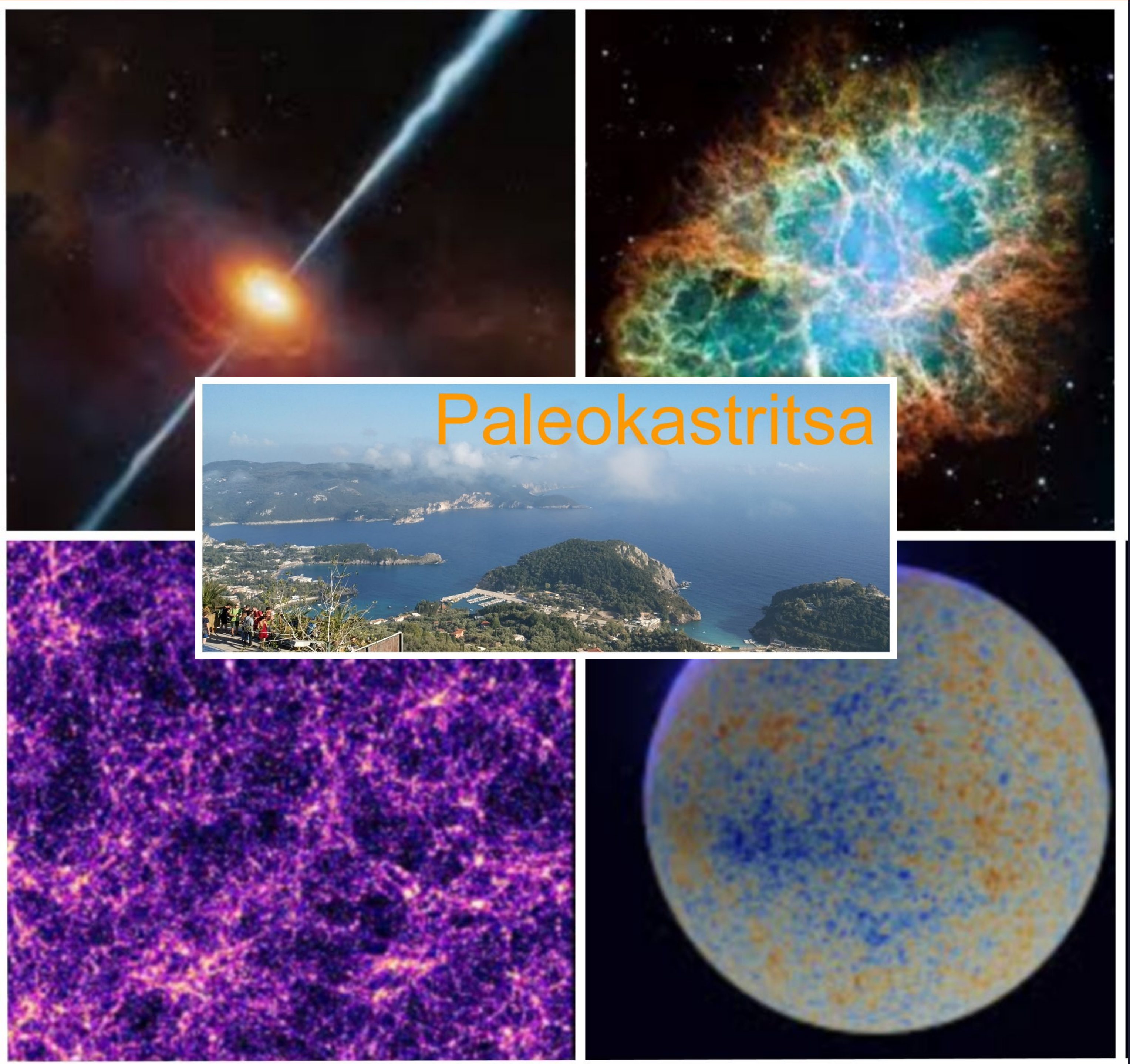
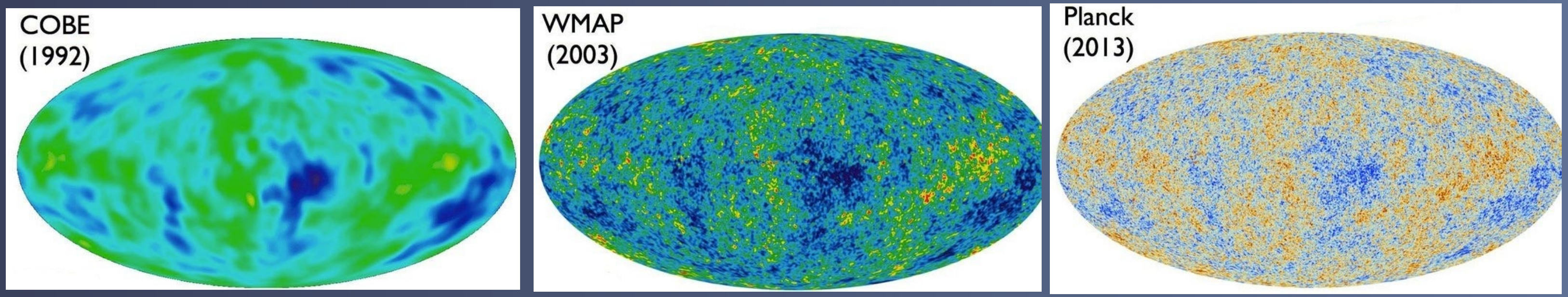


