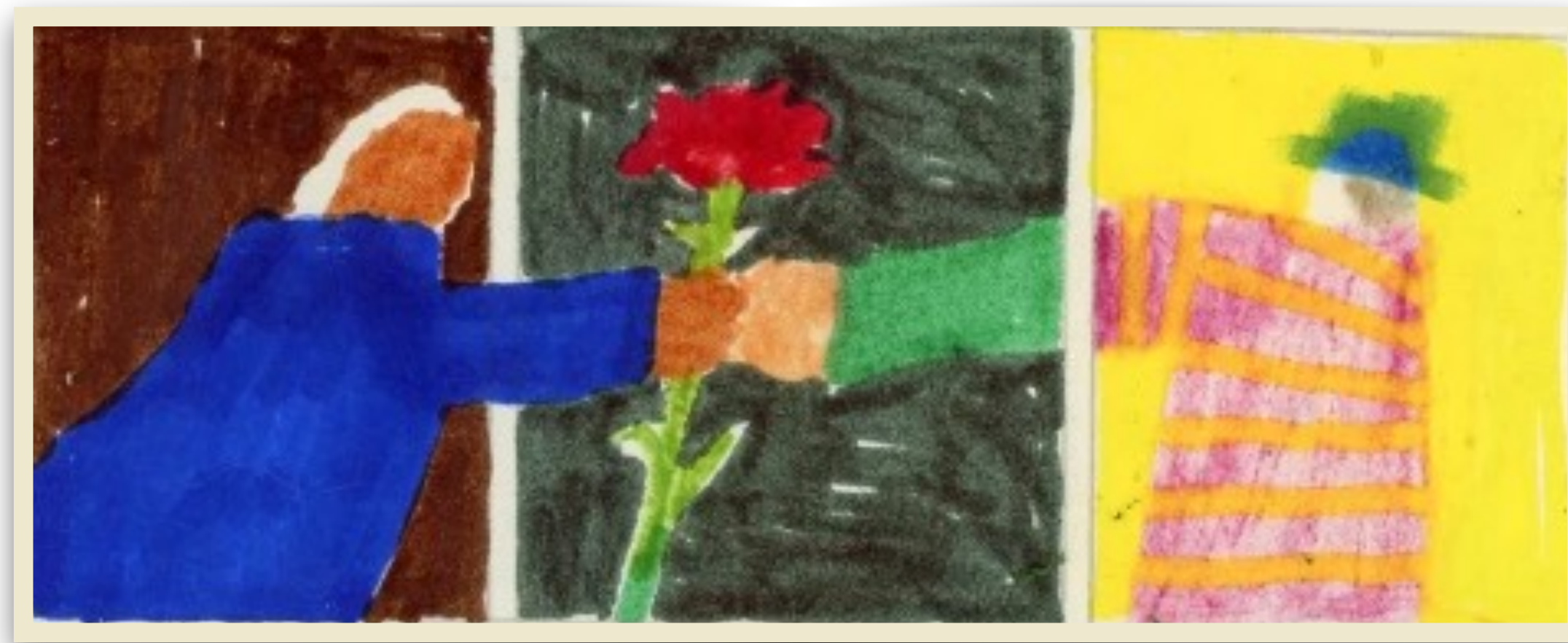


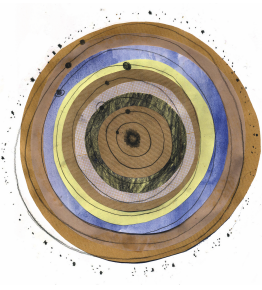
THE HUBBLE TENSION: A HEALTH CHECK OF COSMOLOGICAL MODELS

ELSA M. TEIXEIRA

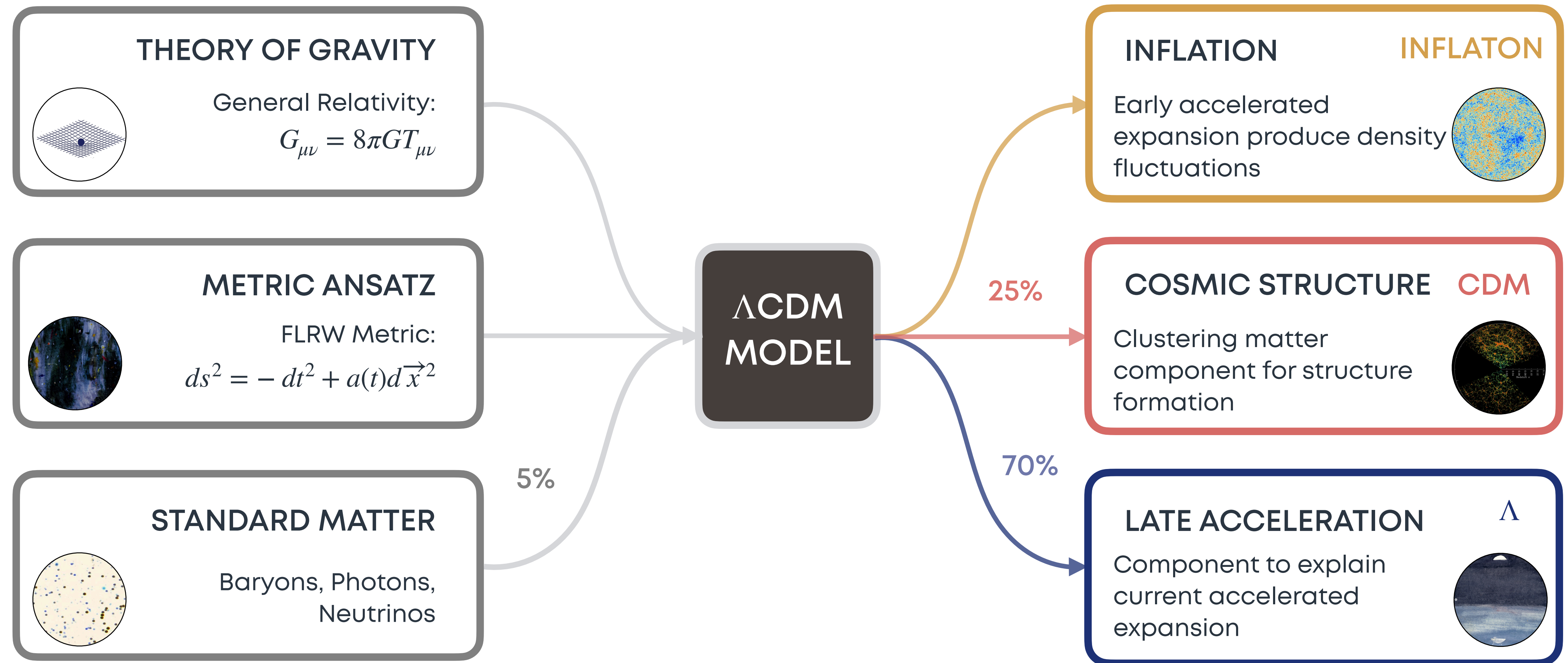
(elsa.teixeira@umontpellier.fr)
Laboratoire Univers et Particules
de Montpellier
CNRS & Université de Montpellier



Illustrations: Inês Viegas Oliveira
(ivoliveira.com)



The Lambda Cold Dark Matter Model





Hubble Constant

Linear relation between the distance to a galaxy and its recession velocity



Cepheids (galactic distance)

$$v = H_0 d$$

- Hubble law estimated by Hubble in 1929 based on previous progress by Slipher and Leavitt: $H_0 \sim 500 \text{ km/s/Mpc}$
- Predictions from expanding cosmologies from Georges Lemaître and others



A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE

BY EDWIN HUBBLE

MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON

Communicated January 17, 1929

Determinations of the motion of the sun with respect to the extra-galactic nebulae have involved a K term of several hundred kilometers which appears to be variable. Explanations of this paradox have been sought in a correlation between apparent radial velocities and distances, but so far the results have not been convincing. The present paper is a re-examination of the question, based on only those nebular distances which are believed to be fairly reliable.

Distances of extra-galactic nebulae depend ultimately upon the application of absolute-luminosity criteria to involved stars whose types can be recognized. These include, among others, Cepheid variables, novae, and blue stars involved in emission nebulae. Numerical values depend upon the zero point of the period-luminosity relation among Cepheids, and other stars whose distances are fairly reliable. This method

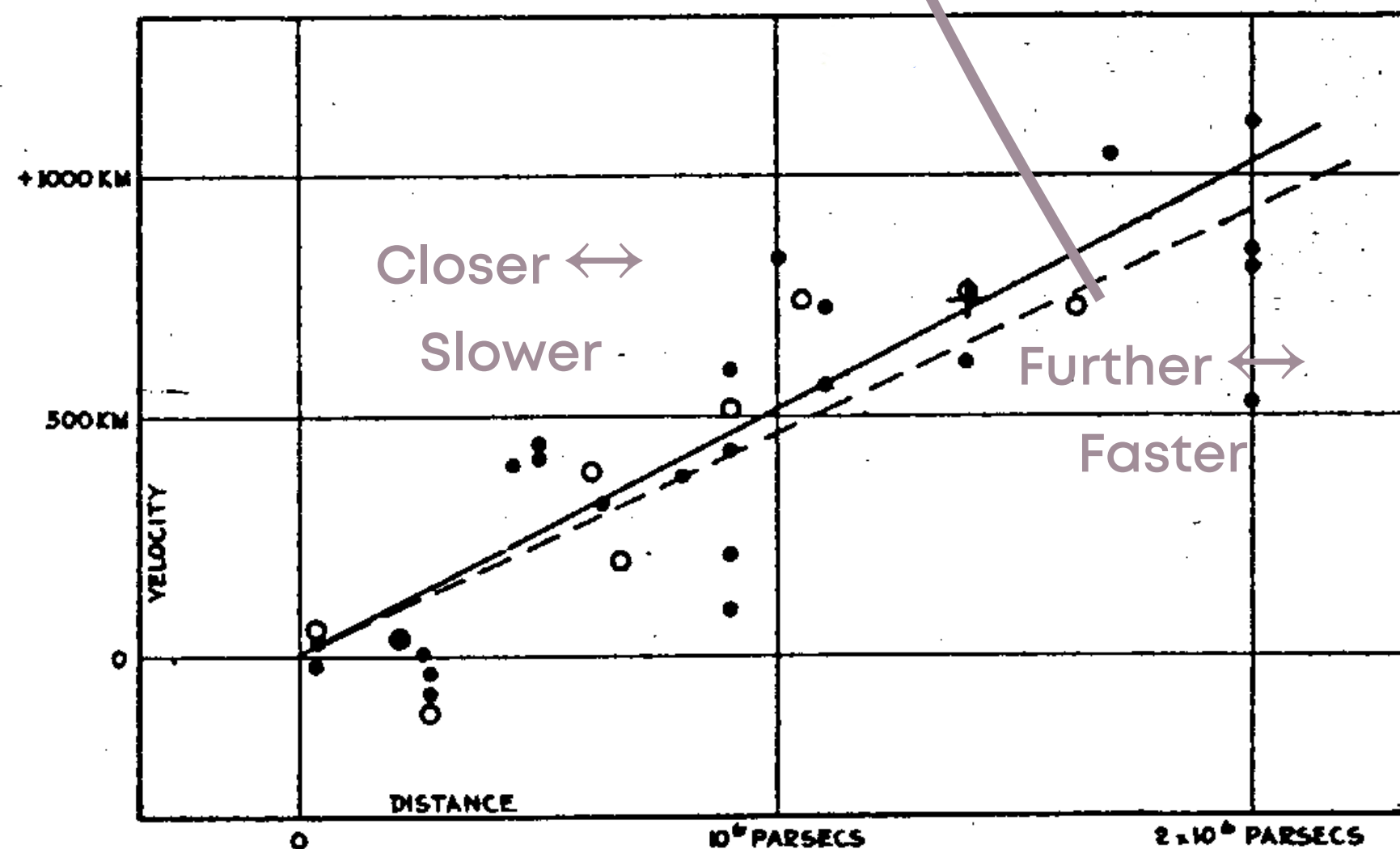


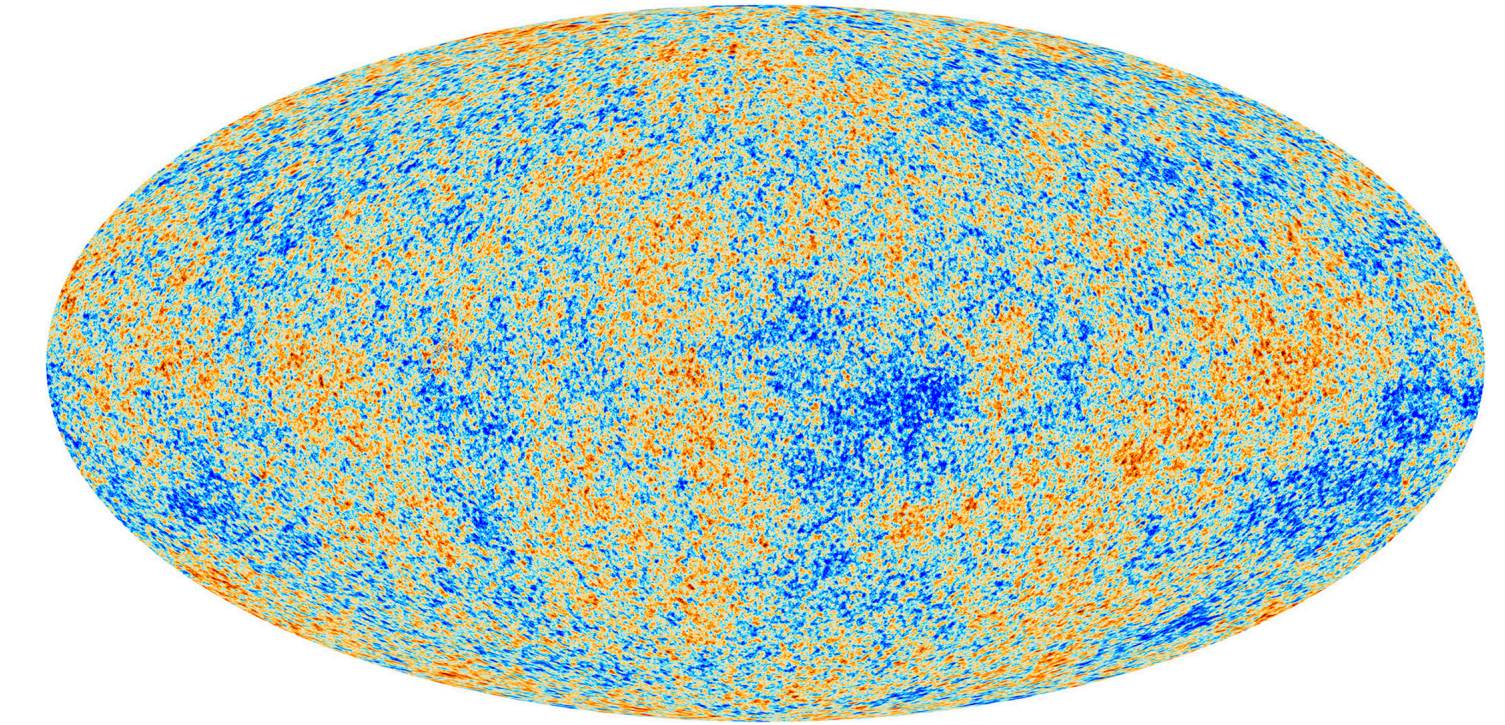
FIGURE 1

Distance to galaxy	Receding velocity
1,000,000	20
2,000,000	40
3,000,000	60
4,000,000	80
5,000,000	100



The Cosmic Microwave Background

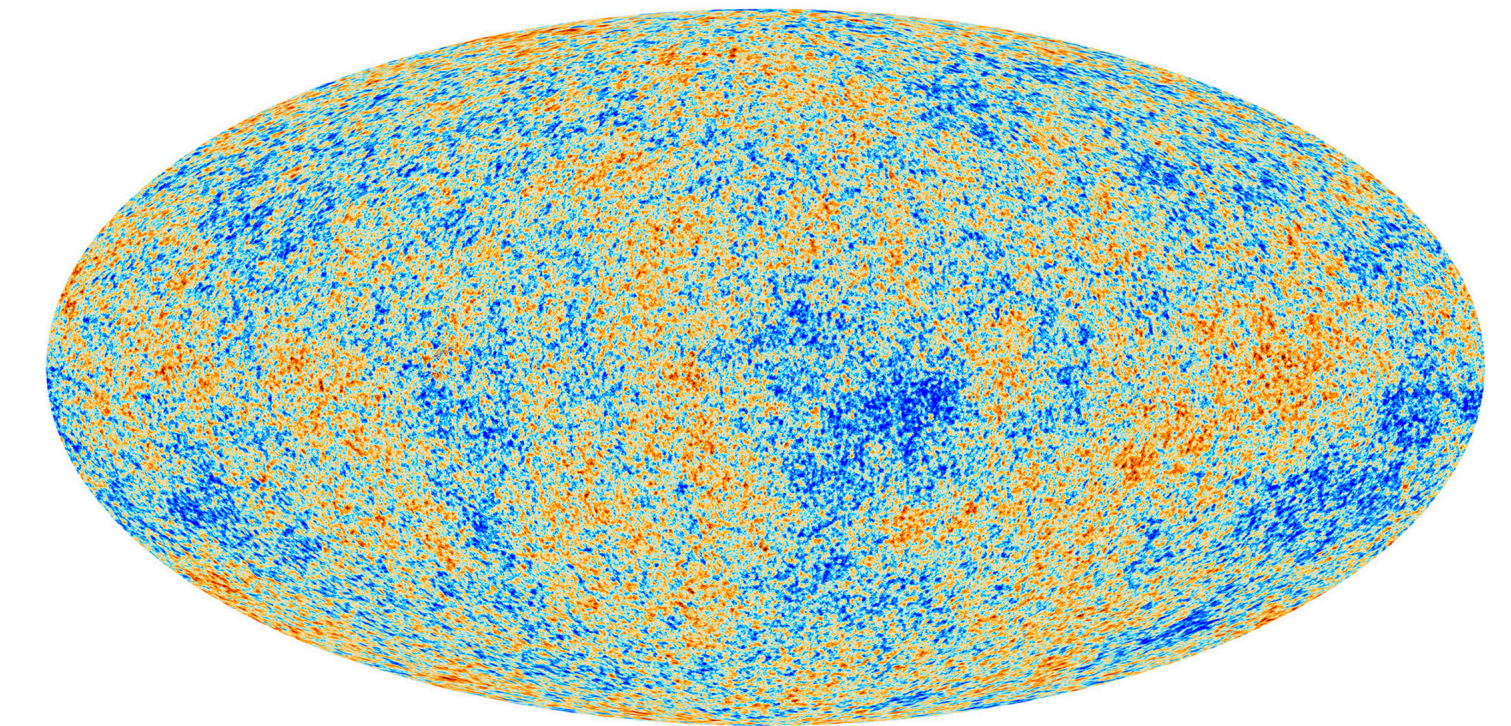
- Relic light from the Big Bang released when the Universe was 380,000 years old
- Shows small temperature anisotropies which mirror the acoustic waves in the primordial plasma





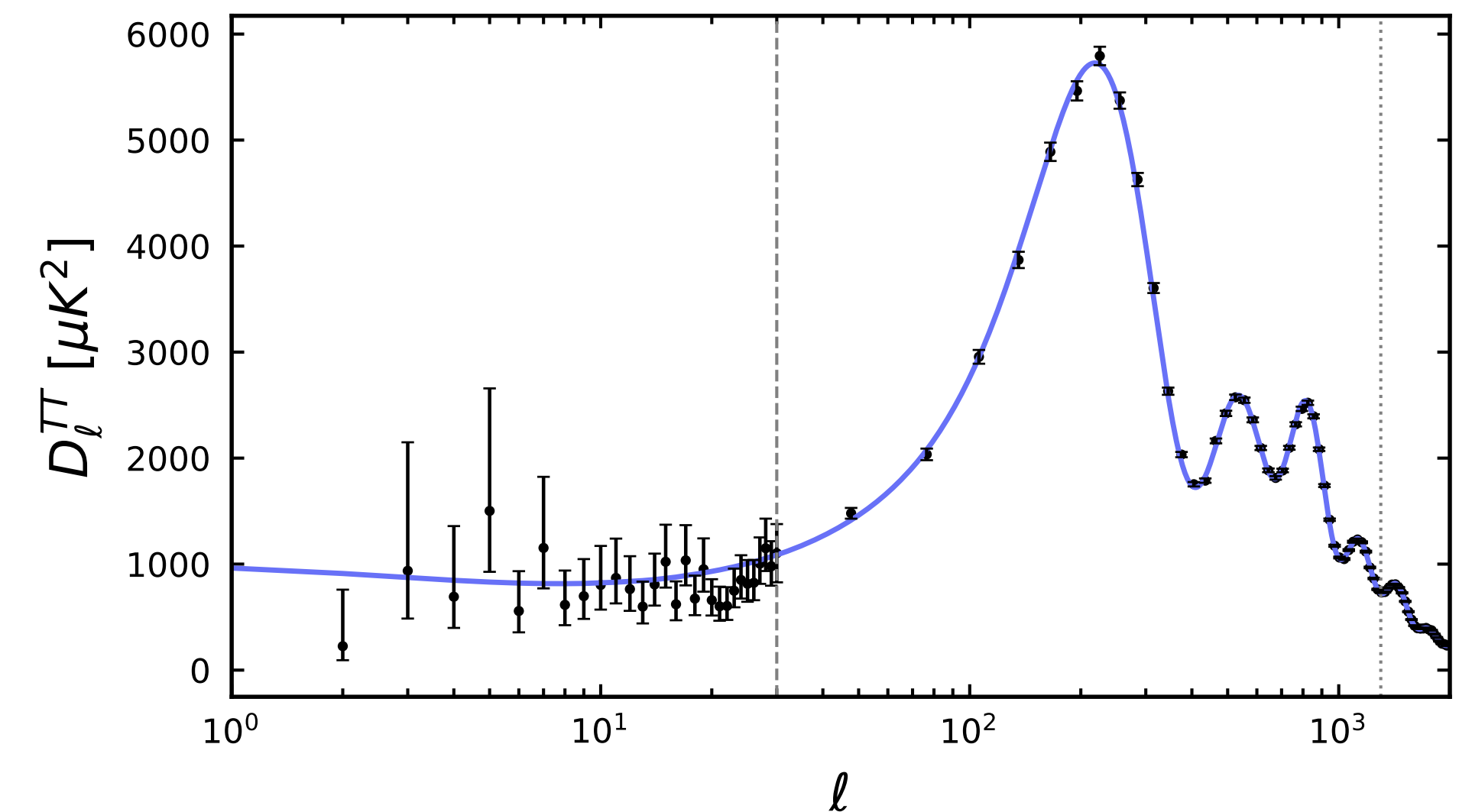
The Cosmic Microwave Background

- Relic light from the Big Bang released when the Universe was 380,000 years old
- Shows small temperature anisotropies which mirror the acoustic waves in the primordial plasma
- Physics of the plasma fixes the angular size of the sound horizon r_s (distance travelled by sound-waves before recombination)
- CMB measures this scale very precisely → “standard ruler” at $z \sim 1100$
- Inferring H_0 requires assuming Λ CDM and propagating the ruler forward



$$D_A \propto 1/H_0$$

$$\theta_s(z) = \frac{r_s(z_*)}{D_A(z)}$$

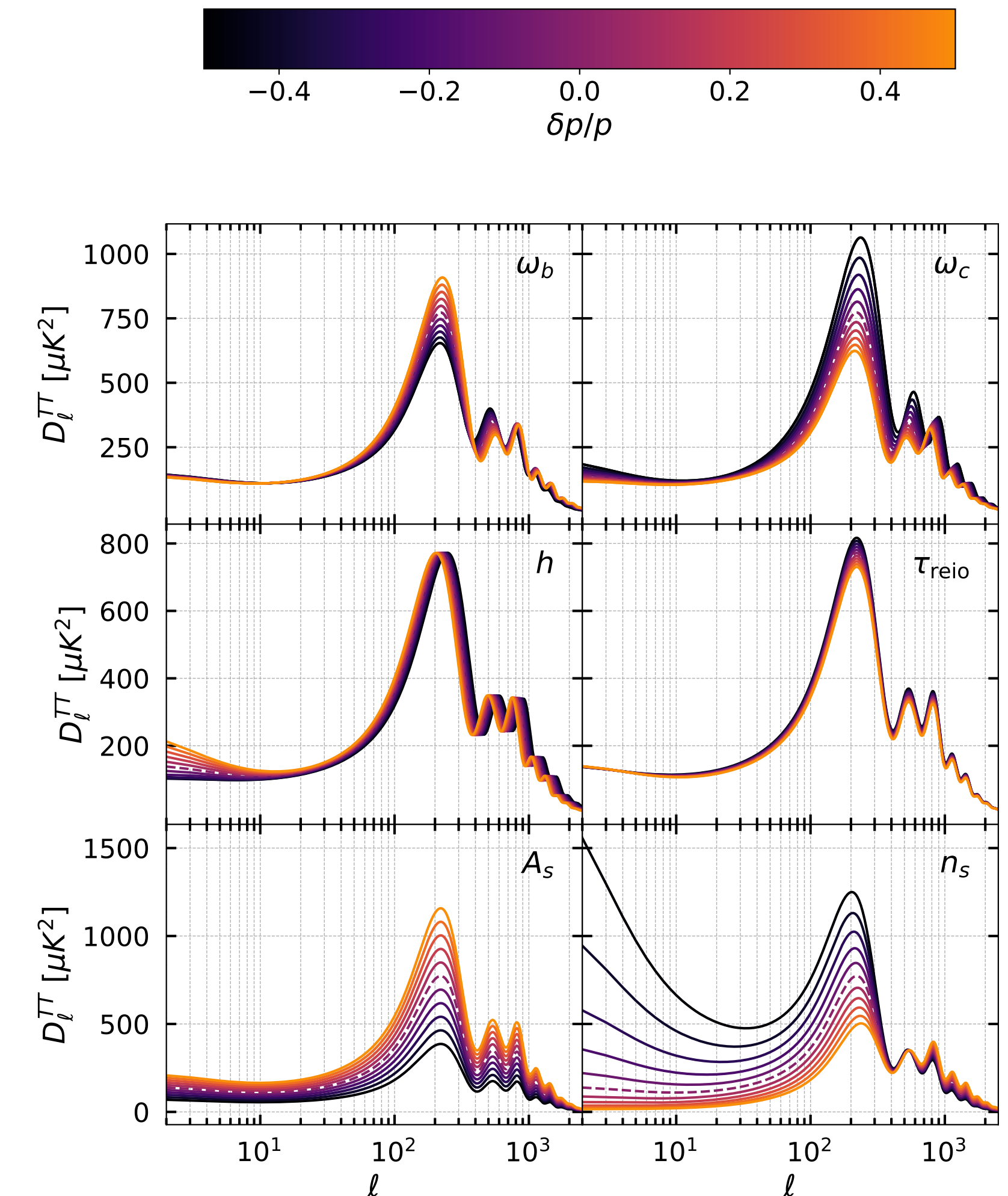


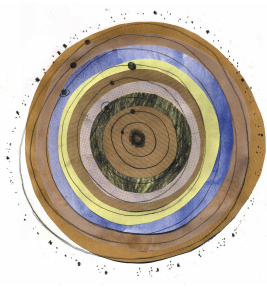
[Planck Collaboration 2018, arxiv:1807.06209]



