The Hubble parameter and quasars as standard(isable) candles

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Dipartimento di Fisica e Astronomia

INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

What H_0 tells us

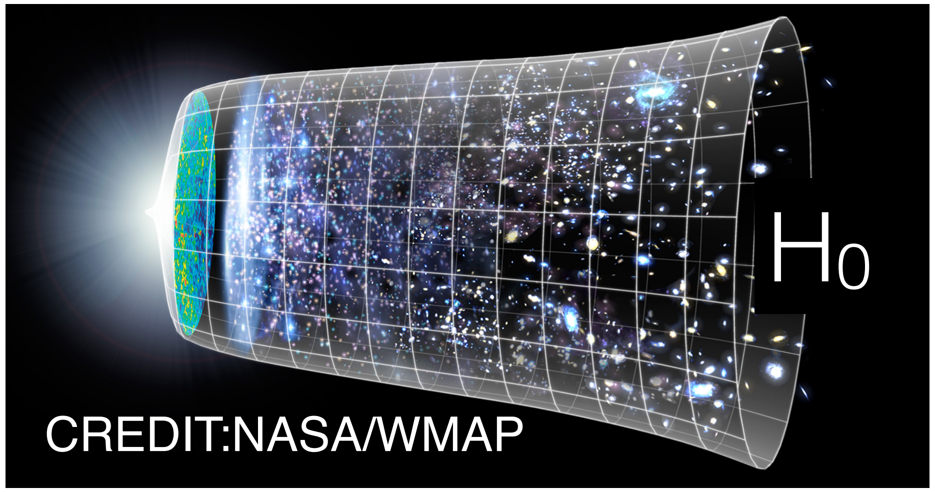
H_0 : normalisation of the Hubble parameter $H(z)$ that describes the current expansion rate of the Universe

1970: Allan Sandage described cosmology as the search for two numbers:

1. the current rate of expansion (H_0)
2. the deceleration/acceleration of the expansion (q_0)

q_0 is directly connected to the energy content of the Universe: discovery that $q_0 < 0$, i.e., expansion rate is increasing with time (Riess+98; Perlmutter+99).

H_0 inv. prop. to distances and age of the Universe: recently also important for measuring the energy content of the Universe (WMAP, Planck collaboration).



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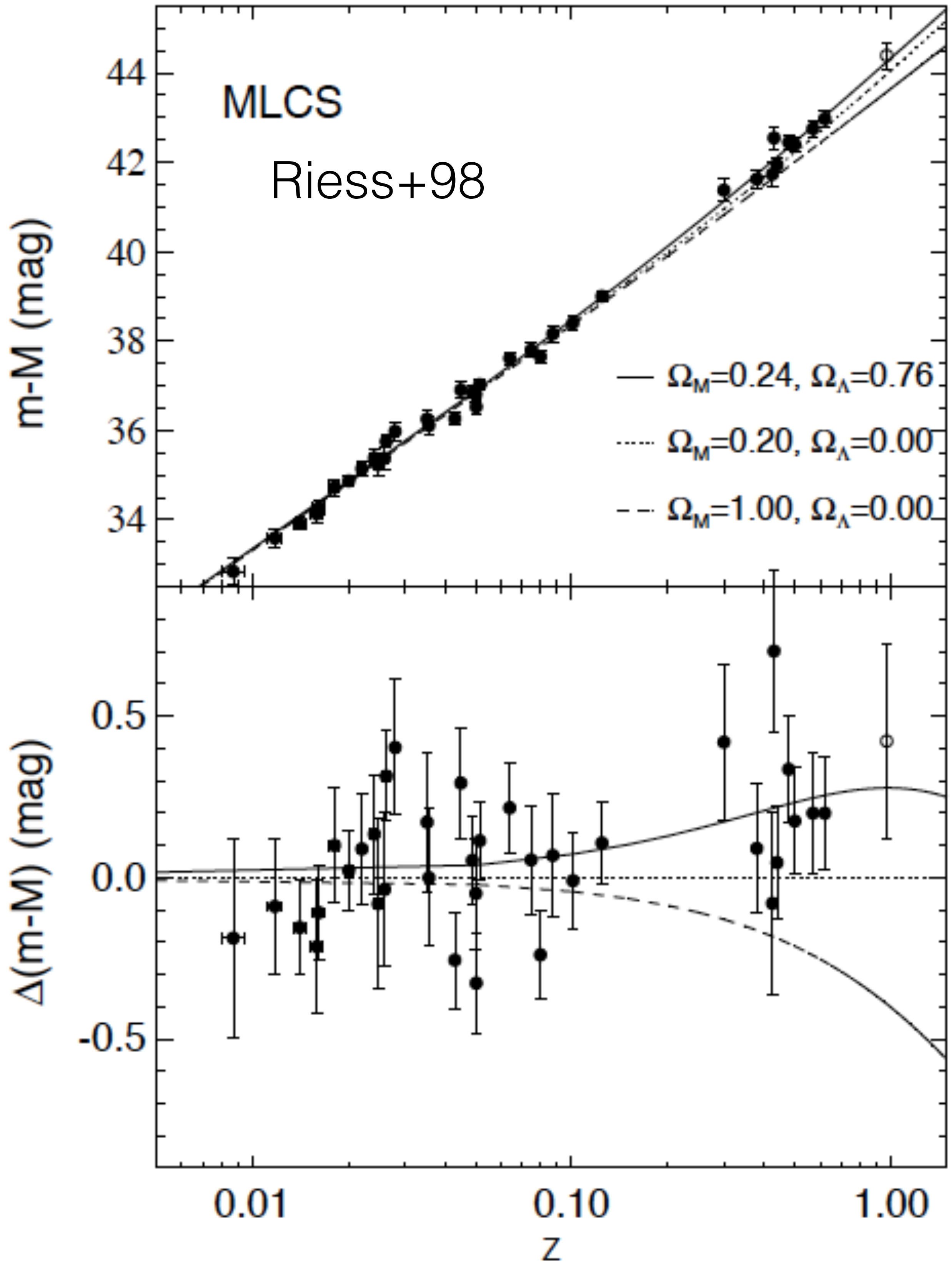

