

Observing and Interpreting the Most Ancient Light in the Universe

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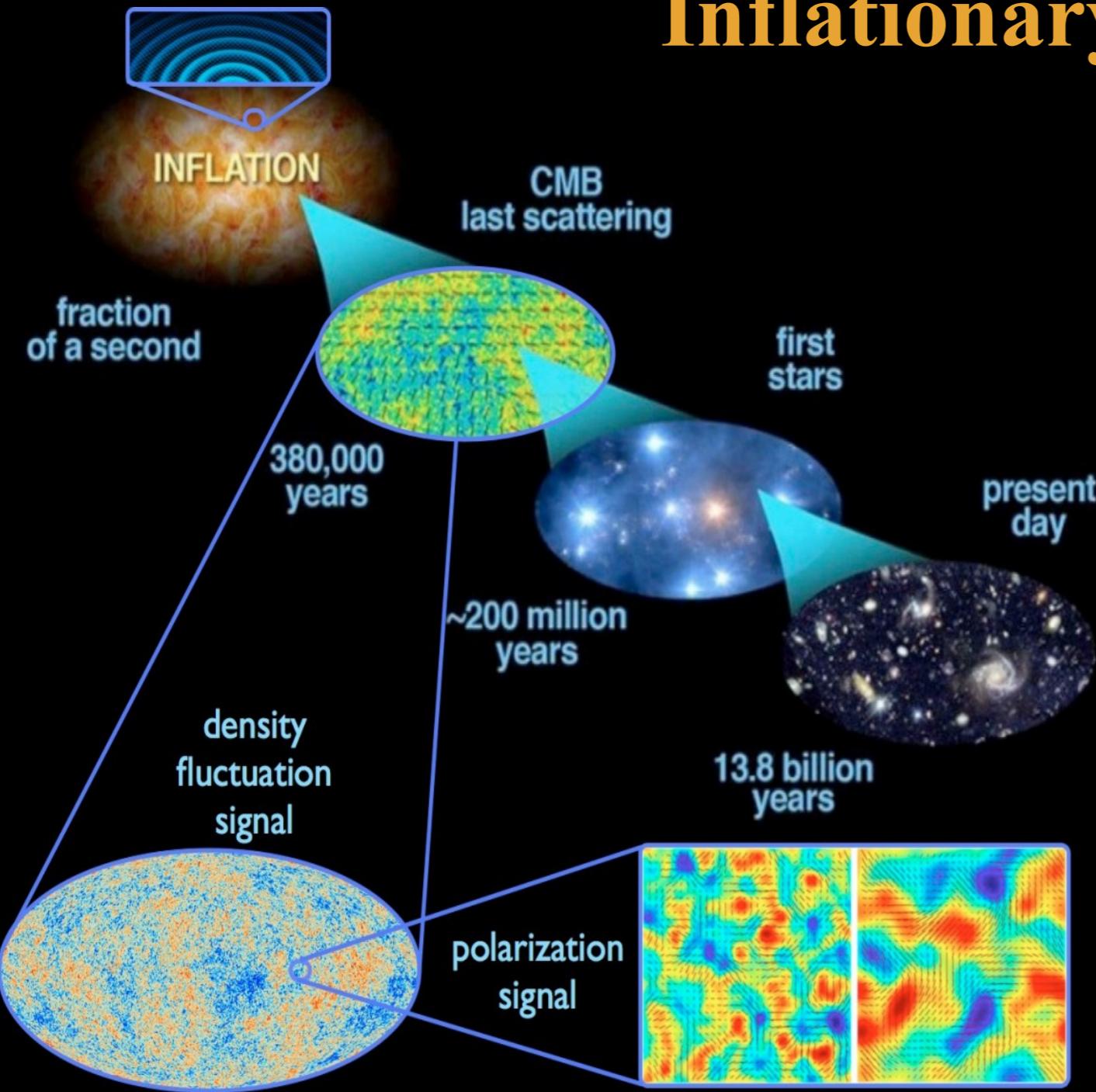
Mini School on Gravitation and Cosmology
IIT-Madras, 25 Nov, 2022

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Concordance cosmology

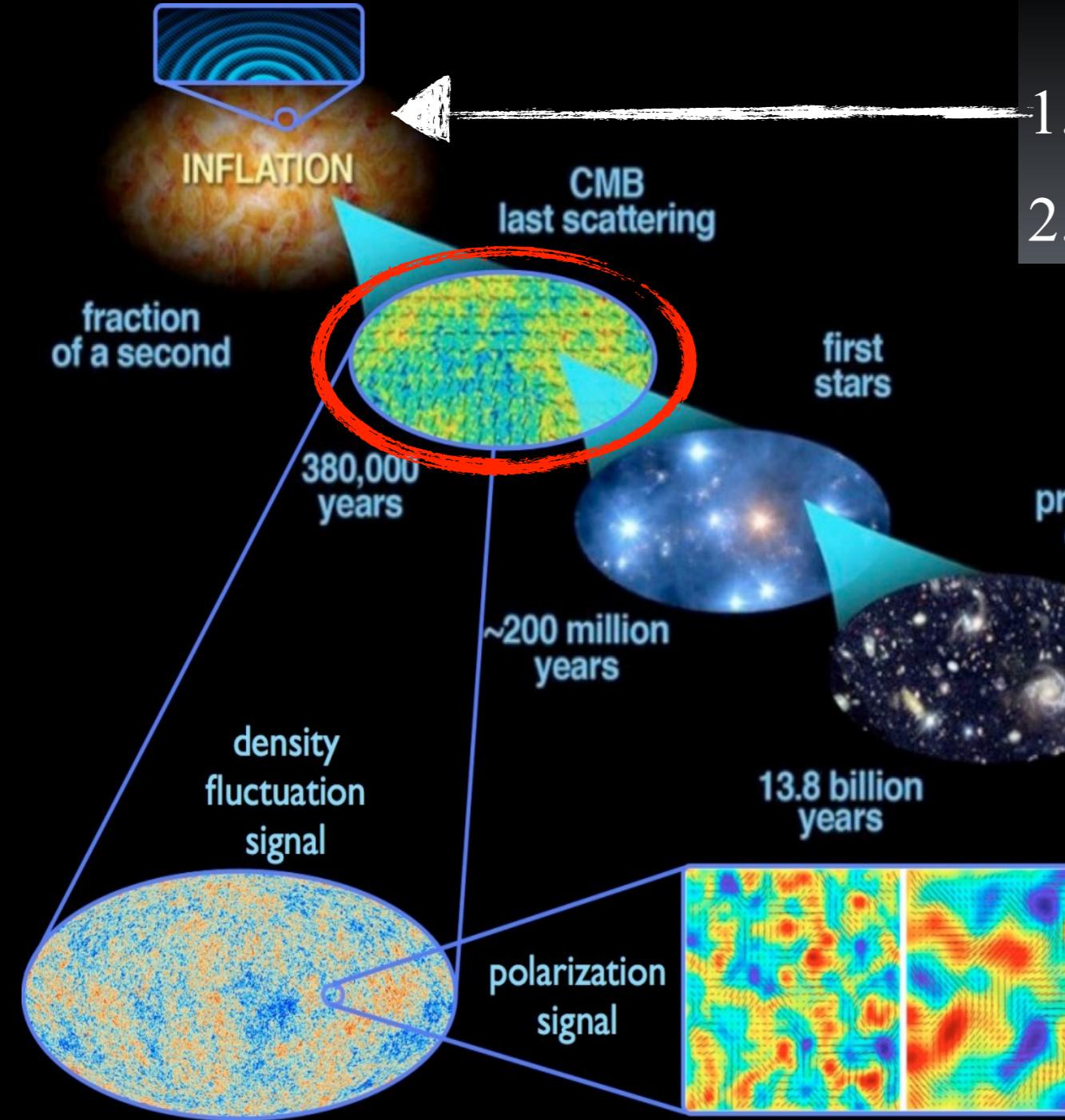
Inflationary Λ - Cold Dark Matter



- Inflation + hot Big-Bang**
- Hierarchical growth**
- Gravity: GR**
- Flat universe**

Image: CTC, Cambridge

Concordance cosmology



Cosmic Microwave Background:

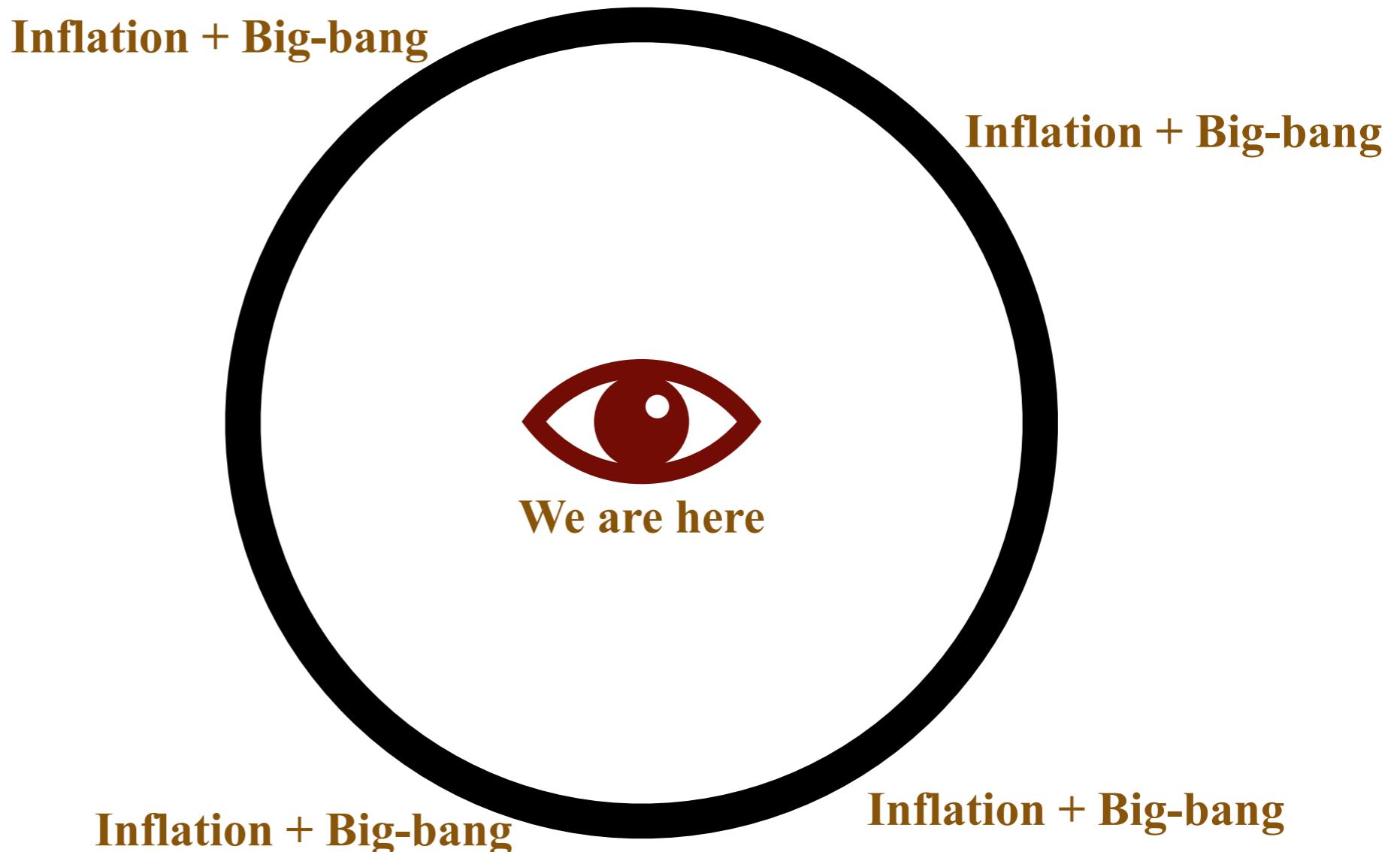
1. Study the early Universe.
2. Study the evolution of the Universe.

Evidence for the Big-Bang

Hubble's discovery of the expansion of the Universe.

Existence of the Cosmic Microwave Background (CMB).

Production of light elements during Big Bang nucleosynthesis.

