AGN as cosmological probes

ESO lunch seminar – 15th April 2025

Matilde Signorini
matilde.signorini@esa.int

INTRODUCTION



University of Florence
PhD supervisor: Prof. Guido Risaliti



UCLA – Visiting grad student
supervisor: Prof. Tommaso Treu

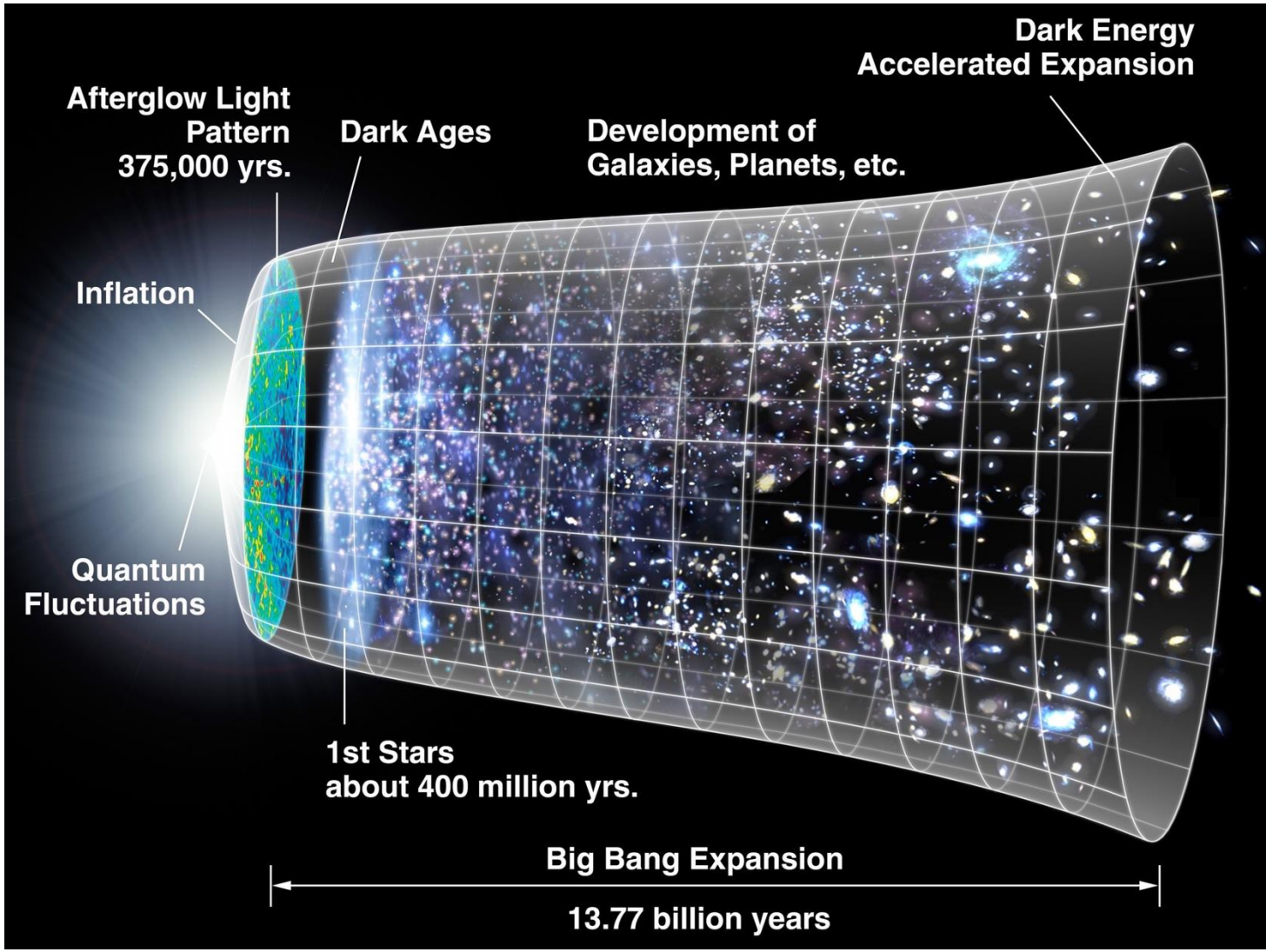


University of Roma3
supervisor: Dr. Federica Ricci



European Space Research and Technology Centre
Research Fellow

COSMOLOGY – THE UNIVERSE AS A WHOLE



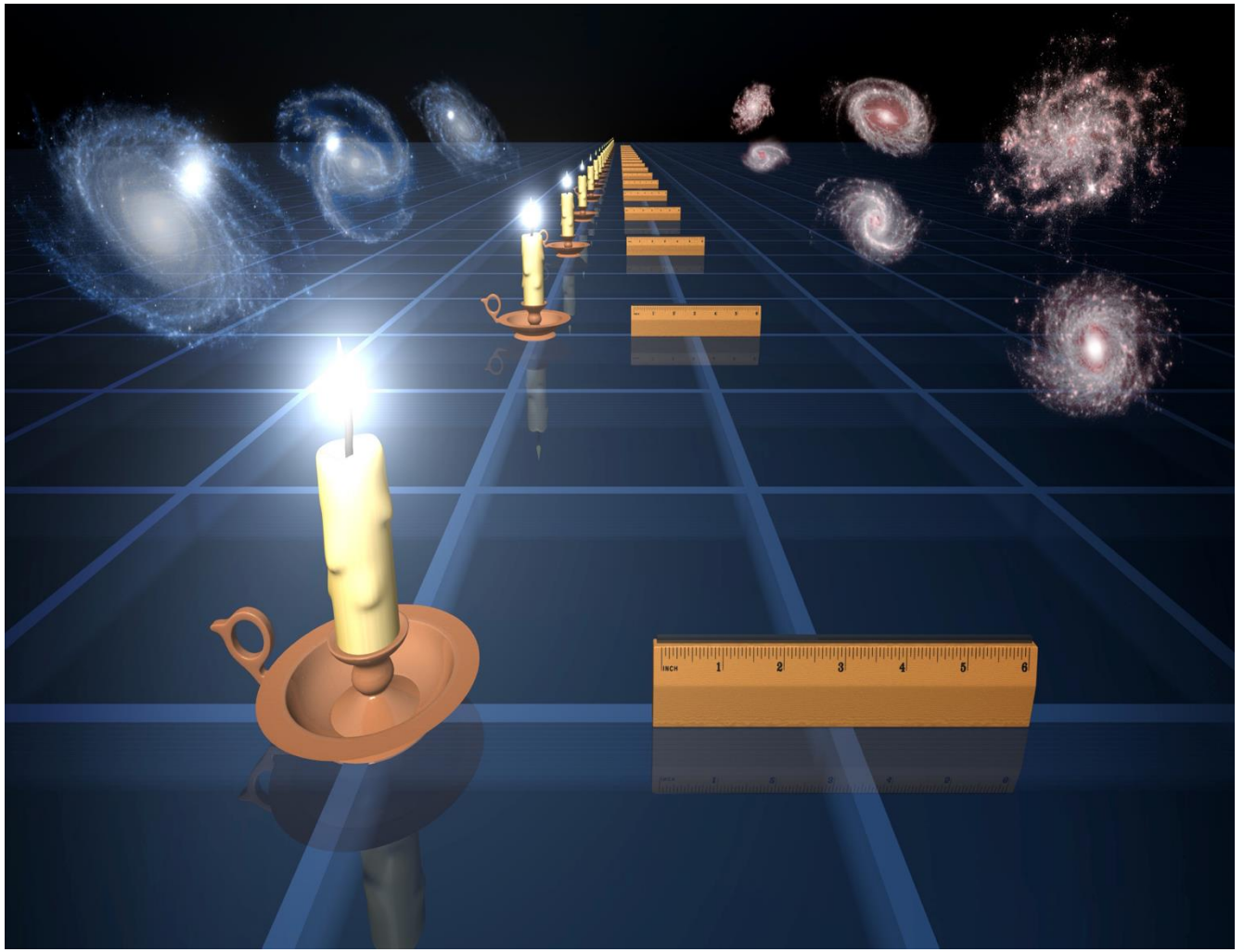
What are the Universe components?

How did they evolve over time?

What is the Universe expansion history?

How did the complex structures we see today form?

COSMOLOGY - STANDARD CANDLES



"an object for which we know the luminosity L in a cosmology-independent way"

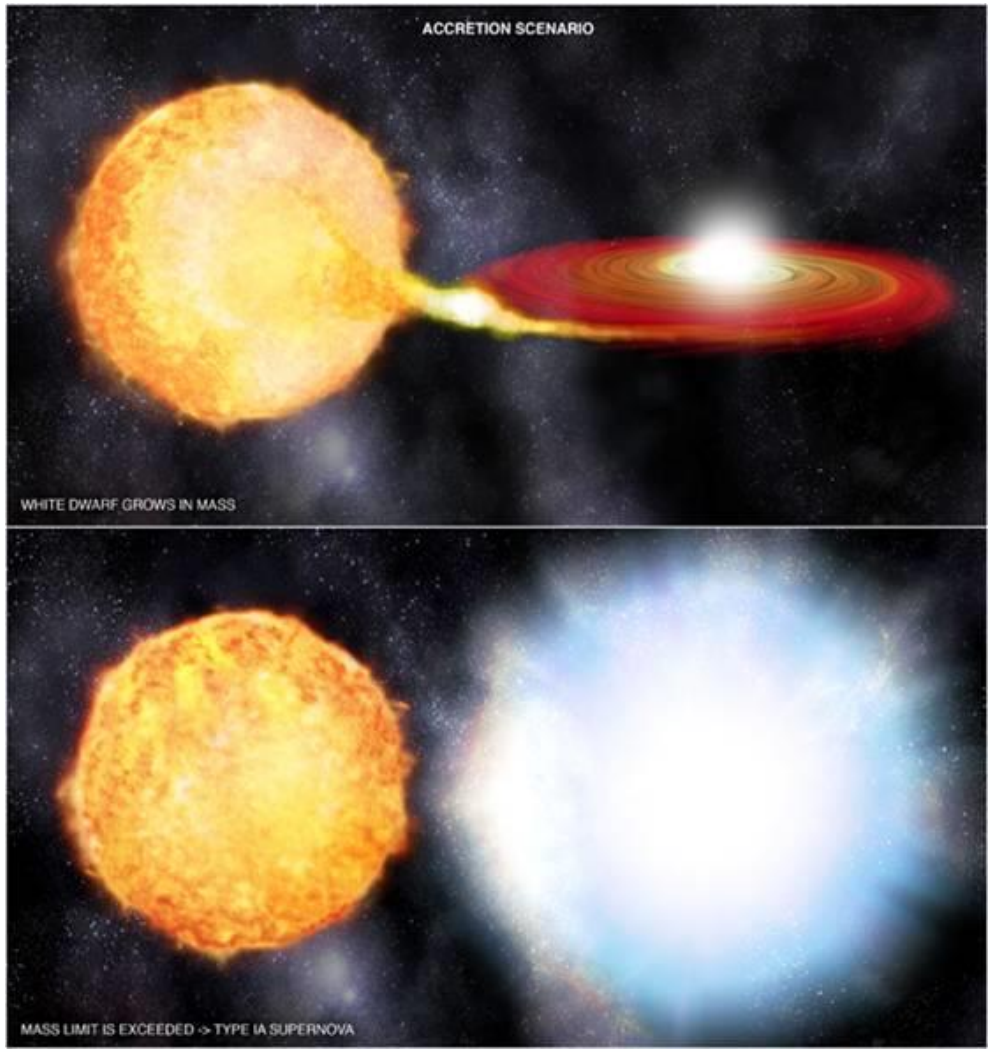
By measuring its flux F, we determine its distance

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

COSMOLOGY - STANDARD CANDLES

Supernova Ia: the most famous standard candles

They happen when a white dwarf accretes on a companion until it reaches the Chandrasekhar limit

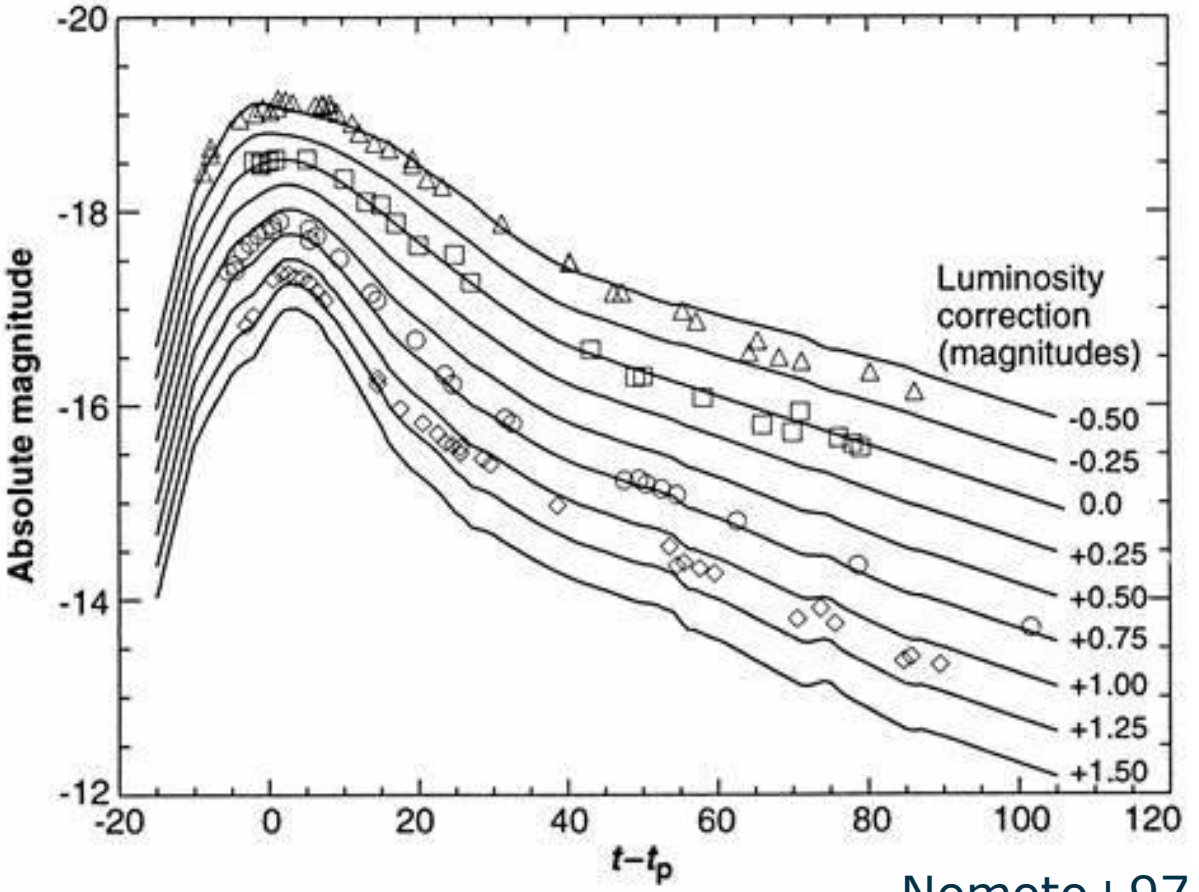


COSMOLOGY - STANDARD CANDLES

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We need the Phillip (1993) relation to know their intrinsic luminosity!



