Reducing the H_0 Tension with Exponential Acoustic Dark Energy

Lu Yin

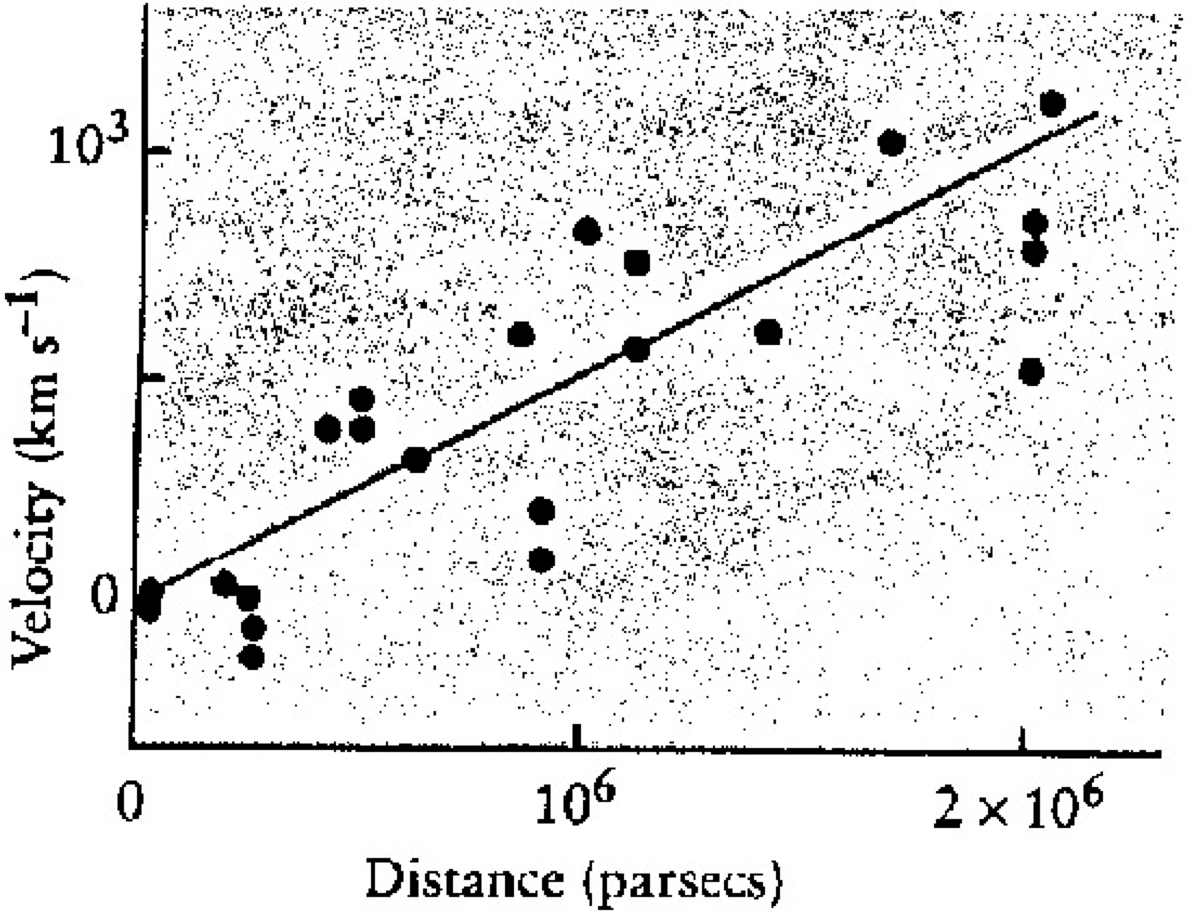
CQUeST

Sogang University

Based on: Eur.Phys.J.C 82 (2022) 1, 78

Workshop: CQUeST 2022, **June 27, 2022 to July 1, 2022**

The discovery of Hubble constant



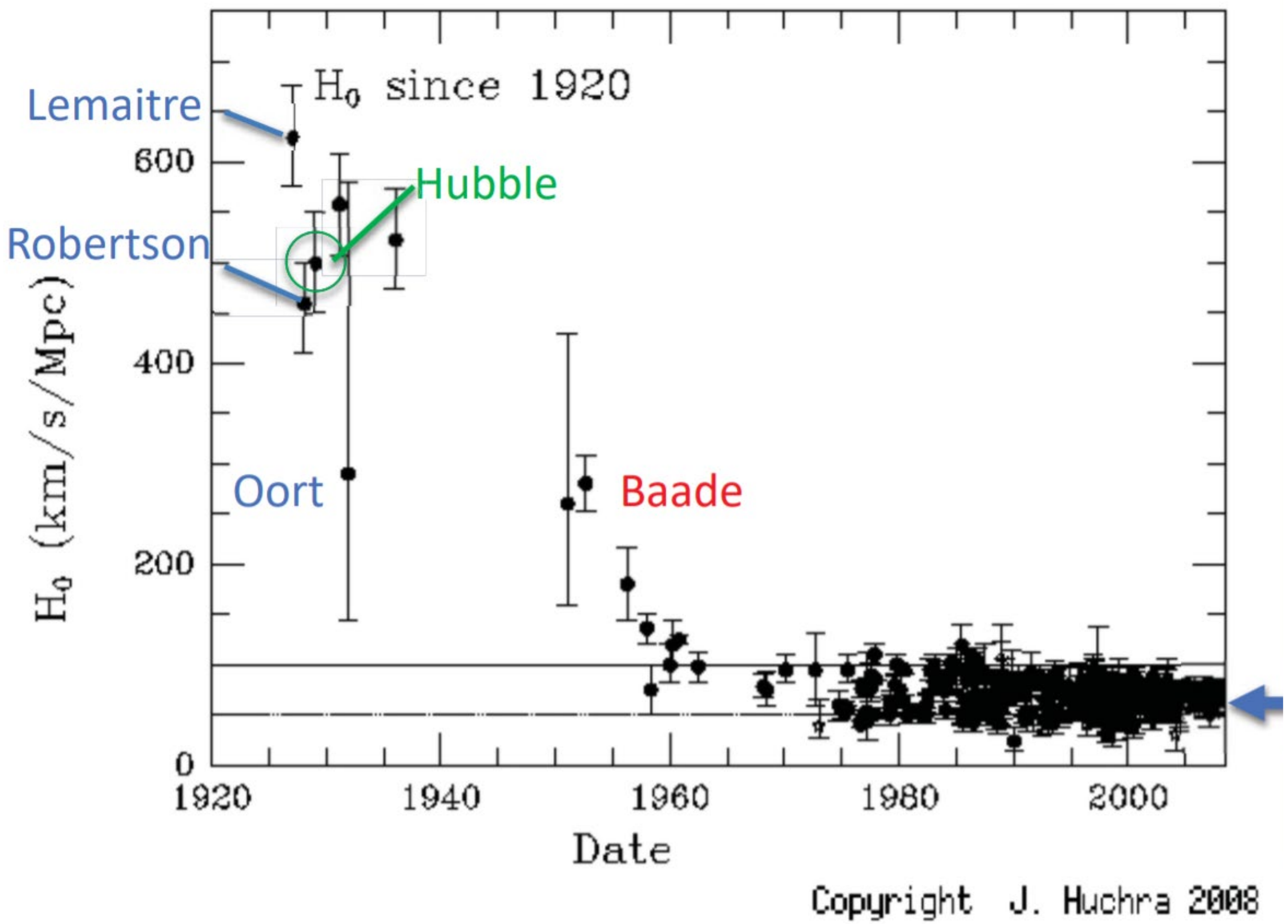
$$v = H_0 \times D$$

