QUASARS AS STANDARD(IZABLE) CANDLES

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INTRODUCTION









INTRODUCTION



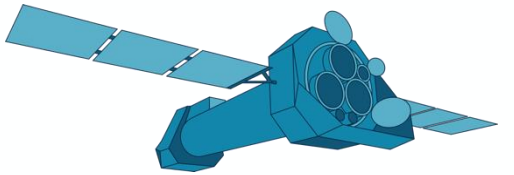
European Space Agency– Noordwijk, Netherlands



INTRODUCTION

"X-rays to uncover the mysteries of AGN"





European Space Agency– Noordwijk, Netherlands



INTRODUCTION

"X-rays to uncover the mysteries of AGN"



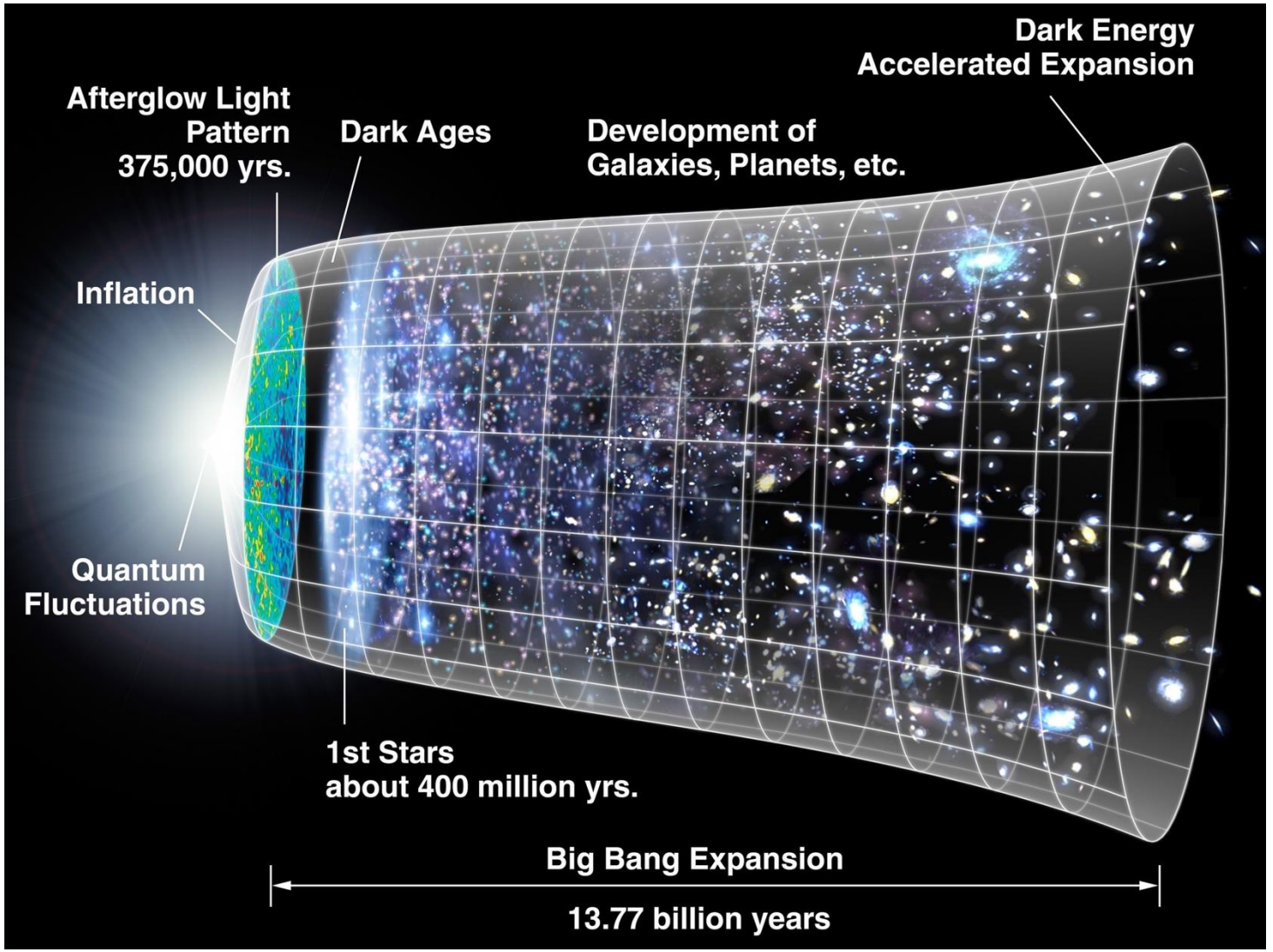
Quasars for cosmology team:
G. Bargiacchi, M. Benetti, S. Capoziello, E. Lusso, E. Nardini, G. Risaliti, A. Sacchi, B. Trefoloni + others

OUTLINE

- What is cosmology?
- Why standard candles?
- What is a quasar?
- Are quasars standard candles?
- If so, what do they tell us about the Universe we live in?



WHAT IS COSMOLOGY?



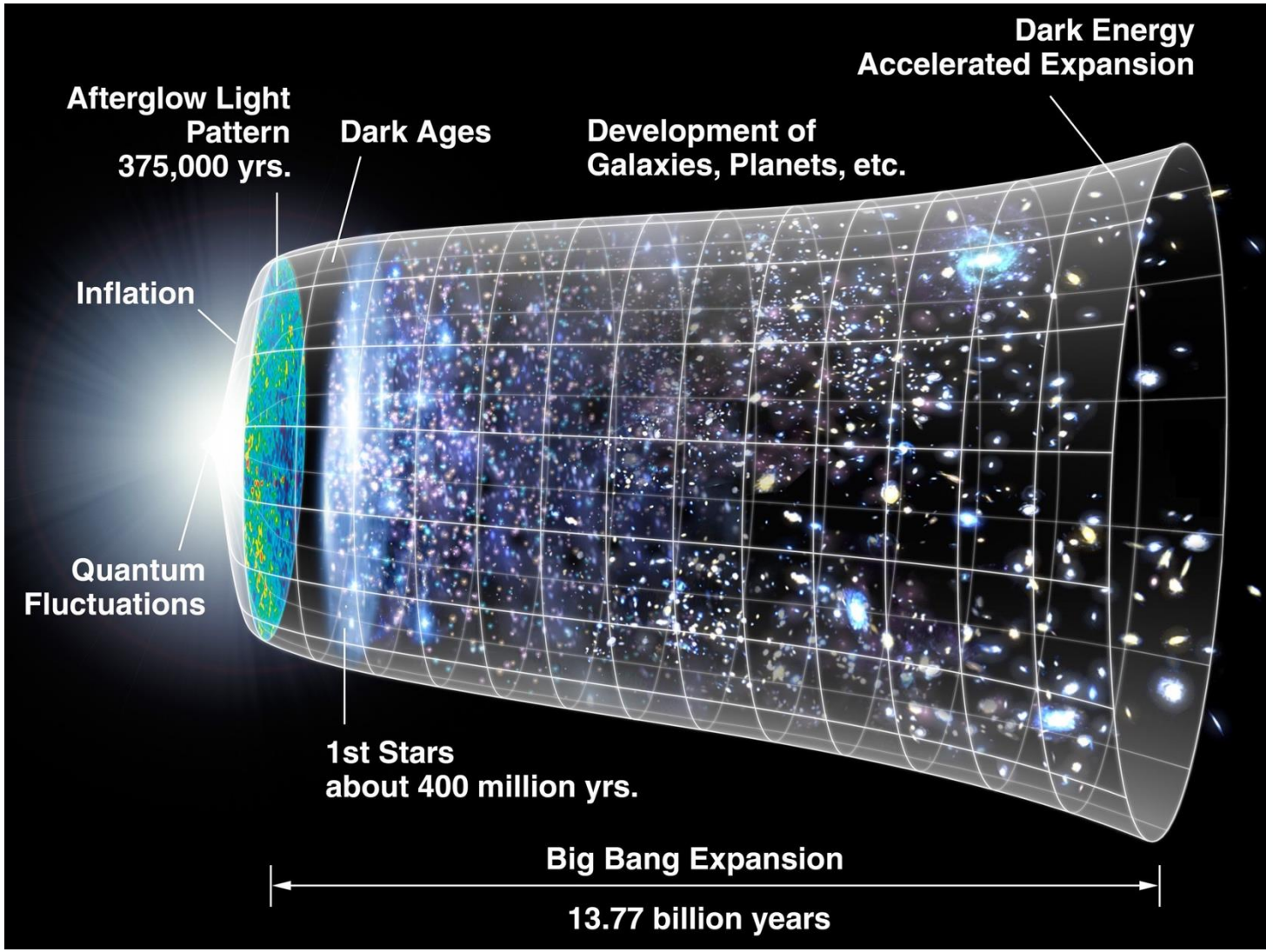
What are the Universe components?

How did they evolve over time?

What is the Universe expansion history?

How did the complex structures we see today form?

WHAT IS COSMOLOGY?



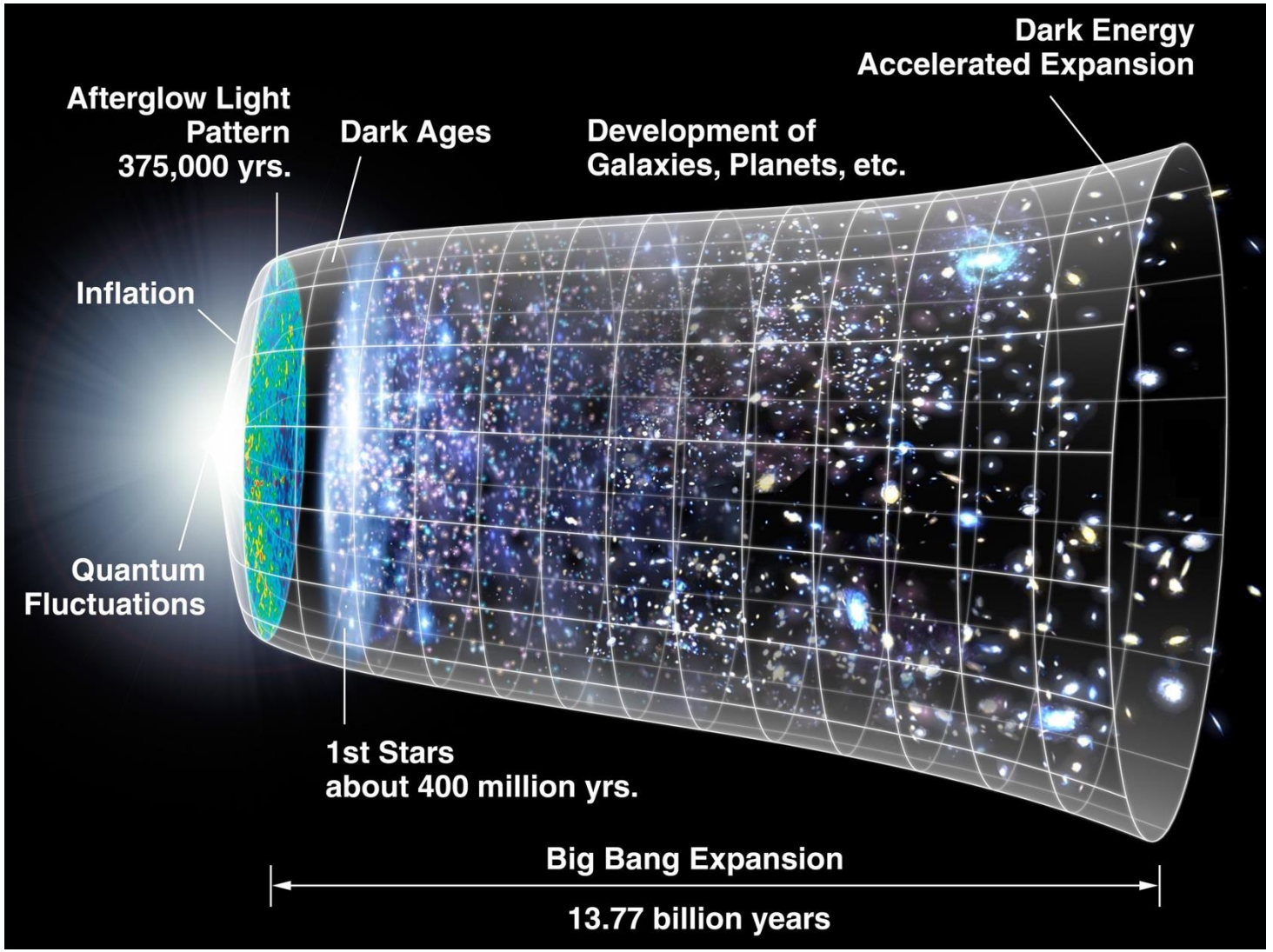
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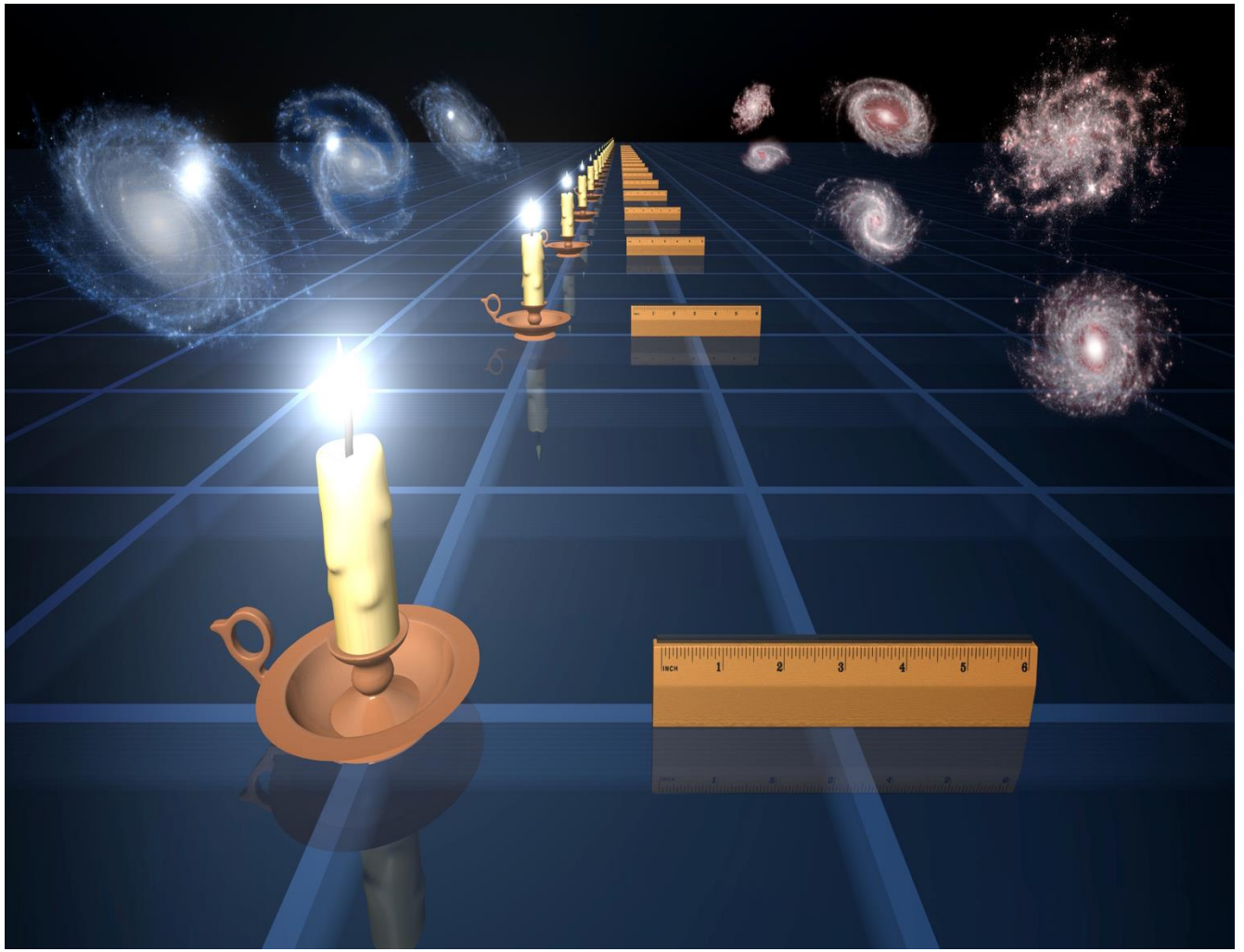


What is the Universe expansion history?

Ingredients

- How far and object is (distance)
- How much it is moving away from us (redshift)

