The Cosmic Microwave Background

Lecture 2: Anisotropy Basics, Line-of-Sight Projection, and Acoustic Physics

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History of Thermal History

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE
AT 4080 Mc/s

Penzias and Wilson (1965)

Wilson Penzias

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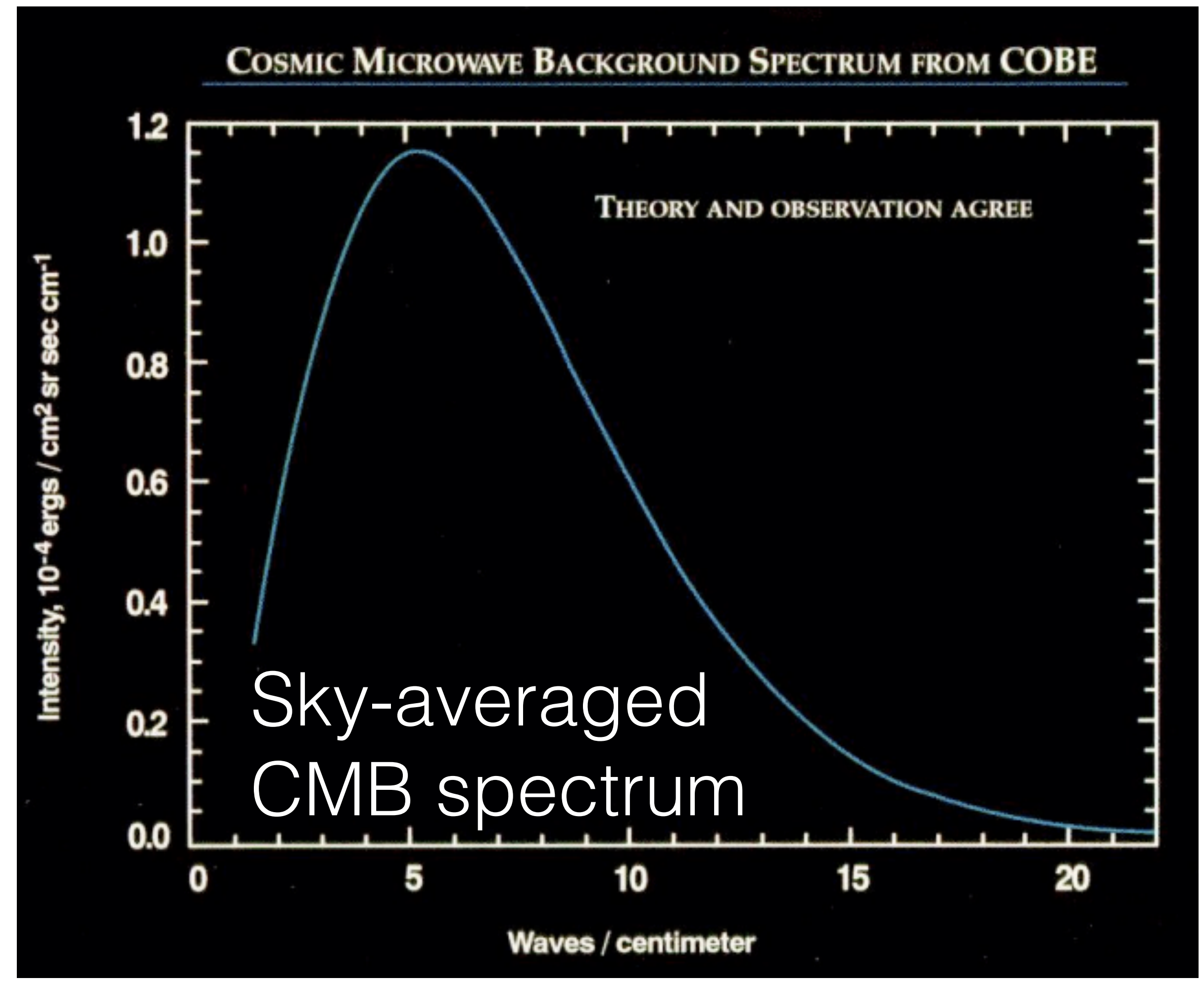
History of Thermal History

CMB
T = 2.7255 +/- 0.0006 K



Spectacular confirmation of the hot Big Bang: the universe was once in a dense, highly thermal state

COBE/FIRAS (1996)

