WHAT QUASARS CAN TELL US ON THE ACCELERATING UNIVERSE

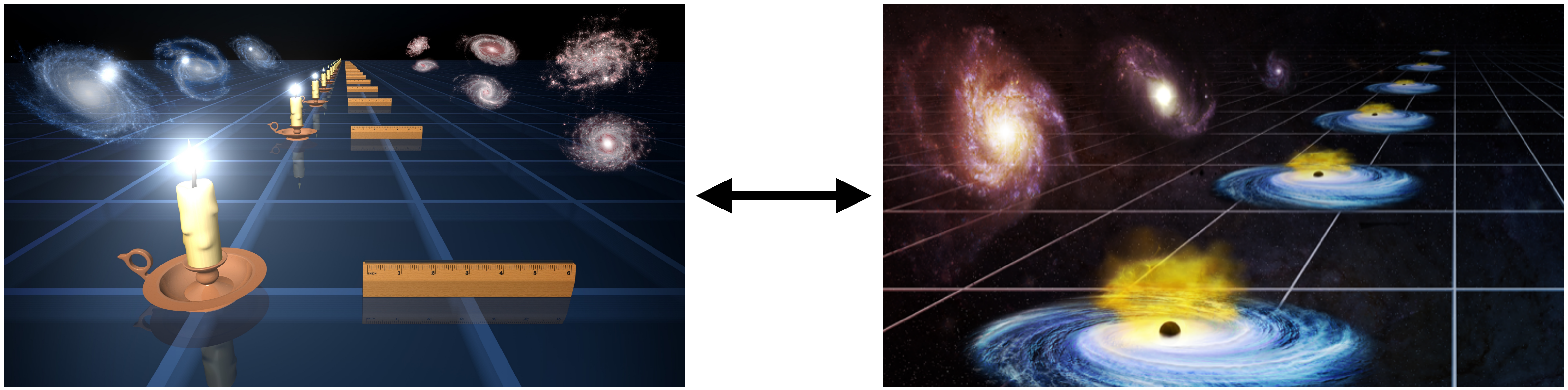
Elisabeta Lusso

University of Firenze, Physics & Astronomy Department
Arcetri Astrophysical Observatory - INAF

Guido Risaliti, G. Bargiacchi, E. Nardini, M. Signorini, B. Trefoloni and others

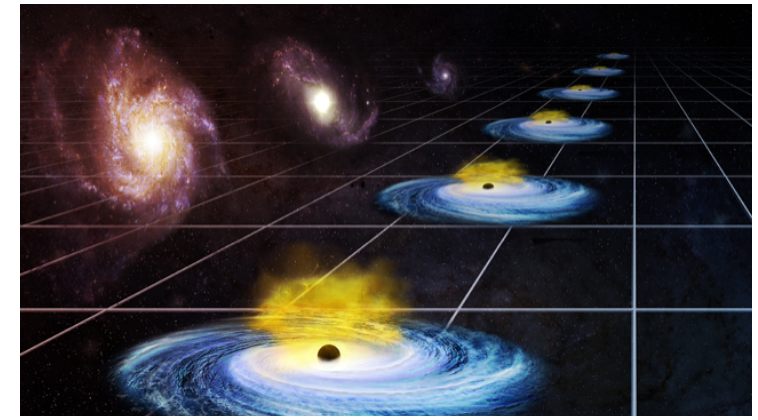
Cosmology 2023 in Miramare
Sept 1st, 2023

STANDARD(IZABLE) CANDLE FOR COSMOLOGY



1. Determine their distance (absolute/intrinsic emission)
2. Observe over a wide redshift range

QUASAR AS STANDARD CANDLES?

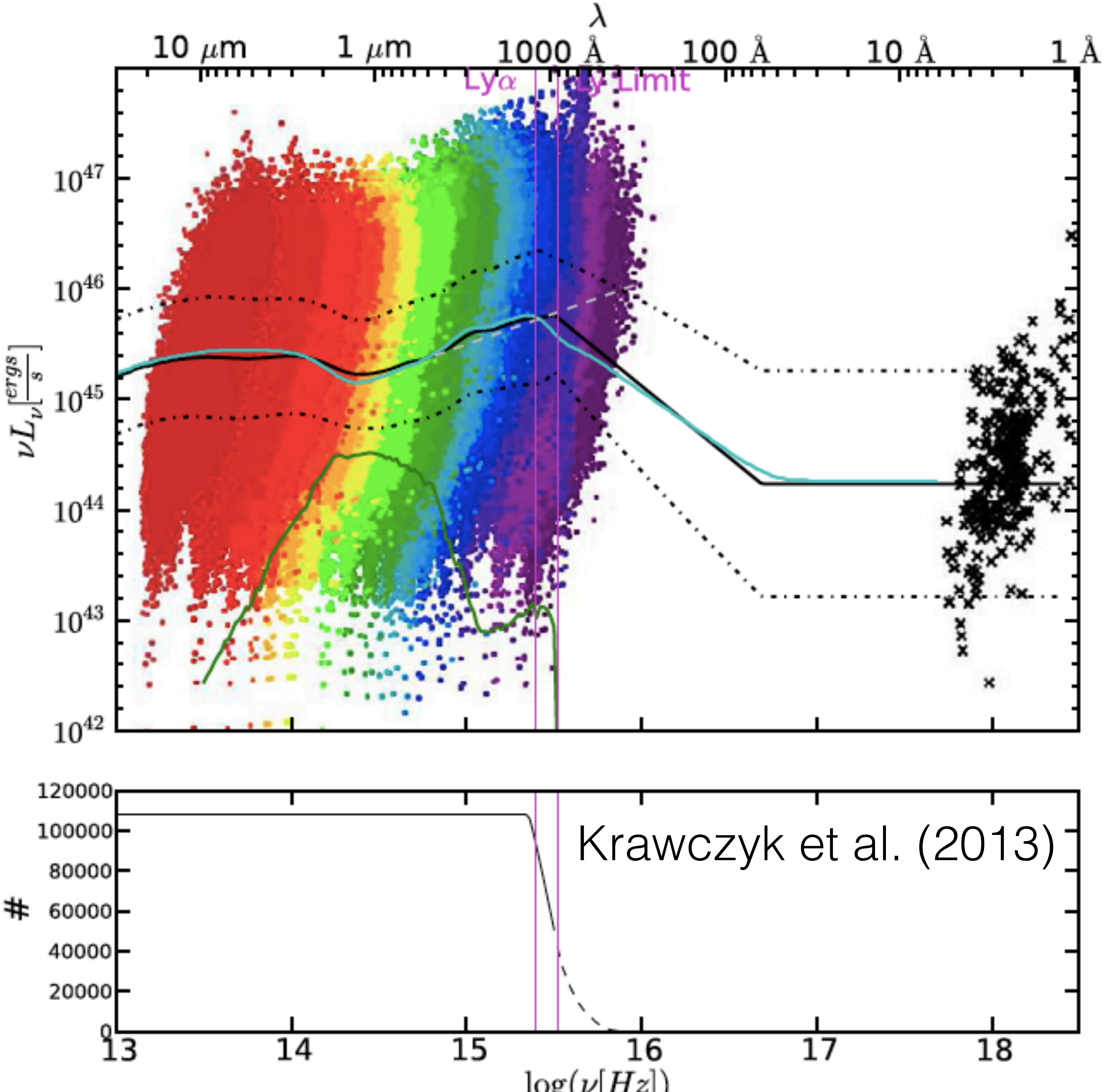


Very luminous objects up to high redshift (z~7.5), but vary in the wavelengths of light they produce

Several experiments:

- *Baldwin* effect (anti-correlation between the EW of em. lines and continuum luminosity, high dispersion)
- Quasar light curves (Dai et al. 2012, telescope time consuming)
- *Radius-luminosity relation* (Watson et al. 2011, Du & Wang 2019, reverberation mapping; Kilerci Eser et al. 2015, low redshift, Narayan et al. 2022)
- *X-ray variability - luminosity relation* (La Franca et al. 2014, high dispersion ~0.6dex)
- *Quasars radiating closest to the Eddington limit* (Marziani & Sulentic 2014)
- Time delays in lensed quasars (COSMOGRAIL - COSmological MOnitoring of GRAvItational Lenses; H0LiCOW - H0 Lenses in COSMOGRAIL's Wellspring)
- *X-ray - UV flux relation* (e.g. Risaliti & Lusso+15, +19; Lusso & Risaliti+16, +17)

QUASAR AS STANDARD CANDLES?

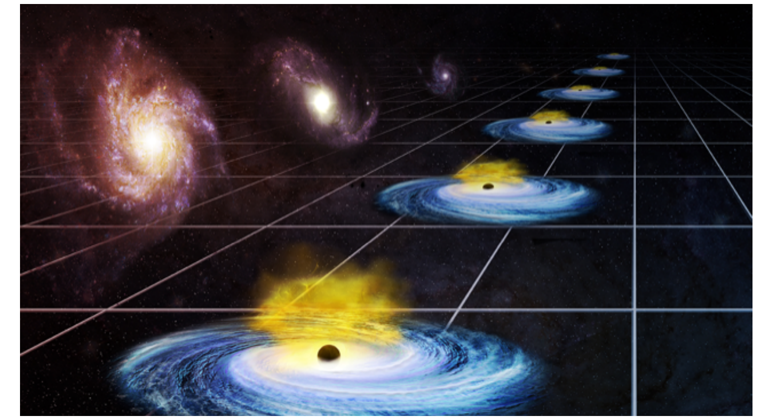


Krawczyk et al. (2013)

Elisabeta Lusso UniFi

QUASAR AS STANDARD CANDLES?

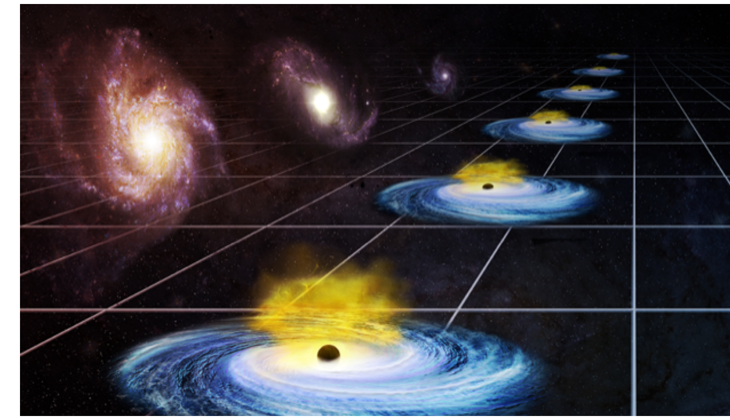
Very luminous objects up to high redshift (z~7.5), but vary in the wavelengths of light they produce



Several experiments:

- *Baldwin* effect (anti-correlation between the EW of em. lines and continuum luminosity, high dispersion)
- Quasar light curves (Dai et al. 2012, telescope time consuming)
- *Radius-luminosity relation* (Watson et al. 2011, Du & Wang 2019, reverberation mapping; Kilerci Eser et al. 2015, low redshift, Narayan et al. 2022)
- *X-ray variability - luminosity relation* (La Franca et al. 2014, high dispersion ~0.6dex)
- *Quasars radiating closest to the Eddington limit* (Marziani & Sulentic 2014)
- Time delays in lensed quasars (COSMOGRAIL - COSmological MOnitoring of GRAvItational Lenses; H0LiCOW - H0 Lenses in COSMOGRAIL's Wellspring)
- *X-ray - UV flux relation* (e.g. Risaliti & Lusso+15, +19; Lusso & Risaliti+16, +17)

QUASAR AS STANDARD CANDLES?

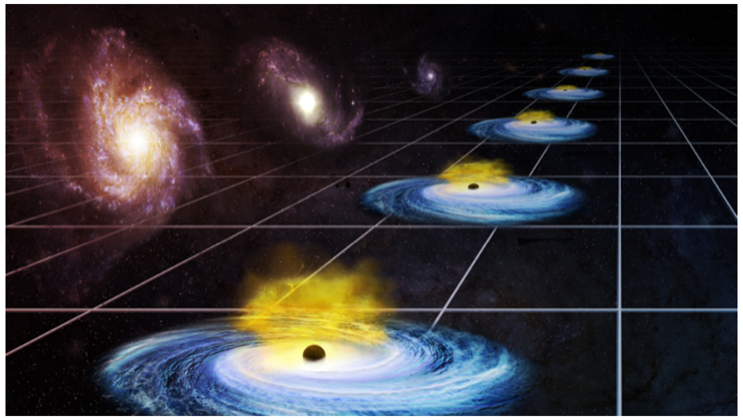


Very luminous objects up to high redshift (z~7.5), but vary in the wavelengths of light they produce

Several experiments:

- *Baldwin* effect (anti-correlation between the EW of em. lines and continuum luminosity, high dispersion)
- Quasar light curves (Dai et al. 2012, telescope time consuming)
- *Radius-luminosity relation* (Watson et al. 2011, Du & Wang 2019, reverberation mapping; Kilerci Eser et al. 2015, low redshift, Narayan et al. 2022)
- *X-ray variability - luminosity relation* (La Franca et al. 2014, high dispersion ~0.6dex)
- *Quasars radiating closest to the Eddington limit* (Marziani & Sulentic 2014)
- Time delays in lensed quasars (COSMOGRAIL - COSmological MOnitoring of GRAvItational Lenses; H0LiCOW - H0 Lenses in COSMOGRAIL's Wellspring)
- *X-ray - UV flux relation* (e.g. Risaliti & Lusso+15, +19; Lusso & Risaliti+16, +17)

QUASAR AS STANDARD CANDLES?



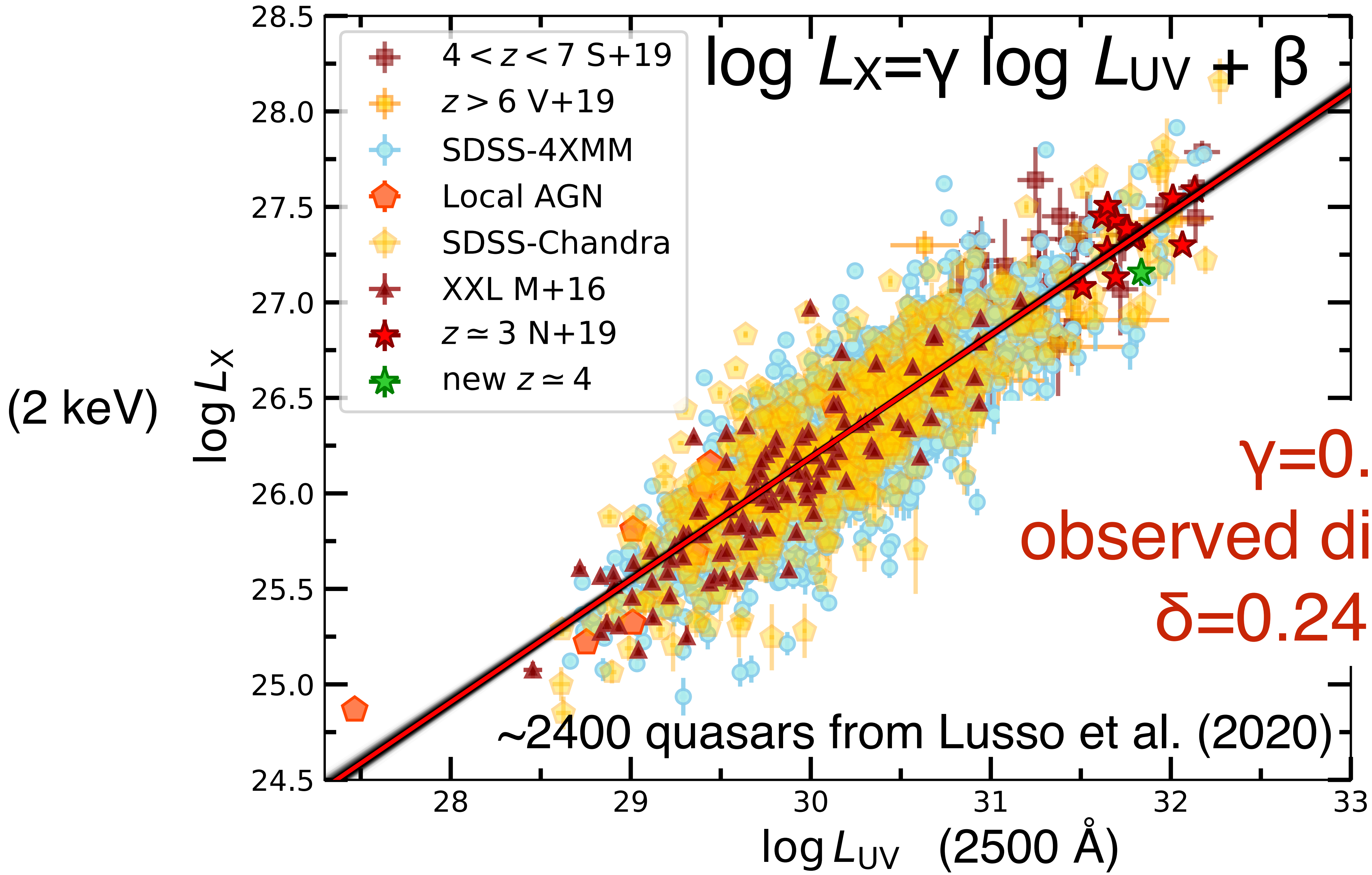
Very luminous objects up to high redshift (z~7.5), but vary in the wavelengths of light they produce

Several experiments:

- *Baldwin* effect (anti-correlation between the EW of em. lines and continuum luminosity, high dispersion)
- Quasar light curves (Dai et al. 2012, telescope time consuming)
- *Radius-luminosity relation* (Watson et al. 2011, Du & Wang 2019, reverberation mapping; Kilerci Eser et al. 2015, low redshift, Narayan et al. 2022)
- *X-ray variability - luminosity relation* (La Franca et al. 2014, high dispersion ~0.6dex)
- *Quasars radiating closest to the Eddington limit* (Marziani & Sulentic 2014)
- Time delays in lensed quasars (COSMOGRAIL - COSmological MOnitoring of GRAvItational Lenses; H0LiCOW - H0 Lenses in COSMOGRAIL's Wellspring)
- *X-ray - UV flux relation* (e.g. Risaliti & Lusso+15, +19; Lusso & Risaliti+16, +17)

THE $L_X - L_{UV}$ RELATION

Moresco et al. (2022, LRR, 25-6)

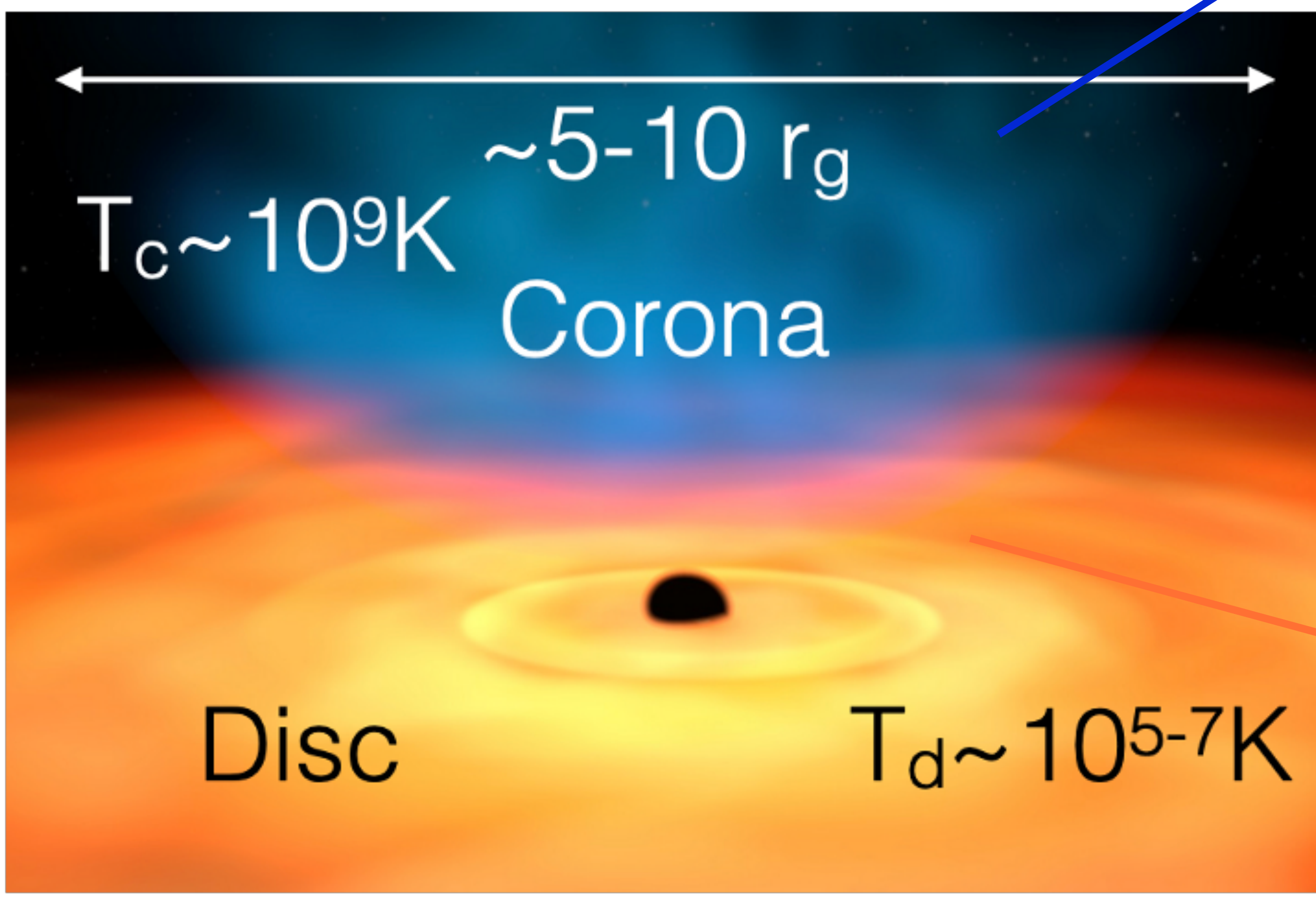


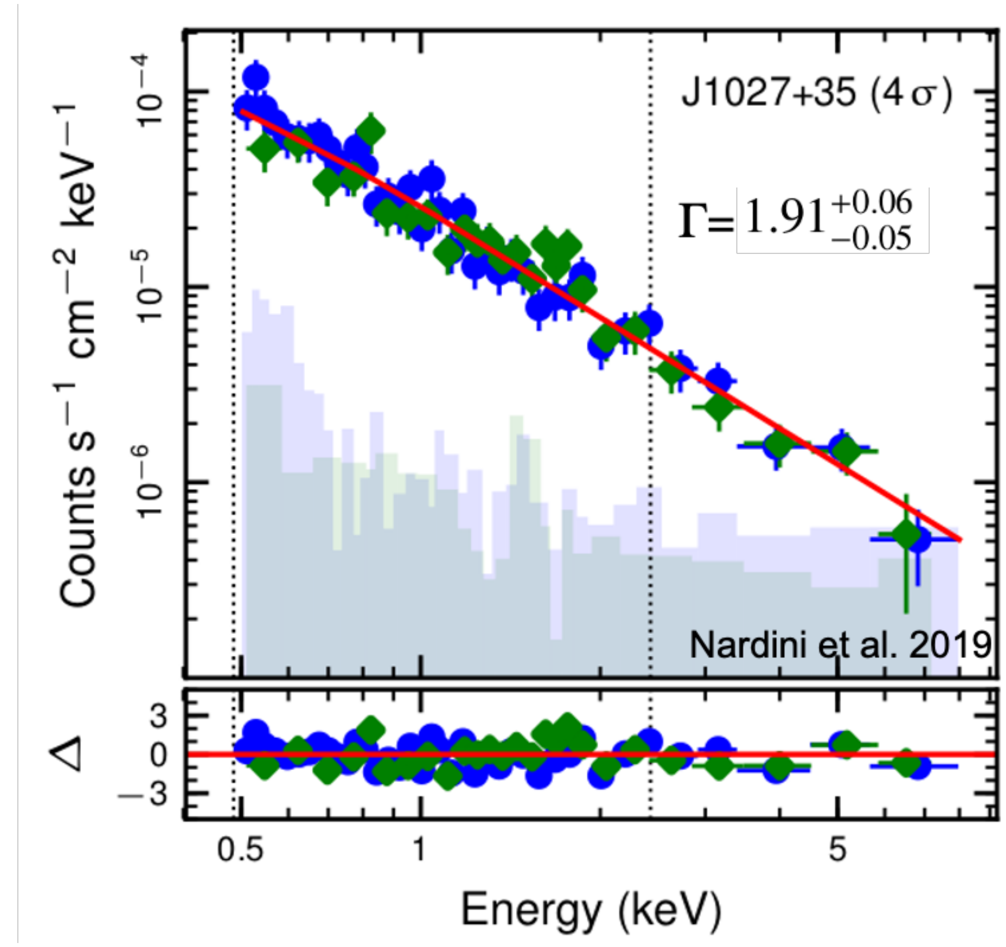
γ=0.6
observed dispersion
δ=0.24 dex

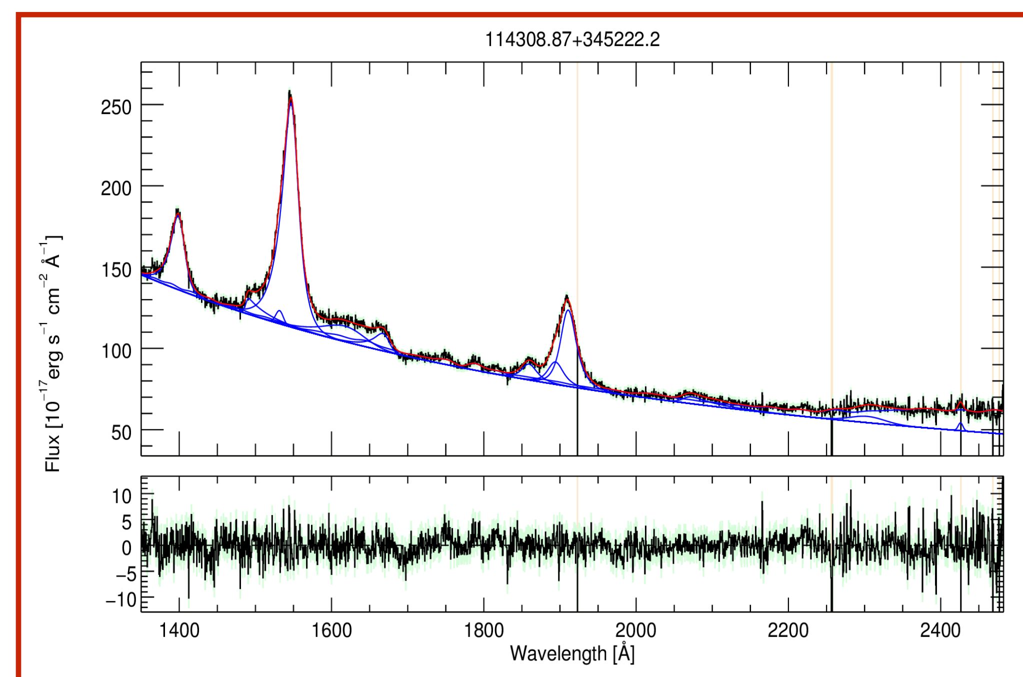
This relation is <u>not new</u>, it is known since the '80s…
(e.g. Tananbaum et al. 1979, Zamorani et al 1981)

THE $L_X - L_{UV}$ RELATION: THE PHYSICS BEHIND

Lusso & Risaliti 2017, Lusso et al. 2021
(Svensson & Zdziarski 1994; Haardt&Maraschi 98, 99; Arcodia et al. 2019, etc etc…)

