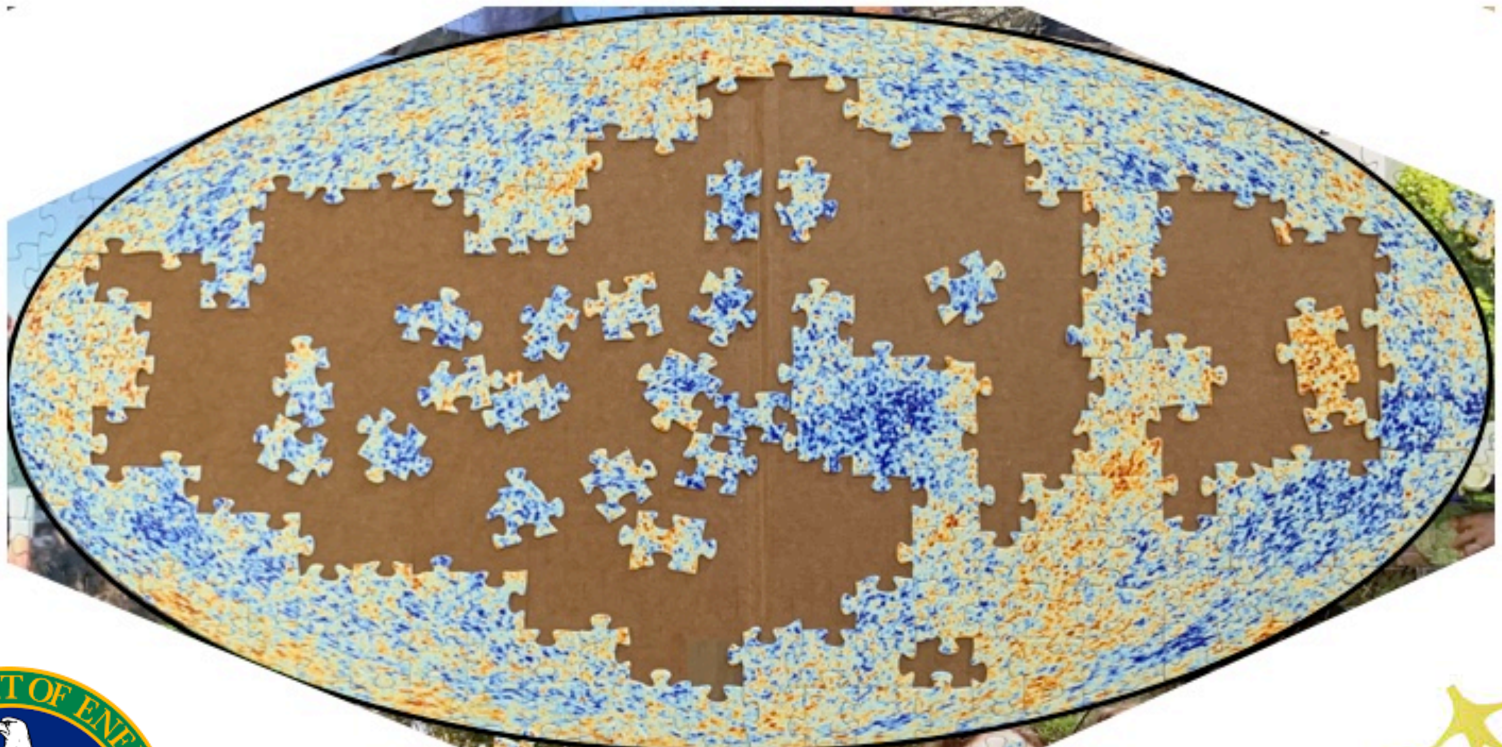
Searching for Cosmological Model Solutions to the H_0 Problem: the Hunt Continues

Lloyd Knox (UC Davis)

February 14, 2023



Searching for Cosmological Model Solutions to the H_0 Problem: the Hunt Continues

Lloyd Knox (UC Davis)

February 14, 2023

Fei Ge, UC Davis

Francis-Yan Cyr-Racine, U New Mexico

Ge, Cyr-Racine, and Knox Phys. Rev. D (2023) and Cyr-Racine, Ge, and Knox Phys. Rev. Lett. (2022)

Searching for Cosmological Model Solutions to the H_0 Problem: the Hunt Continues

Lloyd Knox (UC Davis)

February 14, 2023

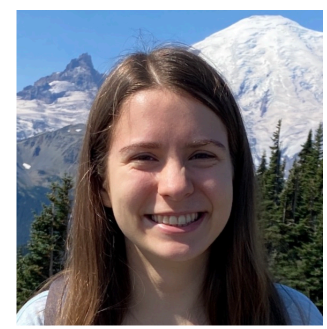
Fei Ge, UC Davis

Francis-Yan Cyr-Racine, U New Mexico

Gabriel Lynch
(UC Davis

Michael Meiers
(UC Davis)

Marius Millea
(UC Davis)

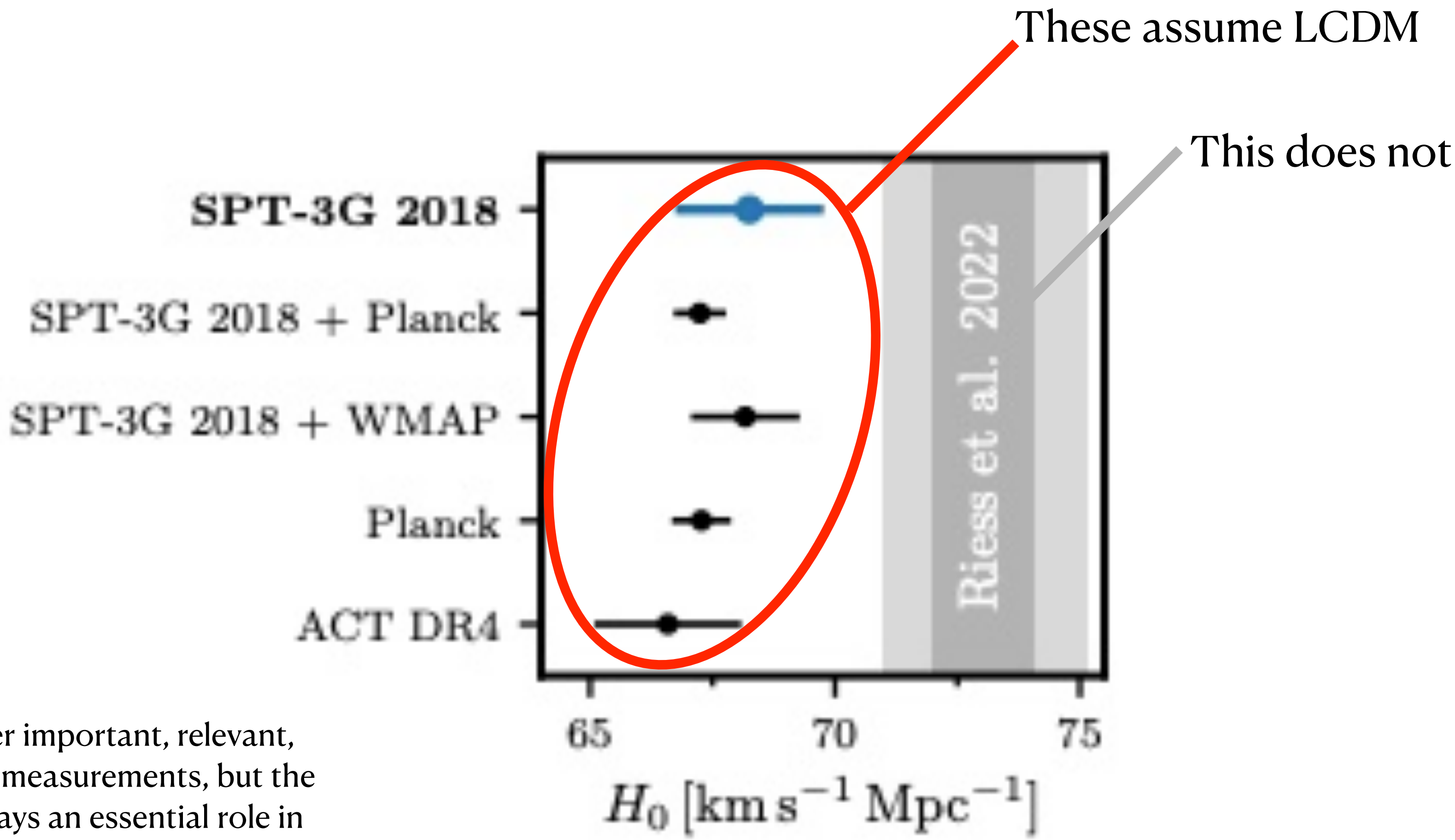


Ellie Hughes
(Bryn Mawr)

Ge, Cyr-Racine, and Knox Phys. Rev. D (2023) and Cyr-Racine, Ge, and Knox Phys. Rev. Lett. (2022)

The H_0 Problem

Cosmological-model-**dependent** vs. cosmological-model-**independent**
(often stated as "Early vs. Late")



Balkenhol + SPT Collaboration (2023)

There are other important, relevant, distance-ladder measurements, but the SHoES work plays an essential role in raising this to the level of a "problem."

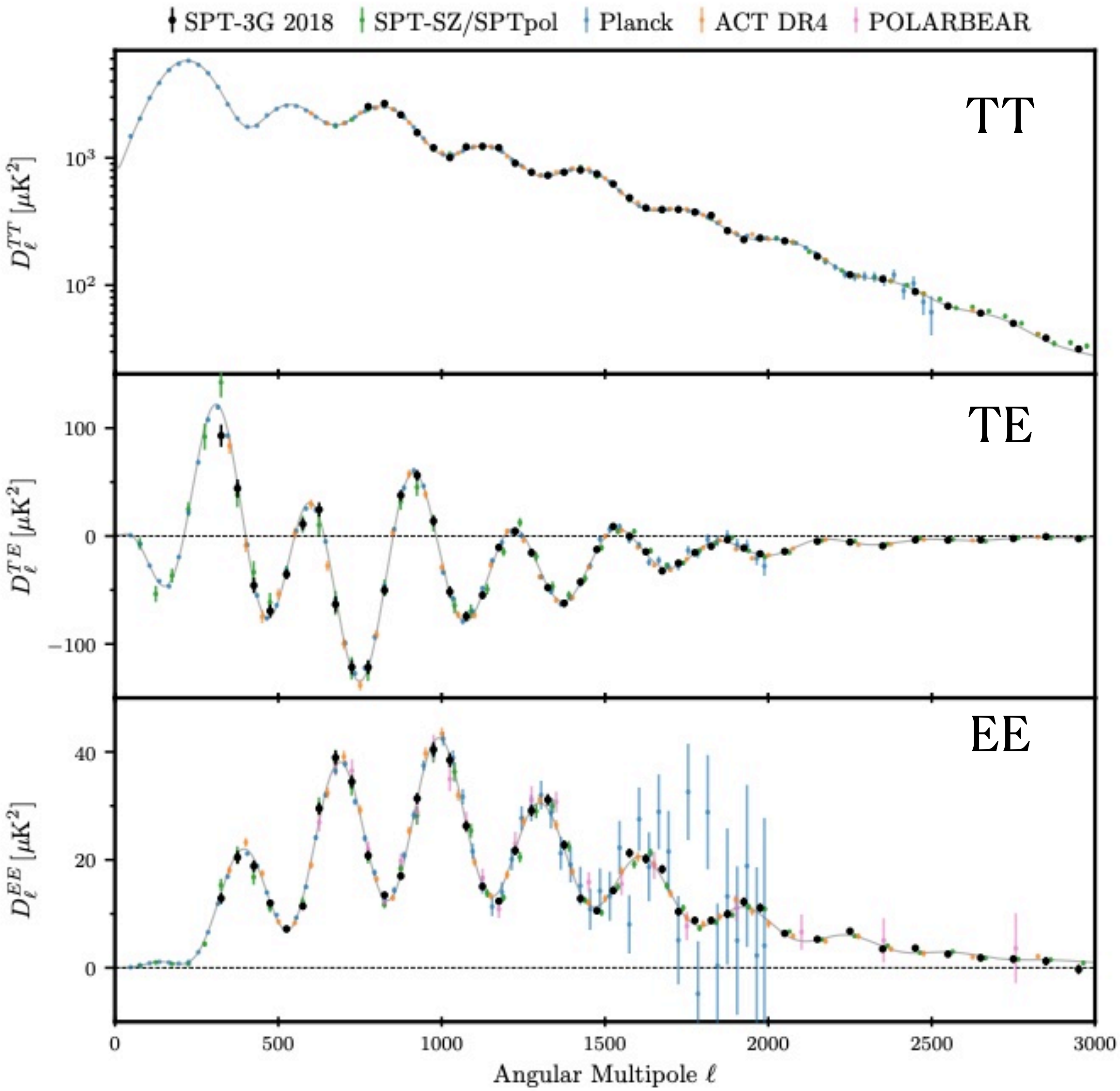
Is it a problem for cosmology or for some subset of distance ladder practitioners?

Questions the problem has led me to

- What changes to cosmological models can lead to concordance? The Hubble Hunter's Guide (LK and Millea 2020)
- More generally: what is allowed by the CMB data and what is not?
  - LCDM provides a good fit, but what else can fit?
  - Can the CMB data accommodate Ho = 73 km/sec/Mpc?
  - Can we accommodate
    - Delta Neff = 2?
    - Early Dark Energy?
    - Non-standard recombination?
    - Dark matter-dark radiation interactions, or other dark sector complexity?
    - etc.
- What can we learn about these questions from the attempts of others to address the Ho problem?

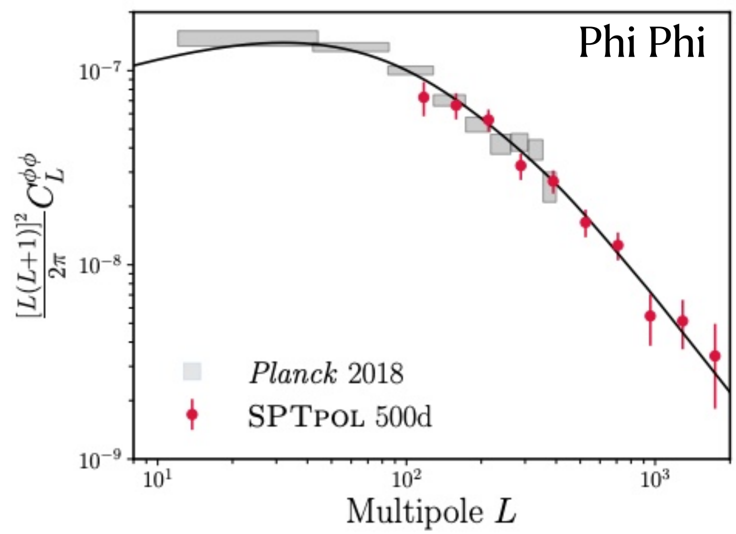
Our Recent Approaches to the question of what the CMB data allow and what they do not

1. Pursuit of analytic understanding
2. Exploration of purely phenomenological high-dimensional cosmological models



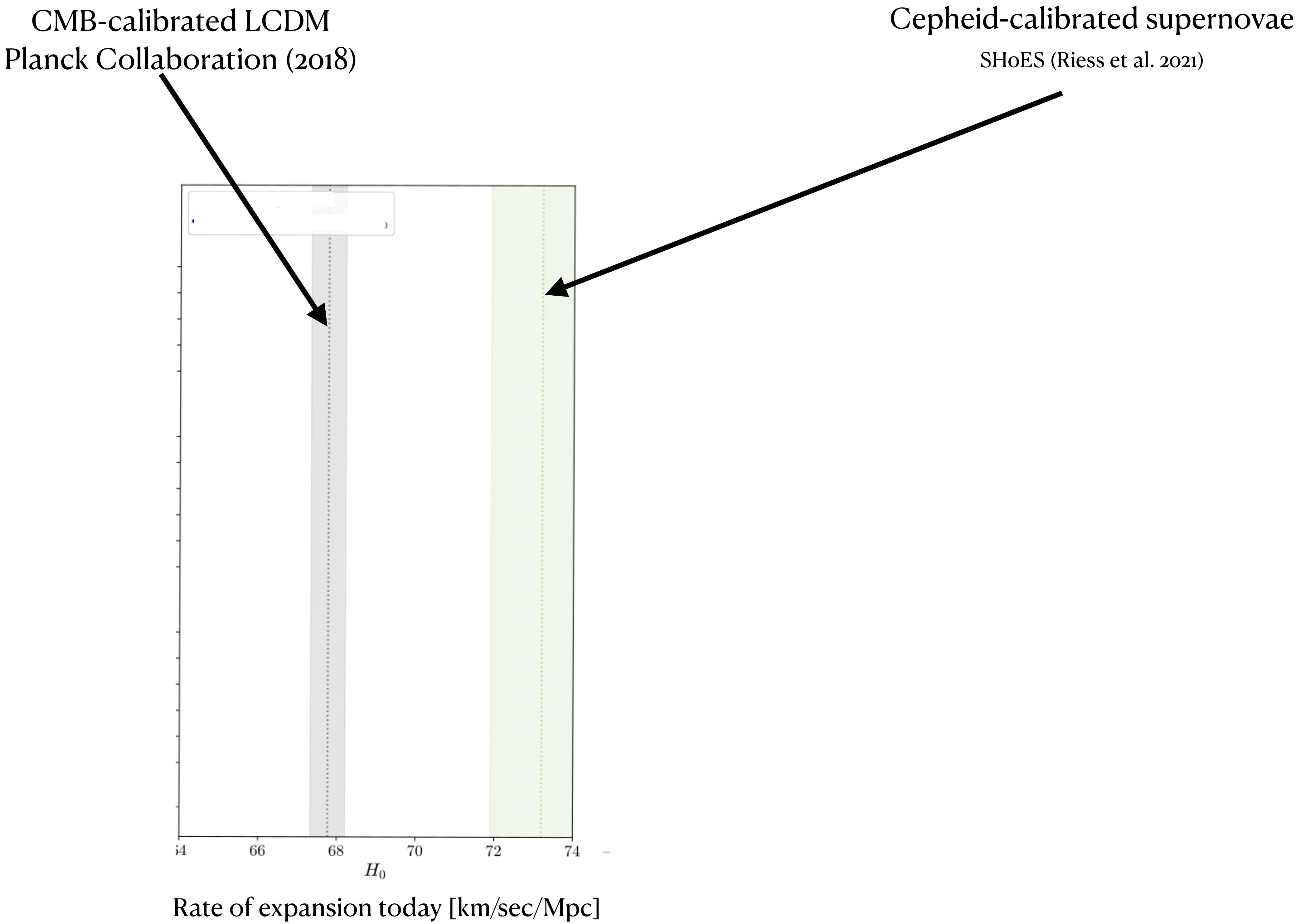
Balkenhol+SPT (2023)

