THE 12TH CONFERENCE OF THE POLISH SOCIETY ON RELATIVITY

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DESI: Is Dark Energy evolving in time?

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NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

Introduction

Golden Age of Cosmology

Beginning of XXth century

It was not known why do stars shine

Static and eternal Universe

Milky Way = Universe

No other galaxies known

A lot of ignored problems …

Nowadays (3rd decade of XXIth century):

Relativistic model of expanding Universe

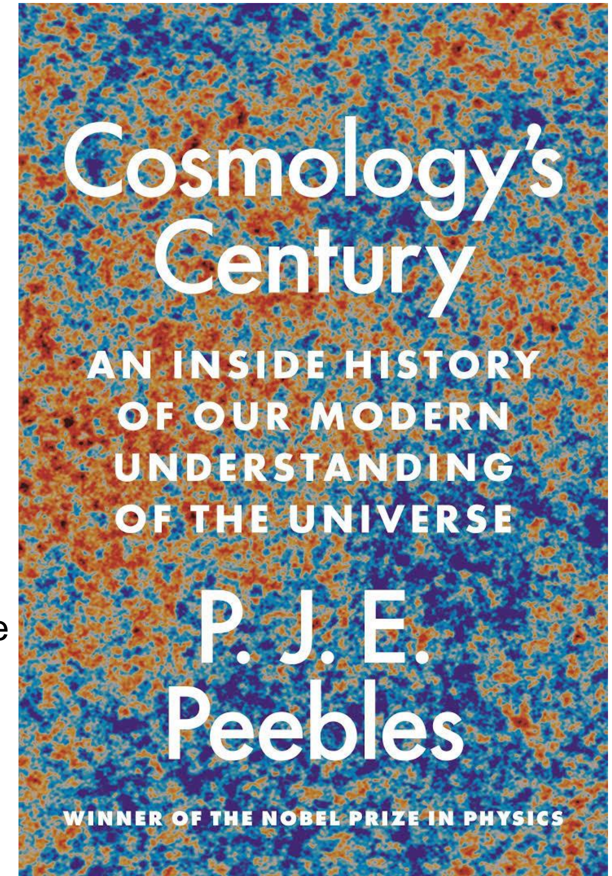
Known geometry of the Universe: it's spatially flat

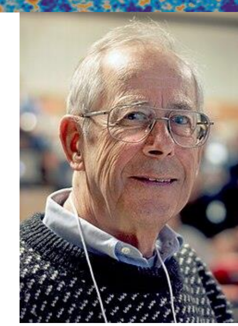
Coherent picture of nucleosynthesis of chemical elements in the Universe (primordial BBN + stellar)

Coherent picture of the emergence of the large scale structure in the Universe (LSS): galaxies and their clusters

Solid theoretical (GR) and observational (CMB, massive galaxy surveys,…) pillars of modern cosmology

Modern cosmology – elevated to <u>the precision science</u>, (ΛCDM model in agreement with most of the data)
but some TENSIONS emerged …





A.Sandage
Physics Today **23**, 2, 34 (1970)
„quest for two numbers”

THE DYNAMICAL PARAMETERS OF THE UNIVERSE: H_o, q_o, Ω_o, Λ, and K

Allan Sandage

Mount Wilson and Las Campanas Observatories of the Carnegie Institution of Washington, Pasadena, CA, USA.

G. A. Tammann*)

1984

Astronomisches Institut der Universität Basel, Binningen, Switzerland and European Southern Observatory, Garching bei Munchen, FRG.

Accelerated expansion of the Universe



Nobel Prize in Physics 2011

What is causing it?

We don’t know

But a tentative answer is already with us - the cosmological constant Λ

General Relativity (1915):

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = -8\pi\, G T_{\mu\nu}$$

geometry *matter*

Cosmological constant
– in order to make the Universe static

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = -8\pi\, G T_{\mu\nu}$$

Einstein's „biggest blunder"

Revives in the 60-ties of XXth century
Yakov Zeldovich, Stephen Weinberg

$$G_{\mu\nu} = -8\pi\, G \left(T_{\mu\nu} + T_{\mu\nu}^{vac}\right)$$

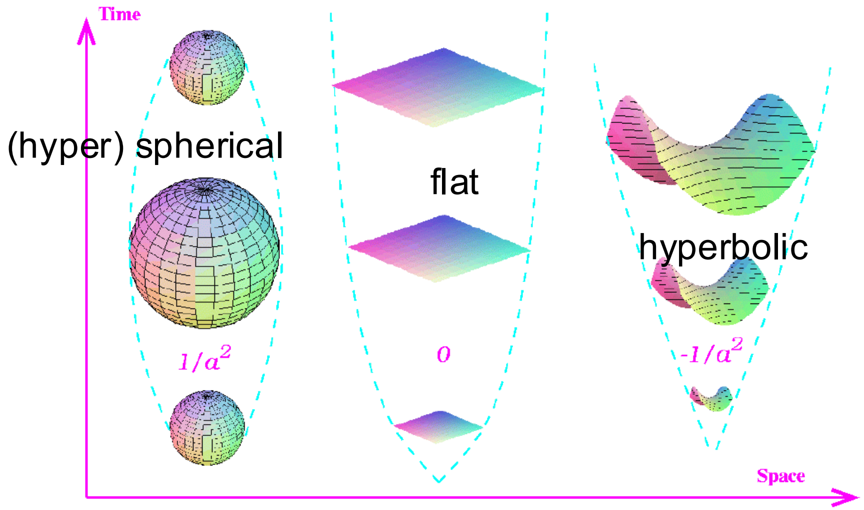
$$T_{\mu\nu}^{vac} = \rho_{vac} g_{\mu\nu} = \frac{\Lambda}{8\pi G} g_{\mu\nu}$$

Currently the ΛCDM model
is the standard cosmological model

ΛCDM model
is very simple,
fits well to all the data, … BUT
is burdened with lots of conceptual problems!

Modern cosmology in brief

$$G_{\mu\nu} = -8\pi G \, T_{\mu\nu}$$



k = +1 k = 0 k = -1

$$T^{\mu\nu} = (\rho + p) u^\mu u^\nu - p \, g^{\mu\nu}$$

Geometry of the Universe

homogeneous, isotropic

Friedman-Lemaitre-Robertson-Walker metric

$$ds^2 = dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right)$$

cosmological redshift

all spatial distances (including wavelength of light) are scaled by *a*(*t*) which changes in time

$$z = \frac{1 - a(t)}{a(t)}$$

$$a(t) = \frac{1}{1+z}$$

Friedman equation

$$\left(\frac{\dot a}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho$$

$$H \equiv \frac{\dot a}{a}$$ expansion rate (Hubble function)

$$H(t)^2 = \Omega_i \, H_0^2 - \frac{k}{a(t)^2}$$

$$\Omega_i = \frac{\rho_i}{\rho_{cr}} = \rho_i \frac{8\pi G}{3 H_0^2}$$

$$\frac{\ddot a}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

$$q \equiv -\frac{\ddot a}{a}\frac{1}{H^2}$$ deceleration parameter

as soon as

$$\rho + 3\,p > 0$$

Friedman equation – clue to cosmological model testing

$$H(z)^2 = H_0^2\left[\Omega_{m,0}(1+z)^3 + \Omega_{r,0}(1+z)^4 + \Omega_k(1+z)^2 + \Omega_{DE,0}(1+z)^{3(1+w_0+w_a)}\exp\left(-\frac{3w_a z}{1+z}\right)\right]$$

CDM + baryonic matter

radiation

Curvature parameter

DE equation of state

DE equation of state – we don't know it

$$p_{DE} = w_{DE}(z)\rho_{DE} \qquad \{w_{DE}(z) = -1\} \equiv \Lambda$$

$$\Omega_\Lambda = const.$$

Assuming that it could be changing in the history of the Universe – first order Taylor expansion

$$w(a) = w_0 + w_a(1-a)$$

$$w(z) = w_0 + w_a\frac{z}{1+z}$$

Chevallier – Polarski – Linder (CPL) parametrization

challenge for observers

reconstruct history of the expansion of the Universe

$$H(z) = H_0\, h(z)$$

Hubble constant

c/H_0 distance scale

$1/H_0$ time scale

$$\Omega_i \quad \{i = m, r, k, DE\}$$

3 types of distances:

- *comoving distance* – not measurable !

$$D_C(z) = \frac{c}{H_0}\int_0^z \frac{dz'}{h(z')}$$

- *luminosity distance* $$D_L(z) = (1+z)D_C(z) = (1+z)\frac{c}{H_0}\int_0^z \frac{dz'}{h(z')}$$

- *angular diameter distance* $$D_A(z) = \frac{1}{1+z}D_C(z) = \frac{1}{1+z}\frac{c}{H_0}\int_0^z \frac{dz'}{h(z')}$$

Standard candles – objects of known (or standardizable) luminosity L; we measure the flux F, and calculate the distance

$$L = 4\pi D_L(z) F$$

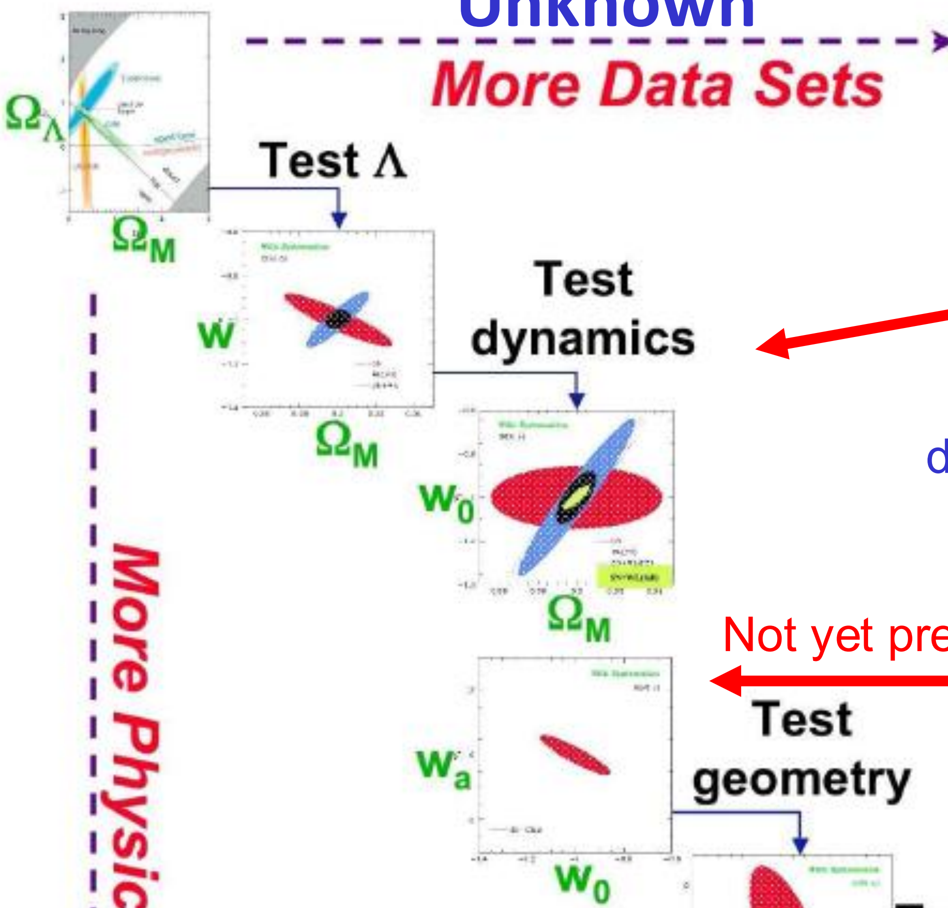
Standard rulers – objects of known sizes D; we measure angular diameter θ and calculate the distance

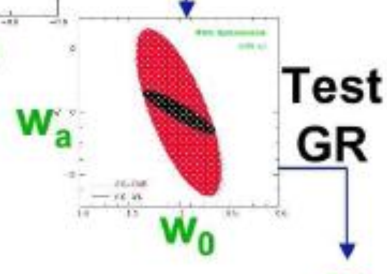
$$D = D_A(z)\theta$$

Standard sirens – coalescing compact binaries

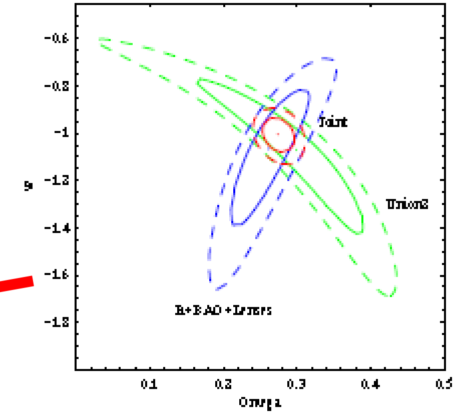
D_L is directly measurable (but z – unknown!)