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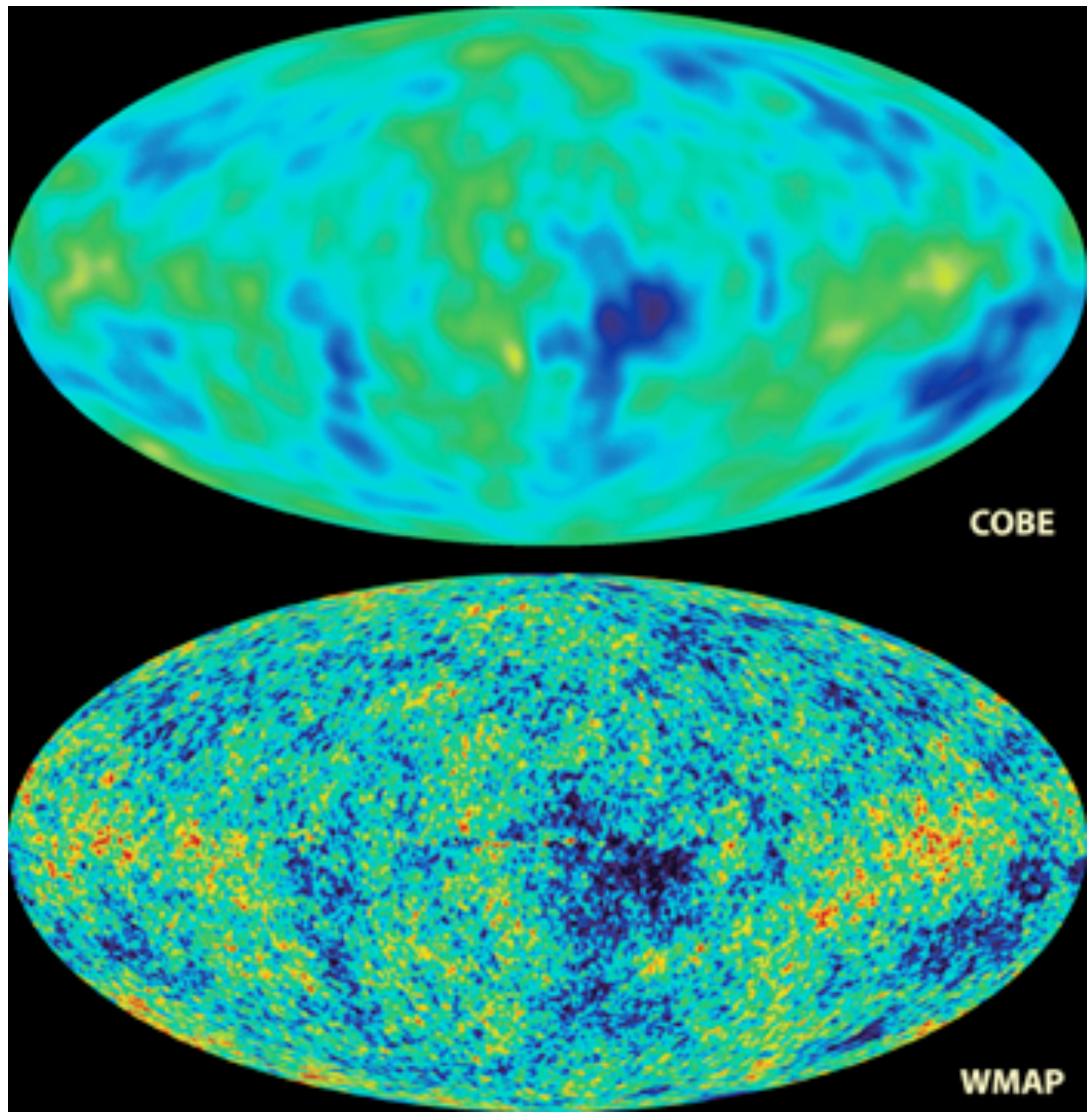
Anisotropy

We know the universe is not uniform today: hence, fluctuations must exist at some level in the CMB. It took ~25-30 years to find them!

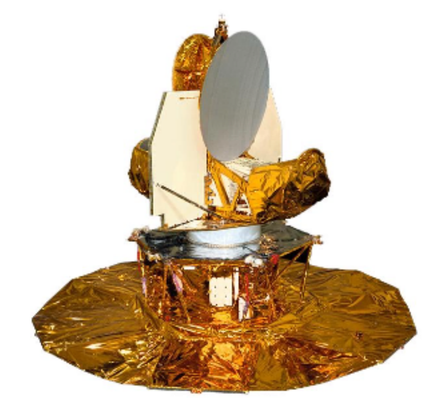
