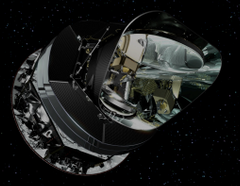
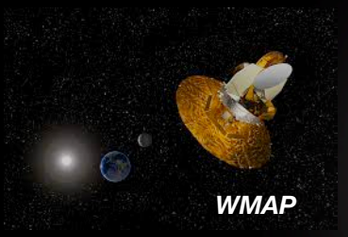


Planck



WMAP

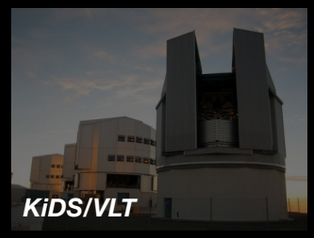
ACT

SPT

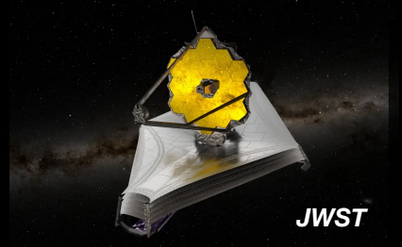
Highlights in Cosmology

DES

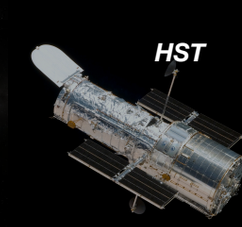
BOSS/SDSS



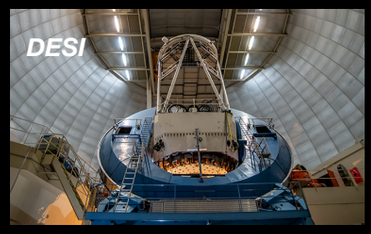
KiDS/VLT



JWST



HST



DESI

Vivian Poulin

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vivian.poulin@umontpellier.fr

SUSY 24
IFT, Madrid, Spain
June 13th, 2024

LUPM LABORATOIRE MONTPELLIER UNIVERS & PARTICULES
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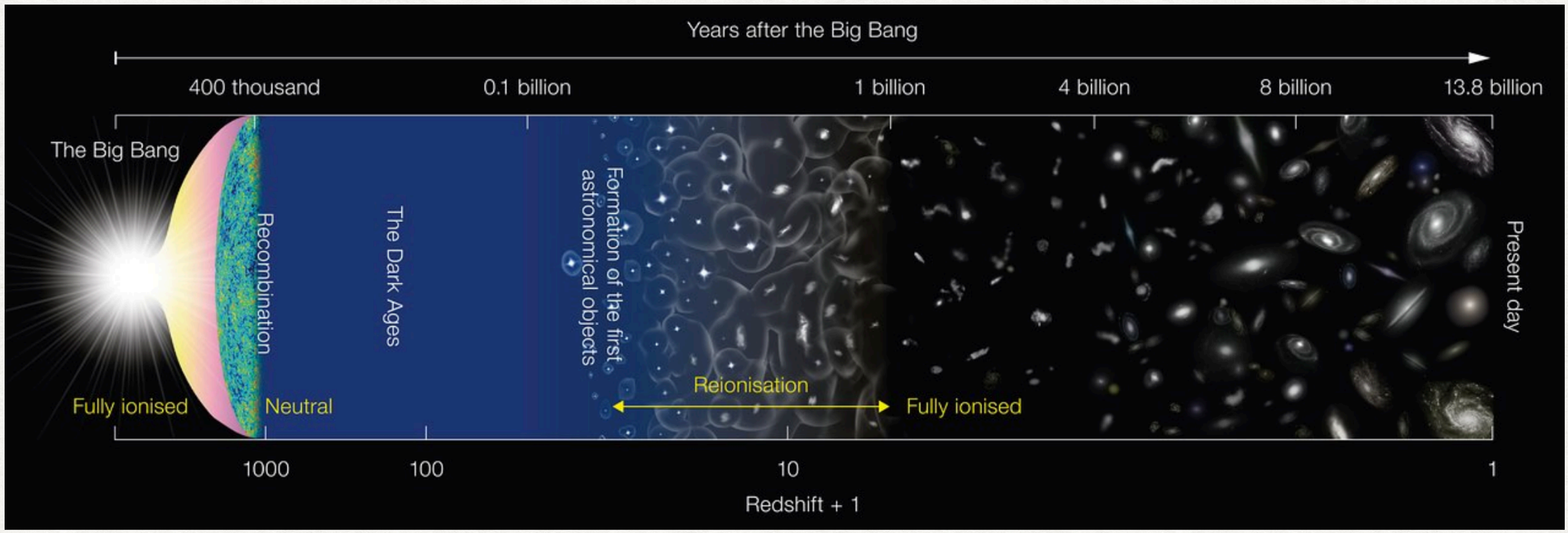
The Era of Precision Cosmology

Astonishing success of ΛCDM Cosmology: GR + Cosmological Principle

$\omega \equiv \Omega h^2, \;\; H_0 = 100h \text{ km/s/Mpc}$ $\quad\quad$ $\{H_0, \;\; \omega_b, \;\; \omega_{\rm cdm}, \;\; A_s, \;\; n_s, \;\; \tau_{\rm reio}\}$ $\quad\quad$ $\Omega_\Lambda = 1 - \Omega_m$



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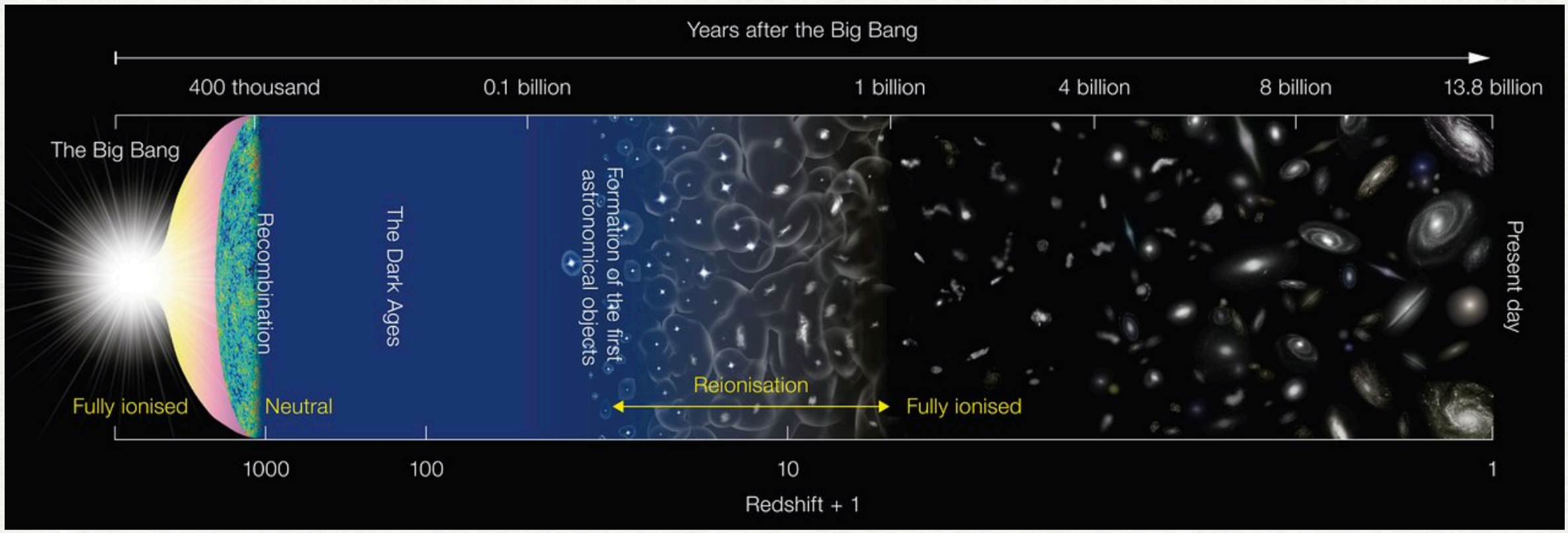
Expansion/matter content



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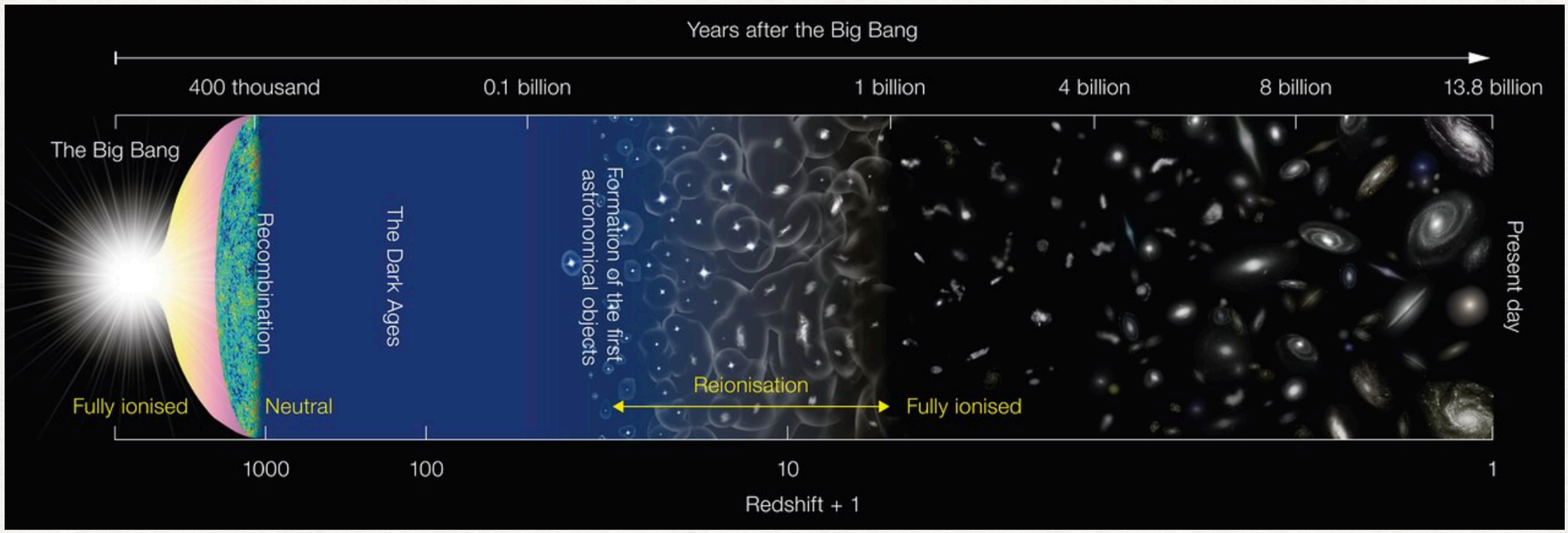
Expansion/matter content **Inflation**



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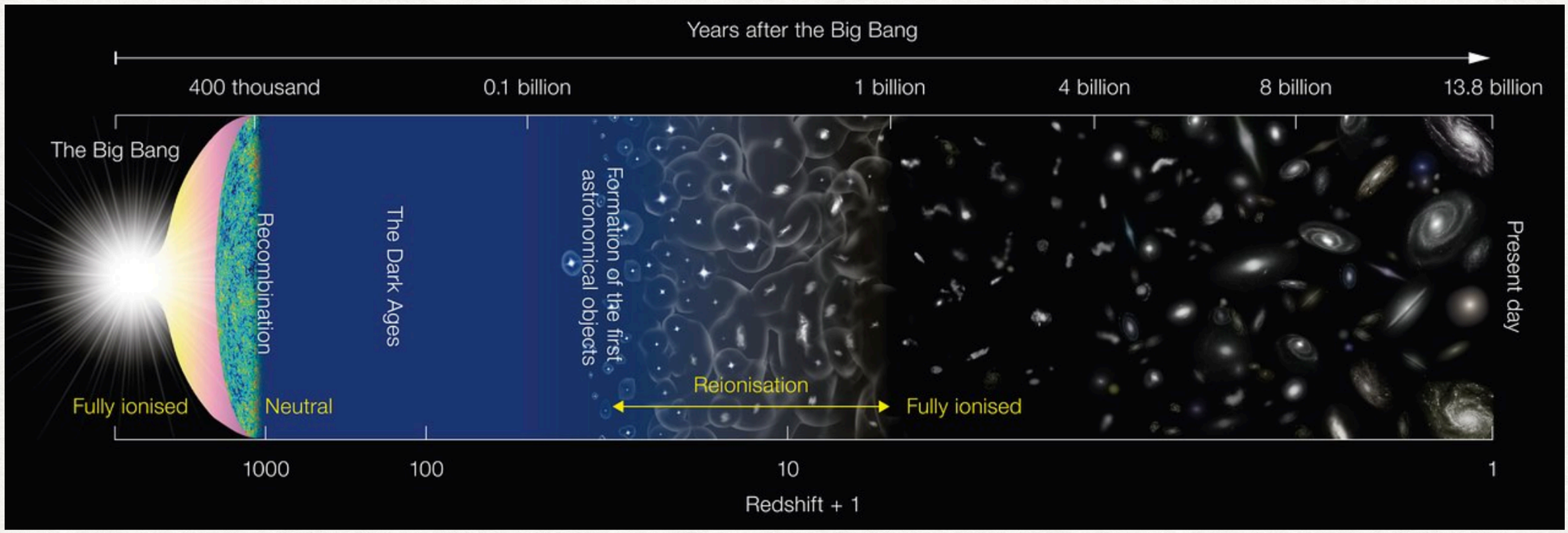
Expansion/matter content **Inflation** **star formation**



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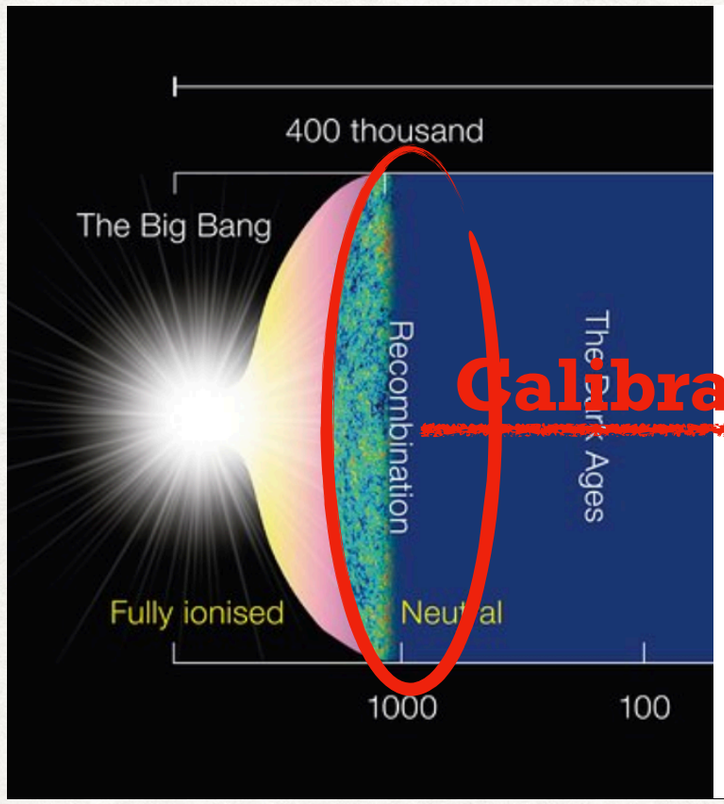
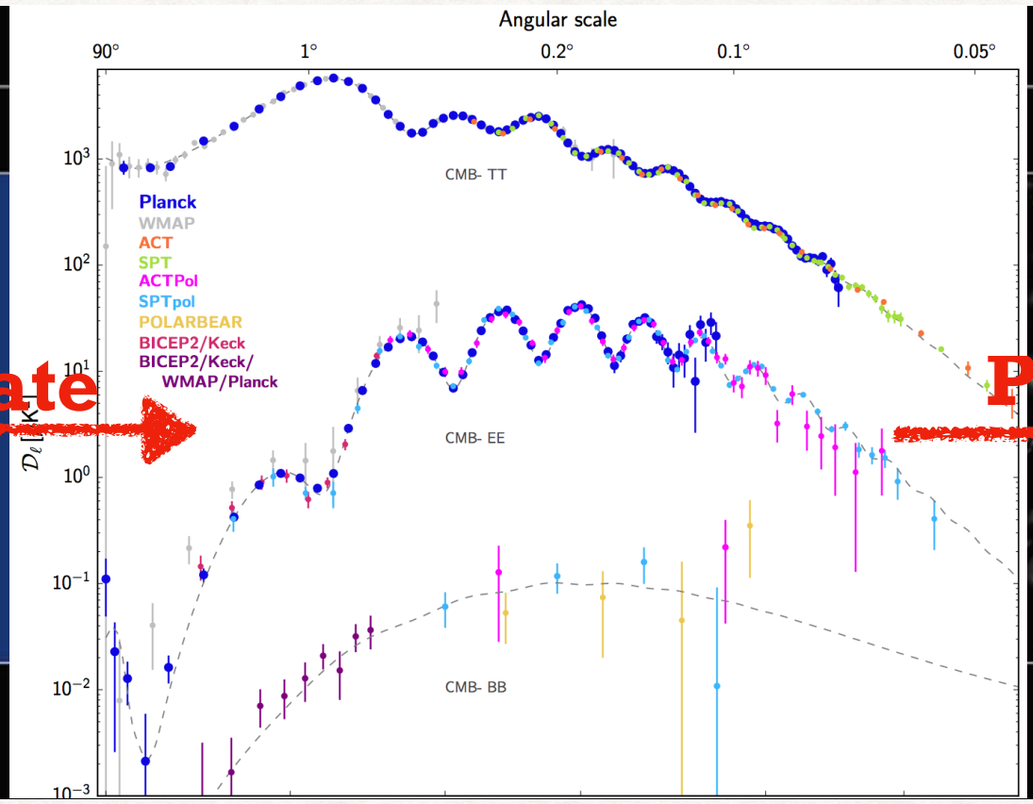
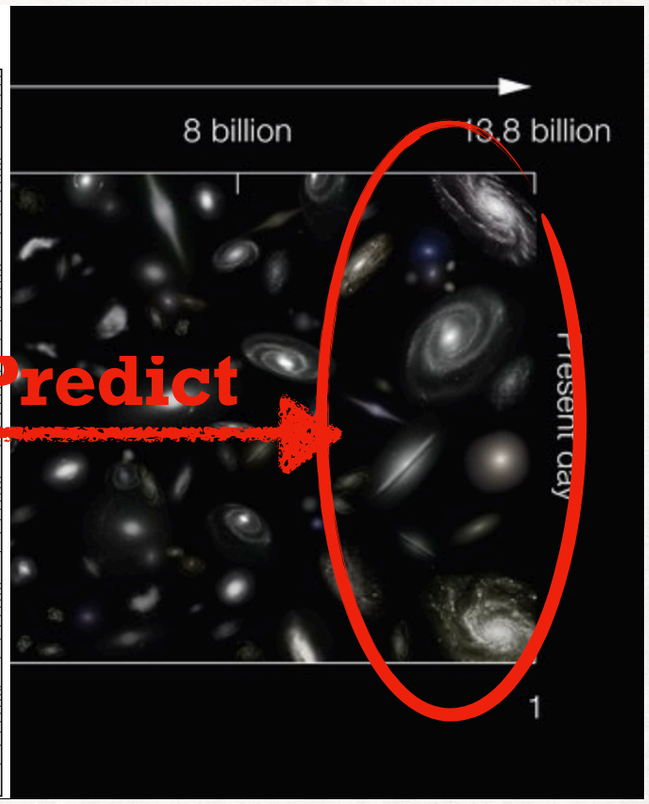


Calibrate



Predict



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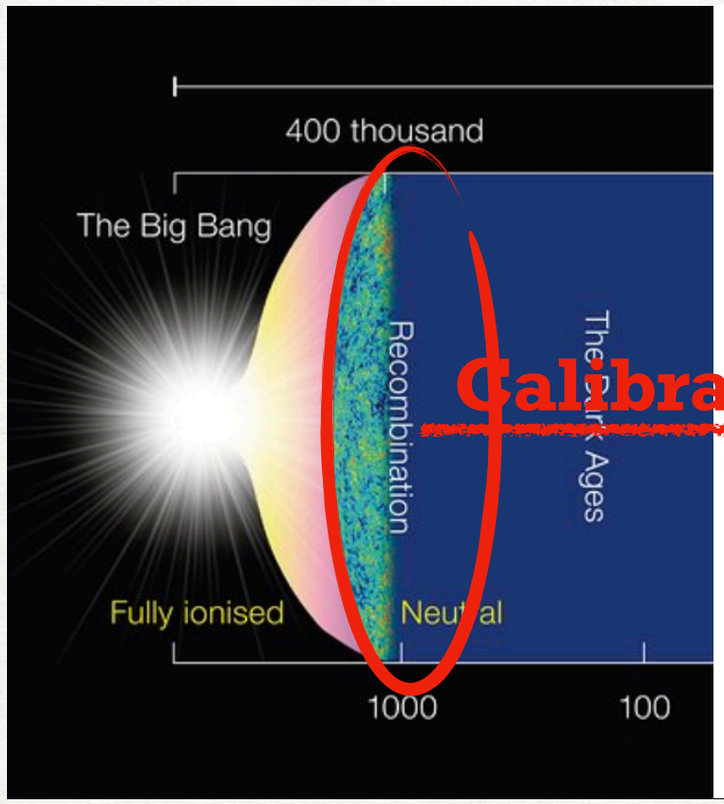

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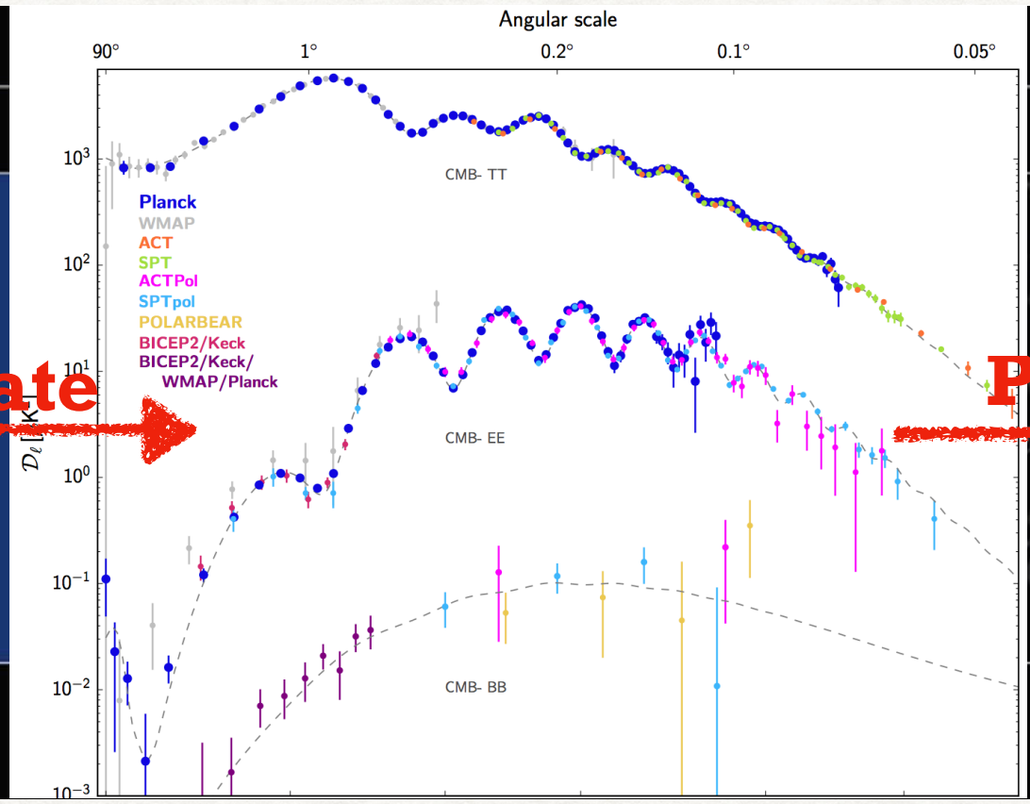

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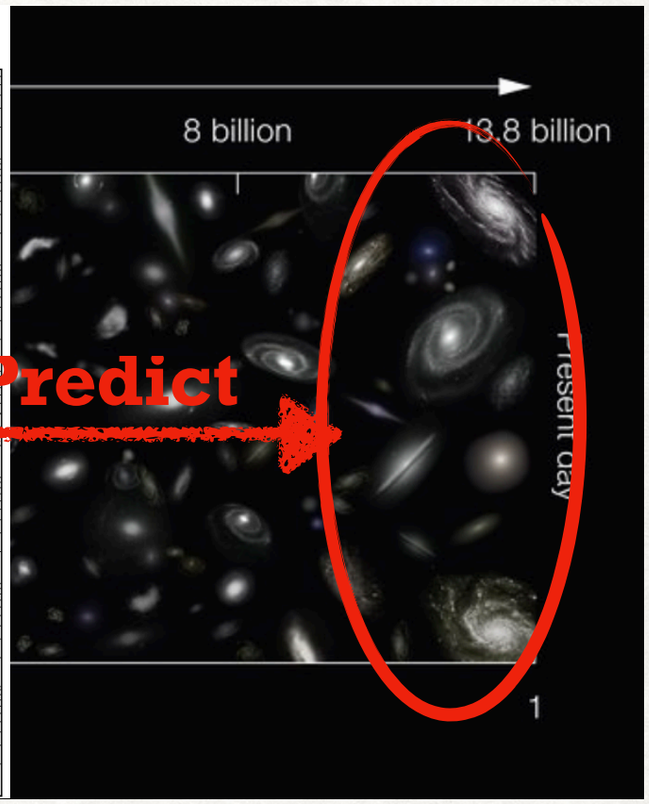

95% of the energy budget today is unknown! 70% Dark Energy, 25% Dark Matter.