Modern cosmology: Incremental Exploration of the Unknown





intrinsic alignment of parameters (w_0 , w_a)

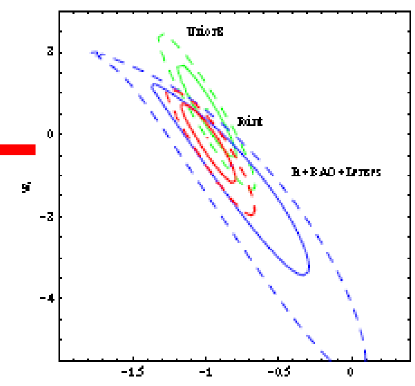


MB, B.Malec, A.Piórkowska 2011

determine DE equation of state

$$p_X = w\rho_X$$

Not yet precise



determine if it changes in time

$$w(z) = w_0 + w_a \frac{z}{1+z}$$

We need **complementary probes** –
to break degeneracies
and for cross-checks

Linder (astro-ph/0511197)

Credit: https://newscenter.lbl.gov/2025/03/19/desi-opens-access-to-the-largest-3d-map-of-the-universe-yet/

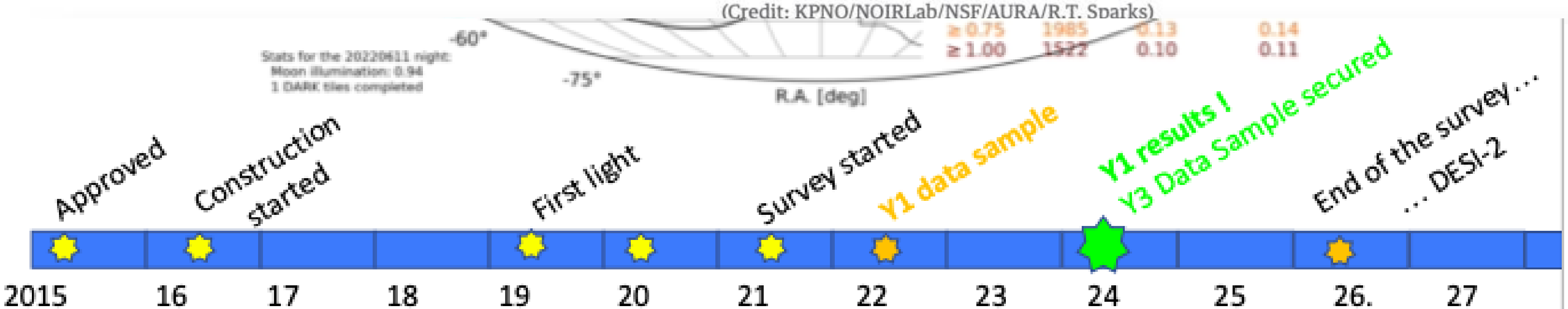
DESI Opens Access to the Largest 3D Map of the Universe Yet

DESI Opens Access to the Largest 3D Map of the Universe Yet

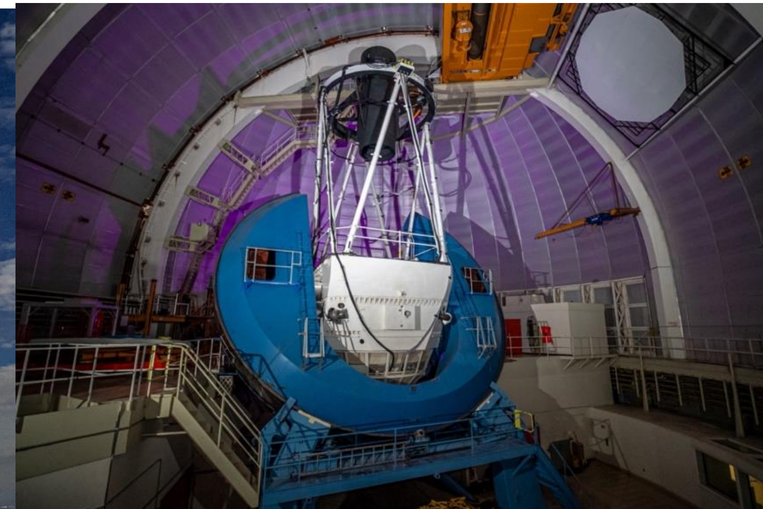
By **Elizabeth Ball and Lauren Biron**
March 19, 2025

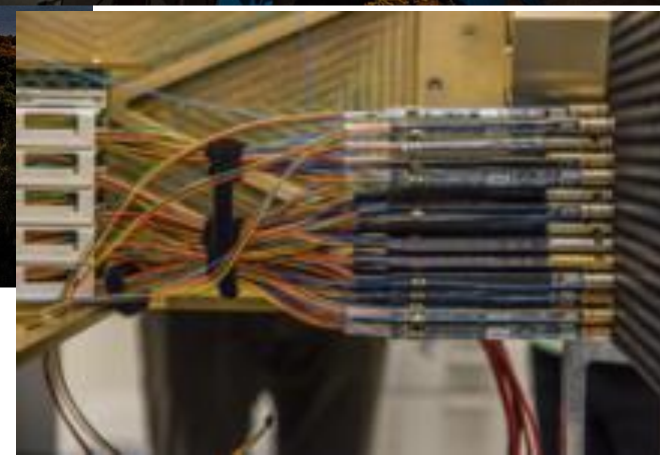
A new data release from the Dark Energy Spectroscopic Instrument is now available for researchers to explore. The collection contains information on 18.7 million galaxies, quasars, and stars – the largest dataset of its kind ever shared.

DESI observes the sky from the Mayall Telescope, shown here beneath the Milky Way. (Credit: KPNO/NOIRLab/NSF/AURA/R.T. Sparks)



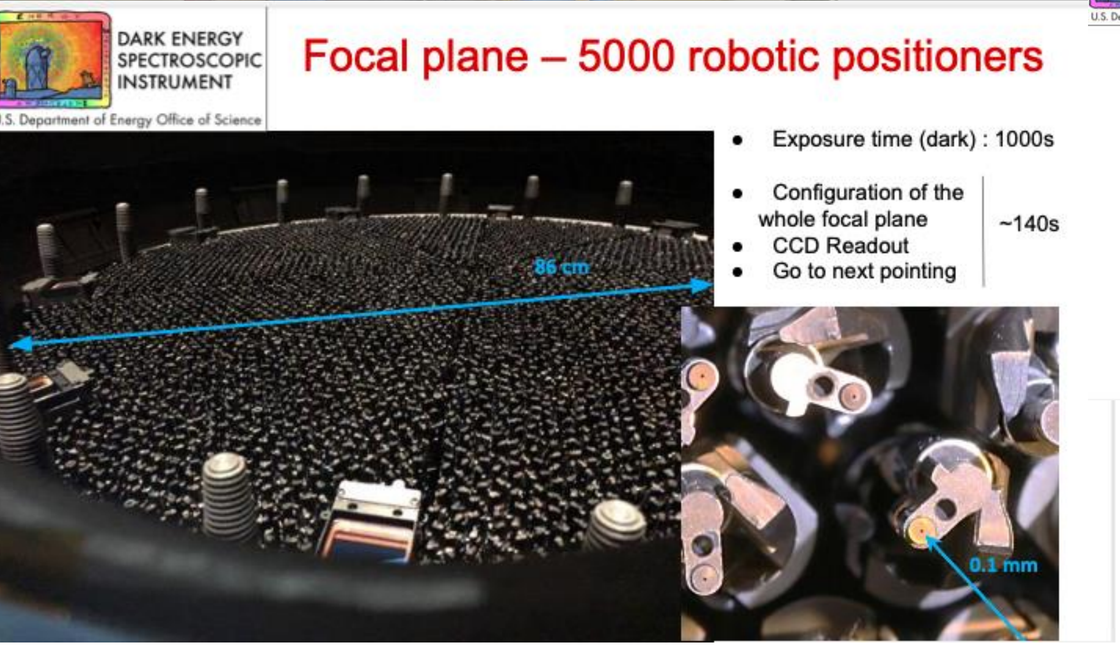
Dark Energy Spectroscopic Instrument
DESI

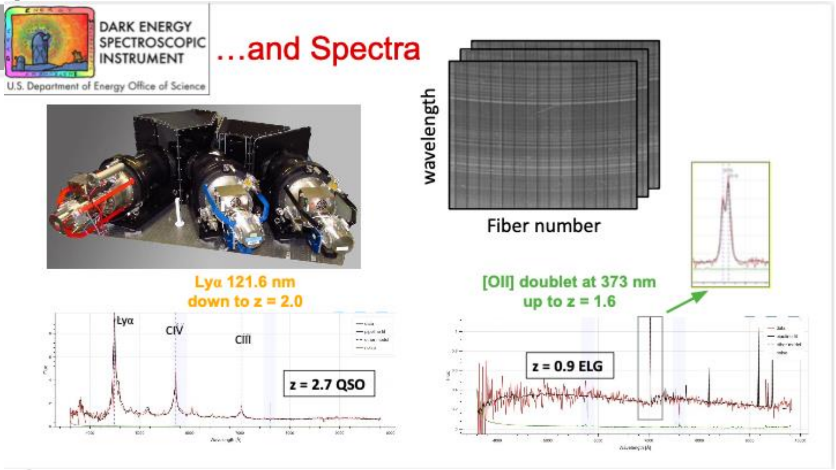




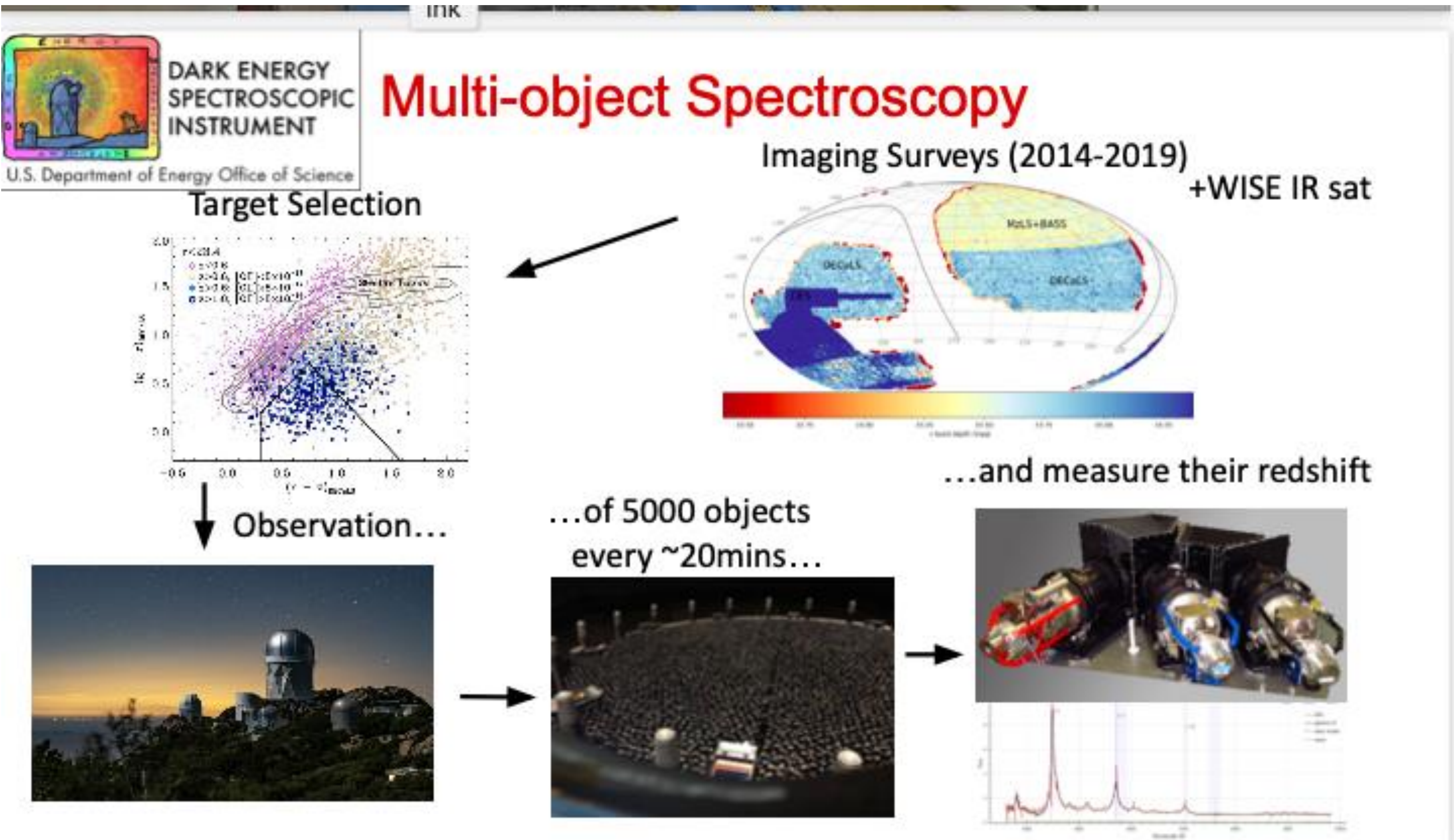
Kitt Peak Observatory, AZ
Mayal 4m telescope

Credits: https://www.desi.lbl.gov/photos/





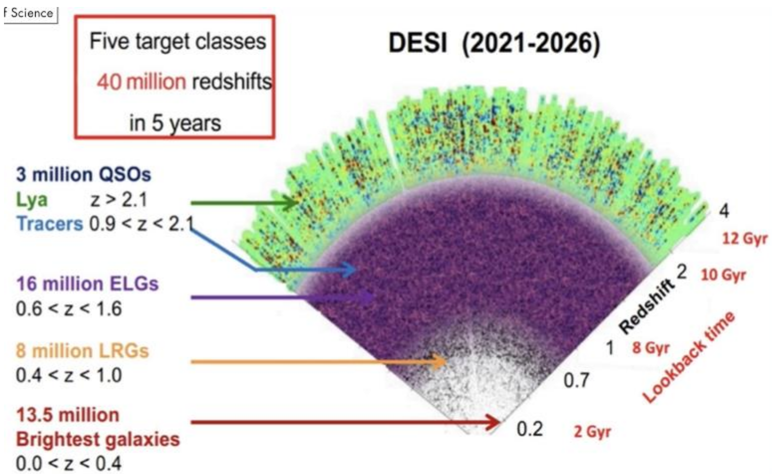
Credit: E. Burtin *Moriond 2024*

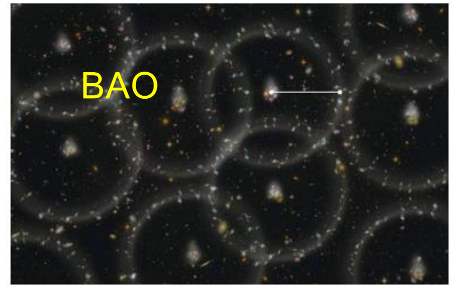


Credit: E. Burtin *Moriond 2024*

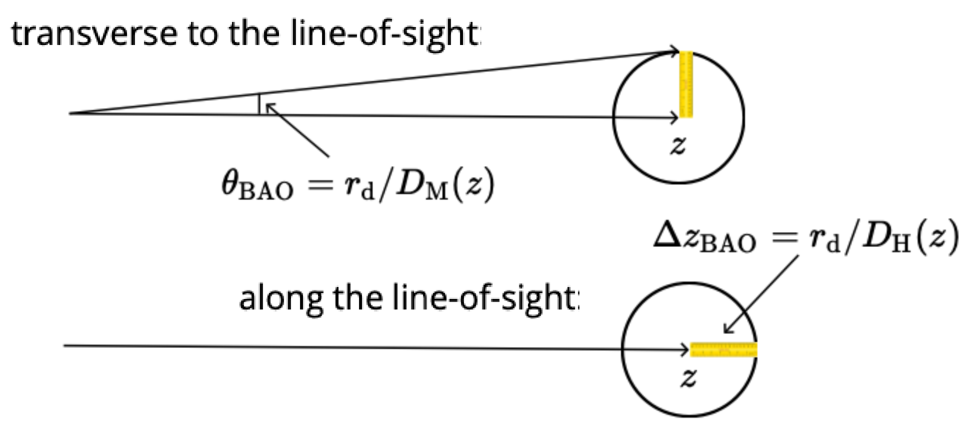
Dark Energy Spectroscopic Instrument DESI