$$\Delta T(\hat{n}) \equiv \frac{T(\hat{n}) - \bar{T}_{\rm CMB}}{\bar{T}_{\rm CMB}}$$

Fluctuation amplitude ~ few x 10^{-5}



1992

2003



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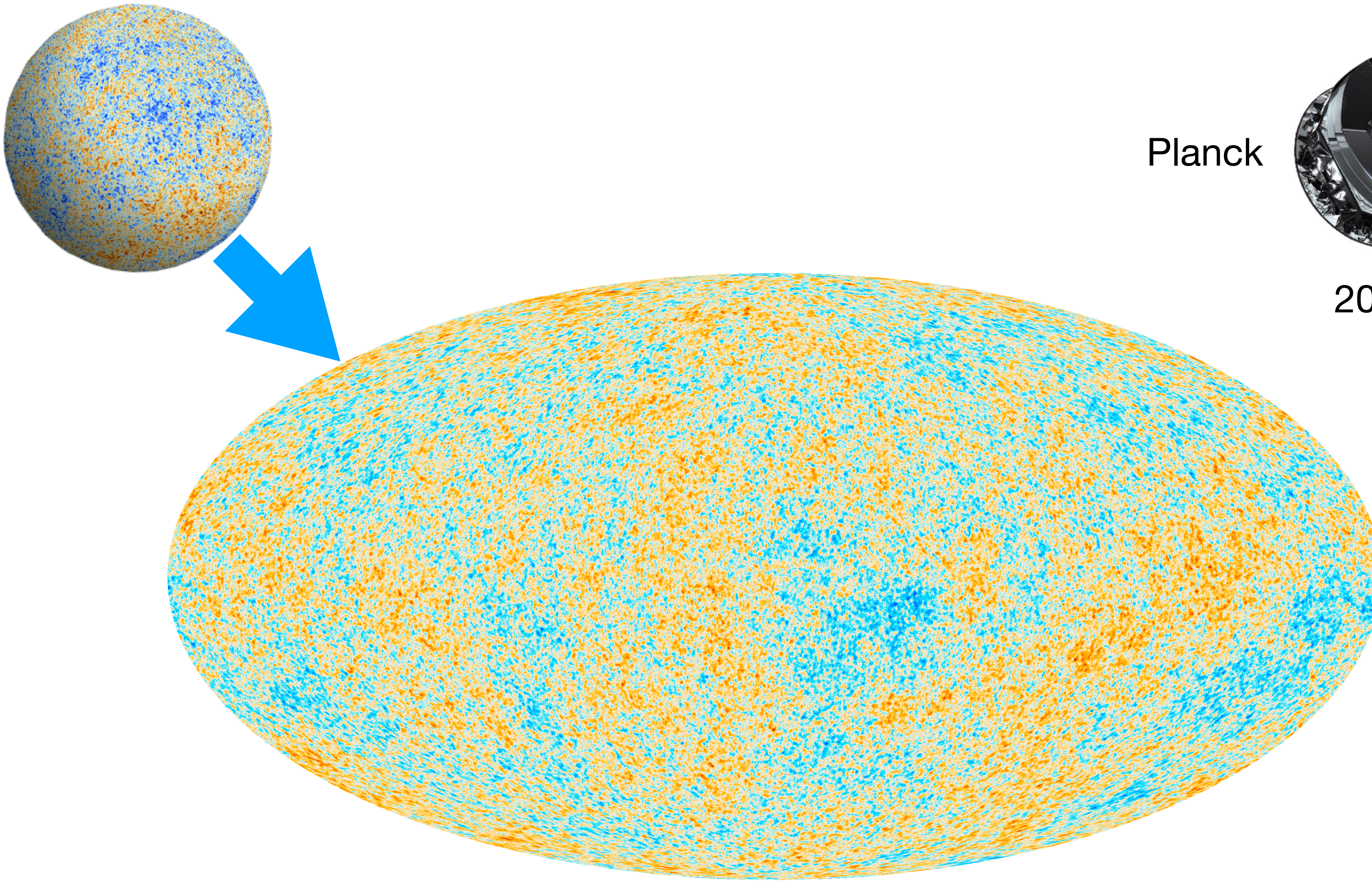
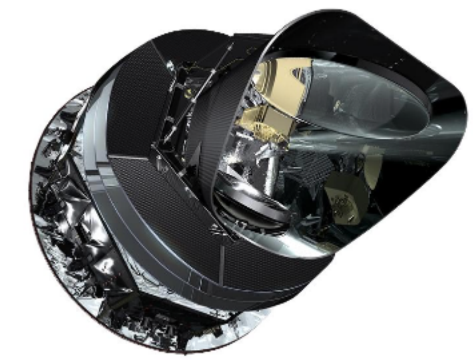
Anisotropy

