OPTICAL TIME-DOMAIN STUDIES OF AGN

POTENTIALS FOR INVESTIGATION OF AGN EXTREME VARIABILITY

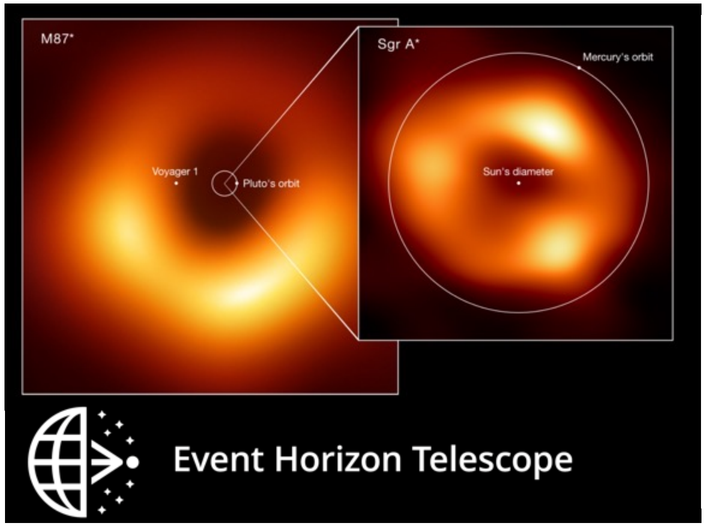
Dragana Ilić
Main collaborators: Luka Popović, Anđelka Kovačević
University of Belgrade – Faculty of Mathematics
Astronomical Observatory Belgrade

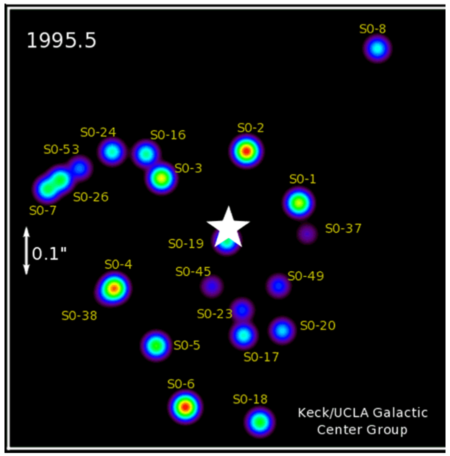
SUPER-MASSIVE BLACK HOLES =SMBH

SMBHs are in the center of (almost all) galaxies

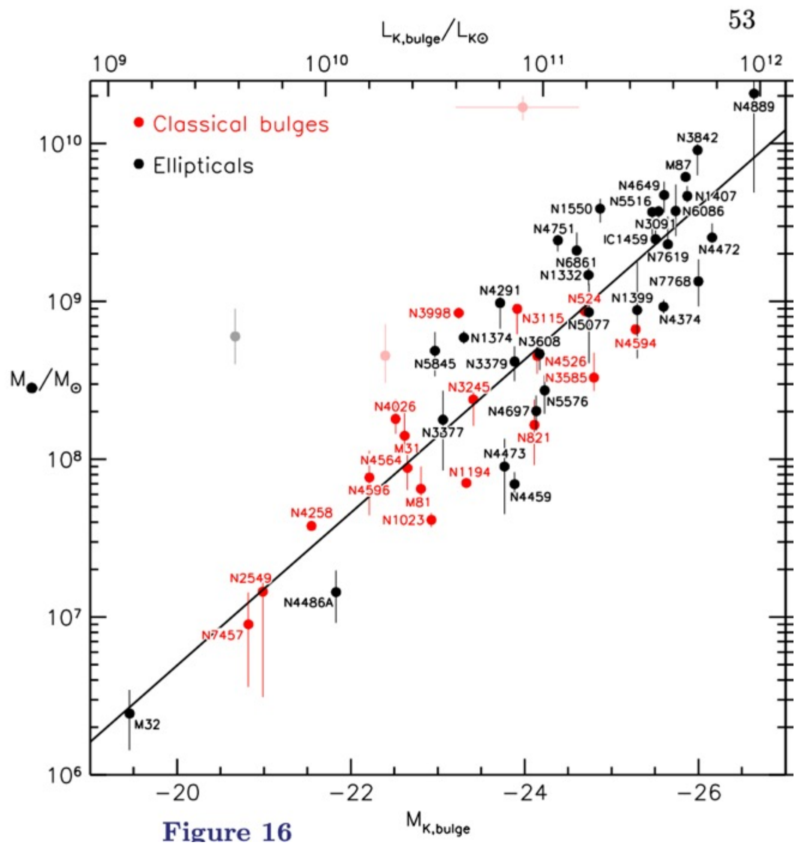
- tight correlation between SMBH mass and bulge mass
- indirect & direct observations (@EHT)

  → galaxy dynamics & evolution



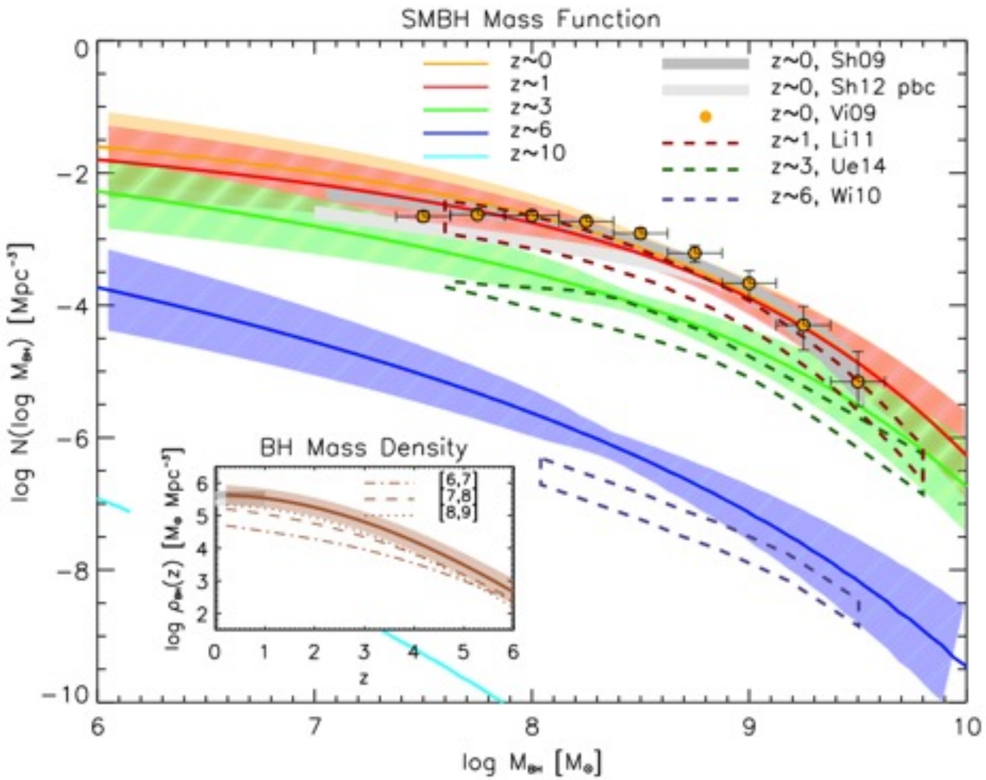


M87* and Sagittarius A*



Kornedy & Ho 2013

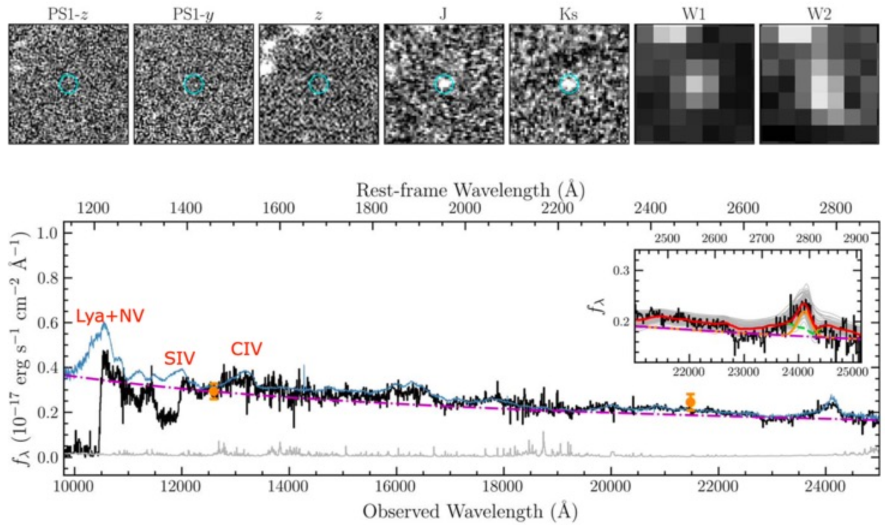
SMBH MASS DISTRIBUTION



Aversa et al. 2015

- where are the intermediate BHs?

- how do we grow SMBH at z~7-8?

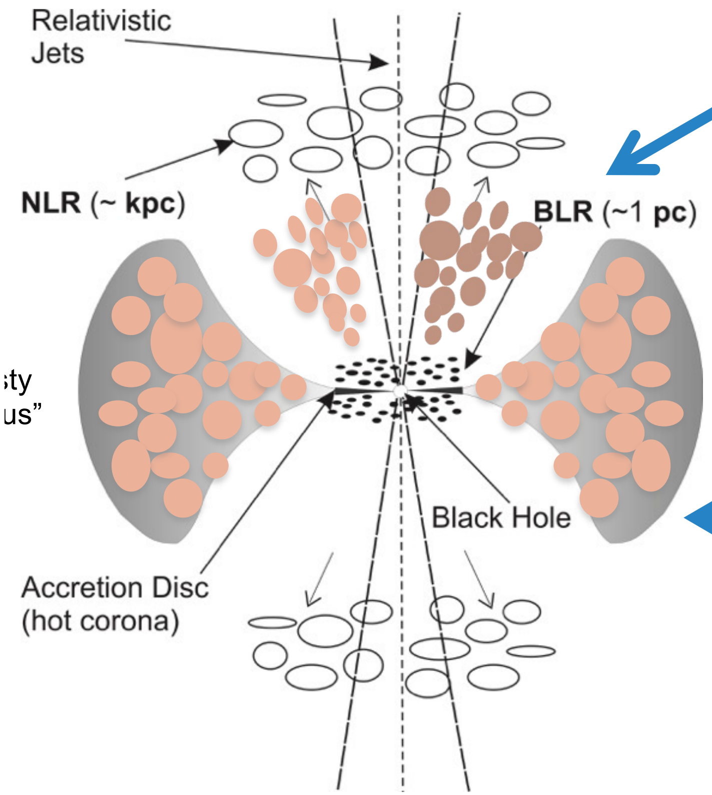


Quasar at z=7.642 (Wang et al. 2021)

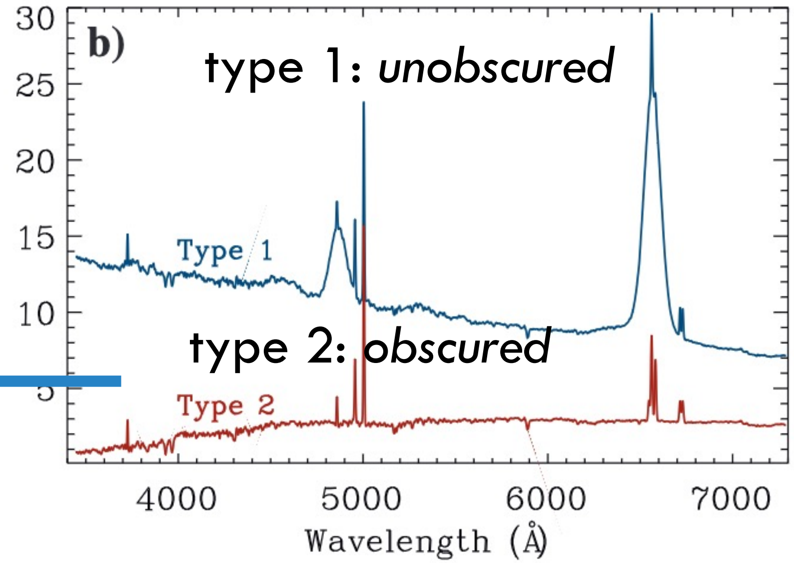
→ See talks by Luis Ho and Tao An

HOW TO “SEE” A BLACK HOLE? → DURING FEEDING

Active Galactic Nuclei (AGN)

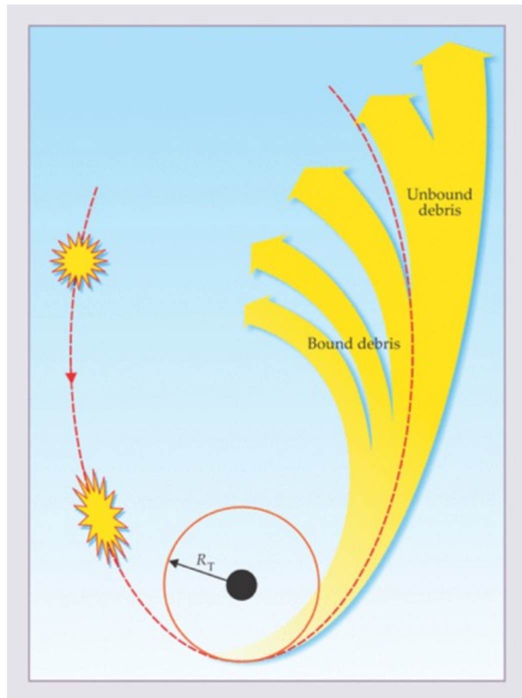


Different viewing angle



Ricci & Trakhtenbrot, 2022

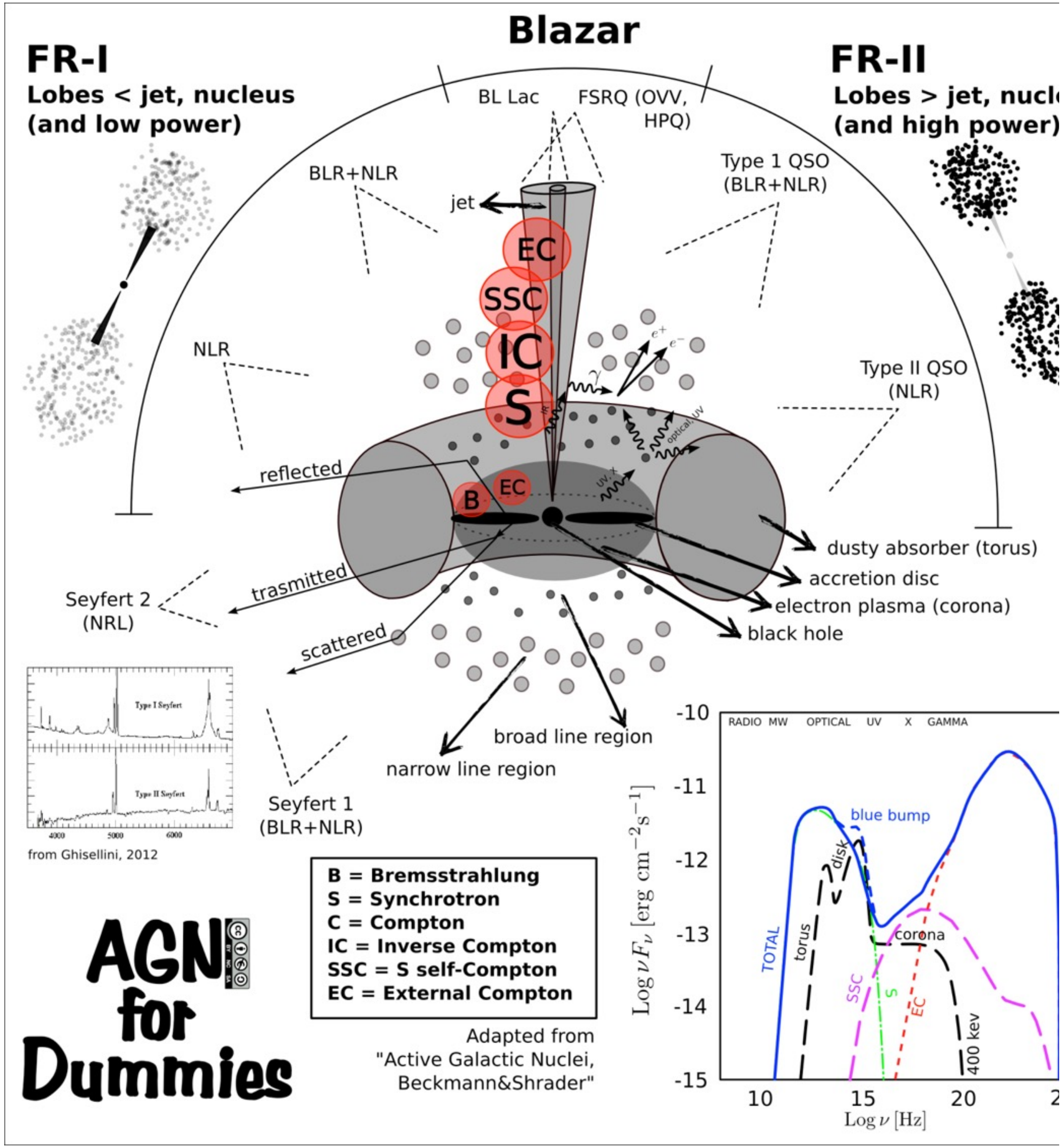
Tidal Distruption Event (TDE)



Rees 1990; Gezari

ACTIVE GALACTIC NUCLEI: KEY FEATURES

- high luminosities:
  → nucleus stronger than the host
- broad non-thermal continuum from γ- to radio
- prominent broad and narrow emission lines
- **strong variability**
  (hrs, days, weeks, months)



VARIABILITY: SEEN FROM THEIR DISCOVERY

1960-1961: First detection of optical variability in the "stellar object" 3C 48

" 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!"

