# Can modifications of the standard ΛCDM model solve the Hubble tension?

NIKKI ARENDSE
RADEK WOJTAK
ADRIANO AGNELLO

# Beyond Standard Model: From Theory to Experiment (BSM-2021)

**BSM**

**March 29-April 2, 2021**

Sponsored by Letters in High Energy Physics (LHEP)

One of the strongest hints for new physics: Hubble tension

# HUBBLE TENSION

CMB

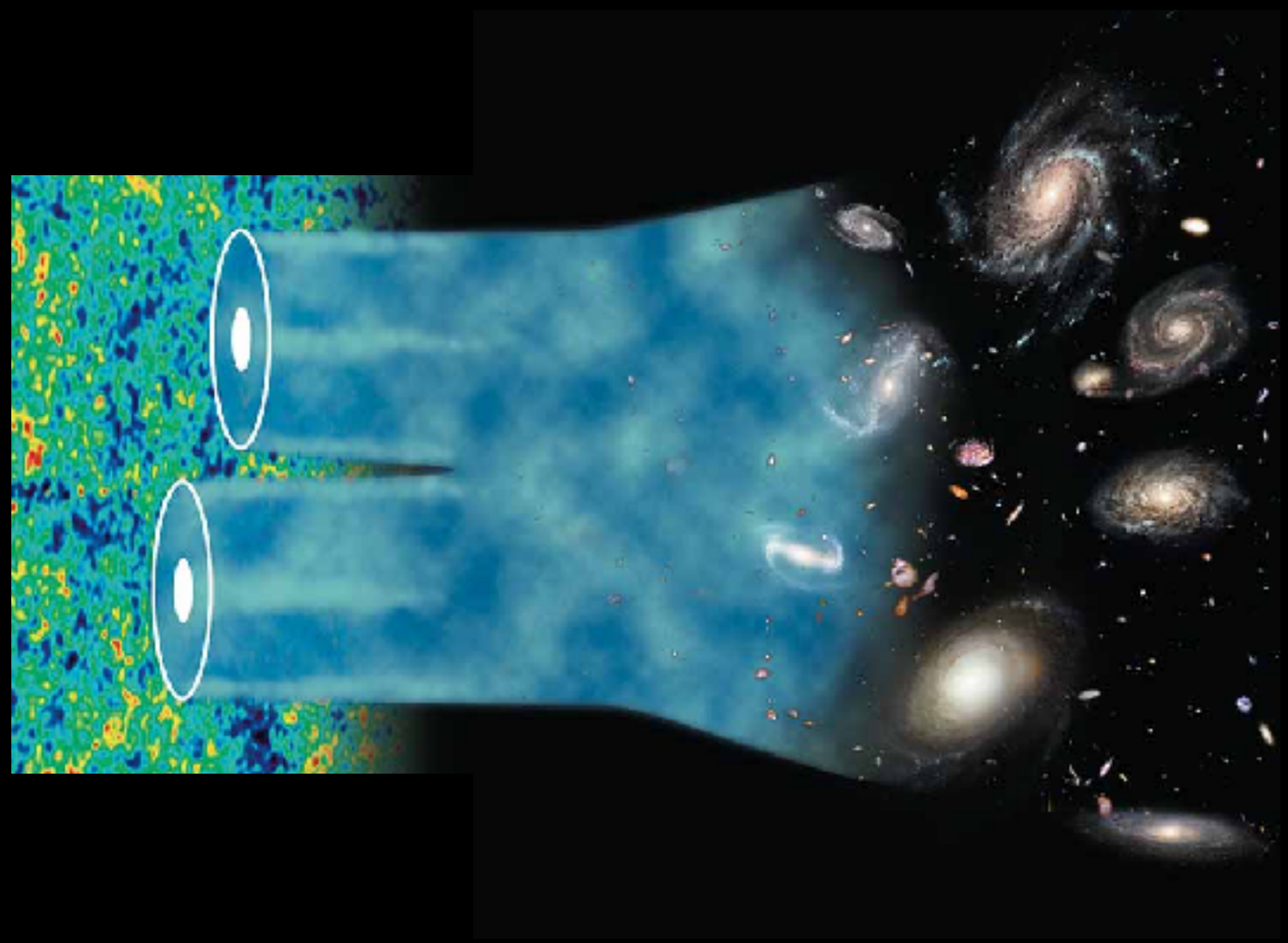
local

**Expansion rate:**

**67.4**

**± 0.5** km/s/Mpc

from Planck



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**± 1.3** km/s/Mpc

from Cepheids (SH0ES)

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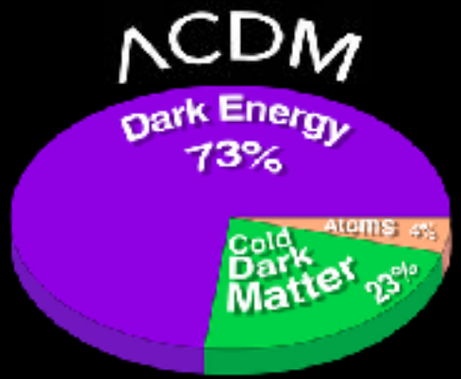


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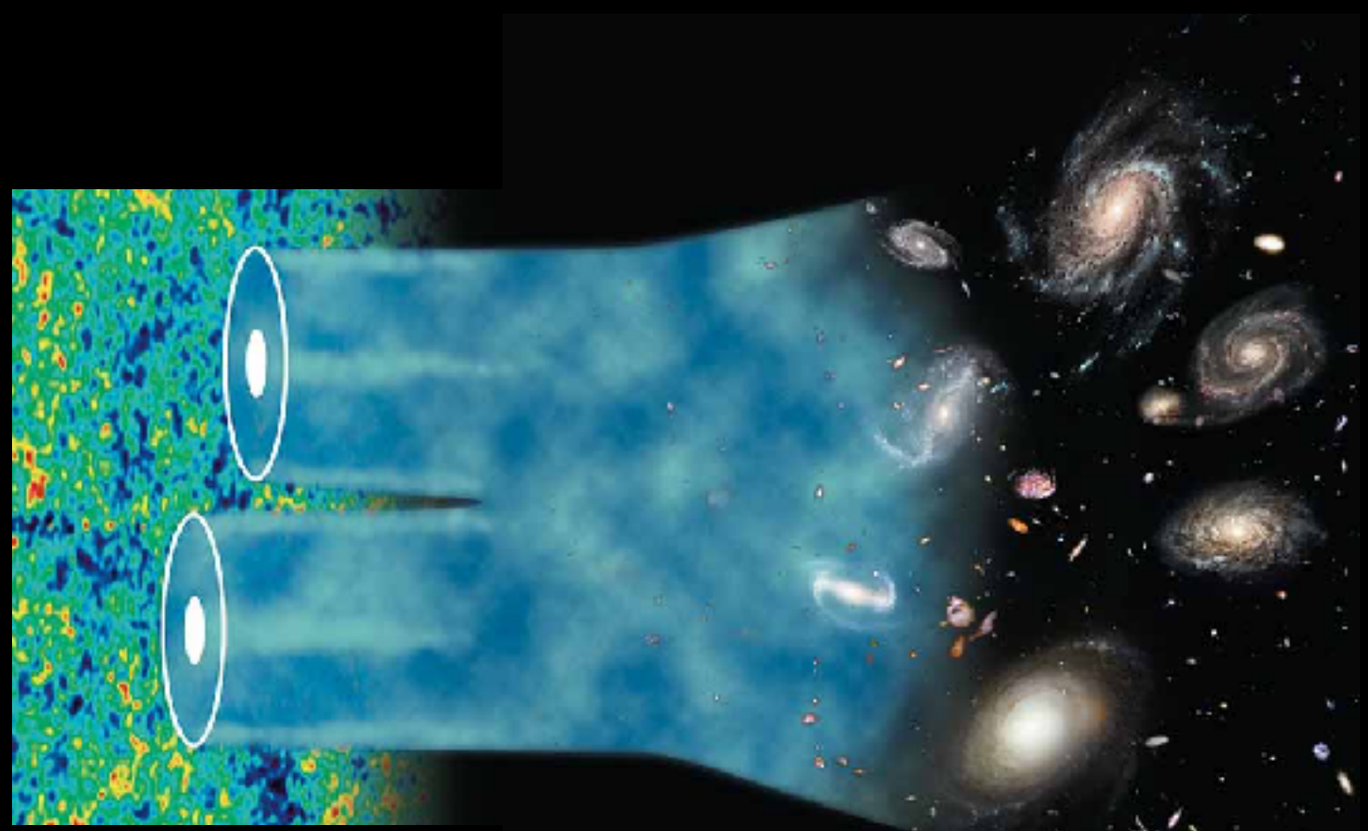

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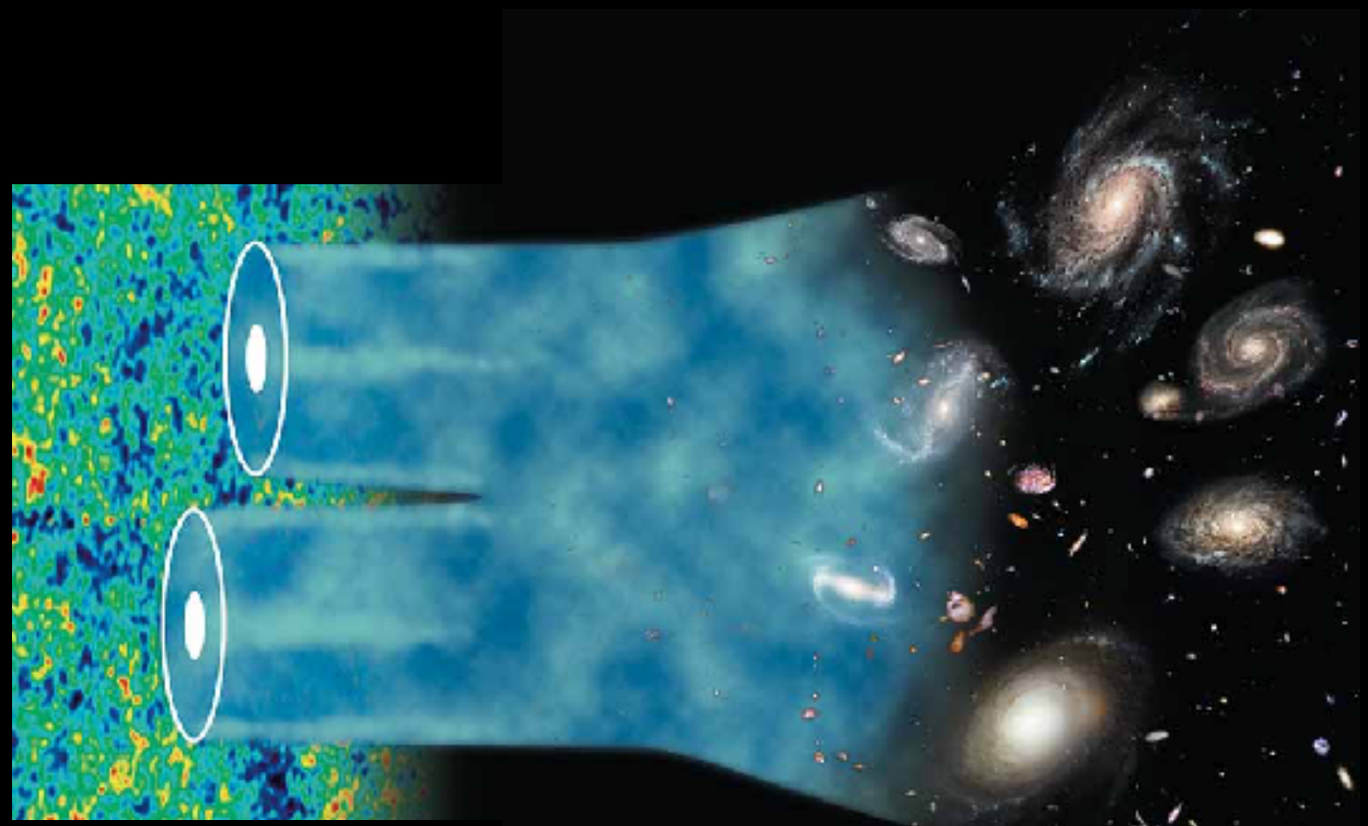

**Not just about $H_0$!**

Another important cosmological parameter is the

**SOUND HORIZON SCALE ($R_S$)**

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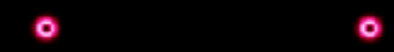

Over-densities

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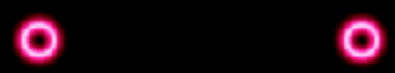

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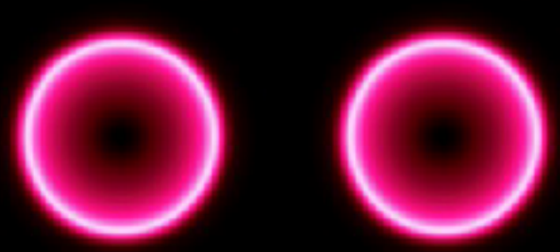

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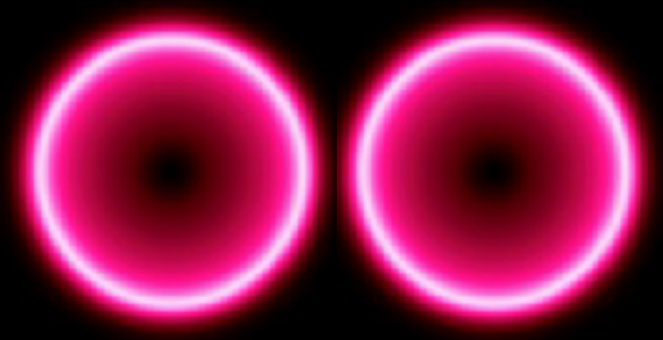

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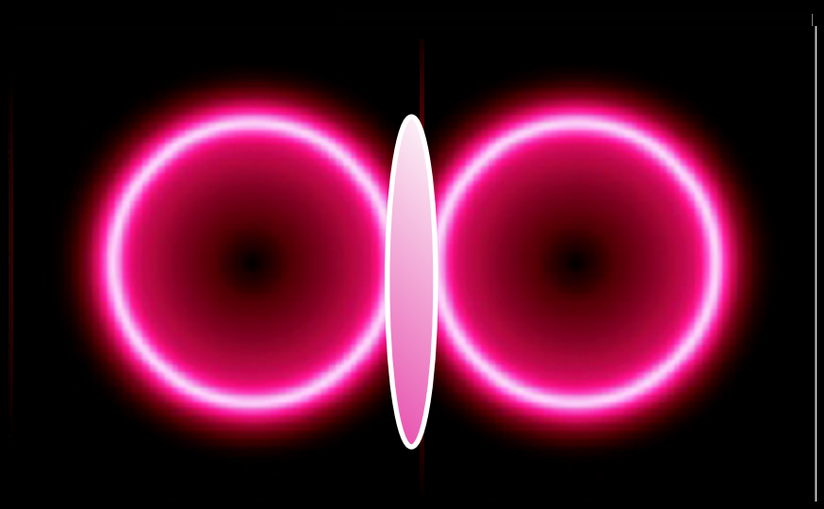

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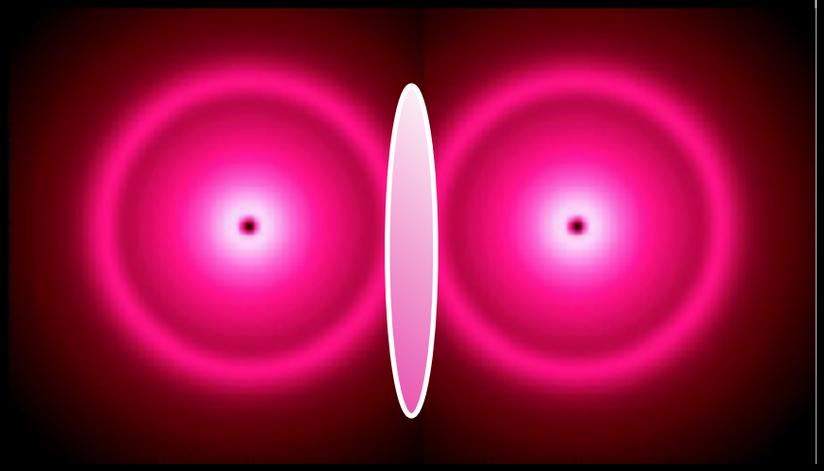

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Universe
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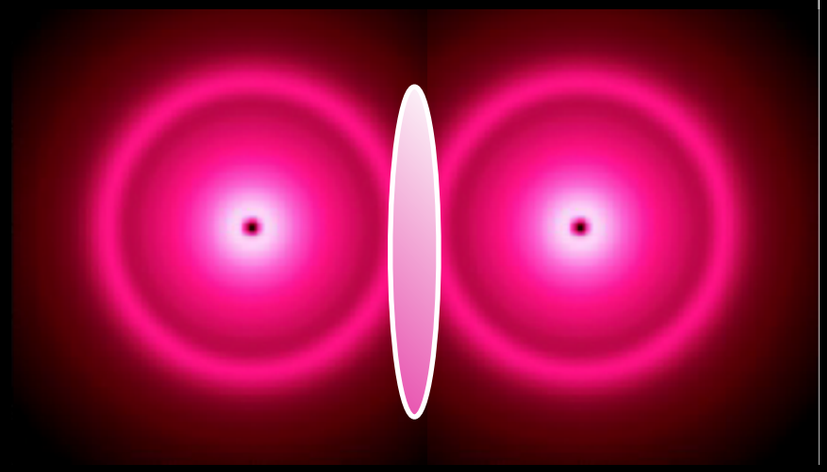

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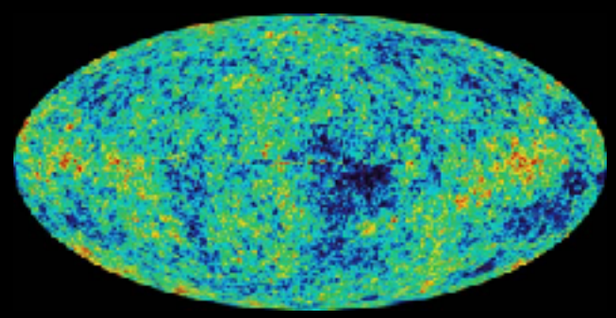

Universe becomes transparant

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

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

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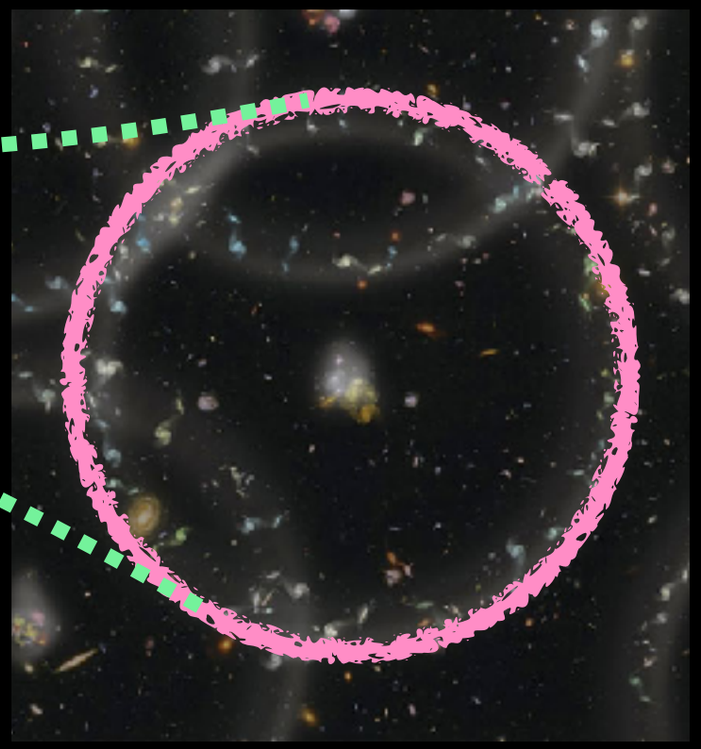

