The Cosmic Microwave Background

Lecture 4: CMB Power Spectrum and Parameter Sensitivity + Polarization Intro

Colin Hill

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ICTP Summer School, Trieste

27 June 2024

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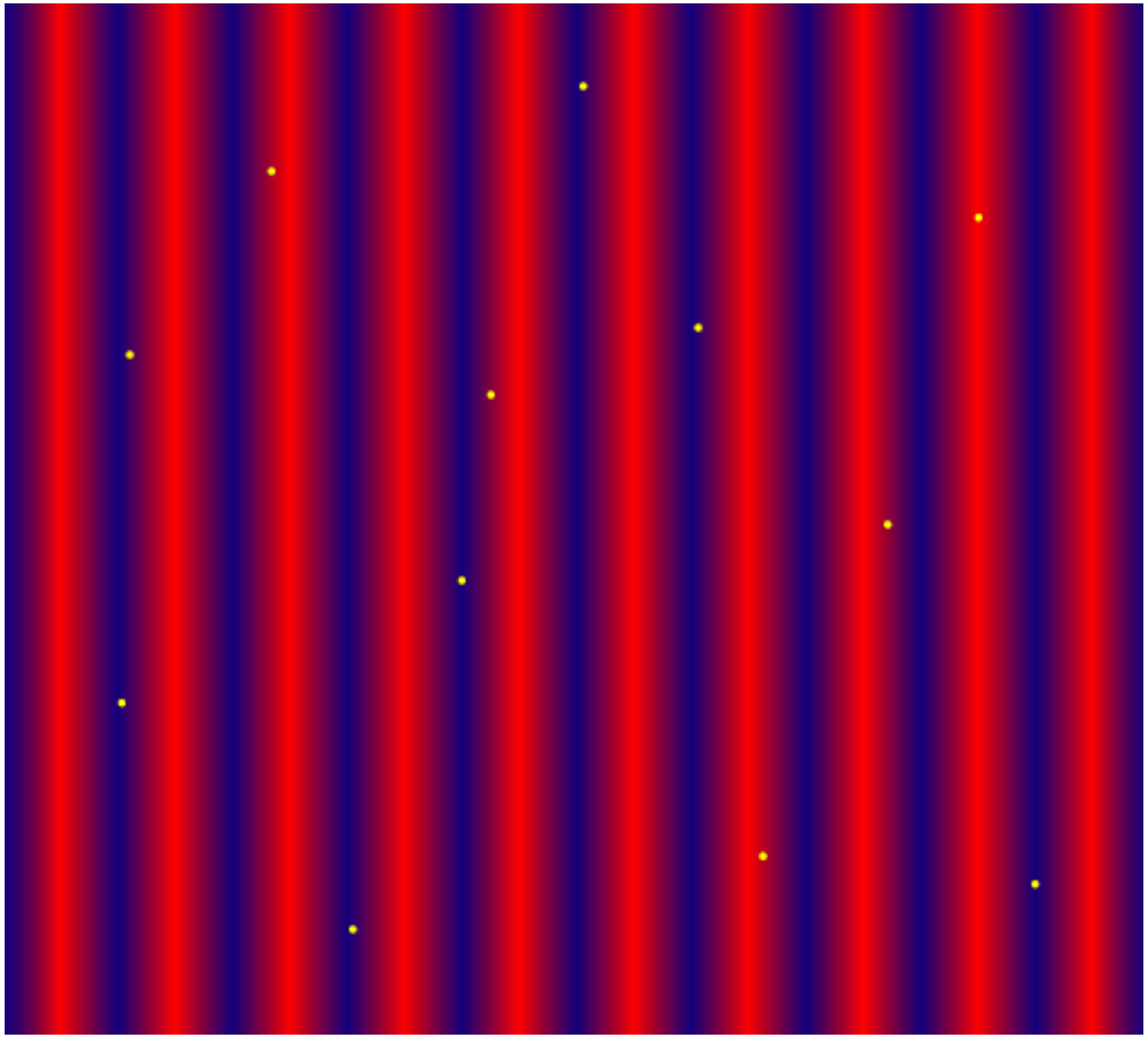
Damping



Hu

Photons random walk during recombination: hot and cold regions mix on small scales, washing out fluctuations

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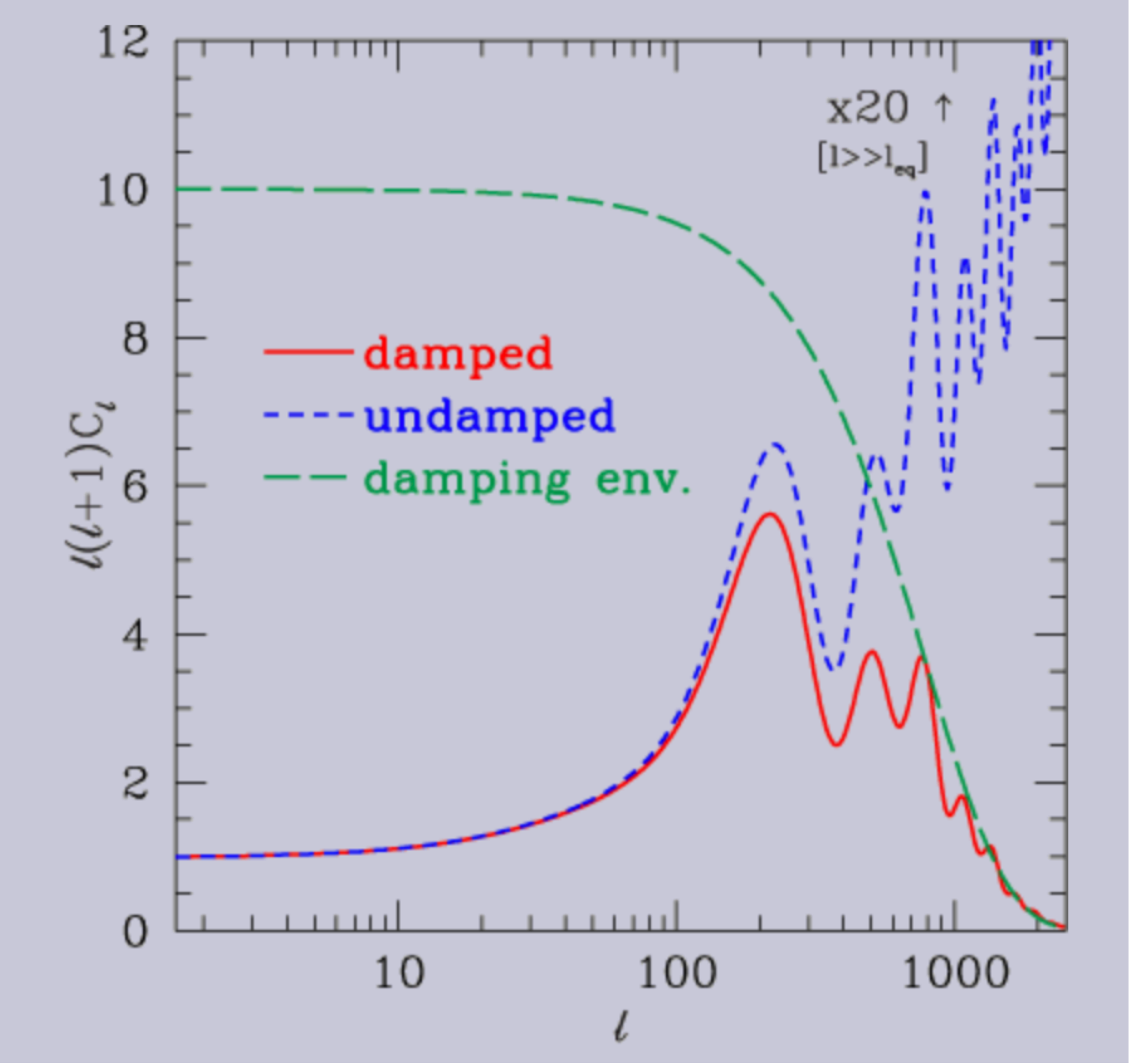
Damping



Hu

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Acoustic Physics

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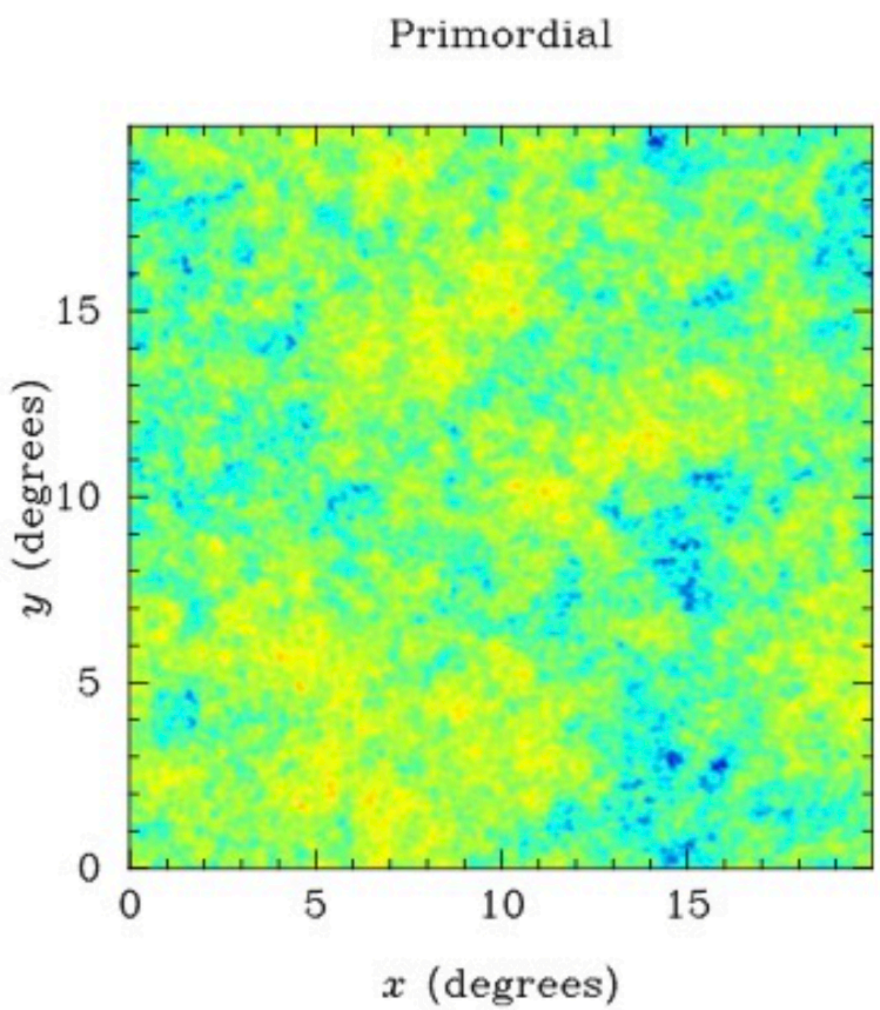
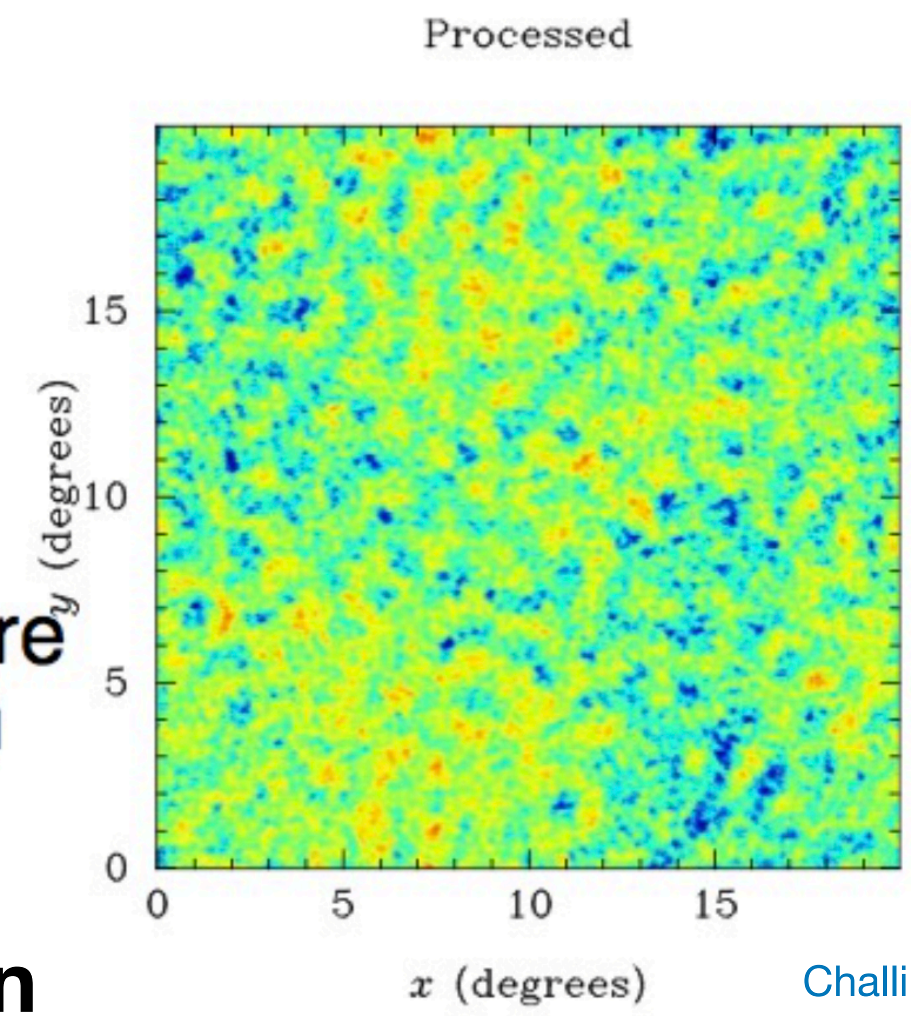


Gravity
Radiation pressure
Photon diffusion

Transfer function
$T_S(k,\eta)$



Challinor

primordial potential fluctuations

observed temperature fluctuations

(characteristic scale is easily visible!)

