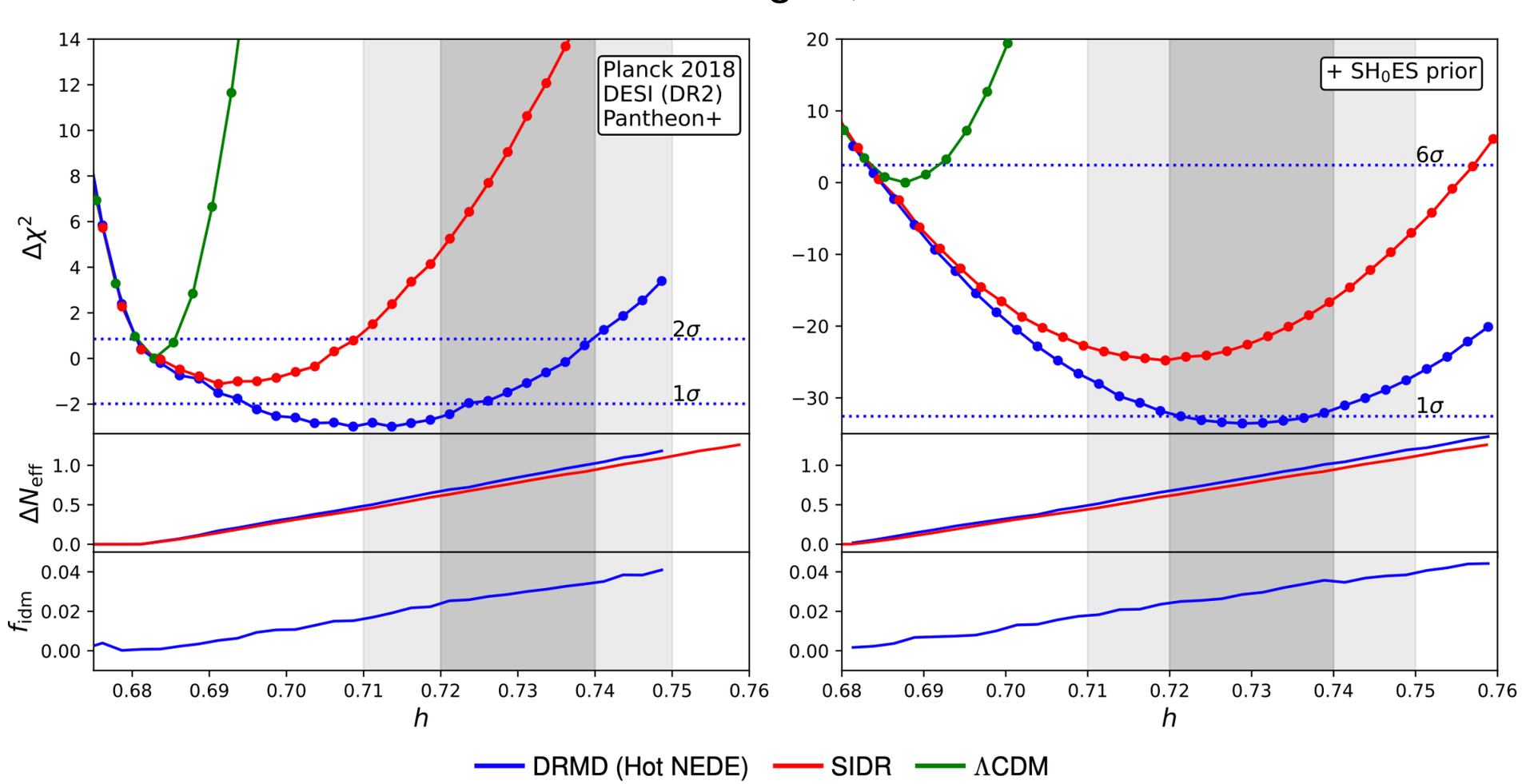
Resolving the Hubble Tension with New Early Dark Energy

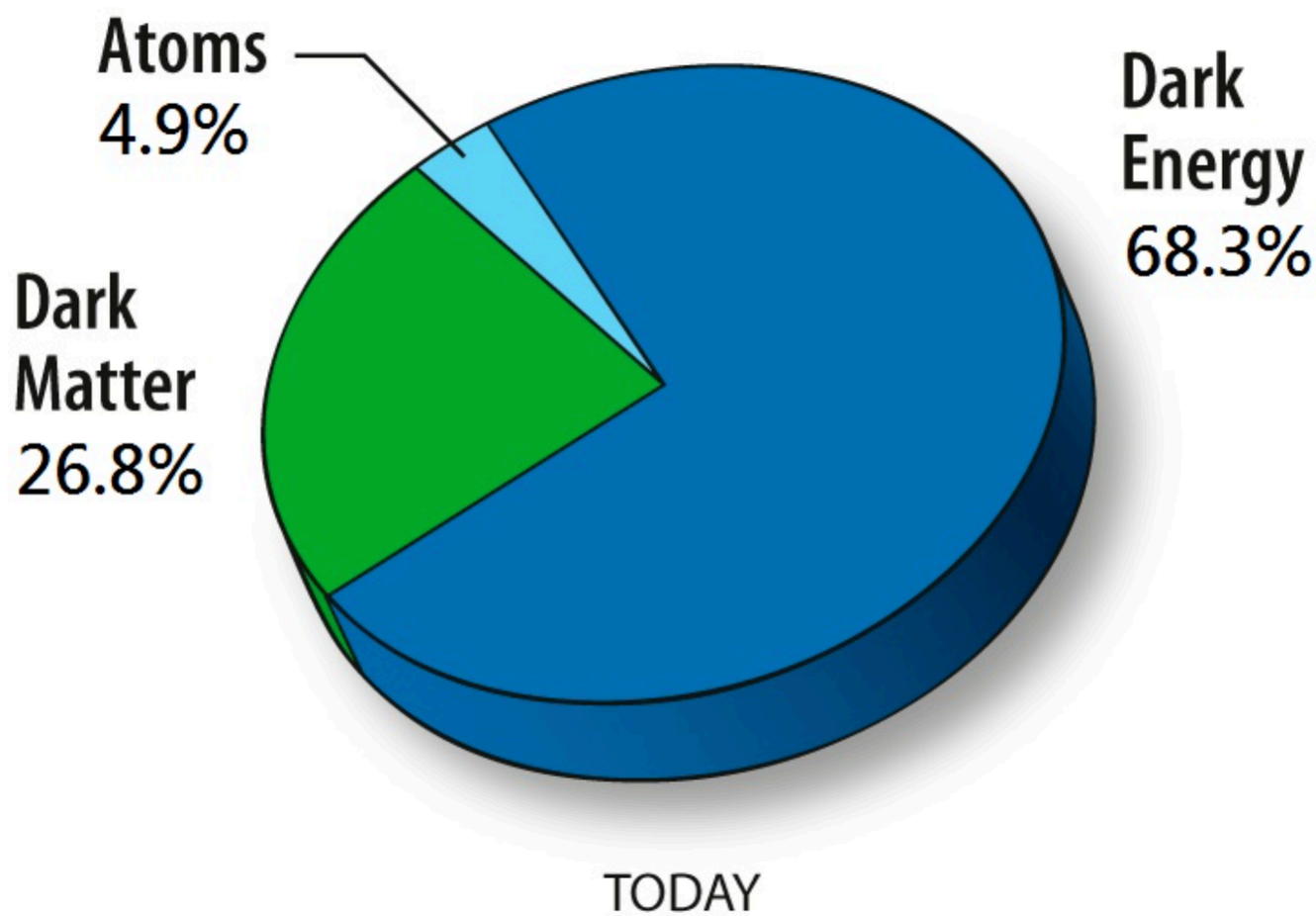
Martin S. Sloth

Universe-Origins, SDU



In collaboration with Florian Niedermann, Mathias Garny, Henrique Rubira, Aleksandr Chatrchyan, Emil Brinch Holm, Vivian Poulin, Thomas Tram, Steen Hannestad, …

ΛCDM



Evidence for ΛCDM

Evidence

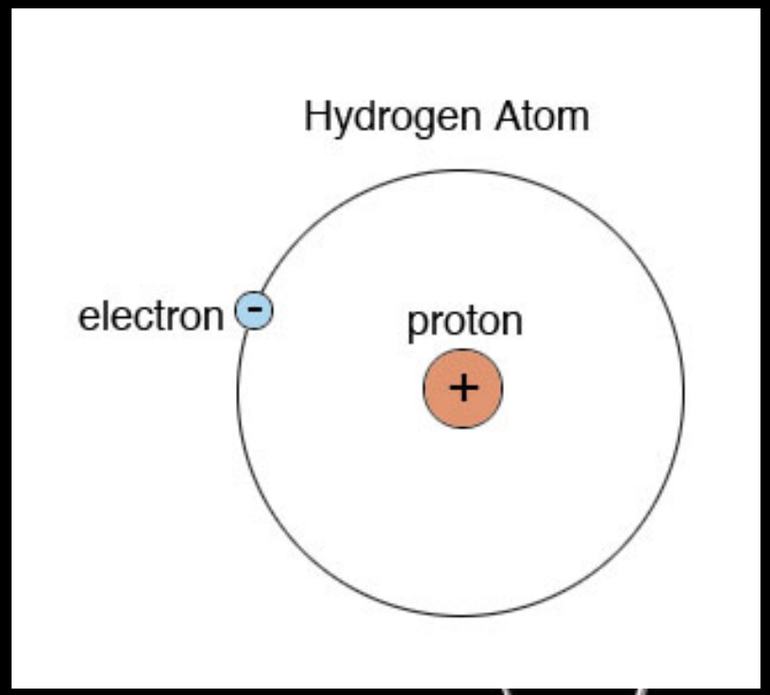
Most important for this talk:

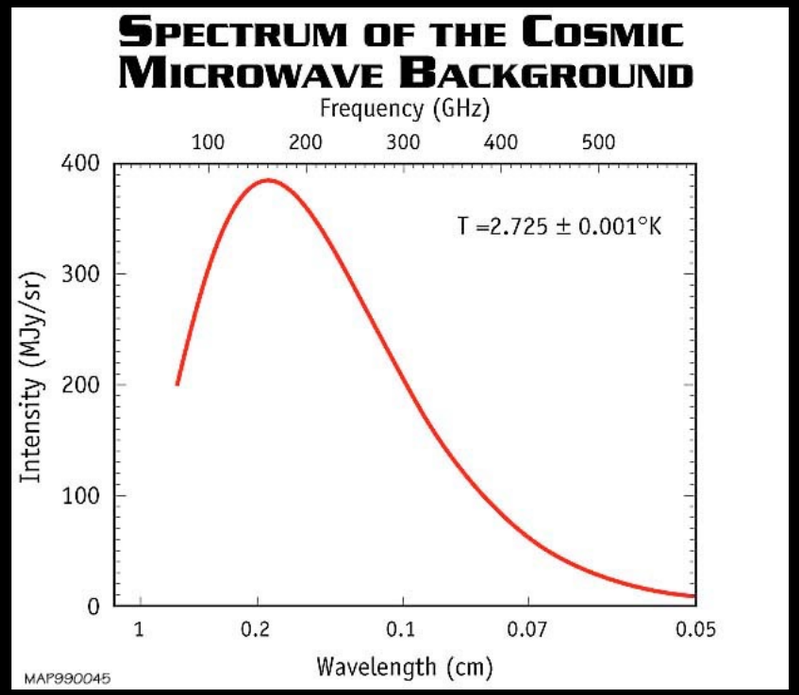
1. CMB (Cosmic Microwave Background)

2. BAO (Baryonic Acoustic Oscillations)

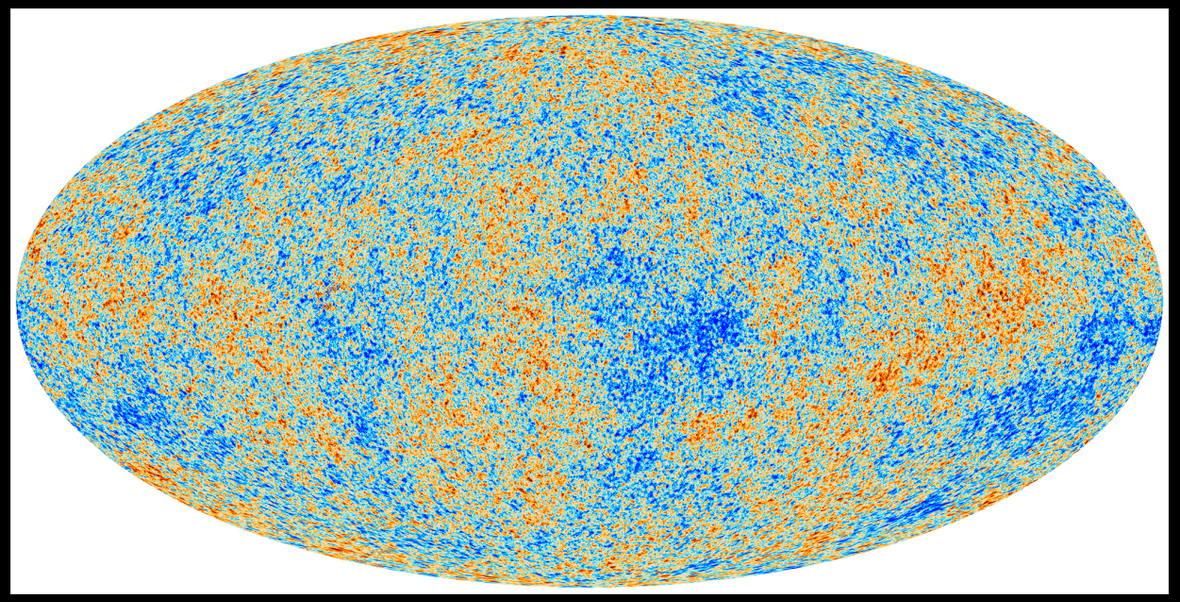
3. SN (Type IA SuperNovae)

CMB created 380.000 years after Big Bang

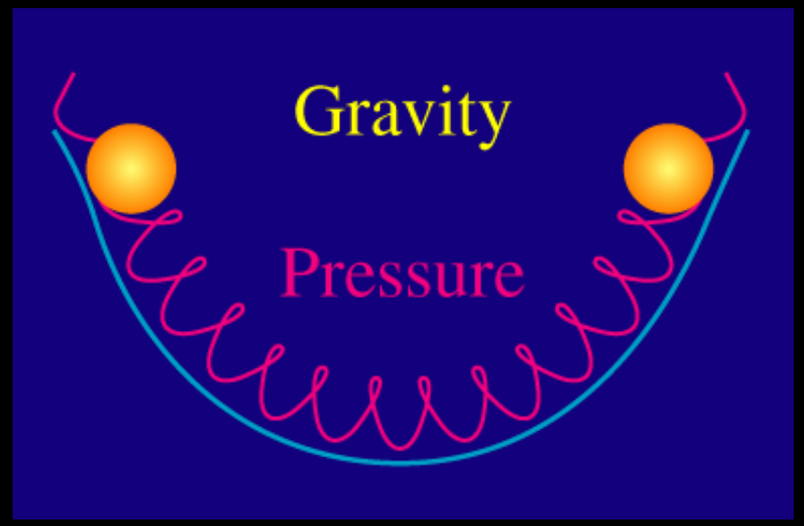


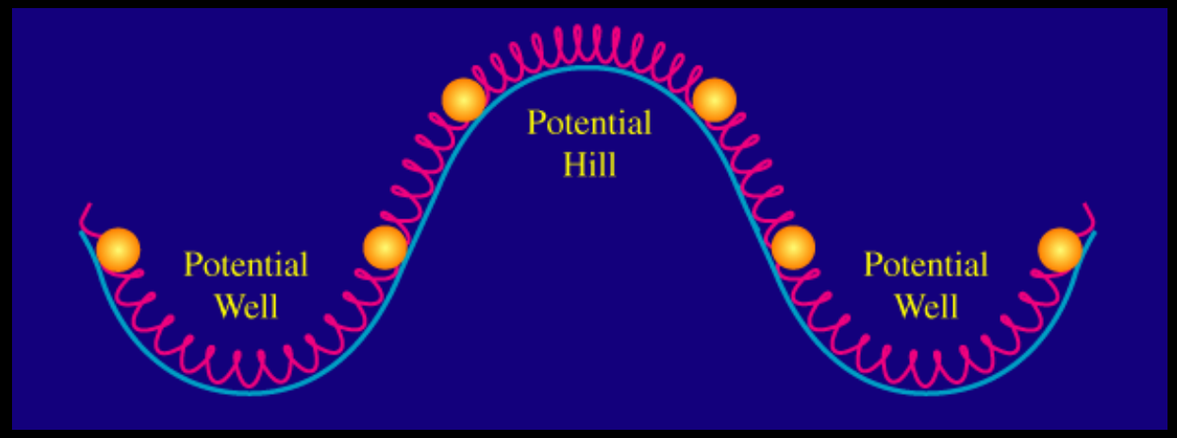


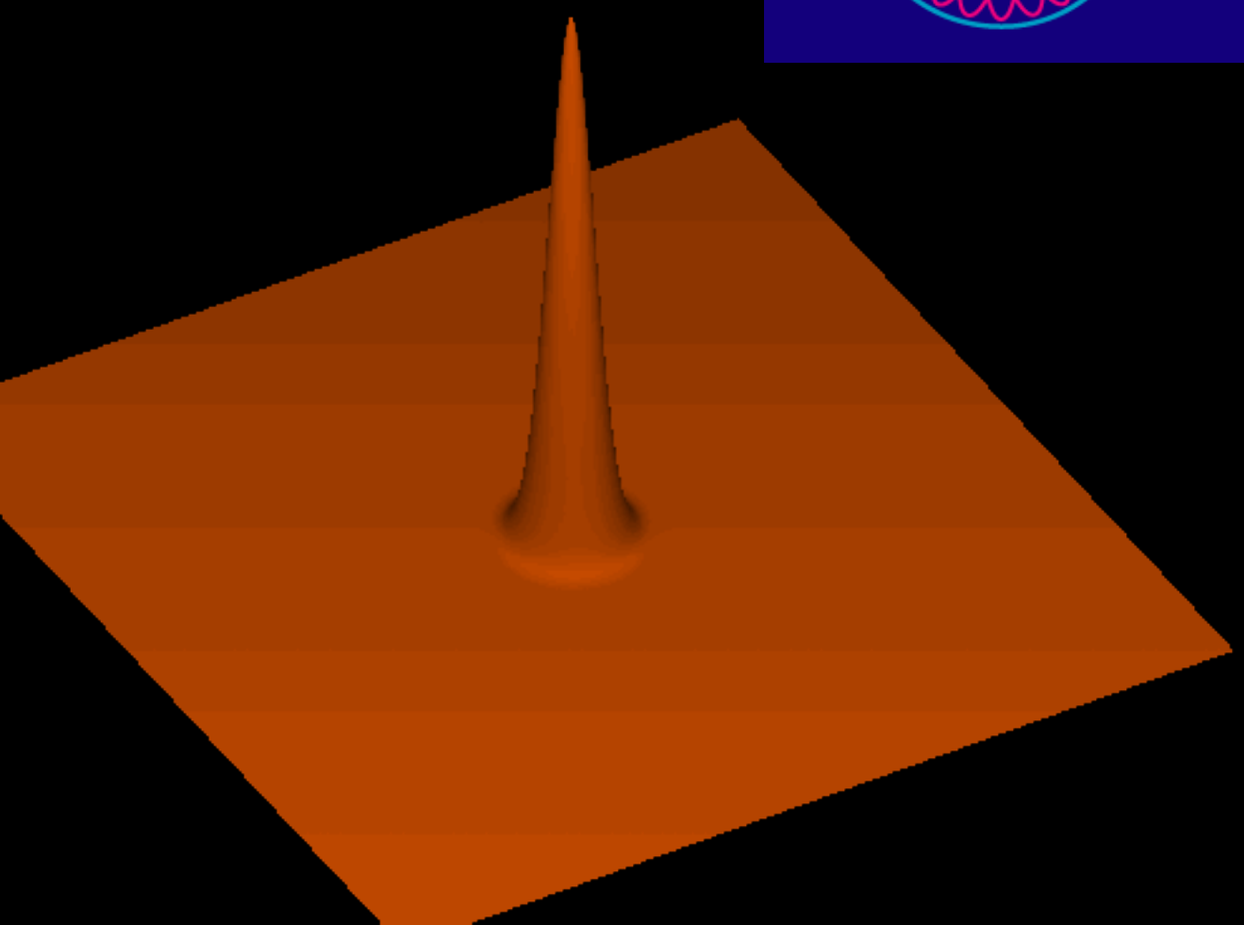
Nobel Prizes, 1978, 2006

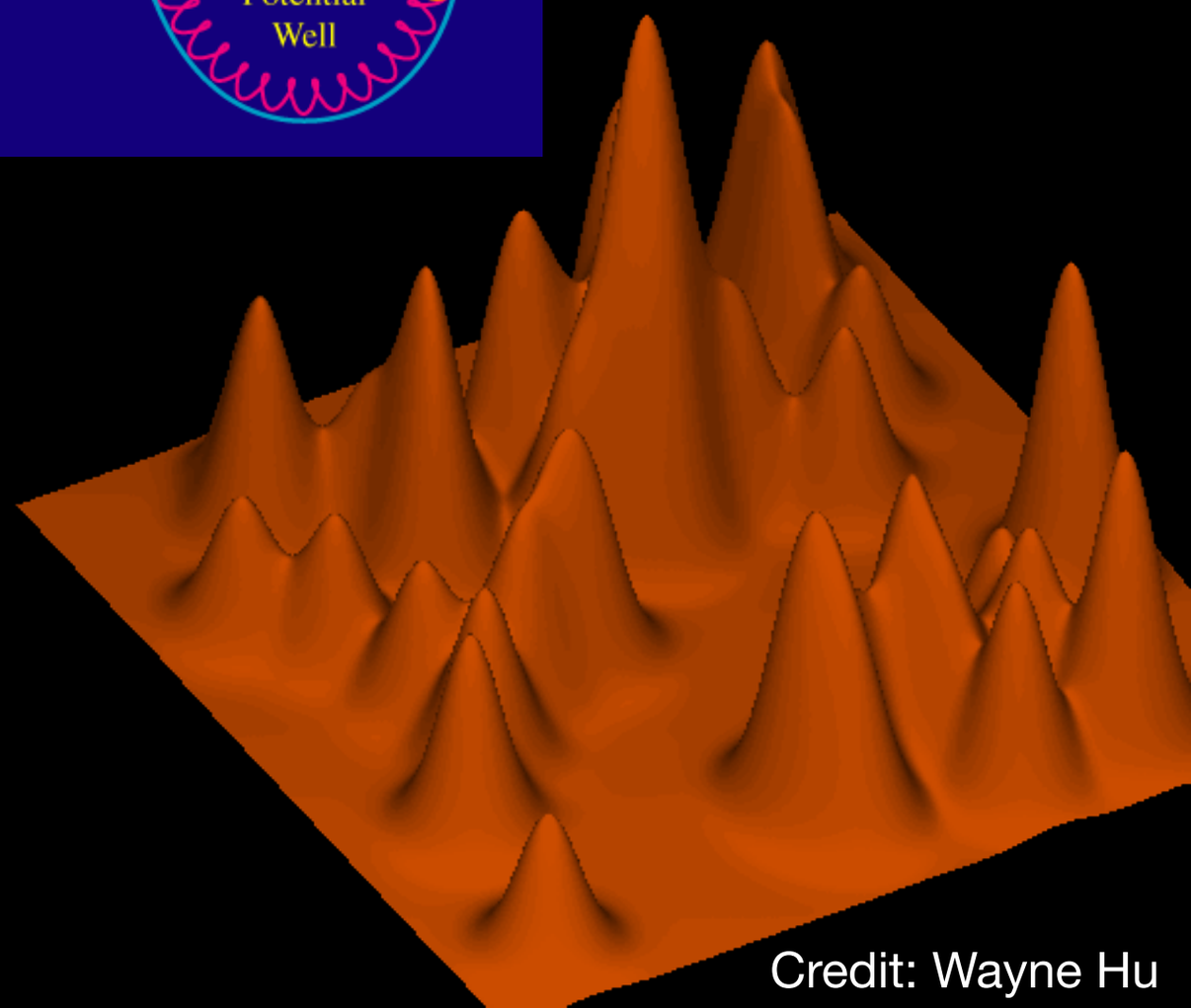


Planck 2013, ESA







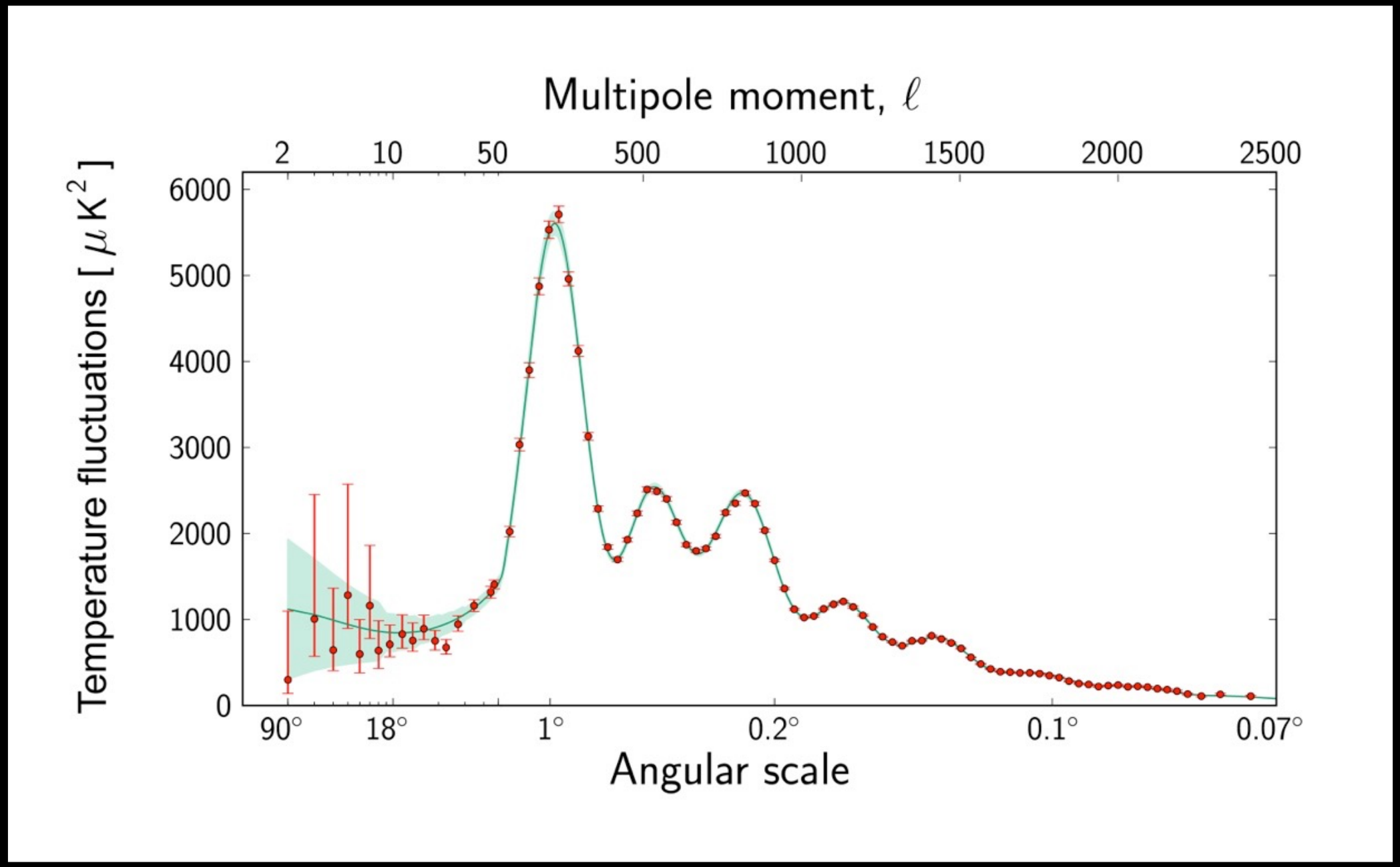


Credit: Wayne Hu

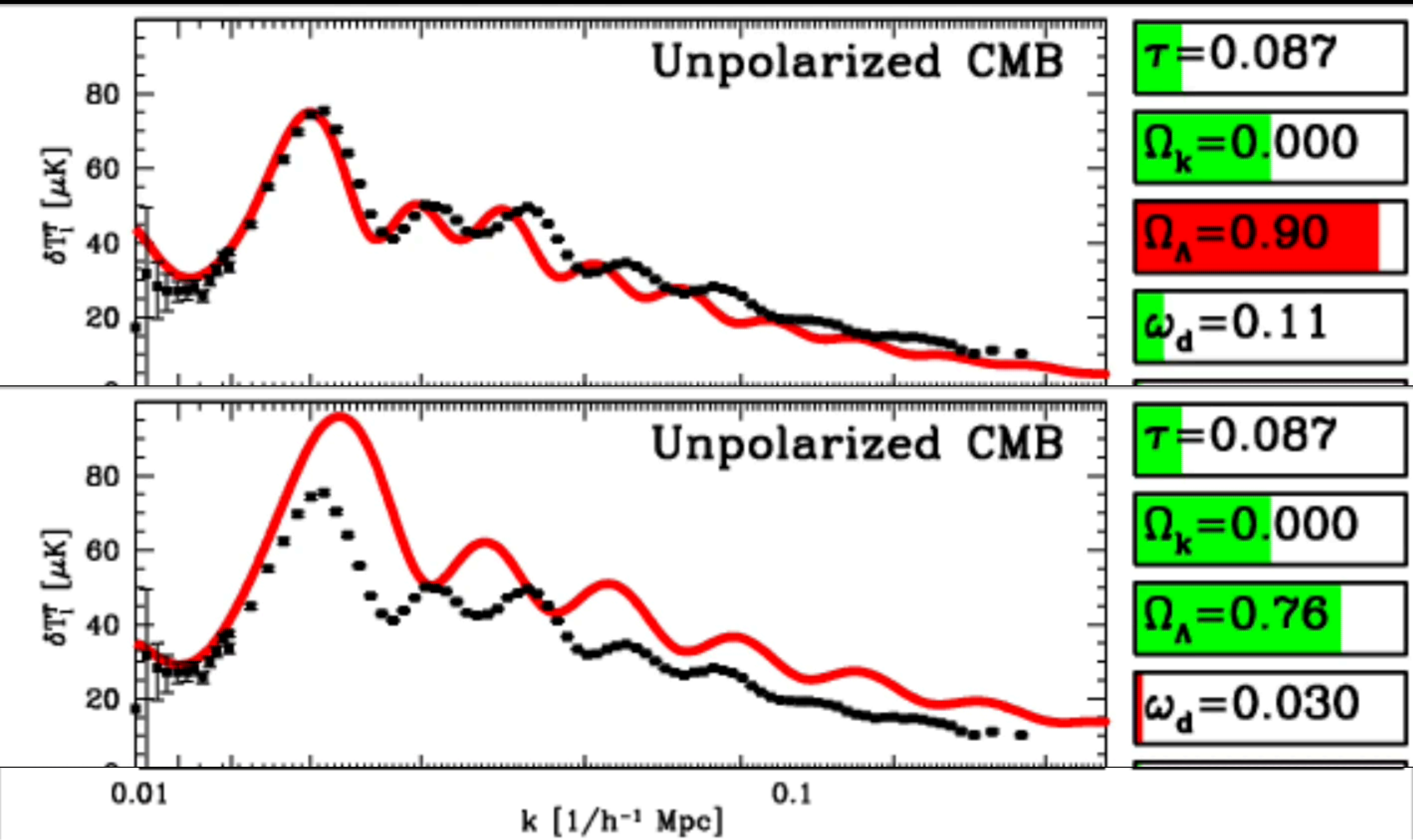
Sound horizon

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

$$\frac{H(z)}{H_0} = \sqrt{\Omega_\Lambda + \Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_X(z)}$$