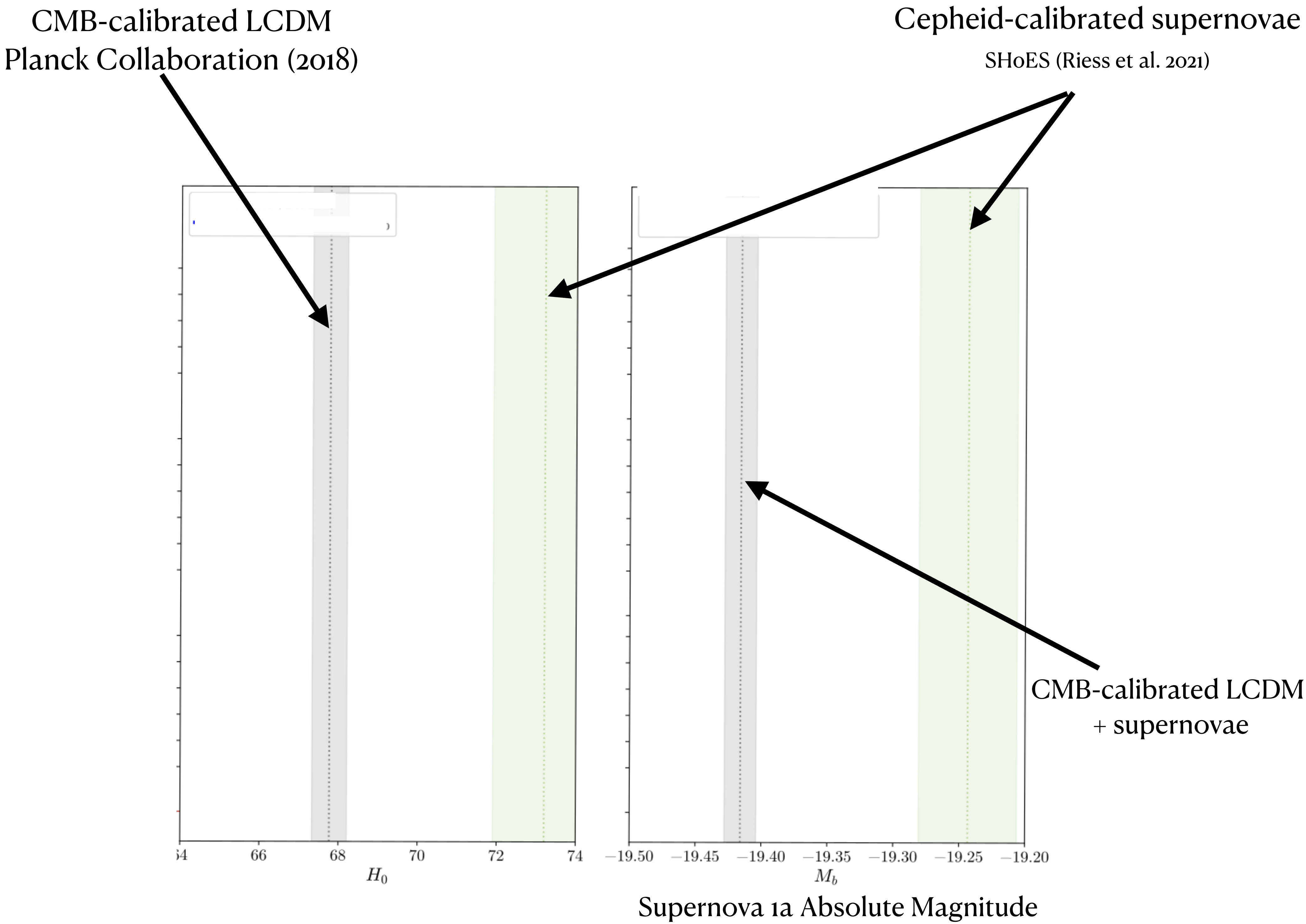
Bianchini+SPT (2020)



We can calculate the spectra
Others have made the measurements
What's left to understand?

Analytic Understanding Supports Model Building

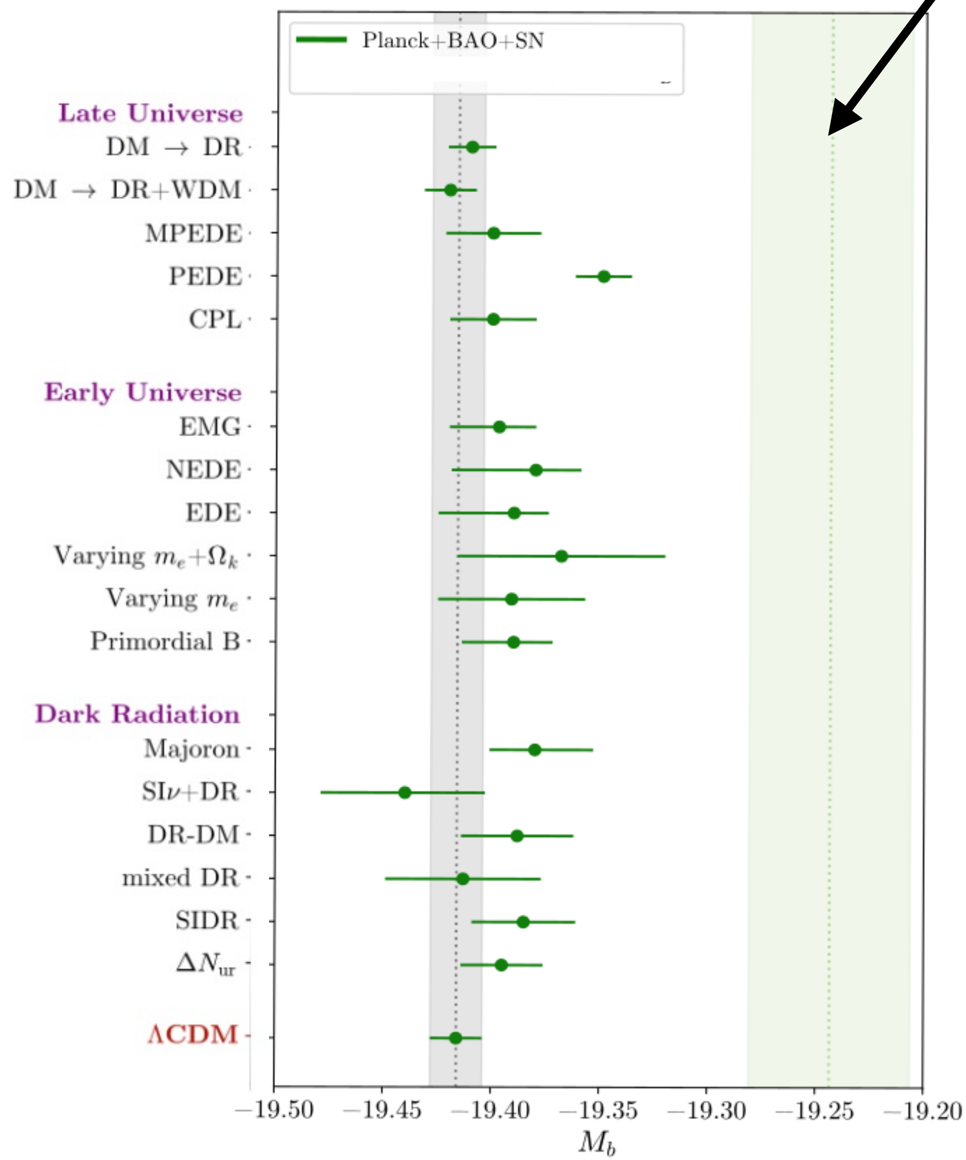

CMB-calibrated LCDM
Planck Collaboration (2018)
Cepheid-calibrated supernovae
SHoES (Riess et al. 2021)
66
68
70
72
74
H_0
Rate of expansion today [km/sec/Mpc]


CMB-calibrated LCDM
Planck Collaboration (2018)
Cepheid-calibrated supernovae
SHoES (Riess et al. 2021)
CMB-calibrated LCDM
+ supernovae
64
66
68
70
72
74
H_0
−19.50
−19.45
−19.40
−19.35
−19.30
−19.25
−19.20
M_b
Supernova 1a Absolute Magnitude

Cepheid-calibrated supernovae

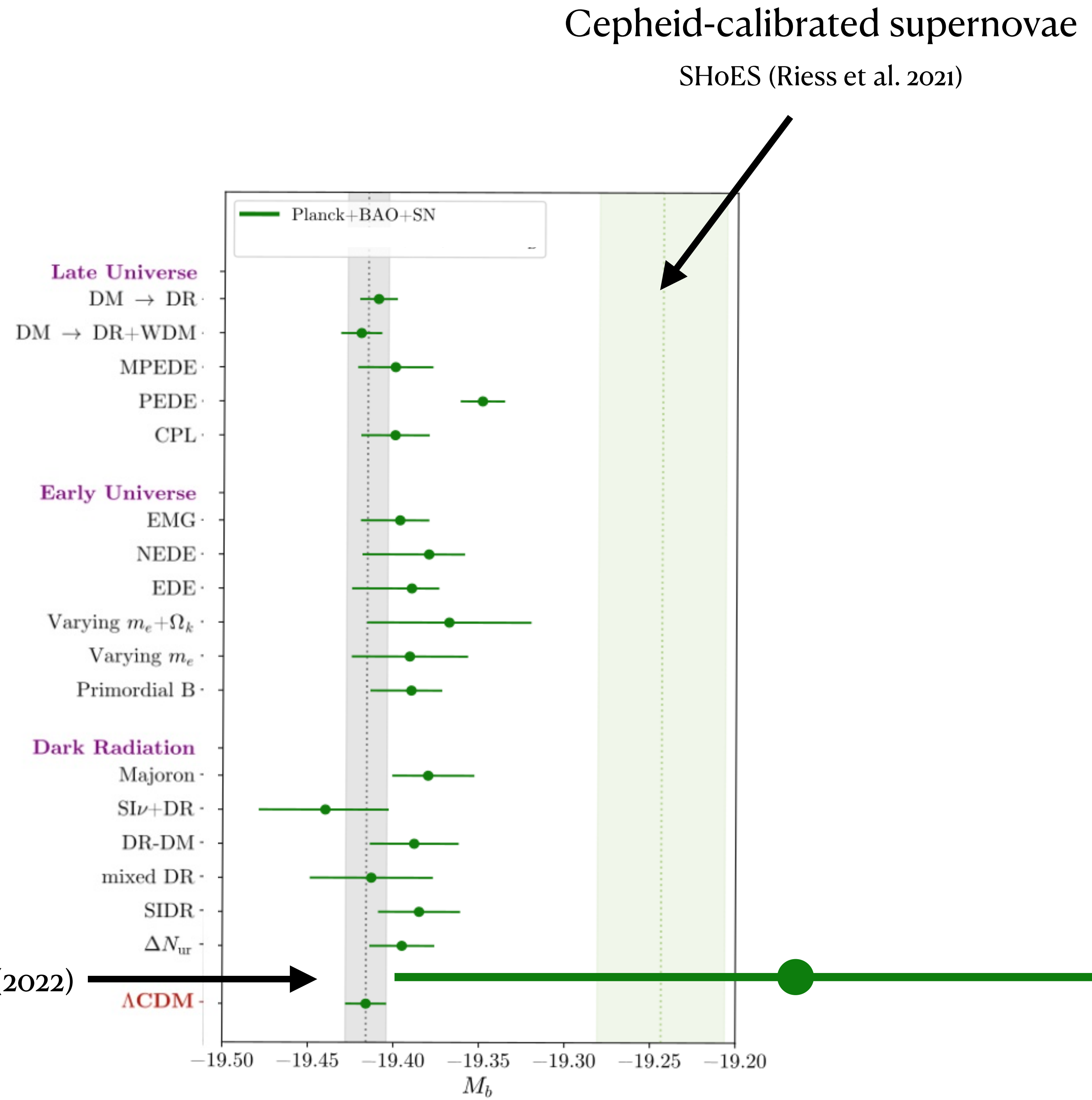
SHoES (Riess et al. 2021)

Figure adapted from "The H₀ Olympics: a Fair Comparison of Models" by Schöneberg et al. (2022)



Supernova 1a Absolute Magnitude

Figure adapted from “The H_0 Olympics: a Fair Comparison of Models” by Schöneberg et al. (2022)



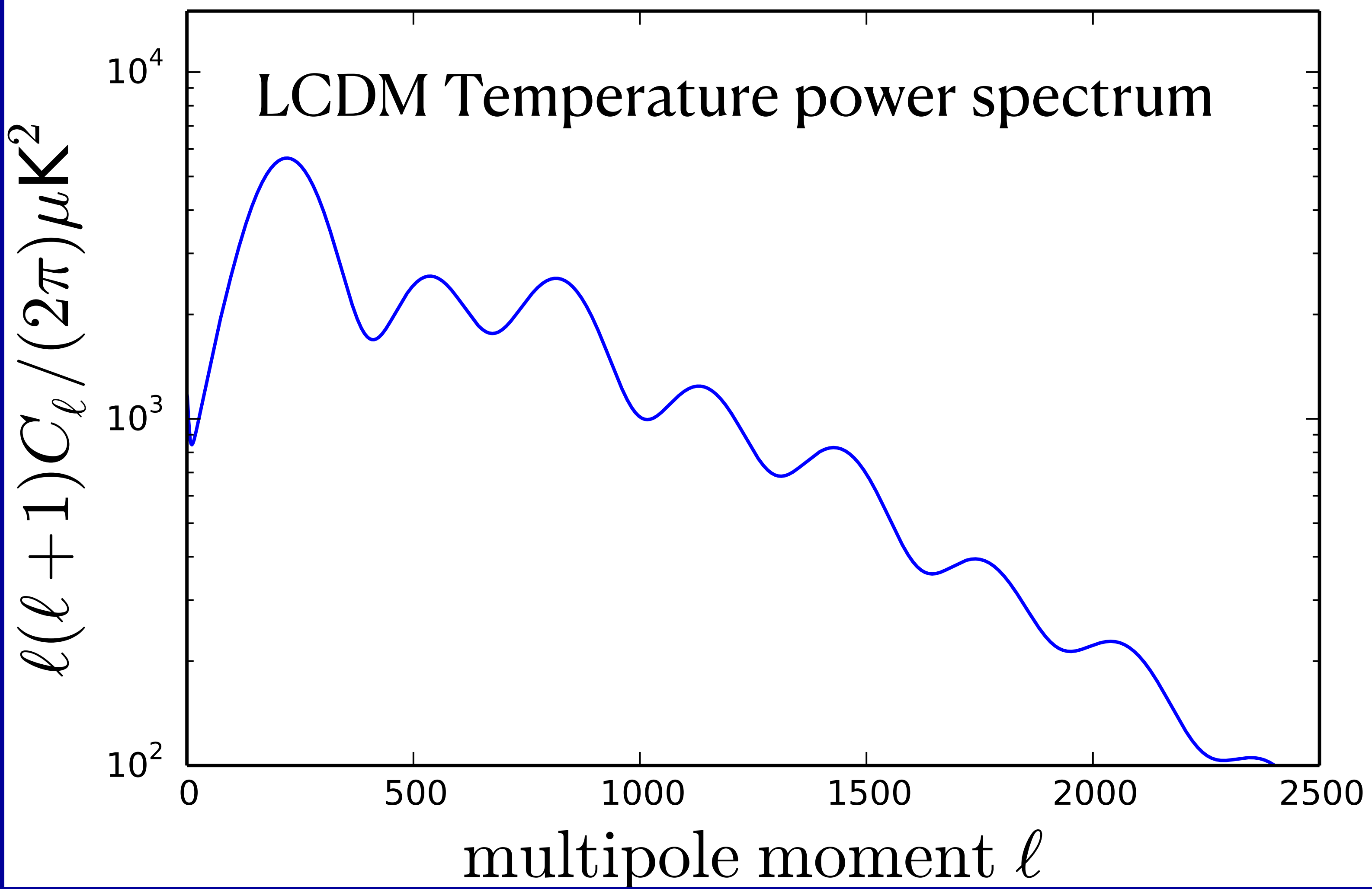
This was a pay off for the analytic understanding we developed.

