October 3rd, 2025
Ay111
Caltech, Pasadena

AGN Variability:

a cornucopia or a phantasmagoria?

Matthew J. Graham
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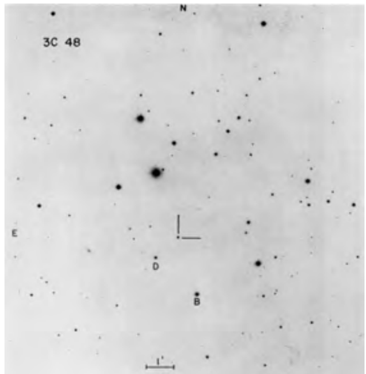
with contributions from
Szymon Nakoneczny,
Barry McKernan, Saavik Ford,
Daniel Stern, Joshua Fagin,
Yutaro Tachibana,and
Weixiang Yu, and others

A brief history of AGN variability



A second-epoch Sky Survey plate was taken by W. C. Miller on January 18/19, 1961, with the 48-inch Schmidt to check for a detectable proper motion. This plate was centered identically with the base plate O 30 of the original Sky Survey taken on December 21/22, 1949, giving an 11-year interval. Inspection of the two plates in a blink comparator showed no detectable proper motion relative to neighboring comparison stars. The proper motion is less than 0".05/yr (a value which could have been detected by this method).

Optical photometry of 3C 48 continued sporadically during 1961, with the results given in Table 1. The most striking feature of these data is that the optical radiation varies! Unfortunately, our time resolution is very poor. The only evidence for short-term

Matthews & Sandage, 1963

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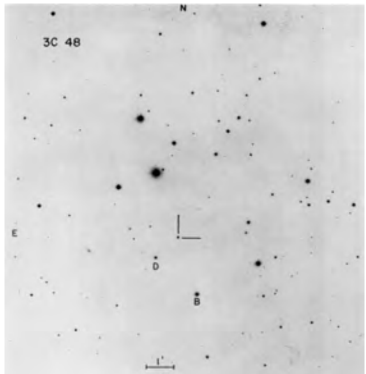

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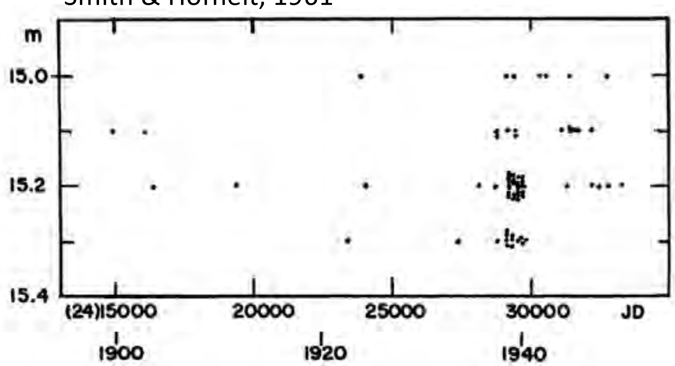
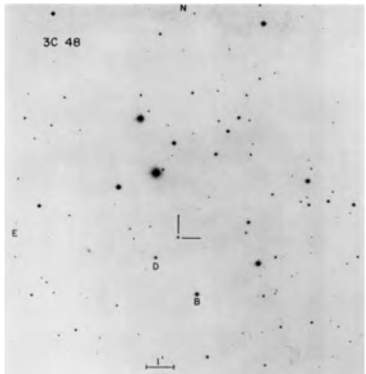


The first AGN light curve!

A brief history of AGN variability



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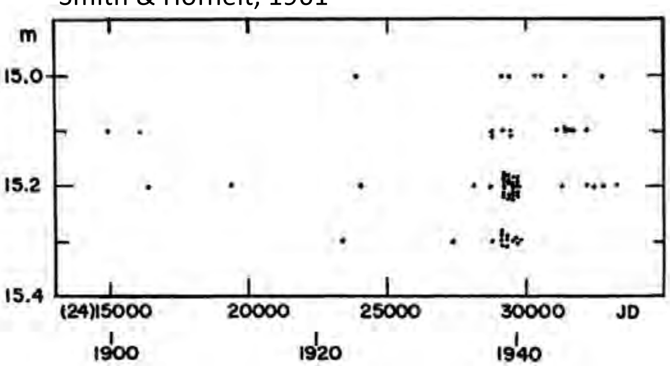


The first AGN light curve!

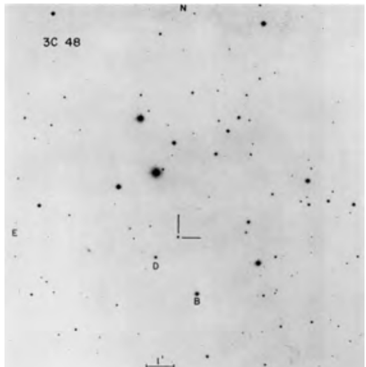
BL Lac

Bezeichnung	Ort 1855	Größen	Art des Lichtwechsels	Bem.
345.1929 Cyg	21h48m.2 +49° 14′	13m–<16m	Mira	
346.1929 »	48.3 +45 43	13.5–<15.5	Algol?	95
347.1929 »	49.9 +49 49	10.5– 11.5	langs. ver.	96
348.1929 »	50.4 +47 40	12 –<15.5	Mira	97
349.1929 »	50.7 +47 21	14 –<16	»	
350.1929 »	51.2 +48 9	12.5–<16	»	
351.1929 »	52.1 +44 52	12.5– 13.5	langs. ver.	
352.1929 »	52.1 +43 45	13 – 14.5	» »	
353.1929 »	52.3 +48 54	14.5– 15.5	» »	98
354.1929 »	52.5 +46 15	13 – 14	Algol	
355.1929 »	52.5 +45 12	11 –<15.5	Mira	
356.1929 »	52.9 +52 41	12 –<16	»	99
Ross 126 »	53.3 +45 28	12 –<16	»	
357.1929 »	53.3 +45 16	13 – 15.5	langperiod.	
358.1929 »	53.5 +44 0	13 – 14	Algol	
359.1929 »	54.0 +51 17	12 – 13	langs. ver.	100
360.1929 Lac	54.8 +42 3	12.5– 13.5	» »	
361.1929 Cyg	55.7 +49 36	13 – 14.5	langperiod.	
64.1919 »	56.0 +48 48	14.5– 16	langs. ver.	101
362.1929 Lac	56.3 +42 53	13 – 14	» »	102
363.1929 »	56.7 +41 34	13 – 15	kurzperiod.	
Ross 91 Cep	56.9 +56 17	11 –<15	Mira	

am Orte $21^h 51^m 11^s$ $+47° 45'.5$ (1875.0) erscheinen. — 98. Schwach von Juli bis Sept. 1928. — 99. Periode wahrscheinlich etwa 400^d. — 100. Rötlich. — 101. Rötlich. — 102. Stark rot. — 103. Nicht raschwechselnd; anscheinend rötlich. — 104. Hell im März und im Okt. und Nov. 1928; rötlich. — 105. Hell im Aug. 1927, im Sept. Abnahme, schwach im Dez., hell von Febr. bis Juli 1928, im Aug. Abnahme, anfangs Nov. noch schwach. — 106. Schwach 1926 und 1927; zunehmend im Dez. 1927; im Jahre 1928 meist hell, zeitweise schwach, besonders im April und August. — 107. Periode etwa 1 Jahr, Maxima im Winter.

Sonneberg, 1929 Juli 4. *C. Hoffmeister.*

A brief history of AGN variability



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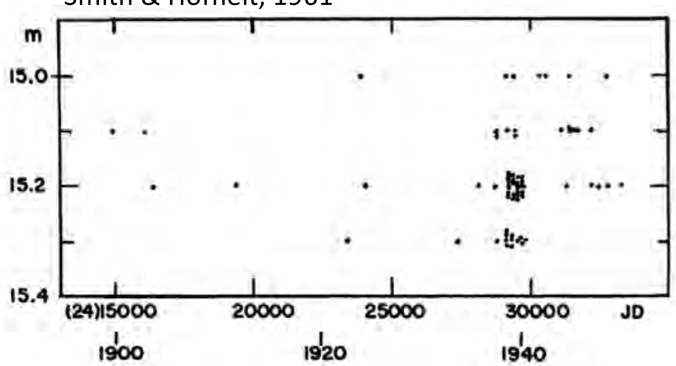
A second-
with the 48-
tered identic
21/22, 1949
tor showed
proper moti
method).
Optical p
given in Ta
varies! Unfo

So what type of variability do AGN show?

98
99
100
101
102

Smith & Hoffleit, 1961



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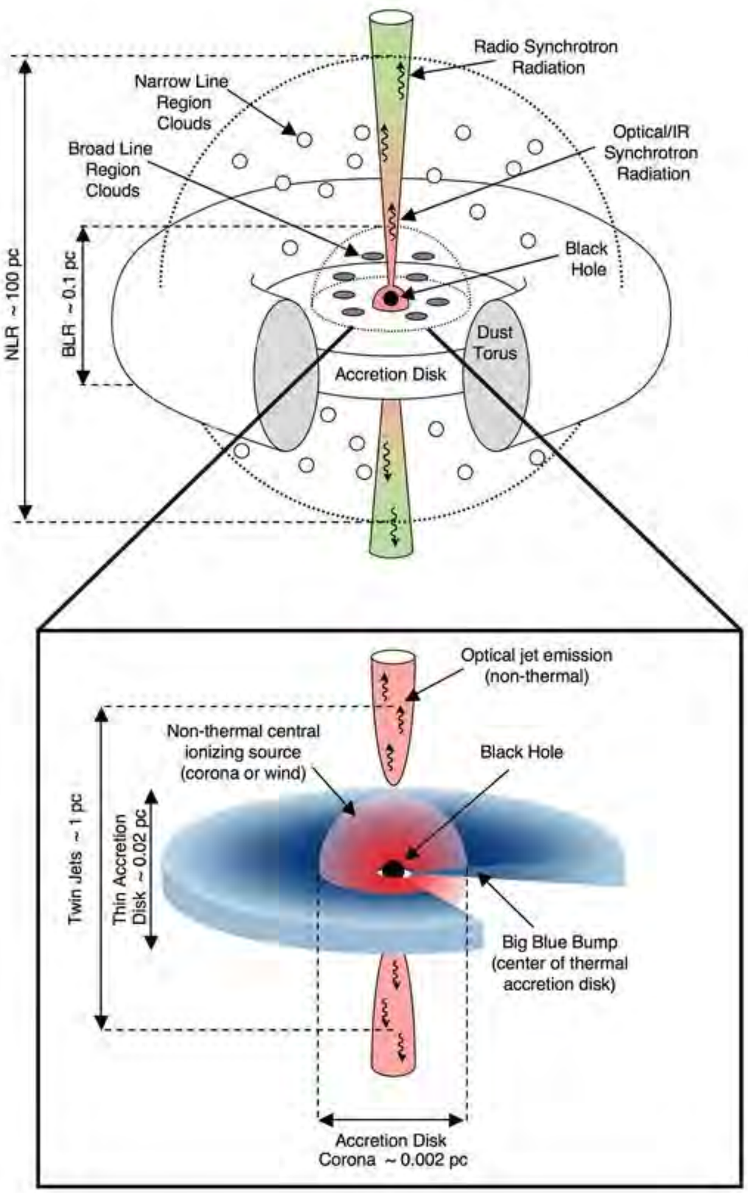
Our standard “unified” model



	Accretion Disk	Broad Line Region
Viscous (“radial drift”)	10,000 yr	-
Light travel	Hours	Days
Dynamical	Days	Years
Thermal	Days-years	-

1973: The Shakura-Sunyaev model describes an geometrically thin but optically thick accretion disk where local viscosity allows inward radial drift of material. It provides an overall steady state temperature profile of the disk.

The simplest model

Based on 100 poorly sampled time series, Kelly (2009) proposed:

$$dX(t) = -\frac{1}{\tau}X(t)dt + \sigma\sqrt{dt}\varepsilon(t) + b dt \quad \tau,\sigma,\mathrm{t} > 0$$

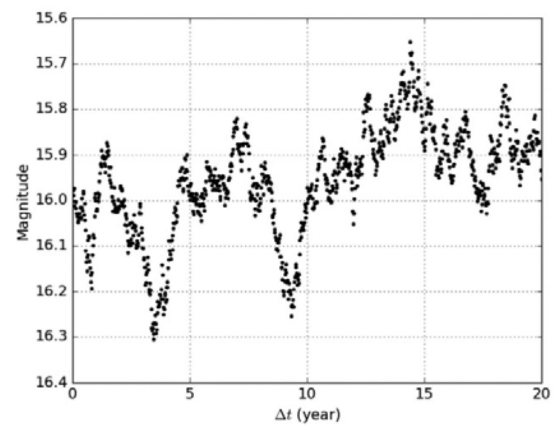
DRW
OU
CARMA(1,0)

but:

- it gives the wrong power spectrum slope on short timescales (< 50 days) – Kepler, TESS, etc.
- it is linear, stationary, reversible, trendless
- it does not describe the correct background in periodicity searches [REF]
- it is not the optimal solution in 2024 (millions of AGN time series)

Technically, as a statistical model:

- Suffers from biased parameter estimation
  - baseline $\gtrsim 10\tau$ (30τ) to recover τ
- Degenerate (Kozlowski 2016) -> Wold's theorem
- CARMA -> CARIMA -> CARFIMA -> …



