X-RAY VARIABILITY IN LOW-REDSHIFT AGN AND ITS LINK WITH OPTICAL AND IR PROPERTIES

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SRON – 03/06/25

INTRODUCTION



University of Florence
PhD supervisor: Prof. Guido Risaliti



UCLA – Visiting grad student
supervisor: Prof. Tommaso Treu

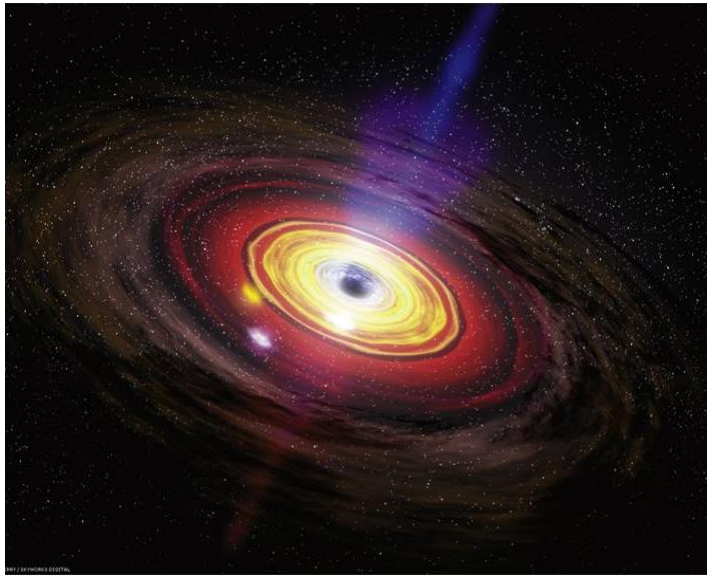


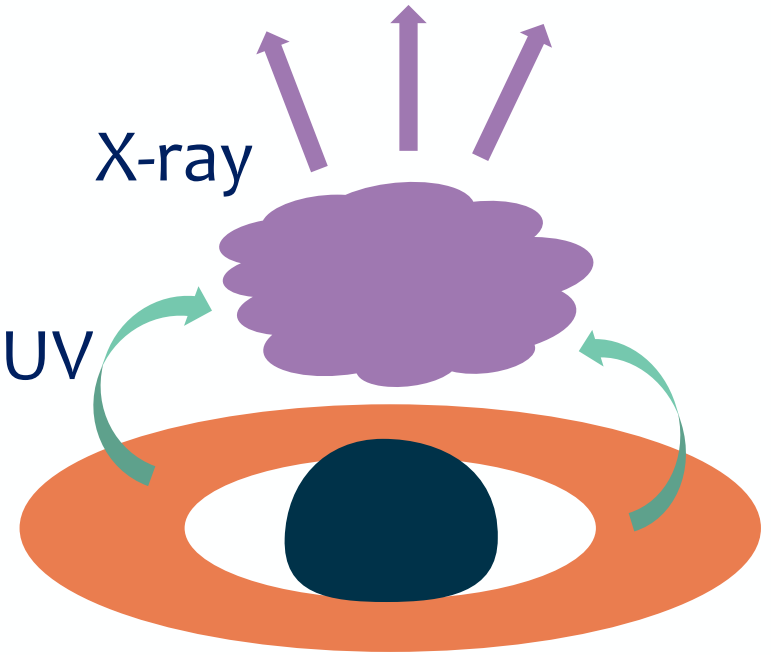
University of Roma3
supervisor: Dr. Federica Ricci

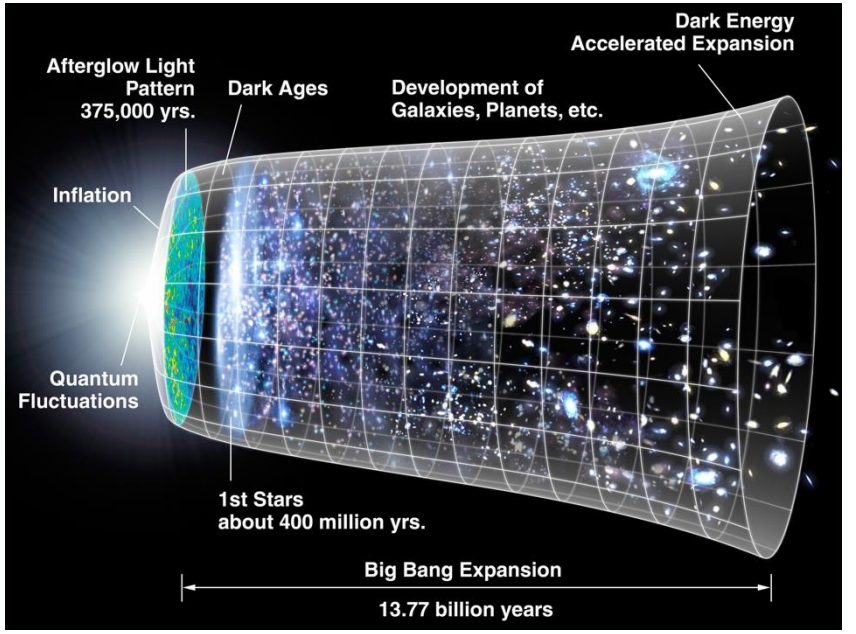


ESA – ESTEC, Research Fellow
"mentor": Dr. Matteo Guainazzi

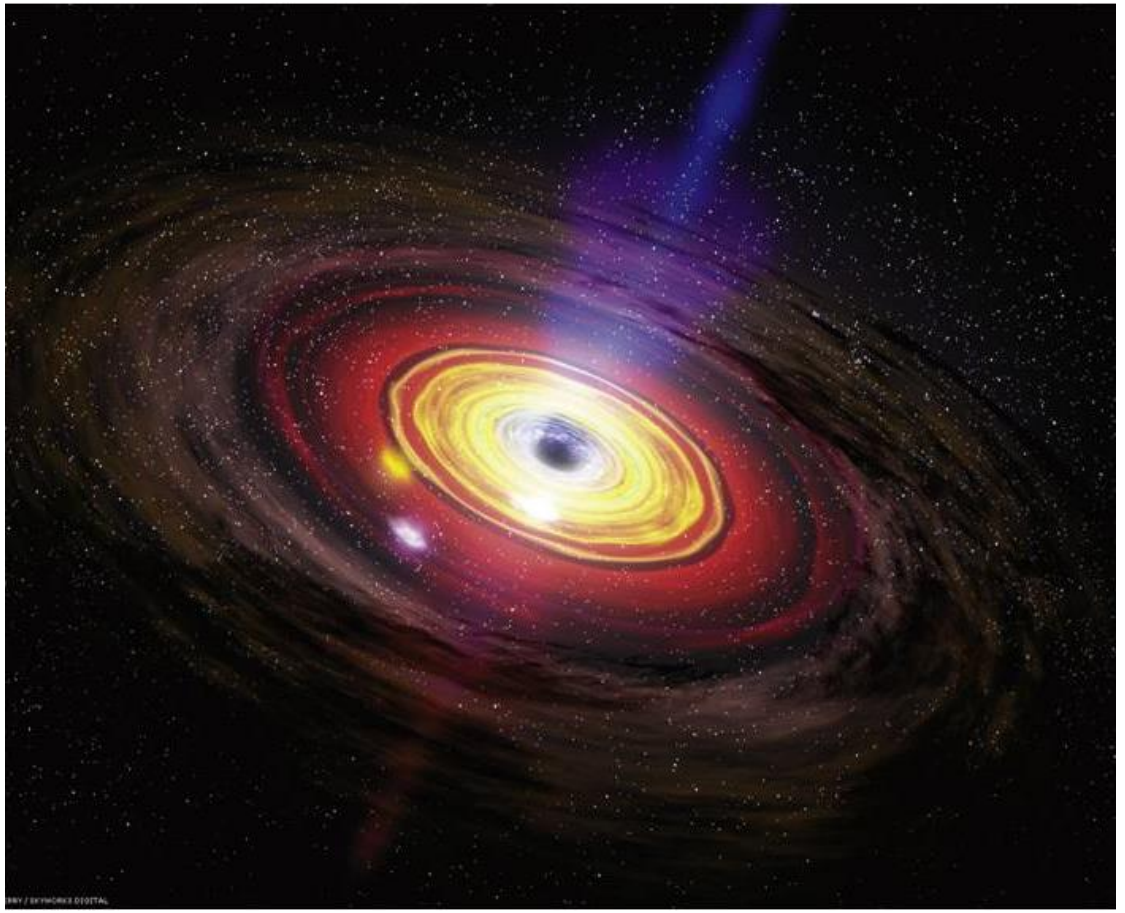
INTRODUCTION







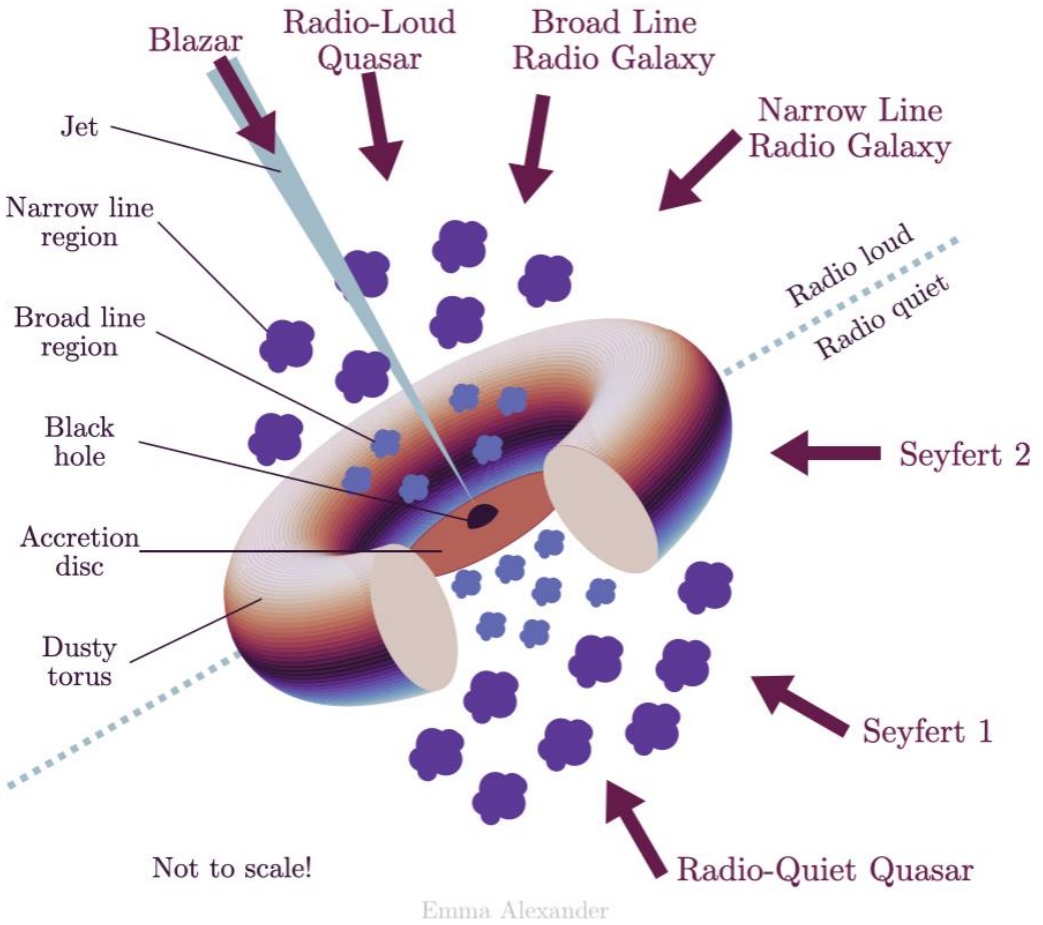
INTRODUCTION



Active Galactic Nuclei

Supermassive Black Hole
($M_{BH}>10^6 M_\odot$) at the centre of a galaxy
+
accretion disc
=
Emission that can outshine the whole host galaxy

INTRODUCTION



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Supermassive Black Hole ($M_{BH}>10^6 M_\odot$) at the centre of a galaxy

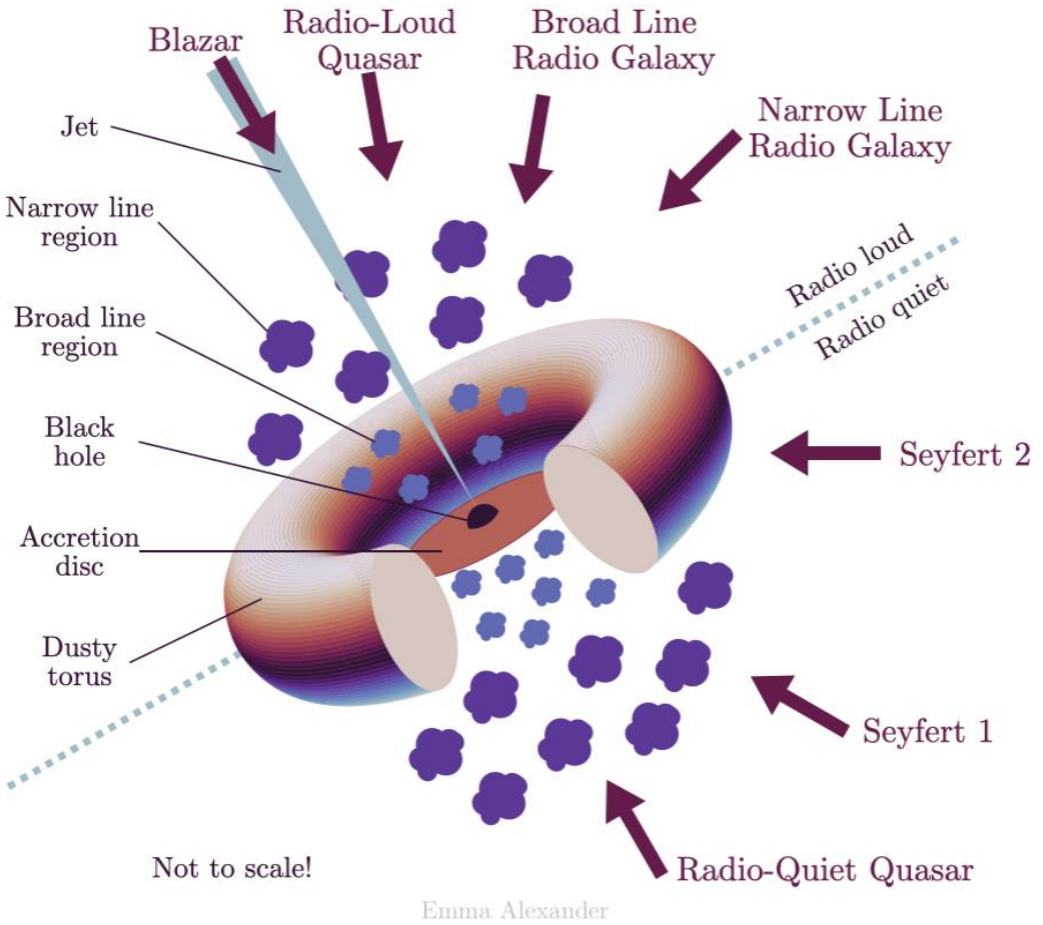
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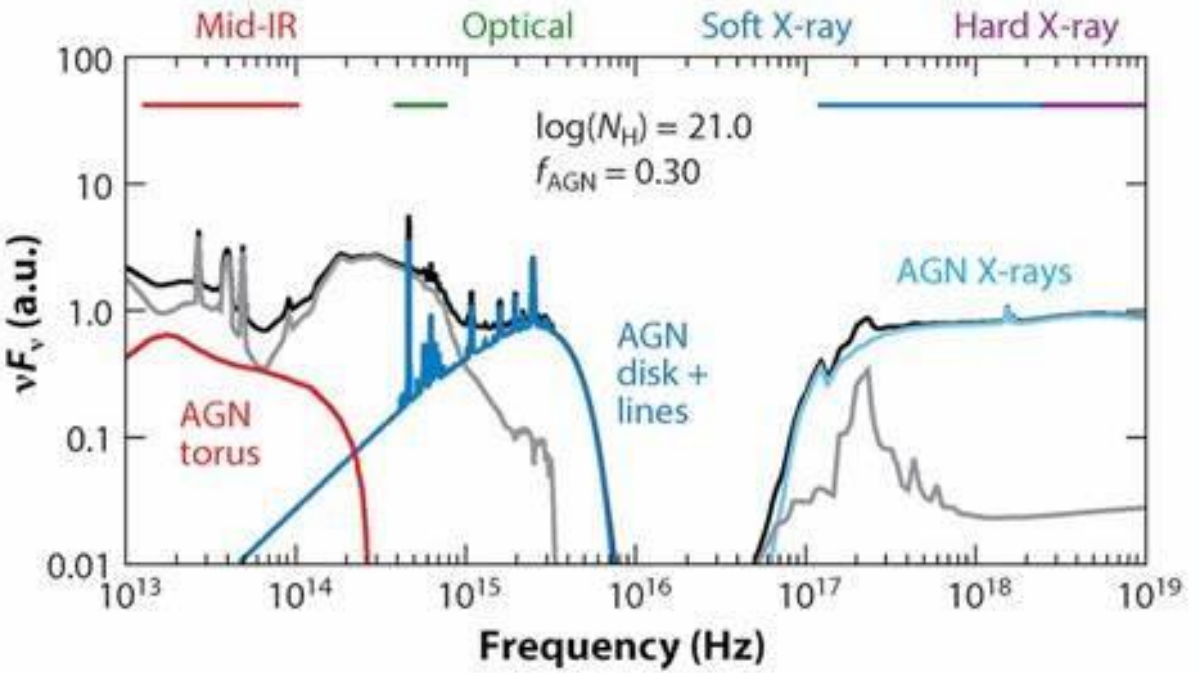
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Emission that can outshine the whole host galaxy

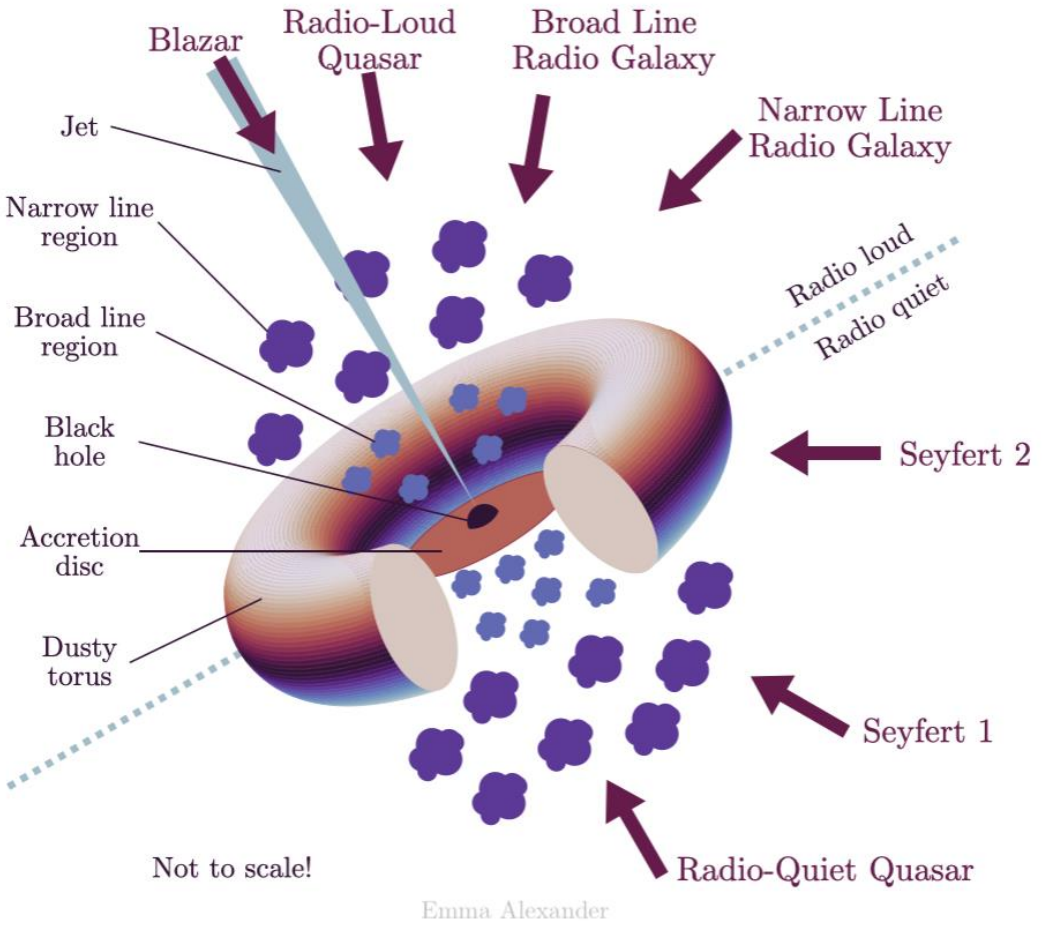
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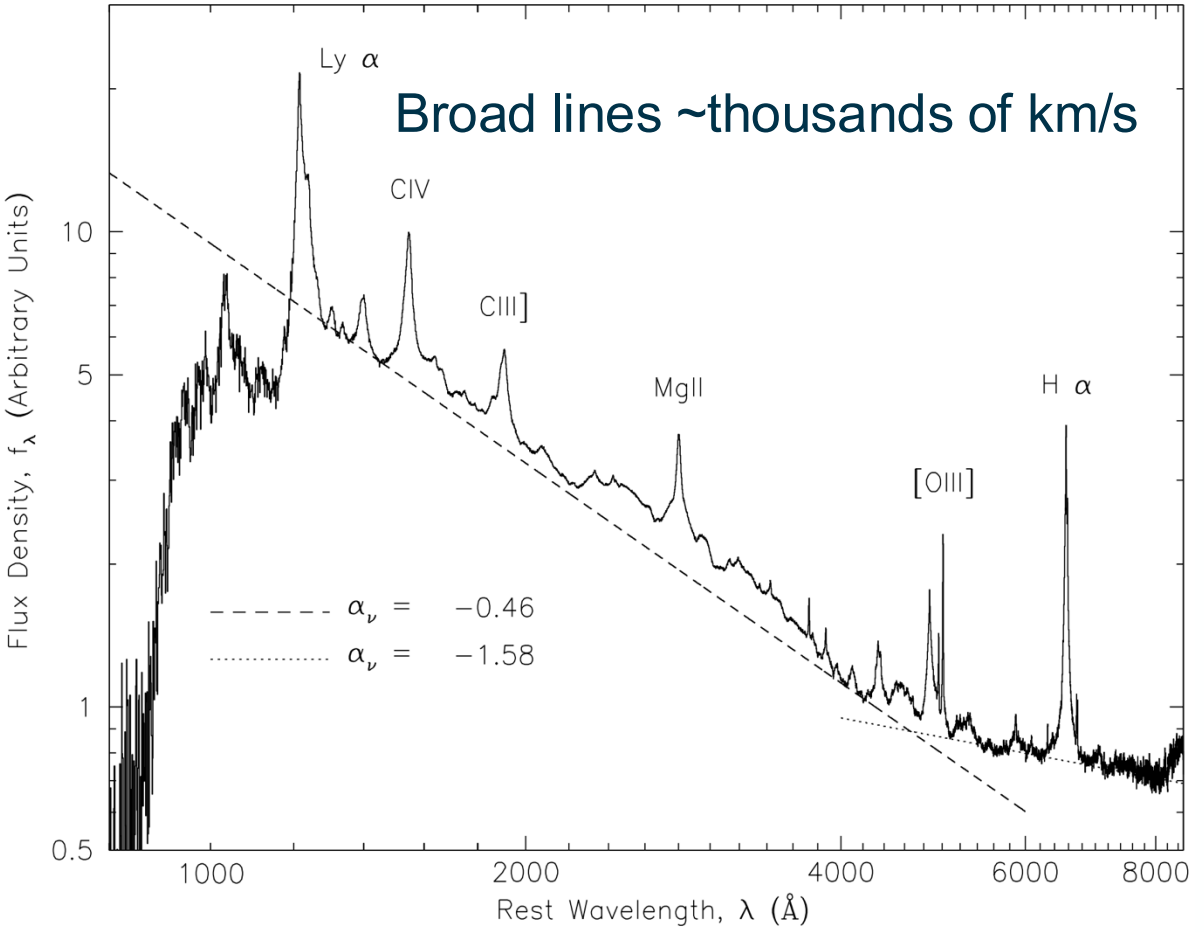




