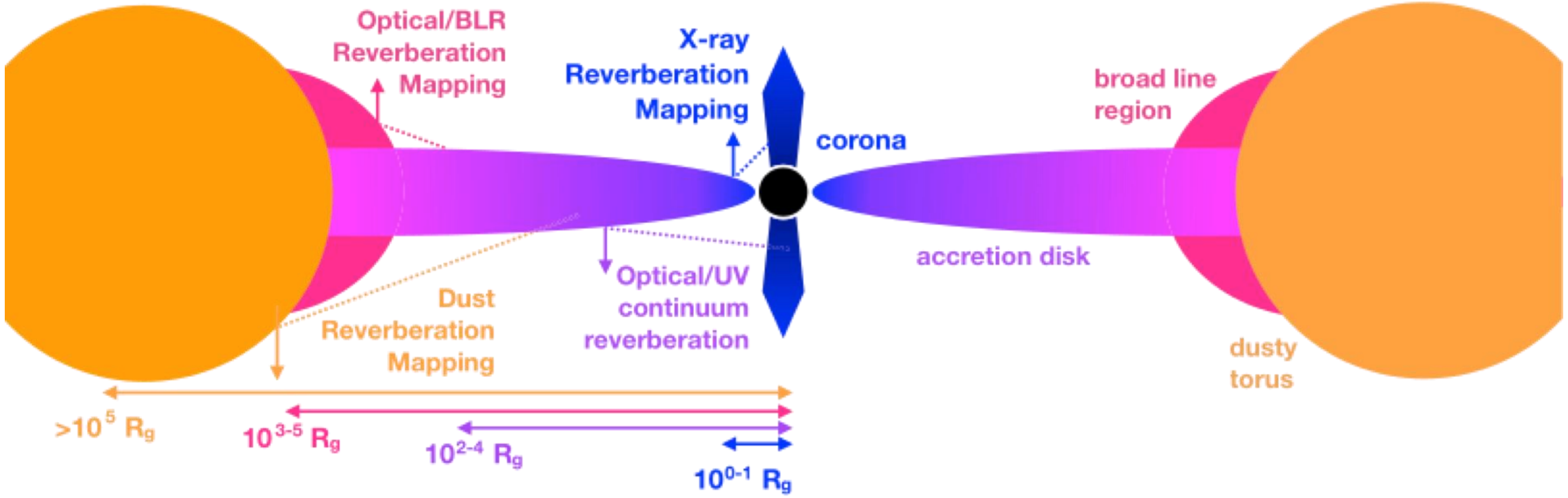
Understanding the Active Galactic Nuclei paradigm through variability studies: a path toward LSST

M.Paolillo with contributions from D.De Cicco, V.Petrecca, I. Papadakis & many others



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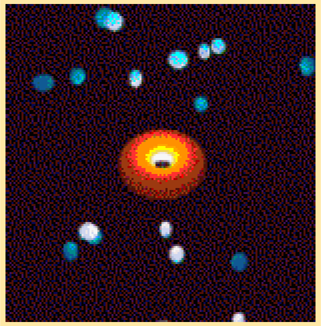
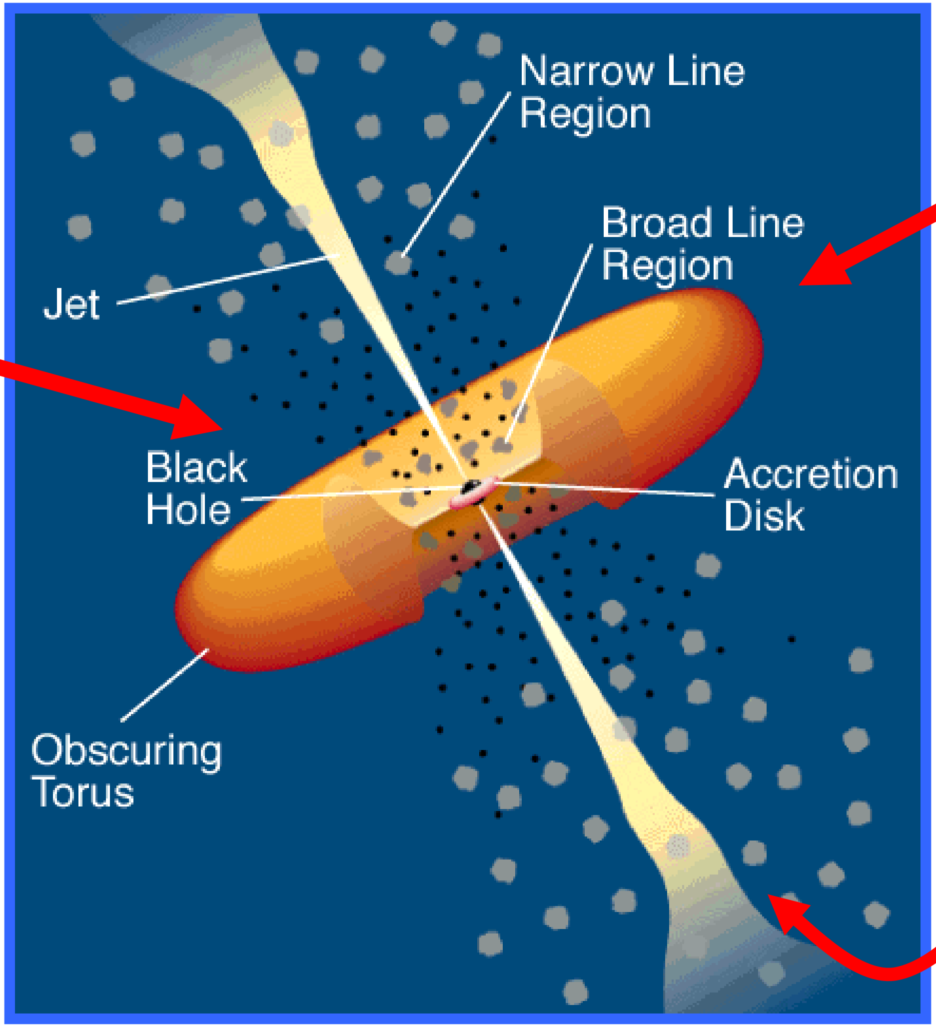
Unified model

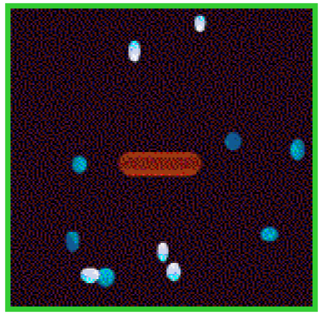
(Antonucci 1993, Urry e Padovani 1995)

What we actually see depends on the viewing angle!

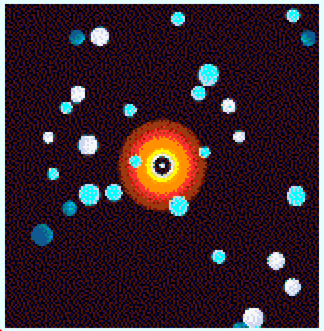
Type 1 objects:
- Seyfert 1s
- Broad Line Radio Galaxies
- Type 1 Quasars





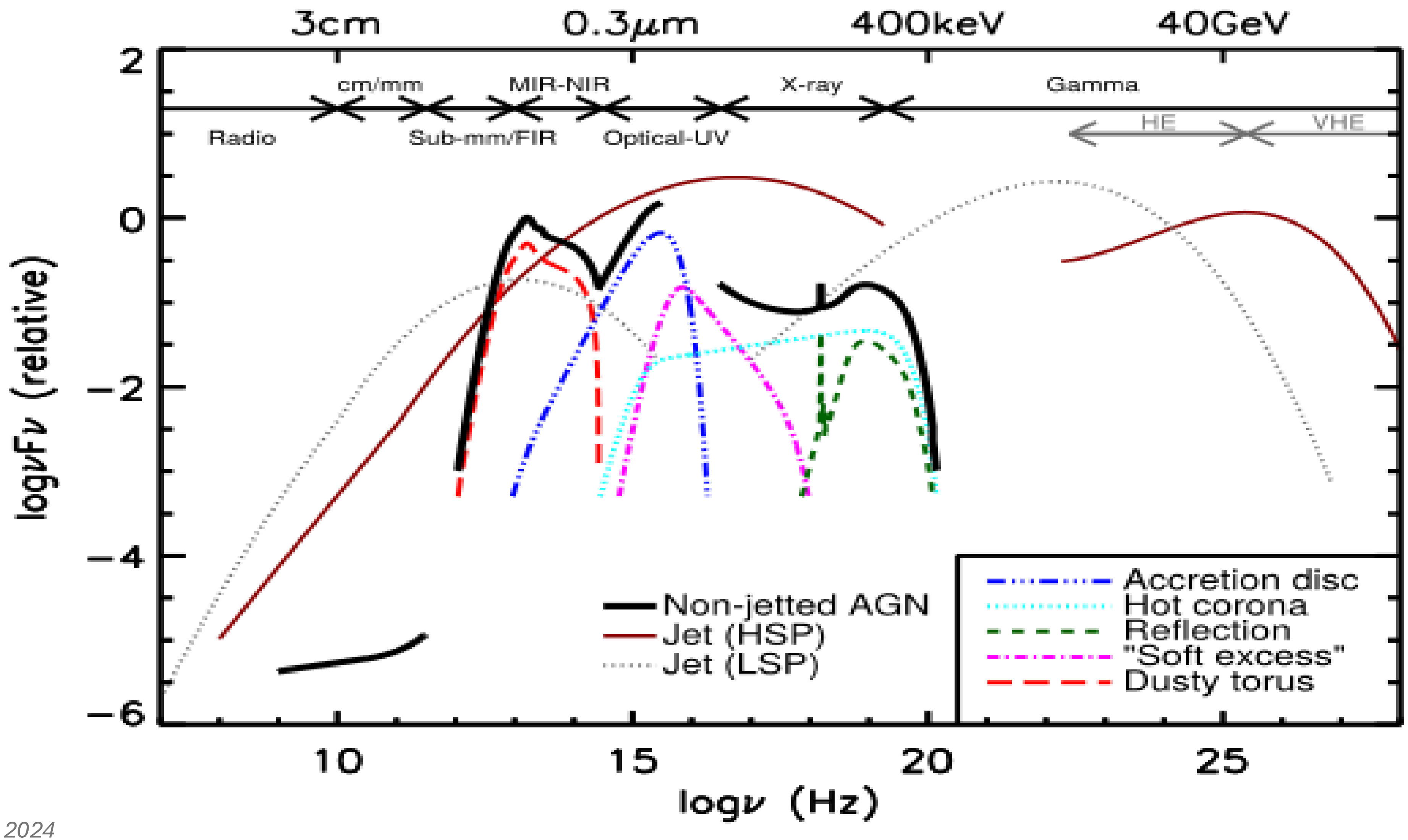


Type 2 objects:
- Seyfert 2s
- Narrow Line Radio Galaxies
- Type 2 Quasars



Blazars:
- BL Lac Objects
- OVVs

Physical complexity reflects in spectral complexity



AGN spectral components

The AGN sed is due to different spatial components emitting in different bands. Here are some of the main components that will enter our discussion:

- Radio/optical/X-ray/gamma emission from the jet due to Synchrotron and Synchrotron self-compton;
- Infrared emission due to reprocessing from the absorbing torus;
- IR, optical and UV emission due to the accretion disk;
- X-ray emission due to inverse compton scattering from the hot corona (?);
- Optical emission from the BLR and NLR;
- Hard X-ray emission reflected by cold/warm reflector in the BLR/torus;
- …….

History bits

Radio variability first, then:

- **1956:** A. Deutsch at the Pulkova Observatory reported that the nucleus of NGC 5548 varied by 1 mag.
- **1958:** Antoinette de Vaucouleurs noticed fluctuations in the photoelectric magnitudes of NGC 3516, NGC 4051, and NGC4151 exceeding the photometric errors
- **1960:** A. Sandage reported variability of 3C 48, i.e. before the true nature of quasars was understood
- **1963:** The basic structure of AGN (central source of optical continuum was surrounded by the emission-line region and a still larger radio-emitting region) was soon hypothesized based on light-travel constraints (Matthews & Sandage 1963; Smith & Hoffleit 1963)
- **1975-1978:** Less than a decade after the discovery of optical variability of AGNs, X-ray variability was discovered from observations made by the OSO-7, Uhuru, Copernicus and Ariel V (Davison+75; Winkler & White+75, Elvis+78)

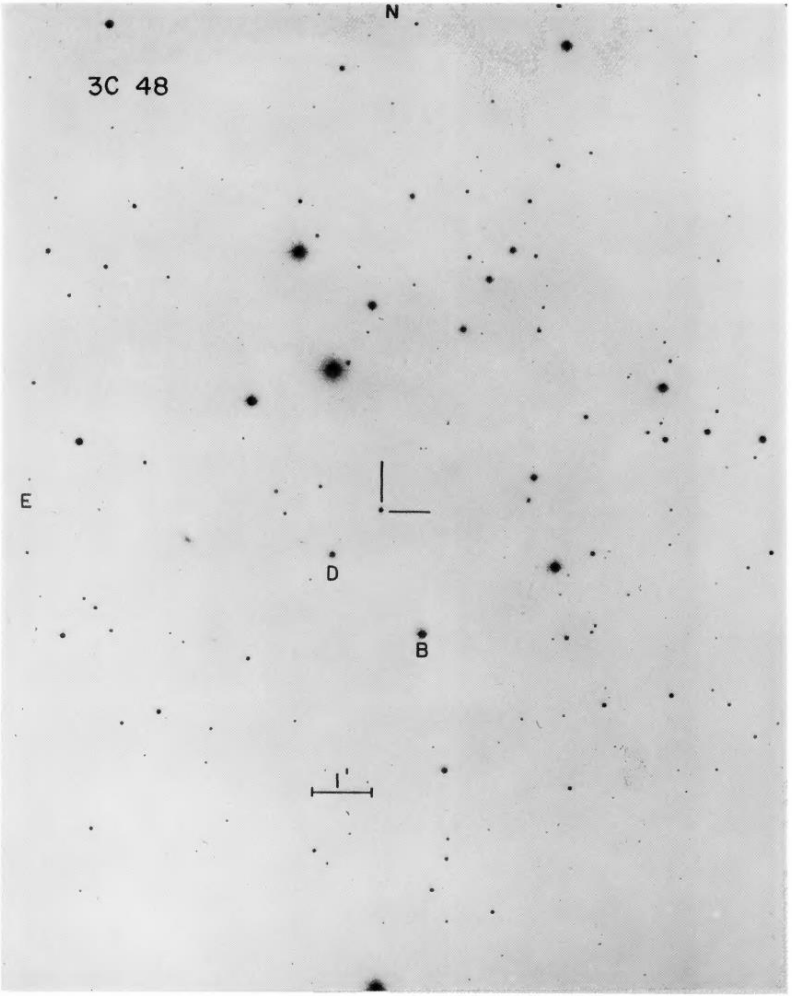
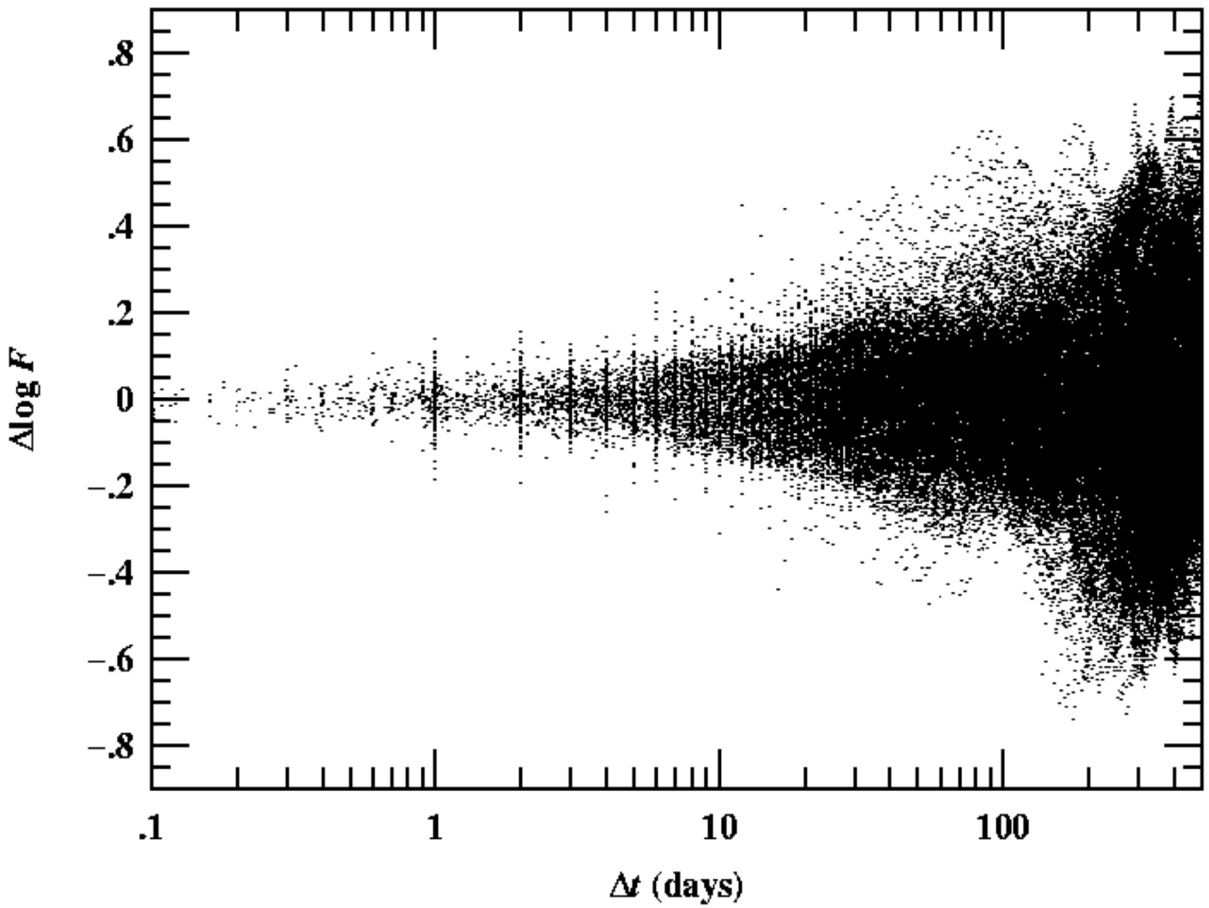


FIG. 2.—Finding chart for 3C 48 taken from a 10-minute exposure with the 200-inch. Local photometric standard stars B and D are marked. The data are $V = 13.53$, $B - V = 0.50$, $U - B = 0.00$ for star B; $V = 14.54$, $B - V = 0.66$, and $U - B = 0.05$ for star D. The plate used was a 103a-O + GG 13.

Matthews&Sandage63

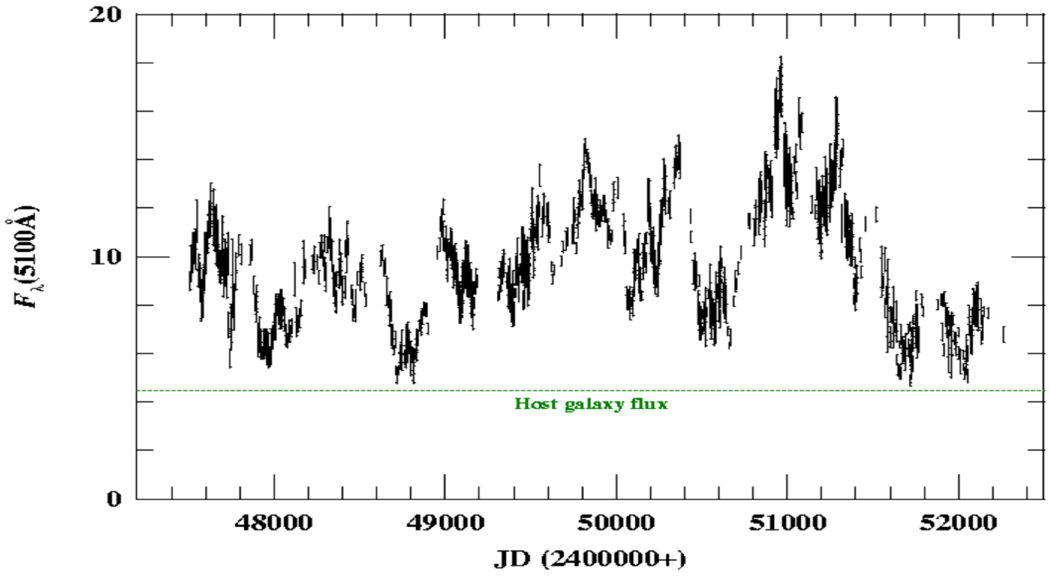
AGN variability in a nutshell

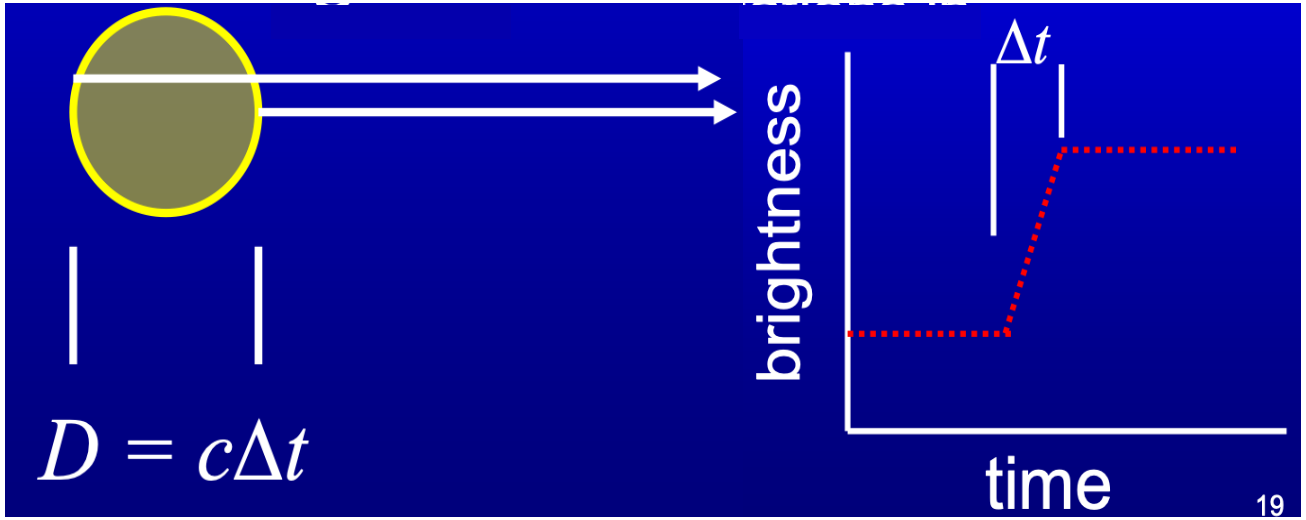
- **Quasars, QSOs, Seyfert nuclei, Blazars:** are all found to be highly variable in brightness.
- **Optical and ultraviolet variability is large!** In optical (e.g. V band) AGNs vary from 0.1 mag on timescales of days up to few mags over years.
- Variations of hundredths of a mag. (found in all AGNs) mean that for a 10^{45} erg/s AGN **the energy equivalent to 10^{10} solar luminosities is switching on and off!**
- **Rapid (intra-night) optical variability** ("microvariability") is common in radio-loud AGNs.