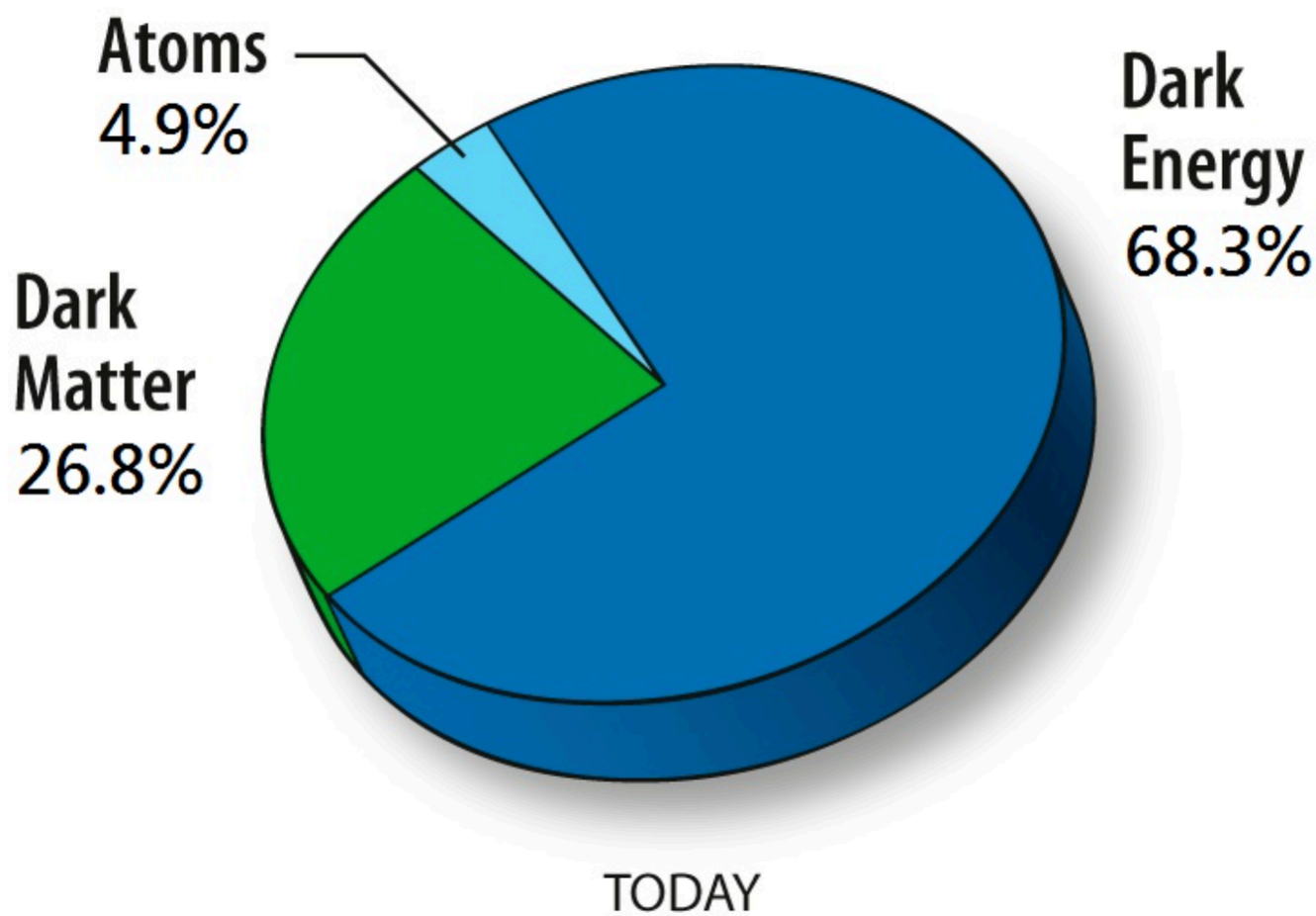


CMB spectrum, Planck 2013, ESA

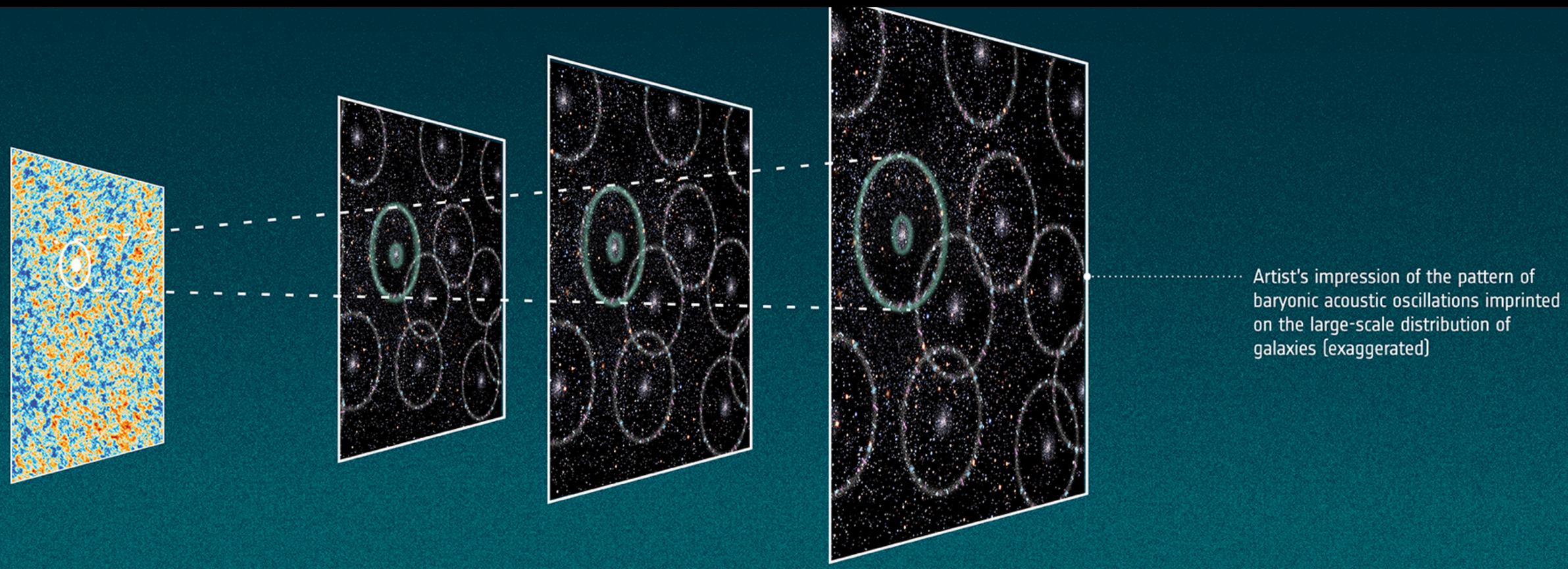


From homepage of Max Tegmark

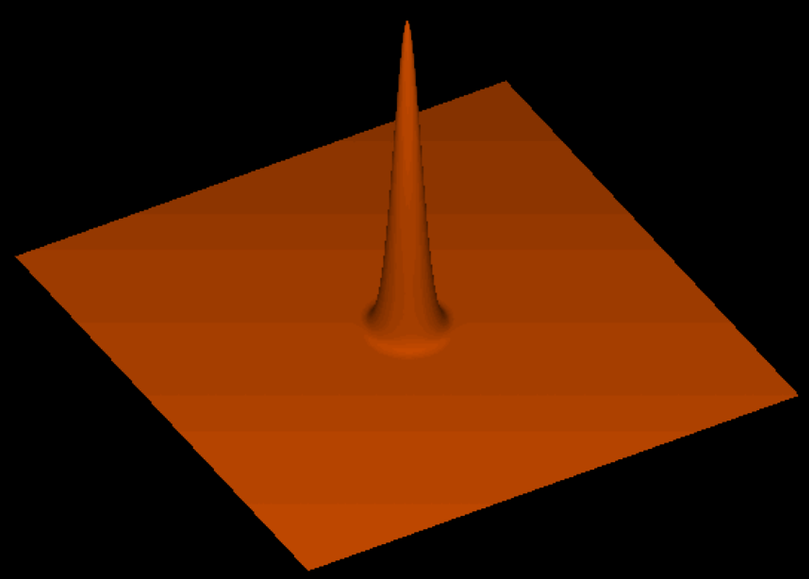
ΛCDM



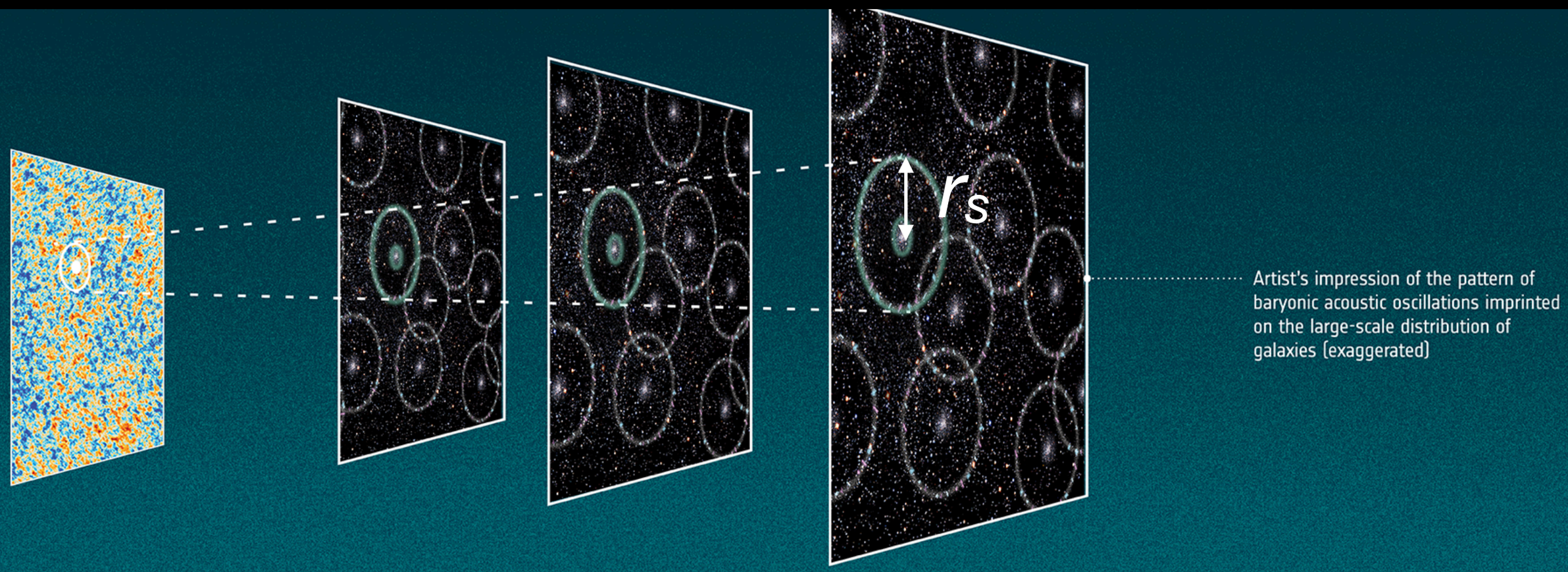
BAO



Source: ESA and the Planck Collaboration / Gabriela Secara / Perimeter Institute



BAO



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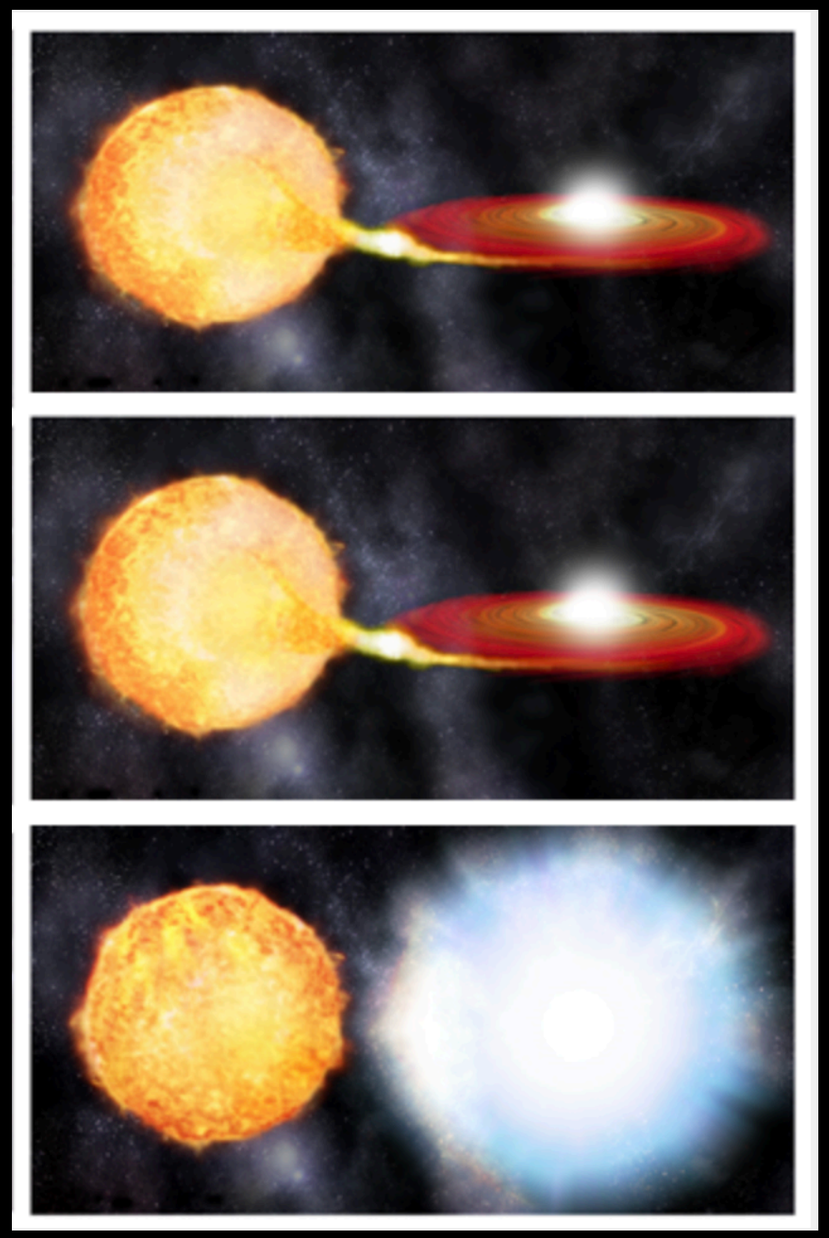
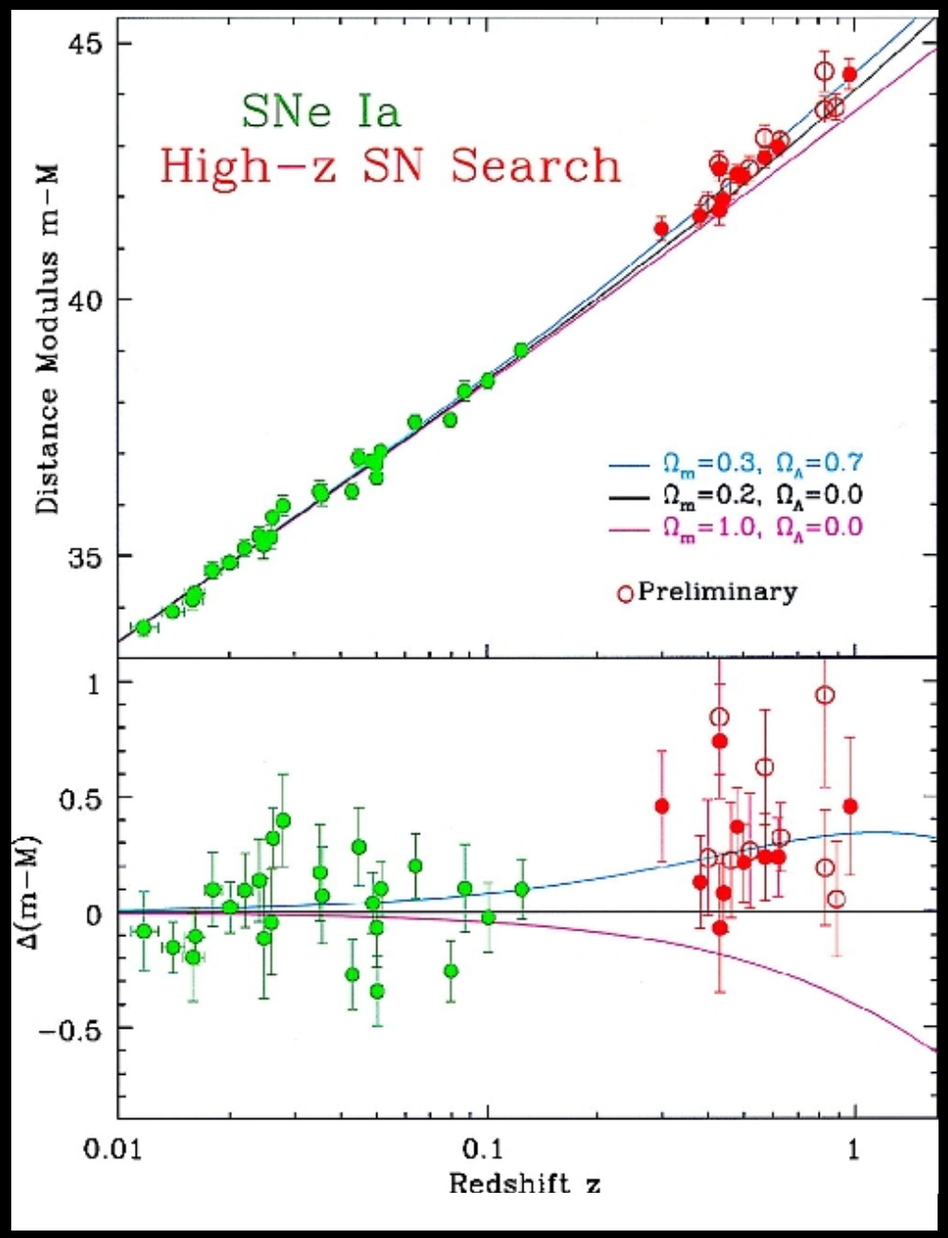
Type Ia supernovae

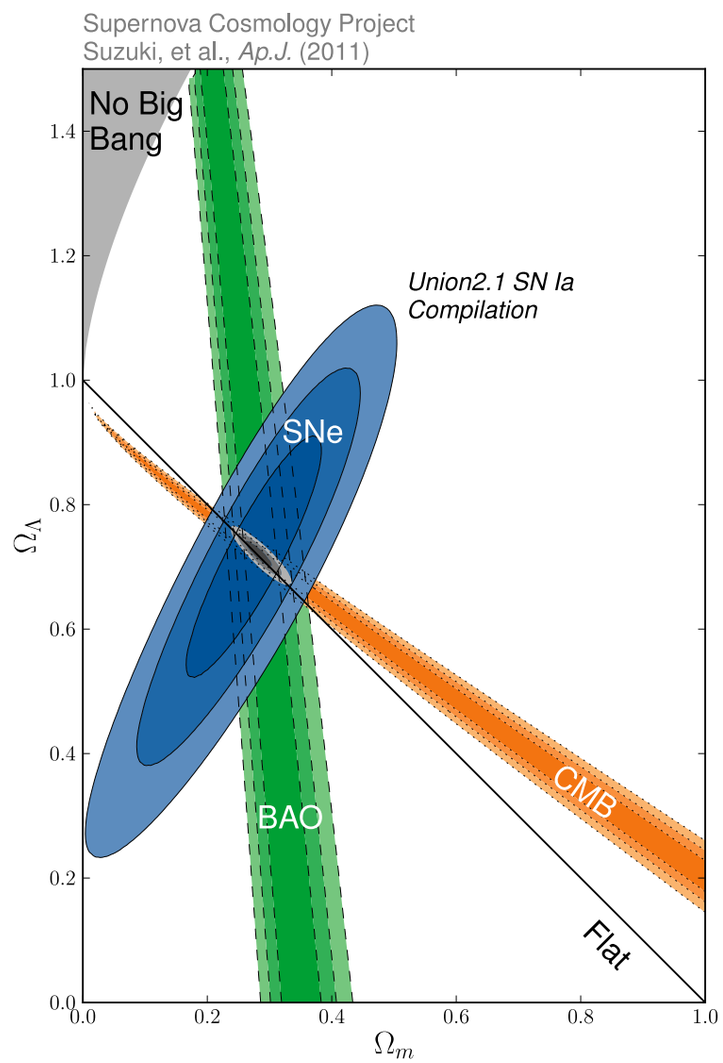




Kirshner (1998)

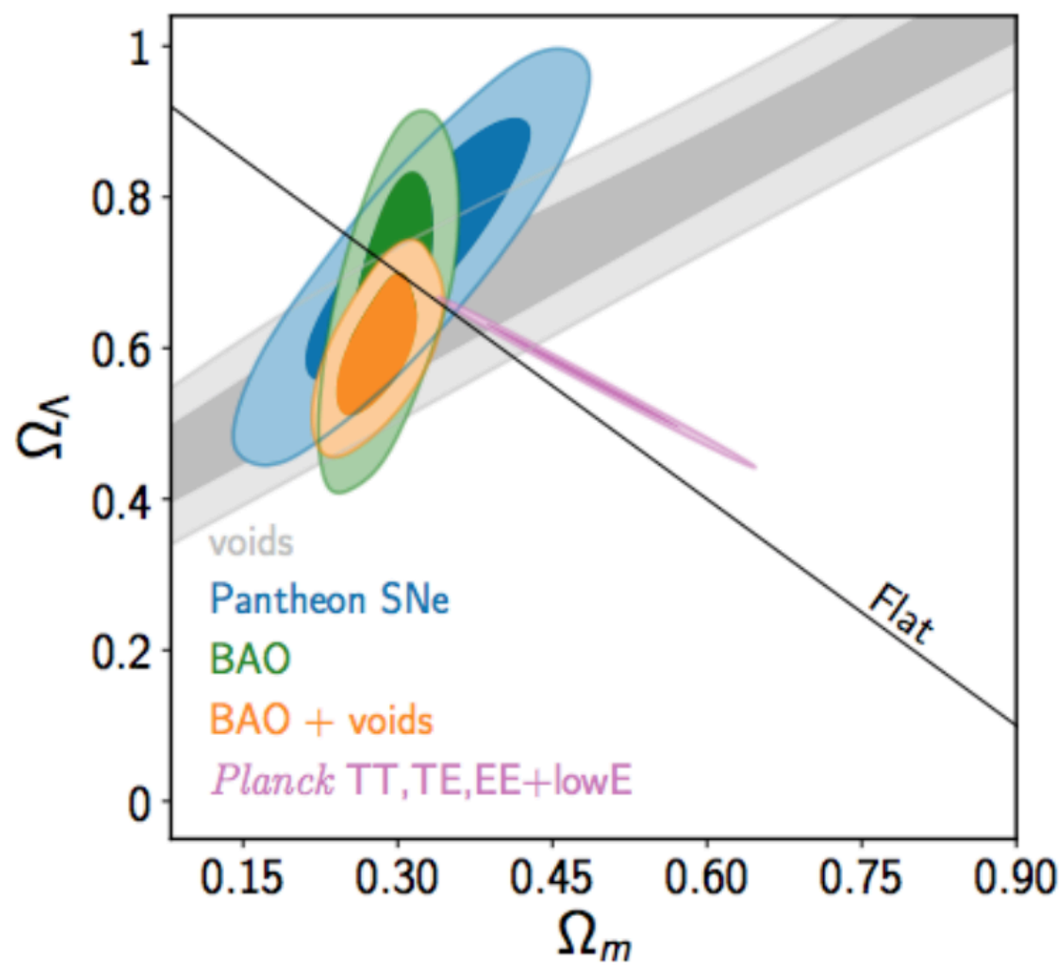
Concordance model

ΛCDM 2011



Concordance model

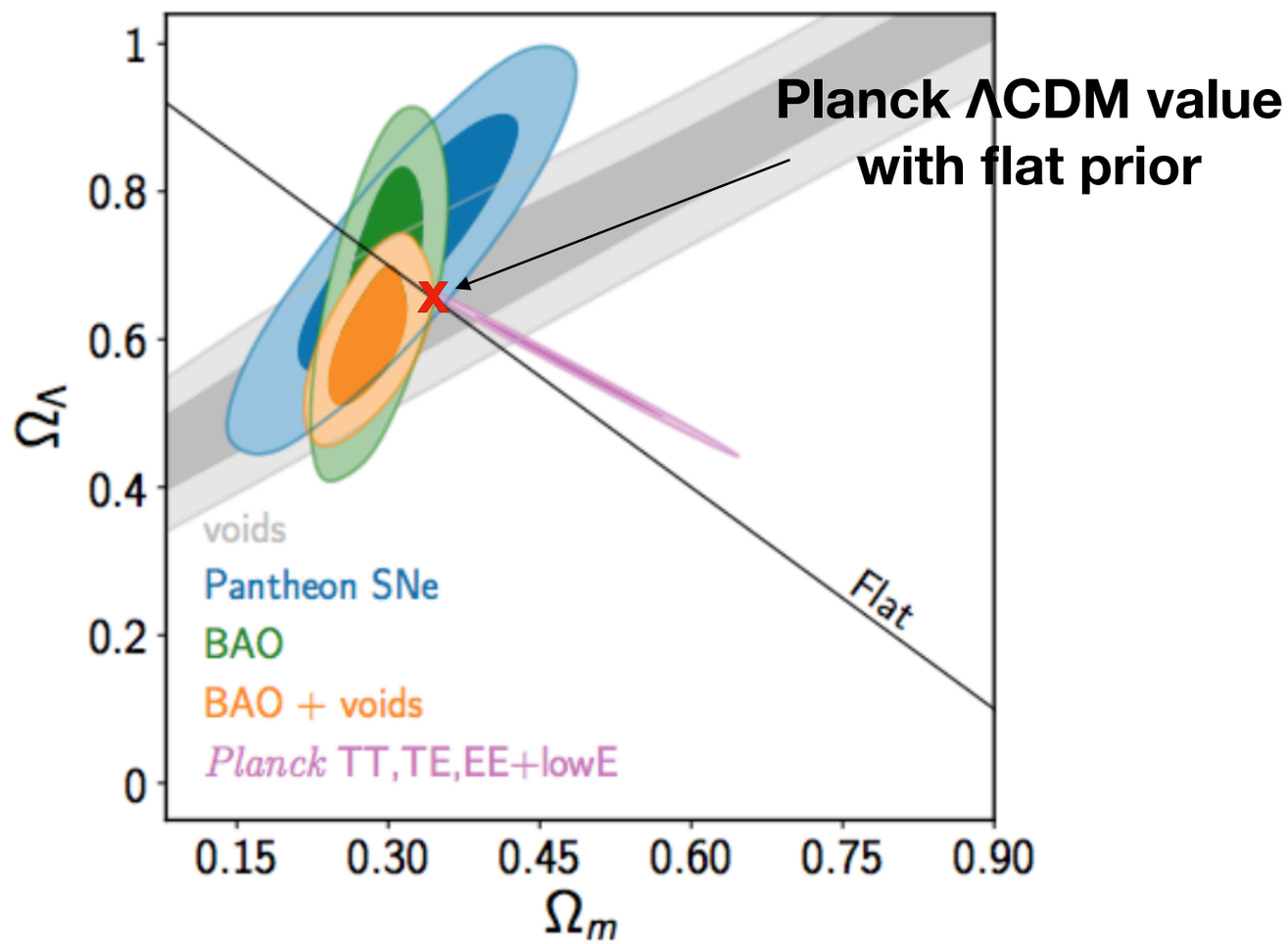
ΛCDM 2020



[Nadathur, Percival, Beutler, Winther; 2020]