Light Relics: Definition and Motivation

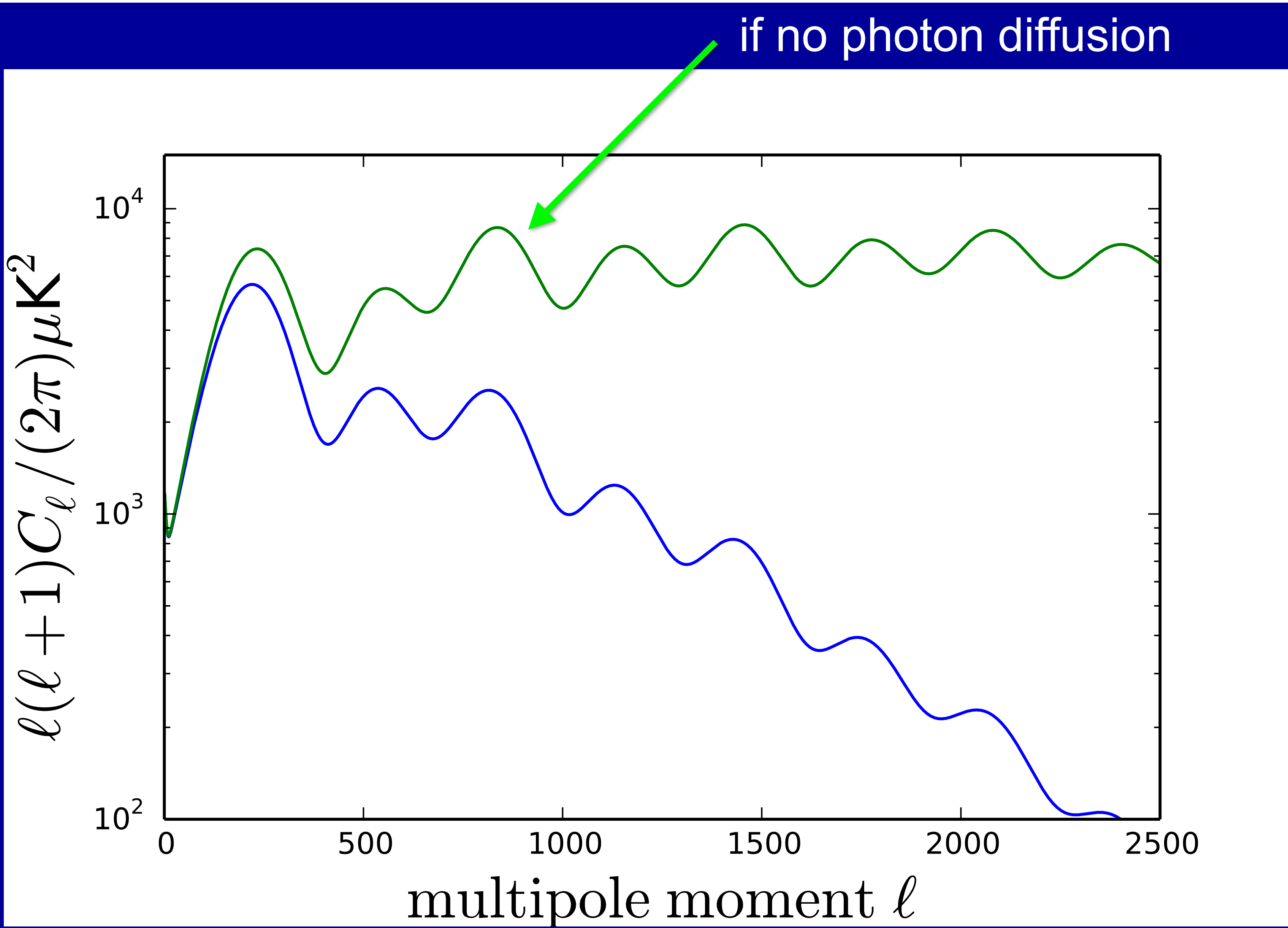
- Light relic definition: Anything still relativistic at CMB decoupling and thermally or otherwise produced in the big bang. Examples:
  - The 3K photon background
  - The cosmic neutrino background
- Motivation
  - Particle physics model building is constrained by our cosmological constraints on light relic densities
  - Analytic understanding is an end in its own right
  - Analytic understanding can be useful for cosmological model building
  - Models with increased light relic densities can potentially solve the Hubble constant problem

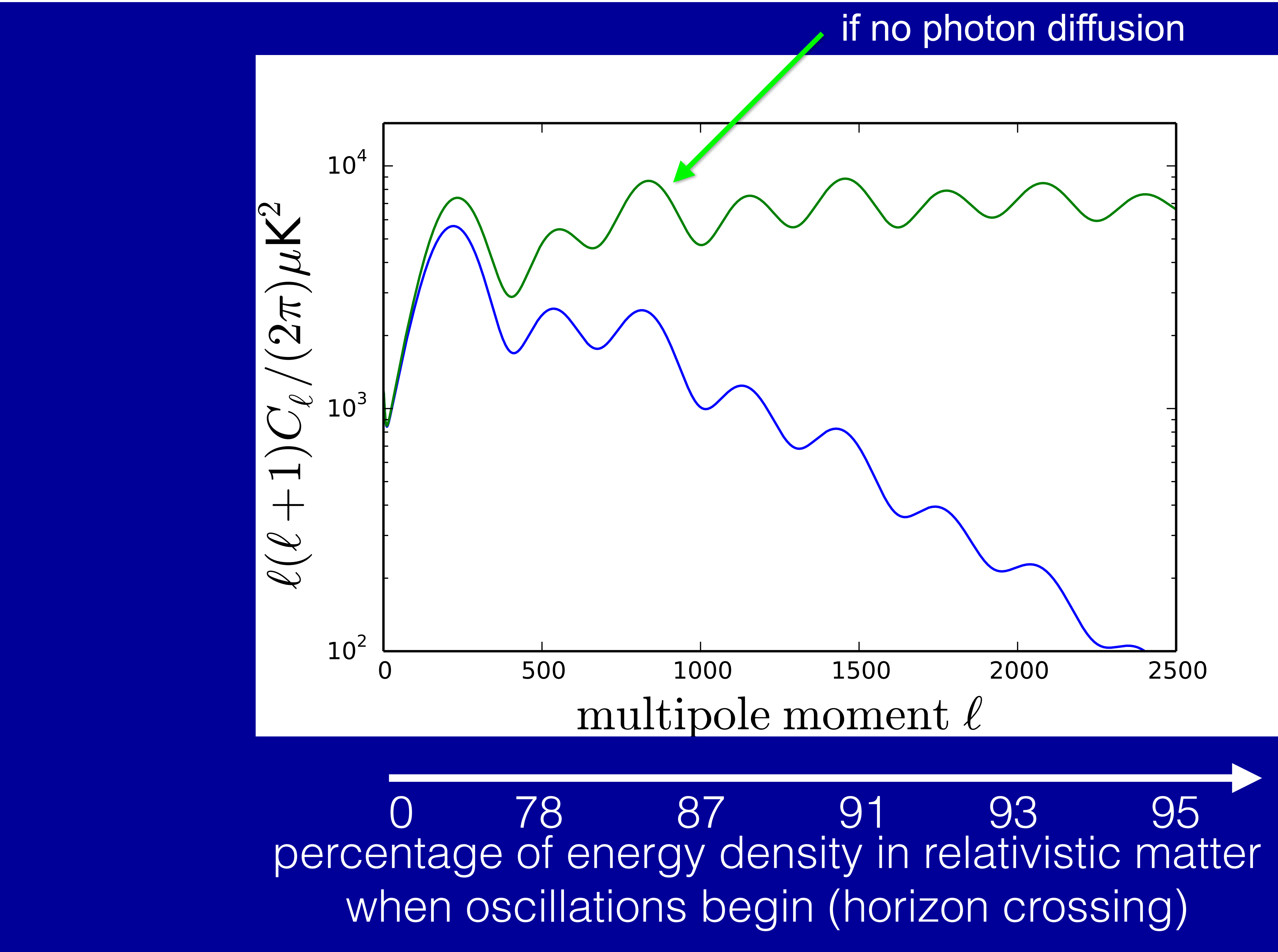
Setting up our starting question

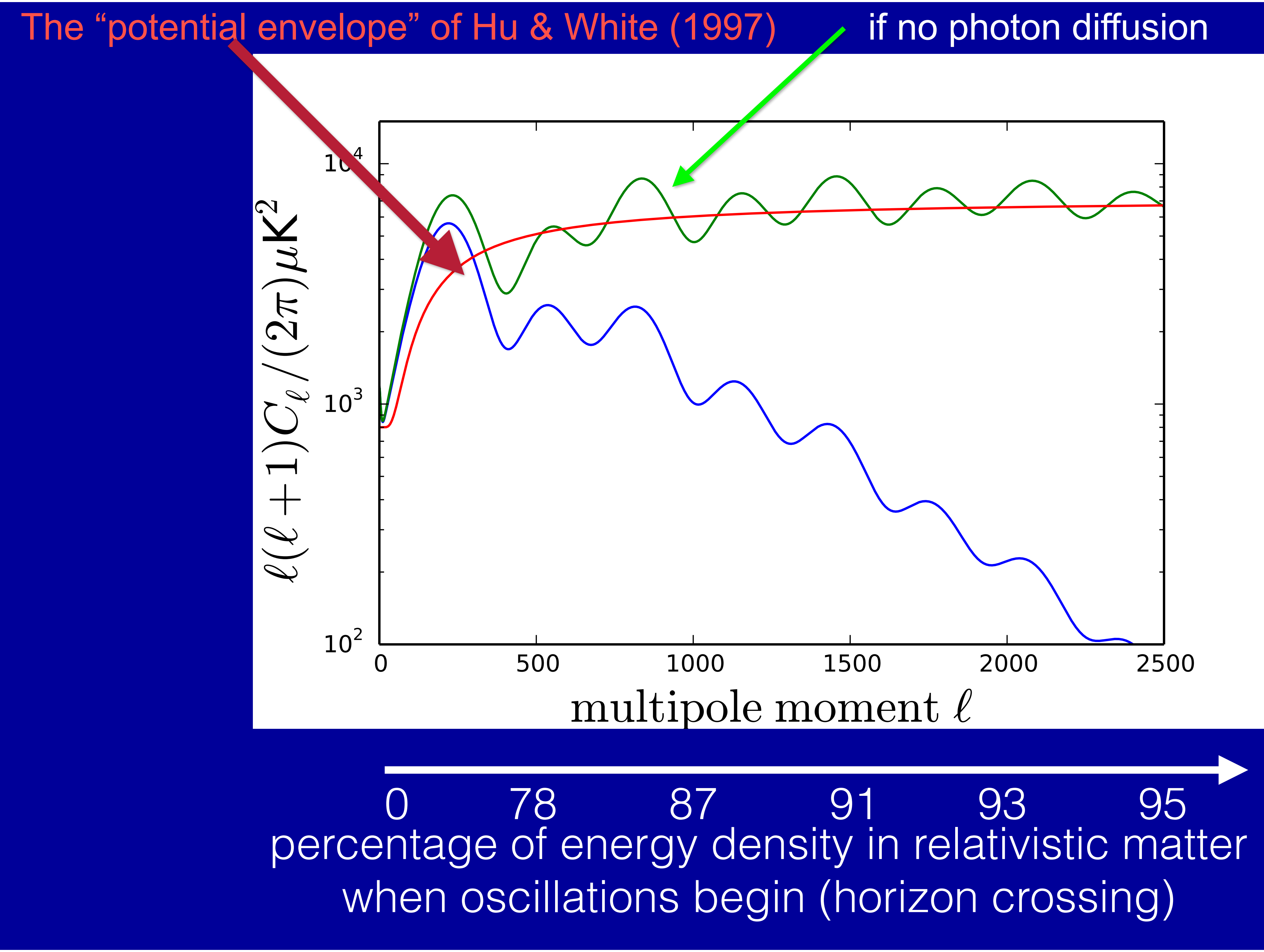
Our prior understanding of the origin of constraints on light relics



LCDM Temperature power spectrum
$\ell(\ell+1)C_\ell/(2\pi)\mu\mathrm{K}^2$
10^4
10^3
10^2
0
500
1000
1500
2000
2500
multipole moment ℓ


if no photon diffusion
$\ell(\ell+1)C_\ell/(2\pi)\mu\mathrm{K}^2$
10^4
10^3
10^2
0
500
1000
1500
2000
2500
multipole moment ℓ


if no photon diffusion
10^4
10^3
10^2
0
500
1000
1500
2000
2500
$\ell(\ell+1)C_\ell/(2\pi)\mu\mathrm{K}^2$
multipole moment ℓ
0
78
87
91
93
95
percentage of energy density in relativistic matter
when oscillations begin (horizon crossing)



The “potential envelope” of Hu & White (1997)
if no photon diffusion
$\ell(\ell+1)C_\ell/(2\pi)\mu K^2$
10^4
10^3
10^2
0
500
1000
1500
2000
2500
multipole moment ℓ
0
78
87
91
93
95
percentage of energy density in relativistic matter
when oscillations begin (horizon crossing)

How to accommodate light relics

Prior understanding

- Radiation driving effects ==> fix rho_m/rho_rad ==> increase cdm density
- Fix acoustic peak scale ==> fix r_s/D_{lss} ==> alter Lambda
- Fix photon diffusion scale ==> fix r_d/D_{lss} ==> alter Y_p
- Fix light relic free-streaming effects ==> fix R_{fs} ==> introduce a mix of free-streaming and fluid light relics

Cosmological Whackamole with Neff

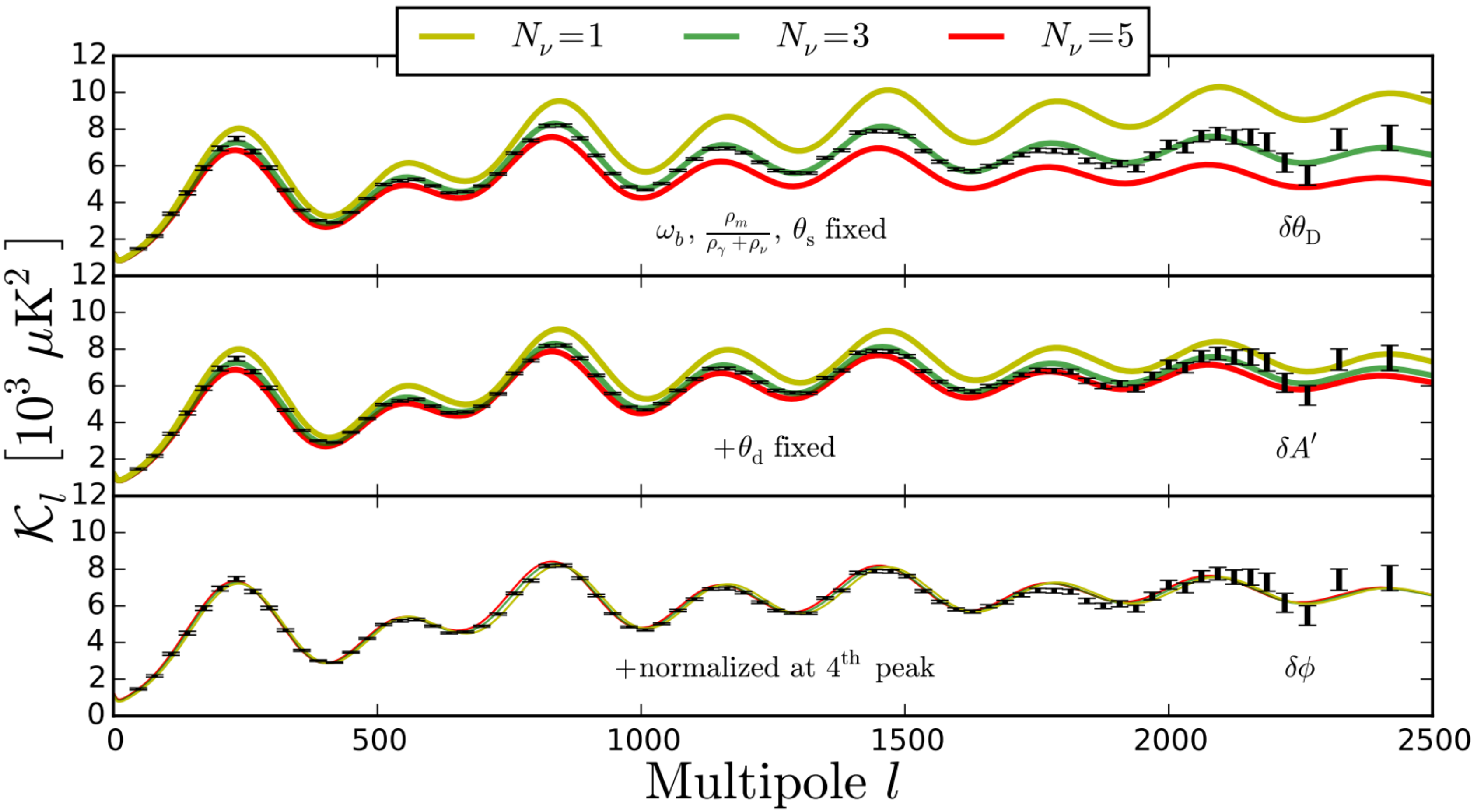
1) To fix rho_m/rho_rad, boost rho_m (top panel)

2) To fix theta_s = r_s/D_{lss}, change Lambda (top panel)

3) To fix theta_d = r_d/D_{lss}, change primordial Helium fraction (middle panel)

4) To prevent oscillator amplitude change and phase shift*, include some fluid light relics to fix rho_{fs}/rho_{fluid} (not shown)

