

(Secondary) CMB anisotropies:
Polarization
Reionization
Sunyaev Zeldovich Effect

arXiv: 1811.02310

arXiv: 1112.1862

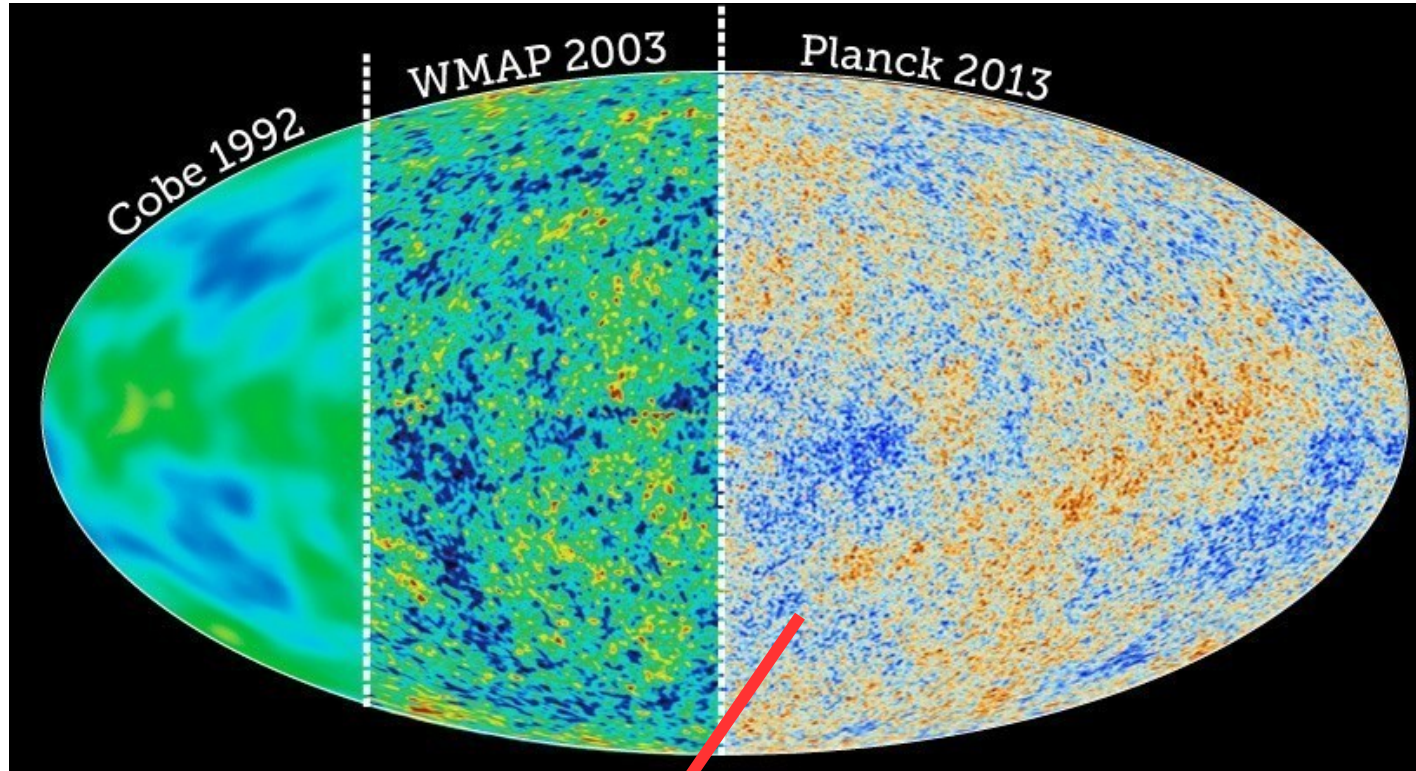
arXiv:1212.1075

arXiv:1511.04335

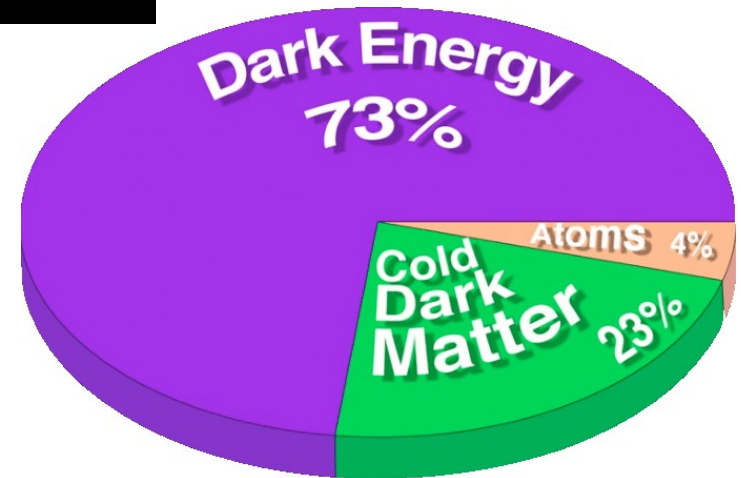
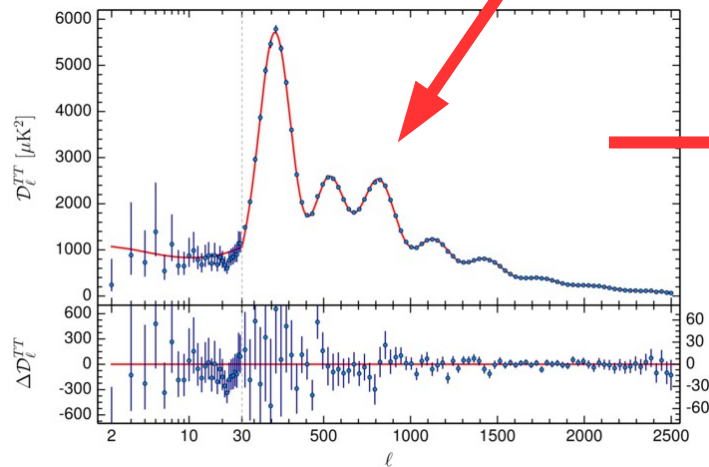
arXiv:1312.2462

