The Hubble tension and Early Dark Energy

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Collaborators

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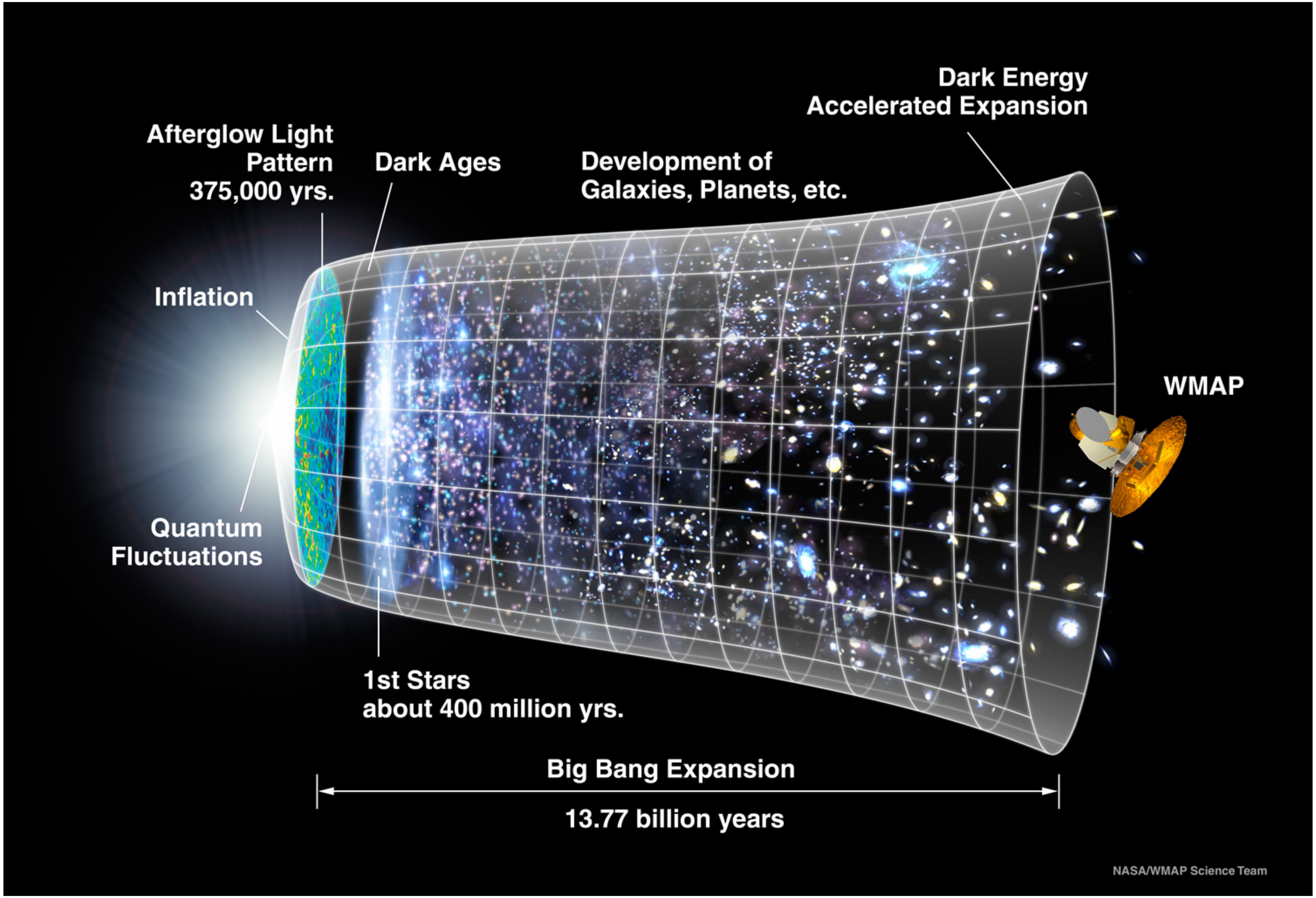
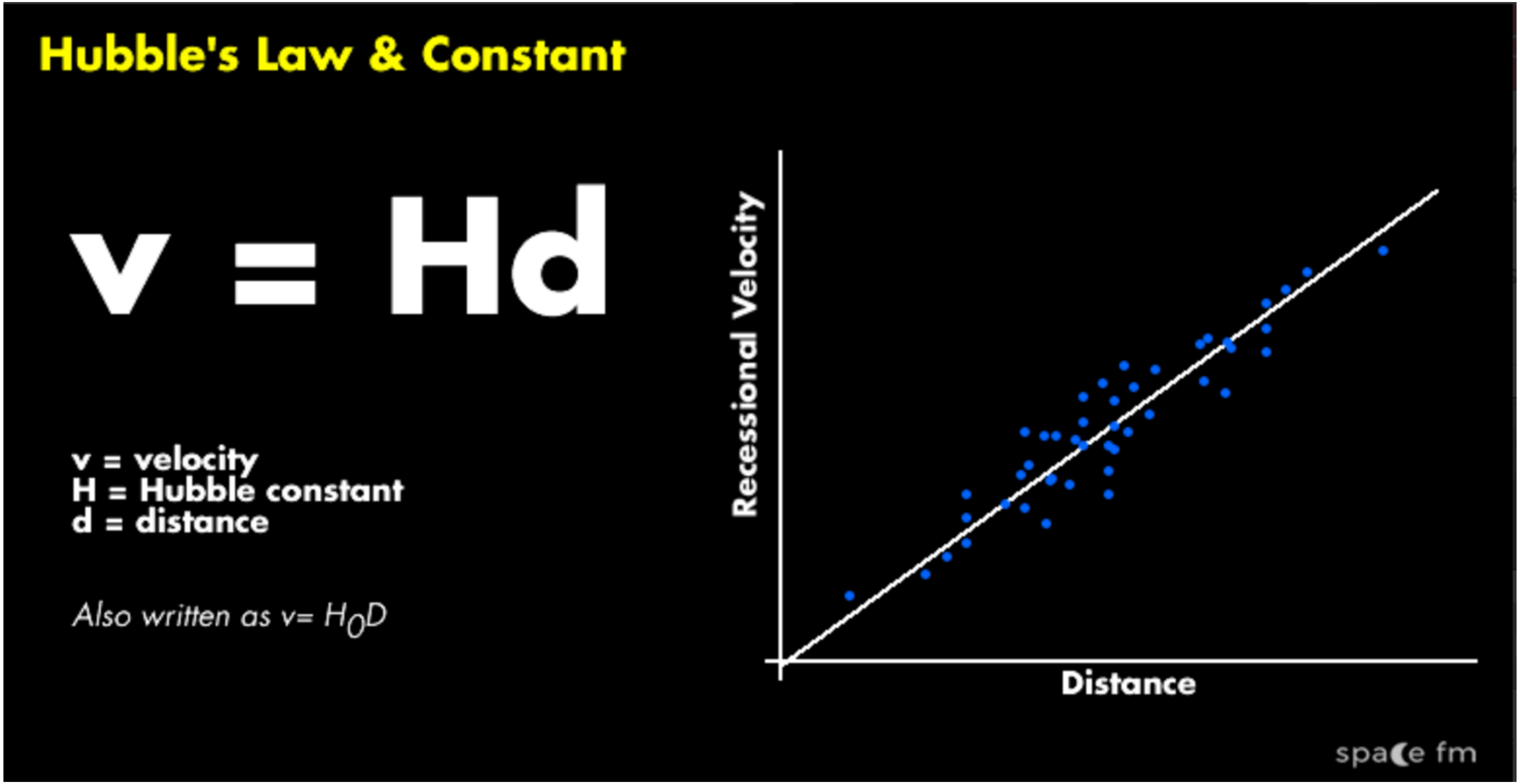
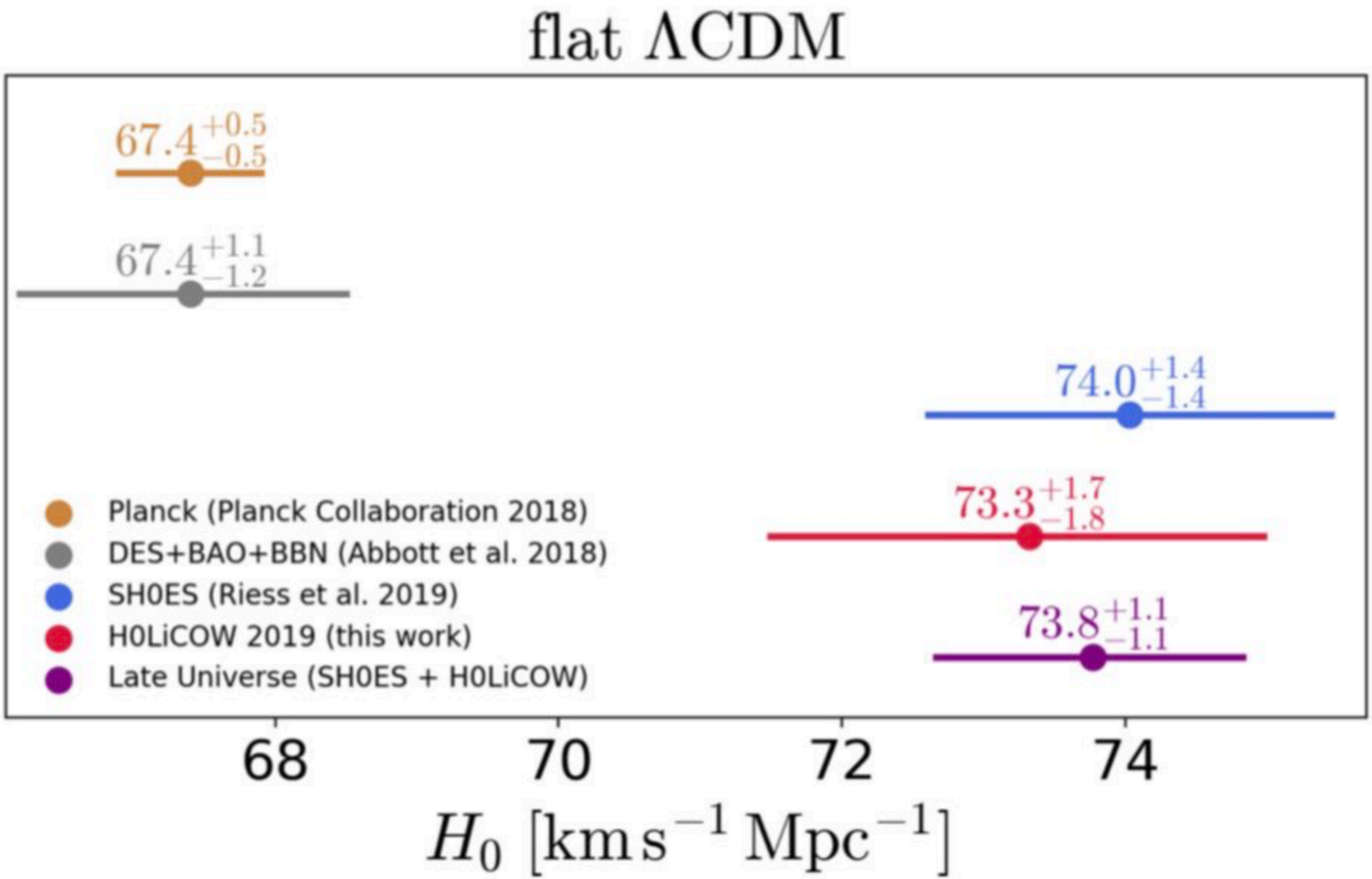

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years
NASA/WMAP Science Team

Hubble law



Hubble's Law & Constant
v = Hd
v = velocity
H = Hubble constant
d = distance
Also written as v= H0D
Recessional Velocity
Distance
space fm


flat ΛCDM
$67.4^{+0.5}_{-0.5}$
$67.4^{+1.1}_{-1.2}$
$74.0^{+1.4}_{-1.4}$
$73.3^{+1.7}_{-1.8}$
$73.8^{+1.1}_{-1.1}$
Planck (Planck Collaboration 2018)
DES+BAO+BBN (Abbott et al. 2018)
SH0ES (Riess et al. 2019)
H0LiCOW 2019 (this work)
Late Universe (SH0ES + H0LiCOW)
68
70
72
74
H_0 [km s^{-1} Mpc^{-1}]

The Hubble “tension”: Why does the expansion rate inferred from the CMB differ from that observed locally?

- Problem with local measurements?
- Problem with CMB measurements?
- Problems with both?
- New physics?

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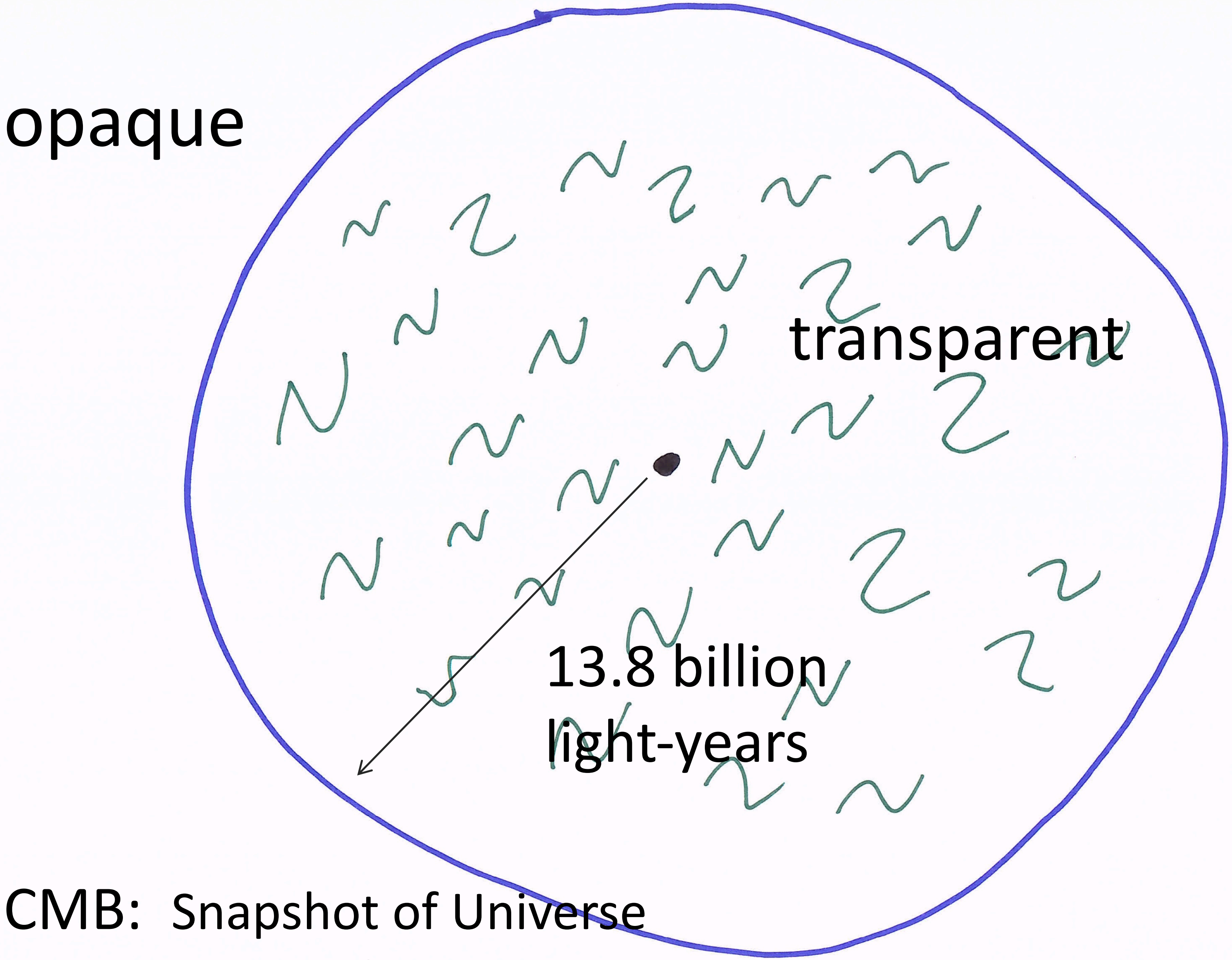
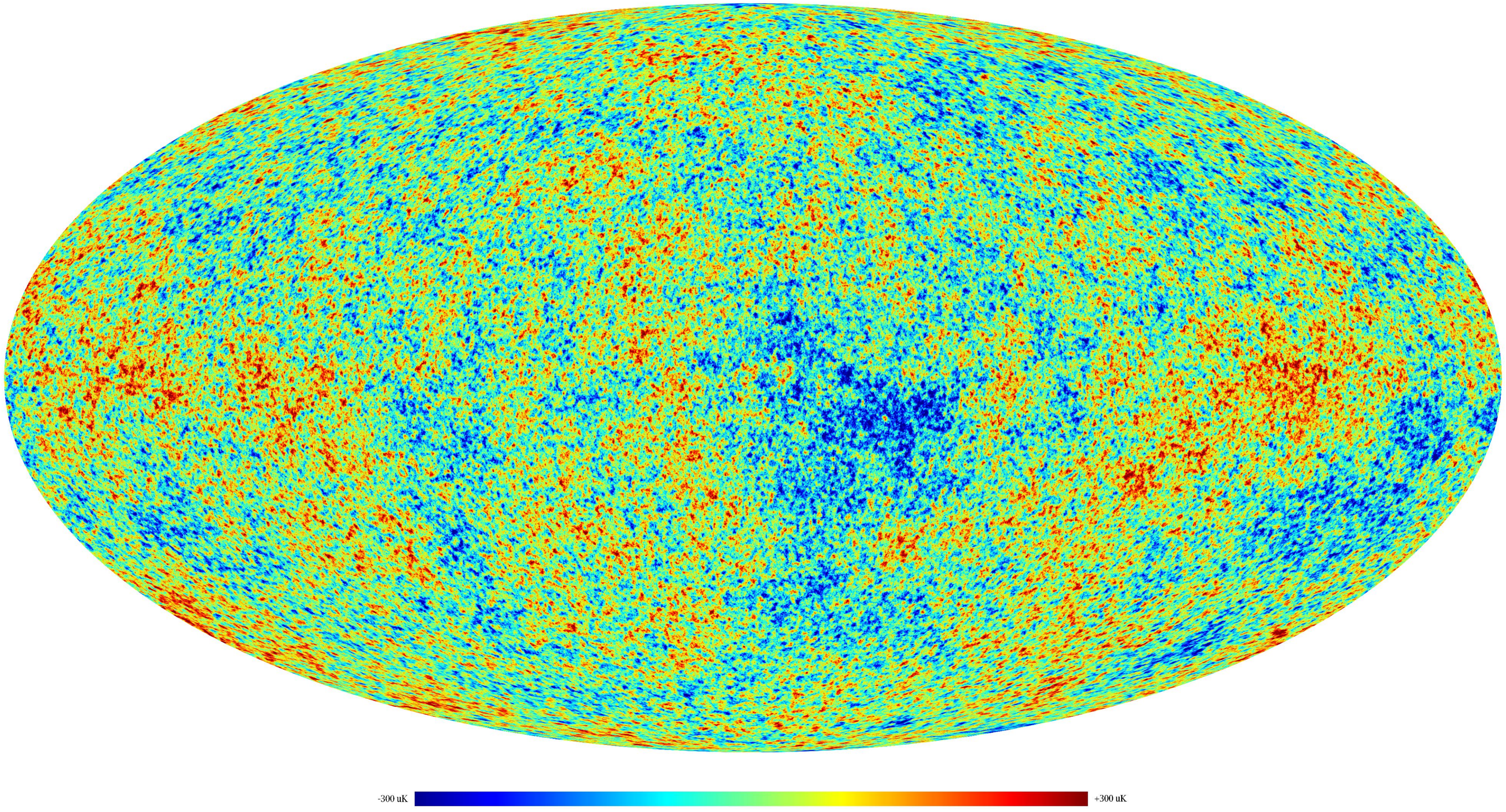