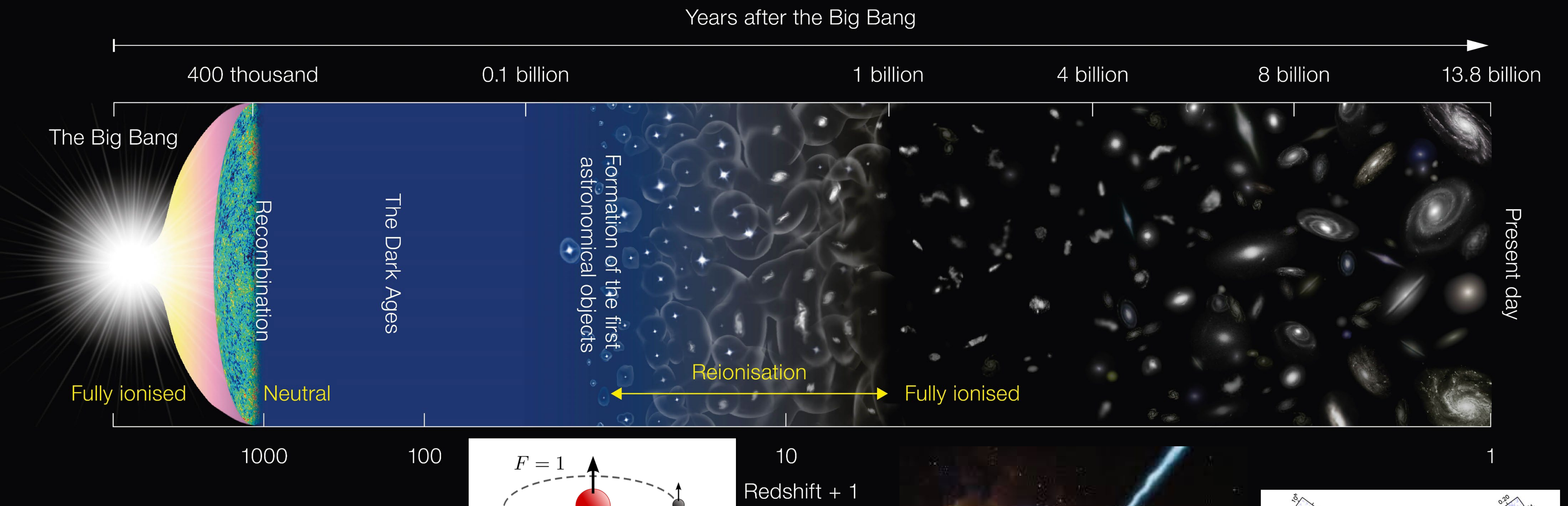
Tensions in Cosmological Probes and Quasar Cosmology

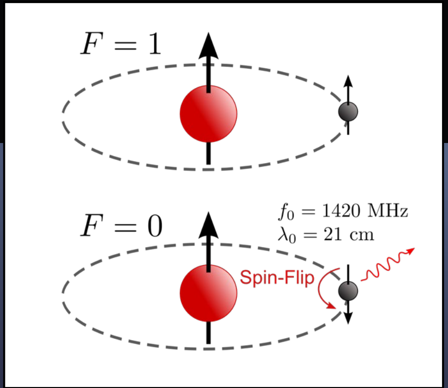
Micol Benetti

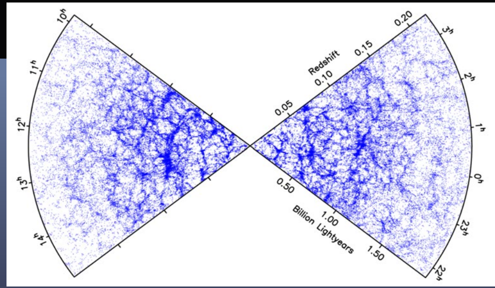
Outline

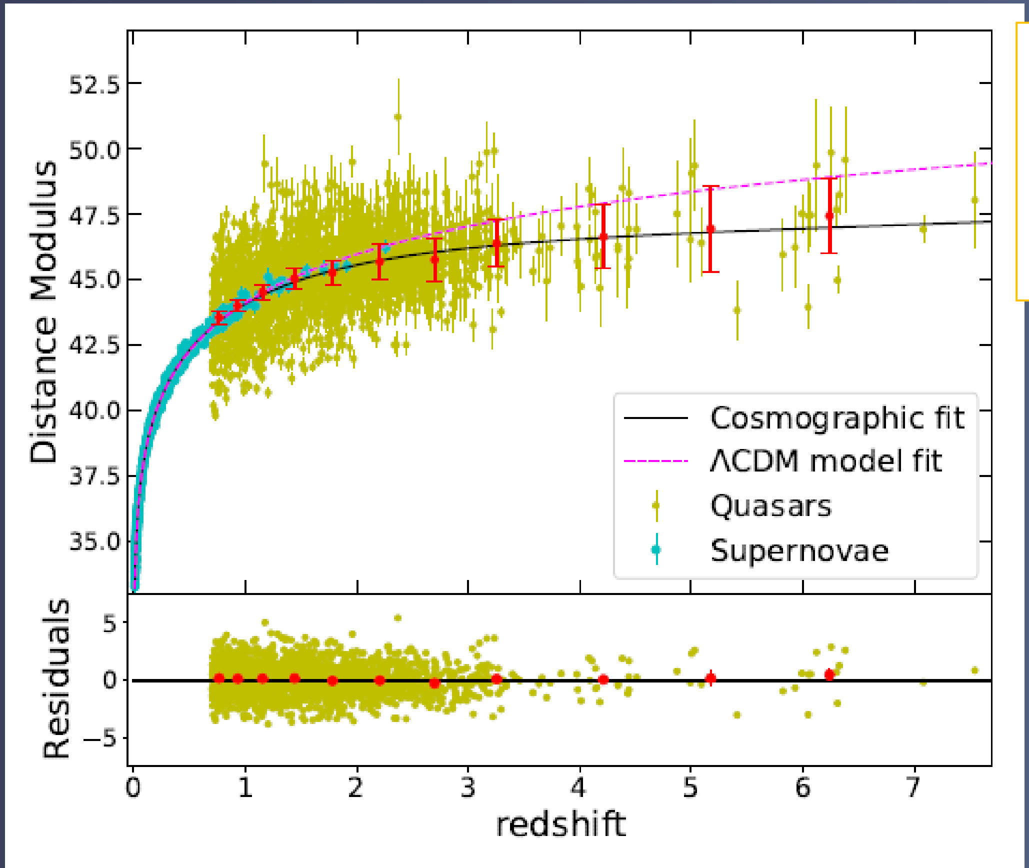
- Quasars as standard candles: limitations and assumptions
- Combining QSOs with other probes: testing the standard model and constraints of dark energy and curvature models
- Conclusions and next goals


COBE
(1992)
WMAP
(2003)
Planck
(2013)

