



# OBSERVATIONAL COSMOLOGY: CMB AND REIONIZATION

## References:

<https://background.uchicago.edu/~whu/intermediate/intermediate.html>

arXiv: 1811.02310

arXiv: 1112.1862

arXiv:1212.1075

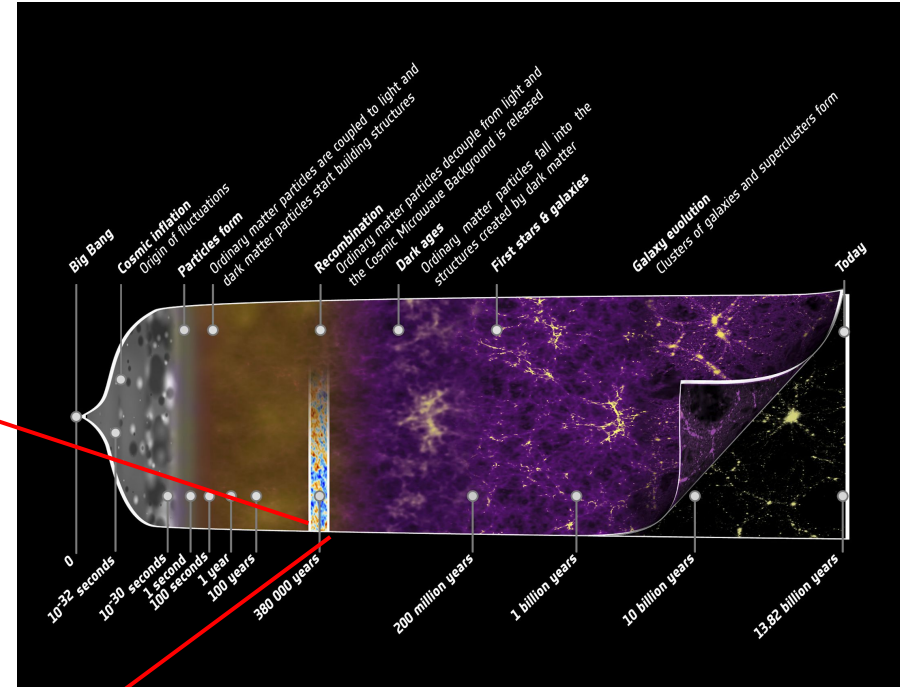
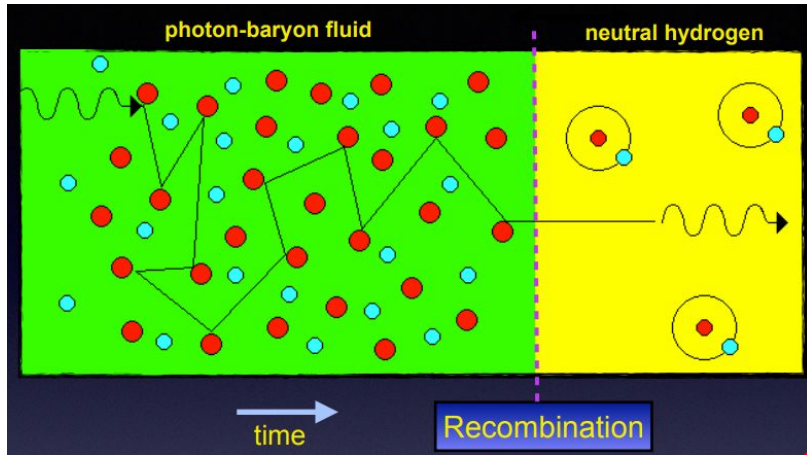
arXiv:1511.04335

arXiv:1312.2462

arXiv:1303.5081

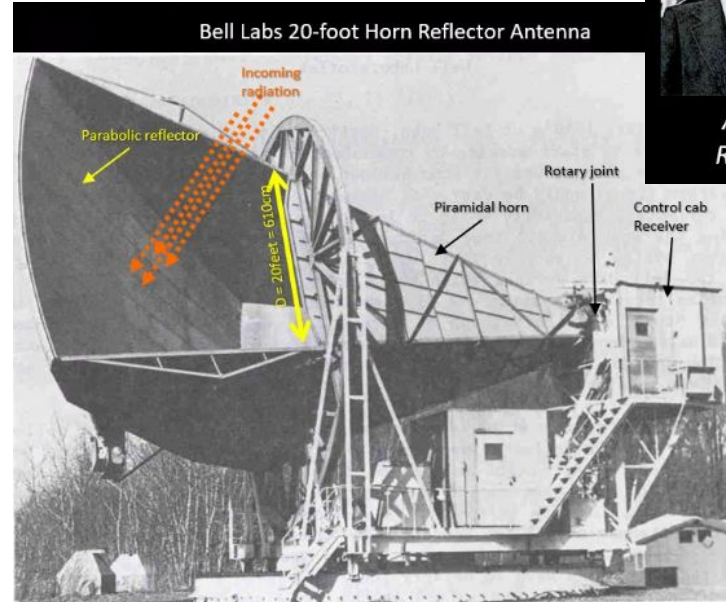
# CMB: DISCOVERY AND DETECTION

- **1948:** The existence of the CMB was first predicted by **George Gamow, Ralph Alpher, and Robert Herman**.
  - if the universe began in a hot, dense state, the intense thermal radiation from that era should still exist today.
  - Because the universe has expanded, this light would have stretched into the microwave part of the electromagnetic spectrum.



# CMB: DISCOVERY AND DETECTION

- **1964:** The radiation was discovered by accident by **Arno Penzias** and **Robert Wilson** at Bell Labs (1978 Nobel prize).
  - They were using a large horn antenna in Holmdel, New Jersey, intended for satellite communication.
  - They kept picking up a persistent, low-level noise coming from every direction in the sky. After cleaning out pigeon droppings from the antenna and ruling out urban interference, they realized they had found the relic radiation predicted decades earlier.
  - This discovery provided the "smoking gun" evidence that confirmed the Big Bang theory over the competing Steady State model.



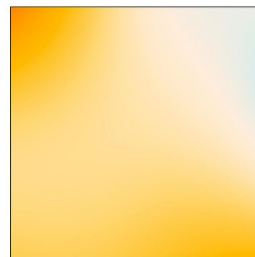
Arno Penzias  
Robert Wilson

## Unique technical characteristics:

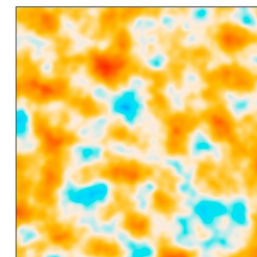
- Low-noise receiver ( $T_{\text{noise}} \sim 25\text{K}$ )
- Low sidelobes antenna ( $< -80\text{ dB}$ )
- Degree-scale resolution ( $\theta \sim 0.8^\circ$ )
- Low atmospheric noise (4GHz,  $T_{\text{atm}} \sim 2.3\text{K}$ )

# CMB: DISCOVERY AND DETECTION

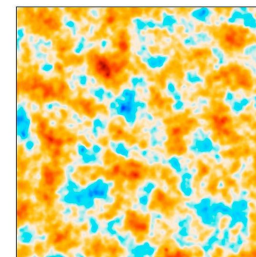
- **1989, COBE satellite:** First all-sky CMB survey founding that the CMB wasn't perfectly smooth
- **1998, BOOMERang:** high-altitude balloon launched from Antarctica. With its higher resolution it was the first experiment to clearly detect the "first acoustic peak" in the CMB power spectrum
- **2001, WMAP satellite:** improved sensitivity and angular resolution. First full-sky detection of E-mode polarization
- **2009, Planck satellite:** most detailed image of the CMB sky today measuring intensity and polarization (E and B-mode) of the radiation



COBE



WMAP



Planck

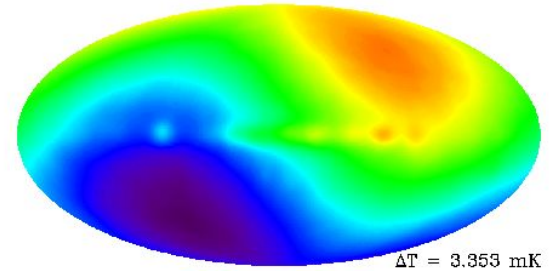
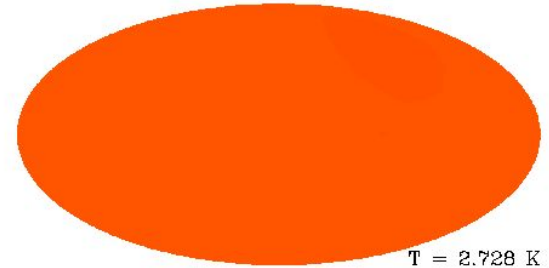
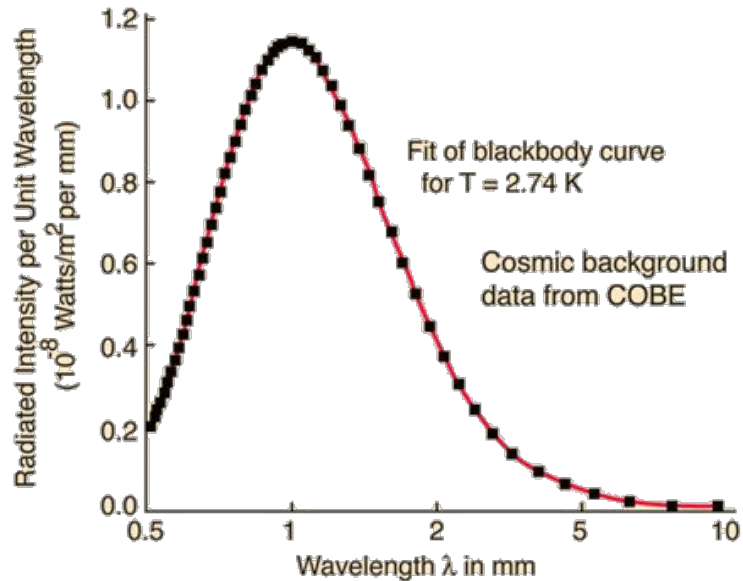
Resolution  $7^\circ$

Resolution  $0.5^\circ$   
5x more sensitive  
than COBE

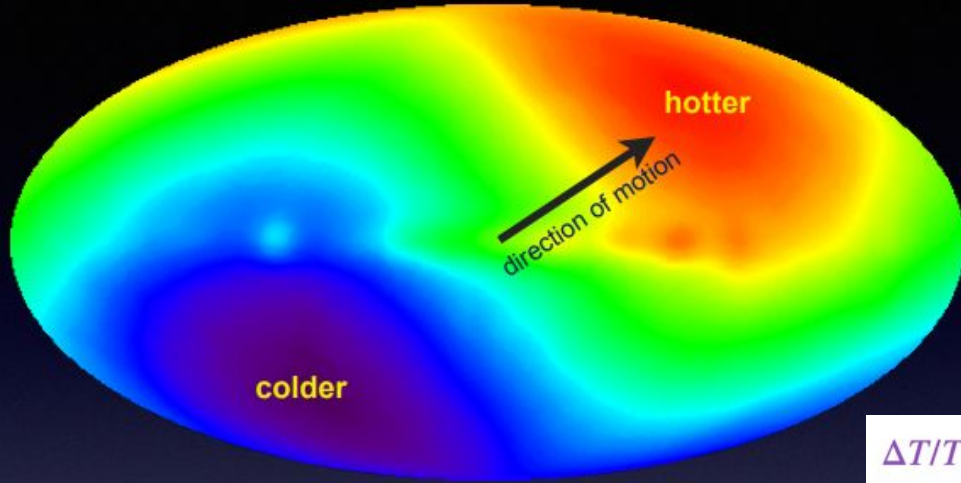
Resolution  $0.16^\circ$   
15x more sensitive  
than COBE

# CMB MONOPOLE

- Almost perfect black body spectrum radiation at  $T=2.725$  K



# CMB DIPOLE



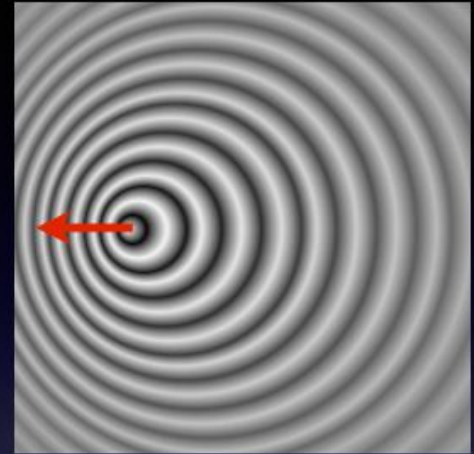
$$\Delta T/T \approx 10^{-3}$$

Our peculiar motion is made up of:

- Motion of Earth around Sun (~30 km/s)
- Motion of Sun around MW center (~220 km/s)
- Motion of MW towards Virgo cluster (~300 km/s)

---

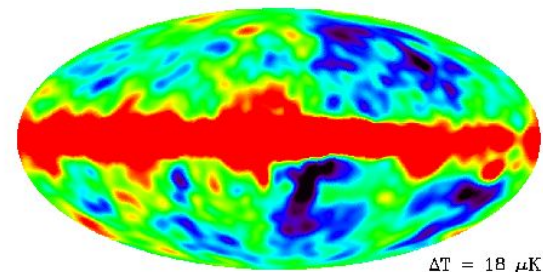
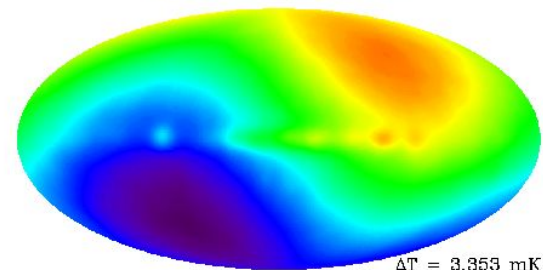
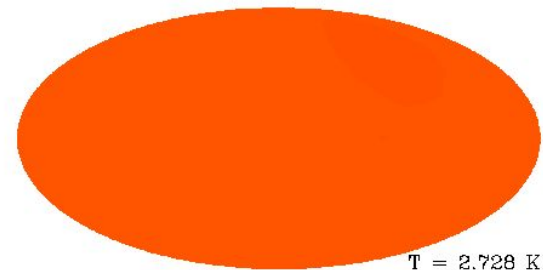
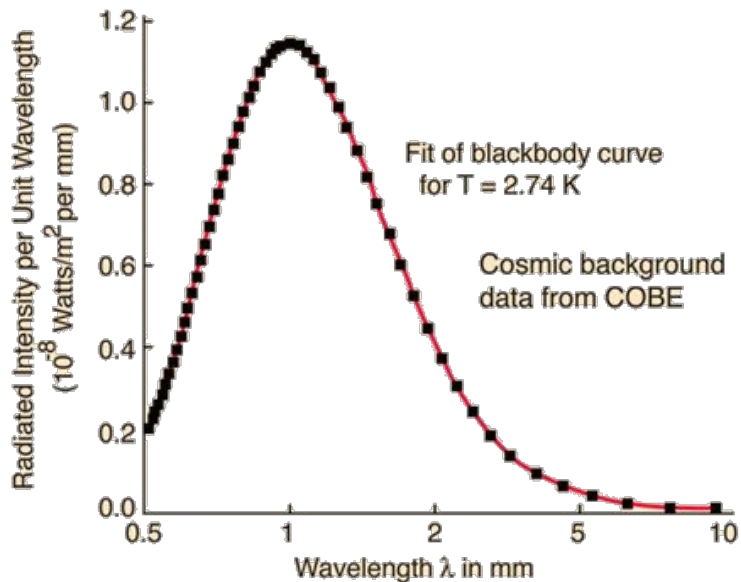
Total vector sum of 369 km/s



