On accelerated expansion and Hubble tension

Yungui Gong
龚云贵
Ningbo University

2024引力与宇宙学专题研讨会，USTC，2024.11.16

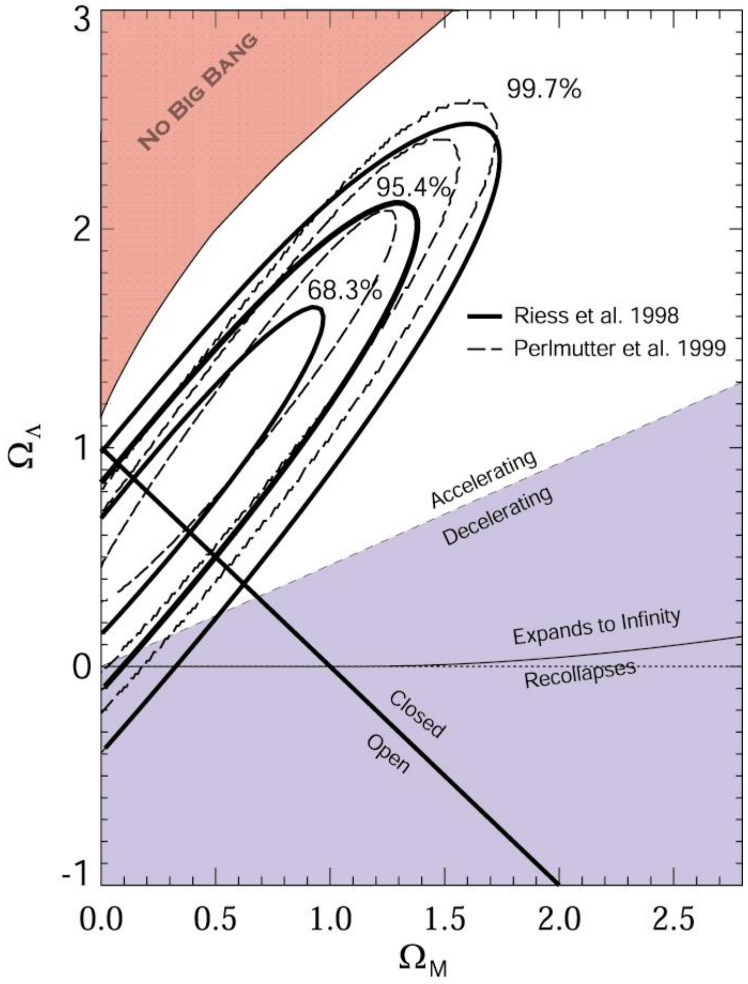
Outline

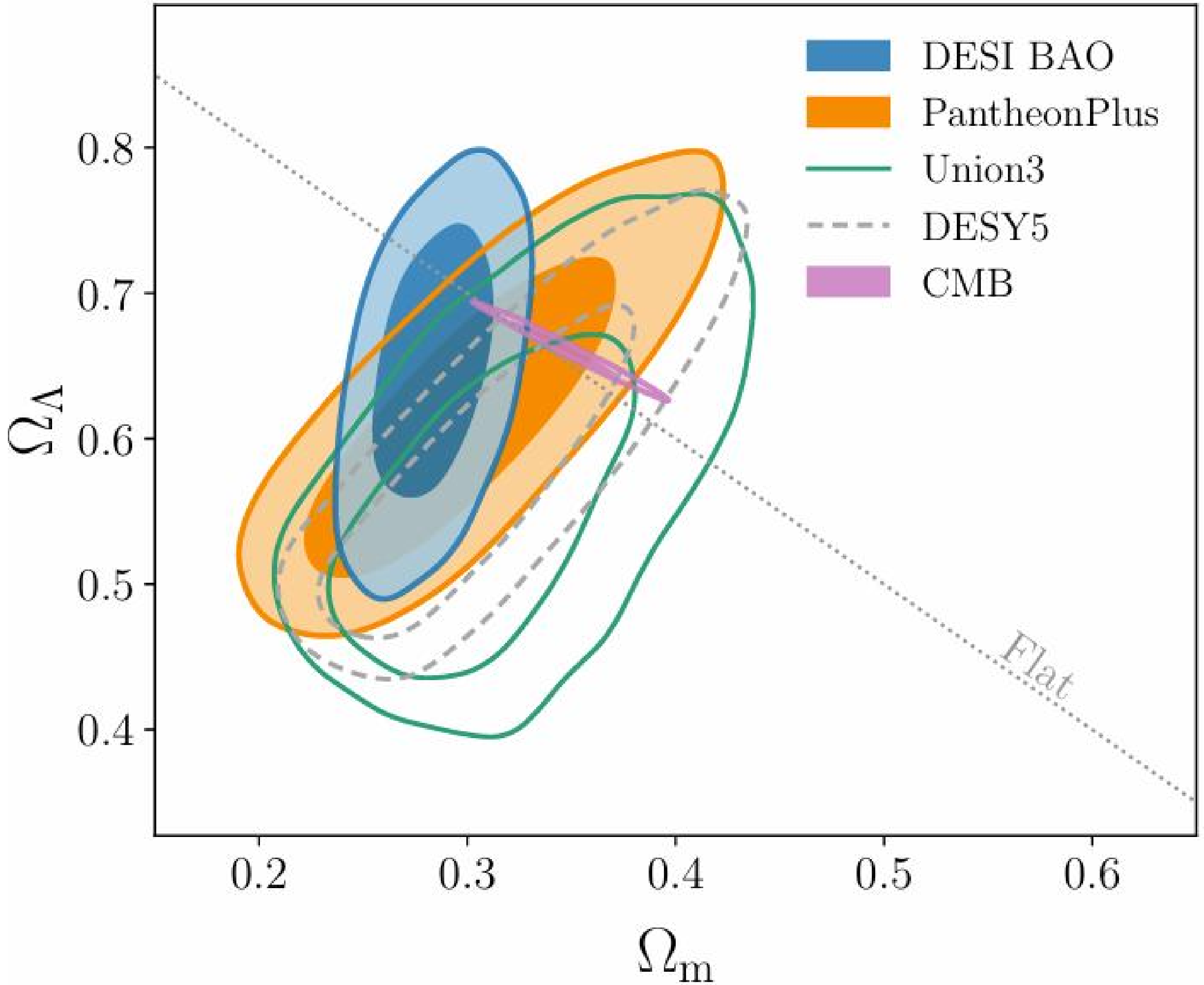
- Observational evidence of accelerated expansion
- Model-independent evidence
- Null hypotheses motivated by energy conditions
- Evidence from DESI BAO data
- Hubble tension

Gong, Wang etal., JCAP 08(2007)018; PLB 652 (2007) 63; Y. Yang and Y. Gong, JCAP 06 (2020) 059; X. Lu & Y. Gong, EPJC 83 (2023) 949; X. Lu, S. Gao & Y. Gong, 2409.13399