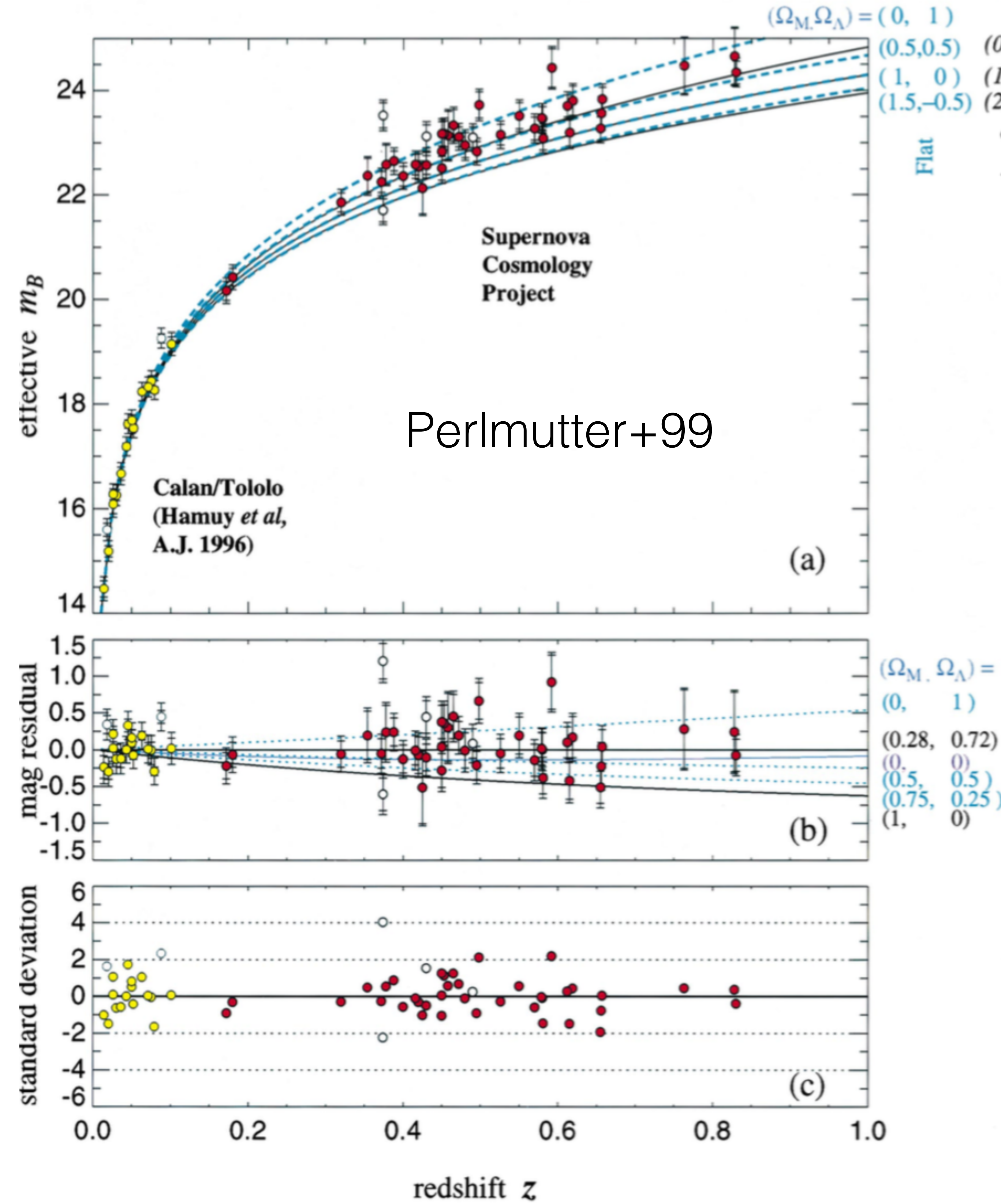

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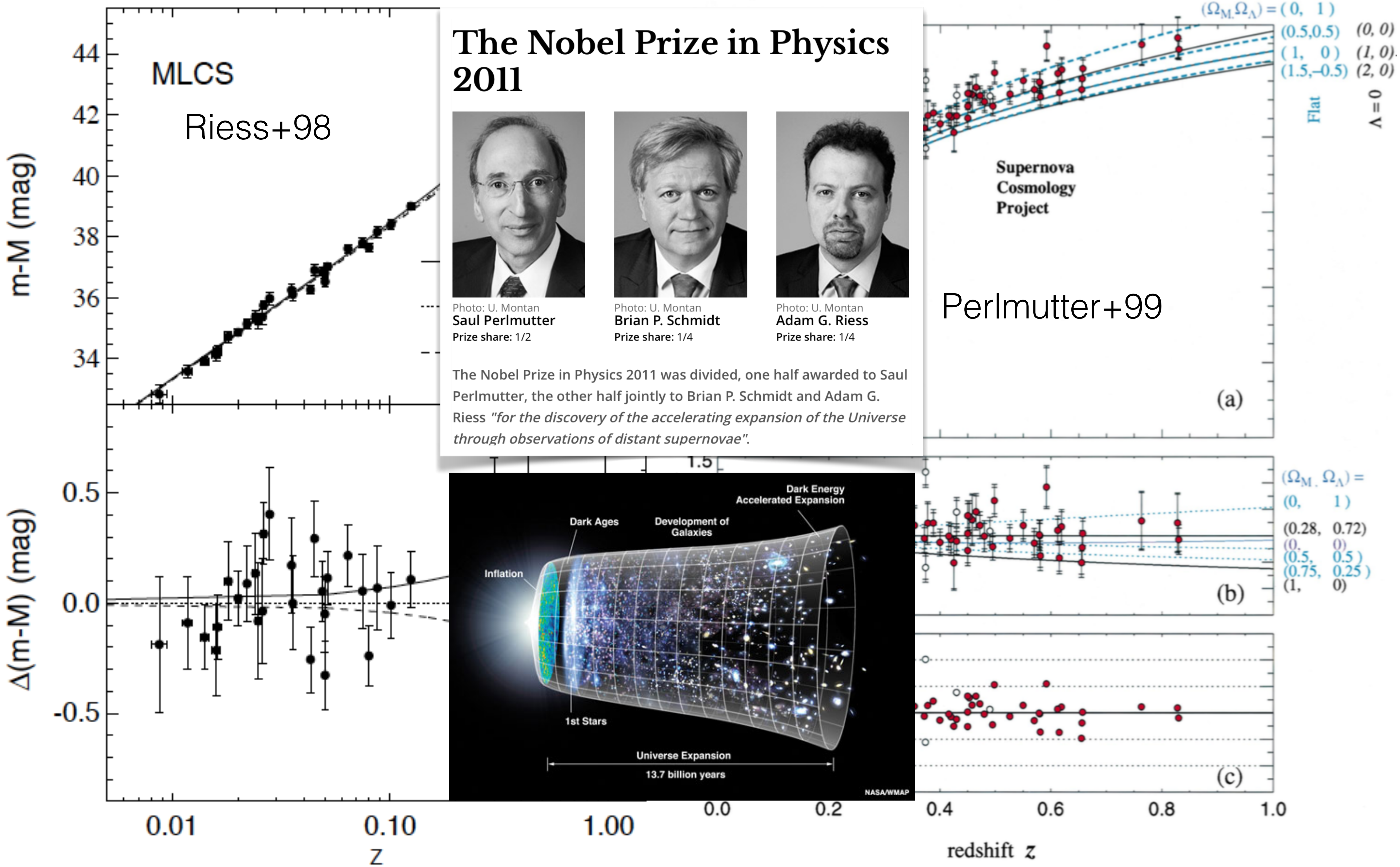
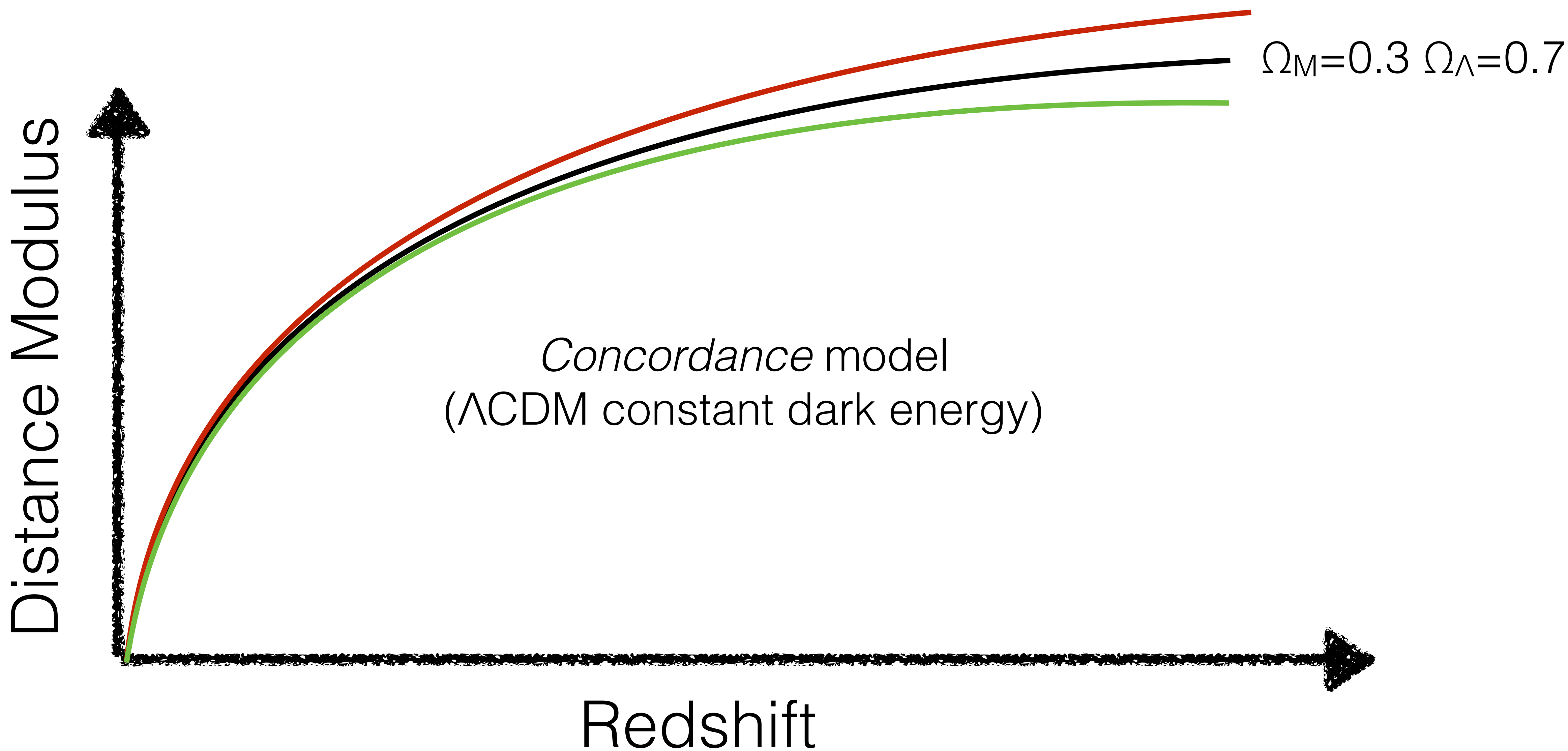


HUBBLE DIAGRAM: THE FATE OF THE UNIVERSE



Ω_M=dark matter

Ω_Λ=dark energy

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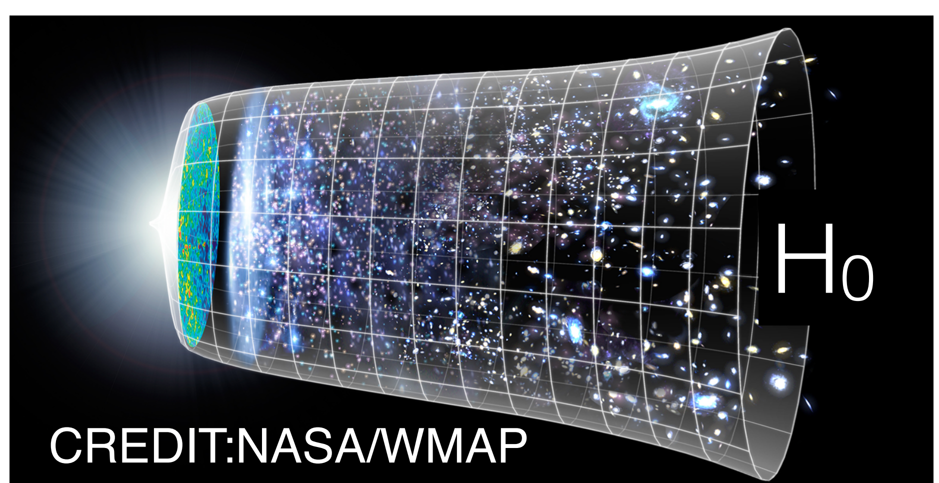


The schism between early & late Universe

Shah, Lemos and Lahav (2021, arXiv2109.01161)

H_0 can be measured

Locally: parallax, Type Ia supernovae, cosmic clocks, quasar strong lensing, GW

Riess et al. (2021)
H_0=73.2±1.3 km s^{-1} Mpc^{-1}

↔

z~1100: angle subtended by the sound horizon as observed in CMB temperature fluctuations

Planck et al. (2018)
H_0=67.4±0.5 km s^{-1} Mpc^{-1}

4σ tension

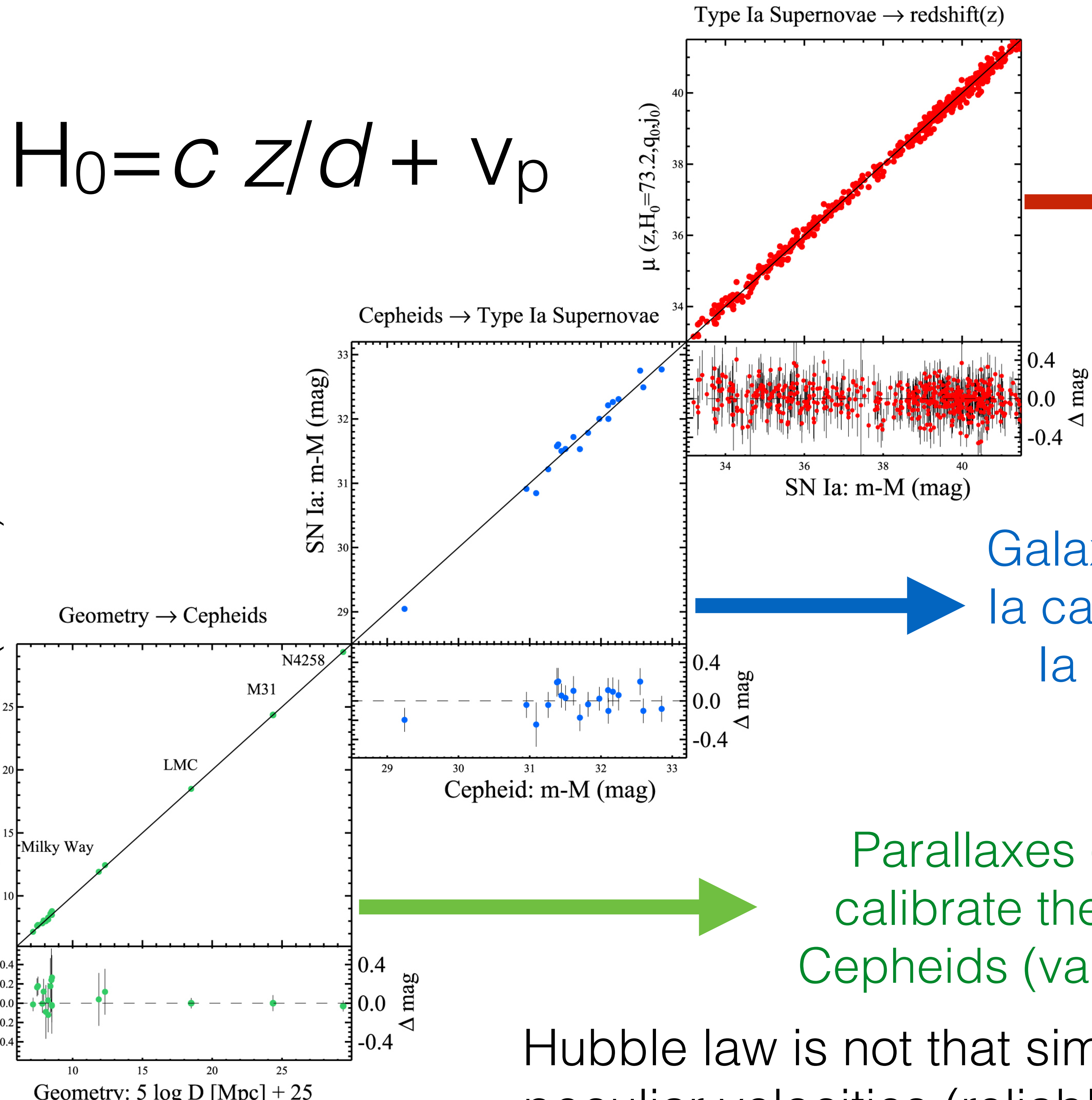
Significant enough to warrant new physics?

estimates of H_0 at the 1% level and from cosmological tools at different redshifts are needed to decisively answer this question! The race has started…

Measure H_0 locally: build the distance ladder

$$H_0 = c\, z/d + v_p$$

(SH0ES) Riess et al. 2016



Redshifts of SN Ia + intrinsic and observed magnitudes (distance modulus): H_0

Galaxies with both Cepheids and SN Ia calibrate intrinsic brightness of SN Ia (19 sources, Riess et al 2016)

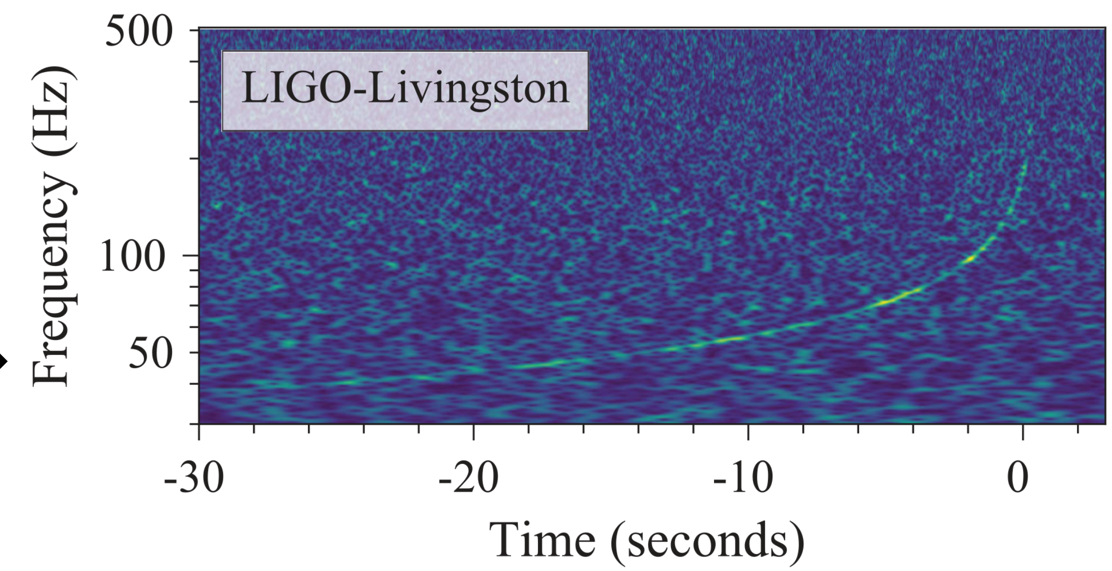
Parallaxes (geometric distances) calibrate the intrinsic brightness of Cepheids (variable stars, P-L relation)

