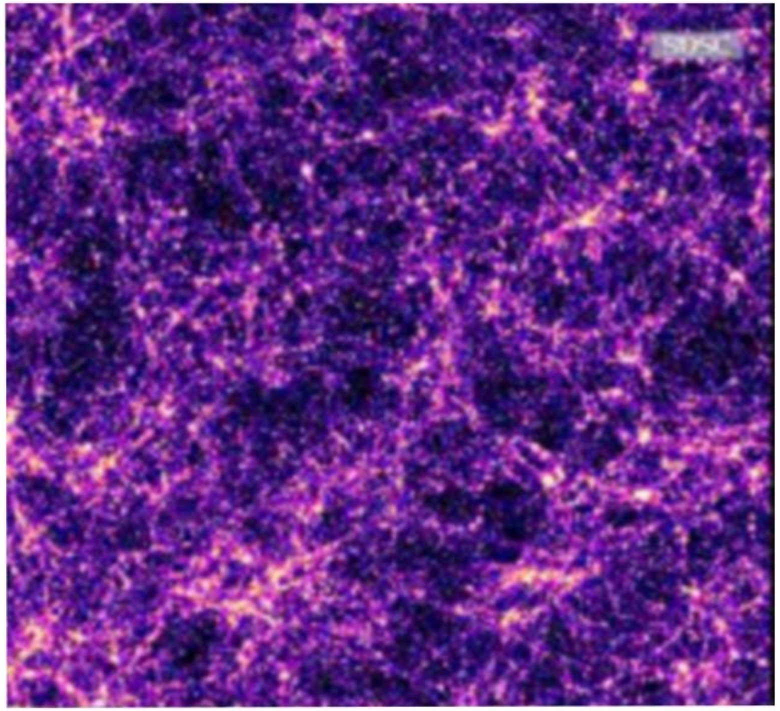

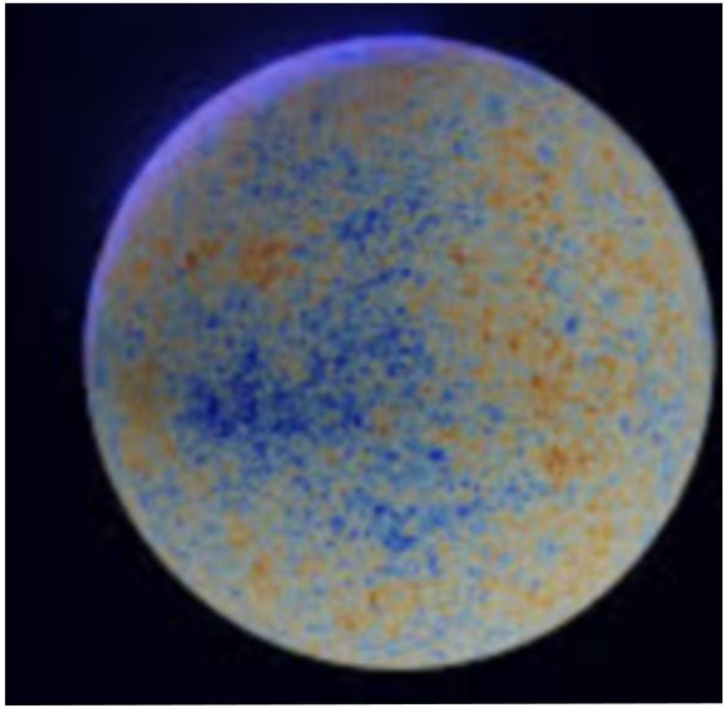

SSM
Scuola Superiore Meridionale

# QUASAR COSMOLOGY
## AND TENSIONS WITH COSMOLOGICAL PROBES

Micol Benetti

QGSKY 2025 Workshop

November 2025

# WHY QUASAR COSMOLOGY IN QGSKY ?

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## QGSKY goals

- Extended theories of gravity
- Non-local QFT and non-local theories of gravity
- Dark Matter and Dark energy
- QFT in curved space-time
- Exact black hole solutions
- Theoretical cosmology

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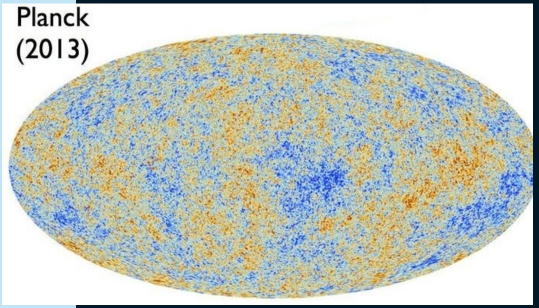
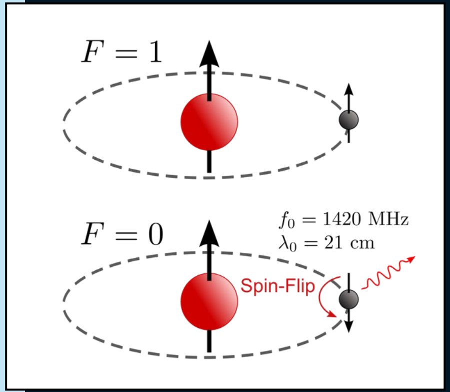
$z = 1100$

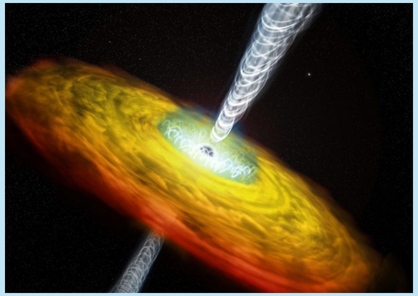
CMB



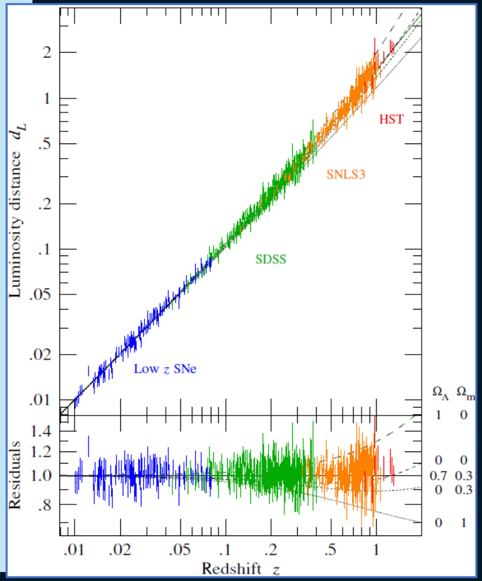

21 cm




QSO



SNe




$z = 0$

# WHY QUASAR COSMOLOGY IN QGSKY ?

## QGSKY goals

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- Exact black hole solutions
- Theoretical cosmology