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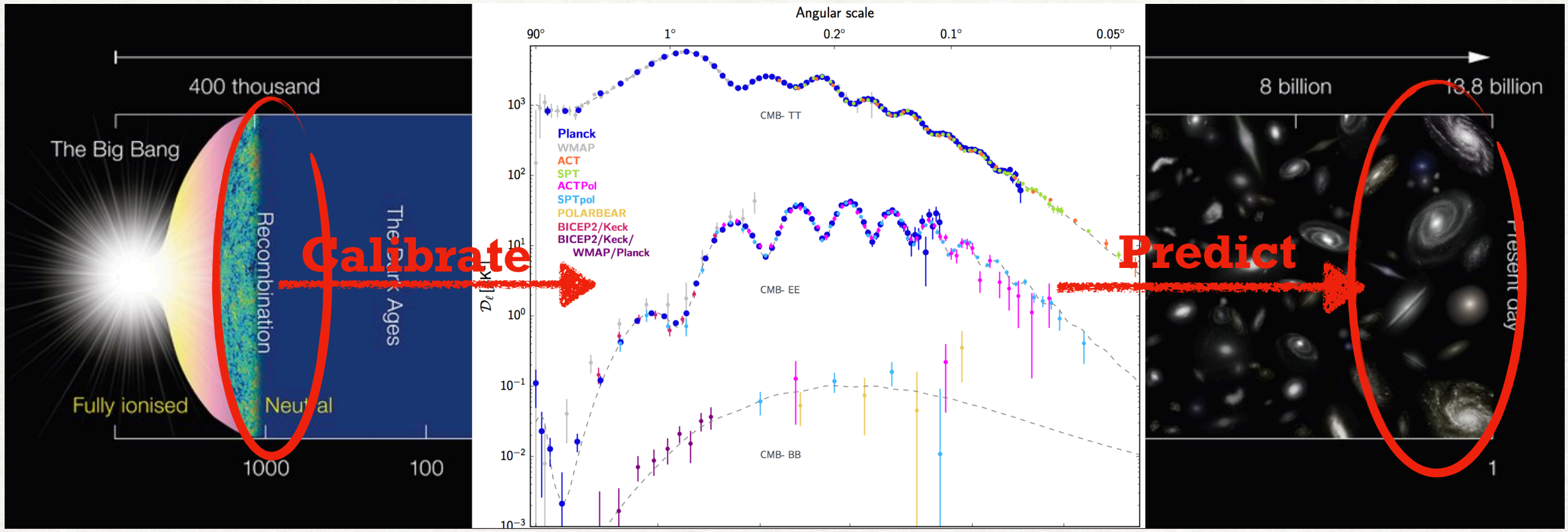

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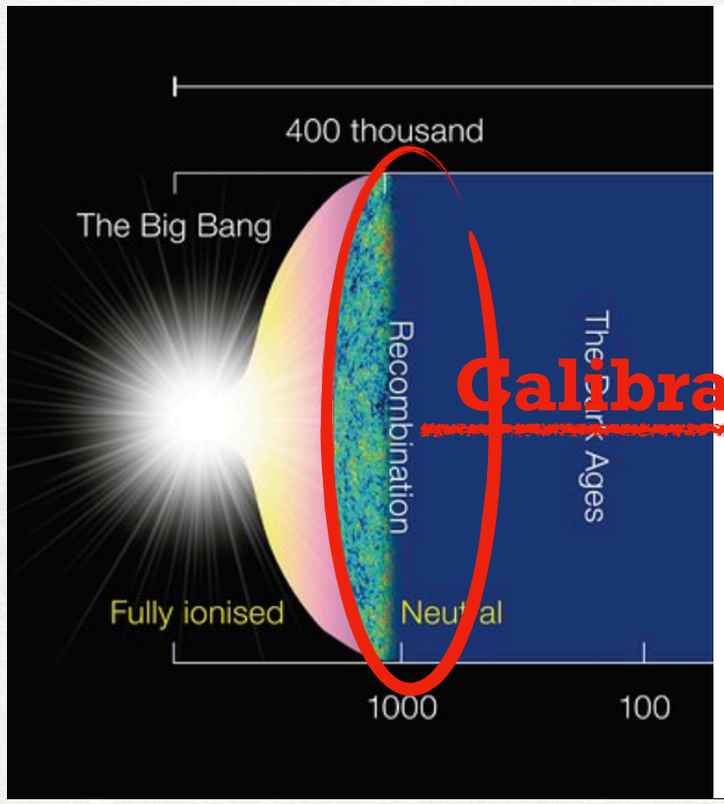

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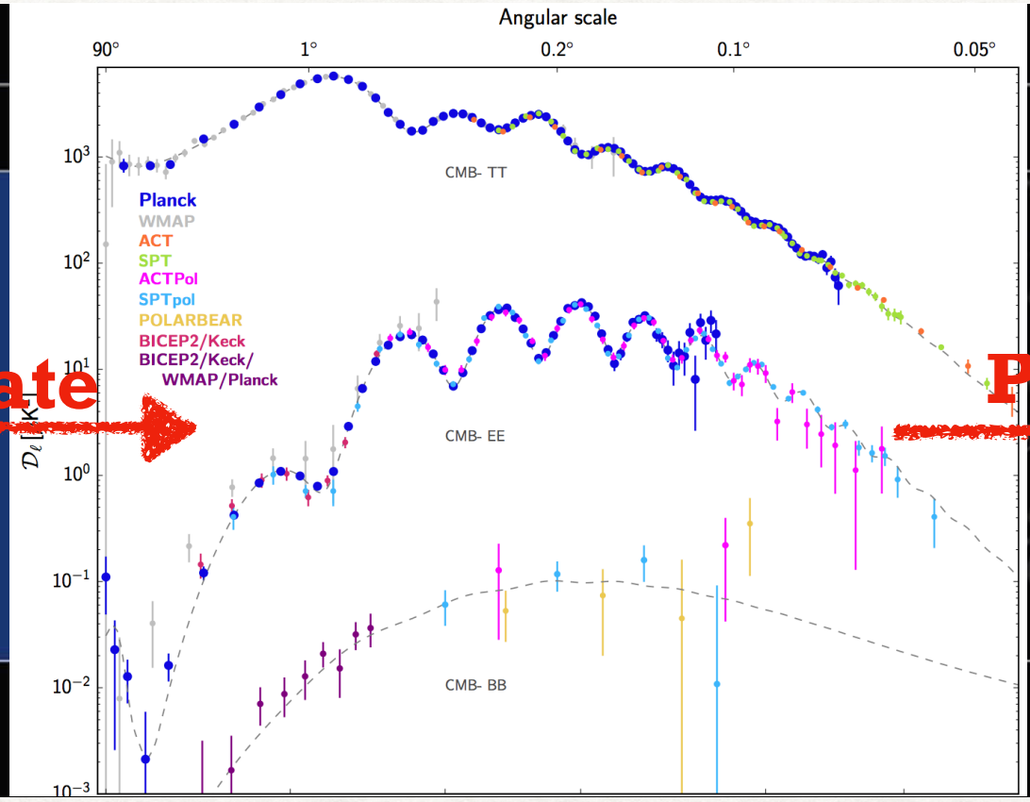

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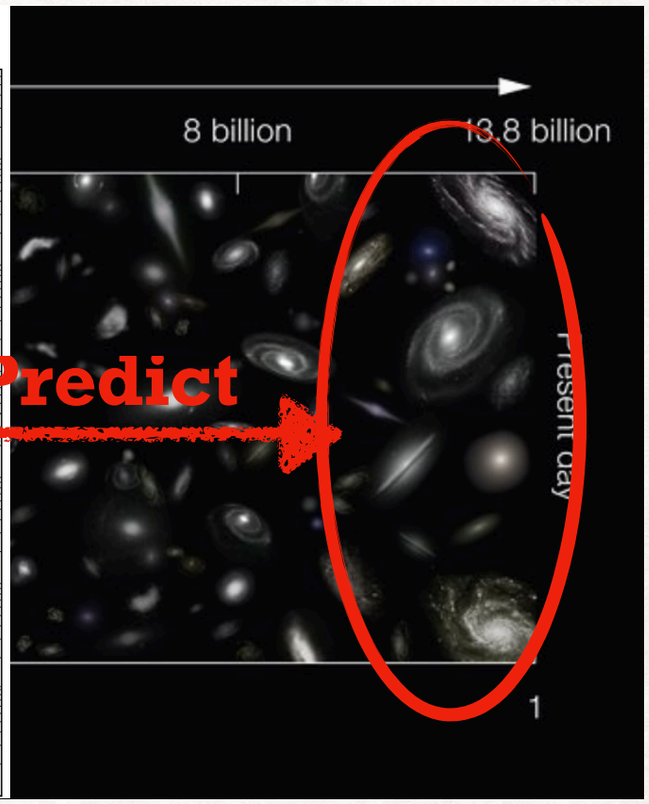

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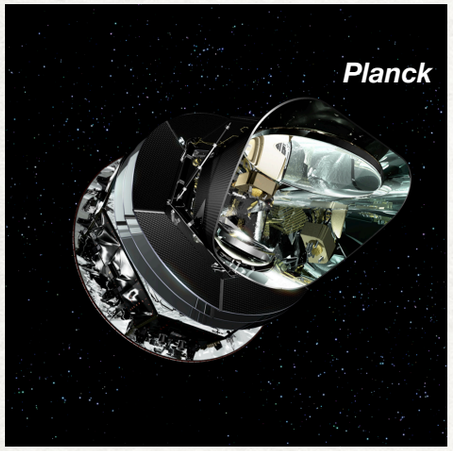
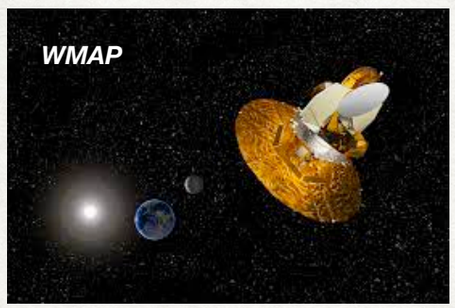
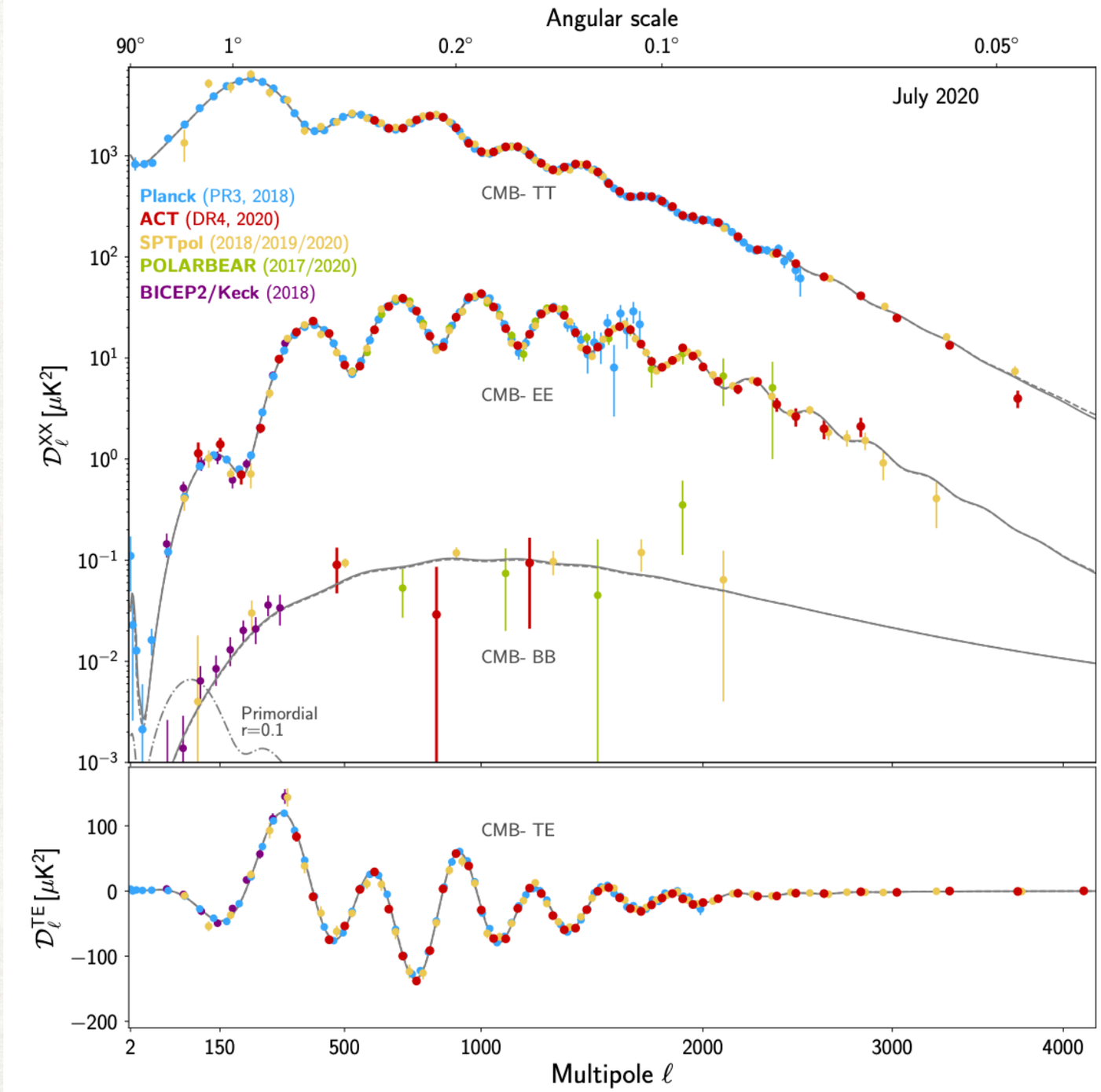
The mechanism behind its initial conditions is unknown.

How star formation happened and re-ionized the universe is unknown.

The Era of Precision Cosmology

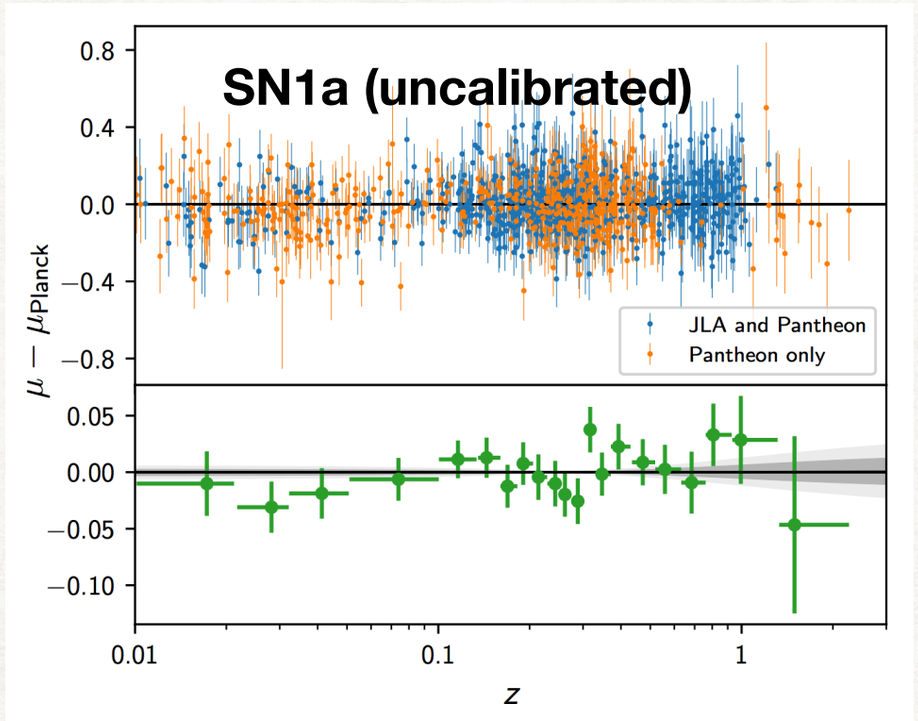




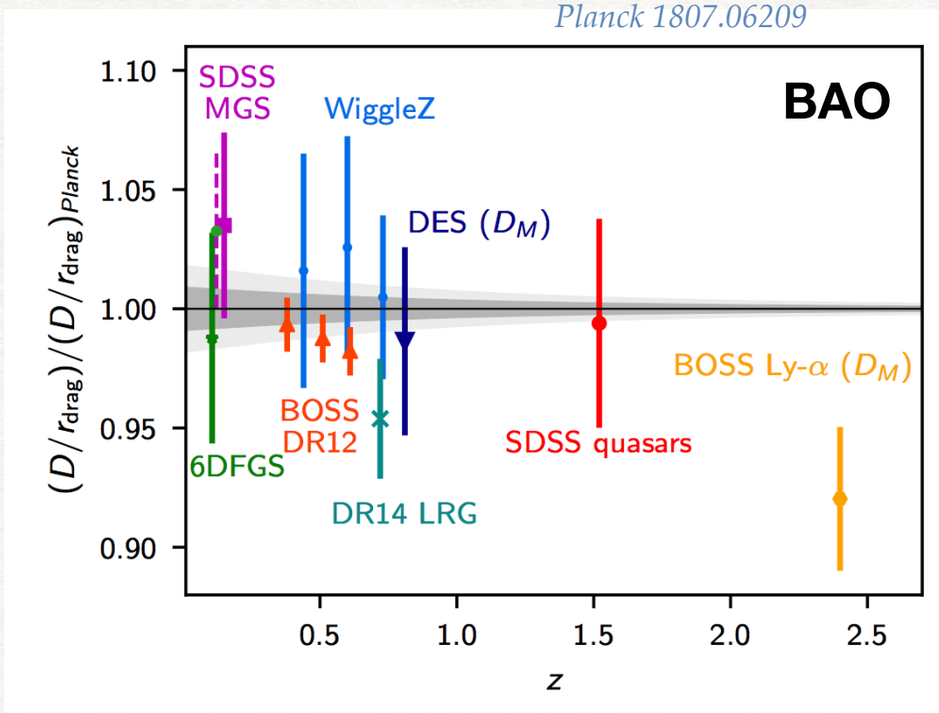


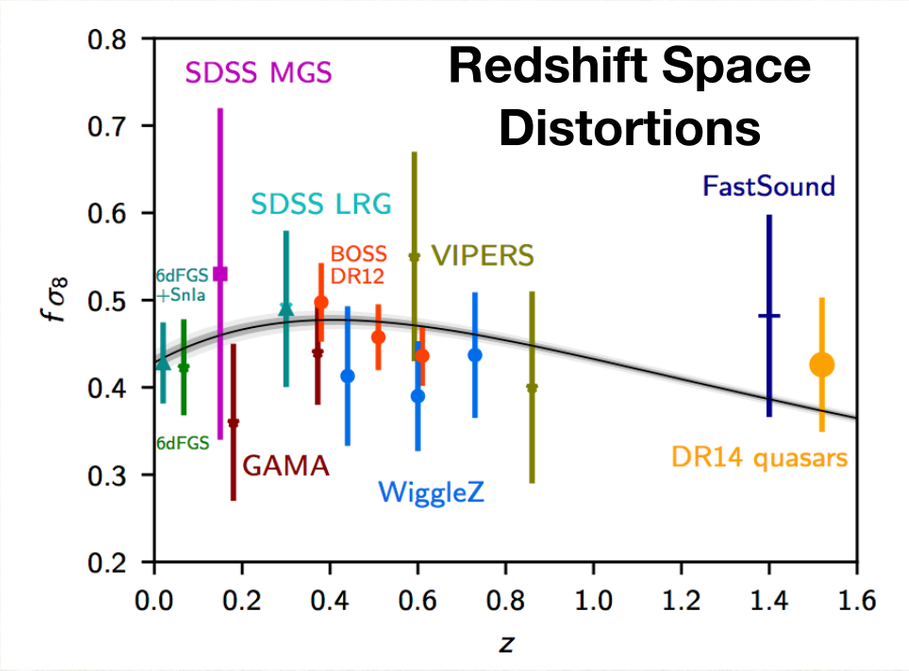
- ΛCDM can fit a wide variety of CMB data (well-)within $1-2\sigma$

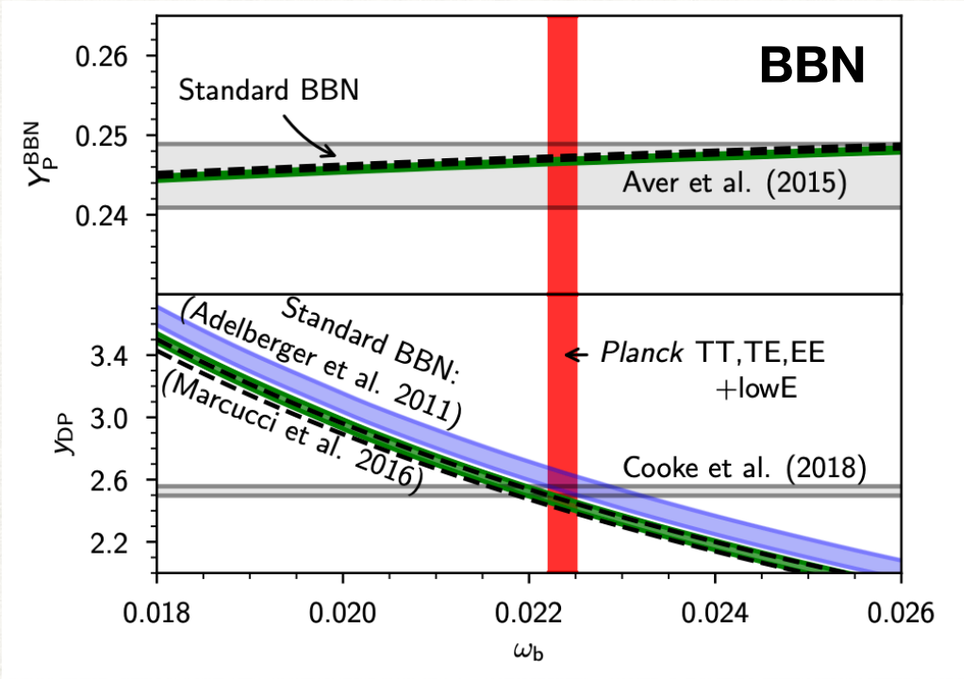
The Era of Precision Cosmology



Planck 1807.06209







- ΛCDM explains a wide variety of data (well-)within $1-2\sigma$

Precision Cosmology or Cosmic discordance?

The ΛCDM Cosmology is under extreme scrutiny… and starts showing cracks

- 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 H_0 and S_8?

  Abdalla++ 2203.06142

- Anomalies in *Planck* and ACT? Evidence for a curved universe?

  Di Valentino++ 1911.02087, Calderón++ 2302.14300

- Hints of 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 DM and DE?

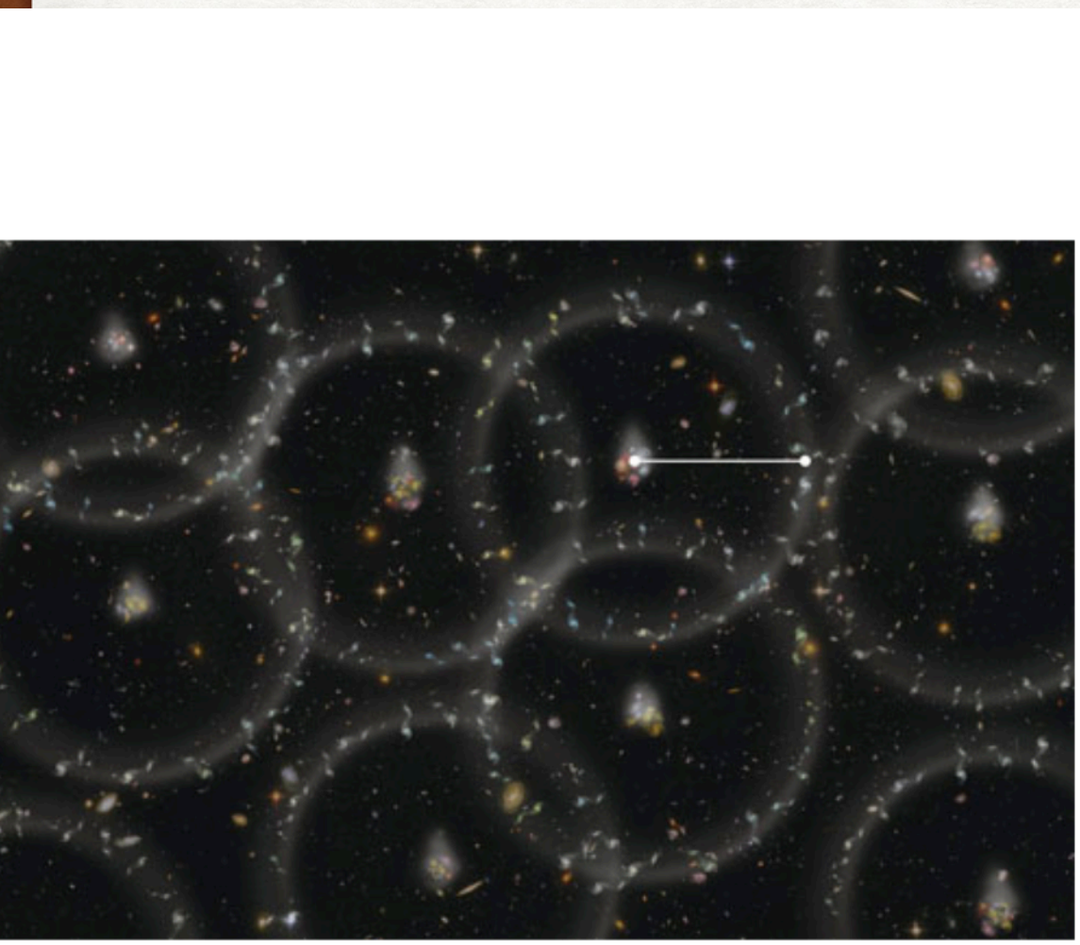
Is this a sign of a break down in the cosmological principle or GR?