Origin of **CMB dipole** is Doppler effect due to our peculiar motion

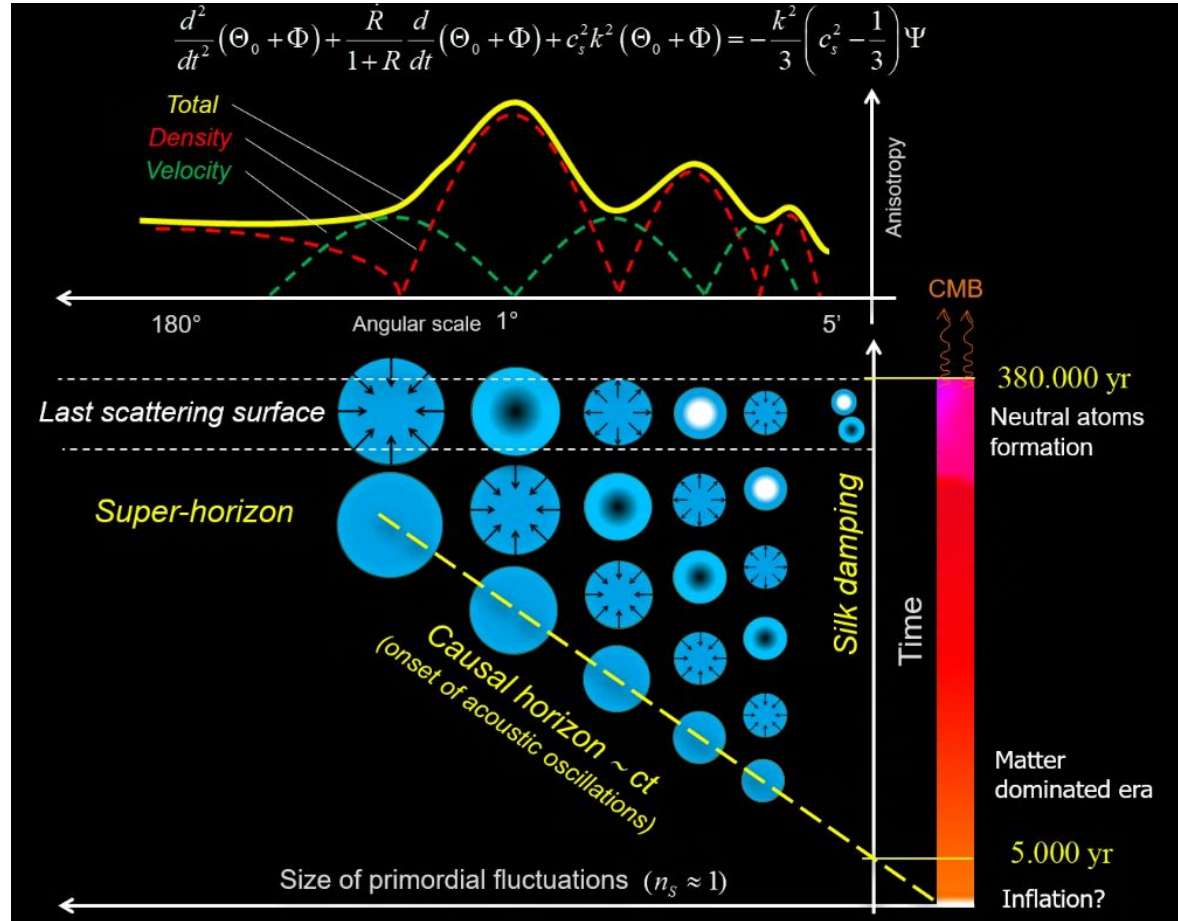
# CMB ANISOTROPIES

- Almost perfect black body spectrum radiation at  $T=2.725$  K
- Remarkably uniform across the sky  $\rightarrow$  Only tiny fluctuations on temperature of the order  $\Delta T/T=10^{-5}$  (after removing the dipole)



# CMB ANISOTROPIES

- Tiny quantum fluctuations are stretched to cosmic scales by inflation, setting the initial density perturbation of the universe.
- Prior to recombination – i.e. formation of neutral hydrogen – the baryon-photon fluid undergoes acoustic oscillations driven by gravity and radiation pressure
- When the Universe cooled enough for neutral hydrogen to form, photons start to free streaming across the cosmos.
- The temperature pattern we observe today provides a picture of the density perturbation at recombination ( $z \approx 1100$ )



# CMB ANISOTROPIES

To statistically analyze the CMB anisotropies:

- Measure the anisotropies distribution over the sky

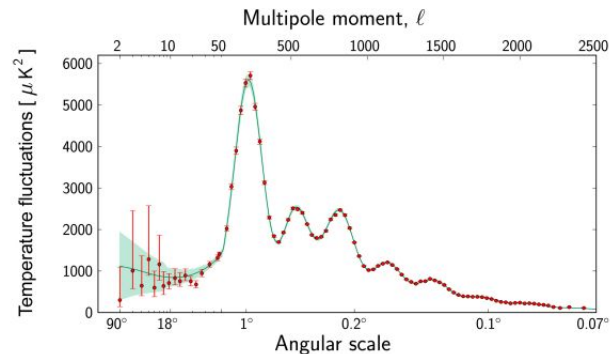
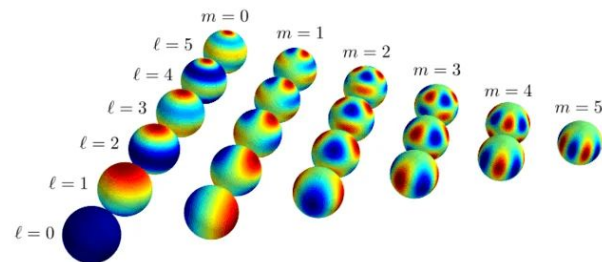
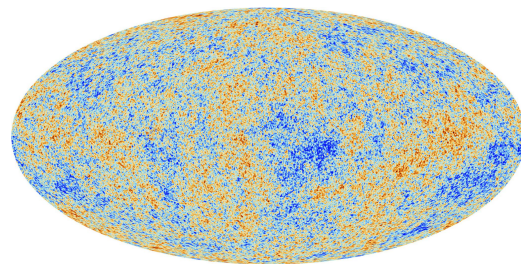
$$\frac{\Delta T}{T}(\theta, \phi) = \frac{T(\theta, \phi) - \bar{T}}{\bar{T}}$$

- Expand in spherical harmonics

$$\frac{\Delta T}{T}(\theta, \phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

- Compute the angular power spectrum

$$C_{\ell} = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} \langle |a_{\ell m}|^2 \rangle$$



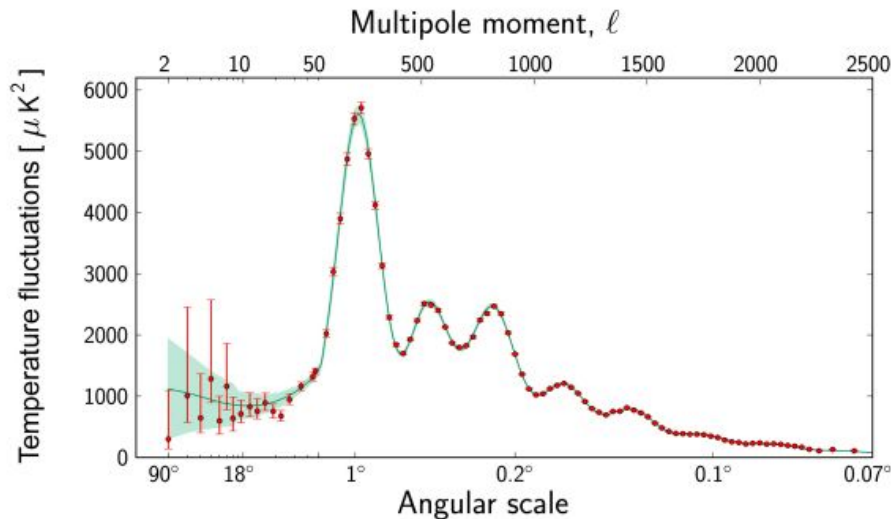
# CMB ANISOTROPIES

The TT power spectrum information is sample-variance limited (we have only one Universe to observe!):

- At low multipoles (i.e. large angular scales) only few modes can be measured, and the sample variance increases:

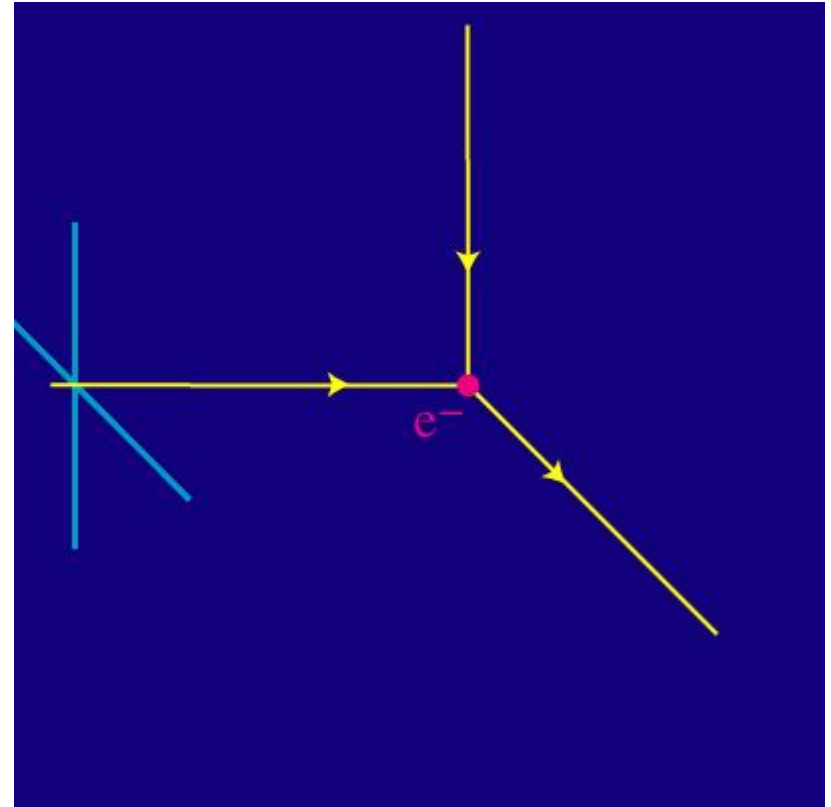
$$\frac{\Delta C_\ell}{C_\ell} = \sqrt{\frac{2}{2\ell+1}}$$

- For almost every scale that contains useful information (up to  $\ell \approx 1500$ ), Planck's sensors were so sensitive that the only remaining source of error is Cosmic Variance itself
- Building a better temperature satellite wouldn't improve our cosmological constraints, but there's still room for improvements by looking at polarization



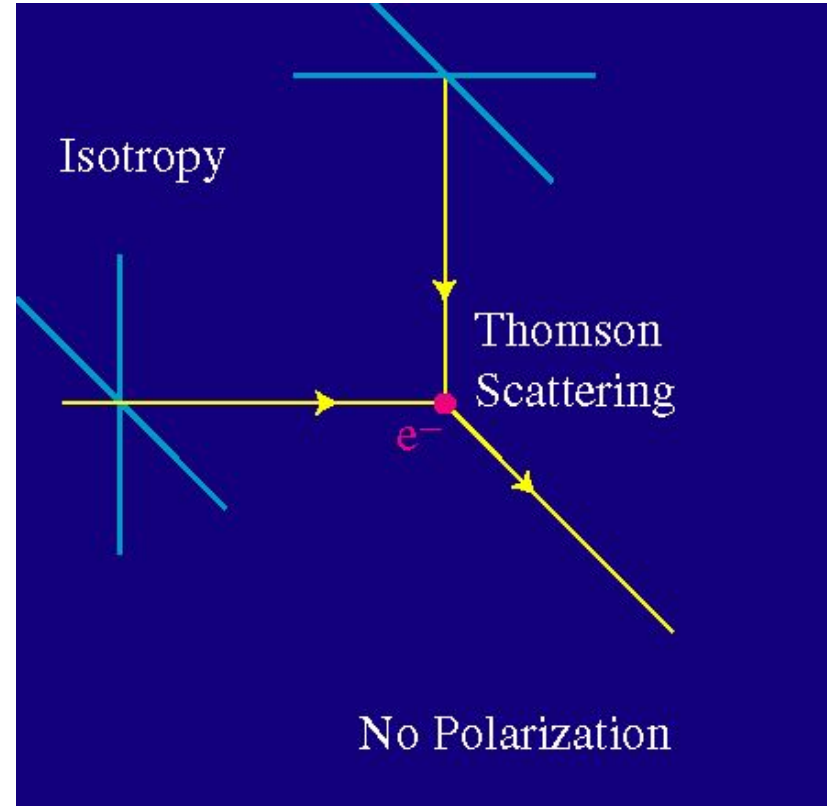
# CMB POLARIZATION

- Consider incoming radiation from the left being scattered by 90 degrees out of the screen from a free electron
- The free electron is accelerated in the direction of the photon's electric field. This makes the electron emit a new photon linearly polarized



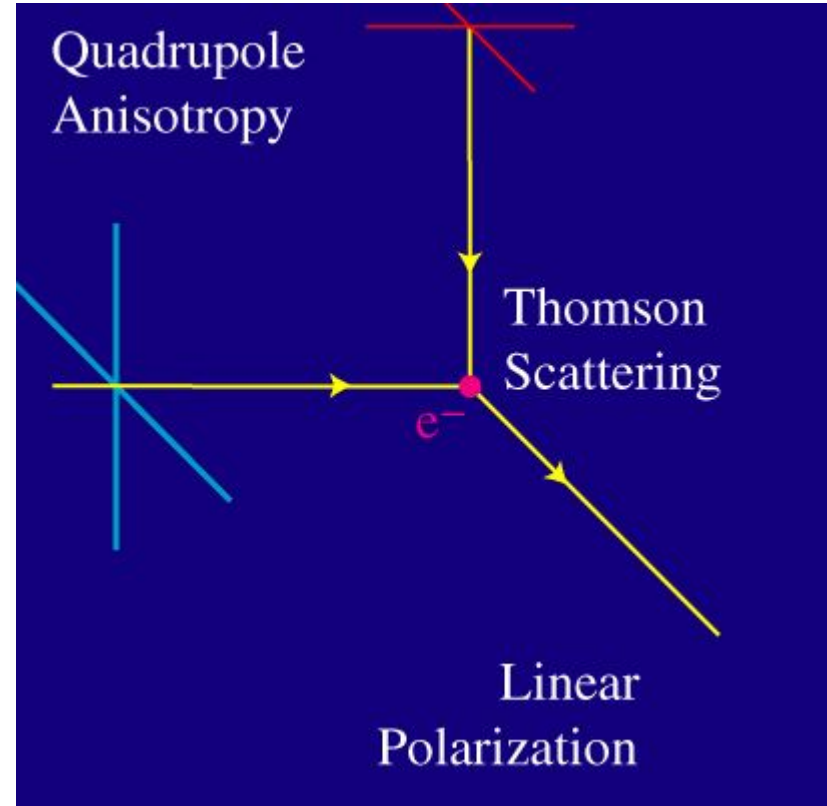
# CMB POLARIZATION

- If the incoming radiation from the left and top are of equal intensity, the result is no polarization in the outgoing direction
- In case of isotropic radiation we do not expect a net polarization of the scattered light