QSO observations

$z = 1100$

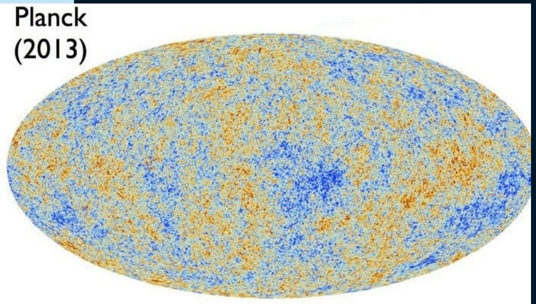
CMB

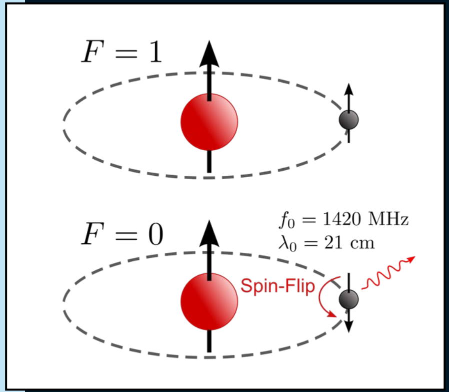
21 cm

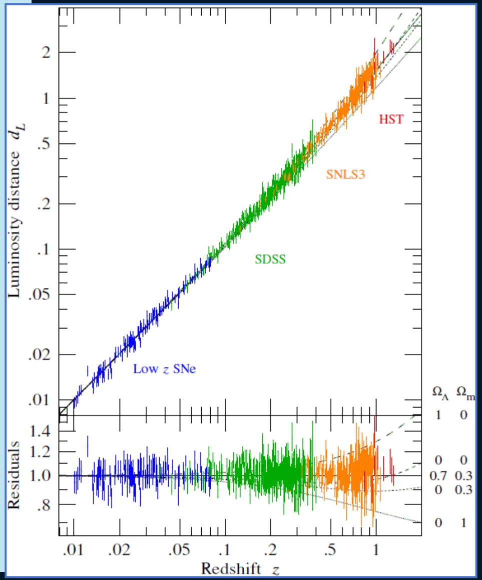
QSO

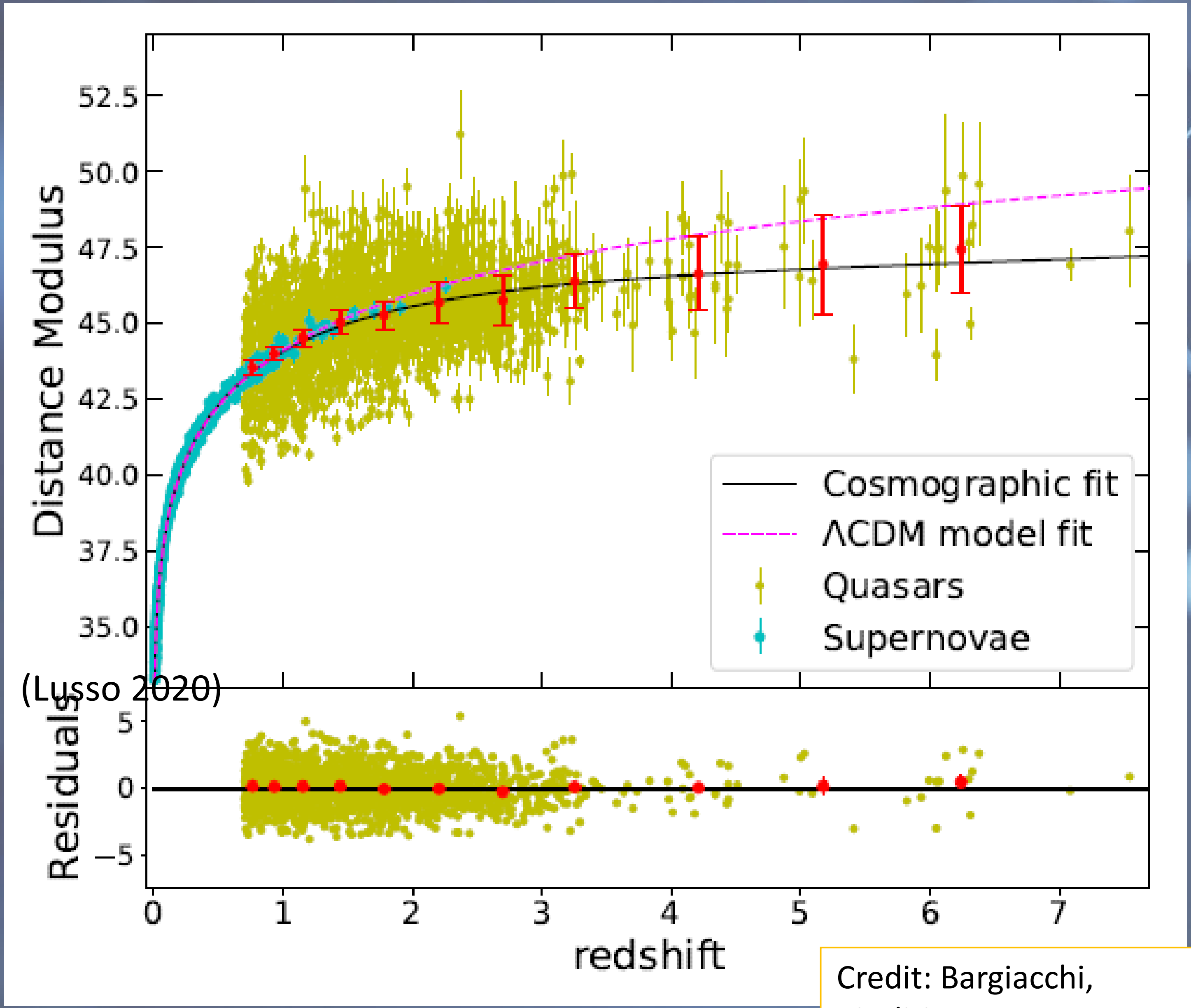
SNe

$z = 0$

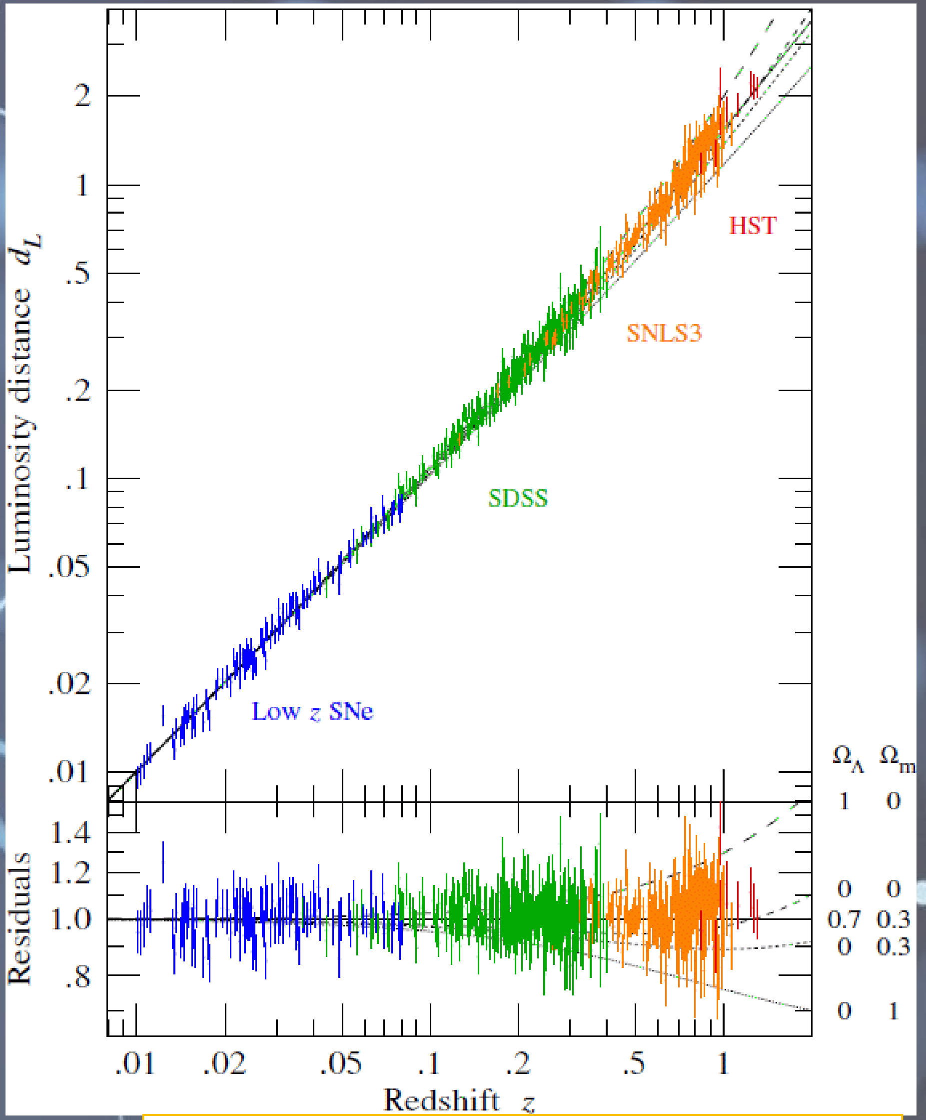





Credit: Bargiacchi, Risaliti, **MB**, Capozziello, E. Lusso, Saccardi, Signorini A&A, 649, A65 (2021)




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

# QSOS AS STANDARD CANDLES

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

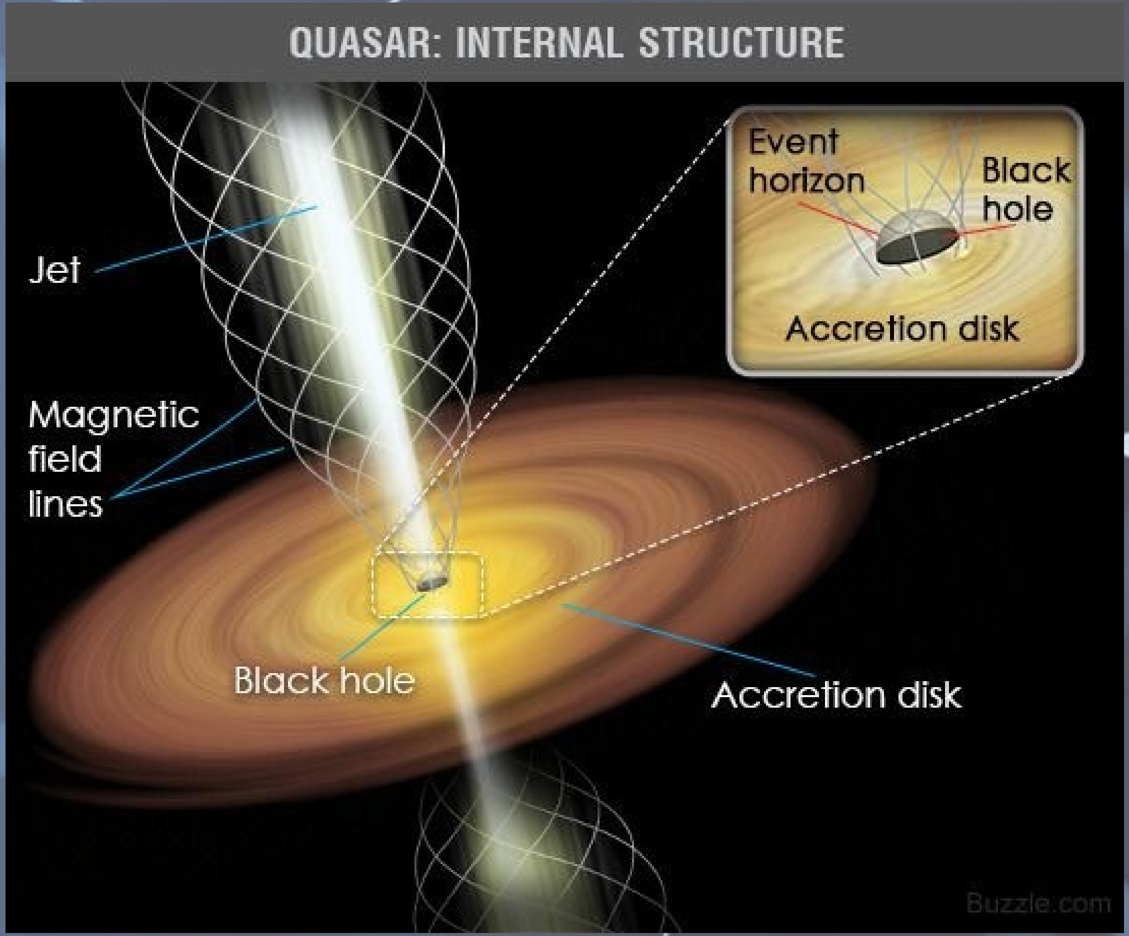
The UV emission are roughly 90% of the quasar bolometric budget.

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 as standard candles is based on two key points:

1- the $L_X - L_{UV}$ relation is due to an observational issue: exist an unknown physical mechanism that links the <u>$L_{UV}$ emission from the accretion disc</u> with that from the <u>X-ray emitting corona</u>

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

Steffen+2006, Just+2007; Lusso+2010; Risaliti+2015, Lusso+2016, Risaliti+2019, Lusso+2019, Lusso+2020; Bargiacchi+2021, Bisogni+2021; Dainotti+2022

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

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Royal Astronomical Society

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Advance Access publication 2022 July 22
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# Quasar cosmology: dark energy evolution and spatial curvature