Today I will highlight

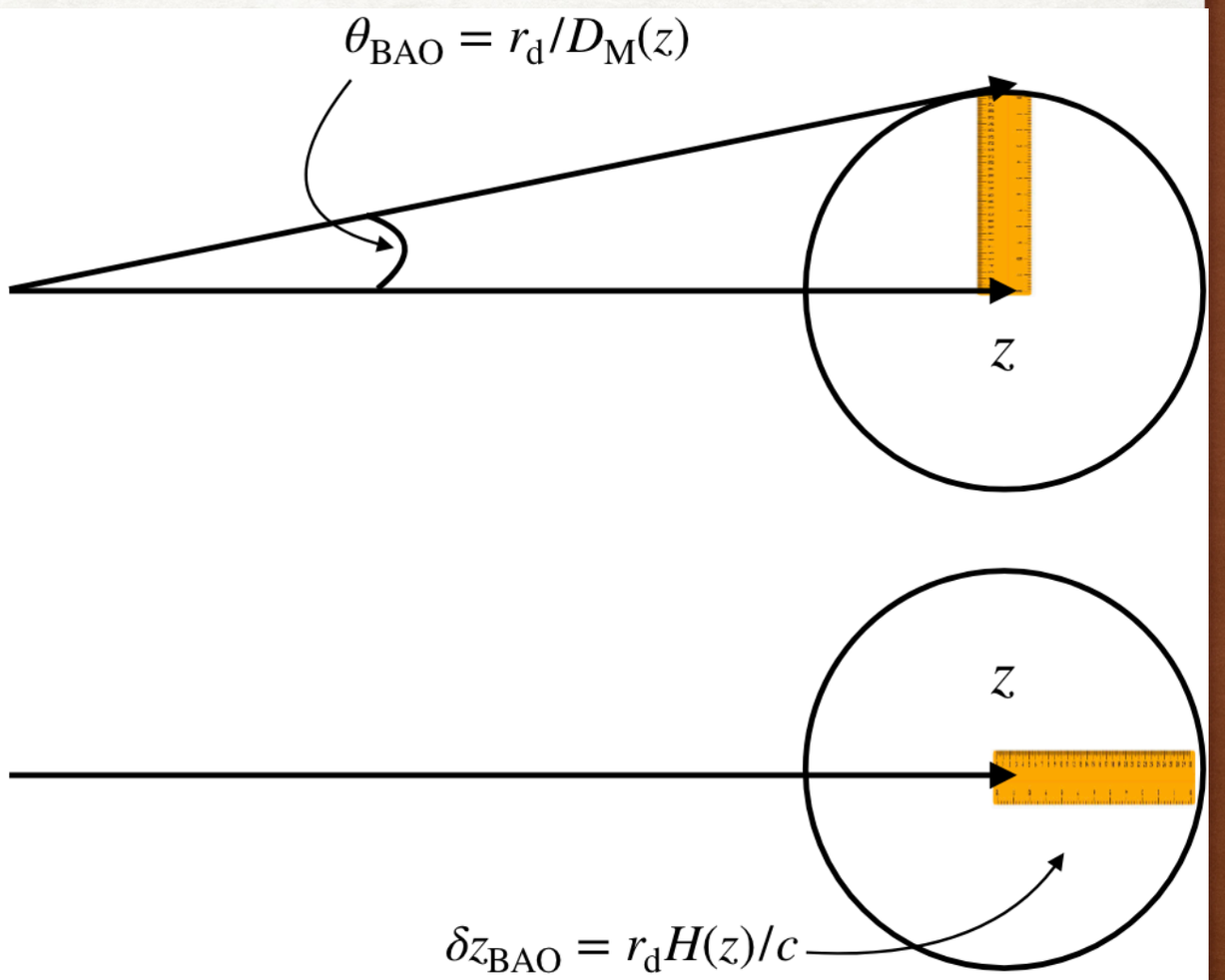
- DESI results on Dark Energy and neutrino masses
- The "Hubble tension" and its implications
- Update on the clustering tension S_8

The Baryonic Acoustic Oscillation with DESI

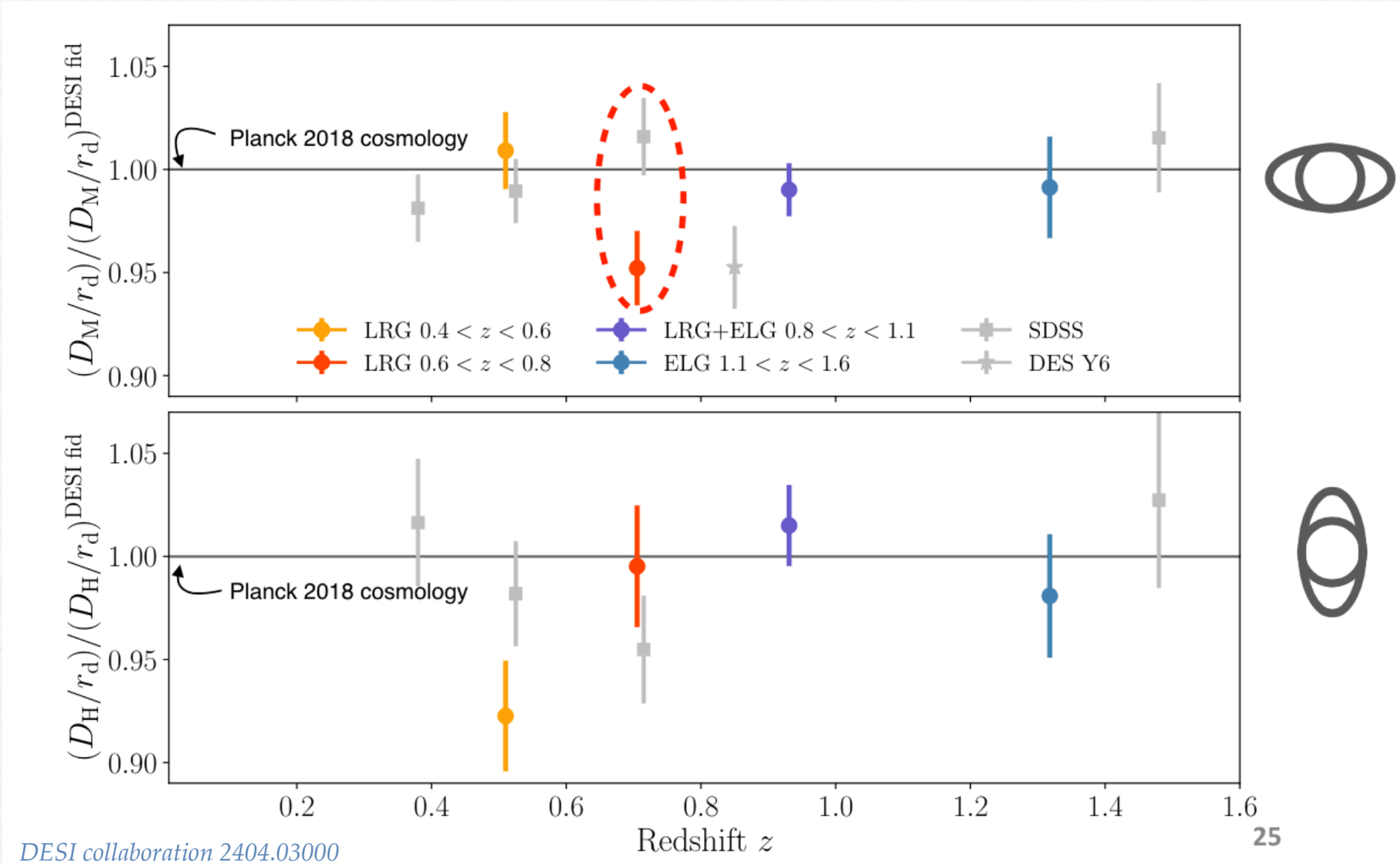
- Galaxy catalogues made of over 5 000 000 objects with $z \sim 0.1 - 2.1$
- They can be used to measure the BAO: sound-wave propagating in the primordial plasma
- They are the baryonic counterparts of what is seen in CMB anisotropies



Picture from Etienne Burtin



A statistical fluke in DESI?

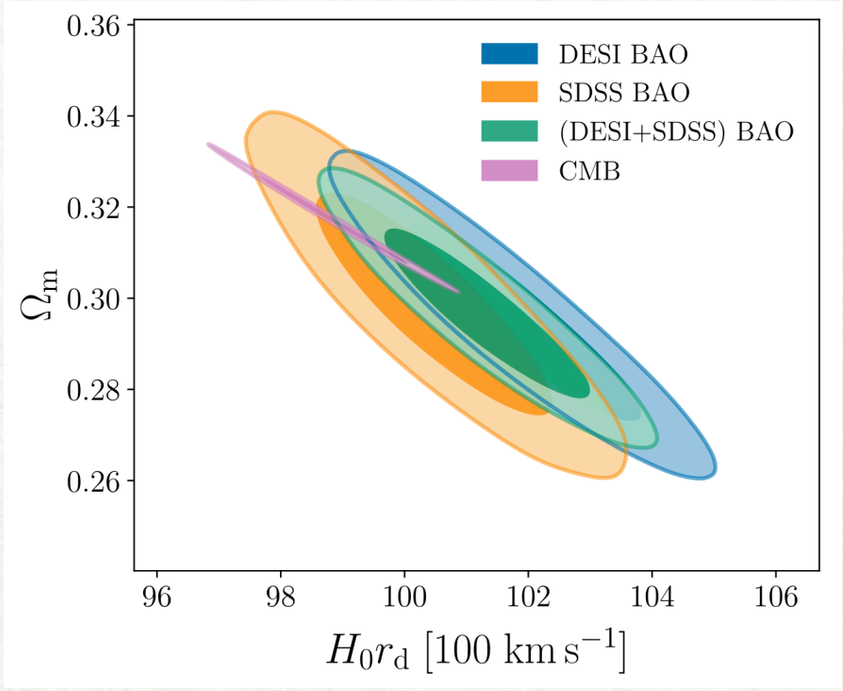


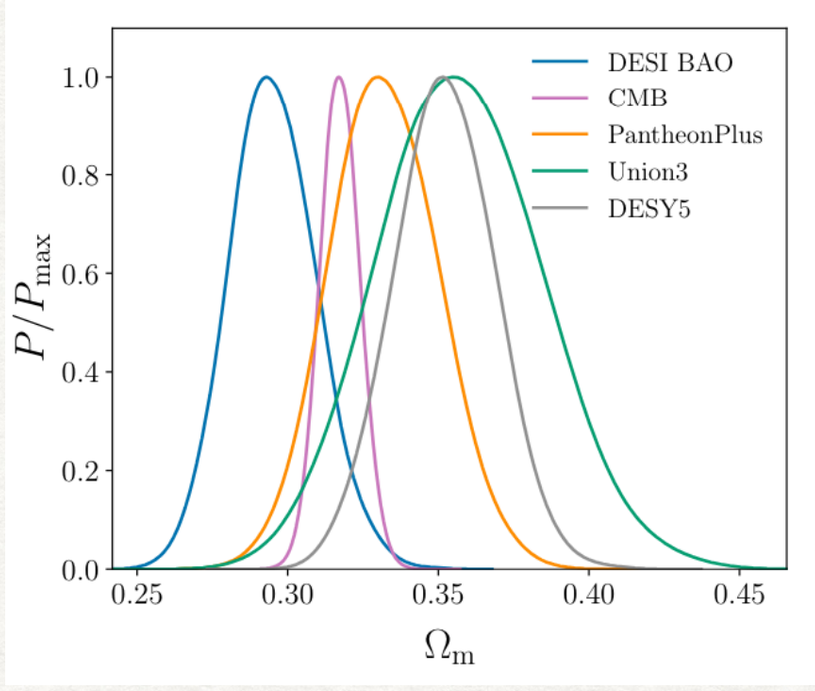
DESI collaboration 2404.03000

25

- DESI in tension at the $\sim 2-3\sigma$ level with SDSS?
- Given some level of correlation between SDSS/DESI, it is compatible with fluke

DESI constraints under ΛCDM

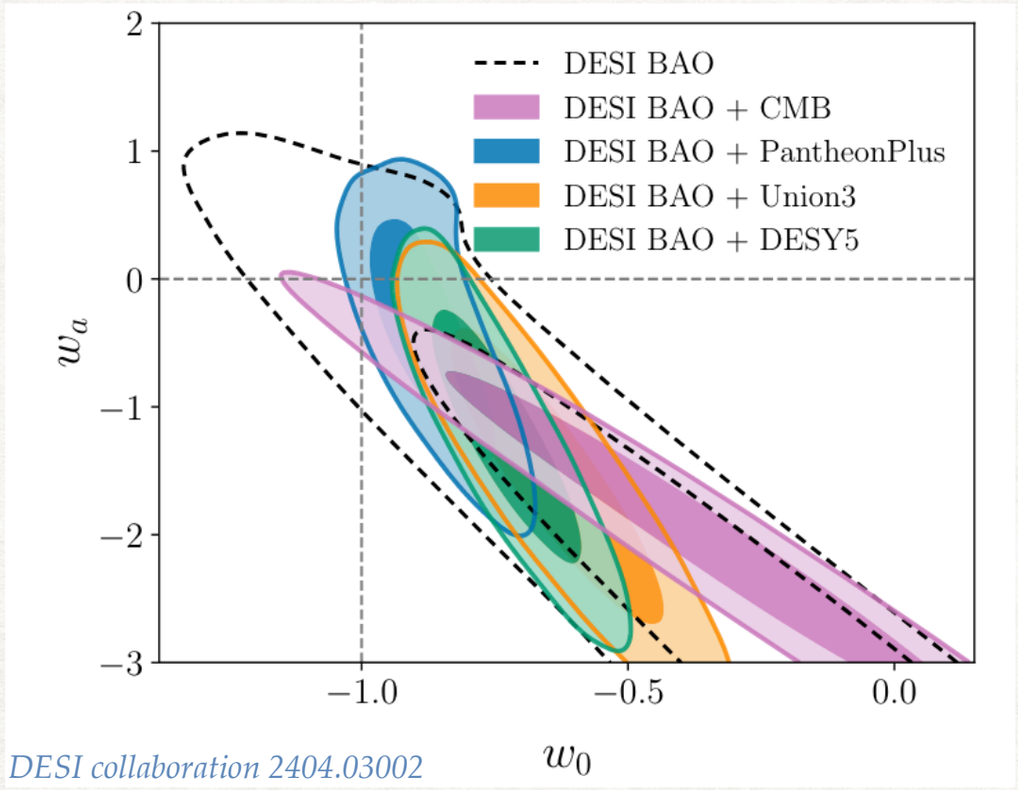




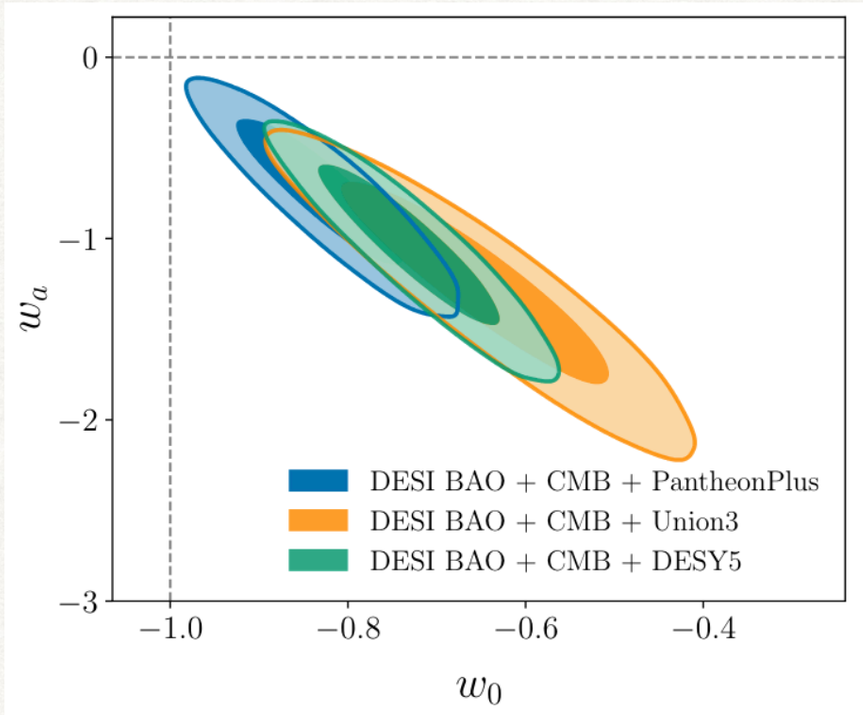
DESI collaboration 2404.03002

- Under ΛCDM, BAO measures Ω_m and the product $H_0 r_d$.
- DESI remains in agreement at the $\sim 2\sigma$ level with the CMB
- DESI+CMB in tension(?) at the $\sim 2-3\sigma$ level with SN1a in the determination of Ω_m

Bounds on Dark Energy properties



DESI collaboration 2404.03002

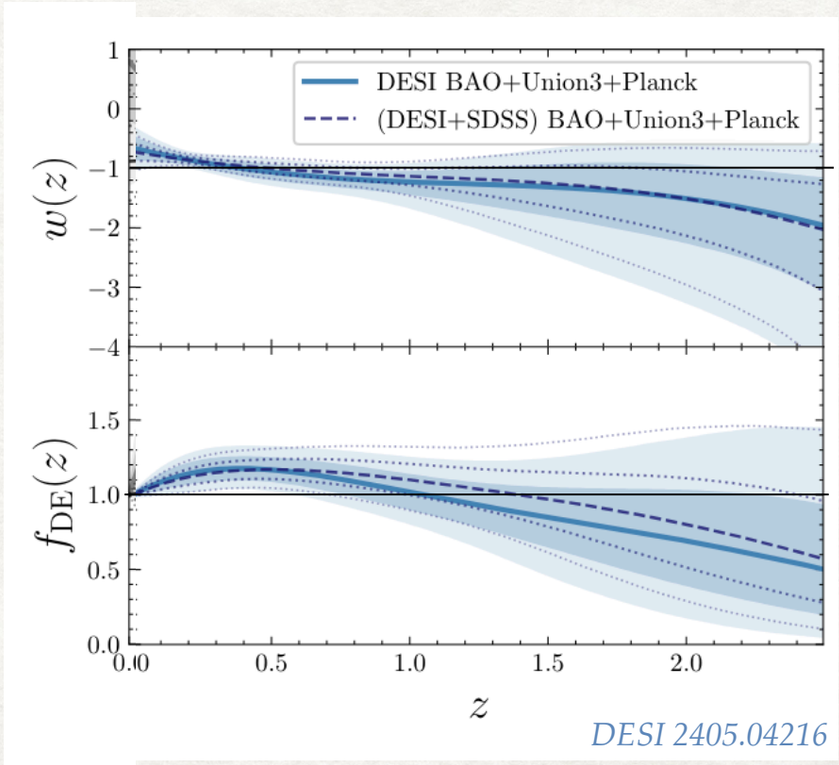


- $w(a) = w_0 + w_a(1-a)$ *Chevallier, Polarski 2001; Linder 2002*
- $2.5-4\sigma$ preference for $w_0 > -1$, $w_a < 0$:
  ==> Phantom crossing? It's artificial!

See also Shlivko&Steinhardt 2405.03933, Berghaus++ 2404.14341, DESI 2405.04216, 2405.13588

- Reduce to $2-3.5\sigma$ with SDSS.
- Universe is compatible at 2σ with no acceleration today!

DESI 2405.04216



DESI 2405.04216

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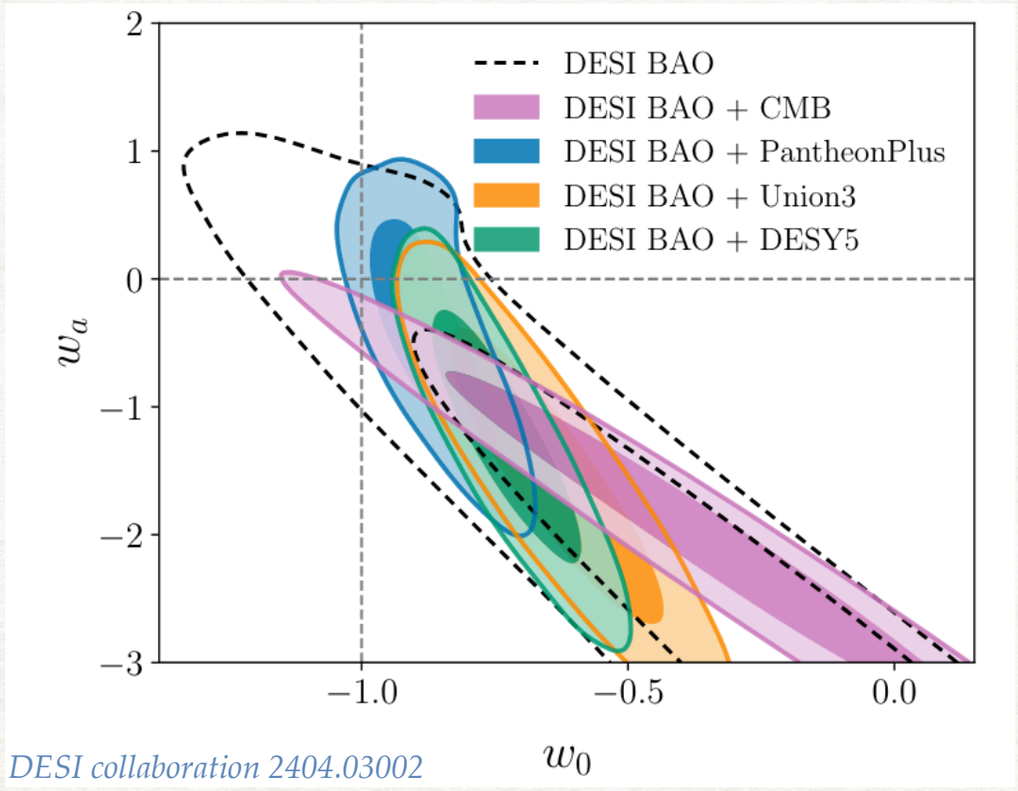
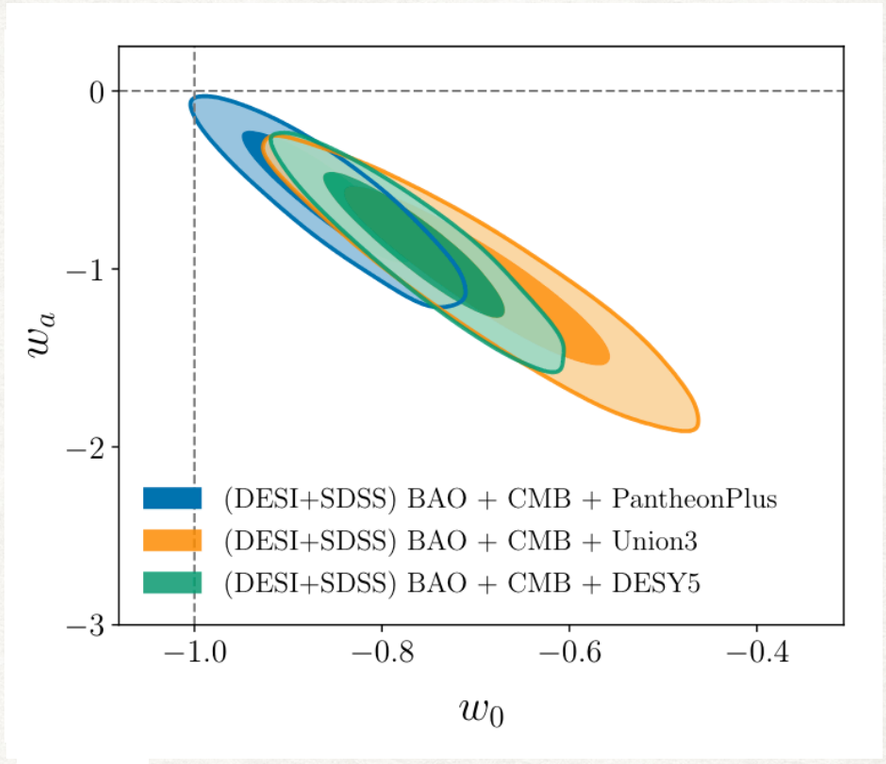