The Cosmic Microwave Background

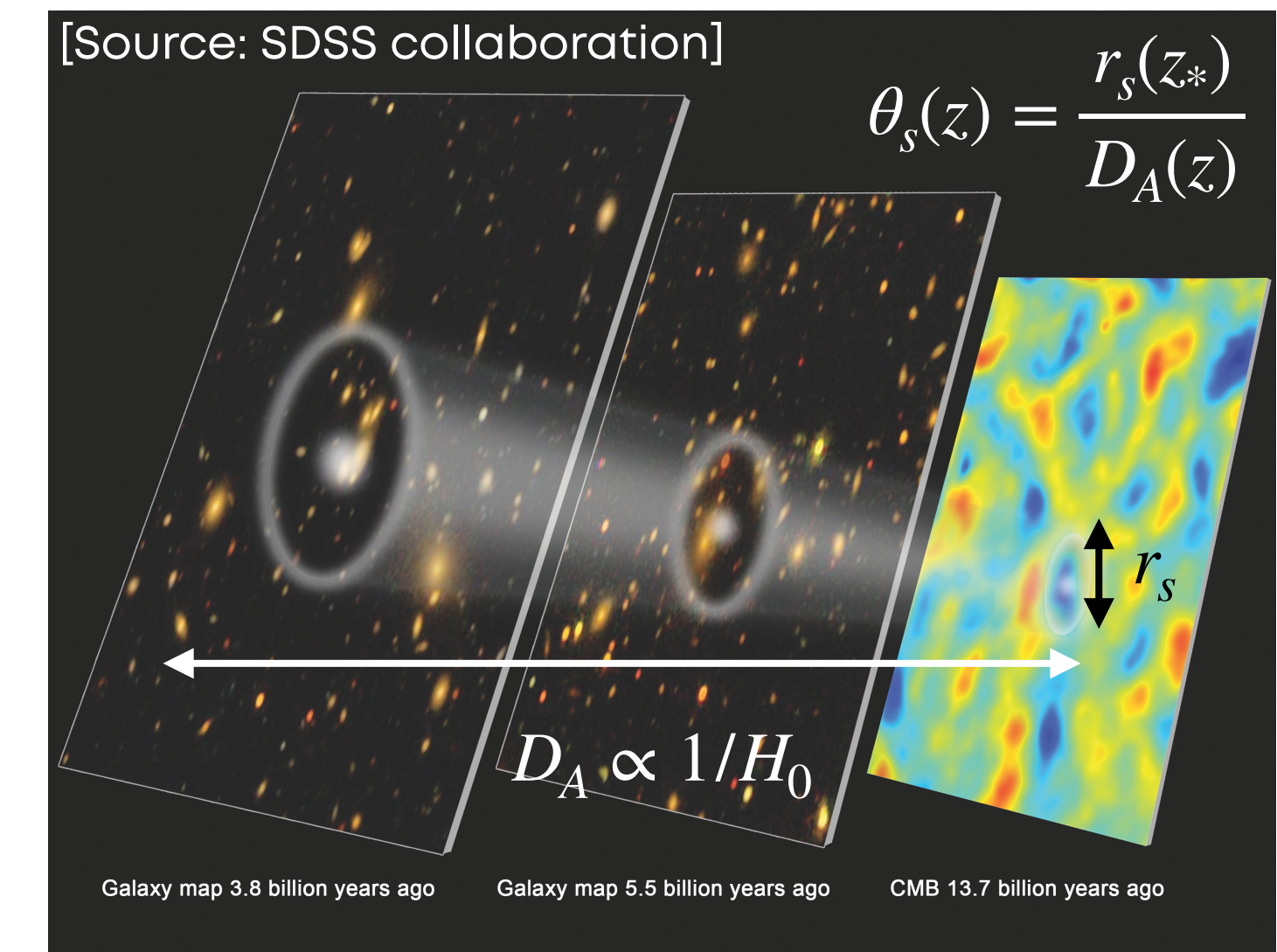
- Relic light from the Big Bang released when the Universe was 380,000 years old
- Shows small temperature anisotropies which mirror the acoustic waves in the primordial plasma
- Physics of the plasma fixes the angular size of the sound horizon r_s (distance travelled by sound-waves before recombination)
- CMB measures this scale very precisely → “standard ruler” at $z \sim 1100$
- Inferring H_0 requires assuming Λ CDM and propagating the ruler forward
- Predictions change under different model assumptions





What BAO measures

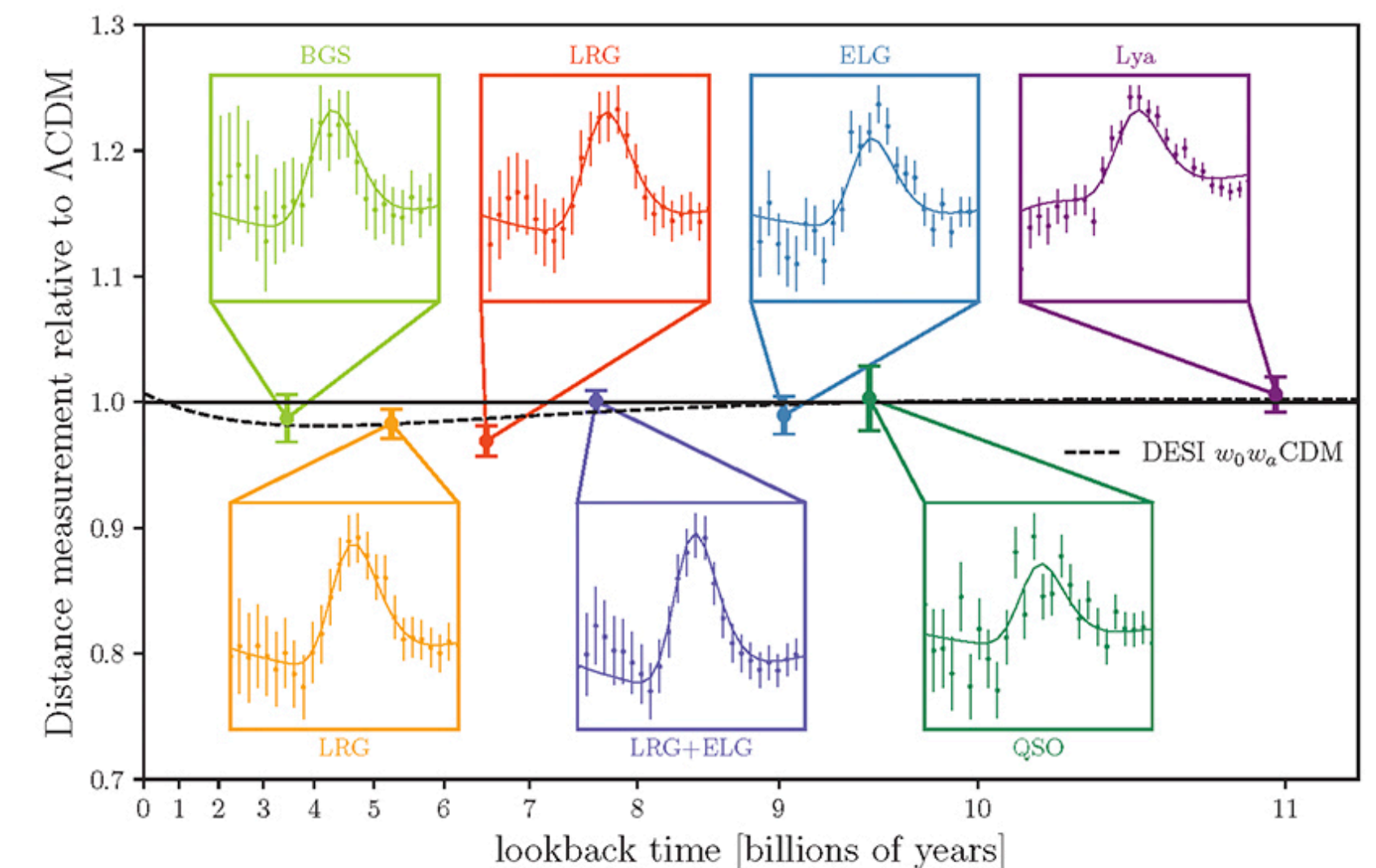
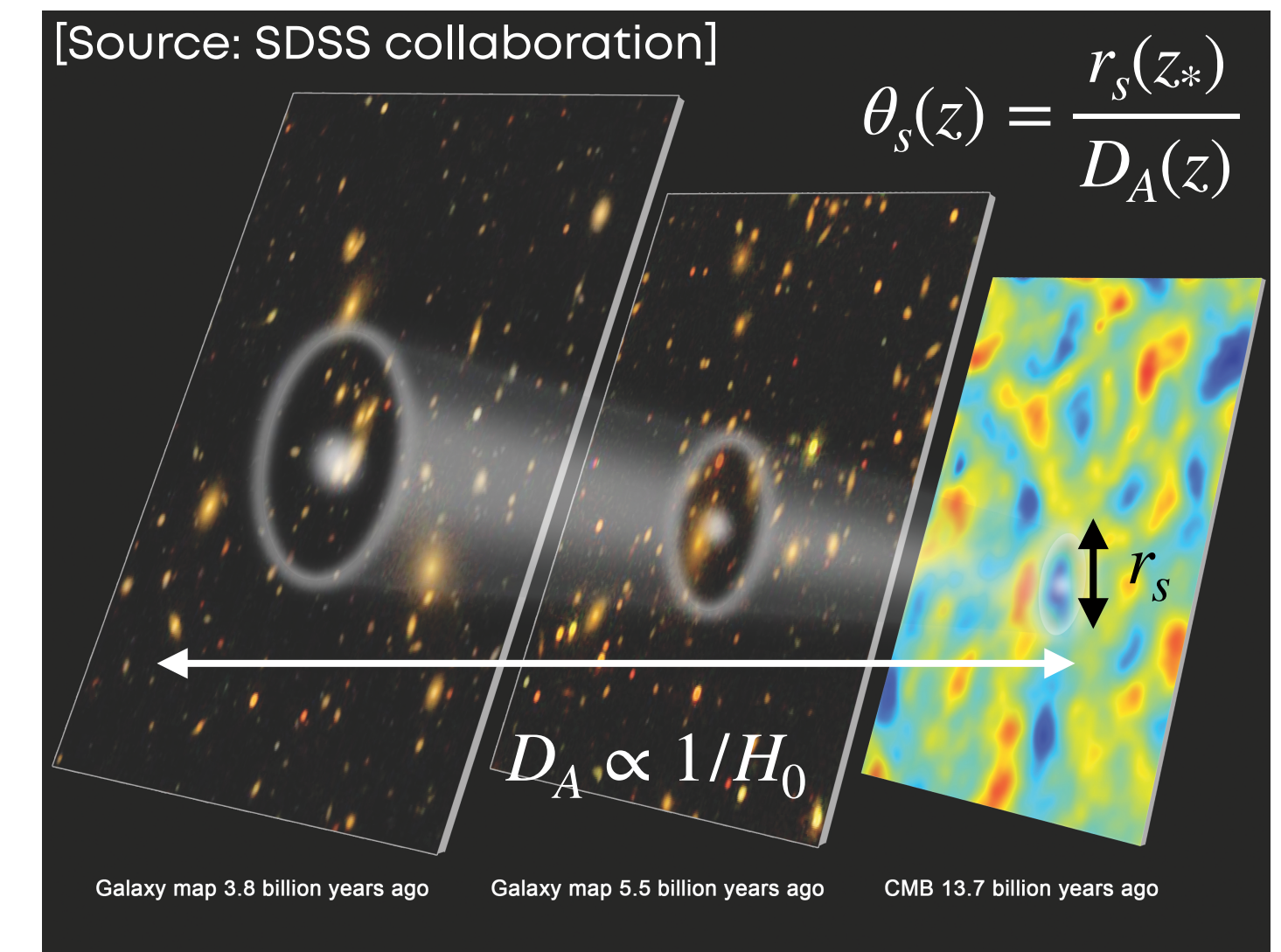
- Barionic acoustic oscillations are the imprint of the same sound waves of the CMB in the distribution of galaxies
- Before recombination the baryons + photons oscillated
- After cooling those waves “froze in”, leaving a preferred separation scale between galaxies (~150 Mpc at present)
- This physical scale is the same sound horizon as in the CMB

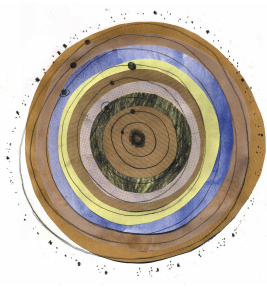




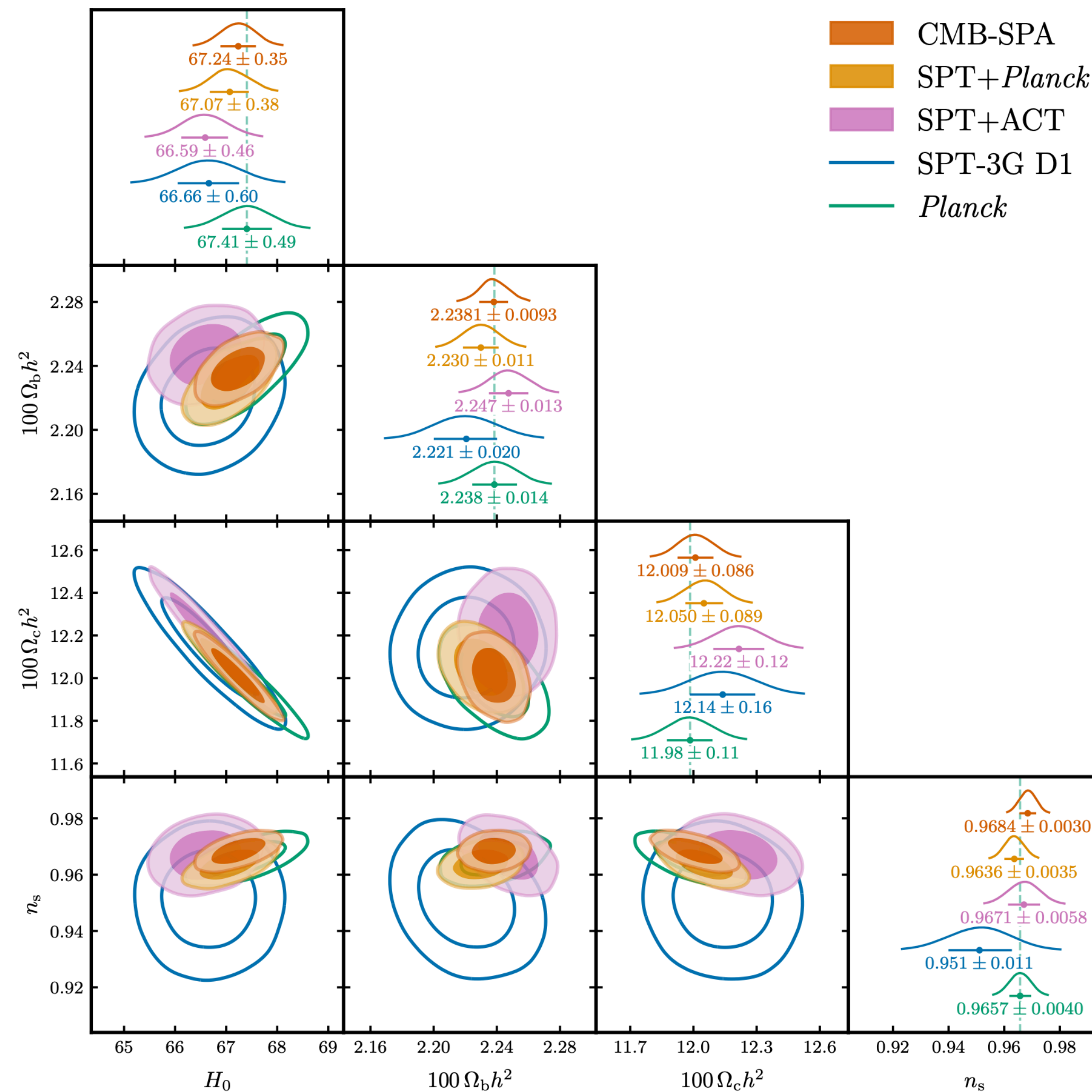
What BAO measures

- Barionic acoustic oscillations are the imprint of the same sound waves of the CMB in the distribution of galaxies
- Before recombination the baryons + photons oscillated
- After cooling those waves “froze in”, leaving a preferred separation scale between galaxies (~150 Mpc at present)
- This physical scale is the same sound horizon as in the CMB
- Measured through galaxy surveys (correlation function/ power spectrum)
- Apparent size at different redshifts → geometric distances
- Requires CMB (or equivalent) calibration of the ruler for cosmological constraints





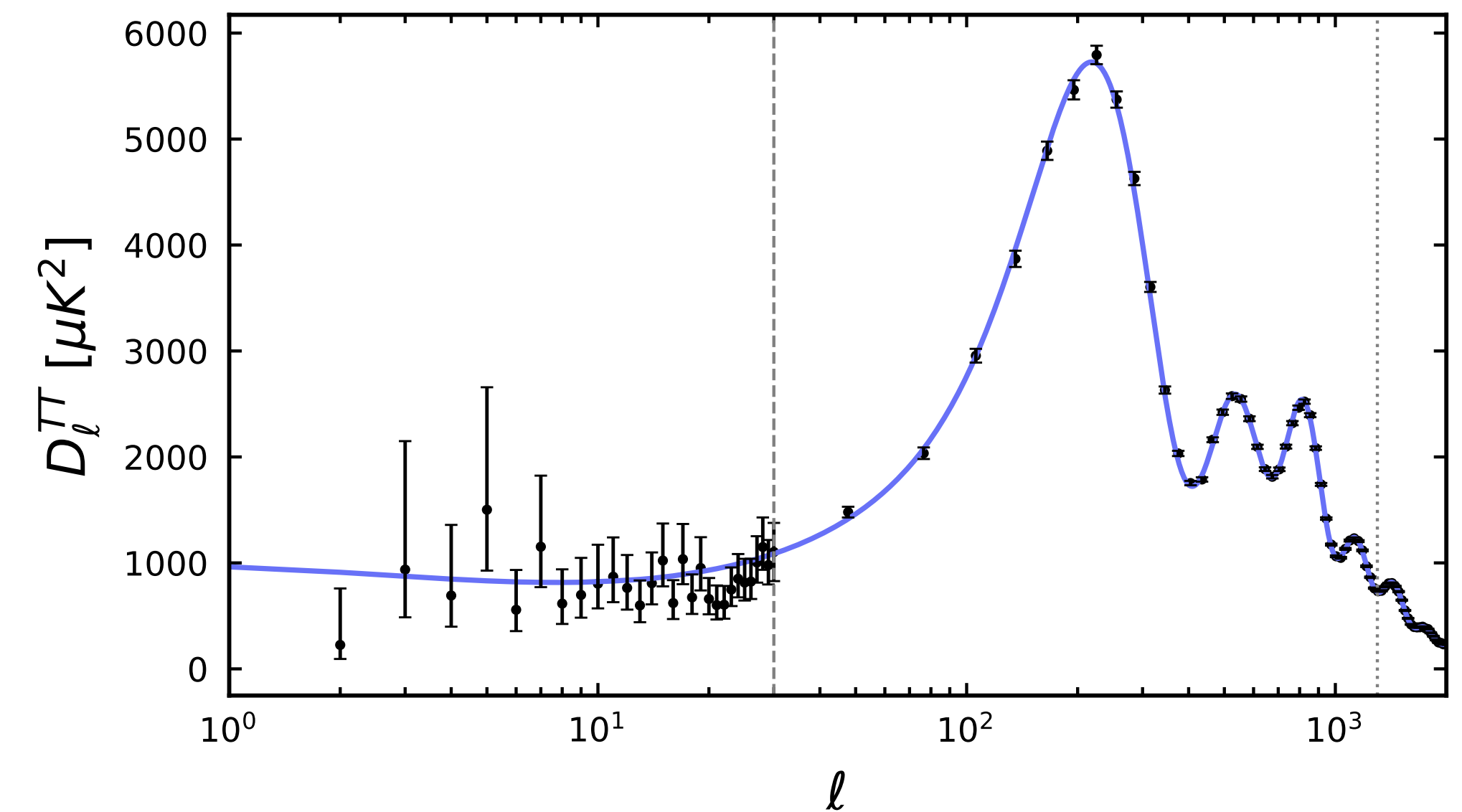
CMB and the Λ CDM Model



[SPT-3G D1 2025, arxiv:2506.20707]

$$\{H_0, \omega_b, \omega_{\text{cdm}}, A_s, n_s, \tau_{\text{reio}}\}$$

With just 6 parameters Λ CDM can fit
a wide variety of different CMB data
within 2σ - Planck, ACT, SPT-3G



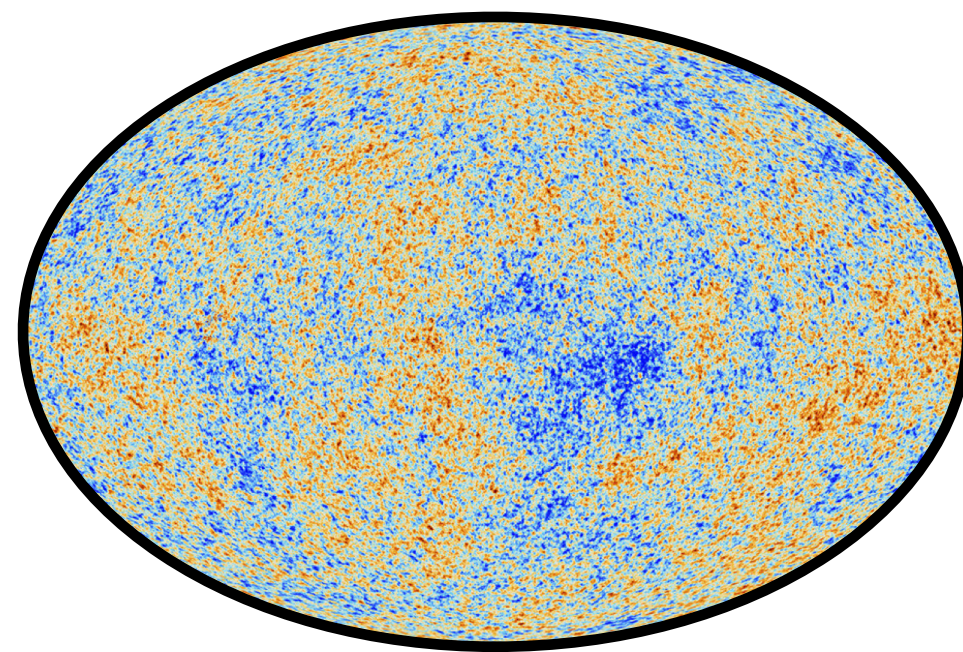
[Planck Collaboration 2018, arxiv:1807.06209]



