Cosmography and high redshift LCDM tension from Quasar

Collaboration with Aritra Banerjee and Eoin Ó Colgáin

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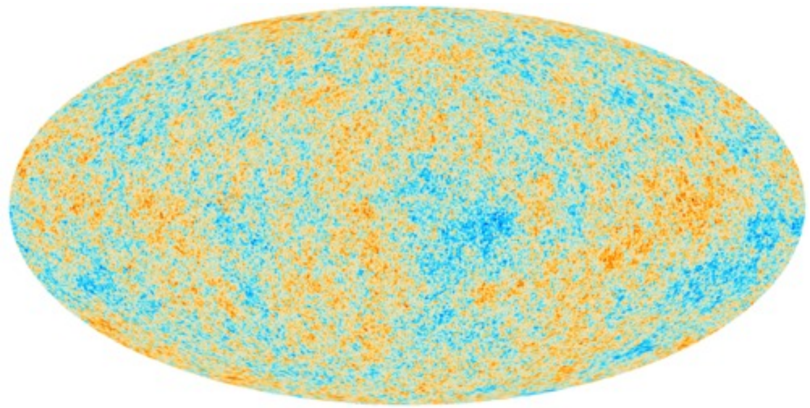
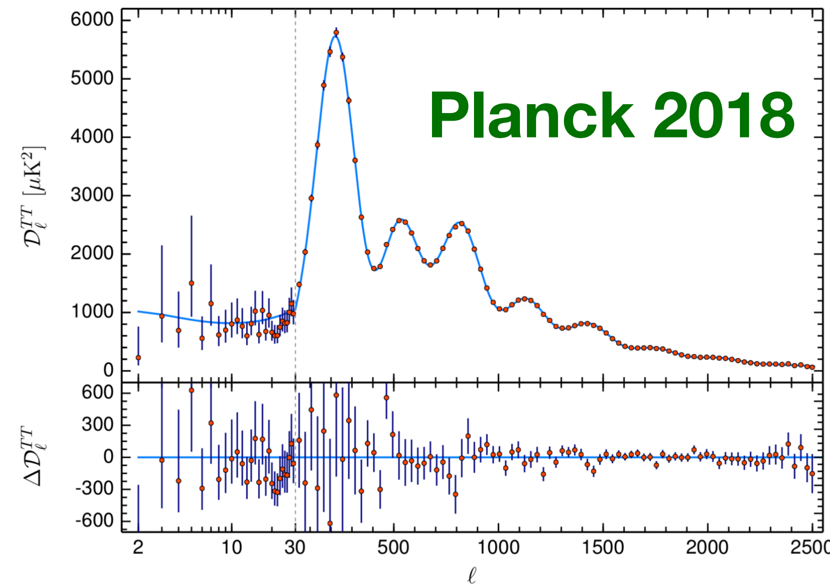
IBS, Daejeon, Dec 24th, 2019

Outline

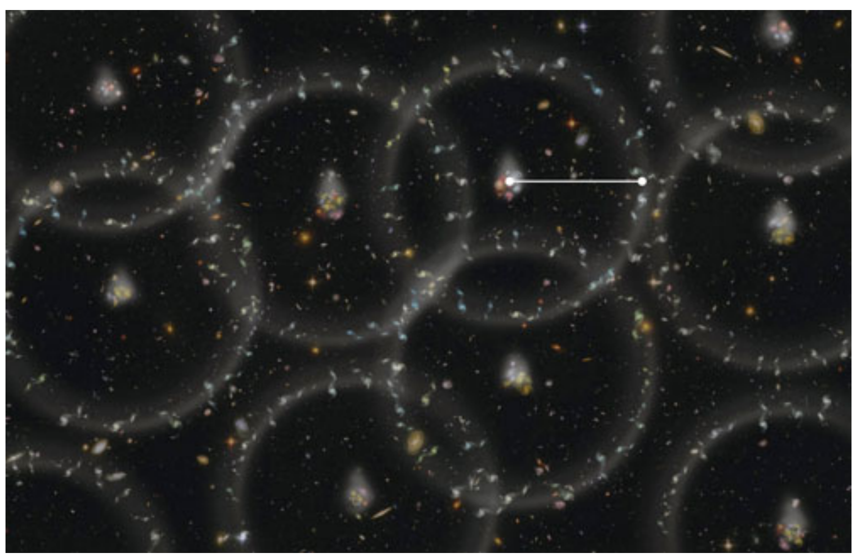
- Brief introduction to Cosmography and its limitations
- The story of high redshift LCDM tension from Quasar
  - Based on Risaliti and Lusso, Nat.Astron. 3 (2019) 272-277 and Lusso et.al., Astron.Astrophys. 628 (2019) L4
- The reanalysis of this tension. Is it a real tension? What's the implication of this tension?
  - Based on T,Yang, A. Banerjee, and E. O. Colgain, arXiv:1911.01681
- Summary

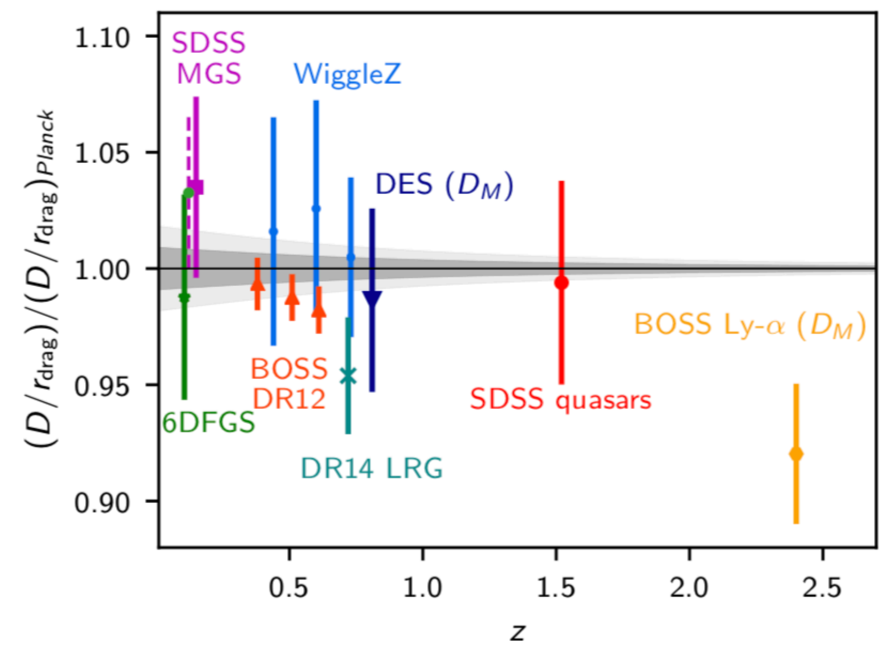
CMB



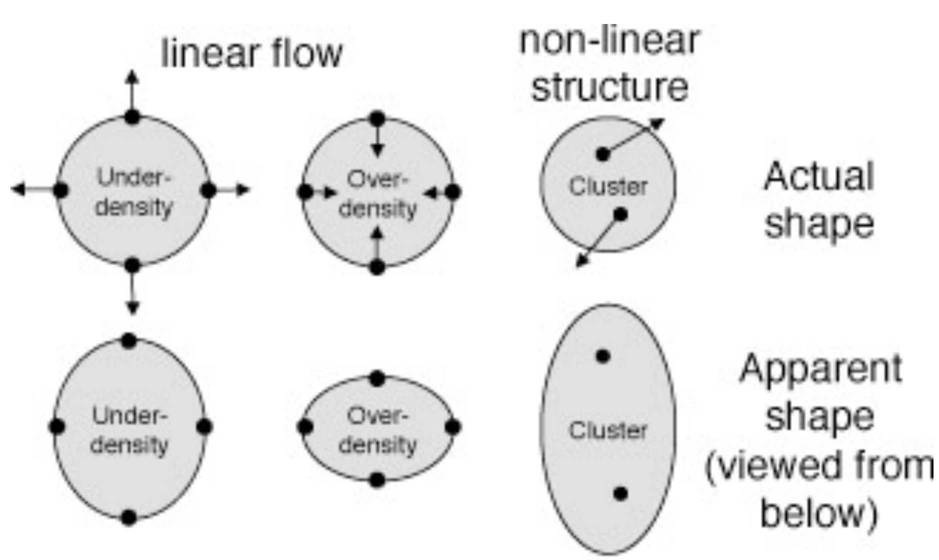

Planck 2018
$\mathcal{D}_\ell^{TT}$ [μK^2]
6000
5000
4000
3000
2000
1000
0
$\Delta\mathcal{D}_\ell^{TT}$
600
300
0
-300
-600
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ

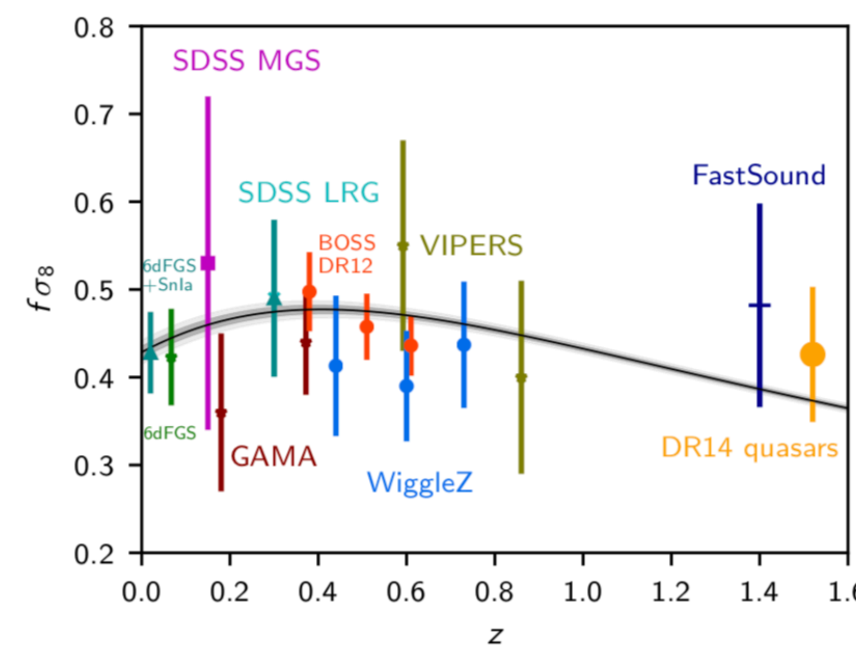
BAO




SDSS MGS
WiggleZ
DES (D_M)
BOSS Ly-α (D_M)
BOSS DR12
SDSS quasars
6DFGS
DR14 LRG
$(D/r_{\rm drag})/(D/r_{\rm drag})_{Planck}$
1.10
1.05
1.00
0.95
0.90
0.5
1.0
1.5
2.0
2.5
z

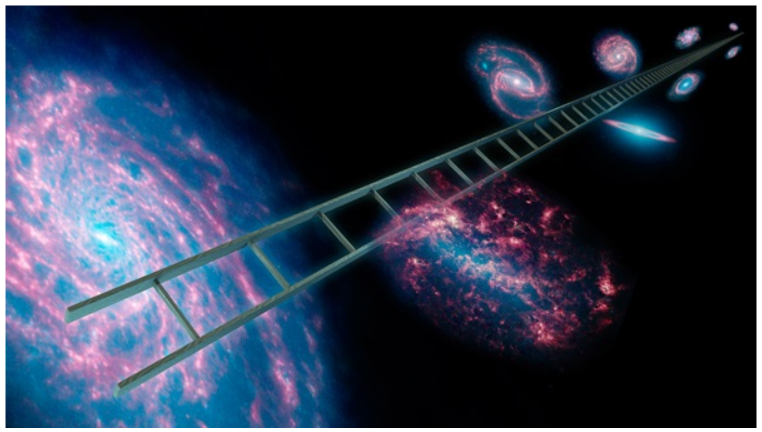
RSD

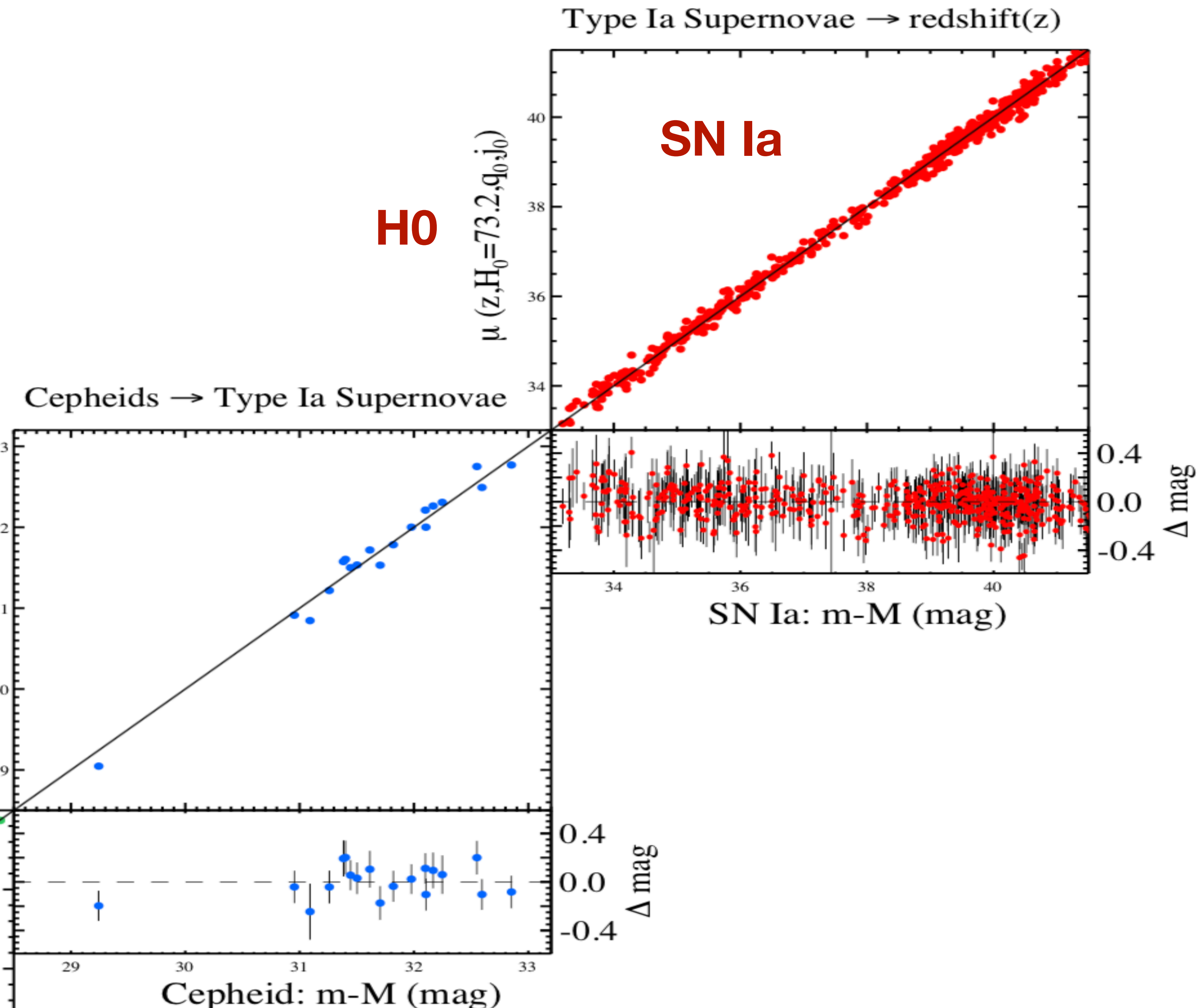

linear flow
non-linear structure
Under-density
Over-density
Cluster
Actual shape
Under-density
Over-density
Cluster
Apparent shape (viewed from below)

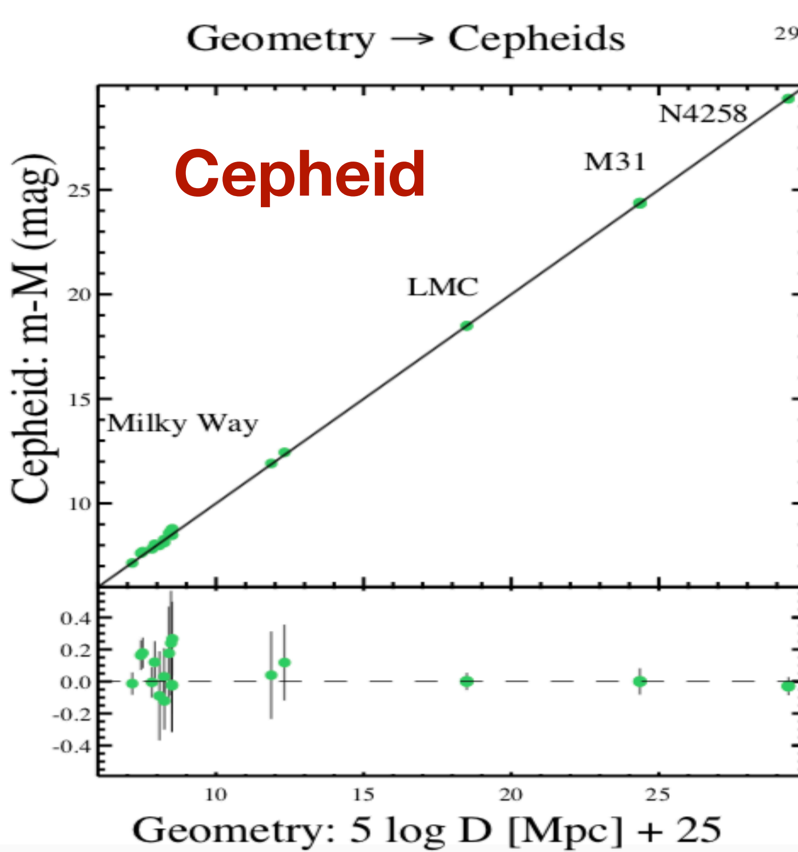

SDSS MGS
SDSS LRG
6dFGS +SnIa
BOSS DR12
VIPERS
FastSound
6dFGS
GAMA
WiggleZ
DR14 quasars
$f\sigma_8$
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
z