DESI collaboration 2404.03002



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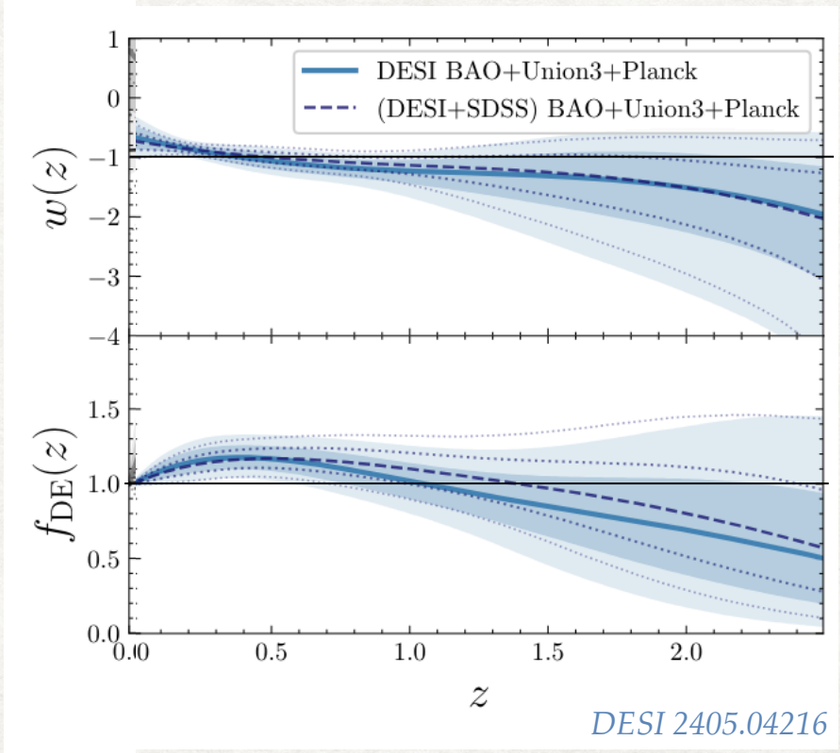


DESI 2405.04216

Bounds on neutrino masses

- Oscillation experiments: $M_\nu = \sum m_\nu \gtrsim 0.06$ eV (NO) or $M_\nu \gtrsim 0.10$ eV (IO)

Katrin: $M_\nu < 2.4$ eV *Nature Physics 18 (2022) 160*

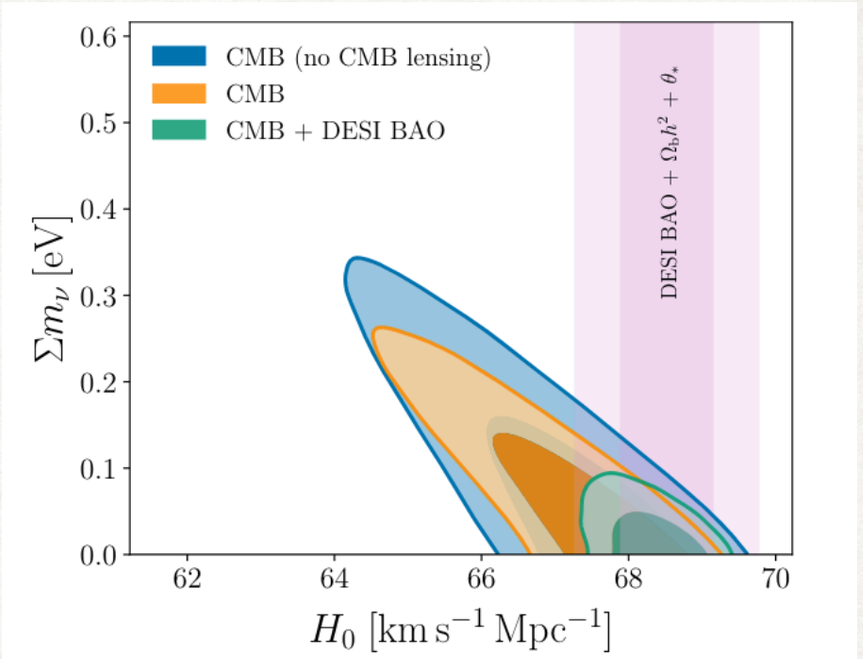
Planck 2018 + BAO: $M_\nu < 0.12$eV *A&A 1807.06209*

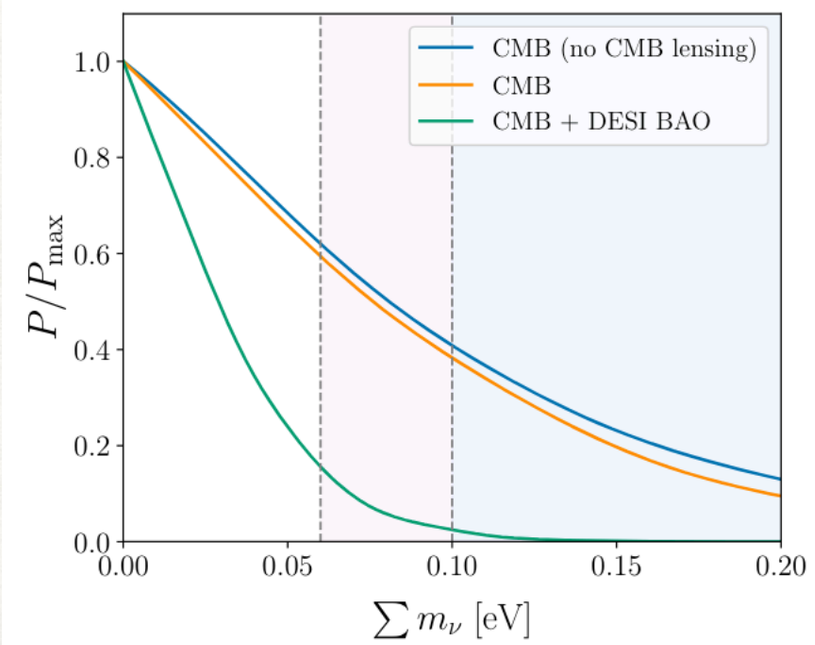
Planck 2018 + BAO + Ly$-\alpha$: $M_\nu < 0.089$eV *Palanque-Delabrouille++ 1911.09073*

Planck 2018 + BOSS + eBOSS: $M_\nu < 0.082$eV *Brieden++ 2204.11868*

Planck 2018 + DESI: $M_\nu < 0.072$eV *DESI collaboration 2404.03002*

Planck 2018 + DESI + $w_0 w_a$: $M_\nu < 0.195$eV



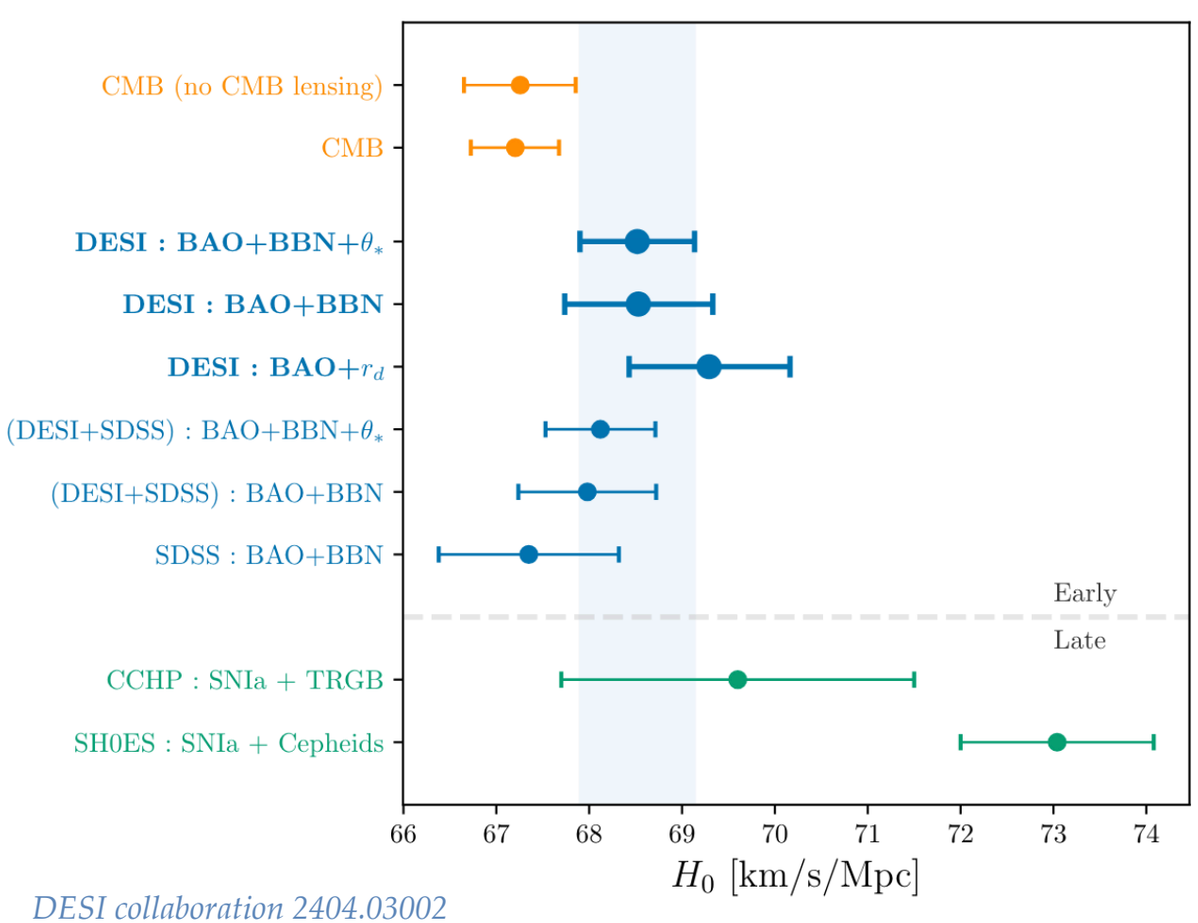


- Could DESI favor "negative neutrino masses?"

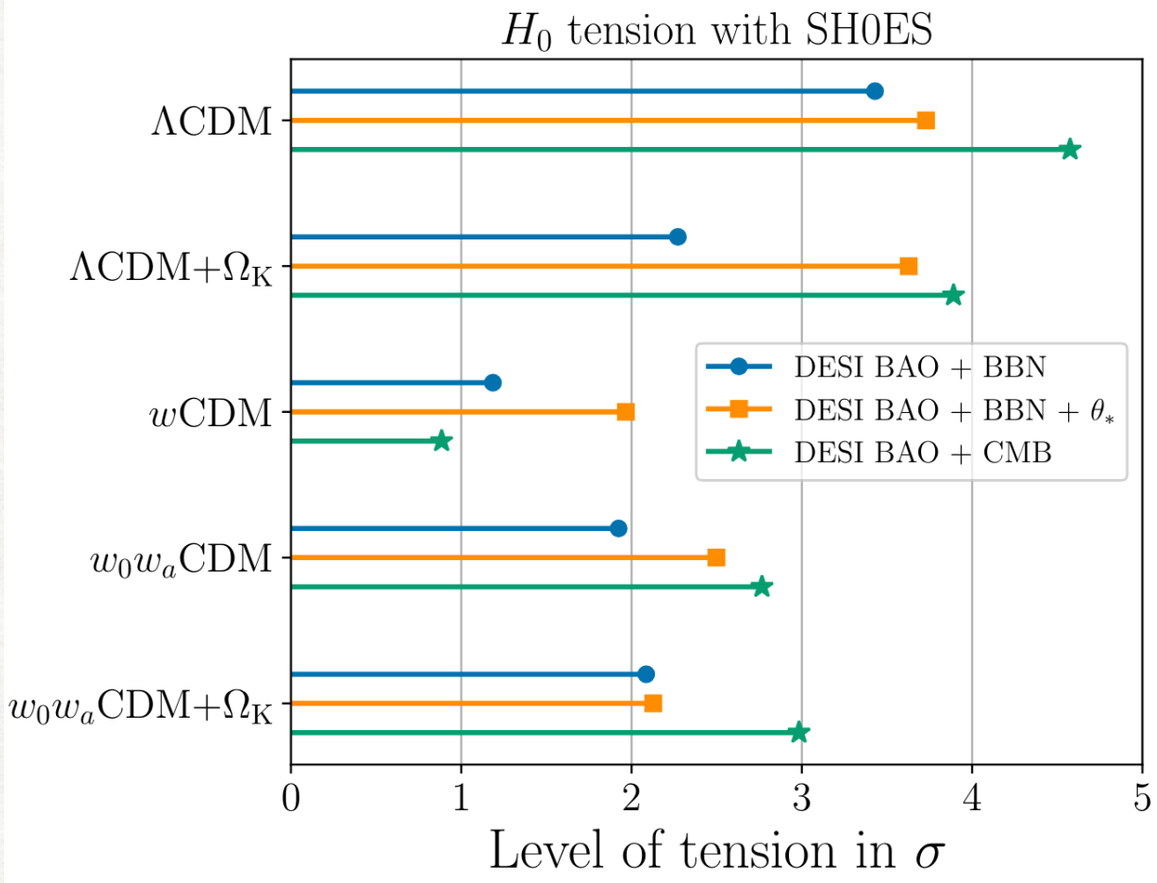
Craig++ 2405.00836
Ongoing work w/ D. Naredo, M. Escudero, E. Fernandez, X. Marcano

Status of the Hubble tension after DESI

- Combining CMB+BAO allows to break the $H_0 r_d$ degeneracy and to measure H_0



DESI collaboration 2404.03002

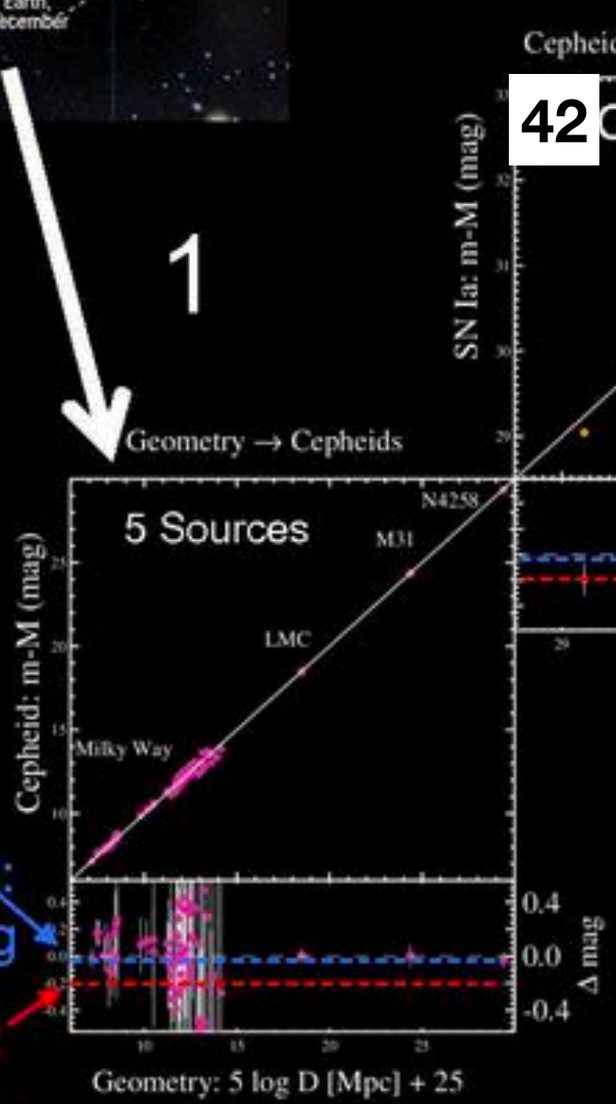


- Under ΛCDM: 4.5σ tension, small upward shift in H_0.
- Under wCDM: less than 1σ tension! Really??

The Hubble Constant in 3 Steps: Present Data

1

Geometry → Cepheids

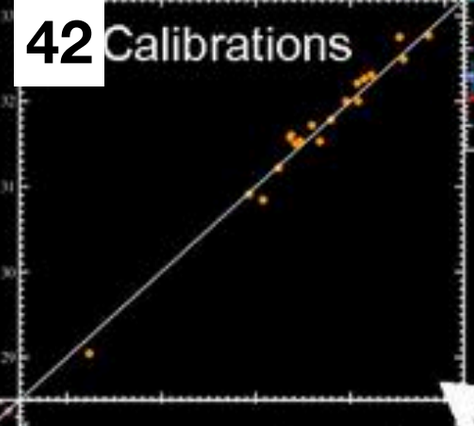


1% Goal: 0.02 mag

Tension: 0.2 mag

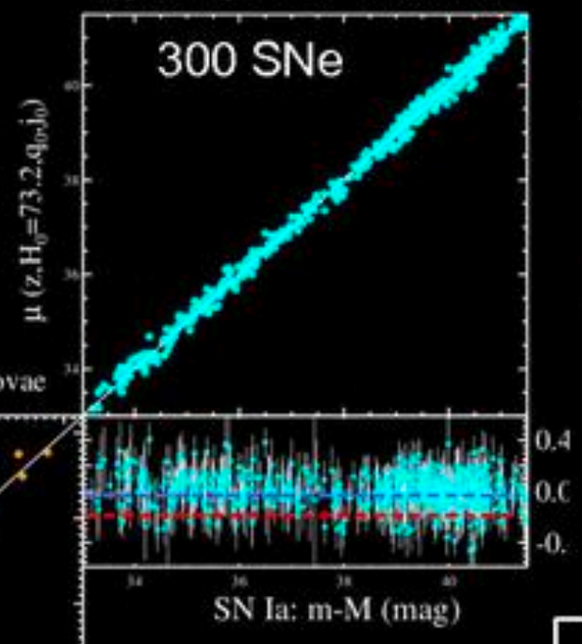
Cepheids → Type Ia Supernovae

42 Calibrations

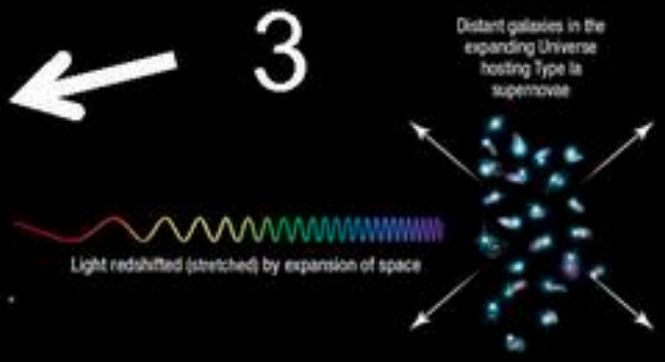


2

Type Ia Supernovae → redshift(z)



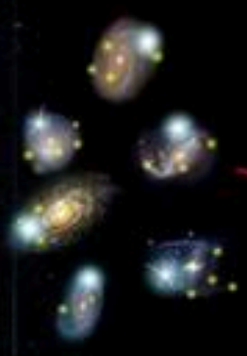
3



$5\log H_0 = M_B^0 + 5a_B + 25$

$H_0 = 73 \pm 1.0$ Km s^{-1} Mpc^{-1} (Riess et al. 2019)

Galaxies hosting Cepheids and Type Ia supernovae



1.4% total uncertainty

5.0 σ from CMB + ΛCDM !

$H_0 = 67.4 \pm 0.5$ km/s/Mpc

Adapted from slide by A. Riess, KITP July 2019

Systematics? A non-exhaustive list

See review Di Valentino++ 2103.01183 for all relevant references

- SH0ES builds a 3 steps distance ladder: anchors => cepheids => SN1a
- Are there issues with distance anchor? (GAIA, LMC, NGC4258)
  Efstathiou++ 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? *Efstathiou++ 2007.10716*
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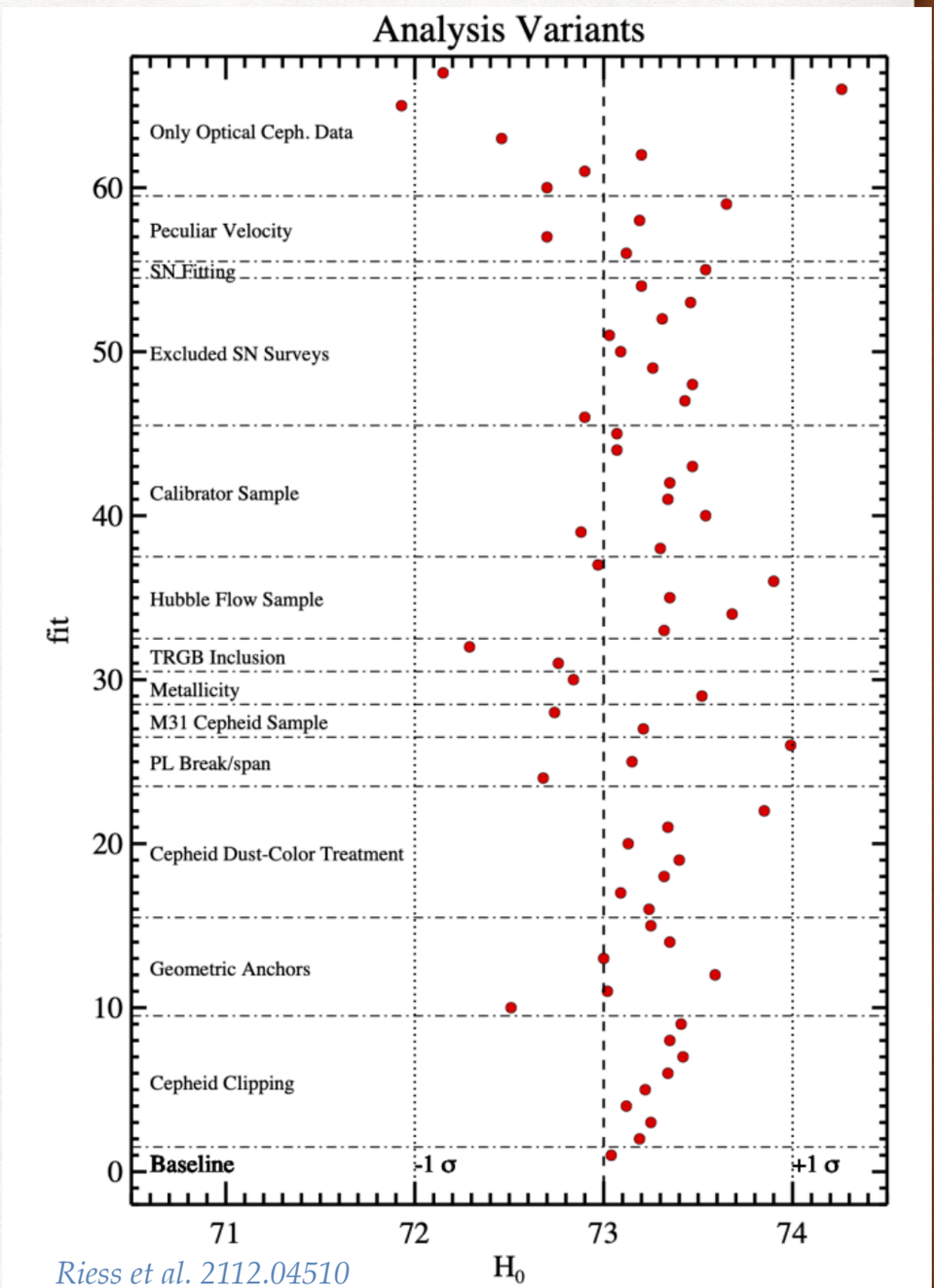

Riess et al. 2112.04510

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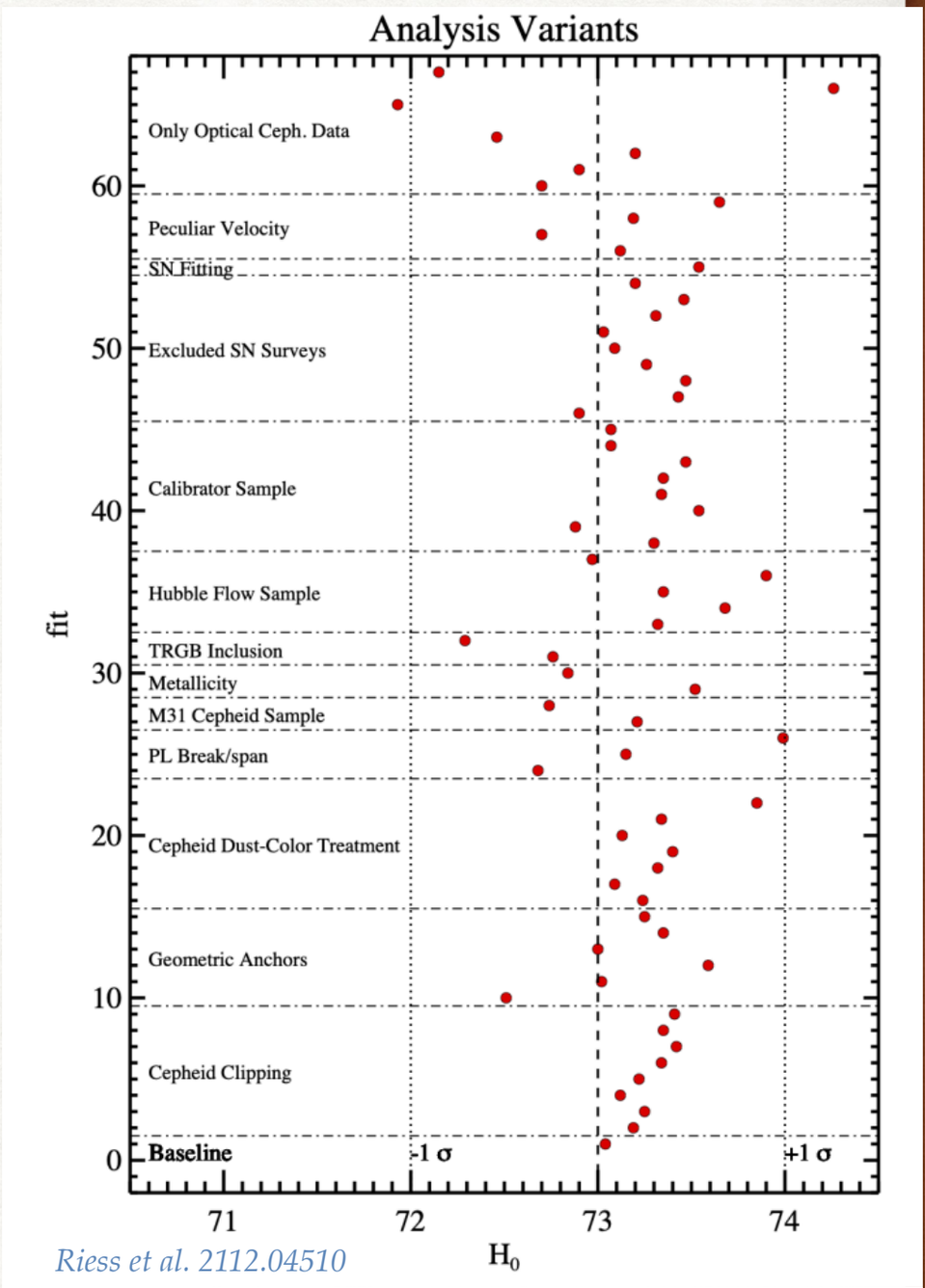
The question of systematics is not settled, but it is not easy to "hide" a 5σ bias!



