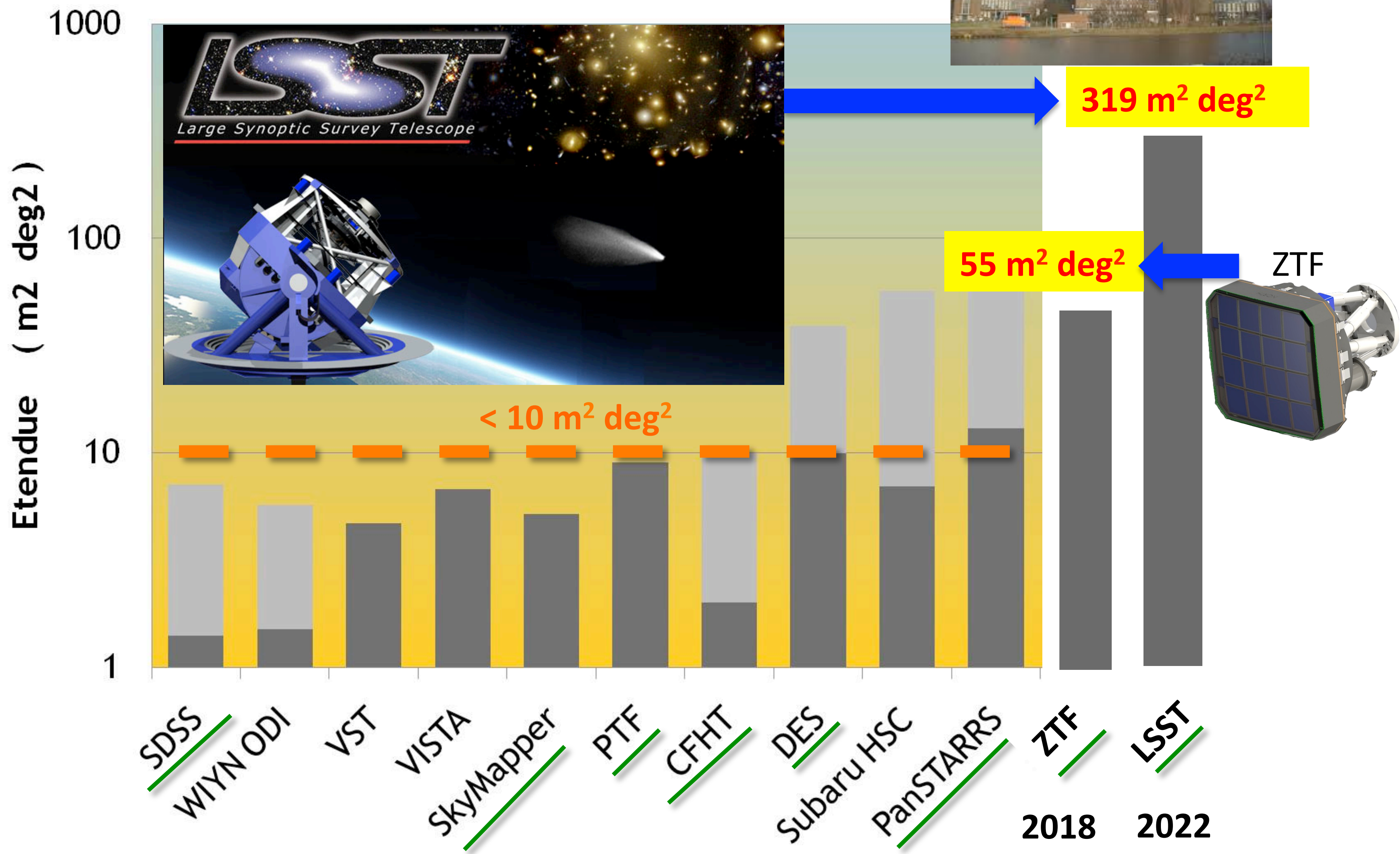
Bonnerot+ 2016, Piran+2015

Patchy Obscuration?



van Velzen, Gezari+ 2020

In Principle, Soon We Will Have



Surveys with time domain component.


Searching Under the Lamppost
Are ground-based optical surveys really the best approach for discovering and characterizing TDEs?
Many advantages to searching in the UV, soft X-rays, mid-infrared, and radio….
Need wide-field capabilities in these areas.