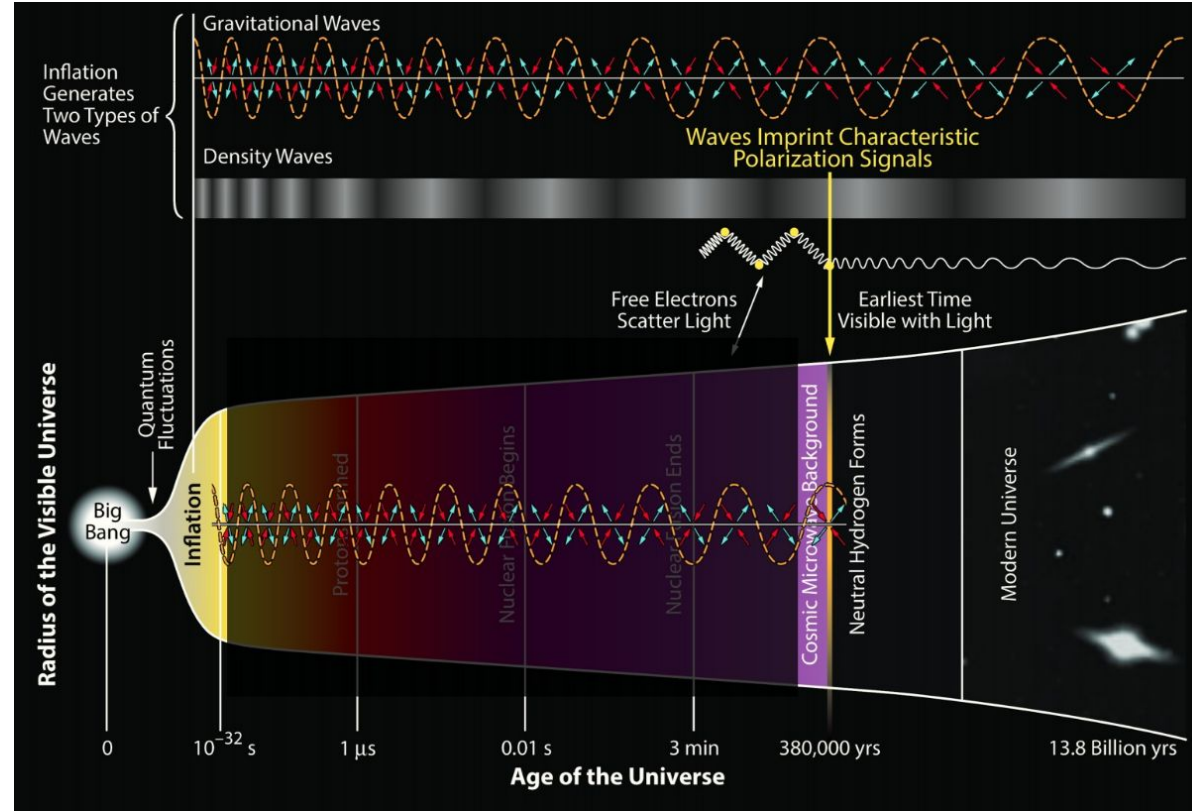
# CMB POLARIZATION

- Only if the intensity of the radiation varies at 90 degrees, i.e. the distribution has a quadrupole pattern, does a net linear polarization result
- In particular there is a net linear polarization ( ~10% ) that is aligned with the cold axis of the quadrupole anisotropy



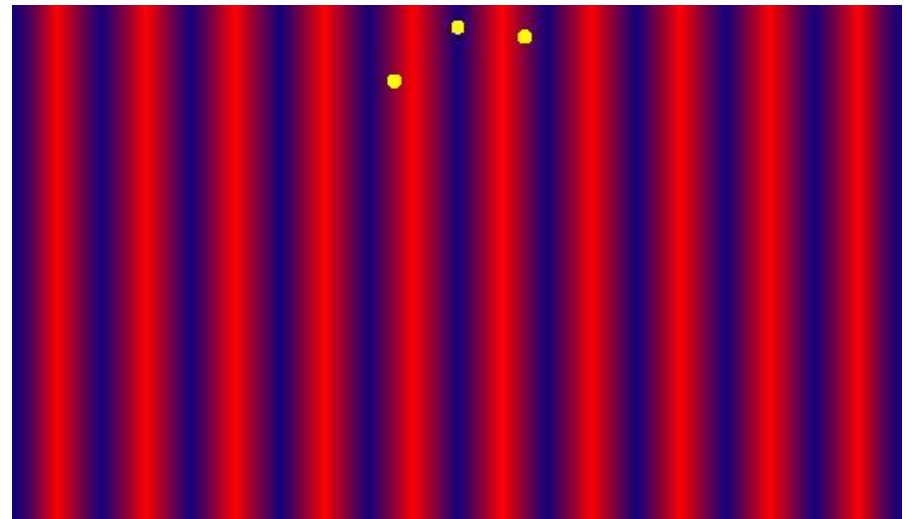
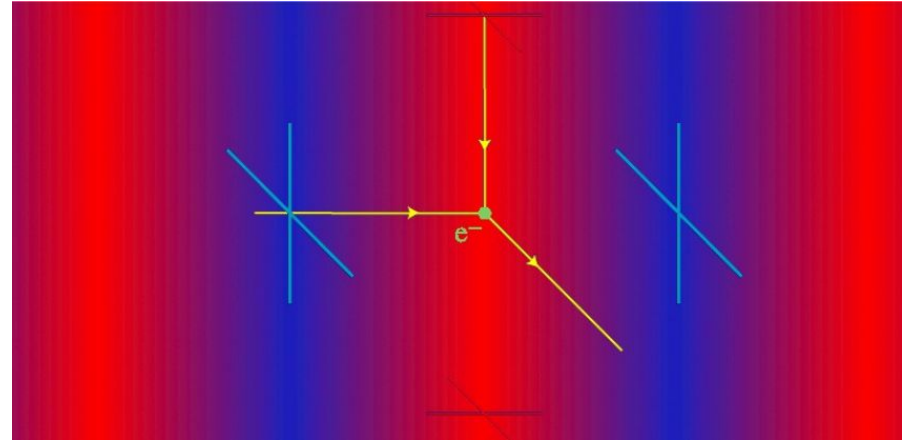
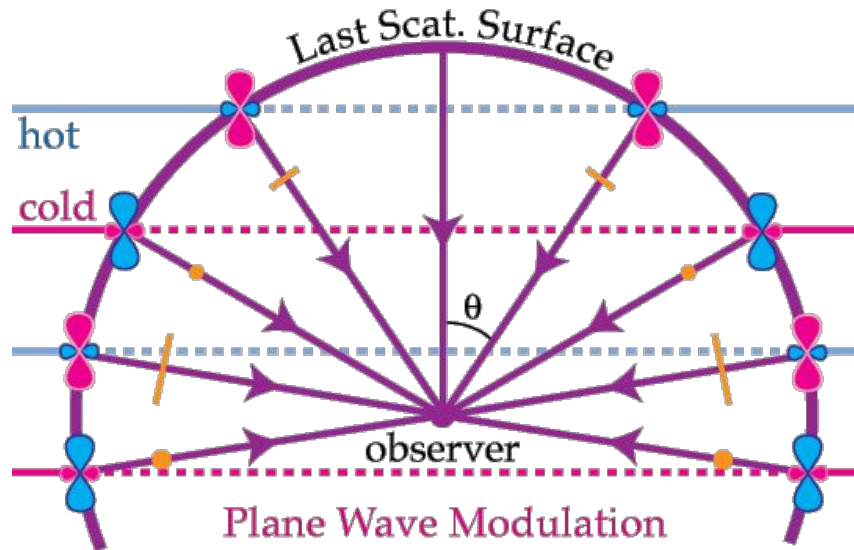
# CMB POLARIZATION

- Thomson scattering of a radiation field with a quadrupole anisotropy produces linear polarization.
- The relevant epoch for the generation of polarization in the CMB is around recombination since at early times scattering is too efficient to allow a significant quadrupole to grow, while after recombination scatterings are very rare (until the universe reionizes).
- There are two main physical mechanism for producing a quadrupole anisotropy: **density fluctuations** and **gravitational waves**



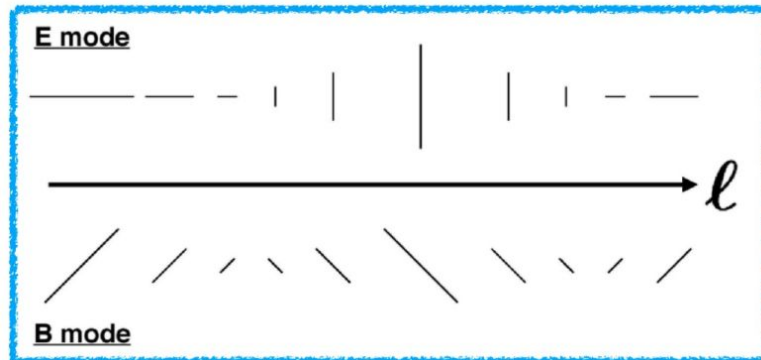
# CMB POLARIZATION

- The observer today sees the linear polarization vary across the sky in a pattern which is the projection of the quadrupole anisotropies at recombination

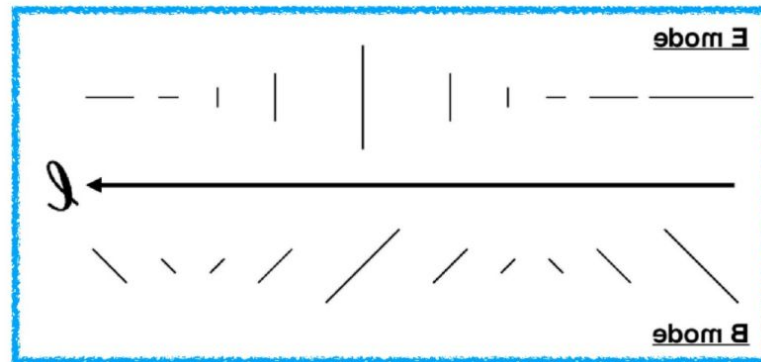


# CMB POLARIZATION

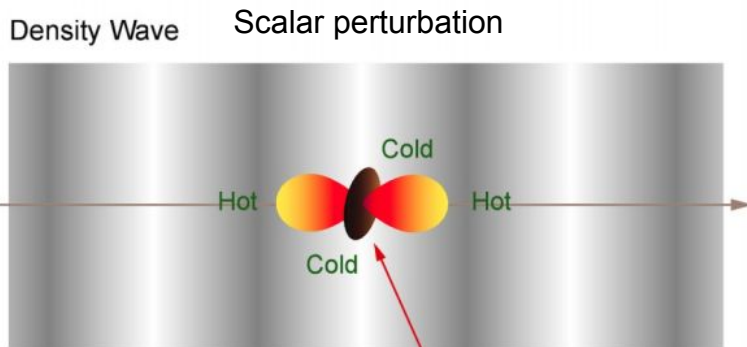
- Polarization is a spin-2 field. We can split it in two orthogonal bases:
- E mode:
  - Polarisation direction parallel or perpendicular to the wavevector
  - Even parity (gradient-like)
- B mode:
  - Polarisation direction  $45^\circ$  tilted with respect to the wavevector
  - Odd parity (curl-like)



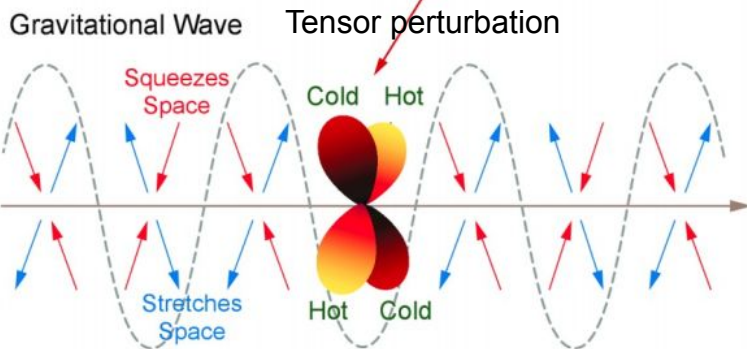
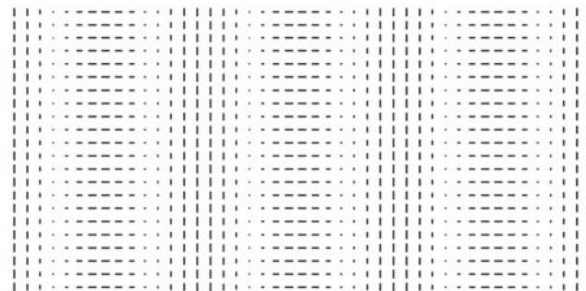
 180° rotation