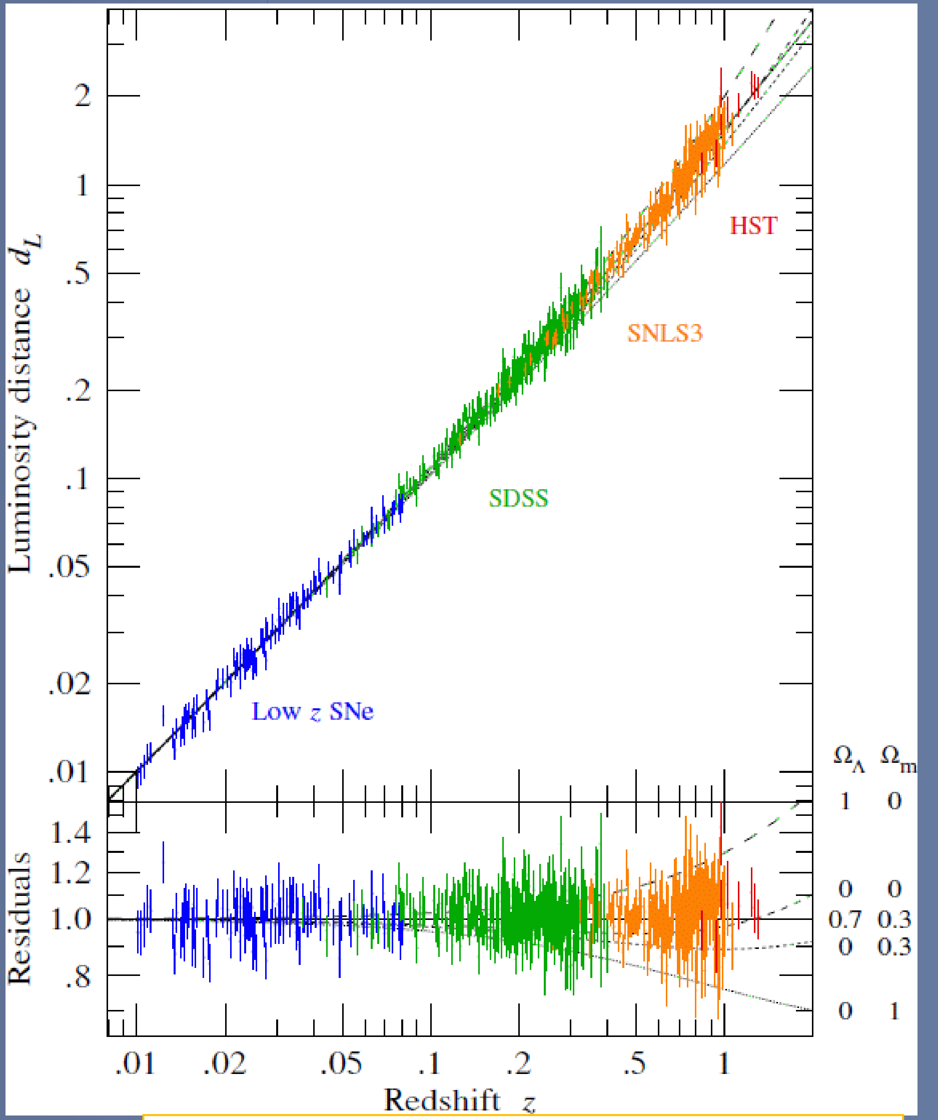

Years after the Big Bang
400 thousand
0.1 billion
1 billion
4 billion
8 billion
13.8 billion
The Big Bang
Recombination
The Dark Ages
Formation of the first astronomical objects
Present day
Fully ionised
Neutral
Reionisation
Fully ionised
1000
100
10
1
Redshift + 1


$F = 1$
$F = 0$
$f_0 = 1420$ MHz
$\lambda_0 = 21$ cm
Spin-Flip

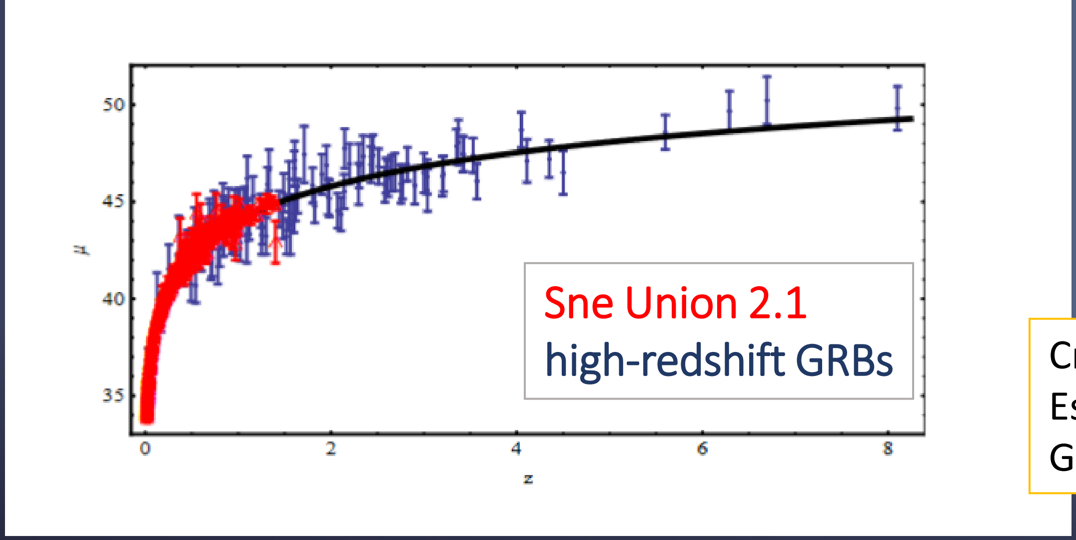

Redshift
0.05
0.10
0.15
0.20
0.50
1.00
1.50
Billion Lightyears



Credit: Bargiacchi, Risaliti, **MB**, Capozziello, E. Lusso, Saccardi, Signorini A&A, 649, A65 (2021)



Credit: Betoule et al. A&A 568 (2014)



Credit: Piedipalumbo, Scudellaro, Esposito, Rubano, Gen. Rel. and Gravit. 44, 10 (2012)

QSOs as standard candles

- QuasiStellar radio sources, are Active Galactic Nuclei with integrated luminosities of 10^{44-48} erg/s over the ultra-violet (UV) to the X-ray energy range.

