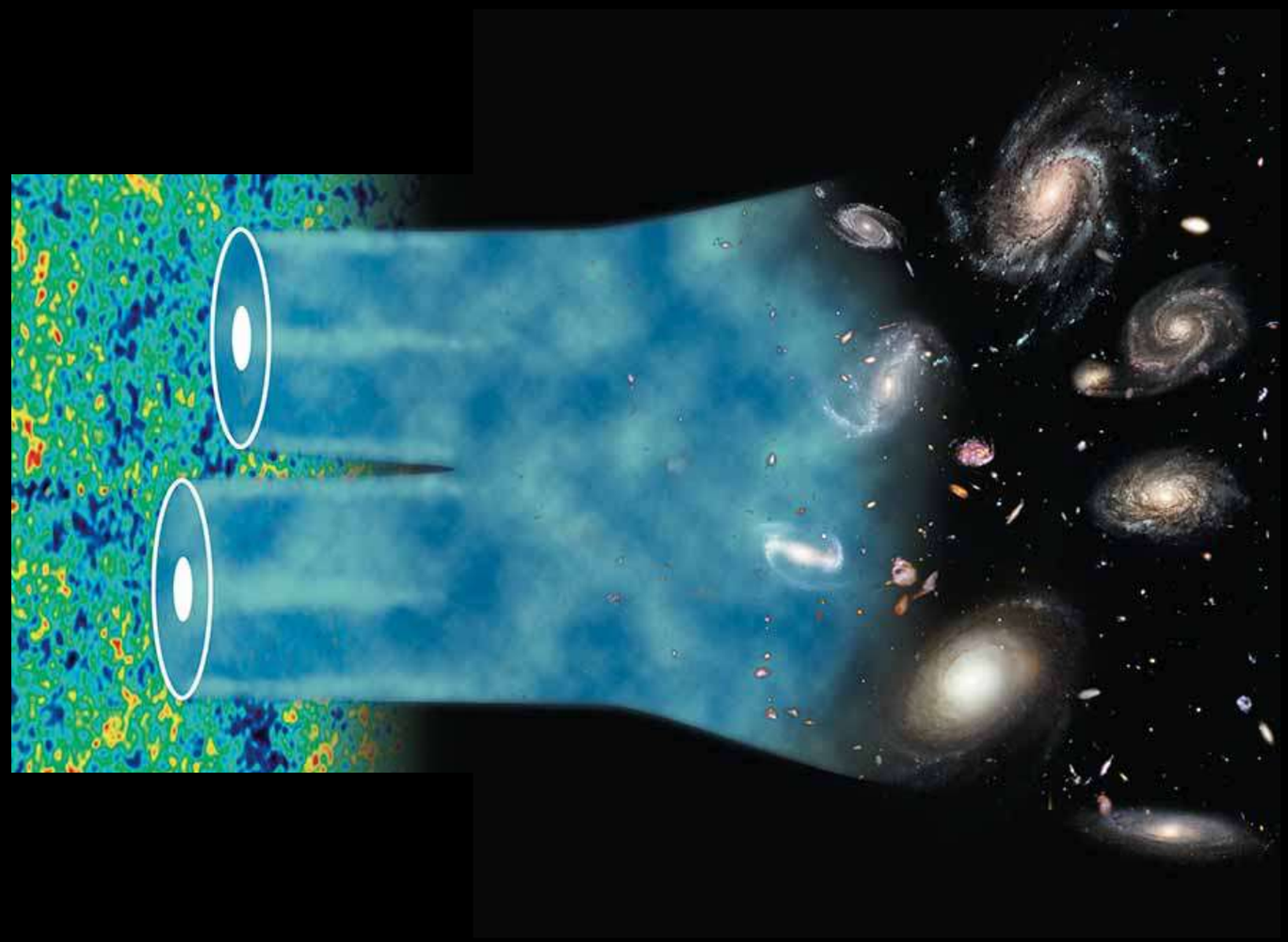
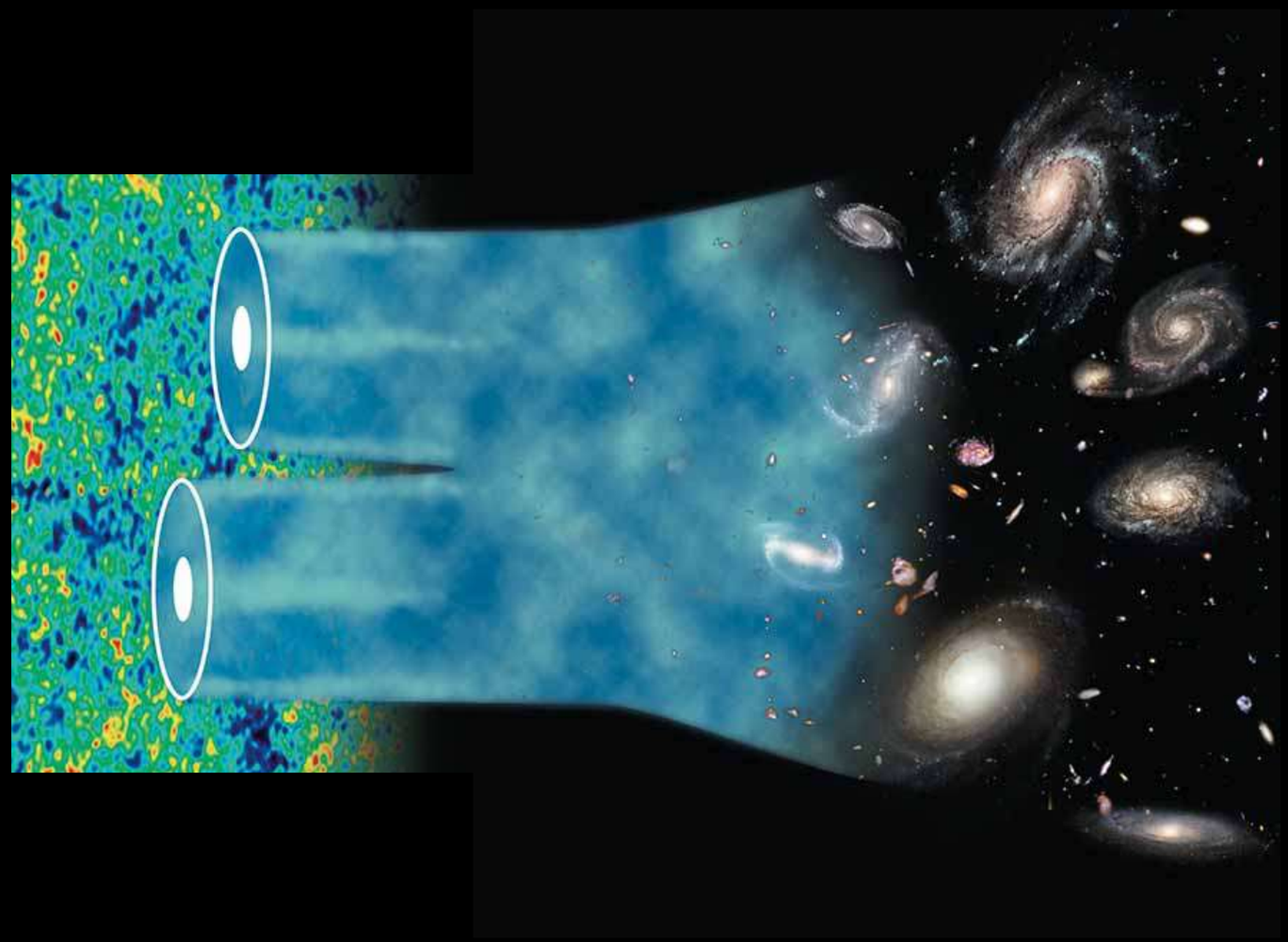
COSMIC DISSONANCE

New physics or systematics behind a short sound horizon?

NIKKI ARENDSE
RADEK WOJTAK
ADRIANO AGNELLO



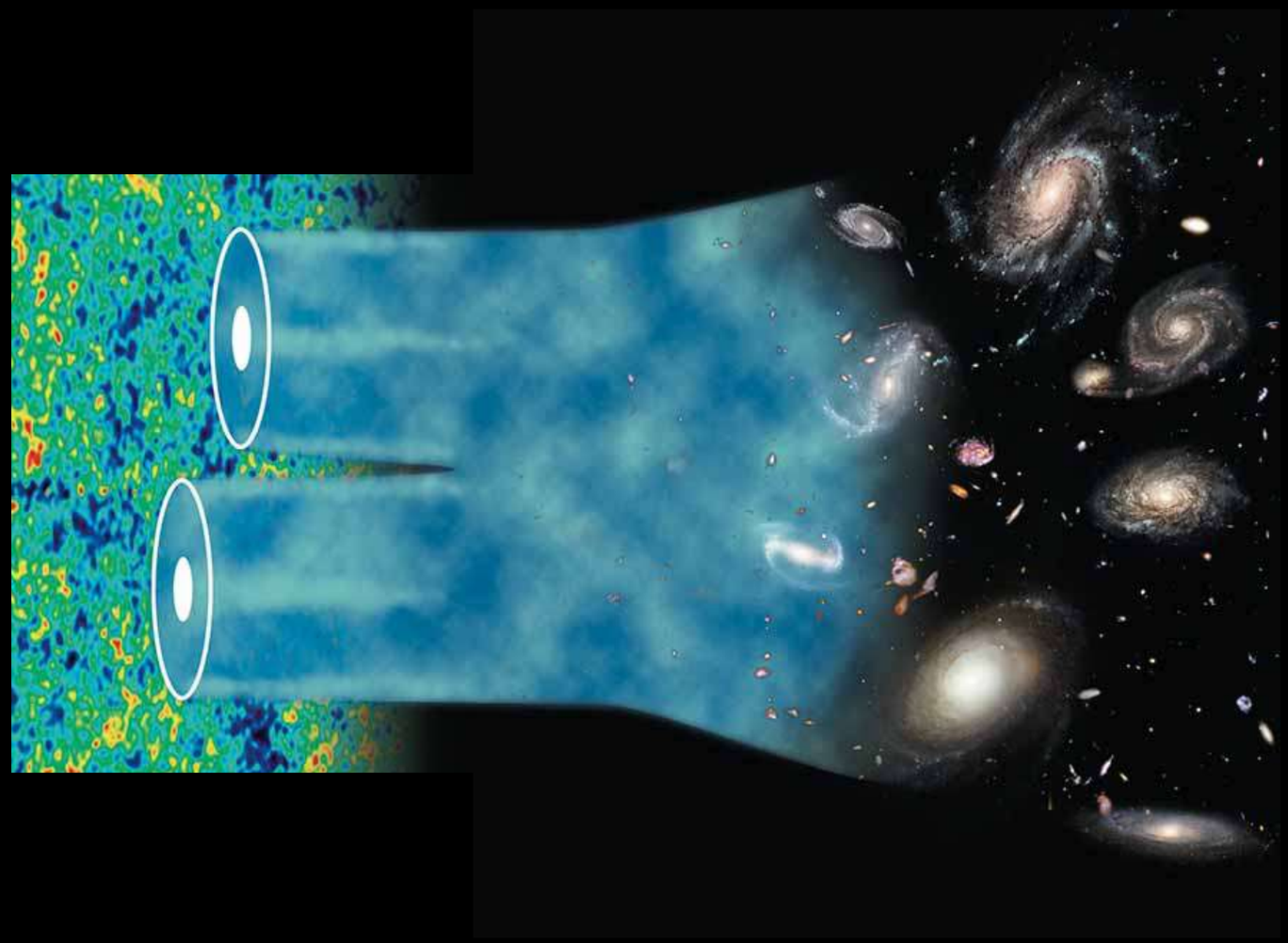
HUBBLE CONSTANT (H_0)



HUBBLE CONSTANT (H_0)

CMB

local



HUBBLE CONSTANT (H_0)

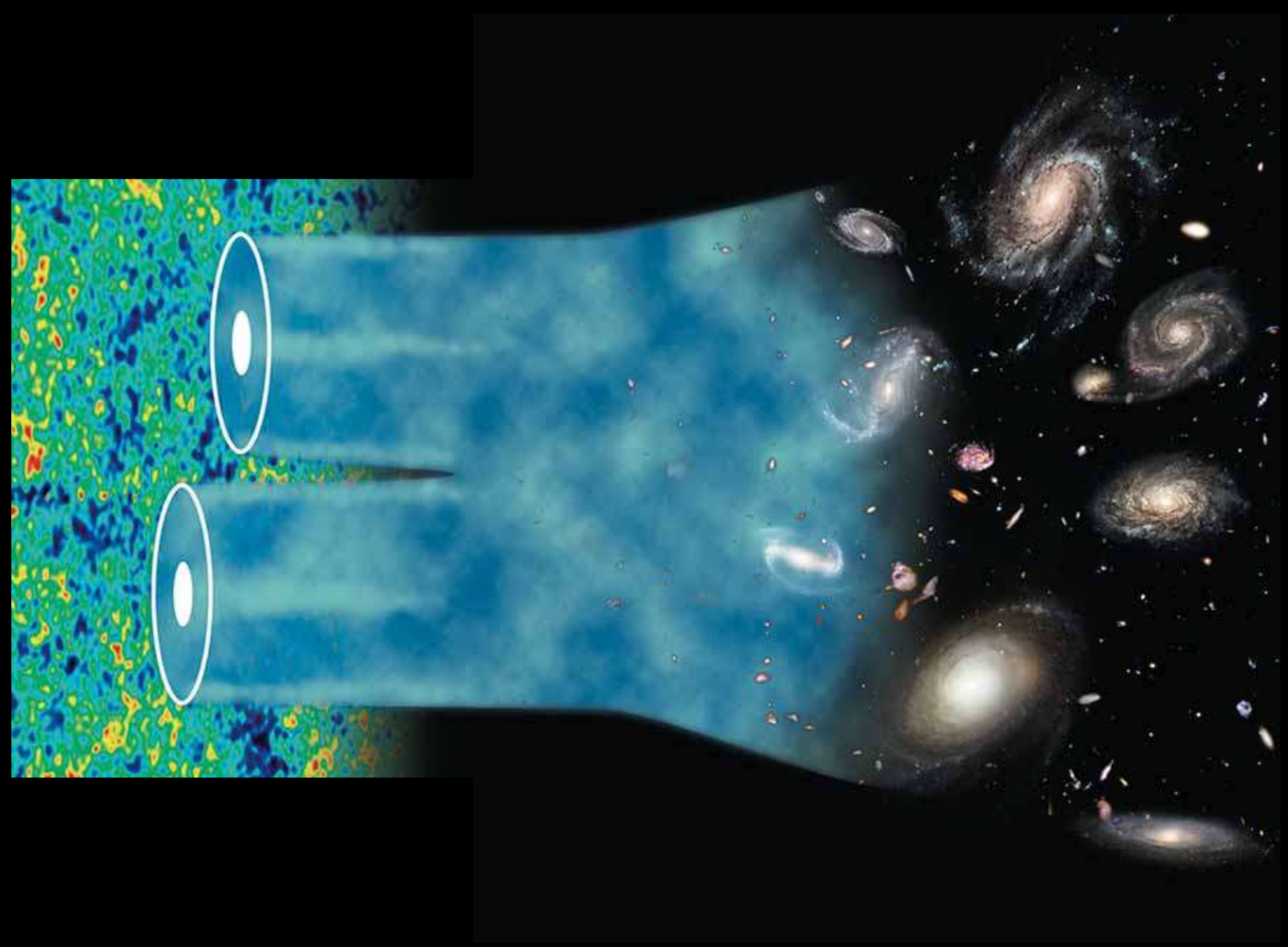
CMB

Expansion rate:

67.4

± 0.5 km/s/Mpc

local



Expansion rate:

74.0

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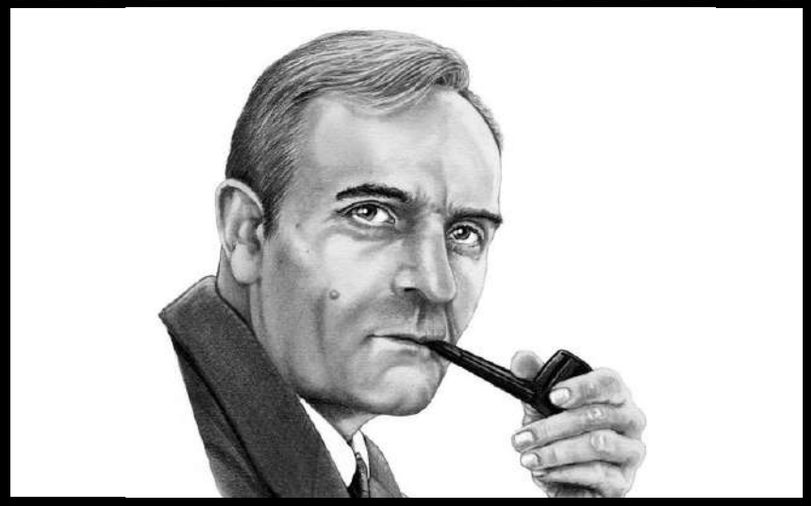
HUBBLE TENSION



CMB

local

Expansion rate:

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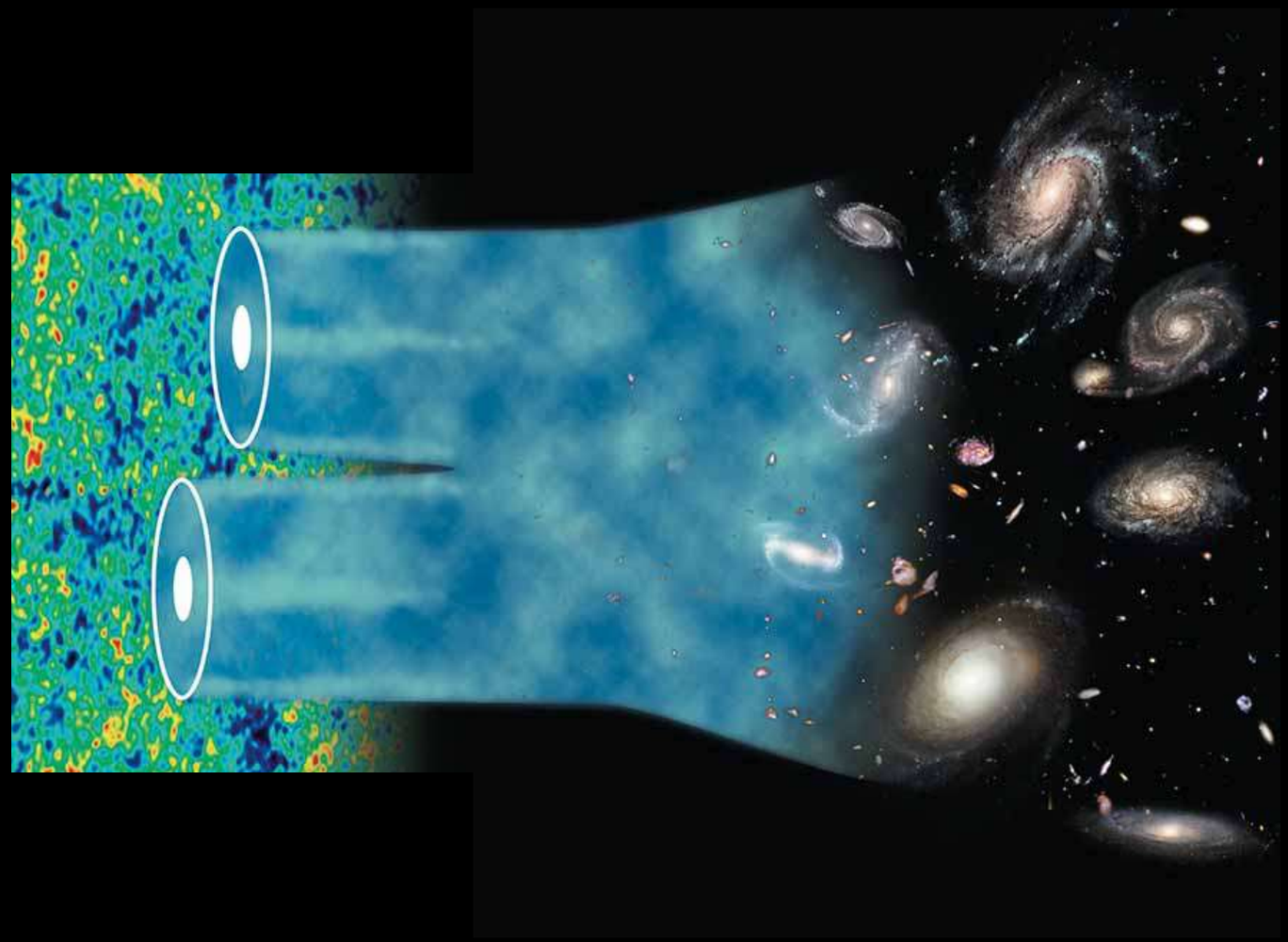
± **0.5** km/s/Mpc