G. Bargiacchi[1,2★], M. Benetti[1,2★], S. Capozziello,[1,2,3] E. Lusso[4,5], G. Risaliti[4,5] and M. Signorini[4,5]

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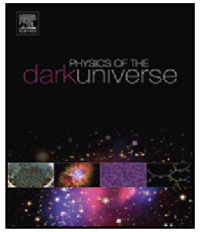


Full length article

# Quasar cosmology II: Joint analyses with cosmic microwave background

M. Benetti[a,b,*], G. Bargiacchi[a,b], G. Risaliti[c,d], S. Capozziello[a,b,e], E. Lusso[c,d], M. Signorini[d,f]

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[f] *Dipartimento di Matematica e Fisica, Università di Roma 3, Via della Vasca Navale 84, Roma, 00146, Italy*

# QSO:

- perfect match with supernovae in the common range (Hubble diagram significantly deviates from the prediction of the flat $\Lambda$CDM model only at redshifts $z \geq 1.5$, which roughly corresponds to the knee in the Hubble diagram)

- indicates a higher contribution of $\Omega_m$ w.r.t. the $\Lambda$CDM model

- not able to constrain $H_0$ (needs to be calibrated by making use of the distance ladder through supernovae Ia: the DM values of quasars are not absolute)

# Data set

Collection of 1048 sources from the Pantheon sample $z$ [0.01–2.26].
(Scolnic et al. 2018)

Dark Energy Survey Year-One (DES-1Y) combination of cosmic shear, galaxy–galaxy lensing, and galaxy clustering, 1321 square degrees of imaging data
(T.M.C. Abbott, et al. 2018)

CMB data from Planck 2018
TTTEEE+lowE+CMBlensing
(Planck Collaboration, N. Aghanim et al 2020)