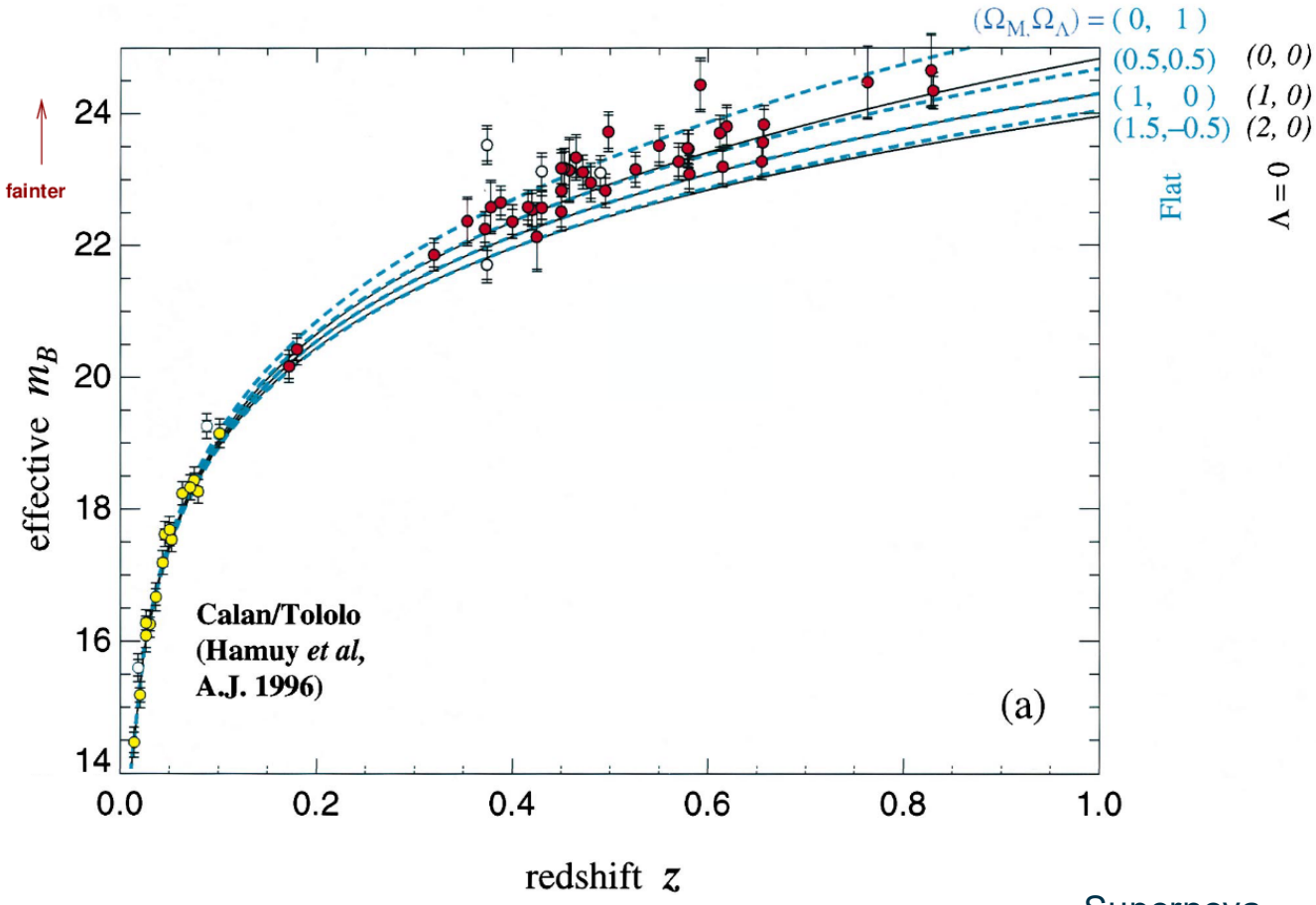
Nomoto+97

COSMOLOGY - STANDARD CANDLES

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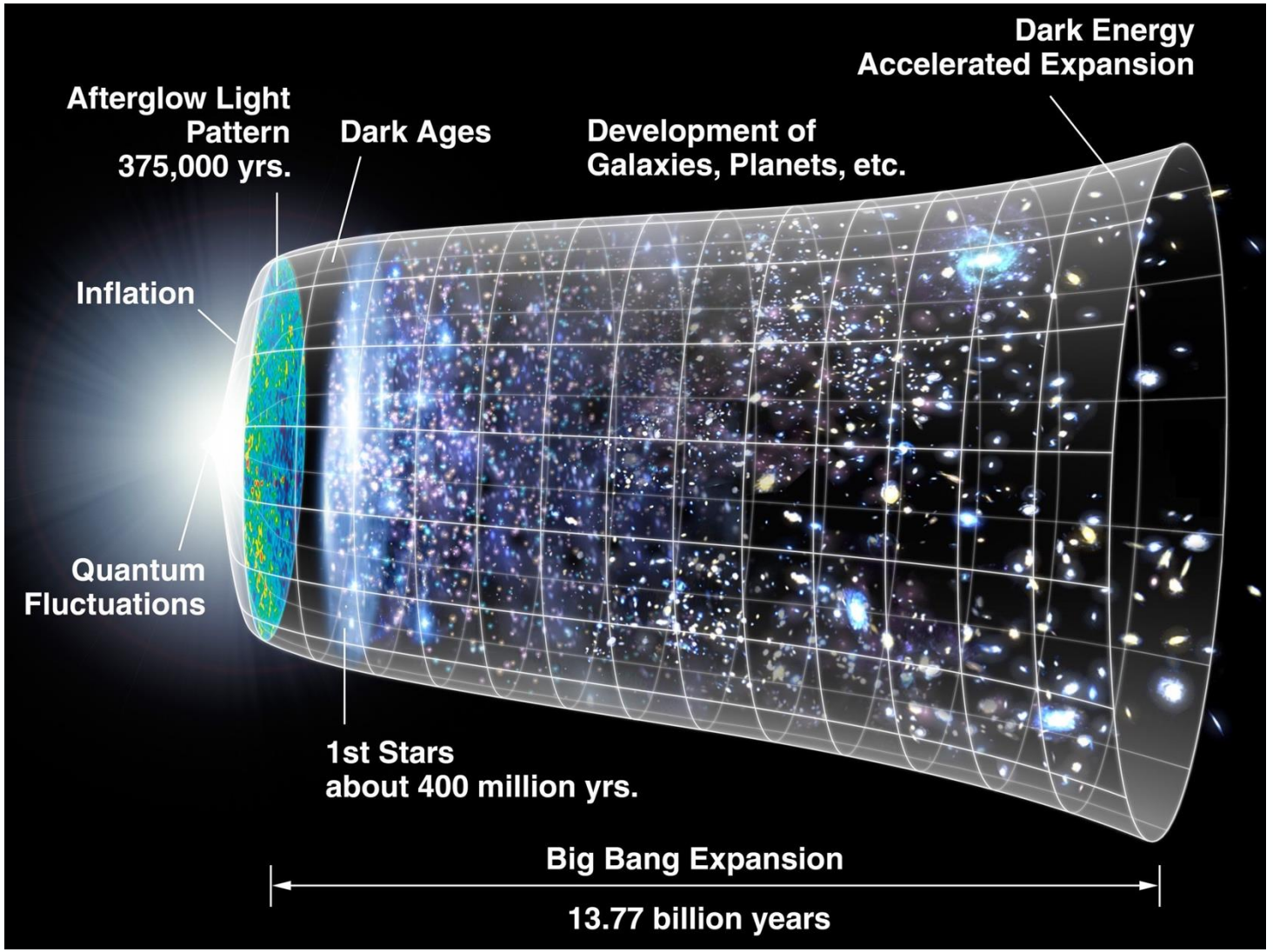
We build the distance-redshift or "Hubble-Lemaître", diagram:

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



Supernova Cosmology Project Perlmutter+1998

COSMOLOGY – THE ΛCDM MODEL



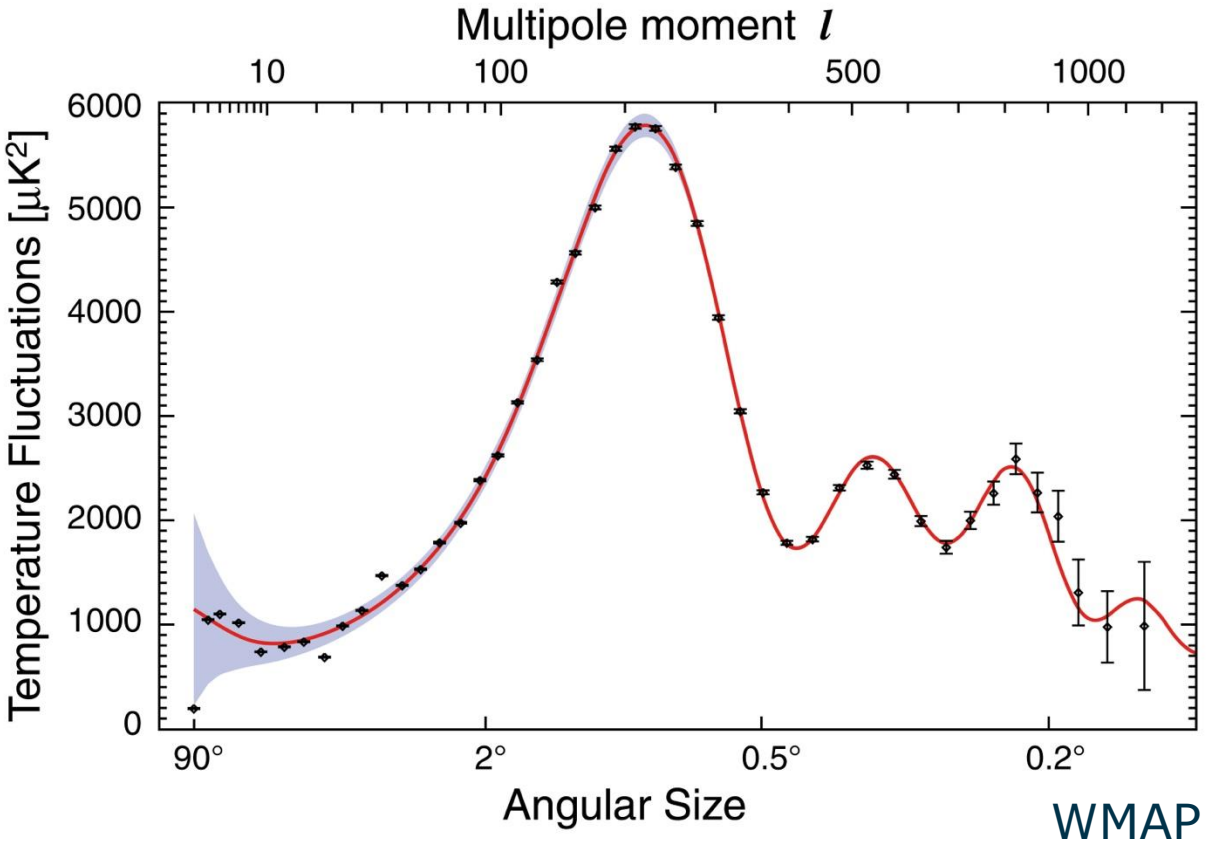
The Universe is made of:

- Dark energy (Λ) – expansion acceleration (~70%)
- Cold Dark matter – drives structure formation (~25%)
- Regular matter – the only component we can directly see (~5%)

COSMOLOGY – THE ΛCDM MODEL

Successes

- CMB anisotropies
- Galaxies formation
- Barionic Acustic Oscillation peak
- Big Bang nucleosynthesis
- Accelerated expansion
- …