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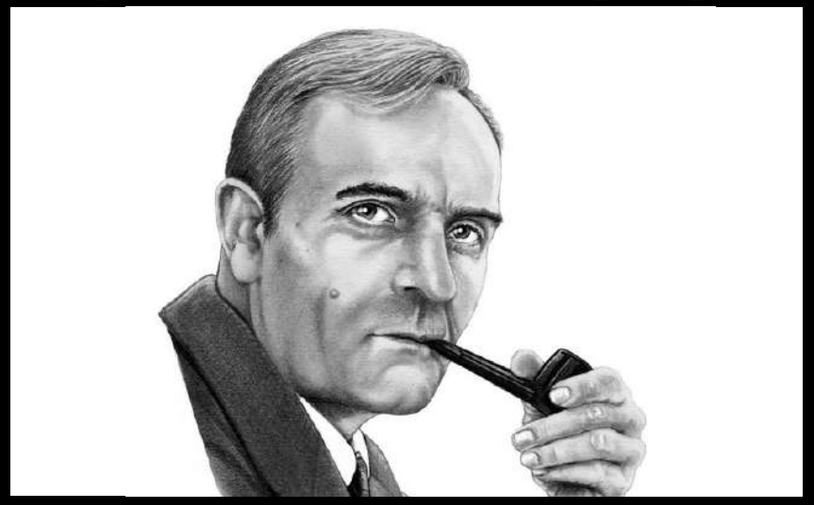

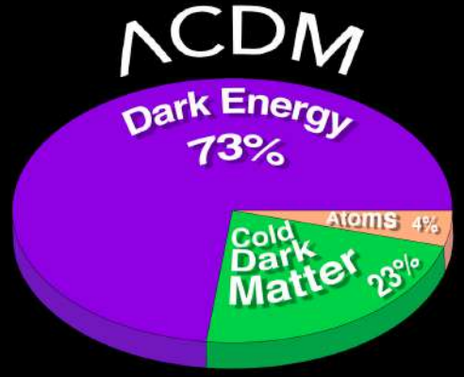

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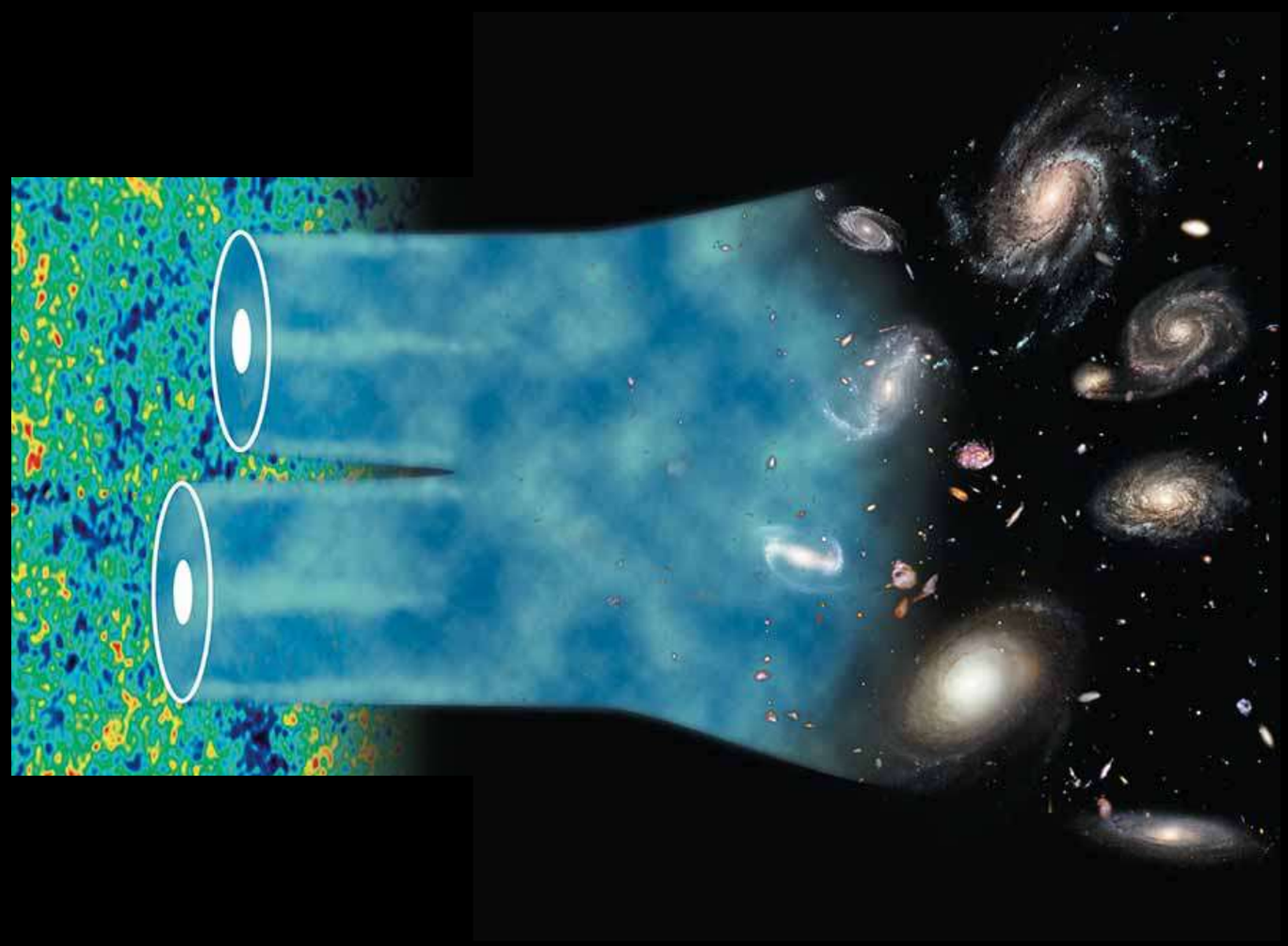

Expansion rate:

74.0

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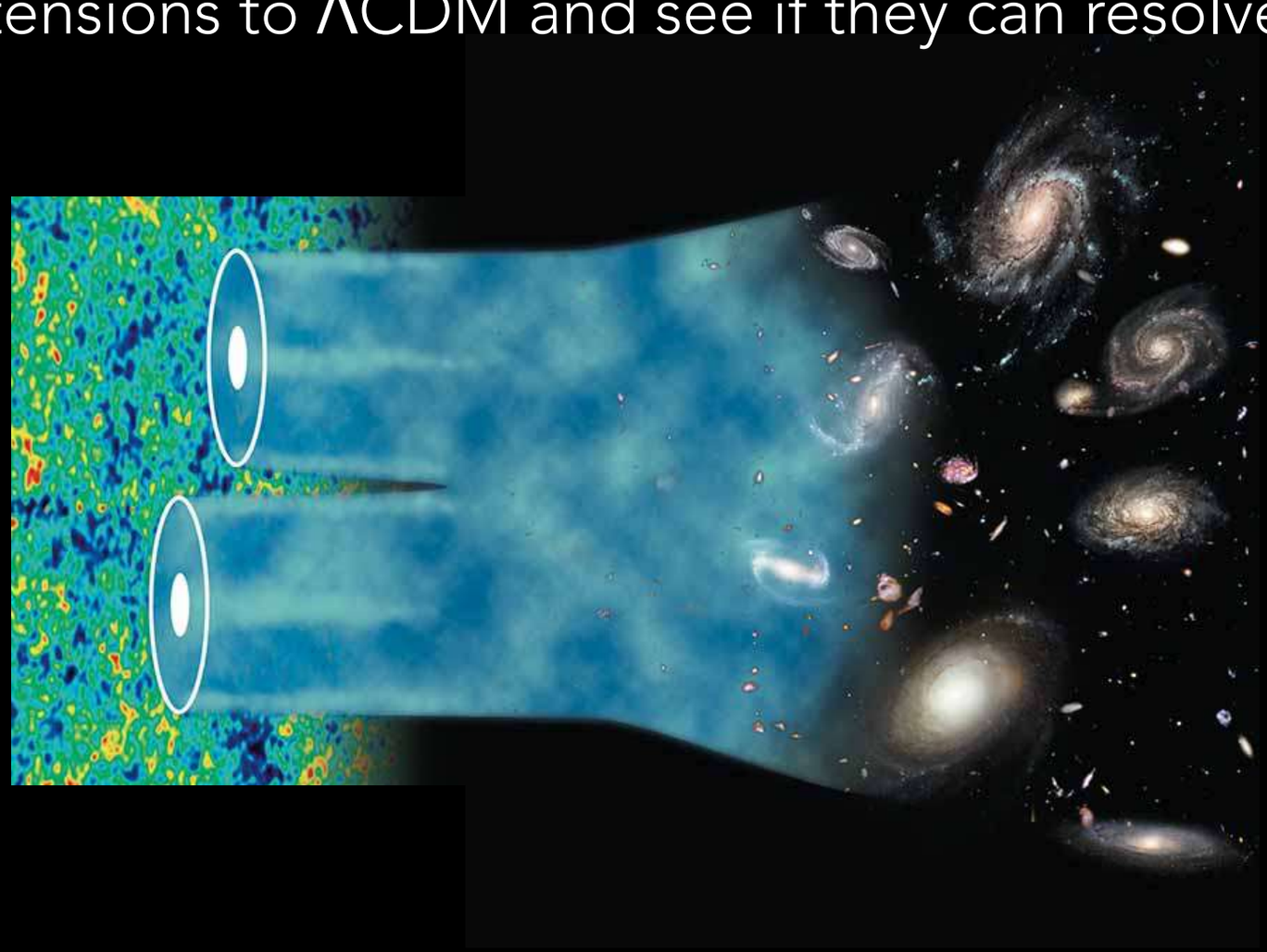
GOALS

- Determine H_0 and r_s from local data without cosmological model
- Explore extensions to ΛCDM and see if they can resolve the tension



Not just about H_0!

Another important cosmological parameter is the

SOUND HORIZON SCALE (R_D)

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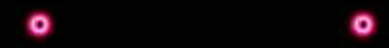

Over-densities

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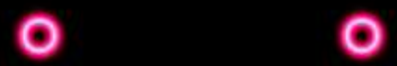

Sound waves

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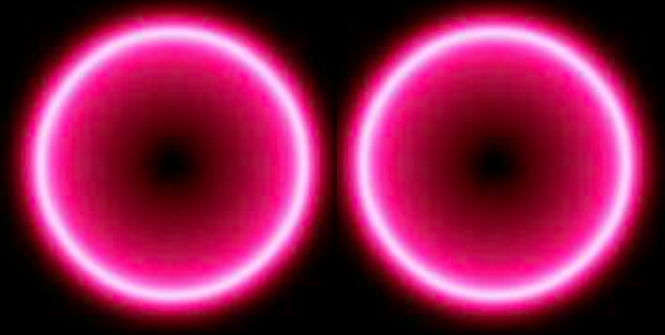

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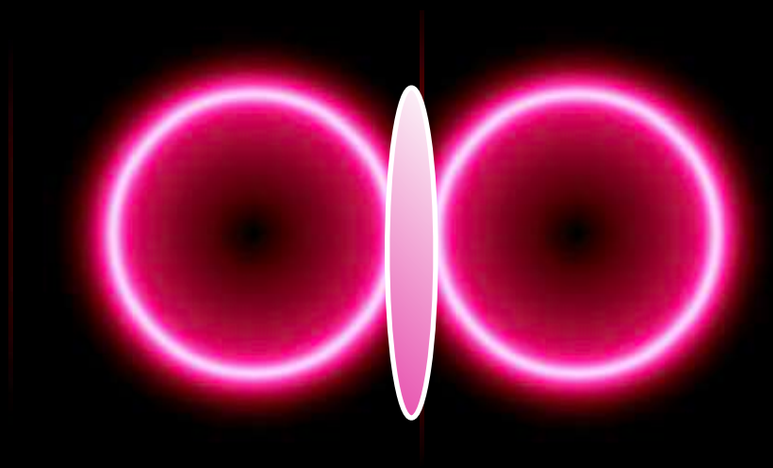

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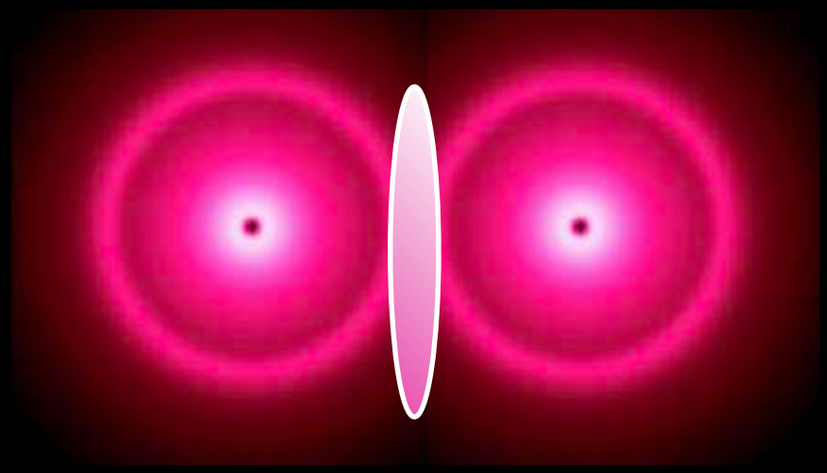
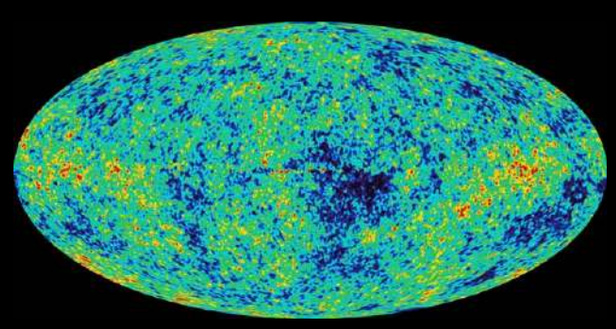


Sound waves



Universe
becomes
transparant

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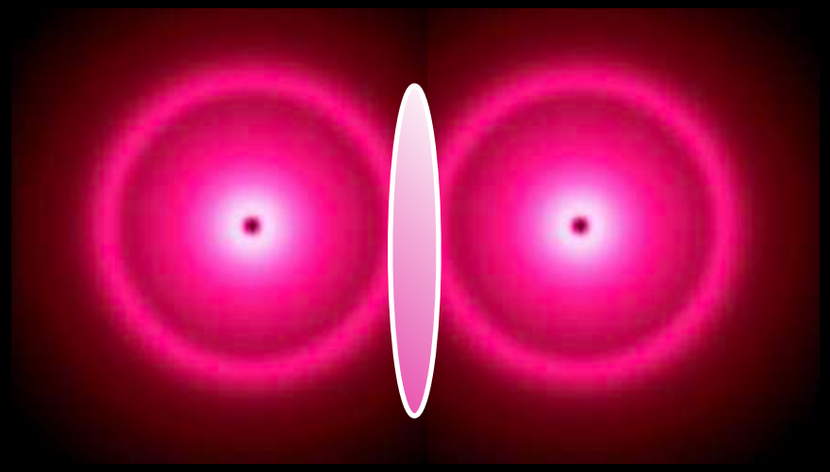
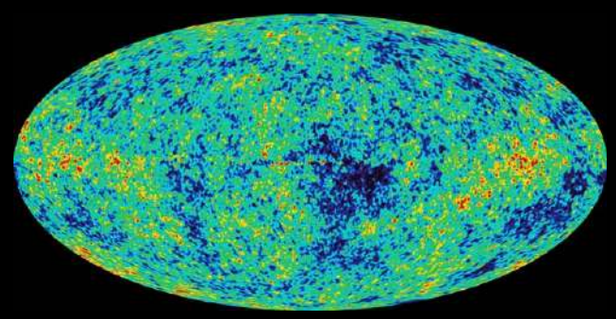


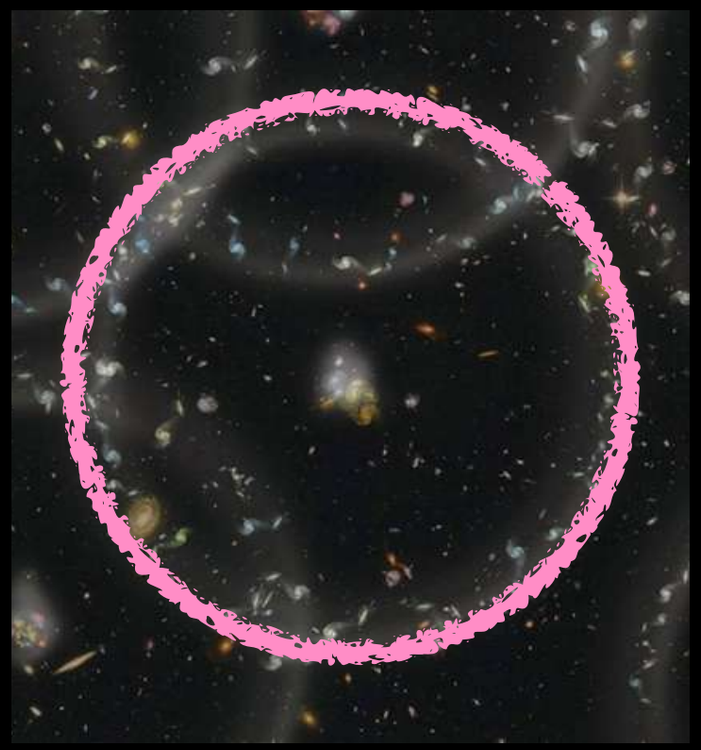
Sound waves



Universe becomes transparant

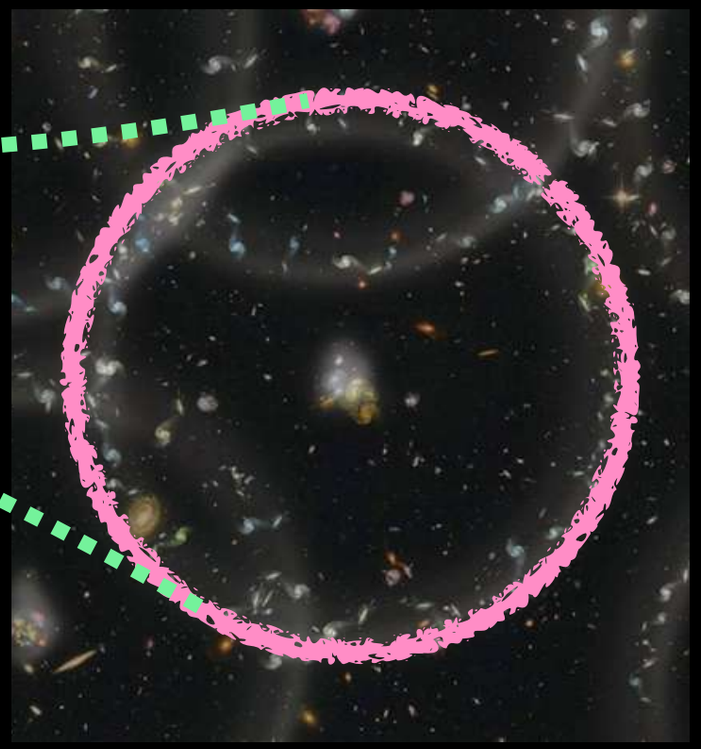
Can be seen in the clustering of galaxies (**BAO**)

Comparing $\mathbf{r_d}$ at recombination (drag epoch) to $\mathbf{r_d}$ at different redshifts tells us about the expansion of the Universe.