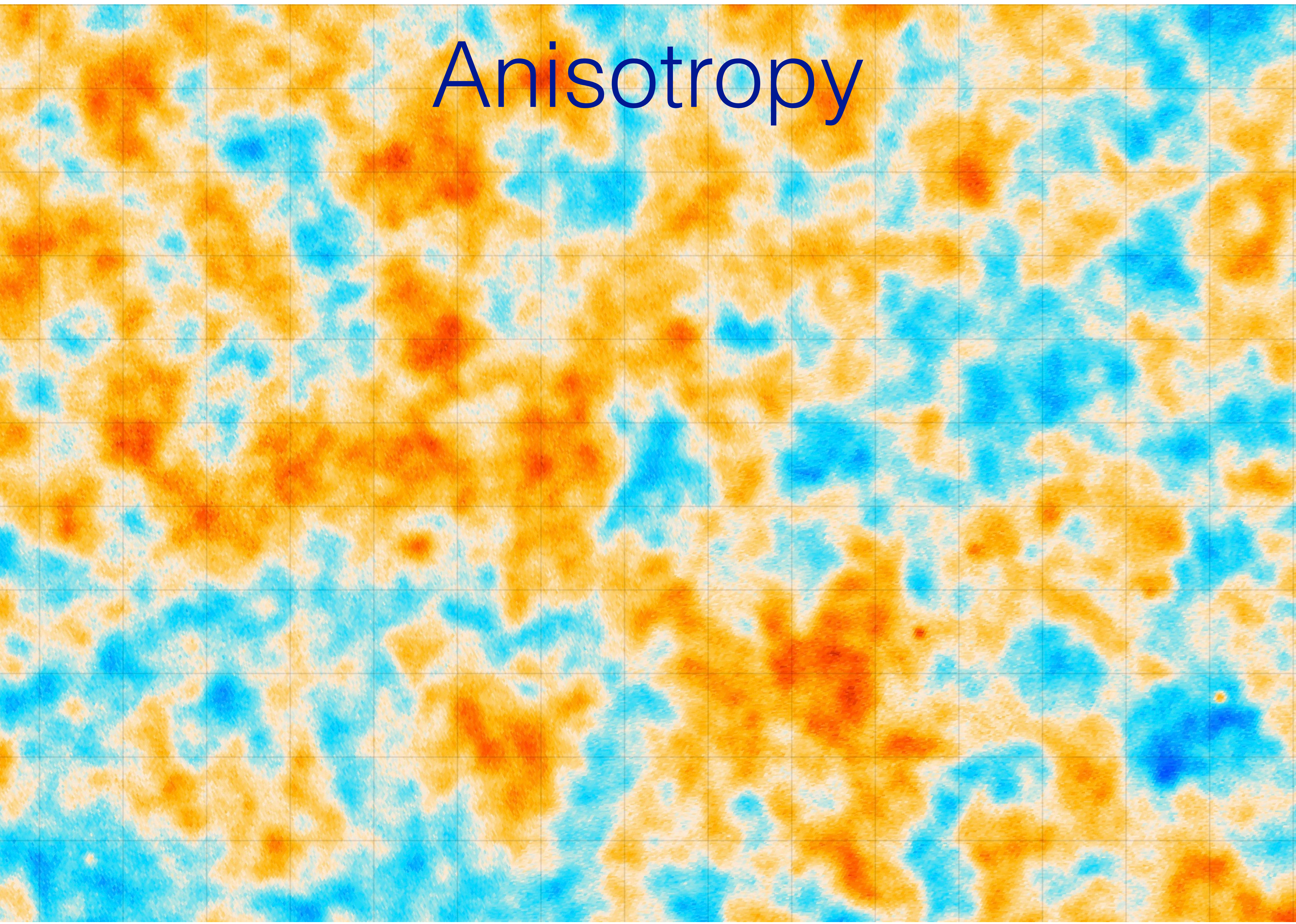


Planck



2013

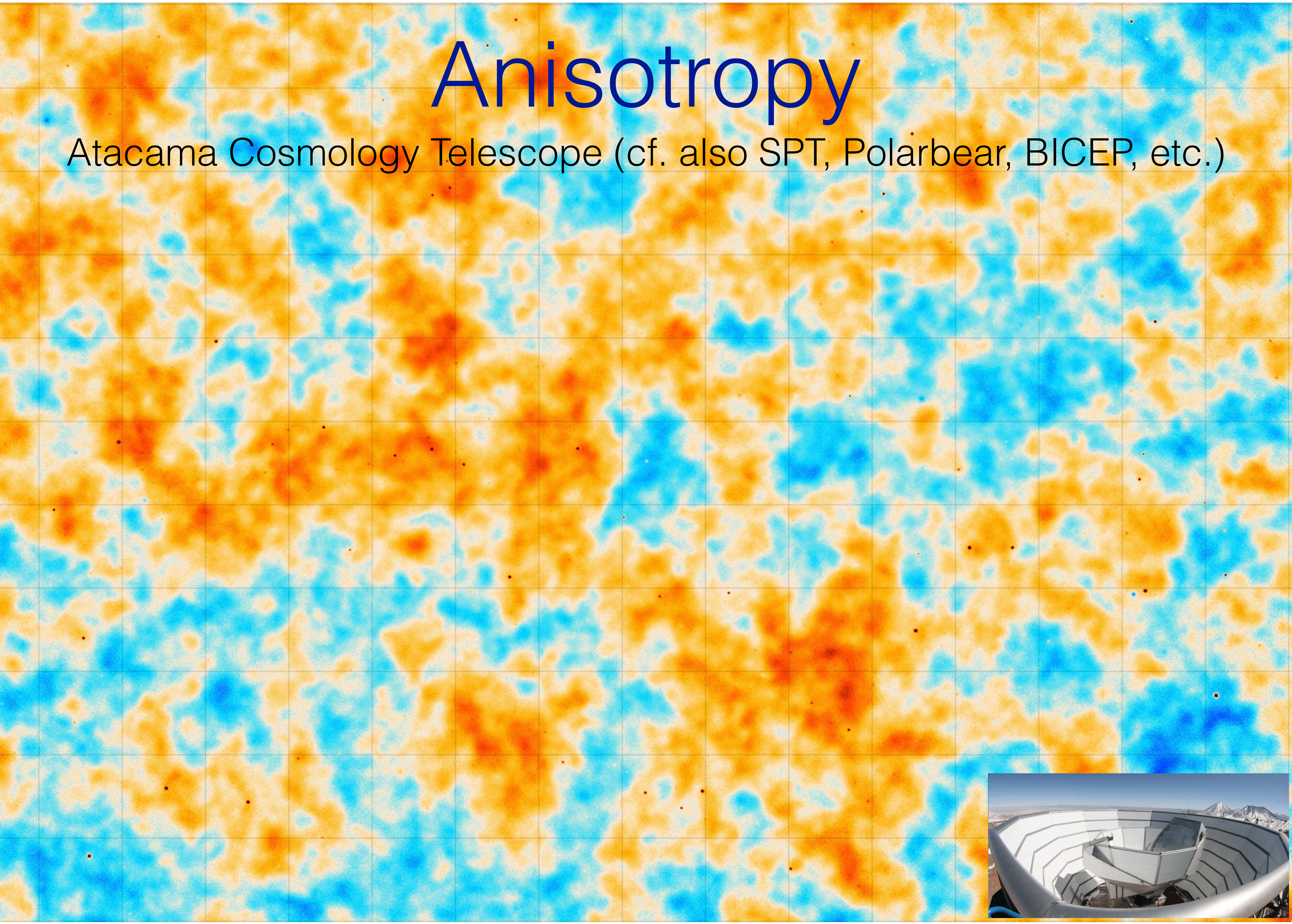
Anisotropy



Sky intensity at 2mm (150 GHz): Planck 30x22 deg^2 patch Naess et al. (2020)

Anisotropy

Atacama Cosmology Telescope (cf. also SPT, Polarbear, BICEP, etc.)



Sky intensity at 2mm (150 GHz): ACT+Planck 30x22 deg^2 patch Naess et al. (2020)