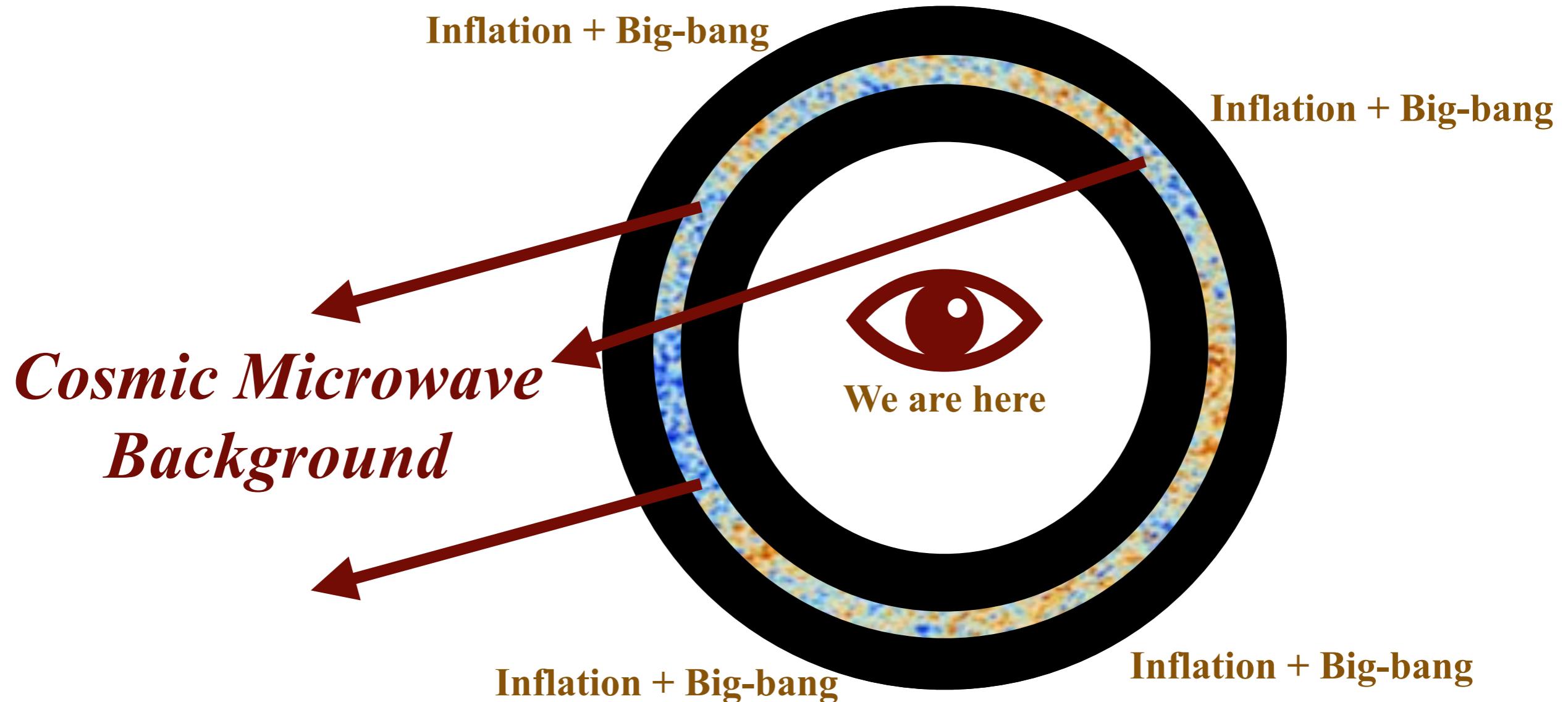


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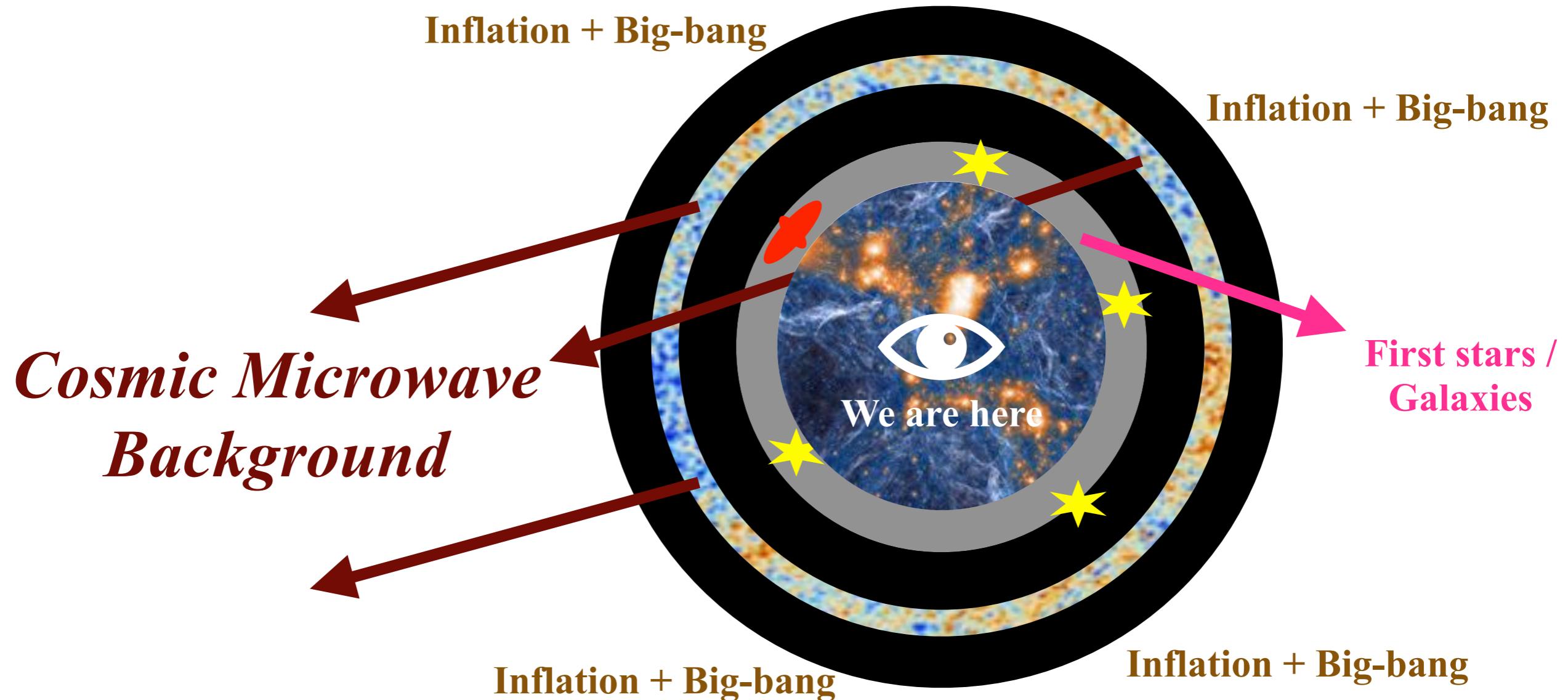


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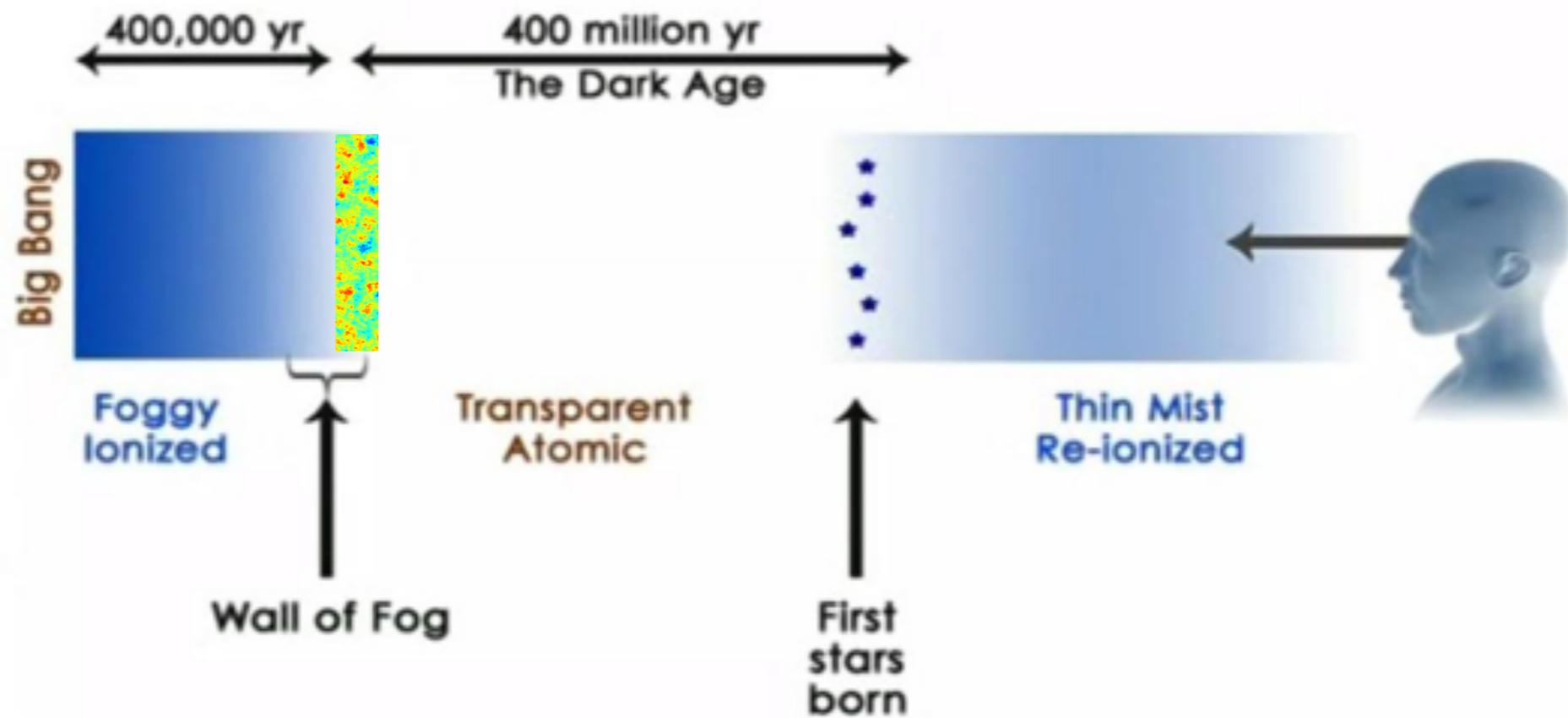
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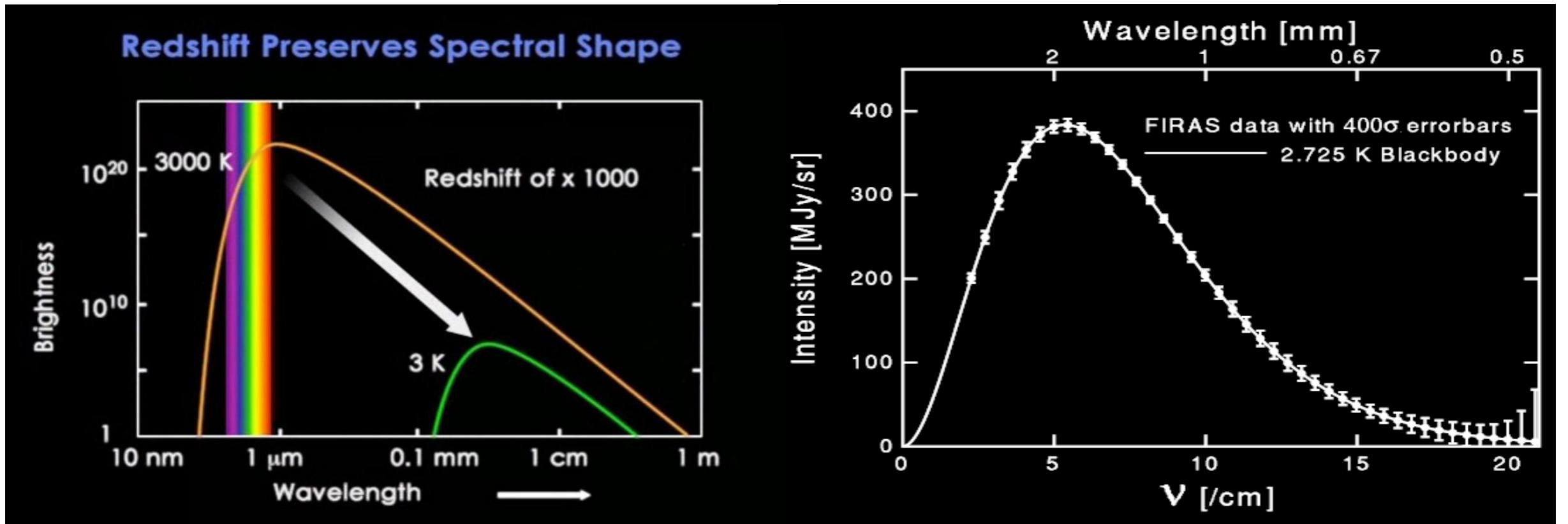


Cosmic Microwave Background



- CMB in the remnant radiation from the Big-Bang.
- Predicted by George Gamow in 1946.
- Accidentally discovered by Arno Penzias and Robert Wilson in 1964.
- Extremely homogenous and isotropic: Same in all locations and all directions.
- Anisotropies are 1 part in a million.

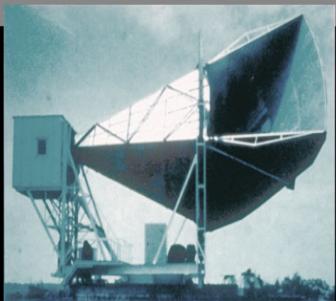
Cosmic Microwave Background



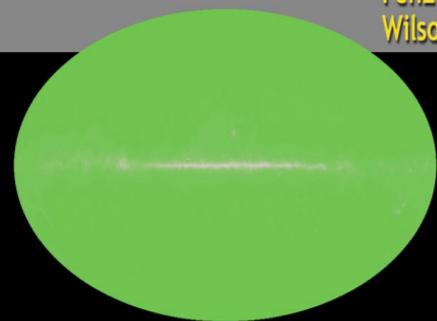
- Black-body peaking around $T_{CMB} = 2.7$ Kelvin.
- Partially polarised (~10%) due to Thomson scattering.
- Small fraction of the CMB photons are affected by intervening structures in our universe — secondary anisotropies in the CMB — .
 - *CMB-lensing, Thermal and Kinematic Sunyaev-Zeldovich effects, ++.*

CMB Temperature

1965



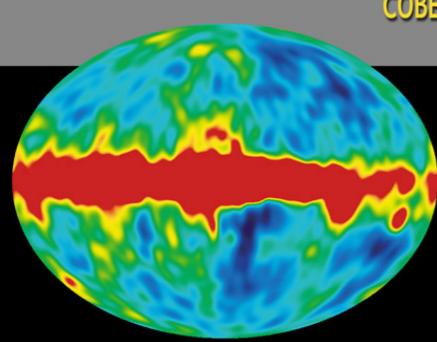
Penzias and Wilson



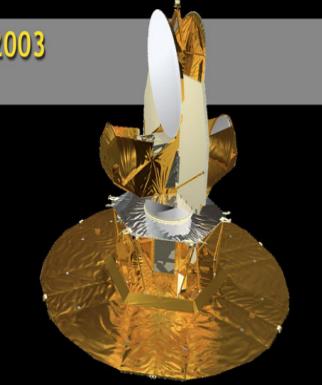
1992



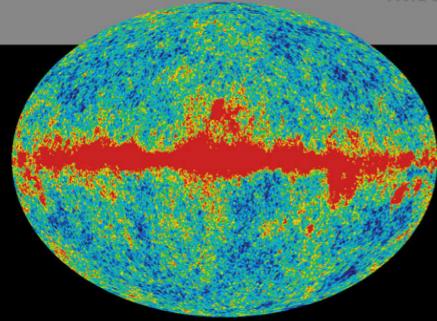
COBE



2003

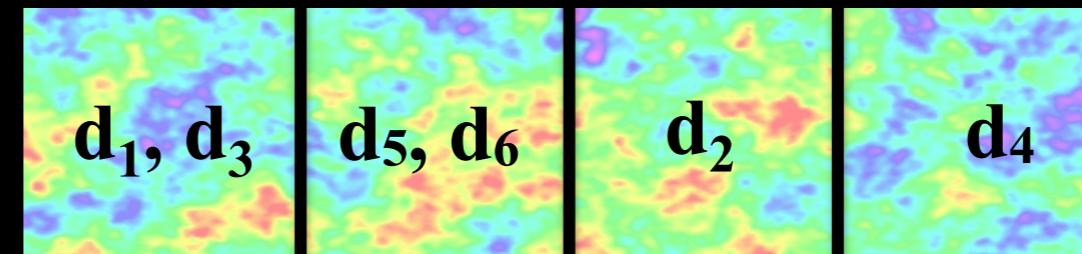


WMAP



Measure the sky temperature in different locations
and subtract the mean to get the map of the “tiny”
CMB anisotropies.