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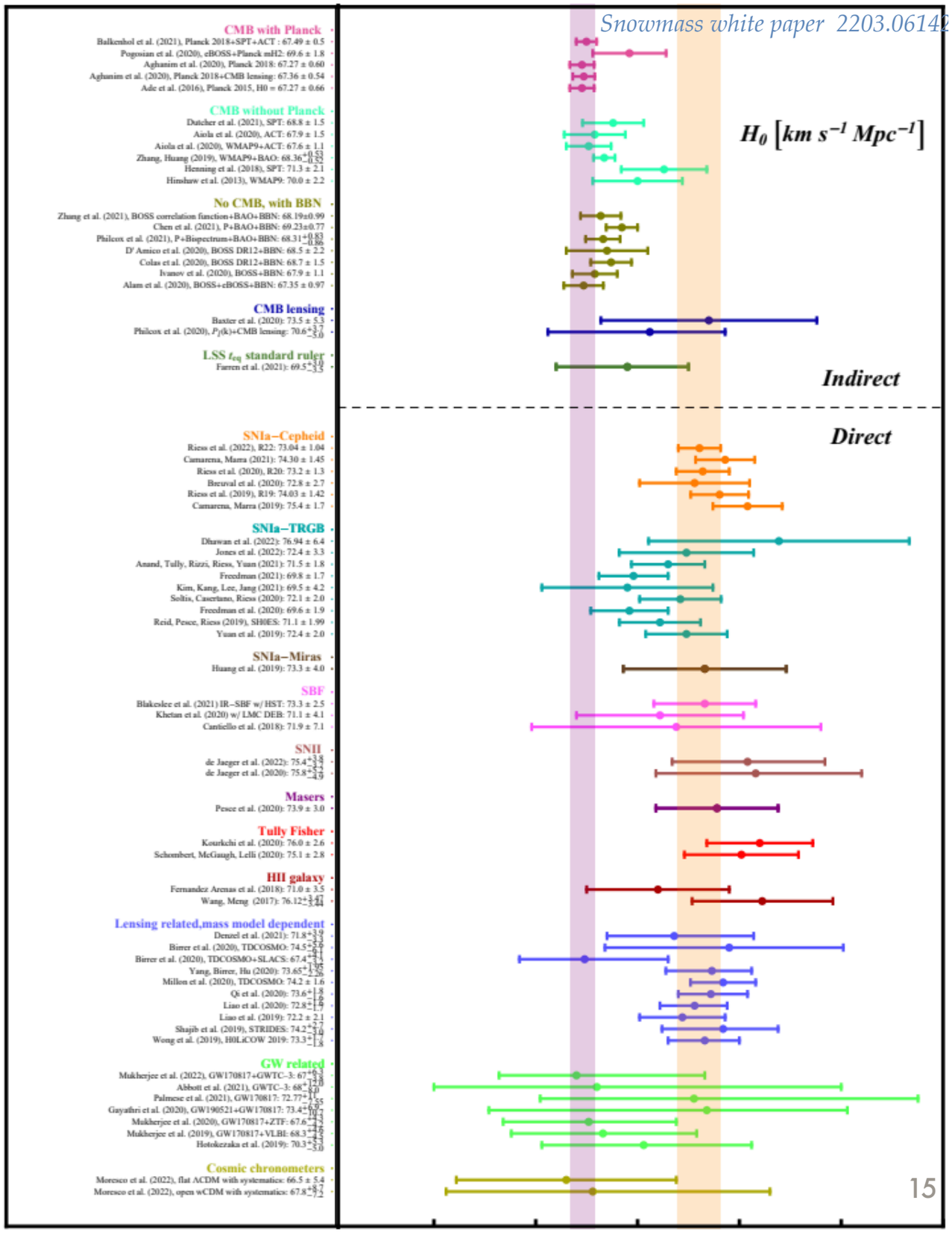
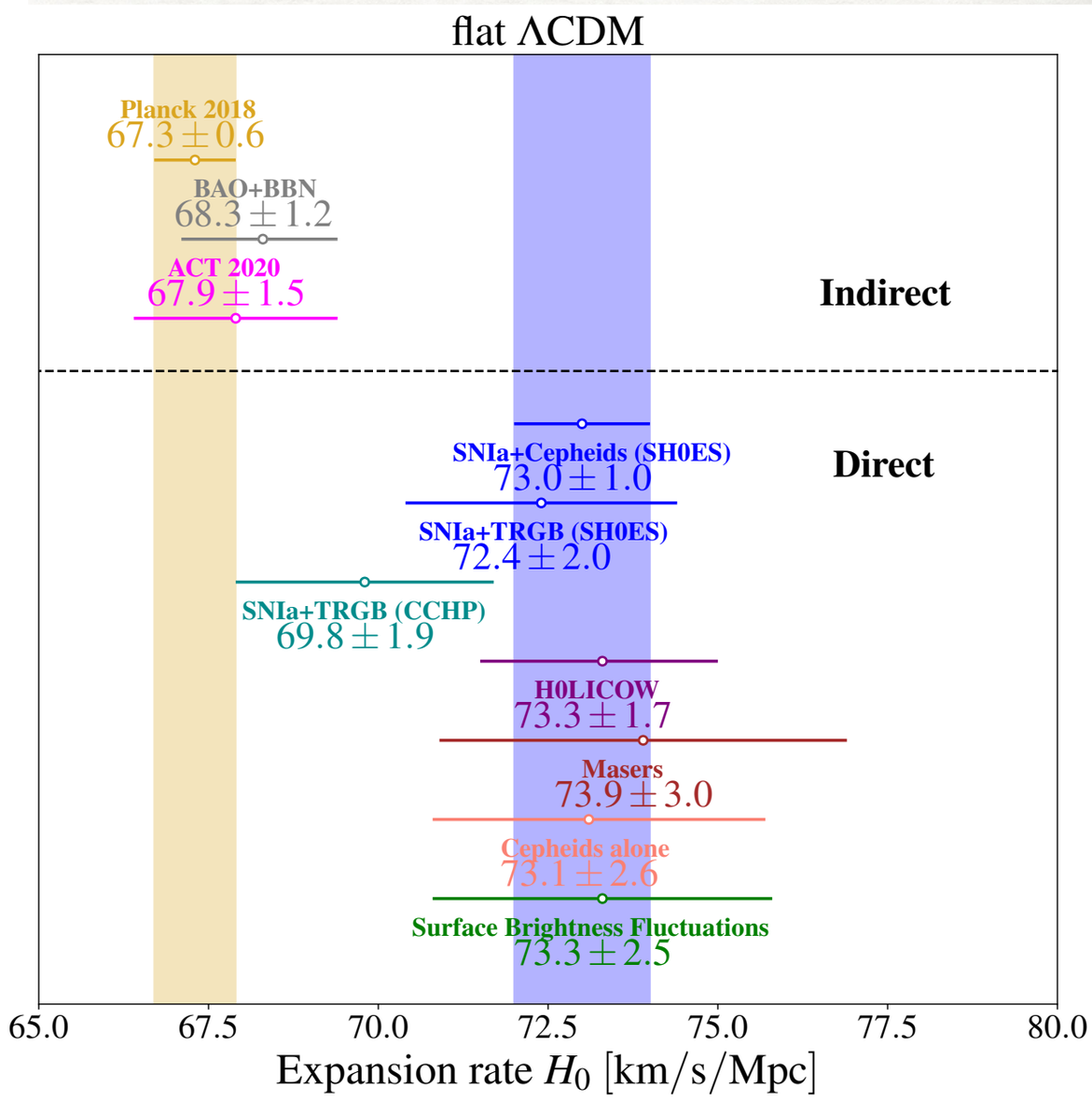
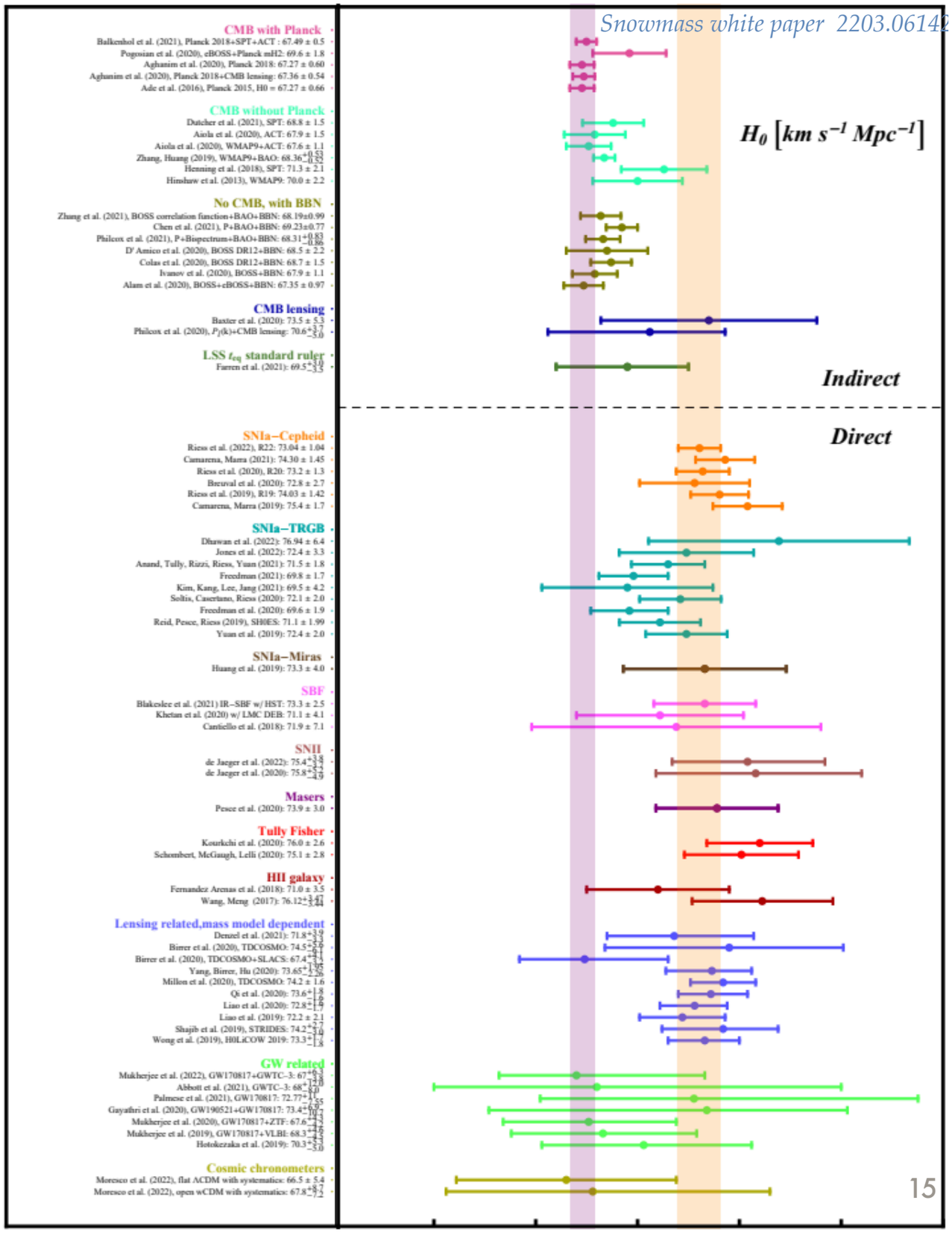
The Hubble tension beyond SHOES & Planck

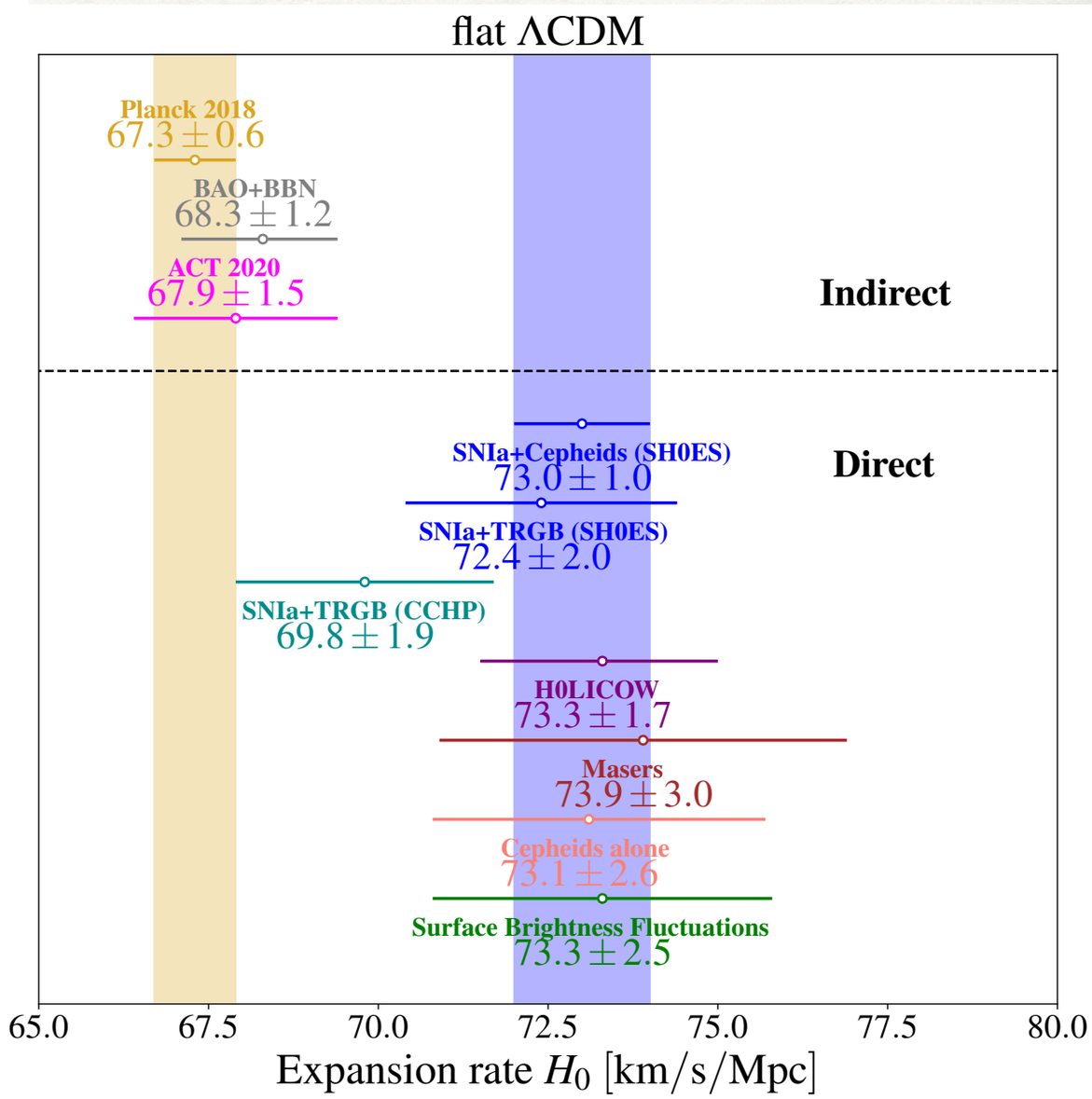




IFT - SUSY24 - 13/06/24

The Hubble tension beyond SHOES & Planck





- High-accuracy measurements (very different systematics) indicate large H_0
- Some debate around H0LICOW results

IFT - SUSY24 - 13/06/24

How do CMB data measure H_0?

- CMB measurements determine the angular size of the sound horizon θ_s
- H_0 appears only in the angular diameter distance d_A
- The physical size of the sound horizon r_s is model-dependent

$$\theta_s \equiv \frac{r_s(z_*)}{d_A(z_*)}$$

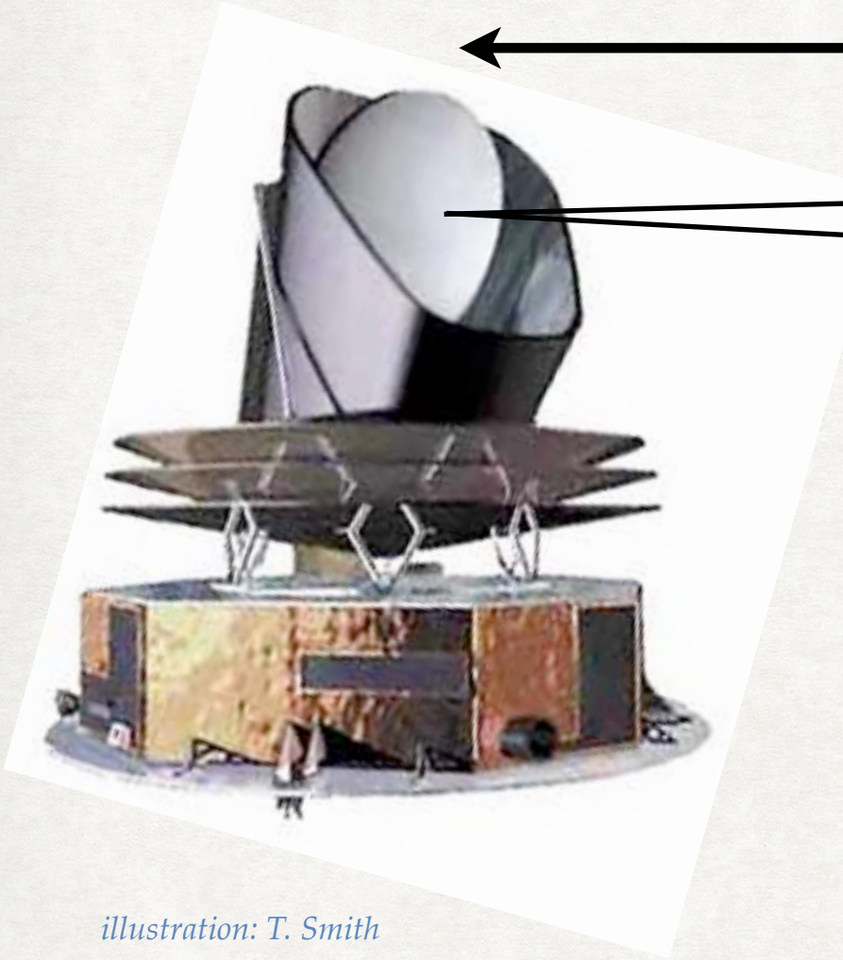


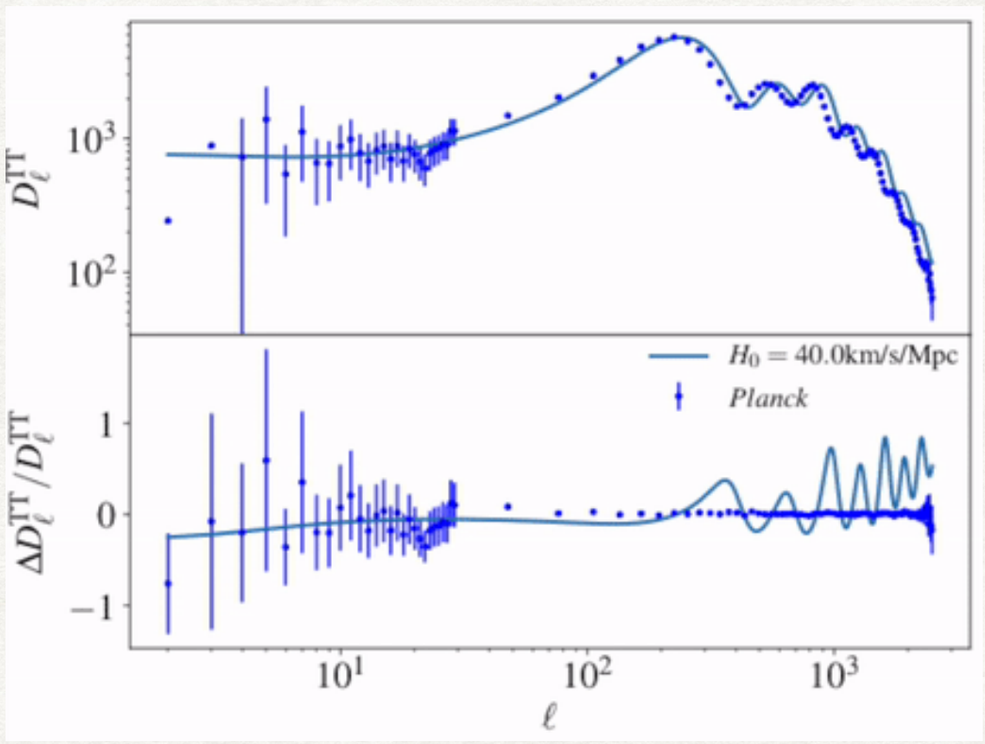
illustration: T. Smith

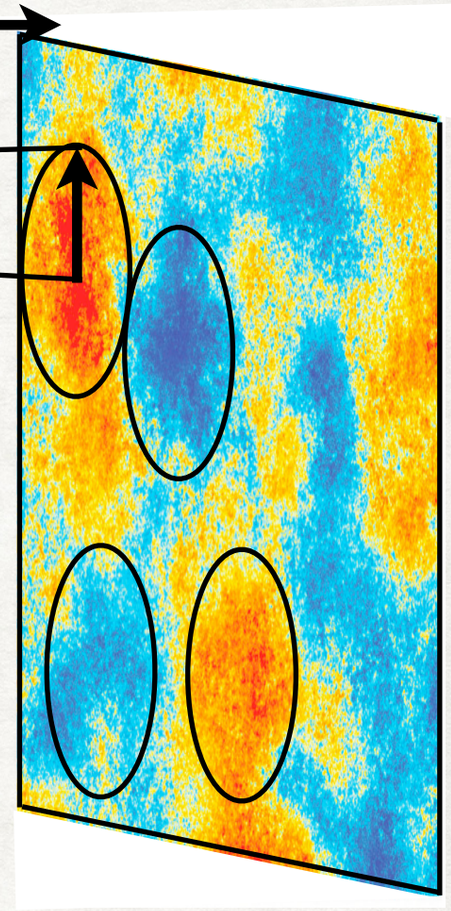
$$d_A \propto 1/H_0 = 1/\sqrt{\rho_{\rm tot}(0)}$$

$\theta_s \simeq 1^\circ$

r_s

0.04% precision!





