ARE QUASARS RELIABLE STANDARD CANDLES?

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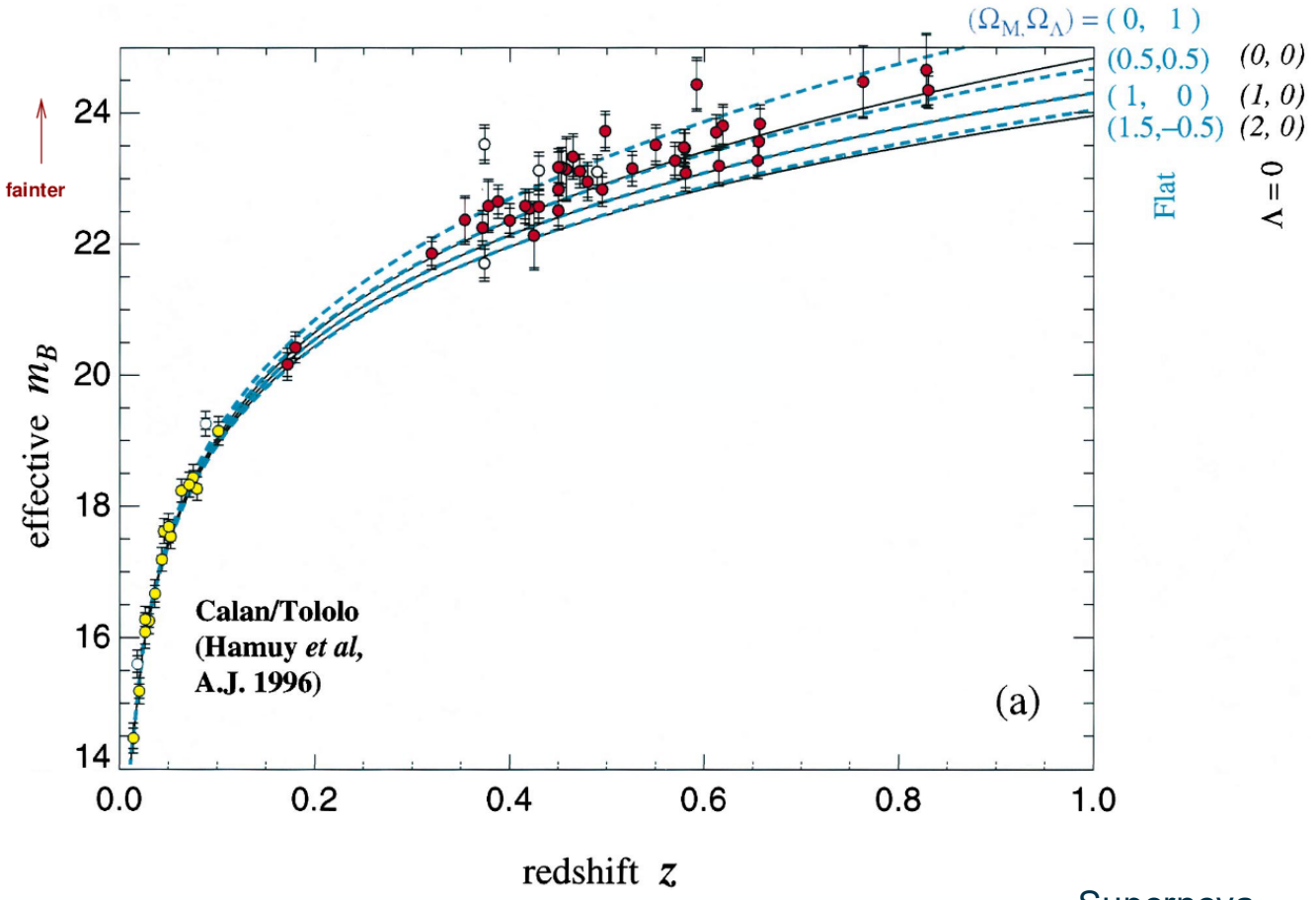
E. Lusso, E. Nardini, G. Risaliti

INTRODUCTION

Supernova Ia

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

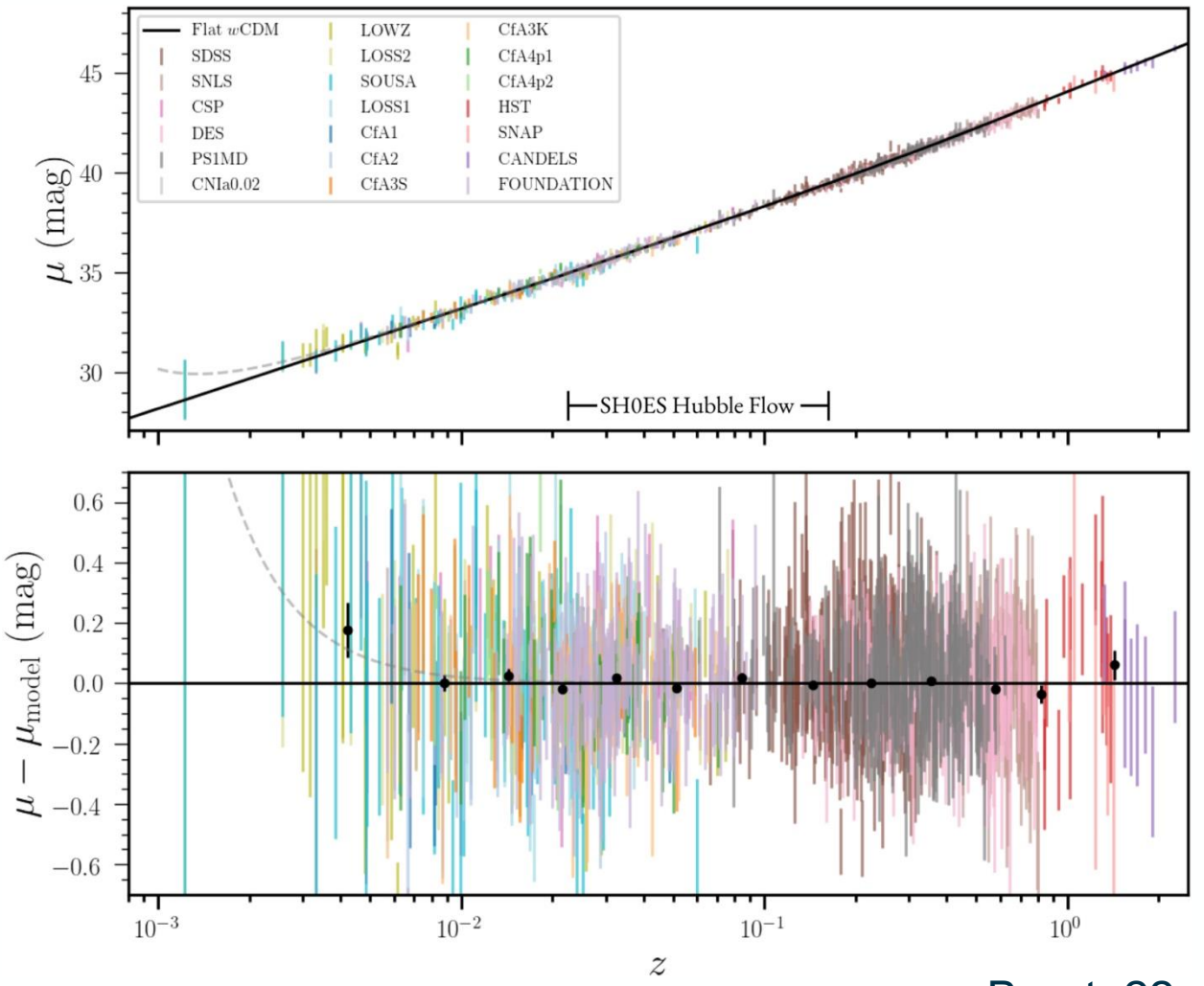
INTRODUCTION

Supernova Ia

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- inside a model, the shape constrains its parameters

…not observed at high redshift!

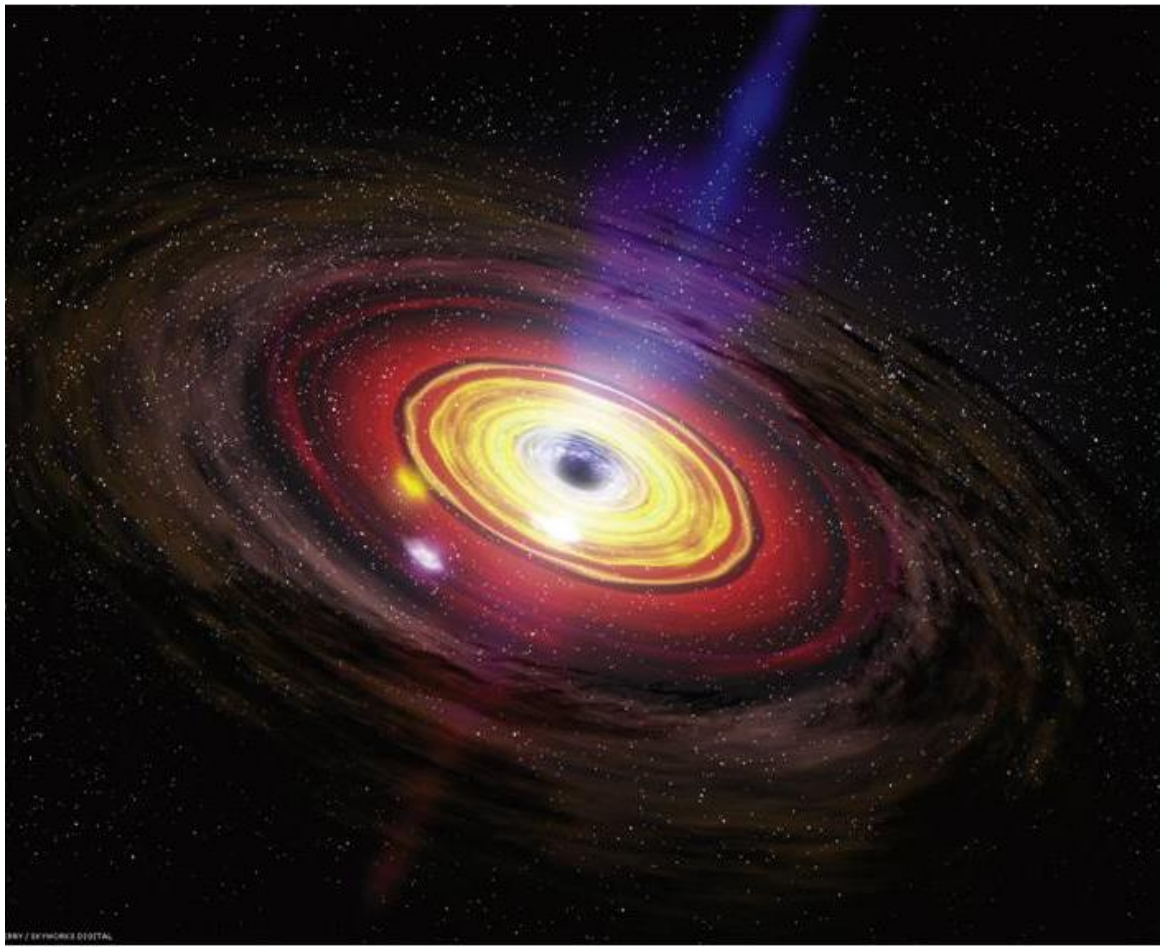


Brout+22

INTRODUCTION

Quasars are interesting candidate for being standard candles:

- Very bright
- Very numerous
- Observed from low (z~0.001) to high (z>10) redshifts



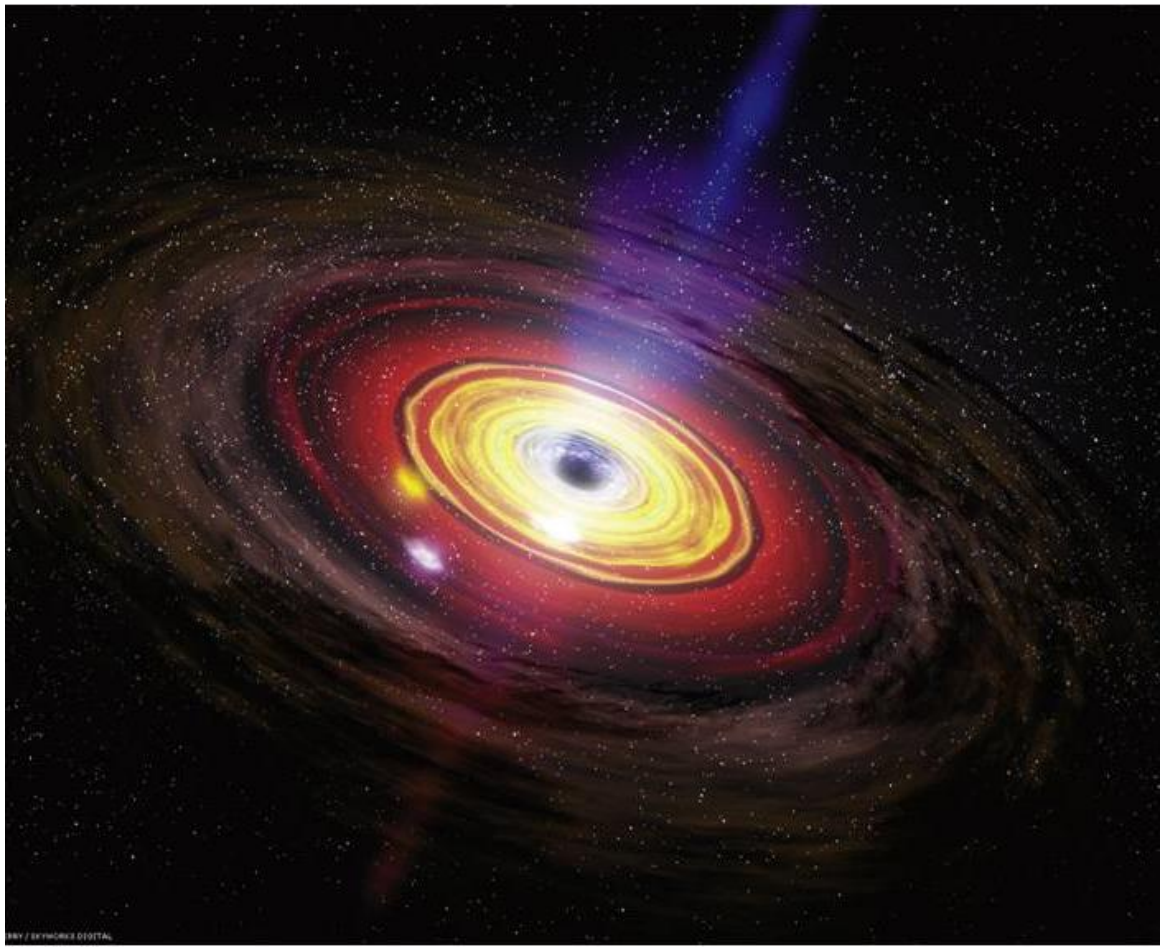
INTRODUCTION

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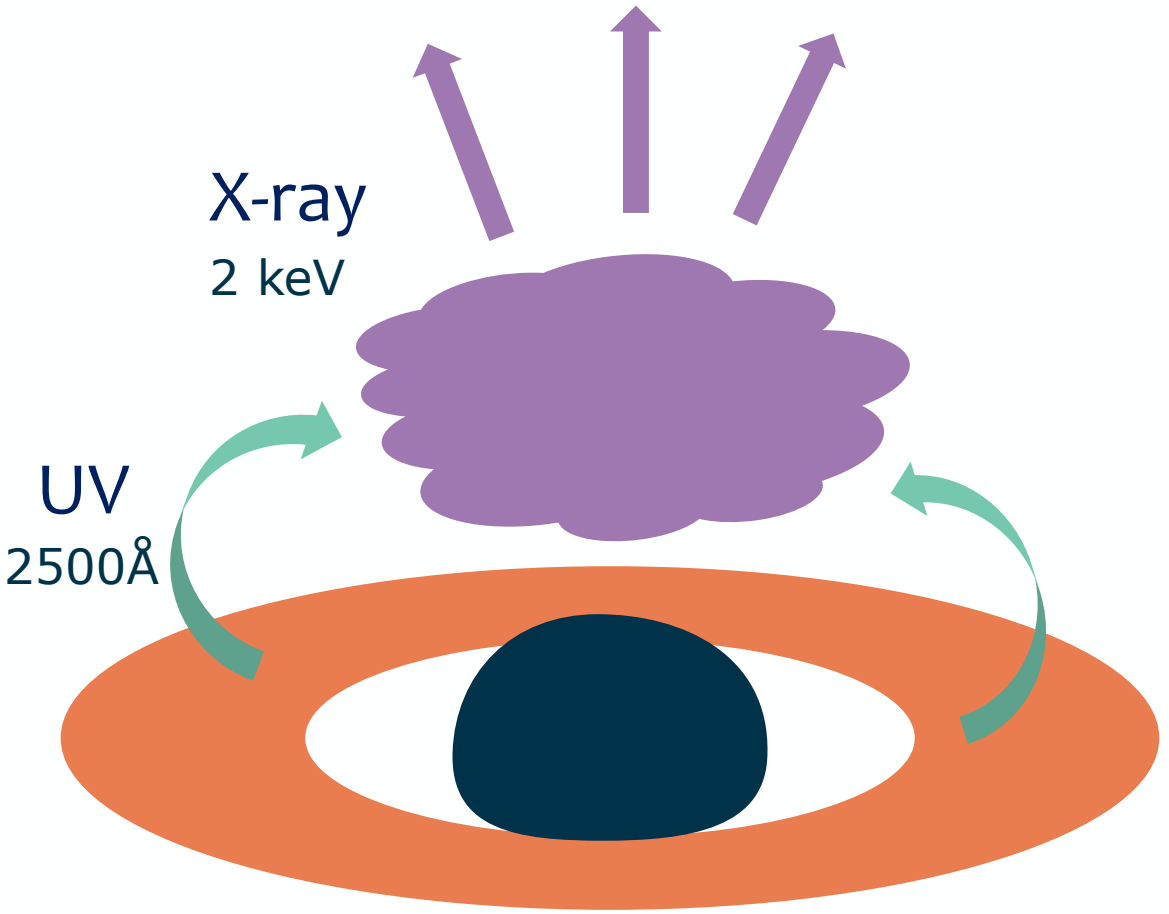
- Very bright
- Very numerous
- Observed from low (z~0.001) to high (z>10) redshifts

However, their emission is clearly not standard!

$L_{bol} \sim 10^{40} - 10^{47}$ erg/s



THE L_X-L_{UV} RELATION



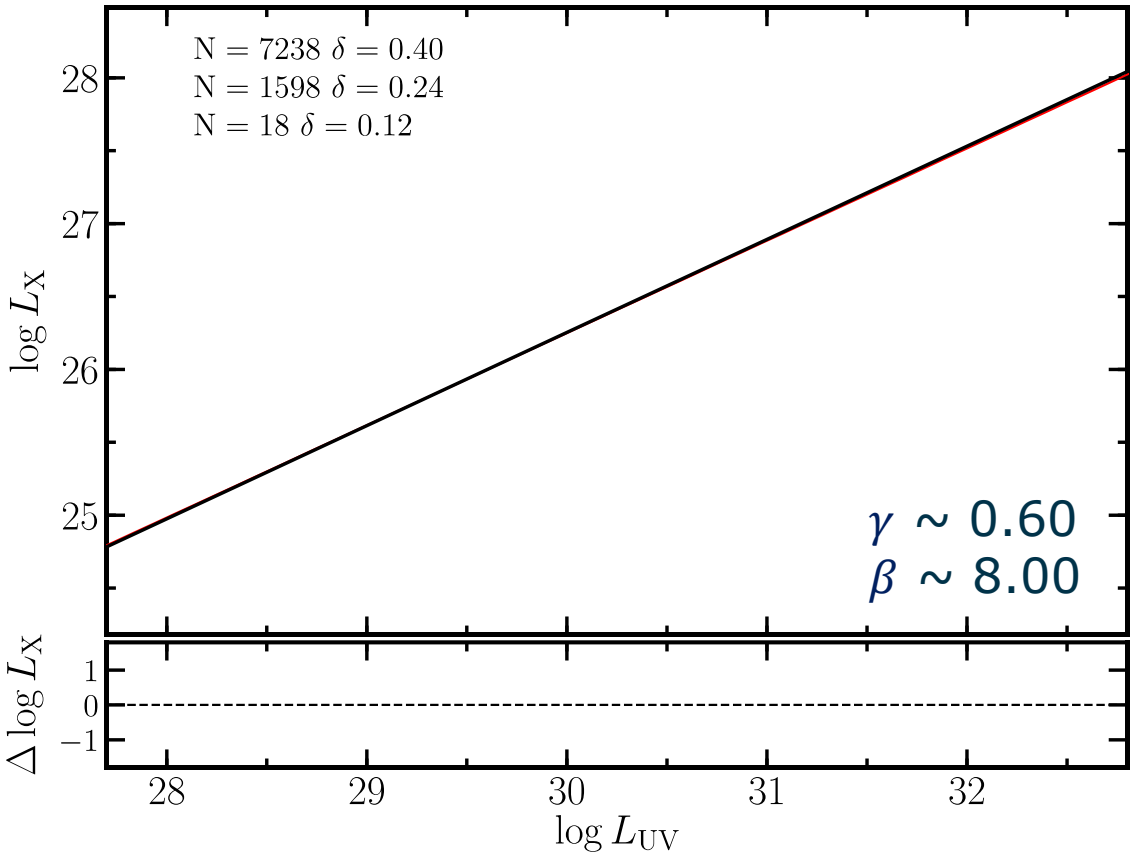
$$\log(L_X) = \gamma \log(L_{UV}) + \beta$$

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

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

Distance measurements!