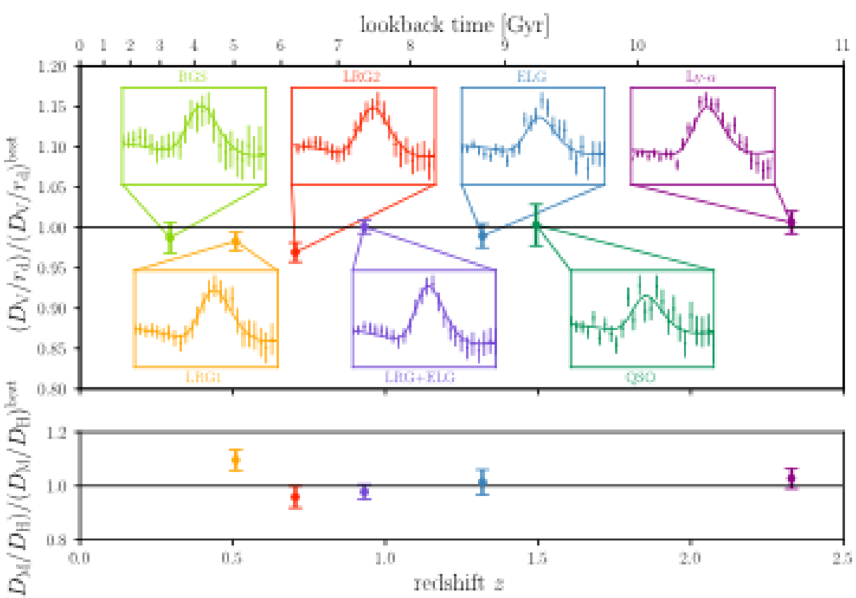
Credit: E. Burtin *Moriond 2024*





BAO measures ratios of distances over the sound horizon scale at the drag epoch ["standard ruler"] r_d

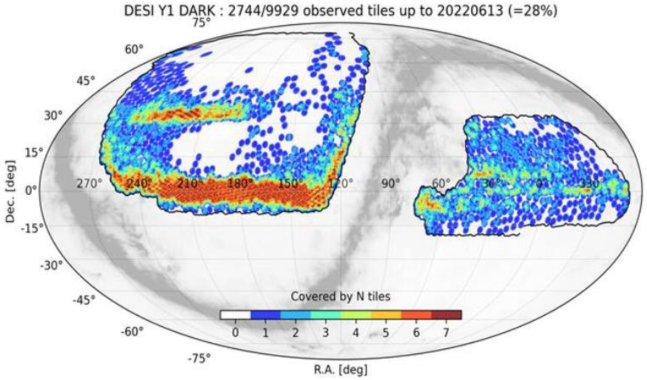




- transverse to the line-of-sight: $D_\mathrm{M}(z)/r_\mathrm{d}$
- along the line-of-sight: $D_\mathrm{H}(z)/r_\mathrm{d} = c/(H(z)r_\mathrm{d})$
- isotropic average: $D_\mathrm{V}(z)/r_\mathrm{d} = (zD_\mathrm{M}^2(z)D_\mathrm{H}(z))^{1/3}/r_\mathrm{d}$

The DESI DR1 sample (DESI 2024)

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science



6M objects
Biggest data set.
Catalog-level blinded analysis

Aggregate distance precision with Year 1 data: 0.49%

Cf. All BAOs over two decades: 0.60%

The DESI DR2 sample (2025)

DARK ENERGY SPECTROSCOPIC INSTRUMENT
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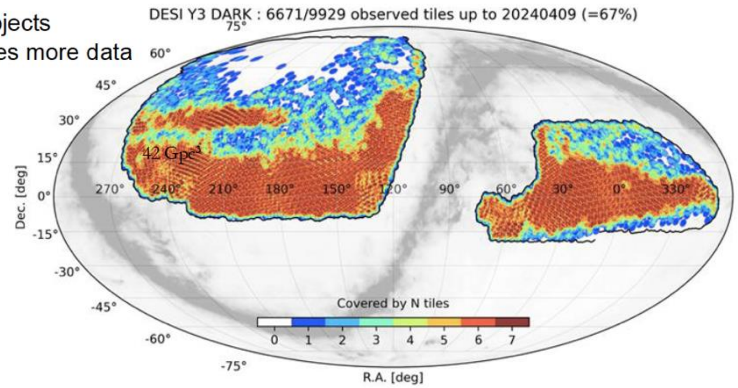
14M objects
2.4 times more data



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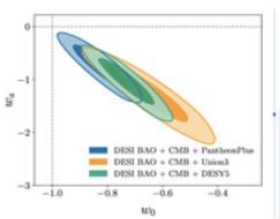
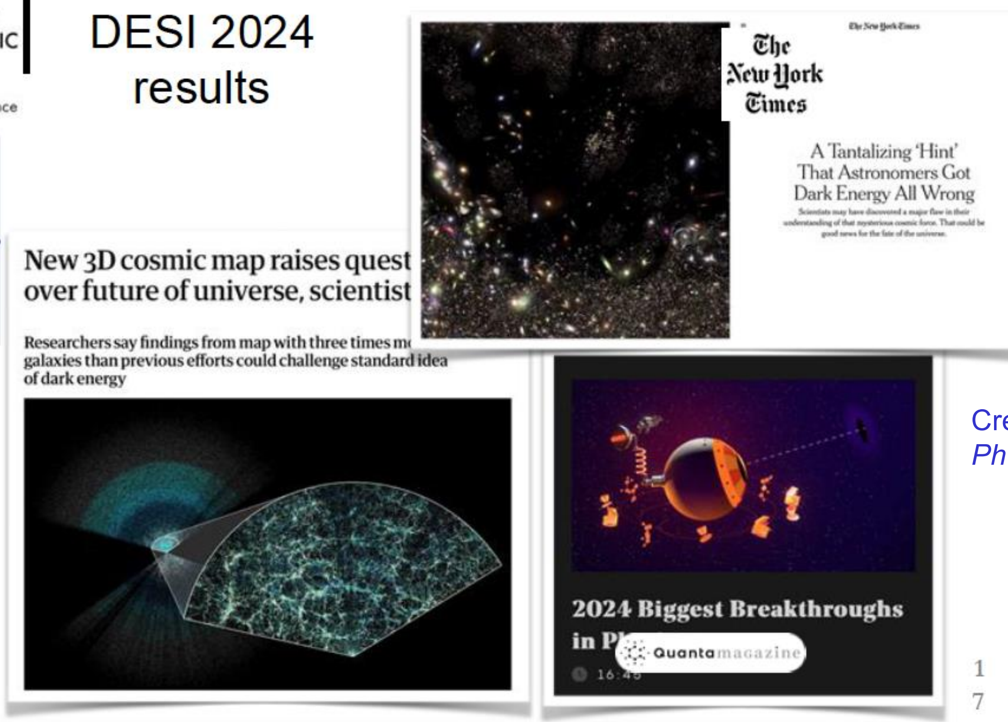
DESI 2024 results



arXiv:2404.03002, 2404.03001, 2404.03002



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Credit: H.-J. Seo
Phenomenology 2025 Symposium

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

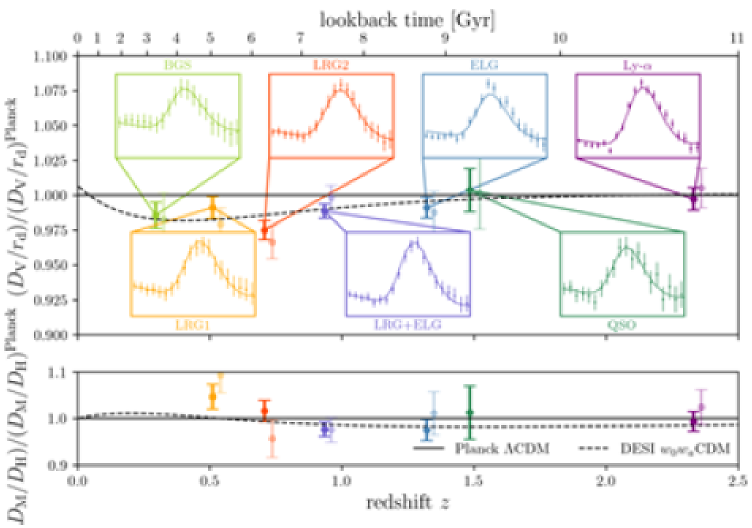
DESI 2025:arXiv:2503.14738

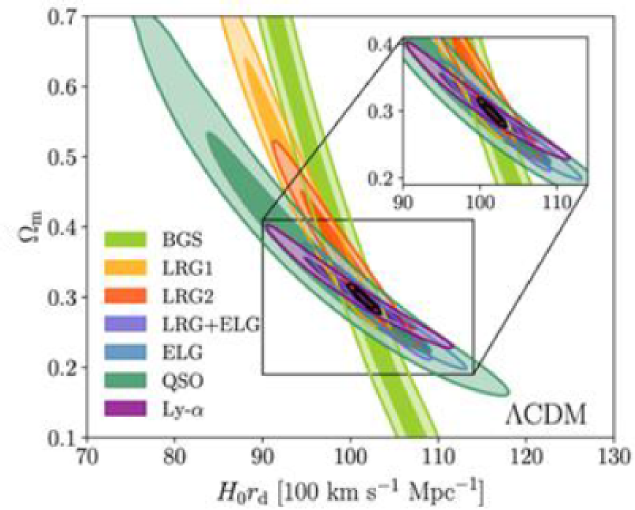
DESI 2025 BAO

BAO data: $\Delta\theta$ and Δz → D_M / r_d and D_H / r_d

$$D_V = \left(z D_M(z)^2 D_H(z)\right)^{1/3}$$

Ω_M and $H_0 r_d$





Aggregated precision on BAO distance scale:
0.28% (vs. 0.49% for DR1)

Agreement & complementarity between tracers

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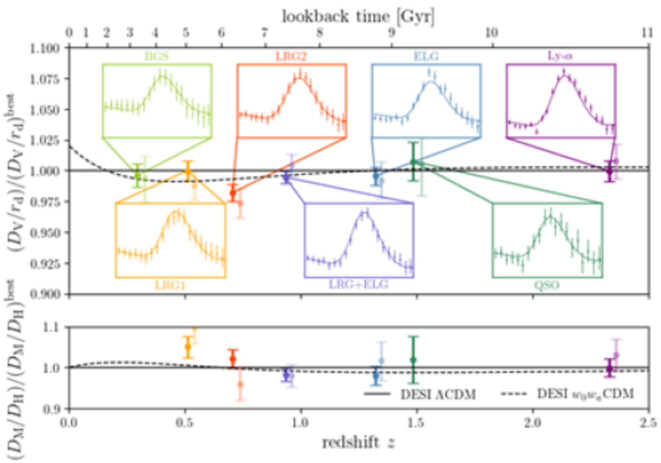
Dark Energy with constant w

Credit: H.-J. Seo
Phenomenology 2025 Symposium



DESI data are comparable with w=-1 (ΛCDM) when w is assumed constant.

But we observe mild tensions between ΛCDM fits of different expansion probes (e.g., CMB and SNe).

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Dark Energy Equation of State

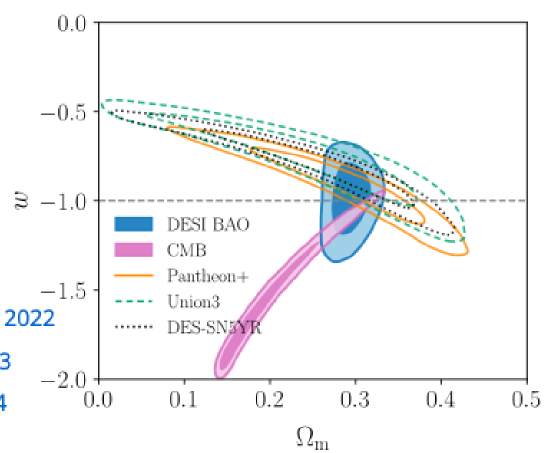
Constant EoS parameter w

$$\Omega_m = 0.293 \pm 0.015 \quad (\mathbf{5.1\%})$$
$$w = -0.99^{+0.15}_{-0.13} \quad (\mathbf{15\%})$$

DESI

SNe:

- Pantheon+ Brout, Scolnic, Popovic et al., 2022
- Union3 Rubin, Aldering, Betoule et al. 2023
- DES-SN5YR DES Collaboration et al. 2024



Credit: A.de Mattia *Moriond 2024*

Credit: A.de Mattia *Moriond 2024*

Dark Energy Equation of State

DR1

Combining all DESI + CMB + SN

$$\underbrace{w_0 = -0.827 \pm 0.063 \qquad w_a = -0.75^{+0.29}_{-0.25}}$$

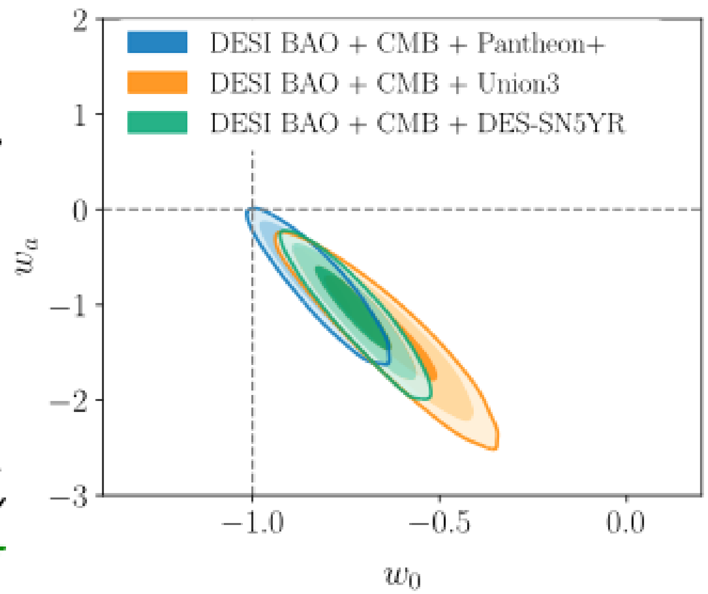
DESI + CMB + Pantheon+ $\Longrightarrow$ 2.5σ

$$\underbrace{w_0 = -0.64 \pm 0.11 \qquad w_a = -1.27^{+0.40}_{-0.34}}$$

DESI + CMB + Union3 $\Longrightarrow$ 3.5σ

$$\underbrace{w_0 = -0.727 \pm 0.067 \qquad w_a = -1.05^{+0.31}_{-0.27}}$$

DESI + CMB + DES-SN5YR $\Longrightarrow$ 3.9σ



$w_0 > -1, w_a < 0$ favored, level varying on the SN dataset

Essentially confidence contours shrink
and become detouched from (w_0 =-1,w_a=0)

