Title: A Symmetry of Cosmological Observables: Looking at Hubble through the Mirror

Speakers: Francis-Yan Cyr-Racine

Series: Cosmology & Gravitation

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Abstract: Many key cosmological observables have a built-in symmetry under rescaling of all important length scales in the problem. This scaling symmetry can be used to make partial progress toward a complete resolution of the Hubble tension. To exploit the symmetry while respecting observational constraints, we are naturally led to a "mirror world" dark sector. A successful implementation of this scaling symmetry requires a means of increasing the cosmic photon scattering rate that respects observational bounds on the primordial helium abundance. We discuss different ideas that could in principle achieve this rescaling, and discuss their advantages and drawbacks. We finally present some general observations about the fundamental nature of the "Hubble tension".

Zoom Link: https://pitp.zoom.us/j/99678466262?pwd=VTY4cWNFUERhU08vYi9lT09MZjJkdz09

Hubble rate: The Landscape

Recent Published H_0 Values

Freedman (2021)
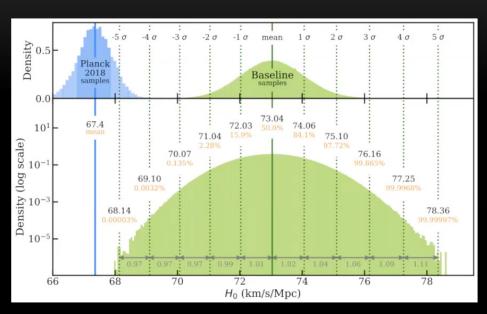
Hubble tension: Latest SH0ES results

Riess et al., arXi:2112.04510

- Now SH0ES nearly 5-sigma away from Planck CMB!

- The seriousness of the tension is now difficult to dismiss.

- Exciting times for cosmology!
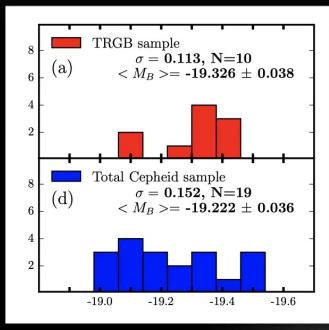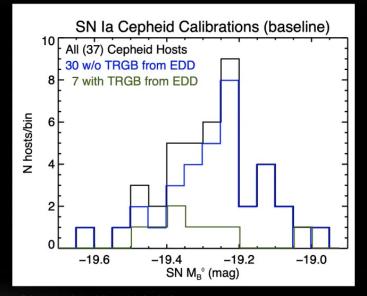
Why you should take this seriously

- Among other important improvements, the doubling of the calibrator supernova host sample is a major step forward.

Freedman et al. (2019)

Riess et al., arXi:2112.04510

Where does this leave us?

- According to this scale, we are in a crisis

  - $< 1\sigma$: Consistency

  - $> 2\sigma$: Curiosity

  - $> 3\sigma$: Tension/discrepancy

  - $> 4\sigma$: Problem
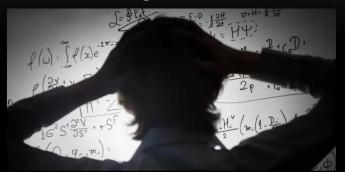
  - $\gtrsim 5\sigma$: Crisis ⬅

DO NOT PANIC

Theorists to the rescue!

In this crisis, our job as theorists is to identify what properties a successful solutions might have.

Bottom line:

We have yet to identify a complete solution that is palatable to both cosmologists and particle physicists but have found important clues about what a successful model would look like.

(quote from KITP Conference July 2019)

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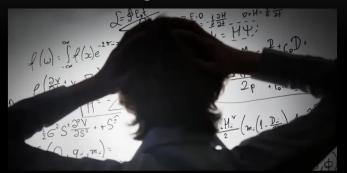
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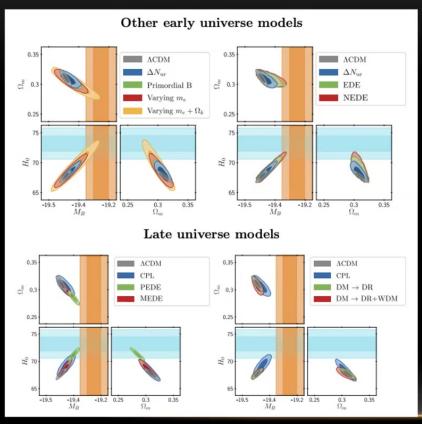
This talk: Why is it so hard to get a large Hubble constant from the CMB + BAO?