CMB Power Spectrum

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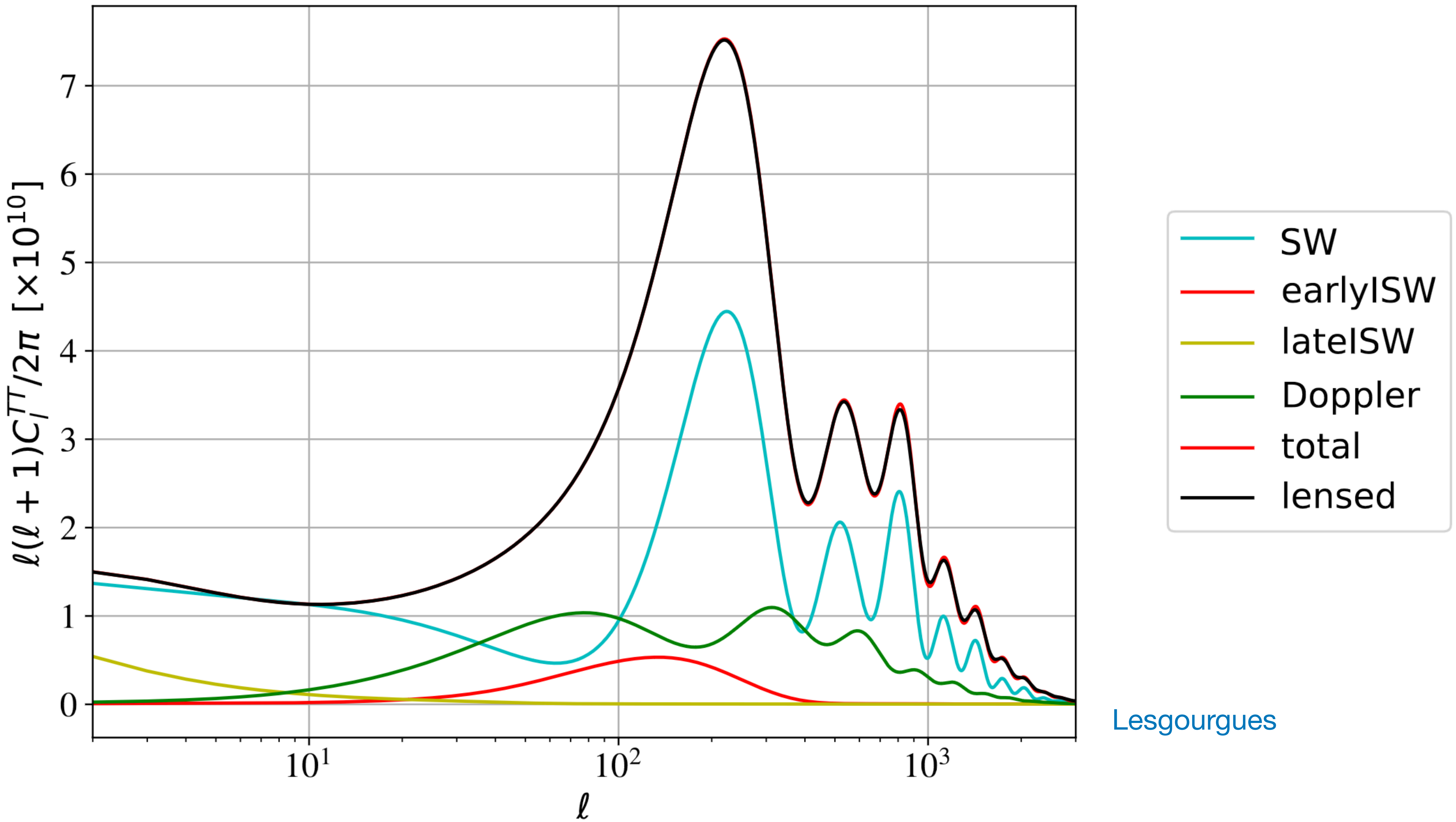

Sachs-Wolfe:

- acoustic oscillations
- odd peaks boosted by baryon loading
- smaller scales enhanced by potential decay due to radiation
- smallest scales damped by diffusion/Landau

Parameter Sensitivity

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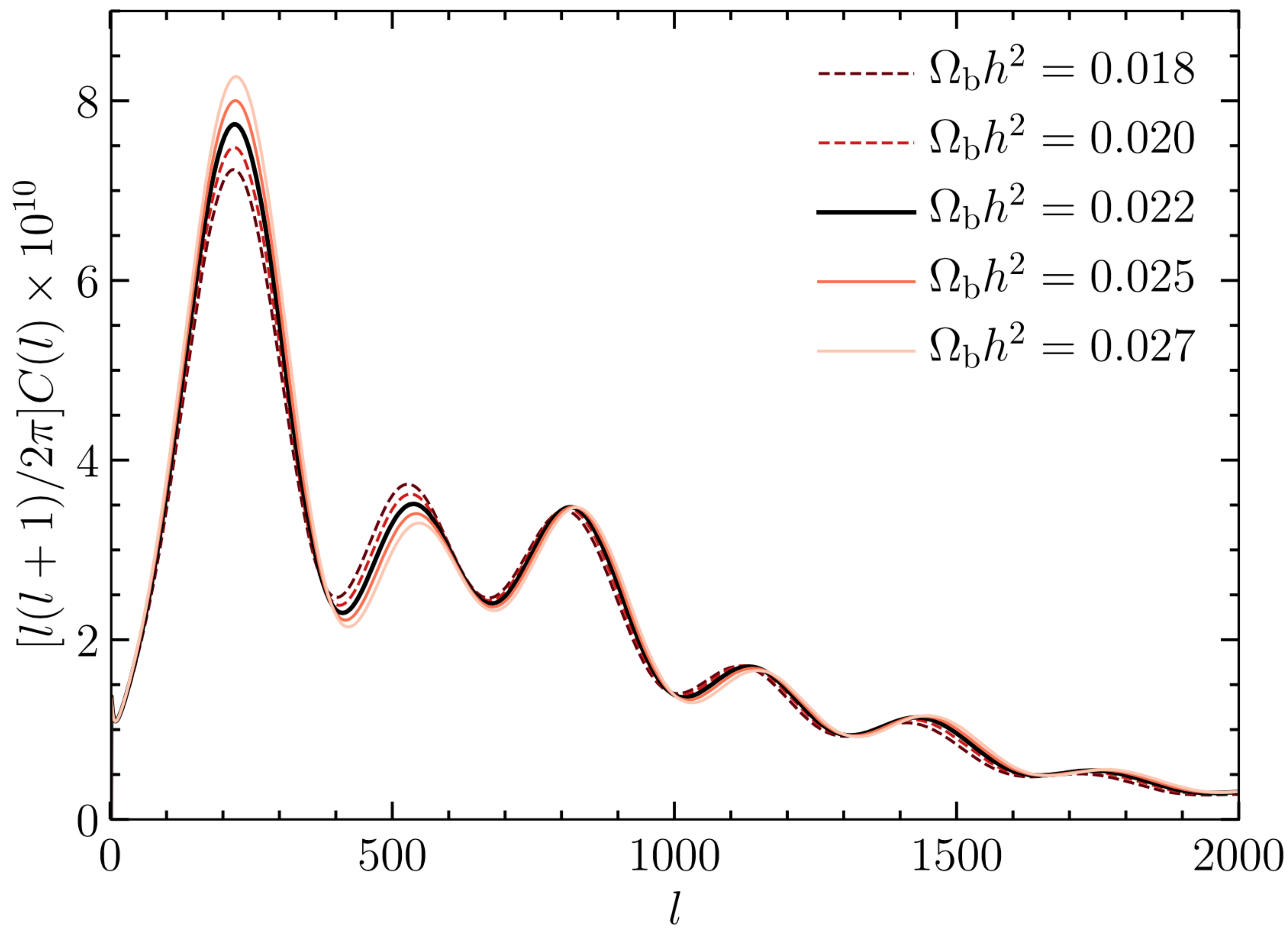
(Physical) baryon density: $\Omega_b h^2$



Dodelson & Schmidt

Increase in $\Omega_b h^2$ boosts odd (compressional) peaks relative to even; shifts peak locations due to change in sound horizon (via R); and reduces diffusion scale (pushes damping to higher multipoles)

Parameter Sensitivity

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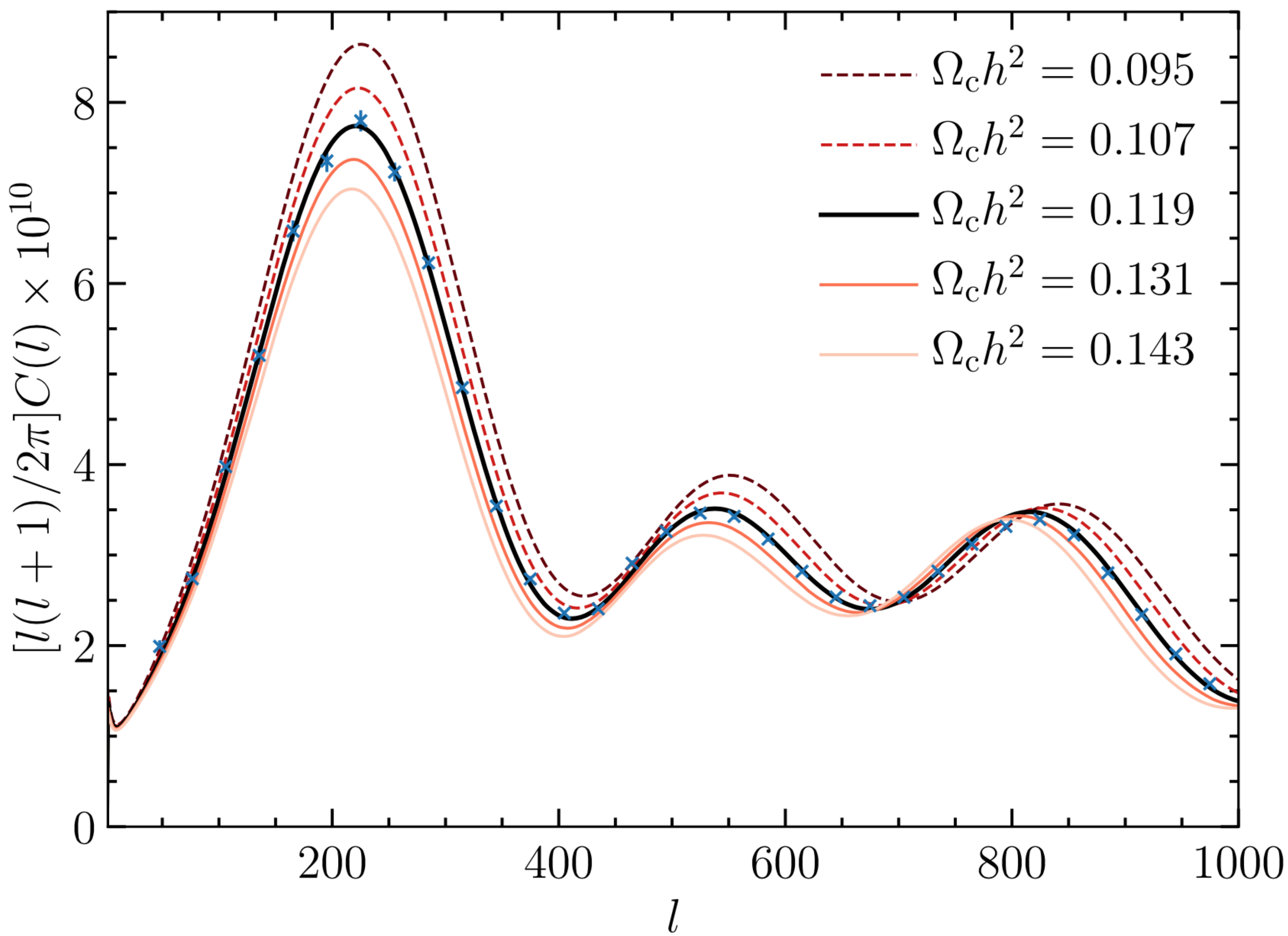
(Physical) dark matter density: $\Omega_c h^2$



Dodelson & Schmidt

Increase in $\Omega_c h^2$ reduces potential-decay enhancement of lowest few peaks (k_{eq} increases); also reduces early ISW effect by reducing radiation-induced potential decay after last-scattering

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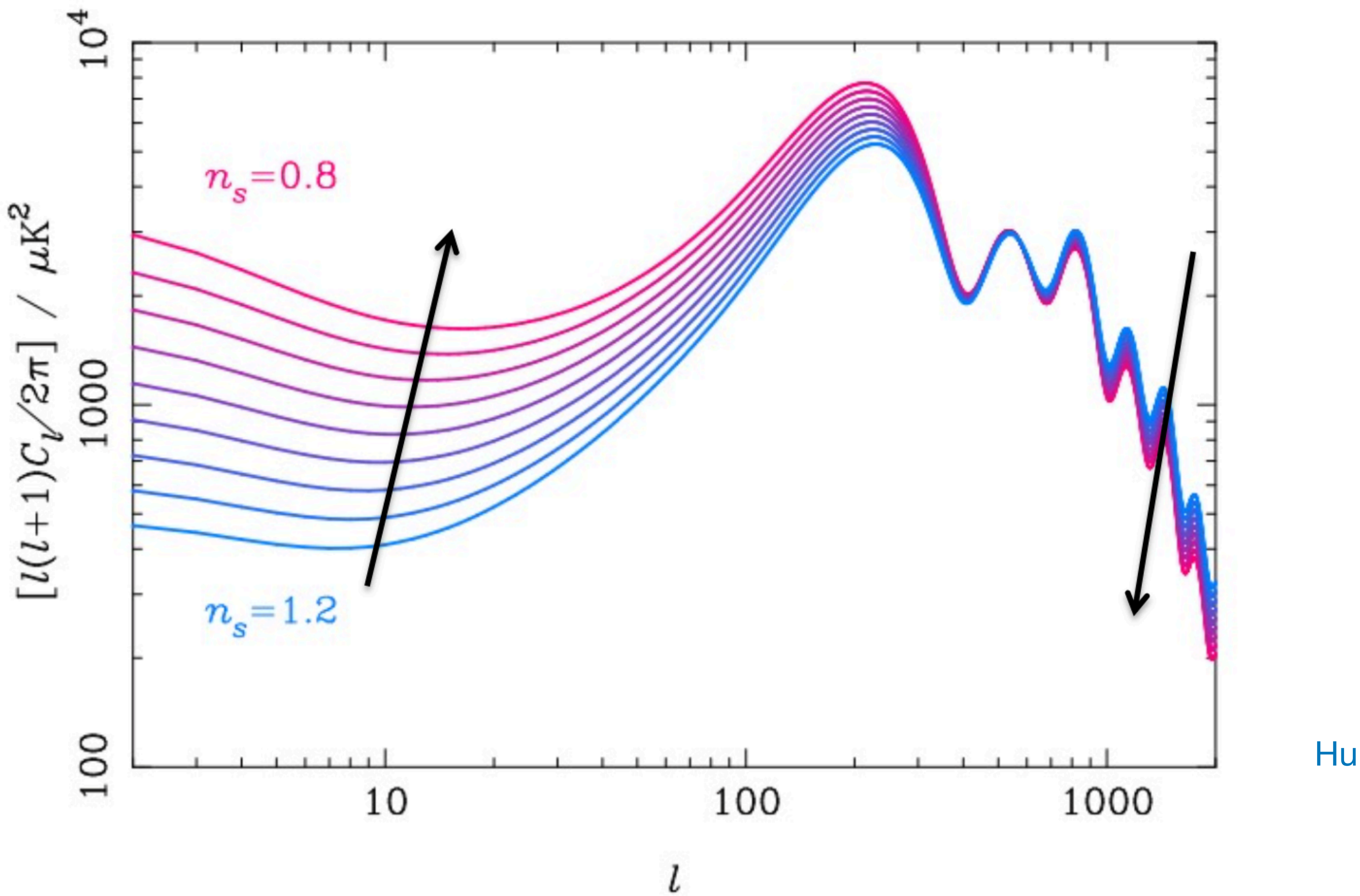
Parameter Sensitivity