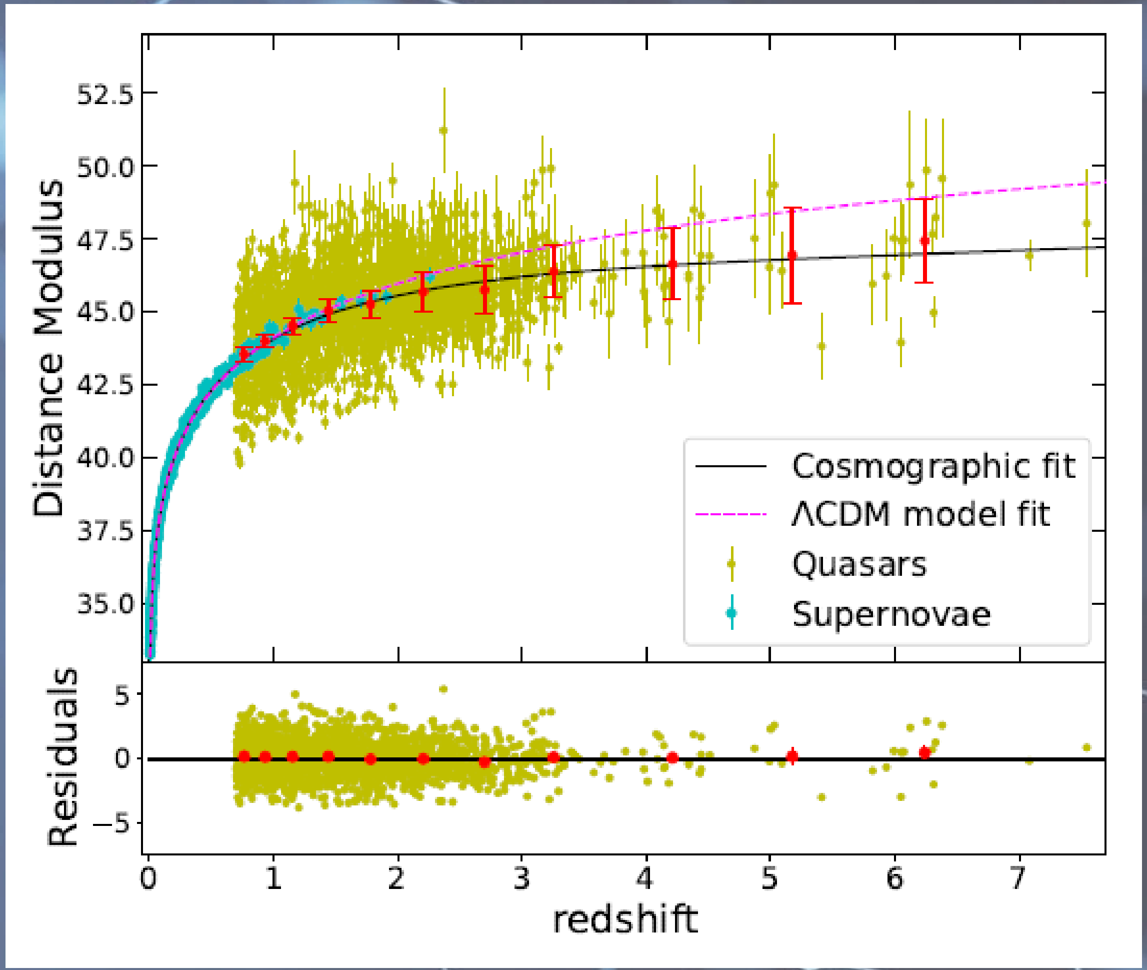
BAO data from the survey 6dFGS, SDSSDR7, BOSS DR12 (covering z [0.106 - 0.61]) and eBOSS ($z$ = 1.52 from DR14 release)
(Beutler et al. 2011)
(Ross et al. 2015)
(Alam et al. 2017)
(Ata et al. 2018)

# Data set

## QSOS

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
Salvestrini et al. ,2019, A&A,631,A120




Lusso2020 selection: 2036 sources covering up to $z = 7.54$

# Data set

non-linear relation between their UV and X-ray luminosity:

$$\log(\mathrm{L}_X) = \gamma\, log(L_{UV}) + \beta$$

X: 2 KeV, UV: 2500 Å

The fitted distance moduli are obtained from

$$\mathbf{DM}(z) = \mathbf{5log[}D\mathbf{L}(z)\mathbf{\ (Mpc)] + 25 +}\ k$$

where

$$\log D_{\mathrm{L}}(z) = \frac{[\log F_X - \beta - \gamma\,(\log F_{UV} + 27.5)]}{2(\gamma - 1)} - \frac{1}{2}\log(4\pi) + 28.5.$$

The slope $\gamma$ and the intercept $\beta$ of the logarithmic X-UV luminosity relation are free parameters of the fit

# Data set

non-linear relation between their UV and X-ray luminosity:

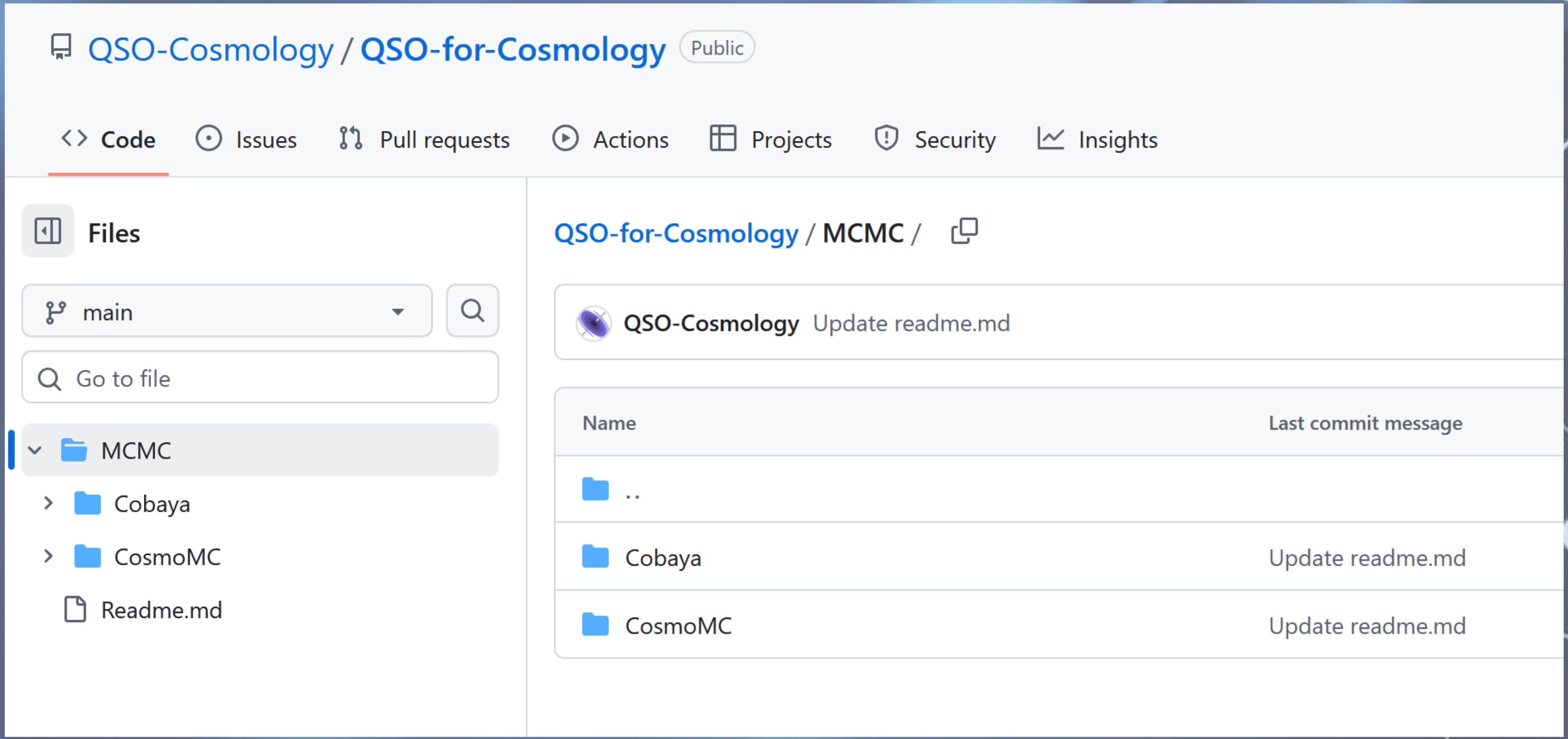
$$\log(\mathrm{L}_X) = \gamma\, log(L_{UV}) + \beta$$ X: 2 KeV, UV: 2500 Å