Other early universe models

Late universe models

Schöneberg et al., arXi:2107.10291

- Lots of ideas out here!
  Why are they struggling
  to get a large value of
  the Hubble rate?
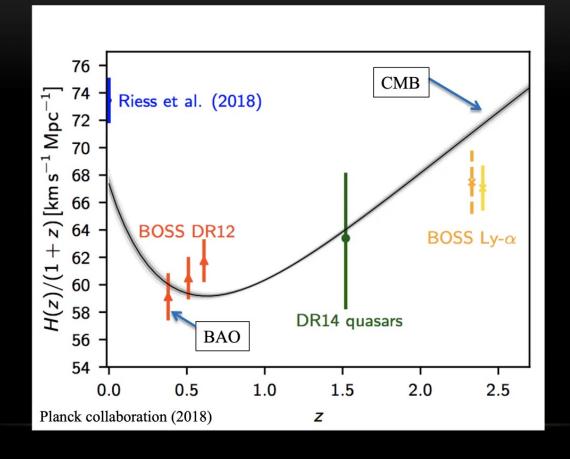
Late solution: Could we just do that?

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

Planck collaboration (2018)
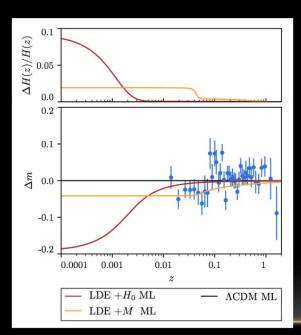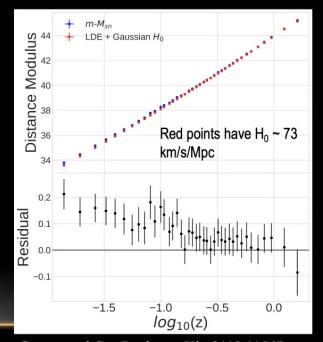
No!! Any model must fit the **distances** to type Ia supernovae

- Just increasing the Hubble rate at very late times **does not** address the root cause of the tension.

Benevento et al. (2020)

Red points have $H_0 \sim 73$ km/s/Mpc

Greene and Cyr-Racine, arXiv:2112.11567
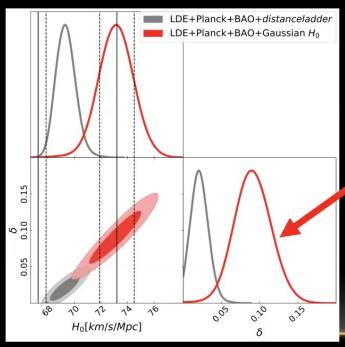
No!! Any model must fit the **distances** to type Ia supernovae

- Not properly taking distances into account can lead to the detection of spurious physics!

Greene and Cyr-Racine, arXiv:2112.11567

- >3sigma detection of a late transition in the abundance of dark energy (bogus!)