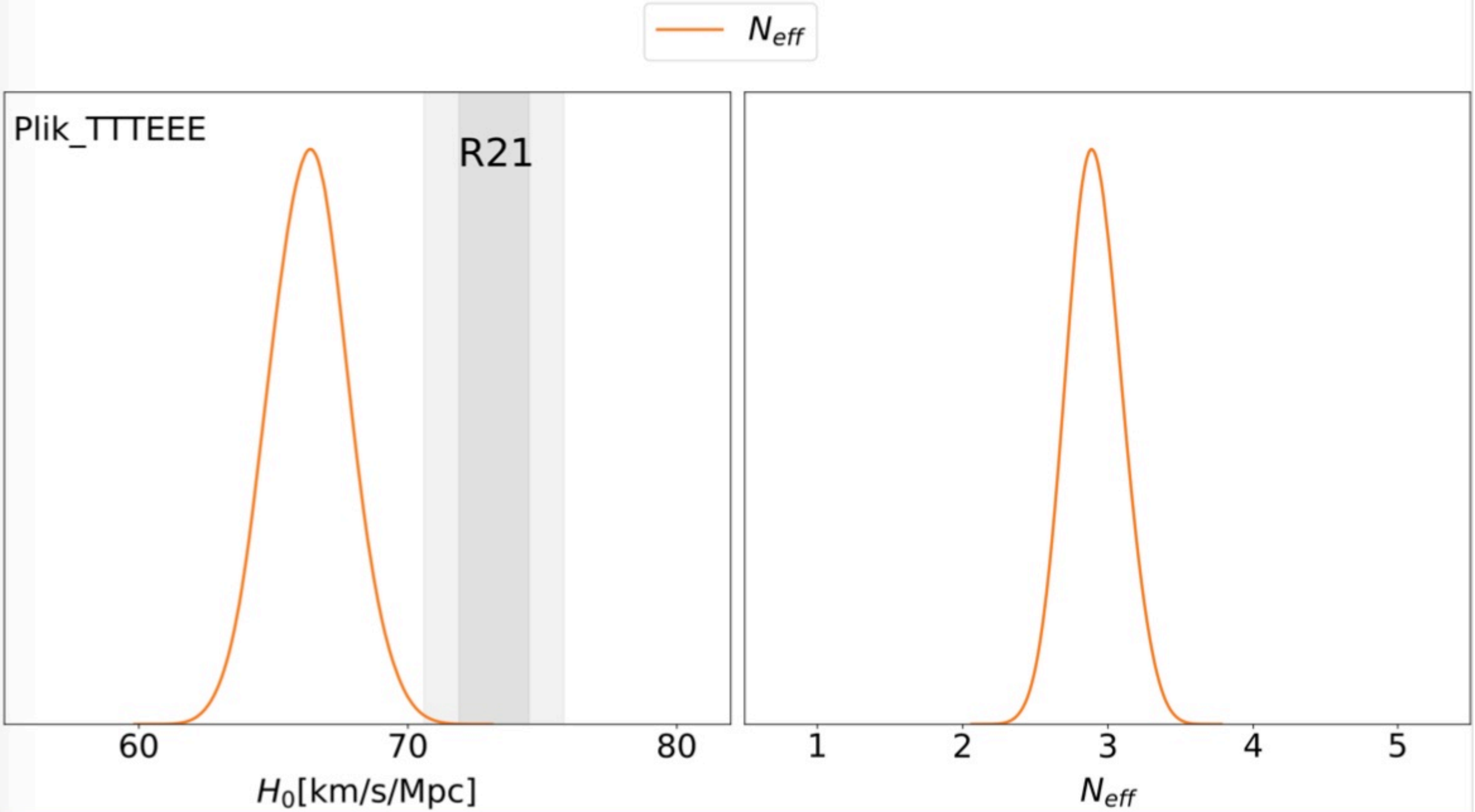
Fiducially Undamped Spectra



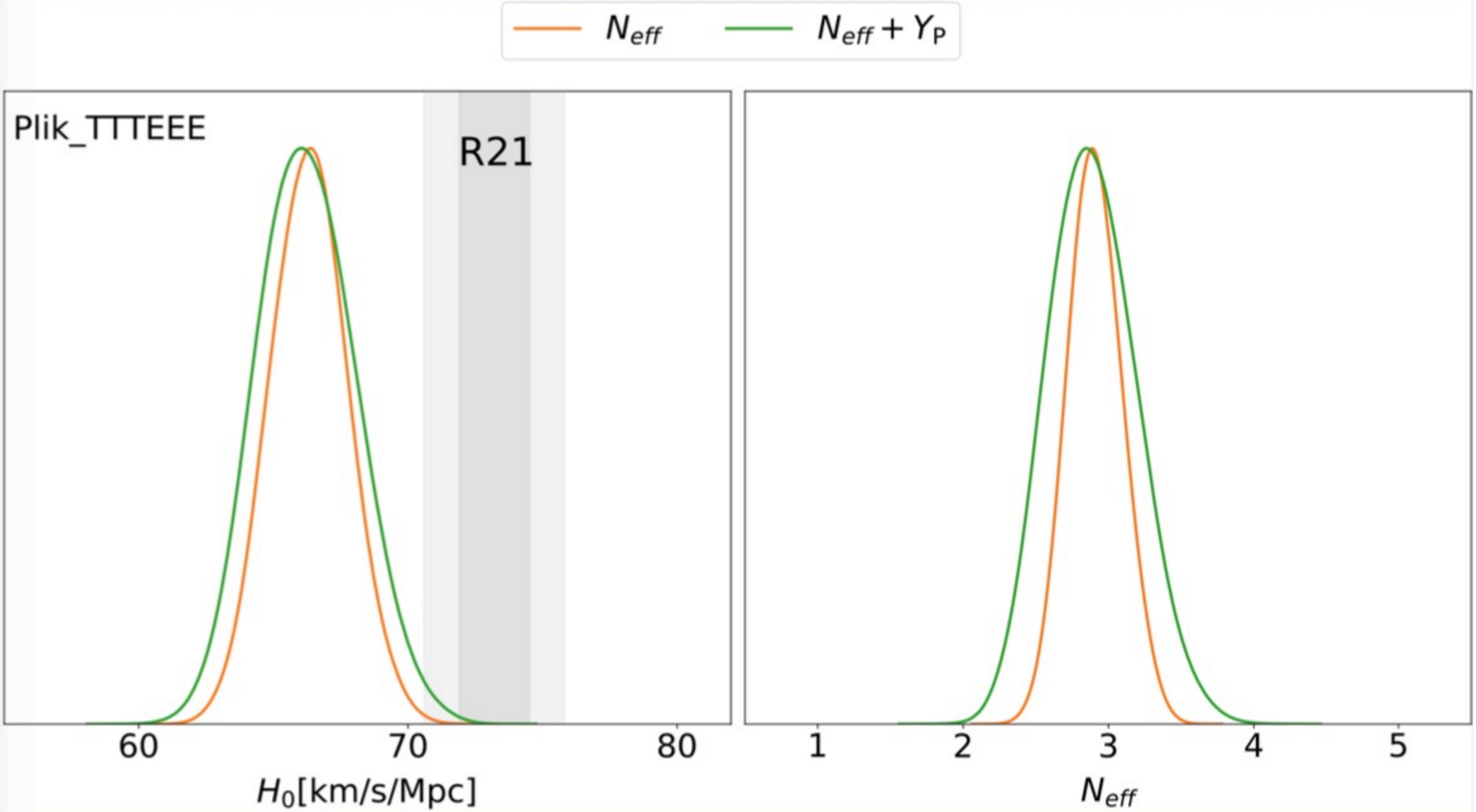
*Bashinsky & Seljak (2004)

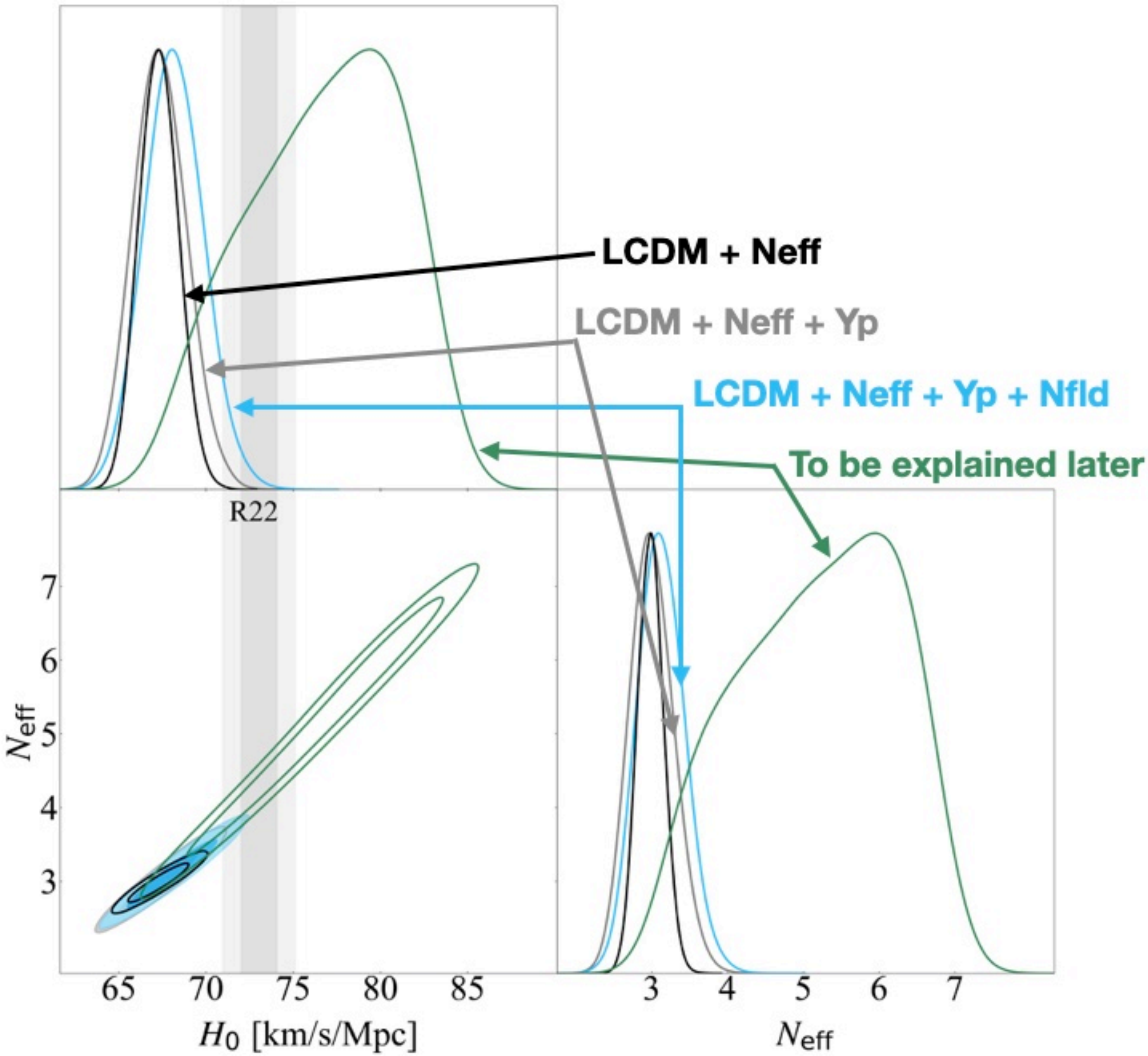
Follin, LK, Millea and Pan (2015)

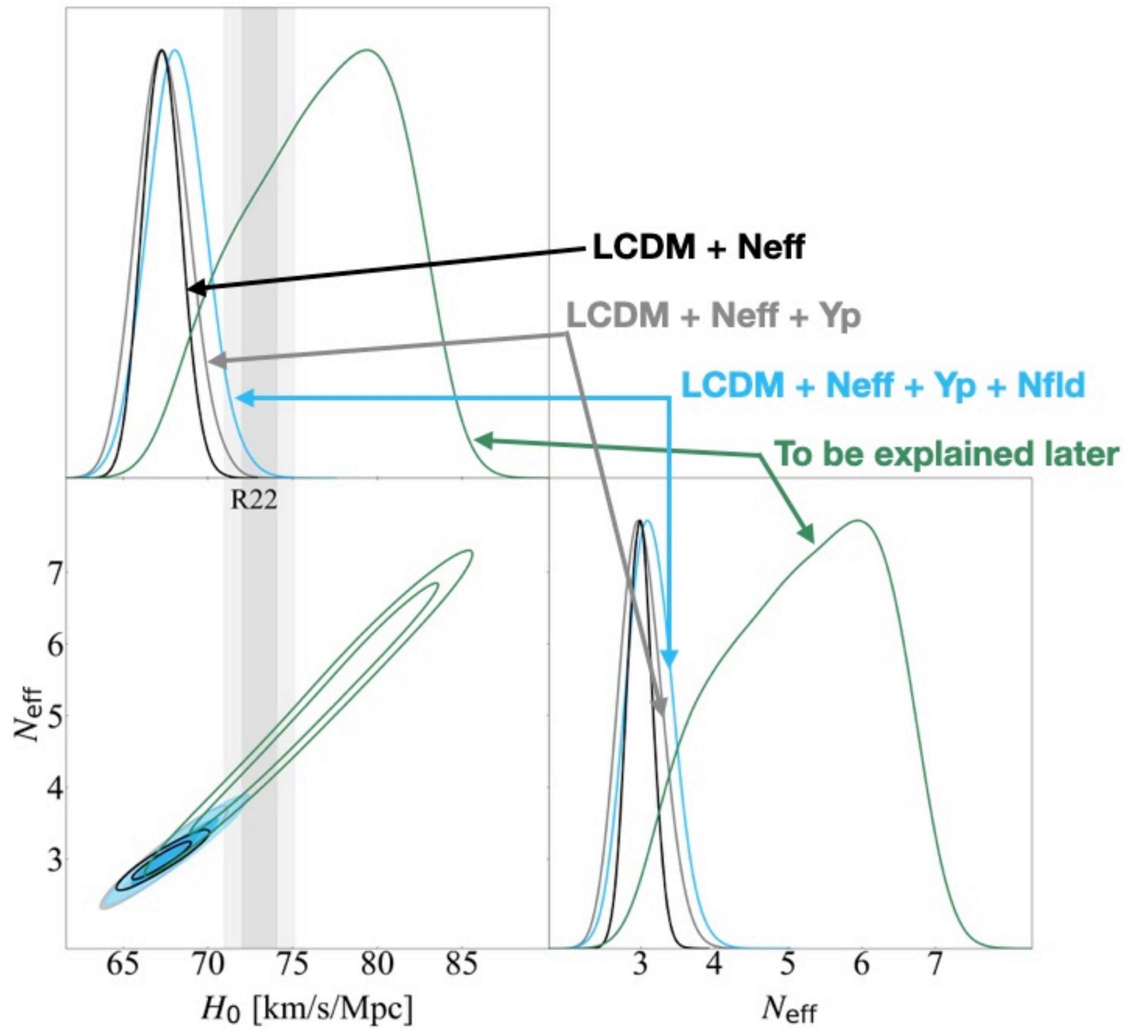
Constraints from Planck 2018 CMB temperature and polarization power spectra



Constraints from Planck 2018 CMB temperature and polarization power spectra




LCDM + Neff
LCDM + Neff + Yp
LCDM + Neff + Yp + Nfld
To be explained later
R22
$N_{\rm eff}$
H_0 [km/s/Mpc]
$N_{\rm eff}$
65 70 75 80 85
3 4 5 6 7
3 4 5 6 7



Why are Ho and Neff still fairly tightly constrained even in a model space that can get the desired angular scales, matter to radiation ratio, and free-streaming ratio?