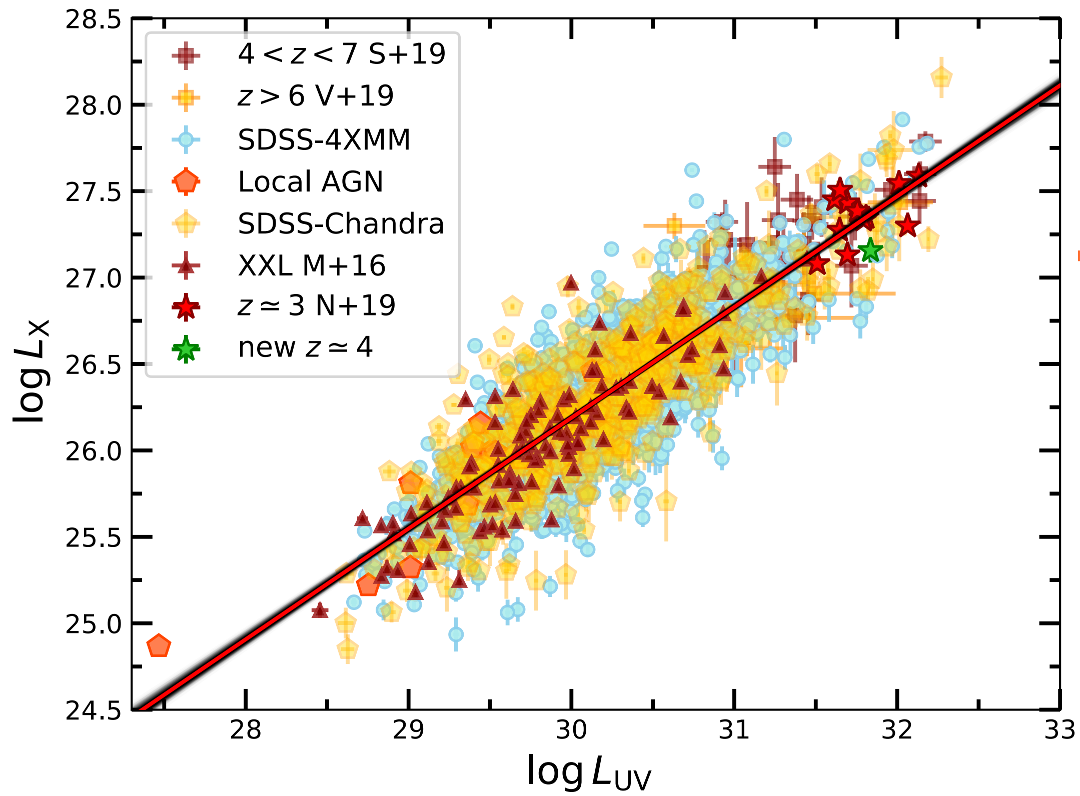


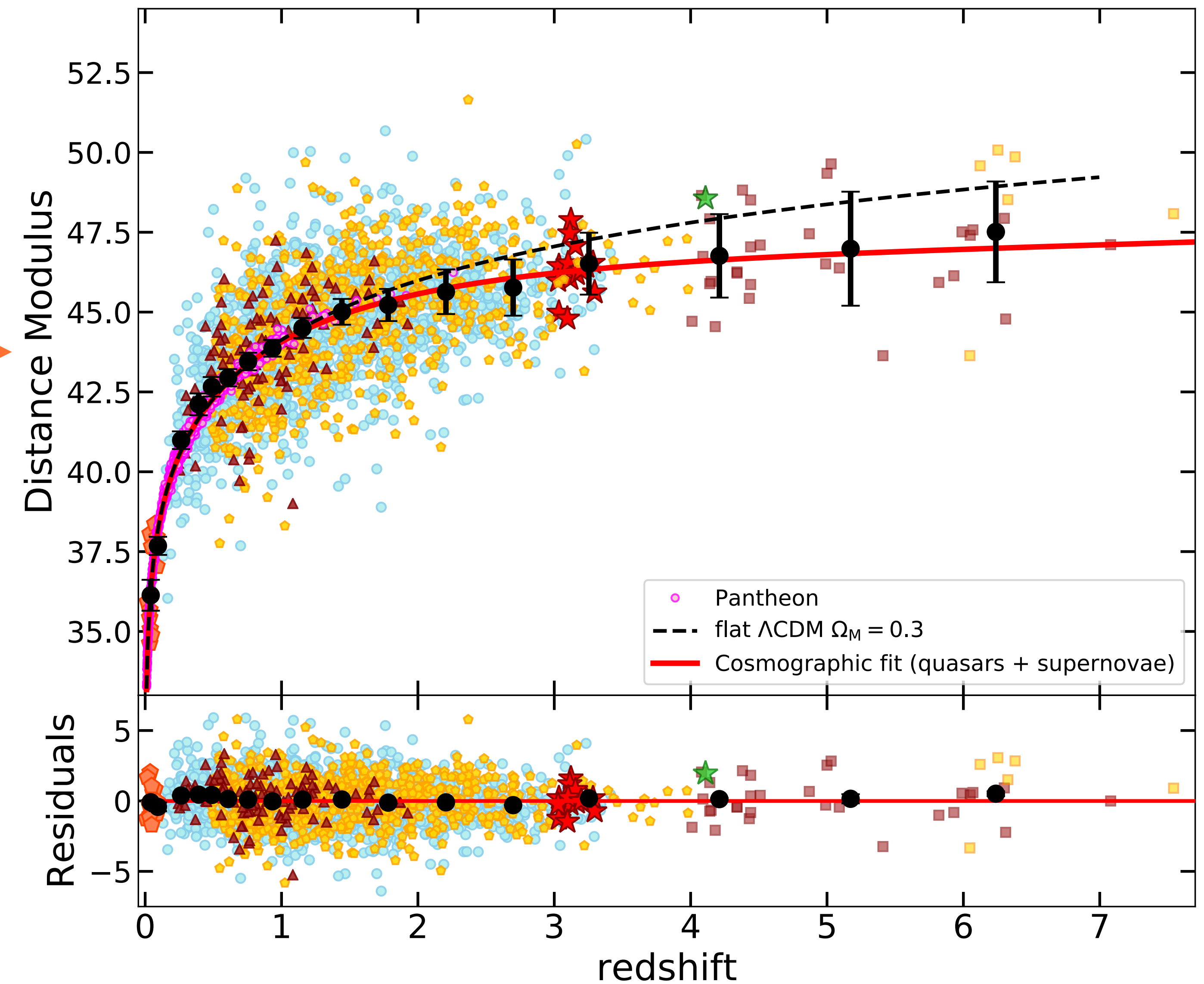




FROM THE L_X—L_{UV} RELATION TO THE HUBBLE DIAGRAM

Moresco et al. (2022, LRR, 25-6)





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

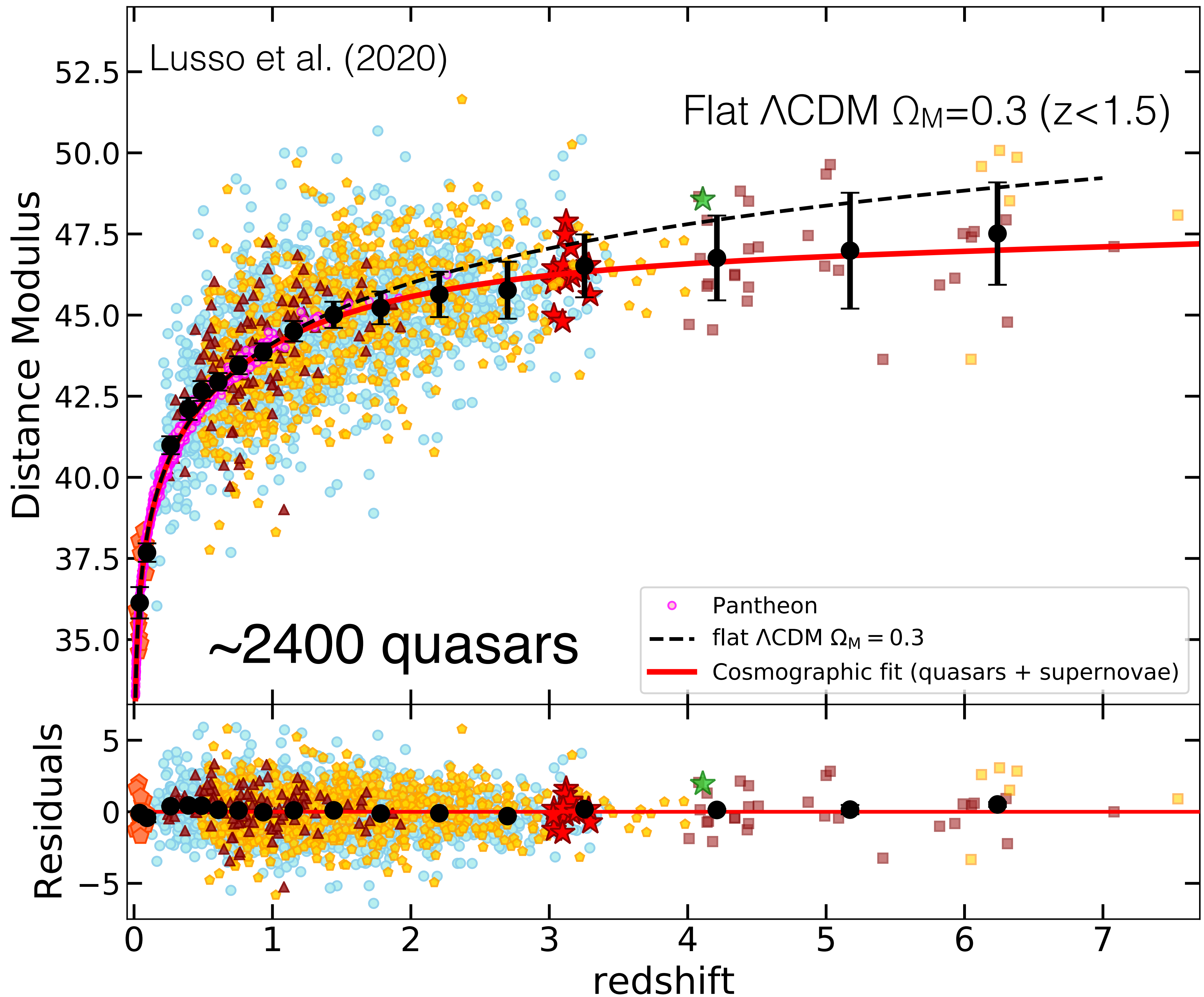
$$\log(D_L) = \frac{\log(F_X) - \beta - \gamma \log(F_{UV})}{2(\gamma - 1)} - \frac{1}{2}\log(4\pi)$$

The F_X—F_{UV} non-linear relation as a way to measure quasar distances

See also Risaliti & Lusso 2015, 2019, Lusso et al. 2020

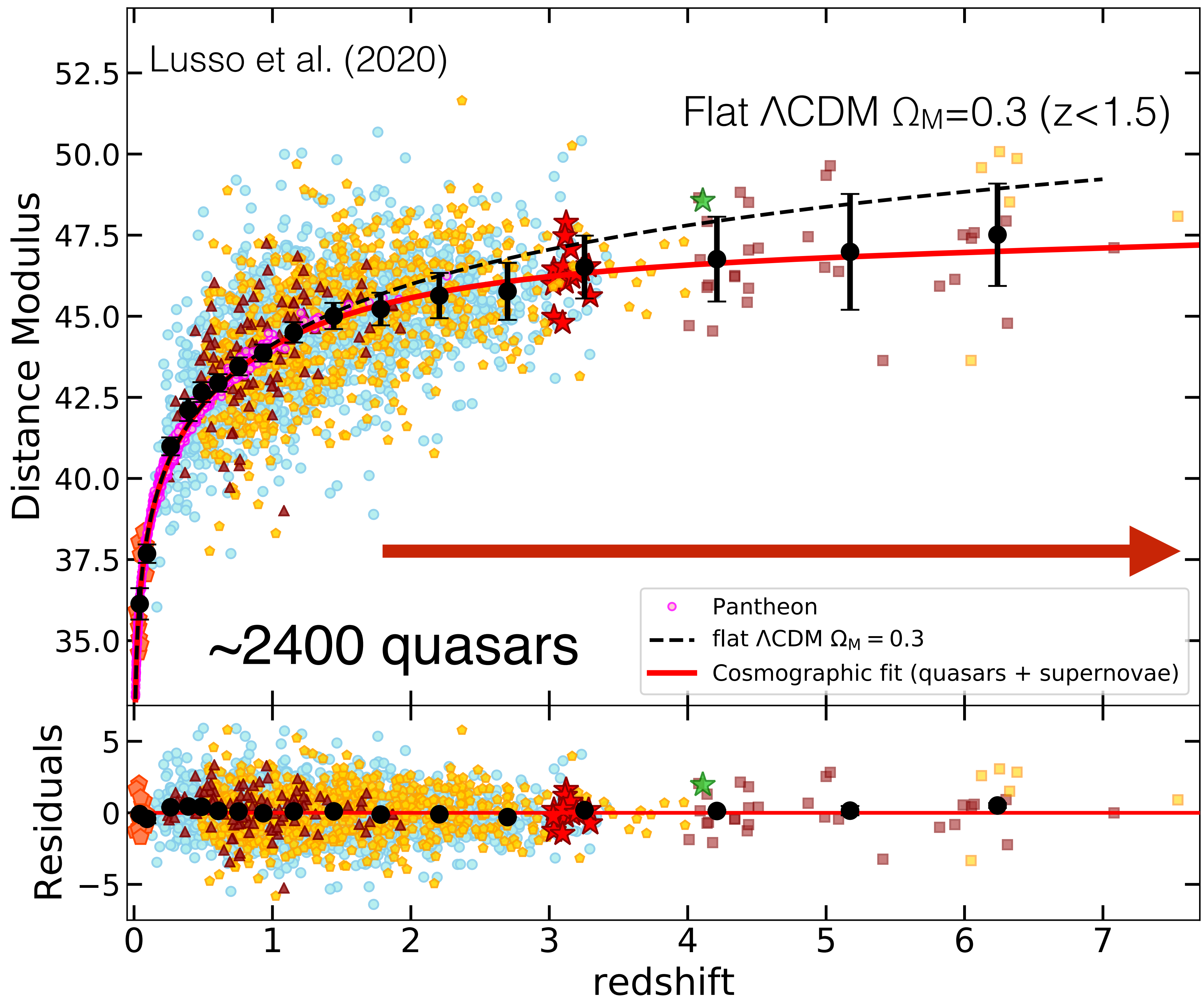
Elisabeta Lusso UniFi

COSMOLOGY WITH QUASARS: THE HUBBLE DIAGRAM

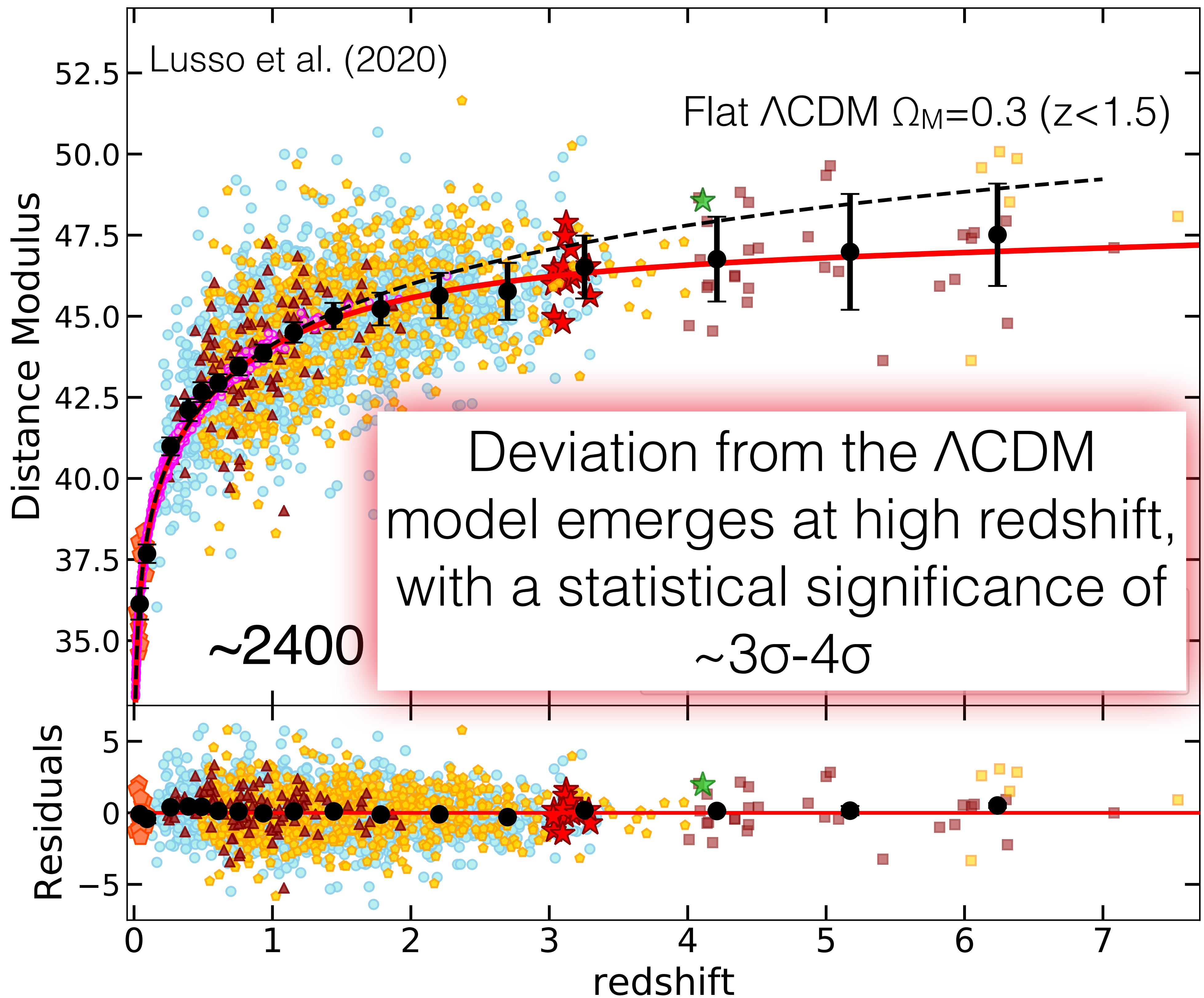


Elisabeta Lusso UniFi

COSMOLOGY WITH QUASARS: THE HUBBLE DIAGRAM



COSMOLOGY WITH QUASARS: THE HUBBLE DIAGRAM

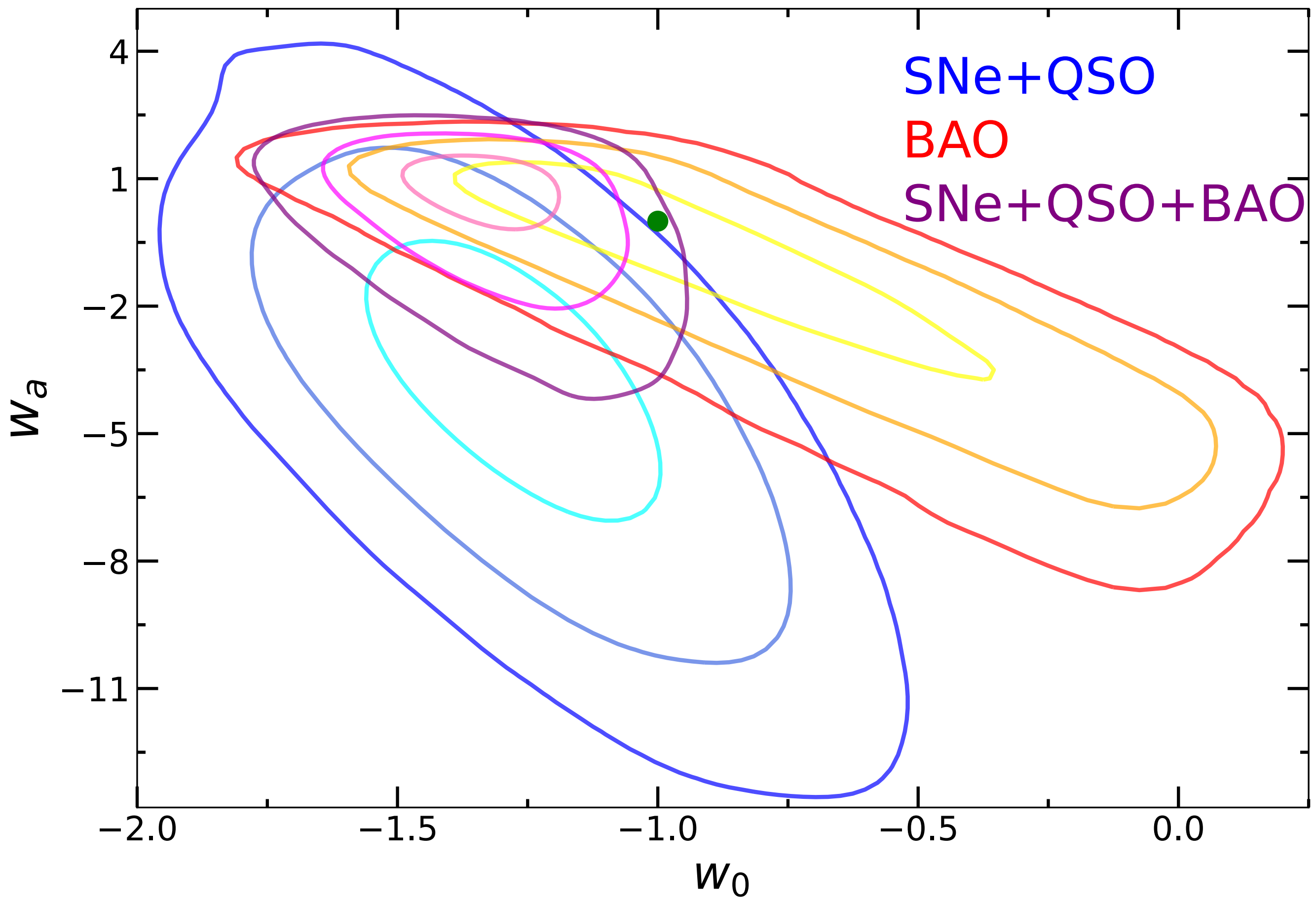


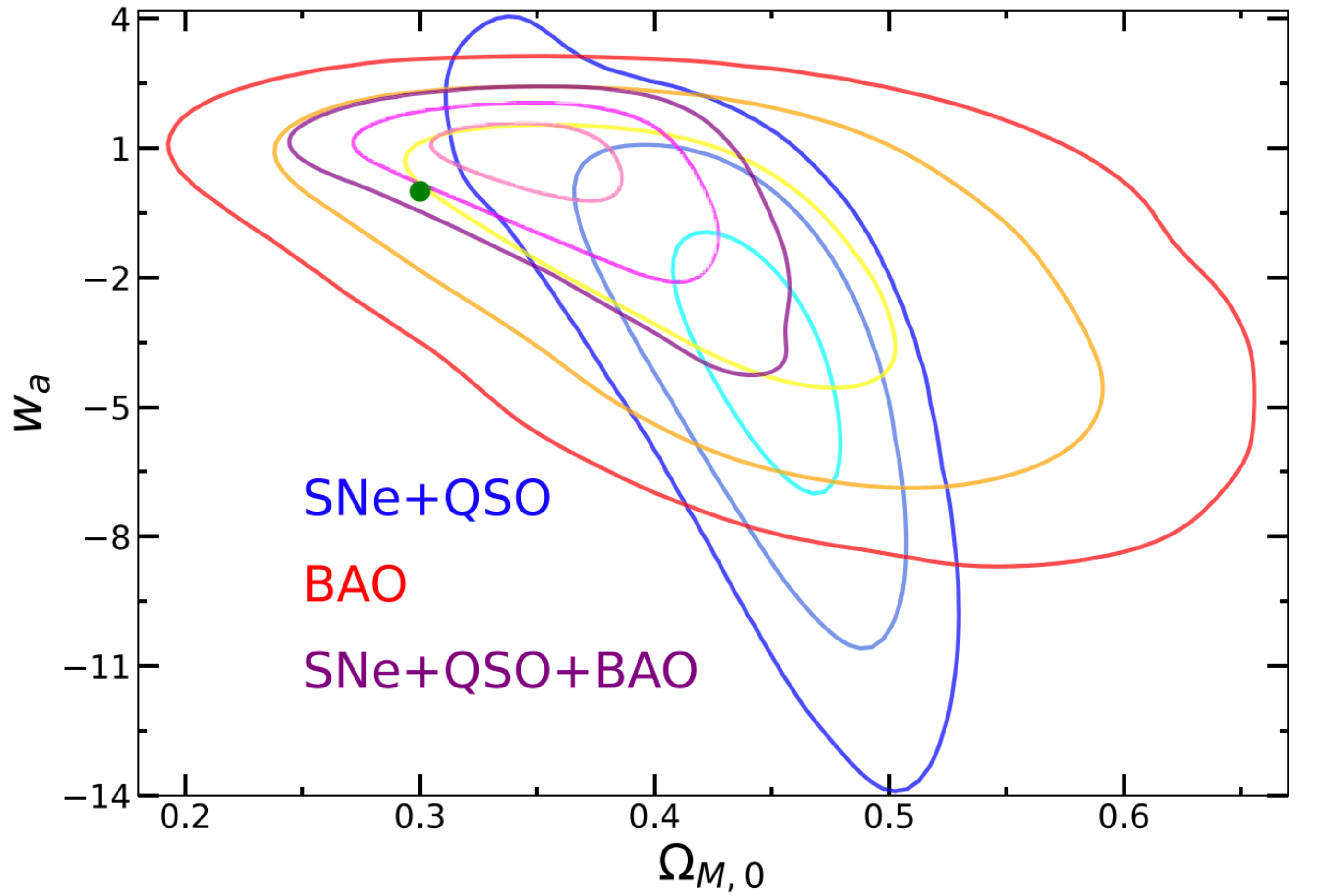
Deviation from the ΛCDM model emerges at high redshift, with a statistical significance of ~3σ-4σ

Elisabeta Lusso UniFi

THE QUASAR HUBBLE DIAGRAM:
TEST OF COSMOLOGY

Bargiacchi, et al. 2022, MNRAS, 515-179





Flat CPL: $w(z)=w_0+w_a\, z/(1+z)$

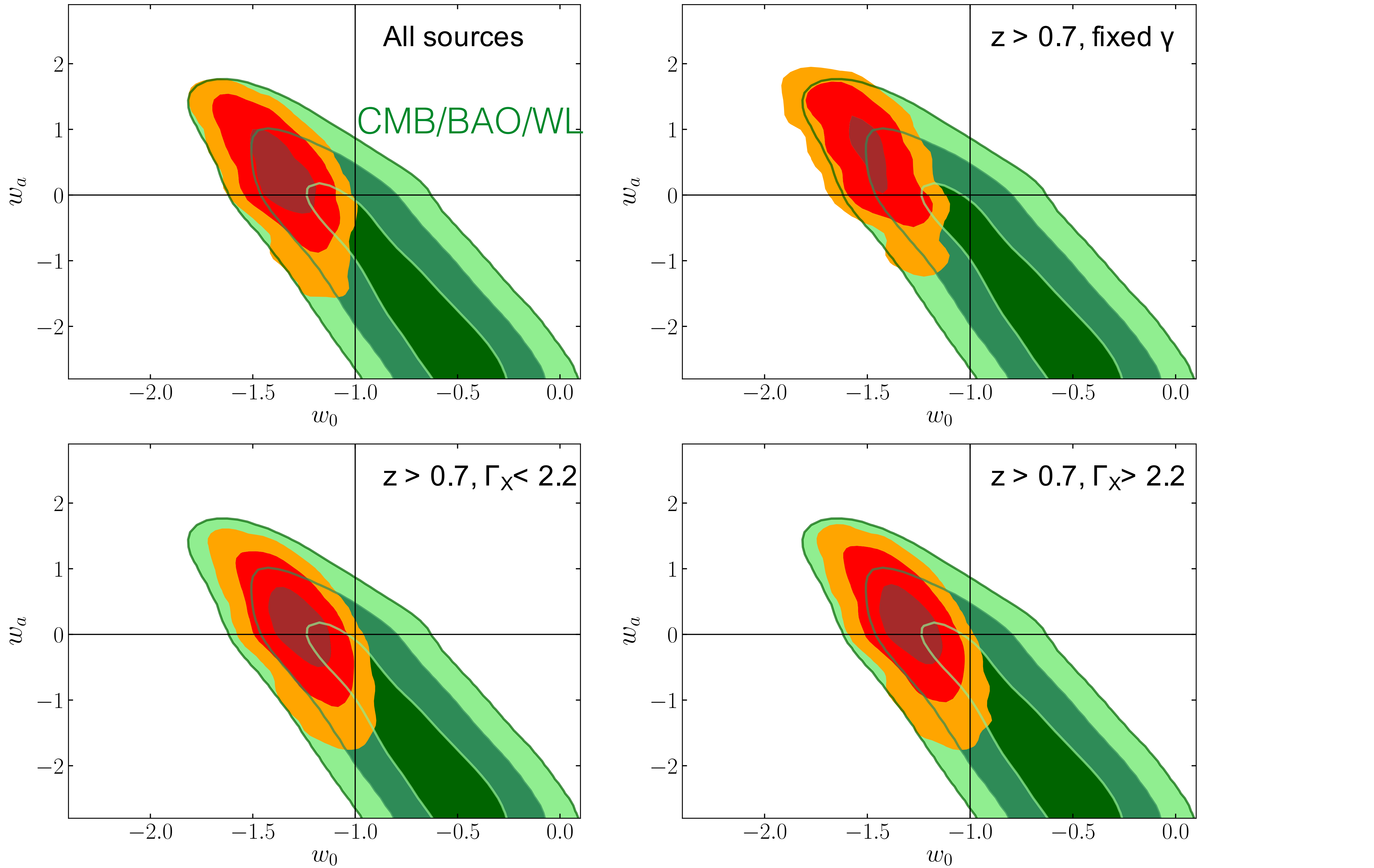
Models with evolving dark energy density

quasars+SNe: $\Omega_M>0.3$ and $w_0<-1$

(*phantom* behaviour)

