Title: A New Symmetry of Cosmological Observables and a High Hubble Constant as an Indicator of a Mirror World Dark Sector

Speakers: Lloyd Knox

Series: Particle Physics

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Abstract: Finding cosmological models that are consistent with a wide range of observations, including those that indicate a high Hubble constant (the current rate of expansion of space), has proved to be very challenging. In this talk I explore why. Our exploration leads us to fundamental sources of length scales in cosmological models: gravitational collapse time scales and photon electron-scattering mean free paths. We find that scaling down these quantities leaves cosmic microwave background (CMB) maps, and many other cosmological observables, nearly invariant, while boosting up the expansion rate. I then introduce a model that takes advantage of this symmetry to boost up model predictions of the Hubble constant given CMB and other cosmological data. Gravitational collapse time scales are scaled down from standard cosmological values by the introduction of a `mirror world' dark sector, and photon mean free paths are scaled down by reducing the amount of helium, thereby freeing up more electrons. I speculate about alternative ways to reduce photon mean free paths, as consistency with the Riess et al. (2021) measurement of the Hubble constant requires there to be less helium in the universe than is observed.

A new symmetry of cosmological observables and its application to the H_0 problem and understanding constraints on light relics

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with

Fei Ge
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U. of New Mexico

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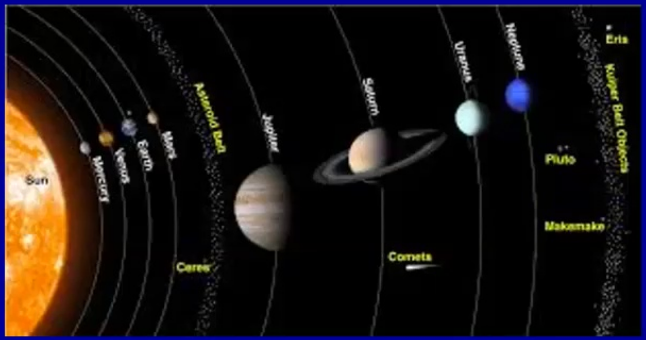
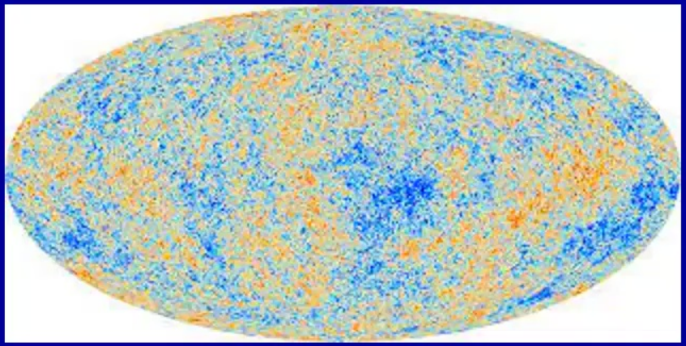
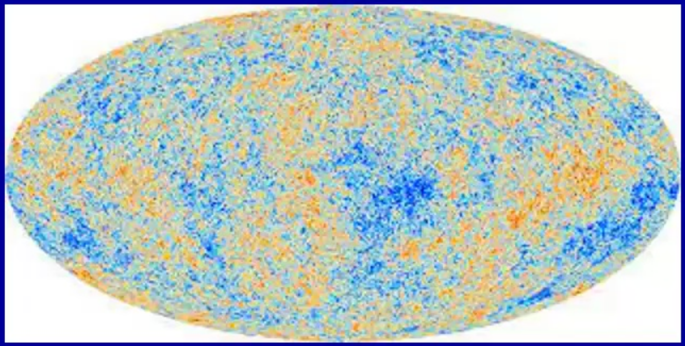


Solar System



Primordial Plasma

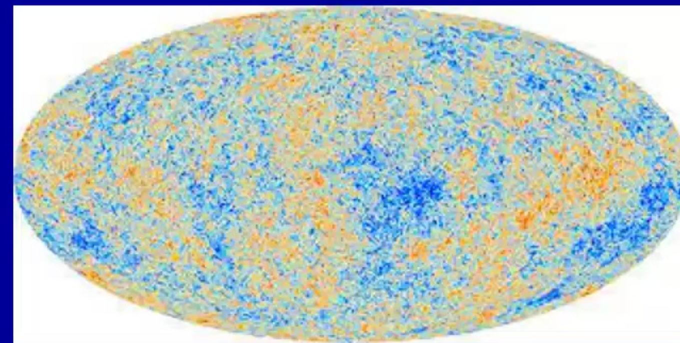
Natural systems where the relevant physics is simple enough that the system is *calculable*.



Newtonian Universal Gravitation

LCDM

Natural systems where the relevant physics is simple enough that the system is *calculable*.



Anomalous Perihelion Precession of Mercury

Anomalously Large H_0

Natural systems where the relevant physics is simple enough that the system is *calculable*.

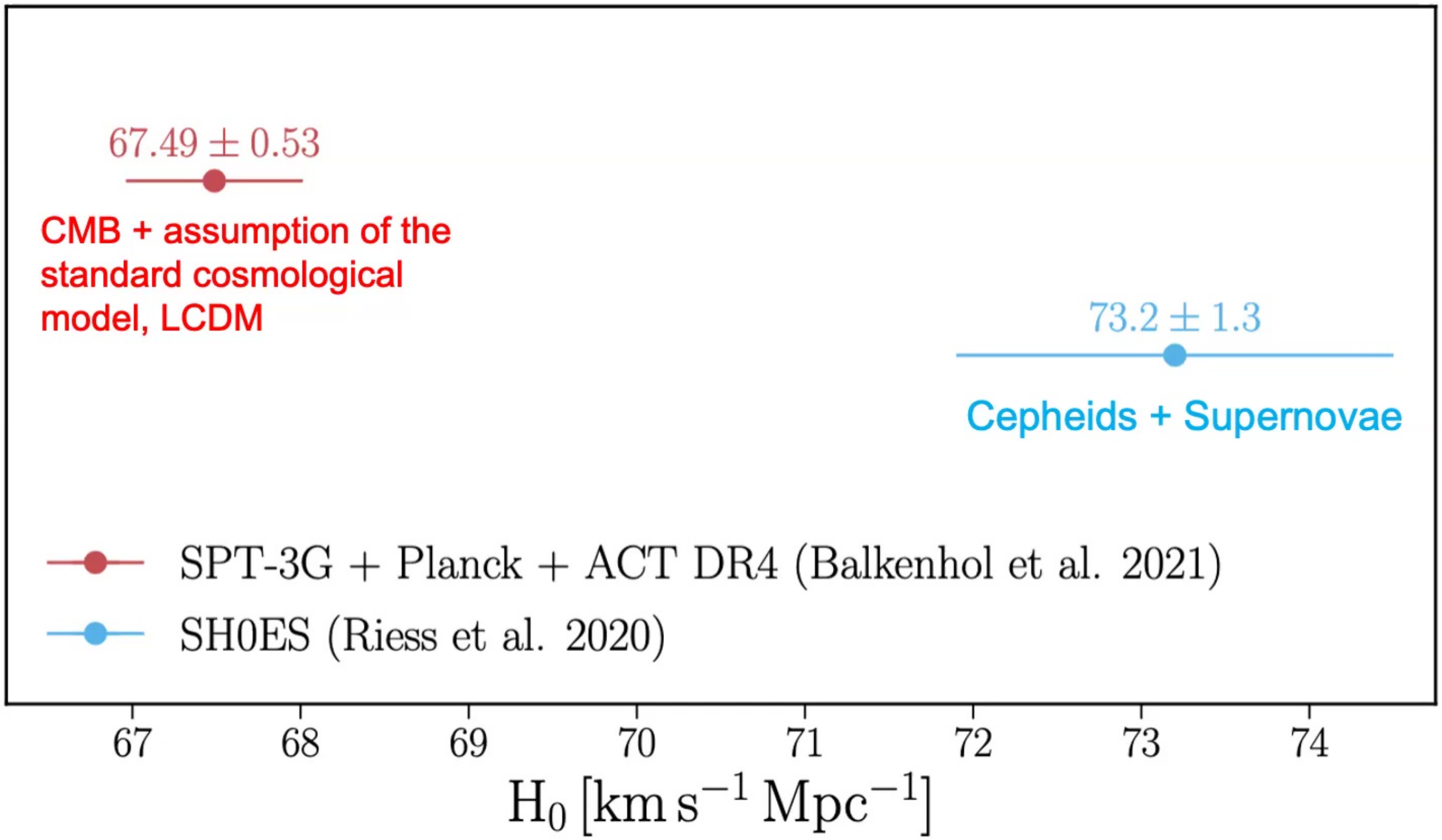
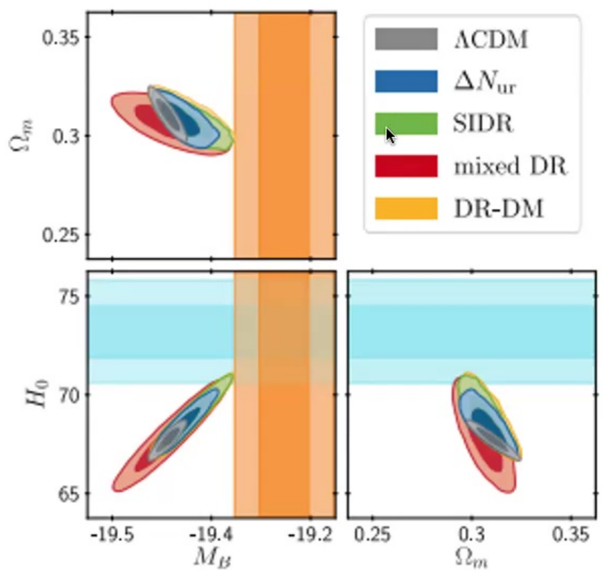


Figure by L. Balkenhol

Schöneberg et al., arXiv posting from July 21, 2021

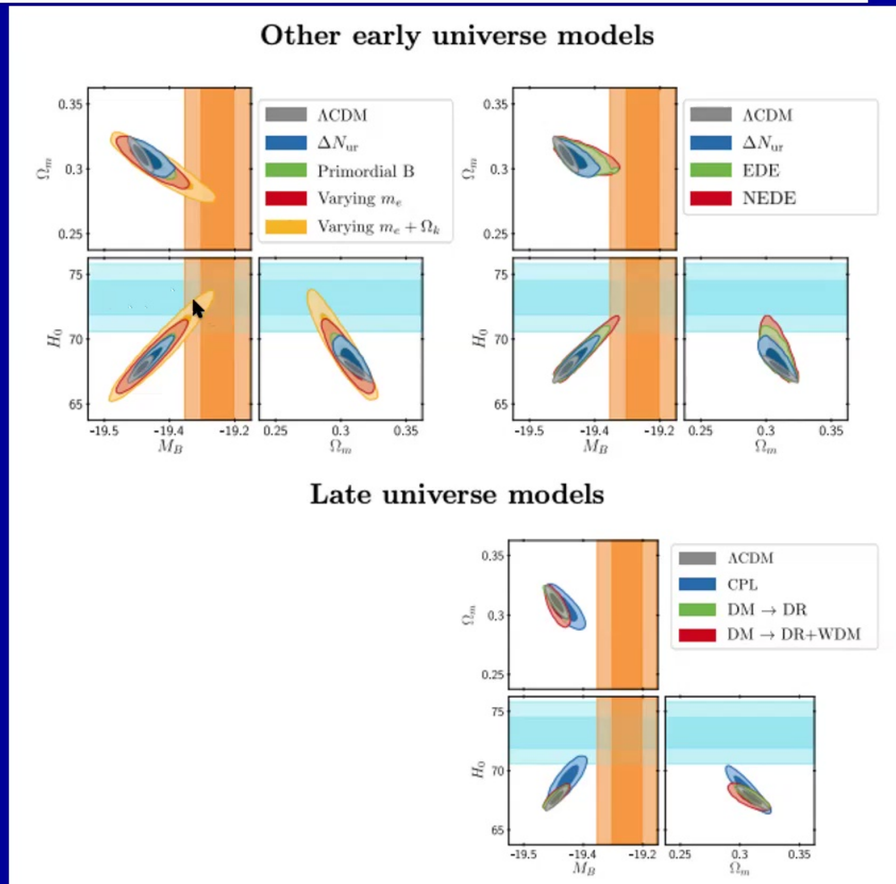
The H_0 Olympics: A fair ranking of proposed models