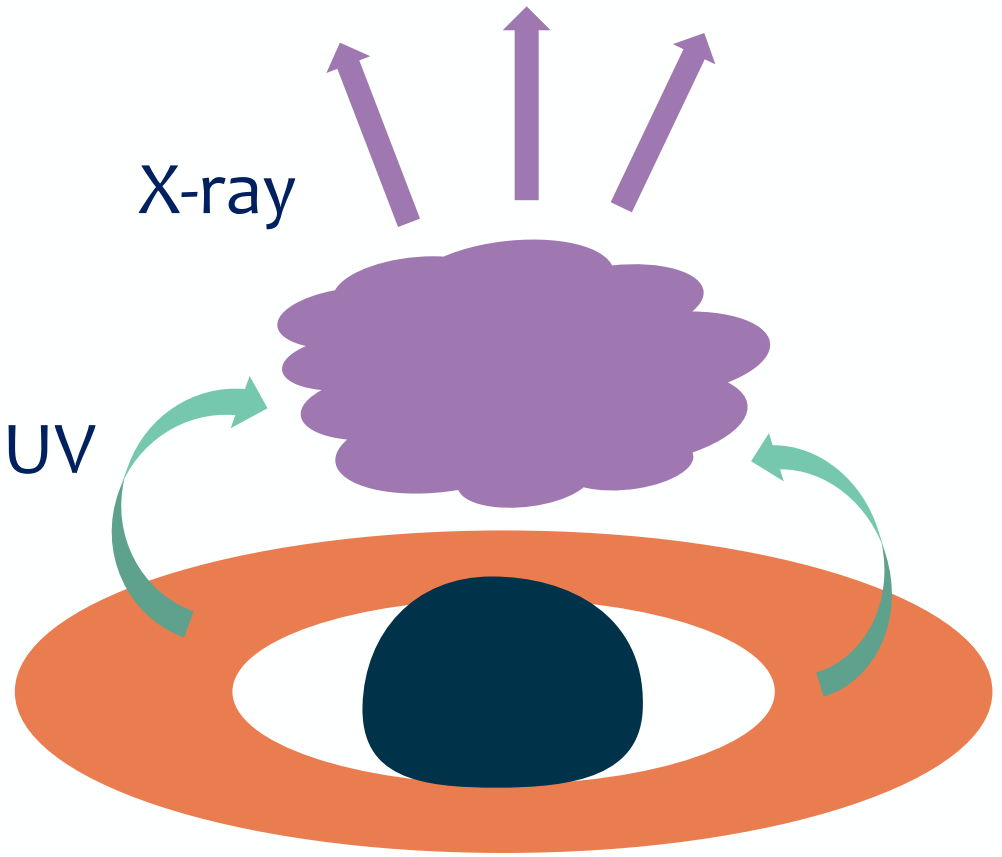
Mccandliss+19

INTRODUCTION





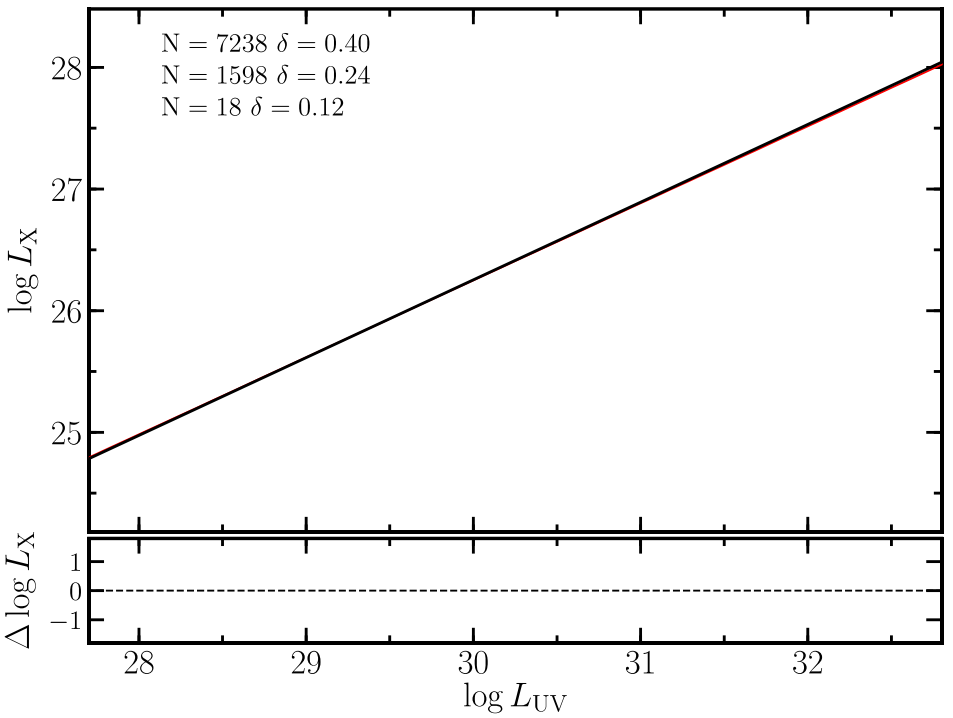
INTRODUCTION



Things we know:

- The disc emission peaks in the UV
- There is a hot electron plasma close to the SMBH where UV photons are up-scattered to X-ray energies

INTRODUCTION



Risaliti&Lusso19

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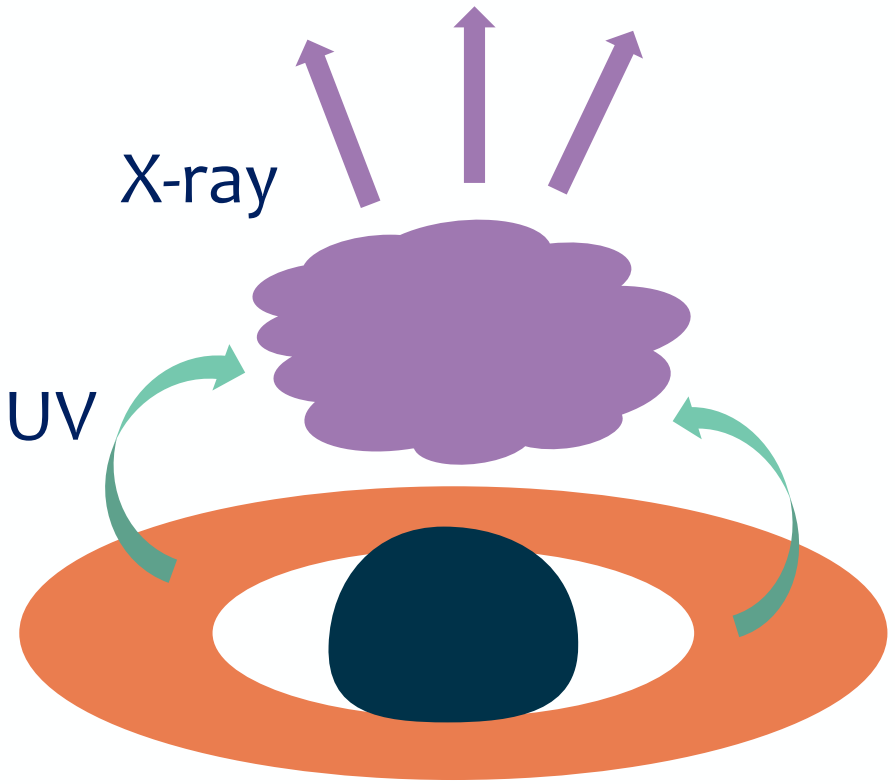
- The disc emission peaks in the UV
- There is a hot electron plasma close to the SMBH where UV photons are up-scattered to X-ray energies
- X-ray emission responds non-linearly to UV emission

$$\log(L_X) = \gamma \log(L_{UV}) + \beta$$

$\gamma \sim 0.6, \beta \sim 8$

The relation is strong using different proxies of UV and X-ray emission (Signorini+23b) and it must be intrinsically very tight (Signorini+24), suggesting a universal disc-corona interaction

INTRODUCTION



Things we know:

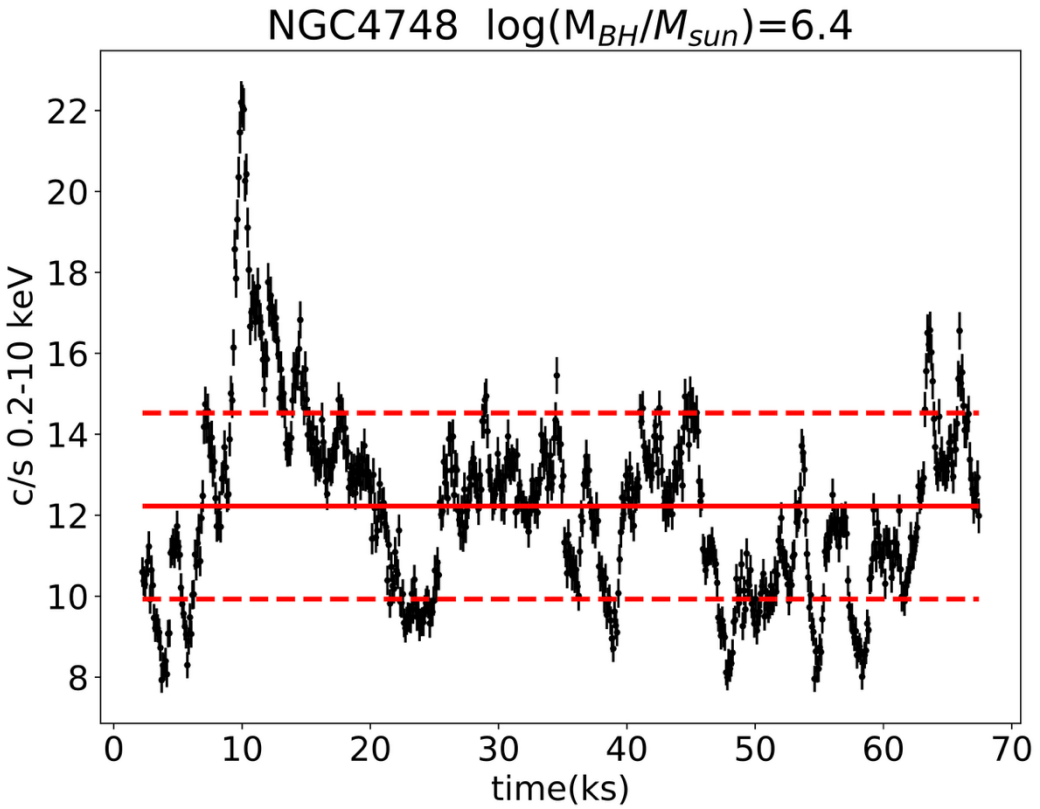
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Thing we know that we don't know:

- What is the exact geometry of the corona?
- What mechanism keeps the corona hot?
- How do variations in the AGN properties reflect into changes in the corona emission?

Things we don't know that we don't know: ?

X-RAY VARIABILITY



Tortosa+23

AGN emission is variable at all wavelengths.

In the X-ray, the timescales are small, ~100s of seconds

What can we learn from it about AGN physics?

Can we use it to measure cosmological distances?

X-RAY VARIABILITY

BASS sample: 151 type-1 AGN at z<0.3 (most below 0.05)



www.bass-survey.com

X-RAY VARIABILITY

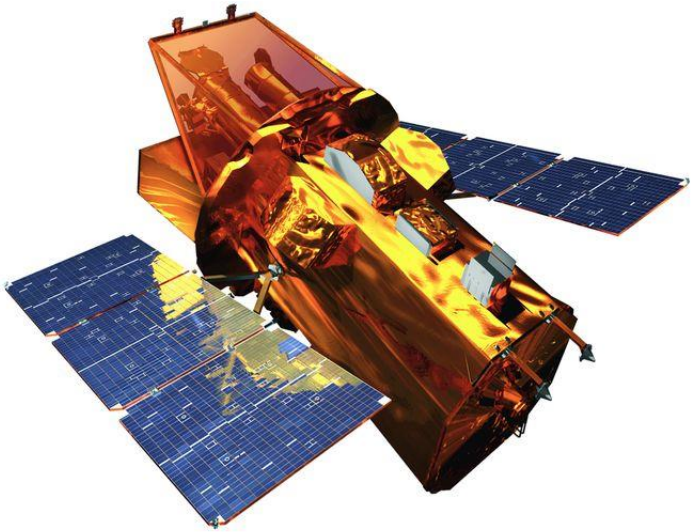
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BAT AGN Spectroscopic Survey: observation of hard X-ray selected AGN with optical spectroscopy

Emission line information

- 140 objects with Ha, Hb line (Mejia-Restrepo+22)
- 40 objects with Paschen lines (Lamperti+17, Ricci+22, Den Brok+22)

Eddington ratios estimates, with bolometric luminosities from SED fitting (Gupta+24)

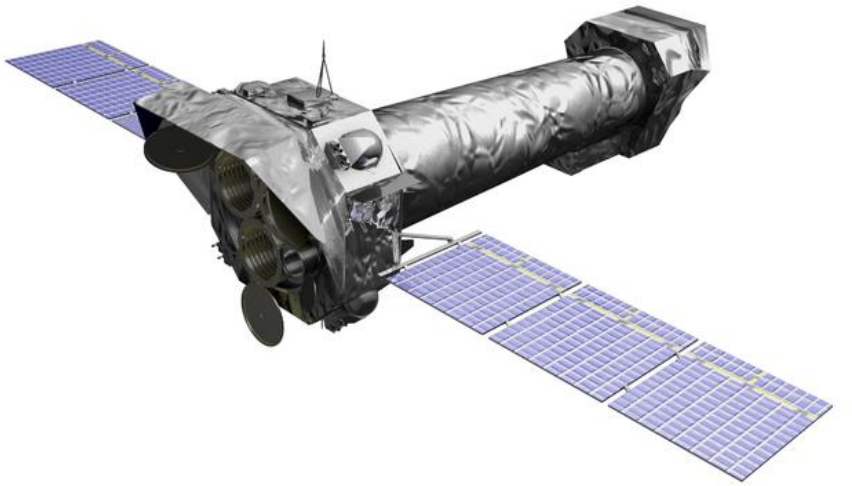


X-RAY VARIABILITY

BASS sample: 151 type-1 AGN at z<0.3 (most below 0.05

XMM-Newton observations: ~20ks-100ks

How do we determine variability?



X-RAY VARIABILITY

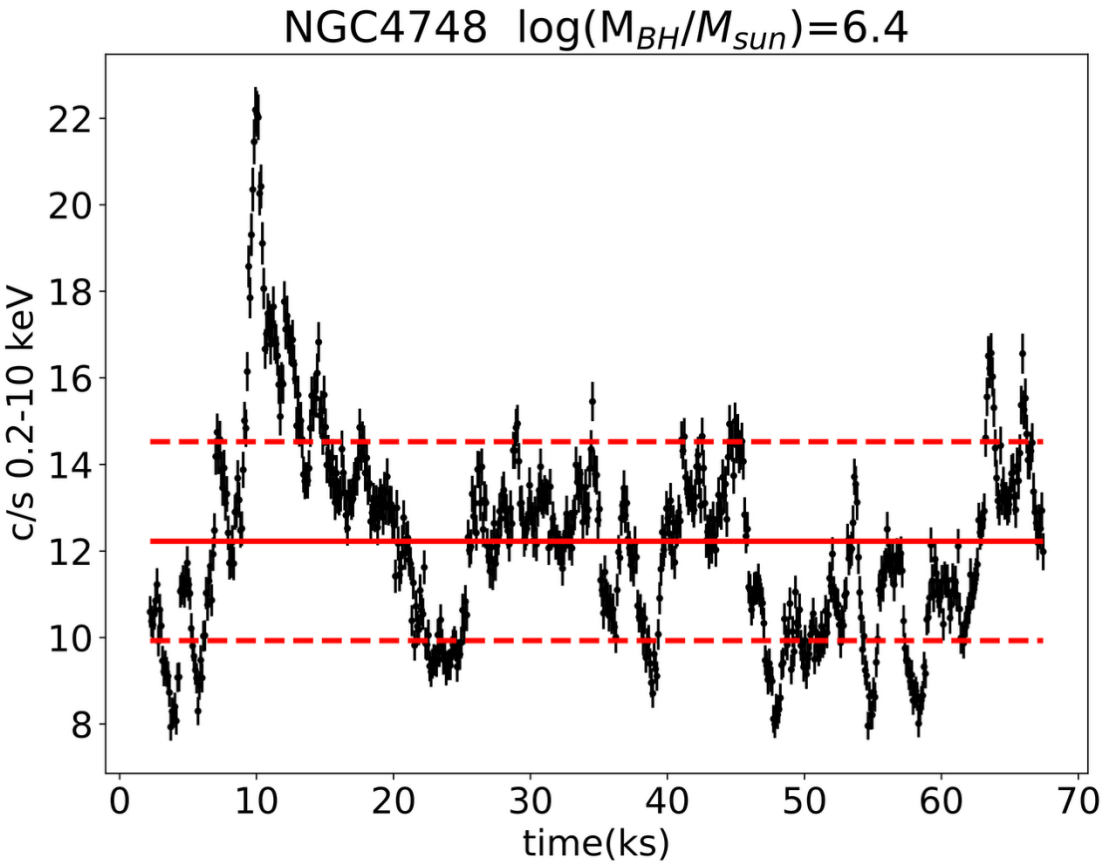
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Tortosa+23

XMM-Newton observations: ~20ks-100ks

How do we determine variability?