Observational evidence of accelerated expansion

- SNe Ia

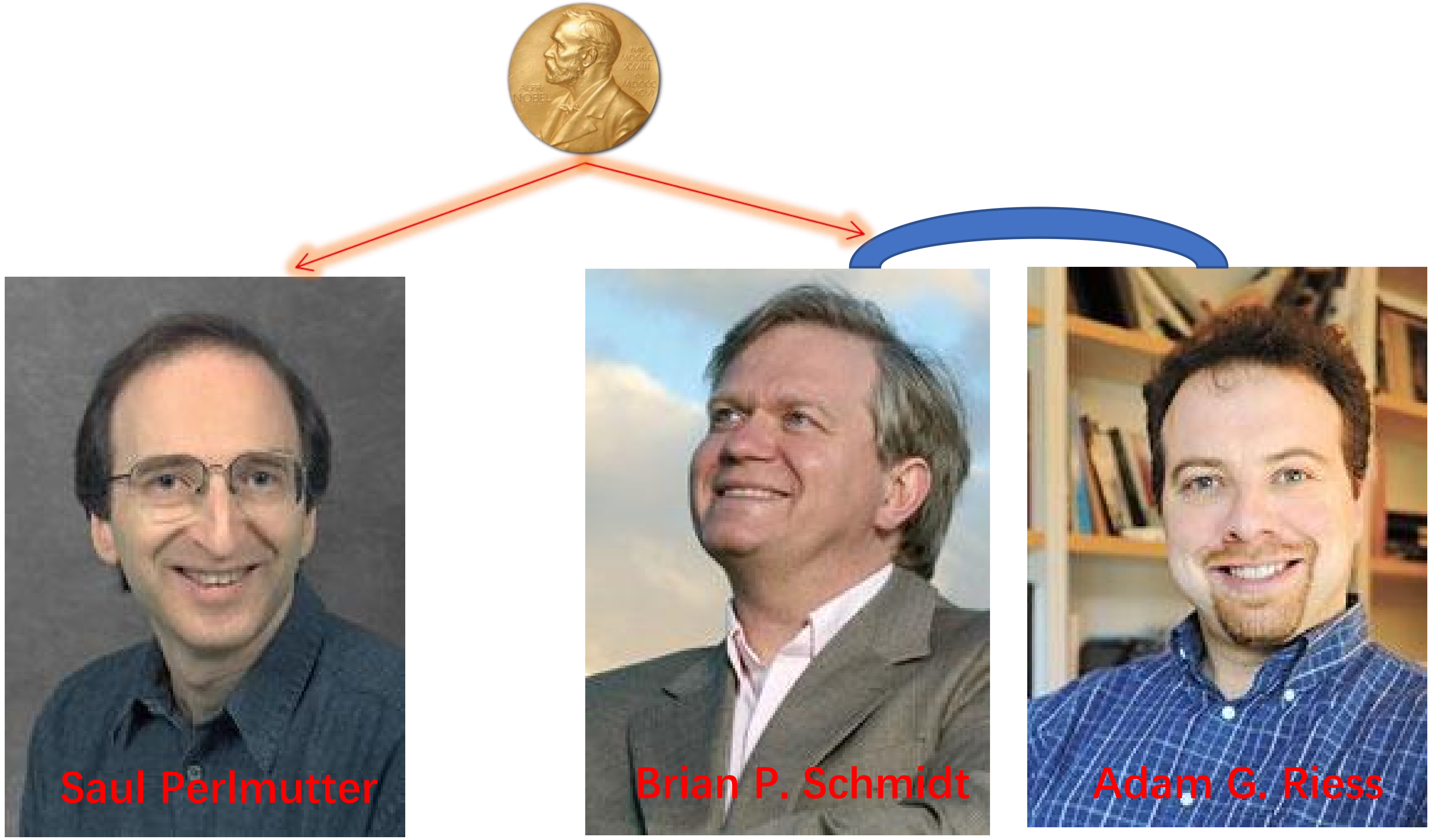




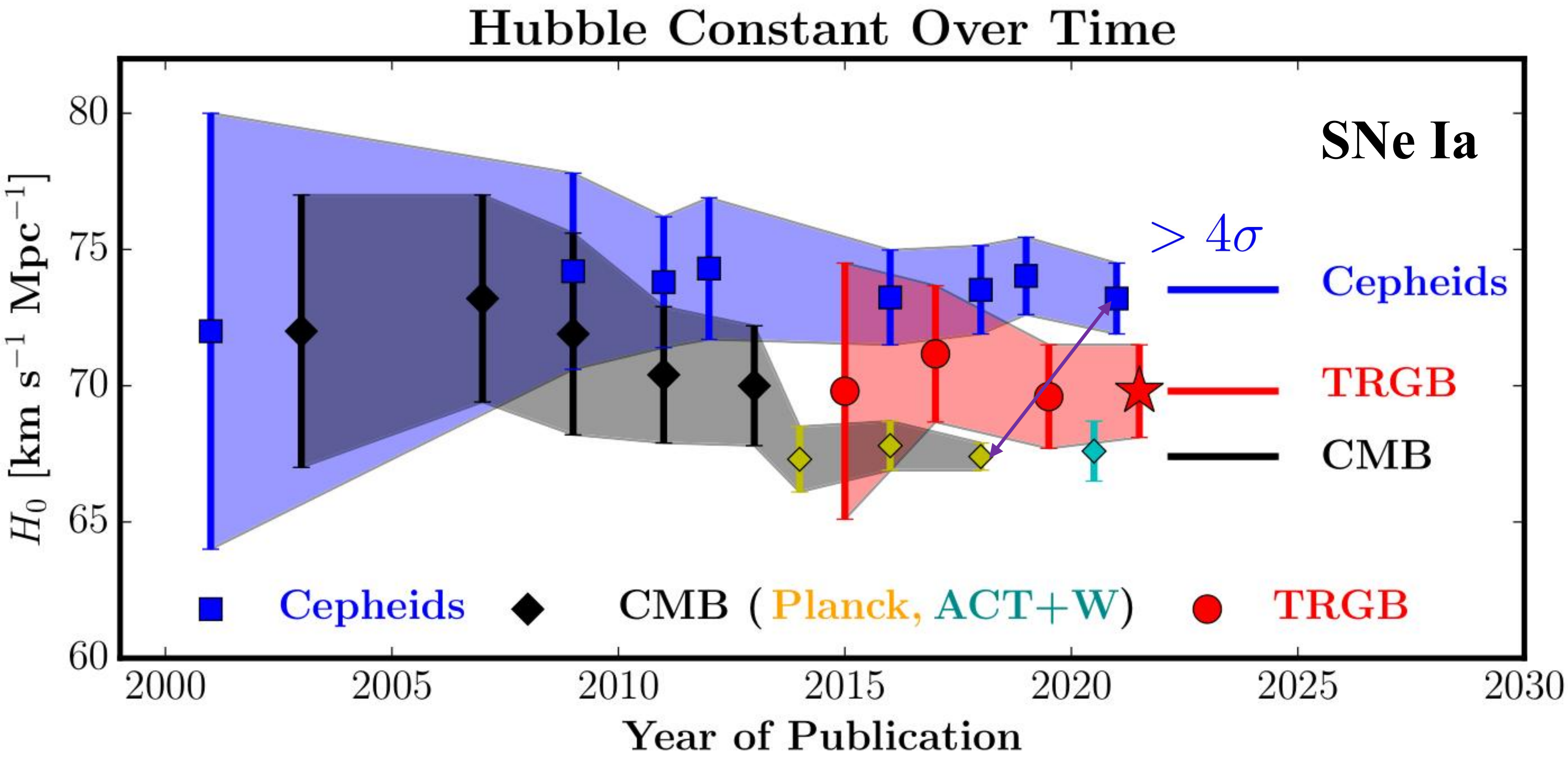
A. G. Riess et al., Astron. J. 116 (1998) 1009; S. Perlmutter et al., ApJ 517 (1999) 565; D. Scolnic et al., ApJ 938 (2022) 113; D. Rubin et al., 2311.12098; T. M. C. Abbott et al., ApJL, 973 (2024) L14; A.G.Adame etal., 2404.03002

2011 Nobel Prize in physics

- For the discovery of the accelerating expansion of the Universe through observations of distant supernovae



Hubble tension



W.L. Freedman, ApJ 919 (2021) 16

Supernova Ia standard candles

- Distance ladders
  - Cepheids: Cepheid period-luminosity (P-L) relation (Leavitt Law, 1908), calibration of Galactic Cepheids with Trigonometric Parallaxes
  - TRGB method
  - maser galaxies
  - Surface Brightness Fluctuation (SBF) Method
  - Extragalactic distances: Tully-Fisher Relation
  - Type Ia supernova standard candles: Correlation between the magnitude of a SN Ia at peak brightness and the rate at which it declines, zero-point calibration problem
- CMB measurement
  - Very accurate
  - depend on LCDM model

The problems

- Observational evidences for the cosmic acceleration: SNe Ia, CMB, BAO etc., all based on the LCDM model
- The Hubble tension: dependence on the LCDM model
- It there model-independent method?
  - Omz

$$Om(z) = \frac{E^2(z) - 1}{(1+z)^3 - 1} = \Omega_{m0}$$ LCDM model

  - Null test

Sahni, Shafieloo & Starobinsky, PRD 78 (2008) 103502

$$\mathcal{L} = 1 + H^2(D_M D_M'' - D_M'^2) + HH' D_M D_M' = 0$$

  - Energy conditions

C. Clarkson, B. Bassett,, T. H.-C. Lu, PRL 101 (2008) 011301

M. Visser, Science 276 (1997) 88; J. Santos, J. S. Alcaniz,, M. J. Reboucas, PRD 74 (2006) 067301; M. Seikel, D. J. Schwarz, JCAP 02 (2008) 007

Energy condition and Acceleration

- Strong Energy Condition $\rho + 3p \geq 0, \quad \rho + p \geq 0$

$\rho + 3p \geq 0$ Deceleration $\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$ $q(t) = -\frac{\ddot{a}}{(aH^2)} \geq 0$

$\rho + p \geq 0$ Super-acceleration $\dot{H} - \frac{k}{a^2} = -4\pi G(\rho + p)$ $\dot{H} - \frac{k}{a^2} \leq 0$

$$q(z) \geq 0 \rightarrow H_0 d_L(z) \leq (1+z)\ln(1+z)$$

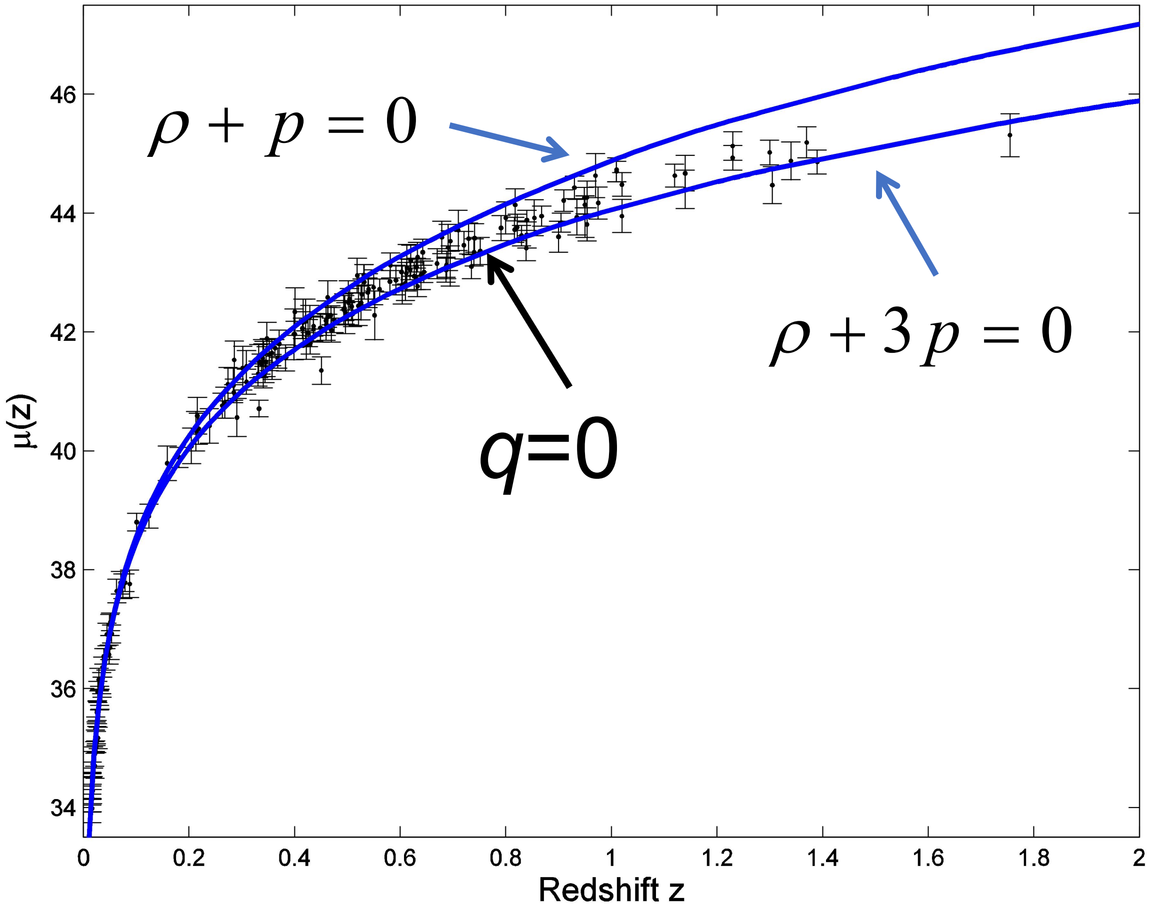
Spatially flat $\dot{H} \leq 0 \rightarrow H_0 d_L(z) \leq z(1+z)$