E. Hubble, Proc. Nat. Acad. Sci. 15 (1929), 168-173

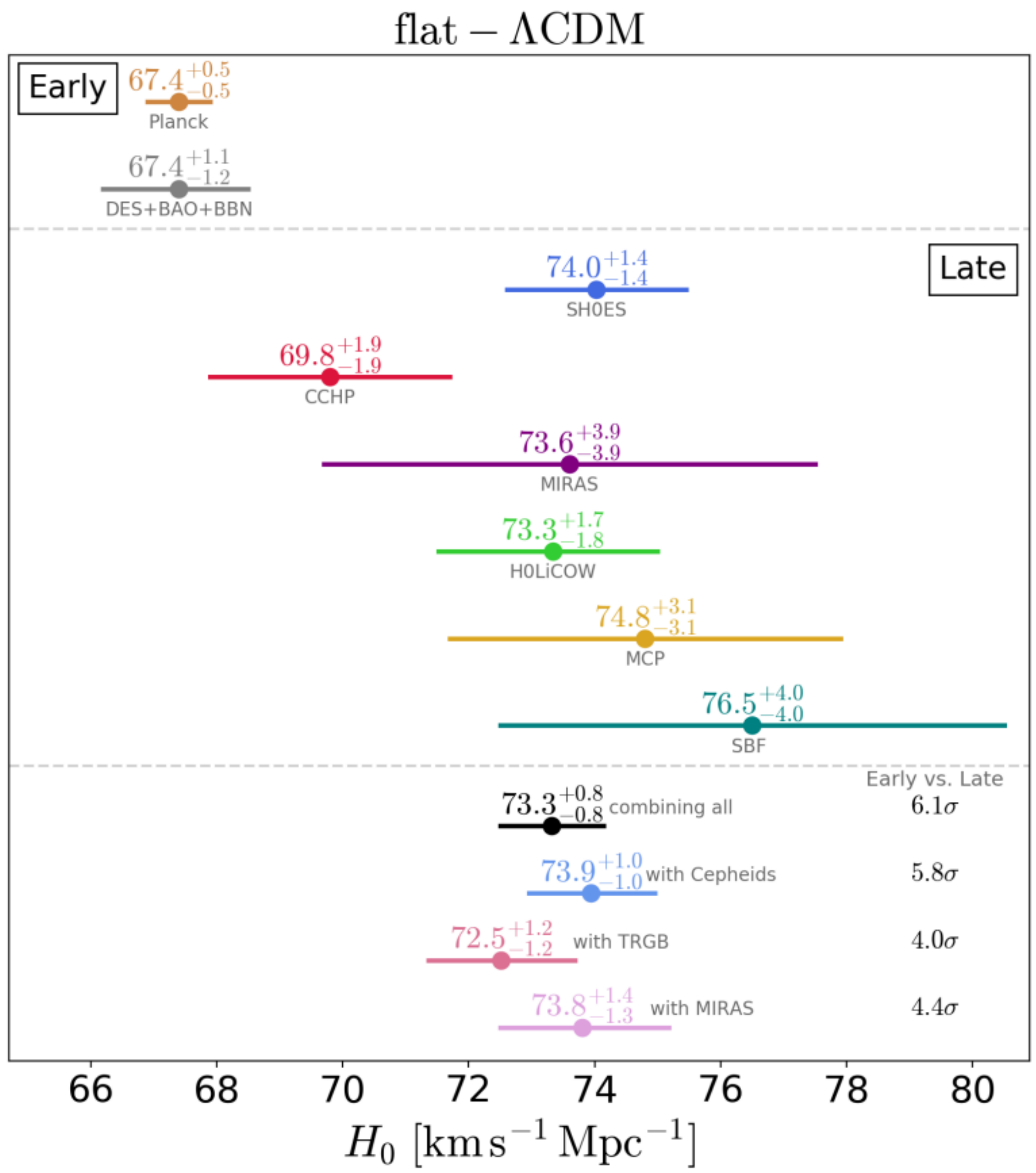
Edwin Hubble

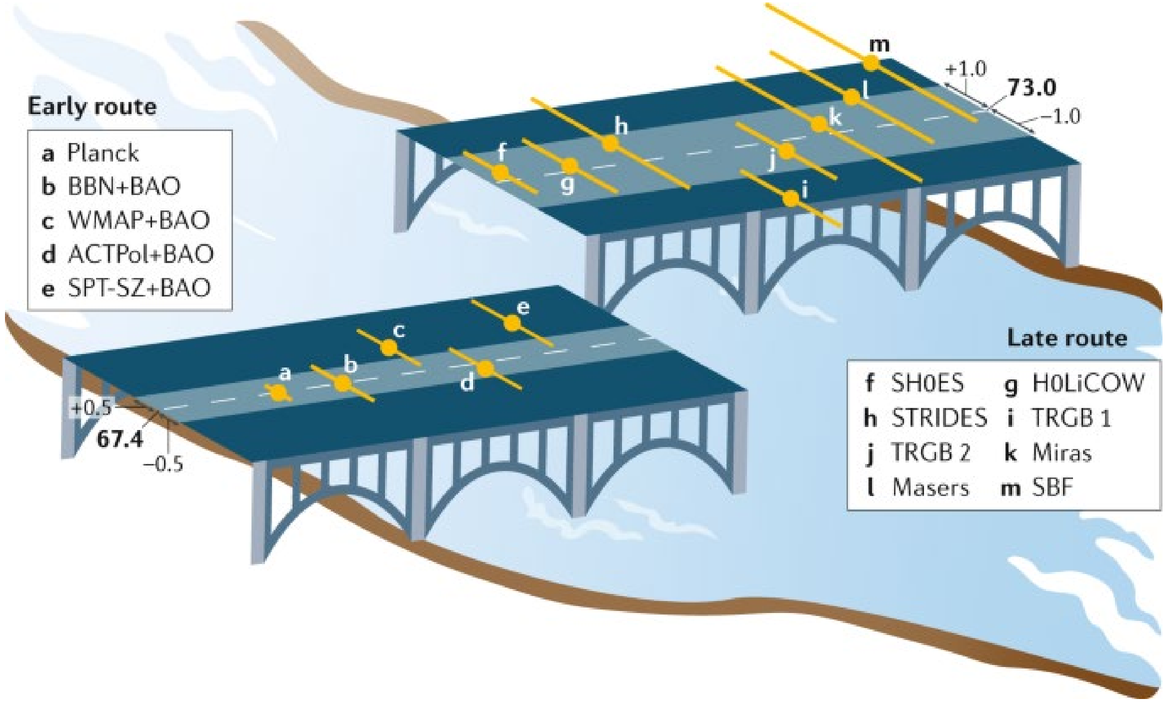
V : recessional velocity
D : the proper distance to the observer
H_0 : Hubble's constant [km/s/Mpc]

History of the Hubble constant



The H_0 tension





[L. Verde, T. Treu and A. G. Riess *Nature Astron.* 3 891]