<u>Excess variance:</u> the variability that we see In excess to the one we expect giving flux measurement uncertainties



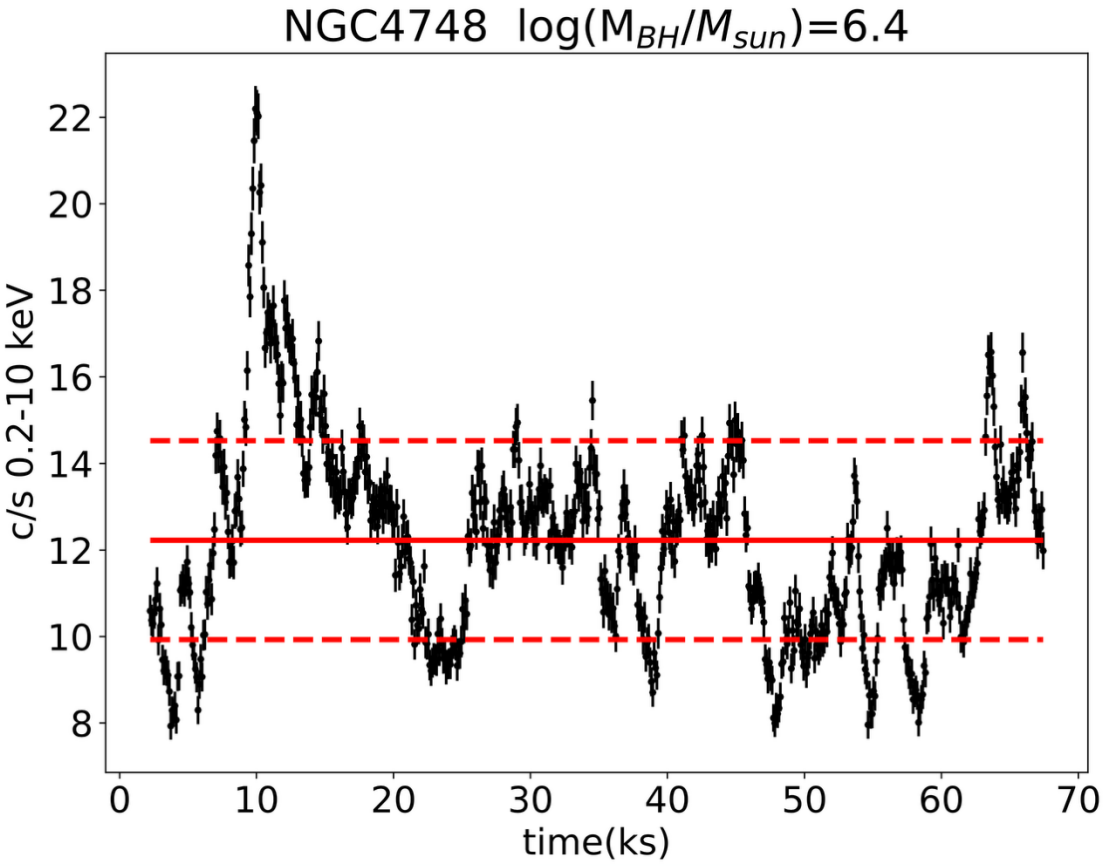
X-RAY VARIABILITY

Excess variance: the variance that we see in excess to the one we expect giving flux measurement uncertainties

$$S^2 = \frac{1}{N-1}\sum_{i=1}^{N}[(x_i - \overline{x_i})^2]$$

$$\sigma^2_{\mathrm{NXS}} = \frac{S^2 - \overline{\sigma^2}}{\overline{x_i^2}}$$

Tortosa+23



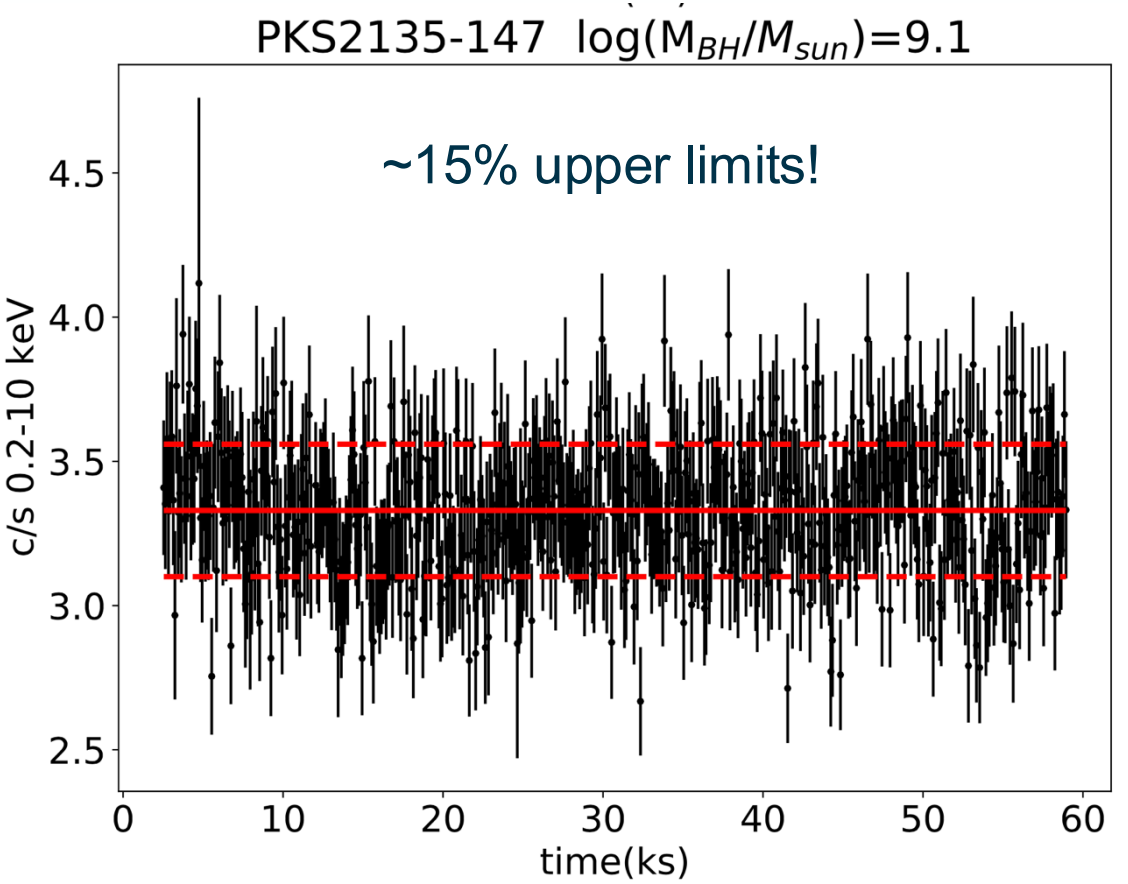
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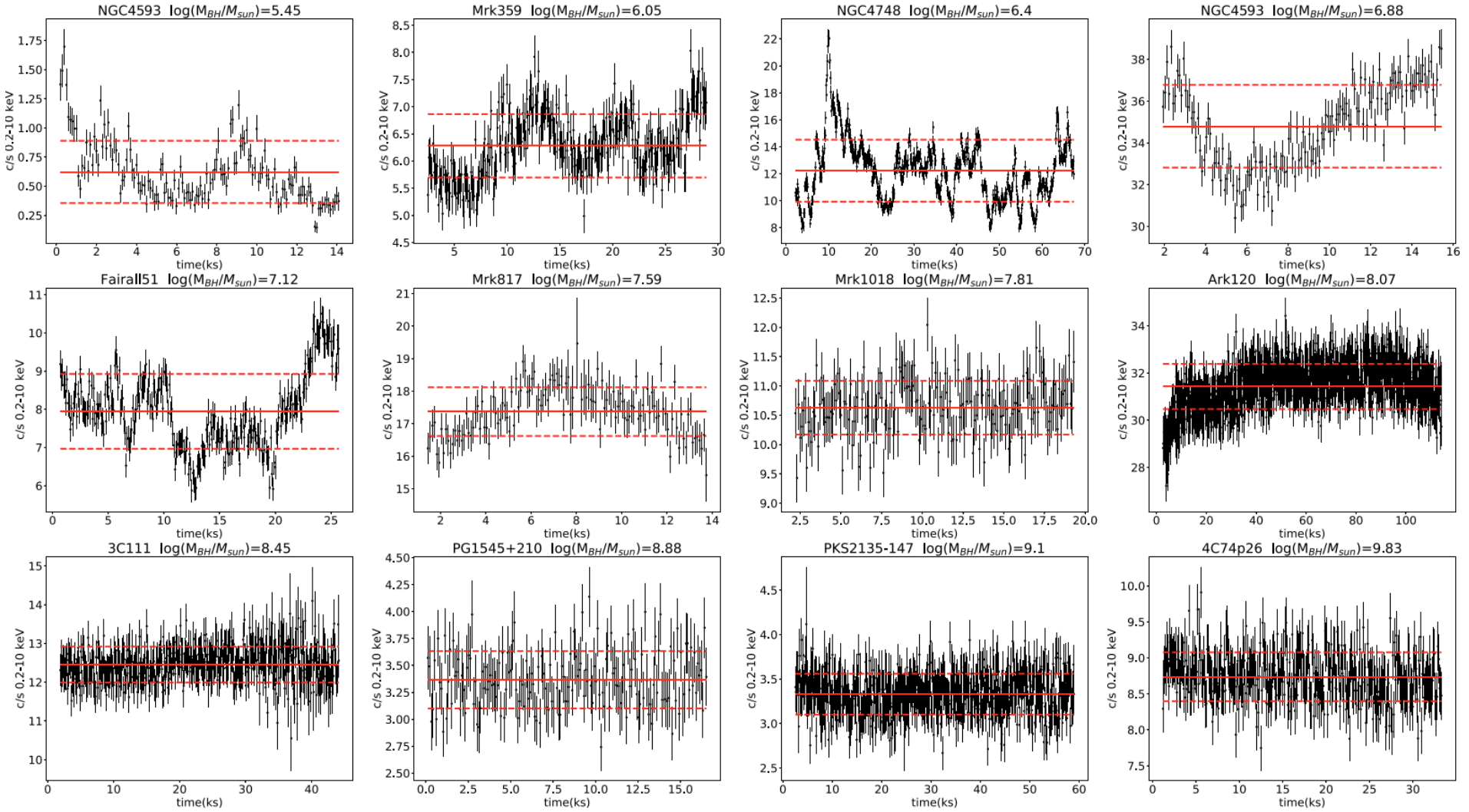
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Tortosa+23



X-RAY VARIABILITY

BASS sample



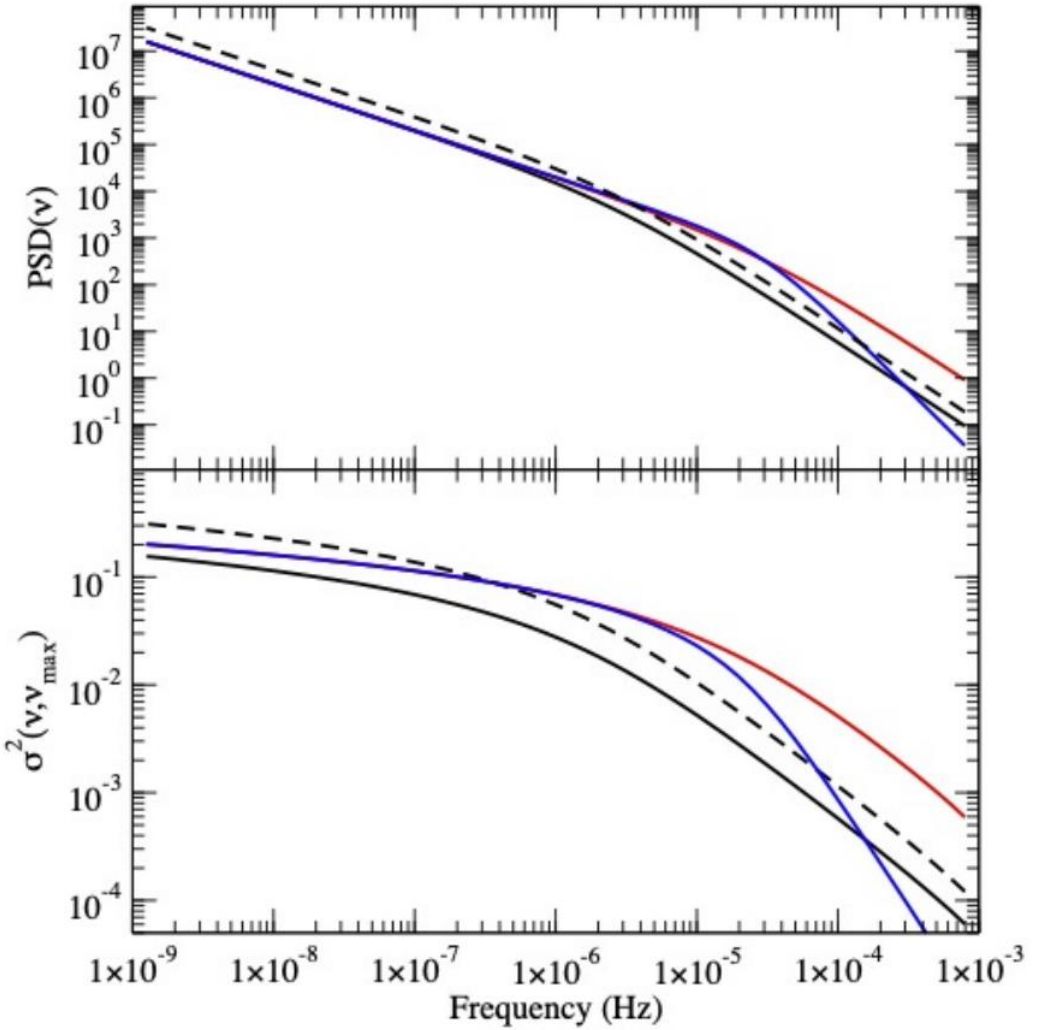
X-RAY VARIABILITY

Excess variance: the variance that we see in excess to the one we expect giving flux measurement uncertainties

It is linked to the Power Spectral Density (PSD)

$$\langle S^2 \rangle = \int_{\nu_1}^{\nu_2} P(\nu) \mathrm{d}\nu$$

Paolillo+23

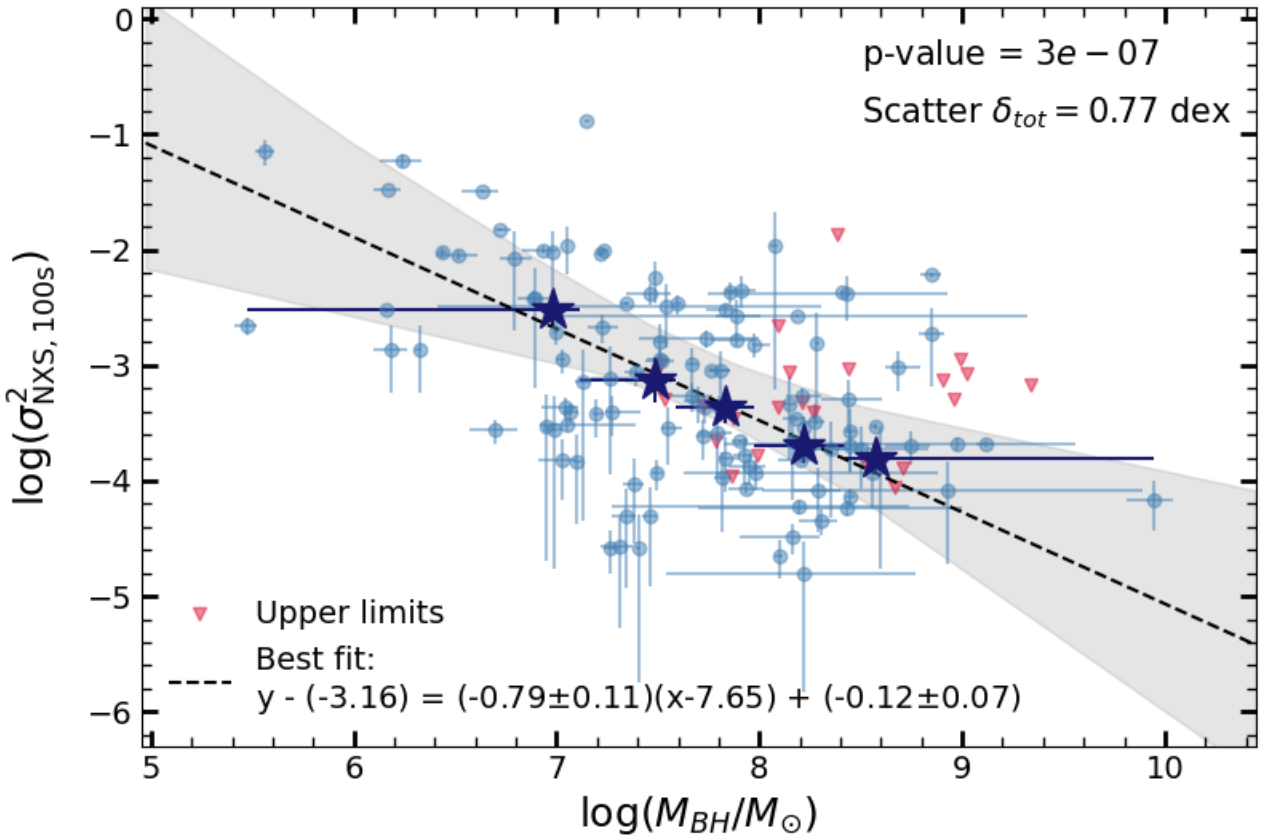


VARIABILITY VS BLACK HOLE MASS

Signorini+25(tbs)

Strong correlation: AGN with bigger SMBH are less variable

Still, there is a big scatter!

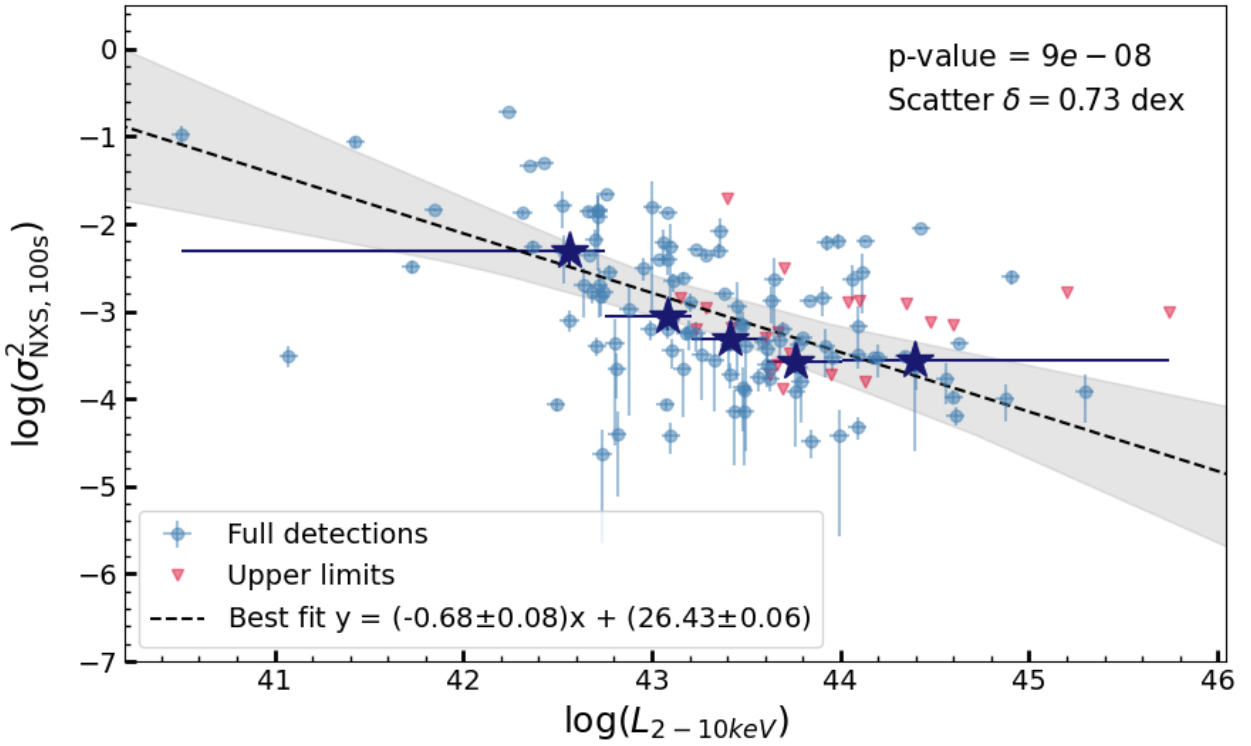


VARIABILITY VS LUMINOSITY

Strong correlation: more luminous AGN with bigger SMBH are less variable

Still, there is a big scatter!