Luminosity distance $d_L(z) = (1+z)D_M(z) = (1+z)\int_0^z \frac{dx}{H(x)}$

$$D_M(z) = \frac{c}{H_0\sqrt{|\Omega_{k0}|}}\text{sinn}\left[\sqrt{|\Omega_{k0}|}\int_0^z \frac{dz'}{E(z')}\right] \qquad E(z) = H(z)/H_0$$

Observational Evidence

- Strong Energy Condition: If SEC was never violated, then all observed SN data will be in the region bounded by the lower curve, otherwise we see the evidence of cosmic acceleration
- Fix the value of Hubble constant

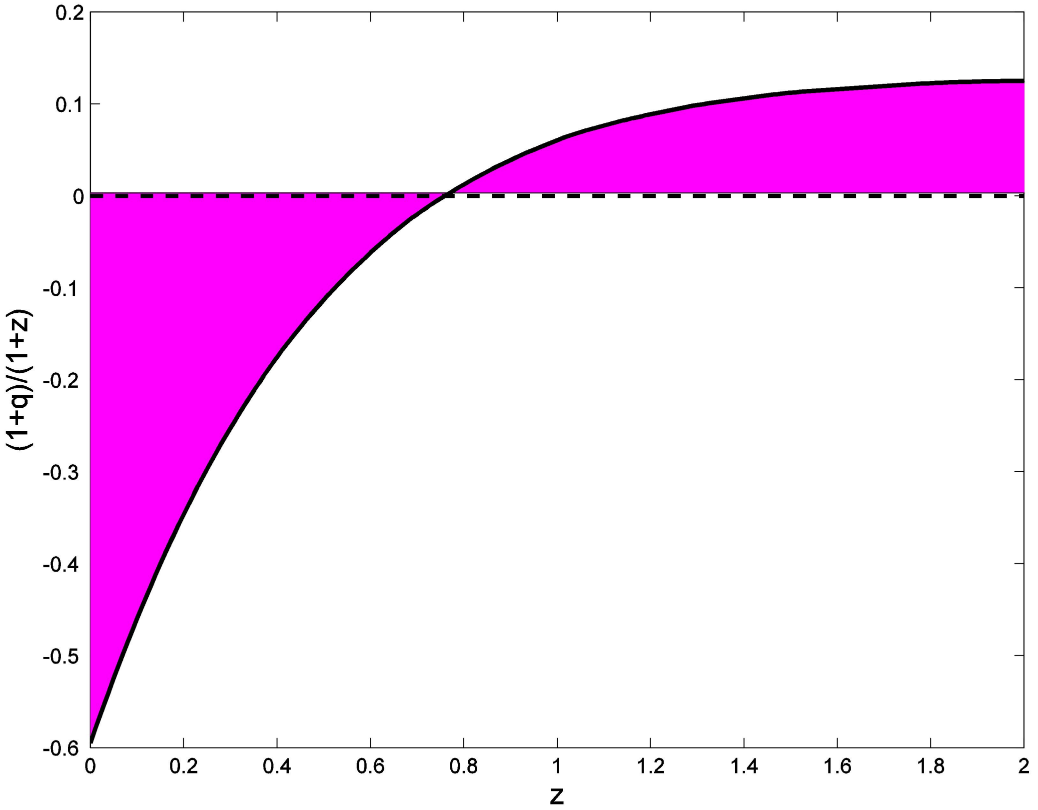


Gong, Wang etal., JCAP 08(2007)018; PLB 652 (2007) 63.

The interpretation of the null hypotheses

- The integration effect
  - Even if some high z SN Ia data are outside the region under the lower solid line, it does not mean that we have evidence of an accelerating expansion in the high z region
  - Even if almost all the SN Ia data are outside the region under the lower solid line, it does not mean there is no evidence for past deceleration.

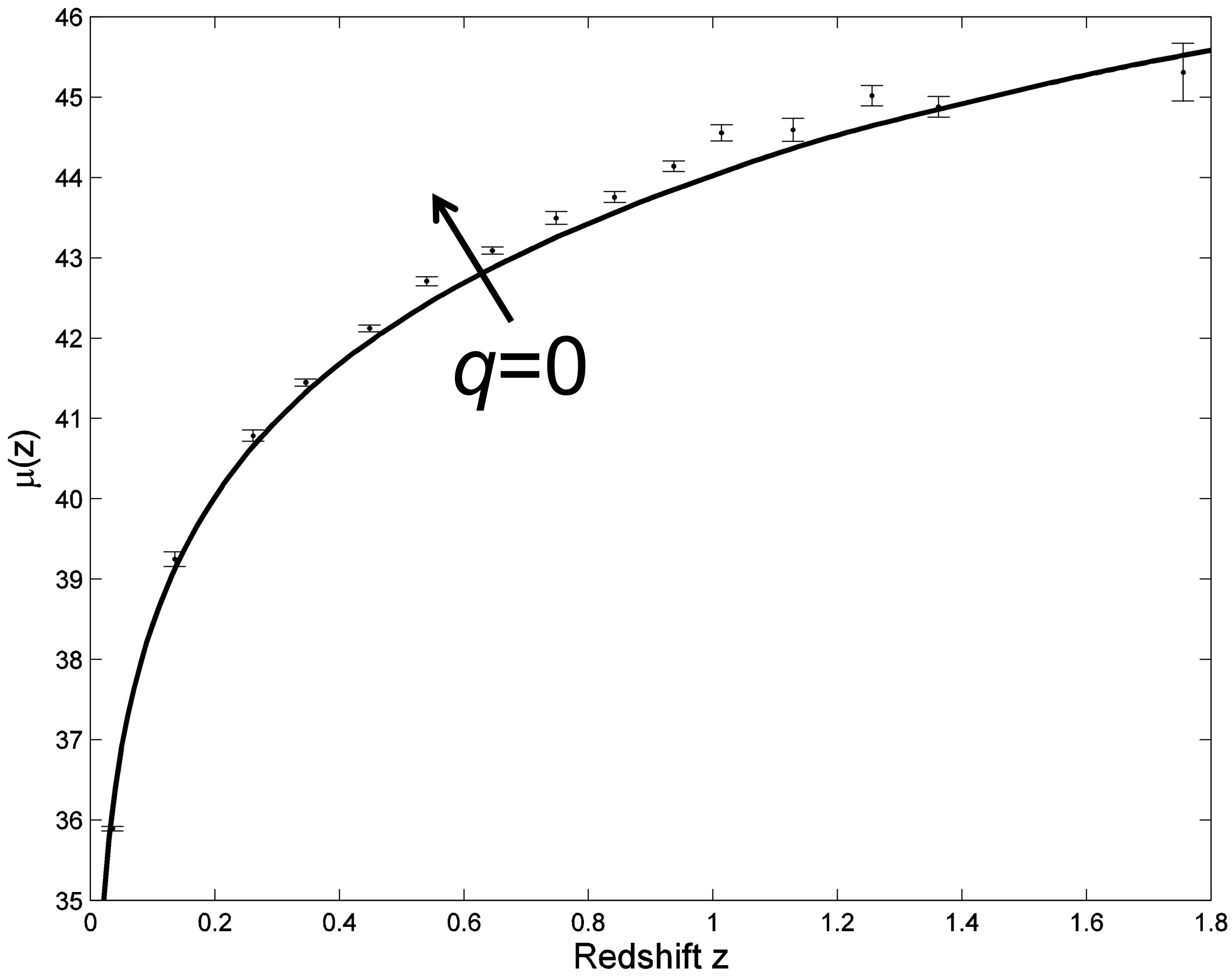
$$H(z) = H_0 \exp\left[\int_0^z [1+q(u)]d\ln(1+u)\right]$$



The difference of the function between the flat LCDM model and the model with q=0

Results

- Need to know the value of Hubble constant
- How to quantify the evidence



Gong, Wang etal., JCAP 08(2007)018; PLB 652 (2007) 63.

Pantheon SNe Ia data

- E(z) (spatially flat)

z	$E(z)$	Correlation Matrix					
0.07	0.994 ± 0.023	1.00					
0.2	1.113 ± 0.020	0.40	1.00				
0.35	1.122 ± 0.037	0.52	-0.13	1.00			
0.55	1.369 ± 0.063	0.35	0.35	-0.18	1.00		
0.9	1.54 ± 0.12	0.02	-0.08	0.19	-0.41	1.00	
1.5	$2.69^{+0.86}_{-0.52}$	0.00	-0.06	-0.05	0.16	-0.21	1.00

$$H_0 d_L(z) = \frac{1+z}{\sqrt{|\Omega_{k0}|}} \mathrm{sinn}\left[\sqrt{|\Omega_{k0}|}\int_0^z \frac{dz'}{E\left(z'\right)}\right]$$