CMB: Snapshot of Universe
380,000 years after big bang

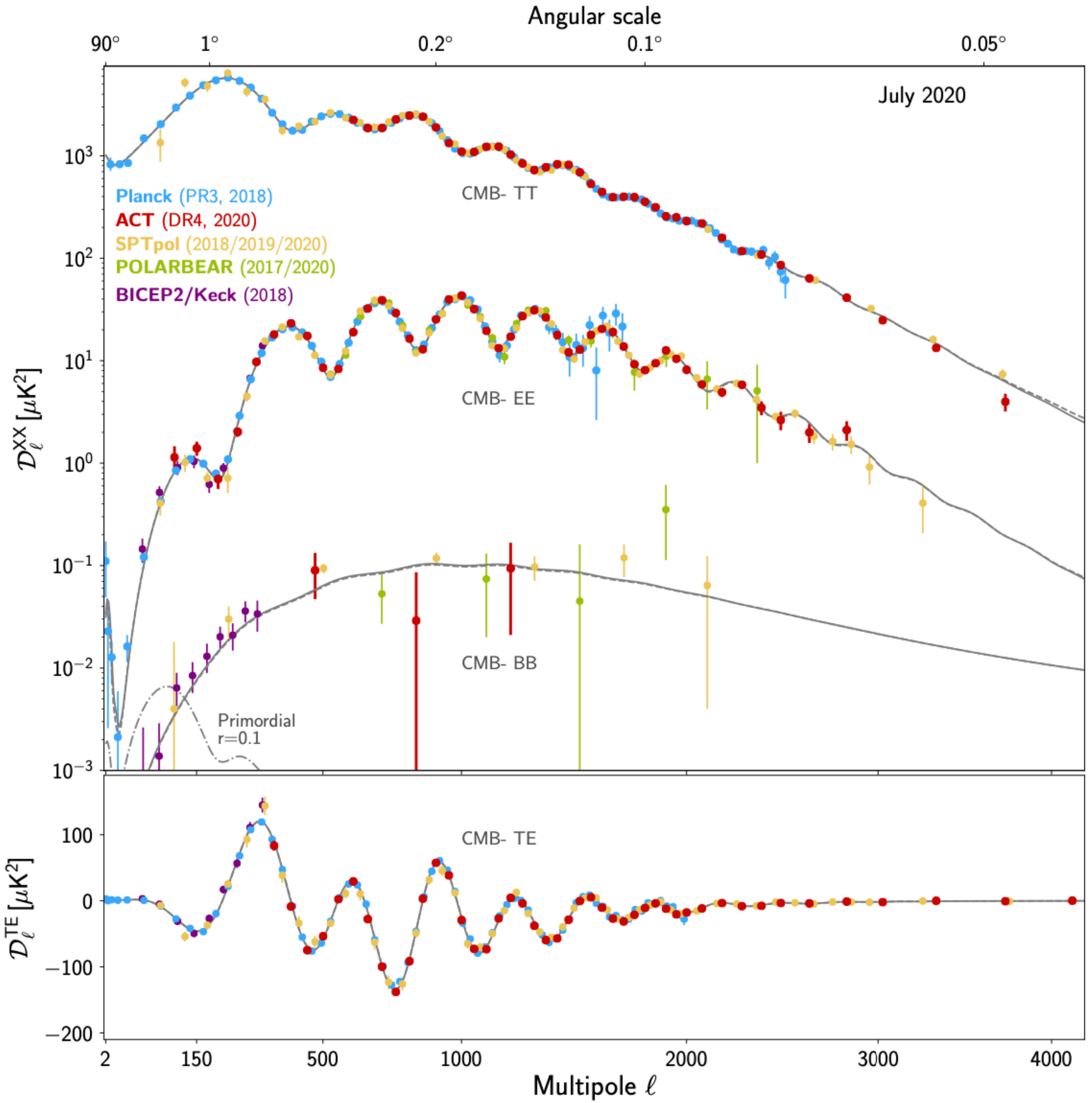

-300 uK
+300 uK

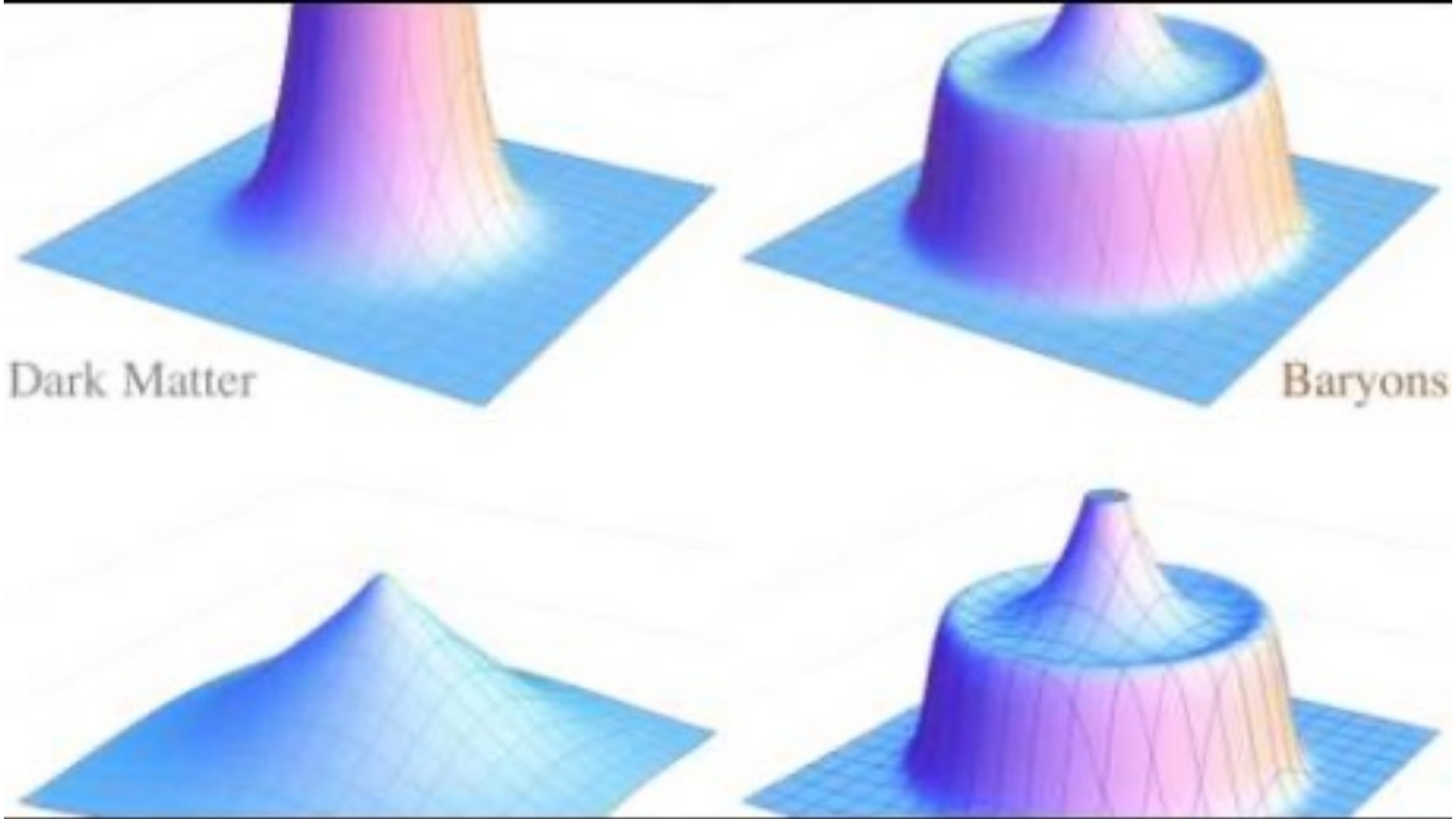
How does CMB data measure H0?

- Inference of H_0 from the CMB is model dependent.
- It comes from the measurement of three angular scales $\theta_s, \theta_d, \theta_{eq}$.

CMB power spectrum:

~ |Fourier transform|^2




Dark Matter
Baryons

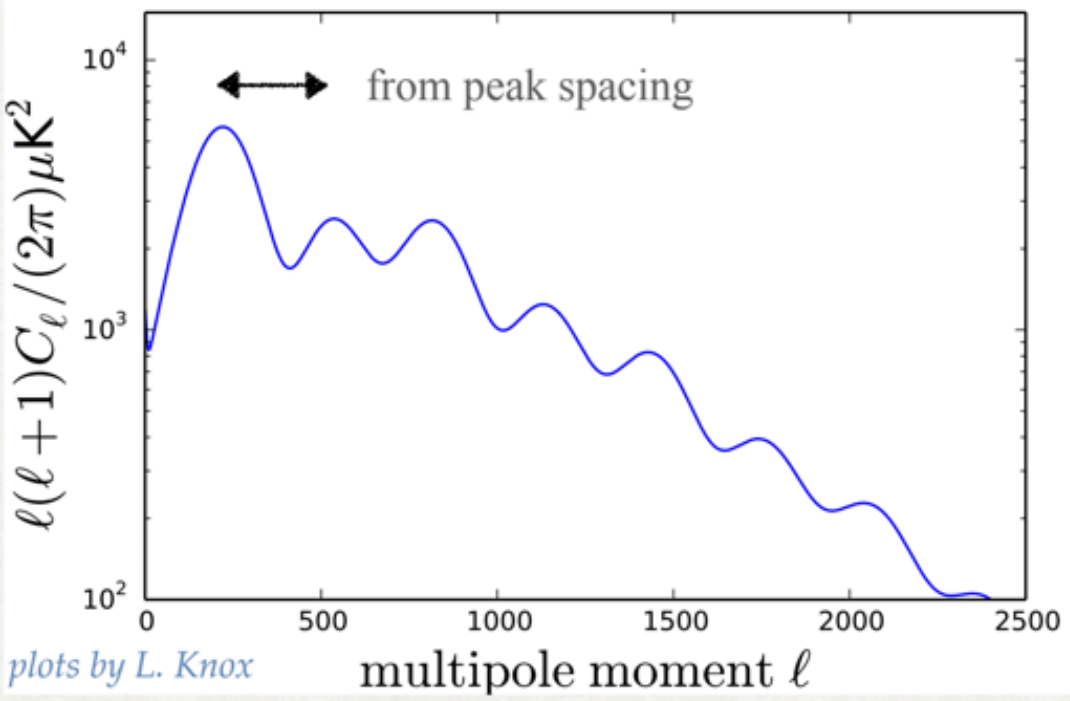
Acoustic peaks come from Fourier-space ”ringing” of these spherical shells

Wavenumber (l) $\propto$ (sound horizon)$^{-1}$

How does CMB data measure H0?

- Inference of H_0 from the CMB is model dependent.
- It comes from the measurement of three angular scales $\theta_s, \theta_d, \theta_{eq}$.

θ_s sound horizon at last scattering ~1.0404

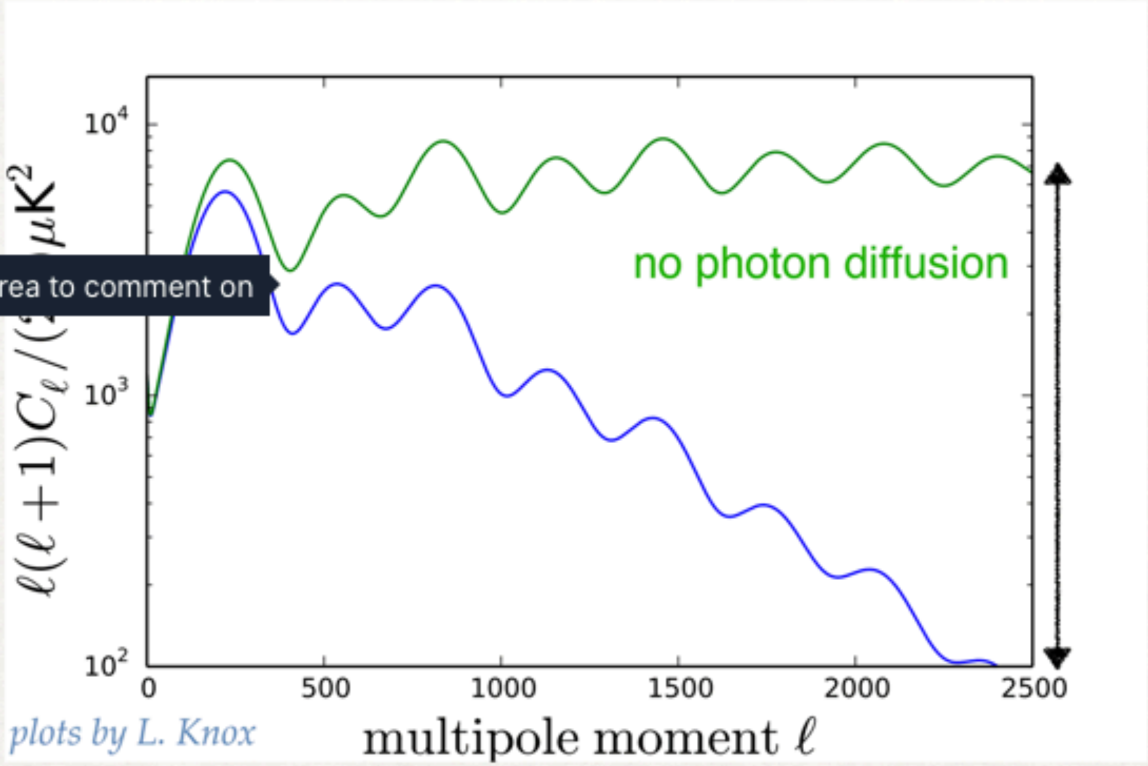


plots by L. Knox

How does CMB data measure H0?

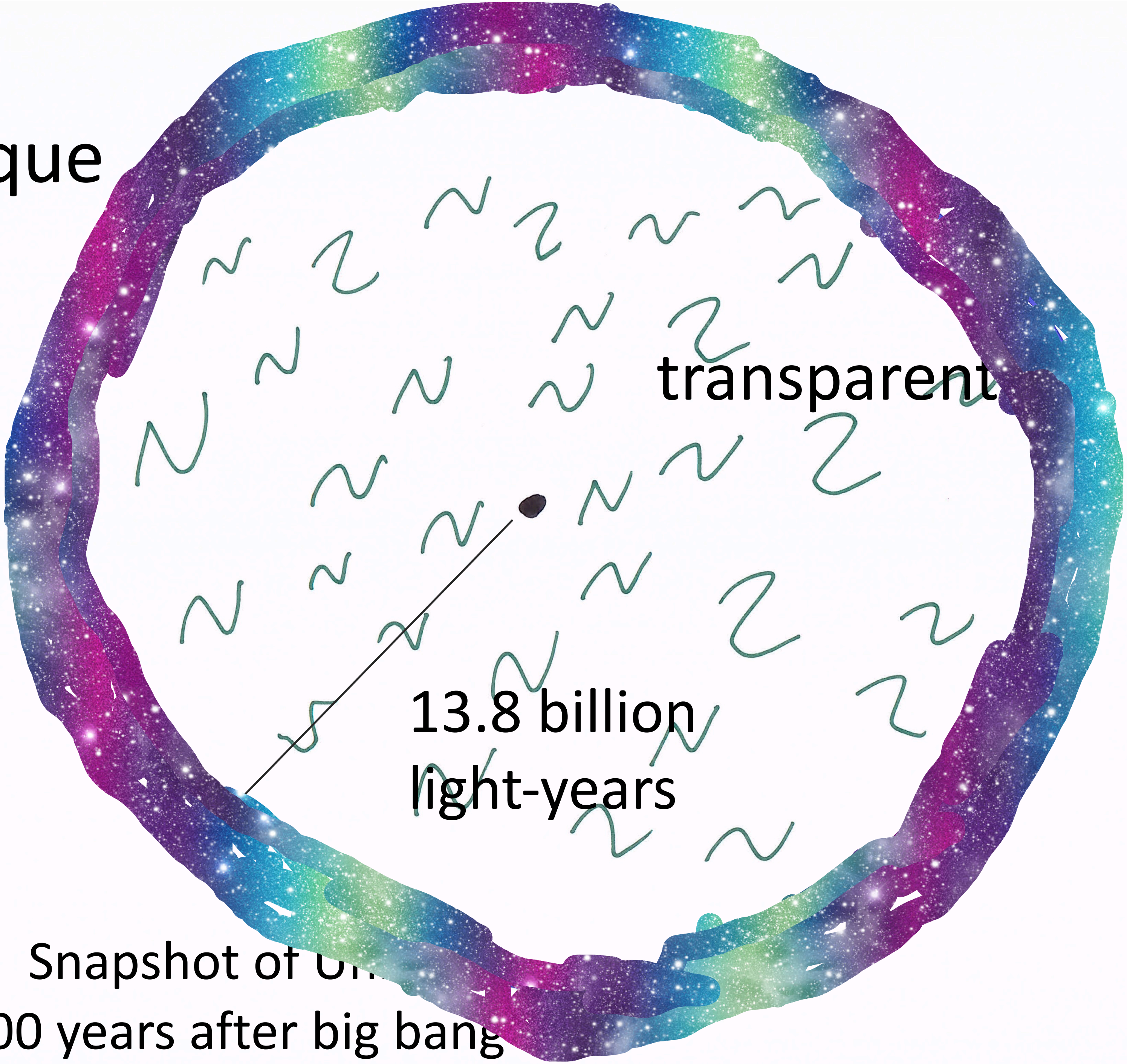
- Inference of H_0 from the CMB is model dependent.
- It comes from the measurement of three angular scales $\theta_s, \theta_d, \theta_{eq}$.