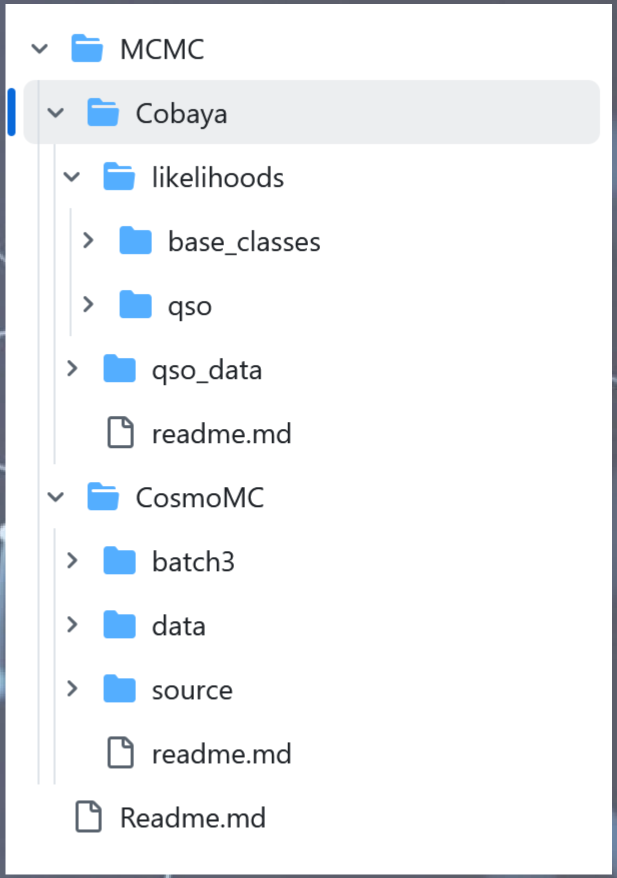
The fitted distance moduli are obtained from

$$\mathbf{DM}(z) = \mathbf{5log}[D\mathbf{L}(z)\ (\mathbf{Mpc})] + \mathbf{25} + k$$

$k$ is a calibration nuisance parameter shared by both SNe and QSOs and is a rigid shift of the QSO Hubble diagram to match the one of SNe in the common redshift range.

# https://github.com/QSO-Cosmology/QSO-for-Cosmology/



# Goals

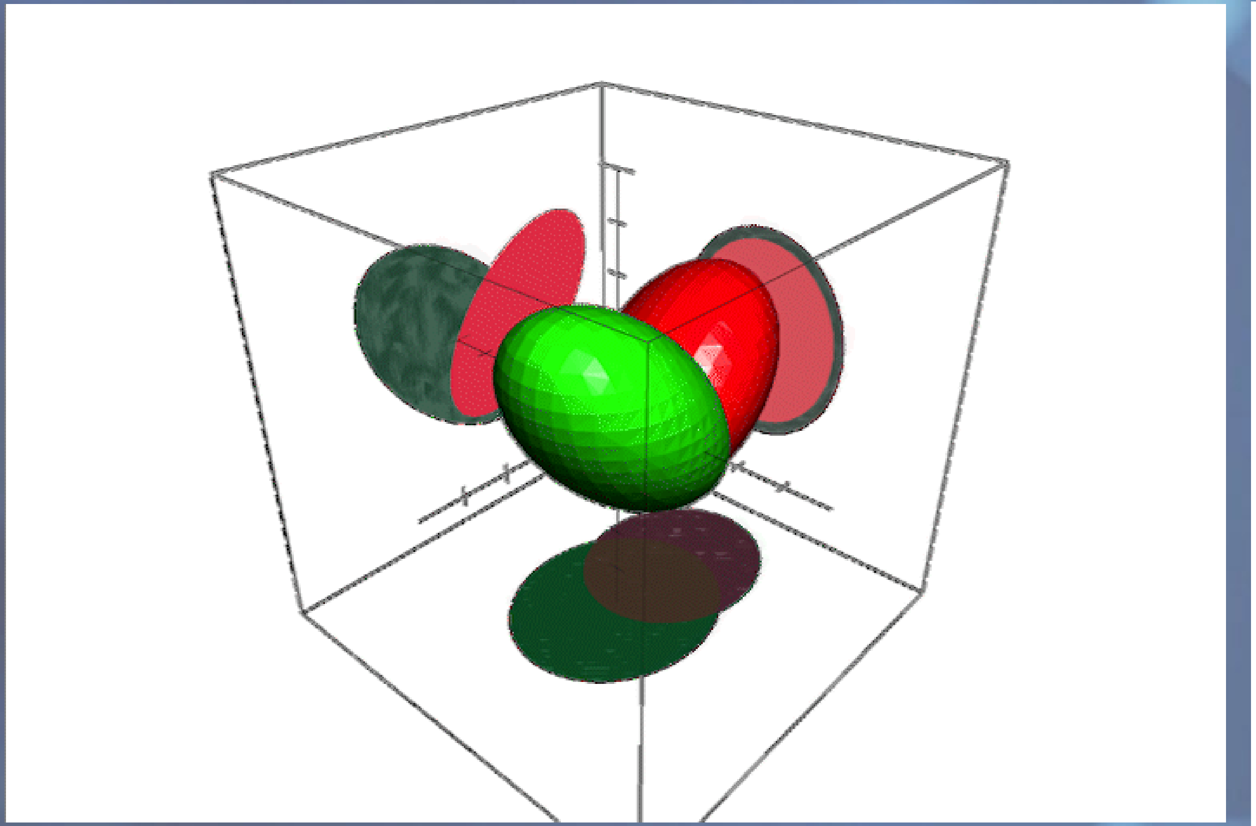
Identify a set of parameters that can be left free for all considered data sets, ensuring the use of consistent assumptions for any model as far as possible.