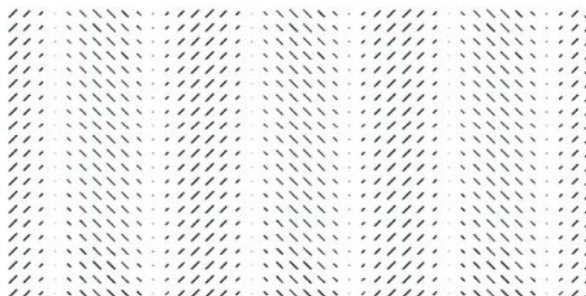
# CMB POLARIZATION



E-Mode Polarization Pattern



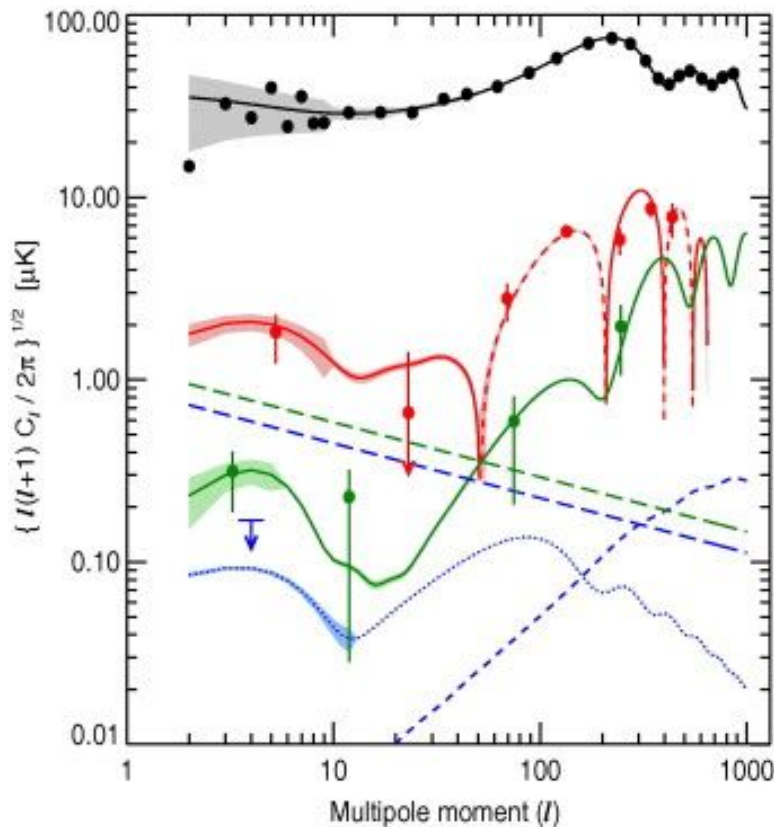
B-Mode Polarization Pattern



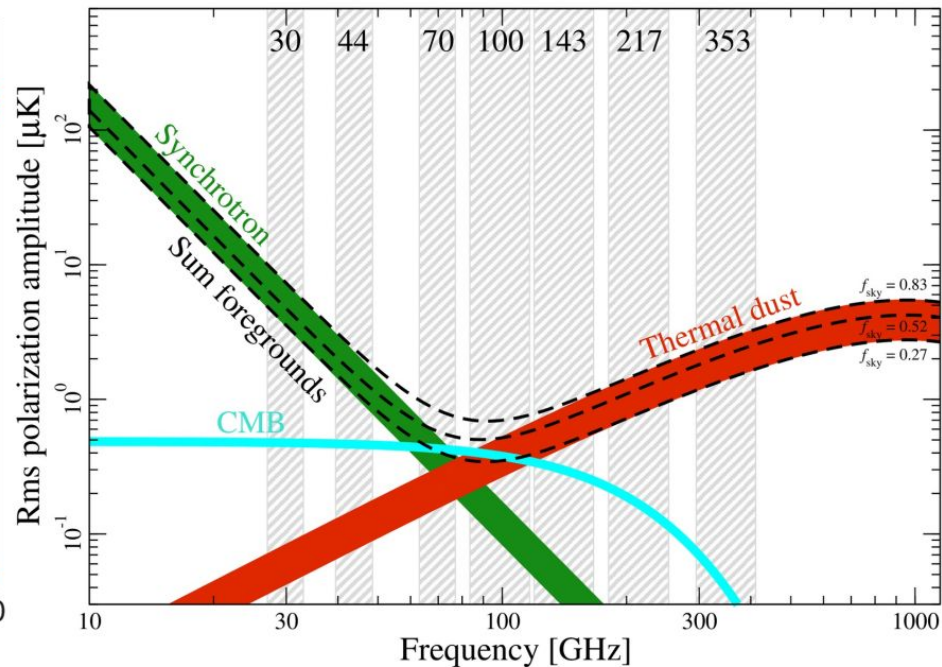
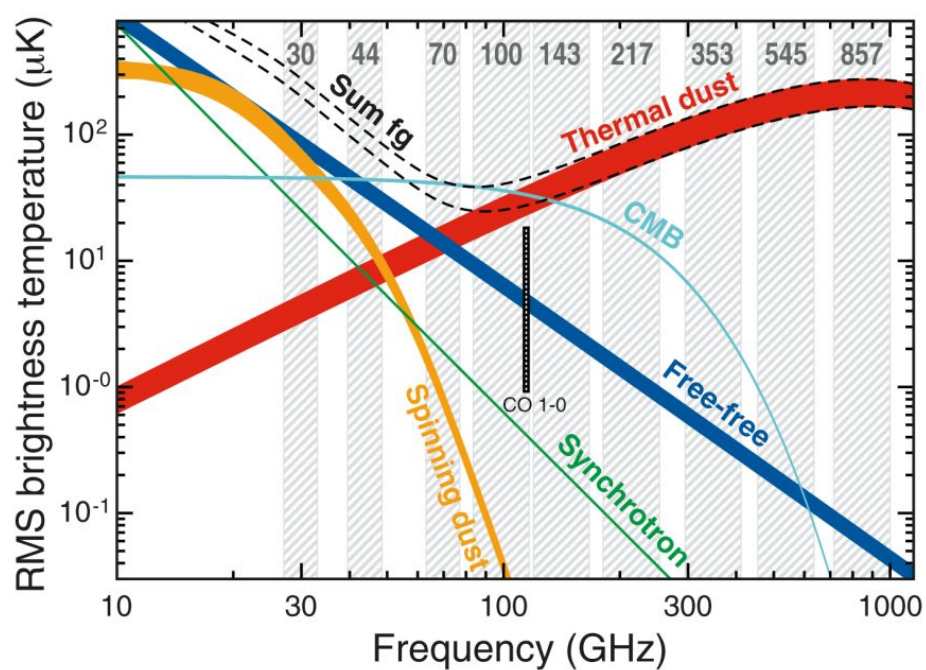
# CMB POLARIZATION

## Polarization Power Spectra:

- $\langle EE \rangle$ ,  $\langle TE \rangle$ ,  $\langle BB \rangle$
- $\langle EB \rangle$  and  $\langle TB \rangle$  vanish for parity-preserving fluctuations (like in our Universe) because  $\langle EB \rangle$  and  $\langle TB \rangle$  change sign under parity flip
- All the polarization spectra are weaker than the TT signal
  - $\langle EE \rangle$  noise limited  $\rightarrow$  reach sample-variance limit at  $l \approx 3000$
  - $BB$  noise limited / undetected



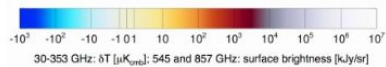
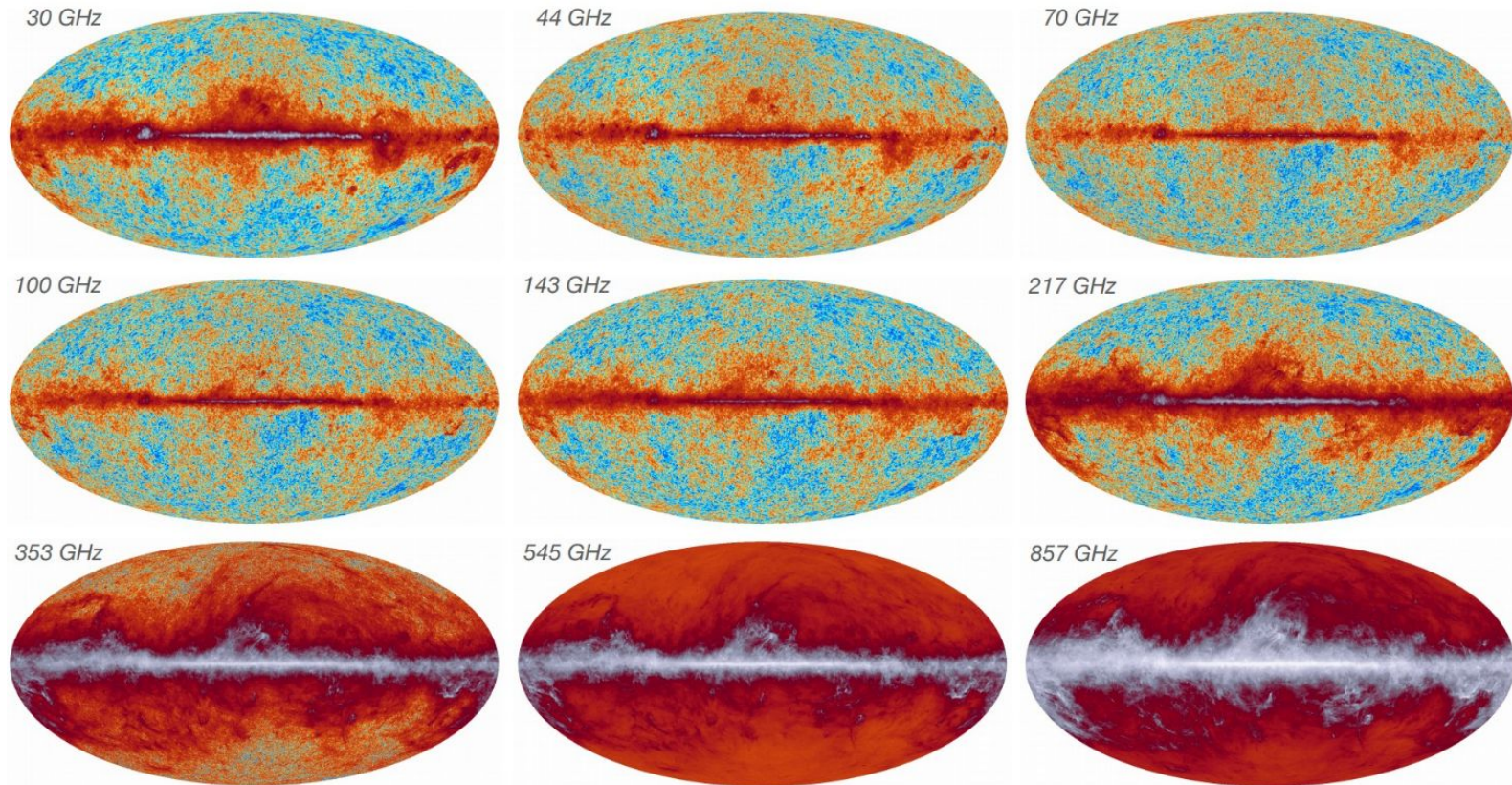
# MEASURING THE CMB



In temperature, there is a “sweet spot” – between 70 GHz and 100 GHz – where the CMB signal dominates over the foreground. The same is not true in polarization

# MEASURING THE CMB

## Planck 18 intensity maps in 9 channels



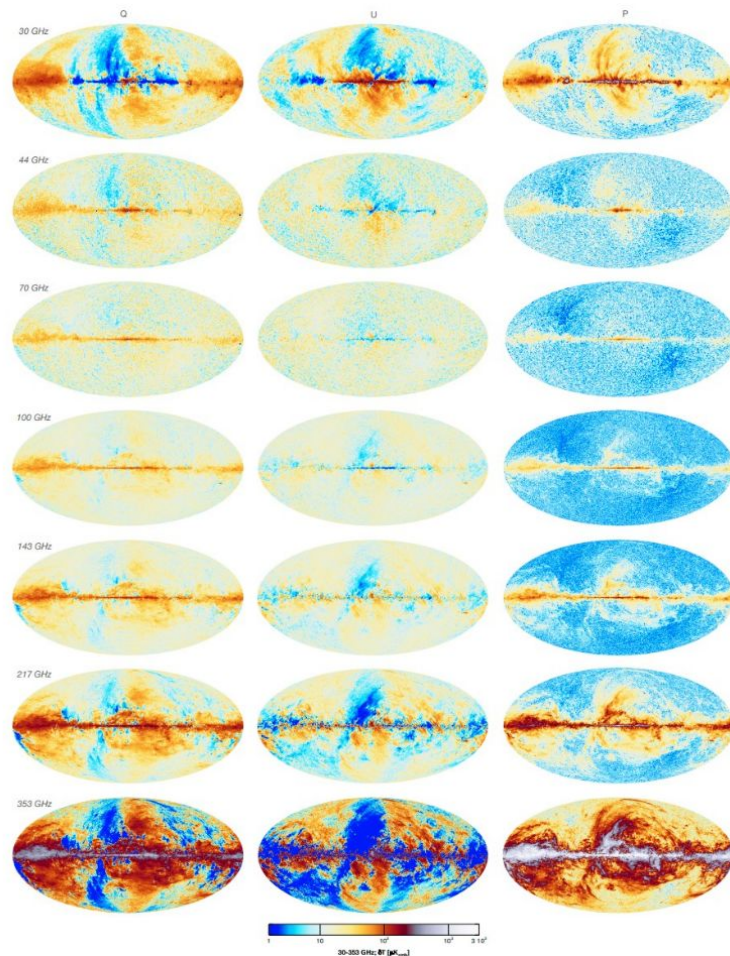
# MEASURING THE CMB

## Planck 18 maps in polarization:

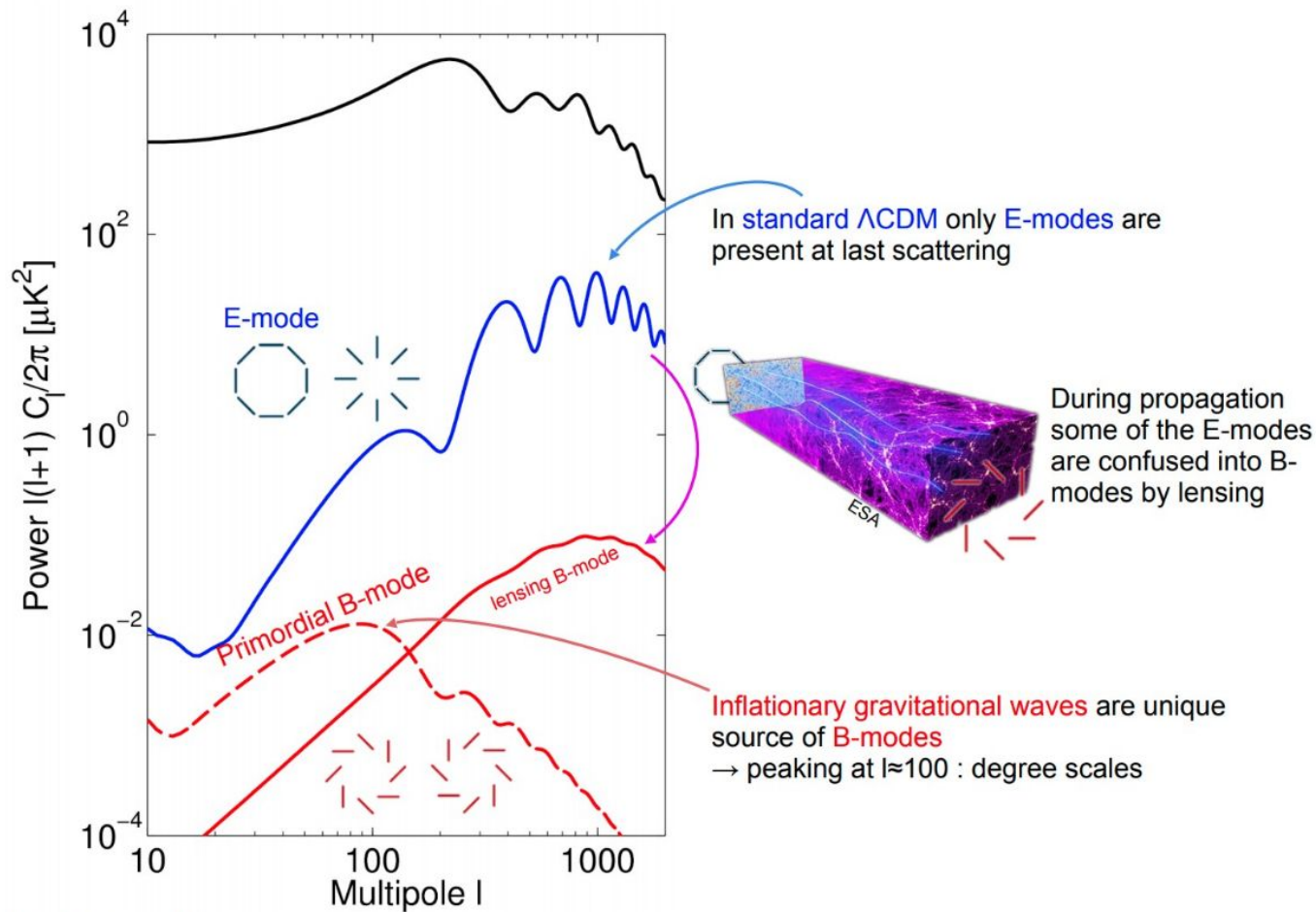
- Maps expressed in terms of Stokes Q and U parameters (local measurements of the orientation of the electric field at a specific point in the sky)
- Q and U polarization are related to E and B modes:

$$Q(\theta) = \int \frac{d^2\ell}{(2\pi)^2} (E_\ell \cos 2\phi_\ell - B_\ell \sin 2\phi_\ell) \exp(i\ell \cdot \theta)$$
$$U(\theta) = \int \frac{d^2\ell}{(2\pi)^2} (E_\ell \sin 2\phi_\ell + B_\ell \cos 2\phi_\ell) \exp(i\ell \cdot \theta)$$