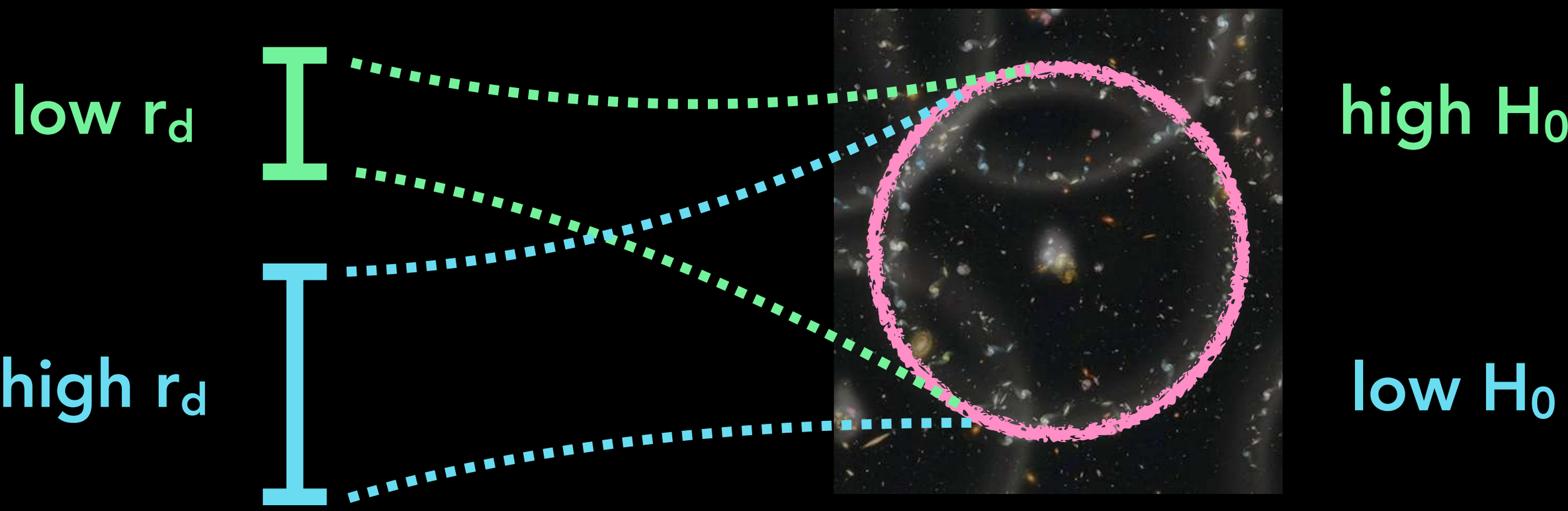
Comparing $\mathbf{r_d}$ at recombination (drag epoch) to $\mathbf{r_d}$ at different redshifts tells us about the expansion of the Universe.

low r_d



high H_0

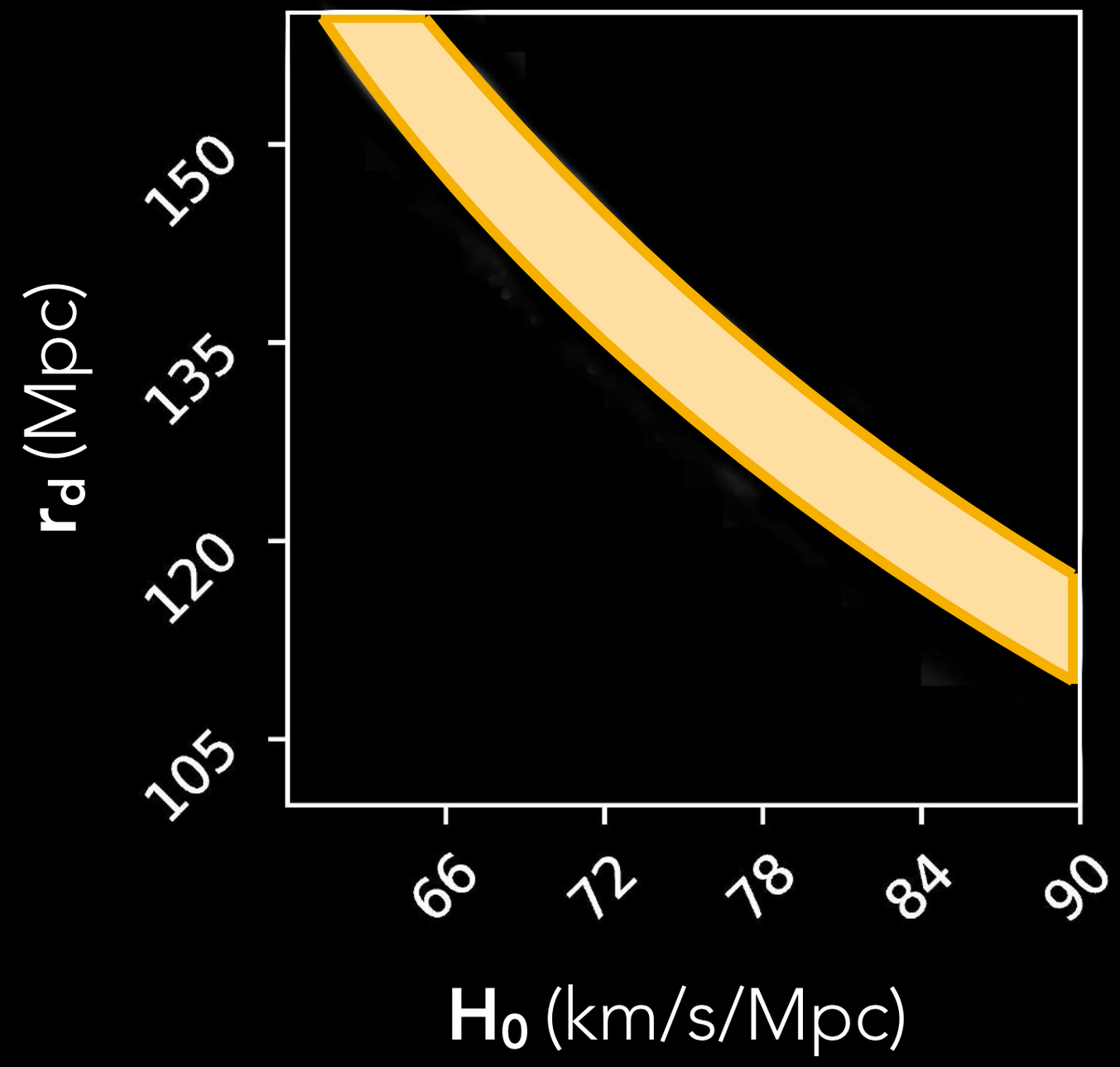
Comparing $\mathbf{r_d}$ at recombination (drag epoch) to $\mathbf{r_d}$ at different redshifts tells us about the expansion of the Universe.



In this way, BAO constrains the product $\mathbf{H_0\ r_d}$.

The tension is a problem in both parameters,

they are degenerate with each other.



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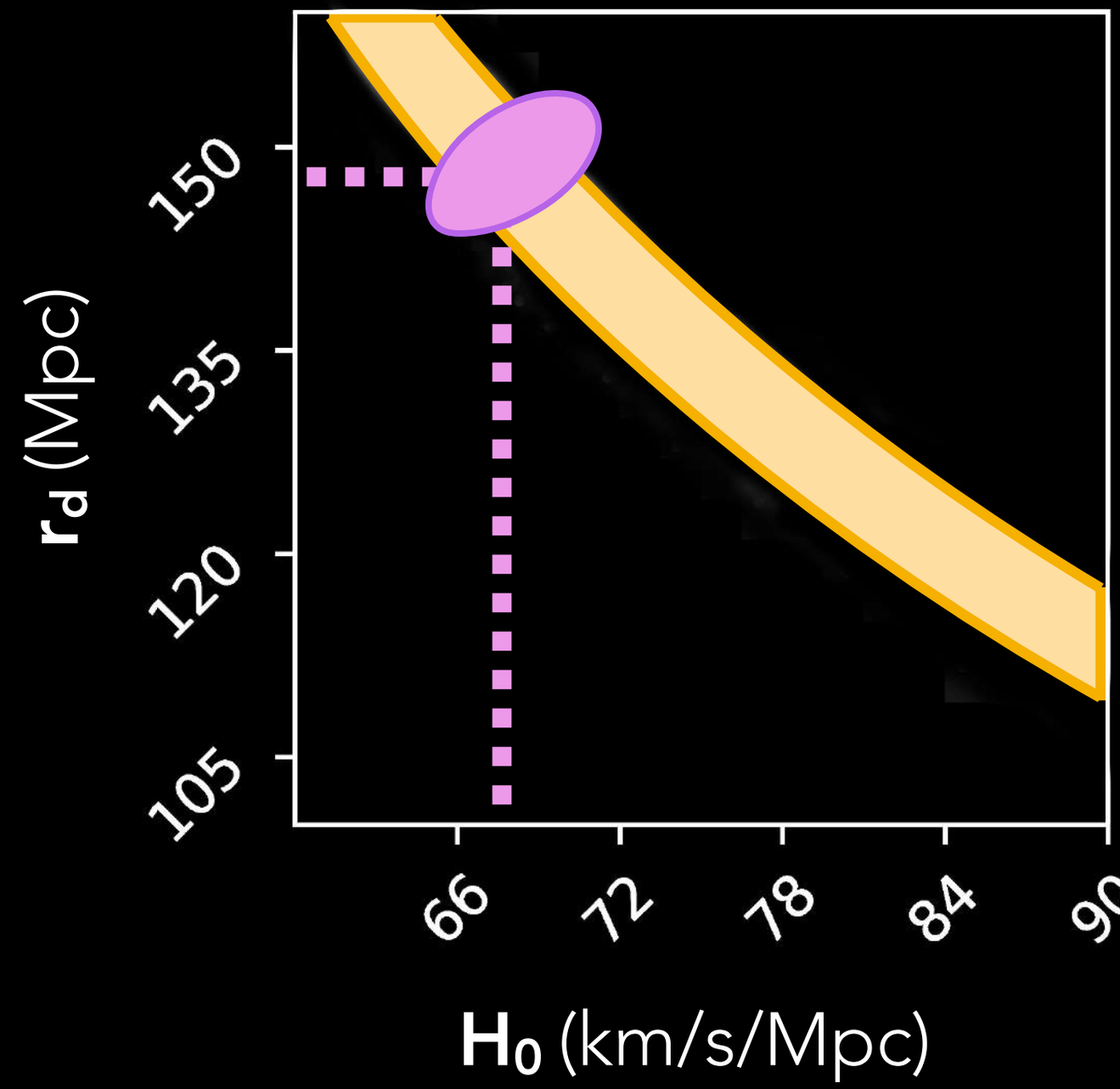

Planck measures a **high r_d** and therefore a **low value of H_0.**

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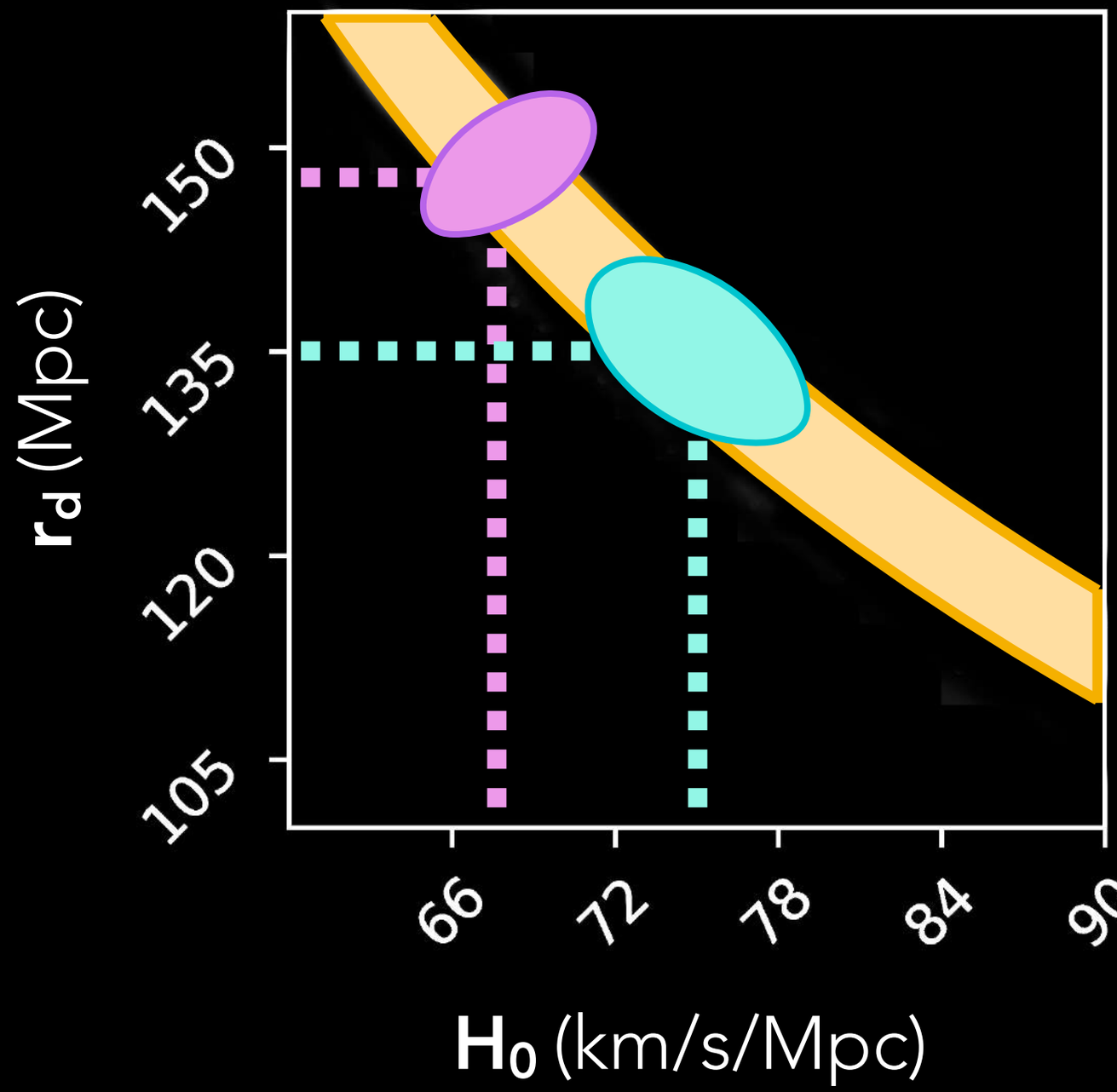
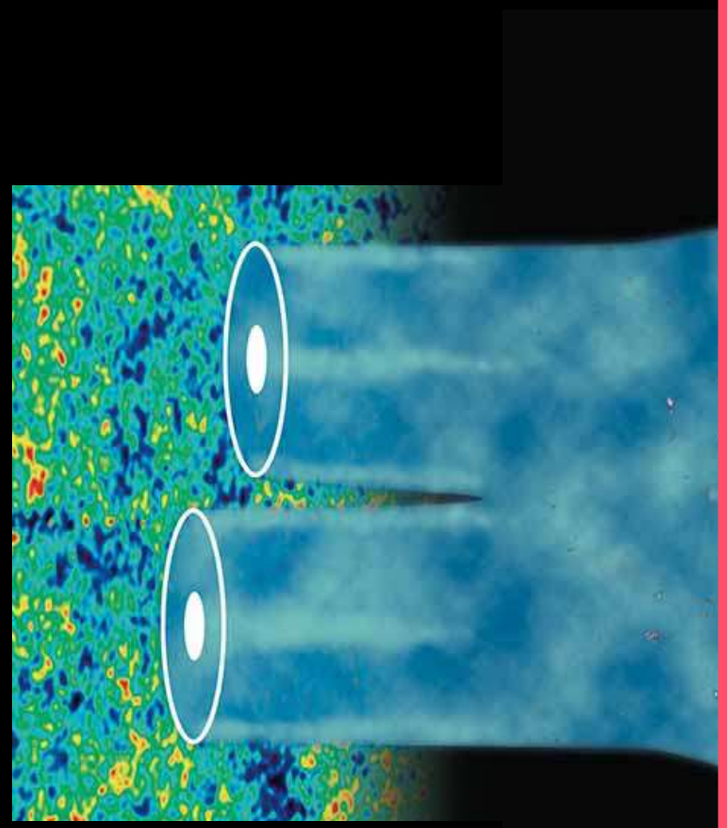


Planck measures a **high r_d** and therefore a **low value of H_0**.

While **local measurements** get a **low r_d** and a **high H_0**.

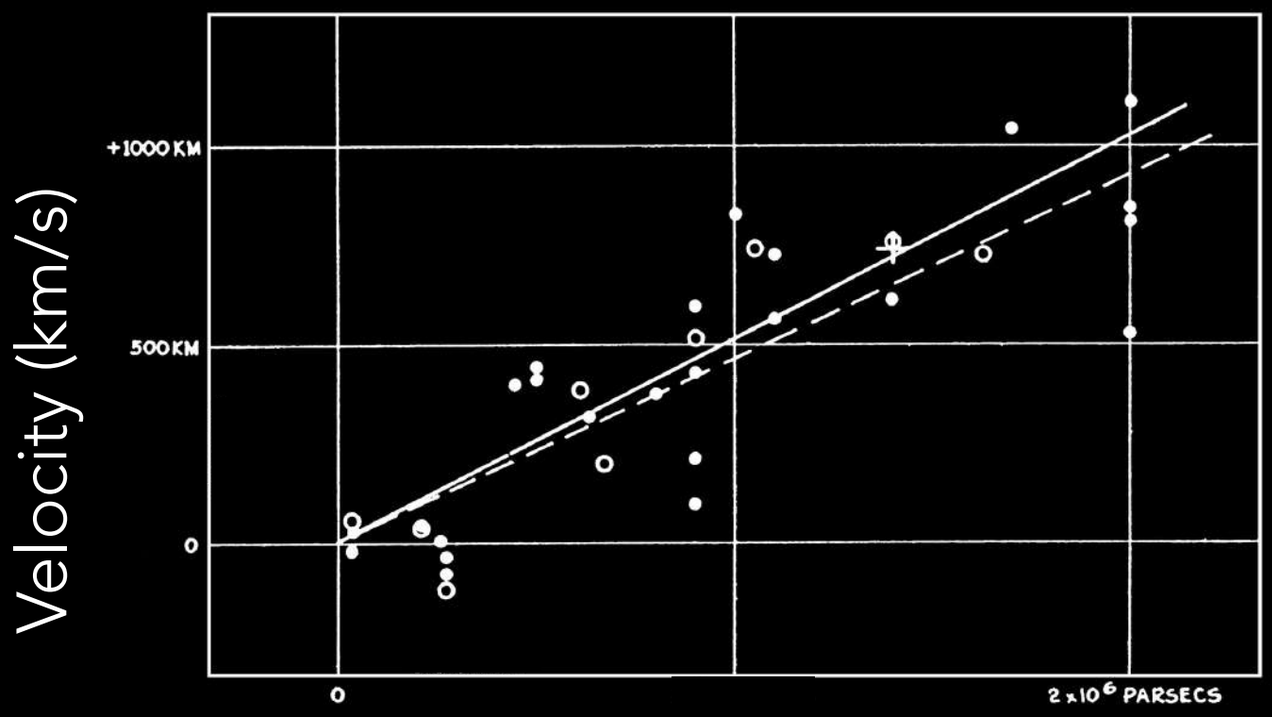
CMB

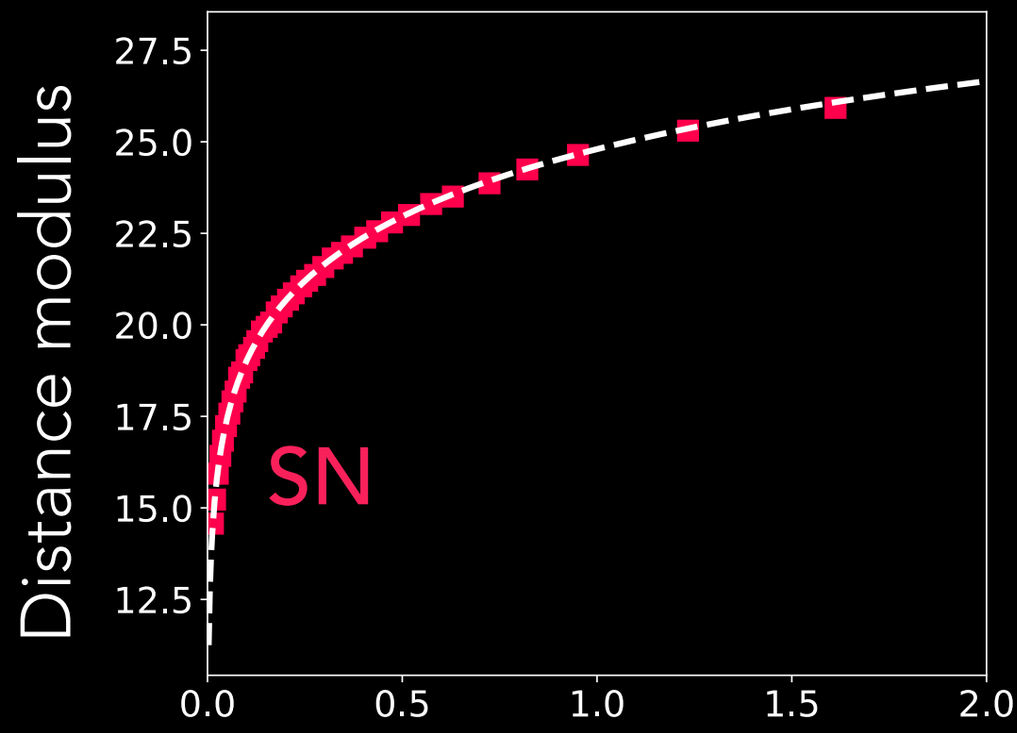


local

LOCAL DETERMINATION OF H_0 AND R_D

Modern & improved Hubble diagram





LOCAL DETERMINATION OF H_0 AND R_D

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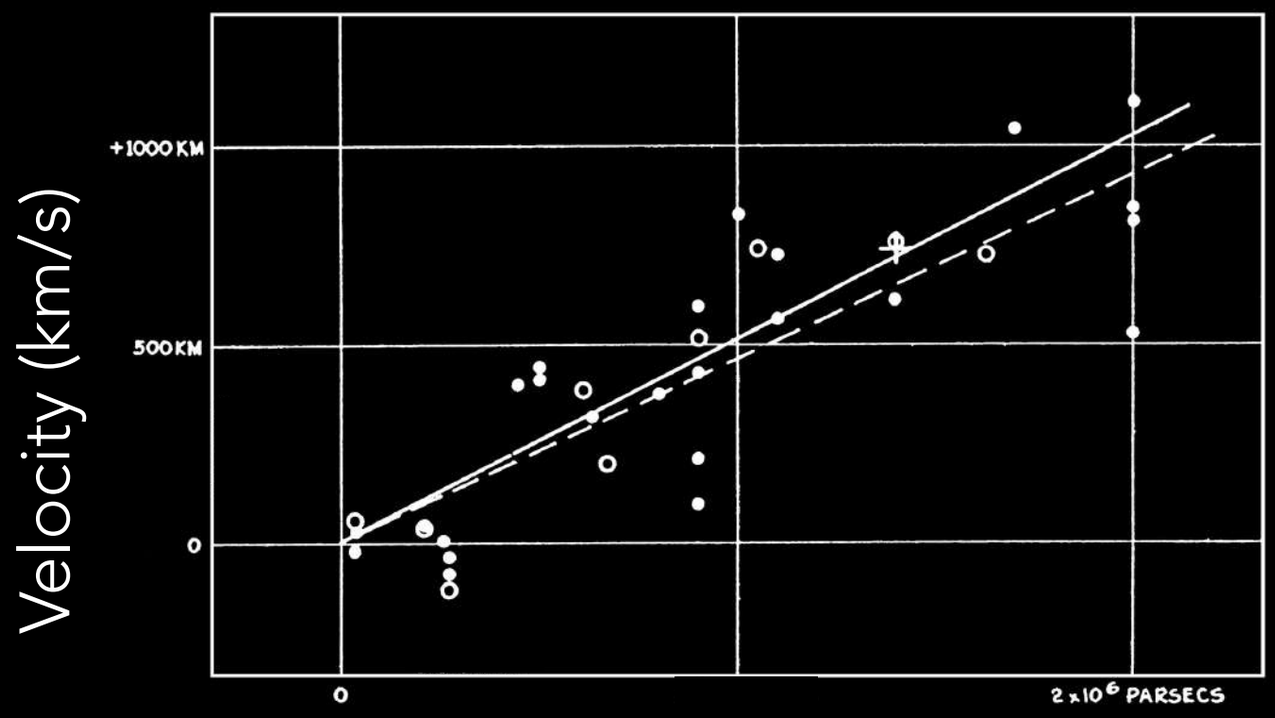