1 part in a million



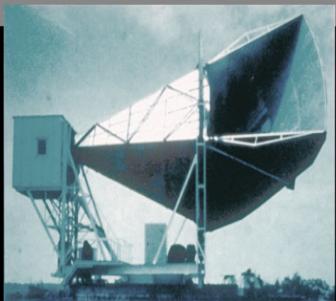
δ =	1	0	0	0
	0	0	1	0
	1	0	0	0
	0	0	0	1
	0	1	0	0
	0	1	0	0

$$T_p = \sum_{i=1}^{N_{\text{det}}} \frac{d_i}{\sigma_i^2} \delta_{pi}$$

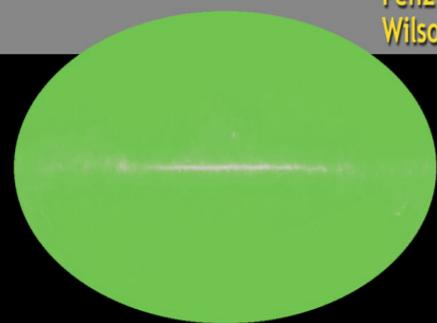
If the detector weights σ_i are removed, the above
equation becomes a simple average.

CMB Temperature

1965



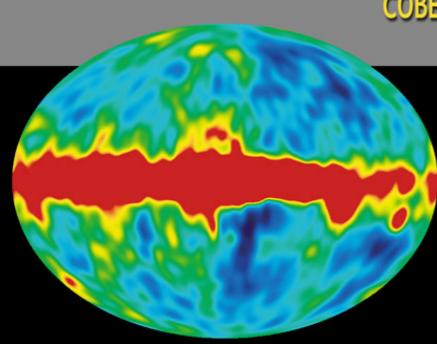
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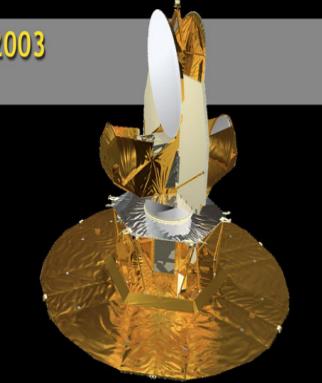
1992



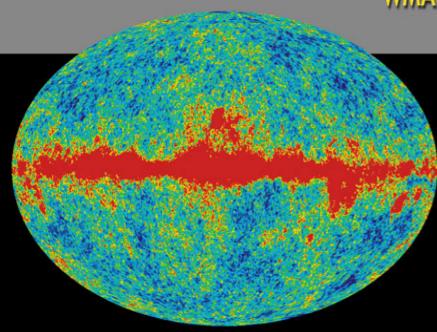
COBE



2003



WMAP

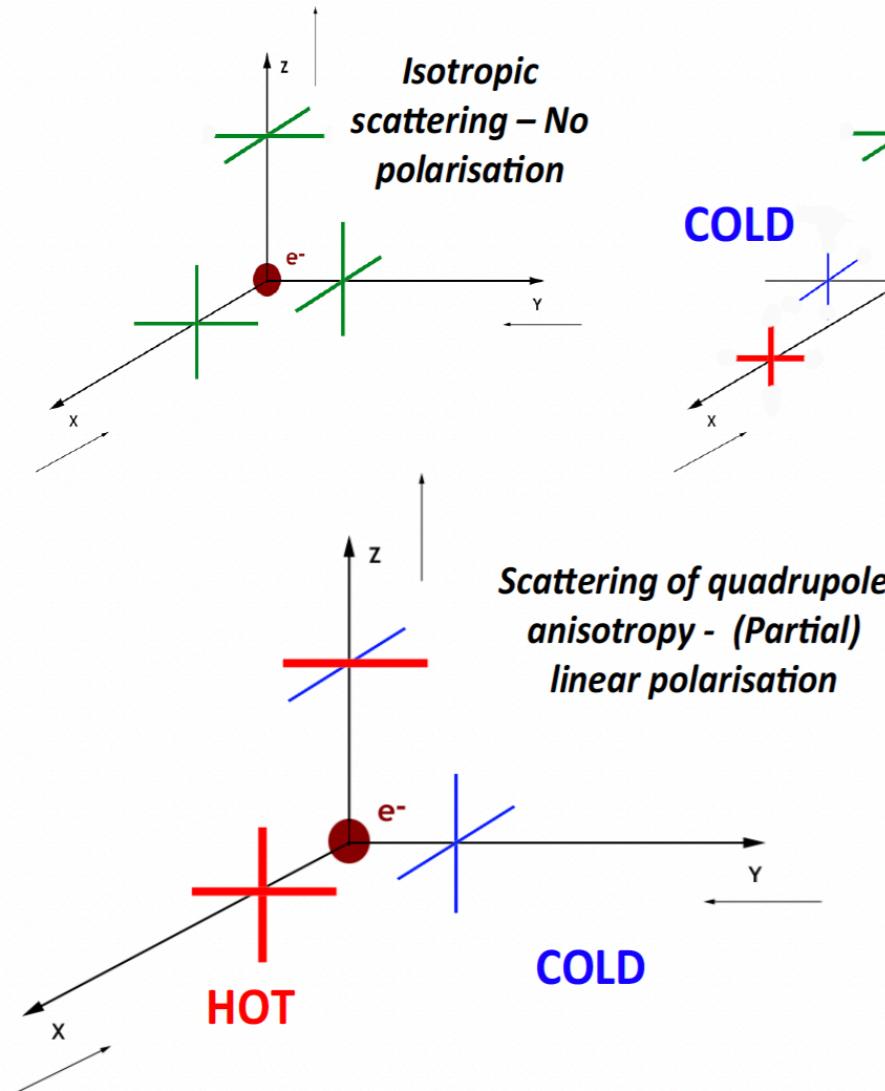


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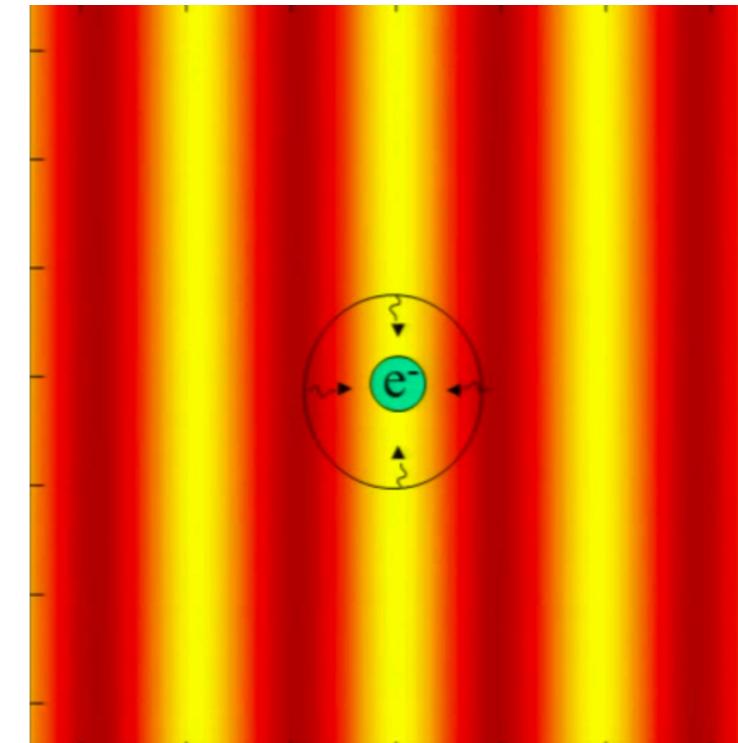
- + **Planck**
 - + **Atacama Cosmology Telescope (ACT @ Chile)**
 - + **BICEP (South Pole)**
 - + **South Pole Telescope (SPT @ South Pole)**
 - + **Simons Observatory (Chile)**
 - + **CMB-S4 (Chile + South Pole)**
- +++

CMB Polarisation

Life of an electron during recombination:



Cold



Hot

Quadrupole anisotropy required to produce (linear) polarisation.

We measure local Stokes Q/U parameters.

Anisotropies - What sourced them?

Primordial anisotropies: Scalar, Vector, and Tensor.

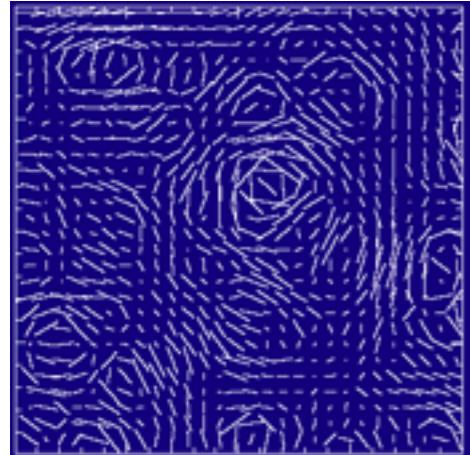
Scalar (density): Temperature and E-mode polarisation.

Tensor (gravity waves): Temperature and equal E/B polarisation.

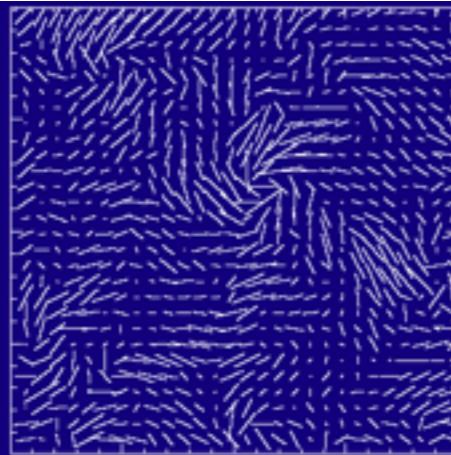
Leading theory: Cosmic Inflation - Accelerated expansion during the initial moments of the Universe.