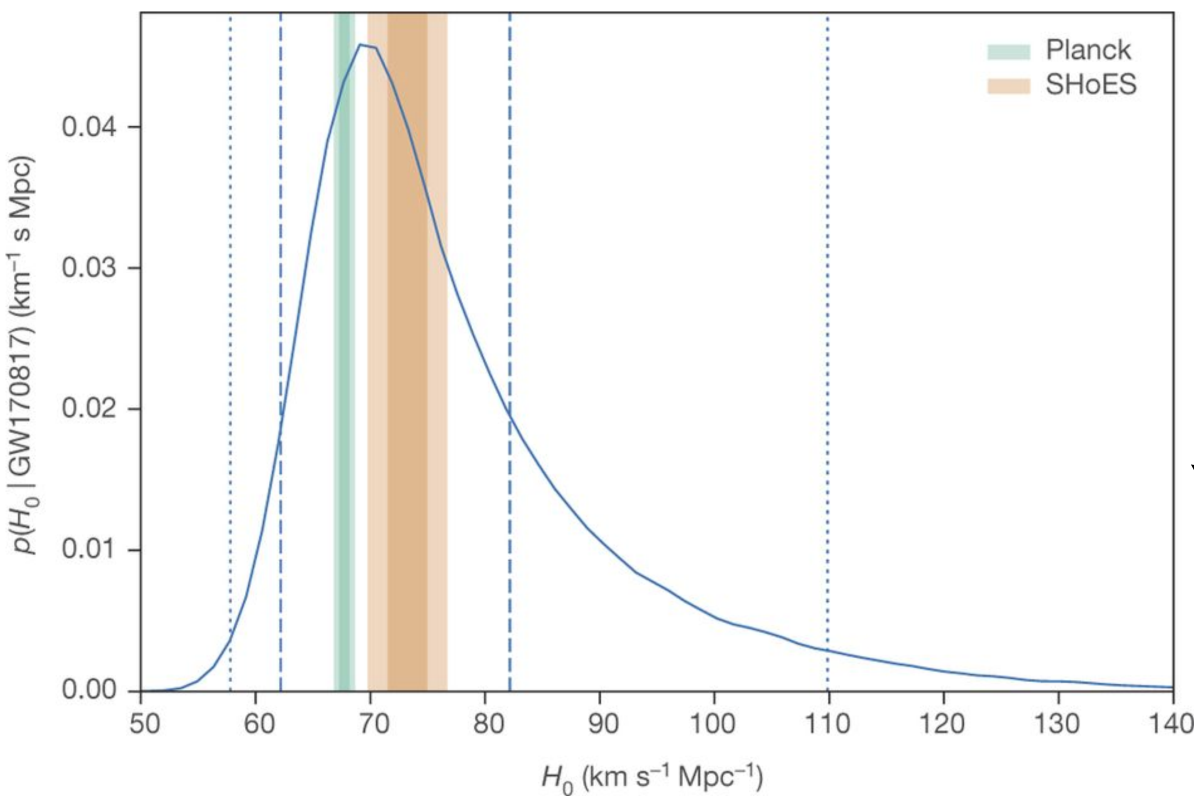
Hubble law is not that simple:
peculiar velocities (reliable z only at high distances)
measure distances only nearby (parallax)

Measure H_0 locally: neutron star binary merger

$$H_0 = c\, z/d$$

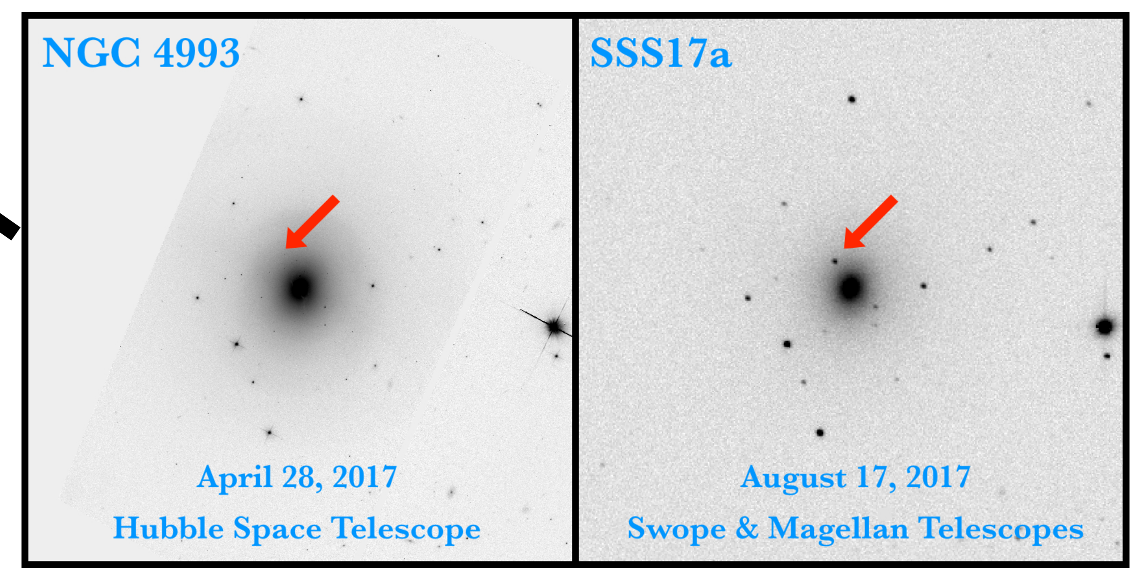
Measure distance from gravitational wave





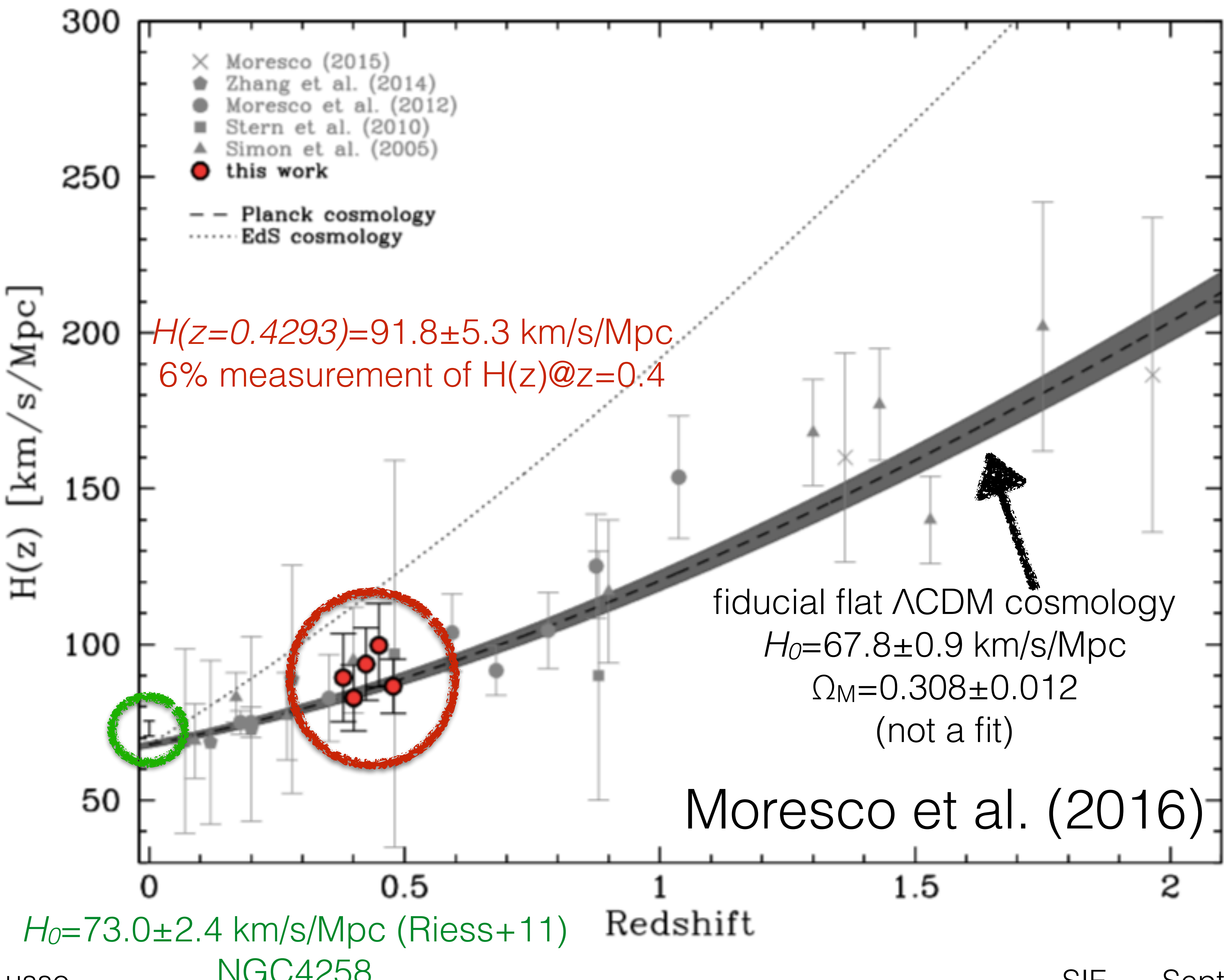
Abbott et al. 2017, Nat.,551-85A

Measure redshift of the e.m. counterpart



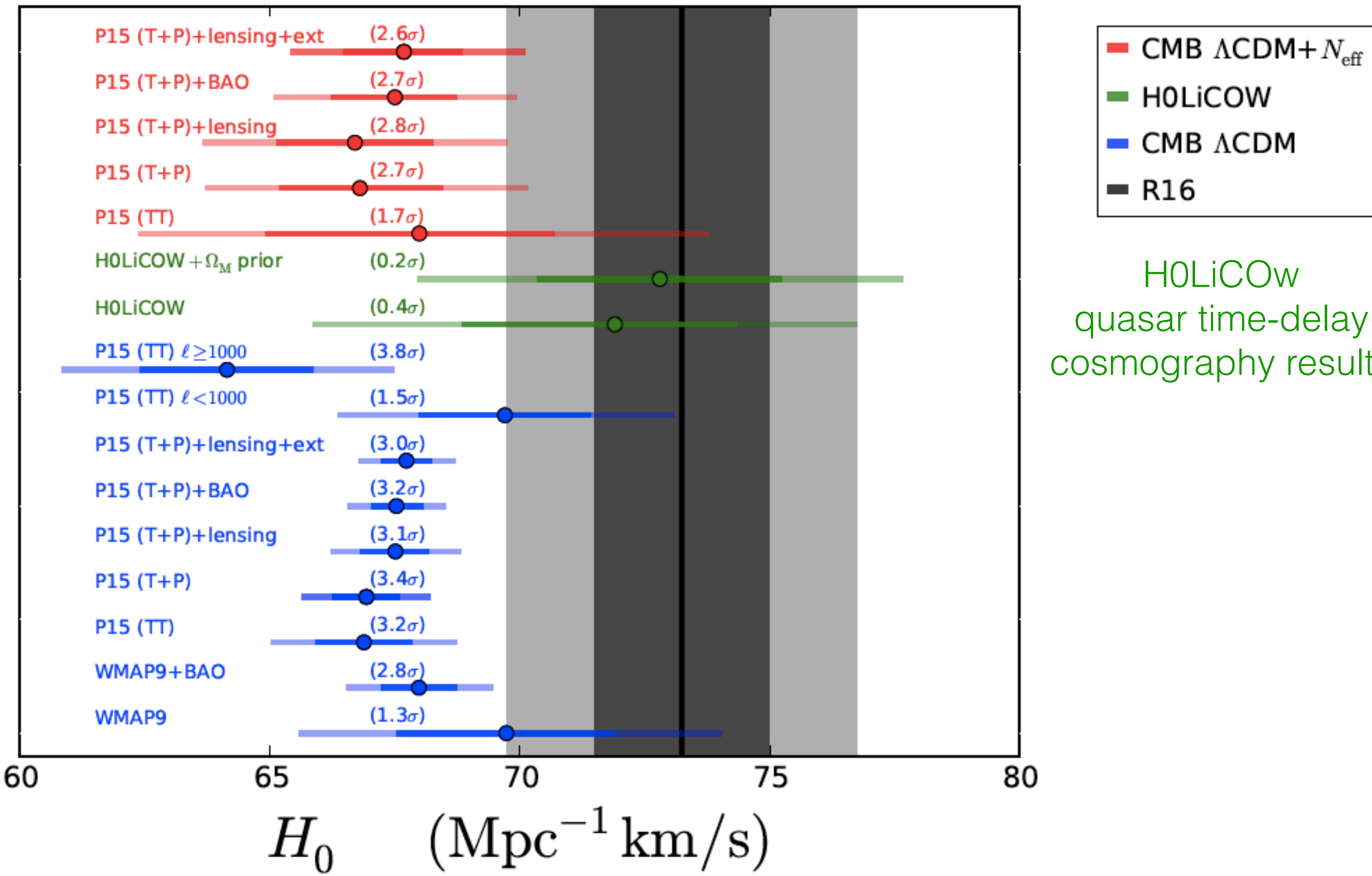
GW170817 measurement of H_0 (LIGO–Virgo collaboration): only assumes GR