Scalar spectral index: n_s



Changing n_s simply tilts the overall spectrum around the pivot scale (conventionally k_0 = 0.05 Mpc^{-1} ⟶ multipole ~ 700)

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Parameter Sensitivity

Scalar fluctuation amplitude: A_s

No plot needed — just rescales the overall spectrum by a constant factor

However: complicated by reionization

CMB temperature power spectrum is sensitive only to the degenerate combination $A_s\ e^{-2\tau}$

Parameter Sensitivity

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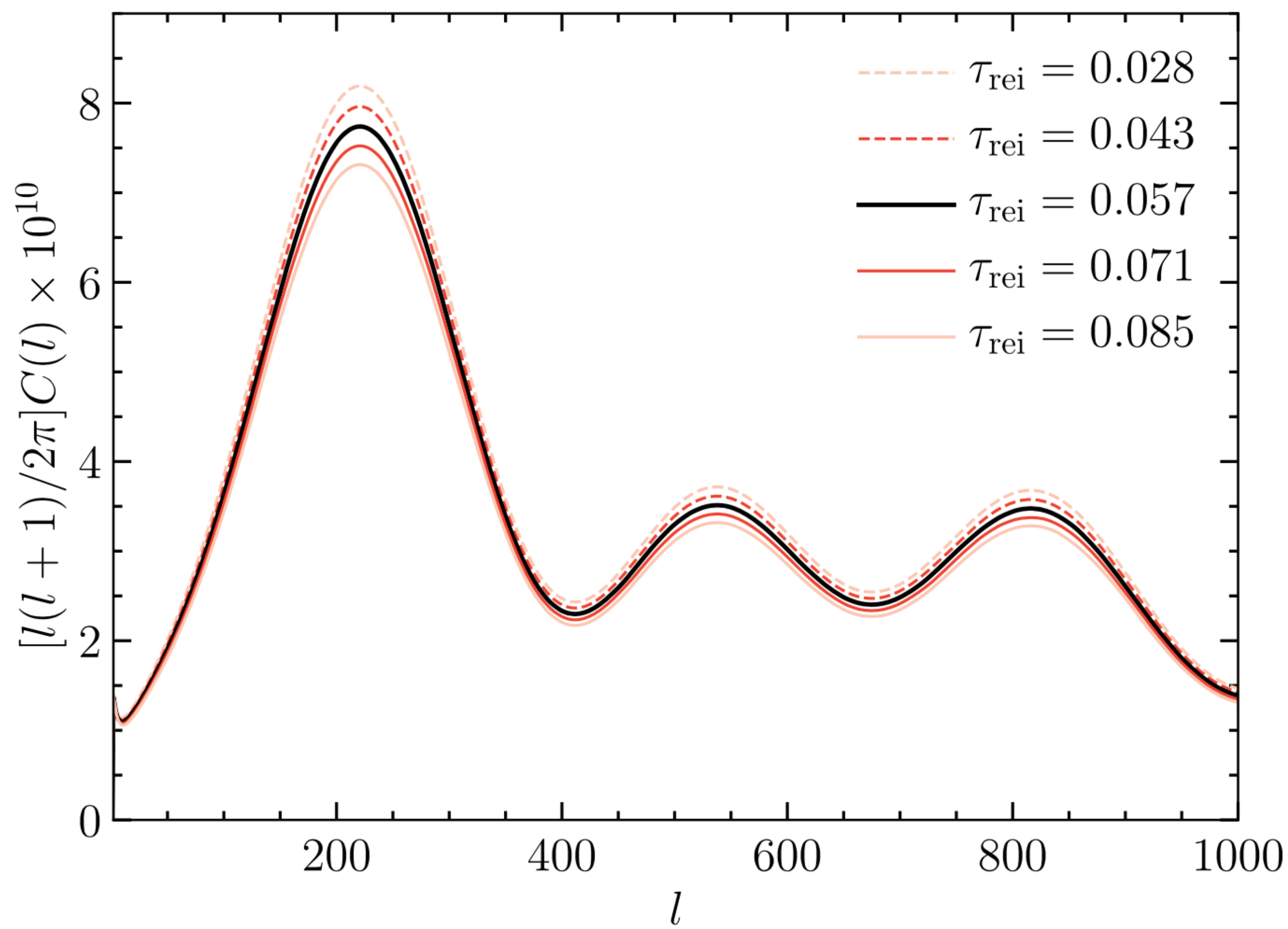
Reionization: τ



Dodelson & Schmidt

At redshifts 6 < z < ~10-15 (very uncertain starting point), the baryonic matter in the universe was reionized by early galaxies (and possibly quasars or X-ray sources). Thus, we see the CMB through this "screen" of free electrons, which suppresses CMB fluctuations for all modes within the horizon during that epoch (ell > 50 or so).

Parameter Sensitivity

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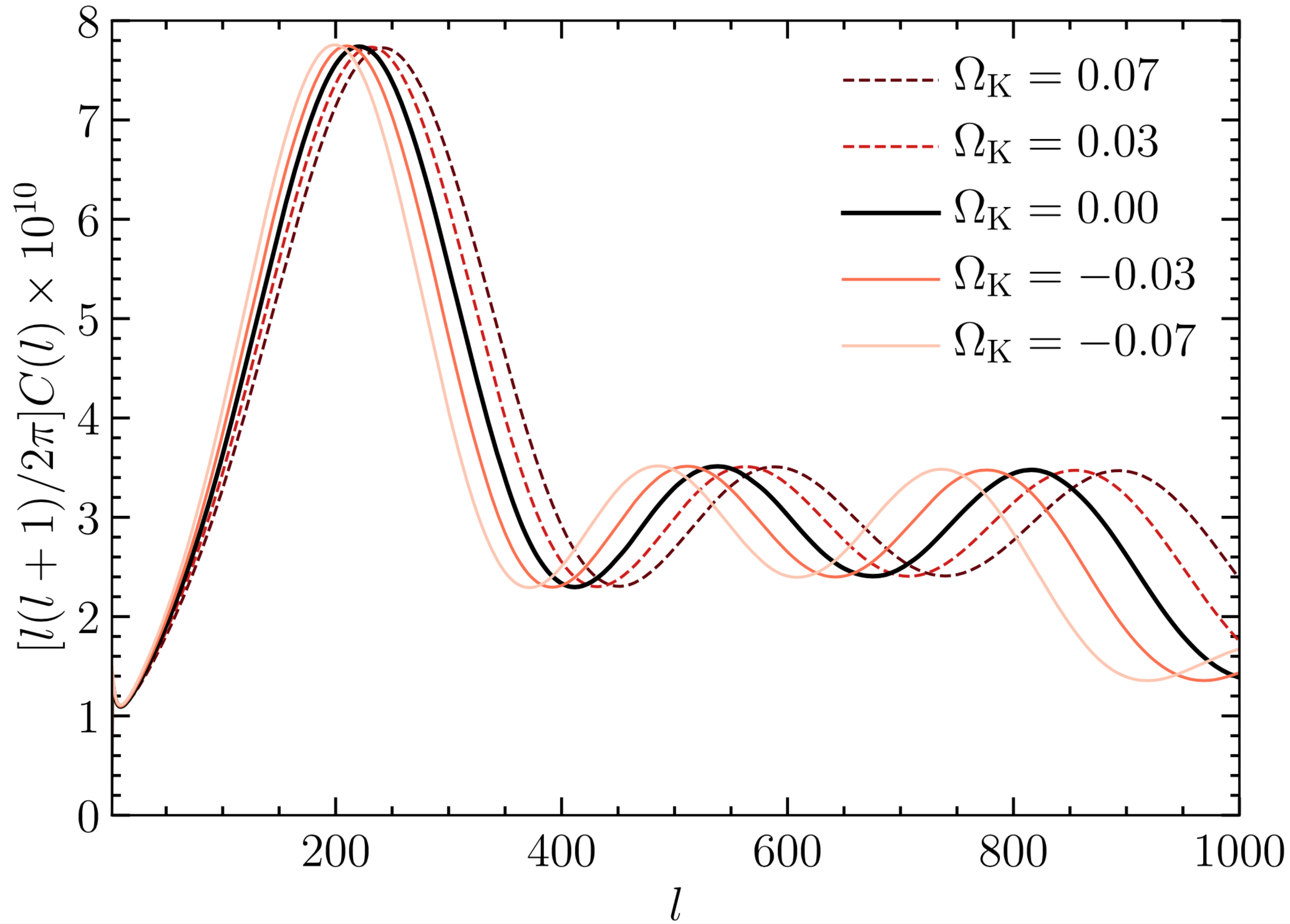
Beyond (flat) ΛCDM: spatial curvature (Ω_k)



Dodelson & Schmidt

Open universe (Ω_k>0) has larger angular diameter distance to last-scattering, thus reducing angular size of the sound horizon and pushing peaks to higher multipoles (vice versa for Ω_k<0).

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Parameter Sensitivity

Hubble constant: H_0

There are many choices for what to use for the "final" parameter in ΛCDM. In most CMB analyses, we use θ_s^*, the angular size of the sound horizon at last-scattering: $\theta_s^* = r_s^*/\chi^*$

We could also use Ω_Λ, the cosmological constant density [exercise: explain why this is equivalent to using H_0 within flat ΛCDM].

How Do We Infer H_0 from the Cosmic Microwave Background?

The Sound Horizon

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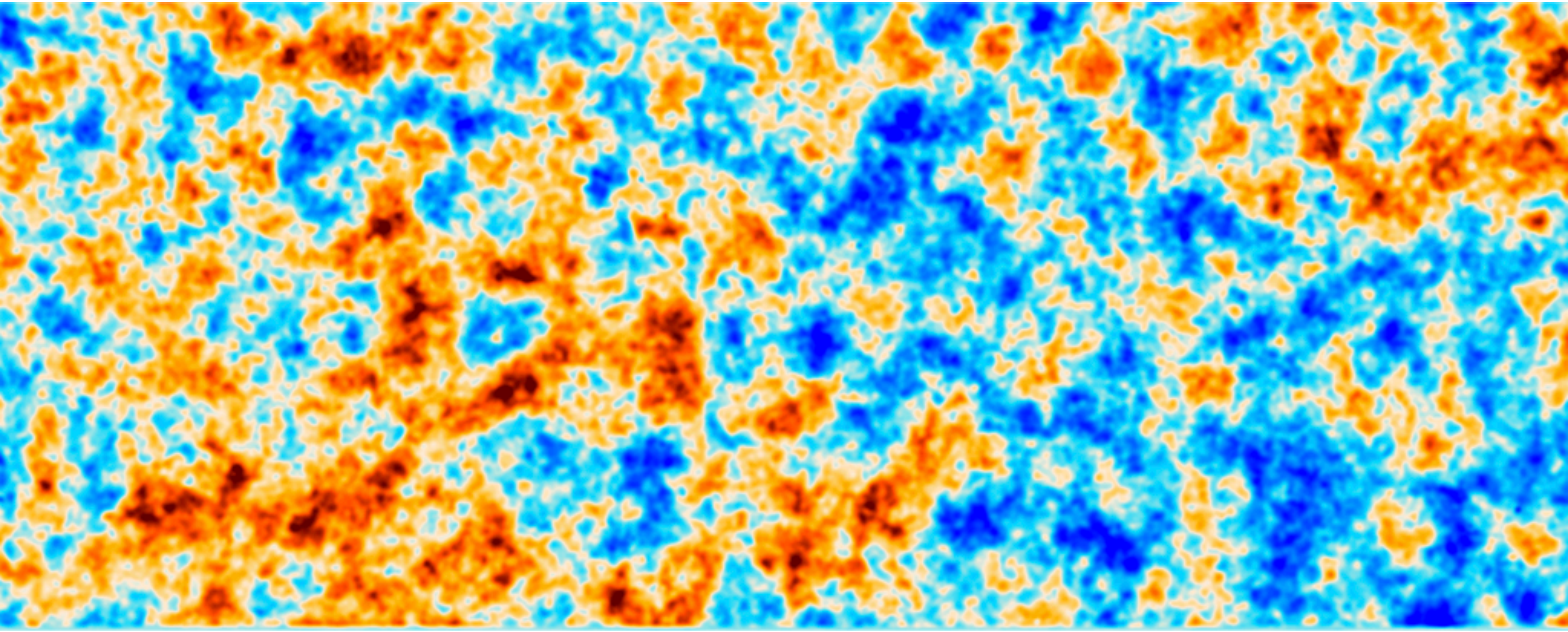
The sound horizon at last-scattering is a “standard ruler” of known physical size imprinted in CMB maps. It is the distance that a sound wave could propagate in the primordial plasma, starting at t=0 (Big Bang) until redshift z = 1100



A small patch of a CMB temperature map made from combination of Planck and ACT DR4 data (25x10 deg^2)

Naess et al. (2020)

