Observing and Interpreting the Most Ancient Light in the Universe

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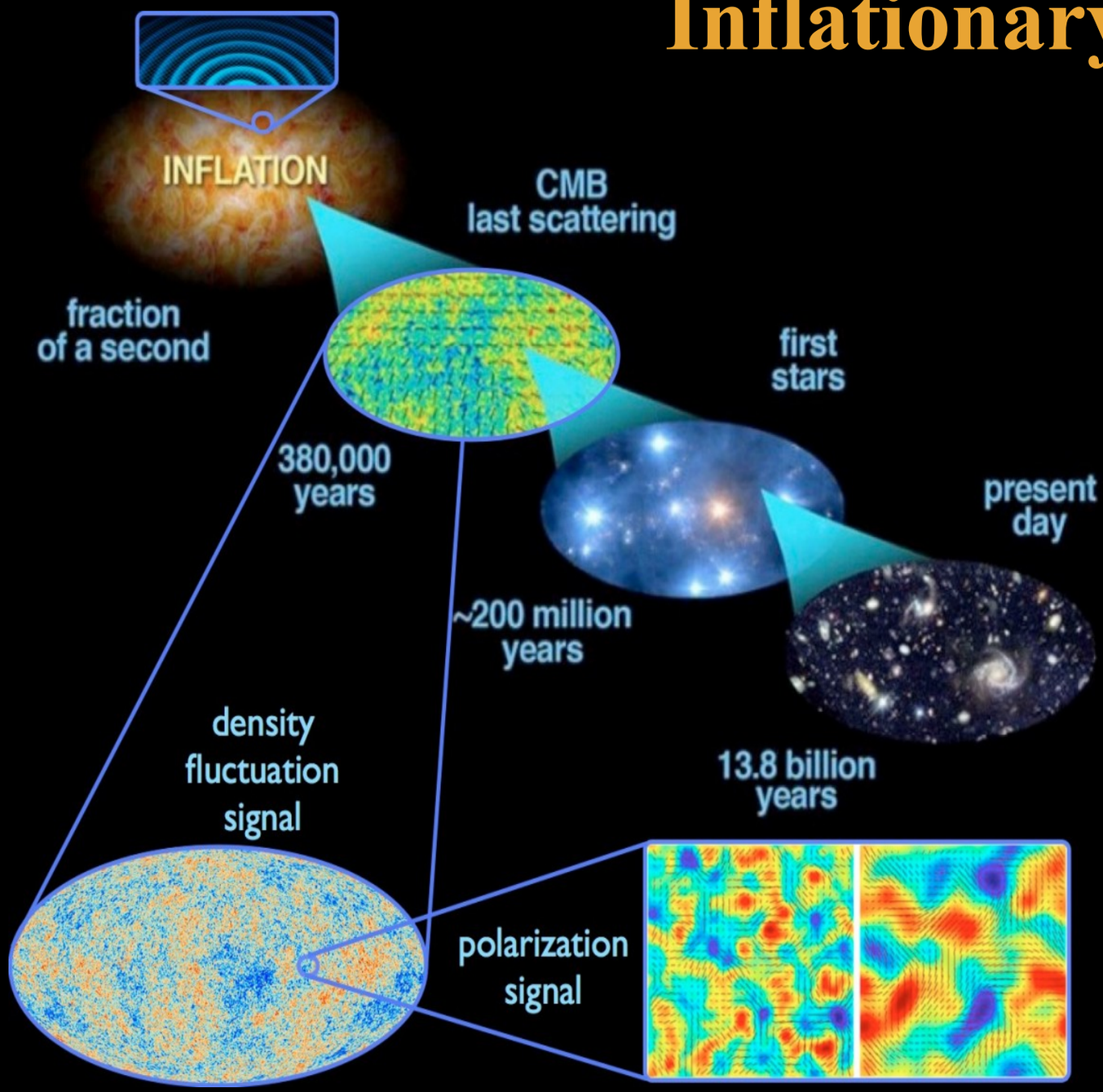
Concordance cosmology

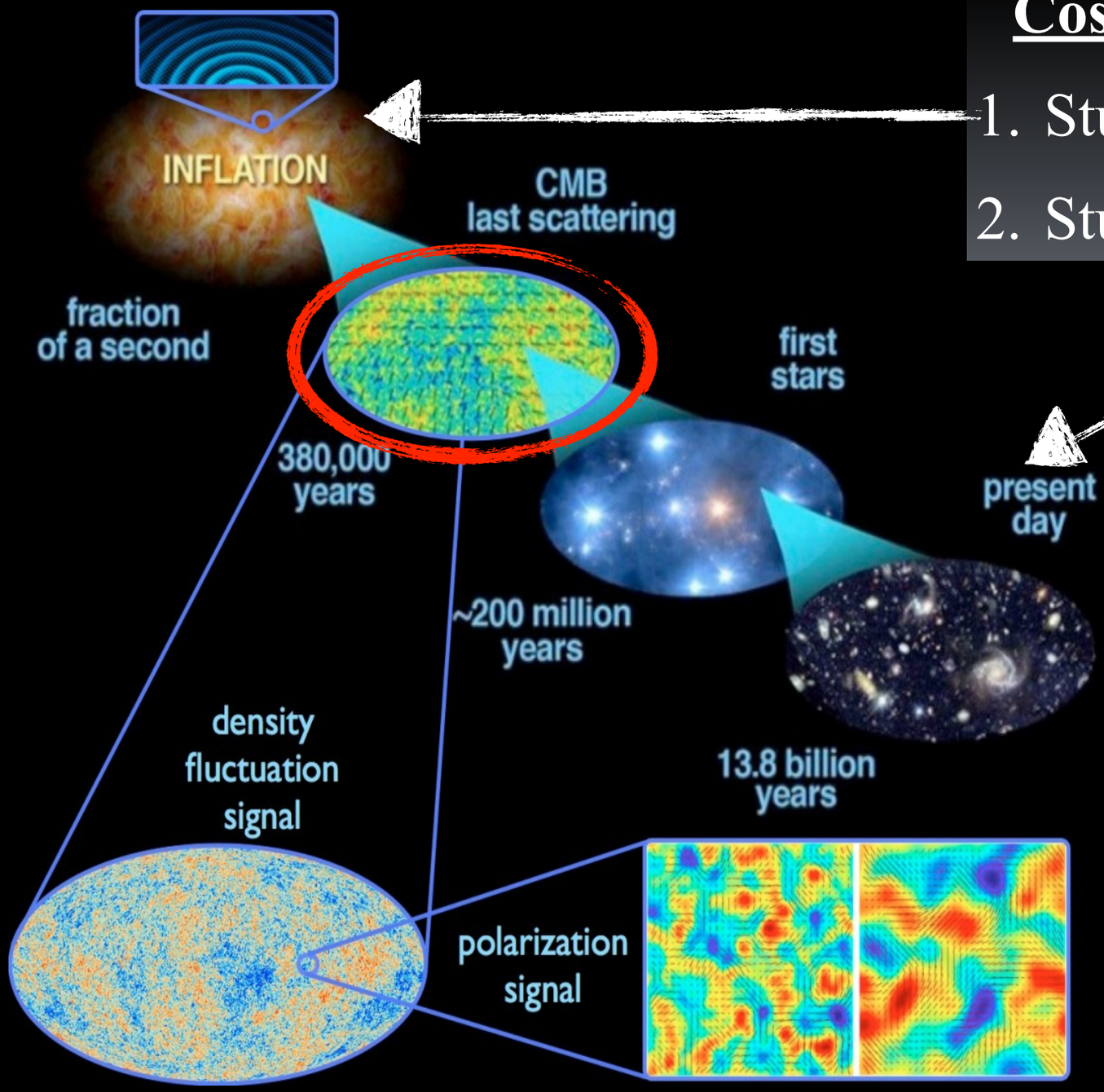
Inflationary Λ - Cold Dark Matter



- ✓ **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.