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

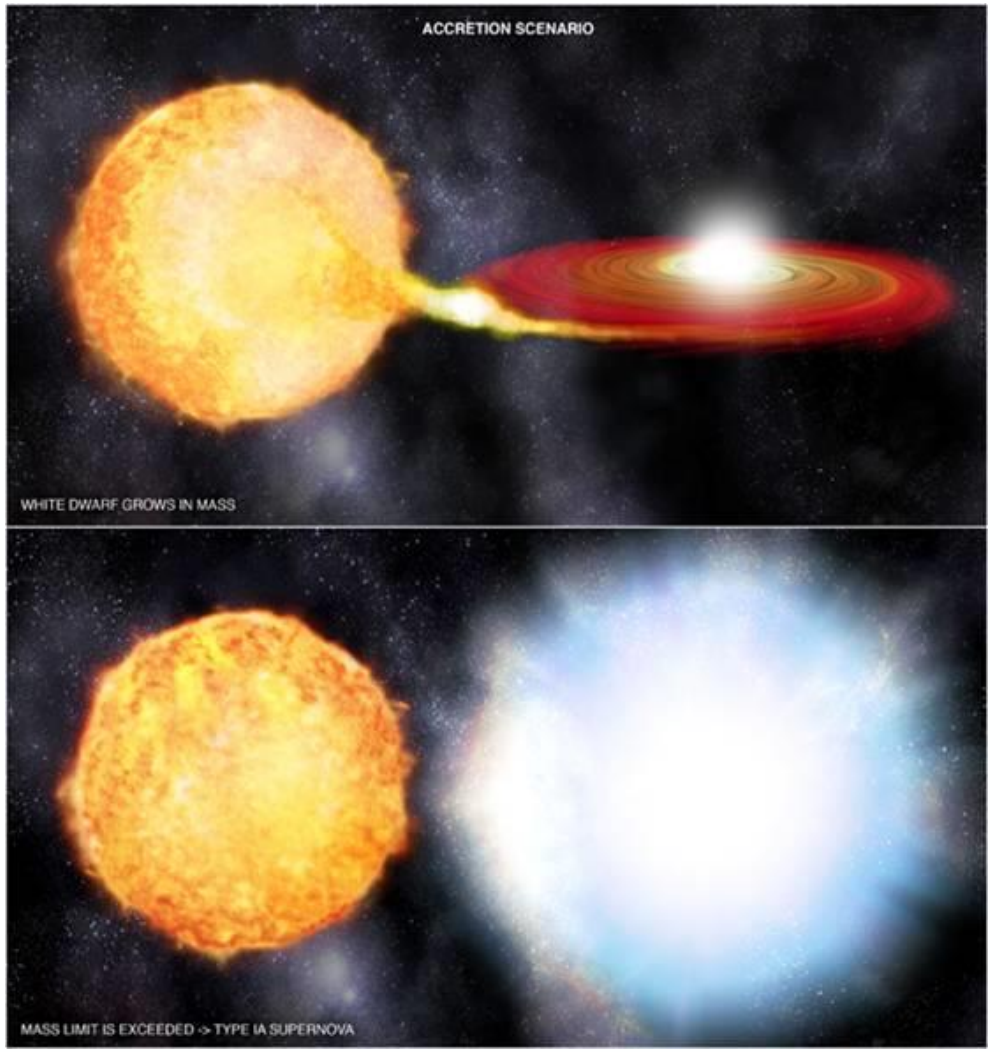
$$F = \frac{L}{4\pi D L^2}$$

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

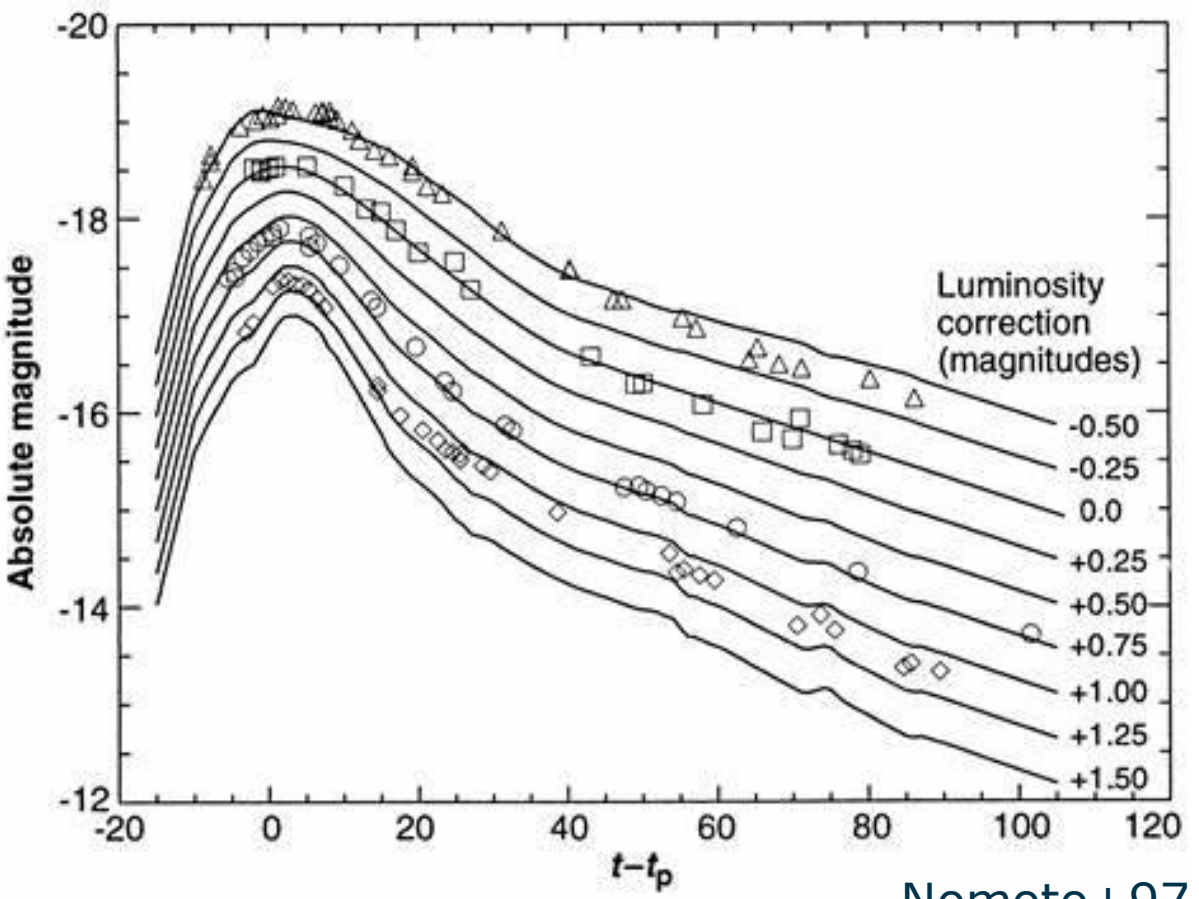
Because the physical process is always the same, the outcome in luminosity is always the same



STANDARD CANDLES

… not exactly

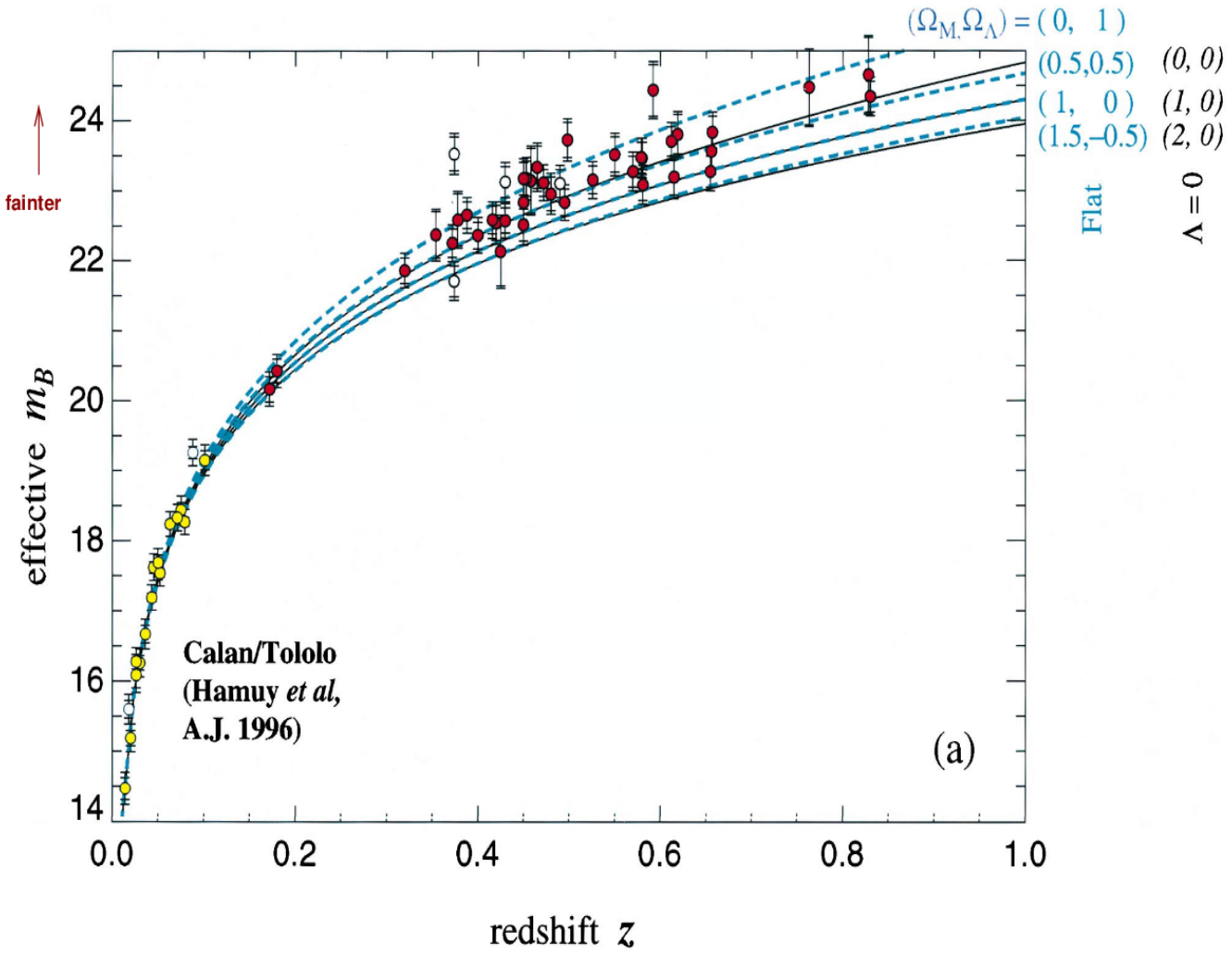
SNIa are *standardizable* candles: we need the Phillip (1993) relation to know their intrinsic luminosity!



Nomoto+97

STANDARD CANDLES

redshift from host galaxy spectrum
+
distance from the Phillips relation
=
distance-redshift (Hubble-Lemaître) diagram

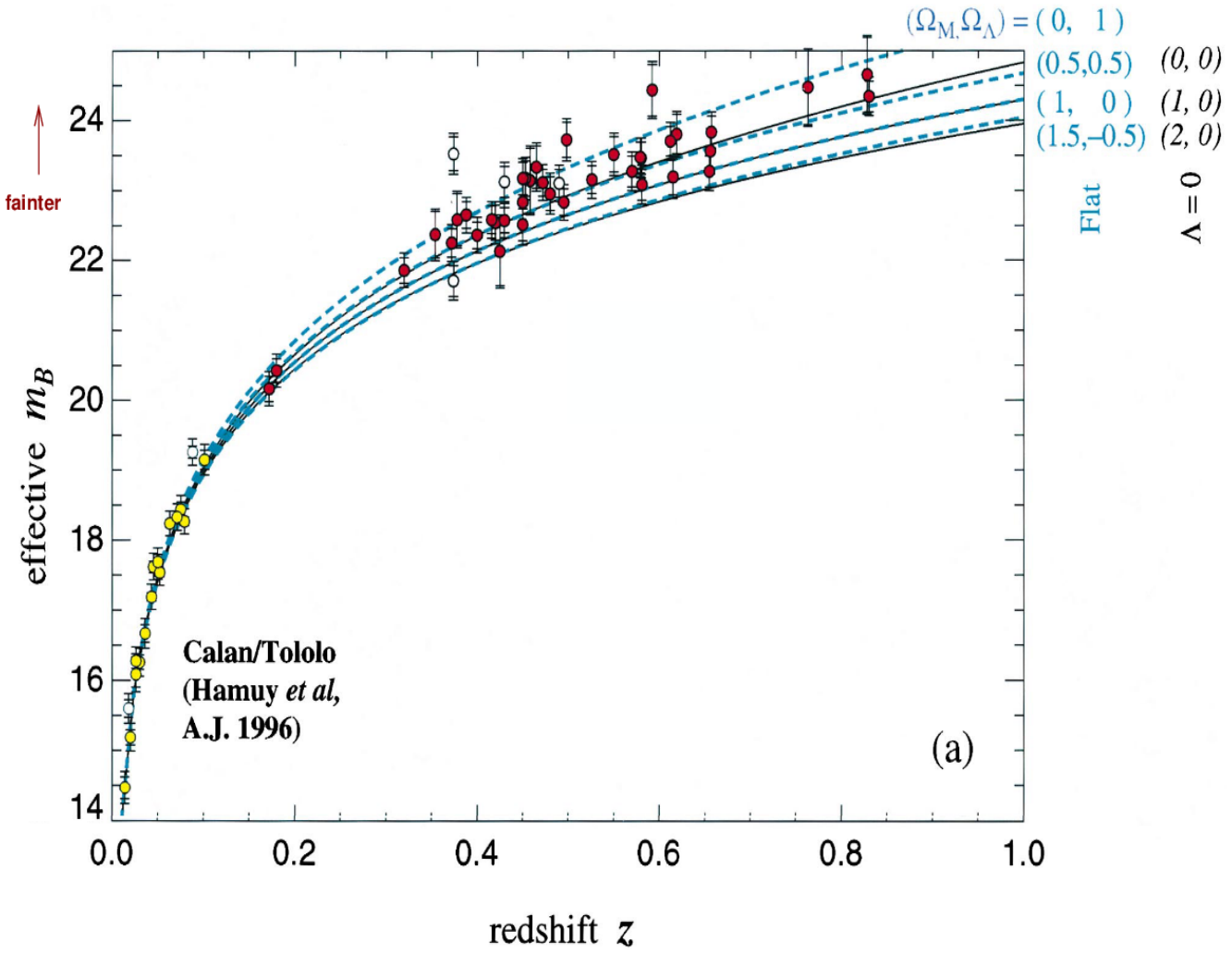


Perlmutter+1998

STANDARD CANDLES

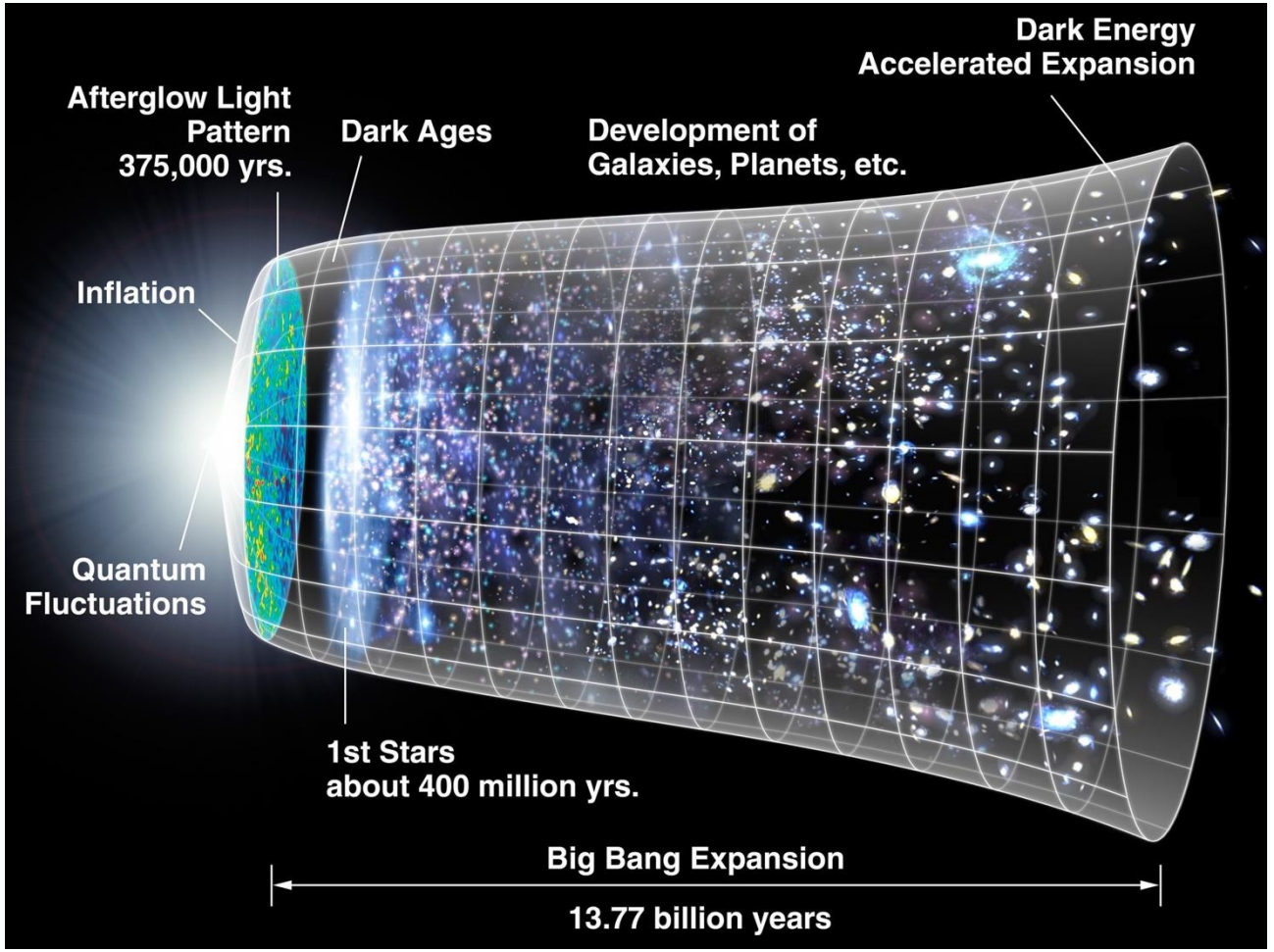
redshift from host galaxy spectrum
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The Universe expansion is accelerating!



Perlmutter+1998

THE ΛCDM MODEL

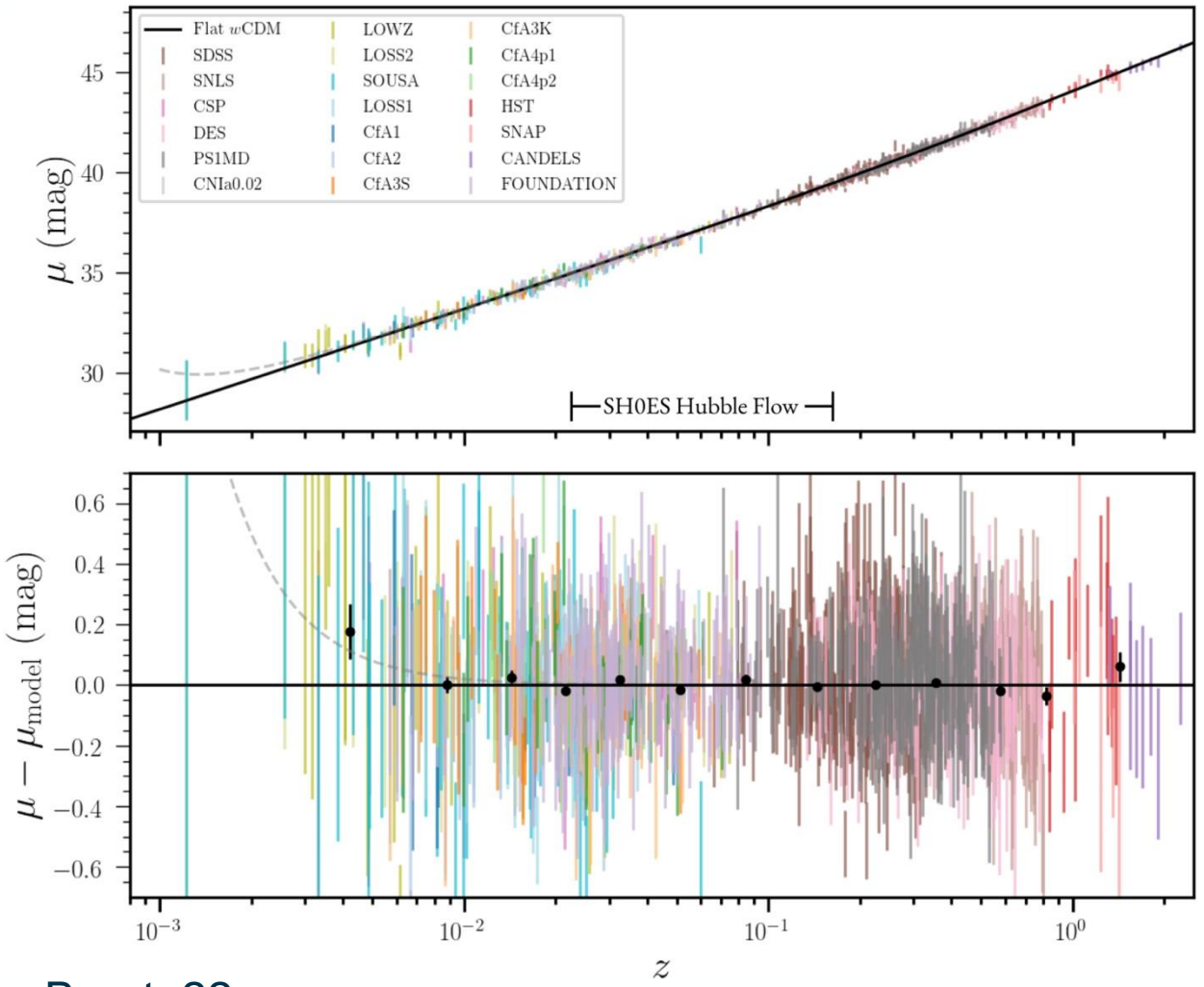


The Universe is made of:

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

$\Omega_\Lambda \sim 0.7$, $\Omega_m \sim 0.3$

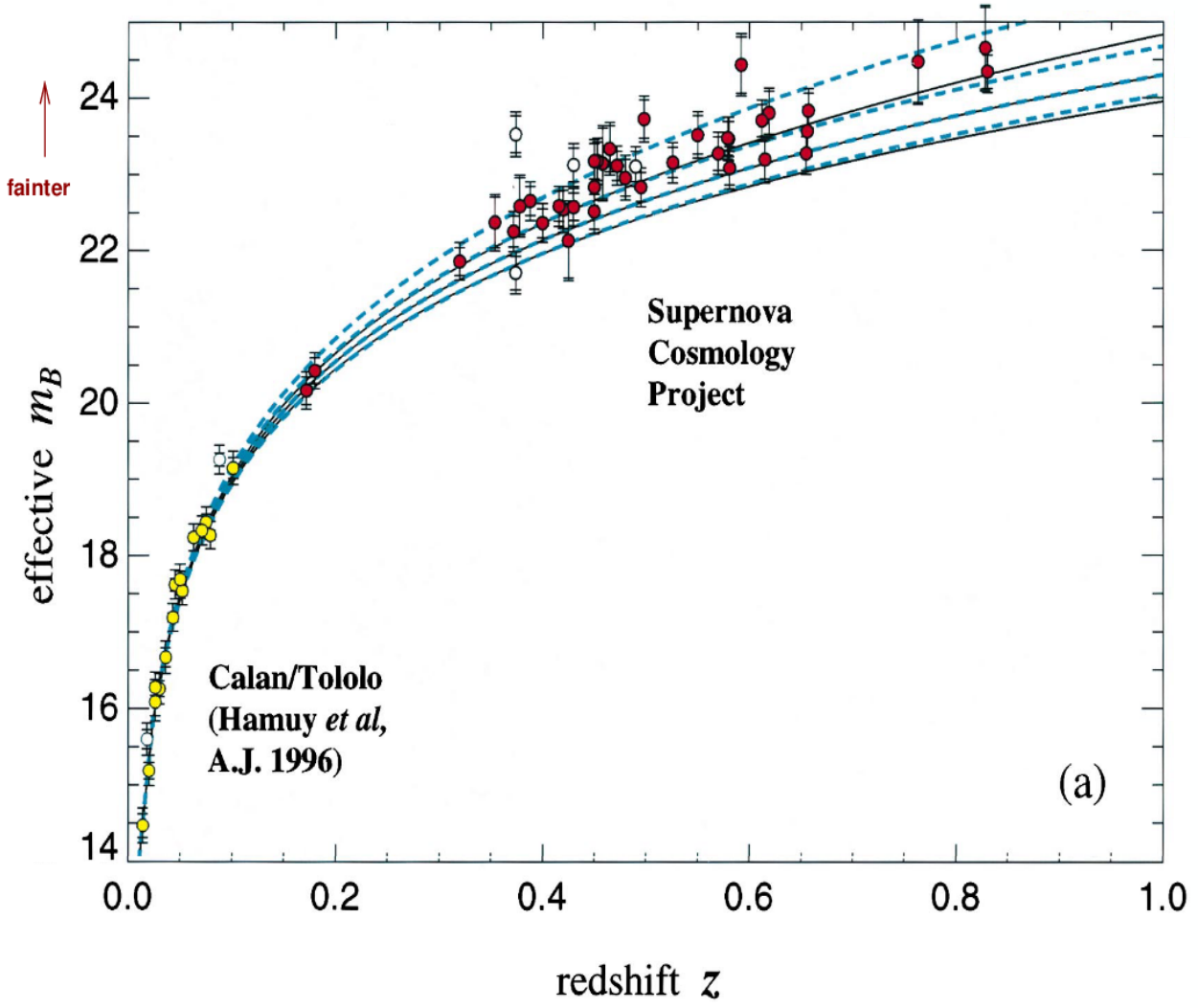
THE ΛCDM MODEL



Brout+22

SNIa are rare at redshift z>1.5 (Universe age:~4 Gyr)

THE ΛCDM MODEL

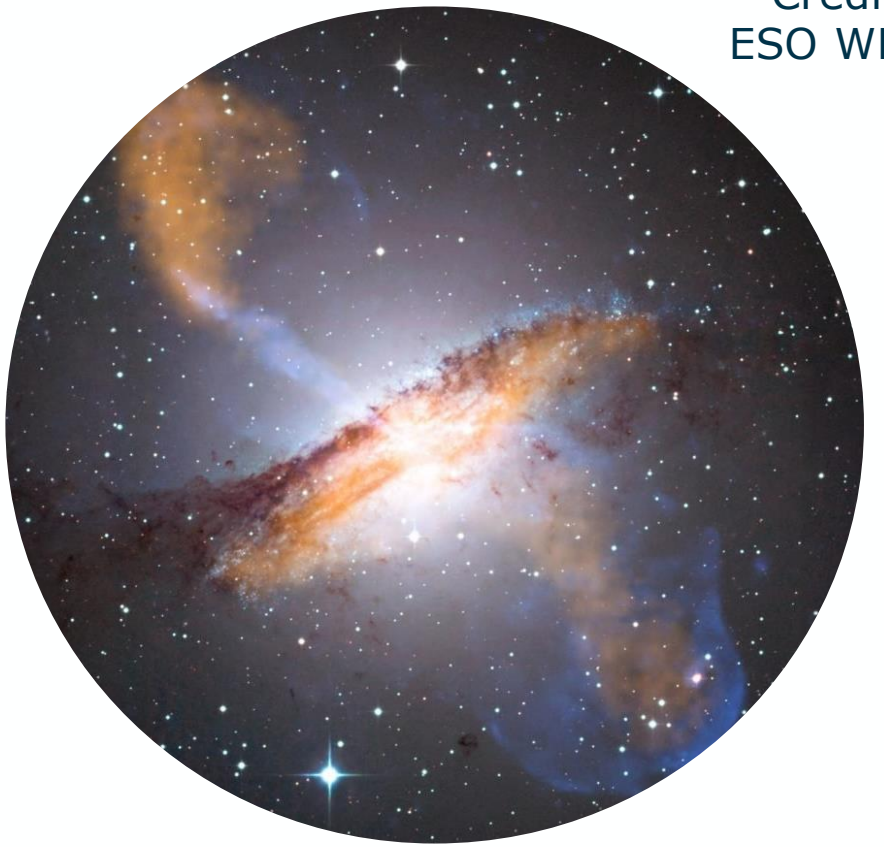


SNIa are rare at redshift z>1.5 (Universe age:~4 Gyr)

but it is easier to distinguish between models at higher z!

QUASARS

NGC5128
Credit:
ESO WFI



Quasars are interesting candidates:

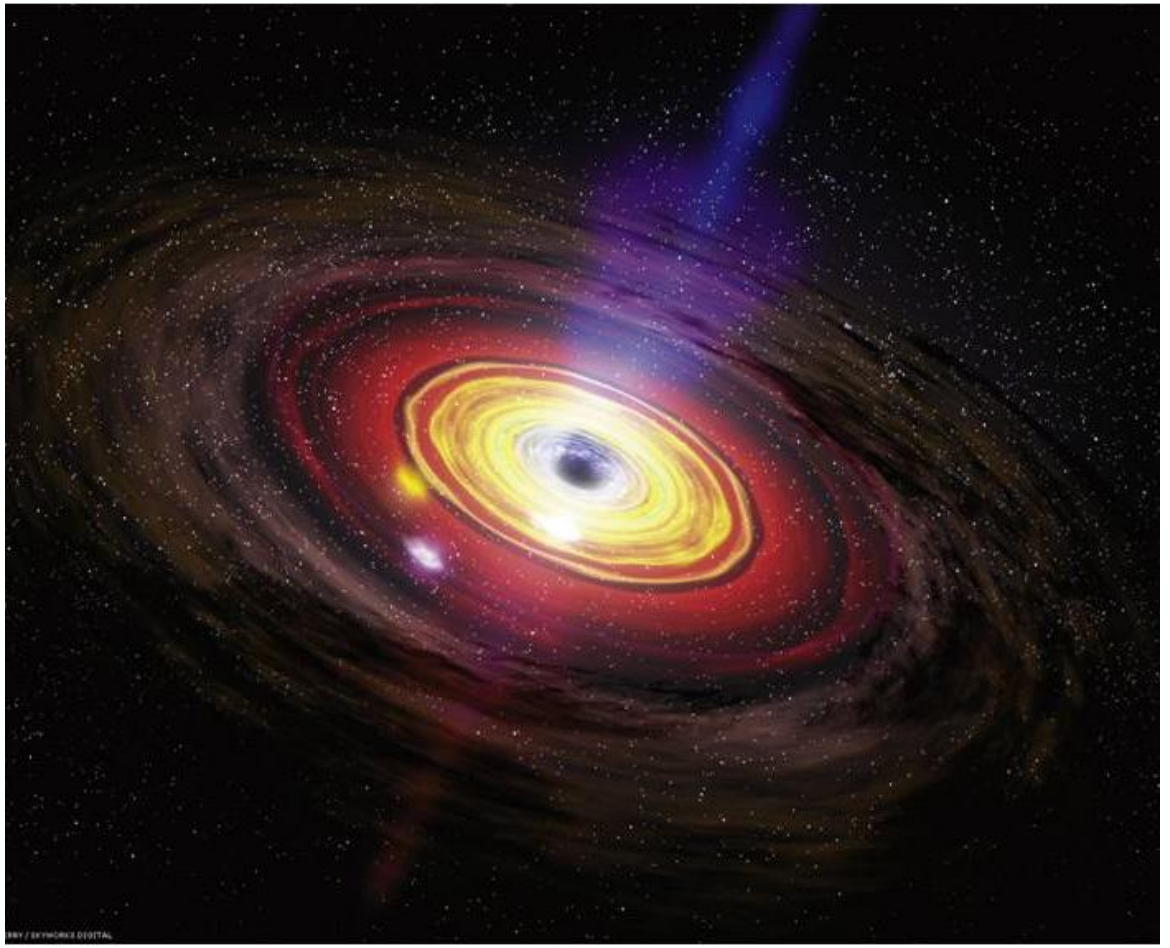
- Very bright (up to 10^{49} erg/s)
- Very numerous
- Observed from low (z~0.001) to high (z>10) redshifts

QUASARS

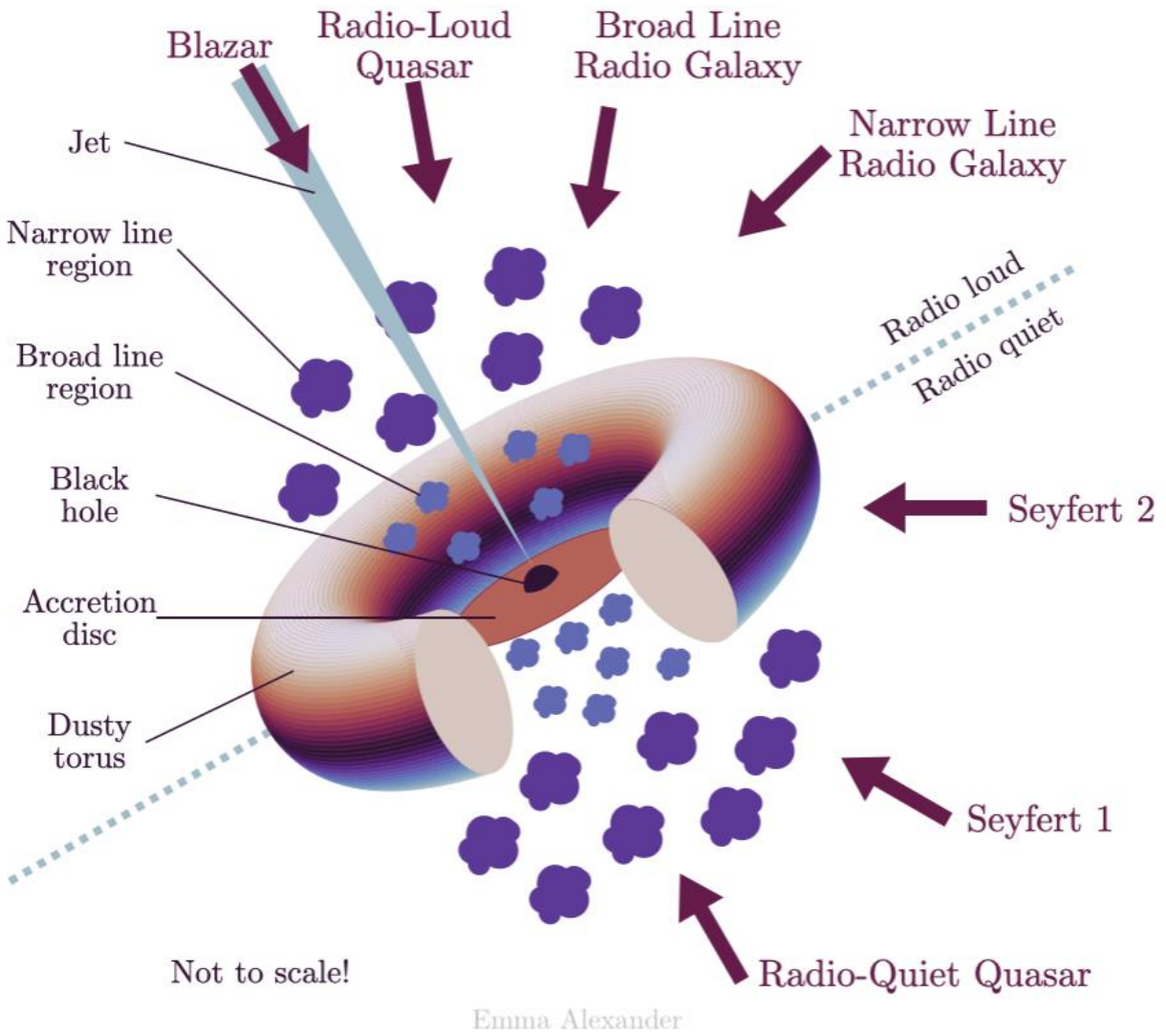
Active Galactic Nucleus (AGN): a galaxy is 'active' when an accretion disc forms around its central Supermassive Black Hole (SMBH, 10^6-10^9 $M_\odot$)

Quasar: AGN in which the nuclear emission exceeds the whole host galaxy emission

Mass-energy conversion: ~6-30%, the most efficient process we know!



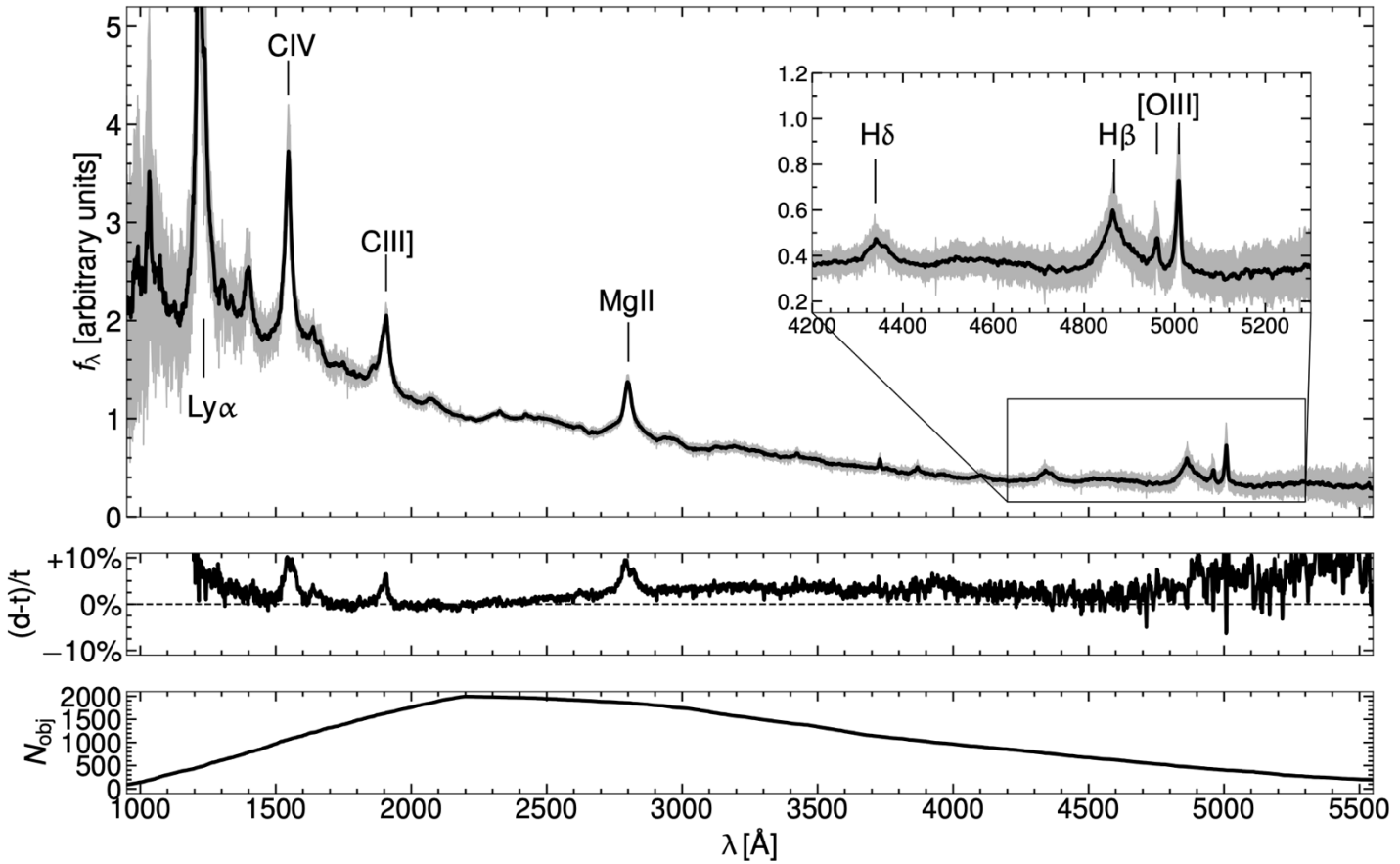
QUASARS



Multi-wavelength emission:

- **Disc**: broadband continuum, peaks in the UV
- **Narrow and Broad Line Region**: IR to UV strong emission lines
- **Dusty torus**: near InfraRed continuum emission
- **Corona**: X-rays
- **Jet**: Radio/X-rays/Gamma