B-modes = (Primordial) Gravity Waves = Inflation

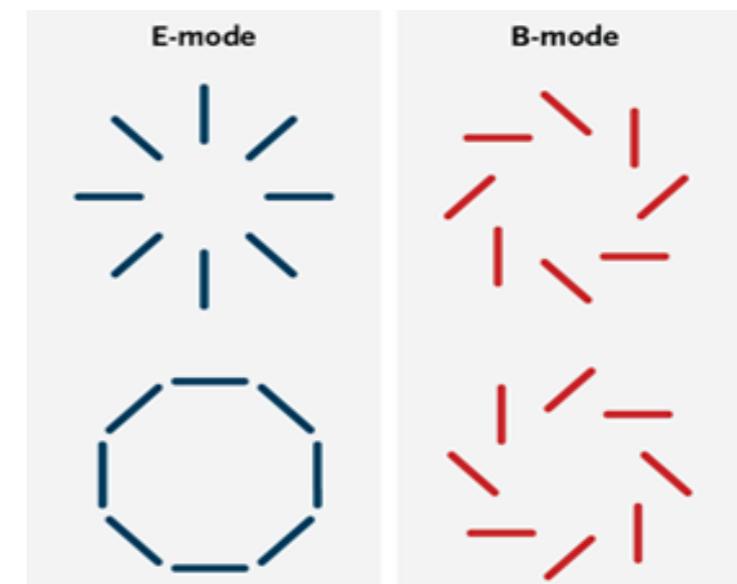
E modes



B modes

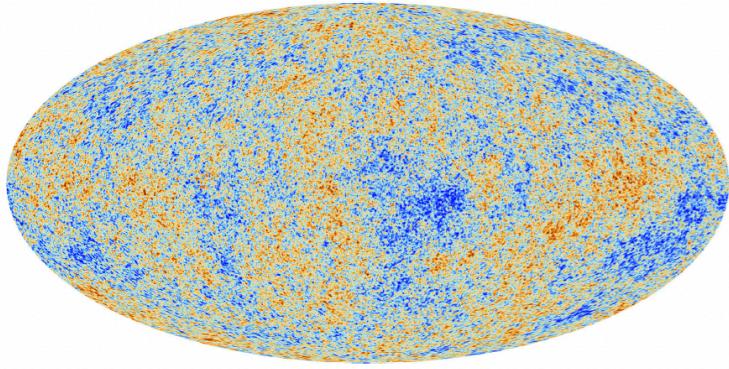


*Scalar and tensor / vector
perturbations*



CMB Power Spectrum

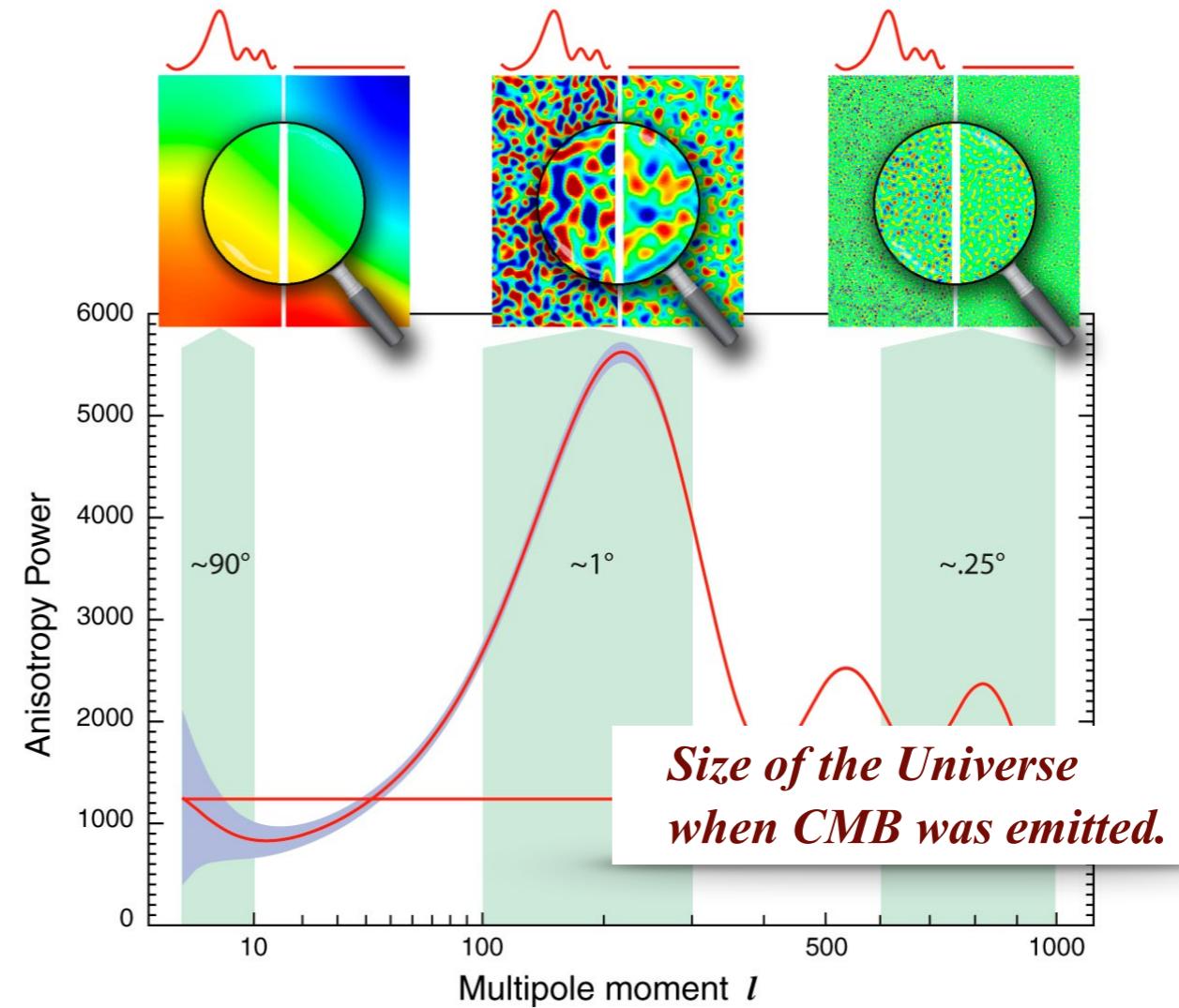
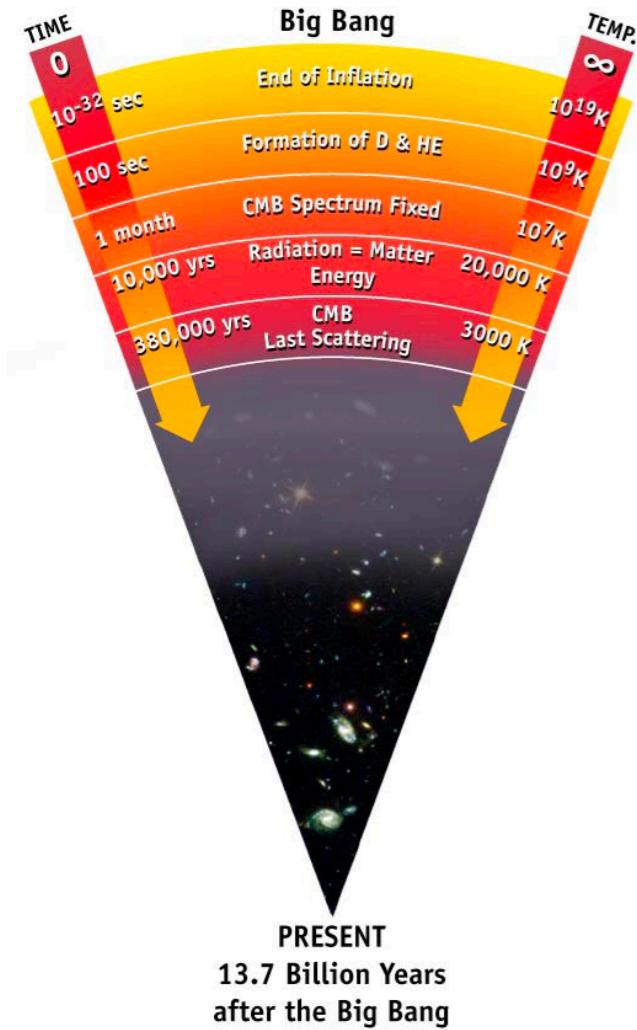
Spherical harmonic transformation (Equivalent to Fourier transforms on small-scales) of CMB maps.



$$\widetilde{C}_\ell^{XX} = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |\tilde{a}_{X,lm}|^2$$