THE L_X-L_{UV} RELATION



Risaliti&Lusso19

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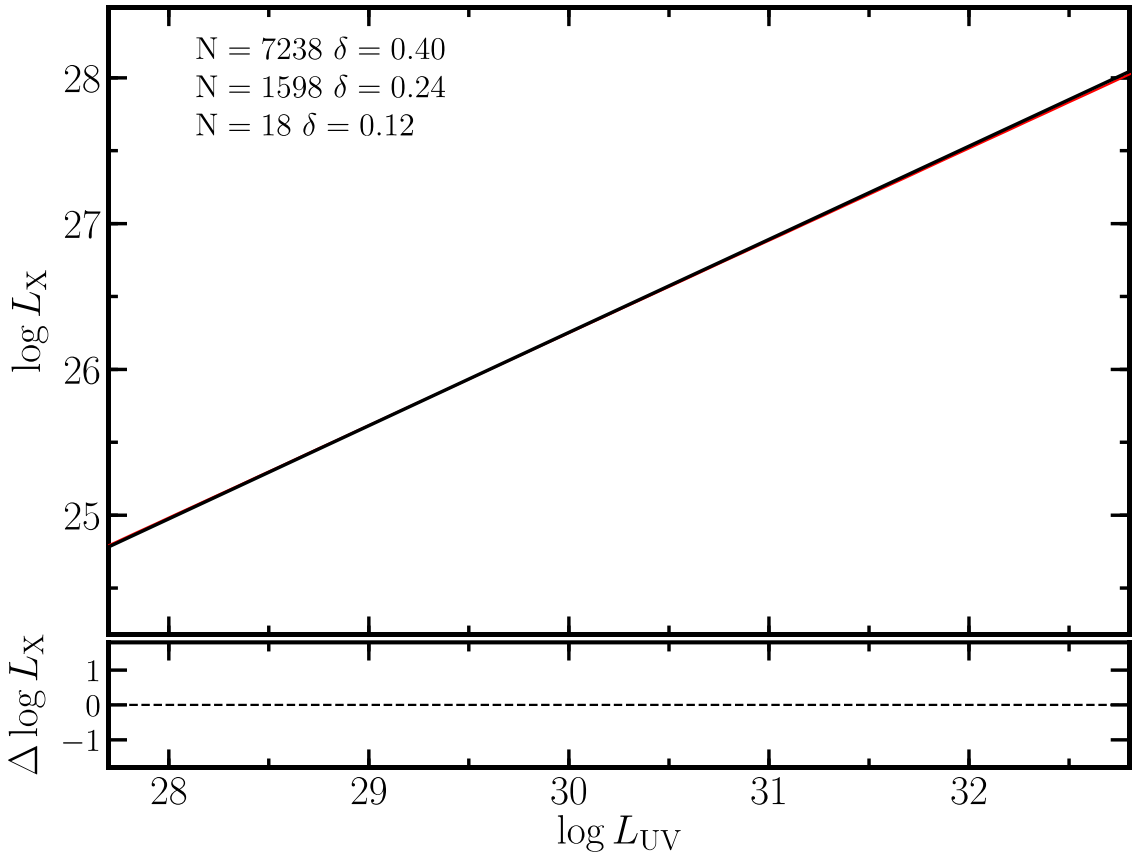
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Distance measurements!

THE L_X-L_{UV} RELATION

δ~0.40 dex δ~0.24 dex δ~0.12 dex

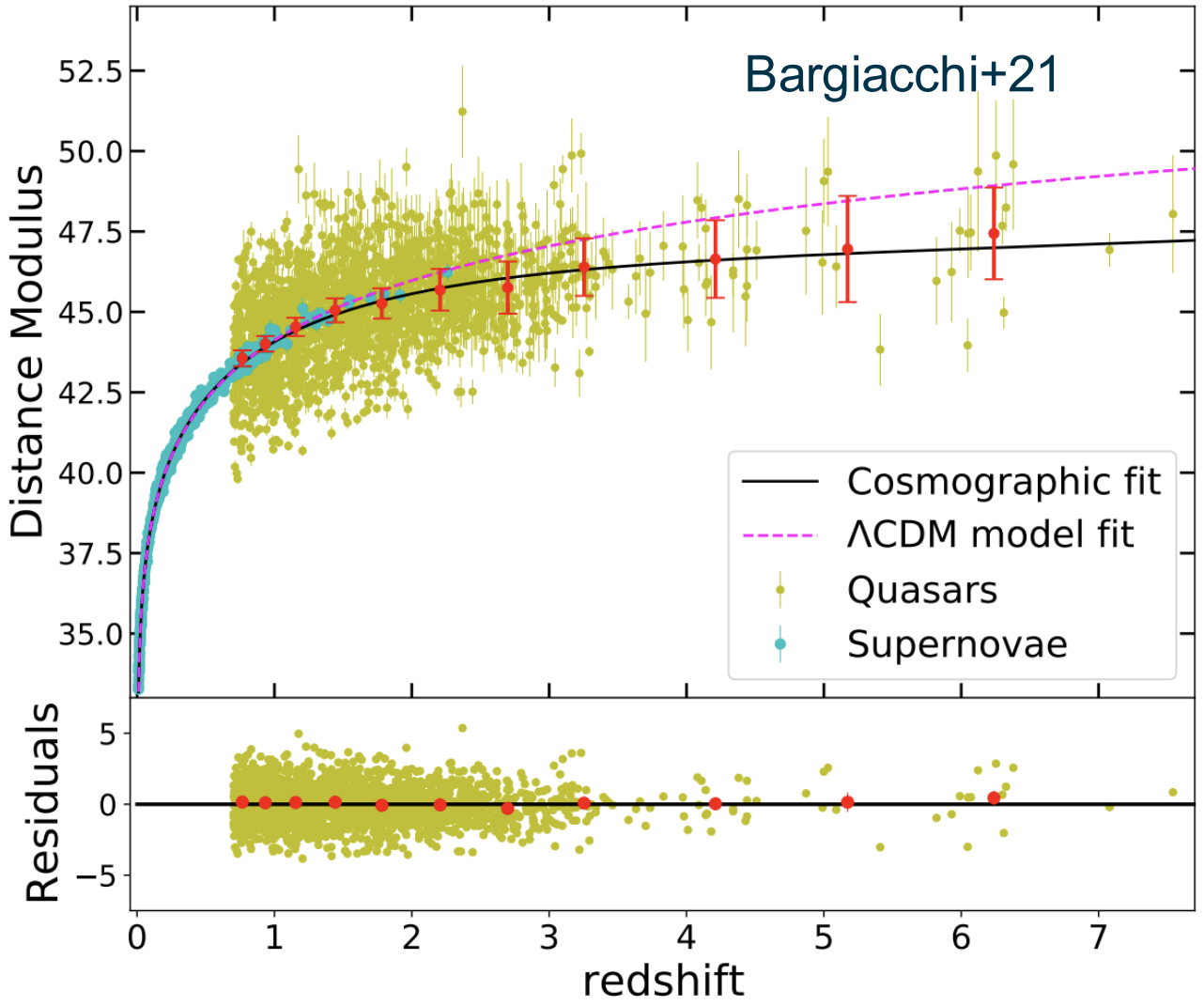


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Sample selection, we remove:

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

THE L_X-L_{UV} RELATION



Extension of the Hubble Diagram

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

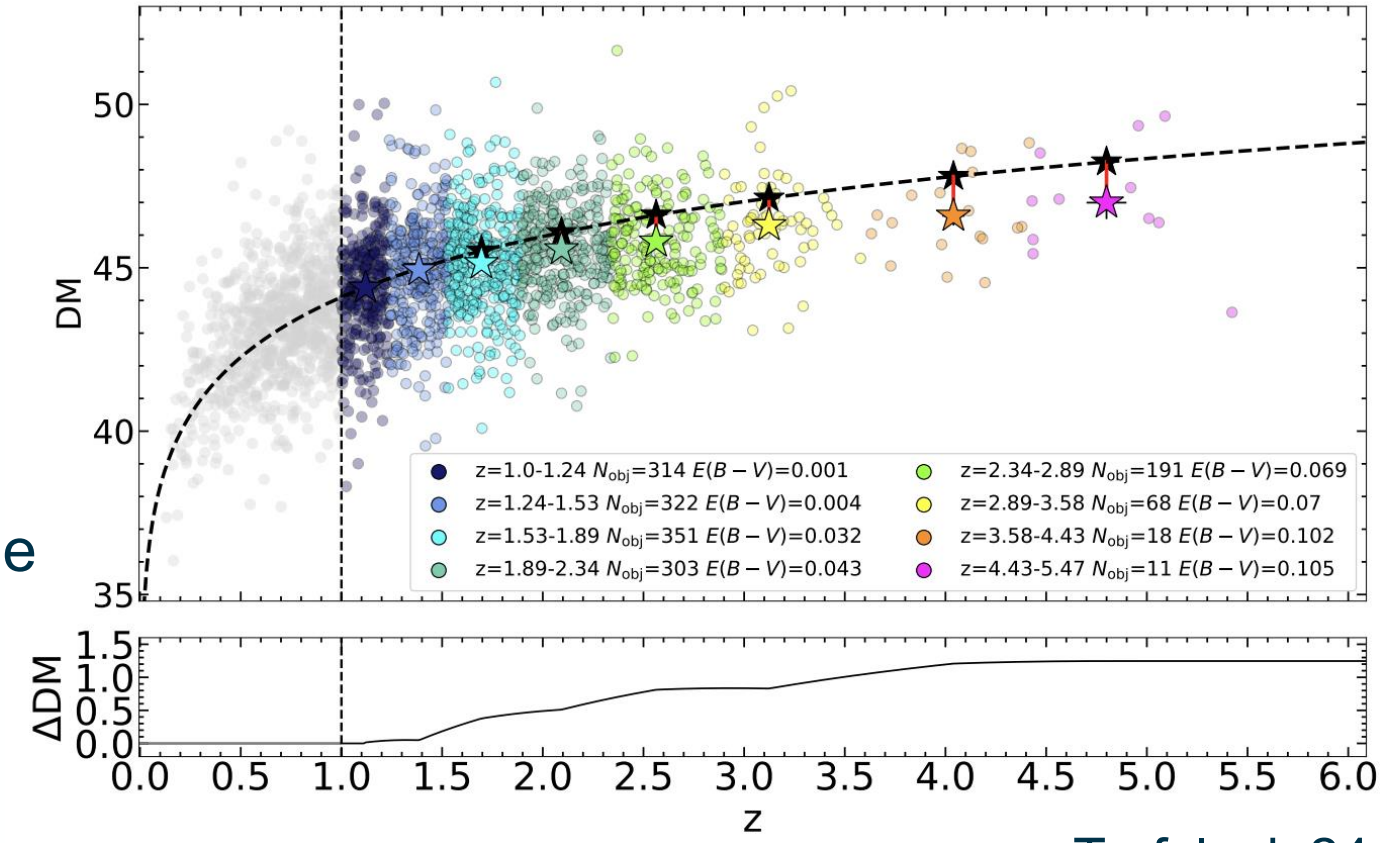
THE L_X-L_{UV} RELATION

Can the tension come from residual reddening? No (Trefoloni+24)

How does the relation change when we use different UV and X-ray indicators? (Signorini+23b)

How low can the dispersion get, when the data quality increases? (Sacchi+22)

What are the causes of the residual dispersion? (Signorini+24)



Trefoloni+24

THE L_X-L_{UV} RELATION

Concerns have been made regarding the method:

- Non-consistency of quasars with SNIa (Khadka & Ratra 2020)
- When studying the relation redshift bins, the bin finiteness biases the results (Petrosian+22)
- When dividing the sample in low and high redshift, there is a discrepancy in the relation parameters (Khadka & Ratra 2020, 2021)
- We need to correct for luminosity evolution with redshift (Singal+2022; Dainotti+2022, 2023; Wang+2022,2024)

I will present the results of Lusso+25 where these concerns are addressed

A&A, 697, A108 (2025)
https://doi.org/10.1051/0004-6361/202453504
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Astronomy & Astrophysics

Are quasars reliable standard candles?