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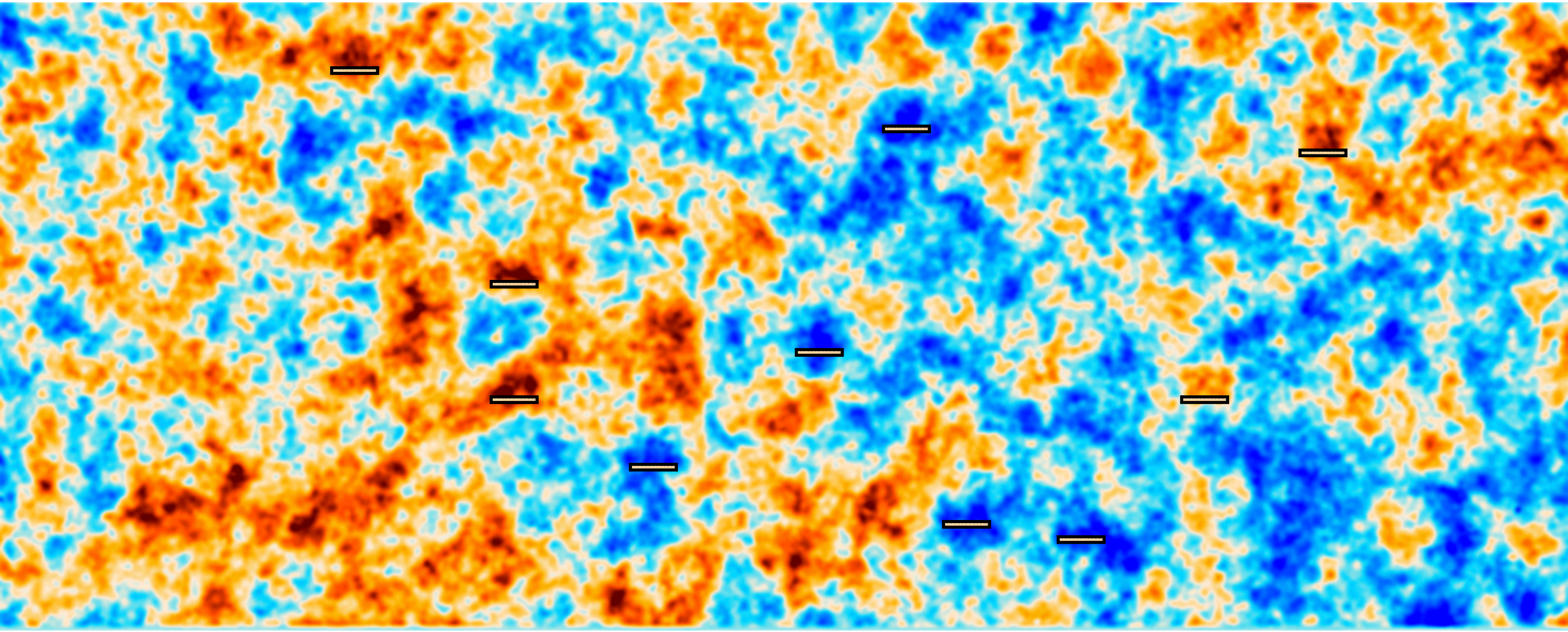

We measure the angular size of this ruler on the sky (θ_s*), and thus infer the distance to the CMB — therefore we have a **distance** and a **redshift**.

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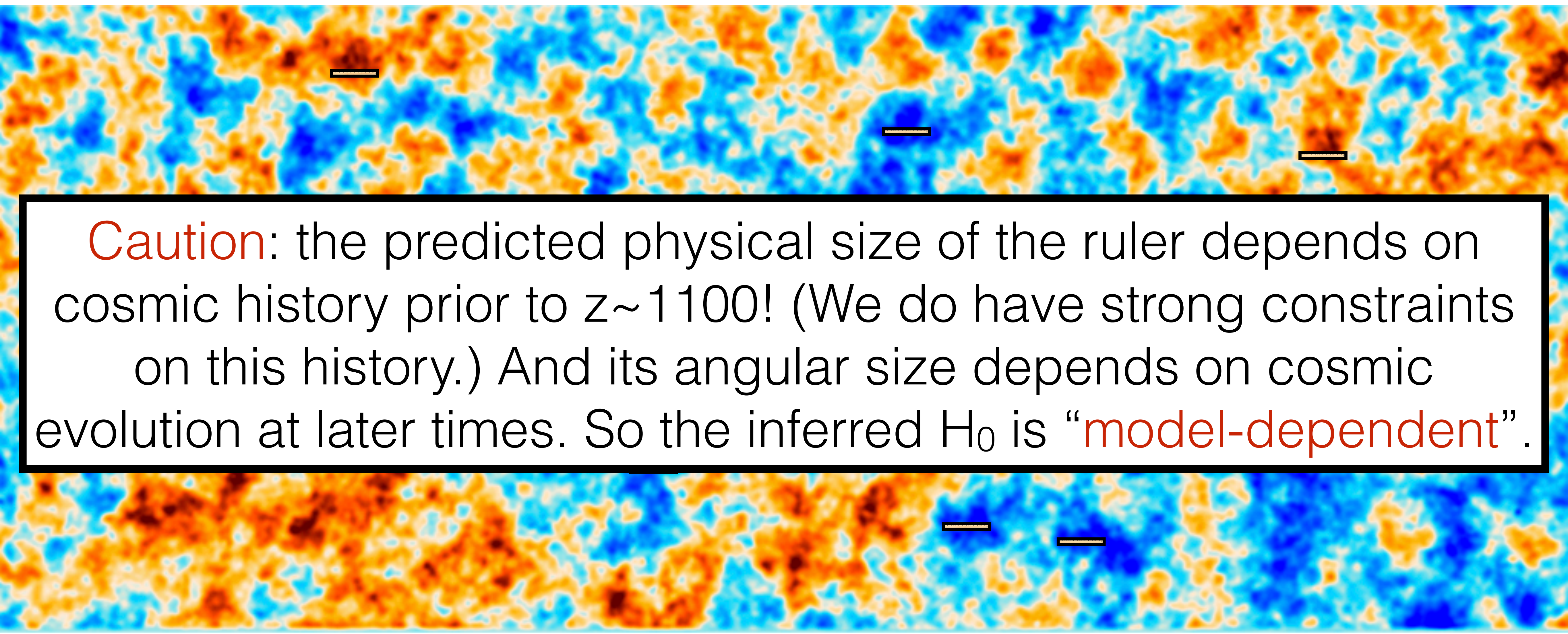

Caution: the predicted physical size of the ruler depends on cosmic history prior to z~1100! (We do have strong constraints on this history.) And its angular size depends on cosmic evolution at later times. So the inferred H_0 is "model-dependent".

We measure the angular size of this ruler on the sky (θ_S^*), and thus infer the distance to the CMB — therefore we have a **distance** and a **redshift**.

Hubble Constant

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How does this work?

Recall the size of the sound horizon imprinted in the CMB:

$$r_s^\star = \int_0^{t_\star} \frac{dt}{a(t)}\, c_s(t) = \int_{z_\star}^{\infty} \frac{dz}{H(z)}\, c_s(z)$$

Relevant ingredients in ΛCDM: ω_b, ω_{cdm}, ω_ν, ω_γ

physical densities of baryons, CDM, neutrinos, photons

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physical densities of baryons, CDM, neutrinos, photons

Angular size of sound horizon is ~related to peak spacing:

measured precisely → $\theta_{\rm s}^{\star} = \pi/\Delta\ell \longrightarrow D_A^{\star} = r_{\rm s}^{\star}/\theta_{\rm s}^{\star} \longrightarrow H_0$

Recall $D_A \sim 1/H_0$

Effect of changing H_0 on CMB power spectrum is very similar to Ω_k ("geometric degeneracy")

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The Hubble Situation

How fast is the universe currently expanding?

NY Times

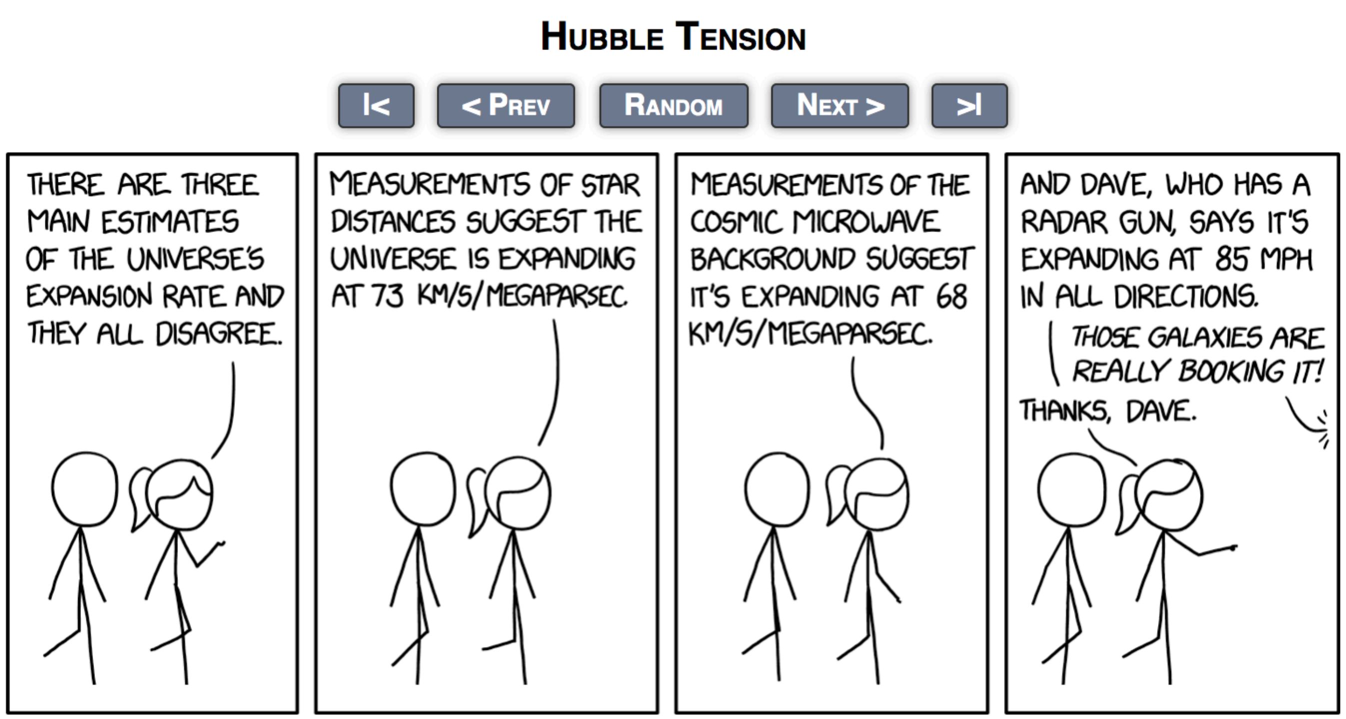
COSMOLOGY

Cosmologists Debate How Fast the Universe Is Expanding

79

New measurements could upend the standard theory of the cosmos that has reigned since the discovery of dark energy 21 years ago.

Quanta



xkcd
9/16/21

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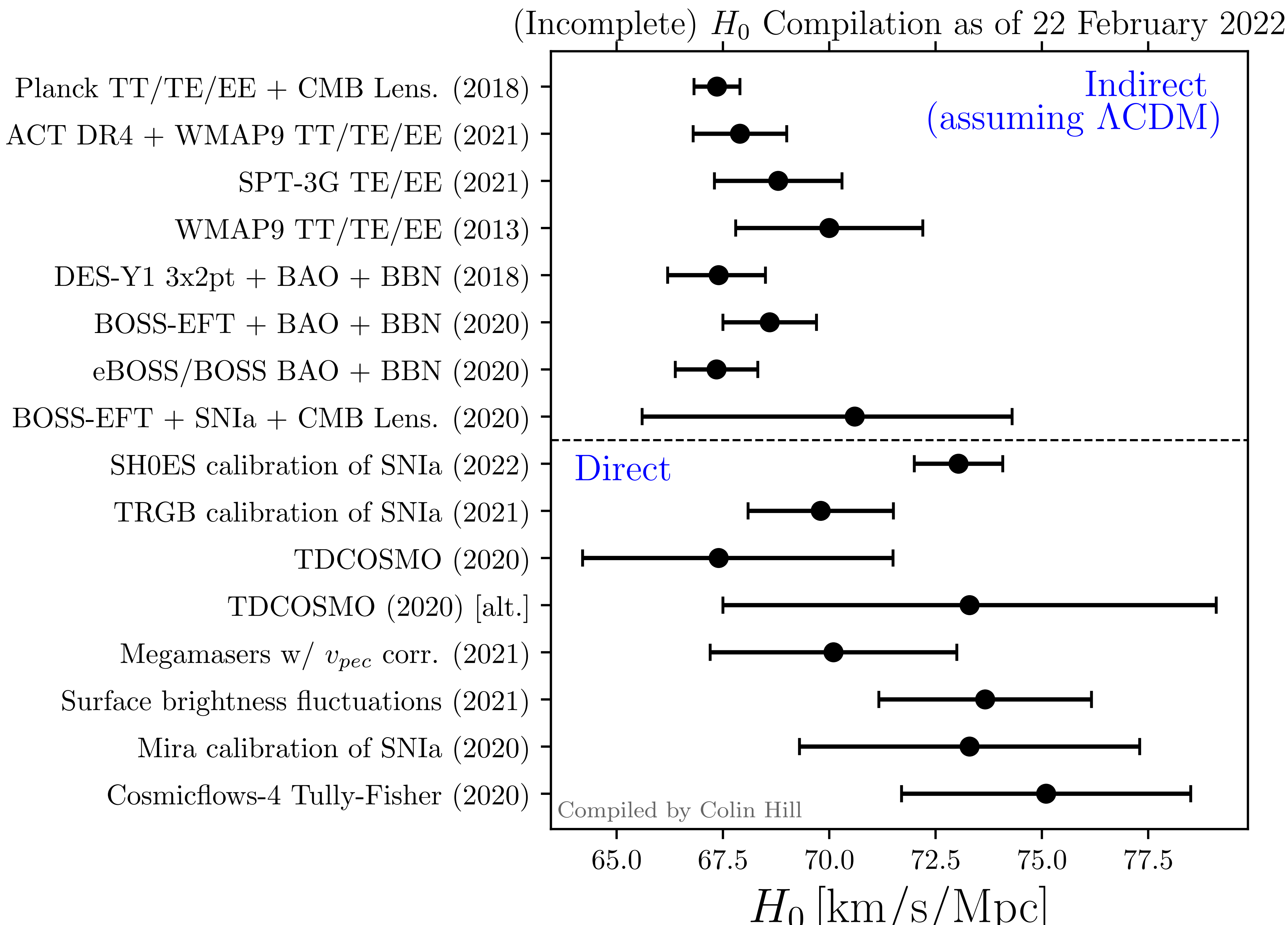
The Hubble Situation

My personal view: observational situation remains unclear



N.B. many of these are not independent

Original discussion: https://twitter.com/jcolinhill/status/1319415667095949312

The Hubble Situation

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If the H_0 discrepancy is not due to systematic error(s), how can we explain it?