Concordance model

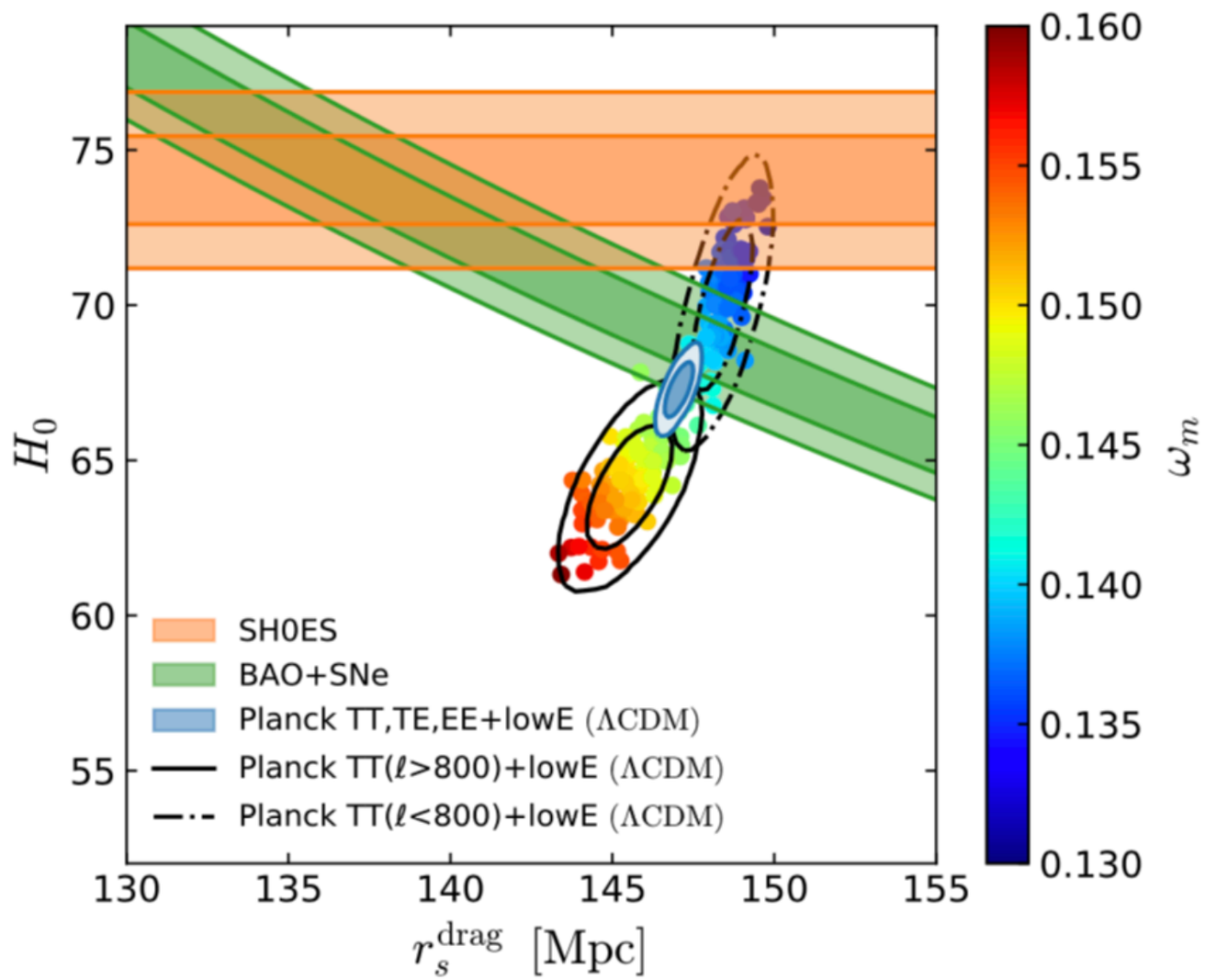
ΛCDM 2020



[Nadathur, Percival, Beutler, Winther; 2020]

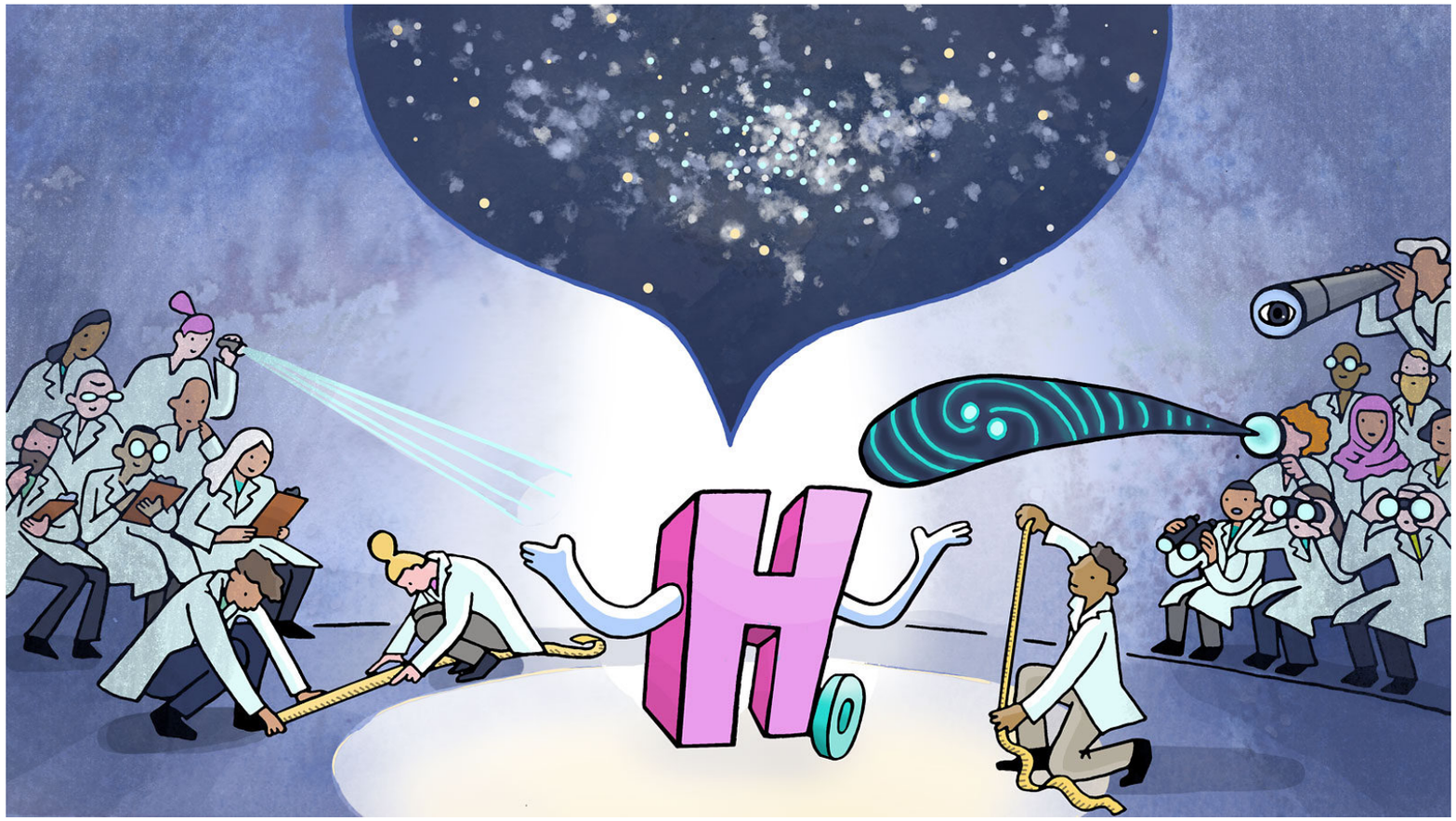
Concordance model

ΛCDM 2020

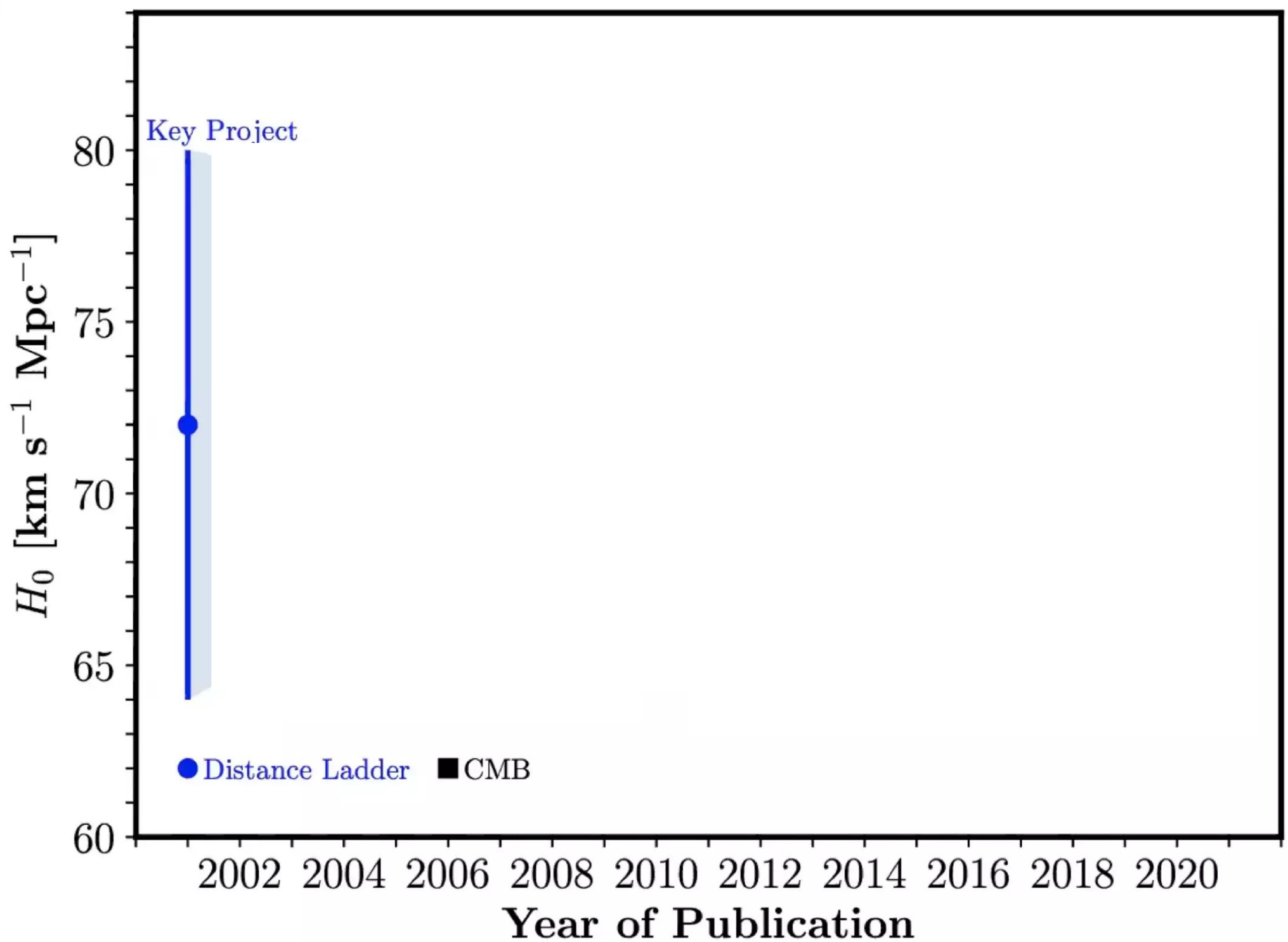


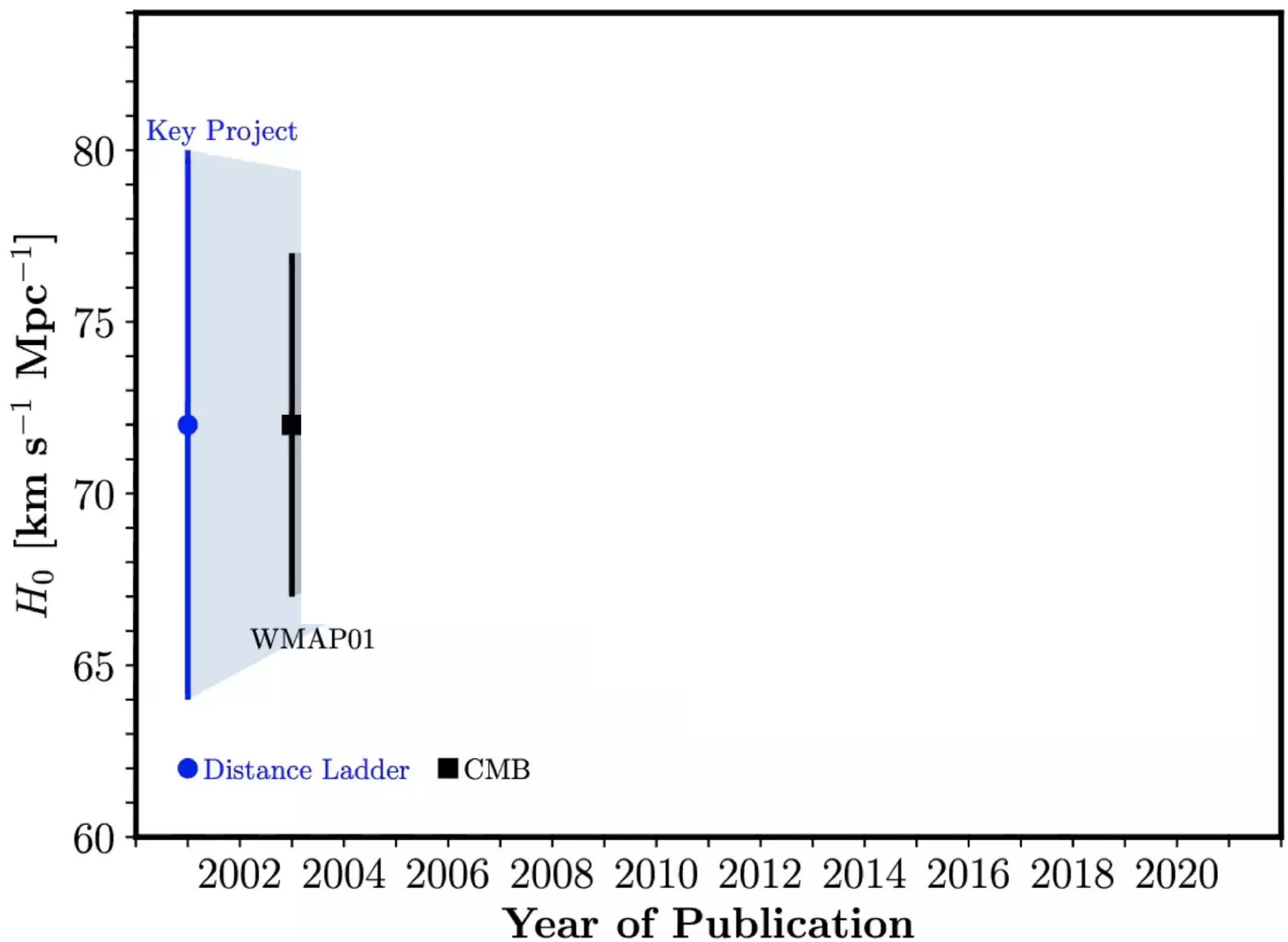
[Knox, Milea; 2019]

What about H_0?



[Illustration Symmetry mag. 2019]


Key Project
80
75
70
65
60
H_0 [km s^{-1} Mpc^{-1}]
Distance Ladder
CMB
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
Year of Publication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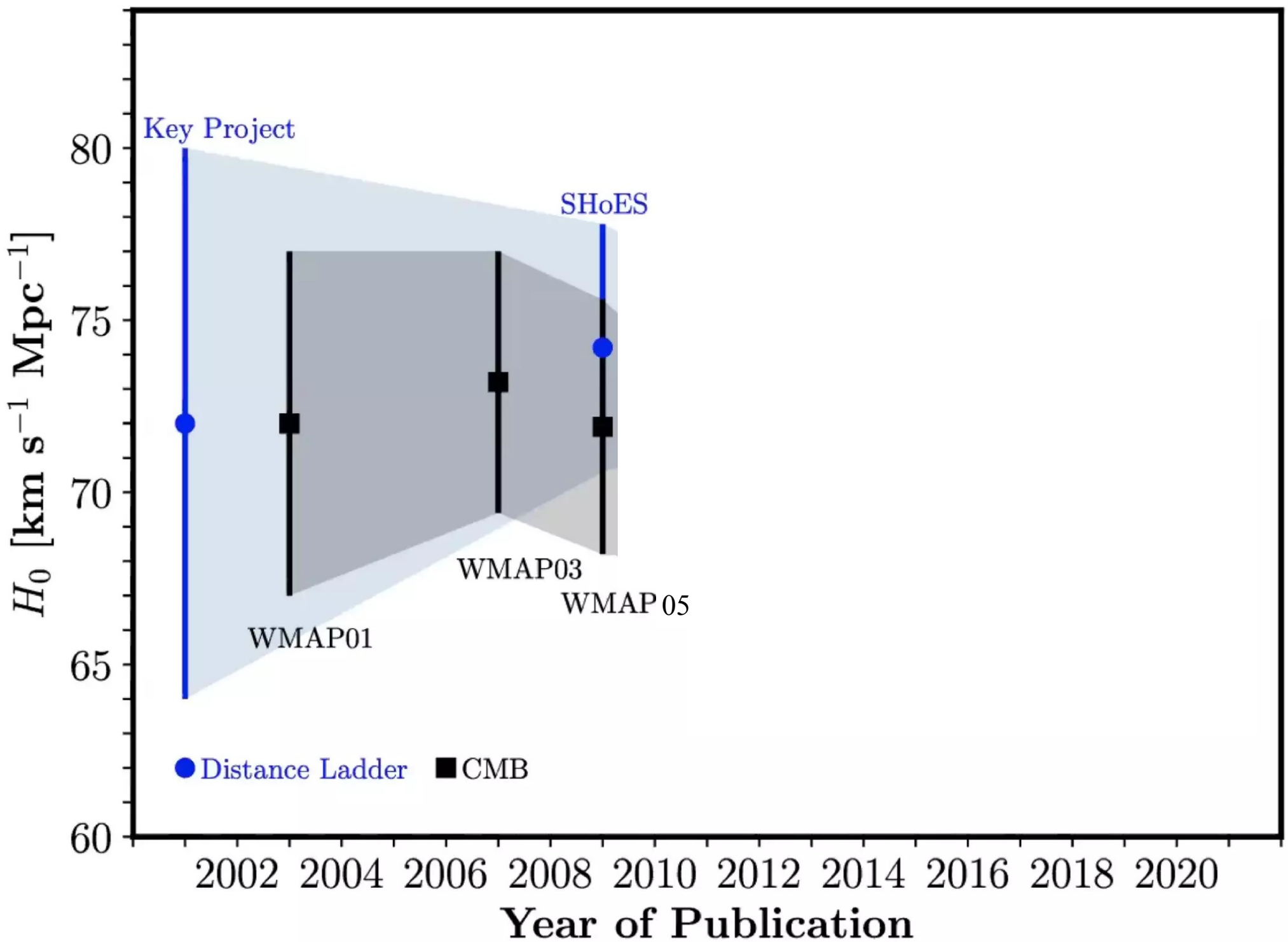
Key Project
SHoES
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WMAP 05
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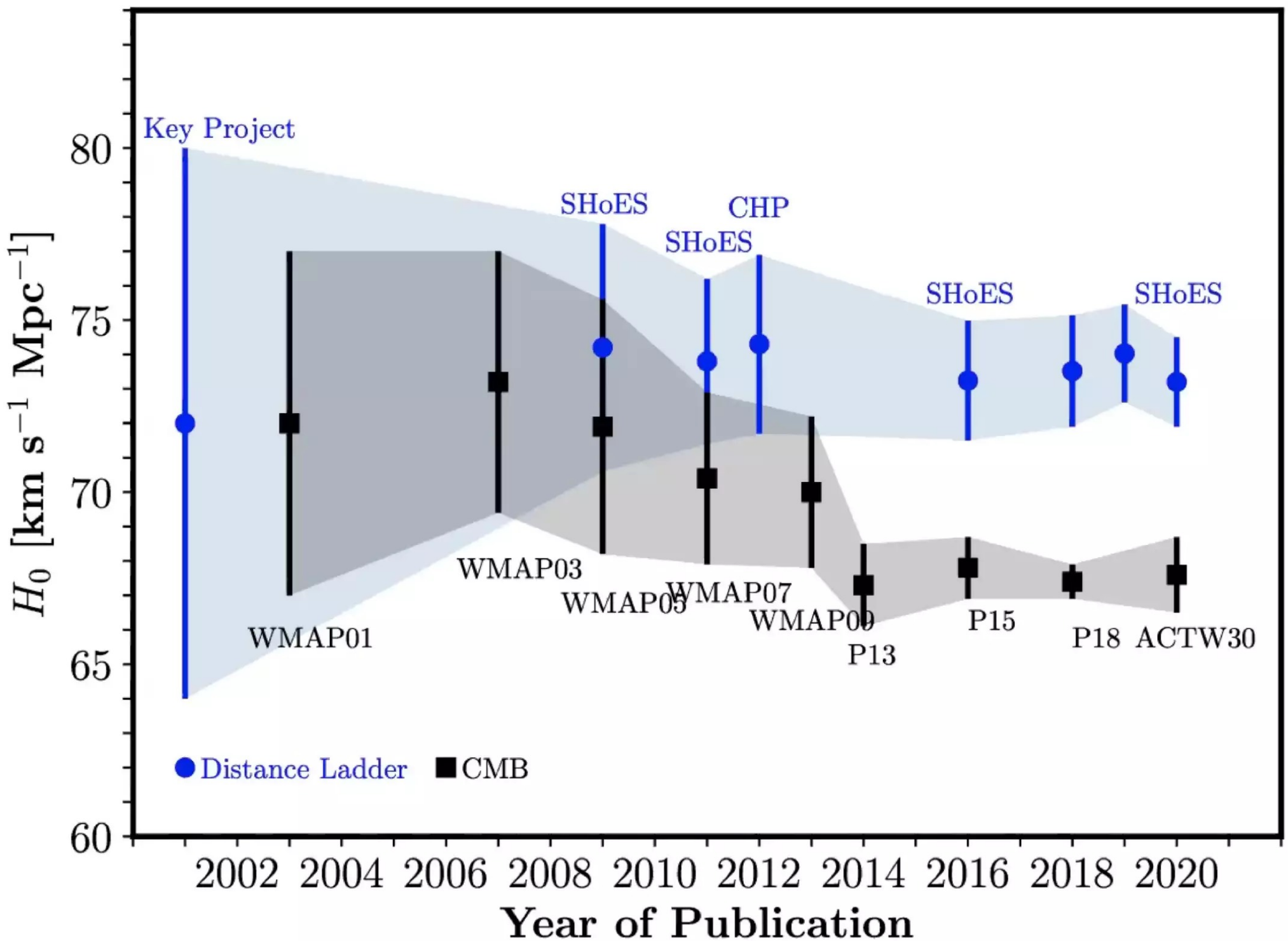
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CHP
SHoES
SHoES
SHoES
WMAP01
WMAP03
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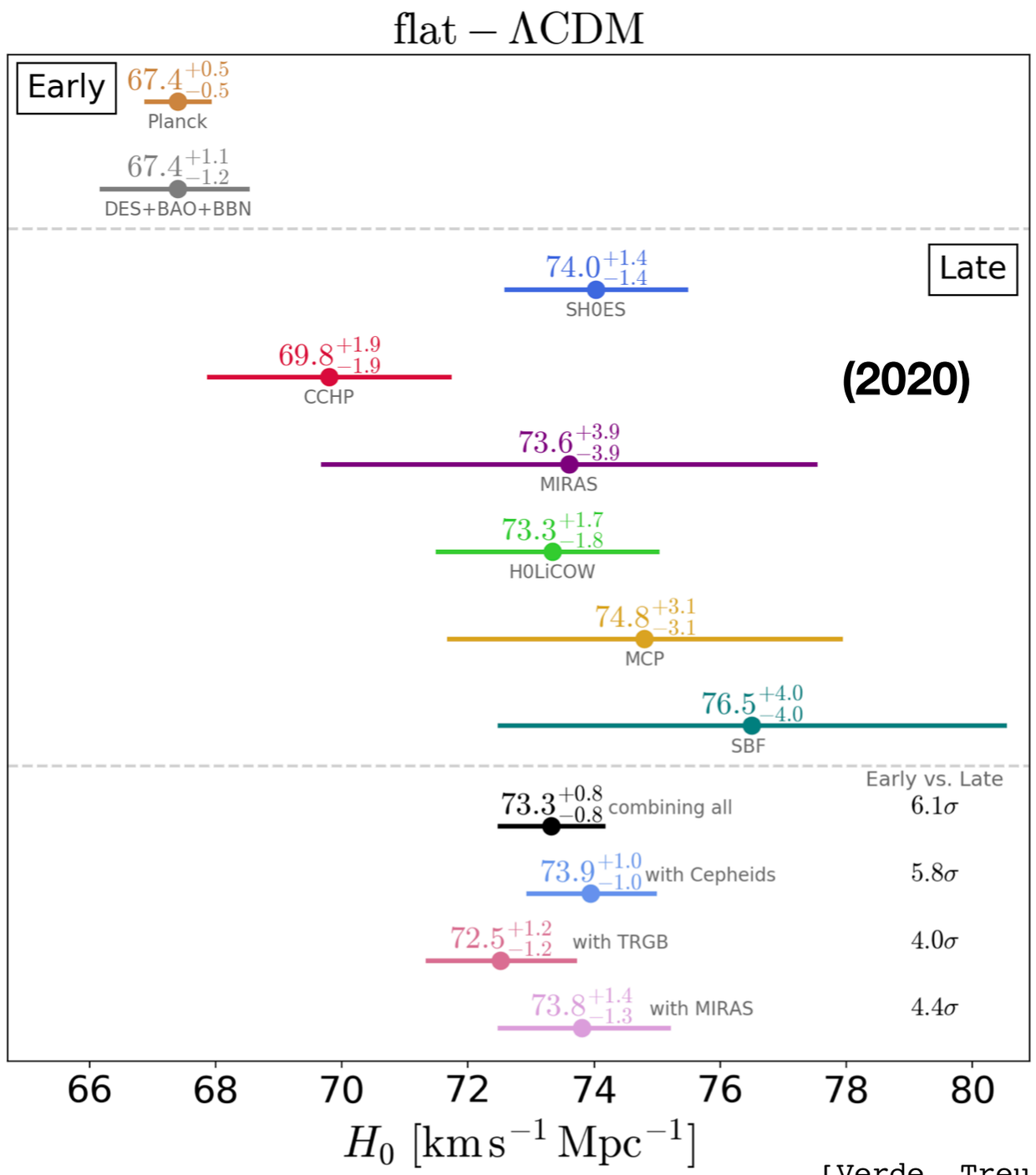
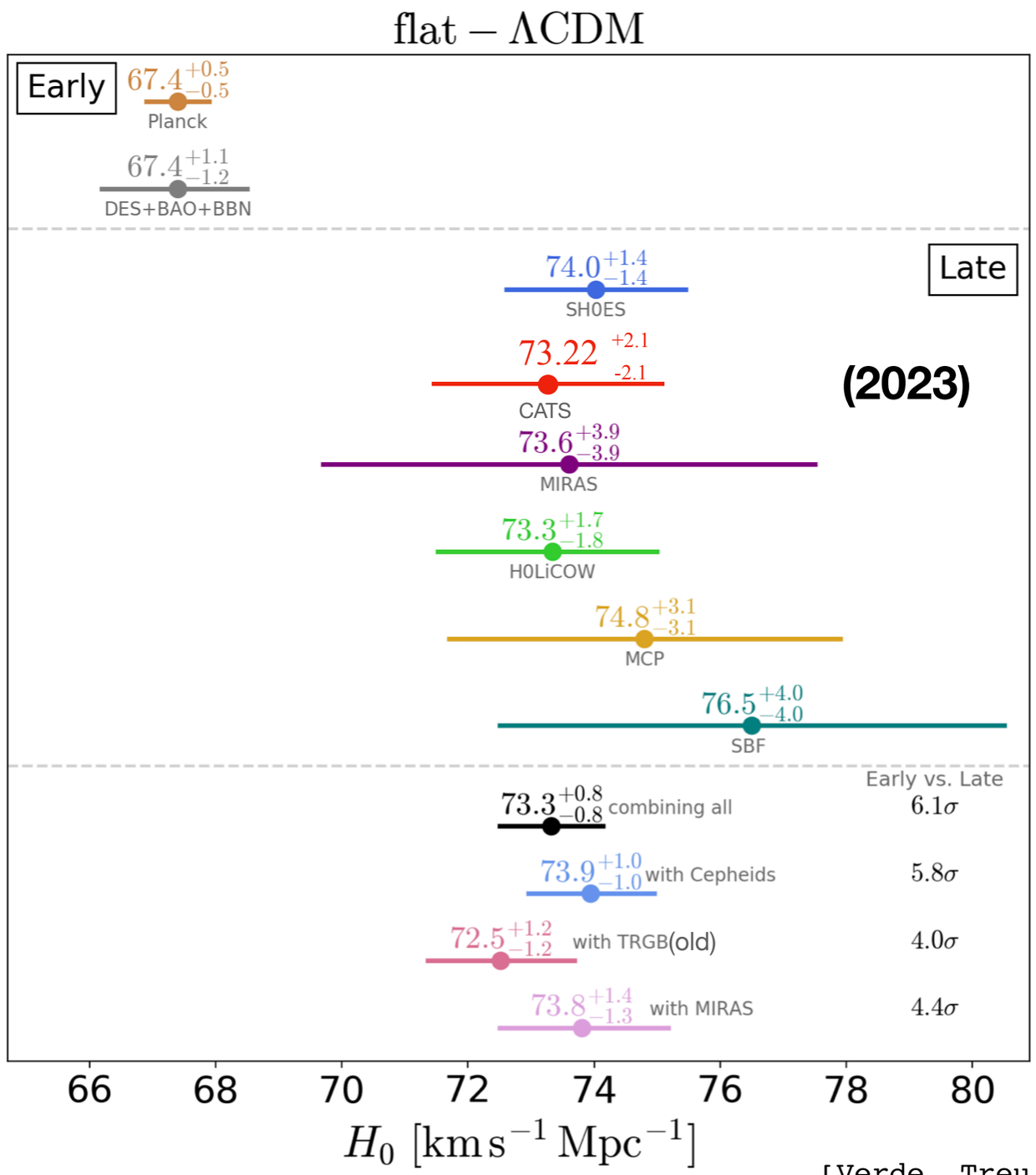
ΛCDM