θ_d photon diffusion length at last scattering ~ 0.1609



"Silk Damping"

e.g. Hu&White astro-ph/9609079, Hu++astro-ph/0006436 opaque



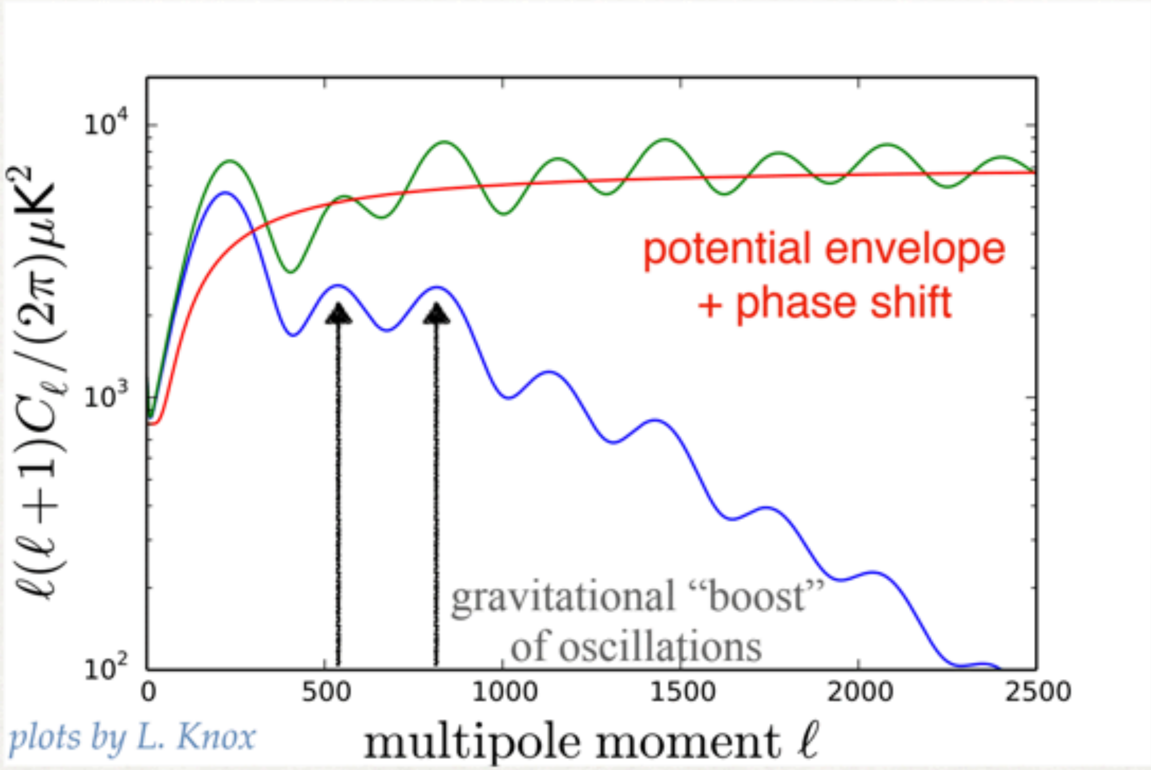
CMB: Snapshot of U
380,000 years after big bang

How does CMB data measure H0?

- Inference of H_0 from the CMB is model dependent.

- It comes from the measurement of three angular scales $\theta_s, \theta_d, \theta_{eq}$.

θ_{eq} horizon size at matter-radiation equality ~ 0.81



e.g. Hu&White astro-ph/9609079, Hu++astro-ph/0006436

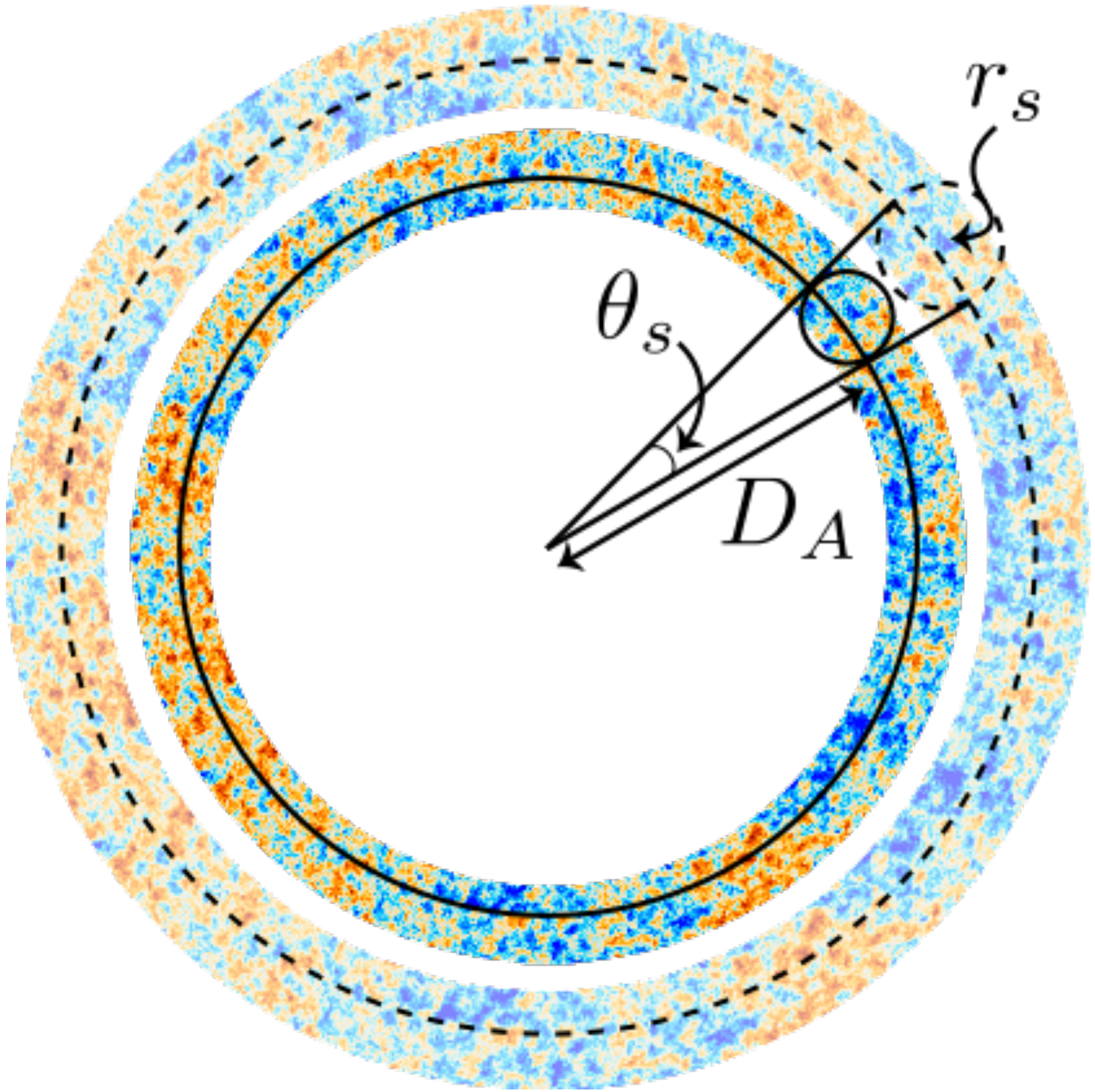
How does CMB measure H_0?

- Three angles:
  - sound horizon
  - damping scale
  - MR equality

- depend on
  - dark-matter density
  - baryon density
  - Hubble constant

- Of three angles, sound-horizon angle determined best (1 part in 10^4)

$$\theta_s = \frac{r_s}{D_A}$$



$$D_A = \frac{c}{H_0} \int_{t_{rec}}^{t_0} \frac{dt/t_0}{[\rho(t)/\rho_0]^{1/2}}$$

$$r_s = \frac{1}{H_{\rm rec}} \int_0^{t_{\rm rec}} \frac{c_s(t)\, dt/t_{\rm rec}}{[\rho(t)/\rho(t_{\rm rec})]^{1/2}}$$

$$H_0 = H_{\rm rec} \frac{\int_{t_{\rm rec}}^{t_0} \frac{c\,dt/t_0}{[\rho(t)/\rho_0]^{1/2}}}{\int_0^{t_{\rm rec}} \frac{c_s(t)\,dt/t_{\rm rec}}{[\rho(t)/\rho(t_{\rm rec})]^{1/2}}}$$

To increase H_0, can

- Decrease matter density at late times
- Decrease sound speed in early Universe
- Increase matter density at early times

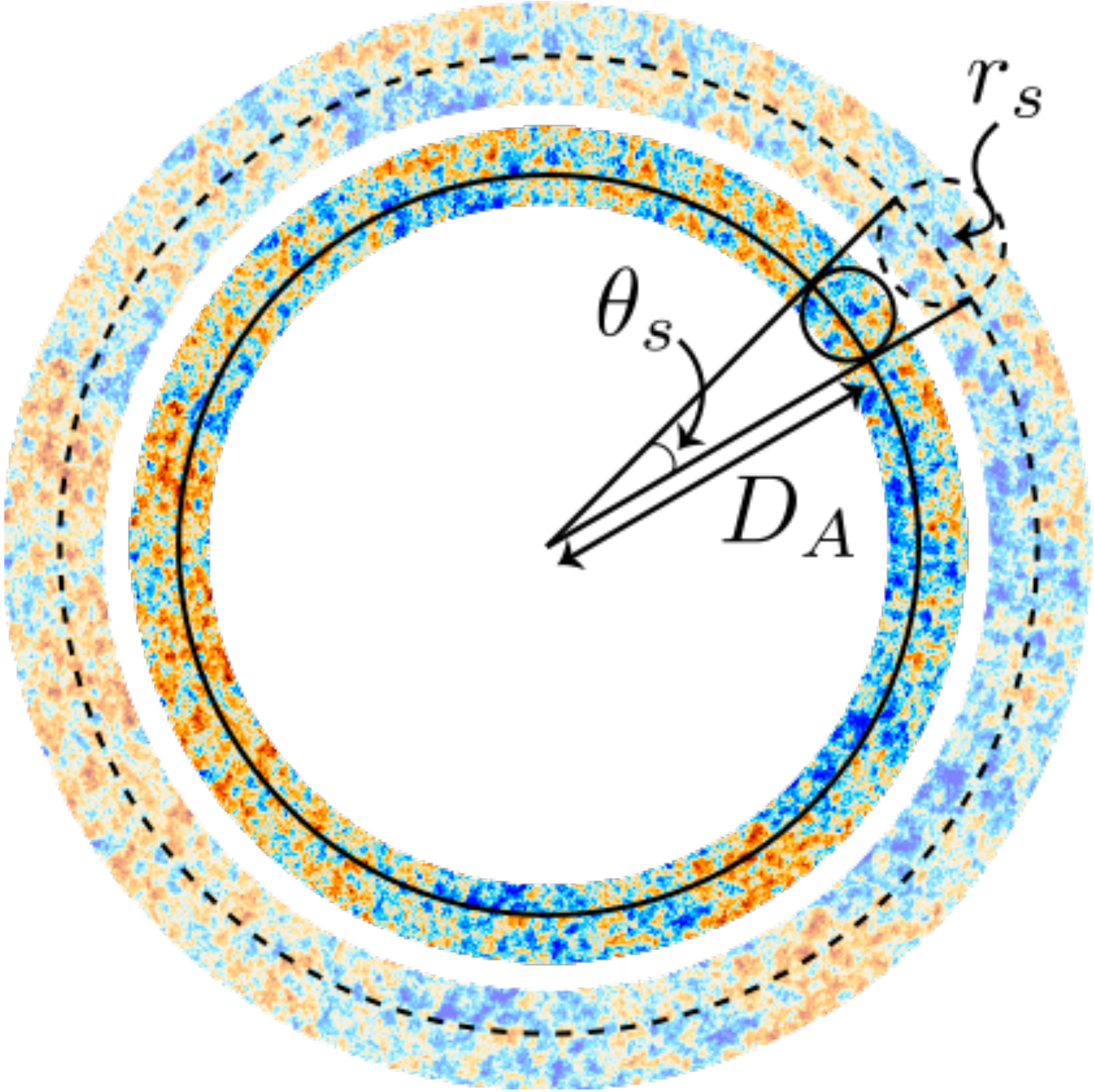
$$H_0 = H_{\rm rec} \frac{\int_{t_{\rm rec}}^{t_0} \frac{c\, dt/t_0}{[\rho(t)/\rho_0]^{1/2}}}{\int_0^{t_{\rm rec}} \frac{c_s(t)\, dt/t_{\rm rec}}{[\rho(t)/\rho(t_{\rm rec})]^{1/2}}}$$

To increase H_0, can

- Decrease matter density at late times (late-time solutions)
- Decrease sound speed in early Universe
- Increase matter density at early times

$$H_{\rm cmb} \propto \frac{1}{D_A} \propto \frac{\theta_s}{r_s}$$

$$\theta_s = \frac{r_s}{D_A}$$

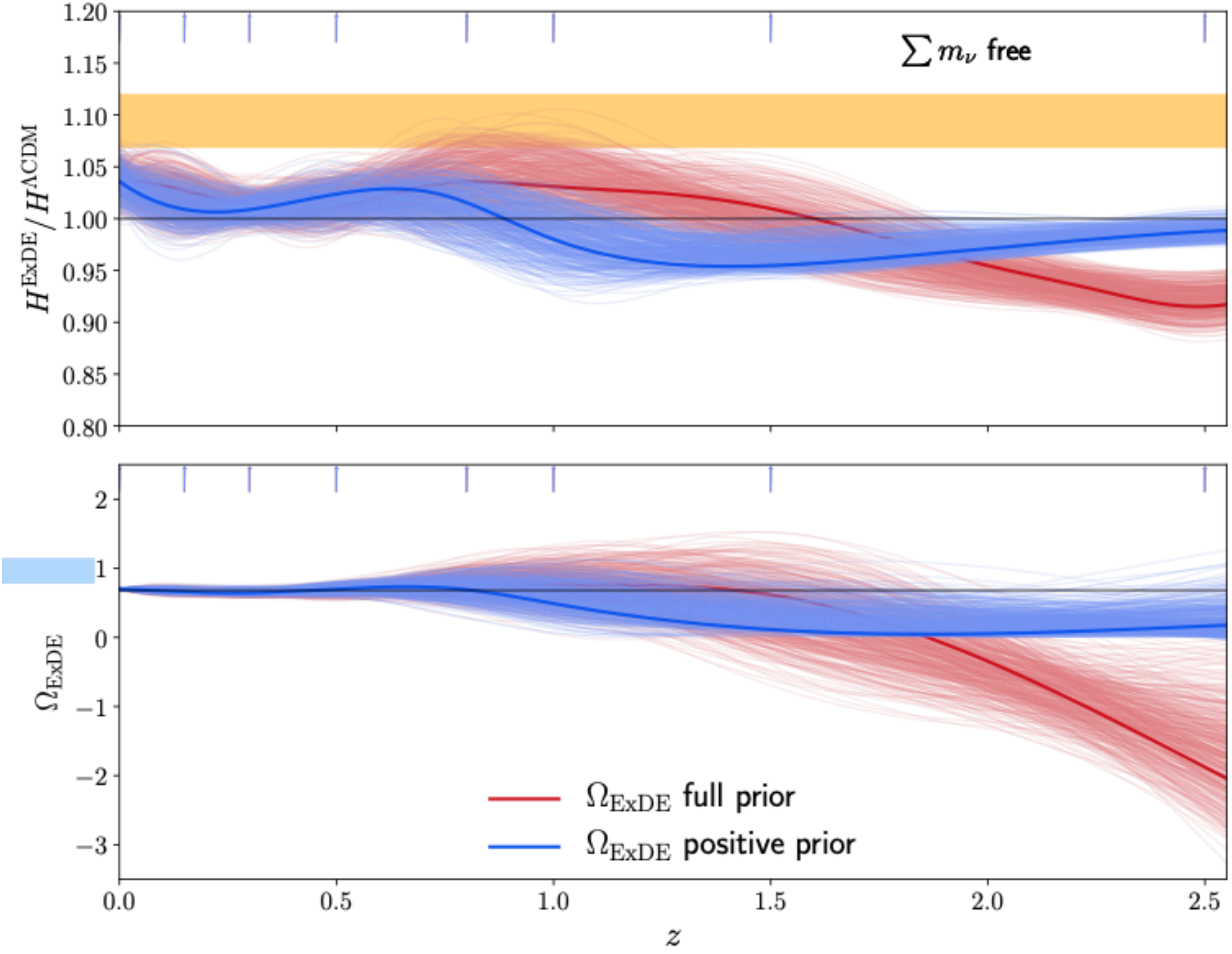


Late-time solutions

Modify late expansion history to increase D_A

e.g., exotic dark energy; phantom energy; exotic dark matter;

Requires energy density *smaller* than in standard model: negative-density matter?!?!   Violation of null energy condition?!?!