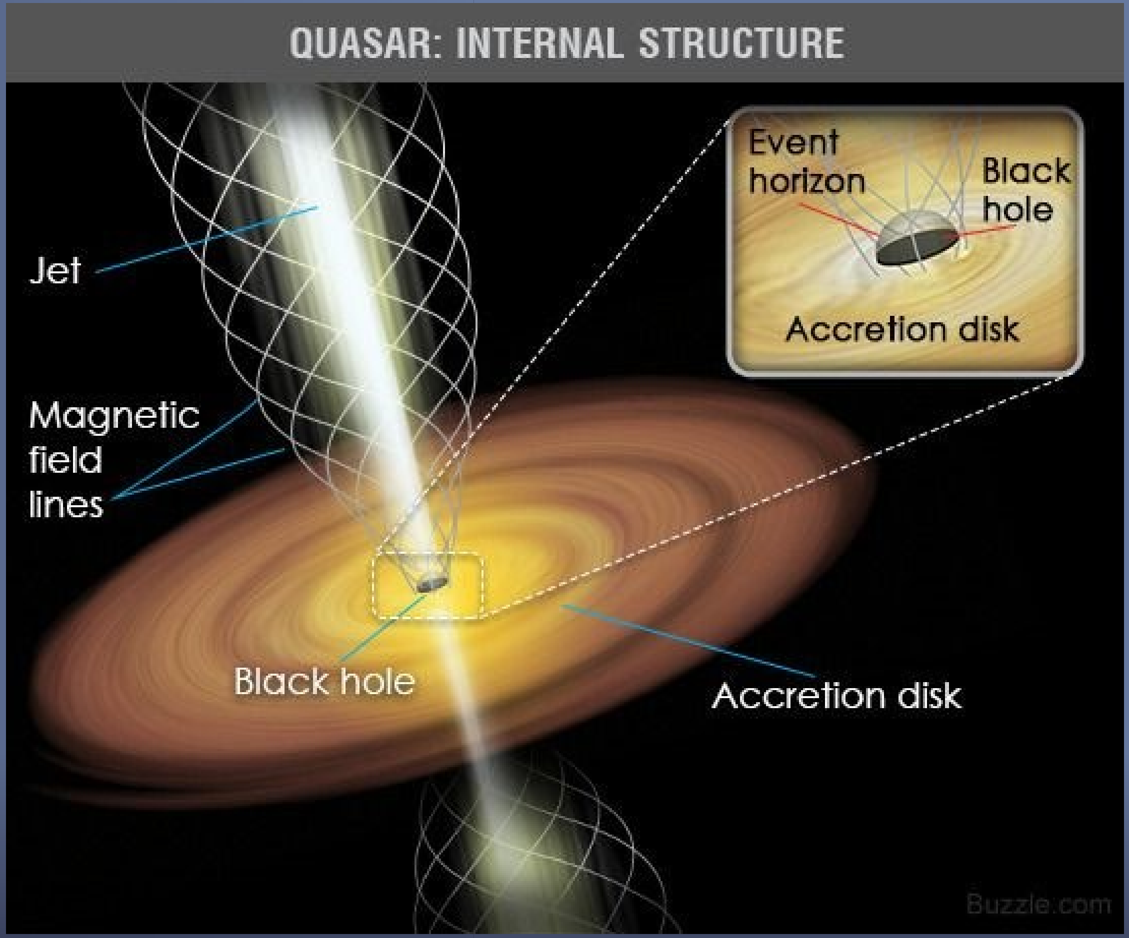
The UV emission are roughly 90% of the quasar bolometric budget.

The X-rays are originate in a hot plasma of relativistic electrons, that Compton up-scatter photons coming from the disk.

The UV and X-ray fluxes obey to non-linear

$$L_X \propto L_{UV}^{\gamma}$$

LUV at the rest frame 2500 Å
LX at the rest frame 2 keV
$\gamma \sim 0.6$



QSO ad standard candles is based on two key points:

1- the observed dispersion in the $L_X - L_{UV}$ relation is not intrinsic but due to observational issues: (gas absorption in the X-rays, dust extinction in the UV calibration uncertainties in the X-rays variability, selection biases)

With an optimal selection of clean sources (i.e. where the intrinsic UV and X-ray quasar emission can be measured), the observed dispersion drops from 0.4 dex to ~ 0.2 dex.

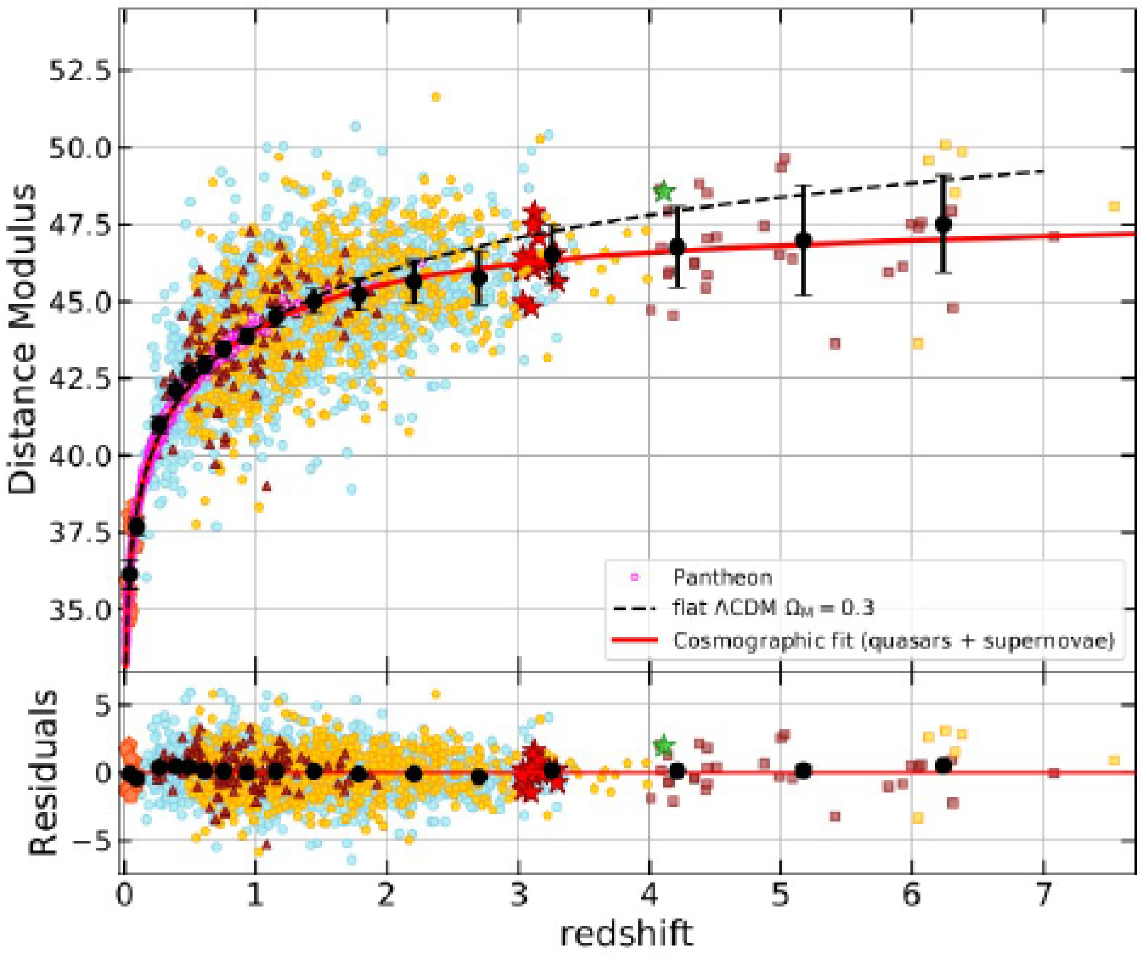
2- the slope of the $L_X - L_{UV}$ relation does not evolve with redshift