Type Ia Supernovae, standard candles

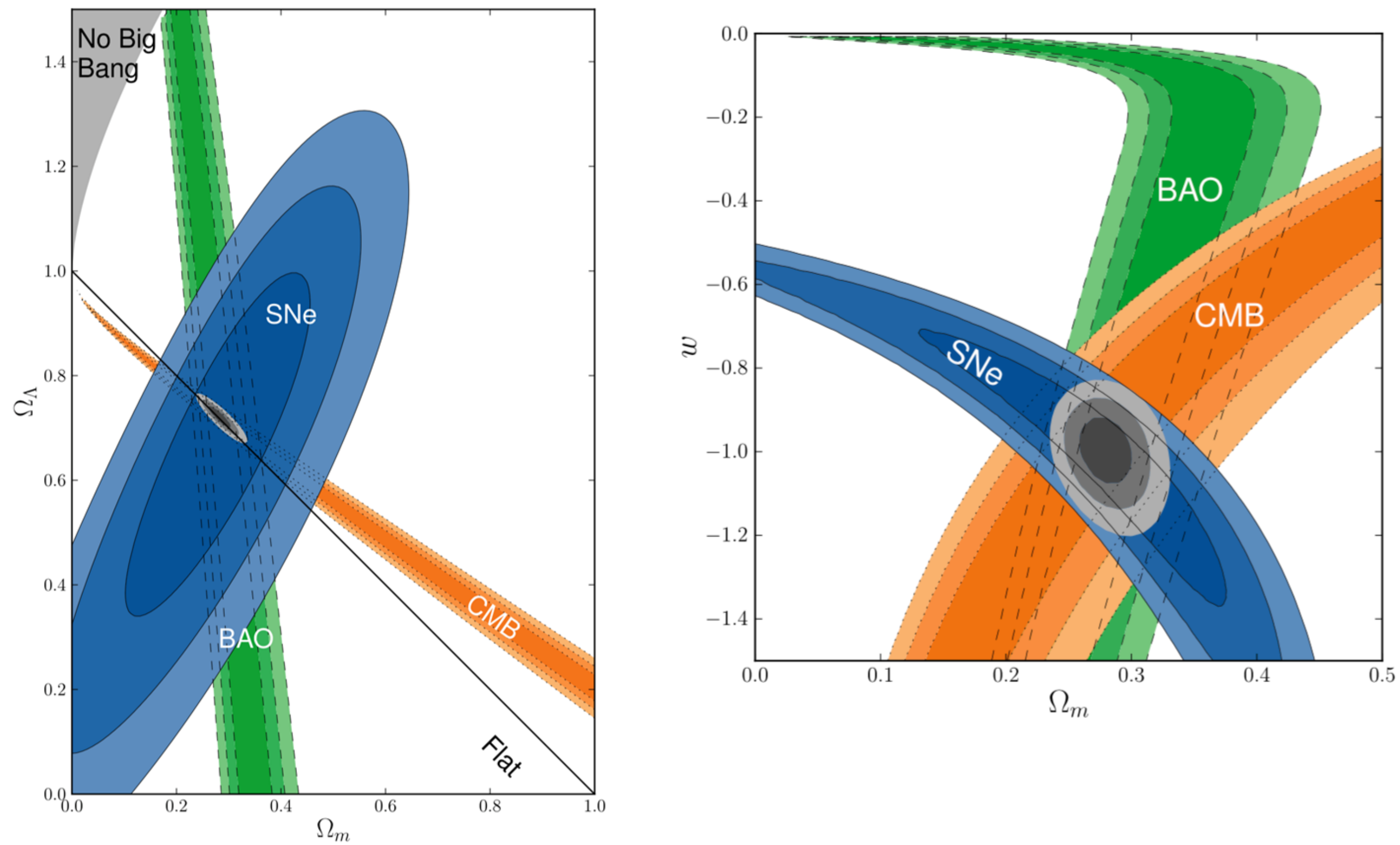
Cosmic distance ladder



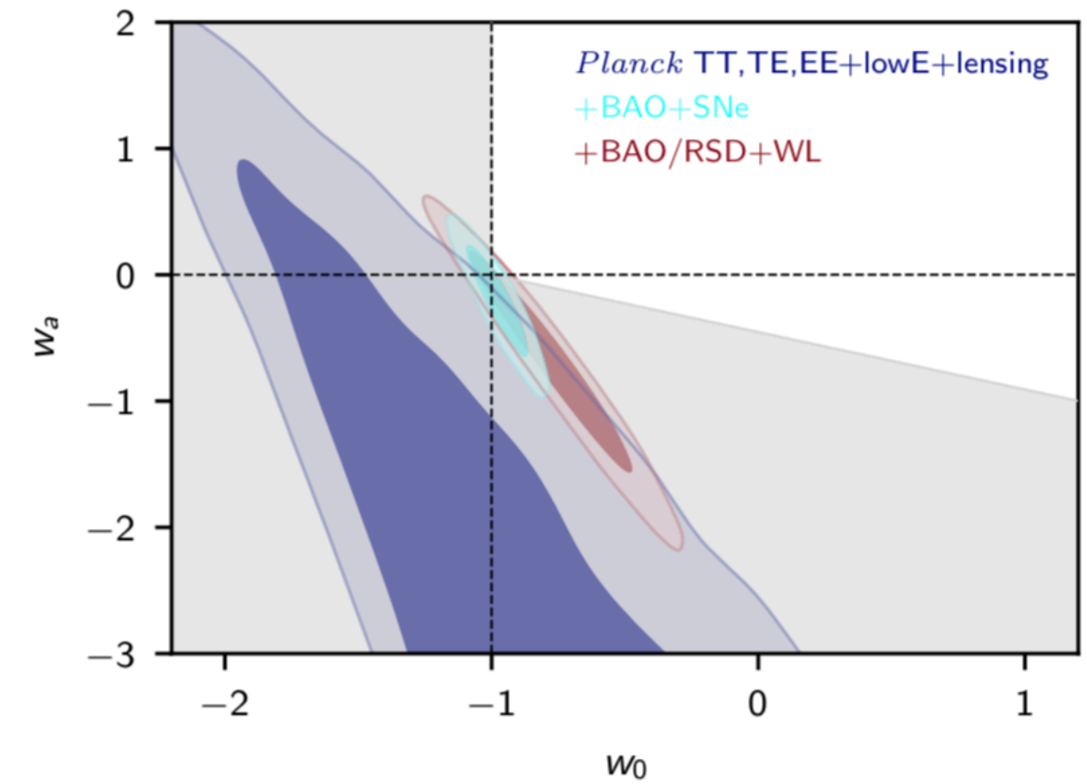




A. G. Riess 2016



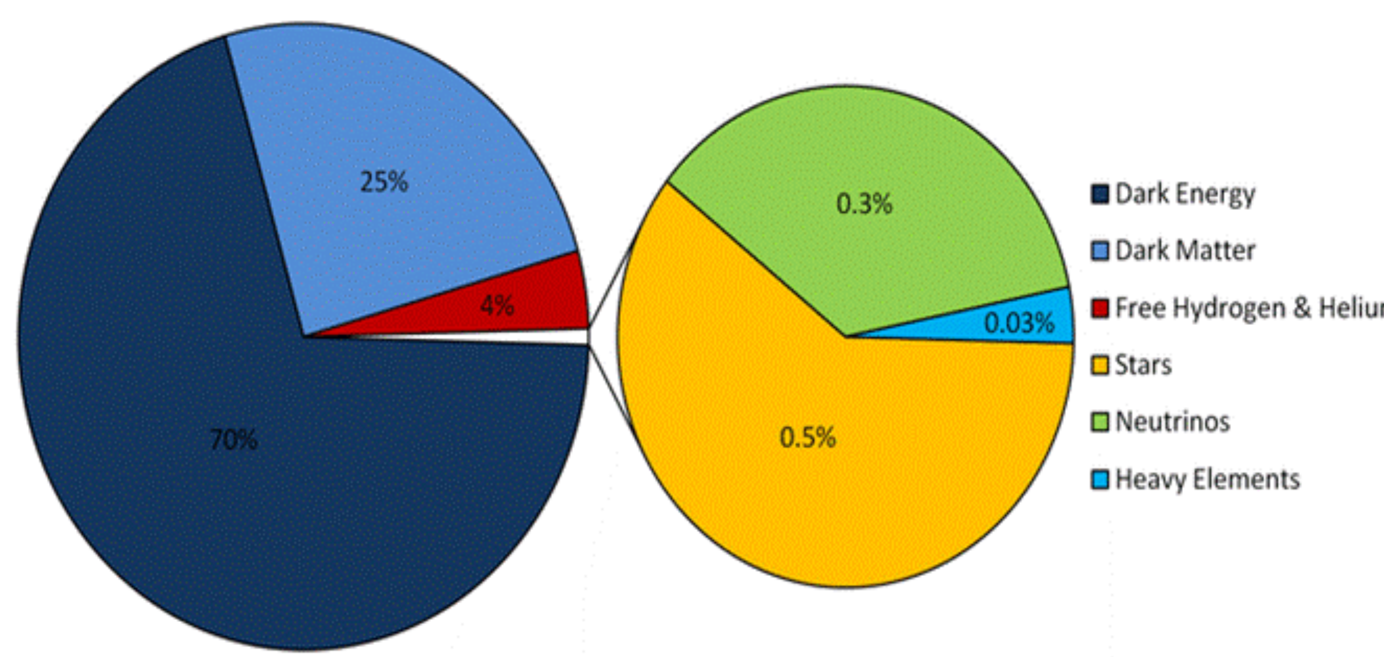
Suzuki 2011



Planck 2018

Concordance cosmological model: flat LCDM model (w=-1)