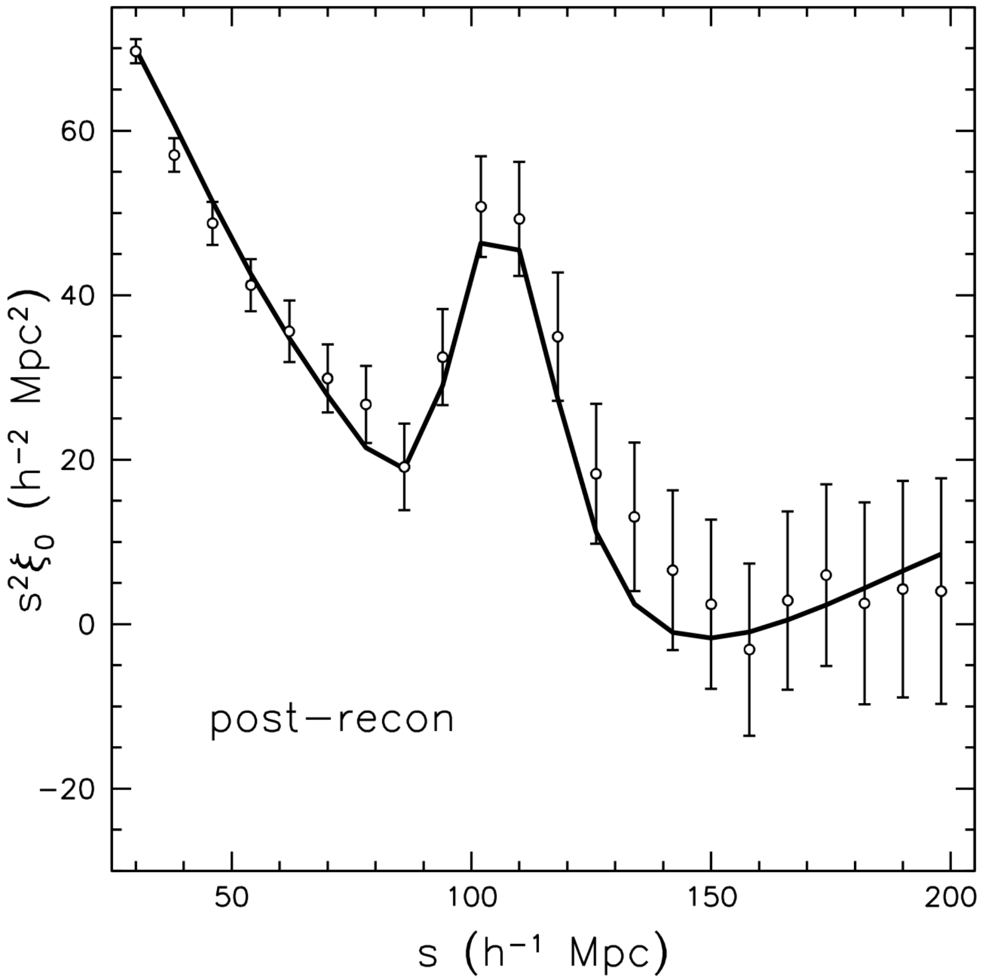


Poulin, Bird, Boddy, MK, arXiv:1803.02474

Late-time solutions: Empirically disfavored by BAO in galaxy distribution

Sound horizon imprinted on galaxy distribution measured in “redshift space”

Provides standard ruler to infer H_0 --> lower H_0



SDSS-BOSS Collaboration
Anderson et al. 2013

$$H_0 = H_{\rm rec} \frac{\int_{t_{\rm rec}}^{t_0} \frac{c\,dt/t_0}{[\rho(t)/\rho_0]^{1/2}}}{\int_0^{t_{\rm rec}} \frac{c_s(t)\,dt/t_{\rm rec}}{[\rho(t)/\rho(t_{\rm rec})]^{1/2}}}$$

To increase H_0, can

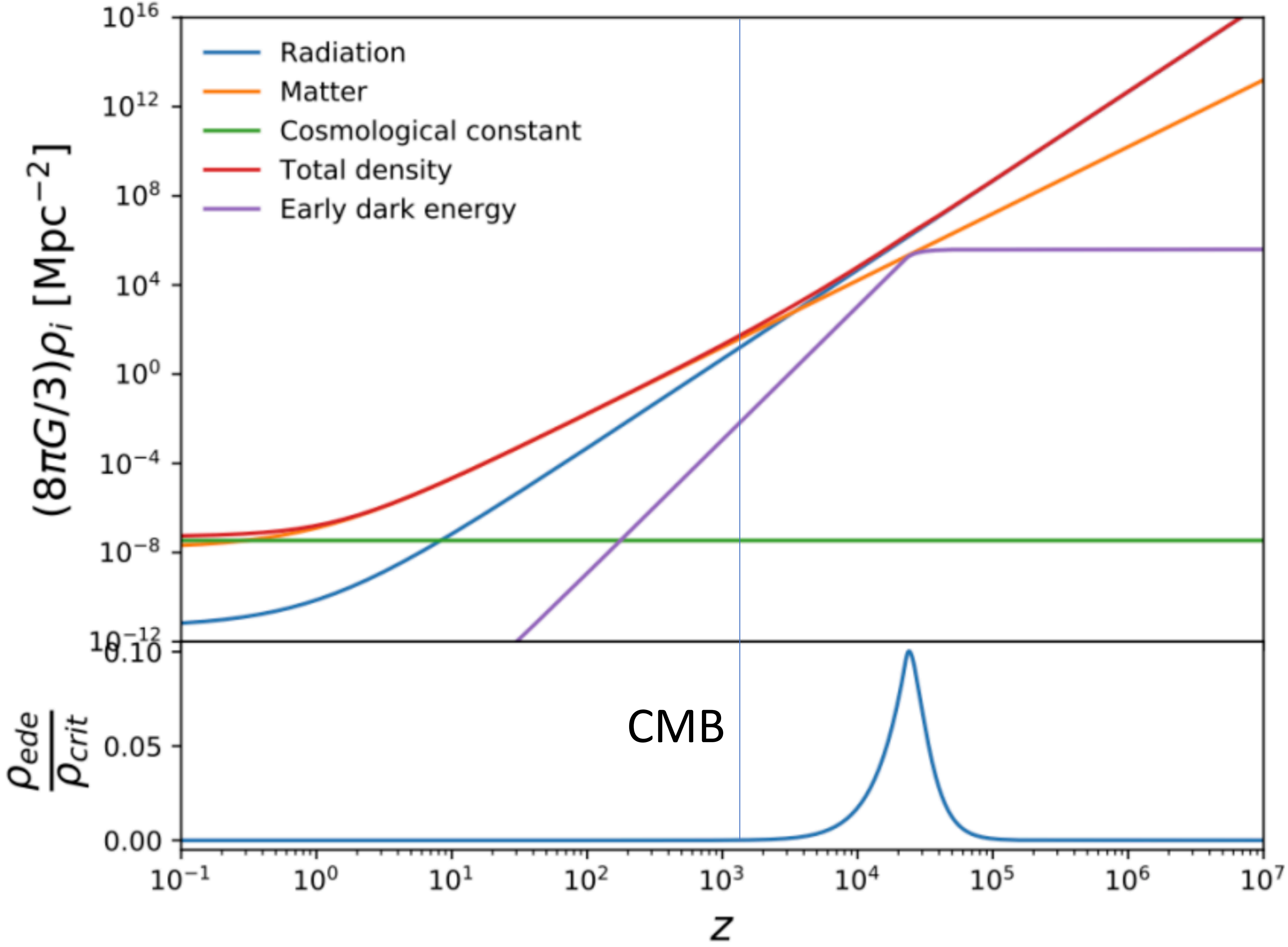
- Decrease matter density at late times (late-time solutions)
- Decrease sound speed in early Universe (not workable yet)
- Increase matter density at early times

$$H_0 = H_{\rm rec} \frac{\int_{t_{\rm rec}}^{t_0} \frac{c\, dt/t_0}{[\rho(t)/\rho_0]^{1/2}}}{\int_0^{t_{\rm rec}} \frac{c_s(t)\, dt/t_{\rm rec}}{[\rho(t)/\rho(t_{\rm rec})]^{1/2}}}$$

To increase H_0, can

- Decrease matter density at late times (late-time solutions)
- Decrease sound speed in early Universe (not workable yet)
- Increase matter density at early times *(early dark energy)*

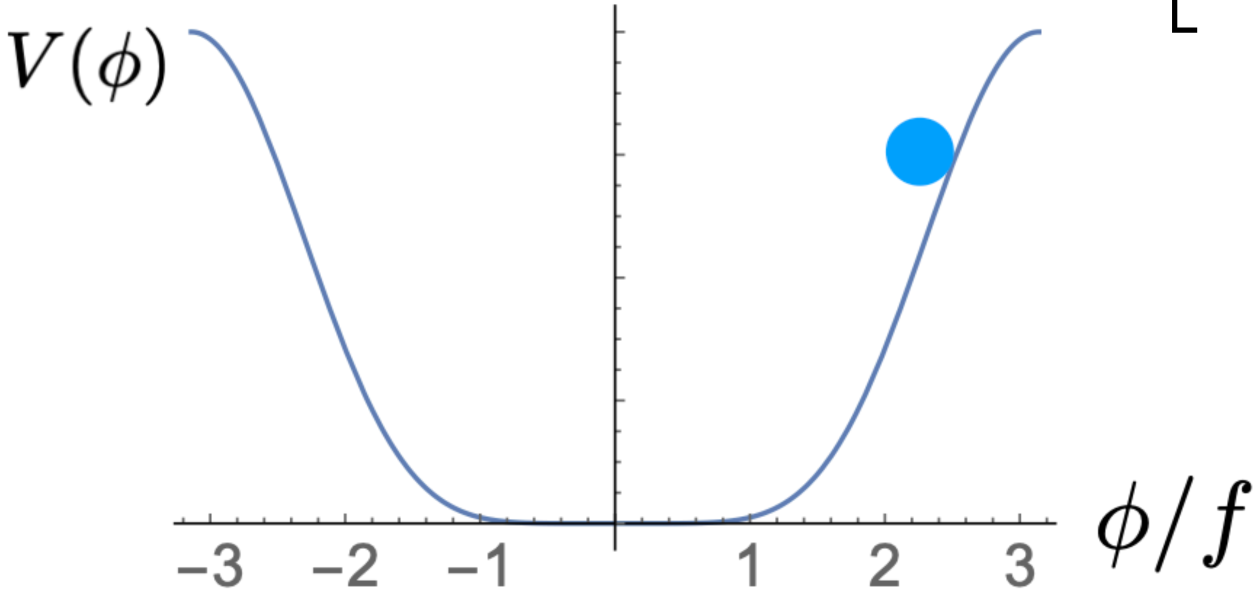
Early dark energy (Karwal & MK, 2016)



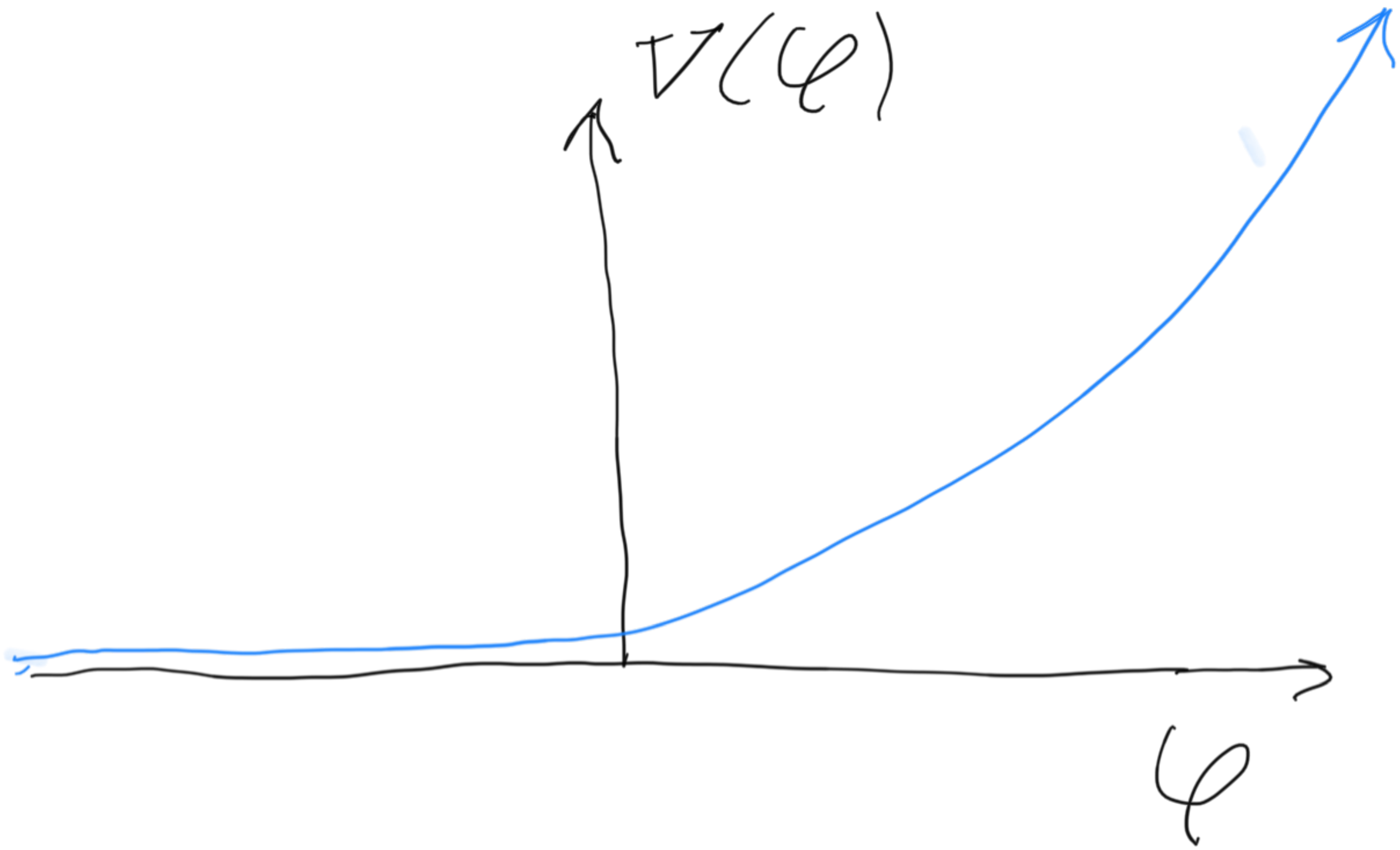
Radiation
Matter
Cosmological constant
Total density
Early dark energy
$(8\pi G/3)\rho_i$ [Mpc^{-2}]
10^{16}
10^{12}
10^{8}
10^{4}
10^{0}
10^{-4}
10^{-8}
10^{-12}
$\frac{\rho_{ede}}{\rho_{crit}}$
0.10
0.05
0.00
CMB
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
z

The (postulated) physics of DE

$$V(\phi) \propto \left[1 - \cos\left(\frac{\phi}{f}\right)\right]^n$$



Behaves like cosmological constant at late times; decays as $(\mathrm{scale\,factor})^{(2n-2)/(2n+2)}$ at late times (MK, Pradler & Walker, 2014) or



Devil is in the details:

Need detailed calculations to show that model predictions are consistent with CMB measurements (Poulin, Karwal, Smith, MK, fall 2018)

Calculations

For each combination of cosmological/EDE parameters (DM density, baryon density, Hubble parameter, scalar amplitude/spectral index, reionization optical depth; scalar-field potential parameters, initial field value)….