A Scaling Transformation Symmetry

Einstein and Boltzmann Equations

$$
\begin{aligned}
\frac{\partial F_{\gamma 0}}{\partial a} &= -\frac{k}{a^2 H} F_{\gamma 1} + 4\frac{\partial \phi}{\partial a}, \qquad (2)\\
a^2 H \frac{\partial F_{\gamma 1}}{\partial a} &= \frac{k}{3}(F_{\gamma 0} - 2F_{\gamma 2}) + \frac{4k}{3}\psi + \dot{\kappa}(\frac{4}{3}v_{\mathrm{b}} - F_{\gamma 1}),\\
a^2 H \frac{\partial F_{\gamma 2}}{\partial a} &= \frac{k}{5}(2F_{\gamma 1} - 3F_{\gamma 3}) - \frac{9}{10}\dot{\kappa} F_{\gamma 2},\\
a^2 H \frac{\partial F_{\gamma l}}{\partial a} &= \frac{k}{2l+1}\left[l F_{\gamma(l-1)} - (l+1) F_{\gamma(l+1)}\right] - \dot{\kappa} F_{\gamma l},\\
\frac{\partial \delta_{\mathrm{b}}}{\partial a} &= -\frac{k}{a^2 H} v_{\mathrm{b}} + 3\frac{\partial \phi}{\partial a},\\
a^2 H \frac{\partial v_{\mathrm{b}}}{\partial a} &= -aH v_{\mathrm{b}} + c_{\mathrm{s}}^2 k \delta_{\mathrm{b}} + k\psi + \frac{\bar{\rho}_\gamma}{\bar{\rho}_{\mathrm{b}}}\dot{\kappa}(F_{\gamma 1} - \frac{4}{3}v_{\mathrm{b}}),
\end{aligned}
$$

where $F_{\gamma l}$ are the multipole moments of the photon temperature perturbation, k is the Fourier wavenumber, $\dot{\kappa} = a\sigma_{\mathrm{T}} n_{\mathrm{e}}$ is the Thomson opacity, δ_{b} is the baryon density perturbation, v_{b} is the baryonic bulk velocity, c_{s} is the baryonic sound speed, and ϕ and ψ are the two gravitational potentials in conformal Newtonian gauge. Note

Some of the Boltzmann equations for evolving spatial perturbations as the scale factor increases

Everything is dimensionless* here except H(a), k, and the photon scattering rate $\dot{\kappa}/a = \sigma_{\mathrm{T}} n_e(a)$

*we set c=1

Boltzmann Equations

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

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

$$a^2 H \frac{\partial F_{\gamma 2}}{\partial a} = \frac{k}{5}(2F_{\gamma 1} - 3F_{\gamma 3}) - \frac{9}{10}\dot{\kappa} F_{\gamma 2},$$

$$a^2 H \frac{\partial F_{\gamma l}}{\partial a} = \frac{k}{2l+1}\left[lF_{\gamma(l-1)} - (l+1)F_{\gamma(l+1)}\right] - \dot{\kappa} F_{\gamma l},$$

$$\frac{\partial \delta_{\rm b}}{\partial a} = -\frac{k}{a^2 H} v_{\rm b} + 3\frac{\partial \phi}{\partial a},$$

$$a^2 H \frac{\partial v_{\rm b}}{\partial a} = -aHv_{\rm b} + c_{\rm s}^2 k \delta_{\rm b} + k\psi + \frac{\bar{\rho}_\gamma}{\bar{\rho}_{\rm b}}\dot{\kappa}(F_{\gamma 1} - \frac{4}{3}v_{\rm b}),$$

where $F_{\gamma l}$ are the multipole moments of the photon temperature perturbation, k is the Fourier wavenumber, $\dot{\kappa} = a\sigma_{\rm T} n_{\rm e}$ is the Thomson opacity, $\delta_{\rm b}$ is the baryon density perturbation, $v_{\rm b}$ is the baryonic bulk velocity, $c_{\rm s}$ is the baryonic sound speed, and ϕ and ψ are the two gravitational potentials in conformal Newtonian gauge. Note

Einstein Equations

$$H = \sqrt{8\pi G \Sigma_i \rho_i / 3}$$

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

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

where δ_i, σ_i and P_i are the energy density perturbation, anisotropic stress and pressure of species i, respectively. These equations are invariant under the trans-

These equations are invariant under a uniform scaling:

$$\sqrt{G\rho_i} \to \lambda\sqrt{G\rho_i},\; k \to \lambda k,\; \sigma_{\rm T} n_{\rm e} \to \lambda \sigma_{\rm T} n_{\rm e}.$$

(which ensures $H(z) \to \lambda H(z)$)

==> for scale-invariant initial conditions, dimensionless observables are also invariant

A scaling of the amplitude can extend this invariance of observables to the case of initial conditions with a power-law power spectrum

This scaling transformation

$$\left\{\sqrt{G\rho_i} \to \lambda\sqrt{G\rho_i},\ \sigma_{\mathrm{T}} n_{\mathrm{e}} \to \lambda\sigma_{\mathrm{T}} n_{\mathrm{e}},\ A_{\mathrm{s}} \to A_{\mathrm{s}}/\lambda^{n_{\mathrm{s}}-1}\right\}$$

leaves dimensionless cosmological observables invariant.

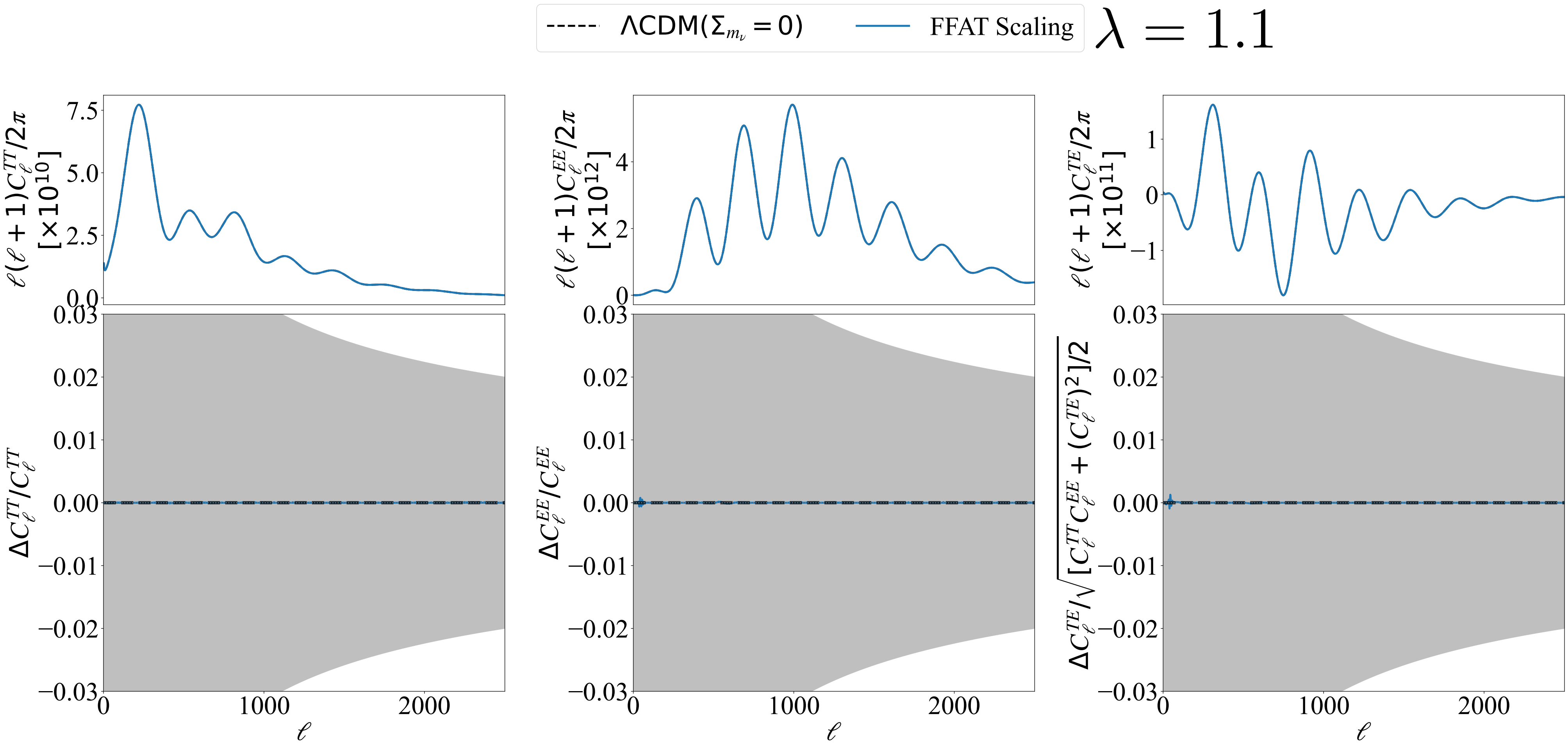
Cyr-Racine, Ge, and Knox (2022)

[See also Zahn and Zaldarriaga (2004) who considered a similar transformation w/o the scattering rate scaling]

A new symmetry of dimensionless cosmological observables (that are derived from the Einstein-Boltzmann equations)

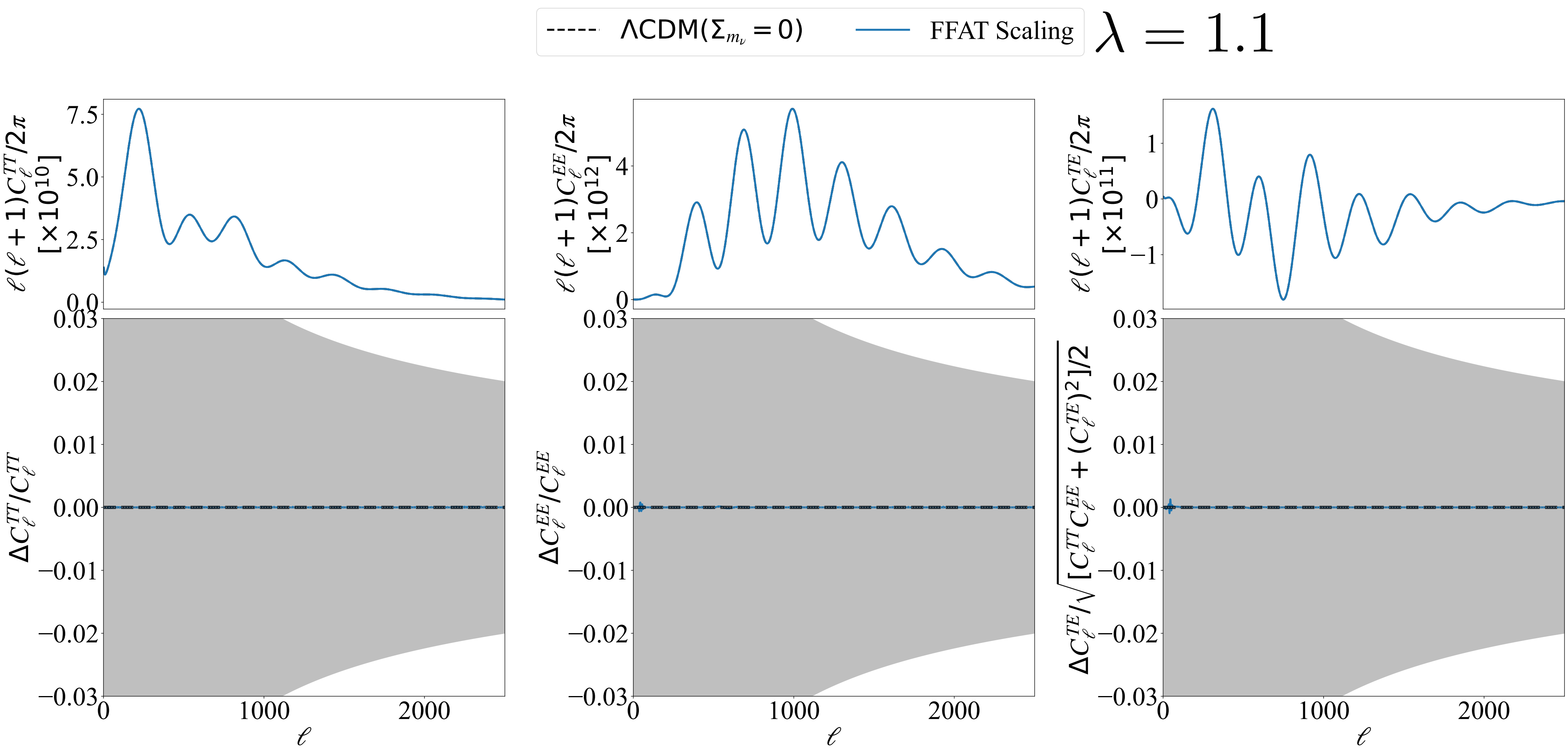
Distance ratios, CMB temperature and polarization maps and their power spectra, galaxy two-point correlation functions, cosmic shear maps, CMB lensing maps, ...

How well does it work?



Perfectly!

How well does it work?



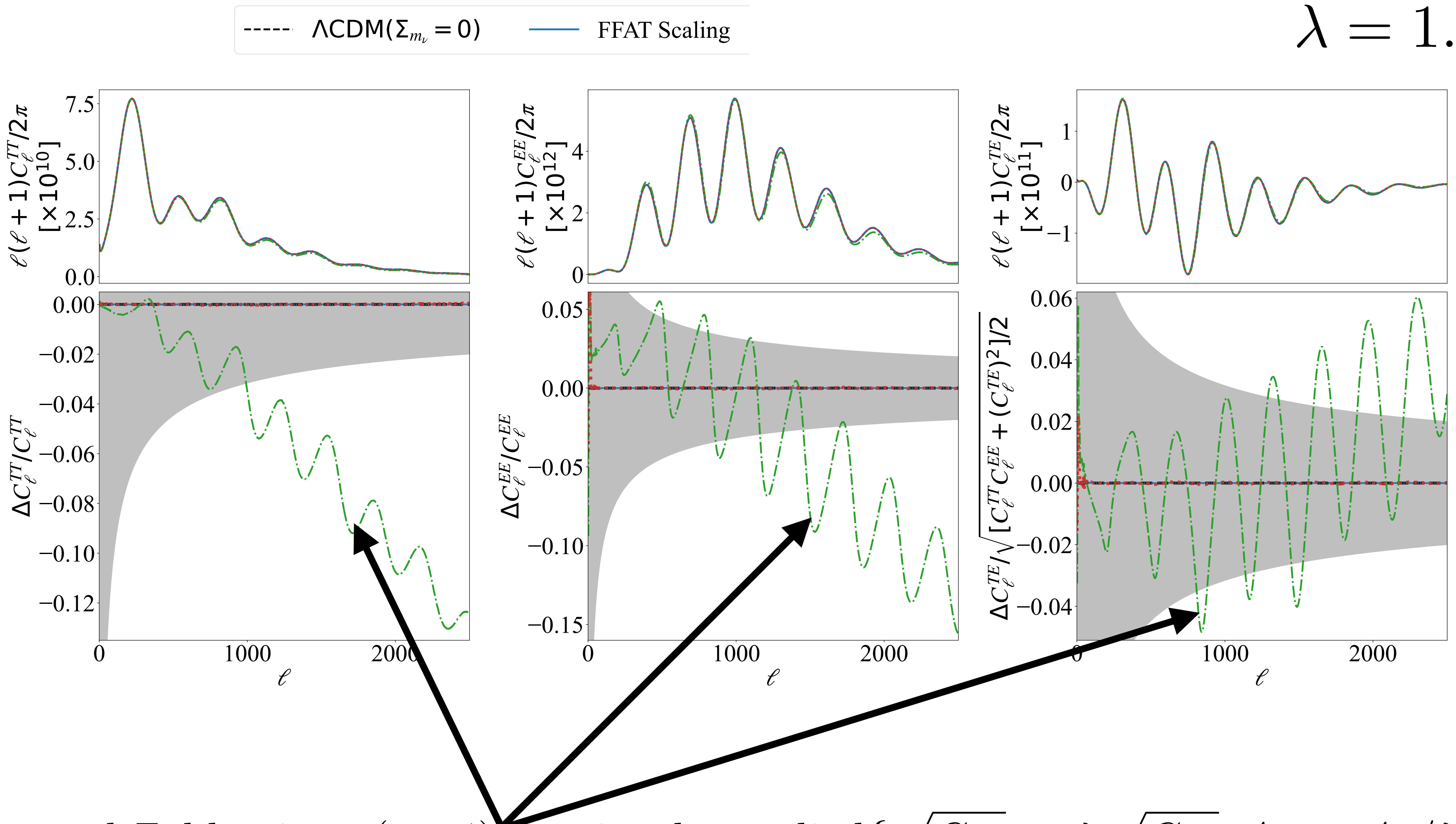
Note: this scaling boosts light relic densities (and the Hubble constant)

==> one can understand constraints on light relics as due to constraints that prevent one from following this scaling transformation

How well does it work?

By the way...

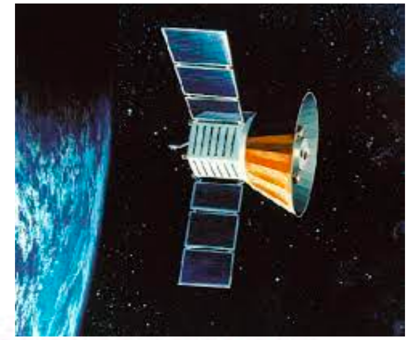
$\lambda = 1.1$

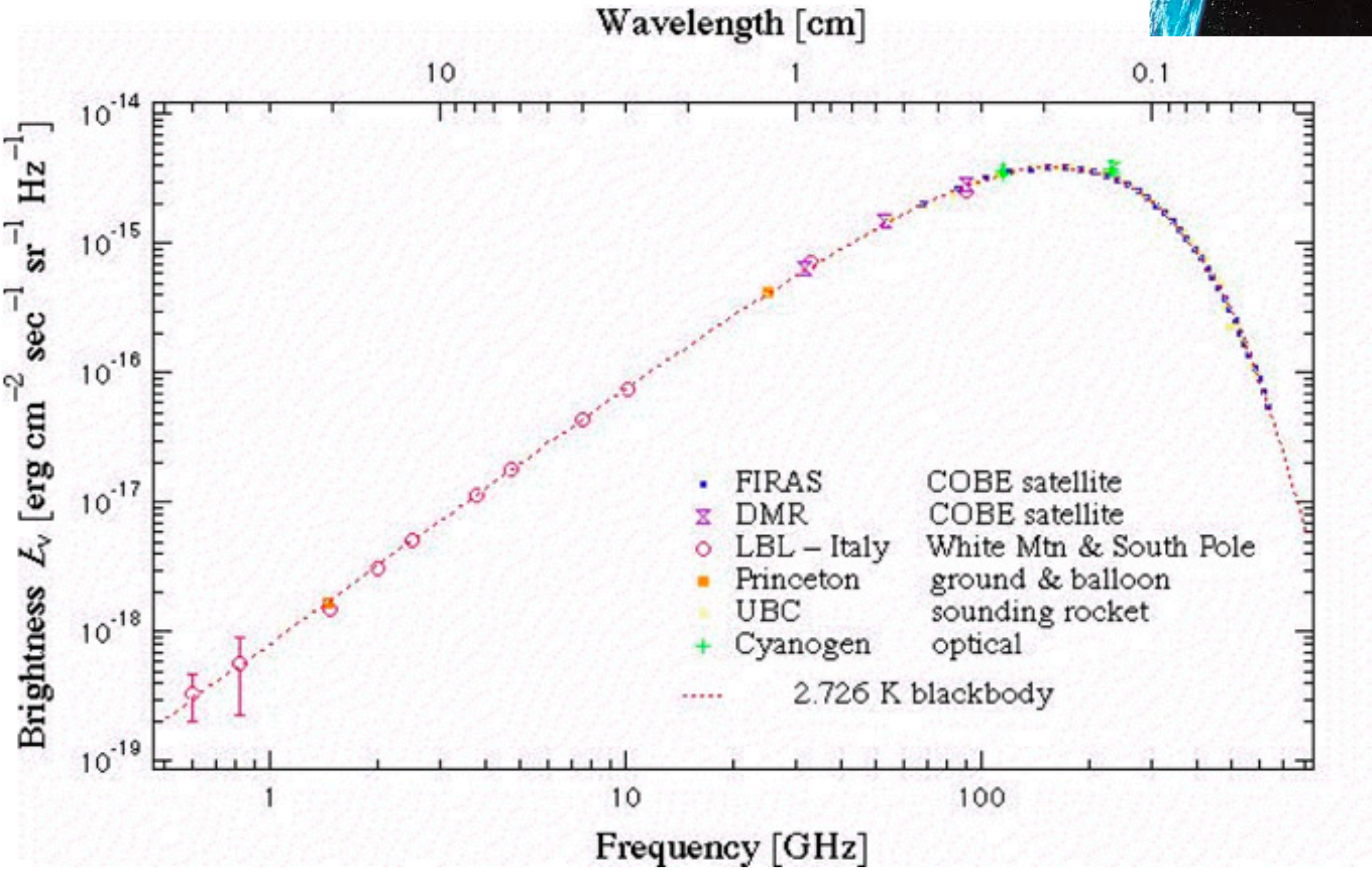


Zahn and Zaldarriaga (2004) previously studied$\{\sqrt{G\rho_i} \to \lambda\sqrt{G\rho_i}, A_s \to A_s/\lambda^{n_s-1}\}$

(no Thomson rate scaling)

Important constraint: we know the photon density today!