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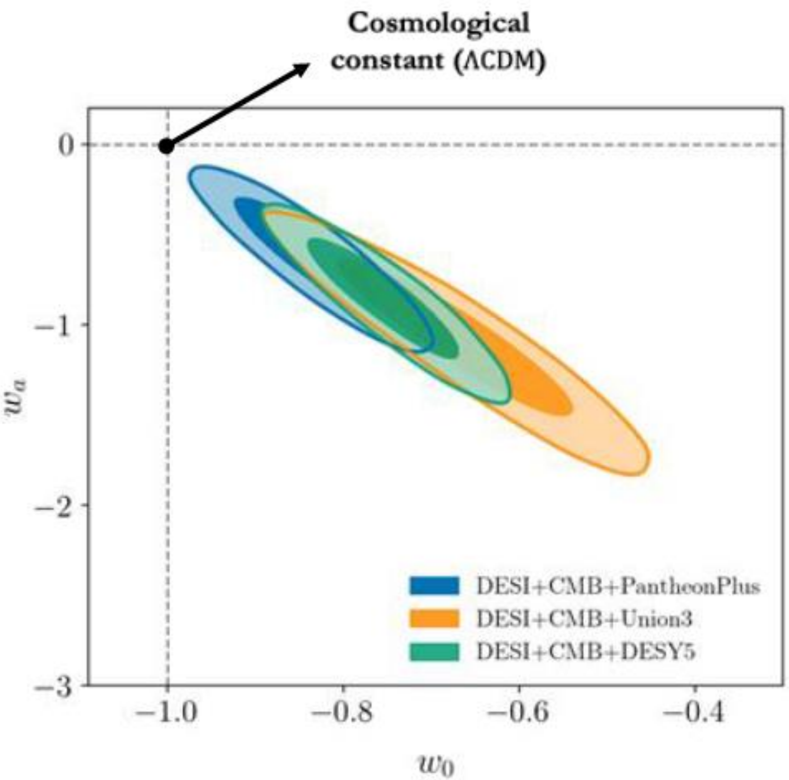
Dynamical Dark Energy: DR2

Varying EoS

$$w(a) = w_0 + (1 - a)w_a$$

- Significance of rejection of ΛCDM:
  - DESI+CMB+Pantheon+: 2.8σ
  - DESI+CMB+Union3 : 3.8σ
  - DESI+CMB+DESY5: 4.2σ

Pantheon+, Union3, DESY5:
SNIa data



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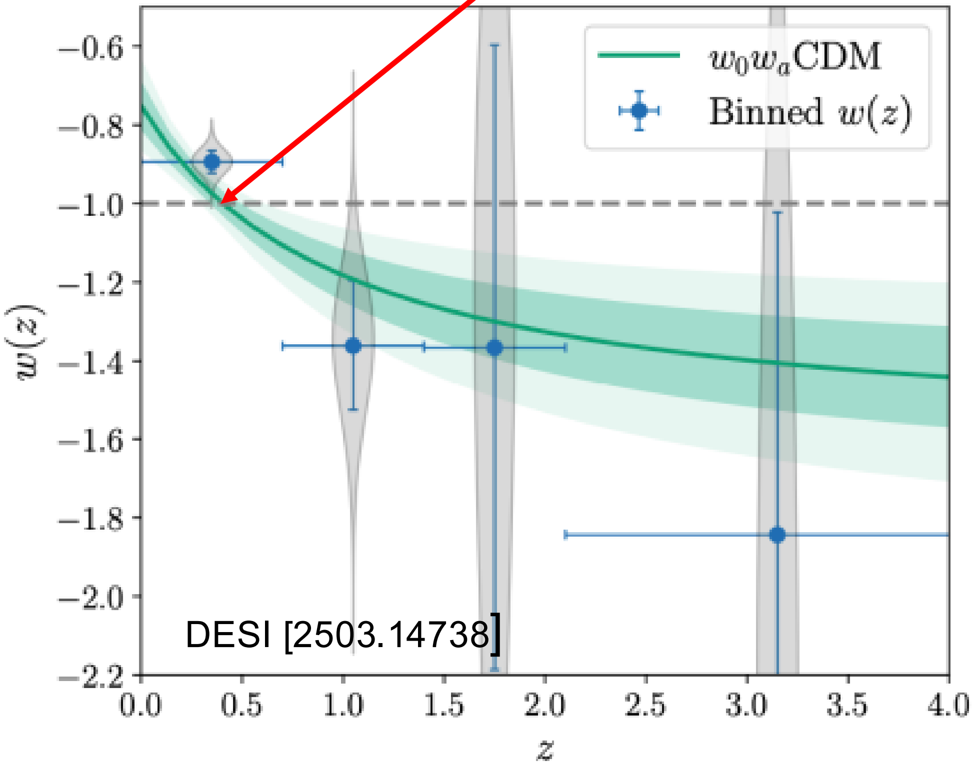
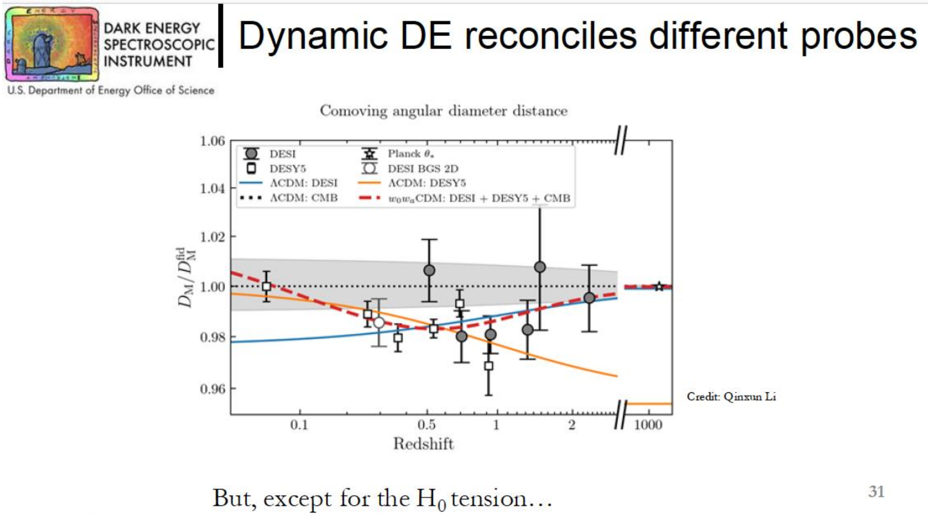
Data prefer phantom crossing

Phenomenologically w(z) is not tracing scalar field DE





Inspired by data-suggested phantom crossing

THE ASTROPHYSICAL JOURNAL LETTERS, 1001:L21 (8pp), 2026 April 10 https://doi.org/10.3847/2041-8213/ae5a36

Metastability in Emergent Dark Energy: A New Framework Confronting Cosmological Observations

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Assumed e.o.s.

$$w(z) = -1 - \Delta \tanh\left(\log_{10}\left(\frac{1+z}{1+z_t}\right)\right).$$

DE density

$$\rho_{\rm de}(z) = \rho_{\rm de,0}\left[\frac{\cosh\left(\log_{10}\left(\frac{1+z}{1+z_t}\right)\right)}{\cosh\left(\log_{10}\left(\frac{1}{1+z_t}\right)\right)}\right]^{-3\Delta\ln 10}$$

linear perturbations

$$\delta'_{\rm de} = -(1+w_{\rm de})(\theta_{\rm de} - 3\phi') - 3\mathcal{H}\delta_{\rm de}(c^2_{\rm s,de} - w_{\rm de}) - 9(1+w_{\rm de})(c^2_{\rm s,de} - c^2_{\rm a,de})\mathcal{H}^2\frac{\theta_{\rm de}}{k^2},$$

$$\theta'_{\rm de} = -(1-3c^2_{\rm s,de})\mathcal{H}\theta_{\rm de} + \frac{c^2_{\rm s,de}}{1+w_{\rm de}}k^2\delta_{\rm de} + k^2\psi.$$

CAMB Boltzmann solver ←

↓

Confront with
CMB, BAO, SNIa

MEDE fitted to the data - Results

Table 1
Constraints on Cosmological Parameters for the Flat MEDE Model

Model	MEDE Model		
Data	CMB+DESI	CMB+DESI+DES-Dovekie	CMB+DESI+PantheonPlus
z_t	$0.500^{+0.130}_{-0.110}$	$0.418^{+0.070}_{-0.085}$	$0.425^{+0.084}_{-0.120}$
Δ	>1.12	1.03 ± 0.32	$0.87^{+0.29}_{-0.35}$
$\Omega_b h^2$	0.02226 ± 0.00012	0.02226 ± 0.00012	0.02226 ± 0.00013
$\Omega_c h^2$	0.11895 ± 0.00078	0.11902 ± 0.00077	0.11890 ± 0.00081
$\log(10^{10} A_s)$	3.046 ± 0.012	3.045 ± 0.012	3.046 ± 0.012
n_s	0.9662 ± 0.0036	0.9661 ± 0.0035	0.9664 ± 0.0035
τ_{reio}	0.0564 ± 0.0067	0.0561 ± 0.0062	0.0567 ± 0.0066
H_0 (km s^{-1} Mpc^{-1})	$66.30^{+1.20}_{-1.40}$	67.43 ± 0.56	67.56 ± 0.58
Ω_m	0.3230 ± 0.0120	0.3122 ± 0.0055	0.3108 ± 0.0056
σ_8	0.8020 ± 0.0120	0.8116 ± 0.0073	0.8120 ± 0.0079
r_{drag}	147.51 ± 0.21	147.49 ± 0.20	147.51 ± 0.20
χ^2_{min}	11006.35	12632.67	12406.45
$\Delta\chi^2_{MEDE-\Lambda CDM}$	-1.65	-8.43	-3.94
$\Delta\chi^2_{MEDE-CPL}$	4.22	4.53	3.39
$\Delta DIC_{MEDE-\Lambda CDM}$	-6.53	-11.36	-9.29
$\Delta DIC_{MEDE-CPL}$	1.71	1.32	0.74

Note. Results are shown for the CMB+DESI, CMB+DESI+DES-Dovekie, and CMB+DESI+PantheonPlus datasets, and we also include the minimum χ^2, $\Delta\chi^2$, and ΔDIC values relative to the ΛCDM and CPL models.

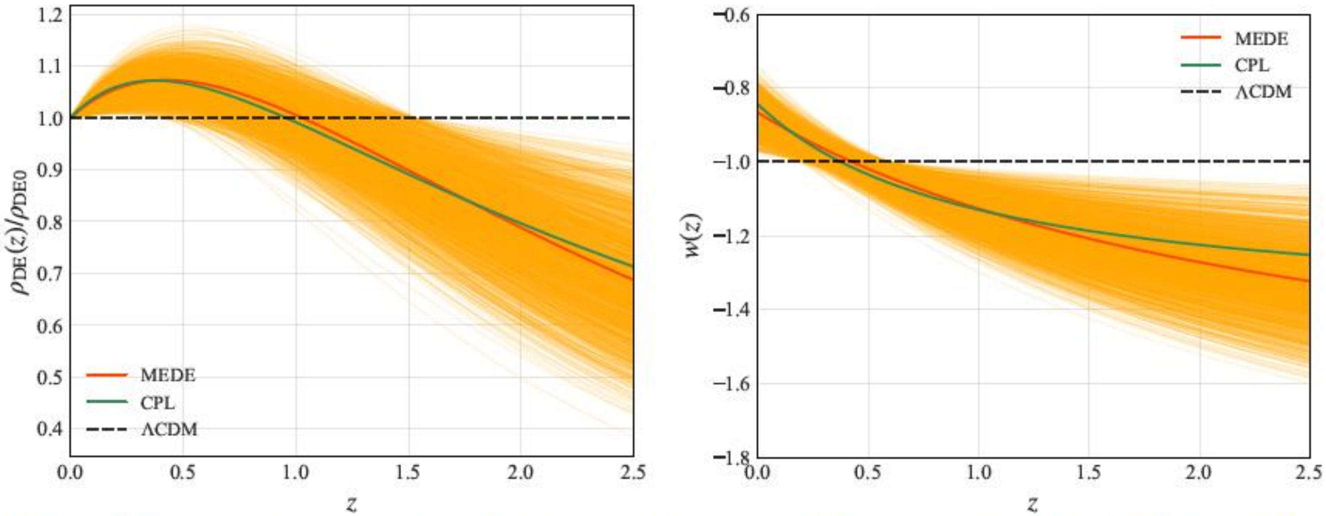


Figure 3. Redshift evolution of the dark-energy sector. Left: the dark-energy density $\rho_{DE}(z)/\rho_{DE0}$. Right: the equation of state $w_{DE}(z)$. The red solid line represents the best-fit MEDE model (CMB+DESI+PantheonPlus). The light-orange region shows the 2σ confidence region derived from MCMC chains, illustrating the posterior distribution of parameters. The green solid line shows the CPL parameterization ((CMB+DESI+PantheonPlus best-fit), and the black dashed line represents ΛCDM. The MEDE model exhibits a smooth transition around $z_t \sim 0.42$, crossing the phantom divide $w = -1$ from phantom-like ($w < -1$) at high redshifts to quintessence-like ($w > -1$) at low redshifts.

correspondence between CPL and MEDE:

$$w_0 = -1 + \Delta \tanh[\log_{10}(1 + z_t)], \tag{8}$$

$$w_a = -\frac{1}{\ln 10}\Delta\,\mathrm{sech}^2[\log_{10}(1 + z_t)]. \tag{9}$$

Substituting the central values of Δ and z_t fitted to the (CMB+DESI+DES-Dovekie) data (see Table 1), one obtains $w_0 = -0.845^{+0.076}_{-0.067}$, $w_a = -0.44^{+0.13}_{-0.13}$, which is within 1σ of the DESI (M. Abdul Karim et al. 2025) best fit $w_0 = -0.838 \pm 0.055$, $w_a = -0.62^{+0.22}_{-0.19}$. This explains the similarity in performance between CPL and MEDE in the redshift range probed by current data: they can be viewed as two sides of the same coin, both conveying the message that an evolving equation of state should be taken seriously as an alternative to the ΛCDM model.