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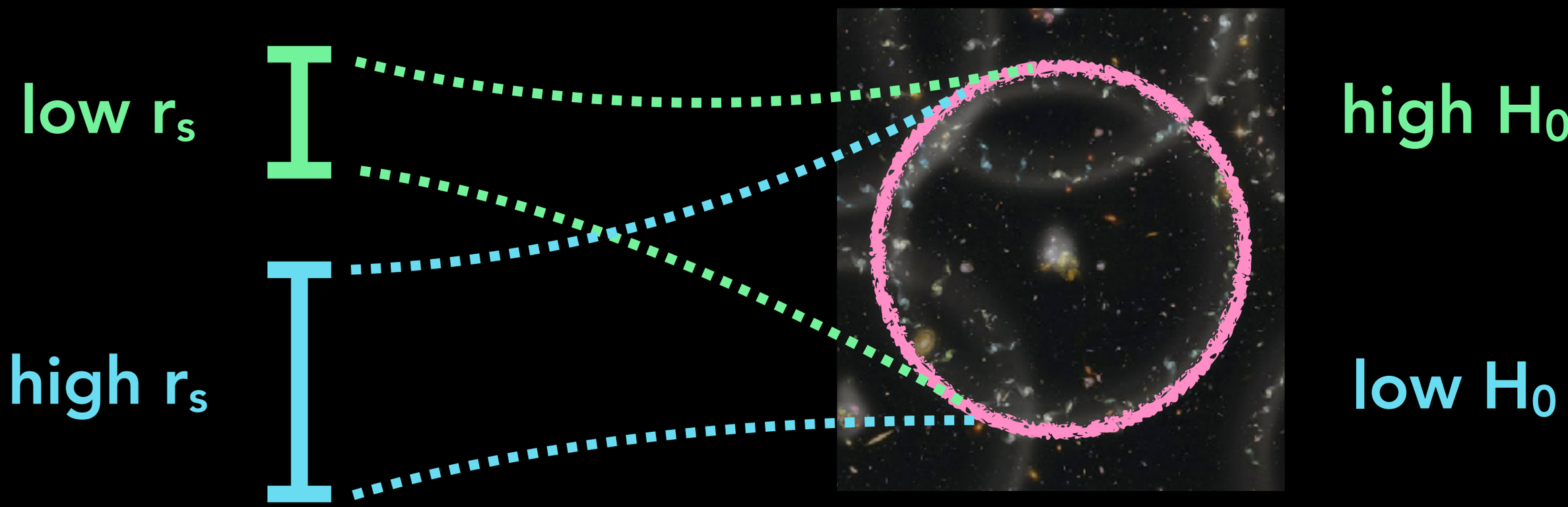
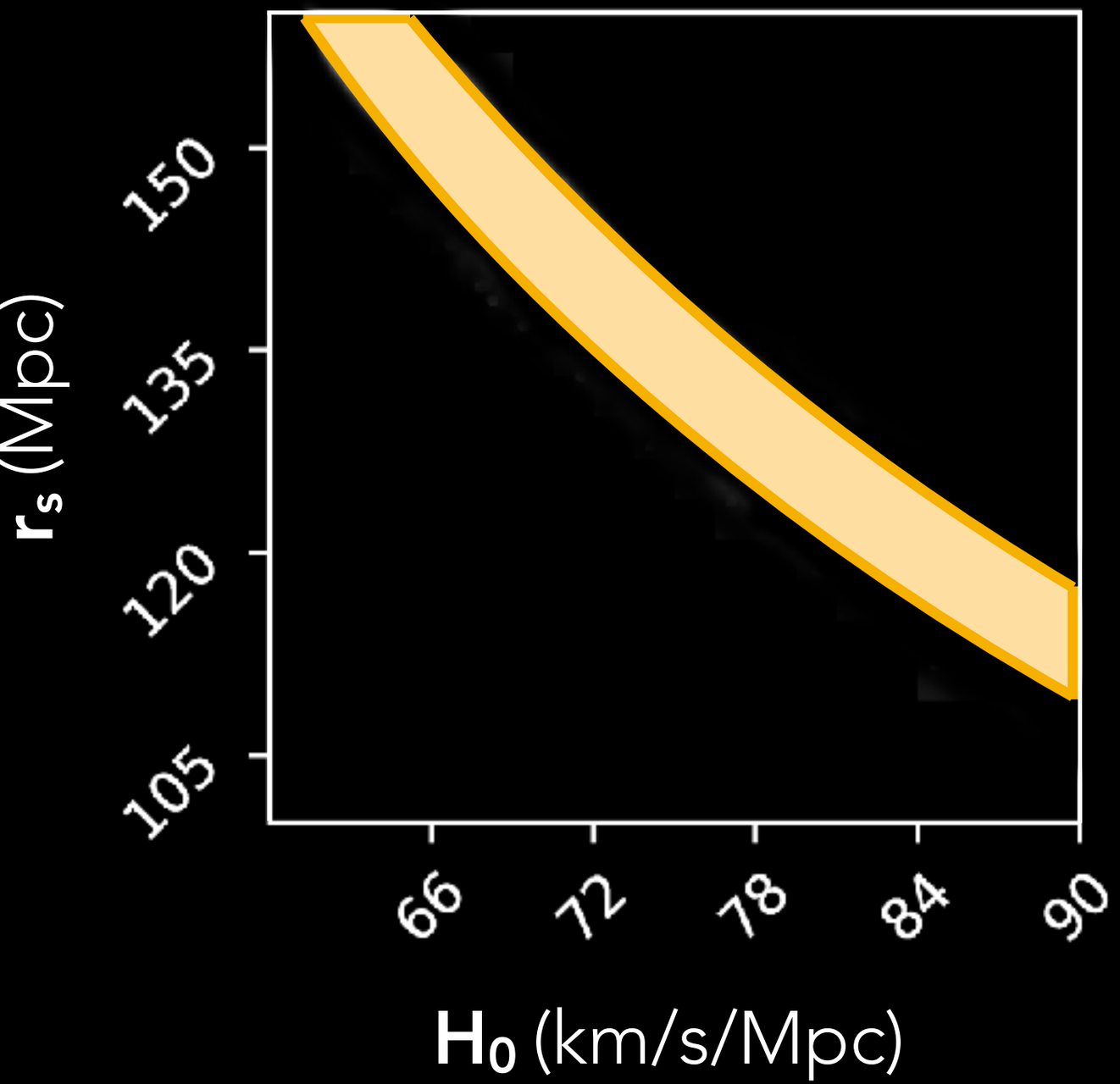



In this way, BAO constrains the product $\mathbf{H_0\ r_s}$.

The tension is a problem in both parameters,

they are degenerate with each other.



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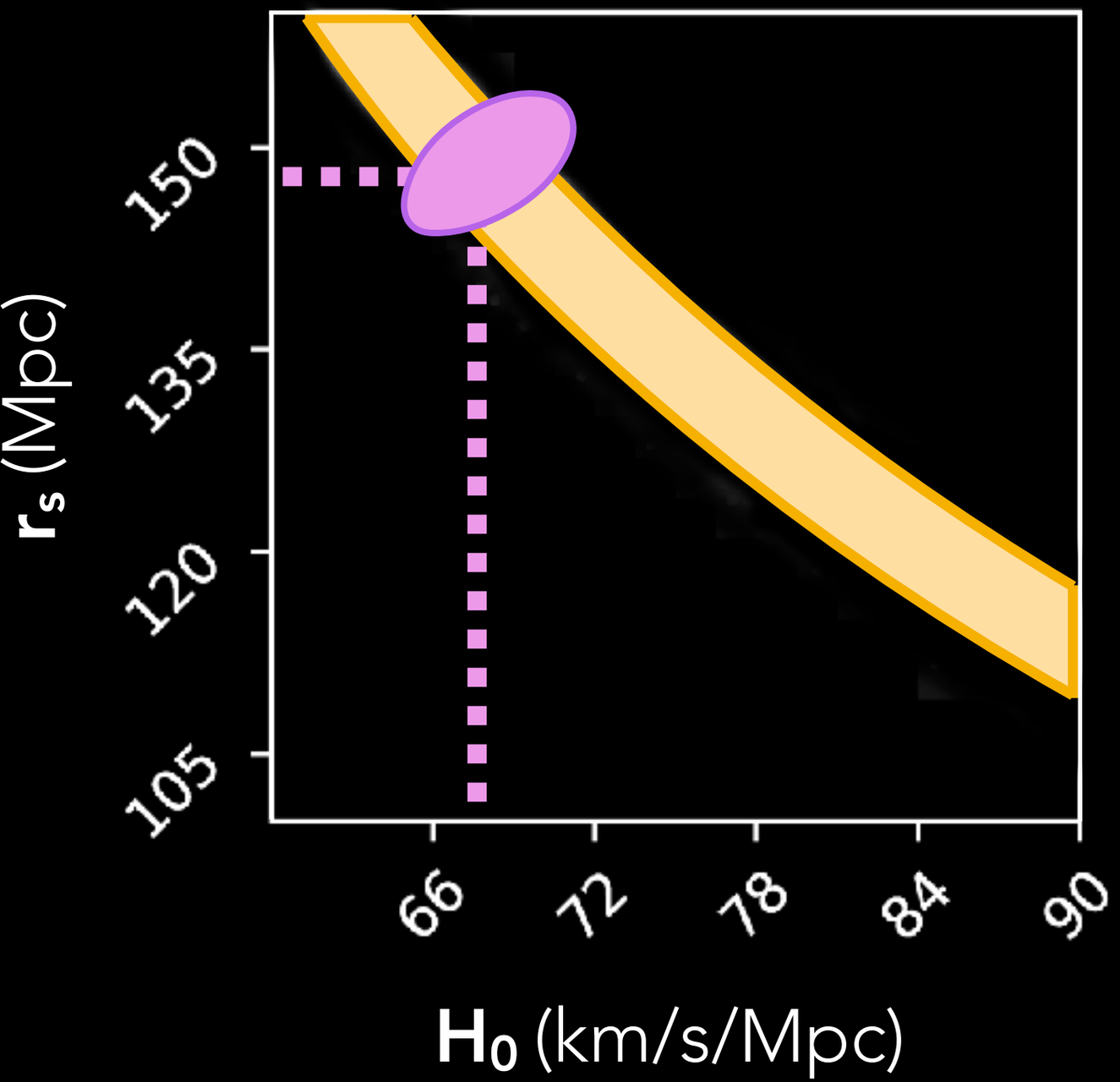


**Planck** measures a **high $r_s$** and

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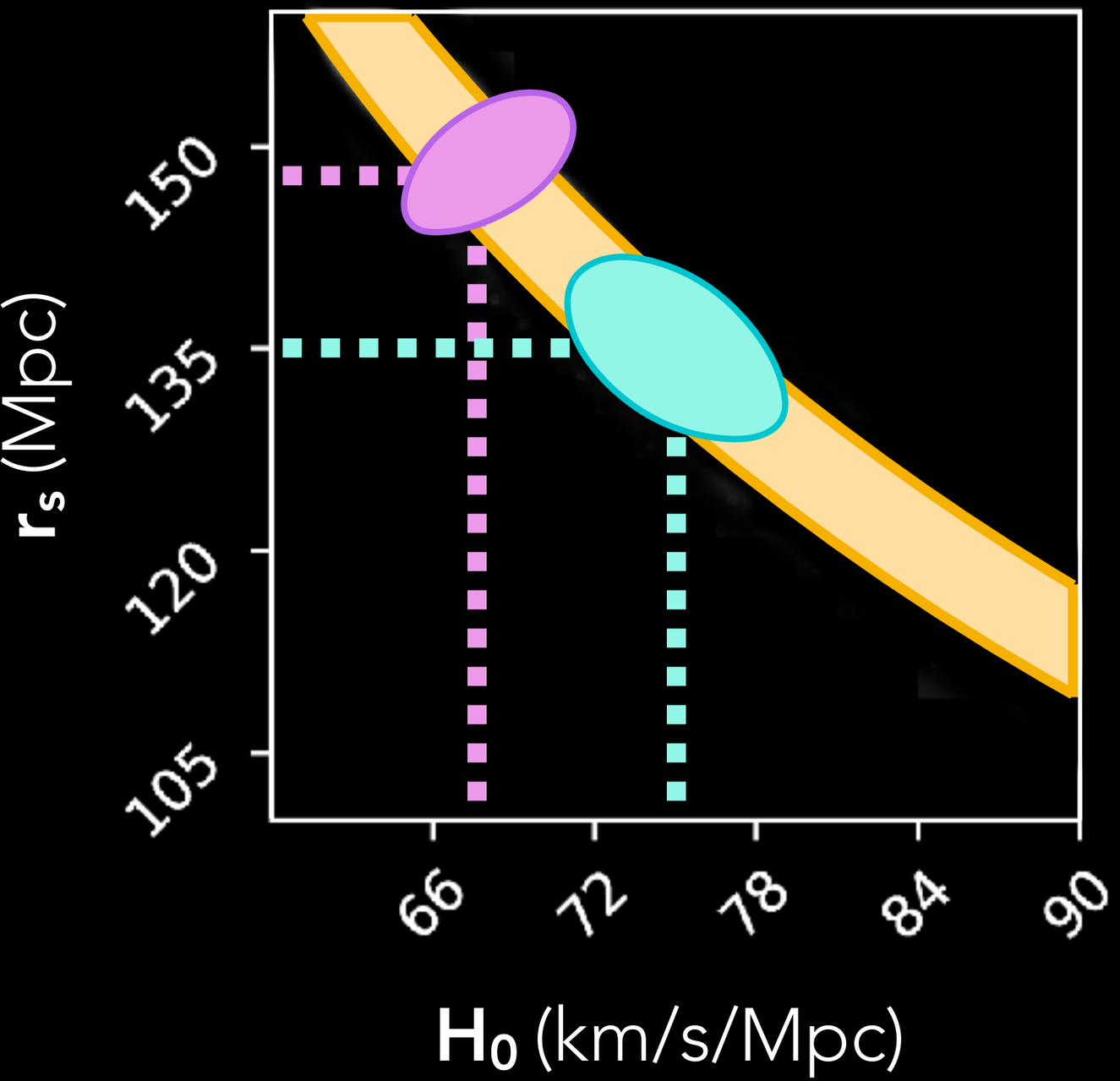
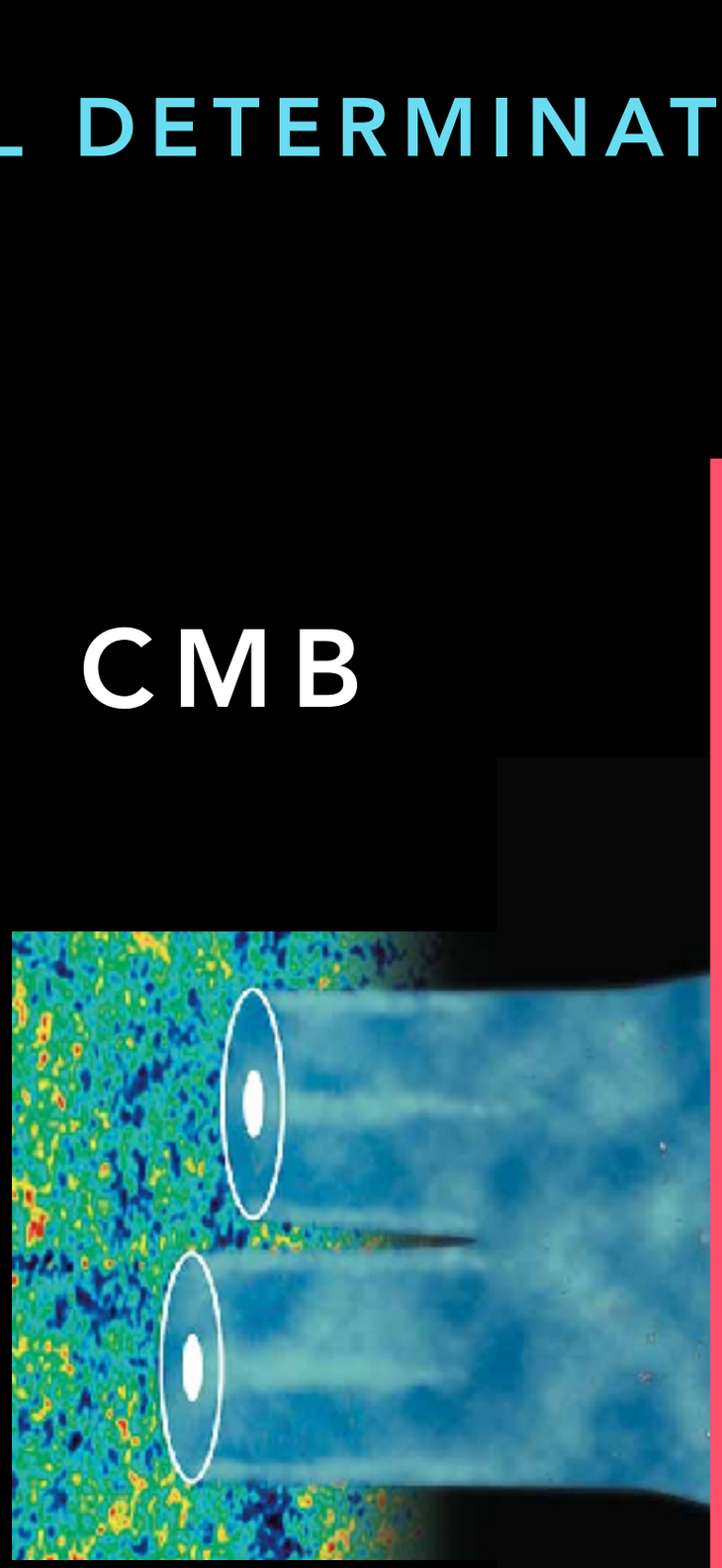



**Planck** measures a **high $r_s$** and therefore a **low value of $H_0$**.

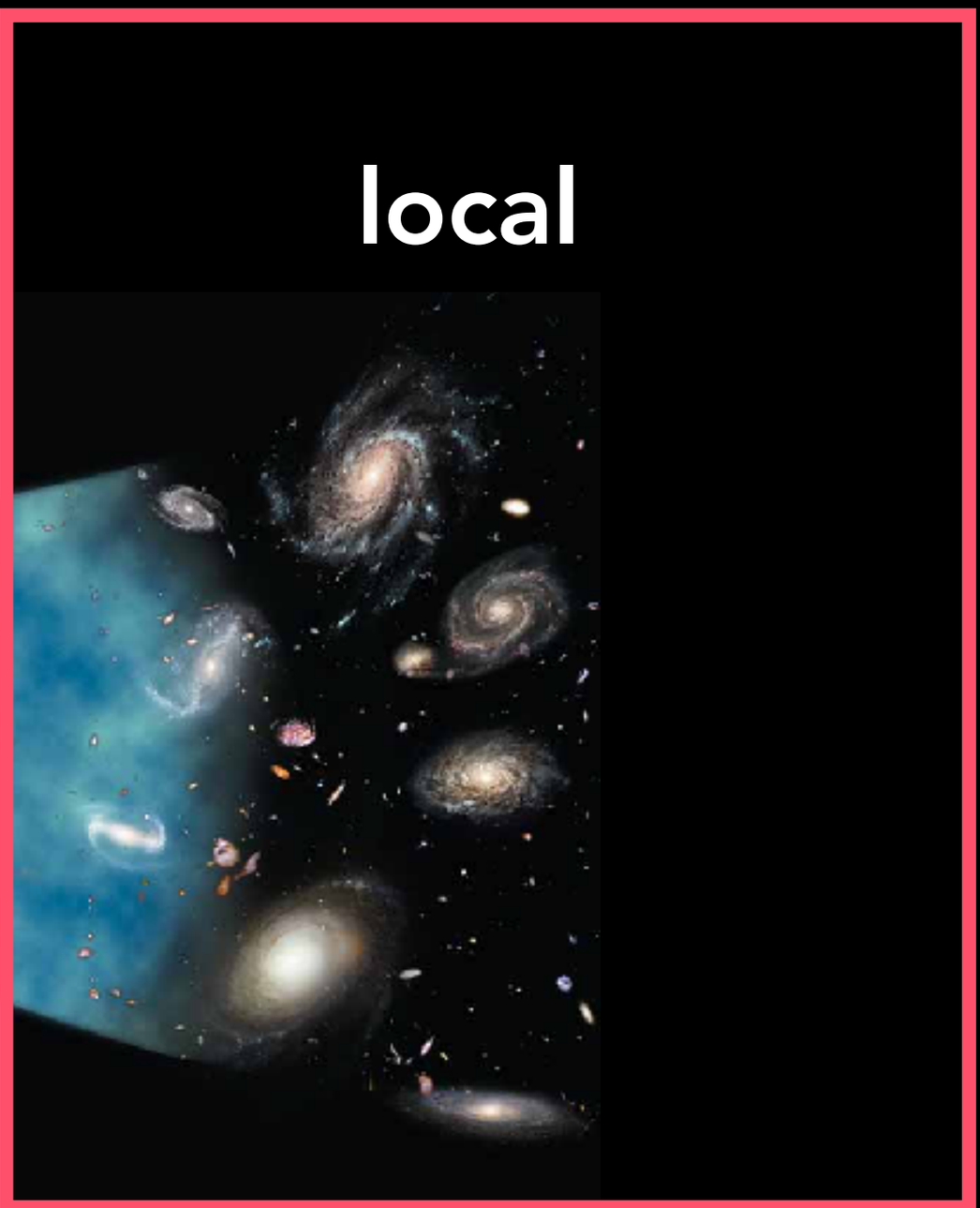
While **local measurements** get a **low $r_s$** and a **high $H_0$**.

# LOCAL DETERMINATION OF $H_0$ AND $R_S$

CMB

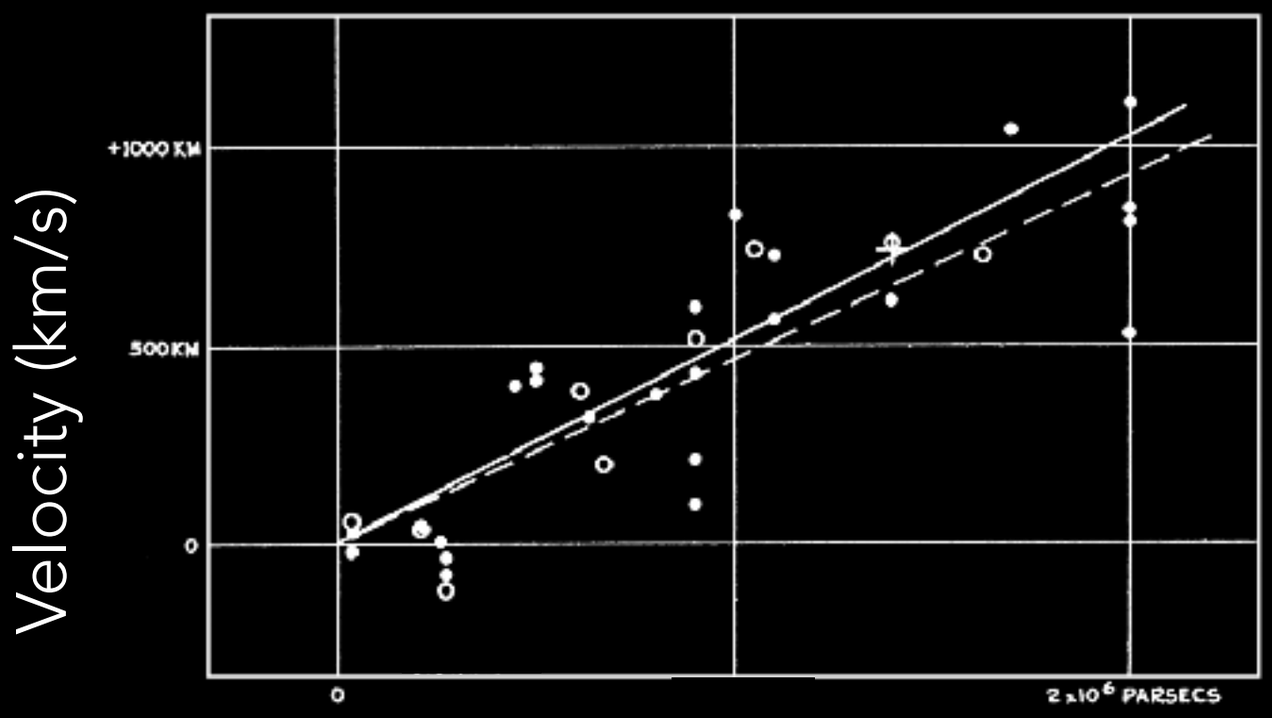


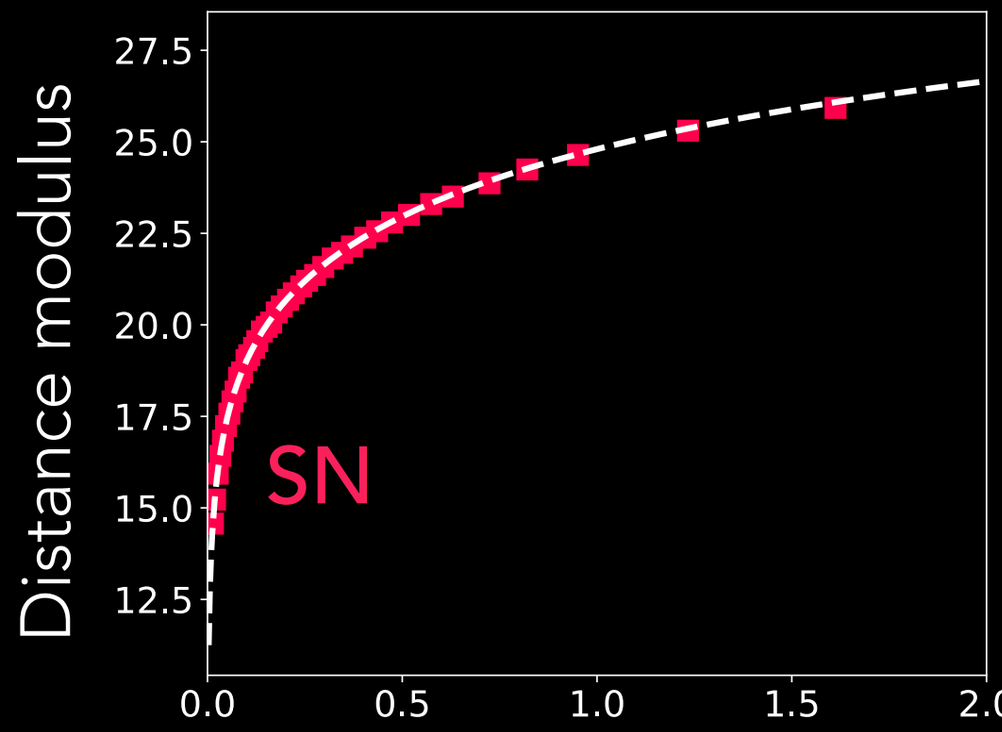
local



# LOCAL DETERMINATION OF $H_0$ AND $R_S$

## Modern & improved Hubble diagram



# RELATIVE DISTANCE INDICATORS

**Supernovae type Ia** (Pantheon, Scolnic et al 2018) and baryon acoustic oscillations **(BAO)** (BOSS, Alam et al 2017) yield relative distance measurements.