Evolve (in time, from big bang to present) coupled differential equations for evolution of

- dark-matter density and velocity
- (moments of) photon distribution function
- neutrino distribution function
- baryon density and velocity
- scalar field
- gravitational potential(s)

For each spatial Fourier mode

Use modified version (Poulin, Smith, Grin, Karwal, MK 2018) of publicly-available CLASS

Calculations

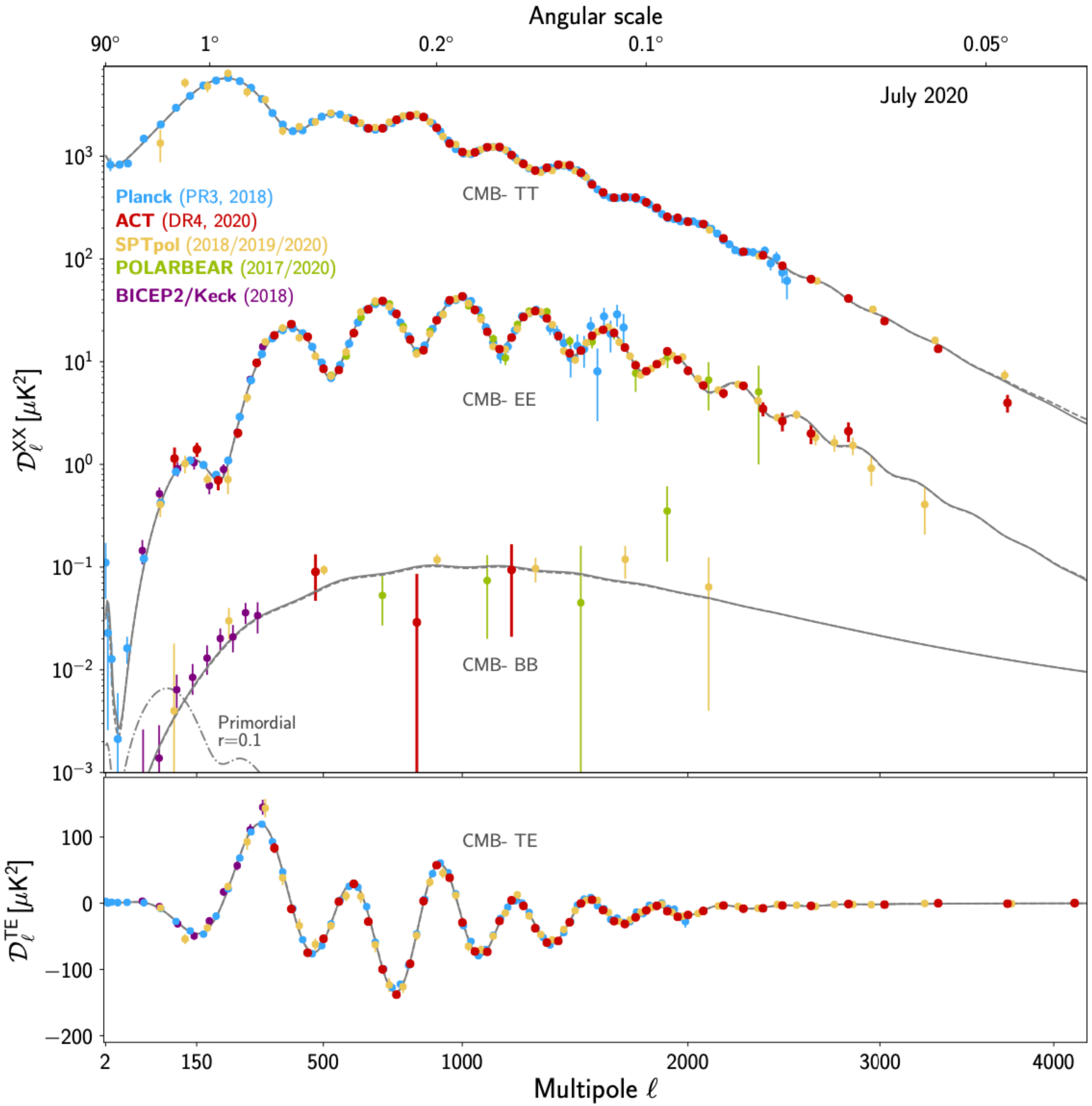
for oscillating-field model, slow-roll model, and phenomenological description in terms of “generalized dark matter” (Hu 1998)

Products:

- CMB temperature/polarization power spectra
- Galaxy power spectrum

Analysis

Determine likelihood for each parameter combination; use MCMC to find peaks in likelihood and seek parameter combinations with high Hubble parameter that provide good fits to data



Angular scale
90°
1°
0.2°
0.1°
0.05°
July 2020
Planck (PR3, 2018)
ACT (DR4, 2020)
SPTpol (2018/2019/2020)
POLARBEAR (2017/2020)
BICEP2/Keck (2018)
CMB- TT
CMB- EE
CMB- BB
Primordial
r=0.1
CMB- TE
$\mathcal{D}_\ell^{XX}\,[\mu K^2]$
$\mathcal{D}_\ell^{TE}\,[\mu K^2]$
Multipole ℓ

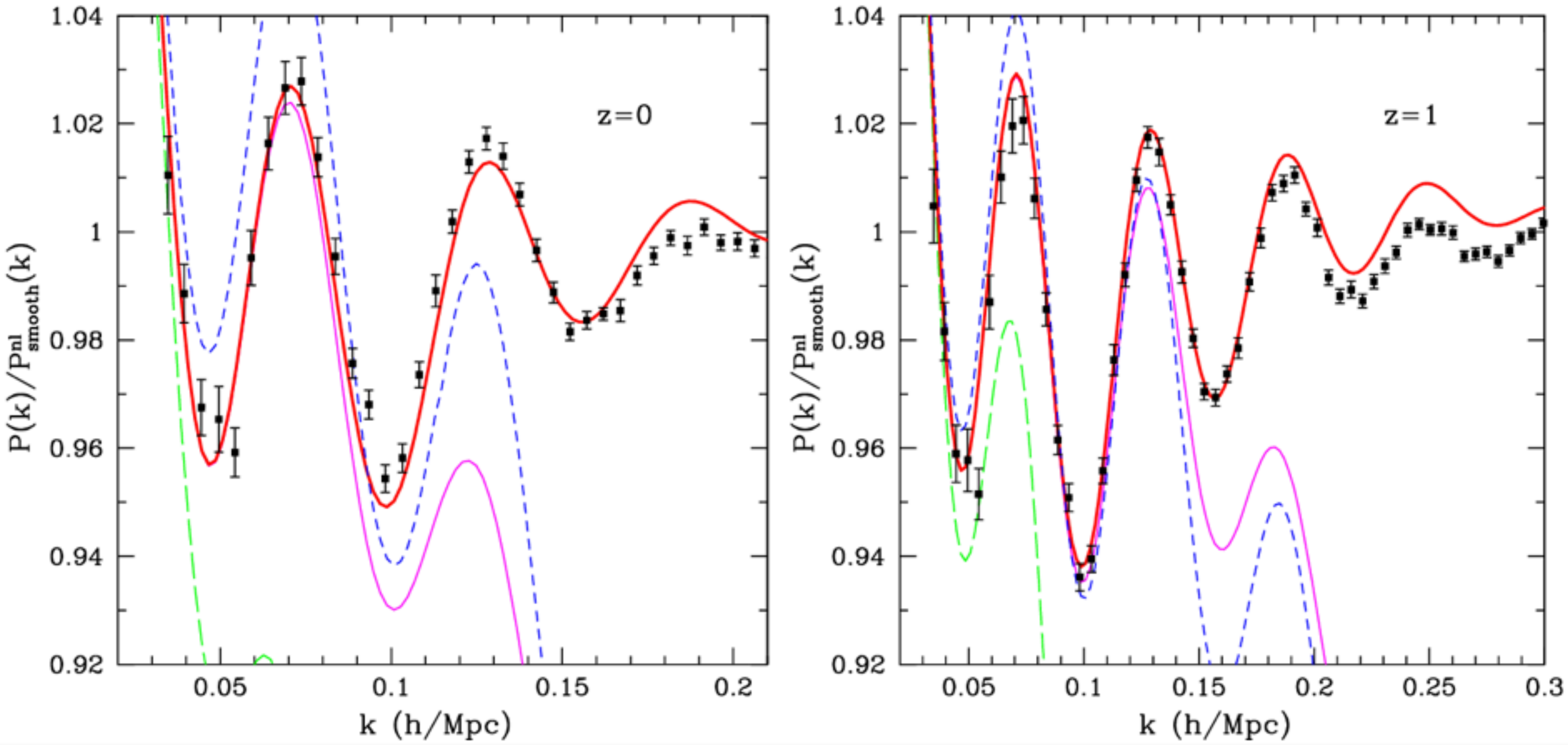


Figure from Crocce & Scoccimarro, arXiv>0704.2783

Product

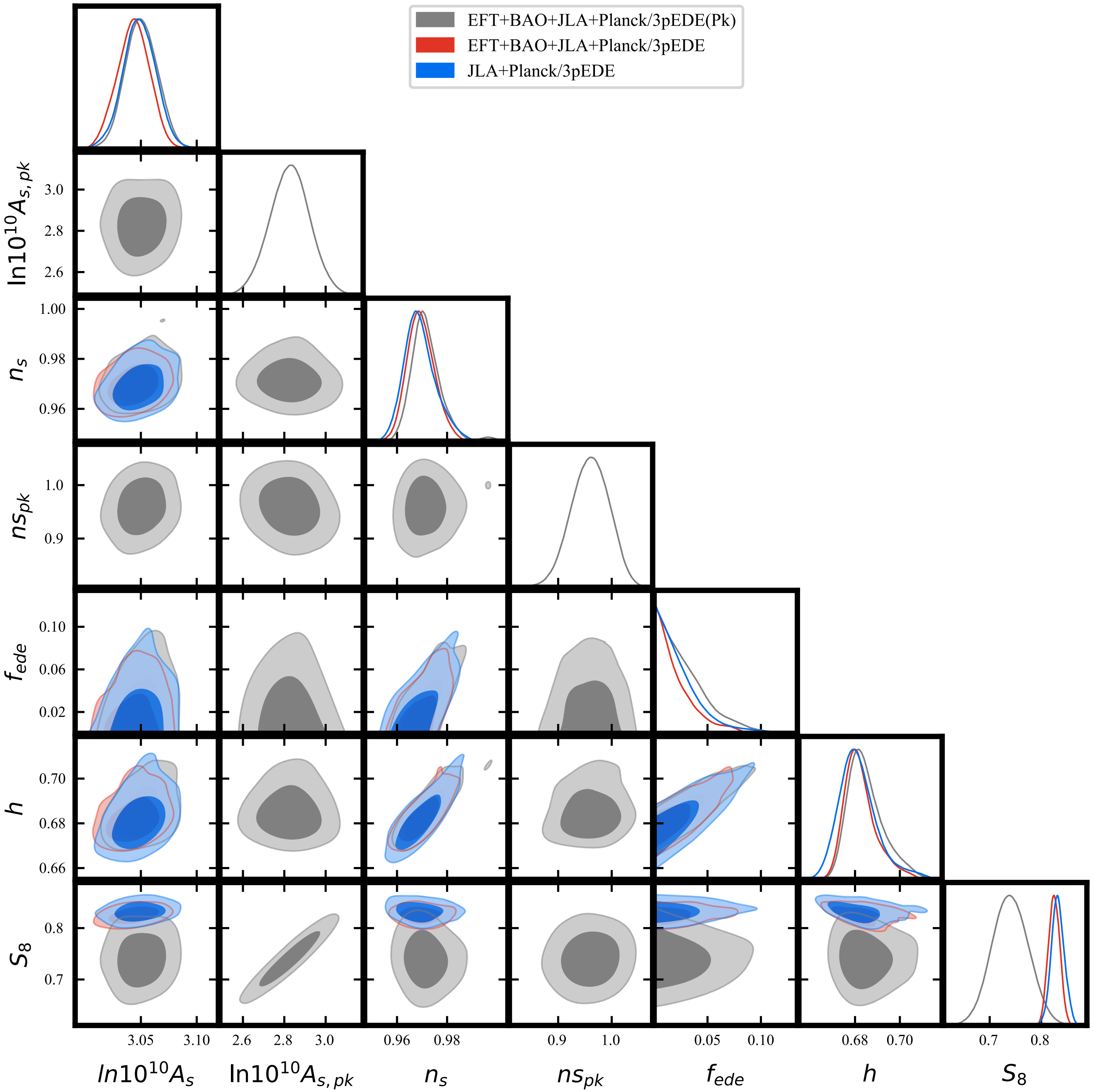
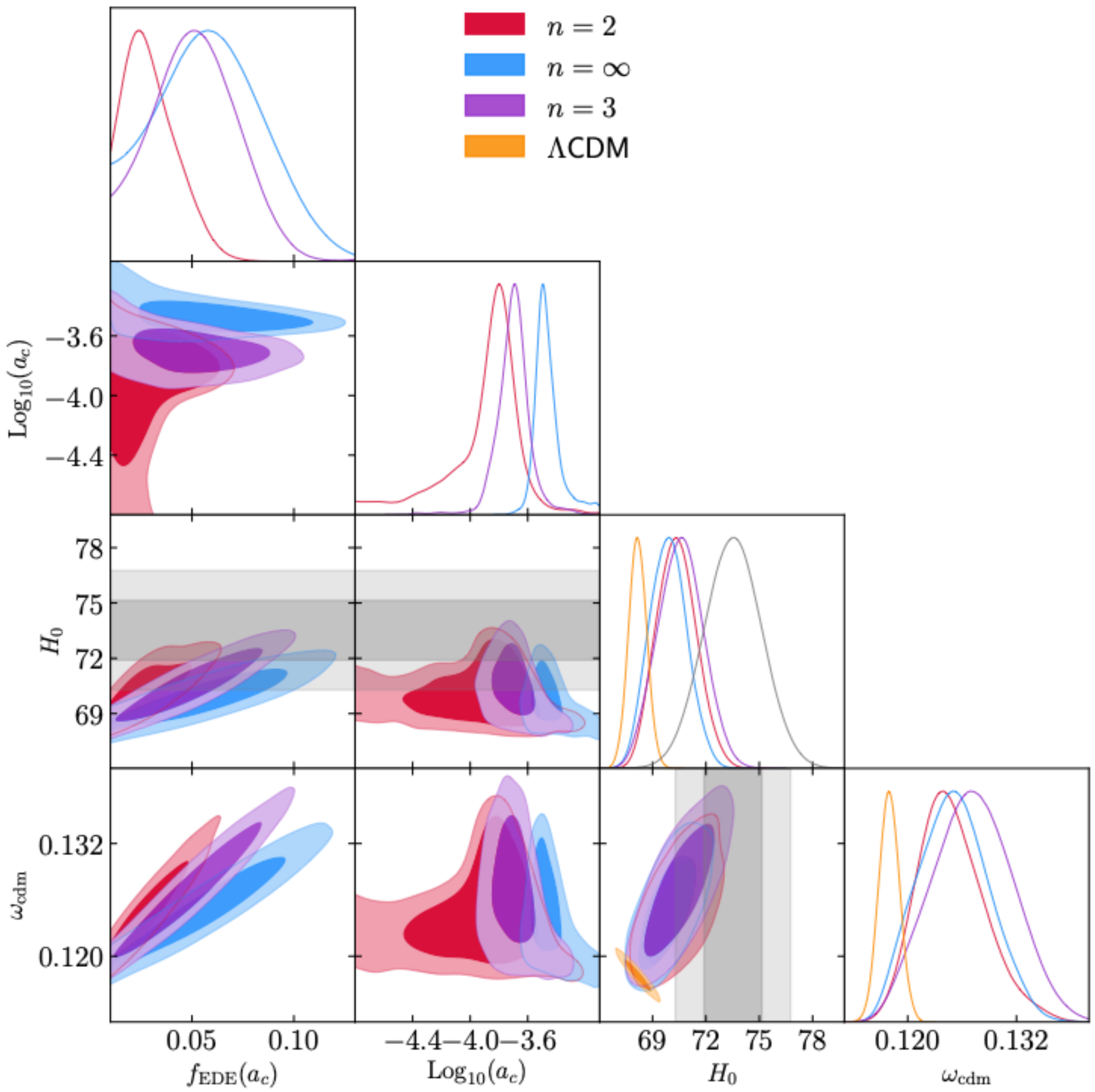