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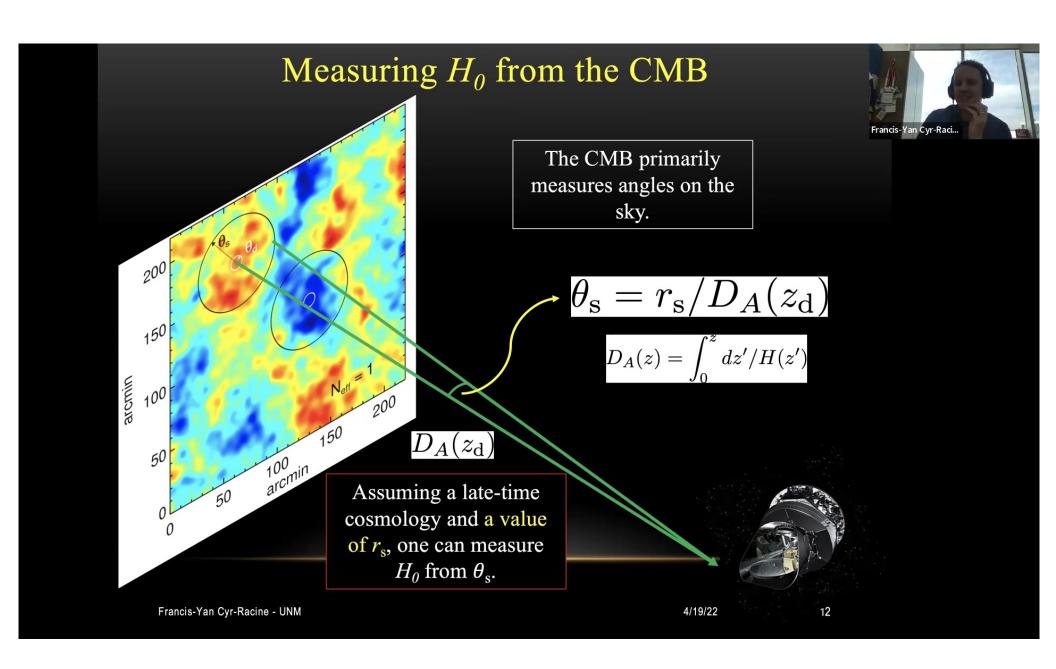
If you are working on a late-time solution, please make sure that your model fit the actual distances to Type Ia supernovae.

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Measuring H_0 from the CMB

The CMB primarily measures angles on the sky.

$$\theta_{\mathrm{s}} = r_{\mathrm{s}}/D_A(z_{\mathrm{d}})$$

$$D_A(z) = \int_0^z dz'/H(z')$$

$D_A(z_{\mathrm{d}})$

Assuming a late-time cosmology and a value of r_{s}, one can measure H_0 from θ_{s}.

θ_s θ_d

$N_{eff} = 1$

arcmin

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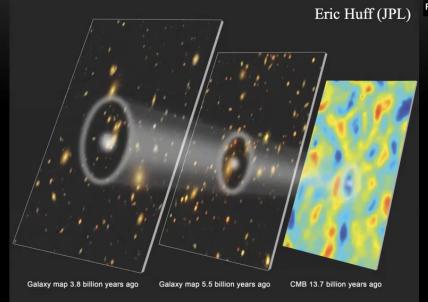
Baryon Acoustic Oscillations (BAO)

BAO primarily measures 2 "processed" versions of the baryon-photon sound horizon.

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

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

Eric Huff (JPL)

Galaxy map 3.8 billion years ago   Galaxy map 5.5 billion years ago   CMB 13.7 billion years ago

If sound horizon is known, then we can use BAO to infer Hubble rate.
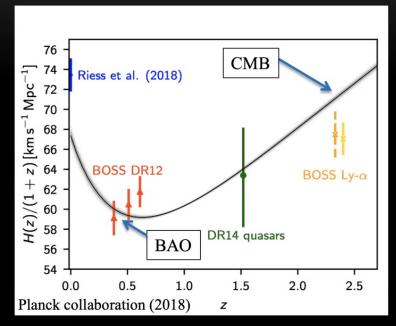
CMB and BAO measurements of the expansion rate are all anchored on the sound horizon

Planck collaboration (2018)

Important:
The baryon-photon sound horizon, r_s, is something we compute theoretically, assuming we understand atomic physics and the energy content of the Universe.

Time of baryon decoupling

$$r_s = \int_0^{t_d} c_s dt/a = \int_0^{a_d} c_s \frac{da}{a^2 H(a)}$$
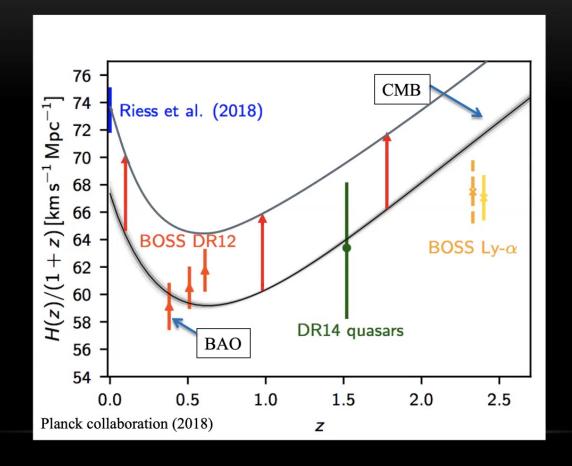
Early solution: Cartoon

