A Mini-Review on the Hubble Tension

PHENO22, Pittsburgh

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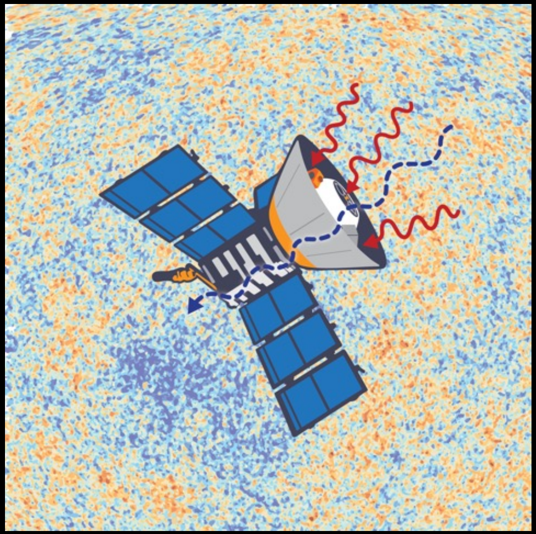
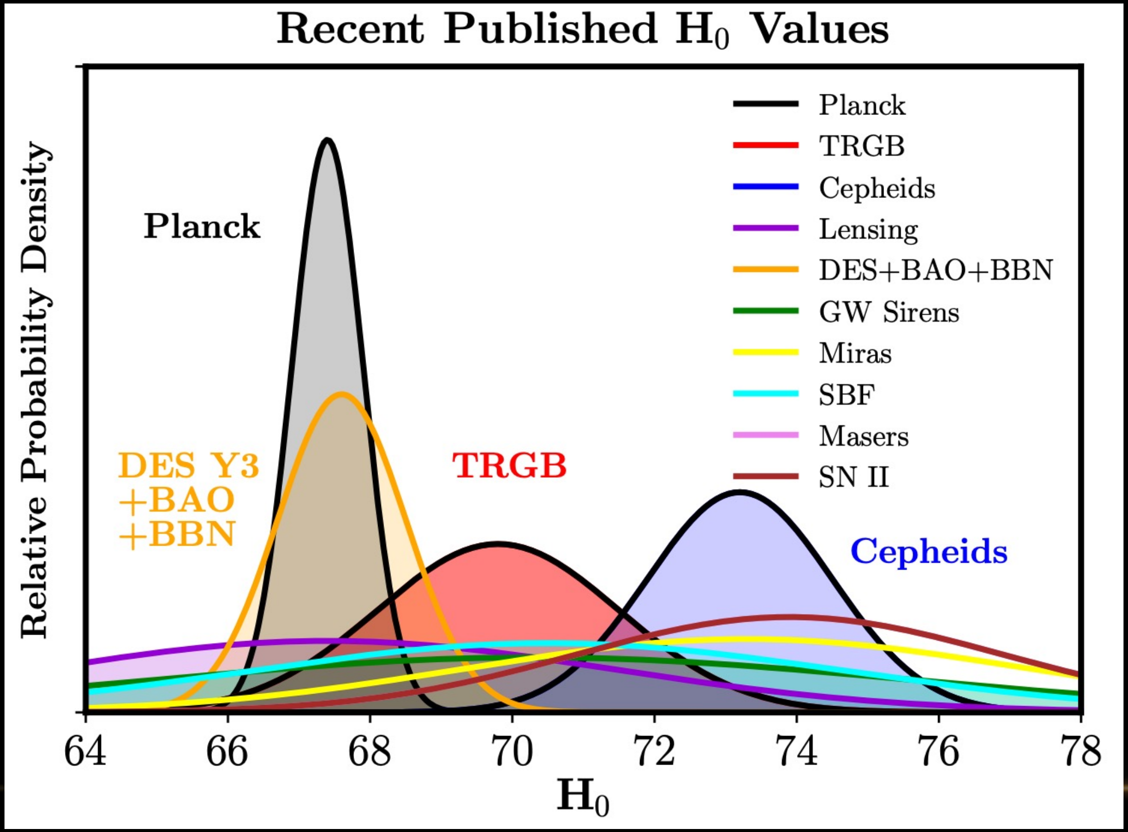


With Fei Ge (UC Davis),
Lloyd Knox (UC Davis),
and Kylar Greene (UNM)

What is the Hubble tension?

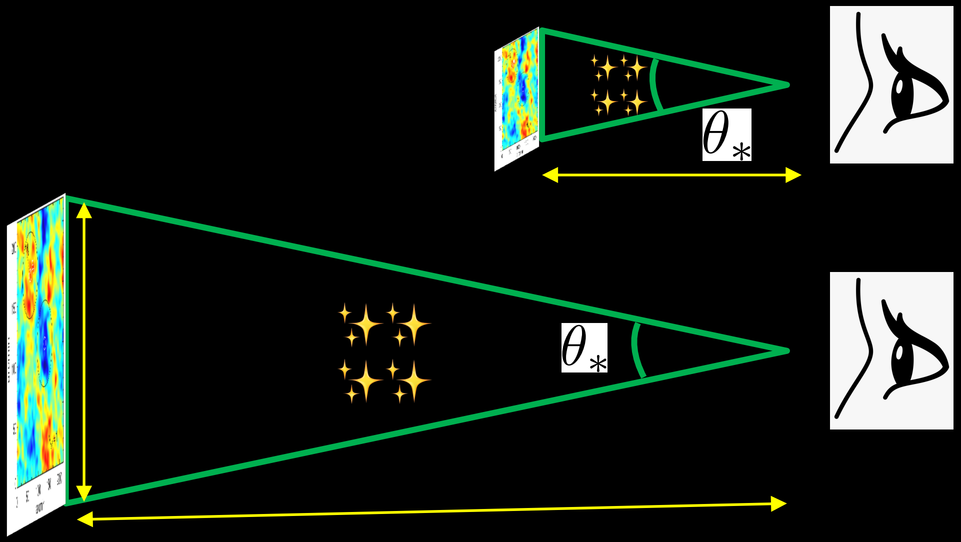
- A simplistic view: A discrepancy between different inferences of the Hubble constant H_0.



Freedman (2021)

What is the Hubble tension?

- In reality, the tension is about **distance measurements**.



- Essentially, different data sets do not agree on how far from us certain objects in the Universe actually are.

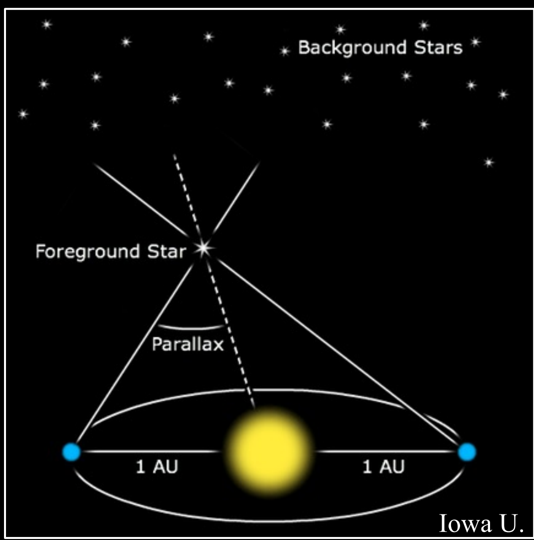
Cause of the Hubble tension

- The discrepancy either arises because
  1. Our distance measurements are incorrect.
  2. The cosmological model we use to fit all those distances is incorrect.
- Assuming that the measurements are correct (?), finding a solution thus requires writing down a cosmological model that can fit all known cosmological distances.
- Simply finding a cosmological model that has H_0~73 km/s/Mpc is **not sufficient**.

How do we measure distances locally?

- We first need an absolute anchor (i.e. a known dimensionful quantity) to set the scale of the problem.

Parallax

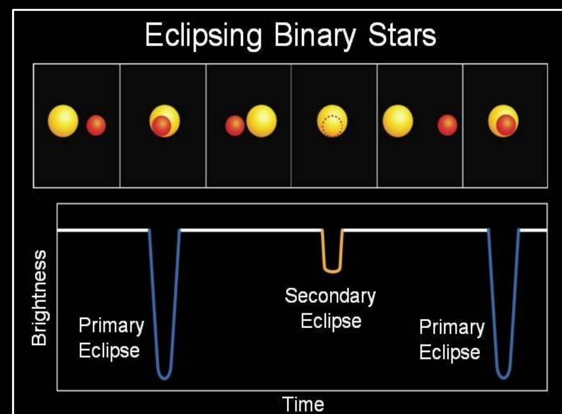


Iowa U.