Measure H(z): Cosmic clocks



The schism between early & late Universe

Bernal, Verde, & Riess 2016



H0LiCOw
quasar time-delay
cosmography results

The schism between early & late Universe

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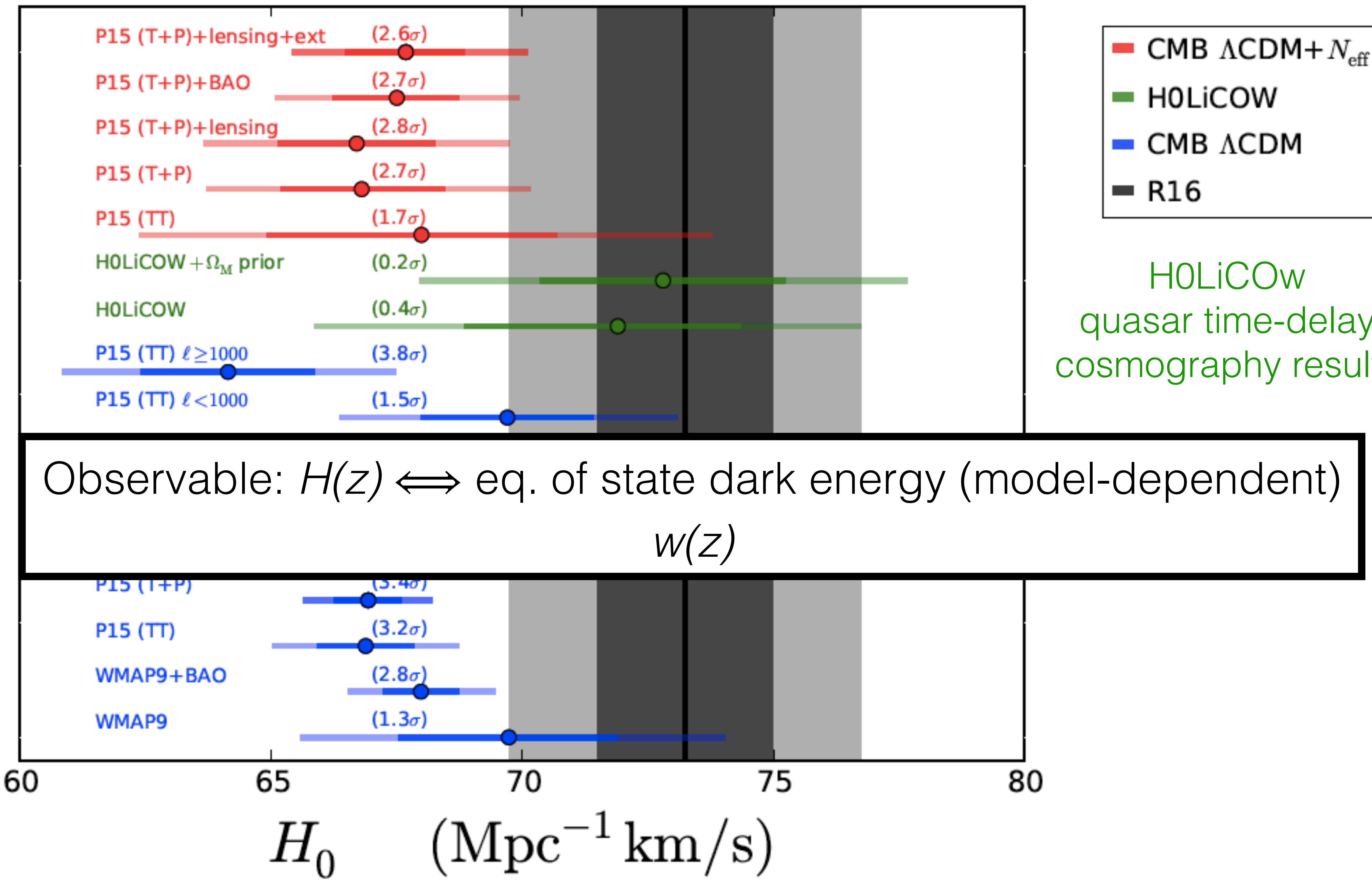
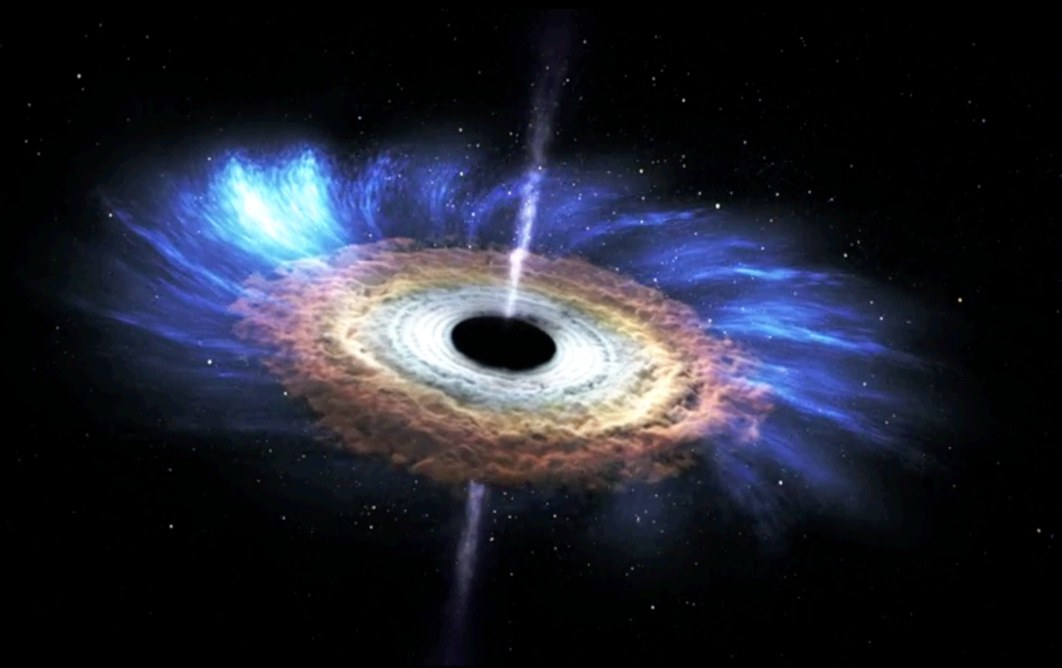


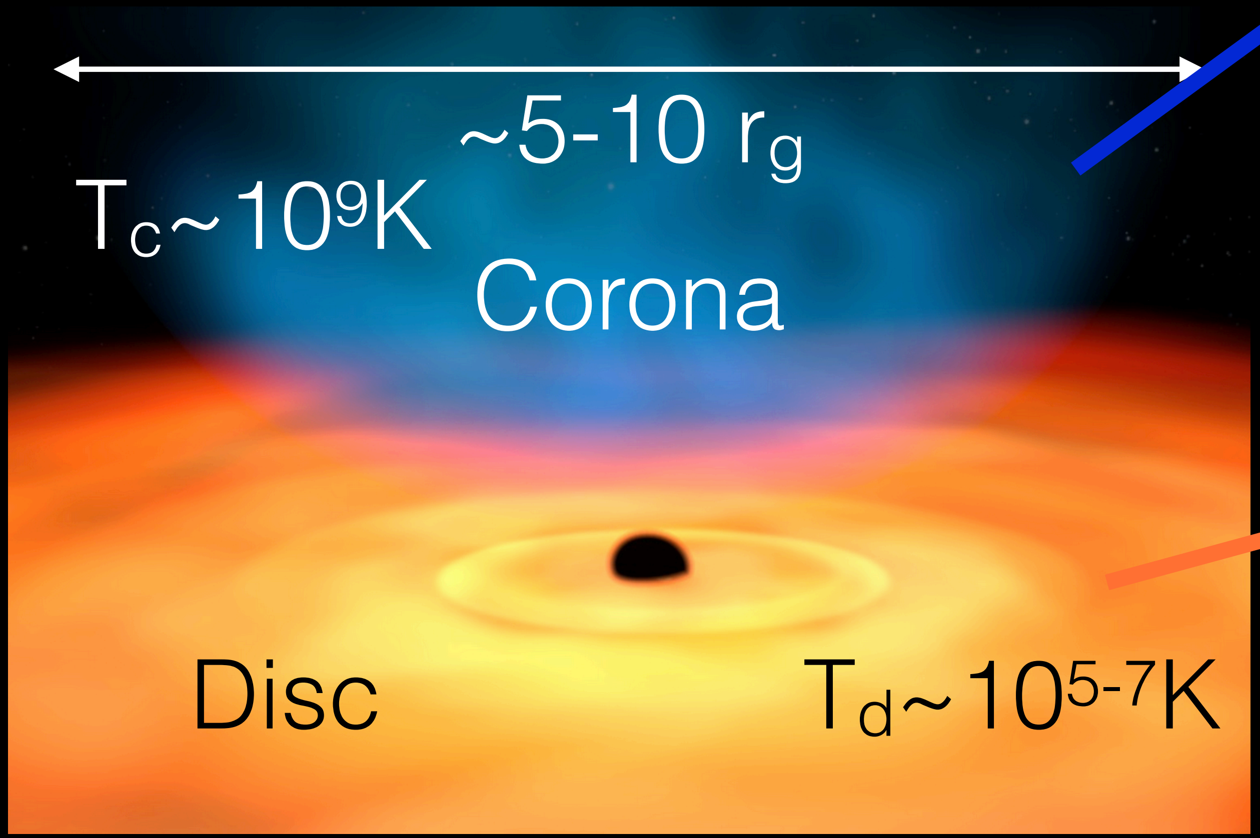
H0LiCOw quasar time-delay cosmography results

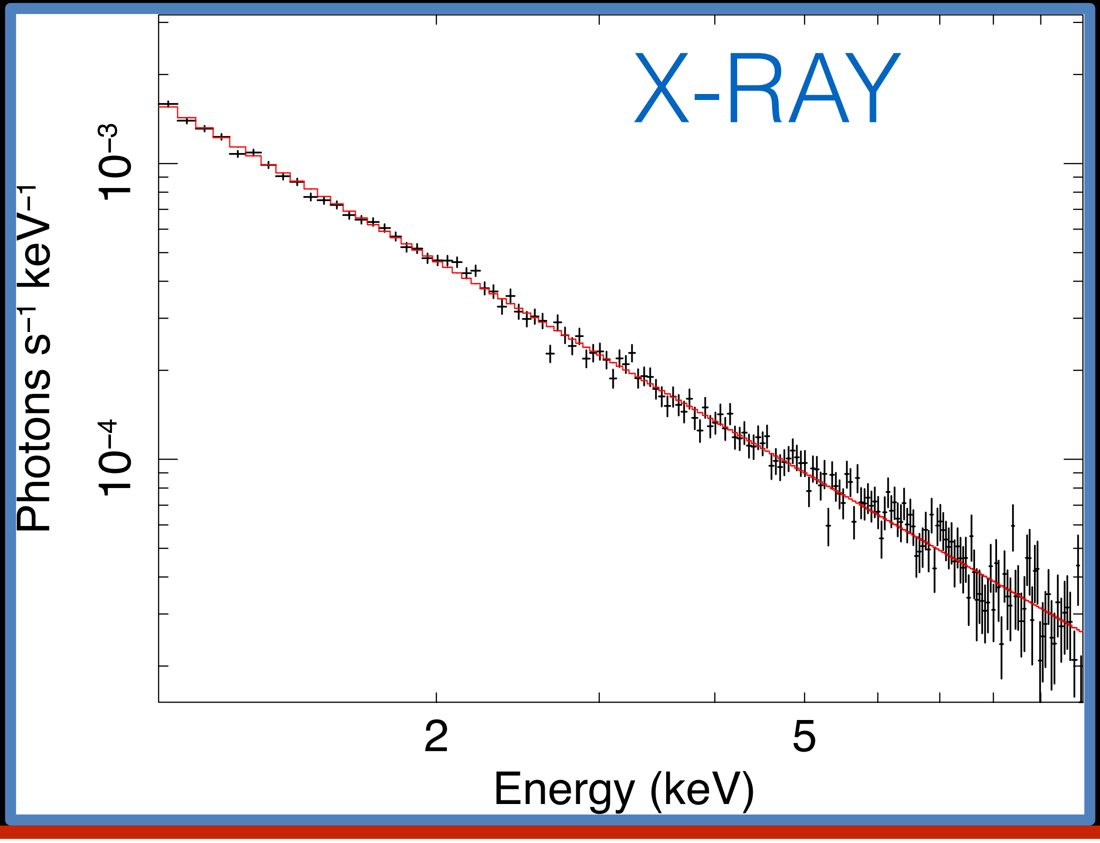
Observable: *H(z)* ⟺ eq. of state dark energy (model-dependent) *w(z)*