Future Space Missions

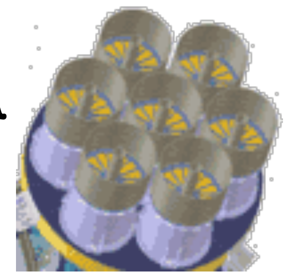
Ultraviolet

Dorado
195nm, 275 nm
NASA Cubesat Mission Study
50 deg^2 FOV, survey 1000 deg^2 every 3 hours
m_{lim}~ 20 mag, 14 arcsec FWHM
Potential to detect 100 TDE yr^{-1}

Soft X-ray

eROSITA on Spectrum-Roentgen-Gamma (SRG)
0.5-10 keV
Russian and German mission
0.83 deg^2 field of view
Survey the whole sky in multiple epochs
Launched in 2019!

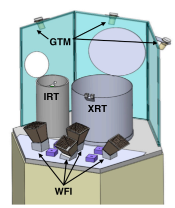
eROSITA



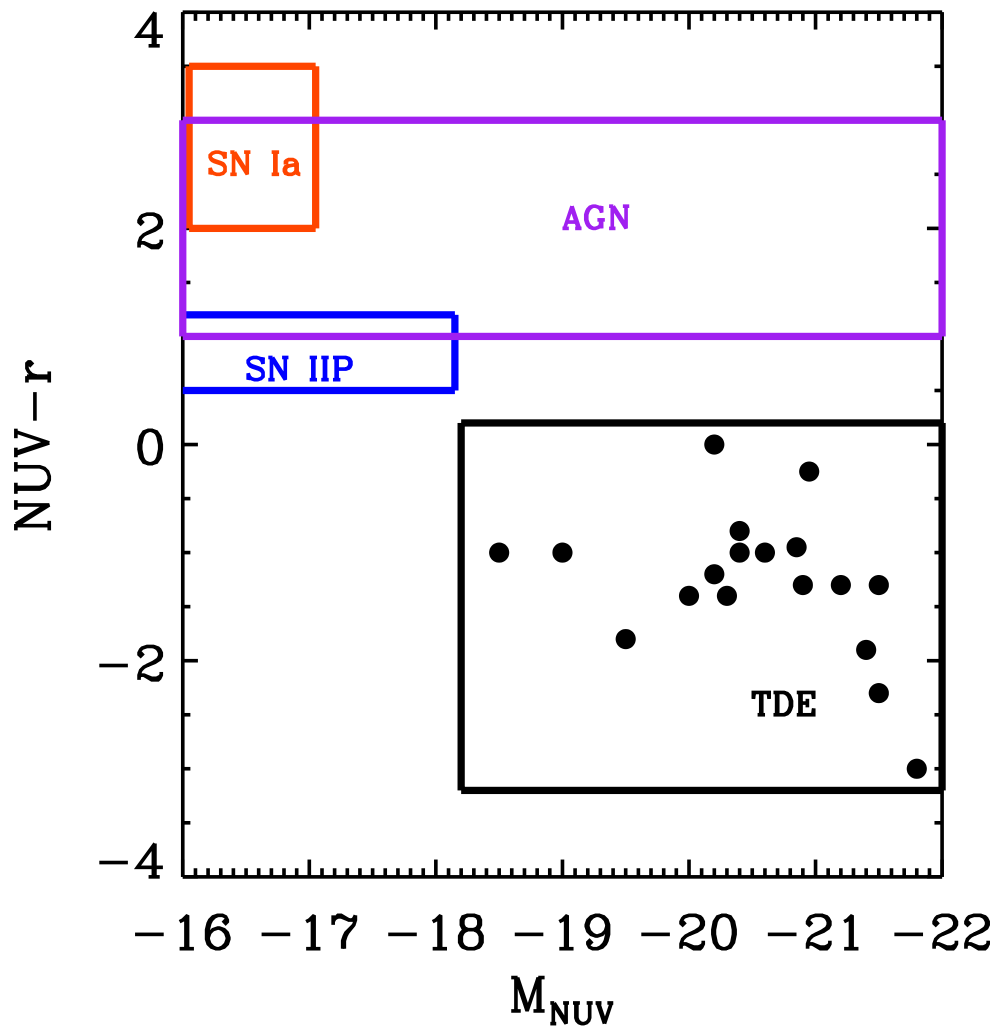
Hard X-ray

TAP (Transient Astrophysics Probe)
0.3-5 keV
Proposed NASA Probe-class Mission
19deg x 19deg field of view
WFI will survey 1/3 of the sky at once
Sensitive to "relativistic" TDE events.