Dark Radiation models



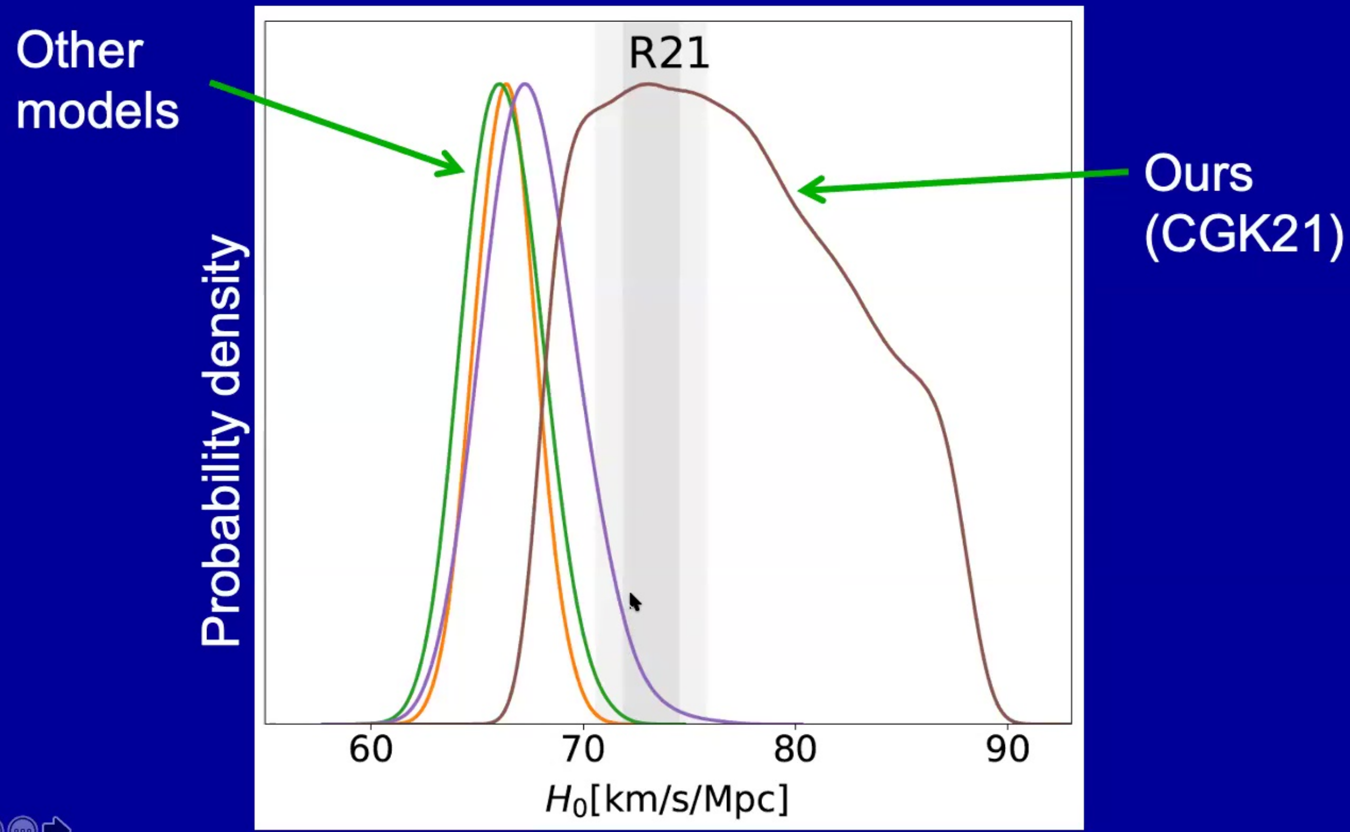
Schöneberg et al., arXiv posting from July 21, 2021

The H_0 Olympics: A fair ranking of proposed models



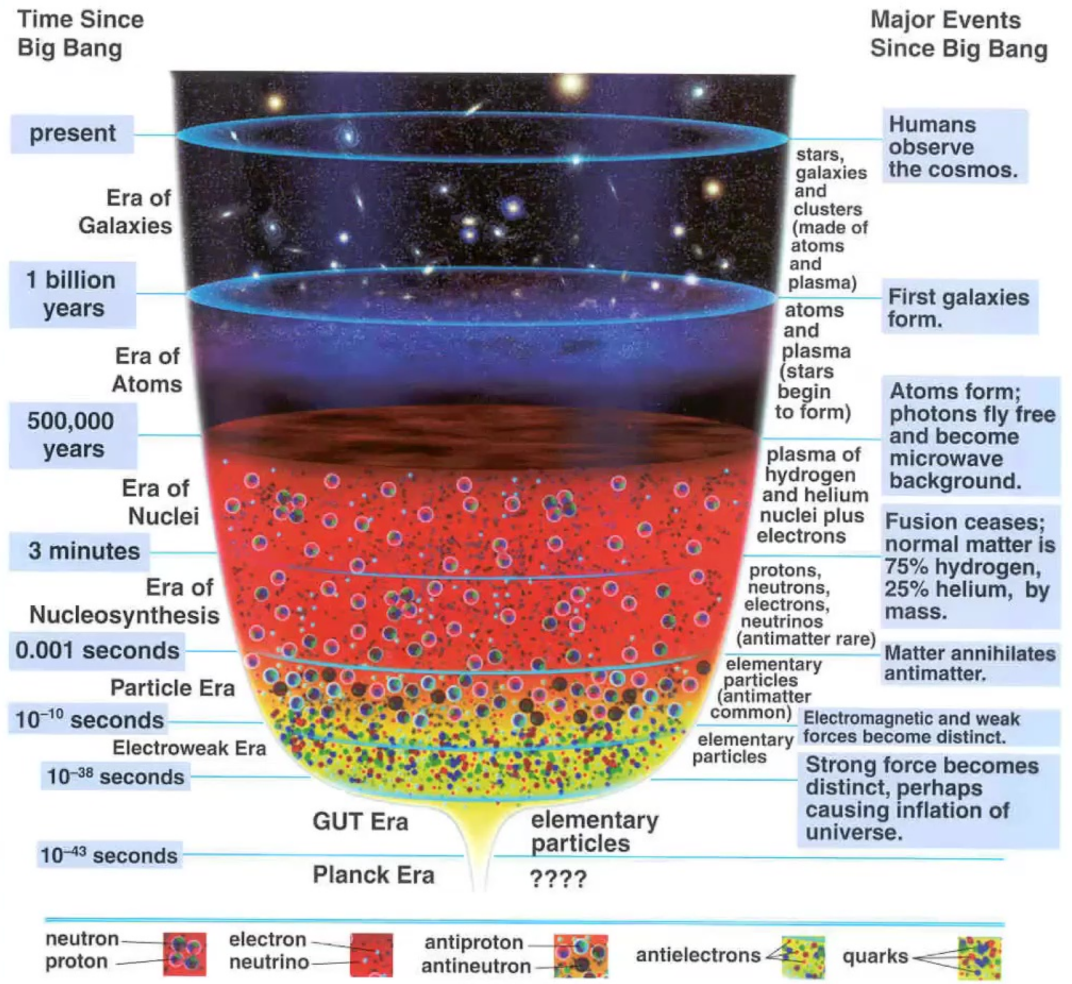
Cyr-Racine, Ge, and LK: arXiv posting from July 27, 2021

A Symmetry of Cosmological Observables, and a High Hubble Constant as an Indicator of a Mirror World Dark Sector

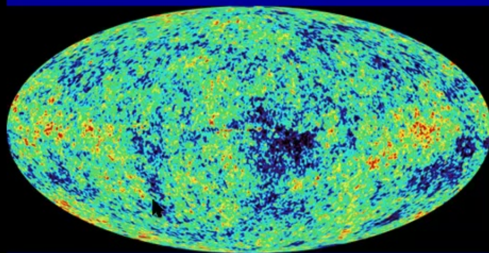


Outline

- Successes of LCDM
- Scaling transformation symmetries in cosmology and symmetry breaking effects
- An exact* symmetry!
- Implementation with a mirror world addition to the dark sector
- New Questions
  – Our helium problem