Matthews&Sandage 1963

TABLE 1

PHOTOMETRIC DATA FOR THE THREE RADIO STARS

Object	Date	V	$B-V$	$U-B$	Remarks
3C 48	Oct. 23/24, 1960	16 06	0 38	−0 61	
	Nov. 19/20, 1960	16 02	48	− 61	60-inch
	Jan 12/13, 1961	16 11	.42	− 61	
	Jan. 13/14, 1961	16 13	.39	− 61	
	Jan. 14/15, 1961	16 02	49	− 60	
	Jan. 16/17, 1961	16 13	40	− .59	
	Aug. 17/18, 1961	16 31	40	− 52	
	Oct 11/12, 1961	16 333	340	− 579	Taken 15 minutes apart
	Oct. 11/12, 1961	16 289	393	− 555	
	Dec. 4/5, 1961	16 44	35	− 57	Obs. by Baum
	Dec 5/6, 1961	16 40	42	− .64	Obs. by Baum
3C 196 .	Mar. 31/1, 1962	17 79	57	−. 43	
3C 286 .	June 2/3, 1962	17 25	0 26	−0 91	

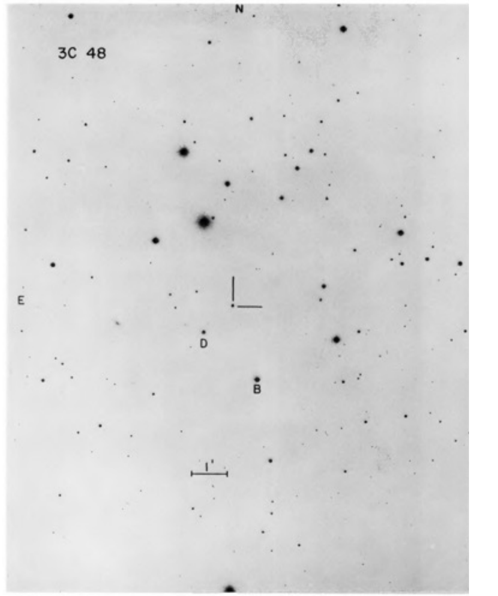
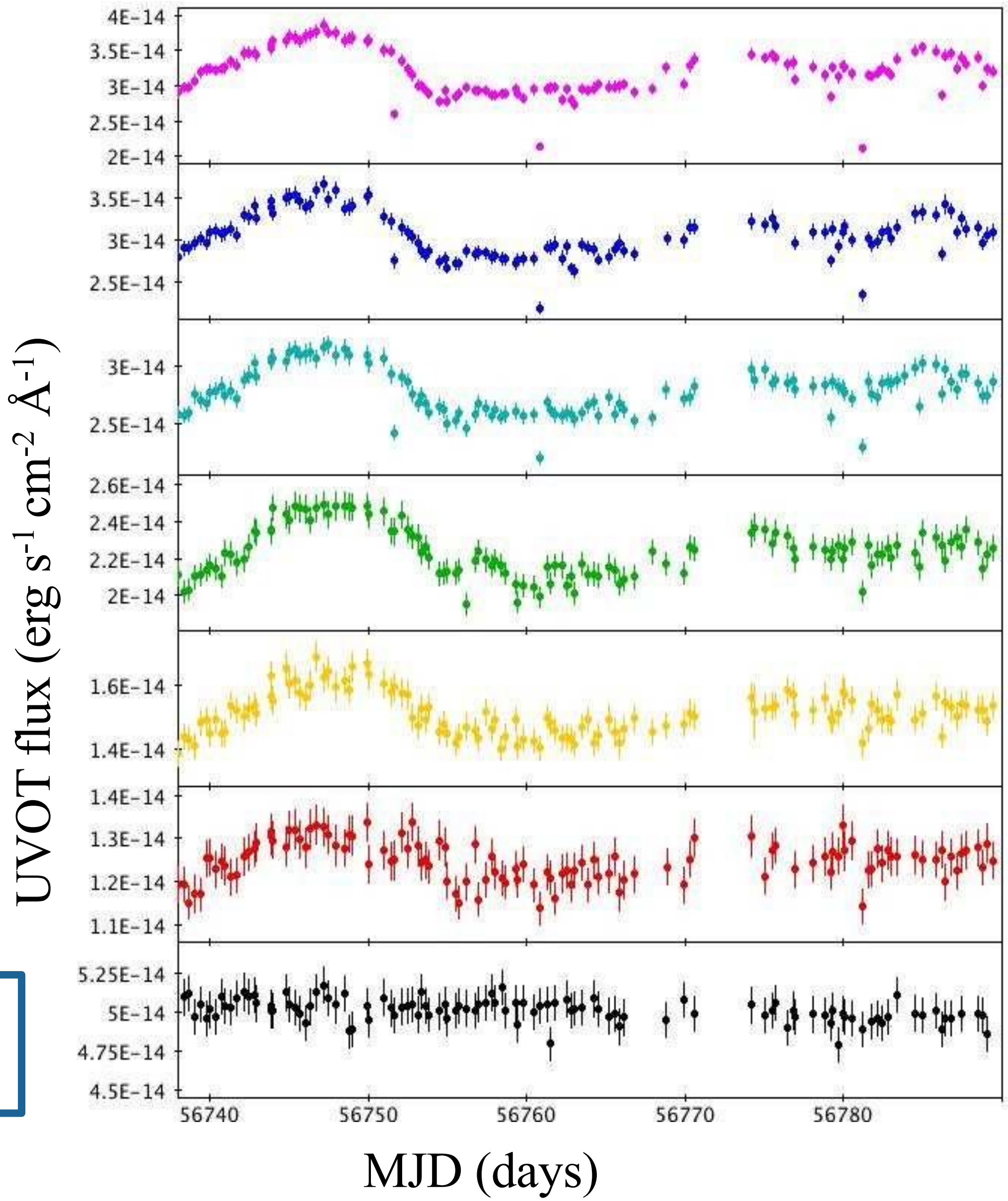


FIG. 2.—Finding chart for 3C 48 taken from a 10-minute exposure with the 200-inch. Local photometric standar stars B and D are marked. The data are $V = 13.53$, $B - V = 0.50$, $U - B = 0.00$ for star B; $V = 14.54$, $B - V$ 0.66, and $U - B = 0.05$ for star D. The plate used was a 103a-O + GG 13.

Slides adapted from lectures by Demetra De C

AGN VARIABILITY PROPERTIES

- ubiquitous;
- present in every waveband;
- amplitude depends on wavelength;
- variations are faster at higher energies;
- in optical: typical amplitudes ~0.1–0.2 magnitudes (Vanden Berk et al. 2004; Sanchez-Saez et al. 2018)

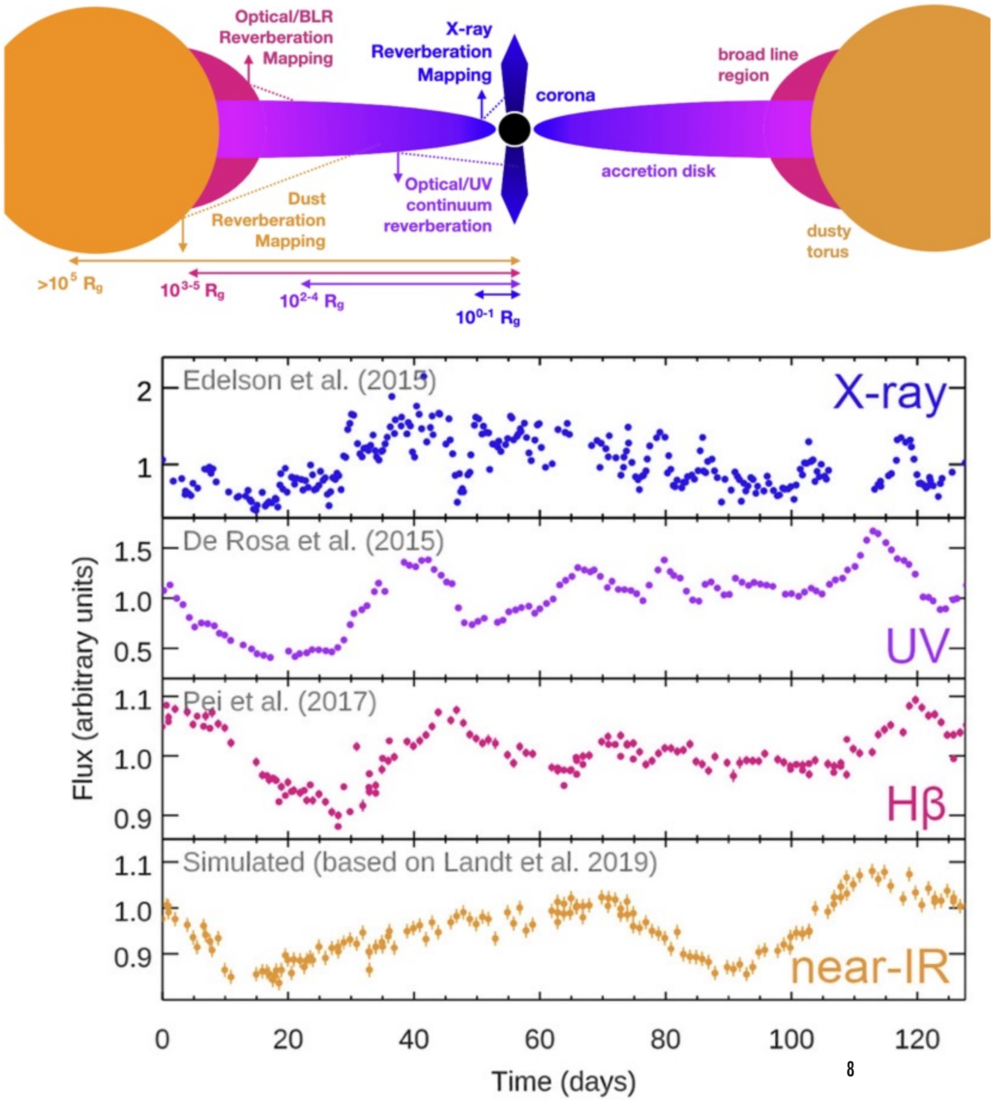


Credit: Gelbor

This week many talks on x-ray and radio:
ia Sotnikova, Sergey Sazonov, Maxim Barkov

AGN VARIABILITY

Cacket et al. 2021



Reverberation (echo) mapping = mapping the structure and kinematics of:

- accretion disk
- broad line region (BLR) → can estimate SMBH mass

$$M_{BH} = f\frac{R_{BLR}FWHM^{2}}{G}$$

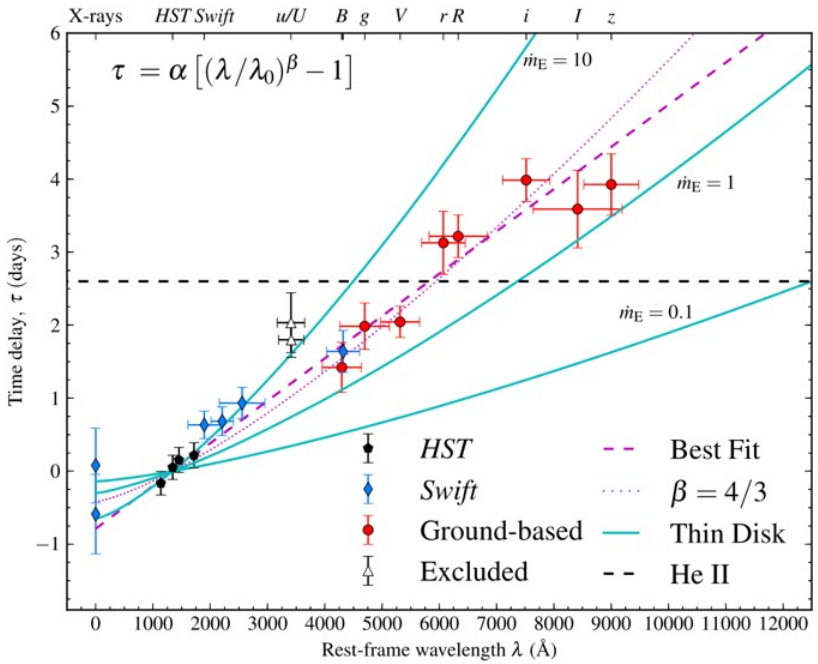
Dibai method

e **Crimean-2021 AGN Conference** for excellent talks: http://lerga.crao.ru/conf/en/

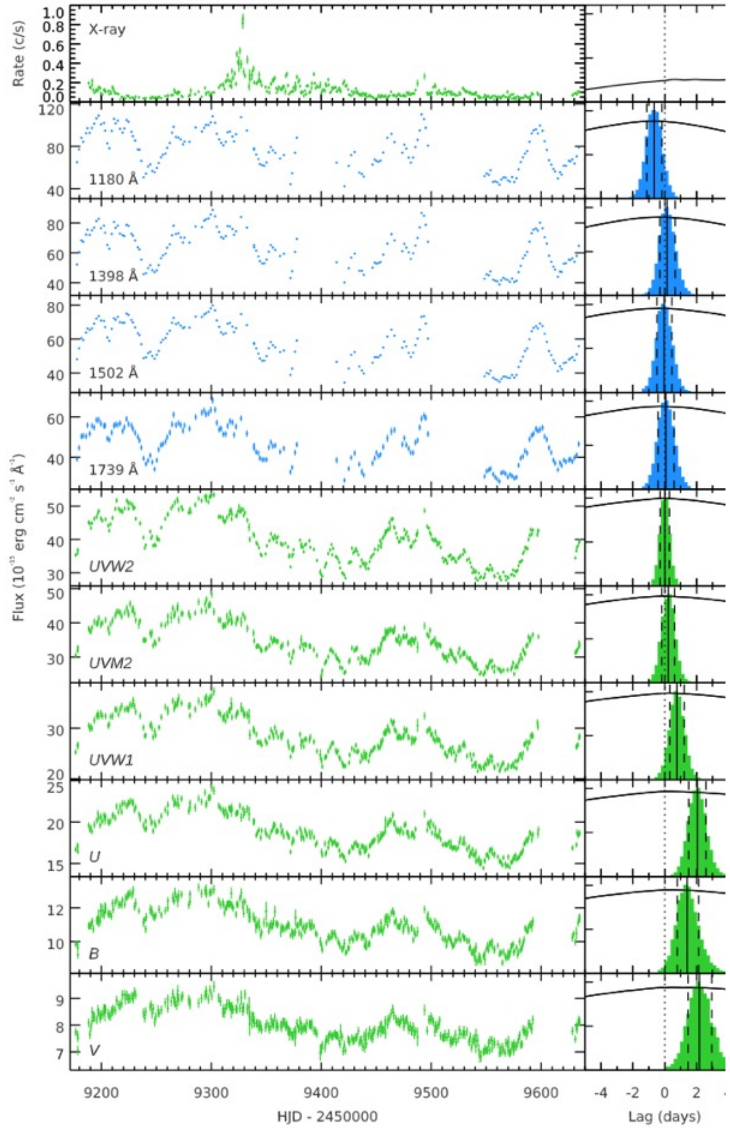
INTENSIVE MONITORING CAMPAIGNS

interband continuum lags, $\tau(\lambda) \propto \lambda^{4/3}$

expected for a geometrically thin, optically thick, centrally illuminated disk



GC 5548, AGNSTORM
usnaugh et al. 2016



Mrk 817, AGNSTORM 2,
Cacket et al. 2023

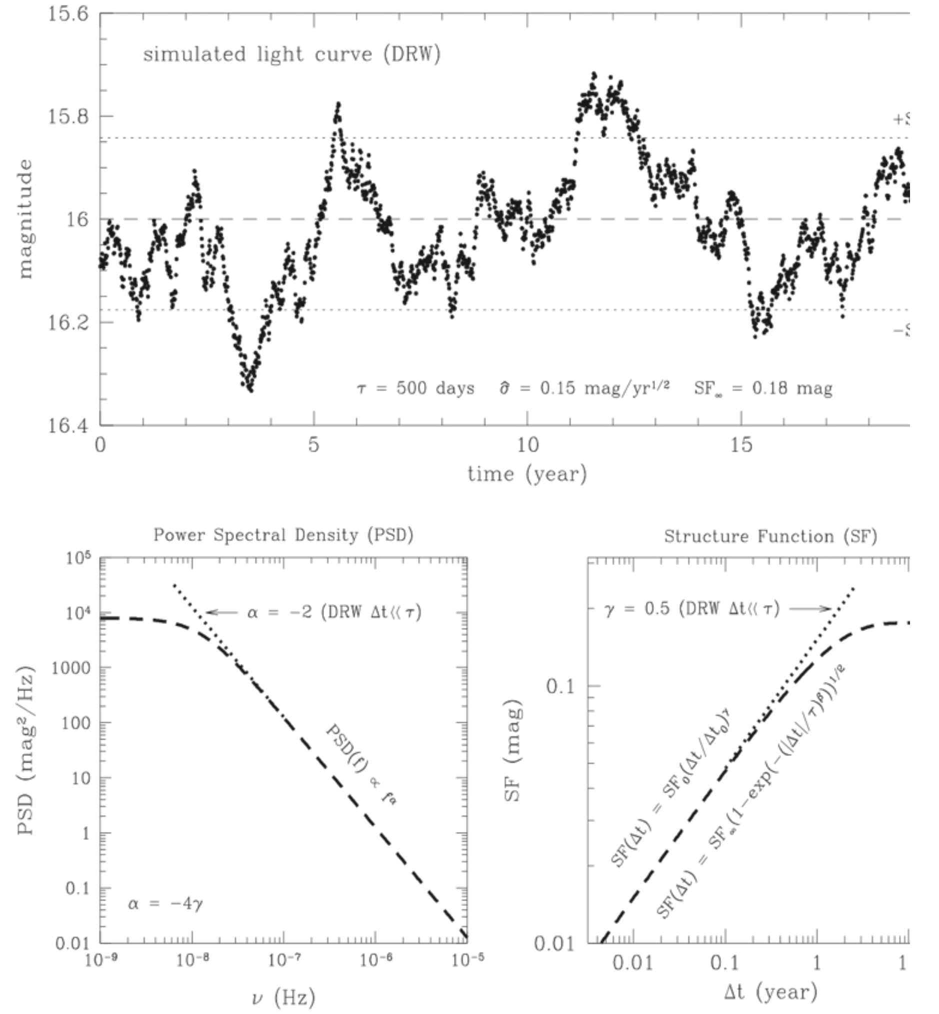
OPTICAL PHOTOMETRIC VARIABILITY

ight curve analysis – structure function (or power-pectral density), see e.g. De Cicco et al. 2022

$$\mathrm{SF_{obs}}(\Delta t) = \sqrt{2\sigma_s^2 + 2\sigma_n^2 - 2\mathrm{cov}(s_i, s_j)}$$

- Variability properties scale with:
  - SMBH mass (e.g. MacLeod et al. 2010, Burke et al. 2021, Petrecca et al. 2024)
  - accretion rate (e.g. Arevalo et al. 2023)
  - luminosity (e.g. Caplar et al. 2017)

lso in X-ray variability (**see talk by Sergey Sazonov**)



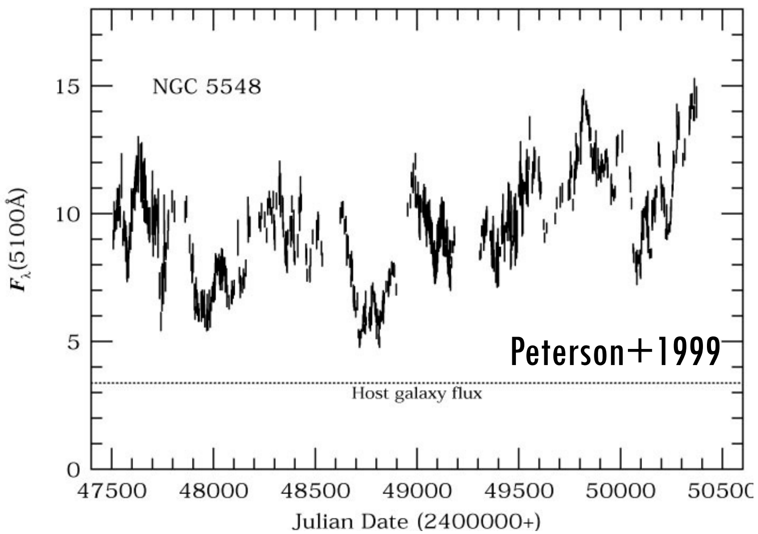
Kozłowski 2016

APPLICATIONS OF OPTICAL AGN VARIABILITY

1. **Reverberation Mapping** of accretion disk (LSST AGN Science Collaboration priority, Brandt+18)

2. constrain **Radius-Luminosity** (e.g., Kaspi+ 2000, Peterson+ 2004, Bentz+2009, etc) and **Mass-Luminosity** relations (e.g., Bonta et al. 2020) → get mass of SMBH

3. hunt periodic systems → candidates **binary SMBHs** (e.g., Graham+2017, Kovačević+2018, 2019, Popović+2021) → **see talk by Alexei Moiseev**