A phenomenological taxonomy

Micro TDE

Tick-Tock

Microlensing

Warped disk

Non-linear behavior

Supernova

TDE

Ionization instability

Disk crosser

Compact object merger

Magnetic instability

SMBH binary

Partial TDE

Obscuration event

Gas cloud

Retrograde

QPO-I

GRB

ANT

Baratheon

QPE

Bowen fluorescence flare

QPO-II

Prograde

Changing-look

Stochastic variability

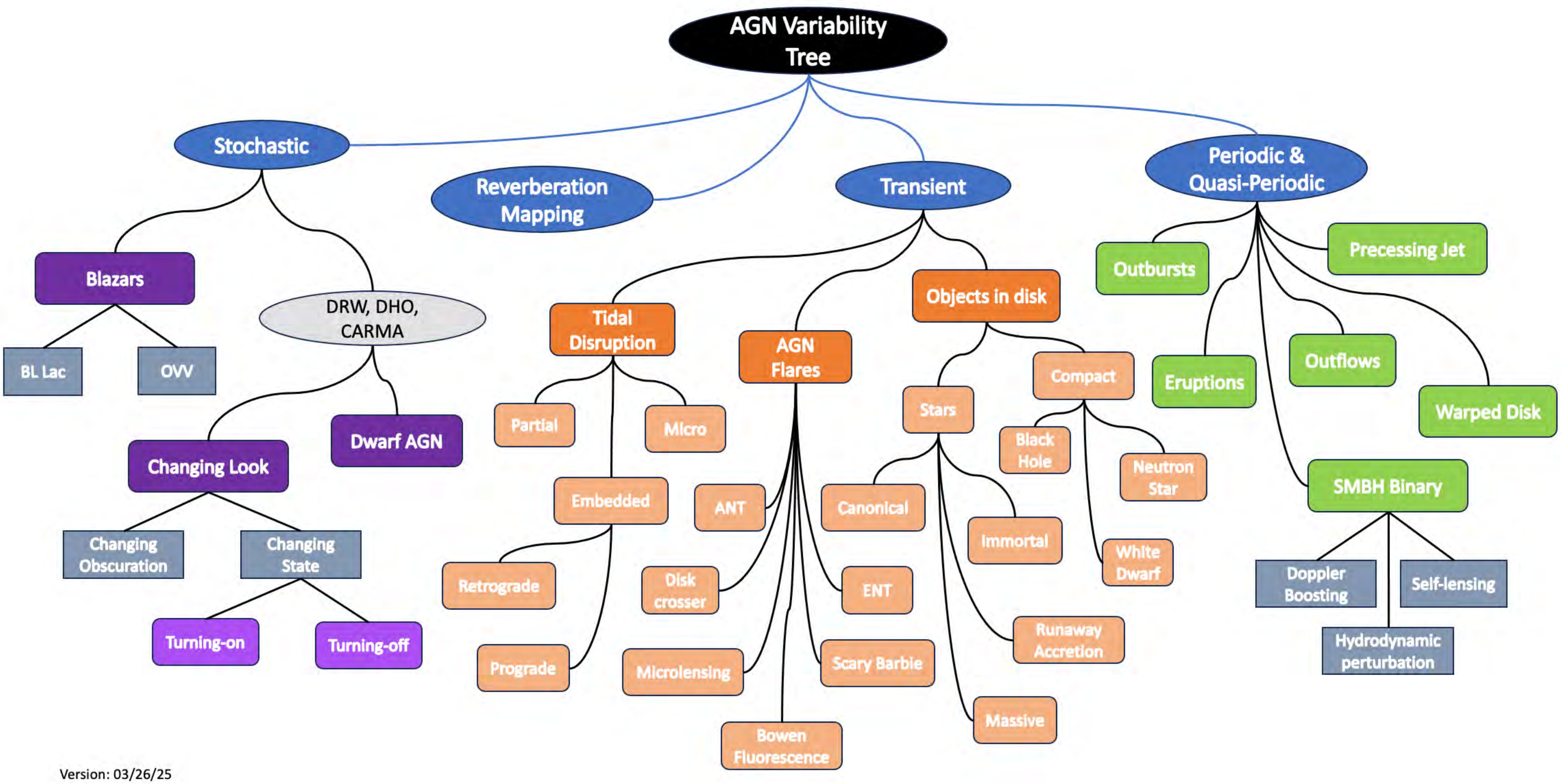
Nonstationarity

Scary Barbie

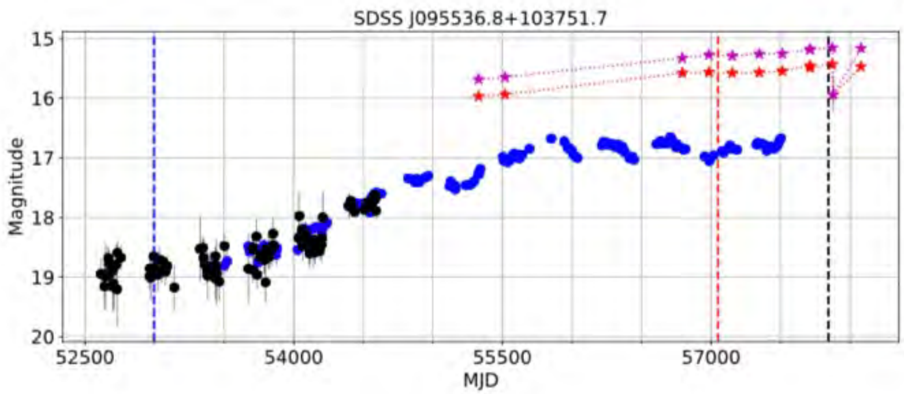
Changing-state

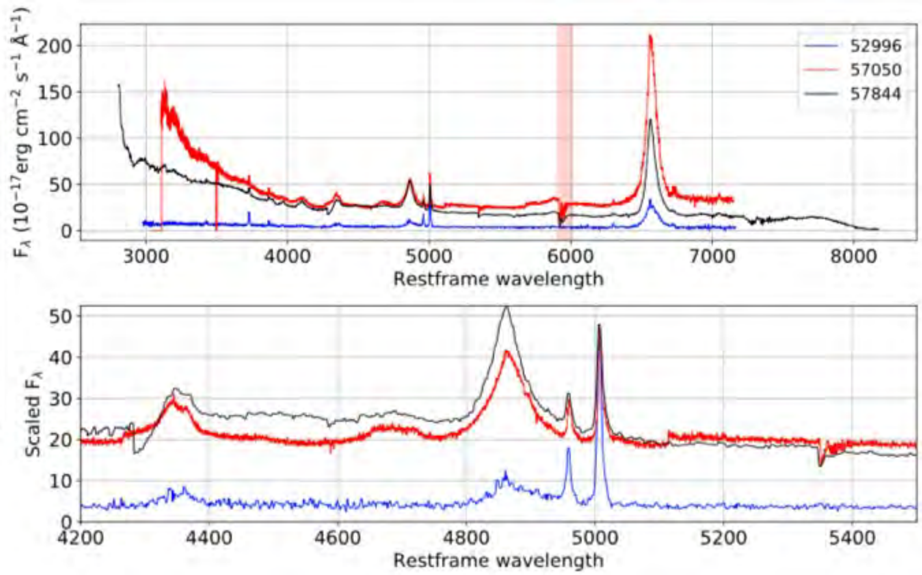
CARMA

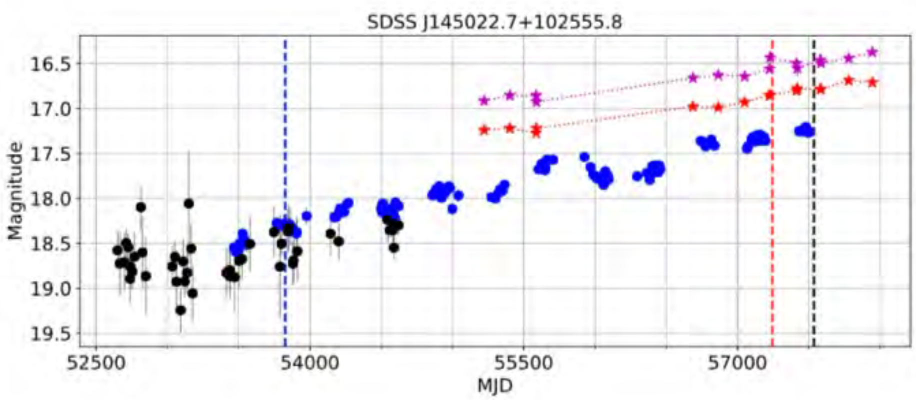
A first attempt at order

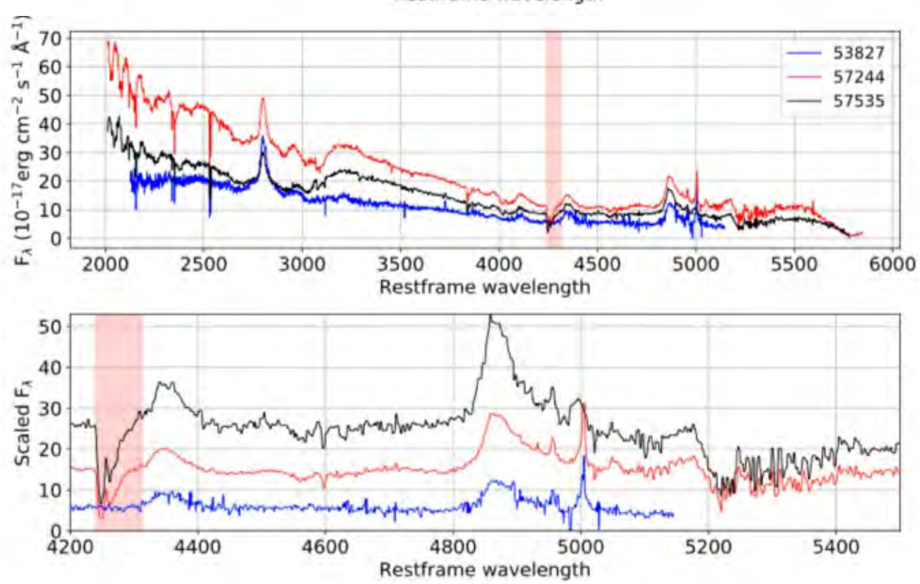


AGN getting brighter…

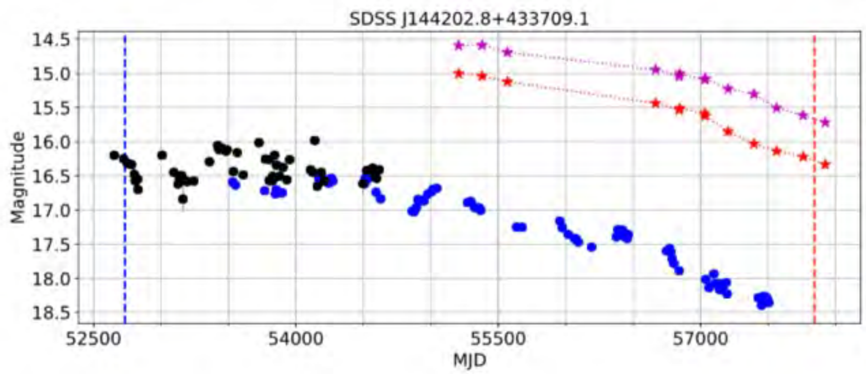


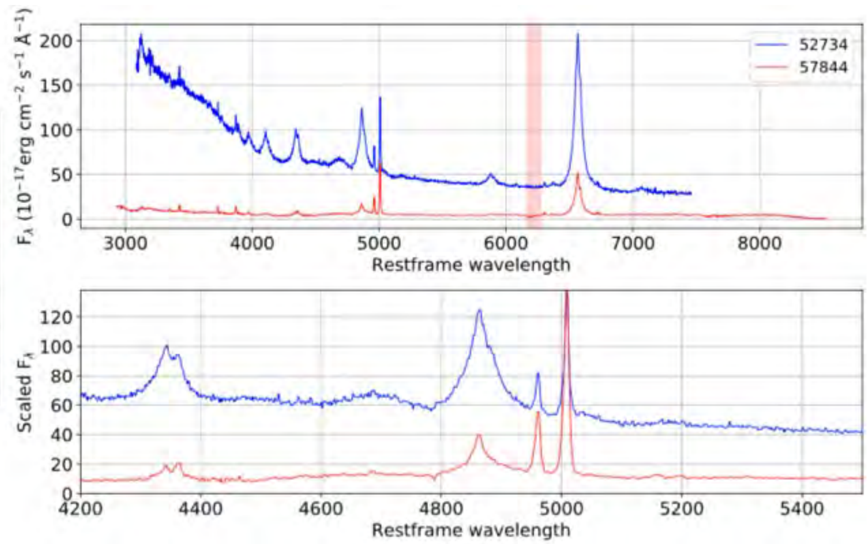


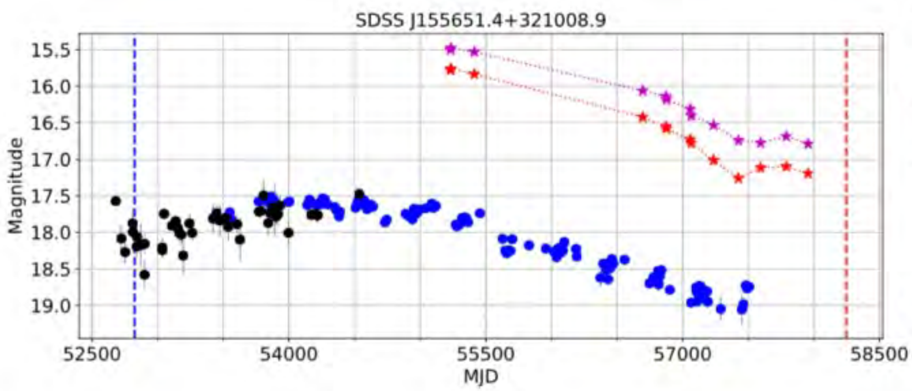


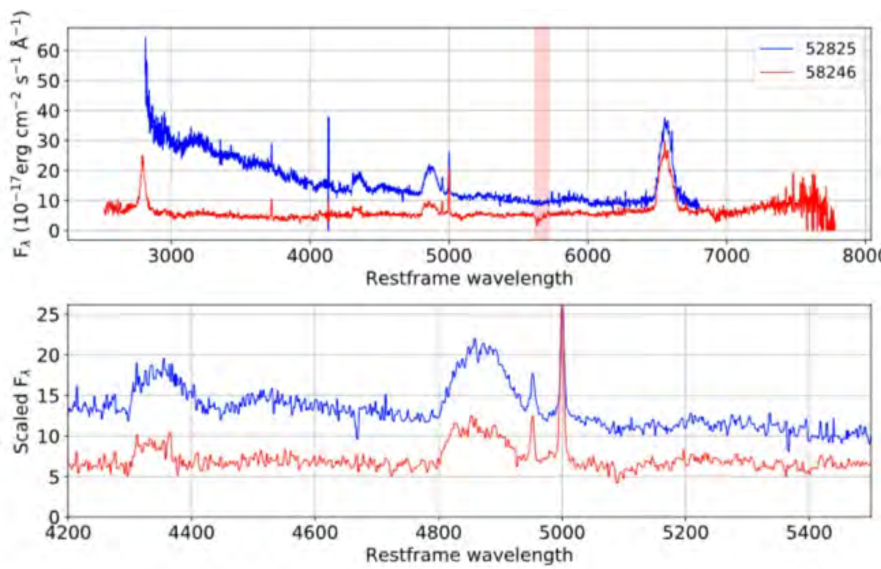


… and dimmer


SDSS J144202.8+433709.1
Magnitude
MJD
14.5
15.0
15.5
16.0
16.5
17.0
17.5
18.0
18.5
52500
54000
55500
57000