Absolute scale: Sun-Earth distance

See e.g. van Leeuwen et al. (2017), Luri et al. (2018), Torra et al. (2019).

Detached eclipsing binaries

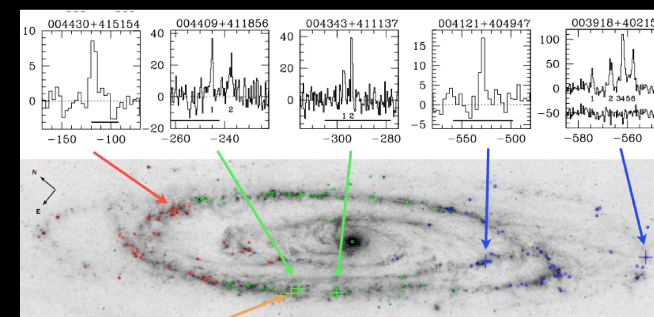


Wikimedia

Absolute scale: Period of the binary

See e.g. Paczynski (1996), Bonanos et al. (2006), Graczyk (2003)

Masers



NRAO

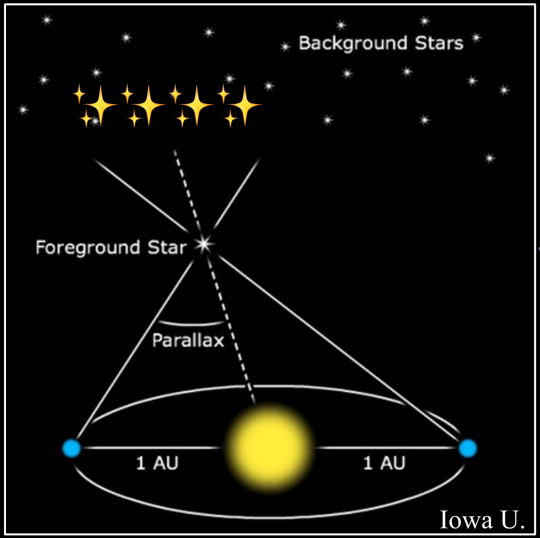
Absolute scale: Acceleration of the masers

See e.g. Reid, Pesce & Riess (2019)

How do we measure distances locally?

- Use these local anchors to calibrate the absolute luminosity of standard candles.

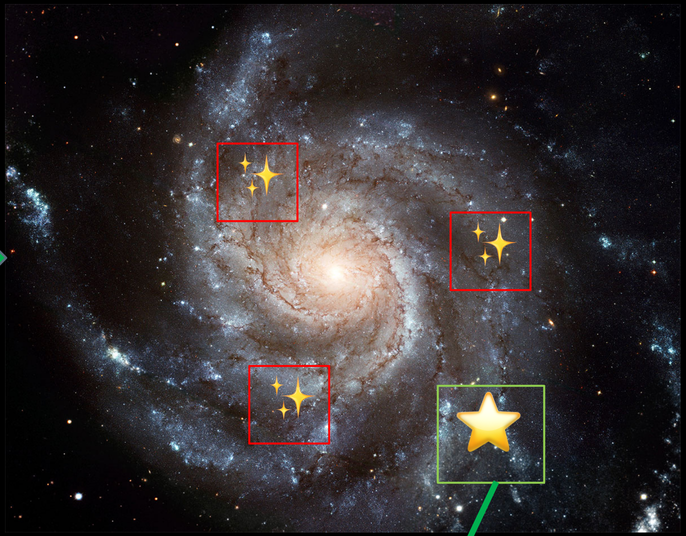
Local absolute anchor



$$L \propto 4\pi d^2 F$$

Compare these to measure distance to galaxies

Calibrator galaxies



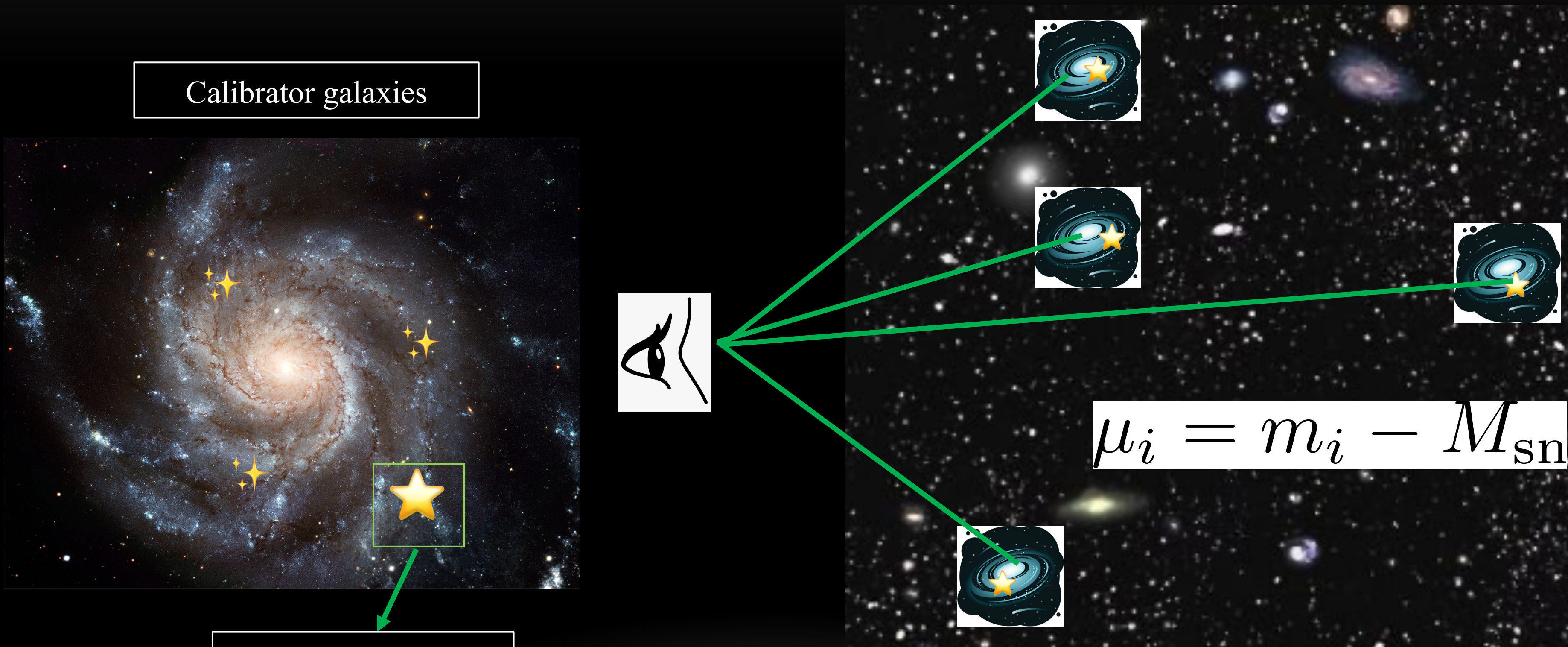
Type Ia Supernova

This determines the absolute SNe Ia magnitude, M_{SN}.

How do we measure distances locally?

- With the absolute supernova magnitude known, measure distances to SNe Ia in the Hubble flow.