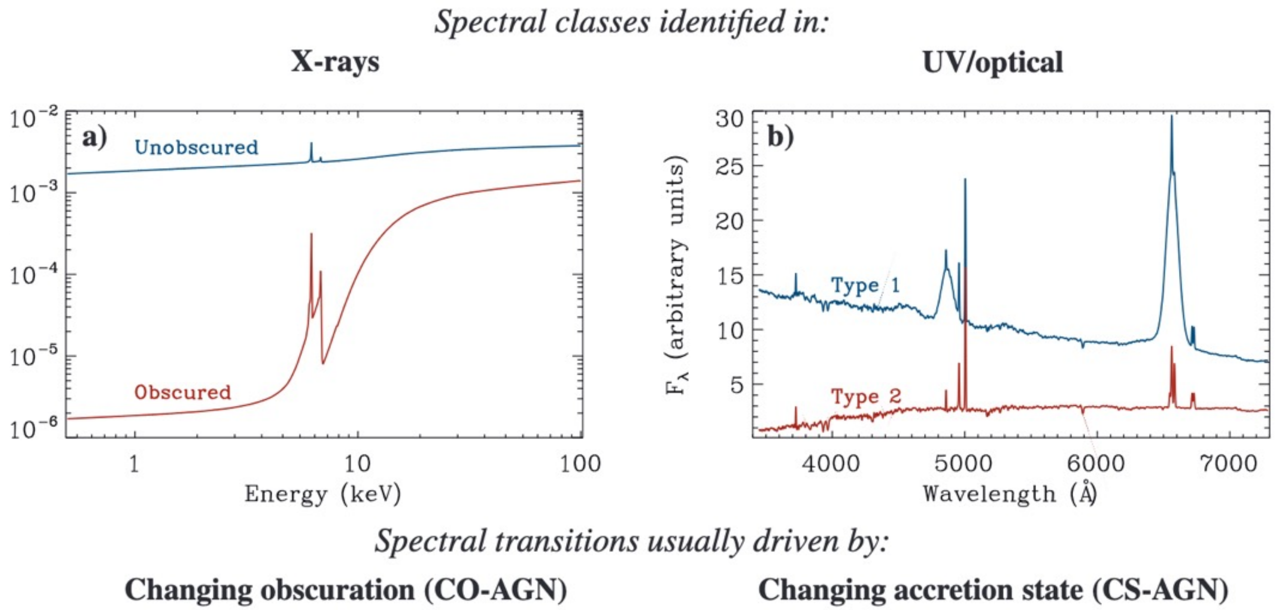


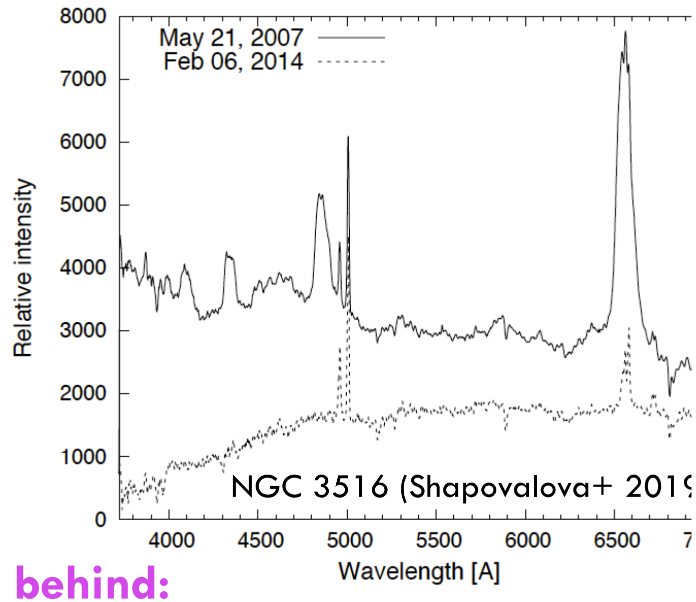
Optical AGN light curves are:

- immersed in red noise (e.g. De Vries+ 05)
- nonlinear and stochastic
- maybe described by Damped Random Walk (DRW) process (Kelly et al. 2009), but there are others (DHO, Yu et al. 2022)
- also sparse, gapped, irregular…

EXTREME AGN VARIABILITY

Changing obscuration vs. **Changing state AGN**
(Ricci & Trakhtenbrot 2022)





Physics behind:

- change of obscuration
- intrinsic change of accretion disk/rate
- TDEs
- Microlensing

Detection:

large-amplitude photometric variability (e.g. delta_mag>1, MacLeod et al. 2016) is a good approach, but not enough

e also Stern et al. 2018, Graham et al. 2020, Runco et al. 2016, Yang et al. 2018, nchez-Saez et al. 2021, Temple et al. 2023, Guo et al. 2024, and many more)

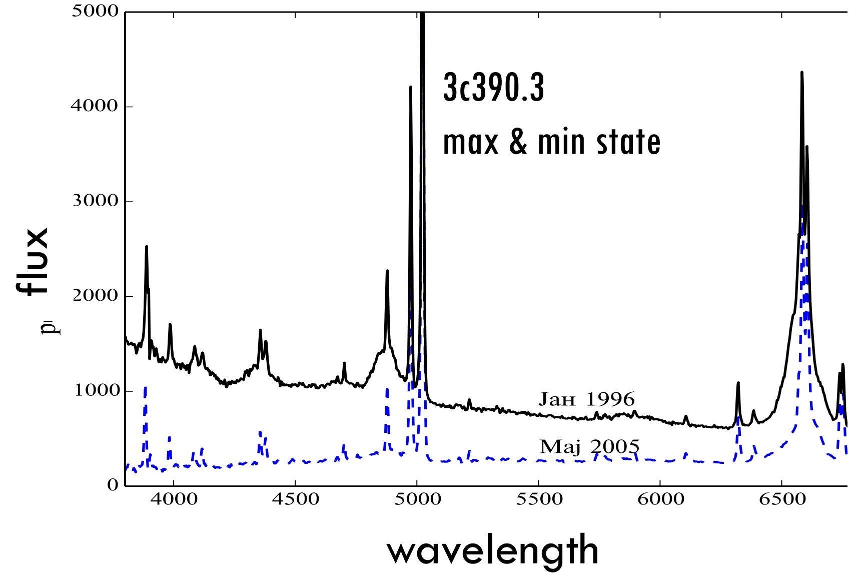
→ **See talk by Wei-Jian Guo, CL AGNs from DESI & SDSS**

OPTICAL SPECTRAL MONITORING

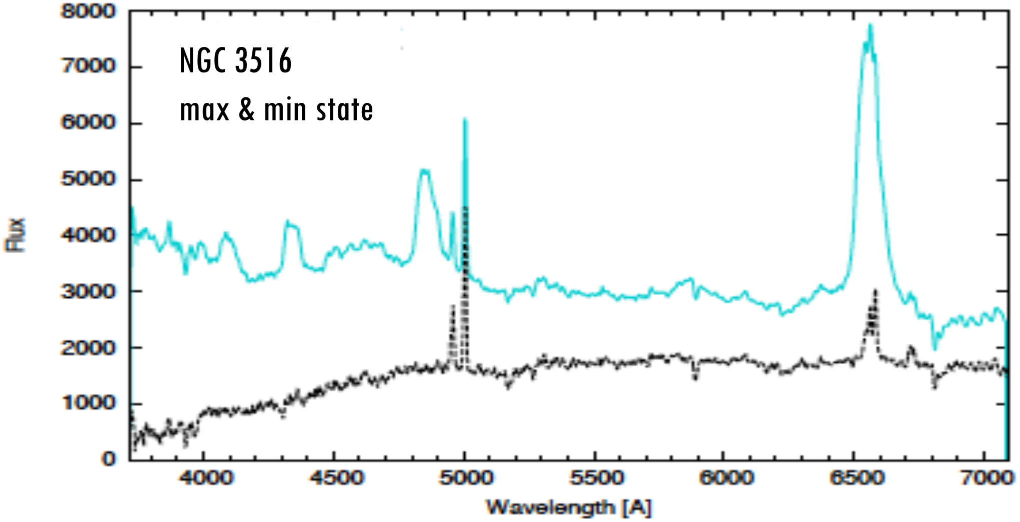
everything varies!

- → line and continuum fluxes
- → line profiles – peaks, bumps, asymmetries
- → can be extreme: e.g. type 1 -> type 2

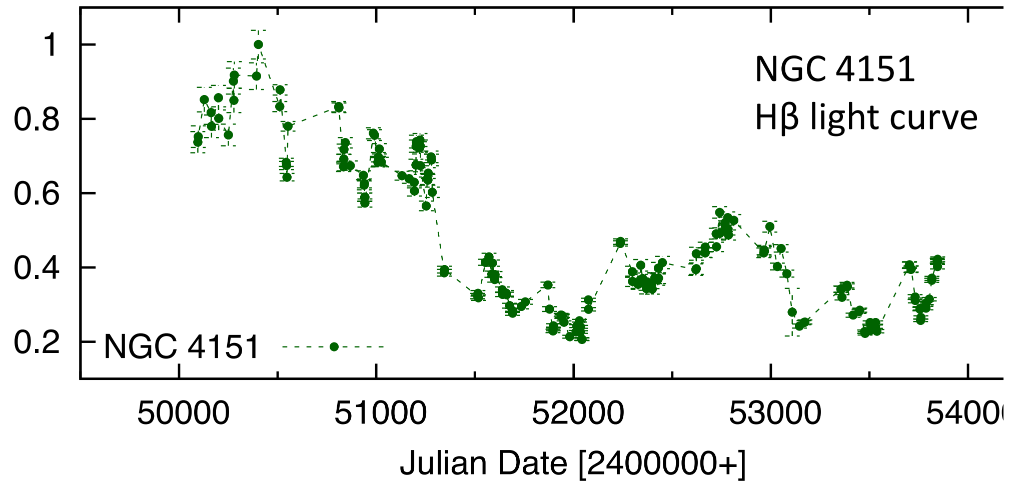
Popovic+ 2011



Shapovalova+ 2019



Shapovalova+ 2008



SPECTRAL RM CAMPAIGNS

complementarity of massive and individual follow up surveys

QUANTITY

SDSS reverberation monitoring

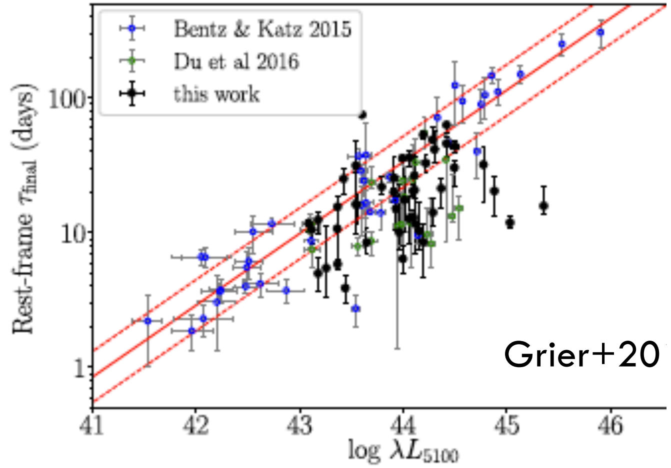
- monitoring 849 quasars, 0.1<z<4.5 (Shen et al. 2014, 2018)
- measured for 44 quasars, z<0.3 (Grier+2017) and 144 quasars, z<1 (Li+2017)

Subaru/FMOS survey (Shultze+2018)

- 234 quasars, highest redshift z=4.6
  based on Hα (211), Hβ (63) and Mg II (4)

OzDES RM campaign (King+2015, Hoormann+2019)

- 23 variable AGNs out of 771 monitored, 0.1<z<4.5

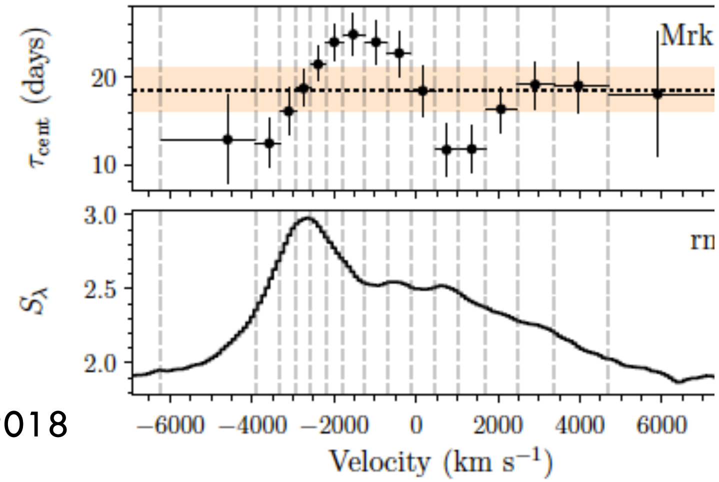


Grier+20

QUALITY

High fidelity RM (Horne+2012) to get velocity-resolved RM (De Rosa+2018, Du+2018)

AGNSTORM campaigns (DeRosa+2018, Kara+2021)



Du+2018

LONG-TERM RM CAMPAIGN (from 1990s)

Alla I. Shapovalova (1941 – 2019)

Typical Seyfert 1s:
NGC 5548 – 9+ years (Shapovalova+ 2004, Ilić 2007, Popović+2008, Bon+2016)
NGC 4151 – 11+ years (Shapovalova+ 2008, 2010a, Ilić+2010, Bon+ 2012)
NGC 7469 – 20 years (Shapovalova+2017)
NGC 3516 – 22 years (Shapovalova+2019, Ilic+2020, Popovic+2023, Ilic+2023)

Narrow Line Seyfert 1:
Ark 564 – 11 years (Shapovalova+ 2011, Shapovalova+ 2012)

Double Peaked Line AGNs (DPLs):
3C 390.3 – 13 years (Shapovalova+ 2001, 2010b, Popović+2011, Jovanović+ 2010, Kovačević+ 2014);
Arp 102B – 12 years (Shapovalova+13, Popović+ 14, Kovačević+ 14, Ilić+15, Rakić+ 17)

Quasar, a binary black hole candidate:
E1821+643 – 25 years (Shapovalova+2016, Kovačević+2017, Kovačević+2018)

*long=decades

SUMMARY OF THE CAMPAIGN

determined the BLR size and the SMBH mass of 8 AGN

periodicities for 2 candidates of SMBH binaries

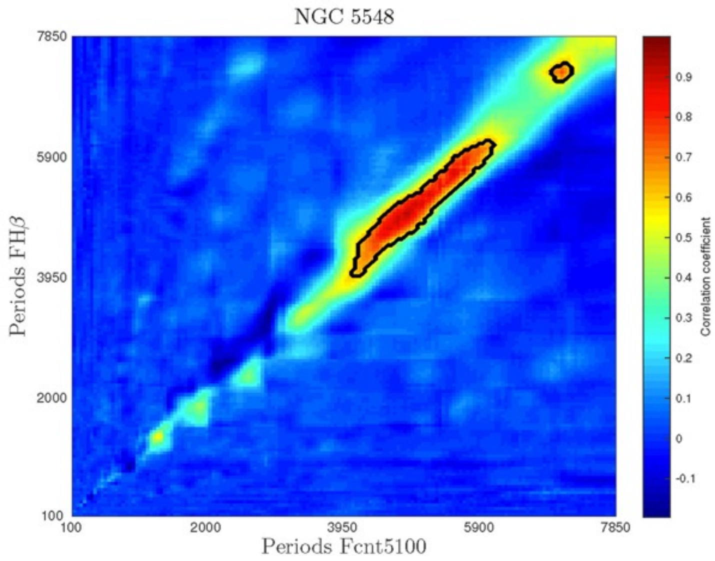
(re)discovery of changing-look AGN NGC 3516

developed spectral fitting tools, light-curve analysis, and physical models

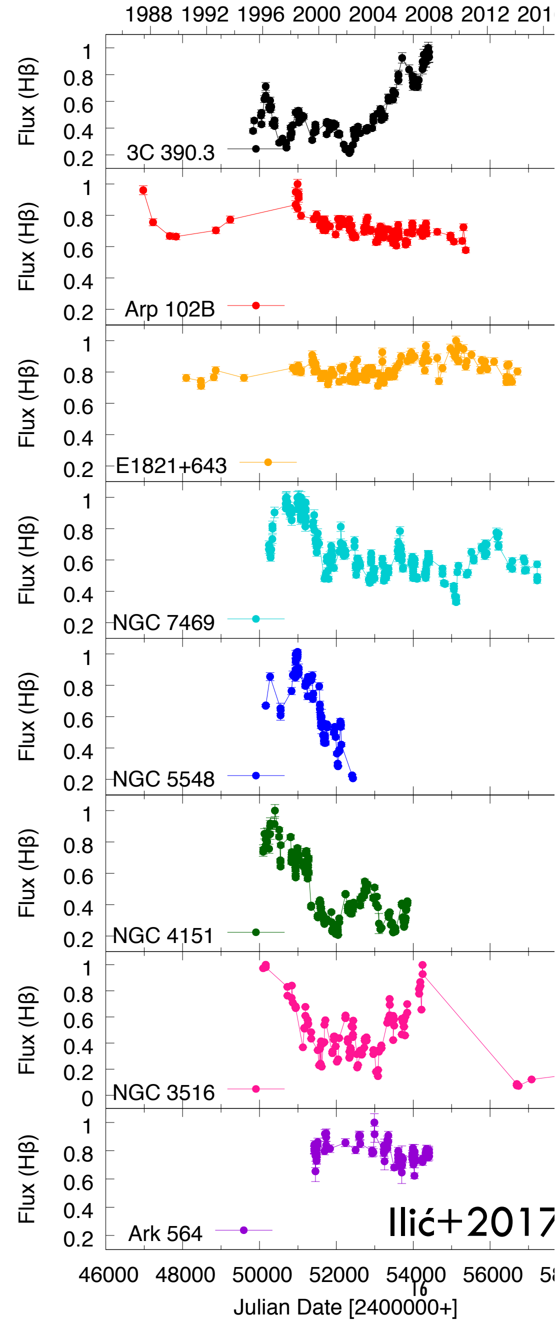
→ novel hybrid method to search for periodic oscillatory behavior (Kovacevic+ 2018, 2019)

→ model of SMBH binary (Popovic & Simic, 2019, Popovic+ 2021)

ičević et
018, 2023



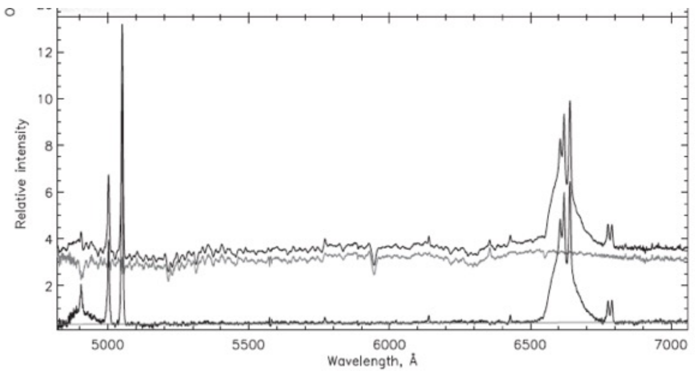
2D correlation maps of periodicities in Hb and continuum of NGC 5548