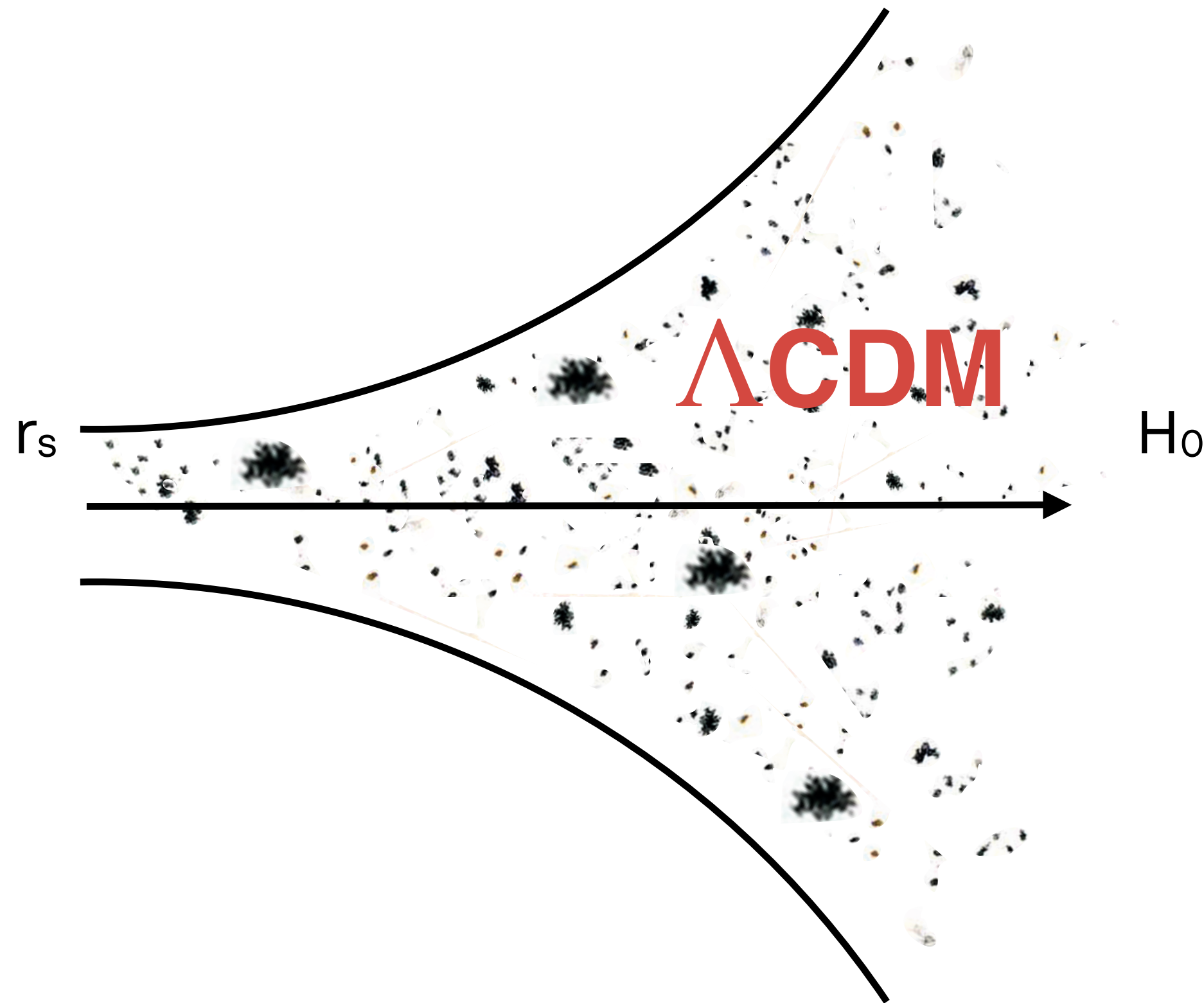
The Hubble Constant

CMB
Calibration

$z \sim 1100$



$67.27 \pm 0.60 \text{ km/s/Mpc}$
from Planck





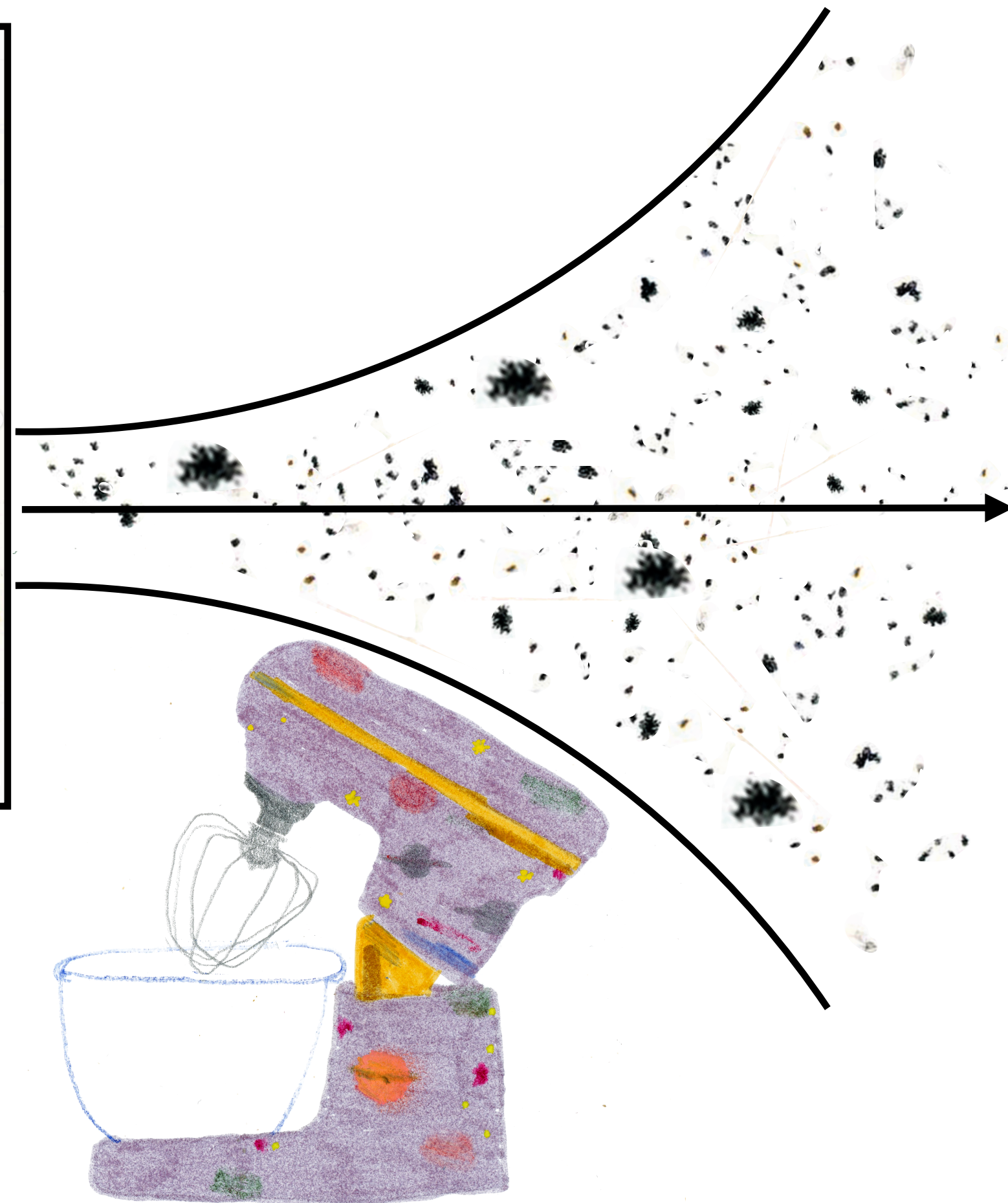
The Hubble Constant

CMB
Calibration

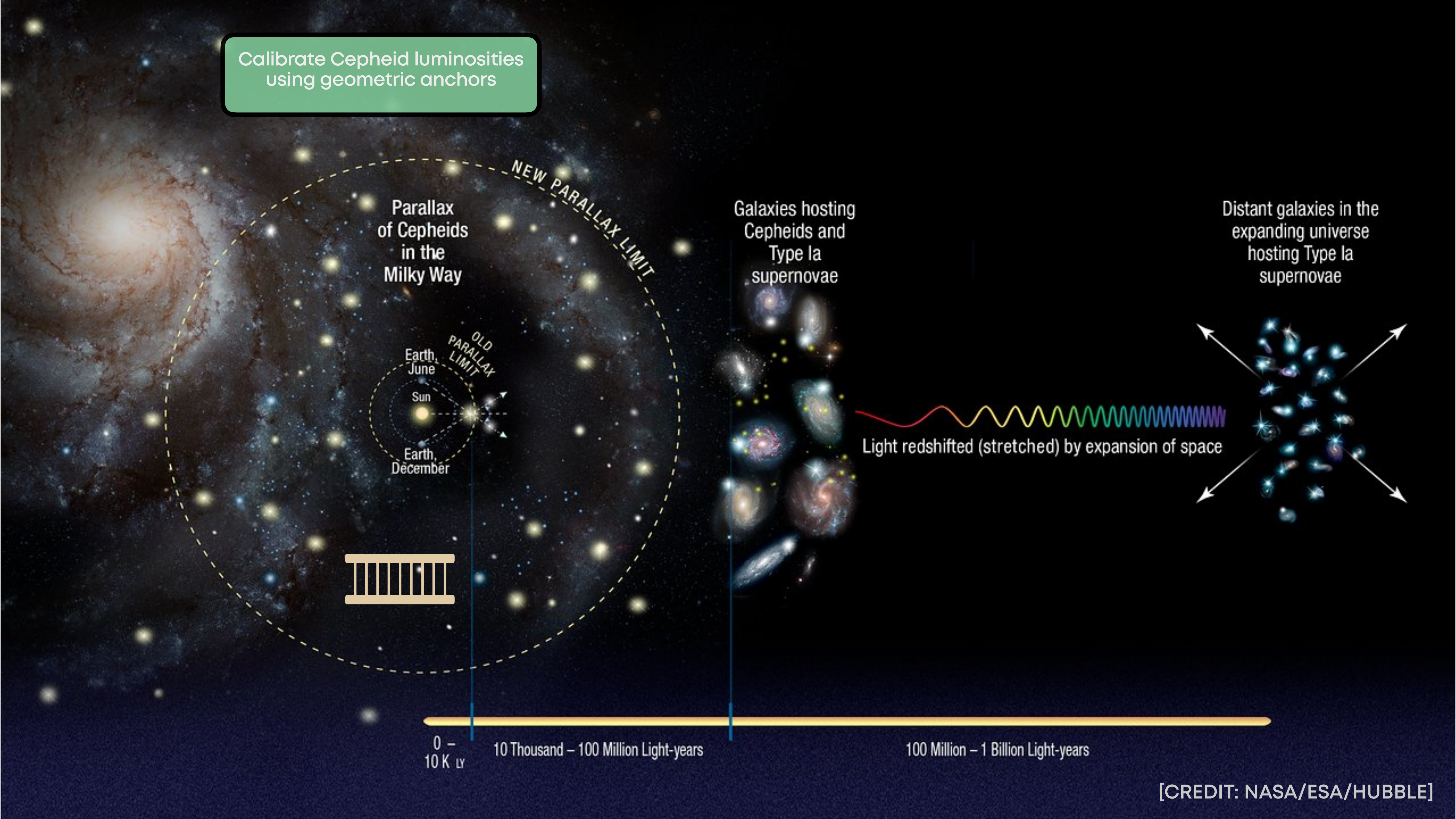


$67.27 \pm 0.60 \text{ km/s/Mpc}$
from Planck

Local
Prediction

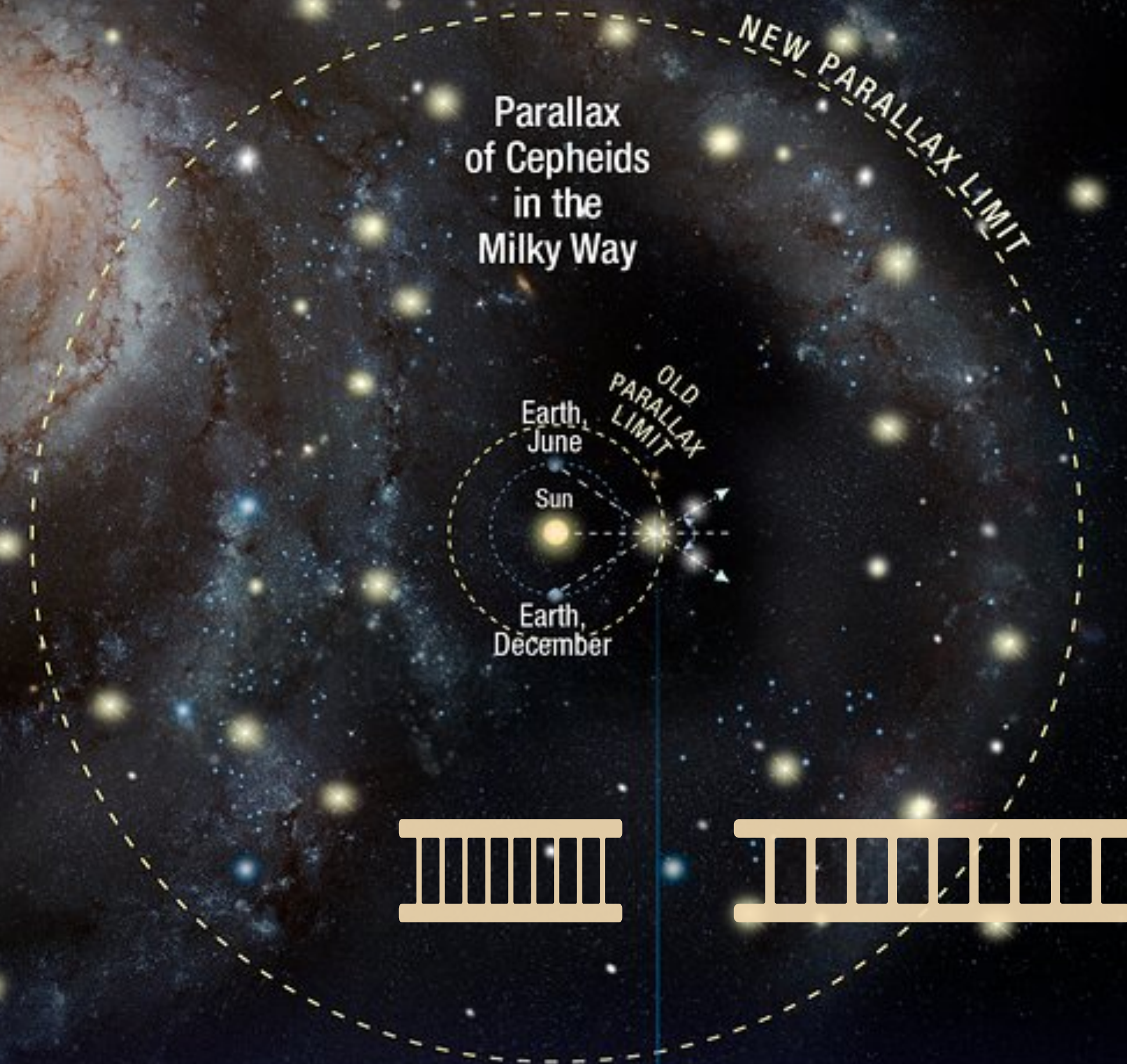


Calibrate Cepheid luminosities
using geometric anchors



Calibrate Cepheid luminosities
using geometric anchors

Calibrate Type Ia supernovae in host
galaxies with Cepheid distances



Galaxies hosting
Cepheids and
Type Ia
supernovae

Distant galaxies in the
expanding universe
hosting Type Ia
supernovae

Light redshifted (stretched) by expansion of space

0 -
10 K LY

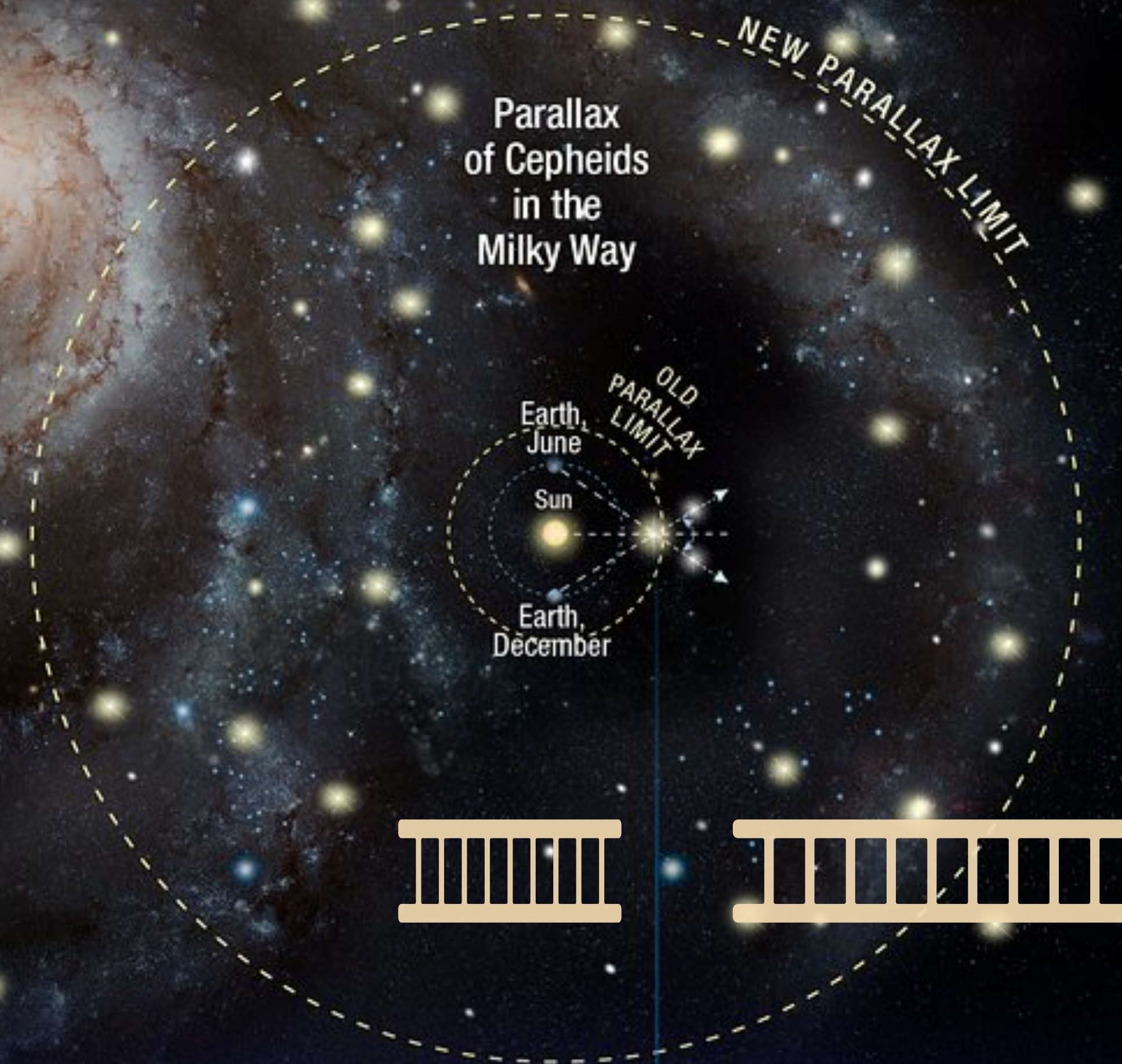
10 Thousand - 100 Million Light-years

100 Million - 1 Billion Light-years

Calibrate Cepheid luminosities
using geometric anchors

Calibrate Type Ia supernovae in host
galaxies with Cepheid distances

Use calibrated supernovae Ia in
the Hubble flow to measure H_0



Galaxies hosting
Cepheids and
Type Ia
supernovae

Distant galaxies in the
expanding universe
hosting Type Ia
supernovae

Light redshifted (stretched) by expansion of space

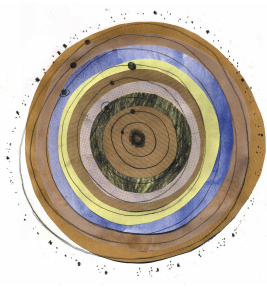
The diagram shows a series of galaxies, some of which are hosting Cepheids and Type Ia supernovae. A wavy line represents light traveling from these galaxies towards the observer. The light is shown as being 'redshifted (stretched) by expansion of space'. To the right, a cluster of distant galaxies is shown with arrows pointing away from each other, illustrating the expansion of the universe.

0 -
10 K LY

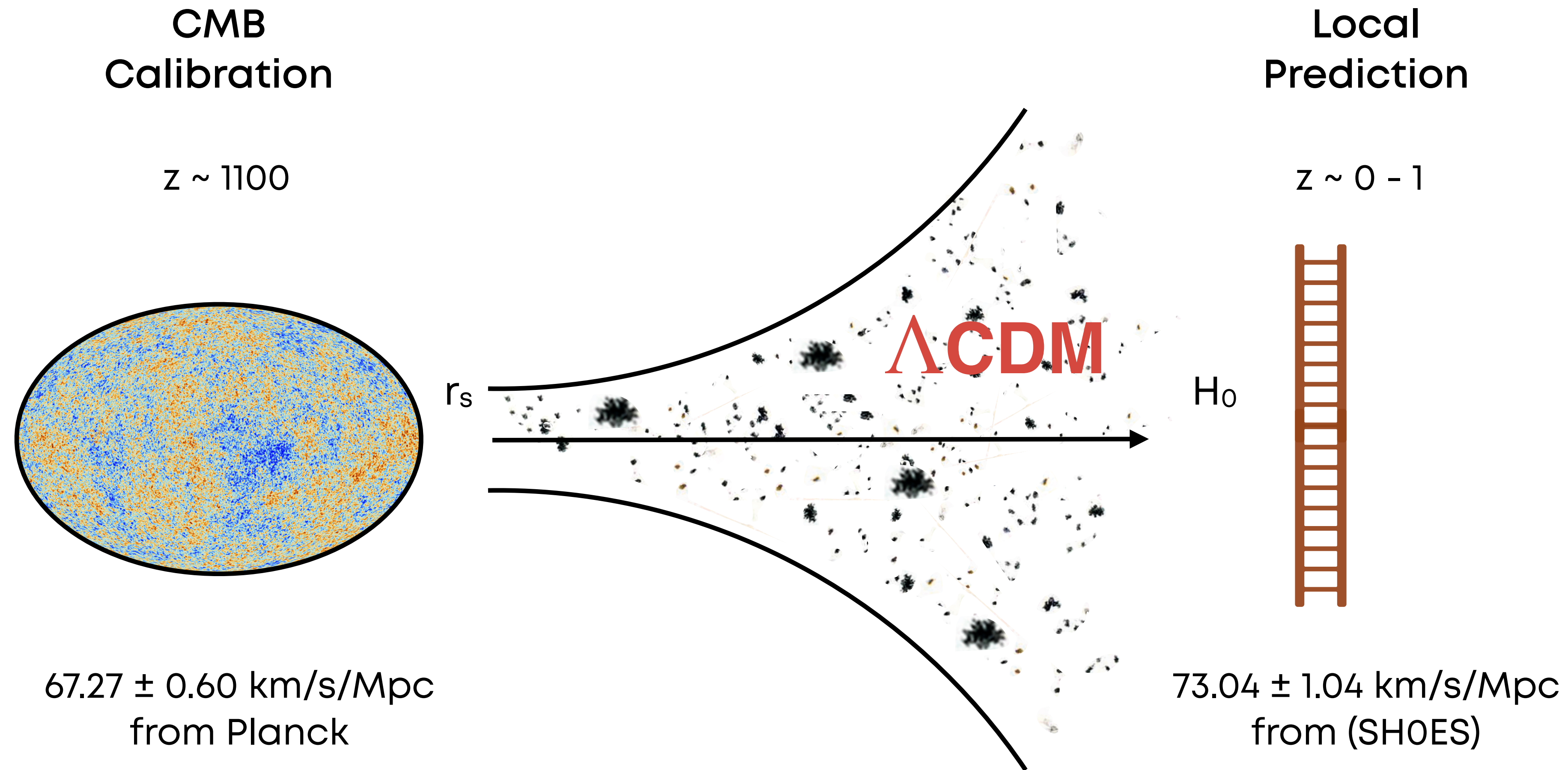
10 Thousand - 100 Million Light-years

100 Million - 1 Billion Light-years

[CREDIT: NASA/ESA/HUBBLE]



The Hubble Tension

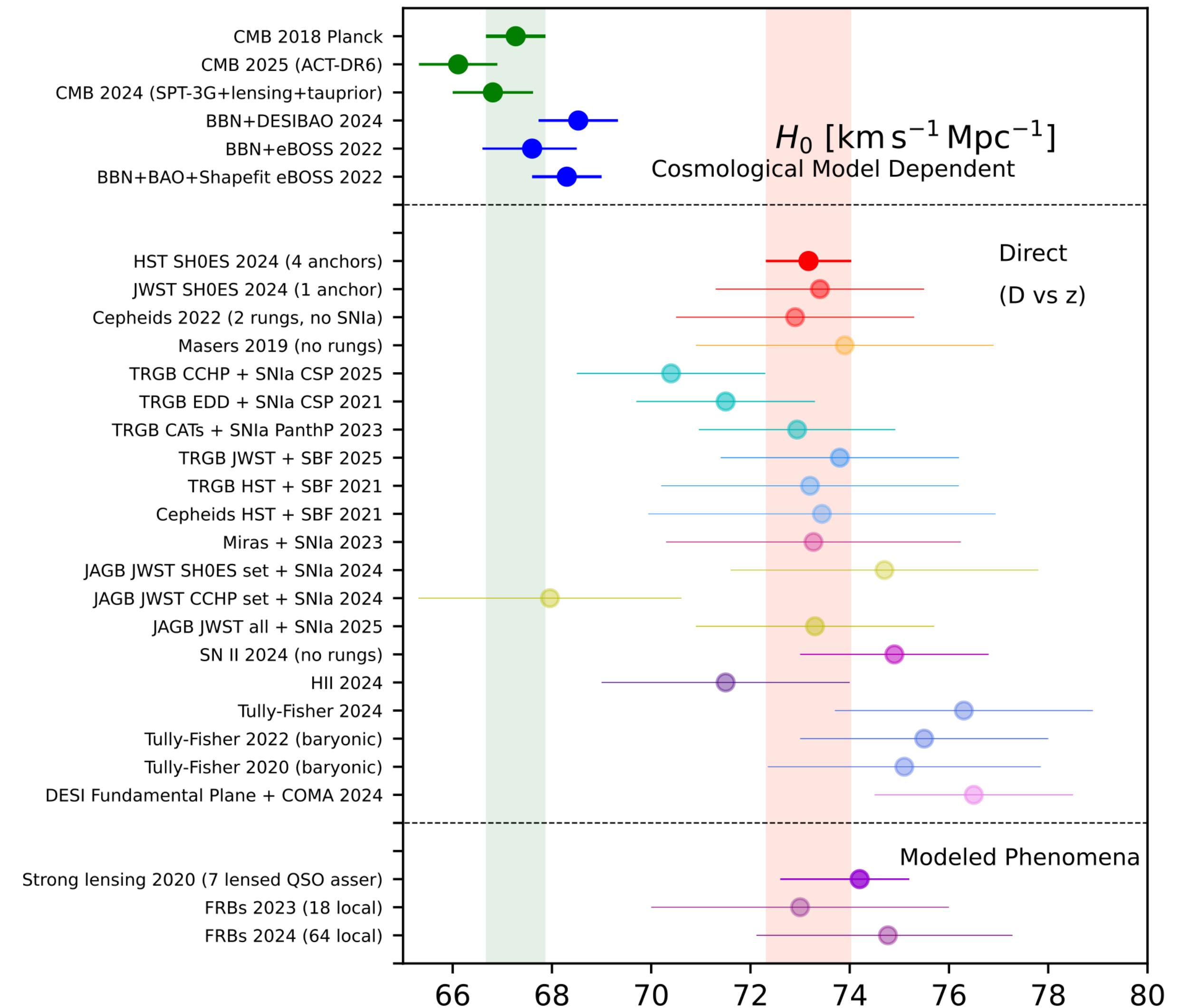




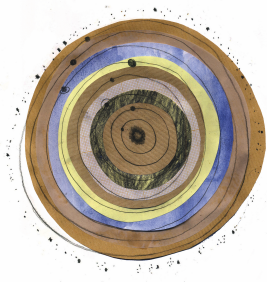
The Hubble Tension

Unreconcilable values for H_0 from the CMB and from direct local distance ladder measurements

- ~5 σ tension between Planck 2018 and SH₀ES:
 - CMB (Planck): $H_0 = 67.27 \pm 0.60$ km/s/Mpc
 - SNe (R22): $H_0 = 73.04 \pm 1.04$ km/s/Mpc
- The CMB data assumes the Λ CDM model
- DESI BAO (+BBN+CMB): $H_0 = 68.45 \pm 0.47$ km/s/Mpc [DESI Collaboration DR2 2025: arXiv:2503.14738]
- Compilation of model-dependent data vs direct measurements that disagree
- Could signal new physics, wrong assumptions in Λ CDM or calibration issues



[Cosmoverse white paper: arxiv:2504.01669]

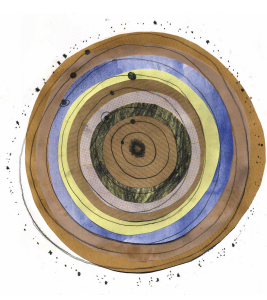


Angular Diameter Distance D_A (BAO)

Luminosity Distance D_L (SN1a)

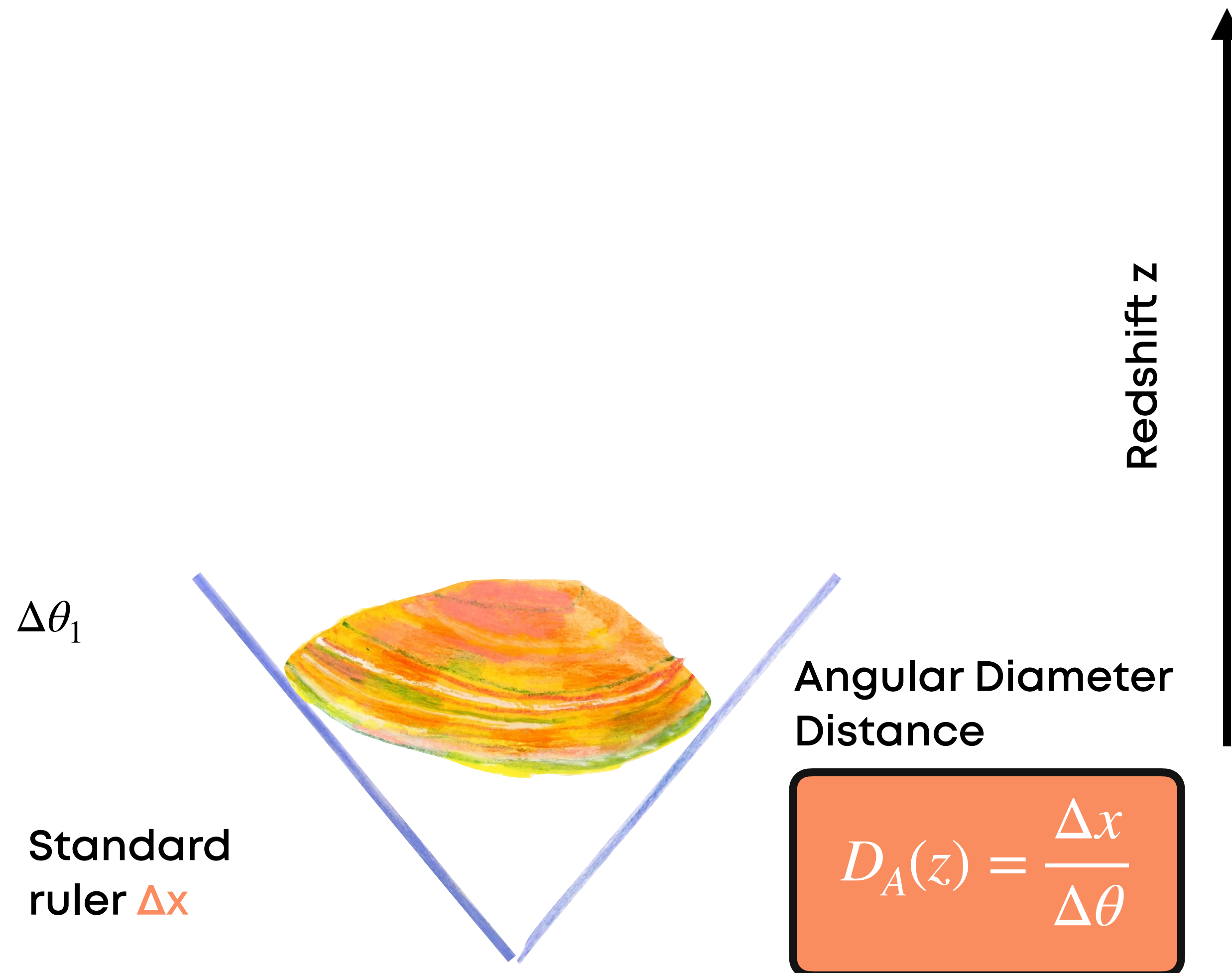
Redshift z





Angular Diameter Distance D_A (BAO)