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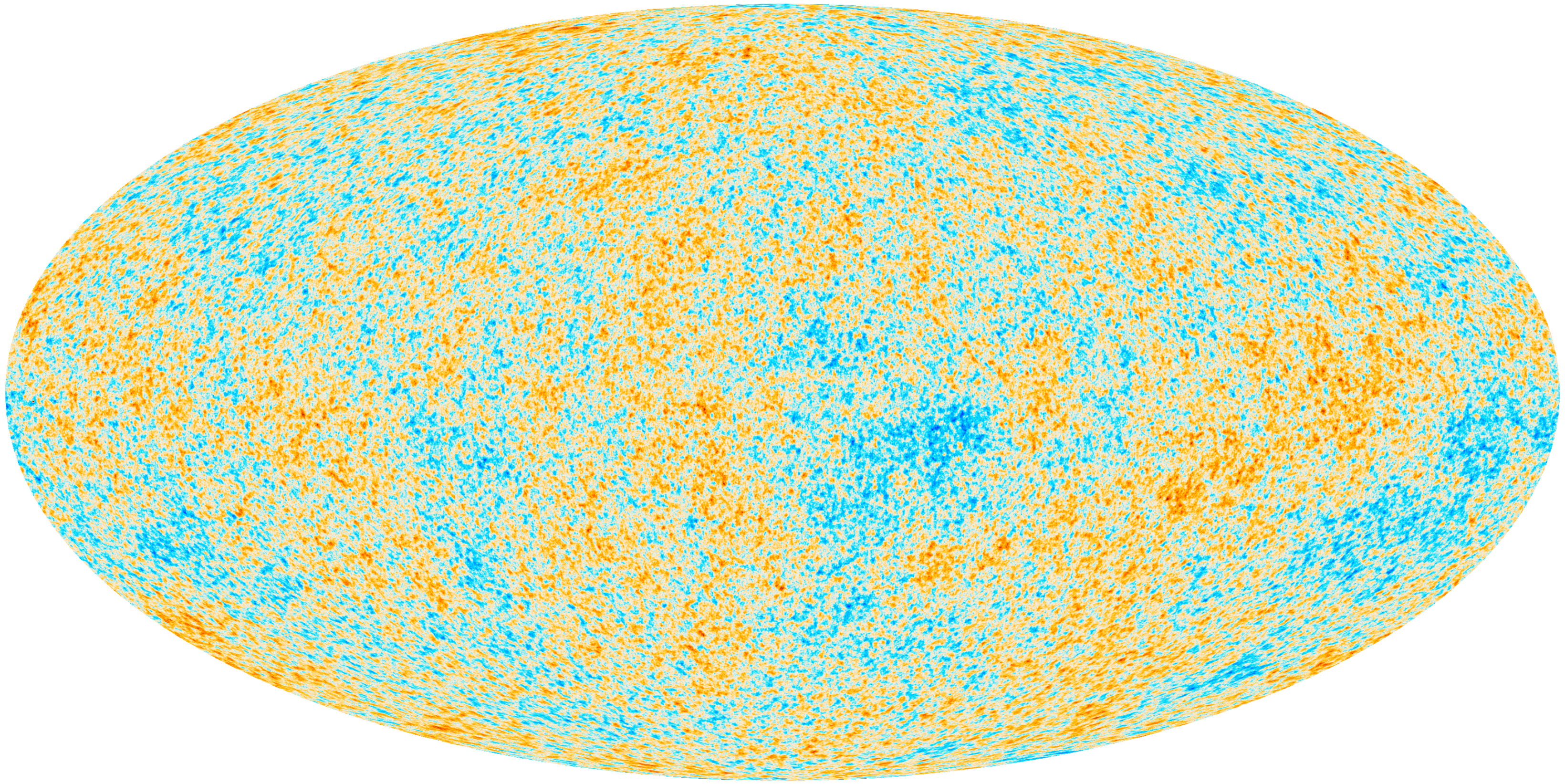
Information



Our theories do not predict the specific realizations of cosmological fields, only their statistical properties, e.g., as defined by correlation functions.

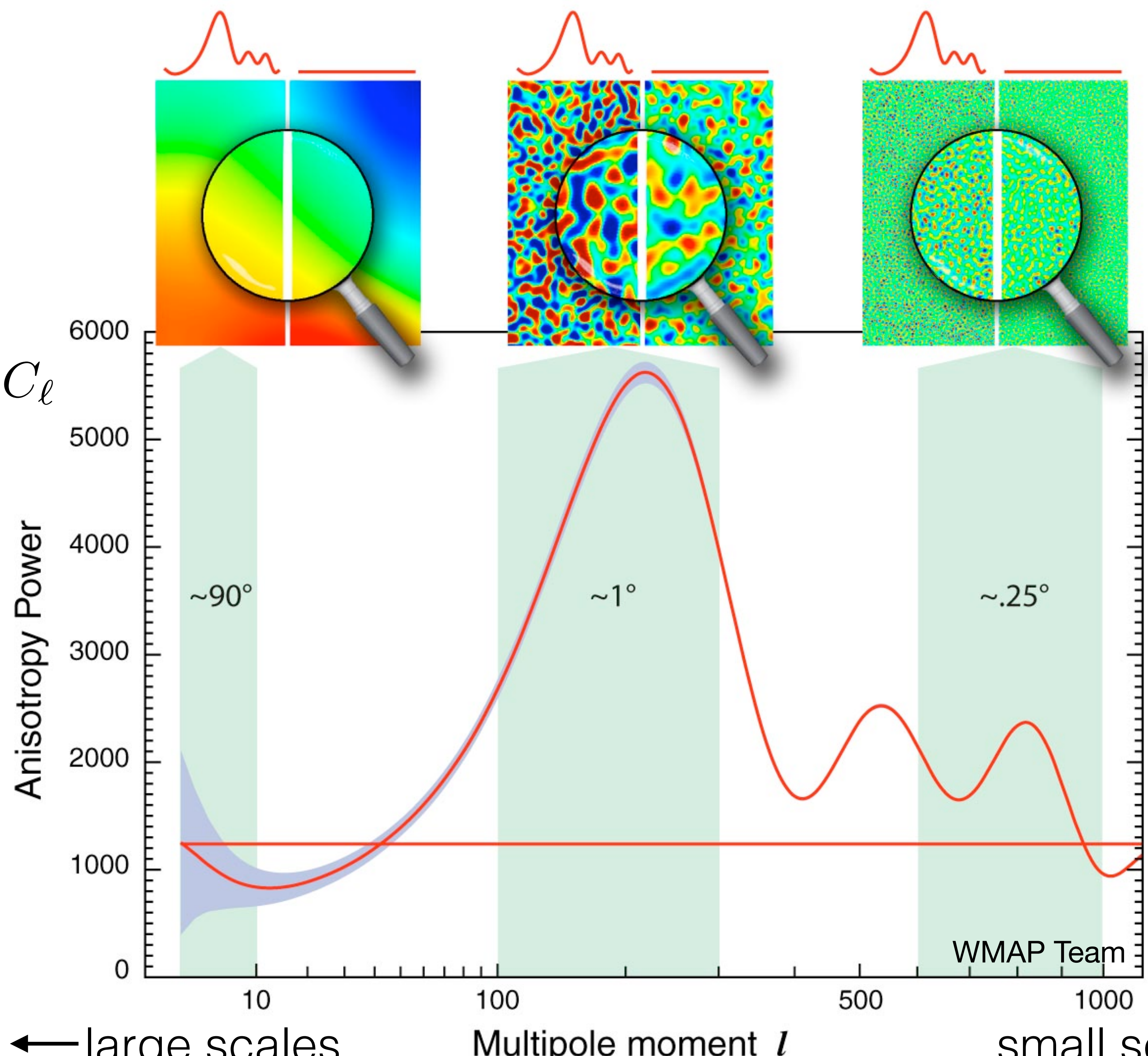
The CMB is extraordinarily close to a *Gaussian random field*, for which all of the underlying physical information is contained in the *angular power spectrum* (2-point function).