THE QUASAR HUBBLE DIAGRAM:
TEST SAMPLE SELECTION

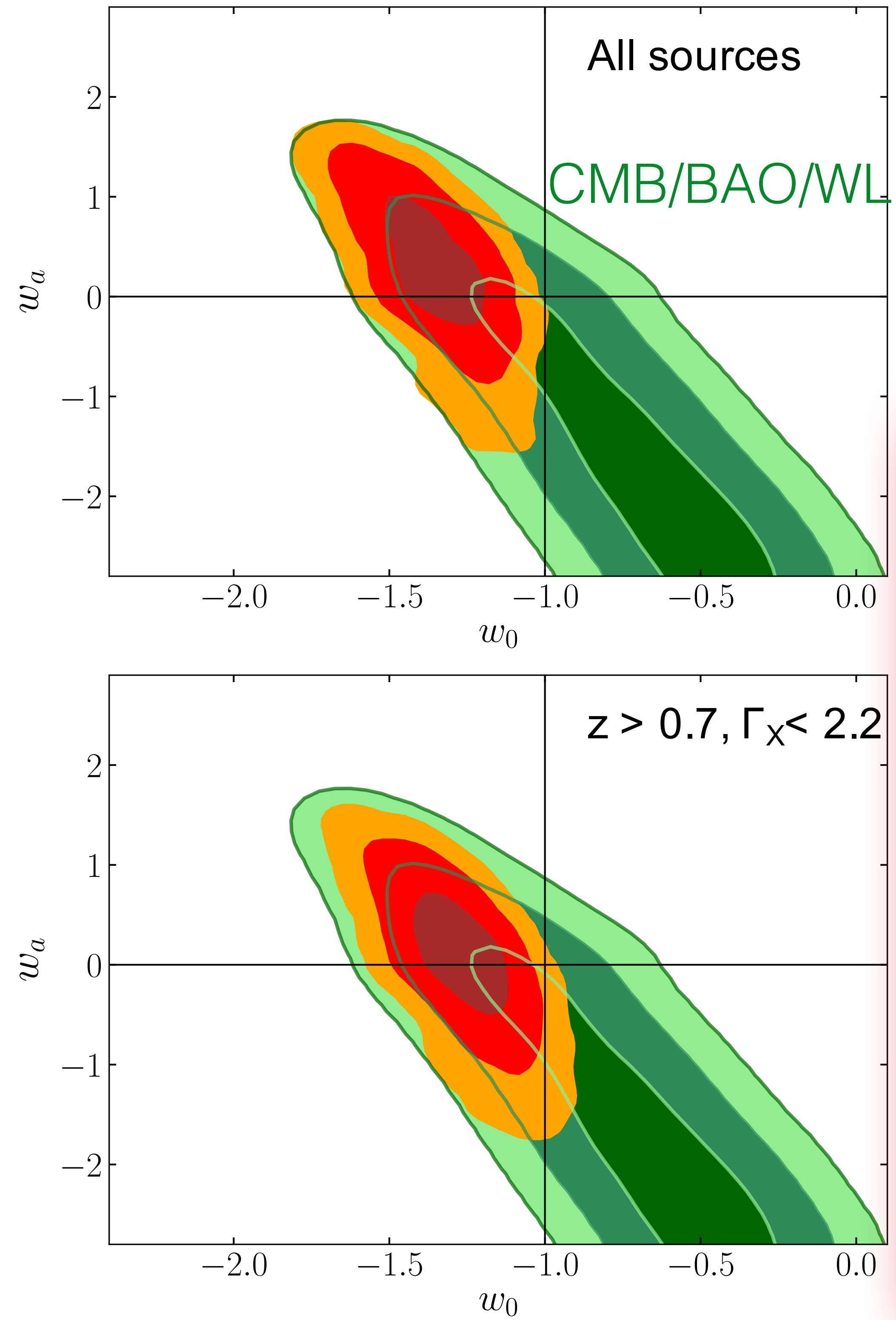
SNe+CMB/BAO/WL+quasars

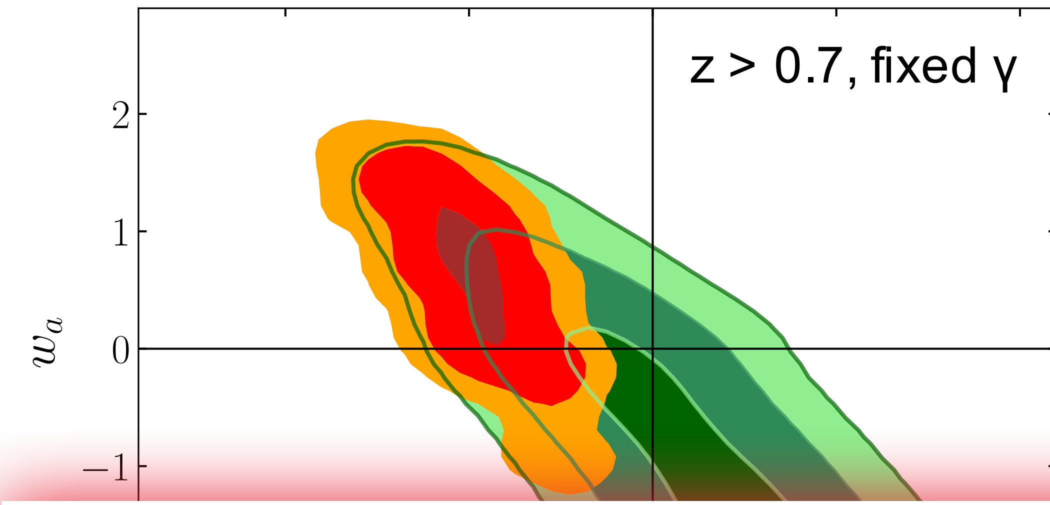


Elisabeta Lusso UniFi

THE QUASAR HUBBLE DIAGRAM:
TEST SAMPLE SELECTION

SNe+CMB/BAO/WL+quasars





An independent test of this result <u>requires observations of other standard candles at high-redshift</u> -> we expect that future observations of type Ia SNe at z>1.5 will confirm the deviation from the concordance model

(Malekjani et al. 2023 arXiv:2301.12725)

Elisabeta Lusso UniFi

ARE QUASARS RELIABLE STANDARD CANDLES?
TEST SOURCES OF BIAS & SYSTEMATICS

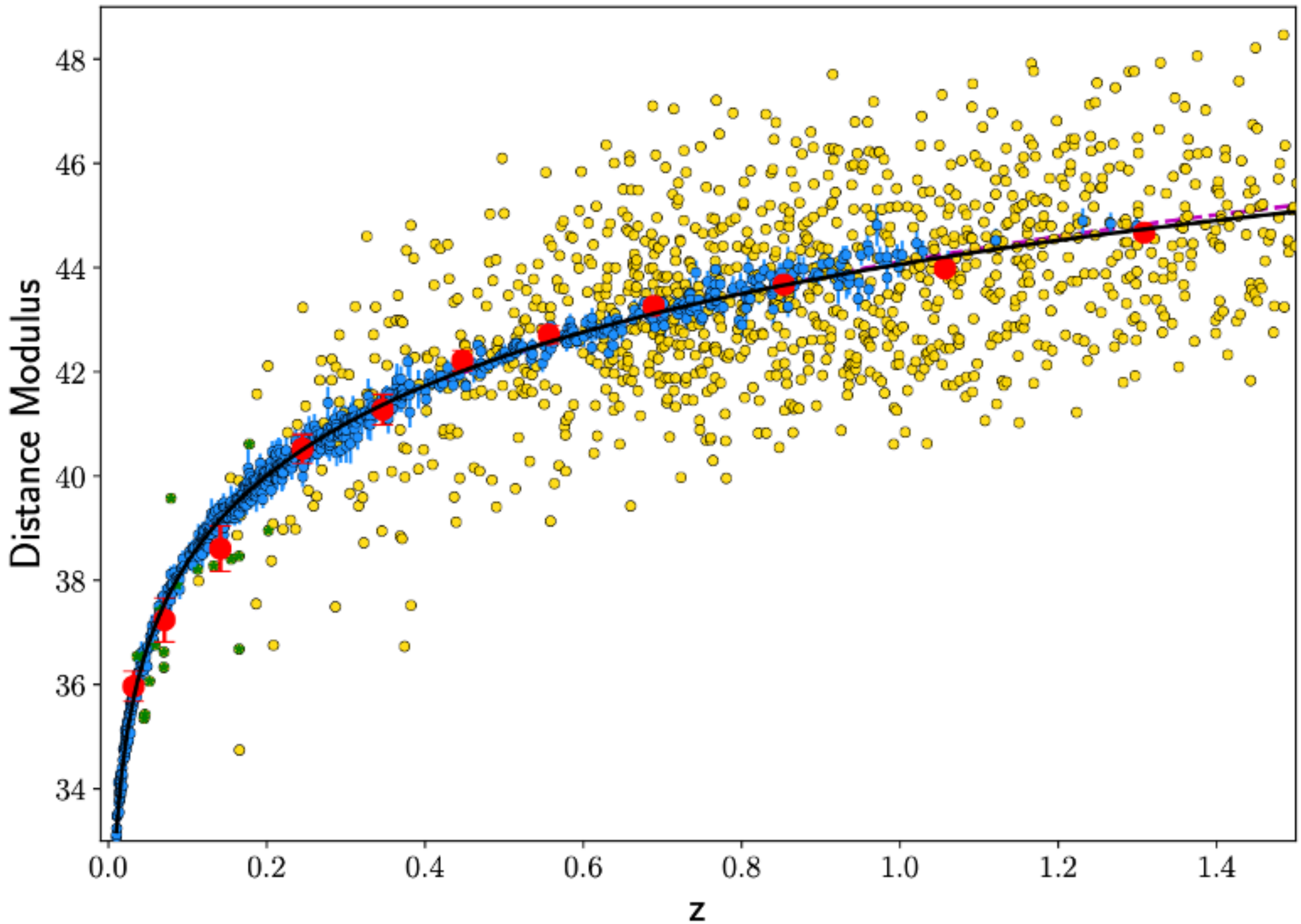
- Redshift evolution, validation of the technique and sample selection through analysis of the Hubble diagram's residuals
  Lusso et al. 2020, A&A, 642-150

- Test of the sample selection at z>2.5
  Sacchi et al. 2022, A&A, 663-7

- Test for intrinsic extinction and host galaxy contamination
  Trefoloni et al. to be submitted

- Test UV and X-ray indicators
  Signorini et al. A&A accepted, arXiv:2306.16438

ARE QUASARS RELIABLE STANDARD CANDLES?
COMPARISON WITH TYPE 1A SUPERNOVAE

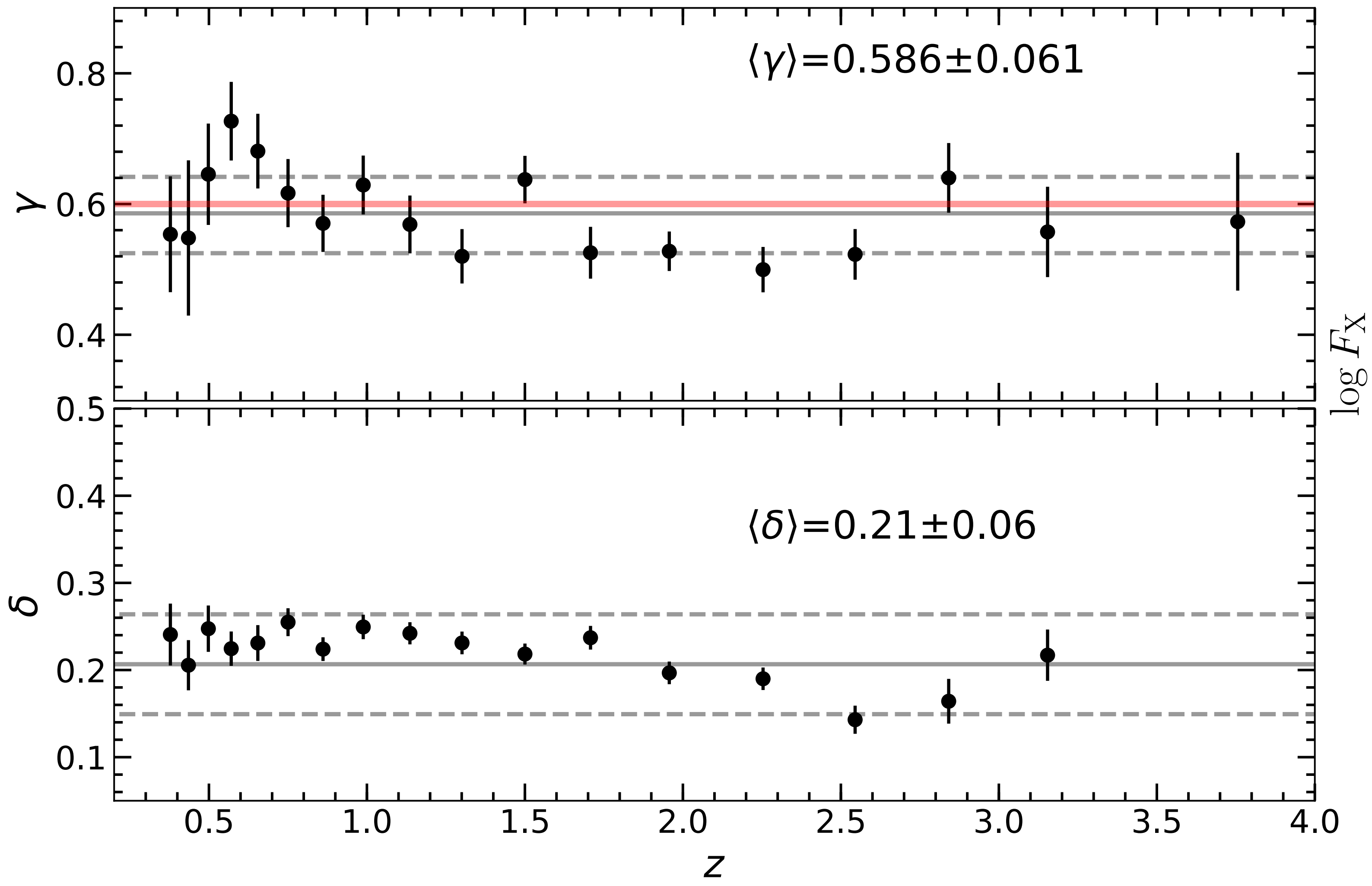


Excellent agreement in the common redshift range!

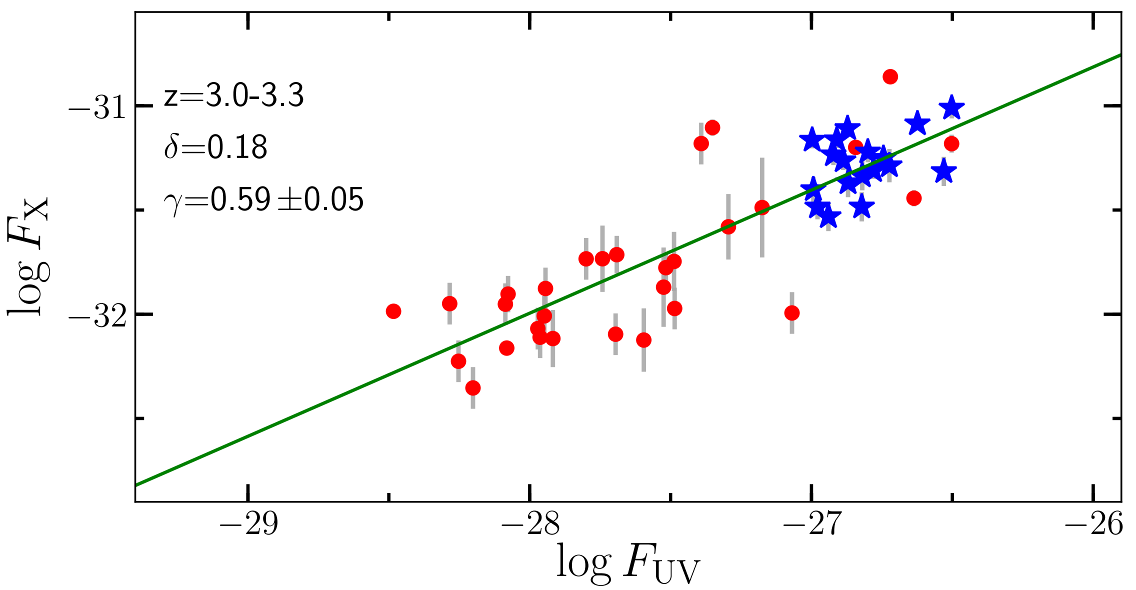
ARE QUASARS RELIABLE STANDARD CANDLES?

NO REDSHIFT EVOLUTION

Lusso et al. (2020)



$$\log(F_X) = \hat{\beta} + \gamma \log(F_{UV})$$

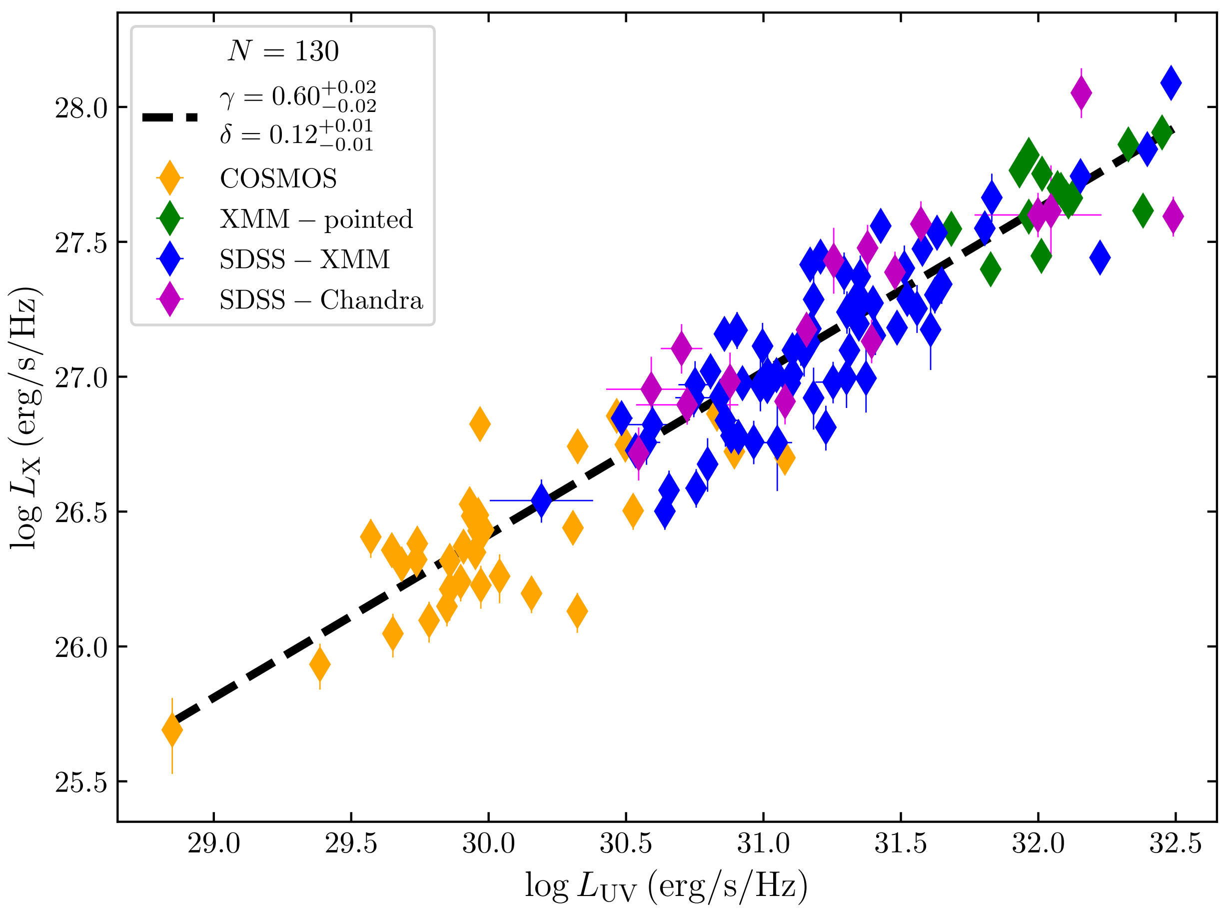


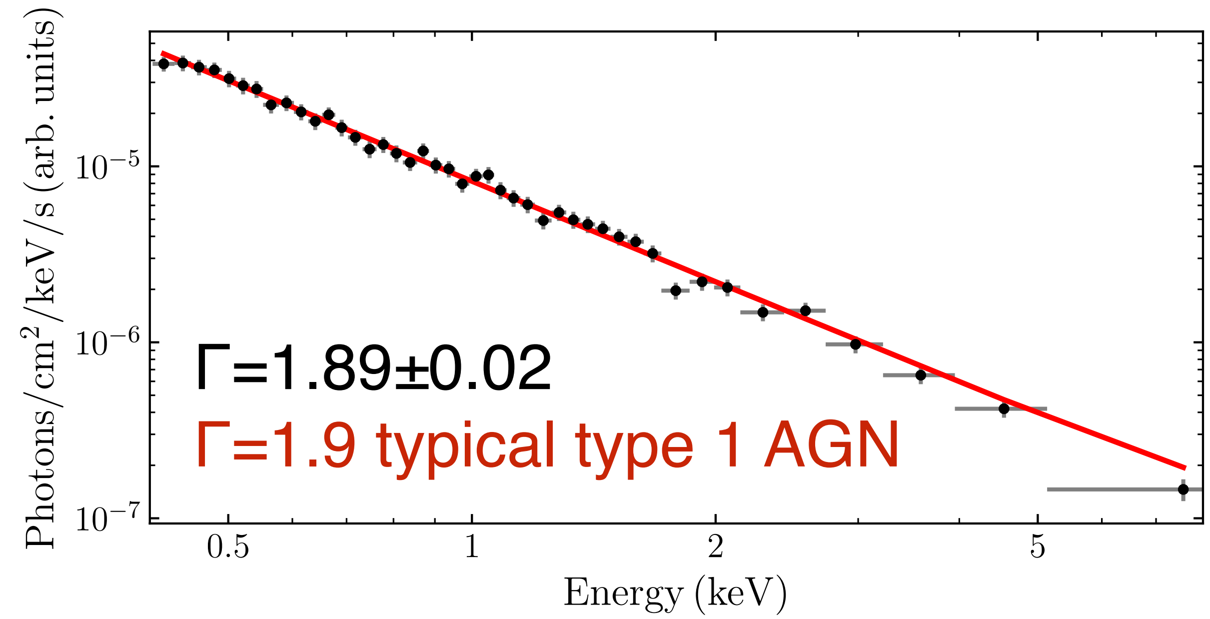
$$\hat{\beta} = \beta + (\gamma - 1)\log(4\pi) + 2(\gamma - 1)\log(D_L)$$

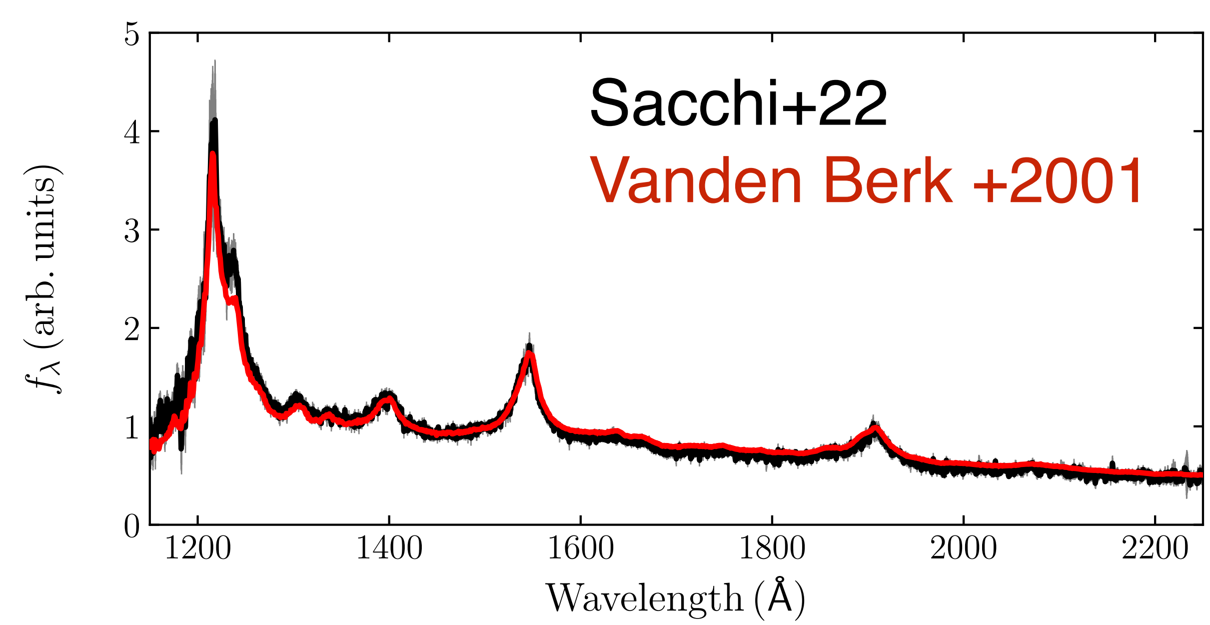
ARE QUASARS RELIABLE STANDARD CANDLES?

TEST SAMPLE SELECTION AT z>2.5

Sacchi et al 2022 (A&A, 663-7)





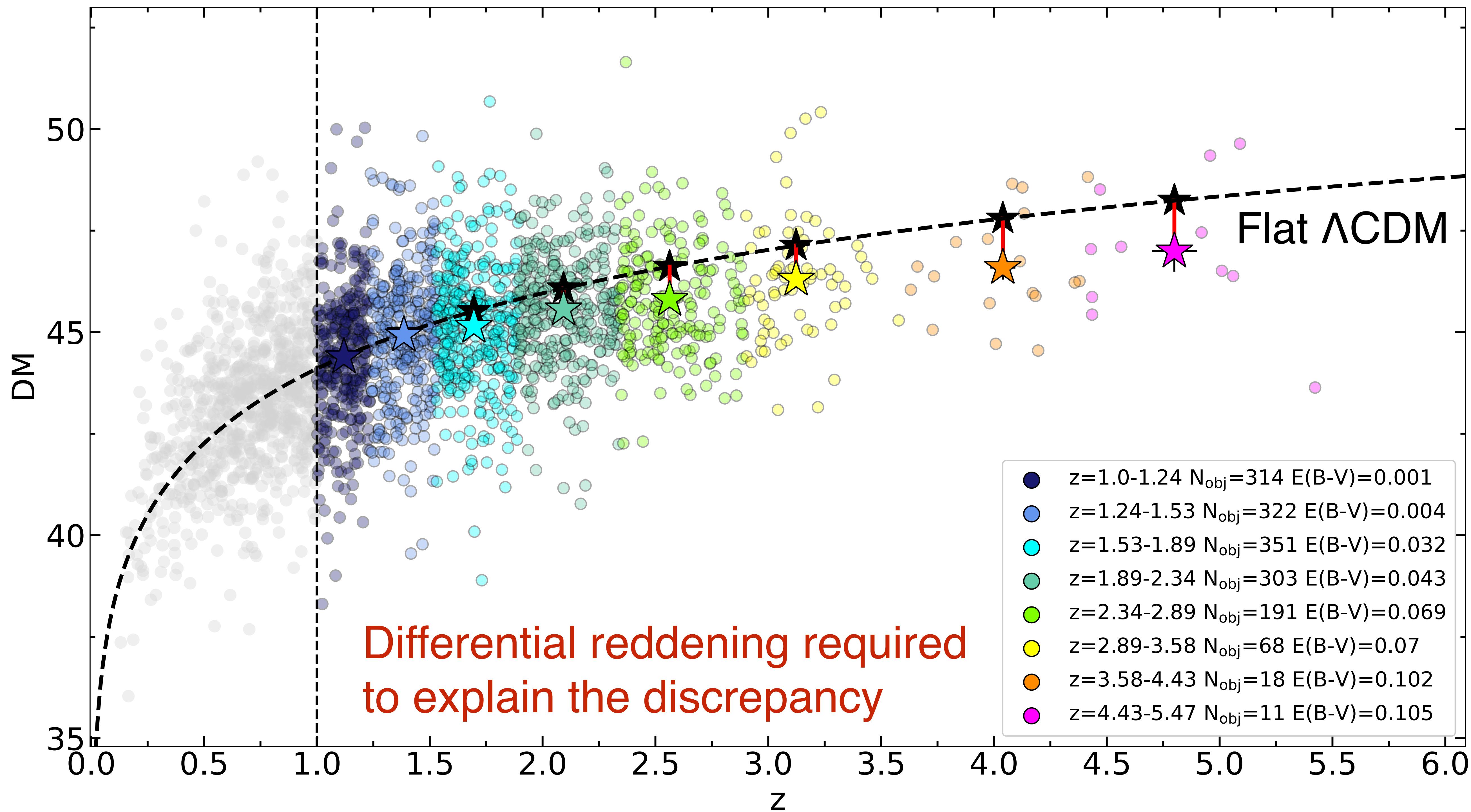


Lower the dispersion with a one-by-one analysis (both @X-ray and @UV)

ARE QUASARS RELIABLE STANDARD CANDLES?