Calibrator galaxies



Determine M_{sn}

$$\mu_i = m_i - M_{\rm sn}$$

$$\mu = 5\log\left(d_{\rm L}/{\rm Mpc}\right) + 25$$

See e.g. Freedman at al. (2001), Riess et al. (2011), Riess et al. (2016), Freedman et al. (2019). Riess et al. (2019), Riess et al. (2021), Freedman (2021)

Turning distances to a Hubble constant

- The luminosity distance can be computed within any cosmological model:

$$d_{\rm L} = (1+z)\frac{c}{H_0}\int_0^z \frac{dz'}{E(z')}$$

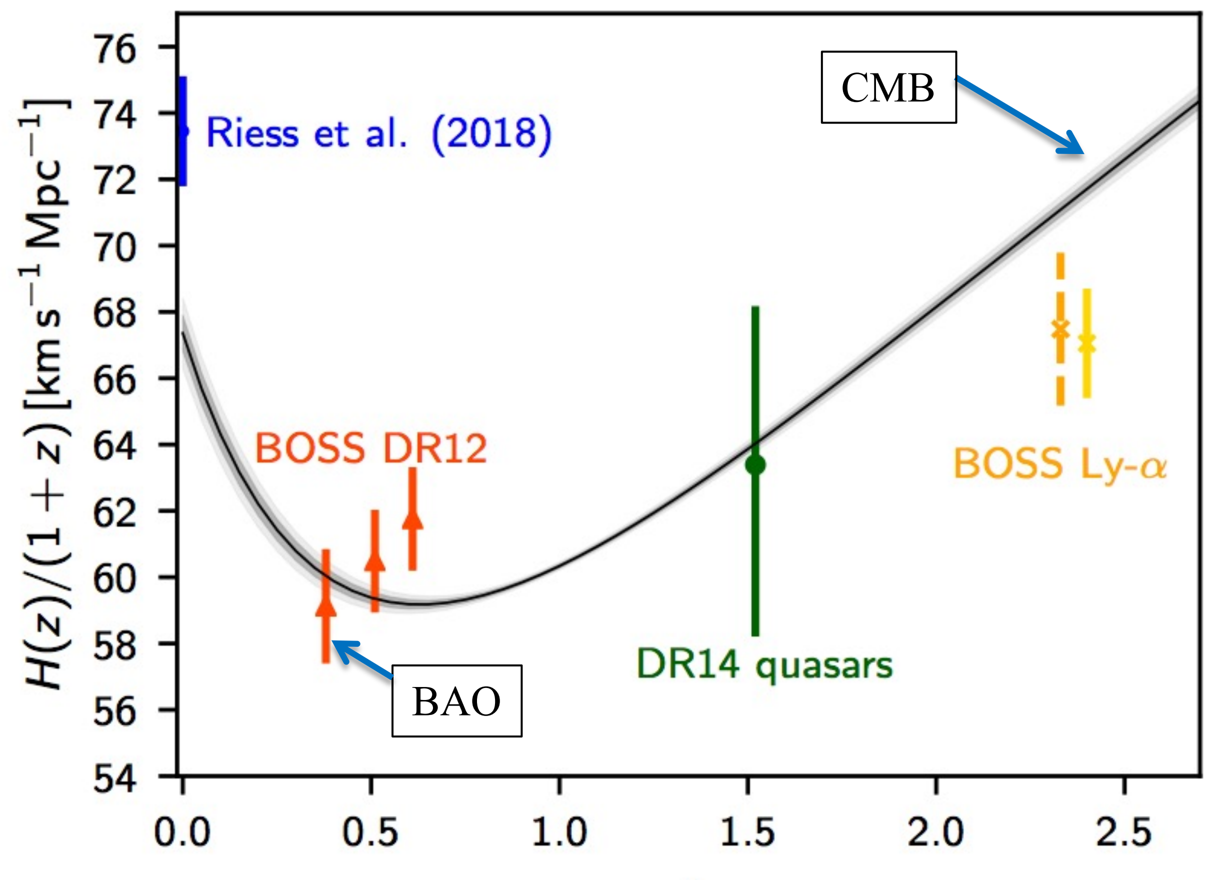
$$E(z) = H(z)/H_0$$

- However, a cosmographic expansion of the luminosity distance is often used to extract H_0 from data.

$$d_{\rm L} \approx \frac{cz}{H_0} + \mathcal{O}(z^2), \qquad z \ll 1$$

This assumes a smooth variation of the luminosity distance with redshift.

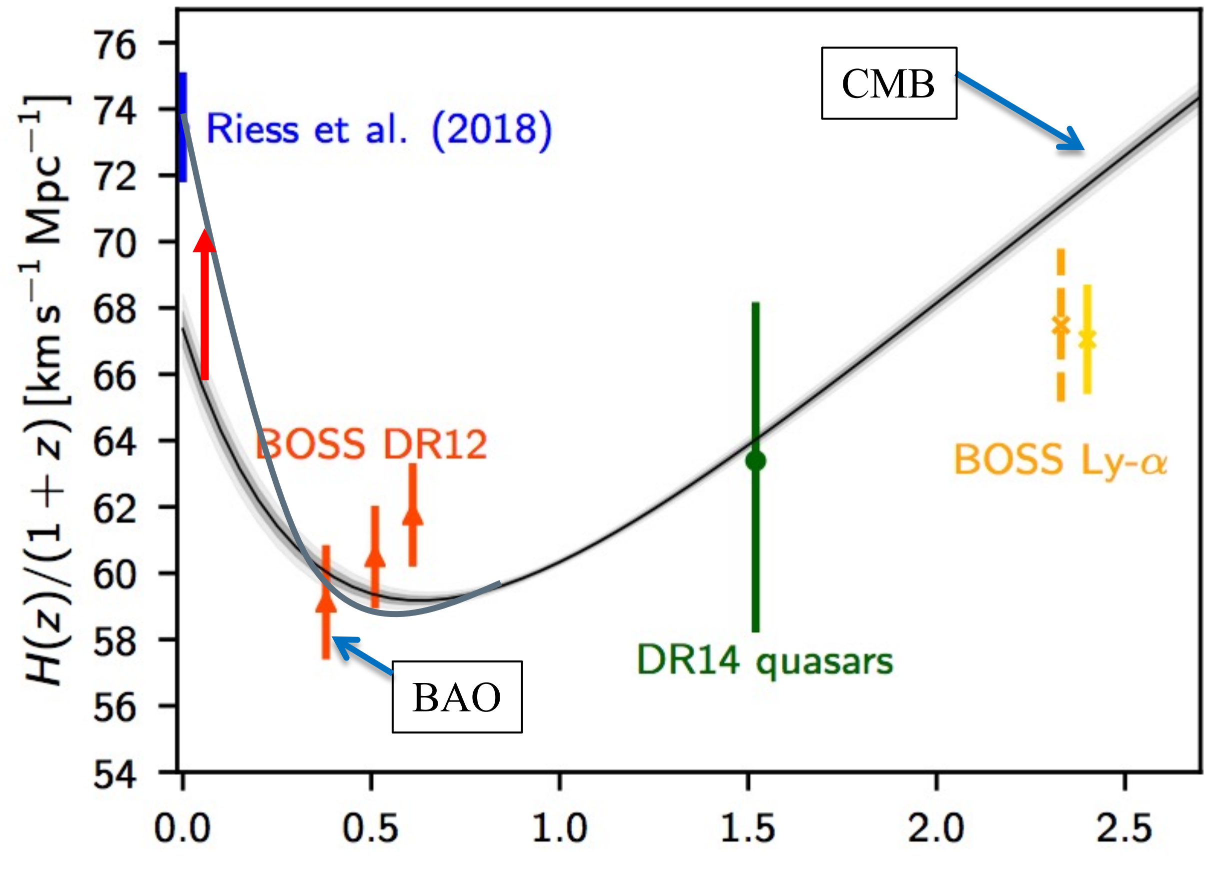
Beware of models simply trying to get a given H_0 value



Planck collaboration (2018)

See e.g. Di Valentino et al. (2021)

Beware of models simply trying to it a given H_0 value

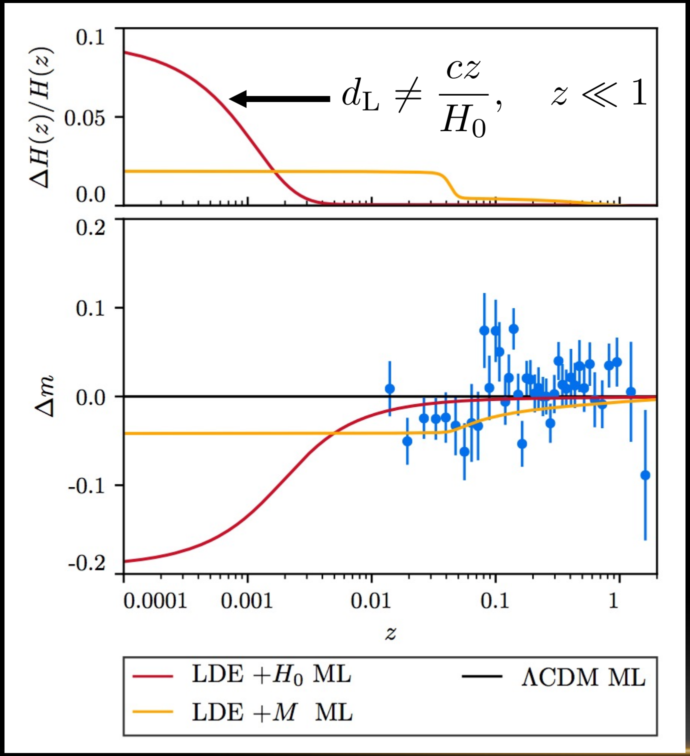


Planck collaboration (2018)