See also: Ivanov, Ali-Haimoud & Lesgourgues (2020)

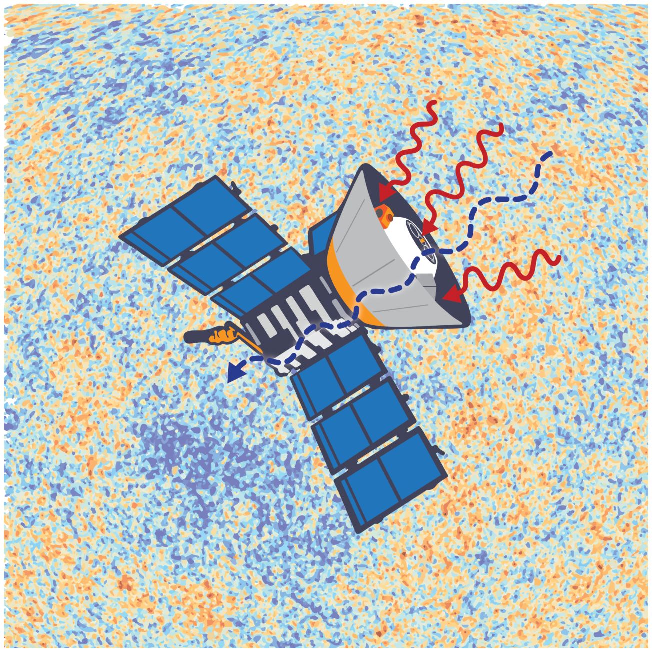
Constraints on FFAT Scaling

- FIRAS is the main challenge for free-fall rate scaling
  - It has a number of consequences, chief among them: CMB spectra are very sensitive to rho_b/rho_gamma so can't scale up rho_b by very much either
- Well-known atomic physics and primordial helium abundance measurements constrain scattering rate (T) scaling, but not as severely.

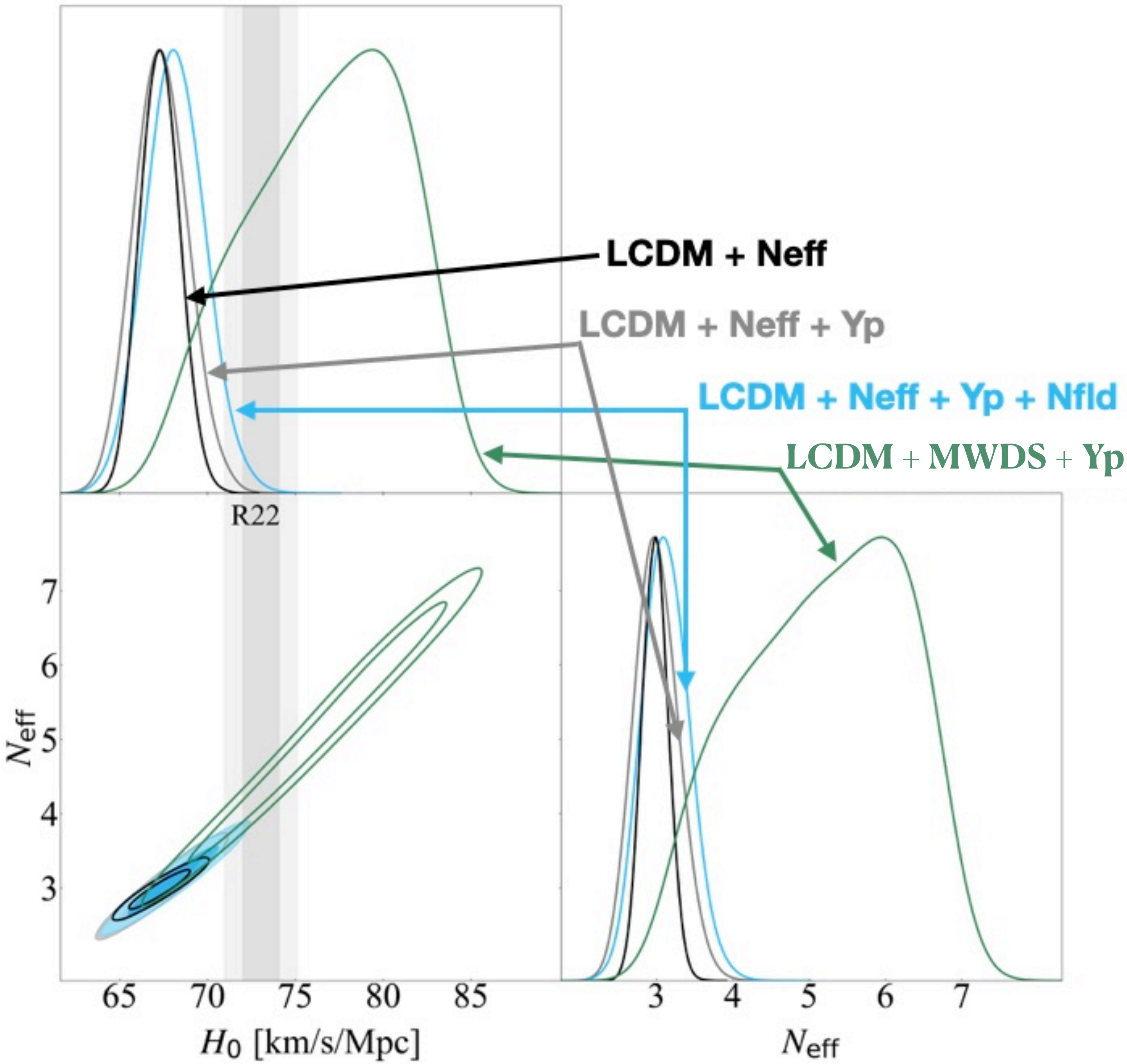
==> We are forced into "incomplete" scaling transformations

Circumventing FIRAS

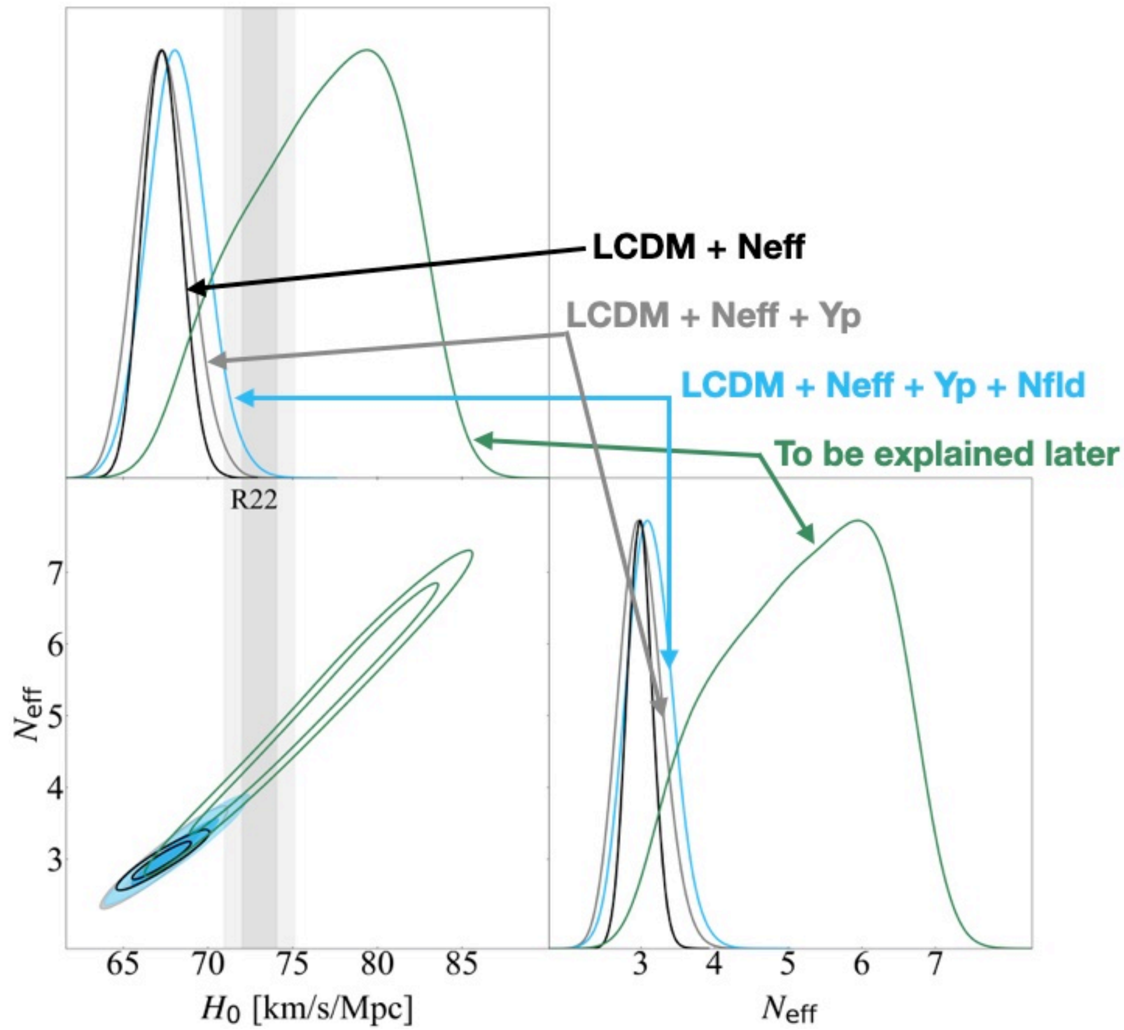
With a Mirror World Dark Sector (cosmological whackamole on steroids?)



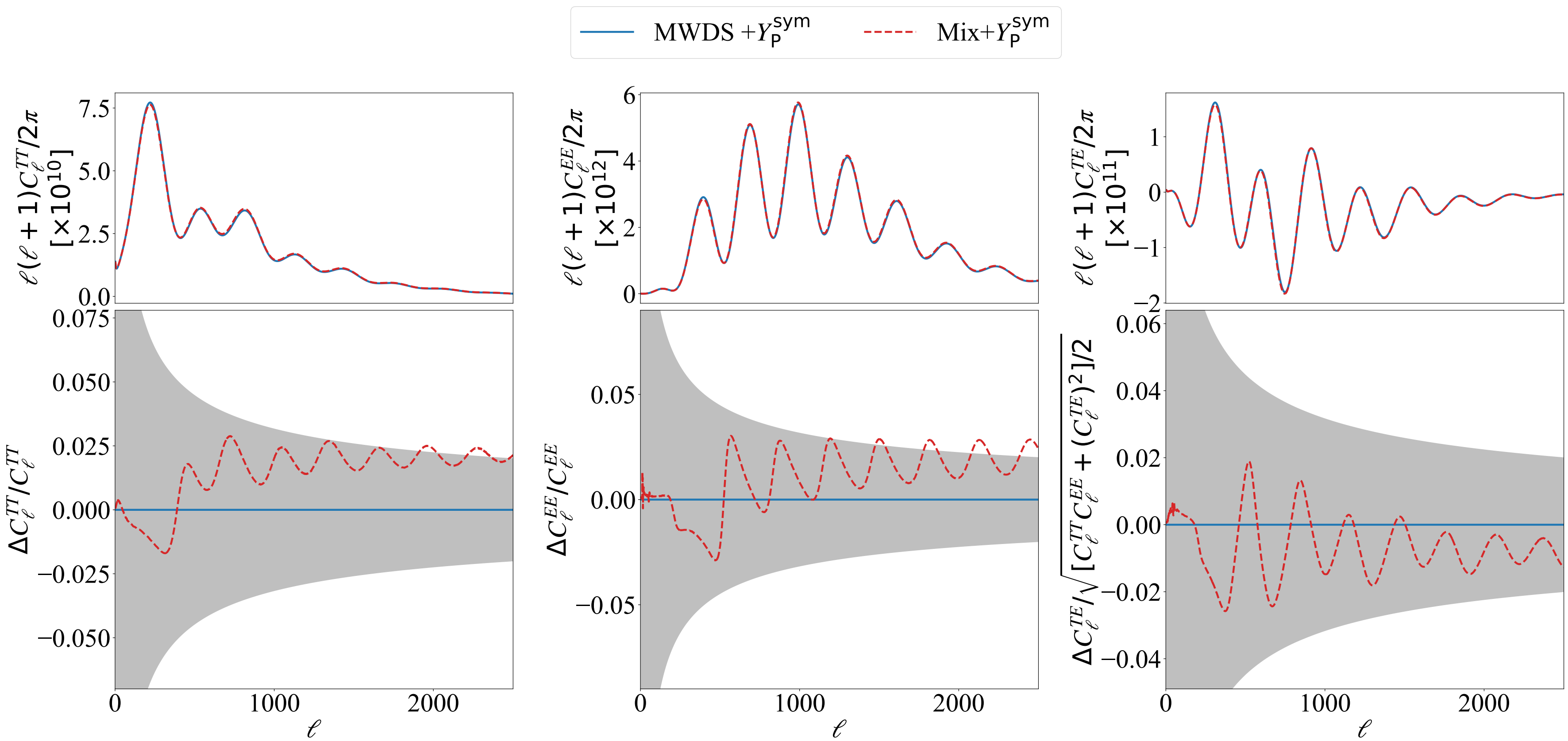
- Adding in dark photons instead of scaling up the (light) photon density would evade the FIRAS constraint
- Fluid —> free streaming at the same time ==> effectively mimic the scaling transformation.
- Adding in dark protons and dark electrons allows for dark recombination and dark last scattering, and completes the mimicking of the scaling transformation.
- Dark neutrinos would allow for scaling up the free-streaming light-relic density.
- Copies of the standard model have been invented for other, completely independent reasons.



LCDM + Neff
LCDM + Neff + Yp
LCDM + Neff + Yp + Nfld
LCDM + MWDS + Yp
R22
N_{eff}
H_0 [km/s/Mpc]
N_{eff}
65 70 75 80 85
3 4 5 6 7



Why are Ho and Neff still fairly tightly constrained even in a model space that can get the desired angular scales, matter to radiation ratio, and free-streaming ratio?