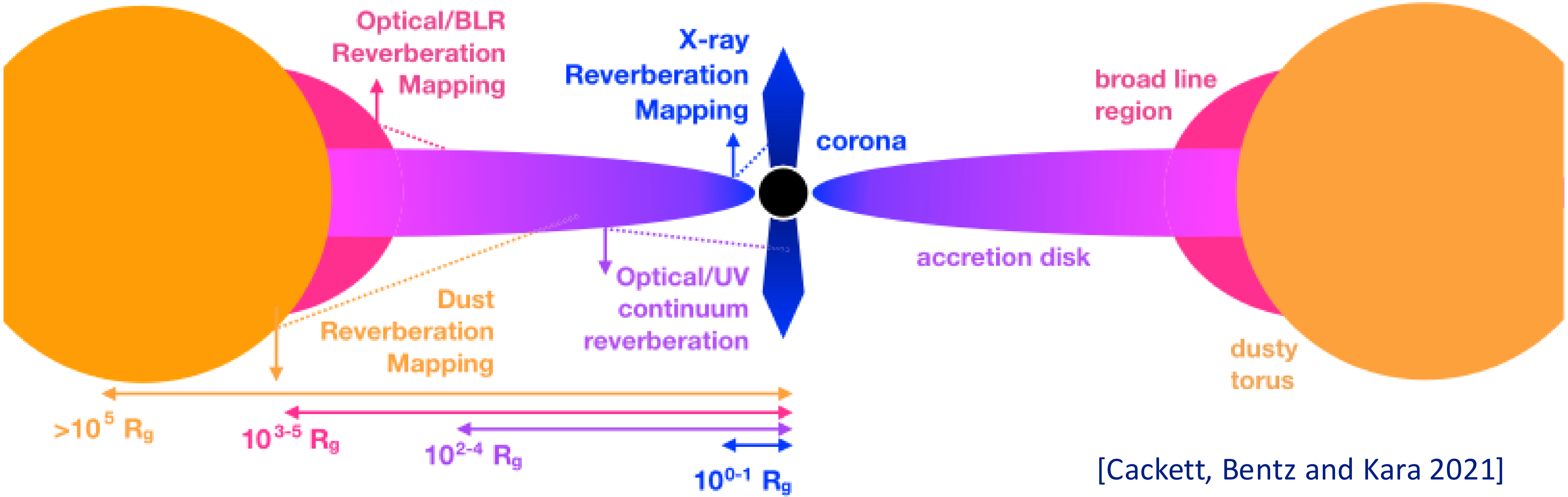
What can variability tell us about a source?

- Coherence: A variable source must be smaller than the light-travel time associated with significant variations in brightness.
- Rapid variability implies that the emitting source must be very small. Variability on time scales as short as one day implies sources that are less than one light day in size.
- The type of variability must be linked to the underlying physical process and to its characteristic timescales

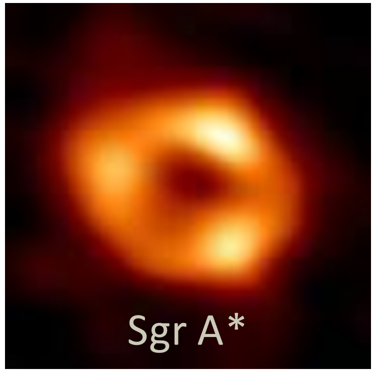


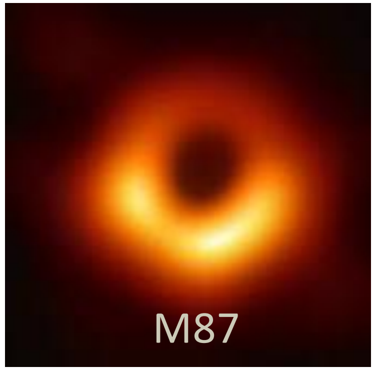


Why timing Active Nuclei?



[Cackett, Bentz and Kara 2021]





Region	Size scale (R_G)	Light-crossing time for a black hole mass of $10^7 M_\odot$	$10^9 M_\odot$
X-ray	10	500s	14 hours
UV/optical disk	$10^2 - 10^4$	0.06 – 6 days	6 – 600 days
BLR	$10^3 - 10^5$	0.6 – 60 days	60 – 6000 days
Dusty torus	$> 10^5$	>60 days	>6000 days

Variability: what's in a name?

Thus…variability is one of the defining properties of AGN

Variability carries clues on the structure of the AGN, the accretion process, its surroundings, interaction with the ISM etc.

Variability comes in many forms:

- (Short-term) Intrinsic persistent variability from accretion steady-state processes
- (Short-term) Extrinsic variability from internal and external causes (i.e. changing-look, obscuration, binary systems)
- (Short-term) Episodic variability due to temporary events (e.g. Tidal Disruption Events, Quasi-Periodic Eruptions)
- Long-term variability due to the AGN duty cycle (e.g. LF, evolution etc.)

Variability colors

Variability is observed across the entire EM spectrum:

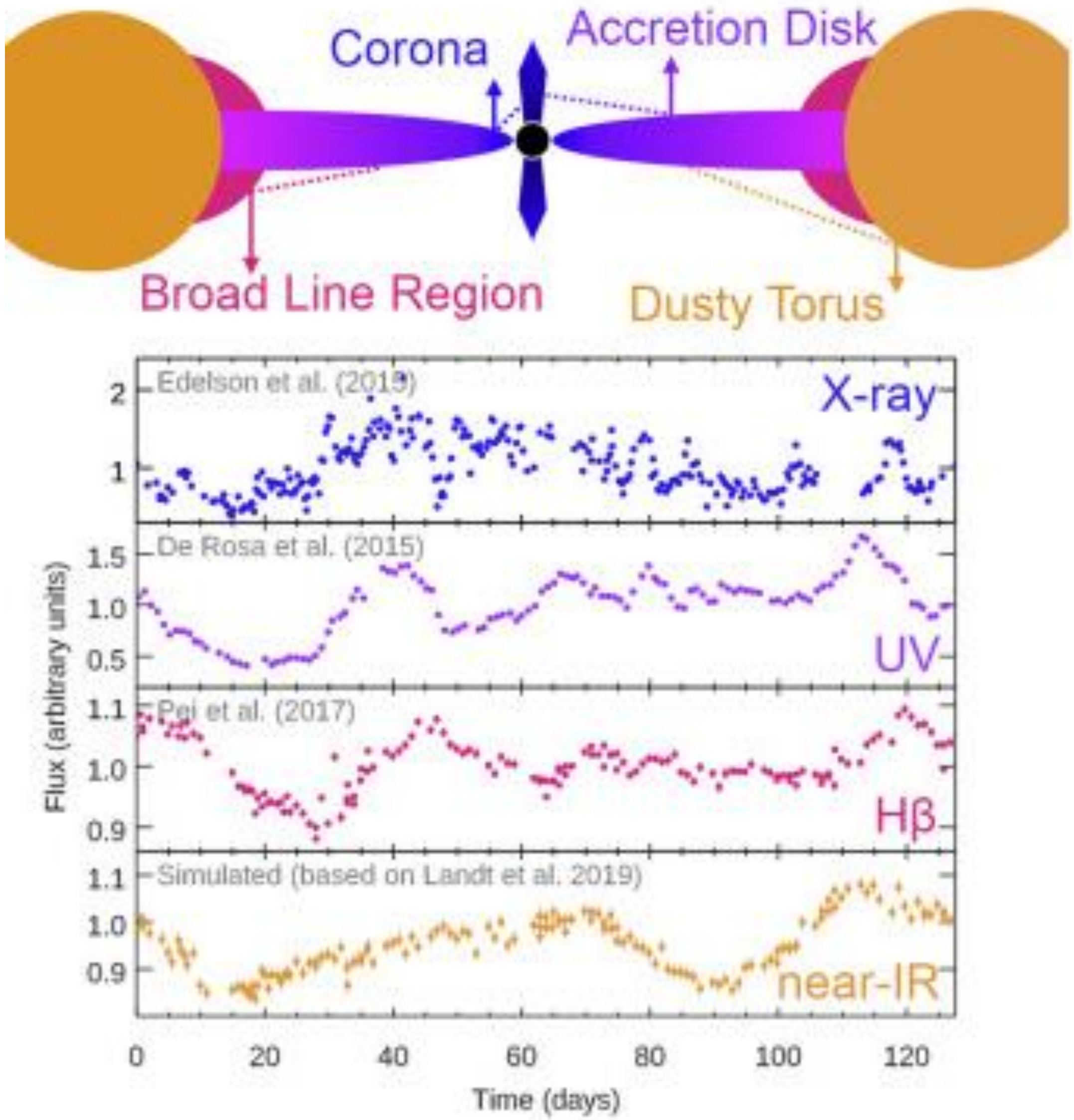
- X-ray variability from the corona
- UV / optical / IR variability from the disk/torus
- Spectra/continuum variability from BLR/winds
- Radio/IR/optical/X-ray/γ-ray variability from the jet

Timescales:

- IR: months/years
- Optical/UV: days/weeks/months
- X-rays: minutes/days/weeks
- Gamma: minutes

Here I will review the properties of intrinsic, persistent variability due to the innermost regions of AGNs in opt/UV/X-ray.

[Cackett, Bentz and Kara 2021]



Fundamental questions?

From Gaskell (2002):

- What is the amplitude of variability in the various wavebands and how are they related?
- What are the timescales of variability? Are the variations chaotic/periodic?
- How are the amplitudes related to the timescales? (Structure Function/Power Spectral Density)
- Are mean variability properties the same for different classes of AGN? (e.g., QSO/Seyfert, radio-loud/radio-quiet, face-on/edge-on, NLS1s/BLS1s)
- Can the variability properties of an AGN change with time? ("are AGNs moody?")

Or in other words:

- What does variability tells us about the properties of the accretion/ejection flow and of the AGN structure
- How does variability changes with physical parameters (mass, luminosity, accretion rate, orientation, obscuration etc.)
- How can variability help us study the evolution of Supermassive Black Holes?

Characterizing variability: Structure Function

Consider a light curve sampled at different moments: $y_i = s_i + n_i$ where s is the "signal" and n is the "noise".

The "Structure function" is defined as (e.e. Kozlowski+16)

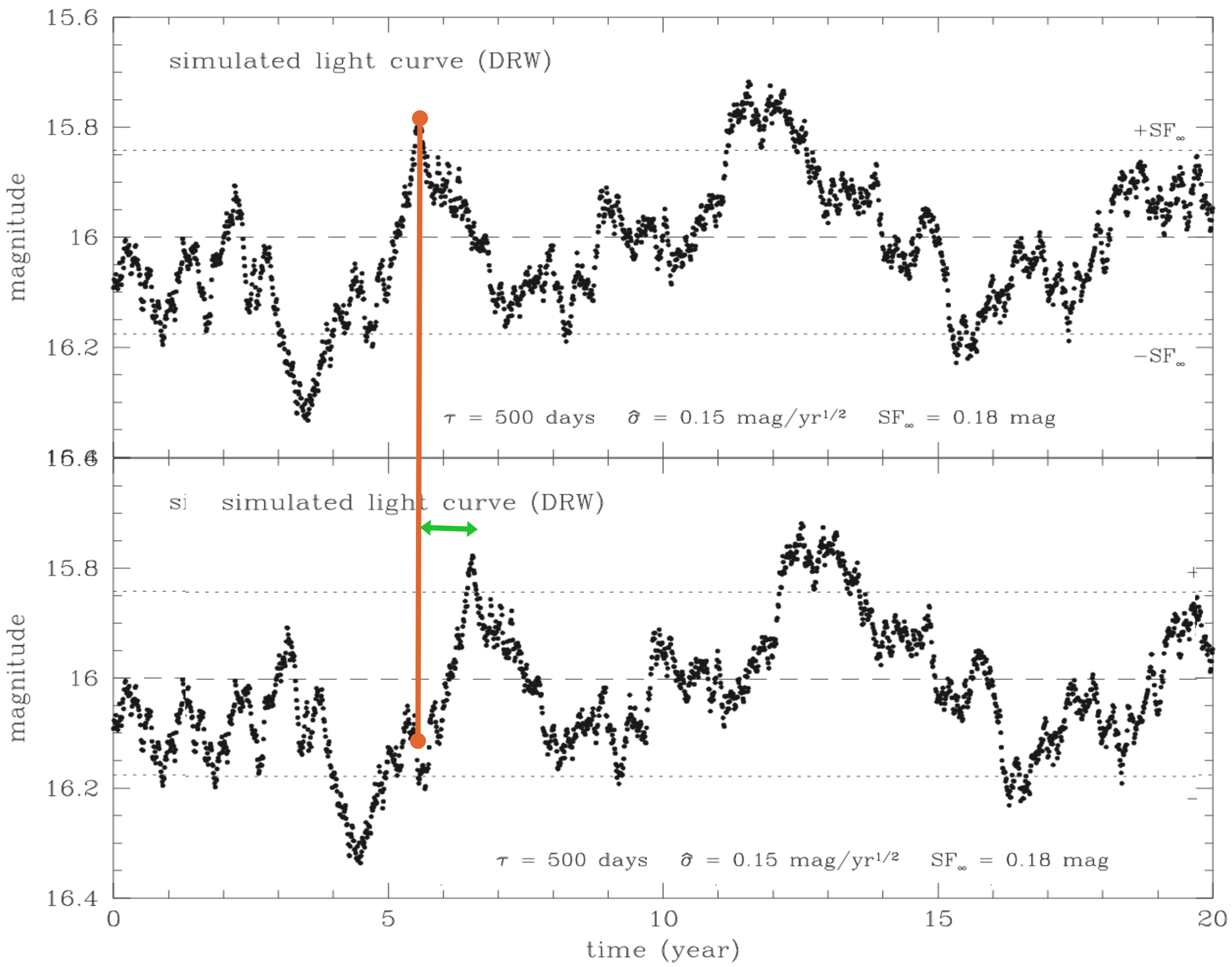
$$\mathrm{SF_{obs}}(\Delta t) = \sqrt{2\sigma_s^2 + 2\sigma_n^2 - 2\mathrm{cov}(s_i, s_j)}$$

where: $\mathrm{var}(s_i) \equiv \sigma_s^2$, $\mathrm{var}(n_i) \equiv \sigma_n^2$,

Signal variance — Noise

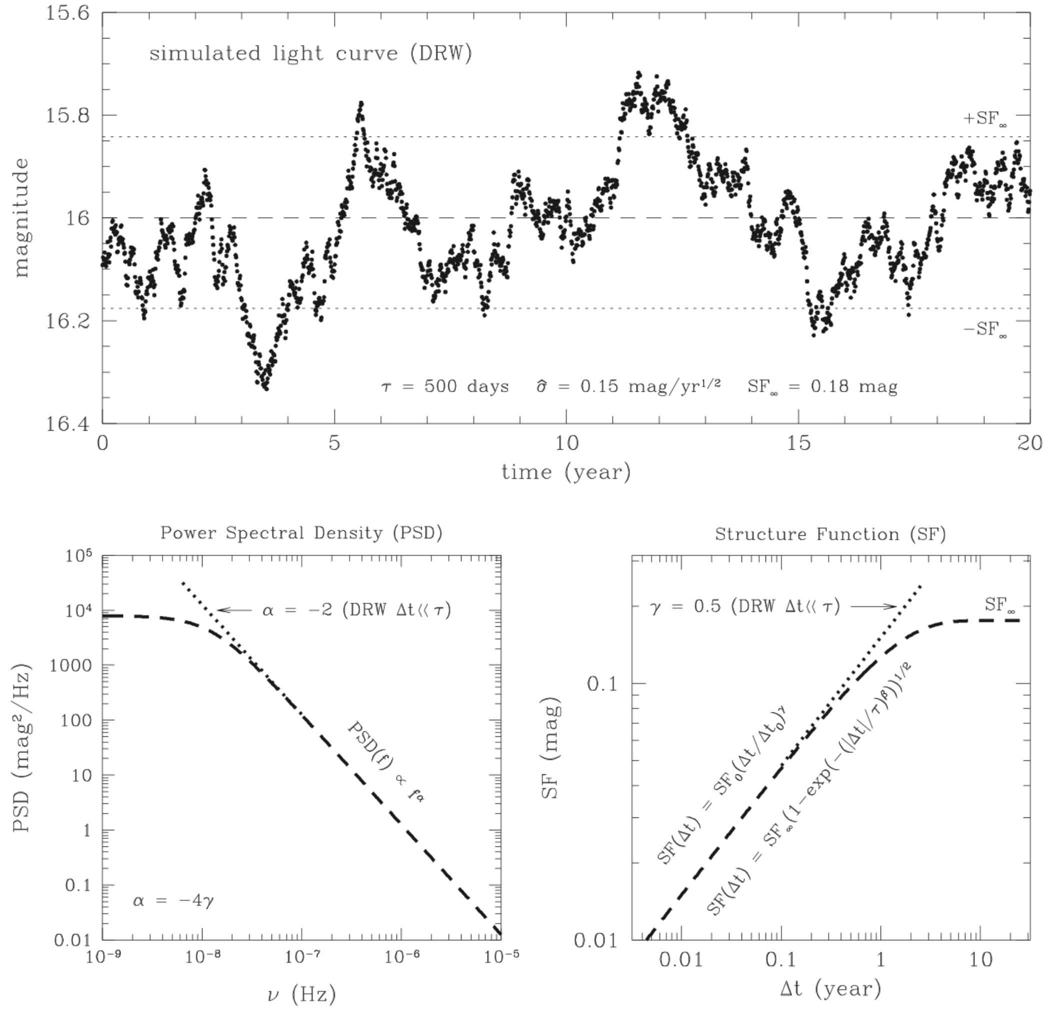
Defining: $\mathrm{ACF}(\Delta t) \equiv \mathrm{cov}(s_i, s_j)/\sigma_s^2$

$$\mathrm{SF_{true}}(\Delta t) = \sqrt{\mathrm{SF_{obs}}(\Delta t)^2 - 2\sigma_n^2} = \sqrt{2\sigma_s^2(1 - \mathrm{ACF}(\Delta t))} = \mathrm{SF}_\infty \sqrt{1 - \mathrm{ACF}(\Delta t)}$$



Power spectrum

Any time series y(t), can be thought of as a combination of periodic signals with frequencies $\boldsymbol{\nu}$



[Kozłowski 2016]

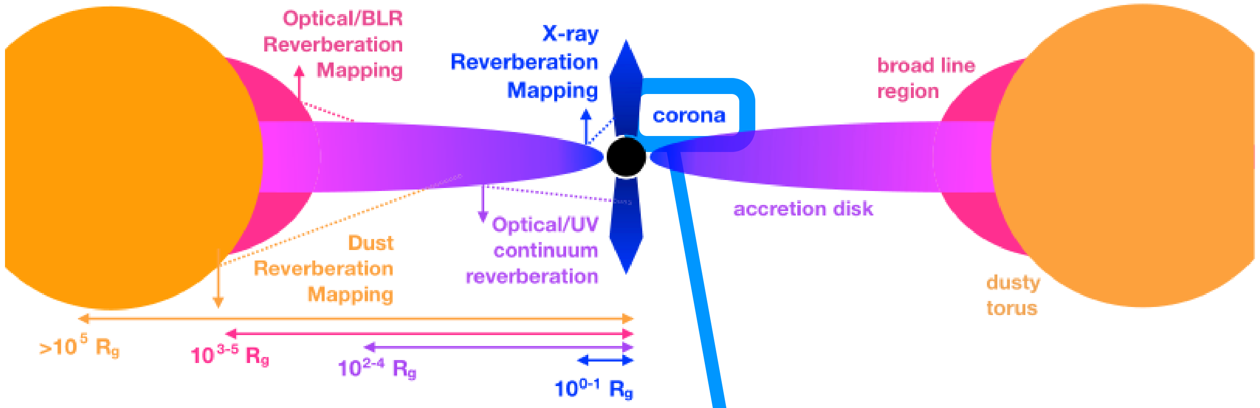
- Defining: $$Y(\nu) = \int_{-\infty}^{+\infty} y(t) e^{-2\pi i \nu t} dt.$$
- The power is: $$\text{total power} \propto \int_{-\infty}^{\infty} \text{PSD}(\nu) d\nu = $$ $$= \int_{-\infty}^{\infty} |y(t)|^2 dt = \int_{-\infty}^{\infty} |Y(\nu)|^2 d\nu.$$
- The Wiener–Khinchin theorem states that the Power Spectral Density is the fourier transform of the ACF: $$\text{PSD}(\nu) = \int_{-\infty}^{\infty} \text{ACF}(\Delta t) e^{-2\pi i \nu \Delta t} \Delta t.$$

so the SF and the PSD are linked through the ACF but the conversion depends on the process.

Properties of X-ray variability

X-ray variability Variability is one of the defining properties of AGN
(e.g. G.A. Shields, "A Brief History of Active Galactic Nuclei," 1999, PASP, 111, 661)

- Fast
- Partially correlated with opt/UV
- Implies compactness of the corona
- Time delays probe distance from the disk
- Dependent on mass (+acc.rate, spin?)