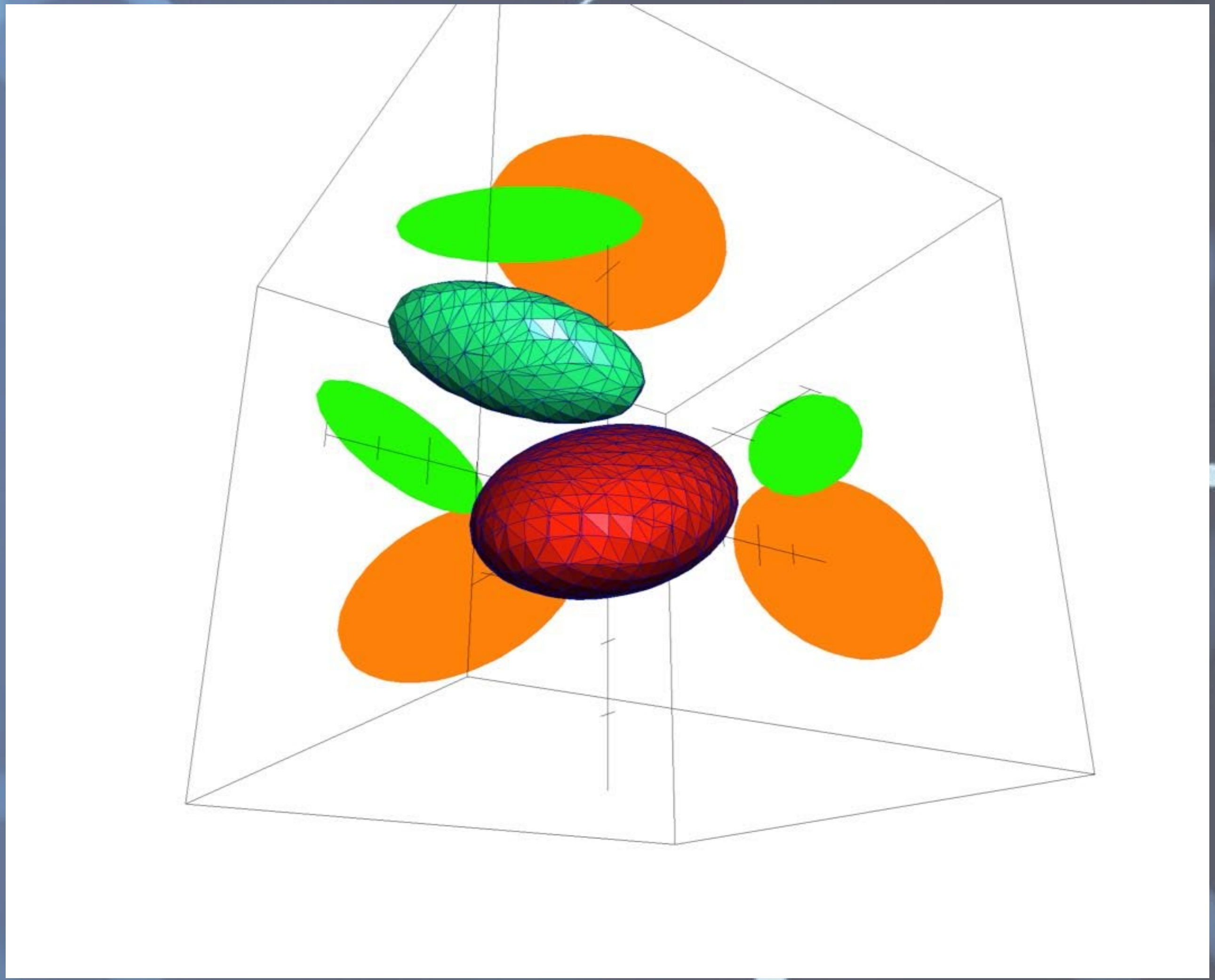
Check the consistency among cosmological and astrophysical data, using several cosmological models.

IMPORTANT!!! Combining incompatible probes would constrain a parameter space that is only the geometric combination of the two, leading to an analysis with no physical meaning !!!

Exploring the results combining the data when are those are compatible. We consider in agreement measurement up to $2\sigma$ compatible, while we report a difference when the analysis meets at $3\sigma$.

# CAN WE BELIEVE IN PROJECTIONS?





Credit: Guido Risaliti

# Goals

Identify a set of parameters that can be left free for all considered data sets, ensuring the use of consistent assumptions for any model as far as possible.

Using SNe Ia, QSOs, BAO, and DES, we use three free parameters: $\Omega_m$, $\Omega_b$, and $H_0$

- we assume the big bang nucleosynthesis (BBN) consistency, interpolating the primordial helium abundance value provided by table from PArthENoPE fits
- we impose a Gaussian prior on the baryon density parameter motivated by observations of D/H abundance, which is $\Omega_b h^2 = 0.0222 \pm 0.0005$.
- we fix the remaining cosmological parameters, as constrained by Planck 2018 (Aghanim et al.)

$ns$=0.965 $\tau$=0.055 $As$=$2.21\times10^{-9}$ $\Omega_k$=0

# Models

## ΛCDM

$$E(z) = \frac{H(z)}{H_0} = \left[\Omega_{M,0}\,(1+z)^3 + \Omega_{r,0}\,(1+z)^4 + \Omega_{\Lambda,0}\right]^{\frac{1}{2}}$$

$$1 = \Omega_{M,0} + \Omega_{r,0} + \Omega_{\Lambda,0}$$

$w(z) = p_\Lambda/\rho_\Lambda$

$$+\,\Omega_{\Lambda,0}\exp\left(3\int_0^z dz'\,\frac{1+w(z')}{1+z'}\right)$$

## DE extensions:

- wCDM (free $w_0$)
- CPL ($w(a)=w_0+w_a(1-a)$ )
- iDE ($p=-A/\rho^{\alpha}$)

# Models

## iDE

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

$1 = \Omega_{M,0} + \Omega_{r,0}$

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

considering an unified dark sector, which behaves like a decomposed generalized Chaplygin gas (GCG) model

$\alpha$ is the interaction parameter between the dark components

$\alpha > 0$ due to the homogeneous creation of dark particles from the expanding vacuum

$\alpha < 0$, matter is annihilated to create vacuum energy

# Results - $\Lambda$CDM

The 5 probes  in agreement in at least within $2\sigma$

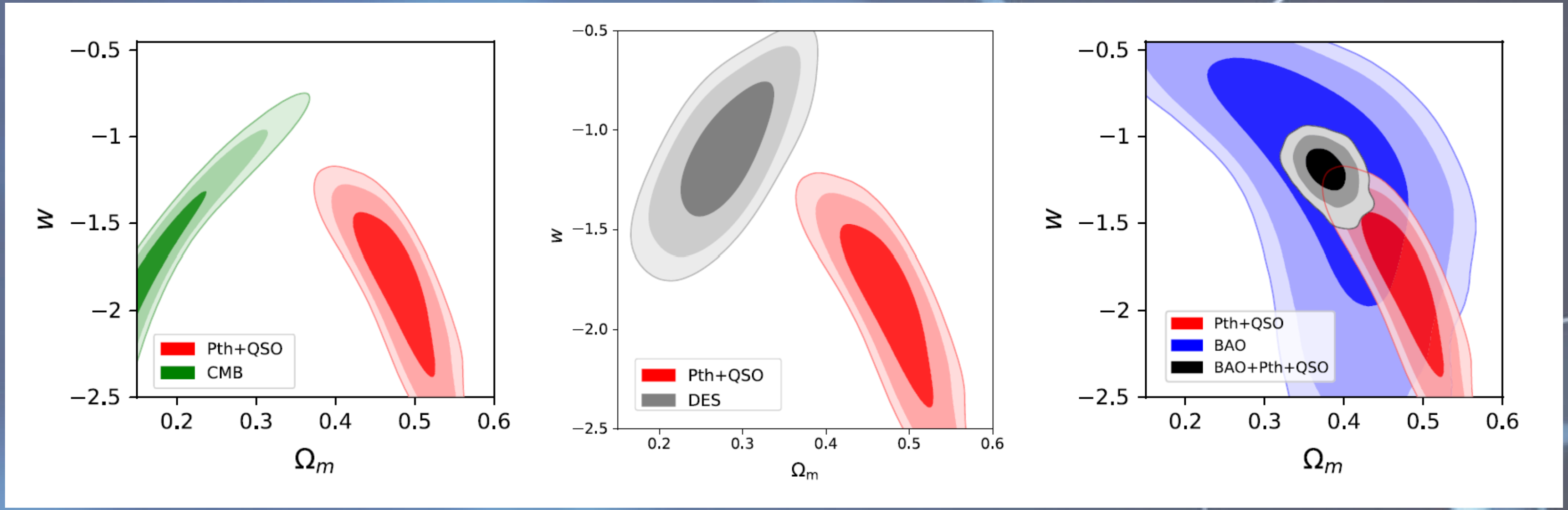
They show different slight preferences

The rigidity of this model, due to the small number of free parameters, could no catch the greater complexity that emerges from the observations.