A key consequence is that the $L_X - L_{UV}$ relation must be the manifestation of a universal mechanism at work in the quasar engines

For any analysis that involves a detailed test of cosmological models, the quasar distances should be crosscalibrated by making use of the distance ladder through supernovae Ia.

In fact, the DM values of quasars are not absolute, thus a cross-calibration parameter (k) is needed. The parameter k should be fitted simultaneously for supernovae Ia and quasars (i.e. k is a rigid shift of the quasar Hubble diagram to match the one of supernovae).

!!! Quasar do not constrain H0 !!!



Lusso et al. 2020

Need for joint fit with SNe Ia to fix the “zero-point” of the diagram

Overlap with SNe Ia in the common redshift range

Information on the cosmic evolution at z>1.5 where different cosmological models can be tested and distinguished

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MNRAS **515,** 1795–1806 (2022) https://doi.org/10.1093/mnras/stac1941
Advance Access publication 2022 July 22

Quasar cosmology: dark energy evolution and spatial curvature

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Data set

Pantheon SNIA

Collection of 1048 sources from the Pantheon sample (Scolnic et al. 2018).

We use the values of the distance moduli to calibrate QSO distances.

BAO

Survey	z	Quantity	Measurement	$r_{s,fid}$
6dFGS	0.106	$\frac{r_s(z_d)}{D_V(z)}$	0.336 ± 0.015	
SDSS DR7(MGS)	0.15	$D_V(z)\frac{r_{s,fid}}{r_s(z_d)}$	664 ± 25	148.69
BOSS DR12	0.38	$D_M(z)\frac{r_{s,fid}}{r_s(z_d)}$	1512.39	147.78
		$H(z)\frac{r_s(z_d)}{r_{s,fid}}$	81.2087	147.78
BOSS DR12	0.51	$D_M(z)\frac{r_{s,fid}}{r_s(z_d)}$	1975.22	147.78
		$H(z)\frac{r_s(z_d)}{r_{s,fid}}$	90.9029	147.78
BOSS DR12	0.61	$D_M(z)\frac{r_{s,fid}}{r_s(z_d)}$	2306.68	147.78
		$H(z)\frac{r_s(z_d)}{r_{s,fid}}$	98.9647	147.78
eBOSS	1.52	$D_V(z)\frac{r_{s,fid}}{r_s(z_d)}$	3843 ± 147	147.78

Data set

QSOs

Lusso2020 selection: 2036 sources covering up to z = 7.54

For detailed description of selection, choices, validation of the procedure used and explanation of the fitting technique used to include them in the cosmological analysis:

Lusso E., et al., 2020, A&A, 642, A150
Risaliti G., Lusso E., 2015, ApJ, 815, 33
Lusso E., Risaliti G., 2016, ApJ, 819, 154
Risaliti G., Lusso E., 2019, Nature Astronomy, p. 195

Flat LCDM model

QSOs+SNe:

$$\Omega_{M,0} = 0.295^{+0.013}_{-0.012}$$

BAO:

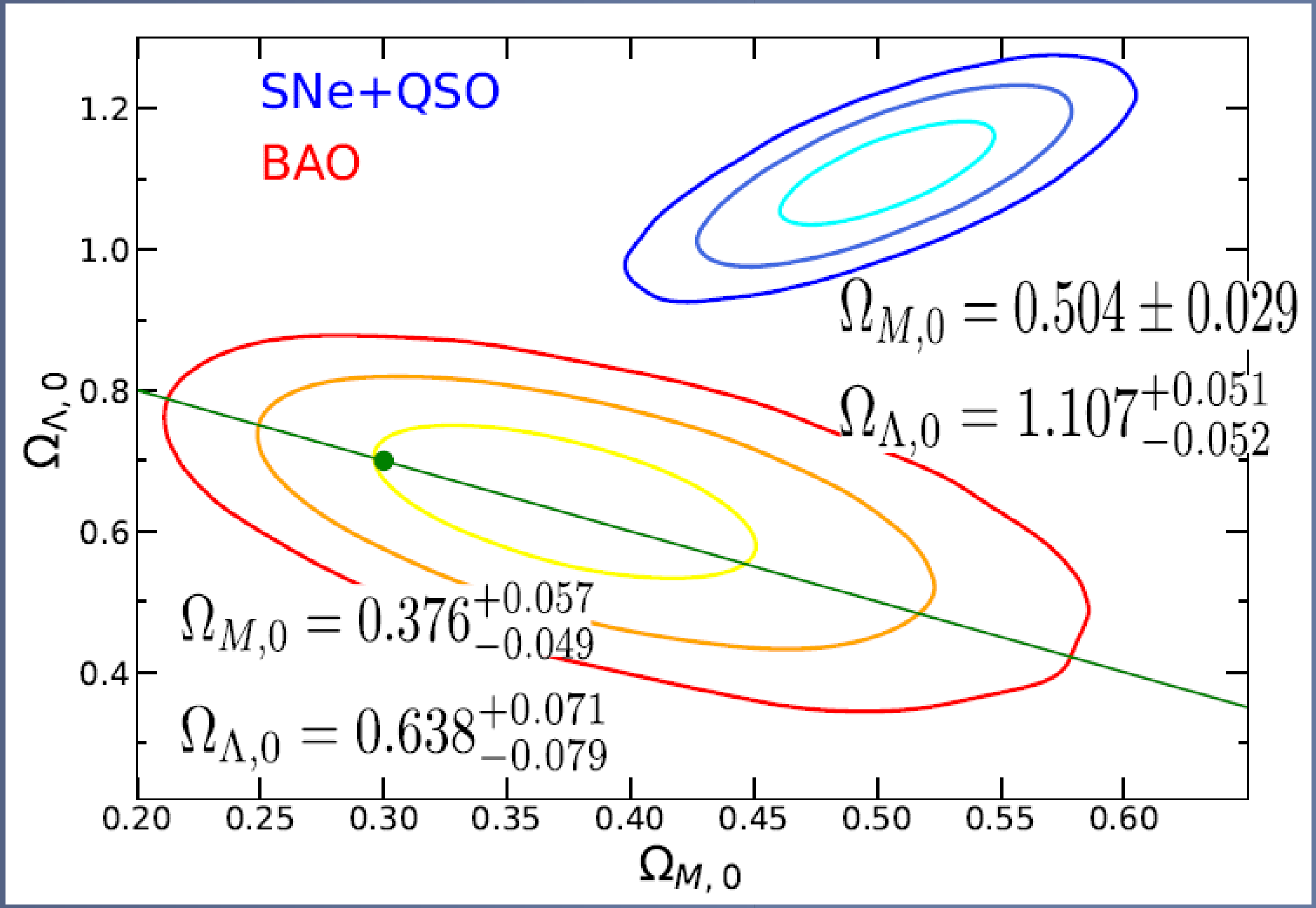
$$\Omega_{M,0} = 0.373^{+0.056}_{-0.048}$$