See e.g. Di Valentino et al. (2021)

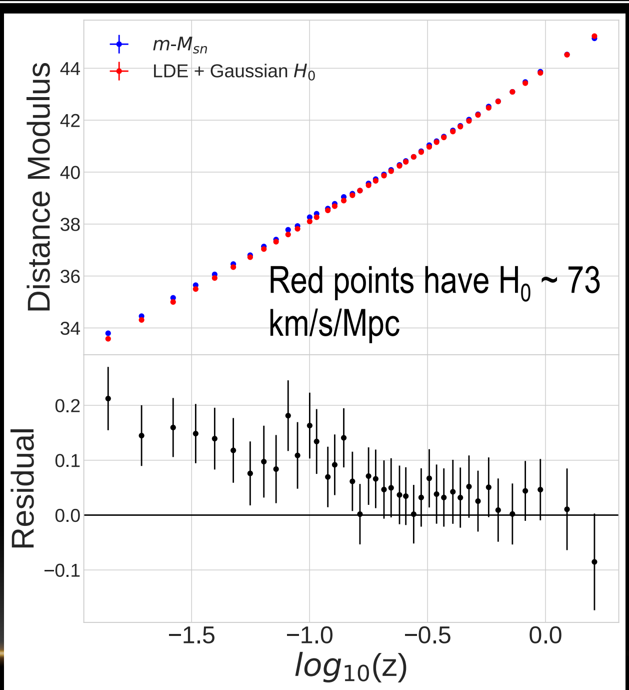
Break down of the cosmographic expansion near z~0

- Dramatically increasing the Hubble rate at very late times breaks down the standard assumptions of the distance ladder analyses.



Benevento et al. (2020)

This results in a poor fit to the actual distances



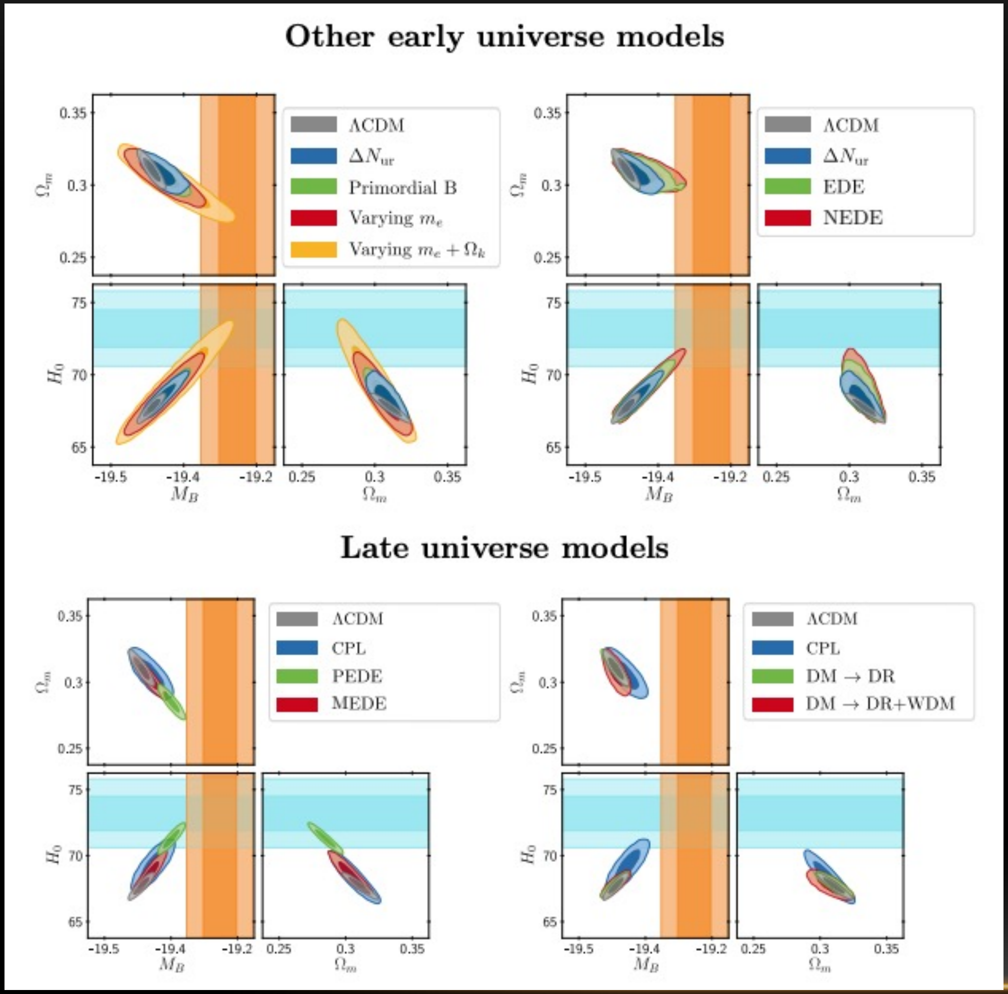
Greene and Cyr-Racine, arXiv:2112.11567, JCAP

Important Lesson

If you are working on a late-time solution, please make sure that your model fit the actual distances to Type Ia supernovae.

Aside: Observational collaboration should release their distance measurements, rather that model-dependent values of H_0.

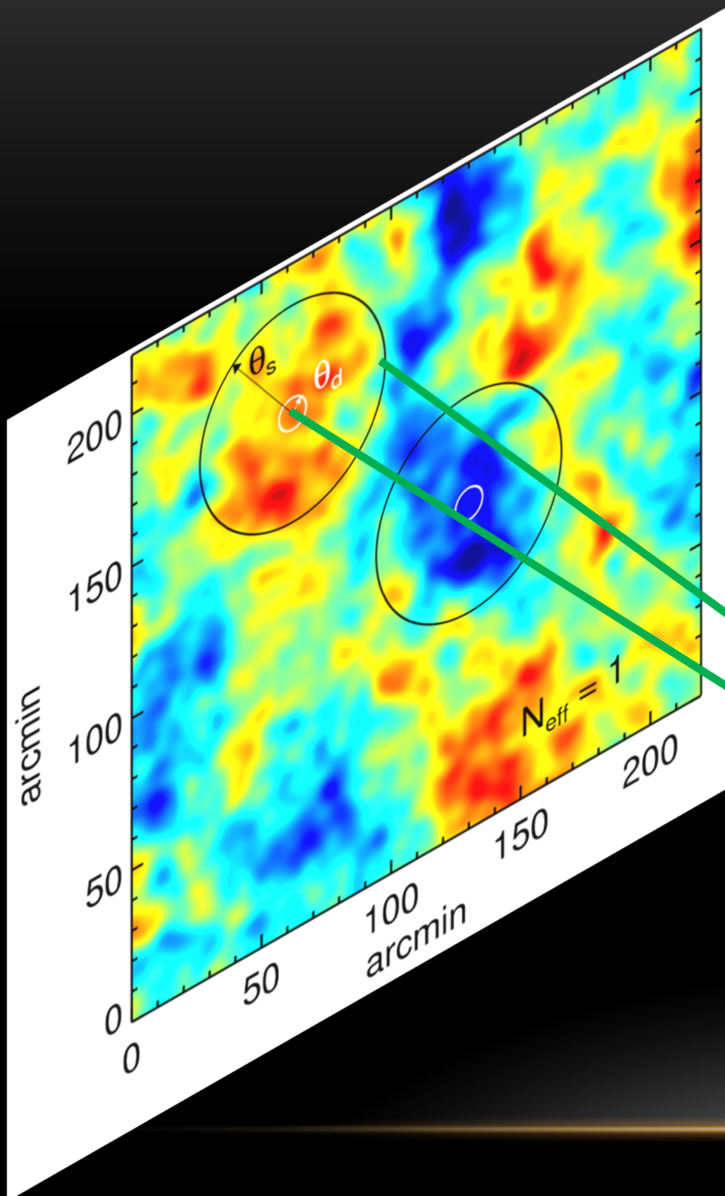
Rest of talk: Why is it so hard to get a large Hubble constant from the CMB + BAO?