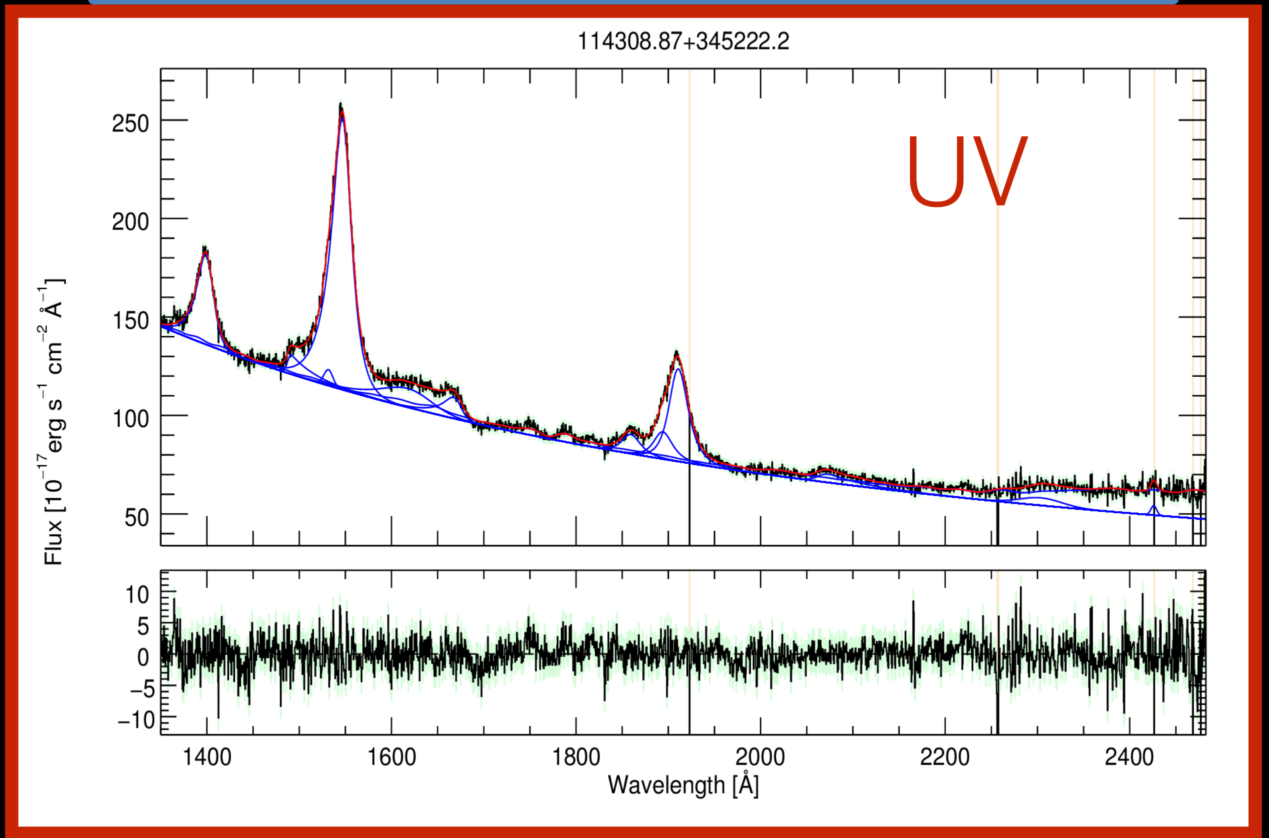
LIGHT FROM A BLACK HOLE: QUASAR



Credit: NASA astrophysics-www.nasa.gov/goddard

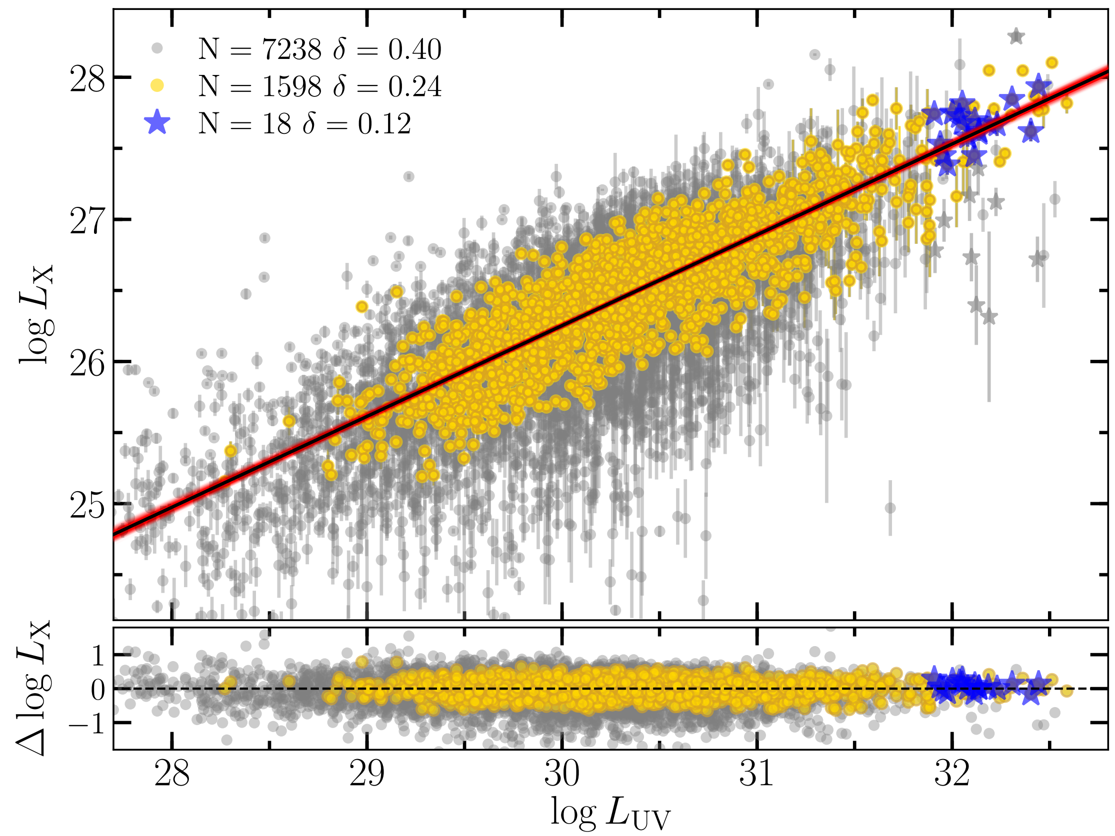






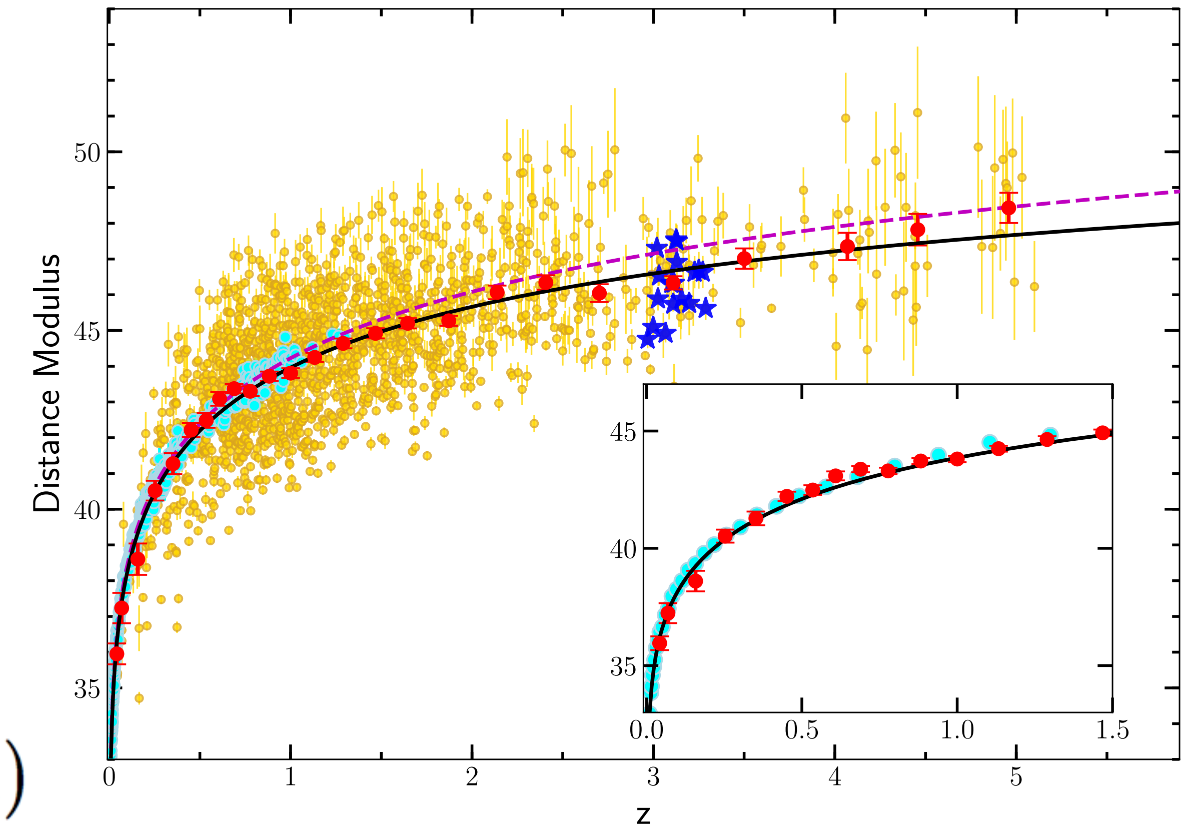
Cosmology with quasars
The distance modulus

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



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

Risaliti & Lusso (2019, *Nat. Astro.*)



Standardise the quasar emission

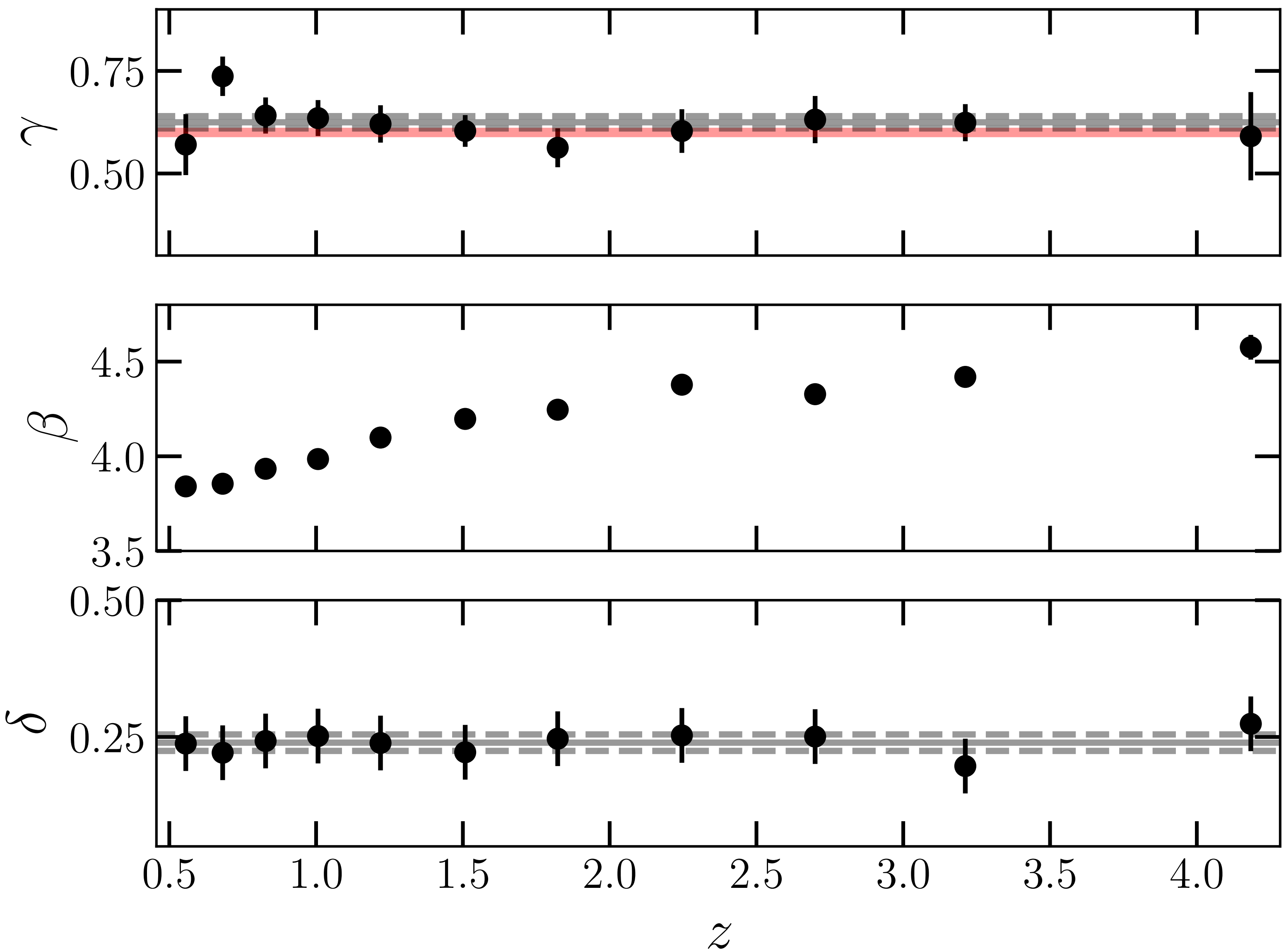
$$\log(F_X) = \Phi(F_{UV}, D_L)$$
$$= \beta' + \gamma \log(F_{UV}) + 2(\gamma - 1)\log(D_L)$$