Planck collaboration (2018)

Question
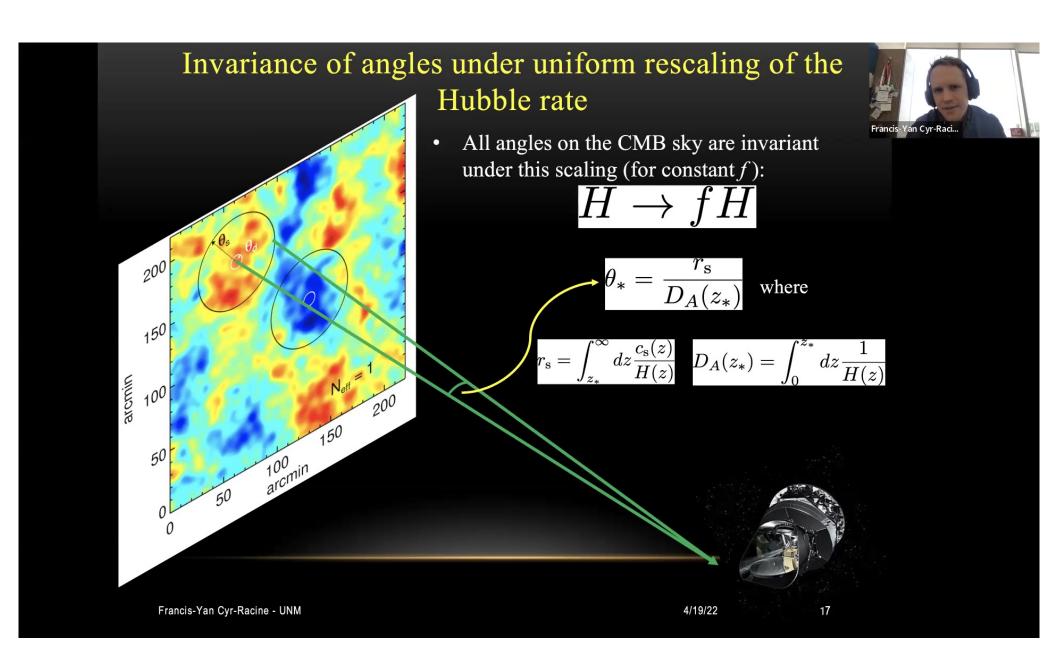
Can we change the cosmological expansion history and leave the CMB/BAO *exactly* invariant?

Invariance of angles under uniform rescaling of the Hubble rate

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

$$H \rightarrow fH$$

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

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

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However, the CMB as a whole is not invariant under $H \rightarrow fH$

- Why? Photon-baryon equations of motion depend on two other dimensionful quantities: wavenumber k and the baryon-photon scattering rate.

- For example, let's look at the continuity equation for photons:

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

However, the CMB as a whole is not invariant under $H \to fH$

- Why? Photon-baryon equations of motion depend on **two other dimensionful quantities**: wavenumber k and the baryon-photon scattering rate.

- For example, let's look at the continuity equation for photons:

Photon temperature monopole perturbation

Depends on ratio of k to H

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

$$\frac{\partial F_{\gamma 0}}{\partial a} = -\frac{k}{a^2 H} F_{\gamma 1} + 4 \frac{\partial \phi}{\partial a},$$

Photon heat flux

Gravitational driving term

However, the CMB as a whole is not invariant under $H \rightarrow fH$

- Why? Photon-baryon equations of motion depend on two other dimensionful quantities: 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.)

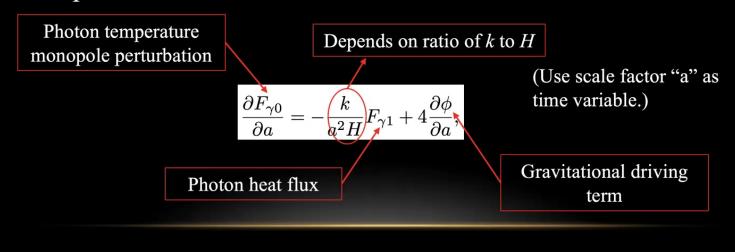Photon heat flux

Photon quadrupole

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

Photon temperature monopole perturbation

Gravitational driving term

Photon-baryon scattering rate

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.