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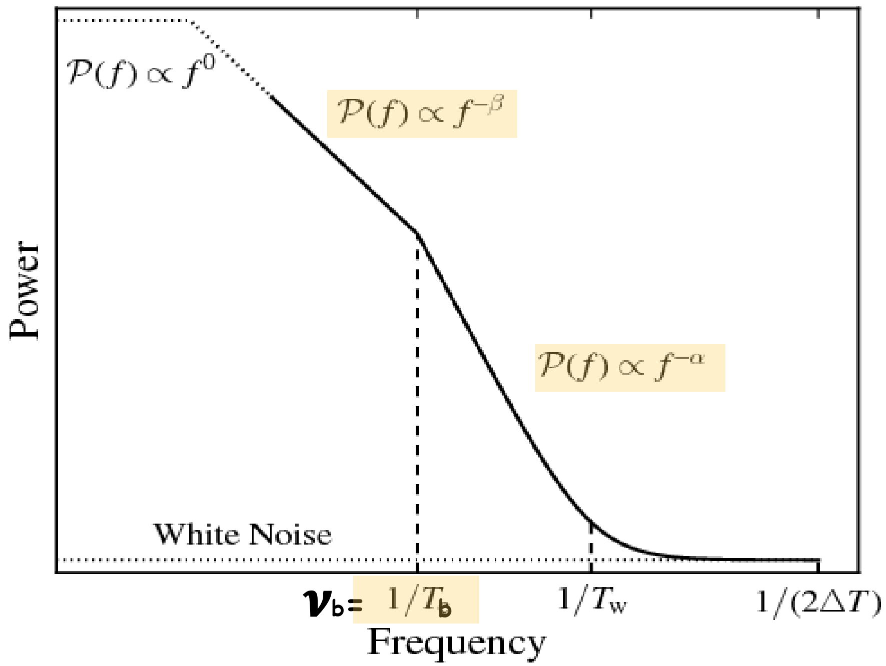
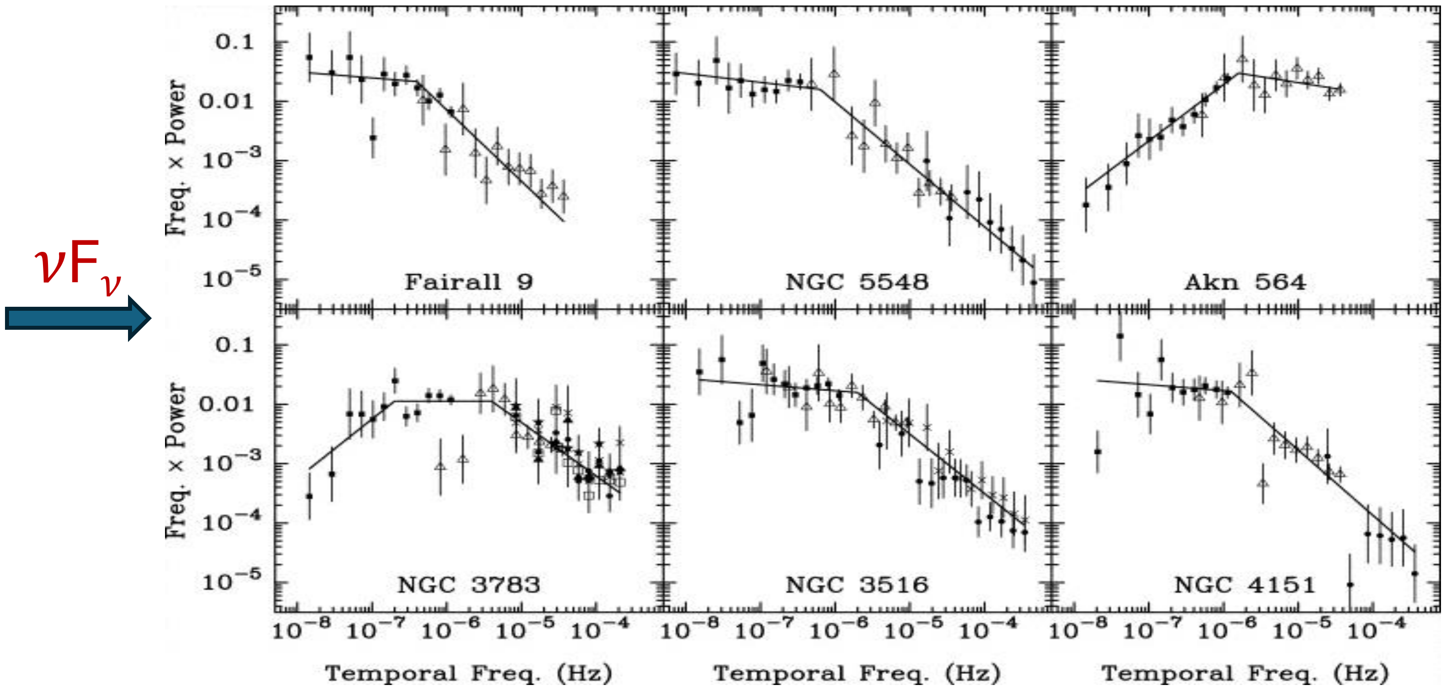
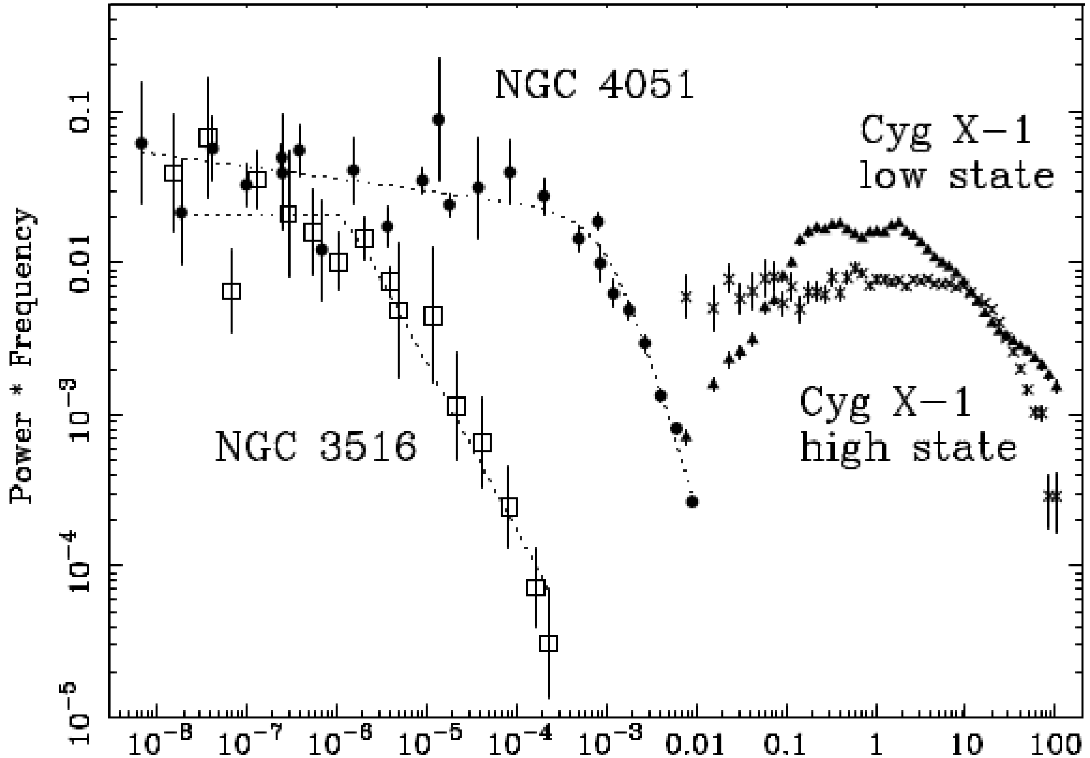
X-ray variability PSD

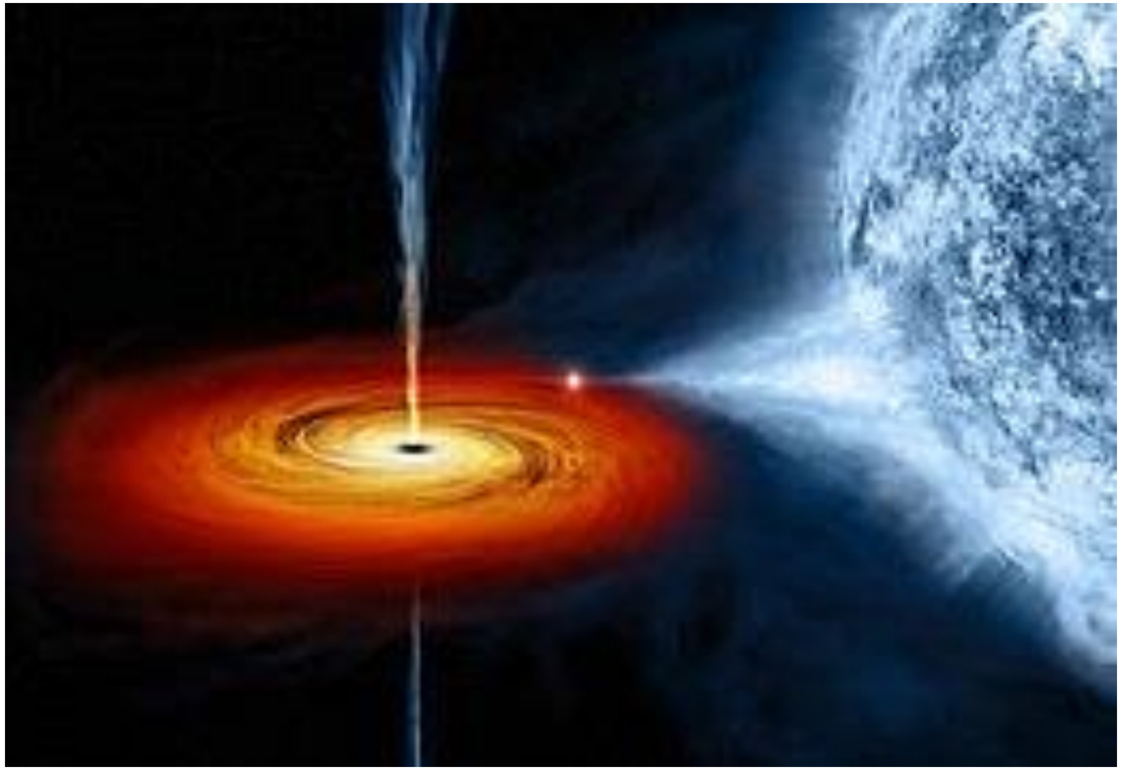




- In the X-ray Band the PSD is modelled with a "bending" or "broken" power-law
- The Break Frequency represents a characteristic Break Timescale $T_b = 1/\nu_b$
- The low and high freq. slopes are commonly assumed to be $\alpha \simeq 2$ and $\beta \simeq 1$ (Markowitz et al. 2003, O'Neil et al. 2005)

Relationship with BHBs

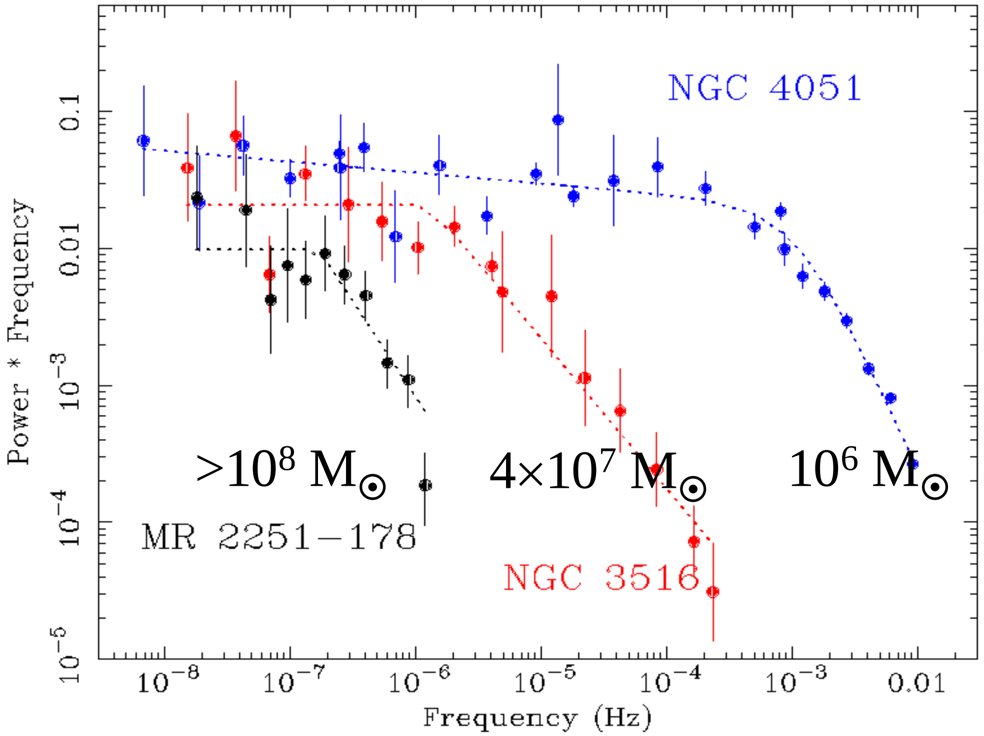


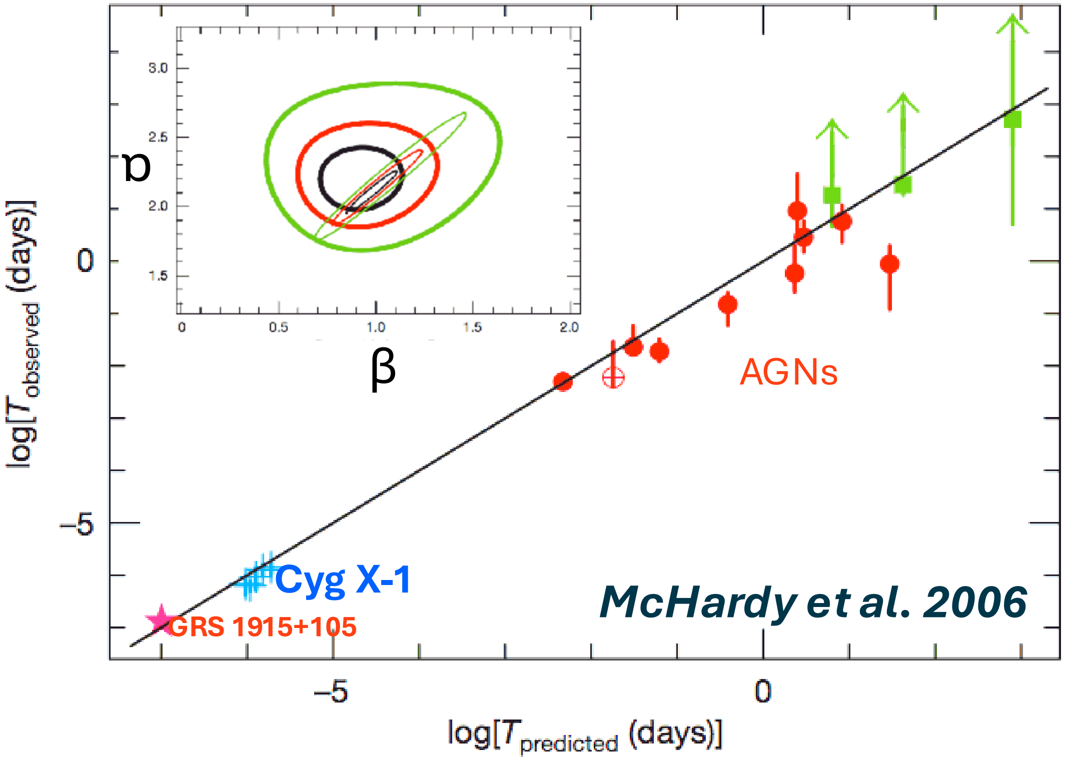


- Galactic Black Hole Binaries show the same PSD shape (McHardy 1988, 2010, Lawrence & Papadakis 1993).
- The PSD breaks scale approximately with mass (i.e 6-7 orders of magnitude)

Variability scaling with BH mass and acc.rate

(courtesy of P. Uttley)





- High frequency break seems to scale with BH mass and luminosity (proxy for accretion rate)
- $t_B \propto M_{BH}^{\alpha}/L_{bol}^{\beta}$ (Uttley & McHardy 2005, Markowitz & Uttley 2005, McHardy 2006)

Accretion dependence challenged by XMM studies

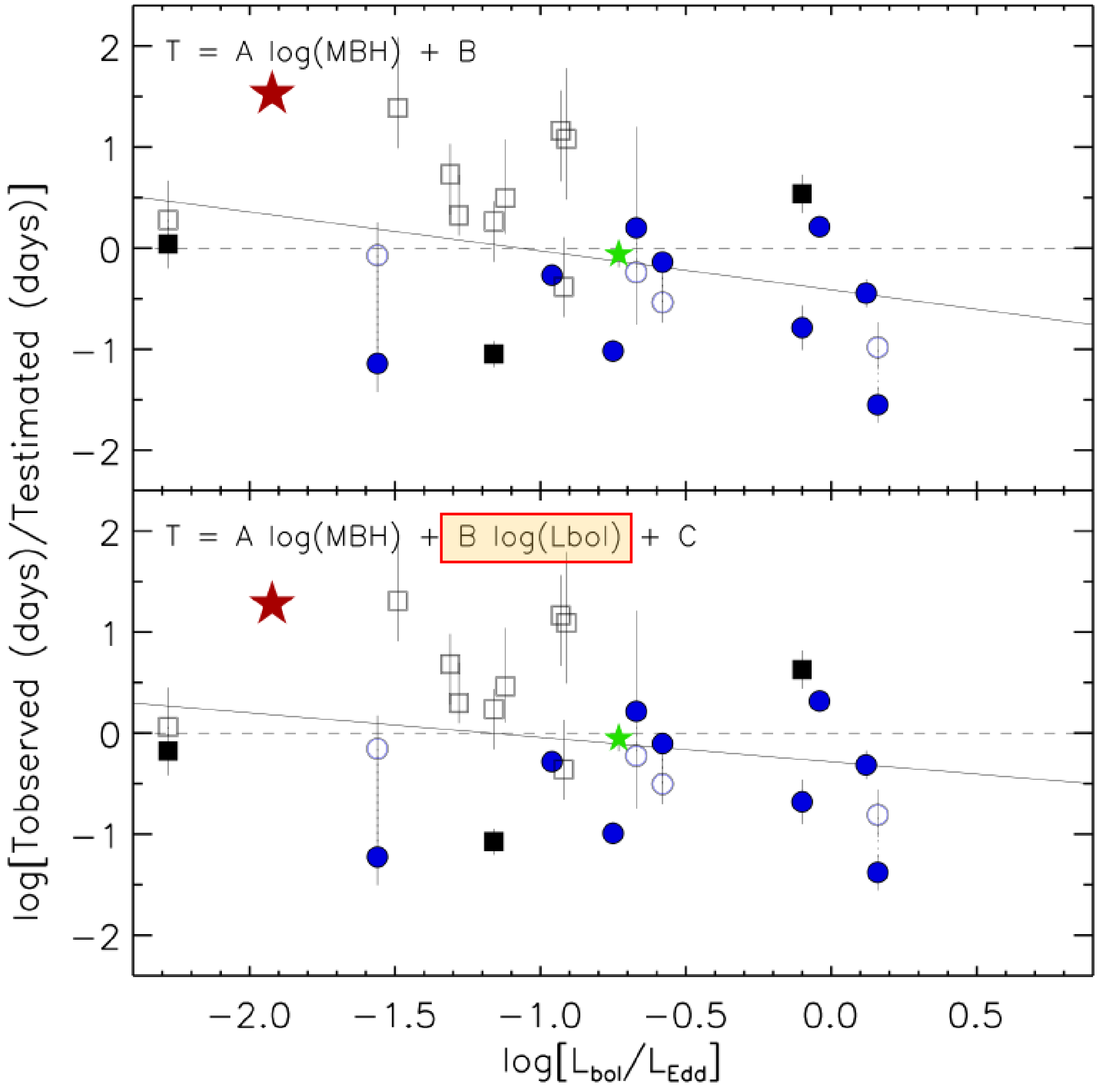
Gonzales-Martin & Vaughan (2012) study 104 nearby AGN from XMM-Newton observations.

Possible scenarios:

- Break timescale depends only on BH mass
- Break timescale depends on BH mass and accretion rate.

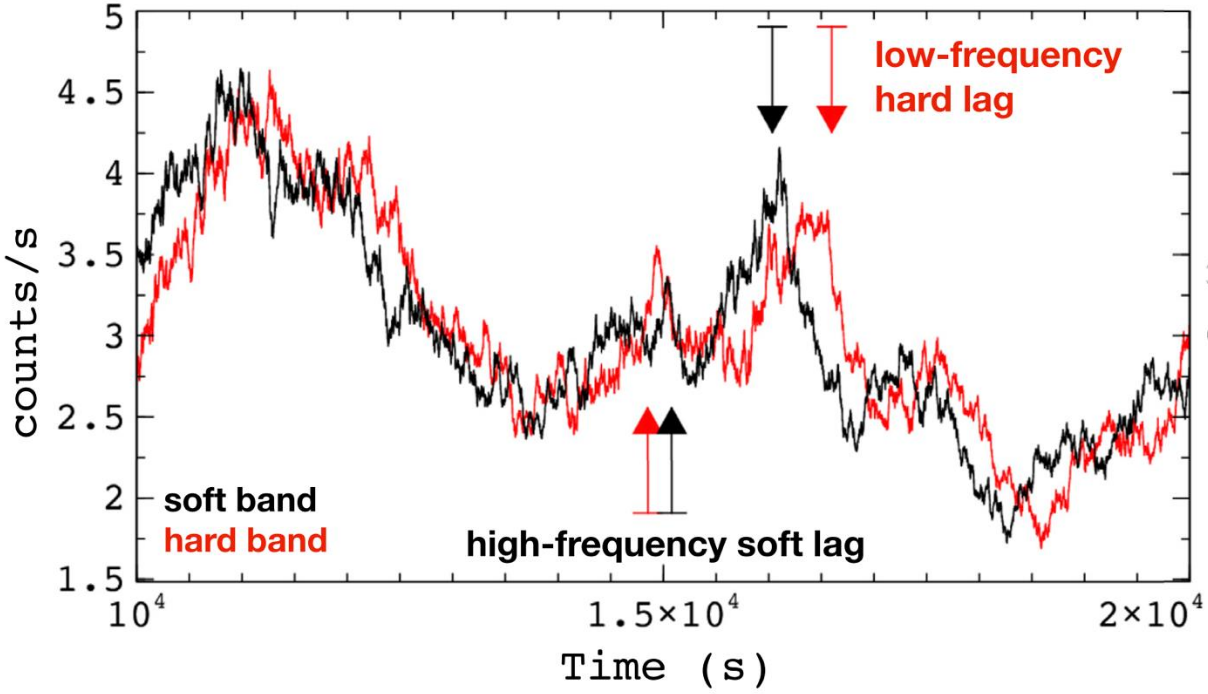
So far no conclusive evidence of either model based on nearby AGN.

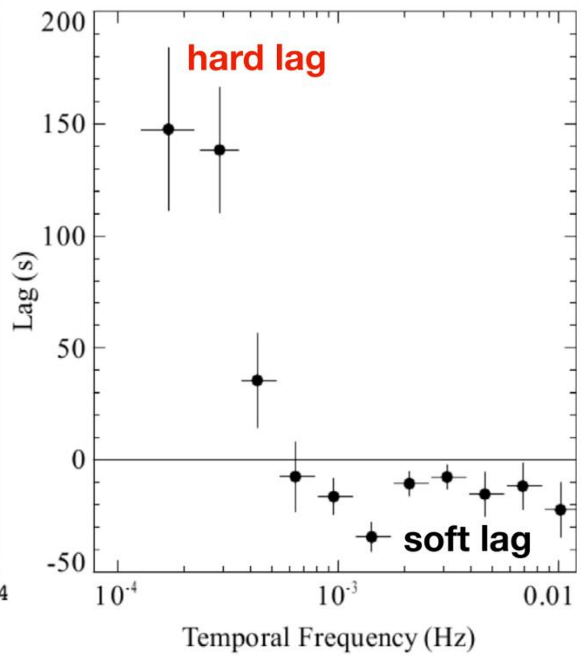
Large sample studies (eROSITA?) may help solve the issue.



X-ray lags and reverberation

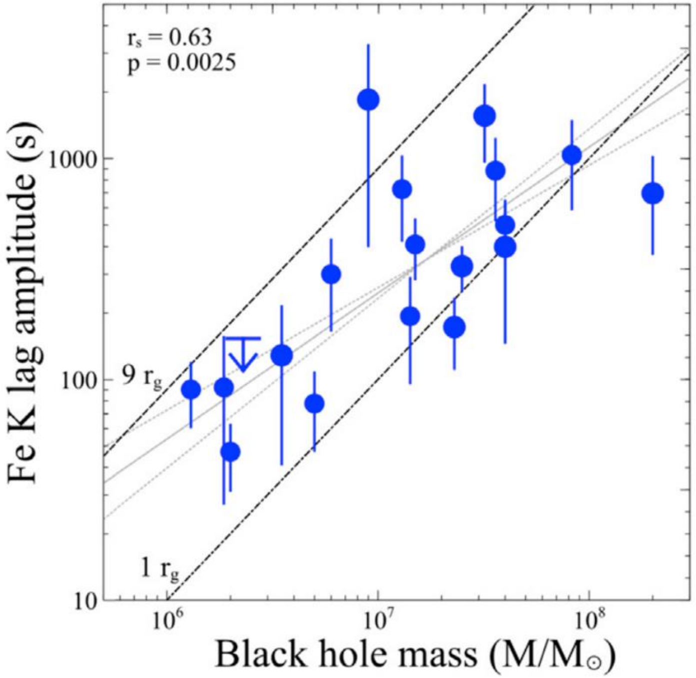
- Reverberation time delays were first discovered in 2009 using the XMM-Newton Observatory (Fabian et al. 2009, Zoghbi et al. 2010, Uttley et al. 2014).
- Lags depend on frequency and energy:
  - Low-frequency hard lags reflect the origin of the soft and hard components: Compton scattering, propagating fluctuations? See later...
  - High-frequency lag trace light-crossing time: X-rays are reprocessing off the inner accretion disk within a few gravitational radii, and trace the height of the corona (brightness dependent).