Power Spectrum Intuition

We infer cosmological parameters from CMB maps via the angular power spectra of fluctuations in temperature and polarization

$$D_\ell \equiv \frac{\ell(\ell+1)}{2\pi} C_\ell$$

$$[\mu\mathrm{K}^2]$$



← large scales

small scales →

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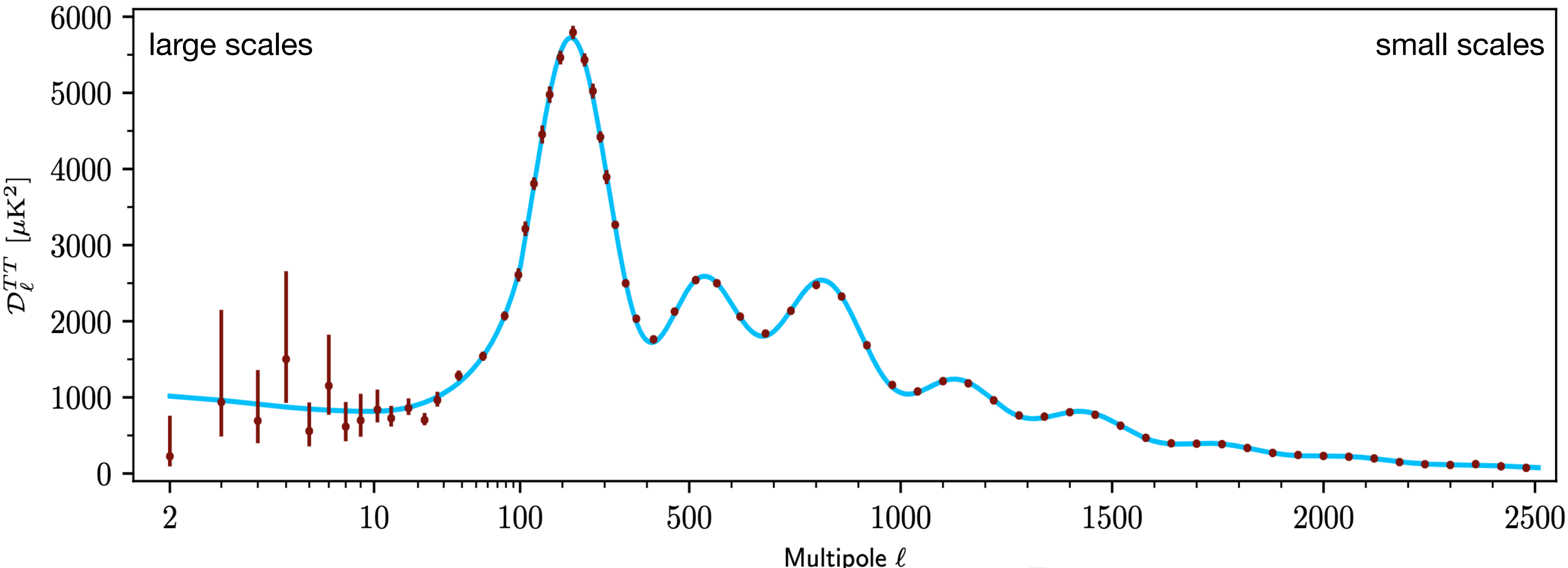
Planck 2018



$$\ell \sim \frac{\pi}{\theta}$$

Spectacular agreement with theoretical prediction (blue). Where does this prediction come from?

Planck Collaboration (2018)

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CMB Anisotropy Physics

- 1) CMB photon propagation: connecting the anisotropies we see to the conditions at the surface of last scattering
- 2) Initial conditions for the perturbations
- 3) The transfer function: acoustic physics that relates the ICs to the observed temperature perturbations

$$\mathcal{R}(\mathbf{k}, 0) \rightarrow (\delta_r, \Phi, \mathbf{v})_{\eta *} \rightarrow \delta T(\hat{\mathbf{n}})$$

initial curvature perturbations

physical quantities at last scattering

observed temperature fluctuations

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CMB Anisotropy Physics

- Important point: recombination/decoupling are determined by the *local* plasma temperature T at each point in spacetime. The temperature at which these processes occur is set by the physics described in Lecture 1, which is universal, i.e., recombination/decoupling occur at the same temperature everywhere.

- So why do we observe fluctuations in the CMB temperature across the sky?

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CMB Anisotropy Physics

- Important point: recombination/decoupling are determined by the *local* plasma temperature T at each point in spacetime. The temperature at which these processes occur is set by the physics described in Lecture 1, which is universal, i.e., recombination/decoupling occur at the same temperature everywhere.

- So why do we observe fluctuations in the CMB temperature across the sky?

Different points reach this T at slightly different times (scale factors)!

Hence there are slightly different amounts of cosmic expansion between us and each point on the last-scattering surface.