$$H^2(z) = H_0^2\sqrt{1-\Omega_m+\Omega_m(1+z)^2}$$



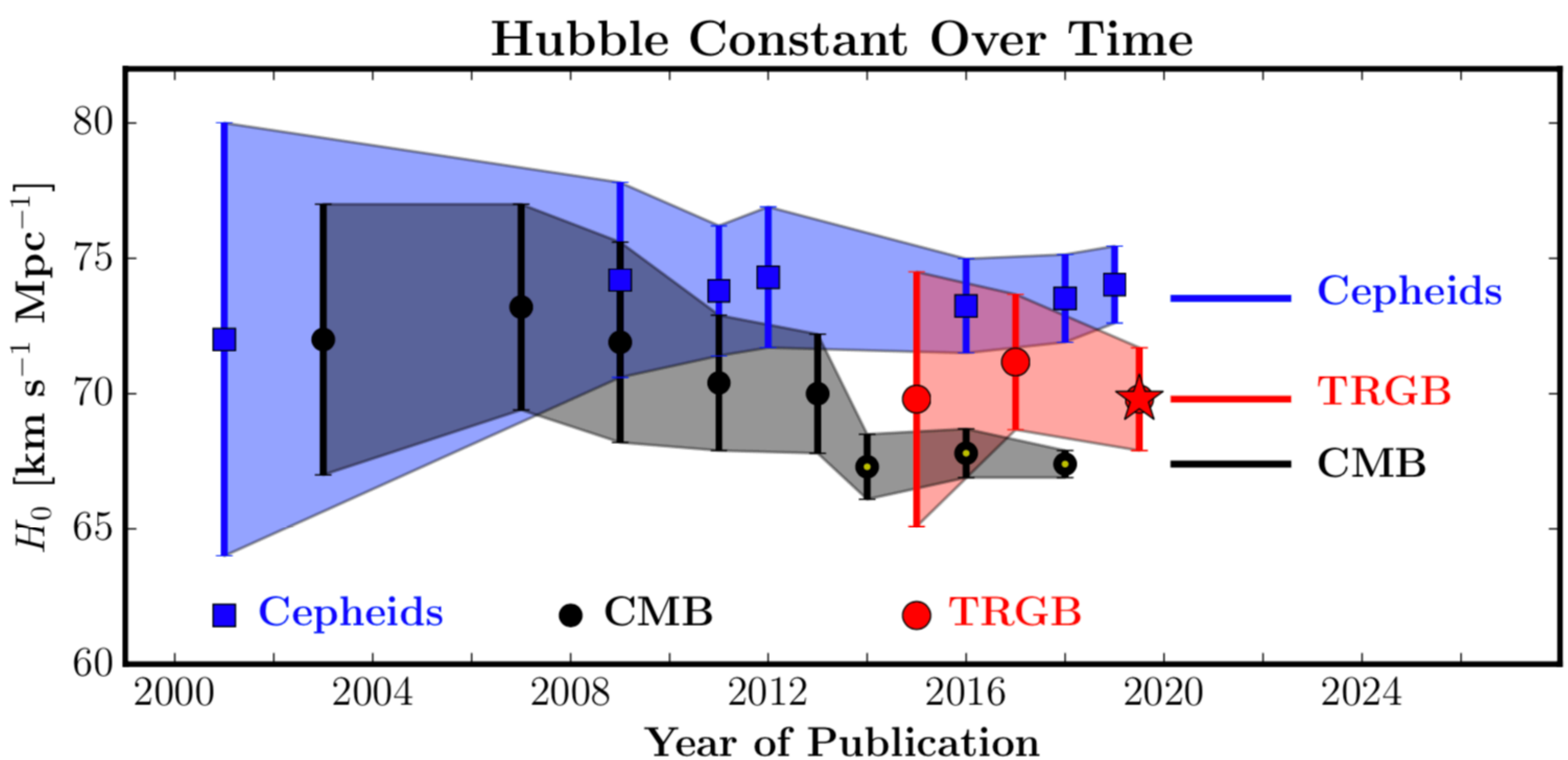
Credit: KIAS

Fine-tuning

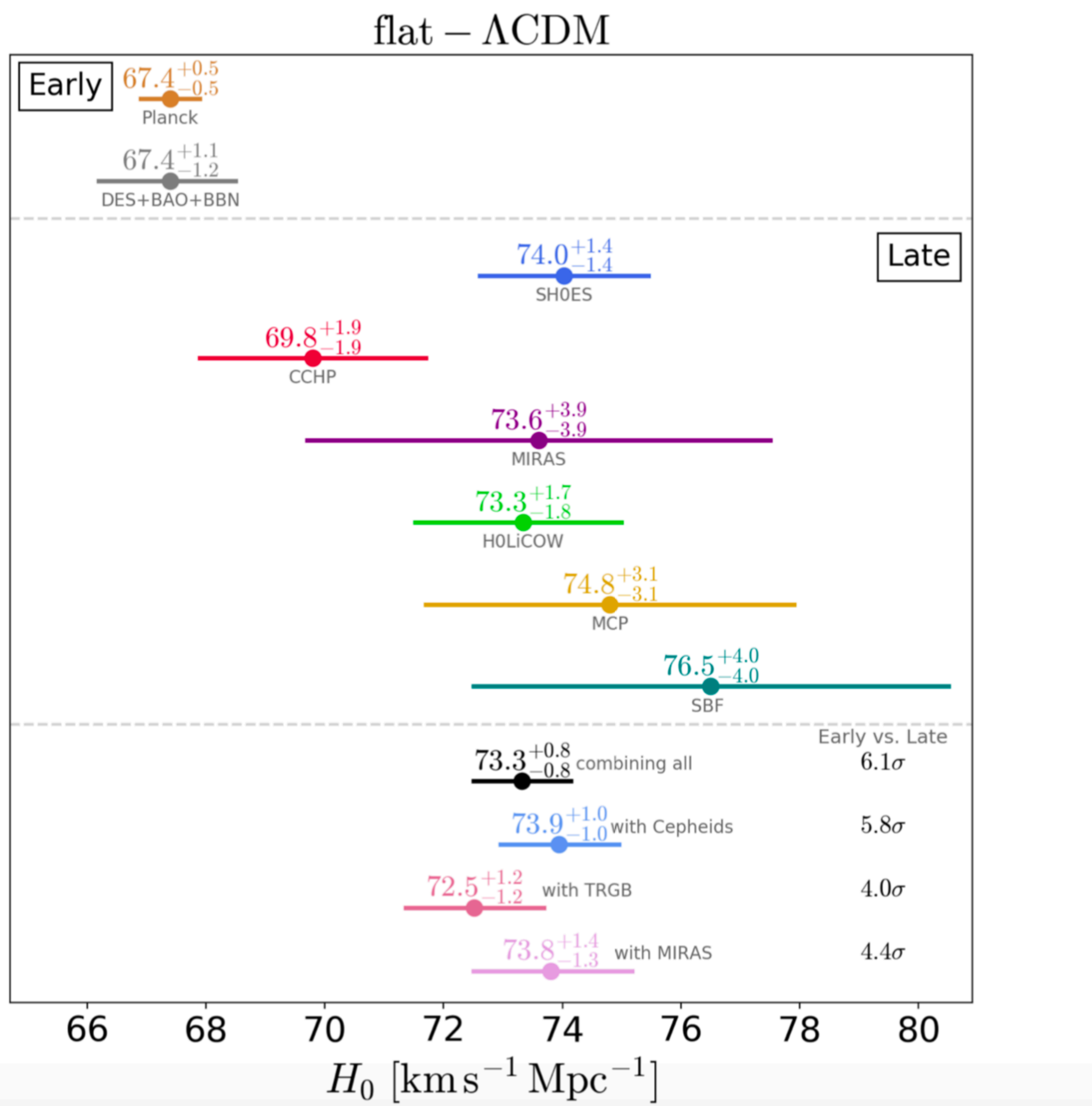
Weinberg, 2000

Coincident problem

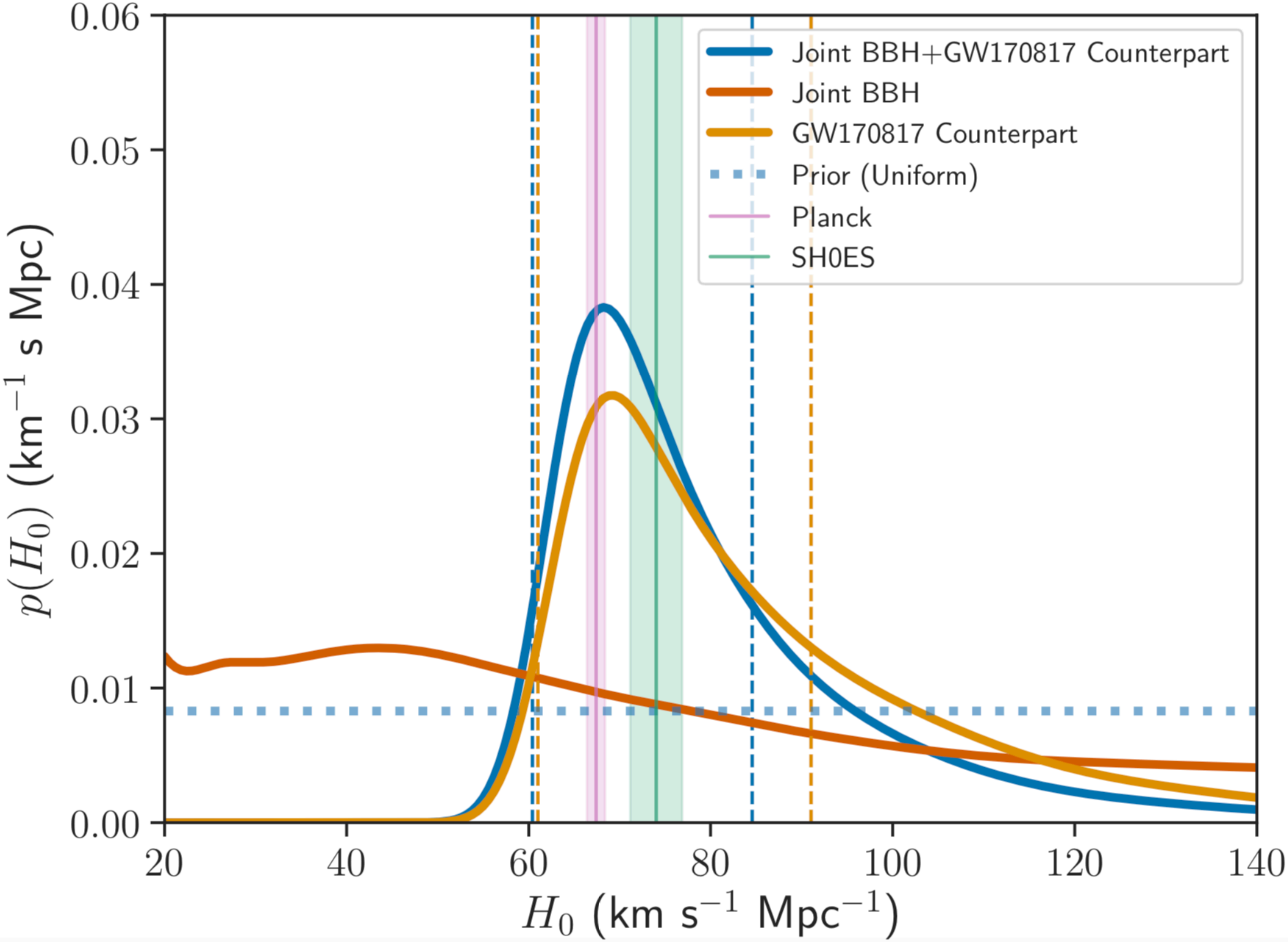
The tension with the Hubble constant



W. L. Freedman, 2019



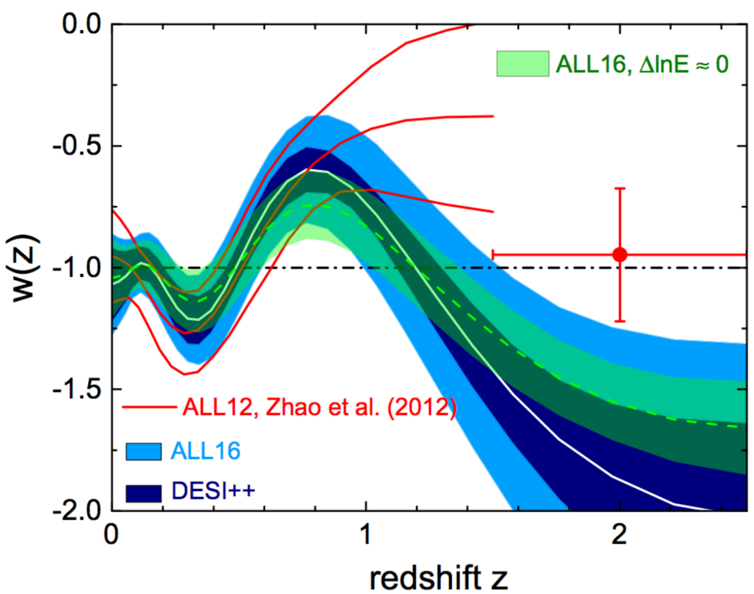
flat − ΛCDM
Early
$67.4^{+0.5}_{-0.5}$
Planck
$67.4^{+1.1}_{-1.2}$
DES+BAO+BBN
Late
$74.0^{+1.4}_{-1.4}$
SH0ES
$69.8^{+1.9}_{-1.9}$
CCHP
$73.6^{+3.9}_{-3.9}$
MIRAS
$73.3^{+1.7}_{-1.8}$
H0LiCOW
$74.8^{+3.1}_{-3.1}$
MCP
$76.5^{+4.0}_{-4.0}$
SBF
Early vs. Late
$73.3^{+0.8}_{-0.8}$ combining all
6.1σ
$73.9^{+1.0}_{-1.0}$ with Cepheids
5.8σ
$72.5^{+1.2}_{-1.2}$ with TRGB
4.0σ
$73.8^{+1.4}_{-1.3}$ with MIRAS
4.4σ
66 68 70 72 74 76 78 80
H_0 [km s^{-1} Mpc^{-1}]



Joint BBH+GW170817 Counterpart
Joint BBH
GW170817 Counterpart
Prior (Uniform)
Planck
SH0ES
0.06
0.05
0.04
0.03
0.02
0.01
0.00
20
40
60
80
100
120
140
$p(H_0)$ (km^{-1} s Mpc)
H_0 (km s^{-1} Mpc^{-1})

Extensions to base LCDM model

Dynamical dark energy?



G. B. Zhao, Nat.Astron. 2017

Interaction in dark sector?

$$\dot{\rho}_m + 3H\rho_m = Q$$

$$\dot{\rho}_{DE} + 3H(1+w)\rho_{DE} = -Q$$

$$Q = 3b^2 H(\rho_m + \rho_{DE})$$

B. Wang 2006

Modified gravity?

Model
ΛCDM . . . .
Background parameterizations:
w . . . .
w_0, w_a . . . .
w higher order expansion . . . . . .
1-parameter $w(a)$ . . . .
w PCA . . . .
ϵ_s, ζ_s, ϵ_∞ . . . .
Early DE . . . .
Perturbation parameterizations:
EFT exponential . . . .
EFT linear . . . .
μ, η scale-independent:
DE-related . . . .
time related . . . .
μ, η scale-dependent: . . . .
DE-related . . . .
time related . . . .
Other particular examples:
DE sound speed and k-essence . .
Equation of state approach: . . . .
Lorentz-violating massive gravity
Generalized scalar fields . . . . .
$f(R)$ . . . .
Coupled DE . . . .

Planck 2015

We need new and independent probe!

We also need new and model-independent data-analysis method!

Cosmography

- It's a model-independent method
- It has serious limitations at high redshift
- It is a popular method 10-15 years ago, nowadays we have more fashionable and developed model-independent numerical methods (Gaussian process etc.)

FRW metric

$$\mathrm{d}s^2 = -c^2\,\mathrm{d}t^2 + a(t)^2\left[\frac{\mathrm{d}r^2}{1-k\,r^2} + r^2\left(\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2\right)\right].$$

$$H(t) = +\frac{1}{a}\,\frac{\mathrm{d}a}{\mathrm{d}t};$$

$$q(t) = -\frac{1}{a}\,\frac{\mathrm{d}^2 a}{\mathrm{d}t^2}\,\left[\frac{1}{a}\,\frac{\mathrm{d}a}{\mathrm{d}t}\right]^{-2};$$

$$j(t) = +\frac{1}{a}\,\frac{\mathrm{d}^3 a}{\mathrm{d}t^3}\,\left[\frac{1}{a}\,\frac{\mathrm{d}a}{\mathrm{d}t}\right]^{-3};$$

$$s(t) = +\frac{1}{a}\,\frac{\mathrm{d}^4 a}{\mathrm{d}t^4}\,\left[\frac{1}{a}\,\frac{\mathrm{d}a}{\mathrm{d}t}\right]^{-4}.$$

$$a(t) = a_0\left\{1 + H_0\,(t-t_0) - \frac{1}{2}\,q_0\,H_0^2\,(t-t_0)^2 + \frac{1}{3!}\,j_0\,H_0^3\,(t-t_0)^3 + \frac{1}{4!}\,s_0\,H_0^4\,(t-t_0)^4 + O([t-t_0]^5)\right\}.$$

$$d_L(z) = \frac{c\,z}{H_0}\left\{1 + \frac{1}{2}\left[1-q_0\right]z - \frac{1}{6}\left[1 - q_0 - 3q_0^2 + j_0 + \frac{kc^2}{H_0^2 a_0^2}\right]z^2 + \frac{1}{24}\left[2 - 2q_0 - 15q_0^2 - 15q_0^3 + 5j_0 + 10q_0 j_0 + s_0 + \frac{2kc^2(1+3q_0)}{H_0^2 a_0^2}\right]z^3 + O(z^4)\right\}.$$

Visser 2005

Y expansion

$$d_L(y) = \frac{c}{H_0}\left\{y - \frac{1}{2}(q_0-3)y^2 + \frac{1}{6}\left[12 - 5q_0 + 3q_0^2 - (j_0+\Omega_0)\right]y^3 + \frac{1}{24}\left[60 - 7j_0 - \right.\right.$$
$$\left.\left. -10\Omega_0 - 32q_0 + 10q_0j_0 + 6q_0\Omega_0 + 21q_0^2 - 15q_0^3 + s_0\right]y^4 + \mathcal{O}(y^5)\right\} \;,$$

$$y = \frac{z}{1+z};$$

$$z \in (0,\infty); \qquad y \in (0,1);$$

$$z = 6; \quad y = 0.857$$

LCDM

$$q_0 = -1 + \frac{3}{2}\Omega_M;$$
$$j_0 = 1;$$
$$s_0 = 1 - \frac{9}{2}\Omega_M\,,$$

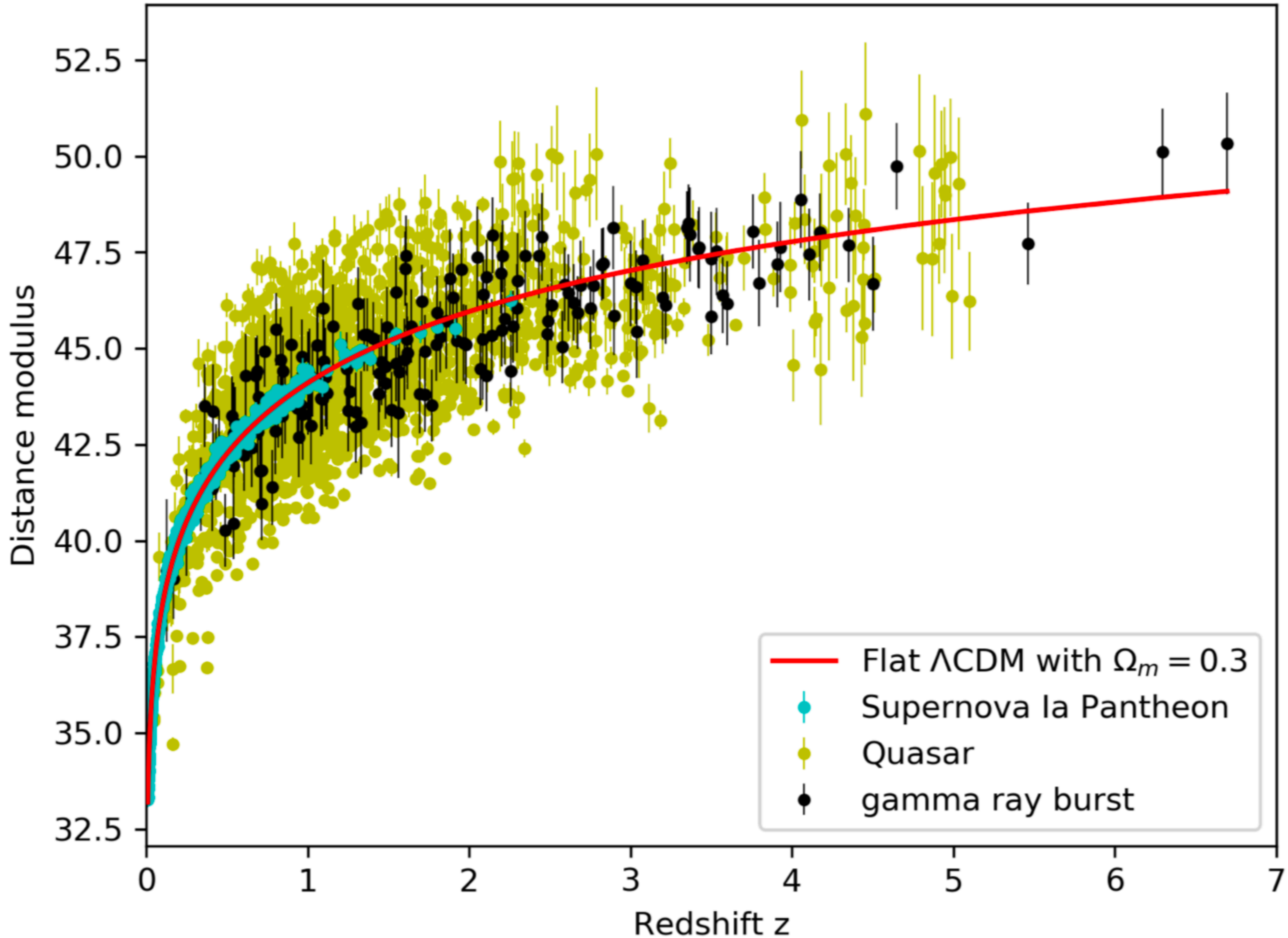
Log10 expansion

$$d_L(z) = \frac{c\ln(10)}{H_0}\Big[\log_{10}(1+z) + a_2\log_{10}^2(1+z) + a_3\log_{10}^3(1+z) + a_4\log_{10}^4(1+z) + \ldots\Big],$$

$$z = 6; \quad \log_{10}(1+z) = 0.845$$

LCDM

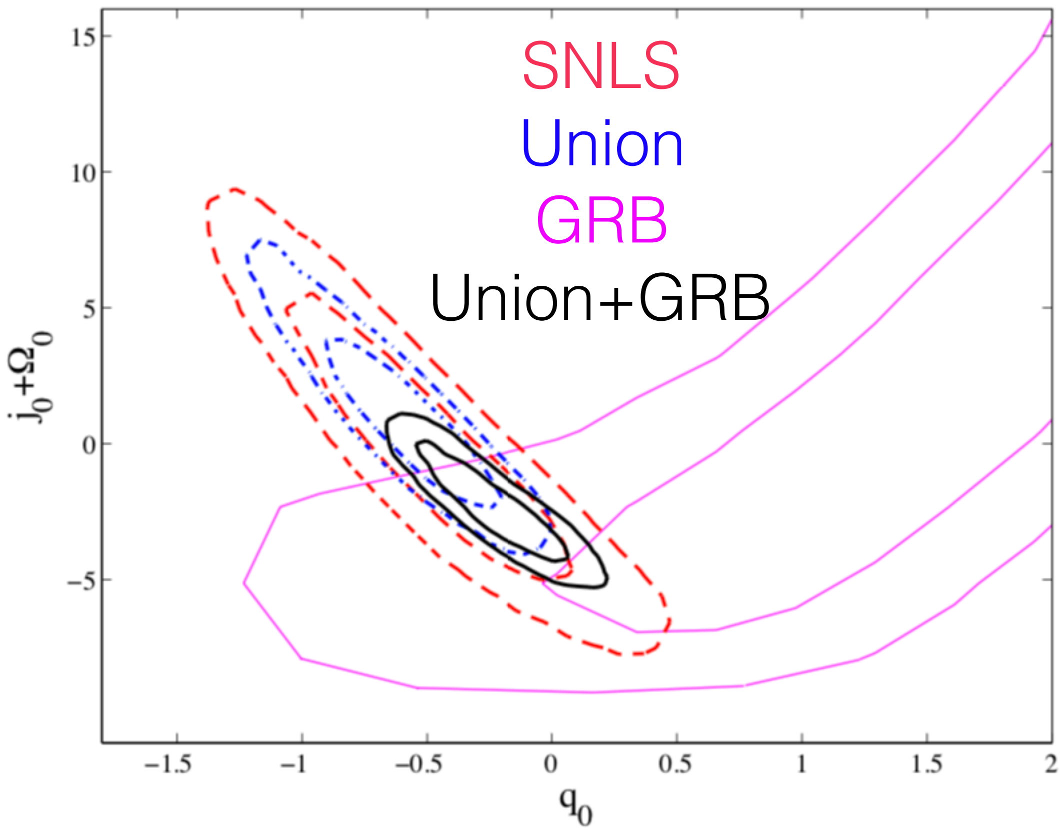
$$a_2 = \ln(10)\left(\frac{3}{2} - \frac{3}{4}\Omega_m,\right),$$
$$a_3 = \ln^2(10)\left(\frac{9}{8}\Omega_m^2 - 2\Omega_m + \frac{7}{6}\right),$$
$$a_4 = \ln^3(10)\left(-\frac{135}{64}\Omega_m^3 + \frac{9}{2}\Omega_m^2 - \frac{47}{16}\Omega_m + \frac{5}{8}\right).$$