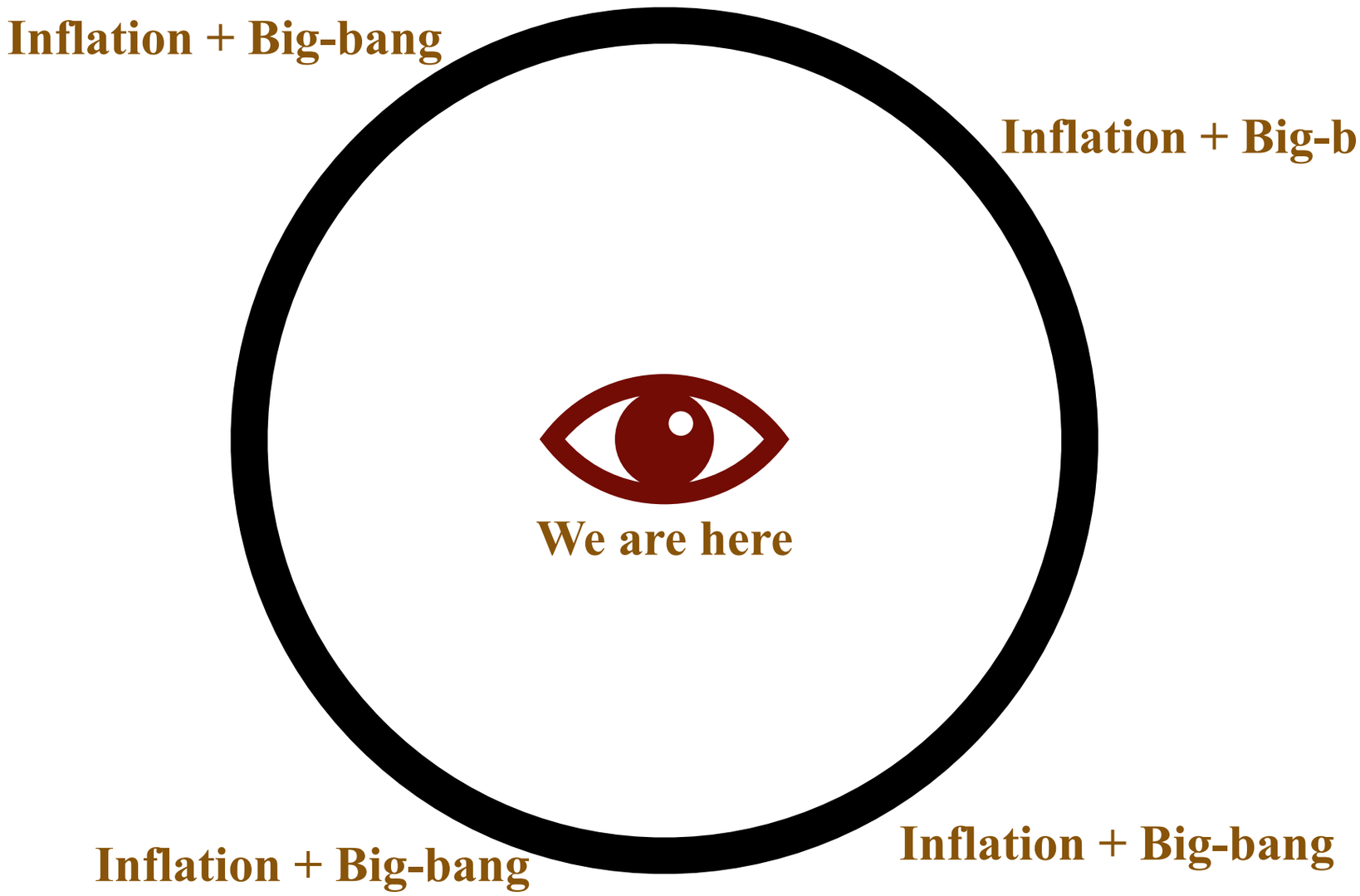
Image: CTC, Cambridge

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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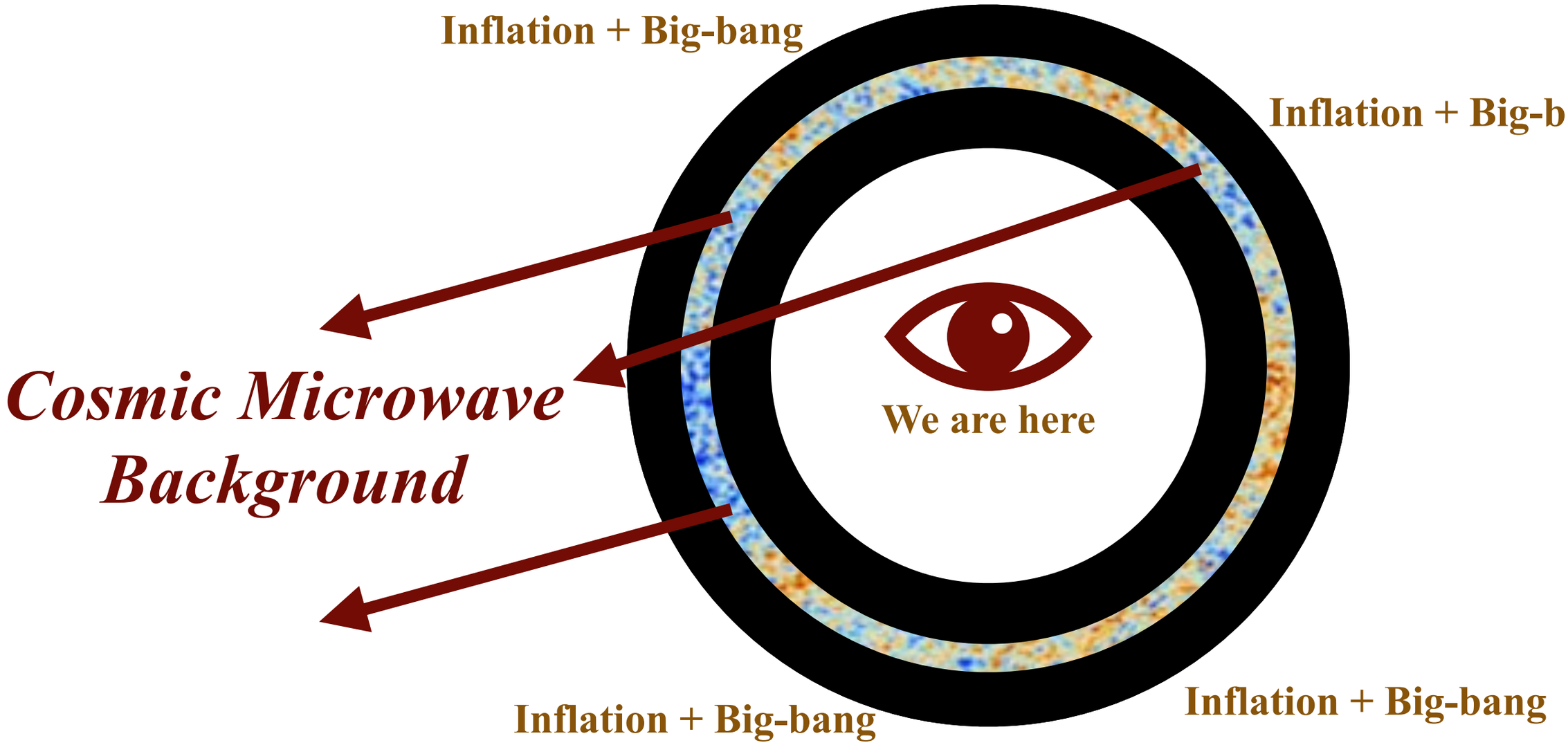

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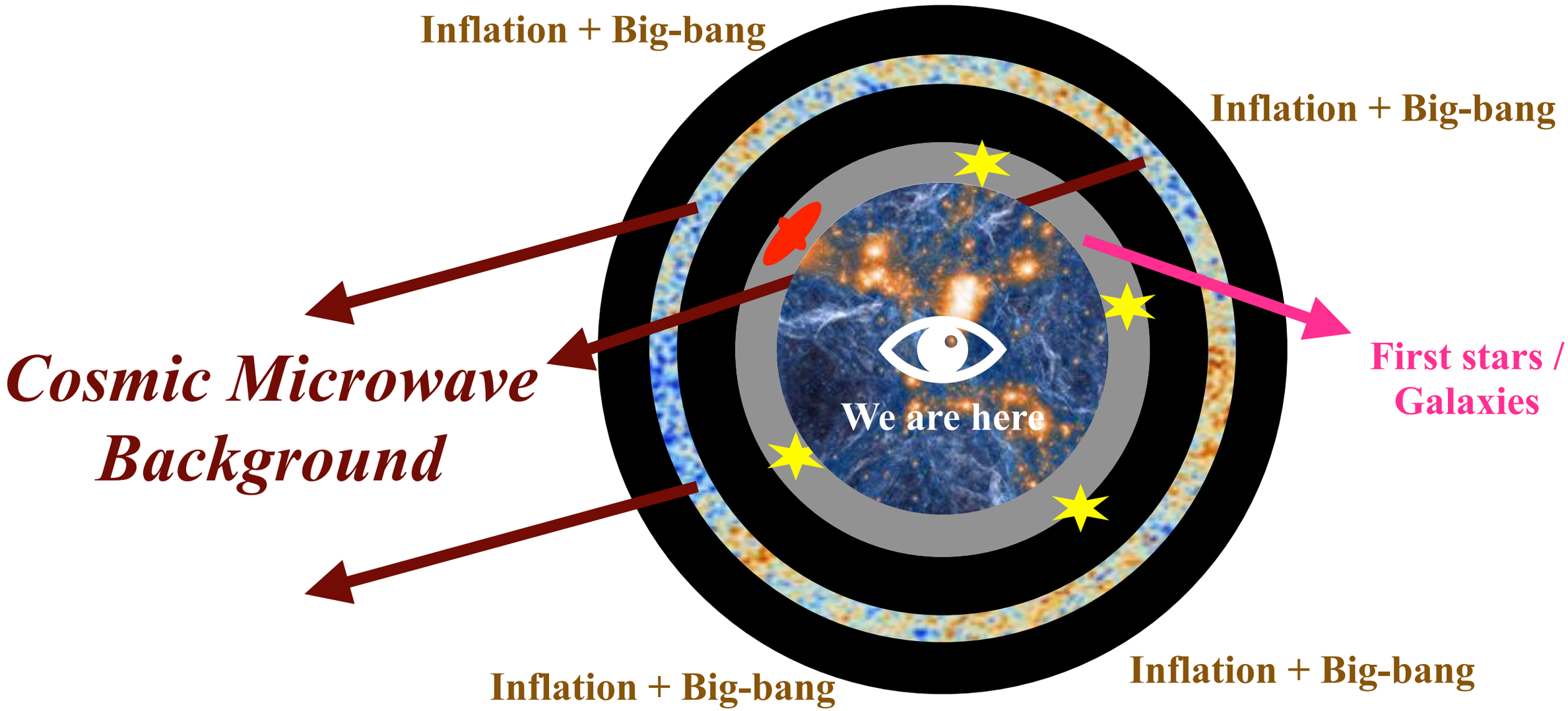
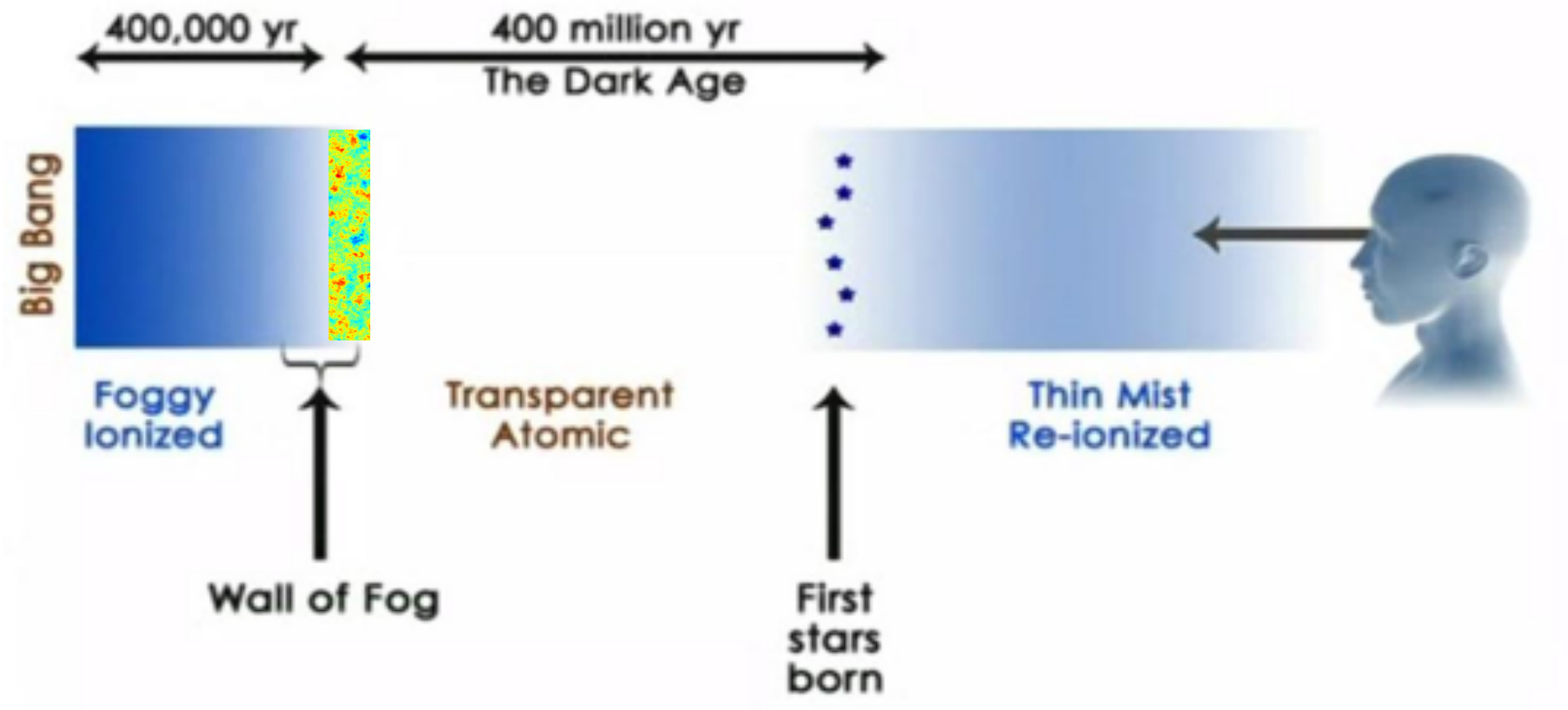
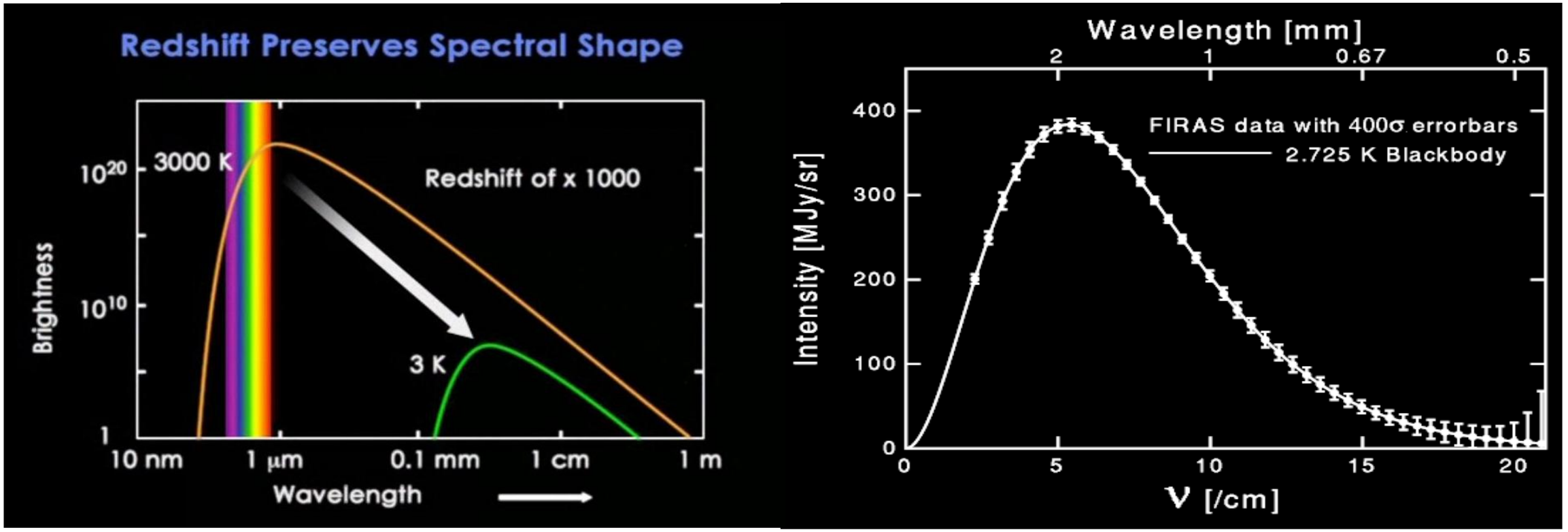