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Received 18 December 2024 / Accepted 27 March 2025

ABSTRACT

In this paper, we address the question of whether the non-linear relation between the X-ray and UV emission of quasars can be used to derive their distances. In previous works of our group, we demonstrated that such a relation does not show any redshift evolution in its slope. The derived distances are in agreement with the concordance (standard) model of cosmology up to $z \sim 1.5$, but they show significant deviations at higher redshifts. Yet, several authors have suggested that this discrepancy is due to inconsistencies between the low- and high-redshift sources within the parent sample, or to a redshift evolution of the relation. Here, we discuss these issues through a quantitative comparison with supernova-derived distances in the common redshift range, complemented by simulations showing that all the claimed inconsistencies would naturally arise from any limitation of the cosmological model adopted for the data analysis; that is, from our ignorance of the "true" cosmology. We argue that the reliability of the method can only be based on a cosmology-independent evaluation of the hypothesis of the non-evolution of the X-ray to UV relation at $z > 1.5$, subsequent to a careful check of the sample selection and of the flux measurements for possible redshift-dependent systematic effects. Since we cannot conceive of any physical reason for a sudden change in the normalisation of the relation at $z > 1.5$, and we can exclude any severe systematic effect in the data selection and flux measurements, we conclude that the application of the X-ray to UV relation to cosmology is well motivated. To further strengthen this point, we need to achieve a better understanding of the physical process behind the observed relation and/or an independent observational proof possibly confirming the discrepancy with ΛCDM found with quasars, such as future supernova measurements at $z \sim 2$ or higher.

Key words. quasars: general – cosmological parameters

1. Introduction

The cosmological concordance model, often called Lambda-CDM, or ΛCDM, where CDM stands for 'cold dark matter' and Λ represents the cosmological constant, is the best description of the current observations. The accelerated expansion of the Universe (see also Riess et al. 1998; Perlmutter et al. 1999; Weinberg et al. 2013 for a review), the cosmic microwave background (CMB; e.g. Bennett et al. 1996), and the measurement of baryon acoustic oscillations (BAOs; see Eisenstein 2005 for a review) are key predictions of ΛCDM, which led to its general consensus amongst the scientific community. Nonetheless, discrepancies with ΛCDM have also been observed, the prevailing ones being the 'σ_8 tension' and the 'Hubble tension' (see Abdalla et al. 2022 for a review of cosmological tensions and anomalies). Most recently, cosmological results from the first year of galaxy, quasar, and Lyman-α forest BAO measurements from the Dark Energy Spectroscopic Instrument (DESI Data Release 1) have shown a preference for $w_0 > -1$ and $w_a < 0$ when a time-varying energy density equation of state, $w(z) = w_0 + w_a z/(1+z)$, is considered, which departs from ΛCDM at about the 3σ statistical level, depending on the specific data set used (Adame et al. 2025). The same overabundance of very high-redshift galaxies that are being discovered by the James Webb Space Telescope (e.g. Finkelstein et al. 2023; Harikane et al. 2023) poses several challenges to the timescale of structure formation in a ΛCDM Universe (e.g. Boylan-Kolchin 2023; Melia 2023). In this landscape, our analysis of the distance-redshift relation (also referred to as the Hubble-Lemaître diagram) of luminous, unobscured active galactic nuclei (AGNs, where quasars represent the most powerful members of this population) has also revealed a deviation from the predictions of the flat ΛCDM model, which emerges at high redshift with a statistical significance of $3–4\sigma$ (Risaliti & Lusso 2019; Lusso et al. 2019, 2020, see also Bargiacchi et al. 2022). While complementary to the traditional resort to supernovae to estimate the cosmological parameters, quasars extend the distance-redshift diagram to a redshift range that is inaccessible to supernovae ($z = 2–7.5$). All the above-mentioned findings, if confirmed, would be important indications of the need of new physics beyond ΛCDM.

The determination of the distance versus redshift relation for quasars, and thus of the cosmological model parameters, is obtained from the empirical correlation between the X-ray and UV emission observed in AGNs (Tananbaum et al. 1979; Zamorani et al. 1981; Avni & Tananbaum 1982, 1986). Such a relation is non-linear, and has been observed over almost five orders of magnitude in UV luminosity with a dispersion of just ~0.2 dex, implying that there must be a ubiquitous physical mechanism that regulates the energy transfer from the accretion disc to the X-ray emitting corona (e.g. Lusso & Risaliti 2017, and references therein). Several models have been proposed to explain the physics behind the X-ray to UV relation, involving, for example, reprocessing of radiation from a non-thermal electron-positron pair cascade (Svensson 1982, 1984; Guilbert et al. 1983; Zdziarski et al. 1990), a two-phase accretion disc model in which the entire gravitational power is dissipated via buoyancy and reconnection of magnetic fields in a uniform hot plasma in close vicinity of the cold opaque disc (Haardt & Maraschi 1991, 1993; Svensson & Zdziarski 1994;

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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?

SNIa + QUASARS – 0.7 < z < 1.6

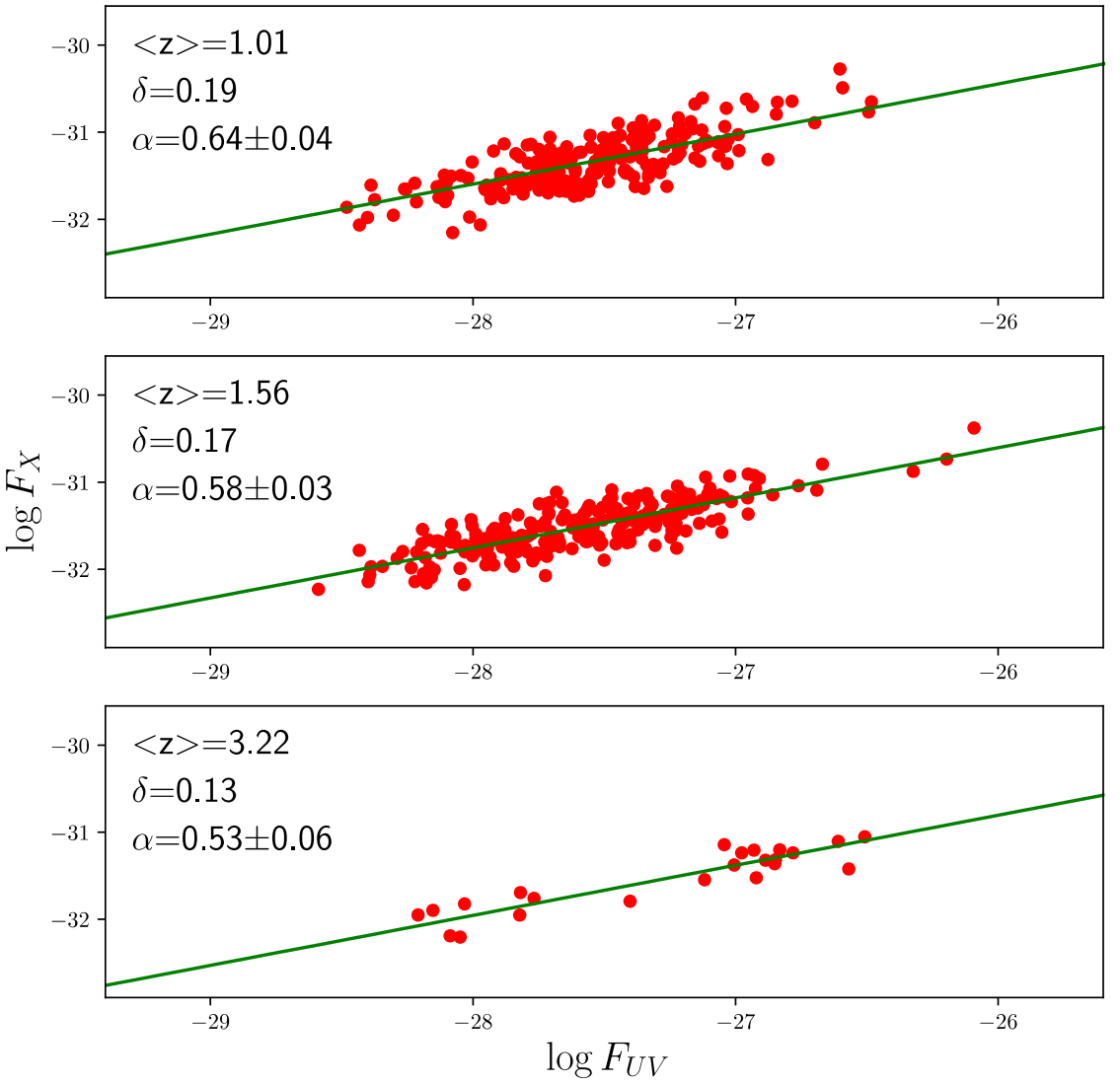
$$\log(L_X) = \gamma \log(L_{UV}) + \beta$$

How do we test γ and β ?

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

(i) we test γ in small redshift bins using fluxes. At redshift below 0.7, the host galaxy can mess up the 2500Å measurement. In the 0.7-1.6 range, we see no redshift evolution