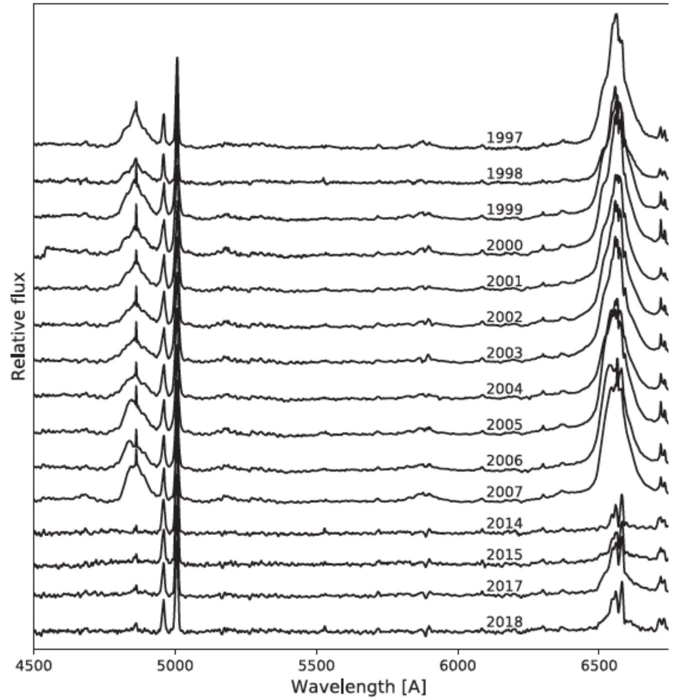
CHANGING LOOK AGN: NGC 3516

collected 22 years of data

captured a disappearance of broad lines in 2014

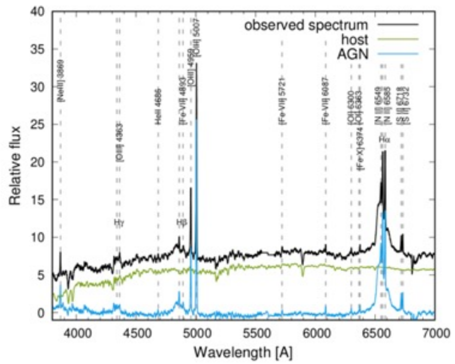


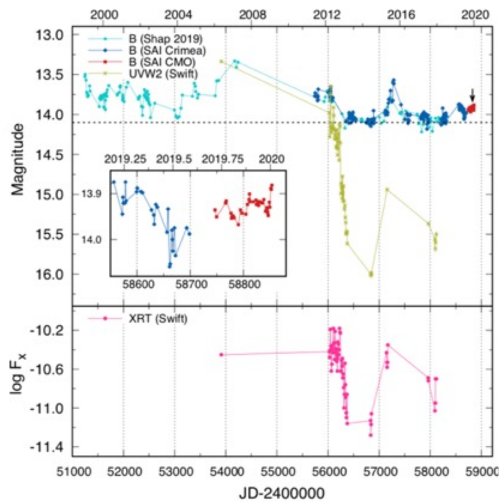
in 2017: still in low state,
but broad lines start to appear



Shapovalova et al. 2019, MNRAS

Ilić et al. 2020, A&A





- Recent (end 2019) observations, indicate that NGC3516 is maybe awakening (increase of coronal emission lines)
- Probably due to change in intrinsic properties of accretion (Popovic et al. 2023)

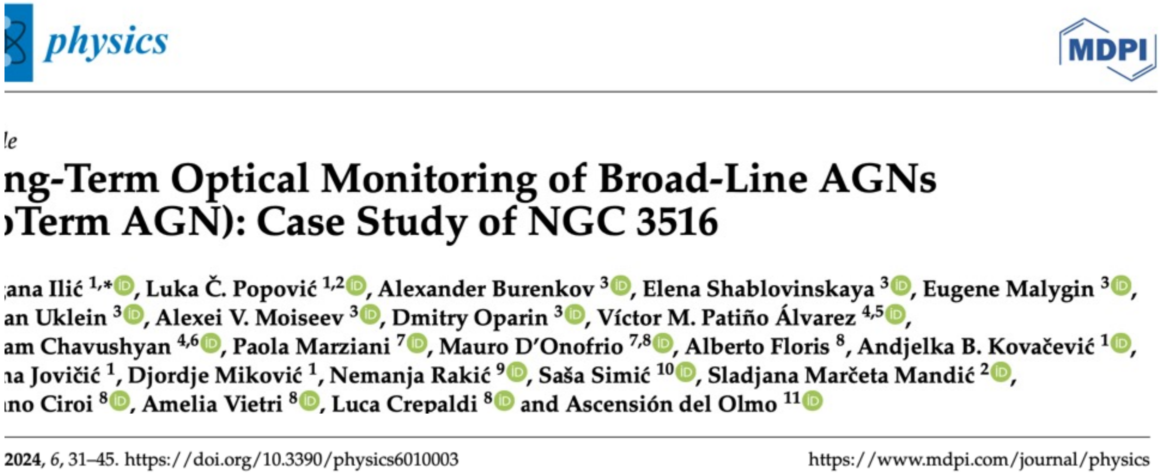
→ **important to continue monitoring of AGN in multi-wavelength**

LONG-TERM MONITORING OF NGC 3516

LoTerm AGN campaign

sustained campaigns to continually collect spectroscopic data of known AGNs over extended timescales

broad Hα line period 2020–2023 - remained active but no change in the profile


physics MDPI

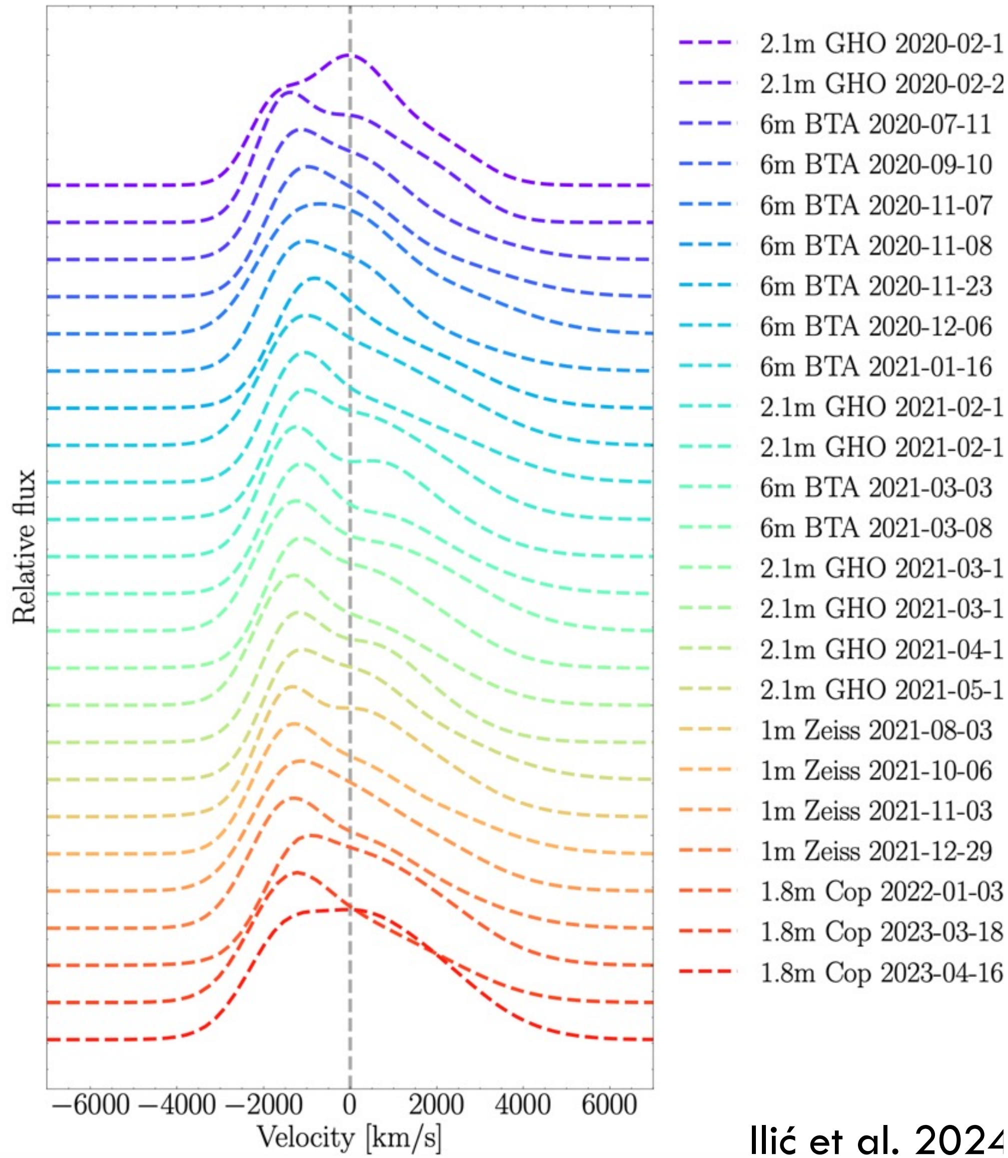
le

ng-Term Optical Monitoring of Broad-Line AGNs
›Term AGN): Case Study of NGC 3516

ana Ilić [1,*], Luka Č. Popović [1,2], Alexander Burenkov [3], Elena Shablovinskaya [3], Eugene Malygin [3],
an Uklein [3], Alexei V. Moiseev [3], Dmitry Oparin [3], Víctor M. Patiño Álvarez [4,5],
am Chavushyan [4,6], Paola Marziani [7], Mauro D'Onofrio [7,8], Alberto Floris [8], Andjelka B. Kovačević [1],
ıa Jovičić [1], Djordje Miković [1], Nemanja Rakić [9], Saša Simić [10], Sladjana Marčeta Mandić [2],
ıno Ciroi [8], Amelia Vietri [8], Luca Crepaldi [8] and Ascensión del Olmo [11]

2024, 6, 31–45. https://doi.org/10.3390/physics6010003 https://www.mdpi.com/journal/physics

Broad Hα line in 2020–2023



Ilić et al. 2024

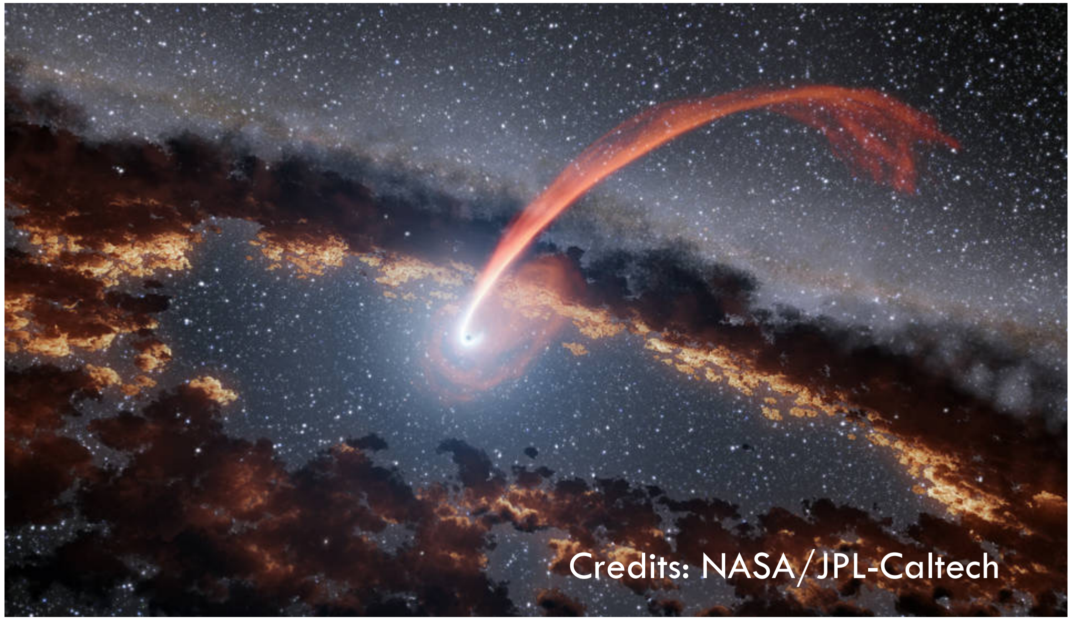
TIDAL BREAK UP OF A STAR → TDEs

Rees 1988 - TDE flares: reveal also non-active BH

~1/2 gaseous stellar debris remains gravitationally bound → Accretion disk is formed → should peak in X-ray

favoured for lower mass SMBH

TDE luminosity is expected to follow the fallback rate ~ $t^{5/3}$



→ See talk by Georgii Khorunzhev

See also https://www.youtube.com/watch?v=grBZVgmNGk8 simulation of a tidal disruption event by Taj Jankovič & Andreja

TDEs

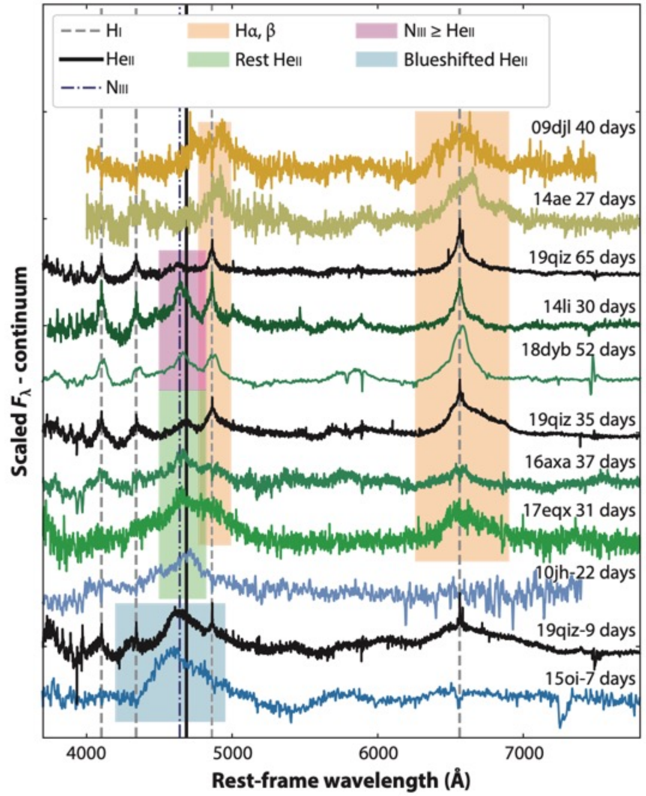
nuclear transients, rate ~ 10^{-4} galaxy^{-1} yr^{-1}

- **Limited samples**: about 100 TDE candidates (review: van Velzen+ 2020, Hammerstein+ 2023; **only few in AGNs**)

Detection:

- Rise ~month, decay $t^{-5/3}$
- blue colours
- constant blue colours

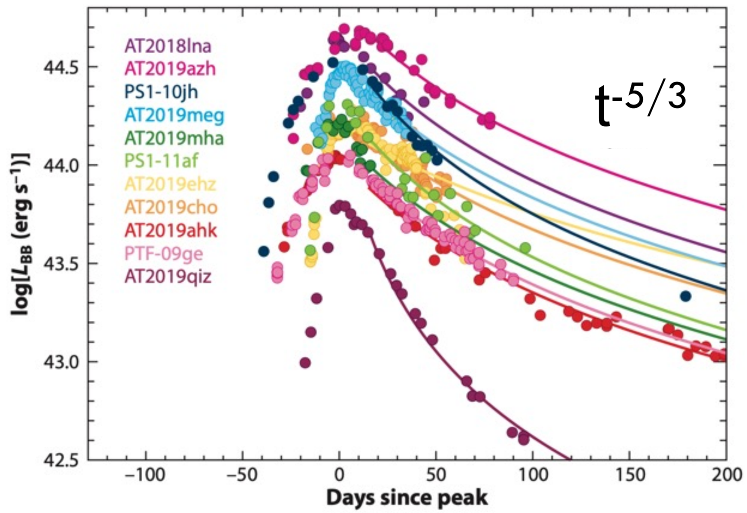
Spectroscopic follow-up crutial for confirmation and characterisation

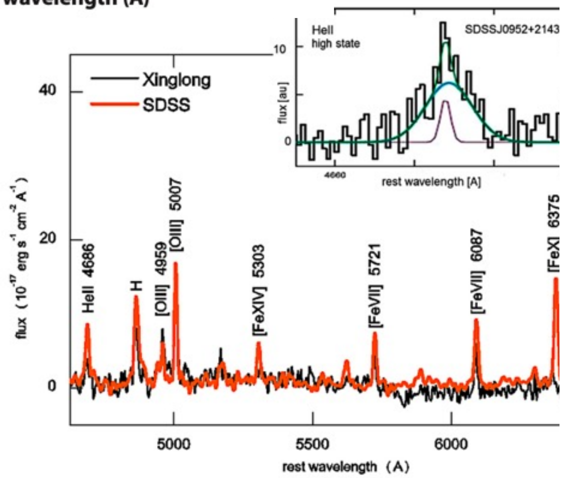


Gezari 2021

Sub-types:

- TDE-H
- TDE-He
- TDE-H+H
- TDE-FeII
- TDE featurele
- w/Bowen fluorescer lines
- w/coronc lines





Komossa 2015

WHAT ABOUT ANTs?

Ambiguous Nuclear Transients (ANTs)

- AT2021lwx - most luminous transients ever discovered
  - powered by massive accretion on SMBH > 10^8 M☉
  - no evidence of AGN activity, but X-rays points to a hot corona or jet
  - TDE of a massive star is unlikely due to the small chance of observing such an event

Wiseman et al. 2023

3994 *P. Wiseman et al.*

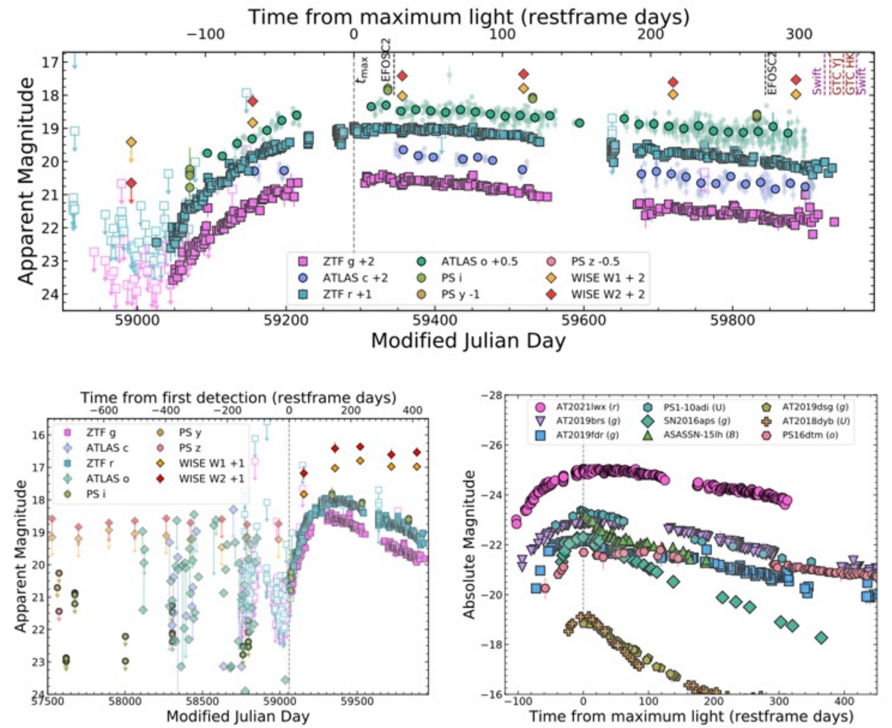
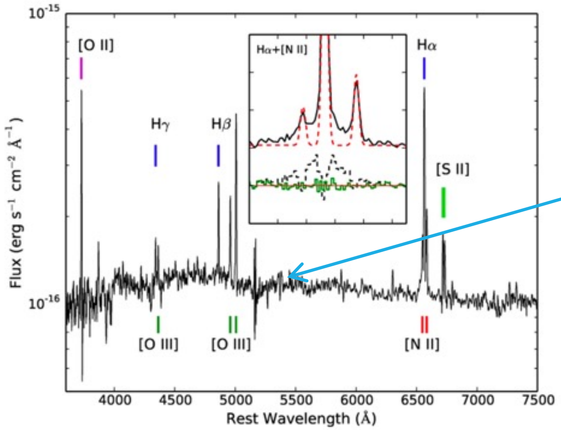


Figure 1. (Upper) Light curve of AT2021lwx. Epochs of our multiwavelength follow-up observations are marked with dashed lines. (Lower left) Pan-STARRS upper limits up to 750 d (rest frame) before the first detection of AT2021lwx. (Lower right) Comparison to similar transients: NLSy1 accretion events AT2019fdr and AT20219brs (Frederick et al. 2021) and the prototype nuclear flare PS1-10adi (Kankare et al. 2017); the most luminous known likely TDE ASASSN-15lh (Leloudas et al. 2016); the most luminous known supernova SN2016aps (Nicholl et al. 2020); a (possibly jetted) TDE AT2019dsg (van Velzen et al. 2021); a typical TDE AT2018dyb (Leloudas et al. 2019); and the MIR-brightening TDE PS16dtm (Petrushevska et al. 2023).