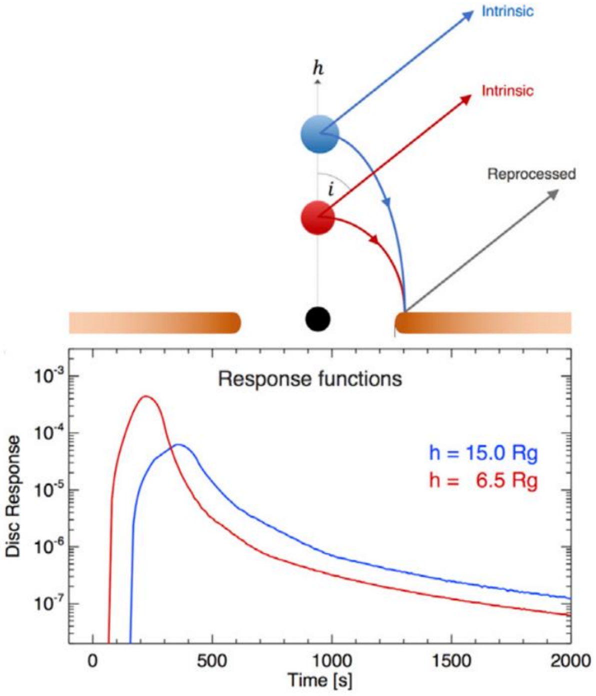




X-ray reverberation

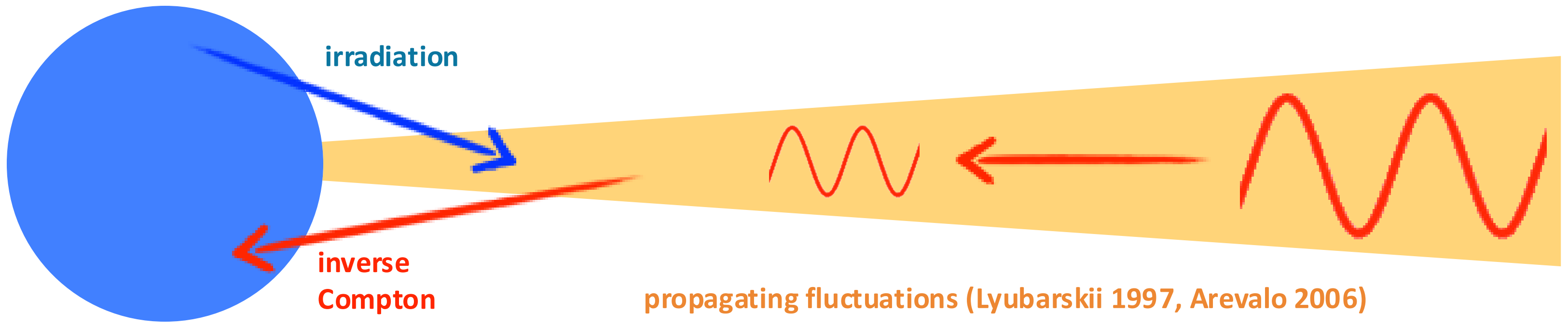
- Reverberation aims to measure the inner edge of the accretion disk in luminous, radiatively efficient AGN, in order to measure a fundamental black hole parameter, mass and spin.
- Modeling the reverberation lags require general relativistic ray-tracing simulations of a compact corona irradiating a thin accretion disk.
- The reflection-dominated band was observed to lag behind the continuum by roughly 30 s or $2R_g/c$ for a $10^6\,M_\odot$ BH. The height of the corona increases with increasing luminosity (Alston et al. 2020).



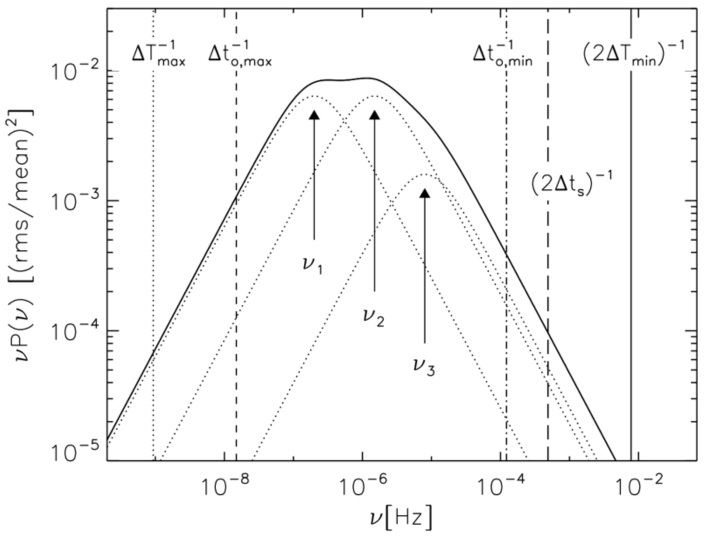


Physical mechanism?

- Microlensing
- Variations in accretion rates (only long timescales), variable obscuration, scattering off extended medium/winds etc.
- Shot noise due to superposition of individual pulses, disk instability (sand-pile models)
- Propagating fluctuations: rms-flux relation, lognormal fluctuation, superposition of Lorentzians in the PSD, reverberation



multiplicative effect (lognormal fluctuations) where outer fluctuations modulate inner ones
[image courtesy of F. Vagnetti]



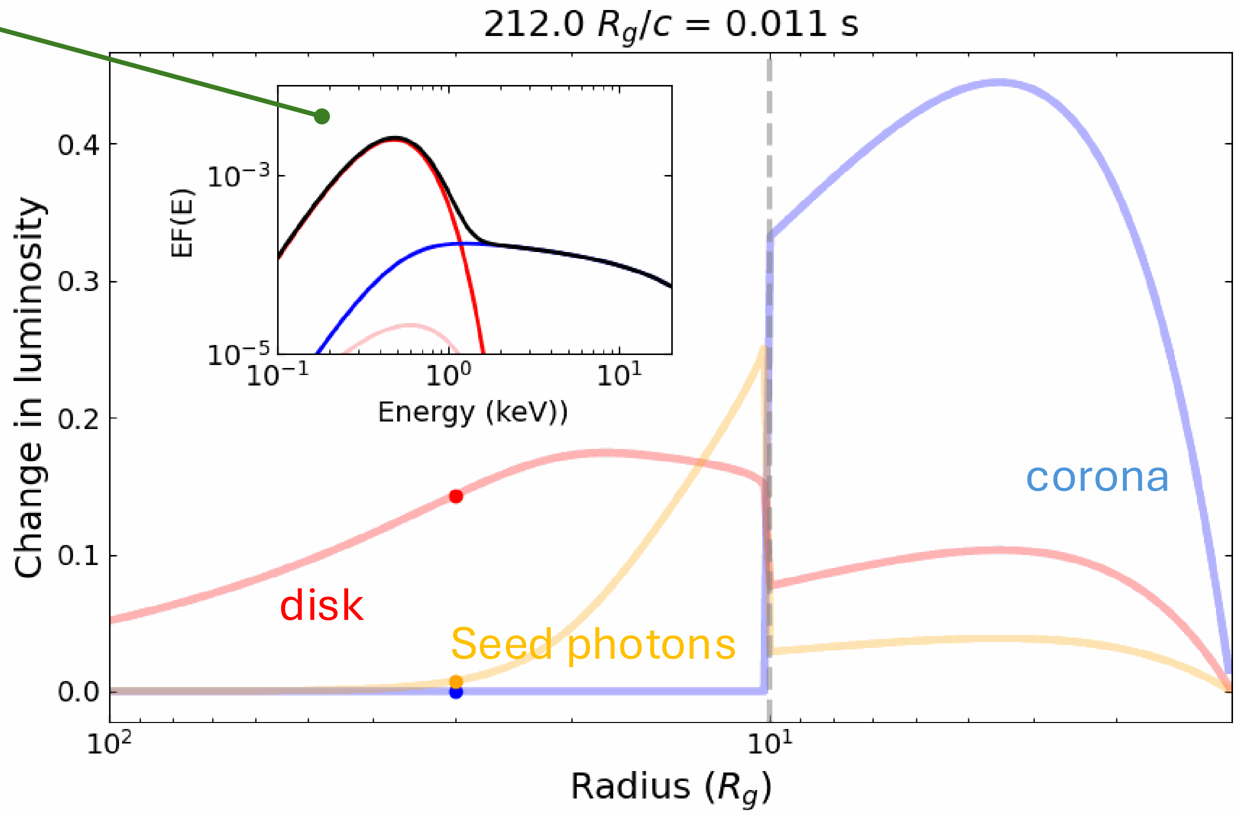
Pessah 2007

Propagating fluctuations

- Luminosity in response to an $\dot{m}$ fluctuation (the dot) of the disk:

  model for a 10 $M_\odot$ BHB but works for AGN rescaling mass and disk temperature

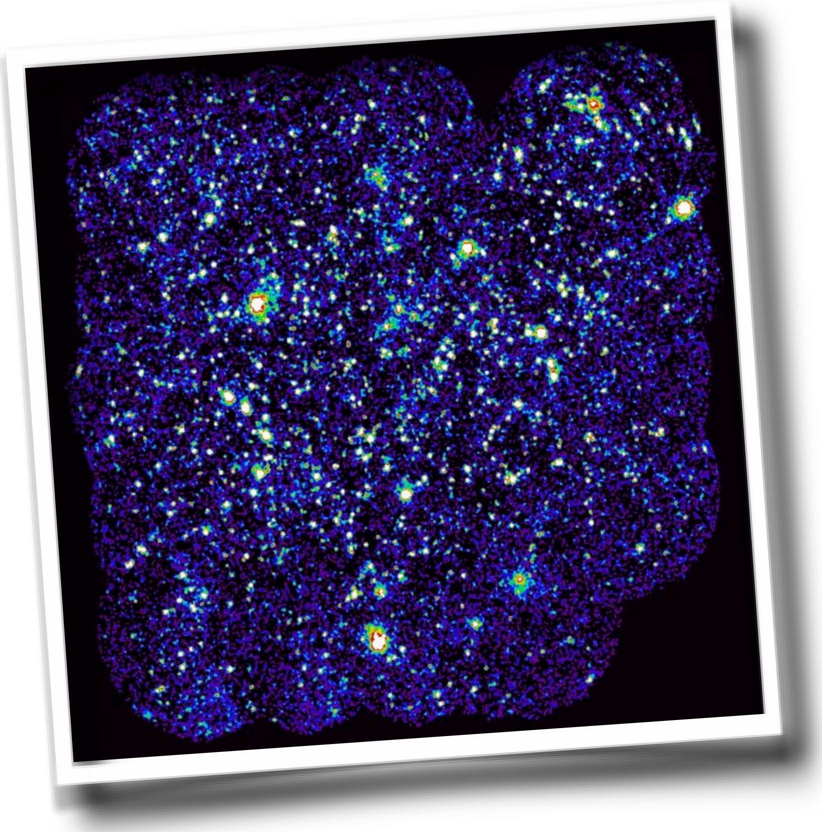
Source spectrum including disk reverberation (pink)

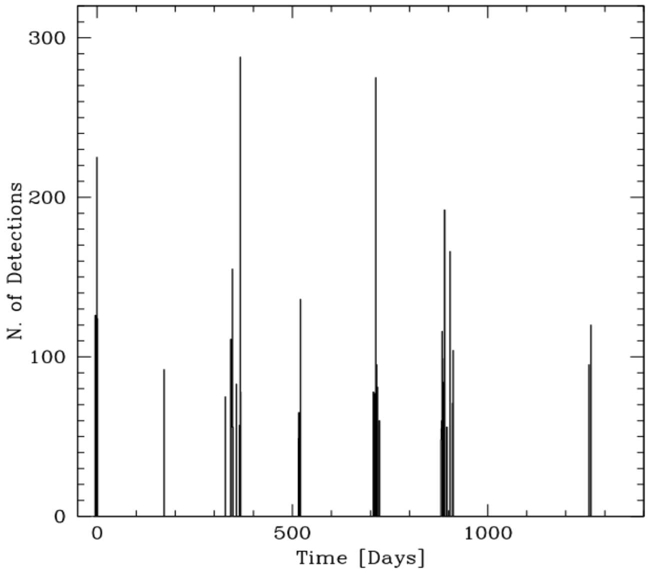


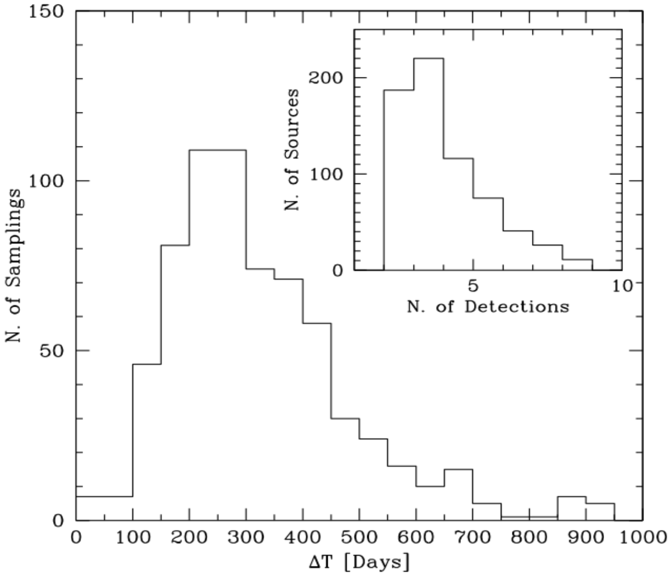
Inverted-cone-like corona:
radius 10 R_g
height 10 R_g
opening angle 30°

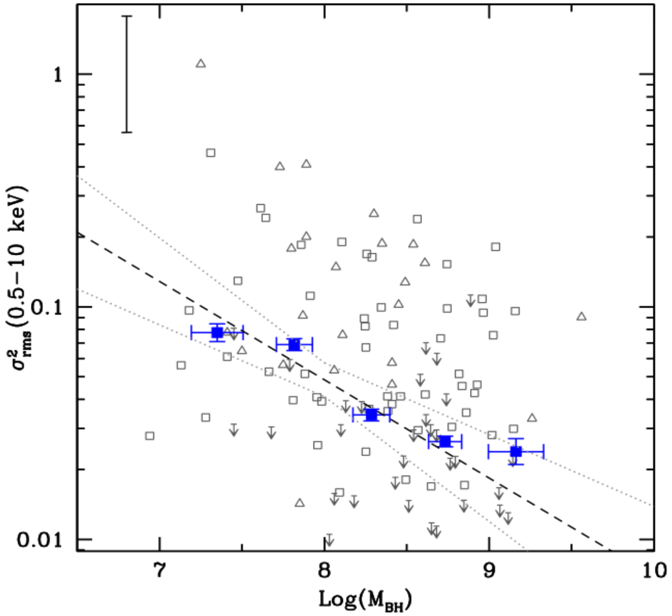
[Courtesy of P.Uttley (Uttley & Malzac 2023)]

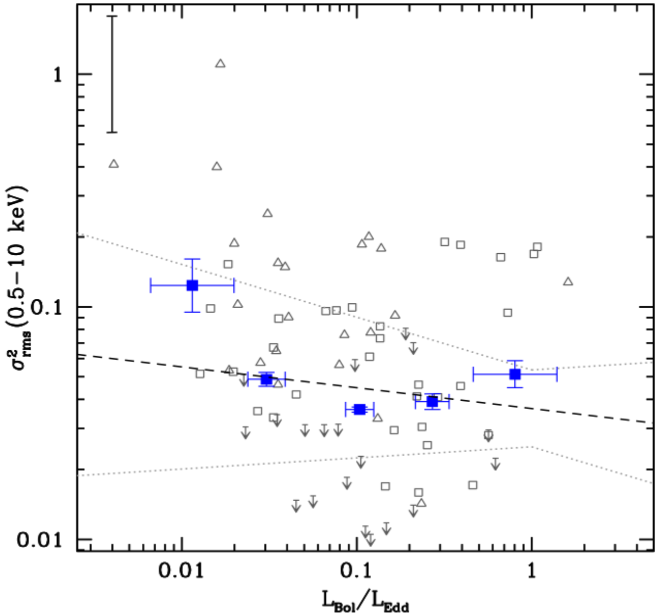
COSMOS field [Lanzuisi et al. 2014]







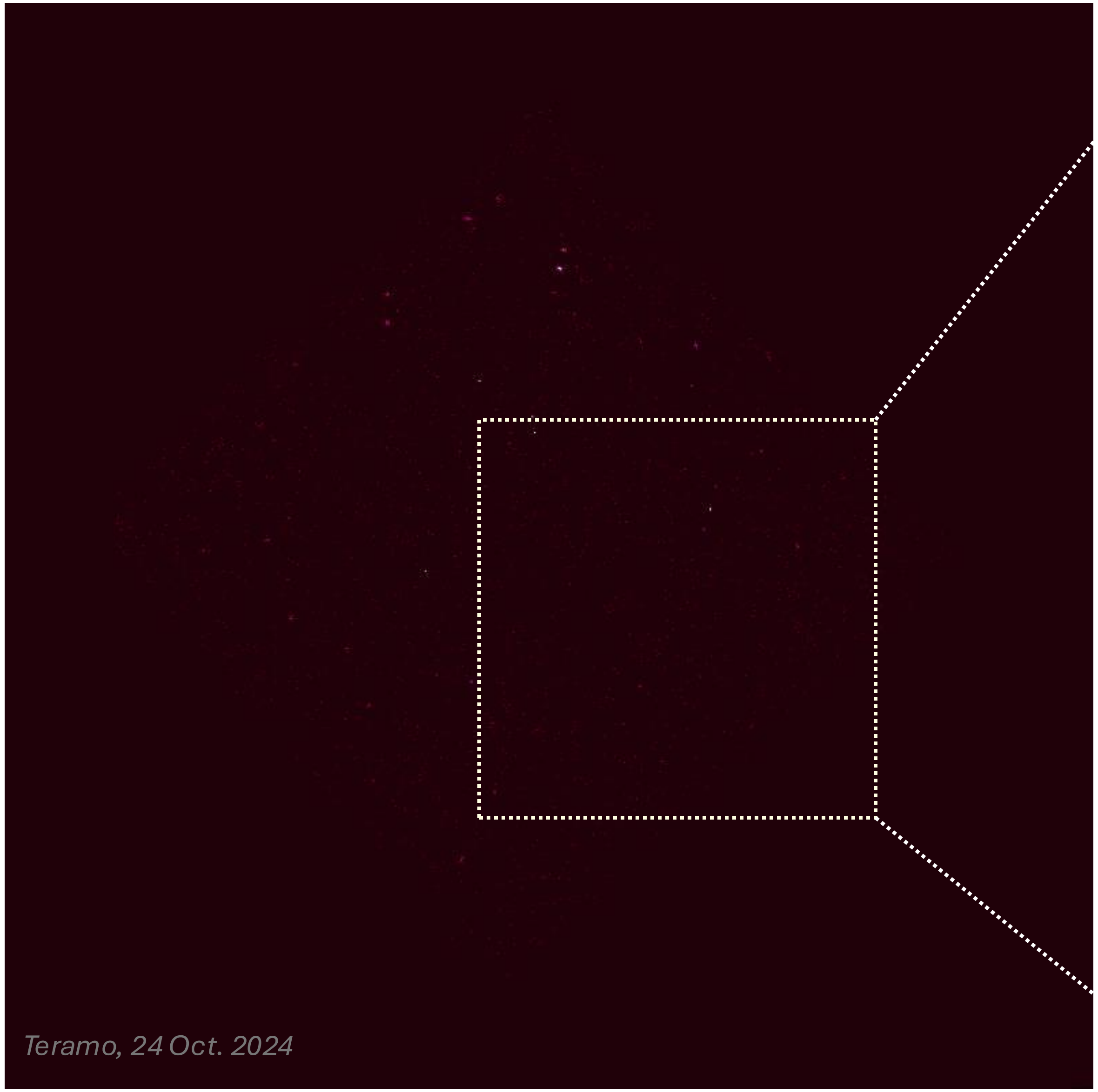


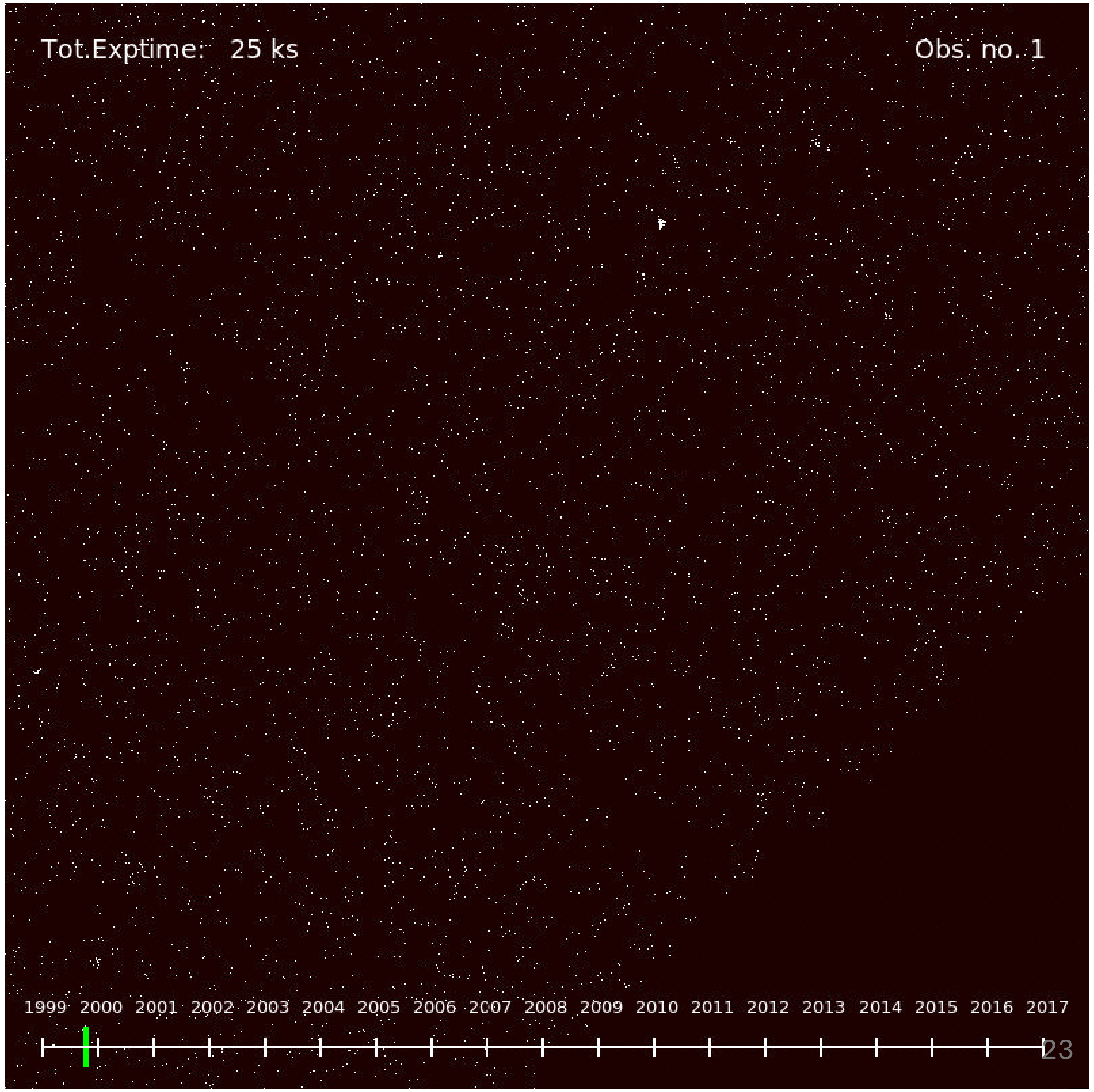


- Dependence on mass, but weak or no dependence on accretion!