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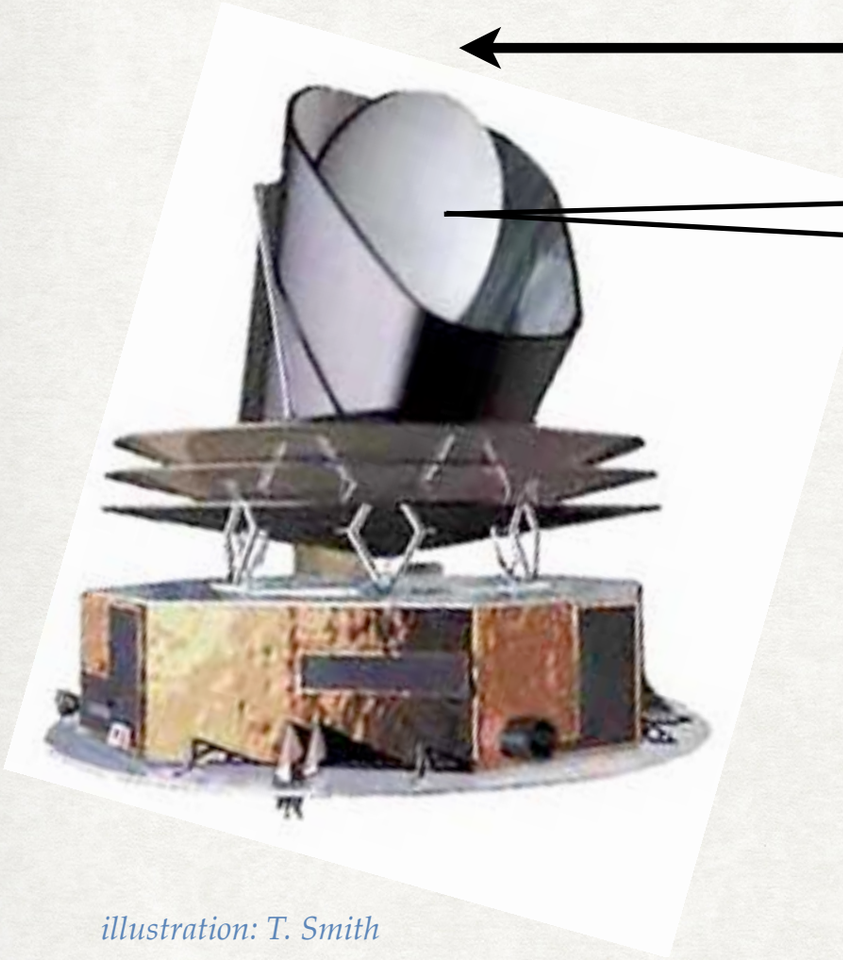

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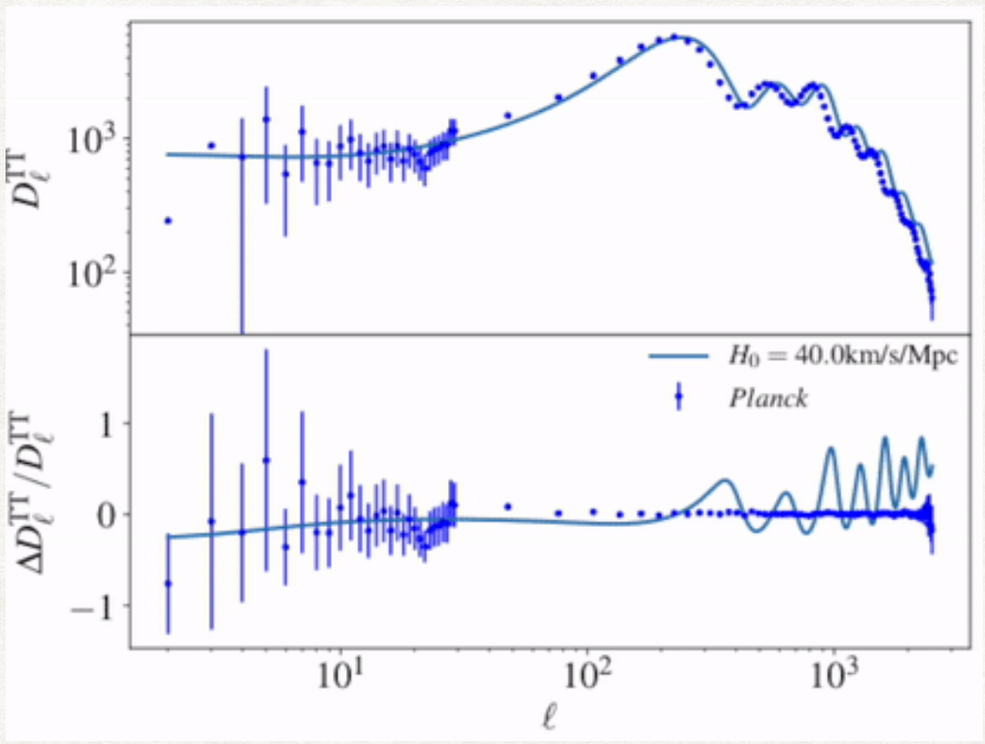

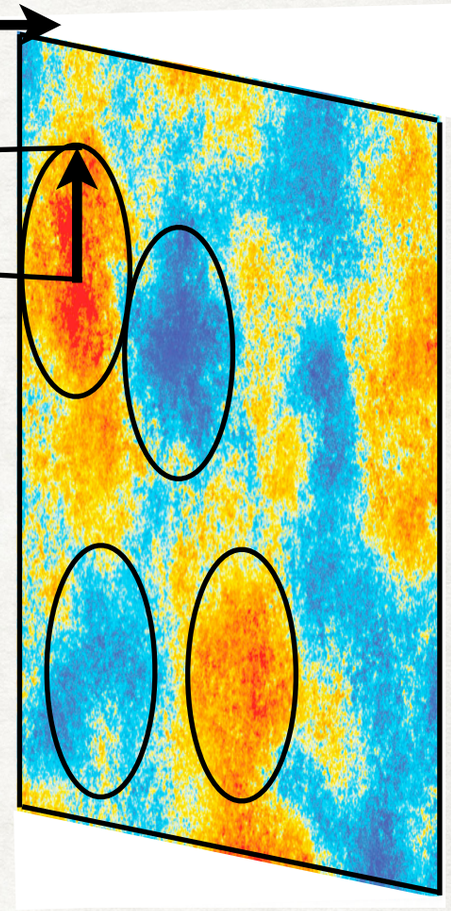

Geometrical degeneracy in the late-universe!

- 'phantom dark energy' $w < -1$, DE phase transition, DE-DM interaction, decaying/annihilating DM, and many more…

$$\theta_s \equiv \frac{H_0 \, r_s(z_*)}{\int_0^{z_*} 1/E(z') \, dz'} \qquad E(z) \equiv \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda(z) + \cdots}$$

[http://arxiv/insert_your_favorite_ model_here.com]

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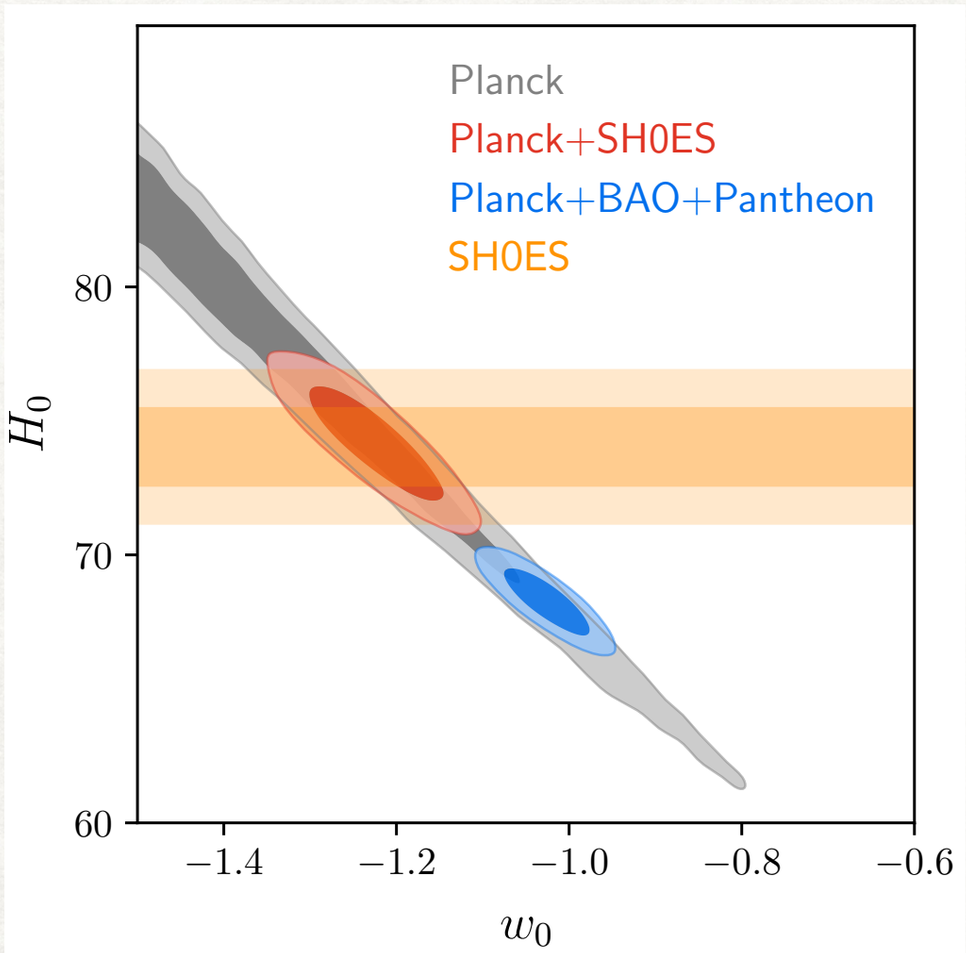
- Planck data can easily accommodate a higher H_0: problem with BAO and Pantheon



The tension is truly between **calibrators**!

BAO: $\theta_d(z) = \dfrac{r_s(z_{\rm drag})}{D_A(z)}$

SN1a: $\mu(z) = 5{\rm Log}_{10} D_L(z) + M_b$

- In GR: $D_A = D_L/(1+z)^2$ ==> it is impossible to resolve the tension without changing calibration!

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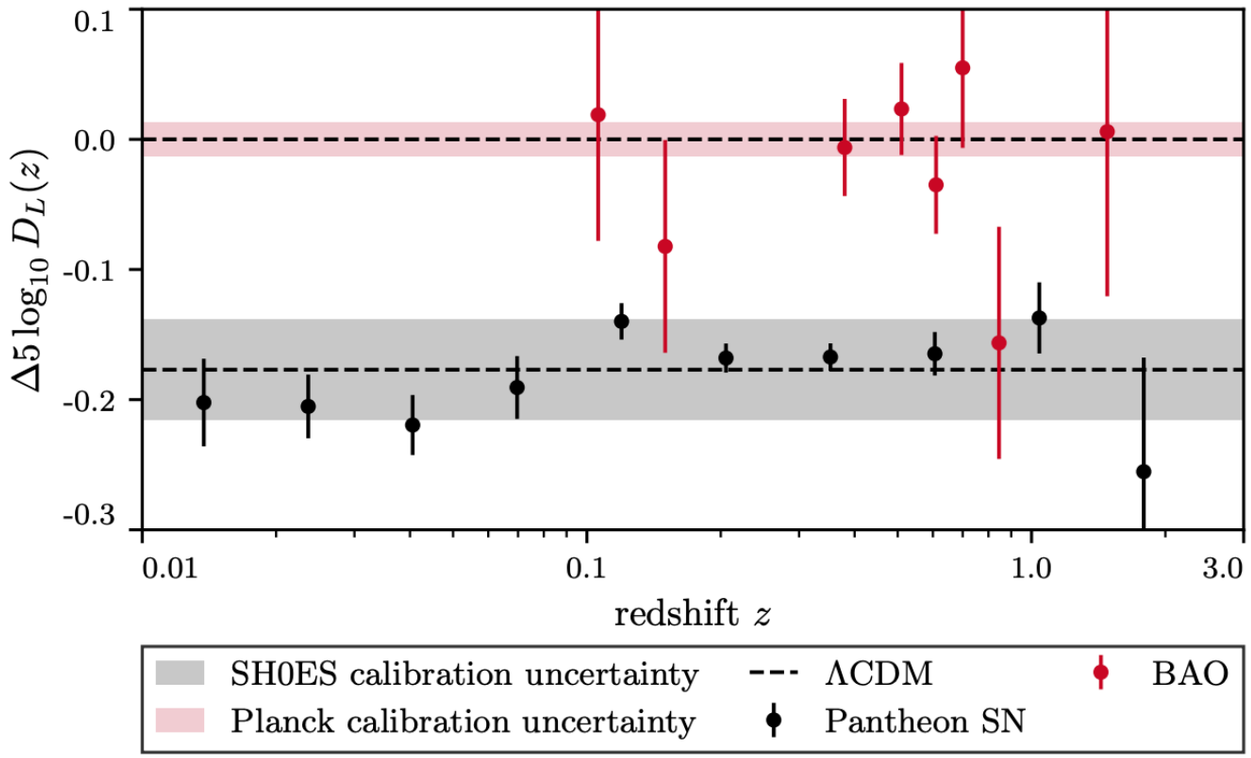
Raveri 2309.06795



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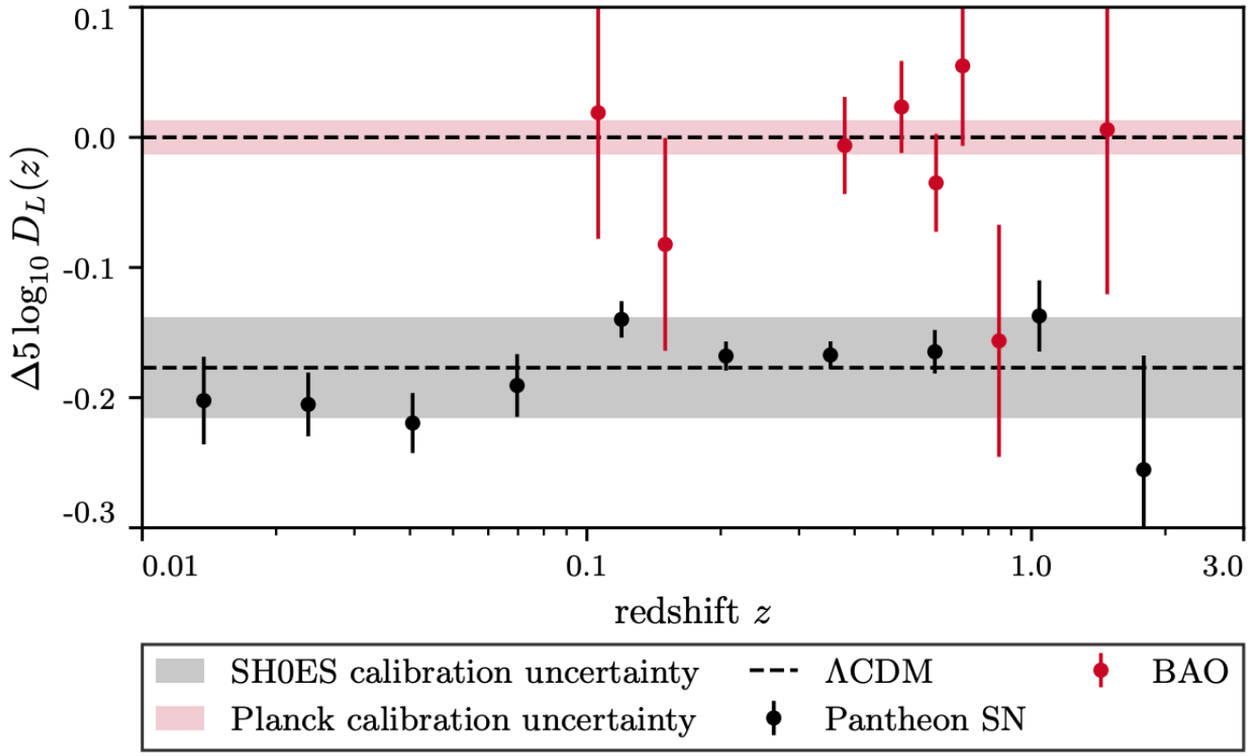

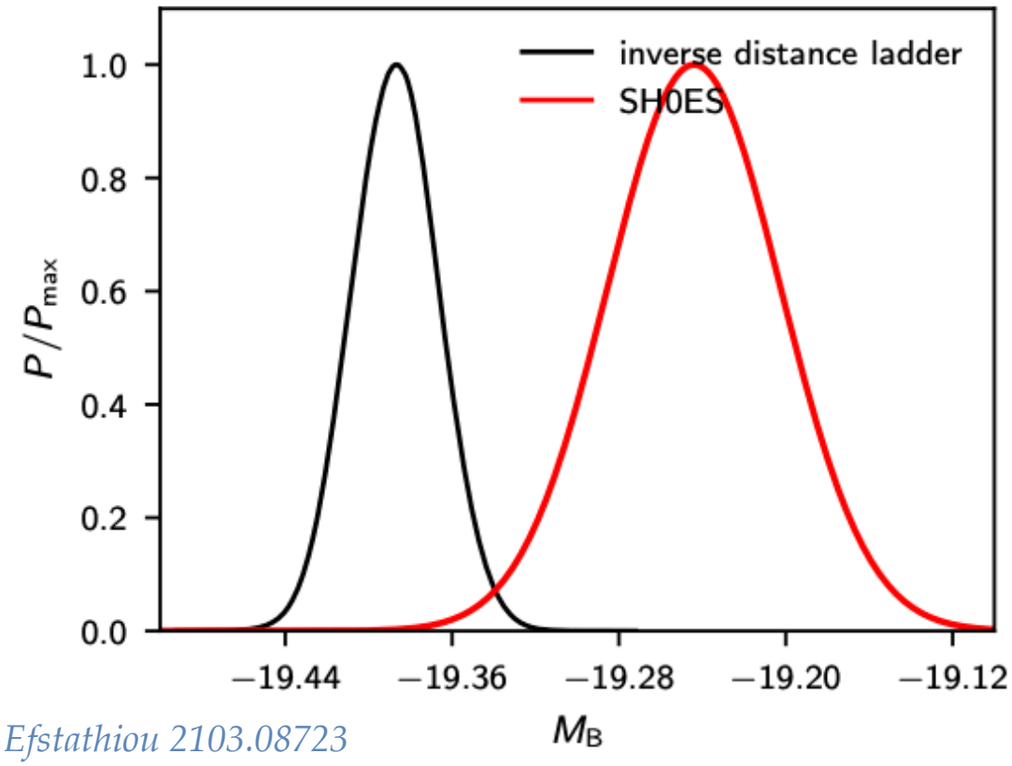

Efstathiou 2103.08723

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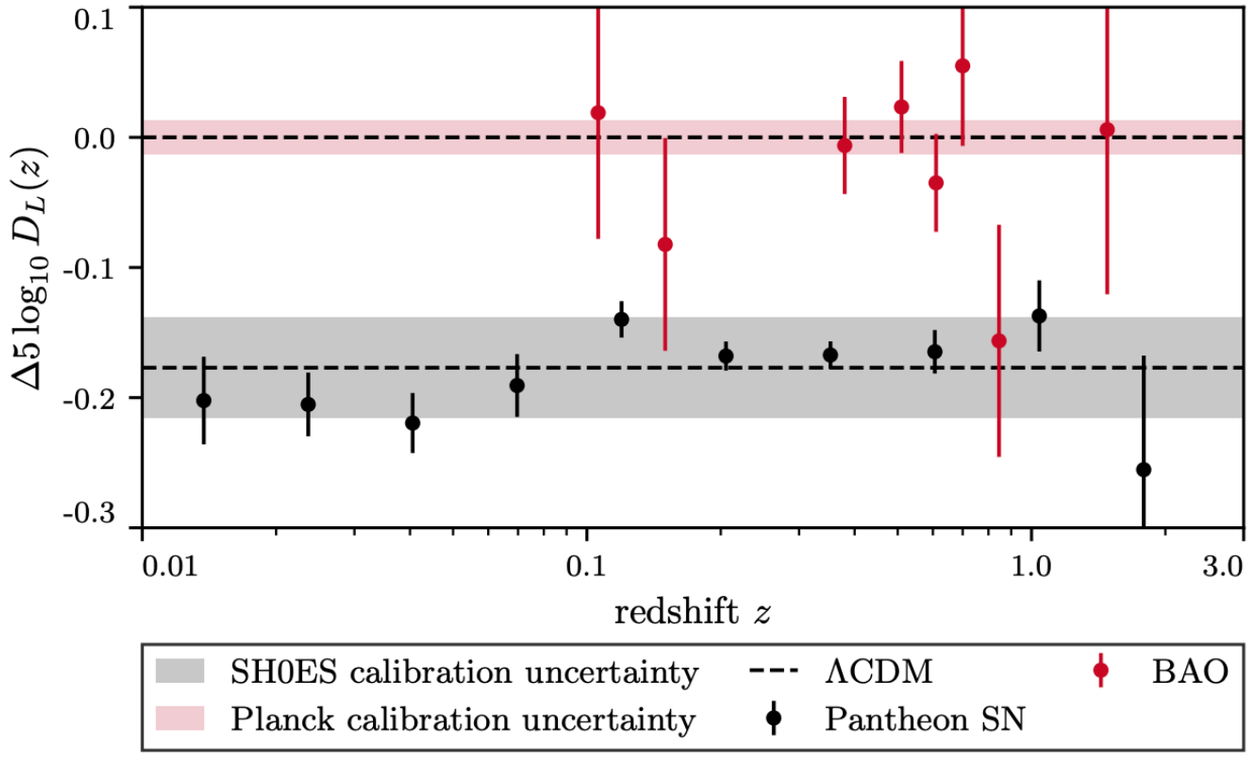
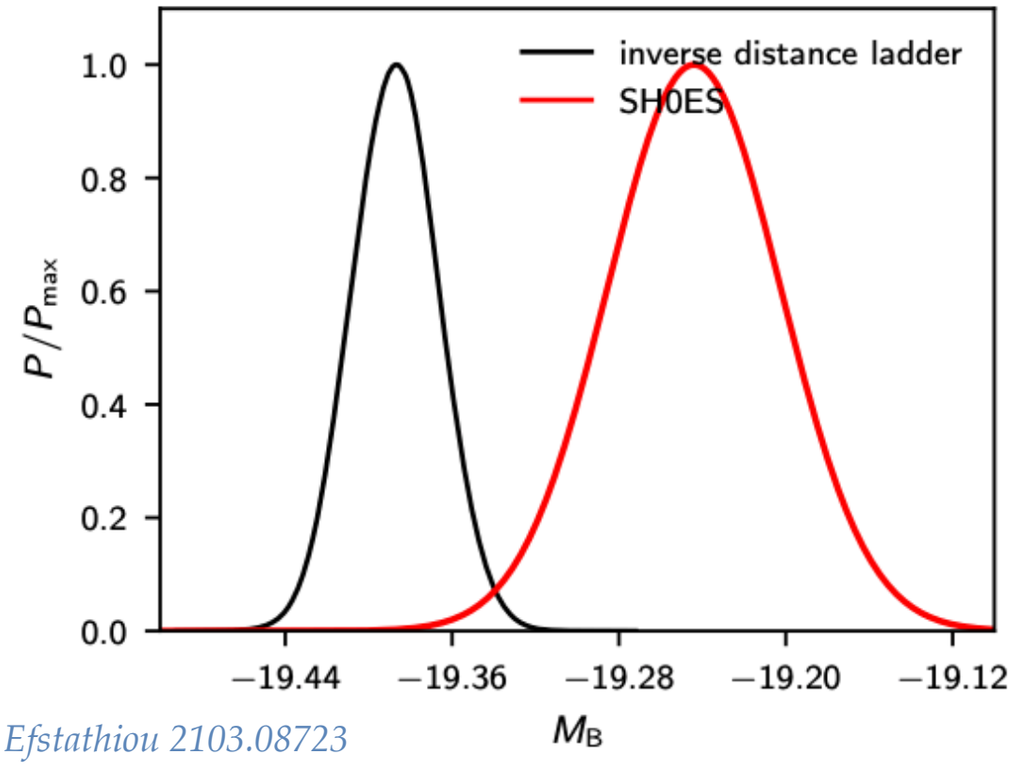
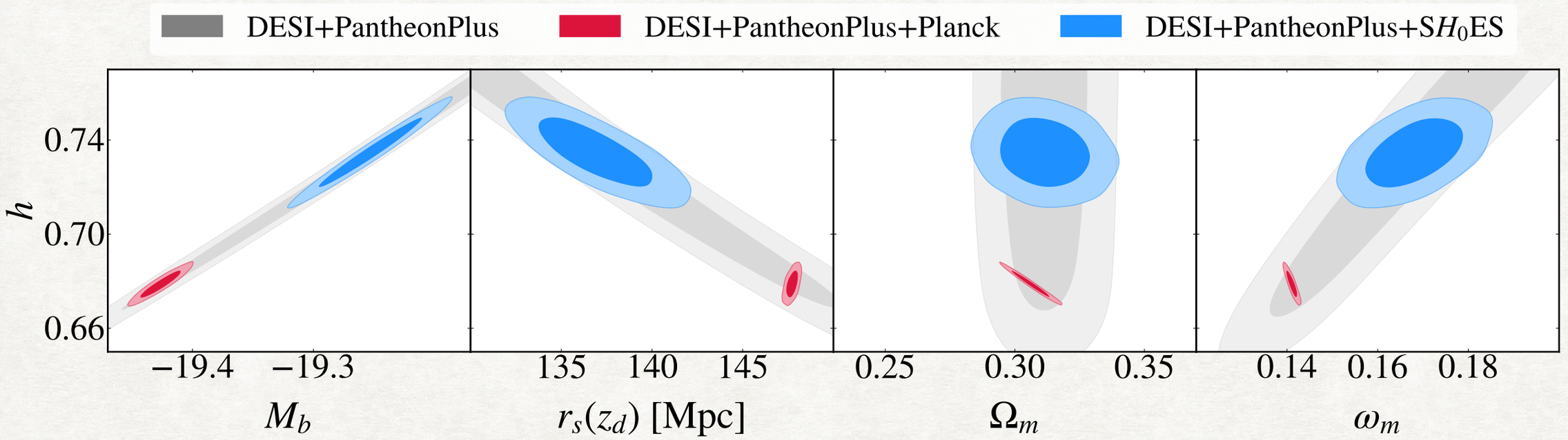