BAO introduce the sound horizon as a free parameter.

# CALIBRATE DATA

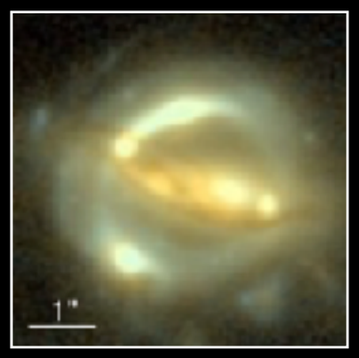
This is often done with **Cepheids,** stars at the Tip of the Red Giant Branch (**TRGB**) or Surface Brightness Fluctuations (**SBF**).

But those can only be measured at low redshifts.

*Images and data by H0LiCOW group*

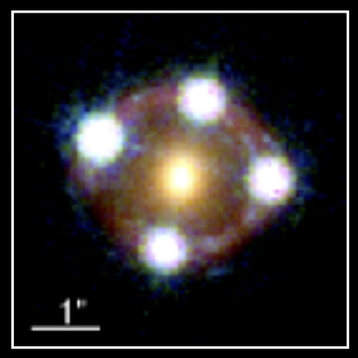
# H0LICOW

## H0 Lenses in COSMOGRAIL Wellspring

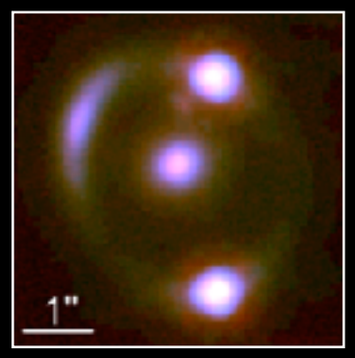



B1608


RXJ1131




HE0435

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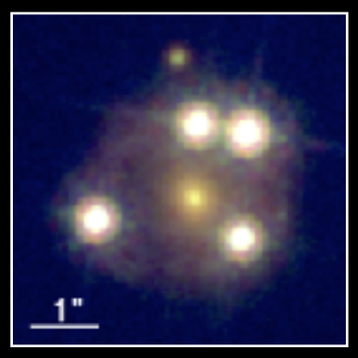
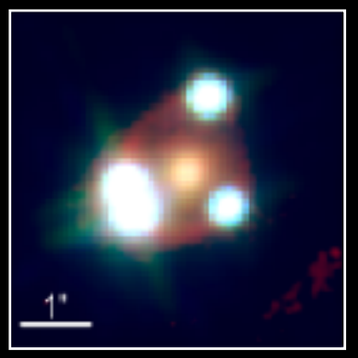
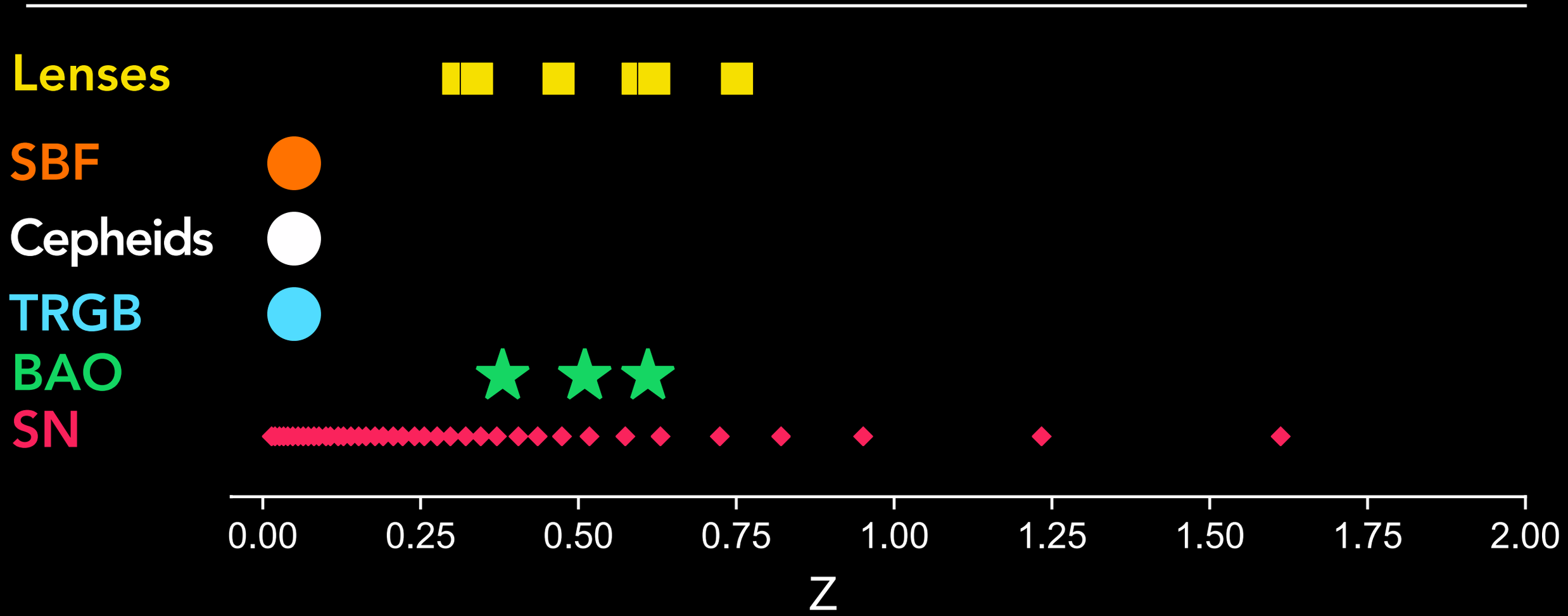



WFI2033

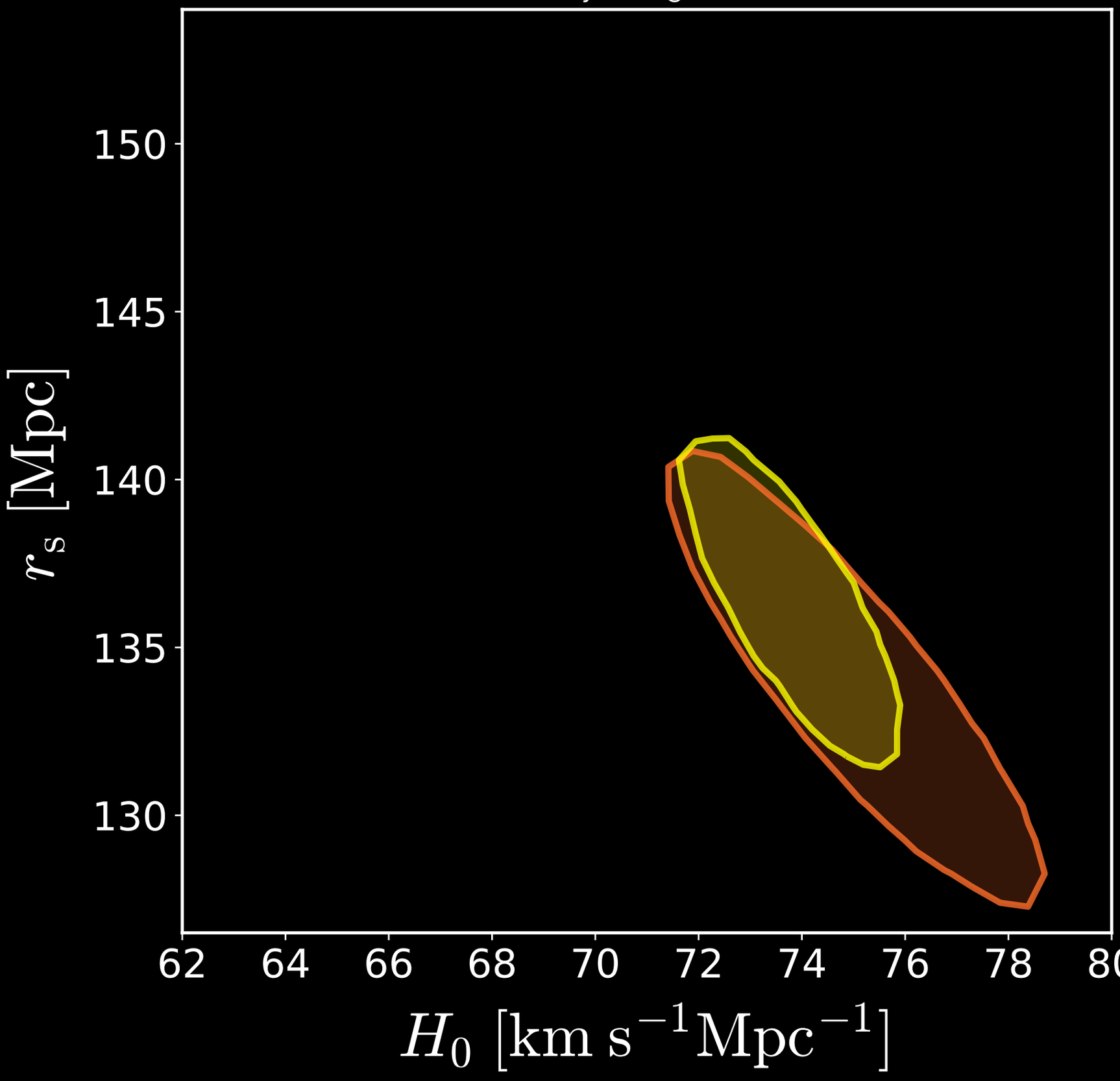



PG1115



# RESULTS

Arendse, Wojtak, Agnello et al. (2020)

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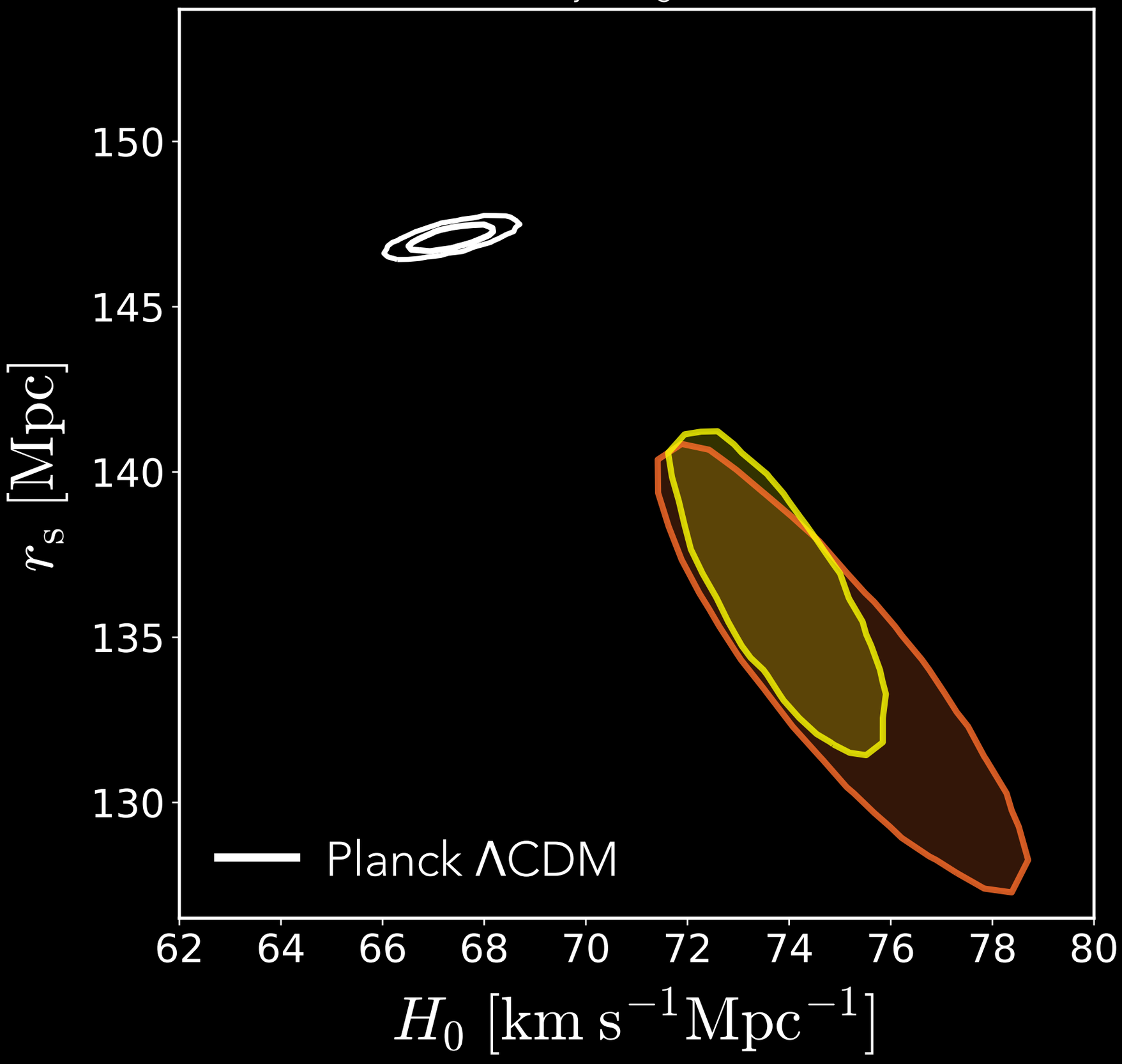


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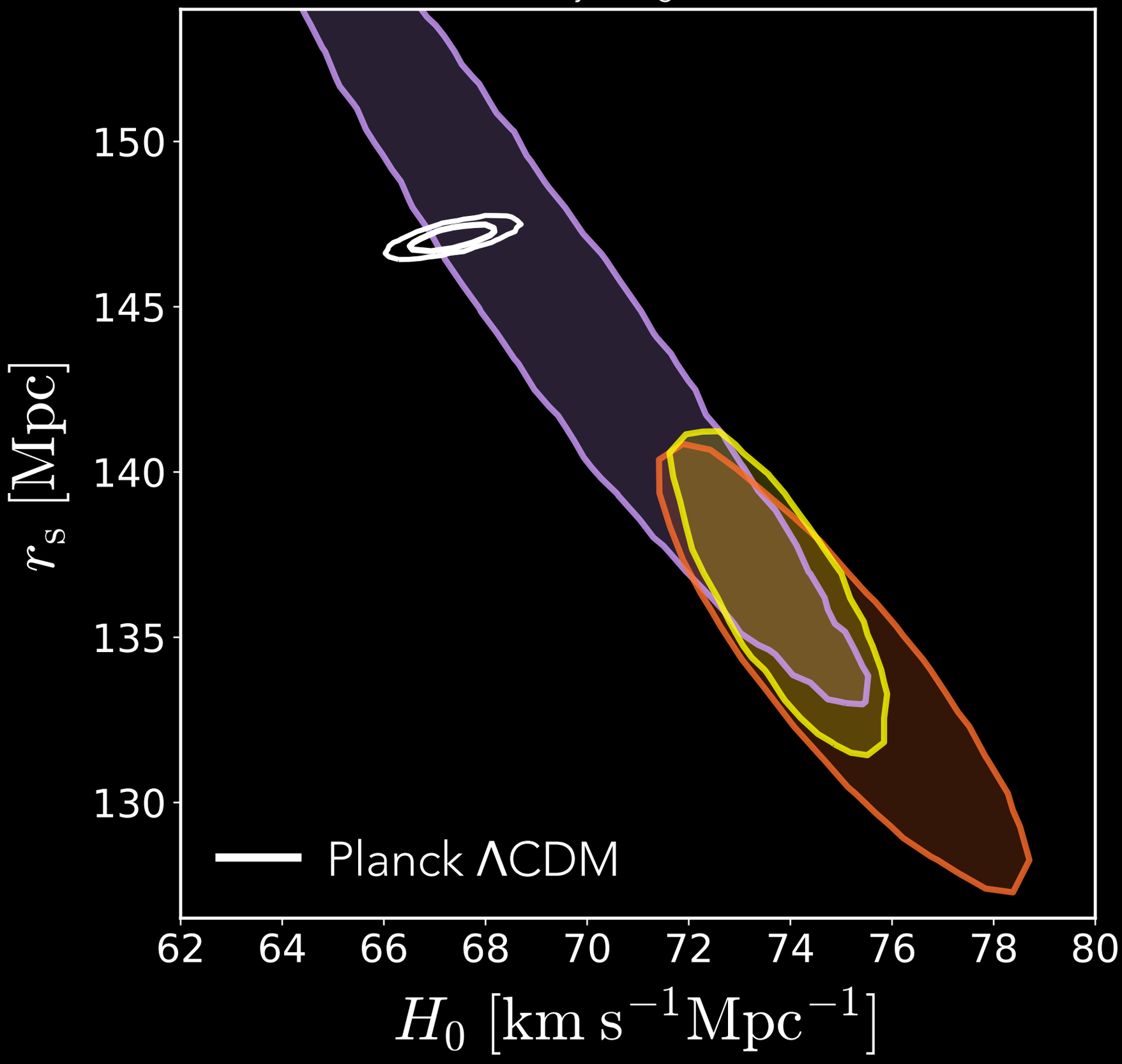


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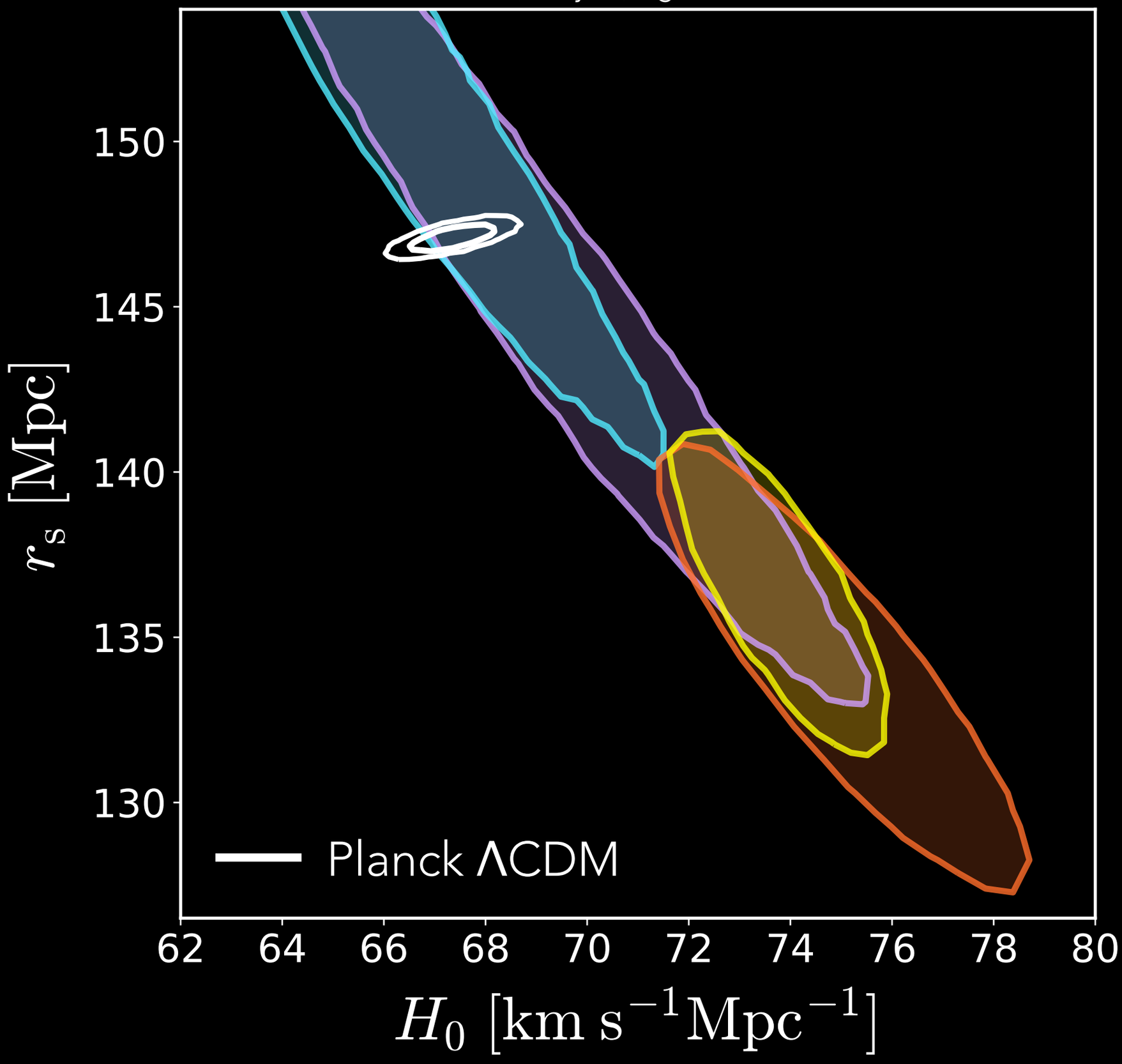