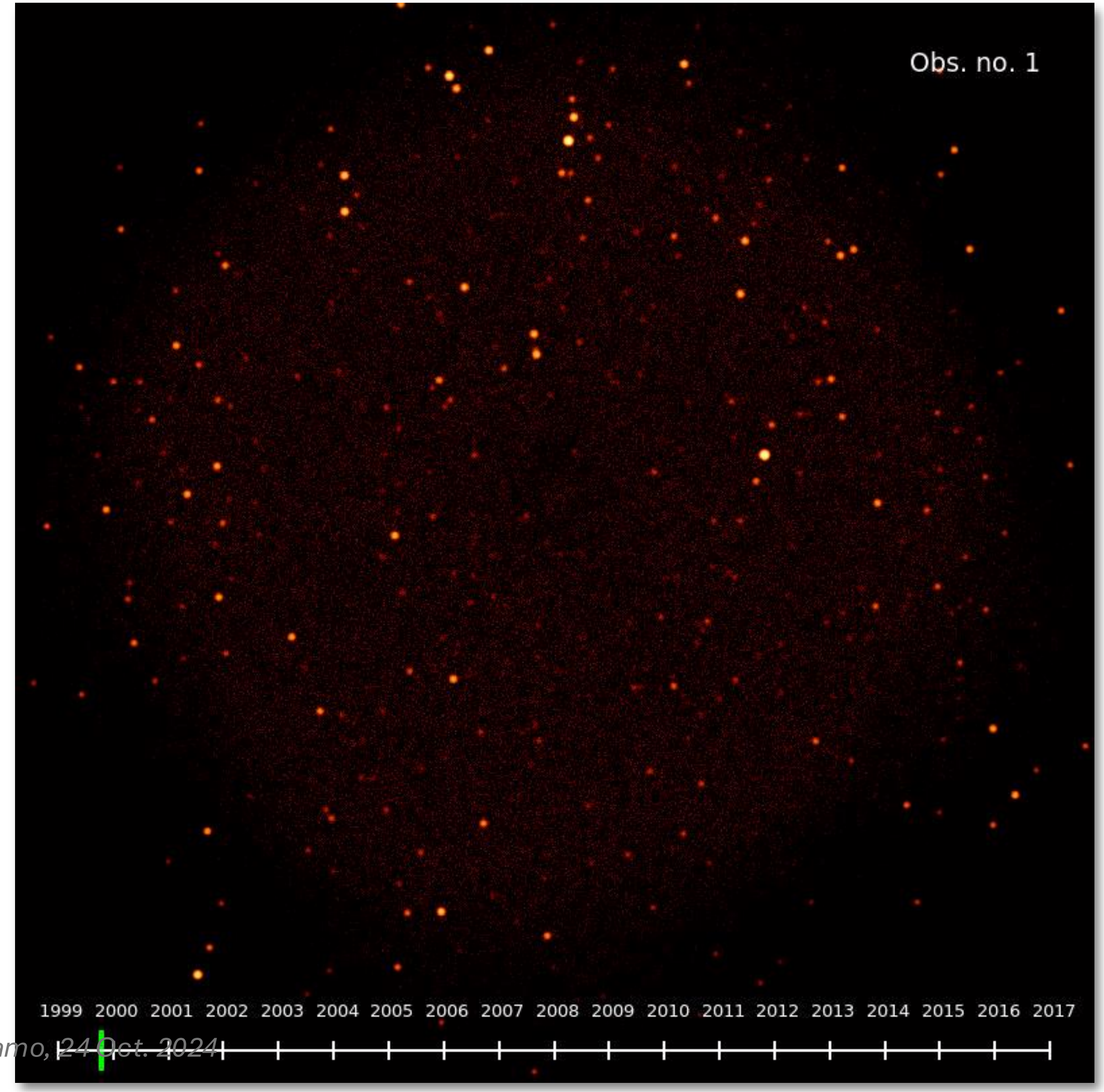
Building deep sky surveys: the cumulative view...

The 7Ms Chandra Deep Field South [Luo et al 2016]

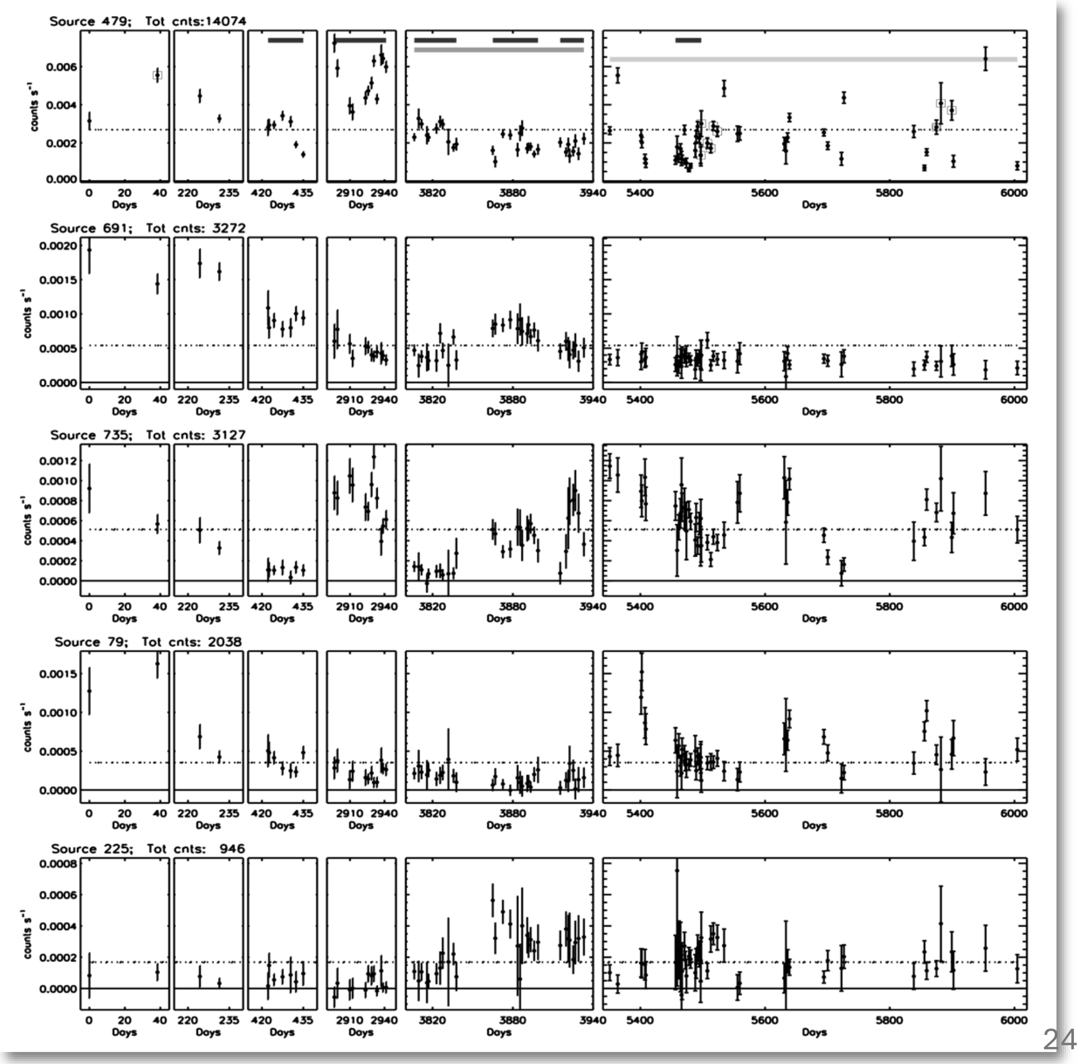




7Ms CDFS: the differential view…

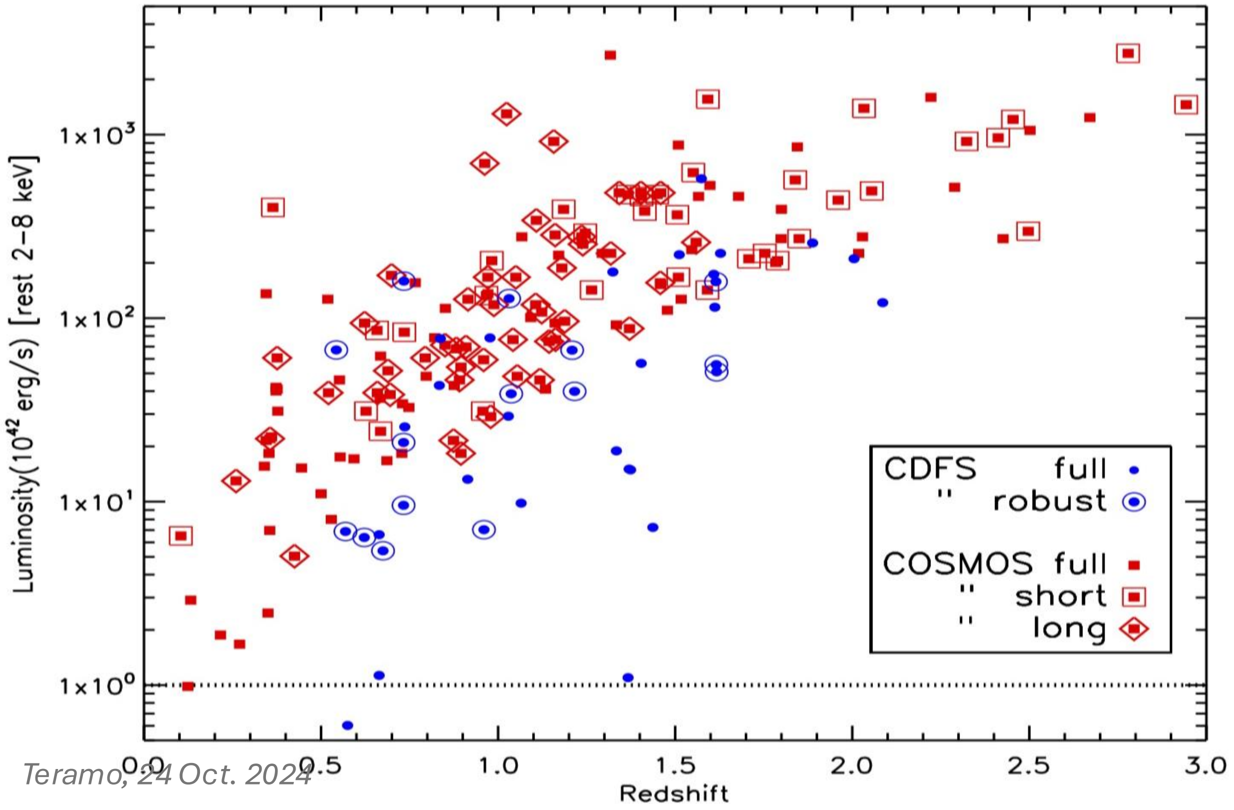


[Paolillo et al. 2017]



Assembling a comprehensive sample… *[Paolillo et al. 2023]*

Survey	T_{obs} (days)	$\Delta t_{min,obs}$ (days)	$\tilde{T}_{rest}$ [range] (days)	$a(T_{obs})$	$b(T_{obs})$
CDF-S	654	0.25	334[±87]	-1.07±0.12	-0.2±0.2
	128	0.95	65[±17]	-1.36±0.16	-0.3±0.3
CAIXA	0.926	0.003	0.926	-2.9±0.2	-0.71±0.16
… +TARTARUS	0.463	"	0.463	-2.98±0.14	-0.75±0.14
long-term RXTE	5110	300	5110	-1.38±0.09	-0.15±0.12
COSMOS	555	0.40	$240[^{+88}_{-107}]$	-1.36±0.10	-0.16±0.14
"	891	0.38	$413[^{+139}_{-69}]$	-1.29±0.07	-0.21±0.13
Swift+RXTE	9.45	~0.5	9.45	-1.81±0.08	-0.42±0.07



Local samples:

16 ASCA Tartarus sources+6 XMM CAIXA on 40 ks timescales,

11 XMM CAIXA sources on 80 ks tmscl,

14 RXTE+Swift sources on 10 days tmscl,

27 RXTE sources on 14 years tmscl.

High redshift samples:

CDFS robust sample: only 15 sources with reliable BH mass, S/N>0.8 per epoch, >90 points in the lightcurve and regular sampling.

COSMOS robust samples: 82 sources split in short (100 days ≤ T_{rest} < 330 days) and long (330 days ≤ T_{rest} < 560 days) timescales, but only 3 to 10 observations each.

Universal PSD of AGN

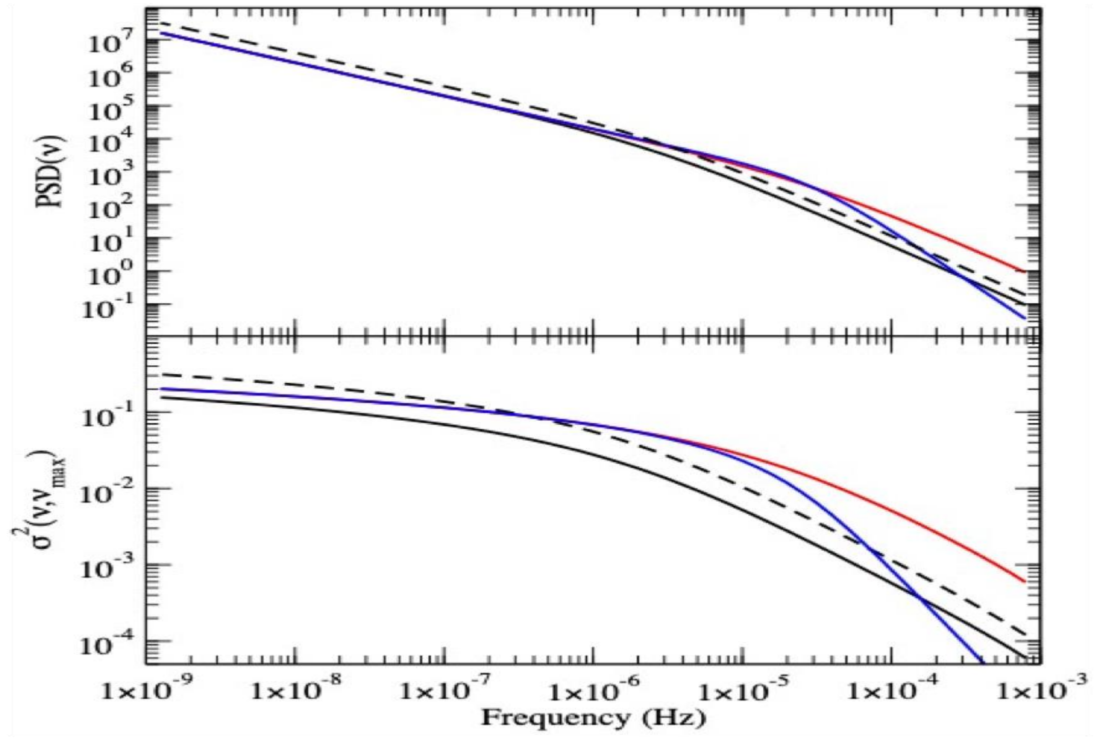
If we model the PSD as a bending power law:

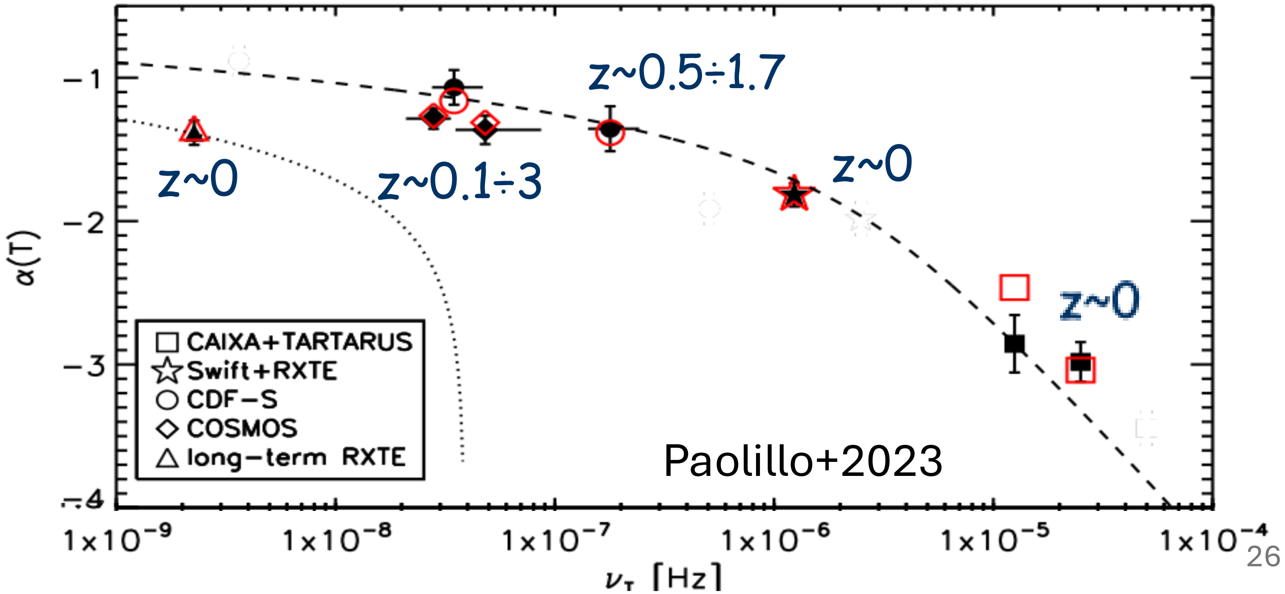
$$\mathrm{PSD}(\nu) = A\nu^{-1}\left[1+\left(\frac{\nu}{\nu_{\mathrm{b}}}\right)^{s}\right]^{-1}$$

the variance is the PSD integral:

$$\sigma^2(\nu_T,\nu_{\max}) = \int_{\nu_{\mathrm{T}}}^{\nu_{\max}} \mathrm{PSD}(\nu)\,\mathrm{d}\nu$$
$$= A\left[\ln\left(\frac{\nu_{\max}}{\nu_{\mathrm{T}}}\right) - \frac{1}{s}\ln\left(\frac{\nu_{\mathrm{b}}^s+\nu_{\max}^s}{\nu_{\mathrm{b}}^s+\nu_T^s}\right)\right],$$

This approach (applied to CDFS, COSMOS, CAIXA, SWIFT samples) shows that high-z AGN behave as local sources!

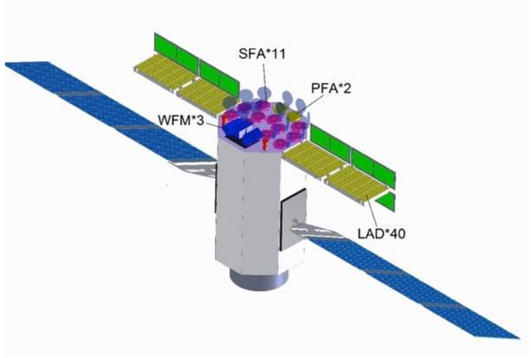


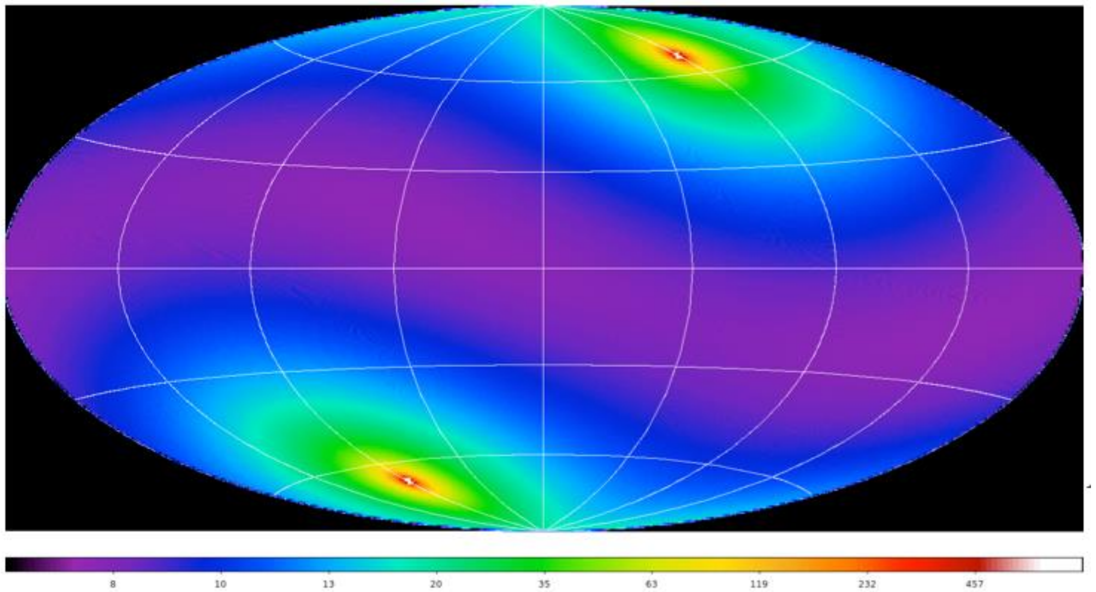


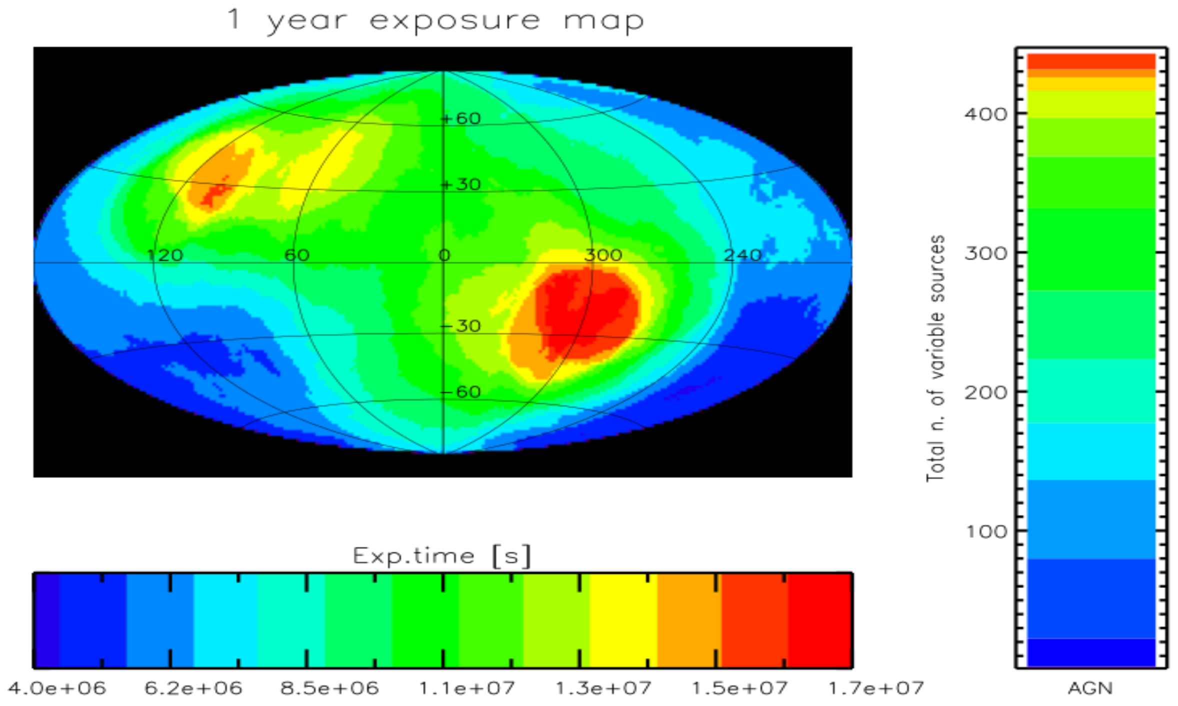
How to improve? eRosita, eXTP, StarX

eROSITA

The enhanced X-ray Timing and Polarimetry mission (eXTP)