MWDS + Yp

Atomic dark matter ———-> fraction of cdm
Dark photons ————-> Dark fluid

Mix + Yp

Adapted from Ge, Cyr-Racine & Knox (2022)

Categorization of Causes of Light Relics Constraints

Rate ratio change	Prior literature	Quantitative Impact on CMB Power Spectra ($\lambda = 1.1$)
1. $\sigma_T n_e(z)/H(z)$	Hu & White (1996), Zahn & Zaldarriaga (2004), Martins et al. (2010), Hou et al. (2013)	10 to 15%
2. $\frac{\sqrt{\rho_{\mathrm{rad,fs}}}}{\sqrt{\rho_{\mathrm{rad,fluid}}}}$	Bashinksy & Seljak (2004), Follin et al. (2015), Baumann et al. (2016)	5 to 6%
3. $\frac{\sqrt{\rho_{\mathrm{m,pressure}}}}{\sqrt{\rho_{\mathrm{m,pressureless}}}}$	None	2 to 3%
4. recombination rates$/H(z)$	Zahn & Zaldarriaga (2004) and now much better understood	1 to 2%

Constraints from Planck + BAO in several model spaces

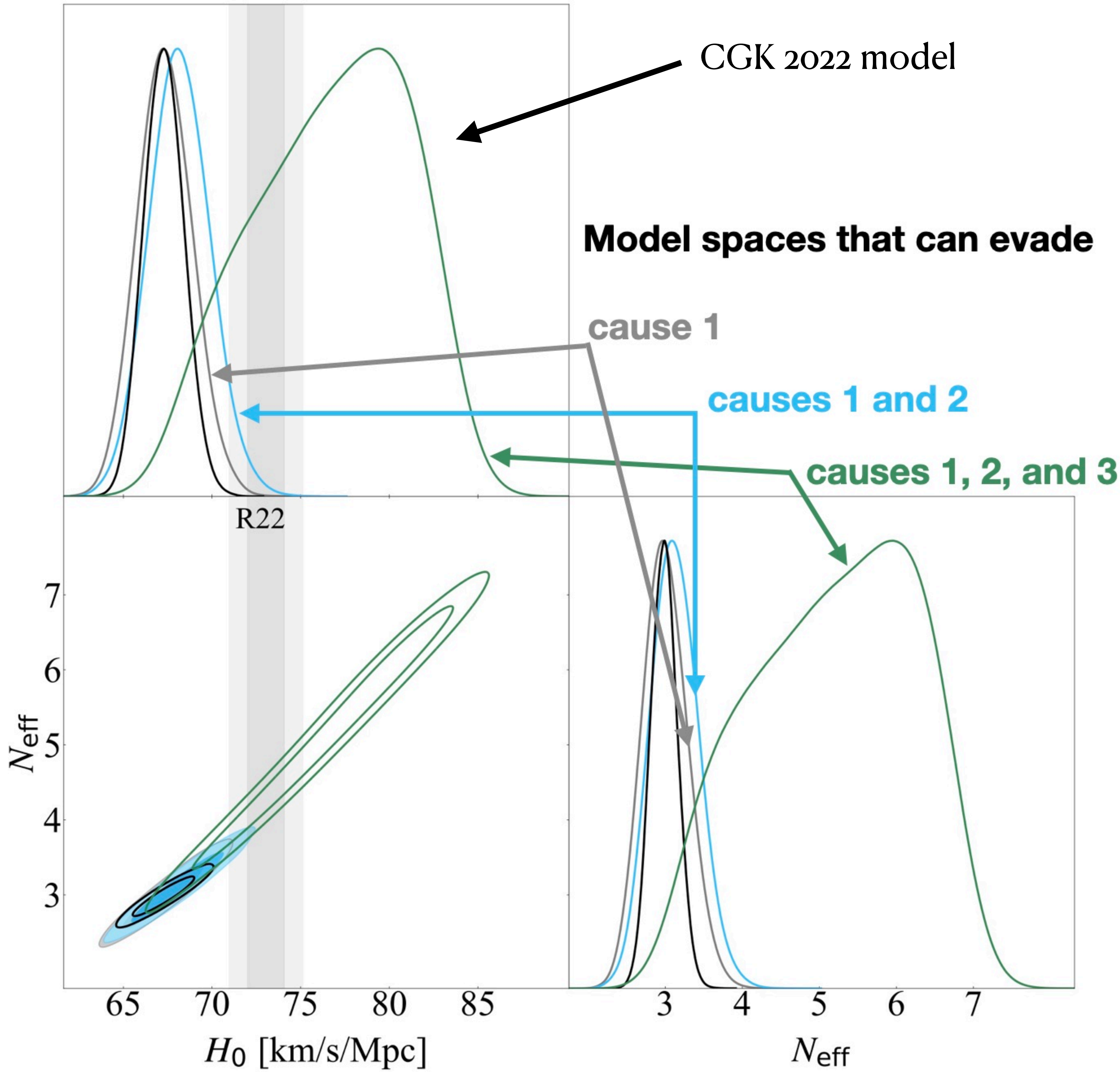
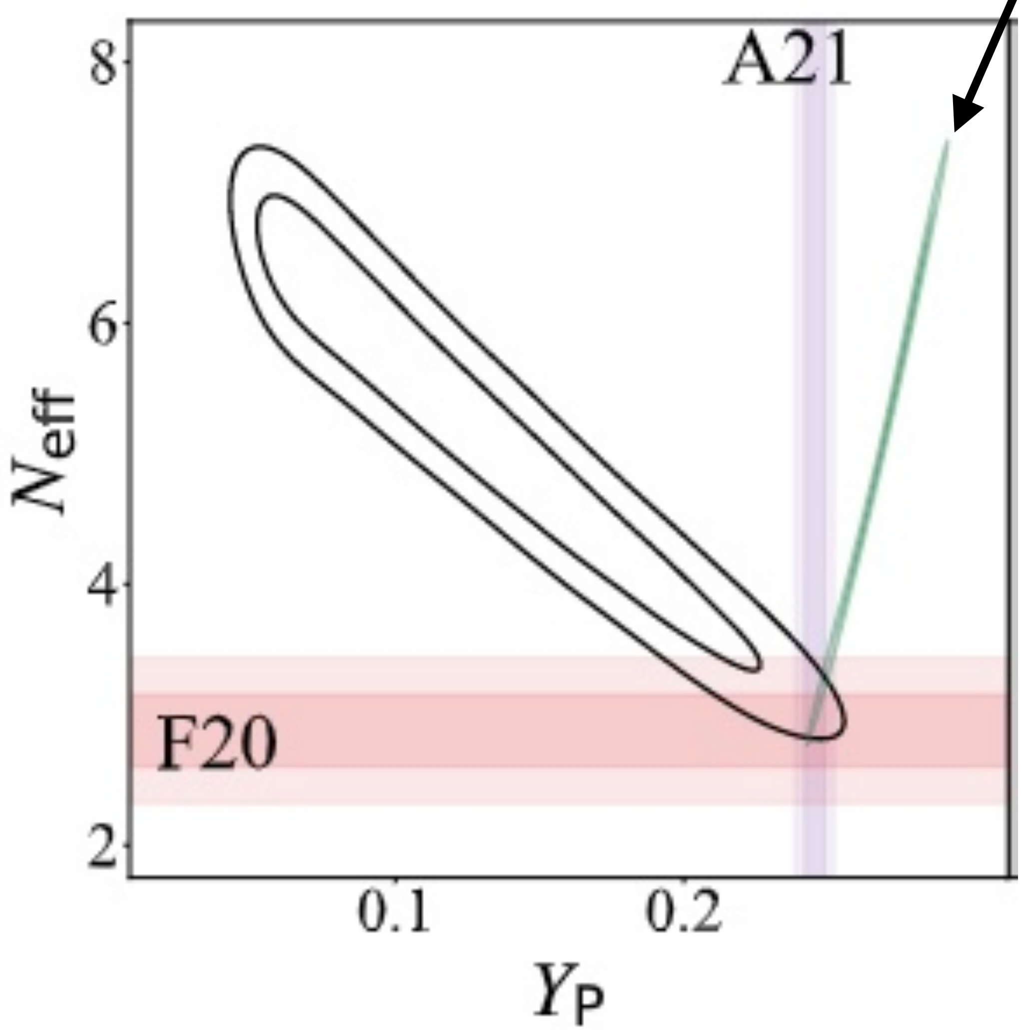


Figure adapted from Ge, Cyr-Racine & Knox (2022)

BBN Consistent Yp

A21 = measurement of Yp (Aver et al. 2021)

Contours assume MWDS + free Yp



F20 = constraints on Neff from BBN + D/H and Yp measurements (Fields et al. 2020)

Our work has opened up a new path towards potential resolution of the H_0 problem.

Another way to boost the scattering rate

Mirror Dark Sector Solution of the Hubble Tension with Time-varying Fine-structure Constant

Show affiliations

Zhang, John ; Frieman, Joshua

We explore a model introduced by Cyr-Racine, Ge, and Knox (arXiv:2107.13000(2)) that resolves the Hubble tension by invoking a ``mirror world" dark sector with energy density a fixed fraction of the ``ordinary" sector of Lambda-CDM. Although it reconciles cosmic microwave background and large-scale structure observations with local measurements of the Hubble constant, the model requires a value of the primordial Helium mass fraction that is discrepant with observations and with the predictions of Big Bang Nucleosynthesis (BBN). We consider a variant of the model with standard Helium mass fraction but with the value of the electromagnetic fine-structure constant slightly different during photon decoupling from its present value. If α at that epoch is lower than its current value by $\Delta\alpha \simeq -2 \times 10^{-5}$, then we can achieve the same Hubble tension resolution as in Cyr-Racine, et al. but with consistent Helium abundance. As an example of such time-evolution, we consider a toy model of an ultra-light scalar field, with mass $m < 4 \times 10^{-29}$ eV, coupled to electromagnetism, which evolves after photon decoupling and that appears to be consistent with late-time constraints on α variation and the weak equivalence principle.

Why is the scattering rate scaling the same as the free-fall rate scaling?

Question raised by Zhang and Frieman

My own take on our work (CGK and GCK)

- The scaling transformation symmetry is a useful aid to analytic understanding
- The model it led us to is quite baroque, conflicts with light element abundance data, probably requires changes away from standard BBN, and leaves the uniformity of T and FF scaling unexplained.
- Future developments could conceivably change this, but right now it is looking to be unlikely that nature is doing something like this.
- The CGK model is an existence proof though that one can make large changes to the underlying model and leave CMB (and other) observables invariant.

Recent Approaches to the question of what the CMB data allow and what they do not

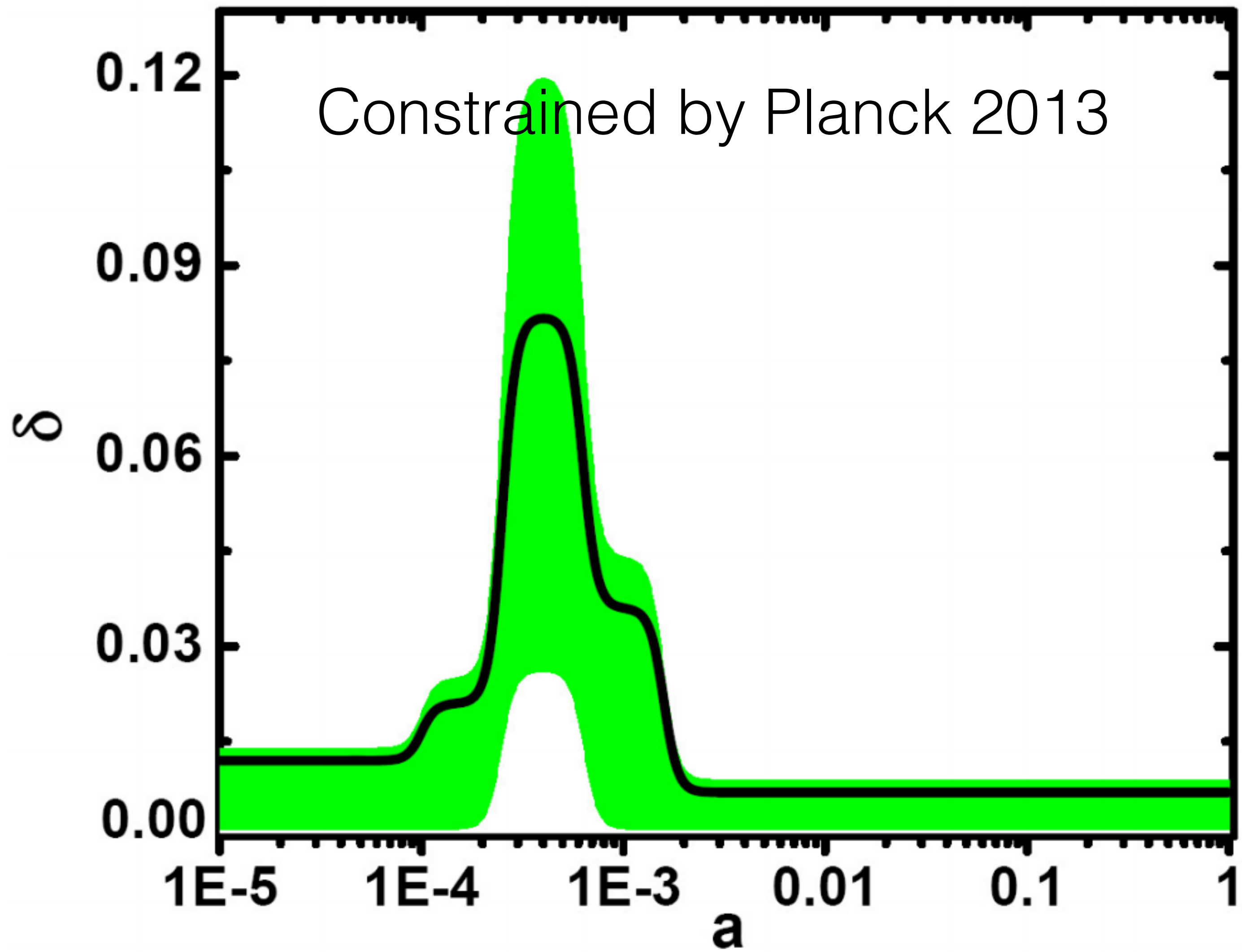
1. Pursuit of analytic understanding
2. Exploration of purely phenomenological high-dimensional cosmological models

Designer H(a)

arXiv:1304.3724

New Constraints on the Early Expansion History

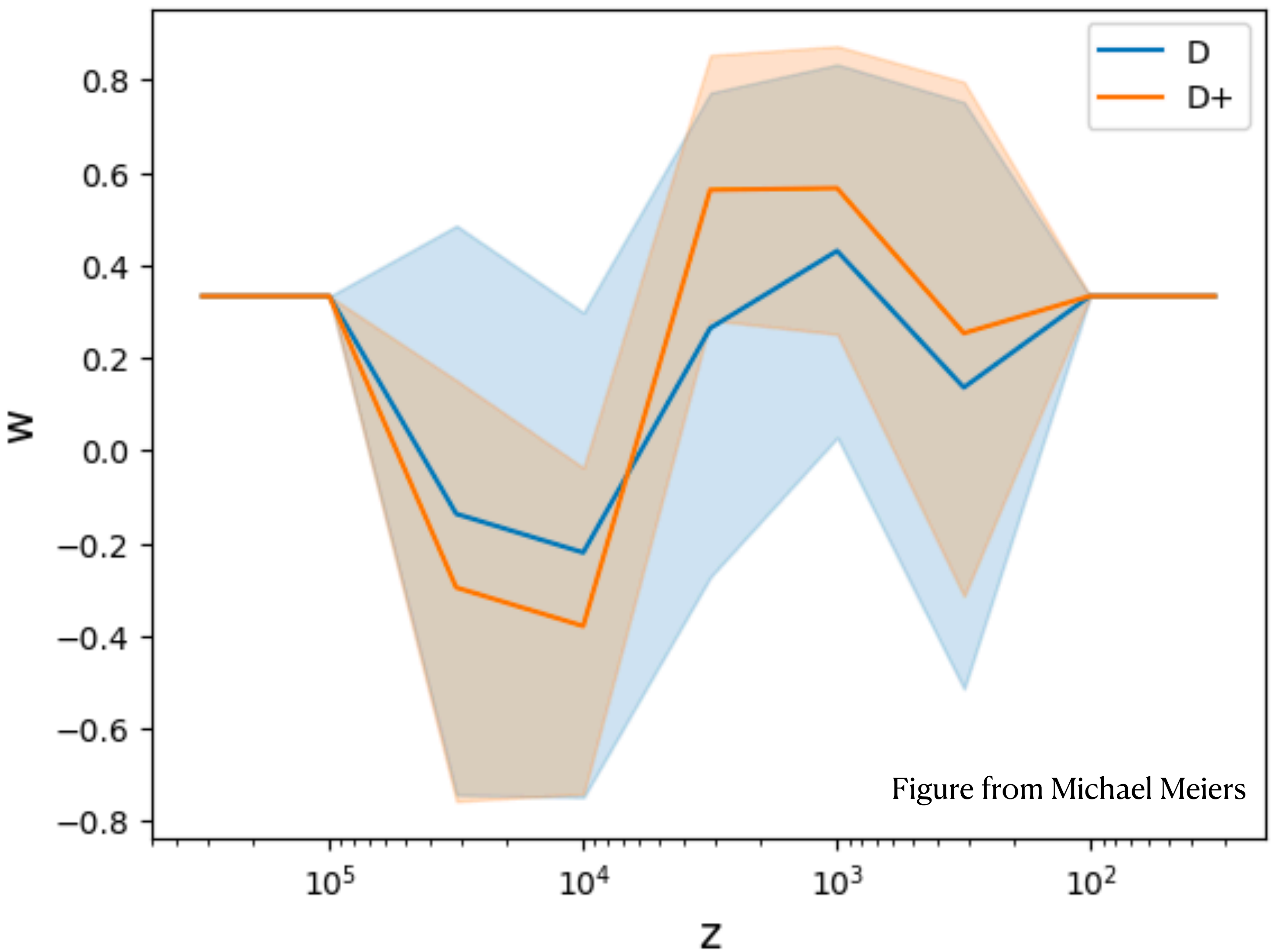
Alireza Hojjati[1], Eric V. Linder[1,2], Johan Samsing[3]