QUASARS

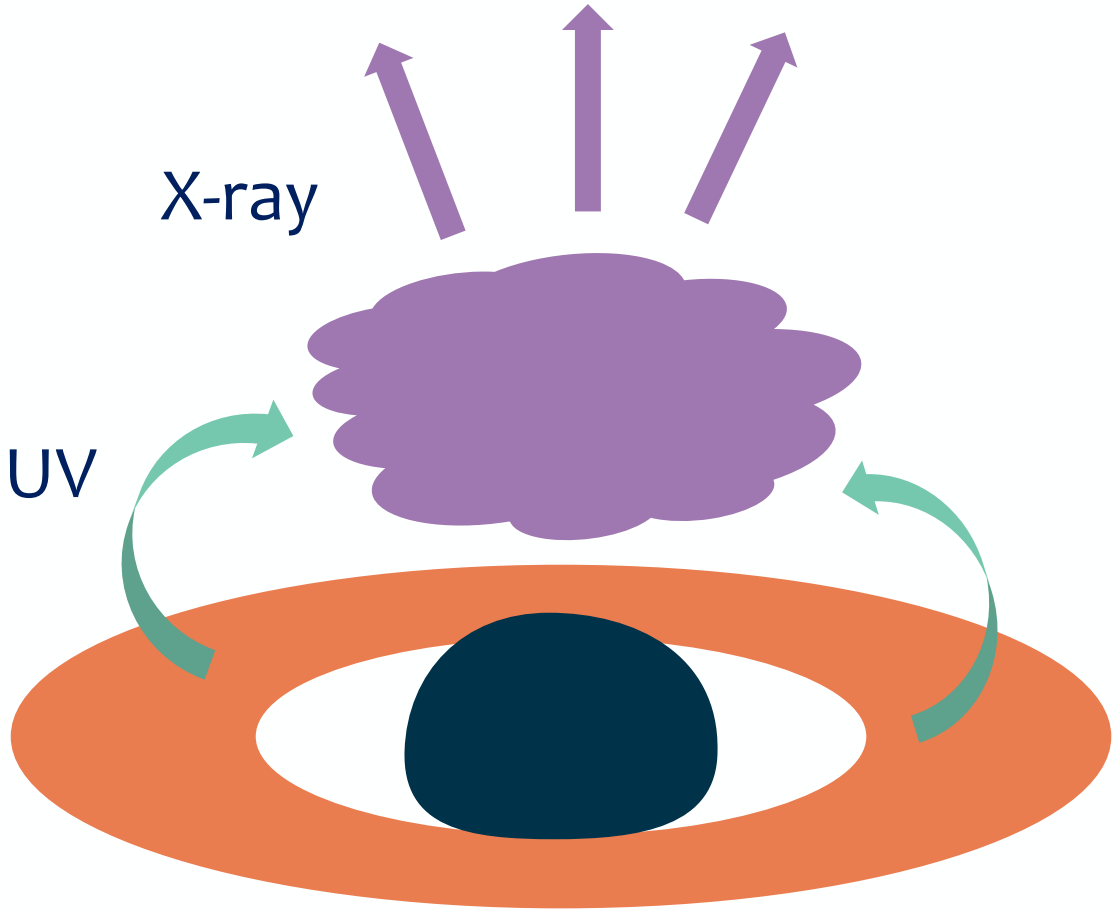


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Trefoloni+24

QUASARS



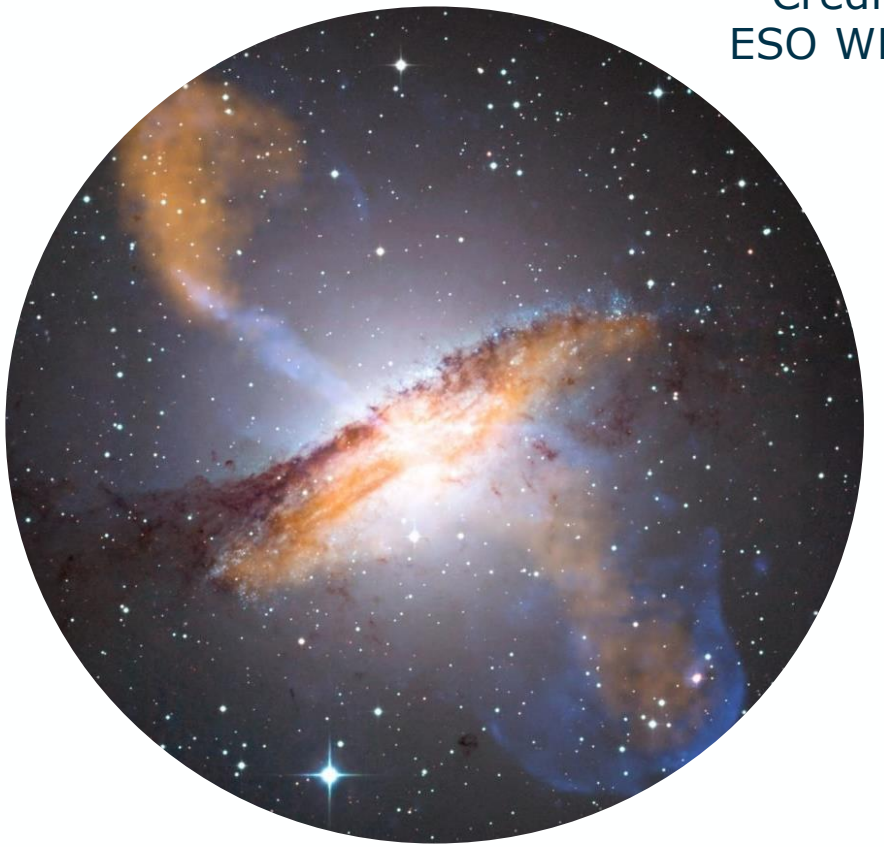
Disc: broadband continuum, peaks in the UV

Corona: X-rays from Inverse Compton scattering of the UV photons from the disc

QUASARS

Quasars are interesting standard candles candidates:

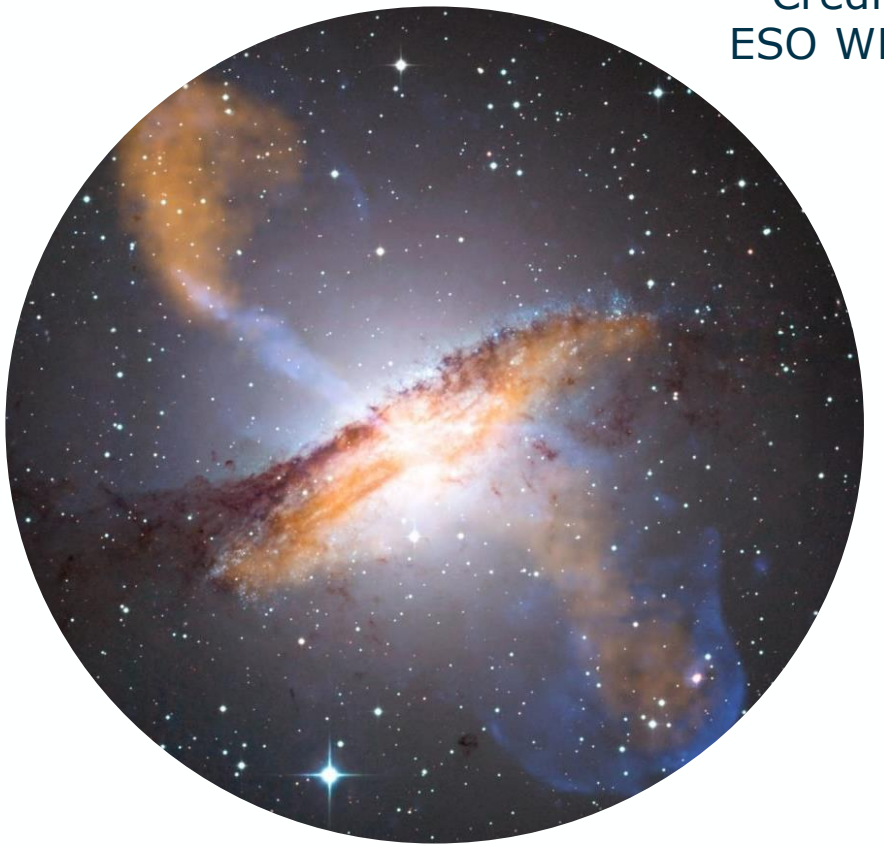
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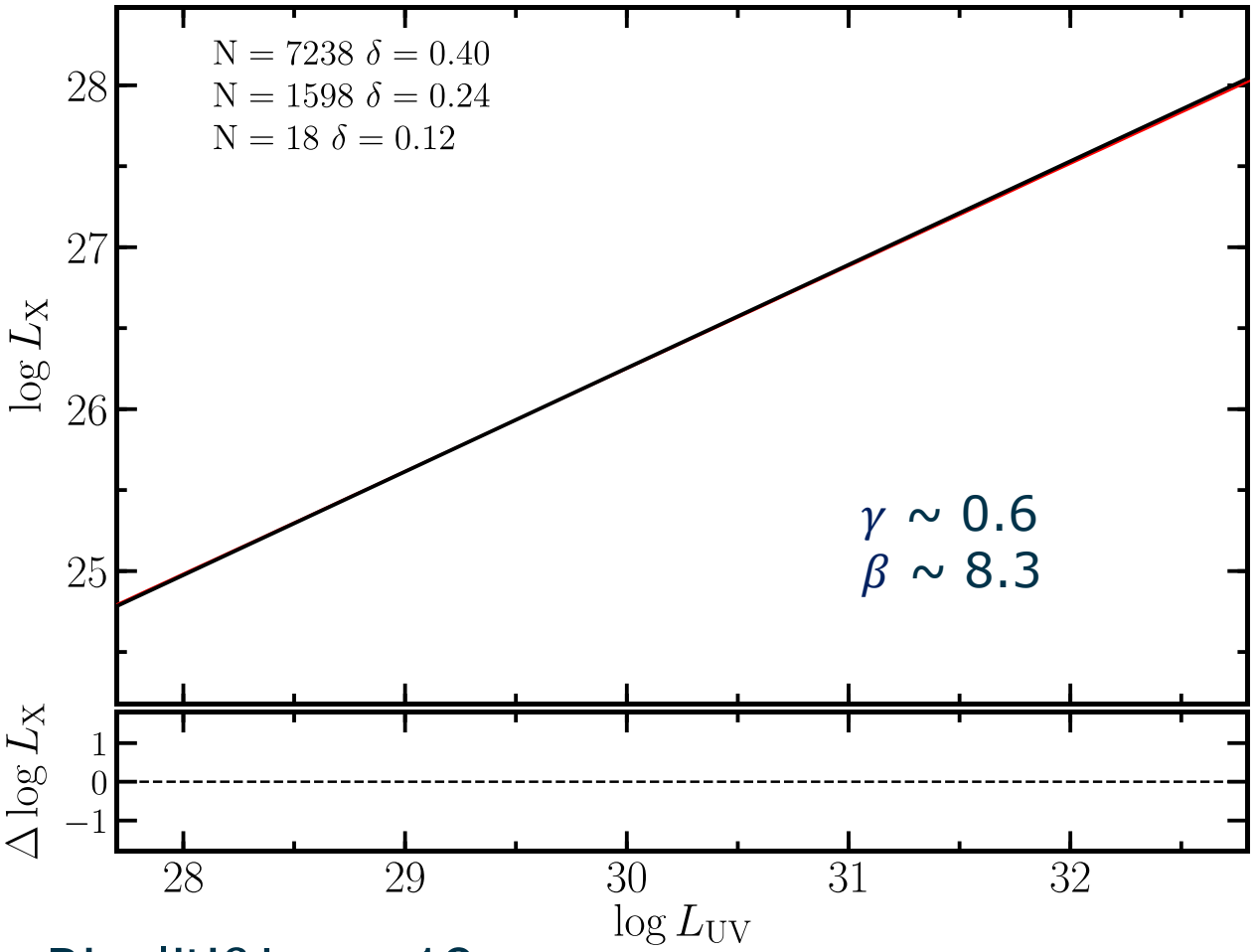


Quasars are interesting standard candles candidates:

- Very bright (up to 10^{49} erg/s)
- Very numerous
- Observed from low (z~0.001) to high (z>10) redshifts

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

THE L_X-L_{UV} RELATION



Risaliti&Lusso19

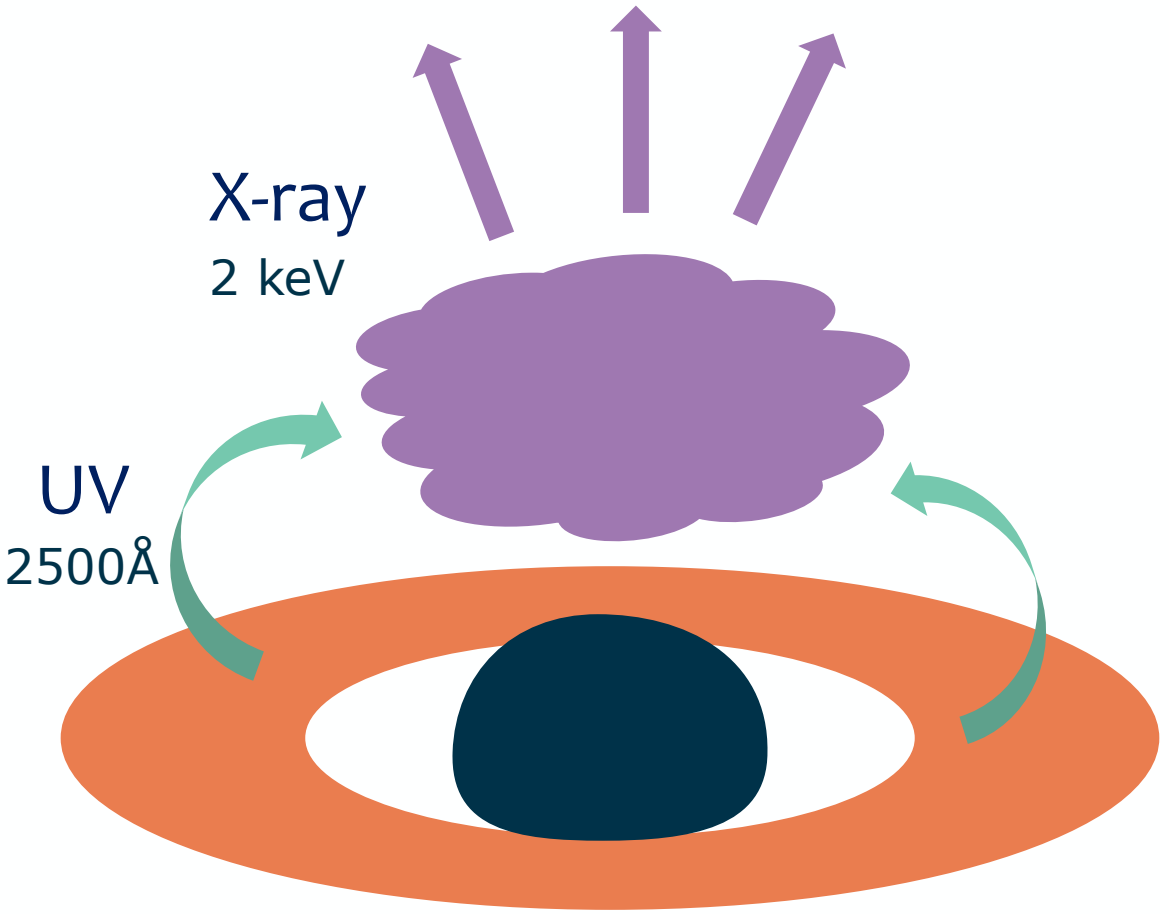
$$\log(L_X) = \gamma \log(L_{UV}) + \beta$$

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

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

Distance measurements!

THE L_X-L_{UV} RELATION



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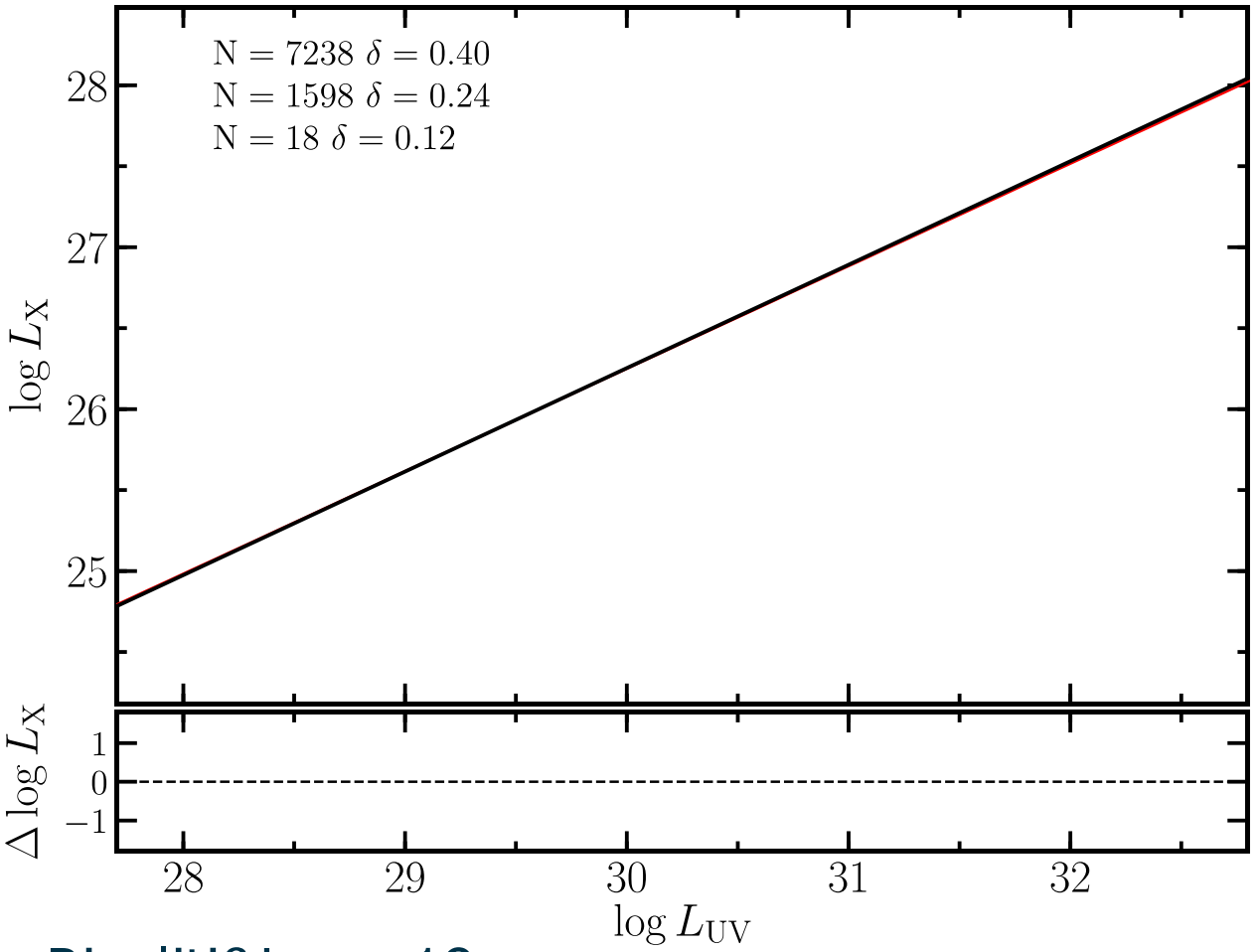
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THE L_X-L_{UV} RELATION