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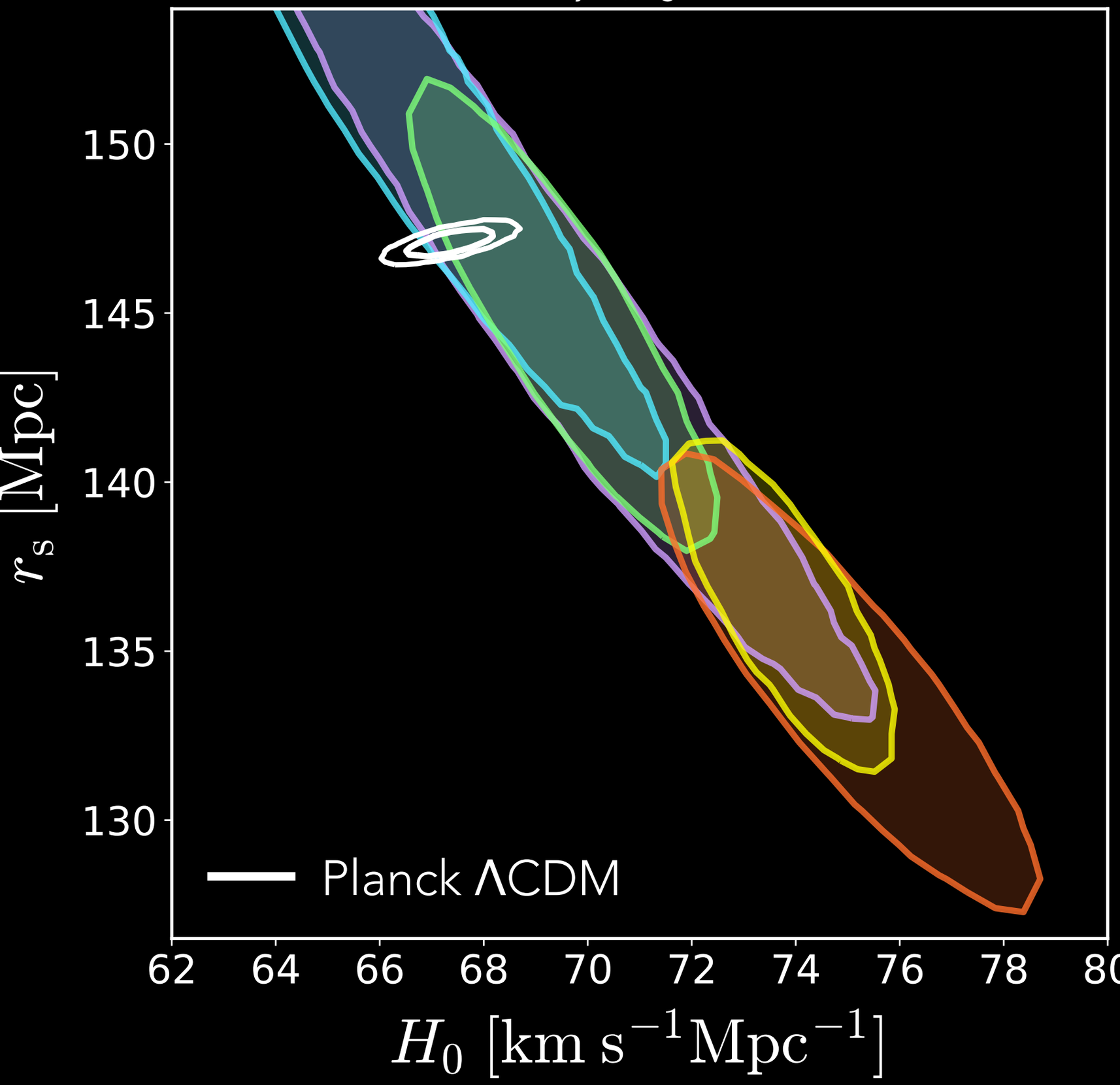


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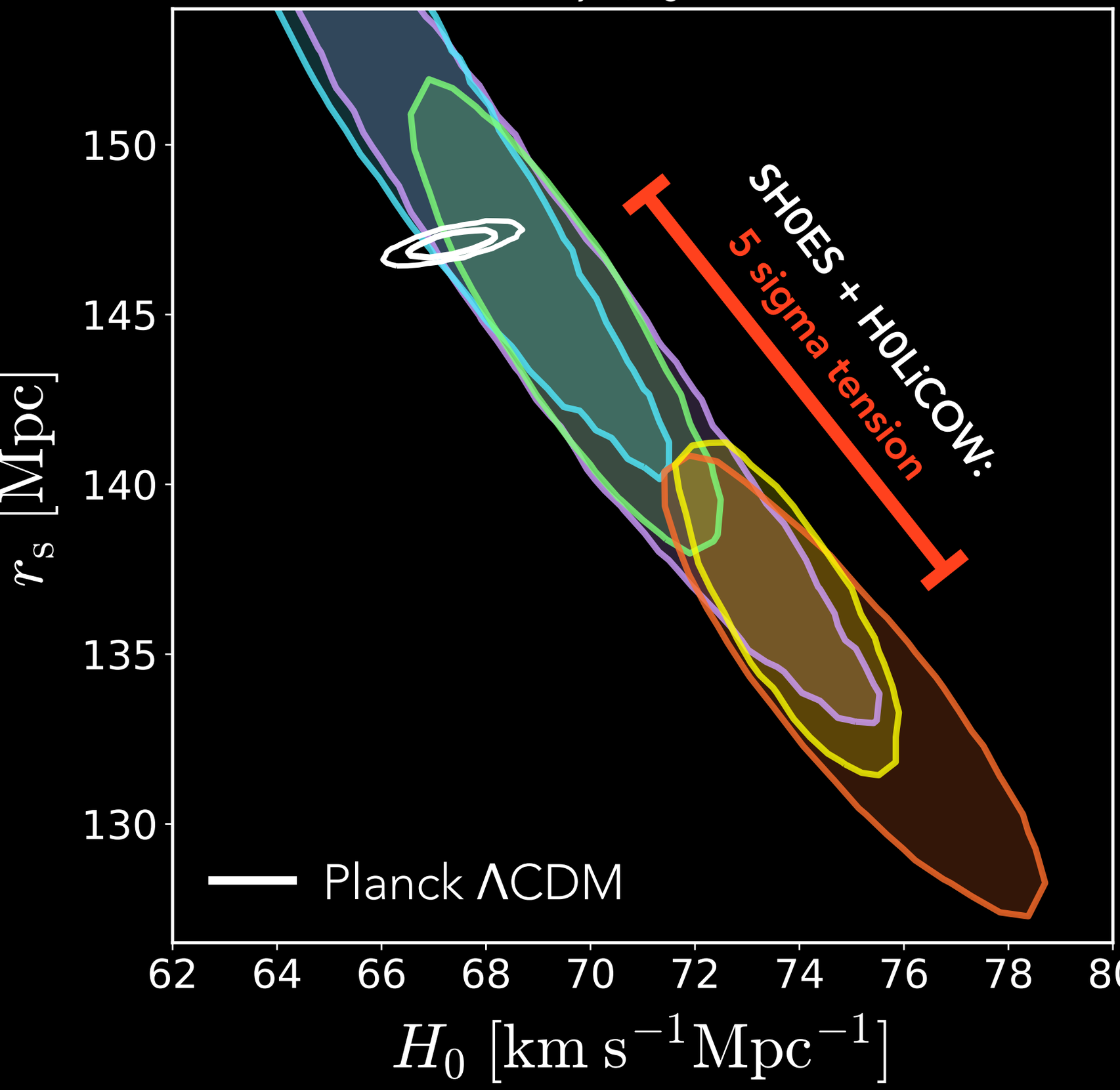


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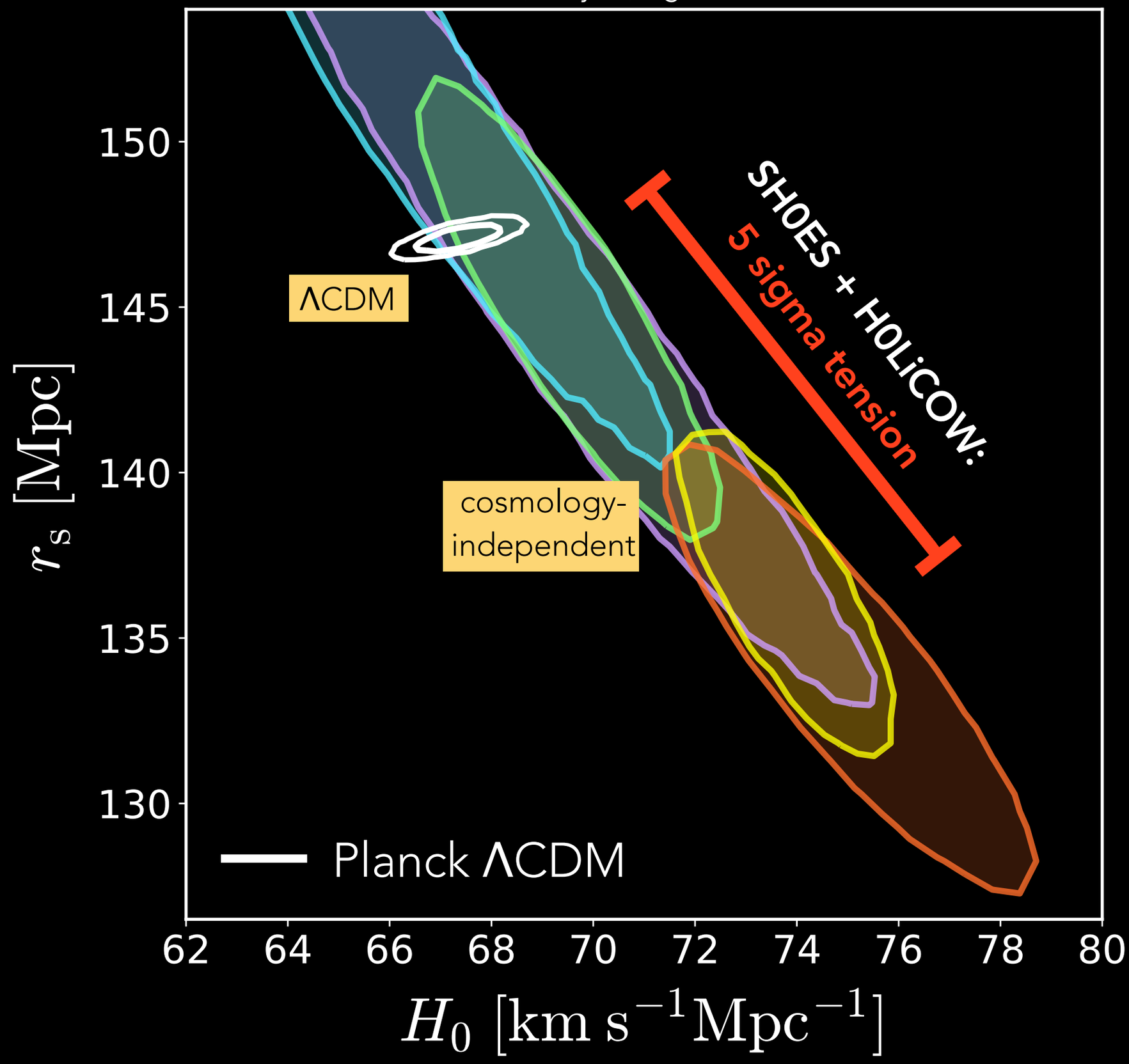


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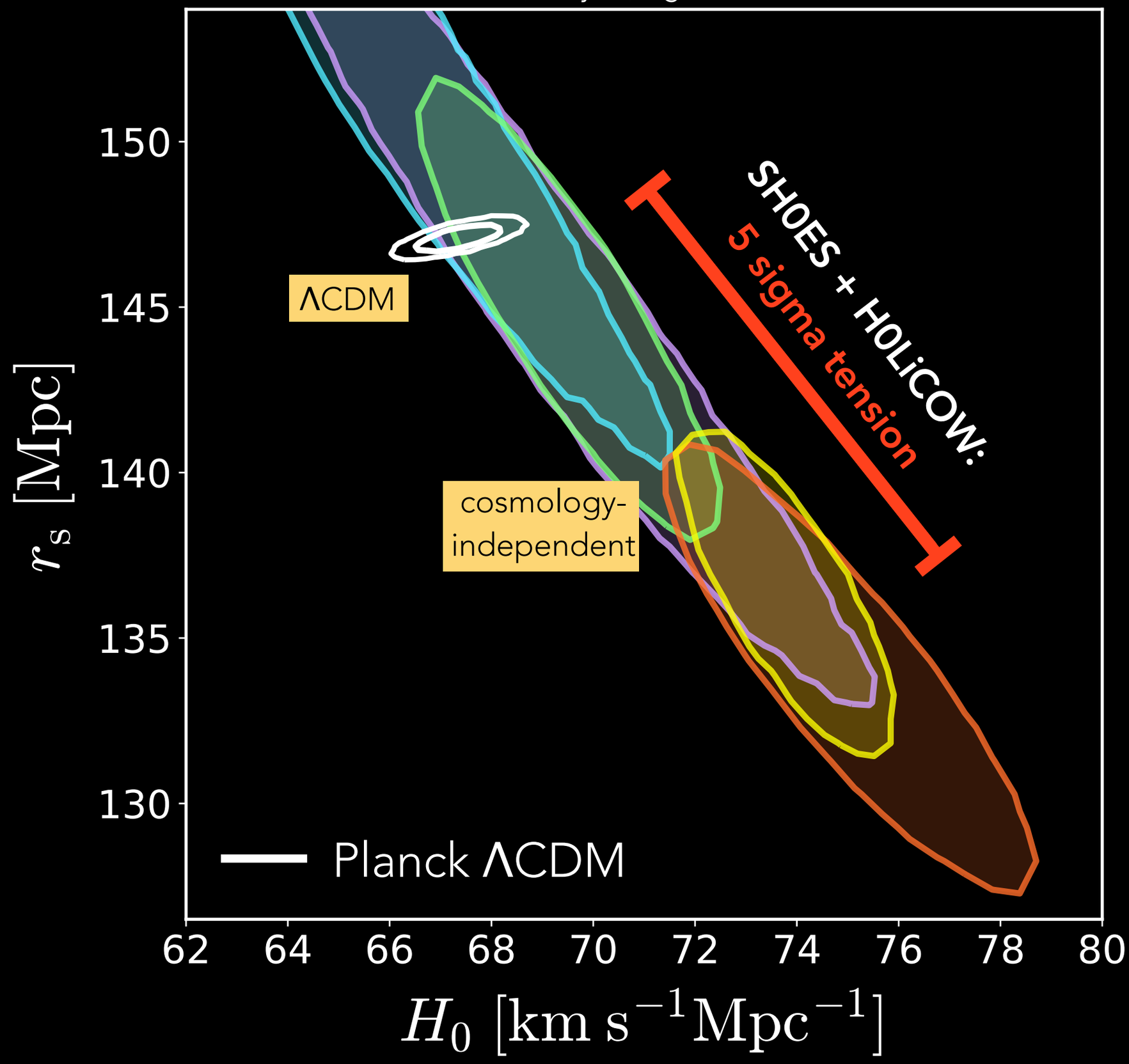


**Can we make changes to ΛCDM that reconcile the tension?**

Consider these 4 extensions of ΛCDM:

| | |
|---|---|
| Extra relativistic particle (**$N_{eff}$**) | Redshift dependent DE (***w*CDM**) |
| Early Dark Energy (**EDE**) | DE model 2 (**PEDE**) |

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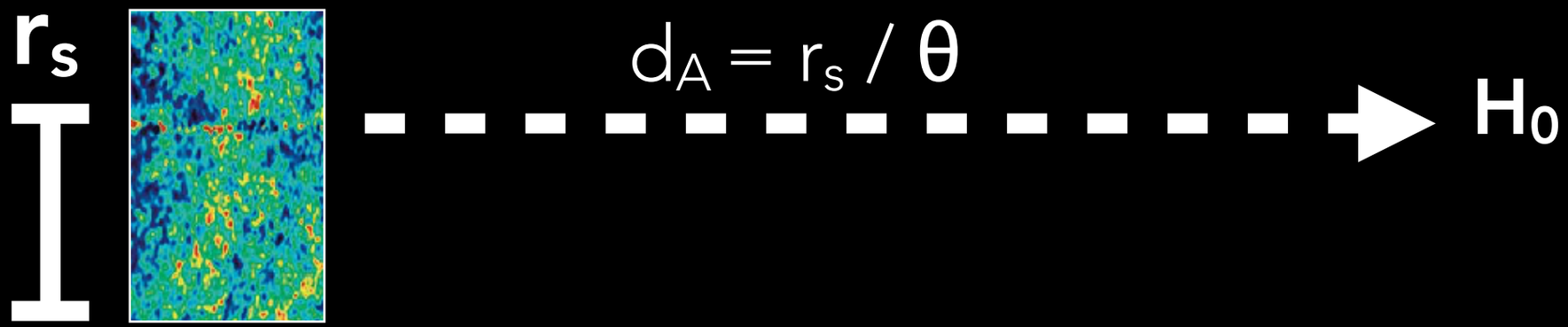


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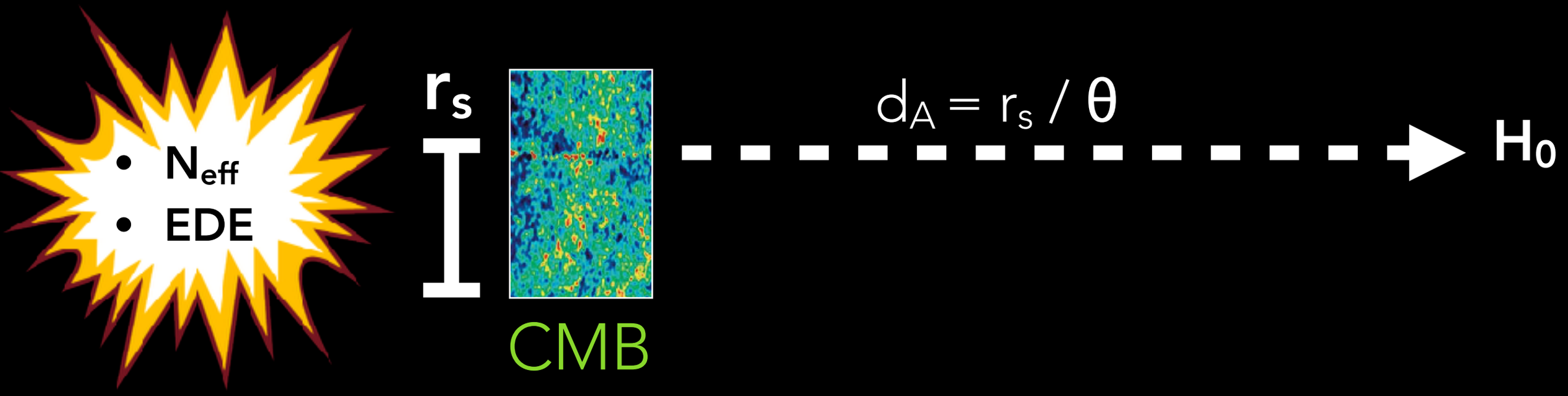


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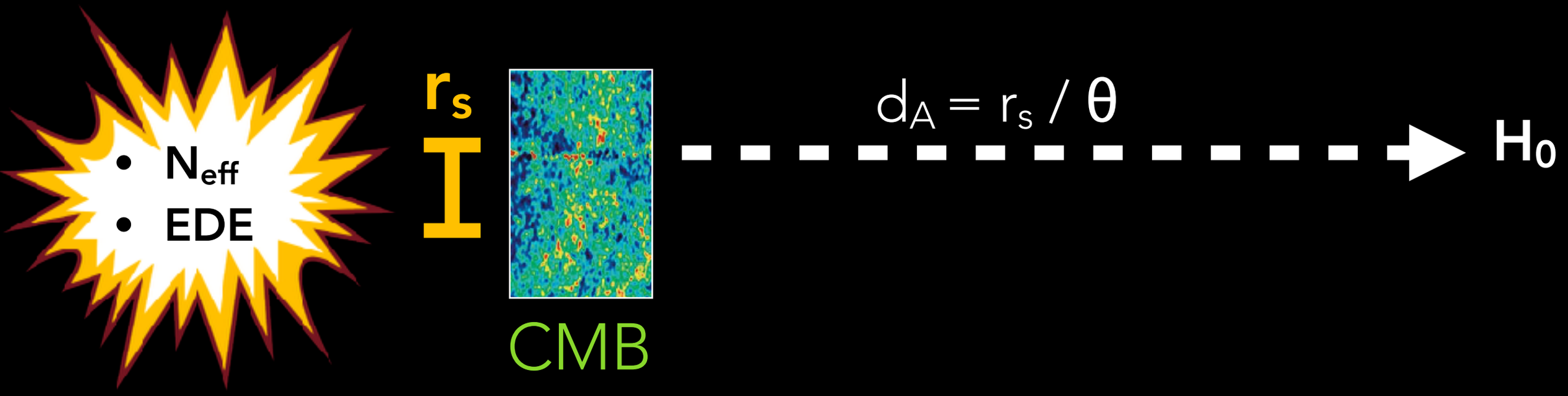


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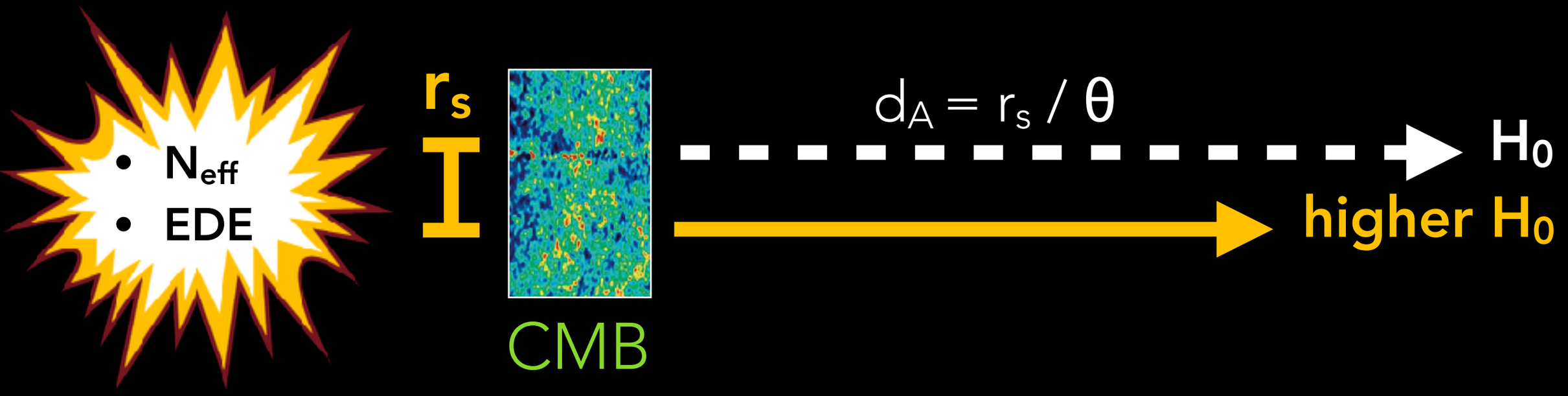