One possibility: some (exotic) new physics altered the physical size of the "ruler" in the CMB

e.g., extra "dark radiation" in the early universe or "early dark energy"

e.g., Smith+ (2019); Agrawal+ (2019); Poulin+ (2018); Lin+ (2019); Knox & Millea (2020); JCH+ (2020)

The Hubble Situation

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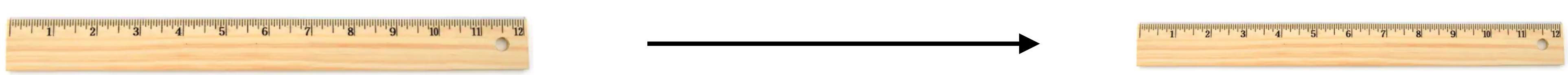
Goal of many such proposals: the new physics acts to *decrease* the physical size of the standard ruler (the sound horizon), so that the distance to the CMB that we infer is also decreased, and our inferred H_0 is *increased*



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The Hubble Situation

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$$r_s^\star = \int_0^{t_\star} \frac{dt}{a(t)}\, c_s(t) = \int_{z_\star}^{\infty} \frac{dz}{H(z)}\, c_s(z)$$

sound horizon

scale factor

sound speed

idea: increase H(z) just prior to z*~1100

e.g., Smith+ (2019); Agrawal+ (2019); Poulin+ (2018); Lin+ (2019); Knox & Millea (2020); JCH+ (2020)

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Then to keep $\theta_s^* = r_s^*/D_A^*$ fixed, H_0 must increase ($D_A \sim 1/H_0$)

e.g., Smith+ (2019); Agrawal+ (2019); Poulin+ (2018); Lin+ (2019); Knox & Millea (2020); JCH+ (2020)

The Hubble Situation

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If the H_0 discrepancy is not due to systematic error(s), how can we explain it?

Another possibility: some new physics altered the dynamics of the epoch of recombination

The Hubble Situation

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If the H_0 discrepancy is not due to systematic error(s), how can we explain it?

Another possibility: some new physics altered the dynamics of the epoch of recombination

e.g., primordial magnetic fields or varying fundamental constants

Goal of many such proposals: the new physics acts to *accelerate* the process of recombination, so that recombination happens earlier (i.e., at higher redshift)

In some such models (but not all), r_s^* is decreased due to higher z^*

e.g., Jedamzik & Pogosian (2018); Sekiguchi & Takahashi (2020); Hart & Chluba (2020); JCH & Bolliet (2023)

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Example: Early Dark Energy

Motivation: increase CMB-inferred H_0

How does this work?

By decreasing the physical size of the sound horizon imprinted in the CMB

$$r_s^\star = \int_0^{t_\star} \frac{dt}{a(t)}\, c_s(t) = \int_{z_\star}^{\infty} \frac{dz}{H(z)}\, c_s(z)$$

Relevant ingredients in **EDE**: ω_b, ω_m, ω_ν, ω_γ **+ EDE parameters**

Angular sound horizon is (approx.) related to peak spacing:

$$\theta_s^\star = \pi/\Delta\ell \longrightarrow D_A^\star = r_s^\star/\theta_s^\star \longrightarrow H_0$$

Poulin+ (2019); Agrawal+ (2019); Lin+ (2019); Smith+ (2019); Knox & Millea (2019)

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Early Dark Energy

New component: (pseudo)-scalar field ϕ

Poulin+ (2019); Agrawal+ (2019); Lin+ (2019); Smith+ (2019)

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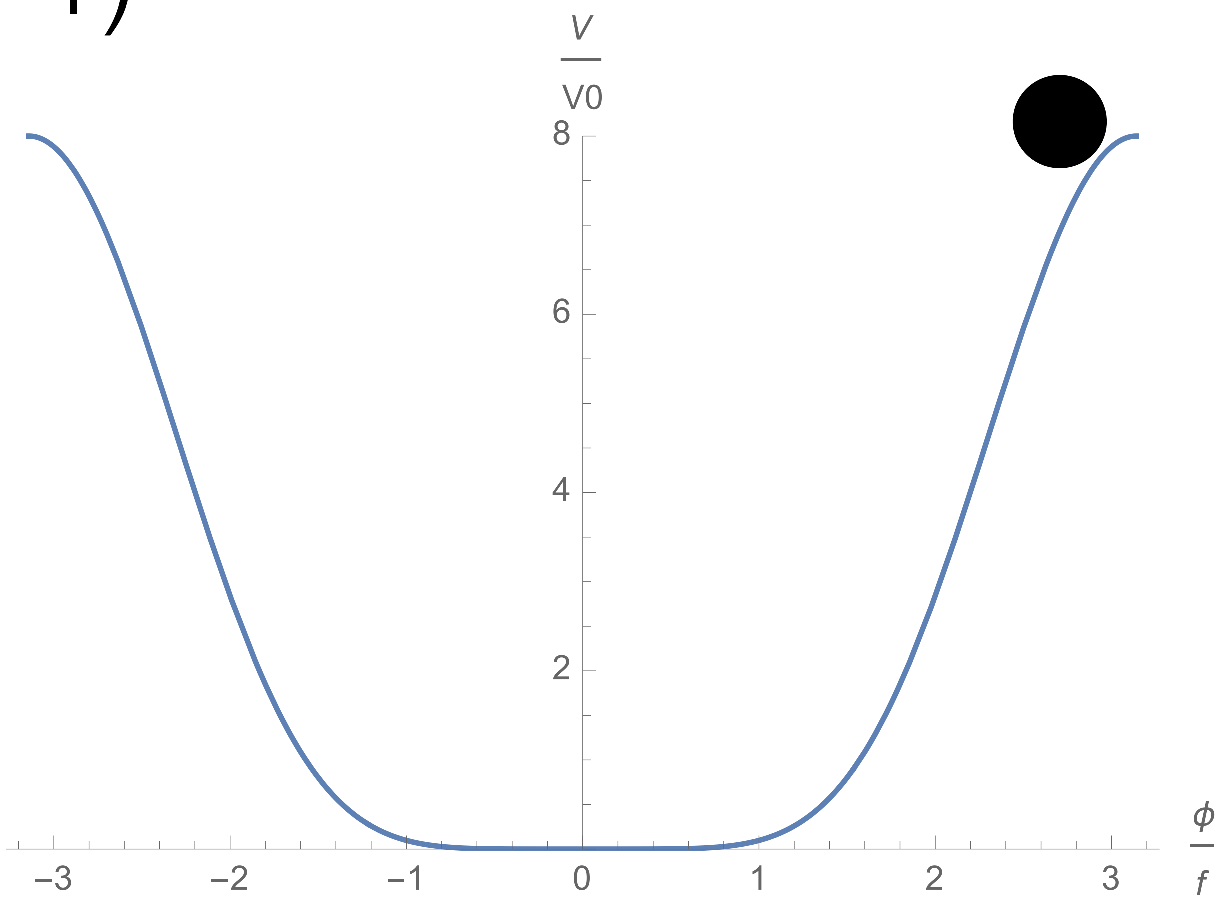
Early Dark Energy

New component: (pseudo)-scalar field ϕ

Idea: field initially frozen on its potential due to Hubble friction — acts as dark energy (equation of state P/ρ=w=-1)



$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

H >> m
initially

Poulin+ (2019); Agrawal+ (2019); Lin+ (2019); Smith+ (2019)

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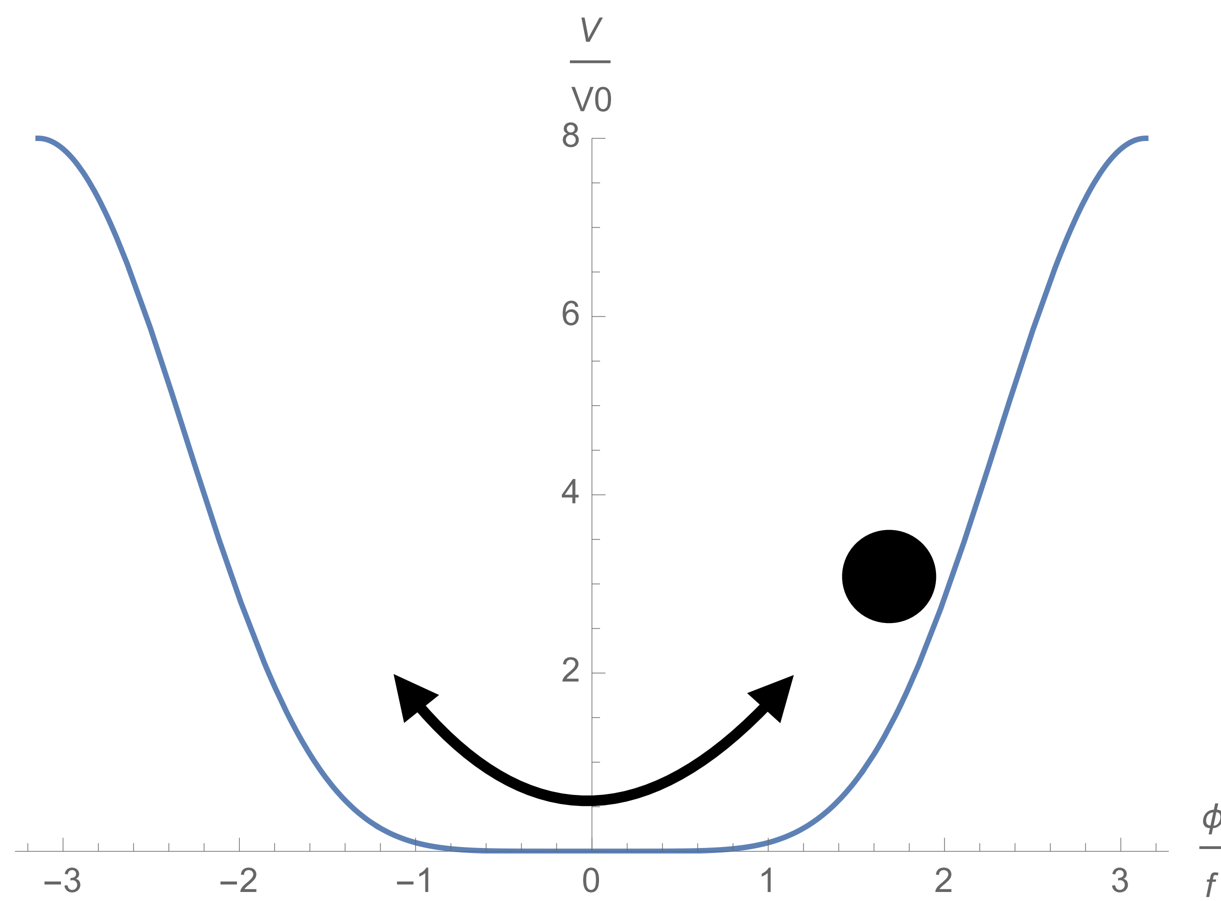
Early Dark Energy

New component: (pseudo)-scalar field ϕ

When H ~ m (field mass), it rolls down its potential and oscillates: effective EoS will depend on potential



For EDE, this must occur near ~z_{CMB}

↓

m ~ 10^{-27} eV

e.g., $\phi(t) = \phi_i a^{-3/2} \cos(mt)$ if $V(\phi) = m^2\phi^2/2$

Poulin+ (2019); Agrawal+ (2019); Lin+ (2019); Smith+ (2019)

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Early Dark Energy

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Important: need late-time w>0 so that EDE energy density contribution decays faster than matter

Poulin+ (2019); Agrawal+ (2019); Lin+ (2019); Smith+ (2019)

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Canonical EDE Potential:

$$V(\phi) = m^2 f^2 \left(1 - \cos\left(\phi/f\right)\right)^n$$

Near minimum, $V \sim \phi^{2n}$ $\longrightarrow$ $w_\phi = \frac{n-1}{n+1}$

$m \sim 10^{-27}$ eV
$f \sim 10^{26\text{-}27}$ eV
n >= 2

[Also important: perturbation dynamics]

Poulin+ (2019); Agrawal+ (2019); Lin+ (2019); Smith+ (2019)