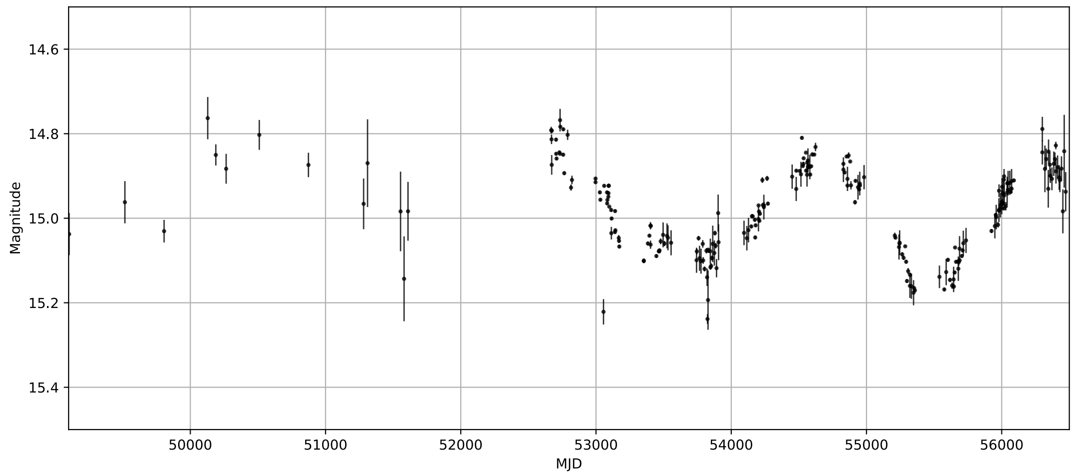

52734
57844
F_λ (10^{-17}erg cm^{-2} s^{-1} Å^{-1})
Restframe wavelength
Scaled F_λ
Restframe wavelength


SDSS J155651.4+321008.9
Magnitude
MJD
15.5
16.0
16.5
17.0
17.5
18.0
18.5
19.0
52500
54000
55500
57000
58500


52825
58246
F_λ (10^{-17}erg cm^{-2} s^{-1} Å^{-1})
Restframe wavelength
Scaled F_λ
Restframe wavelength

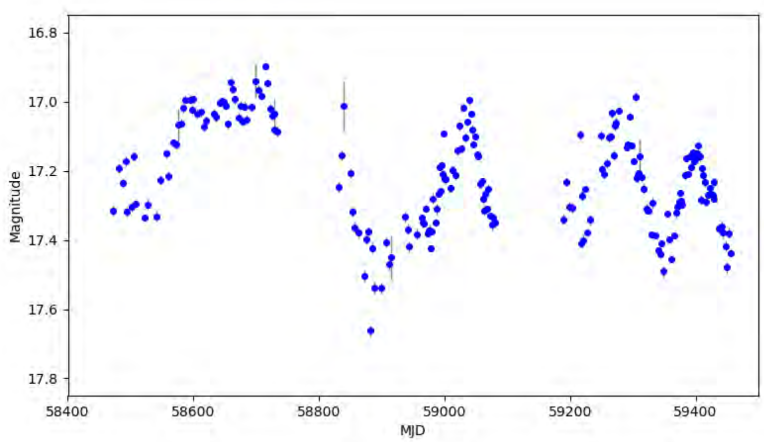
Periodicity

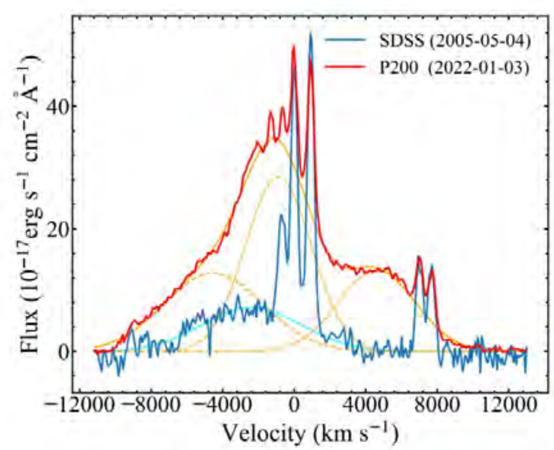
PG 1302-102:



+110 other candidates (Graham+ 2015)

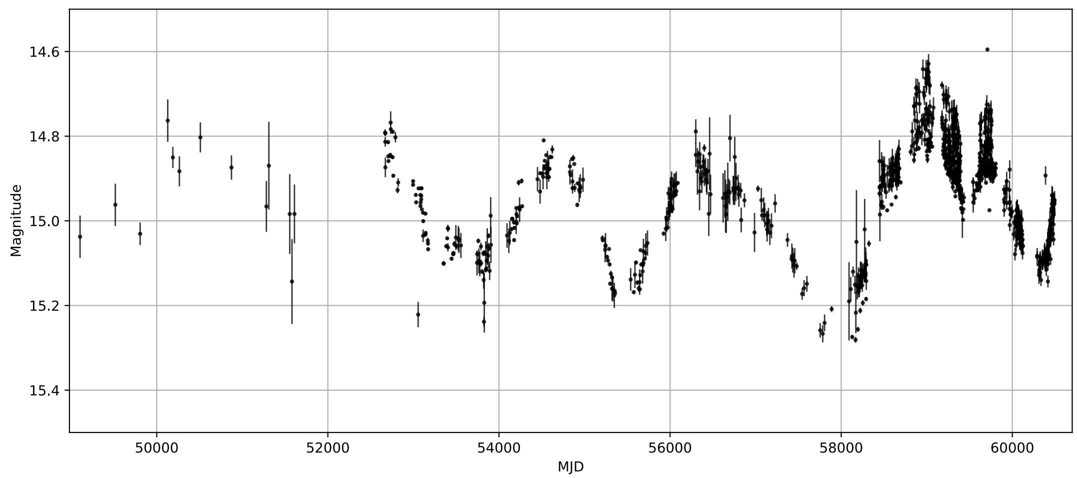
Tick-tock (J143016+230344):





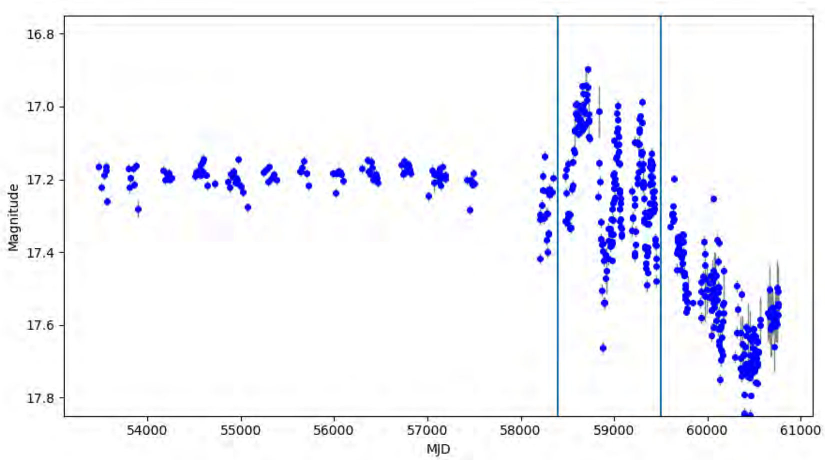
Periodicity (lots of mirages)

PG 1302-102:



>90% no longer viable

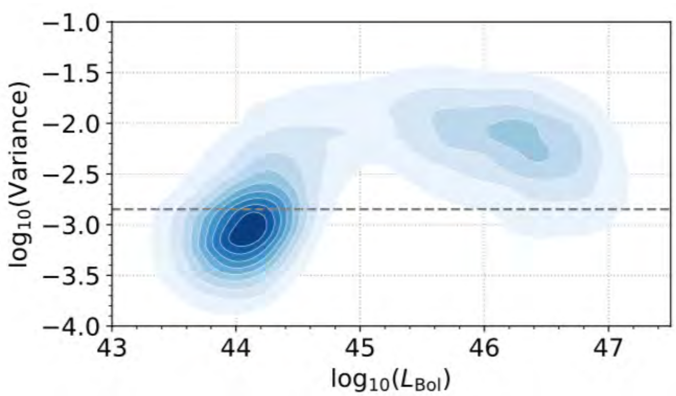
Tick-tock (J143016+230344):



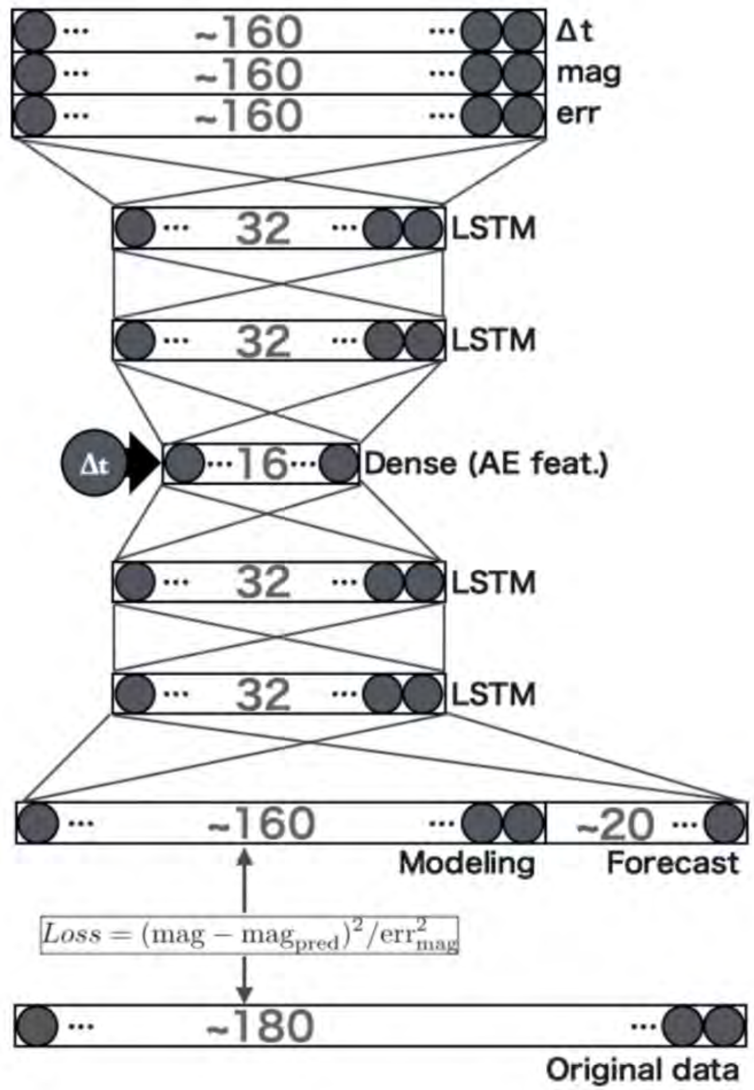
many disk emitters
show three or four peaks

Deep modelling of AGN time series

- Autoencoder model with RNN autoencoder:
  - Consider: $(y_0, \Delta t_0) \bigoplus (\Delta t_0) \rightarrow y_1$
  - Consider: $(y_0, \Delta t_1, \dot{y}_0, \ddot{y}_0) \rightarrow y_1$