| Model | Data set | $\Omega_m$ | $H_0$ ($\mathrm{km\,s^{-1}\,Mpc^{-1}}$) |
|---|---|---|---|
| Flat $\Lambda$CDM | Pth+QSO | $0.357 \pm 0.025$ | $71.79 \pm 1.74$ |
| | CMB | $0.316 \pm 0.007$ | $67.34 \pm 0.54$ |
| | BAO | $0.371^{+0.044}_{-0.053}$ | $72.06^{+3.53}_{-2.68}$ |
| | DES | $0.300 \pm 0.049$ | $66.76 \pm 7.79$ |
| | Pth+QSO+CMB | $0.316 \pm 0.008$ | $67.33 \pm 0.60$ |
| | Pth+QSO+BAO | $0.358 \pm 0.024$ | $71.14 \pm 2.30$ |
| | Pth+QSO+DES | $0.285 \pm 0.014$ | $69.44 \pm 2.35$ |

# Results - wCDM

wCDM does not help to make CMB and DES consistent with Pth+QSO

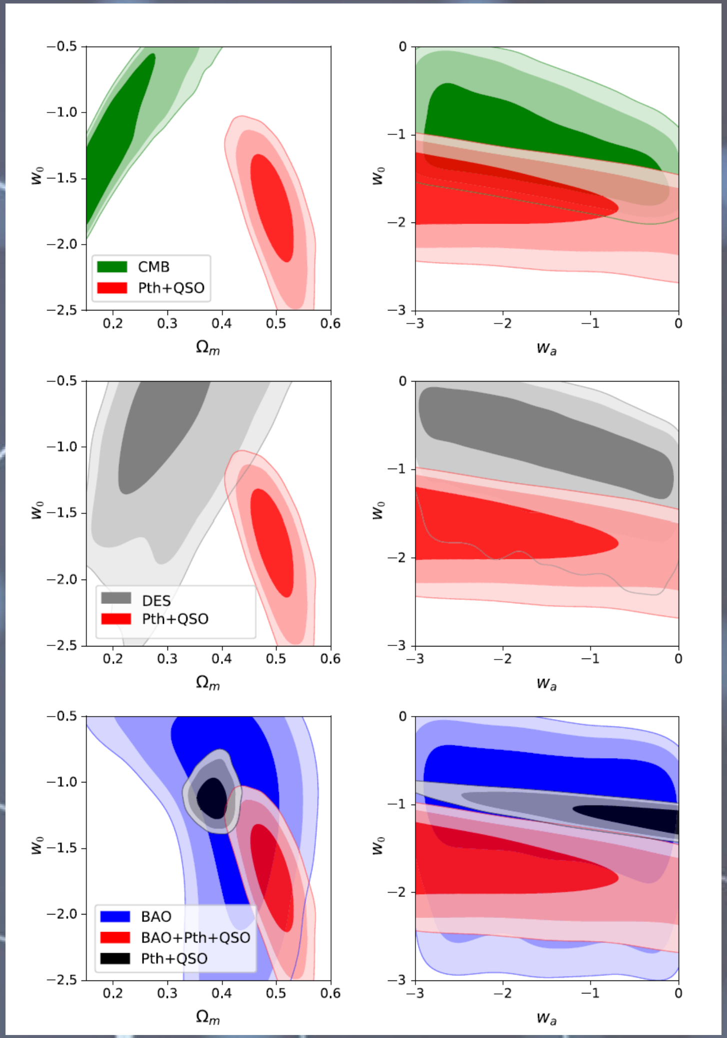



| Model | Data set | $\Omega_m$ | $H_0\,(\mathrm{km\,s^{-1}\,Mpc^{-1}})$ | $w_0$ |
|---|---|---|---|---|
| Flat $w$CDM | Pth+QSO | $0.478 \pm 0.041$ | $71.70 \pm 4.97$ | $-1.87 \pm 0.28$ |
| | CMB | $0.130^{+0.018}_{-0.067}$ | $111.70^{+28.43}_{-20.70}$ | $< -1.24$ |
| | BAO | $0.377^{+0.081}_{-0.053}$ | $78.31^{+12.50}_{-16.54}$ | $-1.26^{+0.62}_{-0.27}$ |
| | DES | $0.281 \pm 0.033$ | $68.53 \pm 4.73$ | $-1.10 \pm 0.21$ |
| | Pth+QSO+BAO | $0.378 \pm 0.017$ | $75.33 \pm 1.74$ | $-1.19 \pm 0.08$ |

# Results - CPL

the data seems to be not sensitive to the parameter that governs the variation of the equation of state with scale, $w_a$

The parametric space restricted by this model is essentially the same as the $w$CDM model with equal or larger error bars depending on the probe considered




| Model | Data set | $\Omega_m$ | $H_0$ (km s$^{-1}$ Mpc$^{-1}$) | $w_0$ | $w_a$ |
|---|---|---|---|---|---|
| Flat CPL | Pth+QSO | $0.494 \pm 0.027$ | $73.37 \pm 1.76$ | $-1.74 \pm 0.28$ | unconstrained |
| | CMB | $0.219^{+0.028}_{-0.091}$ | $82.92 \pm 10.71$ | $< -0.28$ | unconstrained |
| | BAO | $0.414^{+0.067}_{-0.045}$ | $82.87^{+13.98}_{-17.12}$ | $-1.18^{+0.76}_{-0.38}$ | unconstrained |
| | DES | $0.306^{+0.053}_{-0.069}$ | $65.74 \pm 8.57$ | $> -1.48$ | unconstrained |
| | Pth+QSO+BAO | $0.383 \pm 0.018$ | $75.54 \pm 1.73$ | $-1.11 \pm 0.10$ | $> -1.96$ |
| | Pth+QSO+DES | $0.282 \pm 0.009$ | $70.56 \pm 1.61$ | $-0.90 \pm 0.05$ | $> -0.54$ |