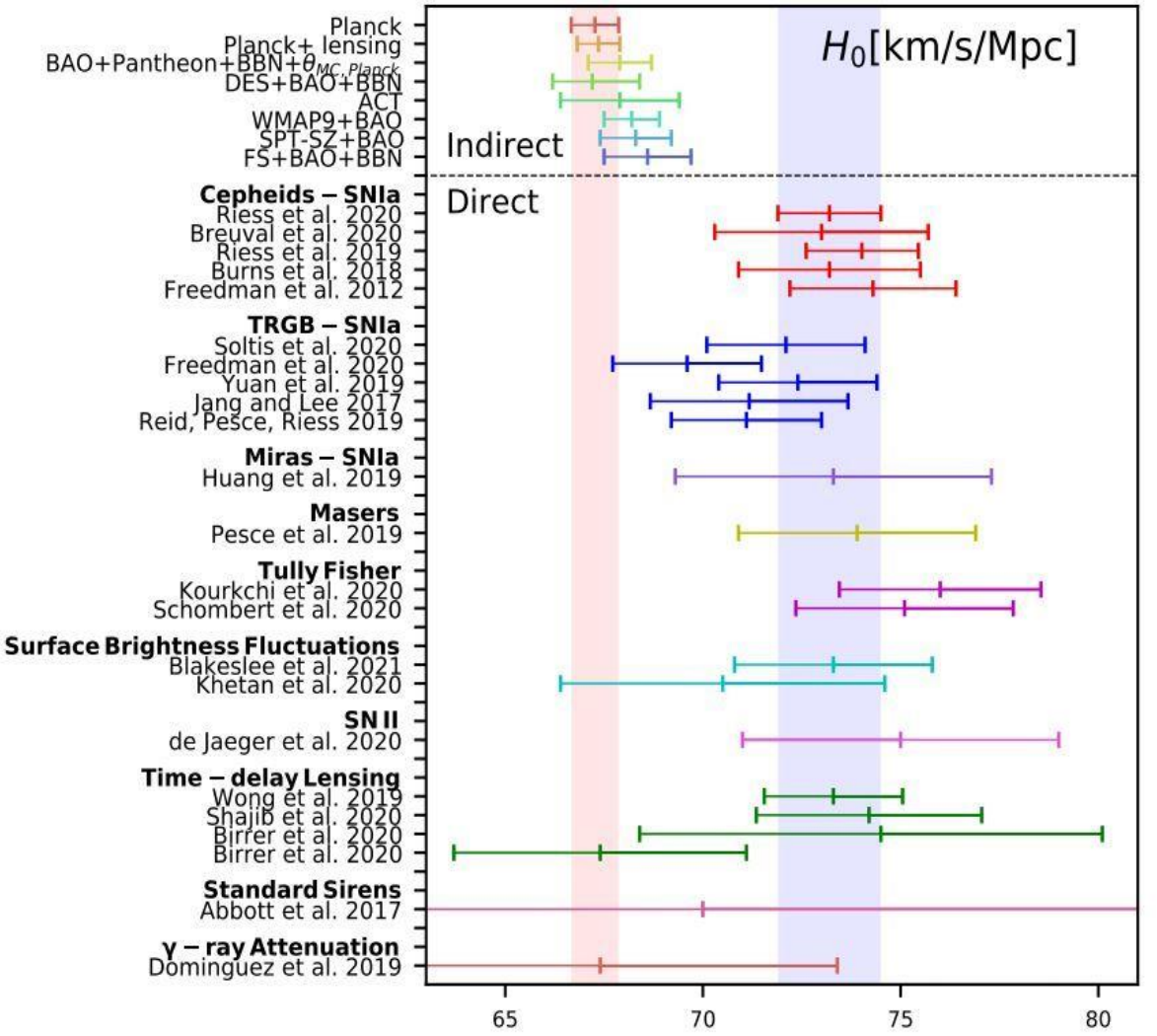


COSMOLOGY – THE ΛCDM MODEL

Issues

- H_0 tension (ΛCDM vs local)
- S_8 tension (ΛCDM vs weak lensing)
- Evidence for evolving Dark Energy (DES 2025)

- What is Dark Energy?
- What is Dark Matter?

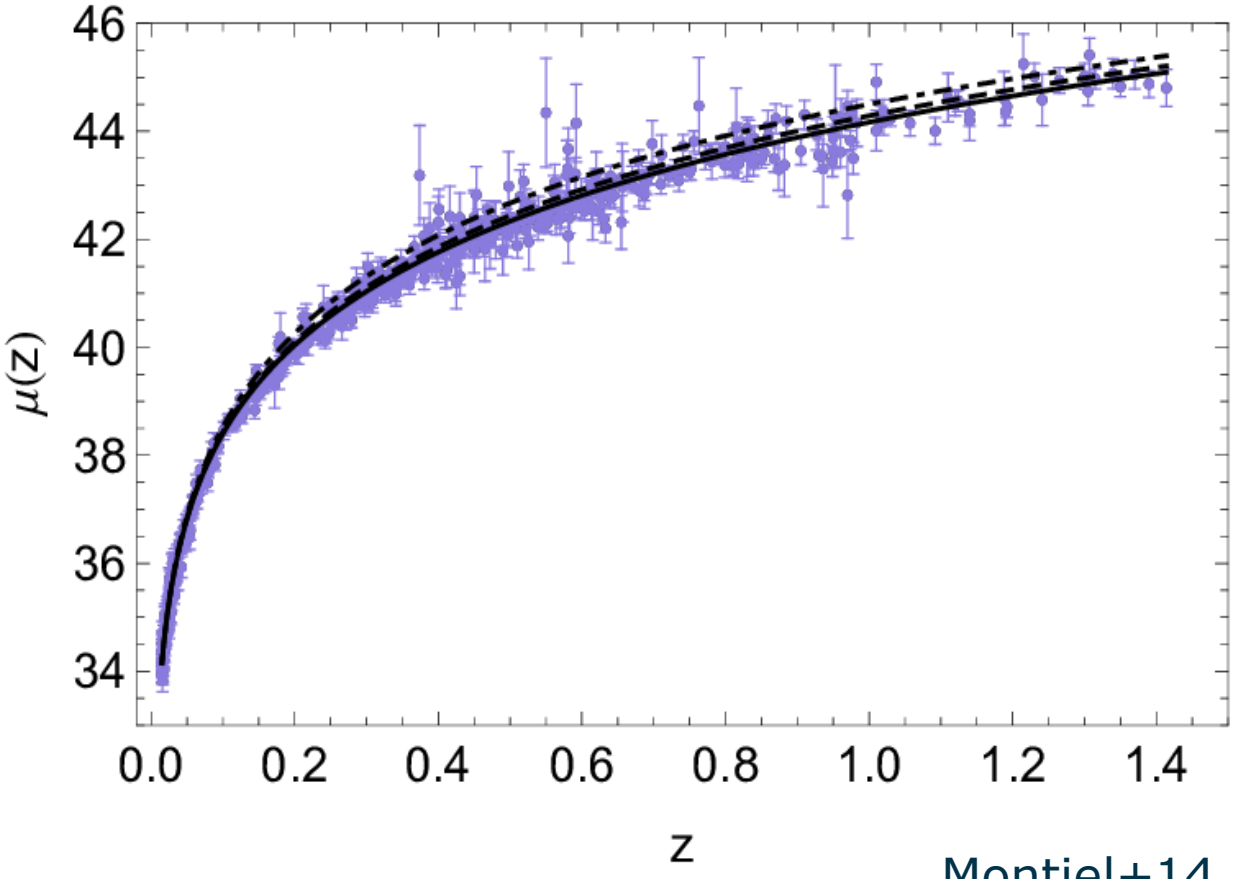


Di Valentino+2020

COSMOLOGY – THE ΛCDM MODEL

How do we test models at high redshifts?

With SNIa, we are missing information from the first 4-5 billion years of the Universe

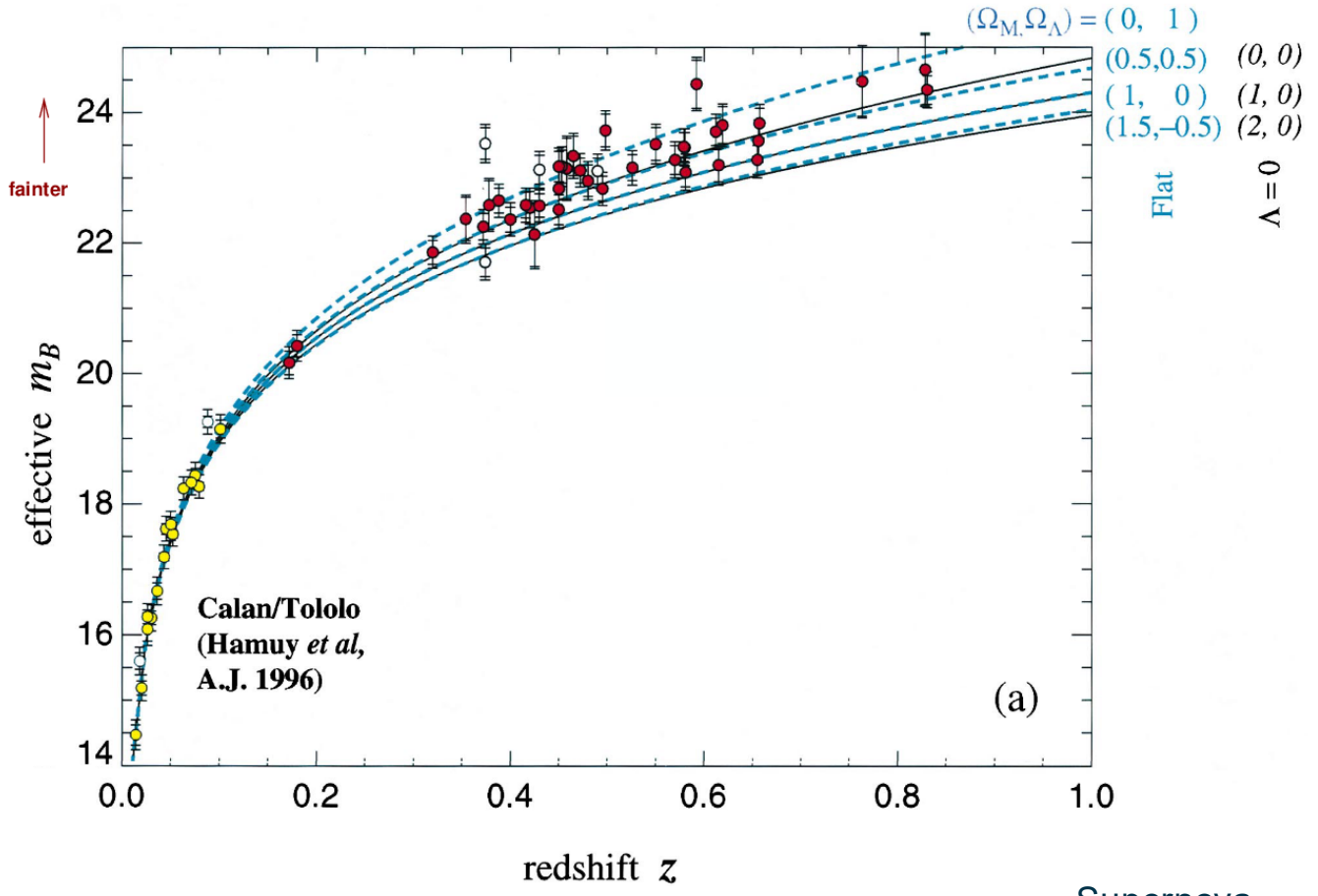


Montiel+14

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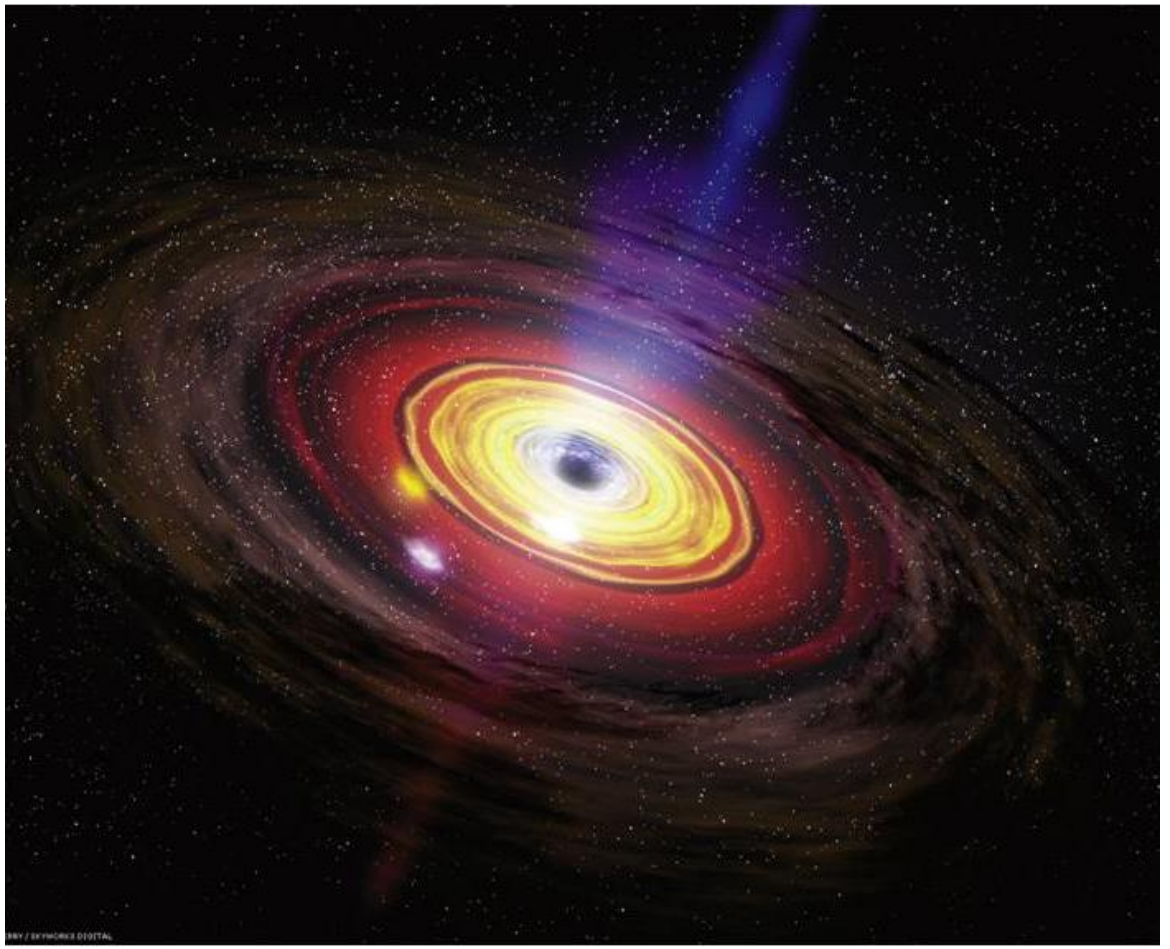


Supernova Cosmology Project
Perlmutter+1998

COSMOLOGY – WHY AGN?