Cosmic Microwave Background



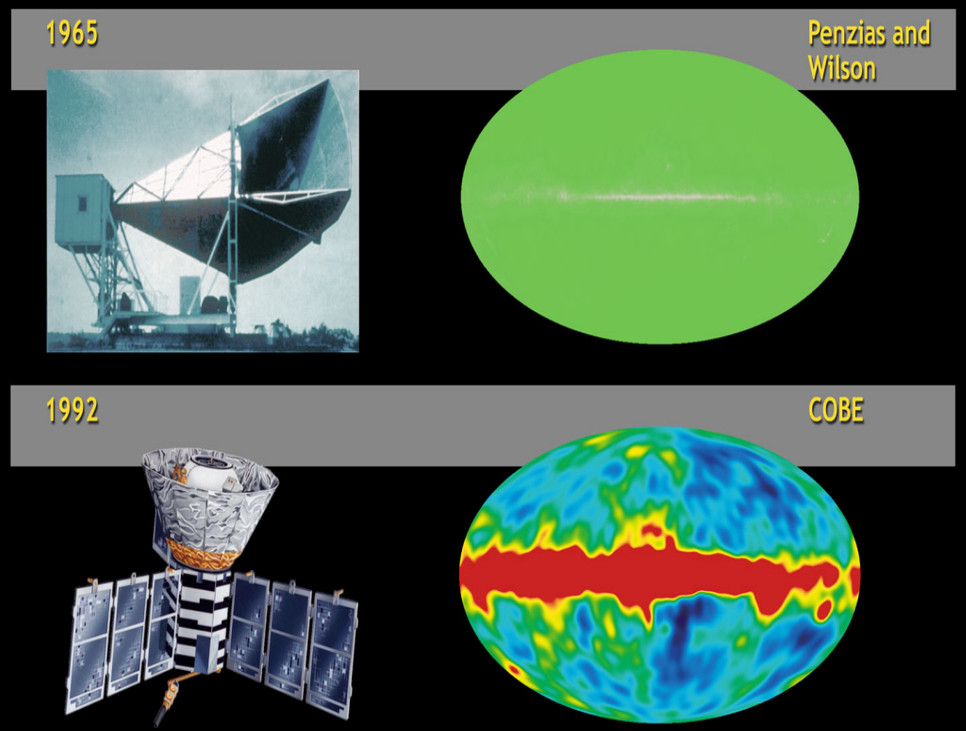
- CMB in the remnant radiation from the Big-Bang.
- Predicted by George Gamow in 1946.
- Accidentally discovered by Arno Penzias and Robert Wilson in 1964.
- Extremely homogenous and isotropic: Same in all locations and all directions.
- Anisotropies are 1 part in a million.

Cosmic Microwave Background



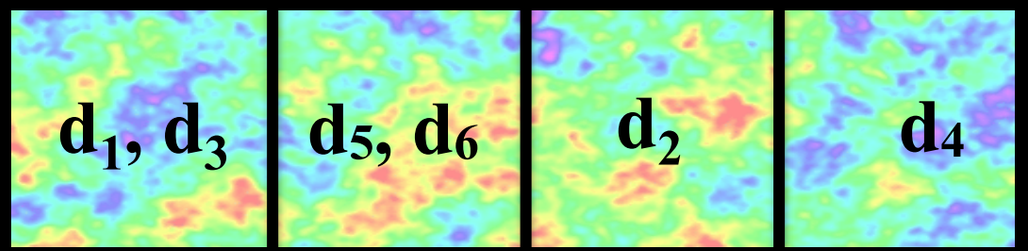
- Black-body peaking around T_{CMB} = 2.7 Kelvin.
- Partially polarised (~10%) due to Thomson scattering.
- Small fraction of the CMB photons are affected by intervening structures in our universe — secondary anisotropies in the CMB — .
  - *CMB-lensing, Thermal and Kinematic Sunyaev-Zeldovich effects,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

CMB Temperature



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

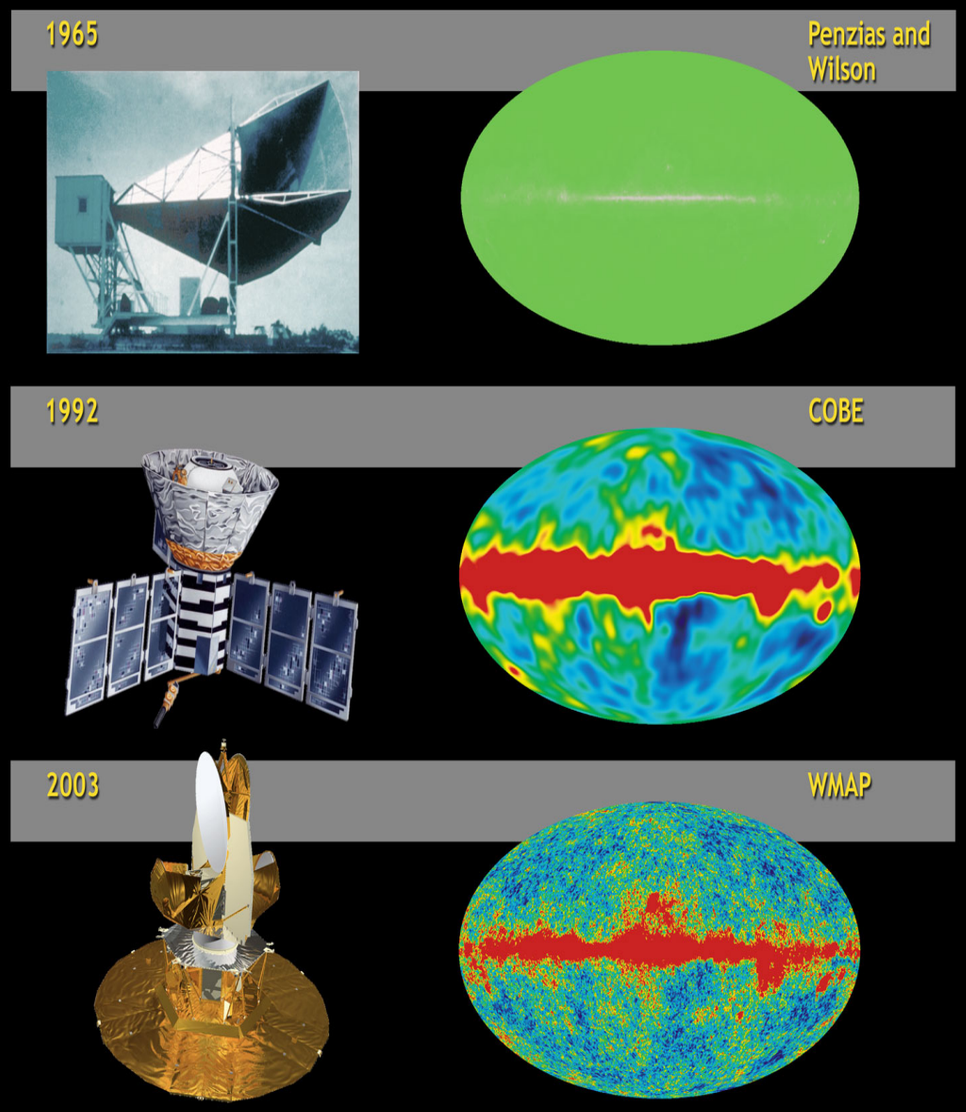


$$\delta = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$

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

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

CMB Temperature



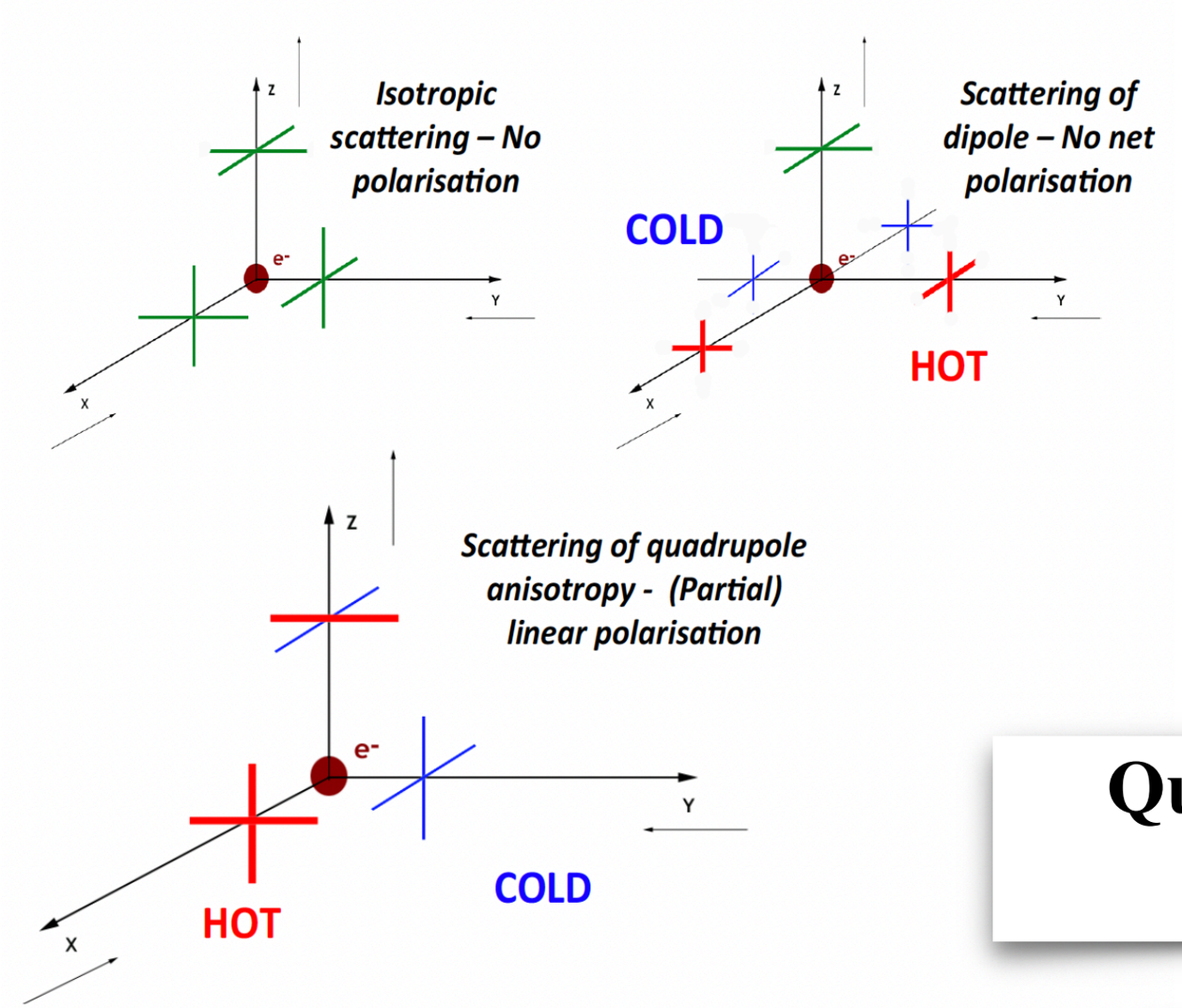
Measure the sky temperature in different locations and subtract the mean to get the map of the "tiny" CMB anisotropies.