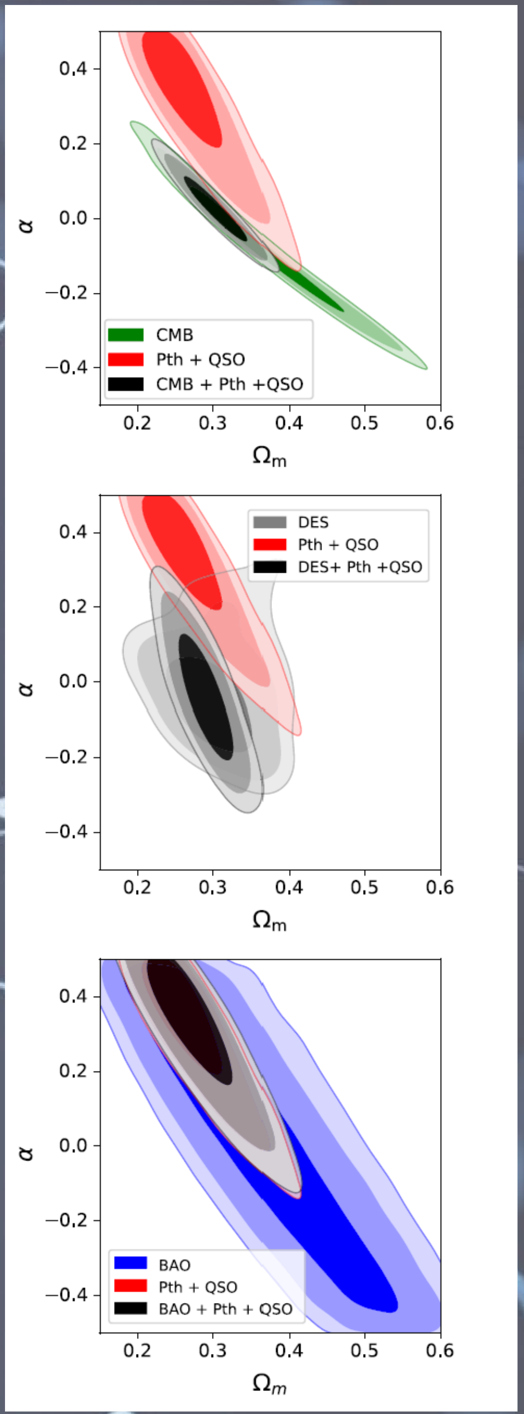
# Results -iDE

seems to be able to reconcile Pth+QSO with all the other probes (recovers $\Lambda$CDM ($\alpha$=0) in 3 $\sigma$)

positive values of $\alpha$ means generates DM particles from vacuum energy, and vice versa

Pth+QSO and Pth+QSO+BAO shows a clear preference for $H_0$ values compatible with direct observations of SNe Ia and a non-zero dissipation mechanism between the dark components.

| Model | Data set | $\Omega_m$ | $H_0\,(\mathrm{km\,s^{-1}\,Mpc^{-1}})$ | $\alpha$ |
|---|---|---|---|---|
| Flat iDE | Pth+QSO | $0.264^{+0.018}_{-0.025}$ | $73.35 \pm 1.82$ | $0.34^{+0.15}_{-0.06}$ |
| | CMB | $0.364^{+0.057}_{-0.081}$ | $65.61^{+2.73}_{-2.15}$ | $-0.08 \pm 0.11$ |
| | BAO | $0.359^{+0.045}_{-0.060}$ | $71.25 \pm 3.83$ | $0.04^{+0.44}_{-0.20}$ |
| | DES | $0.303^{+0.032}_{-0.038}$ | $68.77 \pm 5.55$ | $-0.06 \pm 0.09$ |
| | Pth+QSO+CMB | $0.302 \pm 0.024$ | $67.79 \pm 0.91$ | $0.03 \pm 0.05$ |
| | Pth+QSO+BAO | $0.271^{+0.031}_{-0.040}$ | $73.98^{+2.03}_{-1.99}$ | $0.34^{+0.15}_{-0.06}$ |
| | Pth+QSO+DES | $0.289 \pm 0.021$ | $71.17 \pm 3.21$ | $-0.04 \pm 0.10$ |



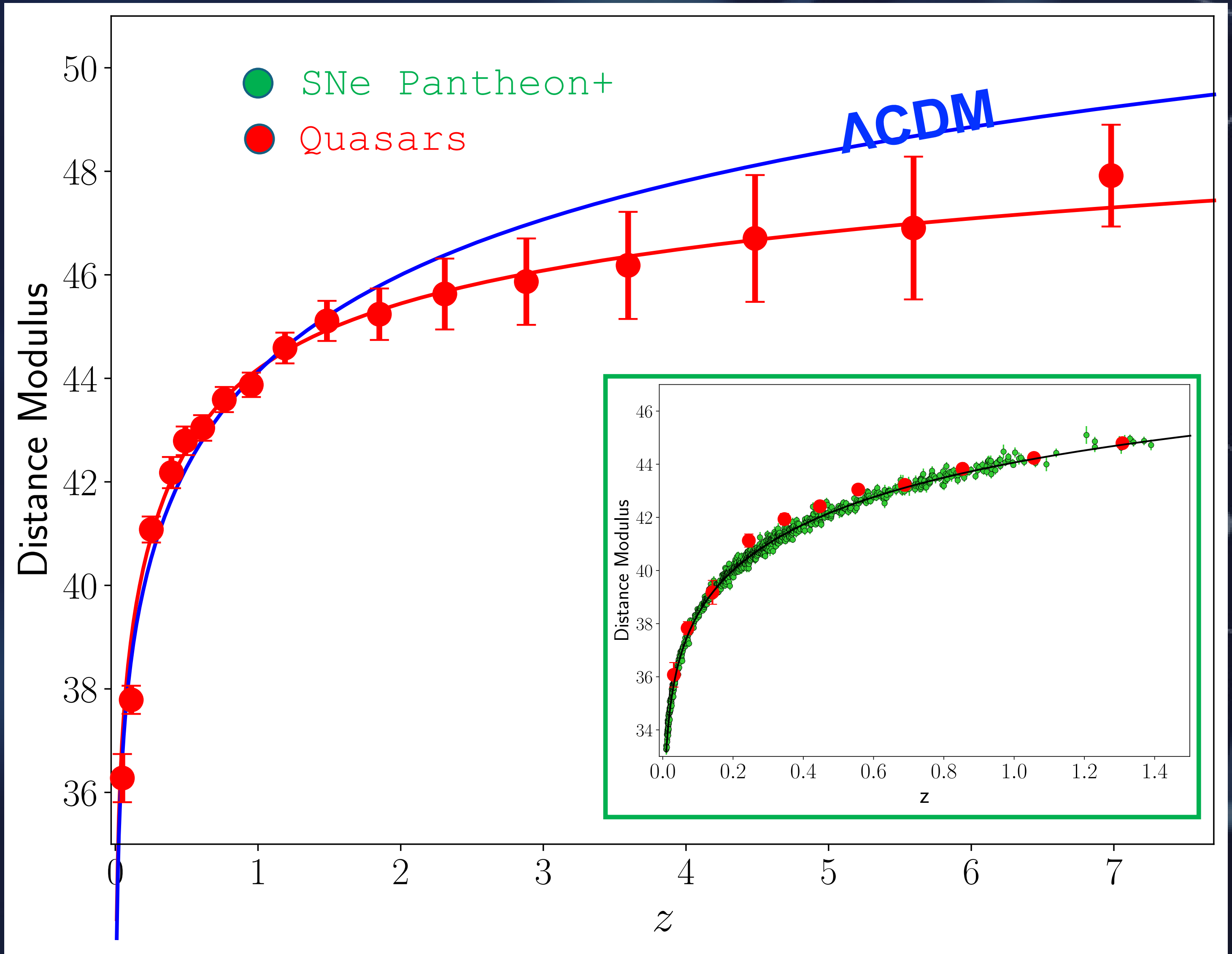
# TAKE-HOME MESSAGE

Quasars are standardizable candles crucial to extend the Hubble diagram

Our results point out that where the simplest models of DE extension fail in describing the Universe evolution at all scales, the more complicated model involving DE-DM interactions can succeed.

# Quasars as Standard Candles: tests of cosmology

Hubble Diagram with 2420 quasars




What's next?

## QGSKY goals

- Extended theories of gravity
- Non-local QFT and non-local theories of gravity
- Dark Matter and Dark energy
- QFT in curved space-time
- Exact black hole solutions
- Theoretical cosmology

Credit: Guido Risaliti

## ARE YOU INTERESTED IN COLLABORATING?

- COSMOLOGICAL ANALYSES INCLUDING OTHER PROBES

- TESTS OF OTHER (MORE INTERESTING) MODEL

- EXPLORE QSO DATA
HTTPS://GITHUB.COM/QSO-COSMOLOGY/QSO-FOR-COSMOLOGY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