Signorini+25(tbs)

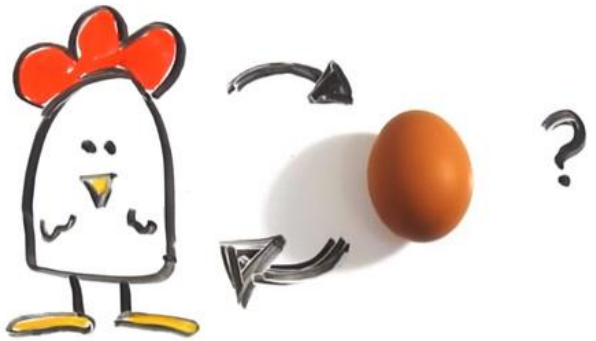


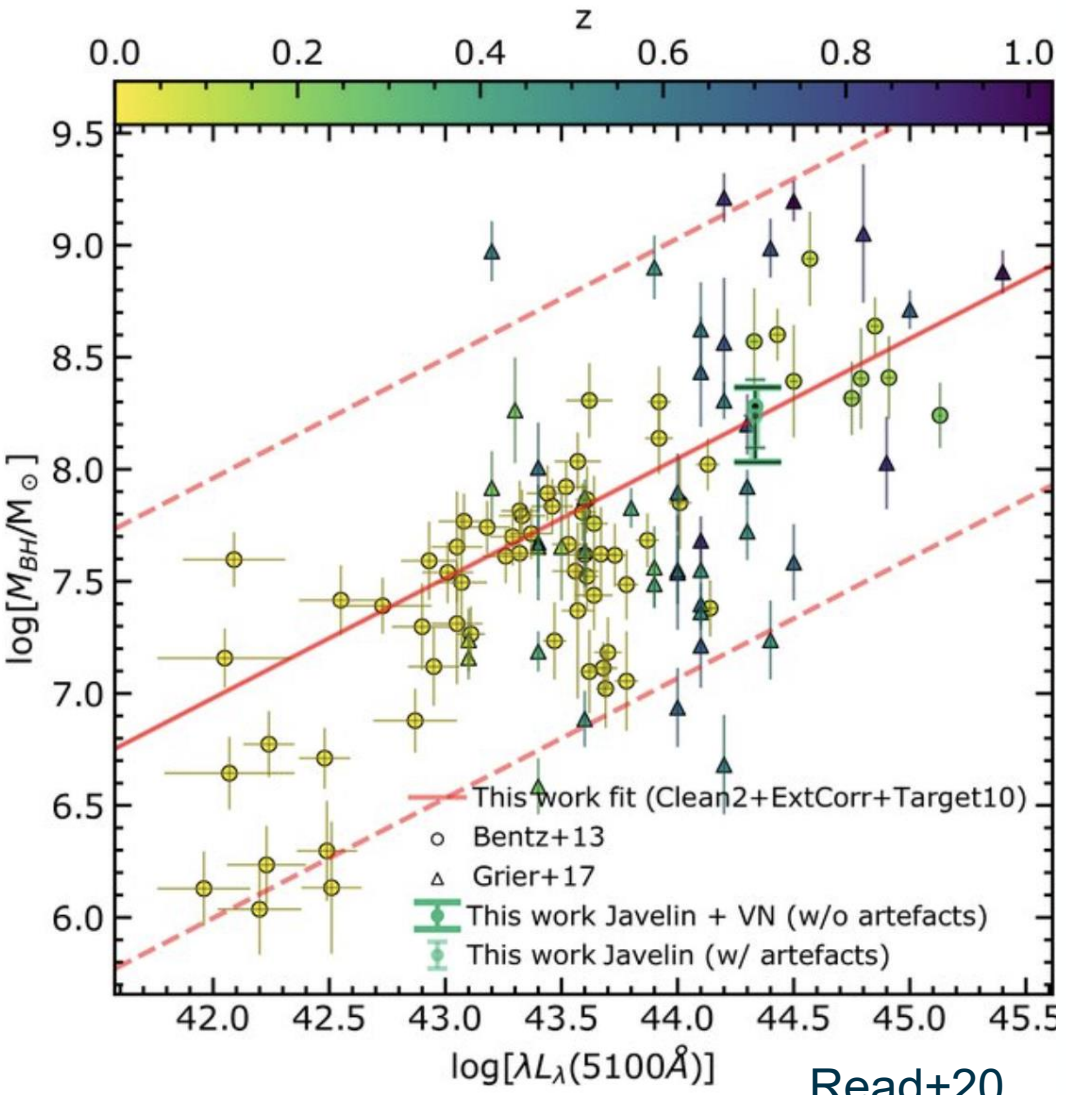
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Still, there is a big scatter!

Black Hole Mass and luminosity also correlate with one another... So what is variability responding to?



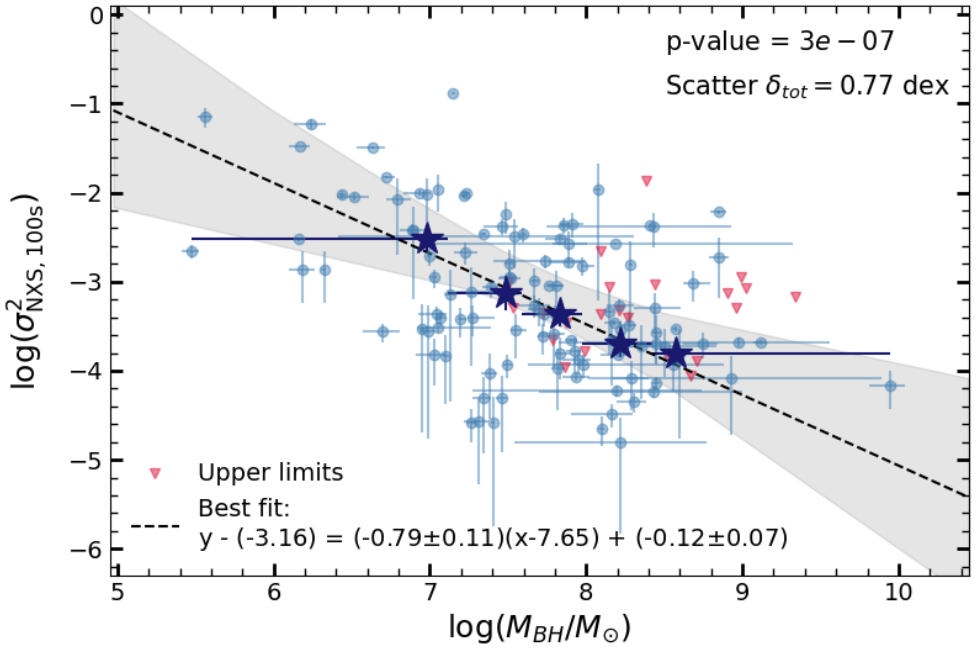


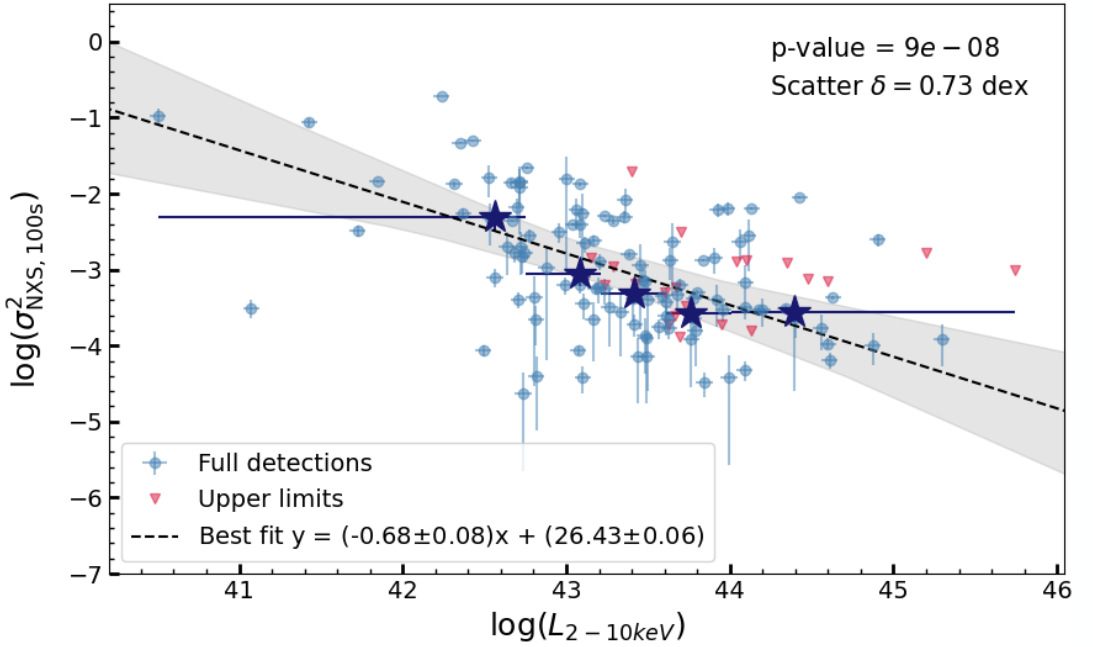
Read+20

VARIABILITY VS LUMINOSITY VS BLACK HOLE MASS

If we look at the scatter, the luminosity has a lower one
0.77 dex vs **0.73 dex**

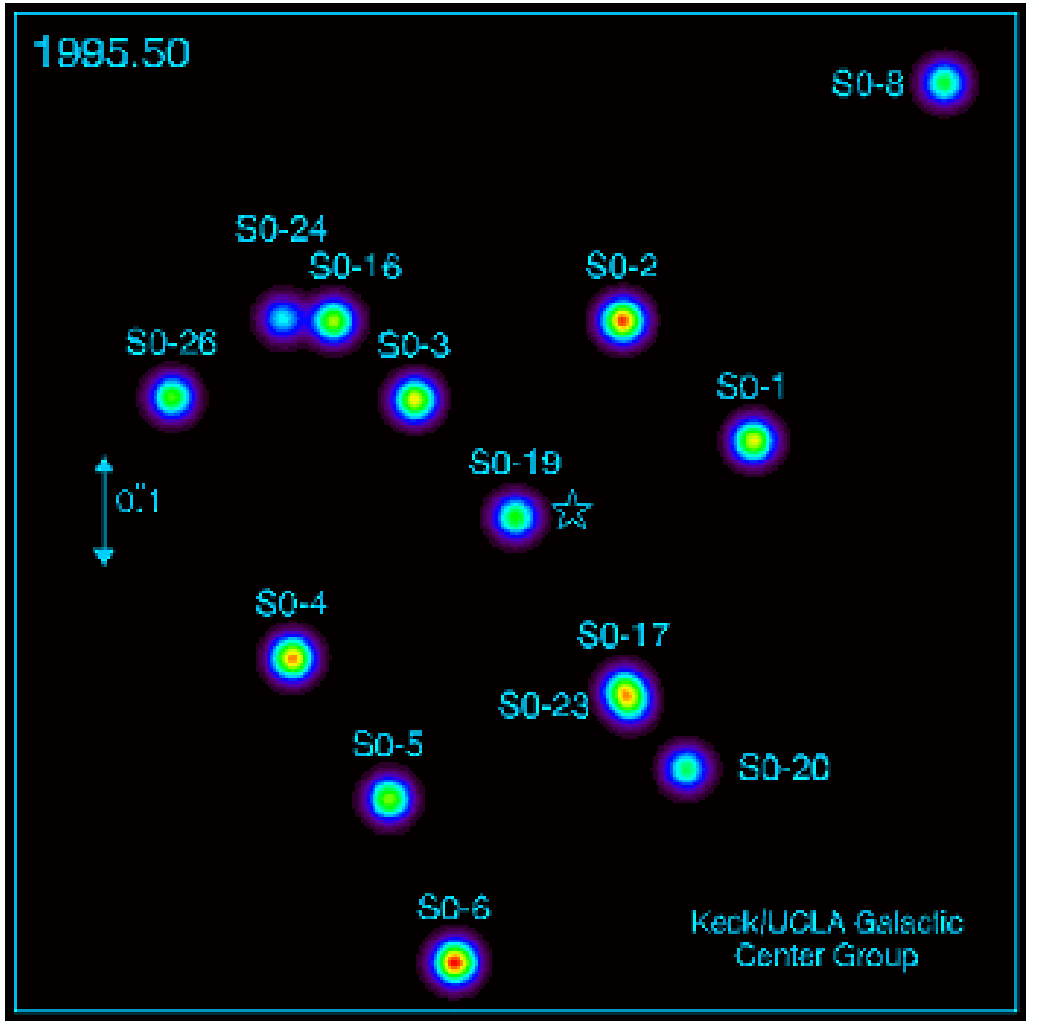
However…





MEASURING BLACK HOLE MASSES

Locally: direct motion of stars/gas

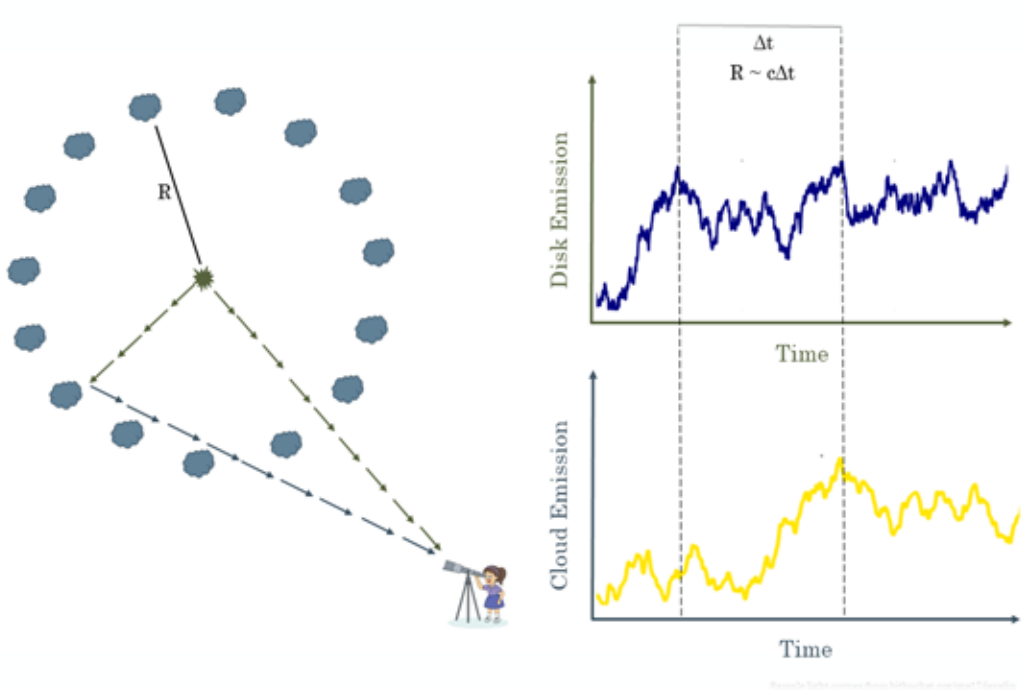


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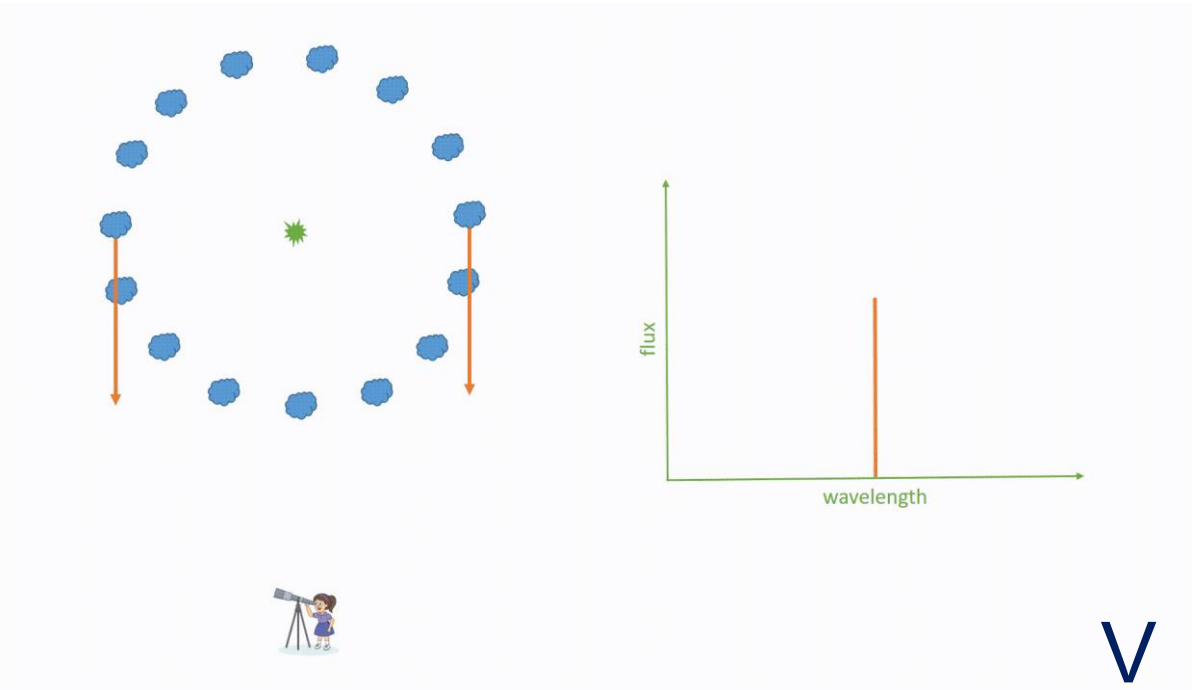
Locally: direct motion of stars/gas

Low-redshift, few object: Reverberation Mapping

$$M_{BH} = f R v^2 / G$$



R



V

https://jhoormann.github.io/

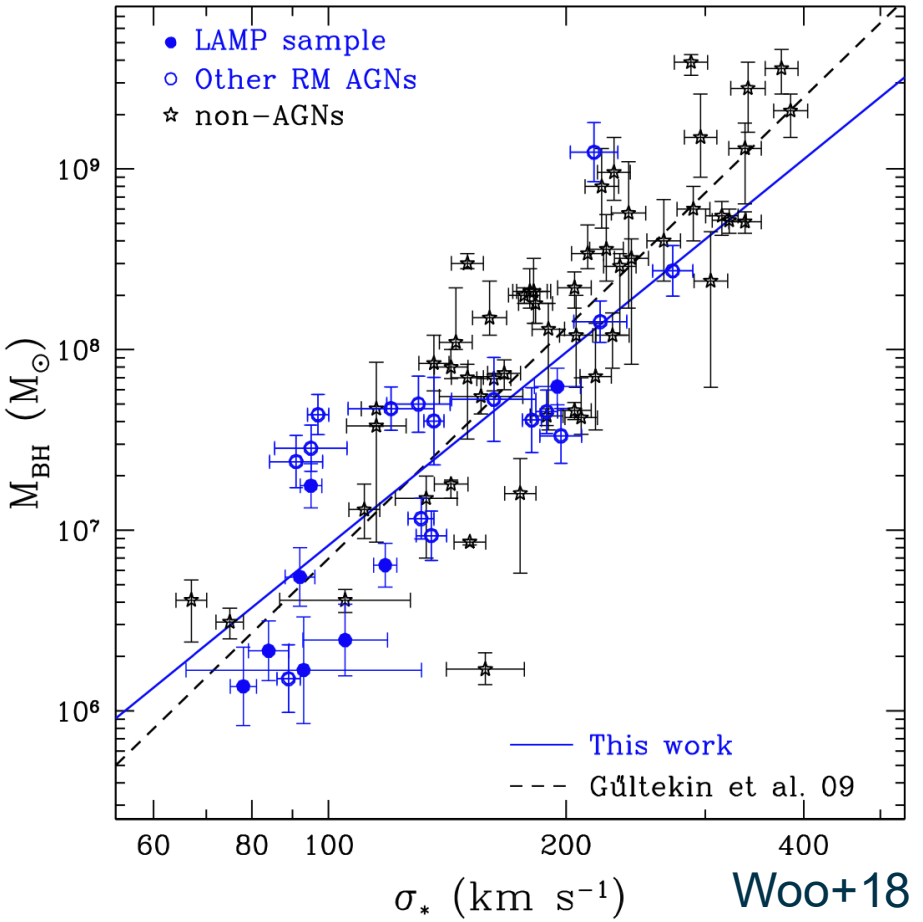
MEASURING BLACK HOLE MASSES

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f : 'virial factor', calibrated by comparing Active and non-Active galaxies