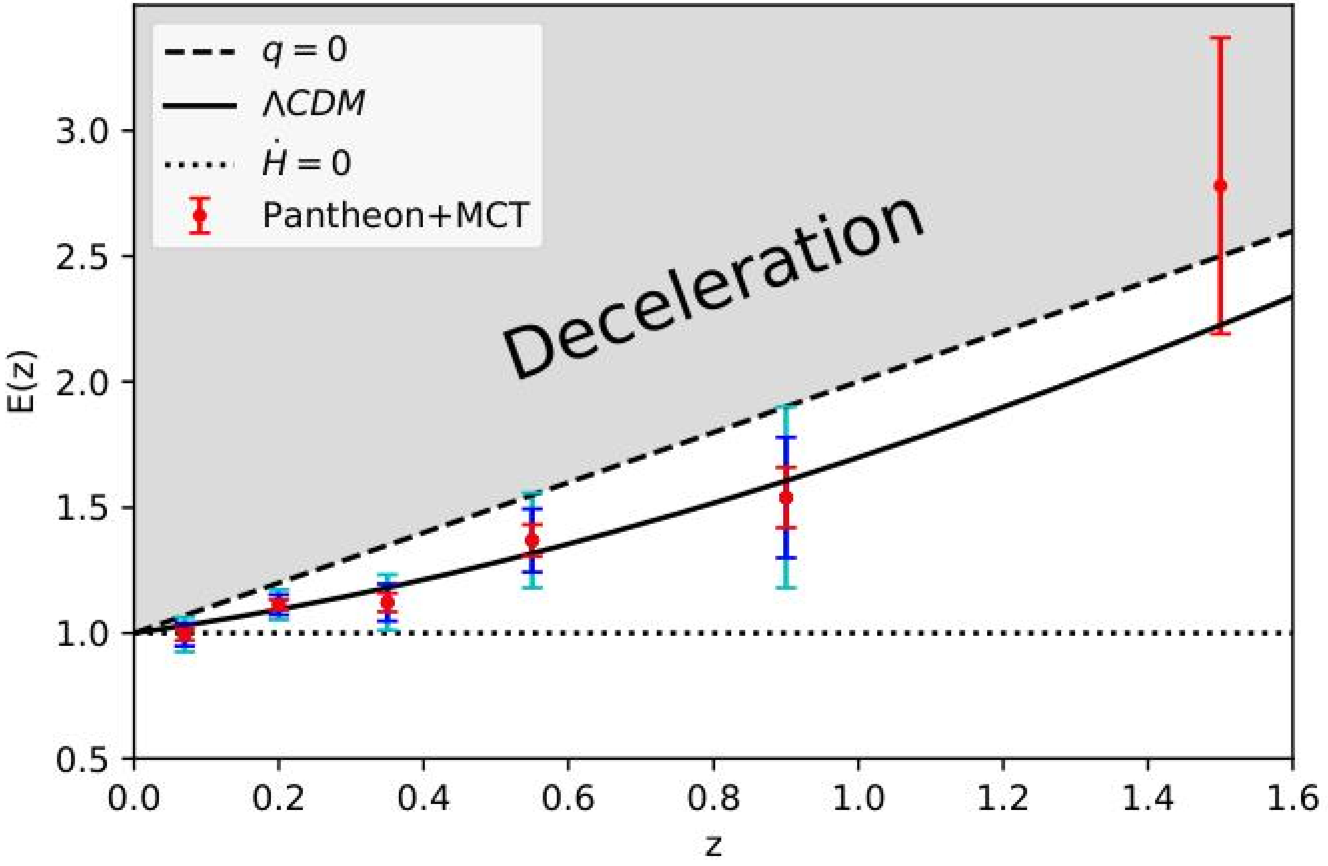
$$H_0 d_L(z) = (1+z)\int_0^z \frac{dx}{E(x)}$$

$$\frac{\mathrm{sinn}(\sqrt{|\Omega_k|}x)}{\sqrt{|\Omega_k|}} = \begin{cases} \sin(\sqrt{|\Omega_k|}x)/\sqrt{|\Omega_k|}, & \text{if } \Omega_k < 0, \\ x, & \text{if } \Omega_k = 0, \\ \sinh(\sqrt{|\Omega_k|}x)/\sqrt{|\Omega_k|}, & \text{if } \Omega_k > 0, \end{cases}$$

A.G. Riess et al., ApJ 853 (2018) 126

Observational Evidence from SNe Ia

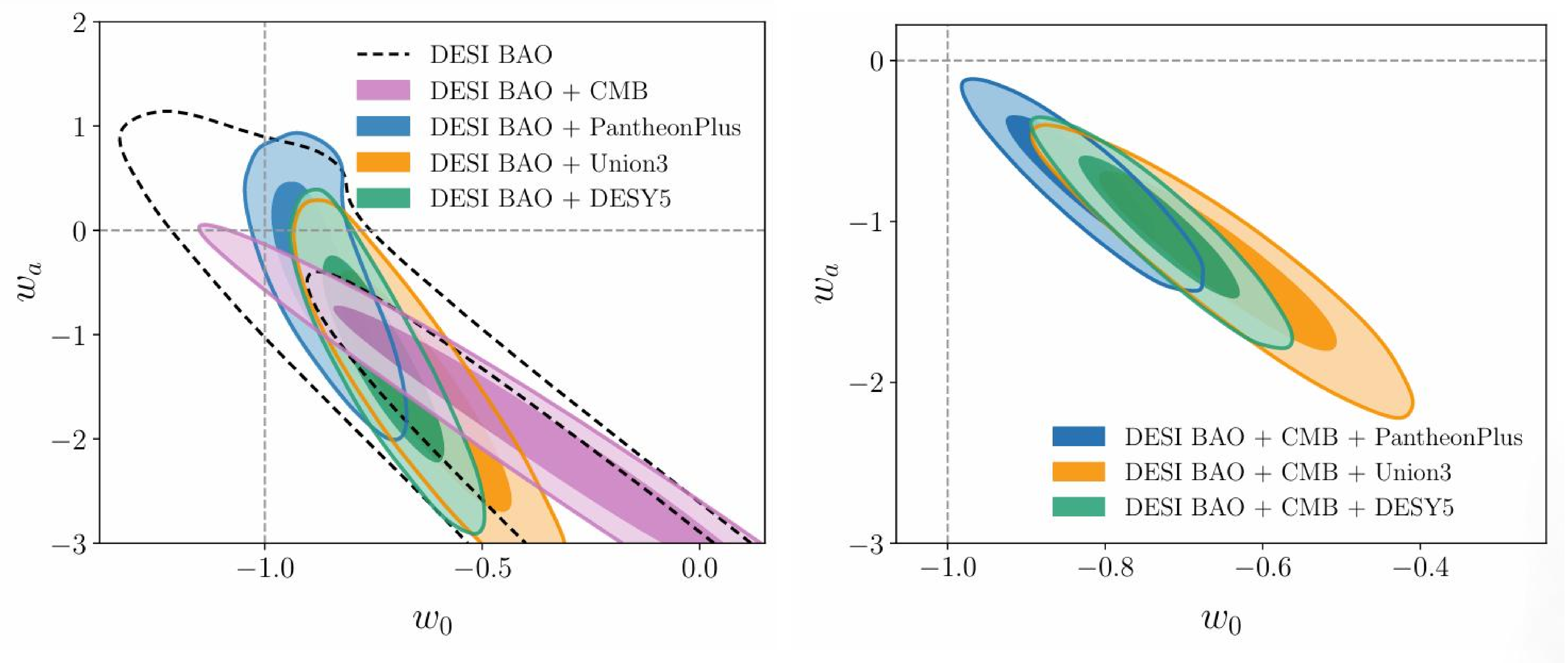
- Null hypotheses from energy conditions (spatially flat)



Y. Yang and Y. Gong, JCAP 06 (2020) 059

BAO data

- DESI BAO (dynamical dark energy)



Observational evidence from BAO

- DESI BAO data

$$D_H = c/H(z)$$

$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)dz}{E(z)}$$

Baryons decouple from photon

tracer	redshift	$N_{\rm tracer}$	$z_{\rm eff}$	$D_{\rm M}/r_{\rm d}$	$D_{\rm H}/r_{\rm d}$	r or $D_{\rm V}/r_{\rm d}$	$V_{\rm eff}$ (Gpc^3)
BGS	$0.1-0.4$	300,017	0.295	—	—	7.93 ± 0.15	1.7
LRG1	$0.4-0.6$	506,905	0.510	13.62 ± 0.25	20.98 ± 0.61	-0.445	2.6
LRG2	$0.6-0.8$	771,875	0.706	16.85 ± 0.32	20.08 ± 0.60	-0.420	4.0
LRG3+ELG1	$0.8-1.1$	1,876,164	0.930	21.71 ± 0.28	17.88 ± 0.35	-0.389	6.5
ELG2	$1.1-1.6$	1,415,687	1.317	27.79 ± 0.69	13.82 ± 0.42	-0.444	2.7
QSO	$0.8-2.1$	856,652	1.491	—	—	26.07 ± 0.67	1.5
Lya QSO	$1.77-4.16$	709,565	2.330	39.71 ± 0.94	8.52 ± 0.17	-0.477	—

$$\frac{D_M}{r_d} \le \frac{c}{r_d H_0} \ln(1+z) \qquad \frac{D_M}{r_d} \le \frac{cz}{r_d H_0}$$