Actual Universe



[Verde, Treu, Riess; 2019]

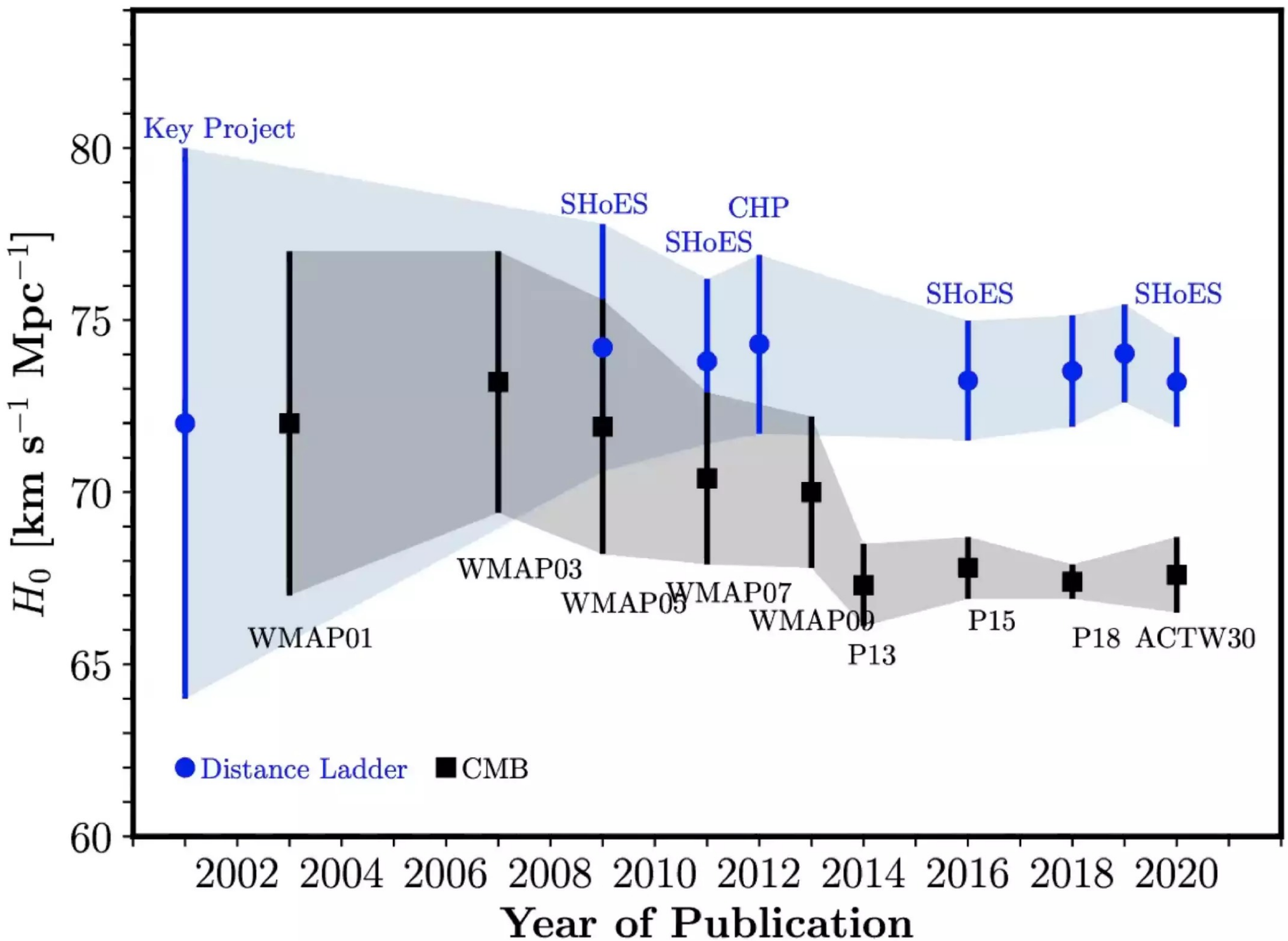


ΛCDM

(2023)

Actual Universe

[Verde, Treu, Riess; 2019]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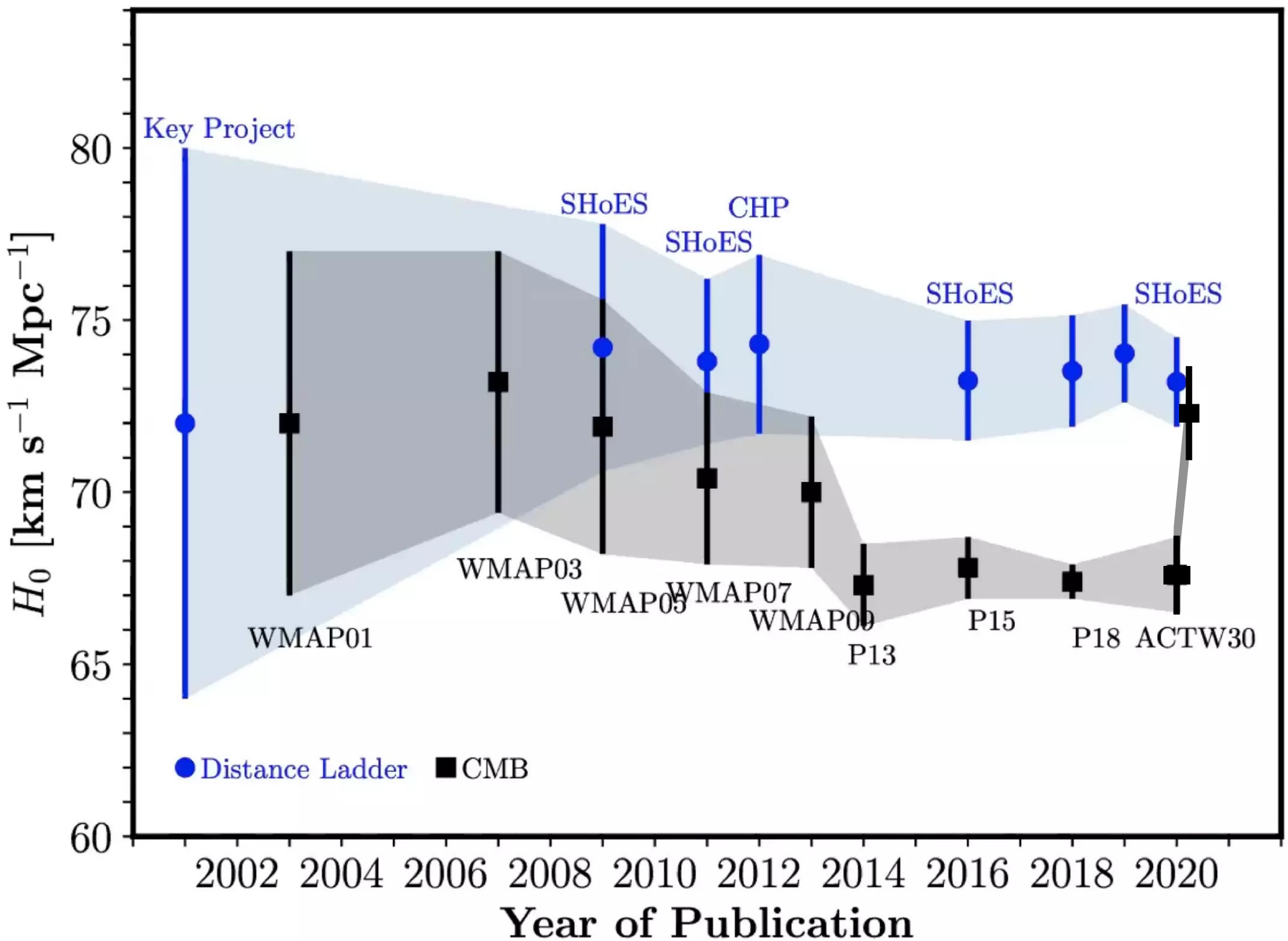
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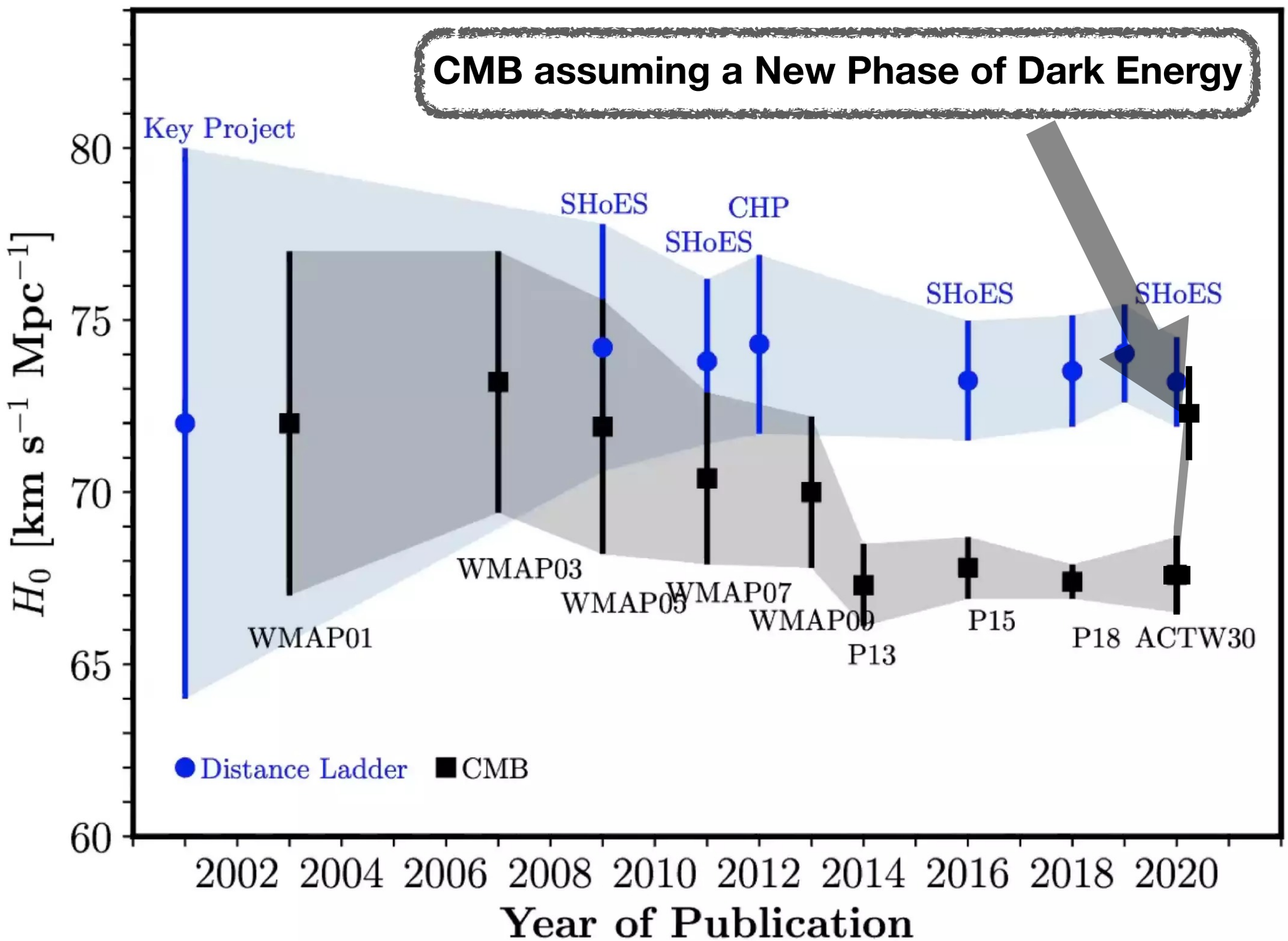
CMB assuming a New Phase of Dark Energy
Key Project
SHoES
CHP
SHoES
SHoES
SHoES
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WMAP03
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How does a New Early Dark Energy (NEDE) Phase Transition resolve the Hubble tension?

The Hubble tension

<u>Model-dependent statement:</u>

- Planck and SH_0ES incompatible

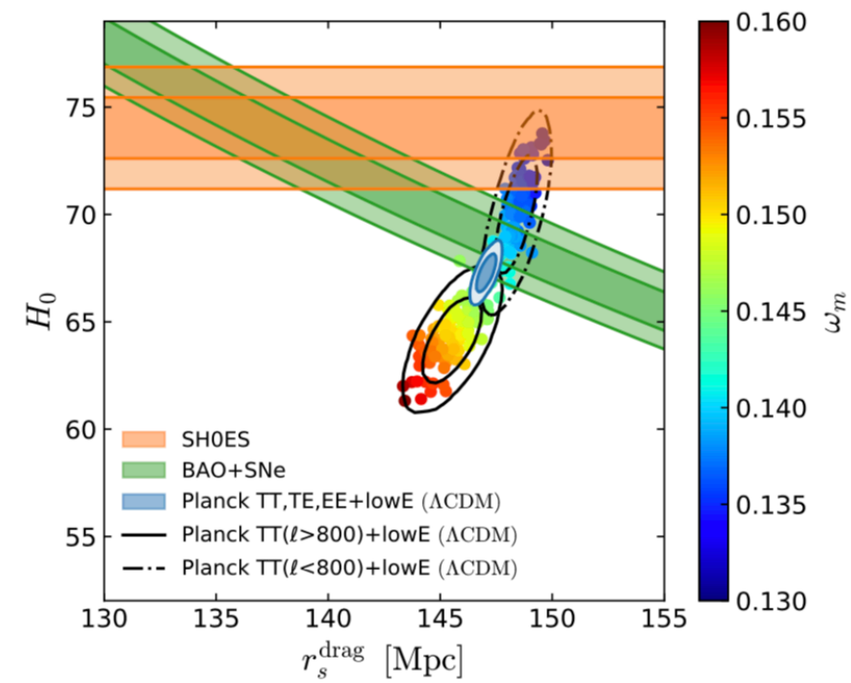
<u>Model-independent statement:</u>

- BAO+SN: $H_0 r_s \approx const$

Where

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

depends on early time physics



[Knox, Milea; 2019]

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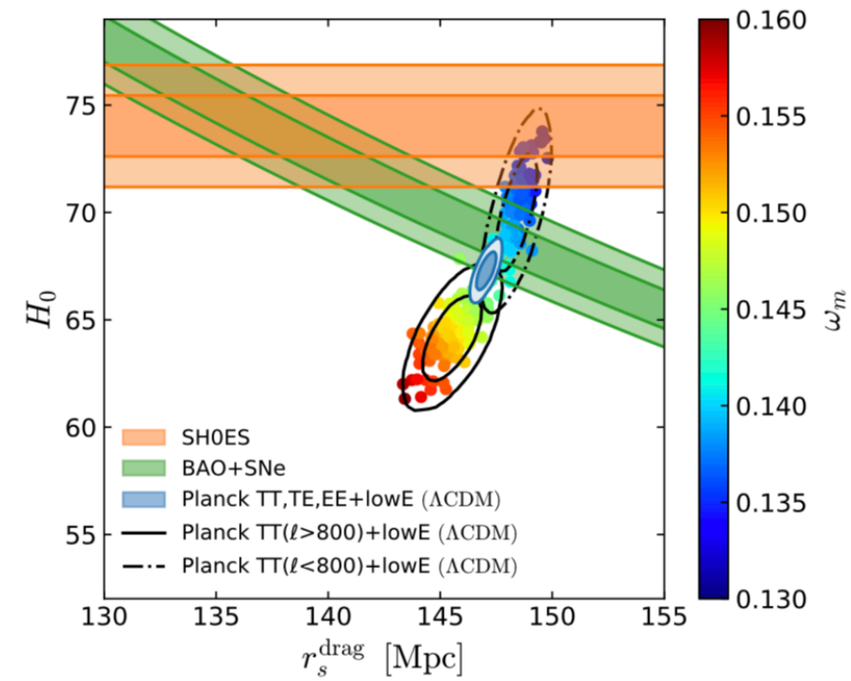

Modification of *ΛCDM* raising H_0 while lowering r_s

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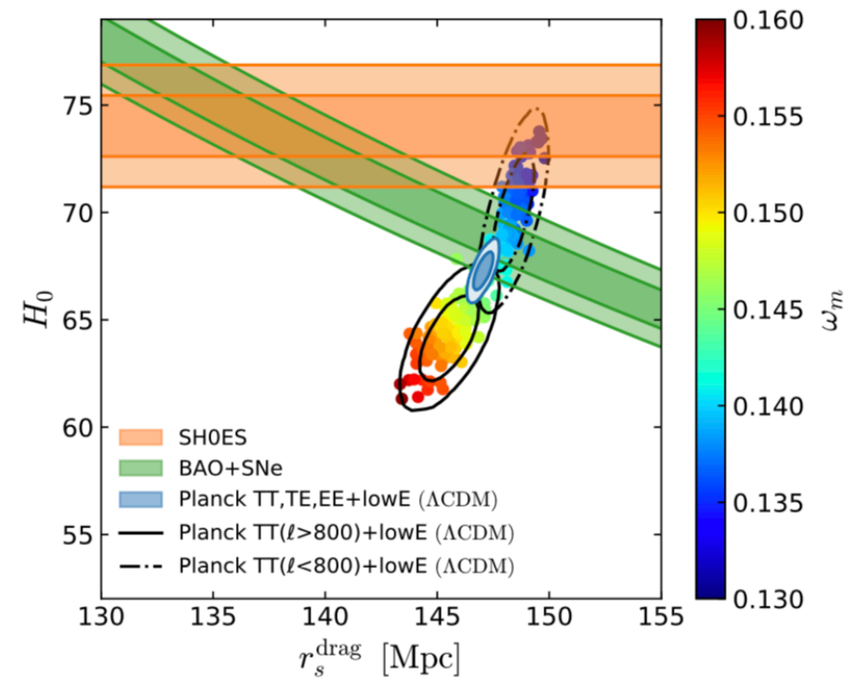


Modification of *ΛCDM* raising H_0 while lowering r_s

Modification of *ΛCDM* just before recombination

Pre-recombination modifications

- Assume new hypothetical matter component is present before recombination

$$\frac{H(z)}{H_0} = \sqrt{\Omega_\Lambda + \Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_X(z)}$$

➡ Increase in H before recombination

➡ Lowering the sound horizon

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

Dark radiation

- Extra relativistic degree of freedom

$$\Omega_X(z) = \Omega_{DR}(1+z)^4$$

➡ Reduces the tension only slightly (~ 4 σ)

[Planck 2018+BAO
+Pantheon+BBN]

$$H_0 = 69.49 \ \pm 0.0085 \ \frac{\mathrm{km}}{\mathrm{s\ Mpc}}$$

[Niedermann, MSS; 2020]

Early Dark Energy

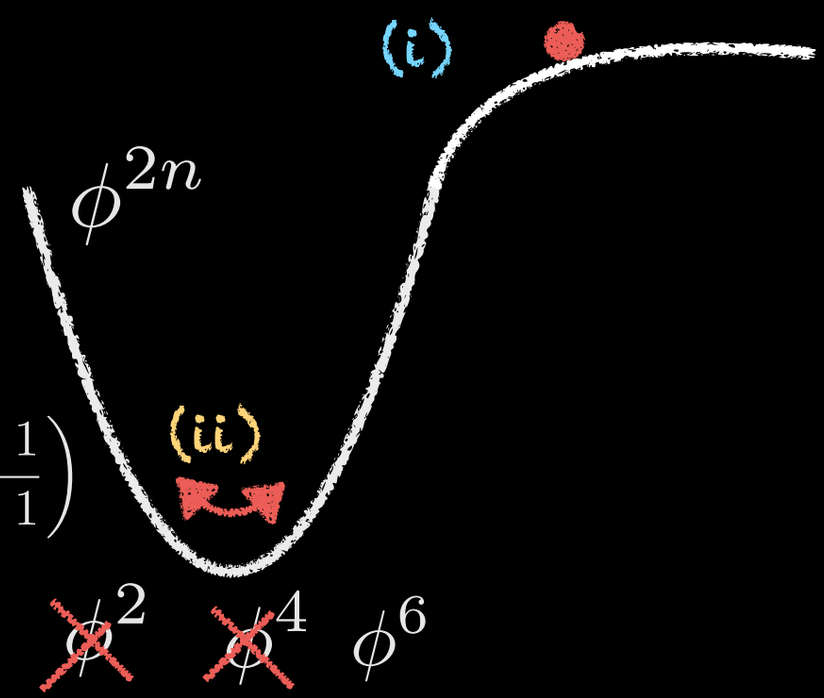
Scalar field model w. slow-roll second-order phase transition

[e.g. Karwal et al., 2016]
[Poulin et al., 2018]

$$V^{(n)}(\phi) = \Lambda_a^4 \left[1 - \cos(\phi/f_a)\right]^n$$

$$\Omega_X(z) \approx \begin{cases} \Omega_{EDE} & ;\ z \gg z_c \ \text{(i)} \\ \Omega_{EDE}\left(\frac{1+z}{1+z_d}\right)^{\alpha \geq 4} & ;\ z \ll z_c \ \text{(ii)} \end{cases}$$

$$\alpha = 3\left(1 + \frac{n-1}{n+1}\right)$$



meanvalues: $n = 3 \quad z_c \approx 4000$

$H_0 = 71.4 \pm 1\text{km/s/Mpc}$

➡ How to make shallow anharmonic potentials natural…?

[Kaloper, 2019]

New Early Dark Energy

NEDE is a fast triggered phase transition in the dark sector

<u>Simple effective cosmological model:</u>

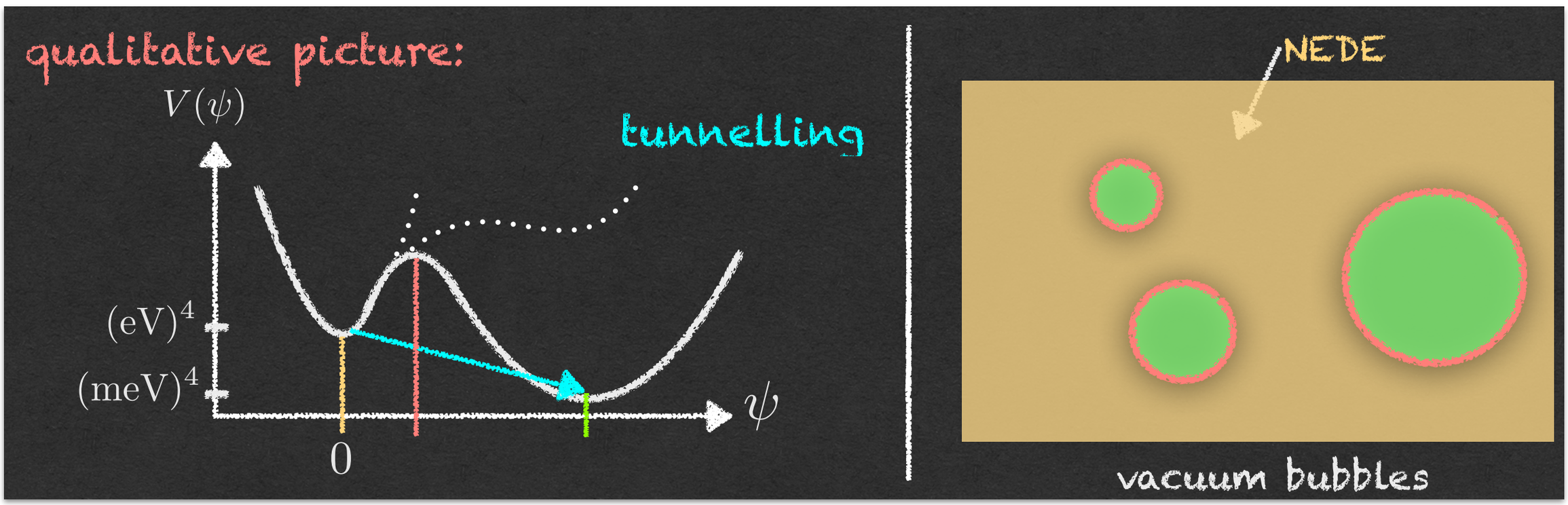
- **Instant decay of New Early Dark Energy component just before recombination**

arXiv: 1910.10739, 2006.06686 w. Florian Niedermann

New Early Dark Energy

Scalar field model w. first order phase transition

[Niedermann, MSS; 2019, 2020]



$$w = -1 \qquad \rightarrow \qquad 1/3 < w < 1$$

- Vacuum energy decays
- Free energy converted to anisotropic stress
- Anisotropic stress partially sources gravitational radiation
- Remaining anisotropic stress decays like a stiff fluid

Cold vs Hot NEDE specs

Spec	Cold NEDE	Hot NEDE
Trigger	ϕ (ultra light scalar)	T_d (dark sector temperature)
redshift of PT	$z_* \sim 10^4$	$10^6 \lesssim z_* \lesssim 10^9$
$\omega_{\rm NEDE}$	$\omega_{\rm NEDE} \sim 2/3$	$\omega_{\rm NEDE} = 1/3$
micro physics realisations	ALPs	Dark Higgs
physics lowering r_s	false vacuum energy	latent heat released in SIDR
Family	natural alternative to EDE	UV completion of (stepped) SIDR

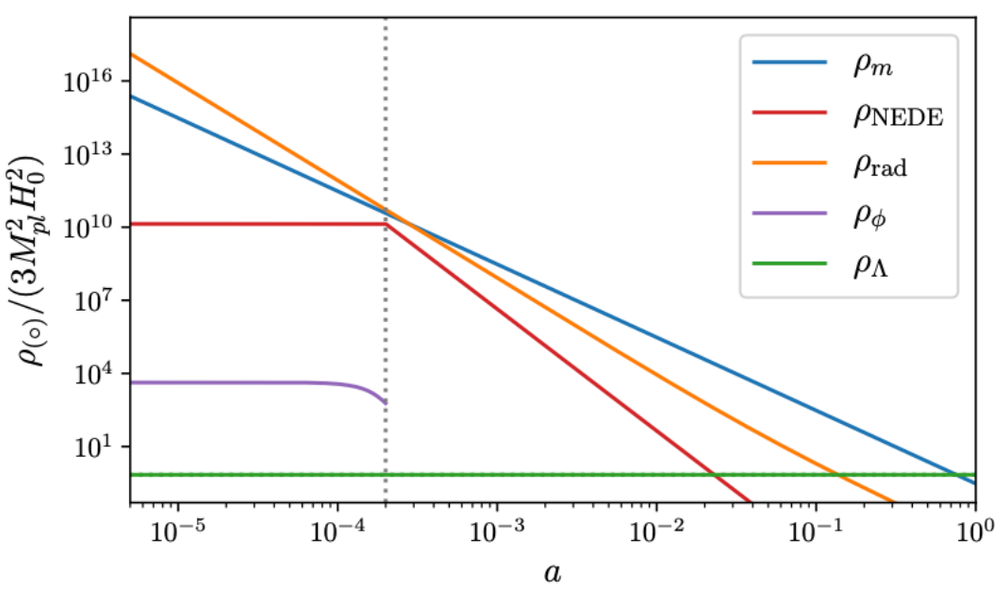
Effective cosmological model

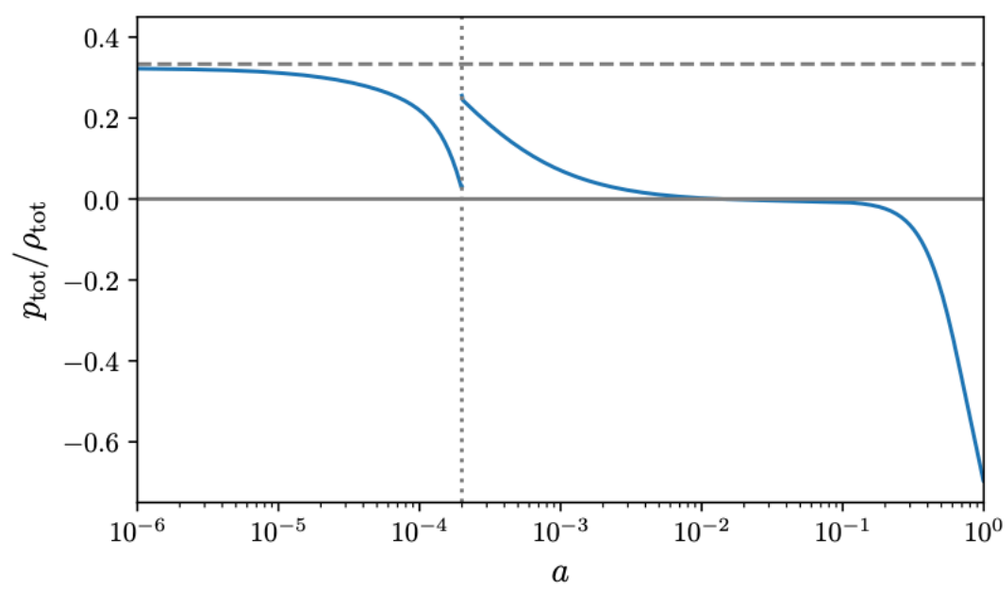
- **Background** picture: Assume that all liberated vacuum energy is converted to a fluid with fixed e.o.s.