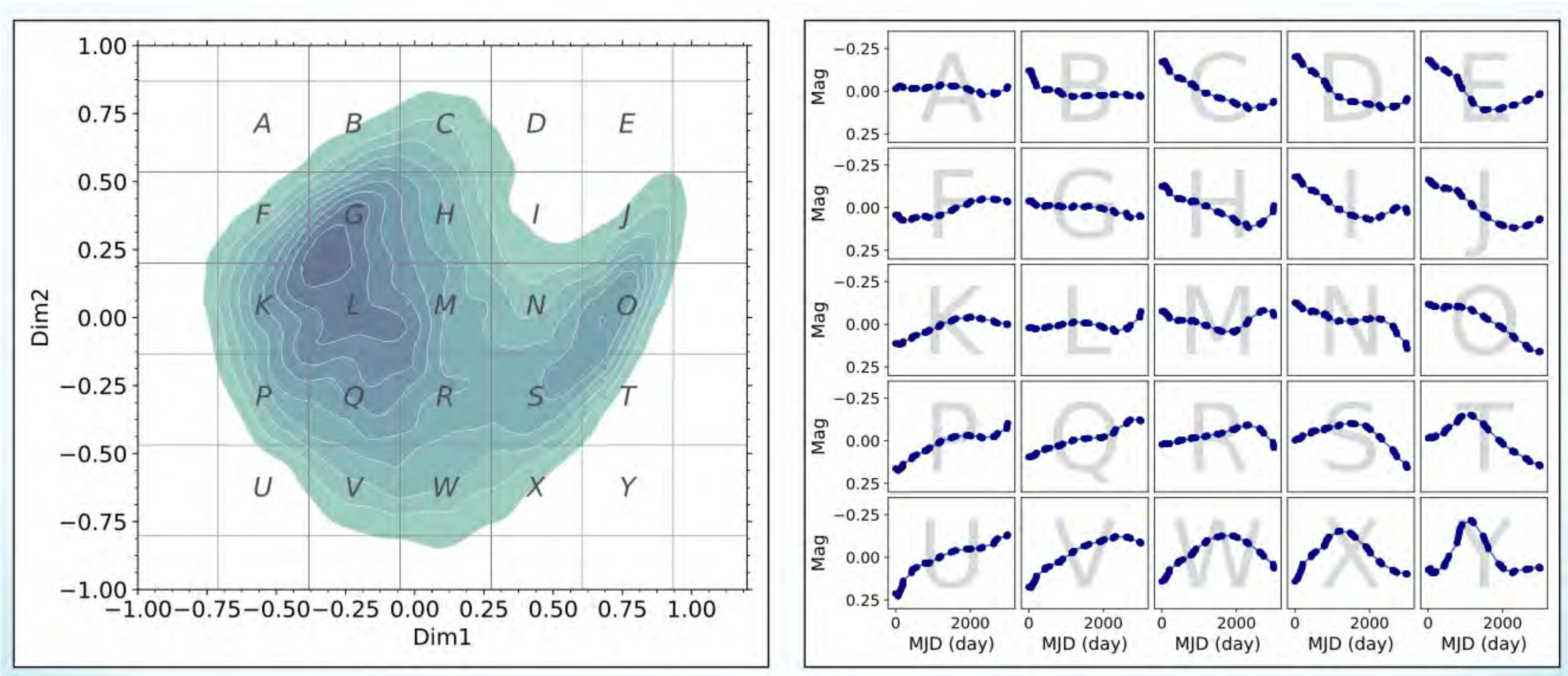
- 12,000 quasars with $\Delta t = 500$ days



Tachibana+ 2020

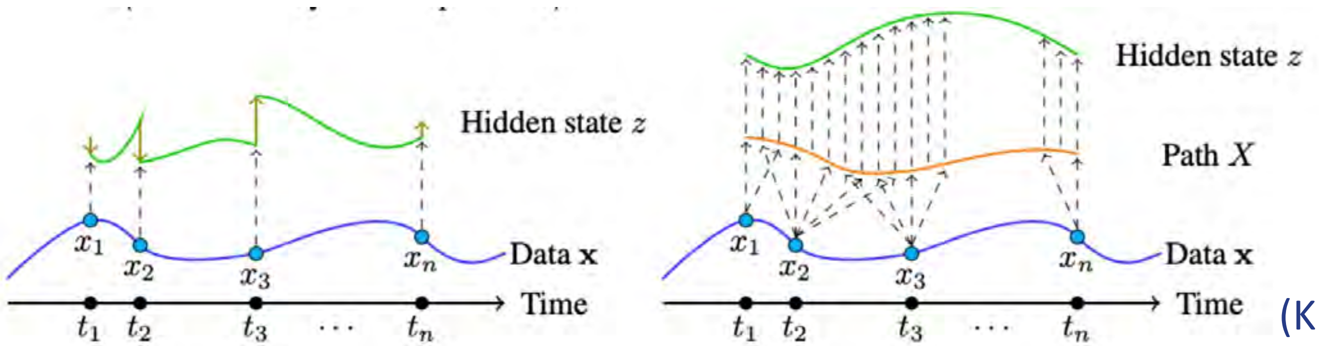
Deep time series features

Is the low dimension representation meaningful?

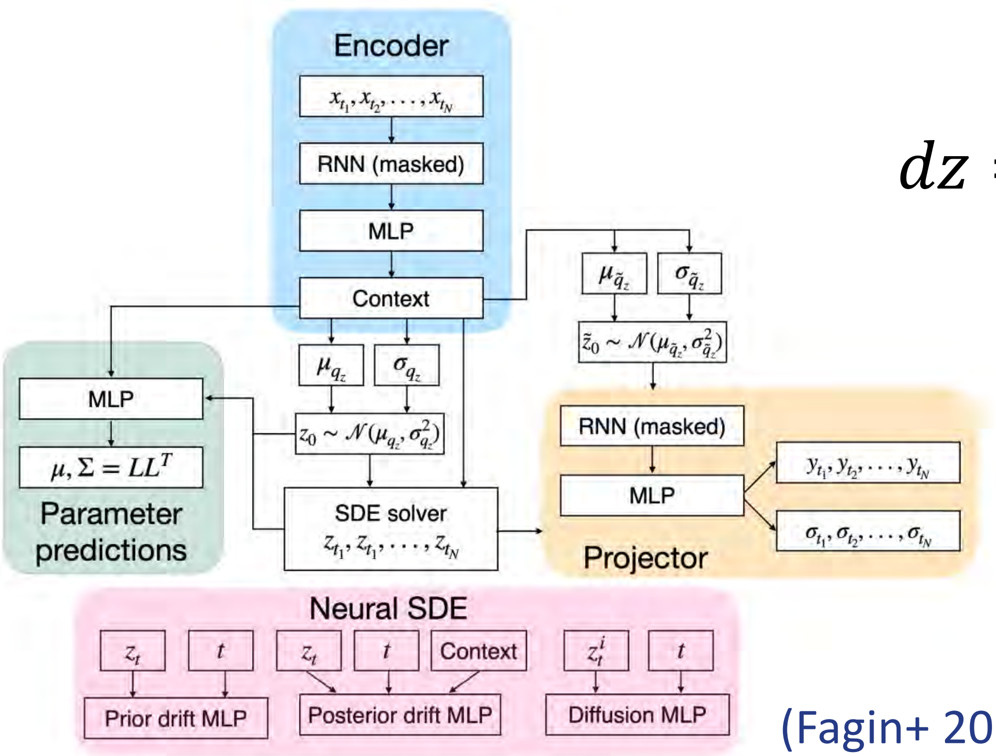


What about an infinite stochastic latent space?

- Latent SDEs to model AGN variability



(Kidger+ 2020)



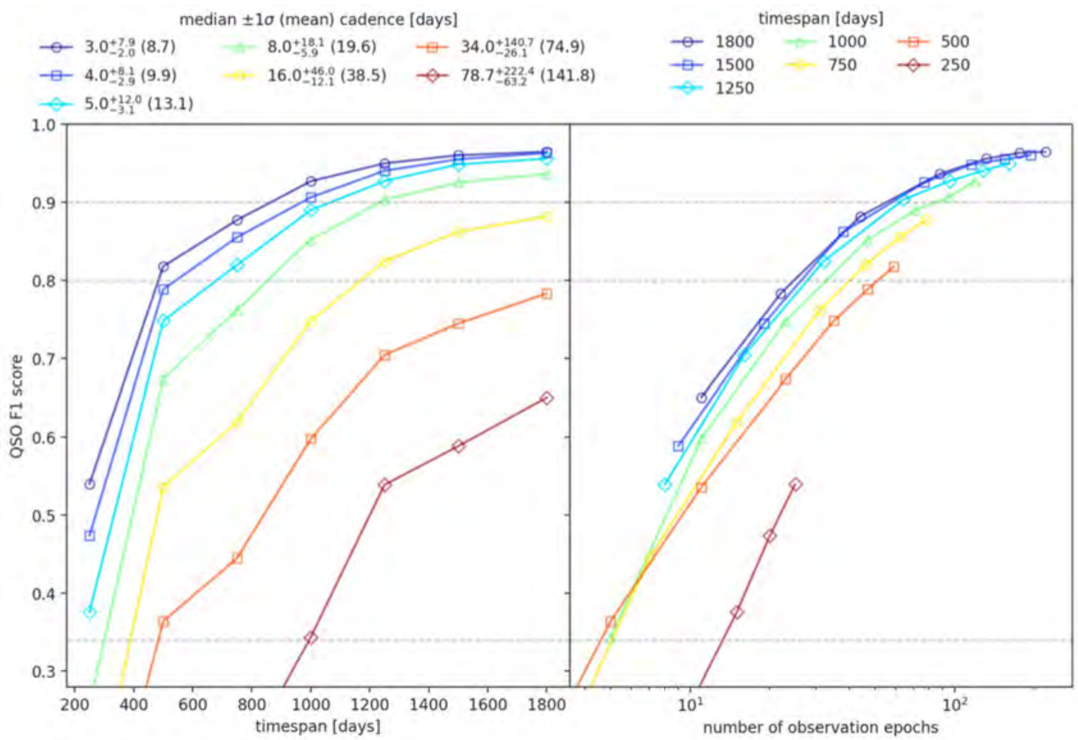
$$dz = \mu(z,t)dt + \sigma(z,t)dW_t$$

Train to output light curves and process/model/physical parameters

(Fagin+ 2024a)

QZO: the ZTF AGN Catalog

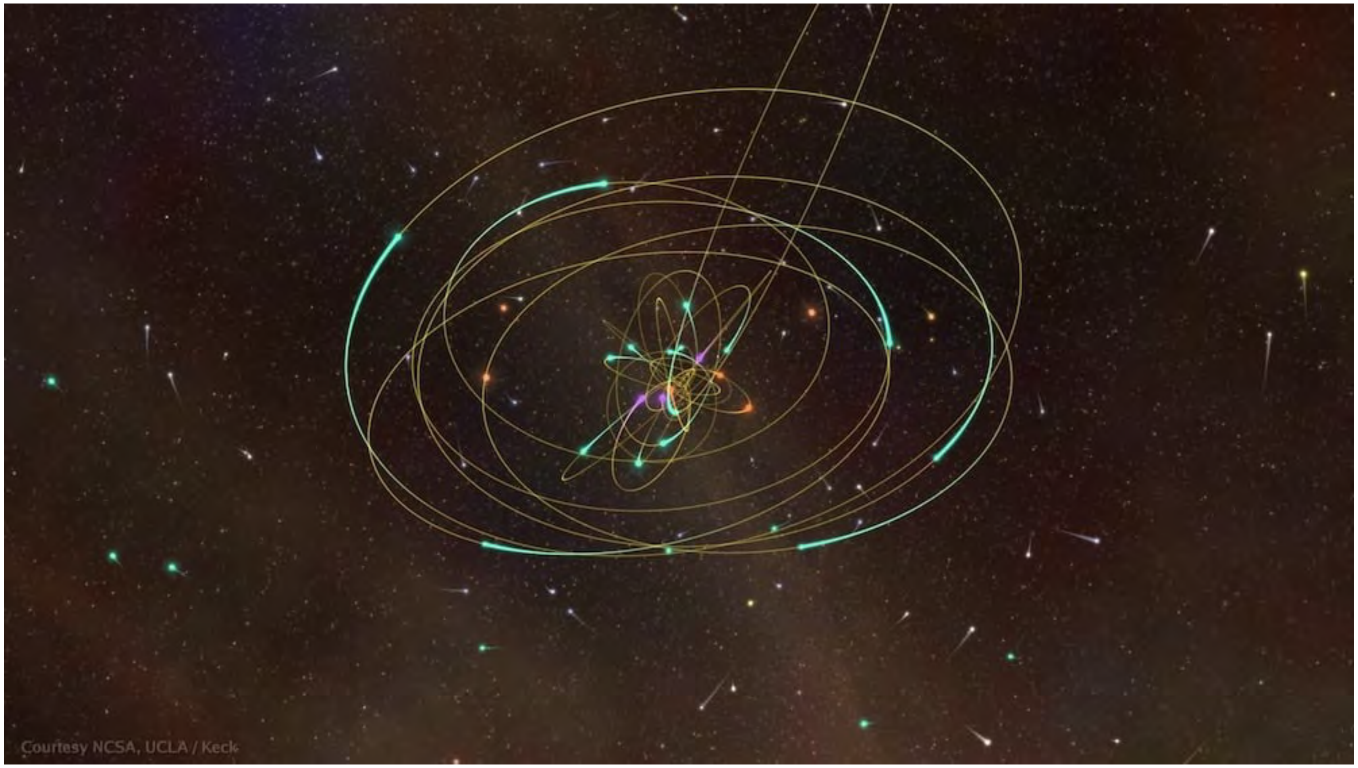
- Uses Astromer with fine tuning for classification
- ZTF DR20 (Jan 2024) *g*-band data: 789M objects for inference
- Training data set: 483k (*g*) and 665k (*r*) – 47%/25%/28% gal/qso/star
- Ensemble with XGBoost with WISE survey data: variability features most important
- 4.8M sources with F1 > 97% for $g < n_{obs}/80 + 20.375$
- Photo-z for 33% with WISE data: $\Delta z/1+z = 0.14$
- F1 = 90% with 3 day cadence and 900 day baseline or 12 day cadence and 1800 day baseline