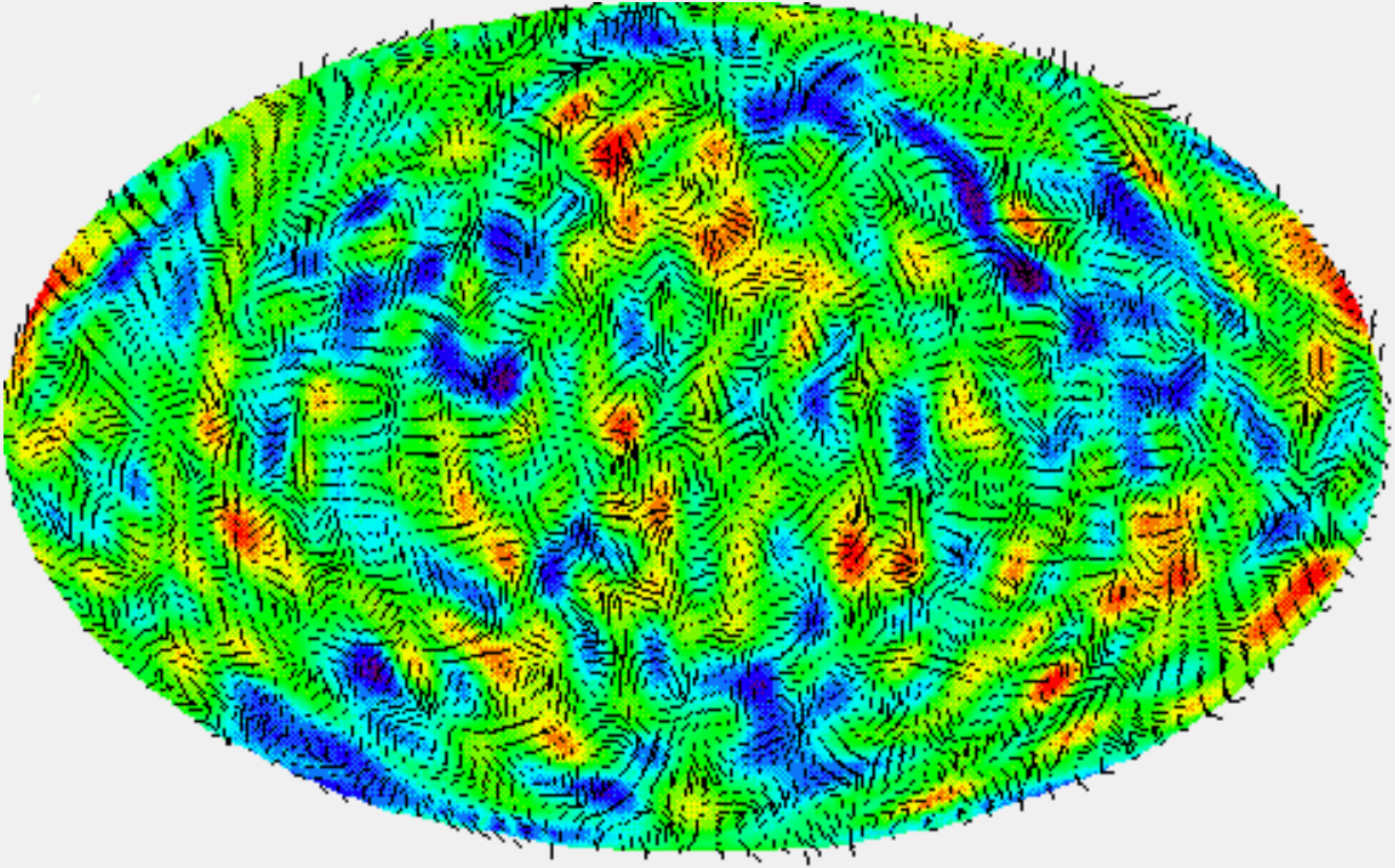
Fig from Smith et al., in prep



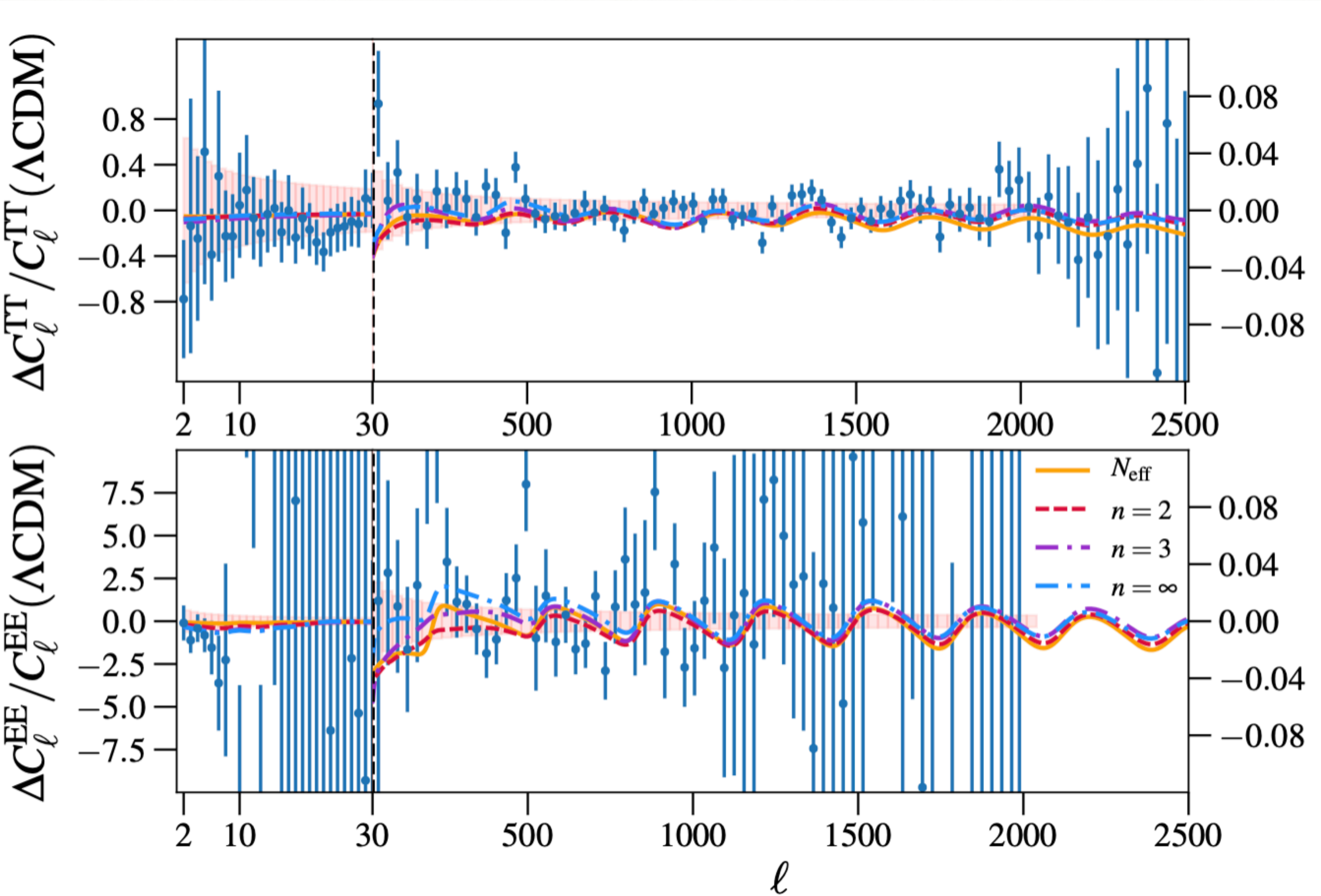
Poulin et al. 2018

New tests of scenario:

Measurements of fine-grain features of CMB polarization by ACTPol/SPT3G/Simons/CMB-S4/etc



Best-fit w/r to “Planck-only” ΛCDM



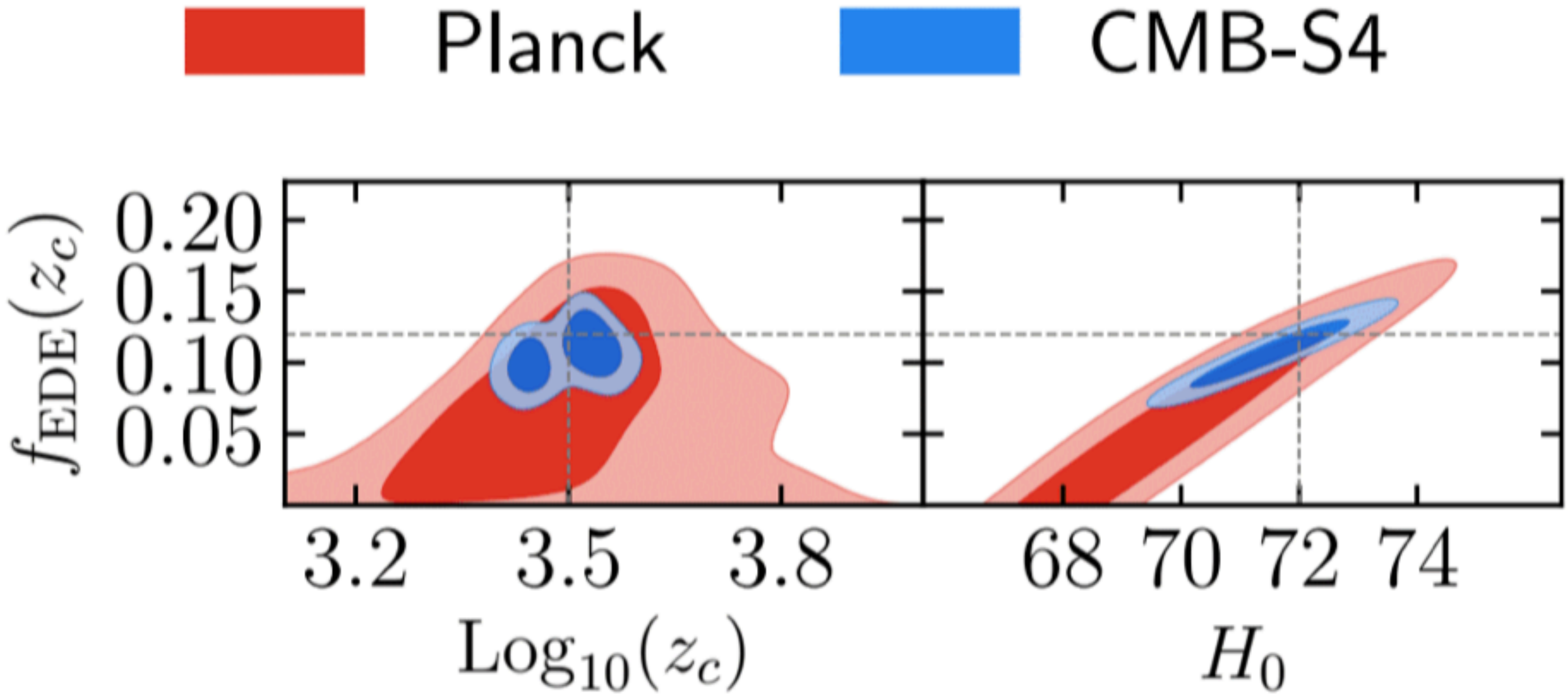


Fig courtesy V. Poulin

Early Dark Energy(s) & Modified Gravity

Not all have the same success…

Early dark energy, the Hubble-parameter tension, and the string axiverse

Tanvi Karwal and Marc Kamionkowski
Department of Physics and Astronomy, Johns Hopkins University,
3400 N. Charles St., Baltimore, MD 21218
(Dated: November 8, 2016)

Rock 'n' Roll Solutions to the Hubble Tension

Prateek Agrawal[1], Francis-Yan Cyr-Racine[1,2], David Pinner[1,3], and Lisa Randall[1]
[1] *Department of Physics, Harvard University, 17 Oxford St., Cambridge, MA 02138, USA*
[2] *Department of Physics and Astronomy, University of New Mexico, 1919 Lomas Blvd NE, Albuquerque, NM 87131, USA*
[3] *Department of Physics, Brown University, 182 Hope St., Providence, RI 02912, USA*

Early dark energy from massive neutrinos — a natural resolution of the Hubble tension

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Center for Particle Cosmology, Department of Physics and Astronomy,
University of Pennsylvania 209 S. 33rd St., Philadelphia, PA 19104, USA

Dark Energy, H_0 and Weak Gravity Conjecture

Nemanja Kaloper[a,1]
[a] *Department of Physics, University of California, Davis, CA 95616, USA*

Early dark energy from massive neutrinos — a natural resolution of the Hubble tension

Jeremy Sakstein* and Mark Trodden†
Center for Particle Cosmology, Department of Physics and Astronomy,
University of Pennsylvania 209 S. 33rd St., Philadelphia, PA 19104, USA

Scalar-tensor theories of gravity, neutrino physics, and the H_0 tension

Mario Ballardini,[a,b,c,d,1] Matteo Braglia,[a,b,c] Fabio Finelli,[b,c] Daniela Paoletti,[b,c] Alexei A. Starobinsky,[e,f] Caterina Umiltà[g]

Early Dark Energy Can Resolve The Hubble Tension

Vivian Poulin[1], Tristan L. Smith[2], Tanvi Karwal[1], and Marc Kamionkowski[1]
[1] *Department of Physics and Astronomy, Johns Hopkins University,*
3400 N. Charles St., Baltimore, MD 21218, United States and
[2] *Department of Physics and Astronomy, Swarthmore College,*
500 College Ave., Swarthmore, PA 19081, United States

Acoustic Dark Energy: Potential Conversion of the Hubble Tension

Meng-Xiang Lin,[1] Giampaolo Benevento,[2,3,1] Wayne Hu,[1] and Marco Raveri[1]
[1] *Kavli Institute for Cosmological Physics, Department of Astronomy & Astrophysics,*
Enrico Fermi Institute, The University of Chicago, Chicago, IL 60637, USA
[2] *Dipartimento di Fisica e Astronomia "G. Galilei",*
Università degli Studi di Padova, via Marzolo 8, I-35131, Padova, Italy
[3] *INFN, Sezione di Padova, via Marzolo 8, I-35131, Padova, Italy*

Is the Hubble tension a hint of AdS around recombination?

Gen Ye[1*] and Yun-Song Piao[1,2†]
[1] *School of Physics, University of Chinese Academy of Sciences, Beijing 100049, China and*
nstitute of Theoretical Physics, Chinese Academy of Sciences, P.O. Box 2735, Beijing 100190, China

Thermal Friction as a Solution to the Hubble Tension

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3400 N. Charles St., Baltimore, MD 21218, United States and
[2] *Center for Particle Cosmology, Department of Physics and Astronomy,*
University of Pennsylvania, 209 S. 33rd St., Philadelphia, PA 19104, United States
(Dated: November 15, 2019)

New Early Dark Energy

Florian Niedermann[1,*] and Martin S. Sloth[1,†]
CP^3-Origins, Center for Cosmology and Particle Physics Phenomenology

Gravity in the Era of Equality: Towards solutions to the Hubble problem without fine-tuned initial conditions

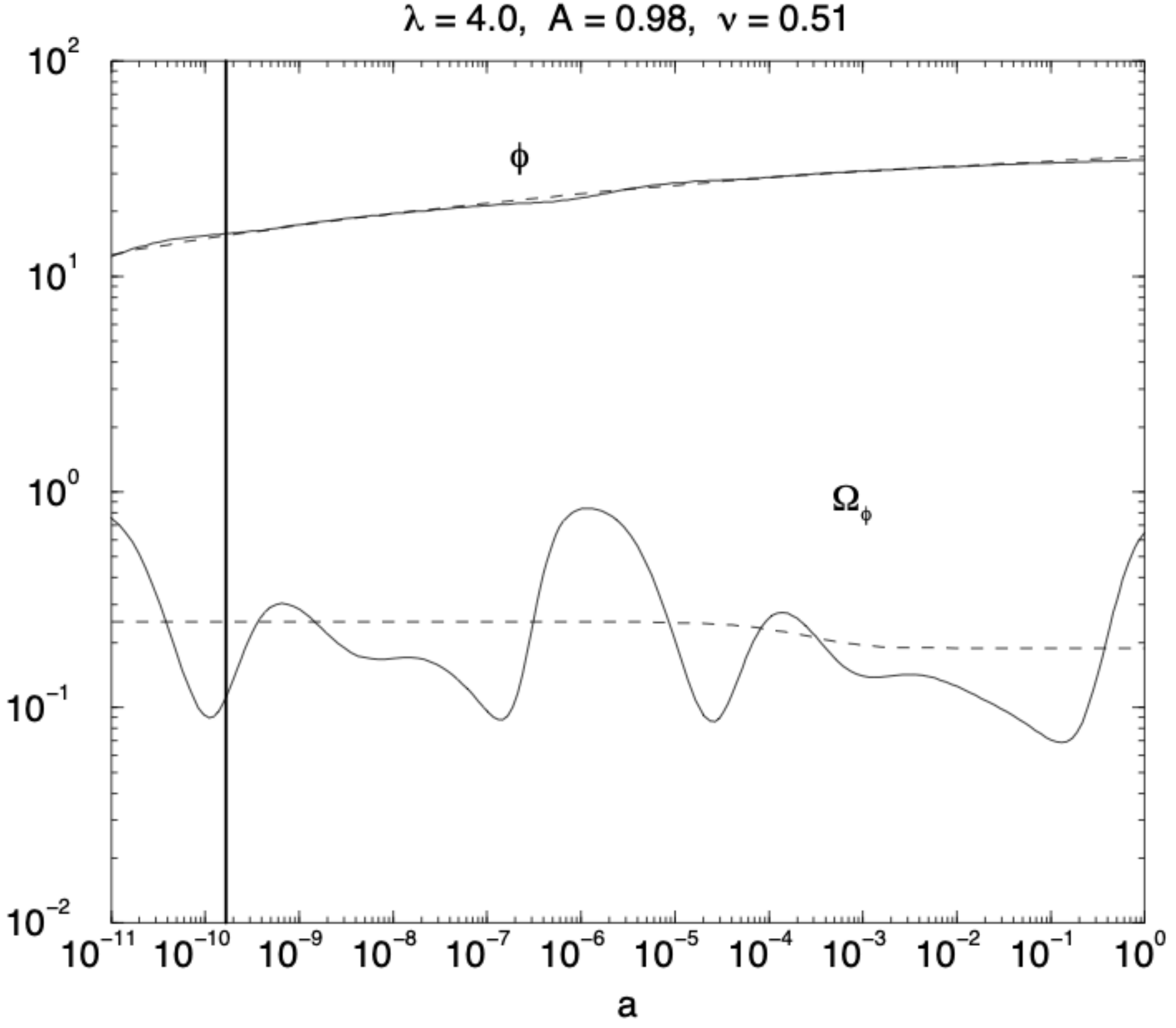
Miguel Zumalacárregui[1,2,3,*]
[1] *Max Planck Institute for Gravitational Physics (Albert Einstein Institute)*
Am Mühlenberg 1, D-14476 Potsdam-Golm, Germany
[2] *Berkeley Center for Cosmological Physics, LBNL and University of California at Berkeley,*
Berkeley, California 94720, USA
[3] *Institut de Physique Théorique, Université Paris Saclay CEA, CNRS, 91191 Gif-sur-Yvette, France*
(Dated: June 11, 2020)

Recurrent dark energy?

- $\Lambda \neq 0$ today
- Inflation → $\Lambda \neq 0$ in the early Universe
- EDE (if this is what's going on) → $\Lambda \neq 0$ at z ~ 10,000

- Recurring periods of "Λ-like" behavior throughout cosmic history?

E.g. tracking oscillating energy (Dodelson, Kaplinghat, Stewart, astro-ph/0002360; Griest, astro-ph/0202052)



String Axiverse? (MK, Pradler, Walker, 2014; based on Arvanitaki et al., 2009; Svrcek & Witten, 2006)

- String theory may imply ~100 axion fields
  - Possibly with masses distributed logarithmically

- At each Log(Hubble time) there's some chance that axion field, if sufficiently displaced from its minimum, may act (at least briefly) like dark energy

Summary

- Local observed cosmic expansion rate disagrees with that inferred from cosmic microwave background
- One possible explanation is early dark energy, a modification to early-Universe dynamics
- Hypothesis to be tested soon with new data
- If correct, implies recurrent periods of something like a cosmological constant throughout cosmic history

EDE ruled out by large-scale structure?

Constraining Early Dark Energy with Large-Scale Structure

Mikhail M. Ivanov,[1,2] Evan McDonough,[3] J. Colin Hill,[4,5] Marko Simonović,[6] Michael W. Toomey,[7] Stephon Alexander,[7] and Matias Zaldarriaga[8]

[1]*Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003, USA*
[2]*Institute for Nuclear Research of the Russian Academy of Sciences, 60th October Anniversary Prospect, 7a, 117312 Moscow, Russia*
[3]*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[4]*Department of Physics, Columbia University, New York, NY, USA 10027*
[5]*Center for Computational Astrophysics, Flatiron Institute, New York, NY, USA 10010*
[6]*Theoretical Physics Department, CERN, 1 Esplanade des Particules, Geneva 23, CH-1211, Switzerland*
[7]*Brown Theoretical Physics Center and Department of Physics, Brown University, Providence, RI 02912, USA*
[8]*School of Natural Sciences, Institute for Advanced Study, 1 Einstein Drive, Princeton, NJ 08540, USA*

An axion-like field comprising ∼ 10% of the energy density of the universe near matter-radiation equality is a candidate to resolve the Hubble tension; this is the "early dark energy" (EDE) model. However, as shown in Hill et al. (2020) [1], the model fails to simultaneously resolve the Hubble tension and maintain a good fit to both cosmic microwave background (CMB) and large-scale structure (LSS) data. Here, we use redshift-space galaxy clustering data to sharpen constraints on the EDE model. We perform the first EDE analysis using the full-shape power spectrum likelihood from the Baryon Oscillation Spectroscopic Survey (BOSS), based on the effective field theory (EFT) of LSS. The inclusion of this likelihood in the EDE analysis yields a 25% tighter error bar on H_0 compared to primary CMB data alone, yielding $H_0 = 68.54^{+0.52}_{-0.95}$ km/s/Mpc (68% CL). In addition, we constrain the maximum fractional energy density contribution of the EDE to $f_{\rm EDE} < 0.072$ (95% CL). We explicitly demonstrate that the EFT BOSS likelihood yields much stronger constraints on EDE than the standard BOSS likelihood. Including further information from photometric LSS surveys,the constraints narrow by an additional 20%, yielding $H_0 = 68.73^{+0.42}_{-0.69}$ km/s/Mpc (68% CL) and $f_{\rm EDE} < 0.053$ (95% CL). These bounds are obtained without including local-universe H_0 data, which is in strong tension with the CMB and LSS, even in the EDE model. We also refute claims that MCMC analyses of EDE that omit SH0ES from the combined dataset yield misleading posteriors. Finally, we show that upcoming *Euclid*/DESI-like spectroscopic galaxy surveys will greatly improve the EDE constraints. We conclude that current data preclude the EDE model as a resolution of the Hubble tension, and that future LSS surveys can close the remaining parameter space of this model.