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

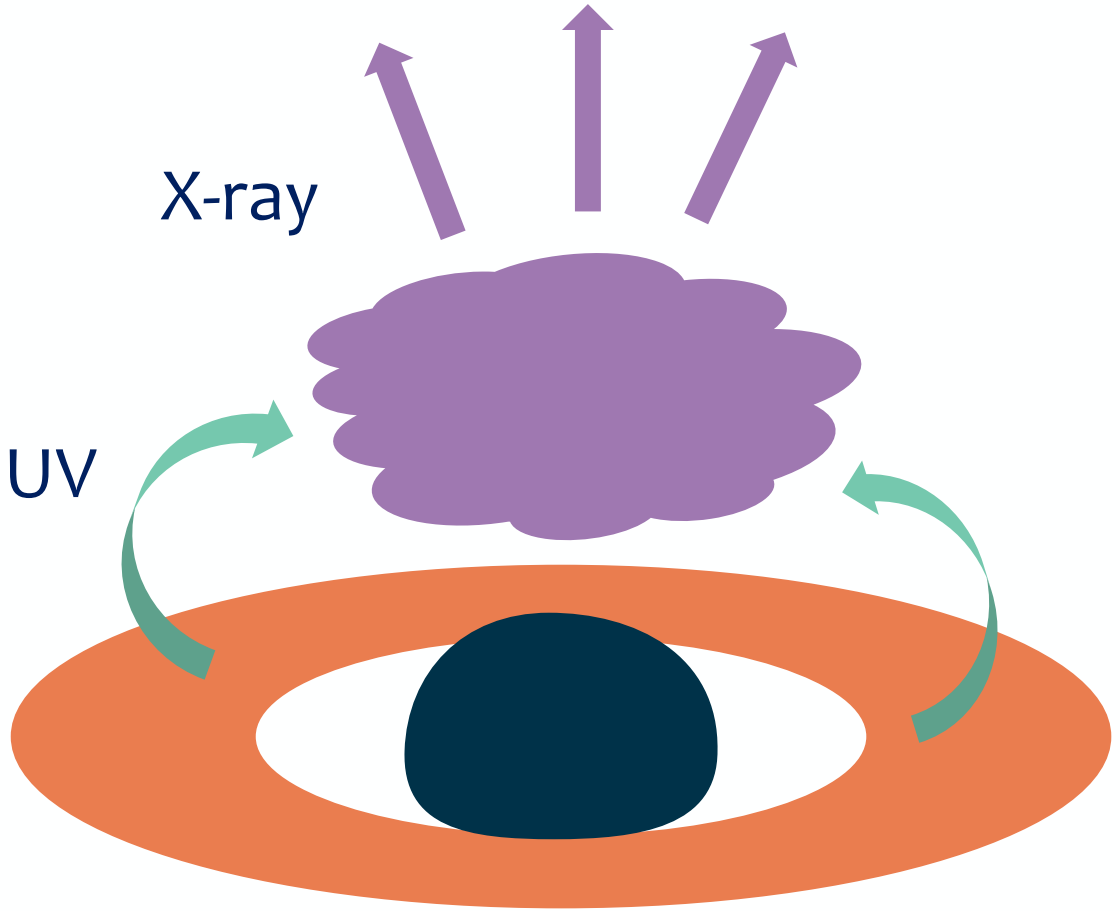


Risaliti&Lusso19

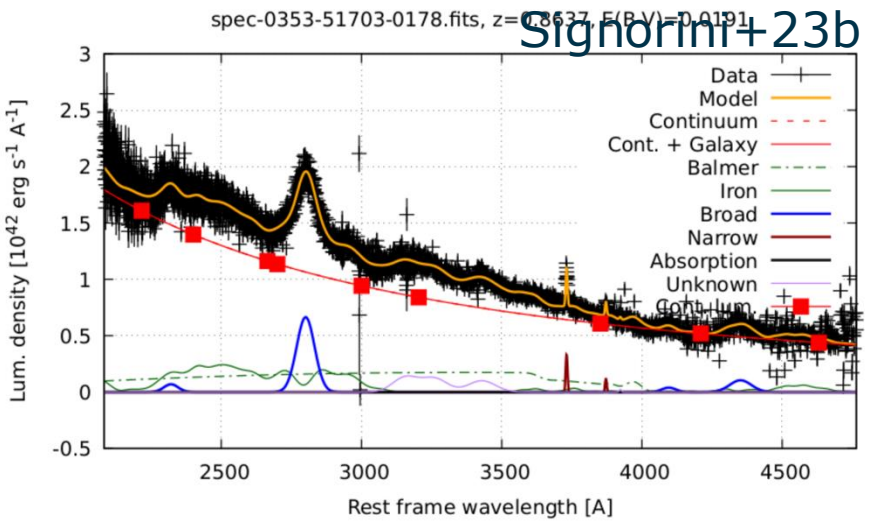
Sample selection, remove:

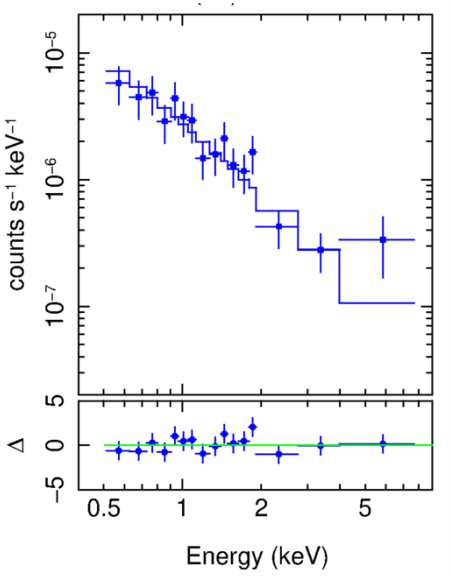
- radio-loud and absorbed objects
- dust-reddened obj. in the UV
- gas-obscured obj. in the X-ray
- obj. that might be affected by the Eddington bias in the X-ray

QUASARS



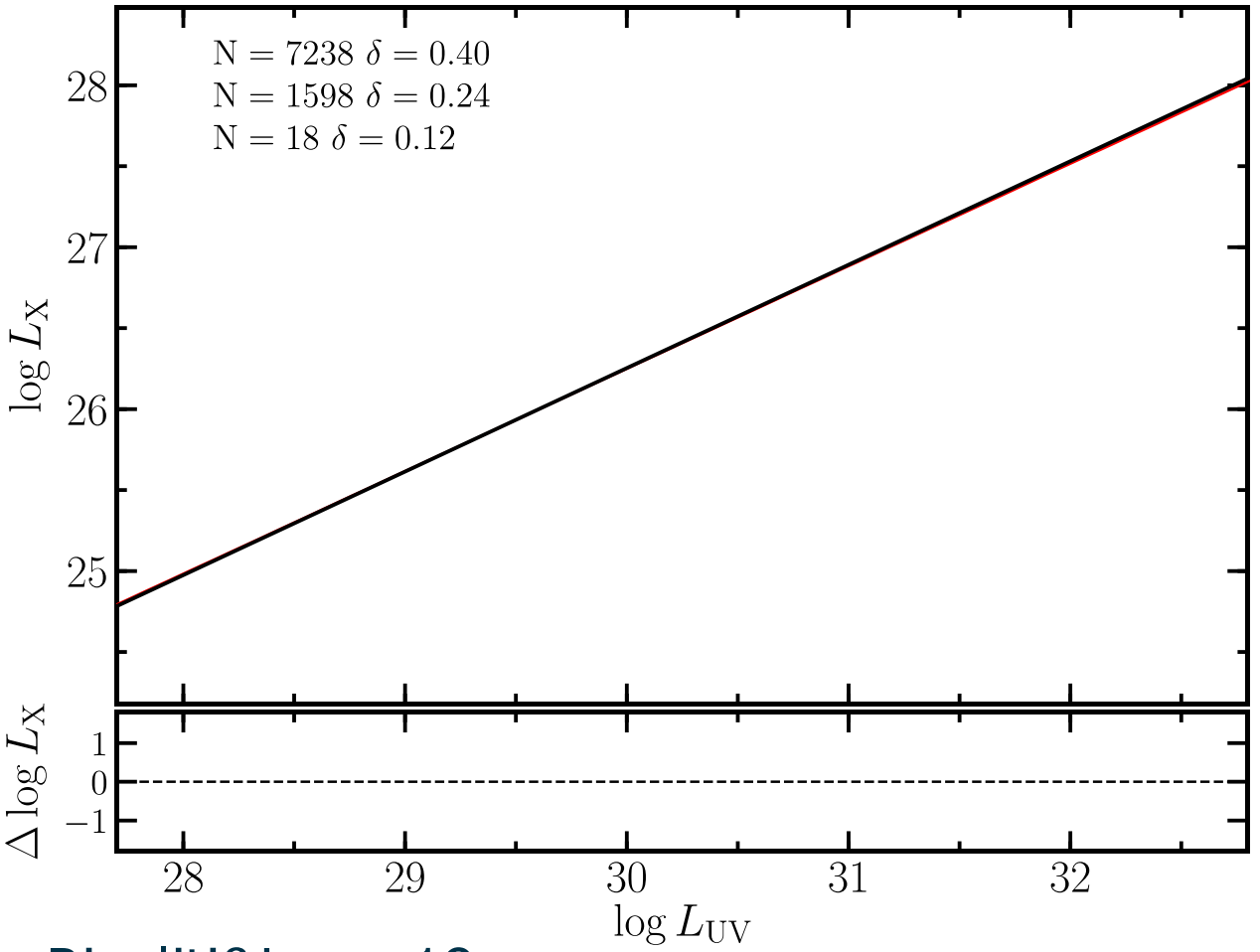
Signorini+23b





THE L_X-L_{UV} RELATION

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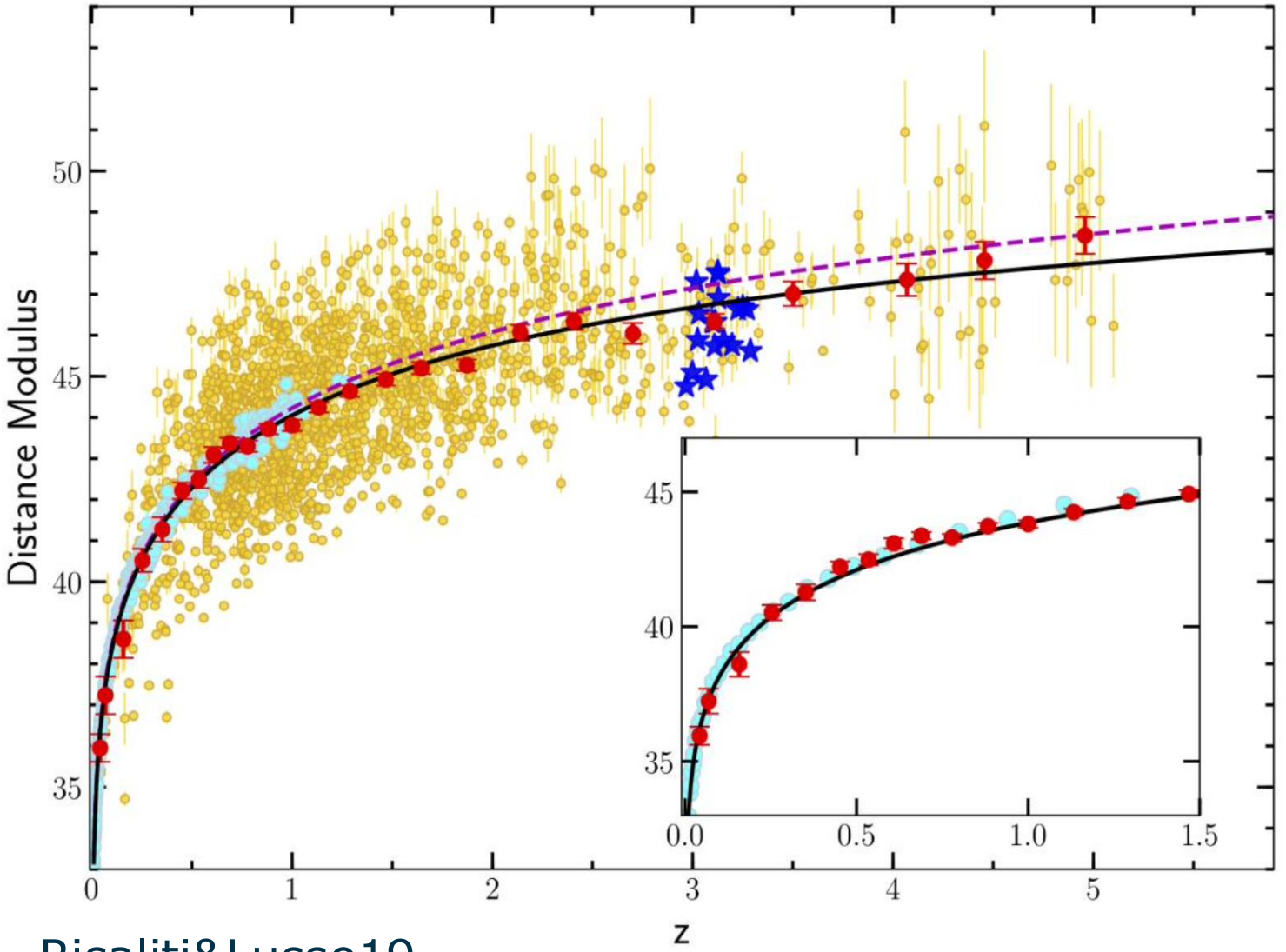


Risaliti&Lusso19

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THE L_X-L_{UV} RELATION



Risaliti&Lusso19

Extension up to when the Universe was less than 1 Gyr old

At high z, a ~4σ tension with the standard flat ΛCDM model builds up

THE L_X-L_{UV} RELATION

(i) Can we determine the parameters of the relation in a cosmological-independent way?

(ii) Can we be sure that the relation does not evolve with the redshift?

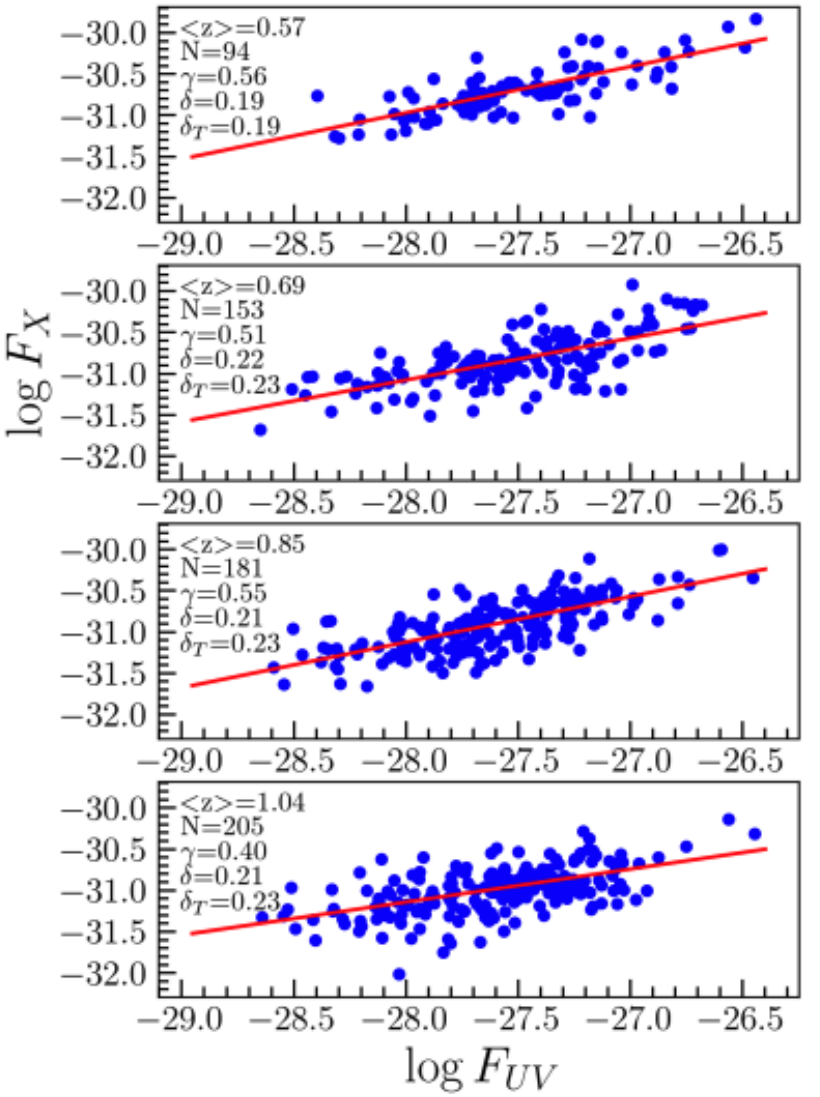
THE L_X-L_{UV} RELATION

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

If we use luminosities, the results are going to be cosmology-dependent

we test γ in small redshift bins using fluxes

$$\log(FX) = \gamma \log(FUV) + \hat{\beta}$$



Signorini+23b

THE L_X-L_{UV} RELATION

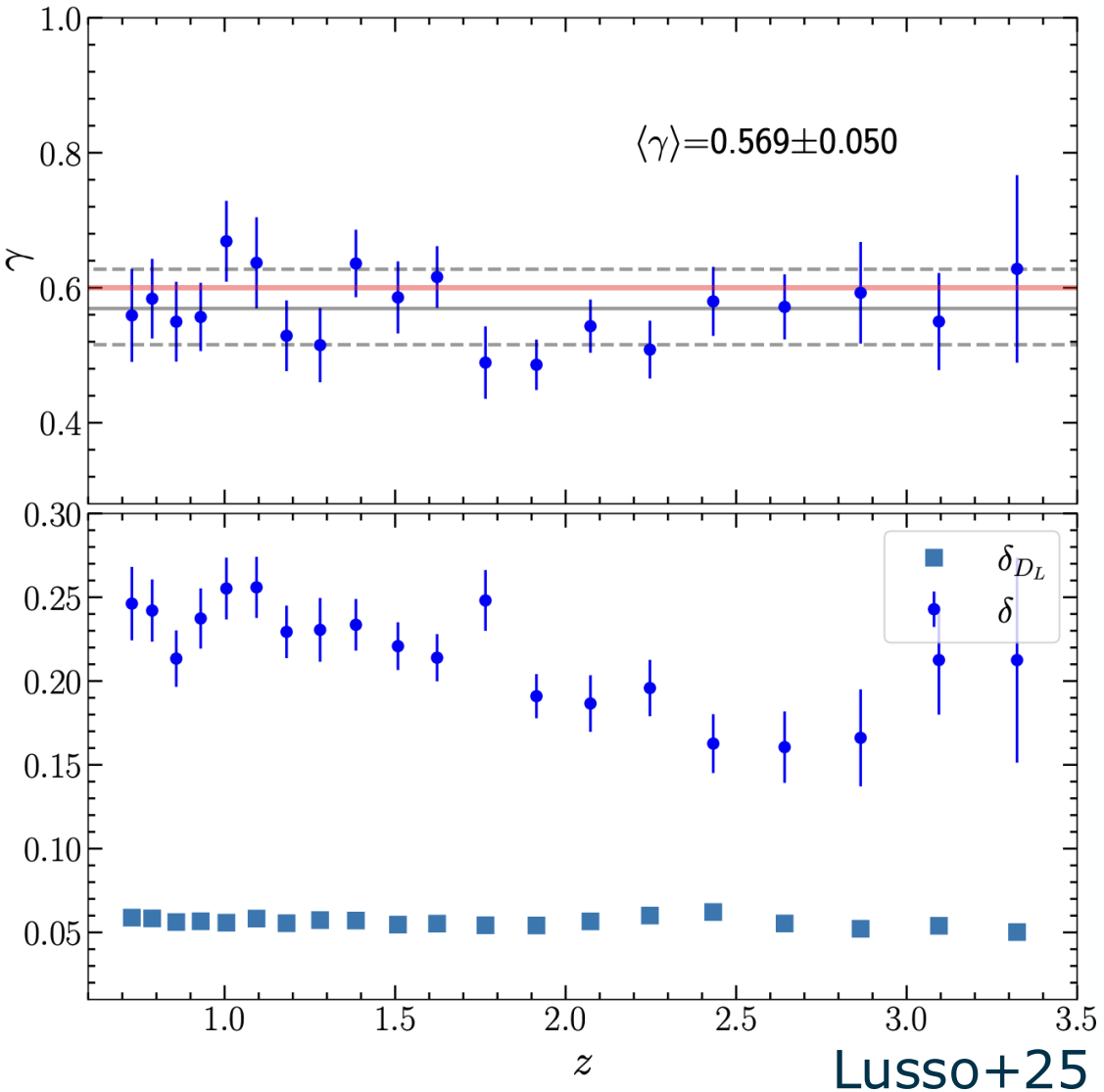
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We see no redshift trend!