TEST FOR EXTINCTION AND HOST GALAXY CONTAMINATION

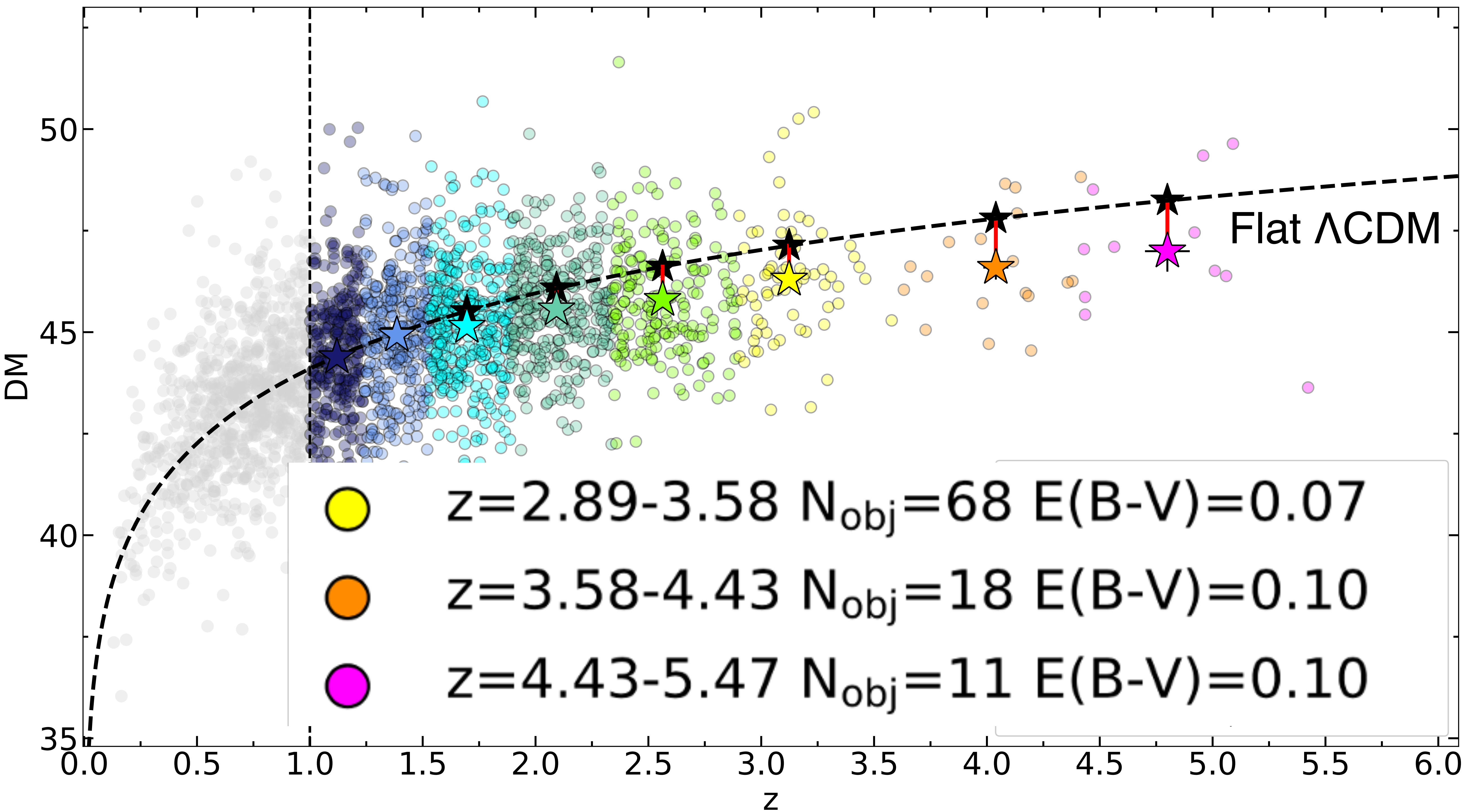
Trefoloni et al. to be submitted



ARE QUASARS RELIABLE STANDARD CANDLES?

TEST FOR EXTINCTION AND HOST GALAXY CONTAMINATION

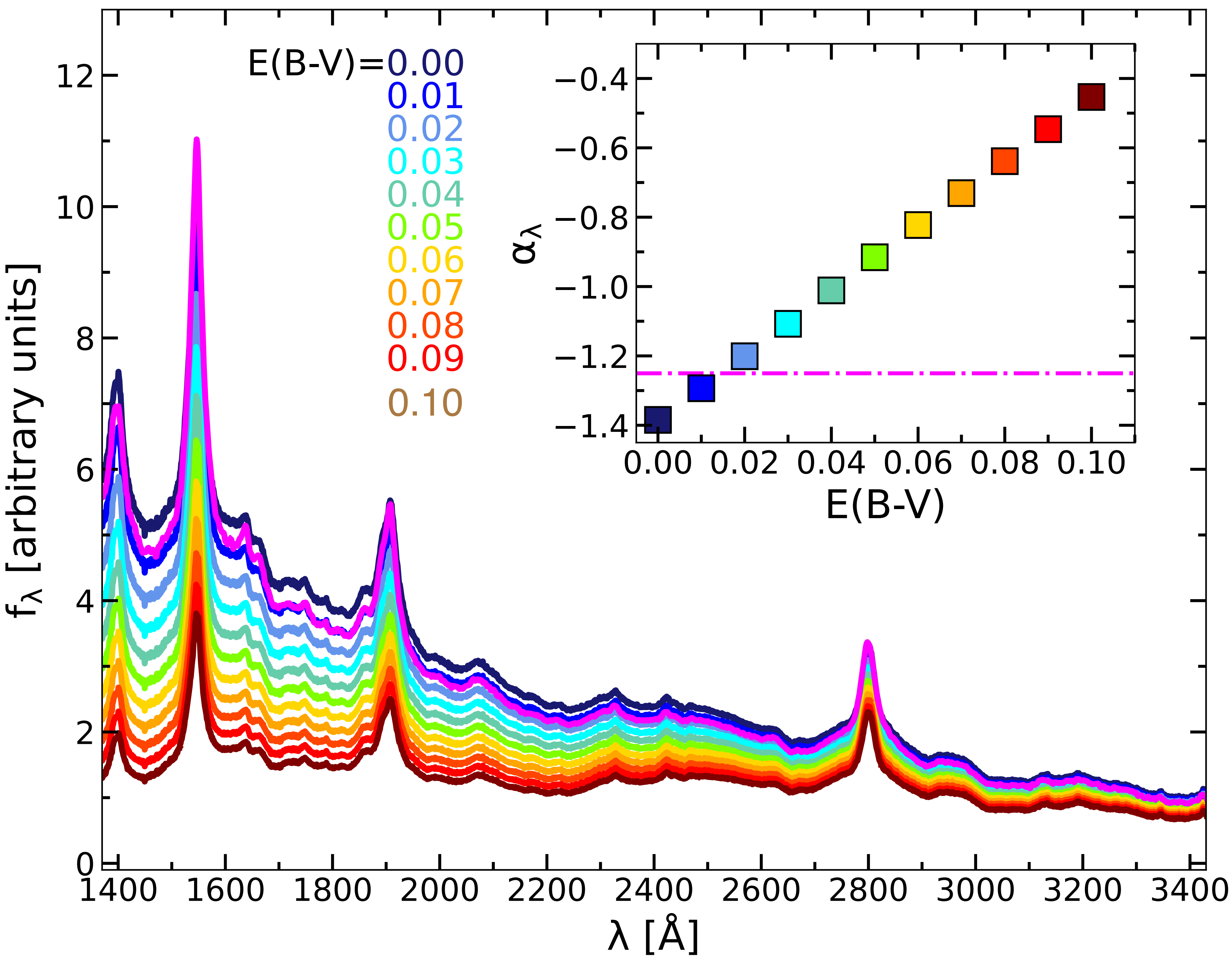
Trefoloni et al. to be submitted



ARE QUASARS RELIABLE STANDARD CANDLES?

TEST FOR EXTINCTION AND HOST GALAXY CONTAMINATION

Trefoloni et al. to be submitted



Vanden Berk+2001 with E(B-V)=[0,0.1]

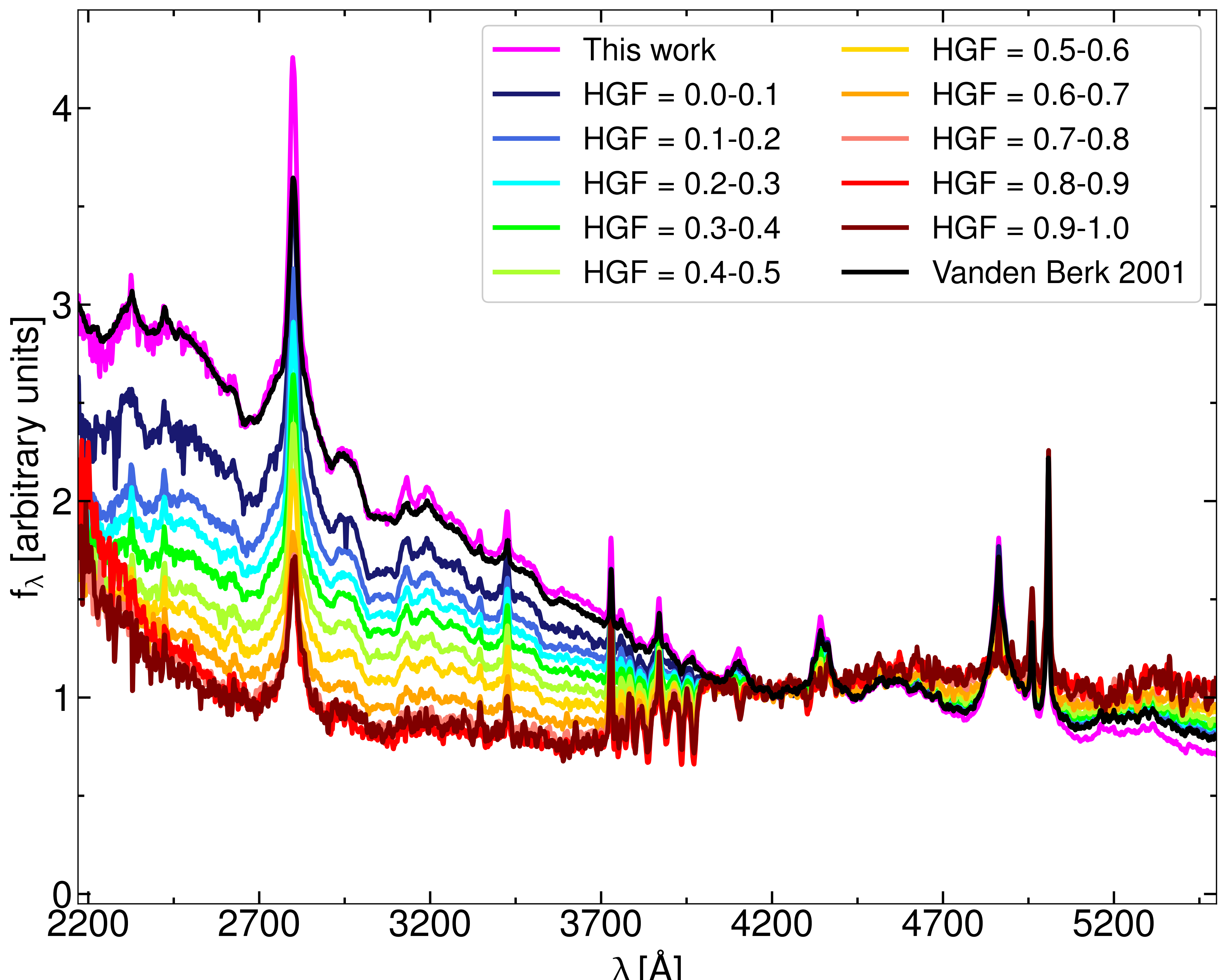
Lusso+2020 composite consistent with E(B-V)=<0.02

Elisabeta Lusso UniFi

ARE QUASARS RELIABLE STANDARD CANDLES?

TEST FOR EXTINCTION AND HOST GALAXY CONTAMINATION

Trefoloni et al. to be submitted



Vanden Berk+2001

Coloured lines: stack of SDSS spectra @z<0.8 in bins of host to galaxy fraction (HGF, Rakshit et al. 2020)

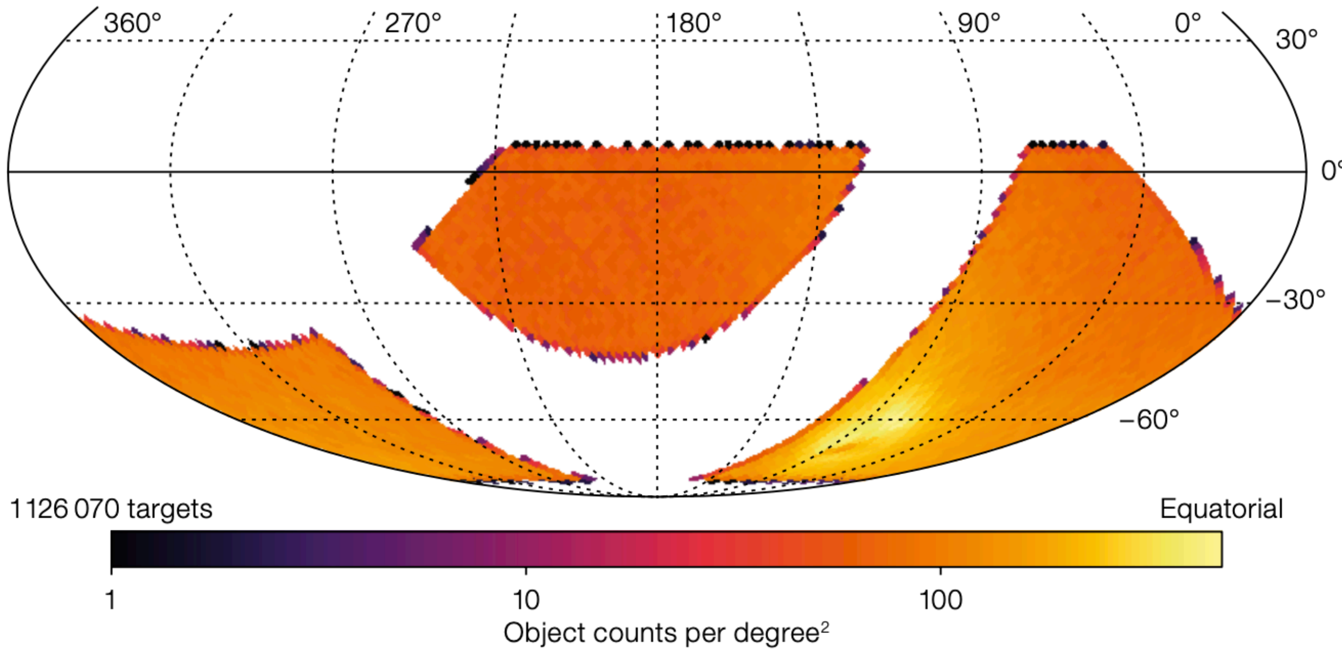
Lusso+2020 composite @z<0.8 consistent with HGF<0.1

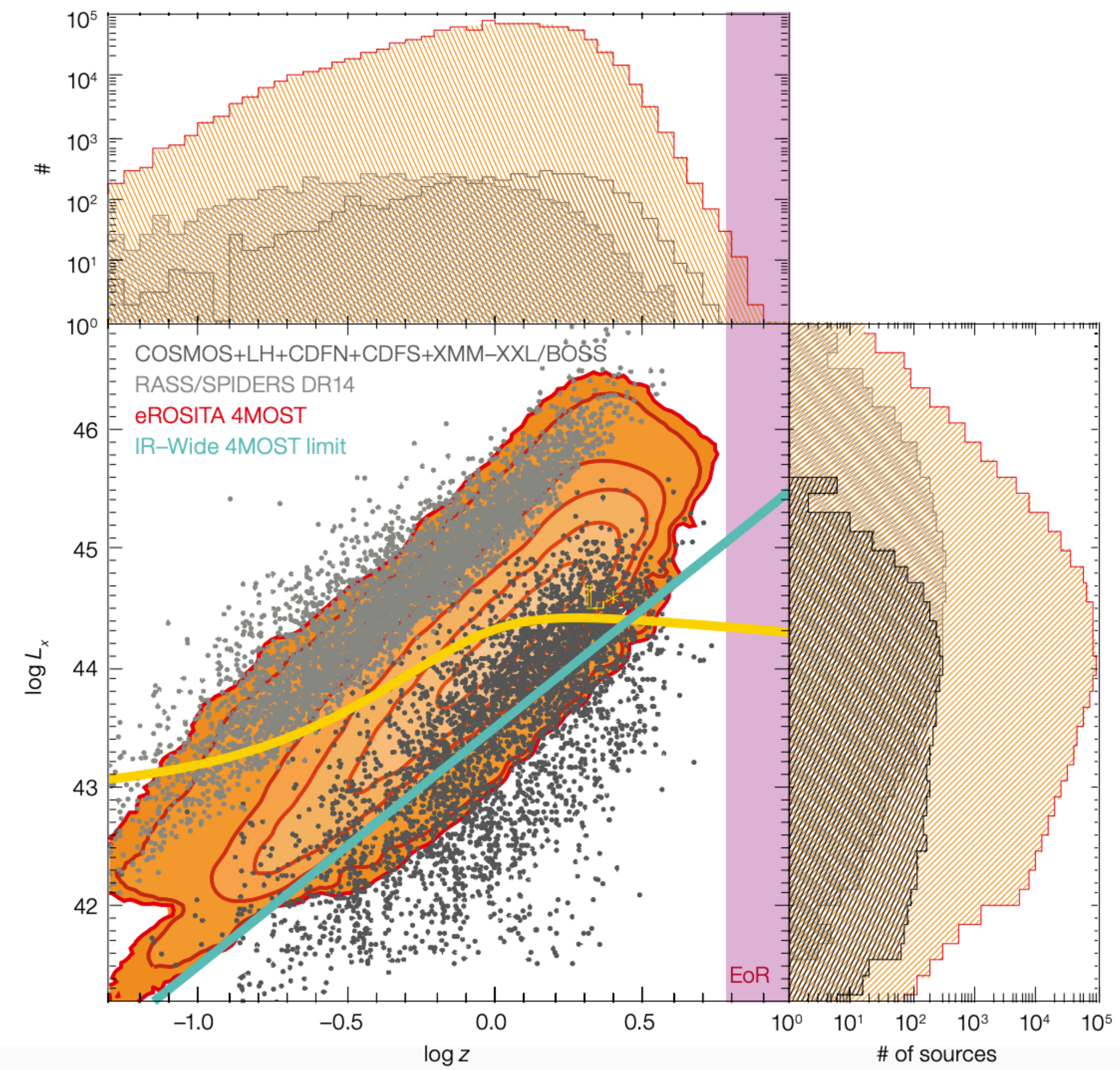
THE FUTURE OF THE
HUBBLE DIAGRAM OF QUASARS

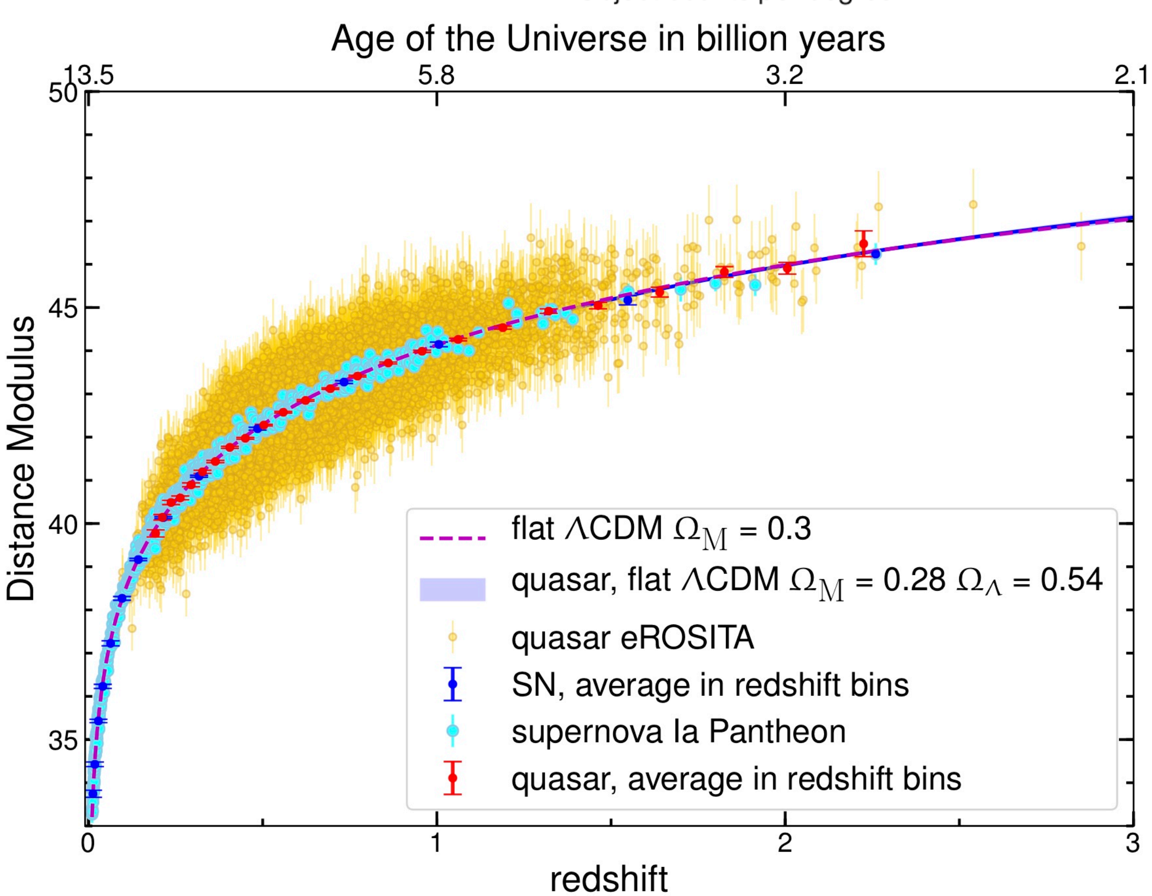
PRESENT AND FUTURE MISSIONS: EROSITA

- All sky "SDSS-like" + X-ray survey that includes the southern sky (e.g. eROSITA/4MOST)

Merloni et al. messenger-no175-42-45







~10,000 simulated quasars
limiting flux $F_S > 3\times10^{-14}$ cgs (1st year)

PRESENT AND FUTURE MISSIONS: EUCLID

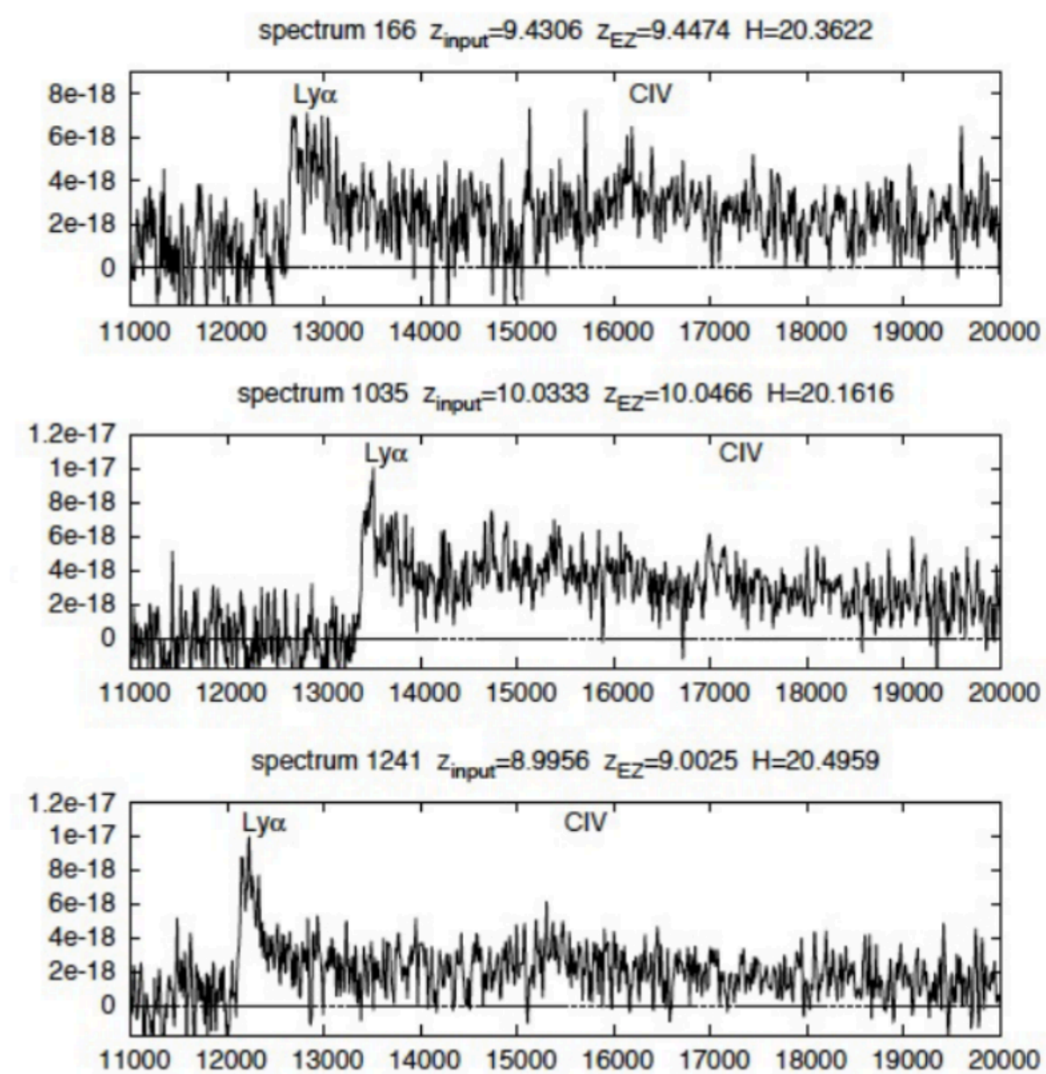
- All sky "SDSS-like" + X-ray survey that includes the southern sky (e.g. eROSITA/4MOST)
  - Euclid (planned launch July 2023!) will add (low resolution slitless) near infrared spectroscopy (NISP, 1250–1850 nm) for 10^6 AGN (X-rays? eROSITA?)