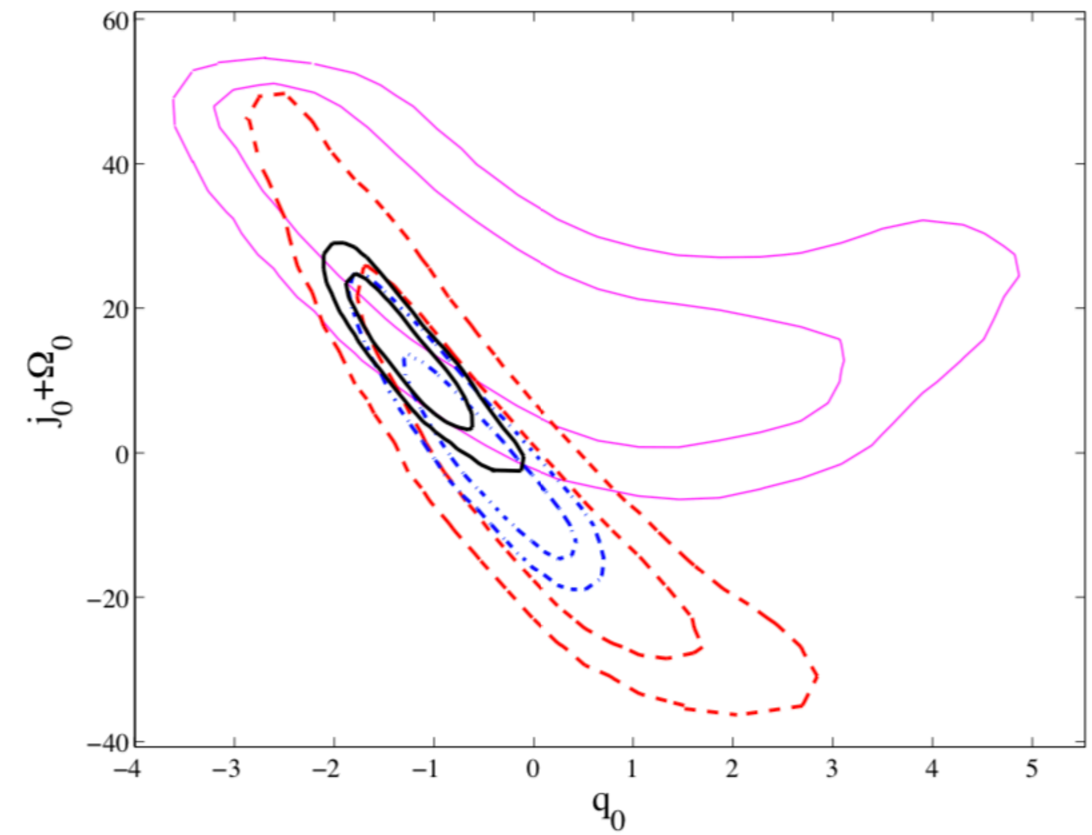
Any deviation or tension from LCDM?

Is Cosmography a reliable tool for cosmology?

Third order (q0, j0)



Fourth order (q0, j0, s0)

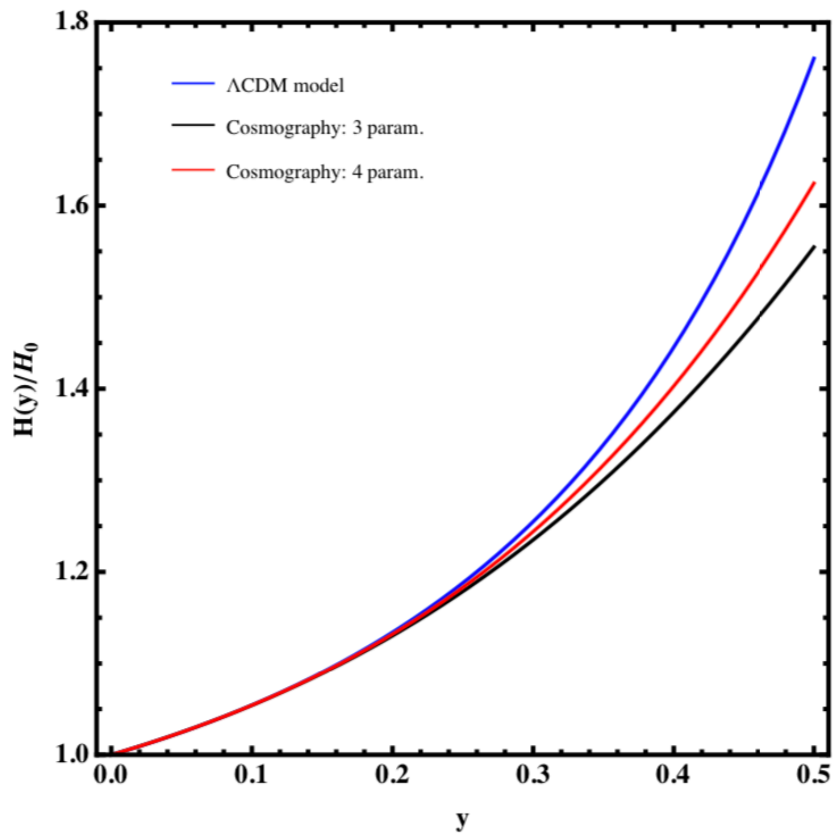


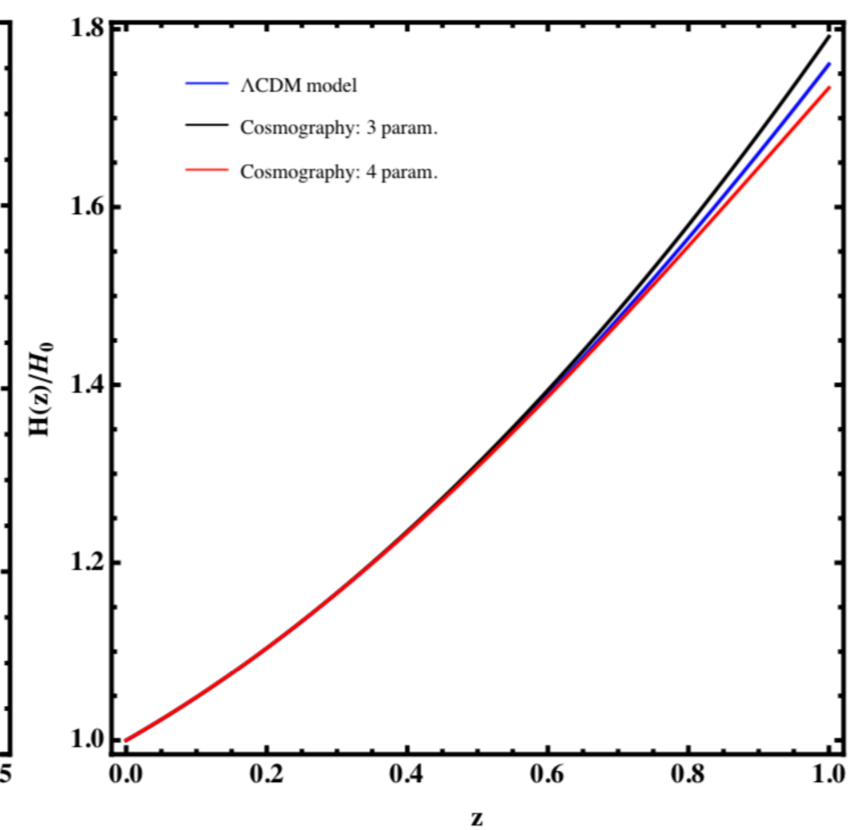
Vitagliano, 2010

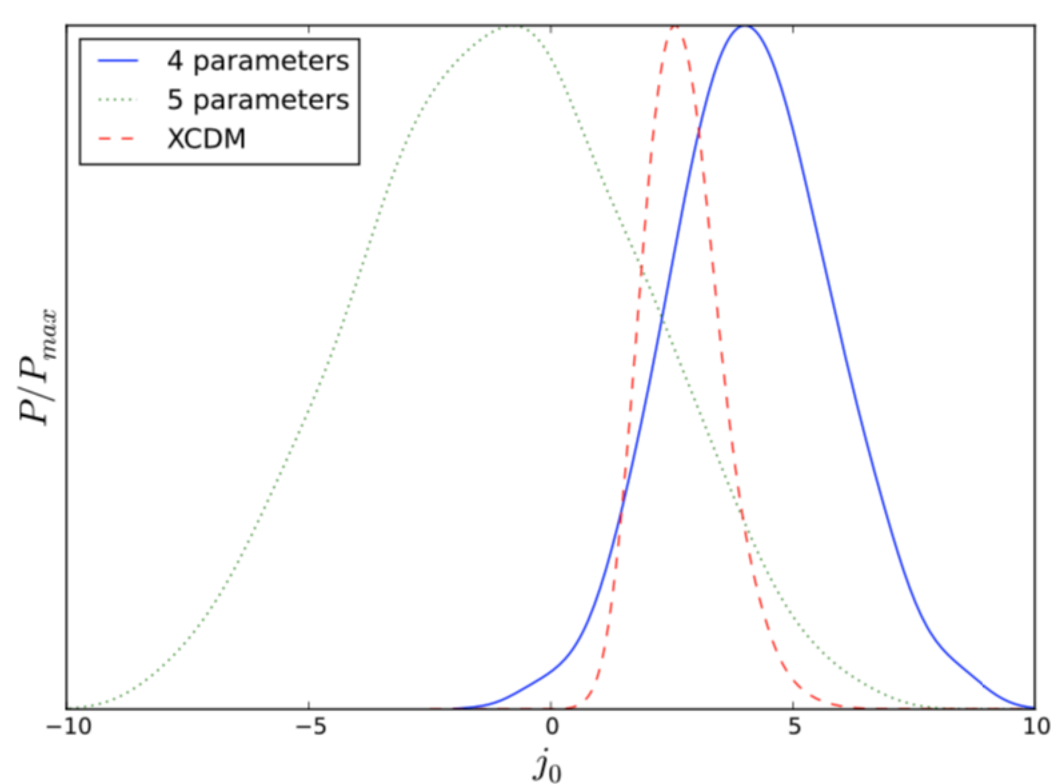
Phys.Rev. D92 (2015) 123512

Is cosmography a useful tool for testing cosmology?

Vinicius C. Busti[a] * Álvaro de la Cruz-Dombriz[a,b] † Peter K. S. Dunsby[a,c] ‡, Diego Sáez-Gómez[a,d] §







The story of 4 sigma LCDM tension from Quasar at high redshift

Risaliti and Lusso, Nat.Astron. 3 (2019) 272-277

Cosmological constraints from the Hubble diagram of quasars at high redshifts

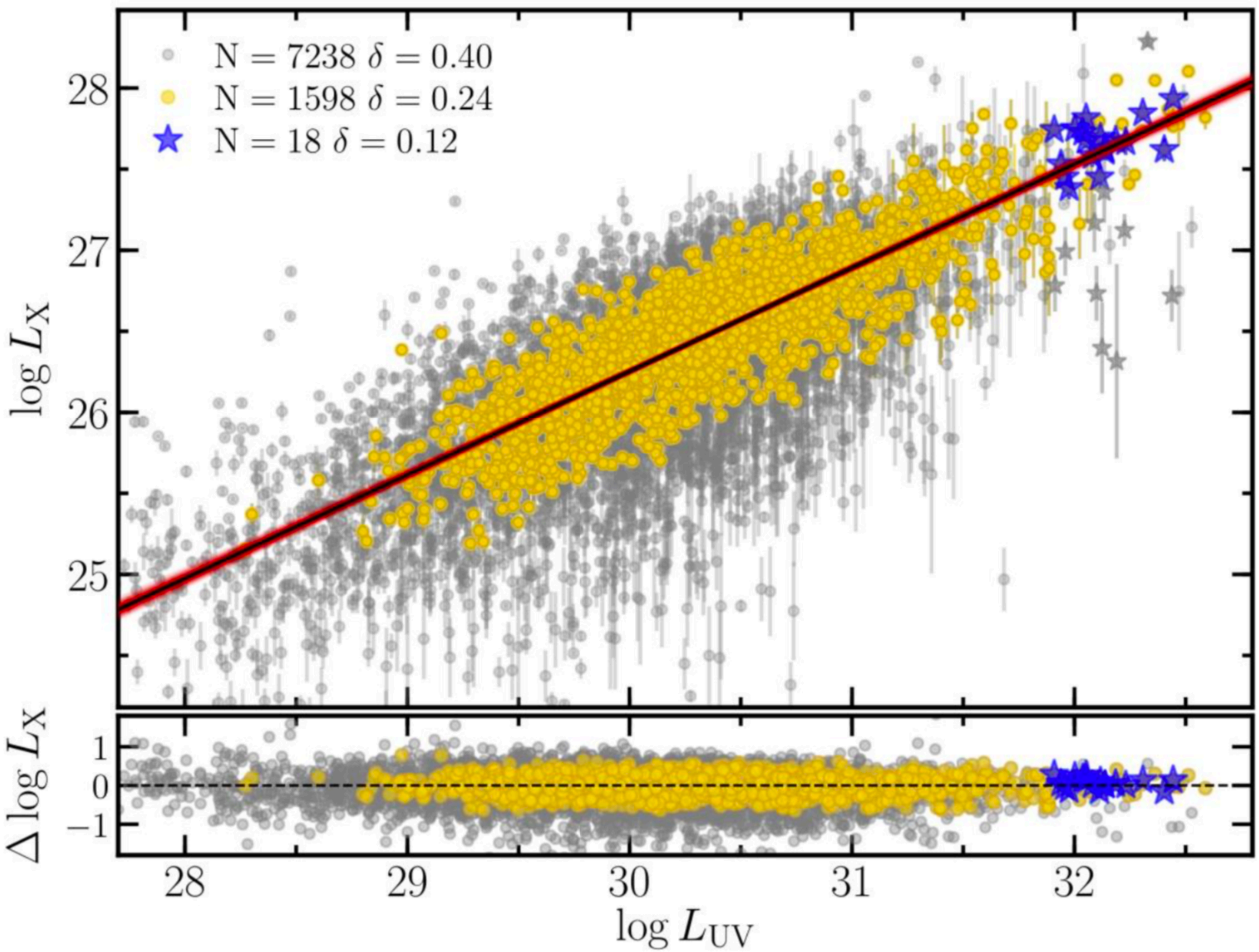
G. Risaliti[1,2*], E. Lusso[3]
[1]Dipartimento di Fisica e Astronomia, Università degli Studi di Firenze, Via. G. Sansone 1, 50019 Sesto Fiorentino (FI), Italy.
[2]INAF- Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5 50125 Firenze, Italy.
[3]Centre for Extragalactic Astronomy, Durham University, South Road, Durham, DH1 3LE, UK.