Sudden transition at time t_*:

$$w_{\rm NEDE}(t) = \begin{cases} -1 & \text{for} \quad t < t_* \\ w^*_{\rm NEDE} & \text{for} \quad t \geq t_* \end{cases}$$

NEDE fluid: $\bar{\rho}_{\rm NEDE}(t) = \bar{\rho}^*_{\rm NEDE} \left(\frac{a_*}{a(t)} \right)^{3[1+w_{\rm NEDE}(t)]}$





Cold NEDE: Cosmological perturbations

- The phase transition affects perturbations in different ways:
  - Perturbations feel the change in the effective e.o.s. → relevant for CMB
  - Transition is triggered at different places at different times due to fluctuations in trigger field phi. → relevant for CMB
  - The bubbles generate perturbations on scales comparable to their size. → irrelevant for CMB
- We use Israel junction conditions to match fluctuations across transition

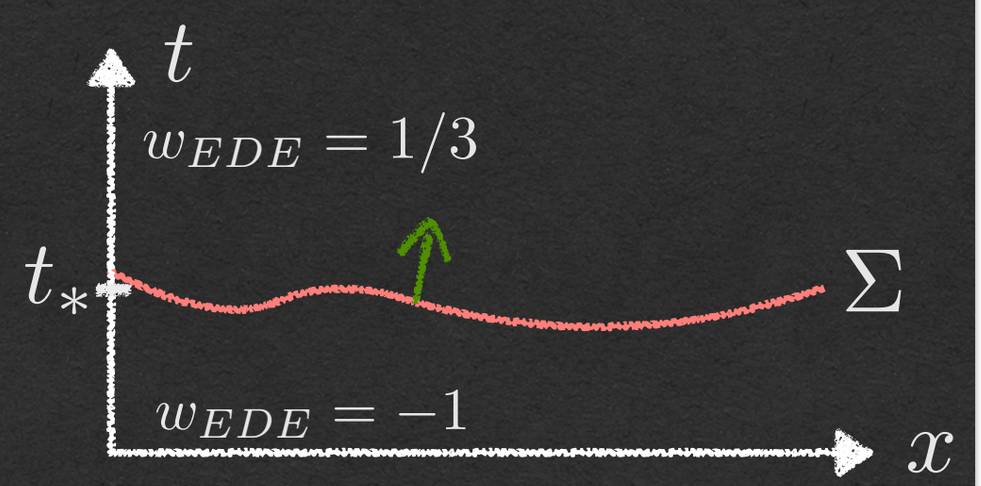
[Deruelle, Mukhanov, 1995]

space like transition surface Σ

synchronous gauge:

$$ds^2 = -dt^2 + a(t)^2 \left(\delta_{ij} + h_{ij}\right) dx^i dx^j \,,$$

where $h_{ij} = \frac{k_i k_j}{k^2} h + \left(\frac{k_i k_j}{k^2} - \frac{1}{3}\delta_{ij}\right) \eta \,,$



- Two metric perturbations: $h(t,k)$ & $\eta(t,k)$

Cosmological perturbations

➡The initial condition for perturbations after the phase-transition depends on the choice of the trigger

➡ The perturbations depend on the microphysical realization of NEDE

- CMB anisotropies and LSS depends on initial perturbations

➡ We can discriminate both between different EDE and between different NEDE microphysical models using CMB and LSS!

$$\text{EDE} \neq \text{Cold NEDE} \neq \text{Hot NEDE}$$

Cold NEDE

➡ Introduce a trigger field for the decay

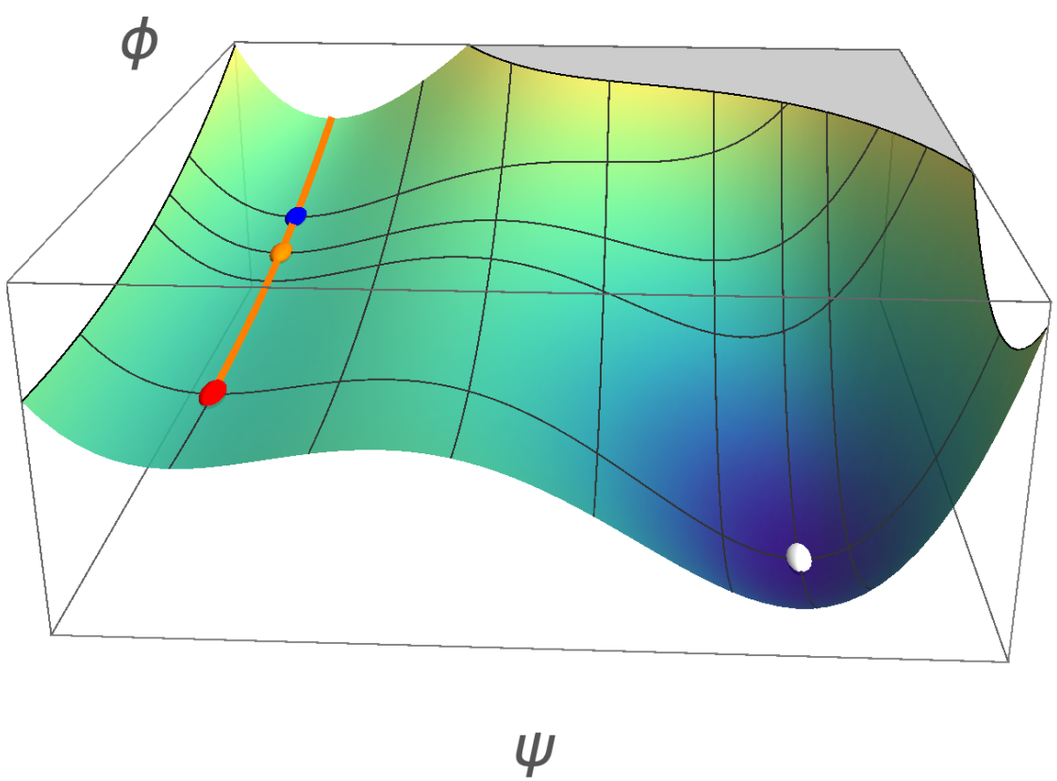
field theory model: $\alpha, \beta, \lambda = \mathcal{O}(1)$

$$V(\psi,\phi) = \underbrace{\frac{1}{2}\beta M^2\psi^2 - \frac{1}{3}\alpha M\psi^3 + \frac{\lambda}{4}\psi^4}_{\text{New Early Dark Energy}} + \underbrace{\frac{1}{2}m^2\phi^2 + \frac{1}{2}\tilde{\lambda}\phi^2\psi^2}_{\text{Clock}} + const$$

'CC tuning'

hierarchy: $M \sim \mathrm{eV} \gg m \sim 10^{-27}\mathrm{eV}$ ultra-light physics

initial condition: $\psi = 0$ sub-dominant trigger: $\phi_{ini} \ll M_{pl}$



(i) for $H \gg m$: $\phi \approx \phi_{ini}$

(ii) for $H \approx m$: ϕ starts evolving

(iii) blue dot: inflection point

(iv) orange dot: $\Gamma = 0,\ \dot{\Gamma} > 0$

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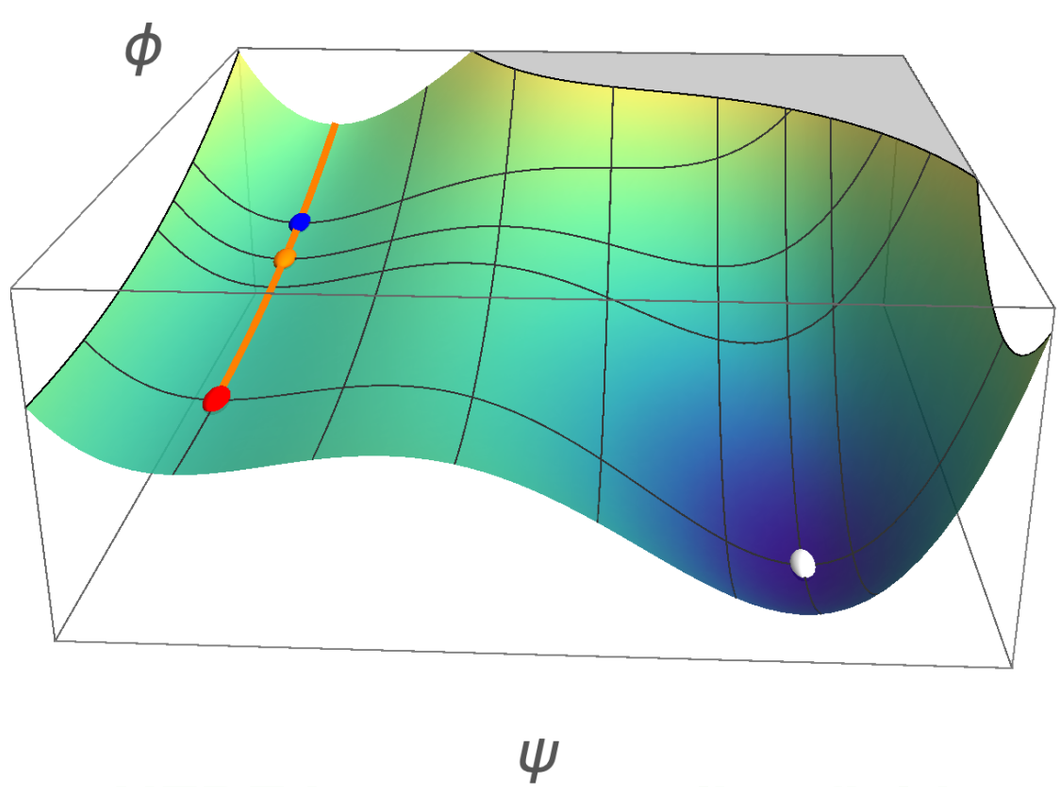

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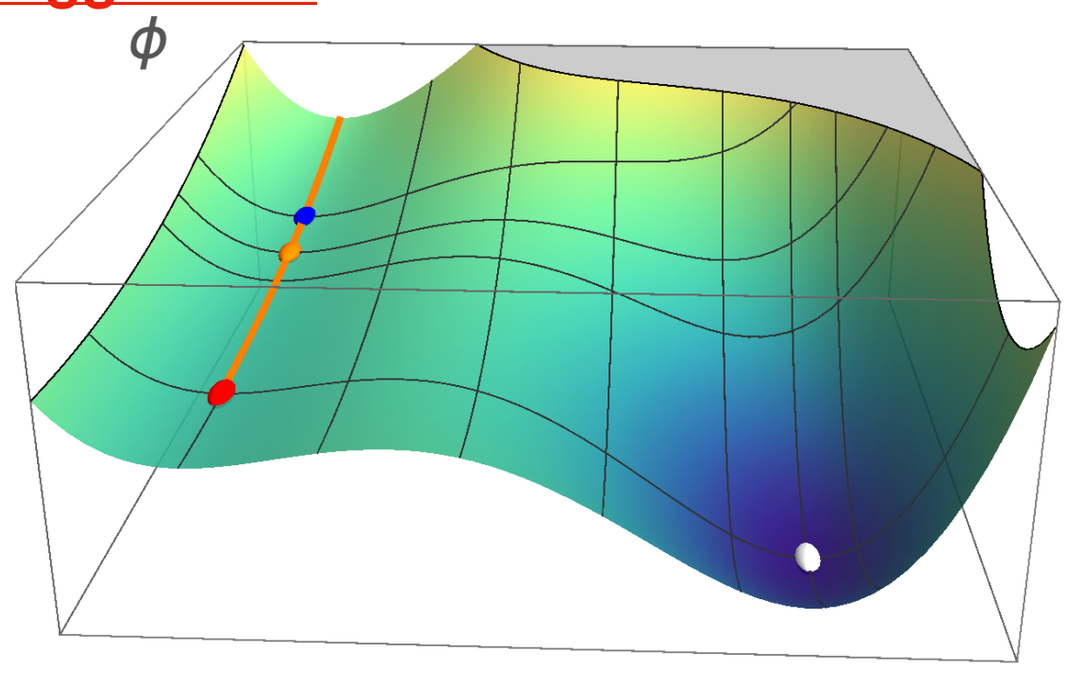
Trigger field



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Cold NEDE: Cosmological perturbations

- The phase transition affects perturbations in different ways:
  - Perturbations feel the change in the effective e.o.s. → relevant for CMB
  - Transition is triggered at different places at different times due to fluctuations in trigger field phi. → relevant for CMB
  - The bubbles generate perturbations on scales comparable to their size. → irrelevant for CMB
- We use Israel junction conditions to match fluctuations across transition

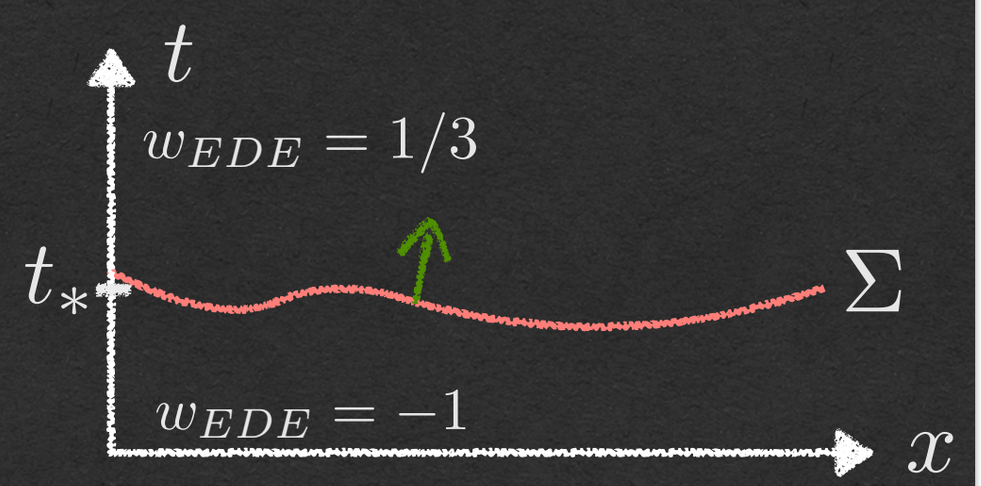
[Deruelle, Mukhanov, 1995]

space like transition surface Σ

synchronous gauge:

$$ds^2 = -dt^2 + a(t)^2 \left(\delta_{ij} + h_{ij}\right) dx^i dx^j \,,$$

where $h_{ij} = \frac{k_i k_j}{k^2} h + \left(\frac{k_i k_j}{k^2} - \frac{1}{3}\delta_{ij}\right) \eta \,,$



- Two metric perturbations: $h(t,k)$ & $\eta(t,k)$

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space like transition surface $\Sigma: \quad \phi(t_*, \mathbf{x})|_\Sigma = const\,.$

synchronous gauge:

$$ds^2 = -dt^2 + a(t)^2\left(\delta_{ij} + h_{ij}\right)dx^i dx^j\,,$$

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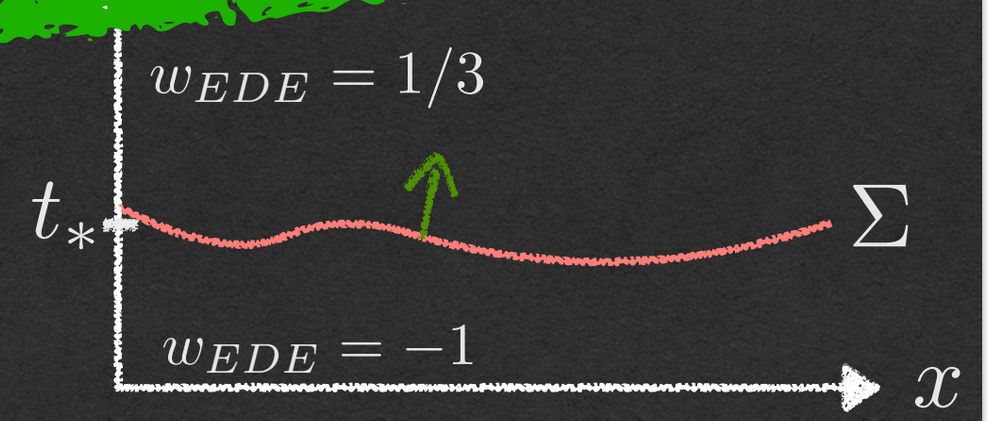


- Two metric perturbations: $h(t,k) \quad \& \quad \eta(t,k)$

Does it work?

The answer is so far, yes; for details, see f.ex. arXiv:2209.02708

A grounded perspective on New Early Dark Energy using ACT, SPT, and BICEP/Keck

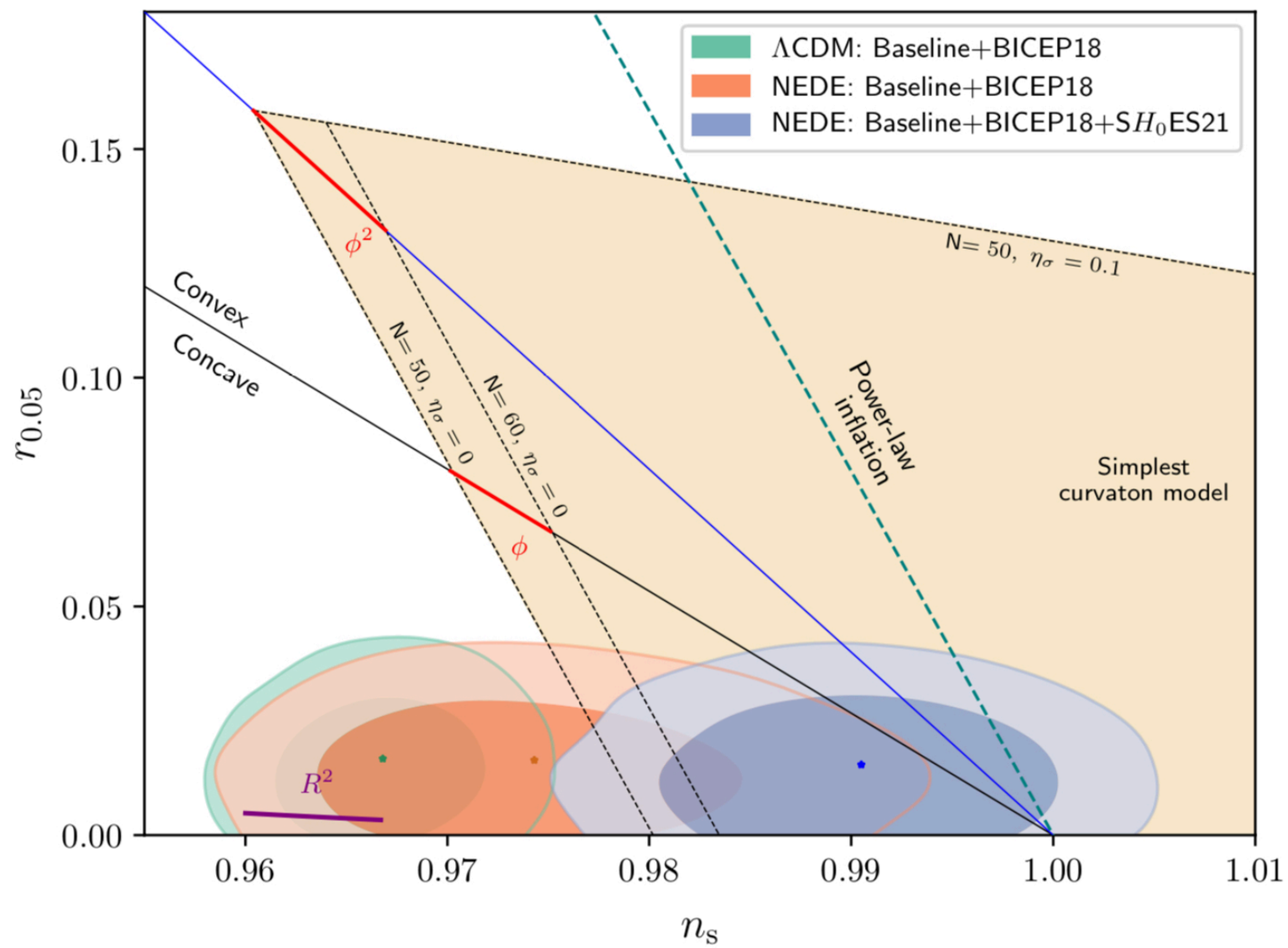
Juan S. Cruz,[1,*] Florian Niedermann,[2,†] and Martin S. Sloth[1,‡]

[1] *CP3-Origins, Center for Cosmology and Particle Physics Phenomenology, University of Southern Denmark, Campusvej 55, 5230 Odense M, Denmark*

[2] *Nordita, KTH Royal Institute of Technology and Stockholm University Hannes Alfvéns väg 12, SE-106 91 Stockholm, Sweden*

We examine further the ability of the New Early Dark Energy model (NEDE) to resolve the current tension between the Cosmic Microwave Background (CMB) and local measurements of H_0 and the consequences for inflation. We perform new Bayesian analyses, including the current datasets from the ground-based CMB telescopes Atacama Cosmology Telescope (ACT), the South Pole Telescope (SPT), and the BICEP/Keck telescopes, employing an updated likelihood for the local measurements coming from the SH_0ES collaboration. Using the SH_0ES prior on H_0, the combined analysis with Baryonic Acoustic Oscillations (BAO), Pantheon, Planck and ACT improves the best-fit by $\Delta\chi^2 = -15.9$ with respect to ΛCDM, favors a non-zero fractional contribution of NEDE, $f_{\rm NEDE} > 0$, by 4.8σ, and gives a best-fit value for the Hubble constant of $H_0 = 72.09$ km/s/Mpc (mean $71.48^{+0.79}_{-0.81}$ with 68% C.L.). A similar analysis using SPT instead of ACT yields consistent results with a $\Delta\chi^2 = -23.1$ over ΛCDM, a preference for non-zero $f_{\rm NEDE}$ of 4.7σ and a best-fit value of $H_0 = 71.77$ km/s/Mpc (mean $71.43^{+0.84}_{-0.84}$ with 68% C.L.). We also provide the constraints on the inflation parameters r and n_s coming from NEDE, including the BICEP/Keck 2018 data, and show that the allowed upper value on the tensor-scalar ratio is consistent with the ΛCDM bound, but, as also originally found, with a more blue scalar spectrum implying that the simplest curvaton model is now favored over the Starobinsky inflation model.

Consequences for Inflation



[arXiv:2209.02708]

Hot NEDE

Hot New Early Dark Energy

- Known cosmological phase transitions (apart from end of inflation) are triggered by redshift of temperature.

➡Let us consider a thermal trigger of the NEDE phase transition.

Hot NEDE: Thermal trigger

Examples of thermal PTs:
Electroweak phase transitions
QCD phase transition
Recombination

Cold NEDE: Scalar field trigger

Example of cold PT:
End of inflation

SU(N) Dark Sector

- Consider dark *SU(N)* with $N \geq 3$

$$\mathcal{L} = \bar{\chi}(i\gamma^\mu D_\mu - m_\chi)\chi + |D\Psi|^2 - V_{\rm cl}(|\Psi|^2) - \frac{1}{4}F^a_{\mu\nu}F^{\mu\nu}_a \,,$$

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$$V_{\rm cl}(|\Psi|^2) = -\mu^2|\Psi|^2 + \lambda|\Psi|^4 + V_0$$

- NEDE gauge boson leads to spontaneous symmetry

$$SU(N) \to SU(N-1)$$

$$\Psi = e^{2i\pi^a\tau^a/v}\begin{pmatrix} 0 \\ \cdots \\ \frac{v}{\sqrt{2}} + \frac{h_\psi}{\sqrt{2}} \end{pmatrix}$$

- The NEDE potential in the one-loop approx

$$V(\psi;T_d) = V_0 - \frac{\mu^2_{\rm eff}}{2}\psi^2\left(1 - \frac{\psi^2}{2v^2}\right) + B\psi^4\left(\ln\frac{\psi^2}{v^2} - \frac{1}{2}\right) + \Delta V_{\rm thermal}(\psi;T_d)$$

- Supercooled happens for light NEDE boson/heavy gauge boson regime

$$m_A \gg T_d^*, m_\psi \;\to\; \begin{cases} T_d \gg gv & \Delta V_{\rm thermal}(\psi;T_d) \to \frac{1}{24}c_0 n_A g^2 T^2\psi^2 \\ T_d \ll gv & \Delta V_{thermal}(\psi;T_d) \to 0 \quad (T_d^* << T_c = gv) \end{cases}$$

Dark Sector reheating

- After the PT the NEDE boson quickly thermalises with the massless gauge bosons

➡Supercooled PT latent heat goes into dark radiation raising

$$\Delta N_{\rm BBN} \to \Delta N_{\rm NEDE} = \frac{5\,(3c_1 + 128 c_0 \pi \gamma)\, n_A}{1024\pi^2 g^*_{\rm rel,d}\gamma^2}\,\Delta N_{\rm BBN}$$

$$\Delta N_{\rm eff} = \frac{4}{7}\left(\frac{11}{4}\right)^{4/3} g_{\rm rel,d}\,\xi^4$$

Right before PT

$$\Delta N_{\rm BBN} \simeq \frac{\pi^2}{30}\frac{f_{\rm NEDE}}{1-f_{\rm NEDE}}\frac{(T_d^*)^4}{\Delta V_*}$$

$$0.055\,\frac{\frac{N^2+N-1}{2N-1}}{11/5}\left(\frac{\gamma}{0.01}\right)^2\frac{52/45}{c_1}\frac{f_{\rm NEDE}}{0.08}$$

Right after PT

$$\left(\xi^{*,\rm after}\right)^4 = \frac{g^*_{\rm rel,vis}}{g^{\rm after}_{\rm rel,d}}\frac{f_{\rm NEDE}}{1-f_{\rm NEDE}}$$

$$\Delta N_{\rm NEDE} \simeq \frac{4}{7}\left(\frac{11}{4}\right)^{4/3} g^*_{\rm rel,vis}\frac{f_{\rm NEDE}}{1-f_{\rm NEDE}}$$

$$\xi = T_d/T_{\rm vis}$$

$$f_{\rm NEDE} = \Delta V_*/\rho_{\rm tot}(T_d^*)$$

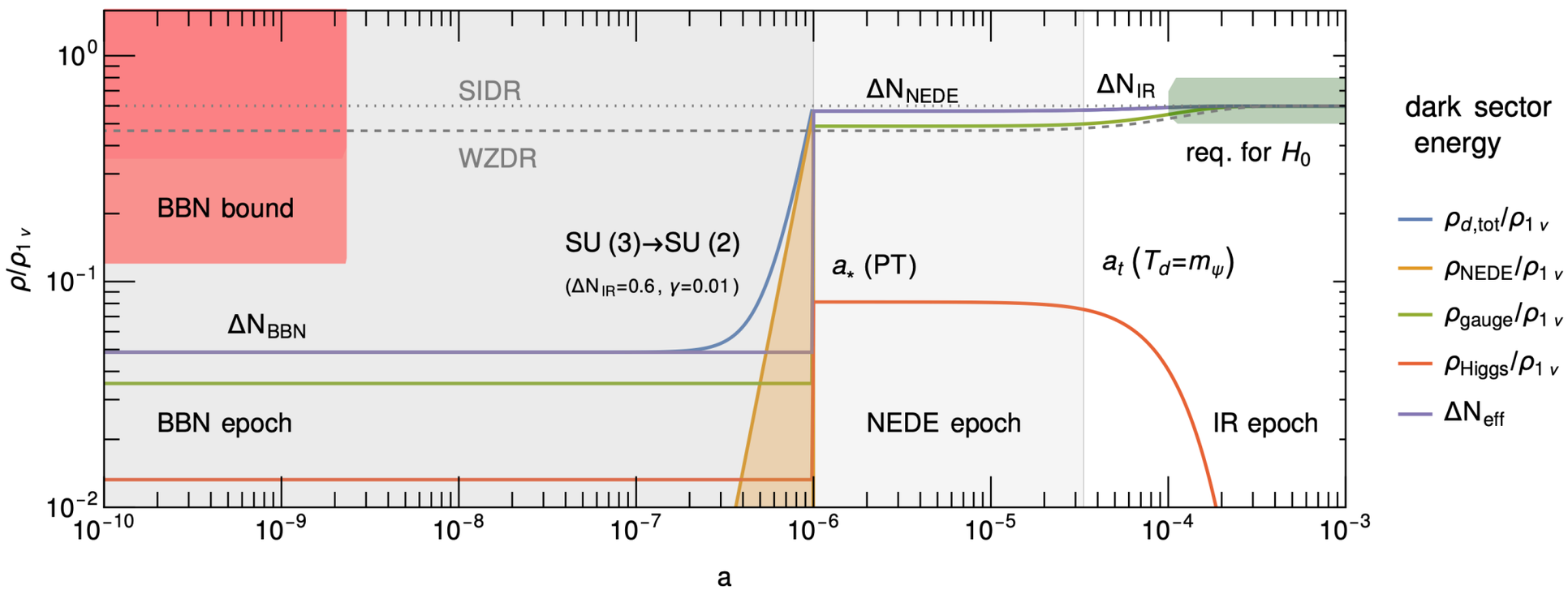
Second step

- As the NEDE boson becomes non-rel. The number of relativistic d.o.f. changes a second time

$$\Delta N_{\rm NEDE} \to \Delta N_{\rm IR} = \Delta N_{\rm NEDE}\,(1+r_g)^{1/3} \qquad . \; r_g^{-1} = 2N(N-2)$$