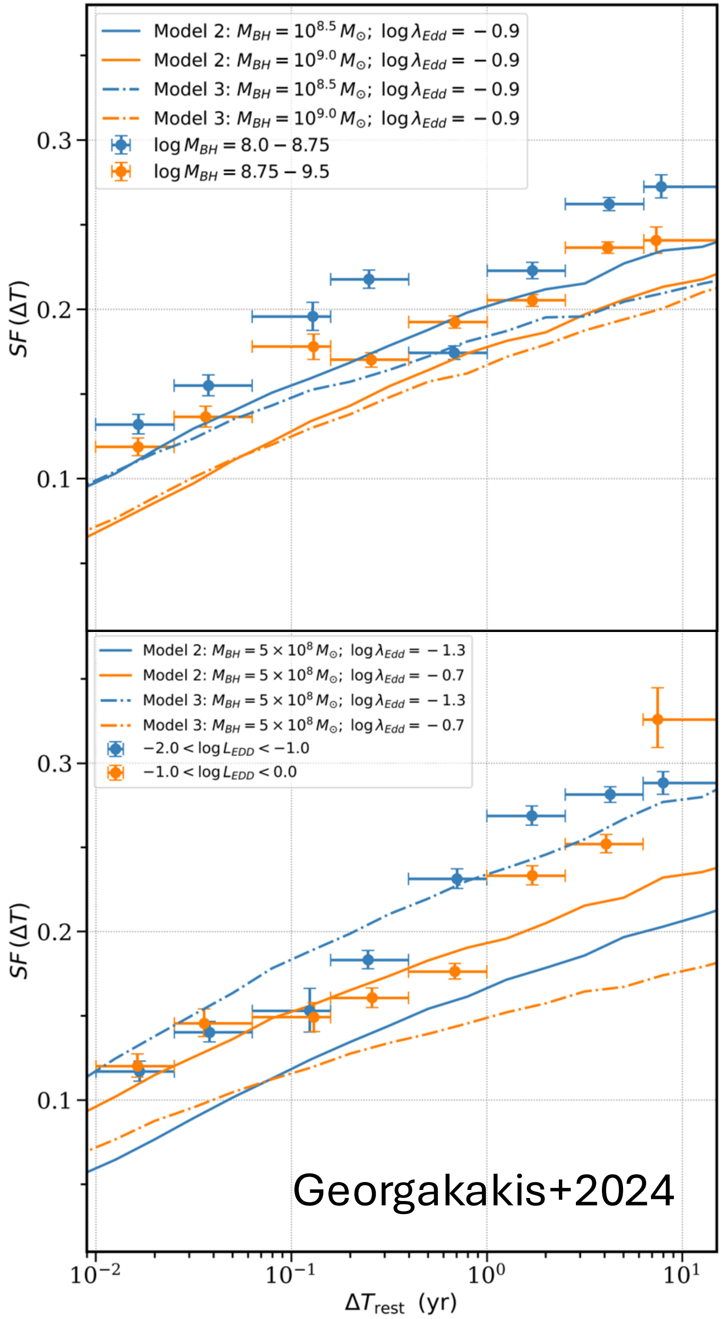
eRosita+XMM results

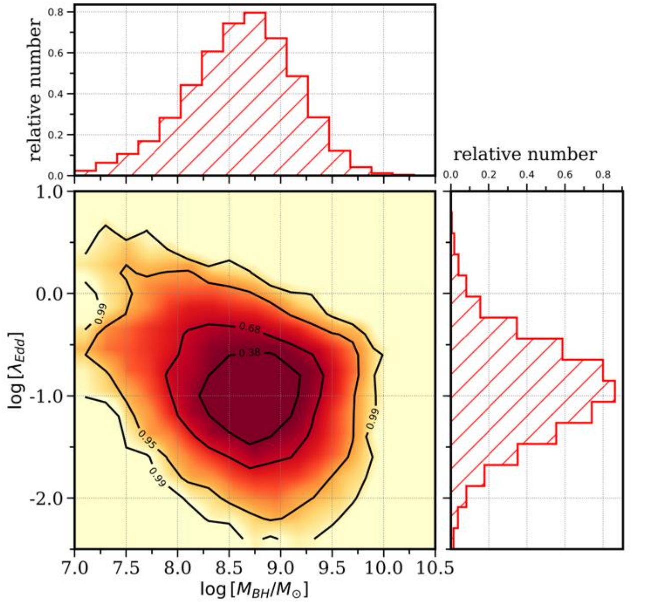
From the first 6 monts (eRASS1) and 15548 SDSS DRQ16 QSO:

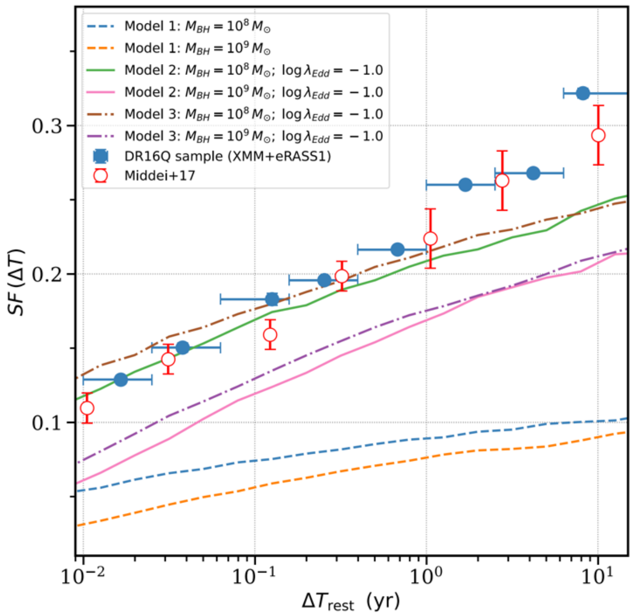
- Using Bayesian variability analysis: SF rises up to 12 years, with little evidence of a break.
- Similar to results from Middei+17
- Anticorrelation with mass
- No clear scaling with accretion rate

No model fits all the data, but some are favoured!

Also see Prokhorenko et al. (2024)

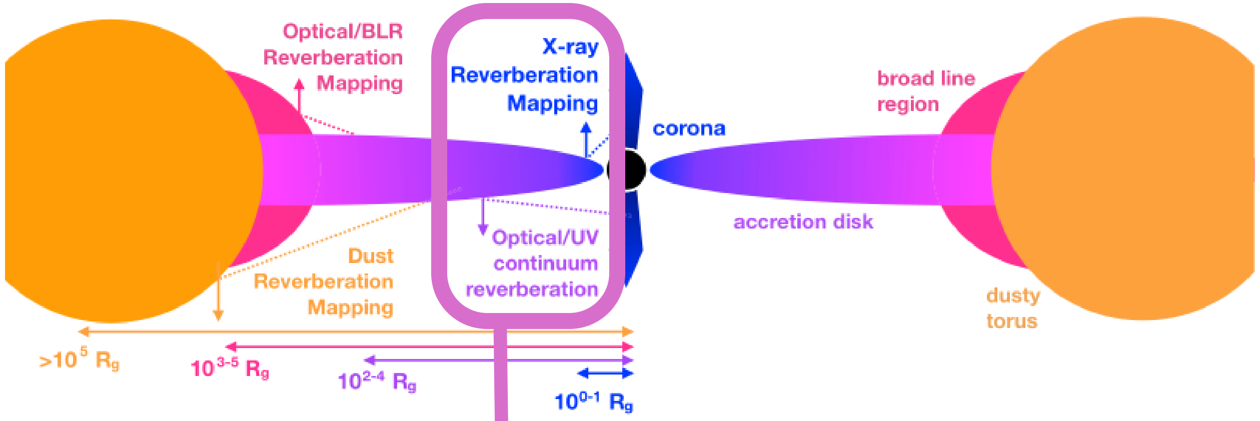






Properties of optical variability

- Aperiodic
- More rapid and intense at shorter wavelengths, bluer when brighter
- Suppressed in the IR (for RQ objects) due to (large) reprocessing regions
- Correlated among wavelengths
- Partially correlated with X-ray on shorter timescales
- Time delays allow thermal reverberation mapping of the disk
- Dependent on acc.rate, mass (spin?)



Region	Size scale (R_G)	Light-crossing time for a black hole mass of $10^7 M_\odot$	$10^9 M_\odot$
X-ray	10	500s	14 hours
UV/optical disk	$10^2 - 10^4$	0.06 – 6 days	6 – 600 days
BLR	$10^3 - 10^5$	0.6 – 60 days	60 – 6000 days
Dusty torus	$> 10^5$	>60 days	>6000 days

Characteristic Disk Timescales

- Dynamic Timescale: timescale to achieve the hydrodynamic equilibrium in the disk

$$T_{dyn} = 104\left(\frac{R}{100R_S}\right)^{3/2}\frac{M_{BH}}{10^8 M_{sun}}[days]$$

Order of days/months

- Thermal Timescale: ratio of internal energy to the cooling or heating rate. The parameter α describe the disk viscosity.

$$T_{th} = 4{,}6\,\frac{\alpha^{-1}}{0{,}01}\,\frac{R}{100R_S}^{3/2}\,\frac{M_{BH}}{10^8 M_{sun}}[years]$$

Order of months/years

- Viscous Timescale: characteristic timescale of a mass flow.

$$T_{visc} = T_{th}\left(\frac{R}{H_d}\right)$$

Order of years!

- If $R/H_d \ll 1$ → $T_{dyn} < T_{th} < T_{vis}$

But keep in mind that the emission does not come from only one radius…

Structure function definitions

Measures the amplitude of variability as a function of the time lag between pairs of observations.

The actual method to measure SFs is ill defined in literature producing inconsistent estimates (see Kozlowski 2016)

$$SF(\Delta t) = \frac{1}{N}\sum_{i=1}^{N}(\Delta m_{ij})^2$$ *(Simonetti+84)*

$$SF(\Delta t) = \left\langle \sqrt{\frac{\pi}{2}}|\Delta m_{ij}| - \langle \sigma^2 \rangle \right\rangle$$ *(Vanden Berk+04)*

$$SF(\Delta t) = \mathrm{med}(\Delta m_{ij}^2)$$ *(Sumi+05)*

$$SF(\Delta t) = \left\langle \sqrt{\frac{\pi}{2}}|\Delta m_{ij}| - \sqrt{\sigma_i^2 + \sigma_j^2} \right\rangle$$ *(Schmidt+10)*

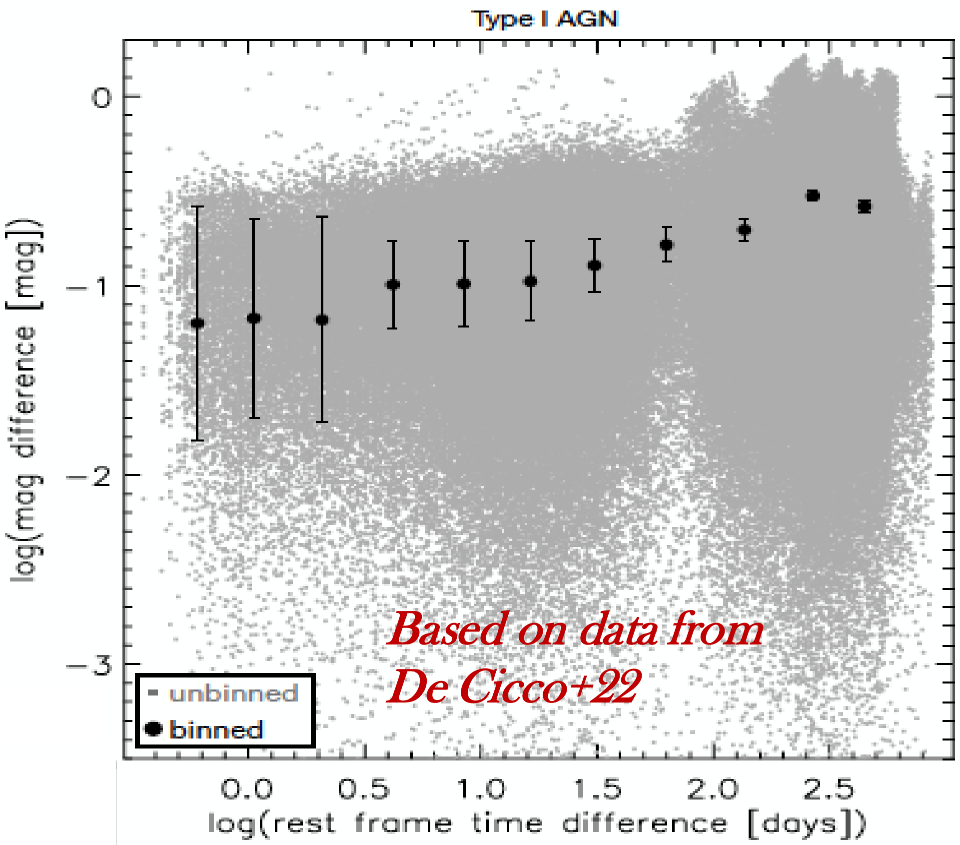
$$SF(\Delta t) = 0.74(IQR)/\sqrt{N-1}$$ *(MacLeod+12)*

$$SF(\Delta t) = \sqrt{\langle \Delta m_{ij}^2 \rangle - \langle \sigma^2 \rangle}$$ *(Bauer+09)*

$$SF(\Delta t) = \sqrt{\left\langle \frac{\pi}{2}\Delta m_{ij} \right\rangle^2 - \langle \sigma^2 \rangle}$$ *(Bauer+09)*

$$SF(\Delta t) = \sqrt{\frac{\pi}{2}\langle |m(t_j) - m(t_i)| \rangle^2 - \langle \sigma^2_{noise} \rangle}$$ *(Di Clemente+96)*

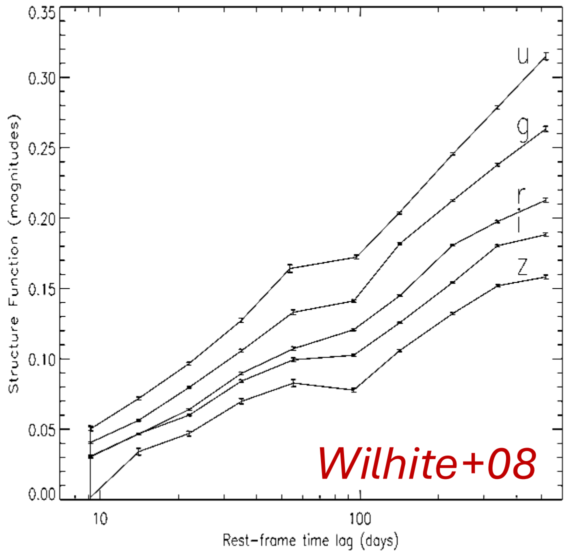
Graham+14

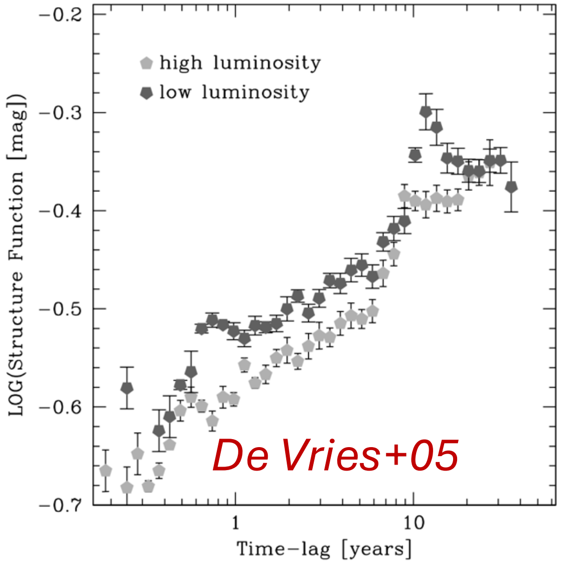


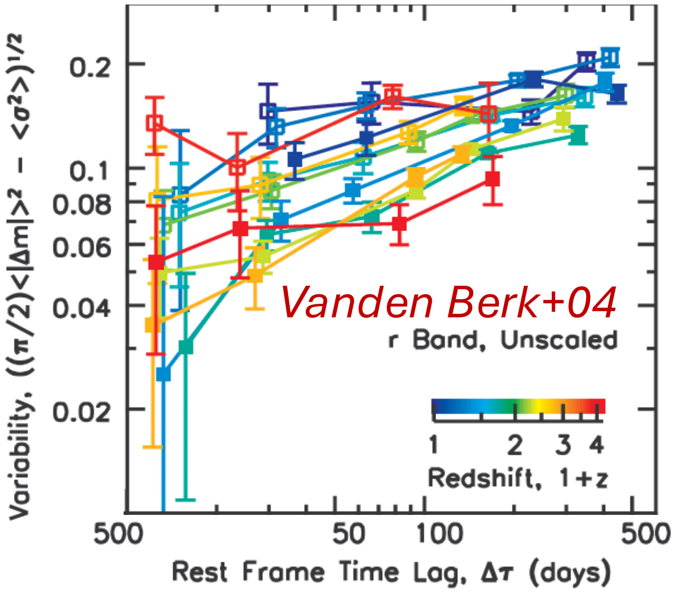
Optical structure function studies

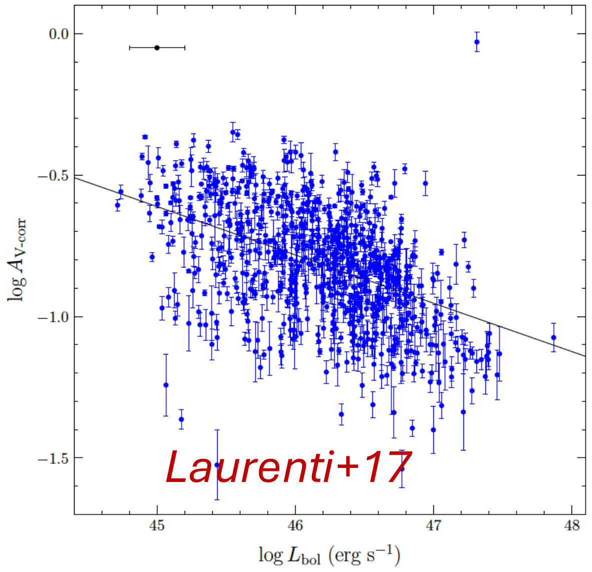
A few examples among the many based on different datasets (DPOSS, SDSS etc.)

- Increasing amplitude with time lag
- No evidence of predicted breaks (DRW)
- Anticorrelation with wavelength and luminosity at fixed mass
- Variability increases with mass at fixed L
- correlation among different bands
- timescales: days – months => amplitude: $10^{-2} – 10^{-1}$ mag





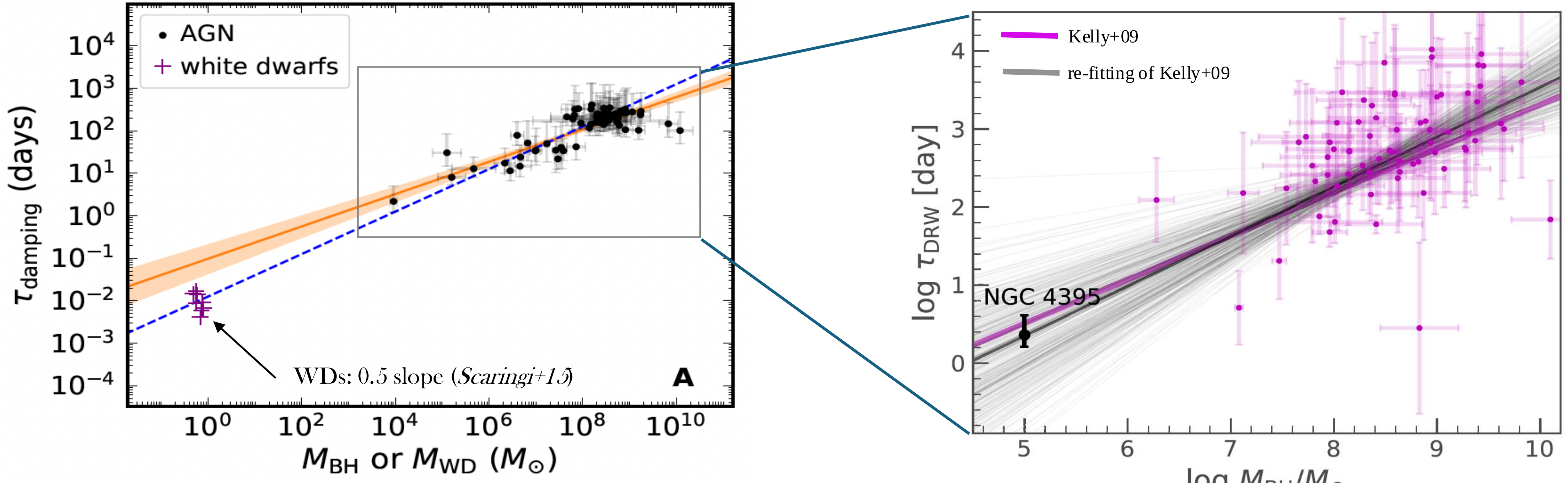




Optical variability timescale

- *Burke+21:* 67 AGN, 10^4 M$_\odot$ < M_{BH} < 10^{10} M$_\odot$
- *Burke+20:* NGC 4395, 10^5 M$_\odot$ SMBH in its center; observed with TESS, month-long baseline, 30 min-cadence

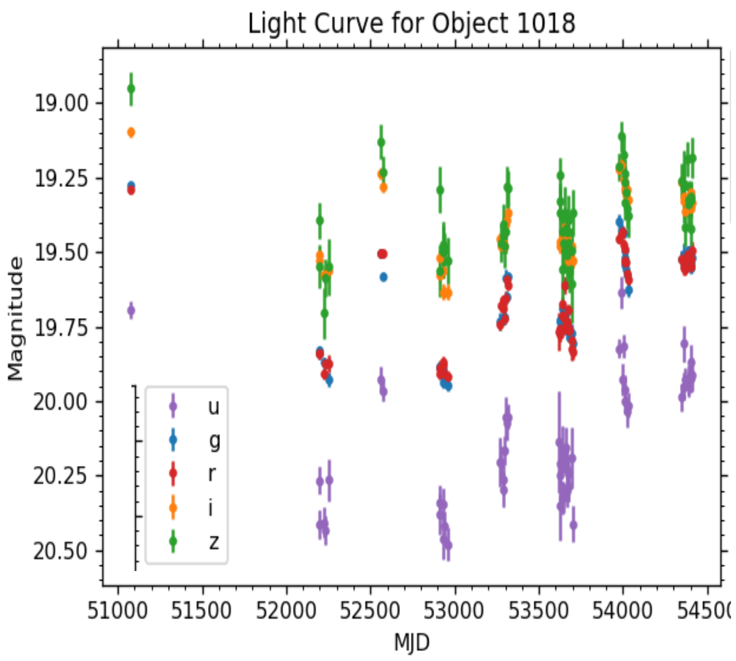
Also see Suberlak, Stone, and Camacho's recent works