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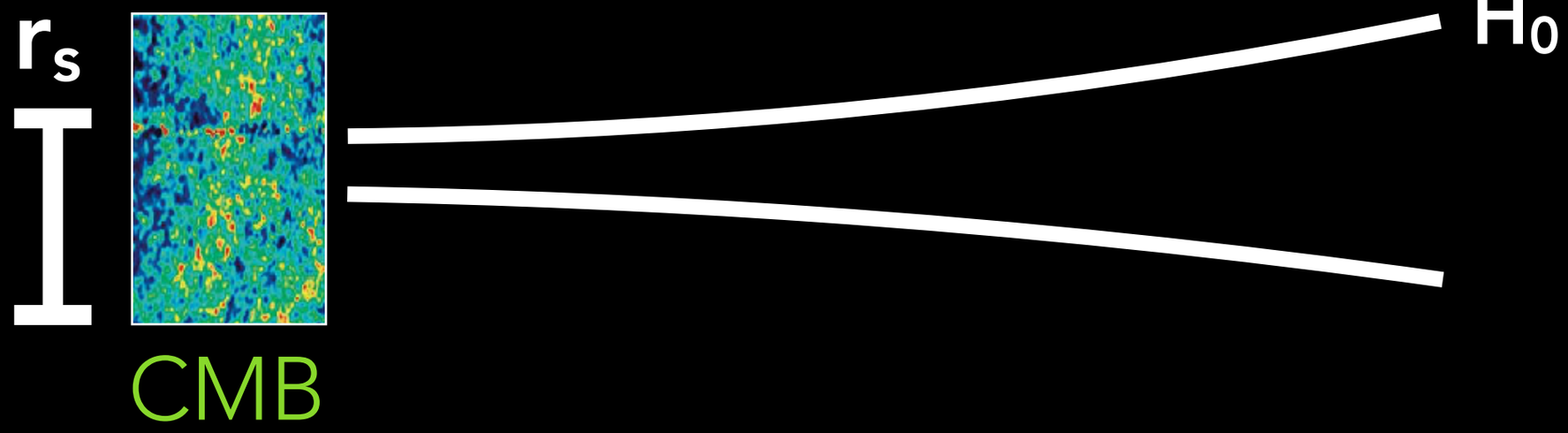

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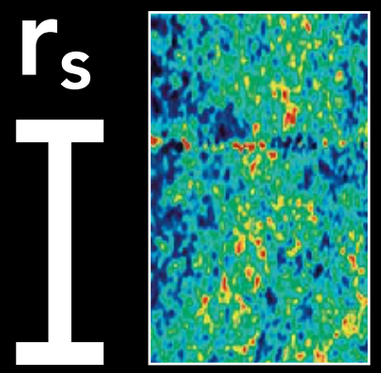
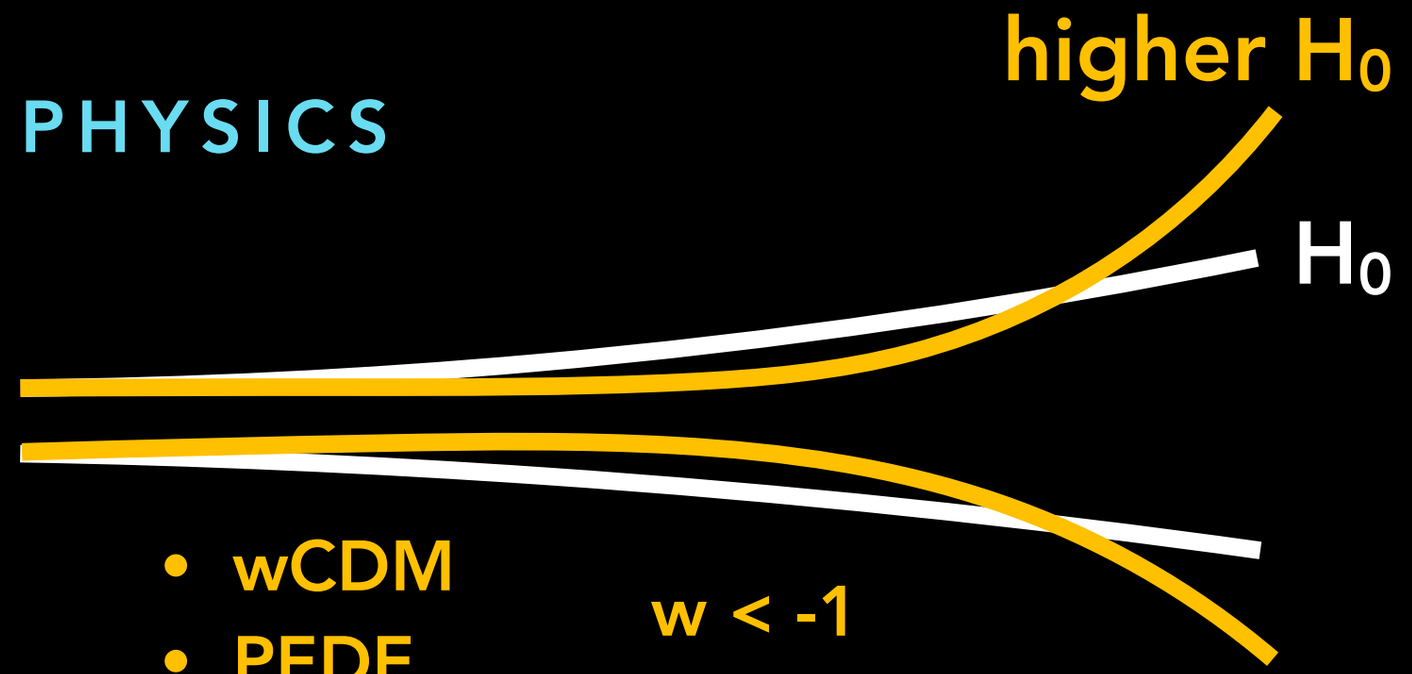


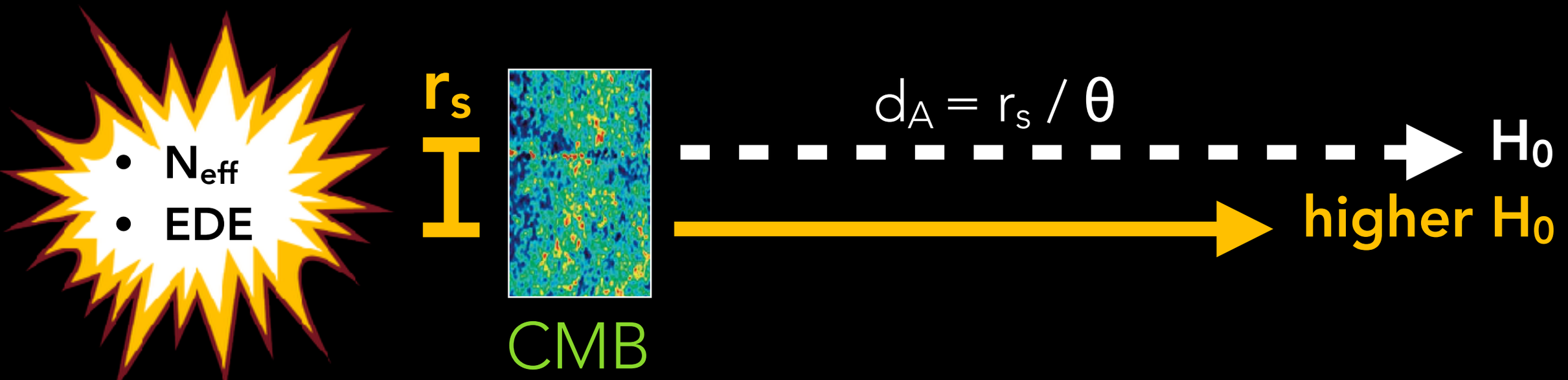

- wCDM
- PEDE

Li & Shafieloo (2019)

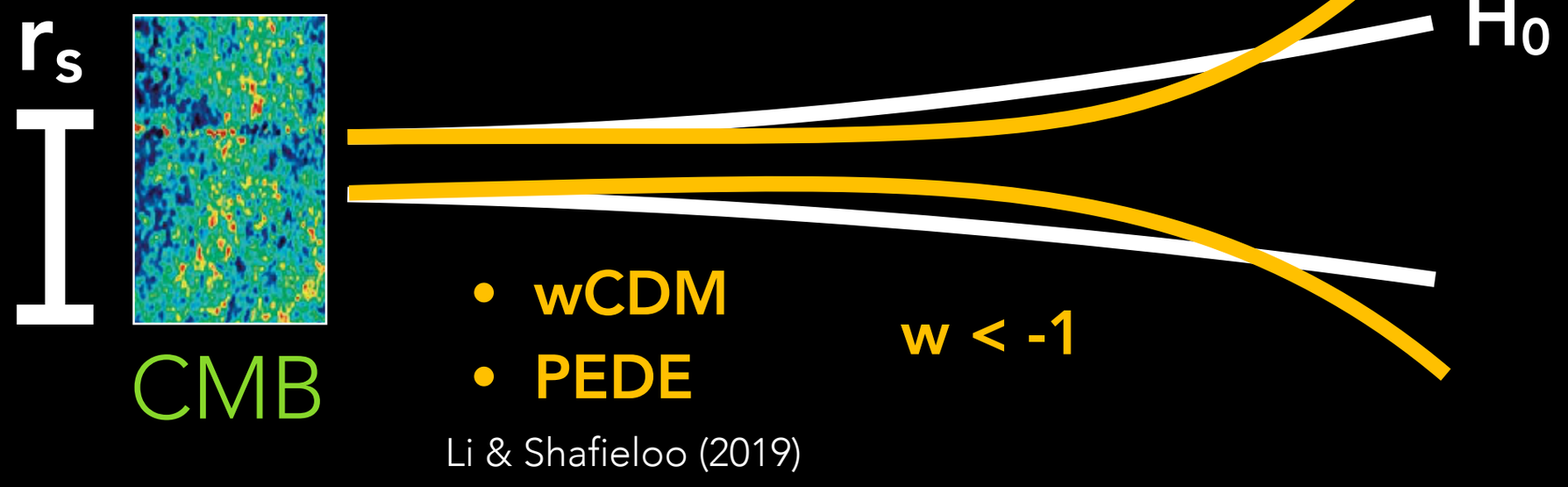
Consider these 4 extensions of ΛCDM:

| | |
|---|---|
| Extra relativistic particle ($N_{eff}$) | Redshift dependent DE (*w*CDM) |
| Early Dark Energy (EDE) | DE model 2 (PEDE) |

## CHANGES TO EARLY PHYSICS



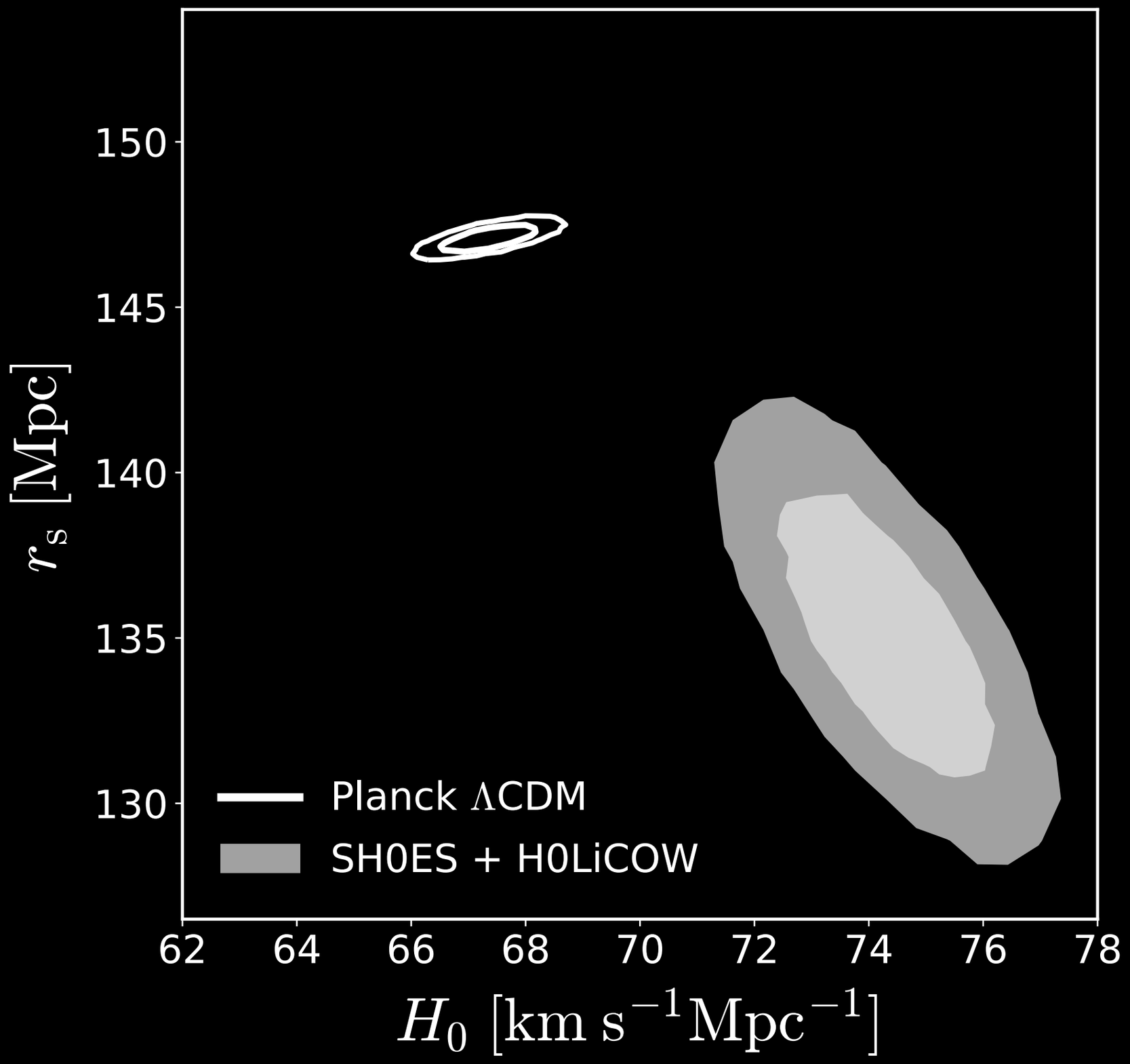

## CHANGES TO LATE PHYSICS




Li & Shafieloo (2019)

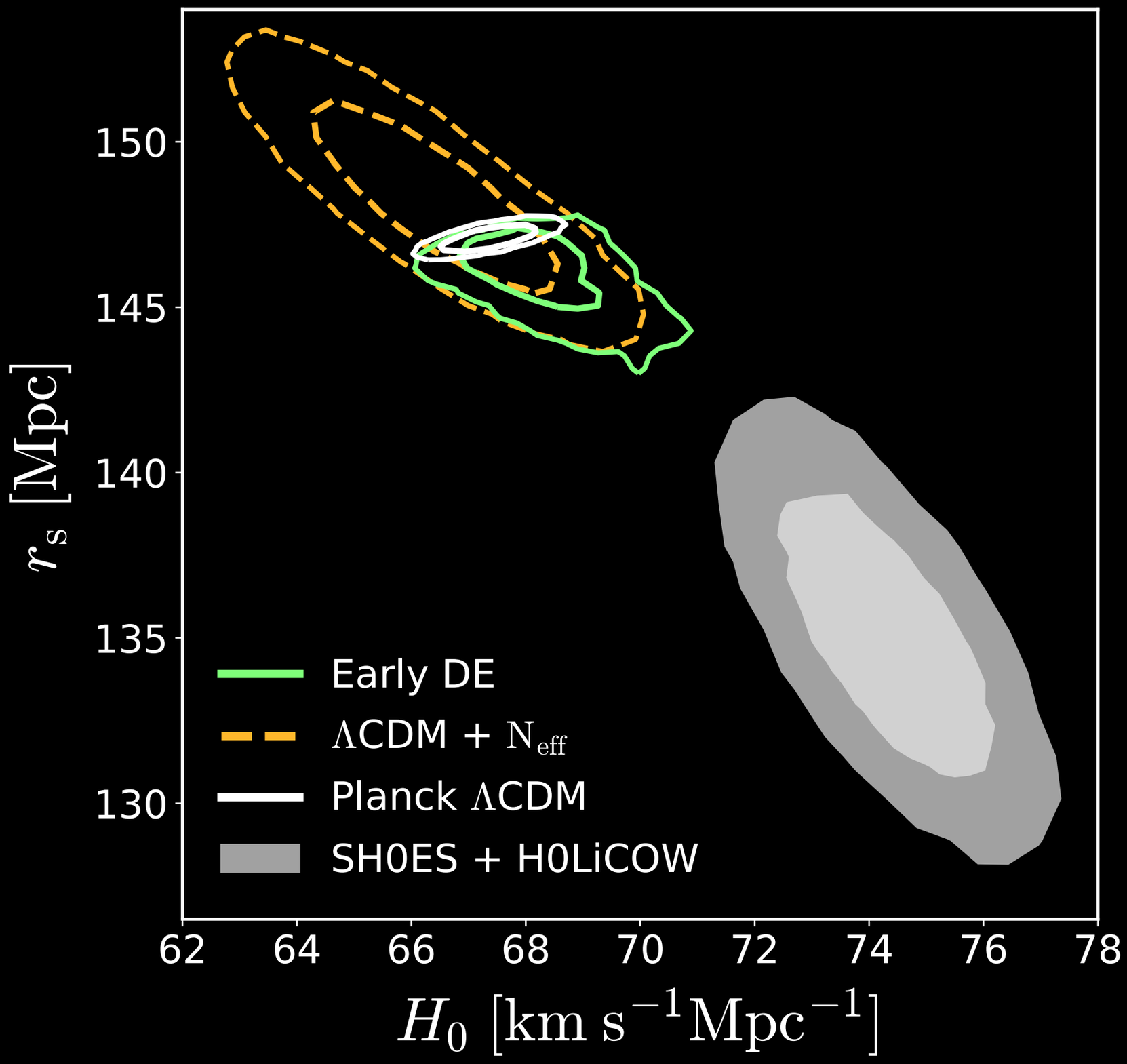
Arendse, Wojtak, Agnello et al. (2020)

# RESULTS



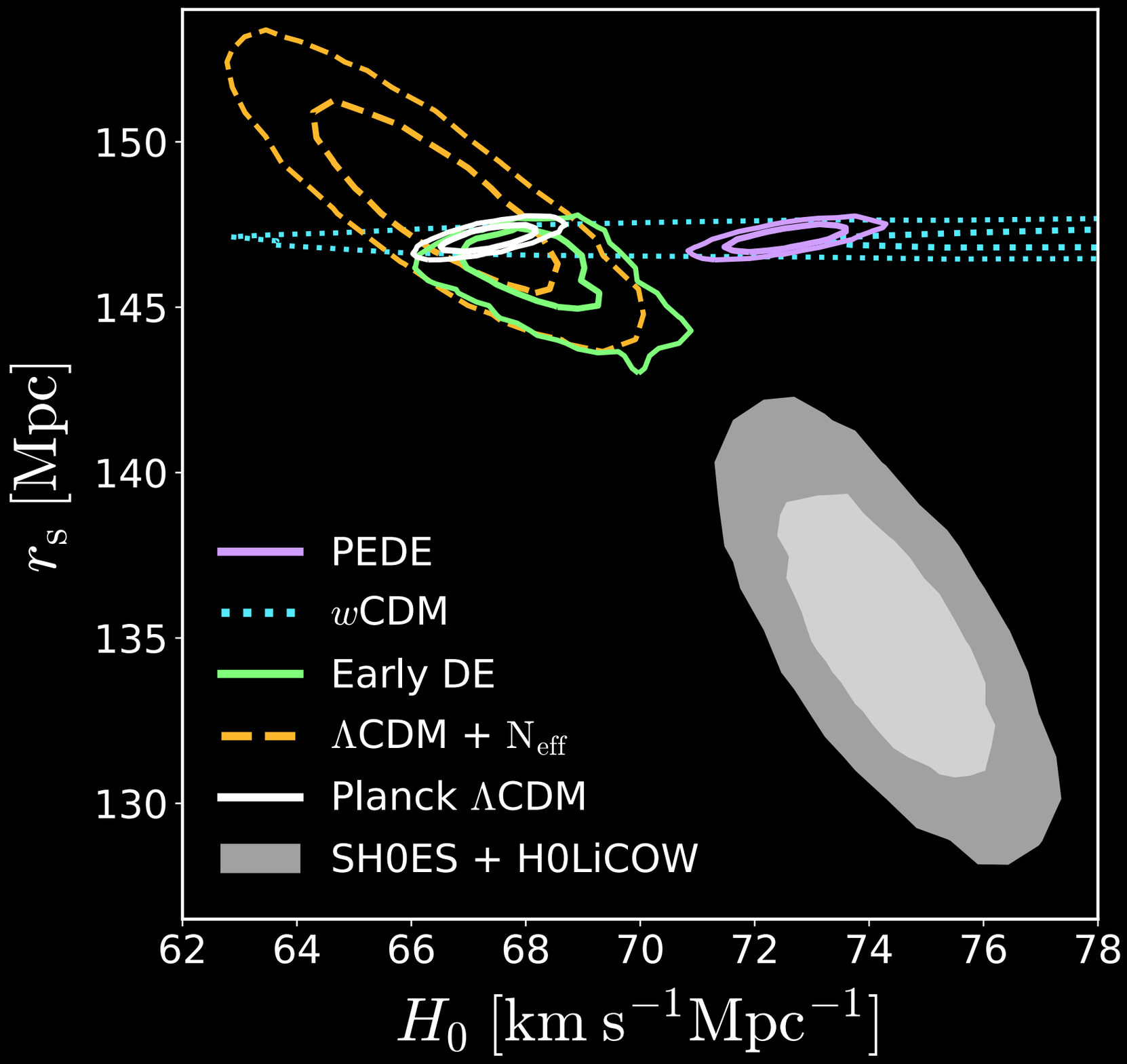
Arendse, Wojtak, Agnello et al. (2020)