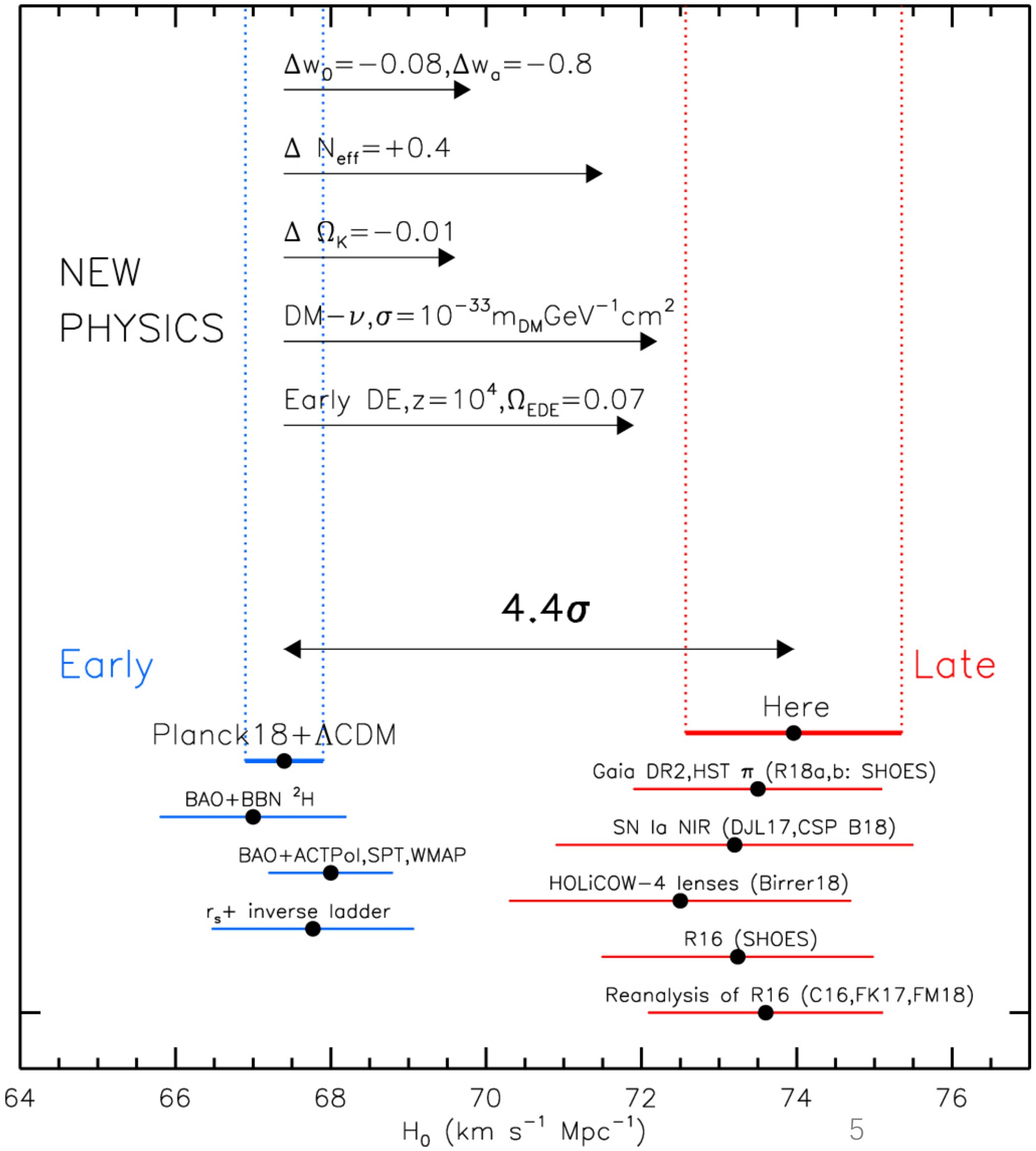
Potential new physics beyond ΛCDM

Another relativistic species
(e.g.,additional neutrino or dark radiation)