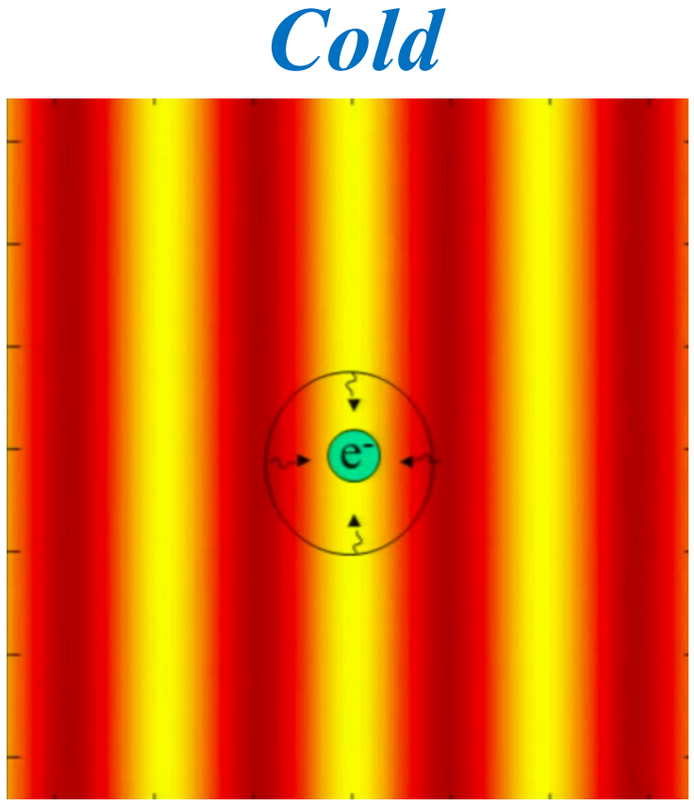
1 part in a million

+ ***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:





Quadrupole anisotropy required to produce (linear) polarisation.

We measure local Stokes Q/U parameters.

Anisotropies - What sourced them?

Primordial anisotropies: Scalar, Vector, and Tensor.

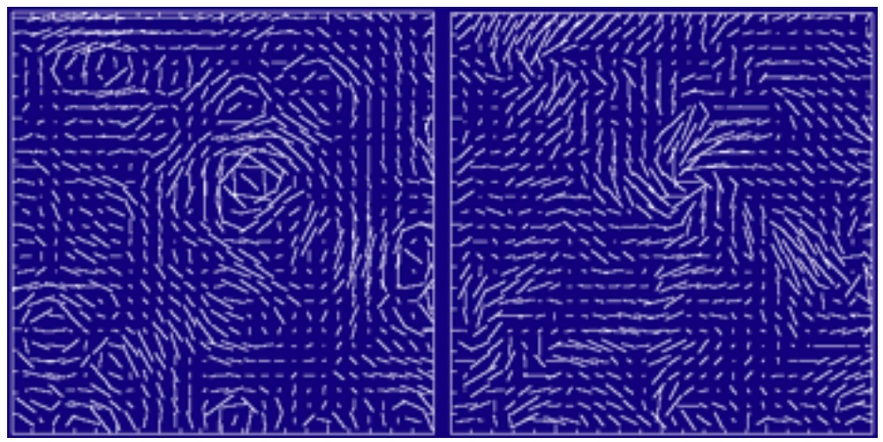
Scalar (density): Temperature and E-mode polarisation.

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

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

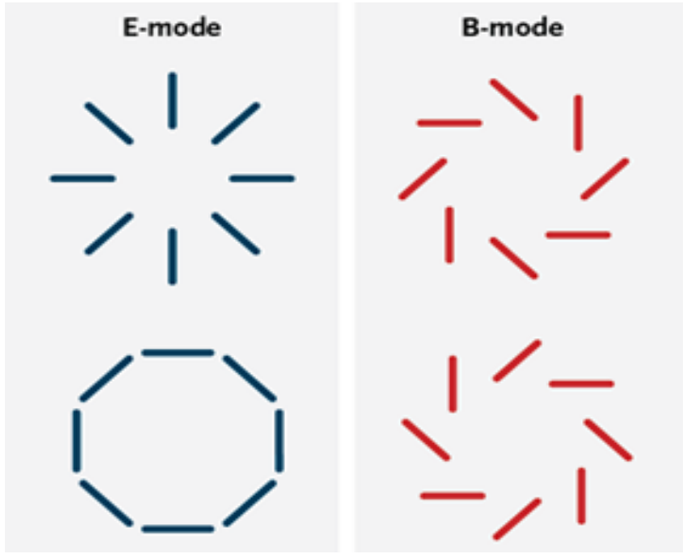
B-modes = (Primordial) Gravity Waves = Inflation

E modes B modes



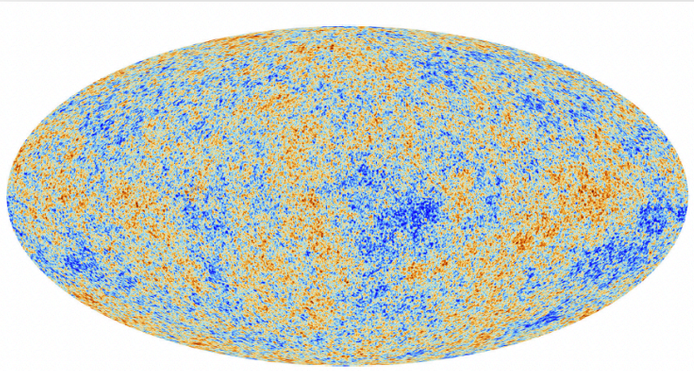
Scalar and tensor perturbations

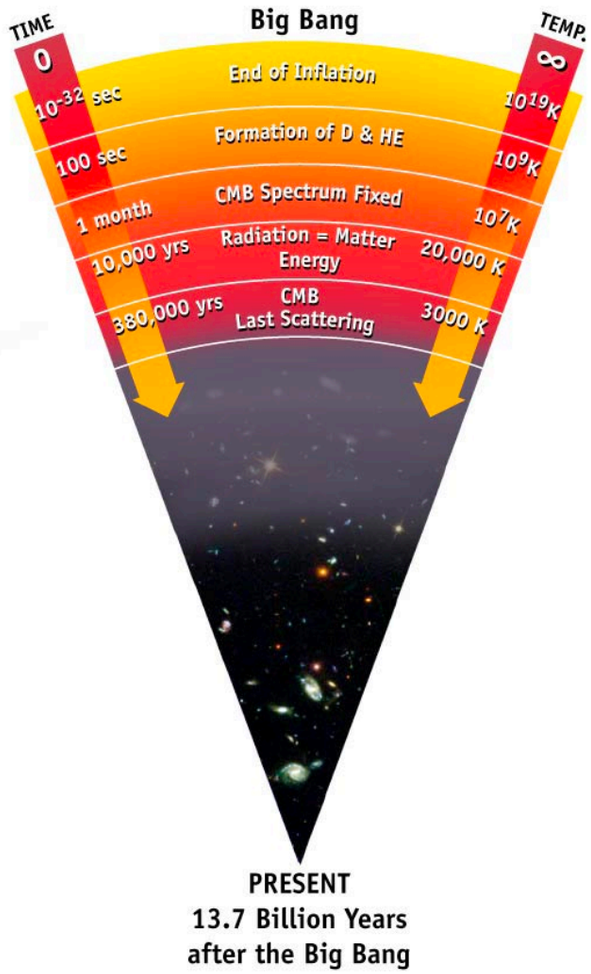
Tensor / vector perturbations



CMB Power Spectrum

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

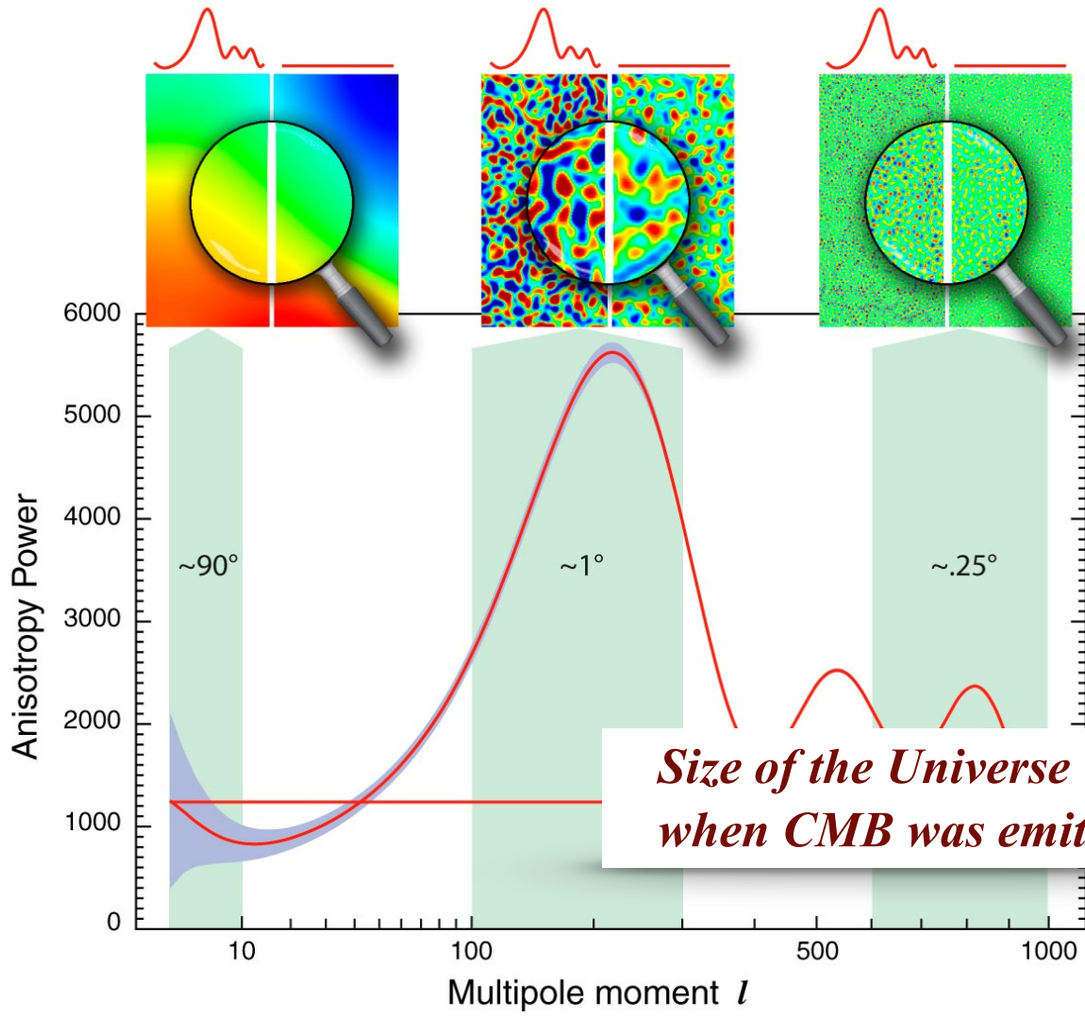




$$\widetilde{C_\ell^{XX}} = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} |\tilde{a}_{X,lm}|^2$$

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

X = Temperature / Polarisation

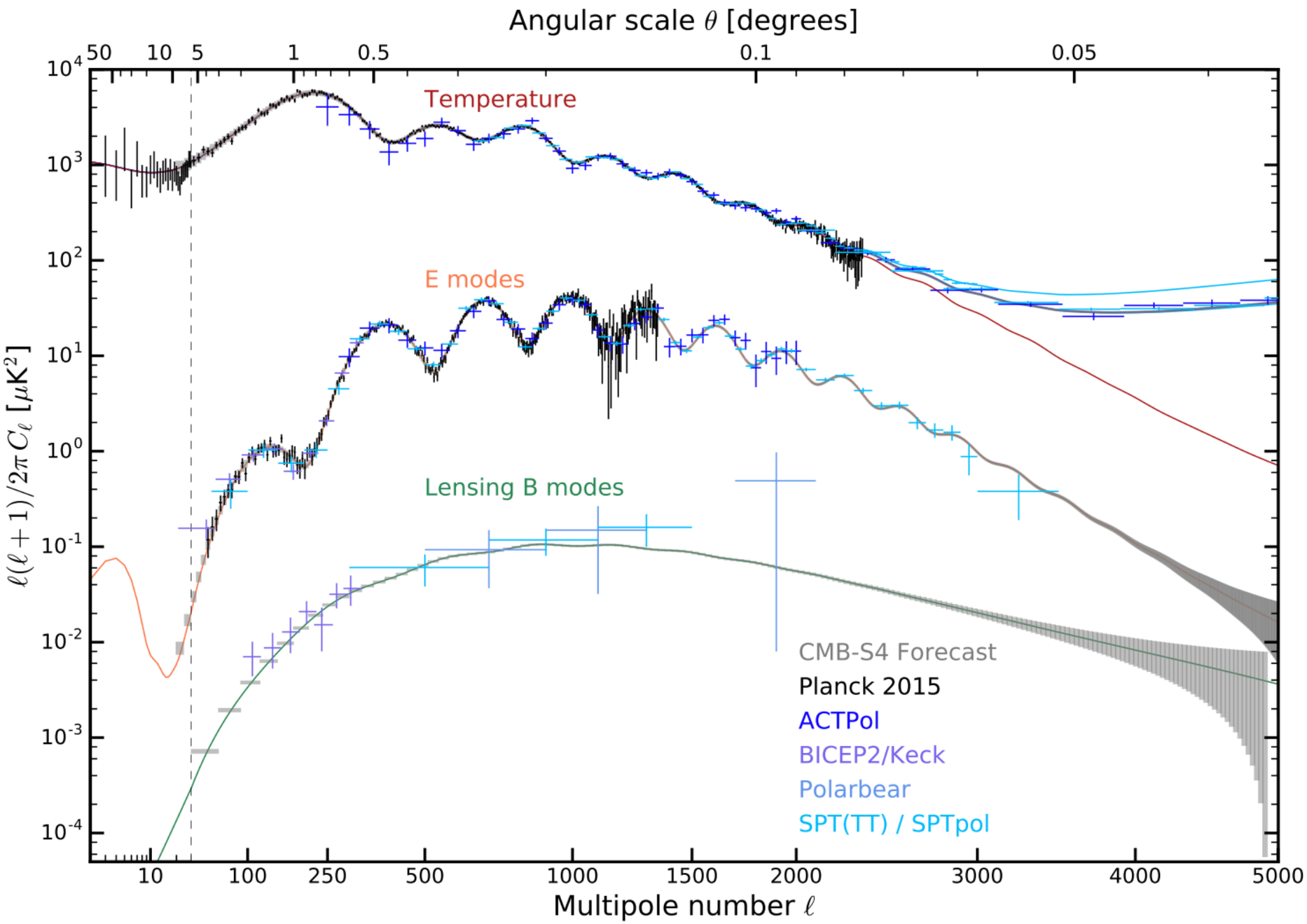


Size of the Universe when CMB was emitted.