Nakoneczny+ 2025

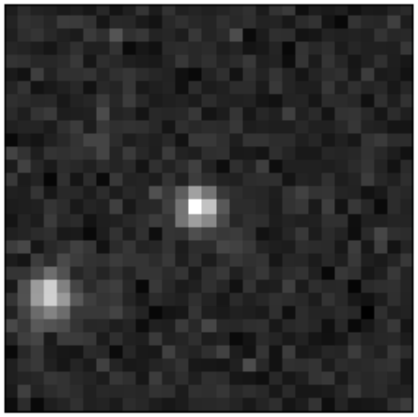
The missing component: environment

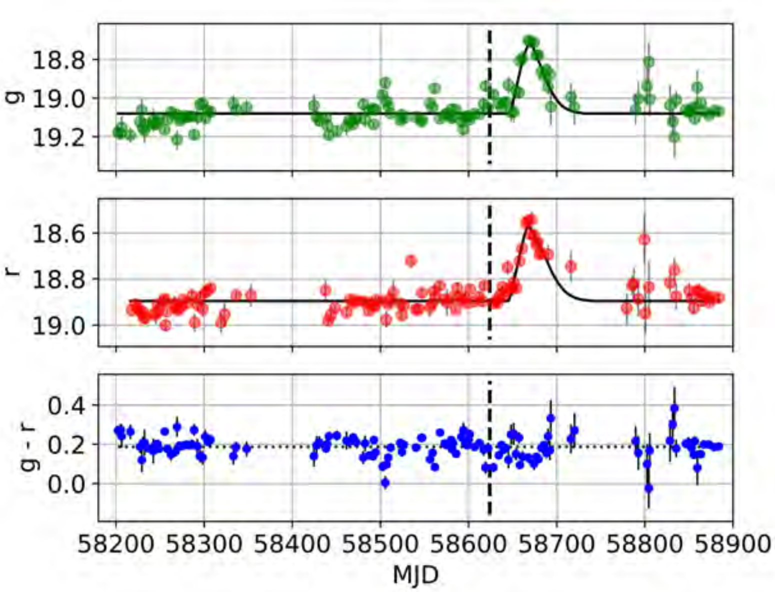
- The primary driver of AGN as transient sources and flares

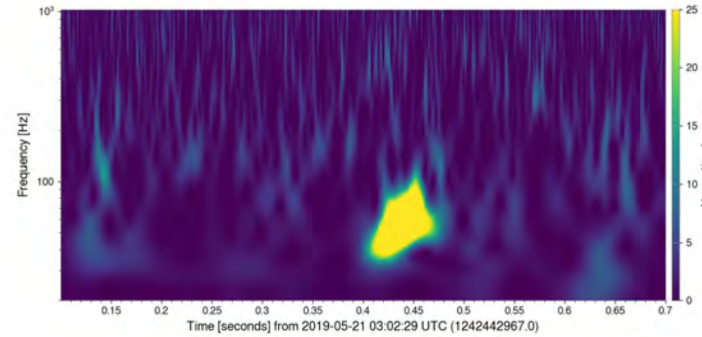


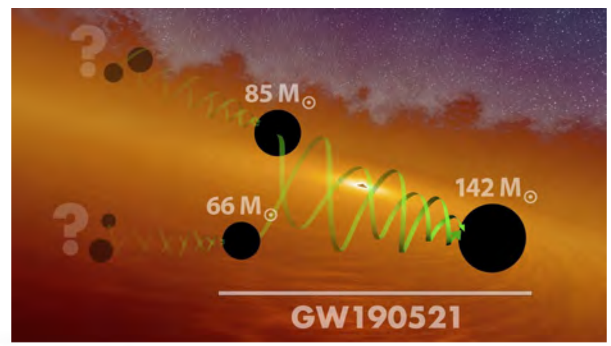
UCLA/NASA

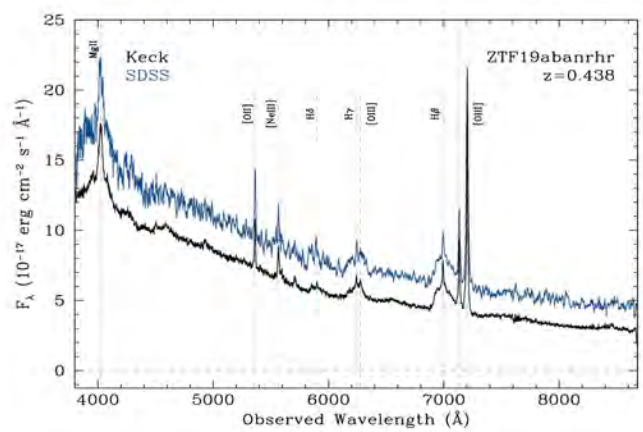
Merging BBHs in the accretion disk









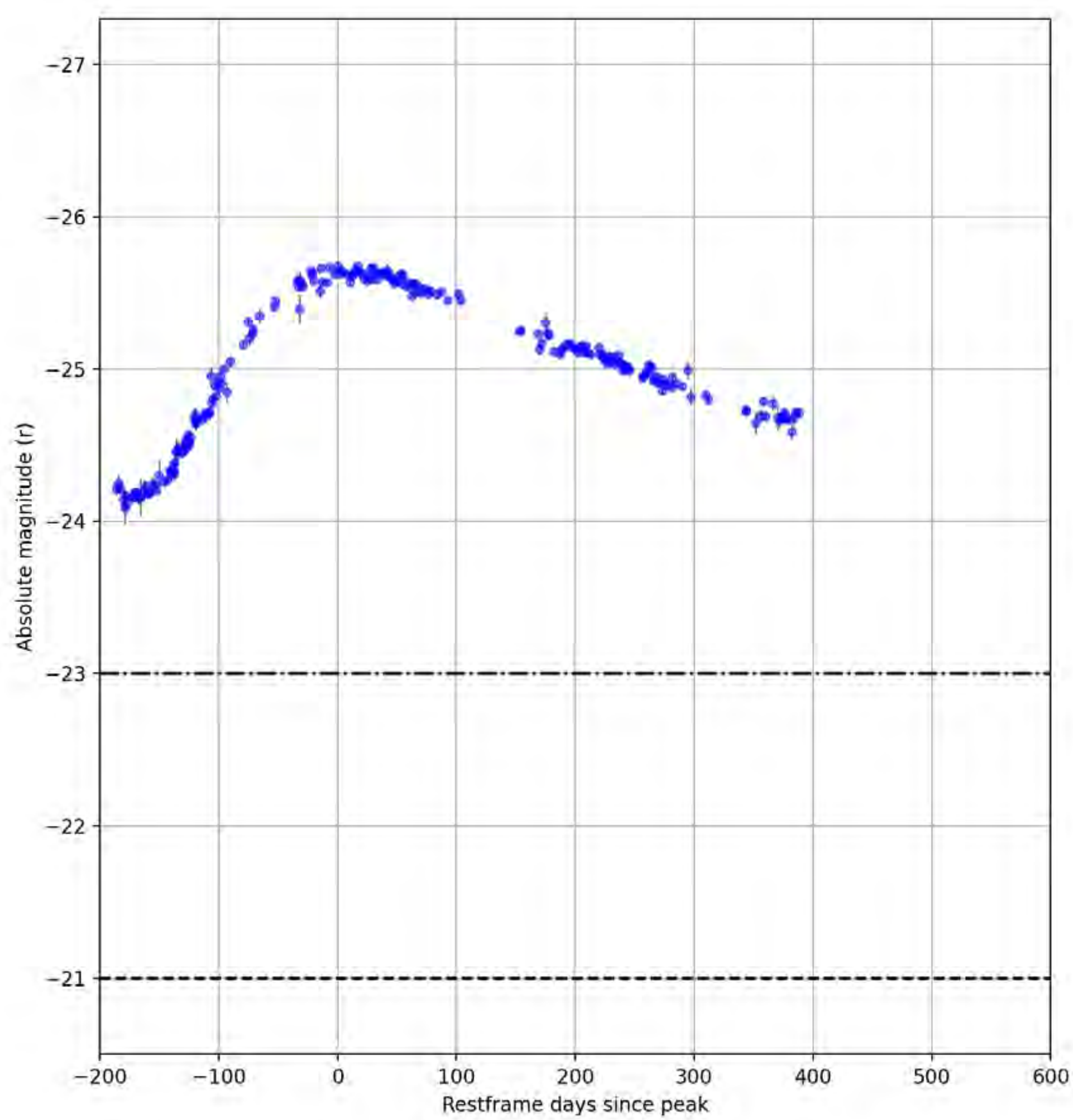


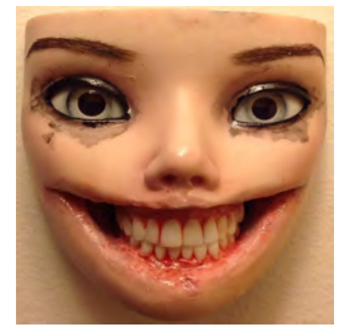
The biggest bang: ZTF20abrbeie

z = 0.995
log L = 45.7 erg/s
E = 1.5 x 10^{53} erg

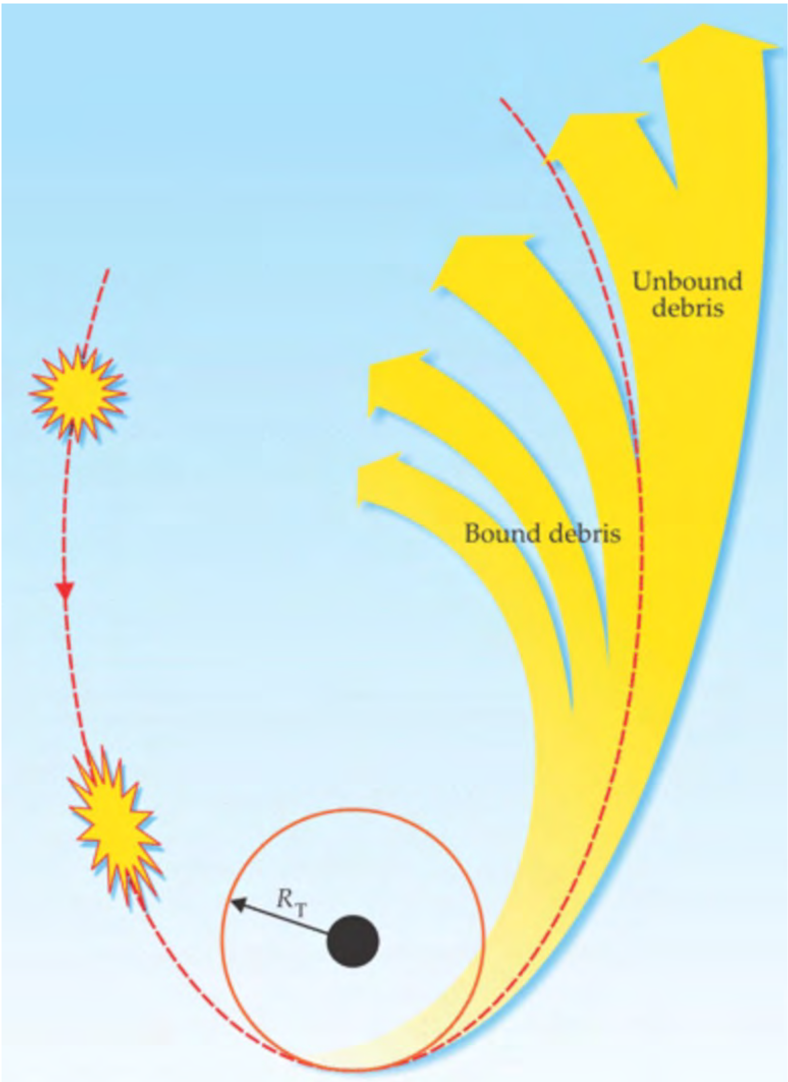
Balmer series,
low-ionization,
semi-forbidden
No [OIII]

WISE echo but no
prior WISE



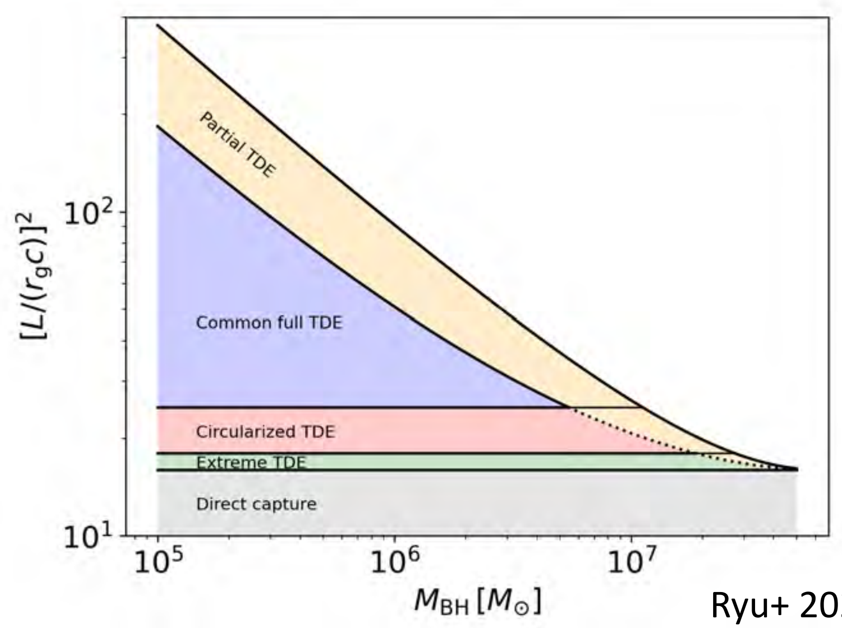


Tidal disruption events: a refresher



Gezari, 2015

- Over 100 now detected (mainly ZTF) in quiescent galaxies
- Four spectroscopic classes: H, He, H+He, featureless
- $10^5 M_\odot \lesssim M_{SMBH} \lesssim 10^8 M_\odot$
- $0.2\ M_\odot \lesssim m_* \lesssim 1\ M_\odot$
- 50% of mass unbound