MEASURING BLACK HOLE MASSES

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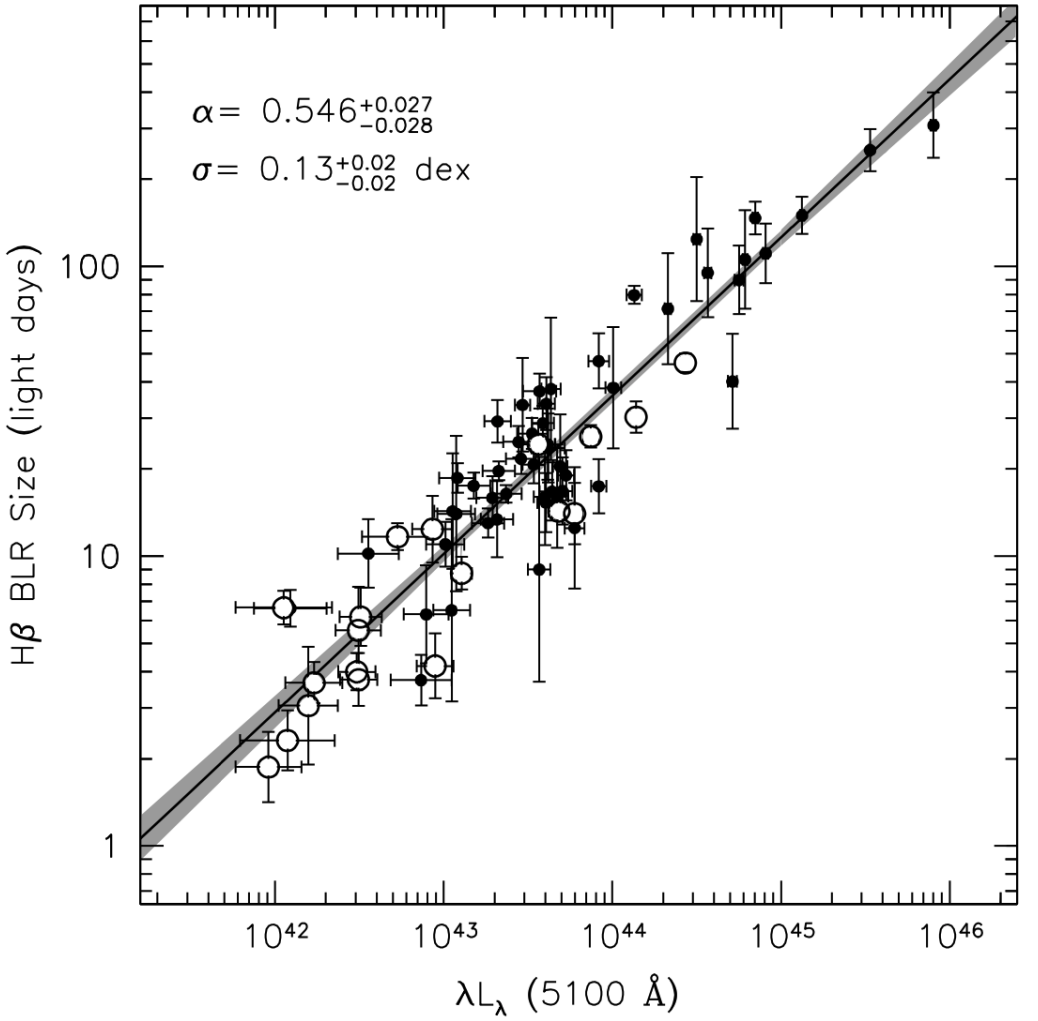
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Everything else: we use Reverberation Mapping to claibrate ‘single-epoch’ mass measurements

$$R \sim L^{\alpha}$$

$$M_{BH} = f R v^2/G$$

$$\rightarrow M_{BH} = f L^{\alpha} FWHM^2/G$$



Bentz+13

MEASURING BLACK HOLE MASSES

Locally: direct motion of stars/gas

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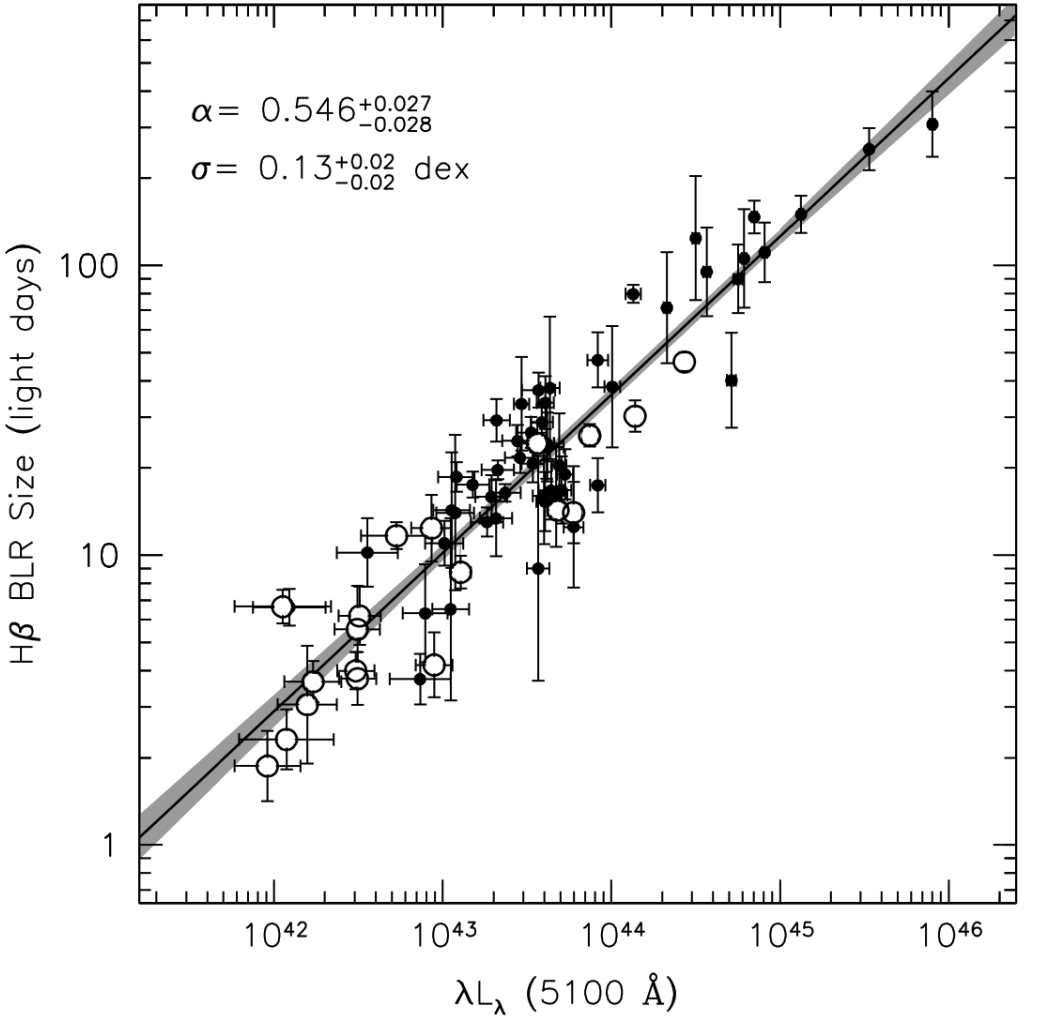
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…the final scatter on M_{BH} is high, ~0.4-0.6 dex!



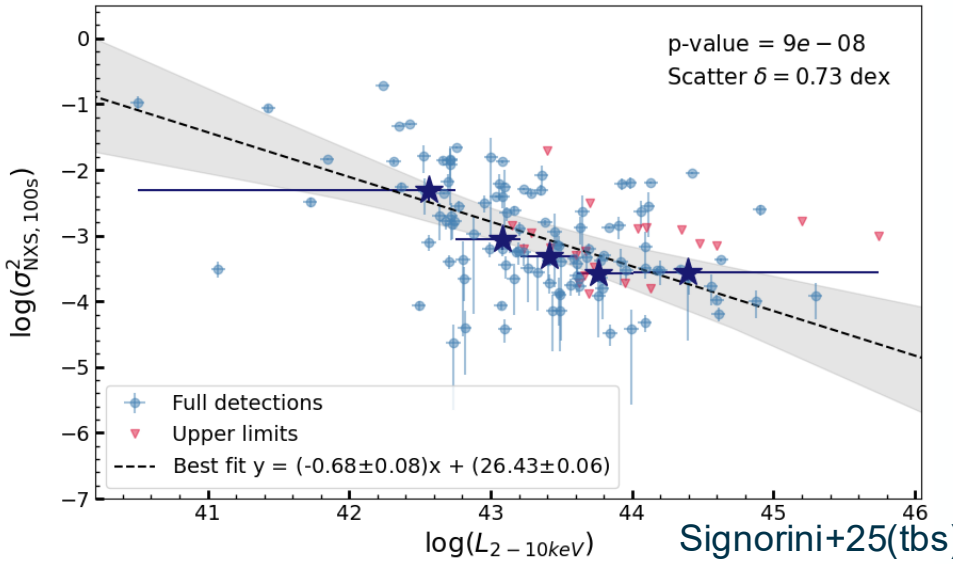
Bentz+13

VARIABILITY VS LUMINOSITY VS BLACK HOLE MASS

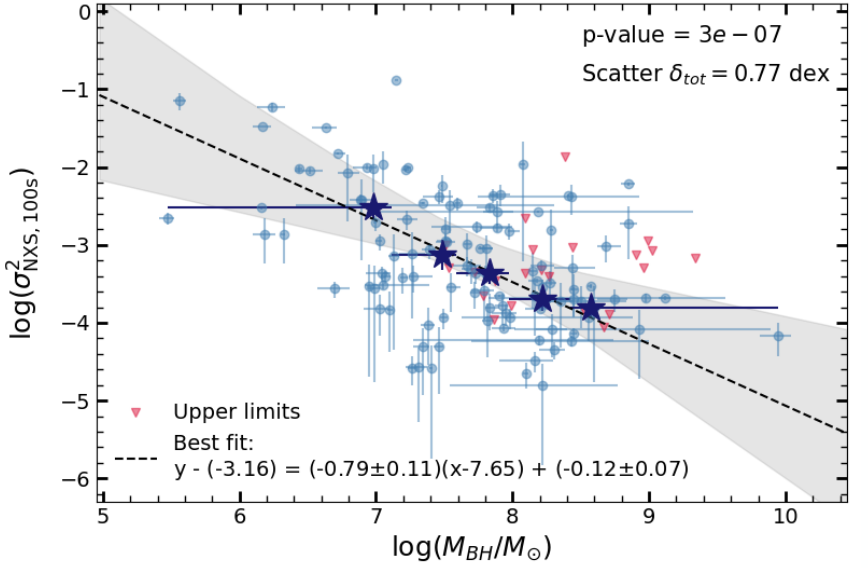
The σ-L relation has a lower scatter compared to the σ-M_{BH} one
0.77 dex vs 0.73 dex

However…

If we consider the scatter on M_{BH}, the *true* scatter in σ-M_{BH} is probably ~0.60 dex, therefore it is <u>tighter</u> than the one in luminosity



Signorini+25(tbs)



VARIABILITY VS EDDINGTON RATIO

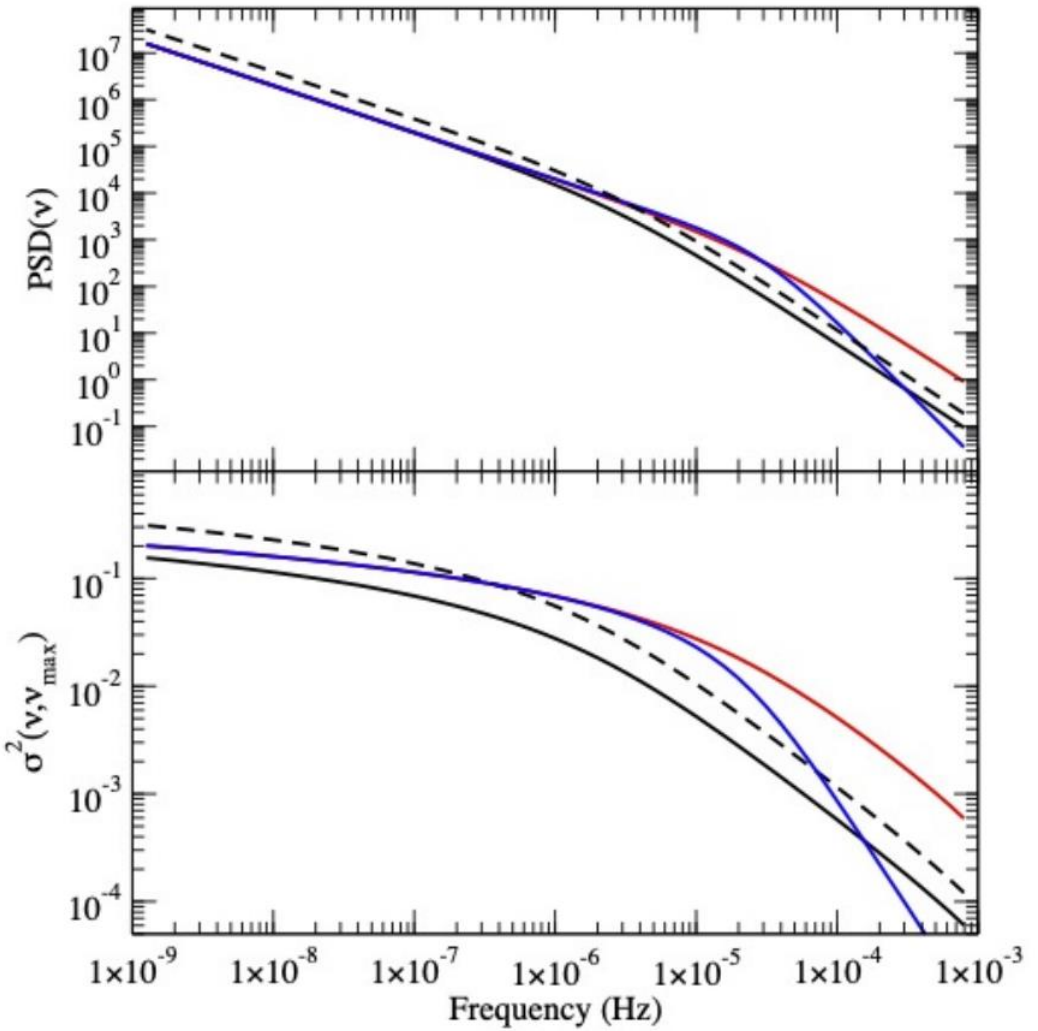
If the PSD of AGN is universal, and the knee only depends on M_{BH}, we expect a strong correlation between σ and the Eddington Ratio λ_{Edd}

$\lambda_{Edd} = L_{bol}/L_{Edd}$

$L_{Edd} = 4\pi G M_{BH} c/k$

For the BASS sample, L_{bol} is accurately determined with SED fitting (Gupta+24)

Paolillo+23



VARIABILITY VS EDDINGTON RATIO

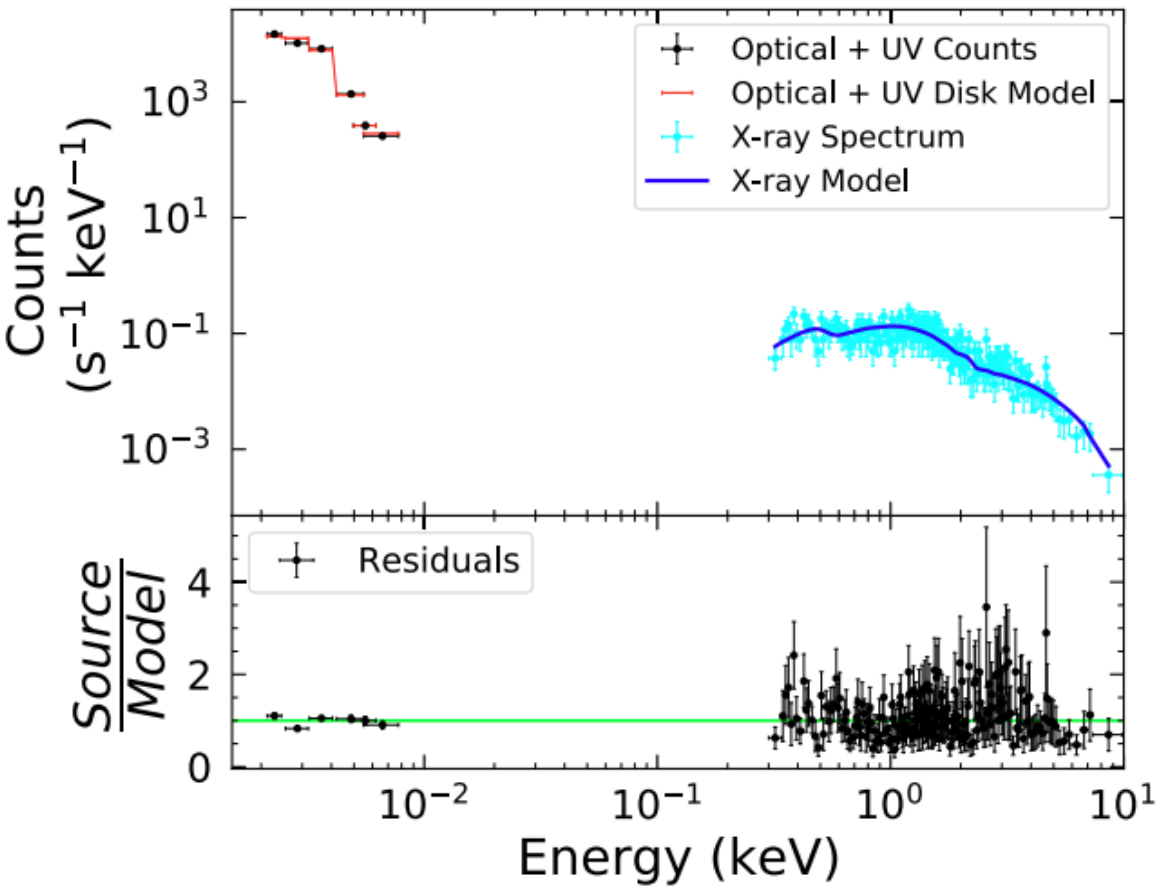
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Gupta+24



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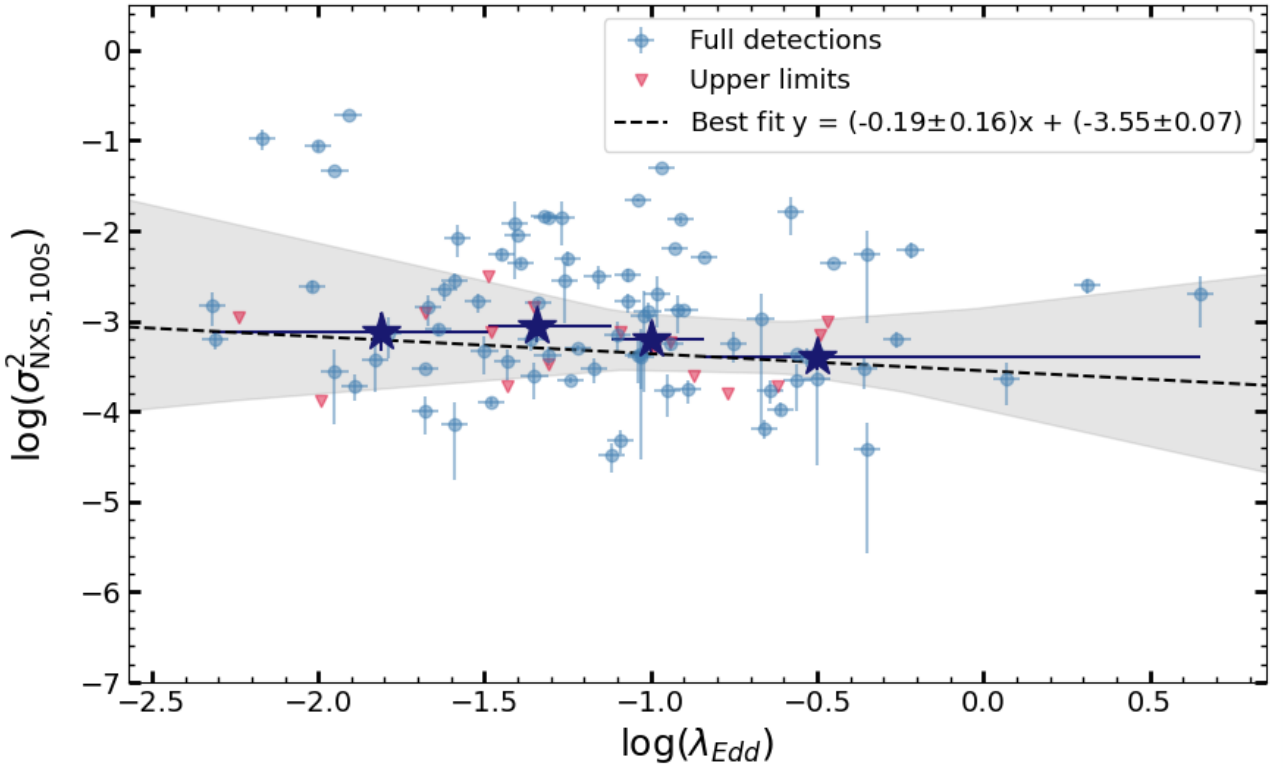
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…but we see no correlation!