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



SNIa + QUASARS – 0.7 < z < 1.6

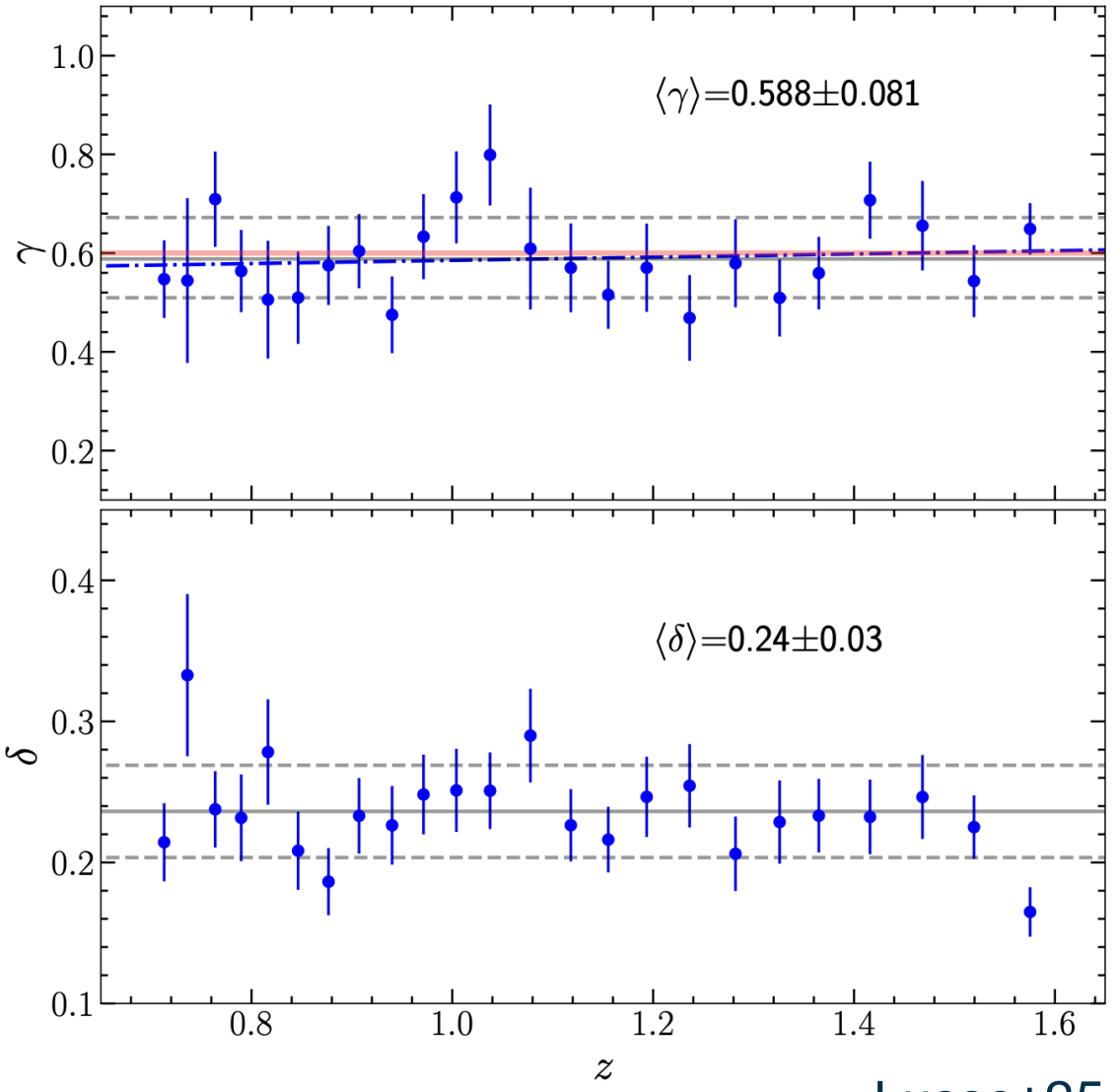
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Lusso+25

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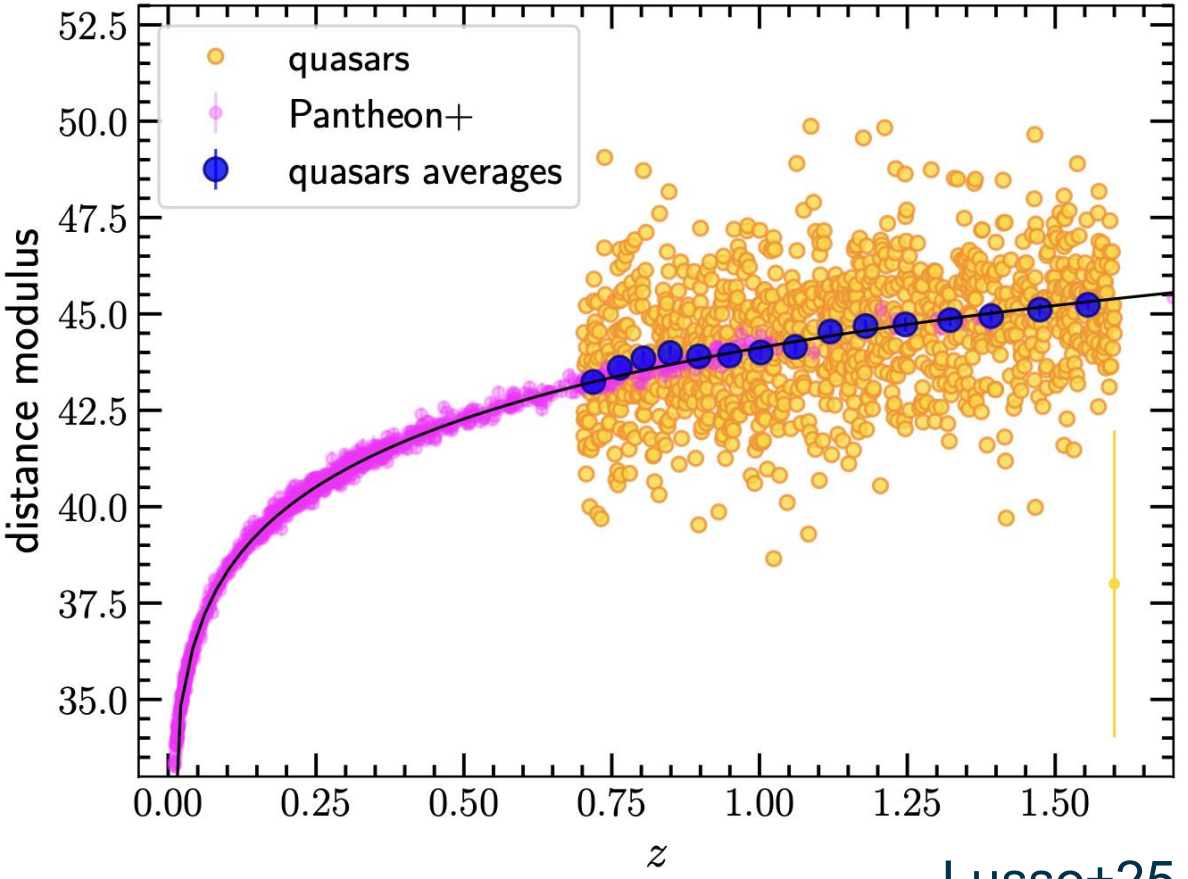
$$\log(L_X) = \gamma \log(L_{UV}) + \beta$$

(ii) 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 DM in the common redshift range to find β



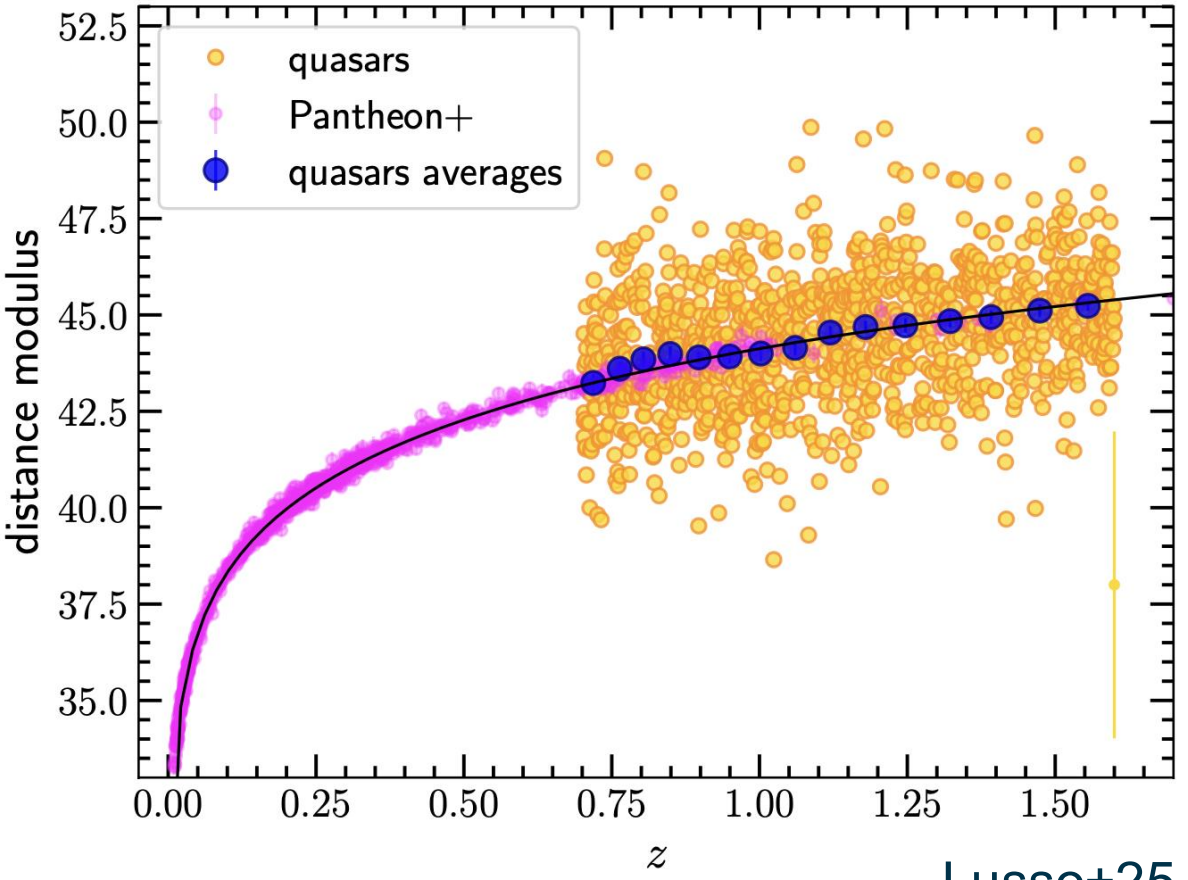
Lusso+25

SNIa + QUASARS – 0.7 < z < 1.6

When assuming flat ΛCDM:
Ω_m = 0.284 ±0.013, γ= 0.605 ±0.015,
β= 8.11±0.46

- the matter parameter is the expected one
- the γ is the same as the average in redshift bins
- the fact that the shape is the same, once the zero-point is set, shows β is not evolving

Results are analogous when performing a cosmographic fit
γ= 0.601 ±0.015 and β= 8.23 ±0.46