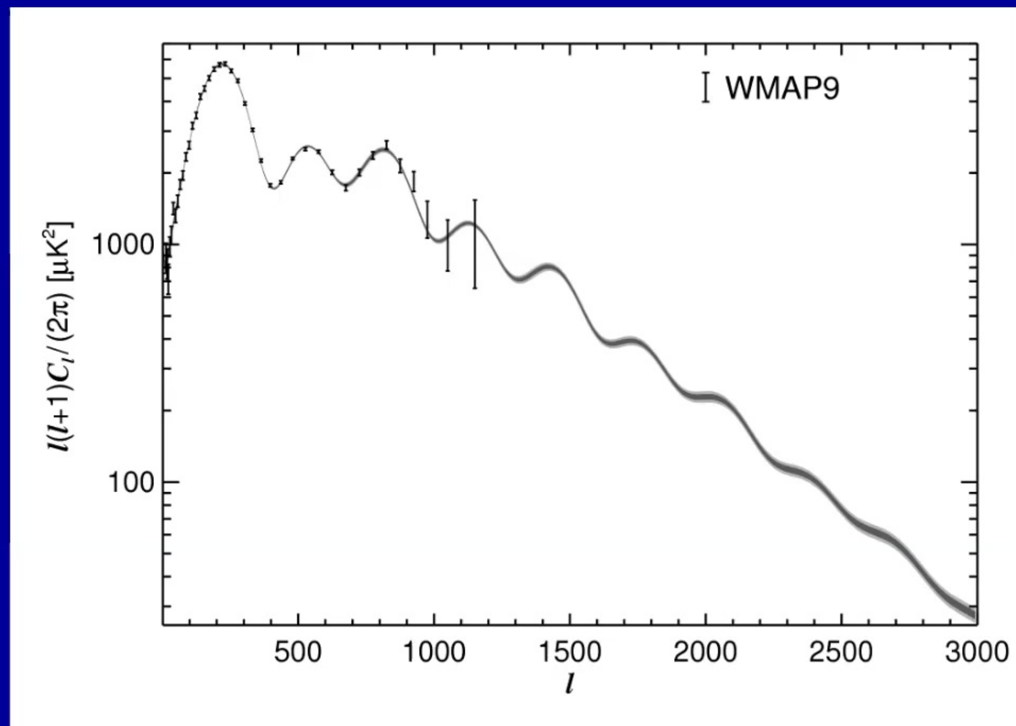
Credit: The Cosmic Perspective



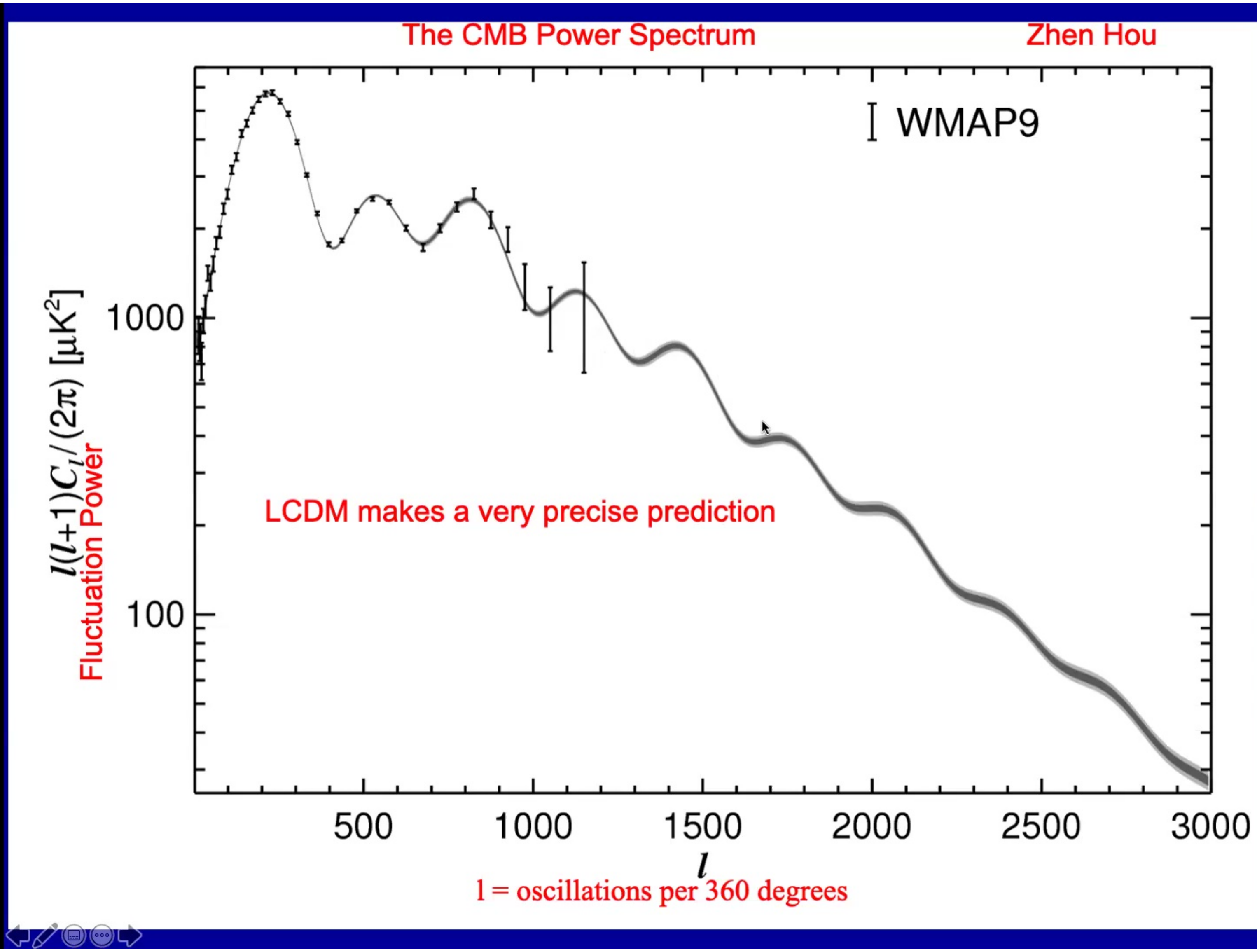
WMAP

The CMB Power Spectrum

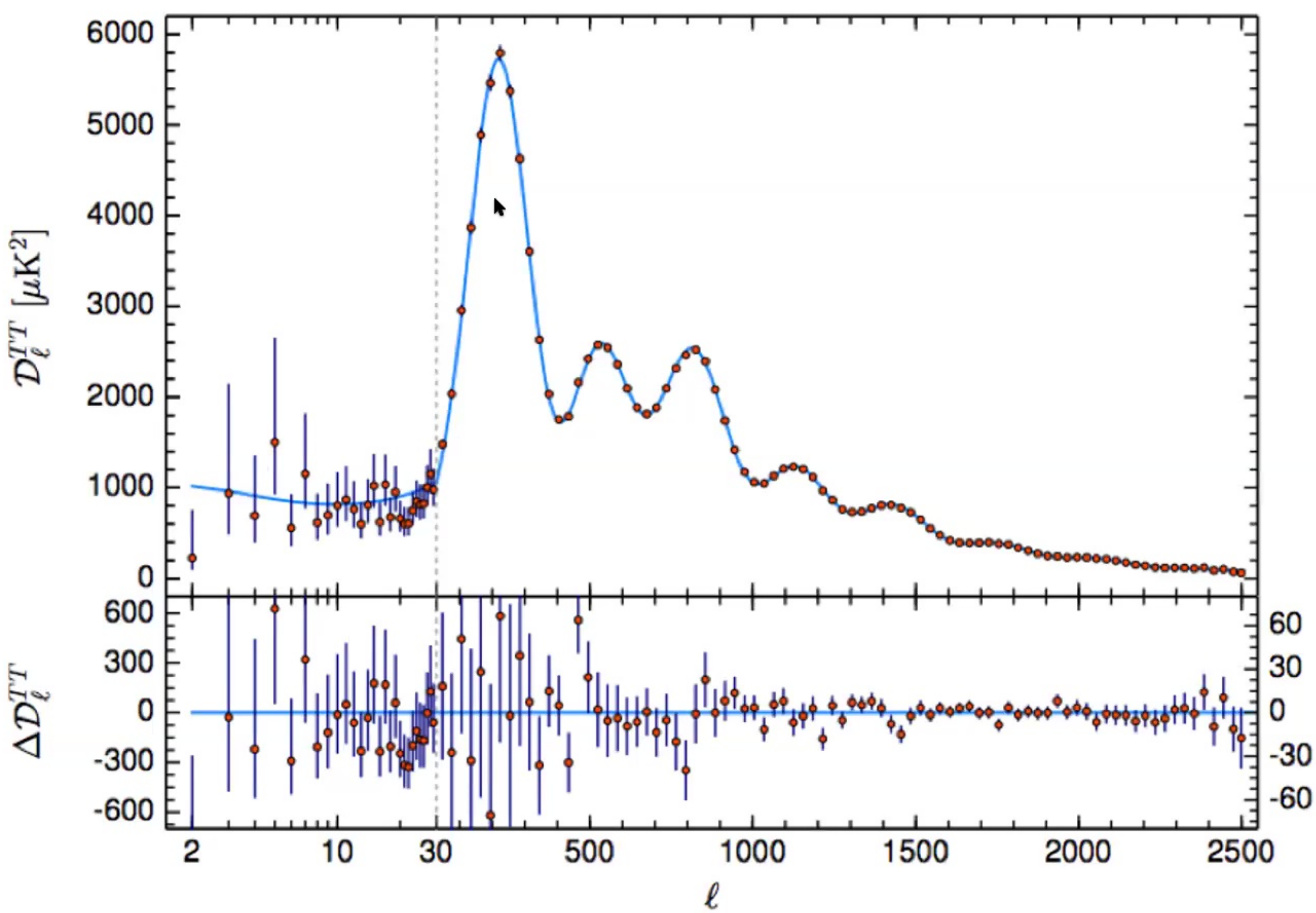
Fluctuation Power



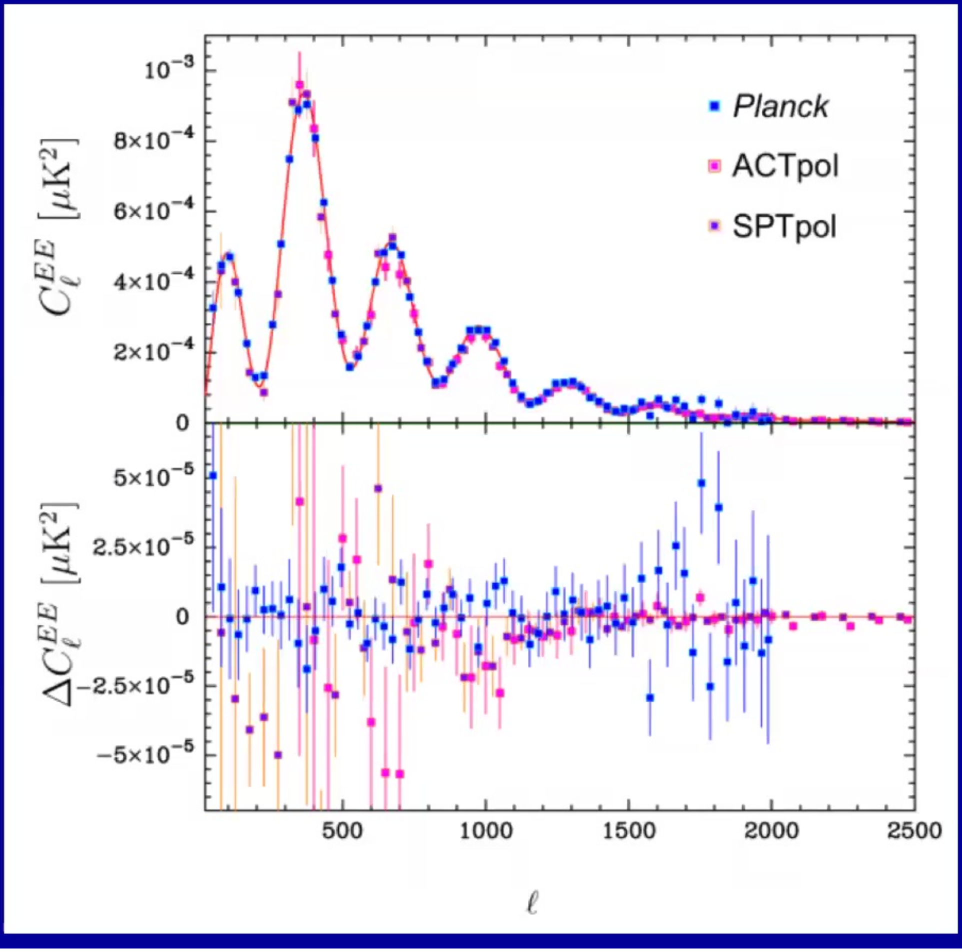
l = oscillations per 360 degrees

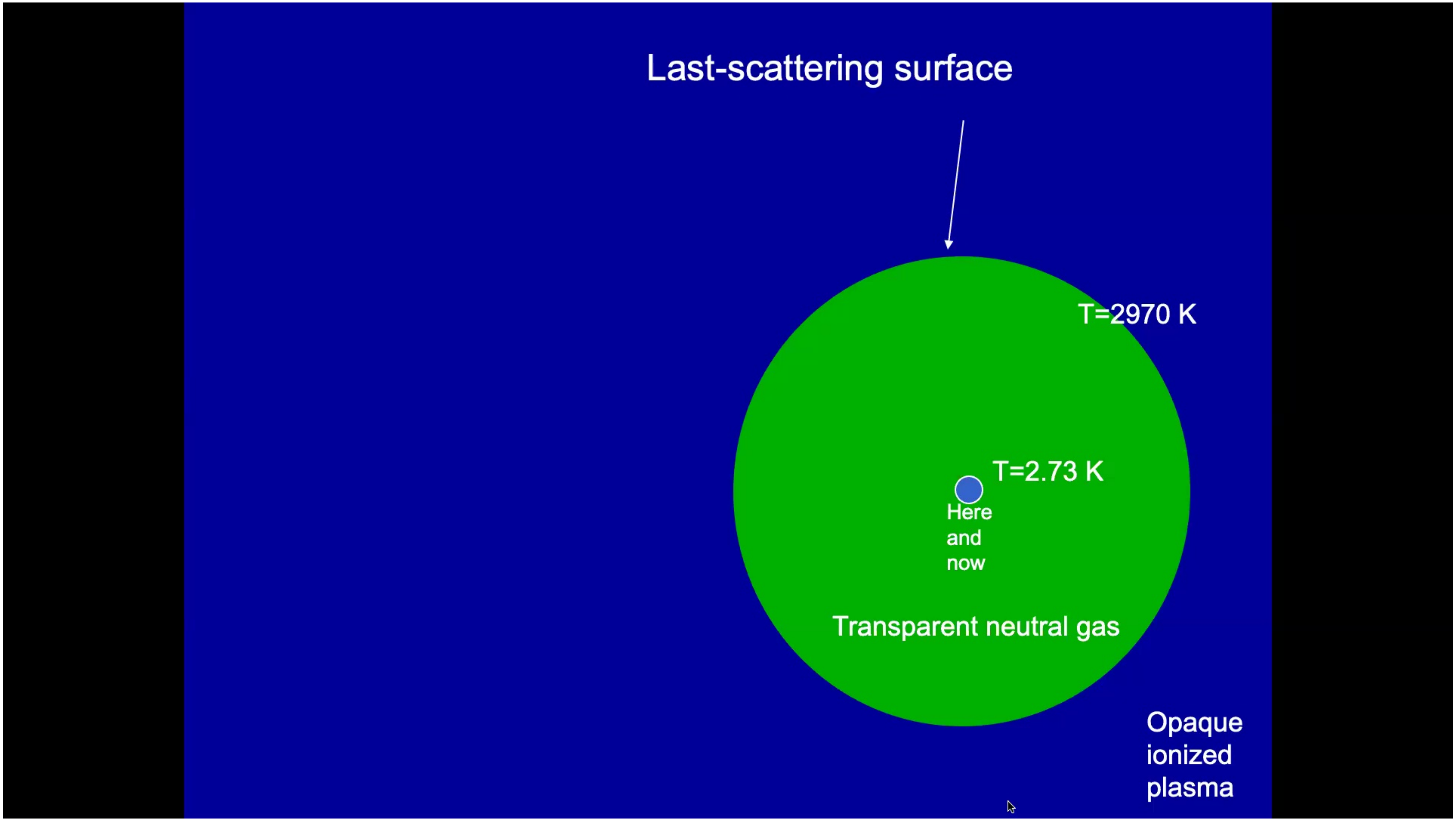


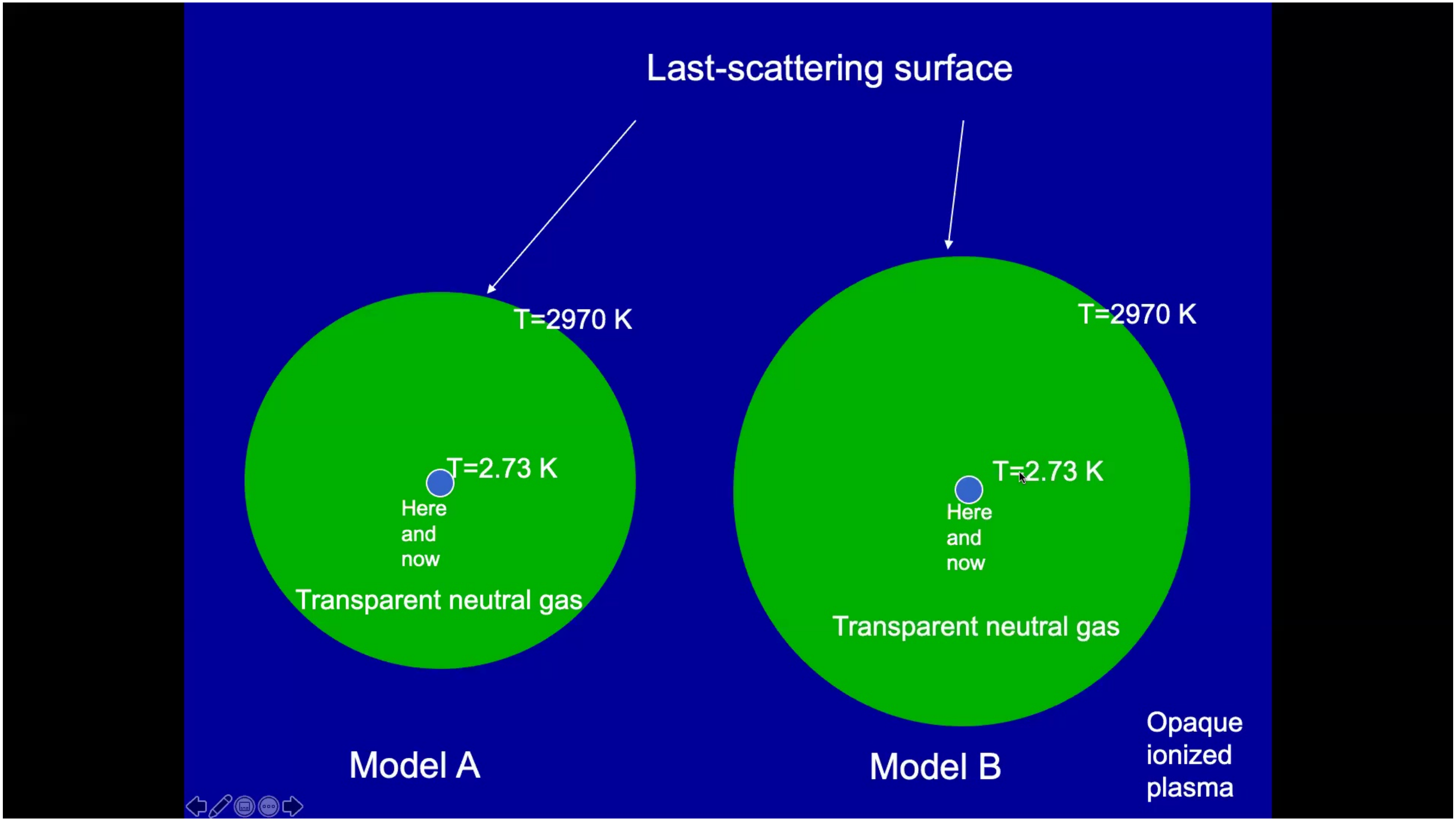
The CMB Power Spectrum
Zhen Hou
WMAP9
1000
100
500
1000
1500
2000
2500
3000
Fluctuation Power
LCDM makes a very precise prediction
l = oscillations per 360 degrees

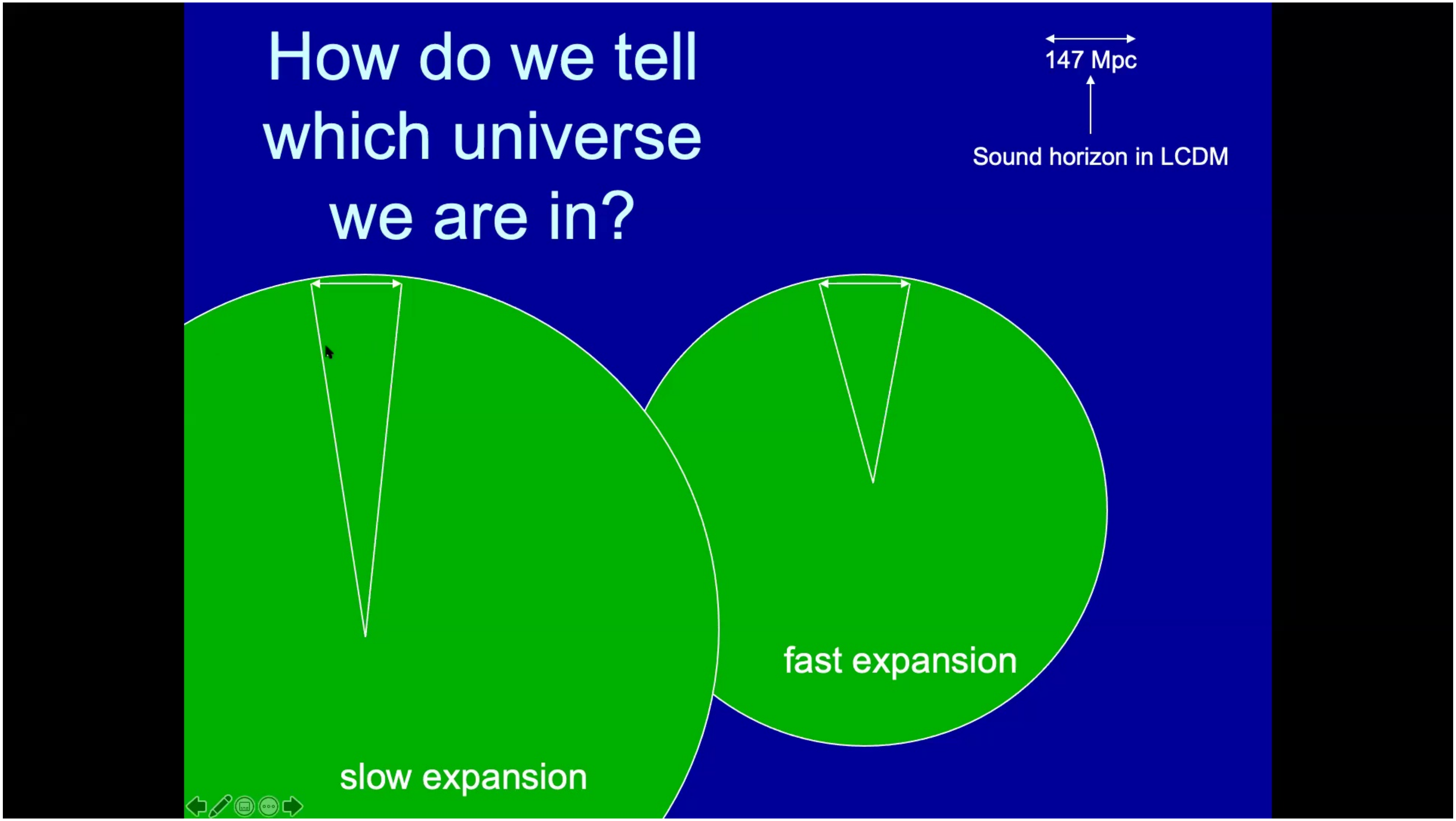

6000
5000
4000
3000
2000
1000
0
600
300
0
-300