<u>Bright High-z Quasars</u>

Euclid-NISP YJH data:

Expected ~30 z>8 QSOs

Euclid should be able to immediately get spectra of the brightest and follow-up the faint ones from ground-based observatories



Roche et al (2011)

Credits: M. Mignoli (INAF Bologna Italy)

TAKE HOME MESSAGES

1. No adequate physical model to explain the $L_X - L_{UV}$ relation (i.e. disc-corona synergy)
2. Dispersion of the quasar Hubble diagram >>

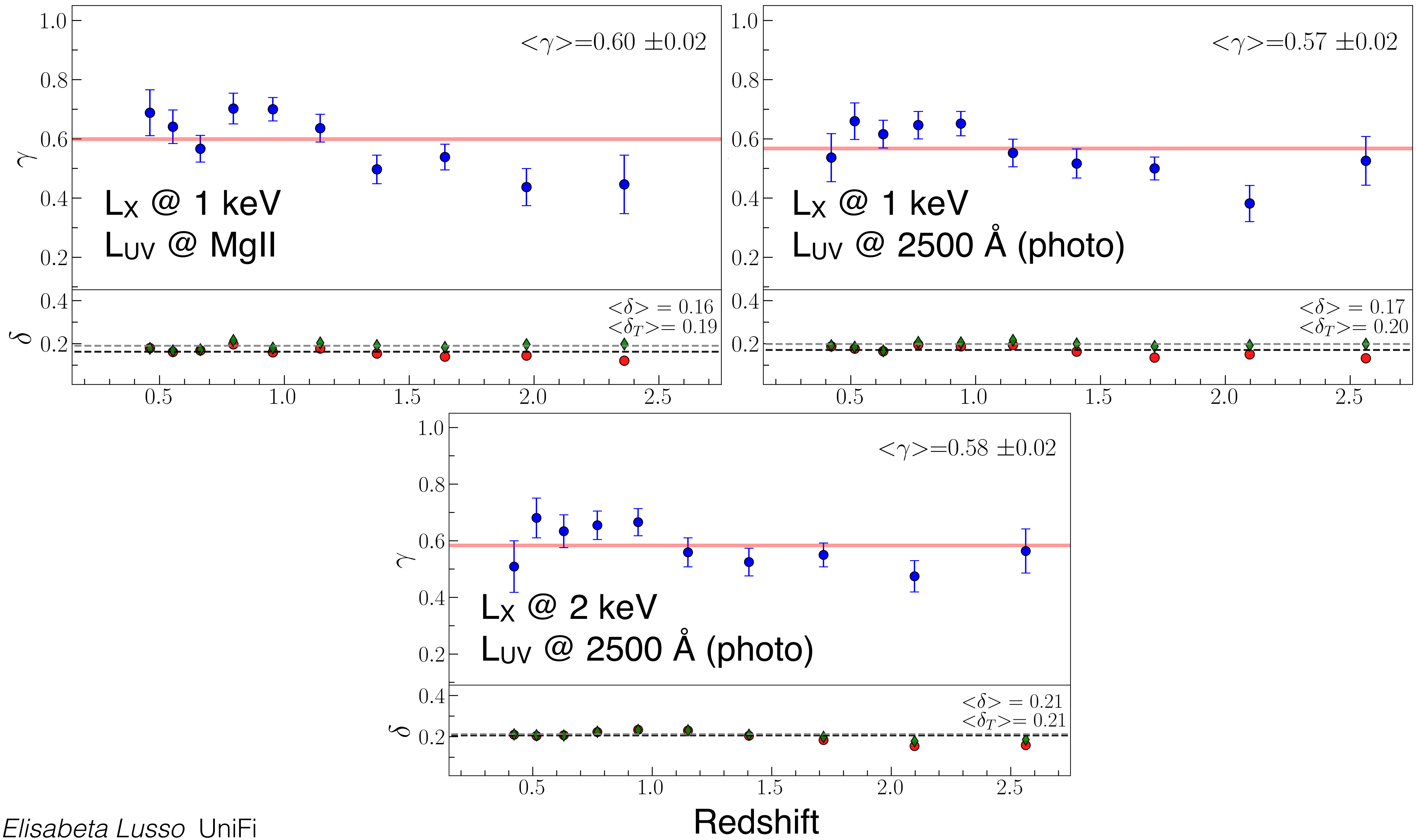
---

1. No evolution of the slope of the $L_X - L_{UV}$ relation with redshift
2. Excellent agreement of the quasar Hubble diagram to that of type 1a SNe in the common redshift range
3. Dispersion decreases with high quality and one-by-one spectral analysis
4. Unphysical (differential) reddening values required to explain the discrepancy of the quasar Hubble diagram
5. No host galaxy contamination

ARE QUASARS RELIABLE STANDARD CANDLES?

TEST UV AND X-RAYS INDICATORS

Signorini et al. A&A accepted, arXiv:2306.16438

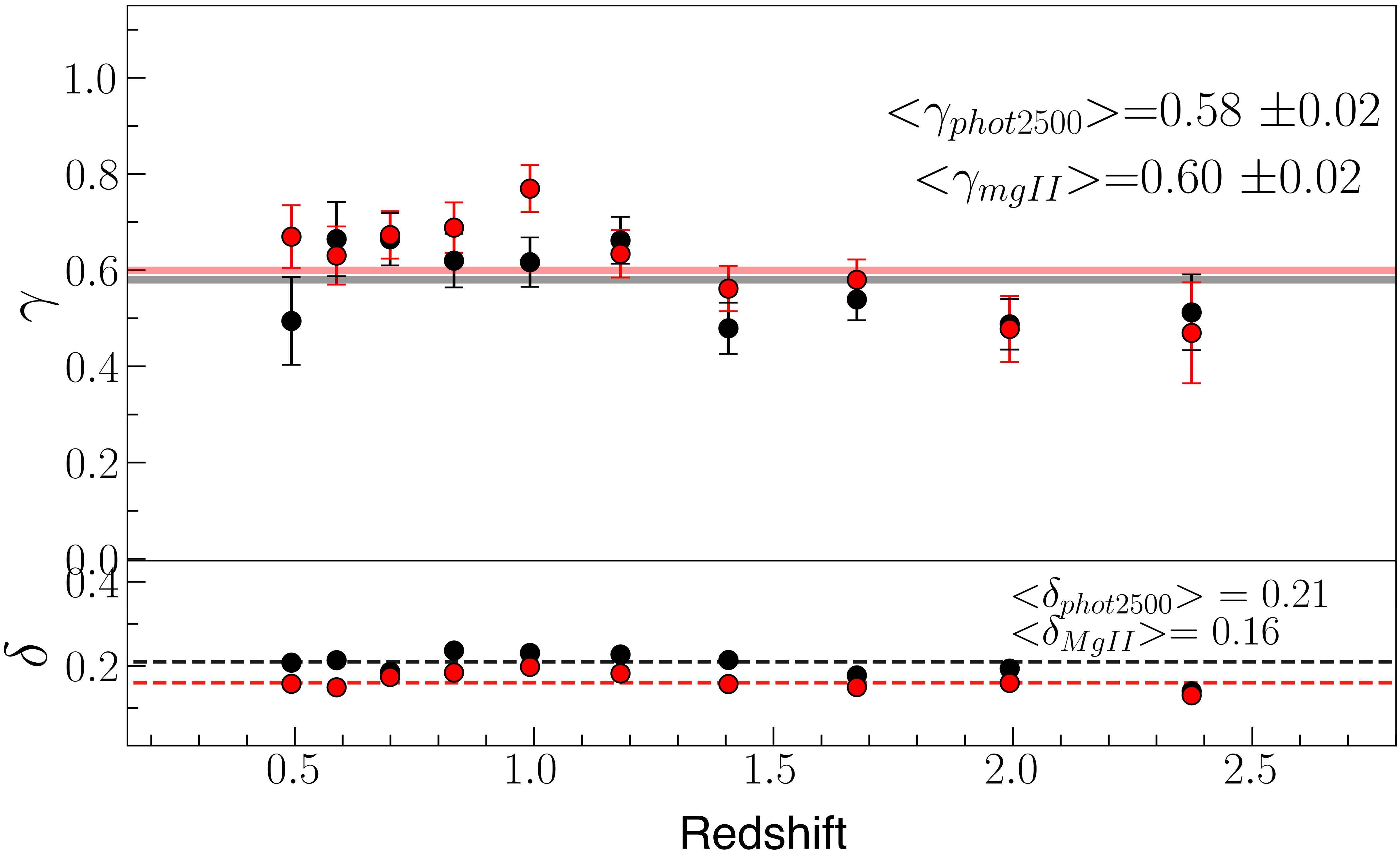


Elisabeta Lusso UniFi

ARE QUASARS RELIABLE STANDARD CANDLES?

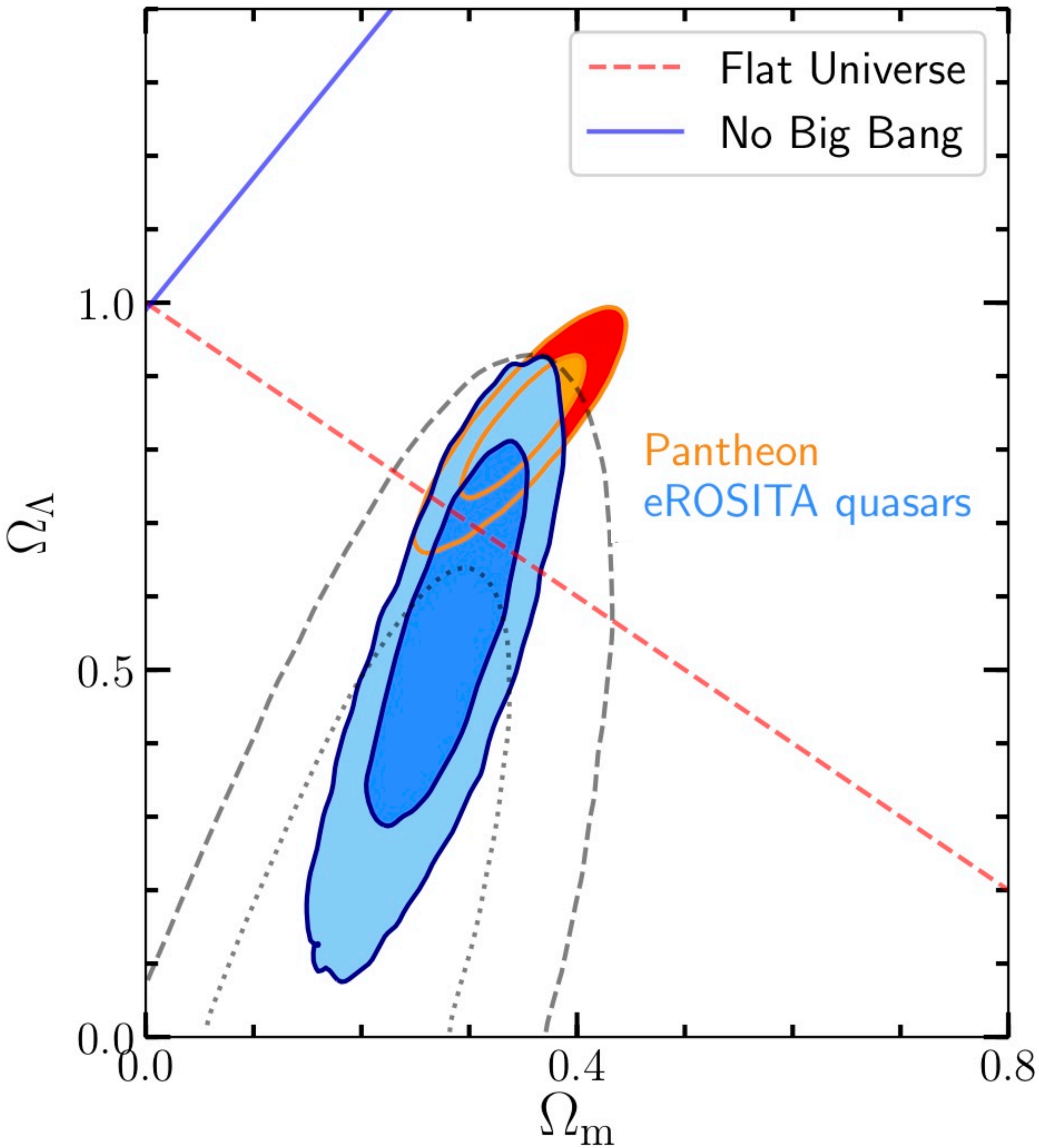
TEST UV AND X-RAYS INDICATORS

Signorini et al. A&A accepted, arXiv:2306.16438



Elisabeta Lusso UniFi

eROSITA: Cosmological parameters



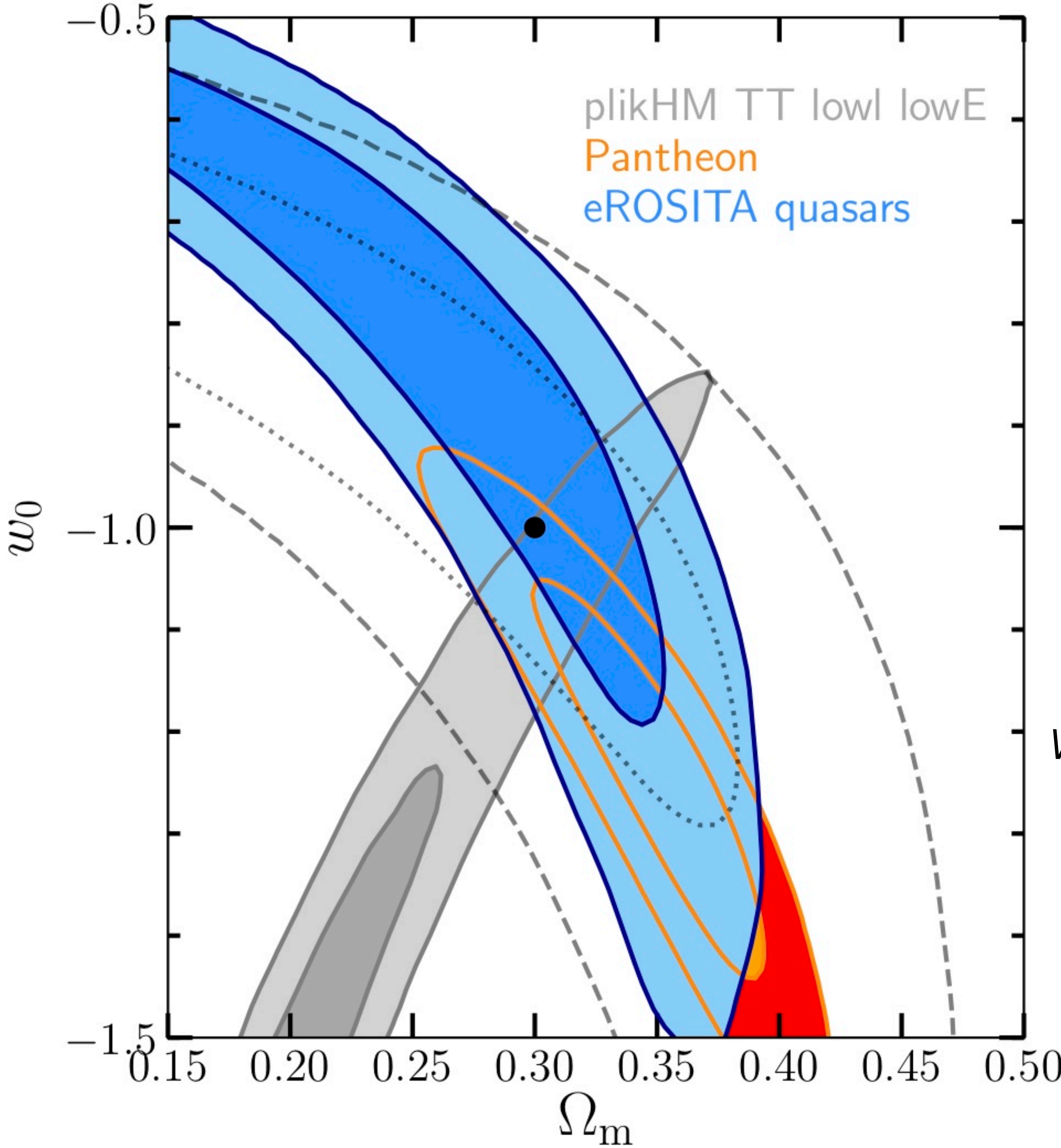
~10,000 simulated quasars
SDSS DR14
limiting flux $F_S > 3\times10^{-14}$ cgs
(eROSITA 1st year)

eROSITA QSOs:
$\Omega_M = 0.28\pm0.05$ (0.35 ± 0.04)
$\Omega_\Lambda = 0.54^{+0.17}_{-0.19}$ (0.83 ± 0.06)

SDSS-DR14
(>500,000 quasars)
SDSS-V(2020-2024)
4MOST(2023-2028)

Elisabeta Lusso UniFi

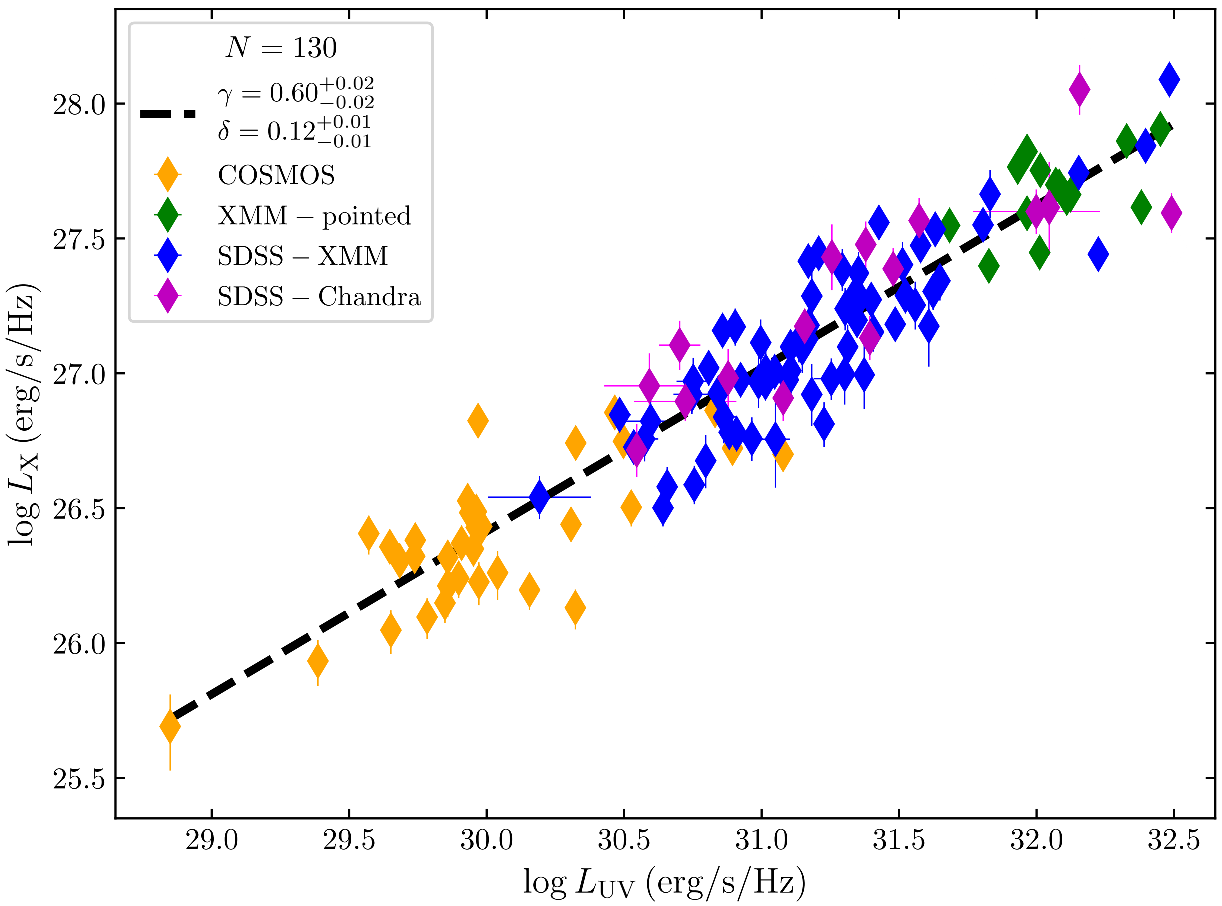
eROSITA: Cosmological parameters

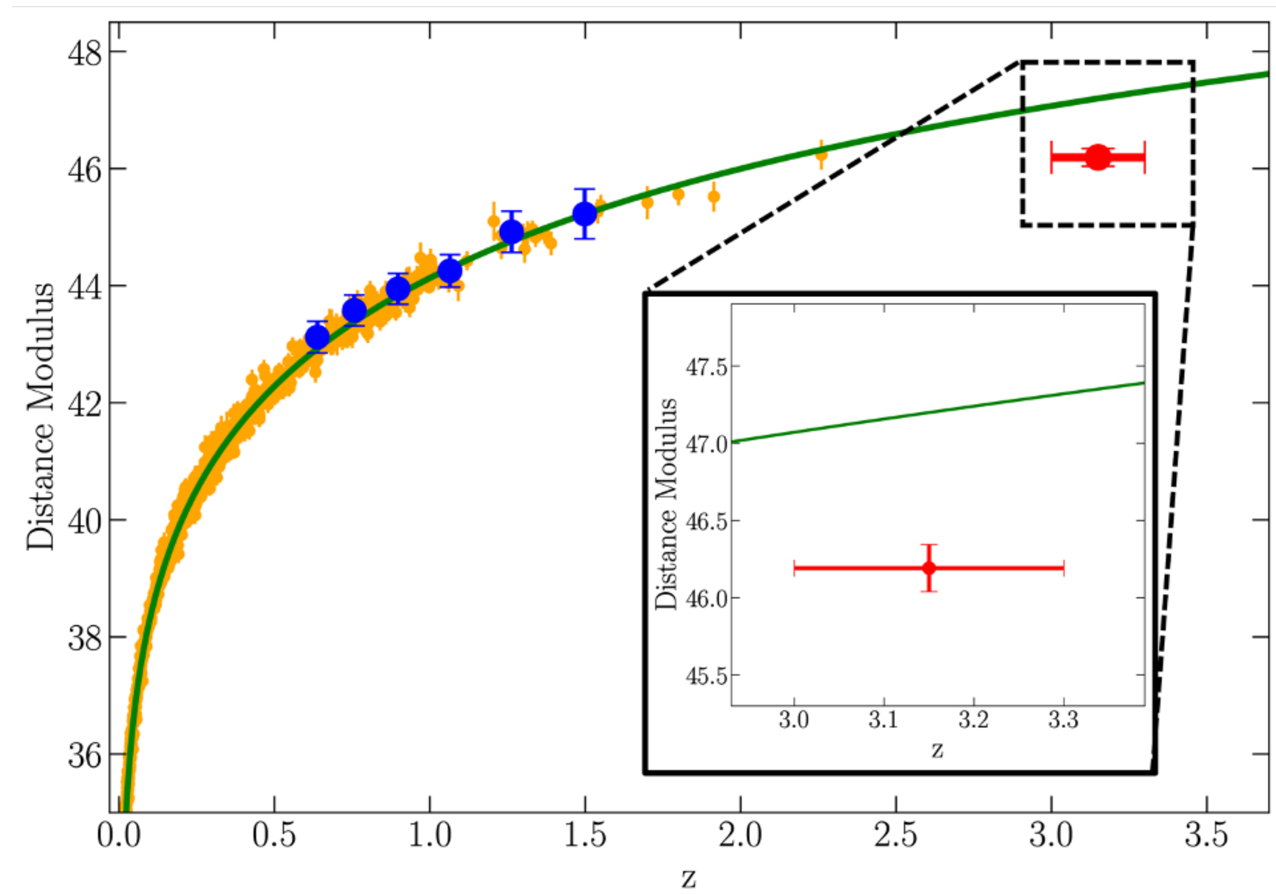


Flat ($\Omega_M + \Omega_\Lambda = 1$),
free *w*,
eROSITA QSOs:
$\Omega_M = 0.26^{+0.07}_{-0.11}$ (0.35±0.04)
dark energy -
equation of state
$w = -0.81^{+0.22}_{-0.28}$ (-1.251±0.144)

THE L_X-L_{UV} RELATION AT HIGH REDSHIFTS: THE TIGHTEST TO DATE

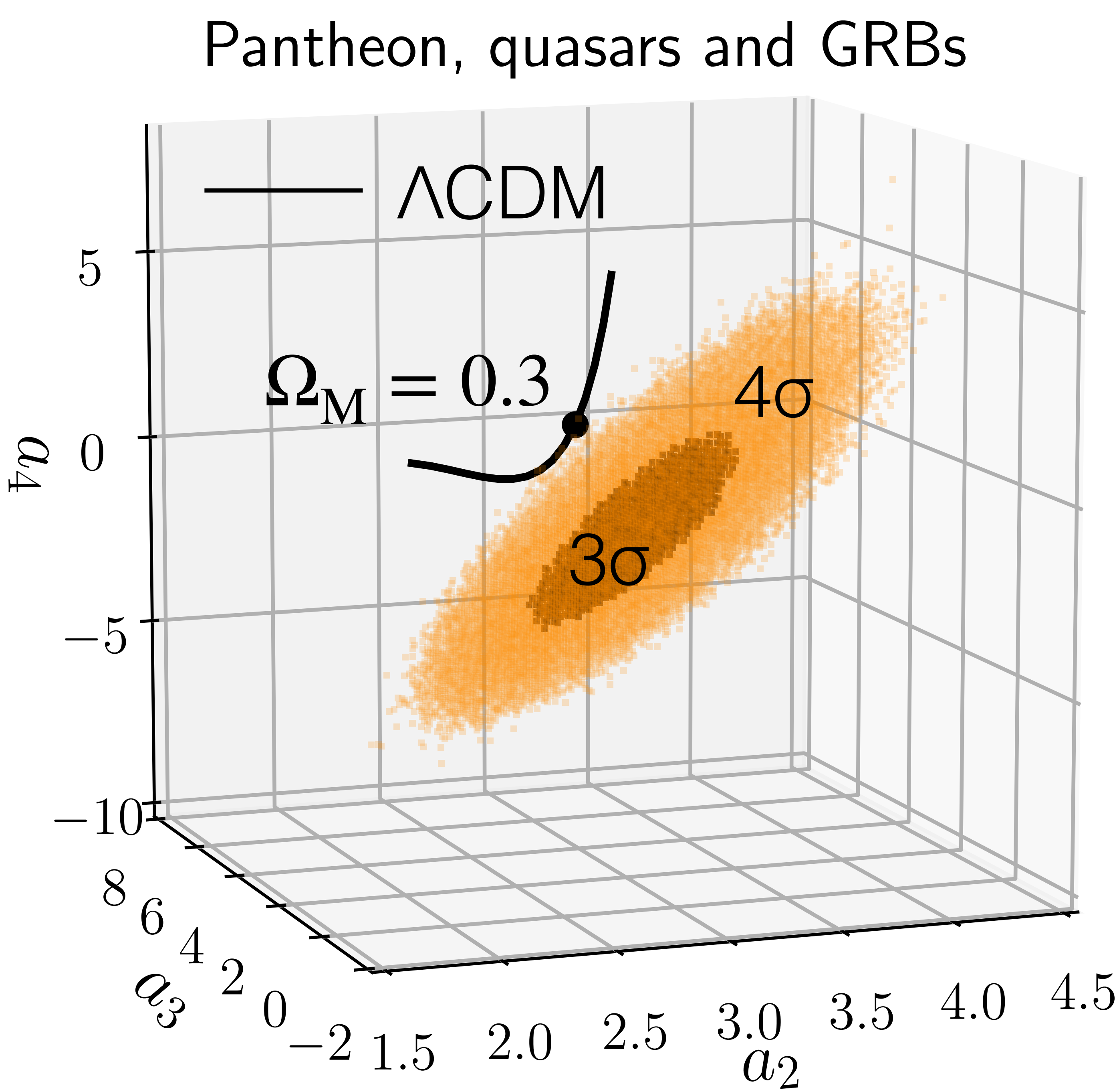
Sacchi et al 2022 (A&A, 663-7)