Ryu+ 2022

The biggest bang: ZTF20abrbeie

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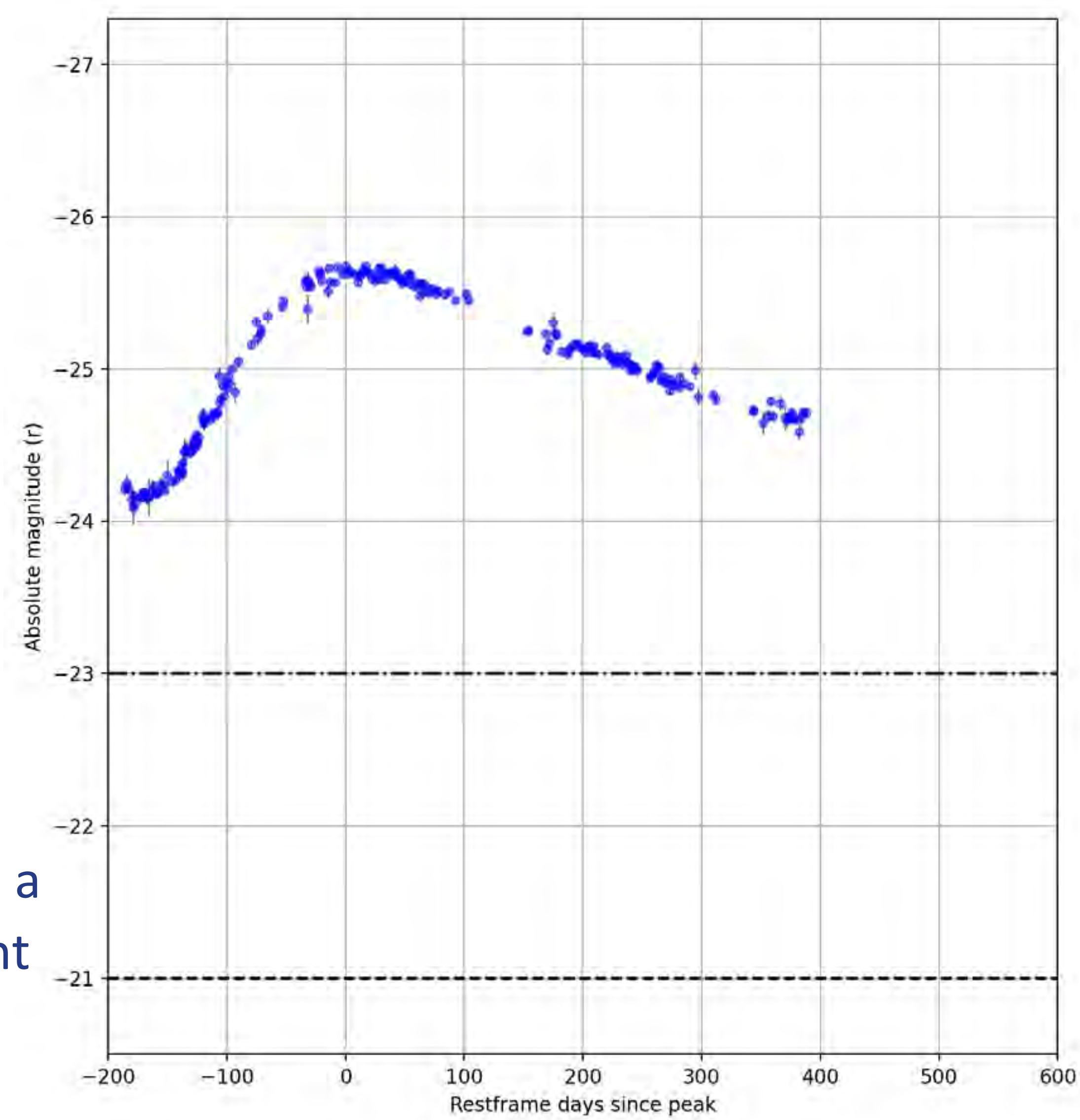
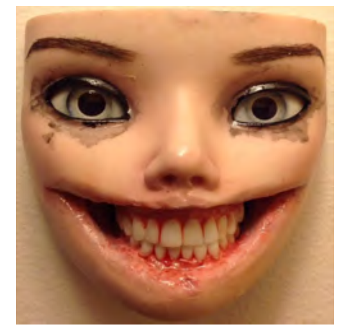
log L = 45.7 erg/s
E = 1.5 x 10^{53} erg

Balmer series,
low-ionization,
semi-forbidden
No [OIII]

WISE echo but no
prior WISE

$10^{8.2}\, M_{\odot}$ TDE with a
14 $M_{\odot}$ star or giant
molecular cloud





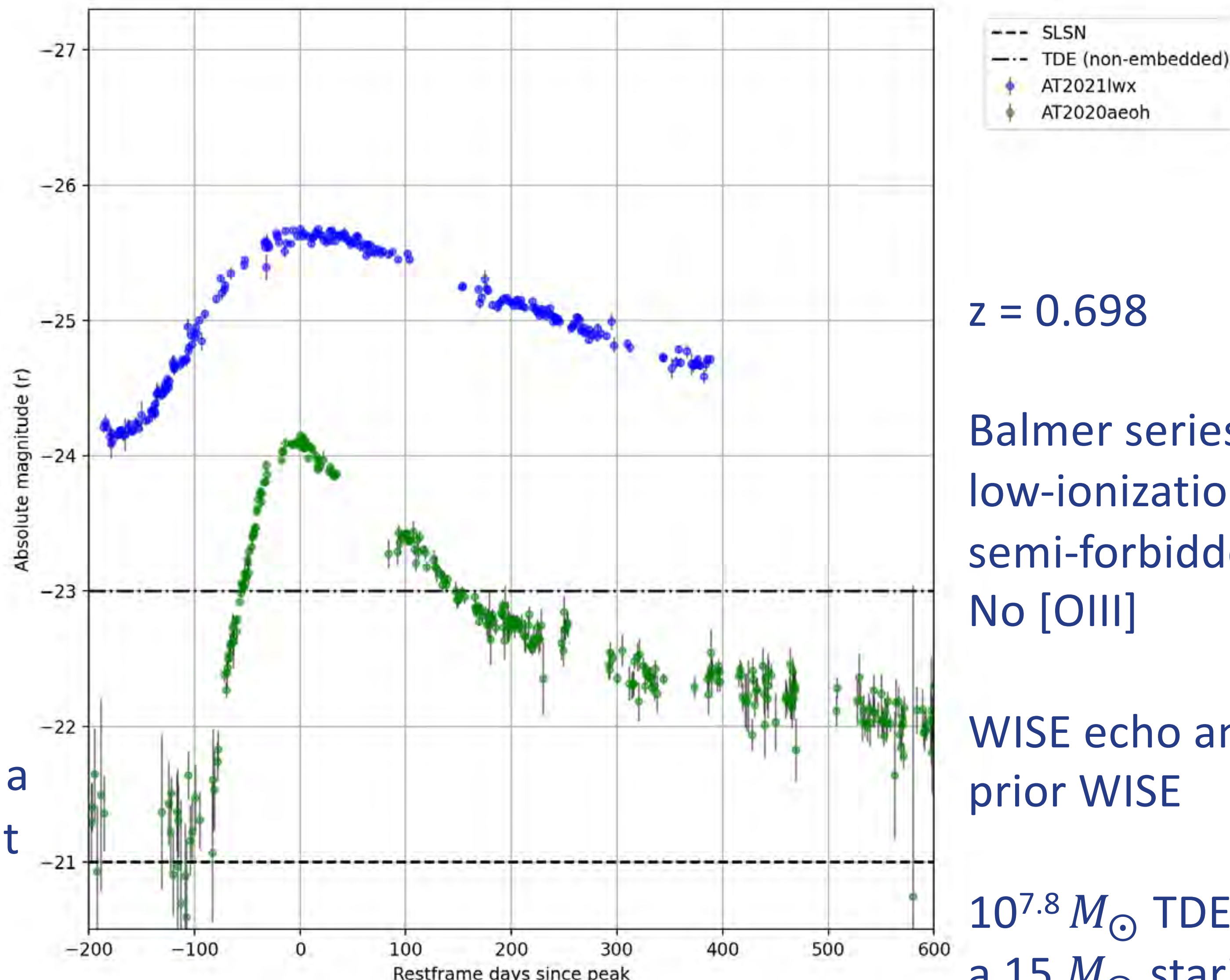
The biggest bangs: loud but different

z = 0.995
log L = 45.7 erg/s
E = 1.5 x 10^{53} erg

Balmer series, low-ionization, semi-forbidden
No [OIII]

WISE echo but no prior WISE

$10^{8.2}\,M_\odot$ TDE with a 14 $M_\odot$ star or giant molecular cloud?



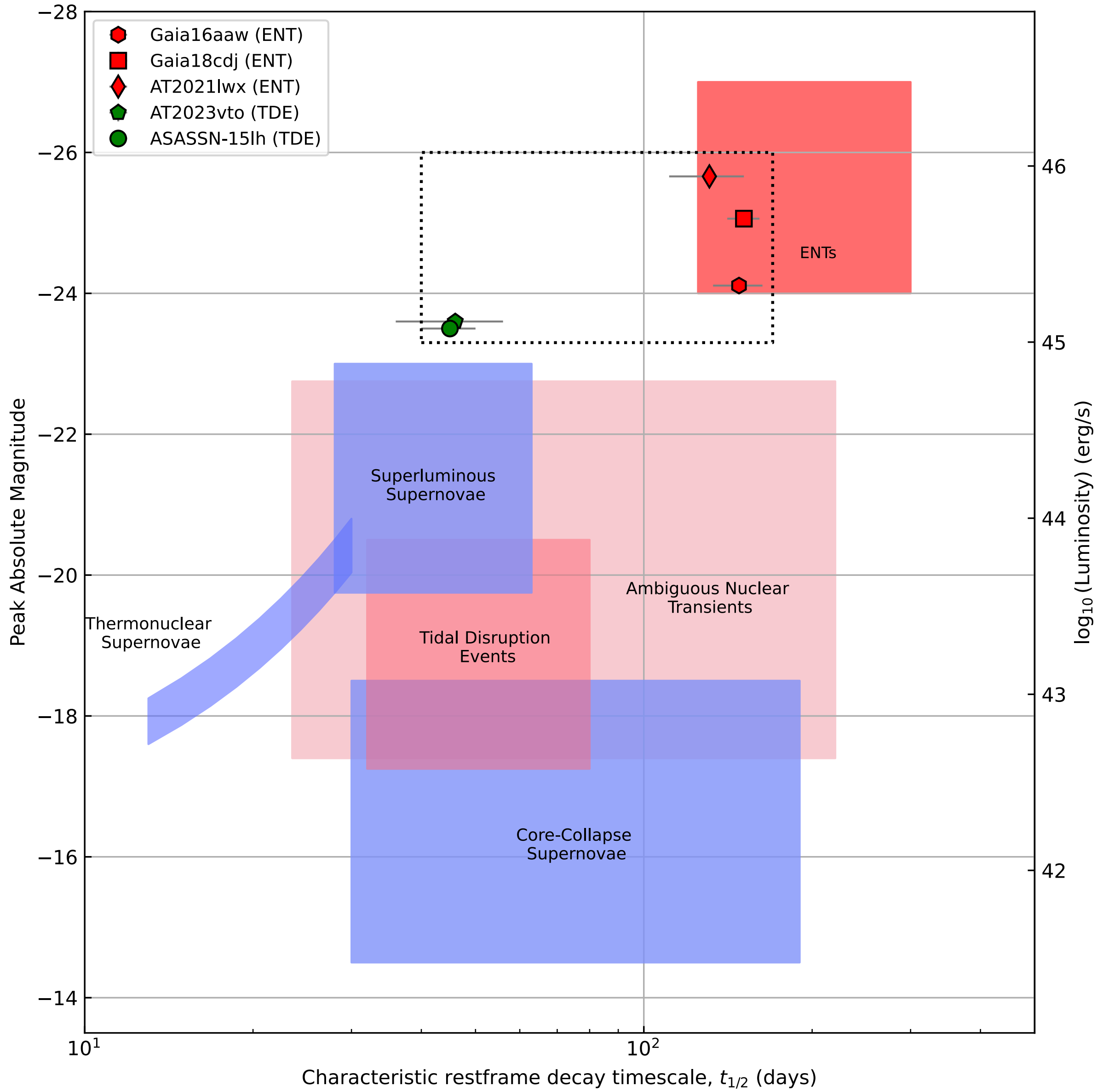
z = 0.698

Balmer series, low-ionization, semi-forbidden
No [OIII]

WISE echo and prior WISE

$10^{7.8}\,M_\odot$ TDE with a 15 $M_\odot$ star?