$$\tilde{a}_{X,lm} = \int d\Omega X(\hat{n}) W(\hat{n}) Y_{lm}(\hat{n})$$

X = Temperature / Polarisation

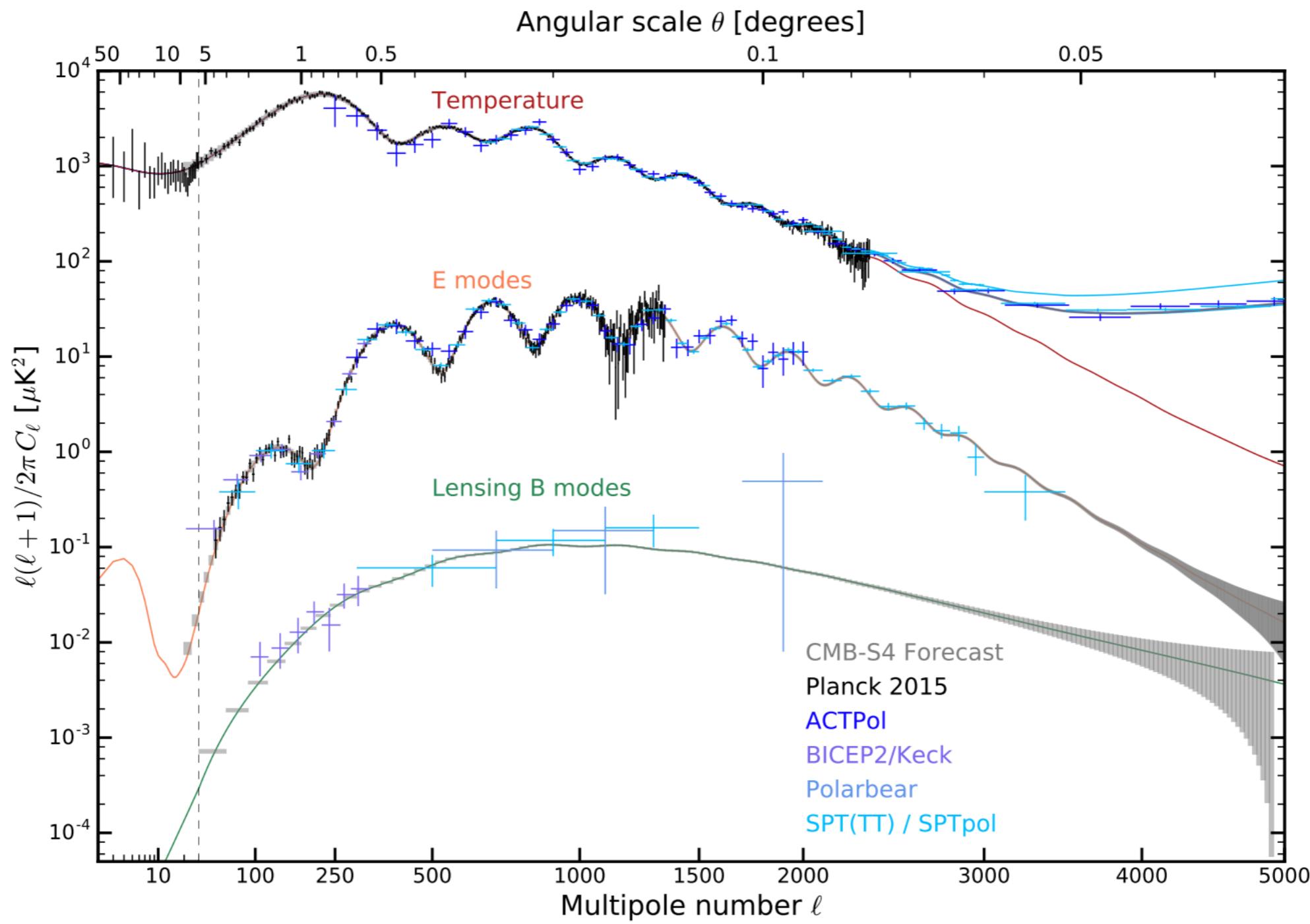


Large-scales

Small-scales

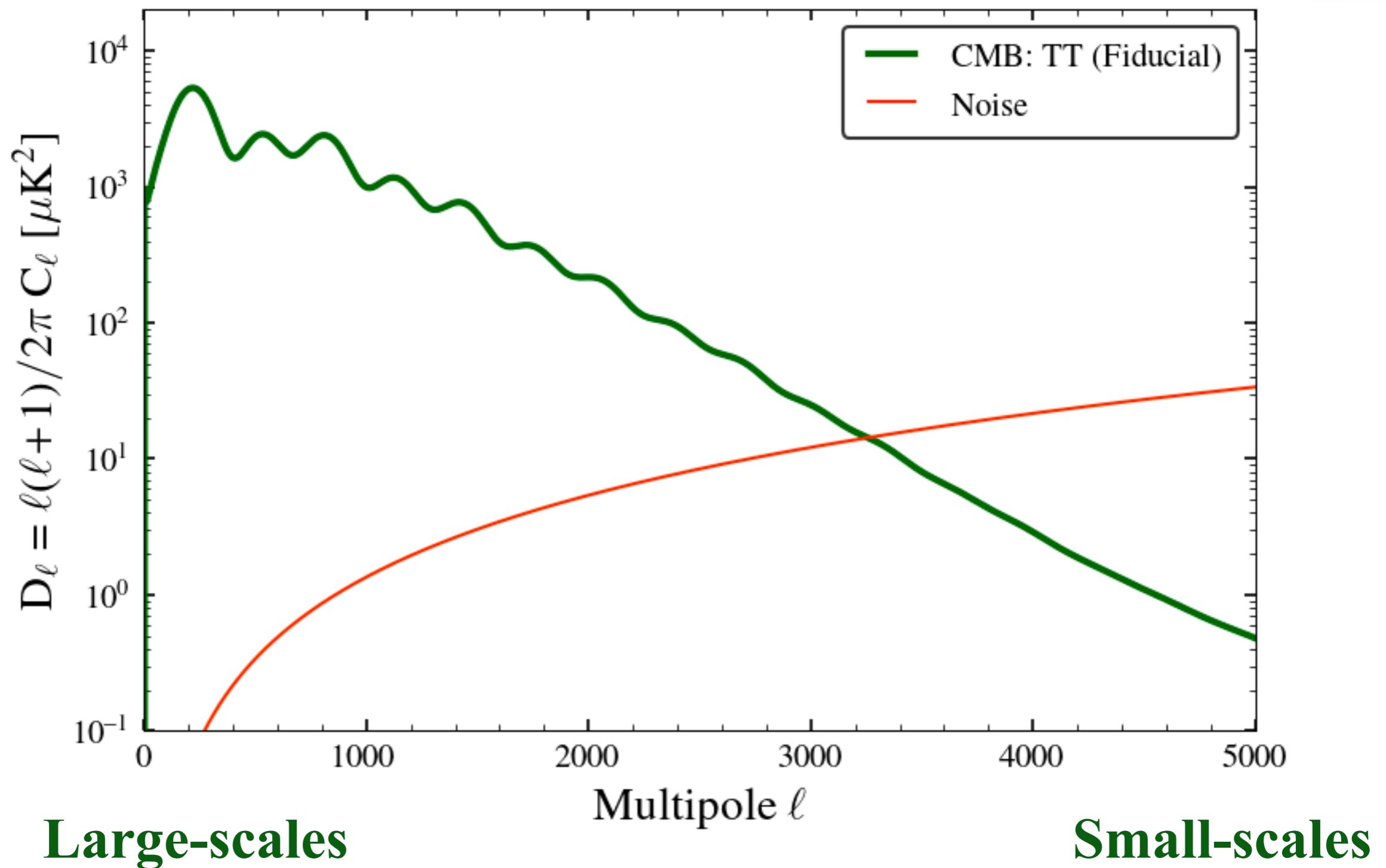
CMB Power Spectra - T/P

Power Spectra



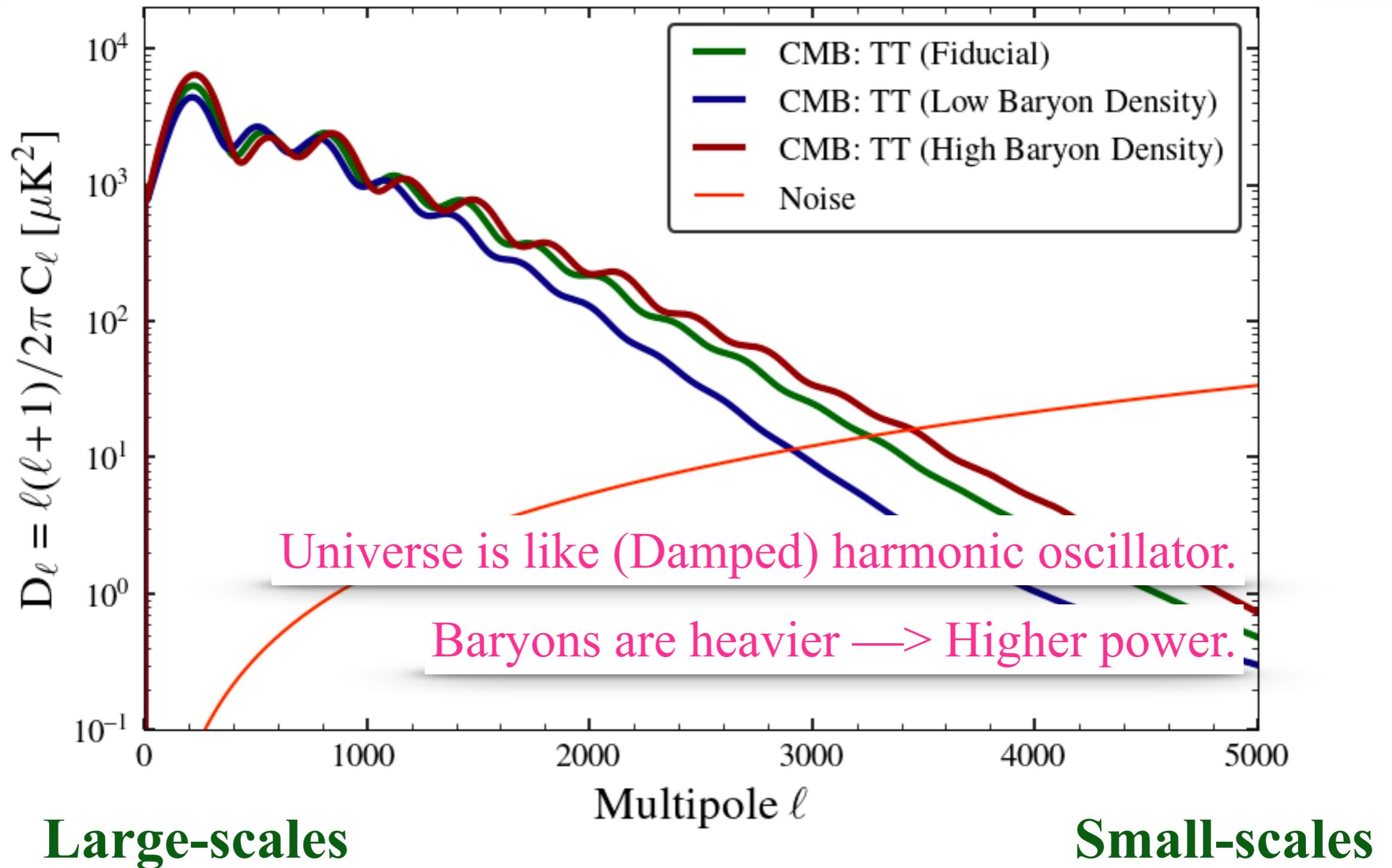
Cosmology from CMB spectra

Generated using **CAMB** (Code for Anisotropies in the Microwave Background) software.



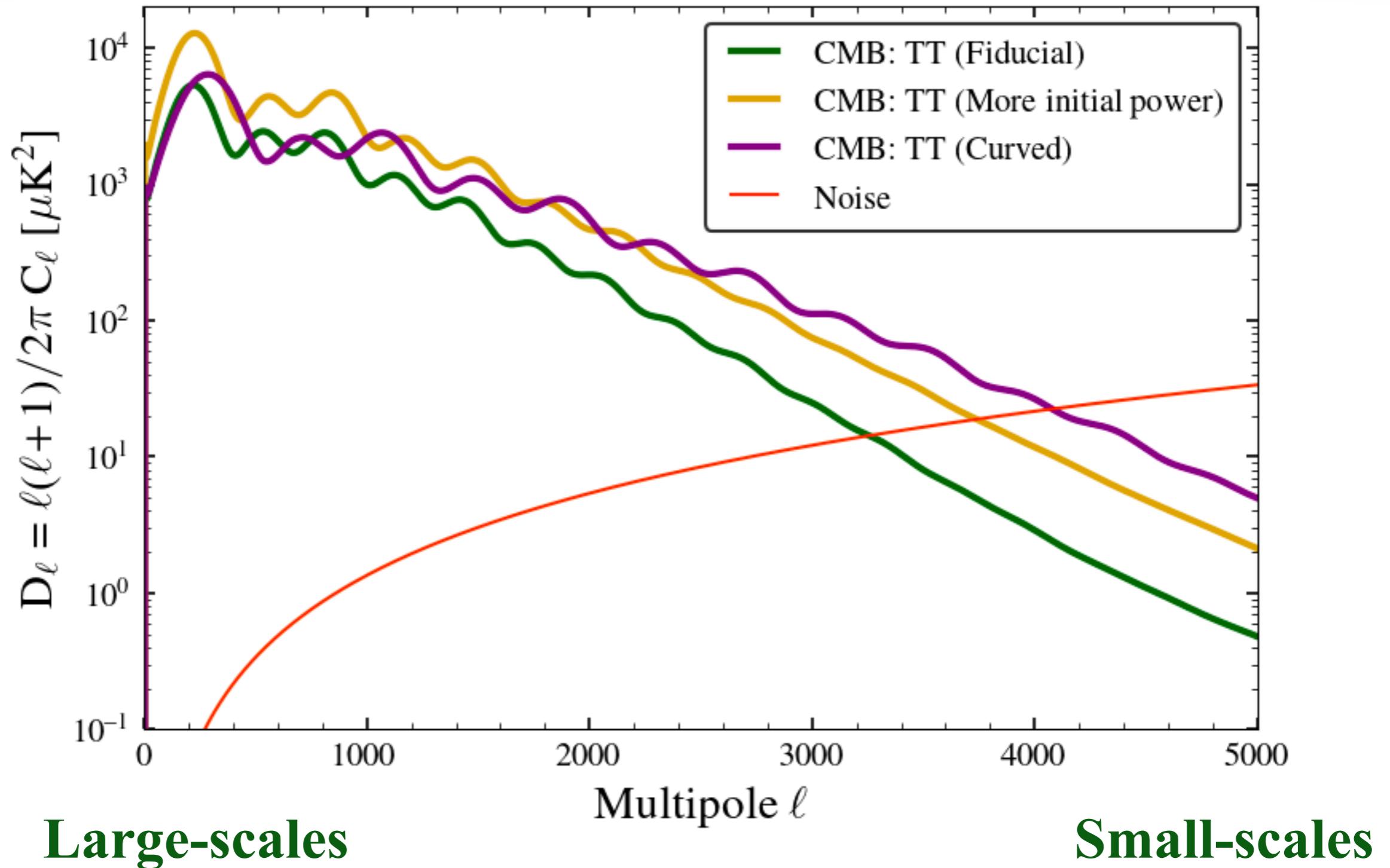
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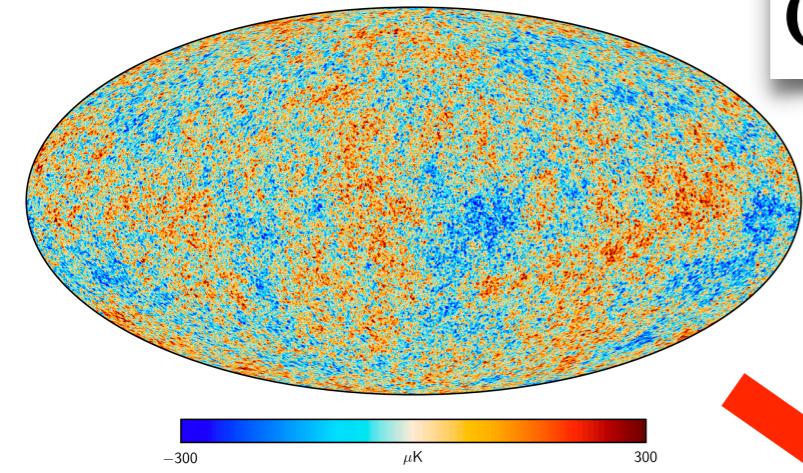


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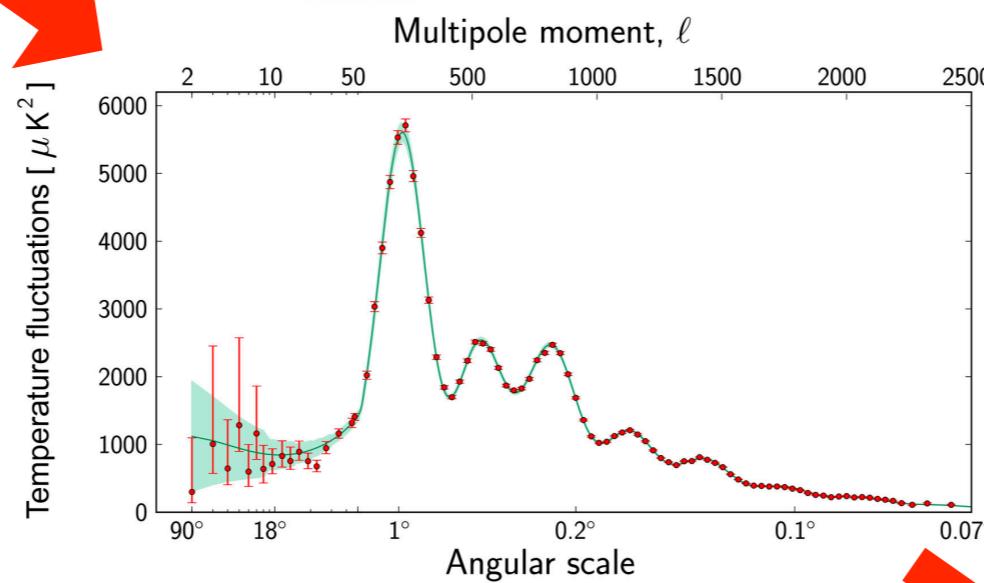


Cosmology from CMB spectra

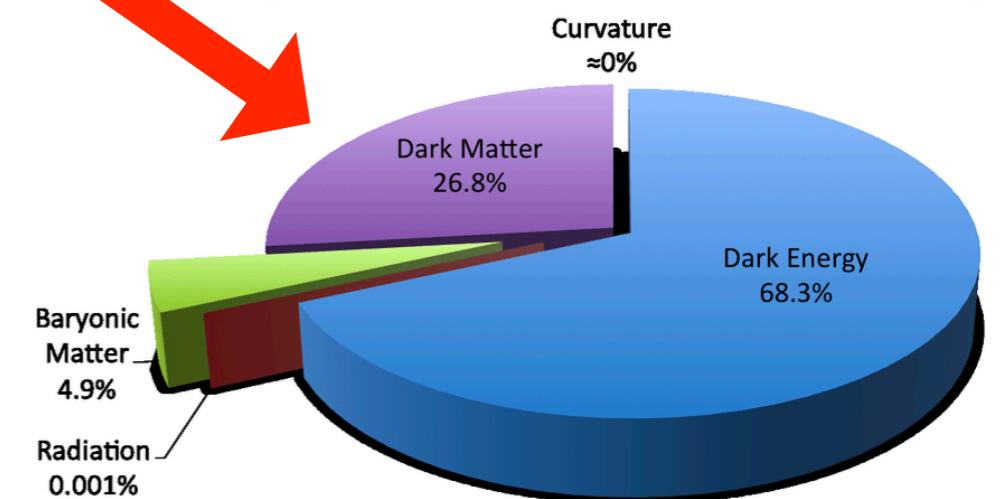


CMB map(s)

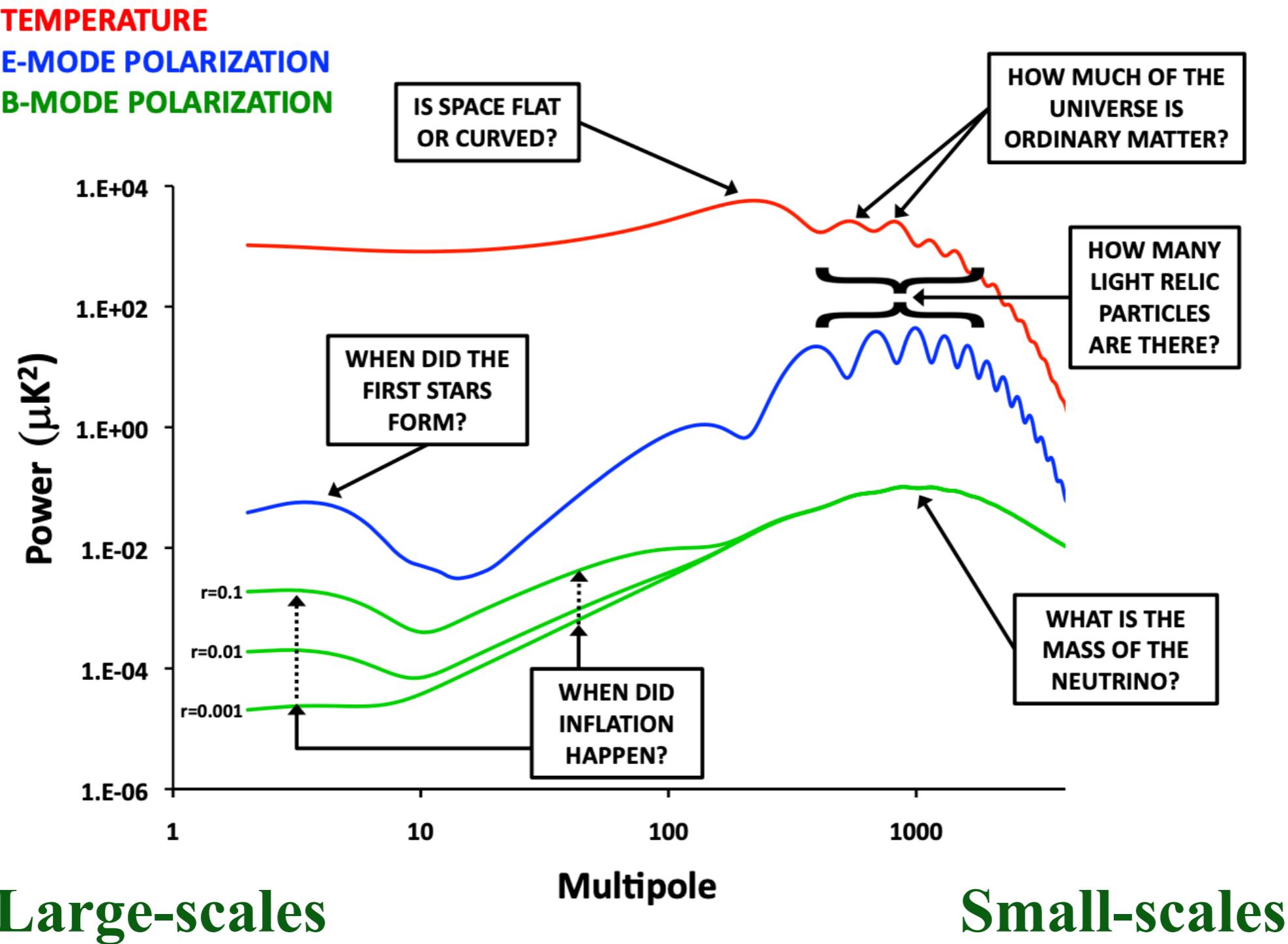
Power spectra (+ external datasets)