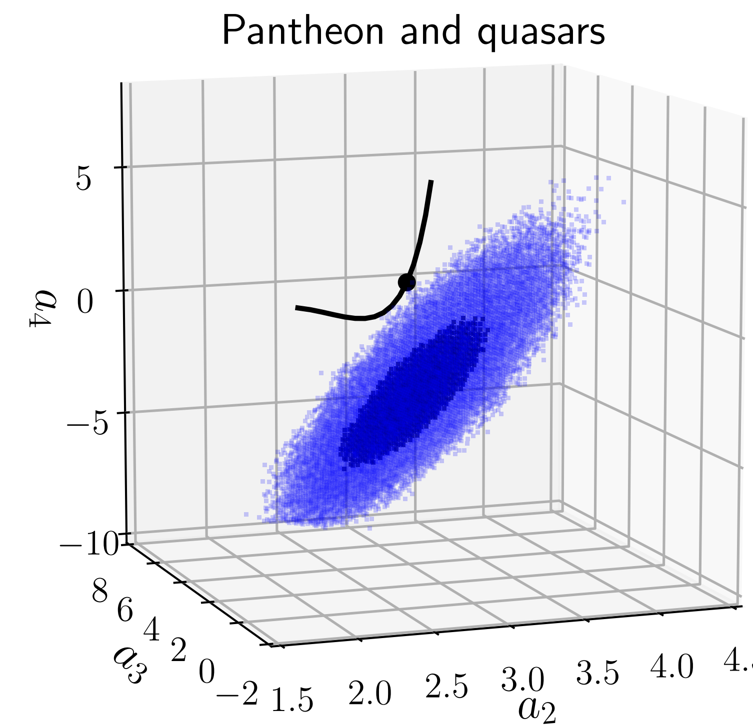


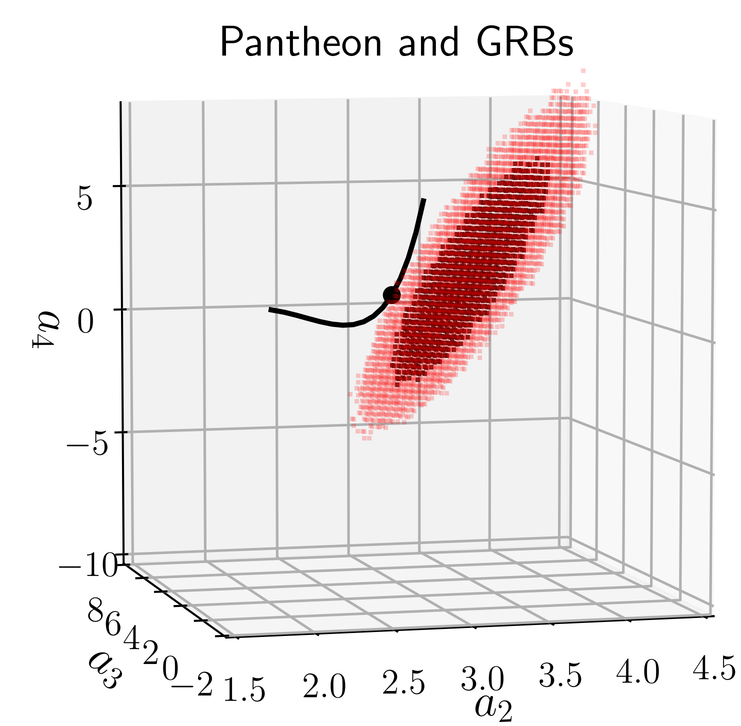
Intrinsic dispersion of 0.12 dex for 130 quasars at redshift > 2.5
(starting sample: 2400 quasars from Lusso+20)
One-by-one analysis (both X-ray and UV)

COSMOLOGY WITH QUASARS, SNe AND GRBs



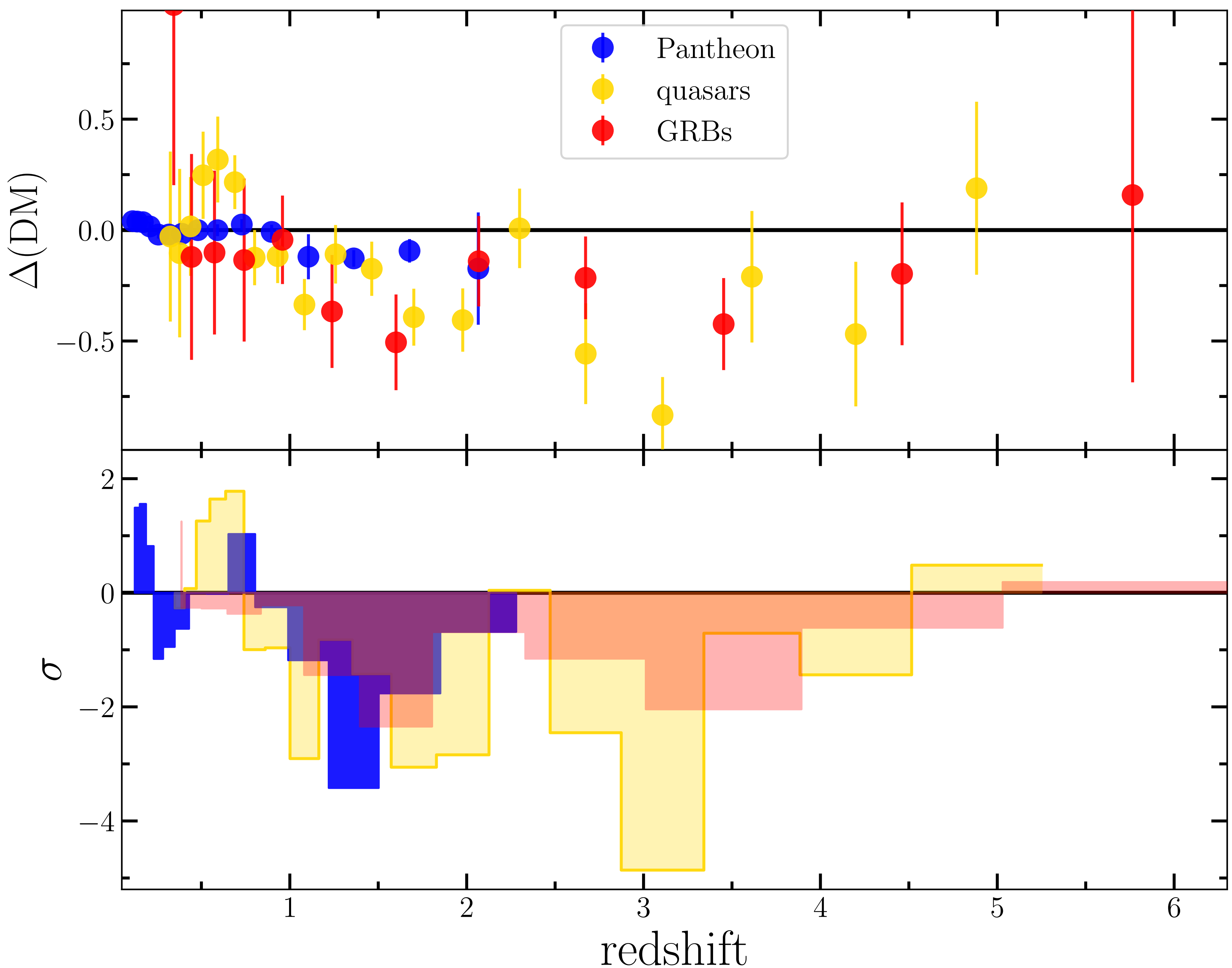
Lusso, et al. 2019 A&A, 628-4





COSMOLOGY WITH QUASARS, SNe AND GRBs

Lusso, et al. 2019 A&A, 628-4



Flat ΛCDM
$\Omega_M = 0.3$

Binning involved…take it with *cum grano salis* but the trend is robust on average…

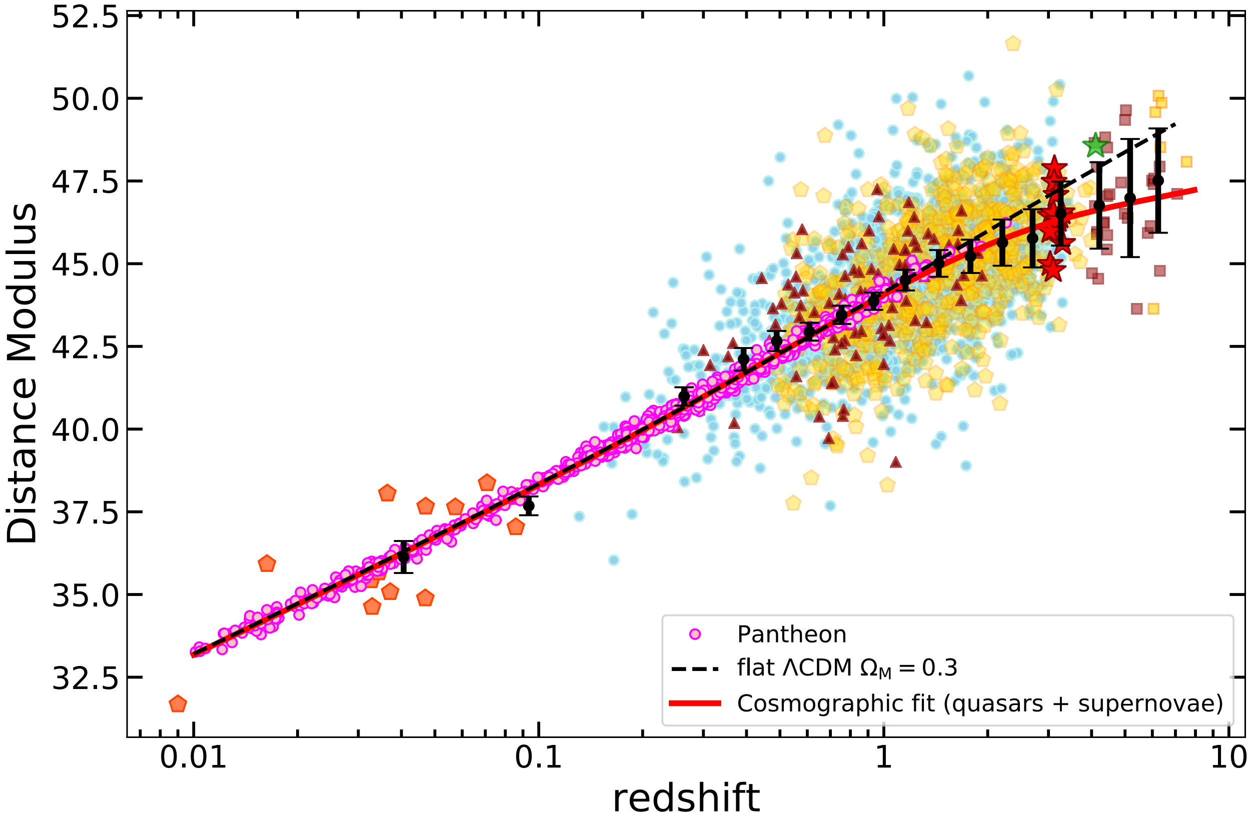
z > 1 type Ia supernovae are needed: *Nancy Grace Roman Space Telescope* (formerly *WFIRST*)

COSMOLOGY WITH QUASARS
TEST SOURCES OF SYSTEMATICS

Lusso et al. (2020), A&A 642A-150

~2400 quasars 0<z<7.5 (available online)

- Verified that L_X-L_{UV} is redshift independent
- Confirmed that a tension with the ΛCDM exists at z>1
- None of the adopted filters to select the *best* sample introduce systematics in our results.
  - (Variable) Dust reddening & host galaxy contamination
  - X-ray gas absorption
  - Eddington bias, etc…



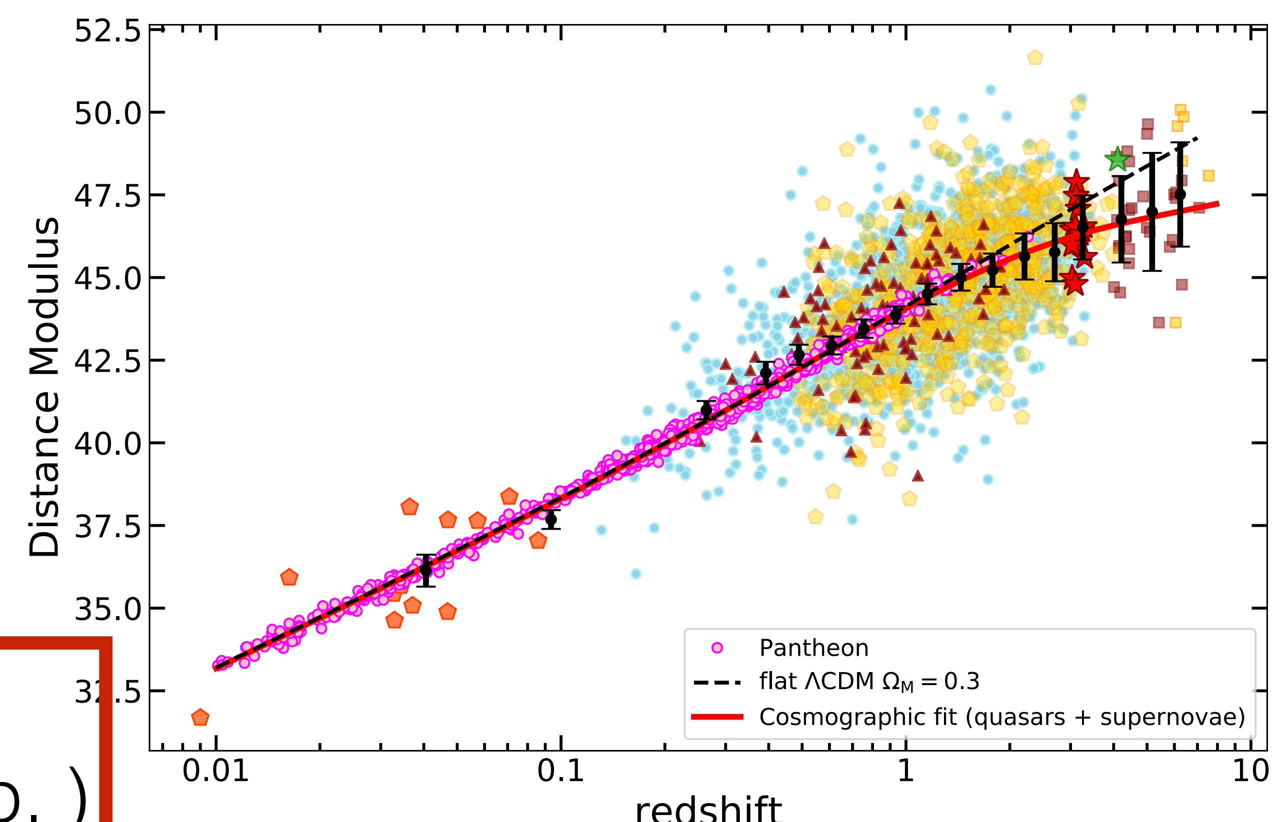
Uncertainties on the distance are as high as 80%…plenty of room for improvement

COSMOLOGY WITH QUASARS
TEST SOURCES OF SYSTEMATICS

Lusso et al. (2020), A&A 642A-150

~2400 quasars 0<z<7.5 (available online)

- Verified that L_X-L_{UV} is redshift independent
- Confirmed that a tension with the ΛCDM exists at z>1
- None of the adopted filters to select the *best* sample introduce systematics in our results.
  - (Variable) Dust reddening & host galaxy contamination
  - X-ray gas absorption
  - Eddington bias, etc…



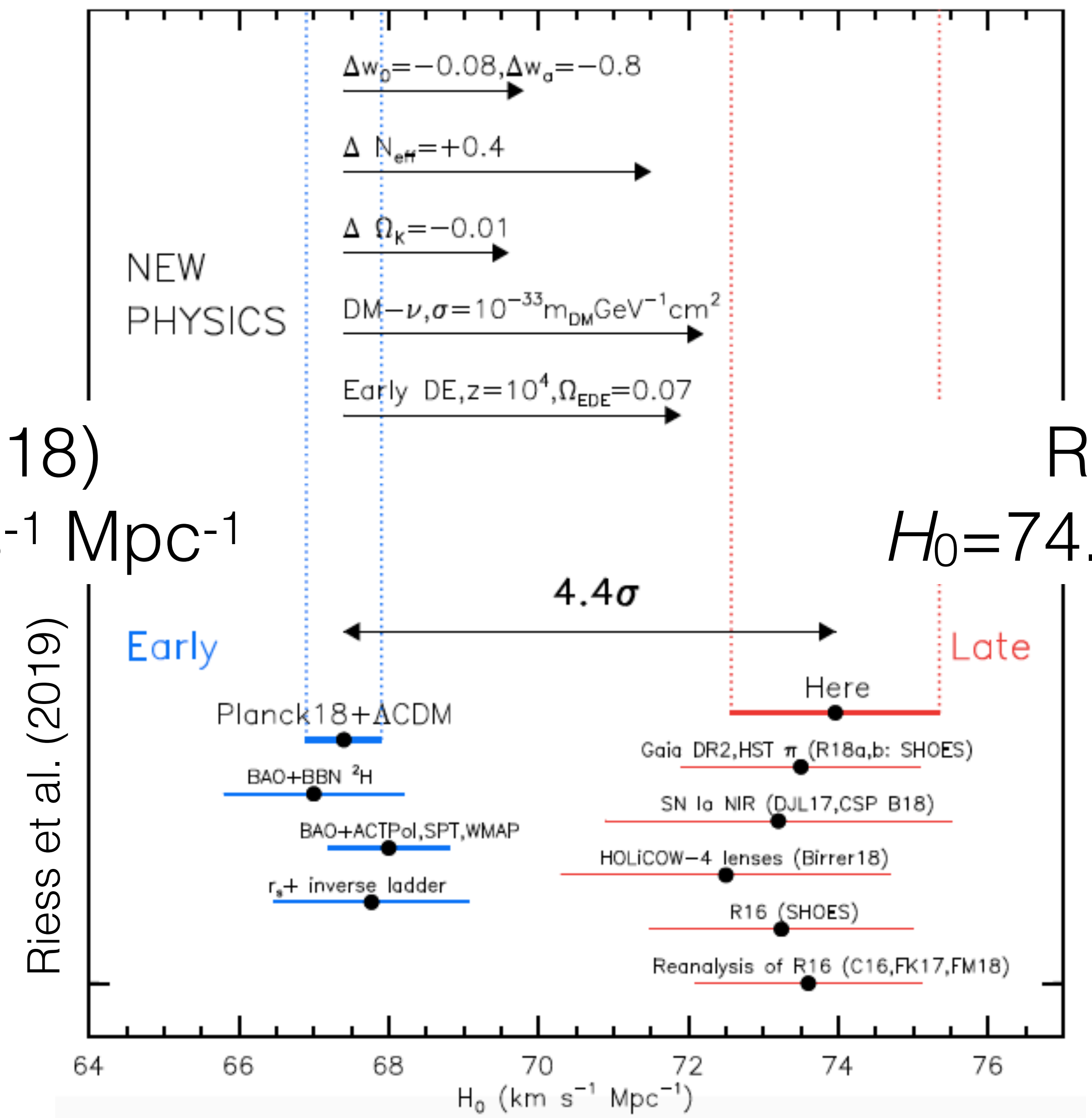
NOW WORKING ON A BIGGER (x2) QUASAR SAMPLE (Sacchi et. al in prep.)

Uncertainties on the distance are as high as 80%…plenty of room for improvement

The schism between the early & late Universe
Do we need an extension to the ΛCDM? Maybe yes…

H_0 : normalisation of the Hubble parameter $H(z)$ that describes the expansion rate of the Universe

Planck et al. (2018)
H_0=67.06±0.62 km s^{-1} Mpc^{-1}

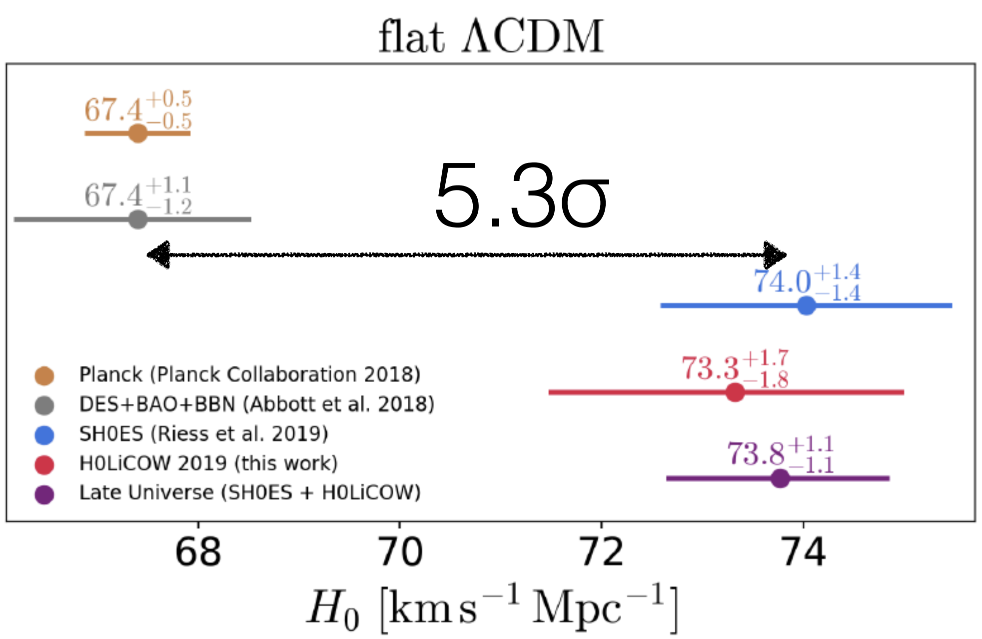


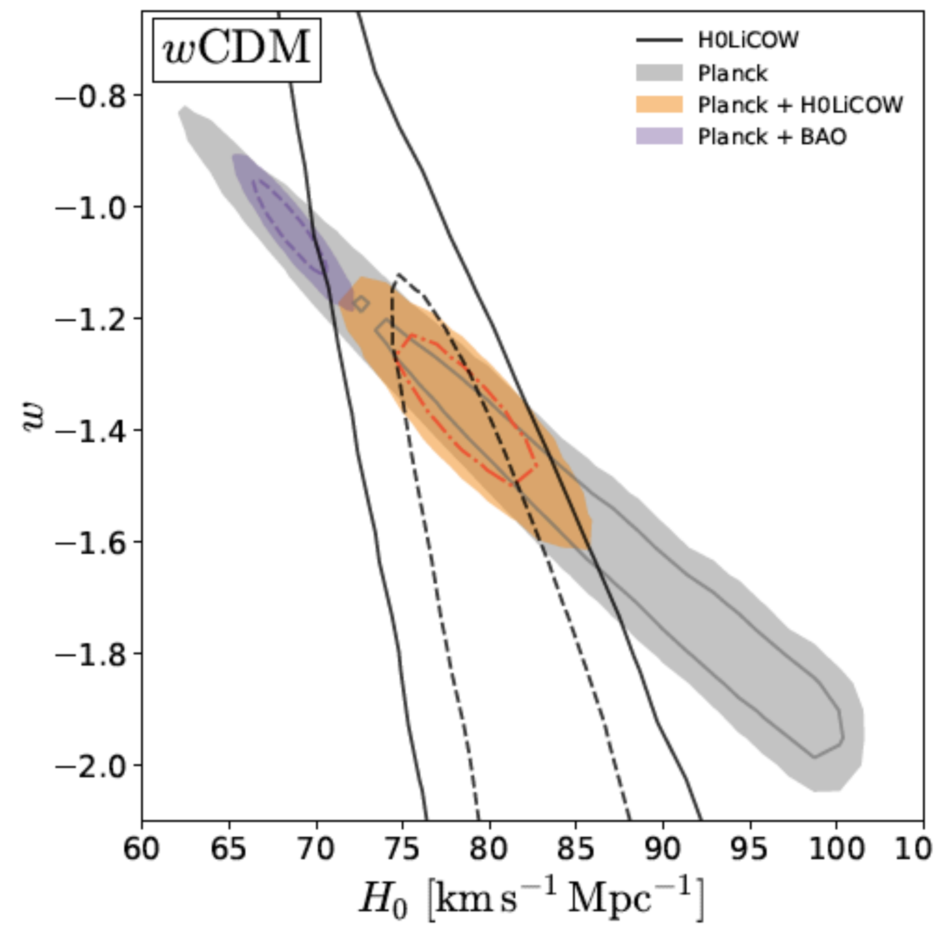
Riess et al. (2019)
H_0=74.03±1.42 km s^{-1} Mpc^{-1}

See also the review Riess, A. 2020, *Nat. Rev. Physics* 2-1
"The Expansion of the Universe is Faster than Expected"

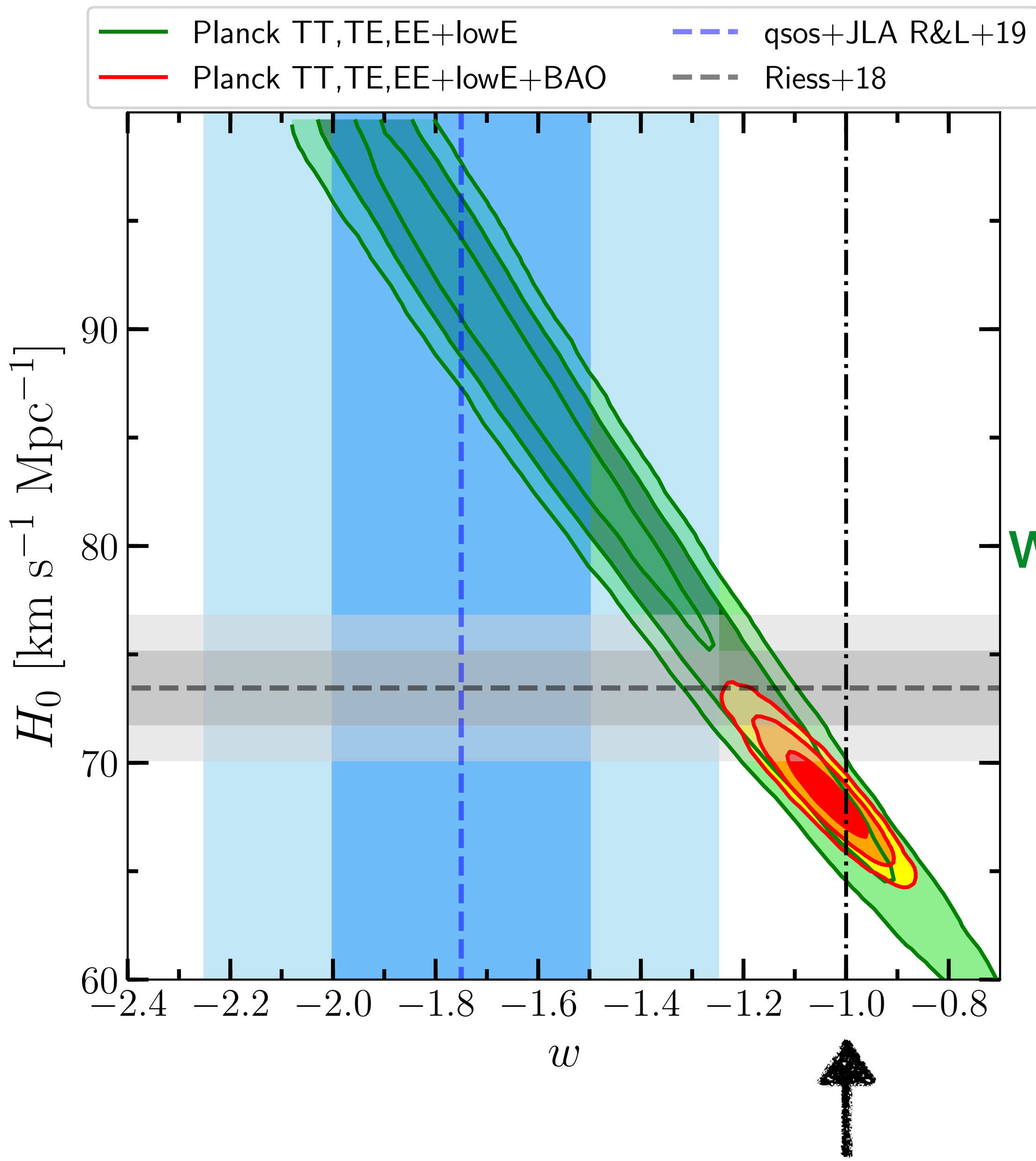
The schism between the early & late Universe
Do we need an extension to the ΛCDM? Maybe yes…

Wong et al. 2019 (H0LiCOW)





The schism between the early & late Universe
Do we need an extension to the ΛCDM? Maybe yes…



QSO+SN
(RL19)
w =
-1.75±0.25

Planck+18
$w = -1.57^{+0.35}_{-0.27}$

Elisabeta Lusso UniFi

Calibrating the quasar Hubble diagram at low redshifts (z<0.7): the Cool Attitude Targets (CAT)

CCT project (PI: F. Civano)

Main goal: reduce the dispersion in the HD at z<0.7 to better cross-calibrate quasars and SNIa —> increase the precision of cosmological constraints based on quasars *alone*.

Calibrating the quasar Hubble diagram at low redshifts (*z*<0.7): the Cool Attitude Targets (CAT)

CCT project (PI: F. Civano)

Main goal: reduce the dispersion in the HD at z<0.7 to better cross-calibrate quasars and SNIa —> increase the precision of cosmological constraints based on quasars *alone*.