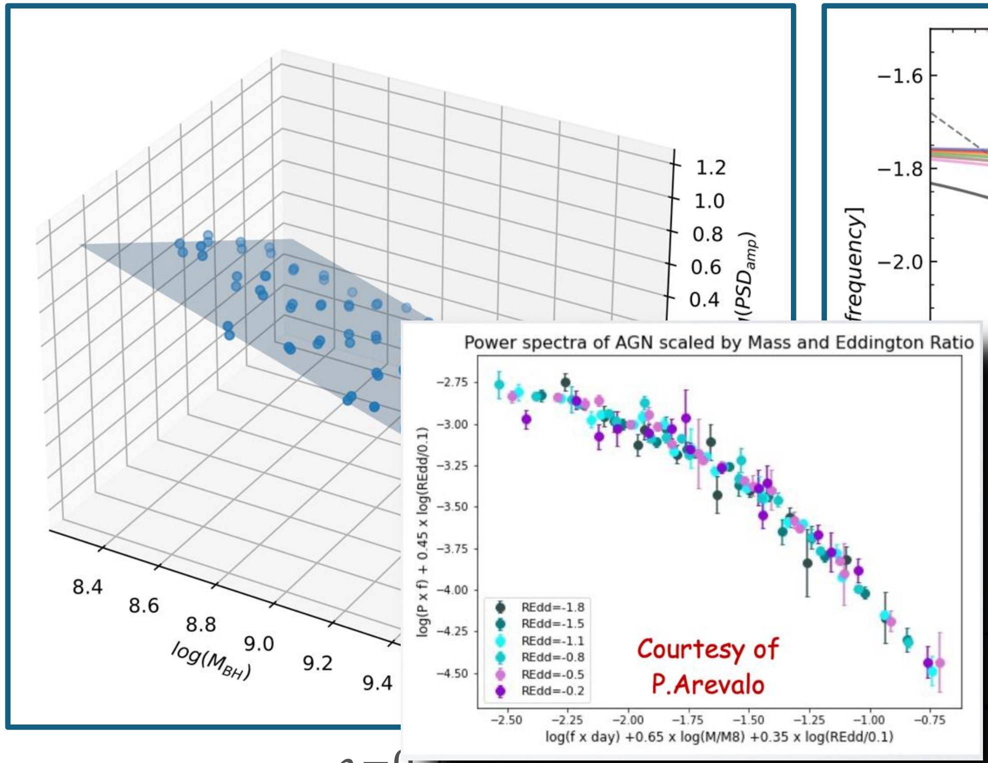


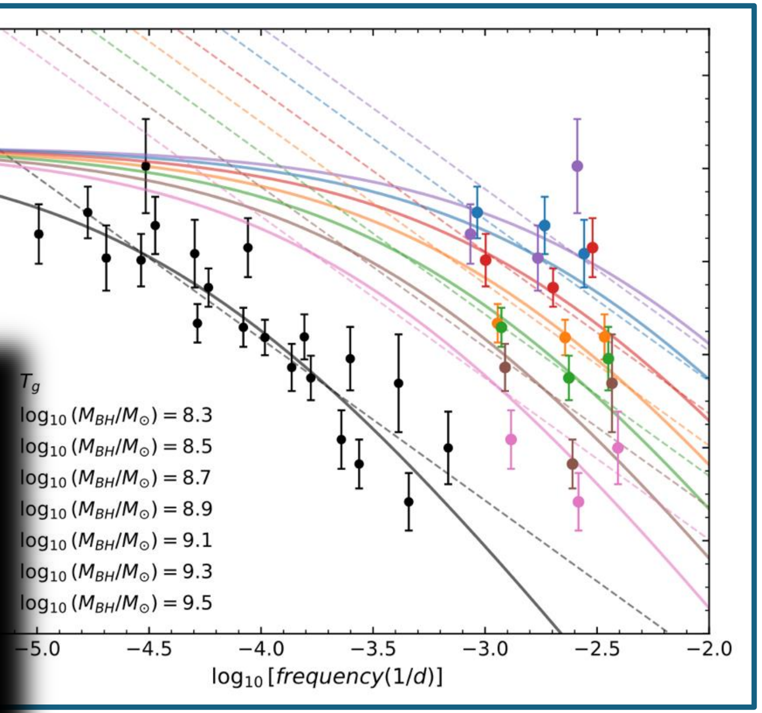
Ensemble PSD analysis

(Petrecca et al. 2024)

- 9186 spectroscopically confirmed Quasars
- Light curves with 60 visits for 10 years in 5 bands ugriz (nearly simultaneous)



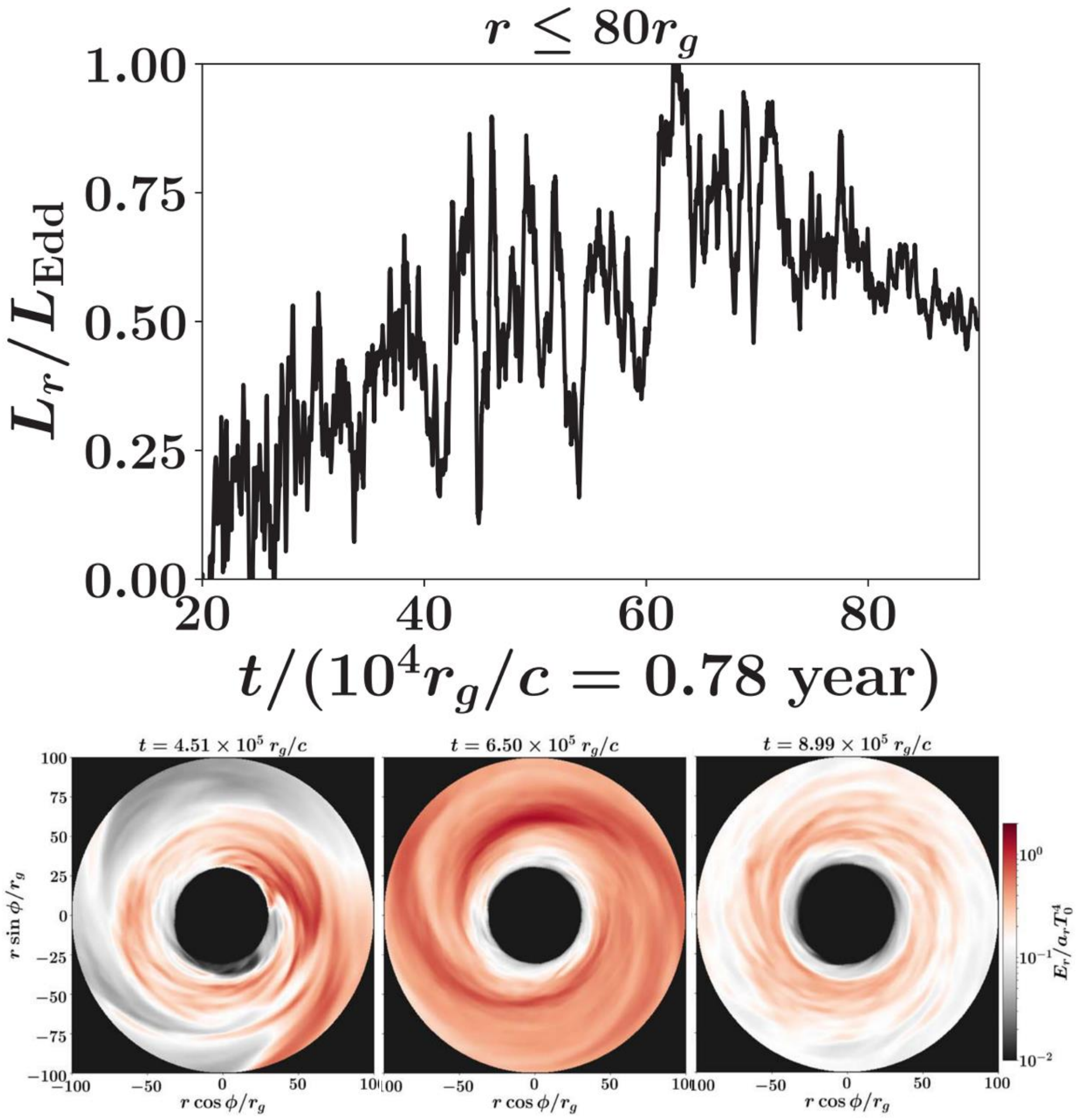




$$PSD_{amp}(M_{BH}, \lambda_{Edd}) \propto \frac{\lambda_{Edd}^{-0.7}}{\sqrt{M_{BH}}} \qquad PSD_{slope}(M_{BH}, \lambda_{Edd}) \propto \frac{\lambda_{Edd}^{-0.4}}{\sqrt{M_{BH}}}$$

Timescale problem: global simulations with realistic opacities

- Observed timescales tend to be faster than predicted by the standard SS73 disks
- Thermal timescales seem the most likely to dominate (e.g. *Kelly+09)*
- However most simulations are performed with free-free and electron scattering, (appropriate for X-ray binaries) while using line opacities drives strong convection that changes the vertical structure and thermal properties of accretion flows (*Jiang+2016, 2019, Jiang & Blaes 2020, also see Davis & Tchekhovskoy 2020 ARA&A*)
- This causes strong oscillations of the disk scale height and luminosity variations from years to decades timescales.

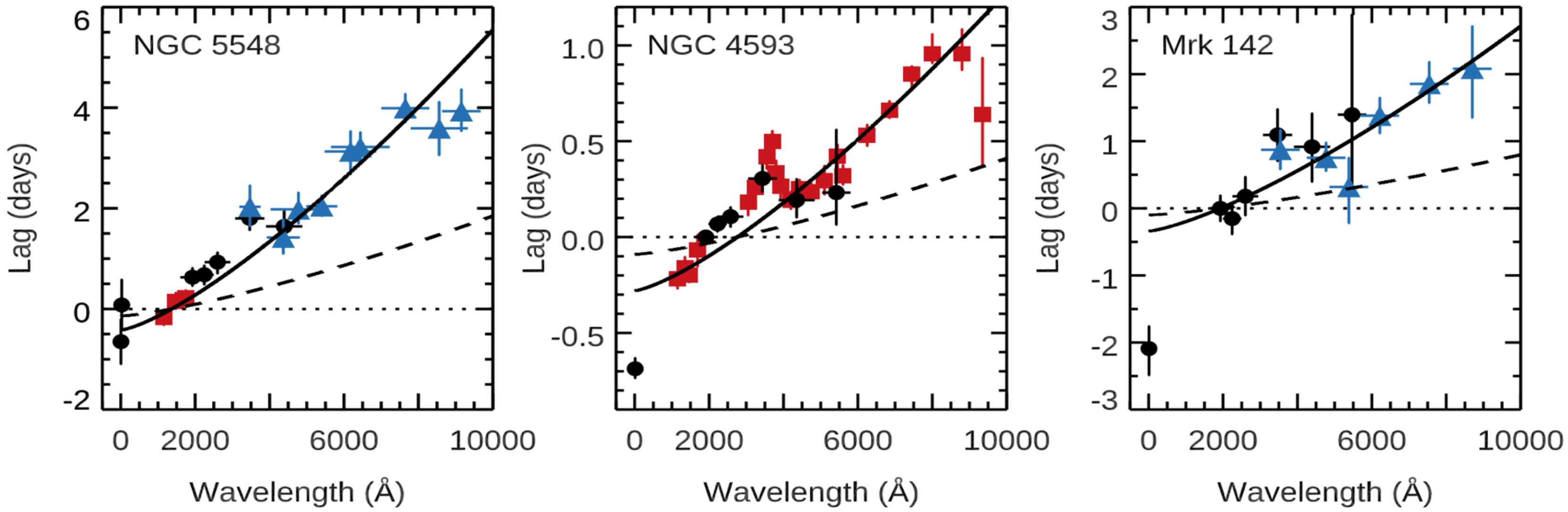


Jiang & Blaes (2020)

Thermal reverberation: the disk size problem

(Uttley+03, Arévalo+08,McHardy+14,16, Cakett, Benz & Kara+21, and references therein)

Lags should scale as $\lambda^{4/3}$, but **observed lags are longer than expected → Accretion disk is too large** (also from microlensing).



Possible solutions (Dexter & Agol '11, Hall+'18, Mummery & Balbus '20, Kammoun+19, 21a, 21b):

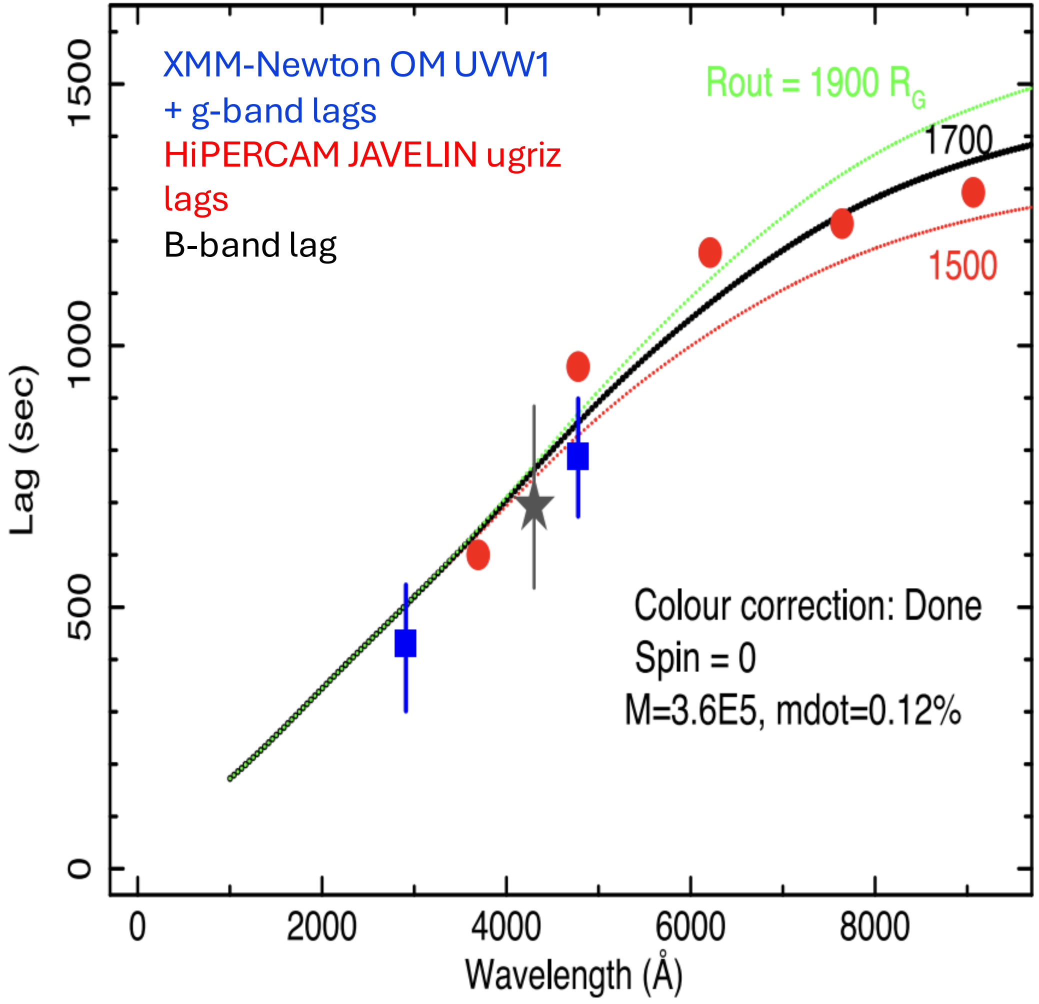
- wrong ṁ estimate or the conversion from wavelength to temperature
- the disk is not a black- body or inhomogeneous, time-dependent disk structure
- low-density scattering atmosphere, which leads to a substantially different temperature profile
- relativistic disk reprocessing models give systematically longer lags

Also, BLR reprocessing contribution

Measuring the outer edge?

First detection of the outer edge of an AGN accretion disc
(McHardy+23)

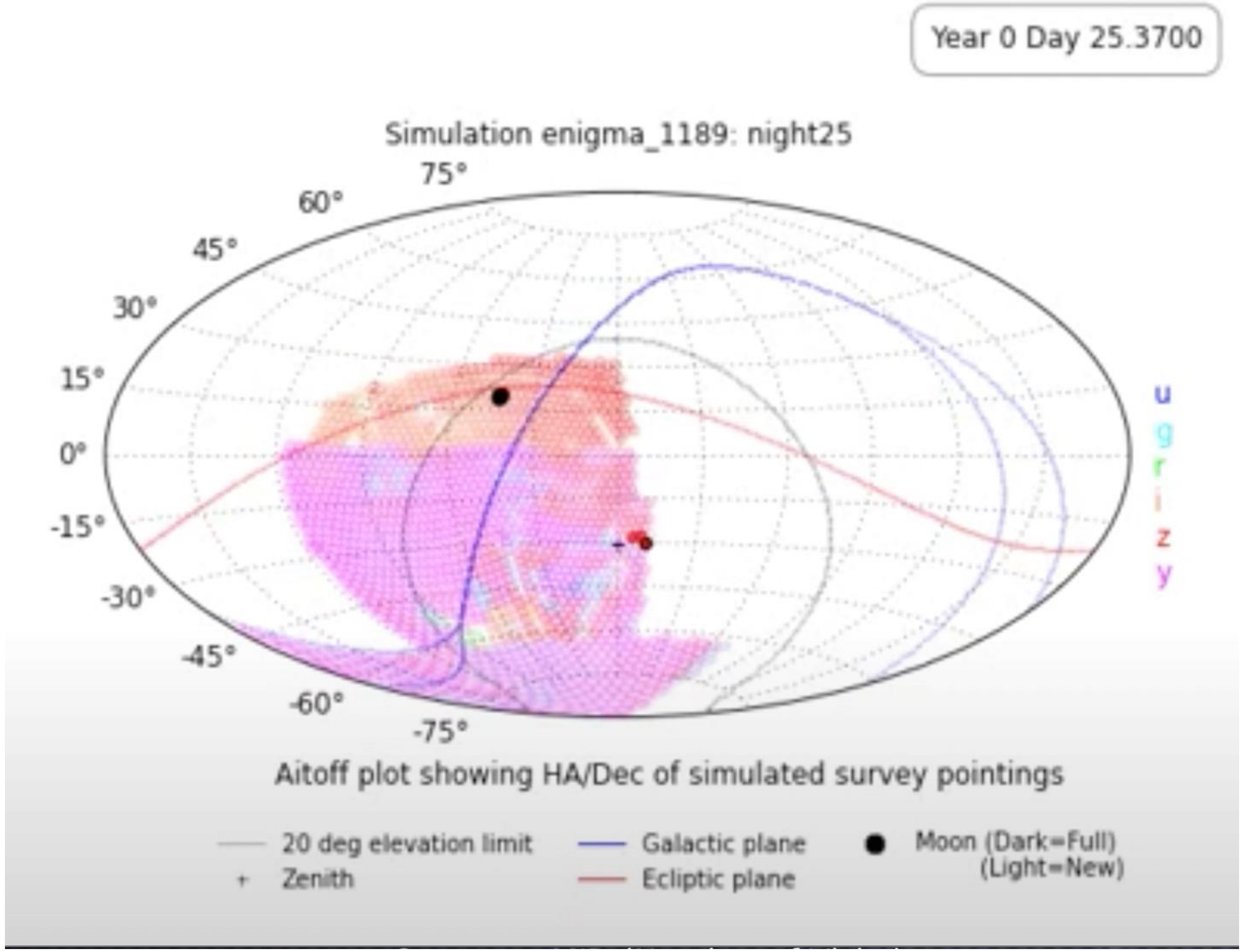
- Lags with respect to the X-ray band: at the longest wavelengths the lag tends to become constant requiring a maximum radius of the reprocessor.
- Lines are lag predictions for different disc outer radii of 1500, 1700, and 1900 R g



The Vera rubin Telescope - Legacy Survey for Space and Time (LSST)

An optical/NIR survey of half the sky in the ugrizy bands to r 27.5 based on 820 visits over a 10-year period.

8.4m (6.7m effective)
10 deg^2
3.2 Gpix camera



Wide-Fast-Deep survey

- The observable southern sky. Each exposure covers 50 full Moons.
- Whole observable sky scanned every 3-4 nights.
- 10-100 times deeper than other very wide-field surveys.