Non-zero spatial curvature

A decaying relic massive dark matter

Early dark energy



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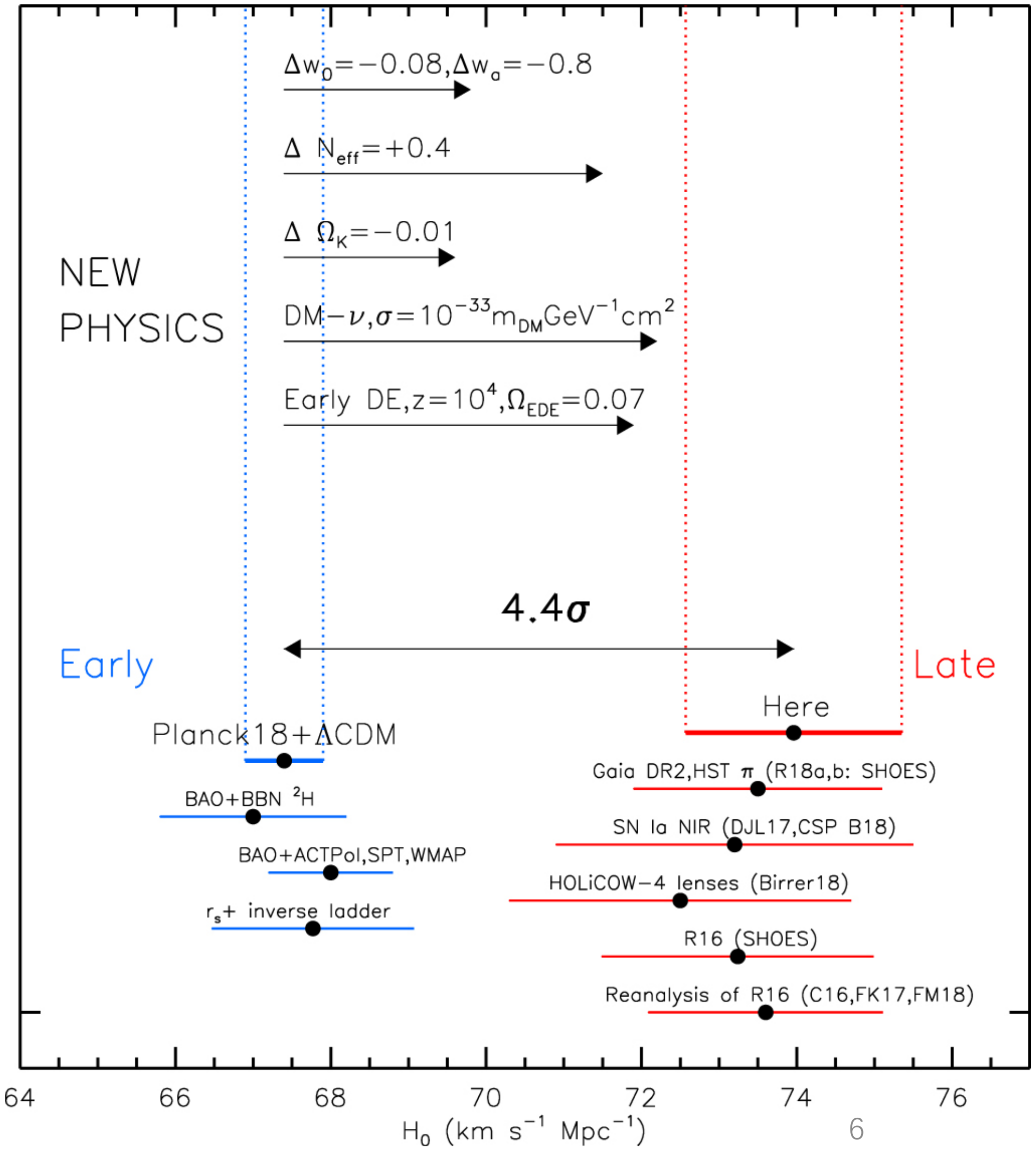
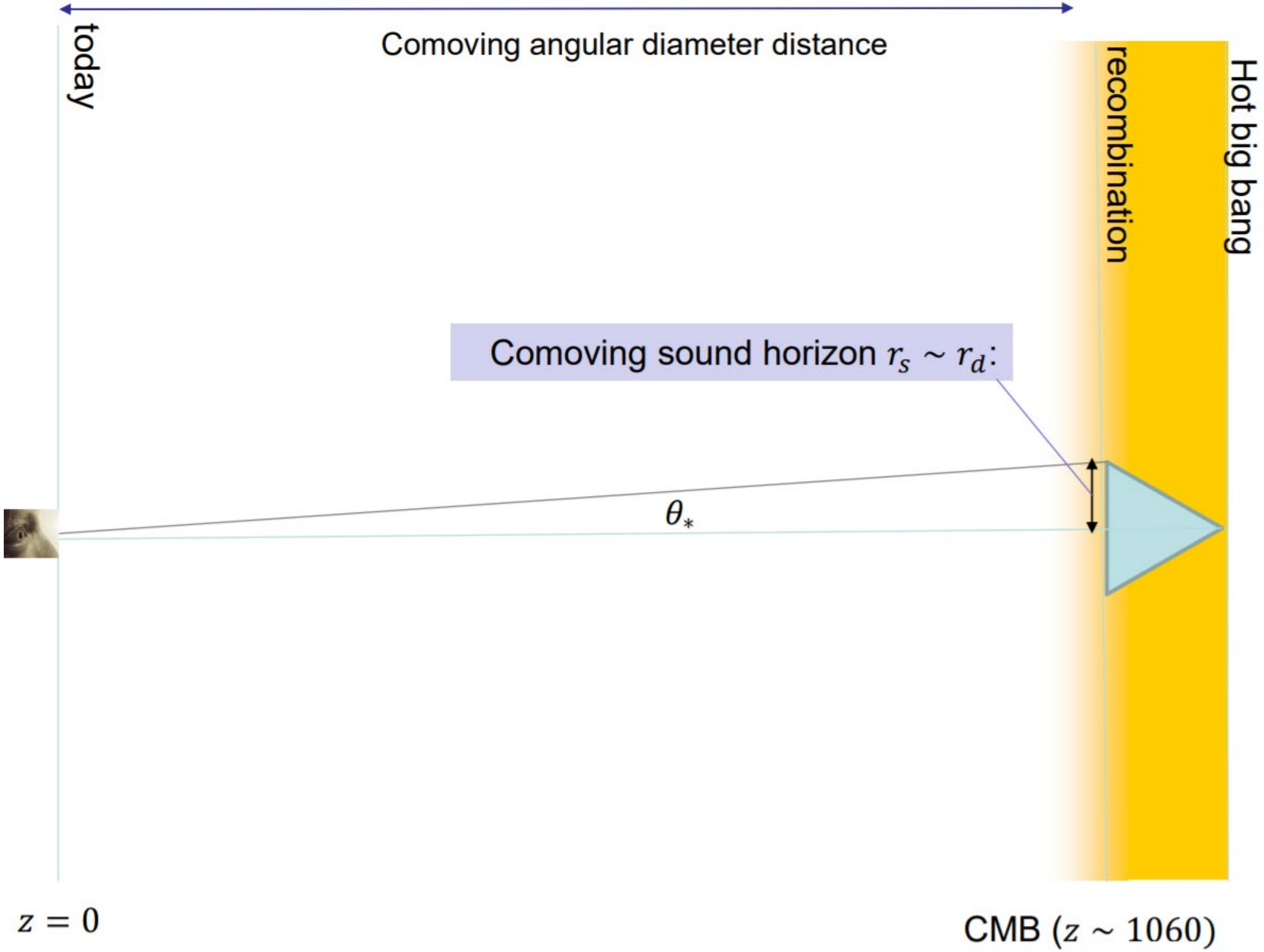
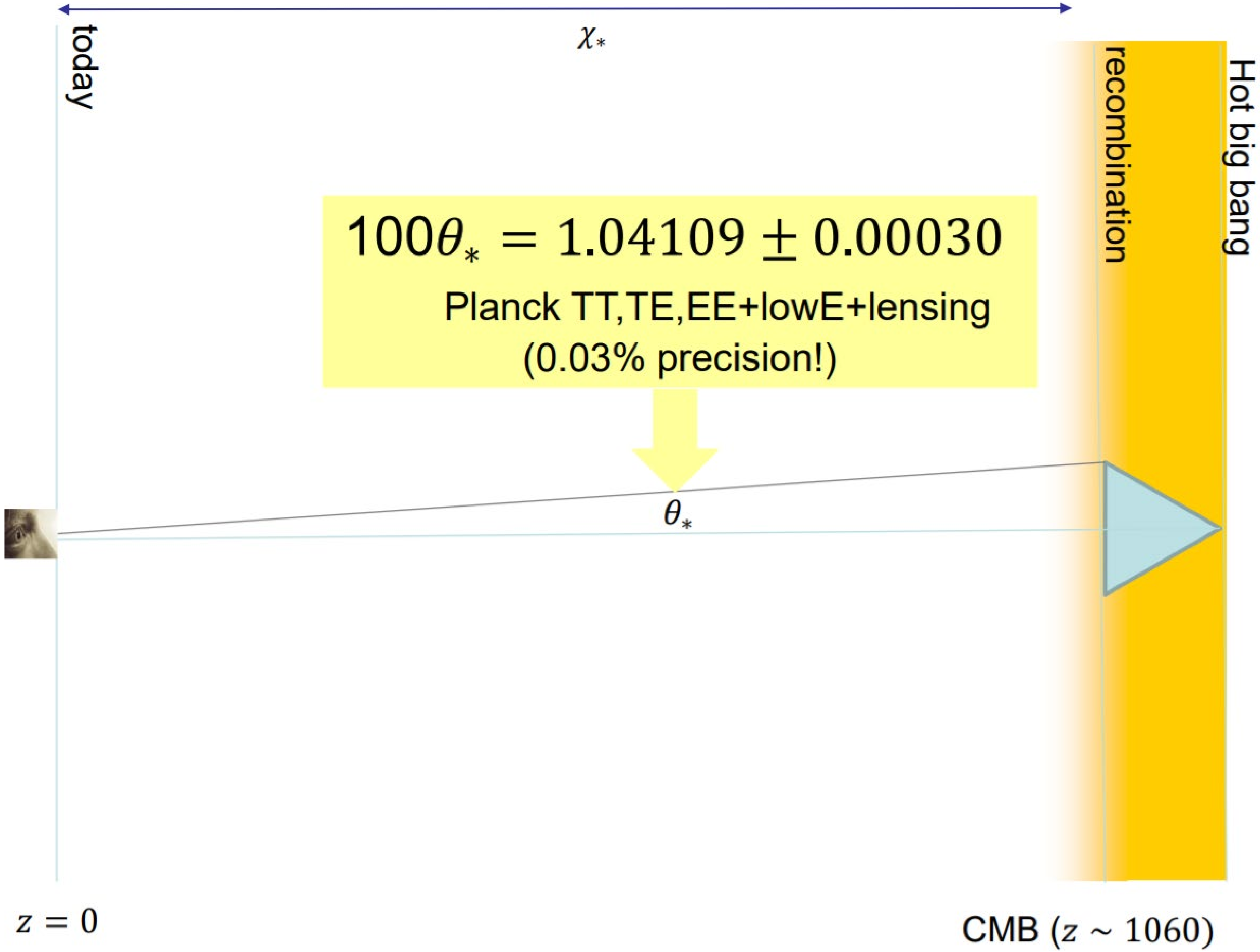