Lusso+25

HIGH(ER) REDSHIFT

But what if γ and β start 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

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

HIGH(ER) REDSHIFT

Test using Pantheon+

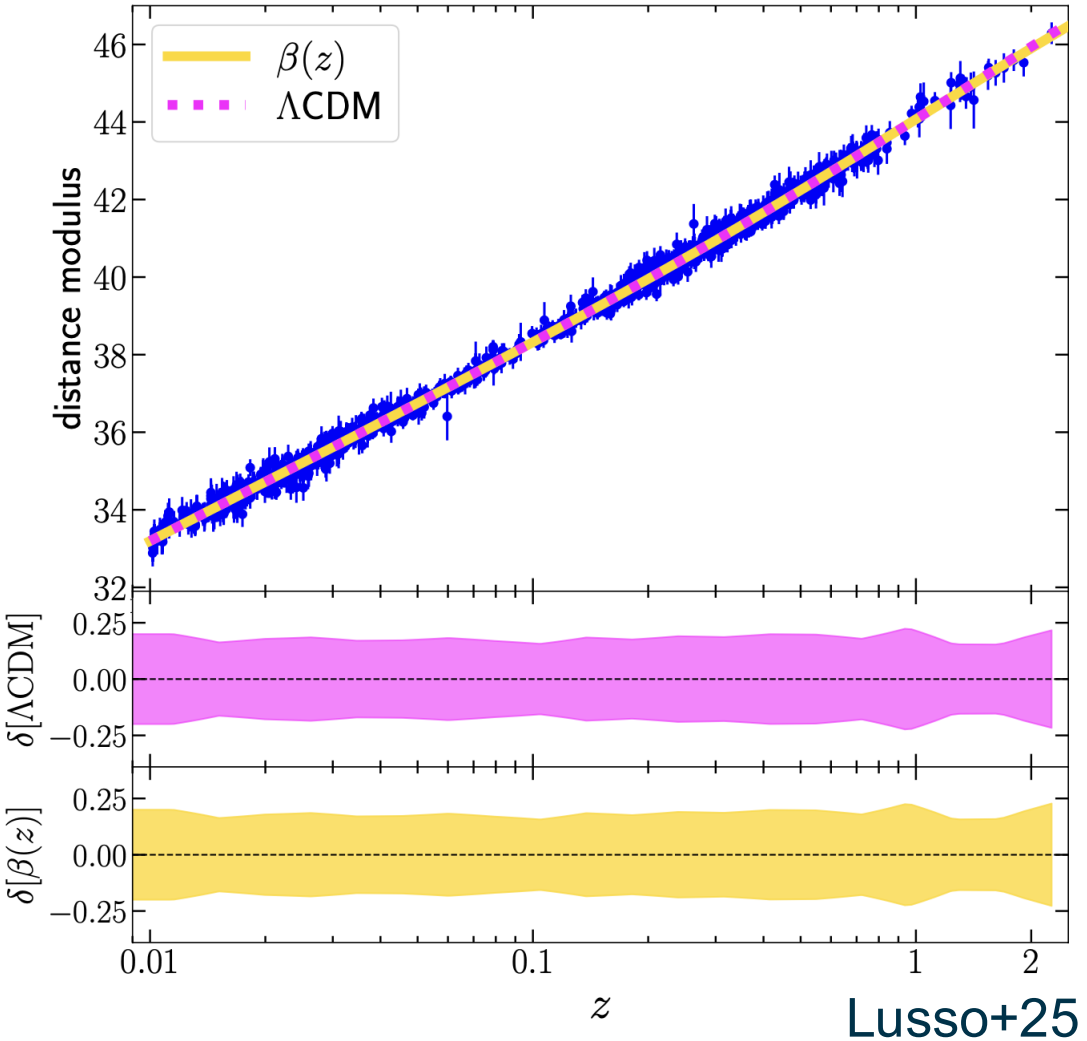
Fit of the HD assuming a fixed ΛCDM model with

$$\Omega_M = 1 \text{ and } \Omega_\Lambda = 0$$
+
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 the ultimate standardisability of a given data set

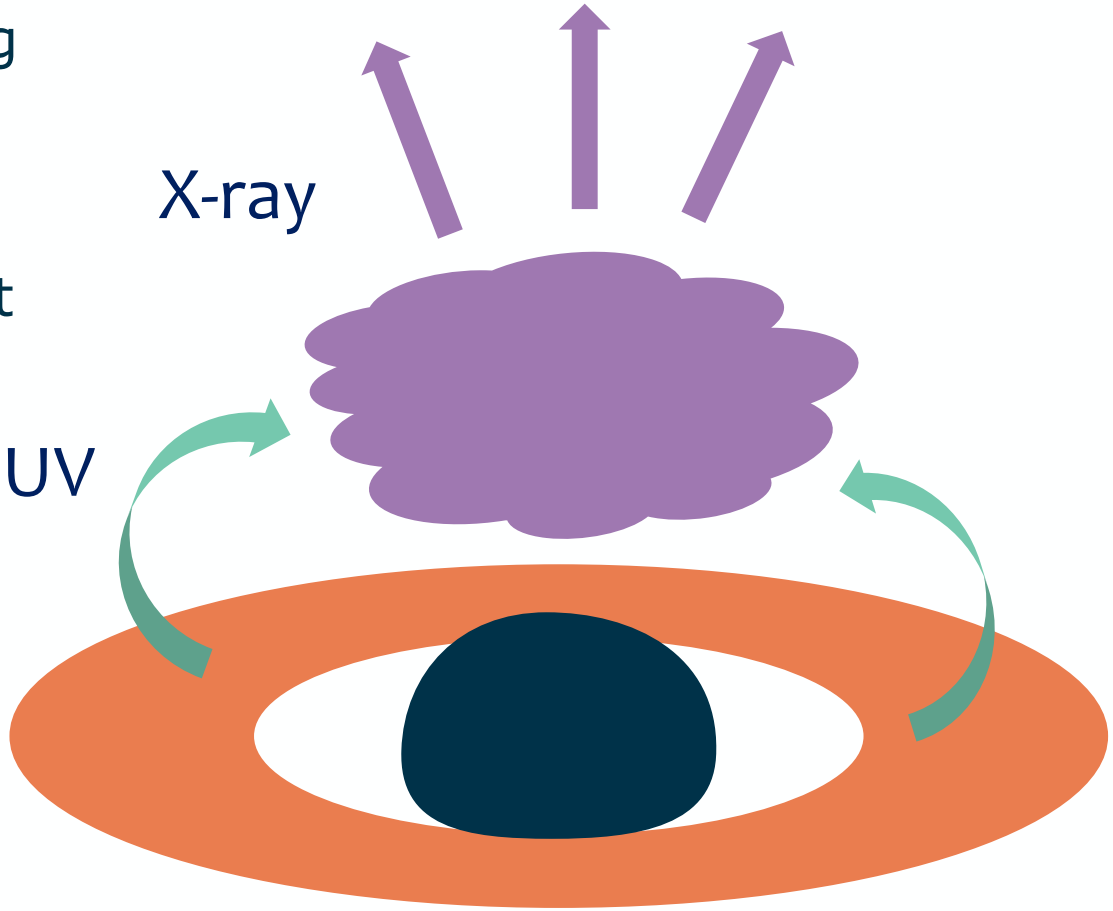


Lusso+25

HIGH(ER) REDSHIFT

We need <u>other reasons</u> to say that β is not evolving

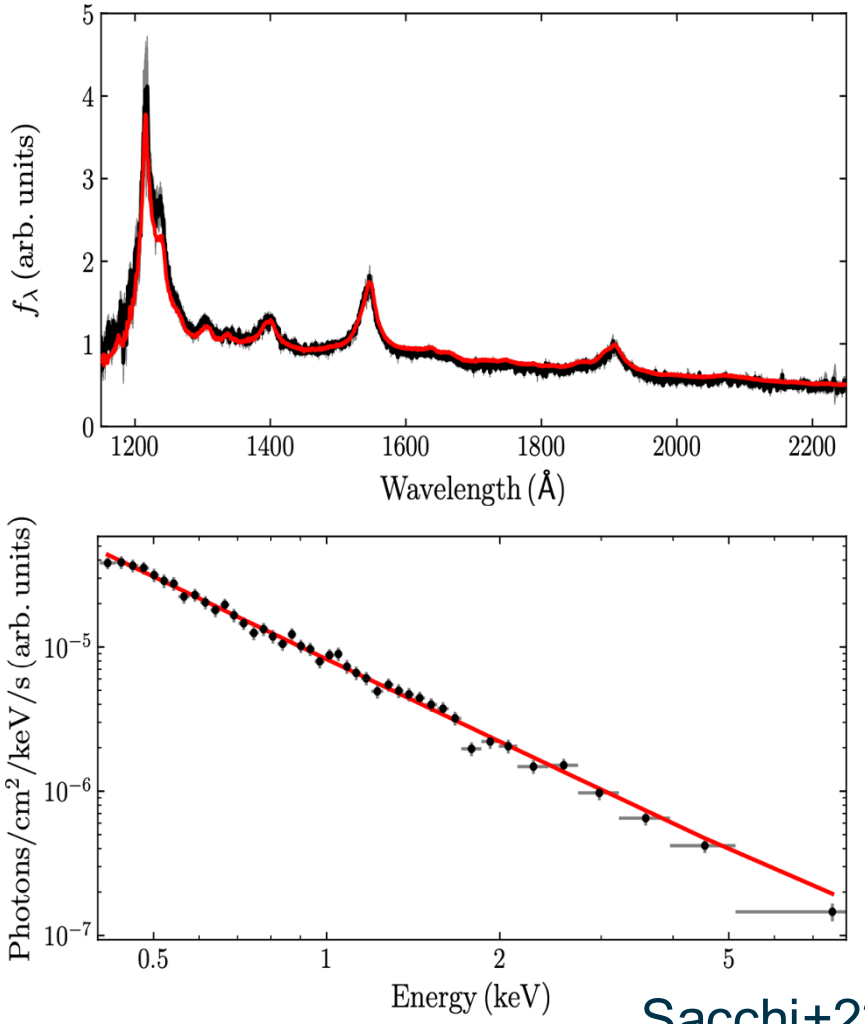
- Accretion physics on SMBH is the same at all z
- Quasars agree with SNIa in the common redshift range; if accretion physics and γ do not evolve, why would β?



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- High redshift UV and X-ray spectra look exactly like the low redshift ones (Sacchi+22, Trefoloni+24a)

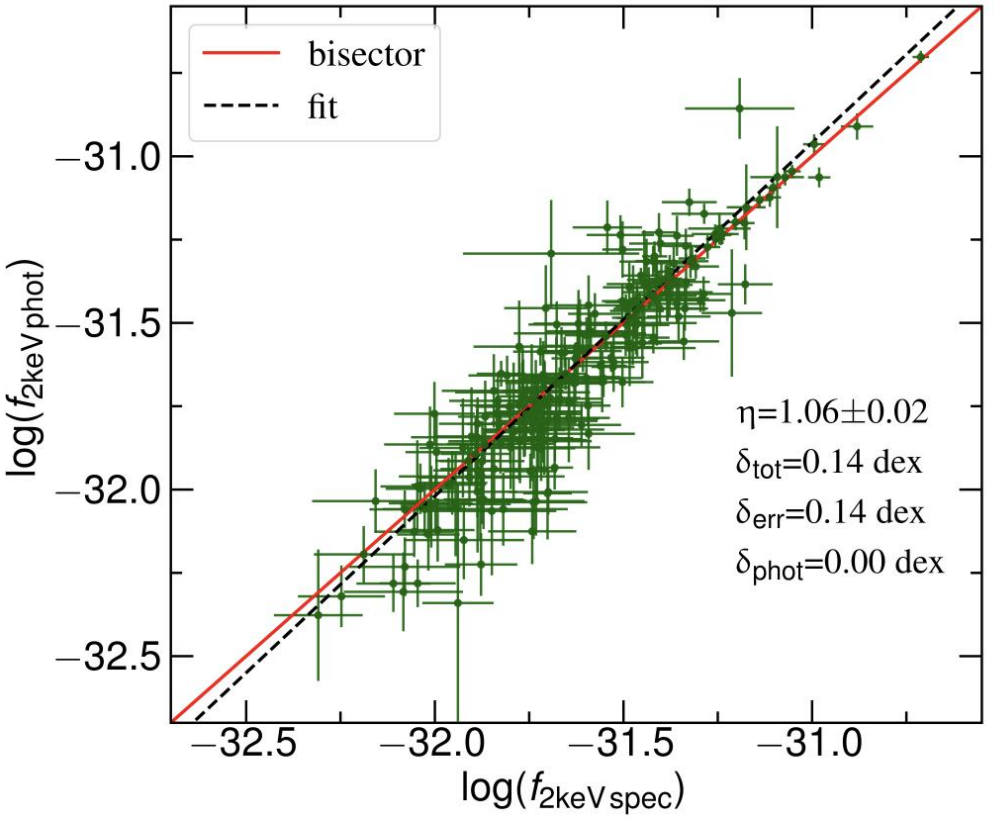


Sacchi+22

HIGH(ER) REDSHIFT

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- High redshift UV and X-ray spectra look exactly like the low redshift ones (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