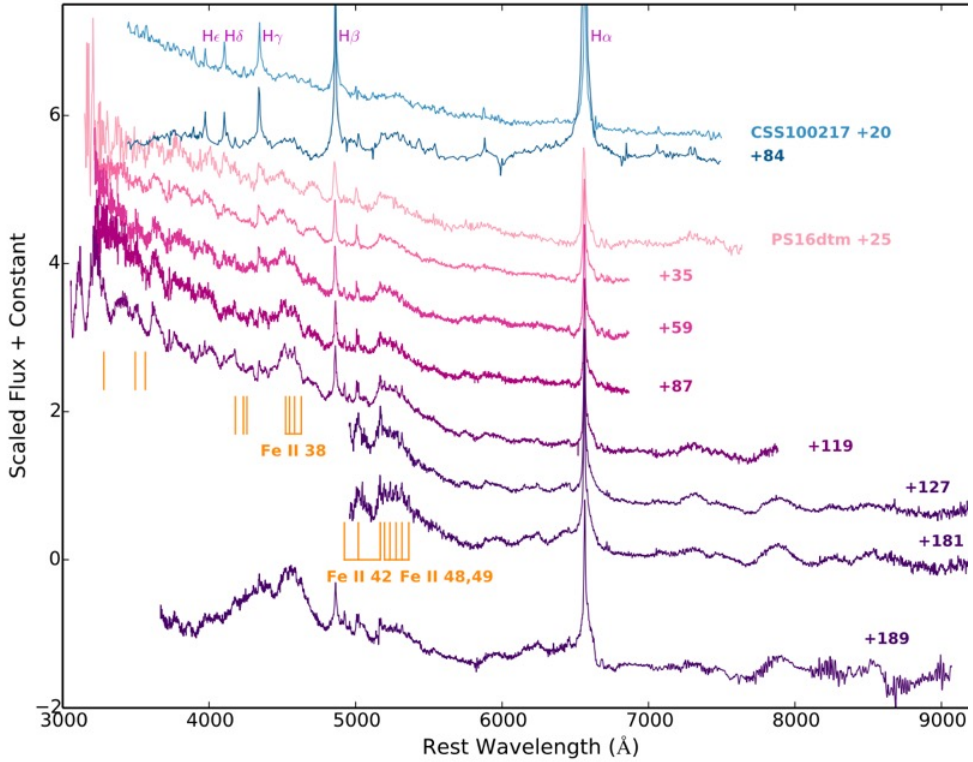
CASE OF PS16DTM

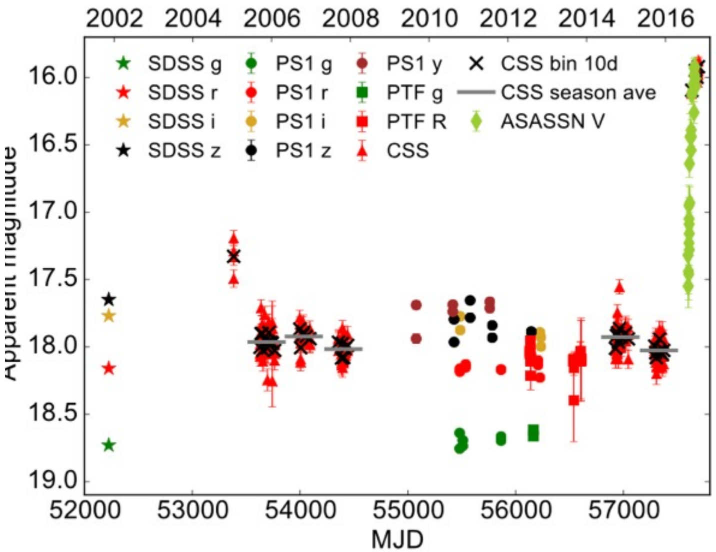


(e)

no (or very weak) Fe II

Blanchard et al. 2017



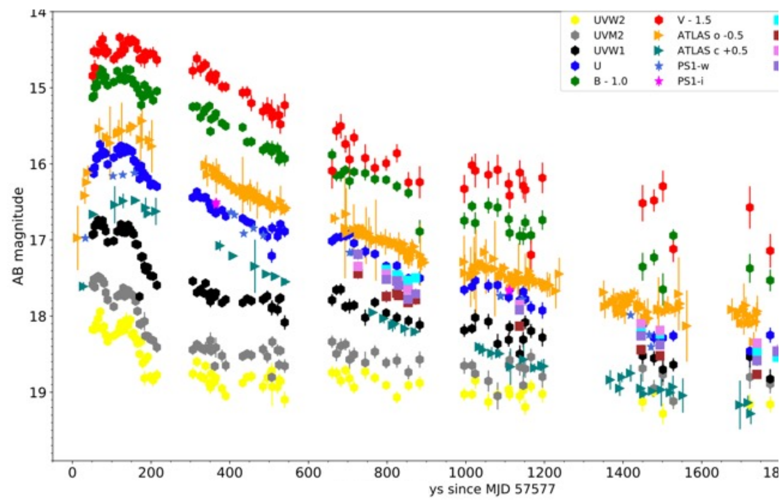


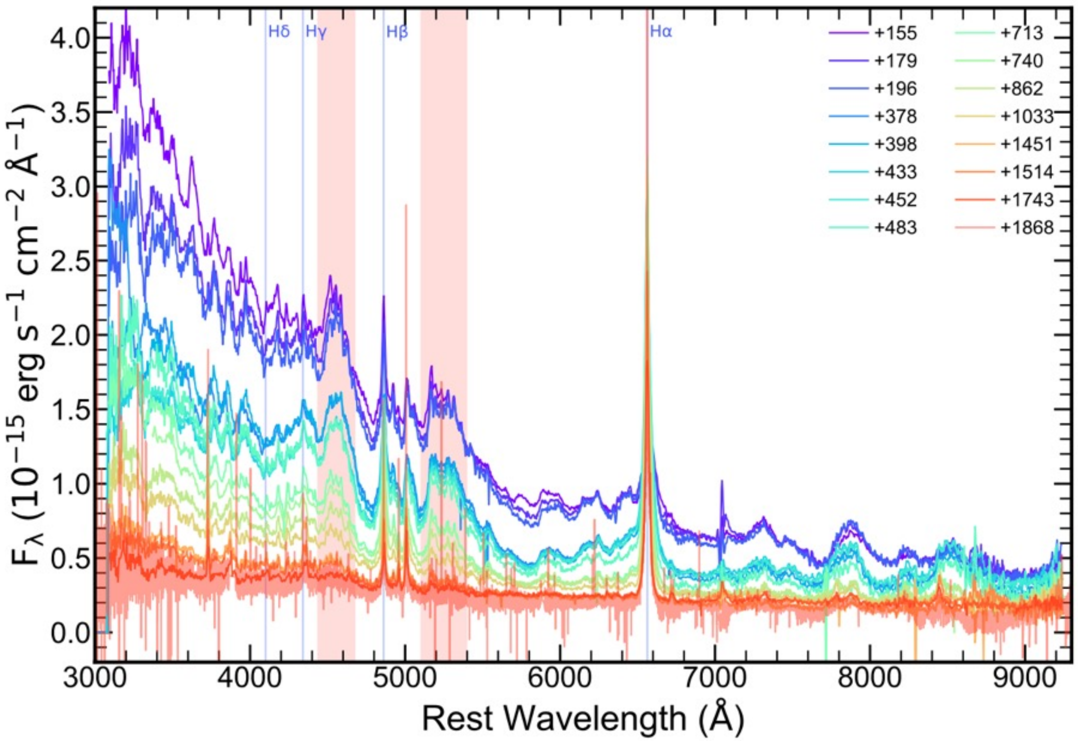
- Discovered by the Catalina Sky Survey
- Host galaxy → NLSy1 (probably), but SF present
- No increase in x-ray emission
- **super strong Fe II after the transient**
- **long-lived transient**

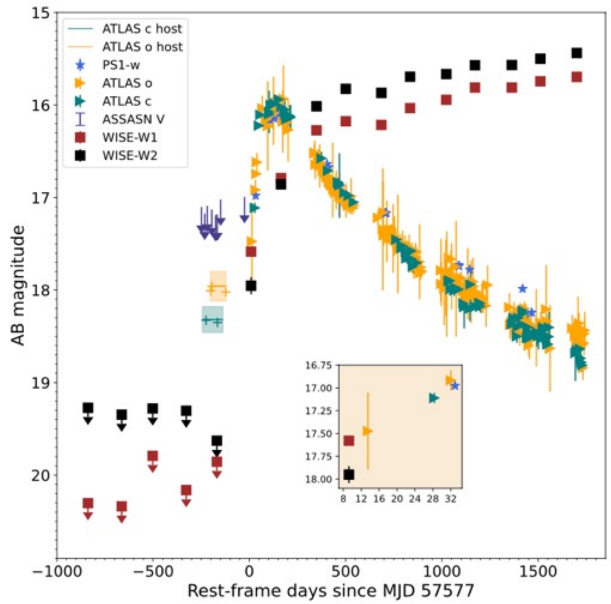
2000-DAYS FOLLOW-UP OF PS16DTM

Multi-wavelength photometric and speftroscopic follow-up
(T. Petrushevska , G. Leloudas, D. Ilic et al. 2023)

Our spectra taken between +155 and +1868 days past the outburst

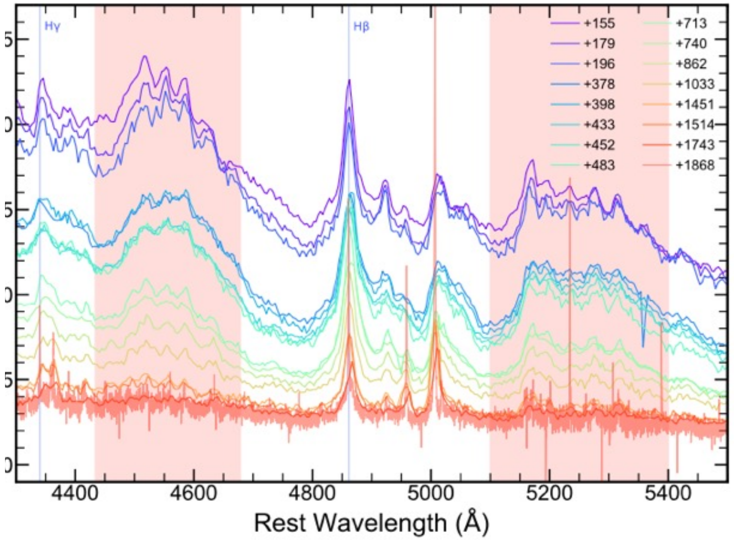


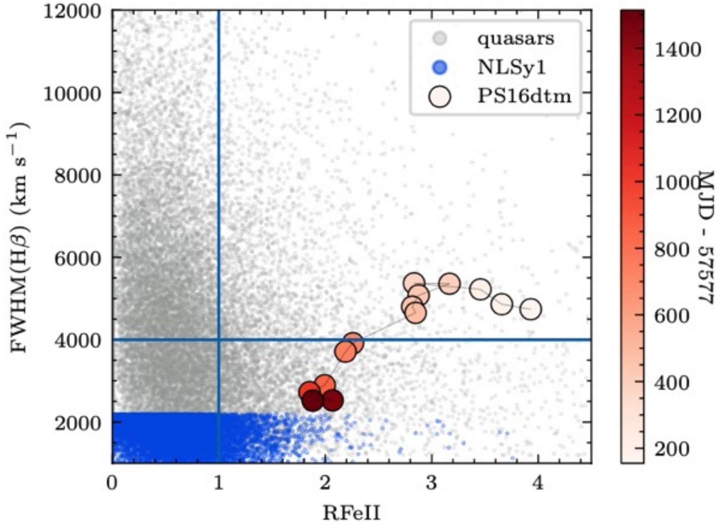


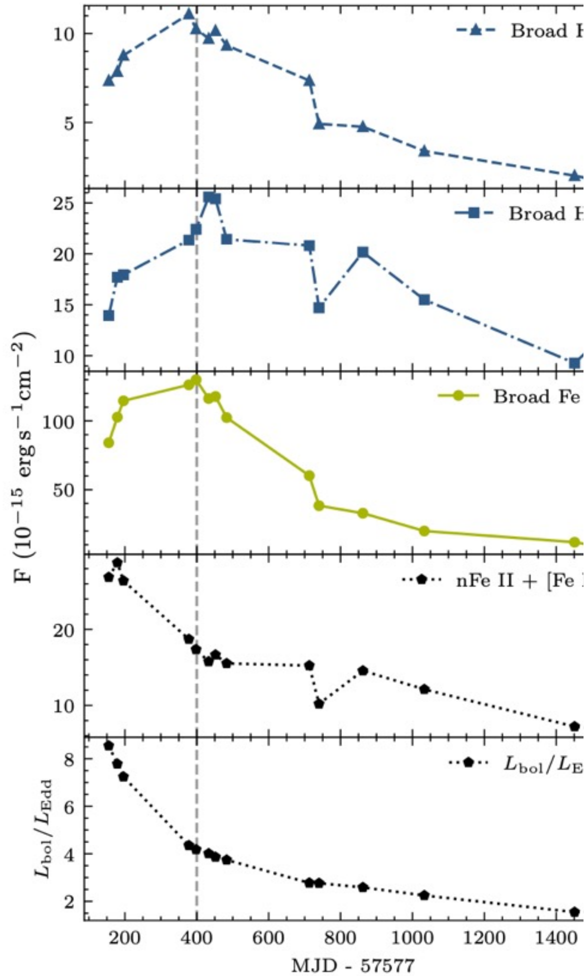


FE II IN TDE

Ilić+ 2023, ApJS





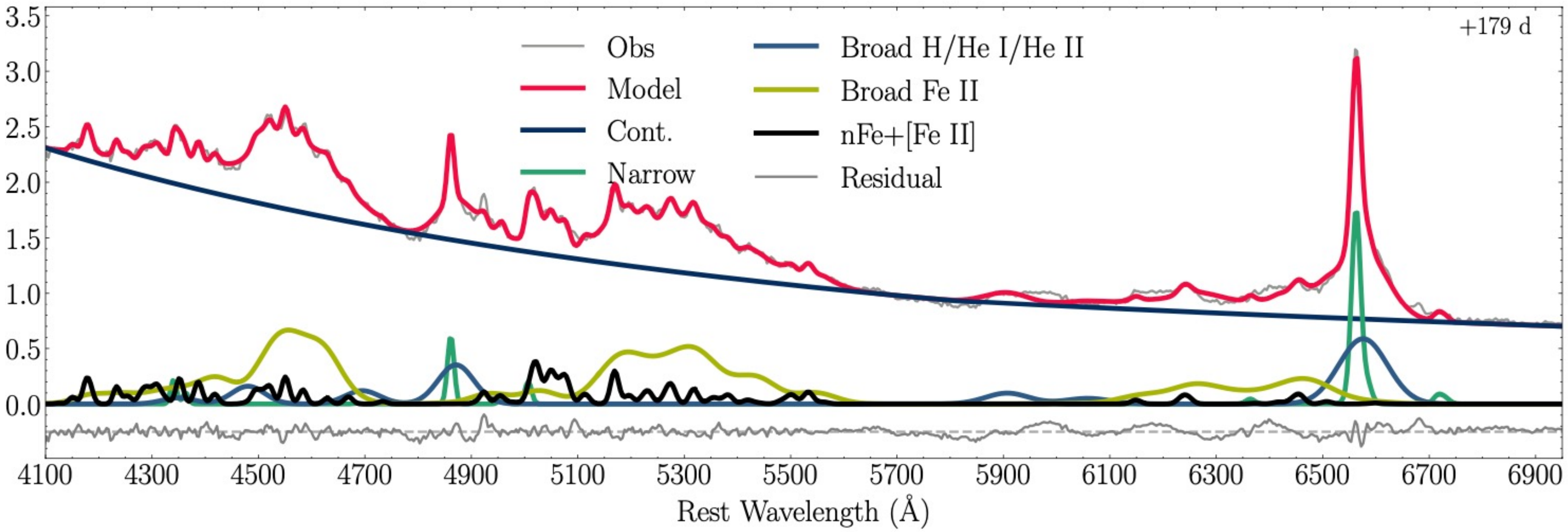


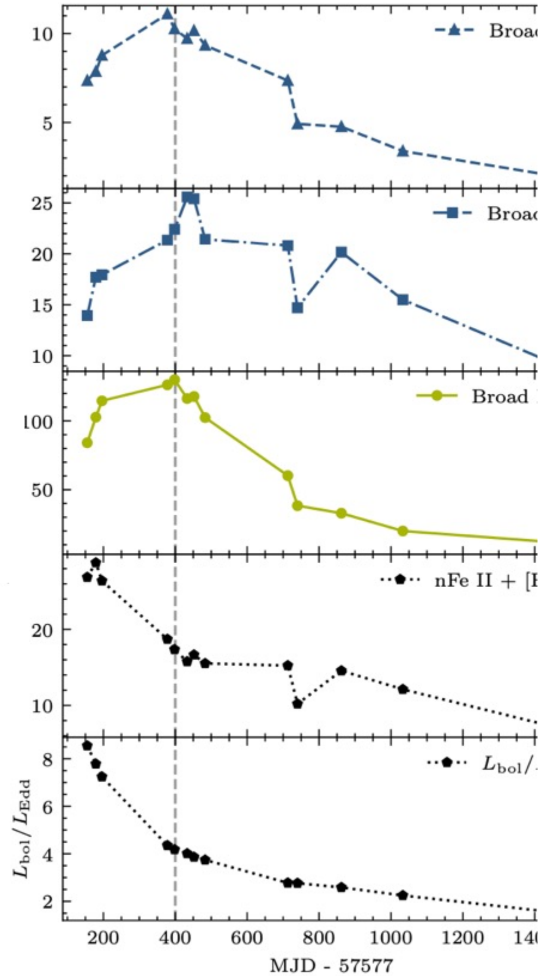
- Fe II (broad and narrow component) - **transient**
- Fe II increases, then decrease, until fully disappears (VLT XShooter spectrum)
- Coronal lines identified after the burst

Petrushevska , G. Leloudas, D. Ilic et al. 2023)

FE II IN TDE

Ilić+ 2023, ApJS





- Fe II (broad and narrow component) - **transient**
- Fe II increases, then decrease, until fully disappears (VLT XShooter spectrum)
- Coronal lines identified after the burst

(Petrushevska , G. Leloudas, D. Ilic et al. 2023)

Ilić+ 2023, ApJS

FANTASY TOOL

Fully **A**utomated pytho**N** **T**ool for **A**GN **S**pectra anal**Y**sis → **FANTASY**

optimized for AGN optical &NIR spectra (3000-11,000A), but also UV

atonomous & flexible

variety of data-produces

open-source: github → **pip install fantasy_agn**

features:

- Different reading classes
- Preparation of spectra (e.g. reddening, redshift, NaN values)
- Host galaxy removal – using eigenvectors
- Libraries of significant emission lines
- FeII lines model
- Fitting uncertainties (Monte Carlo bootstrap method)

FANTASY

Fully Automated pythoN Tool for AGN Spectra analYsis

Rakić 2022, Ilic+20

Example usage in e.g.