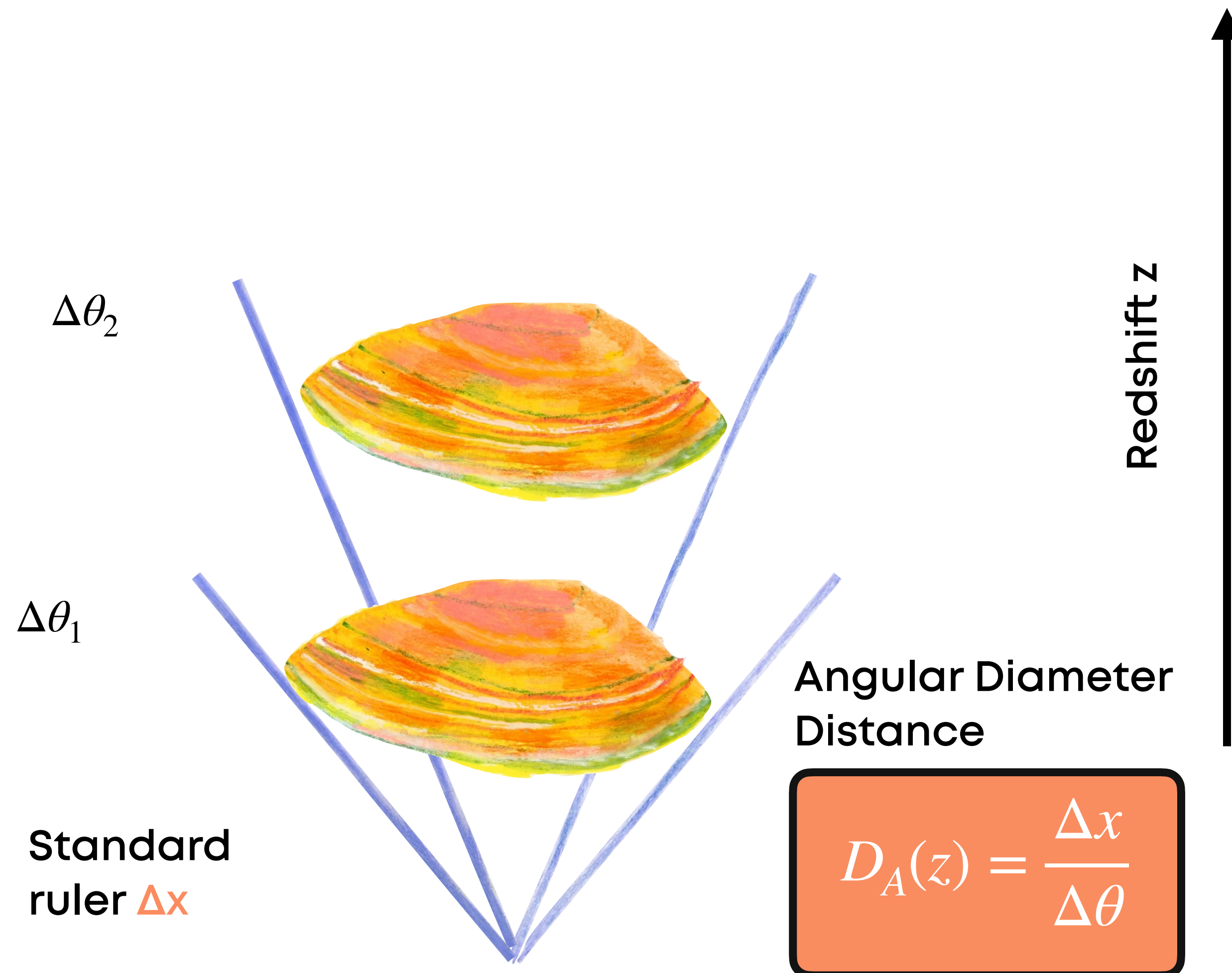
Luminosity Distance D_L (SN1a)





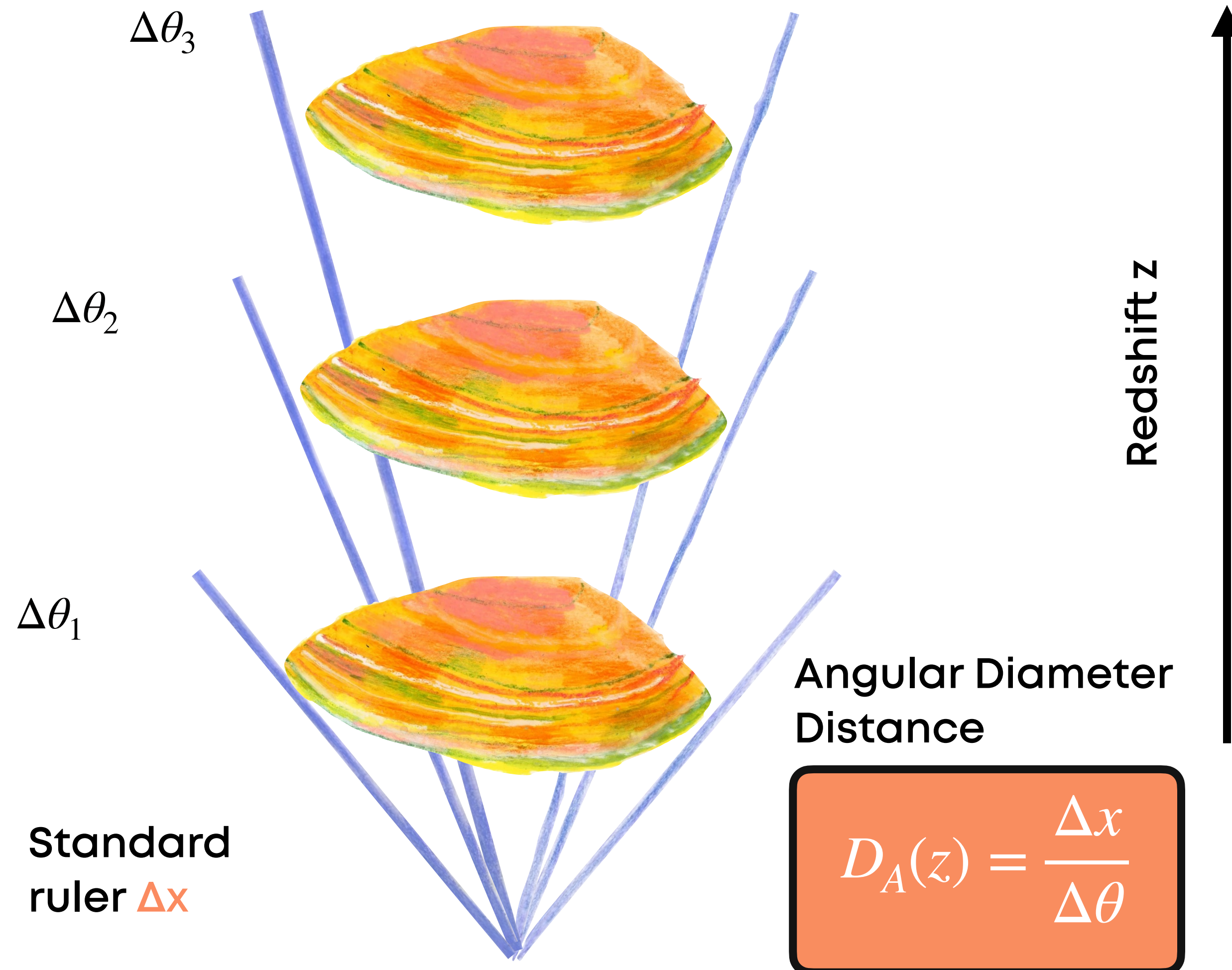
Angular Diameter Distance D_A (BAO)

Luminosity Distance D_L (SN1a)





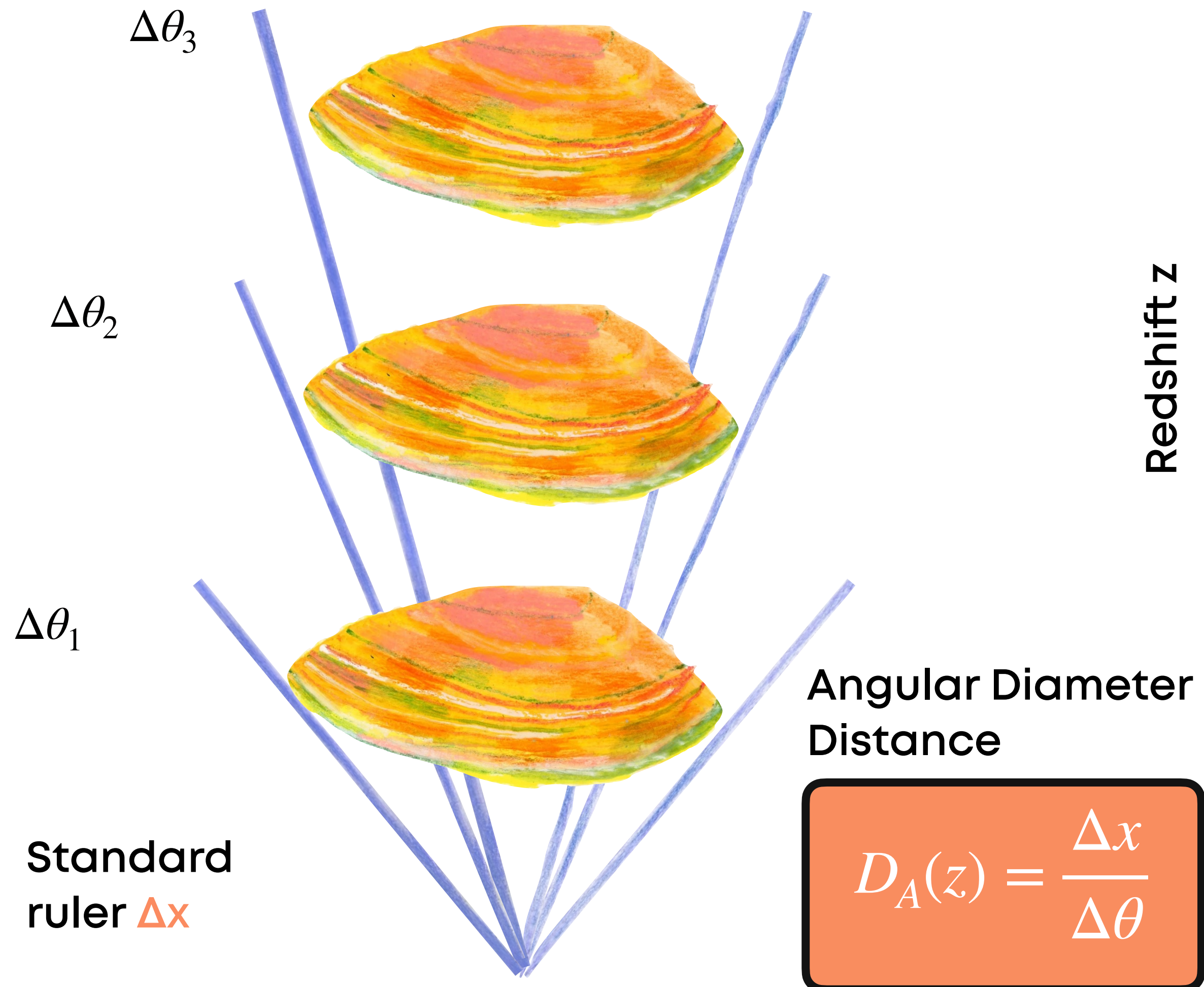
Angular Diameter Distance D_A (BAO)



Luminosity Distance D_L (SN1a)



Angular Diameter Distance D_A (BAO)



Luminosity Distance D_L (SN1a)

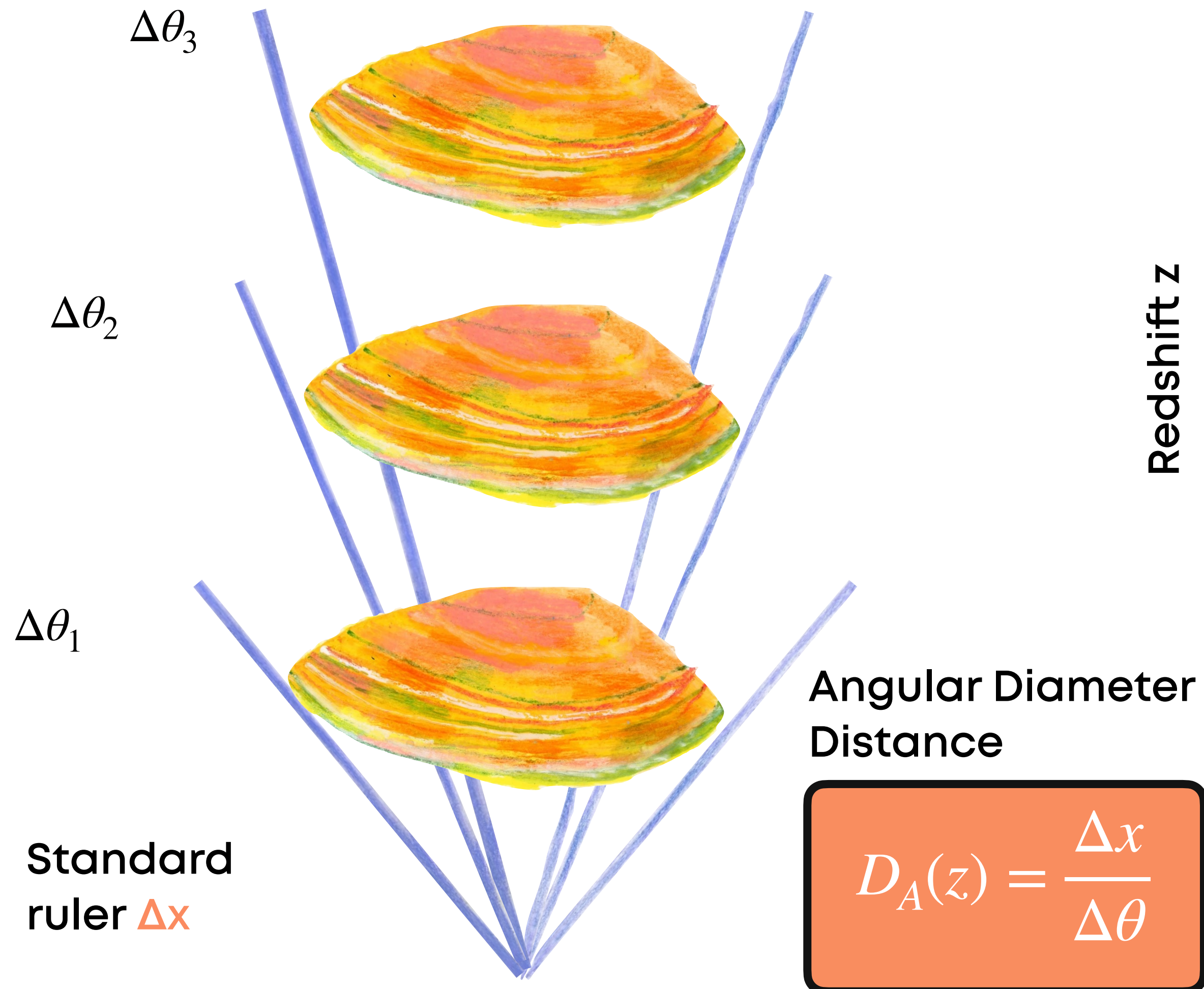
Luminosity Distance

$$D_L^2(z) \equiv \frac{L}{4\pi F}$$

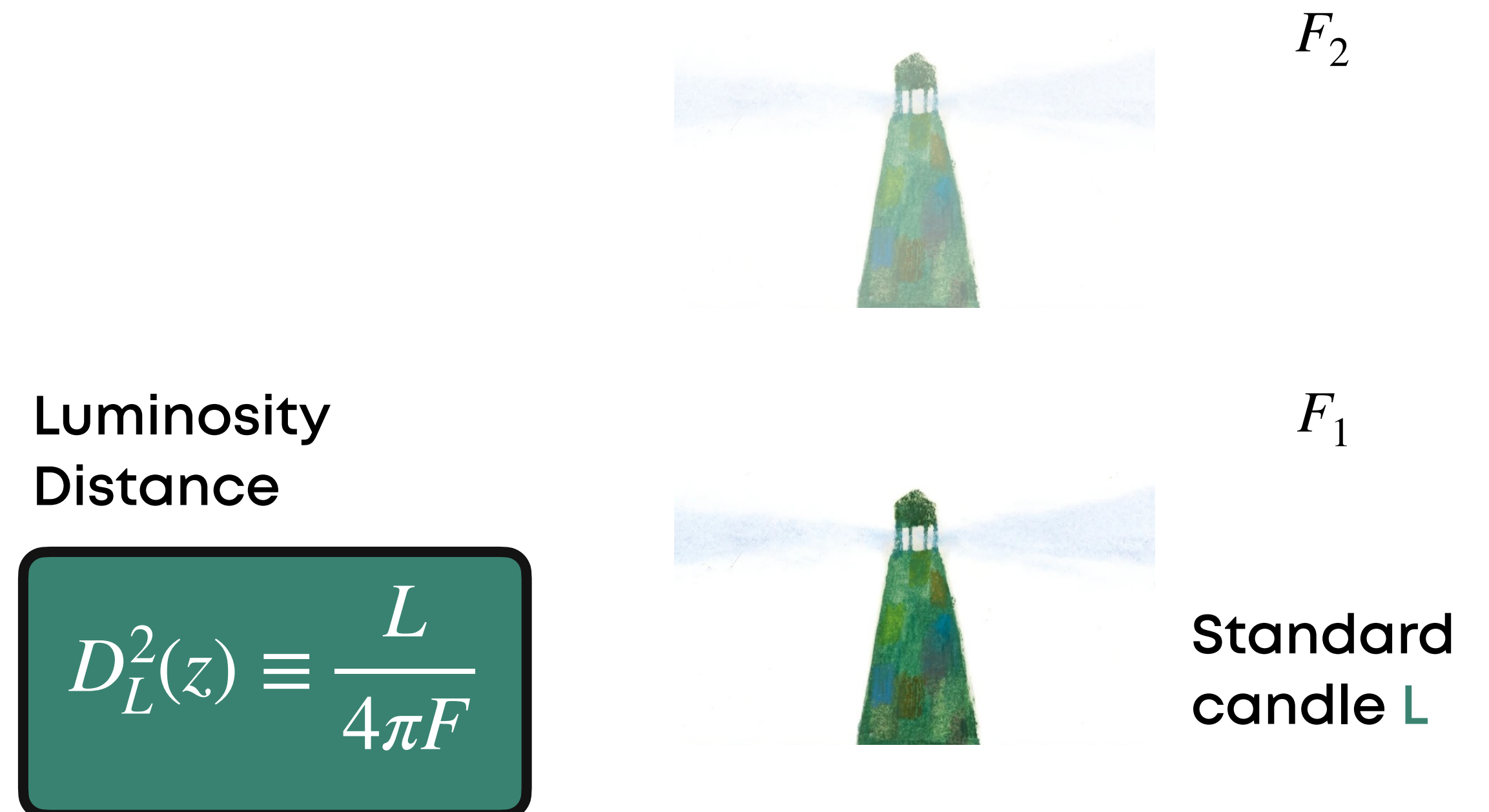




Angular Diameter Distance D_A (BAO)

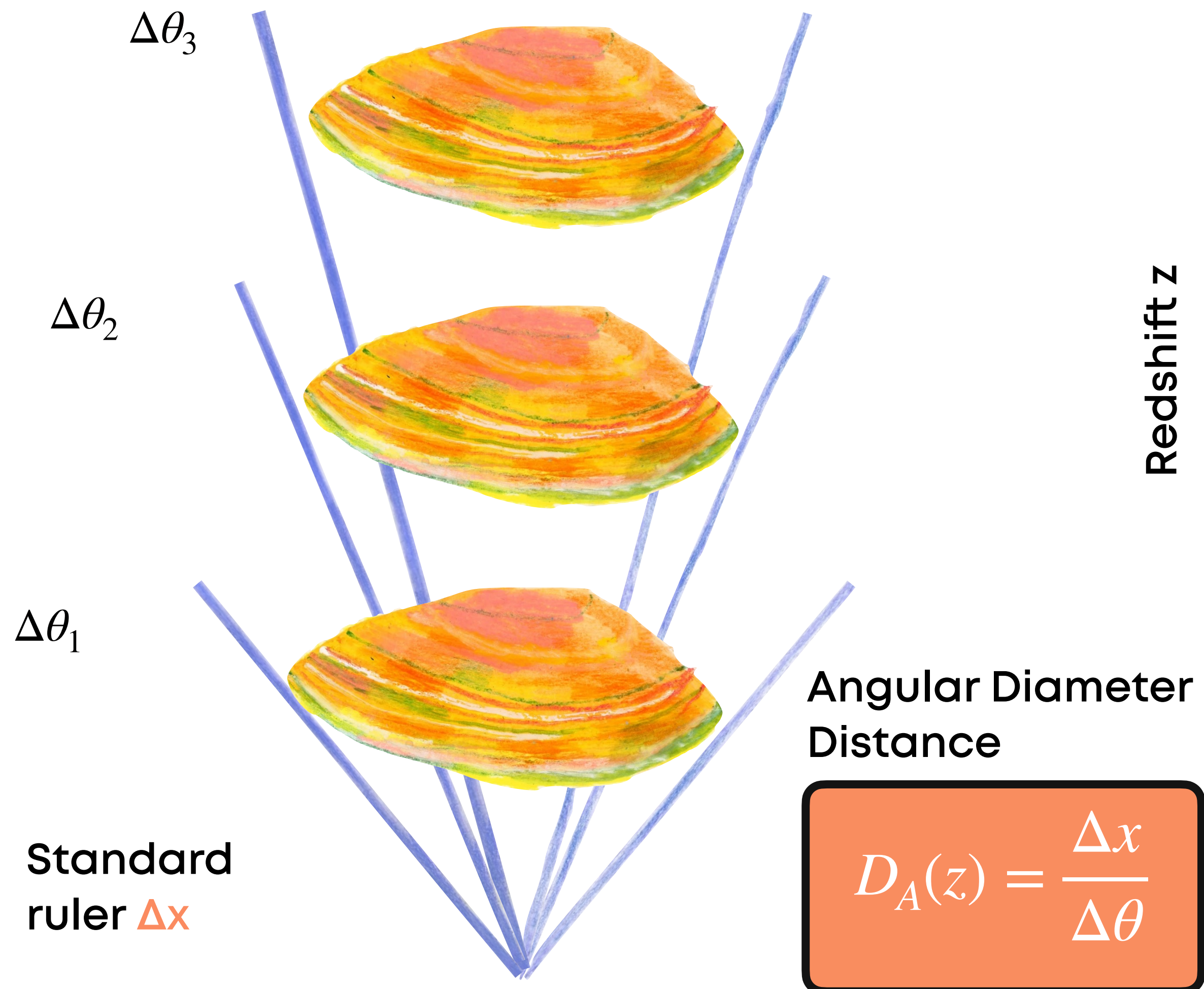


Luminosity Distance D_L (SN1a)

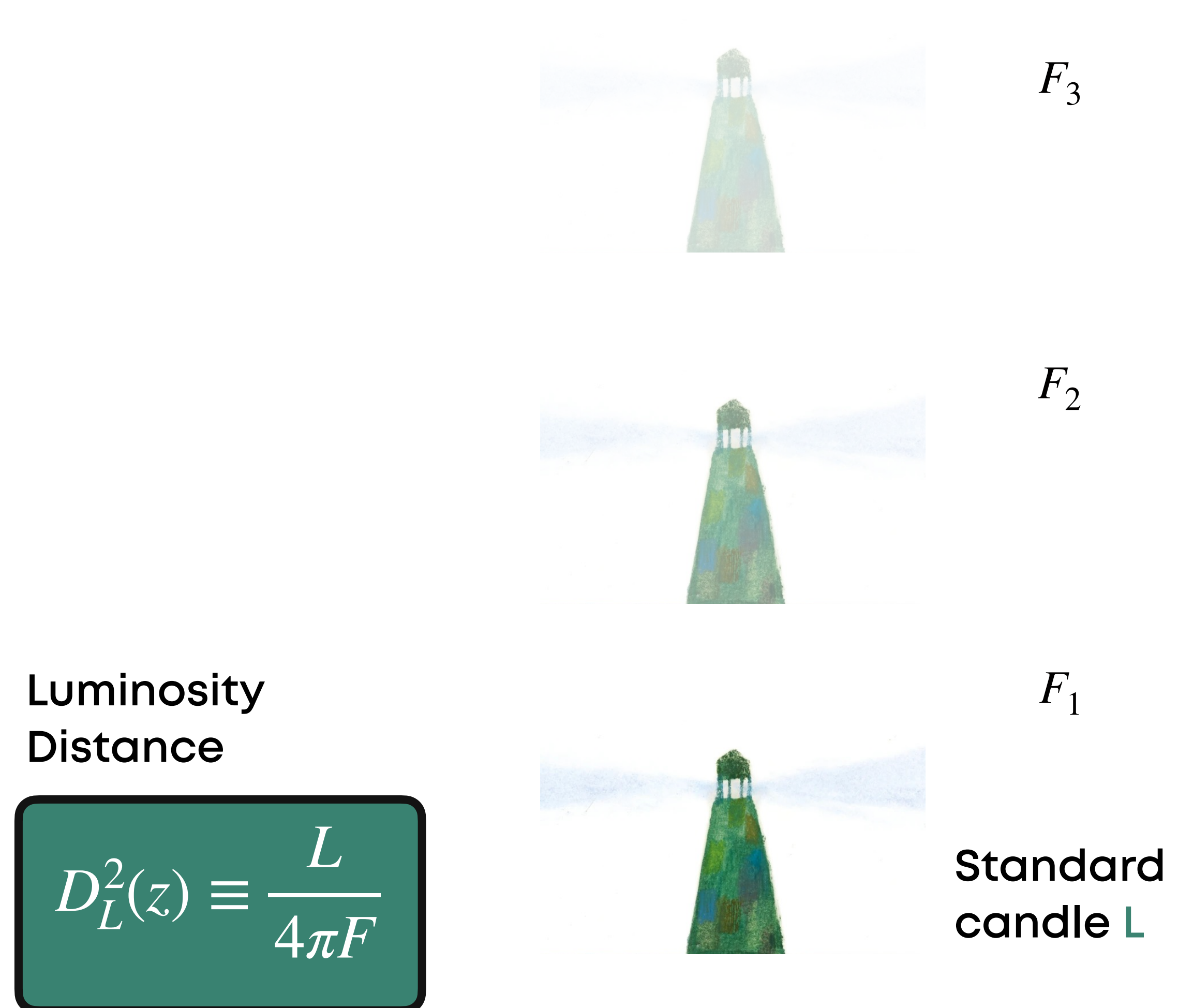




Angular Diameter Distance D_A (BAO)