QSOs+SNe+BAO:

$$\Omega_{M,0} = 0.300 \pm 0.012$$

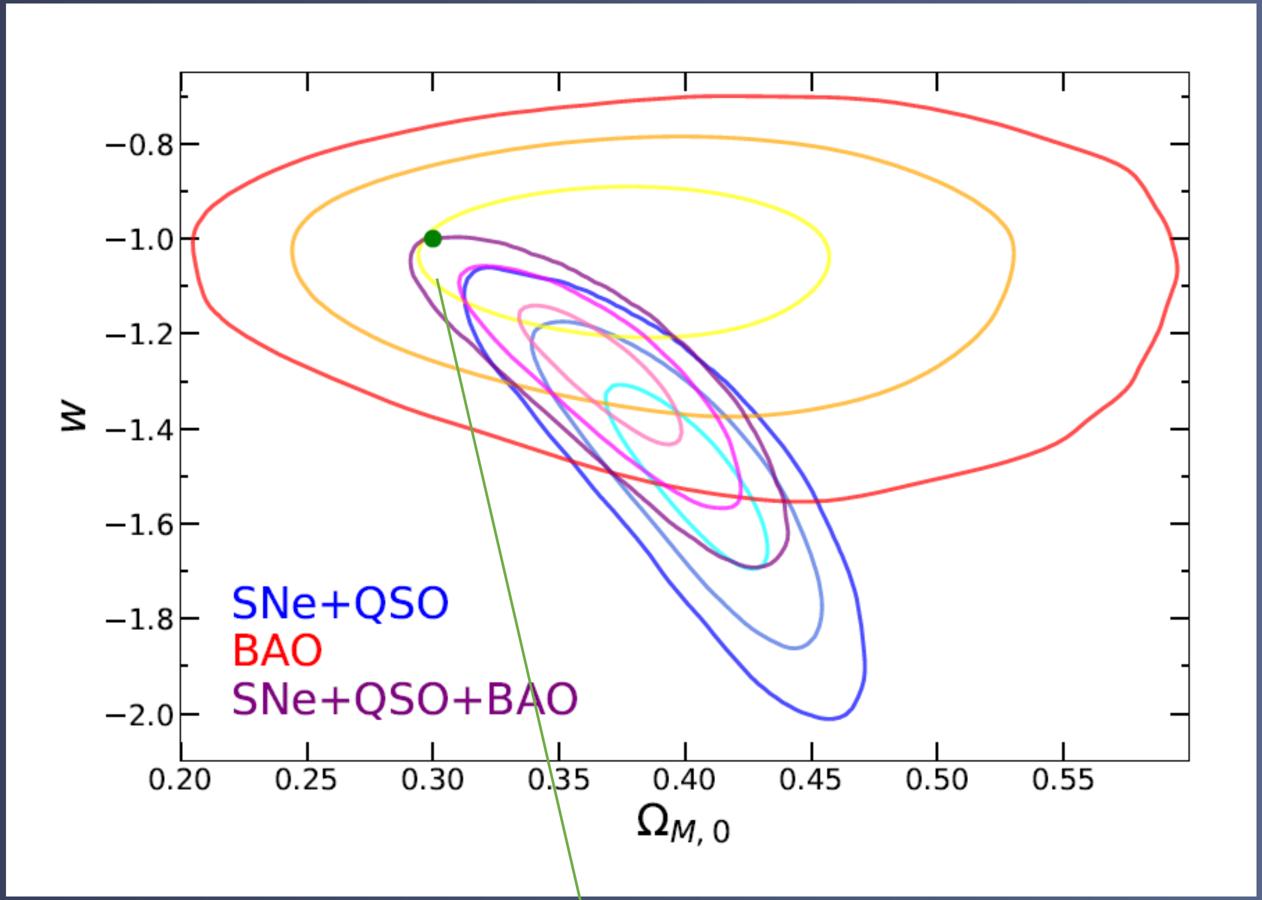
→ Completely agreement with the latest cosmological evidence