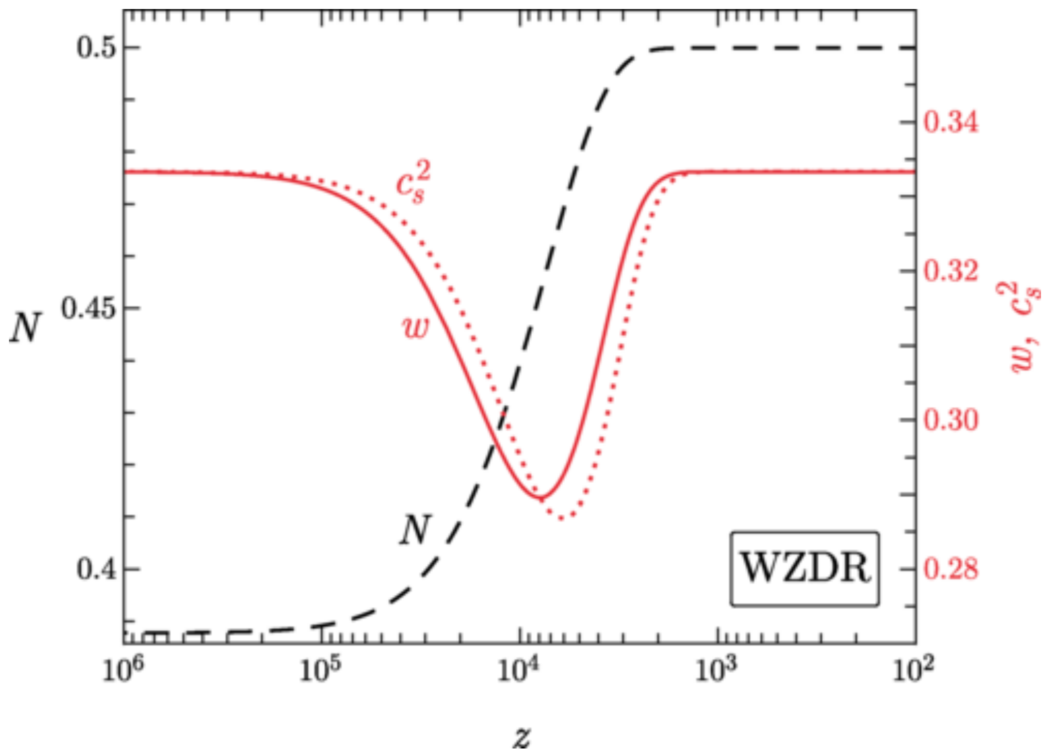
$$H^2(a) = \frac{8\pi G}{3}\left[\rho_m(a) + \rho_r(a) + \rho_\Lambda\right]\left[1 + \delta(a)\right]$$

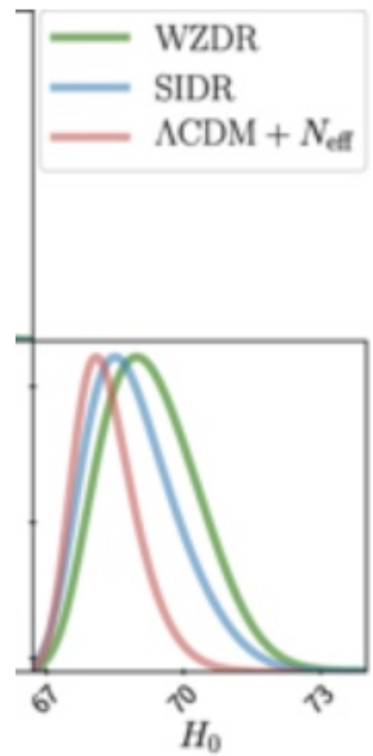
Generalized Dark Matter with “free” w(z)

Example

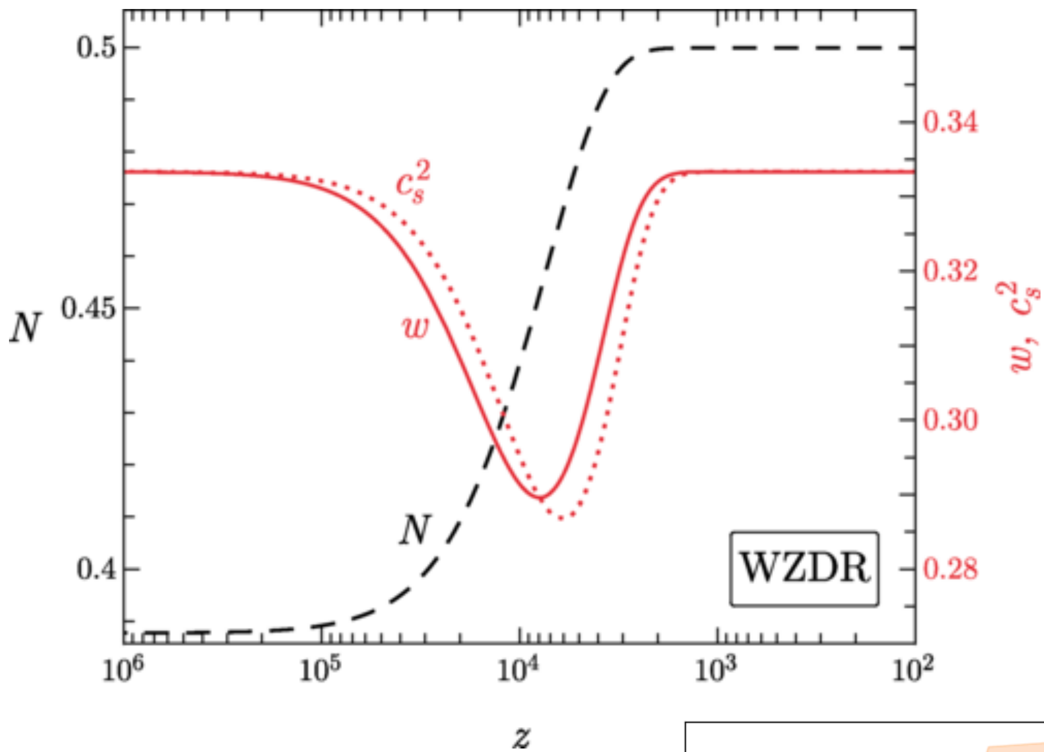


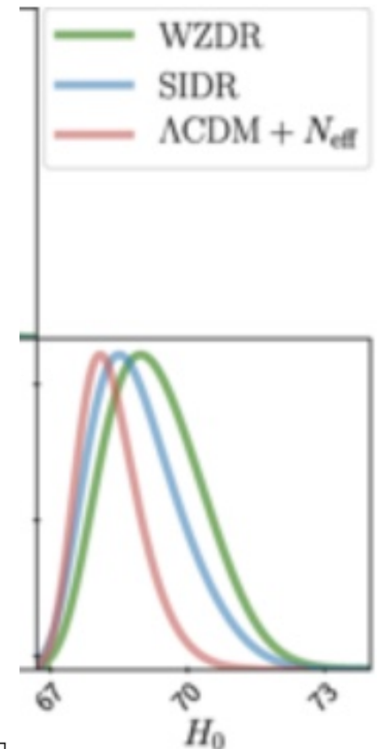
“A Step in Understanding the Hubble Tension” (Aloni et al. 2022)

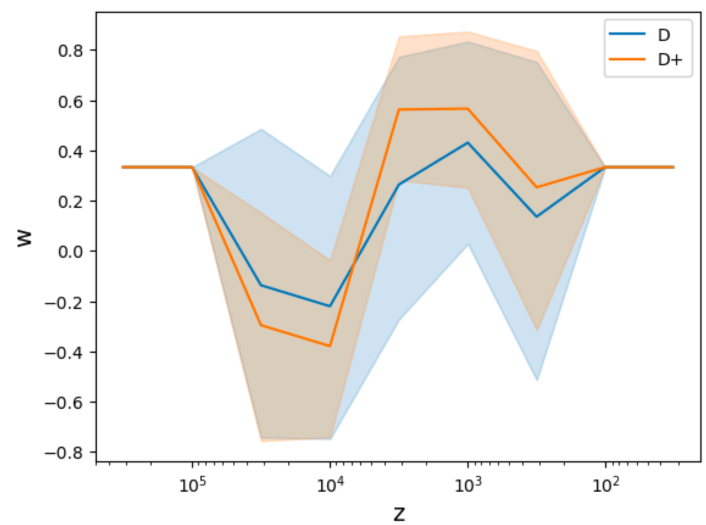




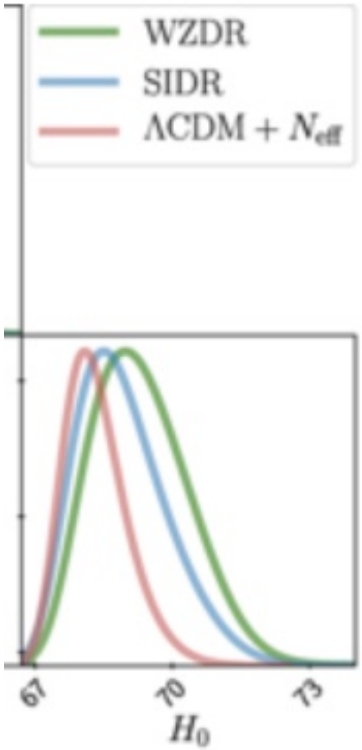
“A Step in Understanding the Hubble Tension” (Aloni et al. 2022)

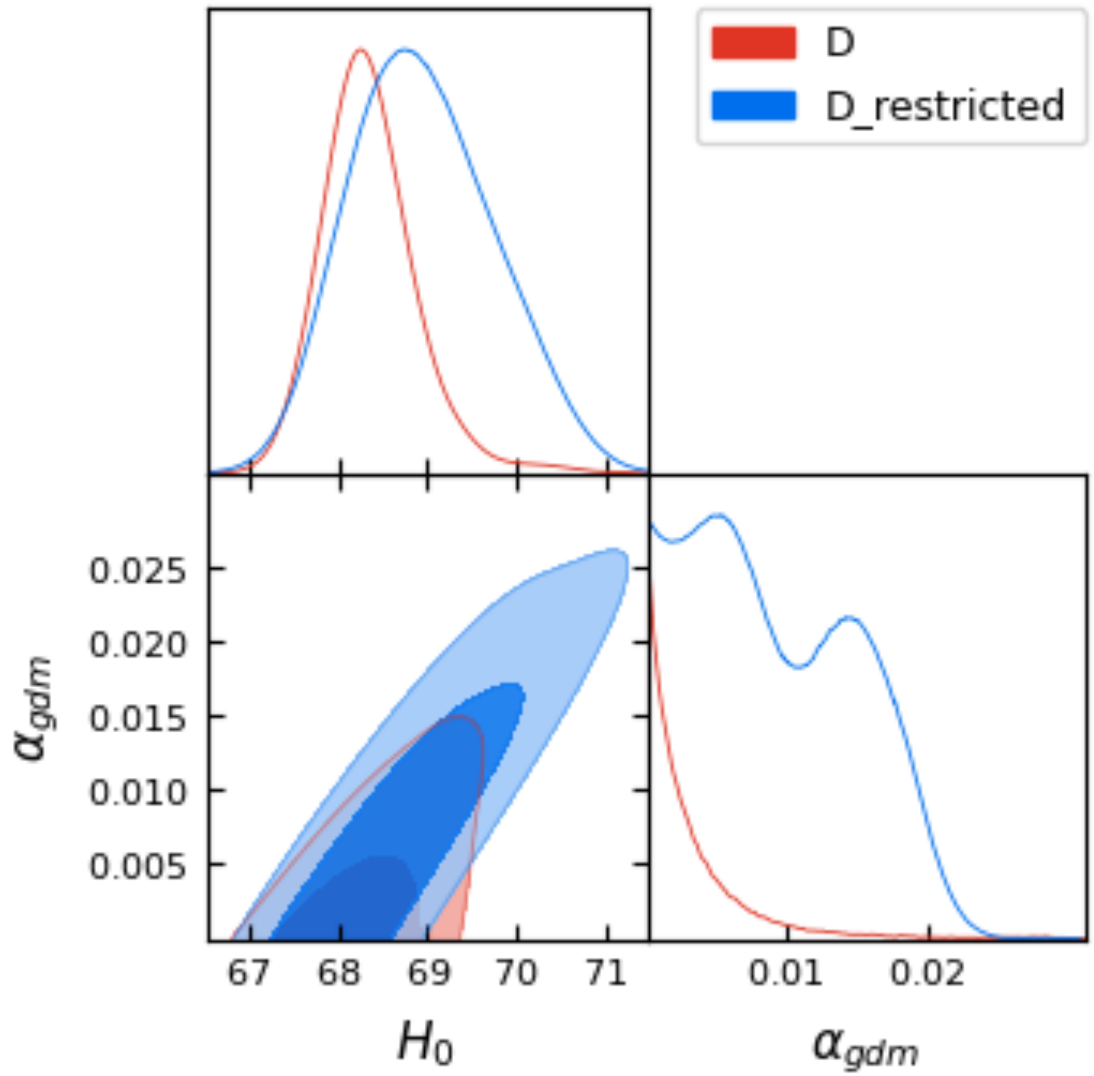






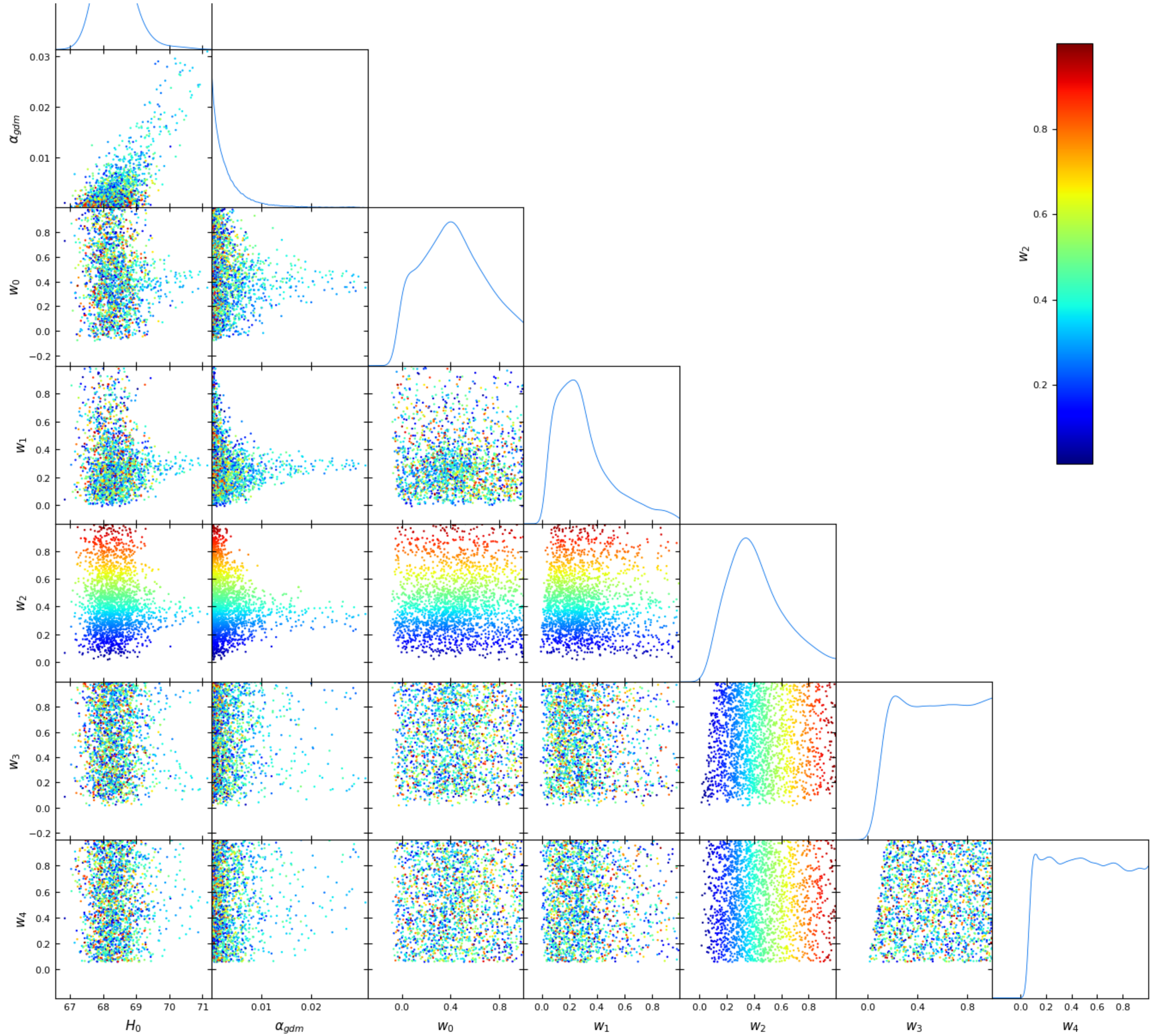
Preliminary Step-like GDM results



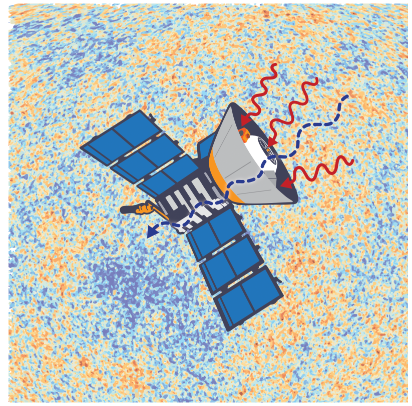


$-1 < w < 1$

$0.2 < w < 0.4$



α_{gdm}
w_0
w_1
w_2
w_3
w_4
H_0
α_{gdm}
w_0
w_1
w_2
w_3
w_4
w_2



Summary

- H_0 problem is inspiration for understanding what the CMB data allow and what they do not, reminding us to make the most of this valuable natural laboratory.
- We are working on this via combination of pursuing analytic understanding and exploration of high-dimensional model spaces.
- Starting from a very detailed question about constraints on light relics we found a uniform scaling of the rates in the problem leads to no changes to dimensionless observables. Things that prevent this scaling transformation lead to constraints on light relics.
- We connected with previous efforts in the literature. The importance of changing the fraction of non-relativistic matter that is pressure supported had not been previously described (to our knowledge).
- Focusing on the key rates in the problem has paid off for understanding light relics constraints. It may be helpful in a broader set of alternative cosmological models as well.
- Troubles: we boosted the scattering rate by requiring less helium than observed, and large light relic densities still have BBN issues. More moles to whack? Seems unlikely to be what nature is doing.
- High-dimensional model space exploration: volume effects are real and priors matter.