Large-scales **Small-scales**

CMB Power Spectra - T/P

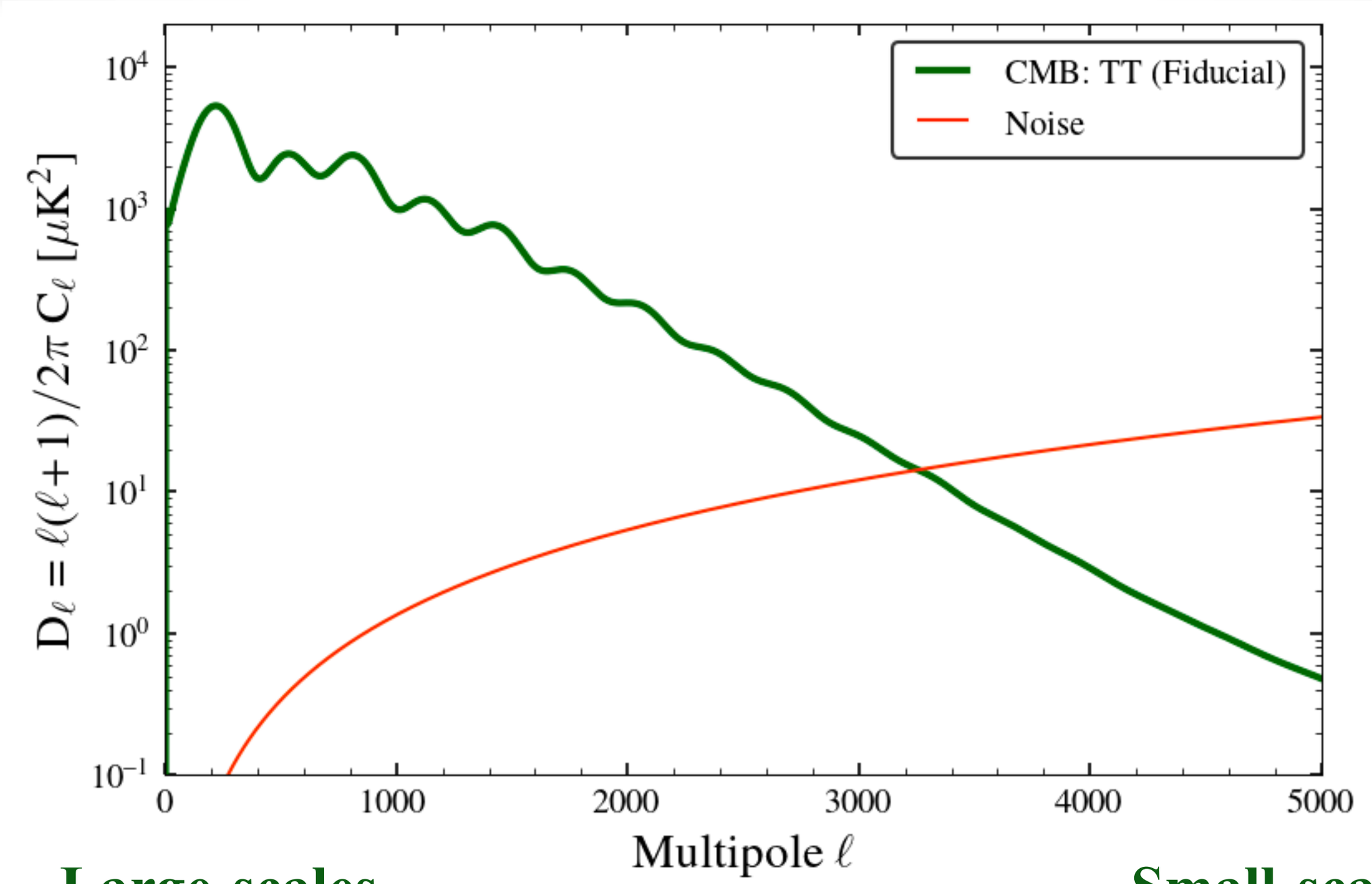
Power Spectra



Large-scales **Small-scales**

Cosmology from CMB spectra

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



Large-scales **Small-scales**

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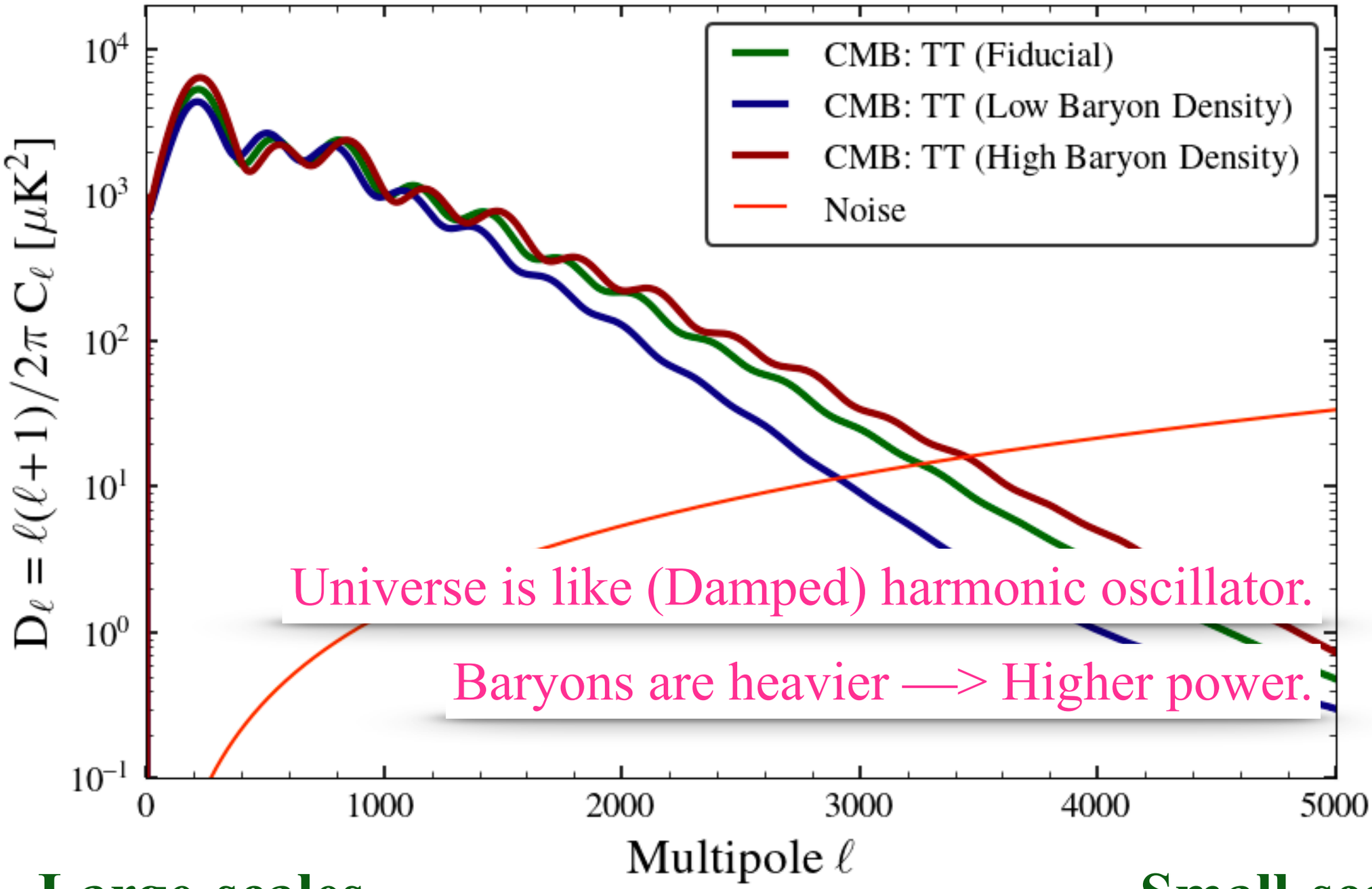

Universe is like (Damped) harmonic oscillator.

Baryons are heavier —> Higher power.

Large-scales **Small-scales**

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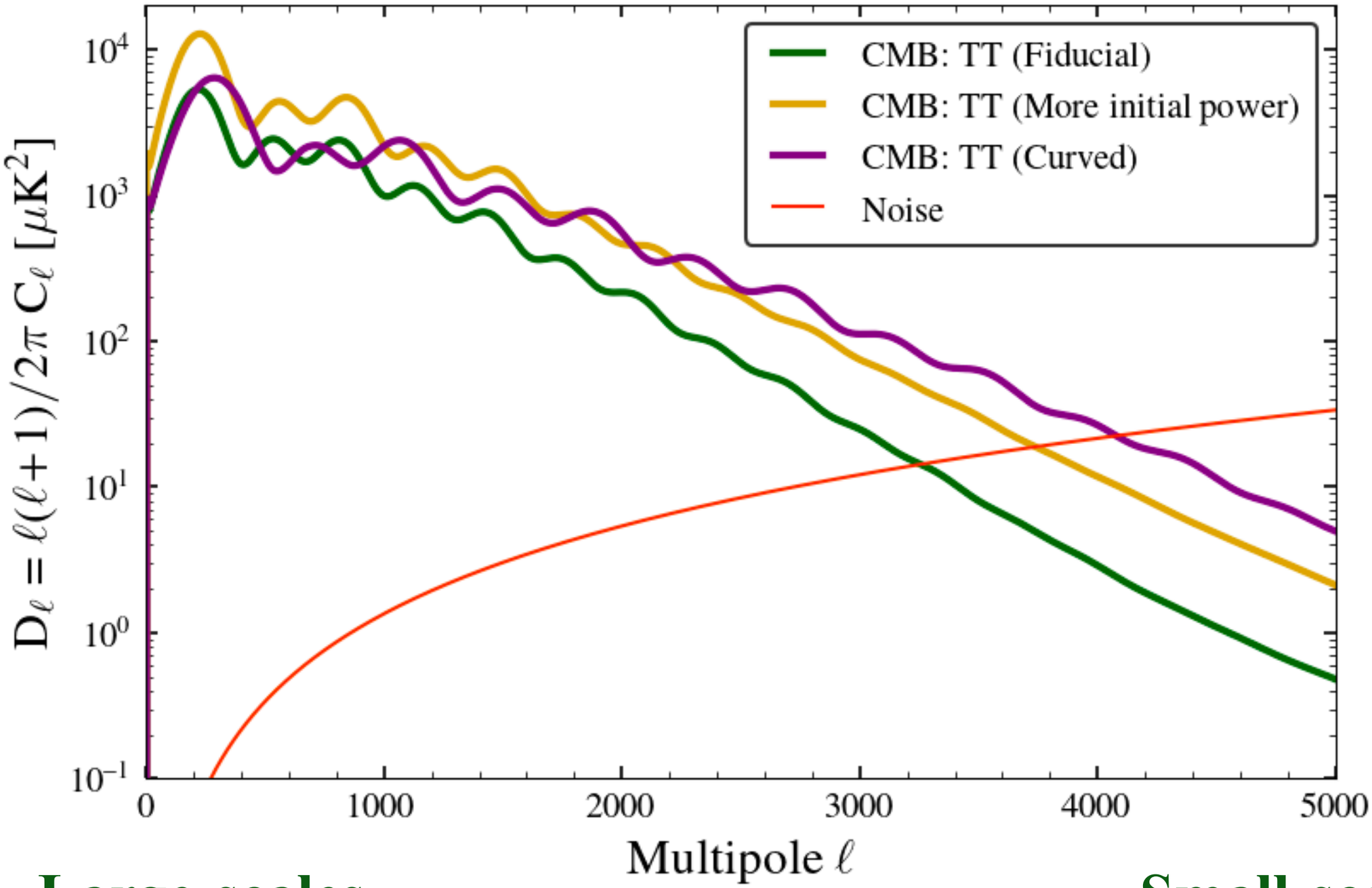
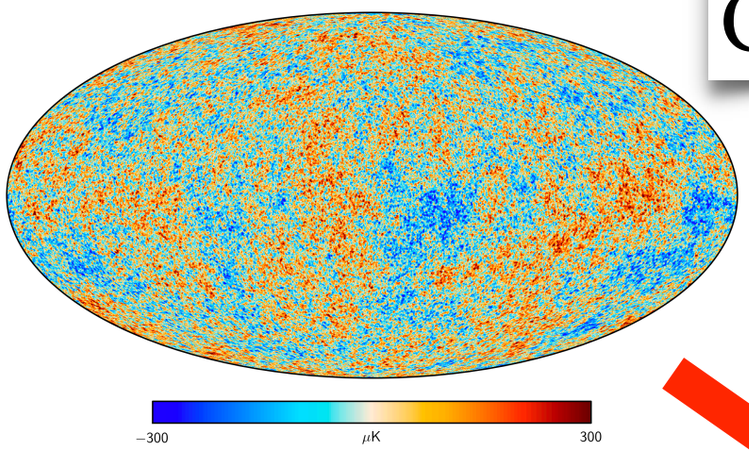