#dof	$z > z_*$ ("BBN")	$z_* > z > z_t$ ("NEDE")	$z < z_t$ ("IR")
$g_{{\rm rel},d}$	$2(N^2+N-1)$	$2(N-1)^2-1$	$2(N-1)^2-2$
massless gauge bosons	$2(N^2-1)$	$2((N-1)^2-1)$	
massive gauge bosons	0	$n_A \equiv 3(N^2-(N-1)^2) = 3(2N-1)$	
Higgs bosons	$2N$	1	

SU(3) -> SU(2)



$$\Delta N_{\rm BBN} \to \Delta N_{\rm NEDE} \to \Delta N_{\rm IR}$$

[Garny, Niedermann, Rubira, Sloth; 2024]

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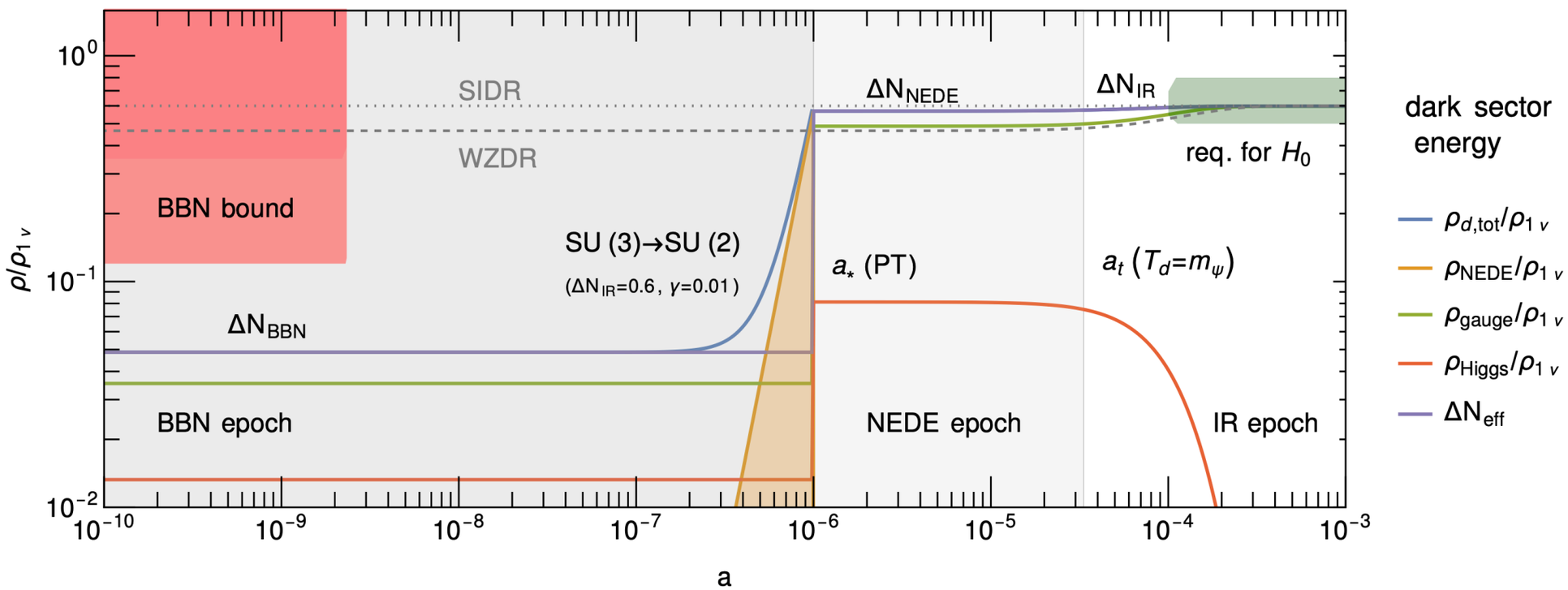

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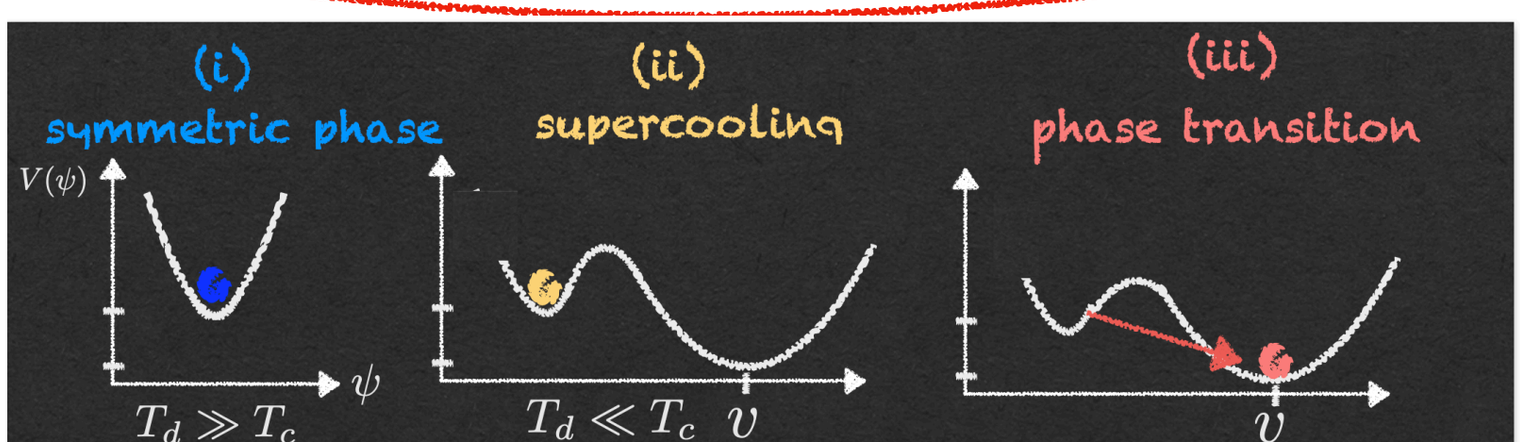

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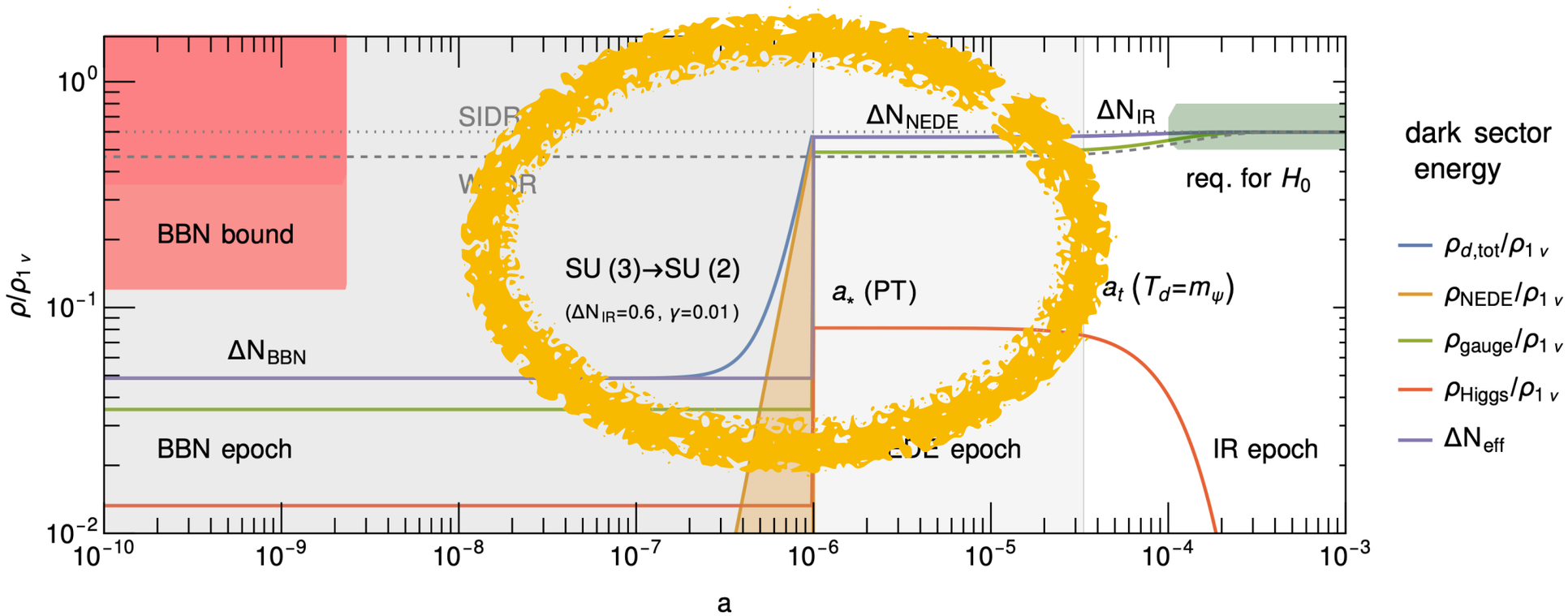

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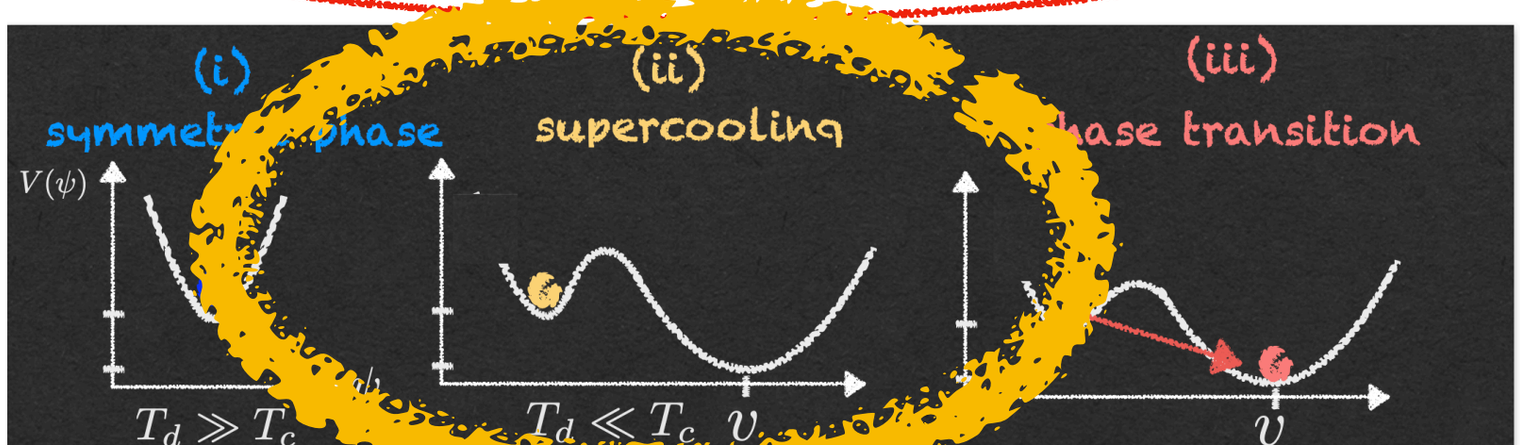

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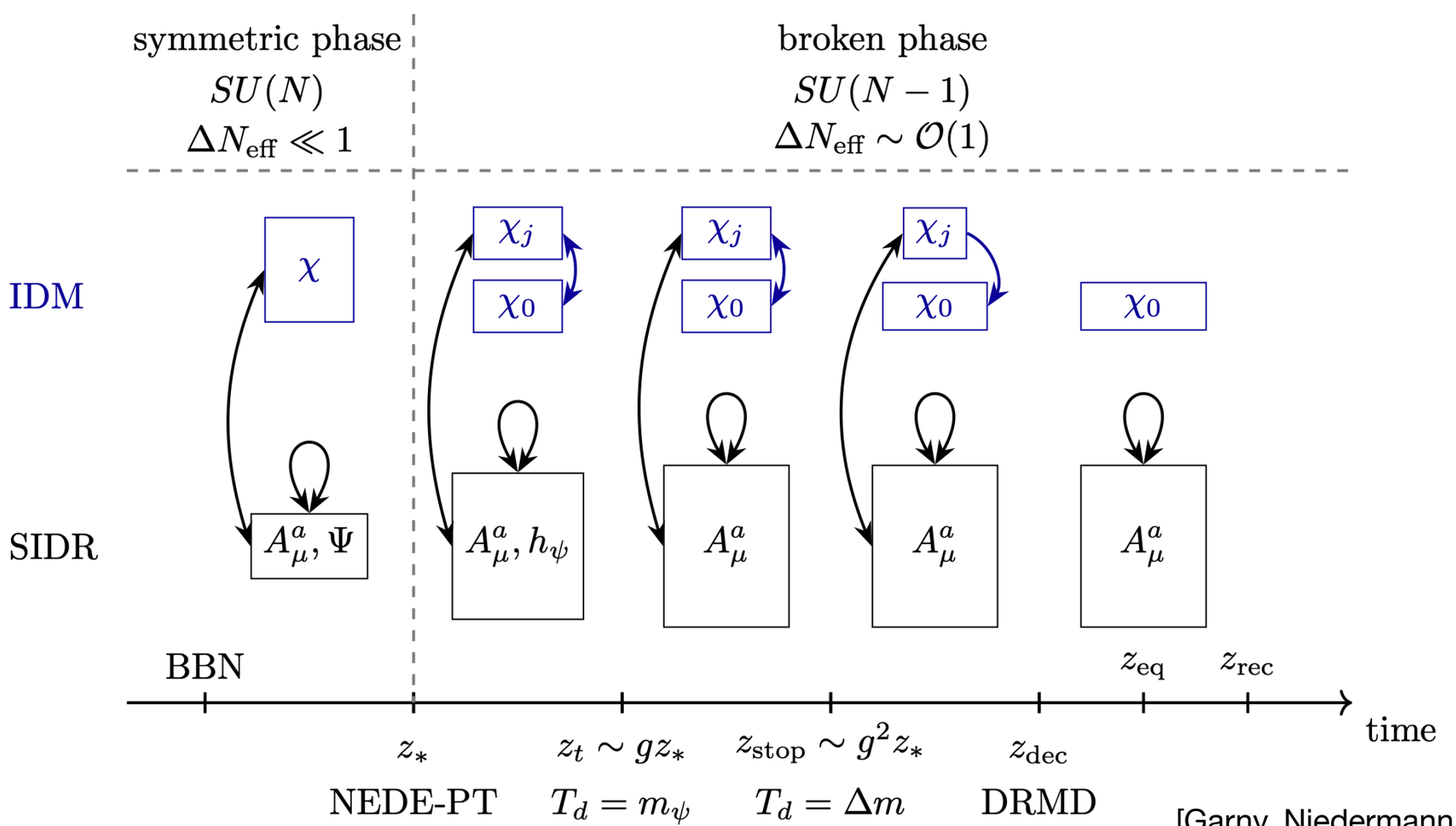

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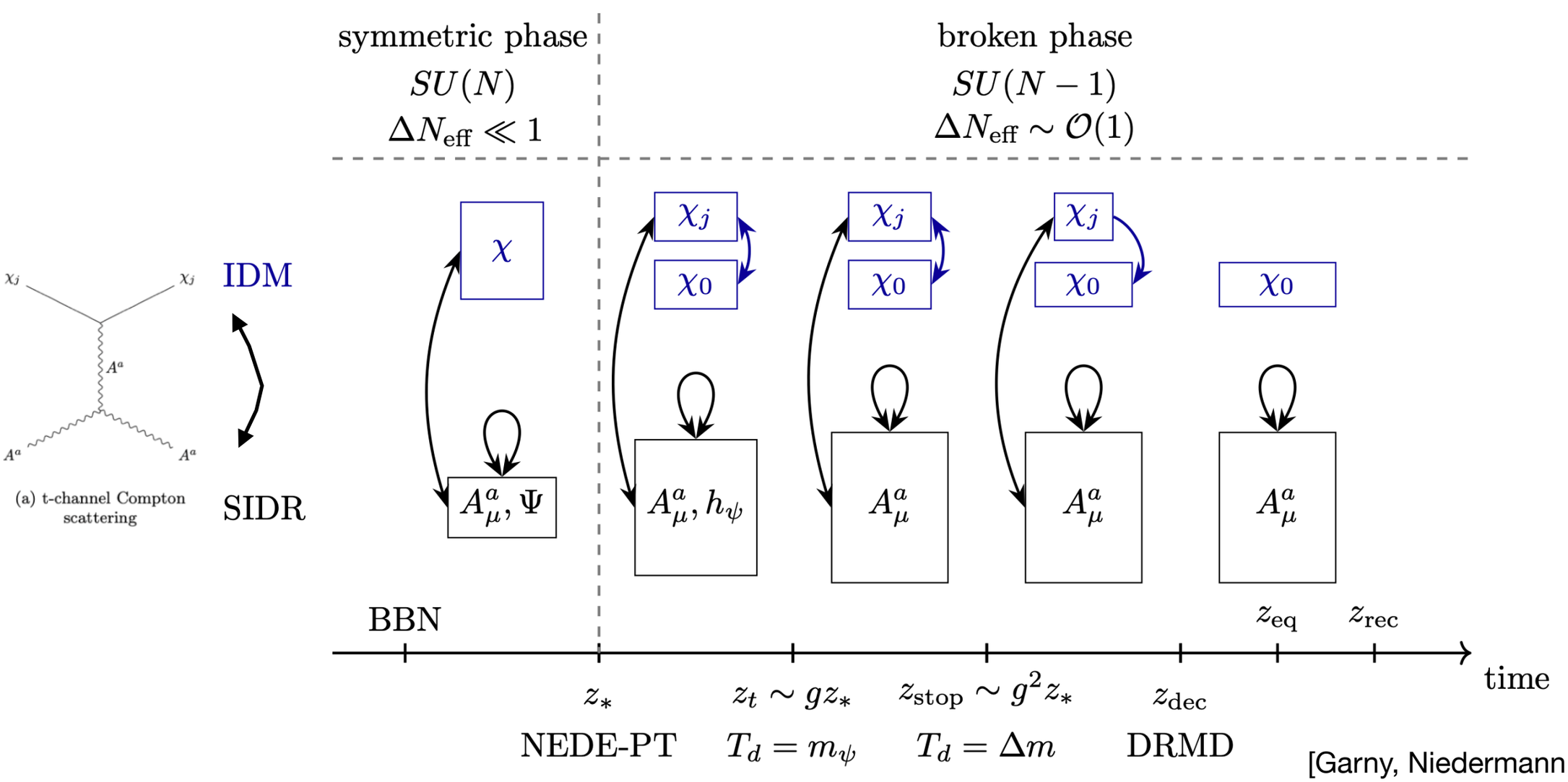

[Garny, Niedermann, Rubira, Sloth; 2025]

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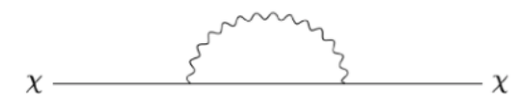
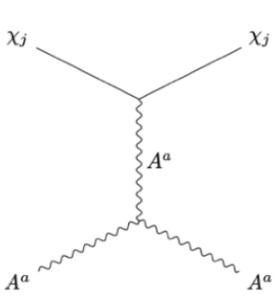


Loop induced mass splitting

$$\Delta m \sim g^3 v/(32\pi)$$

Makes χ_j convert to χ_0

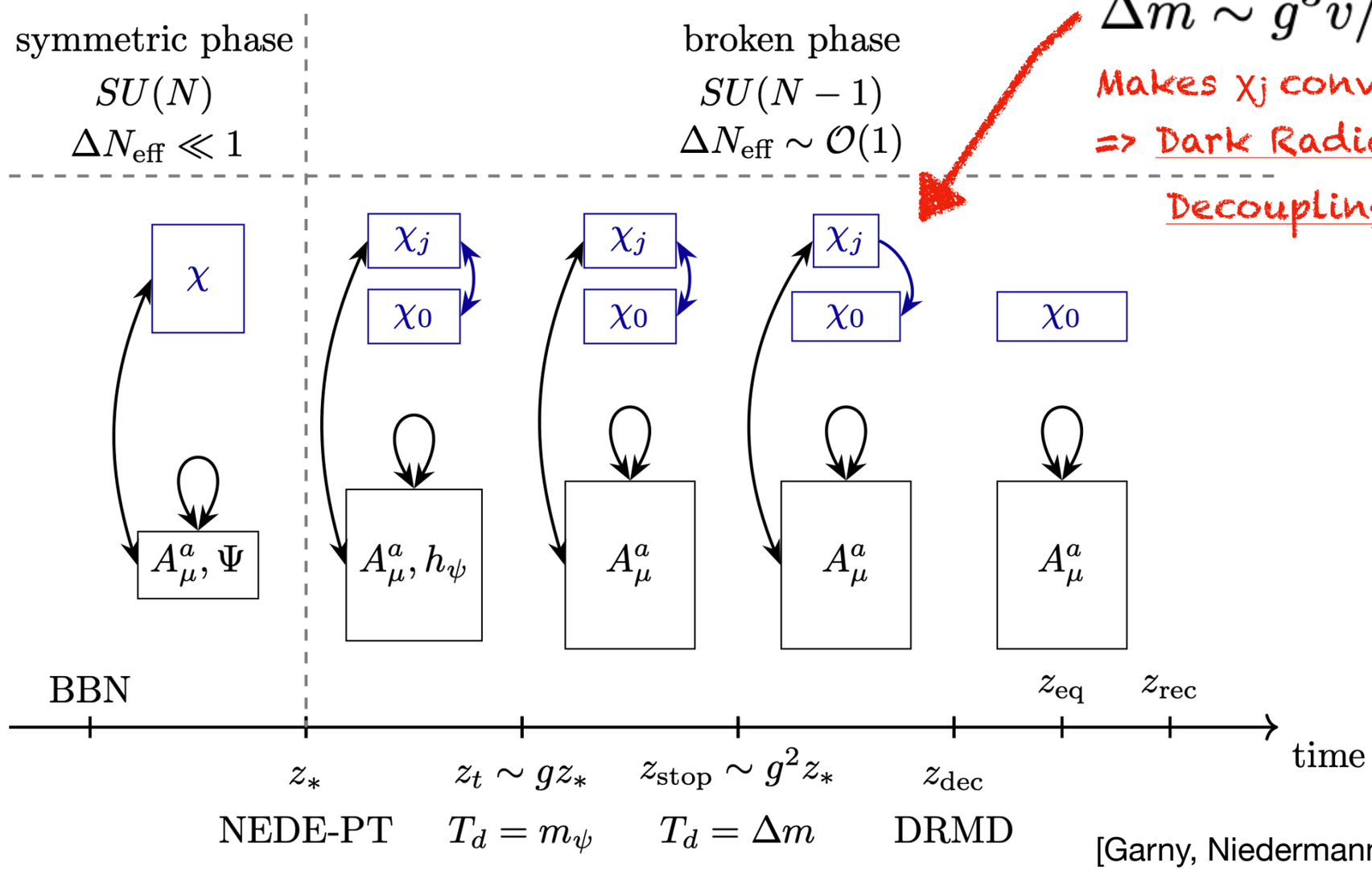
=> Dark Radiation matter Decoupling (DRMD)

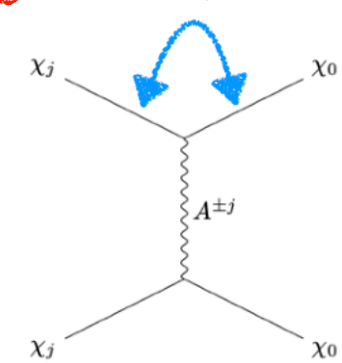


(a) t-channel Compton scattering

IDM

SIDR

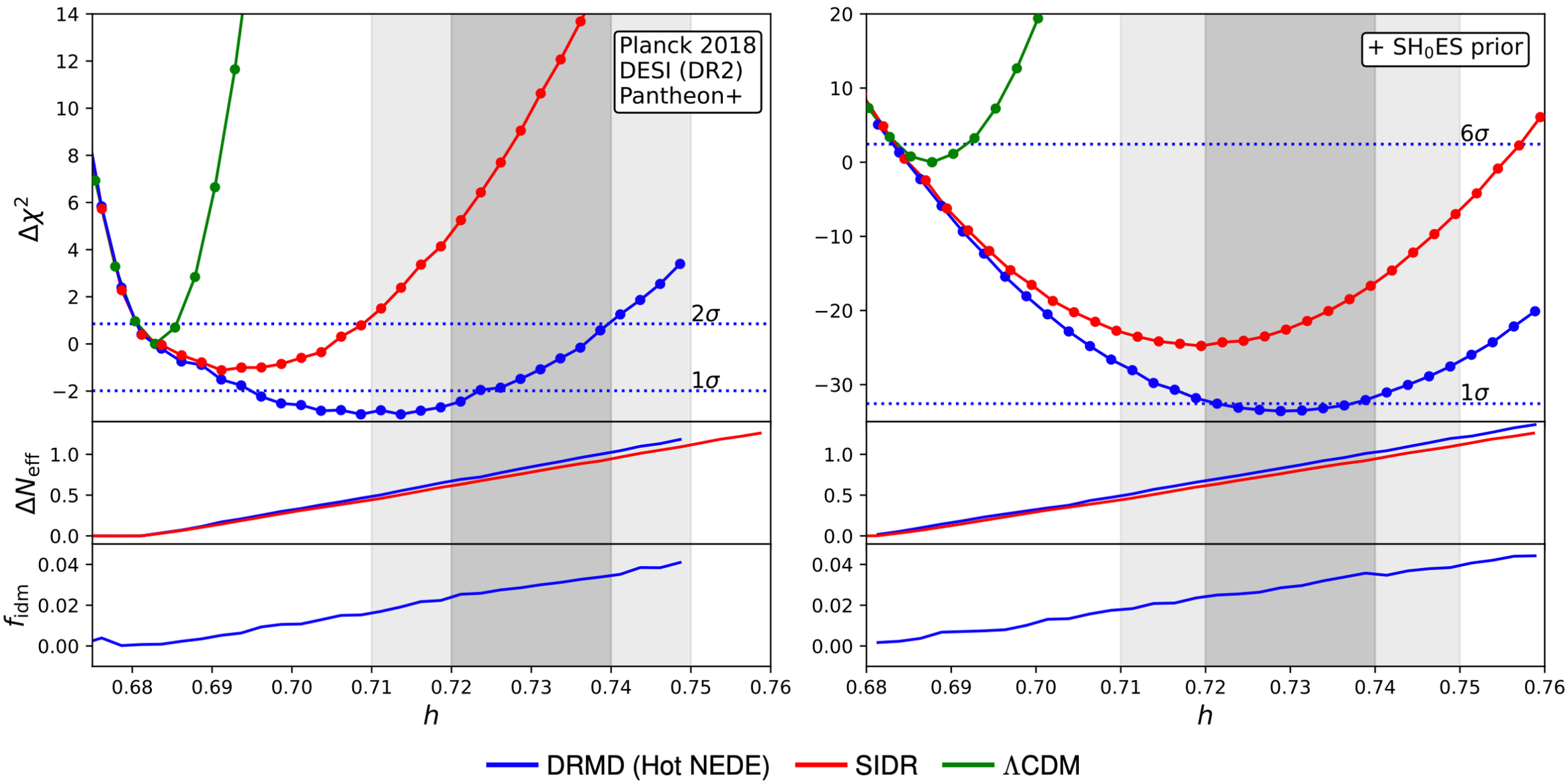




(b) t-channel dark matter conversion

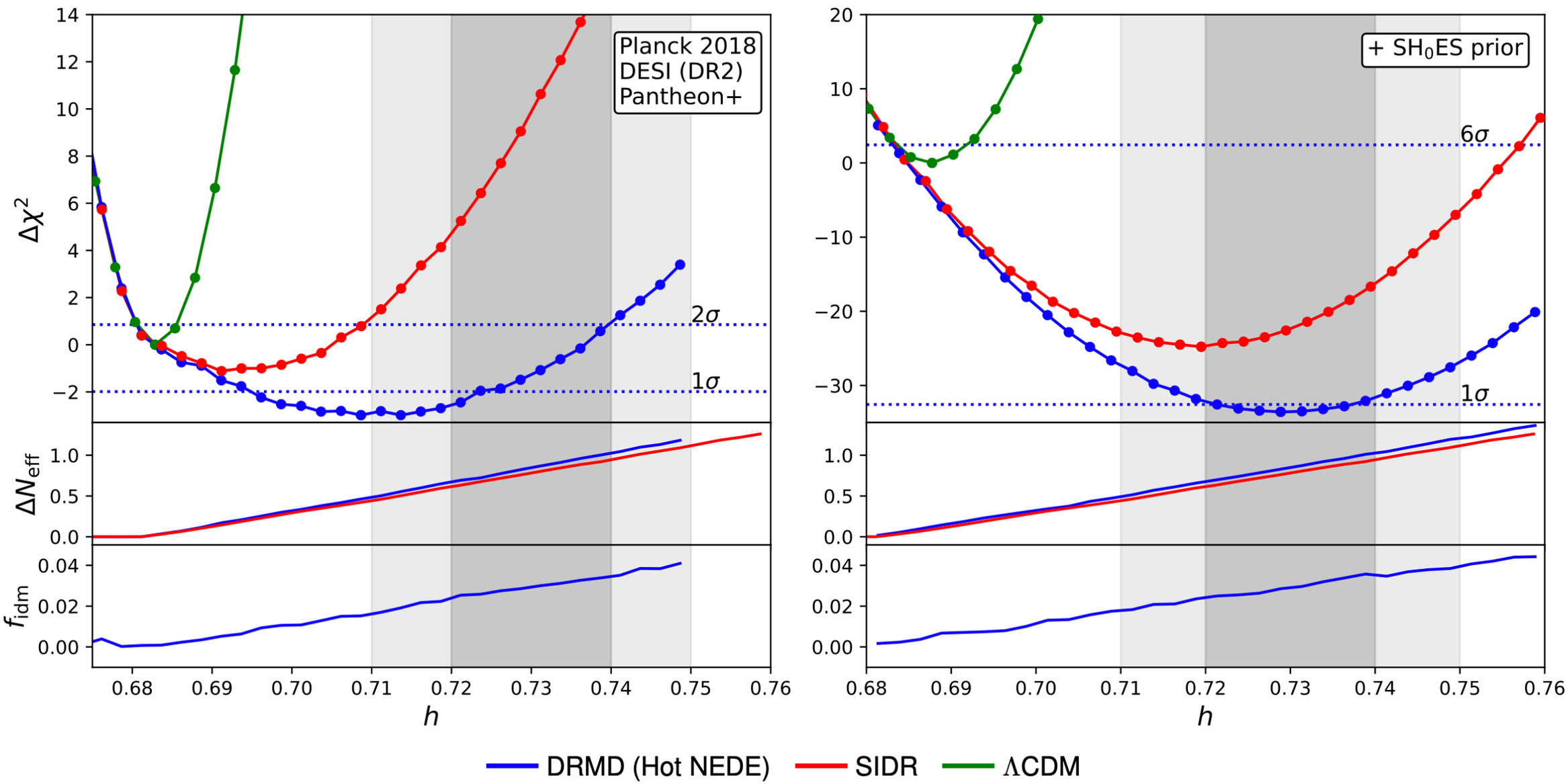
[Garny, Niedermann, Rubira, Sloth; 2025]