-600
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ
$\mathcal{D}_\ell^{TT}$ [μK^2]
$\Delta\mathcal{D}_\ell^{TT}$

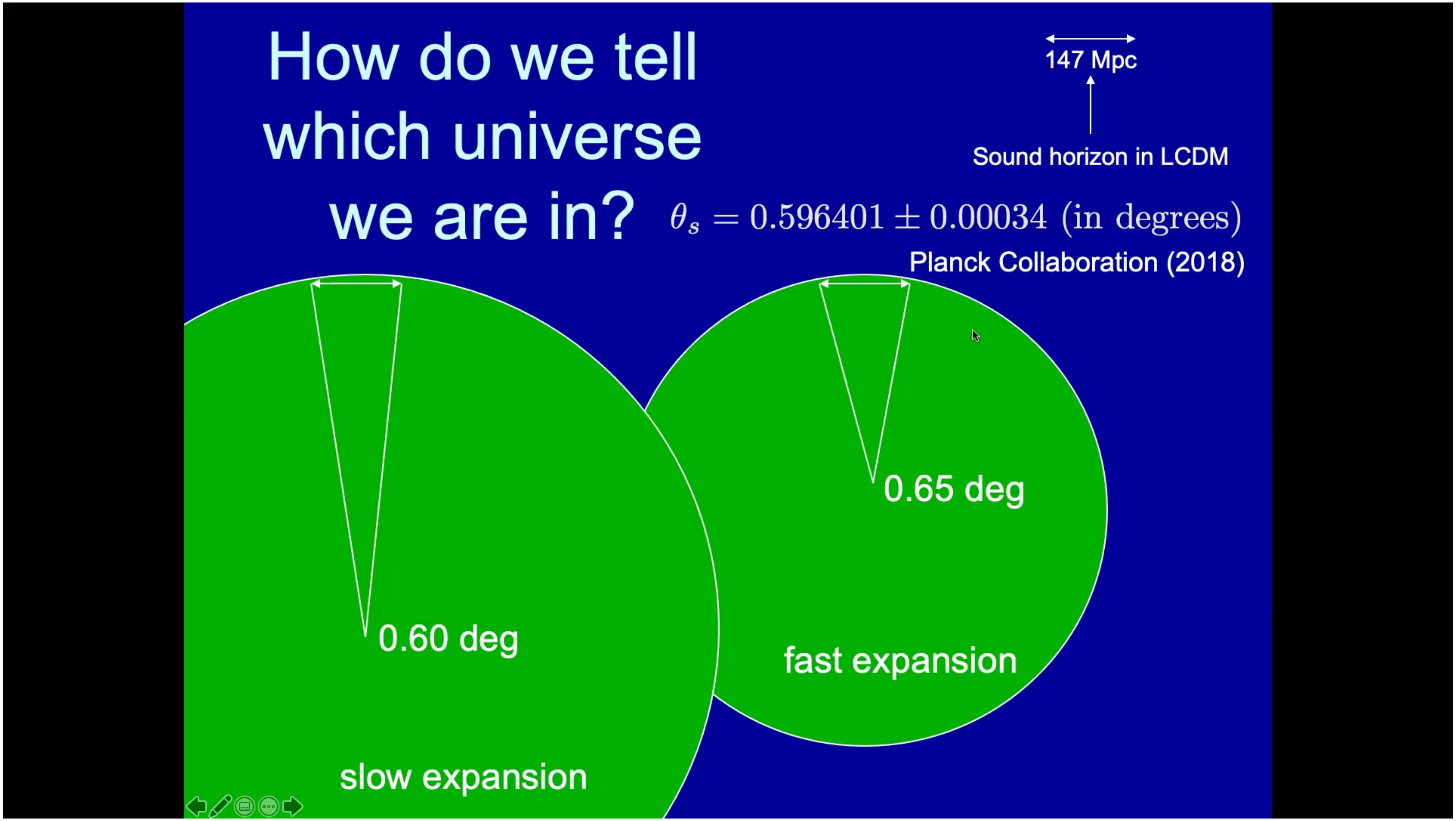
CMB Polarization Power Spectrum



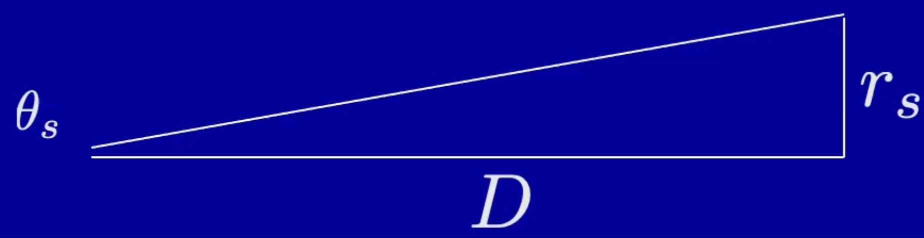

Last-scattering surface
T=2970 K
T=2.73 K
Here
and
now
Transparent neutral gas
Opaque
ionized
plasma


Last-scattering surface
T=2970 K
T=2.73 K
Here
and
now
Transparent neutral gas
T=2970 K
T=2.73 K
Here
and
now
Transparent neutral gas
Model A
Model B
Opaque
ionized
plasma


How do we tell which universe we are in?
147 Mpc
Sound horizon in LCDM
fast expansion
slow expansion