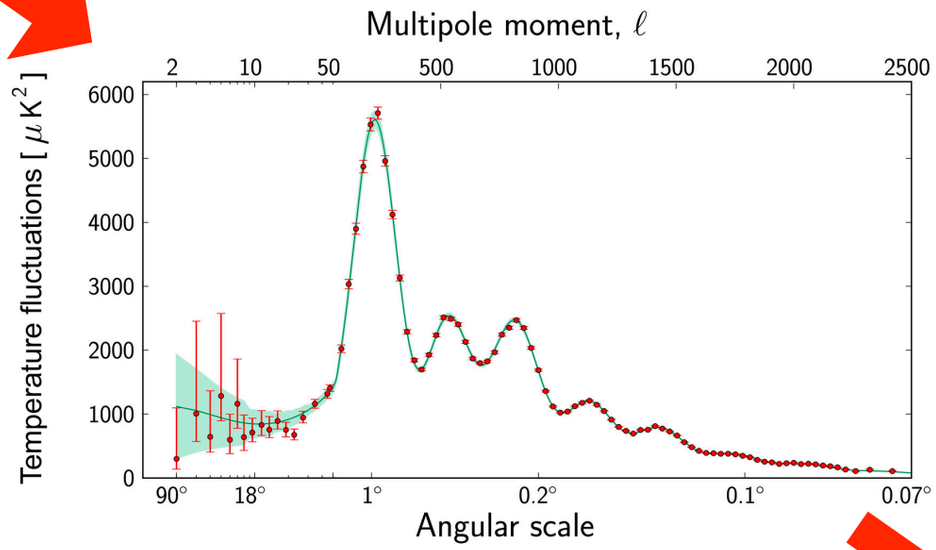
Large-scales **Small-scales**

Cosmology from CMB spectra

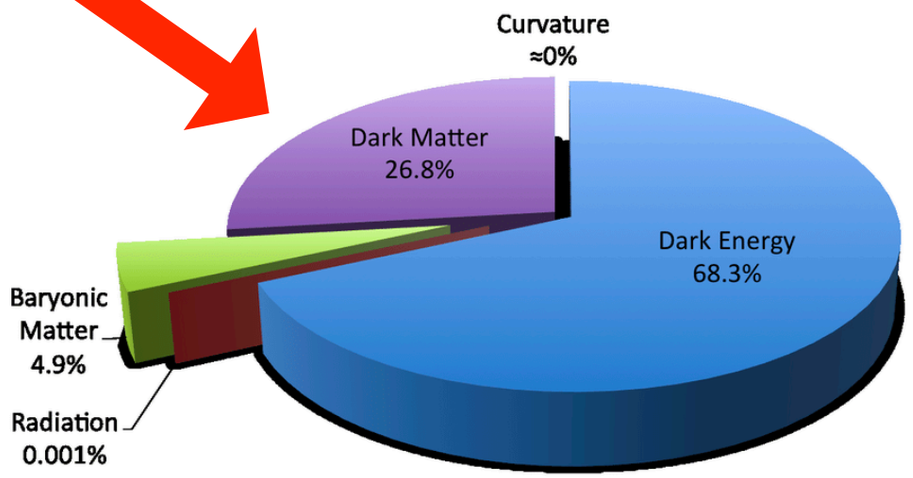
CMB map(s)



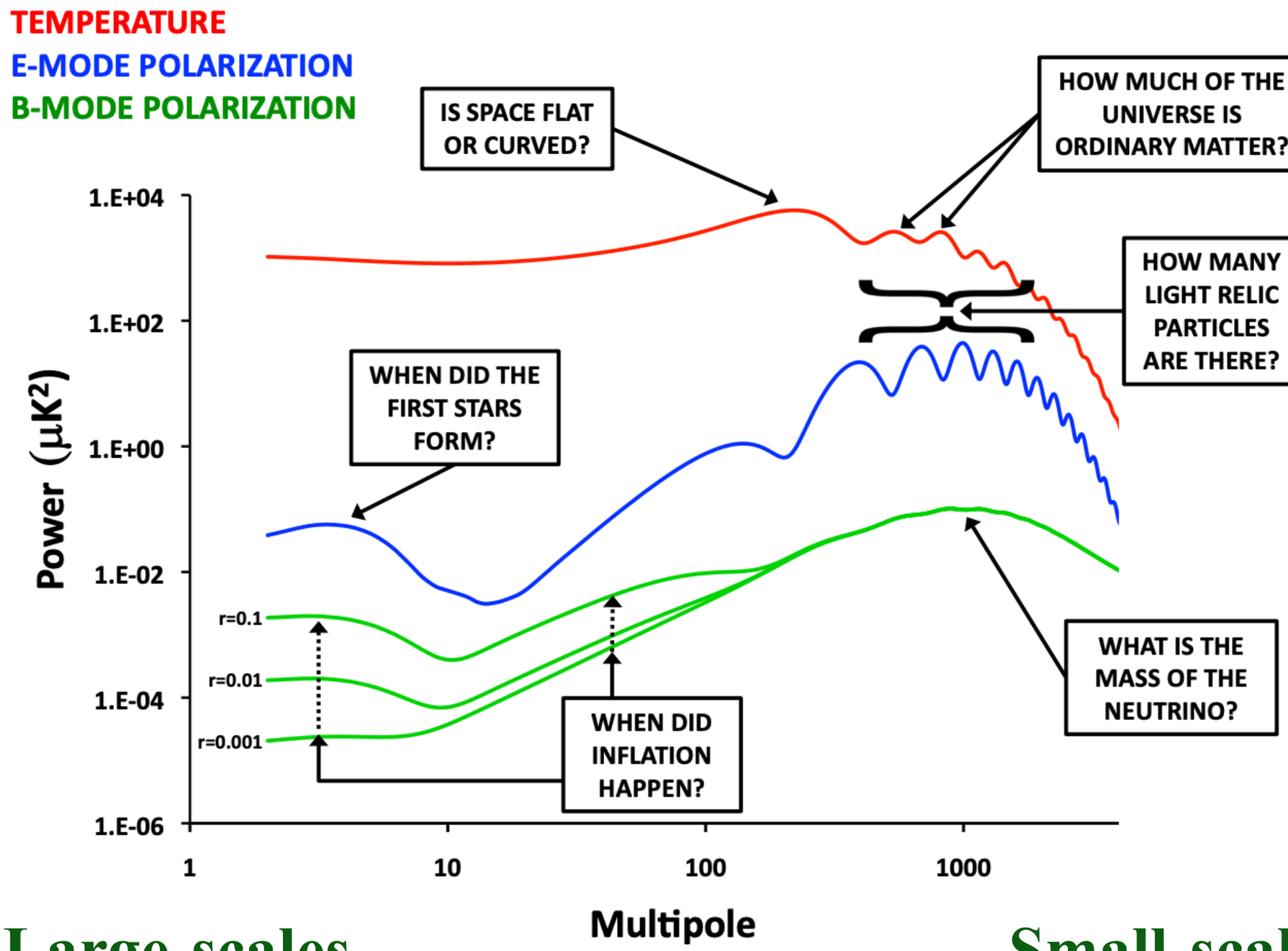
Power spectra (+ external datasets)