THE L_X-L_{UV} RELATION

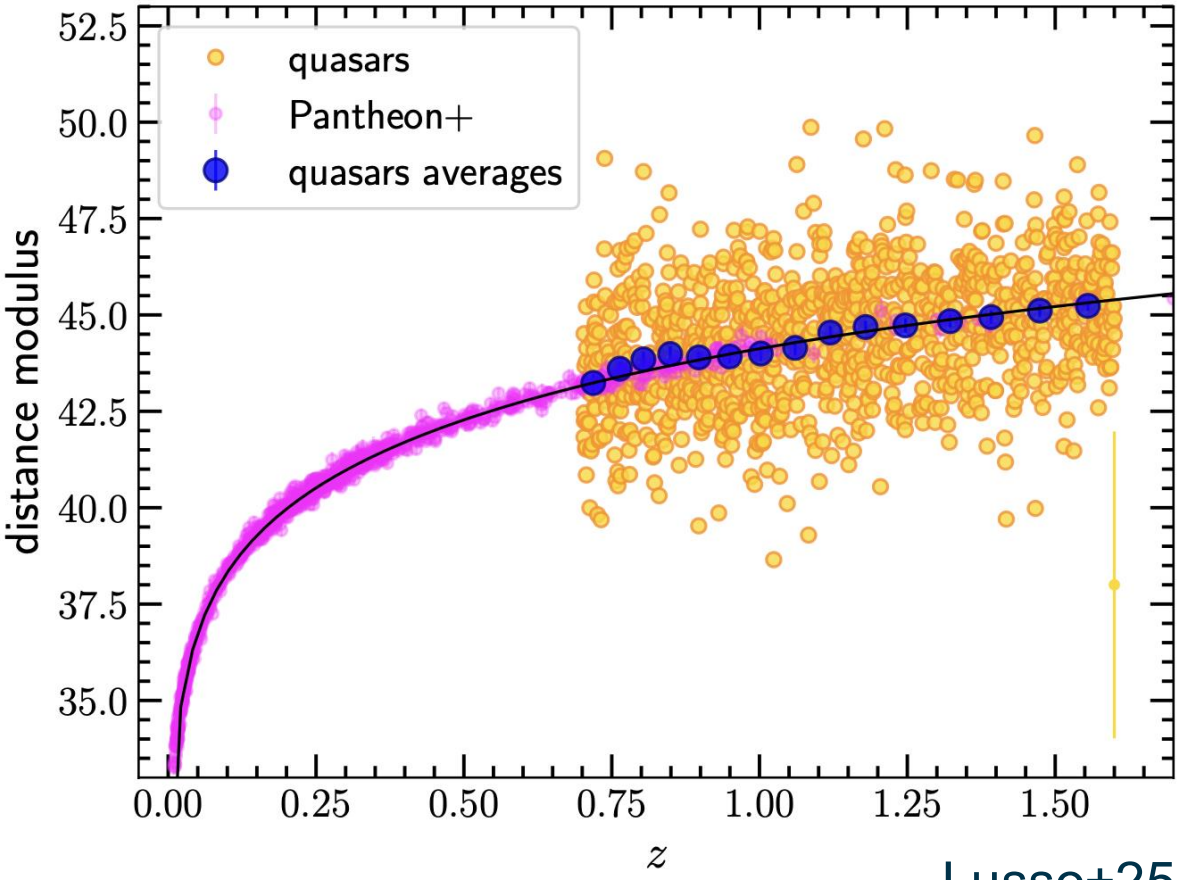
$$\log(L_X) = \gamma \log(L_{UV}) + \beta$$

β is a normalization, it is degenerate with the absolute scale of D_L

$$\log(FX) = \gamma \log(FUV) + \hat{\beta}$$

$$\hat{\beta}(z) = \beta - (1-\gamma)\log(4\pi) - (1-2\gamma)\log D_L$$

We fit SNIa and quasars in the common redshift range to find β



Lusso+25

THE L_X-L_{UV} RELATION

But what if β starts evolving at redshift z>1.6?

Because β is degenerate with the D_L normalization, there is a complete degeneracy between the distance-redshift evolution and a redshift dependence of β

If we assume a 'true' cosmological model and a non-evolving β, the HD can be reproduced with any other model by assuming

$$\beta(z) = \beta - (2 - 2\gamma) log \frac{D^*_L(z)}{D_L(z)}$$

THE L_X-L_{UV} RELATION

Test using Pantheon+

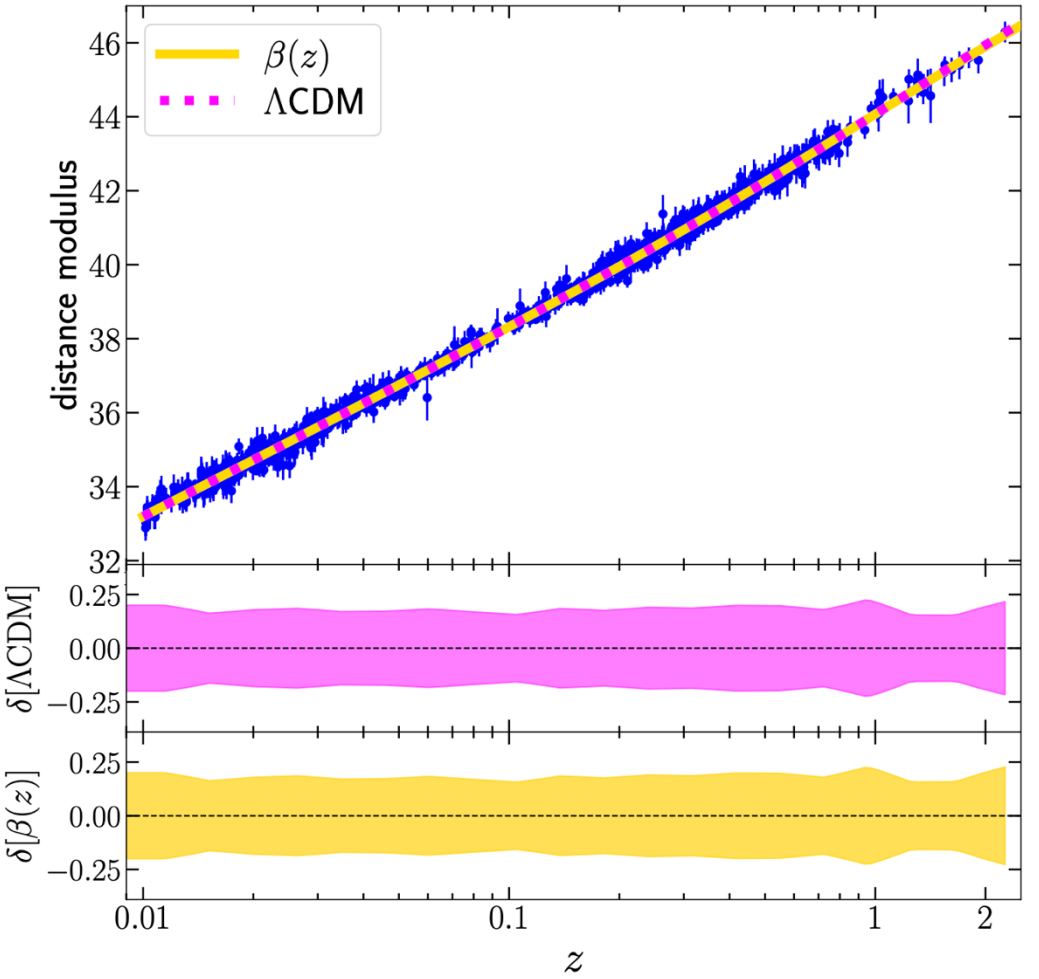
Fit of the HD assuming a fixed ΛCDM model with

$$\Omega_M = 1 \text{ and } \Omega_\Lambda = 0$$
$$+$$
evolution of the zero-point mag like a1exp(a2*z)

We get a1~−0.3; a2~−0.5

The two models are both good enough!

one cannot rely on a cosmological analysis to determine if the normalization evolves



Lusso+25

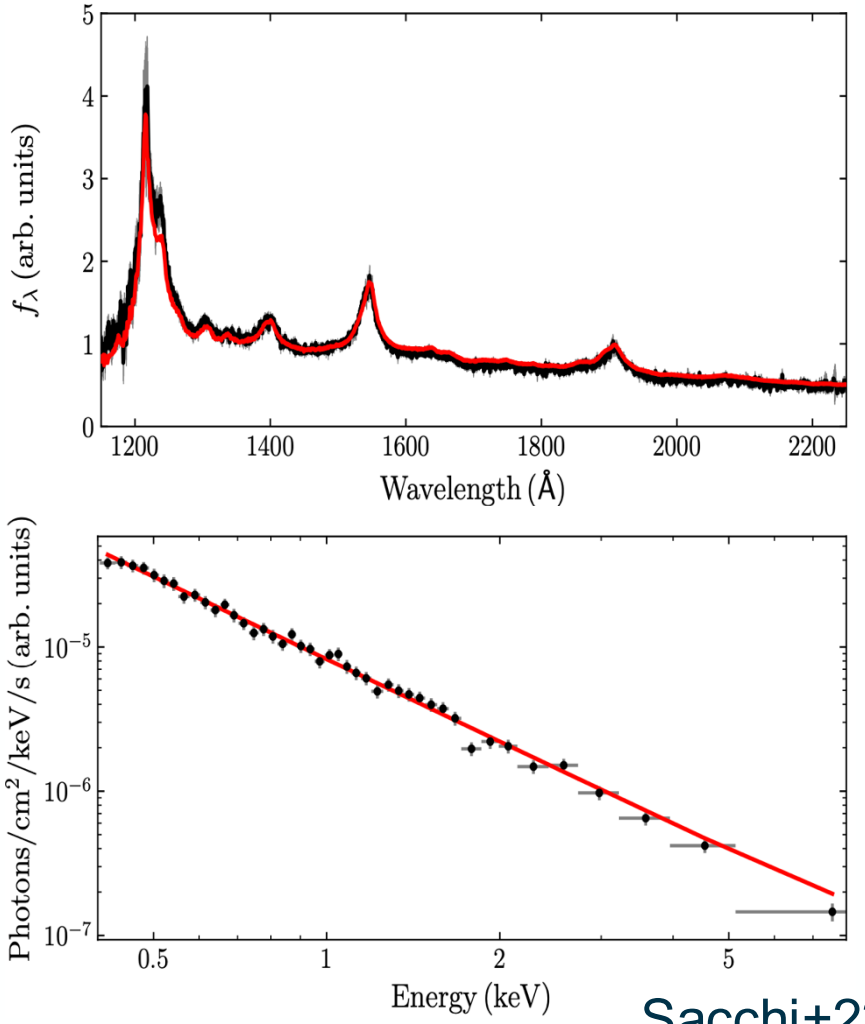
THE L_X-L_{UV} RELATION

We need other reasons to say that β is not evolving

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- In our sample, low and high redshift objects have identical spectra (Sacchi+22, Trefoloni+24a)

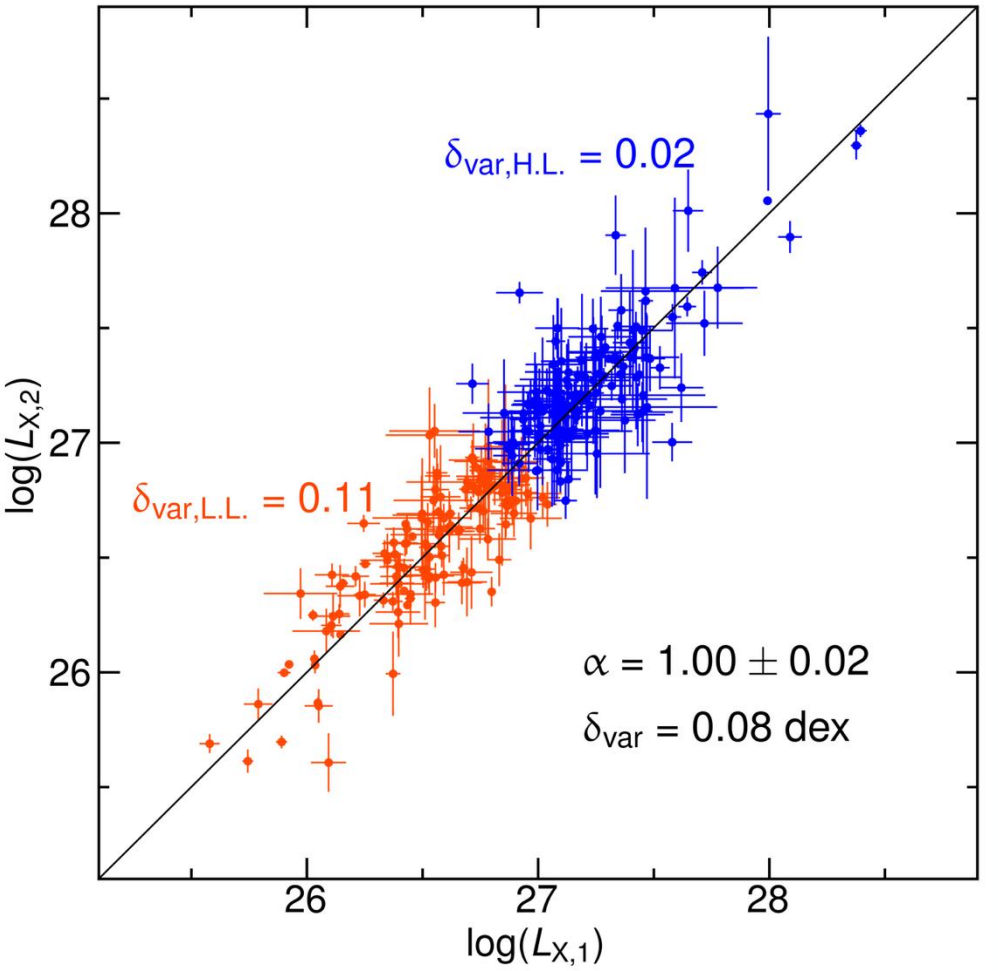


Sacchi+22

THE L_X-L_{UV} RELATION

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- In our sample, low and high redshift objects have identical spectra (Sacchi+22, Trefoloni+24a)
- The intrinsic dispersion of the L_X-L_{UV} is likely very small (~0.06 dex, Signorini+24). If the relation is very tight and spectral shapes do not change, there is no room for an evolution of the relation

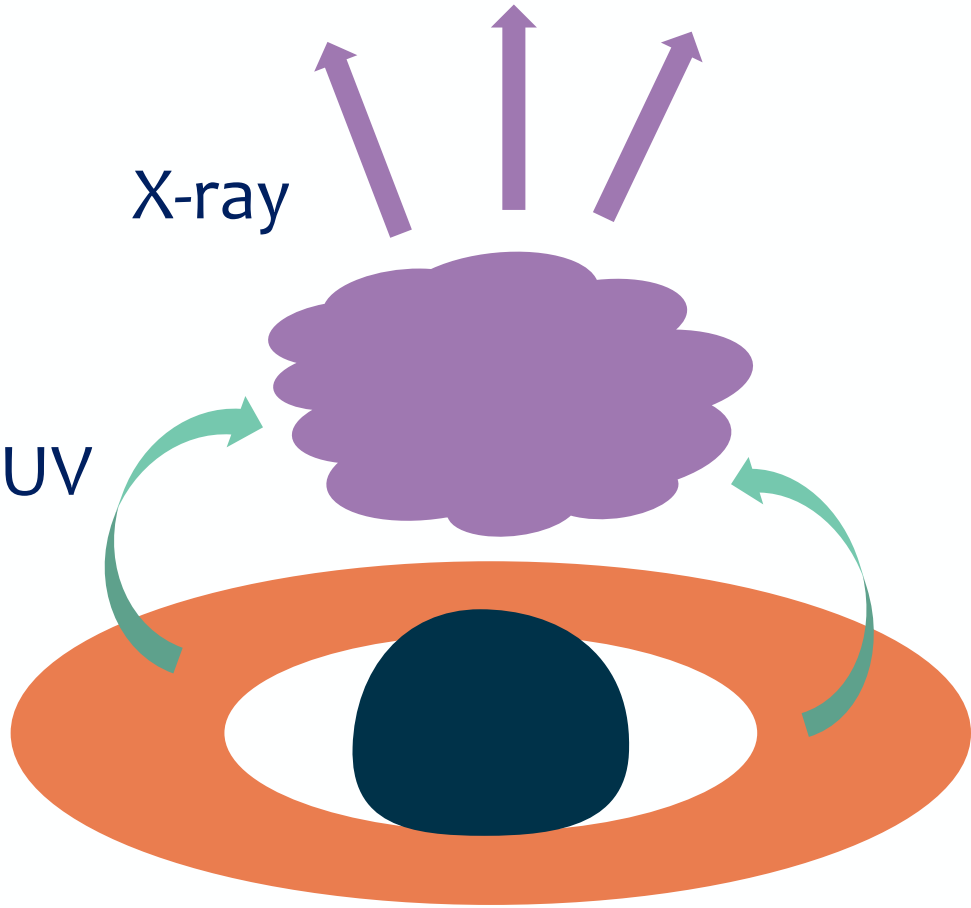


Signorini+24

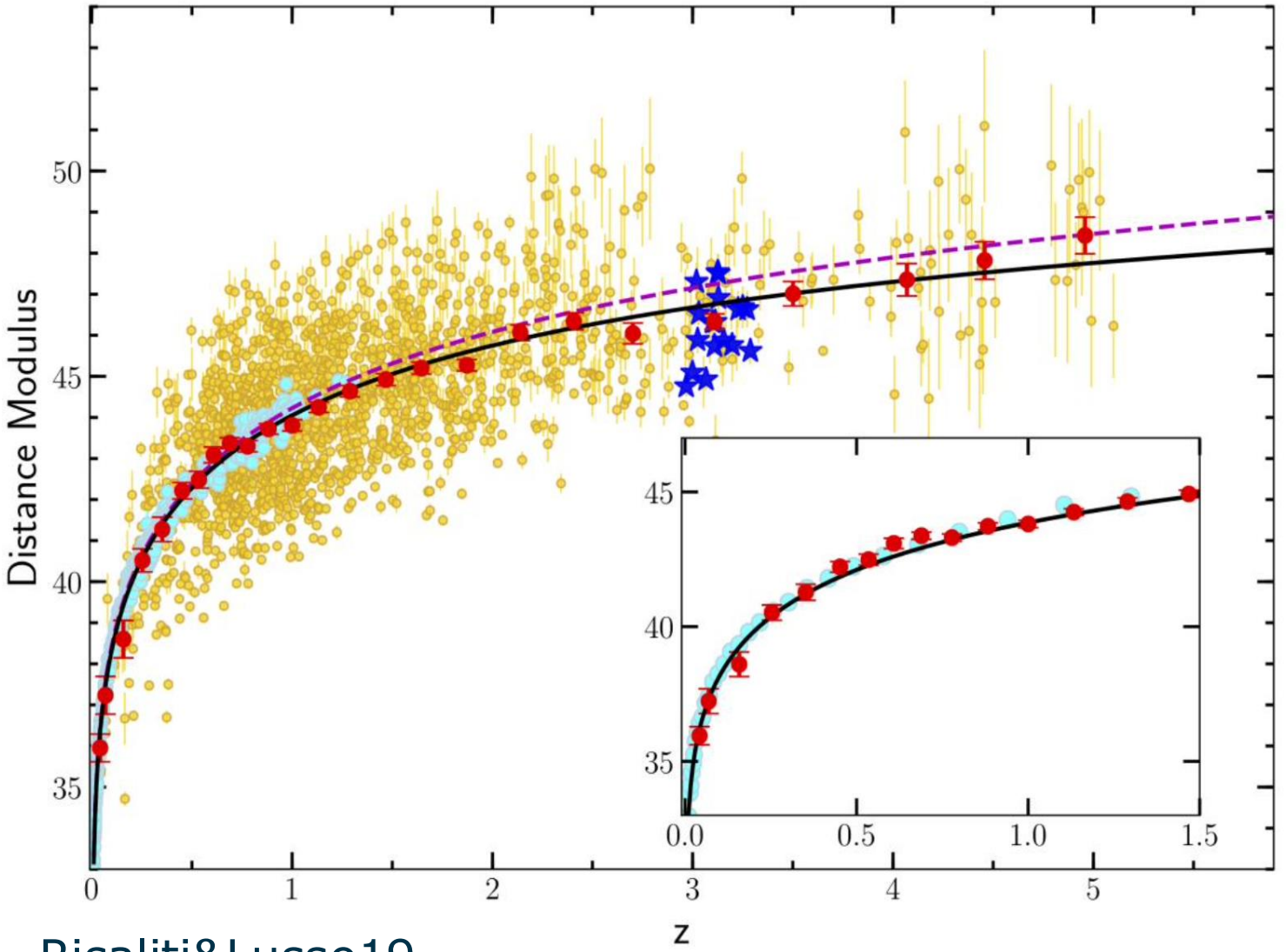
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- The intrinsic dispersion of the L_X-L_{UV} is likely very small (~0.06 dex, Signorini+24). If the relation is very tight and spectral shapes do not change, there is no room for an evolution of the relation
- Quasars agree with SNIa in the common redshift range; if accretion physics and γ do not evolve, why would β, and starting only from redshift 1.6?