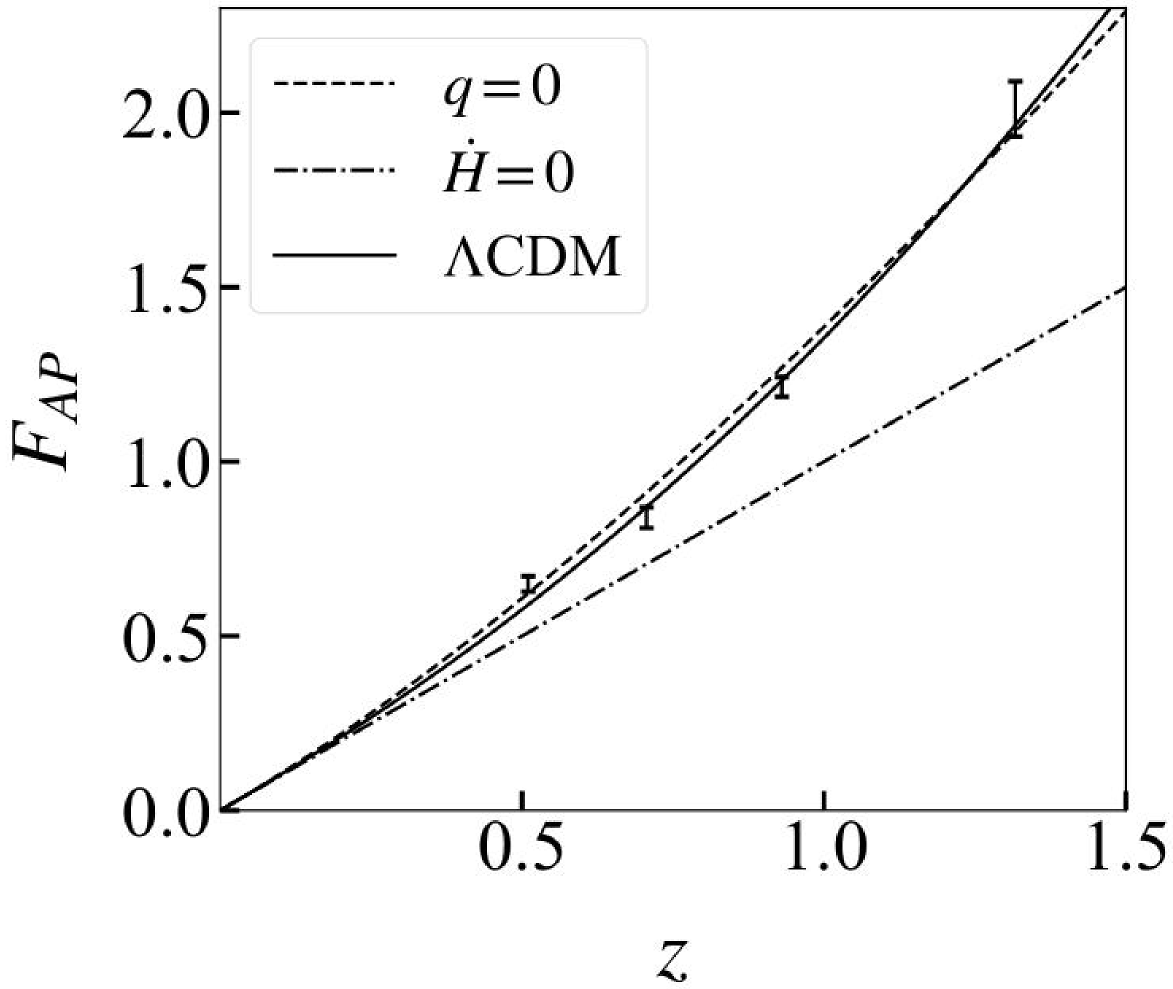
$$\frac{D_H}{r_d} \le \frac{c}{r_d H_0} \frac{1}{1+z} \qquad \frac{D_H}{r_d} \le \frac{c}{r_d H_0}$$