Active Galactic Nuclei can help us gain more information in this complex context

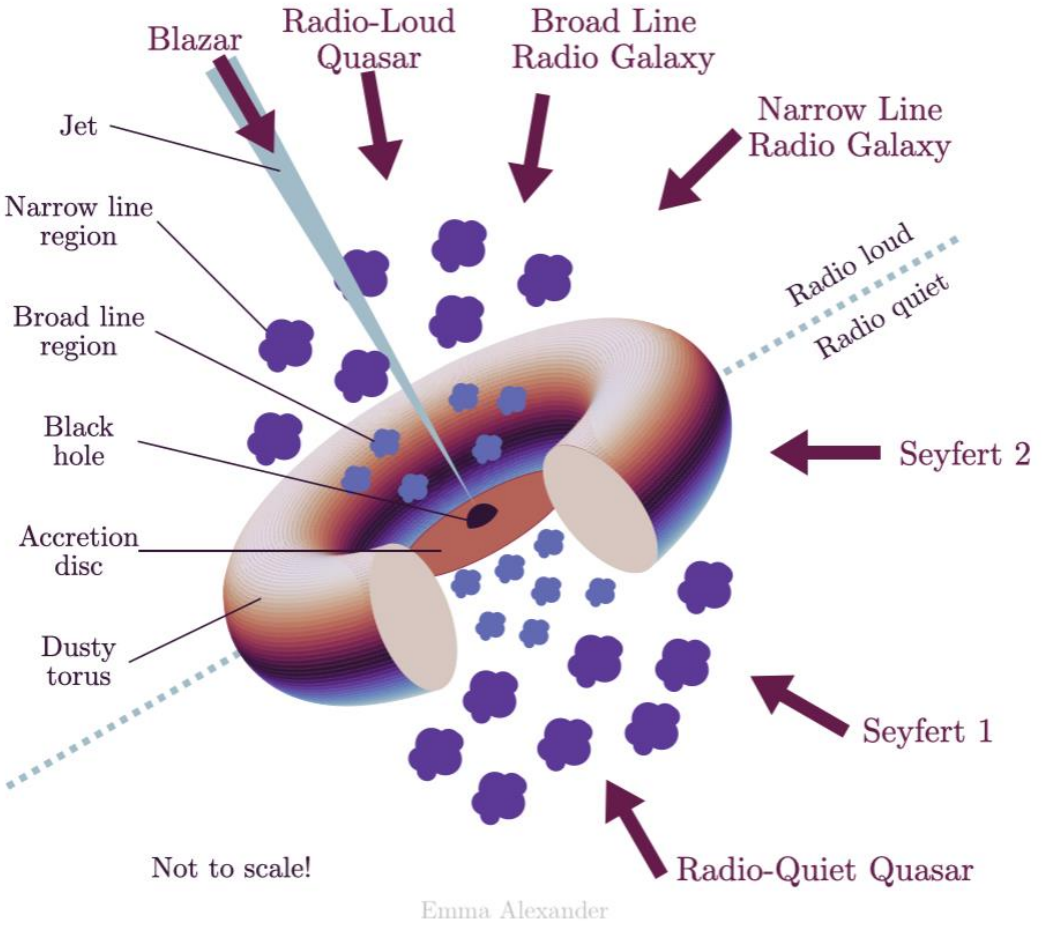
- Very bright (up to ~$10^{14} L_{\odot}$)
- Very numerous
- Observed from low (z~0.001) to high (z>10) redshifts



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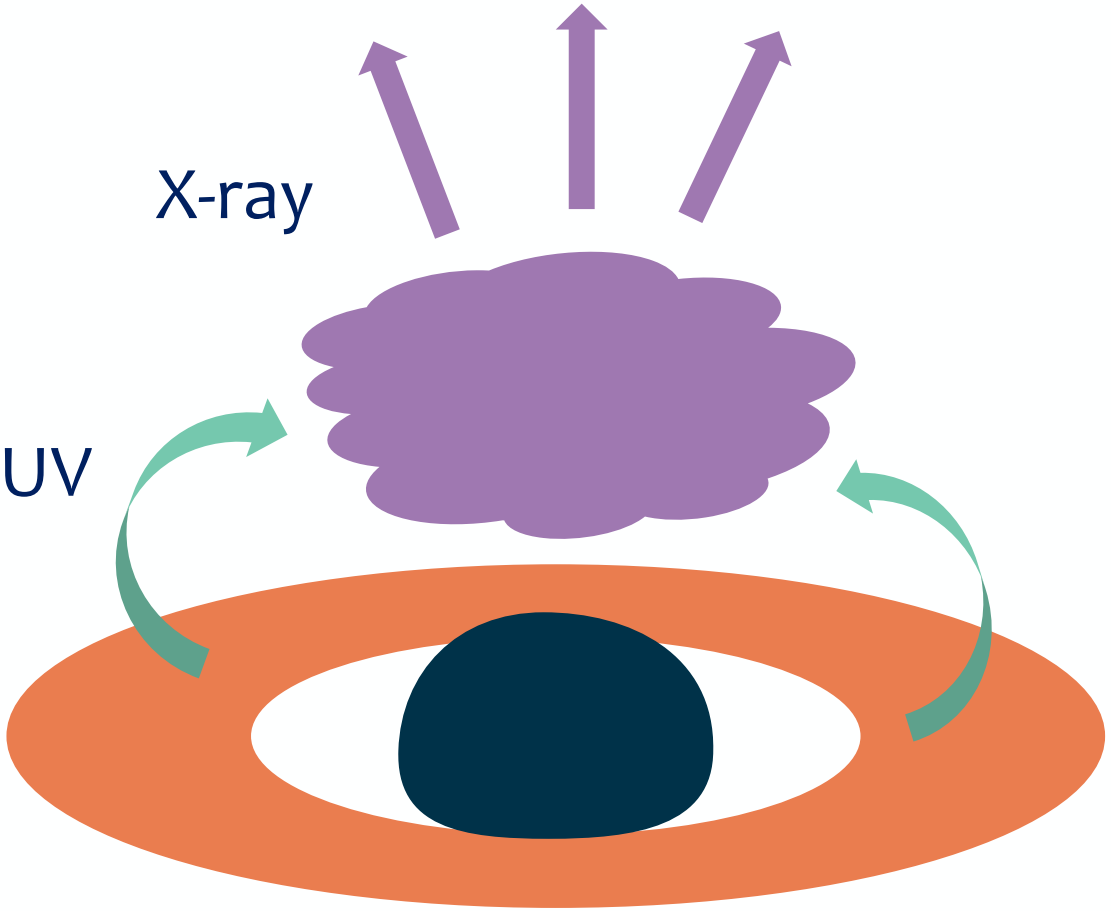
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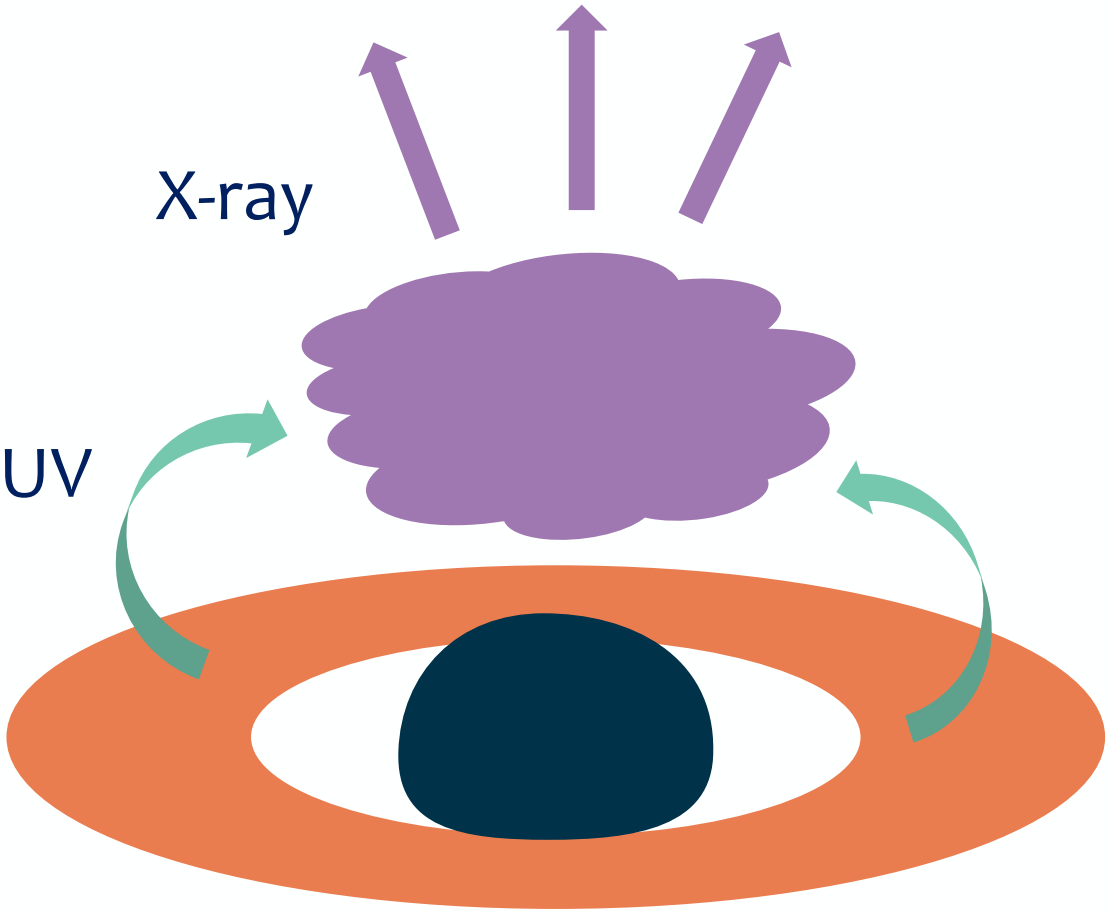


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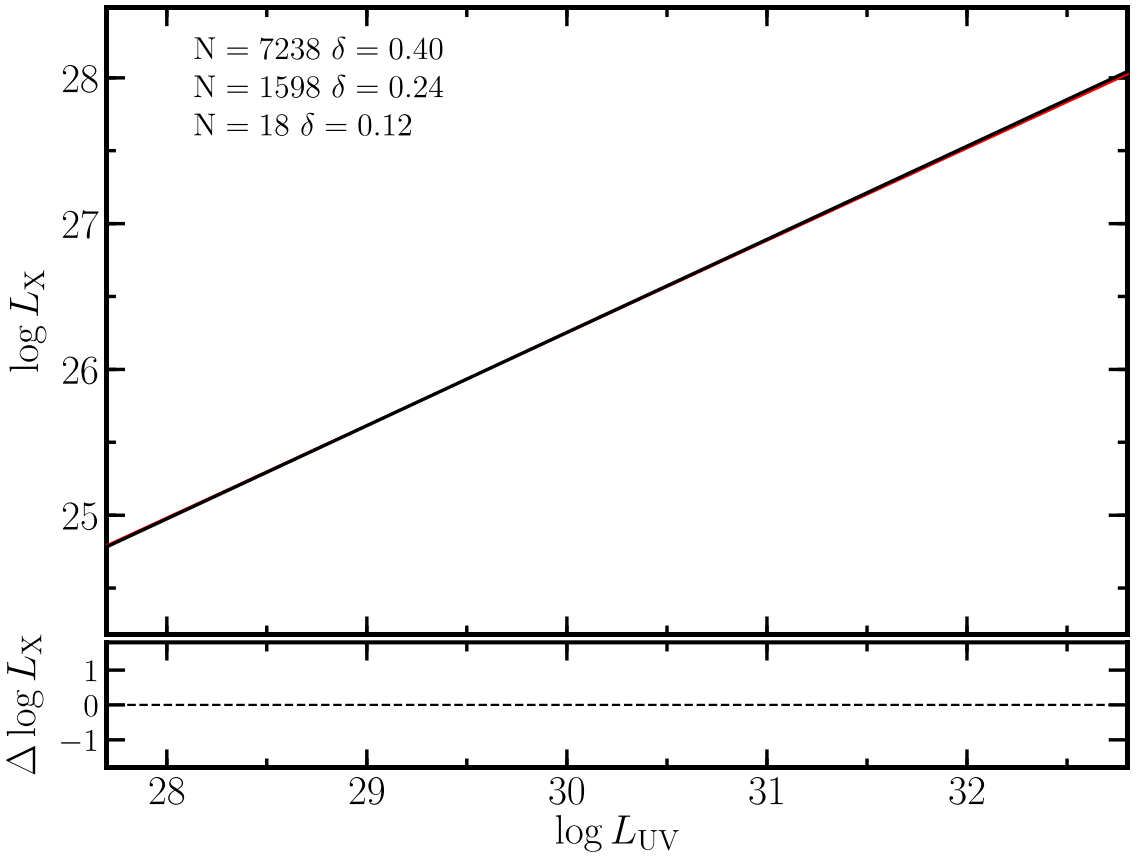
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Sadly, the emission is not standard!
$L_{bol} \sim 10^{11} - 10^{14} L_{\odot}$