Hot NEDE with DRMD



[Garny, Niedermann, Rubira, Sloth; 2025]

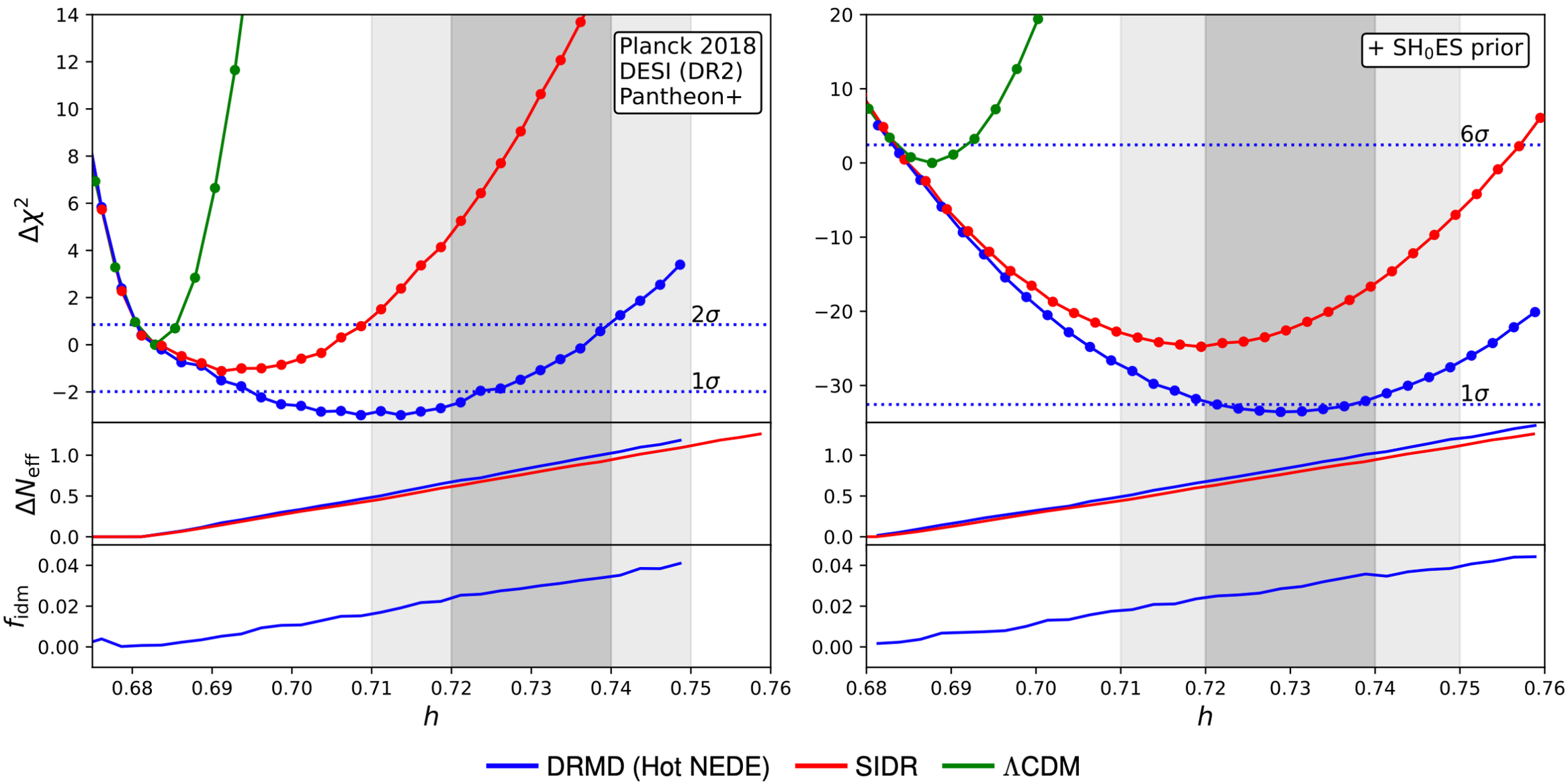
Hot NEDE with DRMD



ΛCDM > 5σ away from SHOES H_0 = 73±1 km/Mpc/s

[Garny, Niedermann, Rubira, Sloth; 2025]

Hot NEDE with DRMD



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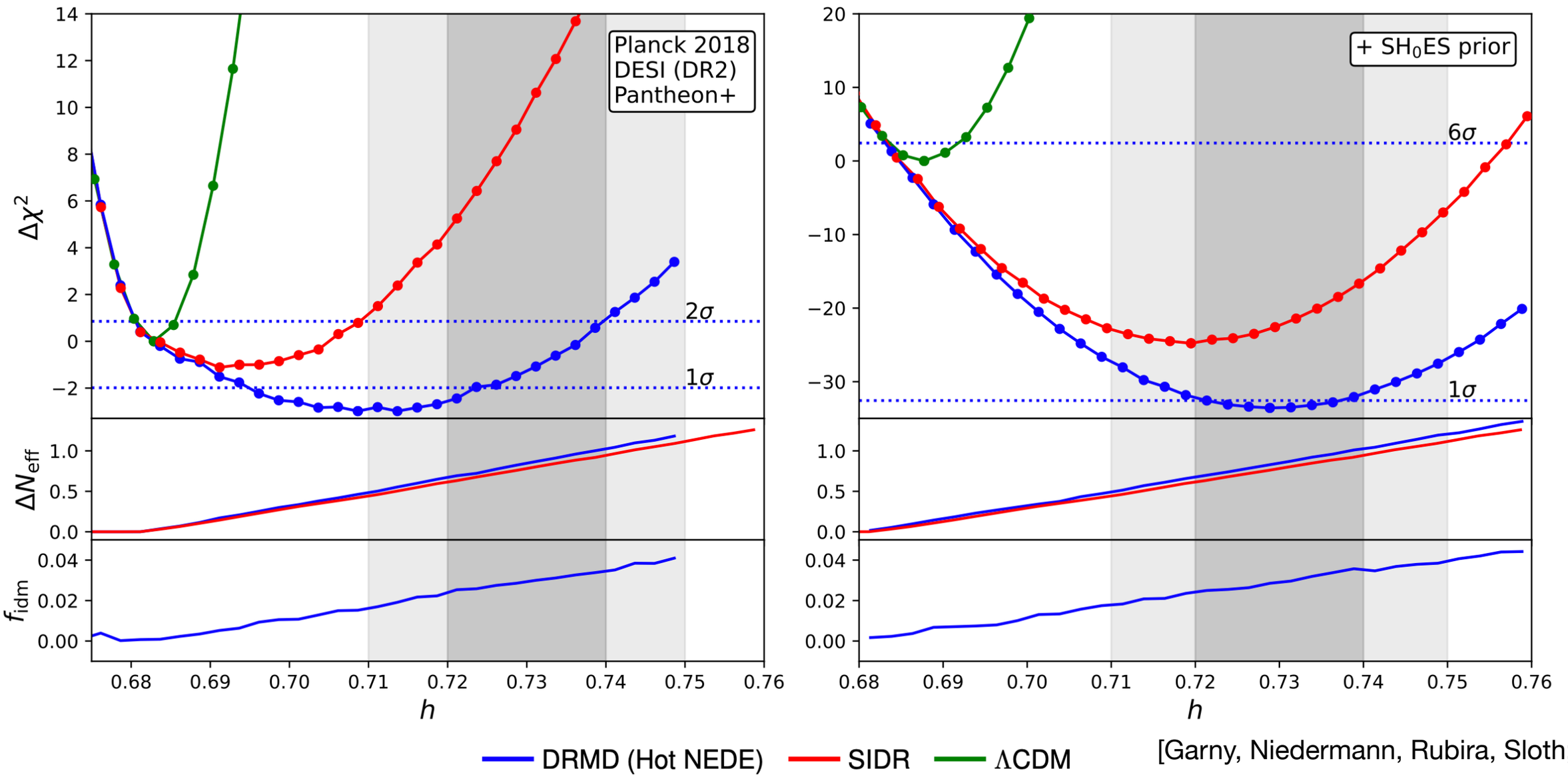
SIDR > 3σ away from SHOES H_0 = 73±1 km/Mpc/s

[Garny, Niedermann, Rubira, Sloth; 2025]

Hot NEDE with DRMD



[Garny, Niedermann, Rubira, Sloth; 2025]

ΛCDM > 5σ away from SHOES H_0 = 73±1 km/s/Mpc

SIDR > 3σ away from SHOES H_0 = 73±1 km/s/Mpc

DRMD > 1.4σ away from SHOES H_0 = 73±1 km/s/Mpc

Future observational signatures

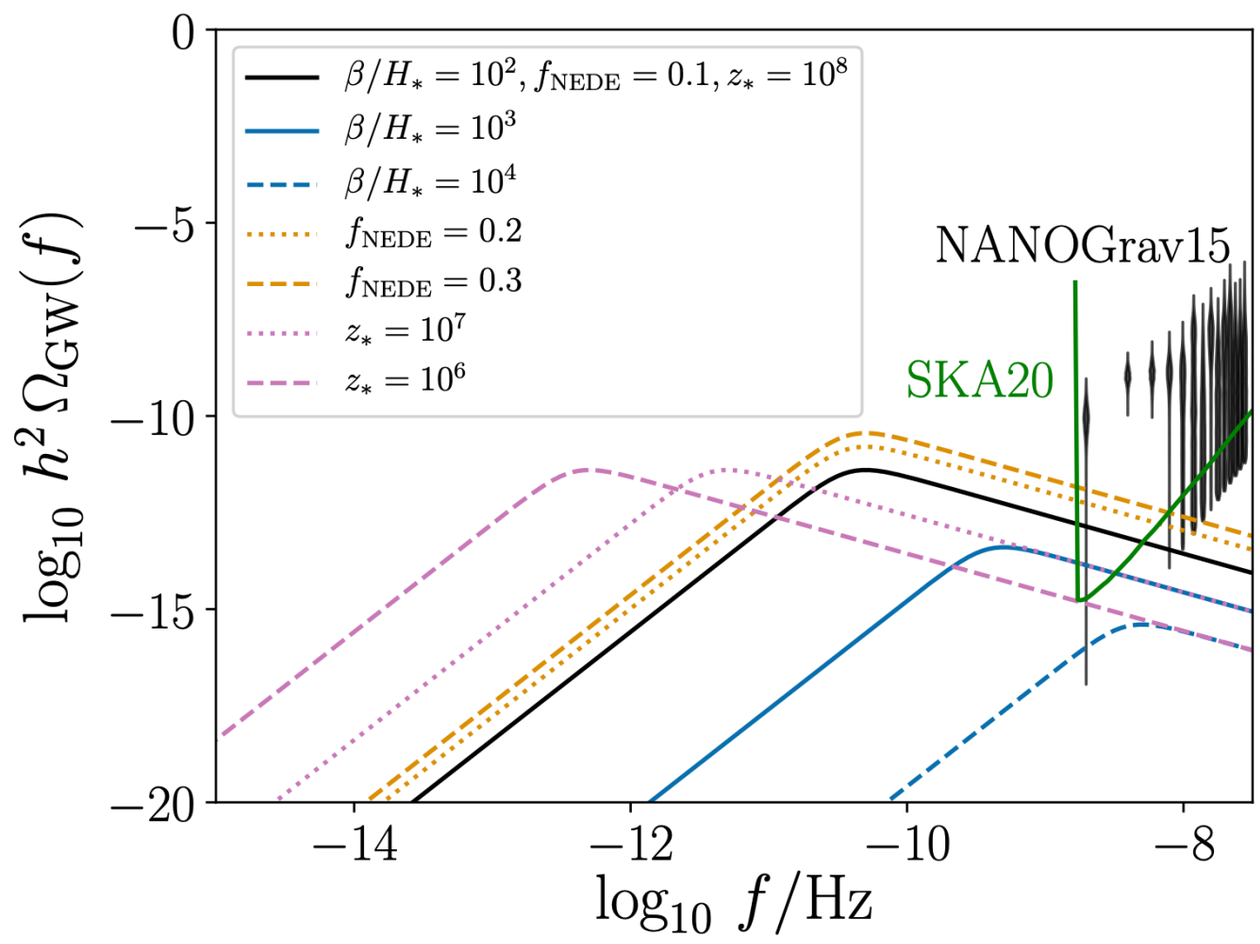
Gravitational waves

First order PT generates stochastic gravitational wave background!

Signal in PTA sensitivity range for PTs that occur close to BBN

$$10^7 \lesssim z_* \lesssim 10^9$$

and creates large bubbles



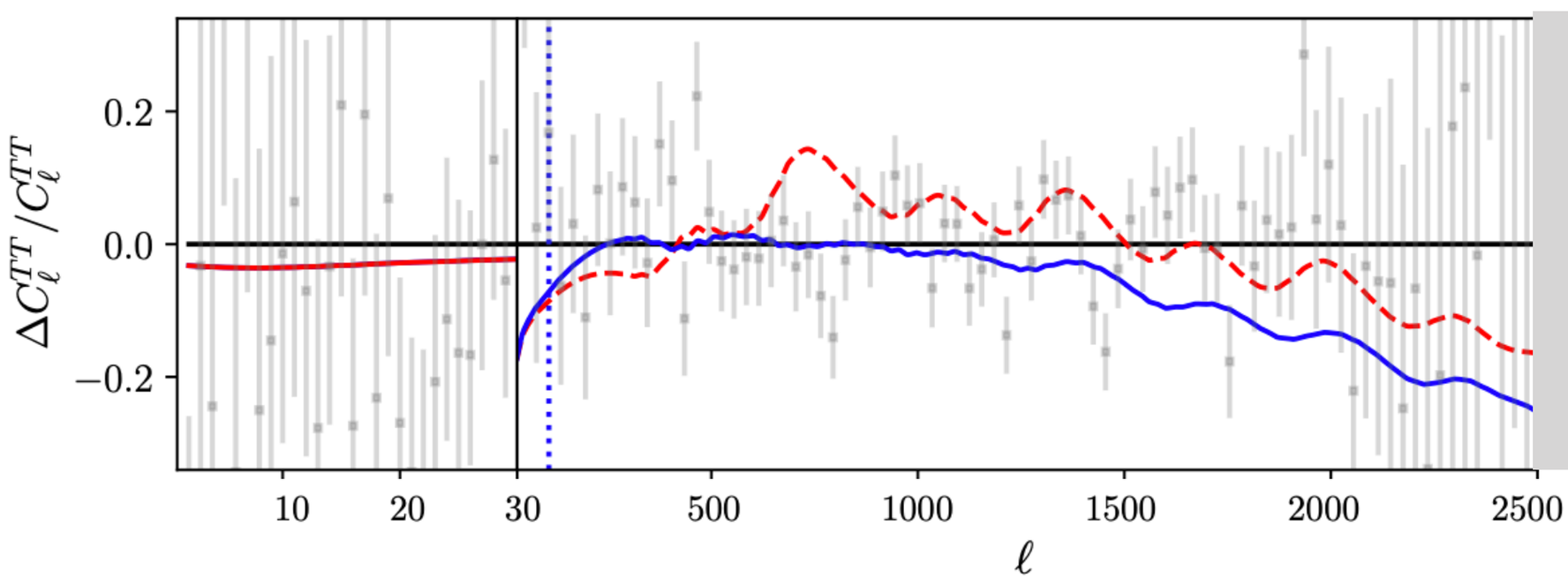
[Garny, Niedermann, Rubira, Sloth; 2025]

Small CMB anisotropies

- The DM-DR interaction suppresses power on small scales

- But higher angular scales probe features at earlier times, and other new features

➡ Can be tested with new small-scale CMB data from SPT and ACT



??????????????

ACT and SPT can probe **earlier features of the model** (mass threshold, phase transition) and other new features

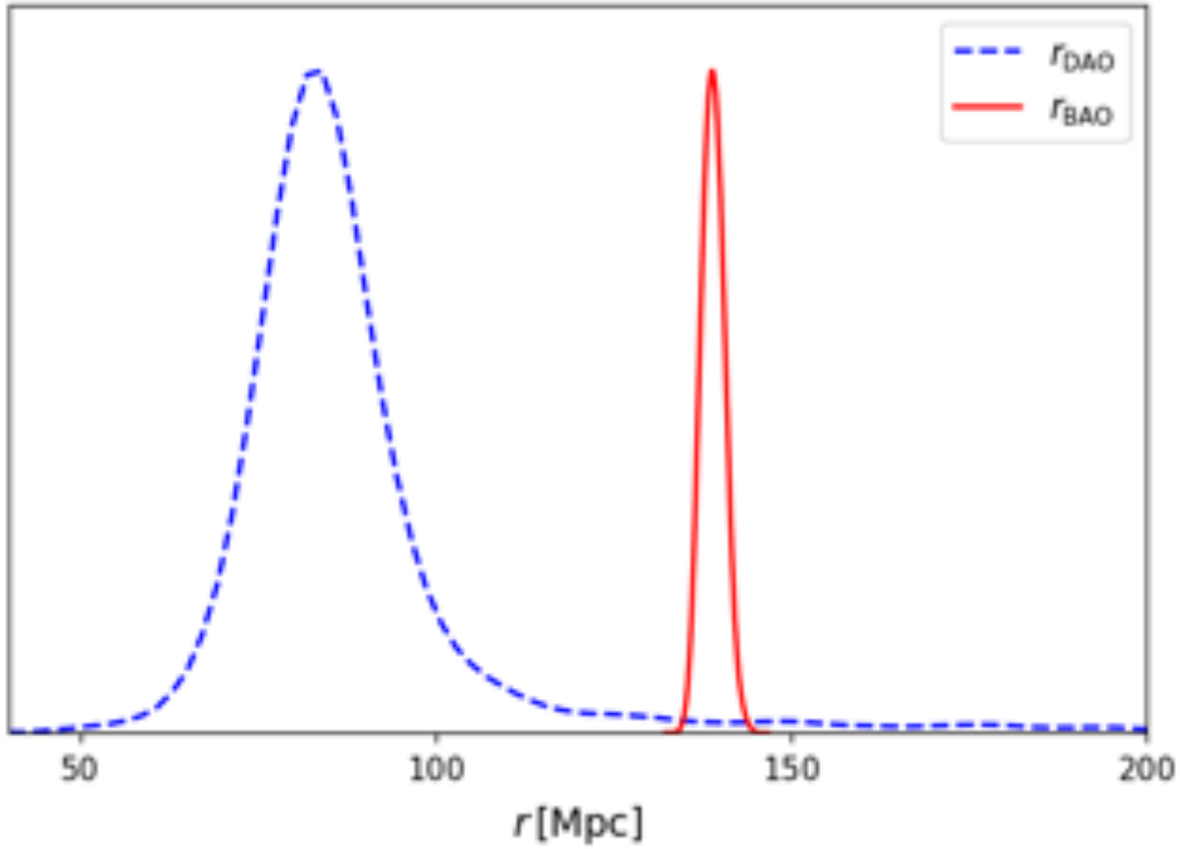
??????????????

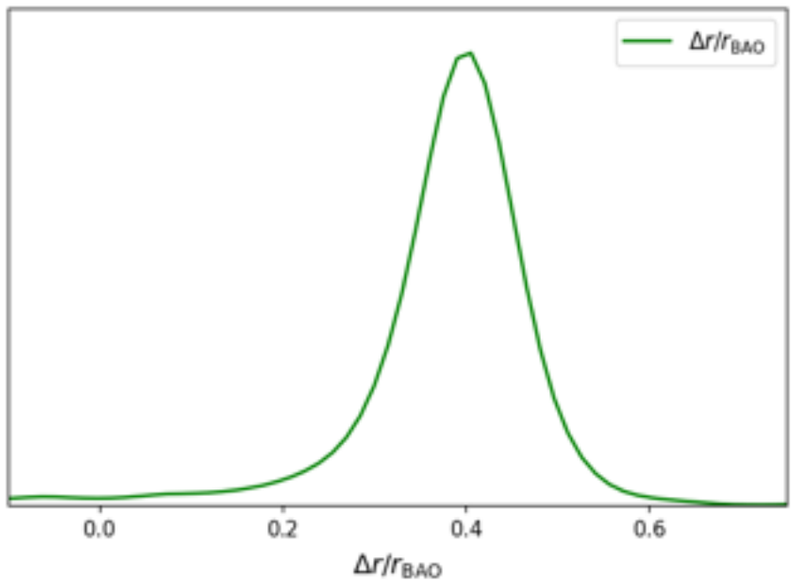
[Garny, Niedermann, Rubira, Sloth; 2025]

Smoking gun of DRMD: Dark Acoustic Oscillations (DAO)

Just like ordinary decoupling creates a BAO

➡ DRMD creates a DAO

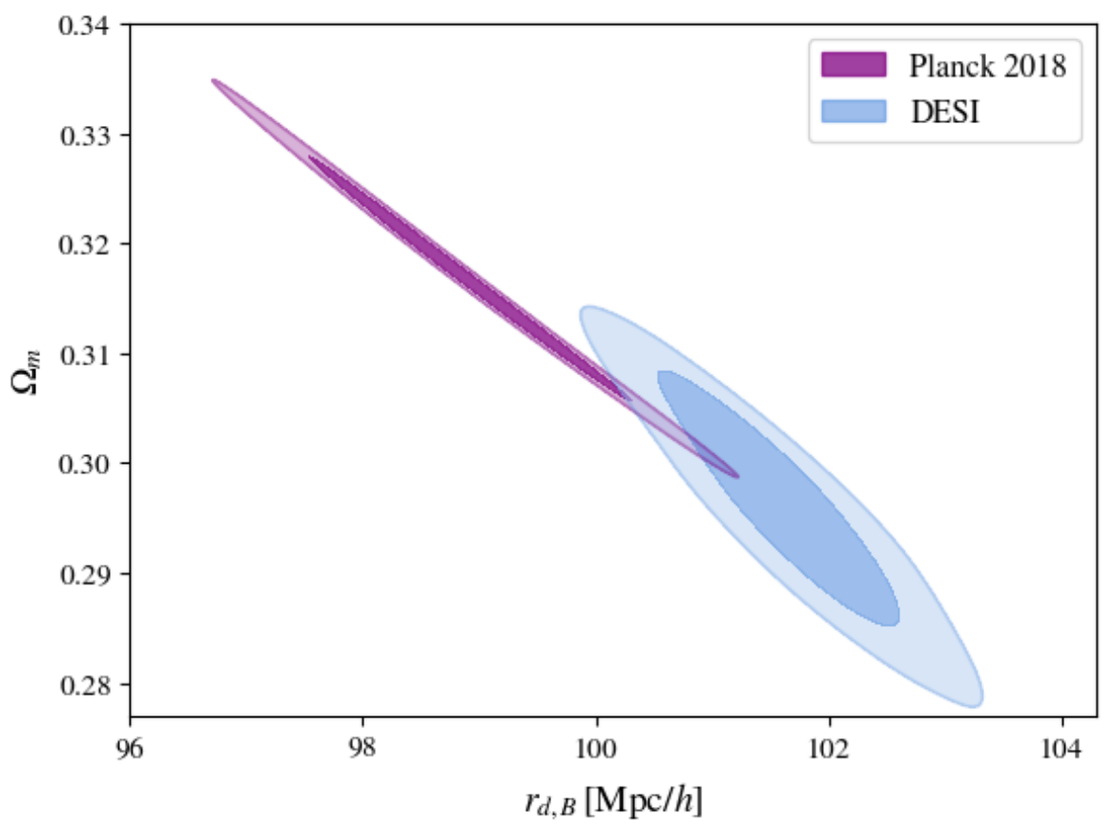




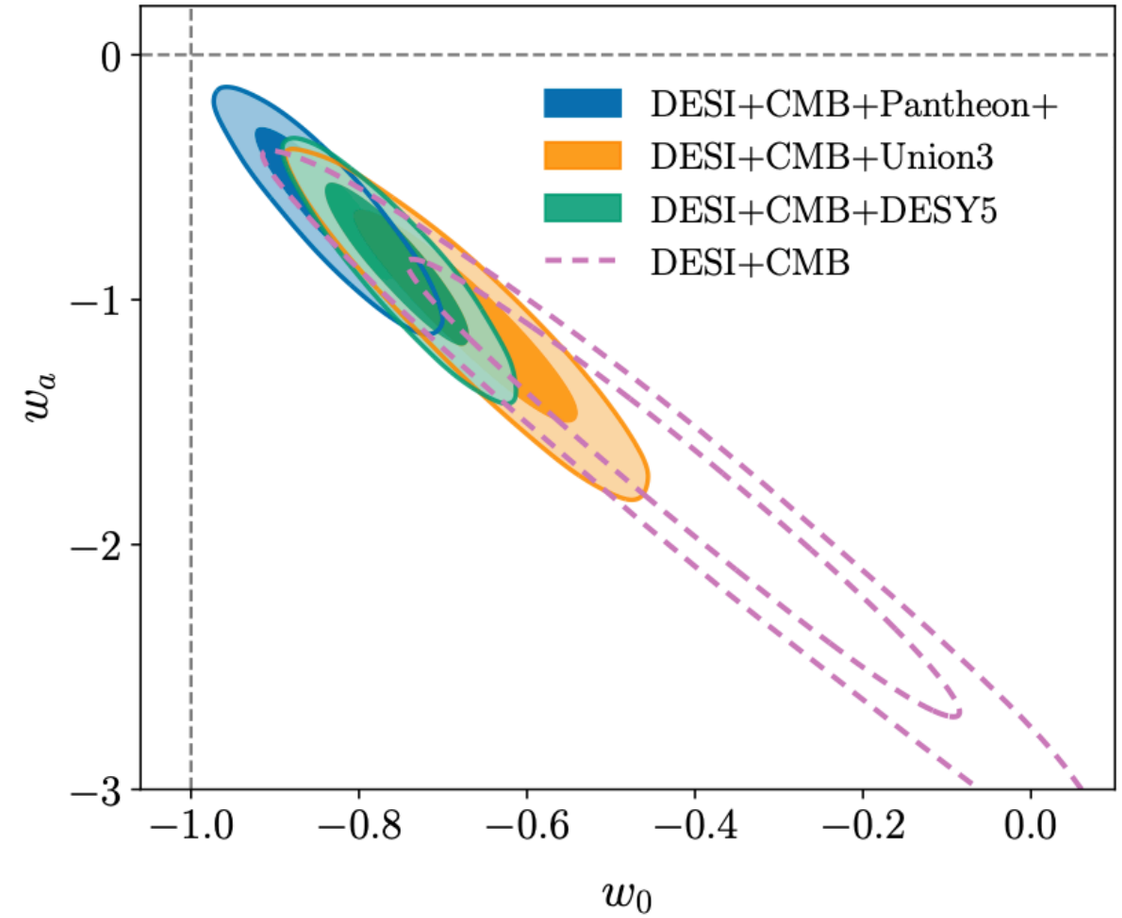
[Garny, Niedermann, Sloth —to appear very soon]