H_0 from CMB and Planck





χ_*
today
recombination
Hot big bang
$100\theta_* = 1.04109 \pm 0.00030$
Planck TT,TE,EE+lowE+lensing
(0.03% precision!)
θ_*
$z = 0$
CMB ($z \sim 1060$)

today

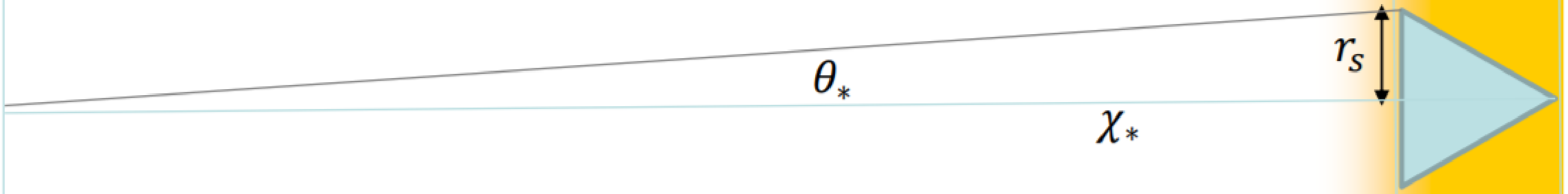
$r_s, \theta_* \Rightarrow$ Comoving radial distance $\chi_* \sim (13.87 \pm 0.03)$ Gpc

recombination

Hot big bang

$$\chi_* = \int \left(\frac{cdt}{a}\right)$$
$$= \int \left(\frac{da}{a^2 H}\right) \approx \int \frac{da}{\sqrt{a\Omega_m H_0^2 + a^4 \Omega_\Lambda H_0^2}}$$

$\Omega_\Lambda H_0^2 = H_0^2 - \Omega_m H_0^2$ and know $\Omega_m h^2 \Rightarrow H_0$



$$\Rightarrow H_0 = (67.3 \pm 0.6)\ \mathrm{km\ s^{-1} Mpc^{-1}}$$

Assume baryons, CDM, photons, 3 neutrinos
Know T_{CMB}, peaks measure $\Omega_m h^2, \Omega_b h^2$

$\Rightarrow$ comoving sound horizon:

$$r_s \approx \int_0^{t_*} \frac{c_s dt}{a} \sim (144.4 \pm 0.3)\ \mathrm{Mpc}$$

$z = 0$

CMB ($z \sim 1060$)

In the Realm of the Hubble tension – a Review of Solutions †

Eleonora Di Valentino[1*], Olga Mena[2], Supriya Pan[3], Luca Visinelli[4], Weiqiang Yang[5], Alessandro Melchiorri[6], David F. Mota[7], Adam G. Riess[8,9], Joseph Silk[8,10,11]

[*Class.Quant.Grav.* 38 (2021) 15, 153001]

4 Early Dark Energy

The difference between EDE, ADE, eADE model

Early dark energy, the Hubble-parameter tension, and the string axiverse

Tanvi Karwal and Marc Kamionkowski
Department of Physics and Astronomy, Johns Hopkins University,
3400 N. Charles St., Baltimore, MD 21218
(Dated: November 8, 2016)

$$w_\varphi(z) = \frac{1 + w_n}{1 + (a_c/a)^{3(1+w_n)}} - 1$$

$$w_n = (n-1)/(n+1)$$

$$n = 2 \quad | \quad n = 3 \quad | \quad n = \infty$$

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Acoustic Dark Energy: Potential Conversion of the Hubble Tension

Meng-Xiang Lin,[1] Giampaolo Benevento,[2,3,1] Wayne Hu,[1] and Marco Raveri[1]
[1] *Kavli Institute for Cosmological Physics, Department of Astronomy & Astrophysics, Enrico Fermi Institute, The University of Chicago, Chicago, IL 60637, USA*
[2] *Dipartimento di Fisica e Astronomia "G. Galilei", Università degli Studi di Padova, via Marzolo 8, I-35131, Padova, Italy*
[3] *INFN, Sezione di Padova, via Marzolo 8, I-35131, Padova, Italy*

$$w_{\rm ADE}(a) = \frac{1 + w_{\rm f}}{[1 + (a_c/a)^{3(1+w_{\rm f})/p}]^p} - 1$$

$$c_s^2 = w_{\rm f} = 1$$

$$p = 1/2$$

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$$w_{\mathrm{ADE}}(a) = \frac{1+w_{\mathrm{f}}}{[1+(a_c/a)^{3(1+w_{\mathrm{f}})/p}]^p} - 1$$

Reducing the H_0 Tension with Exponential Acoustic Dark Energy

Lu Yin[1,2,*]
[1] *Center for Quantum Spacetime, Sogang University, Seoul 04107, Korea*
[2] *Department of Physics, Sogang University, Seoul 04107, Korea*

$$w_{eADE}(a) = 2^{1-\frac{a_c}{2a}} - 1$$

The eADE have less additional parameters

The difference between EDE, ADE, eADE model

Value of EoS	$a \ll a_c$	$a = a_c$	$a = 1$
w_{eADE}	-1	$\sqrt{2}-1$	1
w_{ADE}	-1	$\sqrt{2}-1$	1
w_{EDE} with $n=3$	-1	$-1/4$	$1/2$
w_{EDE} with $n=2$	-1	$-1/3$	$1/3$

$$w_\varphi(z) = \frac{1+w_n}{1+(a_c/a)^{3(1+w_n)}} - 1$$

$$w_{\rm ADE}(a) = \frac{1+w_{\rm f}}{[1+(a_c/a)^{3(1+w_{\rm f})/p}]^p} - 1$$

$$w_{eADE}(a) = 2^{1-\frac{a_c}{2a}} - 1$$

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The eADE have less additional parameters

Background evolution and linear perturbation for eADE

The eADE density evolves as

$$\Omega_{eADE}(a) = \frac{\rho_{eADE}}{\rho_{tot}} = 2f_c\frac{(c_s^2+1)^2-(w_{eADE}+1)^2}{(c_s^2+1)^2}$$

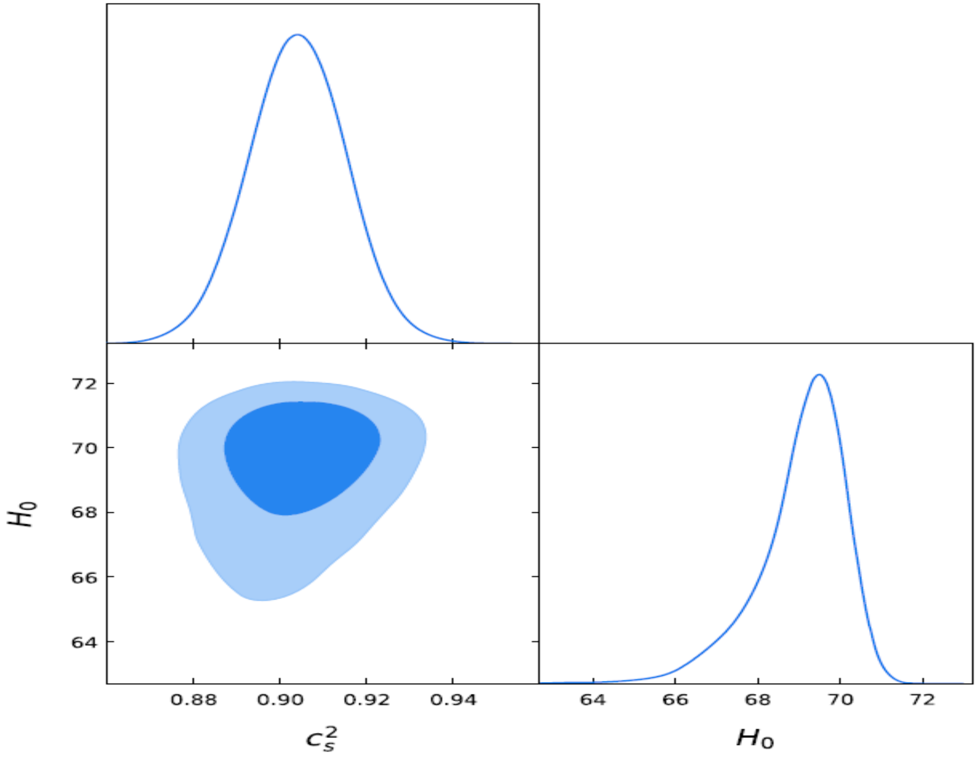
$$1+w_{eADE}(a) = 2^{1-\frac{a_c}{2a}}$$

$$f_c = \frac{\rho_{eADE}(a_c)}{\rho_{tot}(a_c)}$$

When the sound speed equal to 1:

$$\Omega_{eADE}(a) \overset{c_s^2=1}{=} f_c[2-\frac{(w_{eADE}(a)+1)^2}{2}]$$

$$P_{eADE} \overset{c_s^2=1}{=} \frac{6H^2 f_c}{8\pi G}(-2\xi^3+\xi^2+2\xi^1-\xi^0) \qquad \xi(a) = 2^{-\frac{a_c}{2a}}$$