THE L_X-L_{UV} RELATION



Risaliti&Lusso19

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

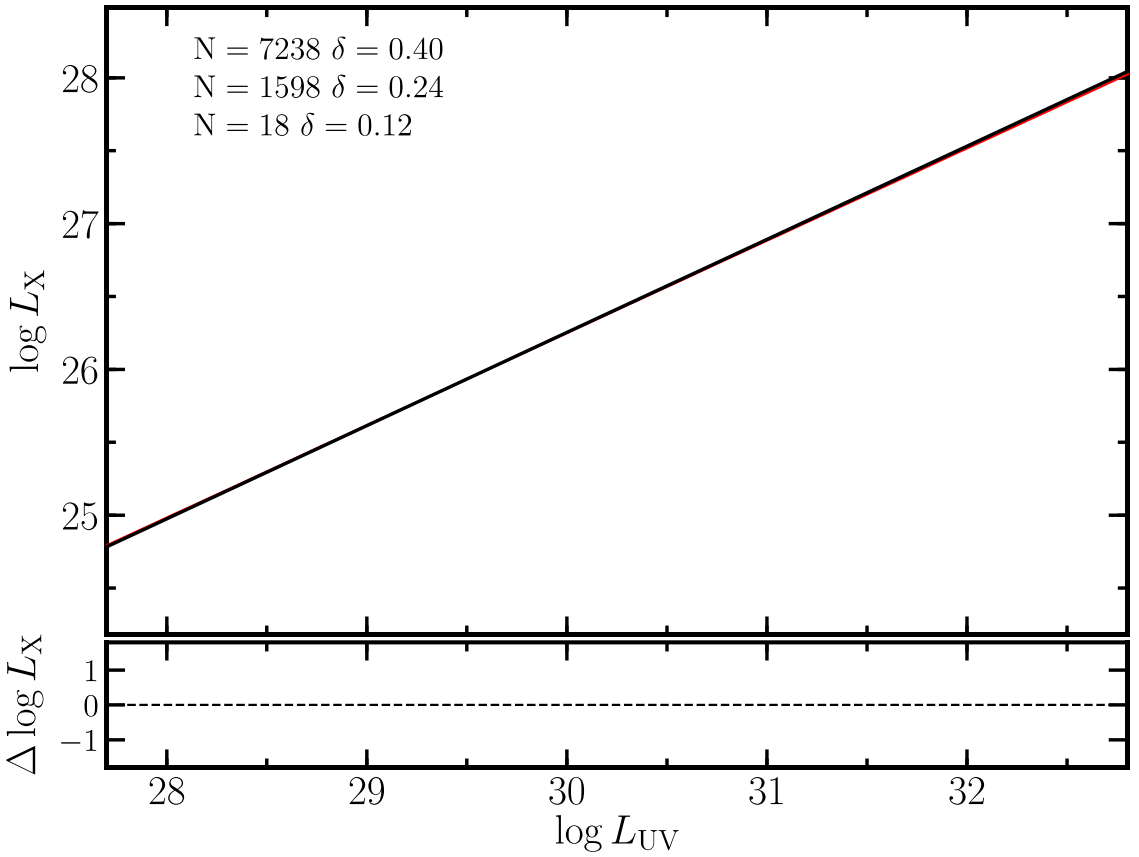
$$f_X = \frac{L_X}{4\pi D L^2} \qquad f_{UV} = \frac{L_{UV}}{4\pi D L^2}$$

$$\log(D_L) = \frac{1}{2 - 2\gamma}(\log(f_X) - \gamma \log(f_{UV})) + \beta'$$

Distance measurements!

THE L_X-L_{UV} RELATION

δ~0.40 dex



Risaliti&Lusso19

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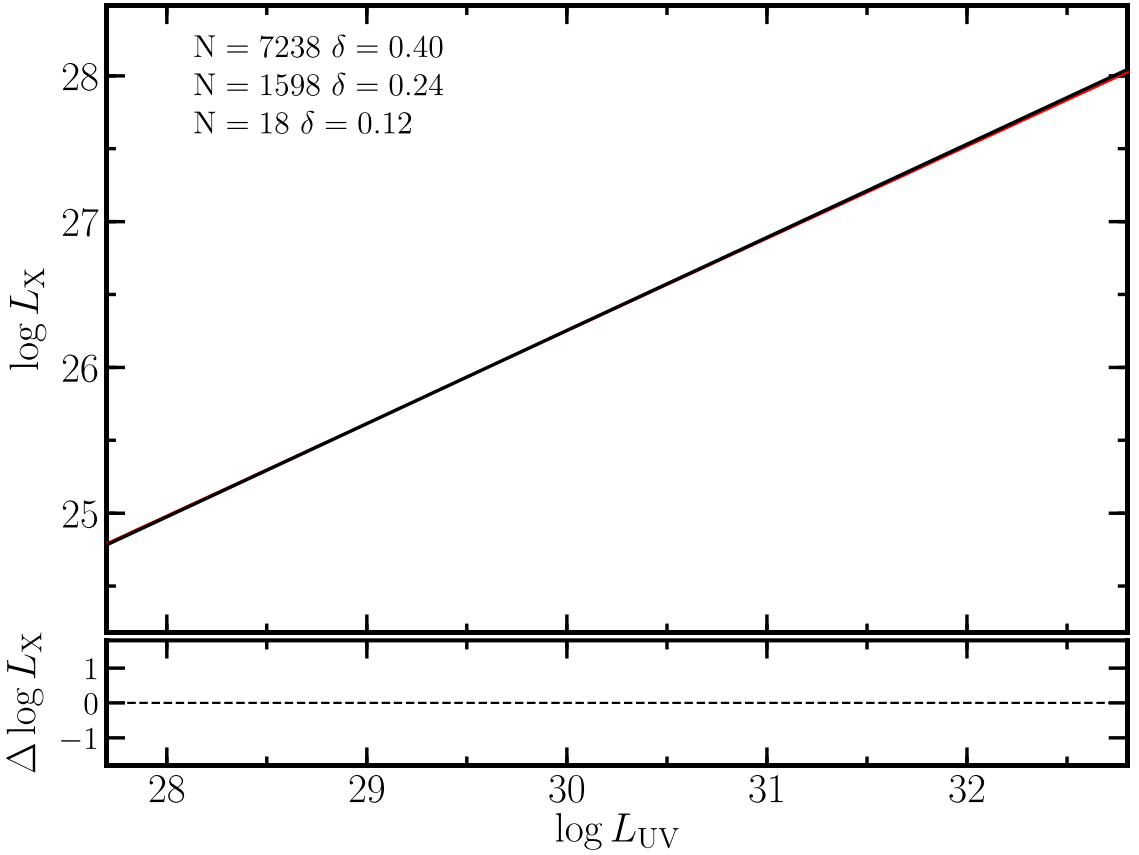
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δ~0.40 dex δ~0.24 dex



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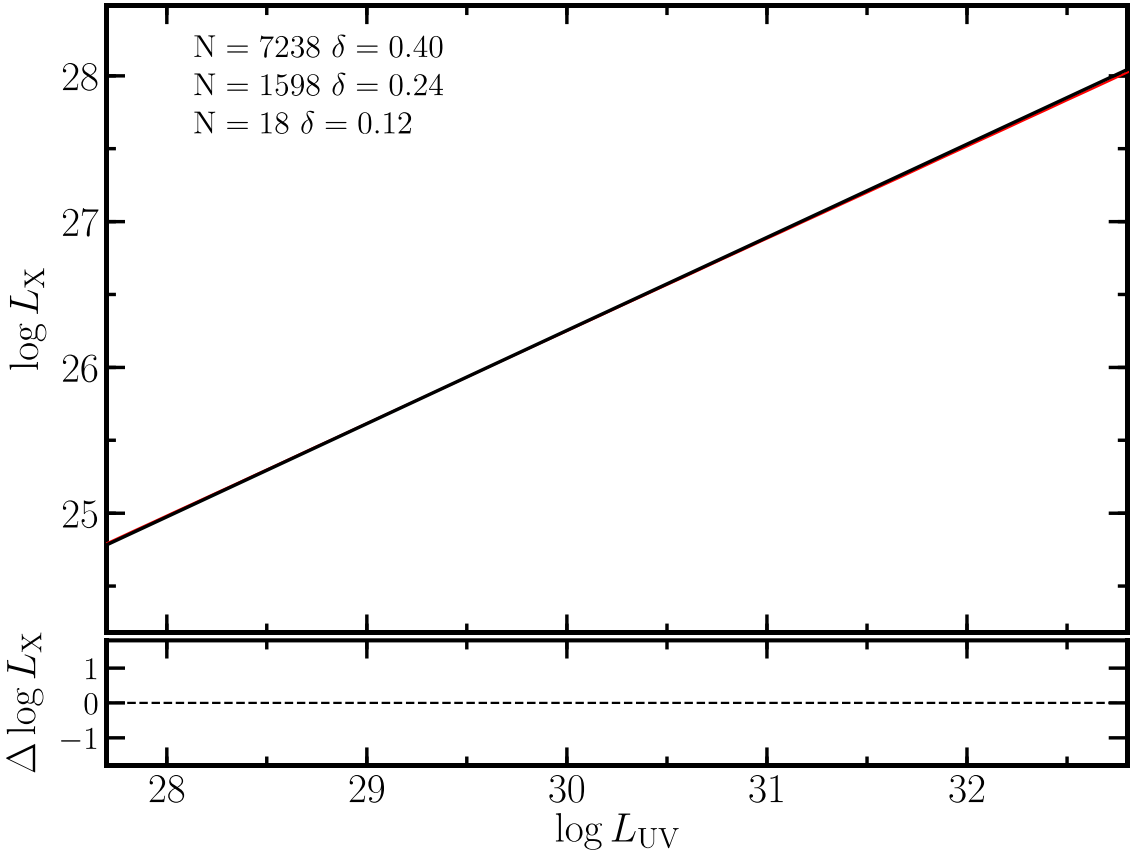
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THE L_X-L_{UV} RELATION

δ~0.40 dex **δ~0.24 dex** **δ~0.12 dex**



Risaliti&Lusso19

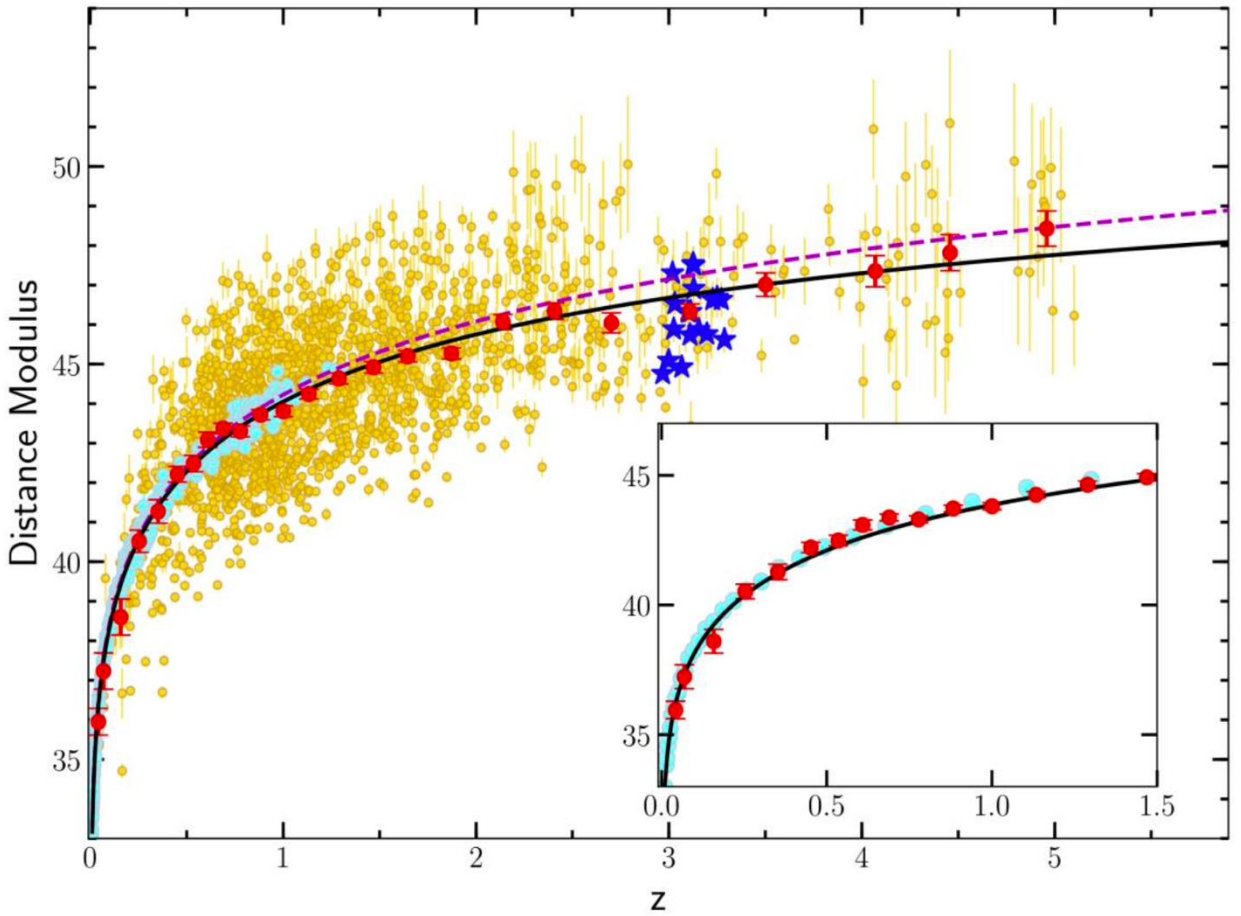
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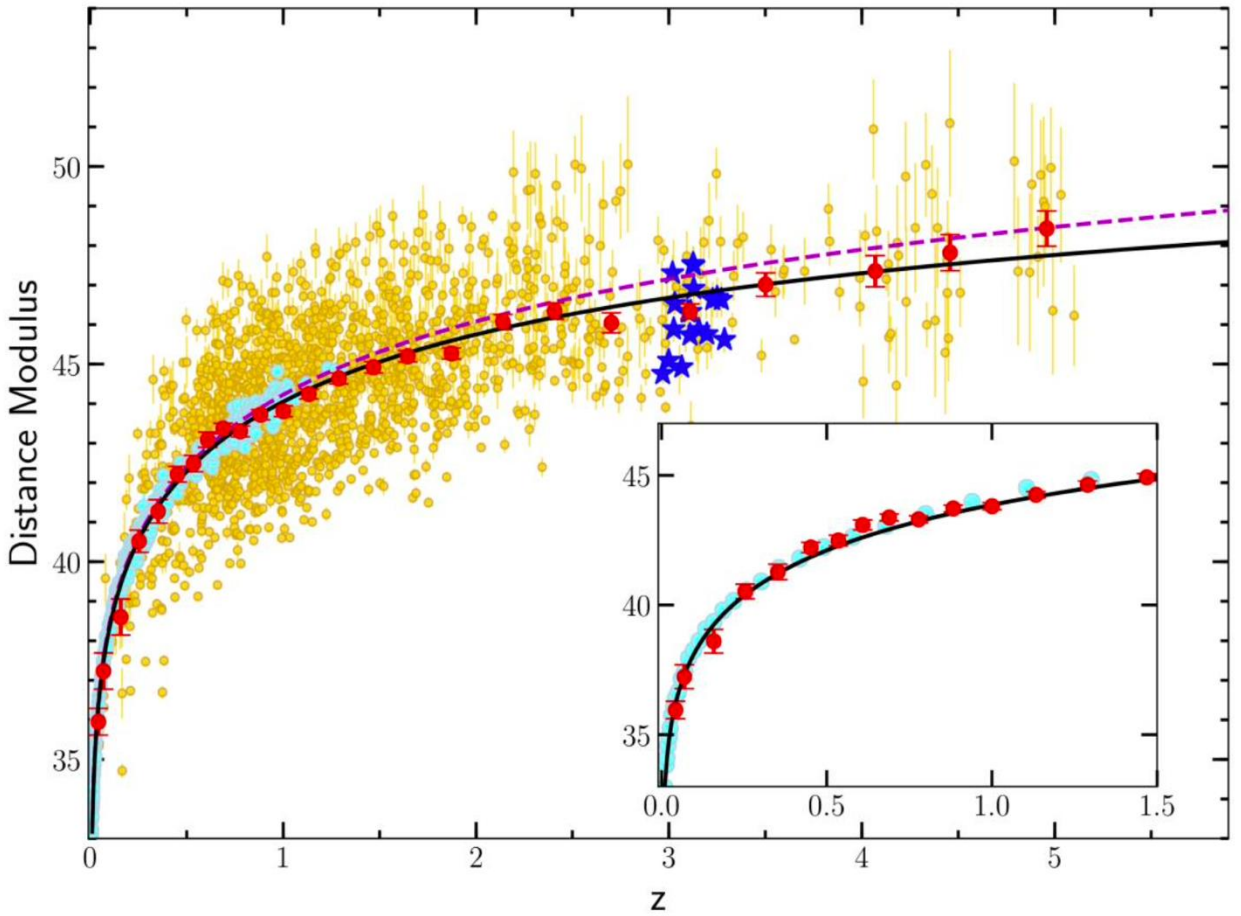
Risaliti&Lusso19