$D_L(z, \Omega_M, \Omega_\Lambda)$

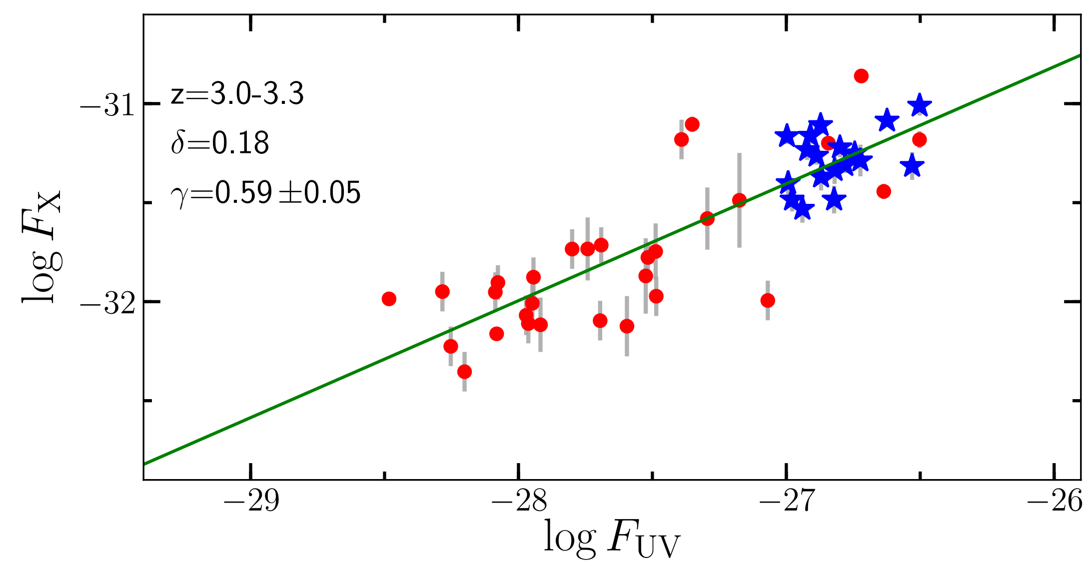
The L_X-L_{UV} non-linear relation as a way to measure quasar distances

Cosmology with quasars

Quasars Hubble Diagram: redshift dependence



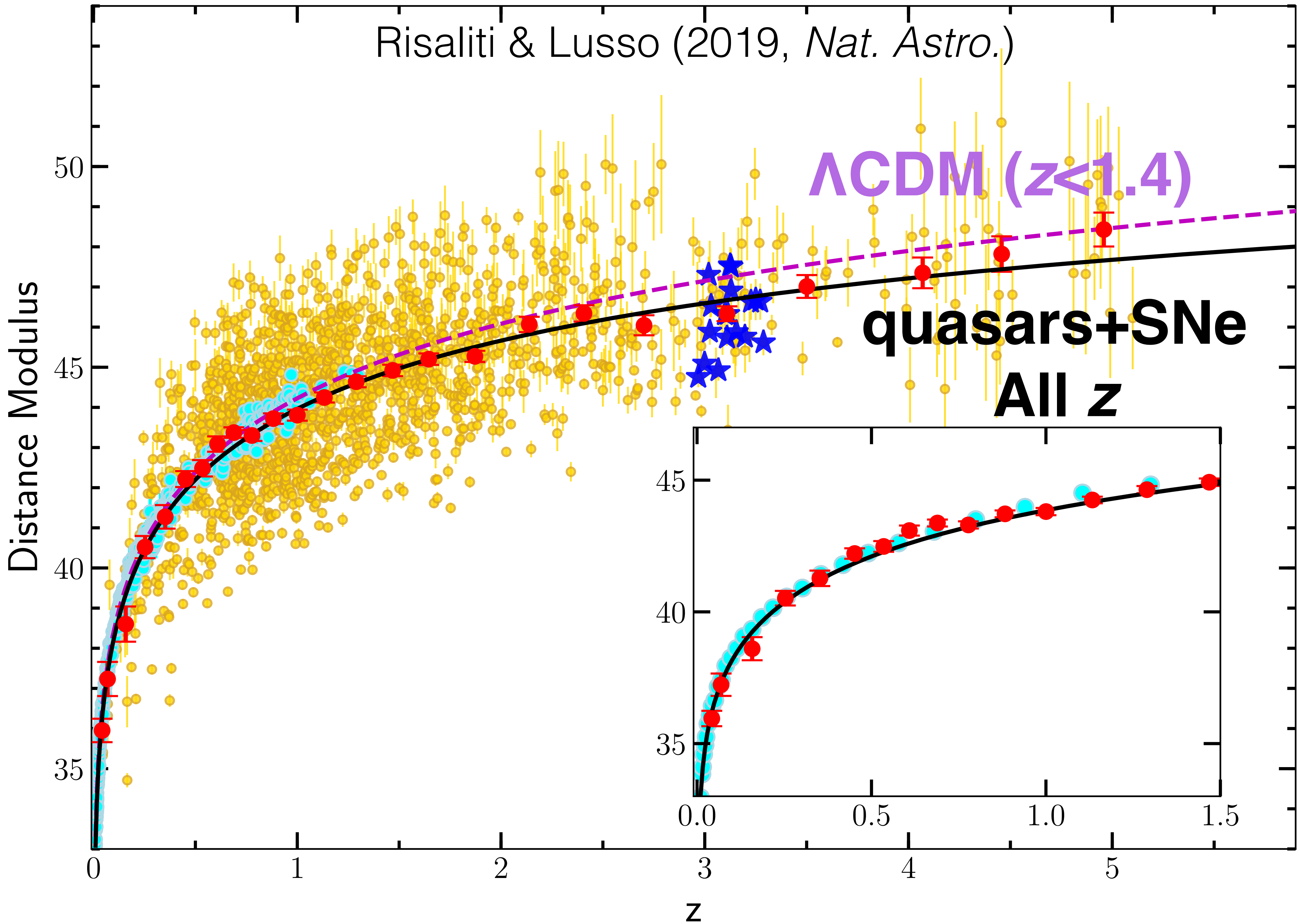
$$\log D_L = \frac{1}{2-2\gamma}(\gamma \log F_{UV} - \log F_X) + \beta.$$



Cosmology with quasars

Quasars Hubble Diagram

~1600 quasars: SDSS+3XMM+XMM LP+archive/literature



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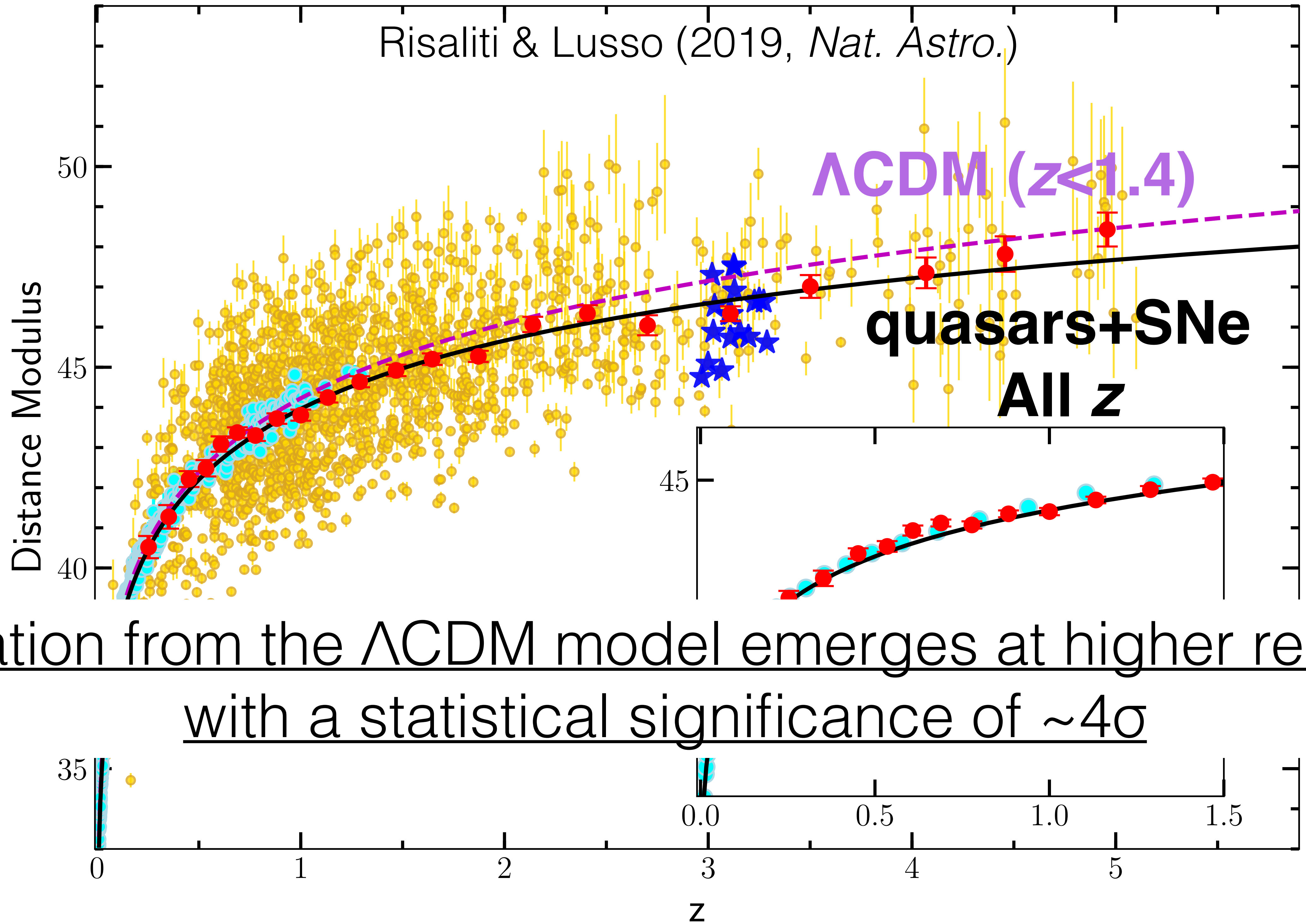
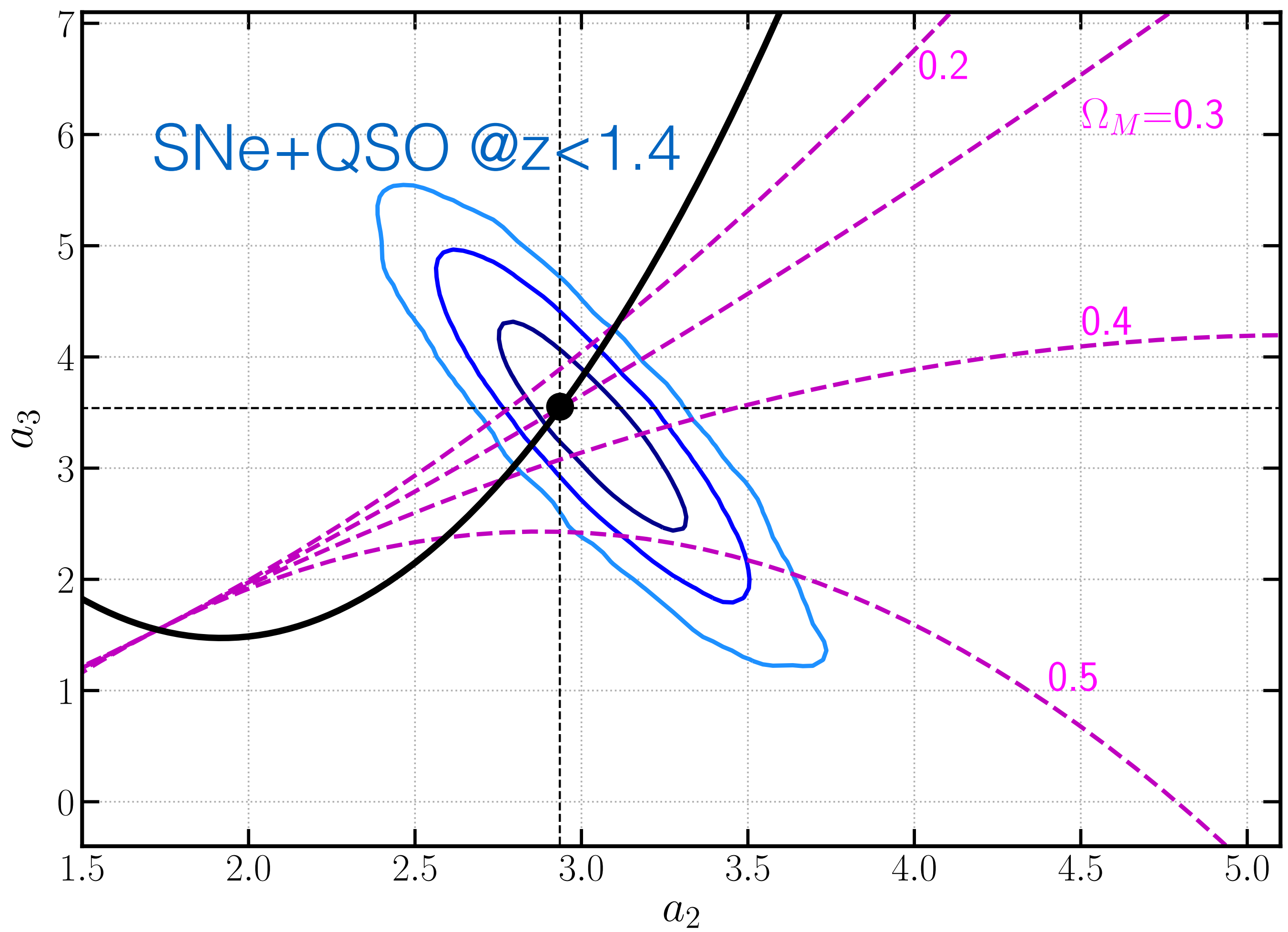