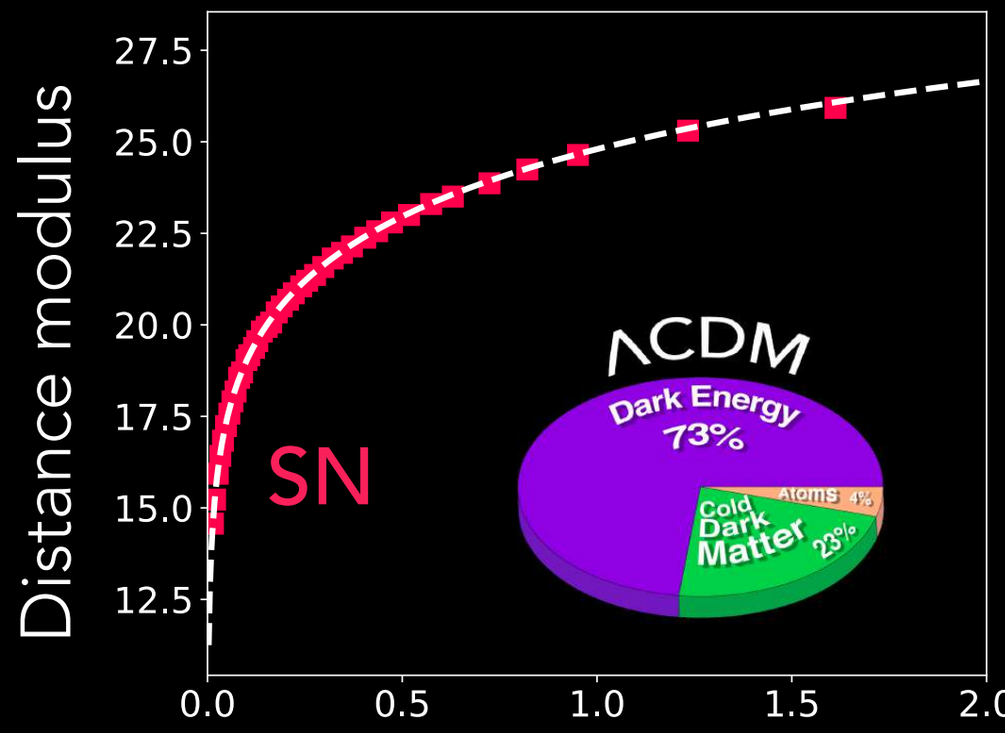

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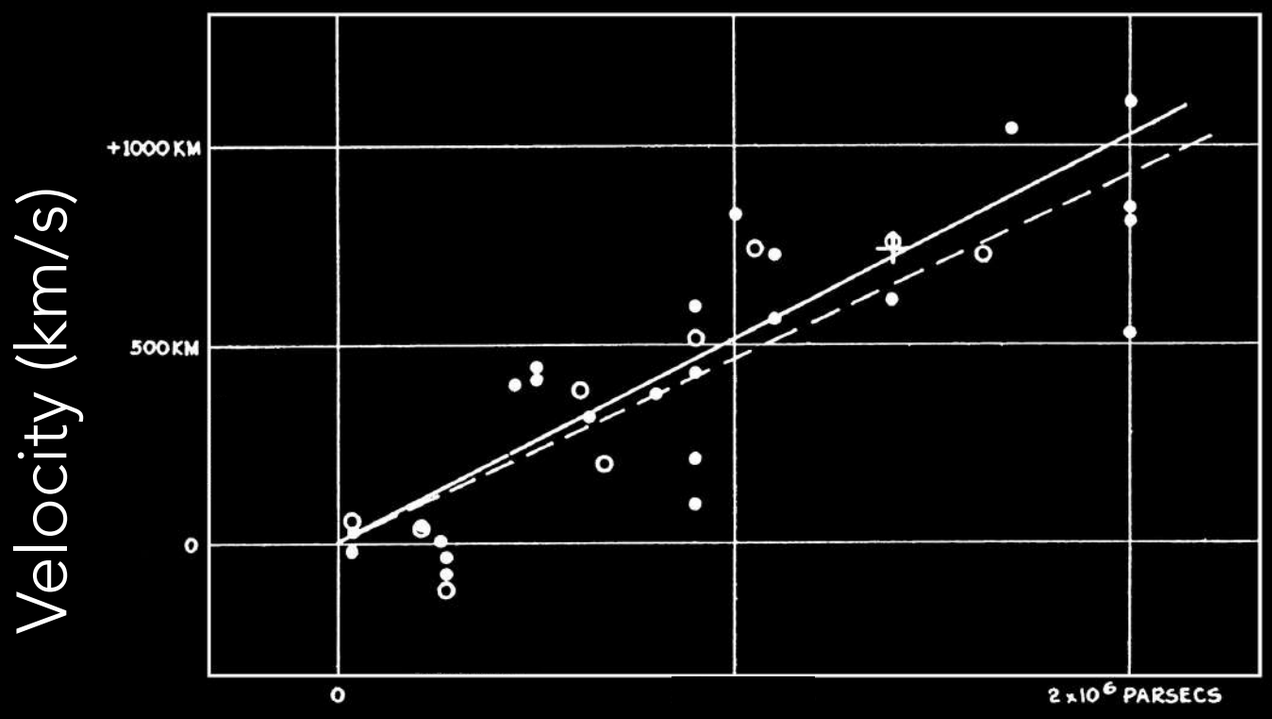
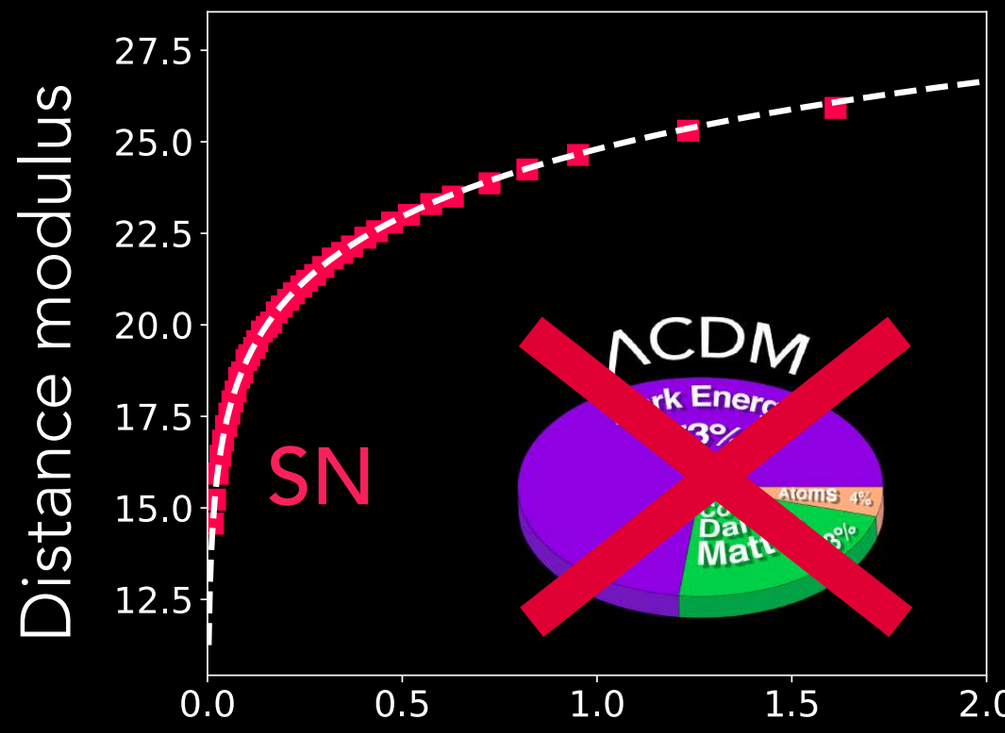




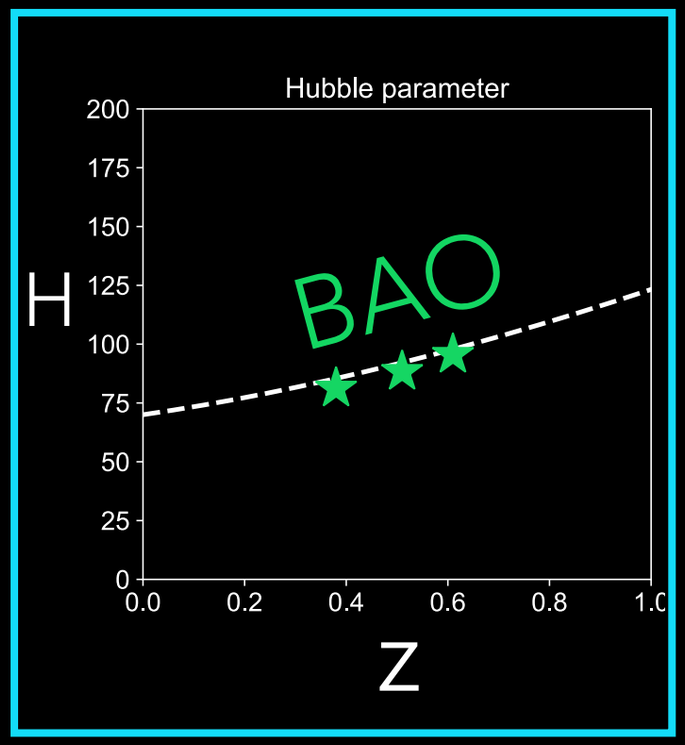
Friedman equations:

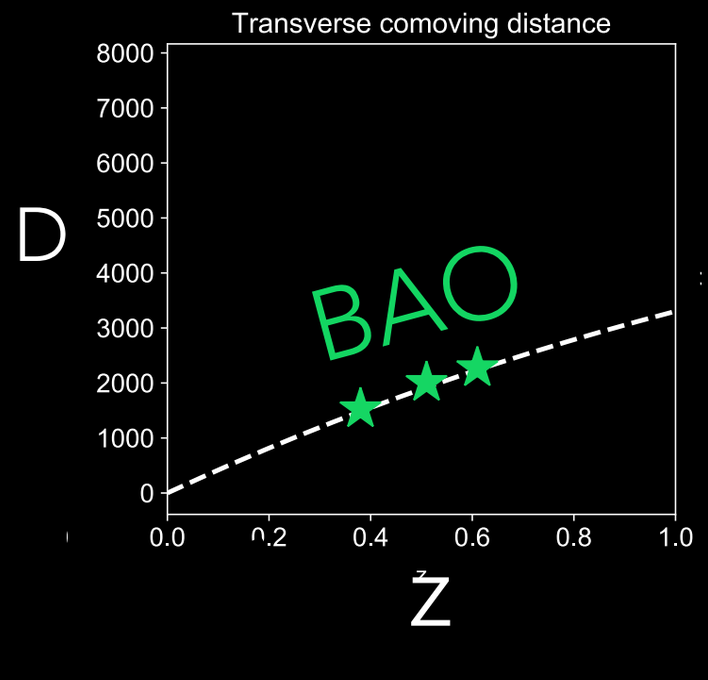
$$H(z) = H_0\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}$$

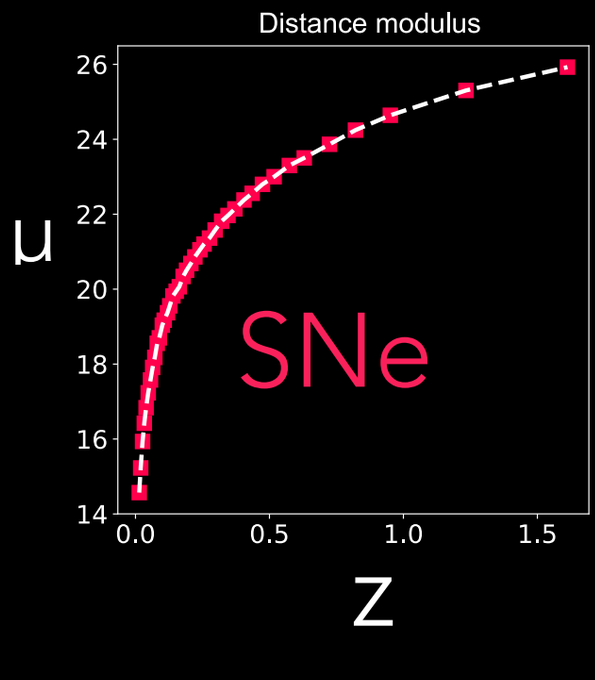
Taylor expansion:

$$H(z) = H_0+c_1z+c_2z^2+\mathcal{O}(z^3)$$

$$c_1 = \left.\frac{dH}{dz}\right|_0 \qquad c_2 = \frac{1}{2}\left.\frac{d^2H}{dz^2}\right|_0$$







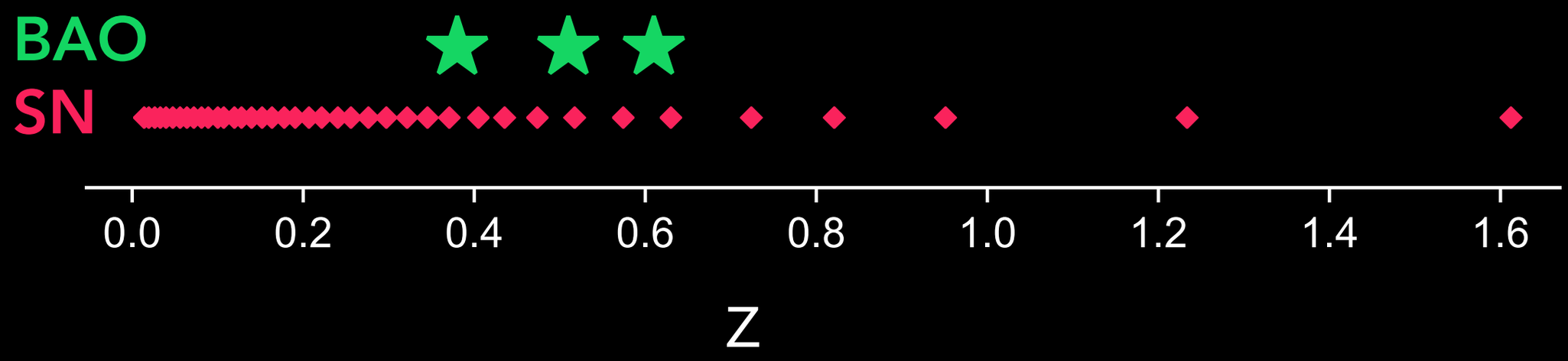
integrate

logarithm

DATA SETS

DATA SETS

- Supernovae (Pantheon sample)
- Baryon Acoustic Oscillations (BOSS)



CALIBRATE DATA

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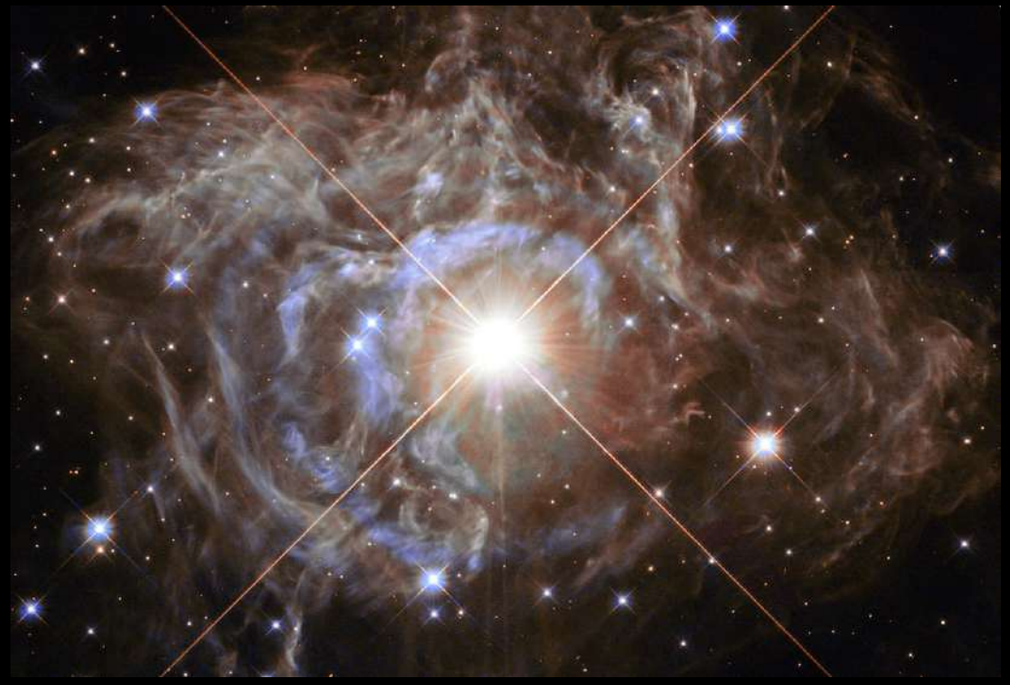
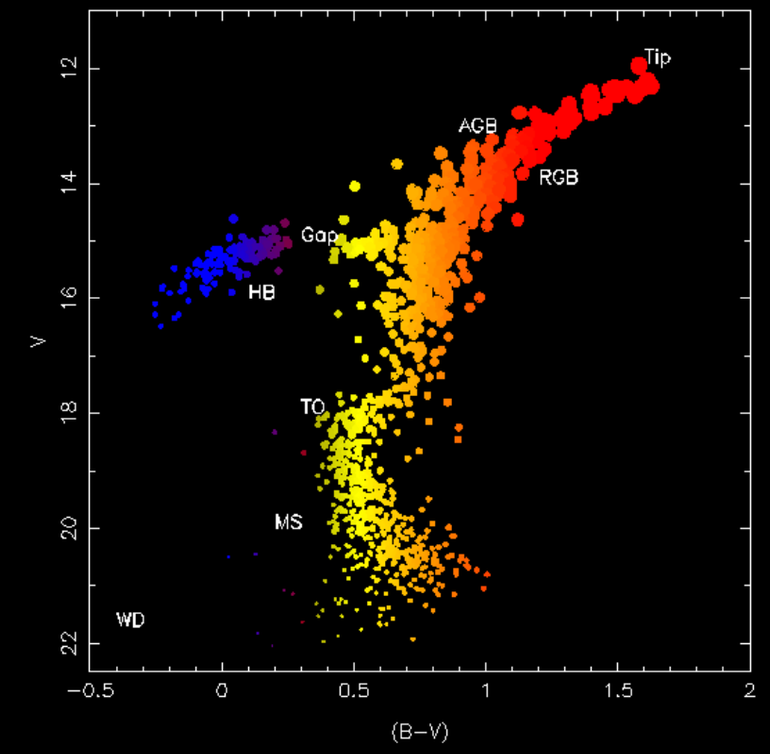
This has usually been done with **Cepheids** or stars at the Tip of the Red Giant Branch (**TRGB**).
But those can only be seen at very low redshifts.





CALIBRATE DATA

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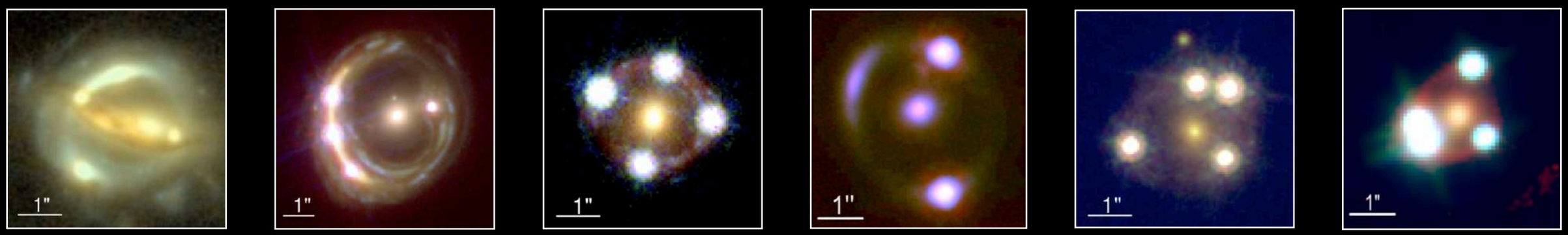
Additionally, we use lensed quasars from the H0LiCOW collaboration.