ENTs



After Hinkle+ 24

The biggest bangs: the brightest

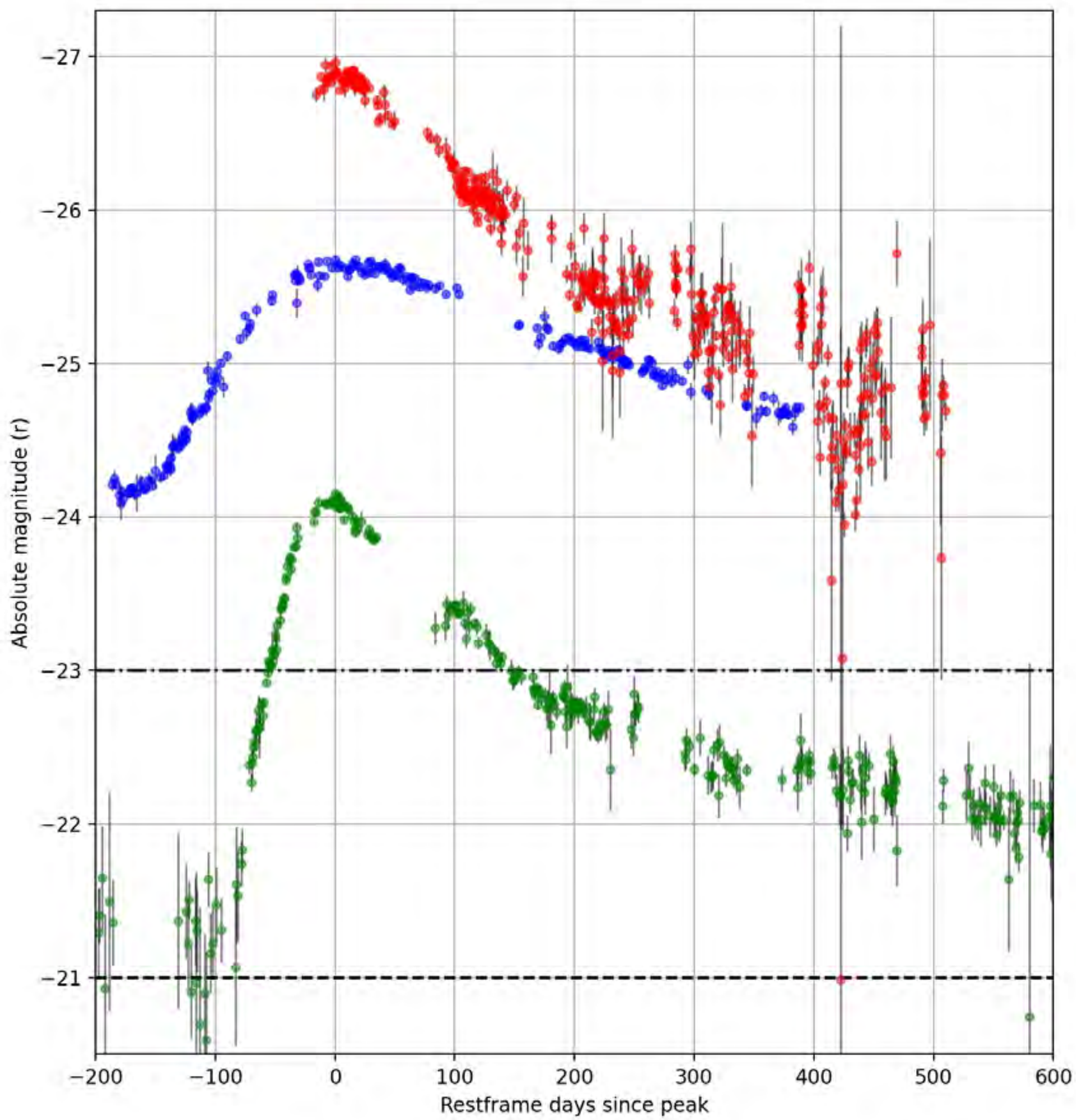
z = 2.556

Ly alpha
low-ionization,
semi-forbidden

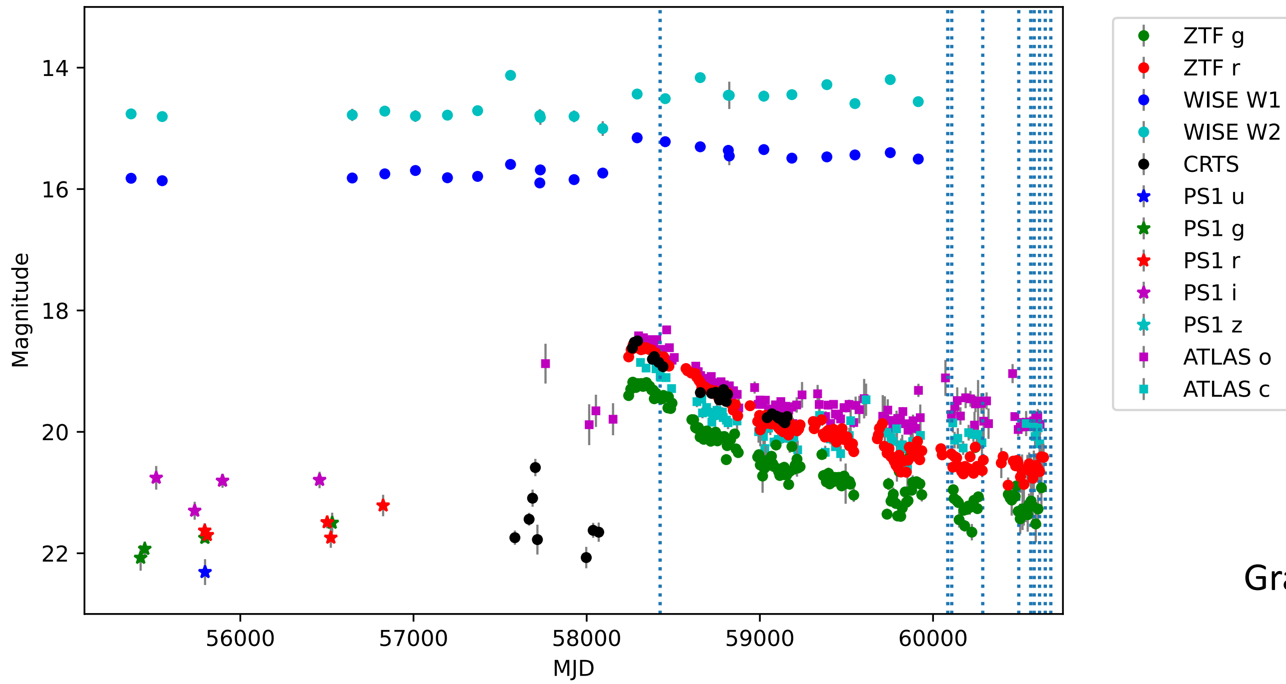
Absorption
Outflow?

WISE echo and
prior WISE

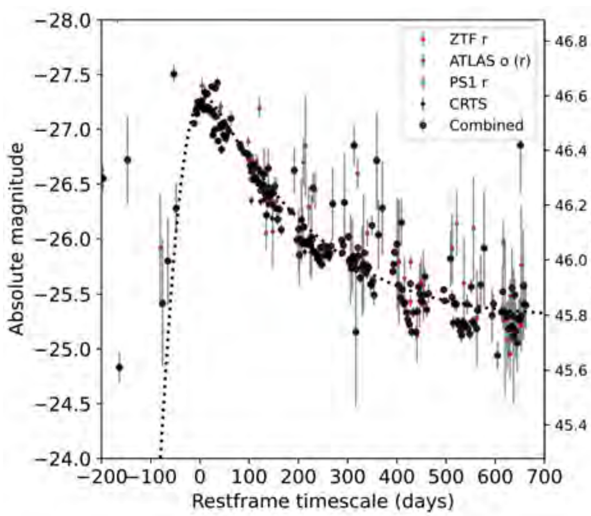
$10^{8.4}\, M_{\odot}$

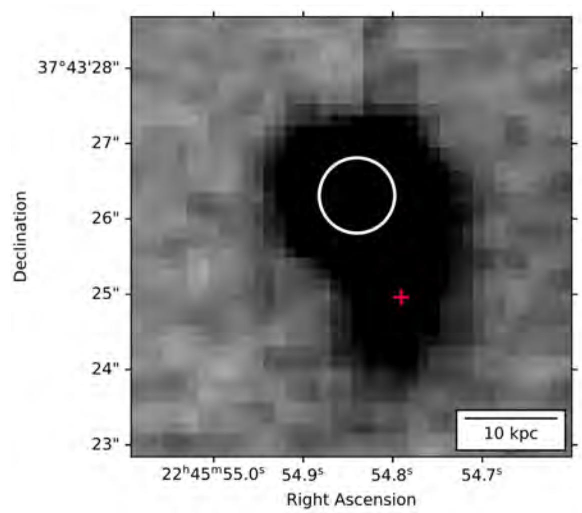


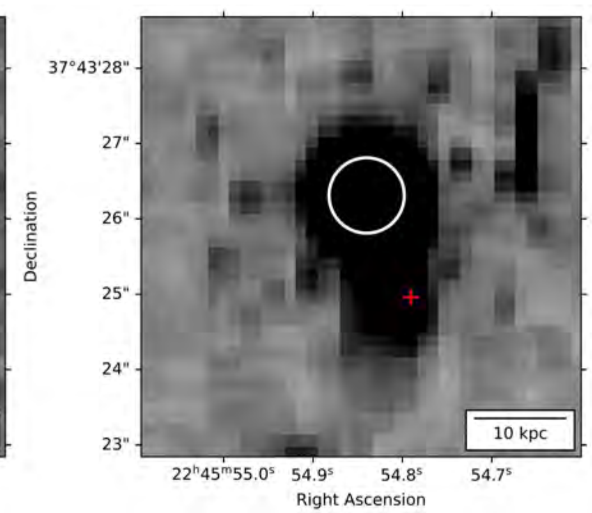
Superman



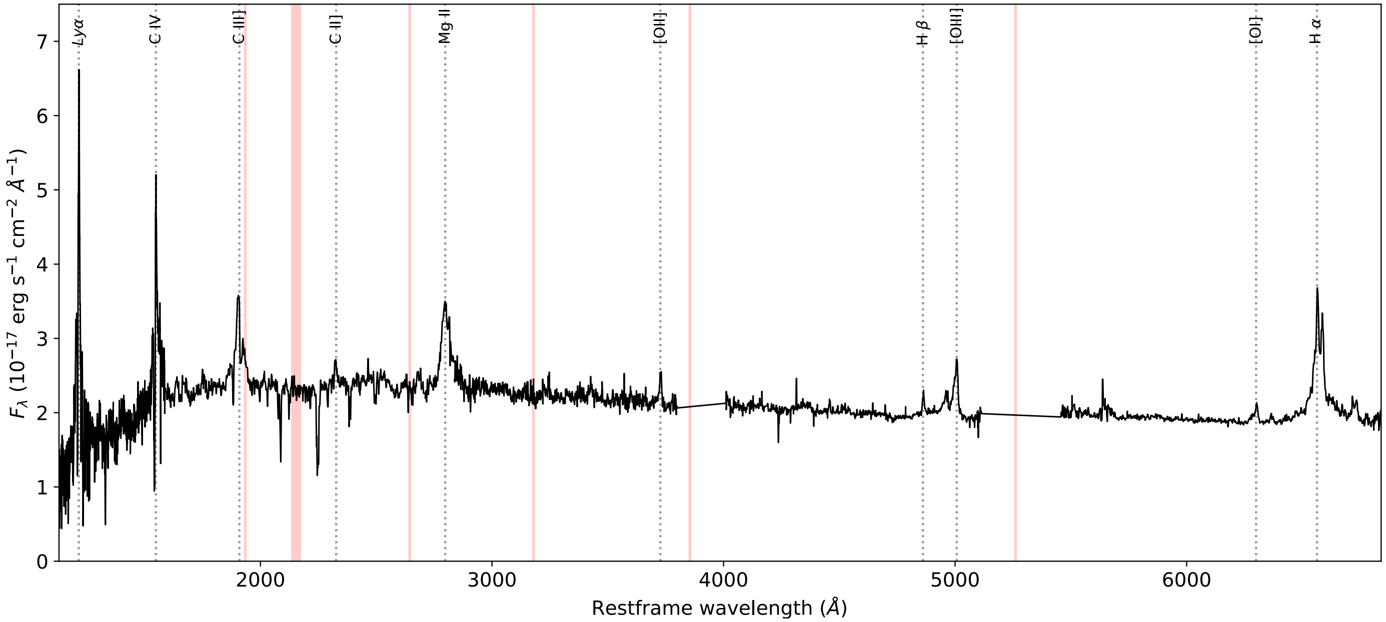
Graham+ 2025, sub.