Non-flat LCDM model

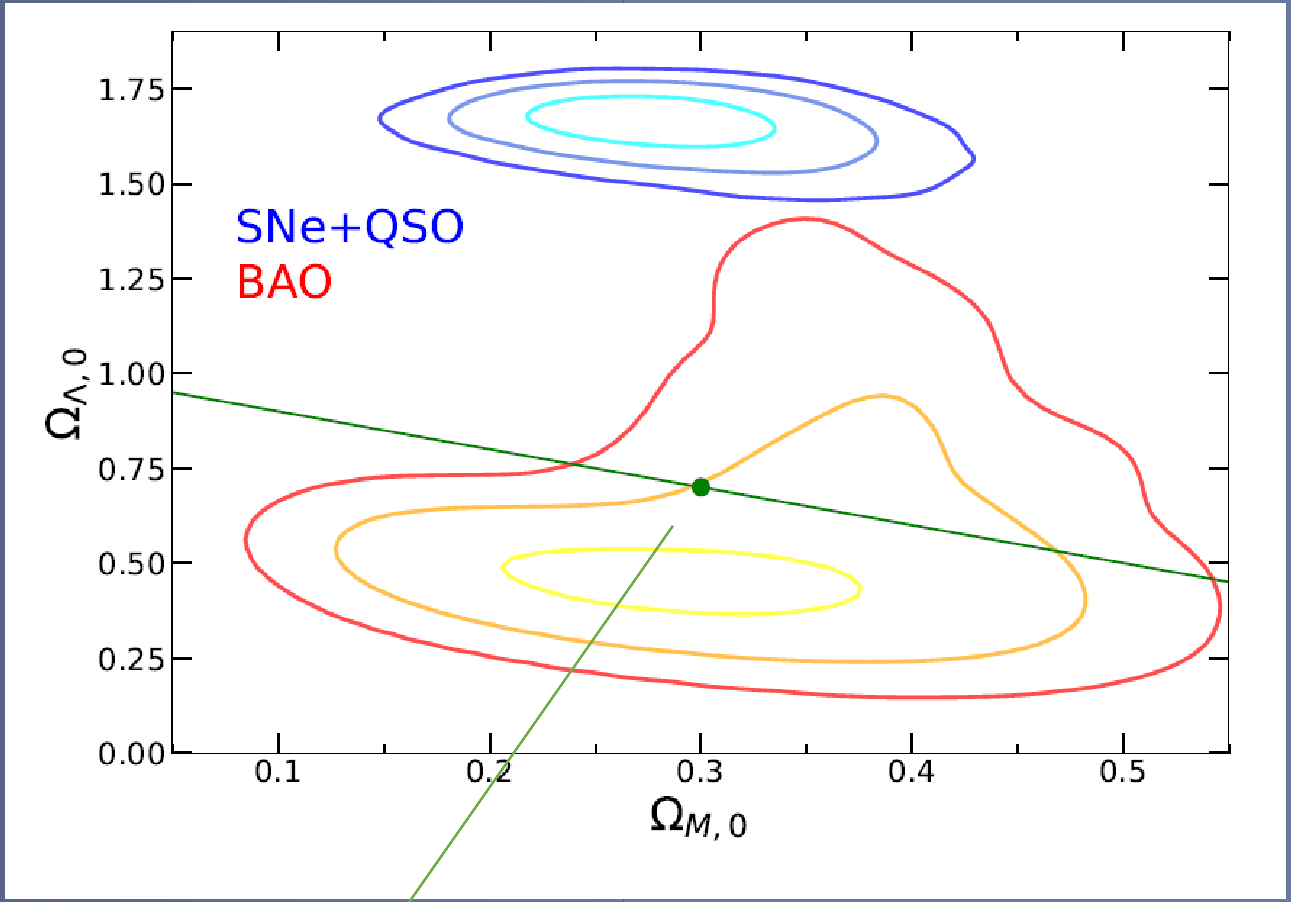


Testing the consistency between cosmological data: the impact of spatial curvature and the dark energy EoS
Gonzalez, **MB**, Von Marttens and Alcaniz,
JCAP 11, no.11, 060 (2021)

Flat wCDM model



Non-flat wCDM model

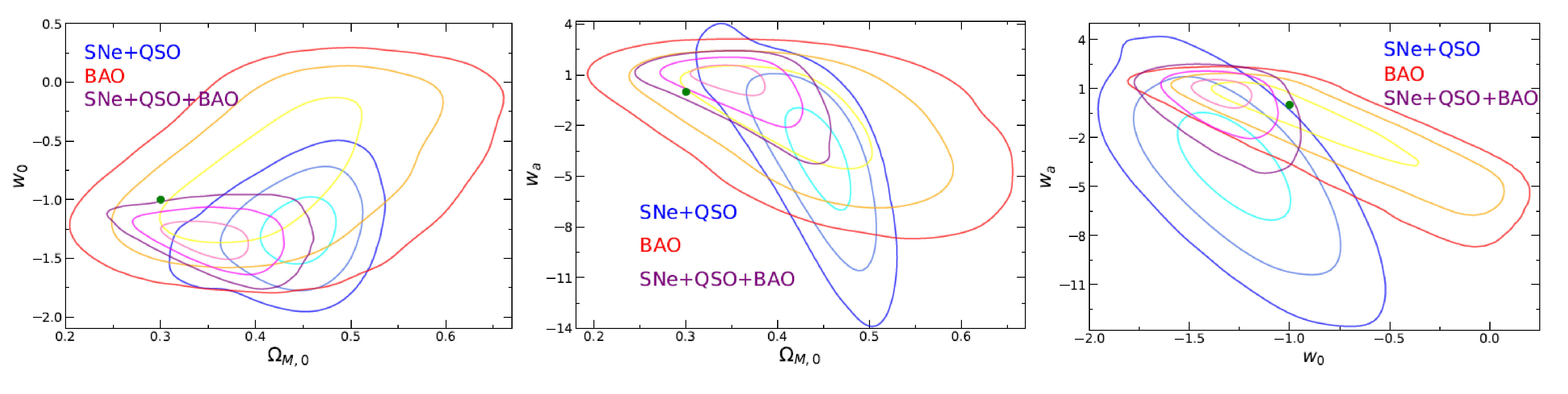


Green point : Best fit LCDM model

Green line: $\Omega\Lambda,0+\Omega M,0+\Omega r,0=1$

Flat CPL model

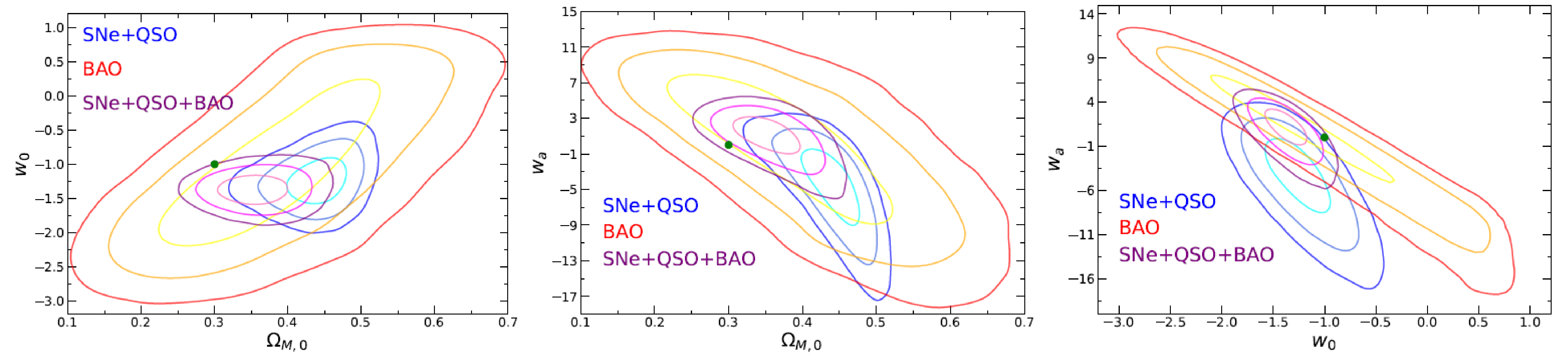
$$w(z) = w_0 + w_a\,(1-a) = w_0 + w_a\,\frac{z}{1+z}$$