θ_*

$r_{\rm s}$

θ_*

$D_A(z_*)$
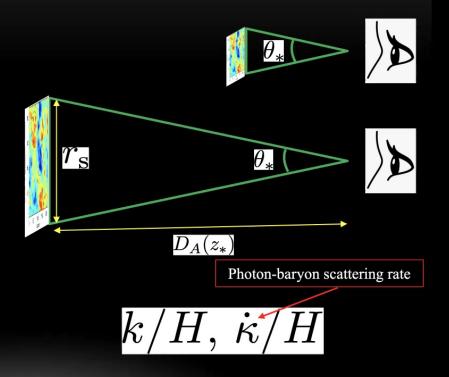
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$$k/H, \, \dot{\kappa}/H$$

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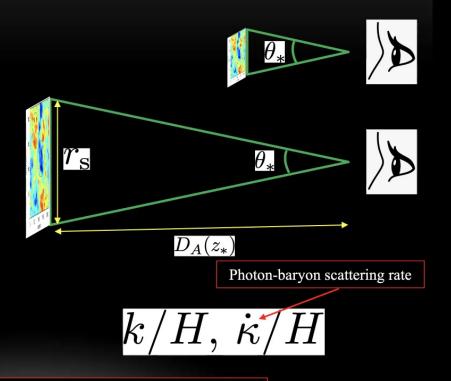
$$\theta_*$$

$$r_{\mathrm{s}}$$

$$\theta_*$$

$$D_A(z_*)$$

Photon-baryon scattering rate

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

Nothing special about cosmology here!

But what if **all** length scales are uniformly rescaled?

- Instead of just rescaling H, do the transformation:

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

- 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.

Special feature of our Universe: Initial conditions

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

$$P(k) = A_{\mathrm{s}}(k/k_{\mathrm{p}})^{n_{\mathrm{s}}-1}$$

- Since $n_{\mathrm{s}} < 1$, the different Fourier modes have slightly different primordial amplitudes.

- Thus, the transformation $k \to fk$ will modify the amplitude of fluctuations (CMB, $P_{\mathrm{m}}(k)$, etc.)

- However, since power laws have no scale, this can be corrected with a trivial rescaling:

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

Zahn and Zaldarriaga (2003)

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The scaling "recipe"

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

$$G\rho_i \rightarrow f^2 G\rho_i \qquad \Longrightarrow \qquad H \rightarrow fH$$

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

$$\sigma_{\mathrm{T}} n_e(a) \rightarrow f\sigma_{\mathrm{T}} n_e(a)$$

3. Adjust the initial amplitude of scalar fluctuations according to

$$A_{\mathrm{s}} \rightarrow A_{\mathrm{s}}/f^{n_{\mathrm{s}}-1}$$

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

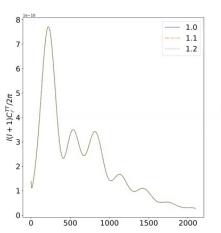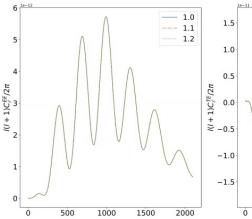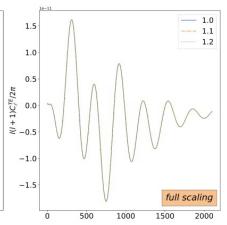Francis-Yan Cyr-Racine - UNM   4/19/22   23