DESI anomalies

CMB-BAO anomaly in ΛCDM

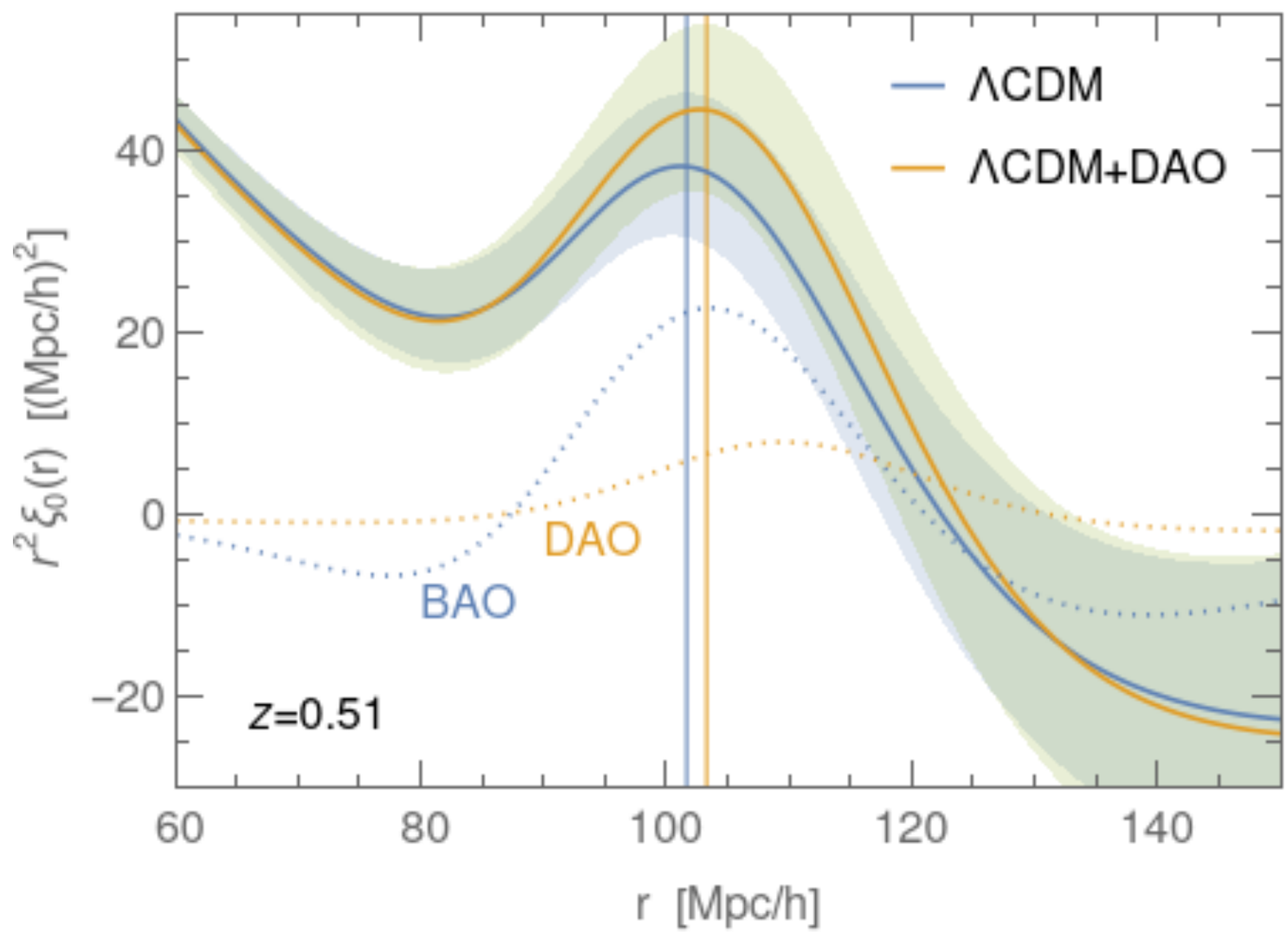


Evidence for late-time evolving Dark Energy



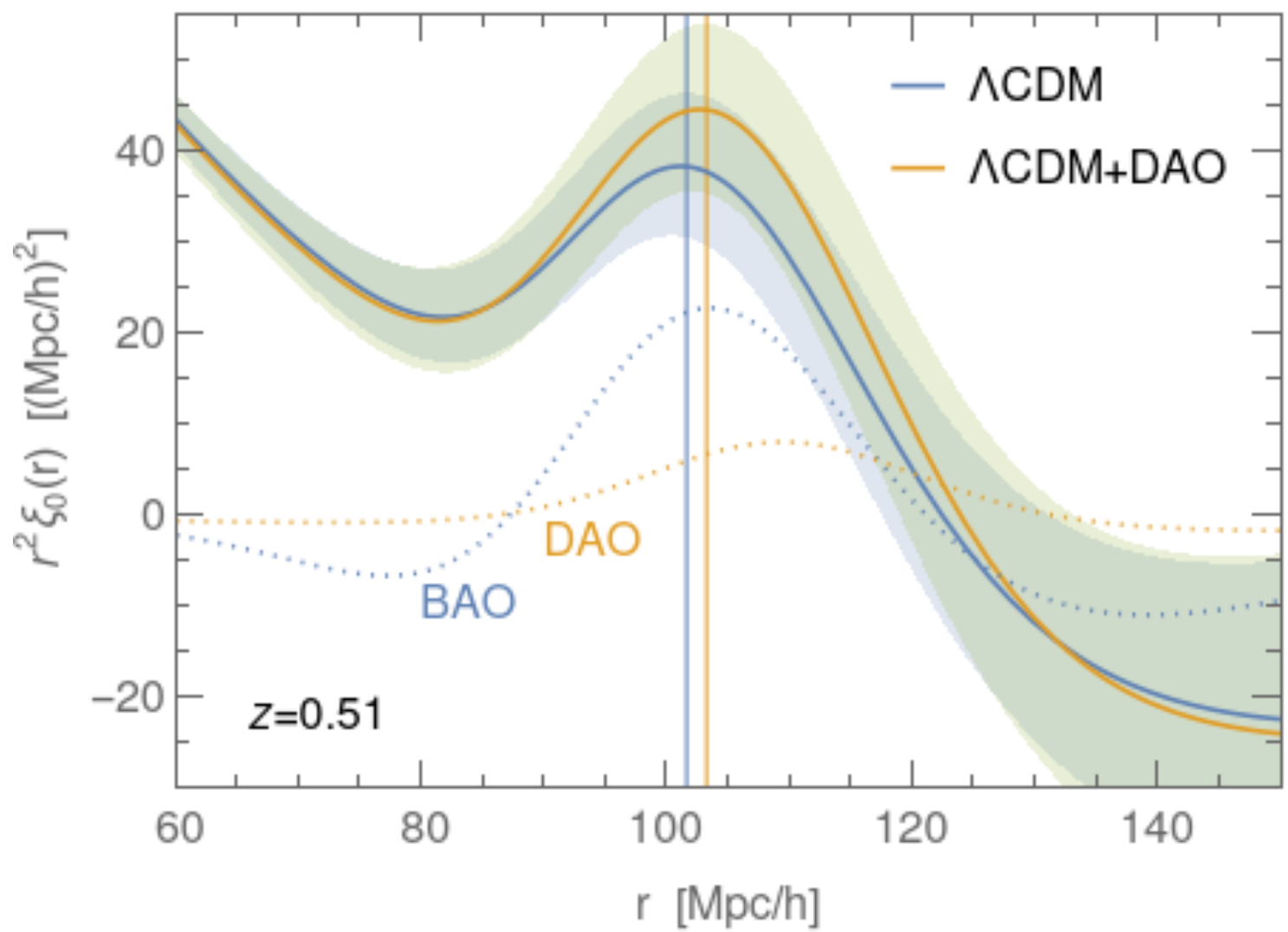
[DESI DR2; 2025]

DESI BAO-DAO confusion



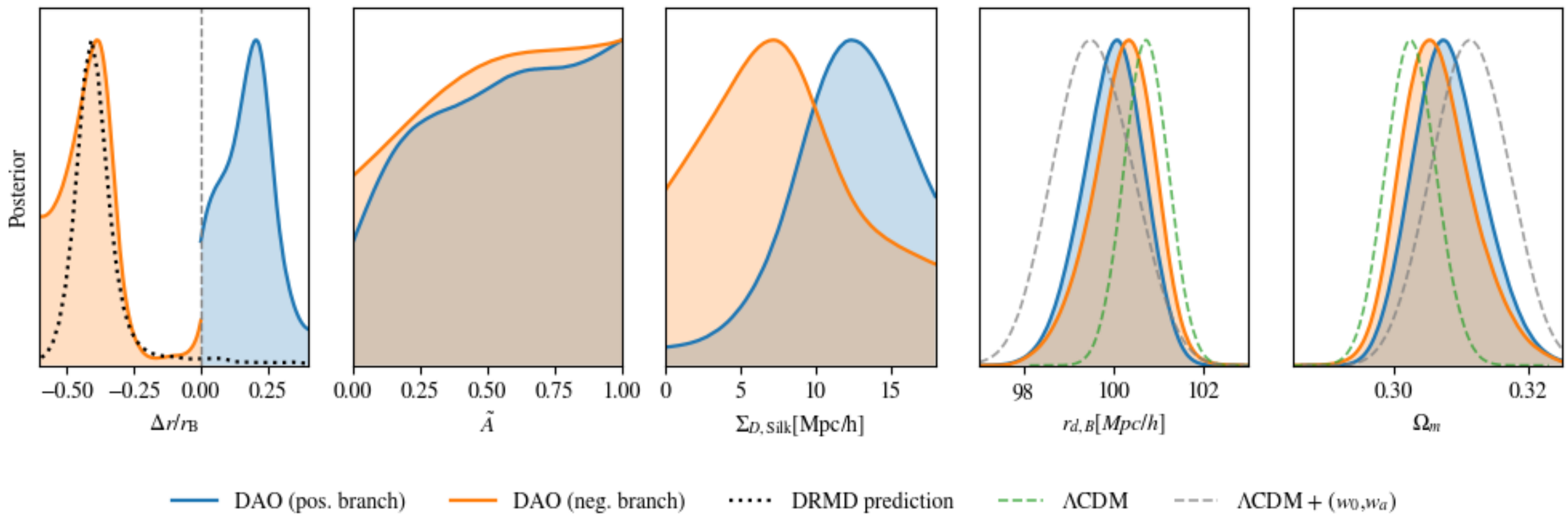
[Garny, Niedermann, Sloth —to appear very soon]

DESI BAO-DAO confusion



Redshift-dependent shift in inferred BAO position due to the presence of DAO is an alternative explanation of the DESI anomaly! [Garny, Niedermann, Sloth —to appear very soon]

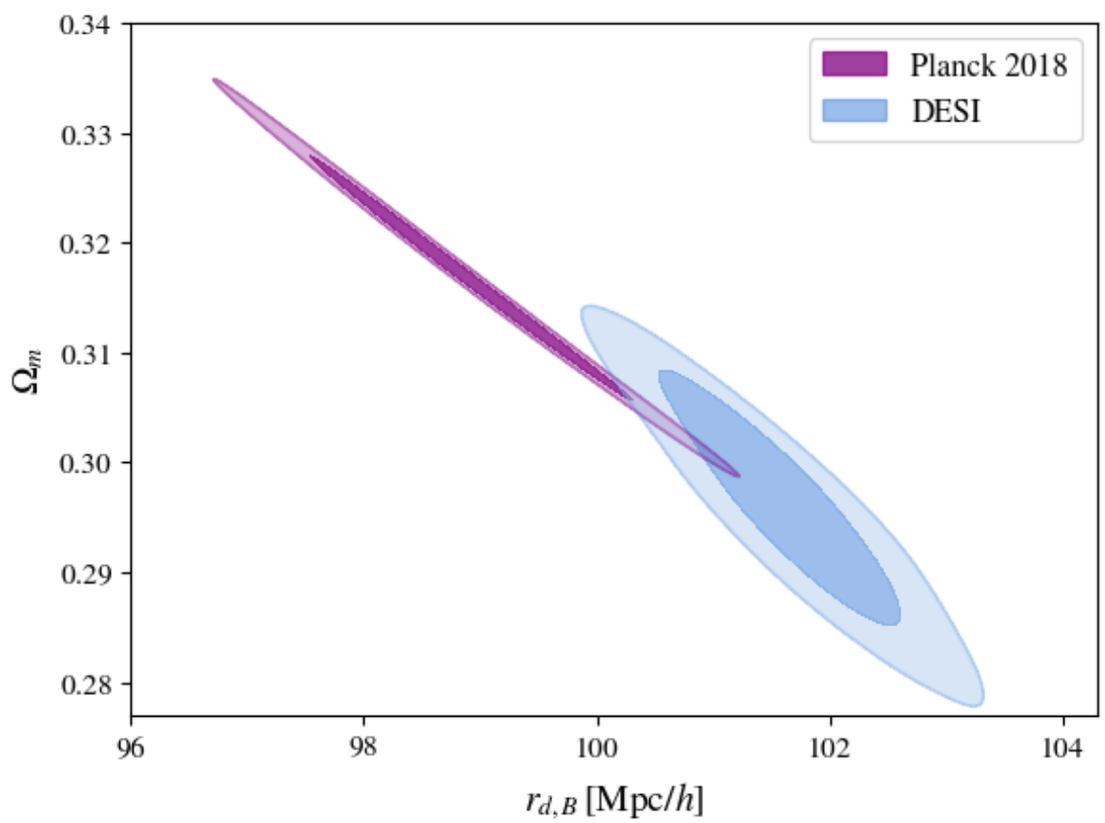
Preliminary validation of DRMD



[Garny, Niedermann, Sloth —to appear very soon]

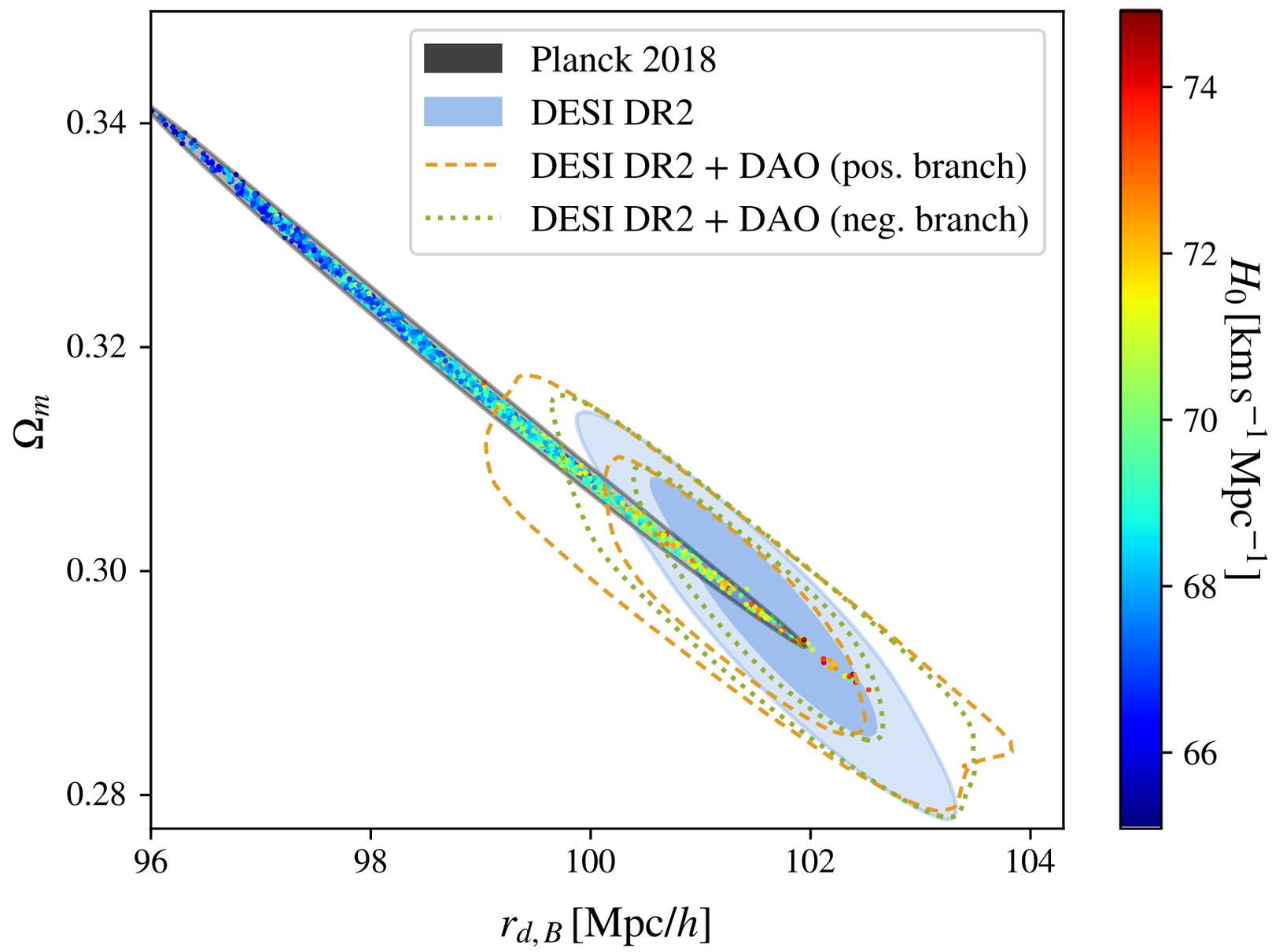
CMB-BAO tension in ΛCDM

What happens to CMB-BAO tension in ΛCDM?



[Garny, Niedermann, Sloth —to appear very soon]

A new concordance model



[Garny, Niedermann, Sloth —to appear very soon]

Conclusions/summary

- The community widely recognises the Hubble tension and the DESI anomaly.
- Models of dark sector physics solving the anomalies are hard to come by

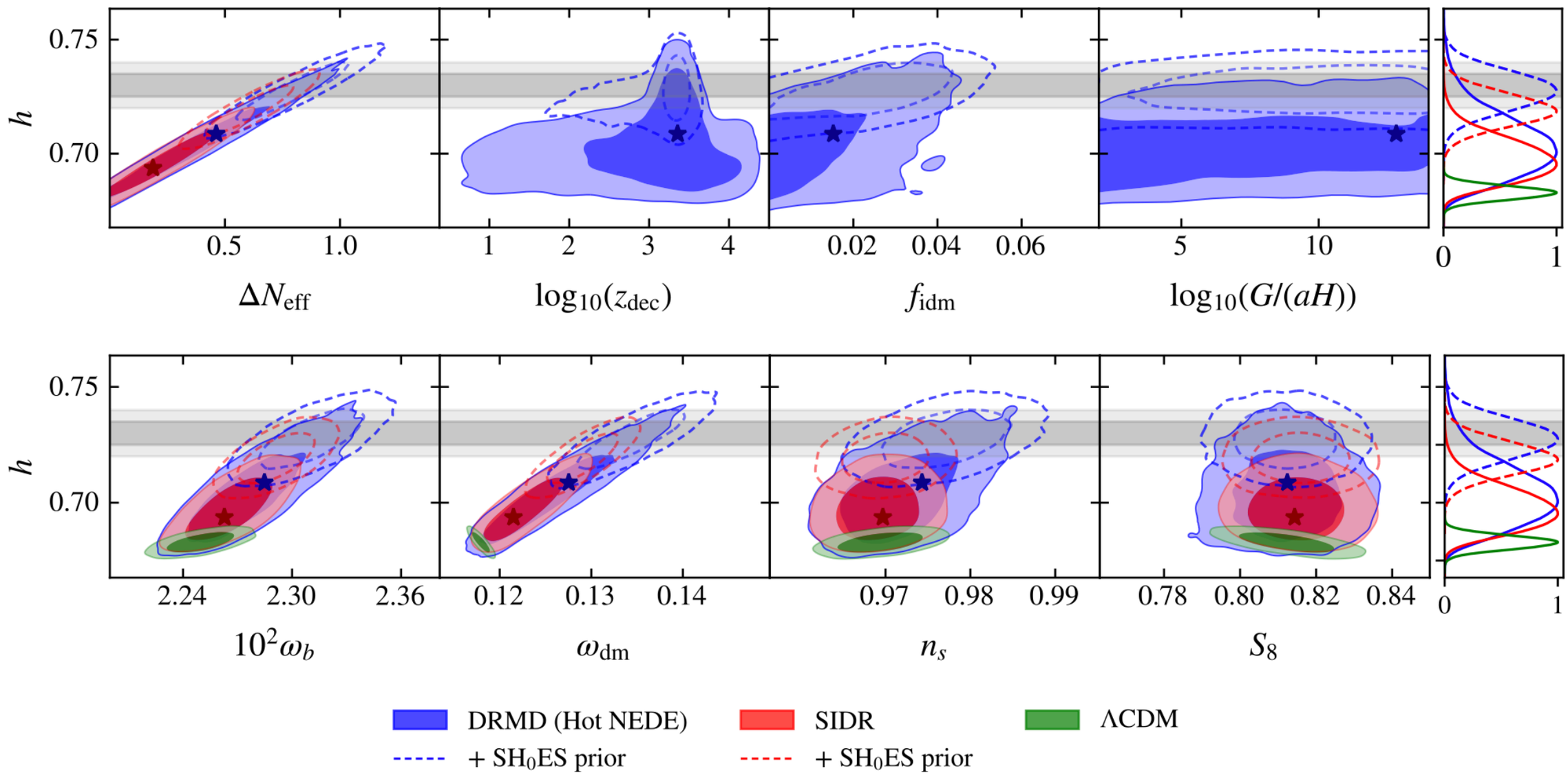
➡Model building offers a unique opportunity to gain insight into the dark sector!

“If you solve the DESI anomaly without solving the Hubble tension, you solved nothing”

— Antony Lewis, 2025

➡Probably not w0, wa (i.e. not evolving Dark Energy)

- However, Hot NEDE with DRMD and a DAO could fit the bill!
- The Hubble tension and the DESI anomaly could provide an exciting window into the dark sector!!!



	Base				Base + SH$_0$ES prior				$Q^M_{\rm DMAP}$	$Q_{\rm Gauss}$
	H_0	$\Delta N_{\rm eff}$	$\Delta\chi^2$	ΔAIC	H_0	$\Delta N_{\rm eff}$	$\Delta\chi^2$	ΔAIC		
ΛCDM	68.30 ± 0.29	–	–	–	68.70 ± 0.29	–	–	–	5.7σ	4.4σ
SIDR	$69.8^{+0.8}_{-1.0}$ (69.4)	< 0.525 (0.188)	-1.2	0.8	71.9 ± 0.7 (72.0)	0.61 ± 0.13 (0.610)	-24.5	-22.5	3.0σ	2.5σ
DRMD	$70.5^{+1.0}_{-1.6}$ (70.9)	< 0.811 (0.462)	-3.0	3.0	72.8 ± 0.8 (72.9)	0.80 ± 0.16 (0.829)	-33.3	-27.3	1.4σ	1.8σ

TABLE I. Comparison between ΛCDM, (post-BBN) SIDR, and DRMD (Hot NEDE) as solutions to the Hubble tension, using standard metrics. While SIDR reduces the QDMAP tension to 3σ, the DRMD model brings it to below 2σ. The (naive) Gaussian tension measure is reported in the last column. After including a prior on M, we report a 4.7σ and 5σ evidence for a non-vanishing fraction of $\Delta N_{\rm eff}$ for SIDR and DRMD, respectively. For a complete account of our cosmological parameter inference see Tab. II.

Appendix A: Table with MCMC results

	ΛCDM		SIDR		DRMD	
	Base	Base + SH_0ES prior	Base	Base + SH_0ES prior	Base	Base + SH_0ES prior
Parameter	68% limits (best fit)	68% limits (best fit)	68% limits (best fit)	68% limits (best fit)	68% limits (best fit)	68% limits (best fit)
$10^2\omega_b$	2.250 ± 0.012 (2.243)	2.261 ± 0.013 (2.263)	2.266 ± 0.016 (2.263)	2.291 ± 0.014 (2.292)	$2.277^{+0.017}_{-0.026}$ (2.285)	2.310 ± 0.018 (2.313)
$\omega_{\rm dm}$	0.11795 ± 0.00064 (0.11923)	0.11710 ± 0.00062 (0.11705)	$0.1228^{+0.0024}_{-0.0034}$ (0.1215)	0.1290 ± 0.0026 (0.1291)	$0.1259^{+0.0034}_{-0.0061}$ (0.1275)	0.1344 ± 0.0037 (0.1353)
h	0.6828 ± 0.0029 (0.6771)	0.6874 ± 0.0028 (0.6877)	$0.6978^{+0.0076}_{-0.010}$ (0.6937)	0.7192 ± 0.0071 (0.7195)	$0.705^{+0.010}_{-0.016}$ (0.709)	0.7276 ± 0.0082 (0.7289)
$\ln(10^{10}A_s)$	3.054 ± 0.015 (3.048)	3.059 ± 0.016 (3.063)	3.048 ± 0.015 (3.049)	$3.042^{+0.014}_{-0.016}$ (3.039)	3.051 ± 0.015 (3.051)	$3.050^{+0.015}_{-0.017}$ (3.050)
$n_{\rm s}$	0.9694 ± 0.0033 (0.9671)	0.9718 ± 0.0033 (0.9730)	0.9692 ± 0.0034 (0.9697)	0.9700 ± 0.0034 (0.9697)	$0.9721^{+0.0039}_{-0.0055}$ (0.9743)	0.9770 ± 0.0048 (0.9783)
$\tau_{\rm reio}$	$0.0611^{+0.0070}_{-0.0078}$ (0.0567)	0.0639 ± 0.0078 (0.0655)	$0.0604^{+0.0068}_{-0.0077}$ (0.0598)	$0.0607^{+0.0068}_{-0.0081}$ (0.0595)	$0.0611^{+0.0071}_{-0.0080}$ (0.0610)	$0.0618^{+0.0068}_{-0.0084}$ (0.0609)
$\Delta N_{\rm eff}$	–	–	< 0.525 (0.188)	0.61 ± 0.13 (0.61)	< 0.811 (0.462)	0.80 ± 0.16 (0.83)
$f_{\rm idm}$	–	–	–	–	< 0.0362 (0.0152)	< 0.0442 (0.0285)
$\log_{10}(\mathcal{G}/\mathcal{H})$	–	–	–	–	unconstrained (12.823)	unconstrained (13.057)
$\log_{10}(z_{\rm stop})$	–	–	–	–	> 2.50 (4.82)	> 3.64 (4.83)
$\log_{10}(z_{\rm dec})$	–	–	–	–	$3.03^{+0.75}_{-0.34}$ (3.36)	$3.25^{+0.22}_{-0.012}$ (3.35)
S_8	0.8125 ± 0.0084 (0.8242)	0.8043 ± 0.0084 (0.8057)	0.8151 ± 0.0086 (0.8143)	0.8157 ± 0.0085 (0.8146)	0.8120 ± 0.0096 (0.8124)	0.8120 ± 0.0089 (0.8115)
hr_d[Mpc]	100.72 ± 0.48 (99.70)	101.46 ± 0.47 (101.51)	101.03 ± 0.52 (100.93)	101.69 ± 0.47 (101.71)	100.95 ± 0.53 (100.96)	101.24 ± 0.52 (101.13)
Ω_m	0.3026 ± 0.0037 (0.3104)	0.2970 ± 0.0035 (0.2967)	0.3001 ± 0.0040 (0.3009)	0.2950 ± 0.0035 (0.2949)	0.3009 ± 0.0040 (0.3007)	0.2987 ± 0.0039 (0.2995)
χ^2 per experiment						
Planck high-ℓ	2348.8	2351.7	2348.9	2354.4	2347.2	2349.5
Planck low-ℓ EE	397.7	399.3	397.3	397.2	397.7	397.6
Planck low-ℓ TT	22.6	22.3	22.5	22.3	21.8	21.3
Planck lensing	9.2	9.3	9.3	9.6	9.4	9.5
DESI BAO	12.8	10.4	11.8	10.4	11.6	11.0
Pantheon+	1412.7	1414.1	1413.1	1414.5	1413.1	1413.4
SH_0ES	–	29.6	–	3.4	–	0.6
Total	**4203.9**	**4236.6**	**4202.9**	**4211.8**	**4200.9**	**4203.0**
$\Delta\chi^2$	0.0	0.0	-1.0	-24.8	-3.0	-33.6
$Q^M_{\rm DMAP}$ [σ]	–	5.7	–	3.0	–	1.4

TABLE II. Results of our MCMC analysis for ΛCDM, SIDR and DRMD. The base data sets consists of Planck 2018, DESI BAO (DR2), and Pantheon+. The SH_0ES measurement is implemented through a prior on the SNe magnitude M. We report the $1\,\sigma$ standard deviation (except for one-sided constraints, which correspond to the $2\,\sigma$ limit).