The perturbation gives as:

$$\dot{\delta}_{eADE} = -(1+w_{eADE})(\theta_{eADE}+\frac{\dot{h}}{2}) - 3\frac{\dot{a}}{a}(c_s^2-w_{eADE})\delta_{eADE} - k\theta_{eADE}\,,$$

$$\dot{\theta}_{eADE} = \frac{\dot{a}}{a}(2w_{eADE}-1)\theta_{eADE} - \frac{\dot{w}_{eADE}}{1+w_{eADE}}\theta_{eADE} + \frac{c_s^2k^2}{a^2(1+w_{eADE})}\delta_{eADE}$$

Background evolution and linear perturbation for eADE

The eADE density evolves as

$$\Omega_{eADE}(a) = \frac{\rho_{eADE}}{\rho_{tot}} = 2 f_c \frac{(c_s^2+1)^2 - (w_{eADE}+1)^2}{(c_s^2+1)^2}$$

$$1 + w_{eADE}(a) = 2^{1-\frac{a_c}{2a}}$$

$$f_c = \frac{\rho_{eADE}(a_c)}{\rho_{tot}(a_c)}$$

When the sound speed equal to 1:

$$\Omega_{eADE}(a) \overset{c_s^2=1}{=} f_c[2 - \frac{(w_{eADE}(a)+1)^2}{2}]$$

$$P_{eADE} \overset{c_s^2=1}{=} \frac{6H^2 f_c}{8\pi G}(-2\xi^3 + \xi^2 + 2\xi^1 - \xi^0)$$

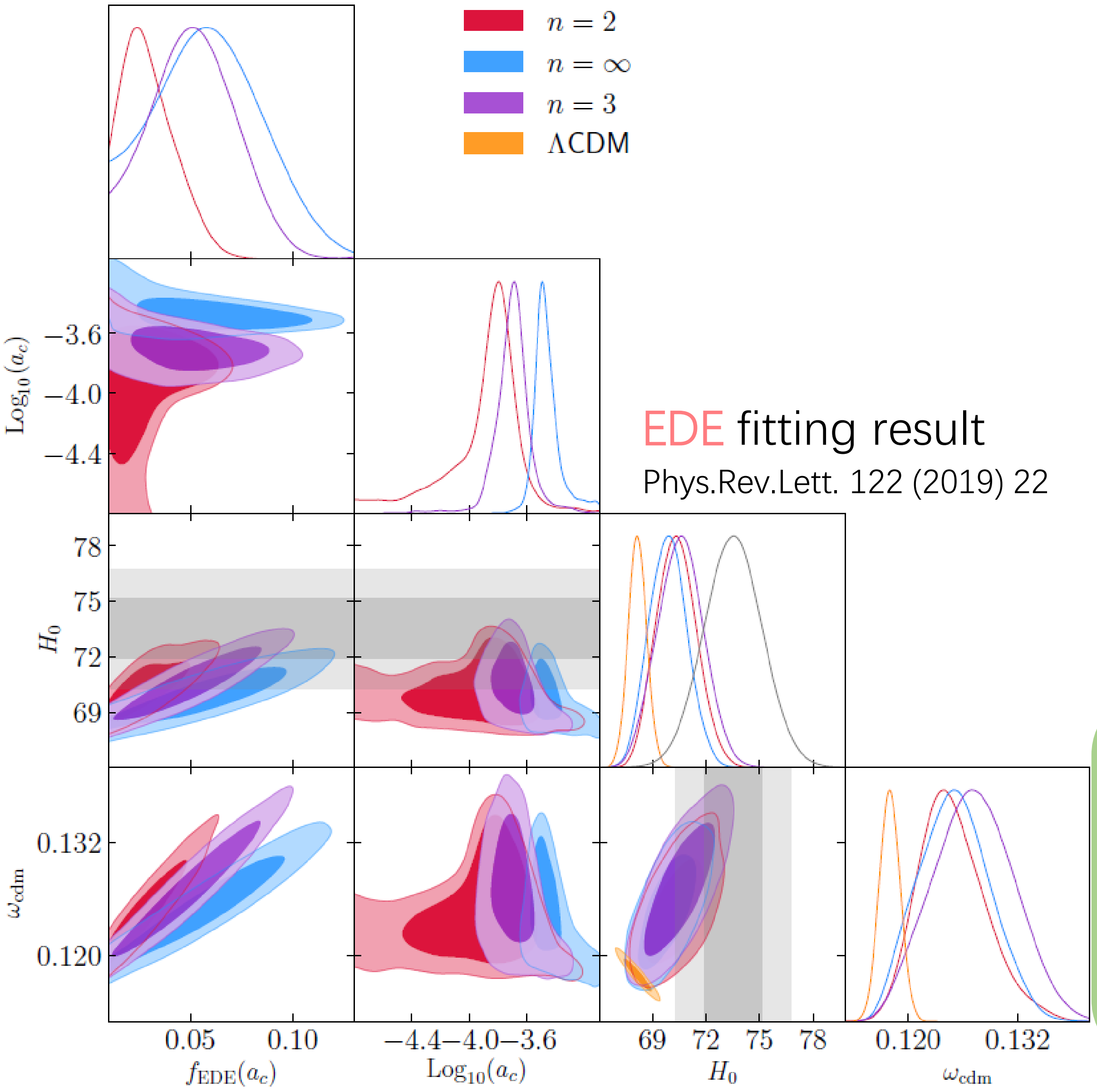
	$n=2$	$n=3$	$n=\infty$
$f_{\mathrm{EDE}}(a_c)$	0.028	0.050	0.054
$f_{\mathrm{ADE}}(a_c)$	0.082		
$f_{e\mathrm{ADE}}(a_c)$	?		

The perturbation gives as:

$$\dot{\delta}_{eADE} = -(1+w_{eADE})(\theta_{eADE} + \frac{\dot{h}}{2}) - 3\frac{\dot{a}}{a}(c_s^2 - w_{eADE})\delta_{eADE} - k\theta_{eADE}\,,$$

$$\dot{\theta}_{eADE} = \frac{\dot{a}}{a}(2w_{eADE} - 1)\theta_{eADE} - \frac{\dot{w}_{eADE}}{1+w_{eADE}}\theta_{eADE} + \frac{c_s^2 k^2}{a^2(1+w_{eADE})}\delta_{eADE}\,,$$

Fitting result for the EDE and ADE model



EDE fitting result

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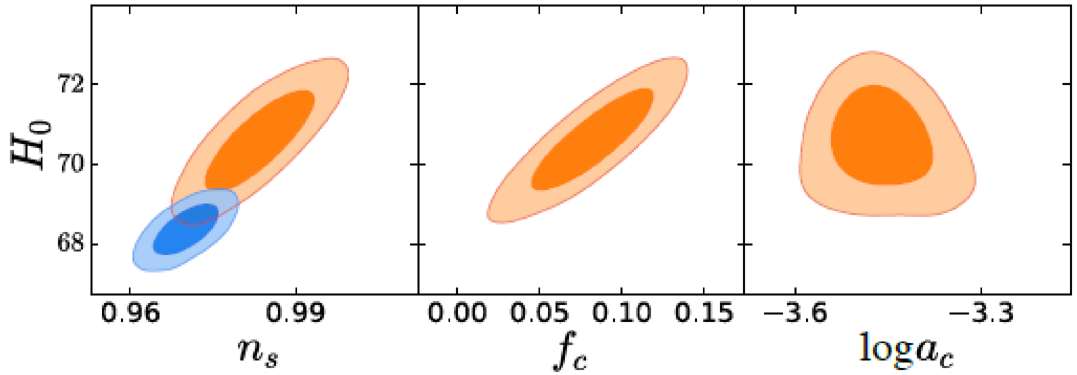