Efstathiou 2103.08723

- Assuming $r_s(\Lambda{\rm CDM})$ and $M_b({\rm SH0ES})$, $D_A(z)$ and $D_L(z)$ are incompatible!
- Two possibilities: break EDDR or change calibrators? *Tutusaus++, 2311.16862*

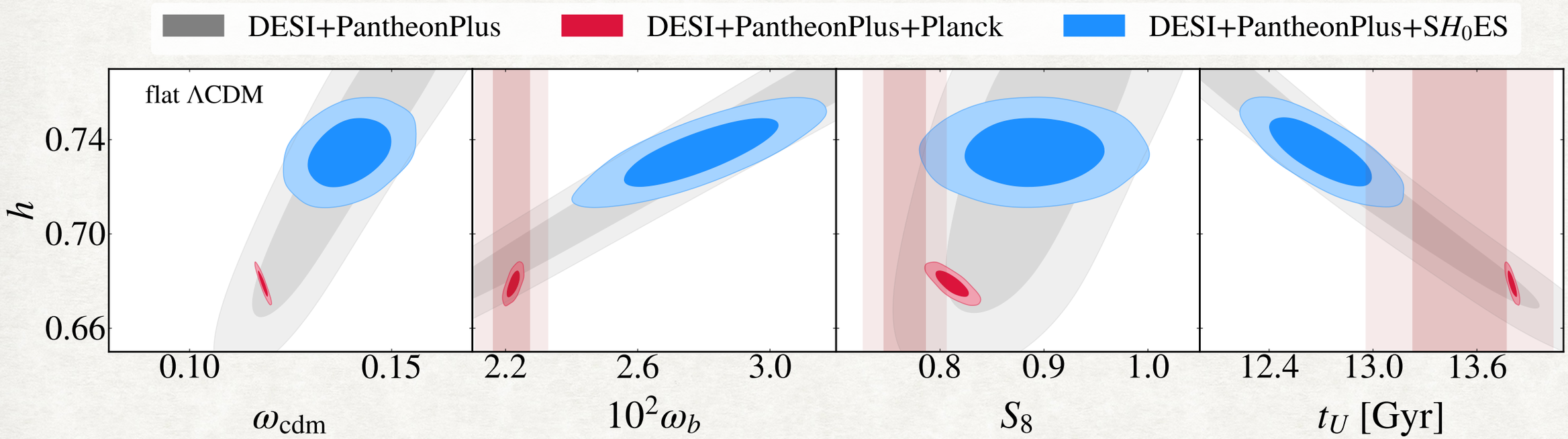
Guideline for new physics



- Uncalibrated BAO and SN1a provide tight constraints to Ω_m and $H_0 r_d$ under flat ΛCDM
- Calibrating the BAO and SN1a allows a measurement of the physical density $\omega_m = \Omega_m h^2$, H_0 and r_d
- Challenge for new physics: Reduce the sound horizon and adjust the impact a larger ω_m on the CMB

Stop calling it Hubble tension!

- Under ΛCDM, the SH_0ES calibration implies additional tensions!

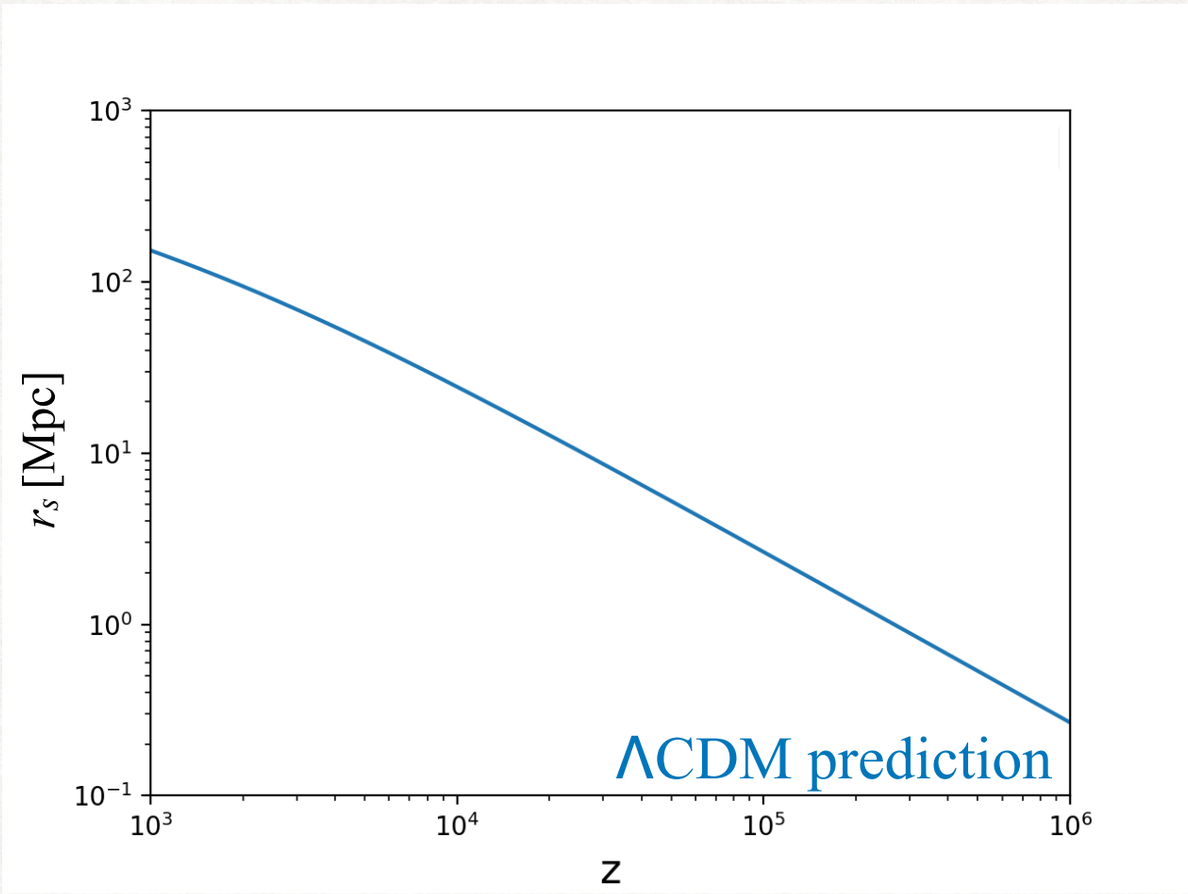


- BBN tension: ω_b is much larger in the "SH_0ES cosmology" in order to adjust the low r_s
- S_8 tension: amplitude of fluctuation increases because of the larger ω_m
- Age of the universe tension: t_U is younger by about 1 Gyr than in Planck/ΛCDM!
- Another challenge for new physics: remove those additional tensions!

How to resolve the cosmic calibration tension

Bernal++ 1607.05617, Raveri 1902.01366, Aylor++1811.00537 , Knox&Milllea 1908.03663, Schöneberg (VP) ++ 2107.10291

$$r_s = \int_{\infty}^{z_*} dz \frac{c_s(z)}{8\pi G/3\sqrt{\rho_{\rm tot}(z)}}$$



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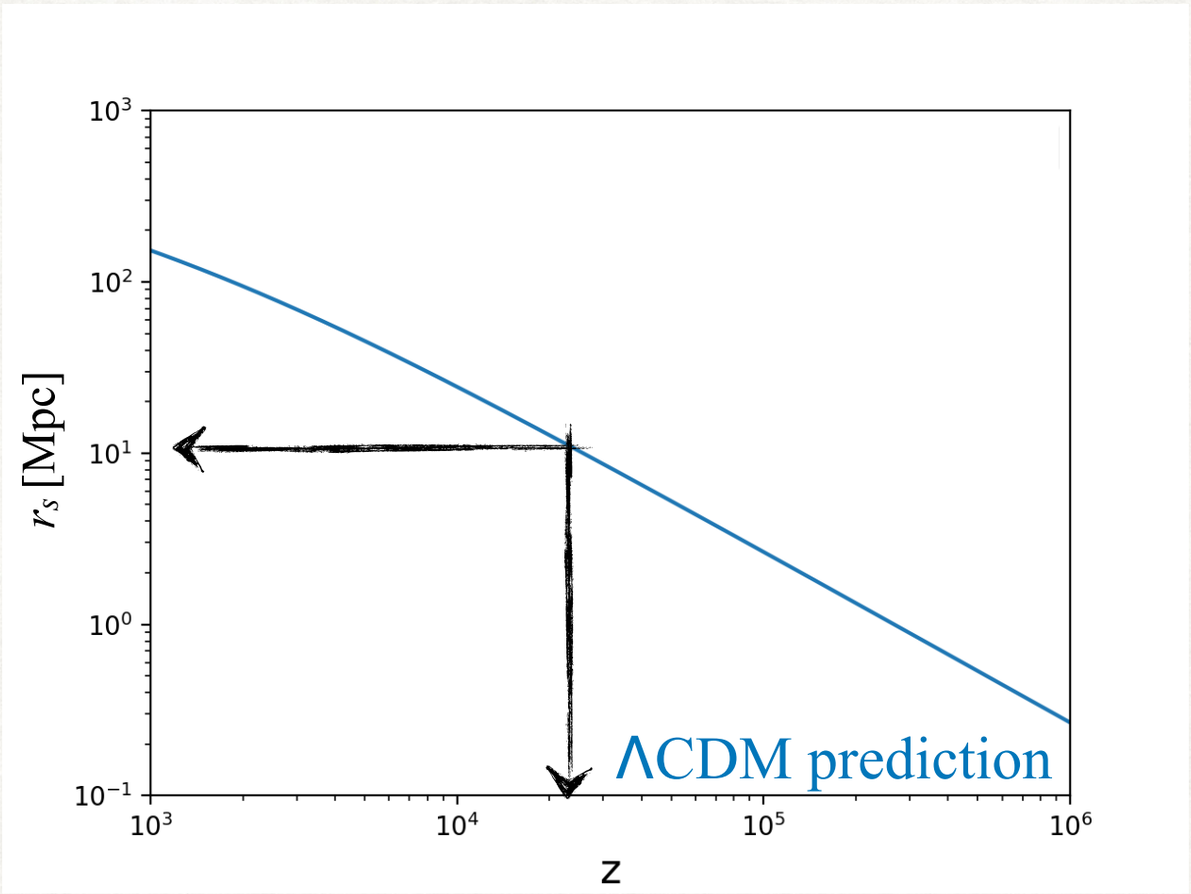

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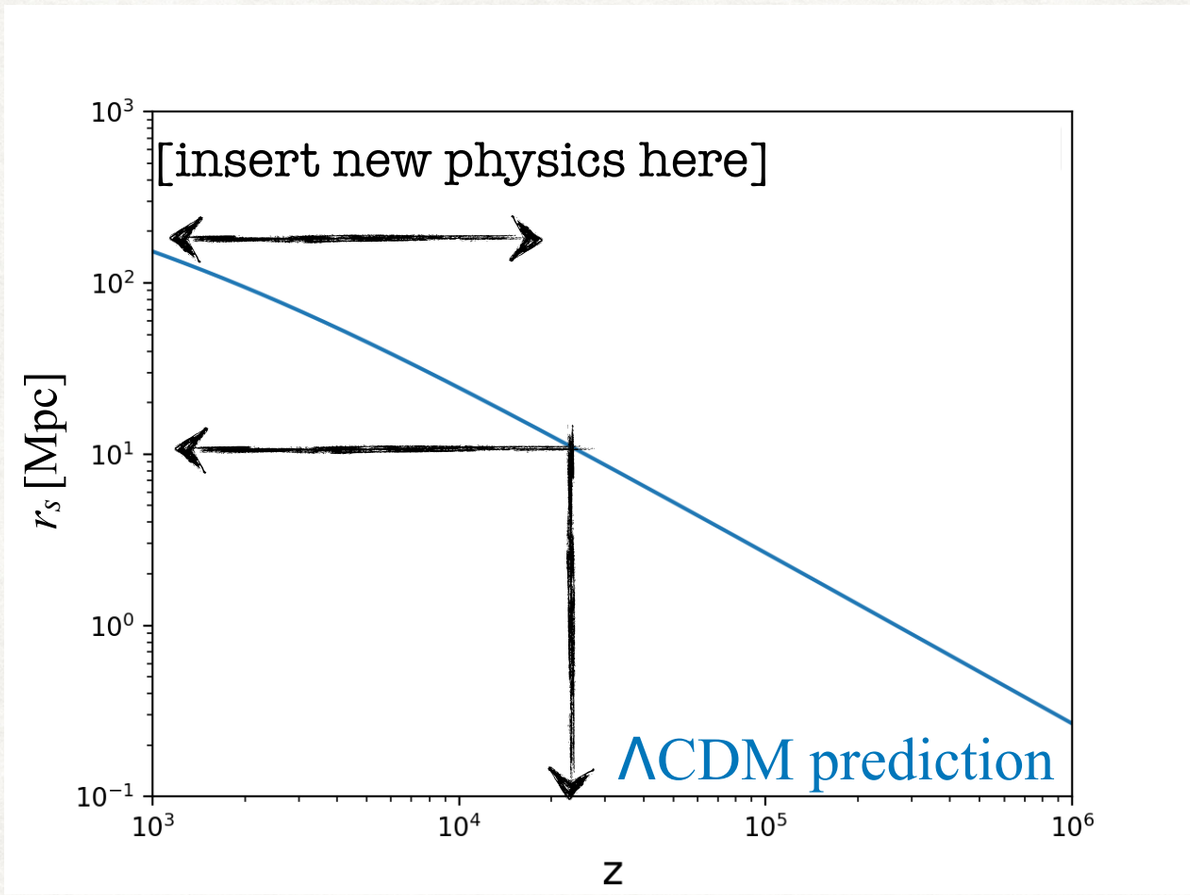

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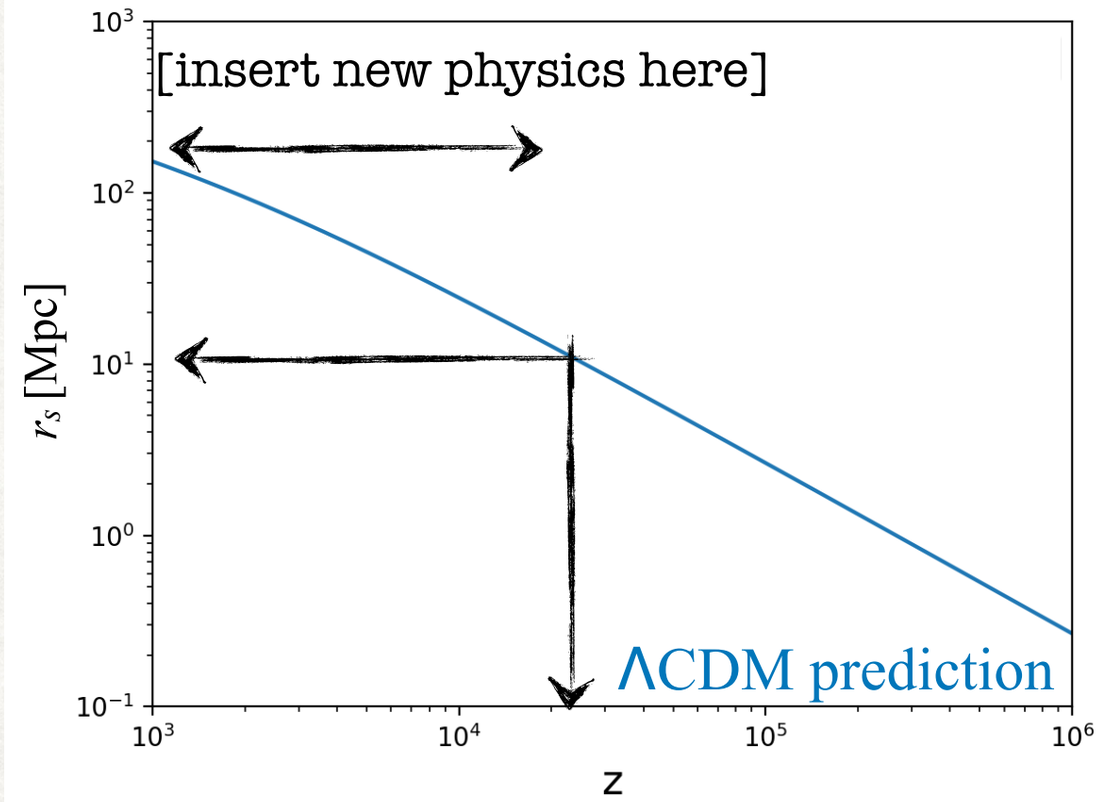

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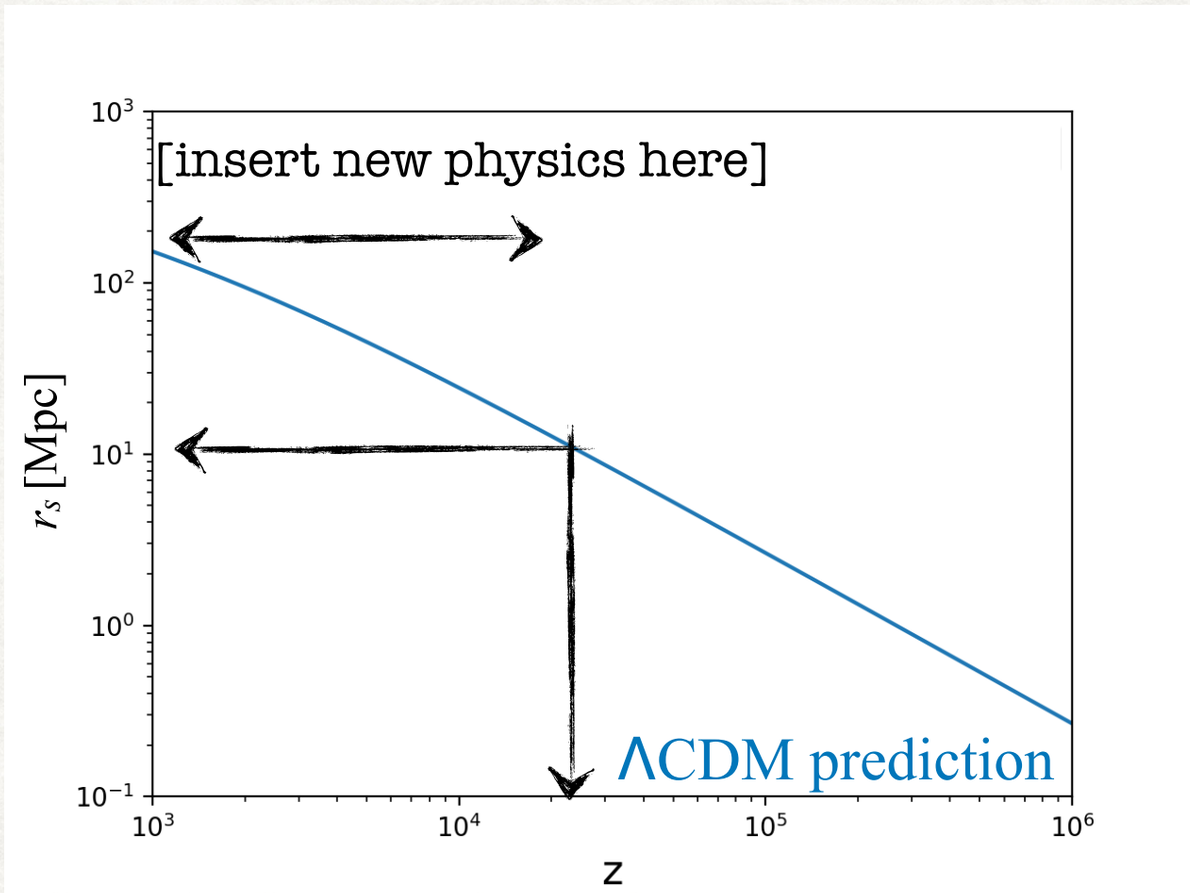

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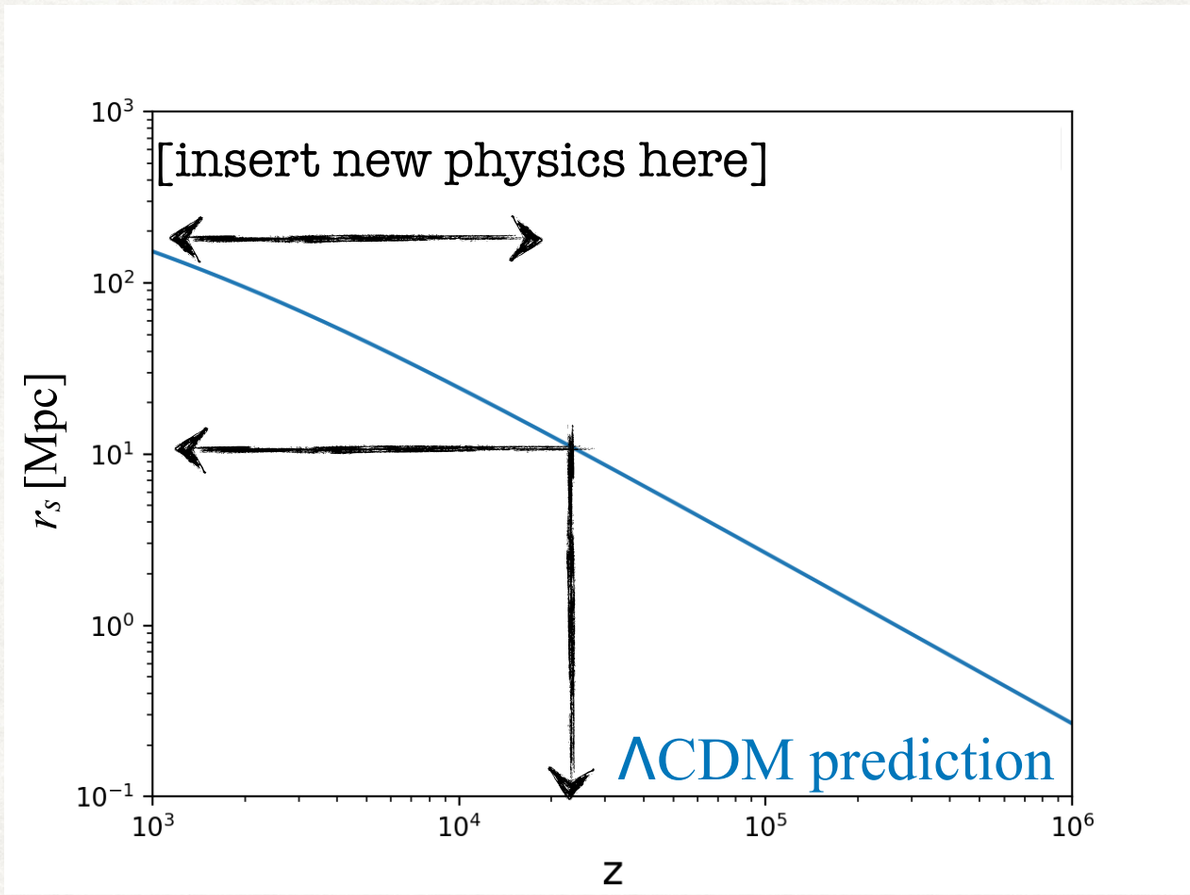
increase $\rho(z)$: Neff? Early Dark Energy? Modified Gravity?