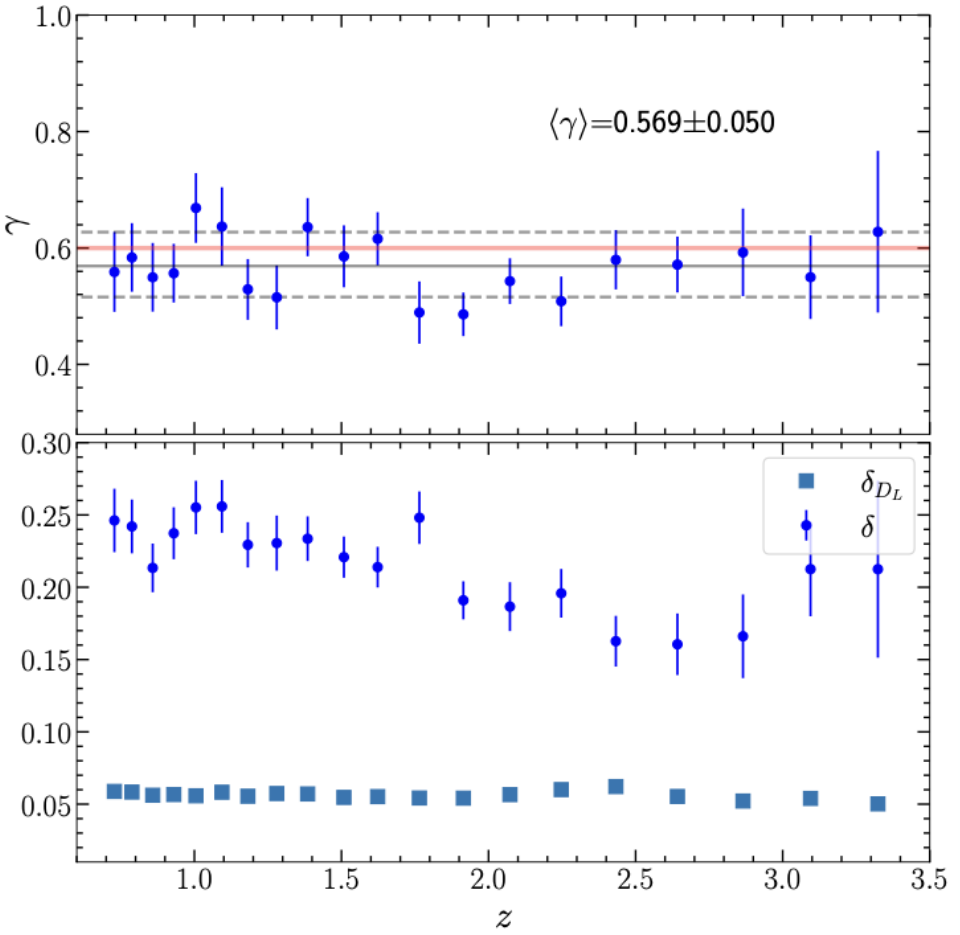


Signorini+24

HIGH(ER) REDSHIFT

Regarding γ at higher z, can the binning influence the mean value?

Lusso+25



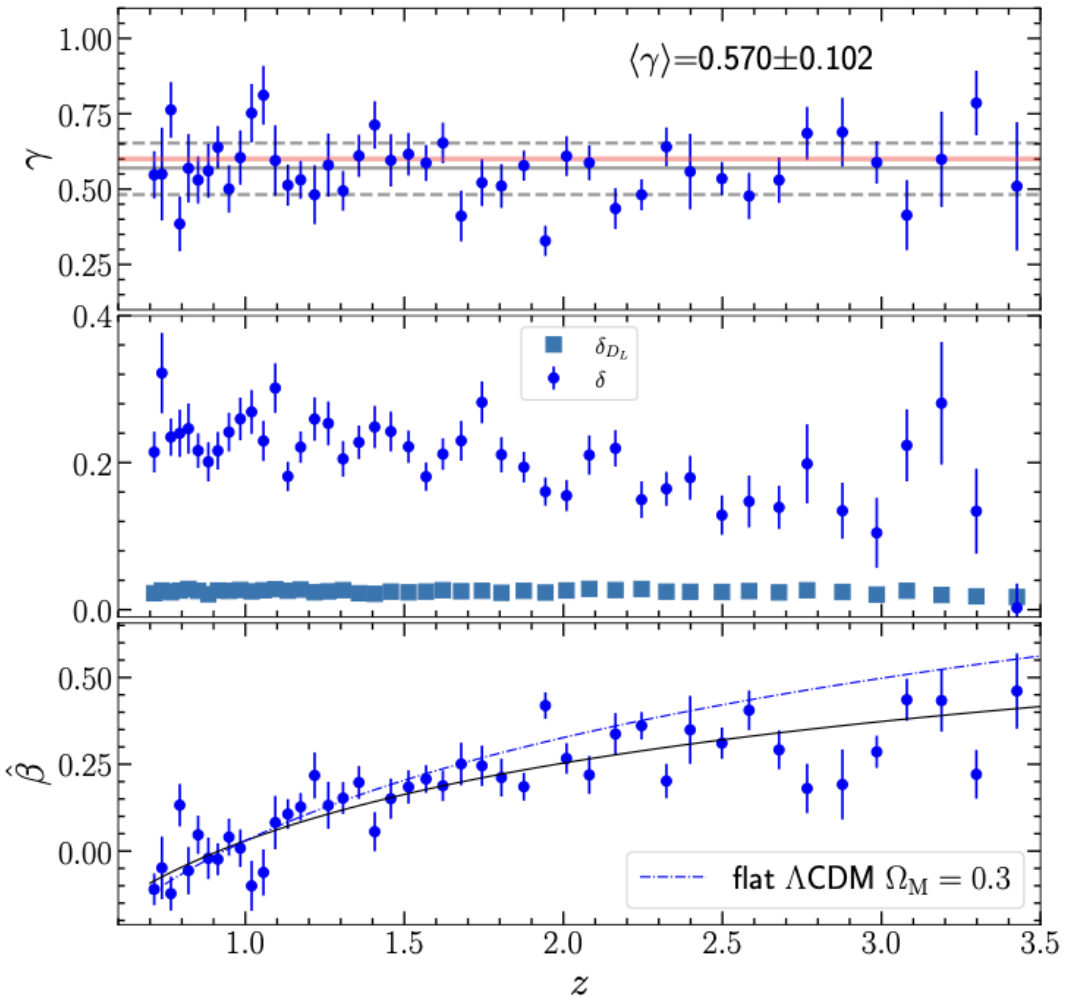
N=20 γ =0.569±0.050

HIGH(ER) REDSHIFT

Regarding γ at higher z, can the binning influence the mean value?

No, as long as the bins are spaced so that the distance dispersion (<0.1 dex) is smaller than the expected intrinsic dispersion of the relation

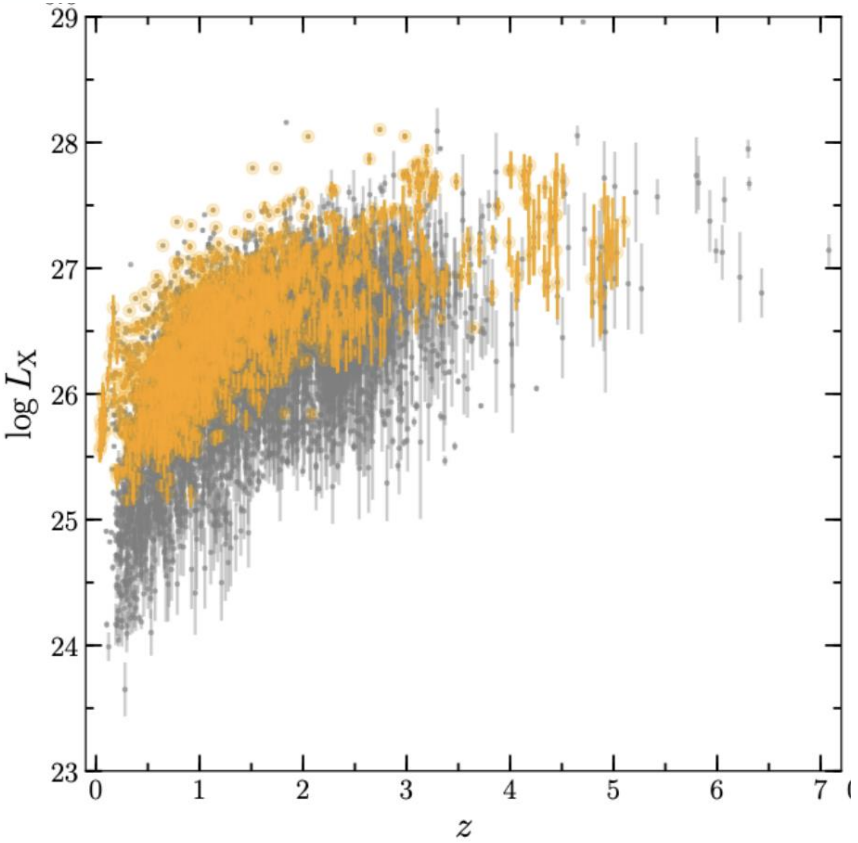
Lusso+25



N=50, γ =0.570±0.102

LUMINOSITY EVOLUTION?

Do we need to apply the Efron-Petrosian correction to quasars?



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$$L' = L/g(z) \qquad g(z) = \frac{(1+z)^{\eta}}{1+\left(\frac{1+z}{Z_{cr}}\right)^{\eta}}$$

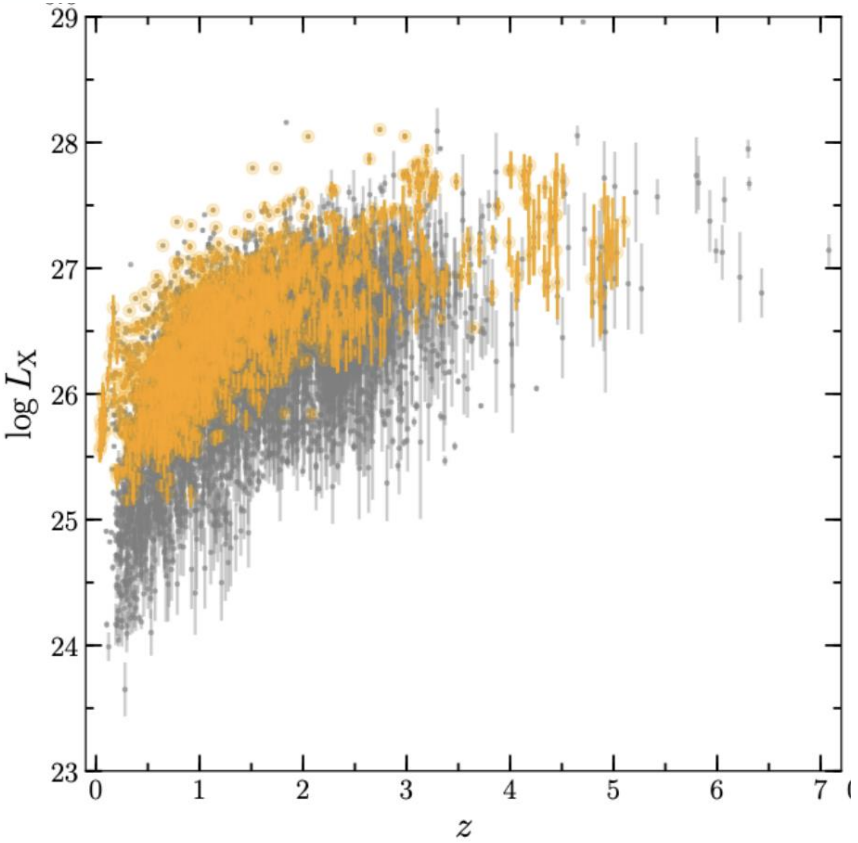
γ~ 0.28 (Singal+22)