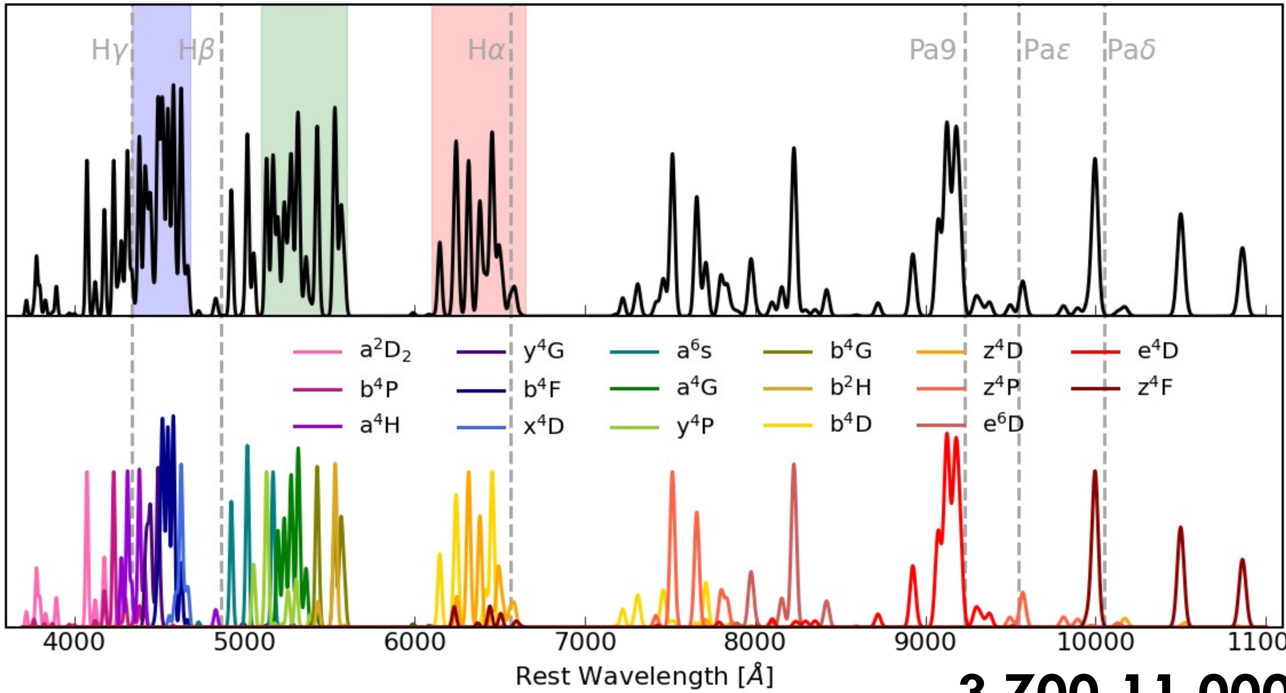
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **532,** 424–437 (2024) https://doi.org/10.1093
Advance Access publication 2024 June 18

[O III] emission in $z \approx 2$ quasars with and without broad absorptio

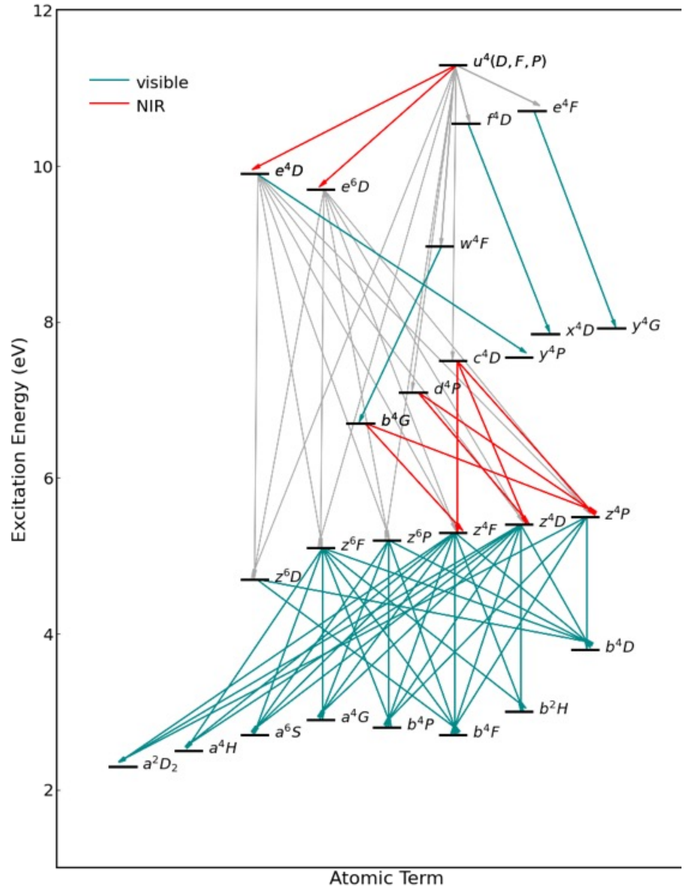
Matthew J. Temple[1,2★] Amy L. Rankine[3] Manda Banerji[4] Joseph F. Hennawi[5,6] Paul C. Hewett[7] James H. Matthews[8] Riccardo Nanni,[5,6] Claudio Ricci[2,9] and Gordon T. Ricl

Fe II MODELL FOR AGN (NOT TEMPLATE)

- Model of FeII emission **(3,700-11,000A)** using atomic data (based on Popovic et al. 2002, Kovacevic et al. 2010)



3,700-11,000A

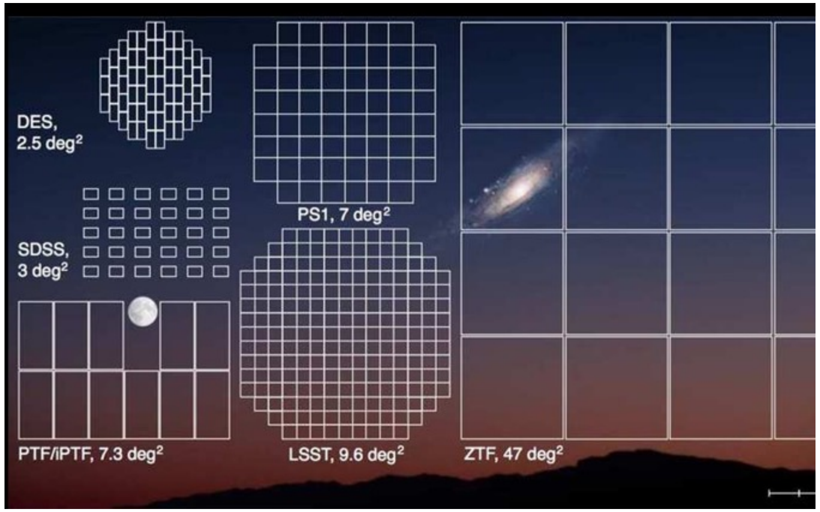


Ilić, Rakić, Popović 2023, ApJS

OPTICAL TIME-DOMAIN FACILITIES

ZTF = ZWICKY TRANSIENT FACILITY

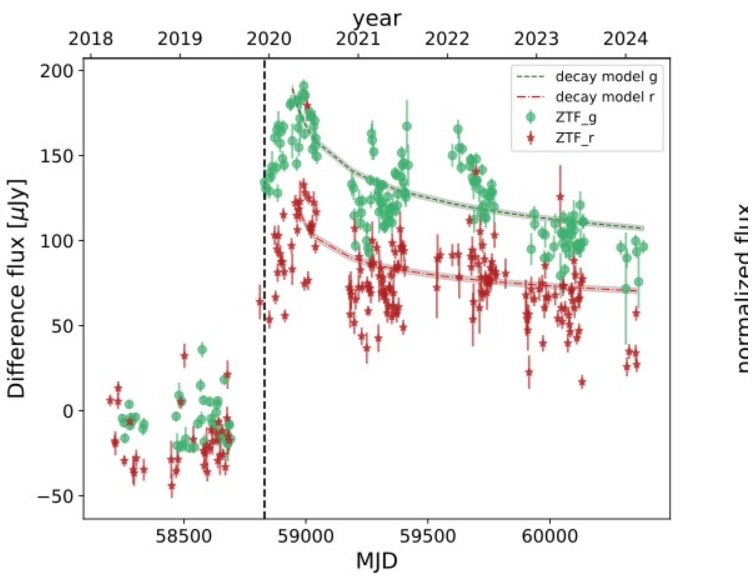
- extremely wide-field of view camera, ZTF scans the entire Northern sky every two days
- generating **alert streams** in real time
- For AGNs, particularly interesting are nuclear transients:
  - tidal disruption events (TDEs);
  - AGN with changing-state events (CSAGNs, also known as changing-look AGNs, see Ricci & Trakhtenbrot 2023);
  - AGNs with anomalous flaring activity (e.g. Trakhtenbrot et al. 2019a; Frederick et al. 2021);
  - ambiguous nuclear transients (ANTs; e.g. Hinkle et al. 2022).

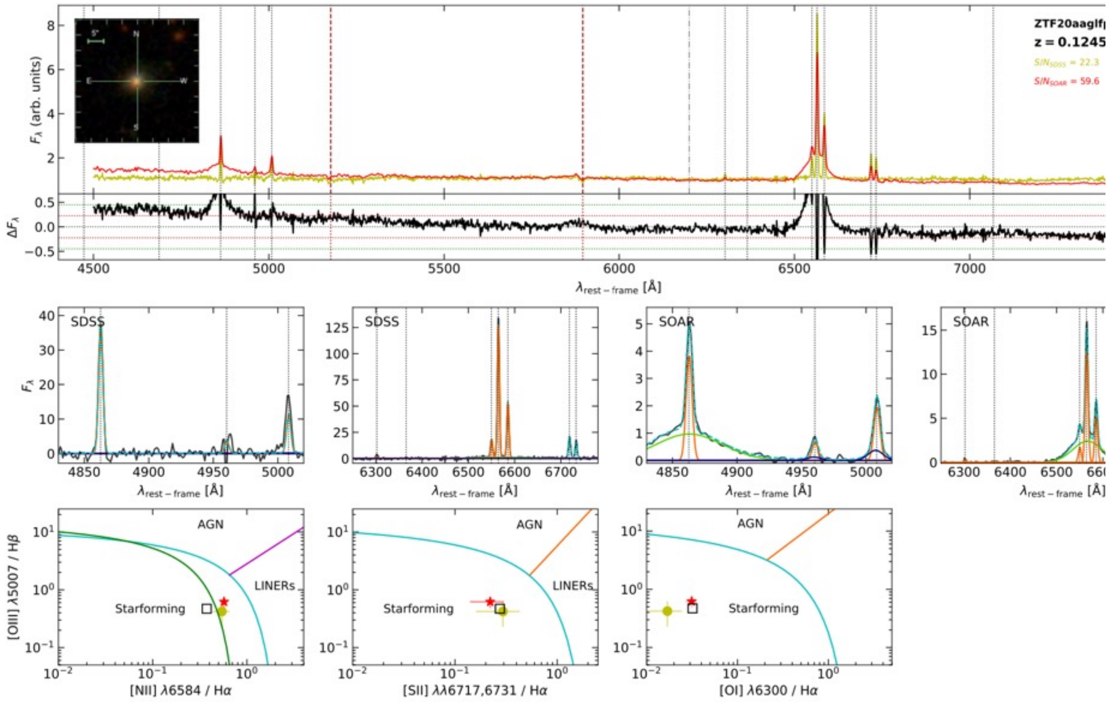


SOME RECENT ZTF DISCOVERIES

Awakening a Supermassive Black Hole: ZTF20aaglfpy (Arevalo et al. 2024): from 2M sources, found 36 candidates for turn-on AGNs

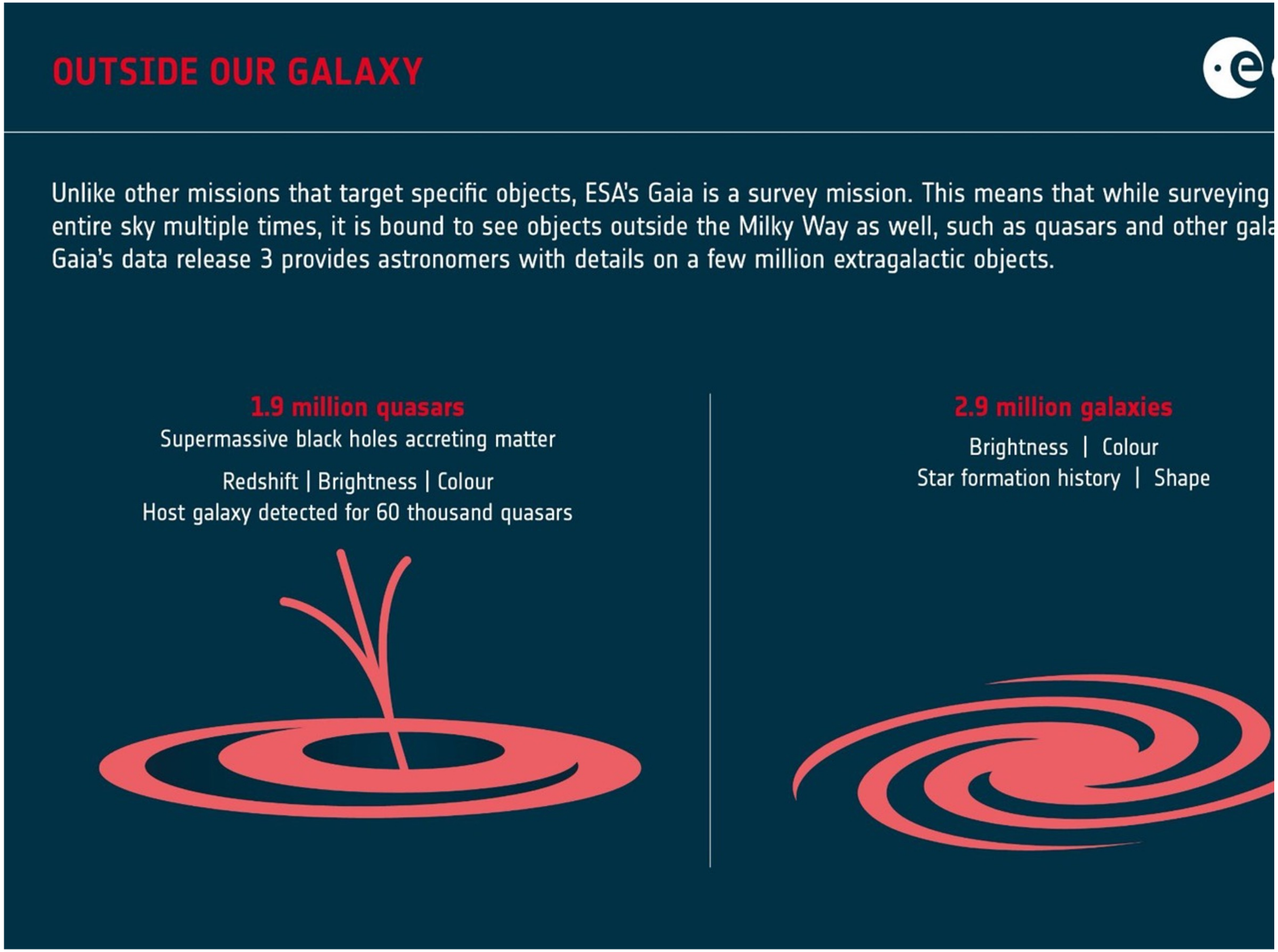
SDSS1335+0728: The awakening of a ~10^6 $M_\odot$ black hole (Sánchez-Sáez et al. 2024)





GAIA

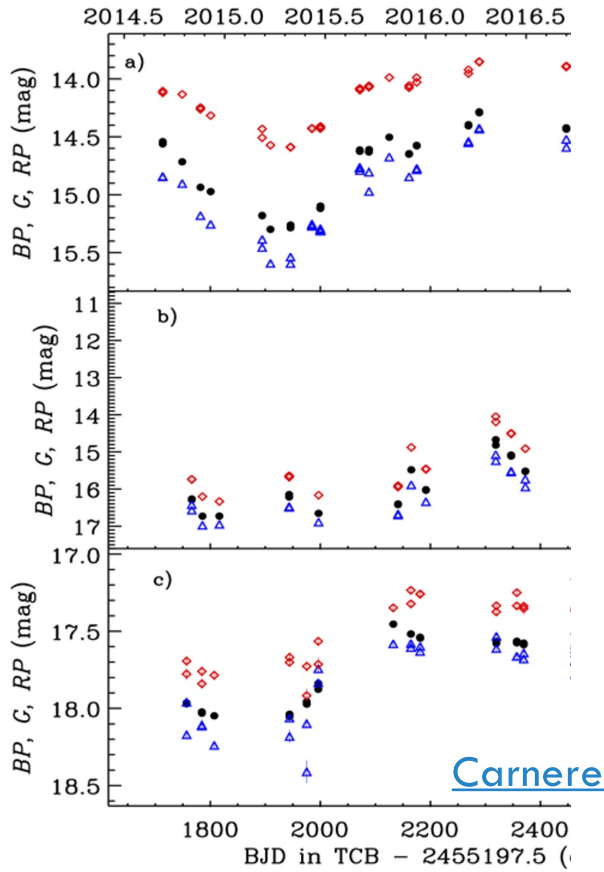
Astrometry mission for Milky Way stars, but also extragalactic



EXTRAGALACTIC SCIENCE WITH GAIA DR3

Gaia Coll., Bailer-Jones 2023

- two "main" DR3 extragal. tables: qso_candidates & galaxy_candidates
- 6.6M & 4.8M sources, respectively; flags available
- light curves available



Examples from Carnerero+ 2023:

Up: Type 1 Seyfert galaxy
PG 0921+525

Mid: blazar CTA 102 during
2016-2017 outburst

Down: quasar B2 0945+22

Carnerero+

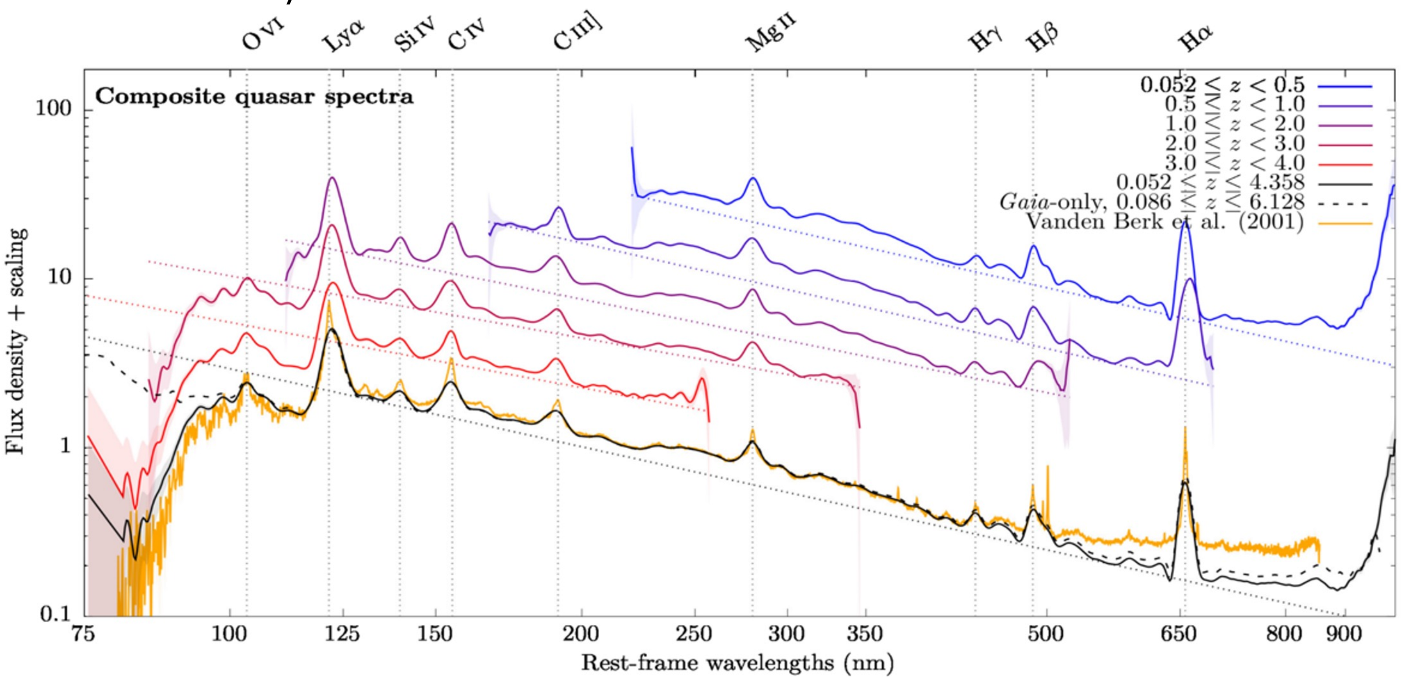
Slides adapted from lectures by Lovro Palaversa