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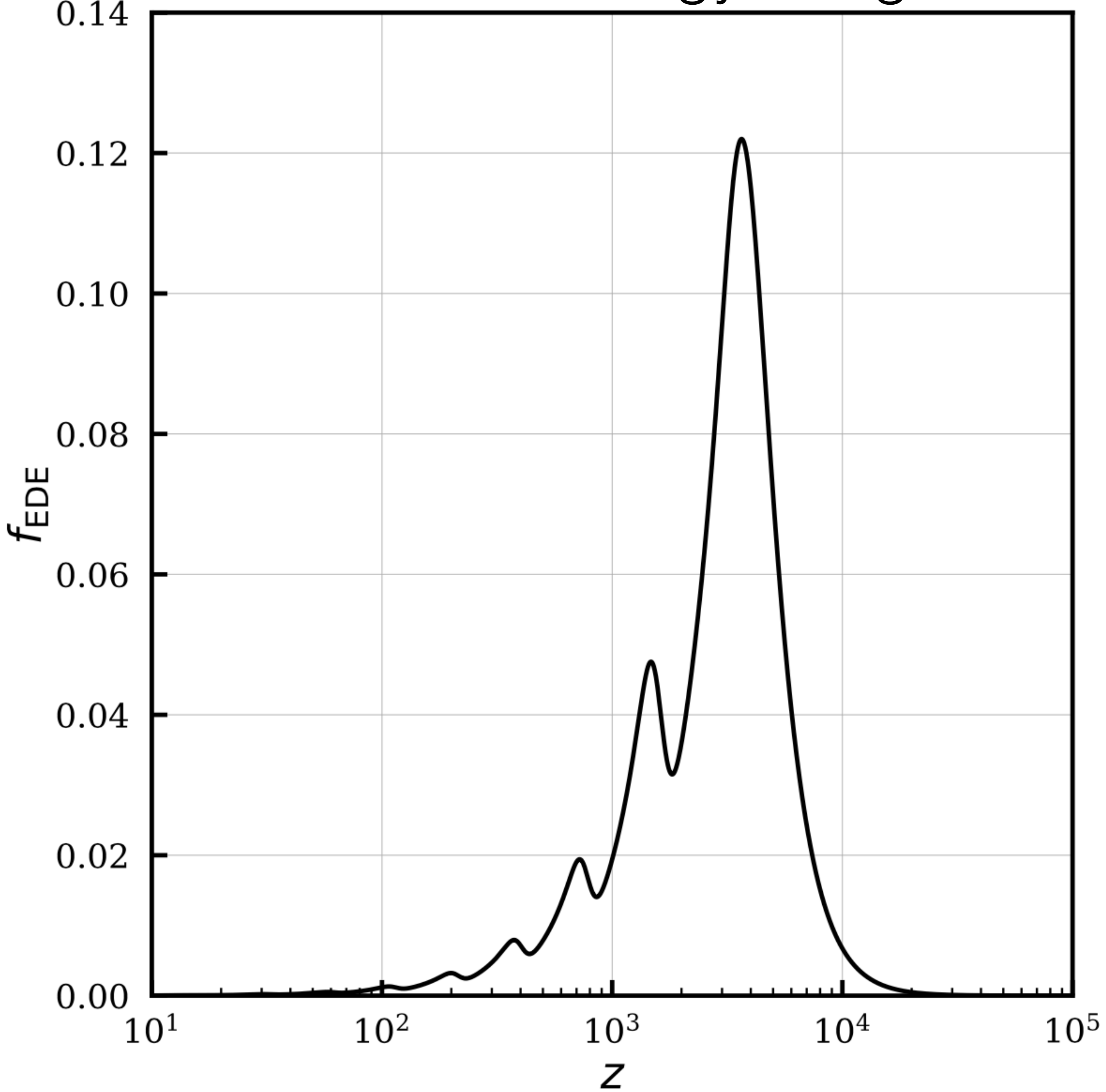
Early Dark Energy

Parameterization

Fractional contribution of EDE
to cosmic energy budget



Poulin+ (2019); Agrawal+ (2019); Lin+ (2019); Smith+ (2019); **JCH**+ (2020)

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Early Dark Energy

Parameterization

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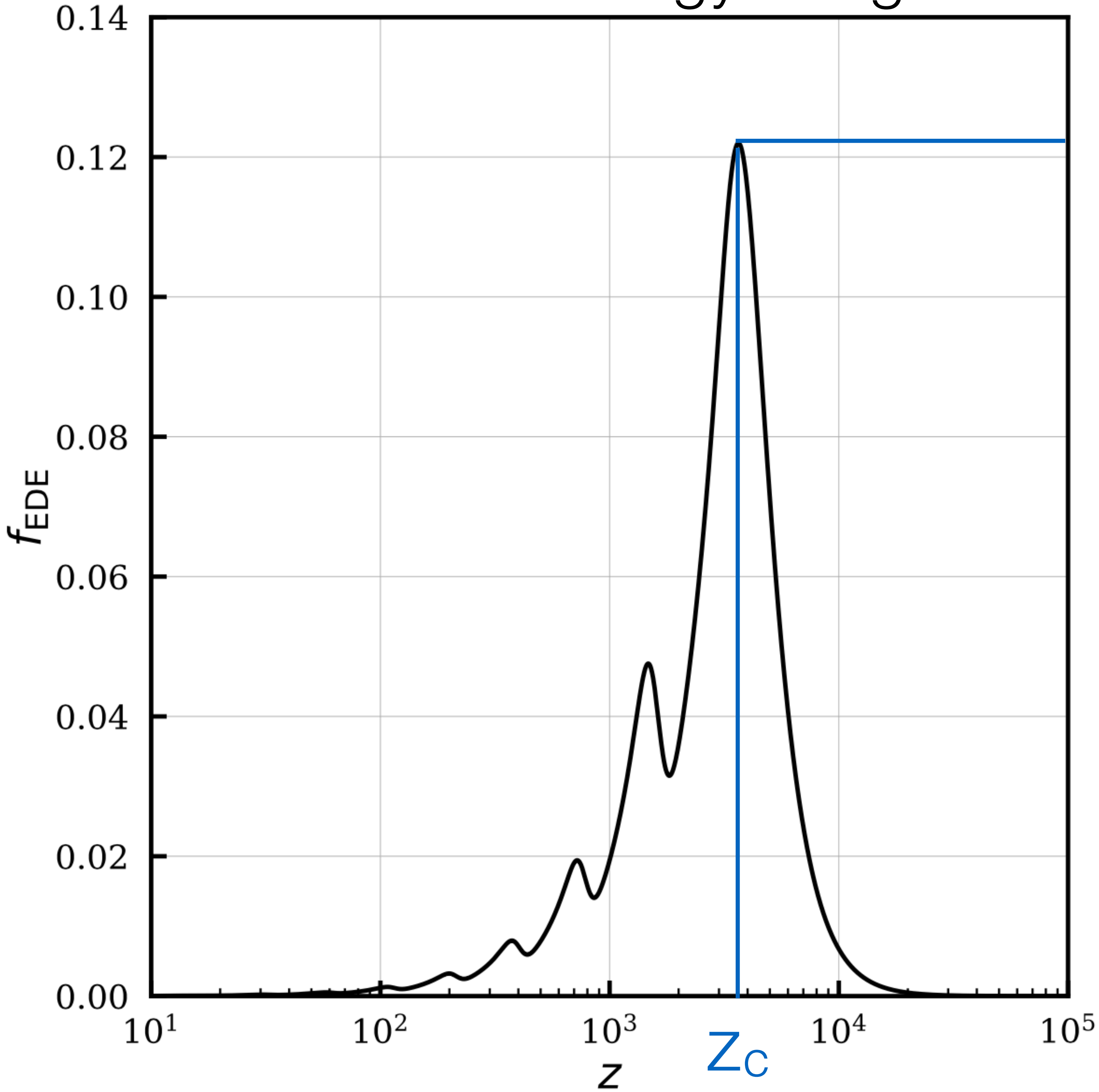

Maximal contribution:

$$f_{\rm EDE}(z_c) \equiv (\rho_{\rm EDE}/3M_{pl}^2 H^2)|_{z_c}$$

which occurs at redshift z_c

Final parameter: $\theta_i = \phi_i/f$ (initial field displacement)

➡ $\{f_{\rm EDE}, z_c, \theta_i\}$

N.B.: highly non-linear relation to physical scalar field parameters

Poulin+ (2019); Agrawal+ (2019); Lin+ (2019); Smith+ (2019); **JCH**+ (2020)

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EDE Puzzles & Problems

McDonough, Lin, JCH, Hu, Zhou (2021); Lin, McDonough, JCH, Hu (2022); JCH+ (2020); Ivanov+ (2020)

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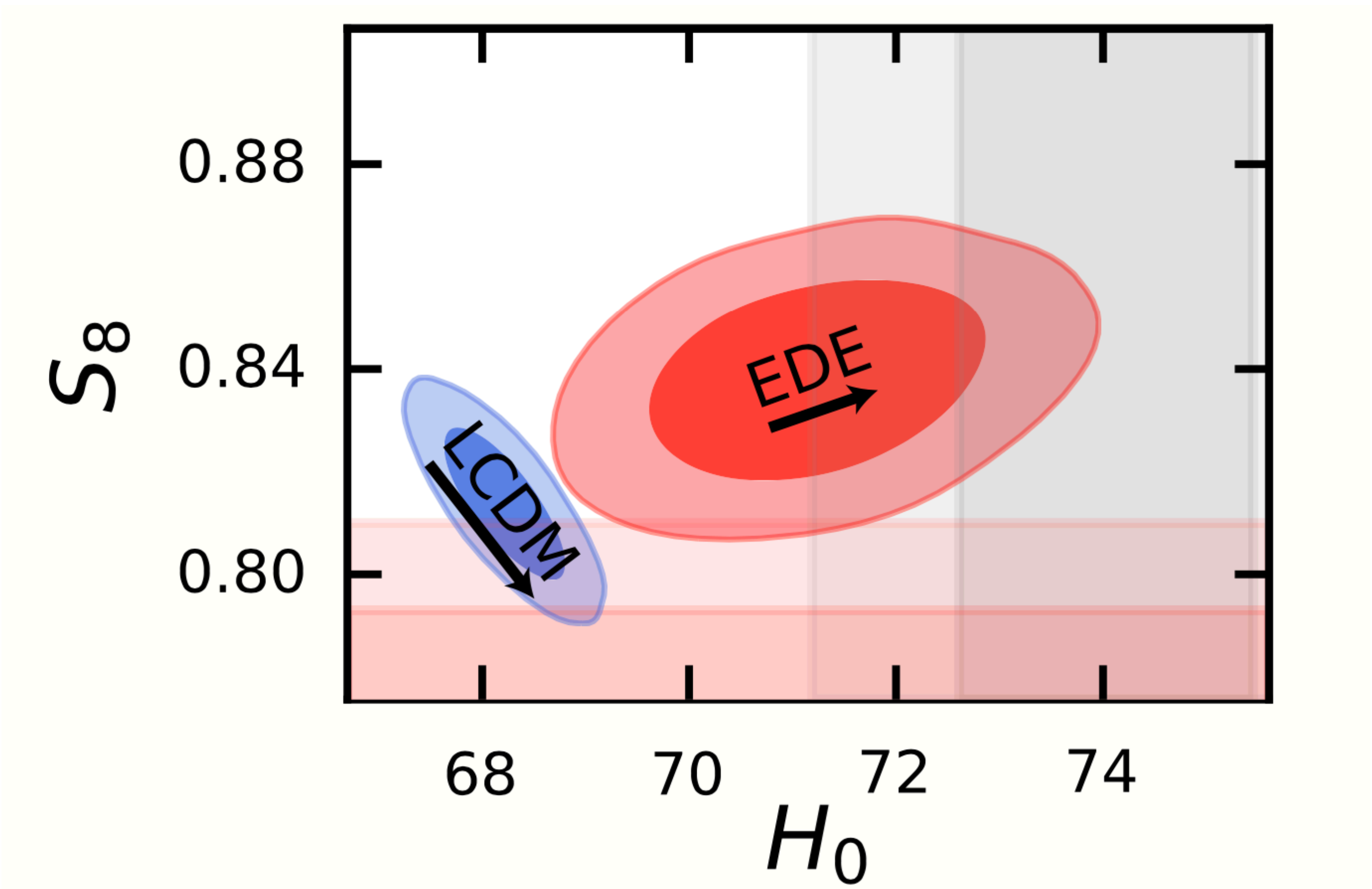
EDE Puzzles & Problems

- Coincidence problem: why should these new dynamics appear near z_{eq}? [—> $V(\phi)$, $V'(\phi)$]
- Initial conditions: axion-like field must start near top of cosine to fit *Planck* data (e.g., Lin, Benevento, Hu, Raveri (2019)) [—>$V''(\phi)$]
- "Tension-trading": H_0 increases in the CMB fit at the cost of adding significantly more dark matter and increasing n_s, hence raising S_8 (and worsening "S_8 tension")



McDonough, Lin, JCH, Hu, Zhou (2021); Lin, McDonough, JCH, Hu (2022); JCH+ (2020); Ivanov+ (2020)

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EDE Puzzles & Problems

Why do ω_c and n_s increase when fitting EDE to CMB data?

- Recall the integrated Sachs-Wolfe (ISW) effect: grav. potentials decay in a non-matter-dominated universe

- Early ISW arises because radiation is still important at z*

—>Enhanced in an EDE cosmology (because the EDE is not matter)

JCH+ (2020); Vagnozzi+ (2021)

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EDE Puzzles & Problems

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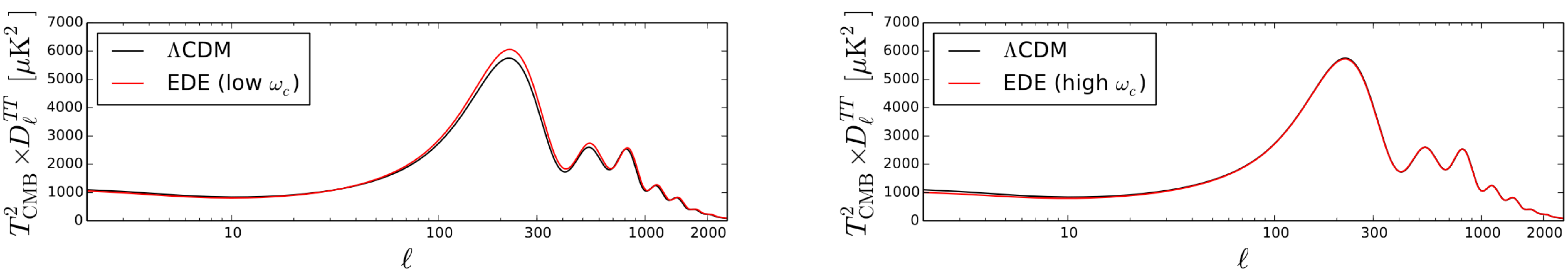

primarily compensated by increasing the CDM density (ω_c), but also by increasing the slope of the power spectrum (n_s)

JCH+ (2020); Vagnozzi+ (2021)