This works

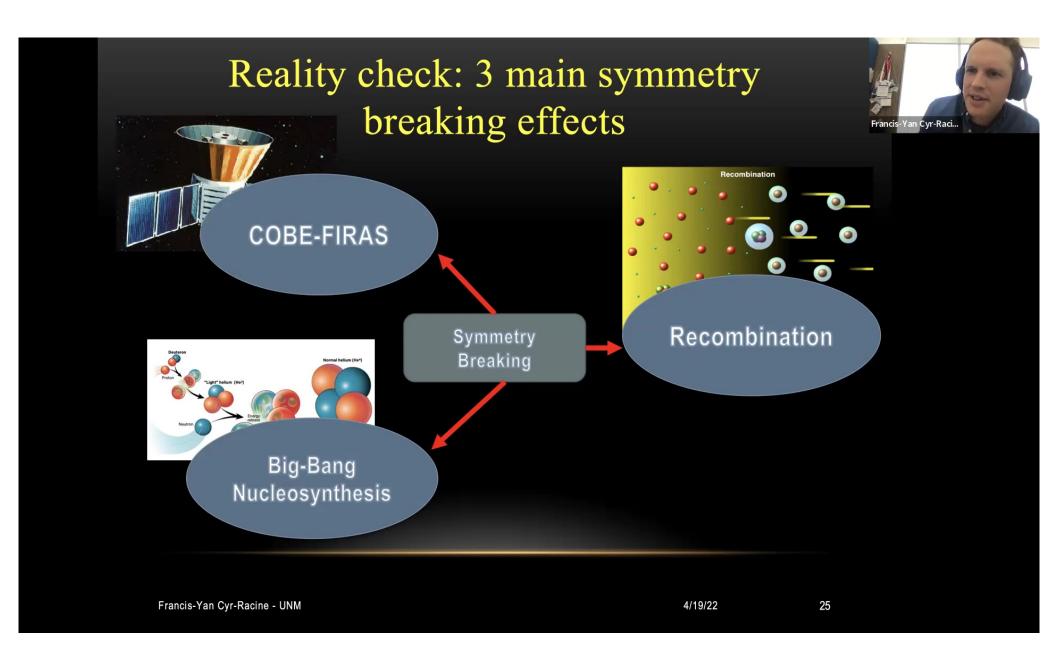- This really leaves the CMB temp/pol invariant (fixing recombination history here)

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

Reality check: 3 main symmetry breaking effects

COBE-FIRAS

Recombination

Symmetry Breaking

Big-Bang Nucleosynthesis
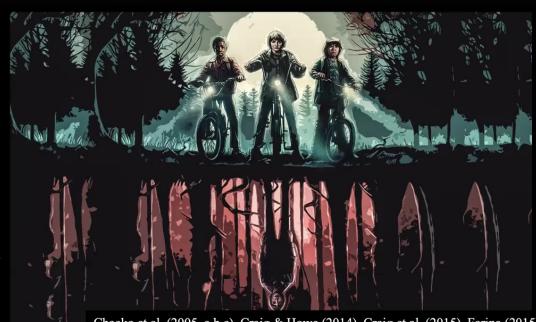
Getting around COBE: Mirror World

- 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

Adjusting the photon scattering rate

- The mirror world ingredients ensure that we "effectively" implement the rescaling

$$\sqrt{G\rho_i(a)} \to f\sqrt{G\rho_i(a)}, \qquad \Longrightarrow \qquad H \to fH$$

  while leaving the perturbation evolution invariant.

- It does not however implement the necessary scaling

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

- Since $n_e \propto (1 - Y_{\mathrm{P}})$, one can implement this scaling by adjusting the helium fraction according to

$$(1 - Y_{\mathrm{P}}) \to f(1 - Y_{\mathrm{P}})$$
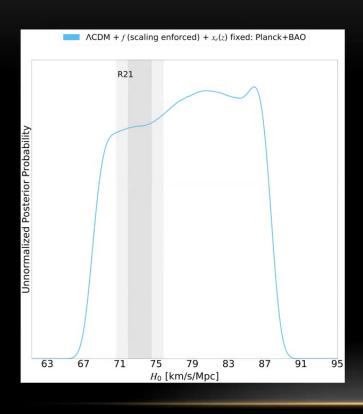
Unlikely to be the right way of doing this!

Zeroth Test: The exact symmetry

ΛCDM + f (scaling enforced) + $x_e(z)$ fixed: Planck+BAO

R21

Unnormalized Posterior Probability

H_0 [km/s/Mpc]

- With a fixed recombination history, we can fit any value of the Hubble constant to CMB + BAO data.

- This is just a numerical realization of the symmetry we already know exists.