Extension of the Hubble Diagram of SNIa up to redshift ~5

Perfect match with SNIa in the common redshift range

At high z, a strong tension with the flat ΛCDM model builds up

THE L_X-L_{UV} RELATION



Risaliti&Lusso19

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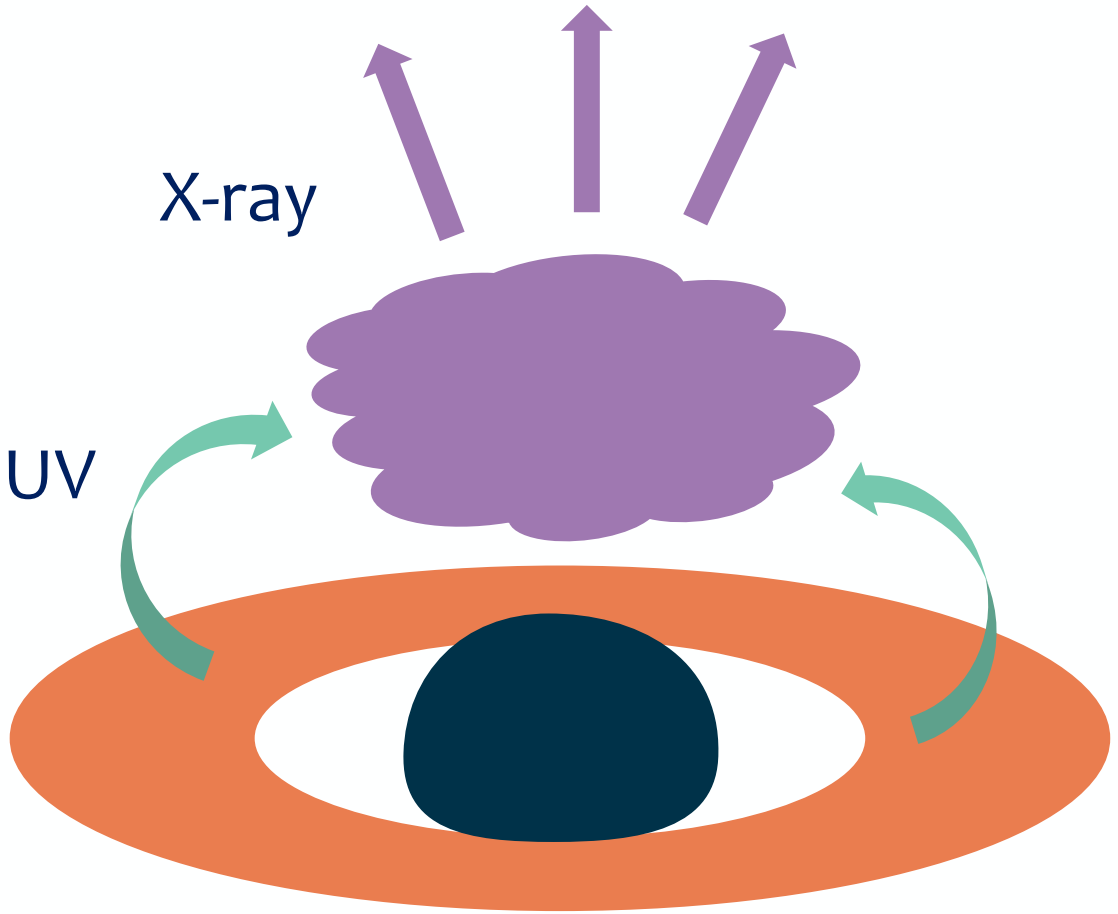
Perfect match with SNIa in the common redshift range

At high z, a strong tension with the flat ΛCDM model builds up

cosmographic fits of the Hubble Diagram (Bargiacchi+21, Giambagli+21)

Test alternative cosmological models (Biargiacchi+22)

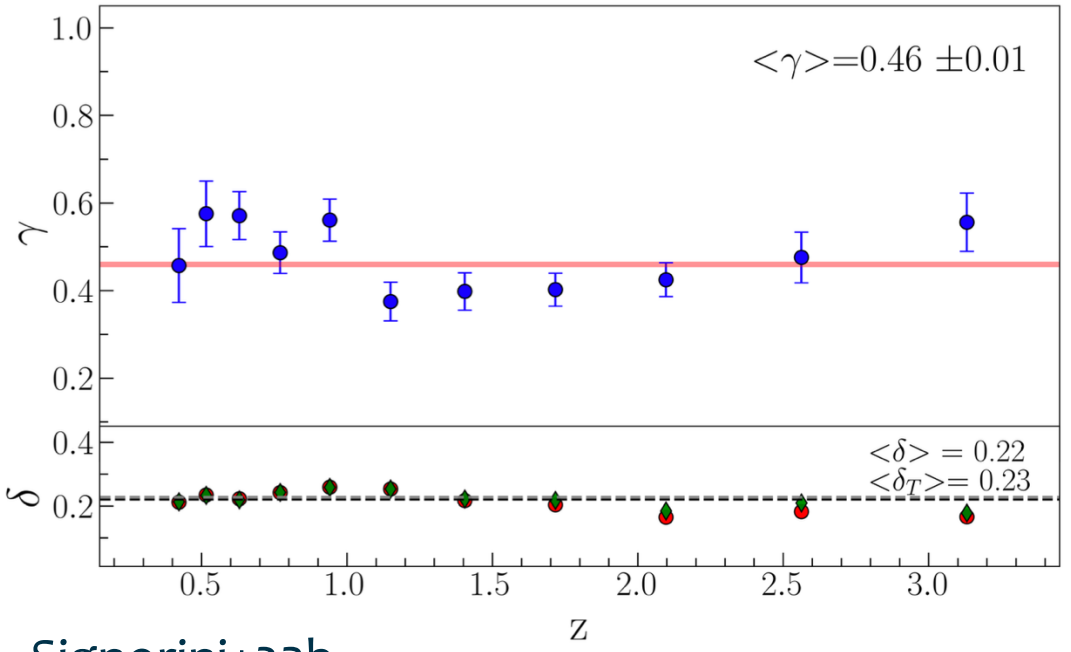
THE L_X-L_{UV} RELATION



We know a relation between the accretion disc and the X-ray Corona must exist, but we do not know the exact mechanism

By studying the relation for cosmology, we get insights on th ephysics!

THE L_X-L_{UV} RELATION

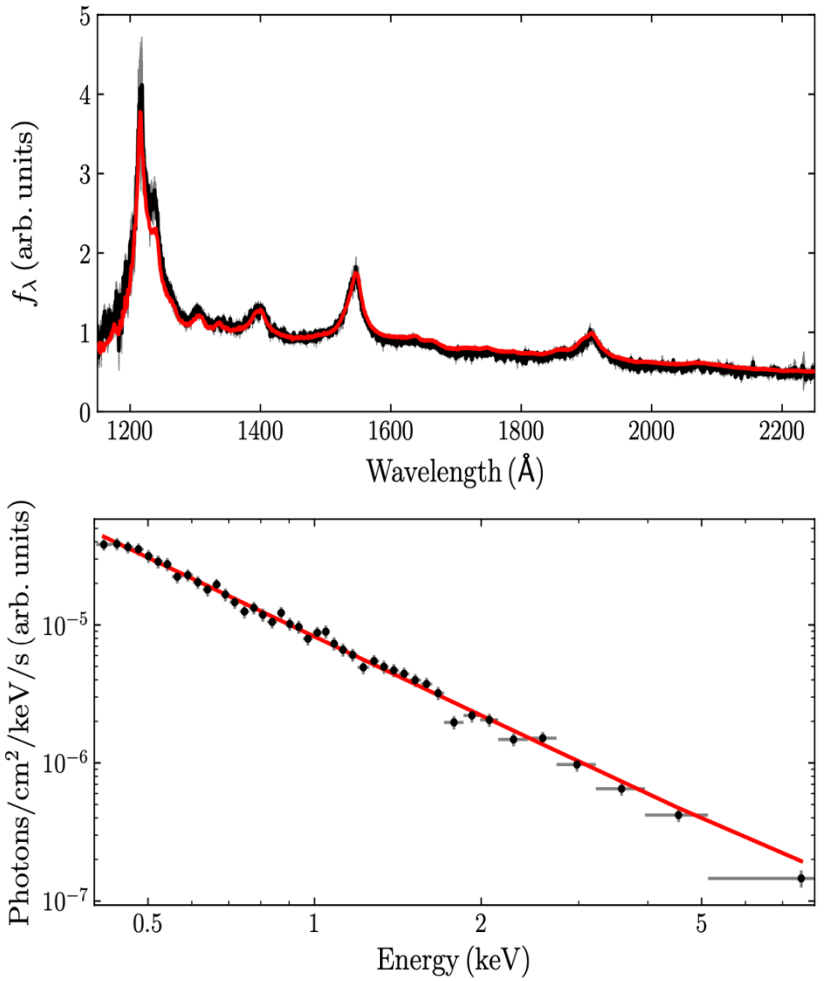


Signorini+23b

What have we learned in recent years?

- The slope parameter does not change with the redshift (Lusso+17, Risaliti+19, Signorini+23b)
- The spectral shape of both the UV and the X-ray side does not evolve with redshift (Sacchi+22, Trefoloni+24)
- The intrinsic dispersion of the relation must be very low, below 0.06 dex (Sacchi+22, Signorini+24)