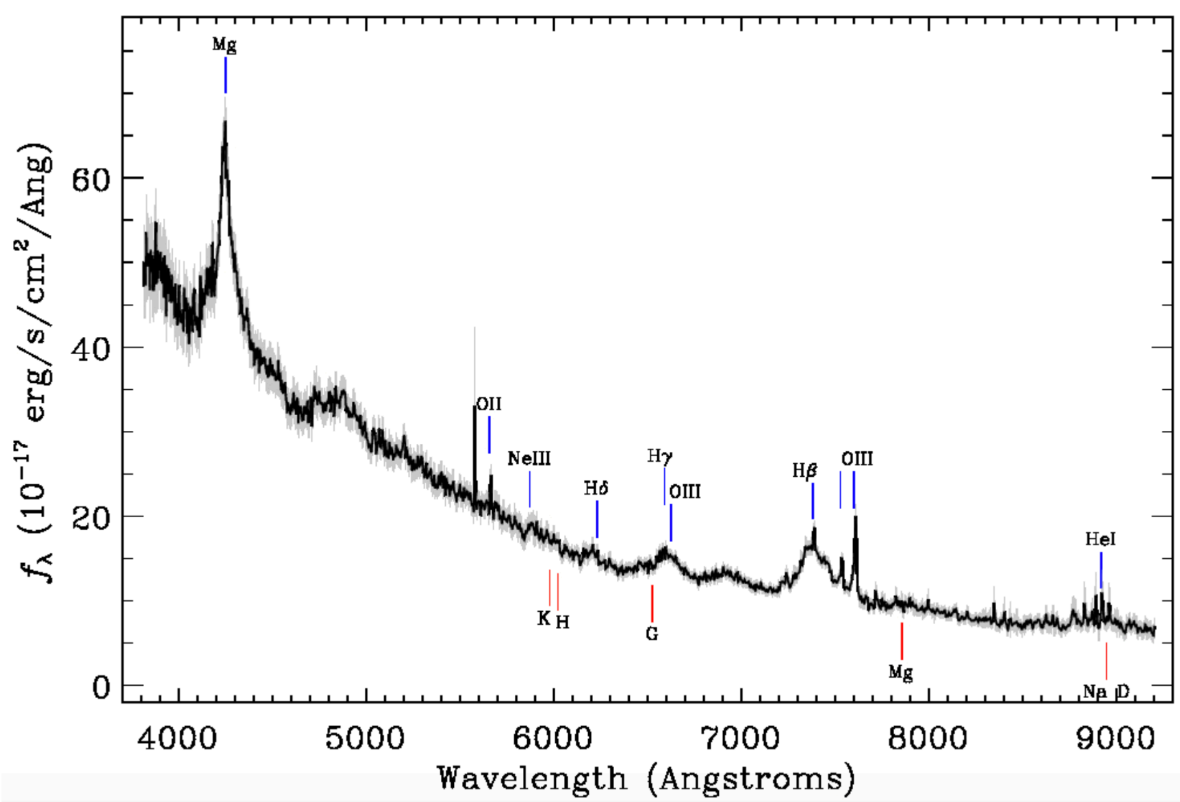
40 targets observed since January 2019 (main sample: ~4000 SDSS AGN)

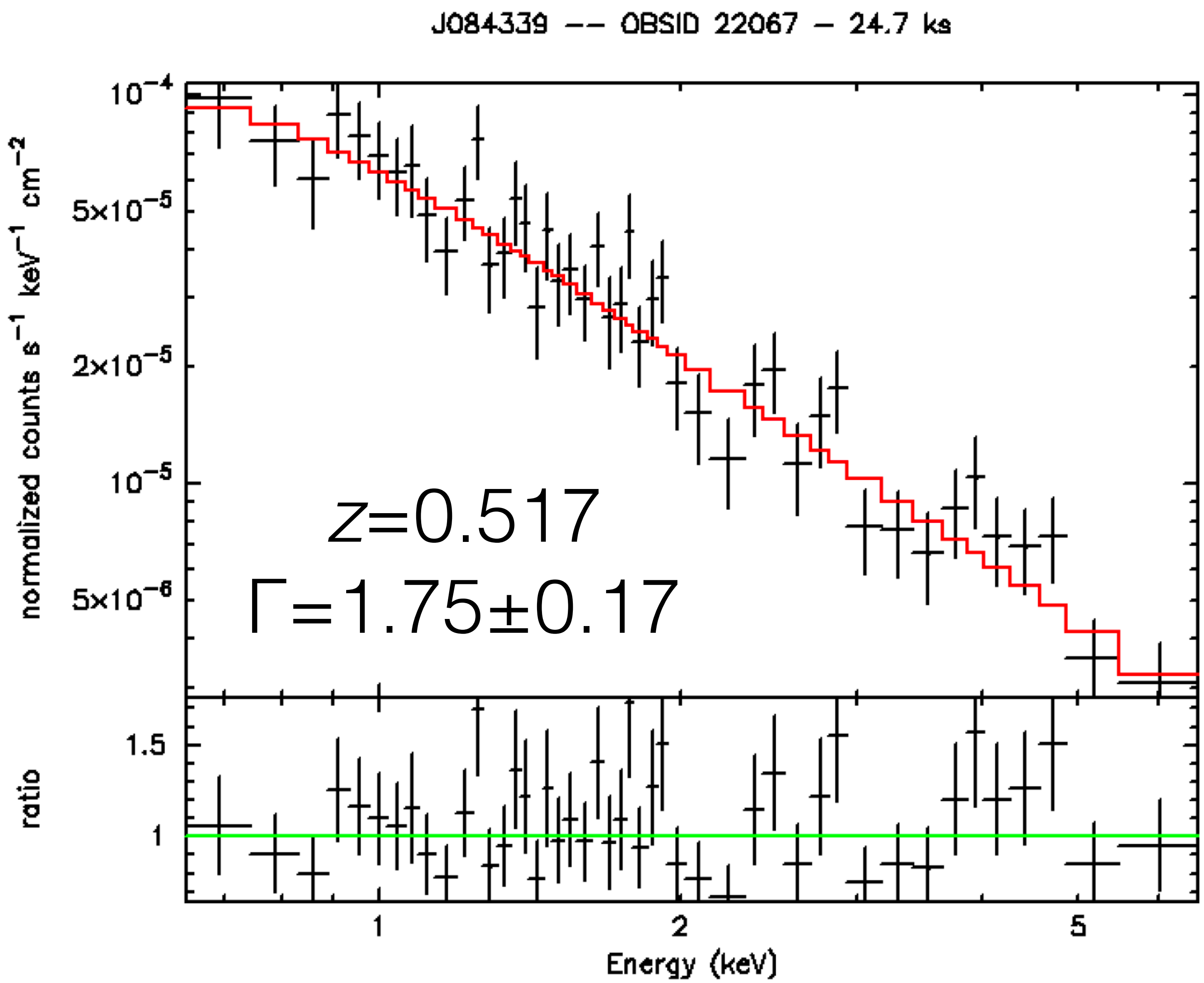
Calibrating the quasar Hubble diagram at low redshifts (z<0.7): the Cool Attitude Targets (CAT)

CCT project (PI: F. Civano)

Main goal: reduce the dispersion in the HD at z<0.7 to better cross-calibrate quasars and SNIa —> increase the precision of cosmological constraints based on quasars *alone*.

40 targets observed since January 2019 (main sample: ~4000 SDSS AGN)





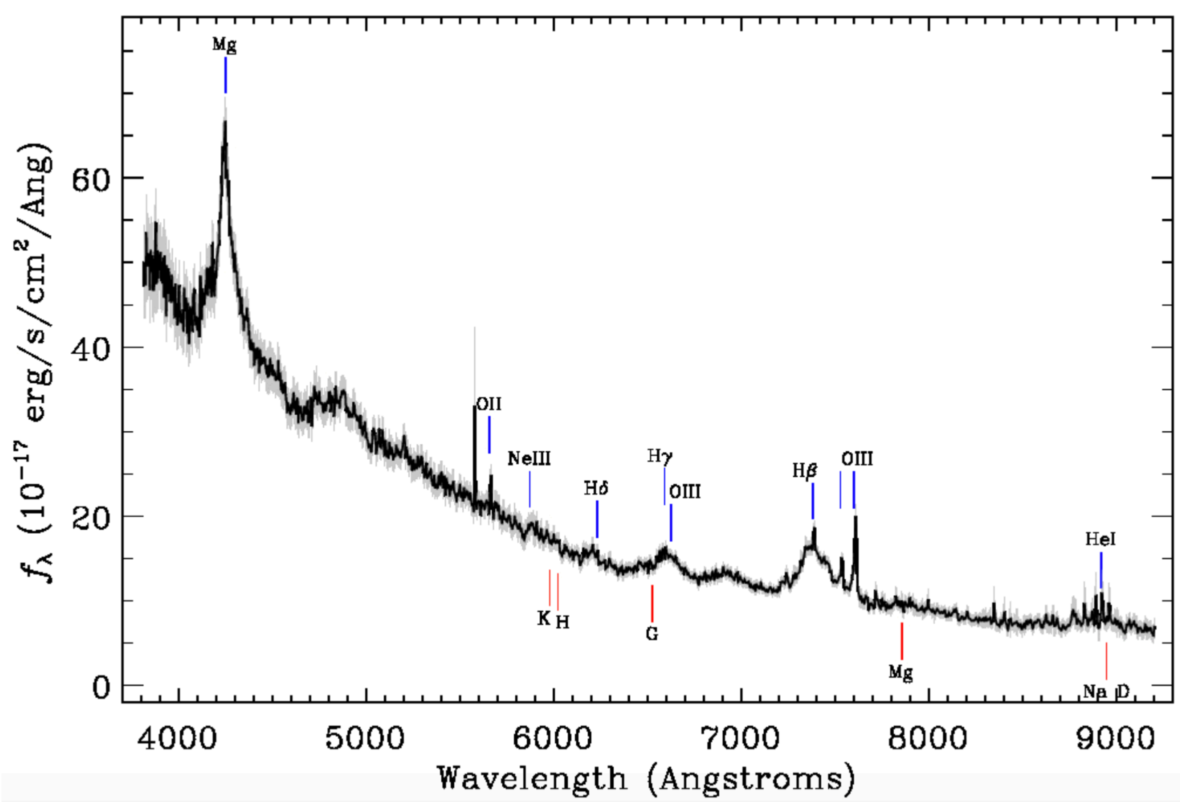
Elisabeta Lusso UniFi

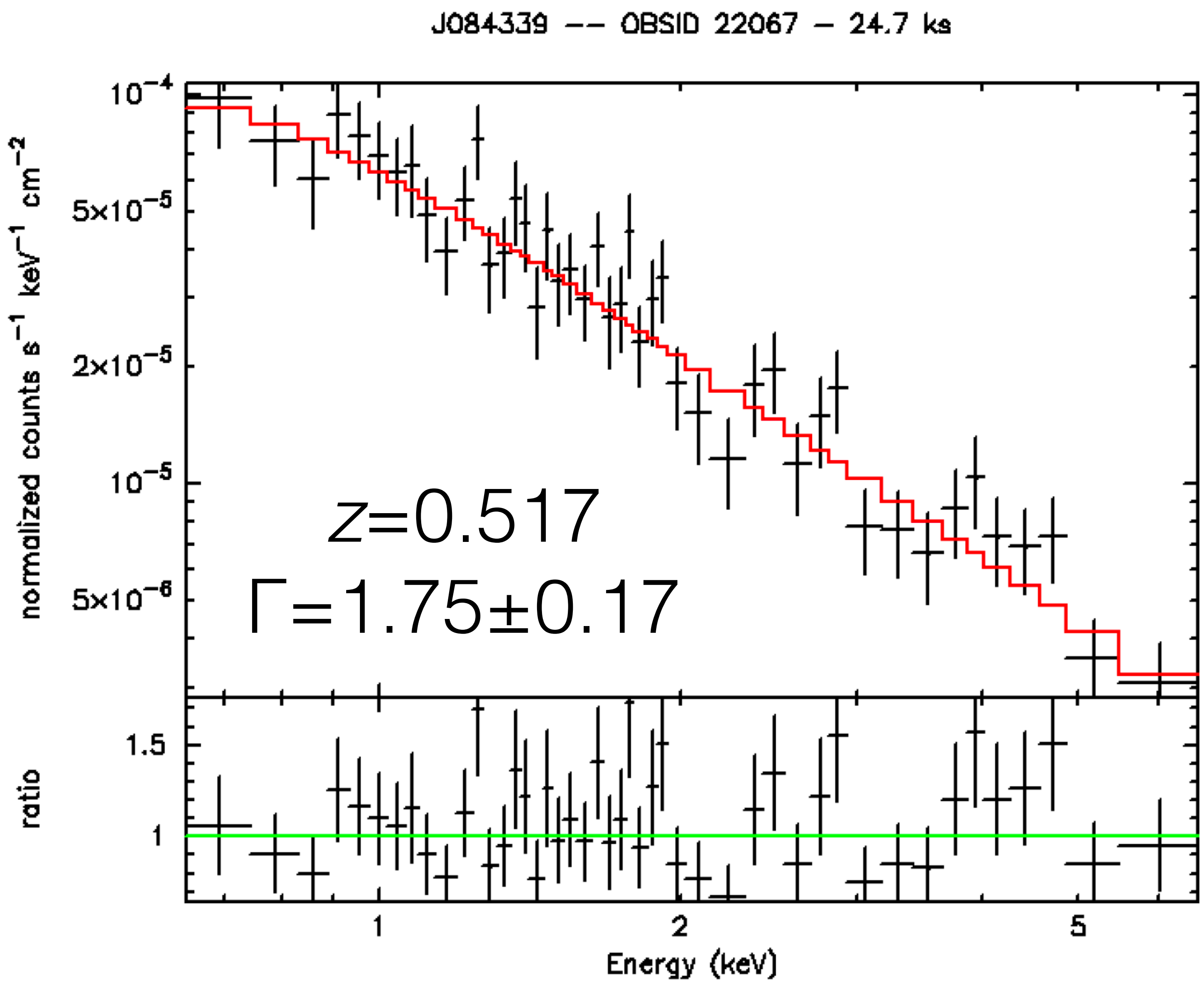
Calibrating the quasar Hubble diagram at low redshifts (z<0.7): the Cool Attitude Targets (CAT)

CCT project (PI: F. Civano)

Main goal: reduce the dispersion in the HD at z<0.7 to better cross-calibrate quasars and SNIa —> increase the precision of cosmological constraints based on quasars *alone*.

40 targets observed since January 2019 (main sample: ~4000 SDSS AGN)





Optical/UV spectra from SDSS
Follow-up (check variability) with:

- FAST/FLWO 1.5m
- OSMOS/MDM 2.4m

Elisabeta Lusso UniFi

SMBH accretion physics

intrinsic dispersion of the UV/X-ray relation

2153 quasars selected from the *Sloan Digital Sky Survey* DR7 with X-ray observations from 3XMM-DR5

Selection criteria

1. Dust reddening and host galaxy contamination
2. Uncertainties on X-ray fluxes do to unreliable source counts
3. X-ray absorption
4. No radio loud (enhance X-ray emission due to the jet)
5. No broad absorption line quasars (affected by dust reddening)
6. Eddington Bias

743 quasars with “clean SED”

Lusso & Risaliti (2016, ApJ, 819, 154)

SMBH accretion physics

intrinsic dispersion of the UV/X-ray relation

2153 quasars selected from the
Sloan Digital Sky Survey DR7 with
X-ray observations from 3XMM-DR5

Selection criteria

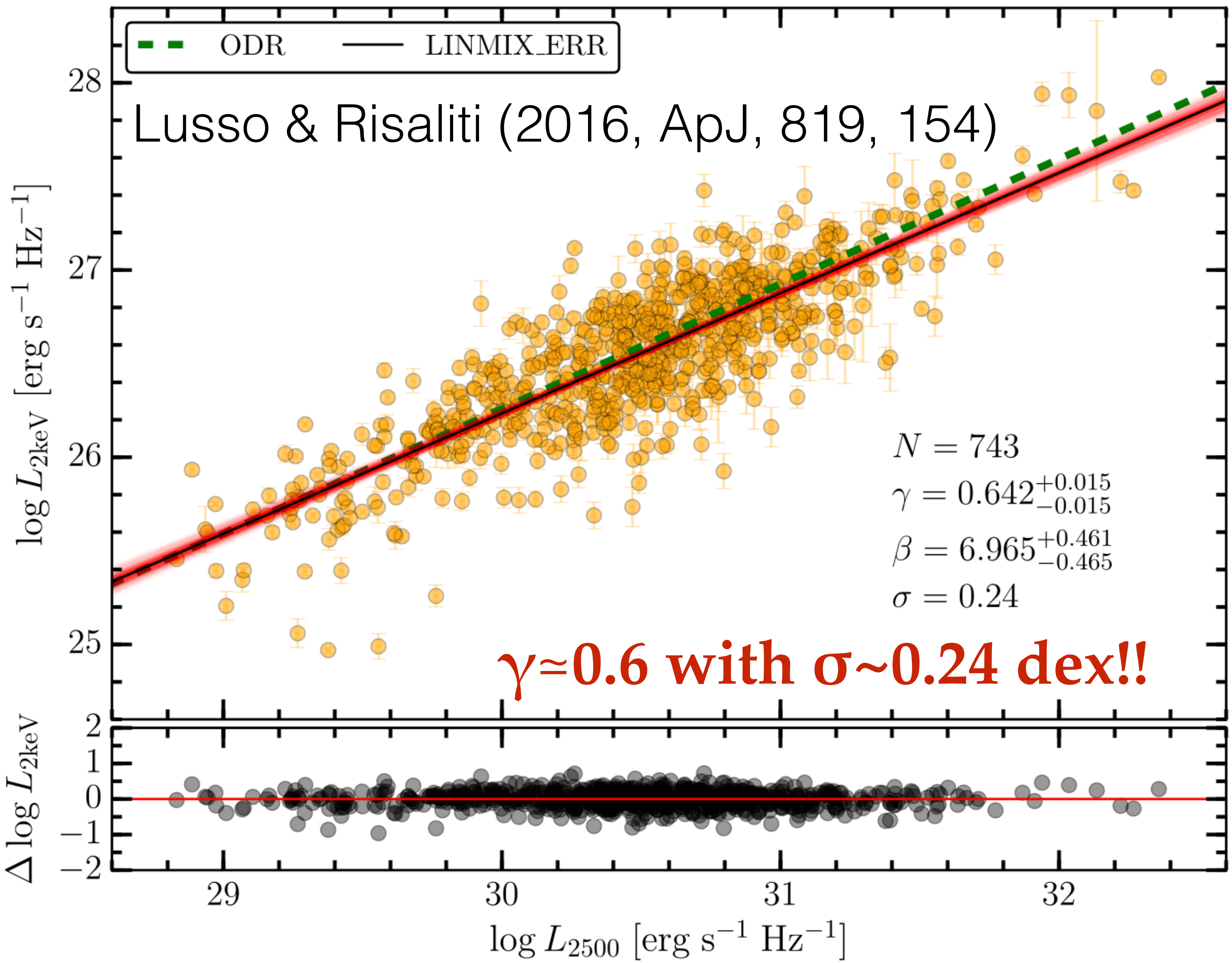
1. Dust reddening and host galaxy contamination
2. Uncertainties on X-ray fluxes do to unreliable source counts
3. X-ray absorption
4. No radio loud (enhance X-ray emission due to the jet)
5. No broad absorption line quasars (affected by dust reddening)
6. Eddington Bias

743 quasars with "clean SED"
Lusso & Risaliti (2016, ApJ, 819, 154)

Validation selection criteria & new quasar sample
Lusso et al (2020, A&A 642A-150)

SMBH accretion physics

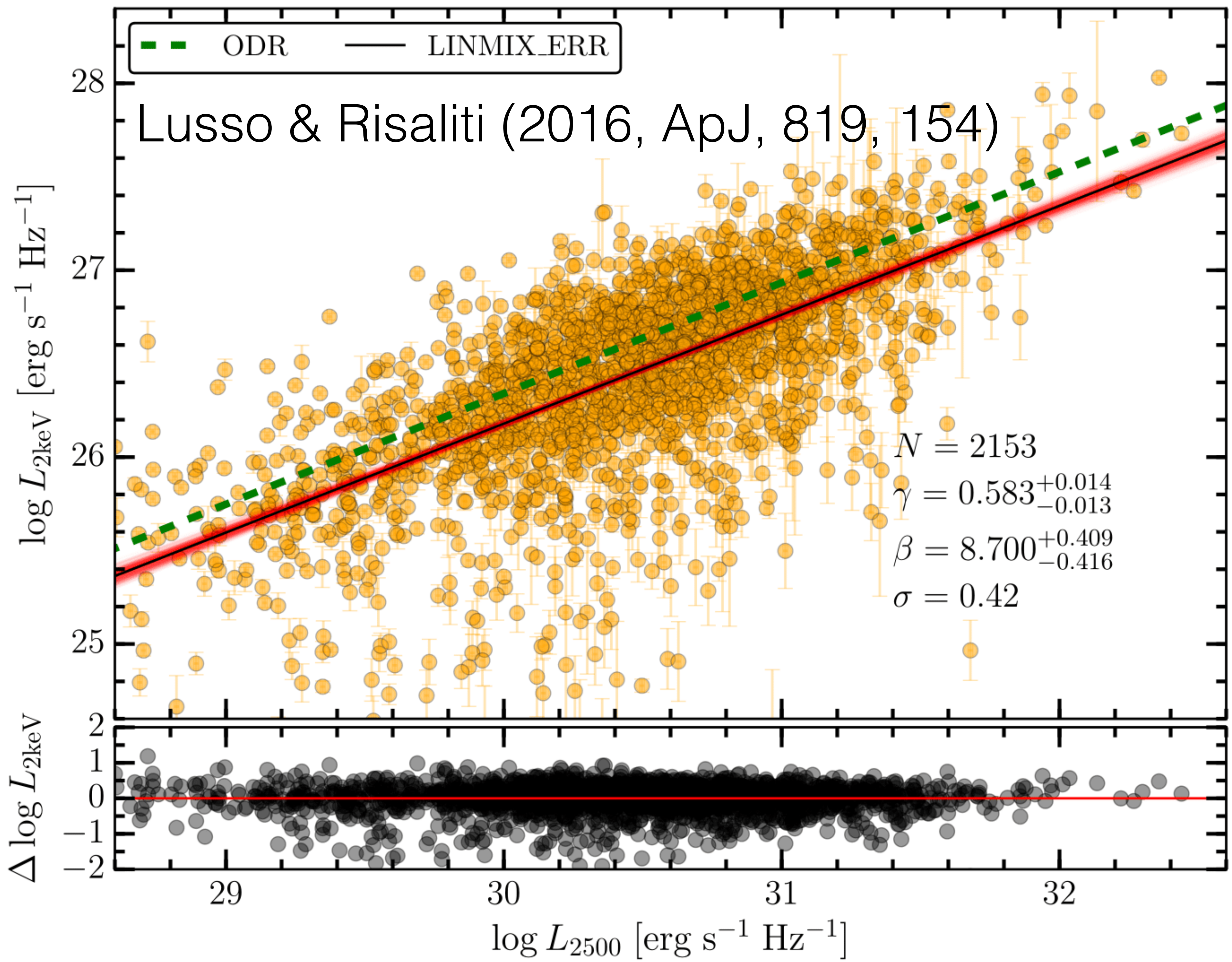
intrinsic dispersion of the UV/X-ray relation



Elisabeta Lusso UniFi

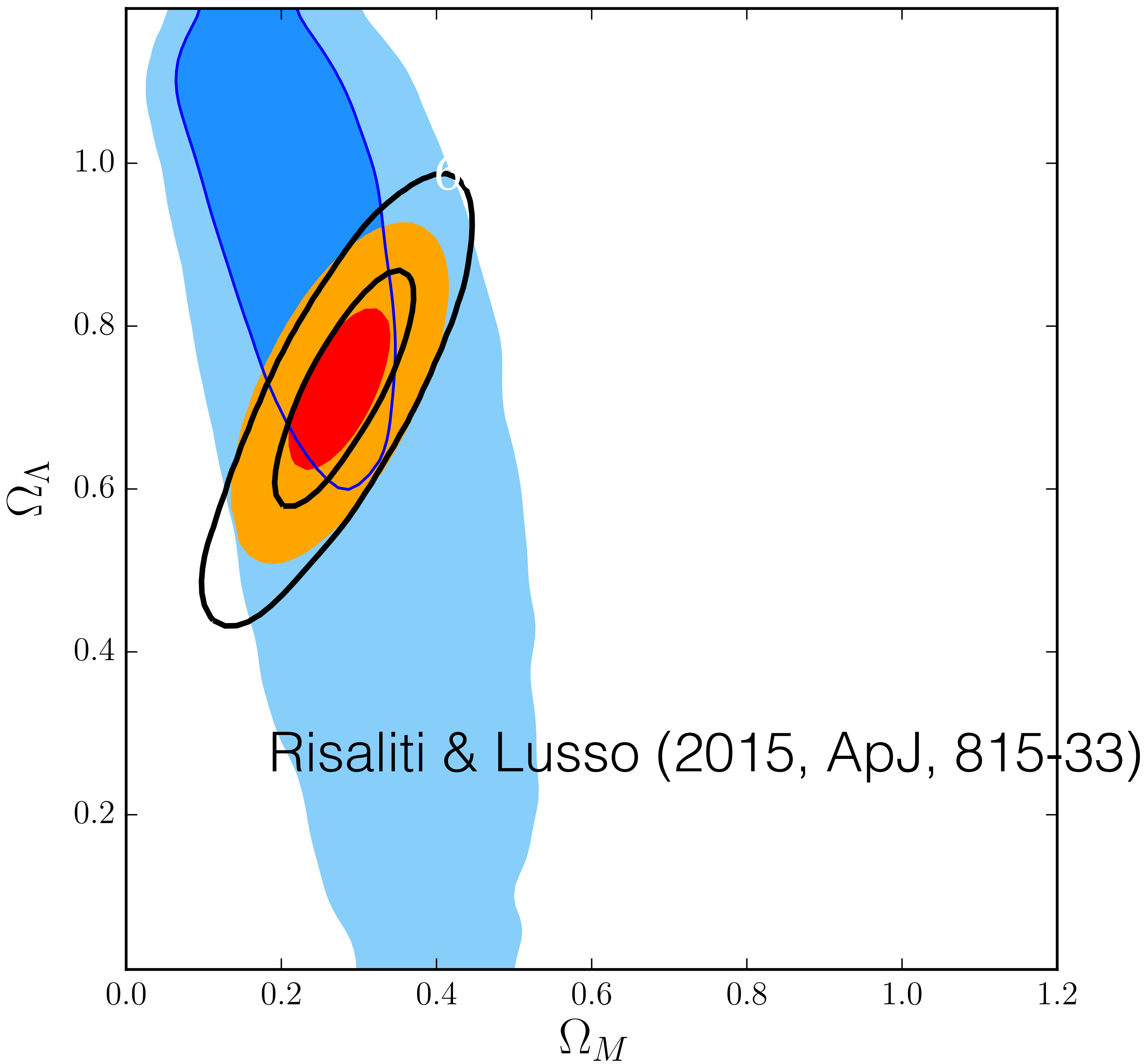
SMBH accretion physics

intrinsic dispersion of the UV/X-ray relation



Elisabeta Lusso UniFi

Cosmology with quasars
Results



Ω_Λ and Ω_M fitted simultaneously

QSOs only:

$\Omega_M = 0.22^{+0.10}_{-0.08}$

$\Omega_\Lambda = 0.92^{+0.18}_{-0.30}$

QSOs + SNe:

$\Omega_M = 0.28^{+0.04}_{-0.04}$

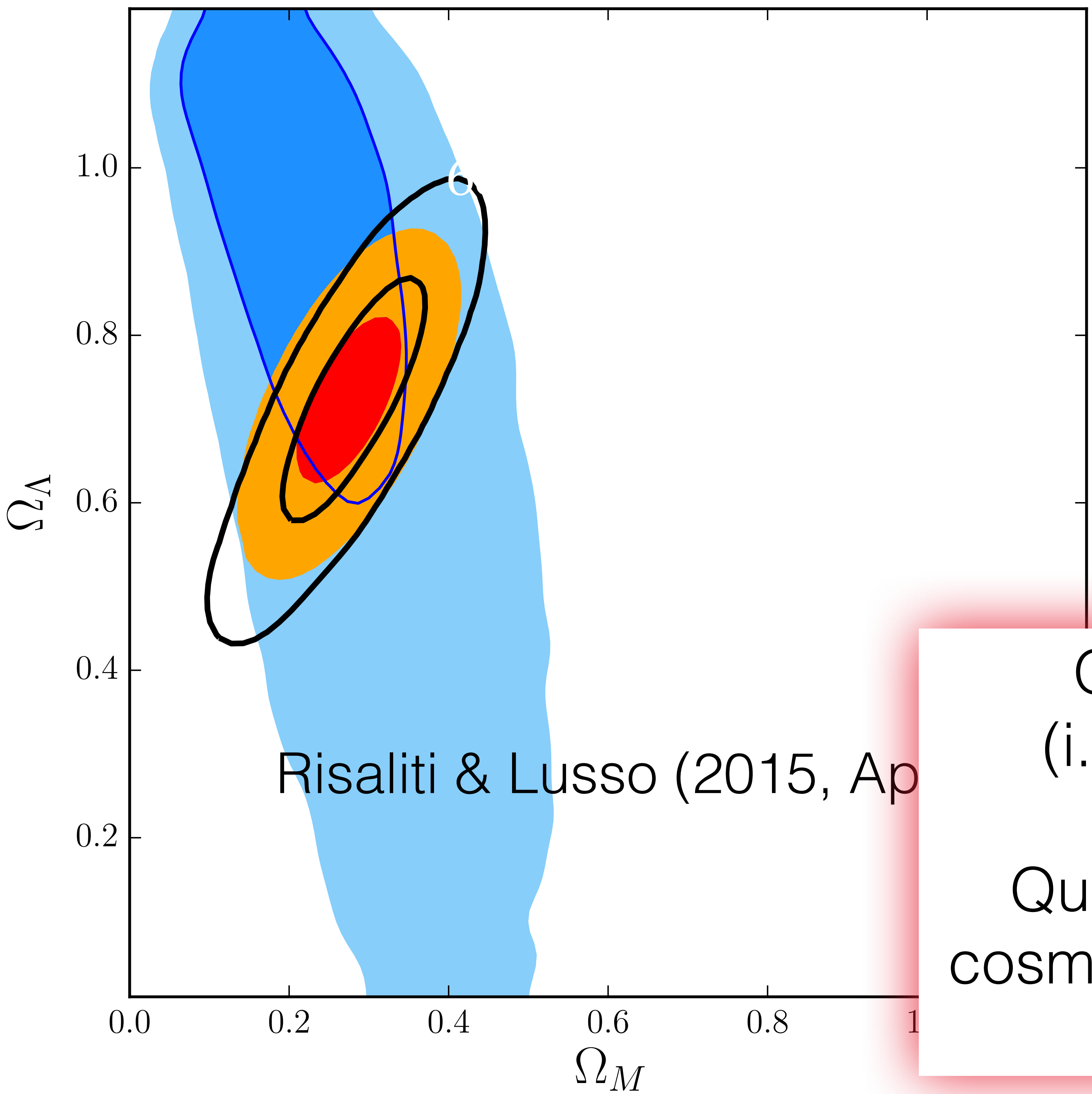
$\Omega_\Lambda = 0.73^{+0.08}_{-0.08}$

Planck 2015 results

$\Omega_M = 0.308 \pm 0.012$

$\Omega_\Lambda = 0.692 \pm 0.012$

Cosmology with quasars
Results



Risaliti & Lusso (2015, Ap

Ω_Λ and Ω_M
fitted simultaneously

QSOs only:
$\Omega_M = 0.22^{+0.10}_{-0.08}$
$\Omega_\Lambda = 0.92^{+0.18}_{-0.30}$

QSOs + SNe:
$\Omega_M = 0.28^{+0.04}_{-0.04}$
$\Omega_\Lambda = 0.73^{+0.08}_{-0.08}$

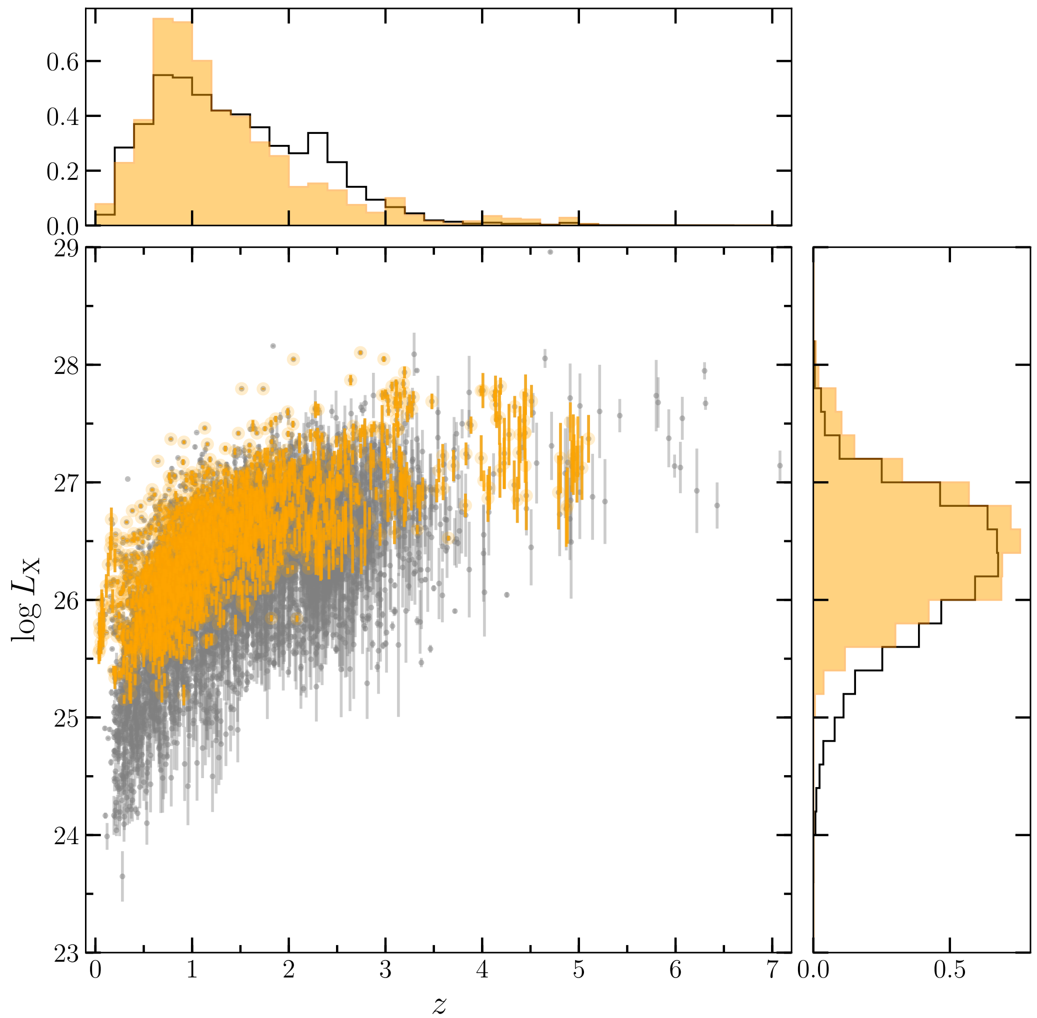
Quasars are complementary (i.e. *orthogonal*) to supernovae

Quasars offer *unique* access to a cosmo epoch (z=1.5-6) that is hard to probe with supernove

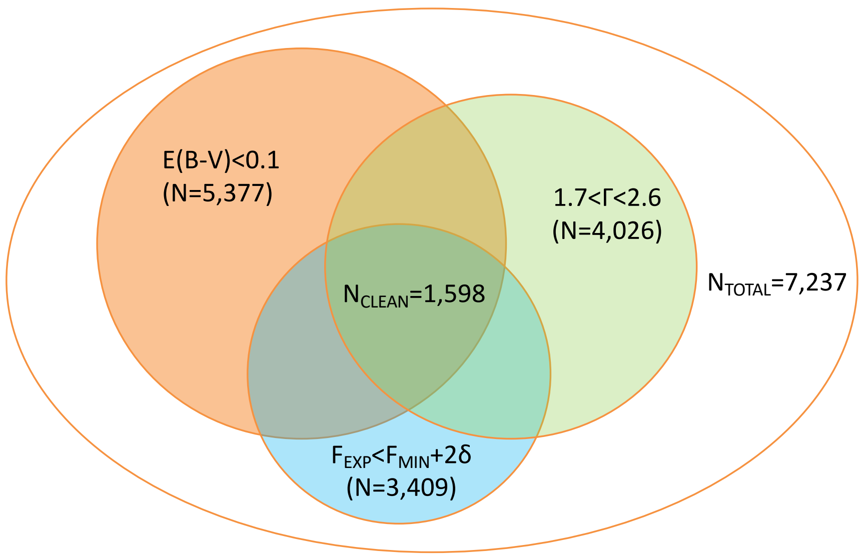
Cosmology with quasars

The Quasar Hubble Diagram: sample

~1600 quasars: SDSS/BOSS+3XMM DR7+
XMM Large Programme z~3+Chandra high-z+literature



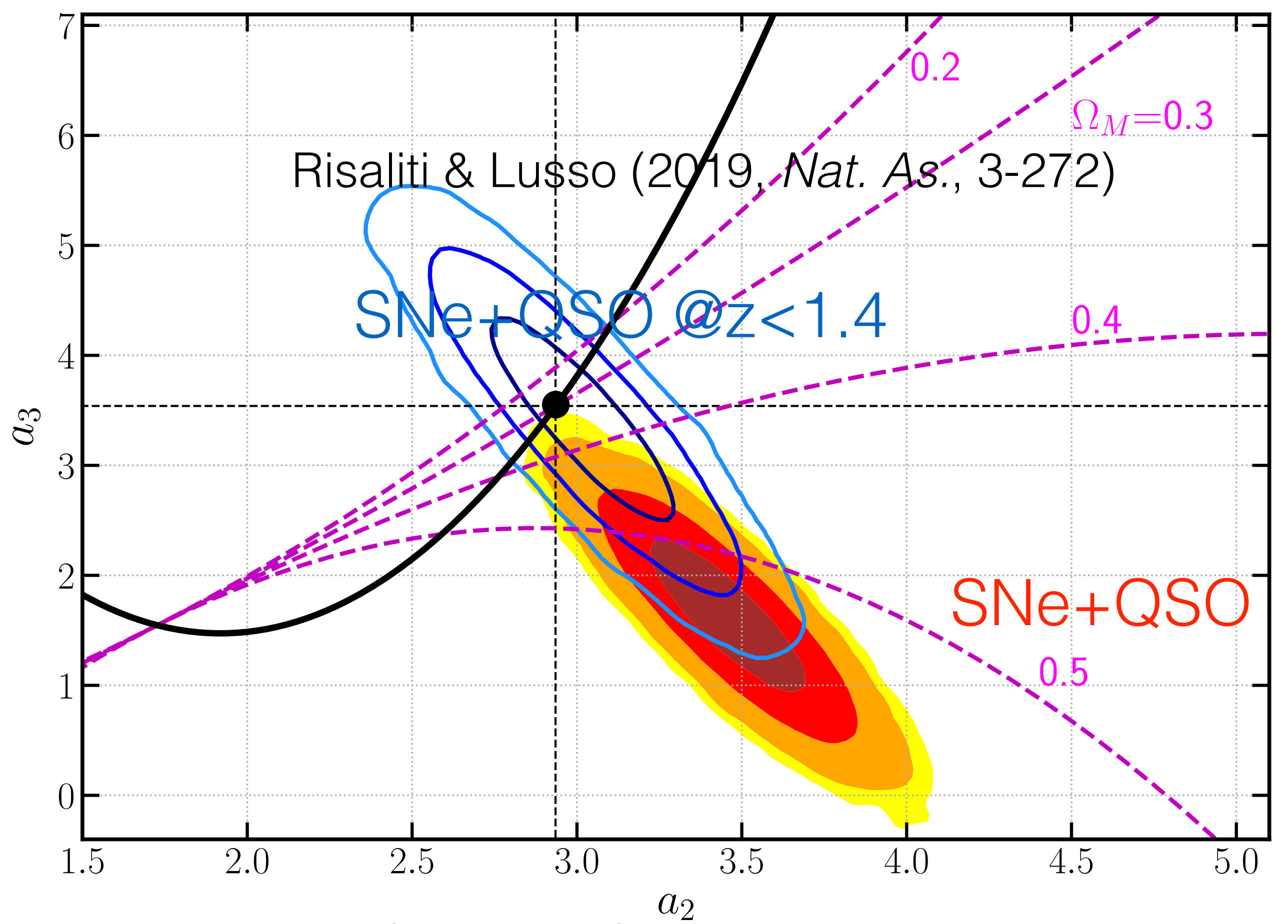
Risaliti & Lusso (2019, *Nat. As.*, 3-272)



~96% 3XMM DR7 catalogue
16 years of XMM-*Newton* observations
(Feb 3, 2000 - 15 Dec, 2016)

Cosmology with quasars

The Quasar Hubble Diagram



w>-1 *w*=-1 Ω_M=0.3 *w*<-1

Cosmographic approach

$$D_L = \frac{c}{H_0} \ln(10) \times \sum_{i=1}^{3} a_i \log^i(1+z)$$

Flat ΛCDM

Flat *w*CDM (free *w*)

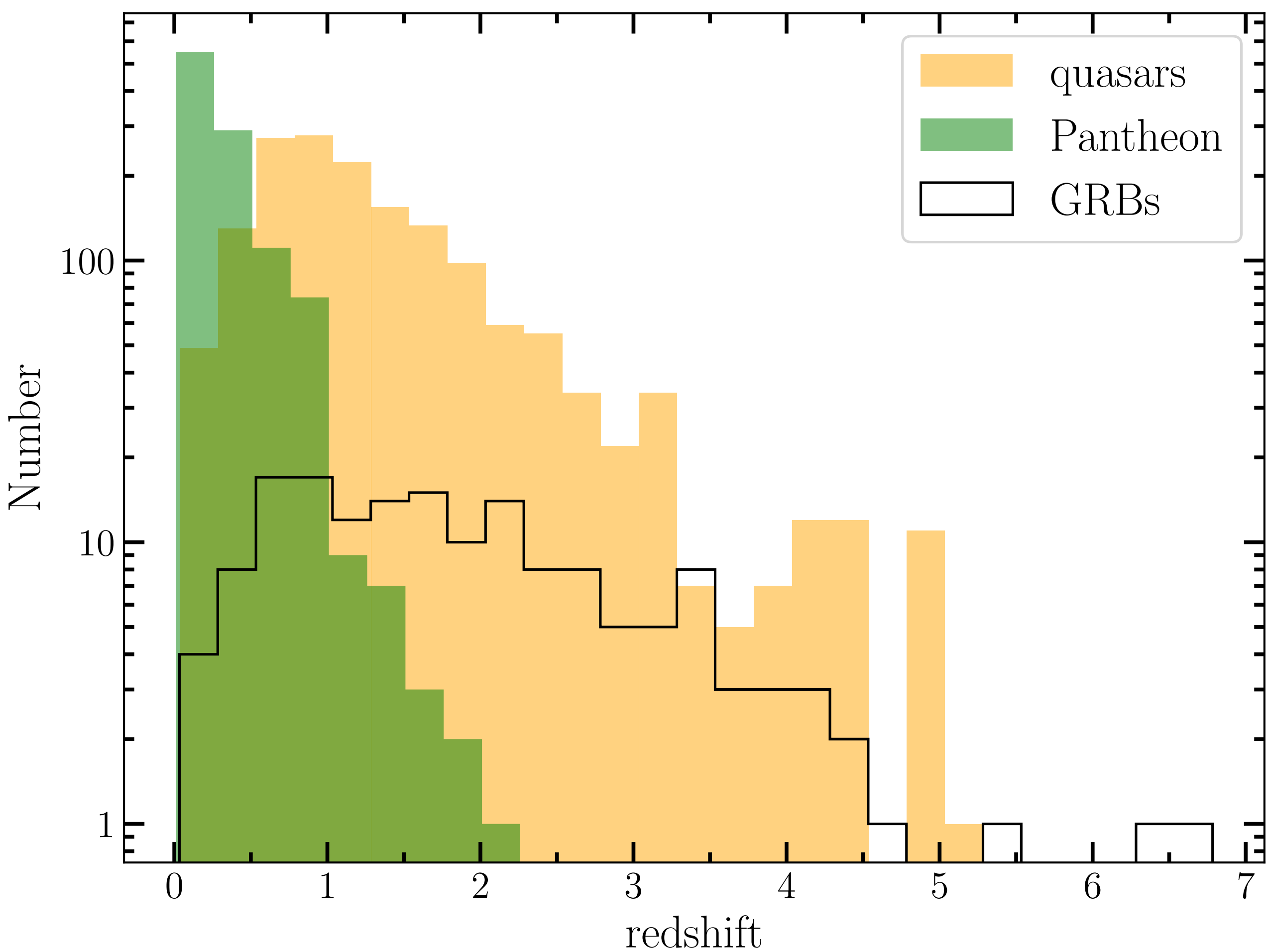
$w(z) = w_0 + w_a * z/(1+z)$

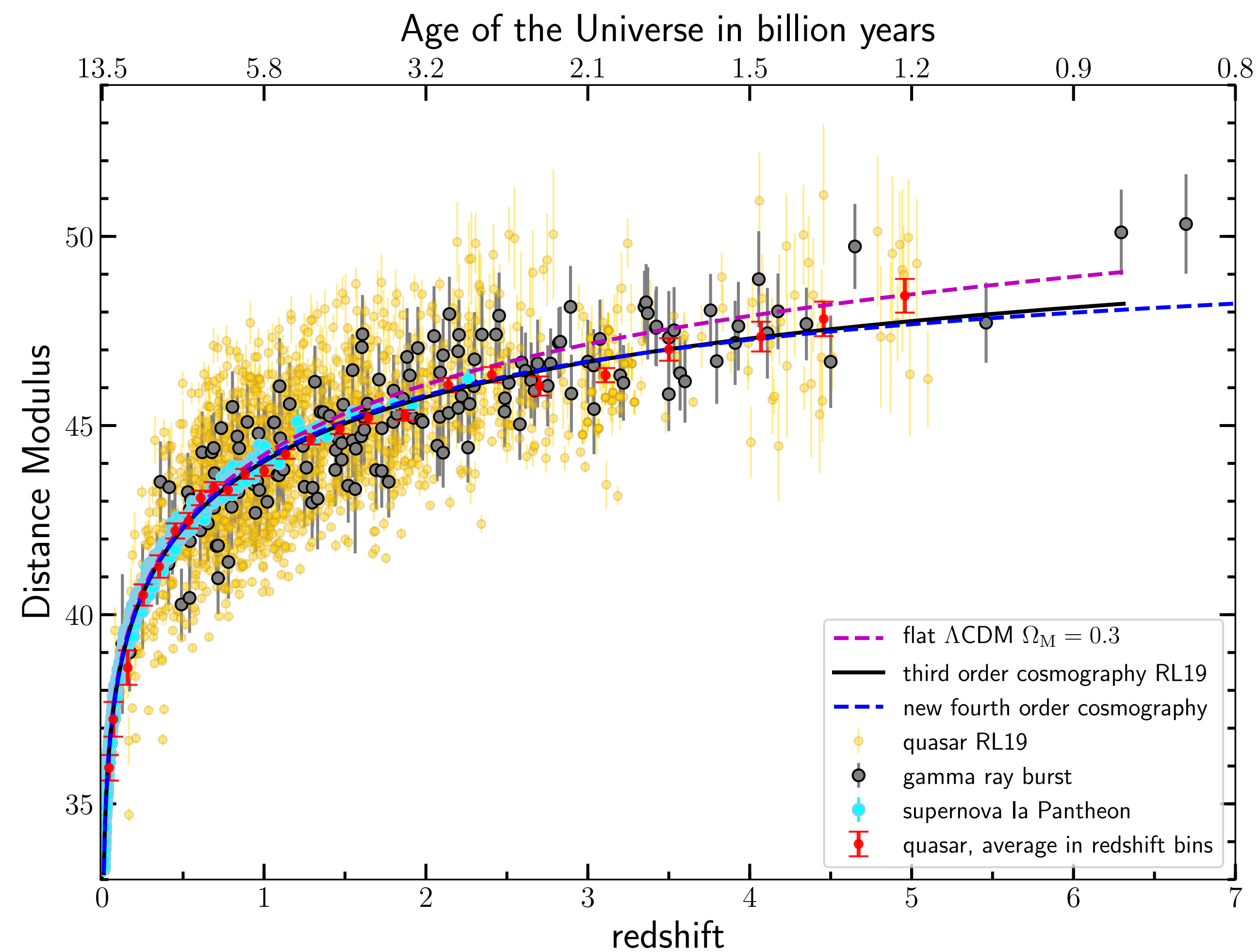
data suggest: **dark energy density increasing with time**. Within the *w*CDM model: Ω_M>0.3 and *w*<-1.3

The Quasars + SNe + GRBs Hubble Diagram

1598 quasars (Risaliti & Lusso 2019)
1048 Type Ia supernovae - *Pantheon* survey (Scolnic et al. 2018)
160 GRBs (Demianski et al. 2017)

Lusso, et al. 2019 A&A, 628-4





Elisabeta Lusso UniFi

Unknowns in a Type Ia supernova explosion:

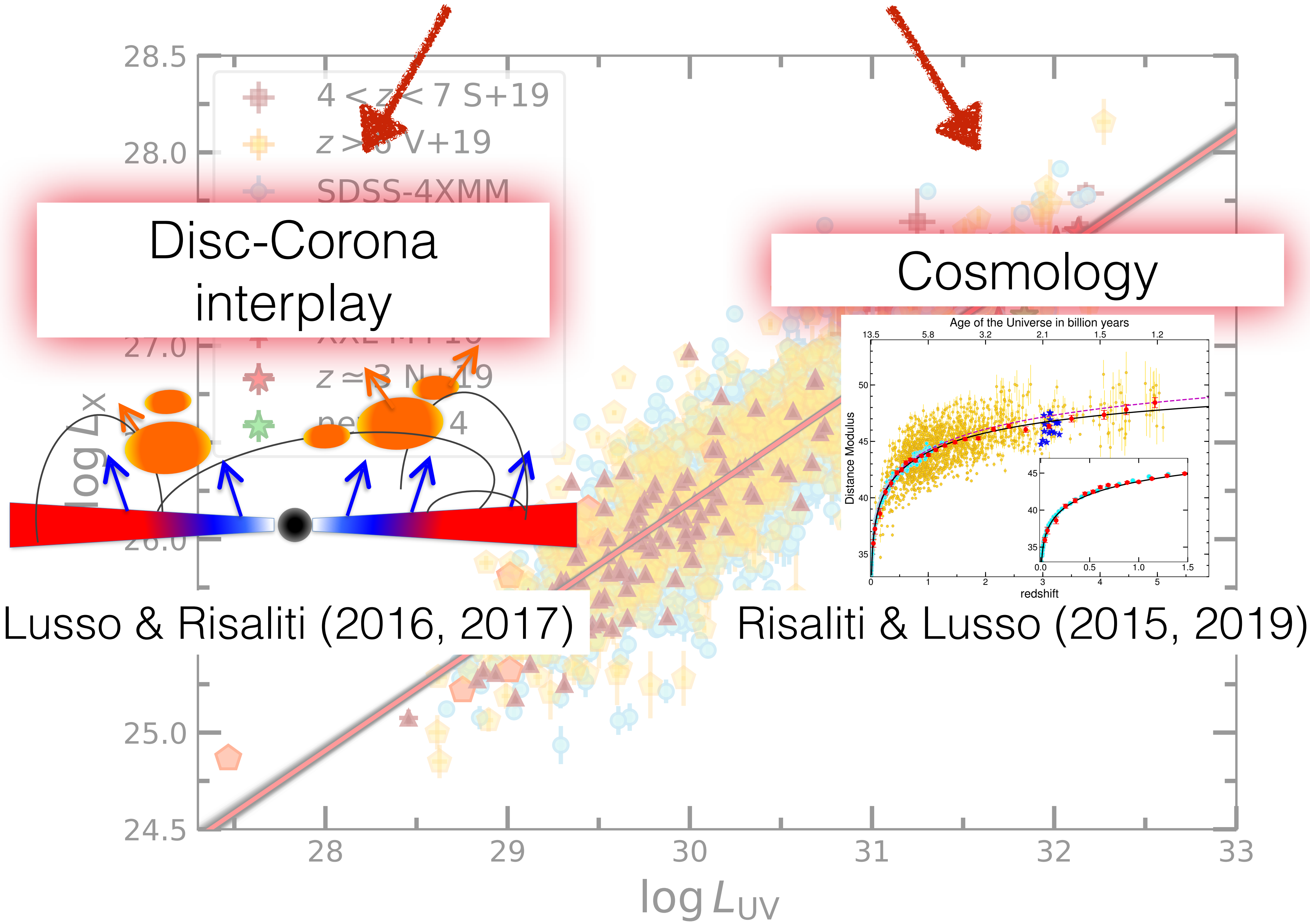
- Progenitor? WD in a binary

- What are the precise ignition conditions? "Close" to the Chandrasekhar limit

- How do we explain the Phillips' relation? Radioactive decay of ^{56}Ni -> ^{56}Co -> ^{56}Fe

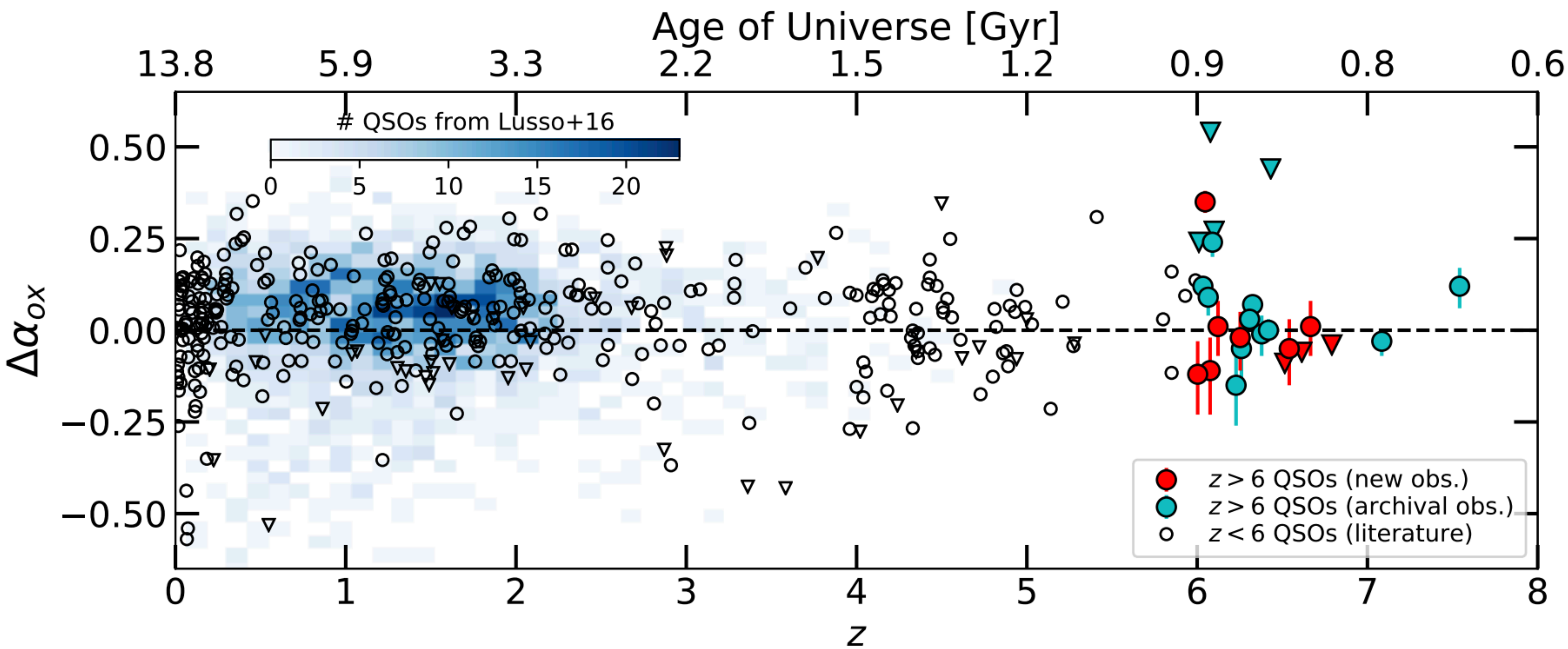
- Type Ia supernovae that do not follow the Phillips' relation exist but not used for cosmology…

THE L_X—L_{UV} RELATION



ARE QUASARS RELIABLE STANDARD CANDLES?
REDSHIFT EVOLUTION

Vito et al. (2019)



NO evolution of accretion physics in the first Gyr of the Universe