The Inhomogeneous Universe

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- Conformal Newtonian-gauge metric: (assuming vanishing anisotropic stress)

$$ds^2 = a^2(\eta)(-(1+2\Phi)d\eta^2 + (1-2\Phi)d\vec{x}^2)$$

usual Newtonian potential in weak-field limit

- As in the homogeneous case, we want to use the geodesic equation to compute evolution of photon energy along trajectory in this spacetime

$$\left(\frac{\Delta T}{\bar{T}}\right)_0 = \Phi_\star + \frac{\delta_r^\star}{4} - (\hat{\mathbf{n}} \cdot \vec{\mathbf{v}}_b)_\star + 2\int_{\eta_\star}^{\eta_0} d\eta\,(\partial_\eta \Phi)$$

Sachs-Wolfe   Doppler   Integrated Sachs-Wolfe

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initial curvature perturbations

physical quantities at last scattering

✓

observed temperature fluctuations

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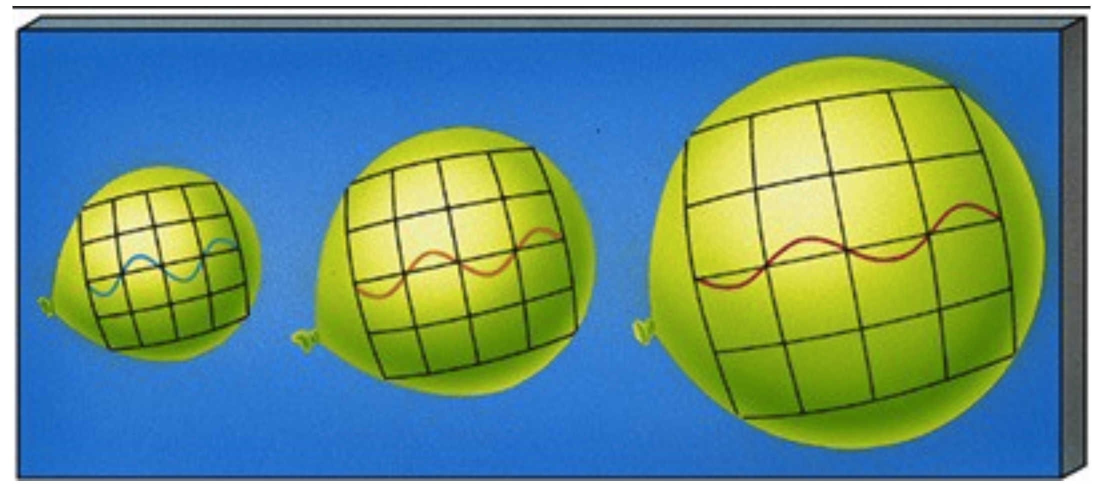
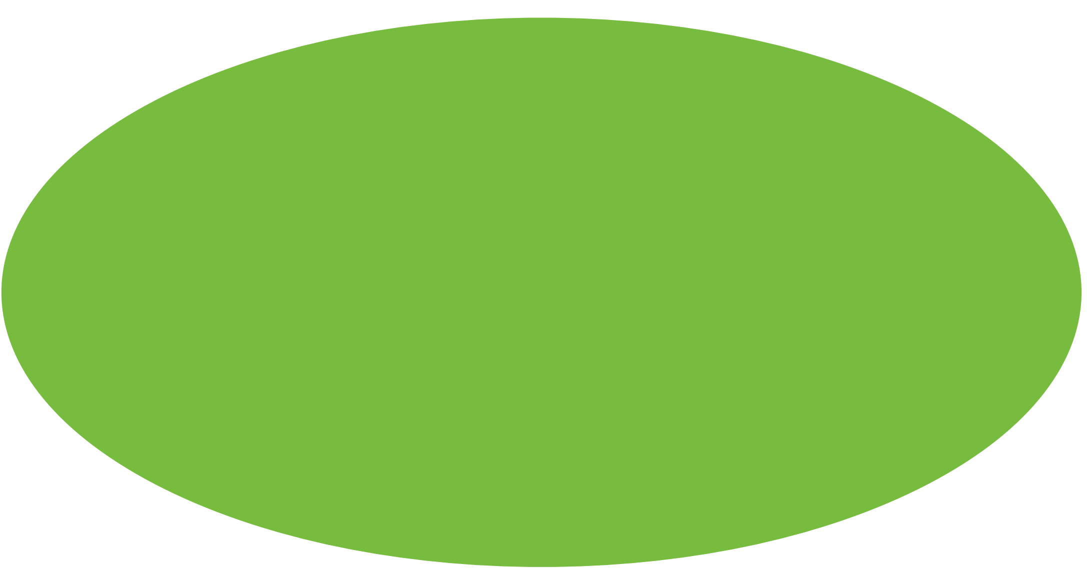
Initial Conditions: Inflation

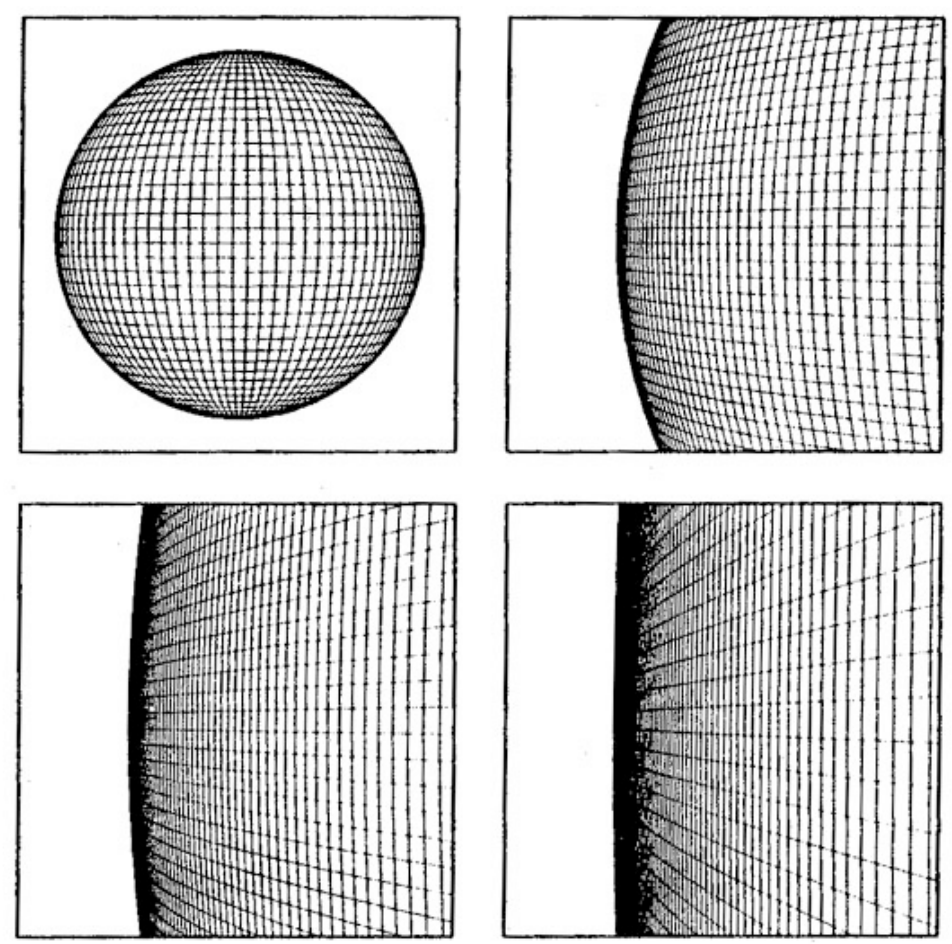
very early (~10^{-42} - 10^{-12} sec) in the universe: exponential, accelerating expansion