Schöneberg et al., arXi:2107.10291

- Lots of ideas out here! Why are they struggling to get a large value of the Hubble rate?

Measuring distances with the CMB

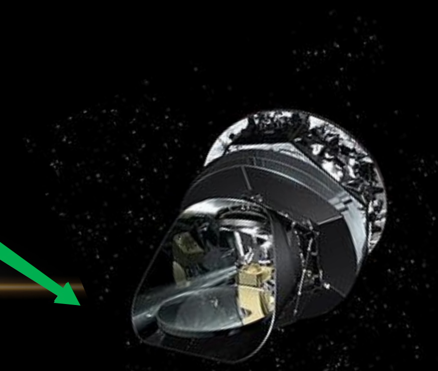


The CMB primarily measures angles on the sky. The whole CMB sky is at the same redshift.

θ_*

The most precise known number in cosmology!

z_*

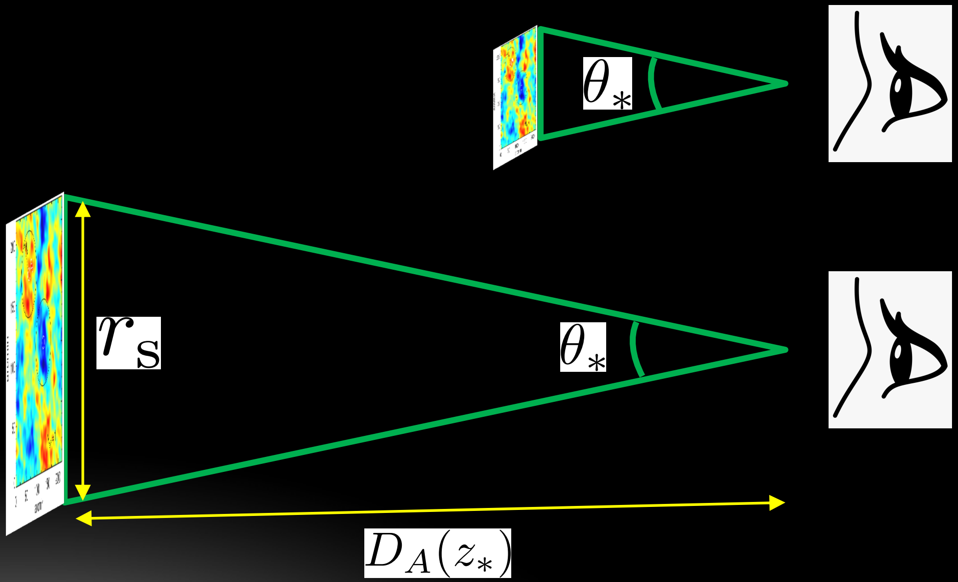


Insensitivity of redshifts/angles to actual distances

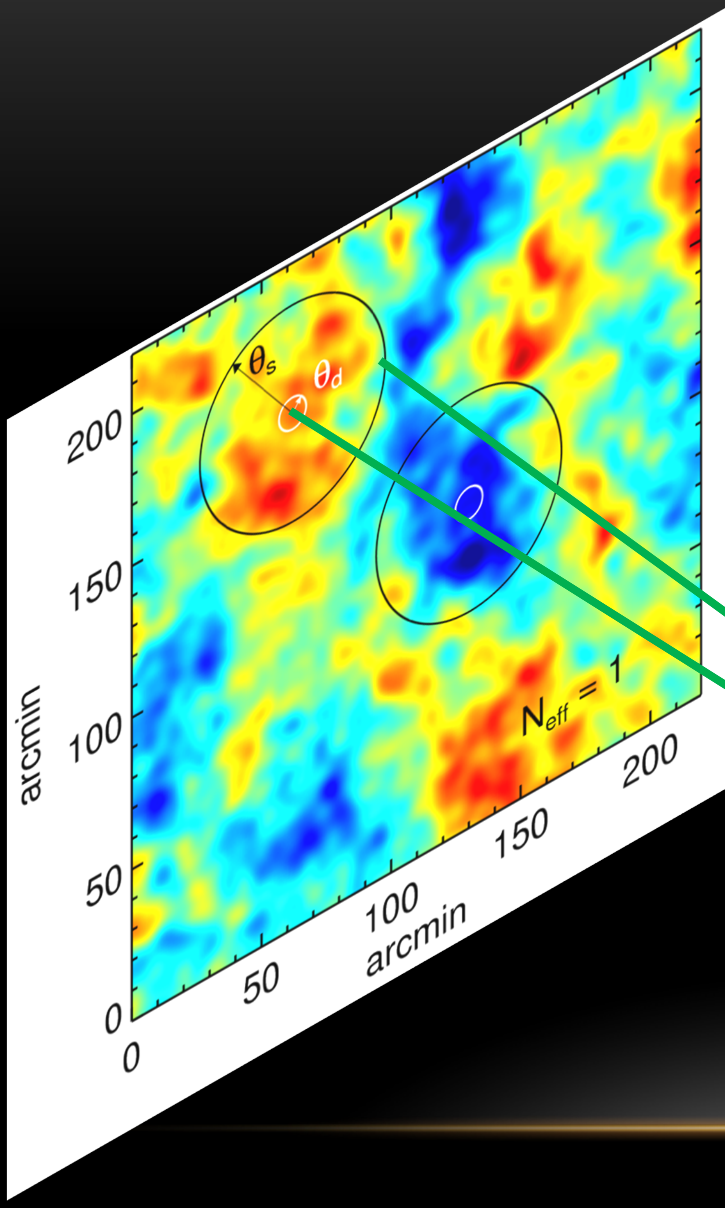
- Fundamentally, we cannot infer the value of the Hubble constant from only measurements of angles and redshifts.
- In general, we cannot measure a dimensionfull quantity from purely dimensionless observables.

Fundamental geometric degeneracy: An observer cannot determine the absolute scale of the problem from just measuring angles.

$$\theta_* = \frac{r_{\rm s}}{D_A(z_*)}$$



Invariance of angles under uniform rescaling of the Hubble rate

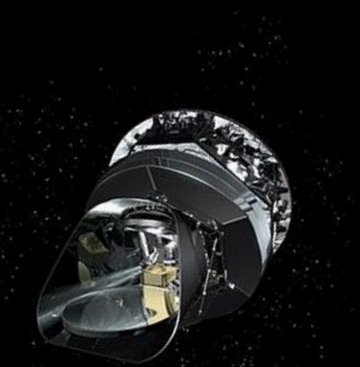


- All angles on the CMB sky are invariant under this scaling (for constant f):

$$H \rightarrow fH$$

$$\theta_* = \frac{r_s}{D_A(z_*)}$$ where

$$r_s = \int_{z_*}^{\infty} dz \frac{c_s(z)}{H(z)} \qquad D_A(z_*) = \int_0^{z_*} dz \frac{1}{H(z)}$$