A.G.Adame etal., 2404.03002

Null hypotheses

- AP parameter

$$F_{AP} = \frac{D_M}{D_H} = E(z)\int_0^z \frac{1}{E(z')}dz'$$

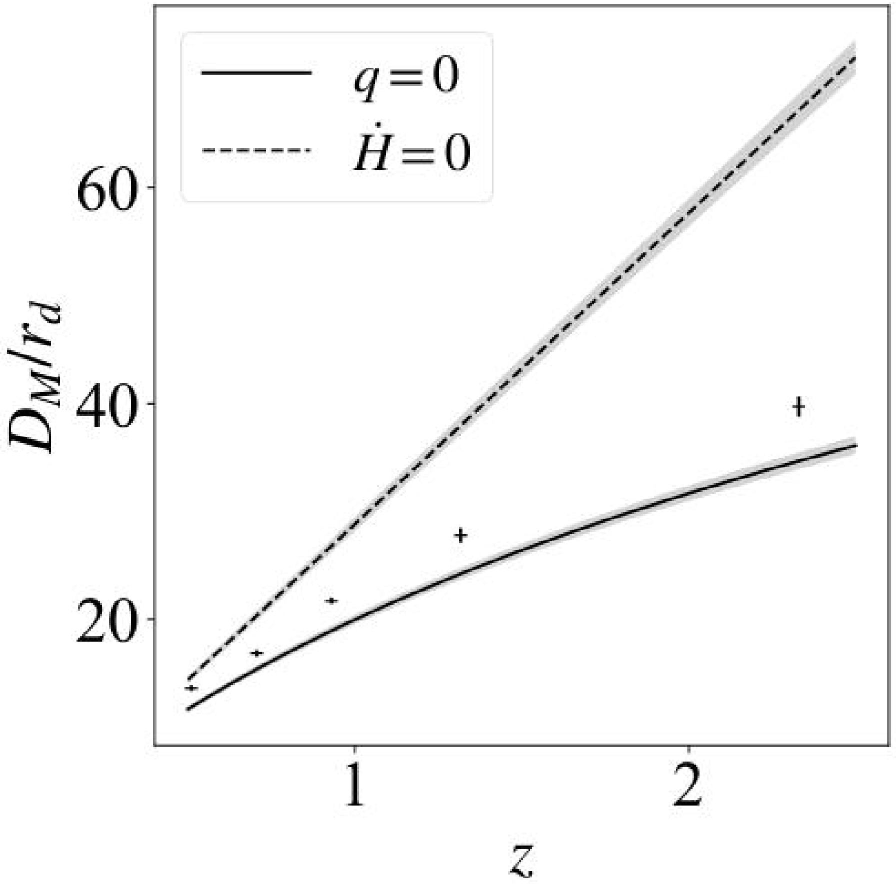


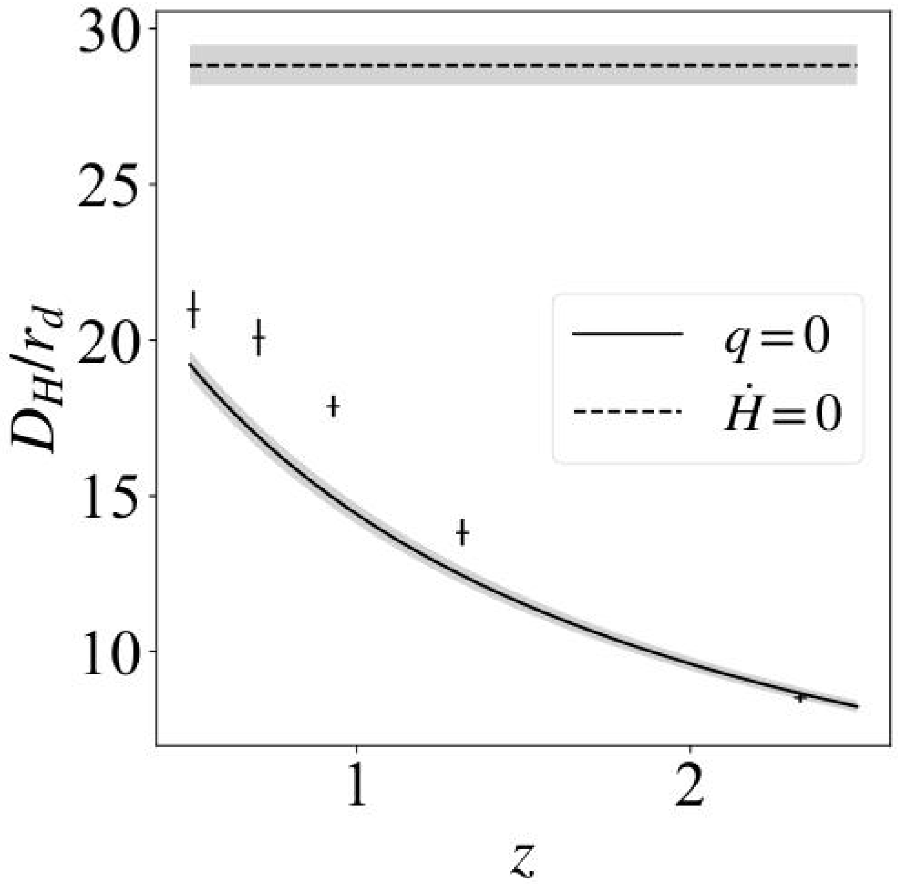
Null hypotheses with BAO data

- Null hypotheses

$$r_d h = (104.02 \pm 2.34)\ \mathrm{Mpc}$$

B. R. Dinda, R. Maartens, 2407.17252



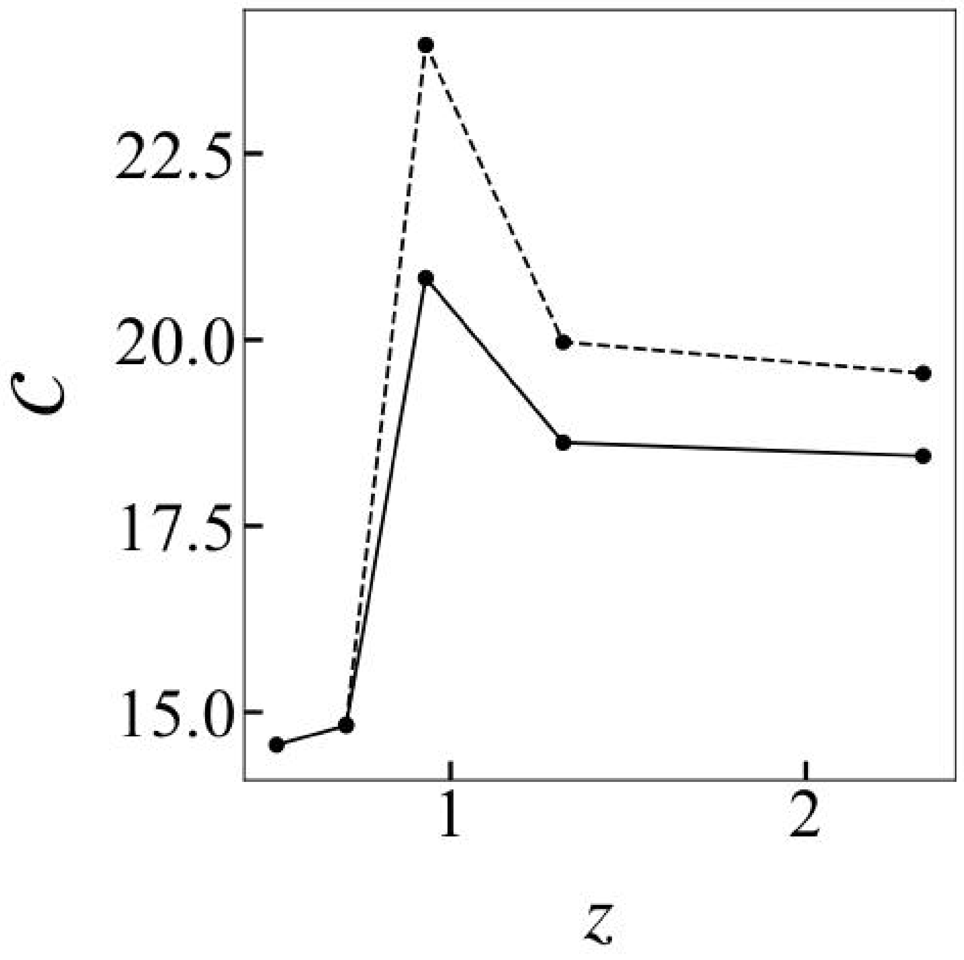


X. Lu, S. Gao & Y. Gong, 2409.13399

Null hypotheses

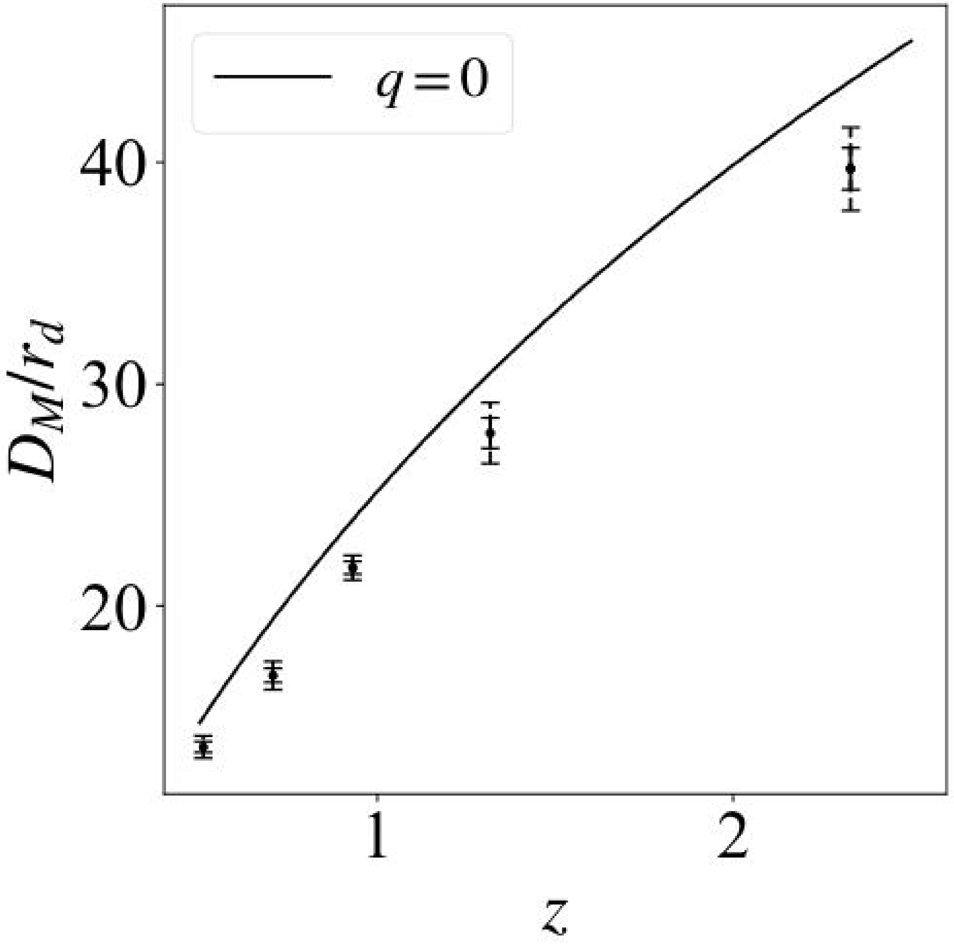
- The measure

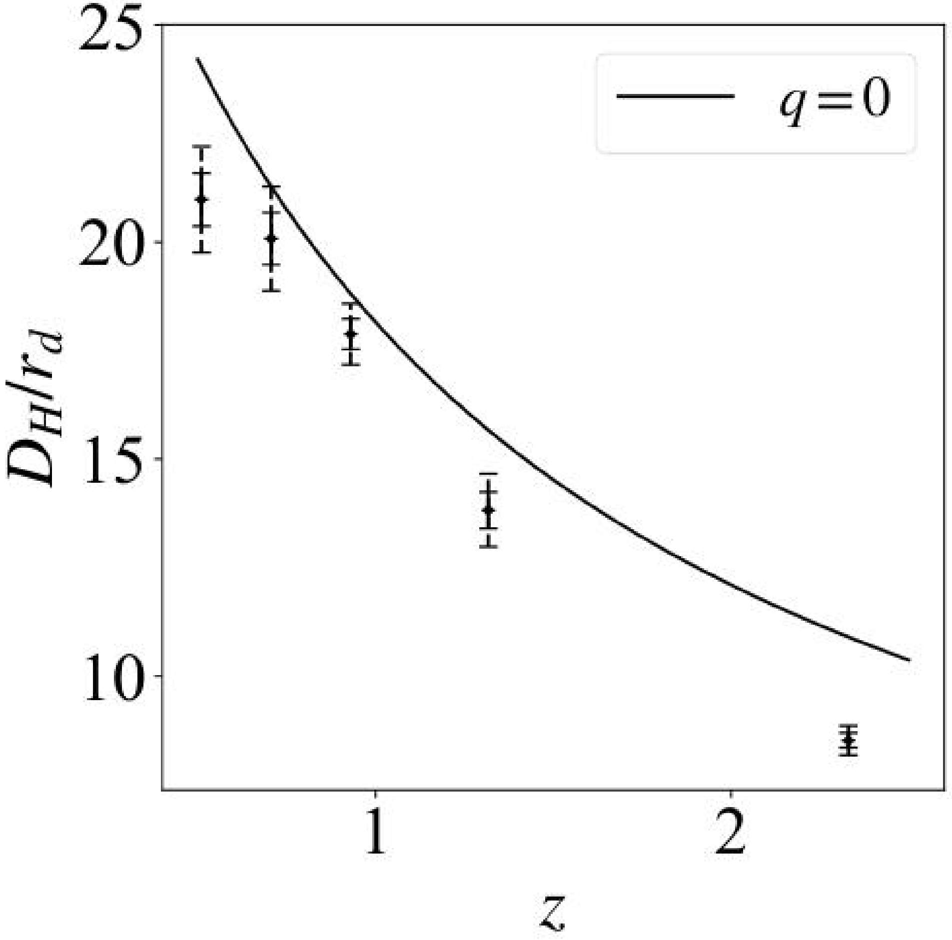
$$\mathcal{C} = \frac{1}{N}\sum_{i=1}^{N}\frac{[(D(z_i)/r_d)_{\rm BAO} - (D(z_i)/r_d)_{\rm null}]^2}{\sigma_i^2}$$