SNIa + QUASARS HUBBLE DIAGRAM



Risaliti&Lusso19

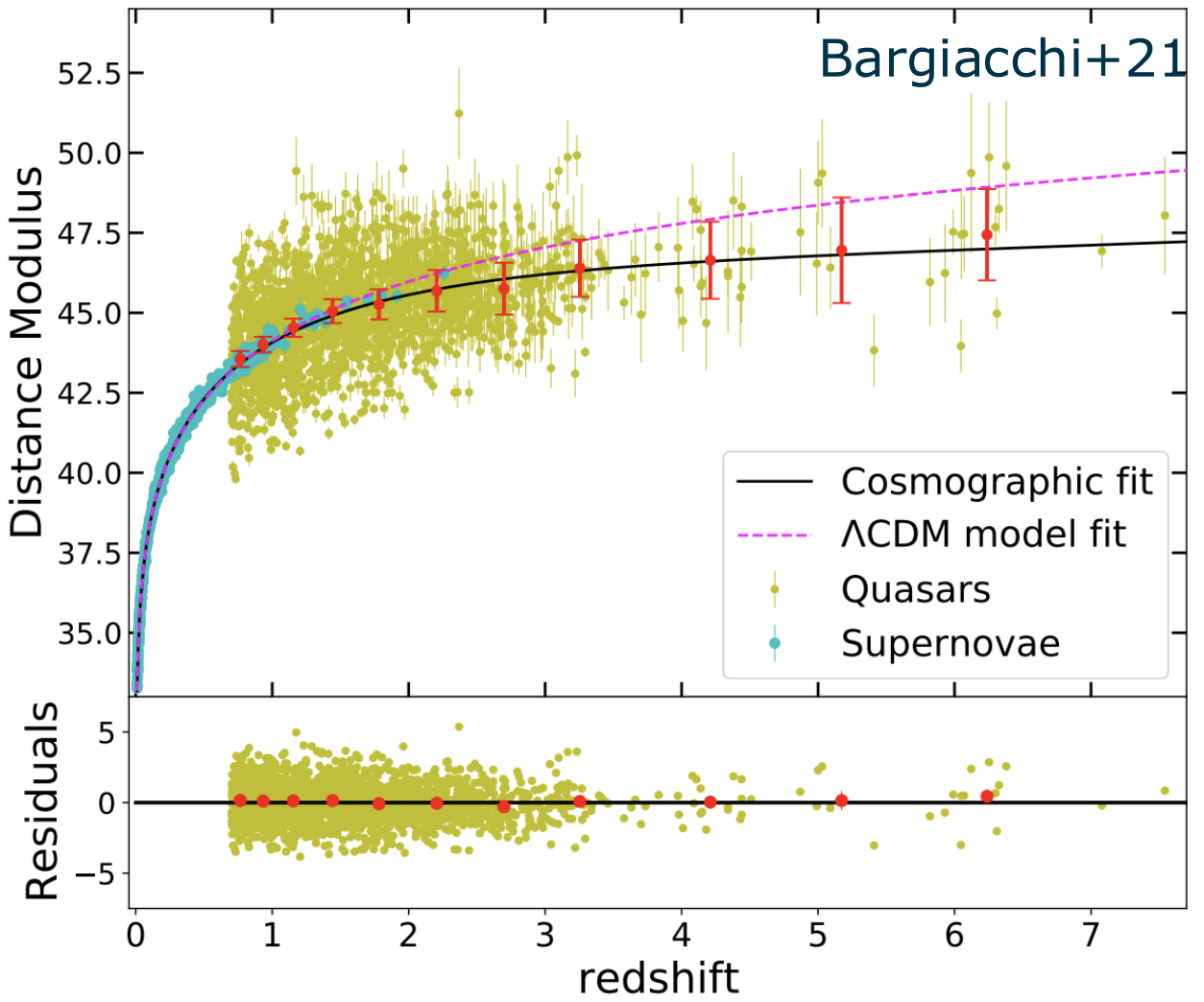
Extension up to when the Universe was less than 1 Gyr old

At high z, a ~4σ tension with the standard flat ΛCDM model builds up

COSMOGRAPHIC FIT

Assume no model, find the function that describes the data best and then compare with model predictions

$$D_{\rm L}(z) = \frac{\ln(10)}{H_0}\Bigg\{\log(1+z) + a_2\log^2(1+z) + a_3\left[k_{32}\log^2(1+z) + \log^3(1+z)\right] + a_4\left[k_{42}\log^2(1+z) + k_{43}\log^3(1+z) + \log^4(1+z)\right] + a_5\left[k_{52}\log^2(1+z) + k_{53}\log^3(1+z) + k_{54}\log^4(1+z) + \log^5(1+z)\right]\Bigg\}.$$

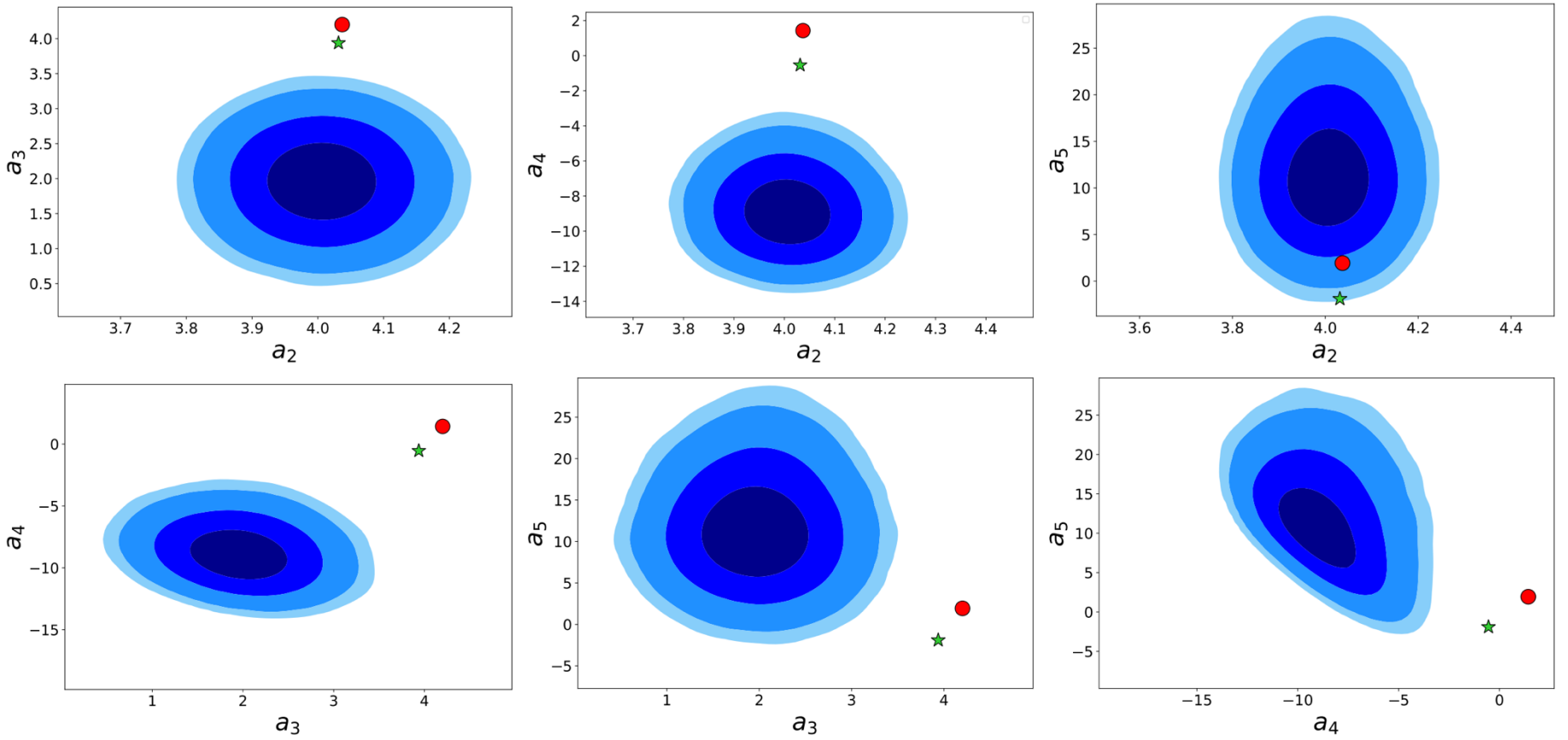


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Bargiacchi+21

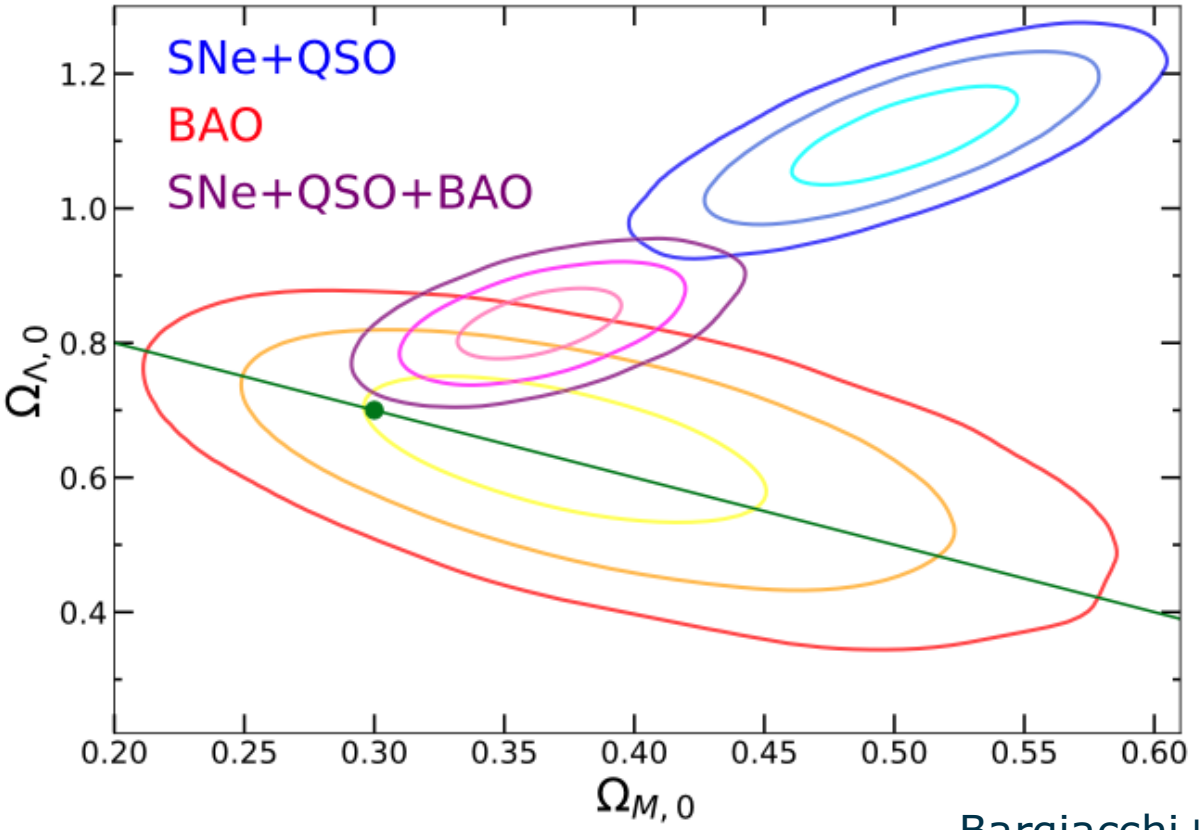
Green star: flat ΛCDM with Ω_m =0.28



COSMOLOGICAL FIT

Assume a model: what are the best-fit values of the parameters?

non-flat ΛCDM: SNIa+quasars prefer a high Ω_m value

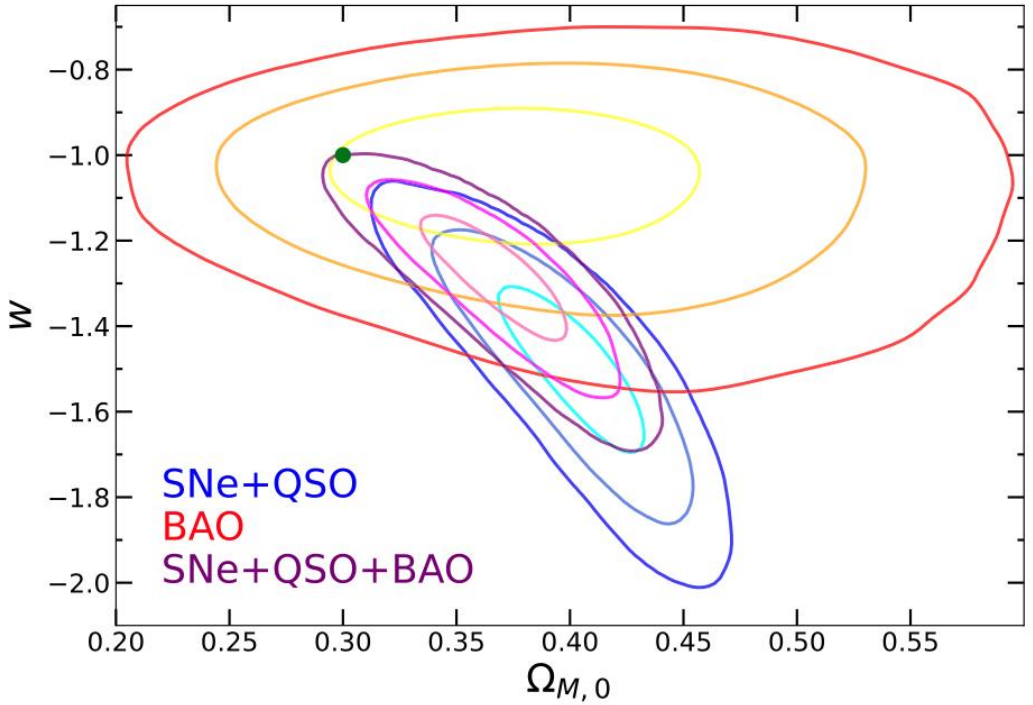


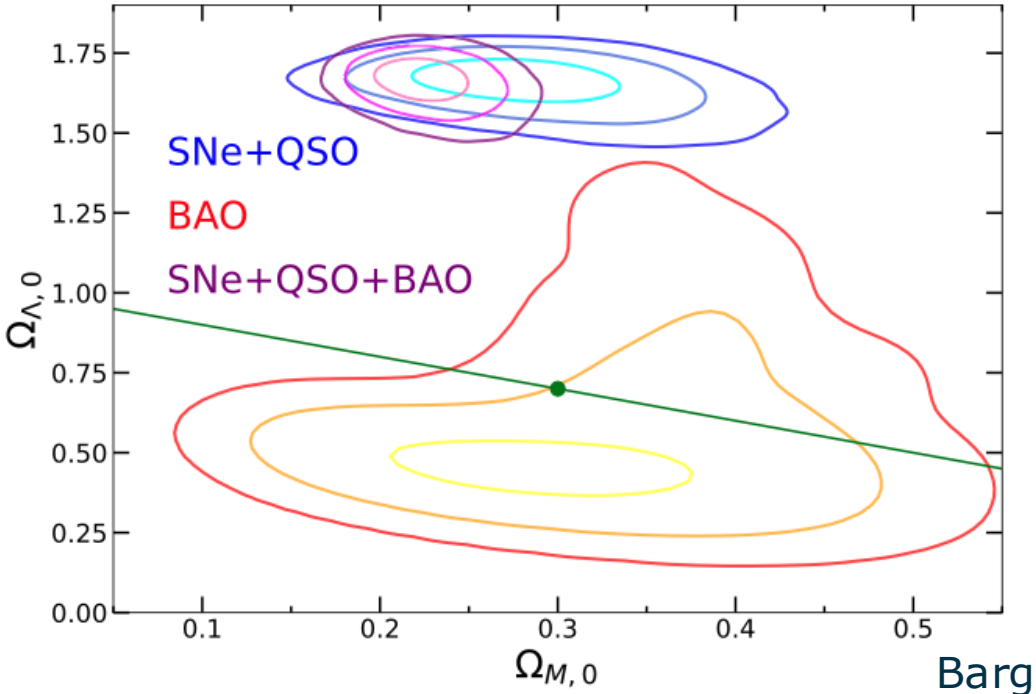
Bargiacchi+22

COSMOLOGICAL FIT

Assume a model: what are the best-fit values of the parameters?