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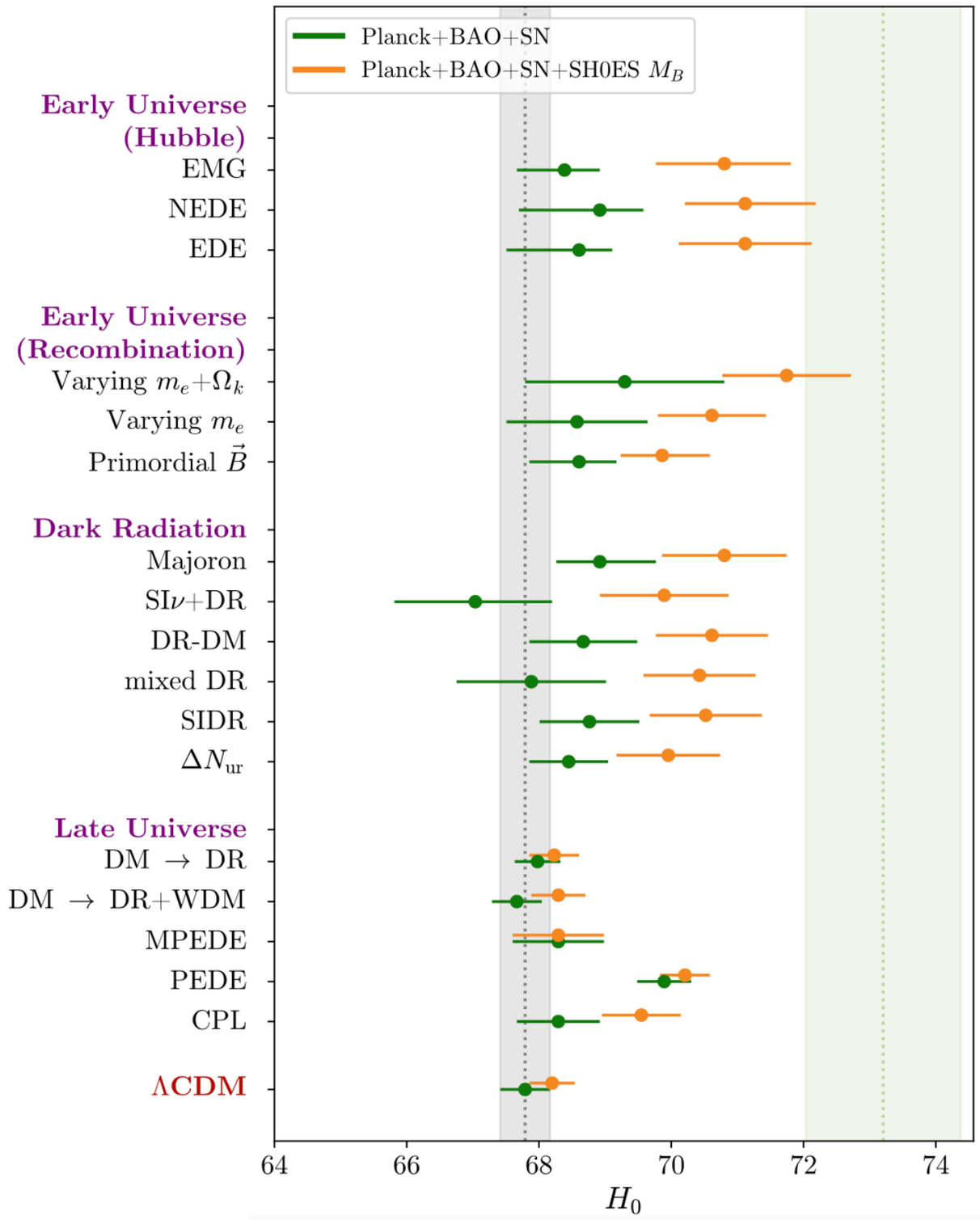
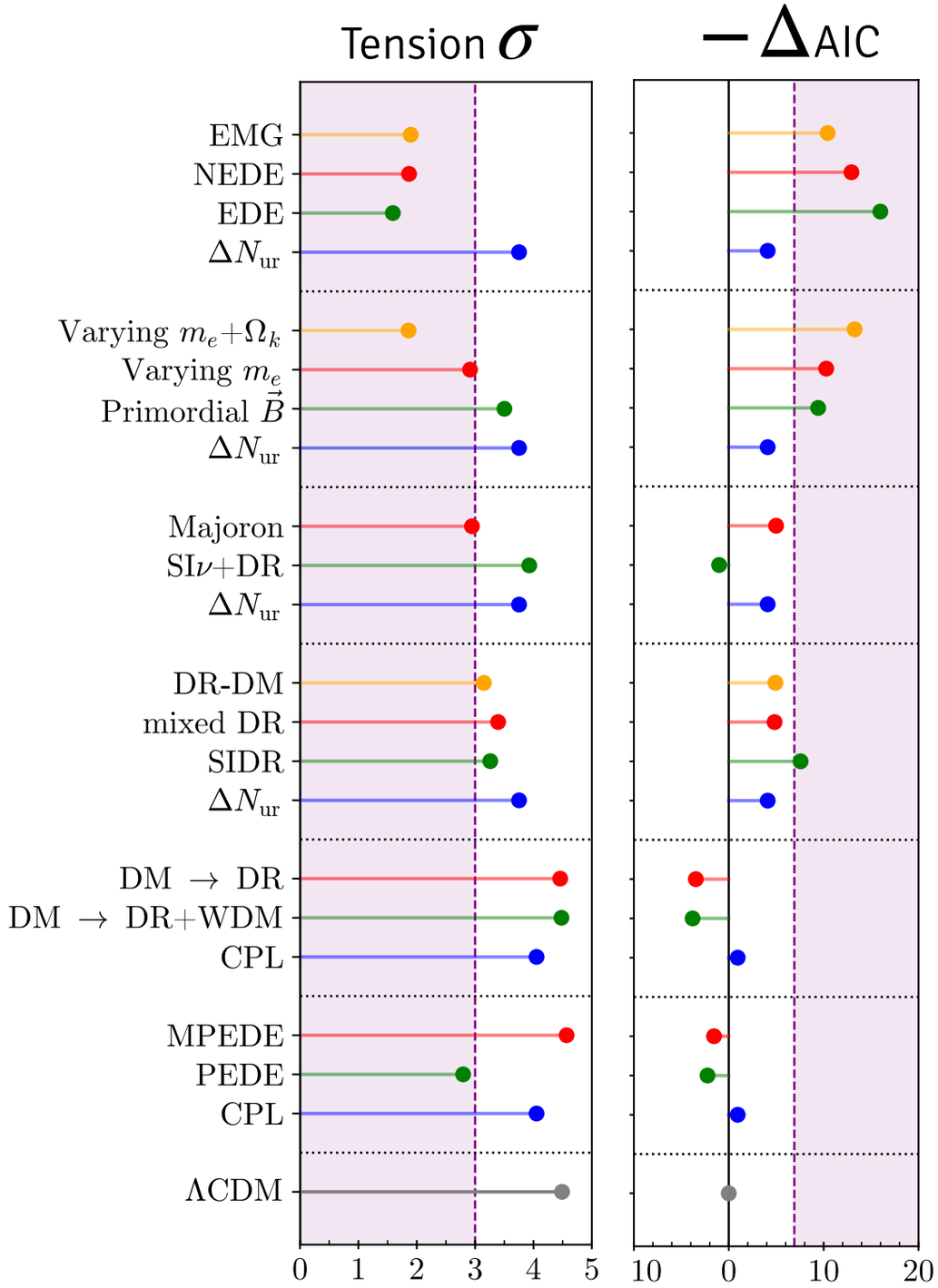
The H_0 olympics: fairly ranking models





Schöneberg (VP) ++ Phys. Report. 2107.10291

Three models as examples

- Exotic expansion history via early dark energy: boost in $H(z \sim 3500)$ through a scalar-field

  VP, Smith, Karwal, 2302.09032

- Exotic expansion history via additional tightly-coupled relativistic species $\Delta N_{\rm fld}$

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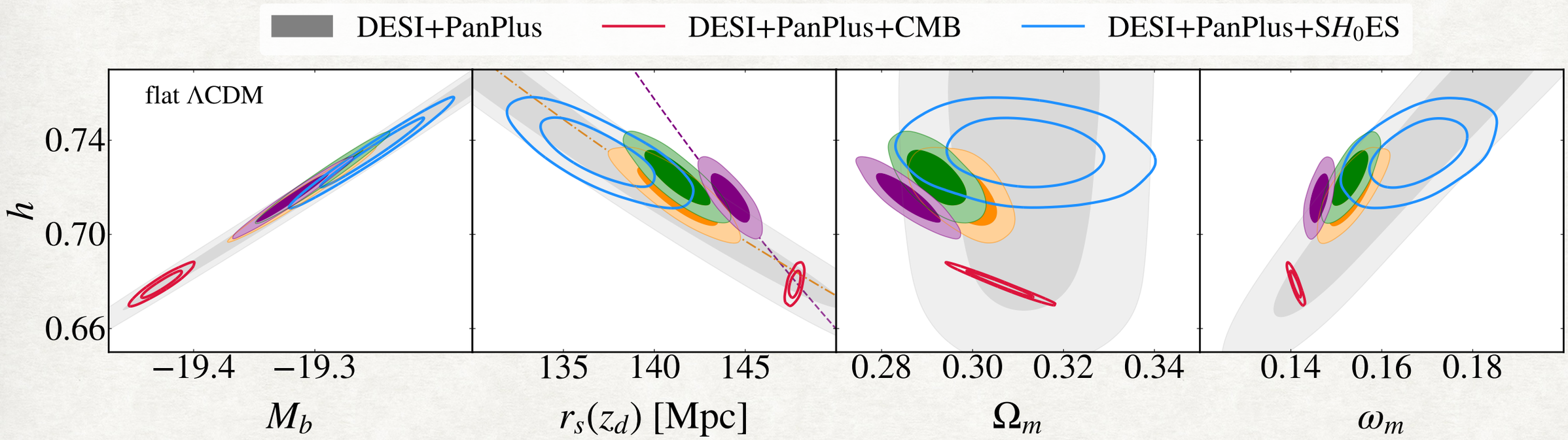


- Models affecting expansion history can reduce tension to $\sim 3\sigma$ level

- Models affecting solely the way recombination proceeds are disfavored.

Lee (VP)++ PRL 2022, Lynch++ 2404.05715

Model-independent Implications

- Exotic expansion history via early dark energy: boost in $H(z \sim 3500)$ through scalar-field

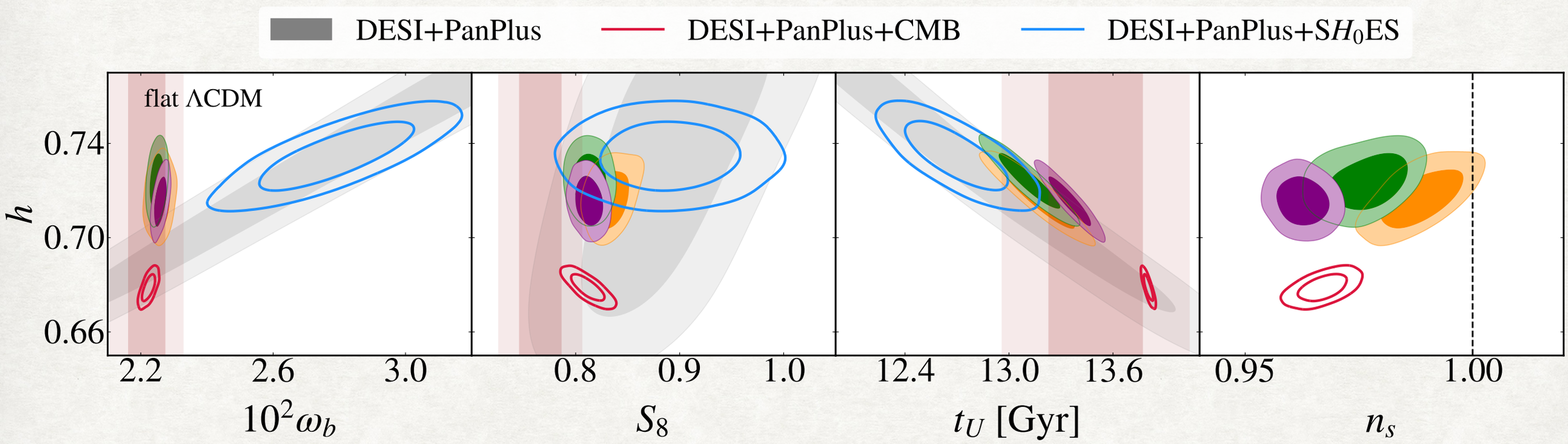
VP, Smith, Karwal, 2302.09032

- Exotic expansion history via additional tightly-coupled relativistic species $\Delta N_{\rm fld}$

Aloni++ 2111.00014

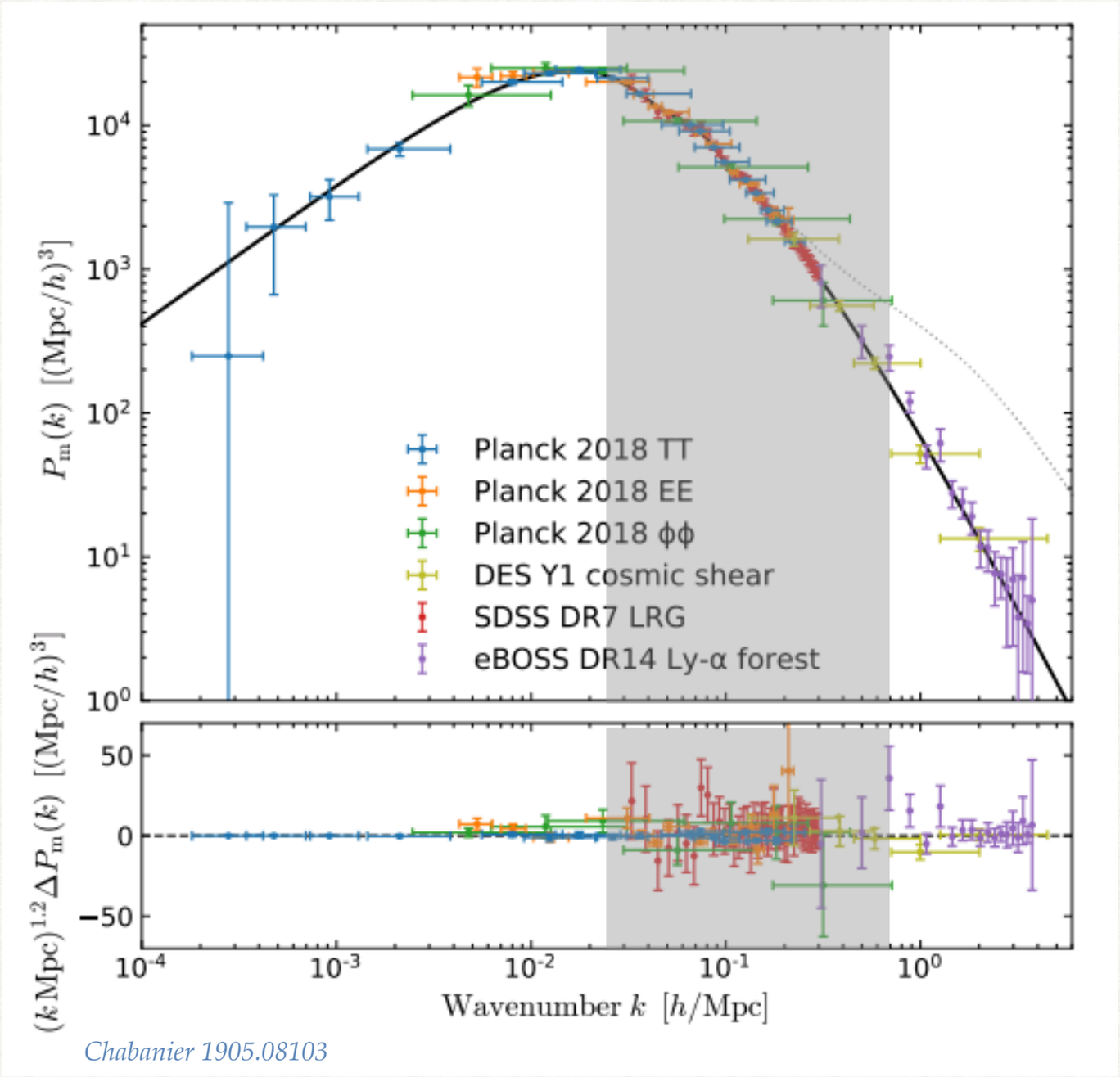
- Exotic recombination via electron mass increase $m_e(z \sim 1000)$

Hart&Chluba 1912.03986



- No more tension with BBN but tension with weak lensing measurements at the $3-3.5\sigma$ level
- Age of the universe $\sim$ 0.7 Gyr younger: problem with old objects? JWST?
- n_s increases! Back to being compatible with 1?

The S_8 parameter



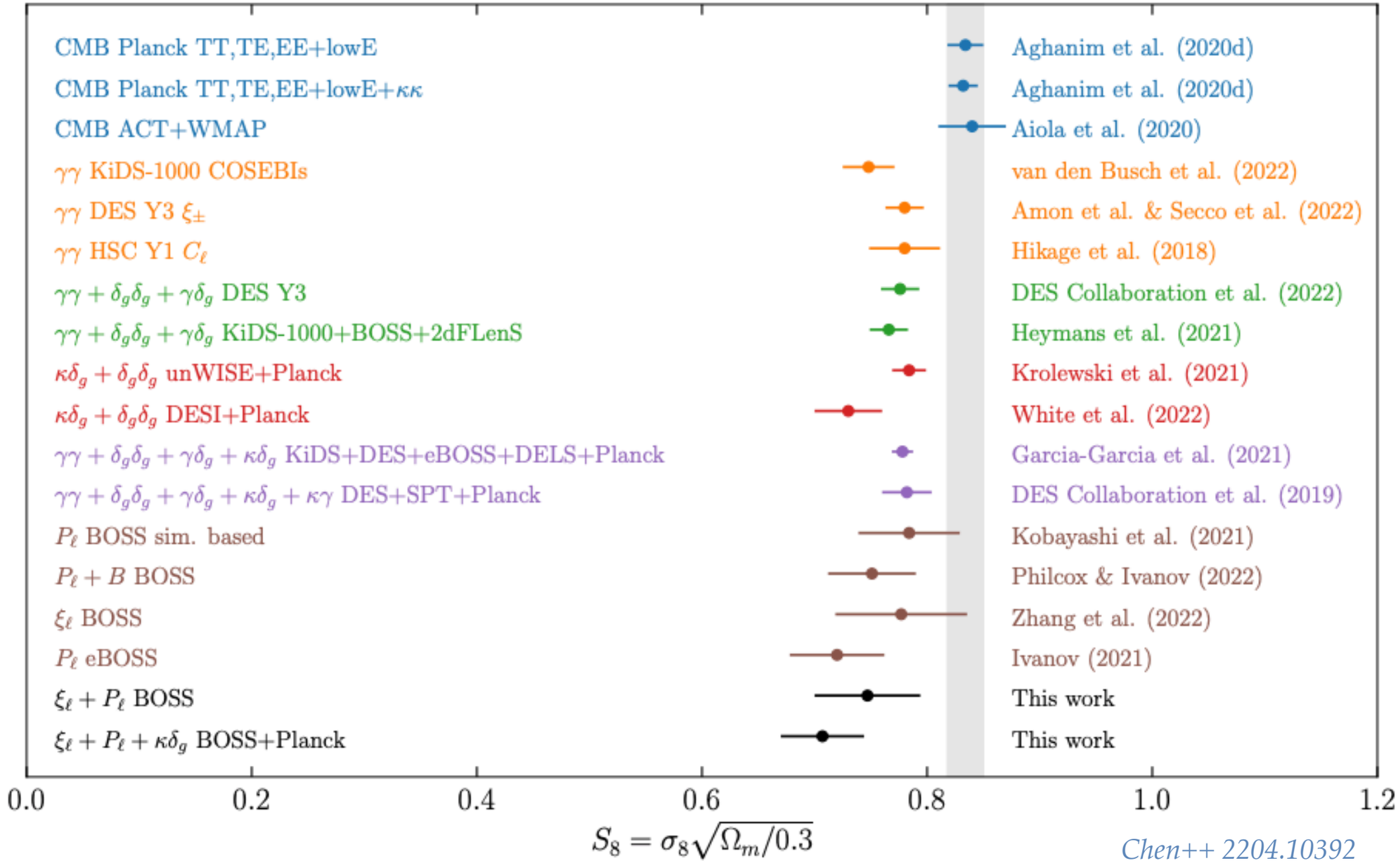
Chabanier 1905.08103

$$S_8 \equiv \sigma_8 \left(\frac{\Omega_m}{0.3} \right)^{0.5}$$

$$\sigma_8^2 = \int_0^\infty \frac{k^3}{2\pi^2} P_{\rm lin}(k) W^2(kR) d\ln k$$

- The S_8 parameter quantifies how "clumpy" the universe is on scales of $\sim$ 8 Mpc

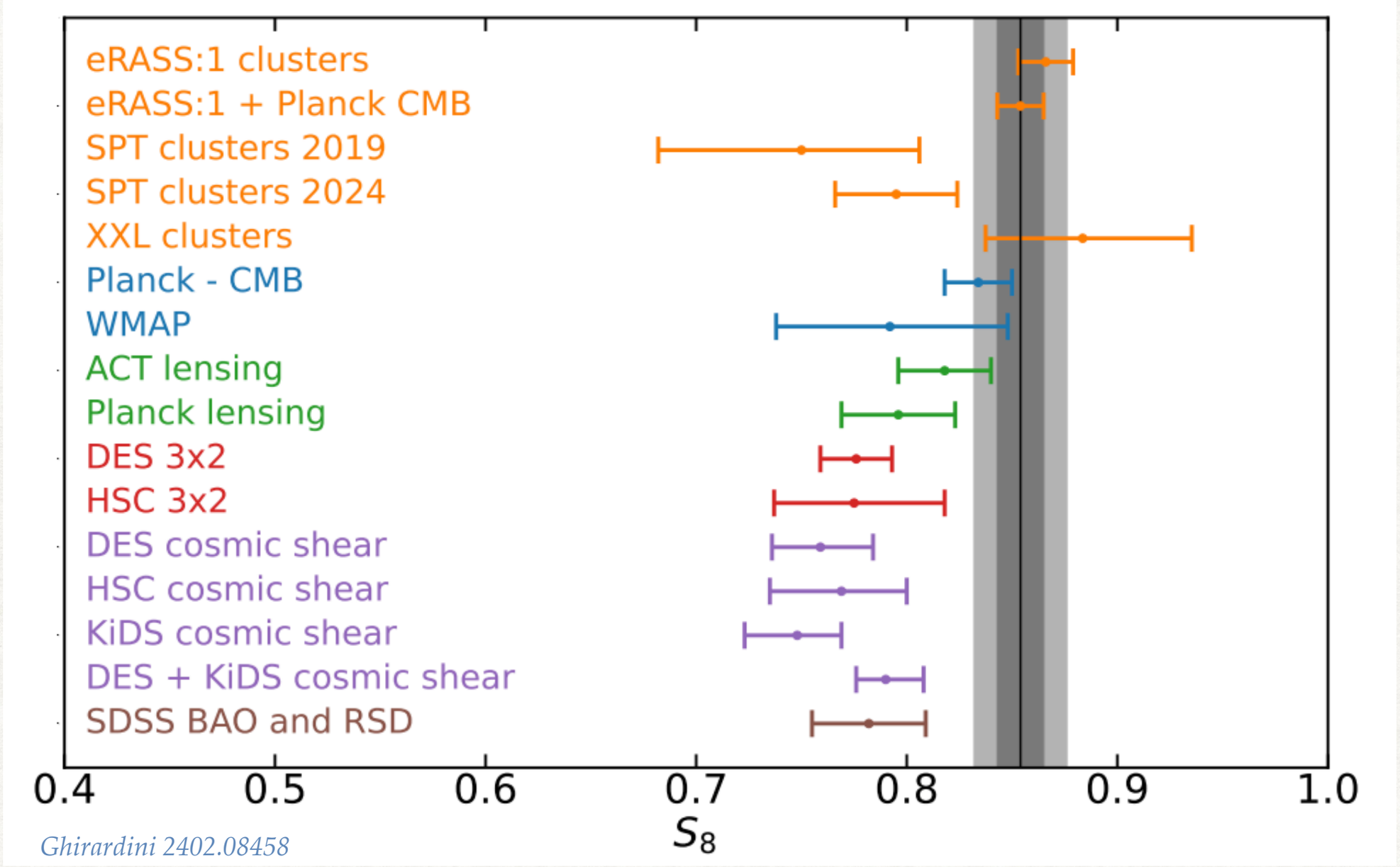
The S_8 tension



Chen++ 2204.10392

There is a 2-3σ tension between S_8 from WL x GC measurements and *Planck*

Is there a S_8 tension after all?



Ghirardini 2402.08458

- Latest S_8 from galaxy cluster number counts by eROSITA is higher than Planck
- A potential systematic in WL surveys was already pointed out: intrinsic alignements, non-linear modeling, baryonic feedback could play a role. *Amon& Efstathiou 2206.11794, Aricò++ 2303.05537, Abbott++ 2305.17173*

Cosmology at a crossroad: Precision or discordance?

- Despite its great success, the ΛCDM model is purely parametric: DM, DE, inflation still unknown
- H_0 at 5σ in tension, S_8 at 3σ in tension, SN1a/BAO at 2-4σ: clues about physics beyond ΛCDM?
- It appears as though these tensions do not lead to a consistent picture (yet).

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- Barring systematics/statistical fluke, the challenge is immense... but worth it!

Cosmology: where are we going next?

- New CMB data are coming: very sensitive to new physics around recombination! (And inflation)
- New LSS data are coming: check DESI result, check S_8 results, measure $\sum m_\nu$.
- JWST and gravitational wave measurements of H_0.