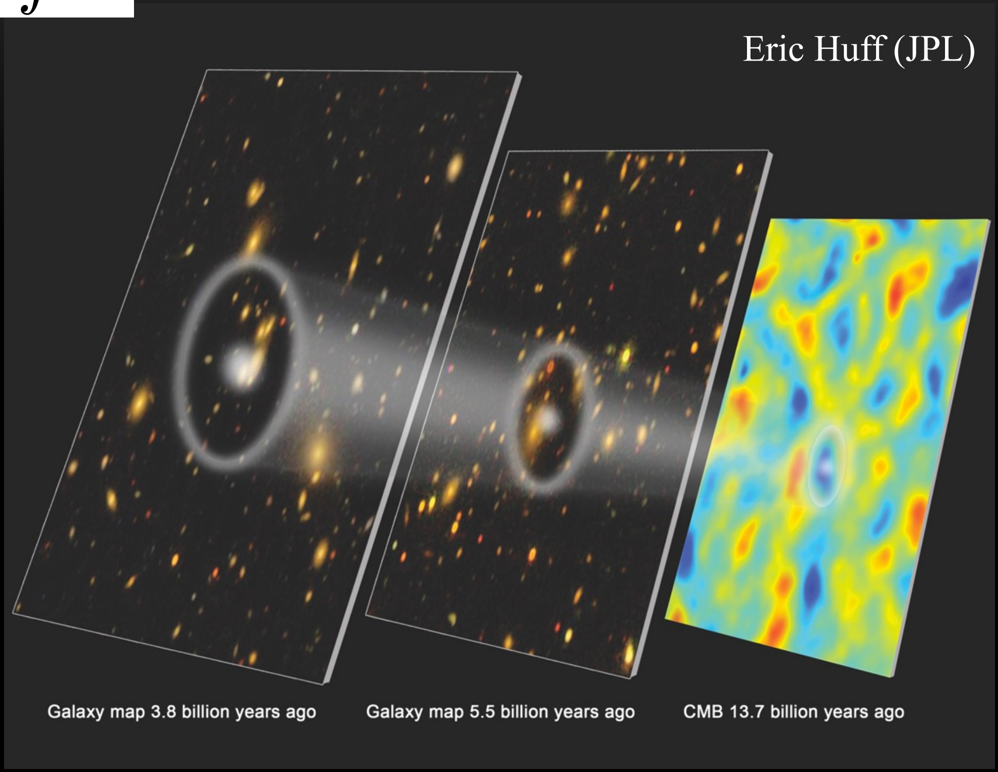


Baryons Acoustic Oscillations are also invariant under $H \to fH$

BAO primarily measures 2 dimensionless combinations

Line of sight: $H(z)r_{\rm s}$

Transverse: $r_{\rm s}/D_A(z)$



Clearly, a uniform rescaling of the Hubble rate leaves all cosmological **angles** invariant

CMB/BAO measurements of H_0

- Since we **are** inferring a value of the Hubble rate from CMB and BAO data, something is breaking this scale invariance.
- What is the absolute calibrator scale here?

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The CMB temperature today!

$$T_0 = 2.7255\,\mathrm{K}$$

COBE

Fixsen et al. (2009)

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COBE

- The Hubble constant from the CMB is

$$H_0 \sim 3.1 \times 10^4 \theta_\star \frac{T_0^2}{M_{\rm pl}}.$$

Fixsen et al. (2009)
Ivanov et al. (2020)
Greene & Cyr-Racine (2022)

Beyond geometric invariance: Other scales

- Other length scales enter the evolution of the early Universe: wavenumber *k* and the baryon-photon scattering rate.
- For example, let's look at the Euler equation for photons:

(Use scale factor "a" as time variable.)

Photon heat flux

Photon quadrupole

$$a^2 H \frac{\partial F_{\gamma 1}}{\partial a} = \frac{k}{3}(F_{\gamma 0} - 2F_{\gamma 2}) + \frac{4k}{3}\psi + \dot{\kappa}\left(\frac{4}{3}v_{\mathrm{b}} - F_{\gamma 1}\right),$$

Photon temperature monopole perturbation

Gravitational driving term

Photon-baryon scattering rate

Two important ratios of scales

$$k/H,\ \dot{\kappa}/H$$

Most "early" solution to the Hubble tension change this ratio in some ways.

- But what if I want to leave these ratios invariant? Scale everything!

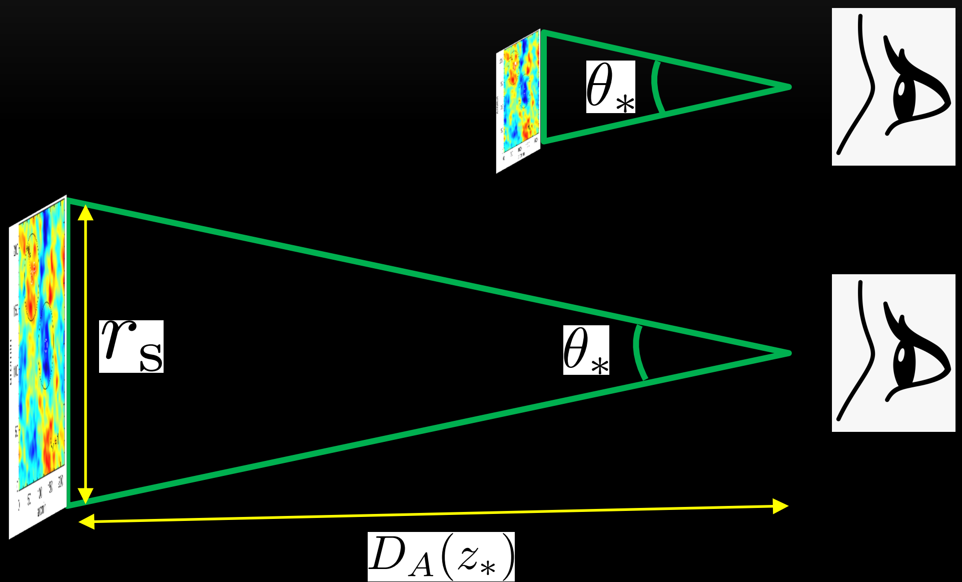
$$H \to fH,\ k \to fk,\ \dot{\kappa} \to f\dot{\kappa}.$$

- By dimensional analysis, all factors of f cancel out in the equations of motion (EOM).

This leaves the photon-baryon (and dark matter and massless neutrinos) EOM invariant.

Hint of a symmetry: Basic geometry and the dimensional analysis

- Dimensionless observables seen in projection on the sky have an intrinsic scale invariance.
- By dimensional analysis, ODEs for the evolution of dimensionless quantities can only depend on dimensionless ratios.



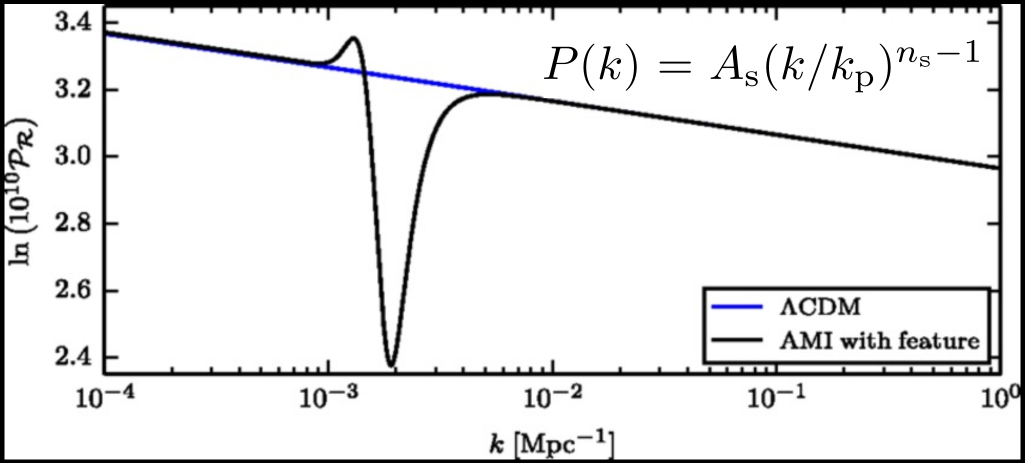
Photon-baryon scattering rate

$$k/H,\ \dot{\kappa}/H$$

Nothing special about cosmology here!

Special feature of our Universe: Initial conditions

- We happen to live in a Universe in which the initial scalar fluctuations have no intrinsic scale.



Cai et al. (2015)

- Thus, a rescaling of wavenumbers can be corrected with a trivial rescaling of the power-law amplitude:

$$k \to fk \quad \Rightarrow \quad A_s \to A_s/f^{n_s-1}$$

Zahn and Zaldarriaga (2003)

Towards an exact solution: The scaling "recipe"