deviation from the ΛCDM model emerges at higher redshift, with a statistical significance of ~4σ

Cosmology with quasars
Quasars Hubble Diagram

Risaliti & Lusso (2019, *Nat. Astro.*)



Cosmographic approach

$P[\log(1+z)]$: $D_L = k \Sigma_i a_i [\log(1+z)]^i$

$k = \ln(10) c/H_0$

$a_2(\Omega_M)$, $a_3(\Omega_M)$

Flat ΛCDM

Flat *w*CDM (free *w*)

Intersections magenta lines and black curve are the points with *w*=1 (left) and *w*=-1 (right), values of *w* decrease from left to right

Cosmology with quasars
Quasars Hubble Diagram

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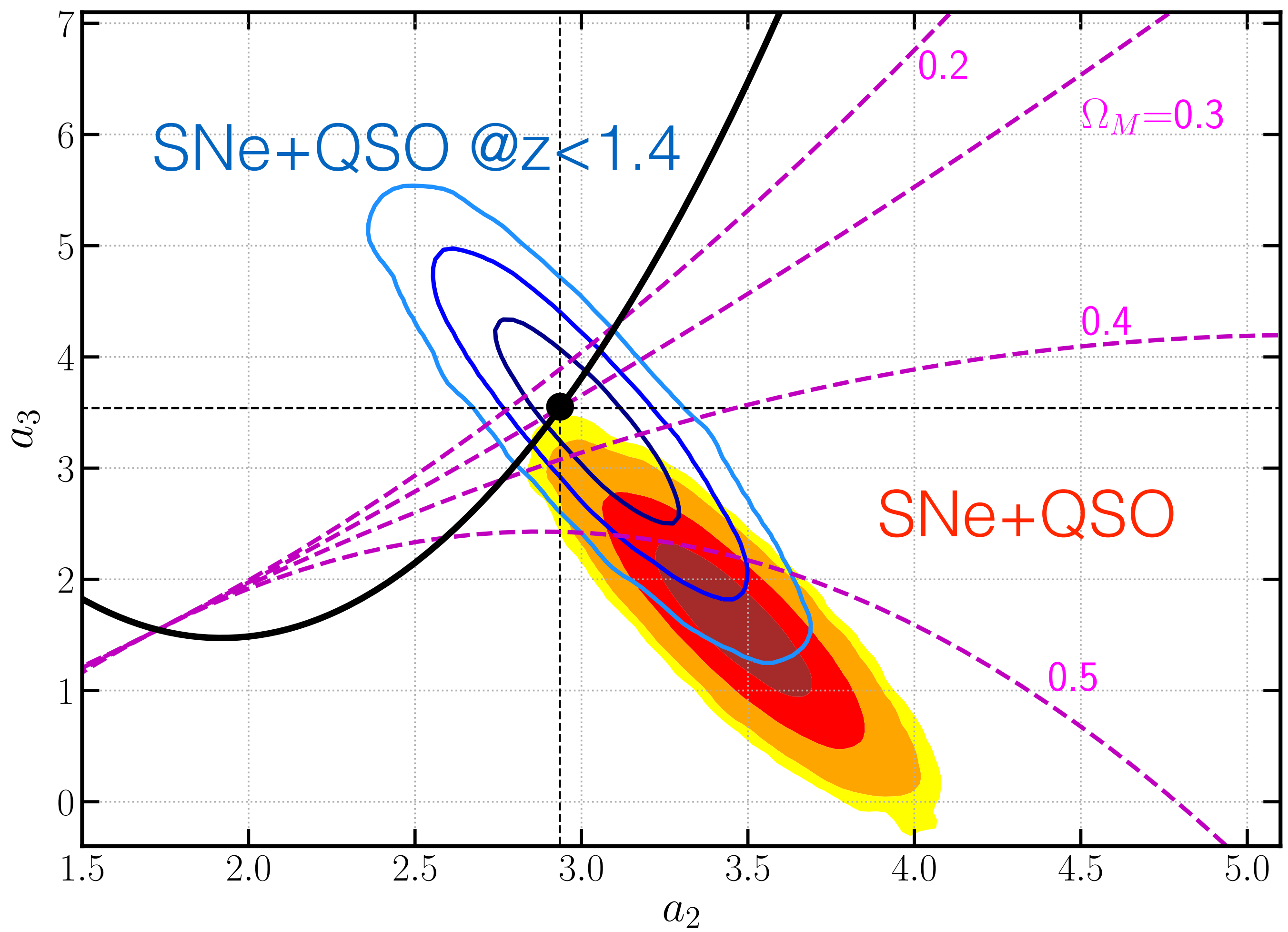

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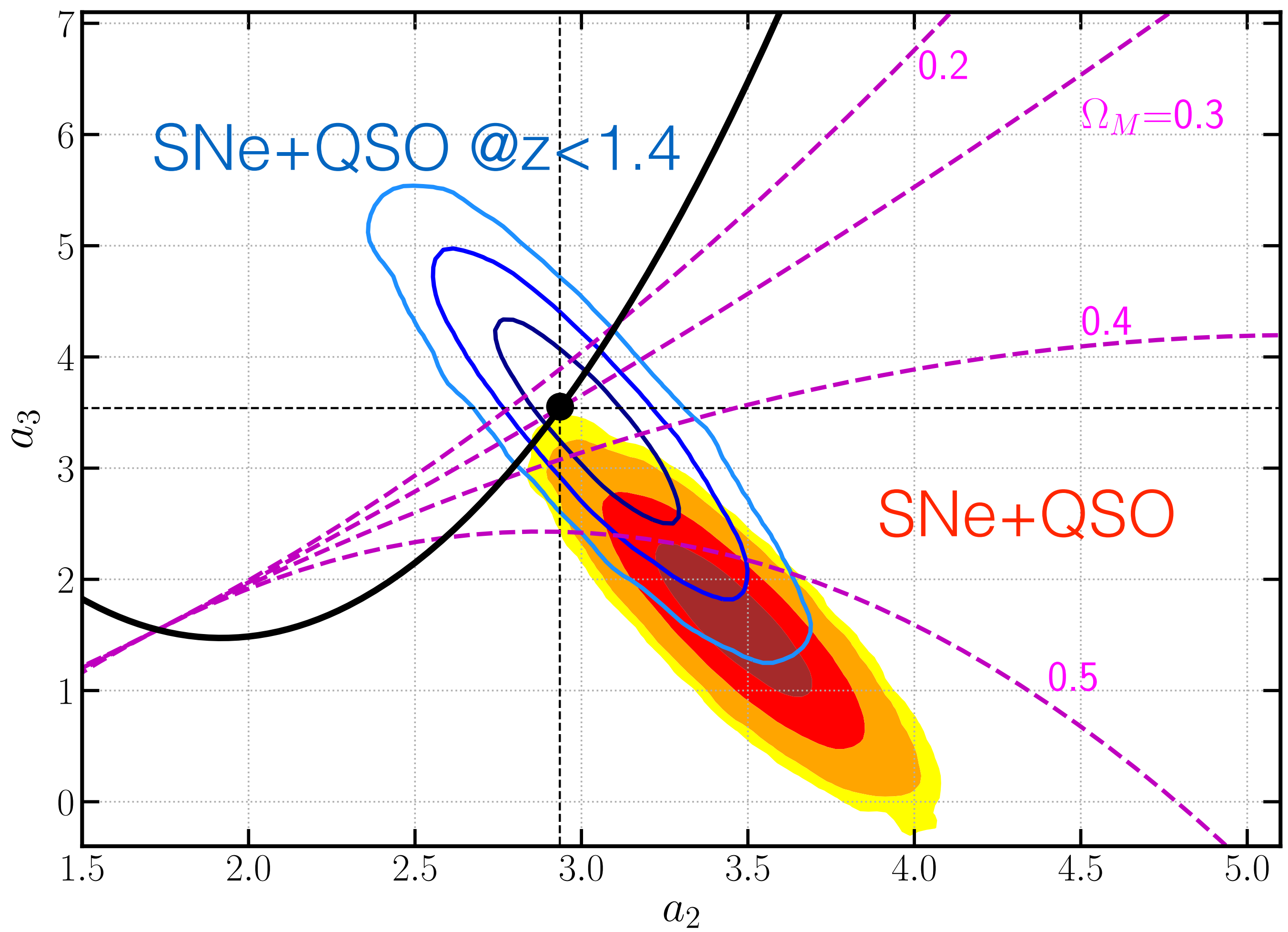

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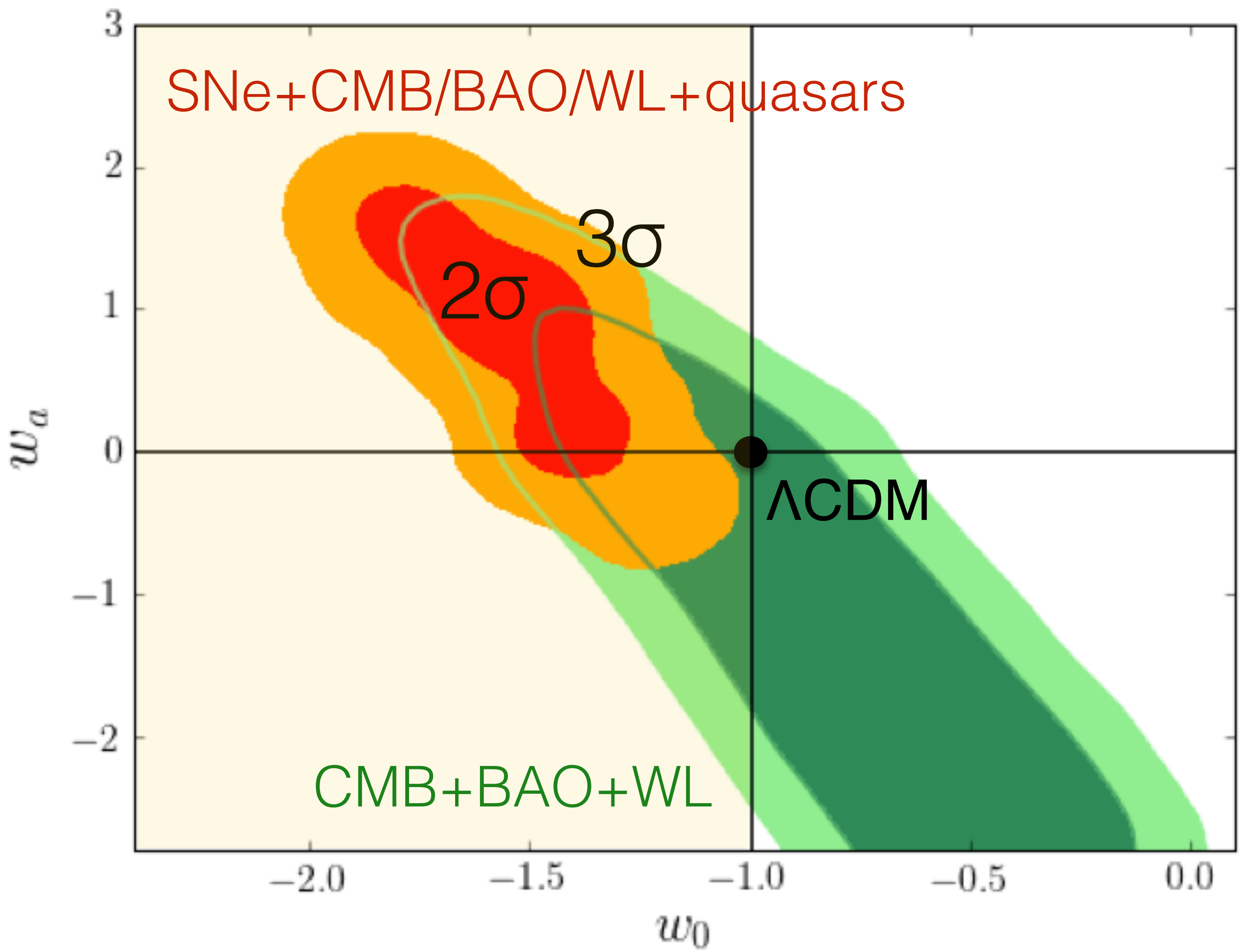
data suggest: **dark energy density increasing with time**.