The constraint on the acoustic scale

- The minimum value (for acceleration) $r_d h \geq 82.58$ Mpc

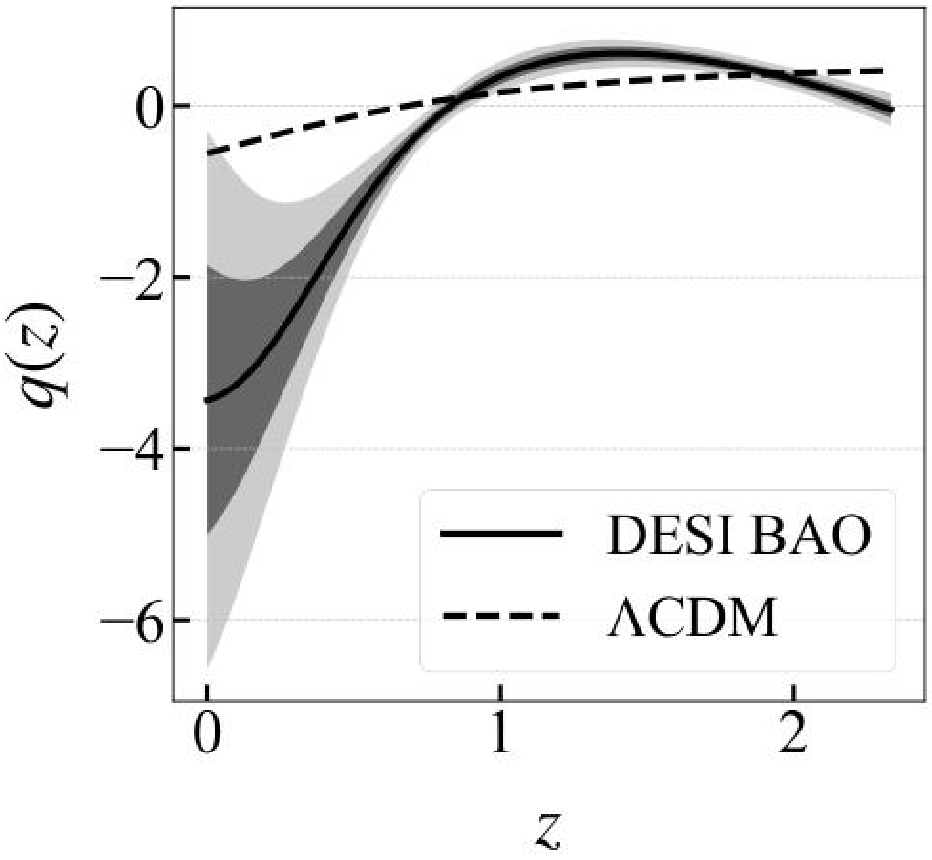


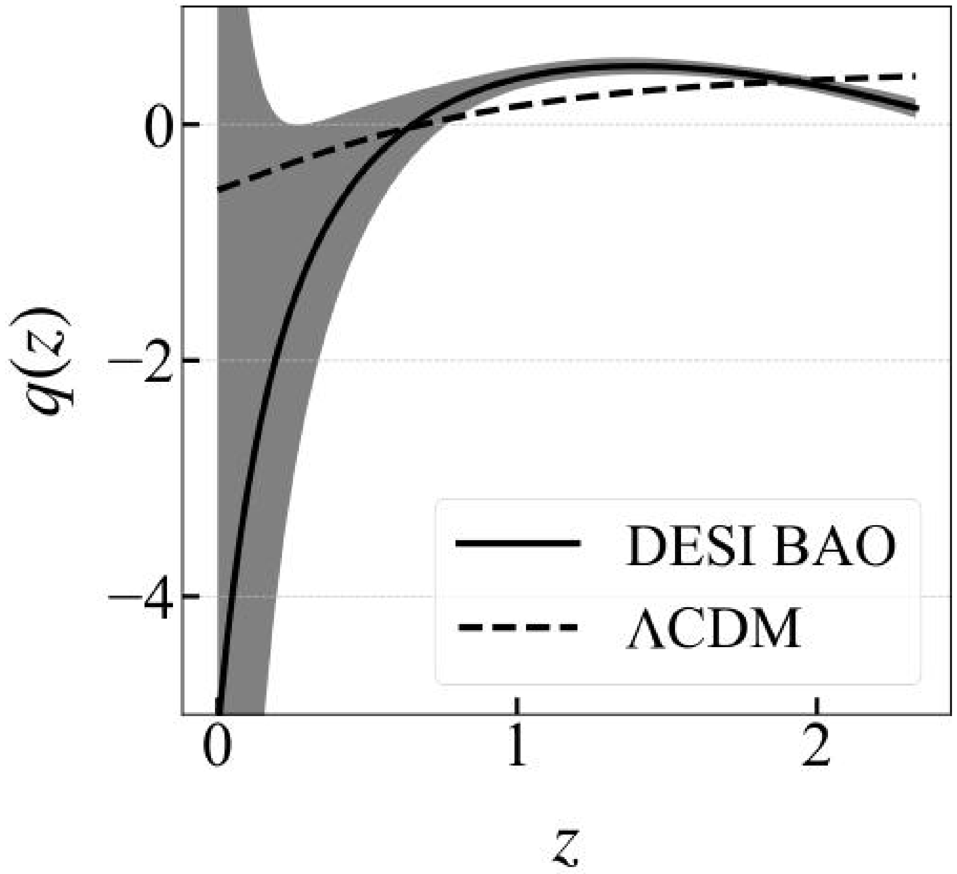


Reconstruction of the deceleration parameter

- Reconstruction of q(z) from DESI BAO data

$$q(z) = \frac{F'_{AP} - 1}{F_{AP}}(1+z) - 1$$





X. Lu, S. Gao & Y. Gong, 2409.13399

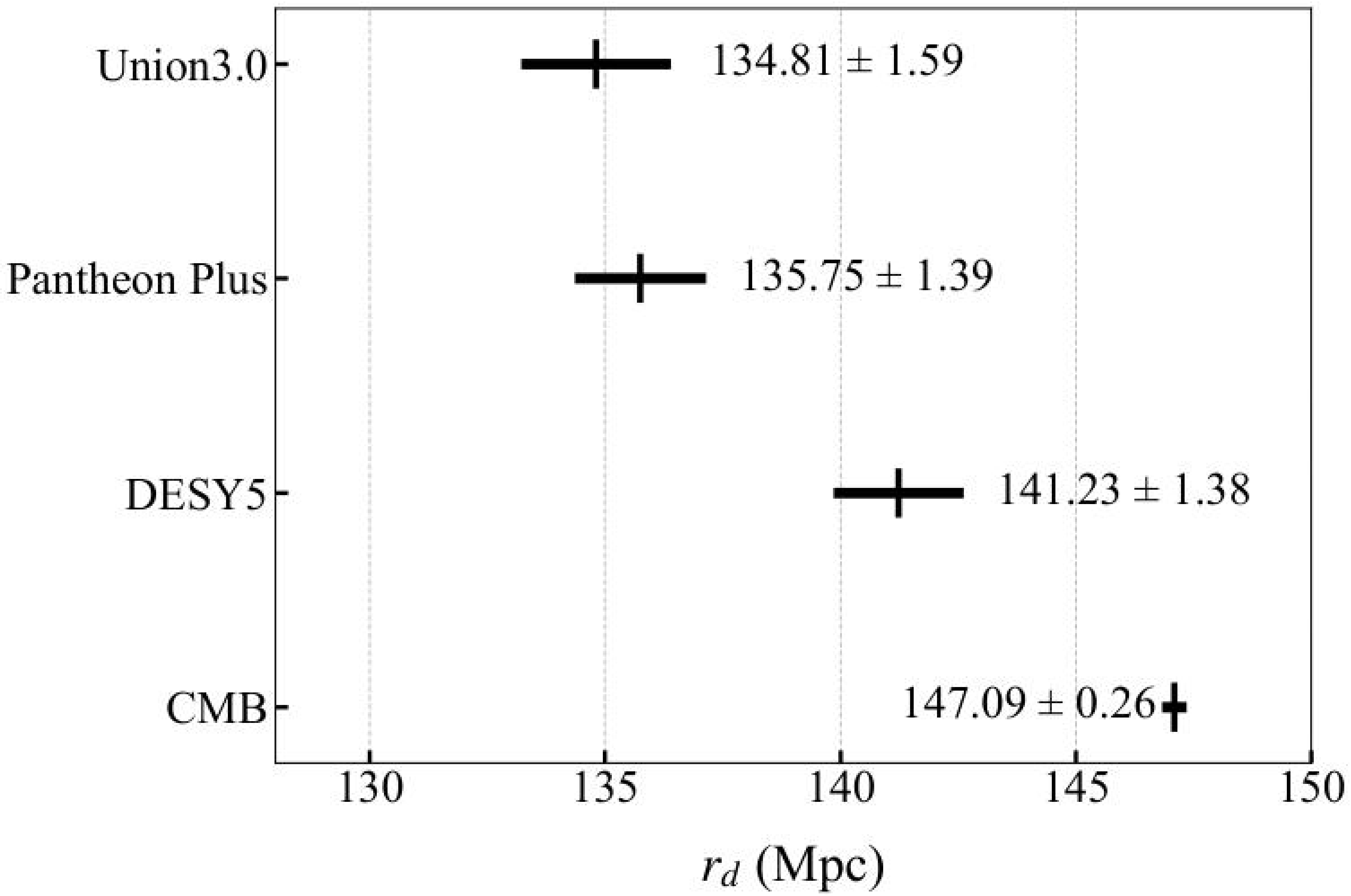
Hubble tension

- Reconstruction distance from SNe Ia using Gaussian process

$$\mu = 5\log_{10}\left[\frac{d_L(z)}{\mathrm{Mpc}}\right] + 25$$

$$d_L(z) = (1+z)D_M(z)$$

$$\chi^2 = \sum_i^N \left[\frac{\left[(D_M/r_d)_i - \tilde{D}(z_i)\right]^2}{(\sigma^i_{D_M/r_d})^2 + (\sigma^i_P)^2}\right]$$



X. Lu, S. Gao & Y. Gong, 2409.13399

GW standard siren

- GW170817 and GRB 170817A

$$H_0 = 70^{+12}_{-8}\ \mathrm{km/s/Mpc}$$

LIGO/Virgo, Nature 551 (2017) 85

- GWTC-3

$$H_0 = 68^{+8}_{-6}\ \mathrm{km/s/Mpc}$$

LIGO/Virgo/KAGRA, 2111.03604

- GW standard sirens (BNS)
  - Distance measurement

Holz and Hughes, ApJ 629 (2005) 15

$$d_L = \frac{5c^6}{96\pi^2}\frac{1}{2^{1/3}f^{5/2}A(f)}\sqrt{\frac{\dot{f}(t)}{f(t)}}$$

  - 2% accuracy within 5 years ~ 50 BNS

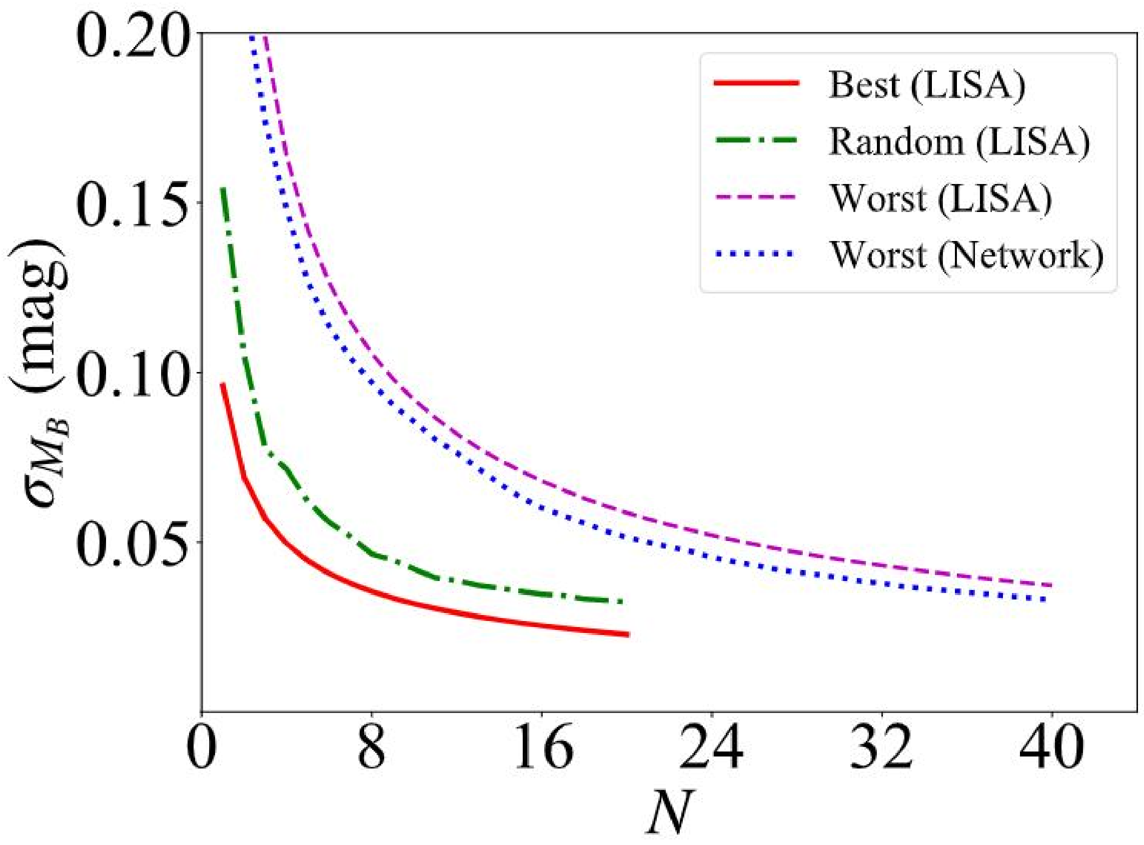
Chen etal., Nature 562 (2018) 545

SNe Ia calibration

- Calibration of the absolute magnitude

$$m_B(z) = 5\log_{10}\left[\frac{d_L(z)}{\mathrm{Mpc}}\right] + 25 + M_B,$$

$$\sigma_{M_B} = \sqrt{(\sigma_{m_B})^2 + \left(\frac{5\sigma_{d_L}}{\ln 10\, d_L}\right)^2}$$