1. Increase Hubble rate at all times by scaling up every energy density:

$$G\rho_i \to f^2 G\rho_i \quad \Rightarrow \quad H \to fH$$

2. Scale up the photon scattering rate $\dot{\kappa} = a n_e \sigma_{\rm T}$ according to:

$$\sigma_{\rm T} n_e(a) \to f \sigma_{\rm T} n_e(a)$$

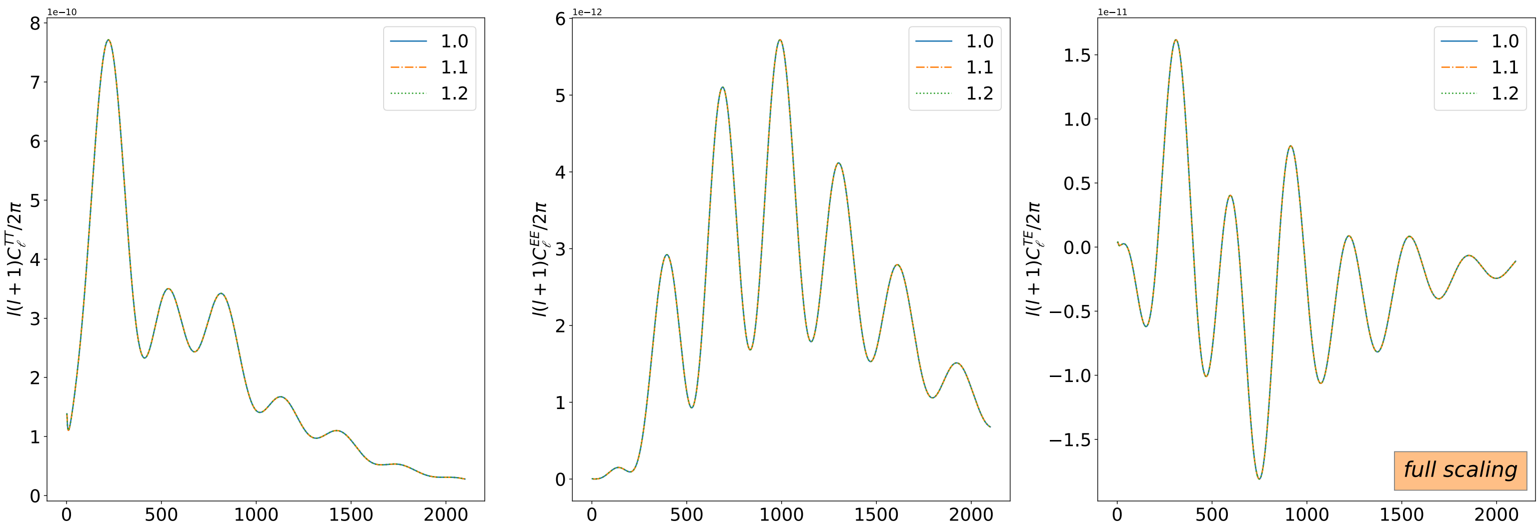
3. Adjust the initial amplitude of scalar fluctuations according to

$$A_{\rm s} \to A_{\rm s}/f^{n_{\rm s}-1}$$

Cyr-Racine, Ge, Knox, arXiv: 2107:13000, PRL accepted.

This works

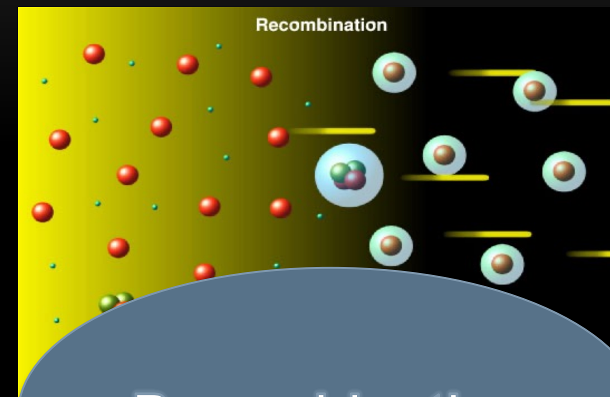
- This really leaves the CMB temp/pol invariant (fixing recombination history here)



$$H_0 = 67.5, 74.3, 81 \mathrm{km/s/Mpc}$$

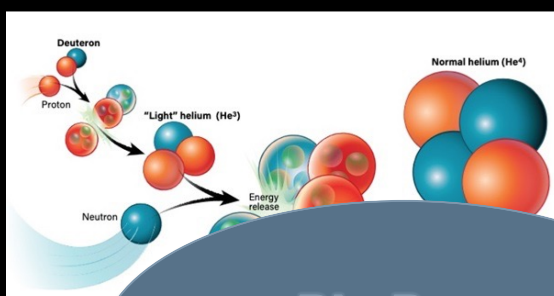
Reality check: 3 main symmetry breaking effects

COBE-FIRAS



Symmetry Breaking

Recombination



Big-Bang Nucleosynthesis

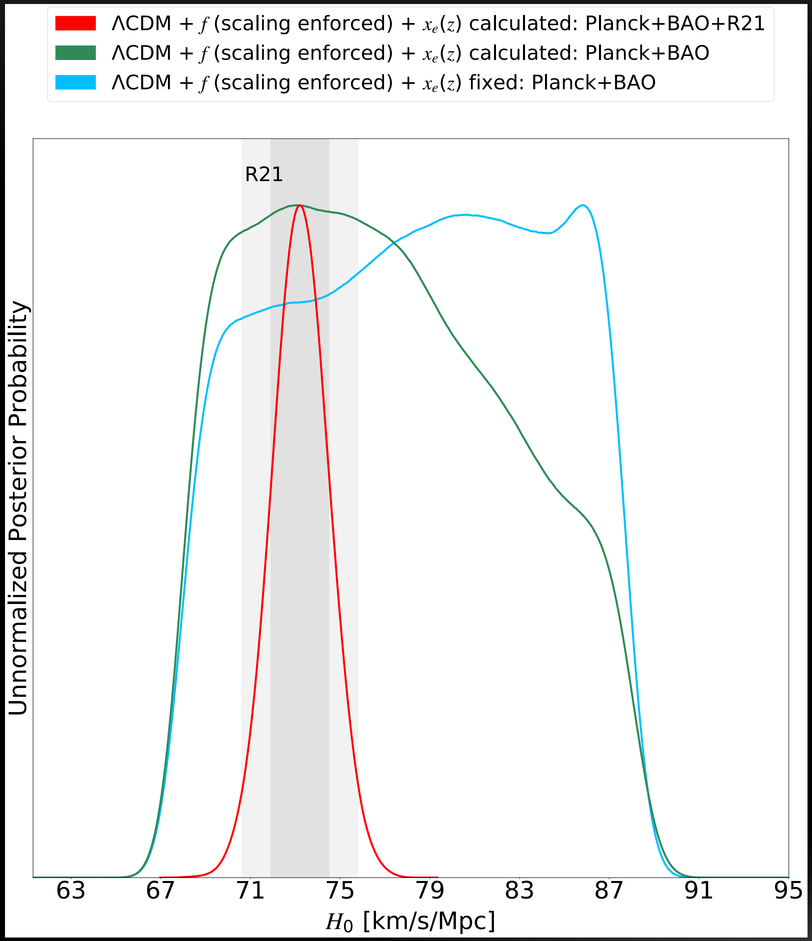
Getting around COBE: Mirror World

- We can’t easily increase the densities of photons/baryons
- So instead add mirror “dark” particles!

Stranger Things

Chacko et al. (2005, a,b,c), Craig & Howe (2014), Craig et al. (2015), Farina (2015), Barbieri et al. (2016), Chacko et al. (2017), Csaki et al. (2017), Hochberg et al. (2017), Harigaya et al. (2017), Ibe et al. (2019), Terning et al. (2019), Curtin & Gryba (2021), Blinov et al. (2021) and many more