First (real!) Test: Recombination

ΛCDM + f (scaling enforced) + $x_e(z)$ calculated: Planck+BAO
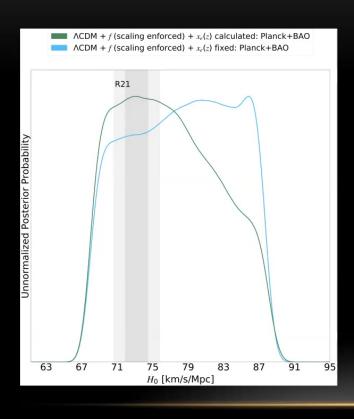ΛCDM + f (scaling enforced) + $x_e(z)$ fixed: Planck+BAO

R21

Unnormalized Posterior Probability

H_0 [km/s/Mpc]

- Symmetry-breaking effects from the self-consistently calculated recombination history are very mild!
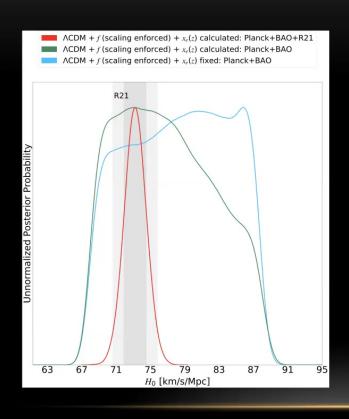
Second Test: Compatibility with the cepheid-calibrated distance ladder

Legend:
- $\Lambda\text{CDM} + f$ (scaling enforced) $+ x_e(z)$ calculated: Planck+BAO+R21
- $\Lambda\text{CDM} + f$ (scaling enforced) $+ x_e(z)$ calculated: Planck+BAO
- $\Lambda\text{CDM} + f$ (scaling enforced) $+ x_e(z)$ fixed: Planck+BAO

Plot axes: Unnormalized Posterior Probability (y-axis); H_0 [km/s/Mpc] (x-axis), labeled R21.

- In principle, the symmetry allows us to completely eliminate the Hubble tension between CMB + BAO and the local distance ladder (R21 here).

- However, we are doing the scaling by fiat here.

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.

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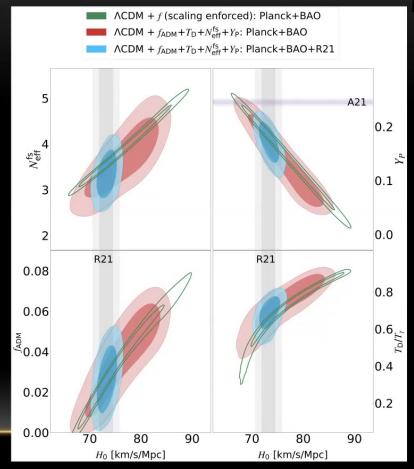
    > These provide clear model-building targets!

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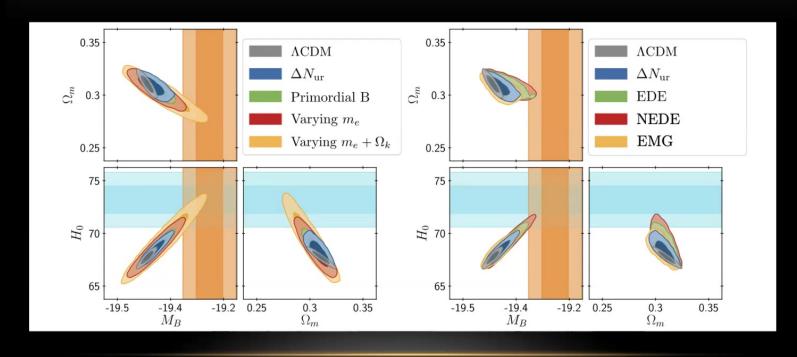
Cyr-Racine, Ge, Knox, arXiv: 2107:13000, PRL accepted

Legend:
- ΛCDM + f (scaling enforced): Planck+BAO
- ΛCDM + f_{ADM} + T_D + N_{eff}^{fs} + Y_P: Planck+BAO
- ΛCDM + f_{ADM} + T_D + N_{eff}^{fs} + Y_P: Planck+BAO+R21

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.

- Early solutions must be able to fit distances to SNe Ia.

- We have identified a previously unnoticed symmetry of cosmological observables projected on the sky.

- If a complete model could be found, it would completely eliminate the Hubble tension.

- This symmetry helps us understand the nature of cosmological constraints.

Open Questions

- Can we achieve a higher photon scattering rate and have consistency with BBN and Y_P ?

- Can we detect the 3% of atomic DM?

- Can a consistent mirror sector be built? (Yes!)

- Impact of nonlinear evolution?

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