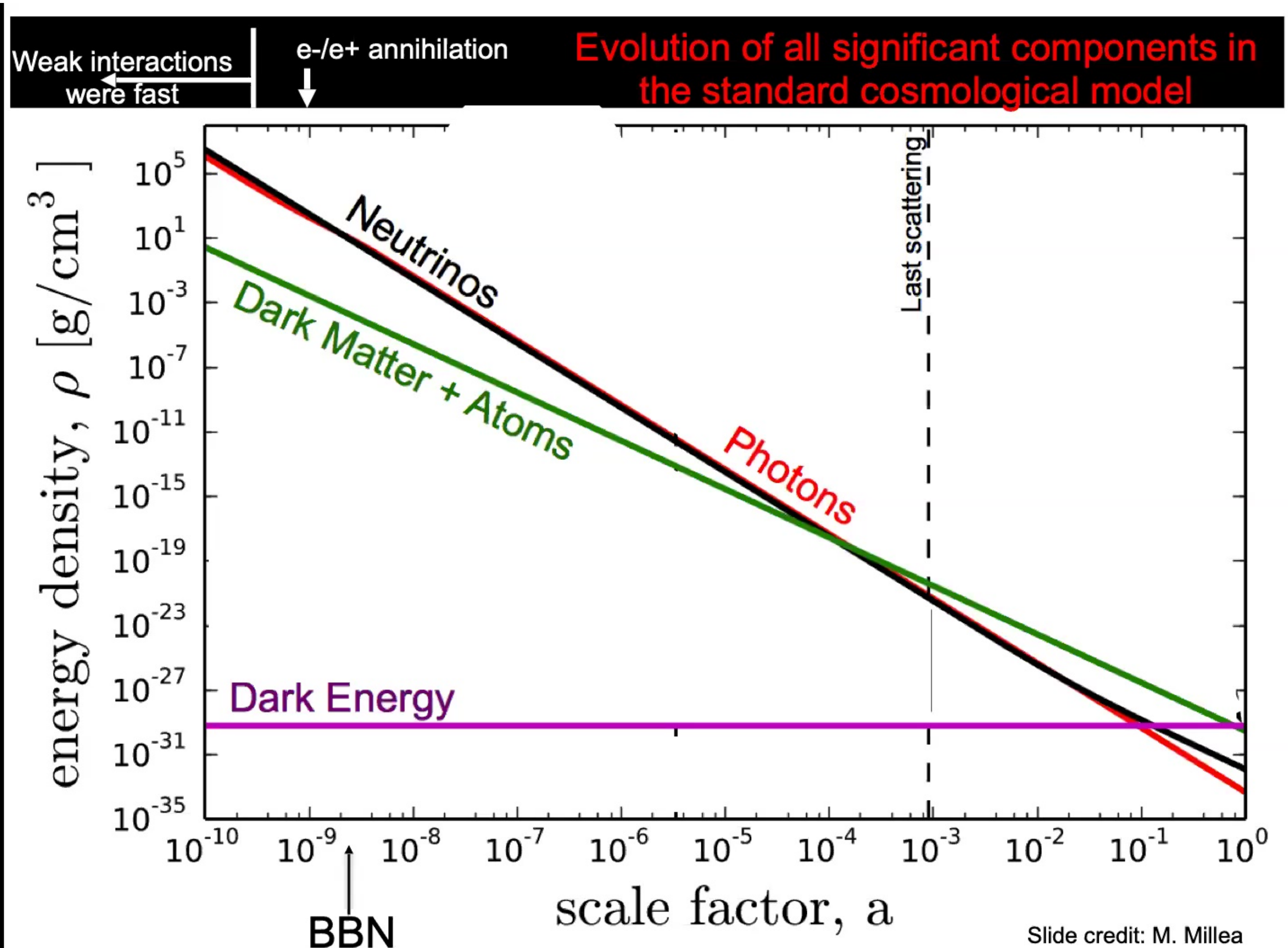

How do we tell which universe we are in?
147 Mpc
Sound horizon in LCDM
$\theta_s = 0.596401 \pm 0.00034$ (in degrees)
Planck Collaboration (2018)
0.65 deg
0.60 deg
fast expansion
slow expansion

Scaling Transformation #1: H(a) → fH(a)



$$D = \int da/(a^2 H) \qquad r_s = \int_0^{a_*} da \frac{c_s}{a^2 H}$$

$\theta_s = r_s/D$ is preserved (has no dependence on f)


Weak interactions were fast
e-/e+ annihilation
Evolution of all significant components in the standard cosmological model
energy density, ρ [g/cm3]
scale factor, a
Neutrinos
Dark Matter + Atoms
Photons
Dark Energy
Last scattering
BBN
10^5
10^1
10^-3
10^-7
10^-11
10^-15
10^-19
10^-23
10^-27
10^-31
10^-35
10^-10
10^-9
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
10^0
Slide credit: M. Millea

Scaling Transformation #1: H(a) → fH(a)

Can be realized with

$$\rho_\Lambda \to f^2 \rho_\Lambda$$

$$\rho_m \to f^2 \rho_m$$

$$\rho_{\rm rad} \to f^2 \rho_{\rm rad}$$

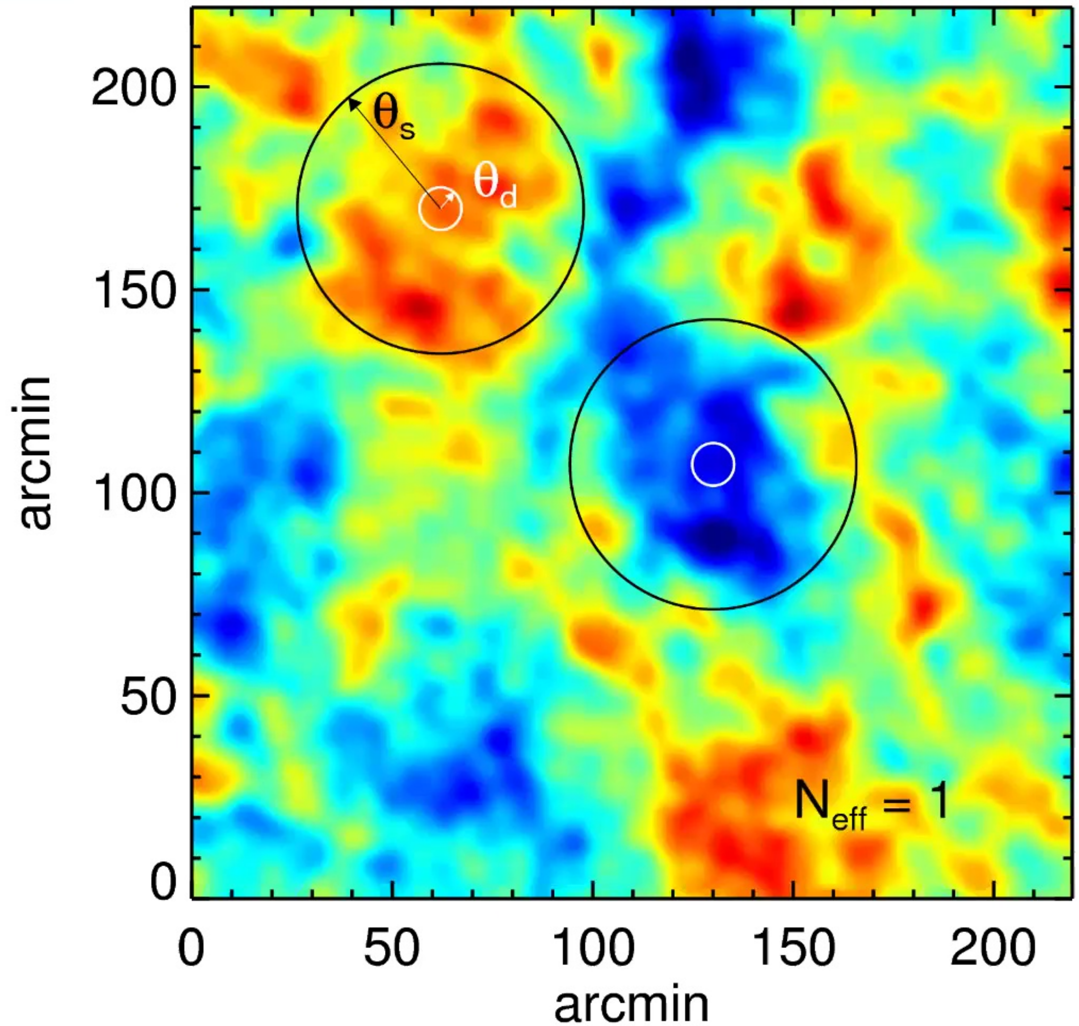
$$H^2(a) = \frac{8\pi G}{3}\left(\rho_\Lambda + \rho_{m,0} a^{-3} + \rho_{{\rm rad},0} a^{-4}\right)$$

Symmetry breaking effect

Photon diffusion

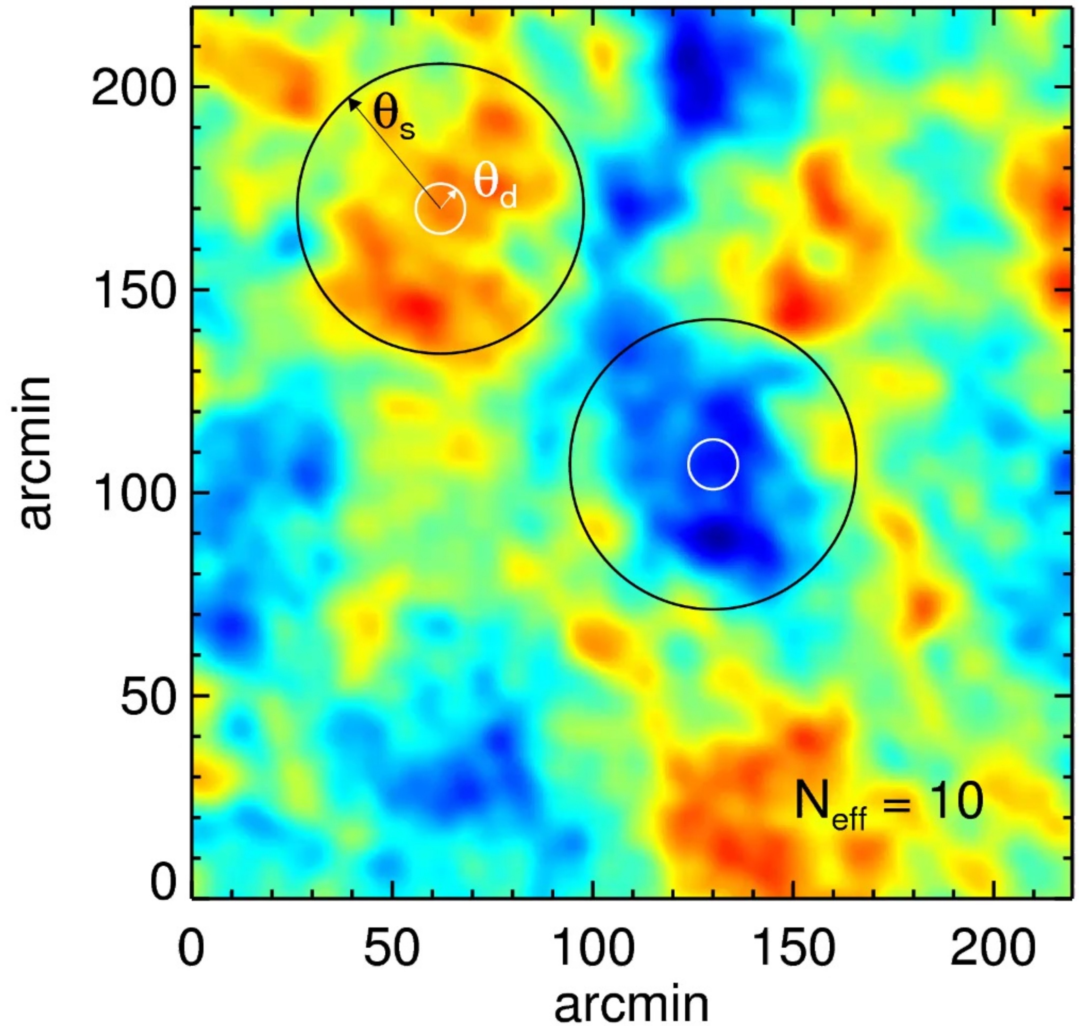
$$r_d^2 \propto \int_0^{a_*} \frac{da}{a^2 H \sigma_T n_e a}$$

How do we distinguish large sound horizon far away, from small sound horizon nearby?



Large sound horizon Far away

How do we distinguish large sound horizon far away, from small sound horizon nearby?