Recombination: A mild symmetry breaking



Credits: Fei Ge

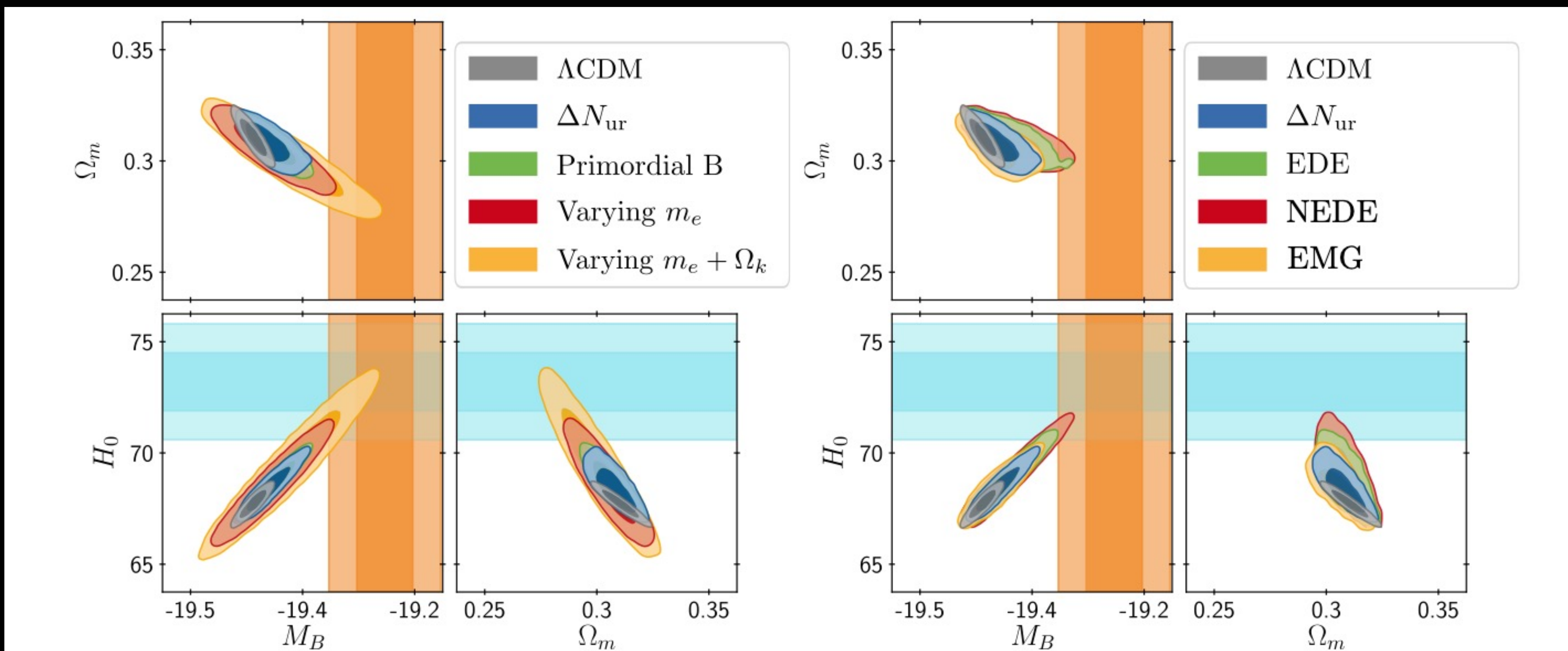
- Since the photon scattering rate and the recombination rate have the same parametric dependence, rescaling one takes care of the other, to a good approximation.

Towards an actual model

- Three key ingredients are necessary to turn this general scaling transformation into an actual model
  - A mirror dark sector that (nearly) mimic the SM (see e.g. Blinov et al., arXiv :2108.11386)
  - A means to rescale the photon scattering rate other than helium (see e.g. Sekiguchi and Takahashi, arXiv :2007.03381; Burgess et al. arXiv:2111.07286).
  - A means to ensure consistency with helium and deuterium abundance measurements.

These provide clear model-building targets!

The scaling symmetry helps understand constraints on other cosmological models



Schöneberg et al., arXiv:2107.10291

Conclusions

- The Hubble tension is really about distance measurements in the Universe.
- A successful cosmological model must be able to fit all known distances.
- CMB, LSS, and BAO are invariant under the scaling transformation

$$\sqrt{G\rho_i(a)} \to f\sqrt{G\rho_i(a)}, \quad \sigma_{\rm T} n_e(a) \to f\sigma_{\rm T} n_e(a)$$
$$\text{and} \quad A_{\rm s} \to A_{\rm s}/f^{(n_{\rm s}-1)}.$$

- If a complete model could be found, it would completely eliminate the Hubble tension.
- This symmetry helps us understand the nature of cosmological constraints, and why new-physics models can (or cannot!) address the tension.

Backup slides

Also need to look at the Einstein Equations

$$H^2 = \frac{8\pi G}{3}\sum_i \rho_i$$

- Via the Friedman equation,

$$H \to fH \quad \Rightarrow \quad G\rho_i \to f^2 G\rho_i$$

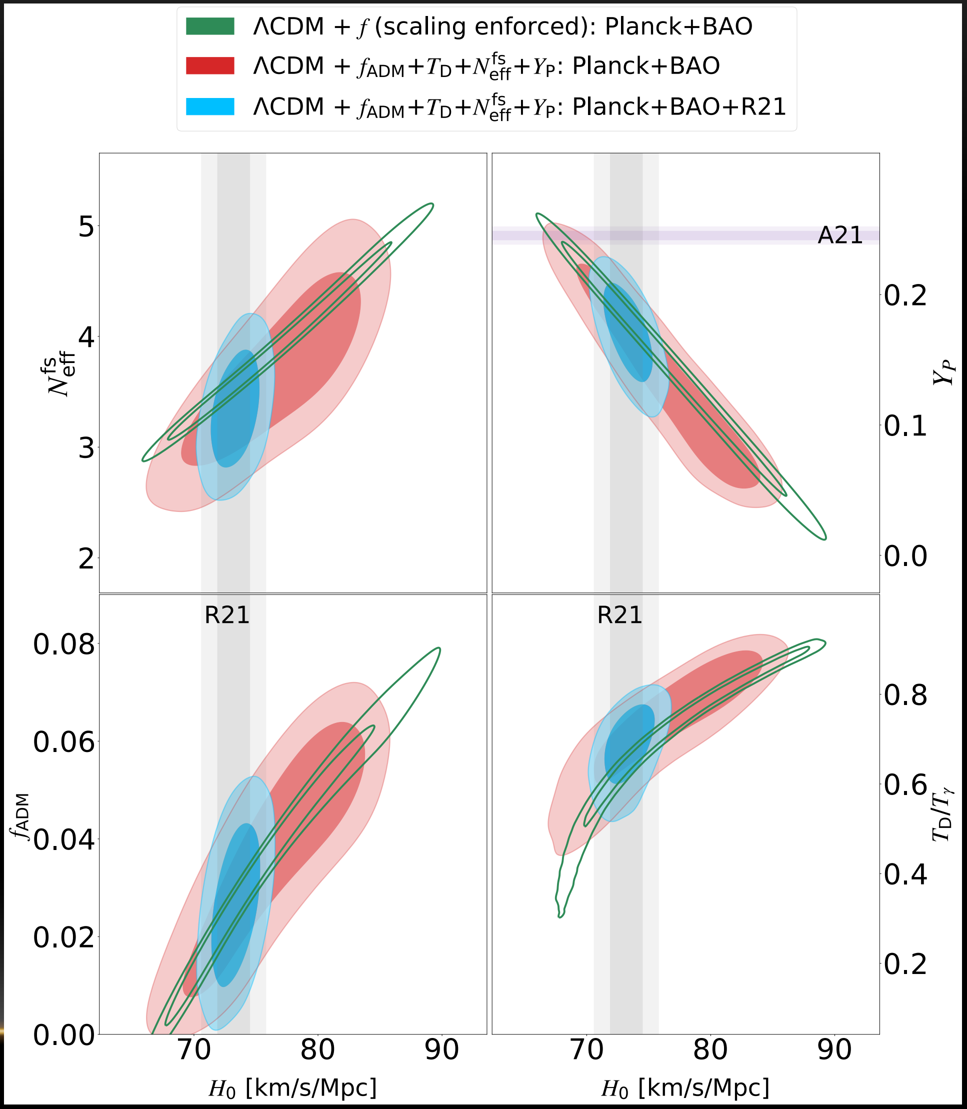
$$k^2\phi + 3aH\left(a^2 H\frac{d\phi}{da} + aH\psi\right) = -4\pi G a^2 \sum_i \rho_i\delta_i, \qquad (5)$$

$$k^2(\phi - \psi) = 12\pi G a^2 \sum (\rho_i + P_i)\sigma_i,$$

This is also invariant under the scaling transformation.

Possible implication: Mirror Sector Freedom

At face value, the direct Hubble measurements predict ~3% in atomic dark matter, and a dark photon bath with a neutrino-like temperature.



Cyr-Racine, Ge, Knox, arXiv: 2107:13000, PRL accepted

Dark Sector scaling relation

- Scaling transform for mirror sector:

$$N_{\rm eff} = f^2 \bar{N}_{\rm eff}, \qquad T_{\rm D} = (f^2 - 1)^{1/4} T_{\rm CMB}$$

$$\rho_{\rm DM} = (f^2 + R_{\rm nc}(f^2-1))\rho_{\rm DM}^{(f=1)},$$

$$f_{\rm adm} = \frac{R_{\rm nc}(f^2-1)}{f^2 + R_{\rm nc}(f^2-1)},$$

$$R_{\rm nc} \equiv \rho_{\rm b}^{(f=1)} / \rho_{\rm DM}^{(f=1)}$$

Keep fixed: B_D/T_D