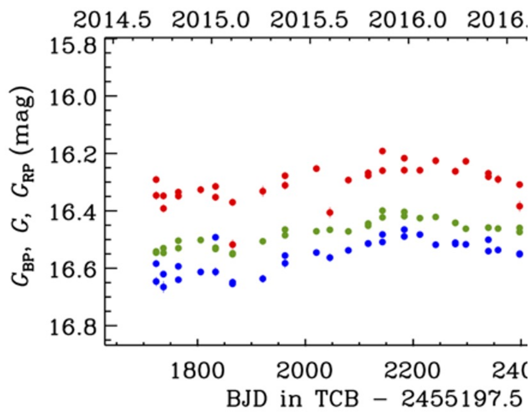
COMPOSITE QUASAR SPECTRA

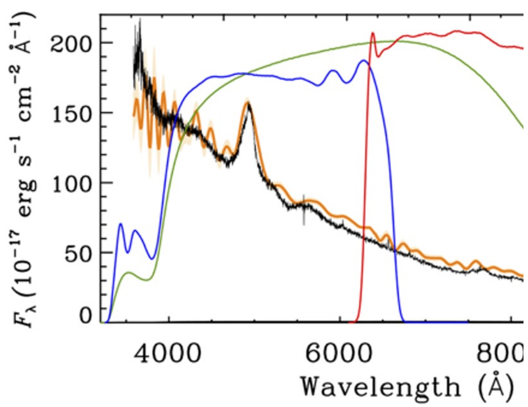
radio-quiet quasar
FBQS J163709.3+41403(
[Carnerero+23]

43k BP/RP spectra with spectroscopical redshifts from Flesch+21

111.5k BP/RP with QSOC redshifts







[Gaia Coll., Bailer-Jones 23]

Slides adapted from lectures by Lovro Palc

Getting ready for

Legacy Survey of Space and Time LSST

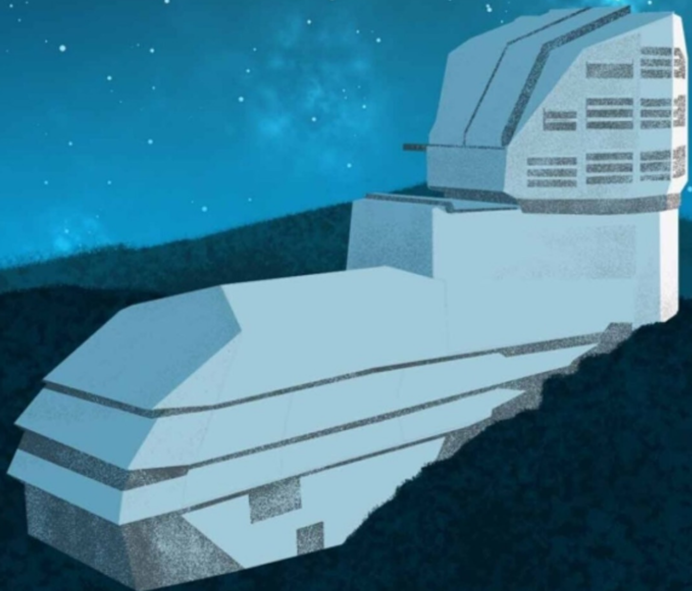
- Vera C. Rubin Observatory
- 10-year Legacy Survey of Space and Time (LSST)
- 8.4m telescope, largest ever CCD
- 500 petabyte set of images and data products
- Massive time domain astronomy
- LSST start in 2025
- **Big data, movie of the sky**

https://www.lsst.org/about/timeline

Rubin Observatory/NSF/AURA/A. Pizarro D

npprecedented data
olume to be
veraged for
ultiple science goals.

LSST - KEY SCIENCE PILLA



1. Understanding the nature of dark matter and dark energy
2. Creating an inventory of the Solar System
3. Mapping the Milky Way
4. **Exploring objects that change position or brightness over time, calle "transients"**

VERA C. RUBIN
OBSERVATORY

AGNs WITHIN THE LSST

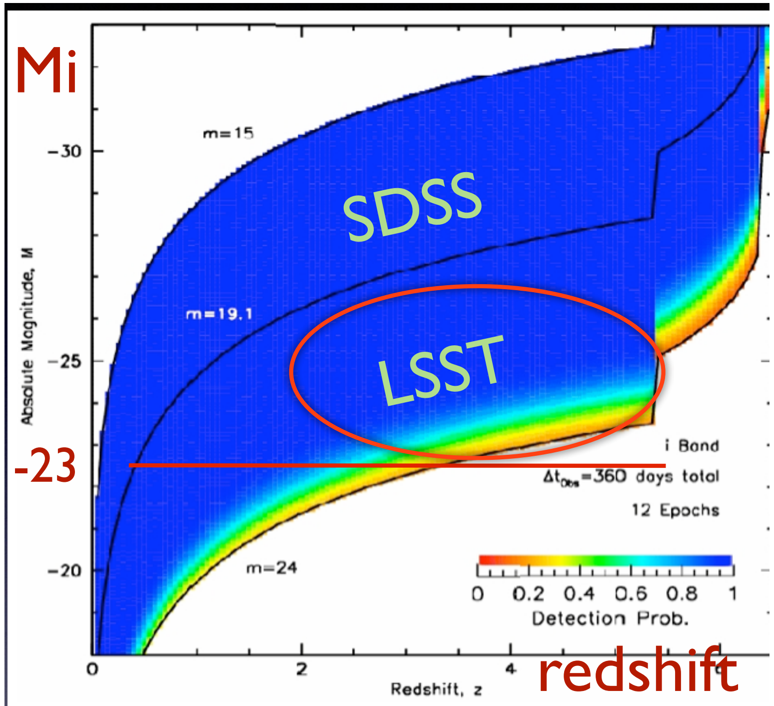
discovery about 10 million quasars

- based on colors, variability, lack of proper motion
- detection of ~10,000 quasars at 6<z<7.5

5 Deep Drilling Fields (DDFs):

- COSMOS, XMM-LSS, ECDFS, ELAIS-S1, EDFS

AGN Variability – based on million of light curves with 1000 epochs over 10 years



Top: absolute magnitude vs. redshift diagram for quasars

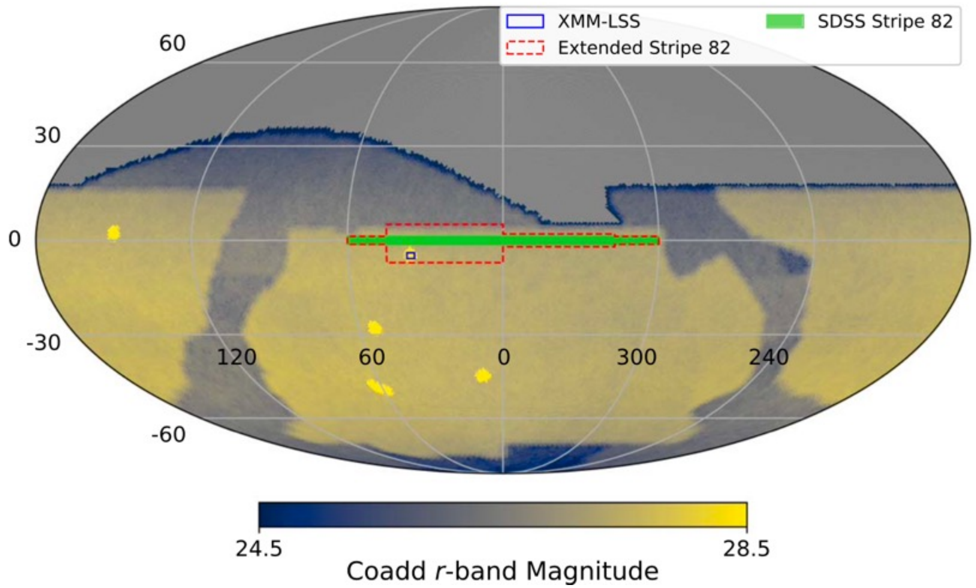
Learn more through AGN Science Collabora
@https://agn.science.lsst.org

LSST AGN DATA CHALLENGE

AGN Science Collaboration:
https://agn.science.lsst.org

Data Challenge in 2021
- **Data sets available**
  https://github.com/RichardsGroup/AGN_DataChallenge

partial prototype of the expected LSST data on AGNs
- SDSS Stripe 82
- XMM-Newton Large Scale Structure Survey
- Multi-wavelength data set + time-domain data from SDSS



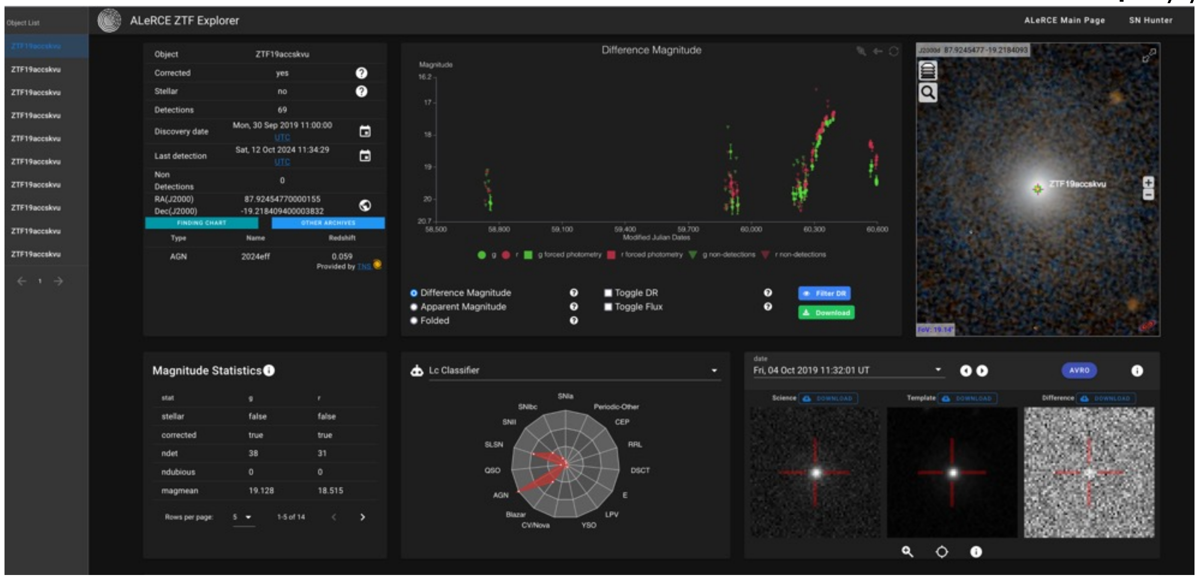
Classification of AGNs based on ML, Savic et al., 2023

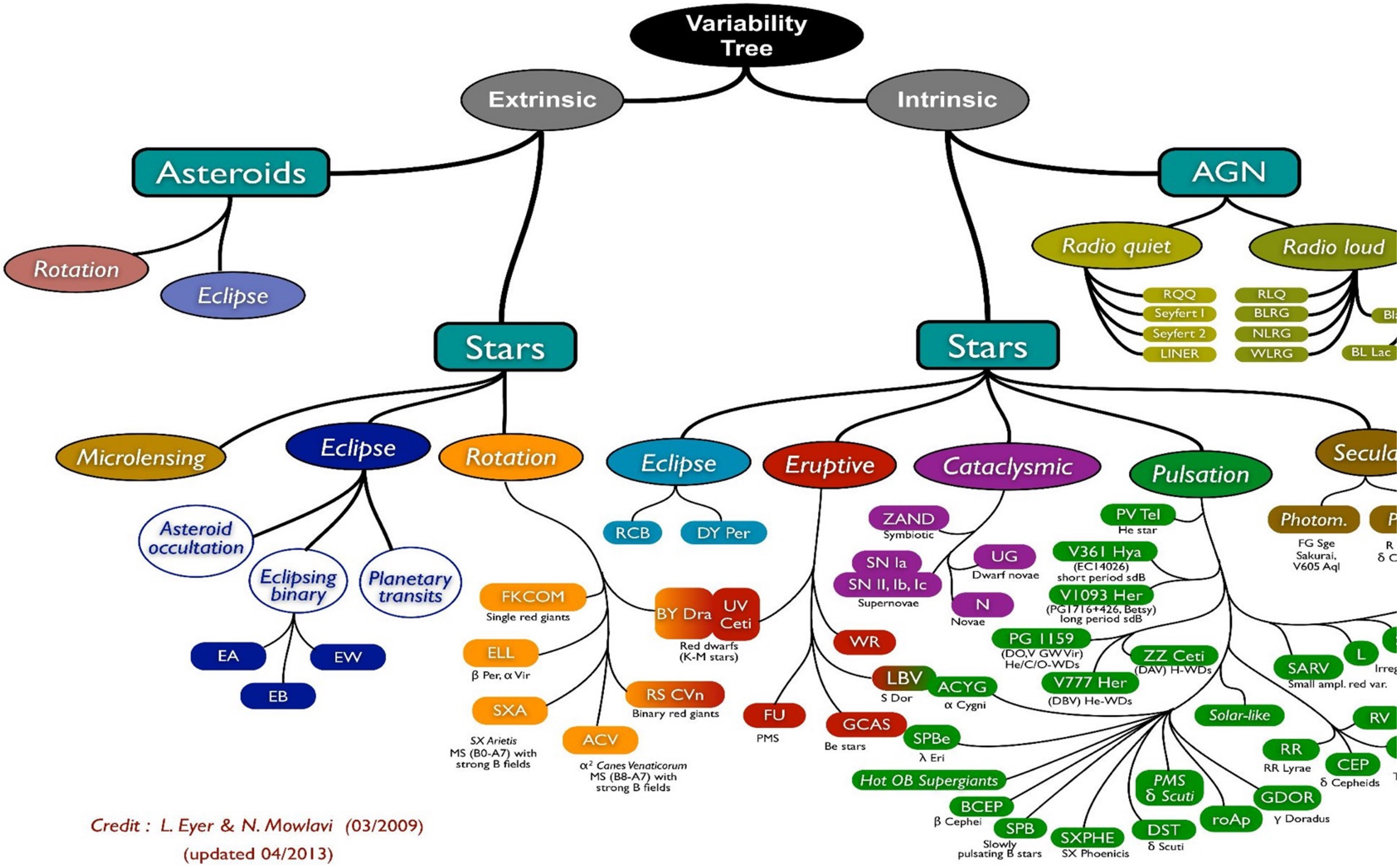
ALERT BROKERS

Letting the community knows what has changed on the sky

- Prompt Data Product – **Public Data**
- Difference Image Analysis
- Alerts in LSST: up to 10 million per night

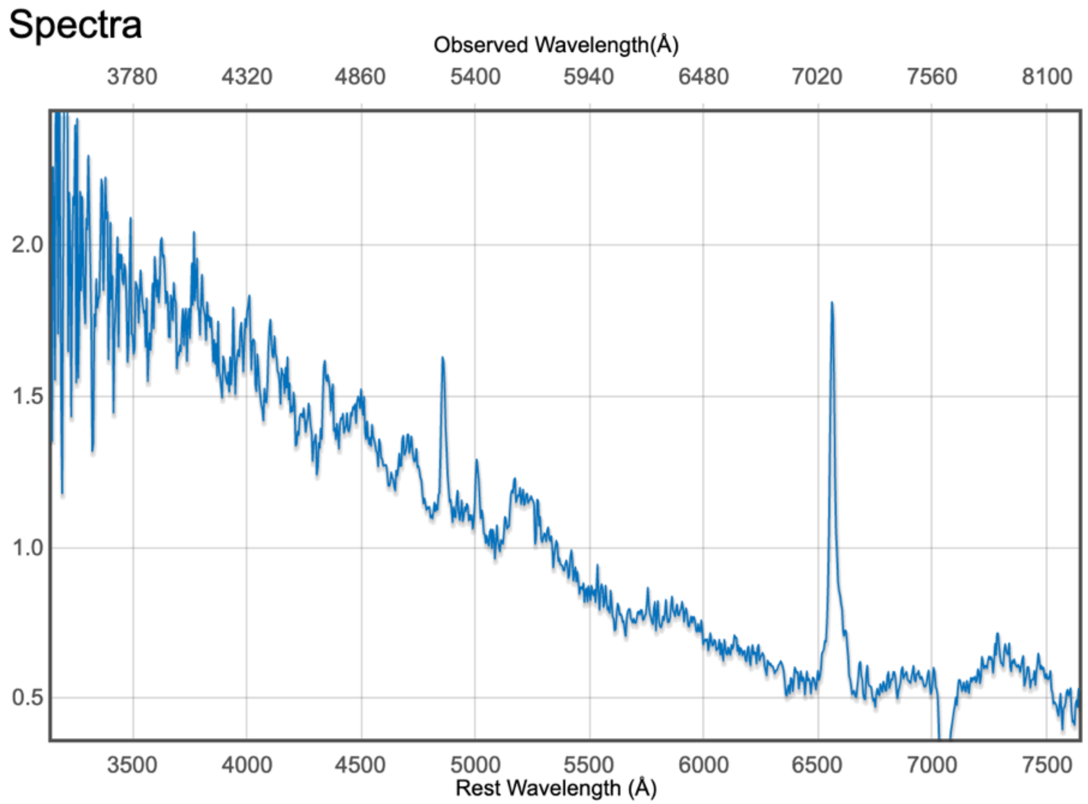
https://alerce.science/





Variability Tree
Extrinsic
Intrinsic
Asteroids
Rotation
Eclipse
Stars
Microlensing
Eclipse
Rotation
Asteroid occultation
Eclipsing binary
Planetary transits
EA
EW
EB
FKCOM
Single red giants
ELL
β Per, α Vir
SXA
SX Arietis
MS (B0-A7) with strong B fields
ACV
α² Canes Venaticorum
MS (B8-A7) with strong B fields
RS CVn
Binary red giants
BY Dra
UV Ceti
Red dwarfs (K-M stars)
AGN
Radio quiet
Radio loud
RQQ
Seyfert 1
Seyfert 2
LINER
RLQ
BLRG
NLRG
WLRG
BL Lac
Stars
Eclipse
RCB
DY Per
Eruptive
FU
PMS
WR
LBV
S Dor
ACYG
α Cygni
GCAS
Be stars
SPBe
λ Eri
Cataclysmic
ZAND
Symbiotic
SN Ia
SN II, Ib, Ic
Supernovae
UG
Dwarf novae
N
Novae
Pulsation
PV Tel
He star
V361 Hya
(EC14026)
short period sdB
V1093 Her
(PG1716+426, Betsy)
long period sdB
PG 1159
(DO,V GW Vir)
He/C/O-WDs
ZZ Ceti
(DAV) H-WDs
V777 Her
(DBV) He-WDs
Hot OB Supergiants
BCEP
β Cephei
SPB
Slowly pulsating B stars
SXPHE
SX Phoenicis
PMS δ Scuti
DST
δ Scuti
roAp
GDOR
γ Doradus
Solar-like
RR
RR Lyrae
CEP
δ Cepheids
RV
SARV
Small ampl. red var.
L
Photom.
FG Sge
Sakurai,
V605 Aql
Credit : L. Eyer & N. Mowlavi (03/2009)
(updated 04/2013)

WHAT IS THE OBJECT BEHIND A SPECTRUM?