Small sound horizon nearby

Scaling Transformation #2

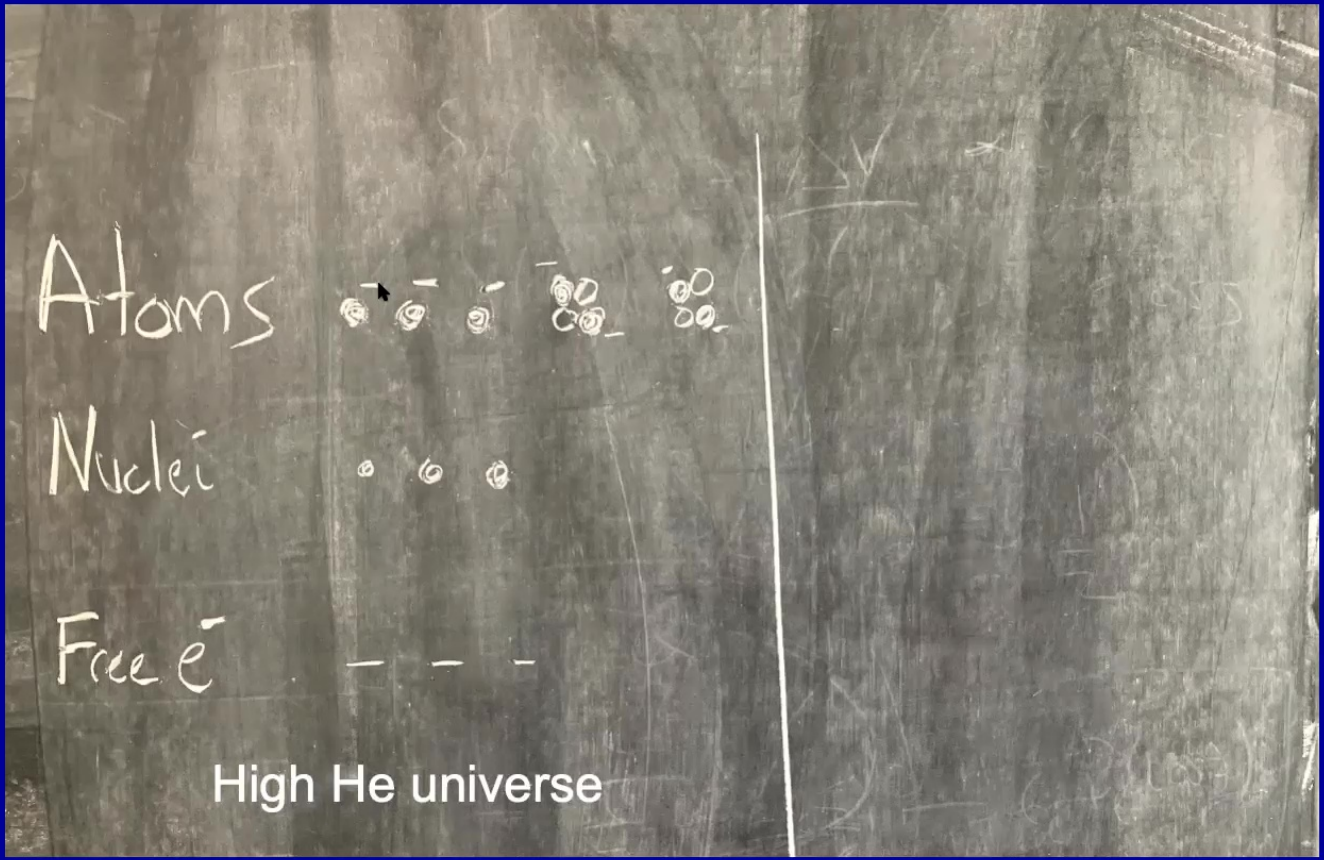
$$H(a) \to f H(a)$$

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

$$r_d^2 \propto \int_0^{a_*} \frac{da}{a^2 H \sigma_T n_e a} \propto (1/f)^2$$

So $\theta_d = r_d / D$ Is independent of f

Decreasing He boosts n_e



An example at $n_e/n_H = 0.5$

Scaling Transformation #2

$$H(a) \to f H(a)$$

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

Can be realized with

$$\rho_\Lambda \to f^2 \rho_\Lambda$$

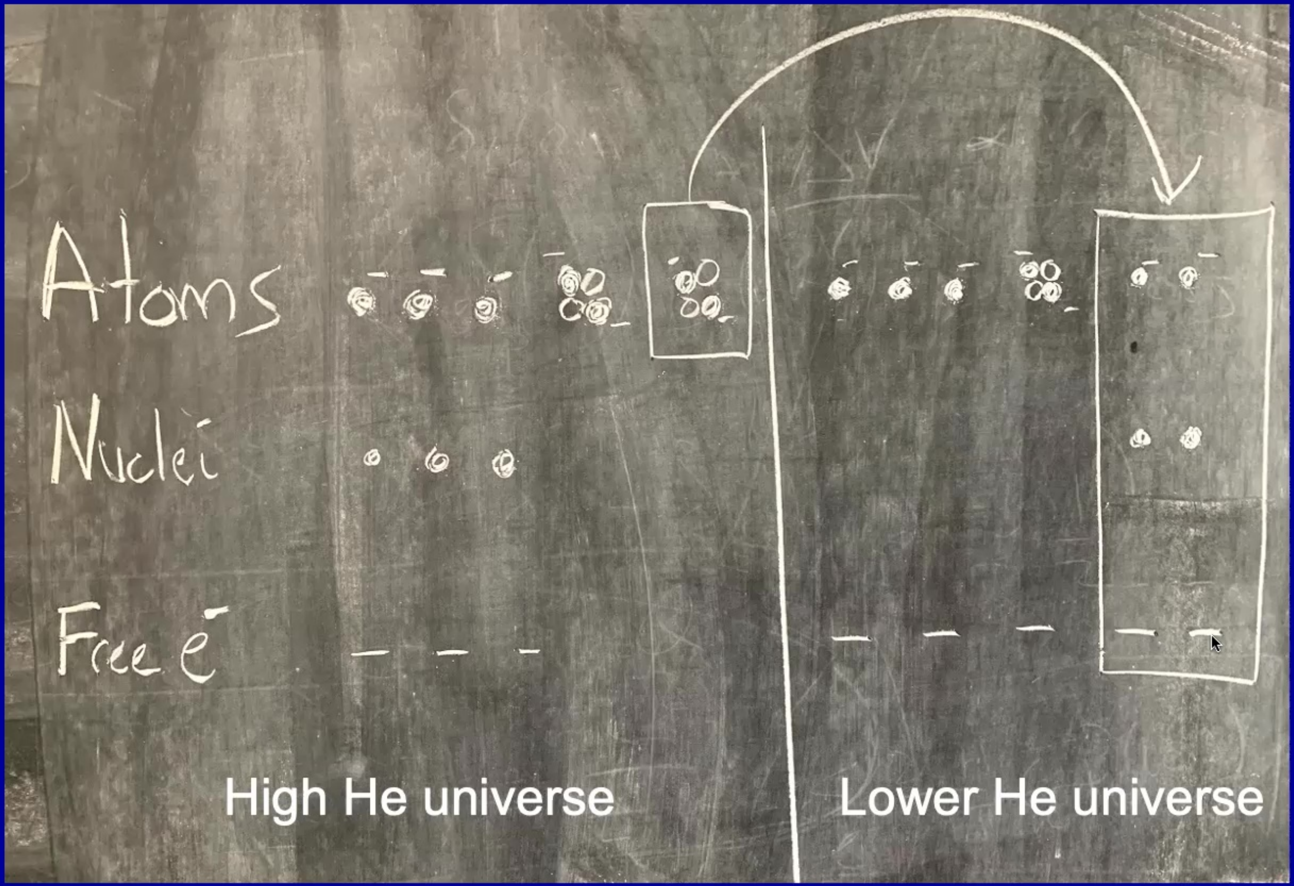
$$\rho_m \to f^2 \rho_m$$

$$\rho_{\mathrm{rad}} \to f^2 \rho_{\mathrm{rad}}$$

$$1 - Y_{\mathrm{P}} \to f(1 - Y_{\mathrm{P}})$$

Fraction of baryonic mass in helium

Decreasing He boosts n_e



An example at $n_e/n_H = 0.5$

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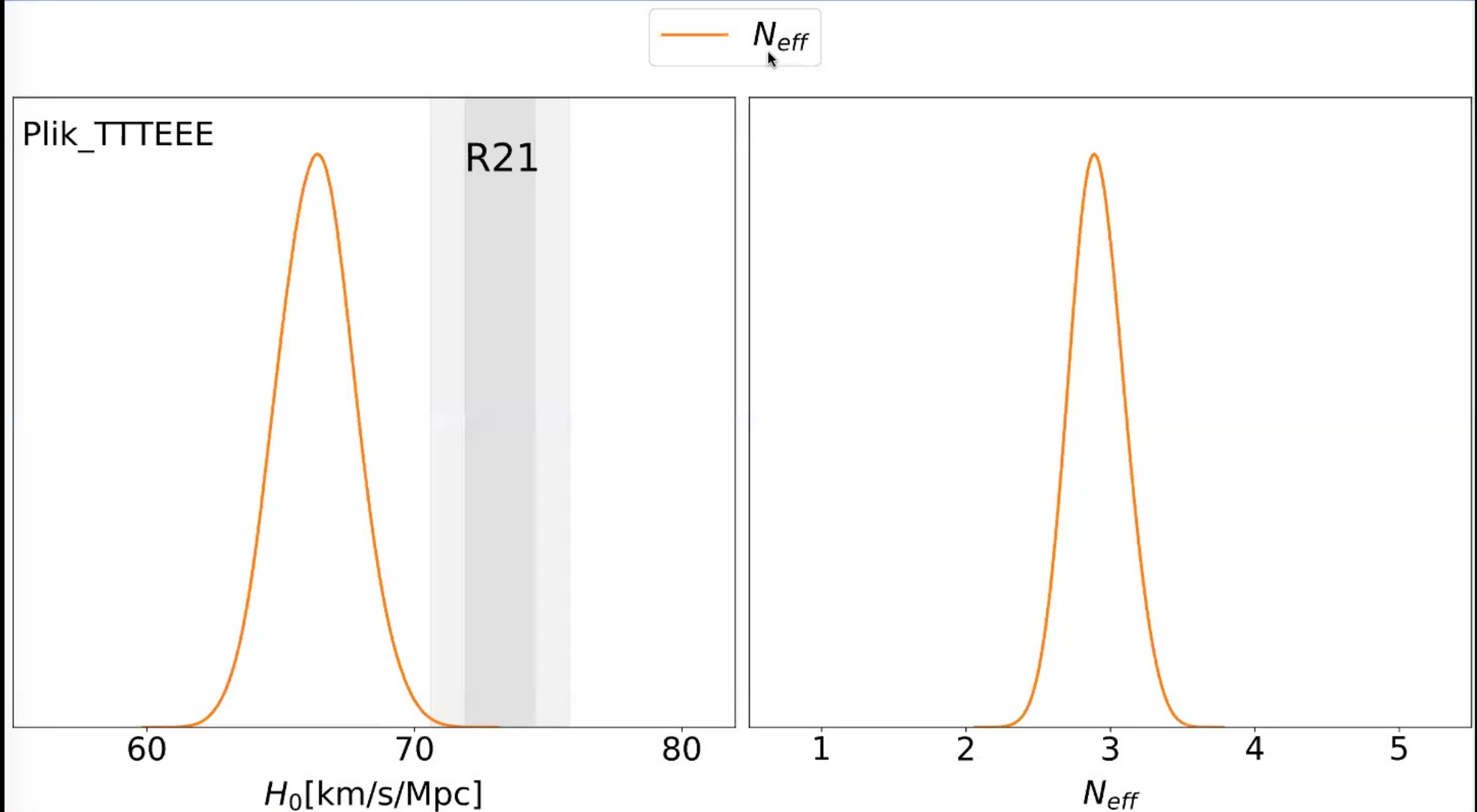
Fraction of baryonic mass in helium