Transient Astrophysics Probe (TAP)

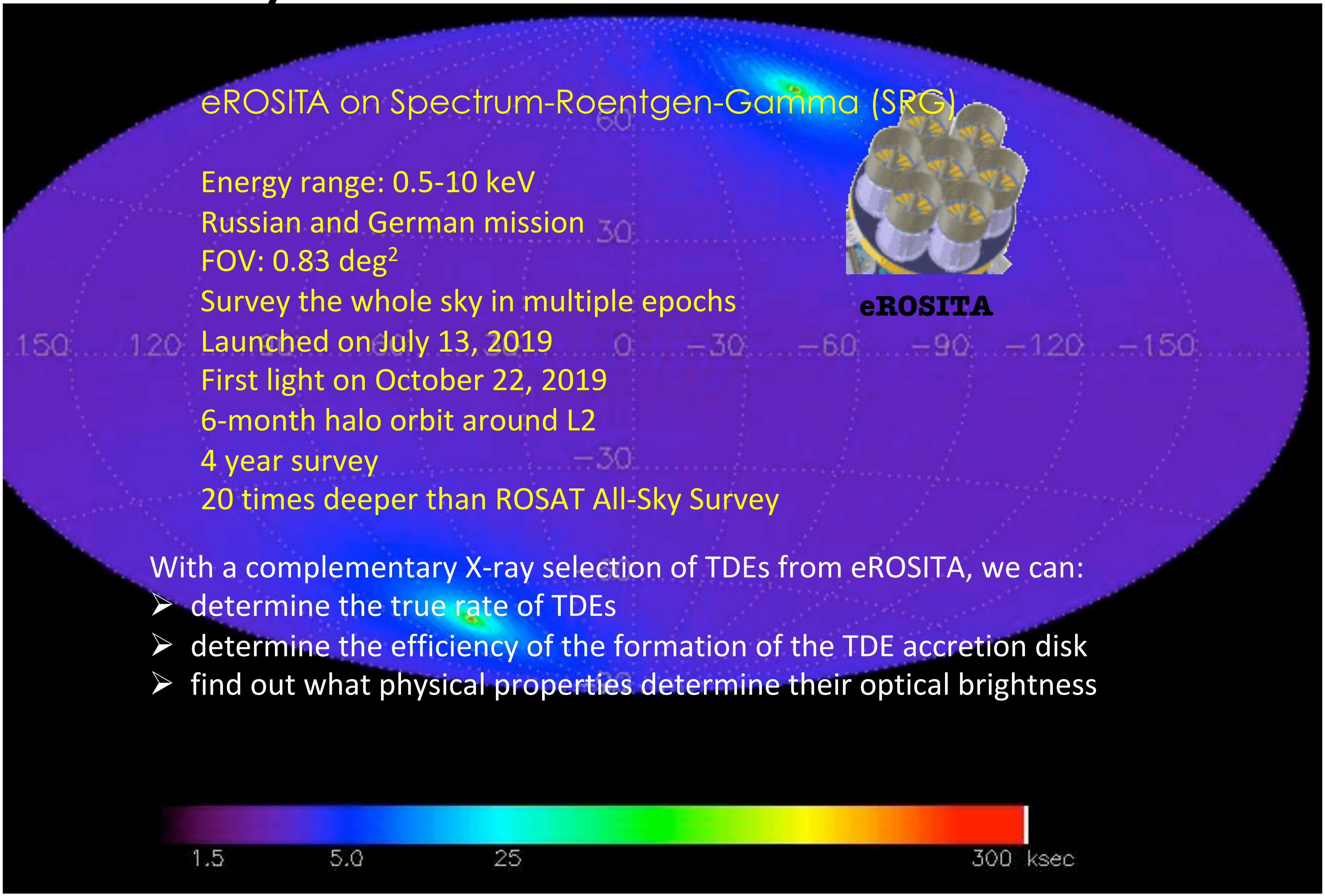


Classification Power of the UV



Gezari 2021

New **X-ray View** of the Transient Universe



eROSITA on Spectrum-Roentgen-Gamma (SRG)

eROSITA

Energy range: 0.5-10 keV
Russian and German mission
FOV: 0.83 deg^2
Survey the whole sky in multiple epochs
Launched on July 13, 2019
First light on October 22, 2019
6-month halo orbit around L2
4 year survey
20 times deeper than ROSAT All-Sky Survey

With a complementary X-ray selection of TDEs from eROSITA, we can:

- determine the true rate of TDEs
- determine the efficiency of the formation of the TDE accretion disk
- find out what physical properties determine their optical brightness

Conclusions

- ZTF is on track to be the first survey to produce a **statistically significant**, **systematically selected** TDE sample
- Will enable **population studies** of TDEs and their host galaxies and central black holes
- **Swift and XMM-Newton** follow-up have been critical for probing the UV and X-ray components
- **Dramatic soft X-ray evolution** may hold the key for unlocking the nature of the UV/optical component, and for probing the real-time formation of the accretion disk
- We are also following up our sources in the **radio** and in **fast time resolution X-ray imaging**…stay tuned!