Luminosity Distance D_L (SN1a)





Angular Diameter Distance D_A (BAO)

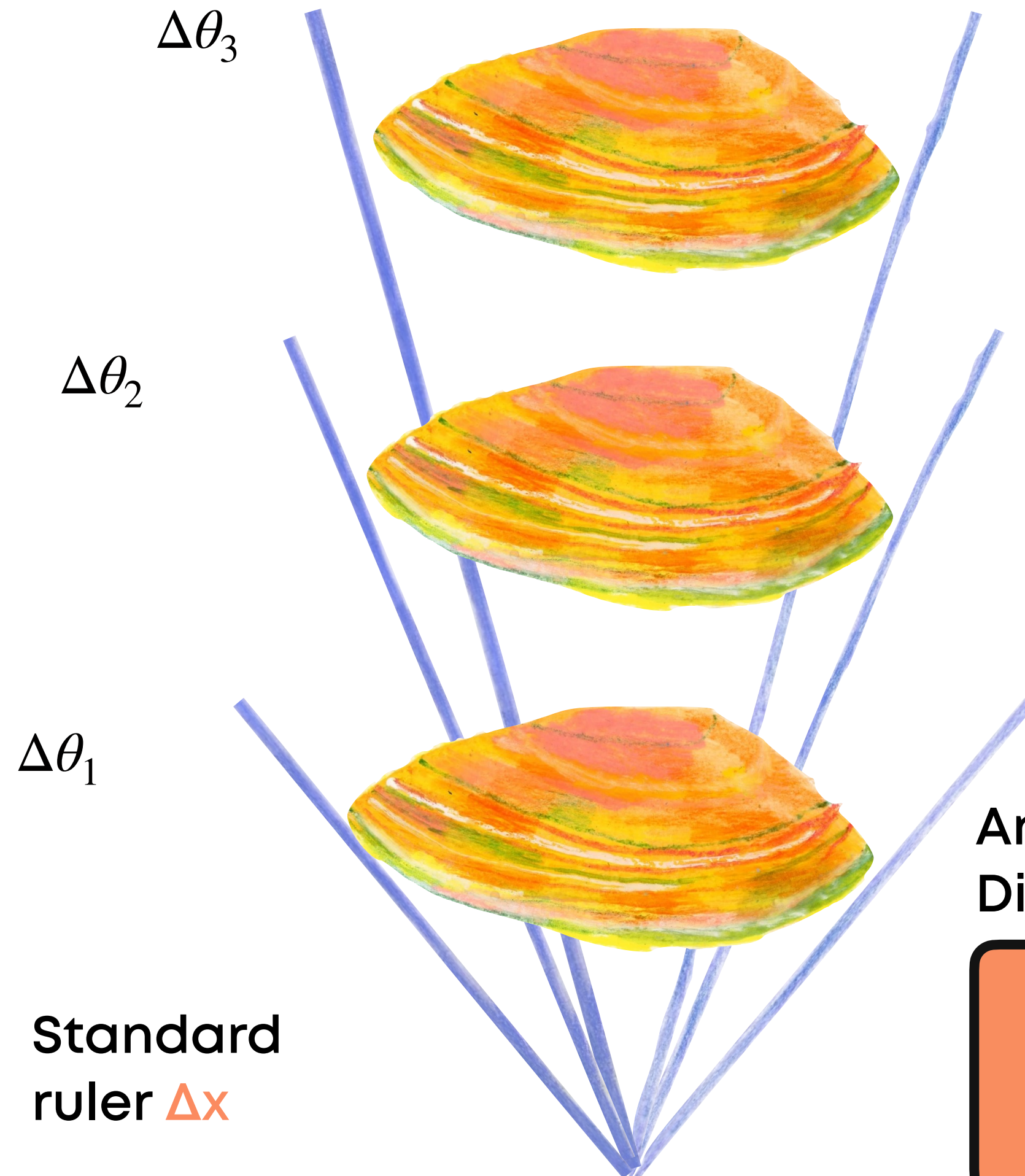
Luminosity Distance D_L (SN1a)

[I. M. H. Etherington (1933)]

$$D_L(z) = (1 + z)^2 D_A(z)$$

Distance Duality Relation (DDR)

Redshift z

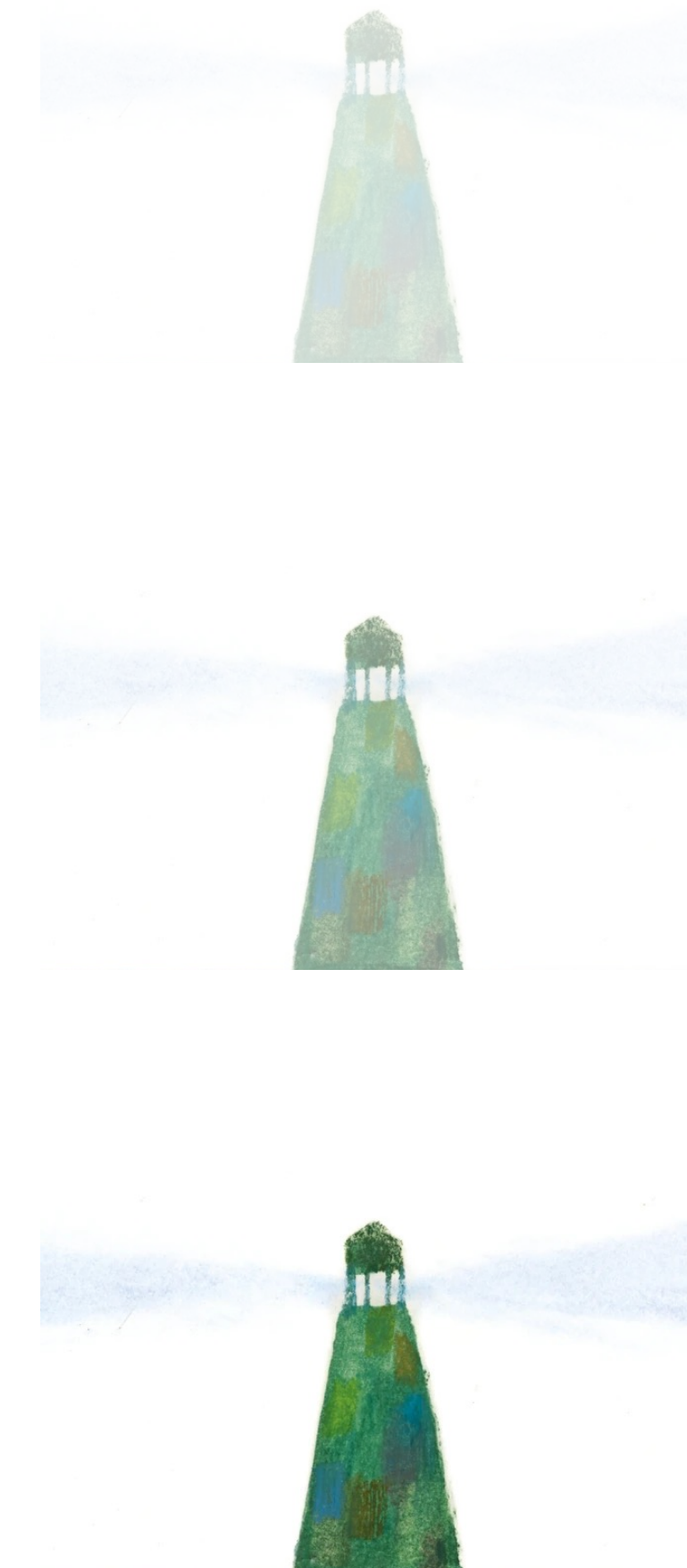


Angular Diameter Distance

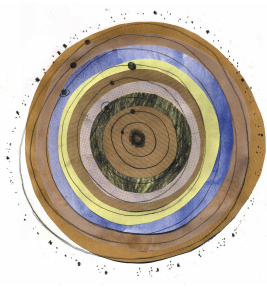
$$D_A(z) = \frac{\Delta x}{\Delta \theta}$$

Luminosity Distance

$$D_L^2(z) \equiv \frac{L}{4\pi F}$$



Standard candle L



Hubble Tension or Distance Tension?

$$\text{BAO: } \theta_d(z) = \frac{r_s(z_{\text{drag}})}{D_A(z)}$$

From *Planck* CMB: $r_s \sim 147$ Mpc:

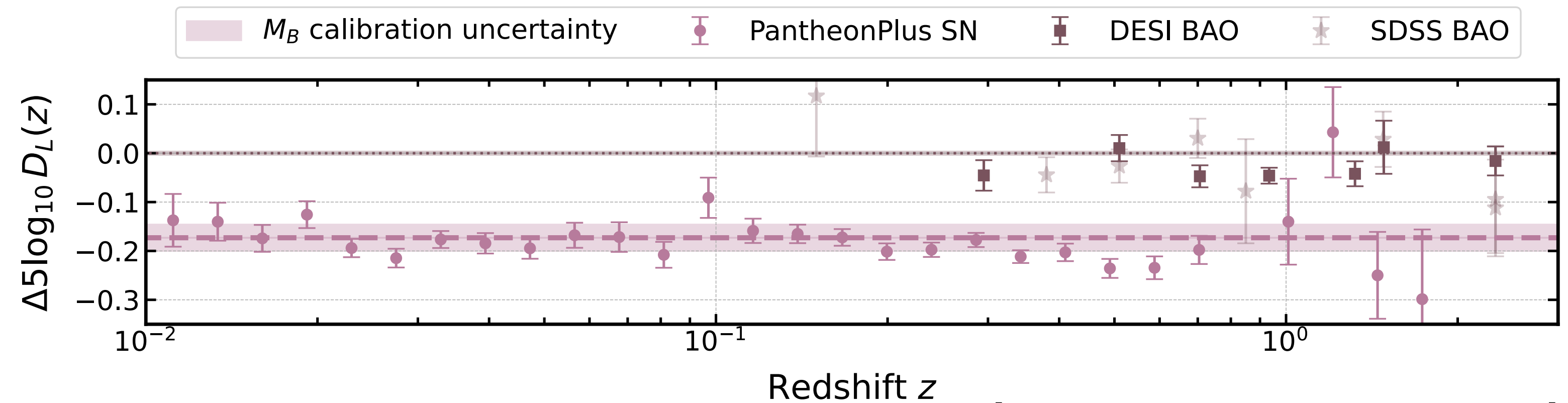
[Aghanim et al.: Astron.Astrophys. 641 (2020) A6]

$D_A(z)$ and $D_L(z)$ are incompatible!

From *SHOES*: $M_b \sim -19.25$

[Riess et. al: Astrophys. J. Lett. 934 (2022) 1 L7]

$$\text{SN1a: } m(z) = 5 \log_{10} (D_L(z)) + M_b$$



[Based on Poulin et al, arxiv:2407.18292]

[Camarena et al.: arXiv: 2101.08641]

[Efsthathiou: arXiv: 2103.08723]

[Raveri: arXiv: 2309.06795]

[Tutusaus et al.: arXiv: 2311.16862]

[EMT et al.: arXiv: 2504.10464]



Hubble Tension or Distance Tension?

$$\text{BAO: } \theta_d(z) = \frac{r_s(z_{\text{drag}})}{D_A(z)}$$

From *Planck* CMB: $r_s \sim 147$ Mpc:

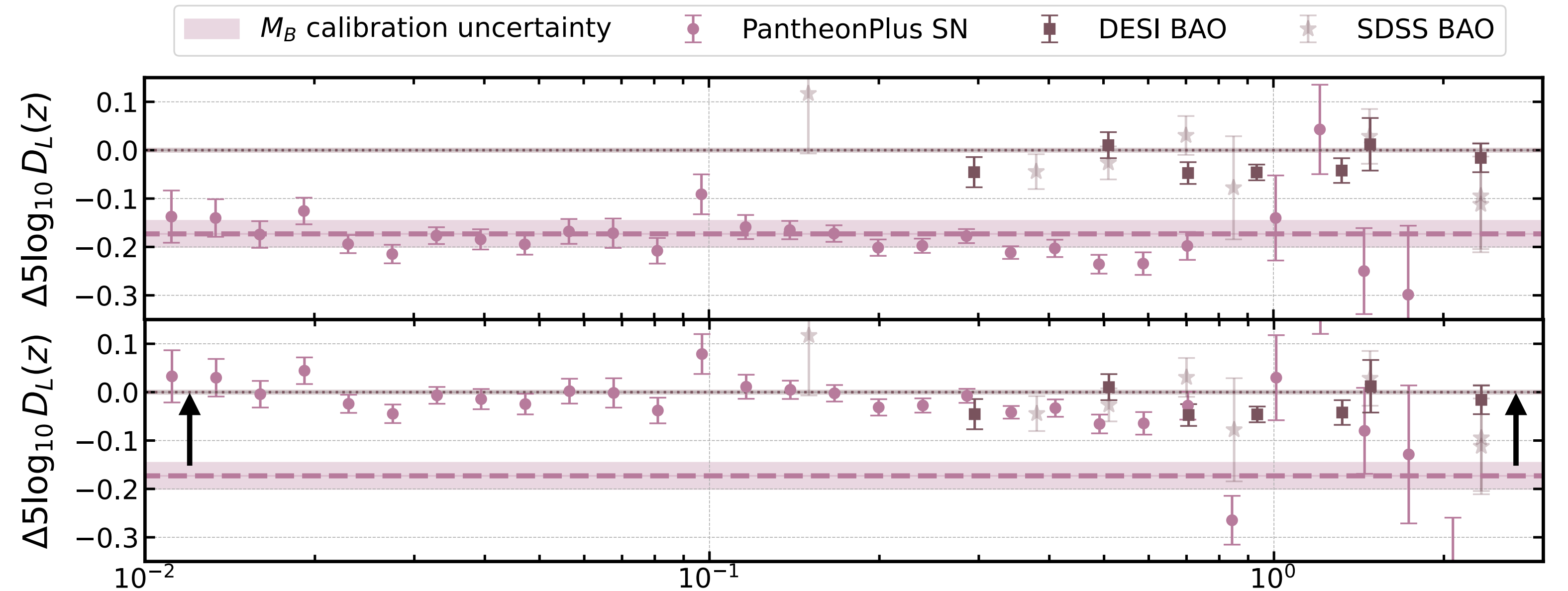
[Aghanim et al.: Astron.Astrophys. 641 (2020) A6]

$D_A(z)$ and $D_L(z)$ are incompatible!

From *SHOES*: $M_b \sim -19.25$

[Riess et. al: Astrophys. J. Lett. 934 (2022) 1 L7]

$$\text{SN1a: } m(z) = 5 \log_{10} (D_L(z)) + M_b$$



Redshift z [Based on Poulin et al, arxiv:2407.18292]

Bring the data sets together:

- Change calibrators, e.g. change M_b (constant overall shift)

[Camarena et al.: arXiv: 2101.08641]

[Efsthathiou: arXiv: 2103.08723]

[Raveri: arXiv: 2309.06795]

[Tutusaus et al.: arXiv: 2311.16862]

[EMT et al.: arXiv: 2504.10464]



Hubble Tension or Distance Tension?

$$\text{BAO: } \theta_d(z) = \frac{r_s(z_{\text{drag}})}{D_A(z)}$$

From *Planck* CMB: $r_s \sim 147$ Mpc:

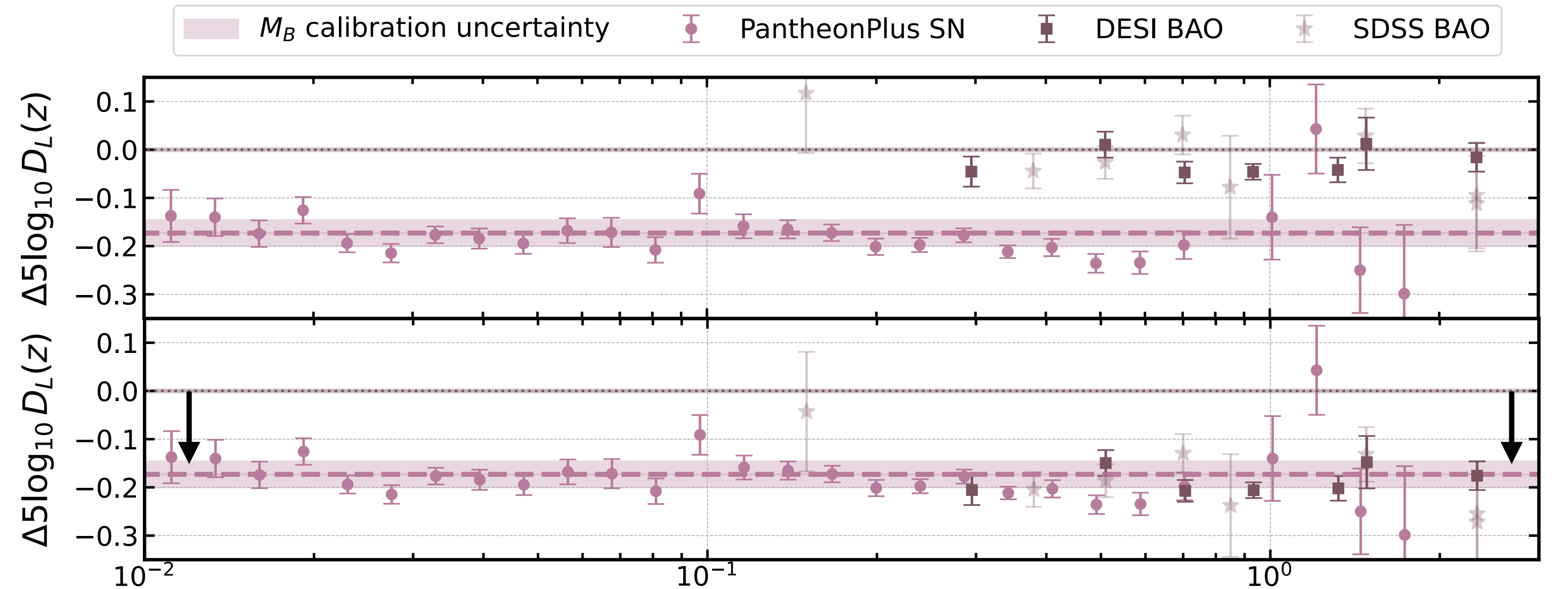
[Aghanim et al.: Astron.Astrophys. 641 (2020) A6]

$D_A(z)$ and $D_L(z)$ are incompatible!

From *SHOES*: $M_b \sim -19.25$

[Riess et. al: Astrophys. J. Lett. 934 (2022) 1 L7]

$$\text{SN1a: } m(z) = 5 \log_{10} D_L(z) + M_b$$



Redshift z [Based on Poulin et al, arxiv:2407.18292]

Bring the data sets together:

- Change calibrators, e.g. change M_B (constant overall shift)
- Change the cosmology/model assumptions, e.g. change $r_s, H(z)$

[Camarena et al.: arXiv: 2101.08641]

[Efstathiou: arXiv: 2103.08723]

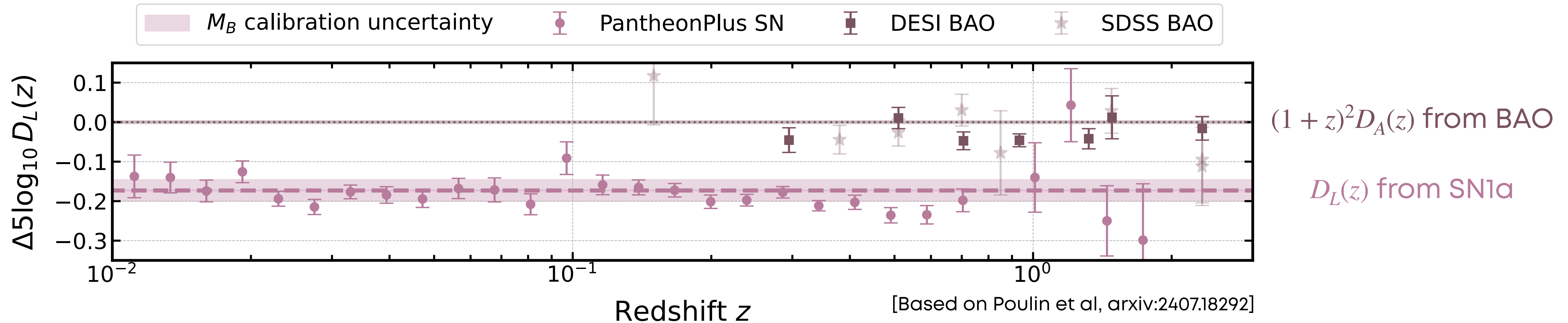
[Raveri: arXiv: 2309.06795]

[Tutusaus et al.: arXiv: 2311.16862]

[EMT et al.: arXiv: 2504.10464]



1. Modified late background expansion



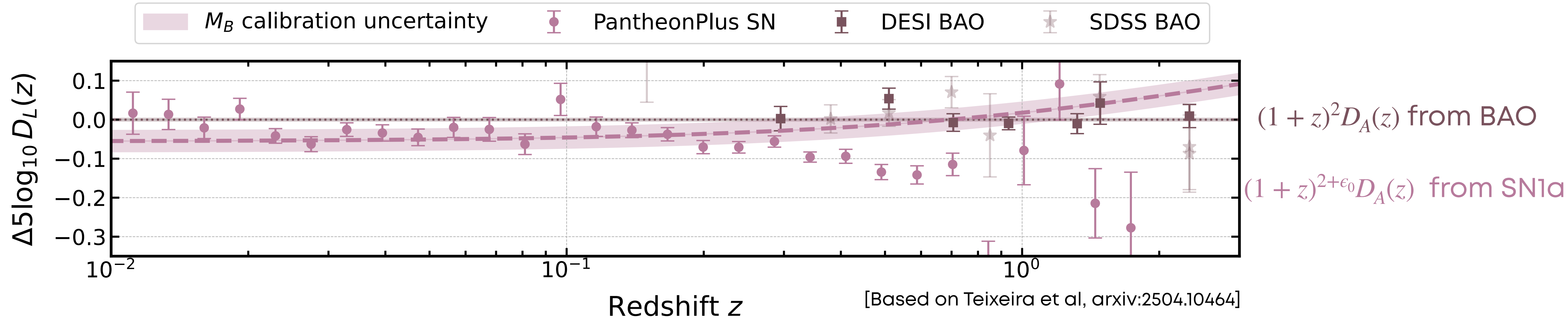
- Change the expansion rate $H(z)$ to achieve higher H_0 with the same $D_L(z)$, e.g. interacting dark sector
[Teixeira et al, arxiv:2211.13653, 2412.14139; Rahimy et al (+ET), arxiv:2503.01961]
- Problem: incompatibility between BAO and SN distances!
 - ▶ r_s derived from CMB or BBN+BAO for the same Λ CDM cosmology at early times
 - ▶ M_B derived from SH0ES

Inevitable incompatibility between $D_L(z) = (1+z)^2 D_A^2$ in the same redshift range



2. Violation of the DDR

$$D_L(z) = (1 + z)^{2+\epsilon_0} D_A(z)$$



- Need non-metric theory of gravity or non-conservation of photon number (ex: BSM particle decays)
- Photon flux must increase during propagation (strong effects for distant SNIa)

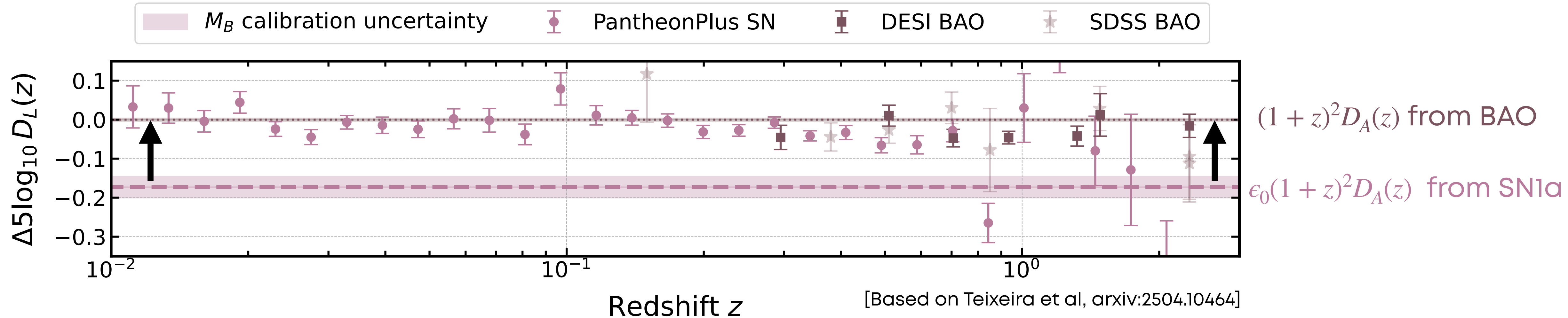
► BAO and SNIa data prefer constant shift (equivalent to change in r_s or M_B): $D_L(z) \sim (1 + z)^{1.866 \pm 0.021} D_A(z)$
[Teixeira et al, arxiv:2504.10464]

► Measurements of $T_{\text{CMB}} = T_0(1 + z)$ show no evidence for deviation: $D_L(z) \sim (1 + z)^{2.0159 \pm 0.0186} D_A(z)$
[Ruchika et al (+ET), arxiv:2505.02909]



2. Violation of the DDR

$$D_L(z) = \epsilon_0(1+z)^2 D_A(z)$$



- Need non-metric theory of gravity or non-conservation of photon number (ex: BSM particle decays)
- Photon flux must increase during propagation (strong effects for distant SN1a)

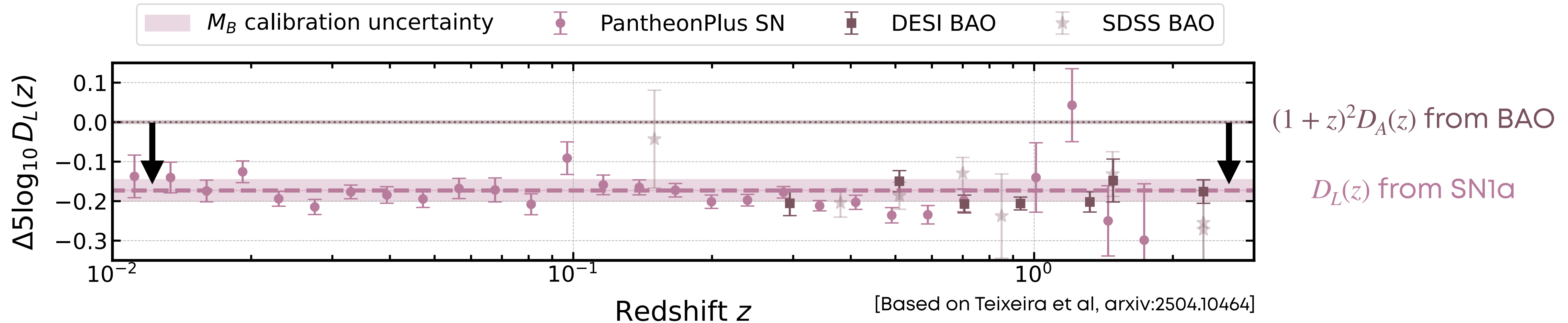
► BAO and SN1a data prefer constant shift (equivalent to change in r_s or M_B): $D_L(z) \sim (1+z)^{1.866 \pm 0.021} D_A(z)$
[Teixeira et al, arxiv:2504.10464]