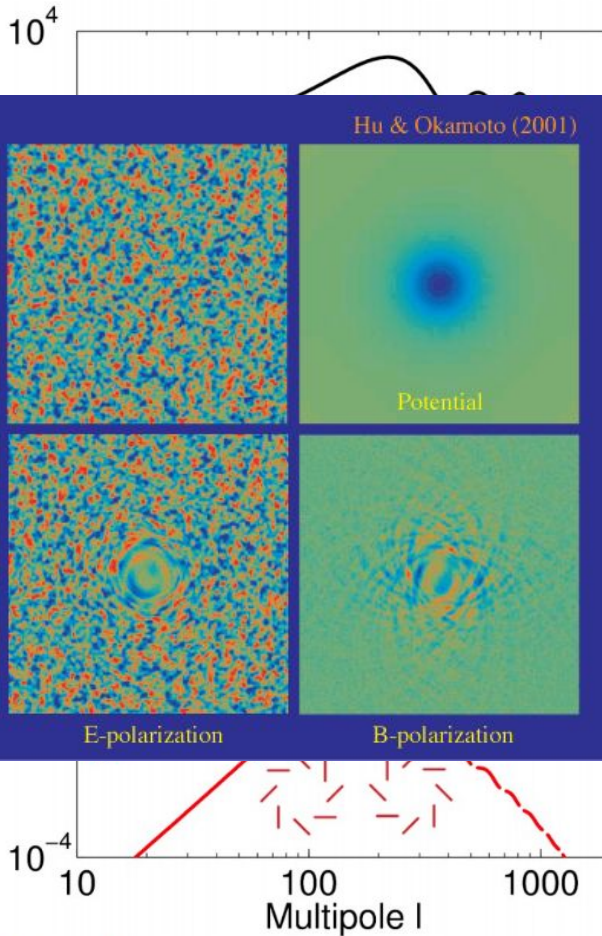
- P maps measure the polarized amplitude



# MEASURING THE CMB: B-modes



# MEASURING THE CMB: B-modes



Hu & Okamoto (2001)

Unlensed

Lensed

Temperature

E-polarization

B-polarization

Potential

$10^{-4}$

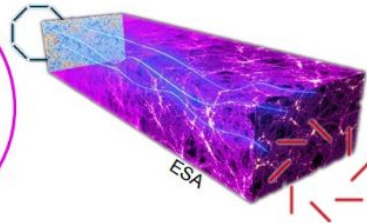
10

Multipole  $l$

100

1000

In standard  $\Lambda$ CDM only E-modes are present at last scattering



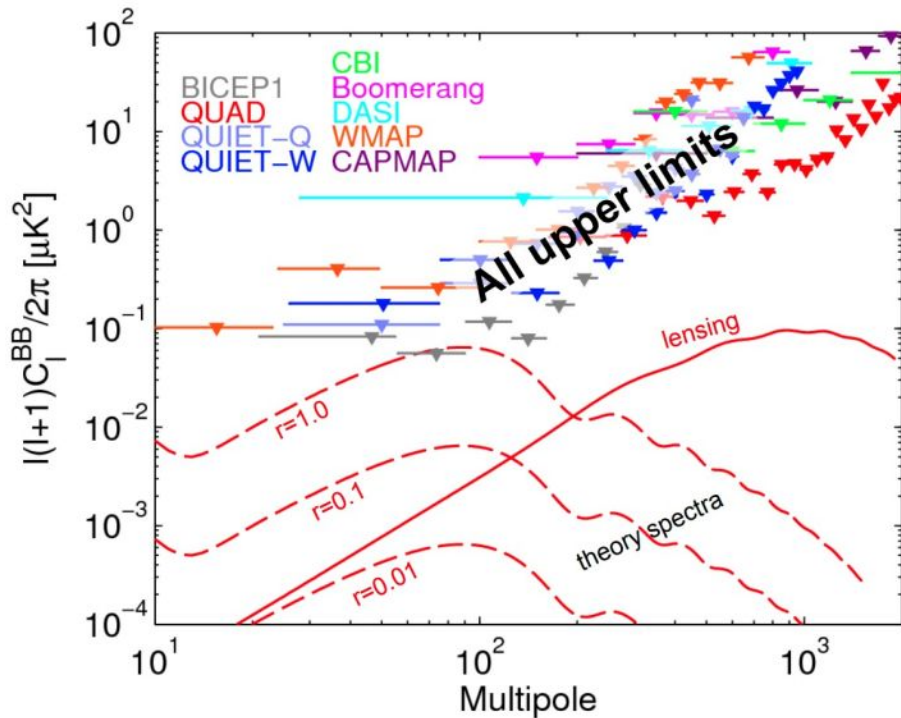
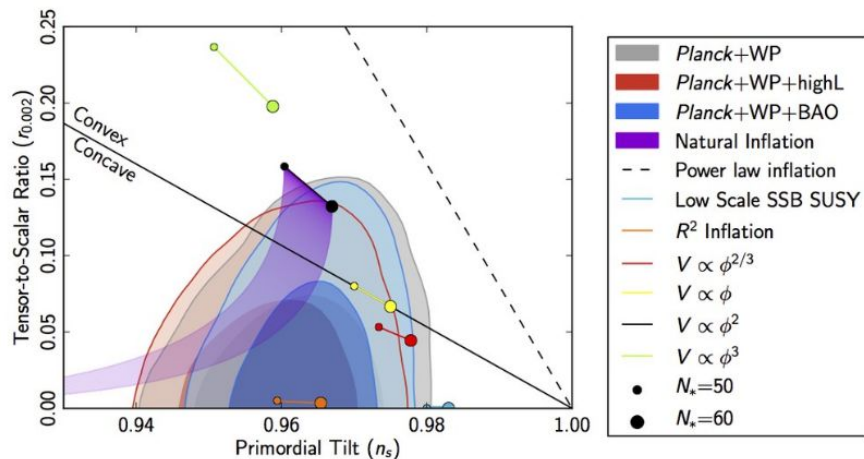
During propagation some of the E-modes are confused into B-modes by lensing

Inflationary gravitational waves are unique source of B-modes  
→ peaking at  $l \approx 100$  : degree scales

# MEASURING THE CMB: B-modes

## Search for B-modes:

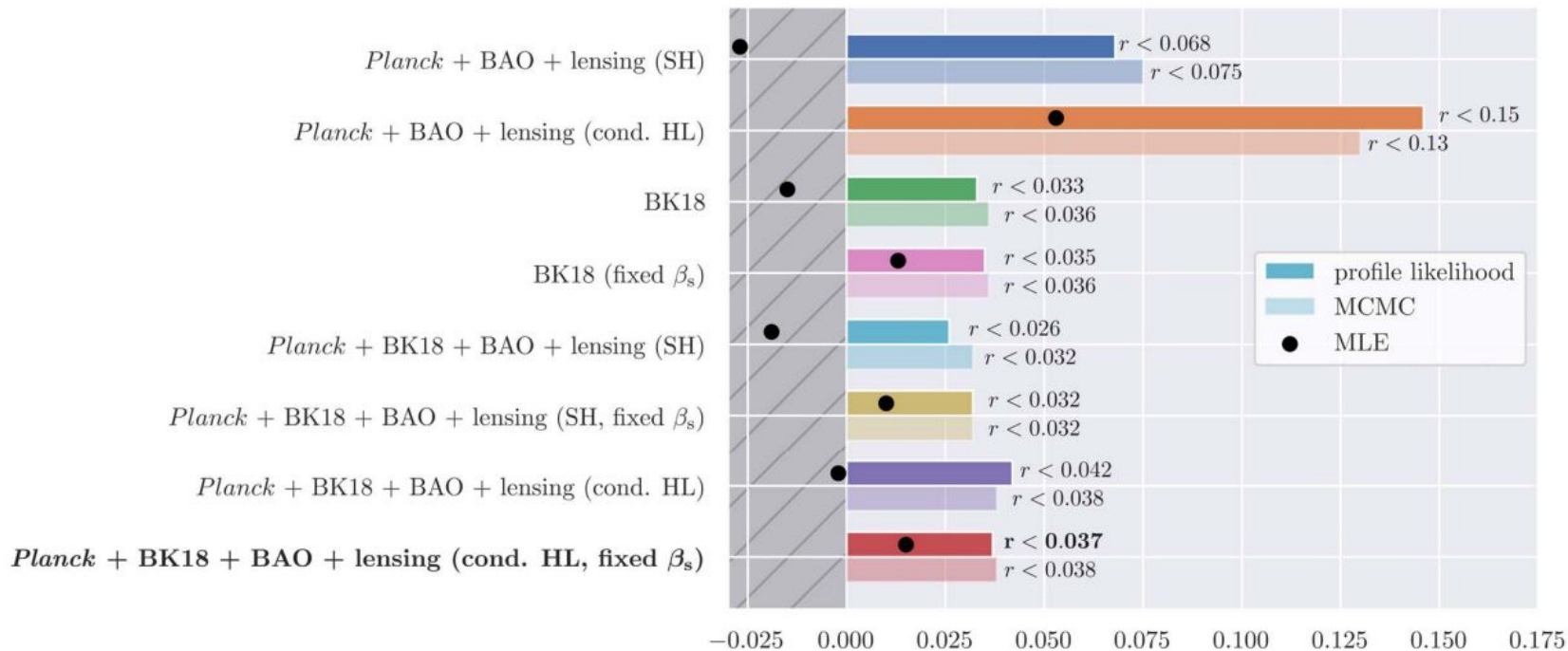
- There are only upper limits from searchers for B-modes in the CMB polarization
- Assuming simple inflationary gravitational wave models the Tensor-to-Scalar ratio parameter,  $r$ , is the only parameter which controls the amplitude of the BB spectrum at large scale
- $2\sigma$  upper limit from BICEP1 (2014):  $r < 0.17$



# MEASURING THE CMB: B-modes

## Search for B-modes:

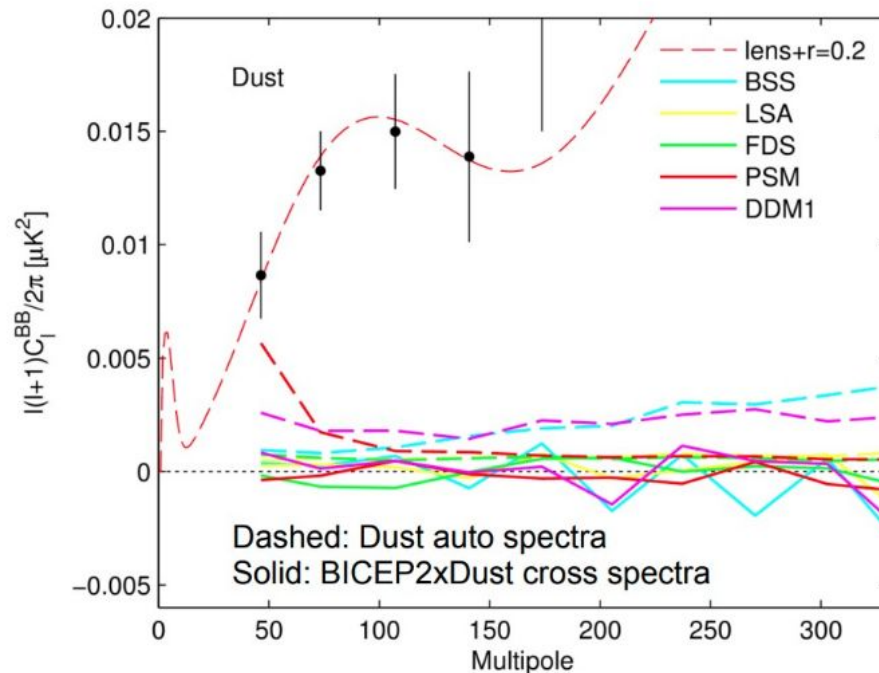
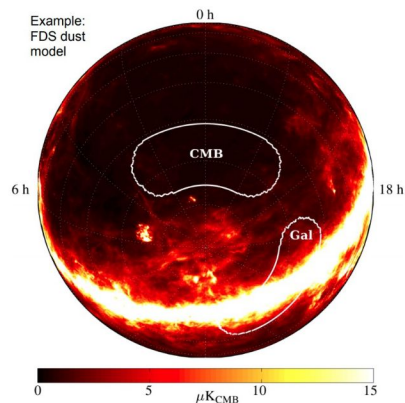
- $2\sigma$  upper limit from Planck + BICEP/Keck (2022):  $r < 0.037$
- This limit has already ruled out several famous, simpler models of inflation.



# MEASURING THE CMB: B-modes

## BICEP2:

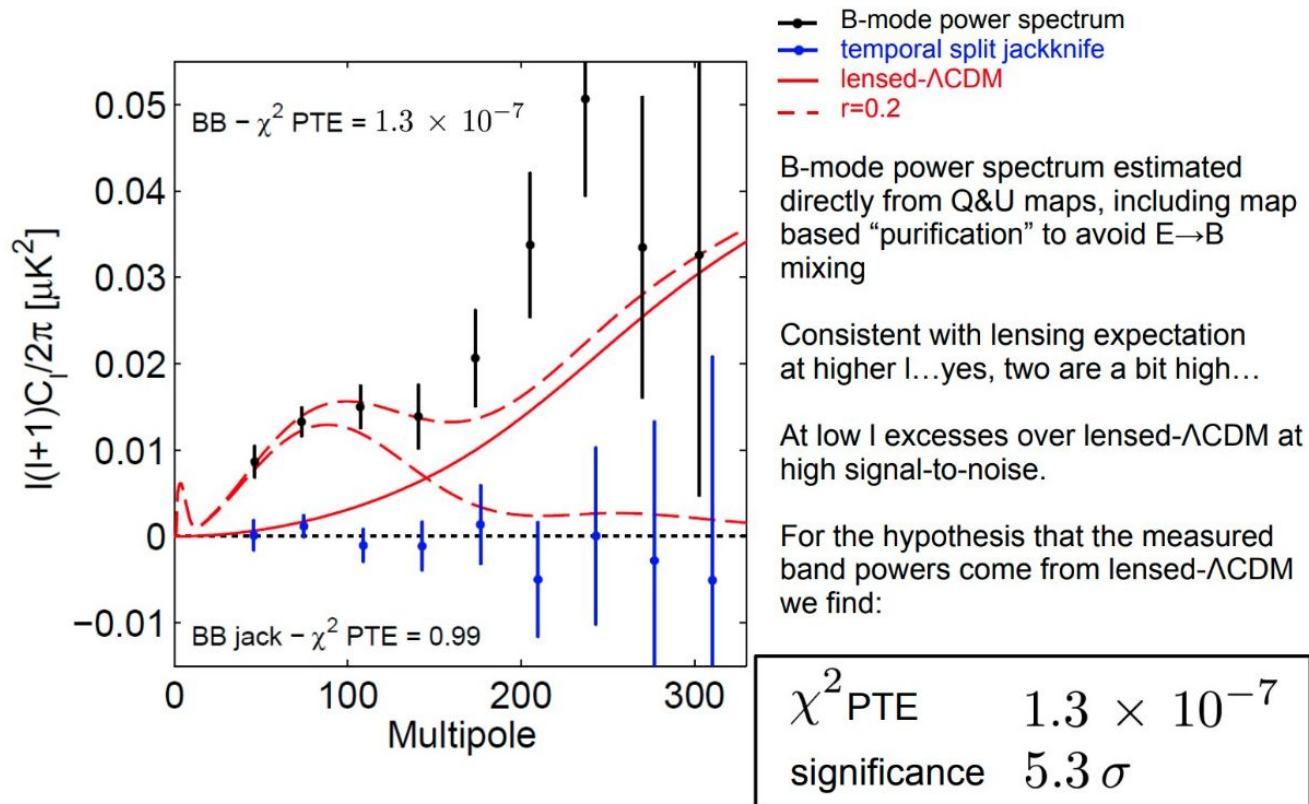
- Detectors tuned to 150 GHz, near the peak of the CMB's 2.7K blackbody spectrum
- Target the “Southern Hole” - a region of the sky though to be exceptionally free of dust and synchrotron foregrounds
  - At 150 GHz the combined dust and synchrotron spectrum is predicted to be at minimum in the Southern Hole
  - Expected foreground contamination of the B-mode power  $r < 0.01$



Used models of polarized dust emission to estimate foregrounds based on pre-Planck data