ADE fitting result

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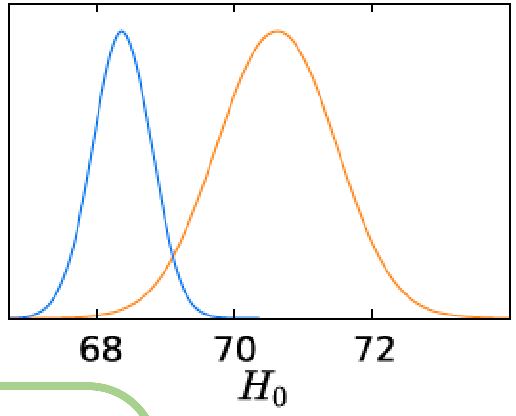


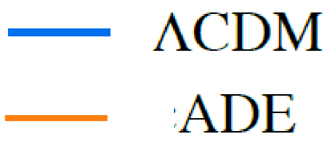


Table result

	EDE (n=2)	ADE
f_c	$0.028^{+0.011}_{-0.016}$	0.079 ± 0.033
$\log_{10} a_c$	$-4.136^{+0.57}_{-0.013}$	-3.50 ± 0.15
H_0	70.3 ± 1.2	70.20 ± 0.88

Fitting result for the eADE model

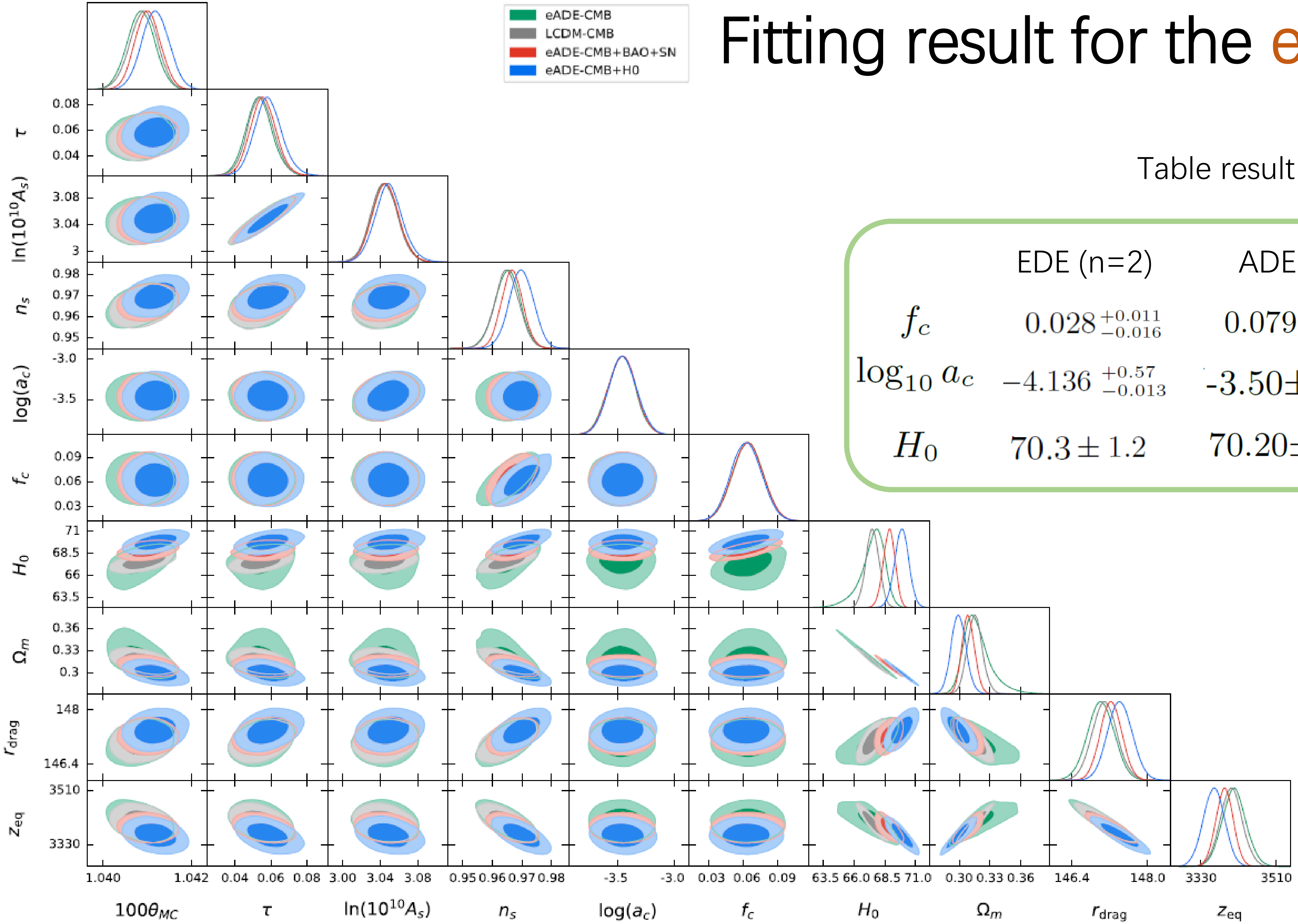
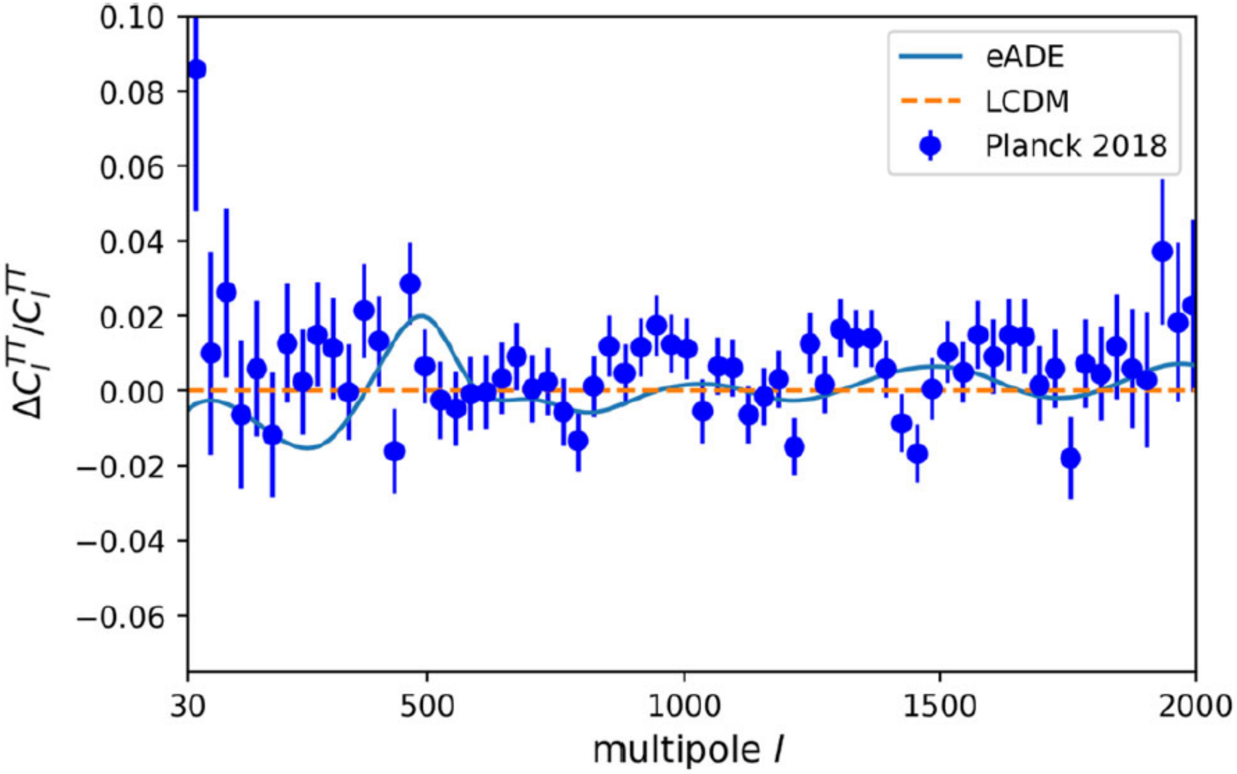
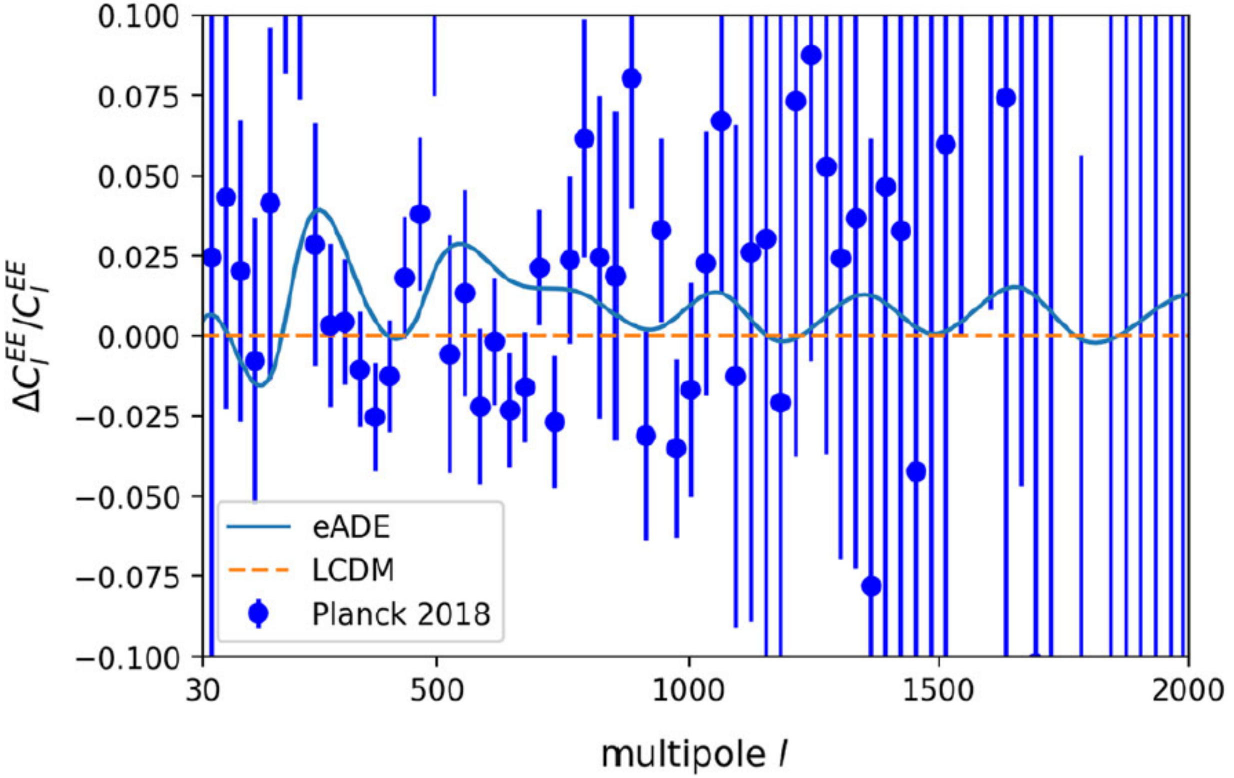