EDE: Latest Updates

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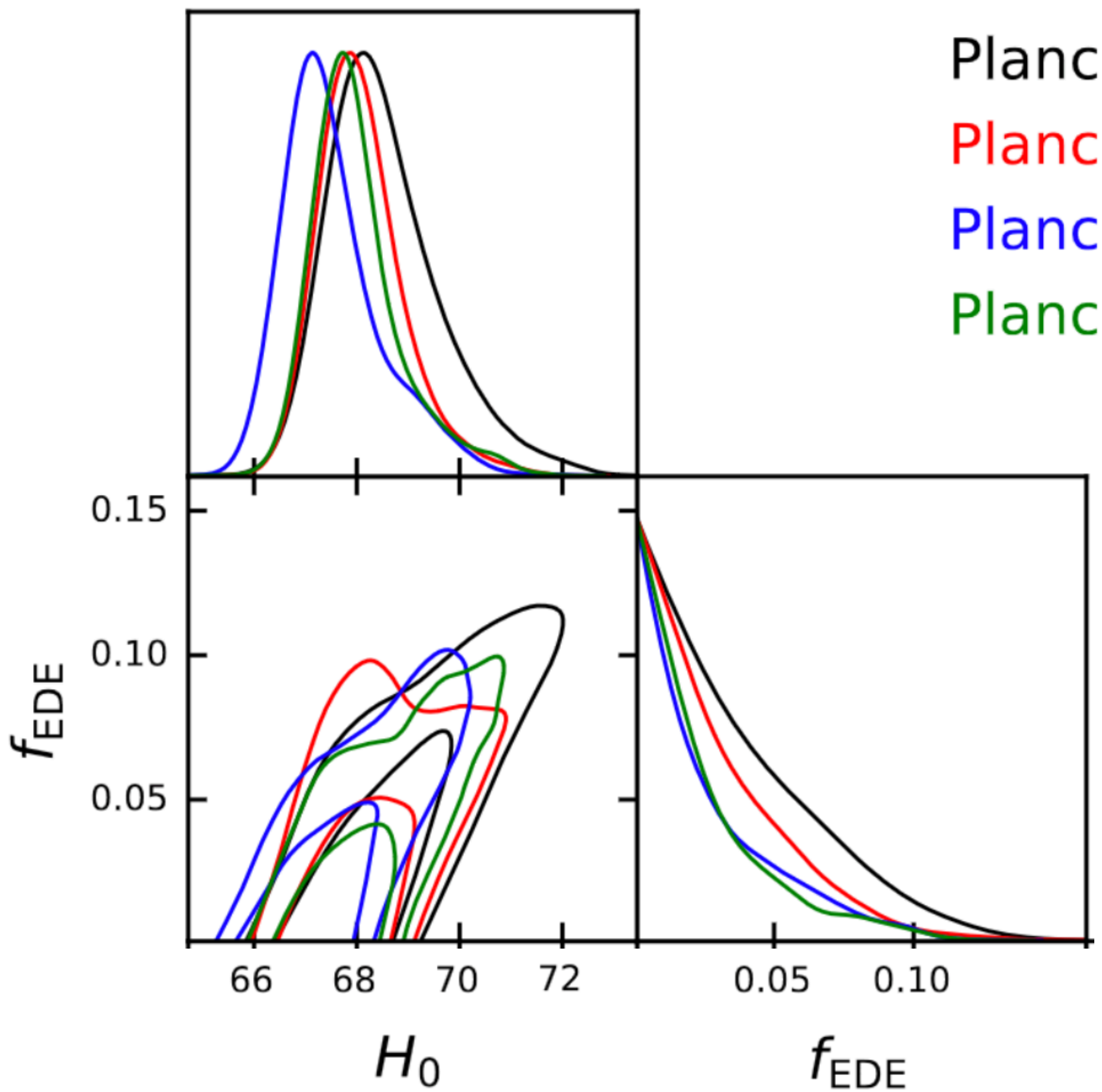
Planck PR4 (NPIPE) data show no hint of EDE and tighten upper bound on f_{EDE} by ~20%



Planck 2018 TTTEEE + lowlTT (Plik) [EDE]
Planck 2018 TTTEEE (Camspec) [EDE]
Planck NPIPE TTTEEE (Hillipop) [EDE]
Planck NPIPE TTTEEE (Camspec) [EDE]

However, a moderate (3σ) hint of non-zero EDE was seen in ACT DR4 data (JCH+2021) — was it a fluctuation or a sign of new physics appearing at high multipoles? Stay tuned

McDonough, JCH, Ivanov, La Posta, Toomey (2023); see also Efstathiou, Rosenberg, Poulin (2023)

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ΛCDM

The standard cosmological model has survived ~25 years of tests, comprising hundreds of very well-understood, robust measurements (e.g., CMB power spectra, BAO, …)

Parameter	*Planck* alone	*Planck* + BAO
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8111 ± 0.0060	0.8102 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$ . . .	0.832 ± 0.013	0.825 ± 0.011
z_{re}	7.67 ± 0.73	7.82 ± 0.71
Age[Gyr]	13.797 ± 0.023	13.787 ± 0.020
r_*[Mpc]	144.43 ± 0.26	144.57 ± 0.22
$100\theta_*$	1.04110 ± 0.00031	1.04119 ± 0.00029
r_{drag}[Mpc]	147.09 ± 0.26	147.57 ± 0.22
z_{eq}	3402 ± 26	3387 ± 21
k_{eq}[Mpc^{-1}]	0.010384 ± 0.000081	0.010339 ± 0.000063
Ω_K	-0.0096 ± 0.0061	0.0007 ± 0.0019
Σm_ν [eV]	< 0.241	< 0.120
N_{eff}	$2.89^{+0.36}_{-0.38}$	$2.99^{+0.34}_{-0.33}$
$r_{0.002}$	< 0.101	< 0.106

Planck Collaboration (2018)

ΛCDM

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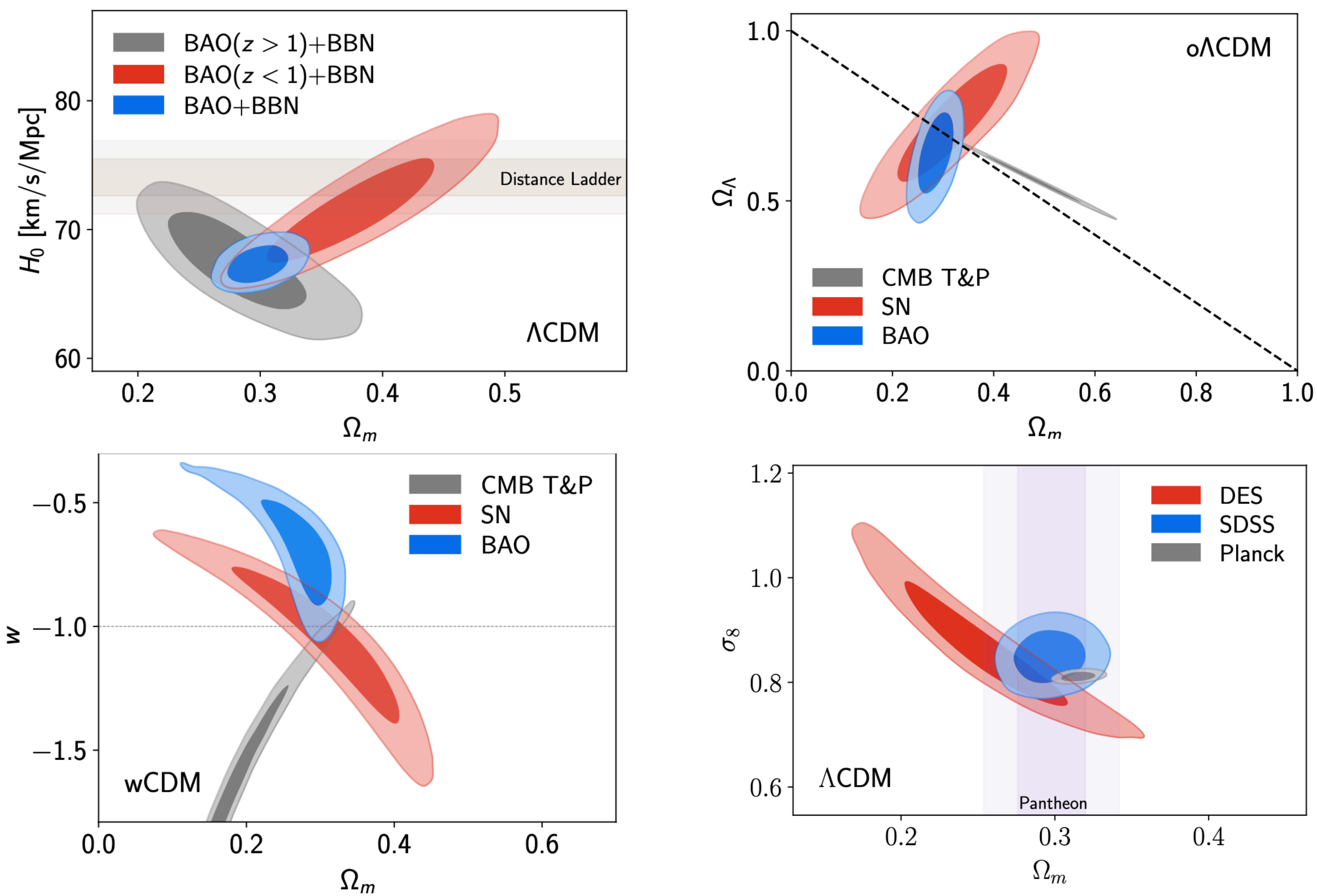

… but I expect nature has more surprises in store for us

eBOSS Collaboration (2021)

CMB Polarization

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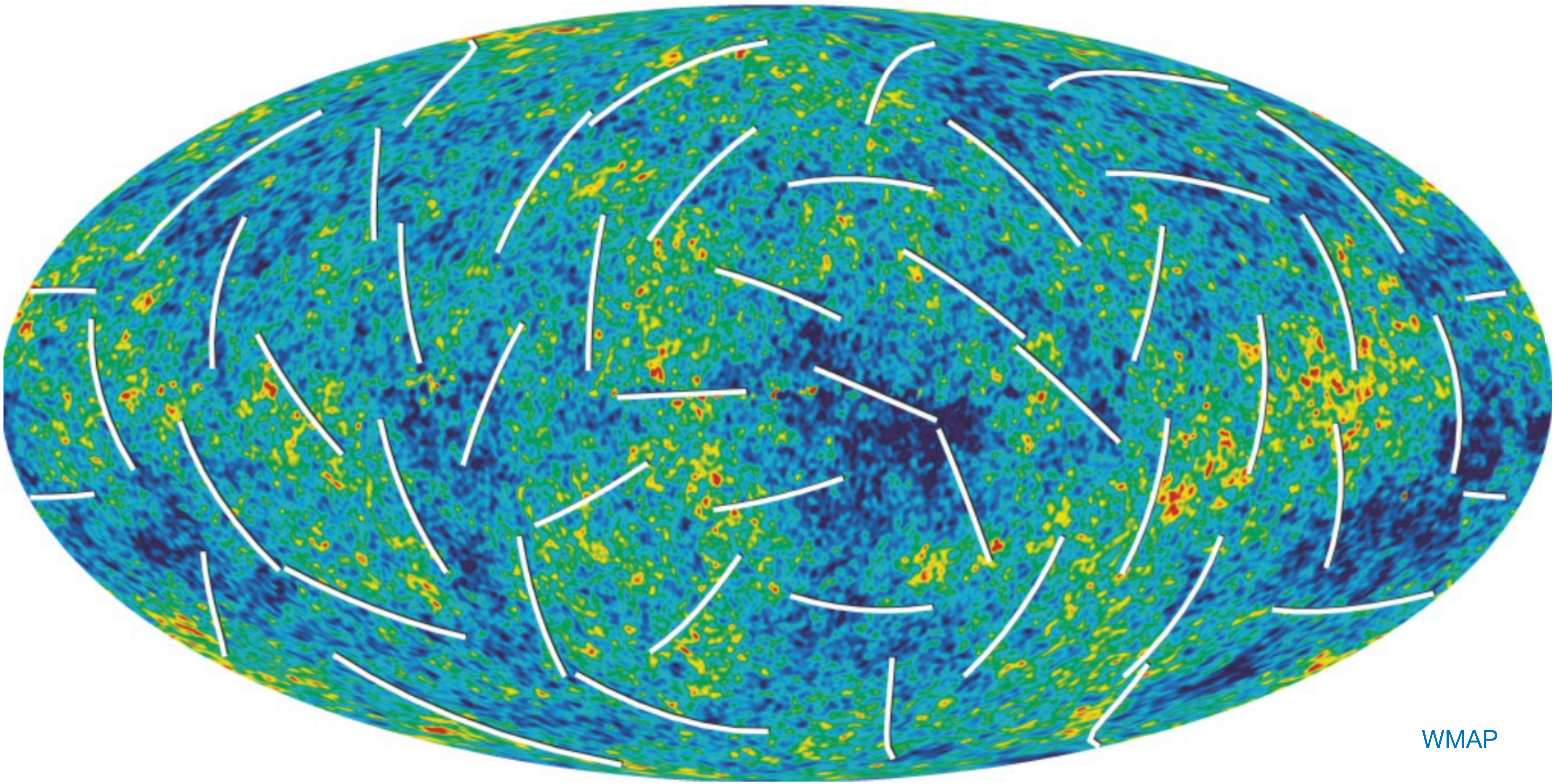
CMB Polarization



CMB photons are observed to be linearly polarized at the 10% level (first detection: DASI Collaboration 2002)