Next step … (will appear in arxiv soon)

Scalar-Quintom Reconstruction of a DESI-Motivated Phantom-Divide Transition

Tonghua Liu,[1] Xiaolei Li,[2] Marek Biesiada,[3] Tian-Nuo Li,[4] Arman Shafieloo,[5,6] and Xin Zhang[4,7,8]

Take MEDE

$$w_{\rm de}(z) = -1 - \Delta \tanh\left[\ln\left(\frac{1+z}{1+z_t}\right)\right]$$

Auxiliary variable $u(z) = \ln\left(\frac{1+z}{1+z_t}\right)$

Suppose that MEDE is derived from the scalar-quintom field theory

scalar quintom

kinetic imbalance

$$\rho_q = \frac{1}{2}\dot{\phi}^2 - \frac{1}{2}\dot{\psi}^2 + V, \quad K(z) = -\frac{\Delta}{2}\tanh u(z)\rho_{\rm de}(z),$$

$$p_q = \frac{1}{2}\dot{\phi}^2 - \frac{1}{2}\dot{\psi}^2 - V, \quad V(z) = \left[1 + \frac{\Delta}{2}\tanh u(z)\right]\rho_{\rm de}(z)$$

$$S_q = \int {\rm d}^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 + \frac{1}{2}(\partial\psi)^2 - V(\phi,\psi)\right] + S_m + S_r.$$

Consistency test:

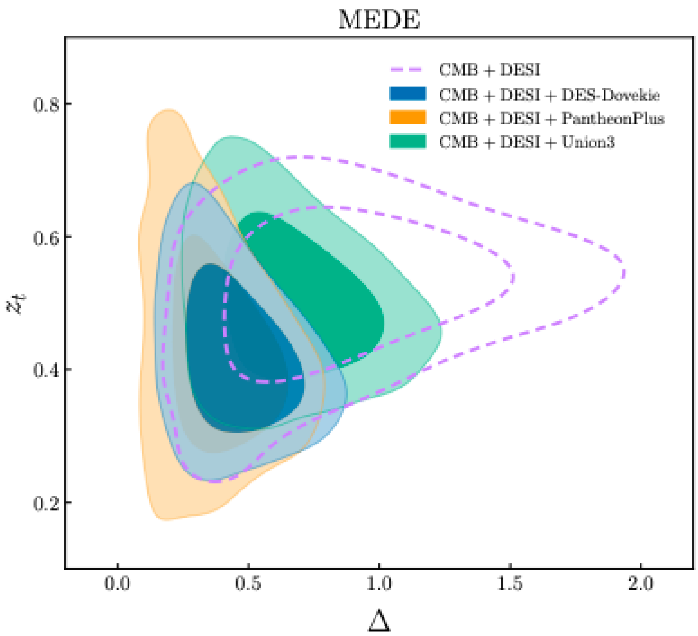
- Fit MEDE parameters to the data CMB+BAO+SNIa
- Take best fit MEDE values to fix reconstructed scalar-quintom fields
- Sample fields around MEDE trajectory and evolve

$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} = 0$$

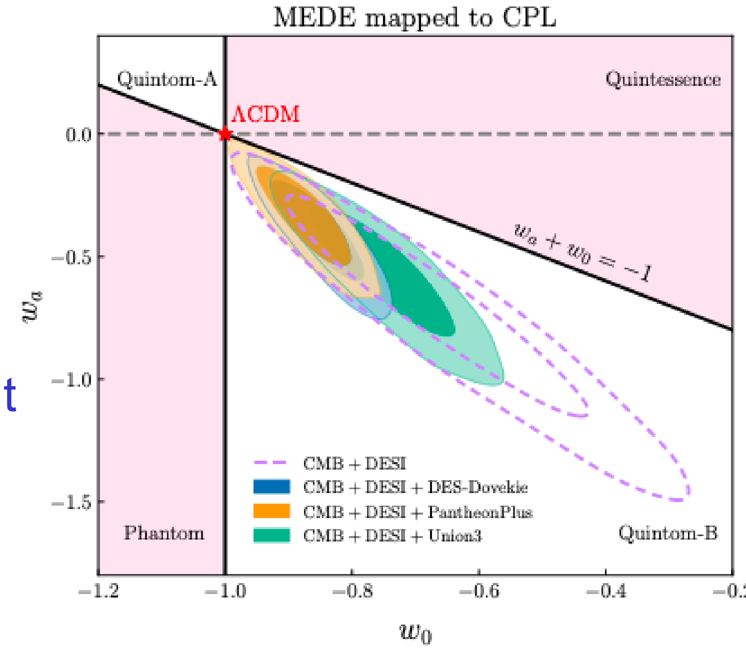
$$\ddot{\psi} + 3H\dot{\psi} - V_{,\psi} = 0.$$

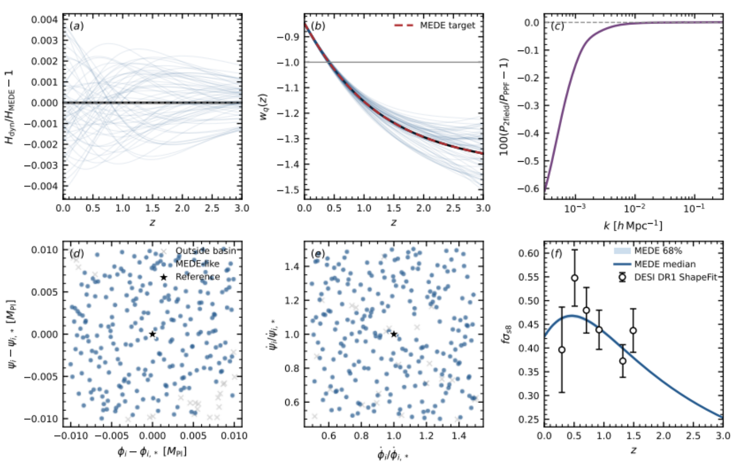
$$3M_{\rm Pl}^2H^2 = \rho_m + \rho_r + \rho_q,$$

$$\dot{H} = -\frac{\rho_m + 4\rho_r/3 + \dot{\phi}^2 - \dot{\psi}^2}{2M_{\rm Pl}^2}.$$



Fit





Conclusion.— Present distance data place a phantom-divide transition near $z \simeq 0.4$–0.5, although CPL fits the same data equally well. The principal result is therefore dynamical rather than statistical. Once a representative potential is fixed, the coupled field and Friedmann equations reproduce the expansion; the crossing persists across a finite range of late-time initial conditions; and the field perturbations remain regular through $w = -1$.

Test

Is Dark Energy evolving in time?

the DESI data for the first time gave a strong support for the time evolving cosmic equation of state

Is this a "funeral" of LCDM ?
Not really – remember Yakov Zeldovich saying

" cosmological constant is like a jinn from the bottle – once released, it's not easy to put it back there "

But we should try – more alternative probes are needed

The power of modern cosmology is not in single dedicated experiments, but in building consistency across various independent and alternative probes and techniques.

Direct measurements of H(z)

1. BAO at different redshifts
2. Redshift drift
3. Cosmic Chronometers

$$H(z)=\frac{\dot{a}}{a}=-\frac{1}{1+z}\frac{dz}{dt}$$

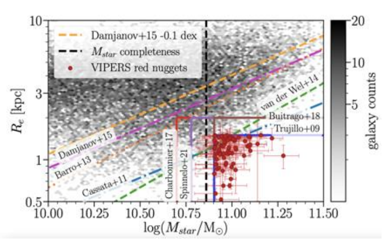
Jimenez & Loeb (2002)

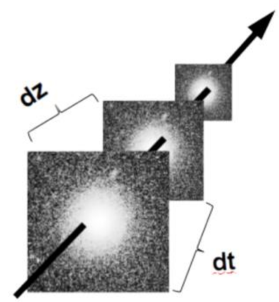
$$H(z)=-\frac{1}{1+z}A(Z,SFH)\frac{dz}{dD4000_n}$$

D4000 break – onset of series of metal absorption features

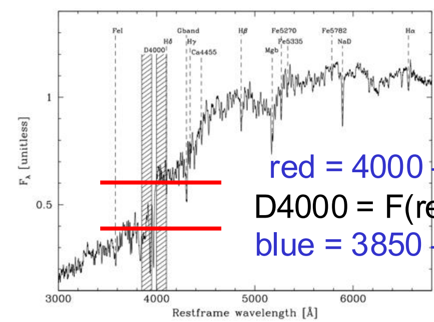
passively evolving galaxies

„red nuggets" – promising CCs (K.Lisiecki et al. A&A 2023)





M.Moresco et al. ApJ 2020



red = 4000 – 4100 Å

D4000 = F(red) / F(blue)

blue = 3850 – 3950 Å

$$D4000=A(Z,\mathrm{SFH})\cdot \mathrm{age}+B$$

Calibrated on stellar pop.syn. models

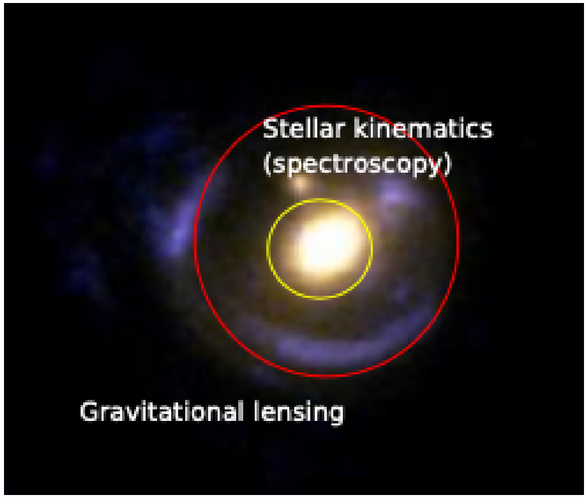
CORN – Chronometers of Relic Nature

I: The first estimate of the expansion rate of the Universe using compact relic galaxies

Krzysztof Lisiecki[1], Nicola Principi Cavaterra[1], Agnieszka Pollo[1,2], Chiara Spiniello[3,4], Laura Hunt[5], Chiara Tortora[4], Marek Biesiada[1], Darko Donevski[1,6], Patryk Matera[1], Giuliano Lorenzon[1], and John Mills[7]

A&A accepted 2026

Strong lensing combined with stellar kinematics



1. The simplest lens model $\rho(r) = \frac{\sigma_v^2}{2\pi G r^2}$

Singular Isothermal Sphere (SIS)

$$\theta_E = 4\pi \left(\frac{\sigma_v}{c}\right)^2 \frac{D_{ls}}{D_s}$$

2. Spherically symmetric power-law mass density profile $\rho(r) \sim r^{-\gamma}$

stellar dynamics (spherically symmetric Jeans equation): mass projected inside the aperture radius scaled to the Einstein radius

Strong lensing: mass inside the Einstein radius

$$M_{lens} = \frac{c^2}{4G}\frac{D_l D_s}{D_{ls}}\theta_E^2 \quad + \quad M_{dyn} = \frac{\pi}{G}\sigma_{ap}^2 D_l \theta_E \left(\frac{\theta_E}{\theta_{ap}}\right)^{2-\gamma} f(\gamma)$$

$$\theta_\mathrm{E} = 4\pi \frac{\sigma_\mathrm{ap}^2}{c^2}\frac{D_\mathrm{ls}}{D_\mathrm{s}}\left(\frac{\theta_\mathrm{E}}{\theta_\mathrm{ap}}\right)^{2-\gamma} f(\gamma)$$

3. More general spherically symmetric power-law model

$\rho(r) = \rho_0 \left(\frac{r}{r_0}\right)^{-\alpha}$ total mass

$\nu(r) = \nu_0 \left(\frac{r}{r_0}\right)^{-\delta}$. luminous matter

$\beta(r) = 1 - \sigma_t^2/\sigma_r^2$ stellar anisotropy

$$\theta_E = 2\sqrt{\pi}\frac{\sigma_{ap}^2}{c^2}\frac{D_{ls}}{D_s}\left(\frac{\theta_E}{\theta_{ap}}\right)^{2-\alpha}(\xi - 2\beta)\lambda(\alpha)$$

10

Strong lensing cosmography – e.o.s. of the Universe

PHYSICAL REVIEW D 73, 023006 (2006)

Strong lensing systems as a probe of dark energy in the universe

Marek Biesiada[1,*]
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(Received 3 November 2005; published 23 January 2006)

Monthly Notices of the Royal Astronomical Society
Mon. Not. R. Astron. Soc. 406, 1055–1059 (2010) doi:10.1111/j.1365-2966.2010.16725.x

Cosmic equation of state from strong gravitational lensing systems

Marek Biesiada,* Aleksandra Piórkowska* and Beata Malec*
Department of Astrophysics and Cosmology, Institute of Physics, University of Silesia, Uniwersytecka 4, 40-007 Katowice, Poland

Accepted 2010 March 22. Received 2010 March 18; in original form 2010 February 5

20 galaxy lenses
from SLACS + LSD

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal
JCAP03 (2012) 016

Constraints on cosmological models from strong gravitational lensing systems

Shuo Cao,[a] Yu Pan,[a,b] Marek Biesiada,[c] Wlodzimierz Godlowski[d] and Zong-Hong Zhu[a,1]

WMAP7+BAO+H0
Ω_m = 0.272
w = -1.10 ± 0.14
w_0 = -0.93 ± 0.13
w_a = -0.41 ± 0.71
Komatsu et al. 2011

10 cluster lenses
70 galaxy lenses
from SLACS

Cosmological model	Best-fitting parameters (n = 80)	Best-fitting parameters (n = 46)
ΛCDM	$\Omega_m = 0.20^{+0.07}_{-0.07}$	$\Omega_m = 0.26^{+0.11}_{-0.10}$
wCDM	$w = -1.02^{+0.26}_{-0.26}$	$w = -1.15^{+0.34}_{-0.35}$
CPL	$w_0 = 0.60 \pm 1.76$	$w_0 = -0.24 \pm 2.42$
	$w_a = -7.37 \pm 8.05$	$w_a = -6.35 \pm 9.75$

The Astrophysical Journal, 806:185 (12pp), 2015 June 20 doi:10.1088/0004-637X/806/2/185