Table result

	EDE (n=2)	ADE	eADE
f_c	$0.028^{+0.011}_{-0.016}$	0.079 ± 0.033	$0.063^{+0.027}_{-0.030}$
$\log_{10} a_c$	$-4.136^{+0.57}_{-0.013}$	-3.50 ± 0.15	$-3.46^{+0.28}_{-0.22}$
H_0	70.3 ± 1.2	70.20 ± 0.88	$70.06^{+1.13}_{-1.09}$

The difference in CMB power spectra





The eADE model closer to the CMB data than LCDM, especially in the EE mode.

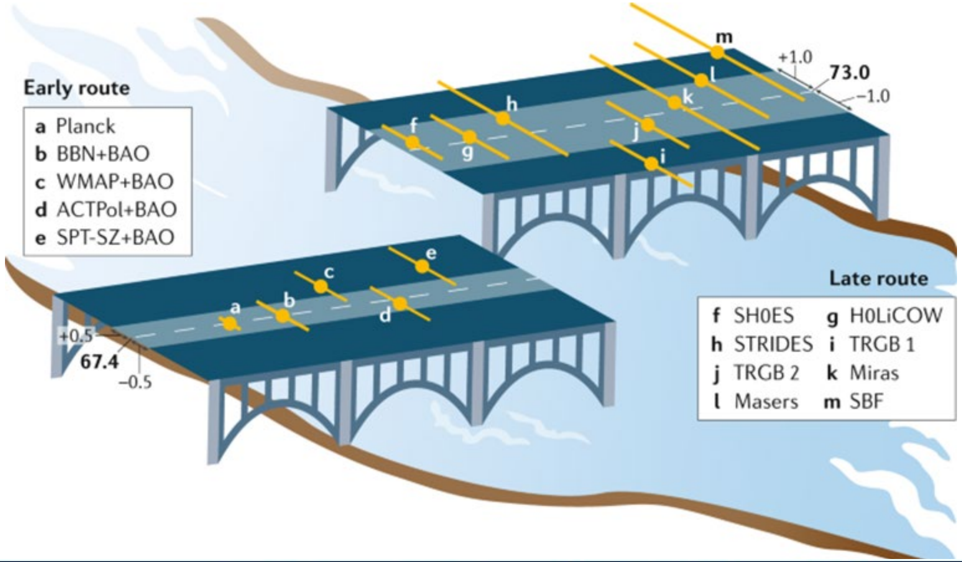
Conclusion

- The eADE is a new dark fluid model with *exponential EoS* to release the H0 tension effectively.
- eADE model has *less additional parameters*
- The eADE is *closer to the CMB observation* than LCDM.

Thanks for your attention!

Summary of recent H_0 values

Cepheids	74.3 ± 2.1	(2.8%)	[WLF+ 2012]
+ SNIa :	73.24 ± 1.74	(2.4%)	[Riess+ 2016]
	73.52 ± 1.62	(2.2%)	[Riess+ 2016]



ΛCDM:	67.8 ± 0.9	(1.3%)	[Planck 2015]
+ polarization	66.93±0.62	(0.9%)	[Planck 2016]
	67.4 ± 0.5	(0.7%)	[Planck 2018]

In the next

- What is the difference between EDE, ADE, eADE model ?
- My model: the eADE model and its fitting result.
- Conclusion

- Release Ho REASON
- TU

$$r_{\mathrm{s}} = \int_0^{t_\star} \frac{dt}{a(t)} c_s = \int_{z_\star}^{\infty} \frac{dz}{H(z)} c_s$$

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