	QSOs + SNe	BAO	QSOs + SNe + BAO
$\Omega_{M,0}$	$0.447^{+0.023}_{-0.027}$	$0.420^{+0.073}_{-0.070}$	$0.354^{+0.032}_{0.030}$
w_0	$-1.267^{+0.196}_{-0.191}$	$-0.821^{+0.469}_{-0.349}$	$-1.323^{+0.103}_{-0.112}$
w_a	$-3.771^{+2.113}_{-2.496}$	$-1.269^{+1.835}_{-2.608}$	$0.745^{+0.483}_{-0.974}$

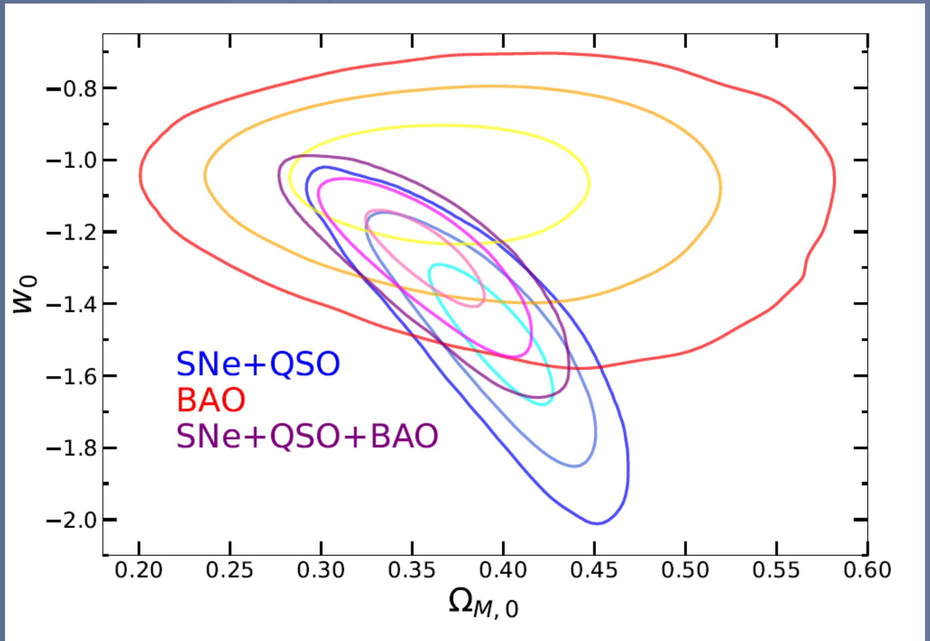
Flat Jassal-Bagla-Padmanabhan model

$$w(z) = w_0 + w_a \frac{z}{(1+z)^2}$$



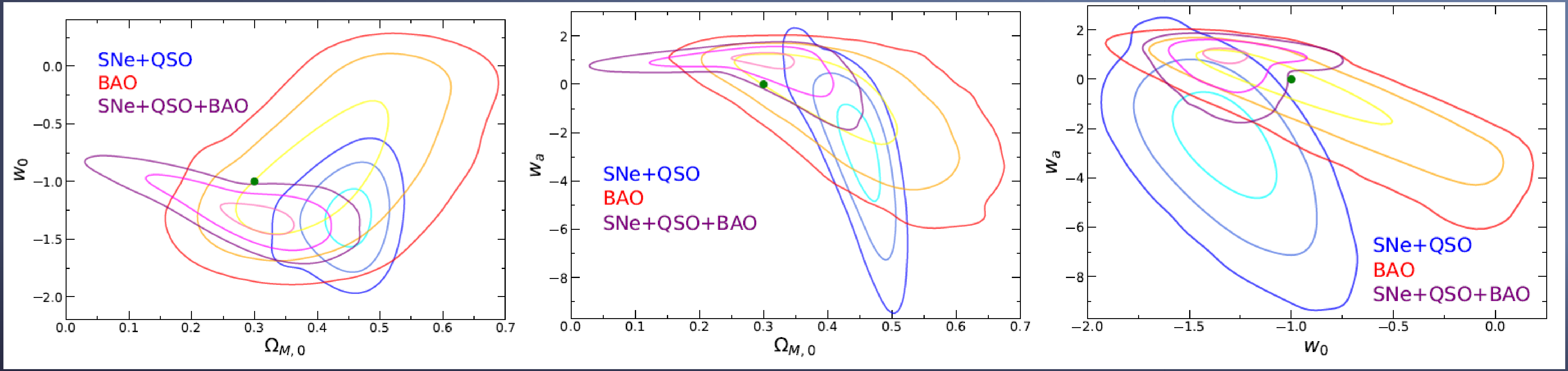
Flat exponential model

$$w(z) = w_0\,(1+z)^{-1}\,e^{\frac{z}{1+z}}$$



Flat Barboza-Alcaniz model

$$w(z) = w_0 + w_a\,z\,(1+z)\,(1+z^2)^{-1}$$



Our Conclusions

Quasars are standardizable candles crucial to extend the Hubble diagram

Assuming flatness:

ΛCDM model: $\Omega_{M,0}$ completely consistent with 0.3 in all data sets

BAO are in agreement with the prediction of the flat ΛCDM model

QSOs+SNe and BAO are consistent in all models

QSOs+SNe+BAO always prefers $\Omega_{M,0}>0.3$, $w_0<-1$ and w_a greater but consistent with 0 and a deviation from LCDM of the order of 2-3σ

Our Conclusions

Quasars are standardizable candles crucial to extend the Hubble diagram

In non-flat models:

BAO confirm flatness

QSOs+SNe show evidence of a closed Universe

Next goals

- Shed light on the physical origin of X-UV relation to strengthen the use of quasars in cosmology
- Implementation of the quasar sample with new catalogues and high quality observations from surveys
- Cosmological analyses including other probes such as CMB, DES, GRBs
- Tests of other models, with particular attention to Interacting Dark Energy