# RESULTS



Arendse, Wojtak, Agnello et al. (2020)

# RESULTS



# ADDITIONAL CHALLENGES

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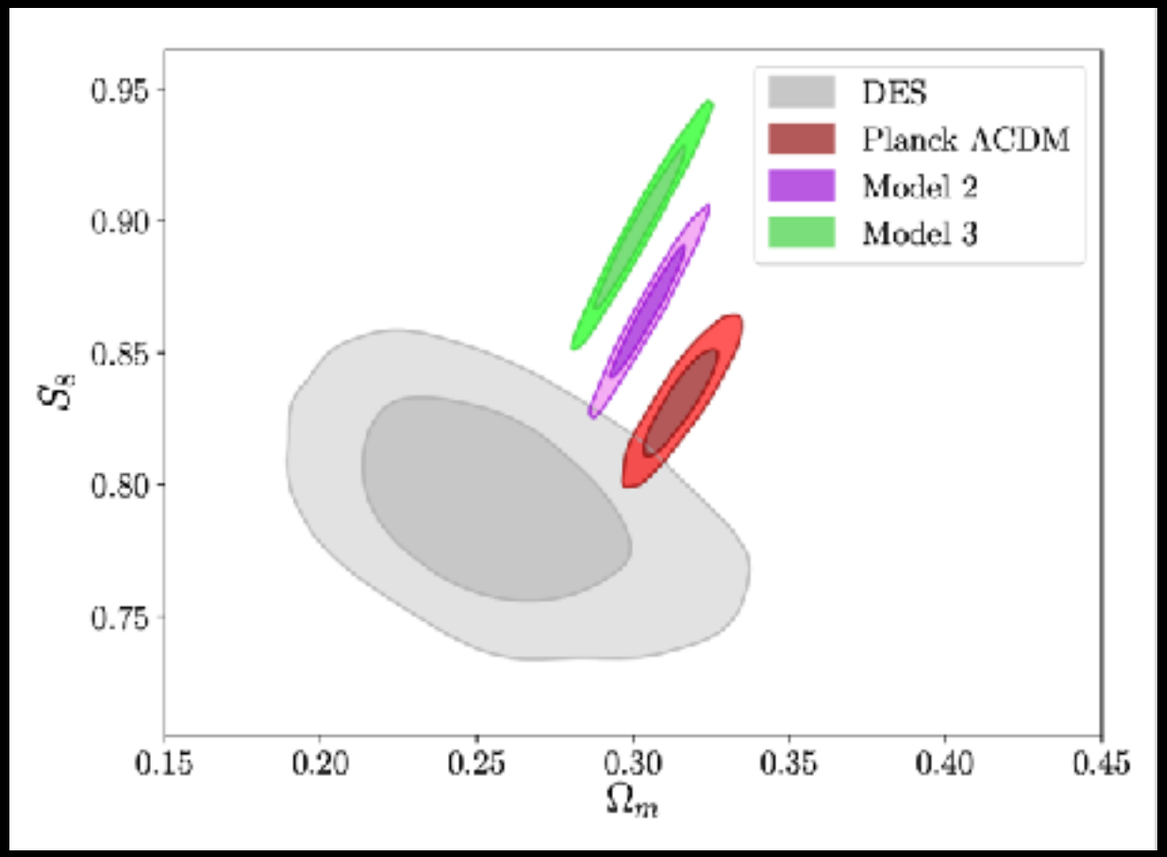
Early-time modifications worsen
the growth tension…




Jedamzik, Pogosian, Zhao (2020)

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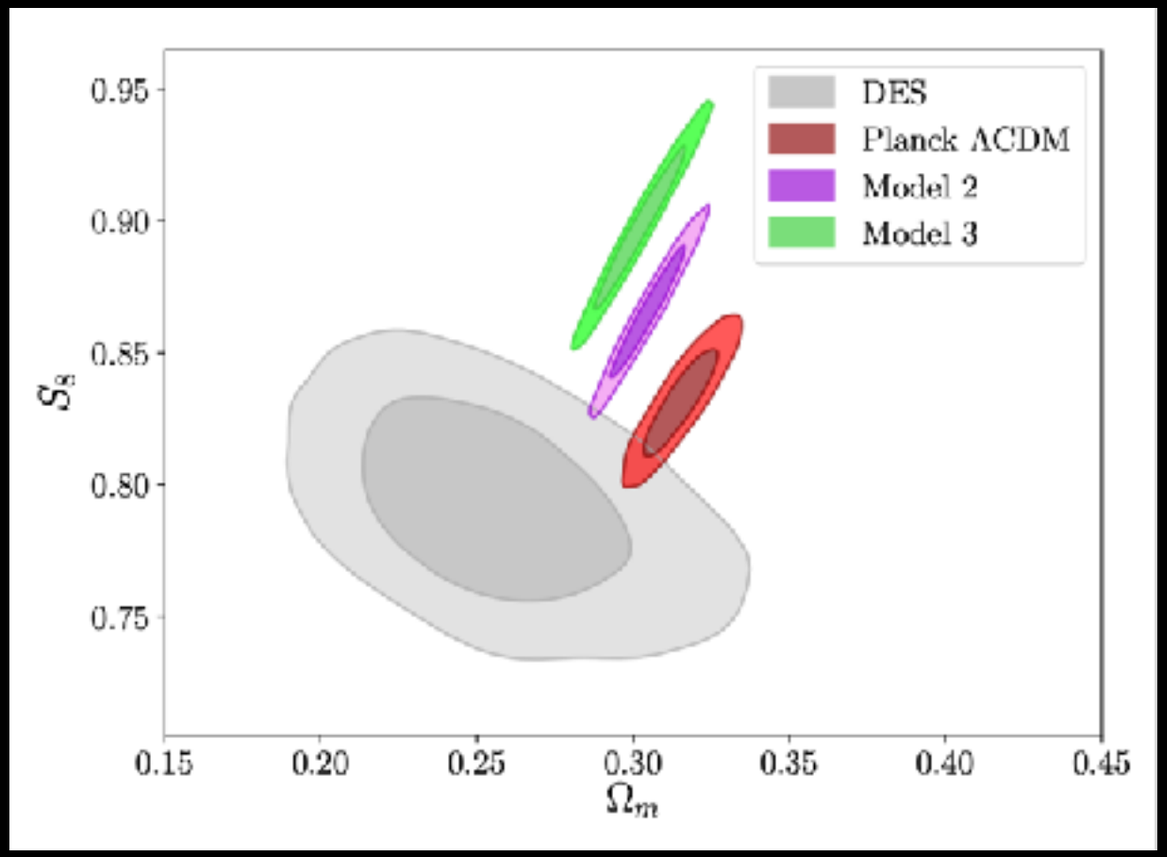
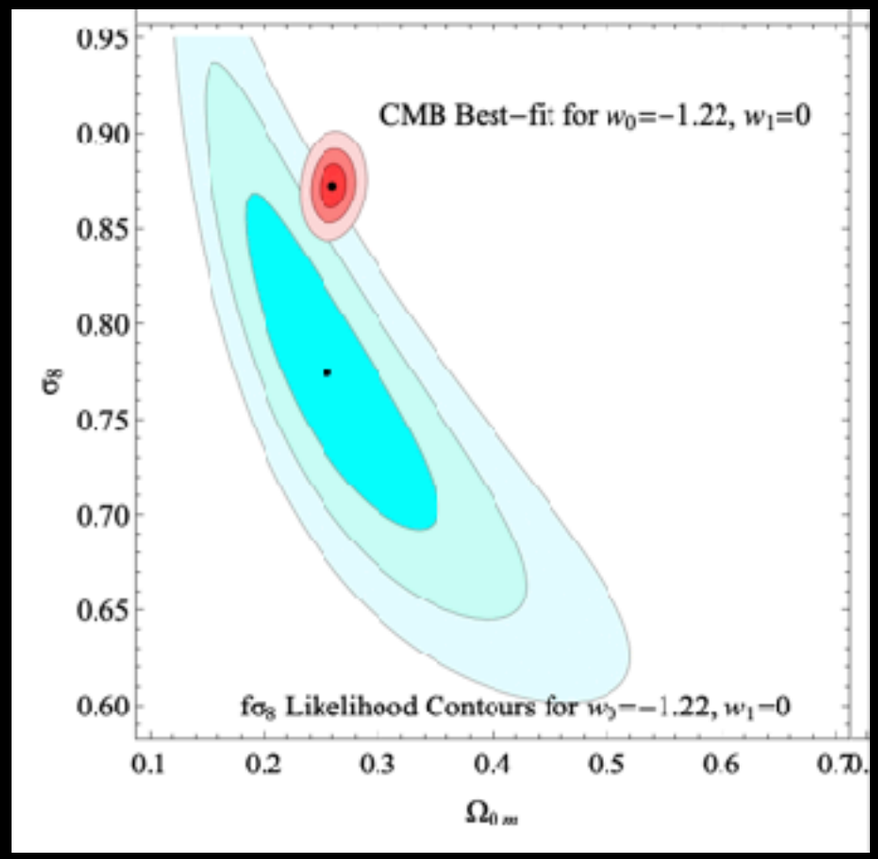
Early-time modifications worsen the growth tension…




Jedamzik, Pogosian, Zhao (2020)

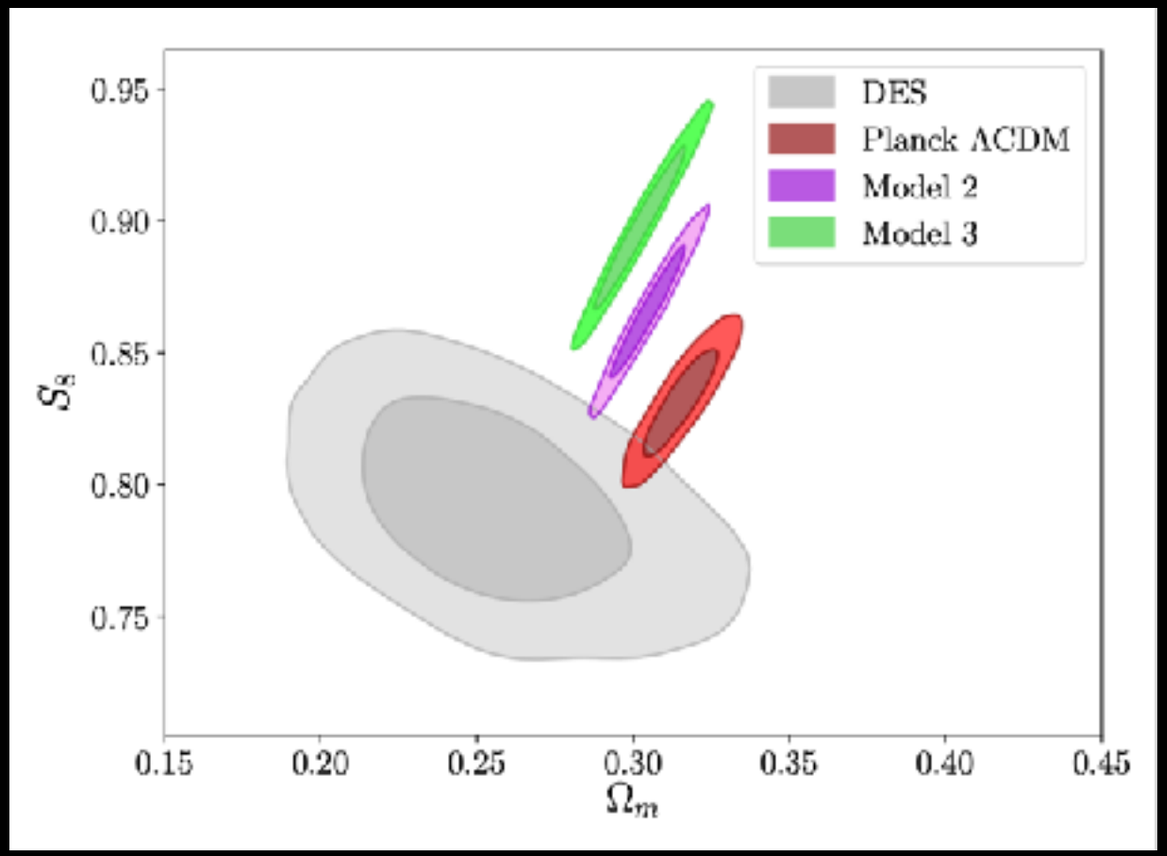
Alestas & Perivolaropoulos (2021)




…and late-time modifications as well!

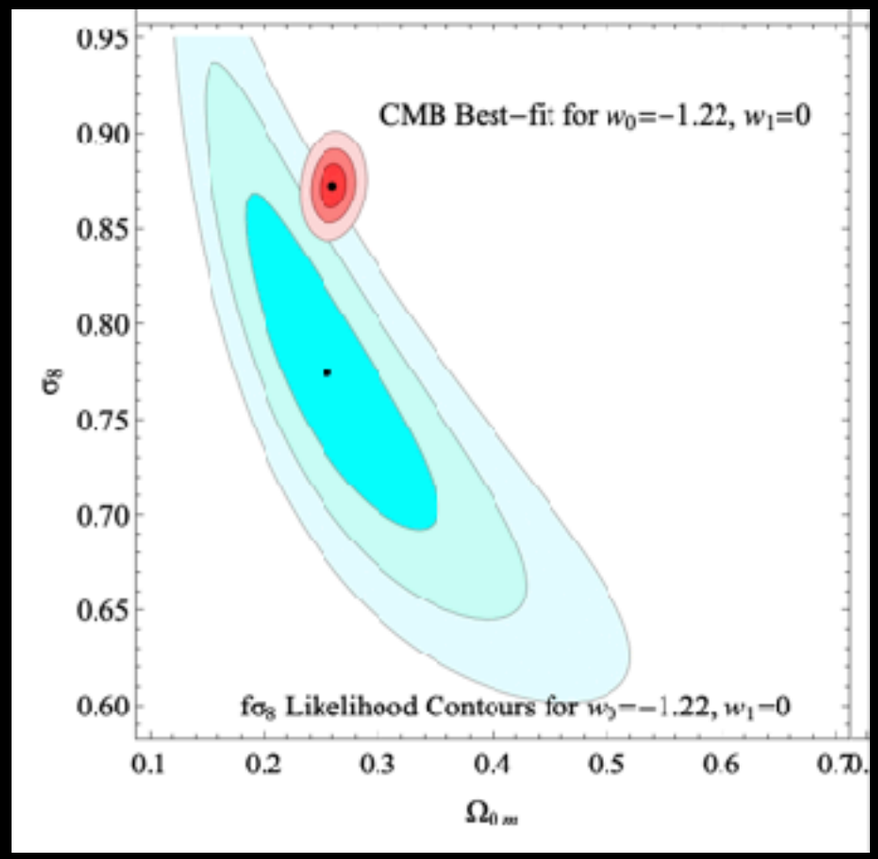
# ADDITIONAL CHALLENGES

Early-time modifications worsen the growth tension…




Jedamzik, Pogosian, Zhao (2020)

Alestas & Perivolaropoulos (2021)




…and late-time modifications as well!

**We should adopt a holistic approach to resolve the Hubble tension**

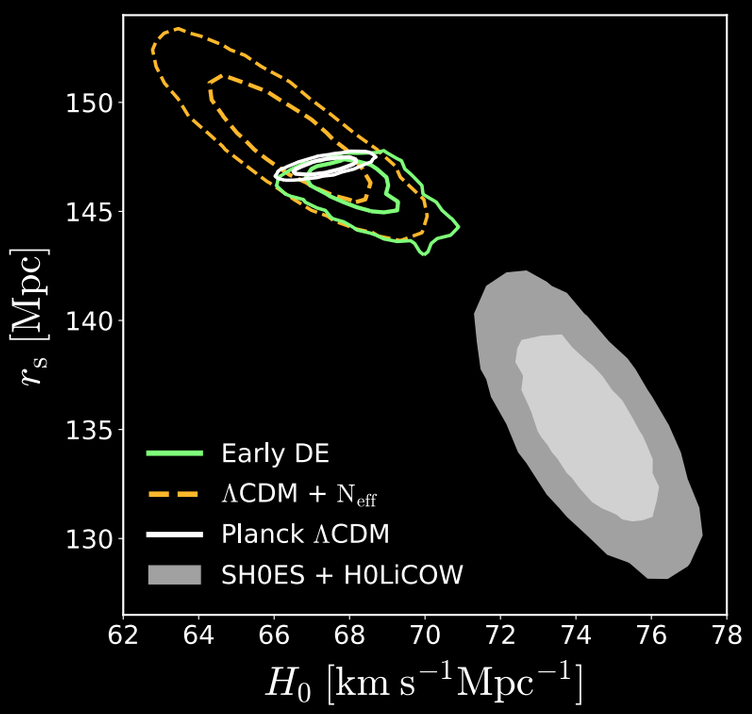
Can modifications of the standard ΛCDM model solve the Hubble tension?

Can modifications of the standard ΛCDM model solve the Hubble tension?

**NO**

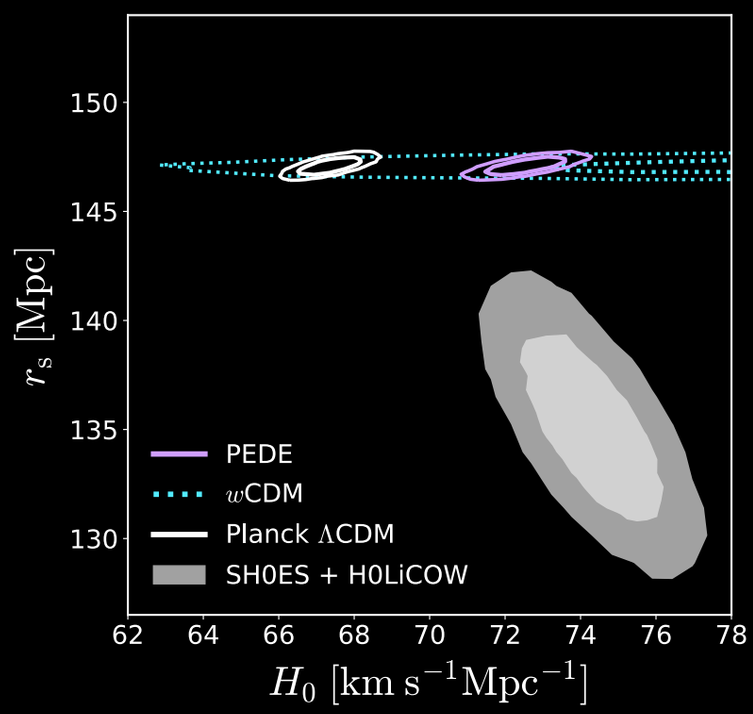
# Can modifications of the standard ΛCDM model solve the Hubble tension?

# NO




**Early-time modifications**

- Small shift of $H_0$ and $r_s$ to local values
- Worsen growth tension



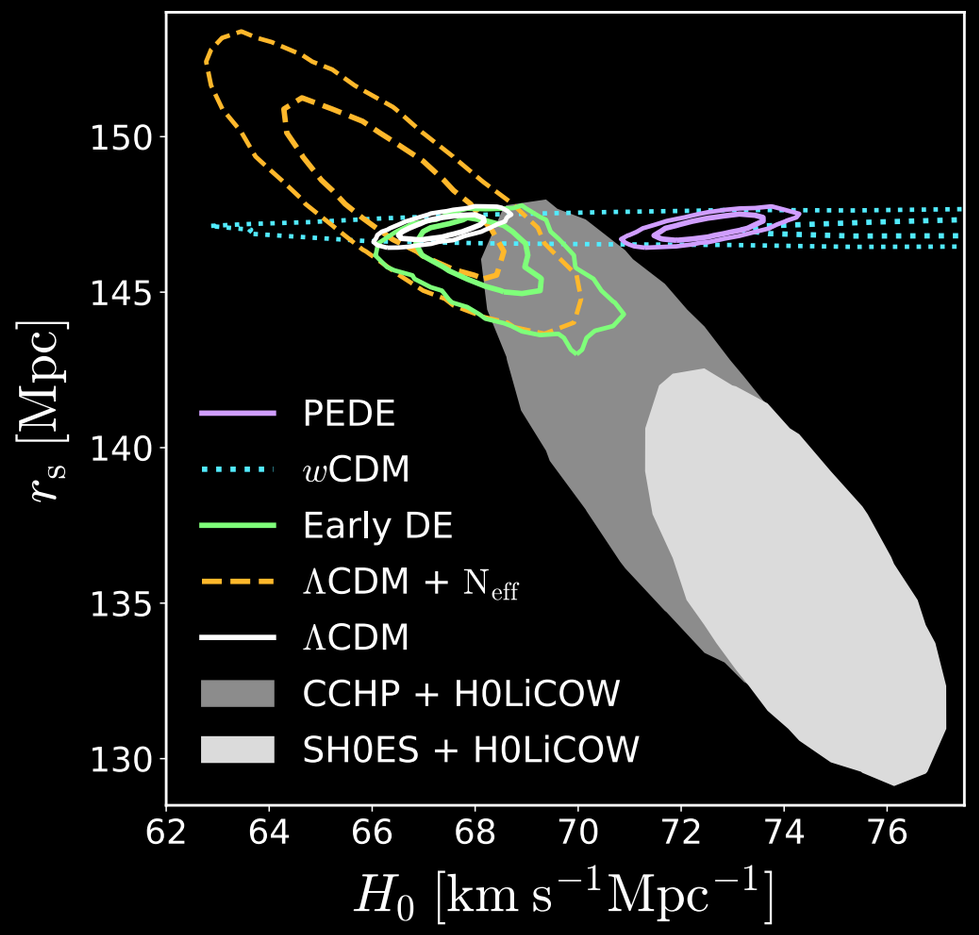

**Late-time modifications**

- Only solves tension in $H_0$, not in $r_s$
- Worsen growth tension

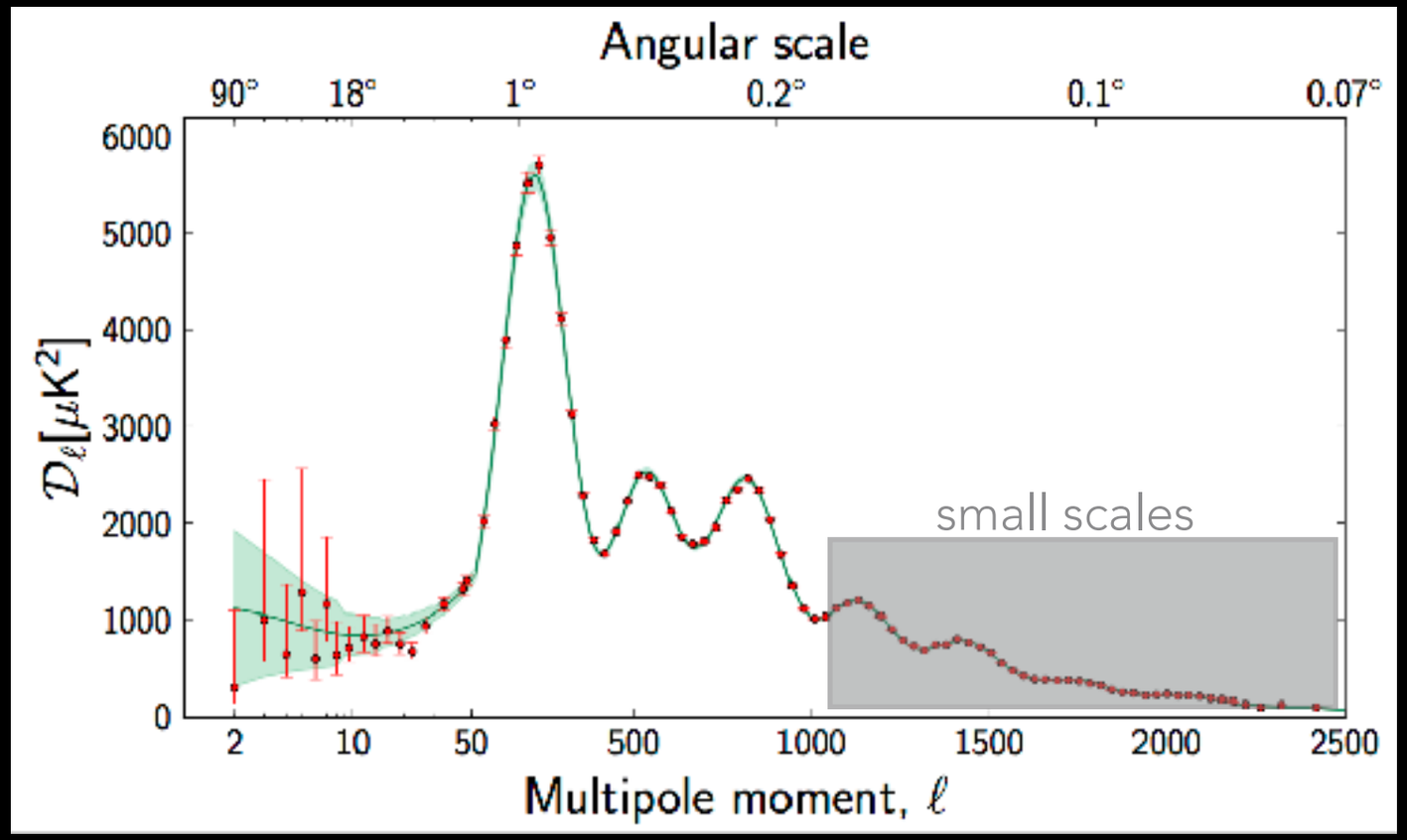
# CONCLUSIONS

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

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




- 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.