COSMOLOGY WITH STRONG-LENSING SYSTEMS

Shuo Cao[1], Marek Biesiada[1,2], Raphaël Gavazzi[3], Aleksandra Piórkowska[2], and Zong-Hong Zhu[1]
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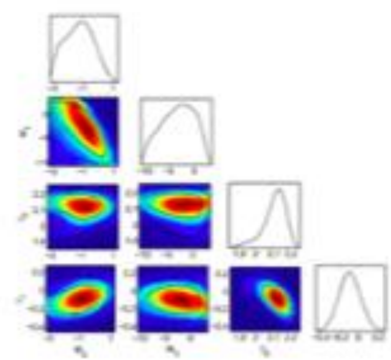
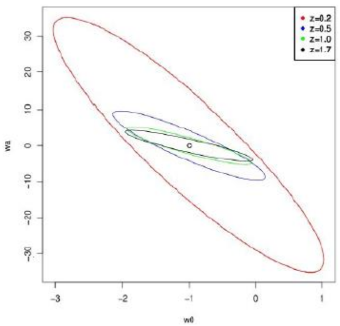
[2] Department of Astrophysics and Cosmology, Institute of Physics, University of Silesia, Uniwersytecka 4, 40-007, Katowice, Poland
[3] Institute d'Astrophysique de Paris, UMR7095 CNRS—Universite Pierre et Marie Curie, 98bis bd Arago, F-75014 Paris, France
Received 2015 January 23; accepted 2015 May 1; published 2015 June 17

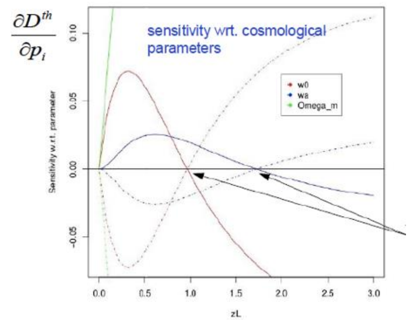


118 lenses from
SLACS sample

Cosmological applications of strong lensing systems

- SL systems may have different degeneracies than SN Ia





A.Piórkowska, MB et al. APP B 2013

The Astrophysical Journal Supplement Series, 285:4 (15pp), 2026 July
https://doi.org/10.3847/1538-4365/ae(

Hierarchical Cosmological Constraints through a Strong-lensing Distance Ratio

Shuaibo Geng[1], Shuo Cao[2,3], Marek Biesiada[1], Xinyue Jiang[1,2,3], Yalong Nan[2,3], and Chenfa Zheng[2,3]

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Received 2026 March 3; revised 2026 April 22; accepted 2026 April 29; published 2026 June 16

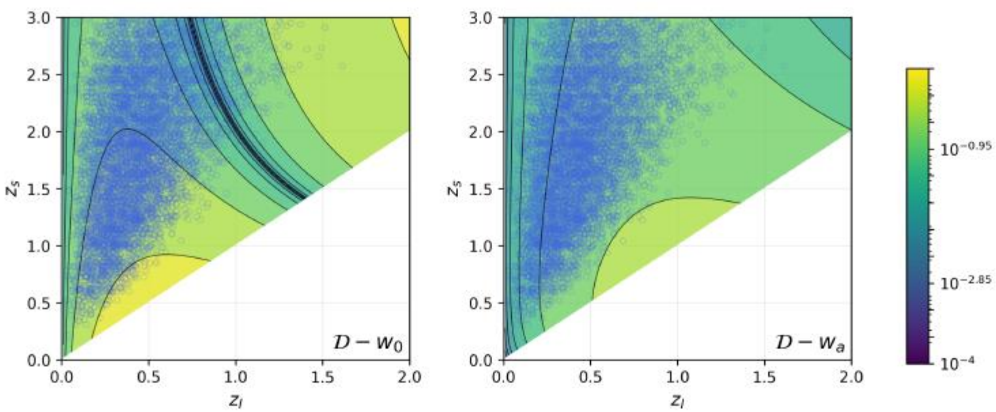
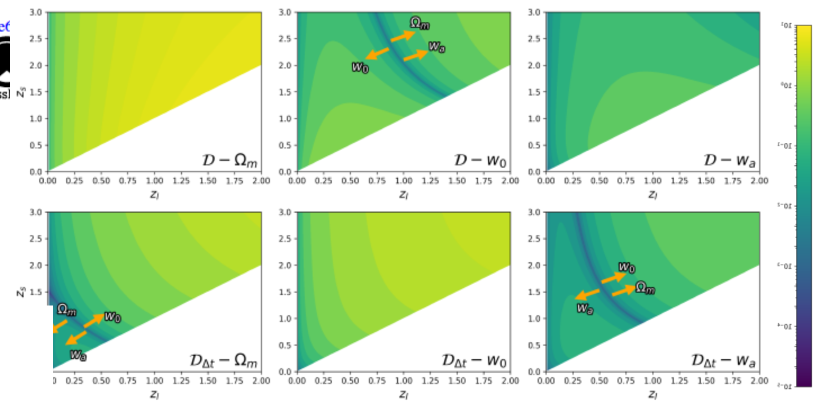


Figure 3. Sensitivity maps for w_0 and w_a assessed using the distance ratio. Blue circles indicate the redshift distribution of the simulation data based on T. E. Collett (2015).



Goal: select the (LSST, Euclid) gold sample best for the purpose

More cosmological applications of strong lensing systems

- Measurements of cosmic curvature

Distance sum rule – valid in any FLRW metric

$$d_{ls} = \sqrt{1+\Omega_k d_l^2}\, d_s - \sqrt{1+\Omega_k d_s^2}\, d_l$$

$$\Omega_k(z_l, z_s) = \frac{d_l^4 + d_s^4 + d_{ls}^4 - 2d_l^2 d_s^2 - 2d_l^2 d_{ls}^2 - 2d_s^2 d_{ls}^2}{4 d_l^2 d_s^2 d_{ls}^2}$$

This is a function of two redshifts, but within the FLRW metric it should be just a single number !

J..Qi, MB et al. MNRAS 2019
S. Cao, MB et al. SciRep 2019
T. Liu MB et al. MNRAS 2020
J. Qi, MB et al. MNRAS 2021
S.Cao, MB et al. ApJ 2022

- Tests of GR – γ PPN parameter and modified gravity

The Astrophysical Journal, 835:92 (7pp), 2017 January 20

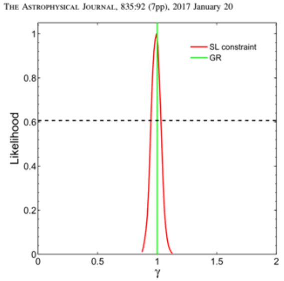


Figure 3. Normalized posterior likelihood of the PPN γ parameter obtained with rigid priors on the nuisance parameters (α, β, δ).

$$\gamma = 0.995^{+0.037}_{-0.047}$$

S. Cao, MB et al. ApJ 2017
Y.Lian MB et al. MNRAS 2021

LSST

$$\frac{\Delta\gamma}{\gamma} \sim 10^{-3} - 10^{-4}$$

Conclusions

History of modern cosmology witnessed numerous tensions.

Age of the Universe vs. globular clusters …
matter budget issues …

Modern tensions are embedded in subtle issues of calibrations and systematics

Their persistent significance may be telling us something,
e.g. that ΛCDM model or even FLRW framework are too simplified.

We need further development of alternative cosmological probes (strong lensing, GW standard sirens, lensing of transient events, AGNs, compact radio-sources, etc.)

Supplementary slides – Hubble tension

Tensions within ΛCDM

- **H_0 tension** – persistent significant disagreement between
  early $H_0 = 67.4 \pm 0.5 \;\; km\, s^{-1}\, Mpc^{-1}$
  and
  late-time cosmological probes

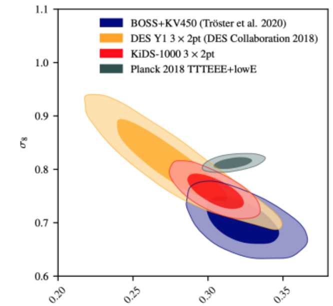
$$H_0 = 73.17 \pm 0.86 \;\; km\, s^{-1}\, Mpc^{-1}$$

CMB

$$S_8 = 0.834 \pm 0.016$$

DES3Y

$$S_8 = 0.772 \pm 0.017$$



Credit:C.Heymans et al. 2020
arXiv:2007.15632

- S_8 tension

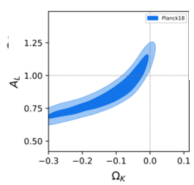
$$S_8 \equiv \sigma_8 \sqrt{\Omega_m / 0.3} \text{ parameter}$$

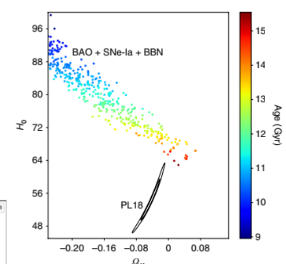
- Curvature parameter Ω_k

ARTICLES
https://doi.org/10.1038/s41550-019-0906-9
nature astronomy

Planck evidence for a closed Universe and a possible crisis for cosmology

Eleonora Di Valentino[1], Alessandro Melchiorri[2*] and Joseph Silk[3,4,5]



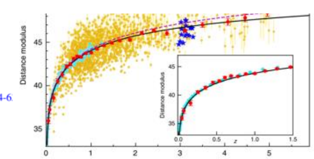


nature astronomy LETTERS
https://doi.org/10.1038/s41550-018-0657-z

Cosmological constraints from the Hubble diagram of quasars at high redshifts

G. Risaliti[1,2*] and E. Lusso[3]

A&A 628, L4 (2019)
https://doi.org/10.1051/0004-6361/...
© ESO 2019



Astronomy & Astrophysics

LETTER TO THE EDITOR

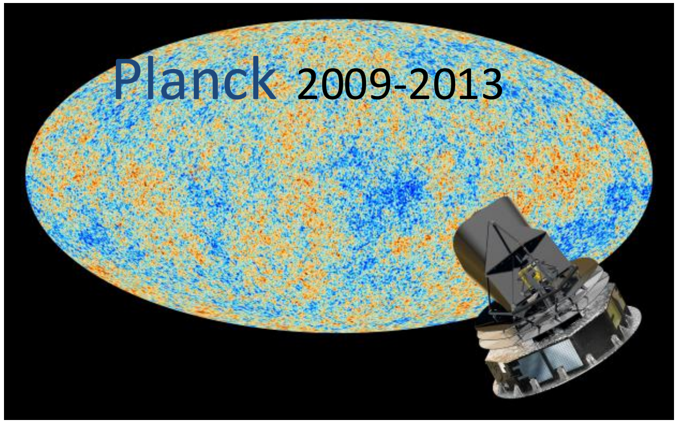
Tension with the flat ΛCDM model from a high-redshift Hubble diagram of supernovae, quasars, and gamma-ray bursts

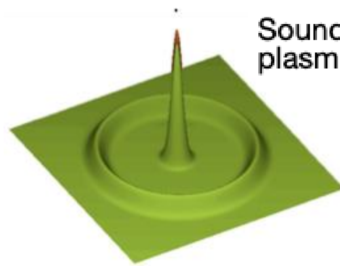
E. Lusso[1,2], E. Piedipalumbo[3,4], G. Risaliti[1,2], M. Paolillo[3,4,5], S. Bisogni[2], E. Nardini[2], and L. Amati[5,6]

- **Validity of ΛCDM itself** – DESI results gave evidence of evolving DE

Early time probes CMB, BAO

$$c_s^2(z) = \frac{1}{3}\left[1 + \frac{3}{4}\frac{\rho_b(z)}{\rho_\gamma(z)}\right]^{-1}$$

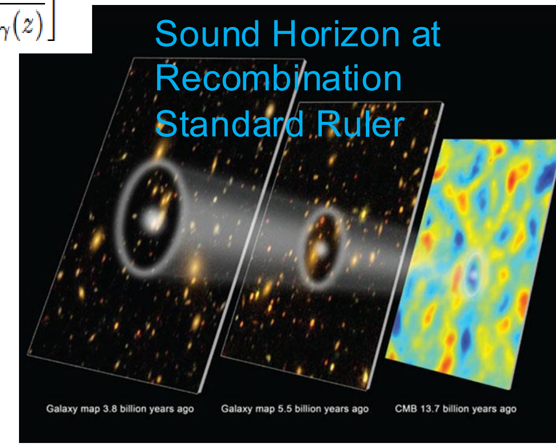


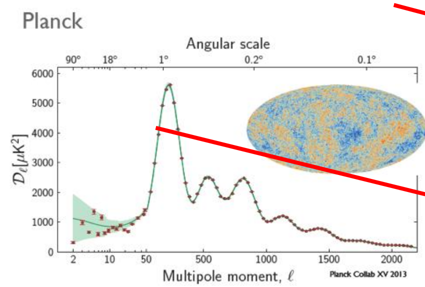


Sound waves in primordial plasma:

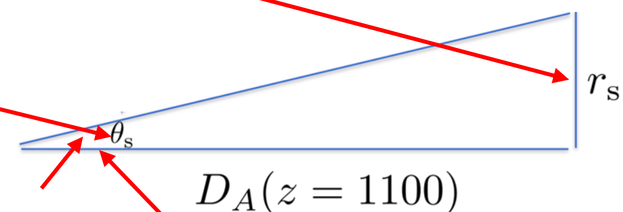
standard ruler – sound horizon

$$r_s = \int_{z_*}^{\infty} \frac{c_s(z)}{H(z)} dz$$





calculated



measured

A&A 641, A6 (2020)
https://doi.org/10.1051/0004-6361/201833910
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Planck 2018 results

Astronomy & Astrophysics
Special issue

Planck 2018 results

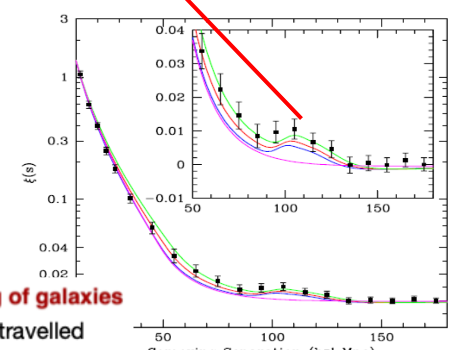
VI. Cosmological parameters

Table 2. Parameter 68% intervals for the base-ΛCDM model from *Planck* CMB power spectra, in combination with CMB lensing reconstruction and BAO.

Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1206 ± 0.0021	[illegible]	[illegible]	[illegible]	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04077 ± 0.000[illegible]	[illegible]	[illegible]	[illegible]	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0522 ± 0.0080	[illegible]	[illegible]	[illegible]	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.040 ± 0.016	[illegible]	[illegible]	[illegible]	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9626 ± 0.0057	0.967 ± 0.011	0.980 ± 0.015	0.9649 ± 0.0044	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0 [km s^{-1} Mpc^{-1}]	66.88 ± 0.92	68.44 ± 0.91	69.9 ± 2.7	67.27 ± 0.60	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.679 ± 0.013	0.699 ± 0.012	$0.711^{+0.033}_{-0.026}$	0.6834 ± 0.0084	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.321 ± 0.013	[illegible]	[illegible]	[illegible]	[illegible].3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1434 ± 0.00[illegible]	[illegible]	[illegible]	[illegible]	[illegible].1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09589 ± 0.0[illegible]	[illegible]	[illegible]	[illegible]	[illegible].09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8118 ± 0.00[illegible]	[illegible]	[illegible]	[illegible]	[illegible].8111 ± 0.0060	0.8102 ± 0.0060
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$	0.840 ± 0.024	[illegible]	[illegible]	[illegible]	[illegible].832 ± 0.013	0.825 ± 0.011
$\sigma_8 \Omega_m^{0.25}$	0.611 ± 0.012	[illegible]	[illegible]	[illegible]	[illegible].6078 ± 0.0064	0.6051 ± 0.0058

6 base parameters

8 derived parameters including H_0



⟹ a residual spherical **peak in clustering of galaxies**

size of feature = distance sound wave travelled

= sound horizon scale at recomb.

≃ 150 Mpc

r_s=147.6 Mpc from Planck and BBN values of ρ_b, ρ_γ and ρ_{CDM}

Measuring H_0 with CMB

Steps within ΛCDM: See e.g. Knox & Millea's *Hubble Hunter's Guide*, PRD 101 (2020) 043533

- Infer ω_b from even/odd peak height modulation
- Infer ω_m from "potential envelope" effect (early ISW effect)
- Calculate $r_s^\star \sim \int_{z_\star}^{\infty} dz\, c_s(z,\omega_b)/\sqrt{\omega_m(1+z)^3+\omega_r(1+z)^4}$
- Measure $\theta_s \sim \pi/\Delta\ell$ from peak spacing
- With $r_s^\star$ and θ_s known, infer $D_A^\star = r_s^\star/\theta_s$

$$\theta_s = \frac{r_s}{D_A(z)} = \frac{H_0\, r_s}{\int_0^z \frac{dz}{E(z)}}$$

Here ΛCDM is assumed

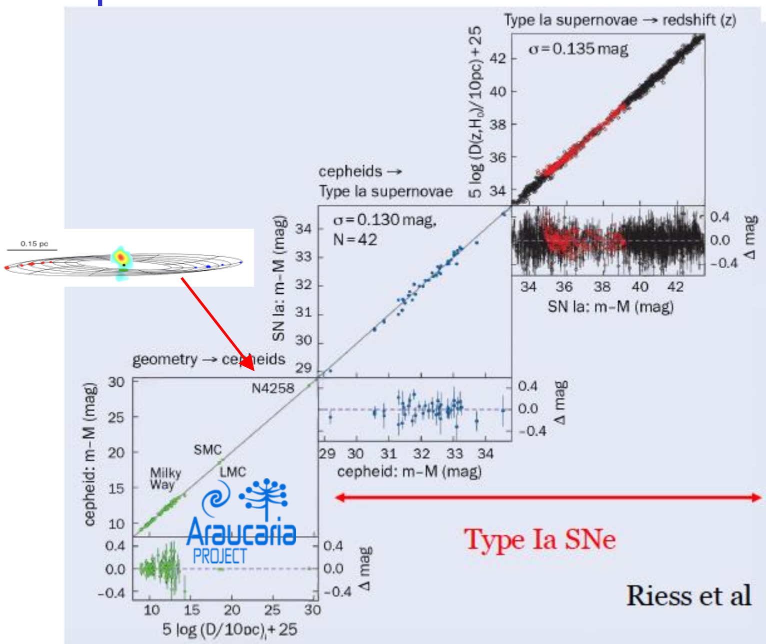
r_s=147.6 Mpc from Planck and BBN values of ρ_b, ρ_γ and ρ_{CDM}

$$E(z) = \left[\Omega_{0m}(1+z)^3 + (1-\Omega_{0m})\right]^{\frac{1}{2}}$$

Degeneracy between r_s and H_0 and E(z).

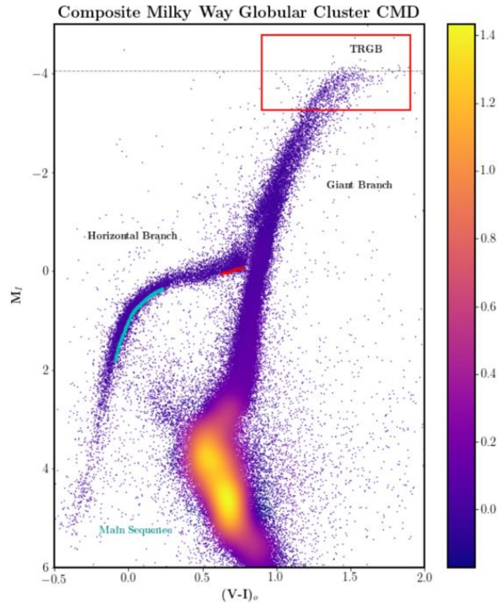
Late time probes

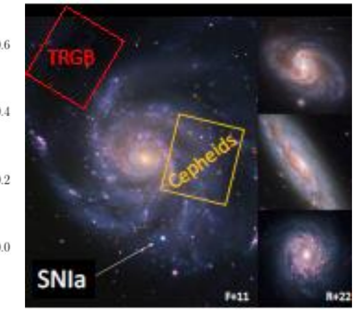
H_0 from 3-rung distance ladder
Cepheids

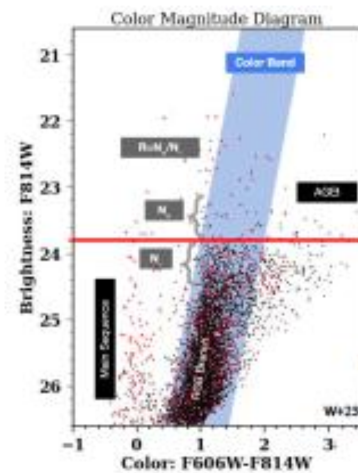


Systematics:
multiple photometric systems 1-2%
crowding
metallicity
Cepheids in binaries

H_0 from
Tip of Red Giant Branch







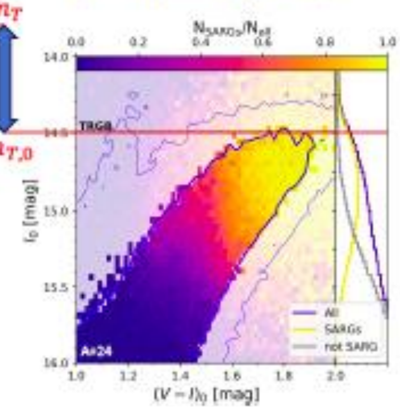
$H_0 \approx cz/10^{0.2(\mu-25)}$

μ_T calibrates SBF or SNeIa
to trace Hubble flow

$\mu_T = m_T - m_{T,0} + \mu_0$

m_T

$m_{T,0}$



μ_0 from geometry
e.g., Gaia, MCs, NGC4258

$$H_0 = 70.39 \pm 1.22\ (\mathrm{stat}) \pm 1.33\ (\mathrm{sys}) \pm 0.70\ (\sigma_{SN})$$

W.Freedman et al. ApJ 2025

Measuring H_0 with standard candles: late time calibrators

Fit for H_0 using SNIa Standard Candles, (0.02<z<0.1)

fit with approximate formula (0.01<z<0.1)

$$d_L = c(1+z)\int_0^z \frac{dz'}{H(z')}$$

$$D_L(z,q_0) = cz\left[1+\frac{1}{2}(1-q_0)z\right]$$

$$m_{th}(z) = M + 5\,log_{10}\left[\frac{d_L(z)}{Mpc}\right] + 25$$

$$m_{th}(z) = M + 5\,log_{10}\left(D_L(z)\right) + 5\,log_{10}\left(\frac{c/H_0}{1Mpc}\right) + 25$$

$$D_L(z) = \frac{H_0\, d_L(z)}{c}$$

measure

measure locally (z<0.01, 40Mpc) using relative distance indicators (e.g. Cepheids)

Fit (assume M is the same in the Hubble flow (z>0.01))

Degeneracy between M (measured at z<0.01) and H_0 (fit at z> 0.01). No $E(z)=H(z)/H_0$ dependence.

Fit for H(z) and cosmological parameters (Ω_{0m}) z_{max}~2.

Parametrize H(z):

$$H(z)^2 = H_0^2\left[\Omega_{0m}(1+z)^3 + (1-\Omega_{0m})\right]$$

$$m_{th}(\Omega_{0m},\mathcal{M}) = 5\ log_{10} D_L(z;\Omega_{0m}) + \mathcal{M}(M,H_0)$$

$$D_L(z,\Omega_{0m}) = c(1+z)\int_0^z \frac{dz'}{\left[\Omega_{0m}(1+z')^3 + (1-\Omega_{0m})\right]^{1/2}}$$

Minimize:

$$\chi^2(\mathcal{M},\Omega_{0m}) = \sum_i \left[\frac{m_{obs,i} - m_{th}(z_i;\Omega_{0m},\mathcal{M})}{\sigma_i^2}\right]$$

$$\mathcal{M} = M + 5log\frac{c/H_0}{Mpc} + 25$$

Issues in the SH0ES Analysis for H_0

SNIa calibration parameters:
absolute magnitude M_B
color and stretch parameters (α,β)

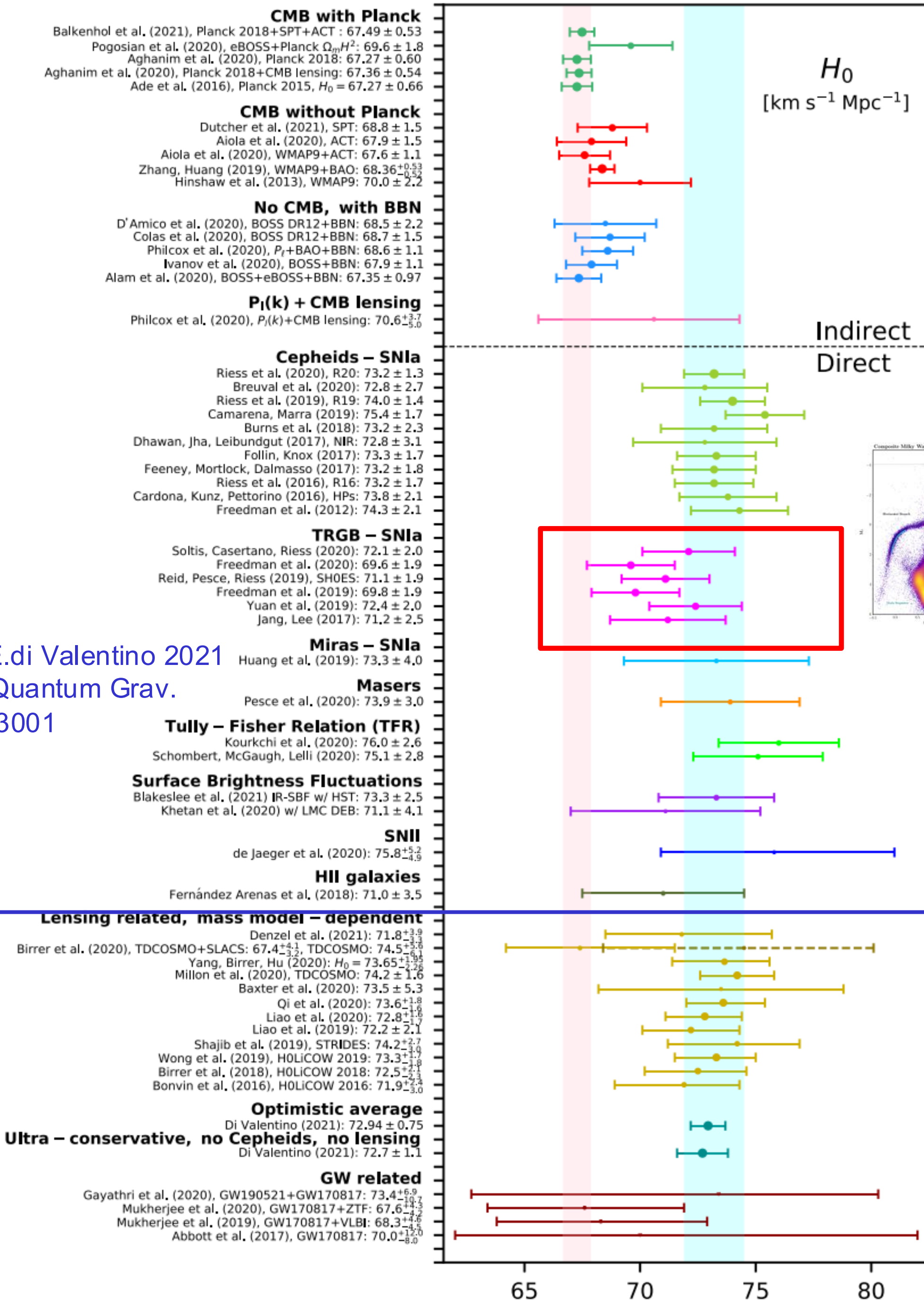
Cepheid calibration parameters:
b_W (period-luminosity),
Z_W (metallicity-luminosity),
M_W (Cepheid zero-point amplitude),
R_W (Cepheid color-luminosity)

best fit values of these parameters
are not consistent among different subgroups of
SNIa+Cepheid data

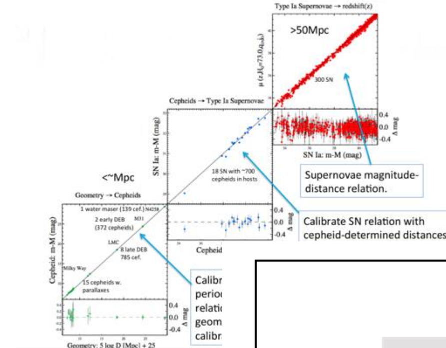
E.Mortsell, A. Goobar, et al. ApJ 2022
R. Wojtak, J. Hjorth, MNRAS 2022

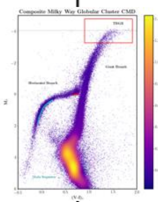
3-rung distance ladder

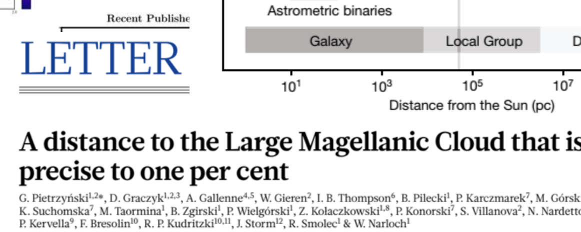
Adapted from Adam Riess and Silvia Galli