THE L_X-L_{UV} RELATION

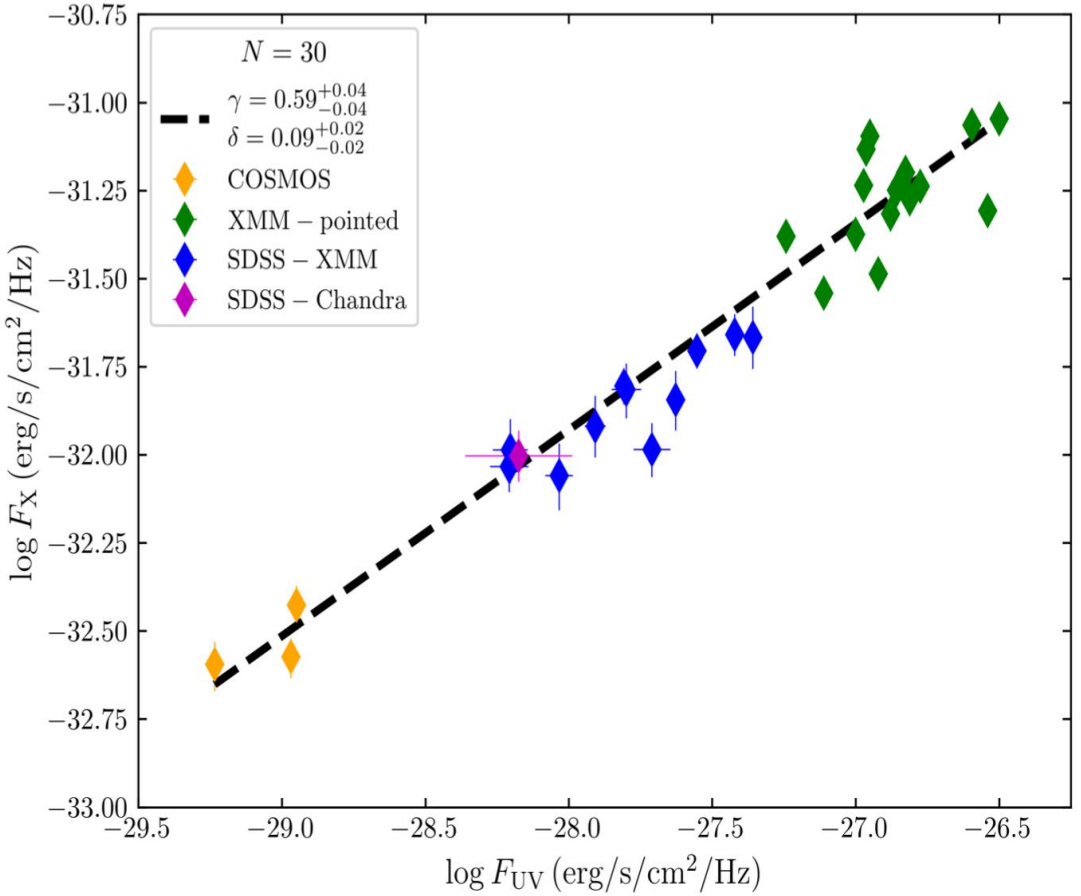


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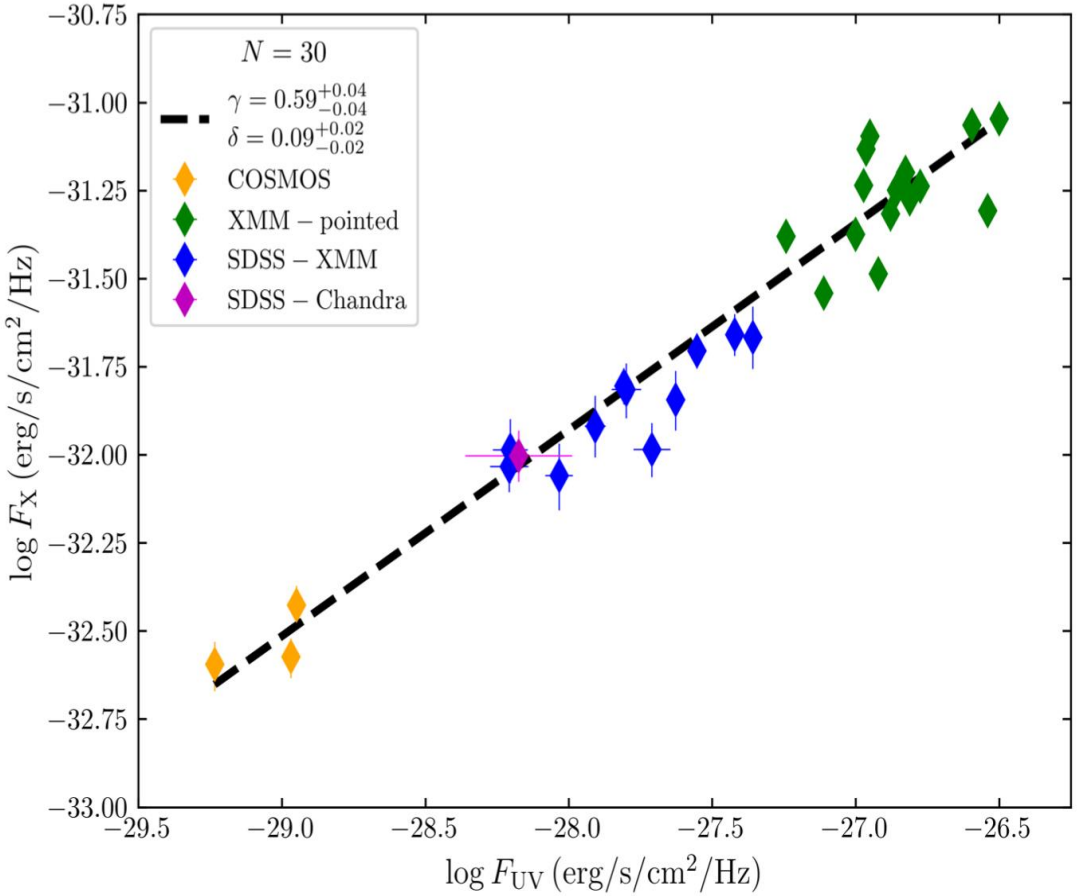


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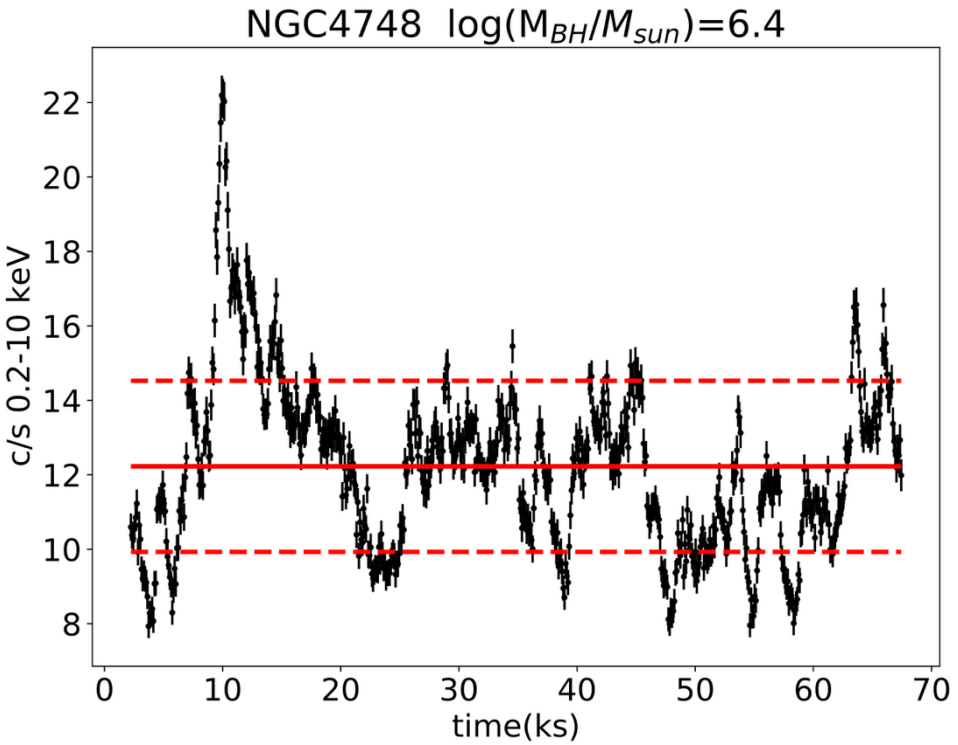
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… new sample in progress!

X-RAY VARIABILITY



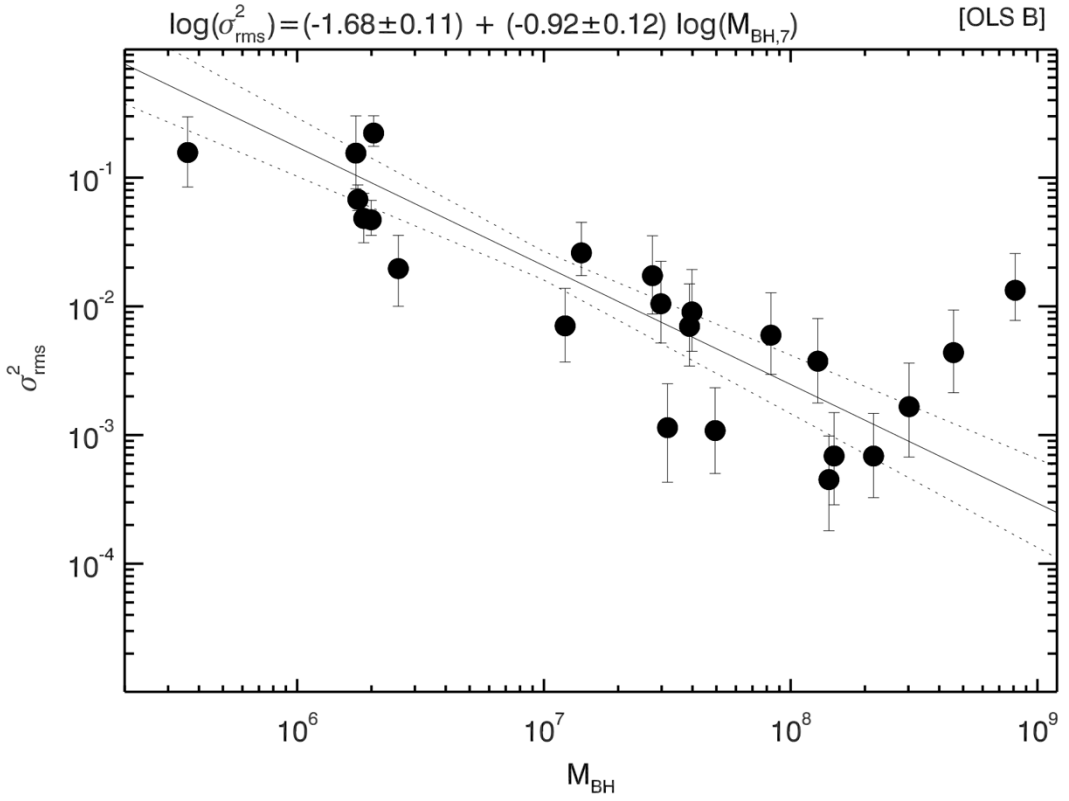
AGN emission is variable at all wavelengths.

In the X-ray, the timescales can be very small, ~100s of seconds

Variability is correlated with the MBH and/or the luminosity – can we use it to measure distances?

Tortosa+23

X-RAY VARIABILITY



Ponti+12

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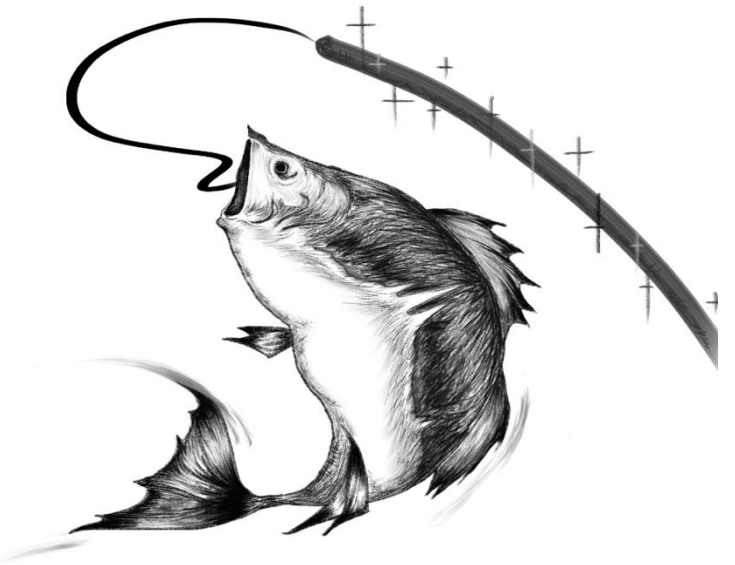
X-RAY VARIABILITY

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

Continuum and 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 – arXiv 2409.12239)



X-RAY VARIABILITY

BASS sample

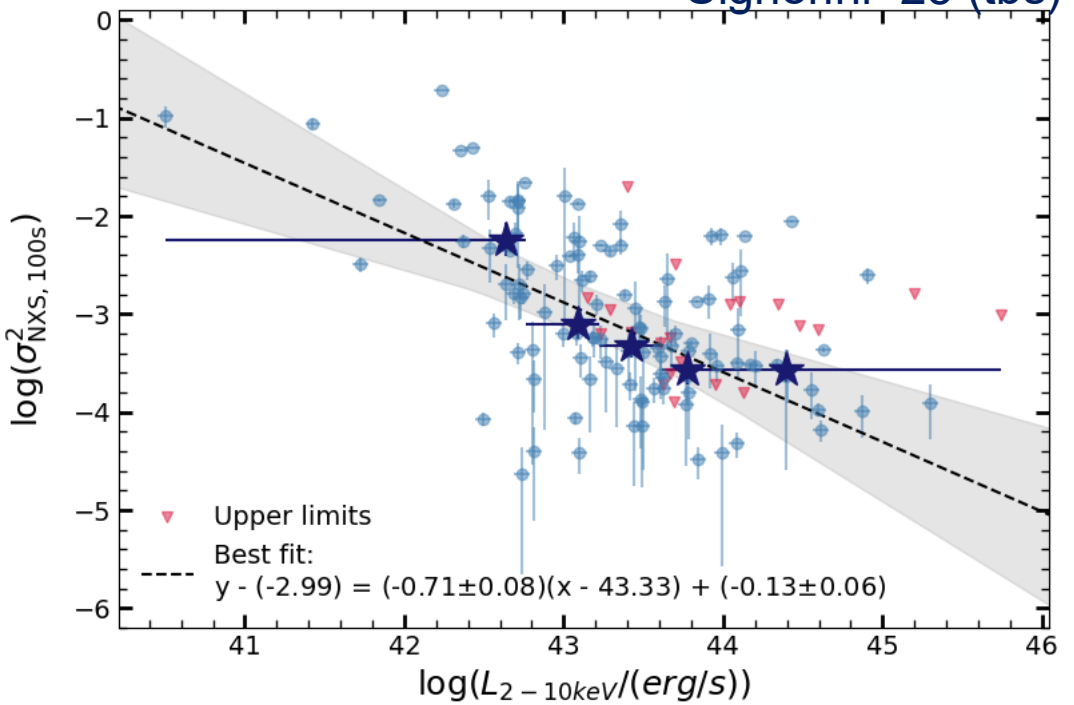
Significant relation between excess variance and luminosity

However, the scatter δ~0.75 dex is too high for a cosmological implementation

We are looking for way to lower the dispersion by including broad-line information

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

Signorini+25 (tbs)

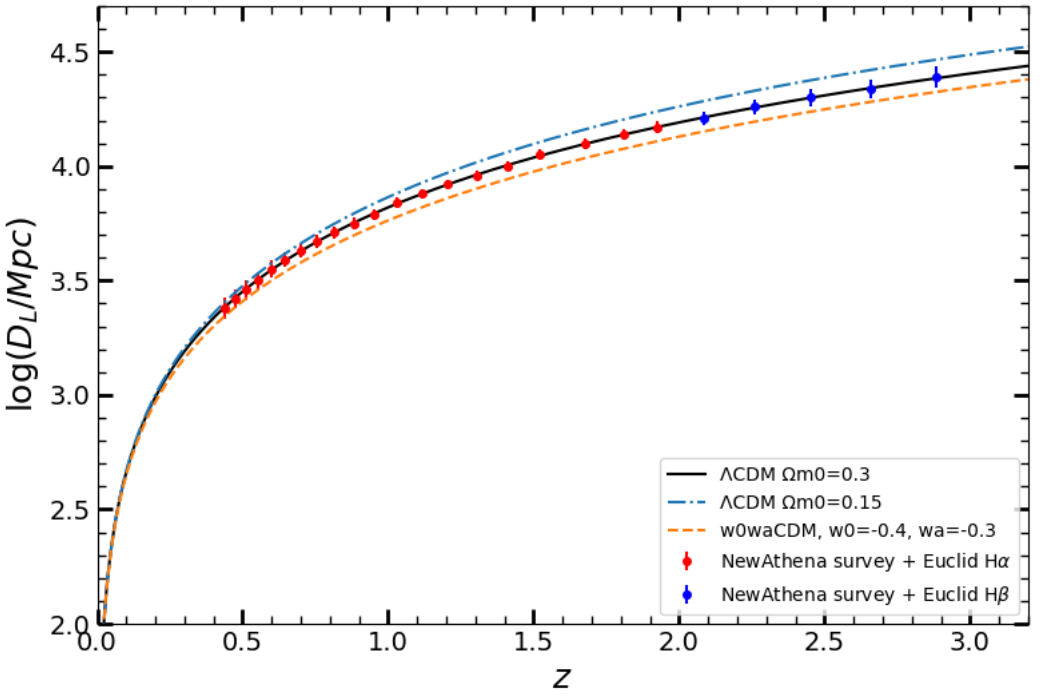


X-RAY VARIABILITY

Signorini+25 (tbs)

In the future, the combination of the Euclid telescope with new X-ray telescopes (AXIS, NewAthena) will give us thousands of objects with X-ray excess variance & broad line measurements

Using them, we can populate the Hubble-Lemaître diagram from z~0.42 to z~3, and constrain variability properties across all redshifts!