Within the *w*CDM model: Ω_M>0.3 and *w*<-1.3

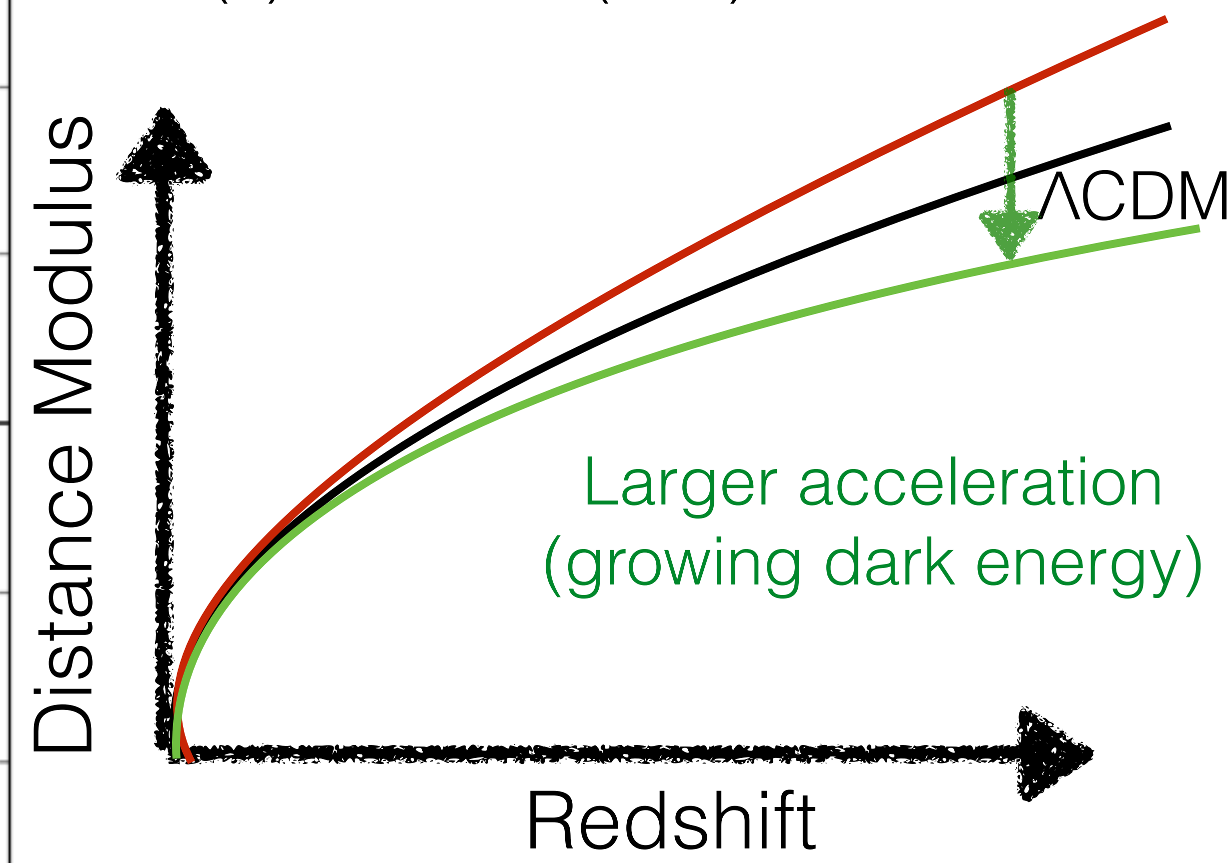
Cosmology with quasars: ΛCDM crises?

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



Flat *w*CDM (free *w*)

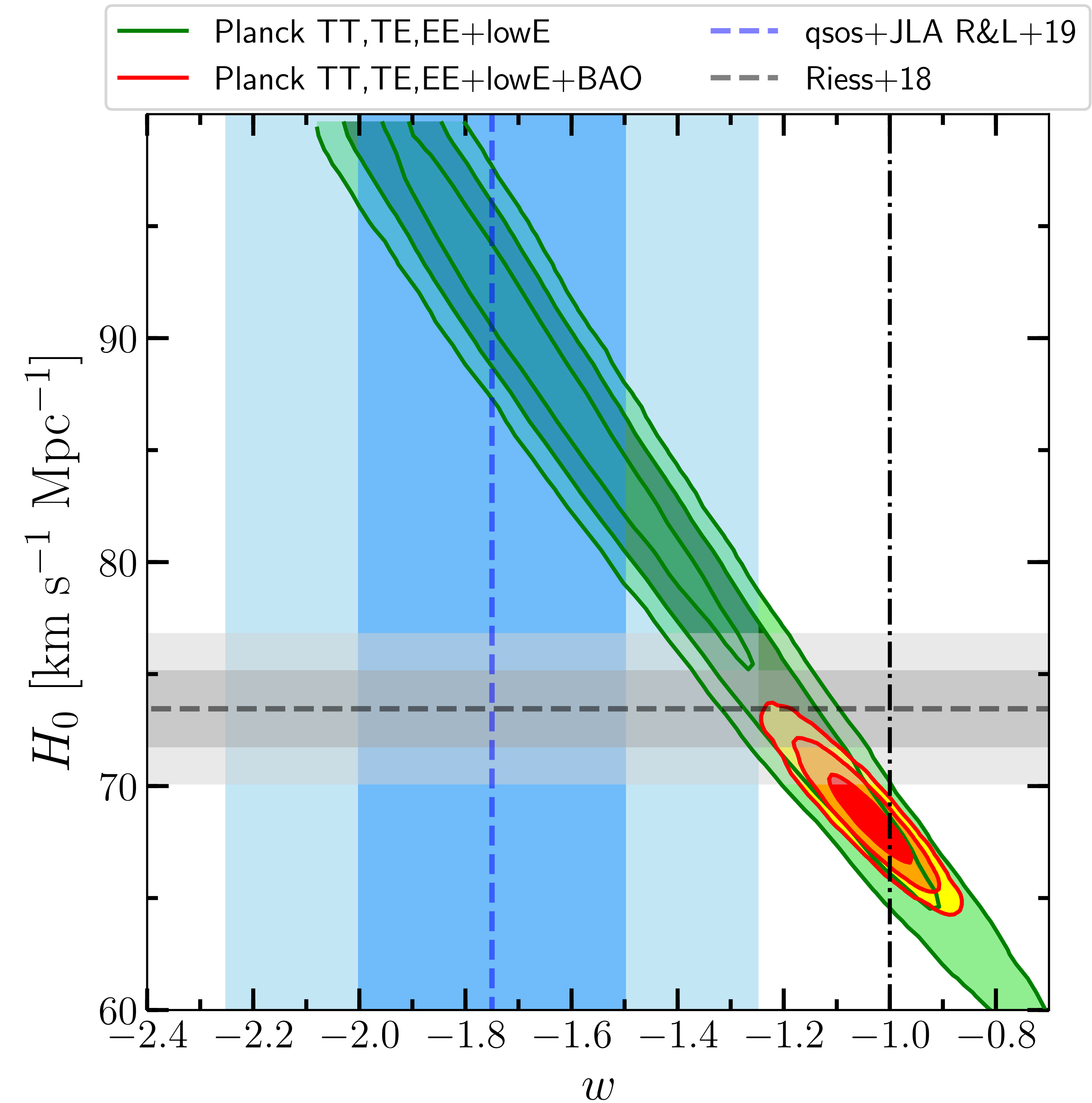
$w(z) = w_0 + w_a * z/(1+z)$



Data suggest: **dark energy density increasing with time**

(i.e. the Universe is accelerating faster than in the past)

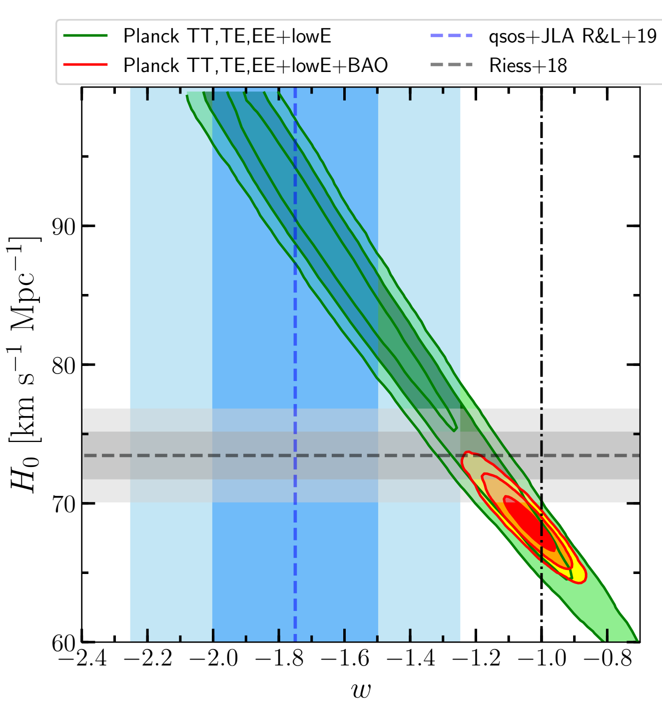
Cosmology with quasars

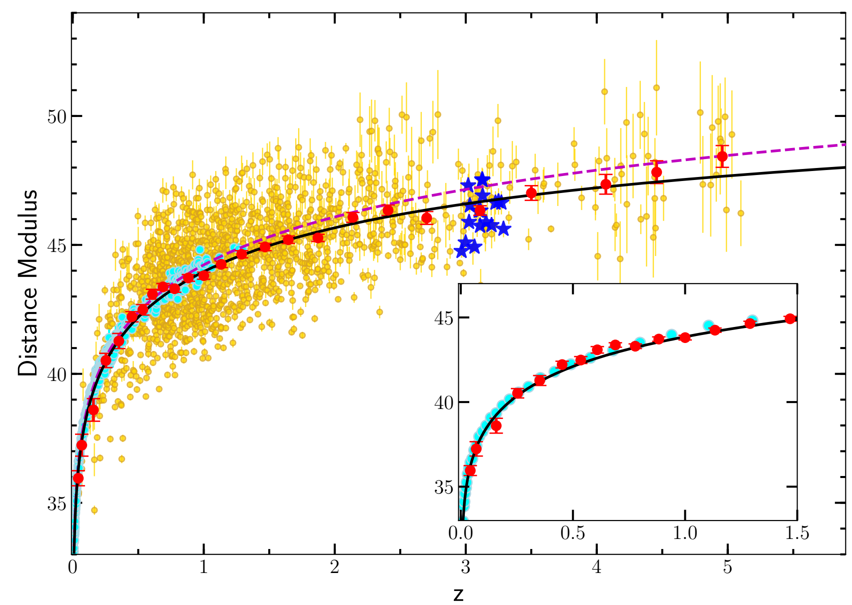


To summarise

We have a novel way to measure cosmological parameters - Ω_M Ω_Λ *w(z)* - that uses quasars are standard(izable) candles.

<u>Deviation from the ΛCDM model at high redshift, with a statistical significance of ~4σ</u>
(could “solve” the H_0 tension between local/CMB)





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