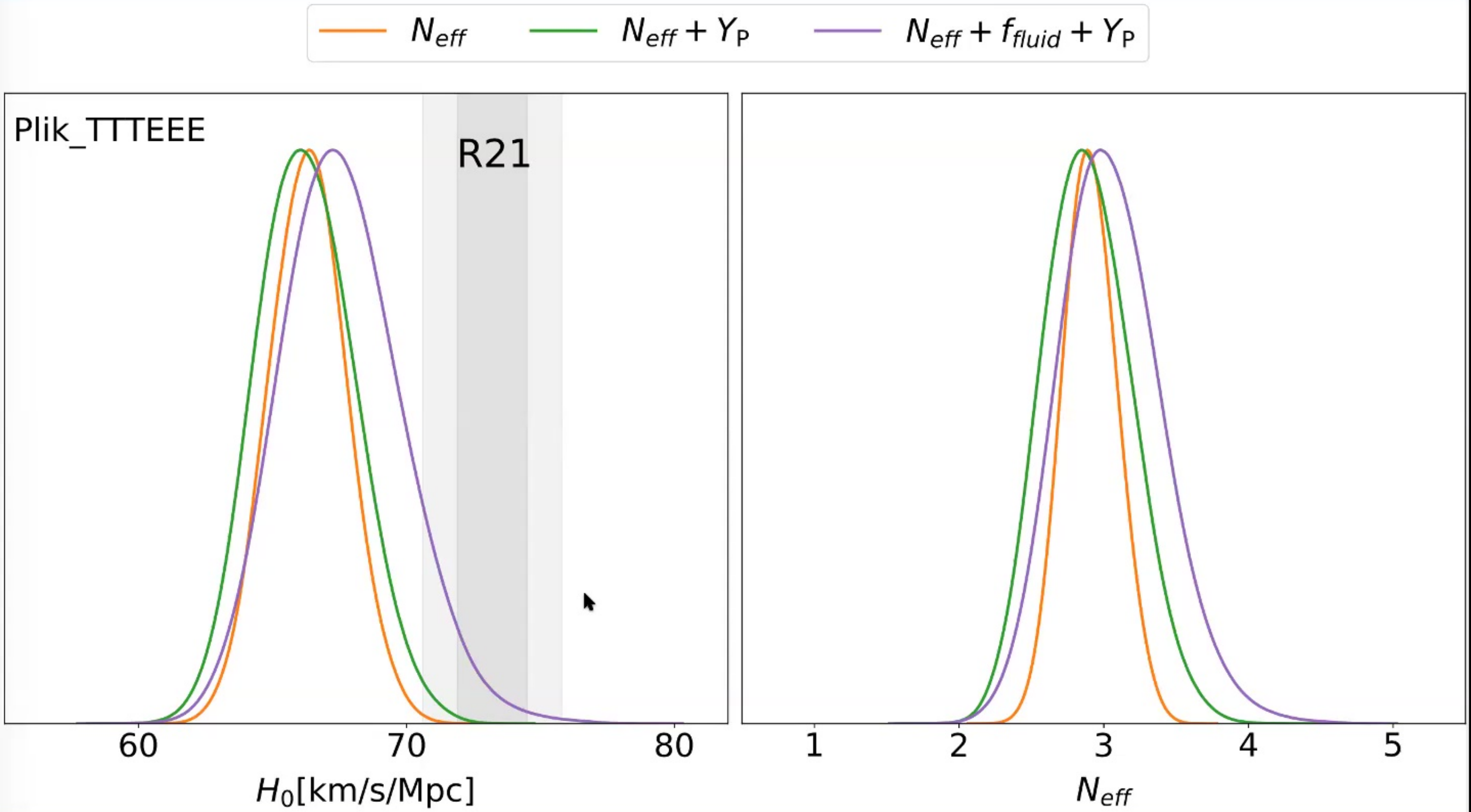
Constraints from Planck 2018 CMB temperature and polarization power spectra



Free-streaming light relic fraction – another symmetry-breaking effect

Bashinsky and Seljak (2004)
Follin, LK, Millea, and Pan (2015)
Baumann, Green, and Wallisch (2016)

Constraints from Planck 2018 CMB temperature and polarization power spectra



Scaling Transformation #3

$$\sqrt{G\rho_i(a)} \to f\sqrt{G\rho_i(a)}$$

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

$$A_s \to A_s / f^{n_s - 1}$$

An exact (if unphysical) scaling symmetry

- In the limit of equilibrium recombination and massless neutrinos, dimensionless cosmological observables are *exactly* invariant under

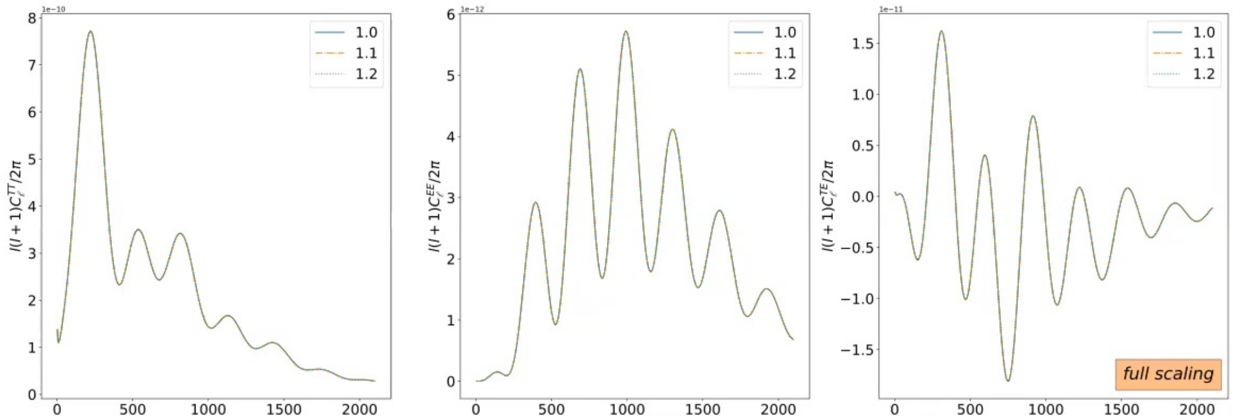
$$\sqrt{G\rho_i(a)} \to f\sqrt{G\rho_i(a)}, \quad \sigma_{\mathrm{T}} n_e(a) \to f \sigma_{\mathrm{T}} n_e(a)$$
$$\text{and} \quad A_{\mathrm{s}} \to A_{\mathrm{s}}/f^{(n_{\mathrm{s}}-1)}.$$

- This includes CMB temperature and polarization, galaxy clustering, BAO, weak lensing.
- Leaves density ratios (Ω), matter-radiation equality, matter fluctuation amplitude (like sigma_8, S_8), free-streaming fraction, baryon-photon ratio exactly invariant.

Zahn and Zaldarriaga (2003) had proposed this scaling without the photon scattering part.

This works

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



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

Slide from Francis-Yan Cyr-Racine - UNM

Q: *Why* does this work?

Scaling Transformation #3

$$\sqrt{G\rho_i(a)} \to f\sqrt{G\rho_i(a)}$$

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

$$A_s \to A_s / f^{n_s - 1}$$

A: Dimensionful coefficients in equations of motion:

$$\sqrt{G\rho_i(a)} \quad \text{and} \quad \sigma_{\mathrm{T}} n_e(a)$$

Dimensionful constants in initial conditions: none!

Example Boltzmann Equation

(for Fourier mode with wavenumber k)

$$a^2 H \frac{d}{da} \Theta_1 = \frac{k}{3} (\Theta_0 + \Psi) + a \sigma_{\mathrm{T}} n_e \left[\Theta_1 - i v_b / 3 \right]$$

Einstein Equations

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

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

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

Special feature of our Universe: Initial conditions

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

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

- Since $n_s < 1$, the different Fourier modes have slightly different primordial amplitudes.
- Thus, the transformation $k \to fk$ will modify the amplitude of fluctuations (CMB, $P_m(k)$, etc.)
- However, since power laws have no scale, this can be corrected with a trivial rescaling:

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

Zahn and Zaldarriaga (2003)

Slide from Francis-Yan Cyr-Racine - UNM

Reality check: Symmetry breaking

- The above transformation scales all energy densities, including that of photons -> BIG PROBLEM!
- The COBE/FIRAS temperature anchors the photon energy density, hence breaking the scaling symmetry. Ivanov et al. (2020)
- Recombination is not an equilibrium process, and is thus not invariant under $H \rightarrow fH$
- Same for Big Bang Nucleosynthesis.
- Neutrino masses (can be eliminated by $m_\nu \rightarrow fm_\nu$)

Exploiting the symmetry: Mirror World

- Can we get around the COBE/FIRAS constraint?
- Instead of adding real photons, add dark photons
- These dark photons need the same streaming history as regular photons, so add dark baryons (atomic dark matter), with similar parameters as in the SM.
- To scale up neutrino density, add dark neutrinos (or other light free streaming species).
- This is basically a mirror sector (been studied a lot see e.g. twin Higgs papers)

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), and many more

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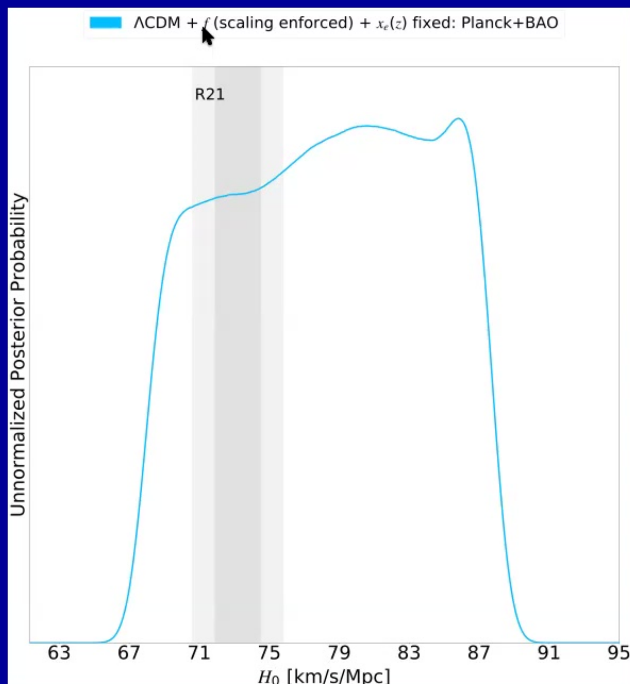
58

Zeroth Test: The exact symmetry



- 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.

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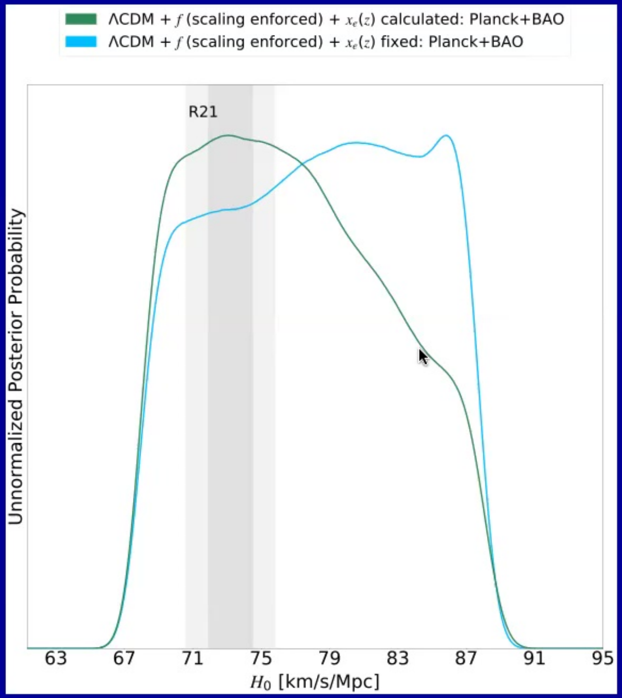
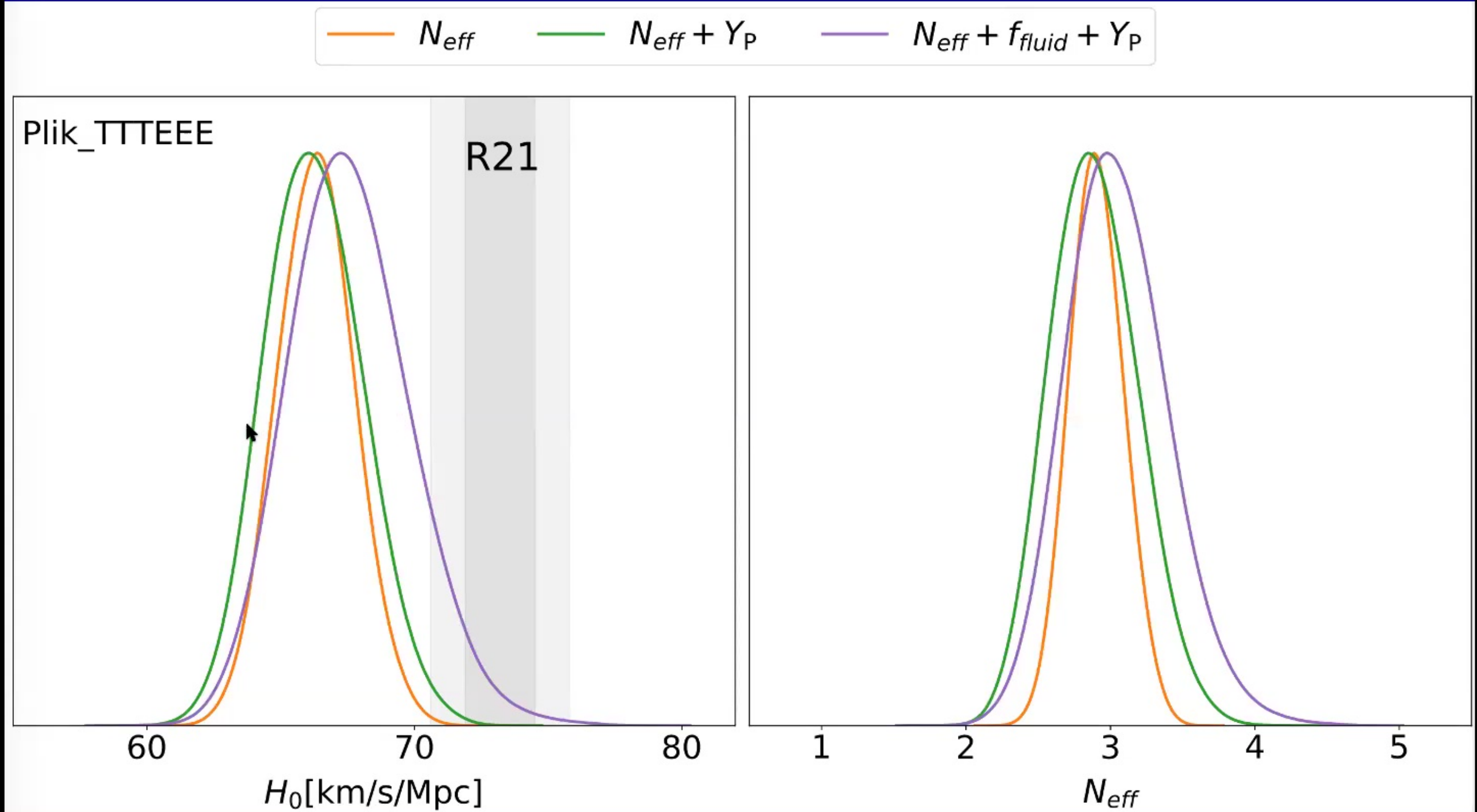
60