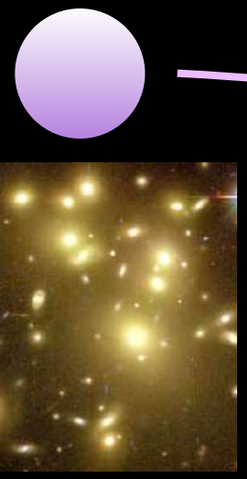
H0LICOW

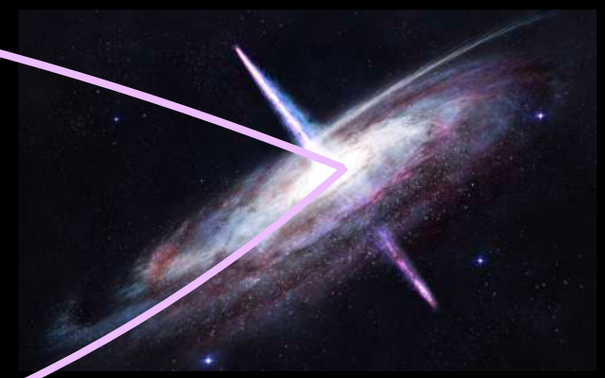
H0 Lenses in COSMOGRAIL Wellspring

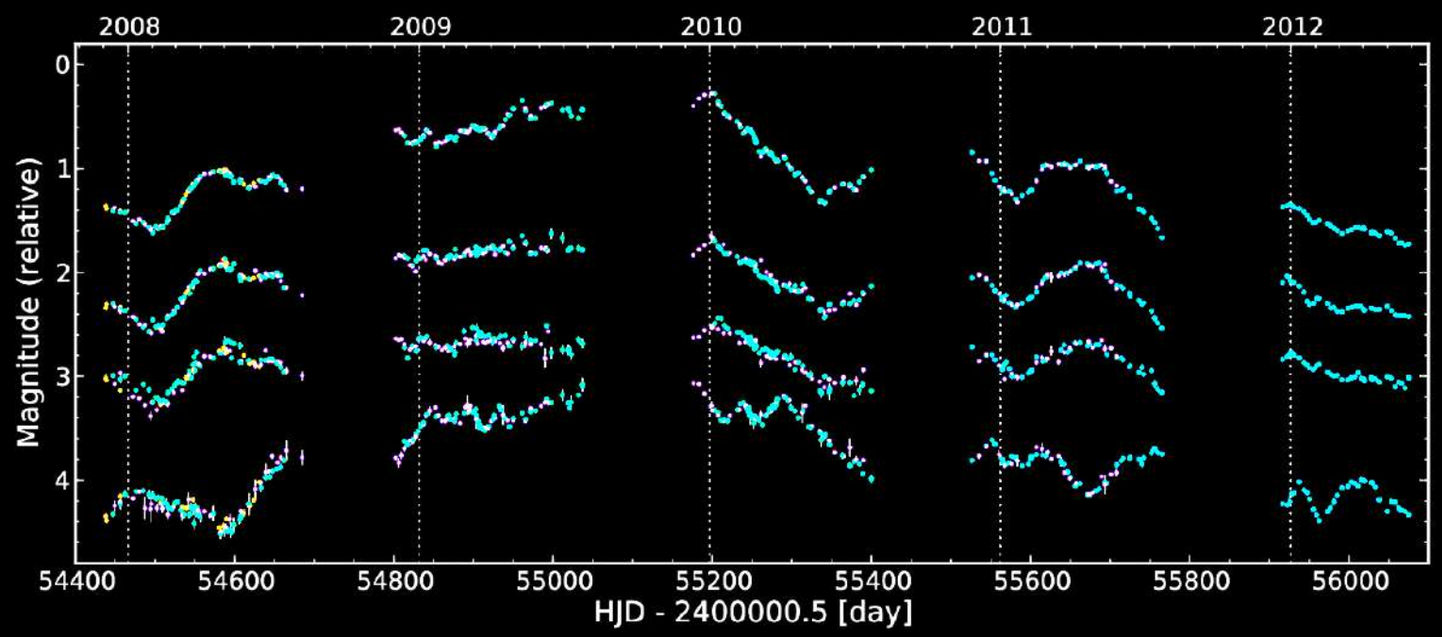


B1608 RXJ1131 HE0435 J1206 WFI2033 PG1115

Images, data and explanation by H0LiCOW group







Time delay relative to the case of no lensing:

$$t = \frac{D_{\Delta t}}{c}\,\phi_{\rm lens}$$

Time delay

$$D_{\Delta t} = (1 + z_l)\,\frac{D_l D_s}{D_{ls}}$$

Images, data and explanation by H0LiCOW group


BAO
SN
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
Z

Cepheids

TRGB

BAO

SN

Cepheids

TRGB

Lenses

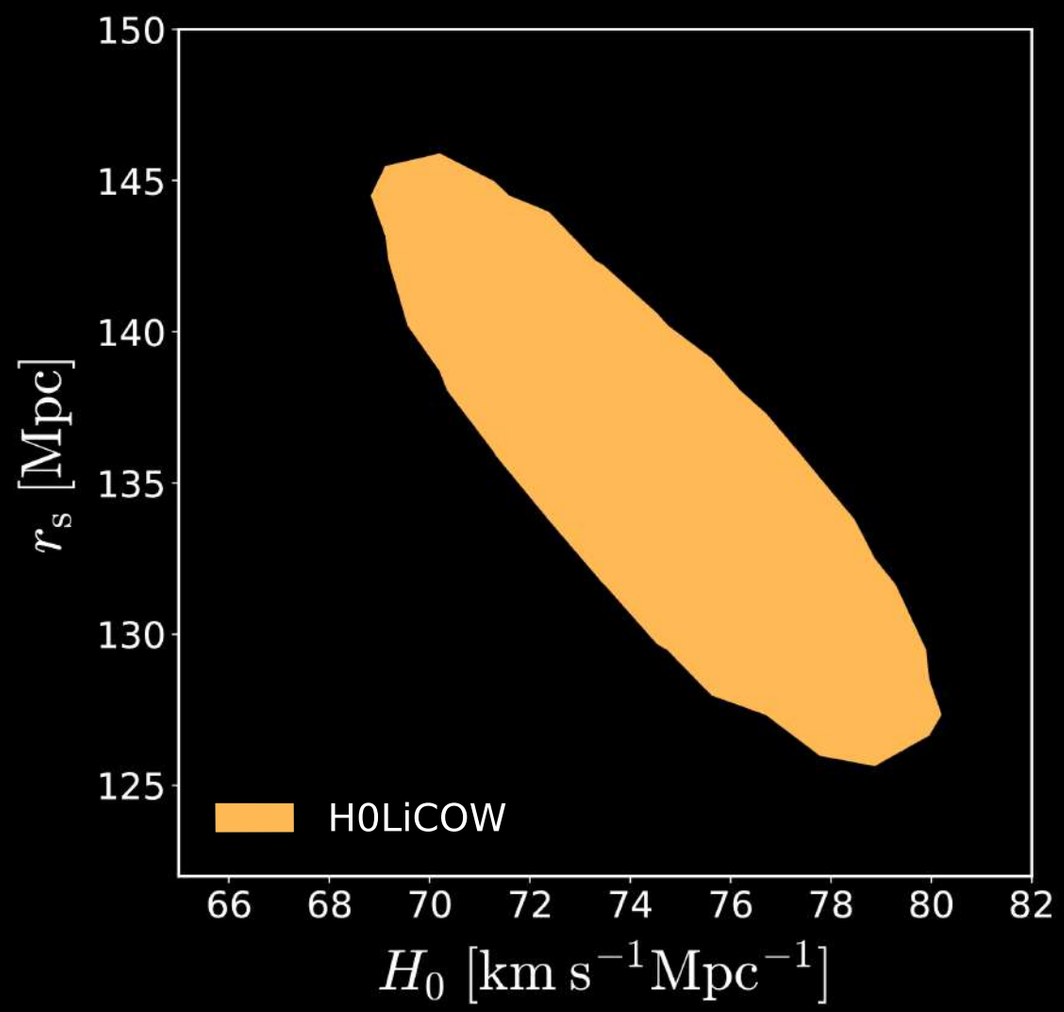
BAO

SN

RESULTS

RESULTS

Arendse, Wojtak, Agnello et al. (2019), arXiv: 1909.07986



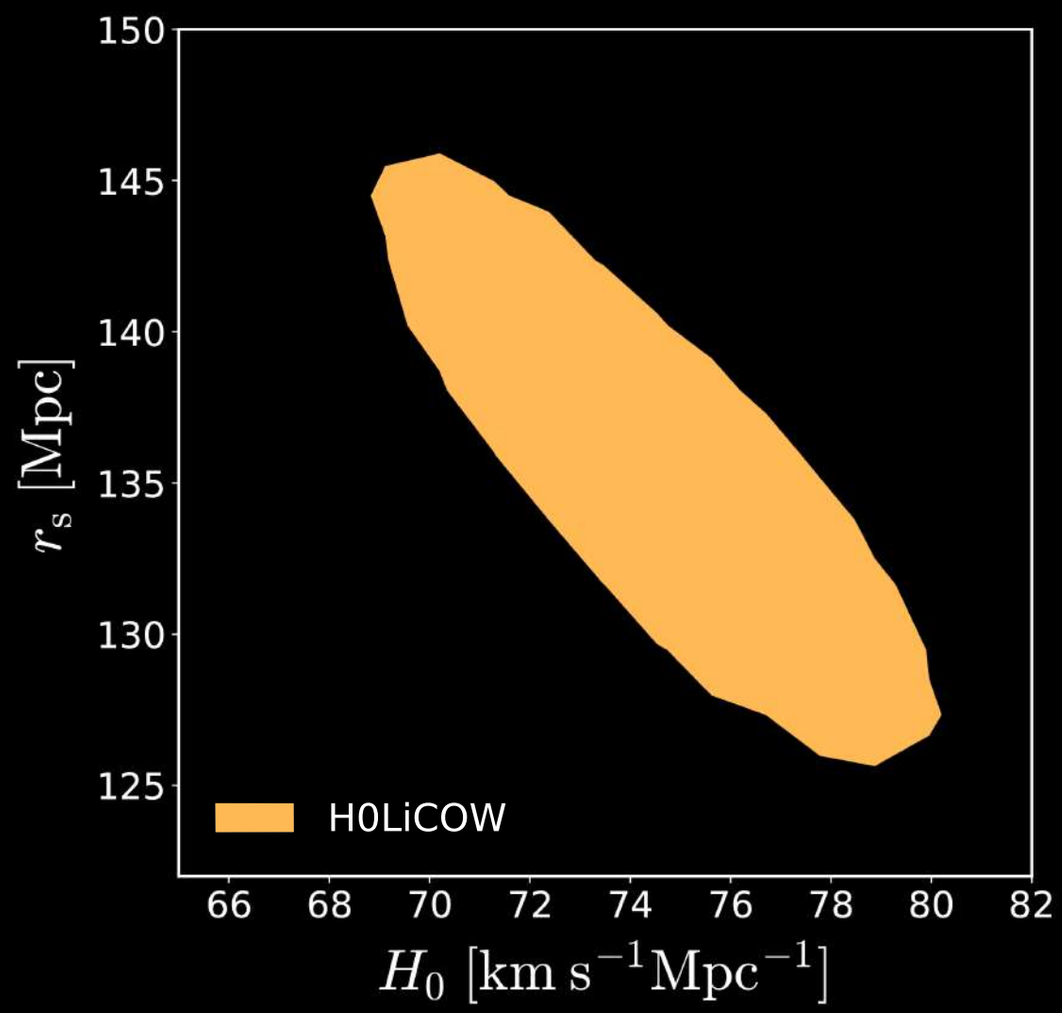
H0LiCOW

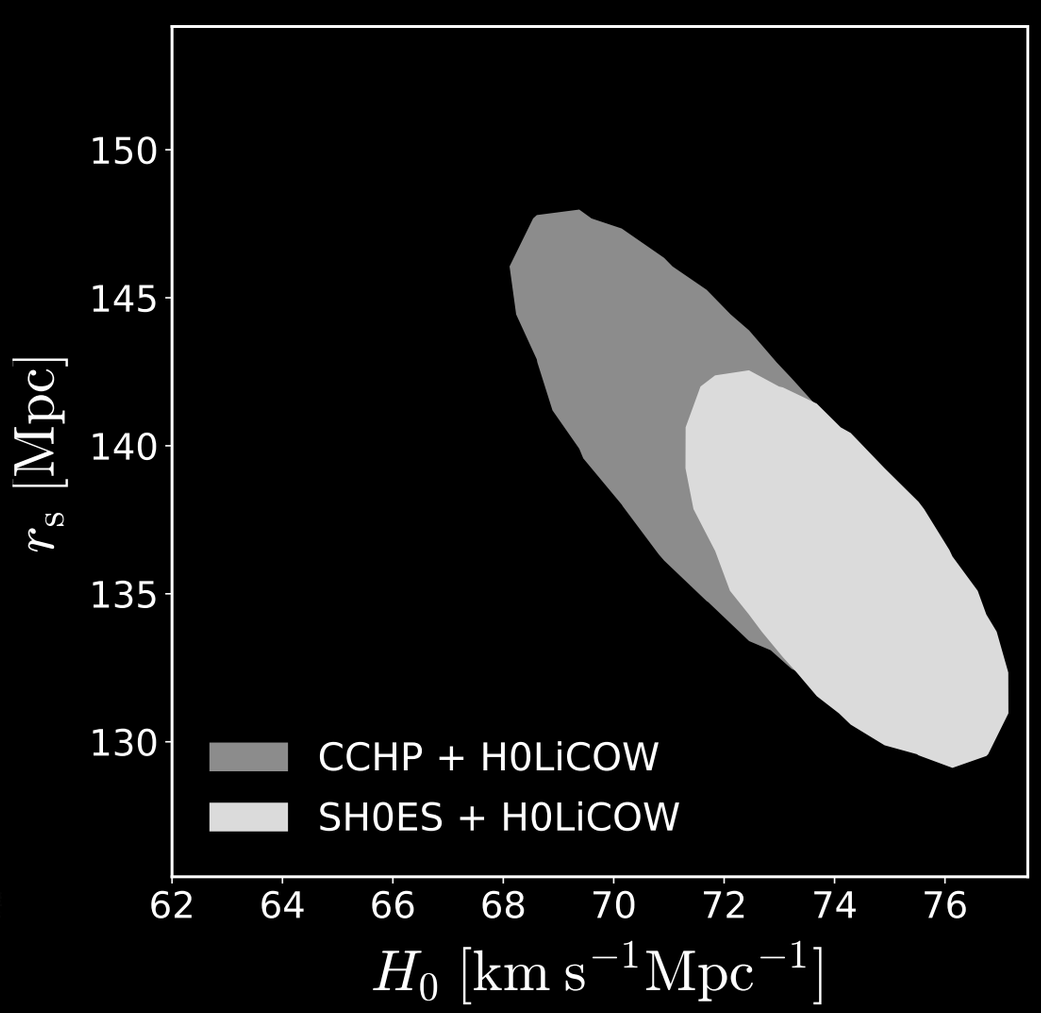
$H_0 = 74.5 \pm 2.2$

$r_s = 135.2 \pm 4.0$

RESULTS

Arendse, Wojtak, Agnello et al. (2019), arXiv: 1909.07986



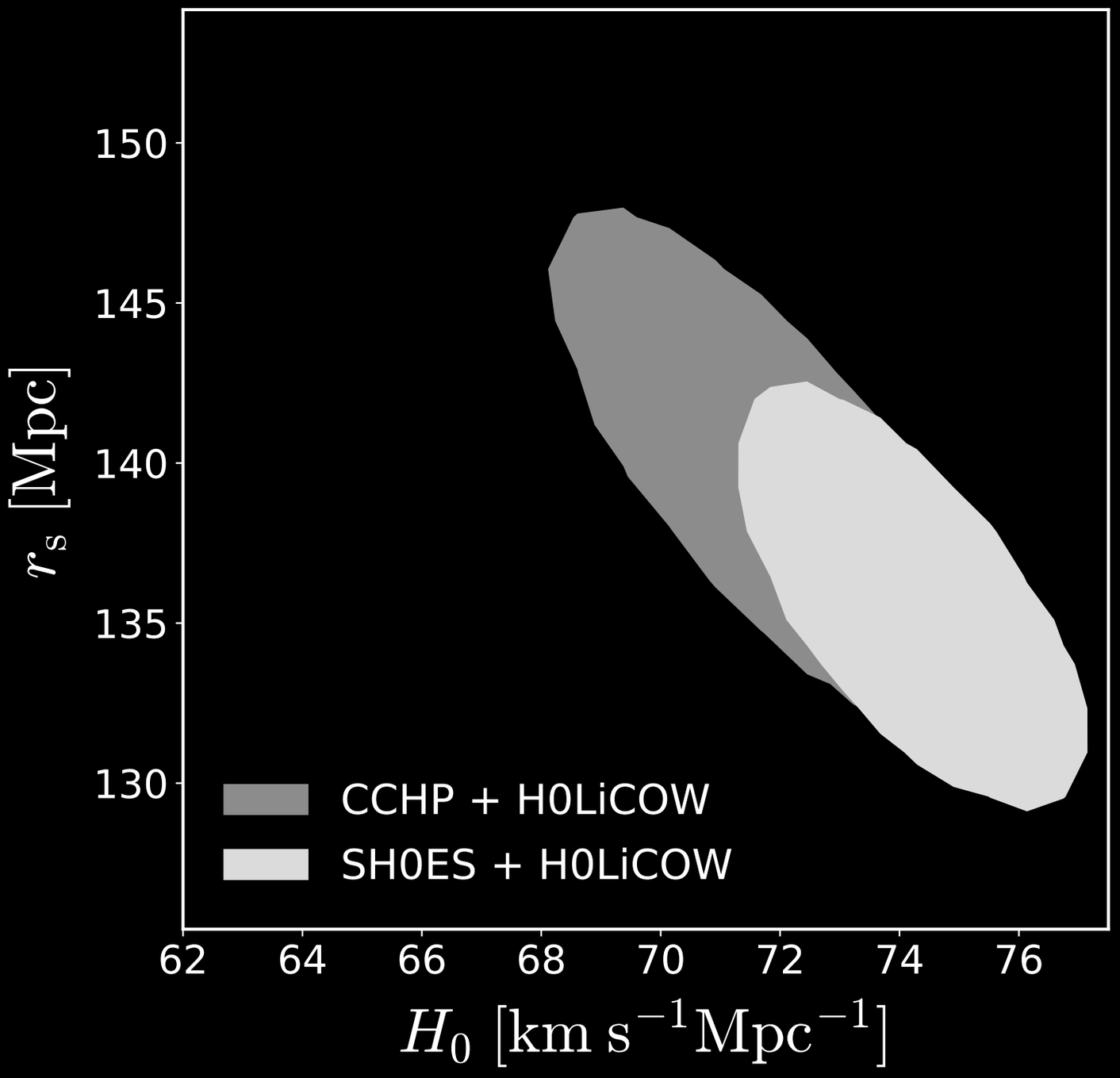


H0LiCOW
$H_0 = 74.5 \pm 2.2$
$r_s = 135.2 \pm 4.0$

CCHP + H0LiCOW
$H_0 = 71.9 \pm 1.5$
$r_s = 139.6 \pm 3.3$

SH0ES + H0LiCOW
$H_0 = 74.2 \pm 1.2$
$r_s = 135.7 \pm 2.7$

COMPARISON WITH PLANCK



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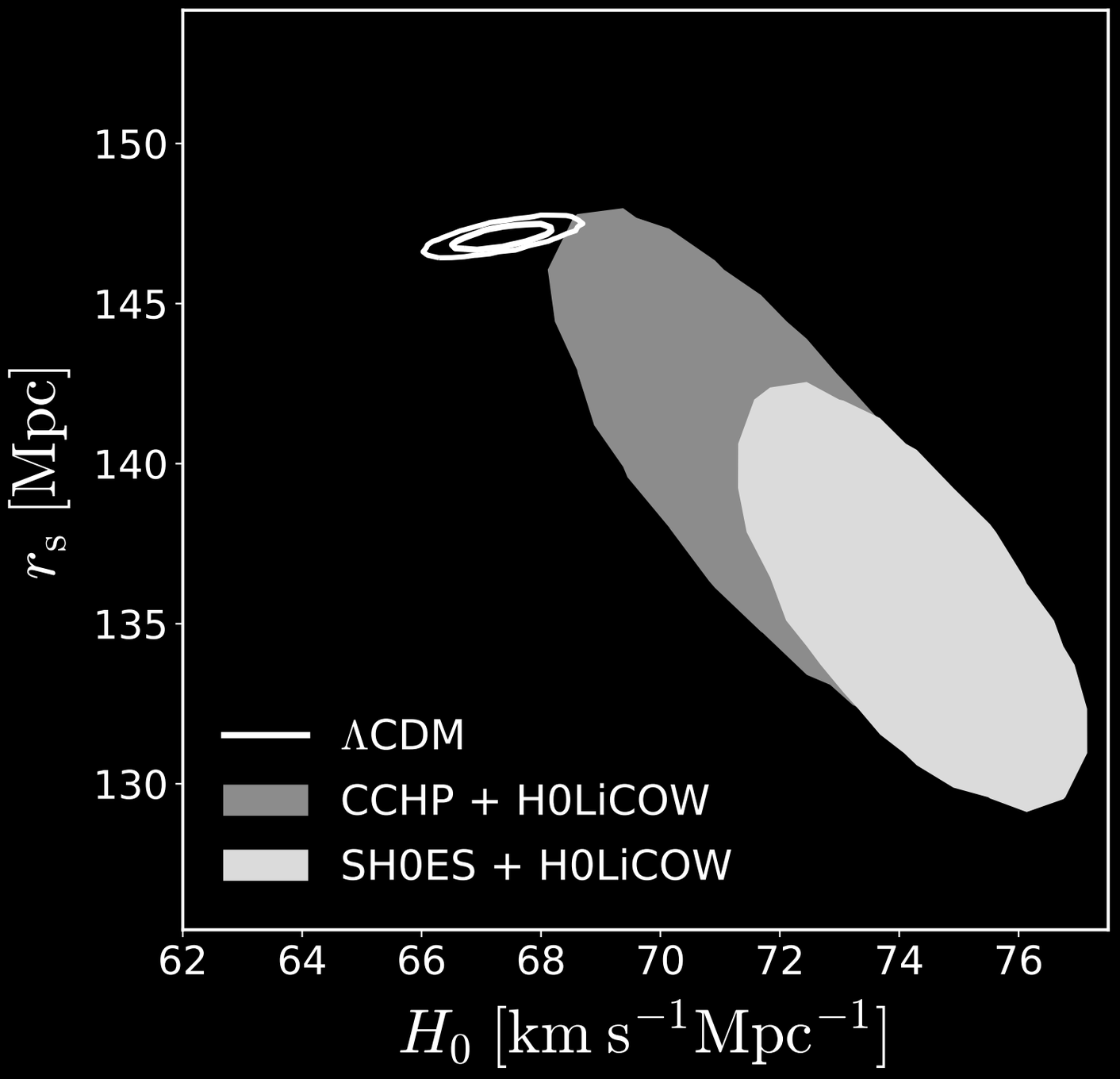