The *concordance* (ΛCDM) model reproduces the main current cosmological observations[1,2,3,4] assuming the validity of general relativity at all scales and epochs, the presence of cold dark matter, and of a cosmological constant, Λ, equivalent to a *dark energy* with constant density in space and time. However, the ΛCDM model is poorly tested in the redshift interval between the farthest observed Type Ia supernovae[5] and that of the Cosmic Microwave background (CMB). We present new measurements of the expansion rate of the Universe in the range $0.5<z<5.5$ based on a Hubble diagram of quasars. The quasar distances are estimated from their X-ray and ultraviolet emission, following a method developed by our group[6,7,8]. The distance modulus-redshift relation of quasars at $z<1.4$ is in agreement with that of supernovae and with the concordance model. Yet, a deviation from the ΛCDM model emerges at higher redshift, with a statistical significance of ~4σ. If an evolution of the dark energy equation of state is allowed, the data suggest a dark energy density increasing with time.

Non-linear relation between ultraviolet and X–ray luminosity of quasars

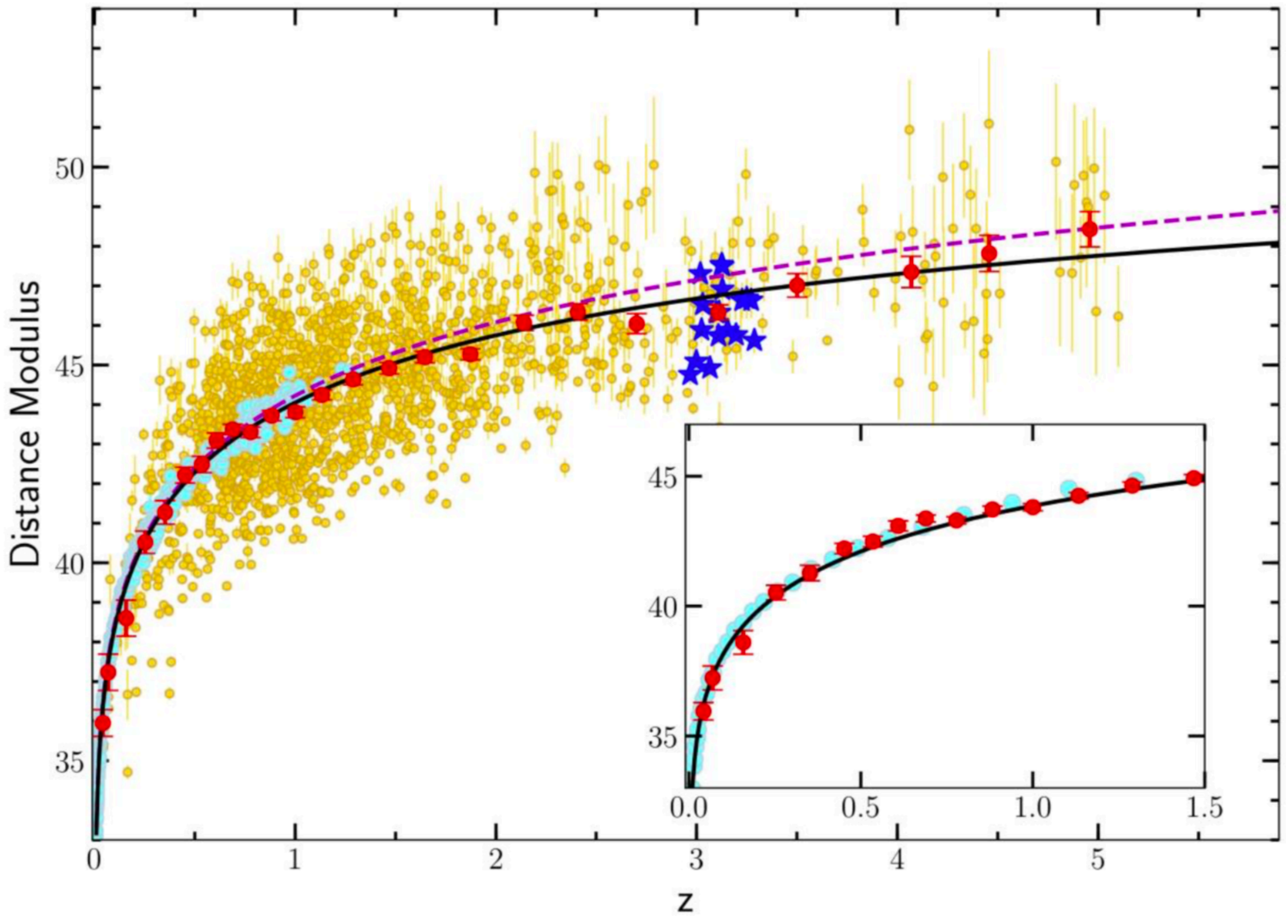
$$\log(L_{\rm X}) = \beta + \gamma \log(L_{\rm UV}).$$

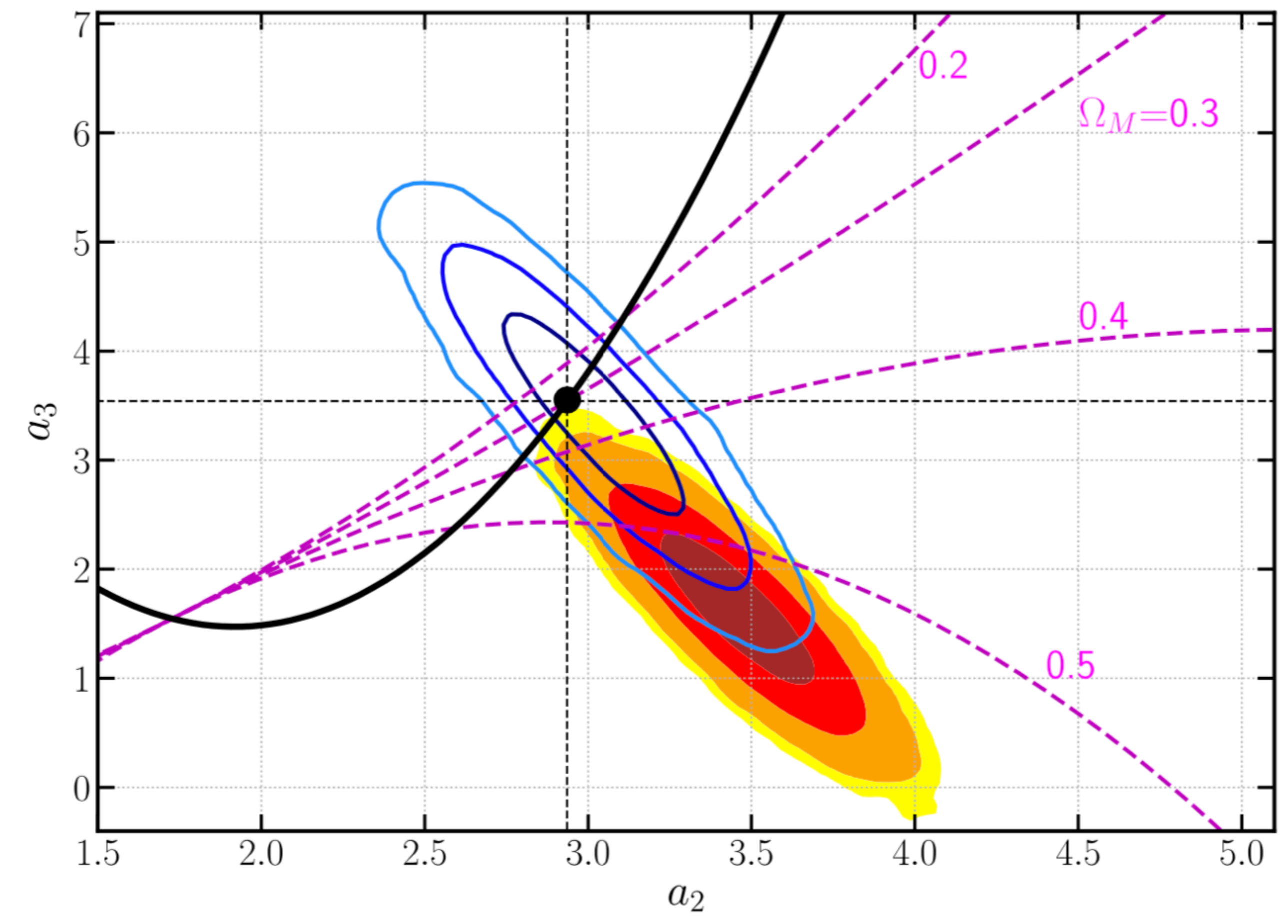
$\beta \sim 9$ and $\gamma \sim 0.6$.



Hubble diagram of quasars

$D_L = \ln(10) c/H_0 \, (x + a_2 x^2 + a_3 x^3)$, $x = \log(1+z)$.





4 sigma tension from high redshift quasar

Astron.Astrophys. 628 (2019) L4

Astronomy & Astrophysics manuscript no. 36223corr
July 25, 2019

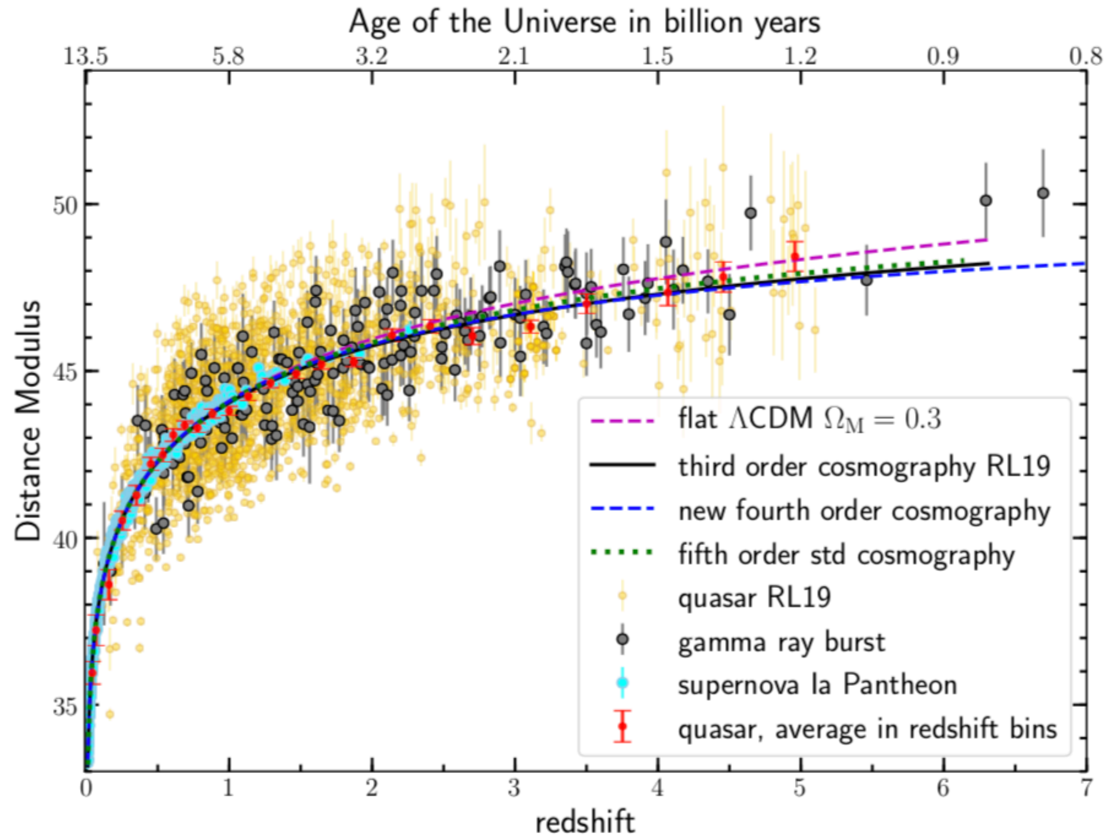
Letter to the Editor

Tension with the flat ΛCDM model from a high-redshift Hubble diagram of supernovae, quasars, and gamma-ray bursts

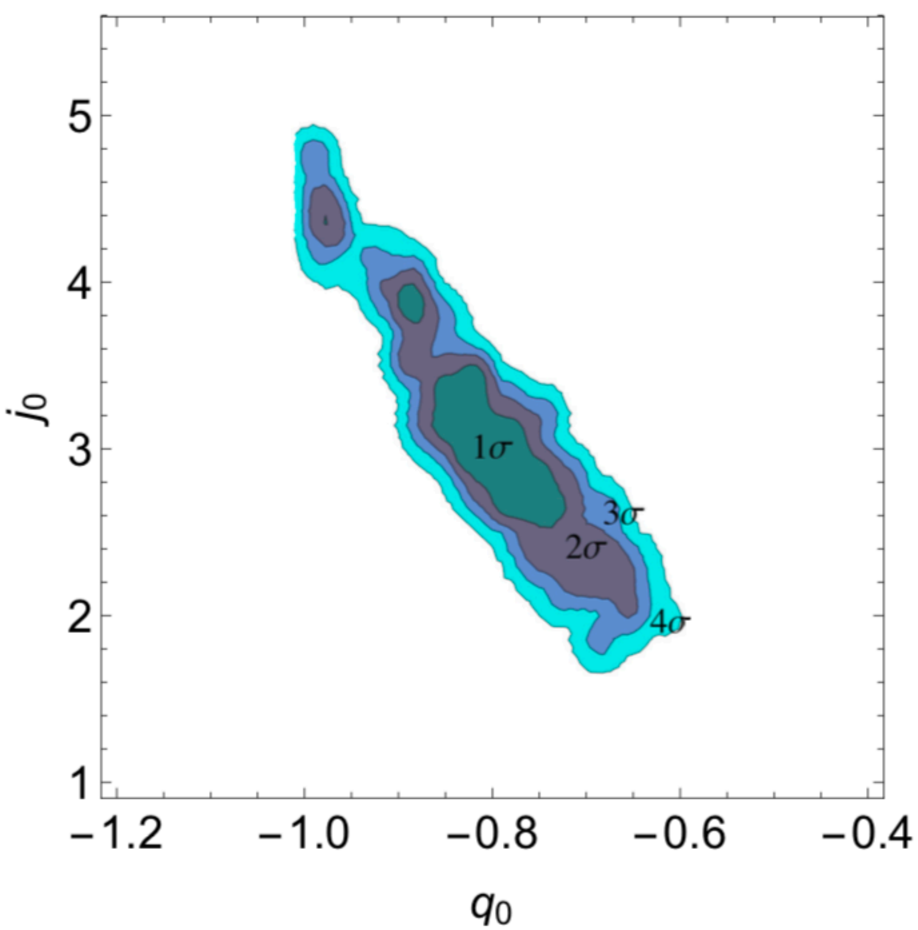
E. Lusso[1,2★], E. Piedipalumbo[3,4], G. Risaliti[1,2], M. Paolillo[3,4,5], S. Bisogni[2], E. Nardini[2] and L. Amati[5].

In the current framework, the standard parametrization of our Universe is the so-called Lambda Cold Dark Matter (ΛCDM) model. Recently, a $\sim 4\,\sigma$ tension with the ΛCDM model was shown to exist via a model-independent parametrization of a Hubble diagram of type Ia supernovae (SNe Ia) from the JLA survey and quasars. Model-independent approaches and independent samples over a wide redshift range are key to testing this tension and any possible systematic errors. Here we present an analysis of a combined Hubble diagram of SNe Ia, quasars, and gamma-ray bursts (GRBs) to check the agreement of the quasar and GRB cosmological parameters at high redshifts ($z > 2$) and to test the *concordance* flat ΛCDM model with improved statistical accuracy. We build a Hubble diagram with SNe Ia, quasars , and GRBs, where quasars are standardised through the observed non-linear relation between their ultraviolet and X-ray emission and GRBs through the correlation between the spectral peak energy and the isotropic-equivalent radiated energy (the so-called *Amati relation*). We fit the data with cosmographic models consisting of a fourth-order logarithmic polynomial and a fifth-order linear polynomial, and compare the results with the expectations from a flat ΛCDM model. We confirm the tension between the best-fit cosmographic parameters and the ΛCDM model at $\sim 4\sigma$ with SNe Ia and quasars, at $\sim 2\sigma$ with SNe Ia and GRBs, and at $> 4\sigma$ with the whole SNe Ia+quasars+GRB data set. The completely independent high-redshift Hubble diagrams of quasars and GRBs are fully consistent with each other, strongly suggesting that the deviation from the standard model is not due to unknown systematic effects but to new physics.