The Hubble Tension in Light of the Full-Shape Analysis of Large-Scale Structure Data

Guido D'Amico[1], Leonardo Senatore[2,3], Pierre Zhang[4,5,6], Henry Zheng[2,3]

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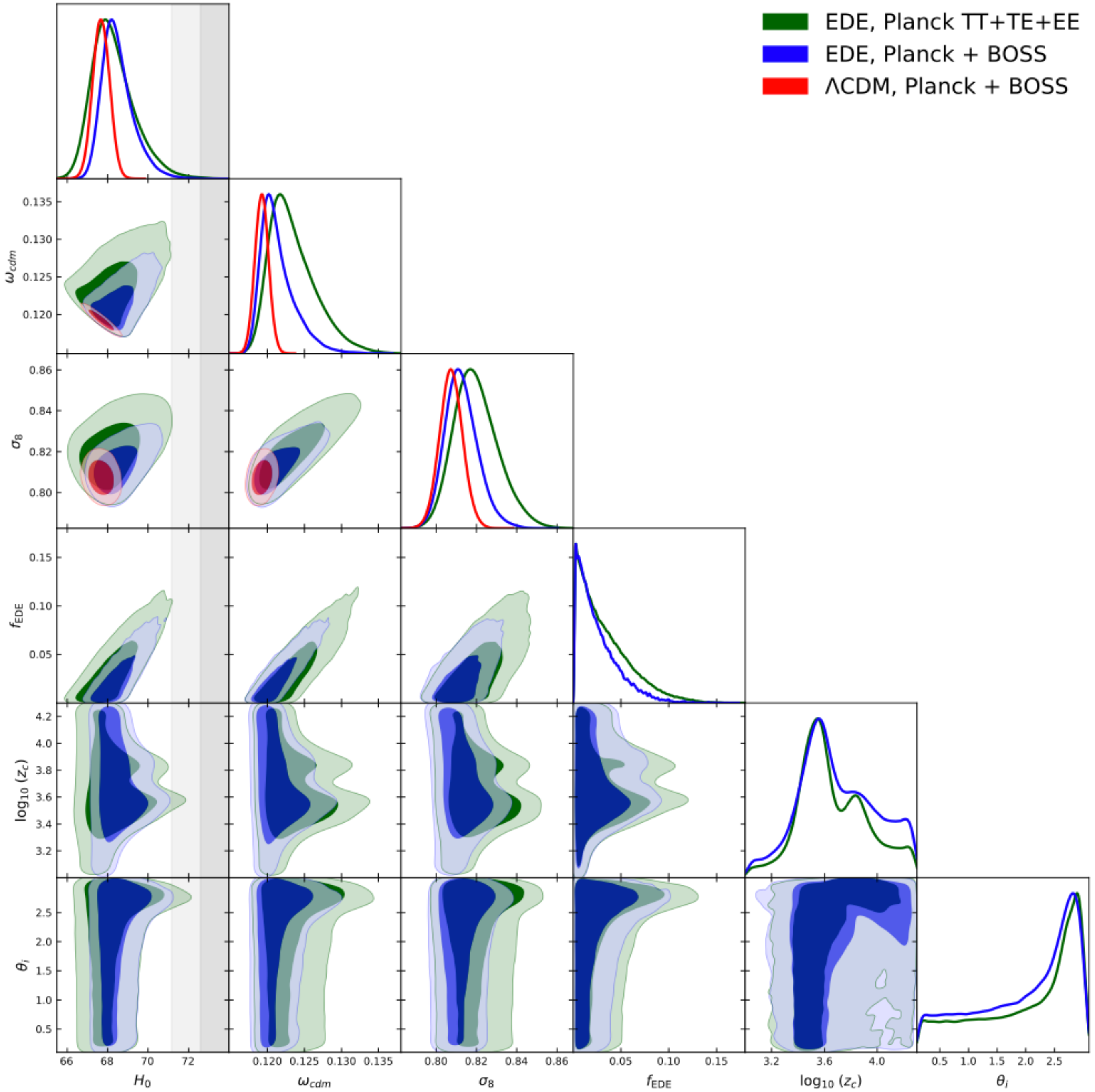
Abstract The disagreement between direct late-time measurements of the Hubble constant from the SH0ES collaboration, and early-universe measurements based on the ΛCDM model from the Planck collaboration might, at least in principle, be explained by new physics in the early universe. Recently, the application of the Effective Field Theory of Large-Scale Structure to the full shape of the power spectrum of the SDSS/BOSS data has revealed a new, rather powerful, way to measure the Hubble constant and the other cosmological parameters from Large-Scale Structure surveys. In light of this, we analyze two models for early universe physics, Early Dark Energy and Rock 'n' Roll, that were designed to significantly ameliorate the Hubble tension. Upon including the information from the full shape to the Planck, BAO, and Supernovae measurements, we find that the degeneracies in the cosmological parameters that were introduced by these models are well broken by the data, so that these two models do not significantly ameliorate the tension.

We disagree:

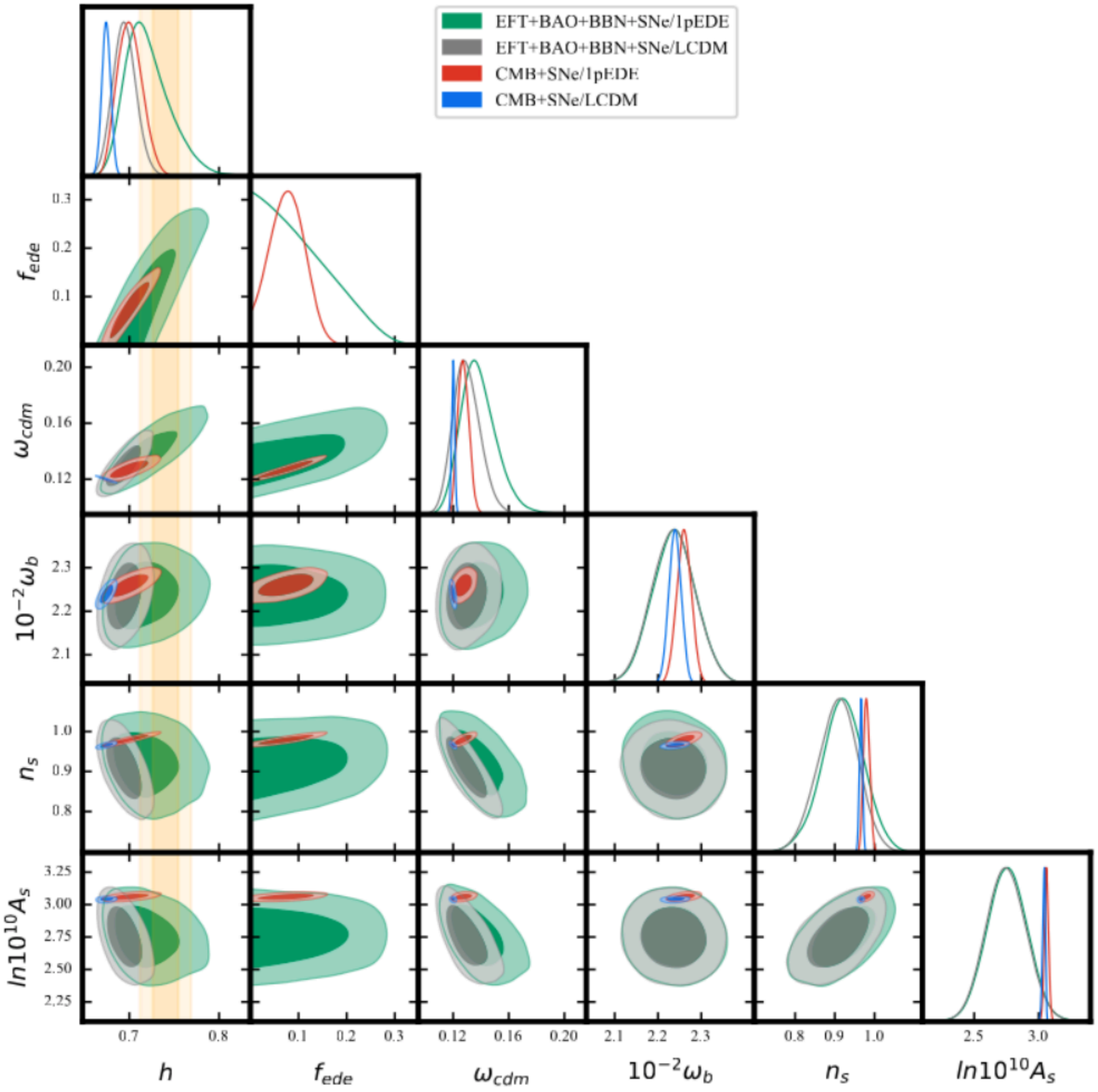
Conclusions follow from their choice of measure on the EDE parameter space.

Best-fit EDE model provides as good a fit to data as LambdaCDM

(Smith et al., in prep)



Power-spectra amplitudes inferred from CMB and LSS in tension, even in LambdaCDM



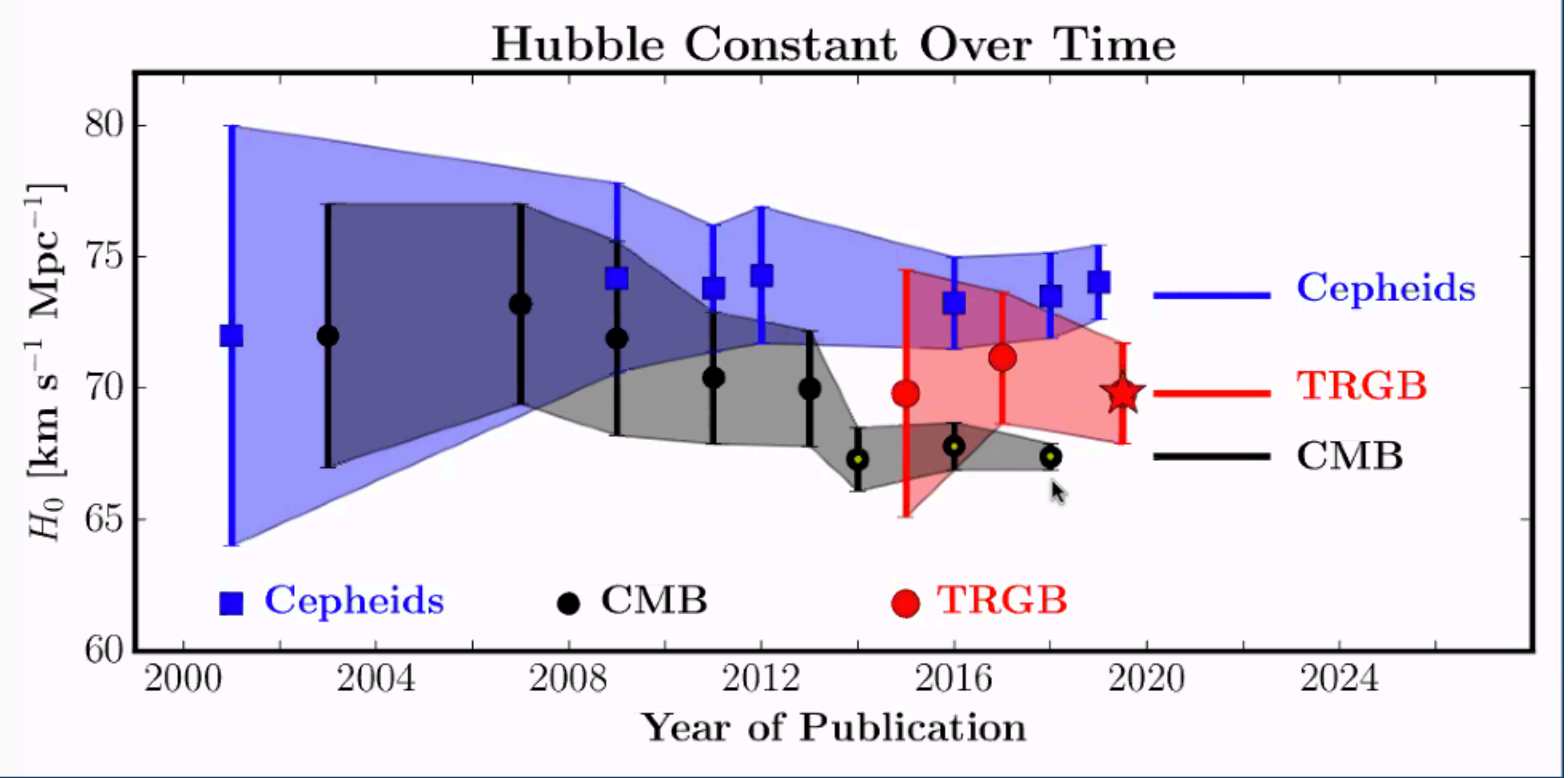
Smith et al., in prep

Have Dark Forces Been Messing With the Cosmos?

Axions? Phantom energy? Astrophysicists scramble to patch a hole in the universe, rewriting cosmic history in the process.

!!THEORY TALK!!

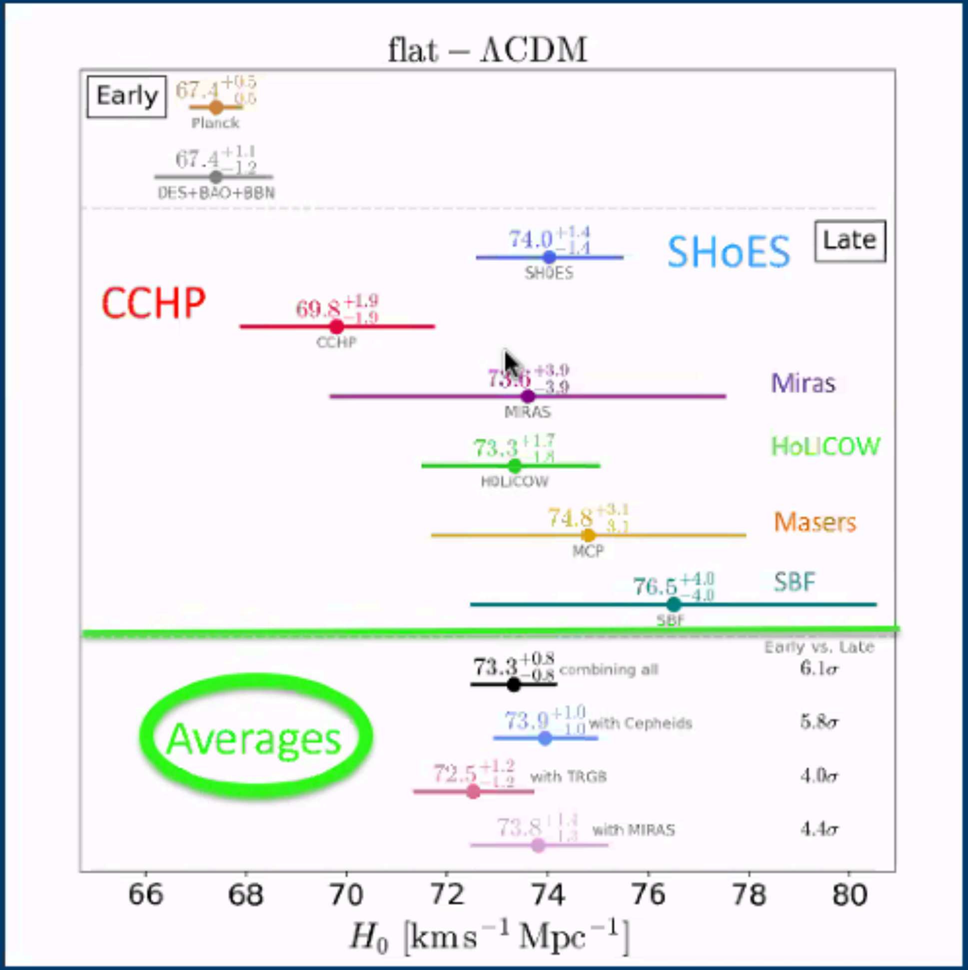
H_o Values With Time



WLF et al. (2019, ApJ)