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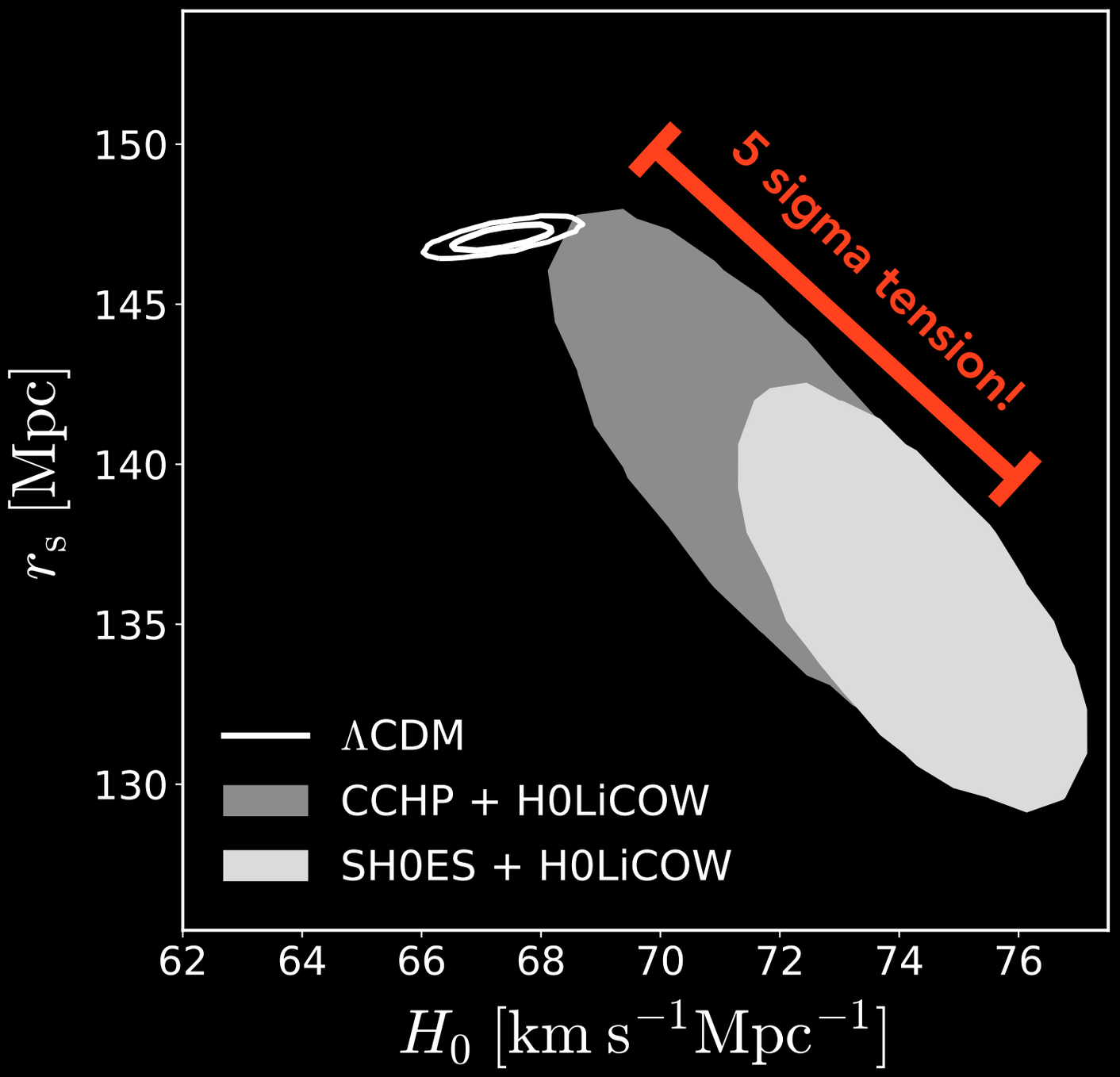

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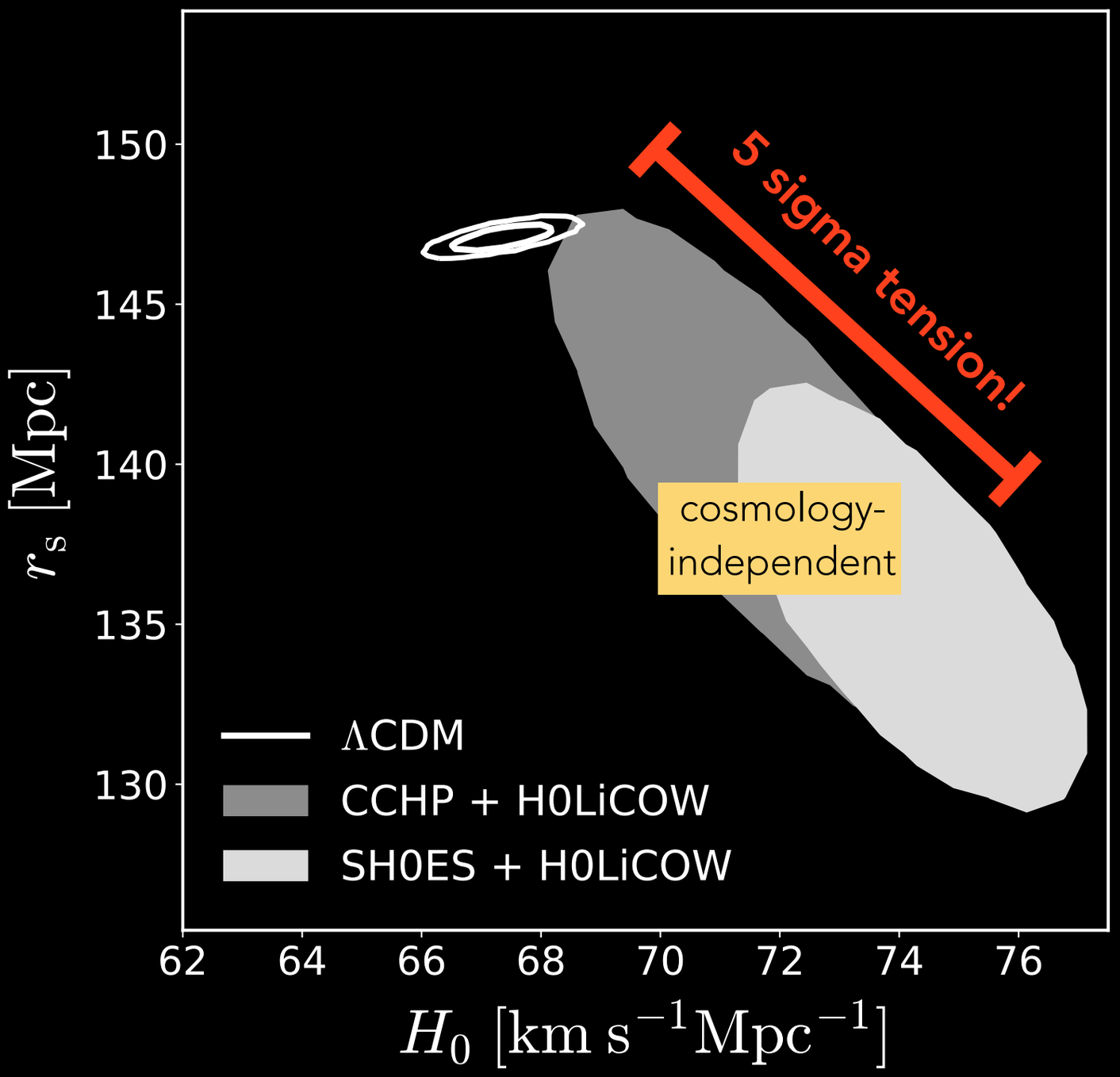

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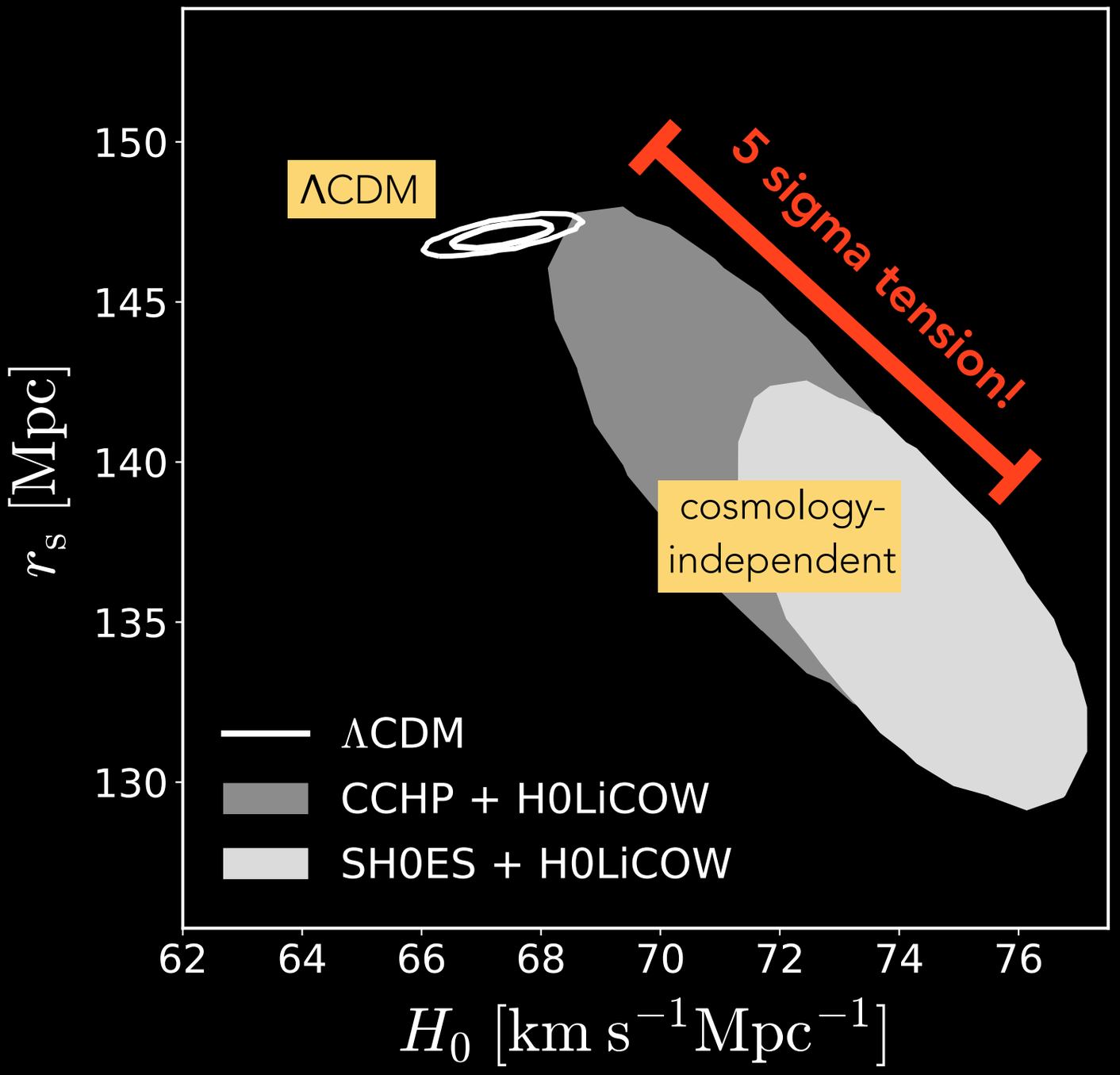
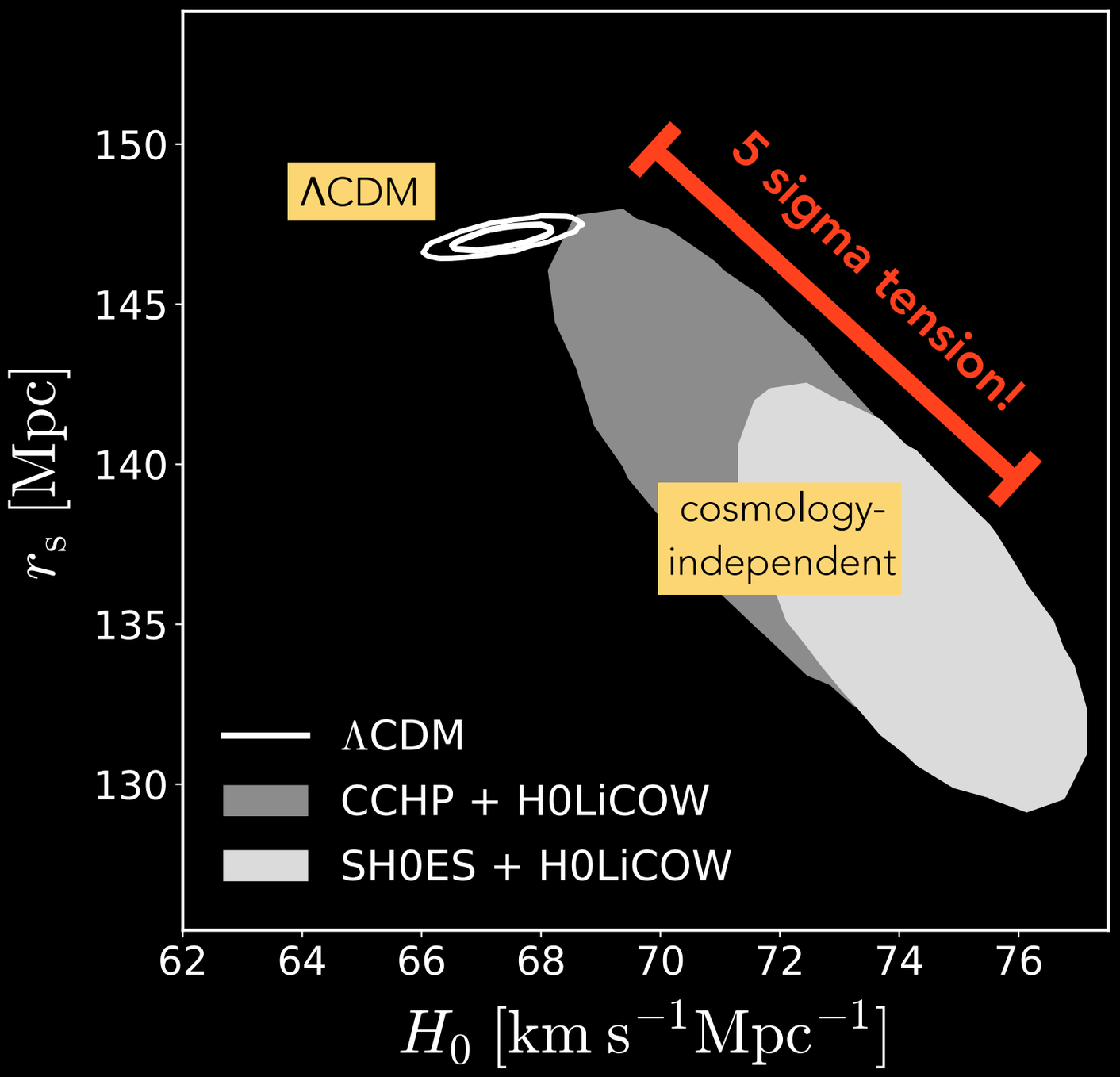


Arendse, Wojtak, Agnello et al. (2019), arXiv: 1909.07986

COMPARISON WITH PLANCK



Can we make changes to ΛCDM that reconcile the tension?

Arendse, Wojtak, Agnello et al. (2019), arXiv: 1909.07986

Consider these 4 extensions of ΛCDM:

Additional relativistic particles ($\mathbf{N_{eff}}$)	Early Dark Energy (**EDE**)
Redshift dependent DE (***w*CDM**)	Phenomenologically Emergent DE (**PEDE**)

PEDE: Phenomenologically emergent dark energy (Li & Shafieloo, arXiv: 1906.08275)

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CHANGES TO EARLY PHYSICS

CHANGES TO LATE PHYSICS

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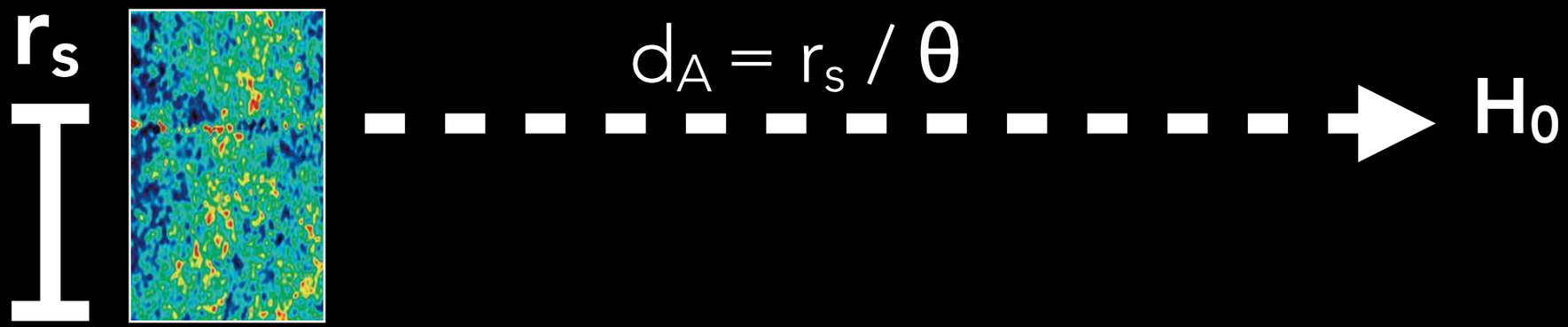

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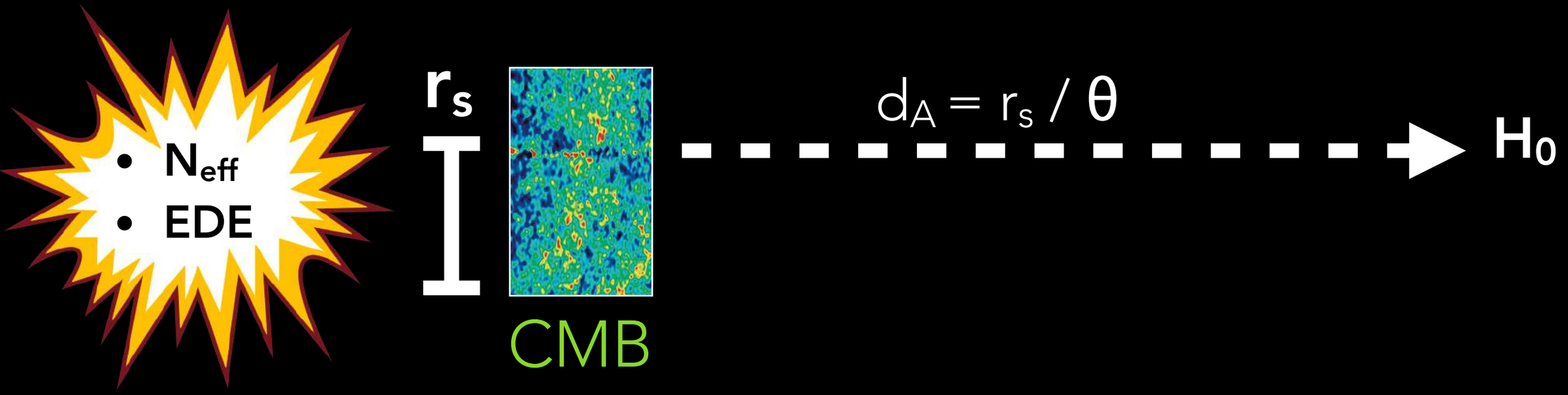