First (real!) Test: Recombination

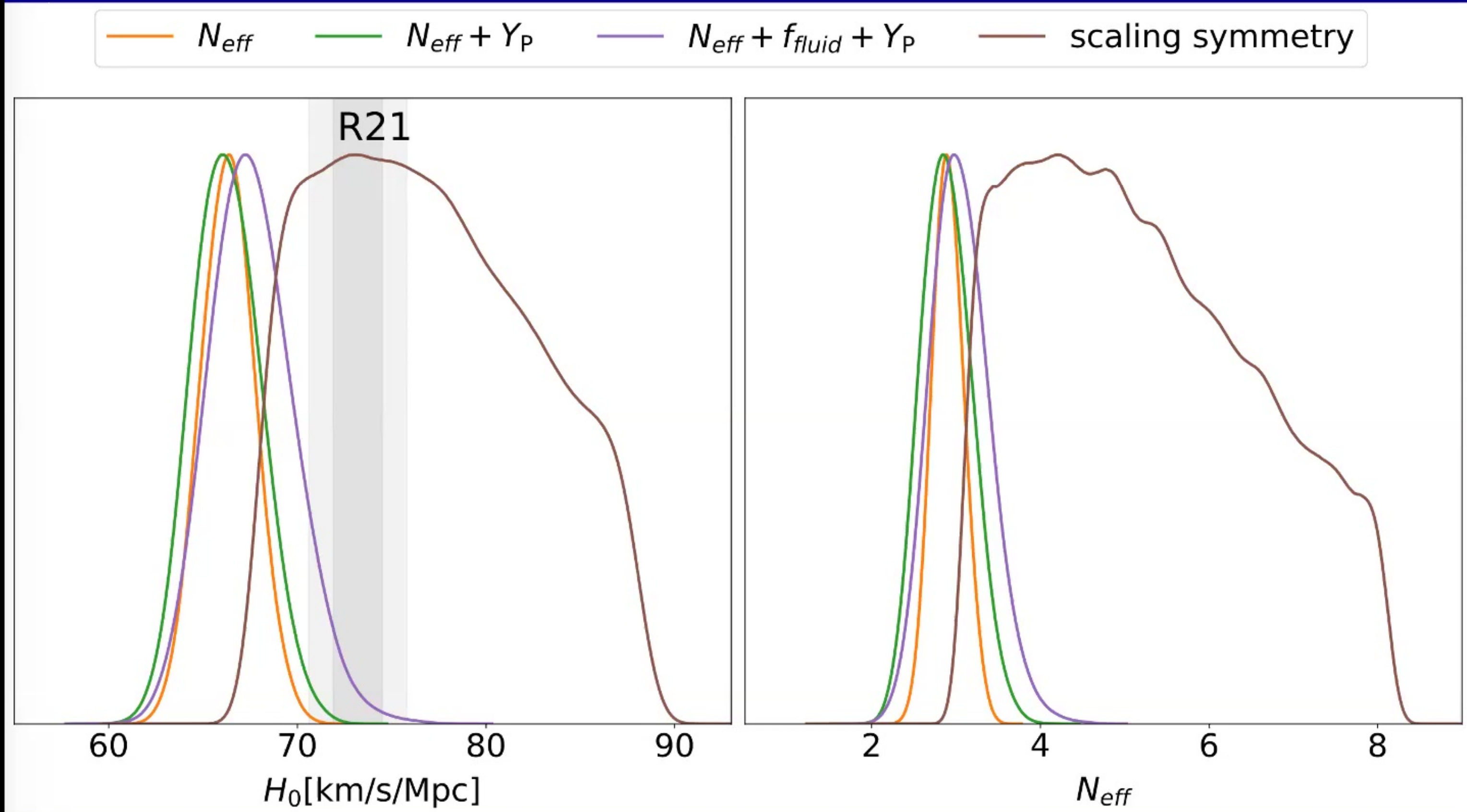


- Symmetry-breaking effects from the self-consistently calculated recombination history are very mild!
- The symmetry allows us to completely eliminate the Hubble tension between CMB + BAO and the local distance ladder (R21 here).

Constraints from Planck 2018 CMB temperature and polarization power spectra



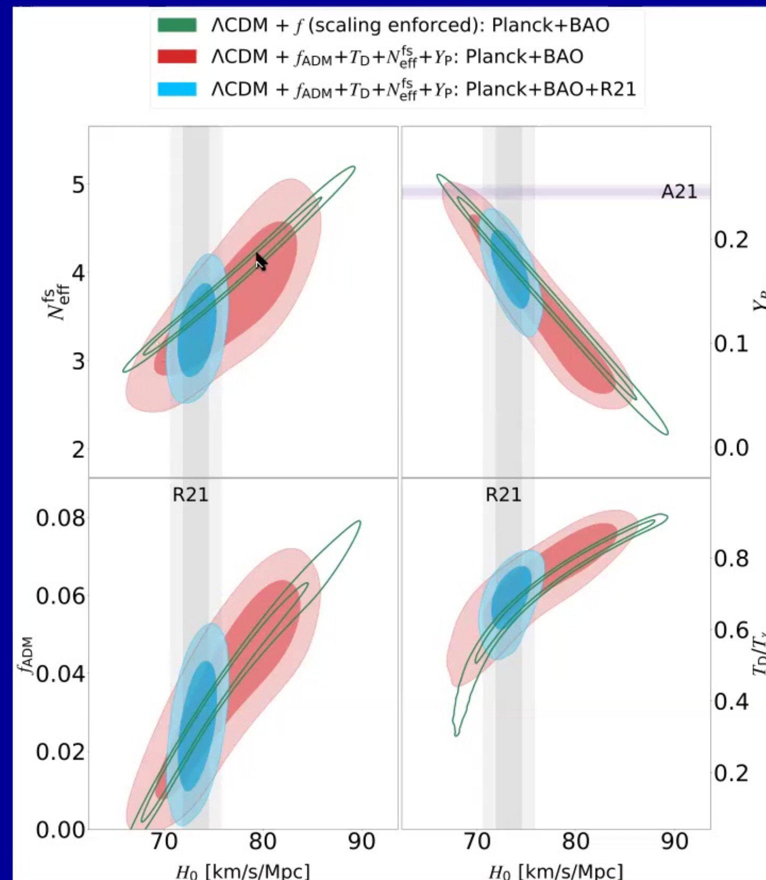
Constraints from Planck 2018 CMB temperature and polarization power spectra



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.

However, Y_P is low!



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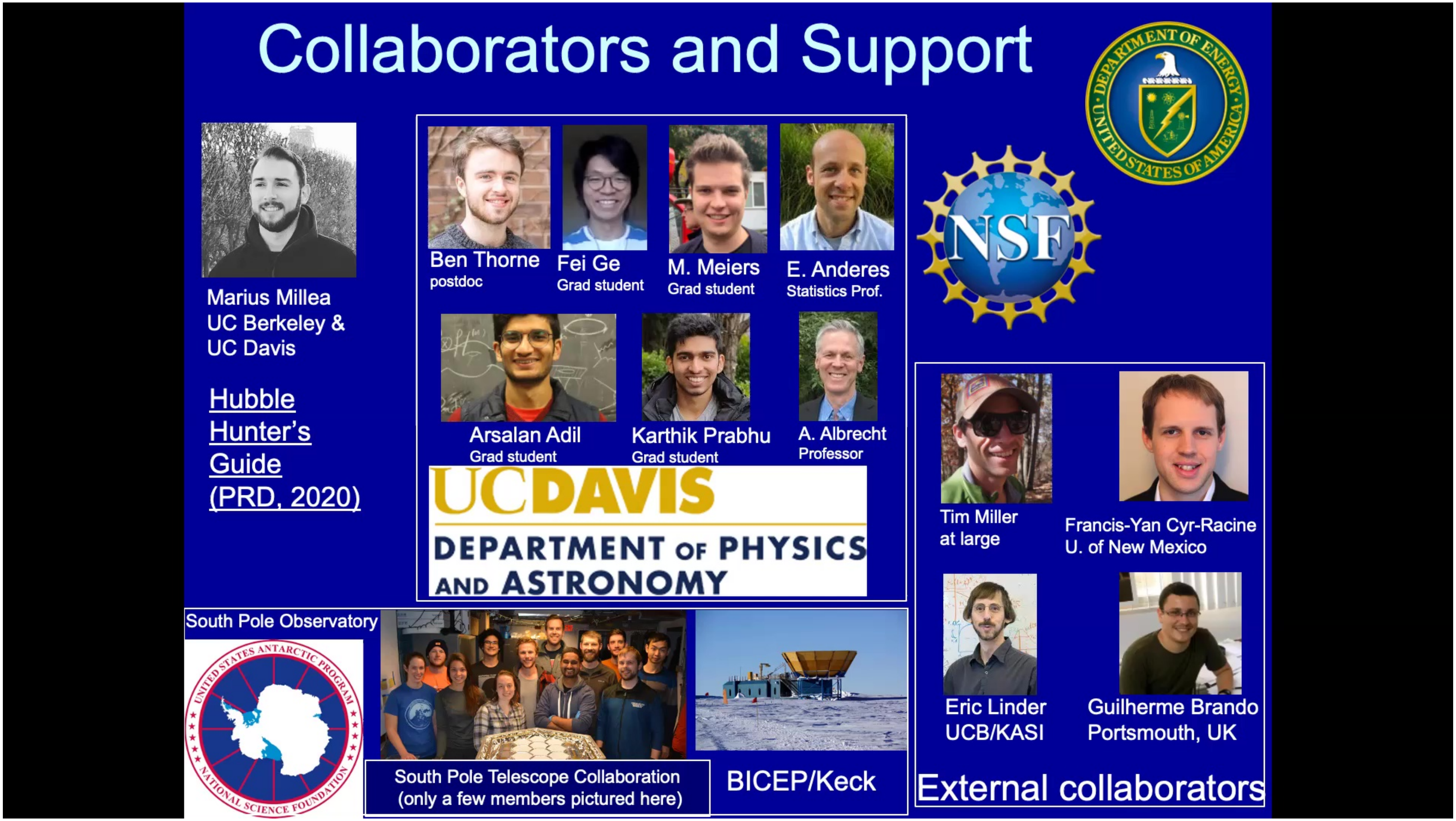
64

Conclusions

- We have identified a previously unnoticed symmetry of dimensionless cosmological observables.
- A dark sector mirroring the Standard Model can exploit this symmetry to completely eliminate the Hubble tension.
- This symmetry can help generate new models that are compatible with cosmological data.

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?
  - Bansal et al. (hep-ph/2110.04317)
  - Blinov, Krnjaic, and Li (hep-ph/2108.11386)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Karthik Prabhu
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South Pole Telescope Collaboration
(only a few members pictured here)
BICEP/Keck