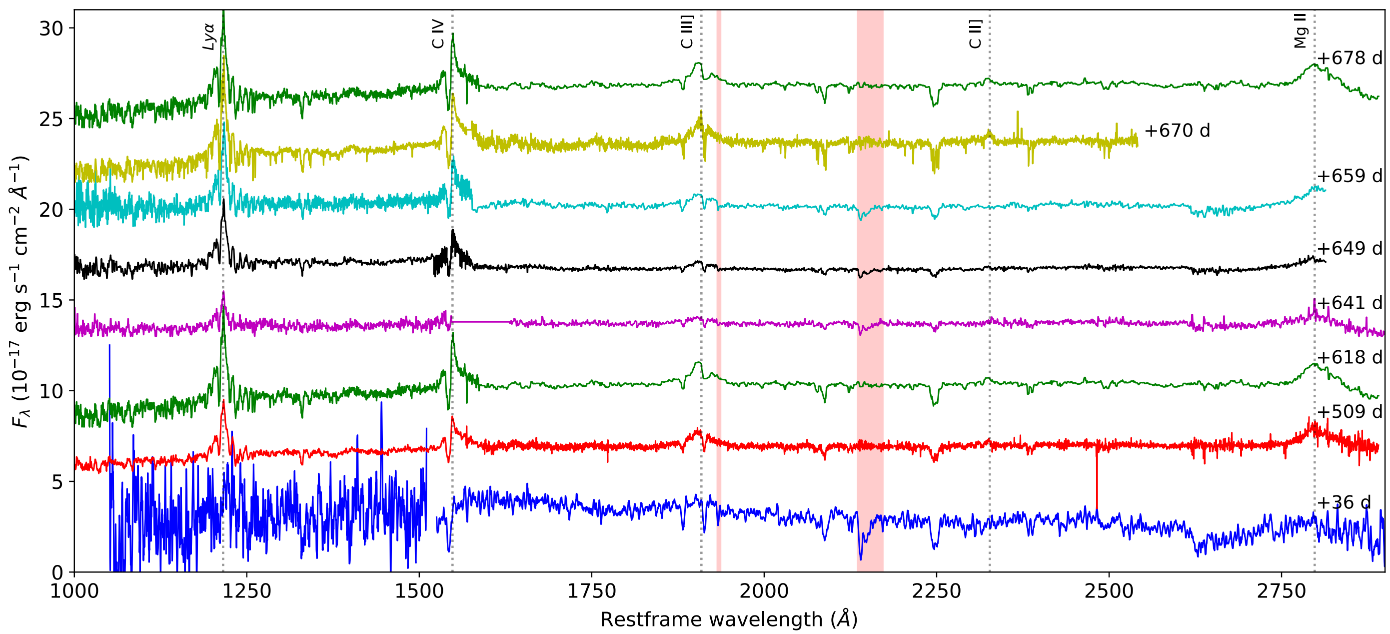






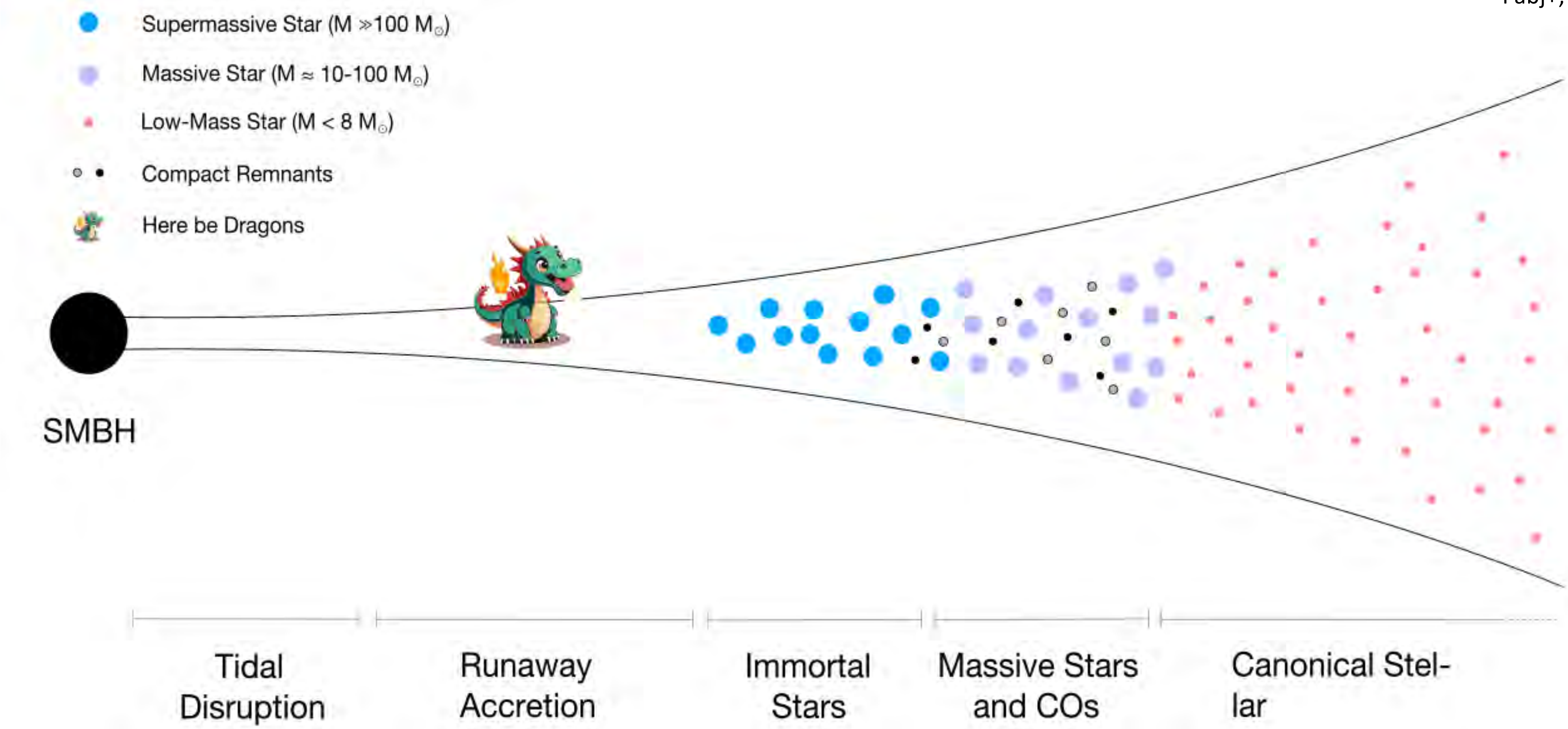
Superman


Lyα
C IV
C III]
C II]
Mg II
[OII]
H β
[OIII]
[OI]
H α
F_λ (10^{-17} erg s^{-1} cm^{-2} Å^{-1})
0
1
2
3
4
5
6
7
2000
3000
4000
5000
6000
Restframe wavelength (Å)


Lyα
C IV
C III]
C II]
Mg II
+678 d
+670 d
+659 d
+649 d
+641 d
+618 d
+509 d
+36 d
F_λ (10^{-17} erg s^{-1} cm^{-2} Å^{-1})
0
5
10
15
20
25
30
1000
1250
1500
1750
2000
2250
2500
2750
Restframe wavelength (Å)

Stars in AGN disks

Fabj+, 2025

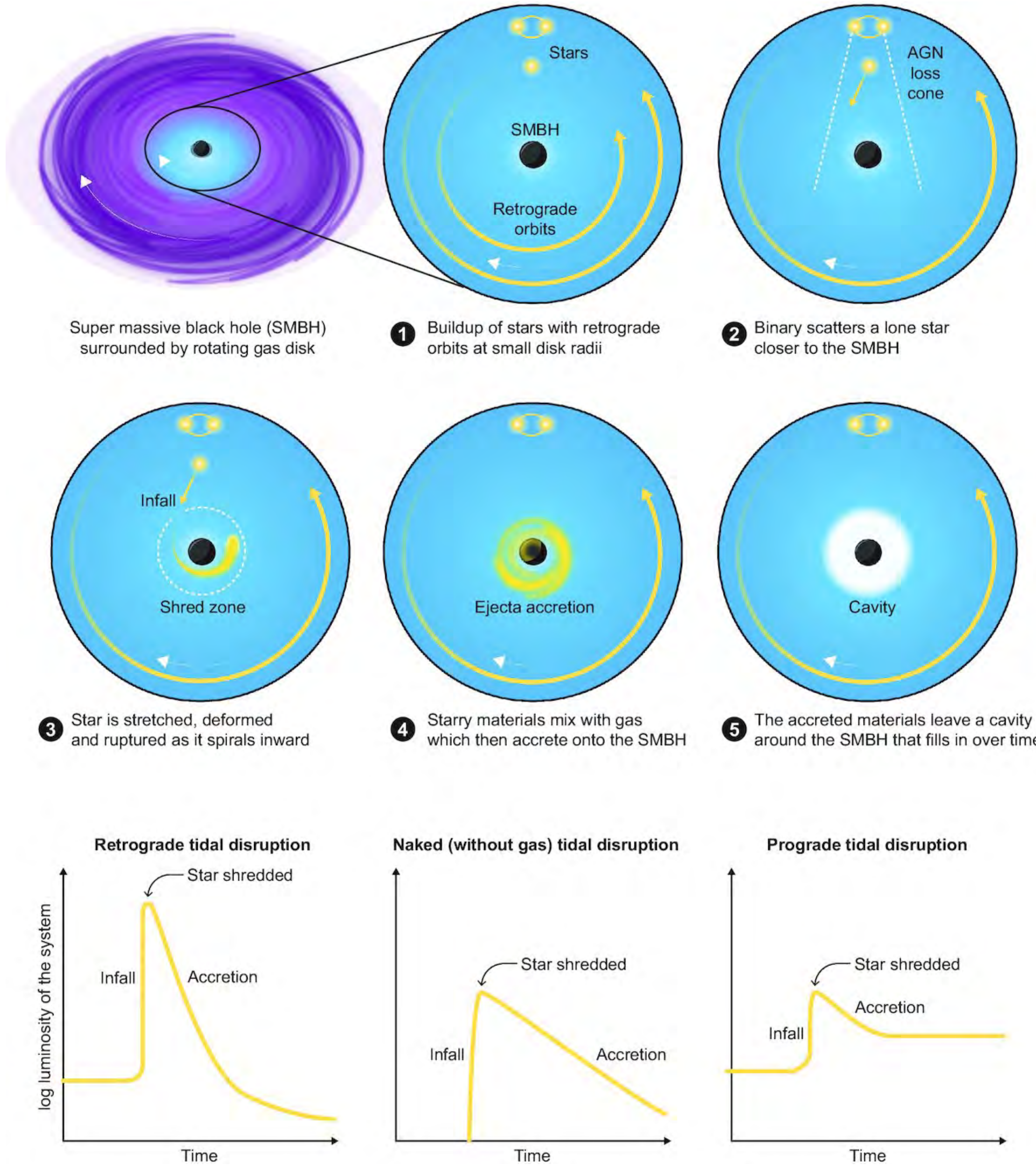


IMBHs

GRBs/SNe

Thorne-Zytkow

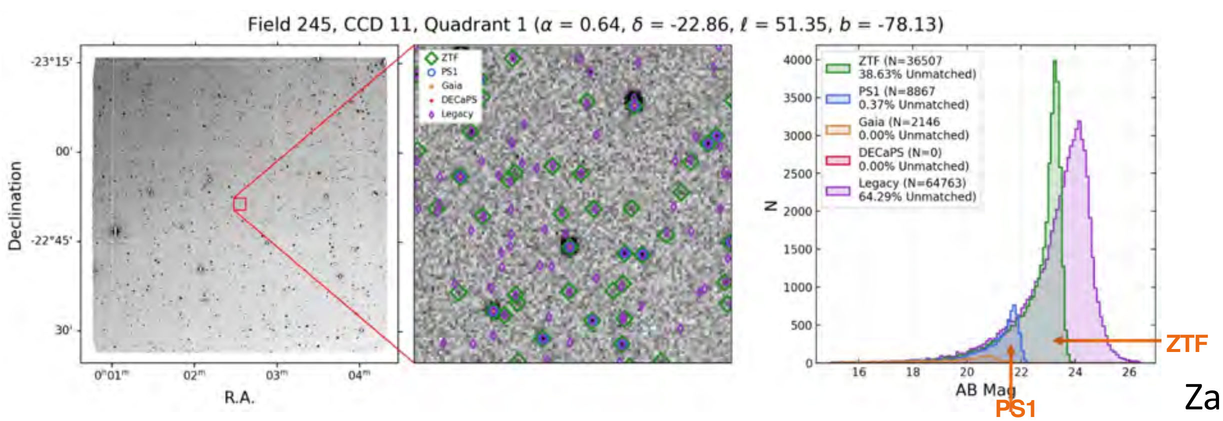
Tidal disruption events in an AGN



McKernan+, 2022

ZVAR – a decadal legacy

- A growing appreciation for ZTF forced photometry data:
  - IPAC service – a few million requests
  - Alert light curves since June 2024 (as LSST will do)
- A data set of ZTF forced photometry at every PS1 position (3 billion):
  - Latest version based on DR21 (June 2024)
  - Extends useful survey limit to g > 22
- Expanding to:
  - Forced photometry from both science and difference images
  - Using ZDC as the background catalog (double number of sources than PS1)
  - Corrected, detrended photometry accurate to 5 mmags at m ~ 16
  - Correcting for proper motions

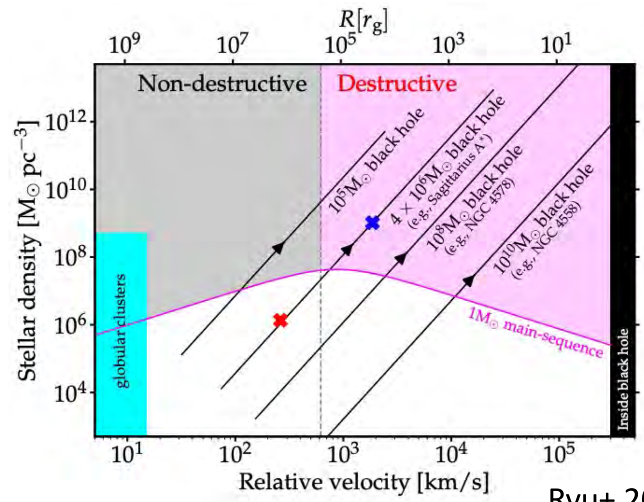


Zach Vanderbosch

UV: the new domain for AGN variability

New AGN phenomena in the UV:

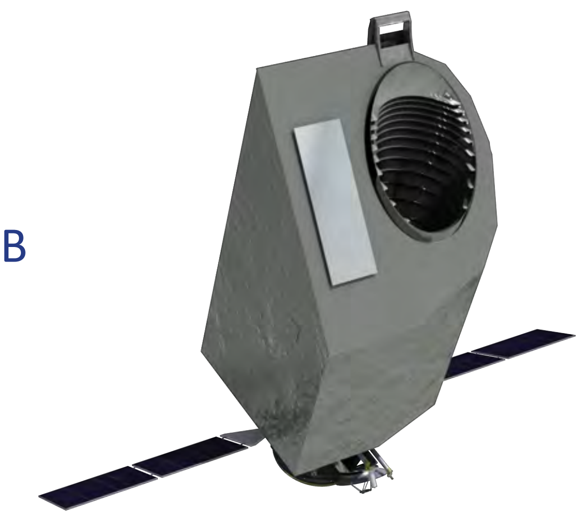
- QP*s
- Stellar collisions in AGN disks
- UV microlensing
- Wavelength dependencies for SMBHB models
- UV collapsars - CLQs



Ryu+ 2025

UVEX:

- 50x deeper than GALEX
- FUV/NUV data probing hours – months timescales
- ~11 visits over 2 years for any point on the sky
- Unprecedented coverage of TDEs, AGN, and sMBHB mergers (O6) via monitoring and ToOs



Summary

- AGN show a rich range of phenomenology that is related to activity in the accretion disk and bears the imprint of the physical system

- Most of our information comes from optical time series and spectra
  - historical records are increasingly important – this a scientific long game

- Our primary methodologies are based on antiquated theory and statistics and do not account for modern phenomenology

- Data-derived models are clearly the way of the future and we are already no longer data starved:
  - millions of light curves vs a hundred

- Things are looking bright