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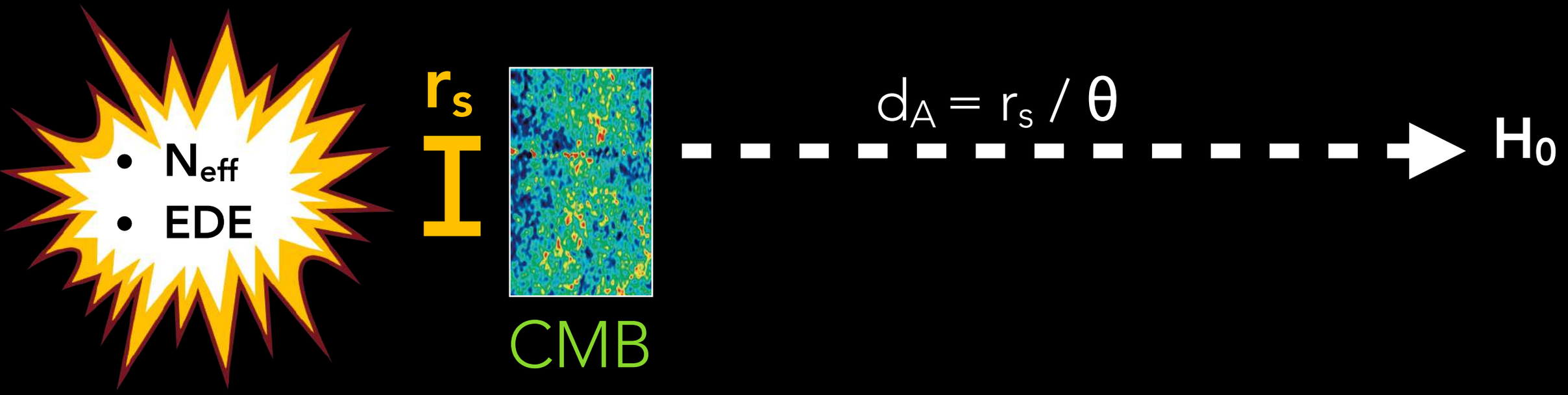

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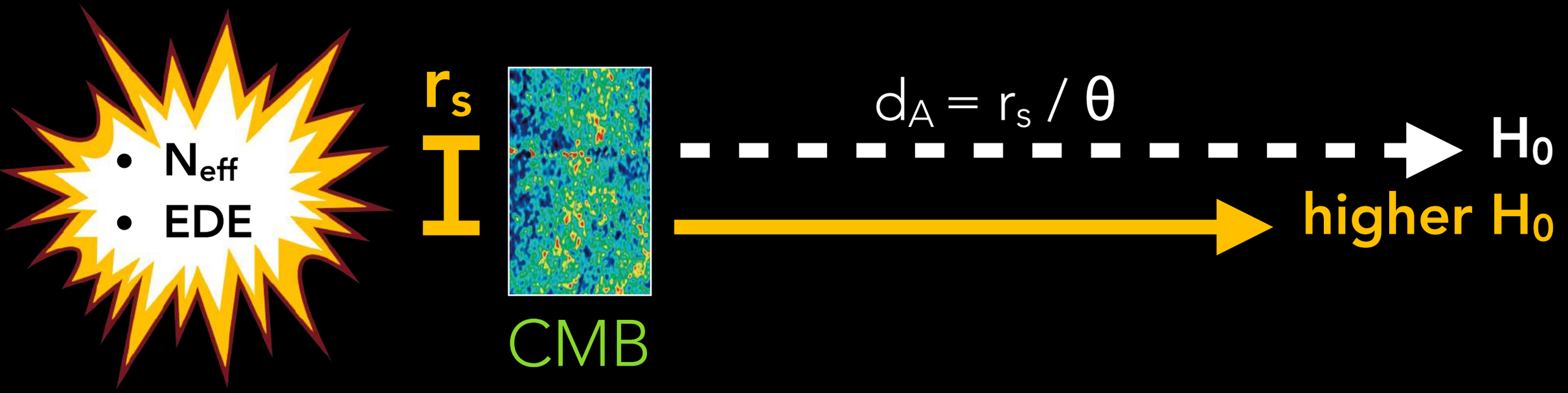

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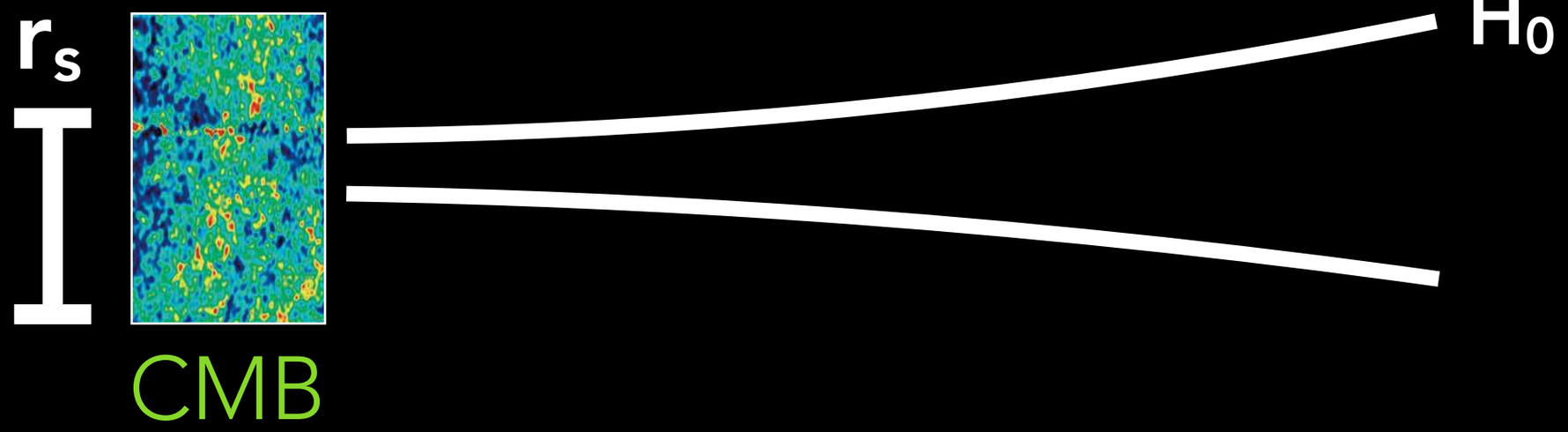

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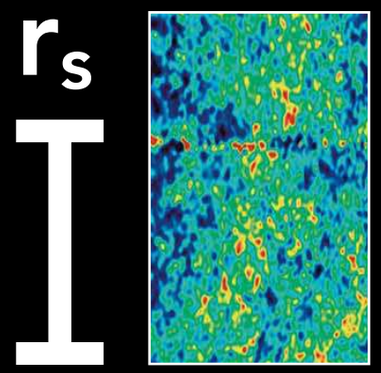

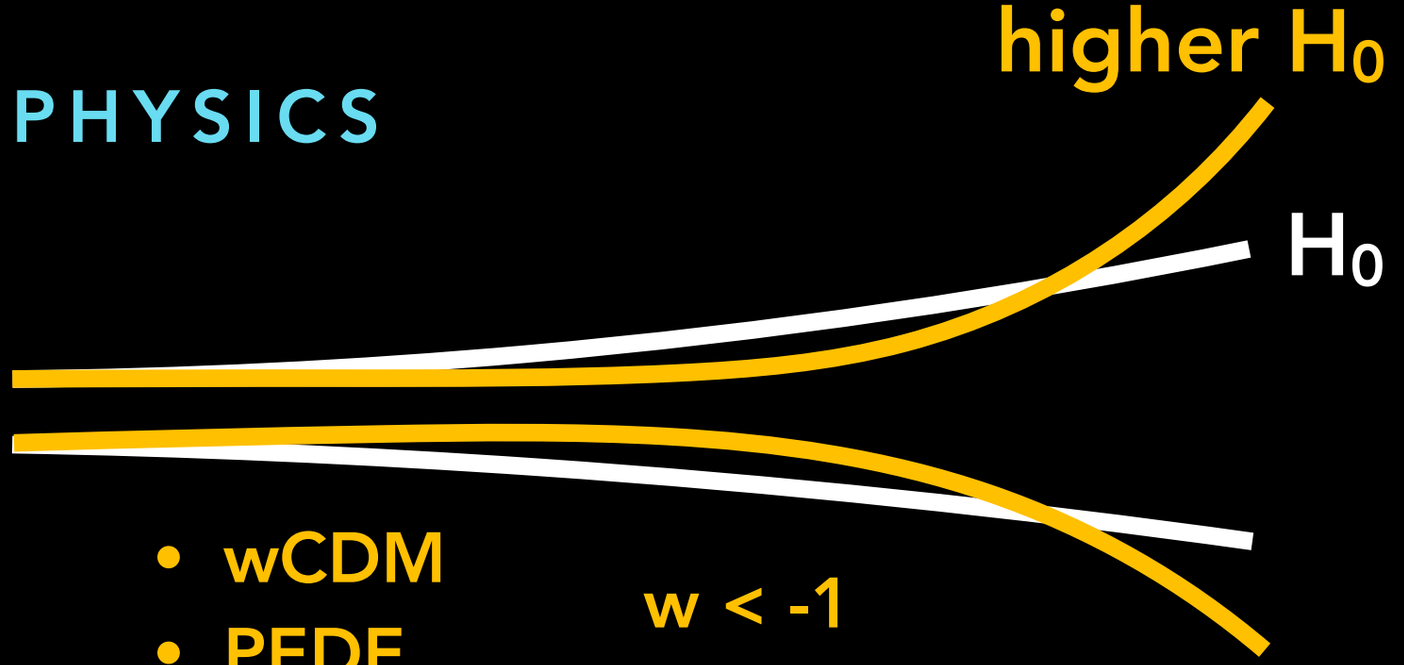

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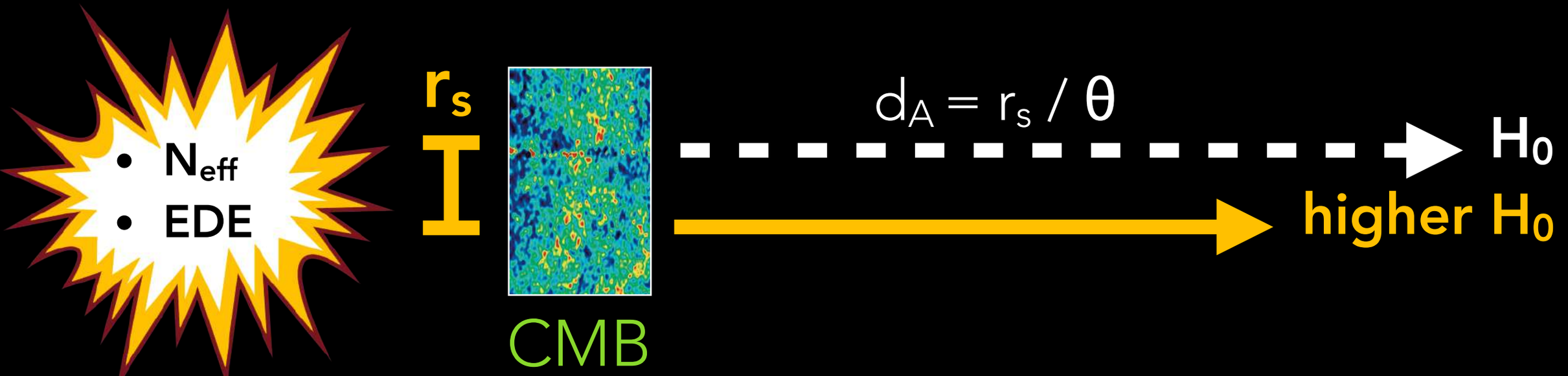

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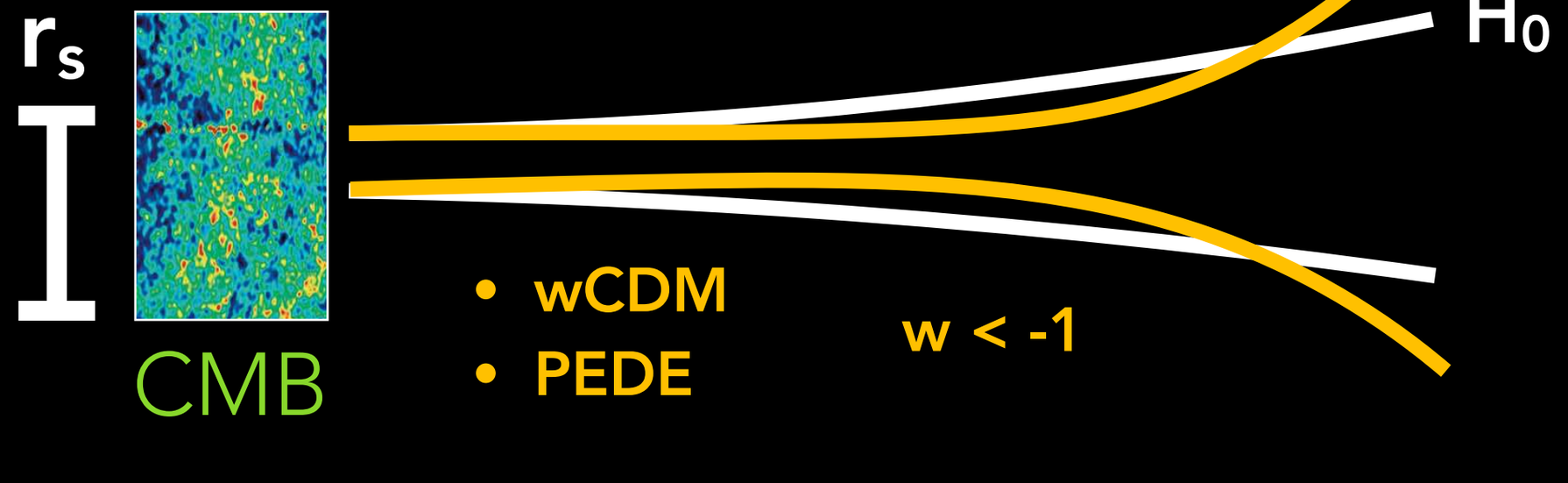
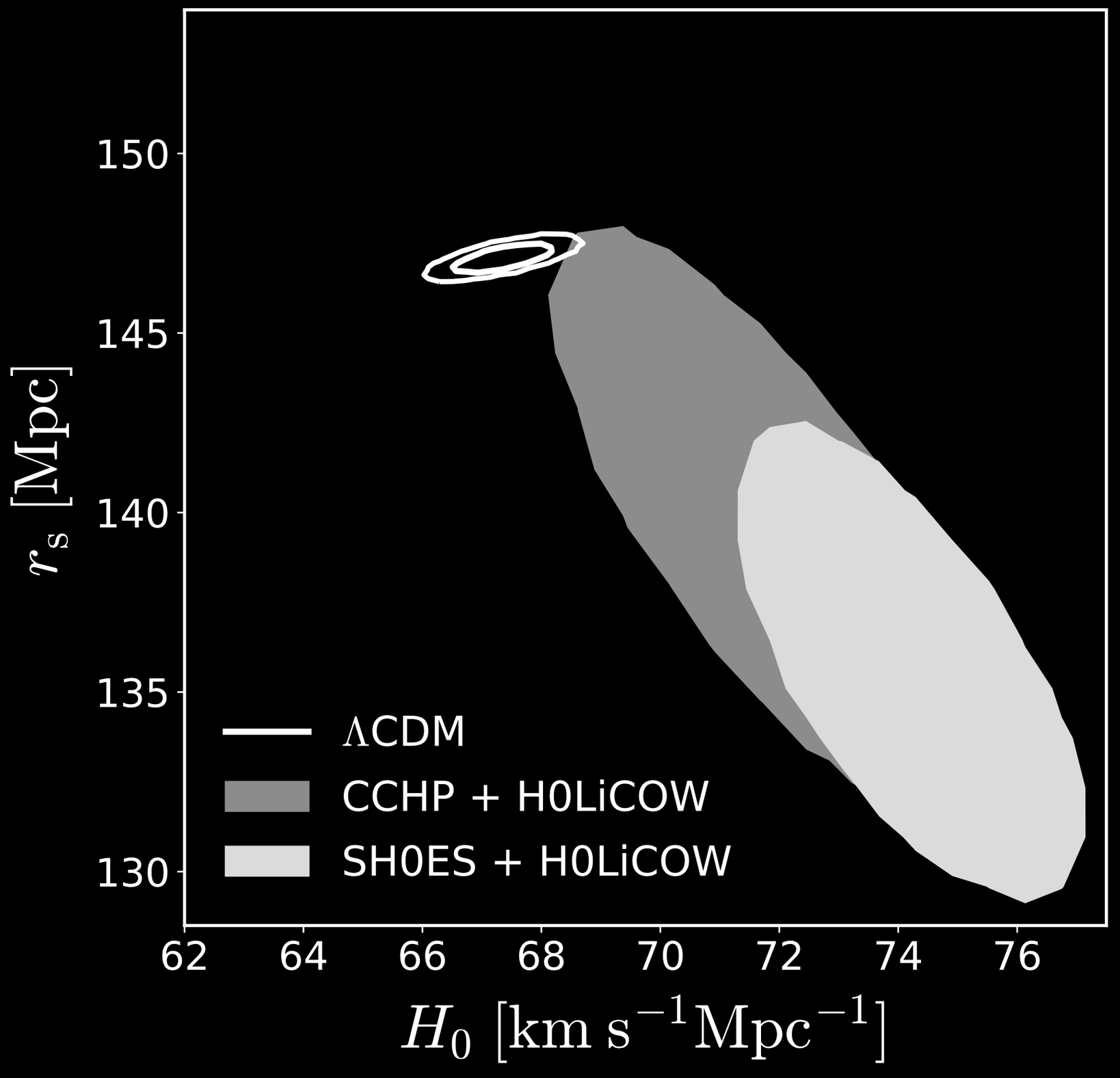


RESULTS


150
145
140
135
130
r_s [Mpc]
62
64
66
68
70
72
74
76
H_0 [km s^{-1}Mpc^{-1}]
ΛCDM
CCHP + H0LiCOW
SH0ES + H0LiCOW

Arendse, Wojtak, Agnello et al. (2019), arXiv: 1909.07986

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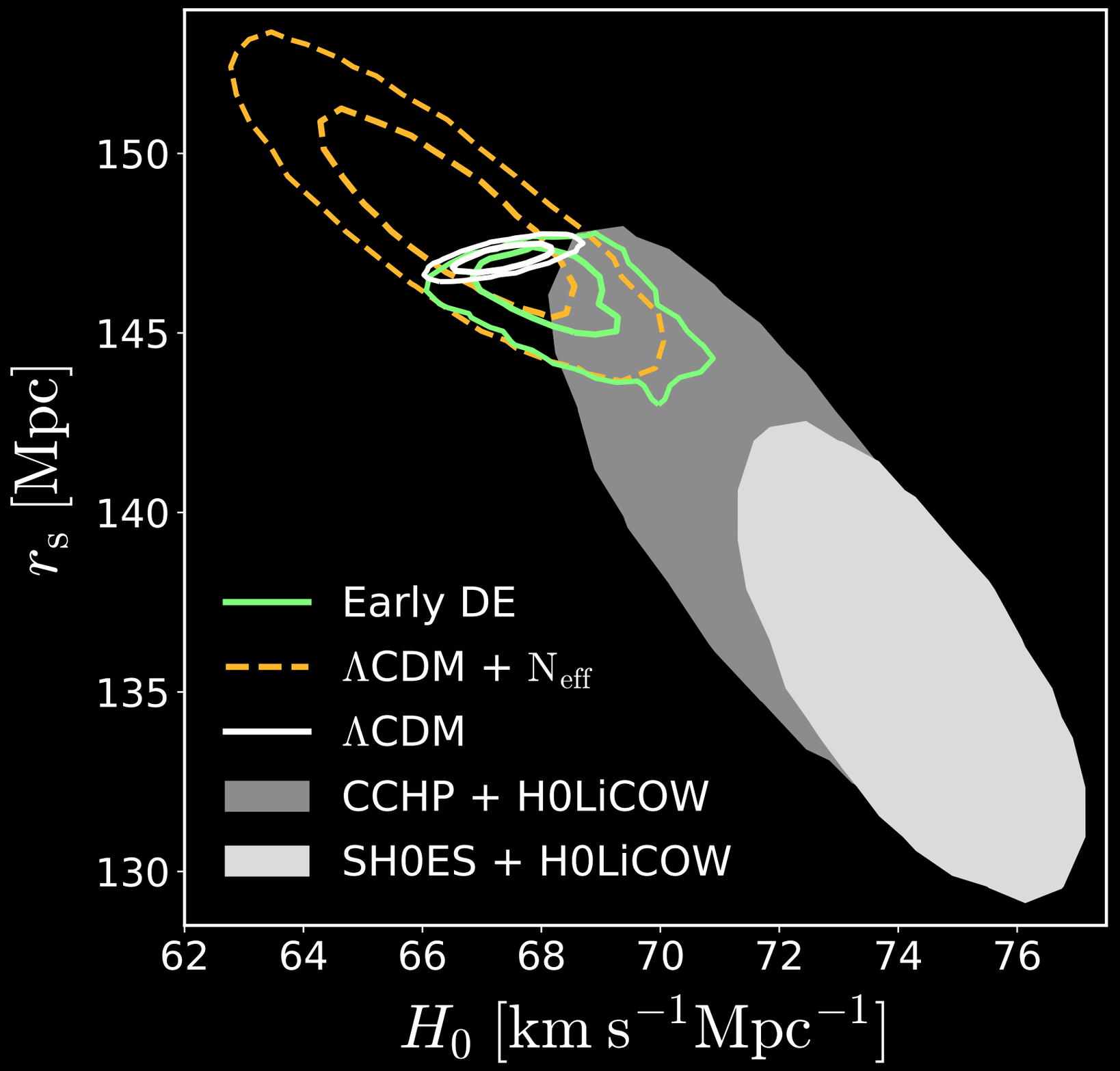