Credit:E.di Valentino 2021 Class. Quantum Grav. 38, 153001



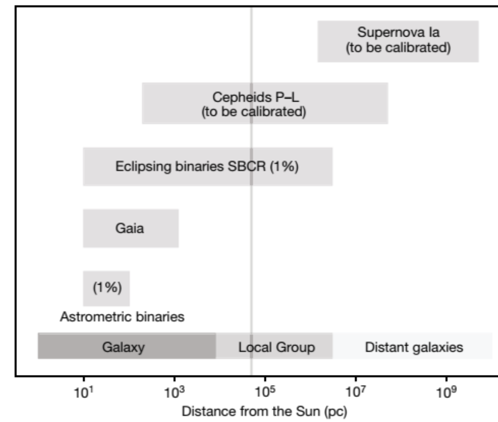



Recent Published

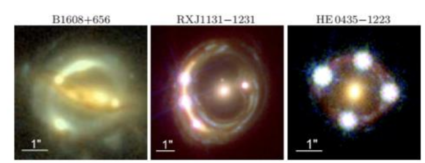
LETTER

A distance to the Large Magellanic Cloud that is precise to one per cent

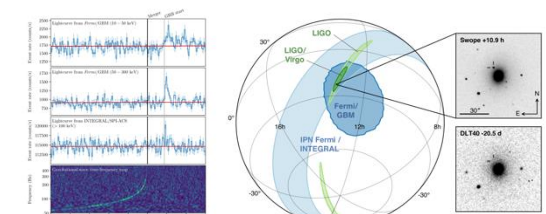
G. Pietrzyński[1,2]*, D. Graczyk[1,2,3], A. Gallenne[4,5], W. Gieren[2], I. B. Thompson[6], B. Pilecki[1], P. Karczmarek[7], M. Górski[2], K. Suchomska[7], M. Taormina[1], B. Zgirski[1], P. Wielgórski[1], Z. Kołaczkowski[1,8], P. Konorski[7], S. Villanova[2], N. Nardetto[5], P. Kervella[9], F. Bresolin[10], R. P. Kudritzki[10,11], J. Storm[12], R. Smolec[1] & W. Narloch[1]



Alternative probes



Strong lensing time delays



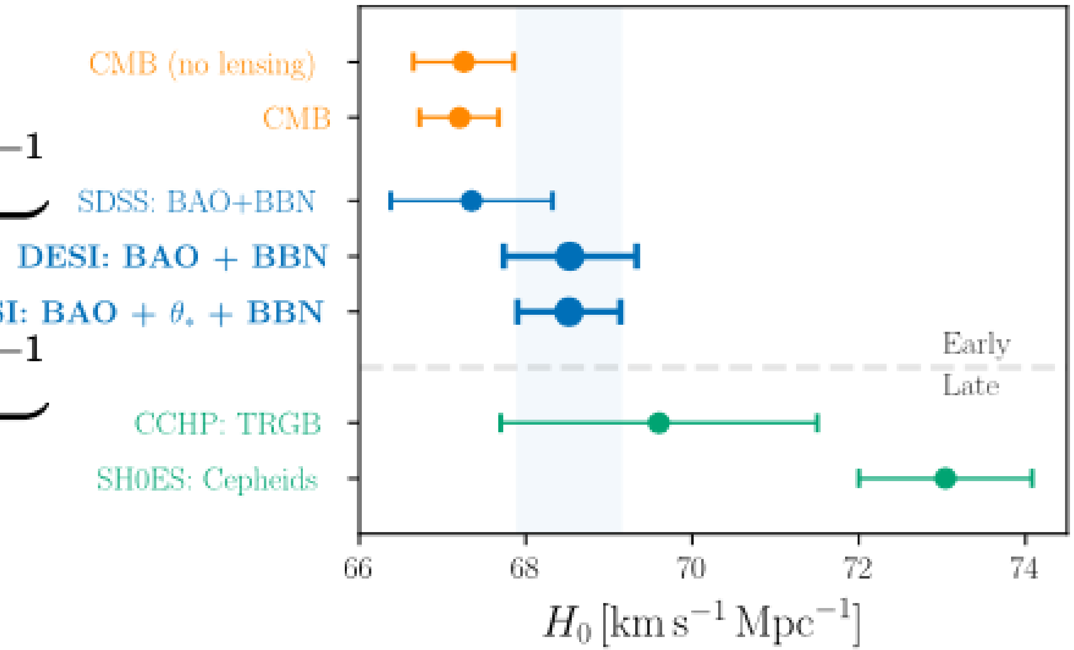
GW170817

Hubble constant

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

$$\underbrace{H_0 = (68.53 \pm 0.80)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}}_{\mathbf{DESI+BBN}}$$

$$\underbrace{H_0 = (68.52 \pm 0.62)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}}_{\mathbf{DESI}+\theta_*+\mathbf{BBN}}$$



- Consistency with SDSS
- In agreement with CMB
- In 3.7σ tension with SH0ES

Credit: A.de Mattia *Moriond 2024*

The Astrophysical Journal Letters, 978:L33 (5pp), 2025 January 10 https://doi.org/10.3847/2041-8213/ada37f

Newest Measurements of Hubble Constant from DESI 2024 Baryon Acoustic Oscillation Observations

Wuzheng Guo[1,2], Qiumin Wang[1,2], Shuo Cao[1,2], Marek Biesiada[3], Tonghua Liu[4], Yujie Lian[1,2], Xinyue Jiang[1,2], Chengsheng Mu[1,2], and Dadian Cheng[1,2]
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Abstract

In this Letter, we use the latest results from the Dark Energy Spectroscopic Instrument (DESI) survey to measure the Hubble constant. Baryon acoustic oscillation (BAO) observations released by the DESI survey, allow us to determine H_0 from the first principles. Our method is purely data-driven and relies on unanchored luminosity distances reconstructed from Type Ia supernovae (SN Ia) data and $H(z)$ reconstruction from cosmic chronometers. Thus, it circumvents calibrations related to the value of the sound horizon size at the baryon drag epoch or intrinsic luminosity of SN Ia. We find $H_0 = 68.4^{+1.0}_{-0.8}$ km s^{-1} Mpc^{-1} at a 68% confidence level, which provides the Hubble constant at an accuracy of 1.3% with minimal assumptions. Our assessments of this fundamental cosmological quantity using the BAO data spanning the redshift range $z = 0.51$–2.33 agree very well with Planck's results and TRGB results within 1σ. This result is still in a 4.3σ tension with the results of the Supernova H0 for the Equation of State.

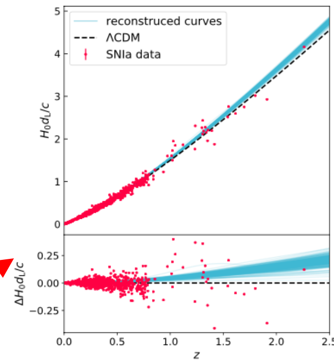


Figure 1. Reconstructed $H_0 d_L$ from SN Ia data using Gaussian regression. The black dashed line shows the best-fitted ΛCDM model. The residuals between reconstructed $H_0 d_L$ and the best-fit ΛCDM are also shown in the bottom panel.

SN Ia Pantheon+

Cosmic Chronometers

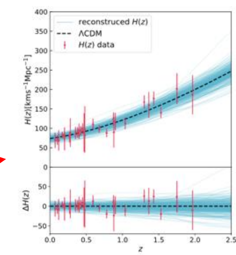


Figure 2. Reconstructed $H(z)$ from CC data using Gaussian regression. The black dashed line shows the best-fit ΛCDM model. The residuals between reconstructed $H(z)$ ... anel.

$$\frac{d_L(z)}{(1+z)^2 d_A(z)} = 1.$$

Etherington relation

$$H_0 = \frac{1}{(1+z)^2}\frac{H_0 d_L(z)}{H(z) d_A(z)} H(z).$$

$$\frac{D_M}{D_H} = \frac{(1+z)d_A(z)}{cH(z)^{-1}} = \frac{1+z}{c}H(z)d_A(z).$$

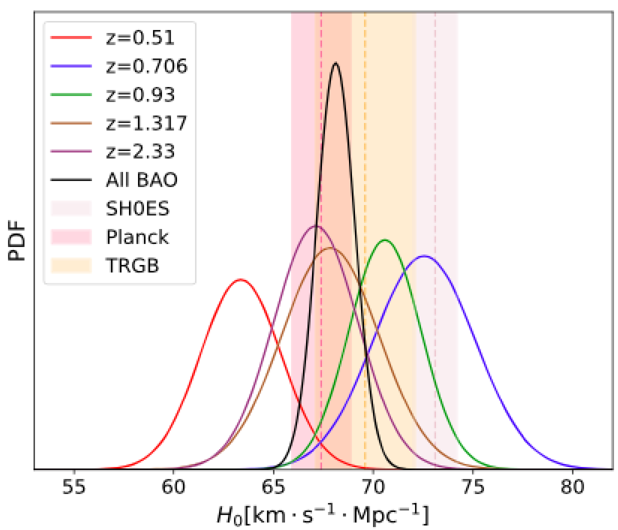
$$H_0 = 68.4^{1.0}_{-0.8}\ km\, s^{-1}\, Mpc^{-1}$$

DESI 2024
5 BAO data points

Table 1
Value of the Hubble Constant at Different Redshifts Corresponding to BAO Data Points from DESI

z	H_0 (km s^{-1} Mpc^{-1})
Total	$68.4^{+1.0}_{-0.8}$
0.51	$63.4^{+2.3}_{-2.1}$
0.706	$72.4^{+2.8}_{-2.5}$
0.93	70.8 ± 1.8
1.317	$67.9^{+2.9}_{-2.4}$
2.33	67.5 ± 2.3

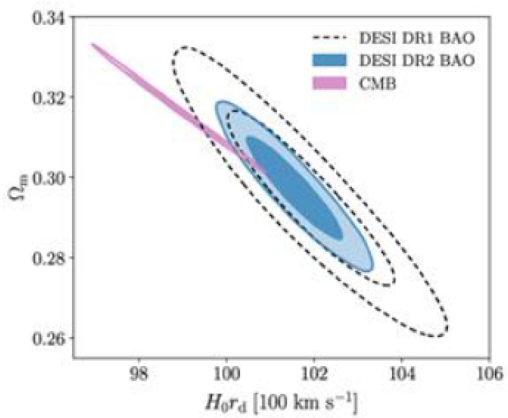
Note. The joint posterior H_0 value is denoted as total.



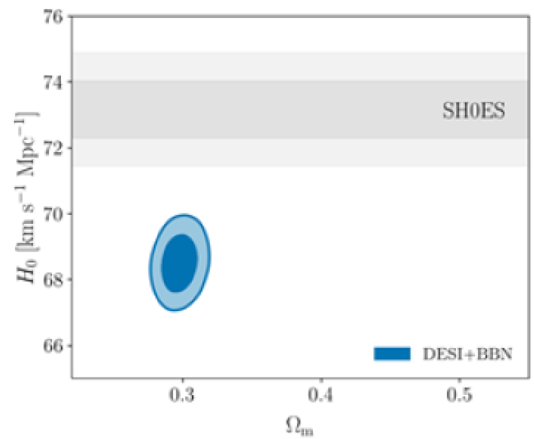
DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

$r_d\,H_0 \rightarrow H_0$

DESI 2025:arXiv:2503.14738



r_d from BBN

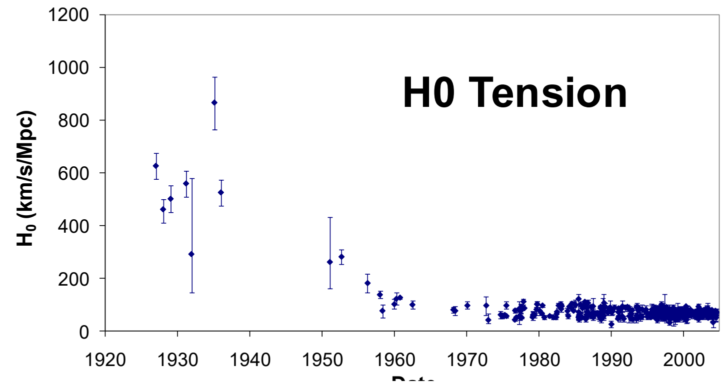


$$H_0 = (68.51 \pm 0.58)\ \mathrm{km\,s^{-1}\,Mpc^{-1}} \quad \text{(DESI+BBN)}$$

In ΛCDM, the tension between the DESI+BBN and SH0ES H_0 (Breuval++2024) now stands at 4.5σ, independent of the CMB.

- **Still in agreement with CMB (1.9->2.3sigma discrepancy)**

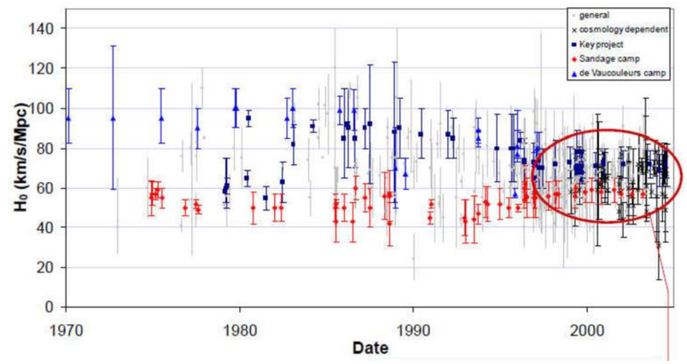
Conclusions

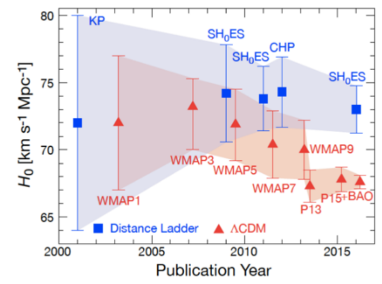


History of modern cosmology witnessed numerous tensions.

Age of the Universe vs. globular clusters …

matter budget issues …





Modern tensions are embedded in subtle issues of calibrations and systematics

Their persistent significance may be telling us something,
e.g. that ΛCDM model or even FLRW framework are too simplified.

We need further development of alternative cosmological probes (strong lensing, GW standard sirens, lensing of transient events, AGNs, compact radio-sources, etc.)