Cosmological constraints

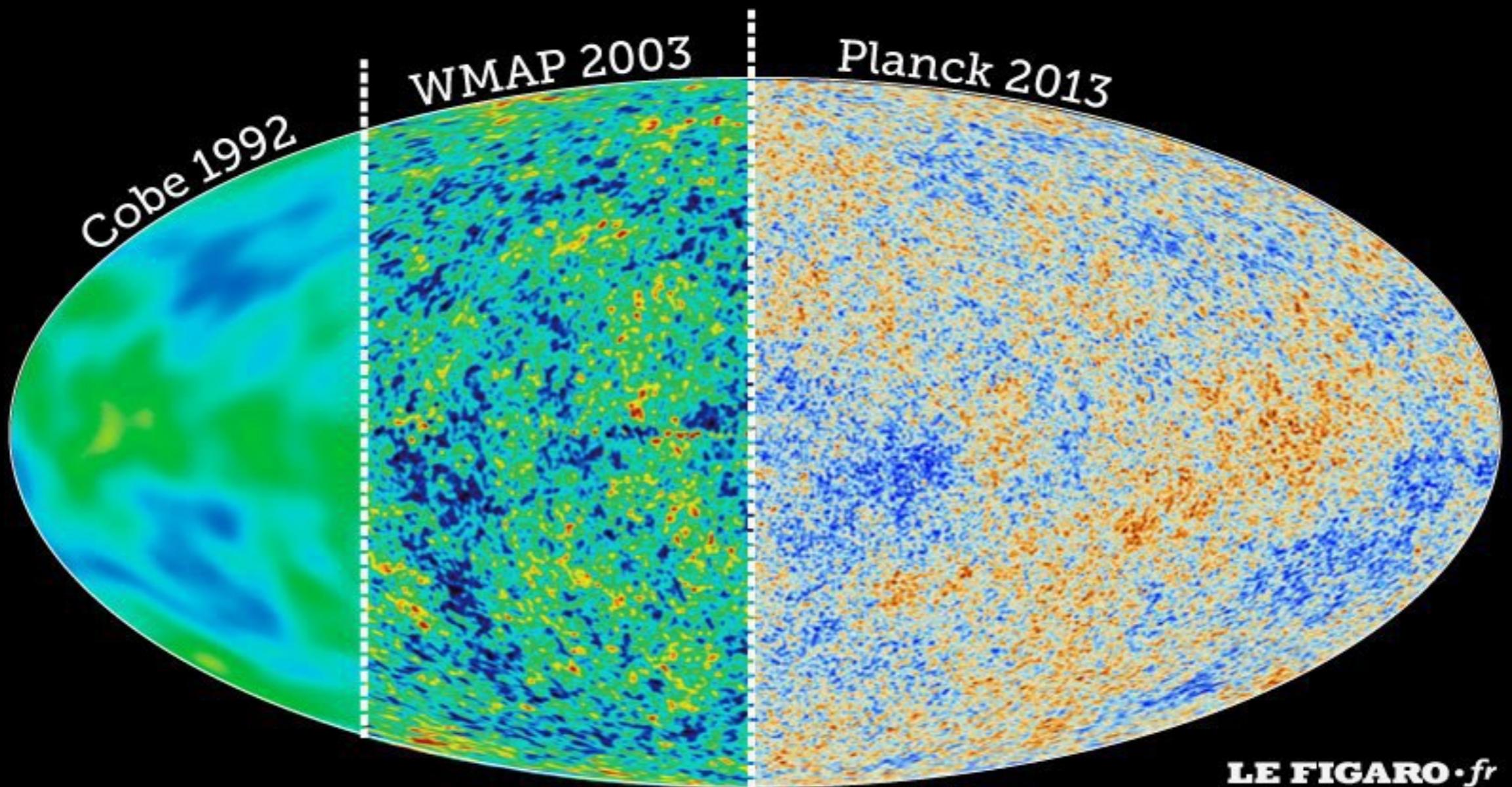


Science from CMB Power Spectra



Chang, Huffenberger et al. 2022 (arXiv: 2203.07638)

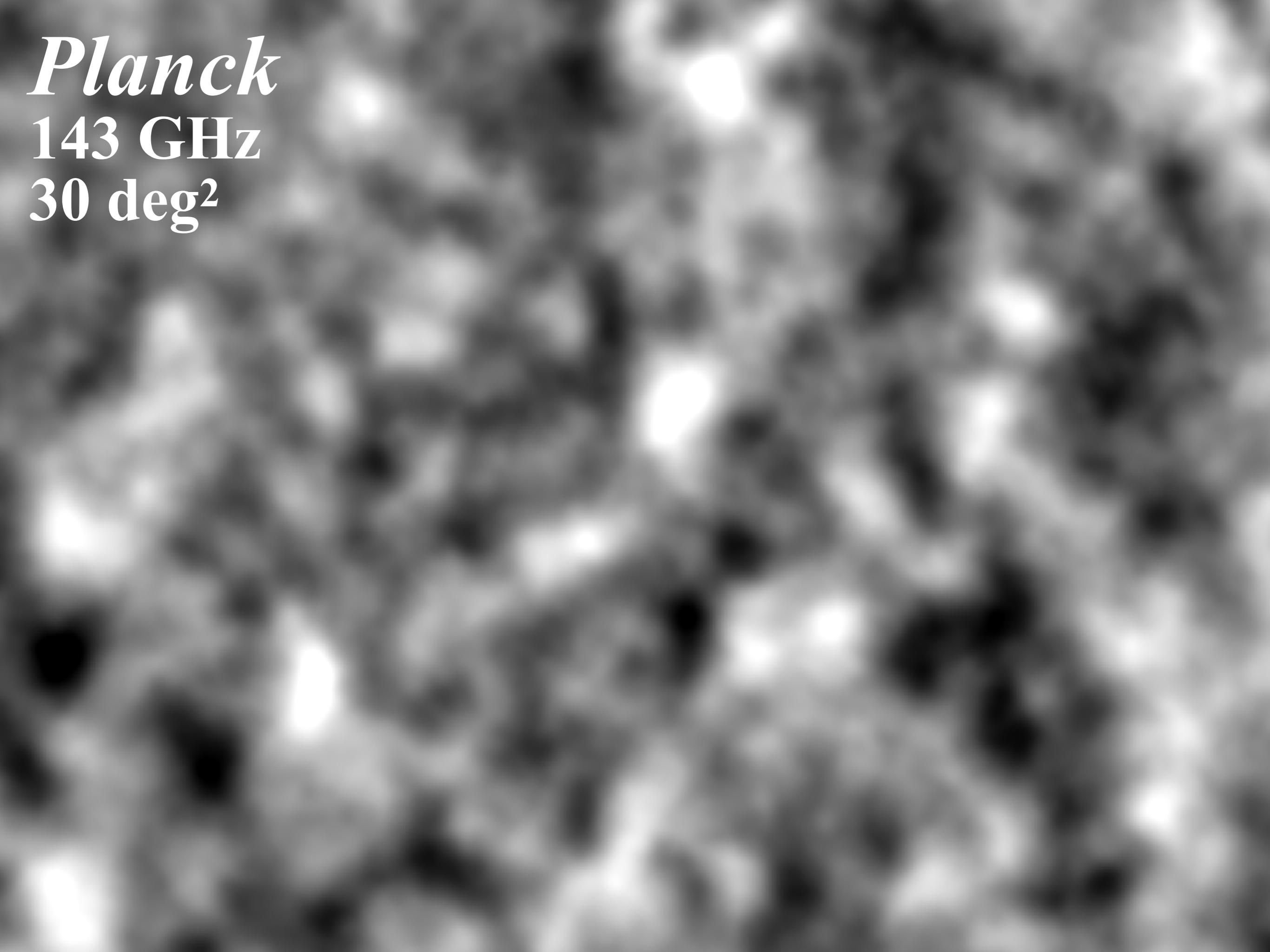
Evolution of CMB experiments



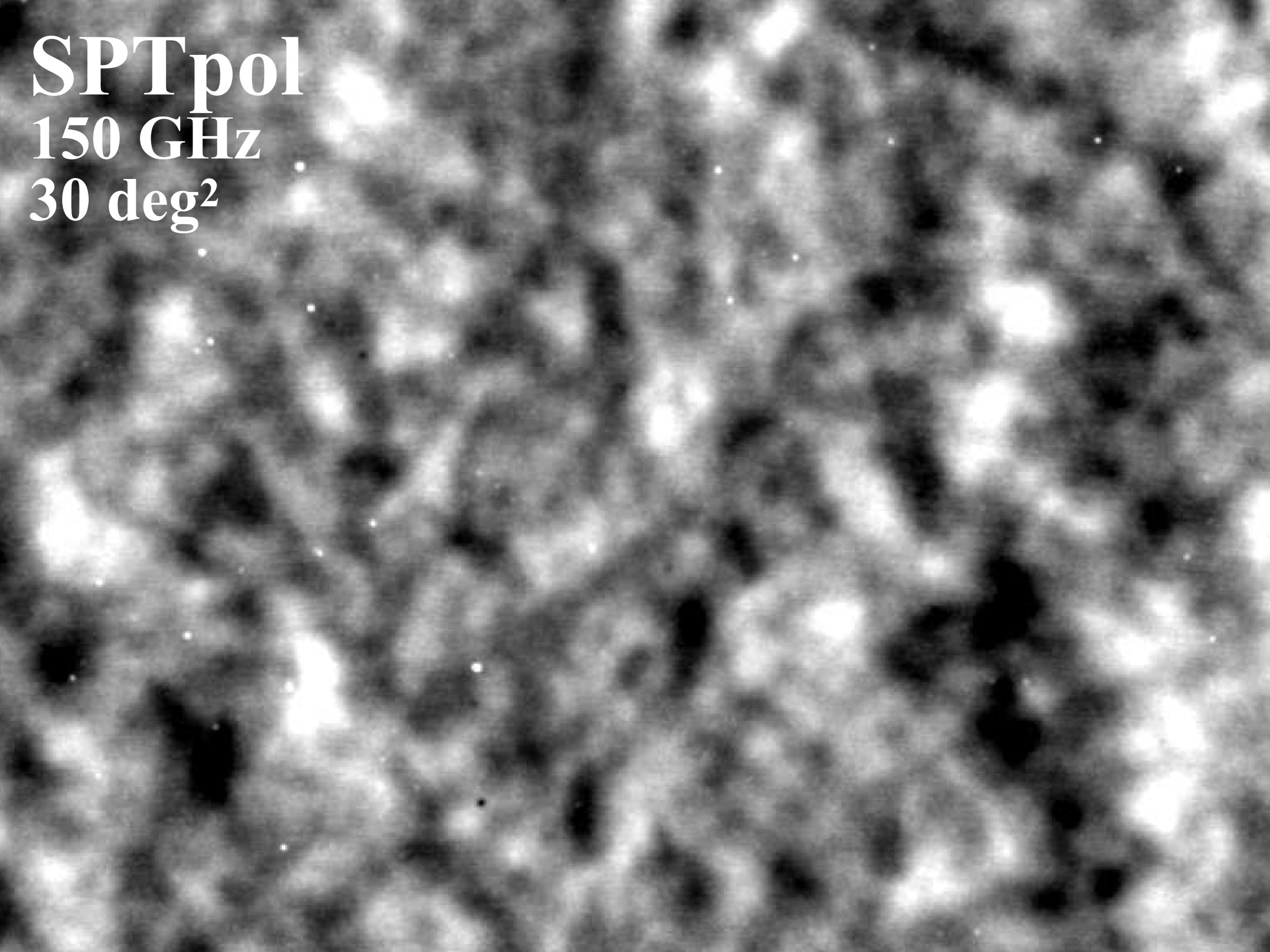
LE FIGARO • fr

WMAP
W-band
30 deg²

Planck
143 GHz
30 deg²



SPTpol
150 GHz
30 deg²



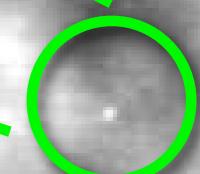
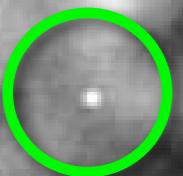
SPTpol
150 GHz
30 deg²

Cosmic microwave background
(CMB)