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γ~0.6 (Lenart+23, Dainotti+22)

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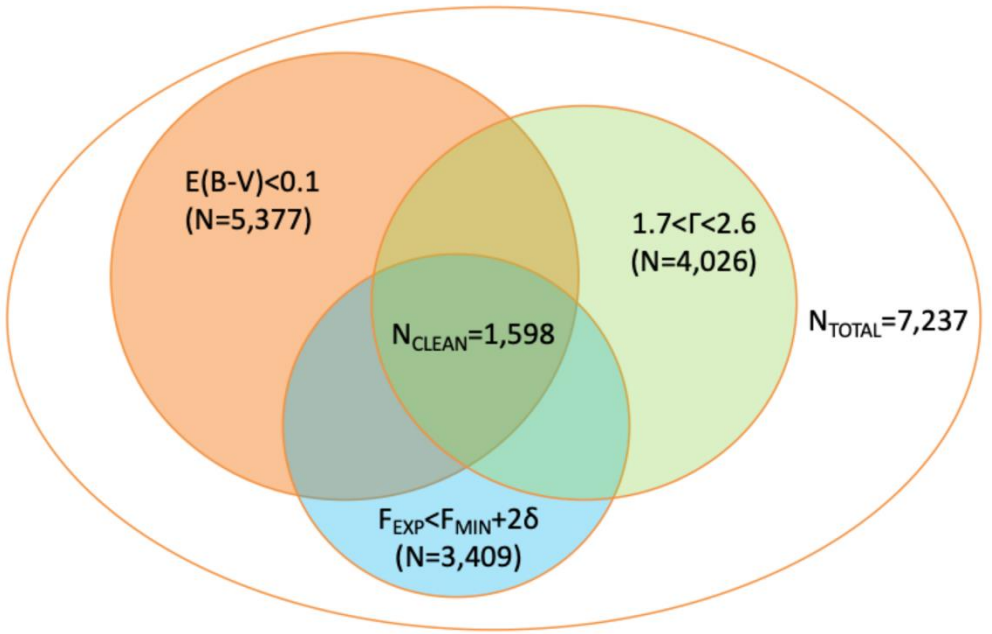
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Do we need to apply the Efron-Petrosian correction to quasars?



Risaliti&Lusso19

But quasars selected for cosmology are not simply a flux-limited sample!

- In the UV, SDSS quasars are color-color selected
- In the X-ray, most sources are serendipitous so the flux threshold changes object to object
- Further selection (at a great statistical cost!) is performed to remove reddened/obscured objects and to avoid the Eddington bias

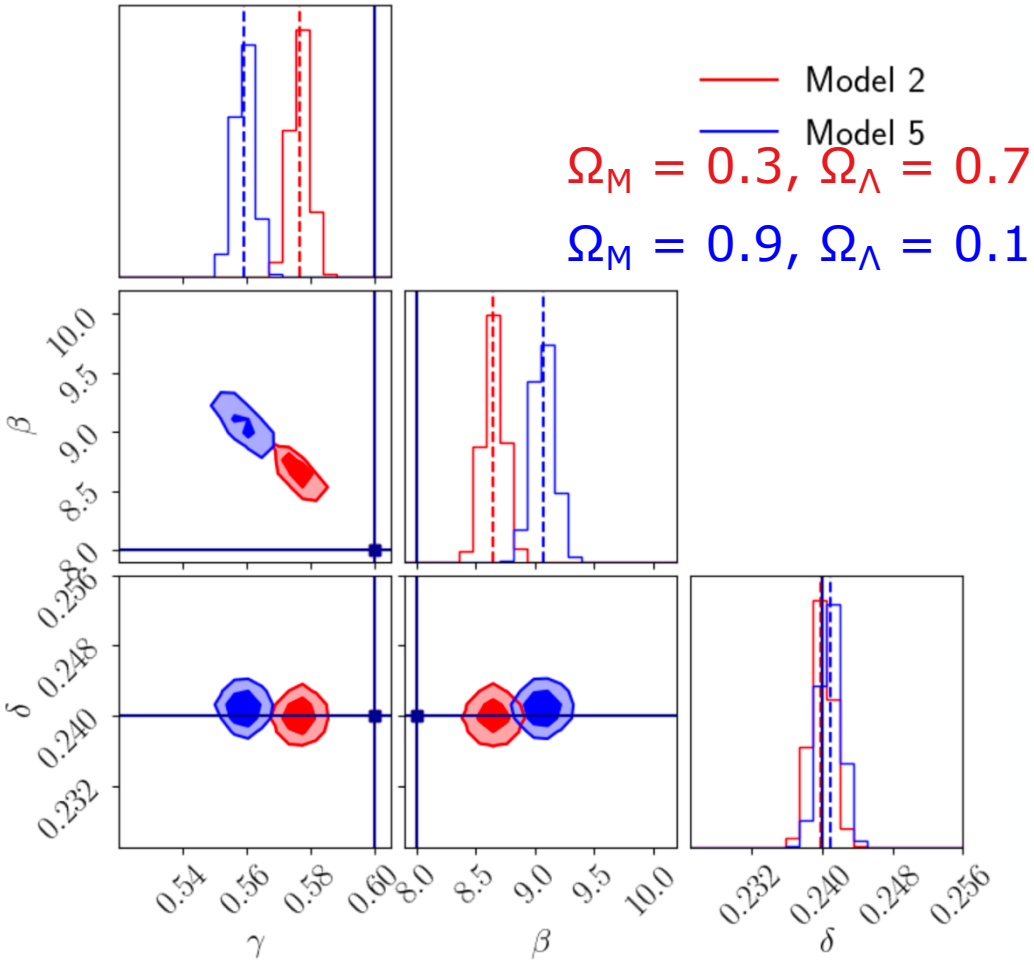
- Non-accurate determinations of the threshold can bias the EP implementation (Byant 2021)

LOW VERSUS HIGH REDSHIFT

Not knowing the correct cosmological model can show up as an apparent discrepancy between the low redshift and high redshift values of γ and β

Mock sample with $\Omega_M = 0.1$ and $\Omega_\Lambda = 0.9$.

We fit with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ (red) and $\Omega_M = 0.9$, $\Omega_\Lambda = 0.1$ (blue).
The value of γ and β obtained are different from the input!



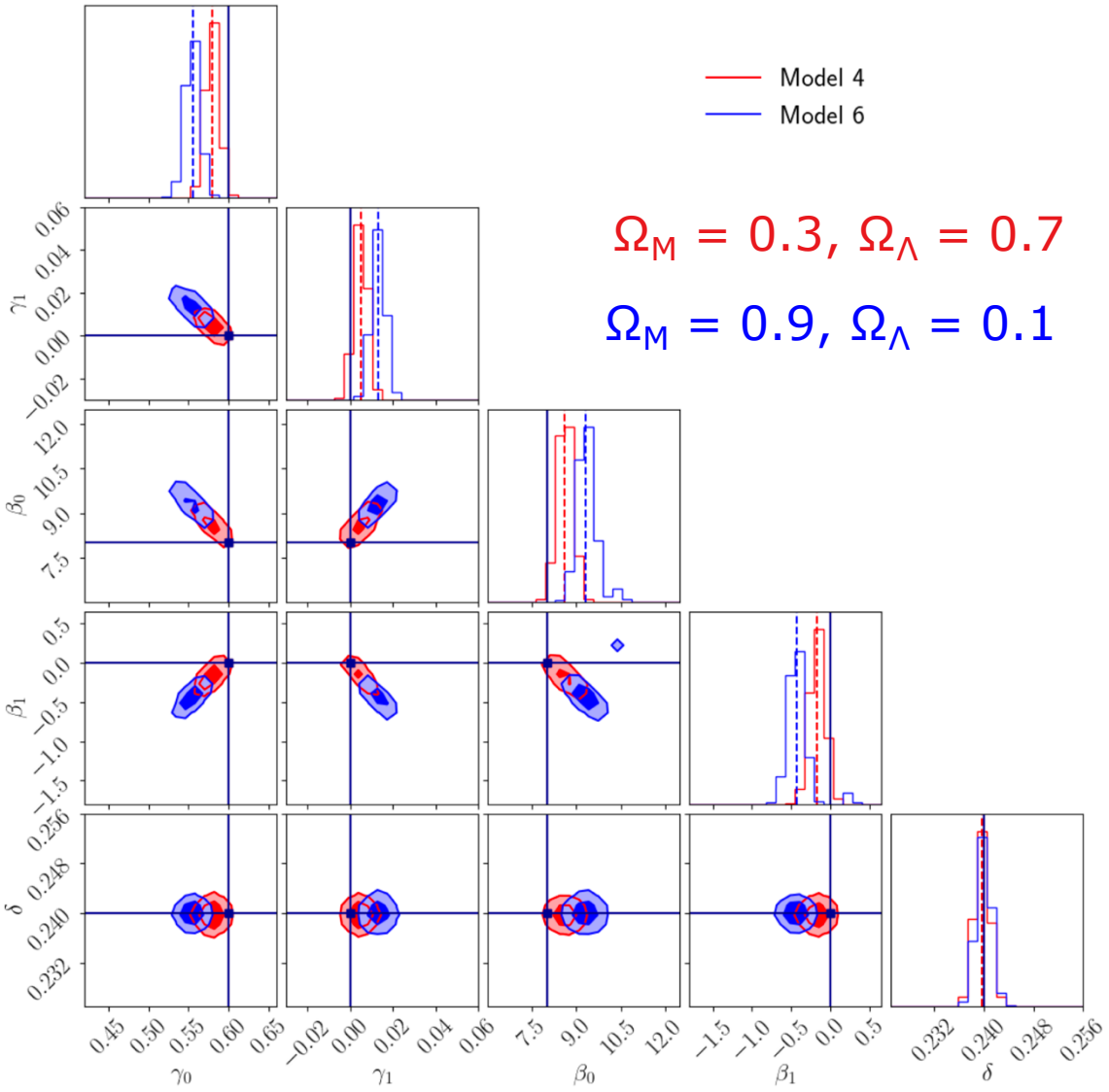
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The value of γ and β obtained are different from the input!

If we allow γ and β to vary, **the further from the 'truth' the chosen model is, the more significant is an evolution of γ and β**



CONCLUSIONS

The L_X-L_{UV} relation in quasars can be used to standardize them and measure distances up to z~7 – and we find a ~4σ tension with ΛCDM

We can not rely on cosmology-dependent tests when validating a standard candle

We can constrain that γ does not evolve with redshift by analysing the flux-flux relation in small redshift bins

We need to rely on physical reasons to believe the non evolution of the normalisation β at high z

Do you want to use quasars to test your favourite alternative cosmological model at high z? Let's chat at the coffee break!