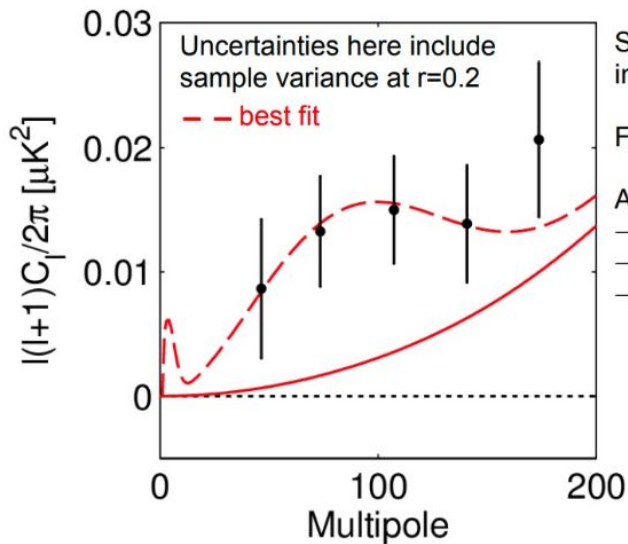
# MEASURING THE CMB: B-modes

BICEP2 results:



# MEASURING THE CMB: B-modes

## BICEP2 results:



Substantial excess power in the region where the inflationary gravitational wave signal is expected to peak

Find the most likely value of the tensor-to-scalar ratio  $r$

Apply "direct likelihood" method, uses:

- lensed- $\Lambda$ CDM + noise simulations
- weighted version of the 5 bandpowers
- B-mode sims scaled to various levels of  $r$  ( $n_T=0$ )

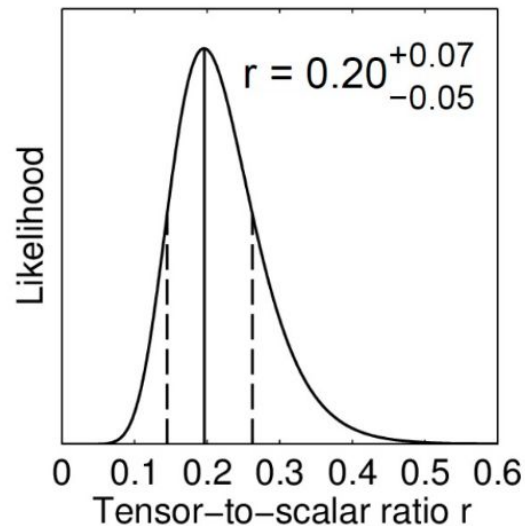
Within this simplistic model we find:

$r = 0.2$  with uncertainties dominated by sample variance

PTE of fit to data: 0.9

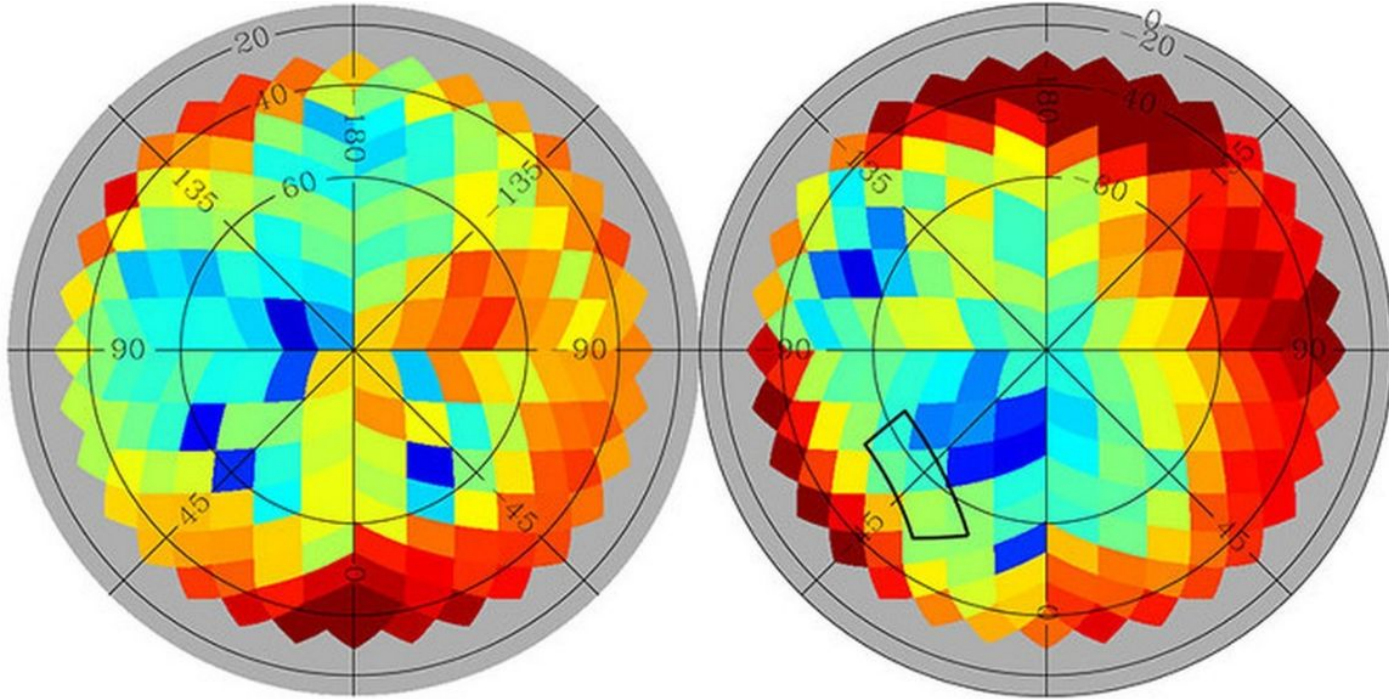
→ model is perfectly acceptable fit to the data

$r = 0$  ruled out at  $7.0\sigma$



# MEASURING THE CMB: B-modes

## BICEP2 results:

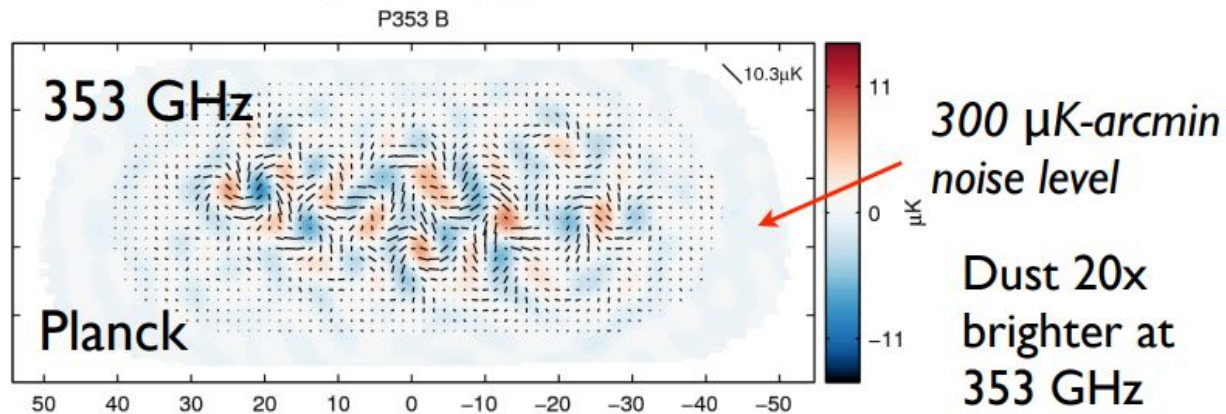
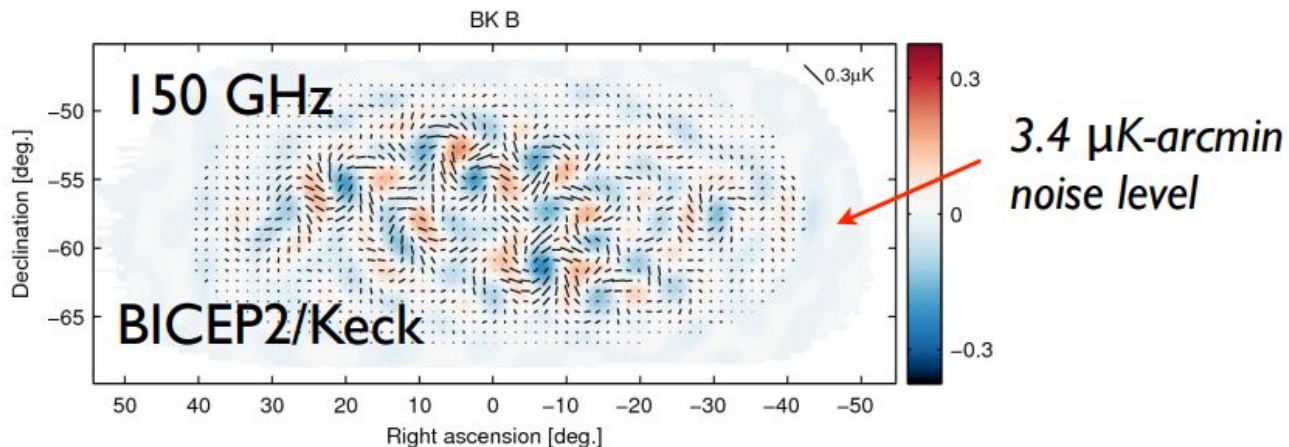


Map of the dust B-mode polarization, as estimated from the Planck data, in units of the signal expected from primordial gravitational waves. The green color corresponds to a Galactic signal comparable to the signal detected by the BICEP2 experiment over the sky patch marked with a black contour. Blue and red colours identify regions of fainter and brighter dust polarization.

The BICEP2 telescope looked at the area surrounded by the black box at right, which shows higher levels of dust than previously assumed. (Planck Collaboration)

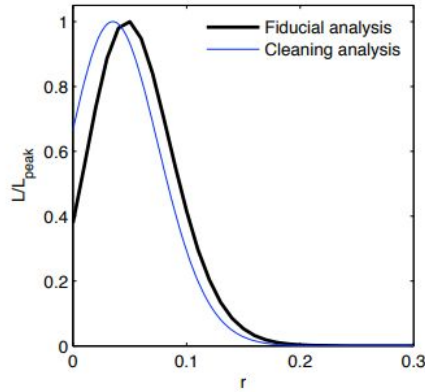
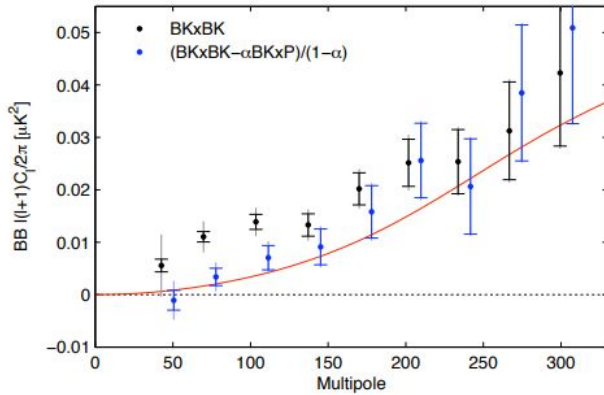
# MEASURING THE CMB: B-modes

BICEP2 results:



# MEASURING THE CMB: B-modes

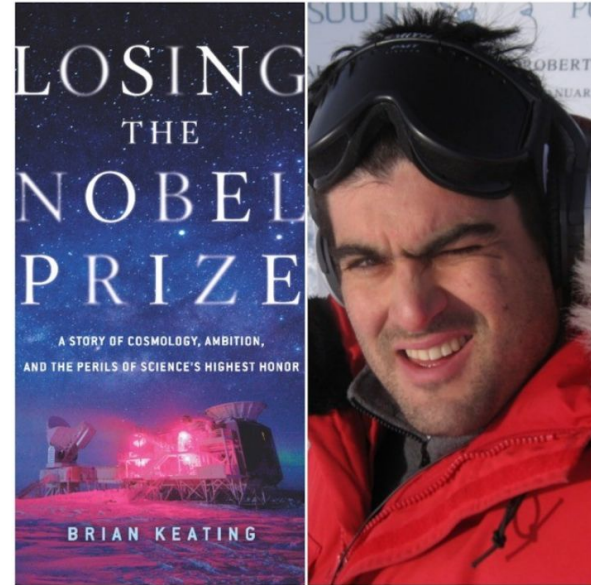
BICEP2+Planck results:



BICEP2/Keck + Planck Collaborations 2015

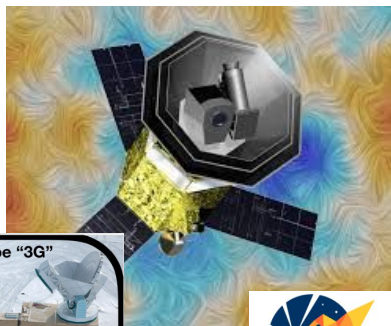
$$r_{0.05} < 0.12 \quad (95\% \text{ CL})$$

- B-modes now as constraining as  $TT$
- Demonstrated power of multi-frequency dust cleaning

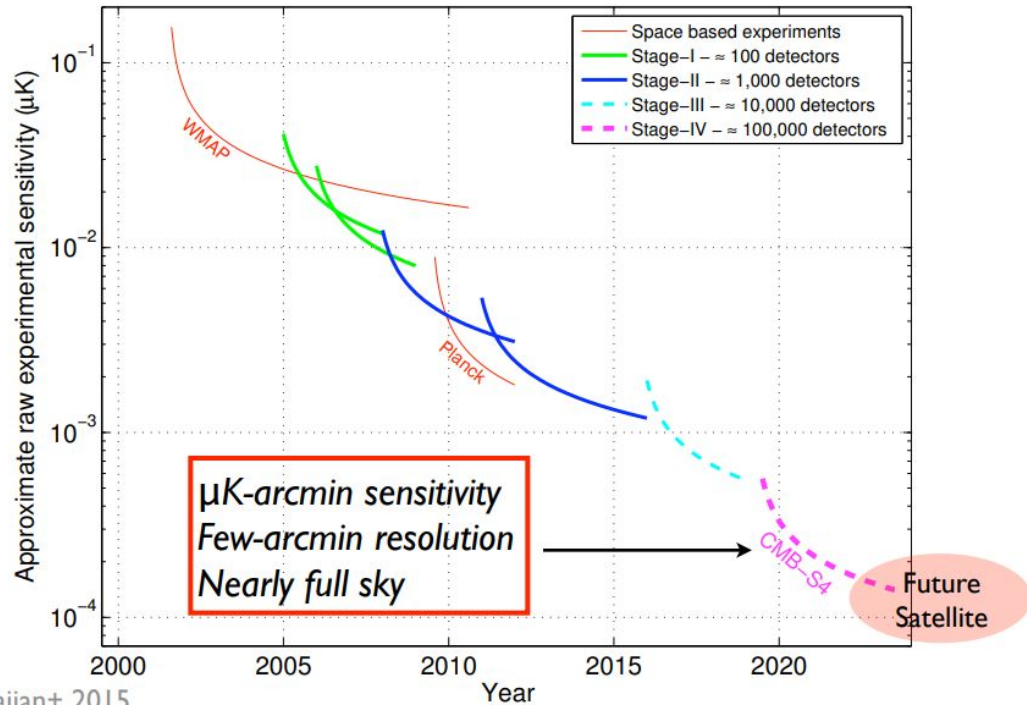


# MEASURING THE CMB: B-modes

- B-mode detection primary objective of future CMB mission
- The future experiment are designed to reach  $\mu\text{k-arcmin}$  sensitivity in polarization (no need for high resolution since we are interested in large angular scales)