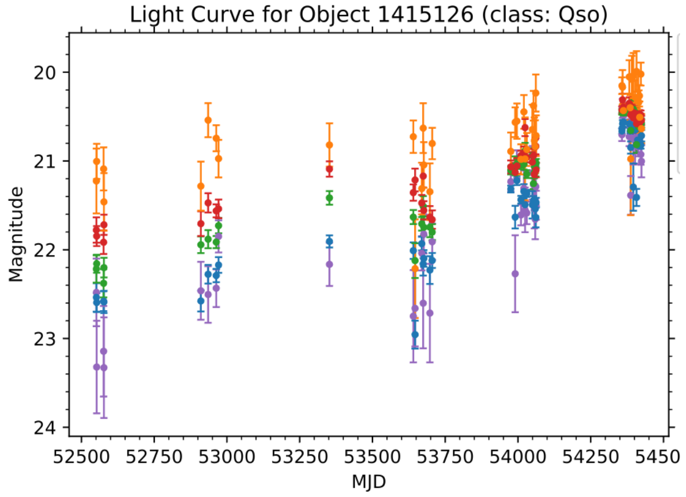
Deep Drilling Fields

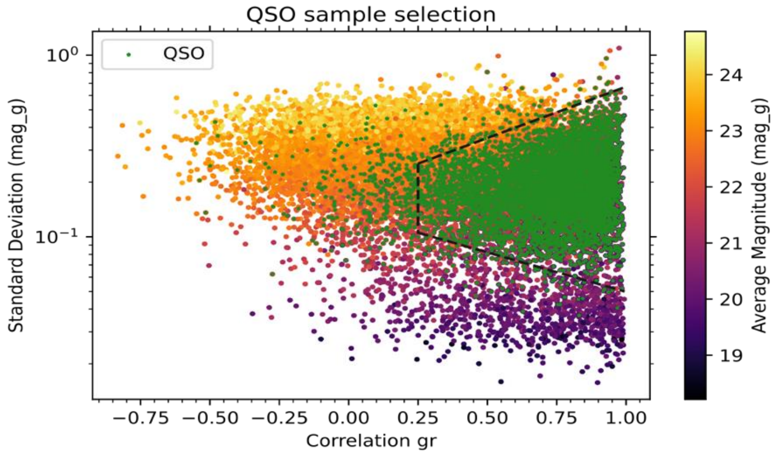
Quantity of Interest	u	g	r	i	z	y
Visits Every 2 Nights	4	1	1	3	5	4
Depth Every 2 Nights	24.6	25.0	24.7	24.6	24.2	22.9
Total Visits in 10 yr	3600	900	900	2700	4500	3600
Total Depth in 10 yr	28.3	28.7	28.4	28.3	27.9	26.5

depths quoted are 5σ design-specification depths

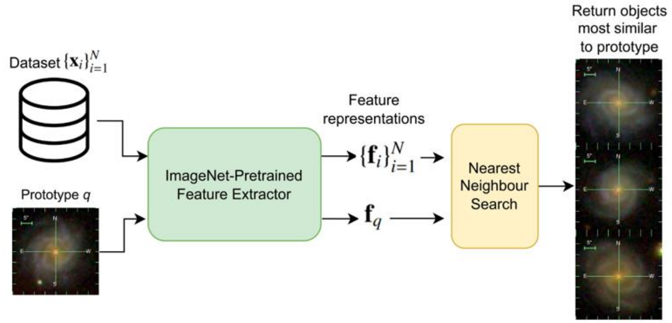
AGN Selection in LSST-AGN data challenge

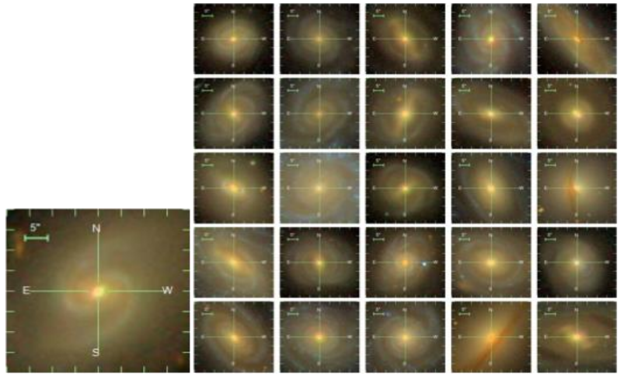
- Traditional methods: photometry + variability
- Machine learning approaches on lightcurves and image (Savić+22, Donenbroos+22)
- Strengths: high completeness and purity
- Weaknesses: tested on Quasar-like sources, not on the average AGN population





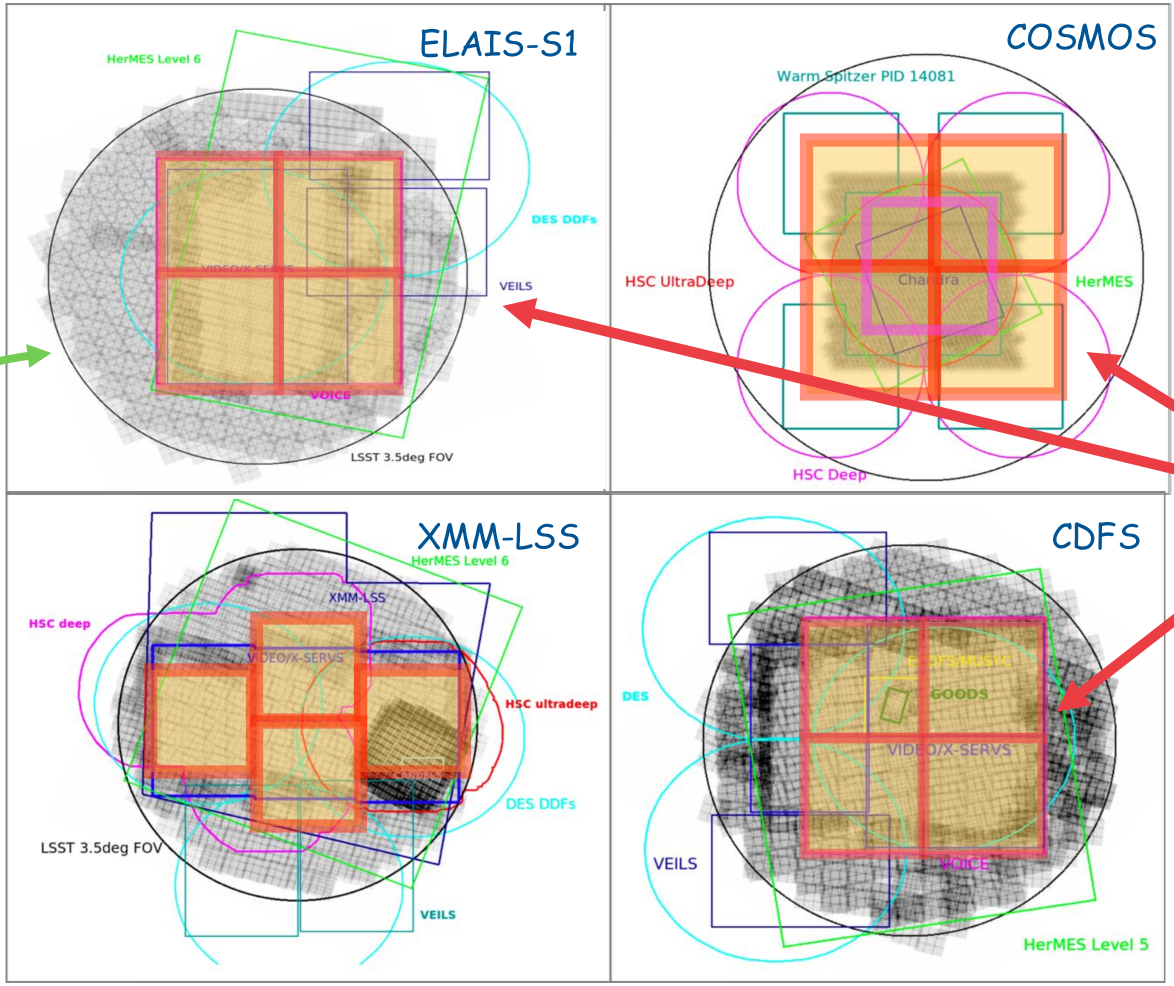
	Completeness (QSO)	Purity (QSO)
Sample		
Wedge	90.9 %	52.0 %
Extendedness	97.6 %	65.4 %
Color	90.3 %	59.8 %
Wedge+Ext.	89.5 %	89.3 %
Col.+Ext.	89.5 %	77.8 %
Wedge+Col.	83.0 %	85.7 %
Wedge+Ext.+Col.	82.4 %	95.0%





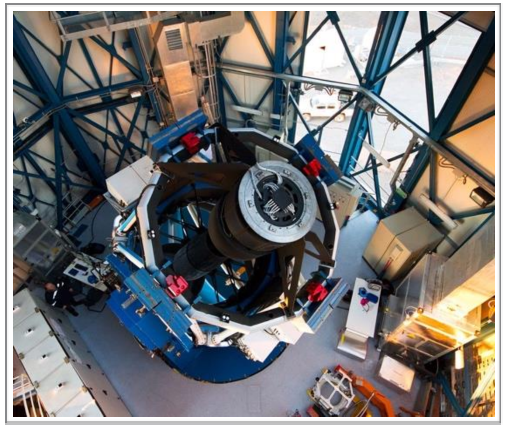
VST as LSST precursor

VST started observing some of the LSST DDFs within the **SUDARE/VOICE, KIDS, VEGAS, VSTxSKA** surveys. **TIMEDOMES** is now extending the temporal and spatial coverage.



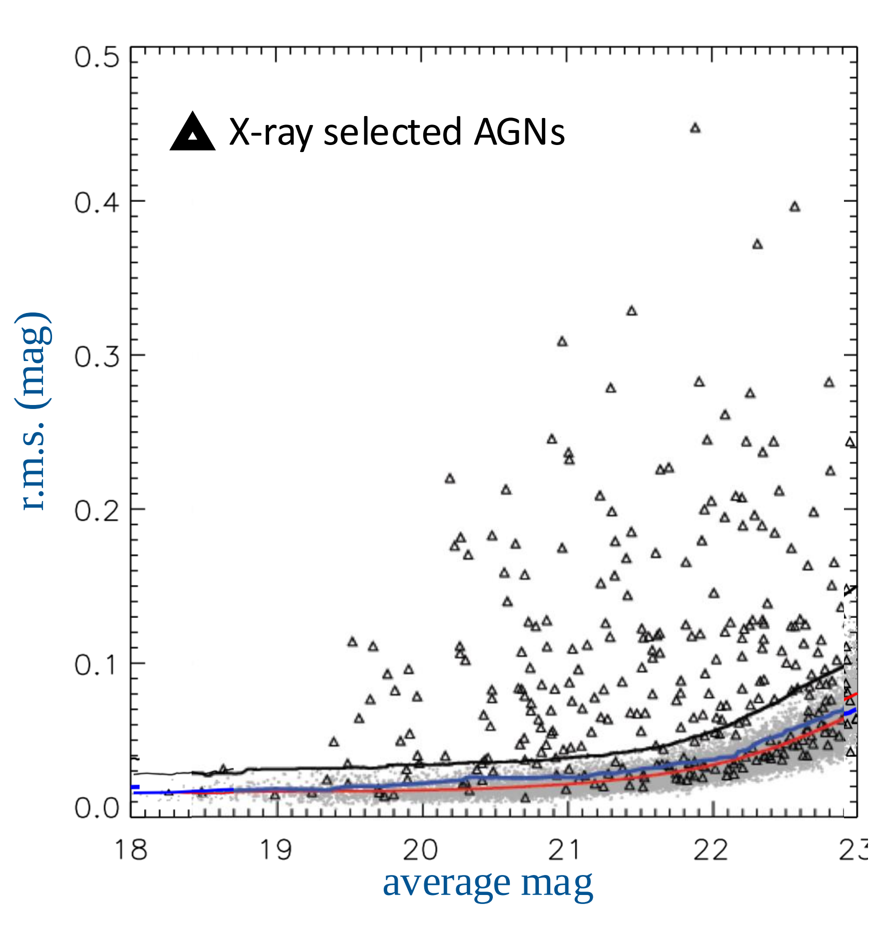
Field Name	Central RA (J2000)	Central Dec (J2000)
ELAIS-S1	00:37:48	−44:01:30
XMM-LSS	02:22:18	−04:49:00
CDF-S	03:31:55	−28:07:00
COSMOS	10:00:26	+02:14:01

multi-epoch VST coverage



Performance: X-ray selected AGNs in COSMOS

[De Cicco et al. 2015, 2019,2021,2022]



All the sources detected in 20% of the epochs and with r < 23 mag constitute our sample.

A source is assumed to be variable if P(>rms)<95%

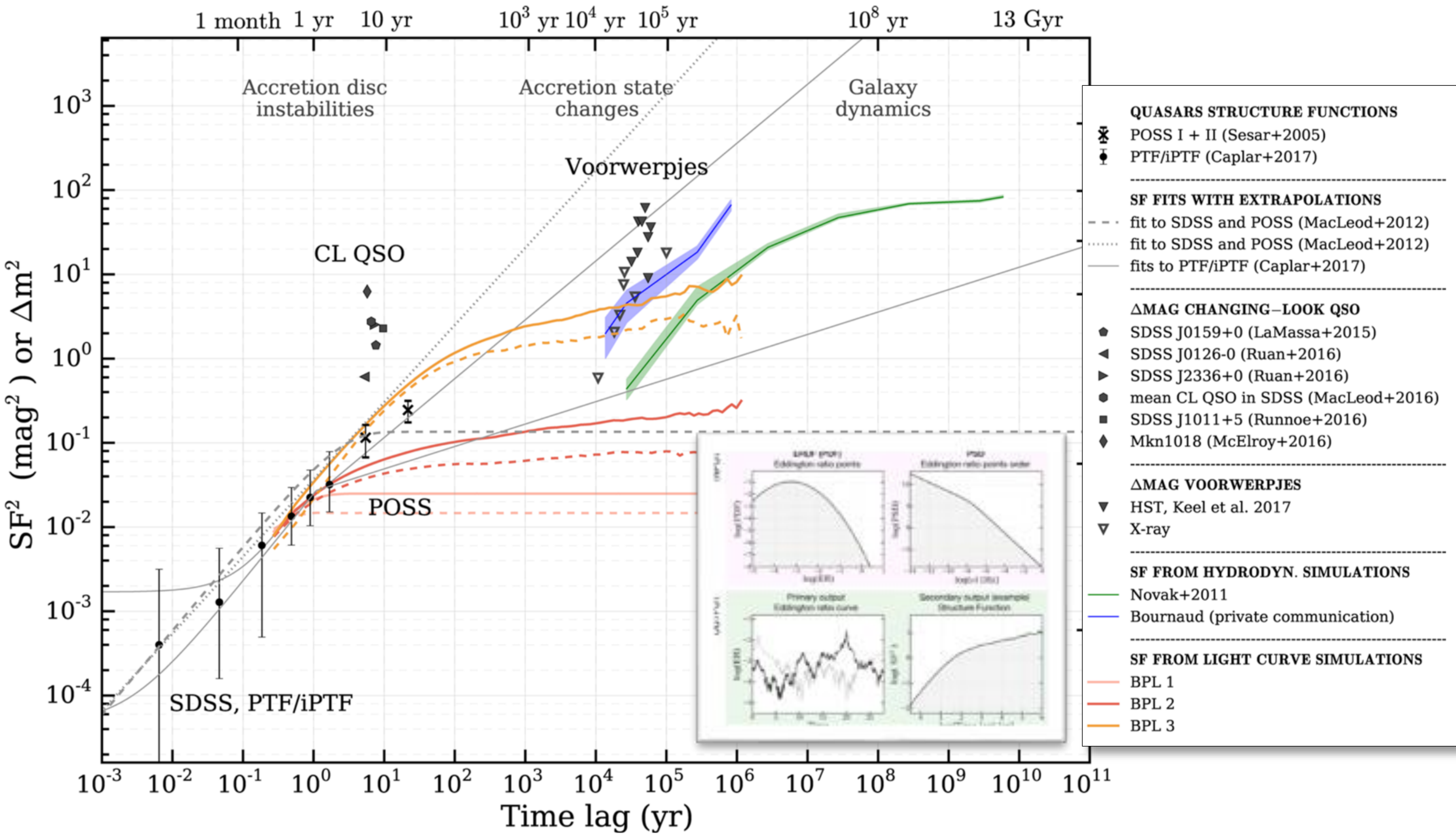
- First 6 months yielded variable sources with Δm~0.1 mag
- Only ~15% of the X-ray selected sample is retrieved

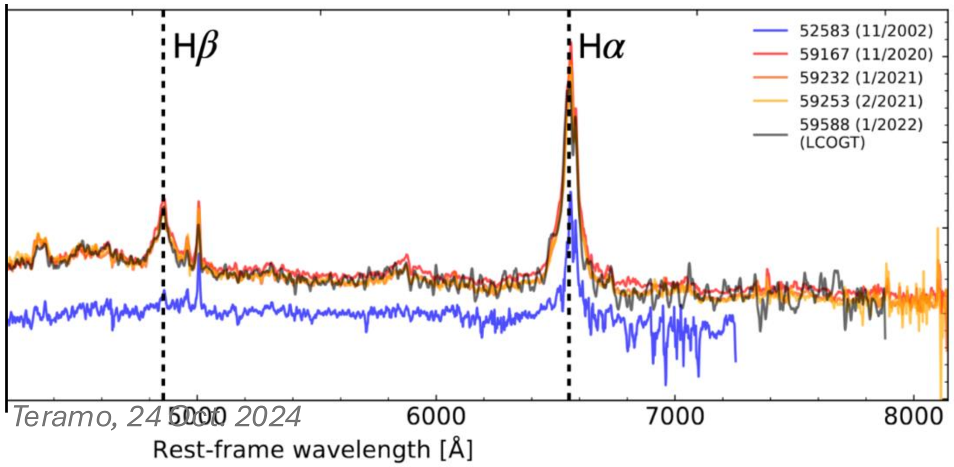
- 3 years extended baseline yields a much larger completeness ~40%

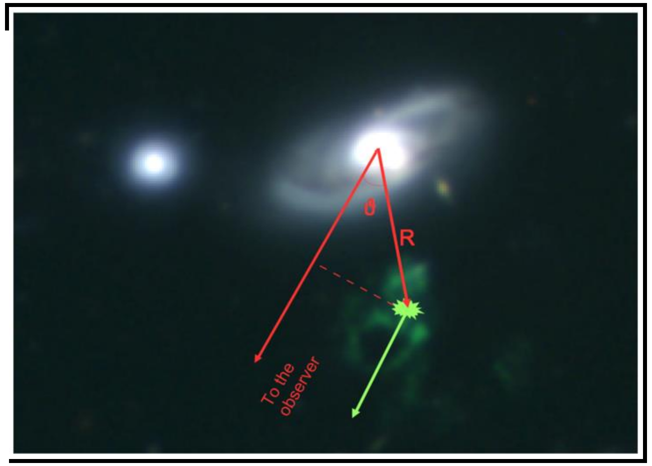
From short to long timescales…

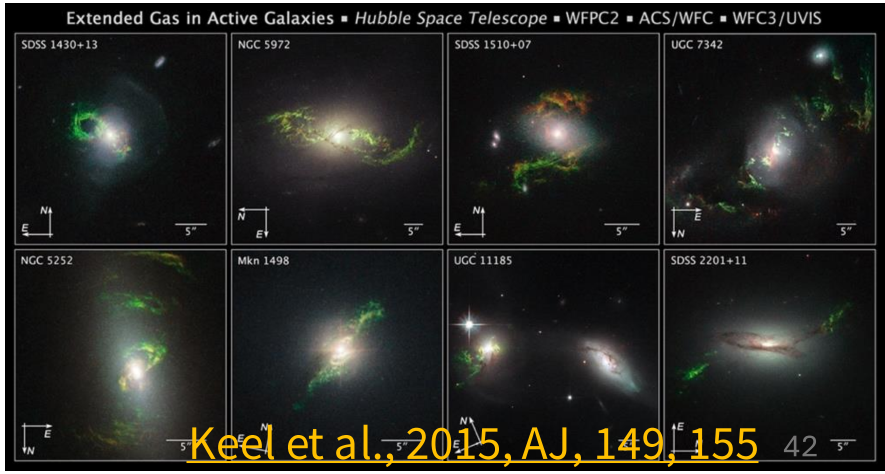
Variability can be extended to long timescale linking it to the AGN duty cycle through the mass function and (Sartori+2018)

CL AGN, light echo's (IC 2497: *Hanny's Voorwerp* type sources)





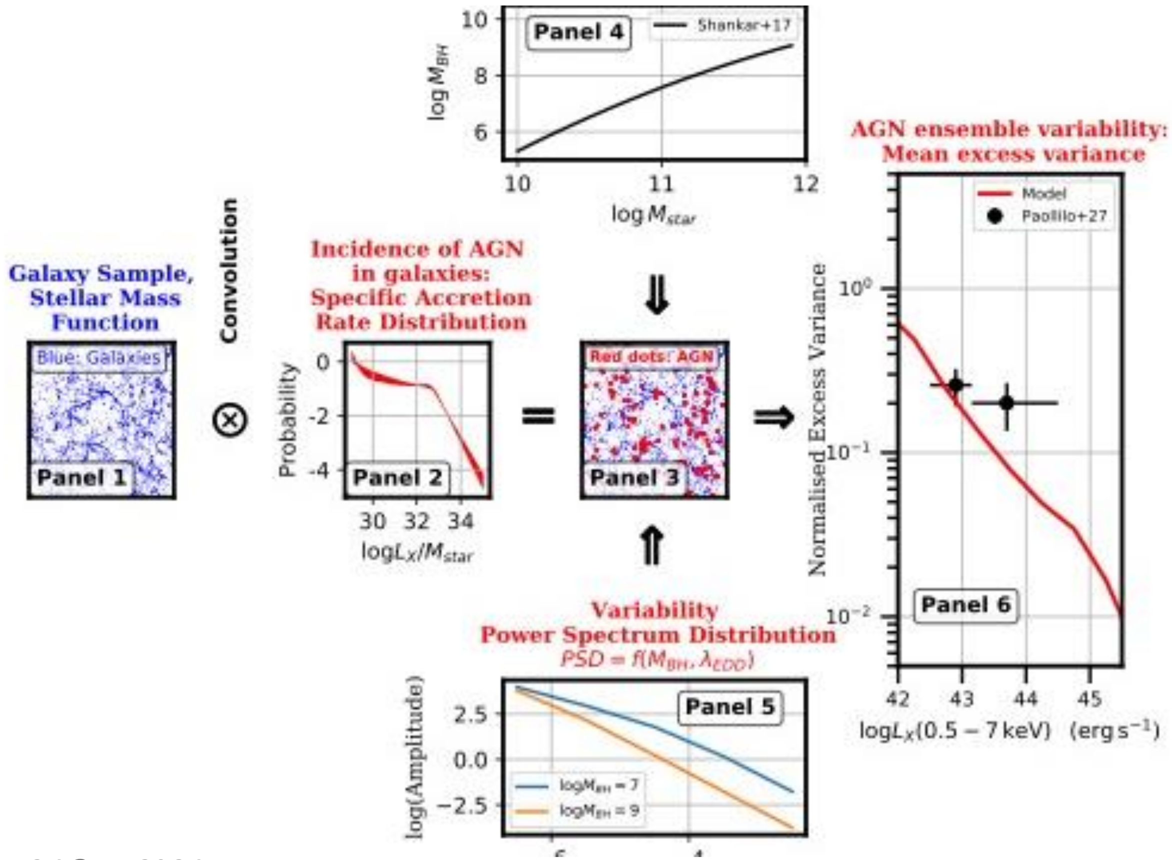


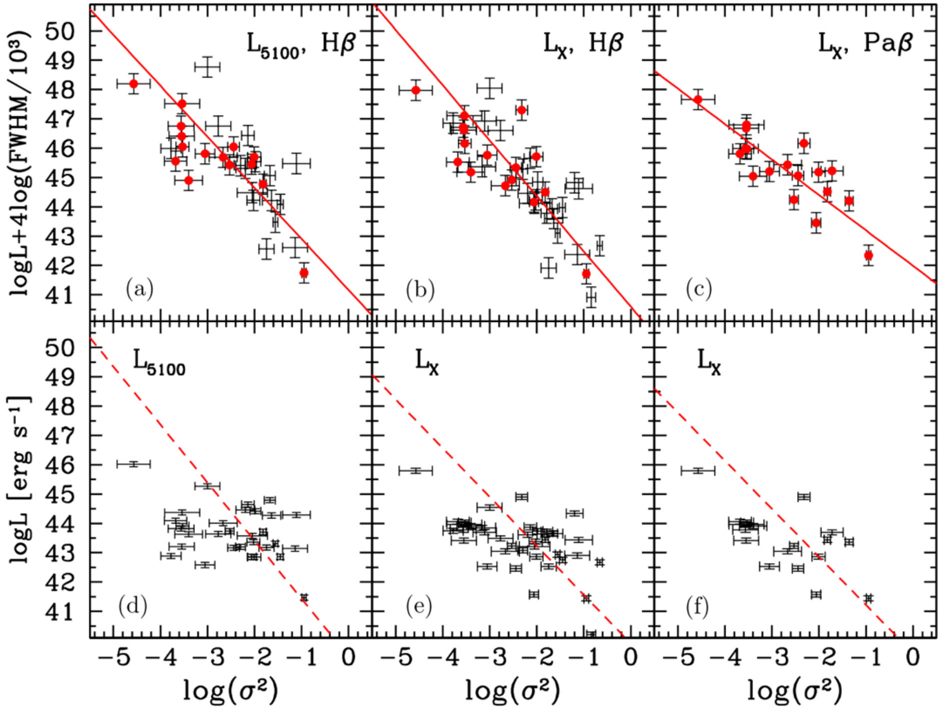


Keel et al., 2015, AJ, 149, 155

New constraints on AGN-Galaxy scaling relations and cosmology

- Constraining BH mass-stellar mass relations through variability [e.g. Sartori+18, Georgakakis, Papadakis & Paolillo 2021]
- Also promising for cosmological studies [La Franca+14]





Summary

- Variability is a defining property of AGN and has been proven fundamental to understand their properties and structure:
- X-ray variability probes the corona shape, height, power and its link to the accretion disk
- Optical/UV variability probes the disk structure and the physics of the accretion process, as well as the feeding of and feedback from the corona
- Variability on its own cannot fully constrain AGN models: need for photometry, spectroscopy, polarization
- Varibility can probe evolution and BH/galaxy connection

New era is opening with synoptic all-sky surveys, e.g. LSST, eRosita.