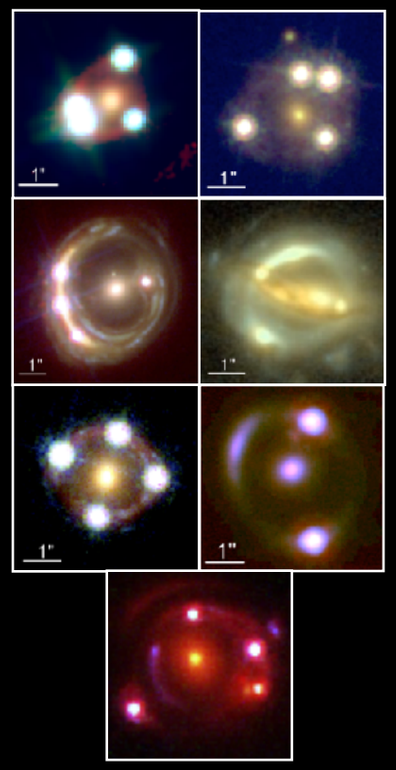



## FUTURE CMB MEASUREMENTS

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

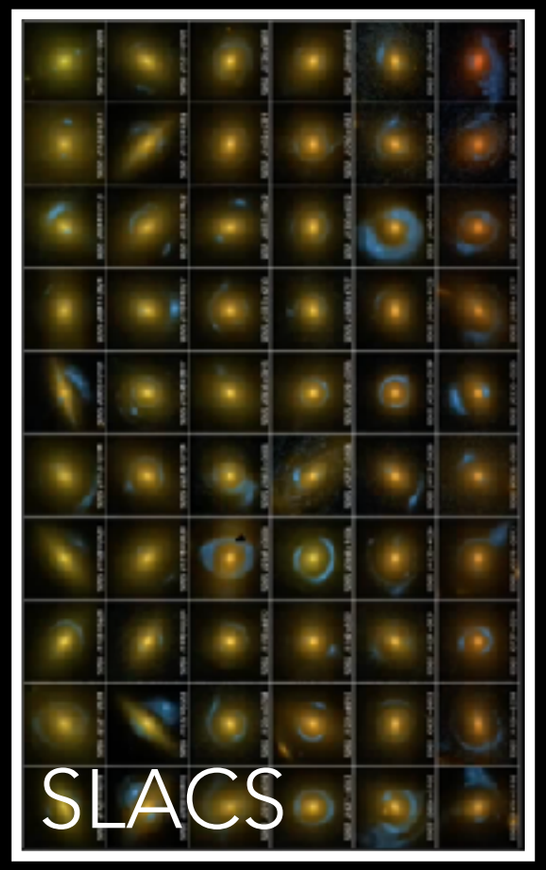
South Pole Telescope (SPT)

## TD COSMO



H0LICOW + STRIDES

Millon et al. (2020)
Birrer et al. (2020)




**Hubble constant:**

**67.4**

**± 4** km/s/Mpc

**Precision forecast:**

Currently **5%**

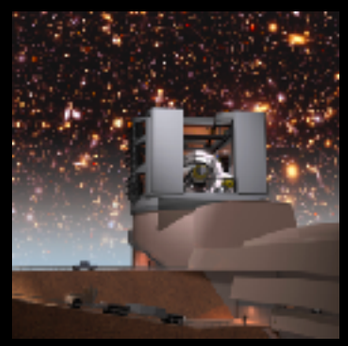
Future **1.5%**

Birrer & Treu (2020)

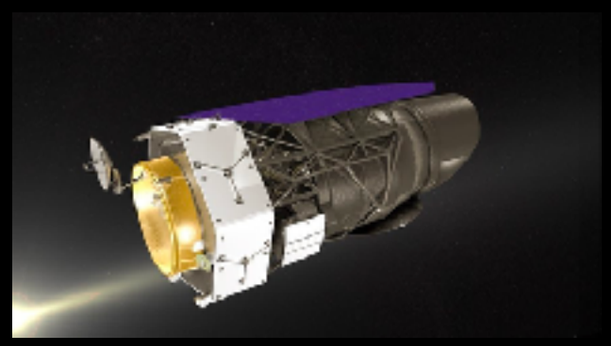
## NEXT-GENERATION MISSIONS

**$10^5$ galaxy-galaxy lenses**

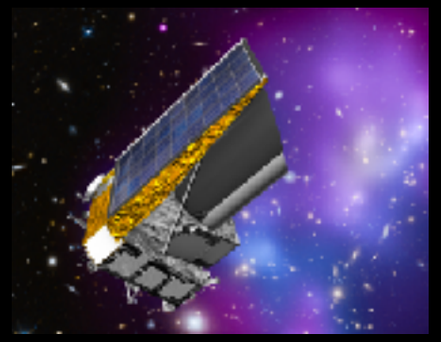
**$10^3$ quasar-galaxy lenses**



Rubin Observatory



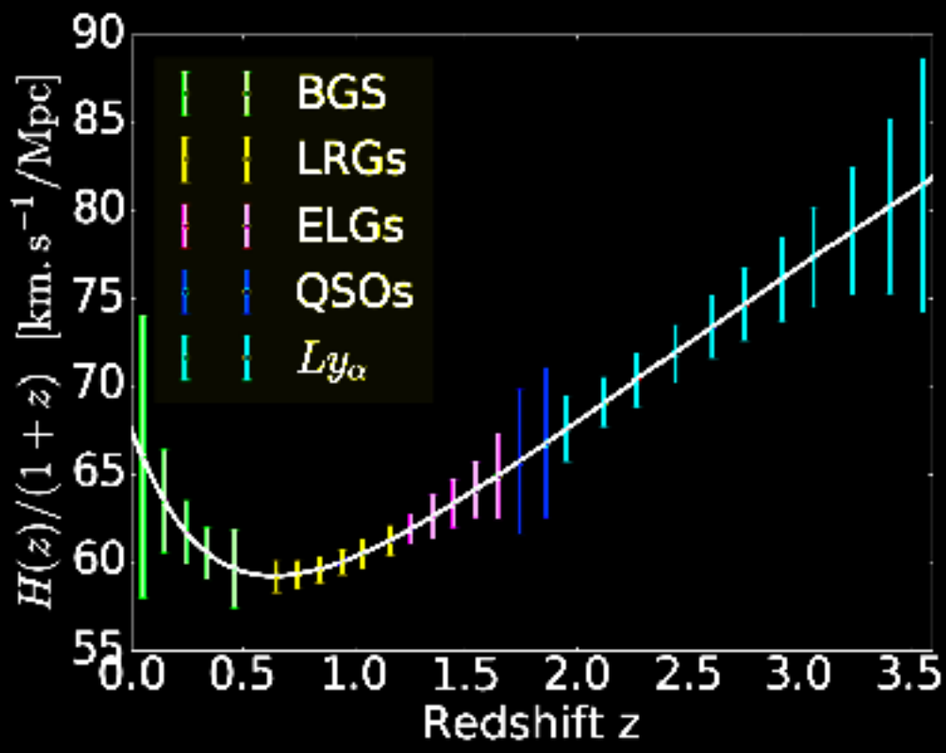
Roman Telescope



EUCLID (2022)

DESI

## DESI

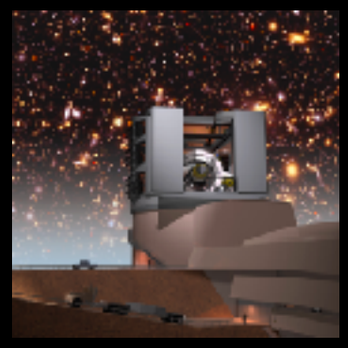



Vargas-Magaña, DESI collaboration, et al. (2019)

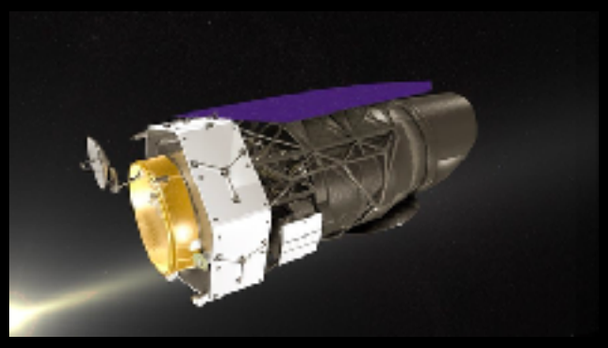
**Order of magnitude improvement on $H_0r_s$**

Pogosian et al. (2020)

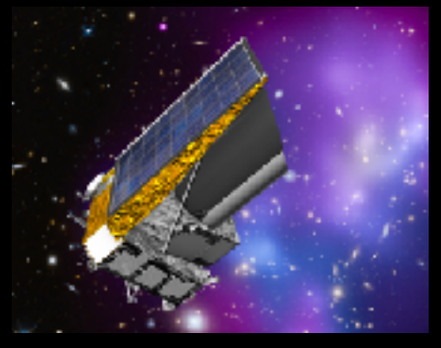
## NEXT-GENERATION MISSIONS



Rubin Observatory



Roman Telescope

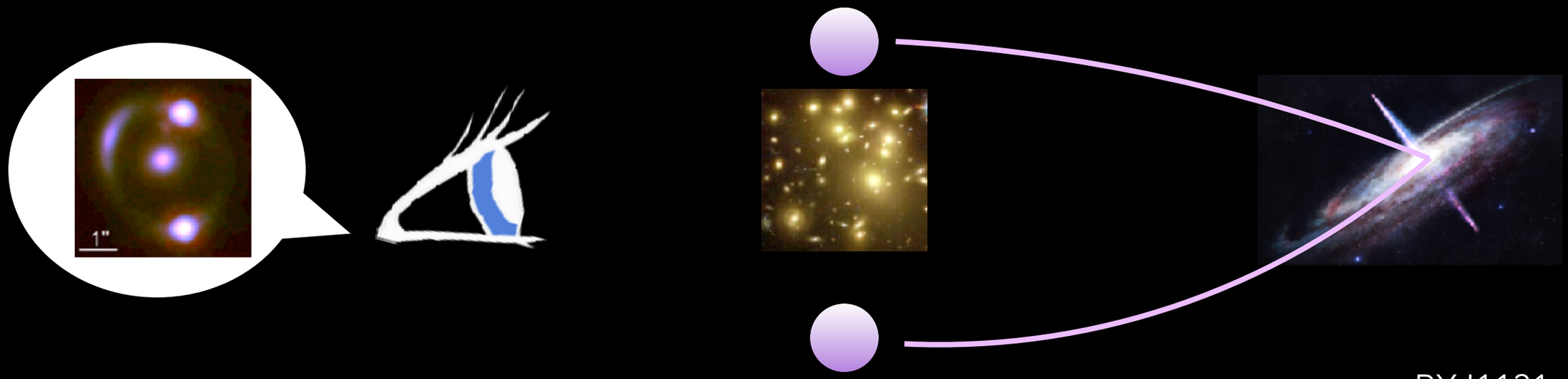


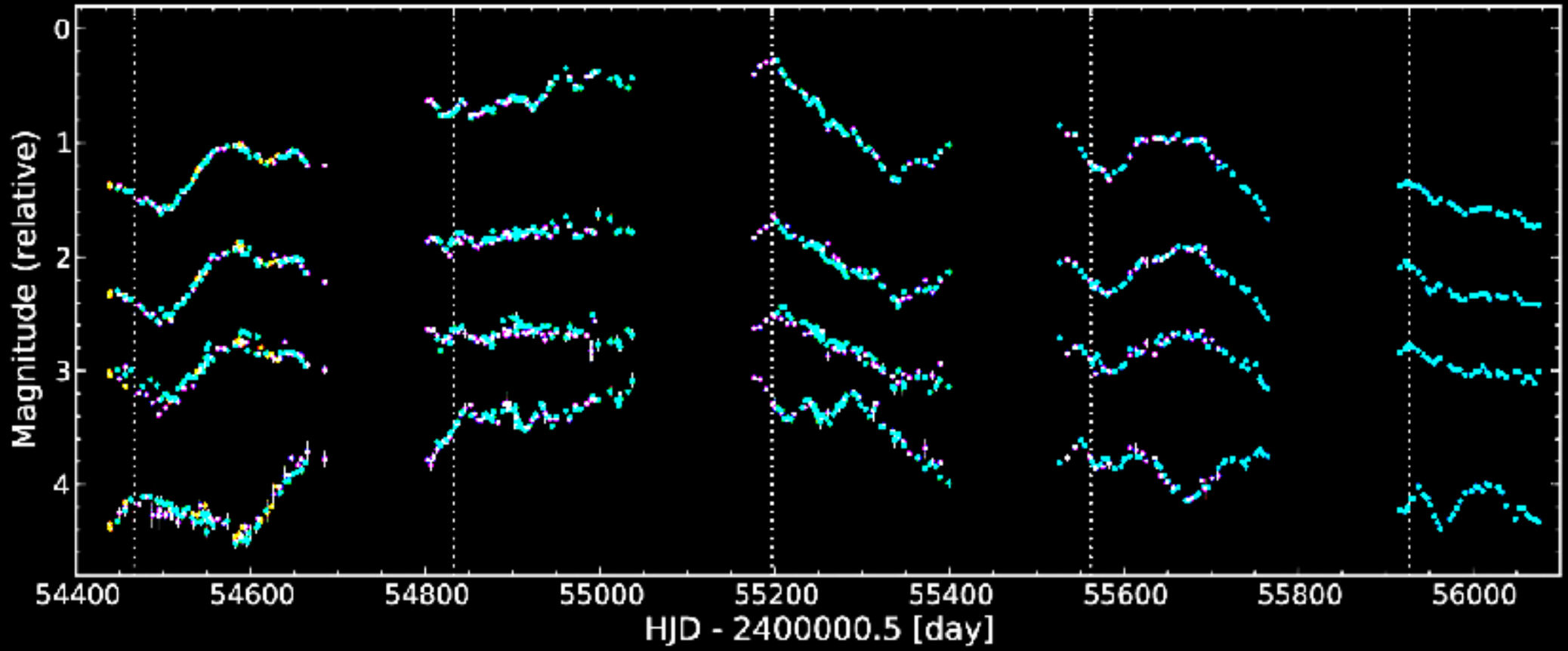
EUCLID (2022)

DESI

# H0LICOW

## H0 Lenses in COSMOGRAIL Wellspring




*Images, data and explanation by H0LiCOW group*

# H0LICOW

## H0 Lenses in COSMOGRAIL Wellspring

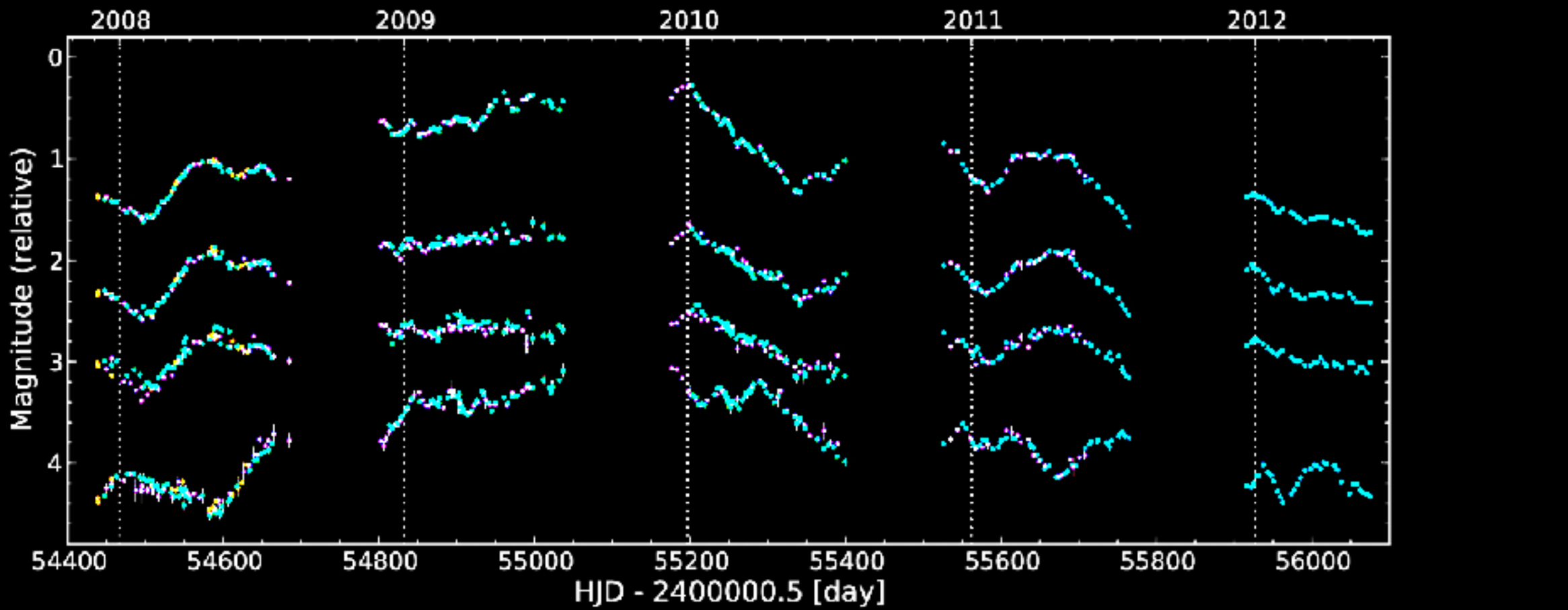
Absolute distances!