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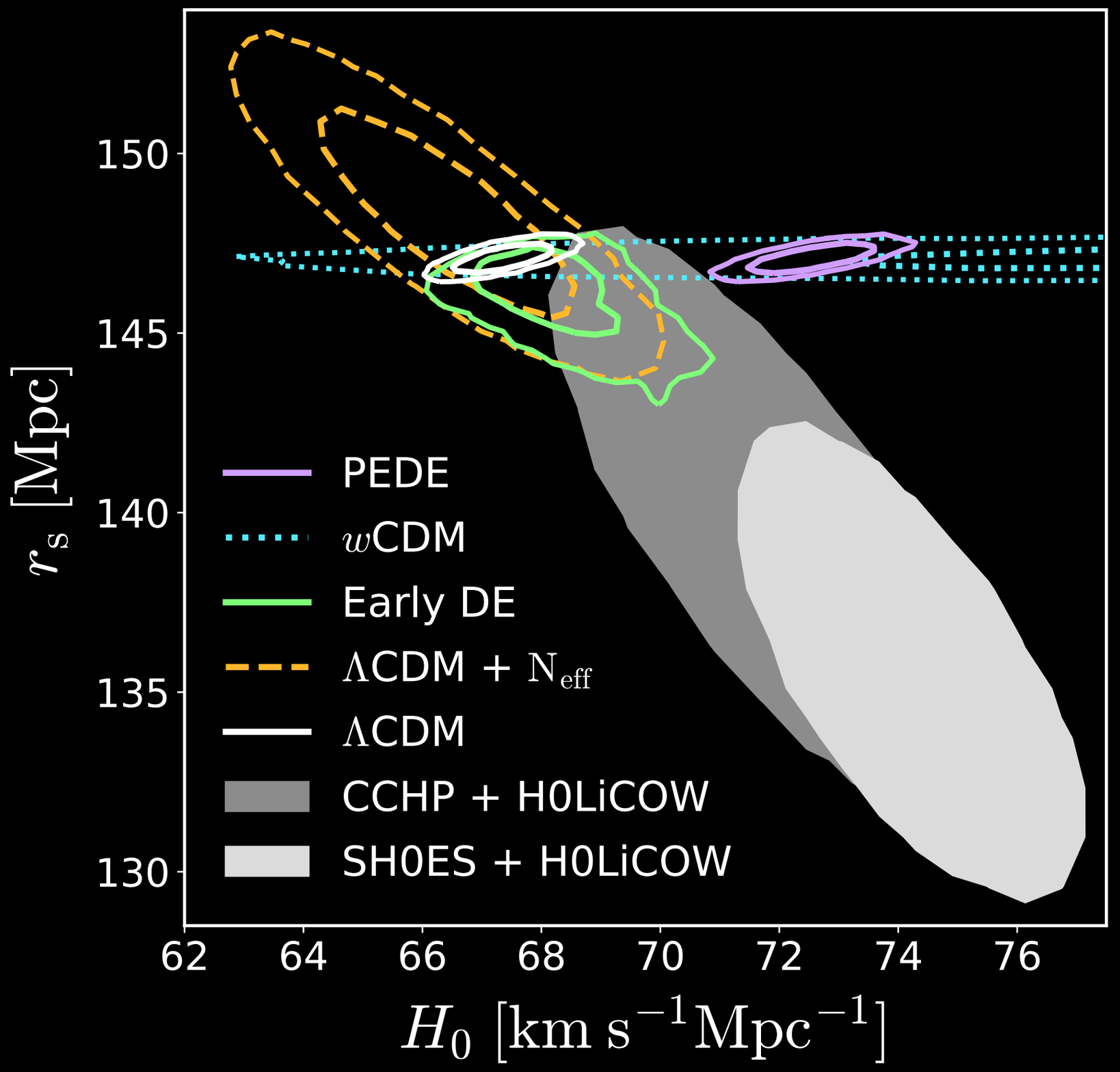
150
145
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r_s [Mpc]
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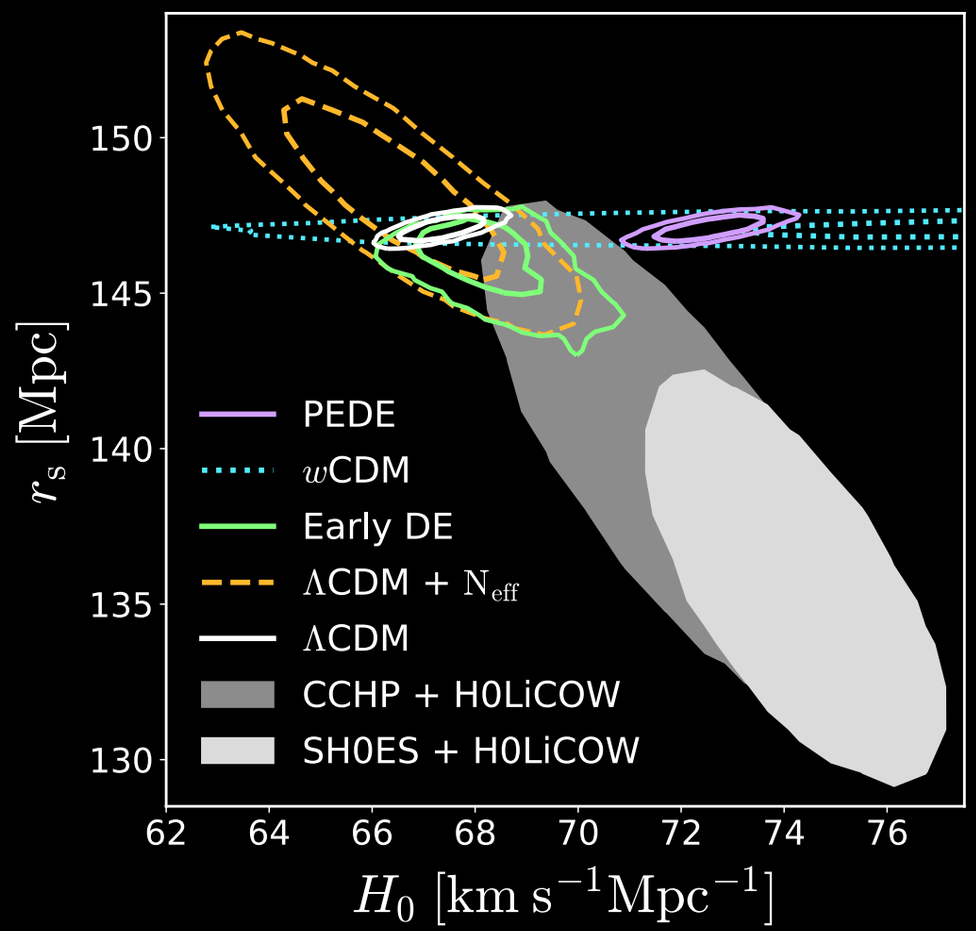
72
74
76
H_0 [km s^{-1}Mpc^{-1}]
PEDE
wCDM
Early DE
ΛCDM + N_{eff}
ΛCDM
CCHP + H0LiCOW
SH0ES + H0LiCOW

CONCLUSIONS

- There is a tension between local and CMB-based measurements of $\mathbf{H_0}$ and $\mathbf{r_s}$.



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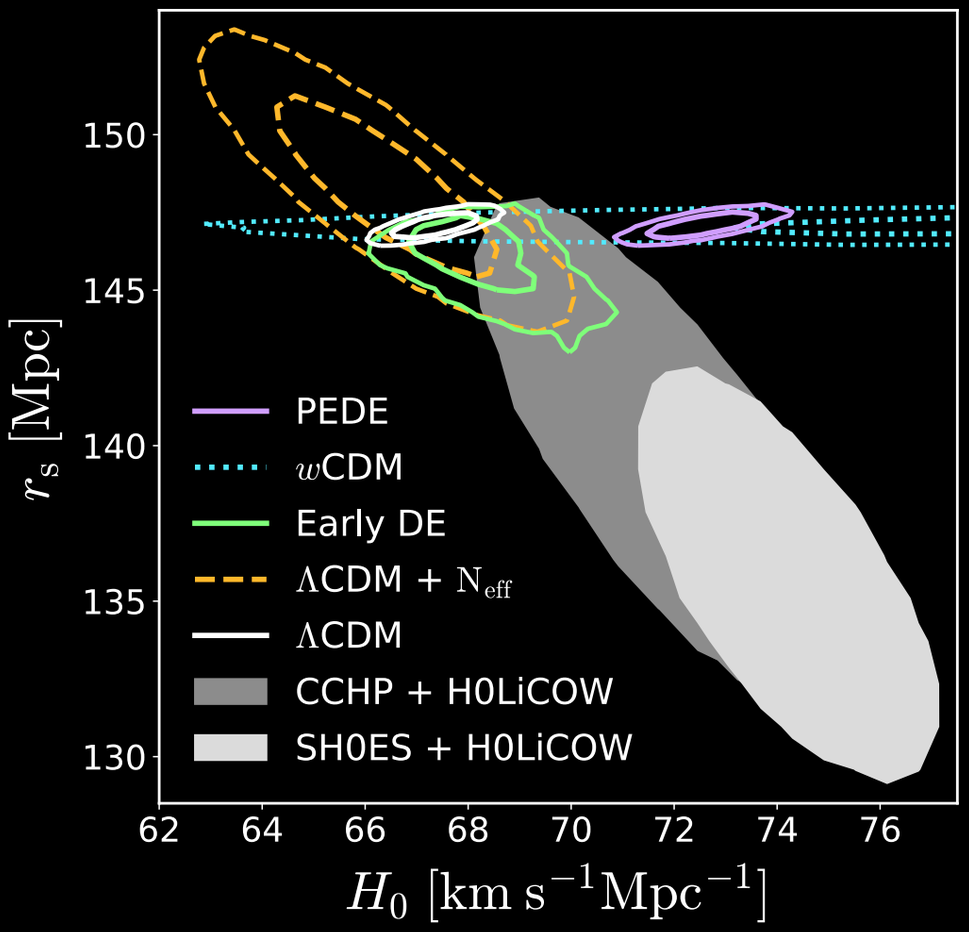
- The measurements using local data can be carried out without assuming a cosmological model.



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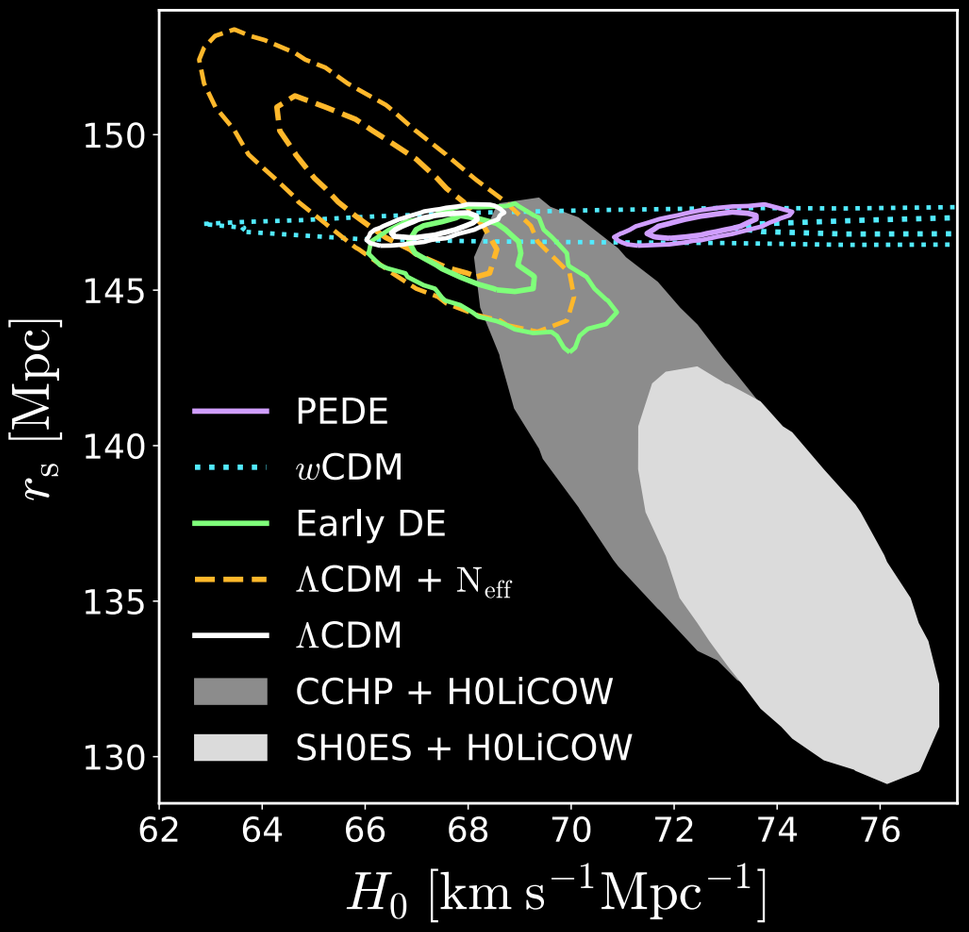
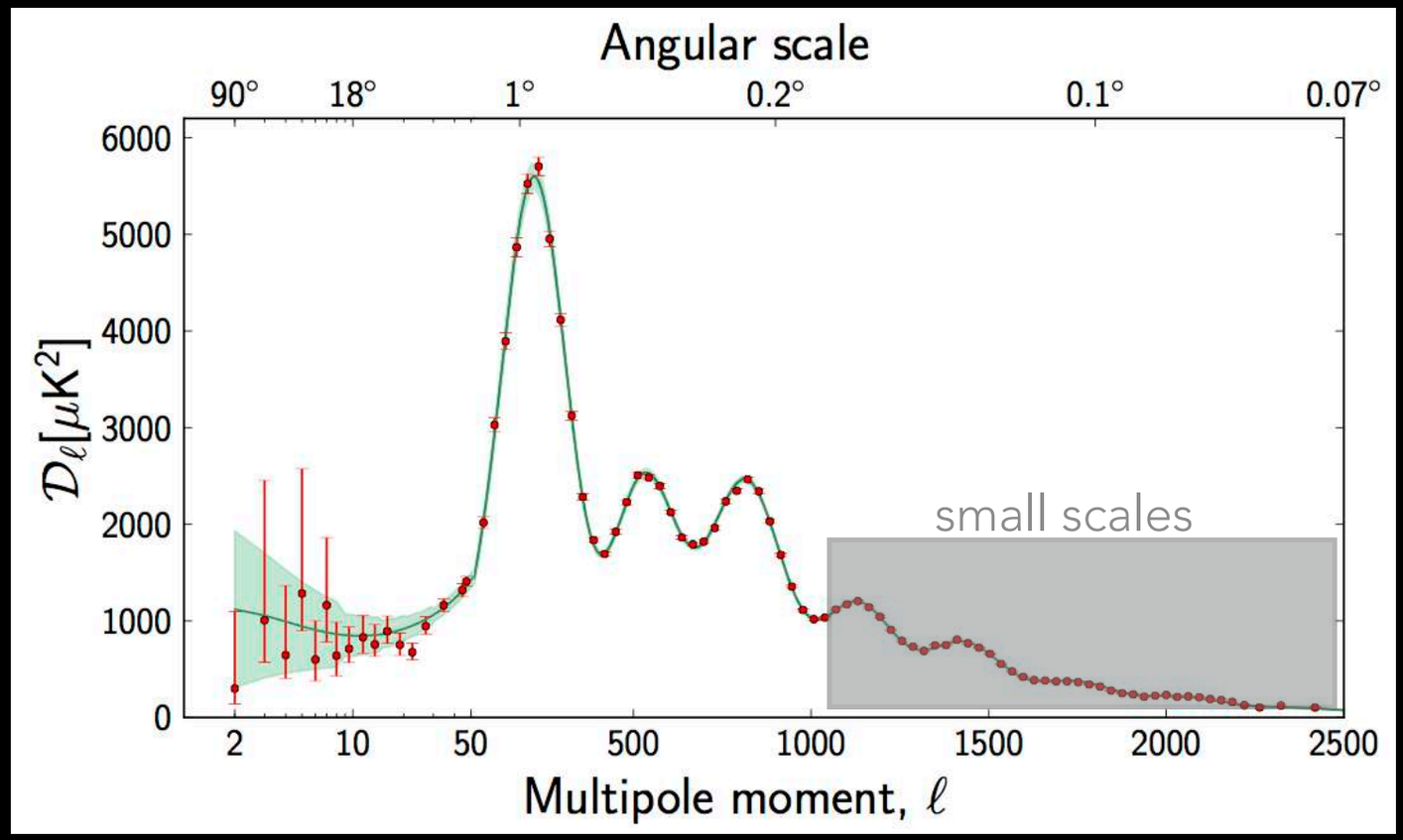
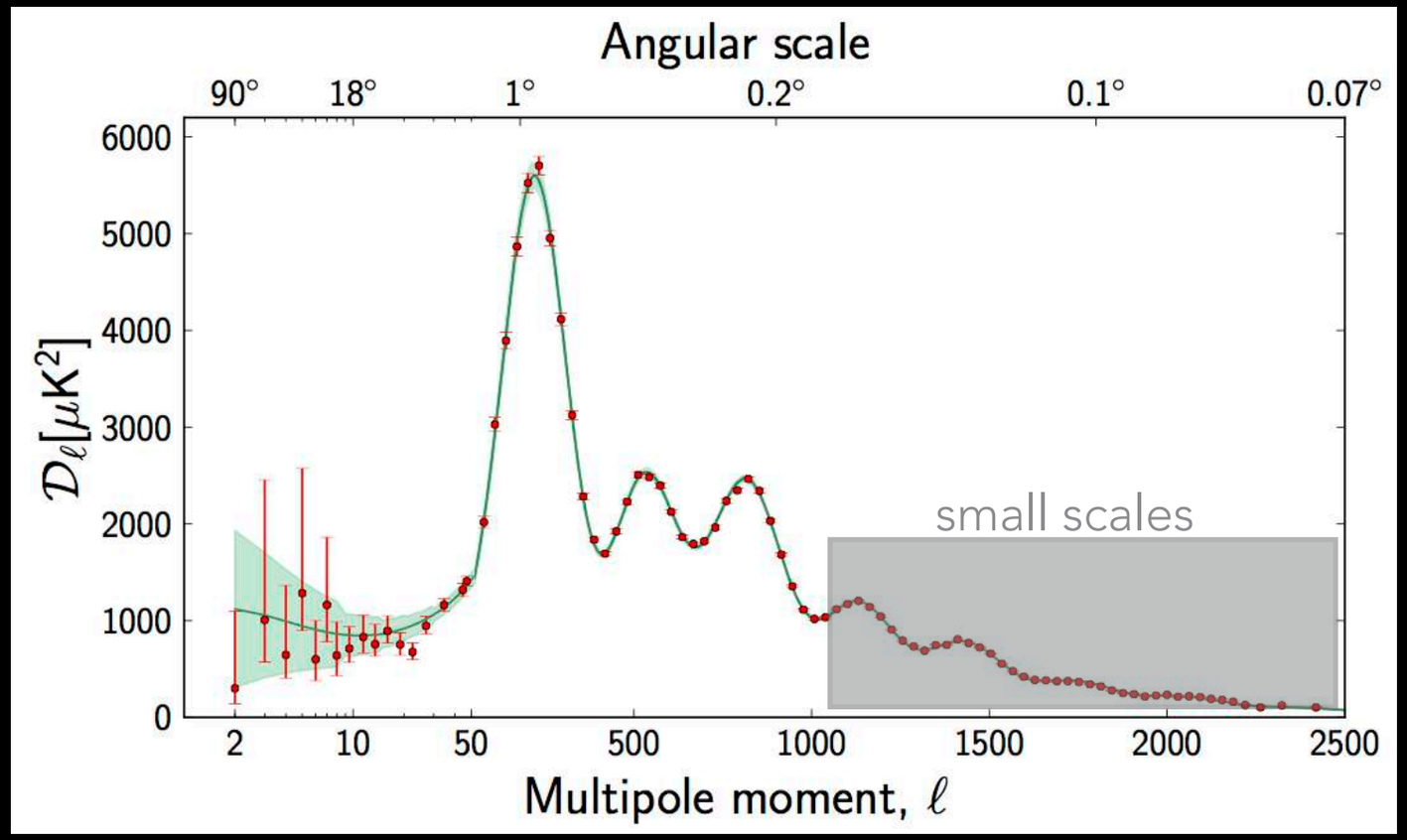


- CMB-based measurements require a cosmological model. Extensions to ΛCDM can follow two strategies:
  - Changing the early (pre-CMB) physics slightly decreases the tension (but not enough).
  - Changing the late physics by adding some additional form of dark energy can only change $\mathbf{H_0}$ and not $\mathbf{r_s}$, and does therefore not solve the problem.


Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell[\mu K^2]$
small scales
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ

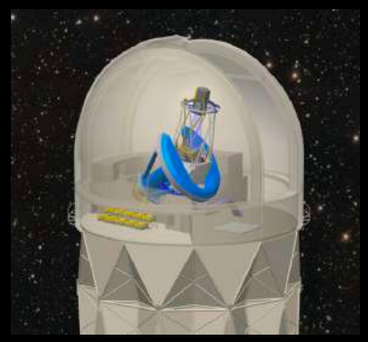


FUTURE CMB MEASUREMENTS

Atacama Cosmology Telescope (ACT)
Aiola et al. (2020)

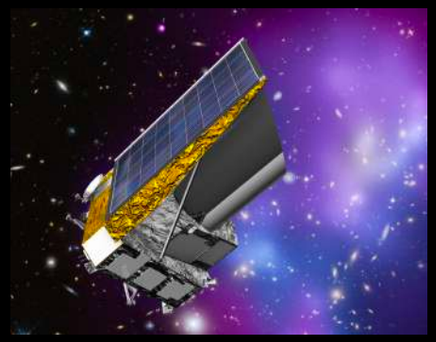
South Pole Telescope (SPT)

FUTURE LOCAL DATA MISSIONS



DESI

Rubin Observatory



EUCLID (2022)

Roman Telescope

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