Flat wCDM: preference for
w<-1, Om~0.4



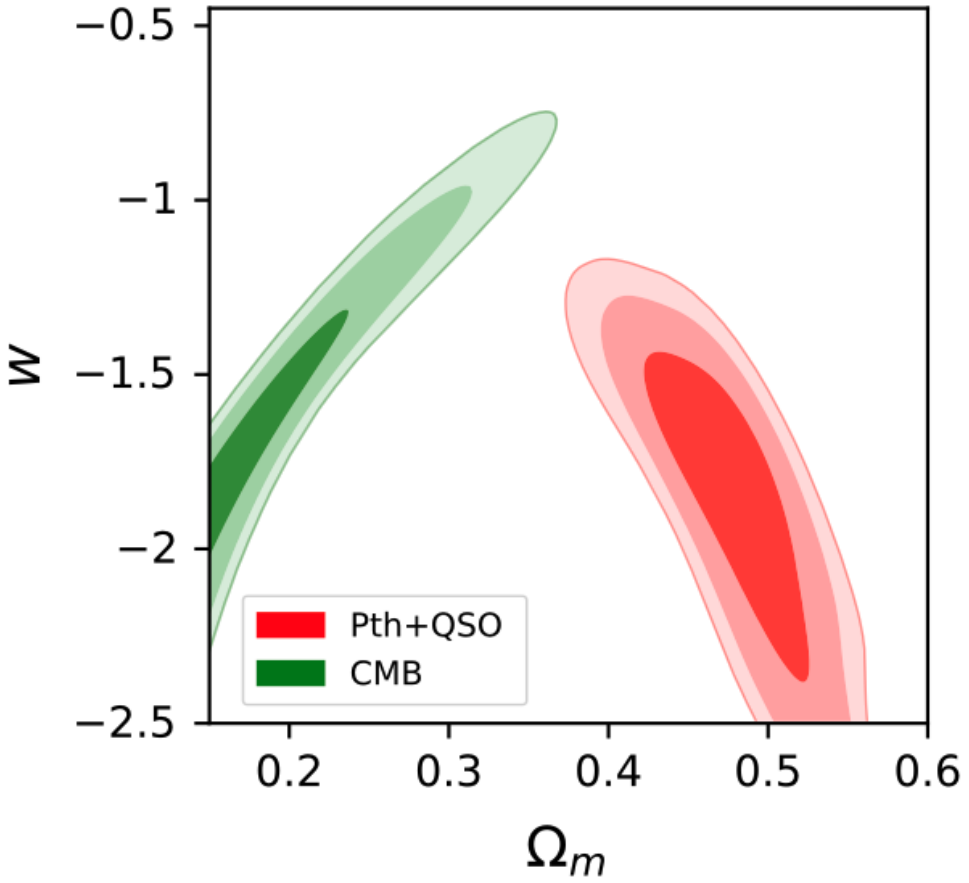


Bargiacchi+22

COSMOLOGICAL FIT

Benetti+25

Add CMB:

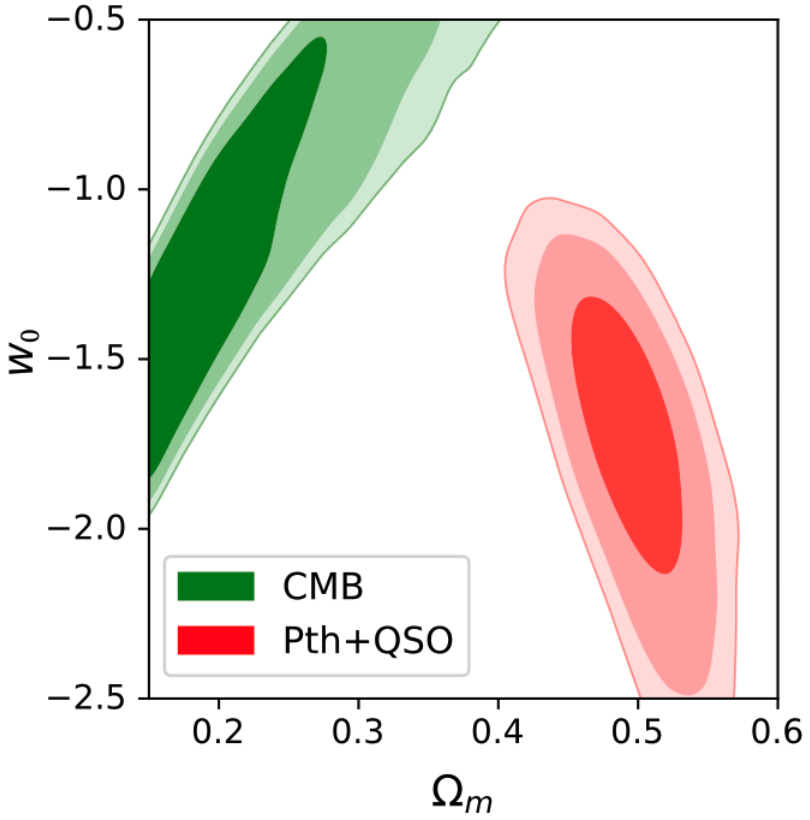


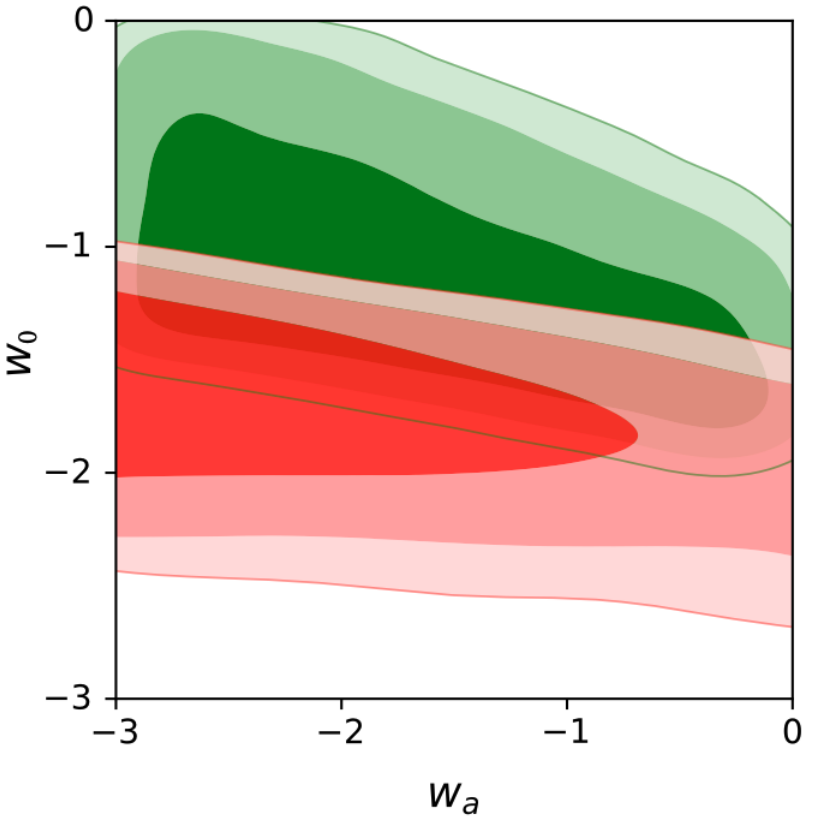
In the wCDM scenario, CMB and SNIa+QSO contours do not touch each other

COSMOLOGICAL FIT

Benetti+25

Add CMB:





Even the w0wa model

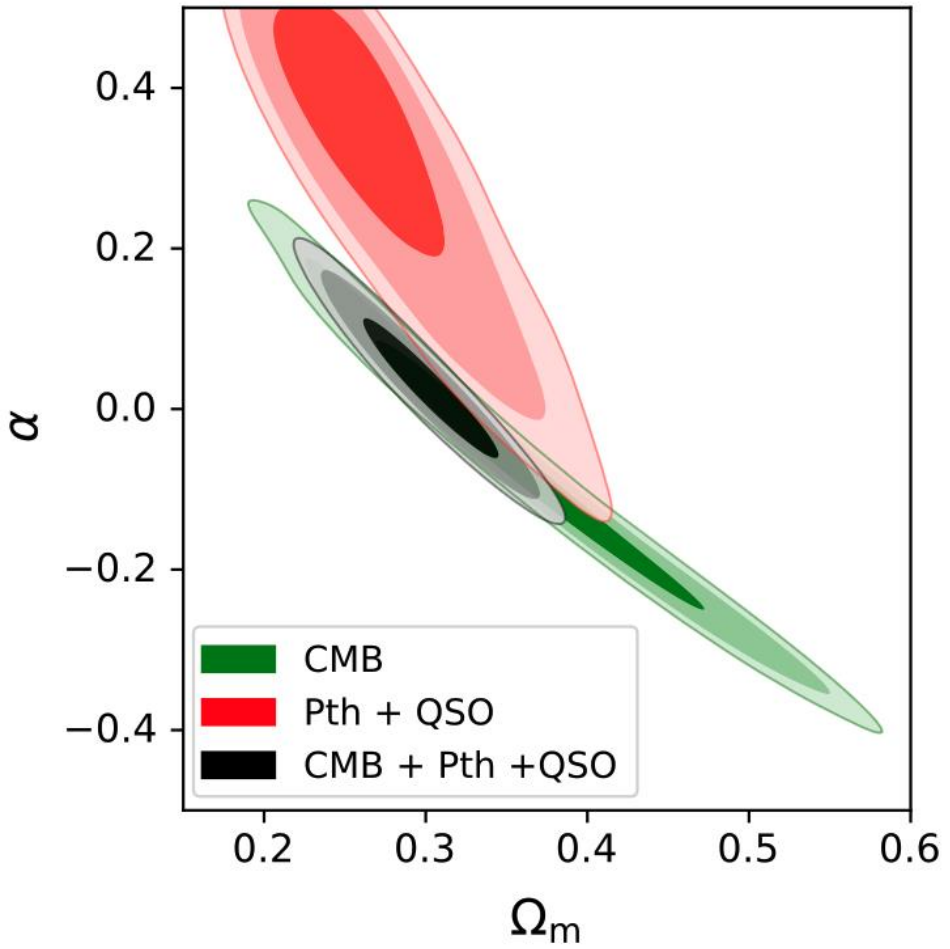
w(z) = w0 + wa (z/1+z)

does not help to reconcile the probes

COSMOLOGICAL FIT

Benetti+25

Add CMB:



Unified dark sector:

$$p = -A/\rho^{\alpha}$$

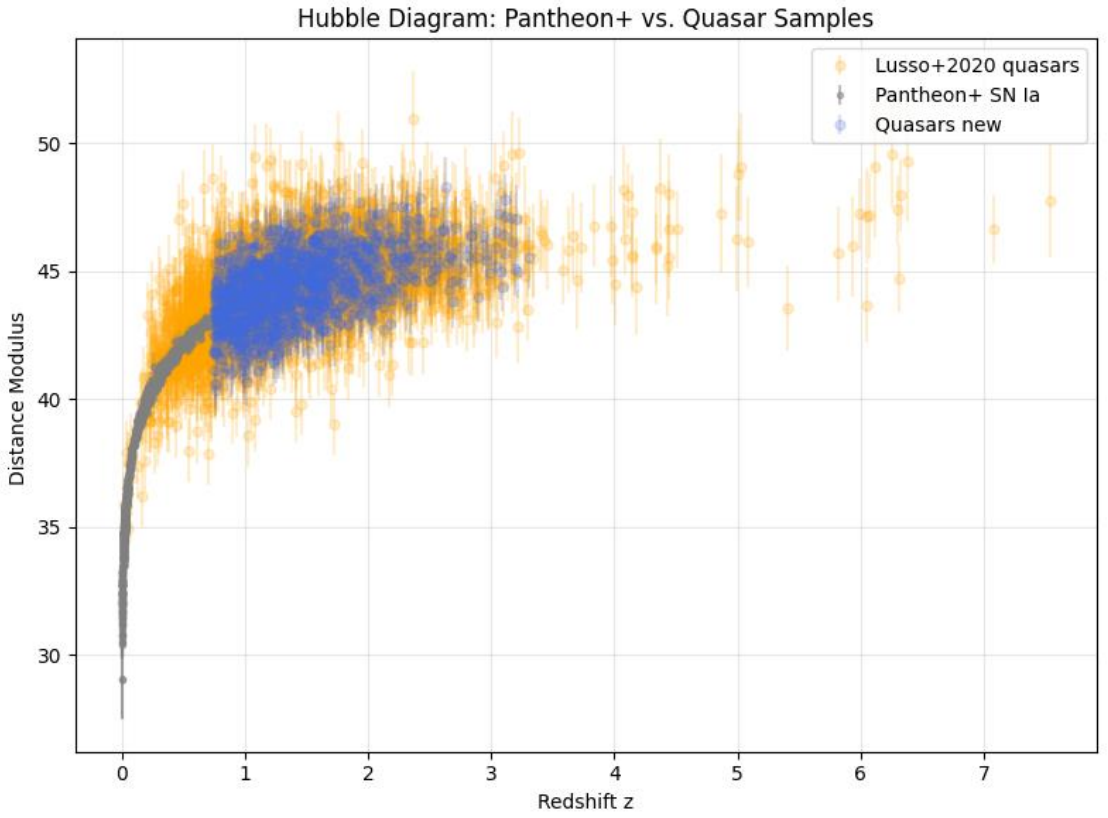
$$\frac{H(z)}{H_0} = \sqrt{\left[(1-\Omega_m) + \Omega_m(1+z)^{3(1+\alpha)}\right]^{\frac{1}{(1+\alpha)}} + \Omega_r(1+z)^4}$$

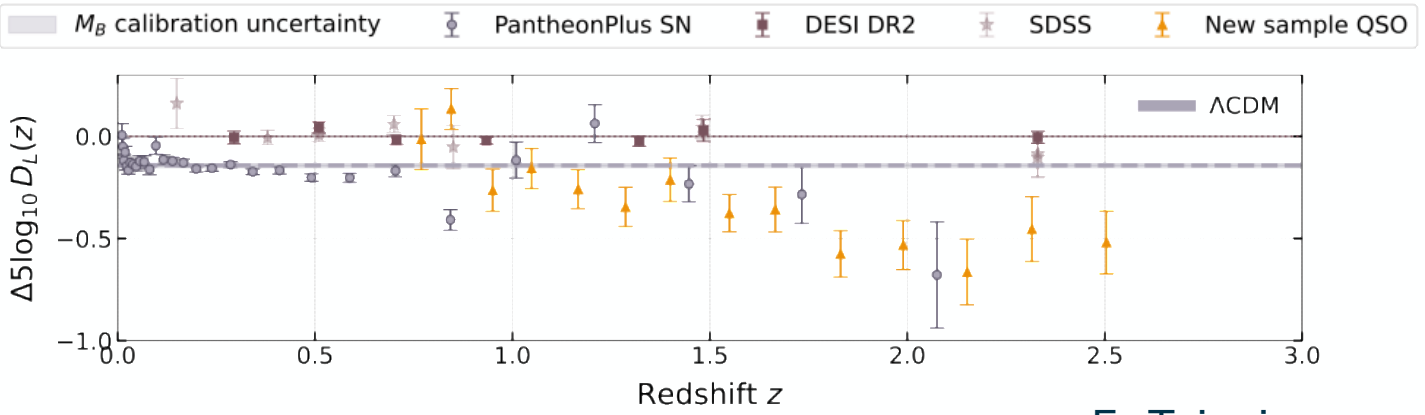
With A positive constant that depends on Ω_m, and α the interaction parameter between dark components

Is this the way to reconcile the CMB and SNIa+Quasars?

FUTURE WORK

- New refined sample of Quasars with a smaller dispersion (coming soon!)





E. Teixeira

FUTURE WORK

- New refined sample of Quasars with a smaller dispersion (coming soon!)
- Pointed X-ray observations at redshift z~4
- Analysis of new catalogues (eRosita, Milliquas) and preparation for future observatories (LSST, NewAthena…)
- Studies about the physics of the L_X-L_{UV} relation
  - "X-ray weak" quasars
  - Detailed spectral analysis of subsamples at different redshift
  - Overall study of the X-ray Corona: variability, dependence on accretion rate efficiency, spectral properties
- Looking deeper into Interacting Dark Sector models and/or more 'exotic' cosmologies that can solve the tension

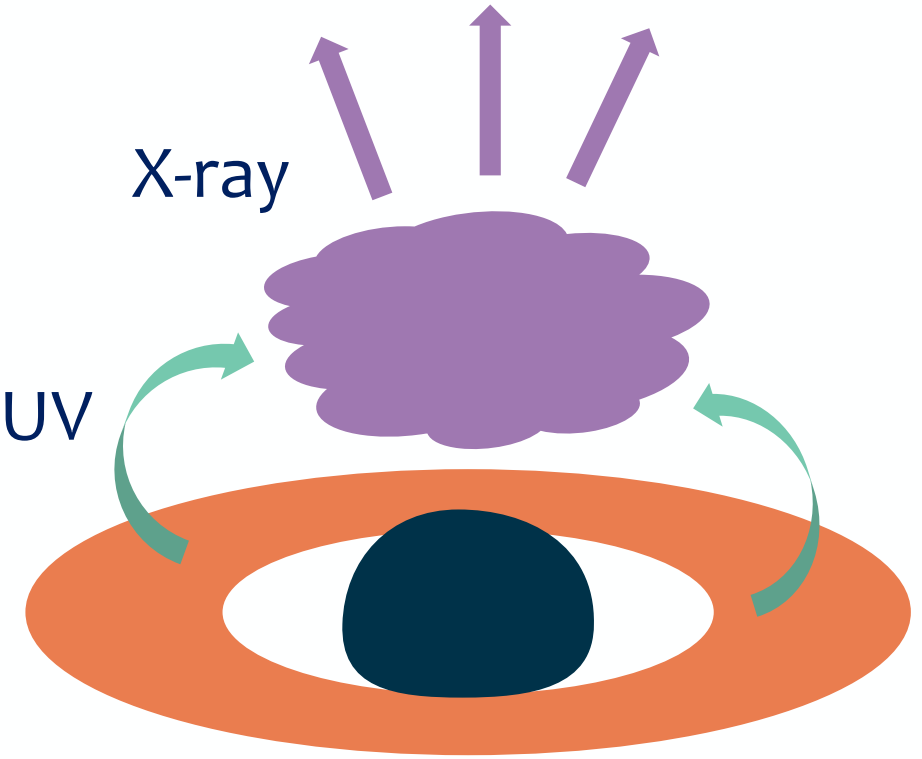
CONCLUSIONS

- We need high-redshift standard candles, and quasars are good candidates

- The L_X-L_{UV} relation can be used to measure distances
  - The parameters γ and β do not evolve with z
  - We can determine them in a cosmology-independent way

- Testing the Hubble-Lemaître diagram for SNIa+QSO we find a ~4σ tension with standard flat ΛCDM cosmology

- "Simple" extensions of ΛCDM do not solve the tension: can an Interacting Dark Sector be the solution?



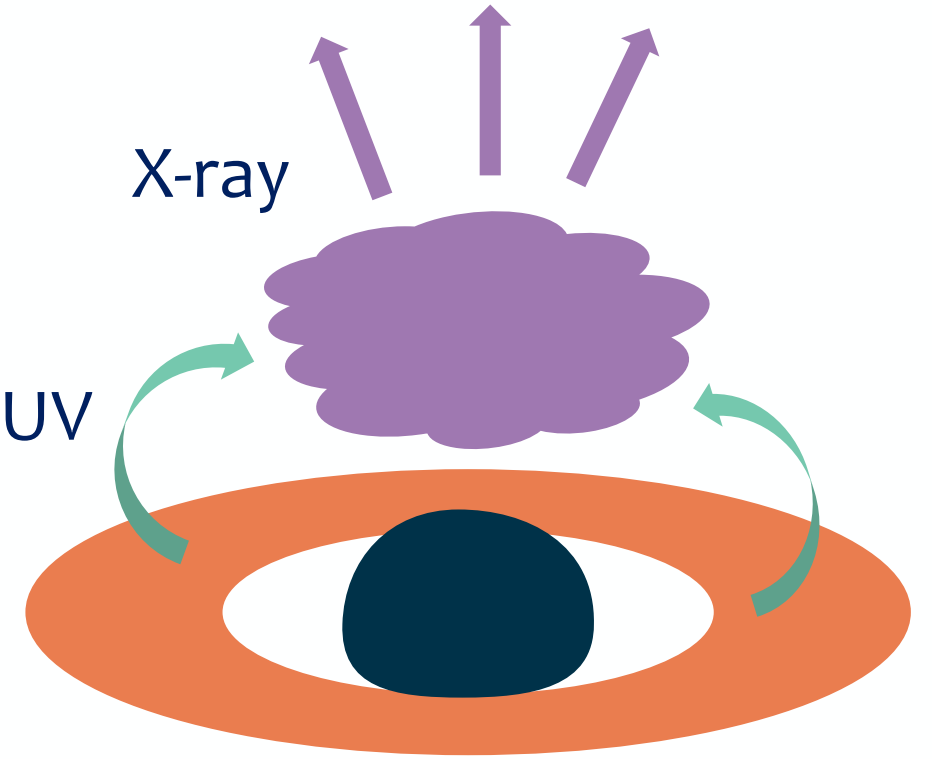
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THANK YOU!