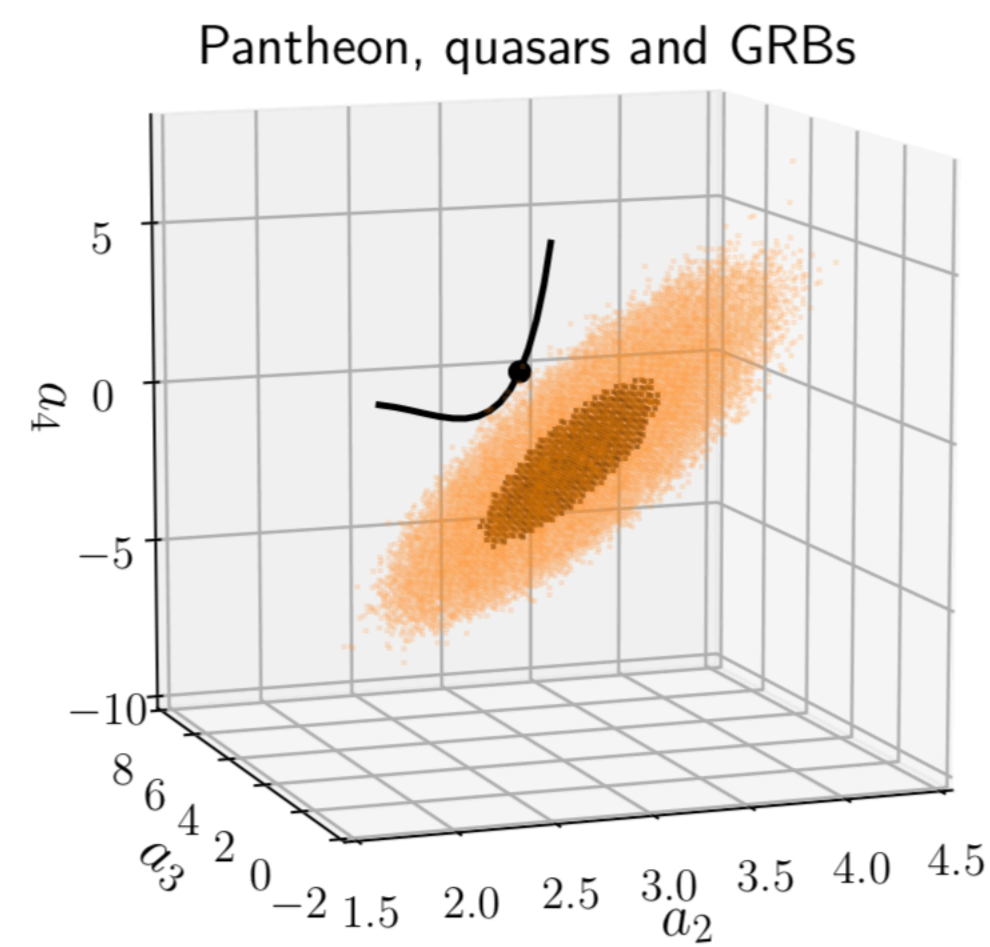
Hubble diagram



Y expansion



Log expansion



4 sigma tension!

1. **Cosmological constraints from the Hubble diagram of quasars at high redshifts**
Guido Risaliti (Florence U.), Elisabeta Lusso (Durham U.). Nov 6, 2018. 6 pp.
Published in **Nat.Astron. 3 (2019) no.3, 272-277**
DOI: 10.1038/s41550-018-0657-z
e-Print: **arXiv:1811.02590 [astro-ph.CO] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; Link to Space.com article
Detailed record - Cited by 27 records

1. **Tension with the flat ΛCDM model from a high-redshift Hubble diagram of supernovae, quasars, and gamma-ray bursts**
E. Lusso, E. Piedipalumbo, G. Risaliti, M. Paolillo, S. Bisogni, E. Nardini, L. Amati. Jul 17, 2019. 5 pp.
Published in **Astron.Astrophys. 628 (2019) L4**
DOI: 10.1051/0004-6361/201936223
e-Print: **arXiv:1907.07692 [astro-ph.CO] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 12 records

Is this tension real?

Mon.Not.Roy.Astron.Soc. 489 (2019) 517-523

Cosmological test using the Hubble diagram of high-z quasars

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E-mail: fmelia@email.arizona.edu

$$\ln(LF) = -\sum_{i=1}^{1598}\left\{\frac{[\log_{10}(F_X)_i - \Phi([F_{UV}]_i, d_L[z_i])]^2}{\tilde{\sigma_i}^2} + \ln\left(\tilde{\sigma_i}^2\right)\right\},$$

Model	$\tilde{\beta}$	γ	δ	Ω_m	a_2	a_3	χ^2_{dof}	BIC	Likelihood
$R_h = ct$	6.618 ± 0.011	0.640 ± 0.0004	0.231 ± 0.0003	—	—	—	1.005	1,625.86	88.70%
ΛCDM	6.618 ± 0.012	0.639 ± 0.0005	0.231 ± 0.0004	0.31 ± 0.05	—	—	1.004	1,630.26	9.79%
Cosmographic	6.249 ± 0.02	0.626 ± 0.0006	0.231 ± 0.001	—	2.93 ± 0.33	2.65 ± 0.80	1.003	1,633.96	1.51%

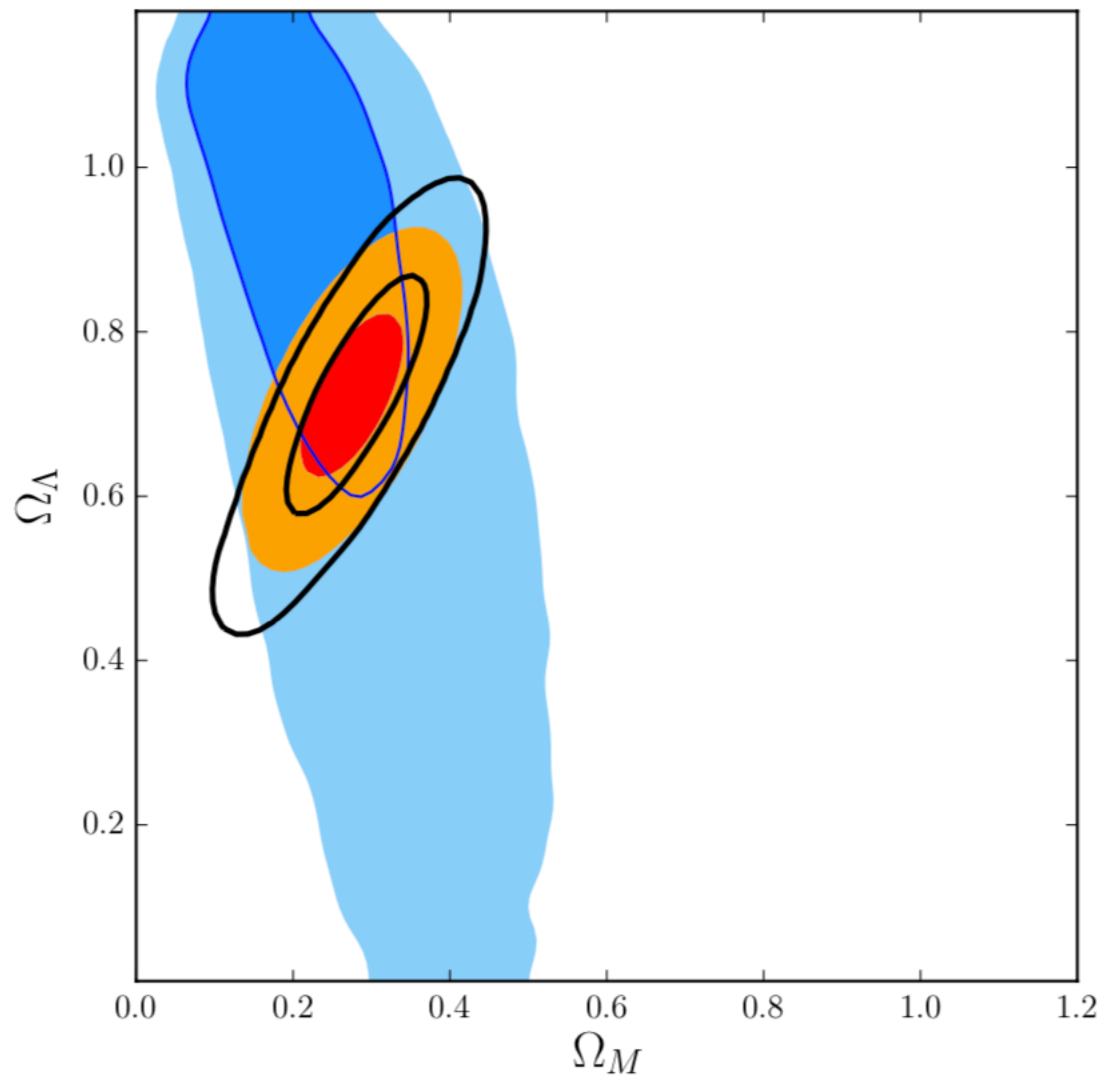
No tension!

Astrophys.J. 815 (2015) 33

A HUBBLE DIAGRAM FOR QUASARS

G. Risaliti[1] and E. Lusso[1]

$$\ln(LF) = -\sum_{i=1}^{N}\left\{\frac{[\log(F_{\rm X})_i - \Phi(F_{UV}, D_L)_i]^2}{s_i^2} + \ln(s_i^2)\right\}$$



No tension!

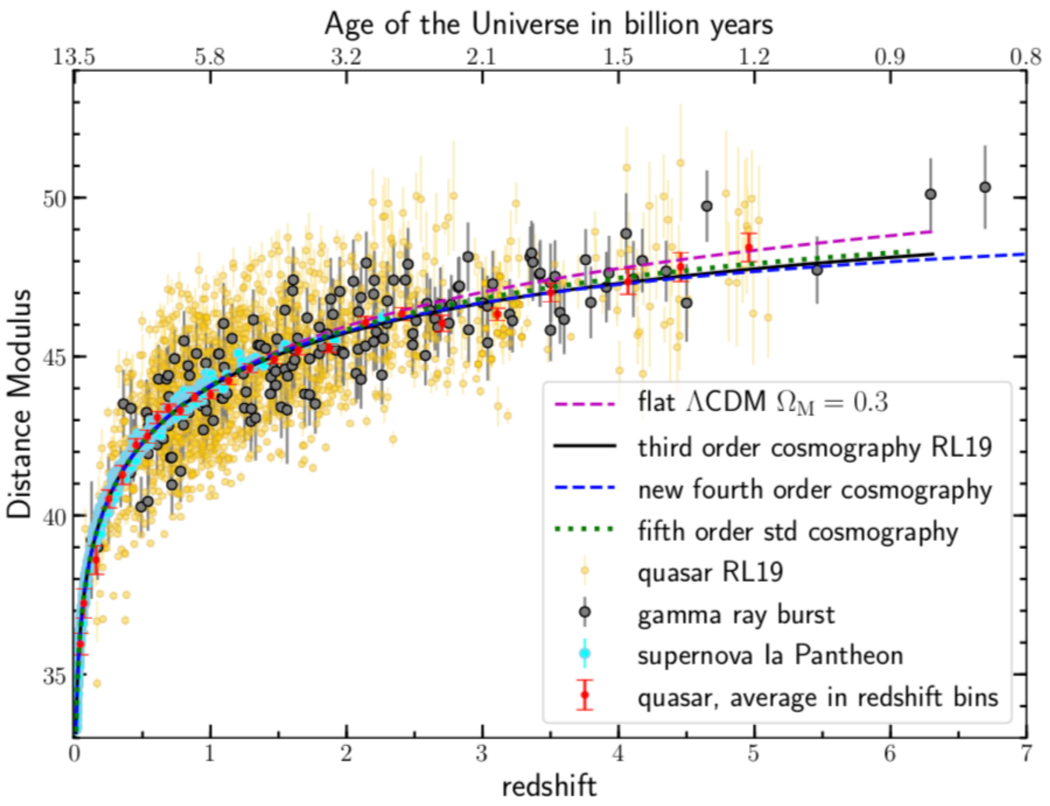
arXiv:1911.01681

On cosmography and flat ΛCDM tensions at high redshift

Tao Yang[1], Aritra Banerjee[1] & Eoin Ó Colgáin[1,2]

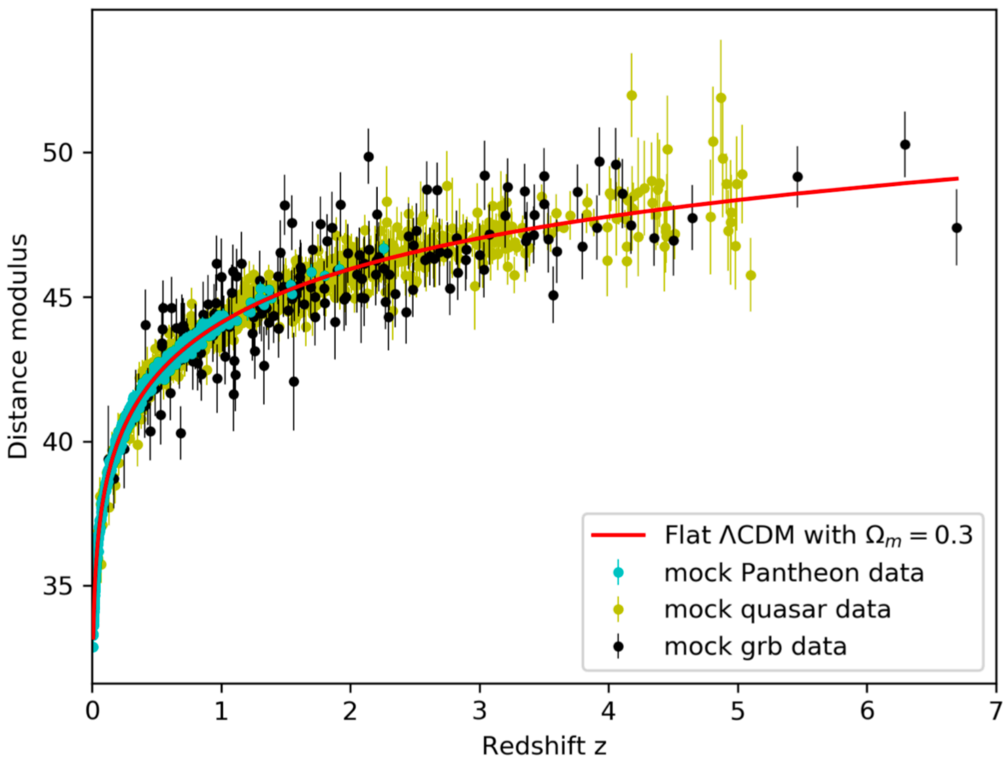
$$d_L(z) = \frac{c\ln(10)}{H_0}\Big[\log_{10}(1+z) + a_2\log_{10}^2(1+z) + a_3\log_{10}^3(1+z) + a_4\log_{10}^4(1+z) + \dots\Big],$$

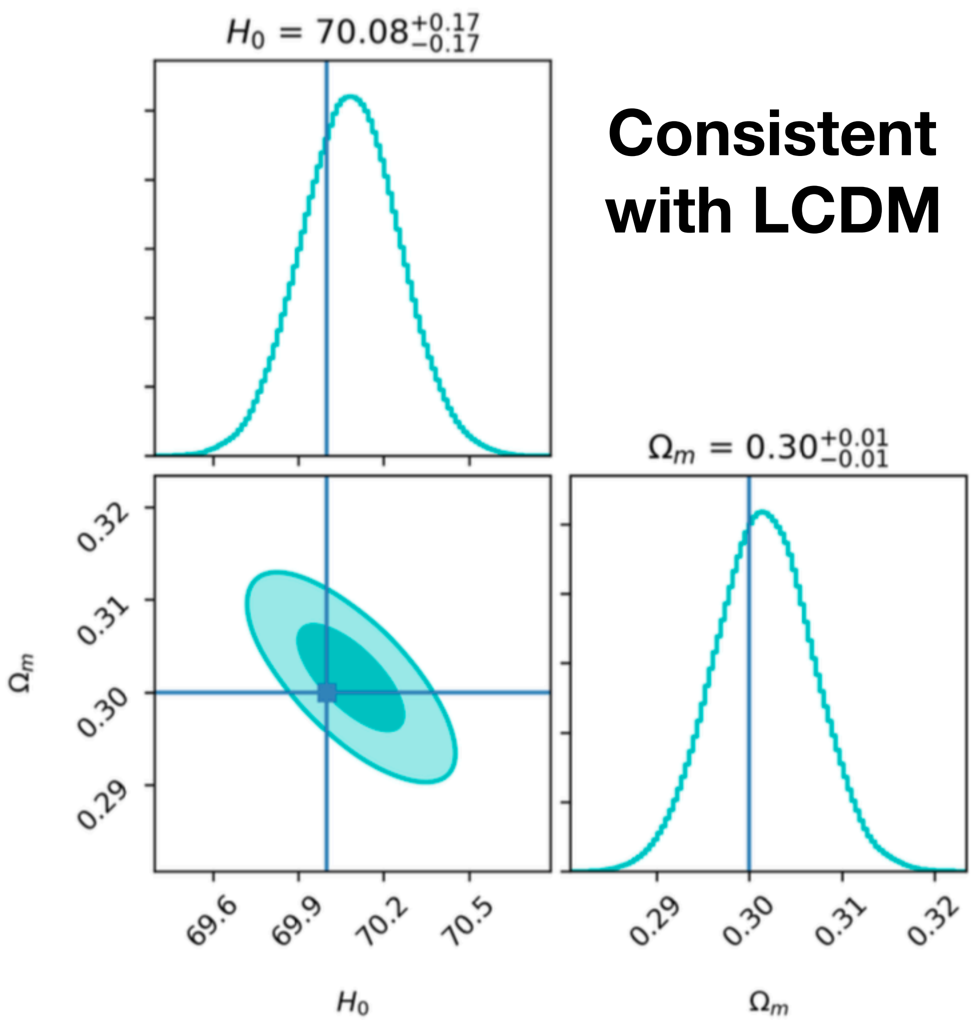
Is cosmography a reliable tool?