smaller than a proton → larger than a grapefruit

exponential expansion smooths and homogenizes the universe





Guth

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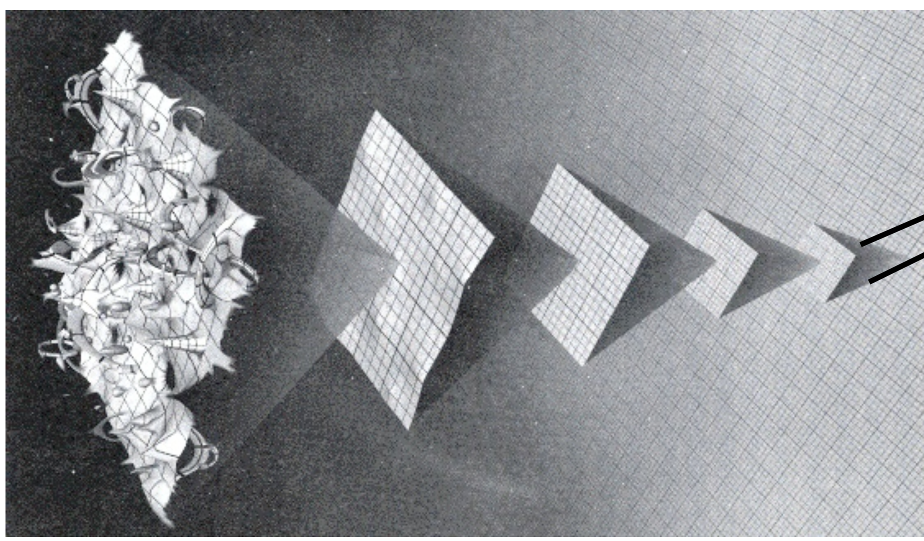
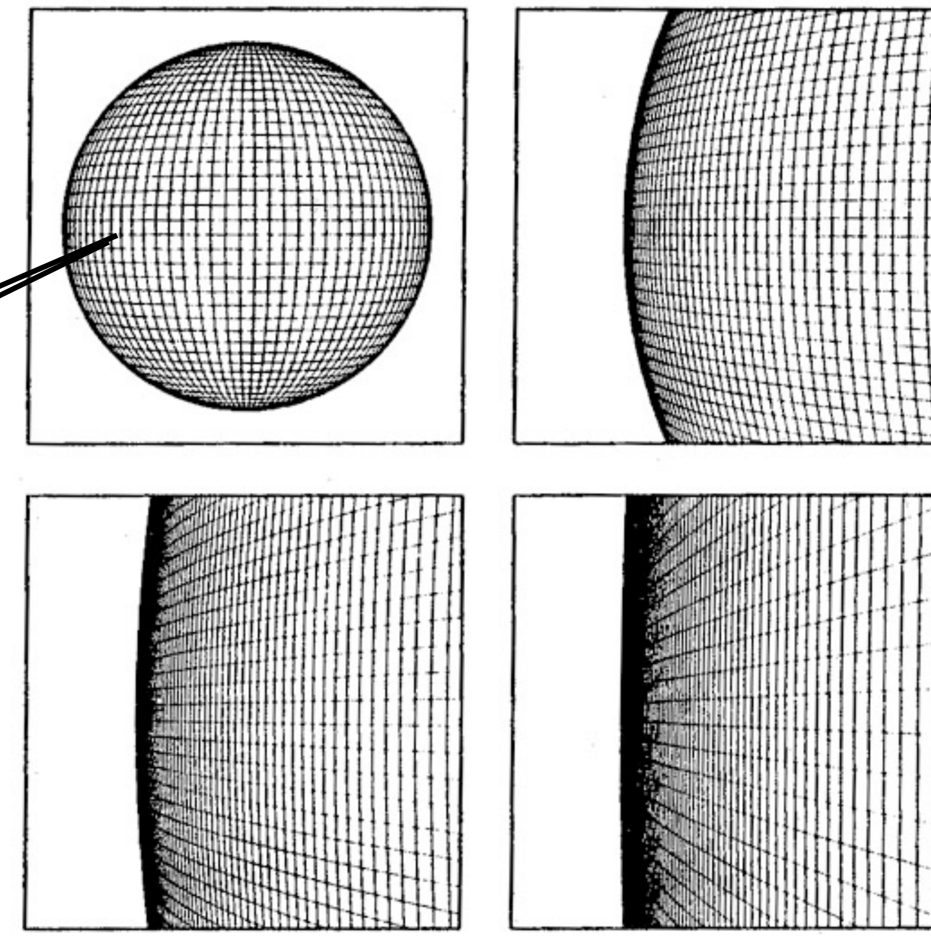
Inflation

but inflation is a quantum mechanical process (very small scales) ⟷ Heisenberg uncertainty principle ⟷ quantum fluctuations





Guth

thus, some patches of the universe stop inflating earlier than others ⟶ more post-inflationary dilution, and thus underdensity in late-time density field