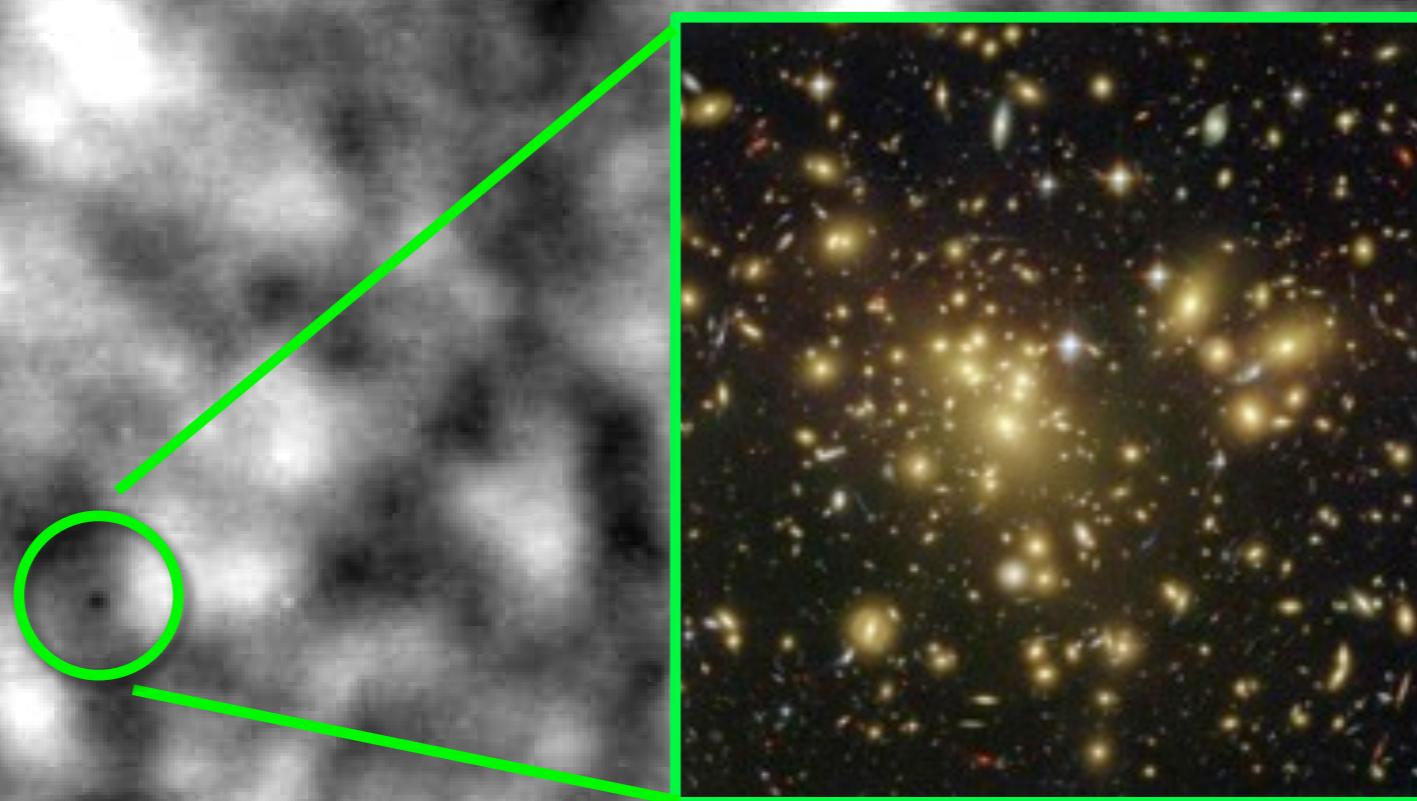
SPTpol
150 GHz
30 deg²

Radio and dusty galaxies show up
as bright spots

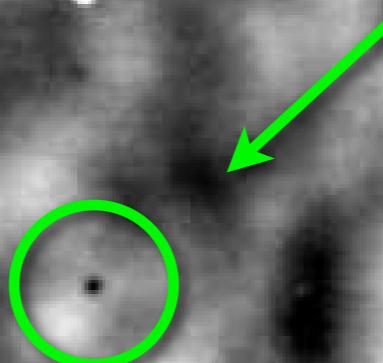
Dusty, starforming galaxy



SPTpol
150 GHz
30 deg²

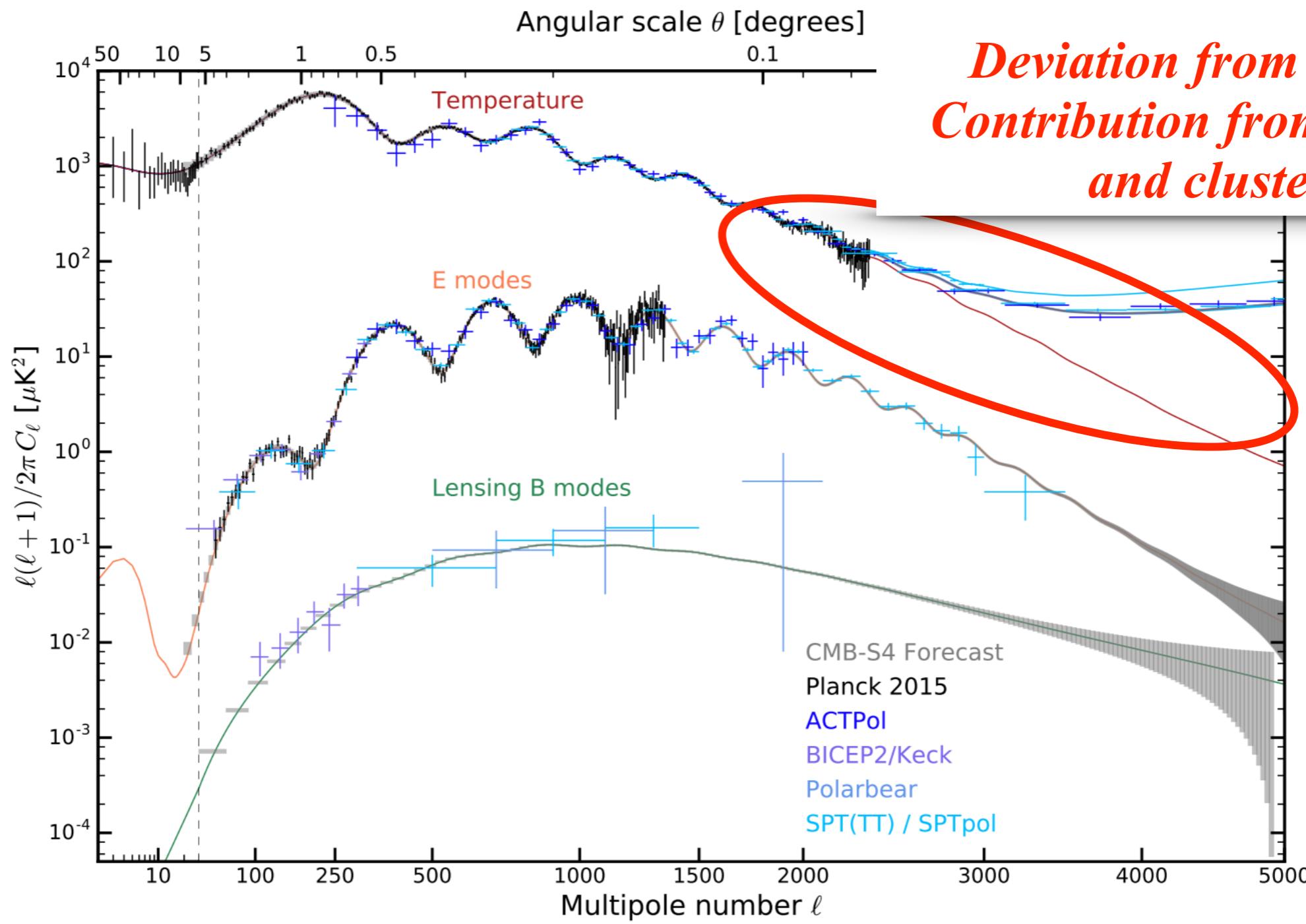


High signal to noise Sunyaev-Zel'dovich (SZ) galaxy cluster detections as “shadows” against the CMB!



CMB Power Spectra - T/P

Power Spectra



CMB experiments: Chile

AdvACTPol: Chile

90/150/220 GHz



Simons Observatory: Chile

30/40/90/150/220/280 GHz



ALMA: Chile



+ CLASS

+ POLABEAR

+ Simons Array

Cerro Chajnantor: High altitude ~5200 metres.

Low water vapour level.

CMB experiments: South Pole



Altitude: ~3000 metres.

Flat giant sheet of ice.

Very low water vapour level.

Extremely stable atmosphere.