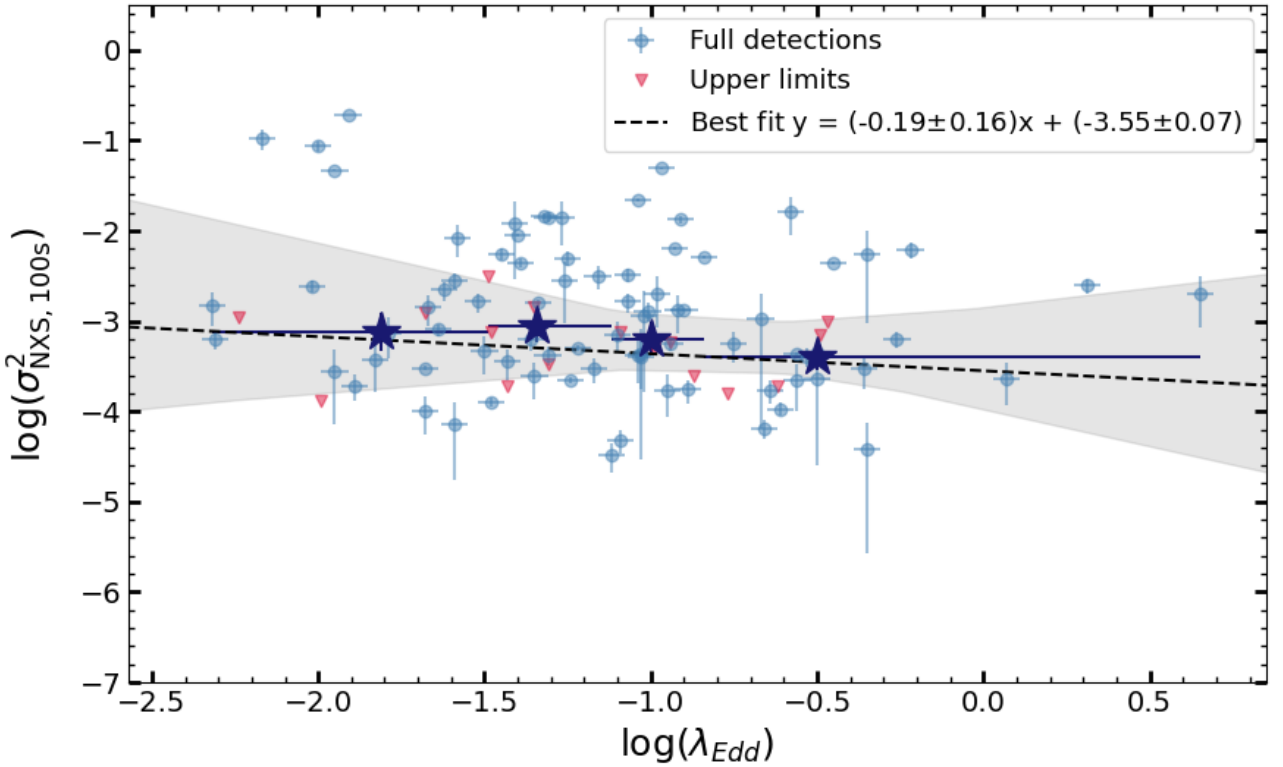
Signorini+25(tbs)



VARIABILITY

- X-ray variability anti-correlates with both M_{BH} and L
- If we account for the spread on signle-epoch M_{BH}, the main driver for variability seems to be the MBH
- However, we *do not* see the expected dependence on the Eddington Ratio
  - Is the PSD not universal?
  - Is the scatter on M_{BH} messing up with our results?

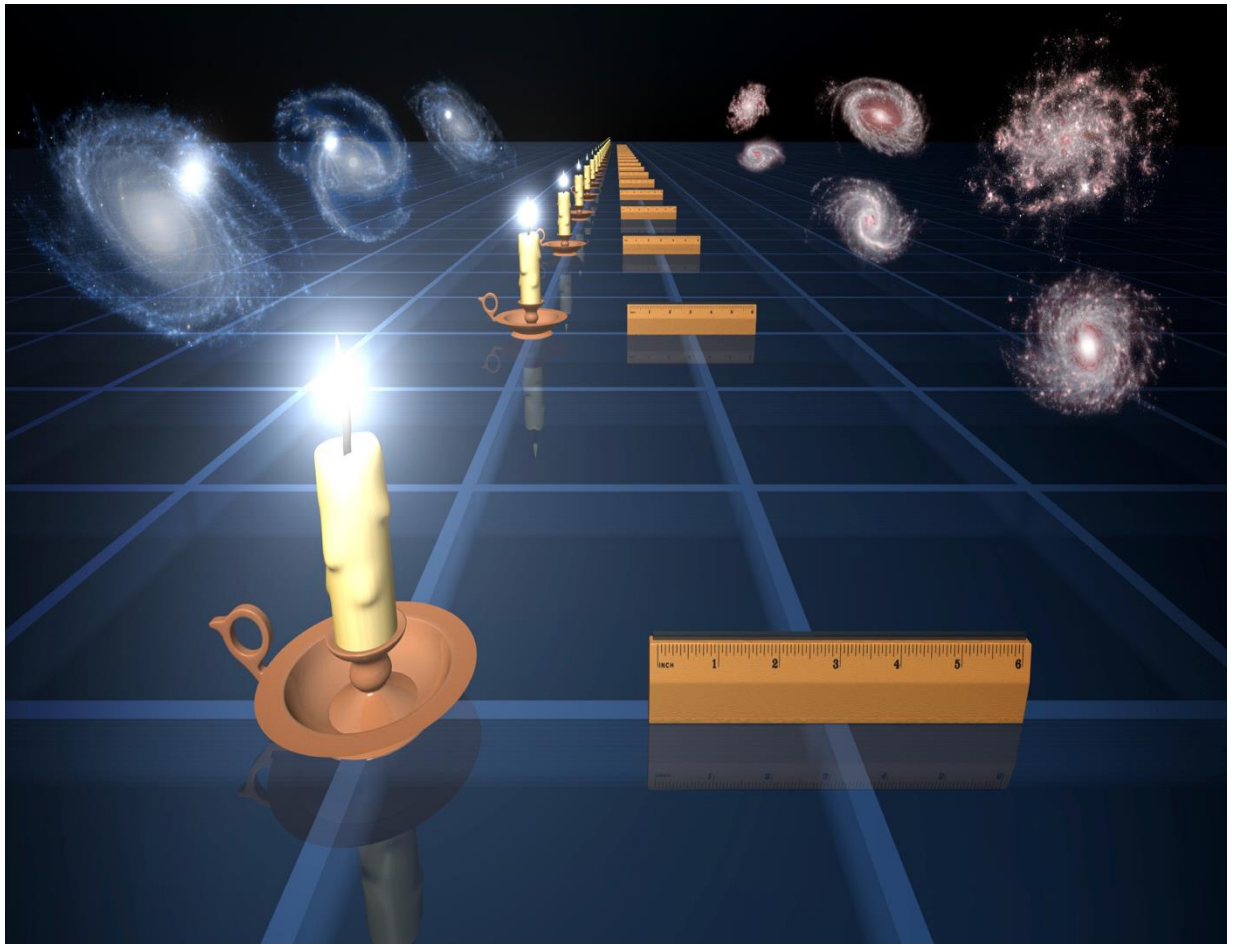
Signorini+25(tbs)



VARIABILITY FOR COSMOLOGY

We can use X-ray variability to estimate the luminosity, therefore using AGN as ‘standard candles’

$$F = \frac{L}{4\pi D L^2}$$

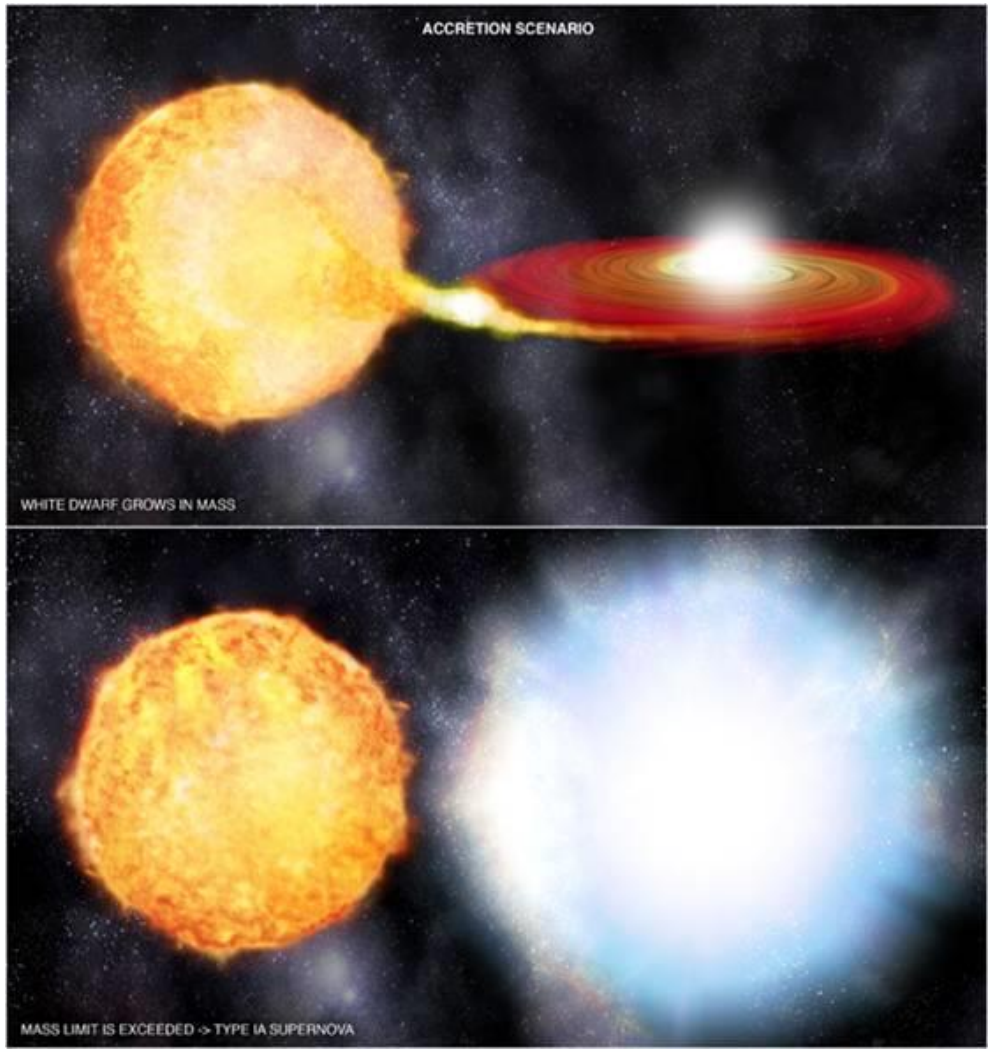


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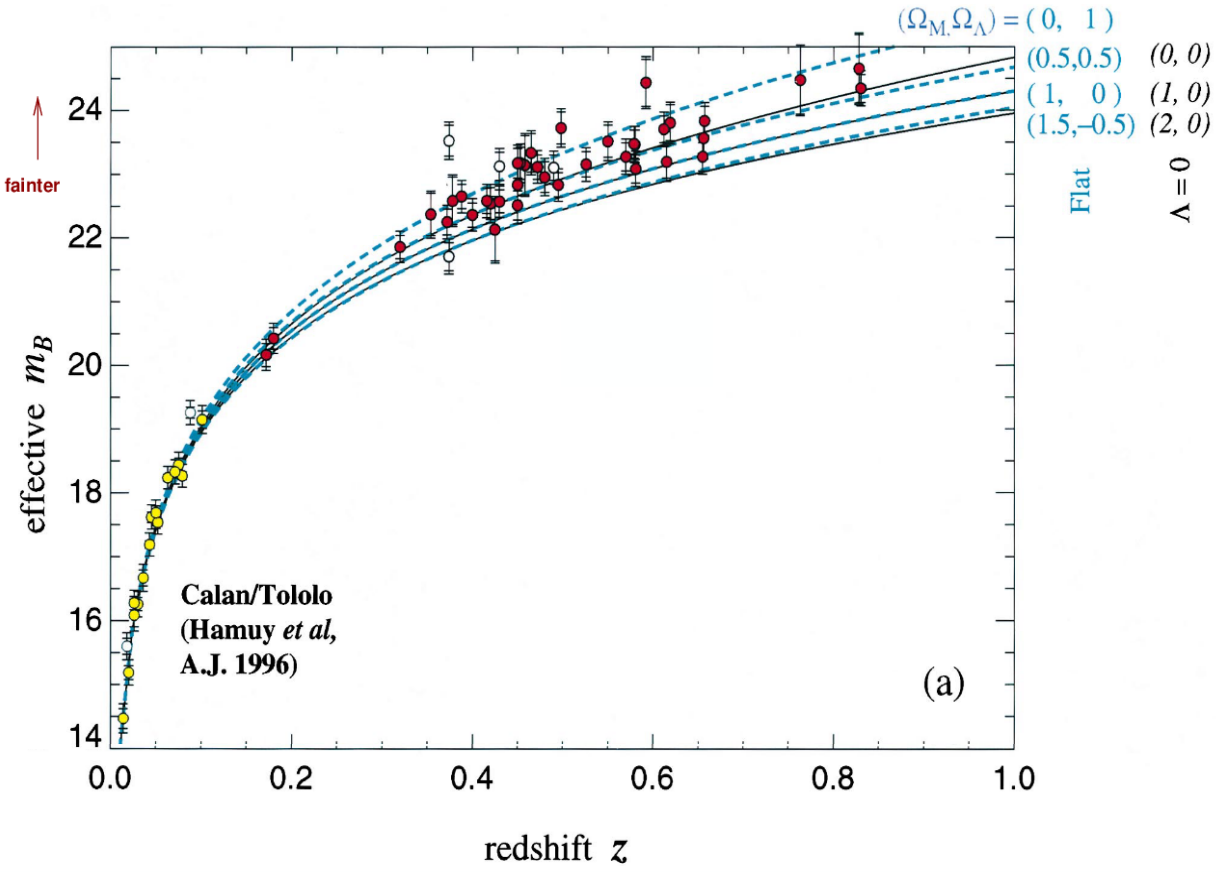
For example, we know Supernovae Ia luminosity given that the process behind them is always the same



VARIABILITY FOR COSMOLOGY

We build the distance-redshift or "Hubble-Lemaître", diagram:

- the shape constrains cosmological models
- inside a model, the shape constrains its parameters



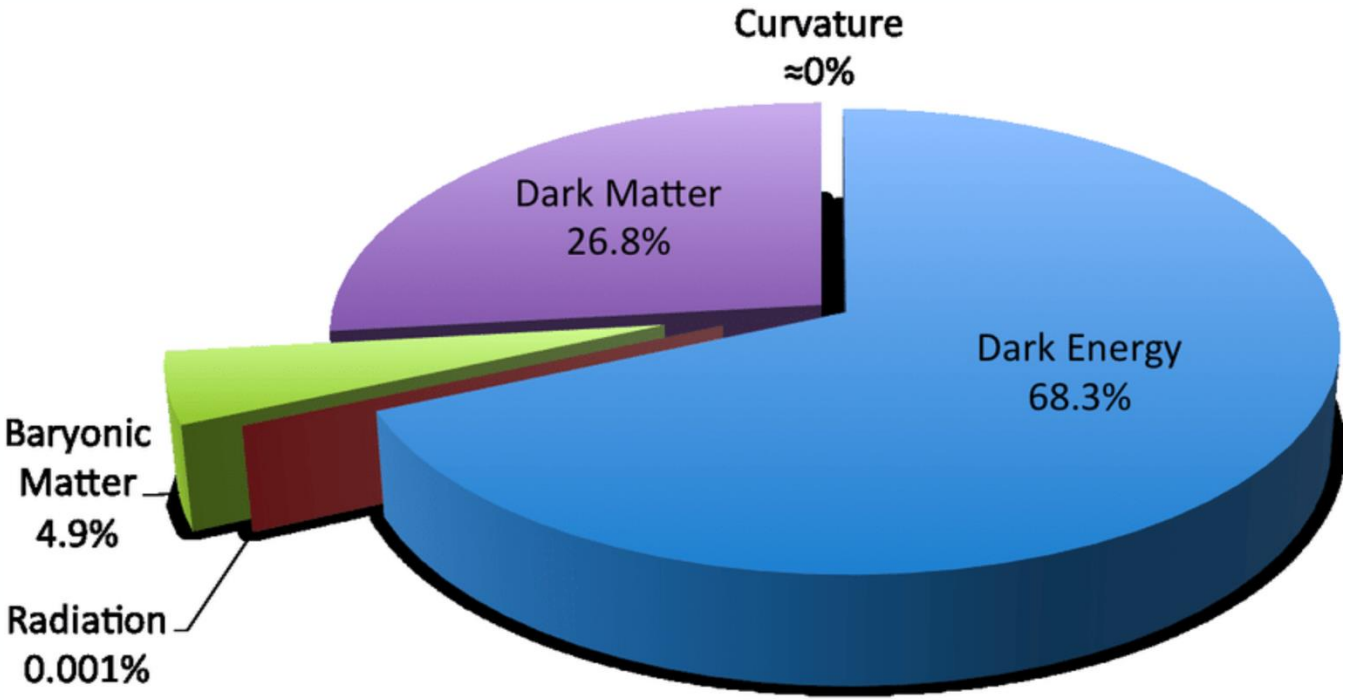
Supernova Cosmology Project Perlmutter+1998

VARIABILITY FOR COSMOLOGY

We build the distance-redshift or "Hubble-Lemaître", diagram:

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ΛCDM

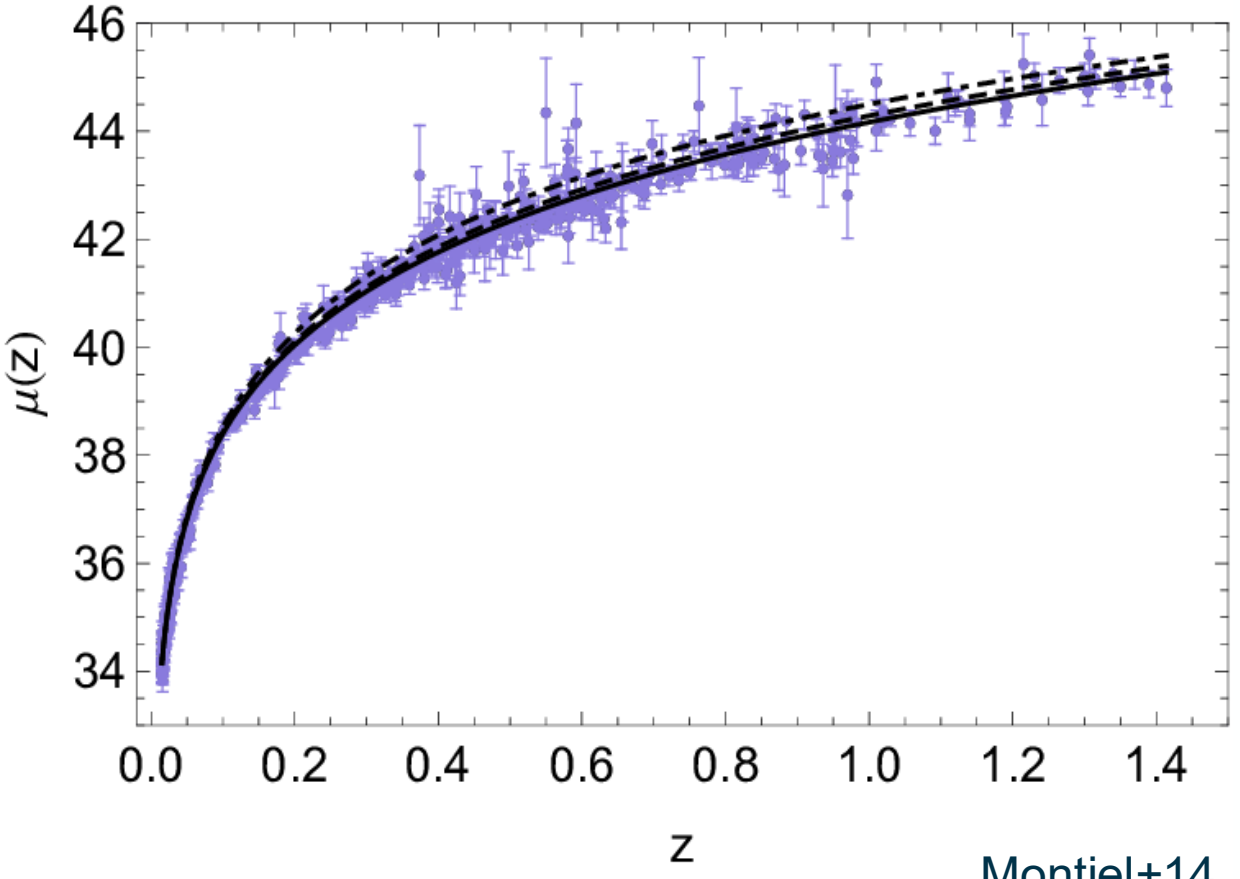


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SNIa now reach z~2… this leaves the first ~3 billion years of the expansion history not investigated!