Abazajian+ 2015

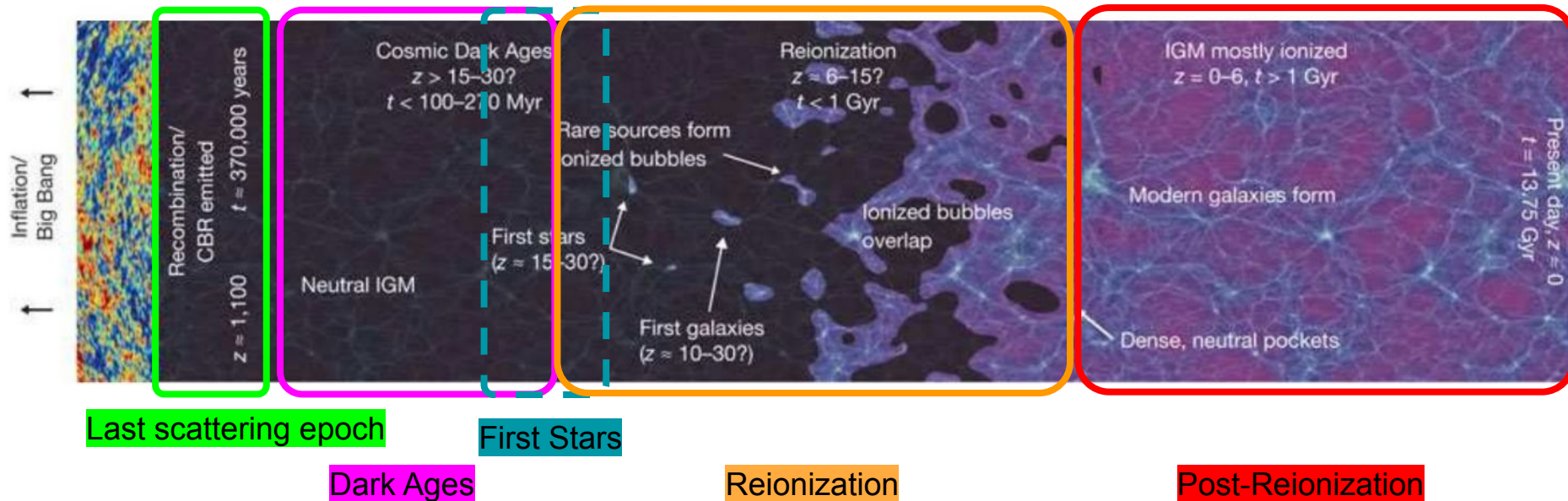


# EPOCH OF REIONIZATION

Big Bang

Universe expanding and cooling

Present day

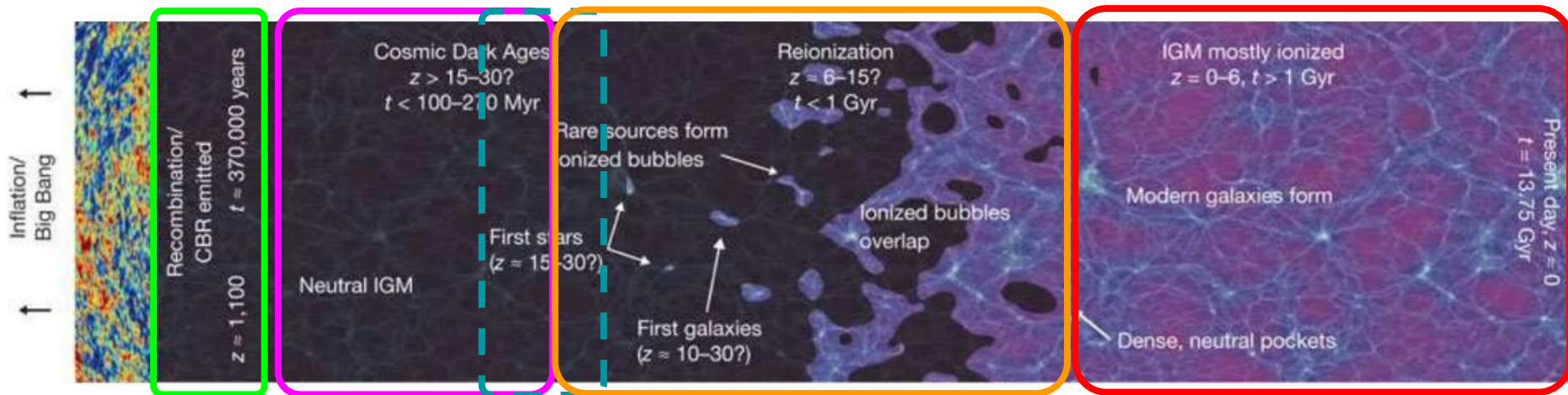


# EPOCH OF REIONIZATION

Big Bang

Universe expanding and cooling

Present day



Last scattering epoch

First Stars

Dark Ages

Reionization

Post-Reionization



Strong probe of cosmology  
21 cm line stretched  
between 10 - 100 MHz  
( → Lunar far side)

First stars  
Cosmology

Galaxy Formation  
Cosmology

# EPOCH OF REIONIZATION: CMB

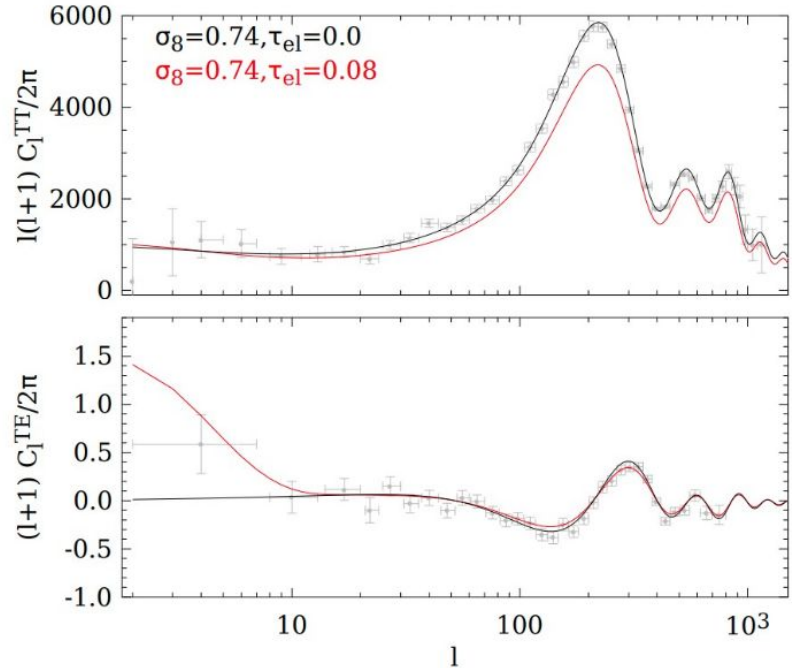
## Evidence for reionization of Inter-Galactic Medium:

- CMB photons scatter off free electrons in the IGM.
- The measured quantity in CMB observations is the optical depth due to Thomson scattering off free electrons:

$$\tau = \int_0^{z_{re}} n_e(z) \sigma_T \frac{c dz}{(1+z)H(z)}$$

- Because this scattering is a random process along the line of sight, it effectively damps the primary fluctuations of the CMB at all scales. The  $C_l^{TT}$  power spectrum is suppressed by a factor:

$$C_l^{TT,obs} = e^{-2\tau} C_l^{TT,primordial}$$



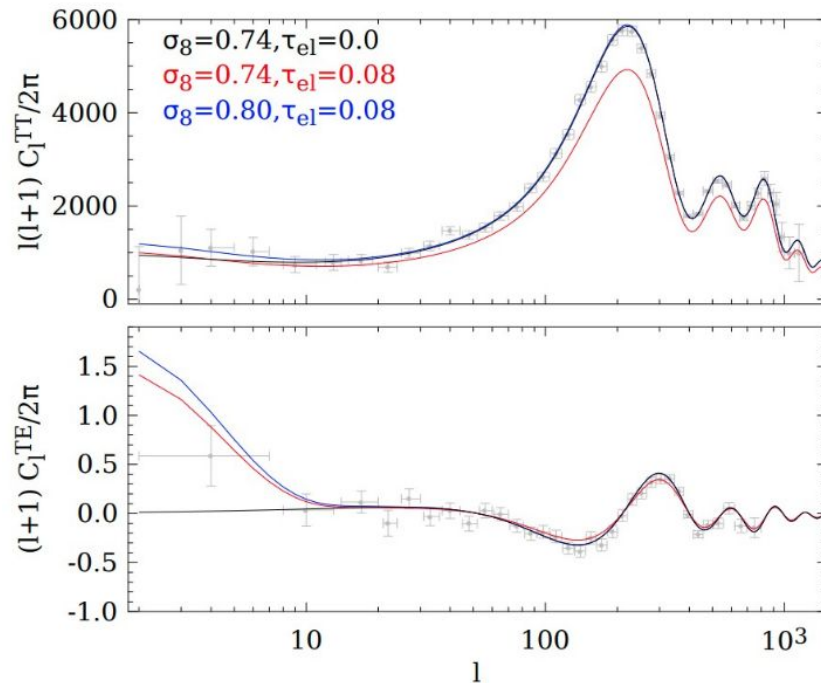
# EPOCH OF REIONIZATION: CMB

## Evidence for reionization of Inter-Galactic Medium:

- The dumping effect is degenerate with the amplitude of the density fluctuations (parametrized with  $A_s$  or  $\sigma_8$ )

$$C_l^{\text{TT,obs}} \propto A_s e^{-2\tau}$$

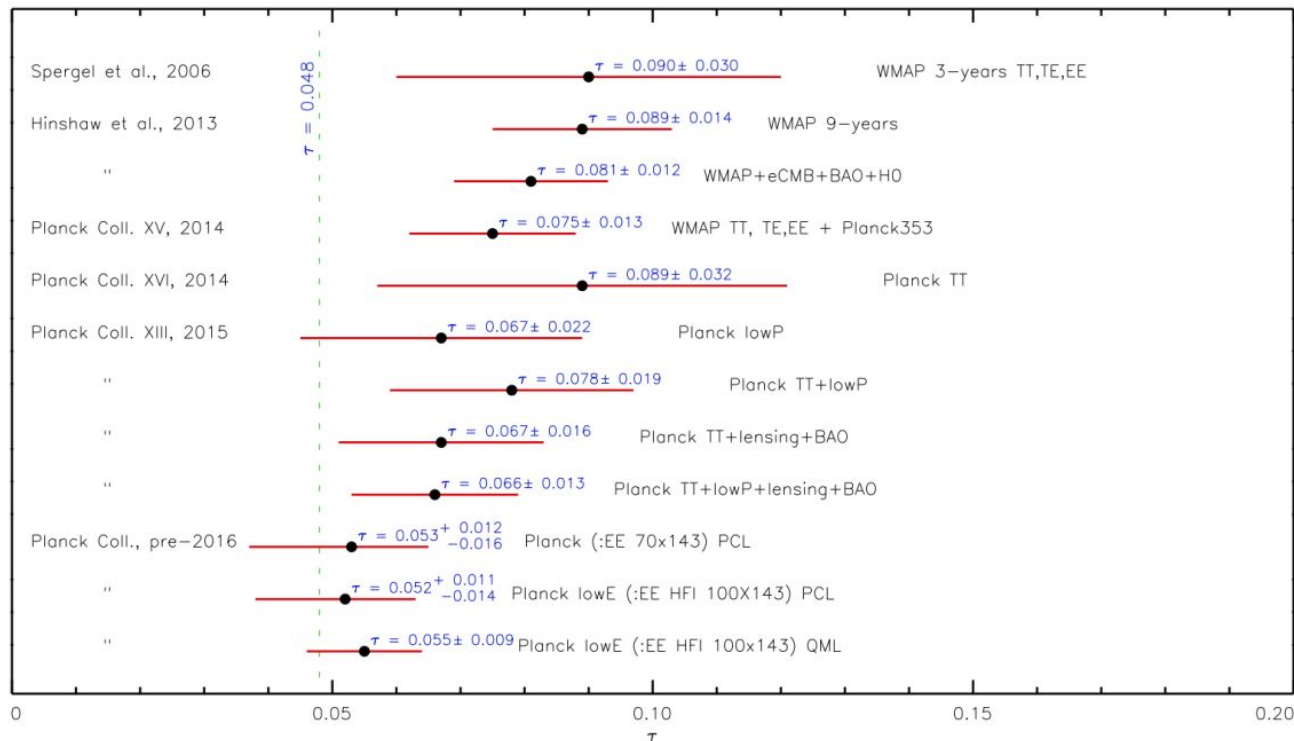
- TE spectrum can break the degeneracy: on large scale ( $l < 10$ ) reionization create a “bump” since the scattering of CMB photons after reionization polarize the light at these scales for the first time since the Big Bang



# EPOCH OF REIONIZATION: CMB

## Constraints on optical depth from CMB experiments:

Planck Collaboration (2016)



# EPOCH OF REIONIZATION: CMB

## Evidence for reionization of Inter-Galactic Medium:

- By assuming a model for the reionization history,  $n_e(z)$ , it is possible to estimate the reionization redshift  $z_{re}$

$$\tau = \int_0^{z_{re}} n_e(z) \sigma_T \frac{c dz}{(1+z)H(z)}$$

- Current analysis based on a “reionization” model, where  $n_e = n_H$  for  $z < z_{re}$ , and  $n_e = 0$  for  $z > z_{re}$ , and the transition is relatively quickly ( $\Delta z = 0.5$ ) and symmetrical (tanh function).

$$x_e(z) = \frac{1 + f_{He}}{2} \left[ 1 + \tanh \left( \frac{(1+z_{re})^{3/2} - (1+z)^{3/2}}{\Delta w} \right) \right]$$

- Current constraints from Planck gives  $z_{re} \approx 7.7$

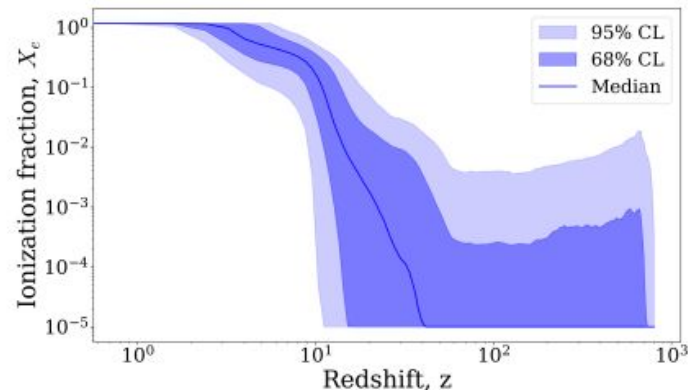
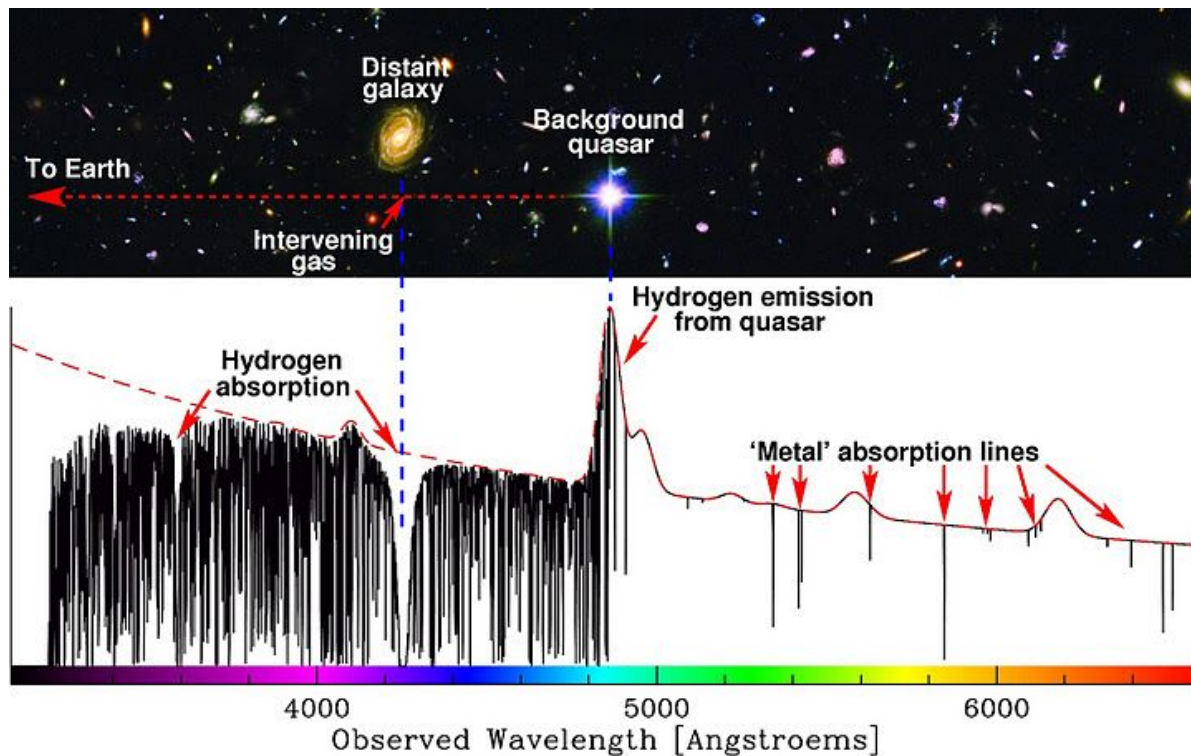


FIG. 1. Model independent reconstruction of the free electron fraction,  $X_e(z)$ , from *Planck* large angle E-mode polarization data, using the Gaussian process method. All other cosmological parameters are fixed to their best-fit values from the *Planck* 2018 TT,TE,EE+lowE analysis [3]. The shaded regions denote the 68% (blue) and 95% (light blue) confidence level (CL), and the solid line marks the median reconstruction.