Cosmological constraints



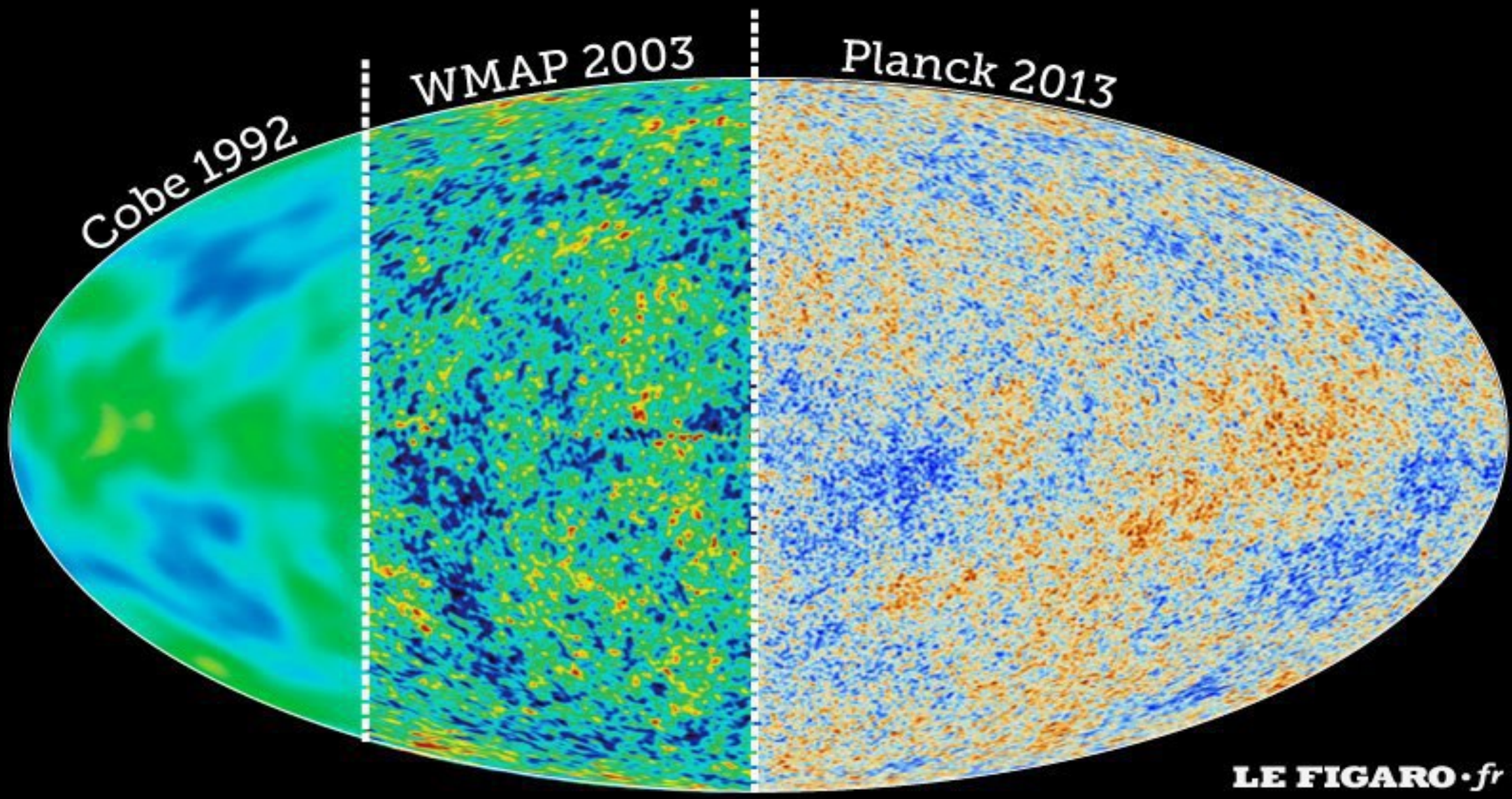
Science from CMB Power Spectra



Large-scales **Small-scales**

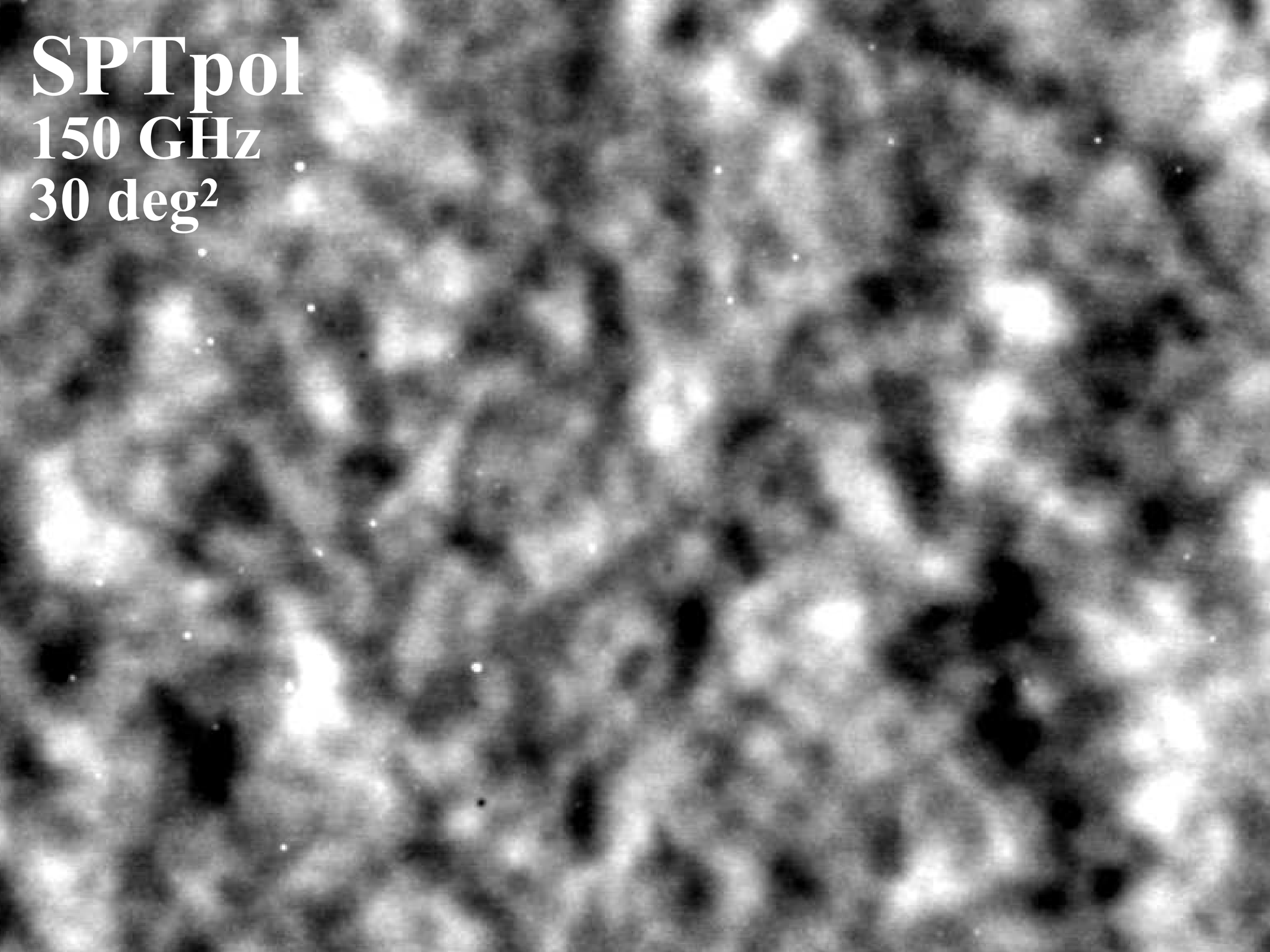
Chang, Huffenberger et al. 2022 (arXiv: 2203.07638)

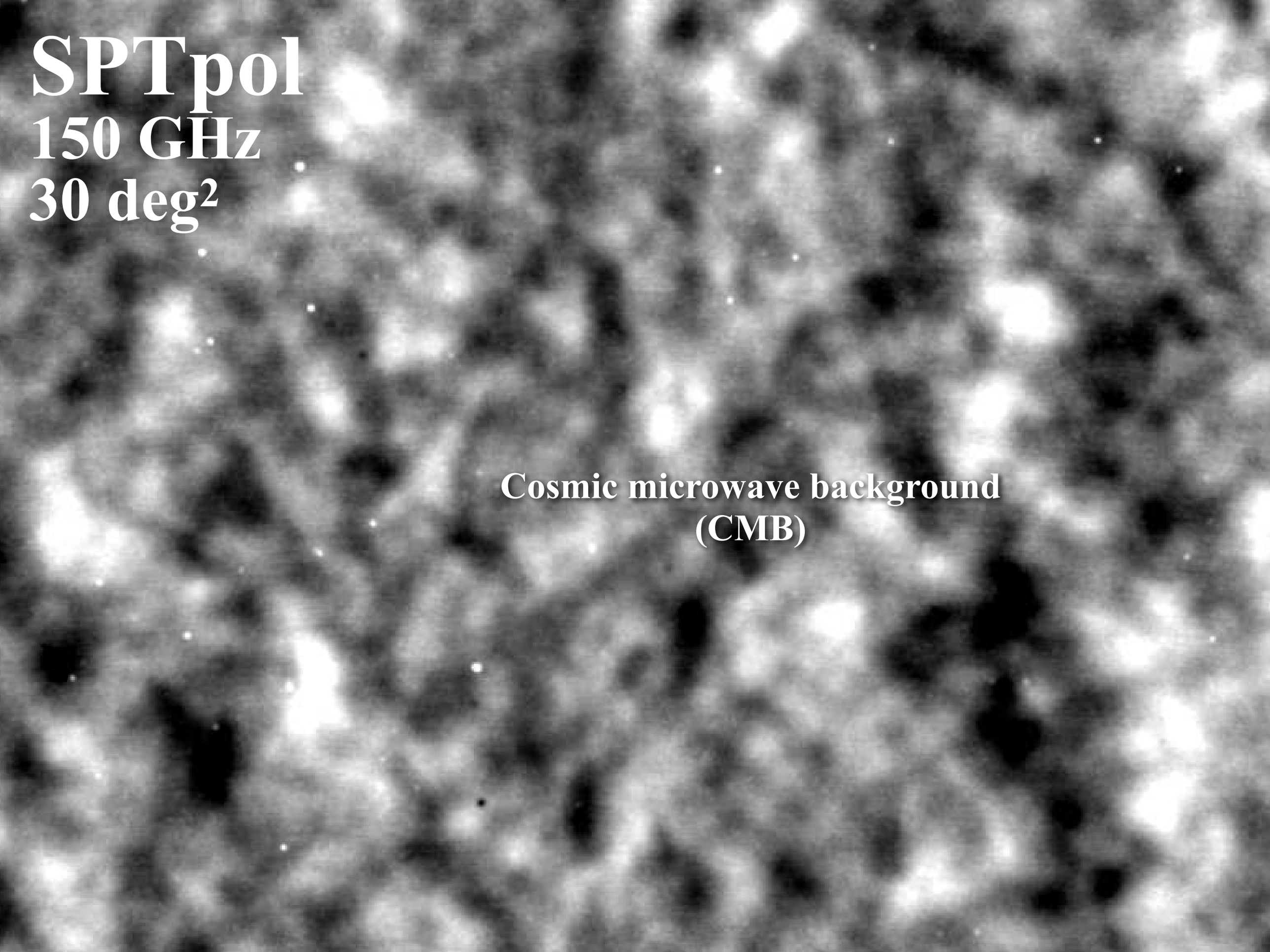
Evolution of CMB experiments



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 deg^2

Radio and dusty galaxies show up as bright spots

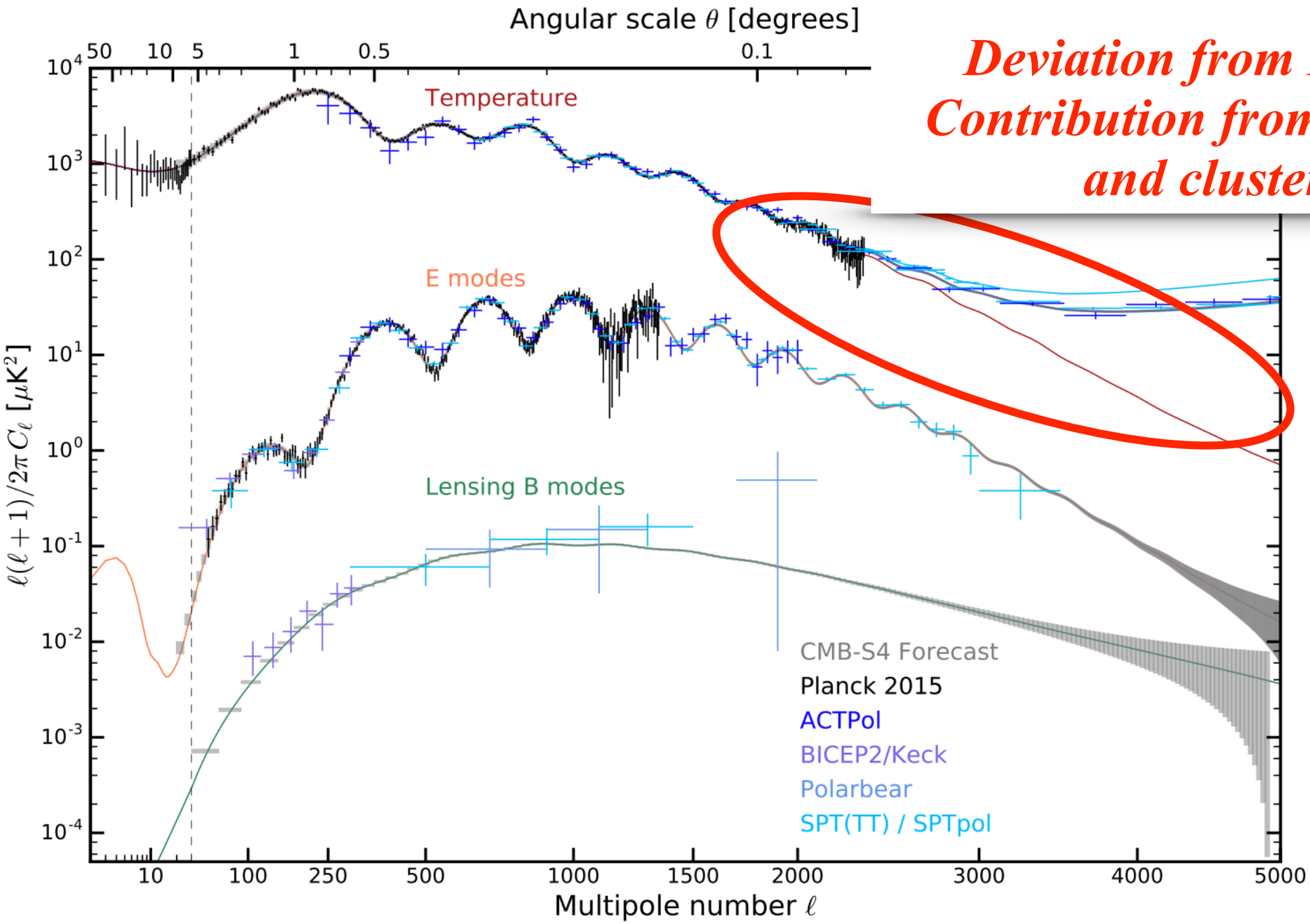
Dusty, starforming galaxy

SPTpol
150 GHz
30 deg^2

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

CMB Power Spectra - T/P

Power Spectra



Deviation from LCDM: Contribution from galaxies and clusters.