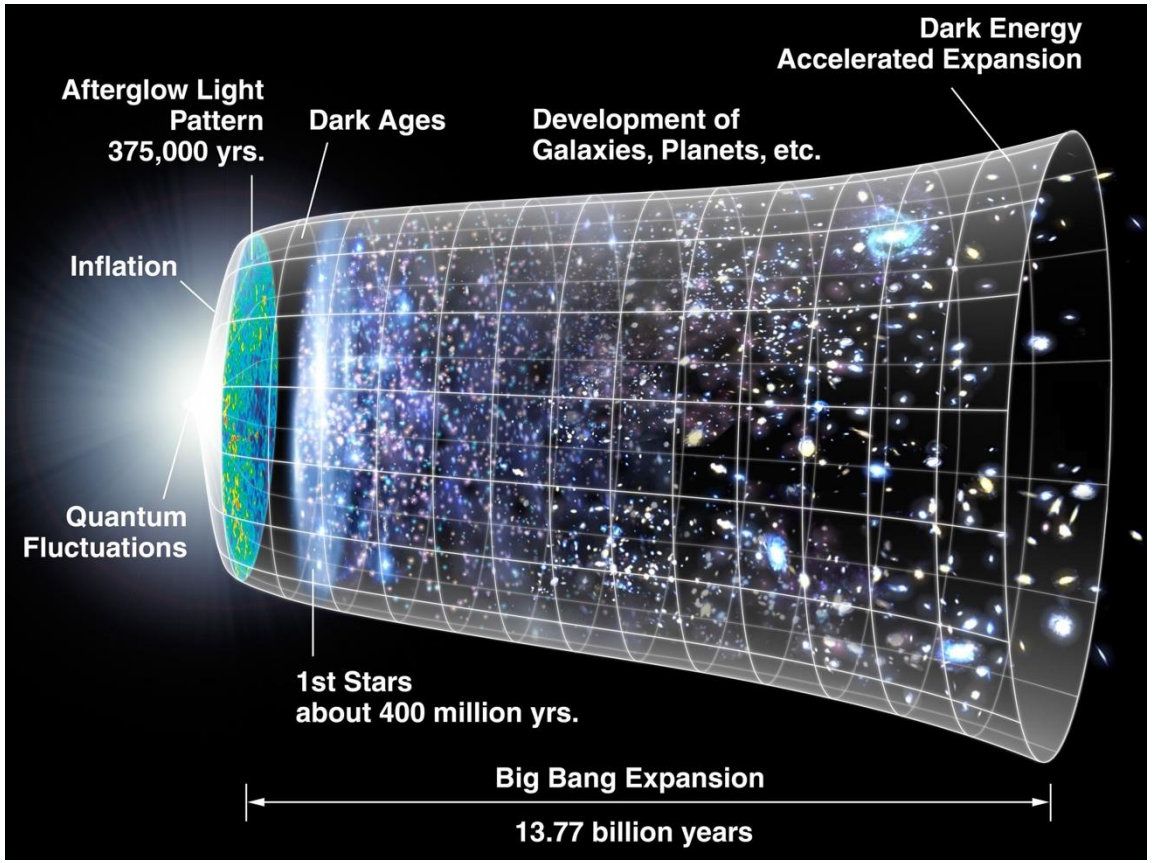
Montiel+14

VARIABILITY FOR COSMOLOGY

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+

There are *tensions* in the ΛCDM model that suggest us to look deeper (H_0, S_8, DESI…)

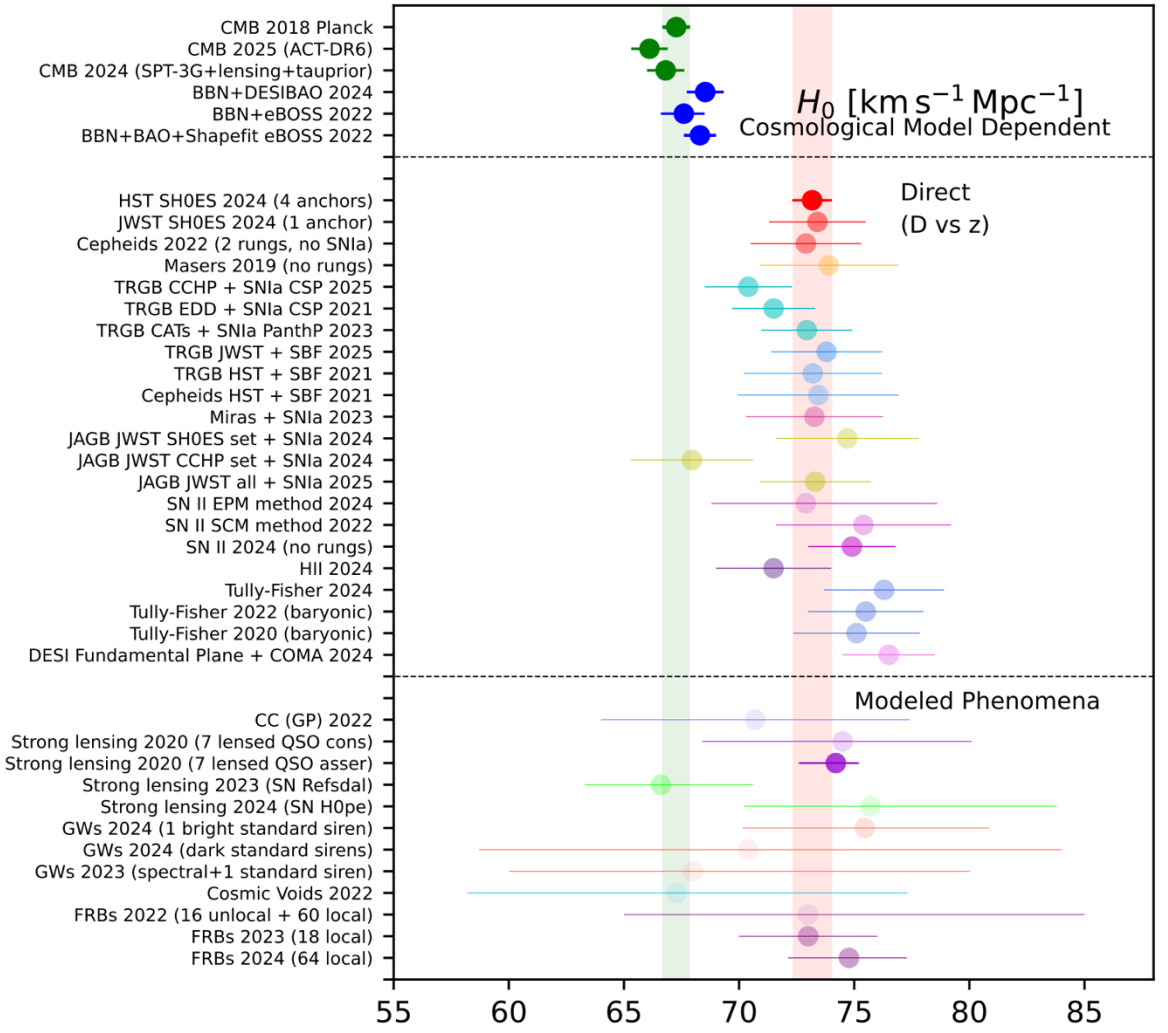


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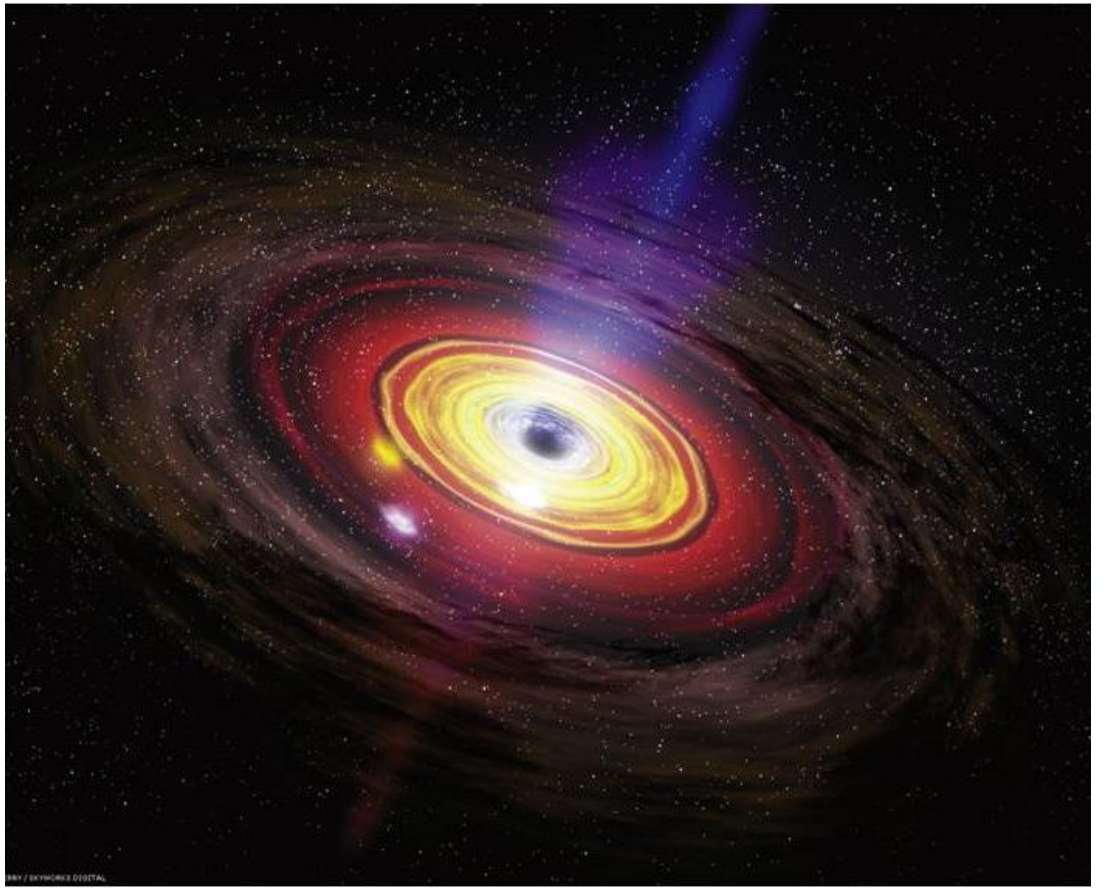
VARIABILITY FOR COSMOLOGY

AGN are great potential cosmological probes!

- Numerous
- Luminous
- Observed at all redshifts (~0.001 to ~10)

Their emission is not standard
$L_{bol} \sim 10^{40} - 10^{47}$ erg/s

Many relations have been suggested to 'standardize' AGN (R_{BLR}-L, L_X-L_{UV}…)



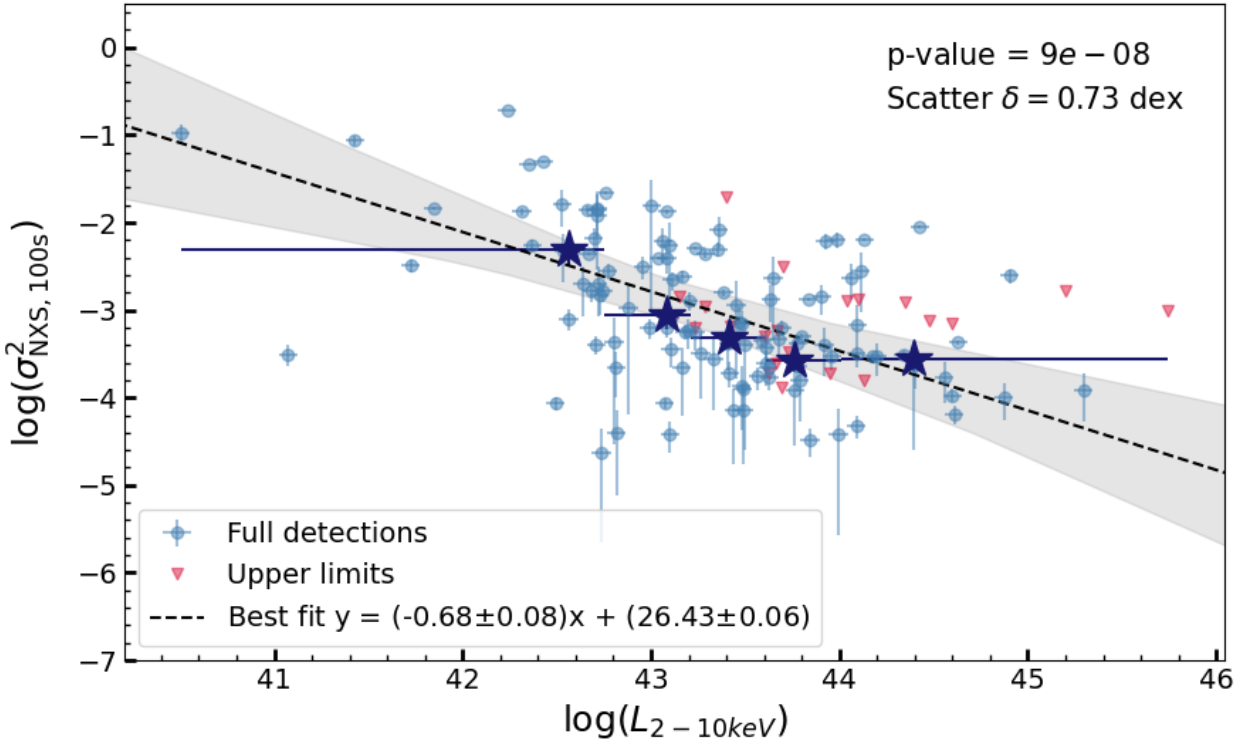
VARIABILITY FOR COSMOLOGY

We can use variability to estimate the luminosity!

… but the scatter is very high, so uncertainties on distances will be huge!

scatter ~0.75 dex

δD_L~90%



VARIABILITY FOR COSMOLOGY

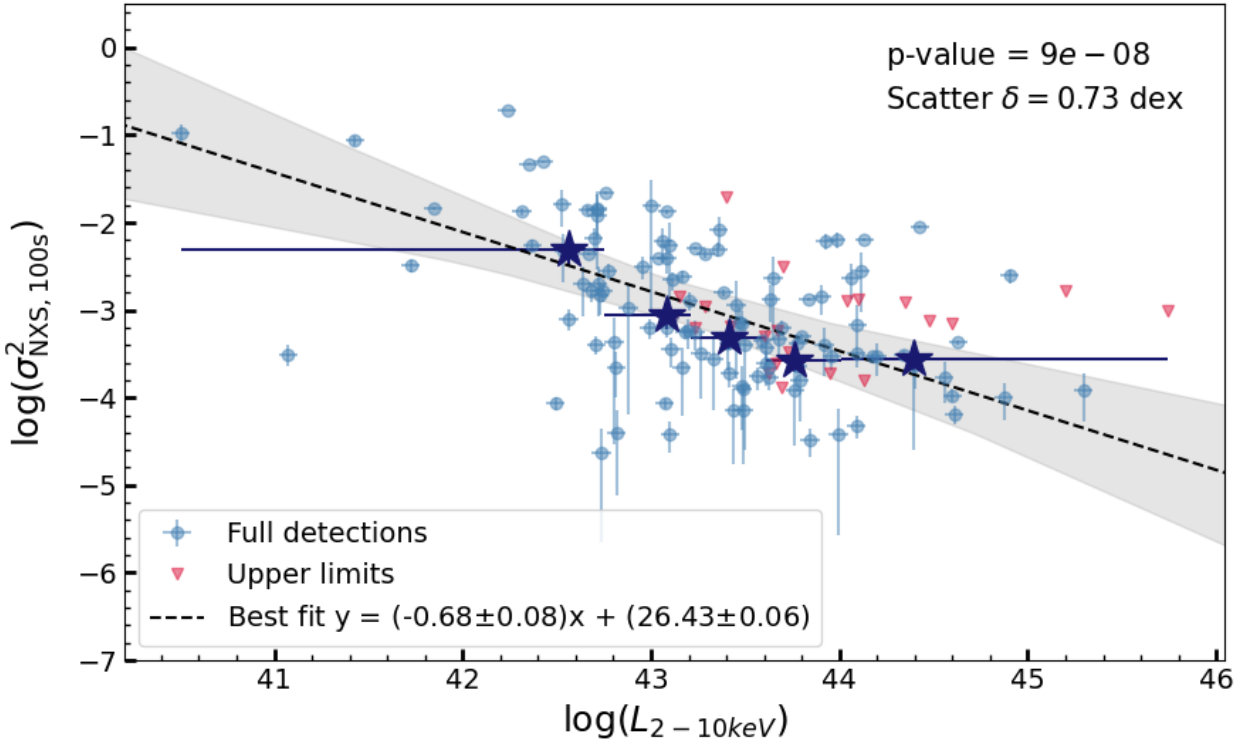
La Franca+14 introduced the width of broad lines as an additional parameter

If the main driver of variability is the M_{BH}

$$M_{BH} = f\frac{L^{\alpha}FWHM^2}{G}$$

assuming $\alpha \sim 0.5$, then adding a 4*log(FWHM) dependence to the σ–L relation would lower the observed dispersion

$$\log L = a * \log \sigma_{NXS} + 4\log FWHM + b$$



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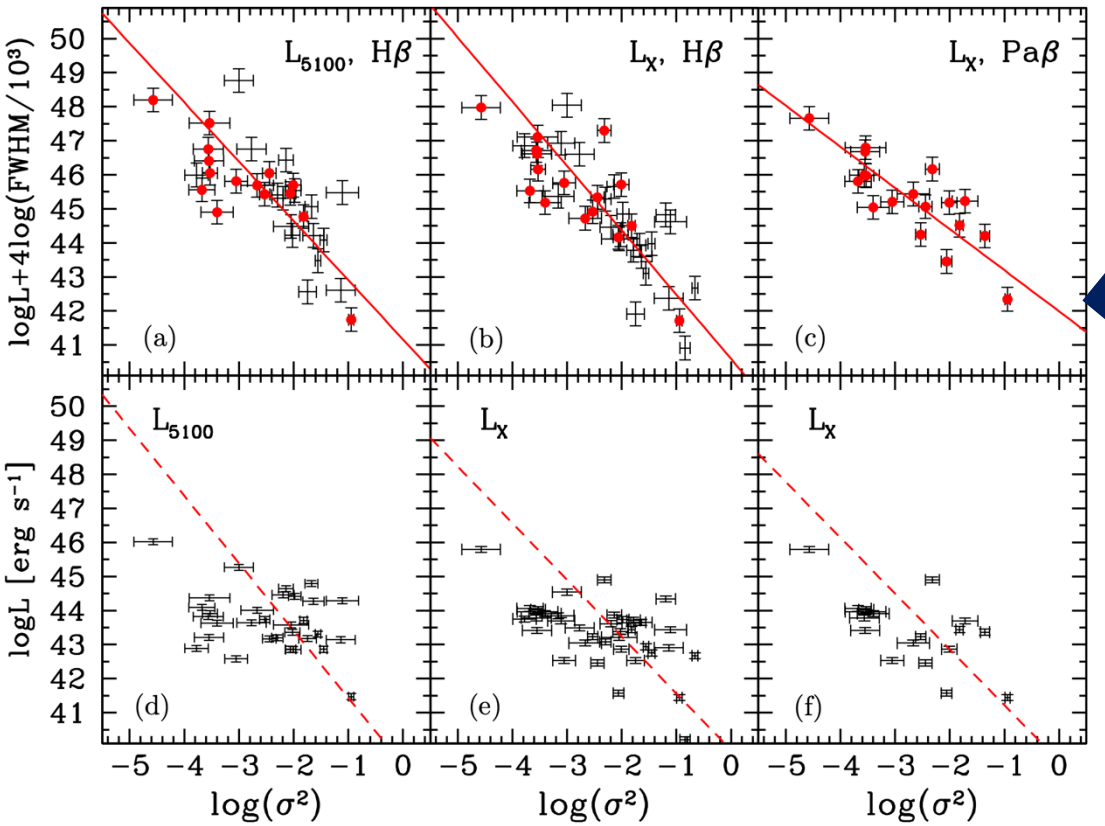
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~1.0 dex



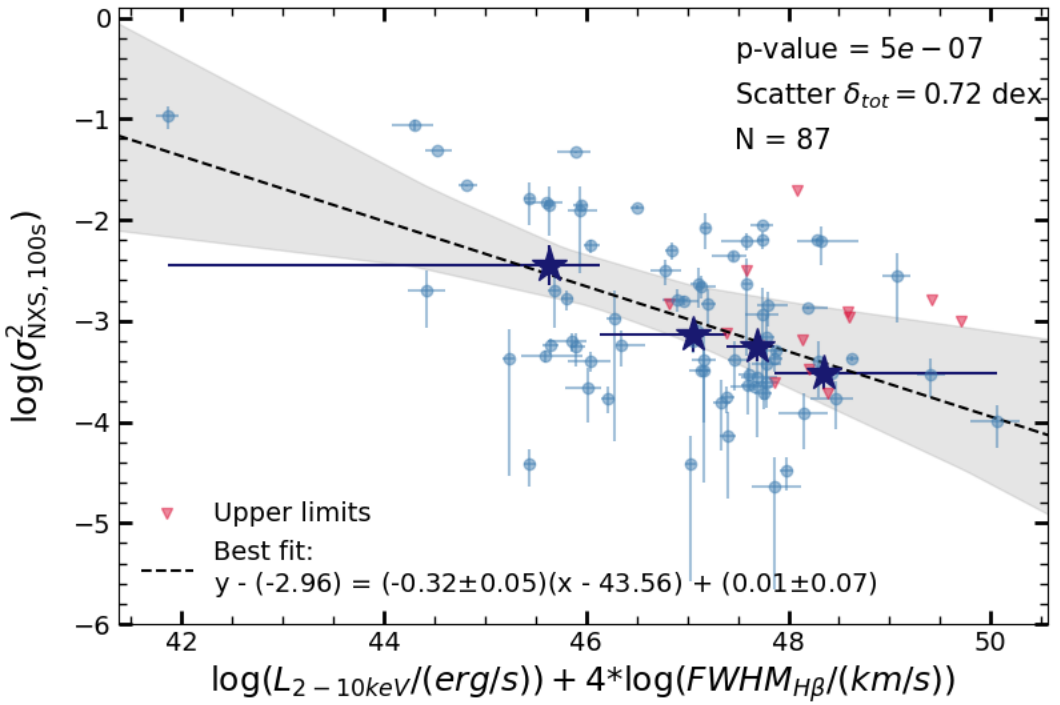
~1.12 dex

La Franca+14

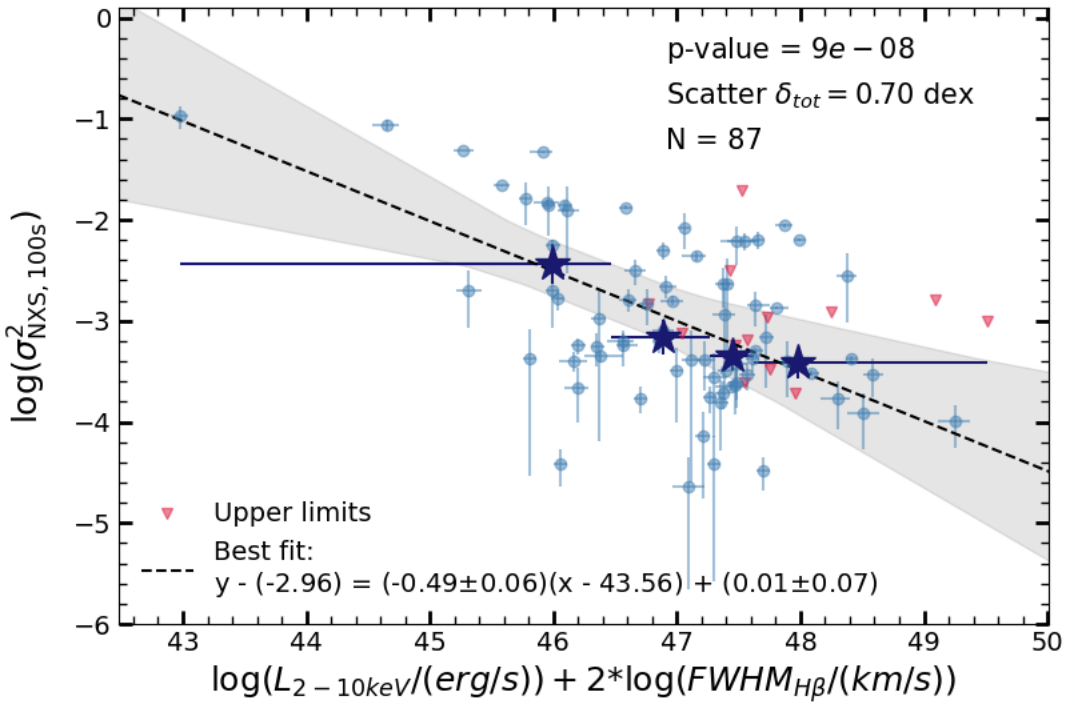
VARIABILITY FOR COSMOLOGY

In the BASS sample, results are a bit more complicated – starting point: 0.73 dex
Using Hβ:

~0.72 dex



~0.70 dex



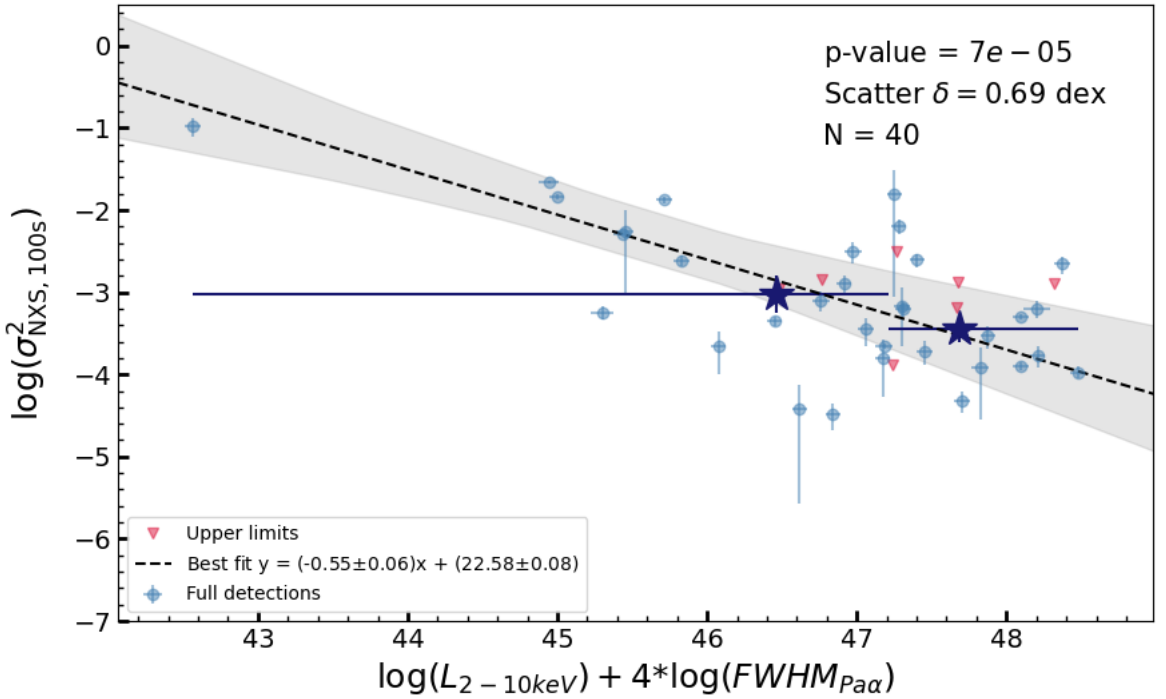
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VARIABILITY FOR COSMOLOGY

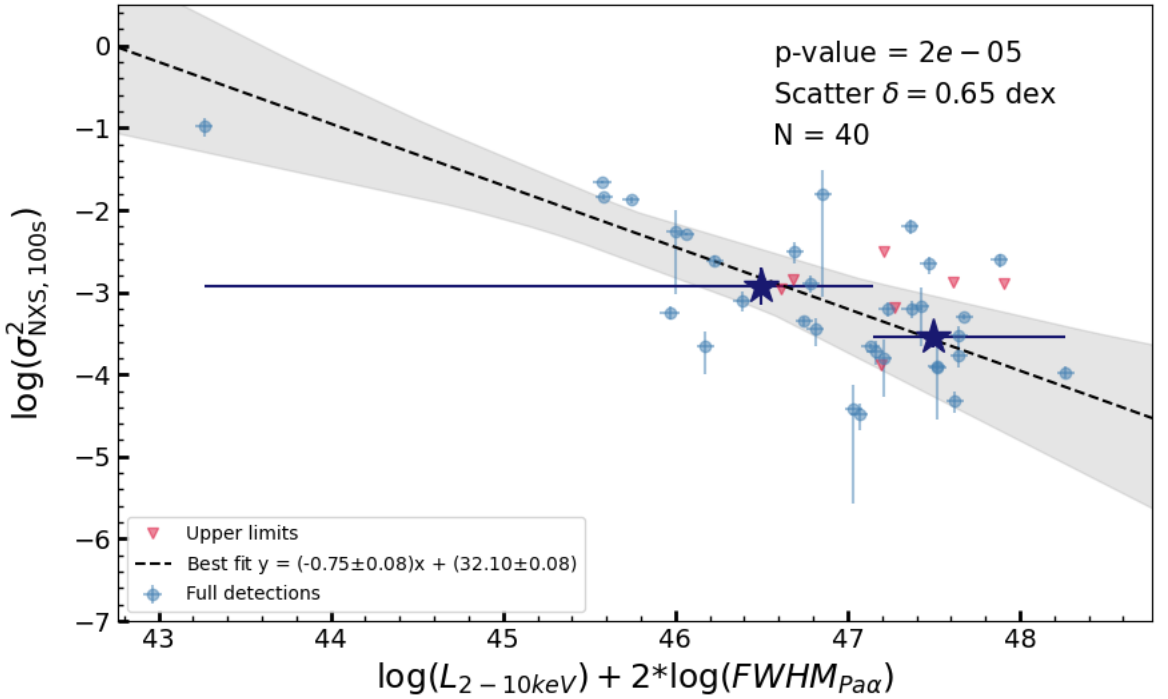
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Using Paα:

~0.69 dex



~0.65 dex



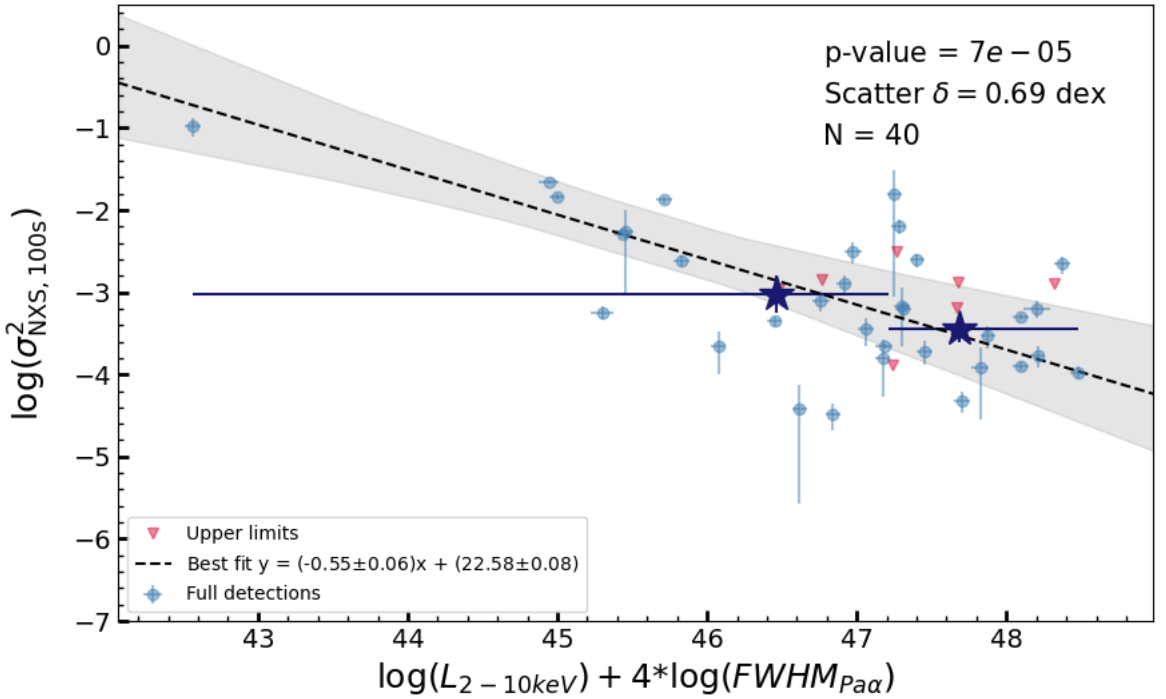
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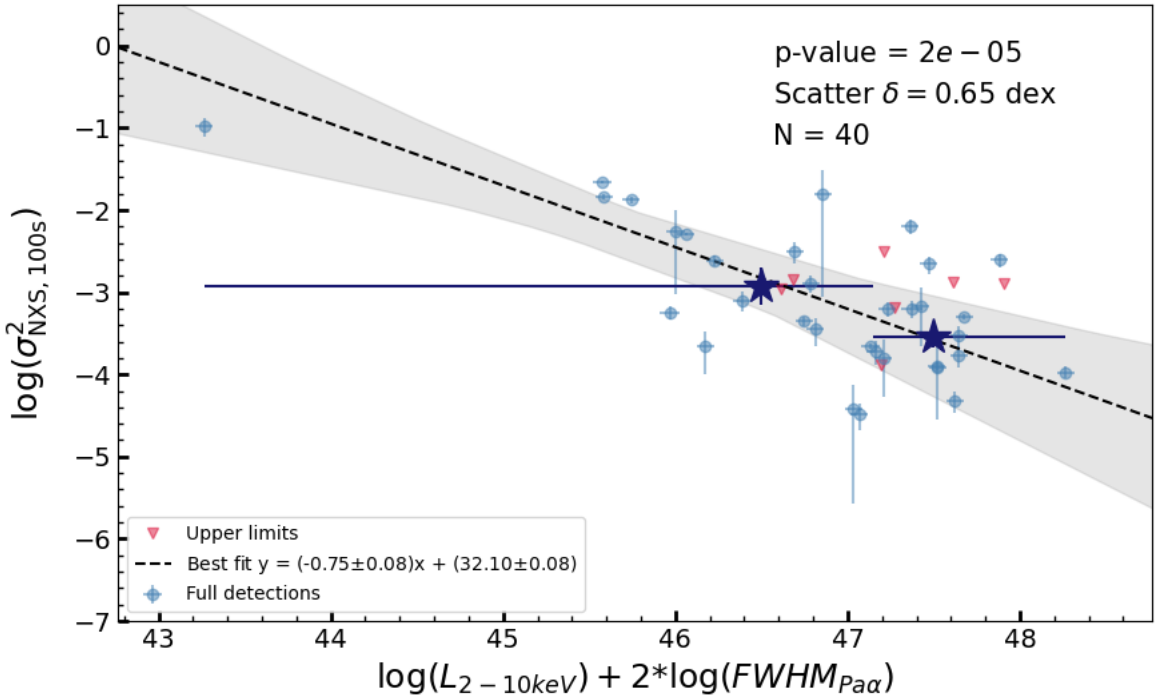
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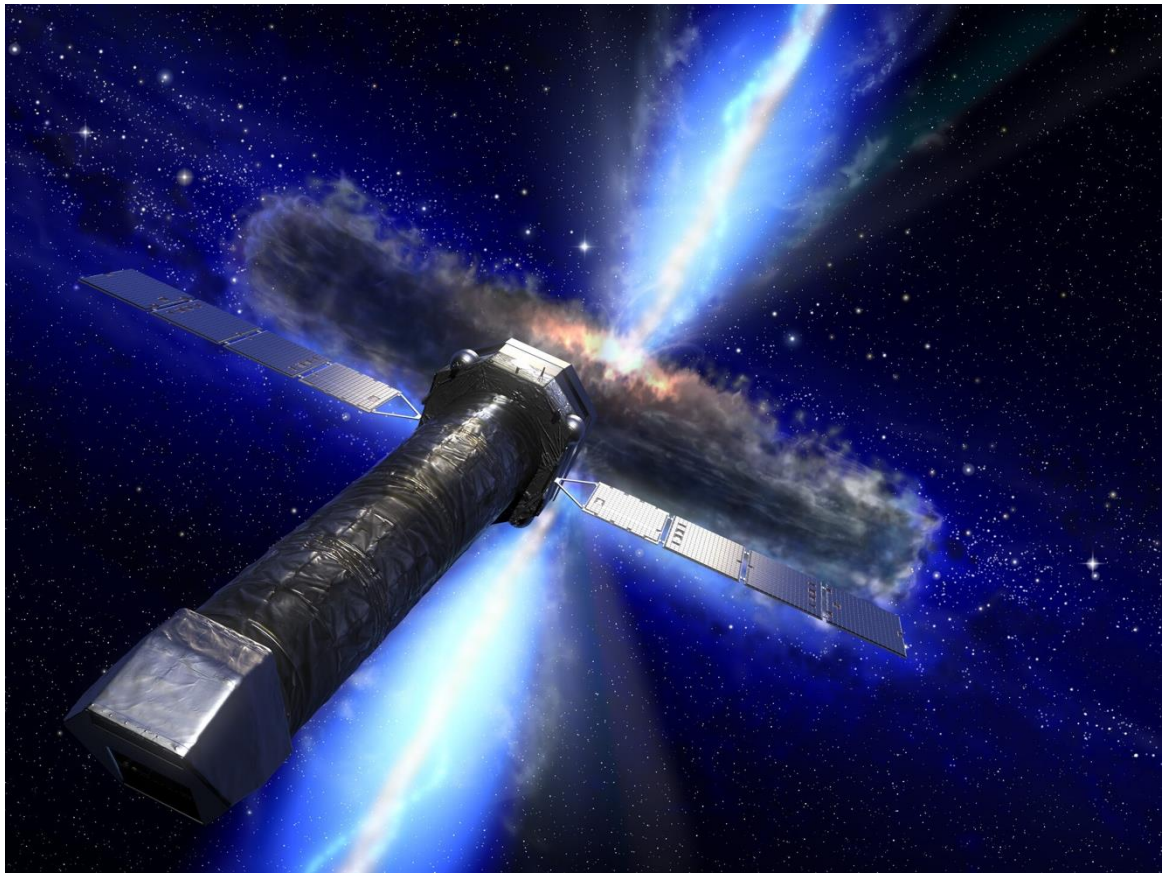


Are there selection effects? The brightest objects are more likely to be detected in IR

VARIABILITY FOR COSMOLOGY – X-RAYS ONLY

NewAthena ~2037

The *Wide Field Imager* can detect the excess variance from ~50.000 unobscured AGN in the first months



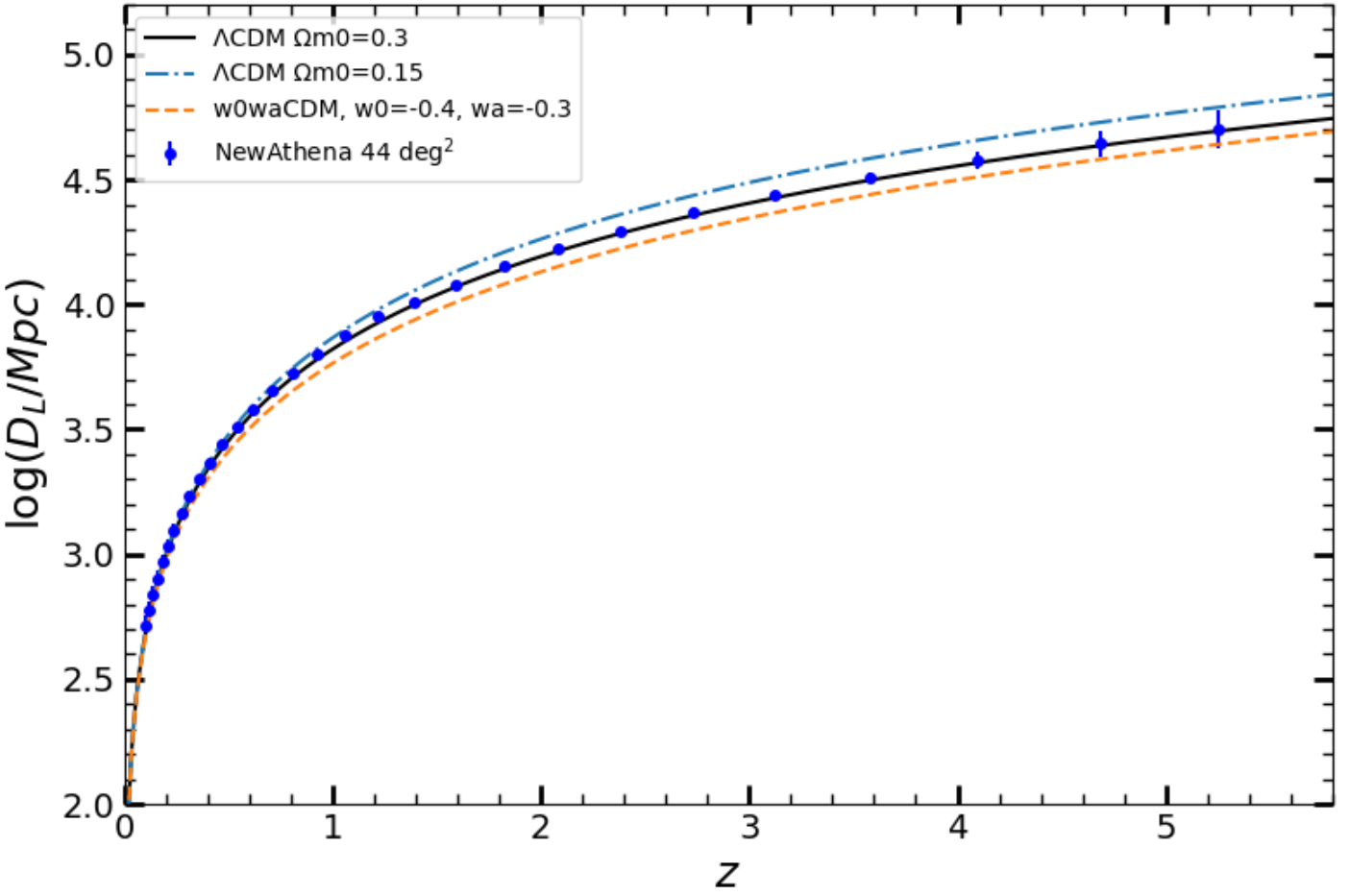
VARIABILITY FOR COSMOLOGY

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For N objects, uncertainty on the distance measurement is lowered by a factor $\sqrt{N}$

We could distinguish between cosmological models that are overlapping at low redshift!



CONCLUSIONS

- X-ray variability is an intrinsic property of AGN that can help us understand their physics
- We confirm in the BASS sample a strong anti-correlation of variability with the M_{BH} and the luminosity, with M_{BH} likely the stronger driver
- The scenario of a universal PSD with a 'knee' only depending on M_{BH} is challenged by the absence of a significant $\sigma - \lambda_{Edd}$ relation
- Uncertainties on single-epoch M_{BH} make it harder to draw conclusions

- We can use variability as a luminosity estimator, using AGN as standard candles
- The current dispersion of the $\sigma - L$ relation is significant, and introducing optical/IR line information does not improve the situation much
- Future generation of X-ray telescopes can help us go deeper in the X-ray sky – with the detection of tens of thousands of objects, we could constrain cosmological models up to redshift ~5

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THANK YOU!