SN 2016ezh

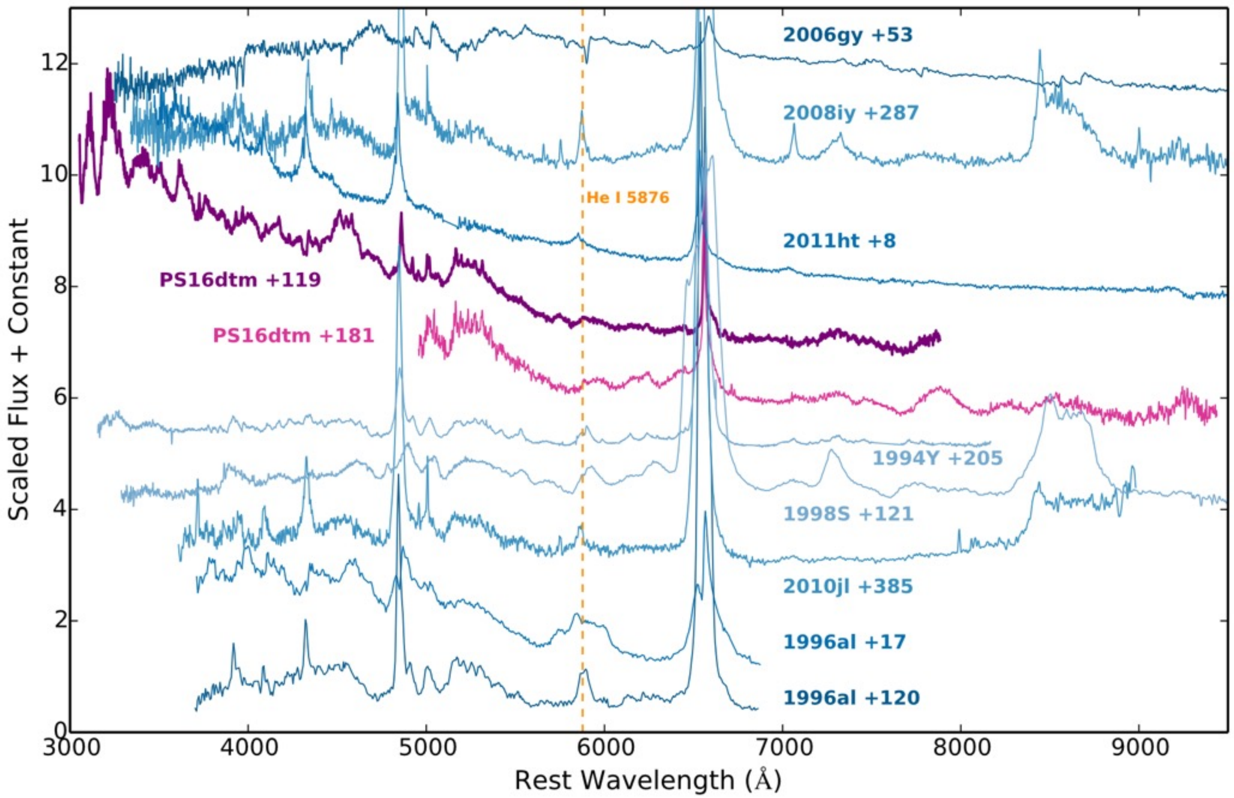
Classified as:
Type: *SN II*
Redshift: *0.08*
(Padova-Asiago Supernova Group)

https://www.wis-tns.org/object/2016ezh
https://ui.adsabs.harvard.edu/abs/2016ATel.9417....1T/abst

WHAT IS THE OBJECT BEHIND A SPECTRUM?

2016ezh
6dtm

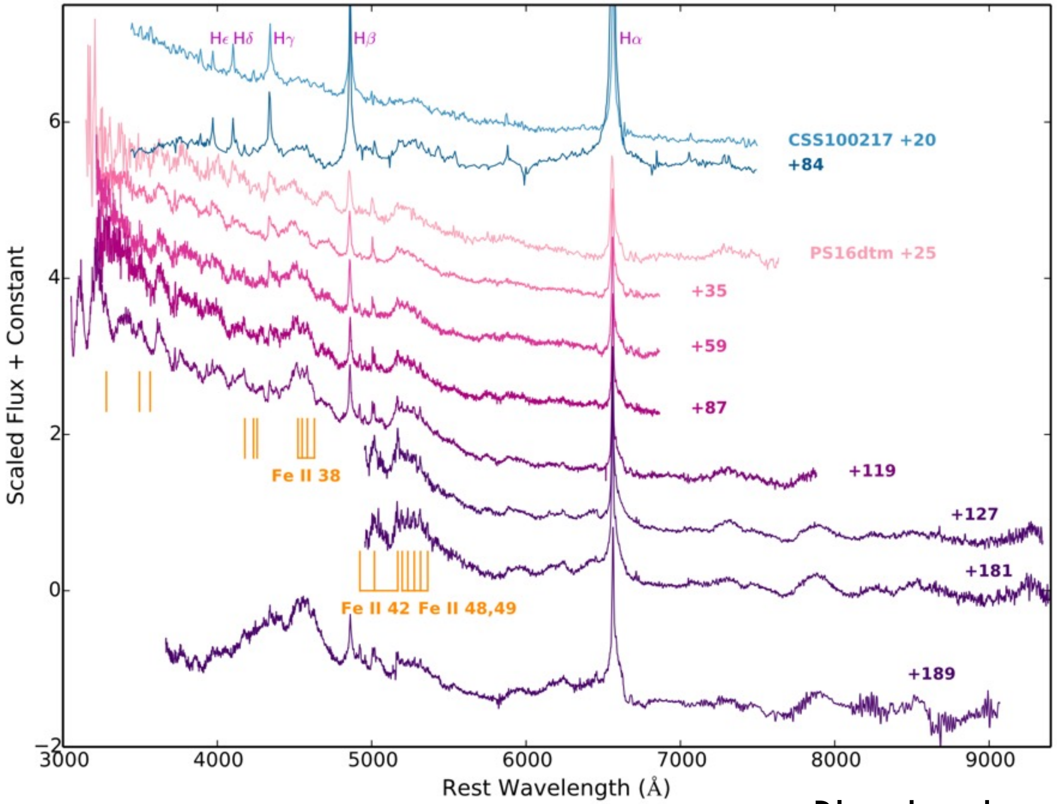
per strong
emission



Degenracy is present.

Blanchard et al. 2017

WHEN SPECTRA WERE TAKEN?



200 days evolution of PS16dtm

- transient event in an AGN (not just any but in a Narrow-line Seyfert 1)

- most argue it is a TDE…

Blanchard et al. 2017

NUCLEAR TRANSIENTS IN AGNs

1. detection
2. classification
3. characterization
4. follow-up

1. DETECTION

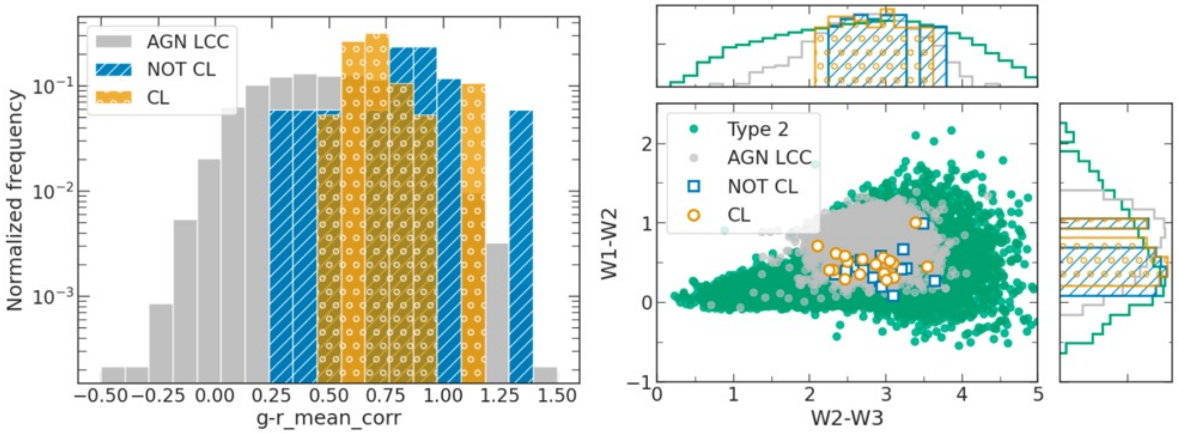
alert stream - 5σ magnitude limits from and r difference images in the previous 3 days, where the target associated with th alert was not detected

Surveys & Brokers are doing an amzingly great work

→ they say that they can do better

→ missing CL AGN

Example: improve detection of turning-on CL AGN with ML on multi-wavelength variability data (optical, mid-infrared, X-ray)

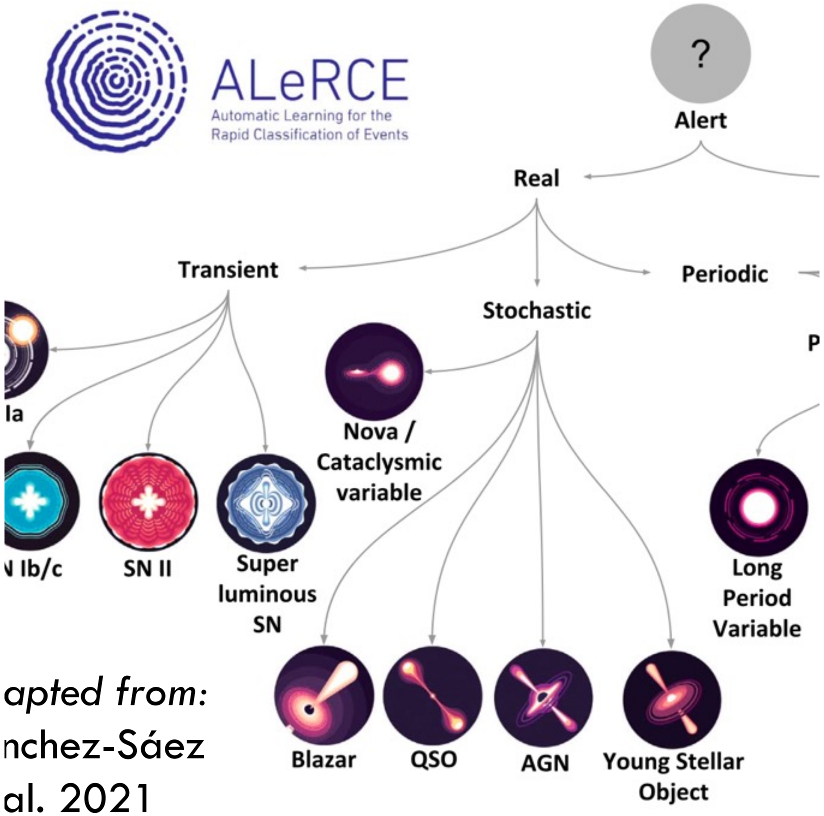


Lopez-Navas et al. 2023

2. CLASSIFICATION

Surveys & Brokers are doing an amzingly great work

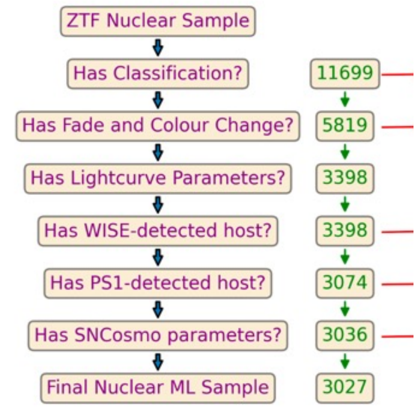
→ they say that they can do better

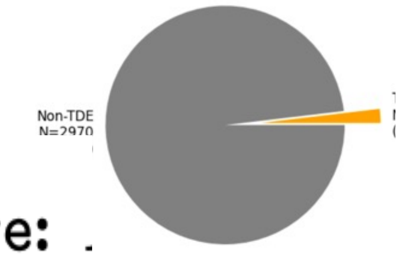


apted from: nchez-Sáez al. 2021

Figure 2. Taxonomy tree used in the current version of the ALe

- identify new training features
- increase training sets
- include pre-alert light curves
  (brokers to have access to forced photometry for xy-time prior to an alert)
- 'AGN—TDEs' ?





tdescore: .

ZTF, Stein et al. 2023

3. CHARACTERISATION

Identify light curve features

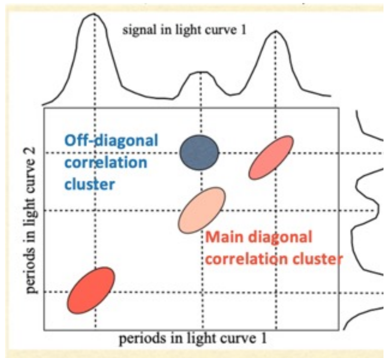
- e.g. detect periodic oscilations in quasar light curves → Quasar harmonic explorer – QhX

- e.g. photometric RM → PyZDCF = Python module of a Fortran program ZDCF (Z-transformed Discrete Correlation Function, Alexander 1997)

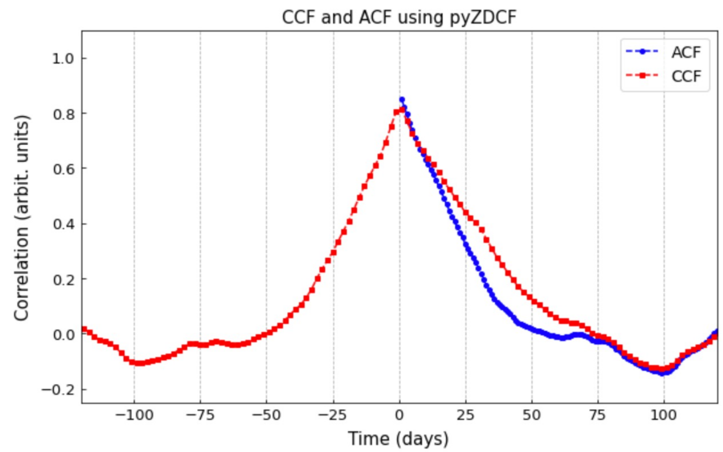
- https://pyzdcf.readthedocs.io/en/latest/index.html

"Photometric reverberation mapping of AGNs" → Notebook on NOIRLab Astro Datalab

Example usage:
LSST AGN DC (Richards & You 2021)
Applied on 40,000 quasars to find periodic variability



Kovacevic et al. 2023
Kovacevic et al. 2018



Jankov, I., Kovačević A. B., Ilić, D., et al. 2022, AN, 343, e210

4. FOLLOW-UP

Absolutly necessary for the characterisation and understanding

- multi-epoch spectroscopy
- multi-epoch photometry
- multi-wavelength

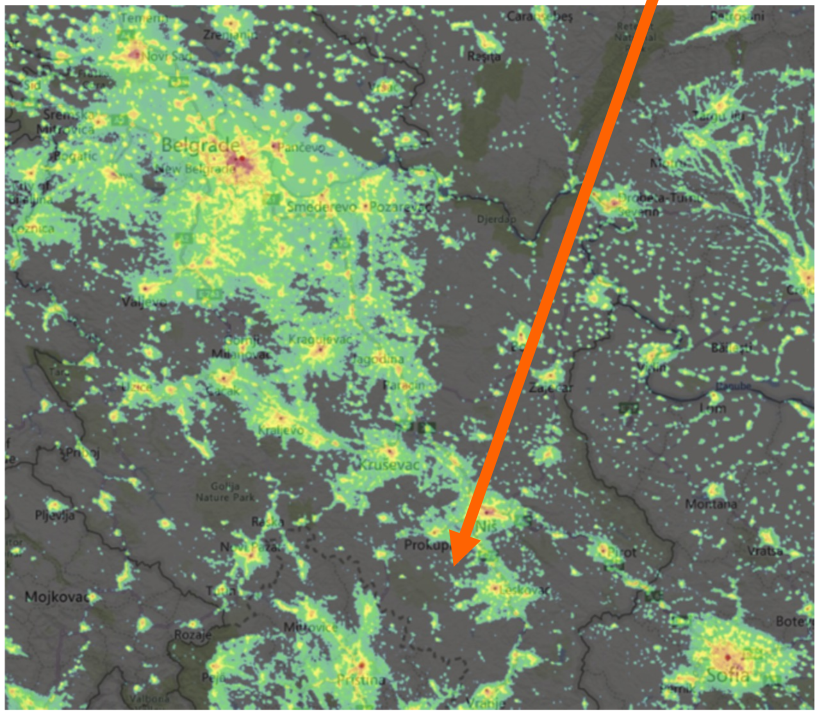
Lo-Term AGN campaign
(Ilic et al. 2024)

3640 transients classified by PESSTO so fa
1142 transients are being followed
PESSTO

ASTRONOMICAL STATION VIDOJEVICA (ASV)

Observation site established by Astronomical Observatory of Belgrade.

ASV located on Mt. Vidojevica - small light pollution, and good seeing conditions.



of light pollution from https://www.lightpollutionmap.info

- About 40% of observational nights at ASV are with very good weather for observations.
- Average seeing is 1”- 2” (best seeing ~ 0.7").
- Largest facility is 1.4m Milankovic telescope
- Possibility of fast response (moving speed is 4-6 degree/sec)
- Currently only photometry
- Plan: upgrade to a multi-purpose instrument with spectroscopy and polarimetry

1.4M TELESCOPE MILANKOVIĆ

Port 1 @ telescope Milanković

Equipped with focal reducer 0.65, focal length 7132 mm (11200 mm).

- Andor iKon-L 936:
  - Active pixels 2048 x 2048
  - Sensor size 27.6 x 27.6 mm
  - Pixel size (W x H) 13.5 µm x 13.5 µm
  - Maximum readout rate 5 MHz
  - Read noise 2.9 e-
  - Maximum cooling -100°C
- Scale 0.39 arcsec/pixel, FoV 13.3 x 13.3 arcmin
- Available filters: B, V, R, I, L, Ha, Ha_cont, SII

Calls for proposals twice per year, https://vidojevica.aob.rs/

Milankovic 1.4 m telescope

CONCLUSIONS

Era of massive time-domain observations of AGNs

→ transient detection (CL AGNs, TDEs)

→ classification & characterization

→ follow-up

Thank you. Questions?

THANK YOU!

SAO, September 2014

SAO, September 2

Oct 2024

SAO, Feb 20

ERASMUS MUNDUS MASTER - MASS

- Erasmus Mundus Joint Master Degree (EMJMD) program in Astrophysics and Space Science
- **Master in Astrophysics and Space Science (MASS)**
- 2 year master studies, 120
- Partner Universities:
  - University of Rome Tor Vergata, Rome Italy
  - University of Belgrade, Belgrade, Serbia
  - University of Bremen, Bremen, Germany
  - University of Côte d'Azur, Nice, France

- Soon Call for 4th Edition starting in 2025 – **Deadline Feb 15, 2025**

- **Important**: student scholarships available + dedicated scholarships for students from underrepresented regions