CMB experiments: South Pole

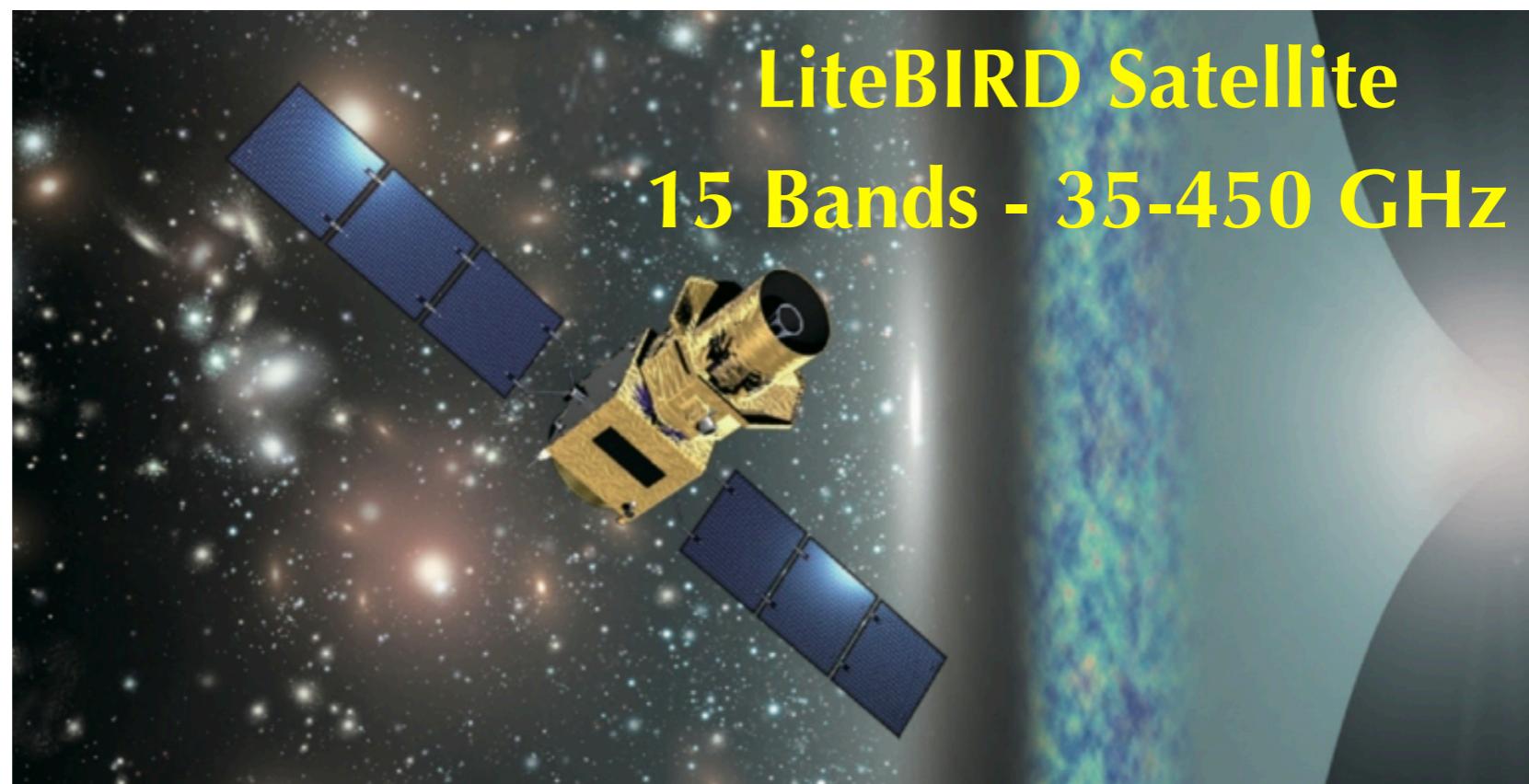
South Pole Telescope
90/150/220 GHz



BICEP / Keck
90/150 GHz

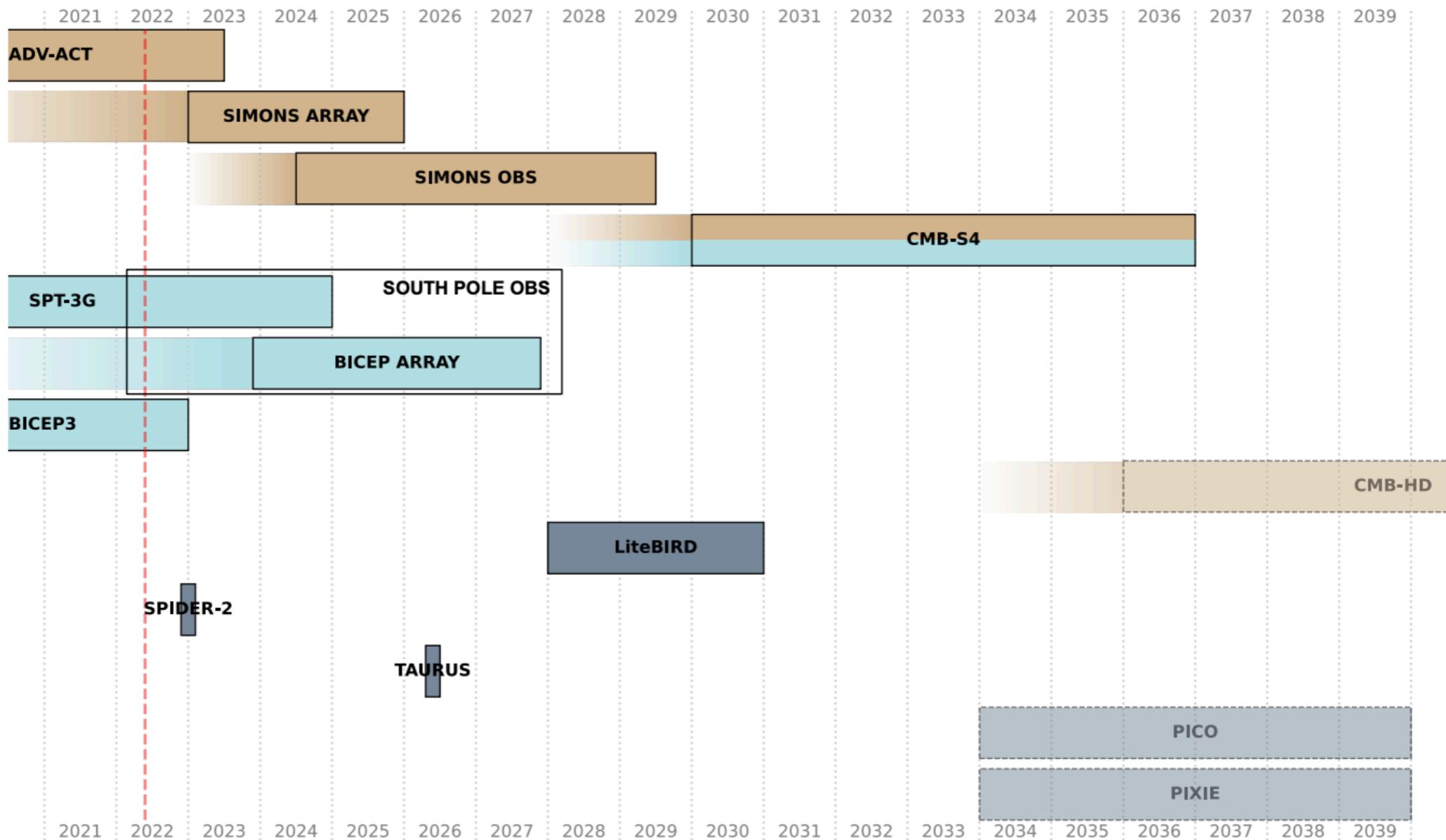


CMB experiments: Future



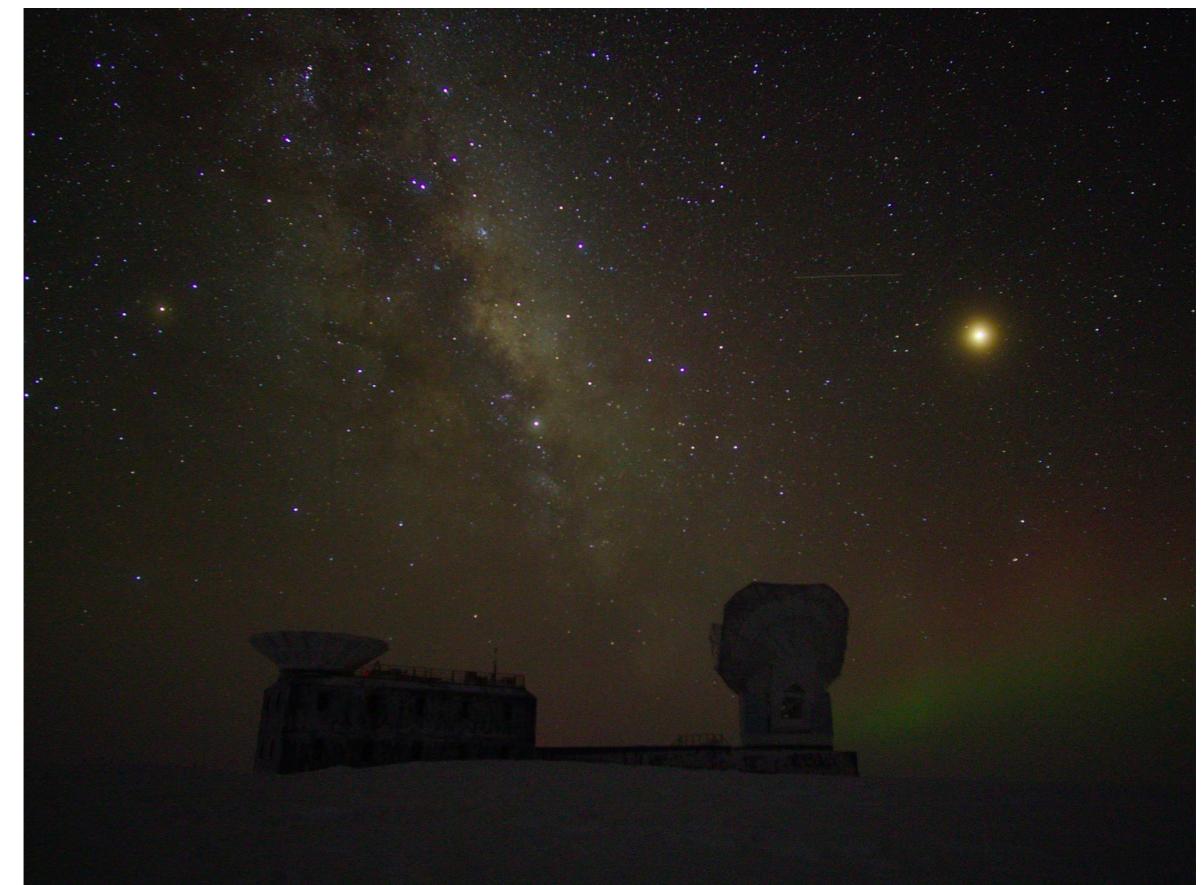
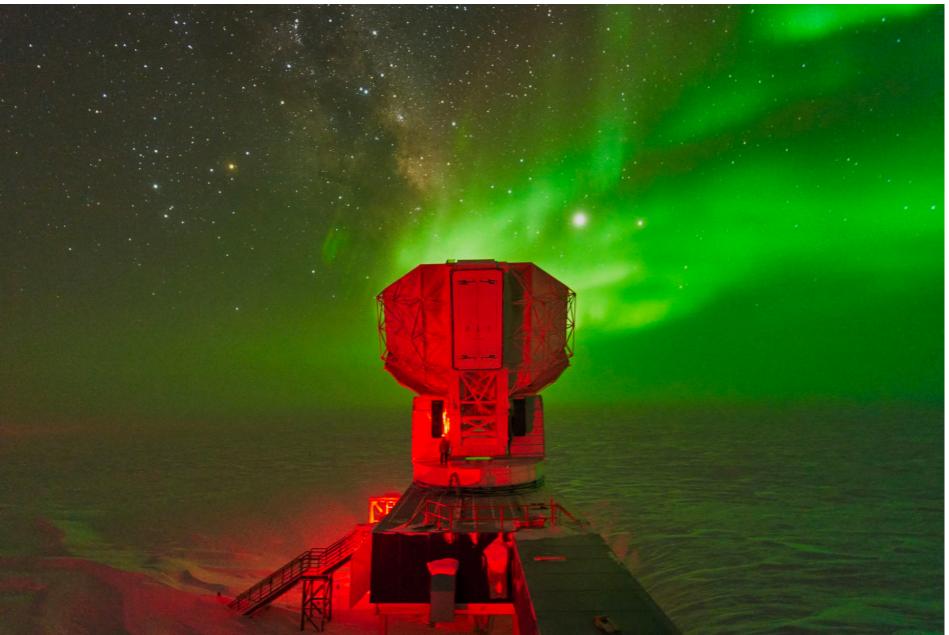
CMB experiments

 Chile
 South Pole
 Balloon/Space



Chang, Huffenberger et al. 2022 (arXiv: 2203.07638)

Pictures from the South Pole



Pictures from the South Pole



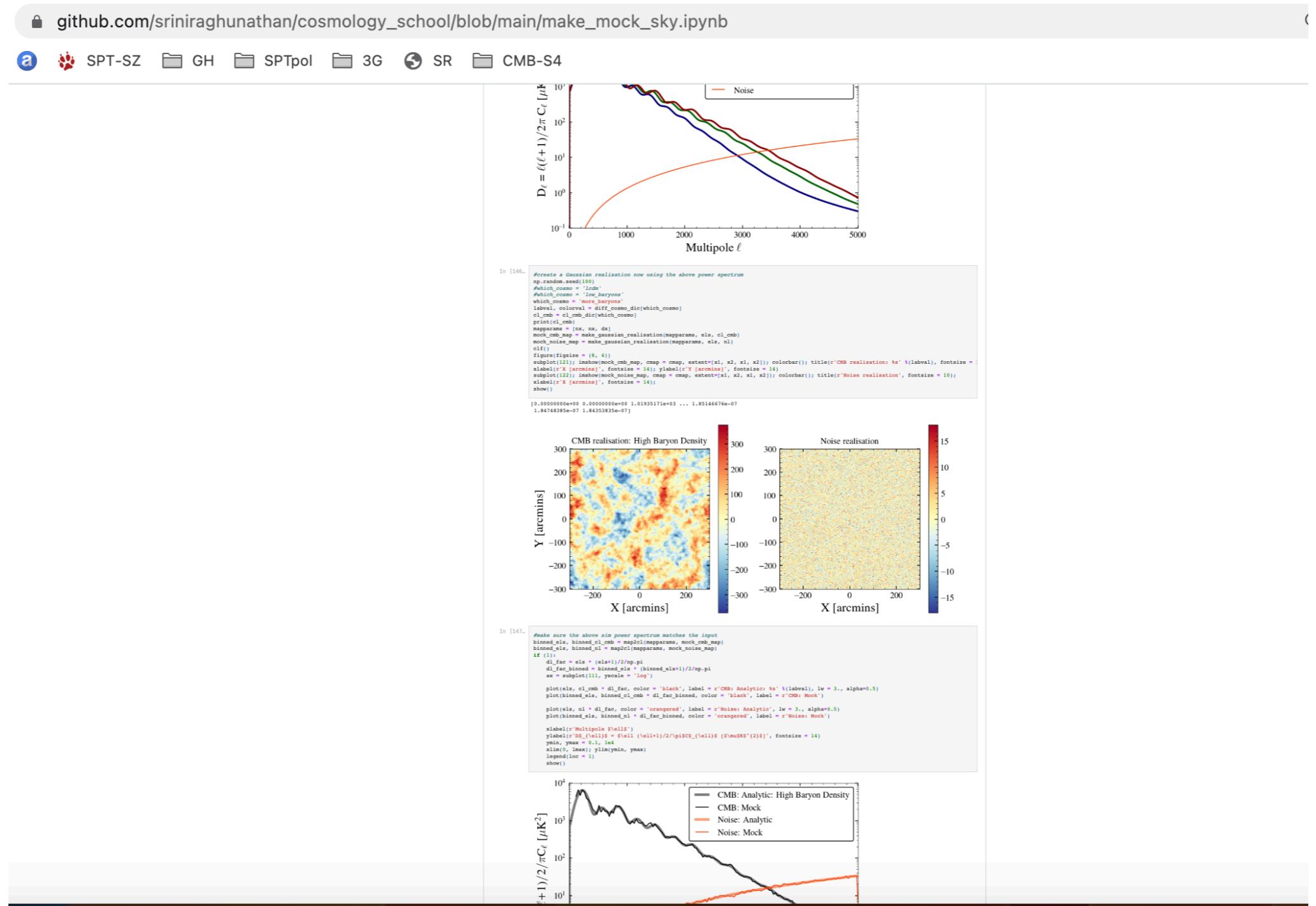
Lunar Eclipse - Taken by SPT Winterover Aman Cholski

Partial Solar Eclipse - Taken by SPT Winterover Aman Cholski



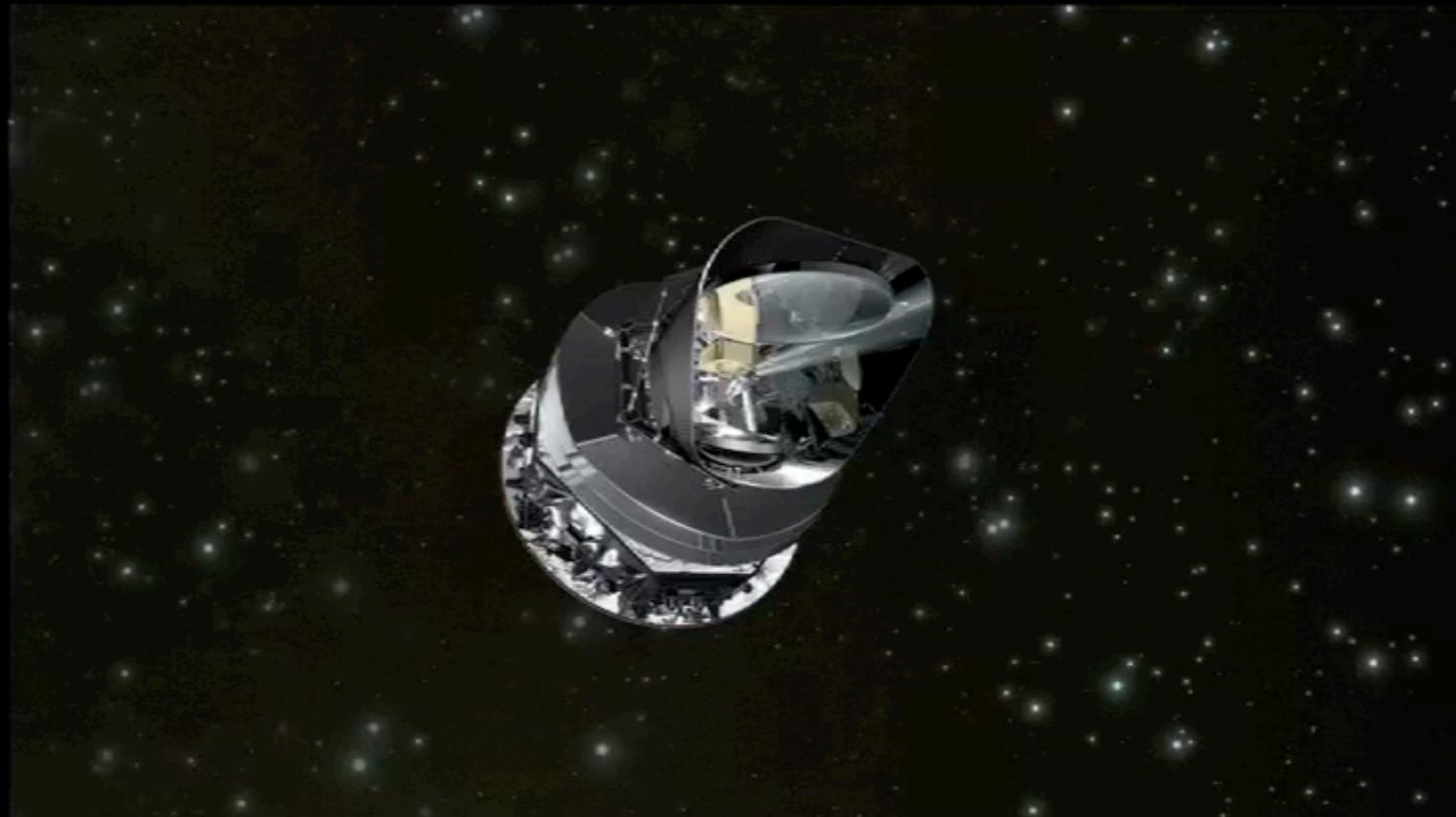
Jupyter notebook example

Link to code: https://github.com/sriniraghunathan/cosmology_school



Life of a CMB photon

A Journey of Light



through Space and Time