► Measurements of $T_{\text{CMB}} = T_0(1+z)$ show no evidence for deviation: $D_L(z) \sim (1+z)^{2.0159 \pm 0.0186} D_A(z)$
[Ruchika et al (+ET), arxiv:2505.02909]

Preferred scenario is still constant shift (equivalent to change in r_s or M_B): $D_L(z) = 0.925(1+z)^2 D_A(z)$



3. Modified recombination/decoupling



[Based on Teixeira et al, arxiv:2504.10464]

• New physics that can shift recombination/decoupling to earlier times

- ▶ Modified recombination from e.g. primordial magnetic fields

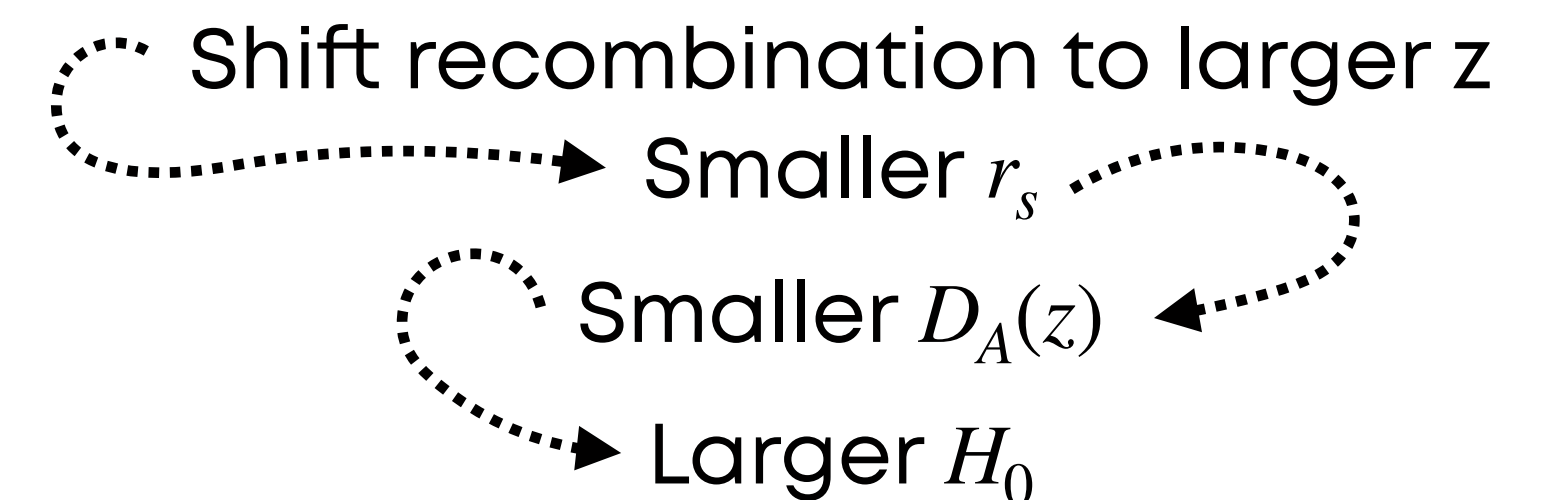
[Jedamzik et al, arxiv:2307.05475,2503.09599; Lynch et al, arxiv:2404.05715,2406.10202]

- ▶ Varying fundamental constants such as α , m_e

[Hart et al, arxiv:1912.03986; Schöneberg et al, arxiv:2507.16845]

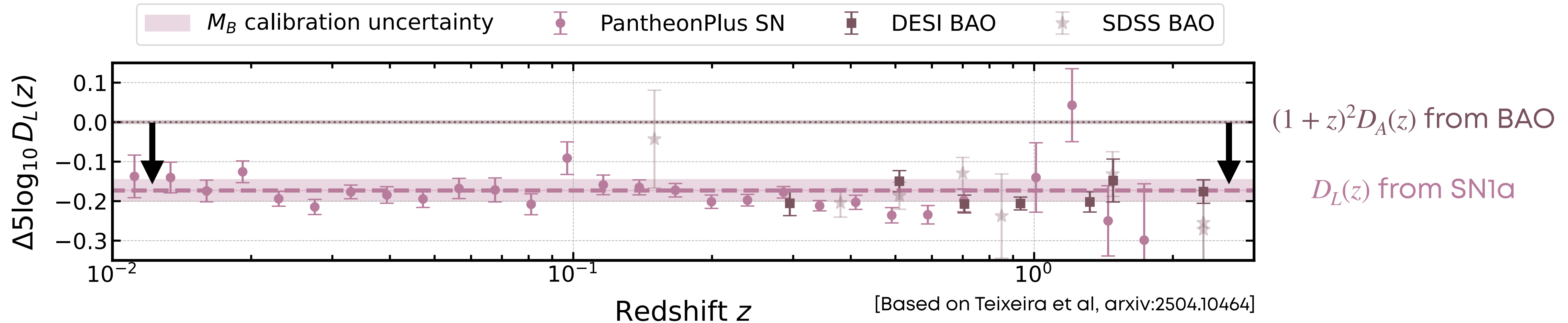
Would produce detectable effects in spectrum of CMB (spectral distortions, damped oscillations, early integrated Sachs-Wolfe effect, etc) and lack fundamental physics explanation

$$r_s = \int_{z_{\text{dec}}}^{\infty} dz c_s(z) H^{-1}(z)$$





4. Modified early background expansion

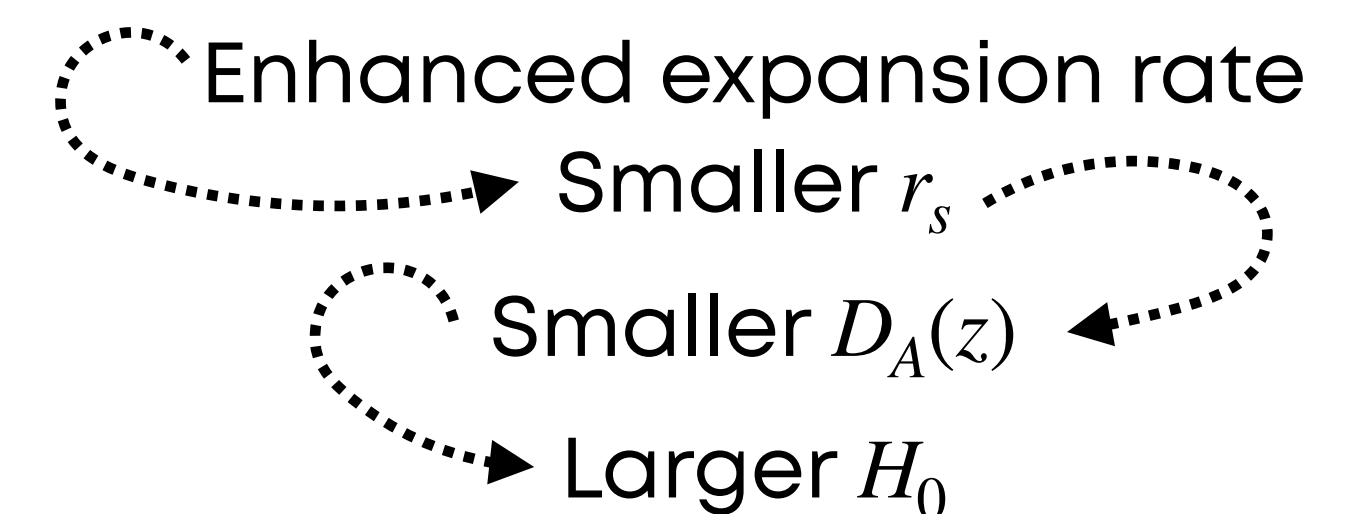


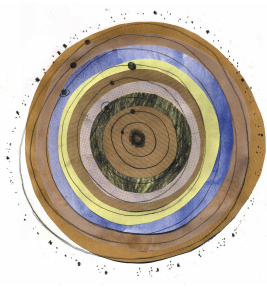
- Additional species before recombination/decoupling enhance expansion ($H(z) \propto \sqrt{\rho_{\text{tot}}}$ is very constrained at BBN)

- Dark radiation: enhance N_{eff} after BBN (extra relativistic dof)
[Aloni et al, arxiv:2111.00014; Brinckmann et al, arxiv:2212.13264]
- Early dark energy: extra accelerating contribution at recombination
[Karwal et al, arxiv:1608.01309, 2007.15414; Poulin et al, arxiv:1811.04083; Niedermann et al, arxiv:2006.06686]
- Early modified gravity (e.g. conformal/disformal theories of gravity)
[Teixeira et al, arxiv:1912.13348, 2007.15414]

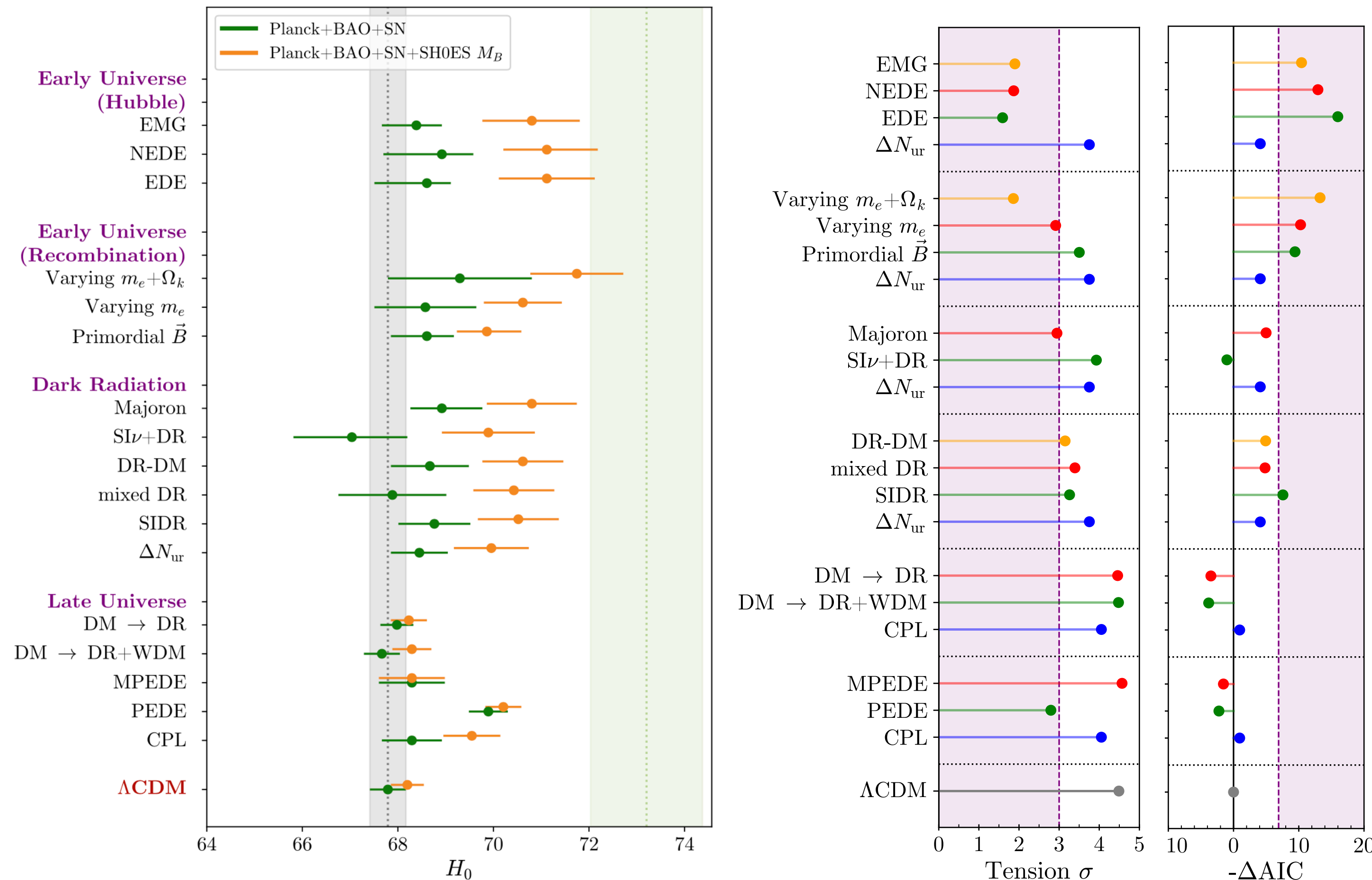
Expect additional effects in CMB and large scale structures

$$r_s = \int_{z_{\text{dec}}}^{\infty} dz c_s(z) H^{-1}(z)$$





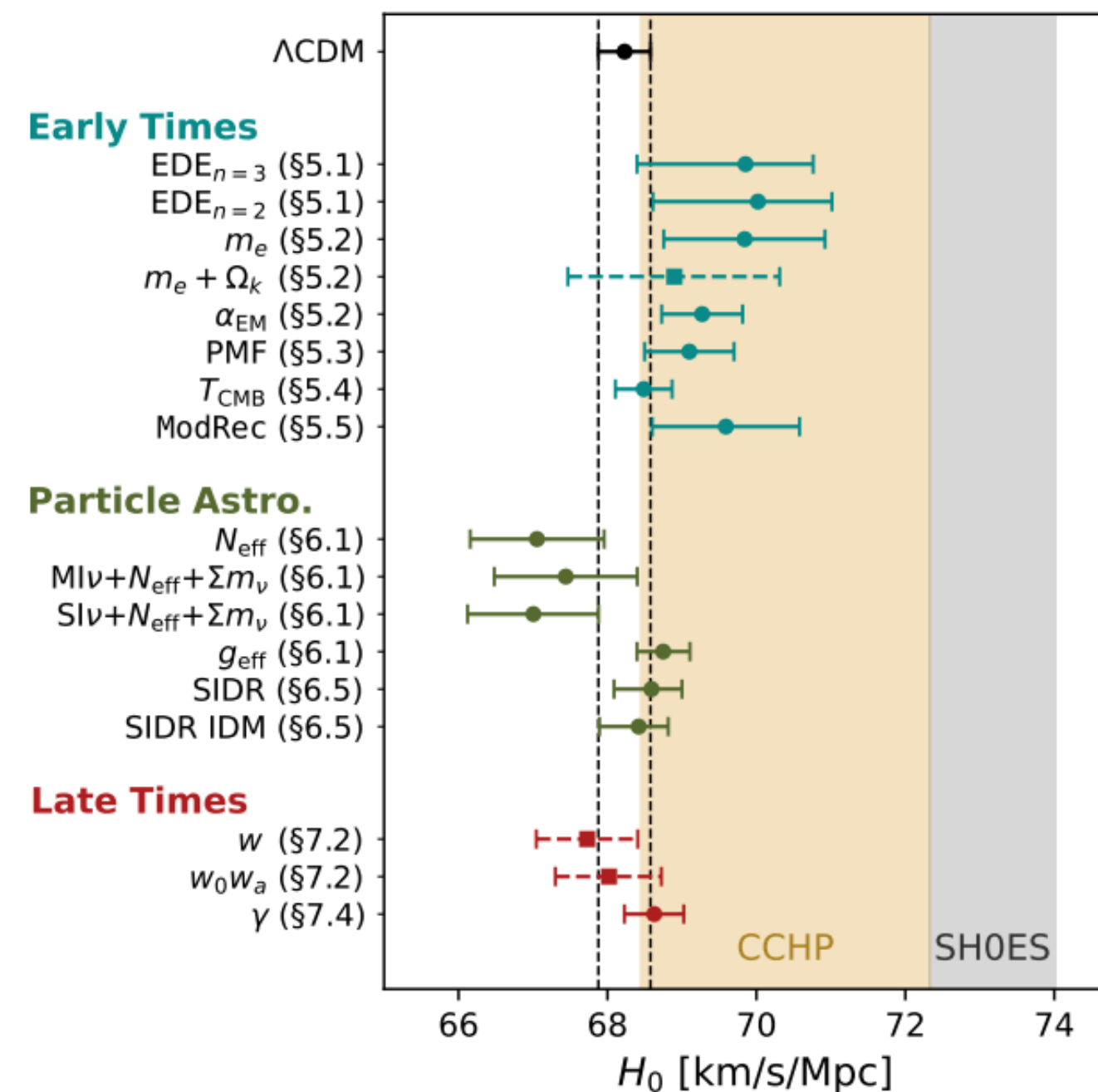
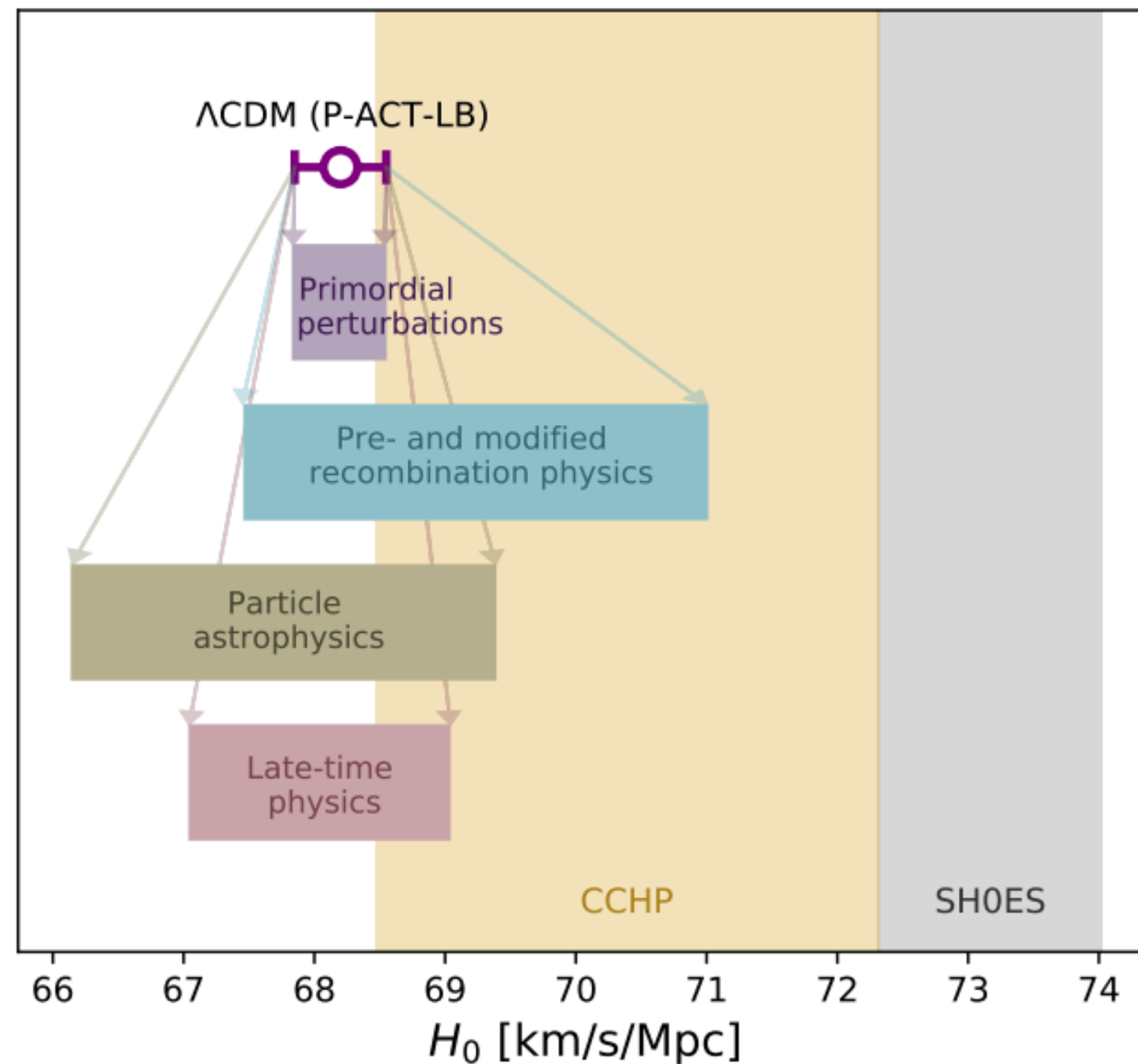
The Hubble olympics



- Selection of representative models in the literature
- Consistently tested with same combinations of data sets and same statistics/conditions
- Different metrics to quantify the tension
- Currently no single model can resolve the Hubble tension
- New theoretical solutions?
- More complicated combinations of models?

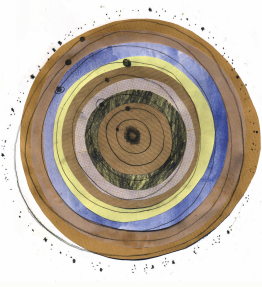


The Hubble olympics in CMB



- Most updated analysis with Planck+ACT CMB data
- Again, no clear preference for any extended models
- Update H_0 olympics to come soon (no expected improvement)

[Calabrese et al (ACT): arXiv:2503.14454]



Conclusions

- Persistent tension between different measurements under the standard Λ CDM model
- The Hubble tension is really a distance tension
- As theorists we must look for isolated effects of each assumption and ingredient in the standard model - don't fear the playground!
- Search for model-independent observables and tests
- Such tests should point us in the direction of a standard model 2.0 mutually consistent with all observations
- Any new physics should be compatible with particle physics as well (e.g. nature of the dark sector, neutrino physics, etc/)
- Exciting precise and independent data sets in the near future - look for independent direct measurements of H_0 (Simons Observatory, Euclid, Rubin Observatory, and many others)



Thank you for your attention!

ELSA M. TEIXEIRA

Laboratoire Univers et Particules de Montpellier
CNRS & Université de Montpellier
elsa.teixeira@umontpellier.fr

Illustrations: Inês Viegas Oliveira
(ivoliveira.com)



Cosmic Discordances

Precision cosmology has revealed incompatibilities in Λ CDM:

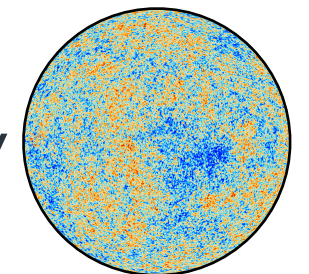
- Cosmic dipole anomaly? The universe is not isotropic? [Colin++ 1703.09376, 1808.04597, Secrest++ 2009.14826, Alari++ 2207.05765, Guandalin++ 2212.04925]
- Cosmic void? The universe is not locally homogeneous? [Wu&Huterer 1706.09723, Kenworthy++ 1901.08681, Cai++ 2012.08292, Camarena++ 2205.05422]
- Tensions in cosmological parameters like H_0 ? [Abdalla++ 2203.06142]
- Anomalies in Planck and ACT? Evidence for a curved universe? [Di Valentino++ 1911.02087, Calderón++ 2302.14300]
- Hints of phantom dynamical dark energy? [Union3 2311.12098, DES 2401.02929, DESI 2404.03002]
- (Too) High redshift galaxies with JWST? [Labbé++ 2207.12446, Boylan-Kolchin 2208.01611]

Are these the first signs of the nature of the break down of Λ CDM's simplified assumptions?