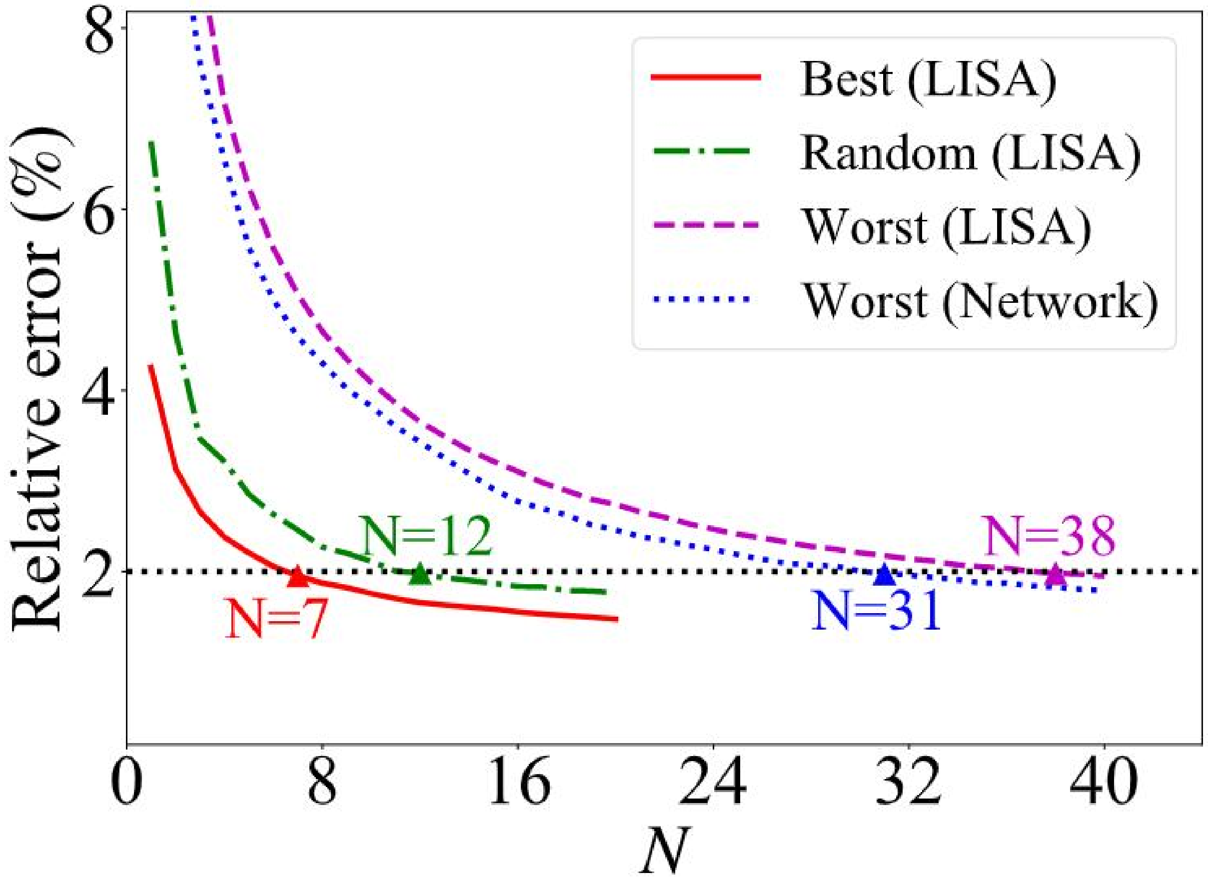
X. Lu & Y. Gong, EPJC 83 (2023) 949

Hubble constant

- Local Hubble constant by low-redshift SNe Ia data (237)
  - 7个超大质量双黑洞并合事件可以用来定标超新星数据，则哈勃常数的测量精度可以达到2%

$$d_L(z) = \frac{cz}{H_0}\left[1 + \frac{1}{2}(1-q_0)z + O\left(z^3\right)\right]$$

$$0.023 < z < 0.15$$



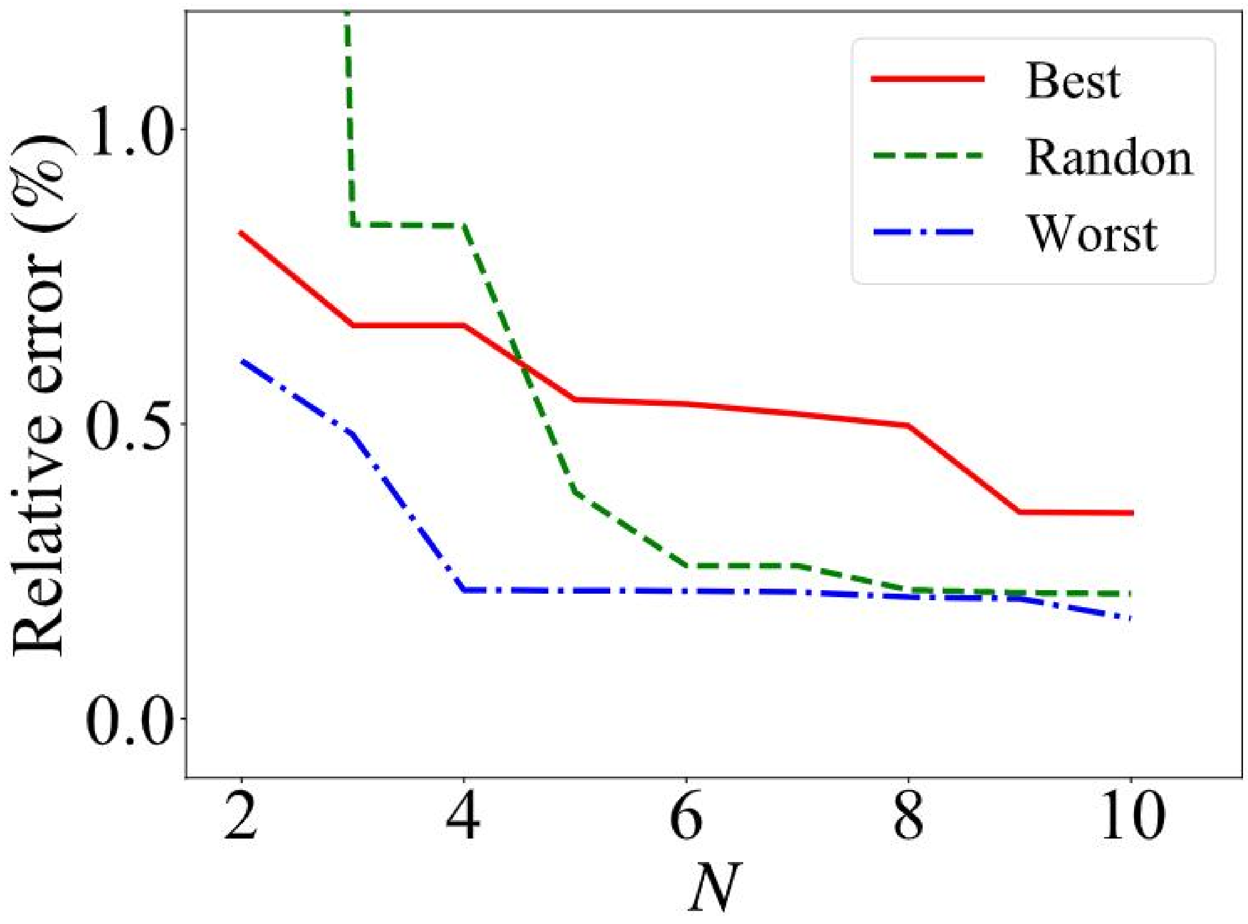
X. Lu & Y. Gong, EPJC 83 (2023) 949

GW standard sirens

- Hubble constant by GW standard sirens (MBBHs)

Baseline model: LCDM model

model dependent



X. Lu & Y. Gong, EPJC 83 (2023) 949

Discussion: the event rate

- SN standard candles calibrated by BNS

3G ground network

$$\sim 0.1\% - 3\%, \quad \leq 300 \text{ Mpc}$$

Zhao & Santos, JCAP 1911 (2019) 009;
Gupta, Fox & Schutz, ApJ 886 (2019) 71

- Standard candles calibrated by MBBHs
  - Coincident MBBHs mergers and SNe Ia in the same galaxy: all SNe Ia calibrated by MBBHs

$$d_L \sim 1300 \text{ Mpc}, \ \Delta d_L \sim 0.8 \text{ Mpc}, \ \Delta\Omega_s \sim 5.1 \times 10^{-5} \text{ deg}^2,$$

$$\Delta V \sim 6.7 \times 10^{-8} \text{ Gpc}^3 \qquad 3 \times 10^6 \text{ Gpc}^{-3}$$

  - Measurement of the Hubble constant by Low-redshift SNe Ia data: Pantheon sample, 237 SNe Ia

$$0.023 < z < 0.15$$

Conclusion

- The null hypotheses (Energy conditions) assume the cosmological principle (Friedman-Robertson Walker metric) and are independent of cosmological models and gravitational theory
- Distance measurements: SNe Ia (Hubble constant, zero-point calibration), BAO (acoustic scale at the drag epoch)
- Propose a method of combining SNe Ia and BAO data
- Propose the calibration of SNe Ia with distance measurements from GWs

Thank you