Time delay relative to the case of no lensing:

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

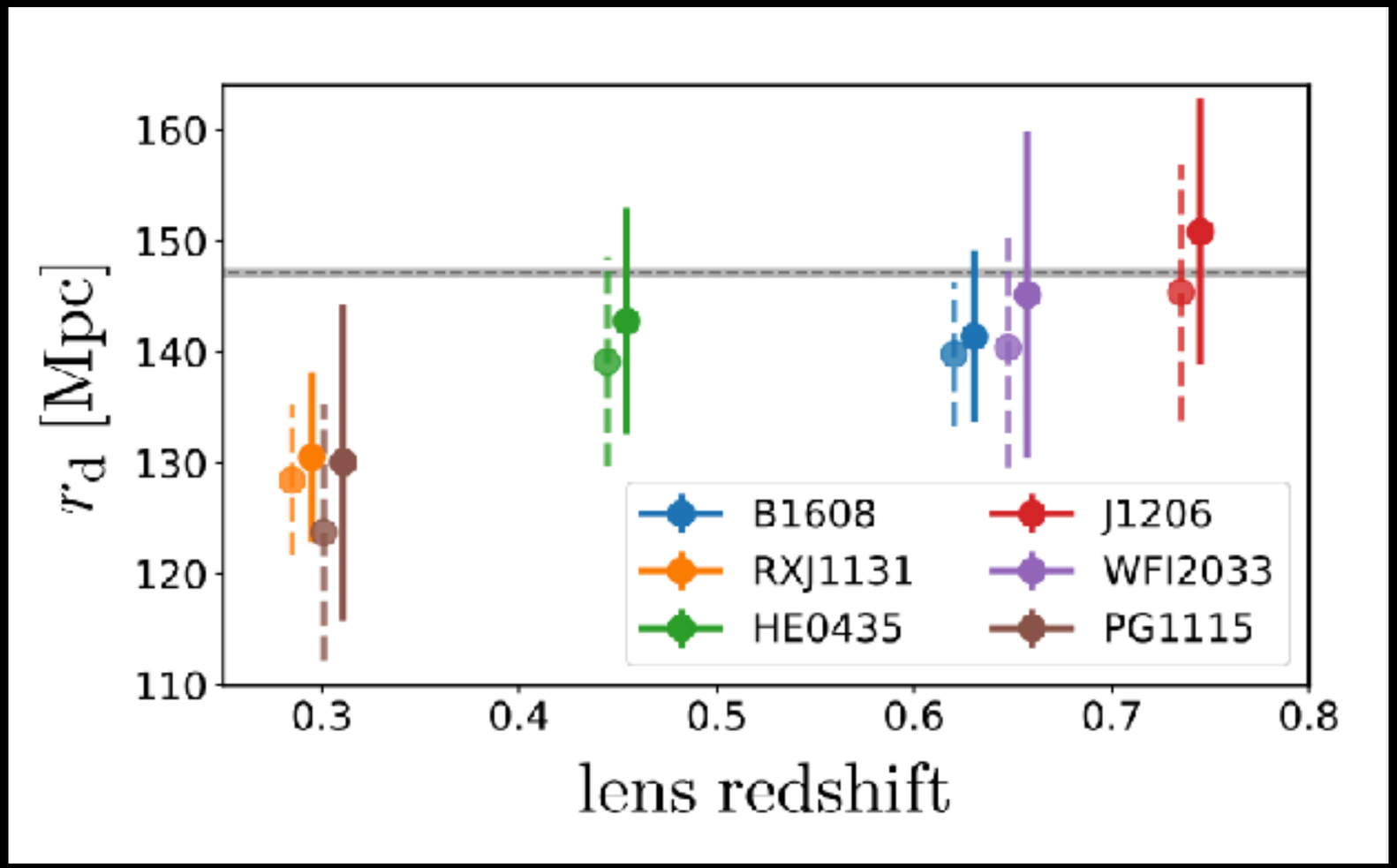
Time delay distance:

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




*Images, data and explanation by H0LiCOW group*

# Redshift trend in the H0LiCOW lens sample

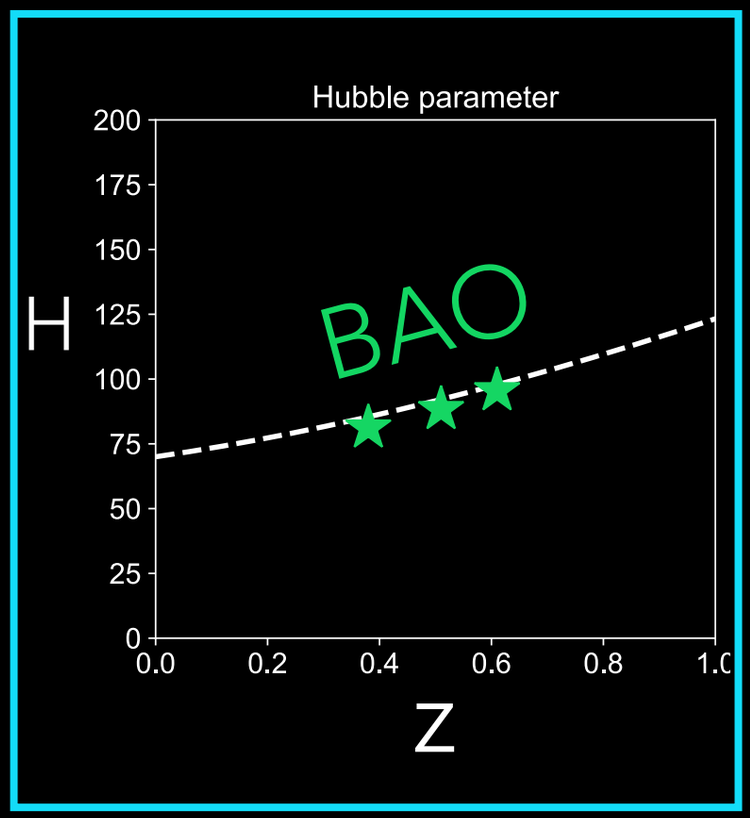


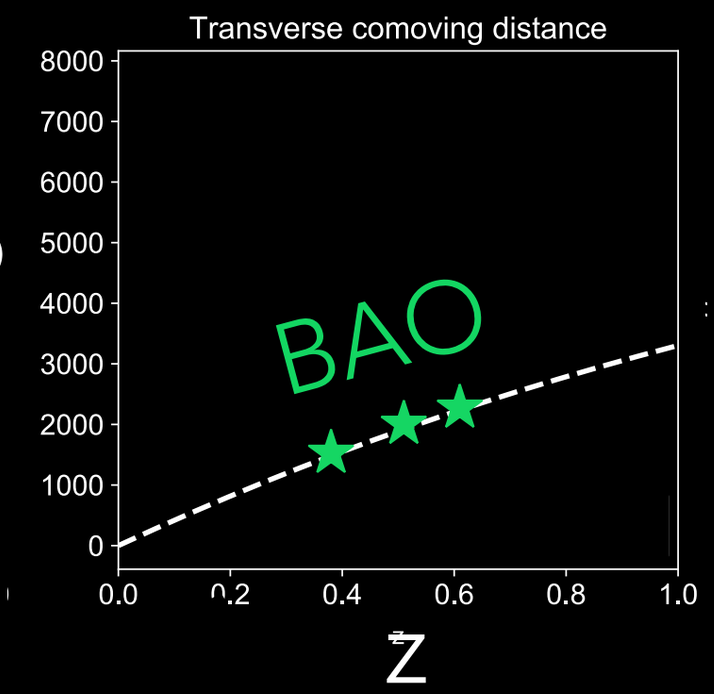
Friedman equations:

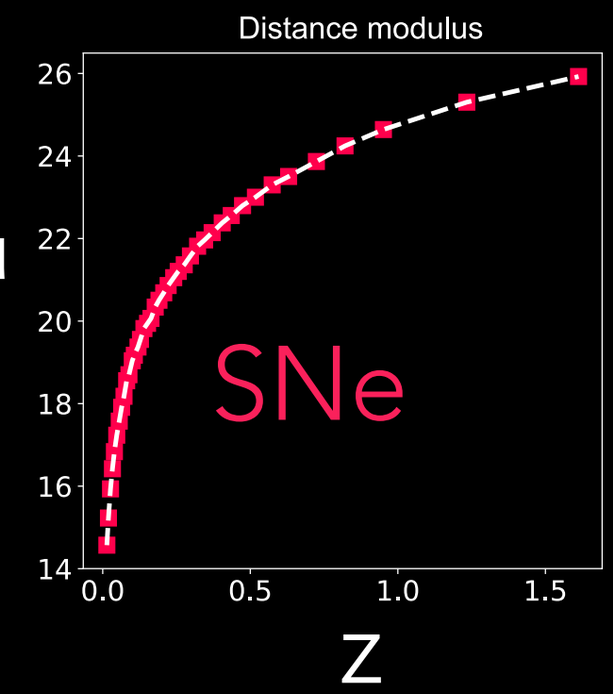
$$H(z) = H_0\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}$$

Taylor expansion:

$$H(z) = H_0 + c_1 z + c_2 z^2 + \mathcal{O}(z^3) \qquad c_1 = \left.\frac{dH}{dz}\right|_0 \qquad c_2 = \frac{1}{2}\left.\frac{d^2H}{dz^2}\right|_0$$



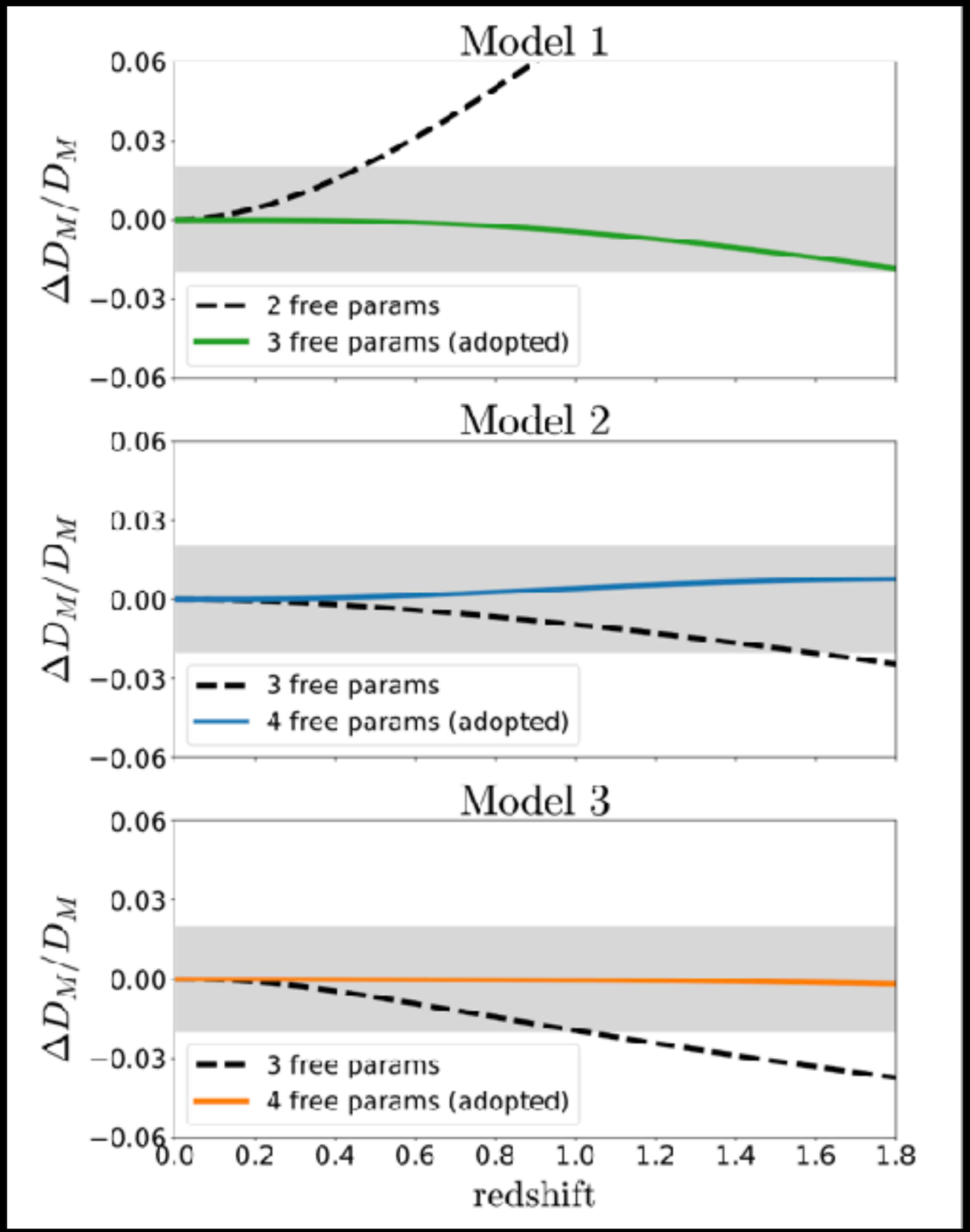

integrate

logarithm

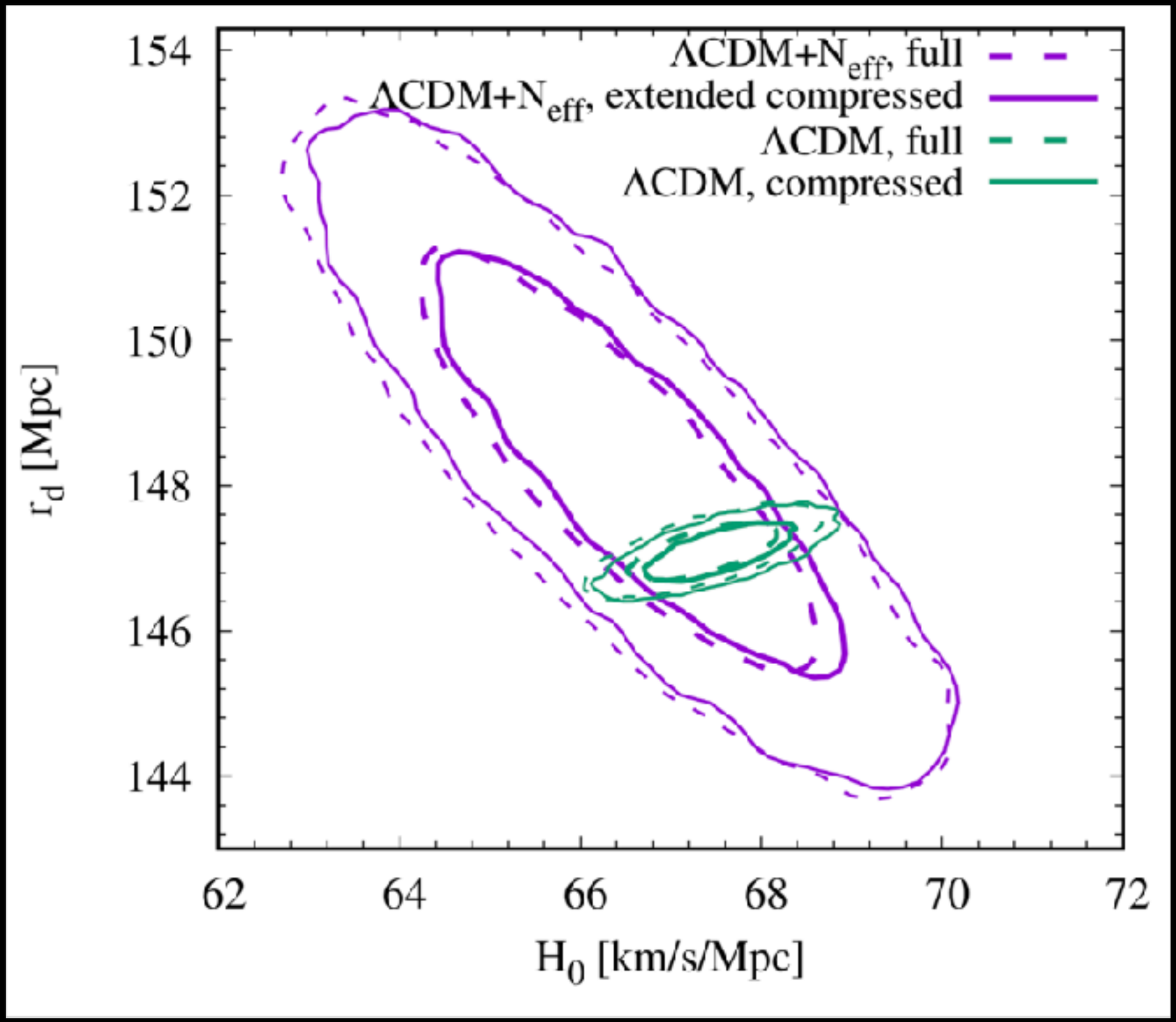
# POLYNOMIAL PARAMETRIZATIONS

| Model | Formula |
|---|---|
| **1** | $H(z) = H_0\left(1 + b_1 z + b_2 z^2\right)$ |
| **2** | $D_L(z) = \frac{c\ln(10)}{H_0}\left(\log(1+z) + c_2[\log(1+z)]^2 + c_3[\log(1+z)]^3 + c_4[\log(1+z)]^4\right)$ |
| **3** | $D_M(z) = \frac{c}{H_0}\left(\frac{z}{1+z} + d_2\left[\frac{z}{1+z}\right]^2 + d_3\left[\frac{z}{1+z}\right]^3 + d_4\left[\frac{z}{1+z}\right]^4\right)$ |
| **4** | $H(z) = H_0\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda + \Omega_k(1+z)^2}$ |

# ...and how they perform in our redshift range

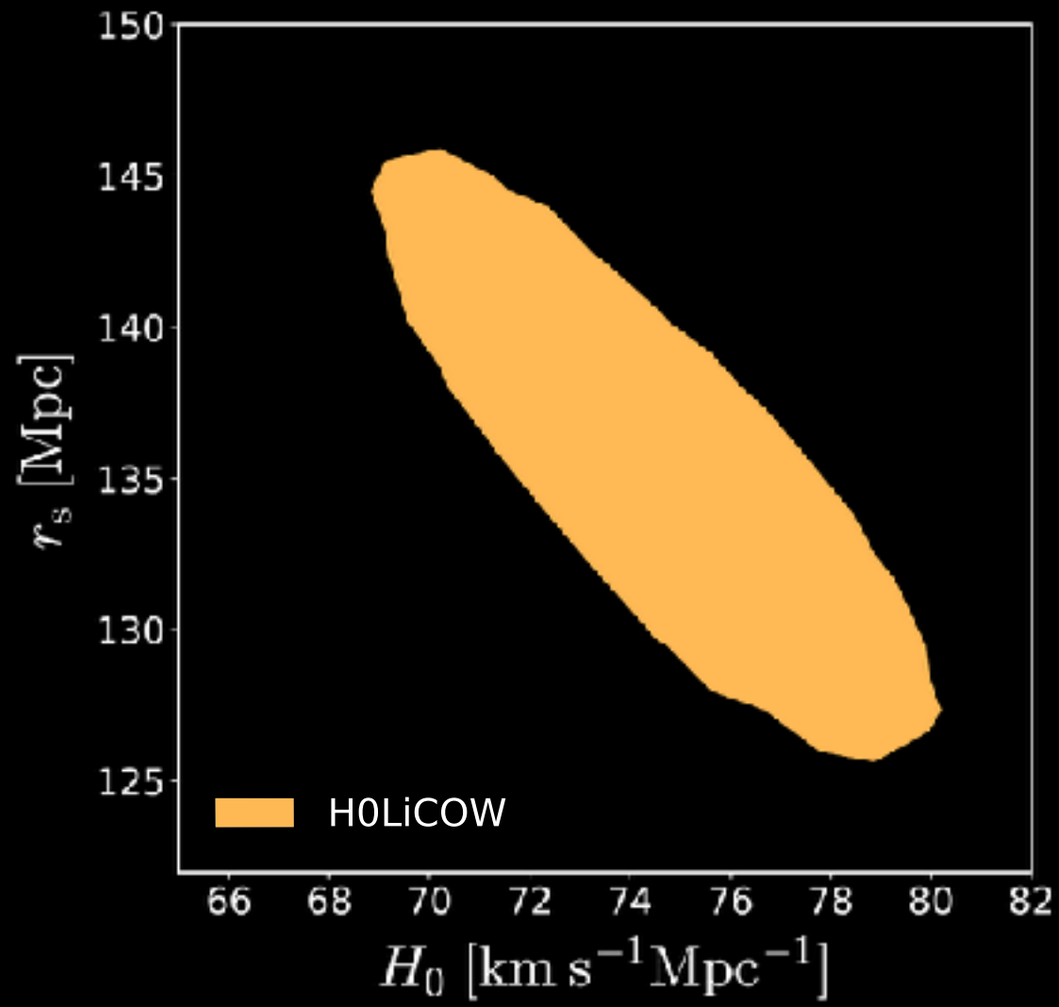


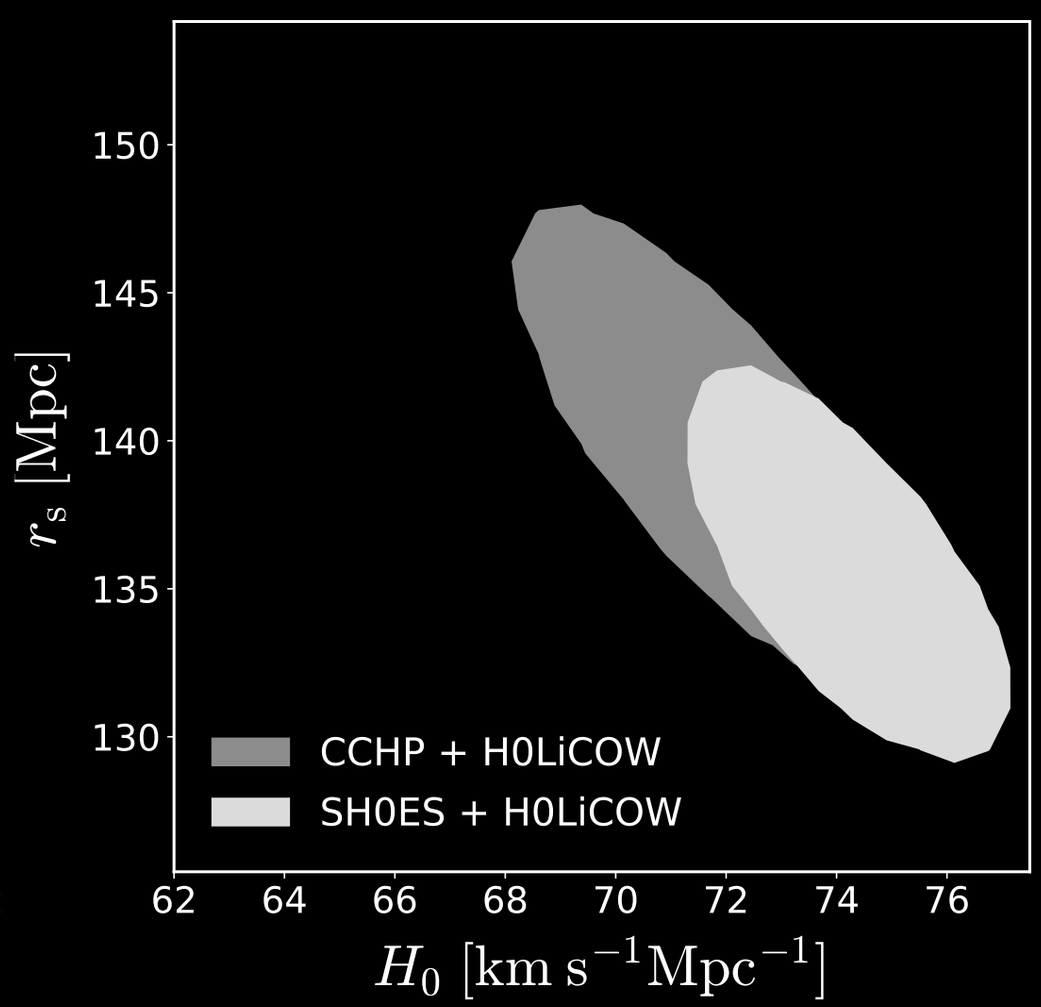
# EXTENDED COMPRESSED PLANCK LIKELIHOOD



# RESULTS

Arendse, Wojtak, Agnello et al. (2020)




**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**

$H_0 = 74.2 \pm 1.2$

$r_s = 135.7 \pm 2.7$

## How to obtain H(z) from $D_M$

From *"General Cosmography Model with Spatial Curvature"*
By En-Kun Li, Minghui Du, and Lixin Xu.

$$H(z,\Omega_K) = \frac{c}{\partial D_M(z)/\partial z}\sqrt{1+\frac{H_0^2\Omega_K}{c^2}D_M(z)^2},$$