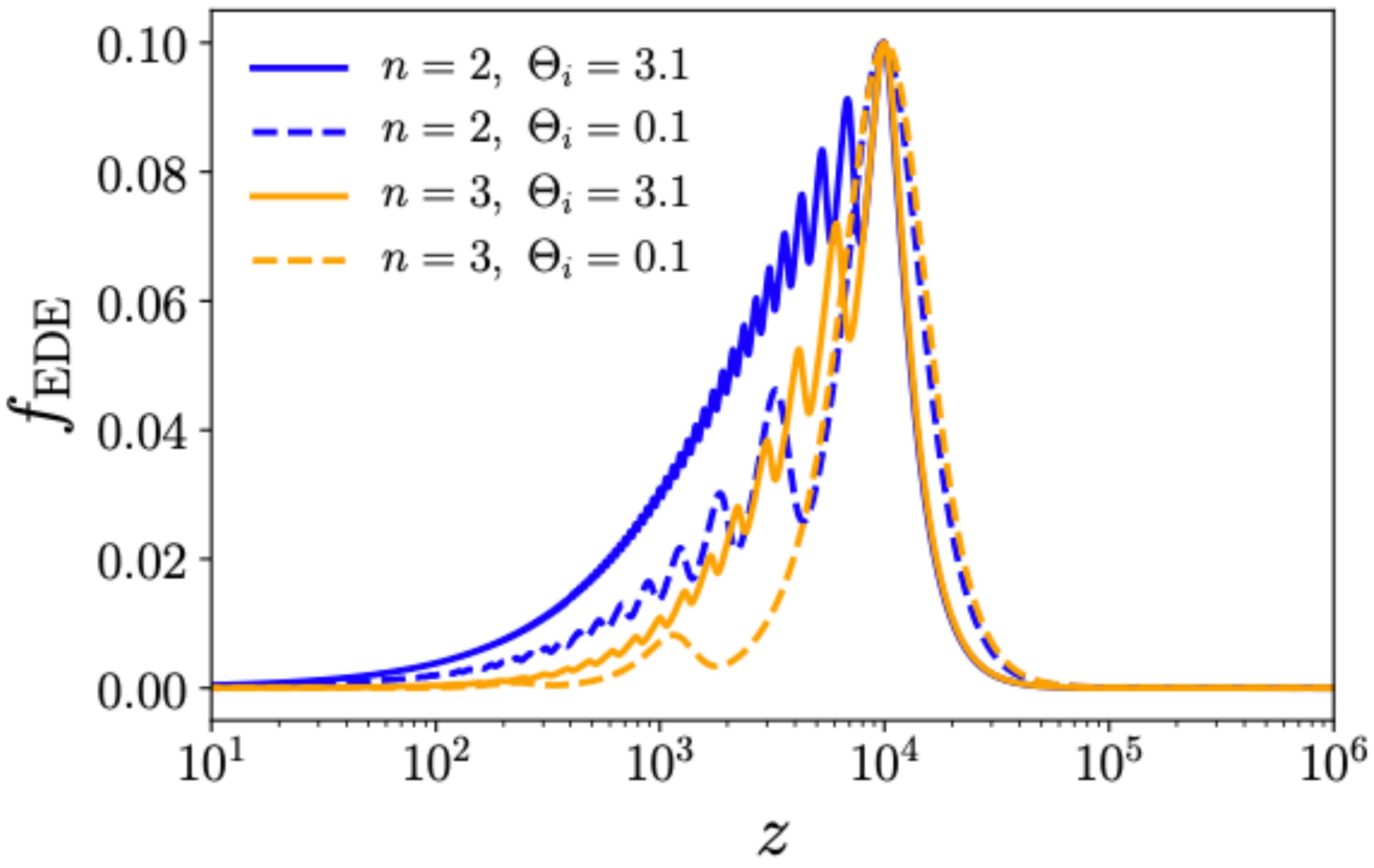
H_o "Consensus"
Kavli Meeting Santa Barbara, July 2019

Coordinators: Adam Riess, Tommaso Treu and Licia Verde

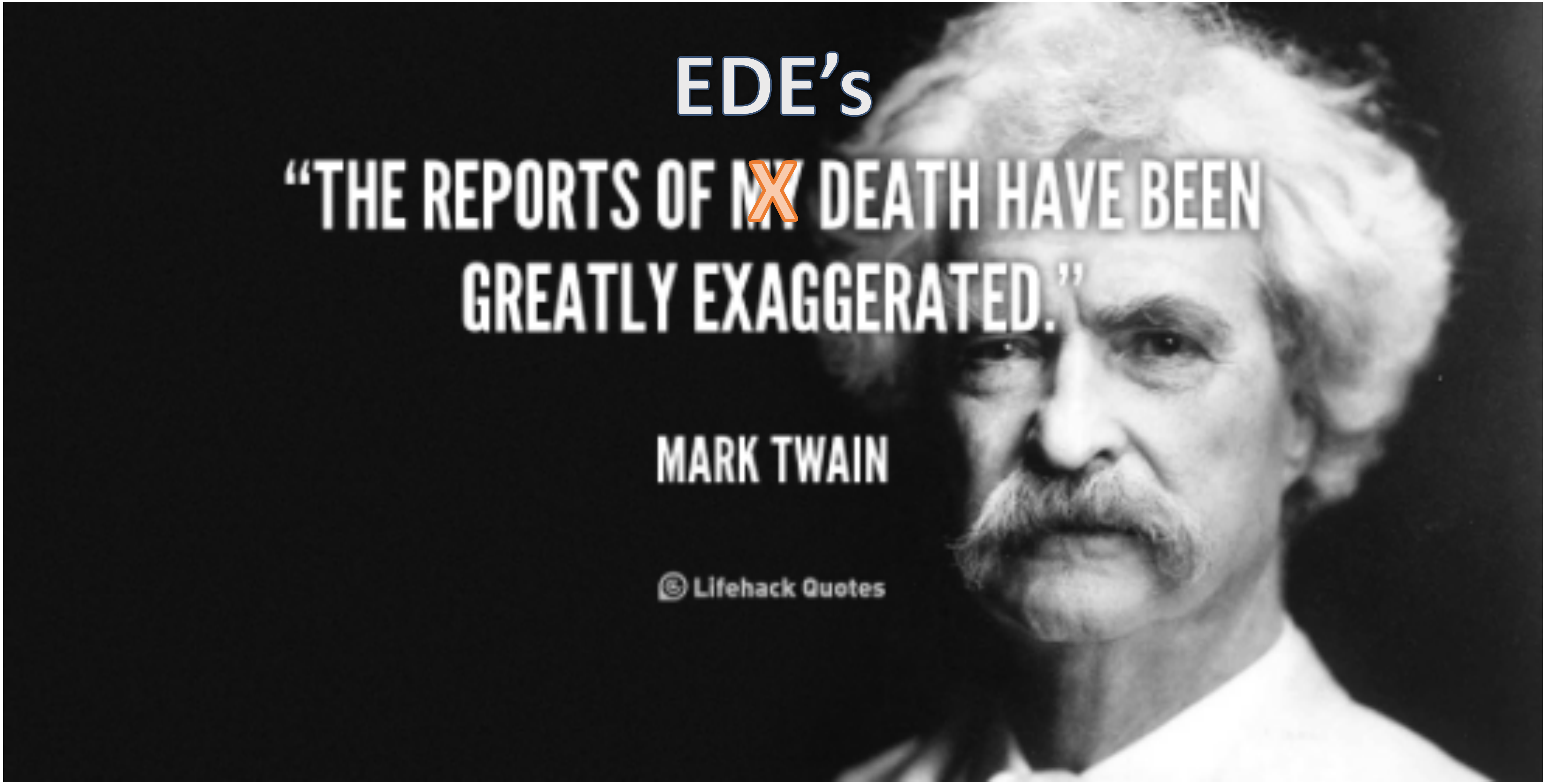


5-sigma Crisis

Verde, Treu & Riess (2019)

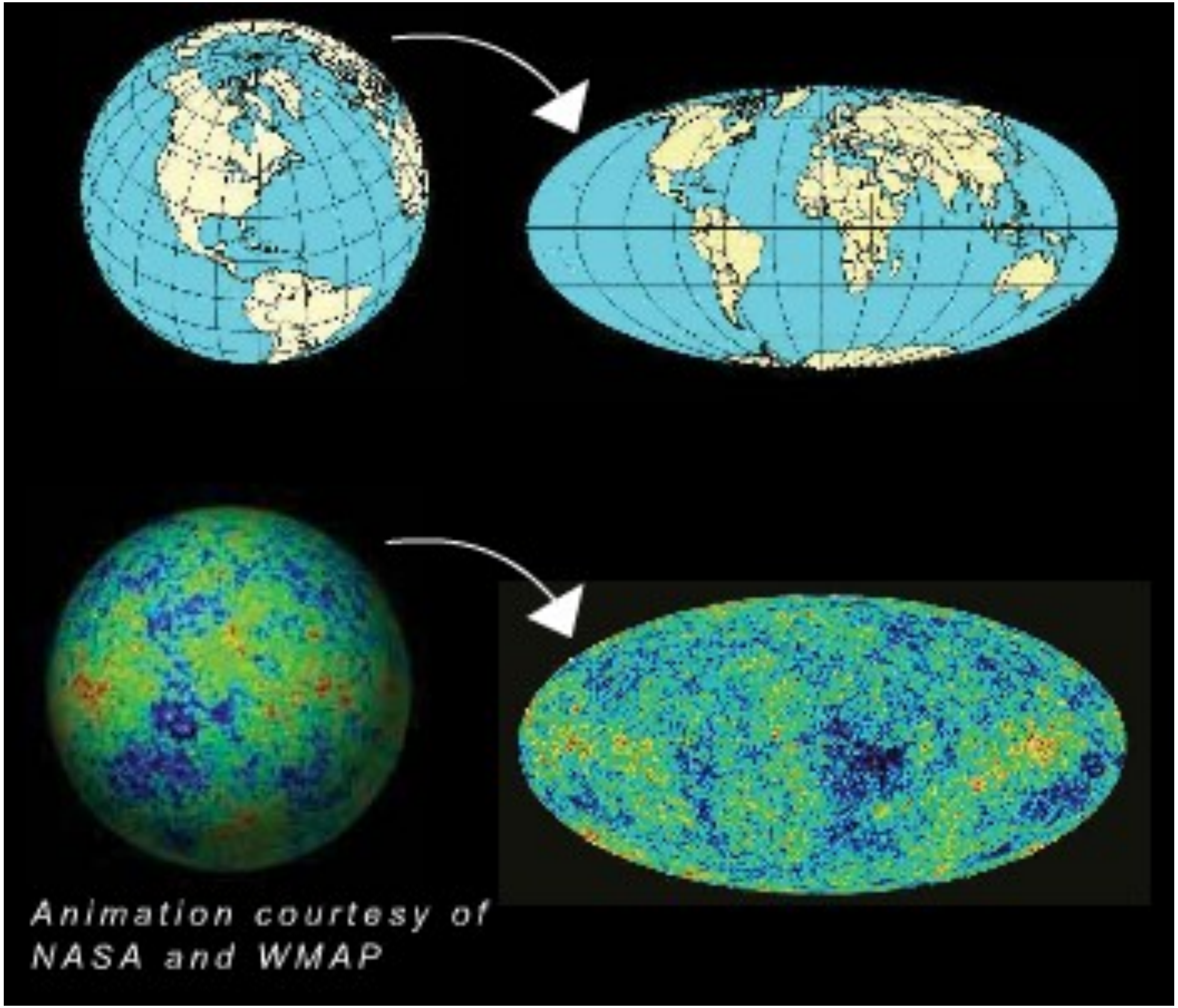


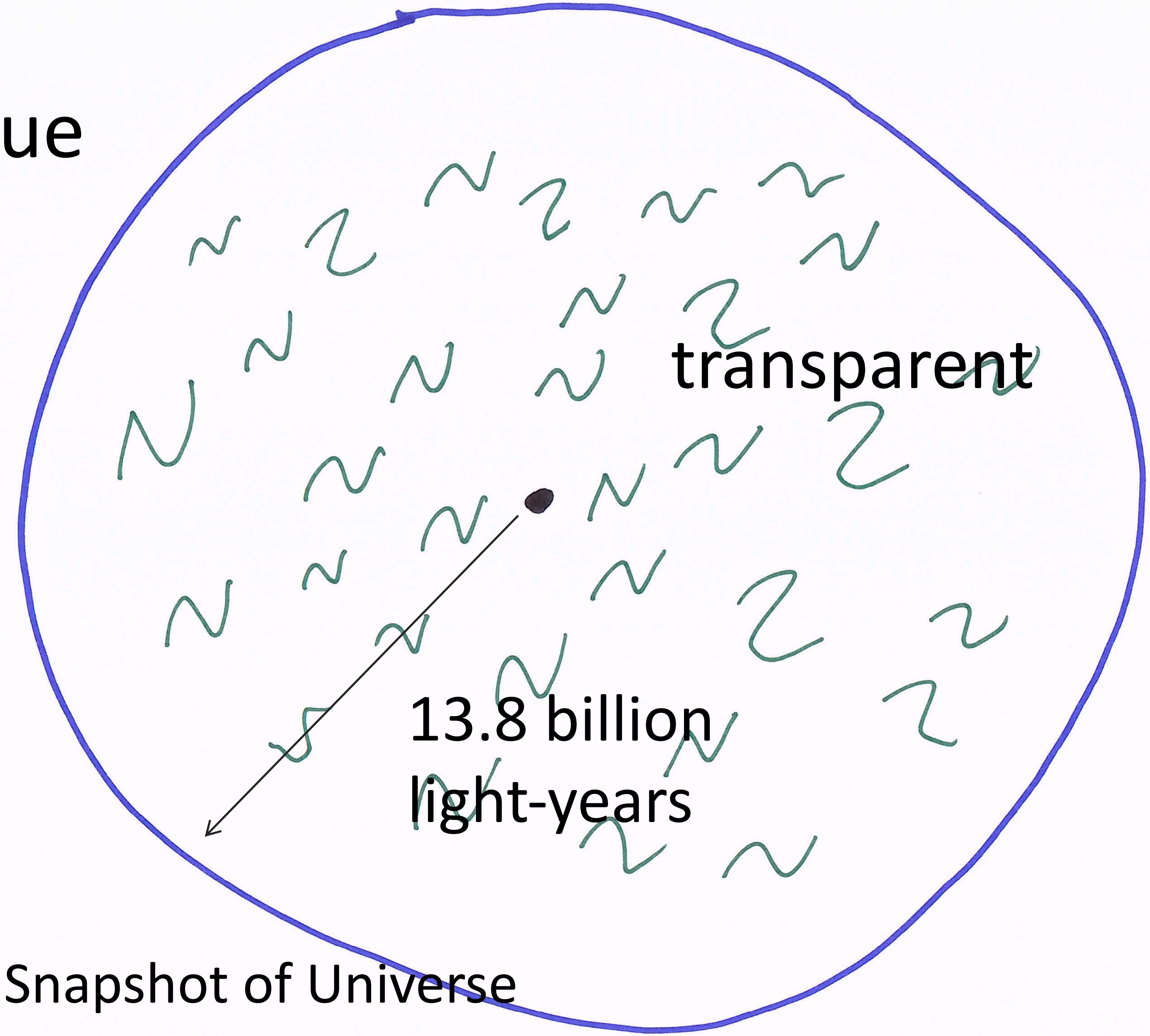
From Smith, Poulin, & Amin, 2019


EDE’s
“THE REPORTS OF MY DEATH HAVE BEEN
GREATLY EXAGGERATED.”
X
MARK TWAIN
Lifehack Quotes

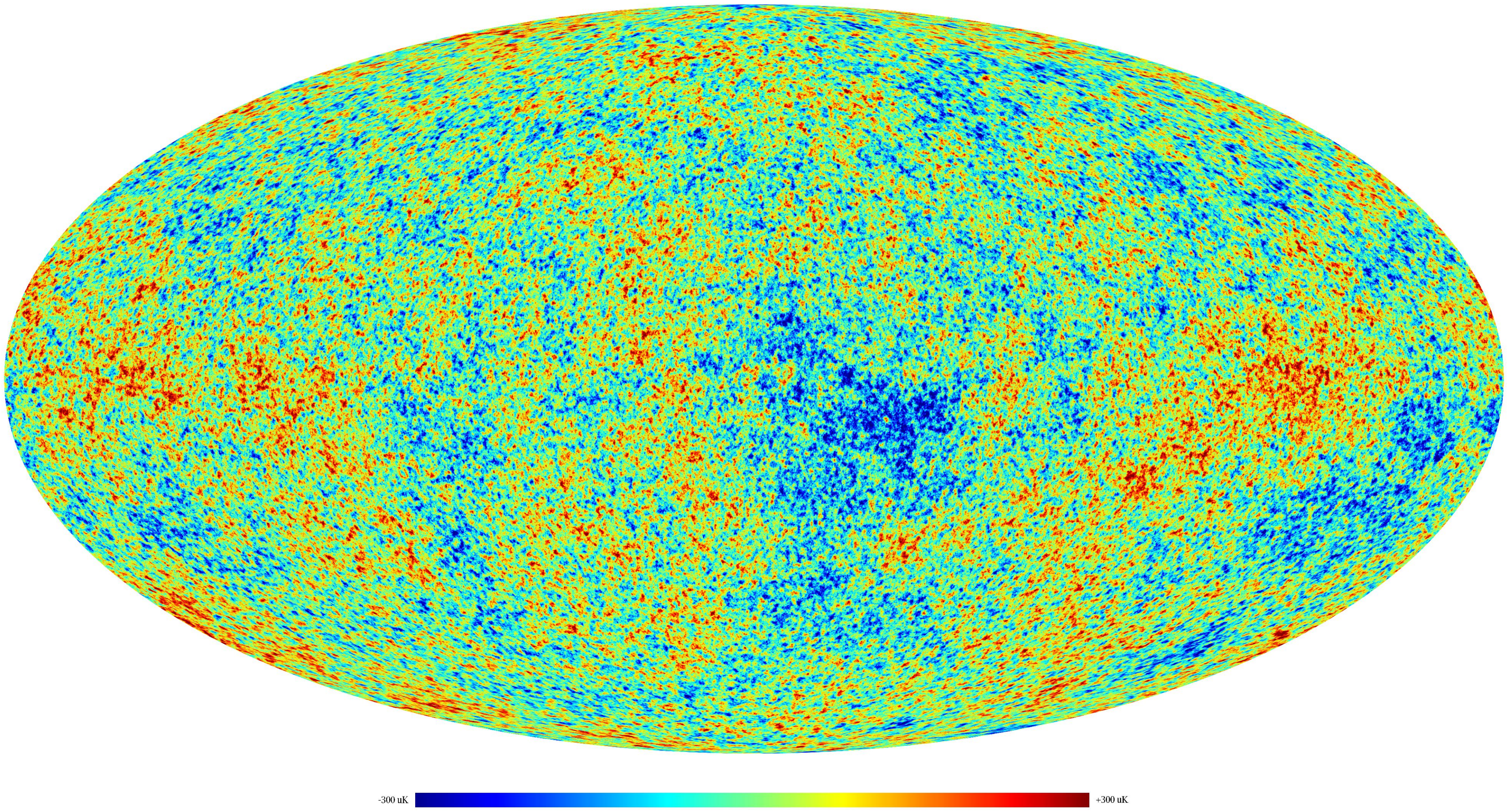
A problem with local measurements?

"I keep reminiscing how similar and different this is to 1998—I find the measurement side probably stronger than then…."
(Adam Riess, email, 31 July 2020)


Animation courtesy of
NASA and WMAP



CMB: Snapshot of Universe
380,000 years after big bang


-300 uK
+300 uK