# EPOCH OF REIONIZATION: Lyman- $\alpha$ Forest

Evidence for reionization of Inter-Galactic Medium:

- The IGM can be studied through the absorption features it produces in the spectrum of a background bright source of light (typically a QSO)

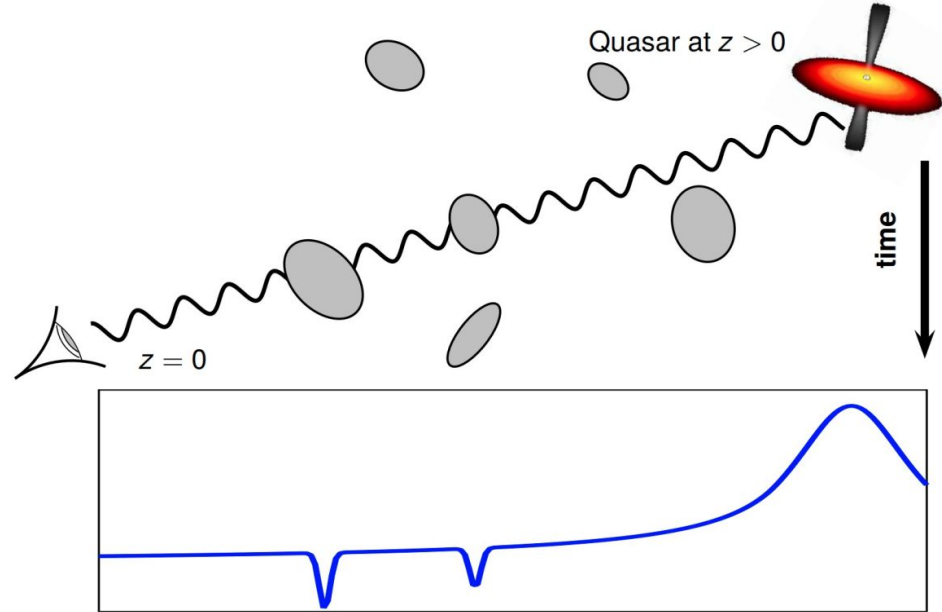


# EPOCH OF REIONIZATION: Lyman- $\alpha$ Forest

## Ly-alpha absorption lines:

- Consider radiation (photons) emitted at QSO rest frame at redshift  $z_Q$  with a frequency  $\nu_Q > \nu_{fi}$ . As the universe expands, the frequency decreases and reaches the resonant frequency  $\nu_{fi}$  at a lower redshift  $z < z_Q$ , determined by:

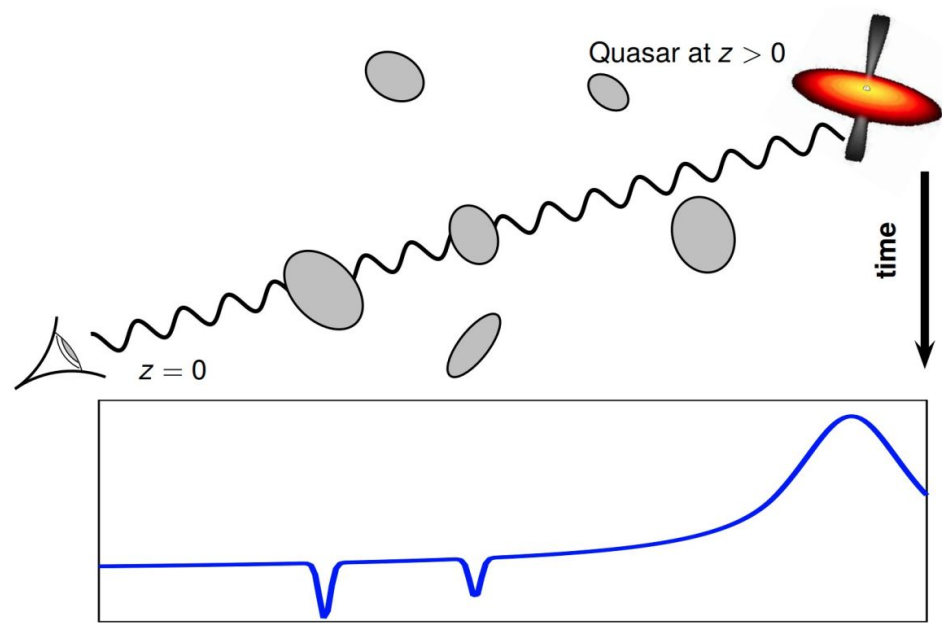
$$\frac{\nu_Q}{1+z_Q} = \frac{\nu_{fi}}{1+z} \implies \lambda_Q(1+z_Q) = \lambda_{fi}(1+z)$$



# EPOCH OF REIONIZATION: Lyman- $\alpha$ Forest

## Ly-alpha absorption lines:

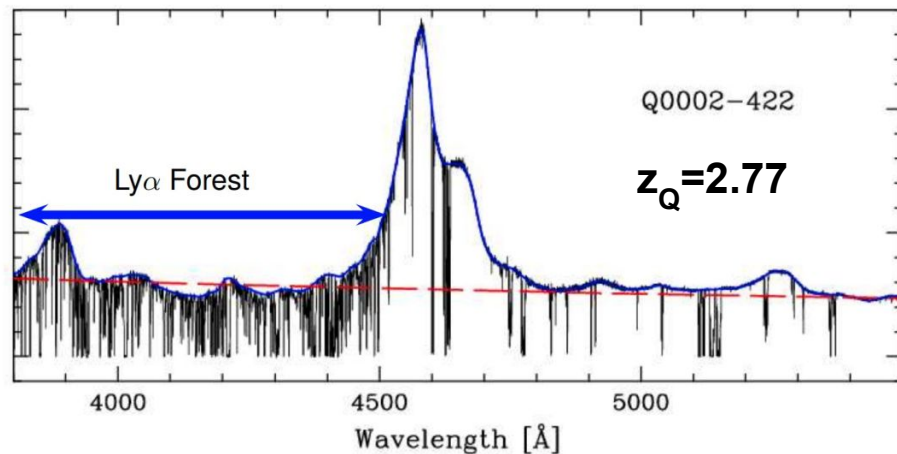
- **Example:** For a QSO at  $z_Q = 3$  emitting a photon at wavelength  $\lambda_Q = 1187 \text{ \AA} < \lambda_{fi}$ , the light reaches the Ly $\alpha$  wavelength  $\lambda_{fi} = 1216 \text{ \AA}$  at:  $z \approx 1187 \times 4/1216 - 1 \approx 2.9$ . If neutral hydrogen is present at that position in space, it will produce a distinct absorption signature in the spectrum.
- We observe this specific feature in the QSO spectrum at  $\lambda = \lambda_Q(1 + z_Q) \approx 4742 \text{ \AA}$ . Therefore, any absorption arising at a specific redshift  $z$  will appear in our observations at:  $\lambda = \lambda_{fi}(1 + z)$



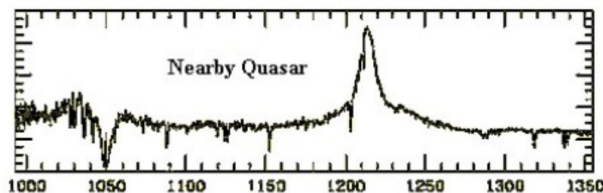
# EPOCH OF REIONIZATION: Lyman- $\alpha$ Forest

## Ly-alpha Forest:

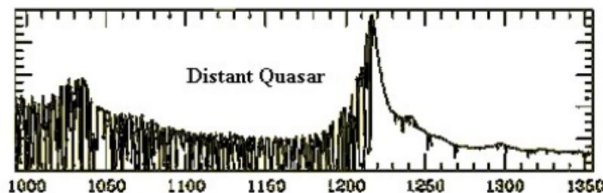
- The absorption lines blueward of the emission line arise from Ly  $\alpha$  transition of HI present between the QSO and us
- The unabsorbed parts of the spectrum correspond to either ionized regions or no matter at all



$z \approx 0$



$z \approx 3$



# EPOCH OF REIONIZATION: Lyman- $\alpha$ Forest

## Gunn-Peterson effect:

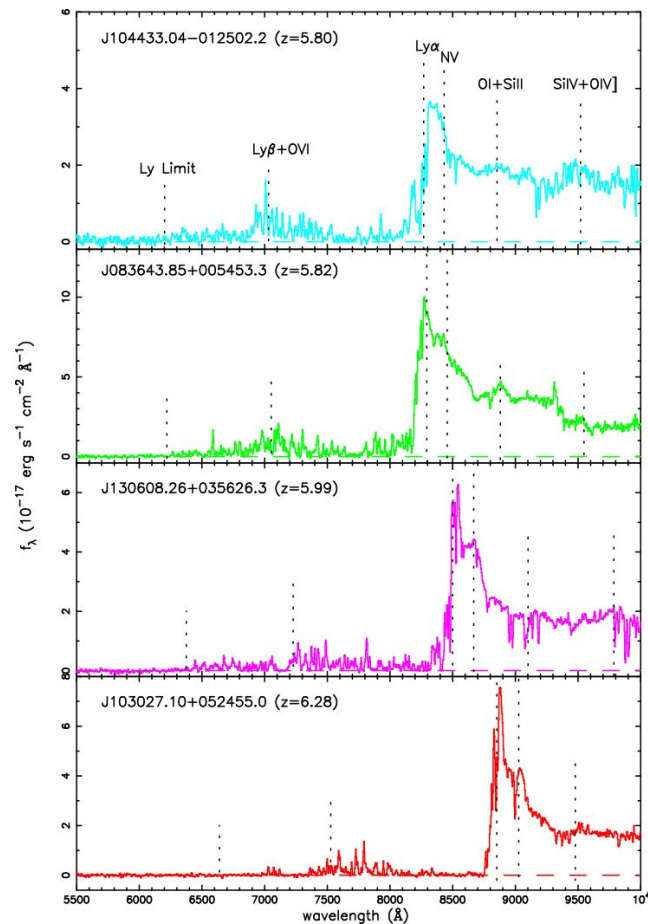
- If the IGM is filled with neutral hydrogen, every single wavelength "blue-ward" of the Ly- $\alpha$  line is eventually absorbed, leading to a zero flux in the spectrum.
- We can determine the reionization epoch by looking at the spectra of QSOs at different redshifts
- A non-zero flux is observed till  $z \sim 5.5$

$z = 5.80$

$z = 5.82$

$z = 5.99$

$z = 6.28$



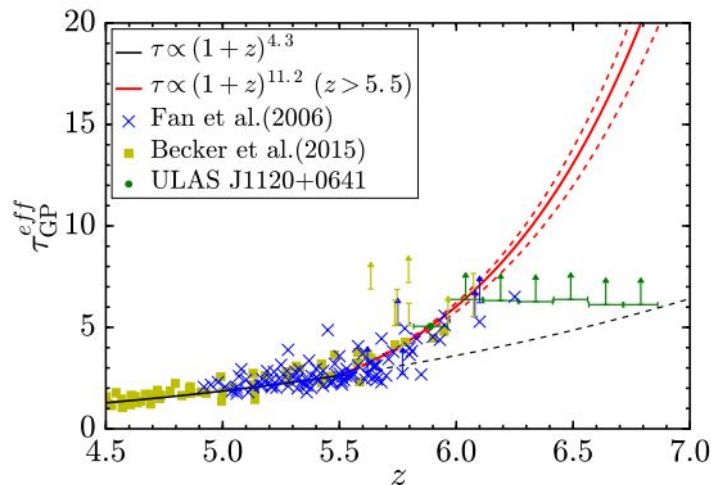
# EPOCH OF REIONIZATION: Lyman- $\alpha$ Forest

## Gunn-Peterson effect:

- The cross-section for Ly- $\alpha$  scattering is so high that even a tiny fraction of neutral hydrogen ( $X_{\text{HI}} = \rho_{\text{HI}} / \rho_{\text{H}} \approx 10^{-4}$ ) is enough to create a complete Gunn-Peterson trough.

$$F \propto e^{-\tau_{\text{GP}}} \quad \tau_{\text{GP}} \approx \left( \frac{\bar{X}_{\text{HI}}}{10^{-5}} \right)$$

- The Ly- $\alpha$  transition saturates easily, and cannot be used to assess the exact level of reionization, but just a lower limit ( $X_{\text{HI}} > 10^{-4}$ )



**Fig. 7.** Evolution of  $\tau_{\text{GP}}^{\text{eff}}$  with redshift as predicted by Eq. (1) (solid lines). The red curve is determined using ULAS J1120+0641 data alone and assumes a fixed normalization at  $z = 5.5$ . The uncertainty in  $\xi$  for  $z > 5.5$  is indicated by the red dashed lines. The black dashed curve indicates the expected optical depth if the low-redshift case were to continue indefinitely. Points indicate direct measurements of  $\tau_{\text{GP}}^{\text{eff}}$  along different lines of sight.

# EPOCH OF REIONIZATION: PERSPECTIVES

- **Interpretation of current data:**
  - QSO absorption spectra imply  $X_{\text{HI}} > 10^{-4}$  at  $z \sim 6$
  - CMB data imply  $z_{\text{re}} \sim 8$  assuming an instantaneous reionization (too simplistic!)
  - There is not tension between the two results, the data collectively suggest that reionization is an extended process, starting at  $z > 8$  and completing around  $z \sim 6$
- **Open questions:**
  - **Epoch of reionization:** When did the sources produce enough photons to ionize the Universe,  $6 < z < 20$ ?
  - **Nature of reionization:** Was the process sudden or gradual? Homogeneous or Inhomogeneous?
  - **Sources of reionization:** The primary drivers are still debated – First stars, quasars, exotic particles?