Large-scales **Small-scales**

CMB experiments: Chile

AdvACTPol: Chile

90/150/220 GHz

Simons Observatory: Chile

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

ALMA: Chile

Cerro Chajnantor: High altitude ~5200 metres.

Low water vapour level.

+ CLASS
+ POLABEAR
+ Simons Array

CMB experiments: South Pole

Altitude: ~3000 metres.

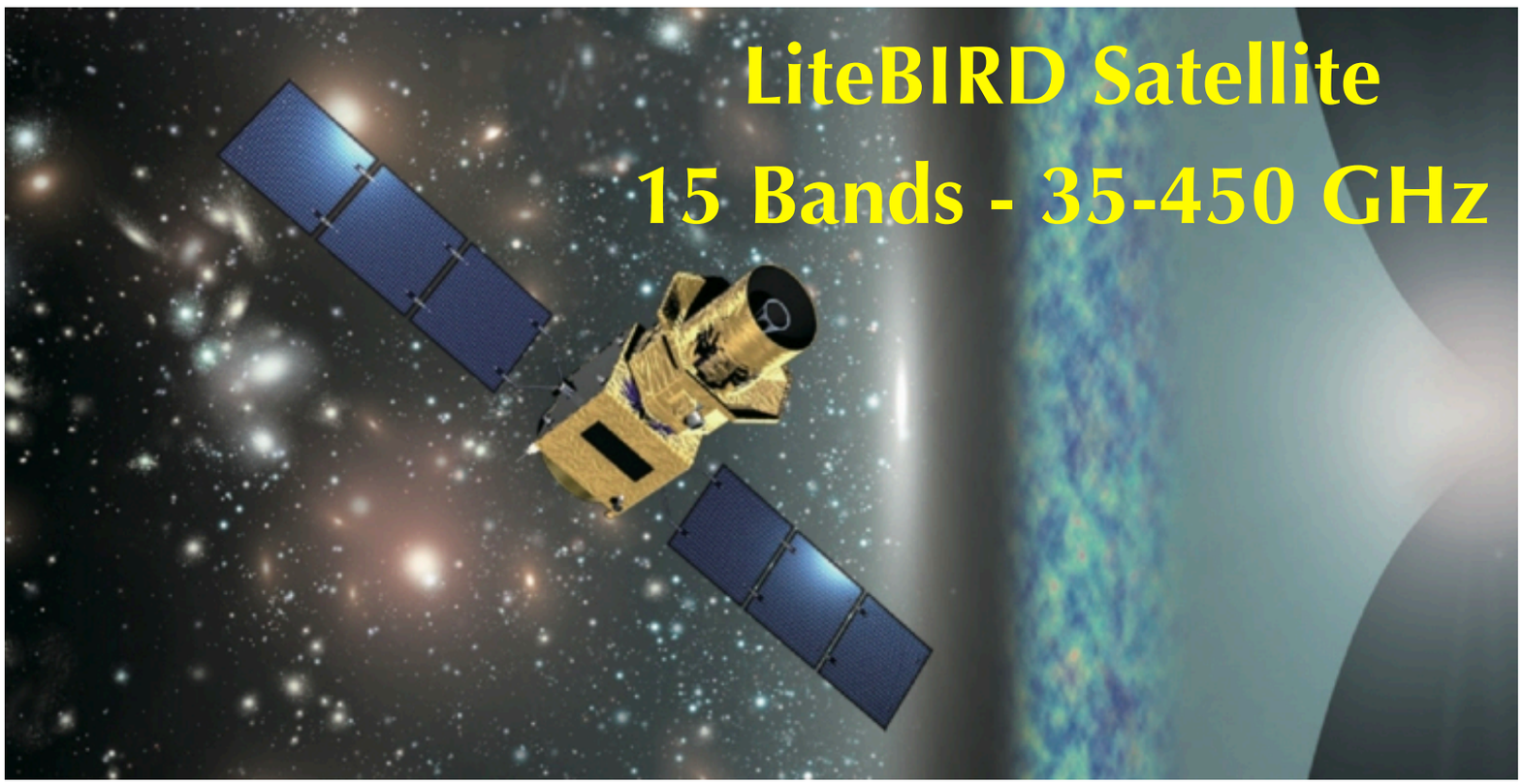
Flat giant sheet of ice.

Very low water vapour level.

Extremely stable atmosphere.

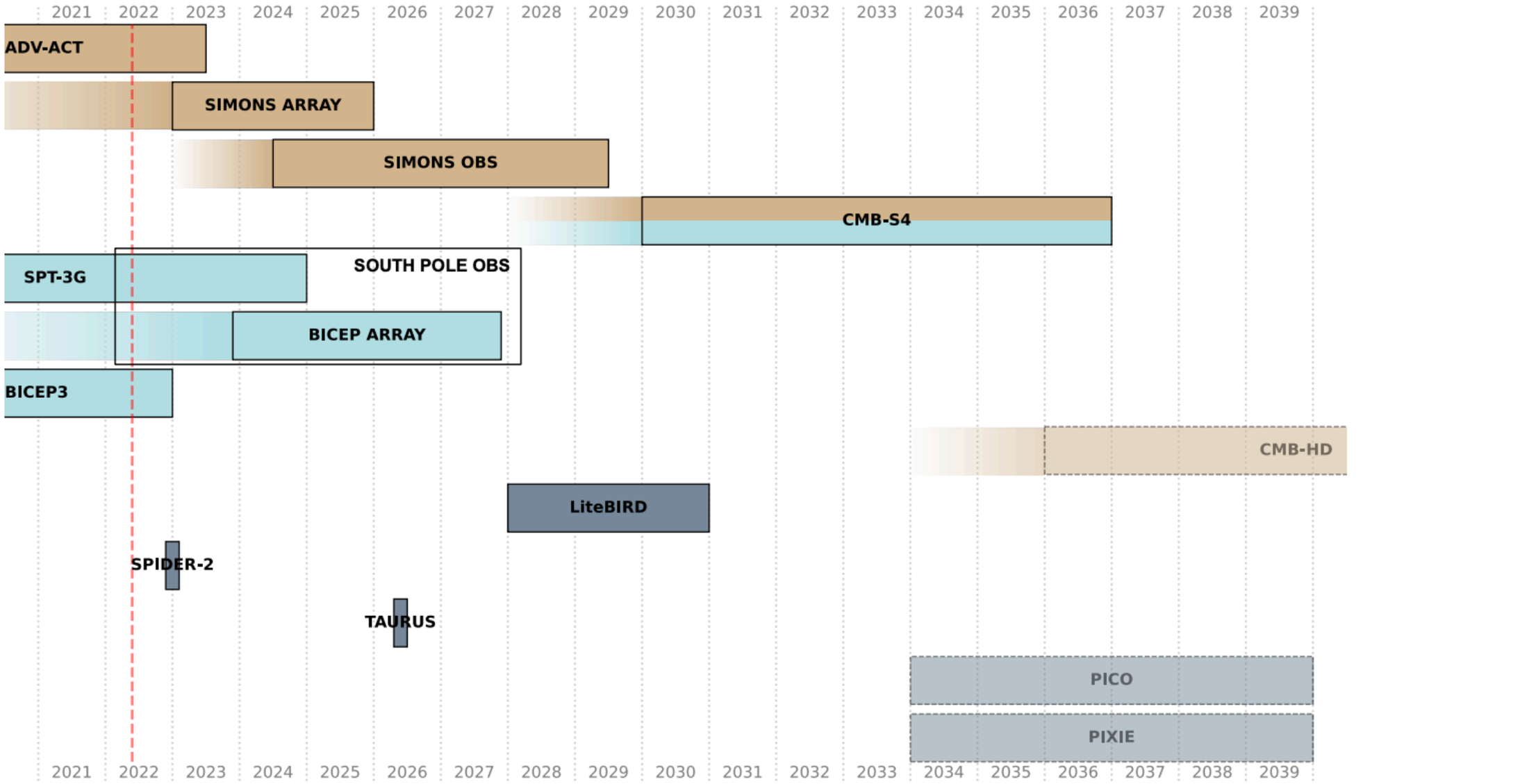
CMB experiments: South Pole

CMB experiments: Future



CMB experiments

Chile
South Pole
Balloon/Space



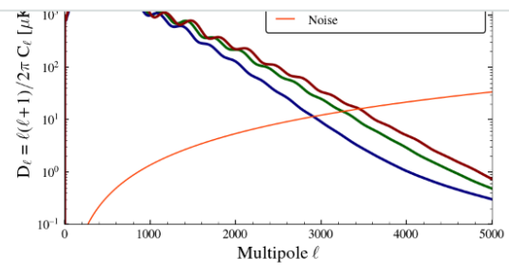
Chang, Huffenberger et al. 2022 (arXiv: 2203.07638)

Jupyter notebook example

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

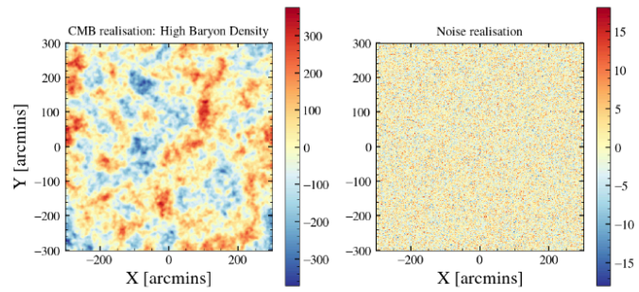
github.com/sriniraghunathan/cosmology_school/blob/main/make_mock_sky.ipynb

SPT-SZ GH SPTpol 3G SR CMB-S4




```
In [146…
#create a Gaussian realisation now using the above power spectrum
np.random.seed(100)
#which_cosmo = 'lcdm'
#which_cosmo = 'low_baryons'
which_cosmo = 'more_baryons'
labval, colorval = diff_cosmo_dic[which_cosmo]
cl_cmb = cl_cmb_dic[which_cosmo]
print(cl_cmb)
mapparams = [nx, ny, dx]
mock_cmb_map = make_gaussian_realisation(mapparams, els, cl_cmb)
mock_noise_map = make_gaussian_realisation(mapparams, els, nl)
clf()
figure(figsize = (8, 4))
subplot(121); imshow(mock_cmb_map, cmap = cmap, extent=[x1, x2, x1, x2]); colorbar(); title(r'CMB realisation: %s' %(labval), fontsize = 
xlabel(r'X [arcmins]', fontsize = 14); ylabel(r'Y [arcmins]', fontsize = 14)
subplot(122); imshow(mock_noise_map, cmap = cmap, extent=[x1, x2, x1, x2]); colorbar(); title(r'Noise realisation', fontsize = 10);
xlabel(r'X [arcmins]', fontsize = 14);
show()

[0.00000000e+00 0.00000000e+00 1.01935171e+03 ... 1.85146676e-07
 1.84748385e-07 1.84353835e-07]
```




```
In [147…
#make sure the above sim power spectrum matches the input
binned_els, binned_cl_cmb = map2cl(mapparams, mock_cmb_map)
binned_els, binned_nl = map2cl(mapparams, mock_noise_map)
if (1):
    dl_fac = els * (els+1)/2/np.pi
    dl_fac_binned = binned_els * (binned_els+1)/2/np.pi
    ax = subplot(111, yscale = 'log')

    plot(els, cl_cmb * dl_fac, color = 'black', label = r'CMB: Analytic: %s' %(labval), lw = 3., alpha=0.5)
    plot(binned_els, binned_cl_cmb * dl_fac_binned, color = 'black', label = r'CMB: Mock')

    plot(els, nl * dl_fac, color = 'orangered', label = r'Noise: Analytic', lw = 3., alpha=0.5)
    plot(binned_els, binned_nl * dl_fac_binned, color = 'orangered', label = r'Noise: Mock')

    xlabel(r'Multipole $\ell$')
    ylabel(r'D$_{\ell}$ = $\ell (\ell+1)/2/\pi$C$_{\ell}$ [$\mu$K$^{2}$]', fontsize = 14)
    ymin, ymax = 0.1, 1e4
    xlim(0, lmax); ylim(ymin, ymax)
    legend(loc = 1)
    show()
```