H_0 WITH AGN

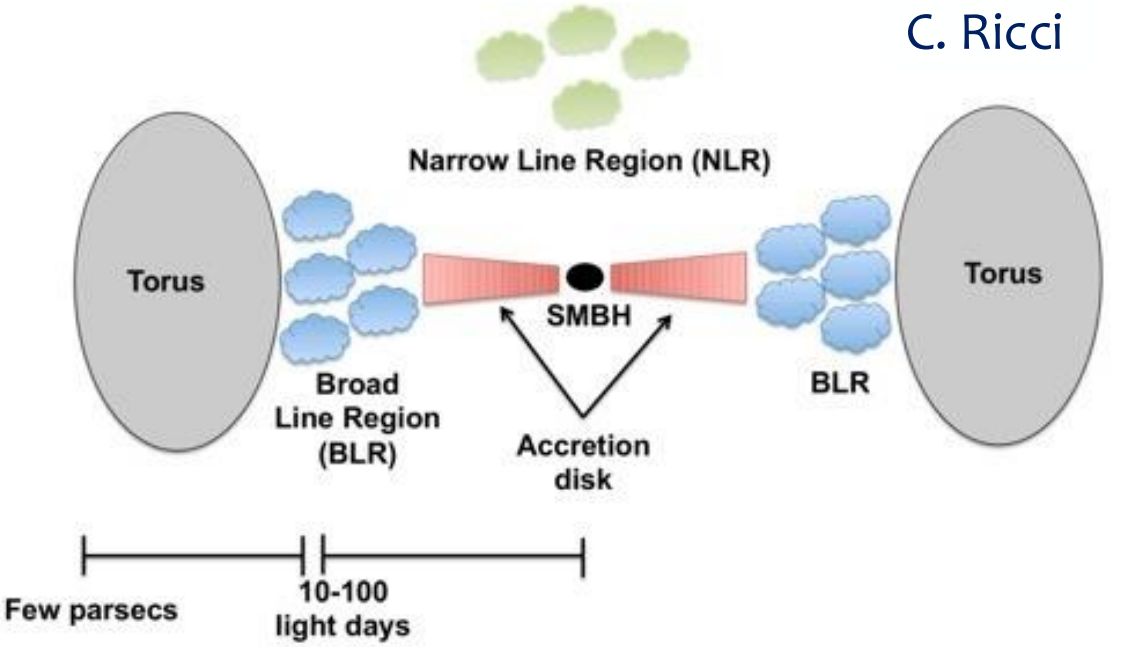
The L_X-L_{UV} relation and the variability correlation can not constrain H_0, as we need SNIa to build the AGN "distance ladder"

H_0 WITH AGN

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Can we use AGN as "standard rulers" instead?

C. Ricci



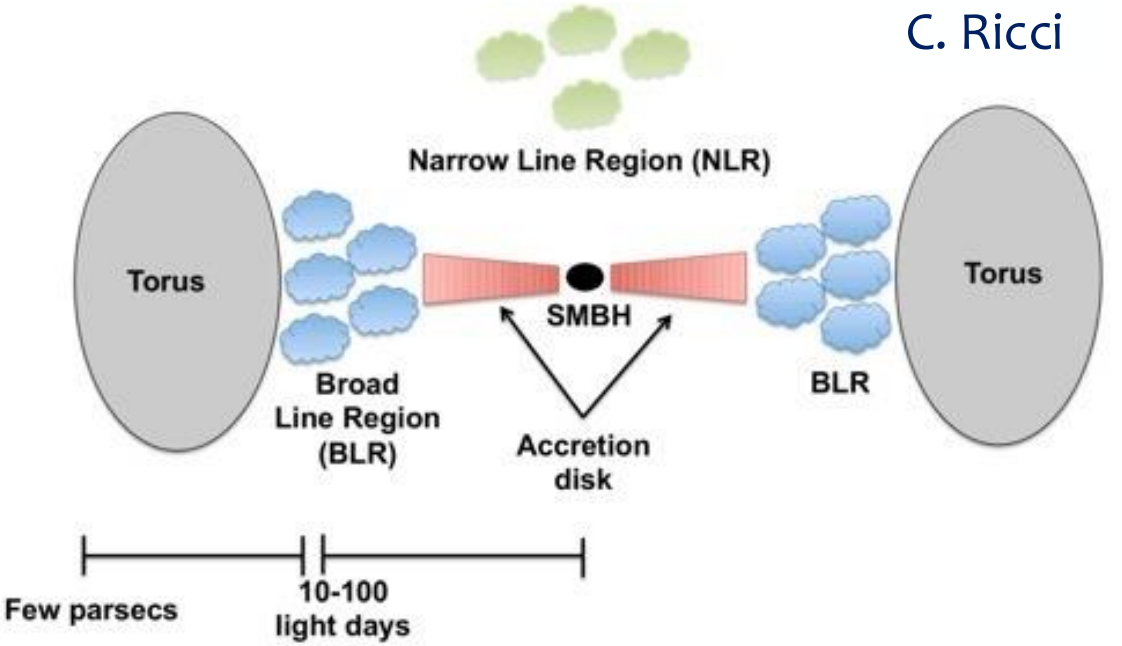
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With GRAVITY we can use interferometry to measure the angular dimension of the Broad Line Region $\Delta\theta$ (~10 objects, GRAVITY collaboration+2024)

C. Ricci

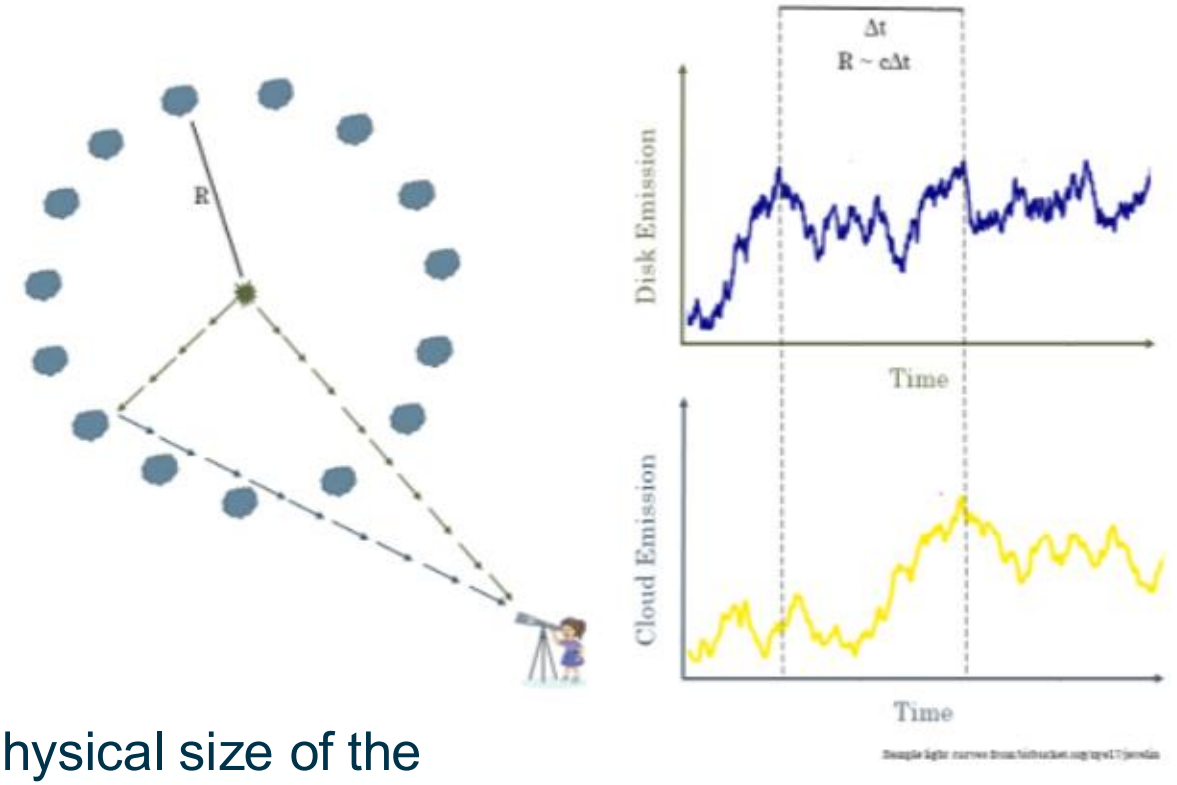


H_0 WITH AGN

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J. Hoorman

Reverberation Mapping uses monitoring to derive the physical size of the BLR ΔR - see **Dr. Lizvette Villafaña AGN coffee talk on Thursday!**

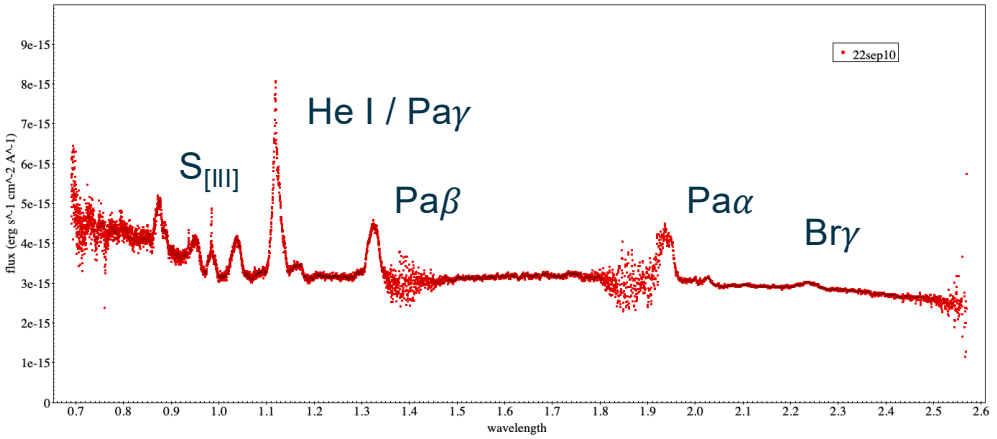
Combining them, we find the angular distance $D_A = \Delta R / \Delta\theta$ independently from any calibration and, from that, H_0

H_0 WITH AGN

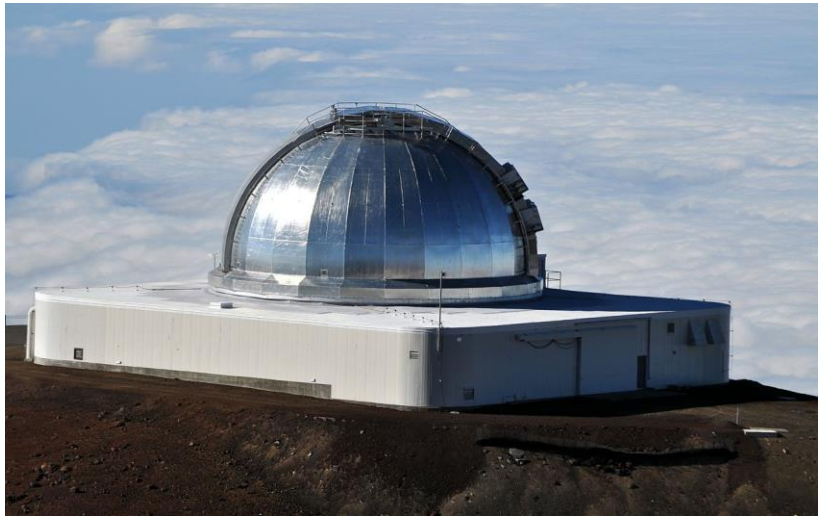
4 objects, Li+25
$H_0 = 69^{+12}_{-10}$ km s^{-1} Mpc^{-1}

but do Infrared (Paα, Brγ) from GRAVITY and optical (Hβ) from RM probe the same region?

We are currently working on Infrared Reverberation Mapping campaigns to figure it out – stay tuned!



Ark120
z = 0.032713





CONCLUSIONS

- AGN are powerful sources observed over a wide redshift range, which makes them interesting as cosmological probes
- They are not standard candles *per se*, but can be “standardized” using relation between observable quantities
- AGN can also be used as standard rulers by combining GRAVITY and Reverberation Mapping measurements of the Broad Line Region, measuring H_0
- In doing so, we also refine our understanding of the physics of AGN, with a positive feedback in which results on the physics of AGN strengthen the cosmological outcomes

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- They are not standard candles *per se*, but can be “standardized” using relation between observable quantities
- AGN can also be used as standard rulers by combining GRAVITY and Reverberation Mapping measurements of the Broad Line Region
- In doing so, we also refine our understanding of the physics of AGN, with a positive feedback in which results on the physics of AGN strengthen the cosmological outcomes

THANK YOU!