INFLATION

INFLATON

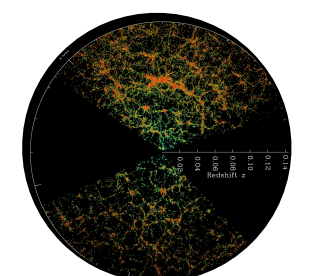
Early accelerated expansion produce density fluctuations



COSMIC STRUCTURE

CDM

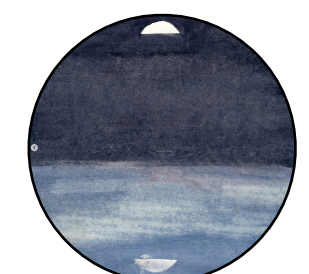
Clustering matter component for structure formation



LATE ACCELERATION

Λ

Component to explain current accelerated expansion

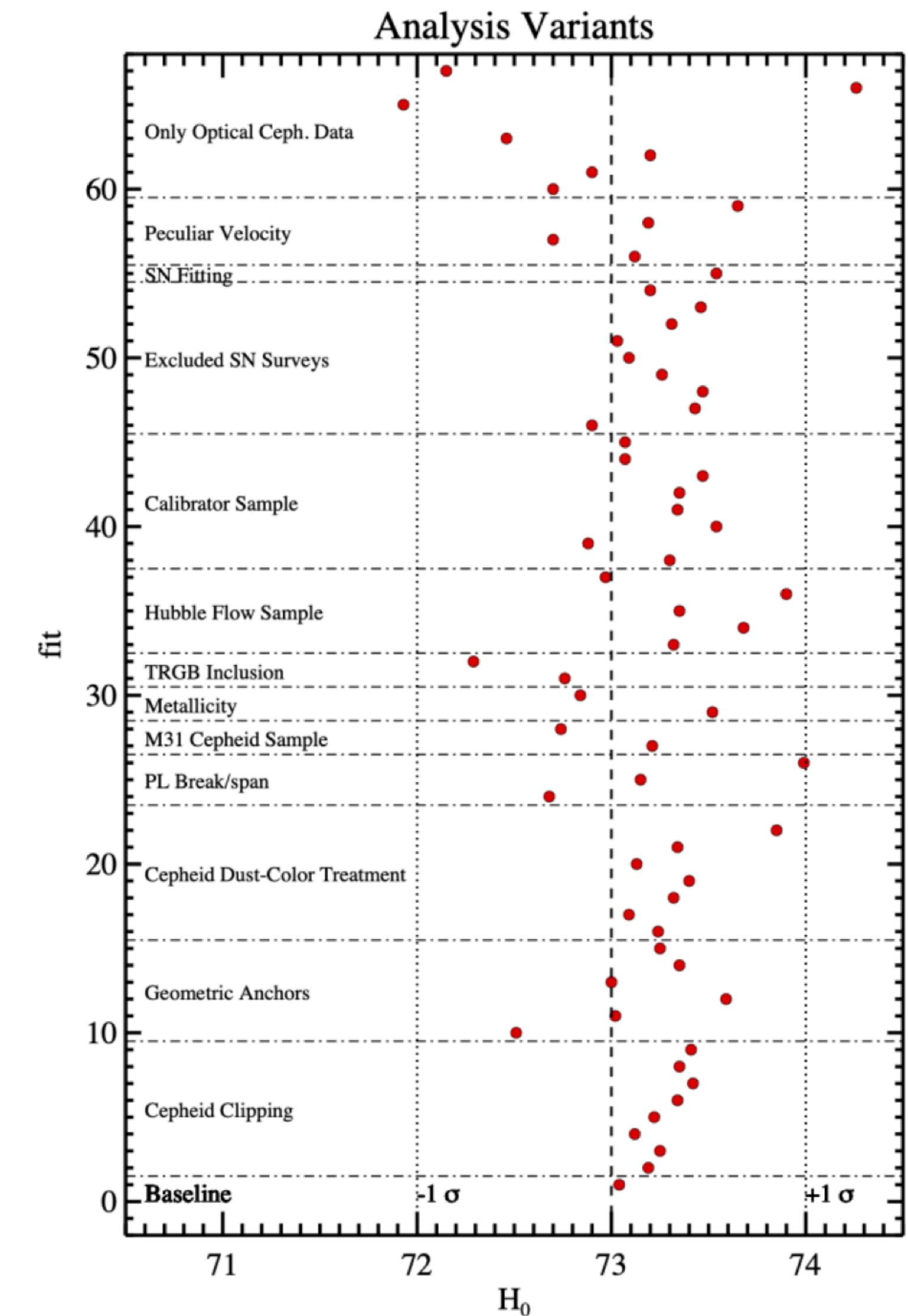




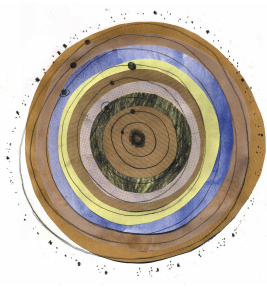
Systematics? [Adapted from V. Poulin]

Still under investigation but not easy to explain a 5σ bias:

- SH0ES builds a 3 steps distance ladder: anchors $\Rightarrow$ cepheids $\Rightarrow$ SNIa
- Are there issues with distance anchor? (GAIA, LMC, NGC4258) [Efsthathiou++ 2007.10716, Soltis++2012.09196]
- Are there issues with cepheids?
 - Cepheids vs TRGB: disagreement? [Freedman++ 2106.15656, Anand++ 2108.00007]
 - Effect of Dust? [Mortsell++ 2105.11461]
 - Cepheid crowding? [Riess++ 2401.04773]
 - Is the metallicity correction correct? [Efsthathiou++ 2007.10716]
- Are there issues with SNIa? different populations of SNIa between “cepheid-SNIa calibrator” and Hubble flow SNIa? [Rigault++ 1412.6501, Jones+ +1805.05911, Brout&Scolnic 2004.10206]
- Are there issues with the CMB? [Di Valentino++ 1911.02087, Calderón++ 2302.14300]

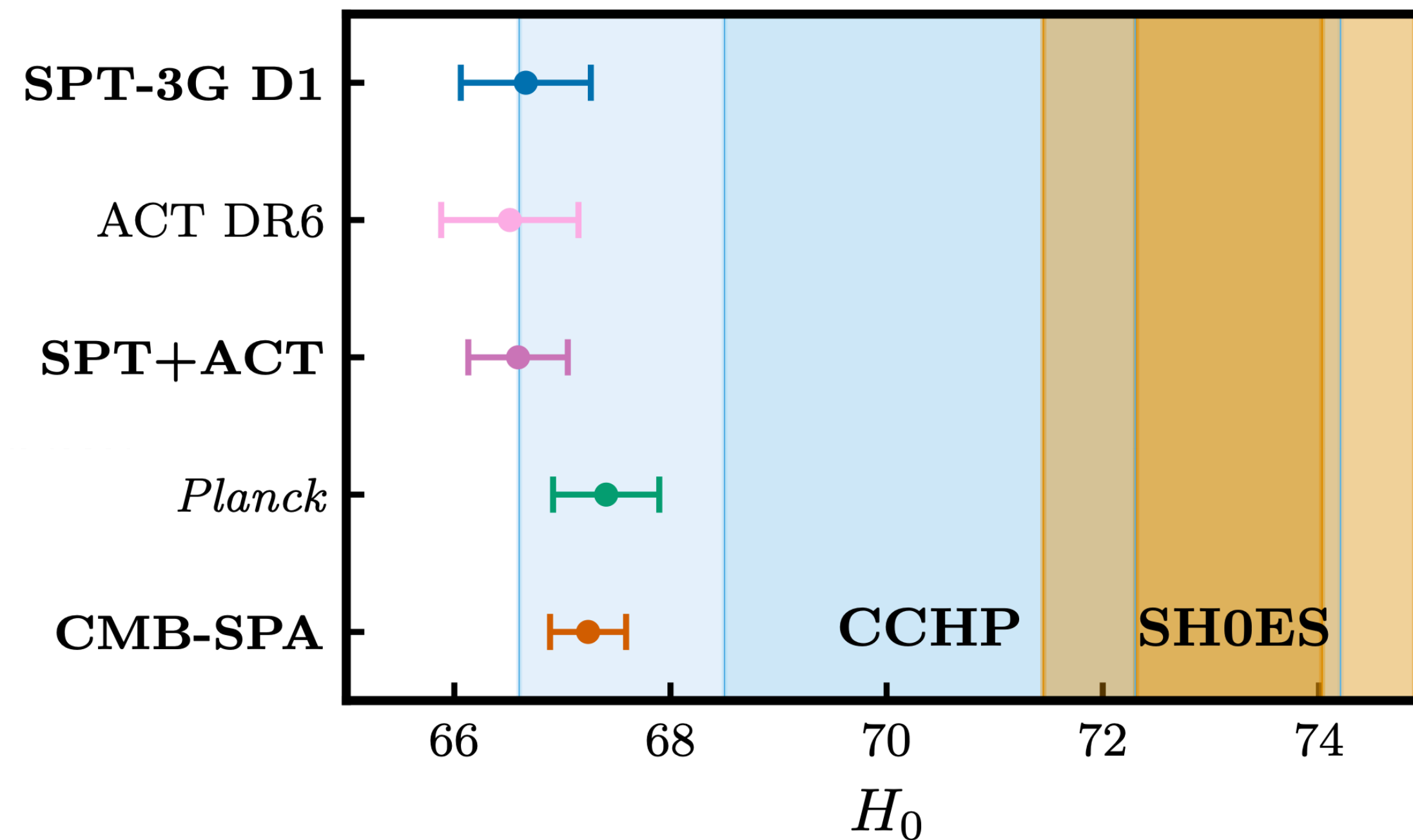


Riess++ 2401.04773

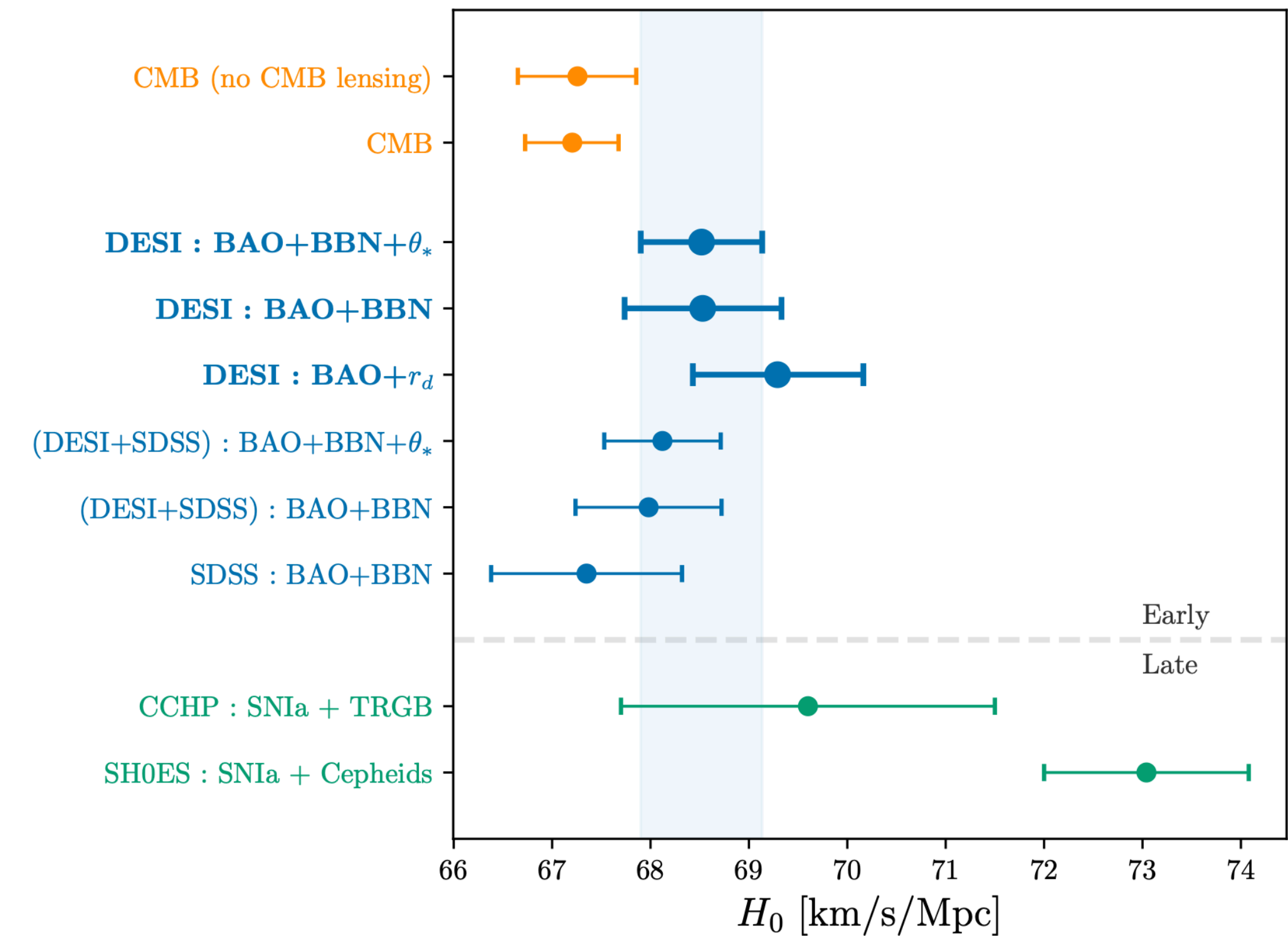


The Hubble Tension

Under Λ CDM, 6.4σ tension between most recent CMB (Planck+ACT+SPT) and SH0ES 24 data
(could replace CMB by BAO+BBN and SH0ES by TRGB, distance to Coma cluster, strong lensing, etc)



[SPT-3G D1 2025, arxiv:2506.20707]



[DESI DR1 Results 2024, arxiv:2404.03002]



Bayesian Parameter Inference

Given a data set d , we want to sample posteriors on the model parameters θ that maximise the likelihood

$$p(\theta | d) = \frac{p(d | \theta) p(\theta)}{p(d)} \Leftrightarrow \text{Posterior} = \frac{\text{likelihood} \times \text{prior}}{\text{evidence}}$$

Modified version of Einstein-Boltzmann code CLASS
interfaced with the MontePython sampler

[Blas, Lesgourgues, Tram: JCAP 1107 (2011) 034; Audren et al.: JCAP 1302 (2013) 001; Brinckmann, Lesgourgues: Phys. Dark Univ. 24 (2019) 100260]

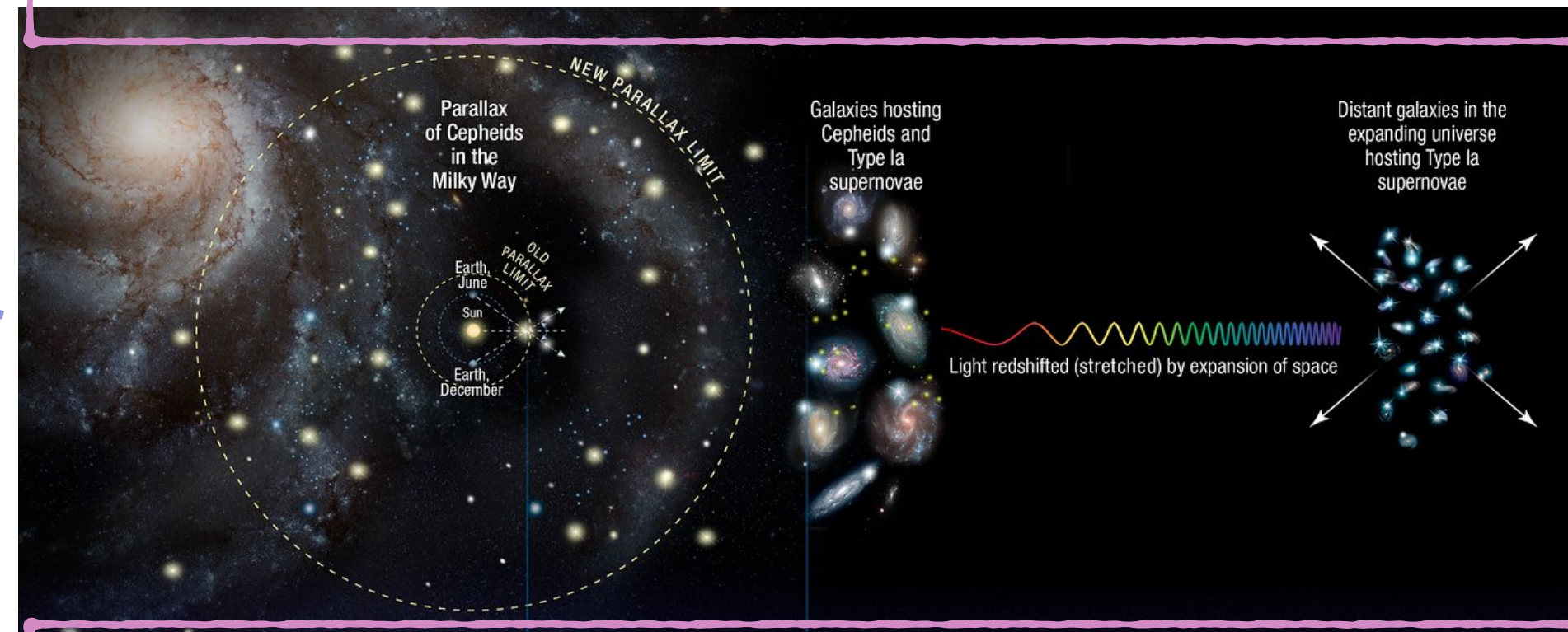
Employ an MCMC sampling method and analyse results
in GetDist [Lewis: arXiv:2008.11284]



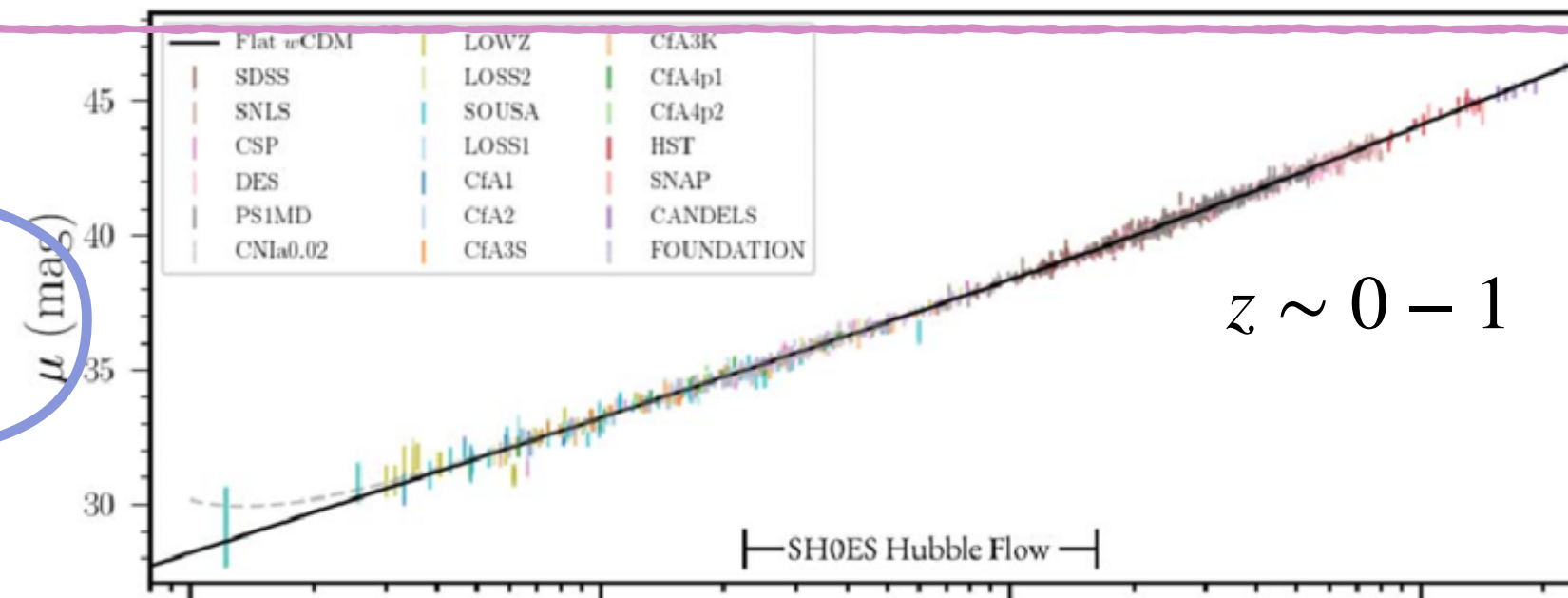


Distance Ladder

Parallax → Cepheids/TRGB/JGB → SNIa



Standardised SNIa luminosity L or absolute magnitude M_B



Ratio $D_L(z)/\sqrt{L}$ and the cross product $H(z)r_s$

Inverse Distance Ladder

Cosmological observables sensitive to matter density (CMB, BBN+BAO, ...)

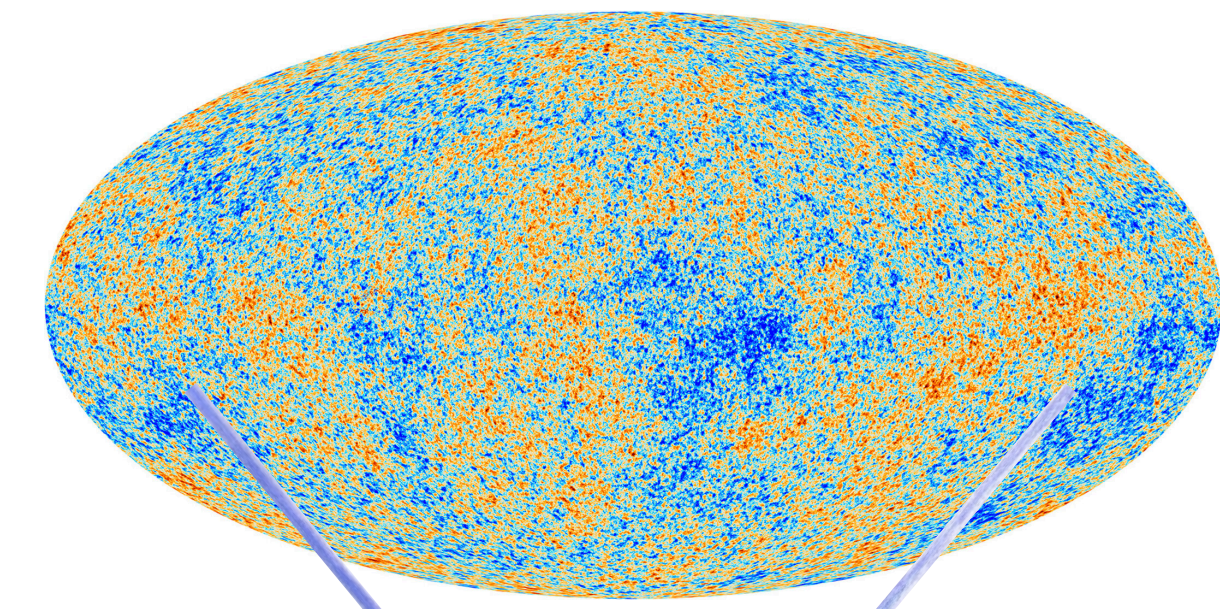
Measure model-dependent sound horizon r_s

Correlation of Galaxies



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

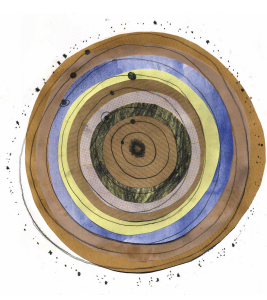
Correlation of CMB anisotropies



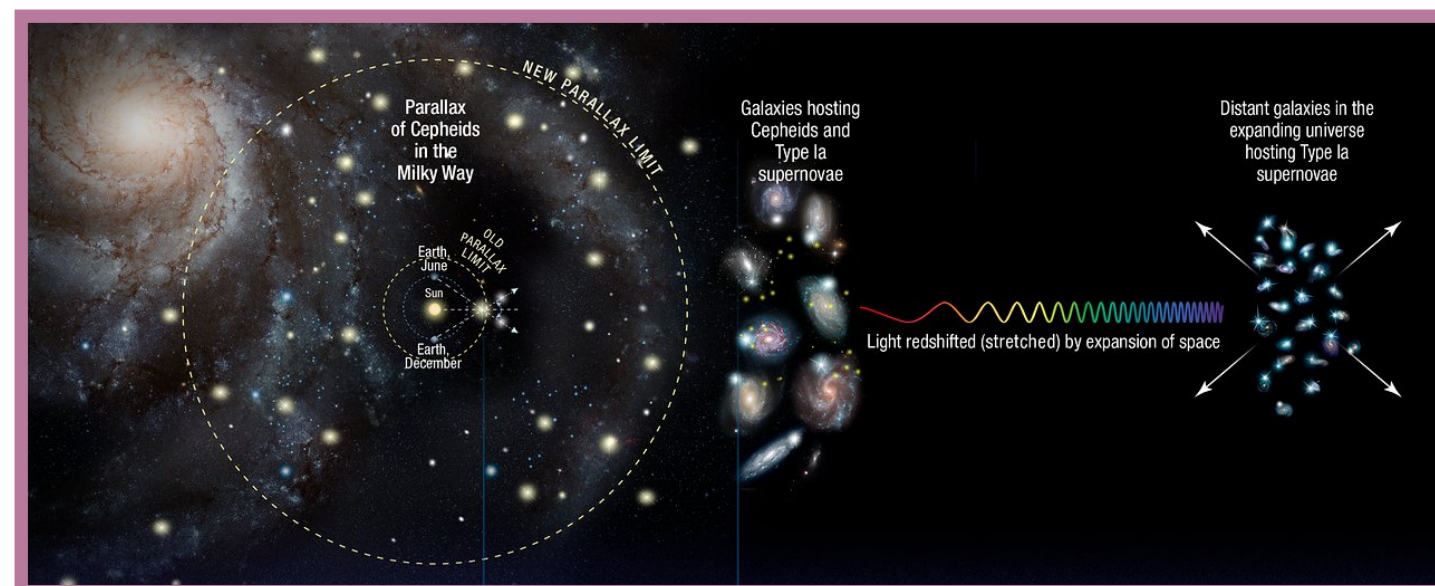
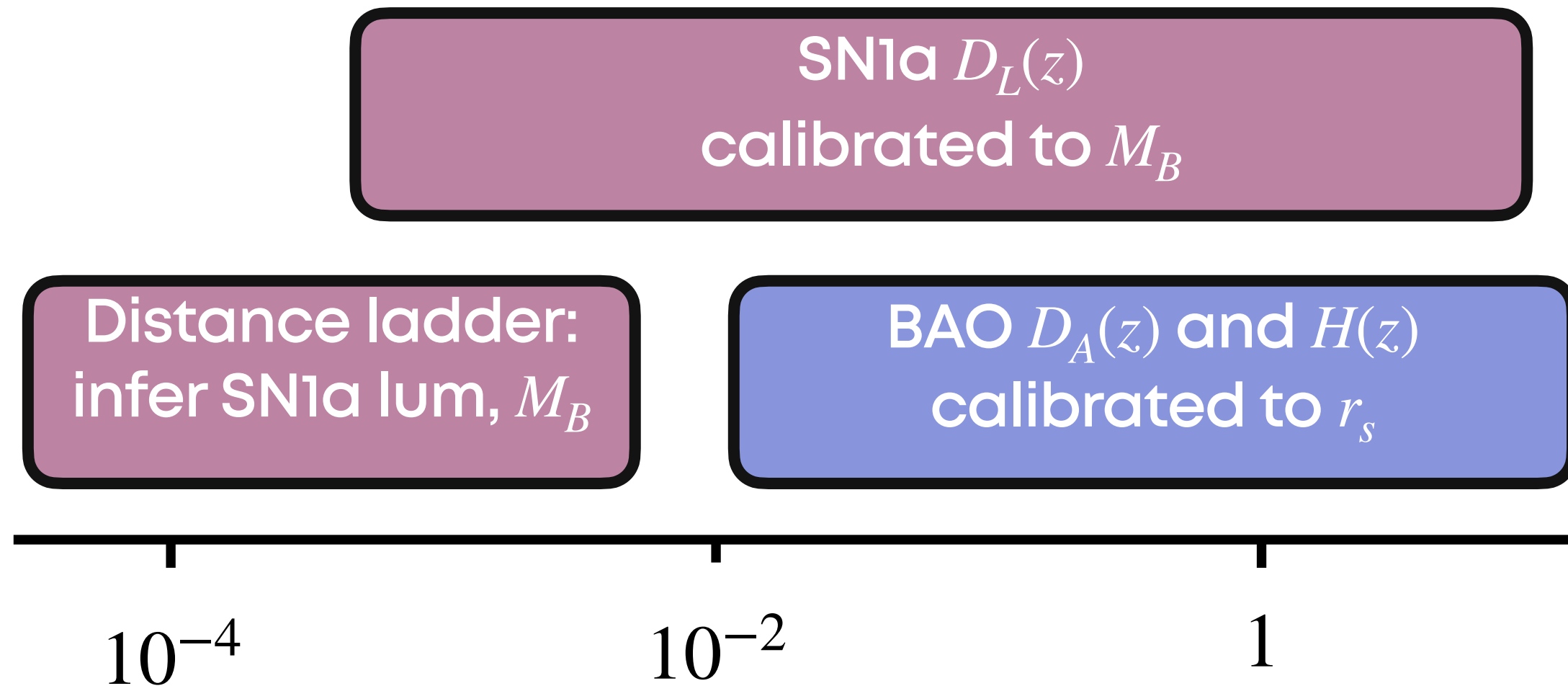
$$D_A(z_*) \propto 1/H_0$$