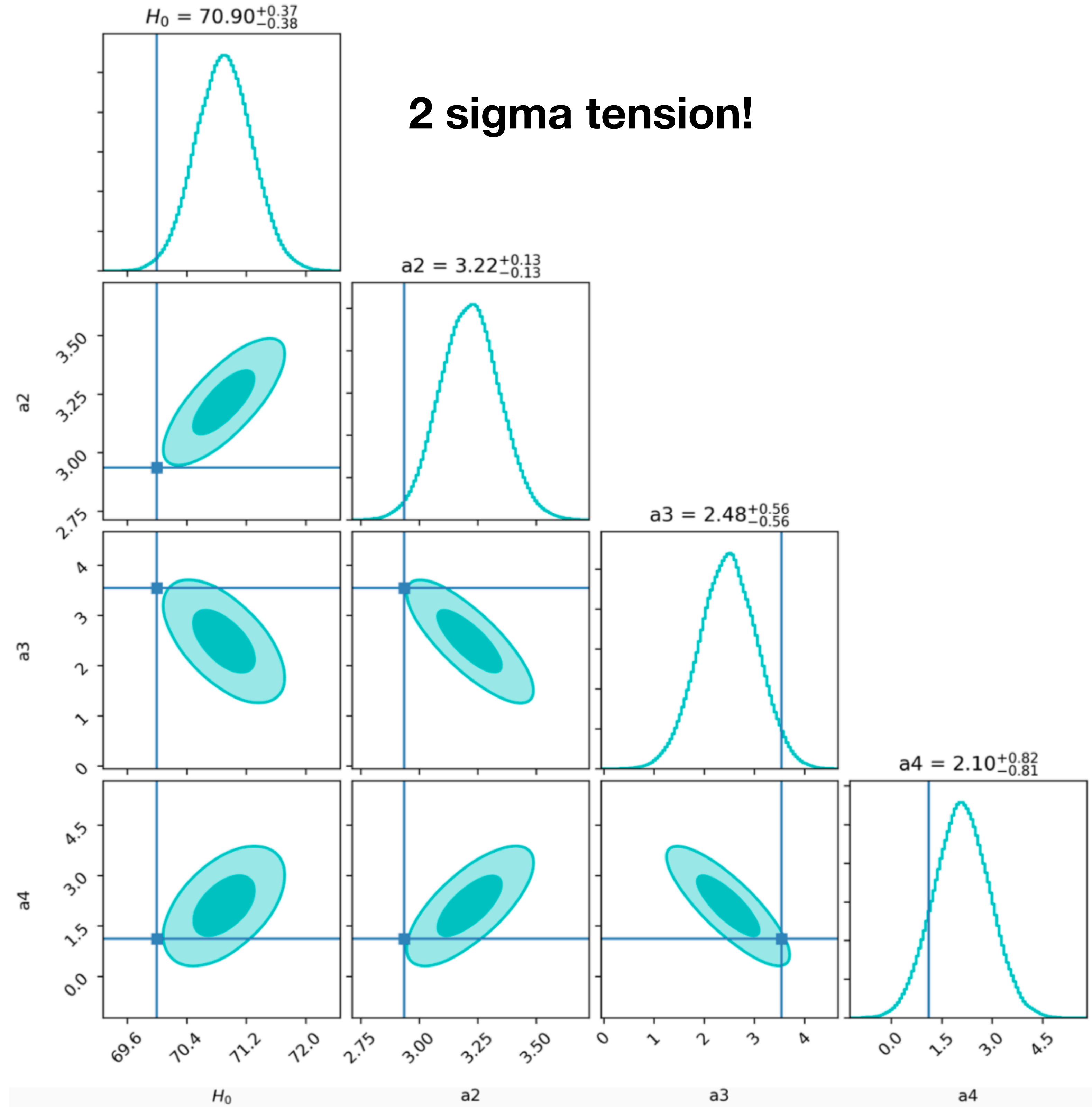
Is the quasar a reasonable data set?

Test log cosmography with the mock data sets



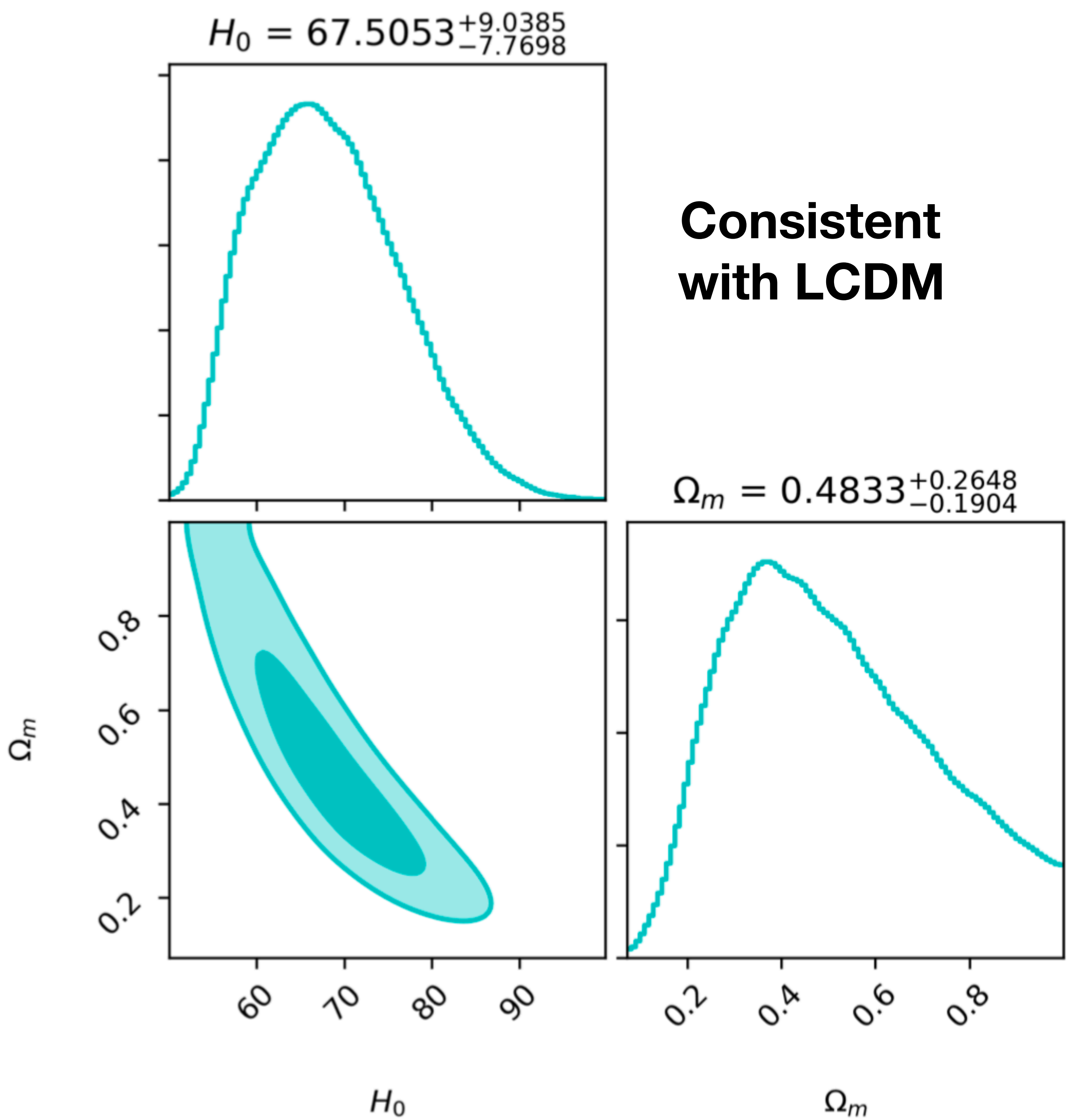


Consistent with LCDM



2 sigma tension!

Test Y expansion with real GRB data



Consistent with LCDM

$$d_L(y) = \frac{c}{H_0}\left(y + C_1 y^2 + C_2 y^3 + C_3 y^4 + C_4 y^5\right),$$

$$C_1 = \frac{1}{2}(3 - q_0), \quad C_2 = \frac{1}{6}\left(11 - 5q_0 + 3q_0^2 - j_0\right).$$

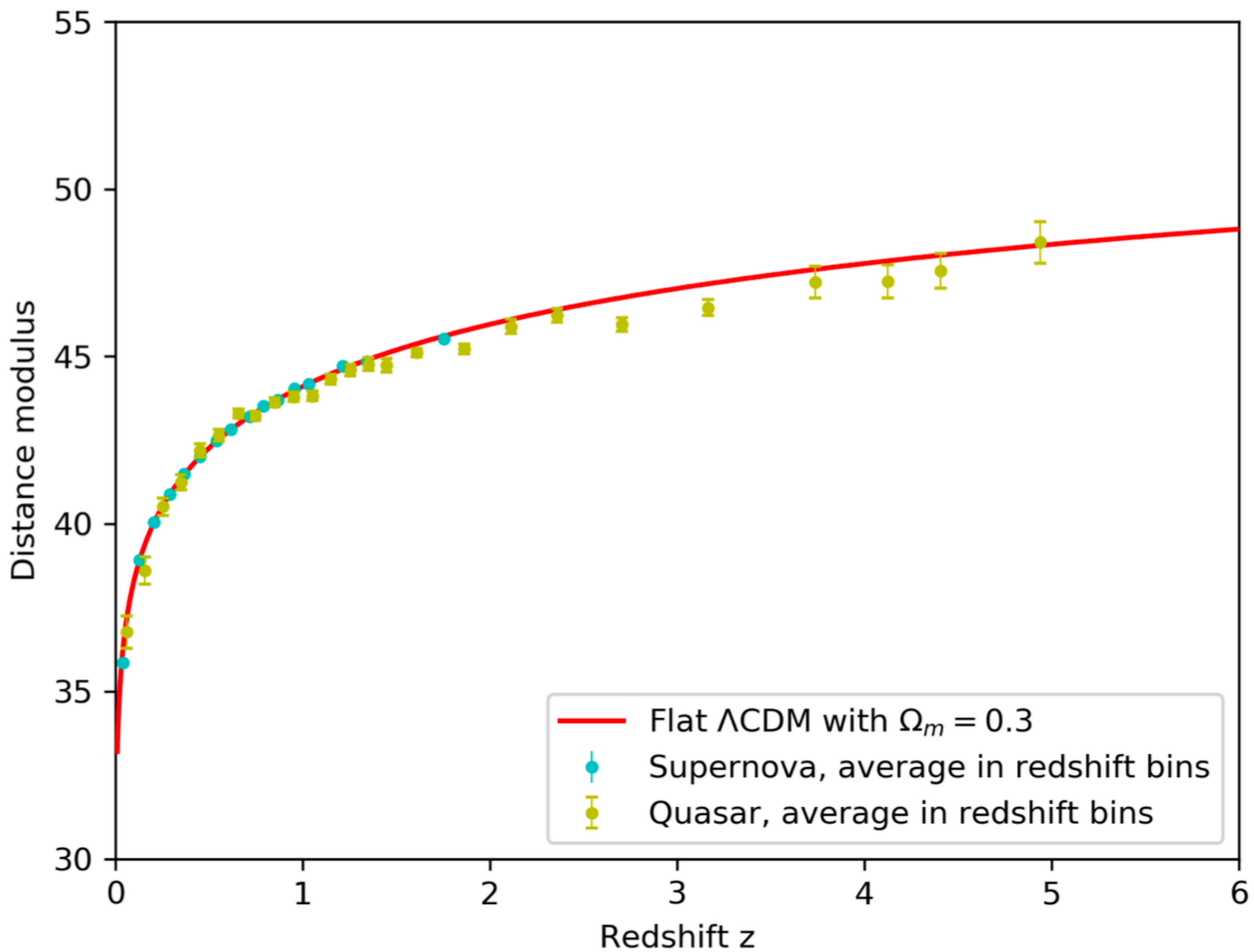
LCDM value $C_1 = 1.775, \quad C_2 = 2.27652.$

H_0	C_1	C_2	C_3	C_4
$51.2^{+26.4}_{-26.4}$	$-9.0^{+5.3}_{-5.3}$	$72.2^{+28.6}_{-28.6}$	$-160.5^{+64.6}_{-64.6}$	$121.3^{+50.0}_{-50.0}$

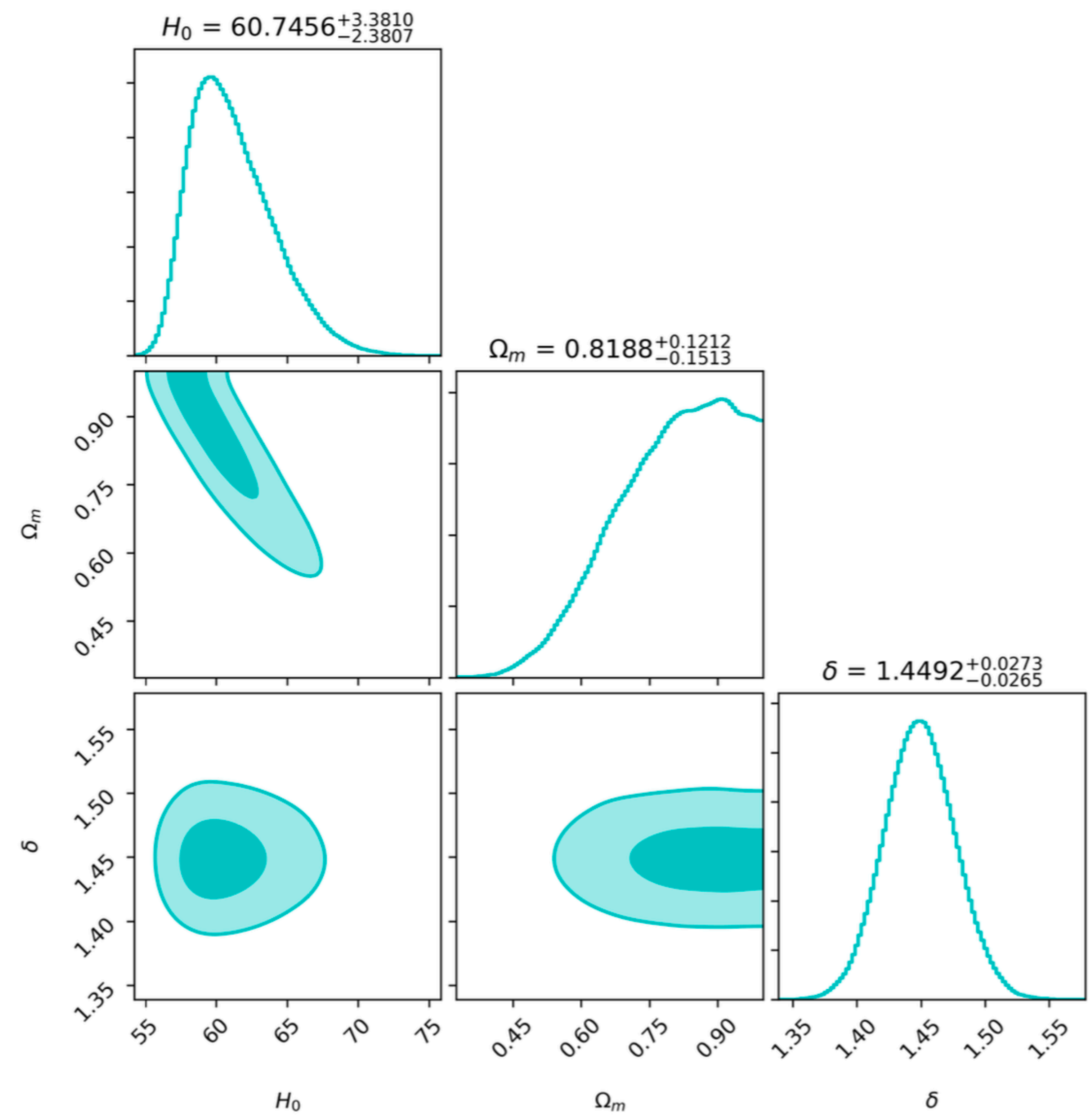
2 sigma tension!

Is quasar data reasonable?

Bin data of quasar



3.5 sigma tension from Om=0.3
1.5 sigma tension from Om=1



arXiv:1911.11848

Is the Hubble diagram of quasars in tension with concordance cosmology?