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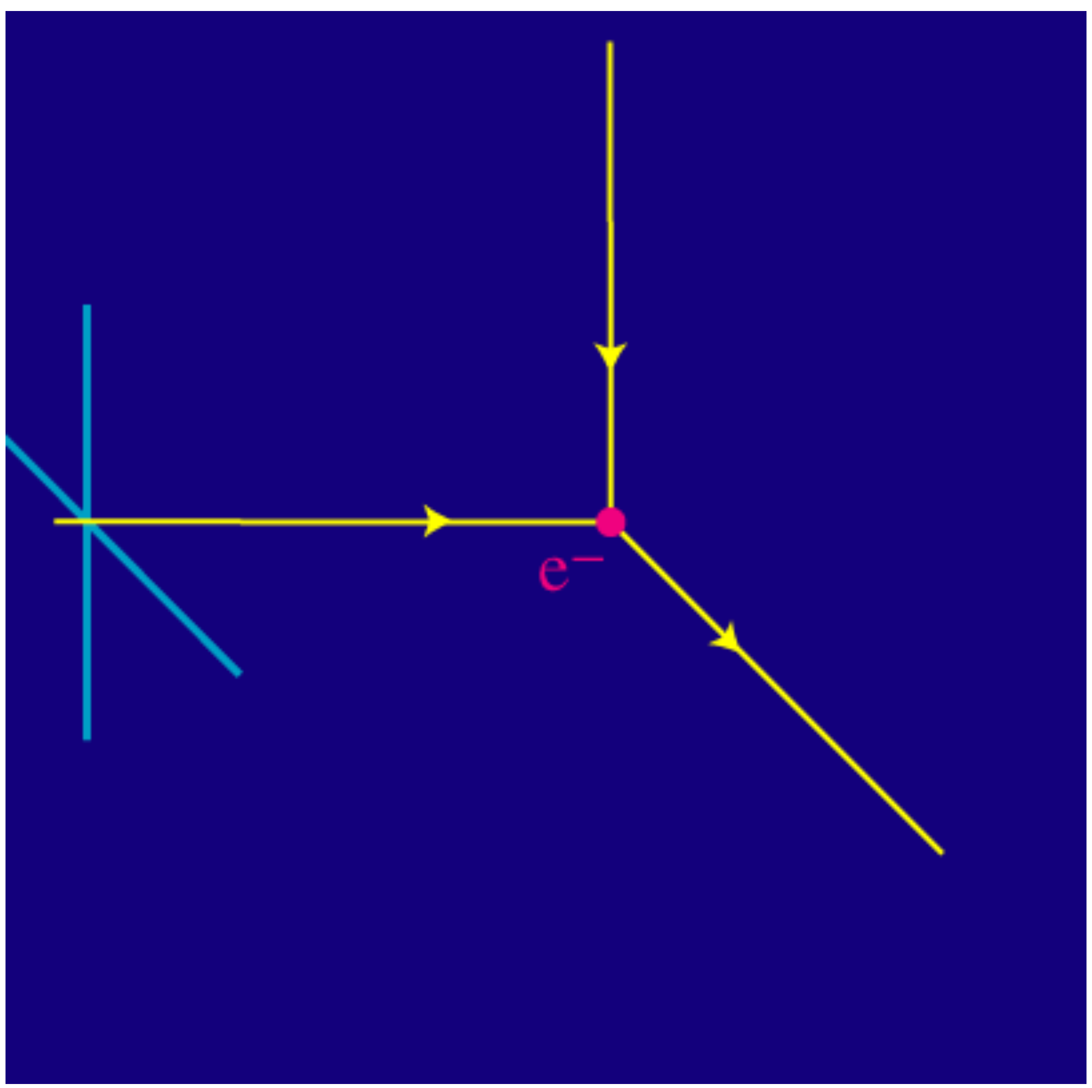
CMB Polarization

Origin of CMB polarization: quadrupolar dependence of Thomson scattering cross-section

$$\frac{d\sigma_T}{d\Omega} \propto |\hat{\epsilon} \cdot \hat{\epsilon}'|^2$$

Polarization directions of incident and scattered light

Incoming light



The outgoing photons cannot be longitudinally polarized (like all photons), so linear polarization is generated

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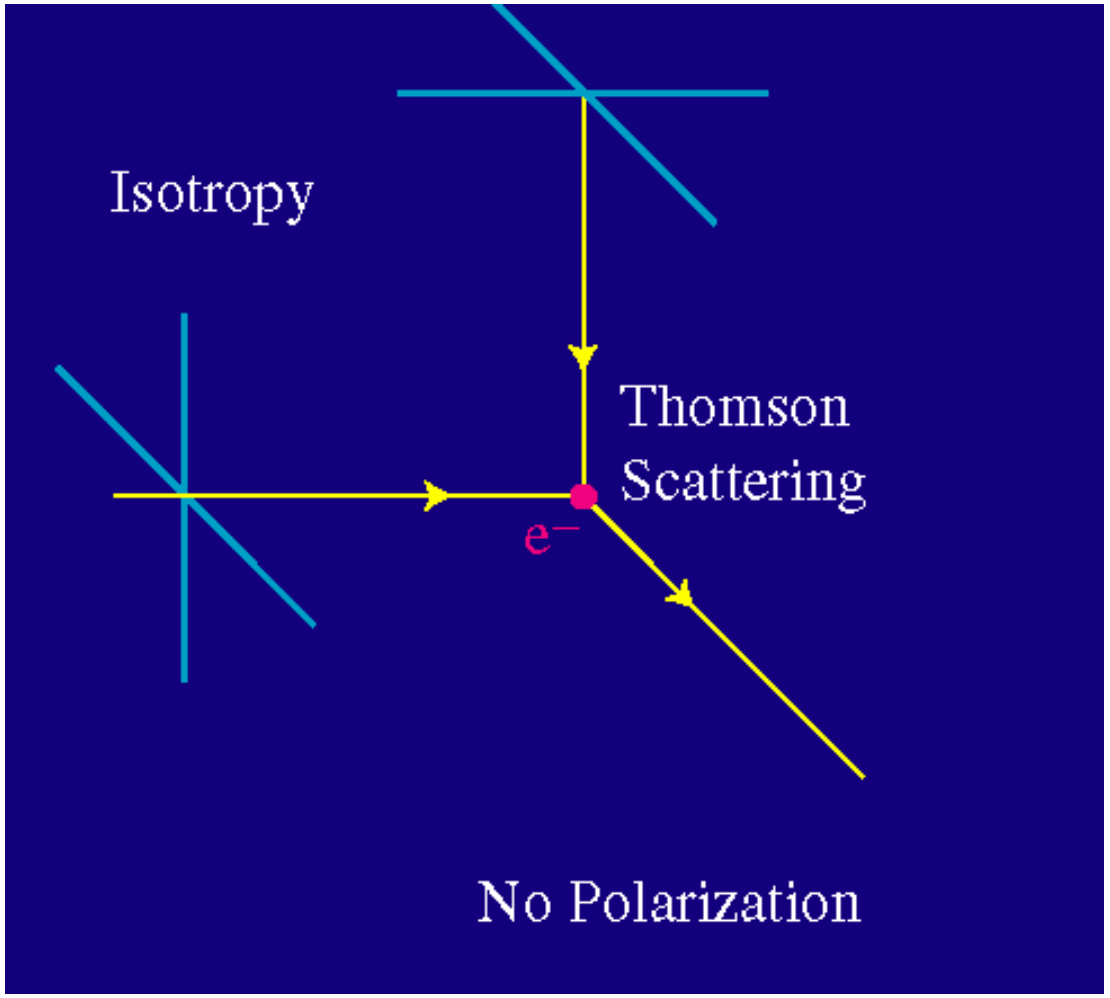

If the incoming radiation field is isotropic, no net linear polarization is generated by Thomson scattering

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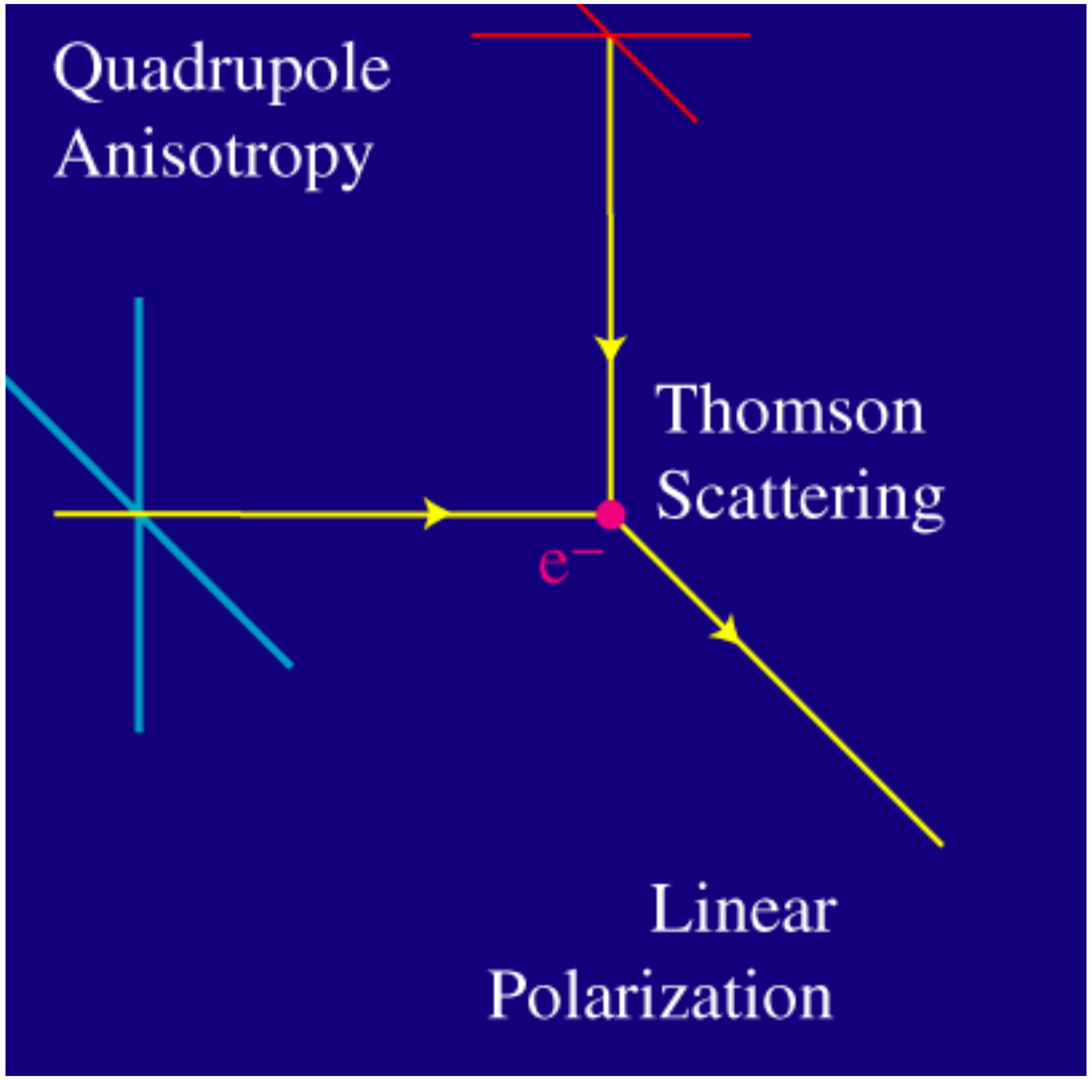
Incoming light (cold)

Incoming light (hot)



But the local radiation field seen by electrons at last-scattering is not isotropic: there is a quadrupole anisotropy

Thus net linear polarization is generated (aligned with cold axis of incoming anisotropy)

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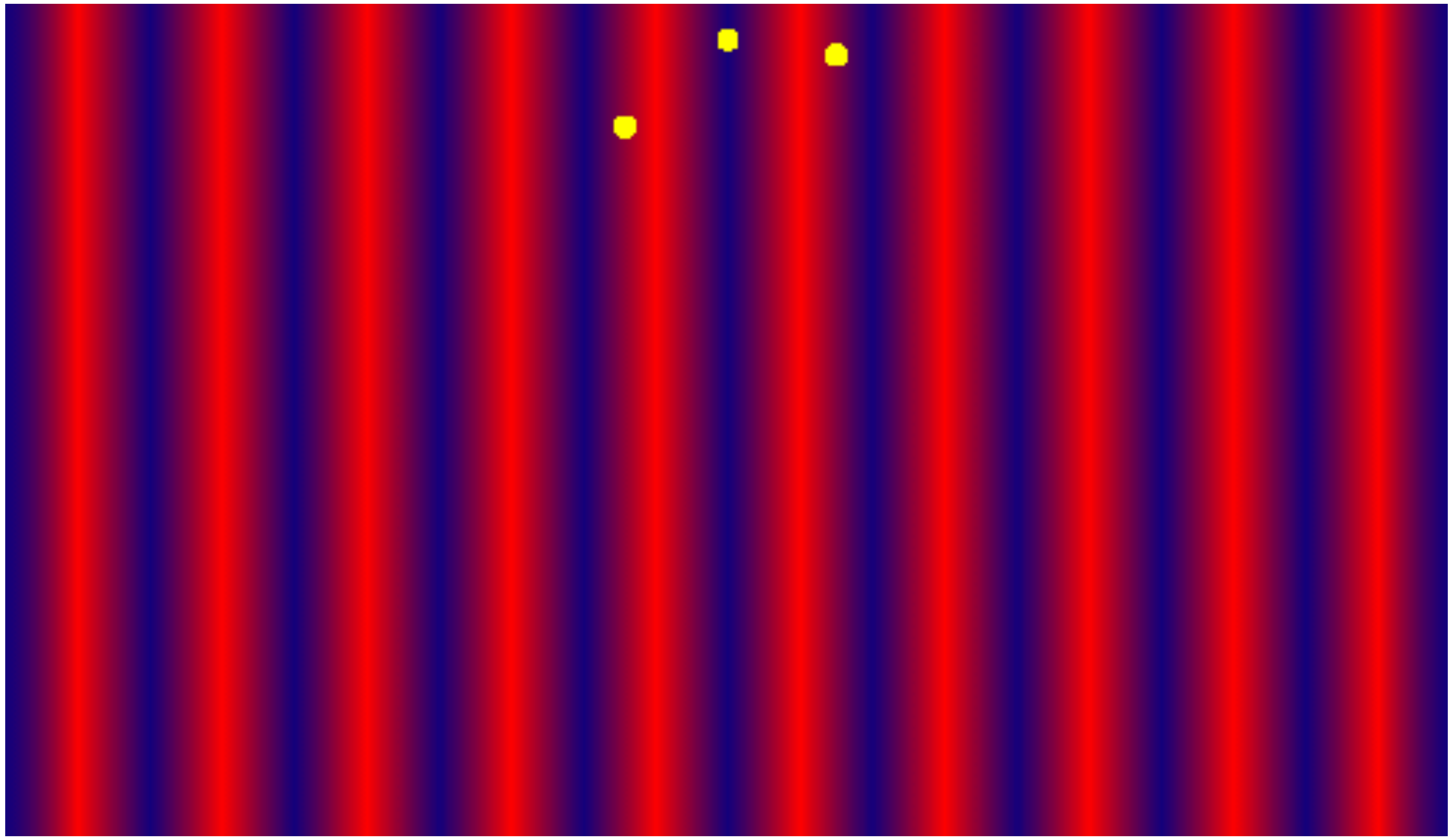
CMB Polarization

Quadrupole anisotropy at last scattering

Origin: diffusion of photons out of hot and cold regions near the end of recombination (electron needs to be able to "see" photons from different regions in order to see a local quadrupole)



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- Visibility function for polarization is thus very sharply peaked
- Expect peak in (E-mode) polarization power near the damping scale
- The polarization pattern we see is precisely the projection of the local quadrupole anisotropies at recombination