$$\theta_s(z) = \frac{r_s(z_*)}{D_A(z)}$$

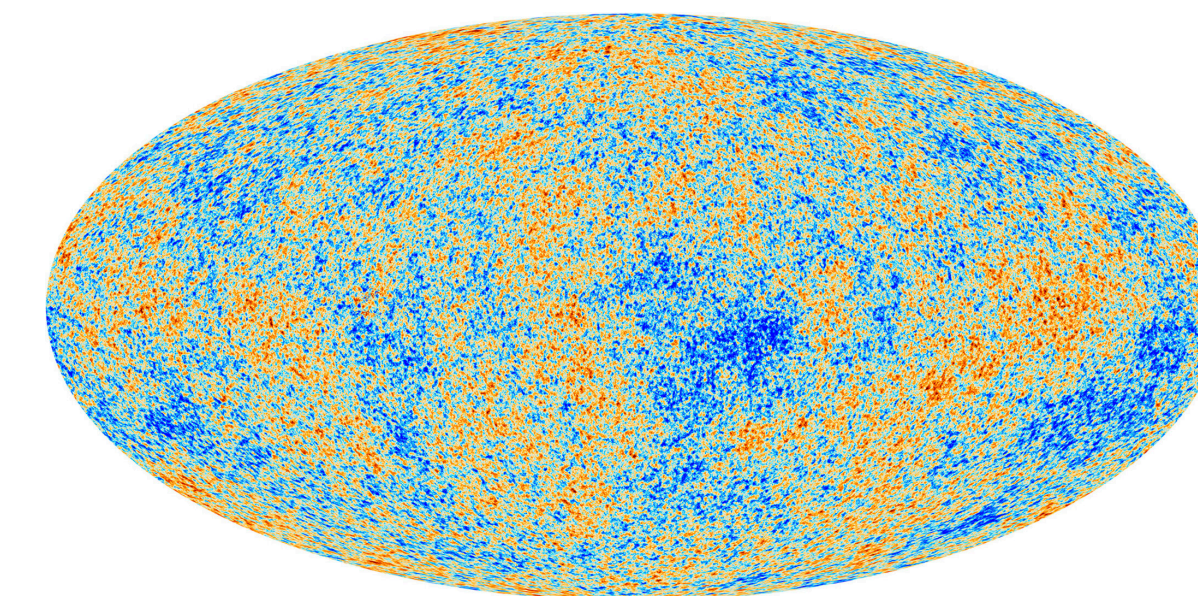
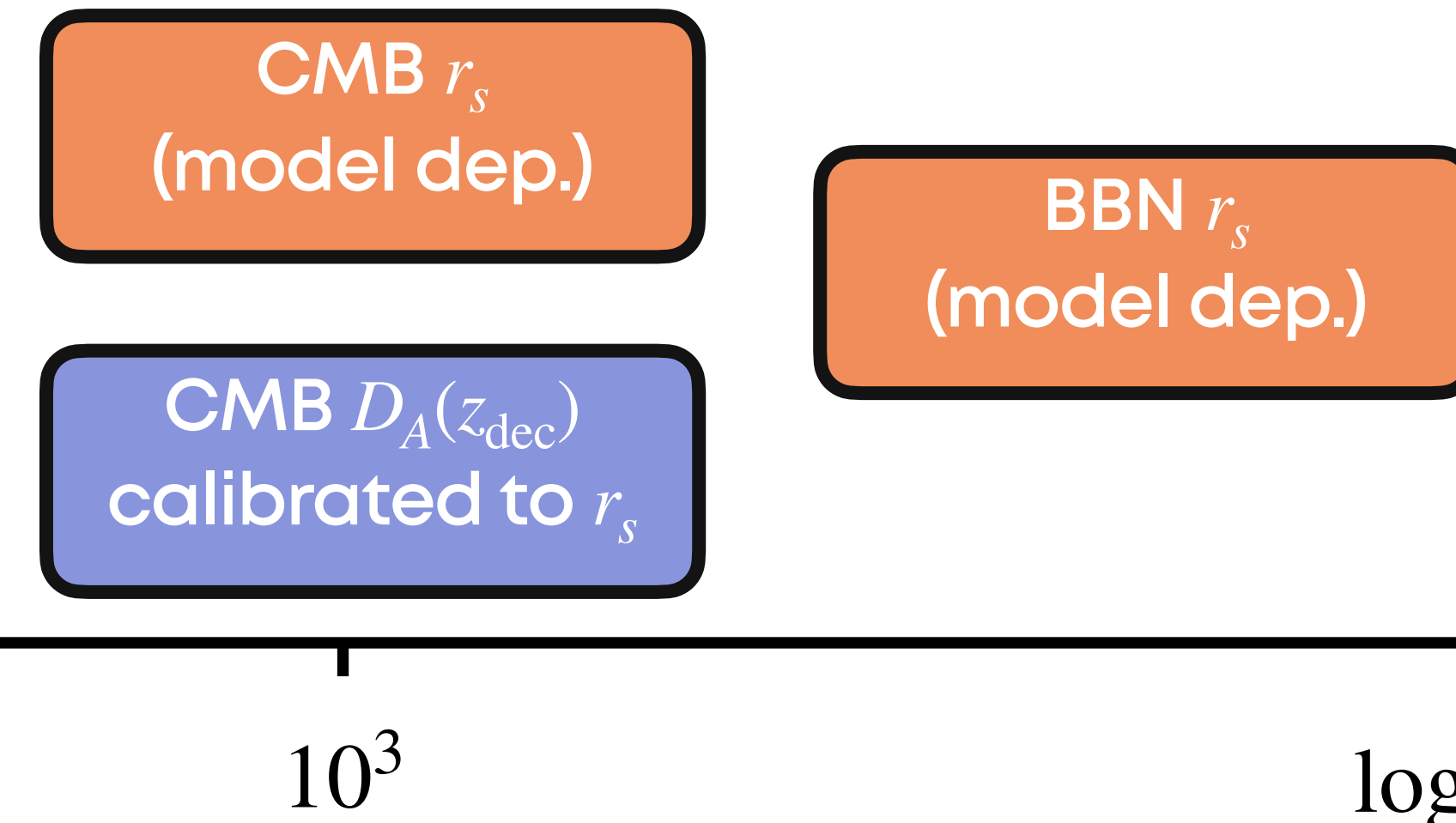
Ratio $D_A(z)/r_s$ and the cross product $H(z)r_s$



Distance Ladder



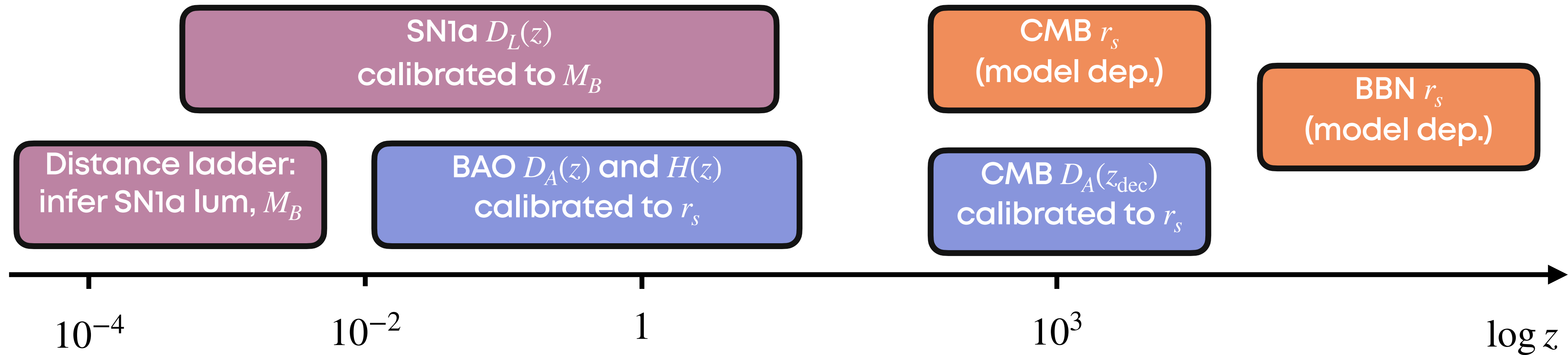
Inverse Distance Ladder





Distance Ladder

Inverse Distance Ladder



The Hubble tension is really a tension between the value of $H_0 = H(z = 0)$ inferred through

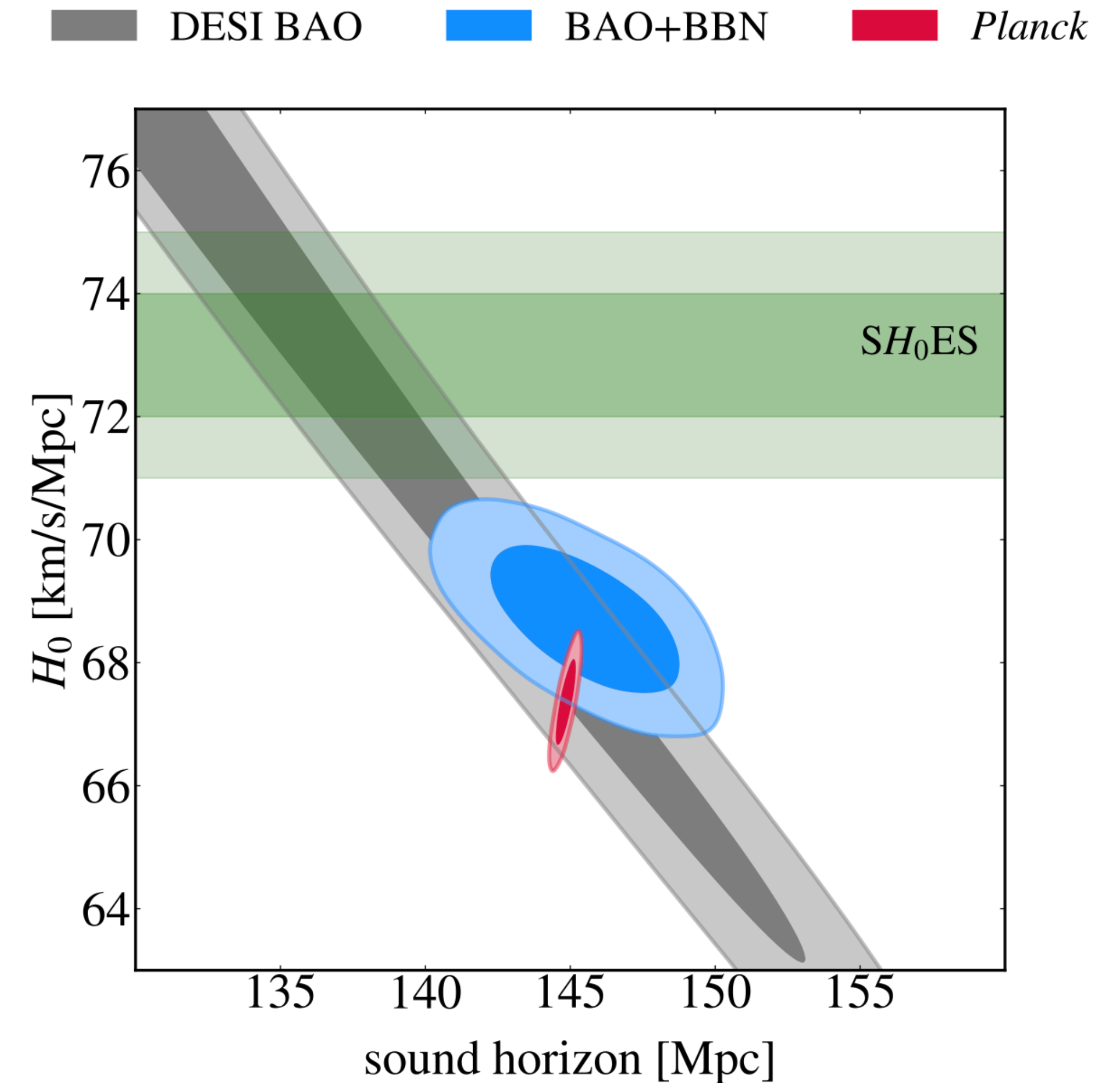
- ▶ $D_L(z)$ from supernovae, calibrated to M_B from distance ladder (e.g. SH0ES)
- ▶ $D_A(z)$ and $H(z)$ from BAO and CMB, calibrated to r_s from CMB or from BAO+BBN, assuming the Λ CDM model



The Hubble Tension

DESI confirms the Hubble tension without CMB

- The degeneracy of DESI measurements of H_0 with the sound horizon r_s can be resolved by **estimates of ω_b from BBN**, yielding a Λ CDM fit compatible with **measurements of the CMB** by Planck: 3.5σ
- **SH0ES data** implies a lower value for the sound horizon, suggesting beyond- Λ CDM physics
- The estimate from Planck has small error bars and is very robust to systematic errors but depends on the cosmological model!



[Credit: V. Poulin]

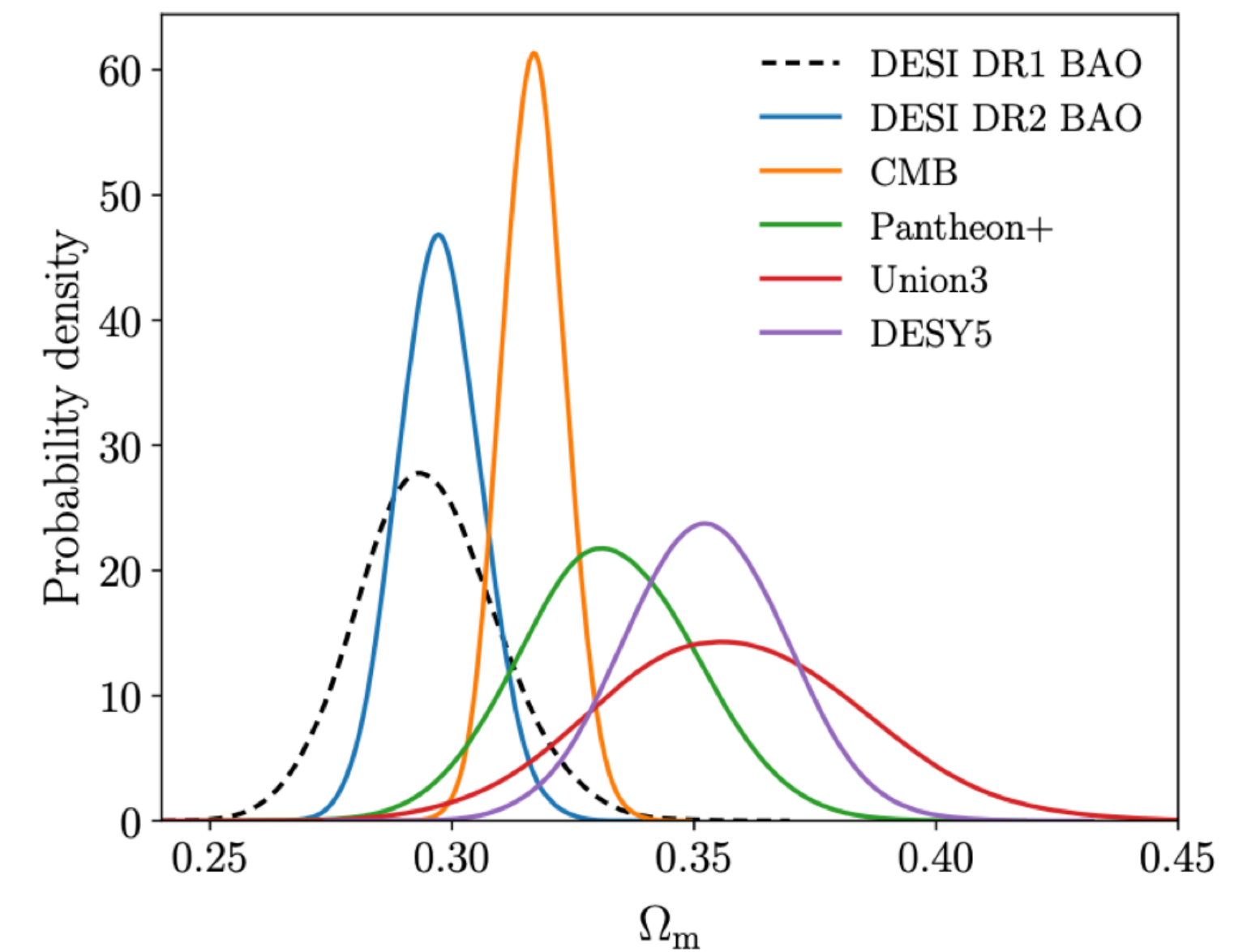
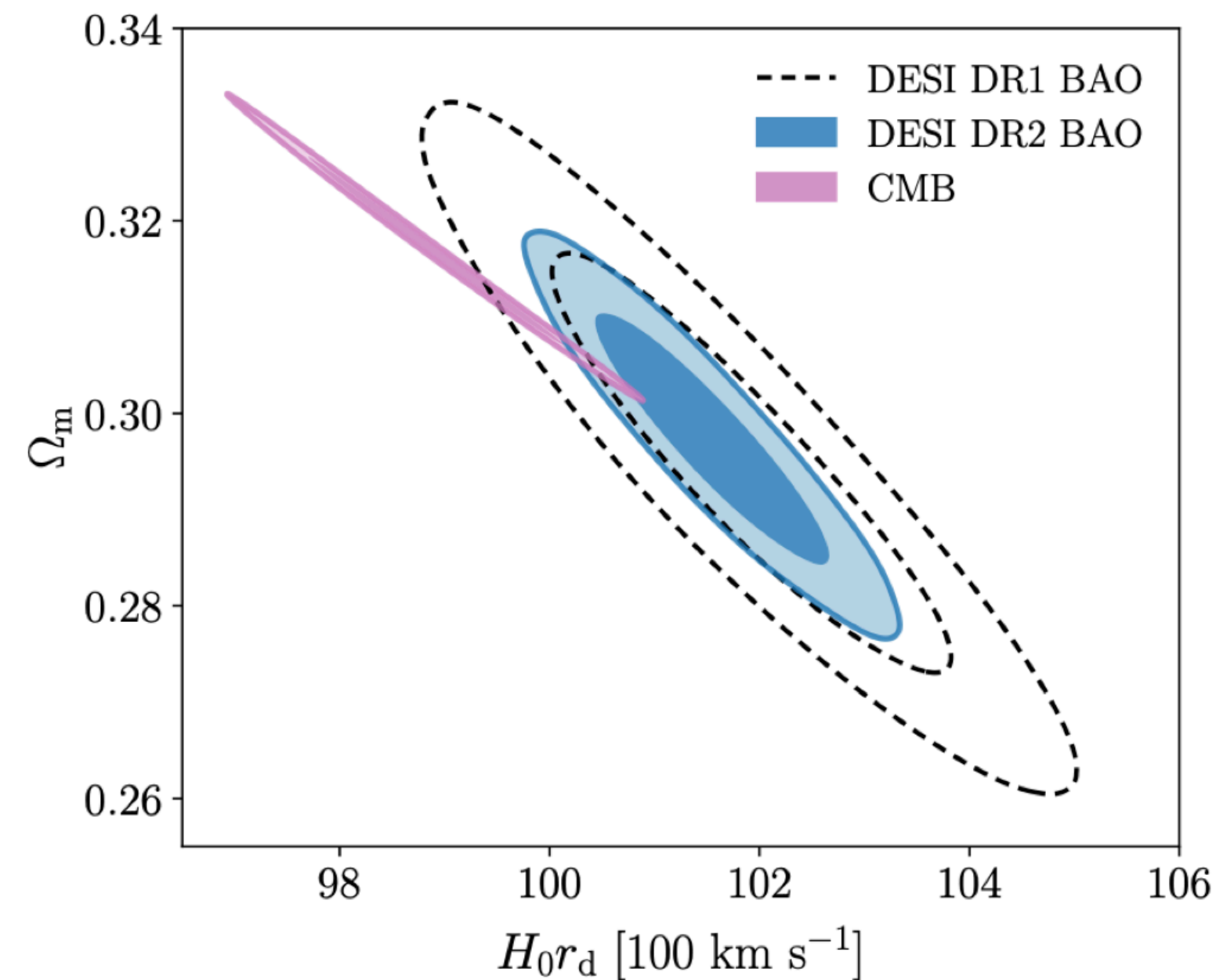


DESI BAO: Hints of new physics?

Under CDM, the BAO allows to measure $H_0 r_d$ and Ω_m

$$\frac{r_d}{D_M} \equiv \frac{H_0 r_s(z_d)}{\int_0^z dz (\Omega_m [(1+z)^3 - 1] + 1)^{-1/2}}$$

$$\frac{r_d}{D_H} \equiv H_0 r_s(z_d) \sqrt{\Omega_m [(1+z)^3 - 1] + 1}$$



DESI+CMB in tension at the 2-3 σ level with SNIa in the determination of Ω_m

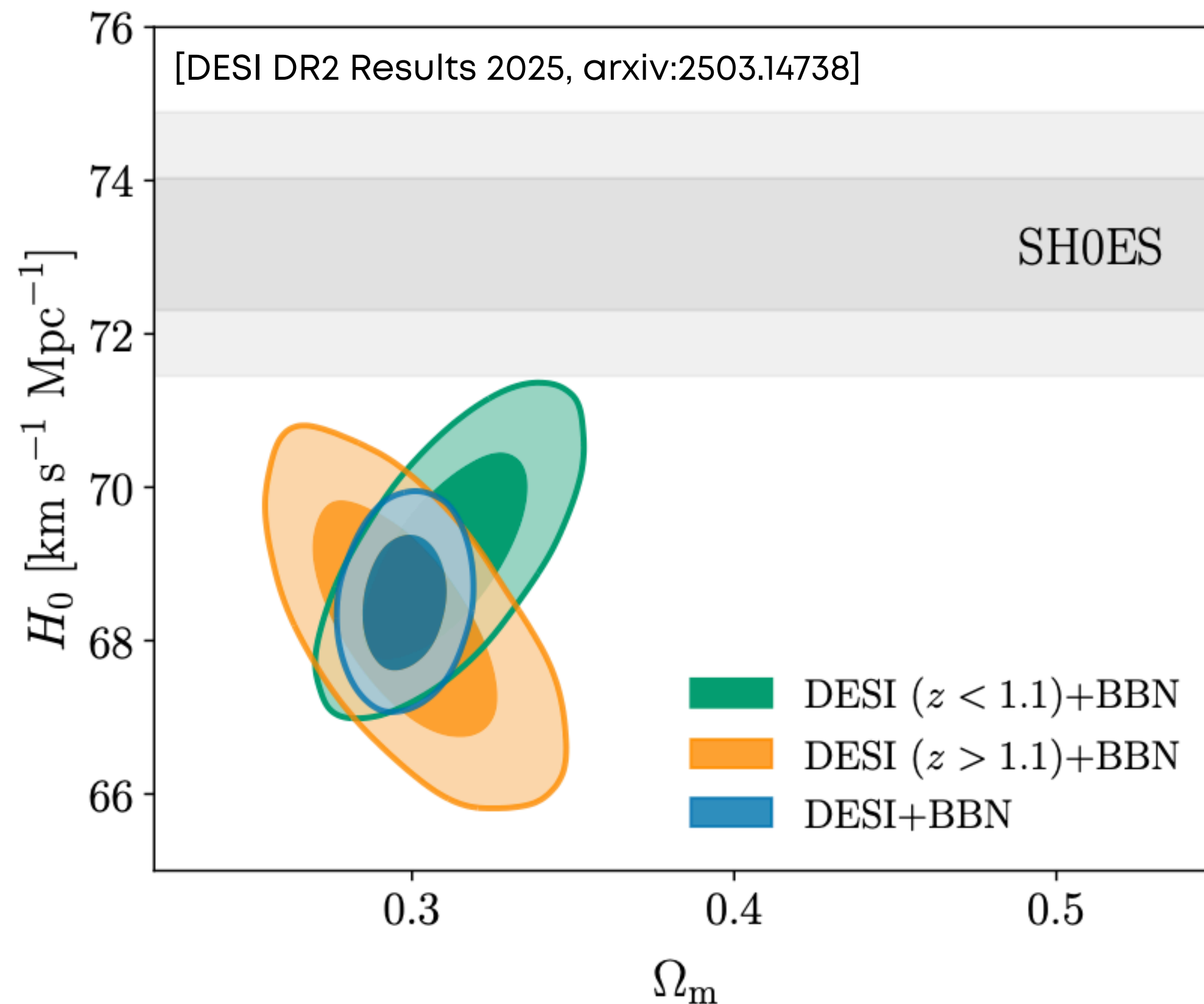
[DESI DR2 Results 2025, arxiv:2503.14738]



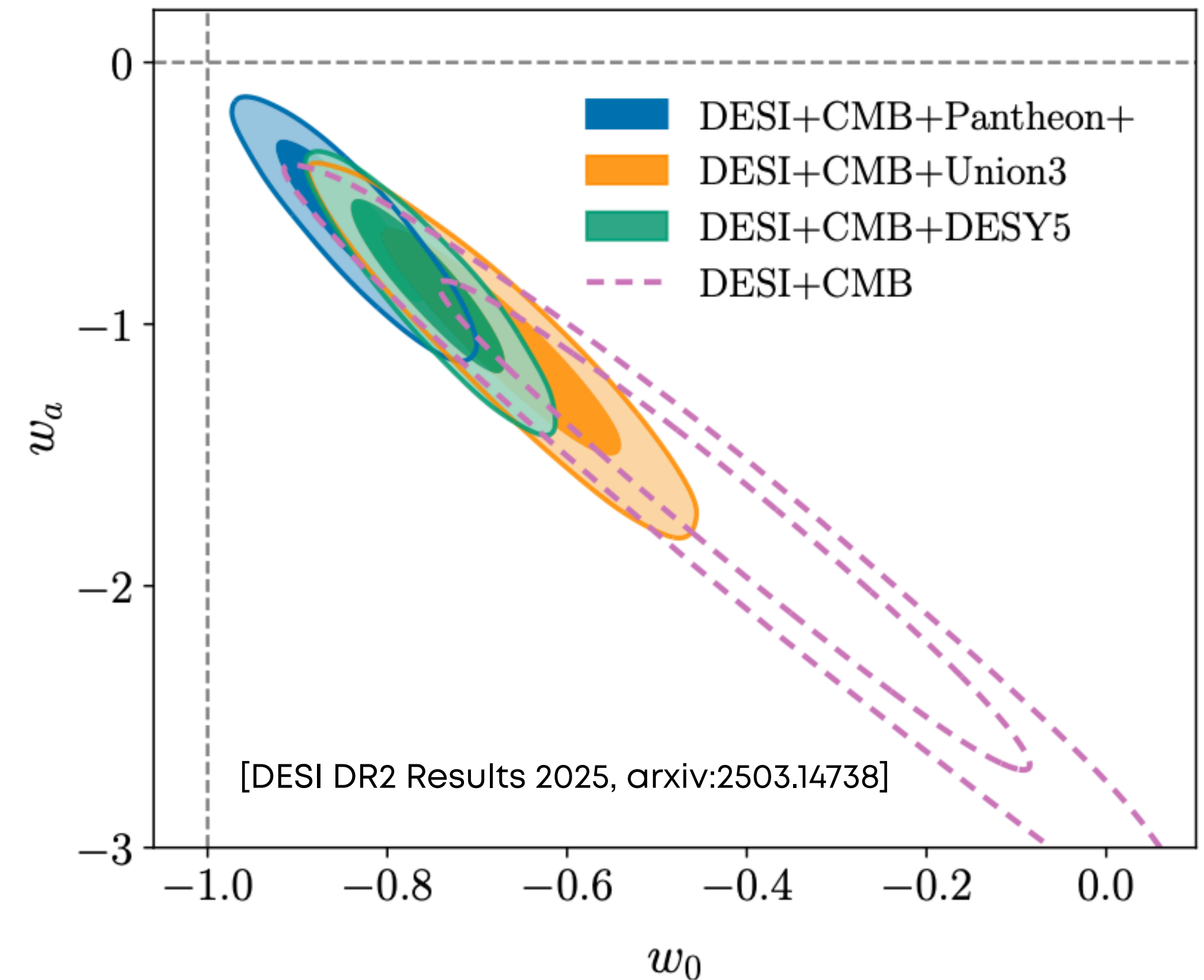
The H_0 tension at late times

● Tension of more than 3σ with SH0ES

● Hints of dynamical DE in DESI data



$$\dot{\rho}_{\text{DE}} + 3H\rho_{\text{DE}}(1 + w) = 0, \quad w = w_0 + w_a(1 - a)$$





Extensions to Λ CDM

“Late-time” solutions to the Hubble tension from extensions in the dark sector

- ‘Phantom dark energy’ ($w < -1$), DE-DM interactions, decaying DM, and many more...
- Planck data can easily accommodate a higher H_0 , but BAO and SN1a exclude this resolution
- Models affecting expansion history can reduce tension to 2-3 σ level

[Poulin et al, arxiv:2407.18292]

$$\text{CMB: } \theta_s \equiv \frac{r_s(z_*)}{D_A(z_*)}$$

$$D_A(z) \equiv \int_0^z \frac{dz'}{H_0 \sqrt{\Omega_m(1+z)^3 + \Omega_{DE}(1+z)^{3(1+w)}}} \dots$$