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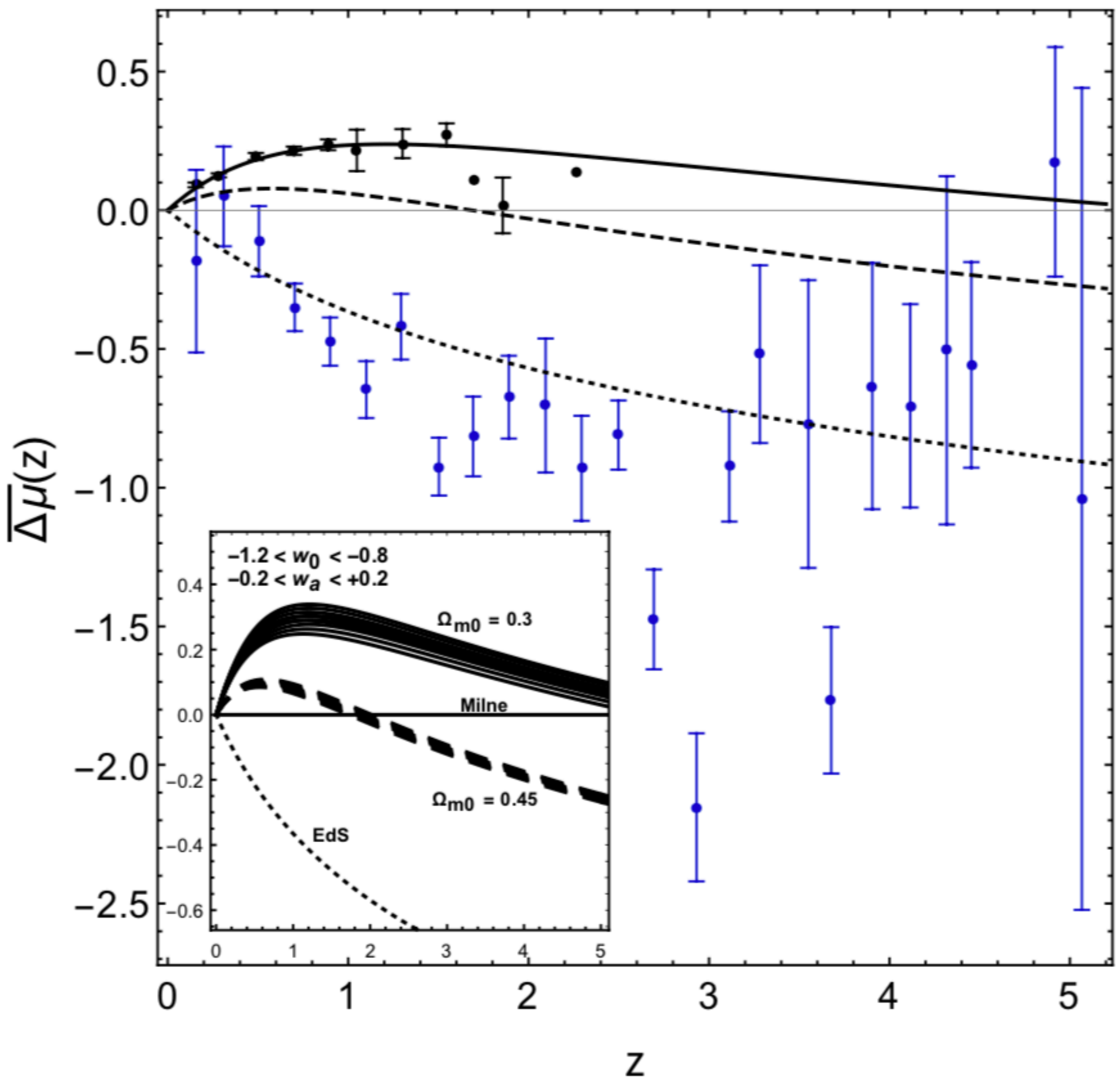
(Dated: November 28, 2019)

$$\Delta\mu_{obs}(z_i) = \mu_{obs}(z_i) - \mu(q=0)$$



Summary of the quasar story

- Though cosmography is a model-independent technology, it is not a reliable tool for cosmology especially in high redshift region

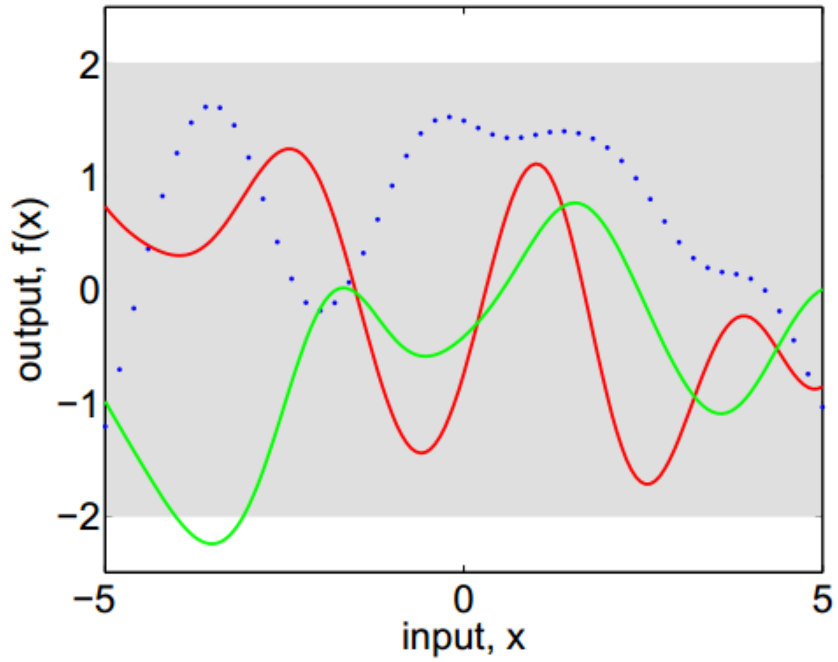
- Quasars are powerful cosmology "candles", but the calibration should be treated carefully.

- Other model-independent numerical methods should developed to analyze these high redshift data (QSO, GRB, GW StS, etc.)

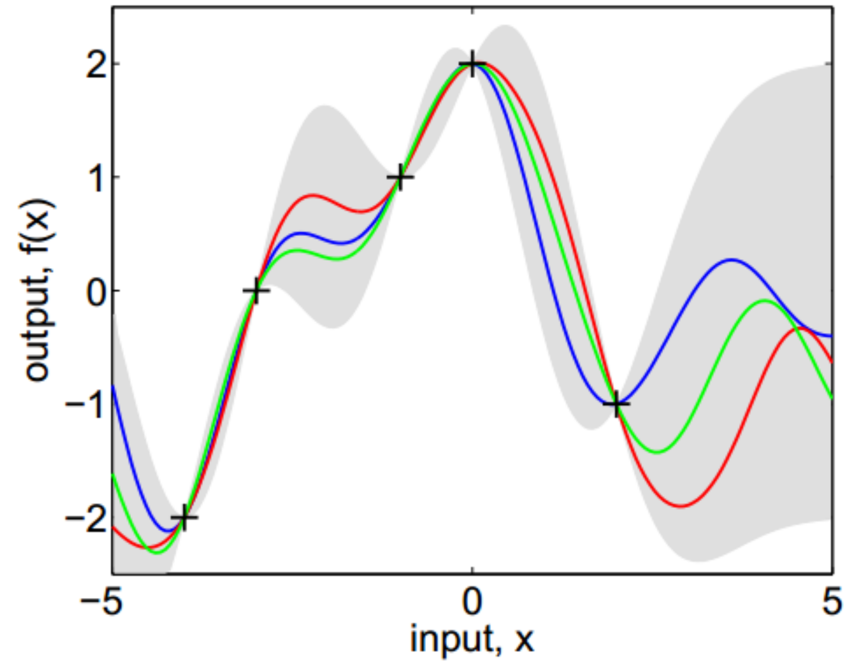
You can try Gaussian process

Gaussian process

A regression method in supervised machine learning



(a), prior



(b), posterior

$$\begin{aligned} \mu(x) &= \mathbb{E}[f(x)]\,, \\ k(x,\tilde{x}) &= \mathbb{E}[(f(x)-\mu(x))(f(\tilde{x})-\mu(\tilde{x}))]\,, \\ \mathrm{Var}(x) &= k(x,x)\,. \end{aligned}$$

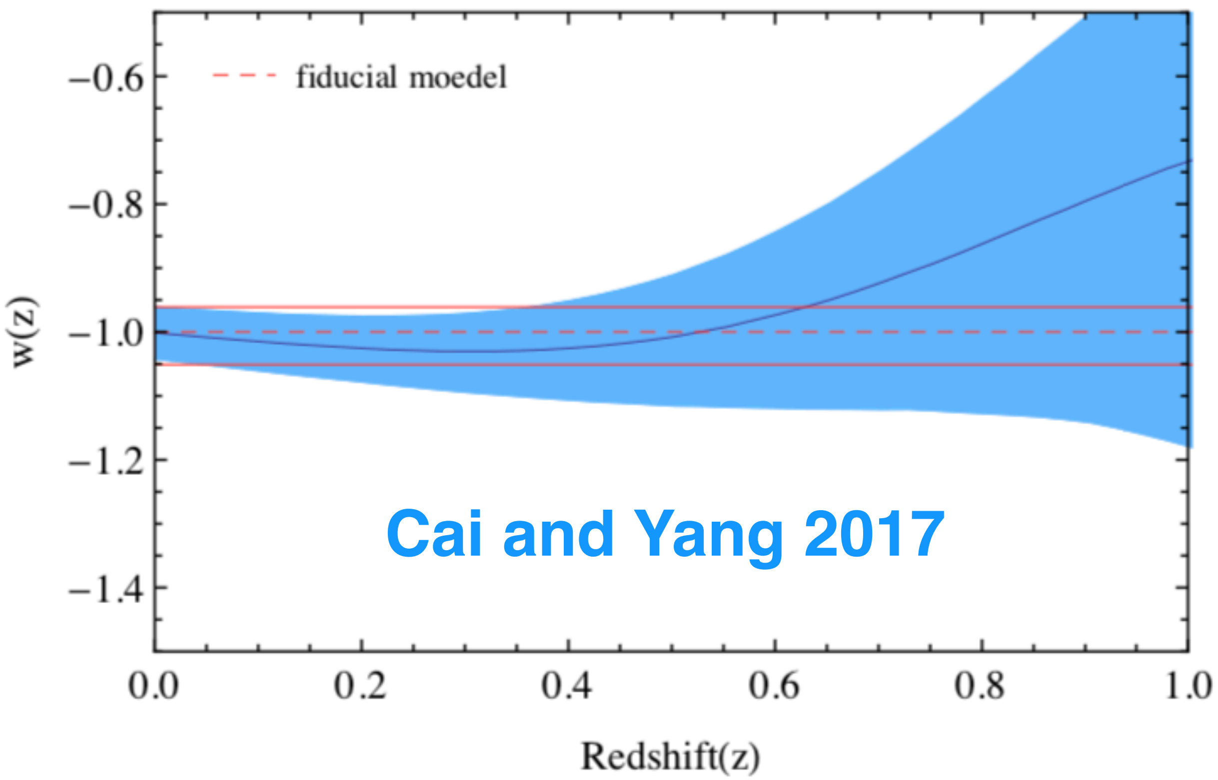
$$f(x) \sim \mathcal{GP}\left(\mu(x), k(x,\tilde{x})\right)\ .$$

$$k(x,\tilde{x}) = \sigma_f^2 \exp\left(-\frac{(x-\tilde{x})^2}{2\ell^2}\right)$$

Kernel function trained from data

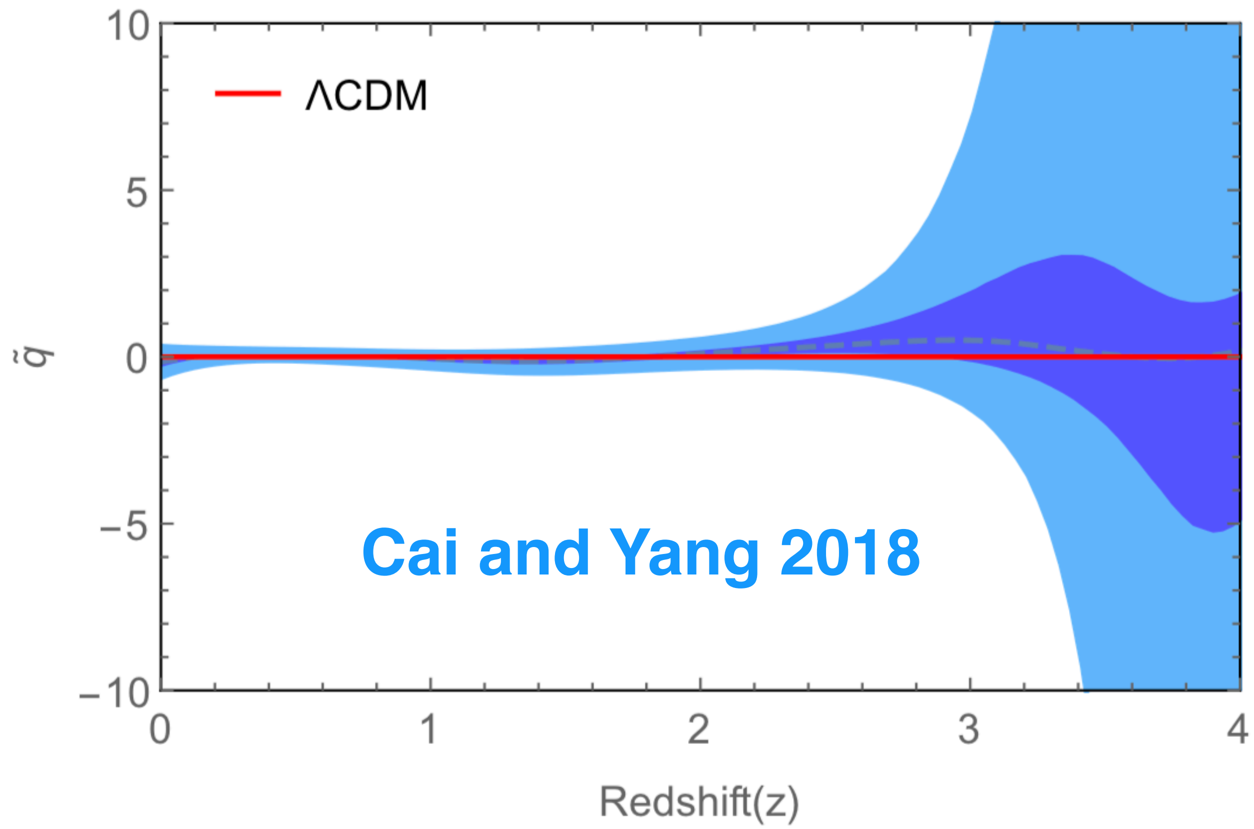
Applications in gravitational wave cosmology

Simulation of ET to reconstruct w

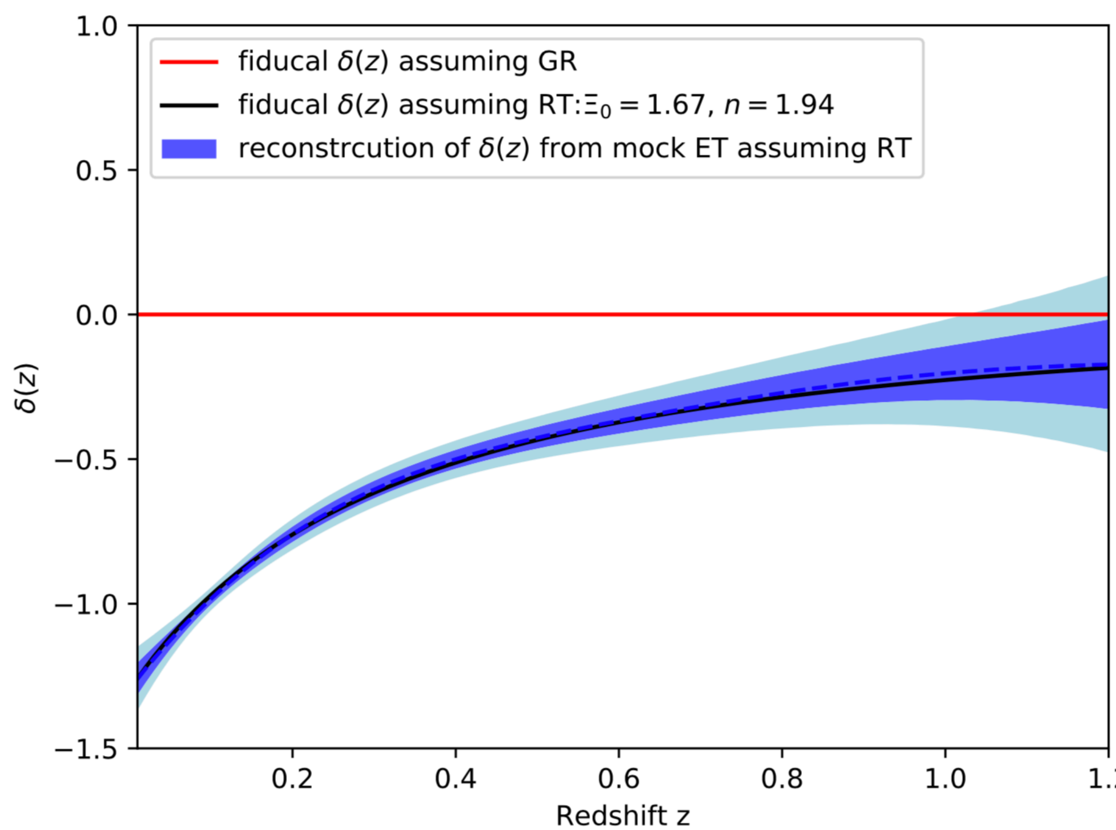


(a) 700 events

Simulation of LISA to reconstruct interaction of dark sector



Test modified gravity theory



Collaboration with Maggiore et.al., 2019

Thanks for your attention!