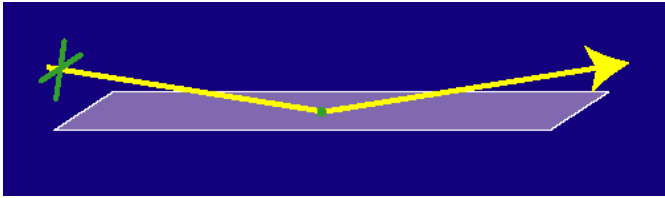
arXiv:1303.5081

CMB



TT Power Spectrum information is sample-variance limited

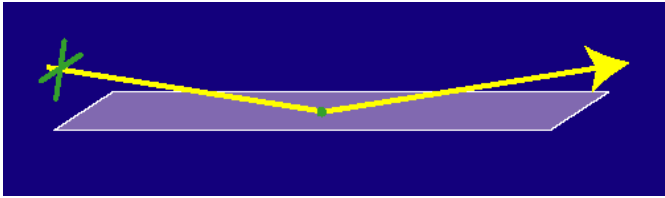




Polarization

Photo Credit: TALEX





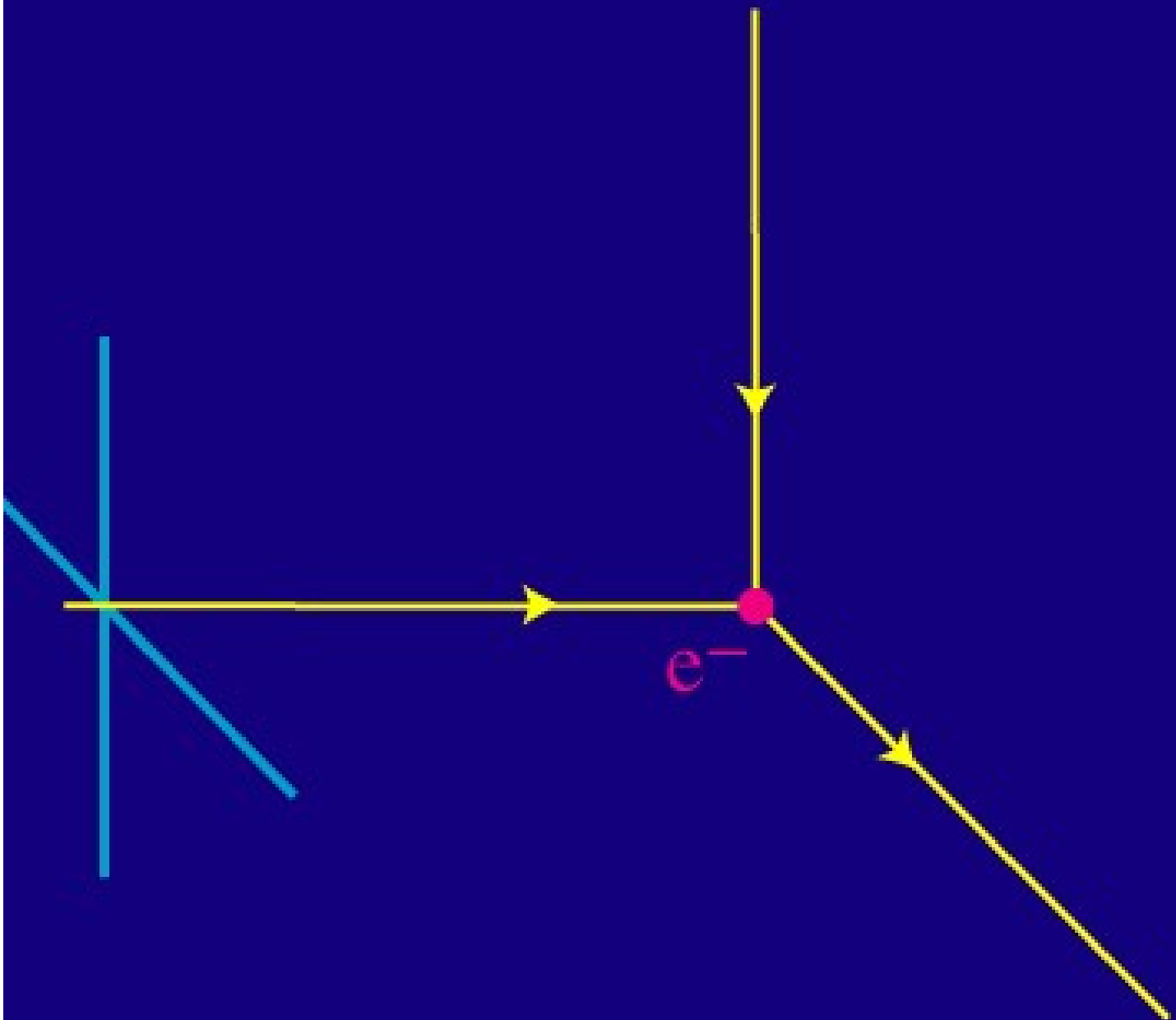
Polarization

Photo Credit: TALEX

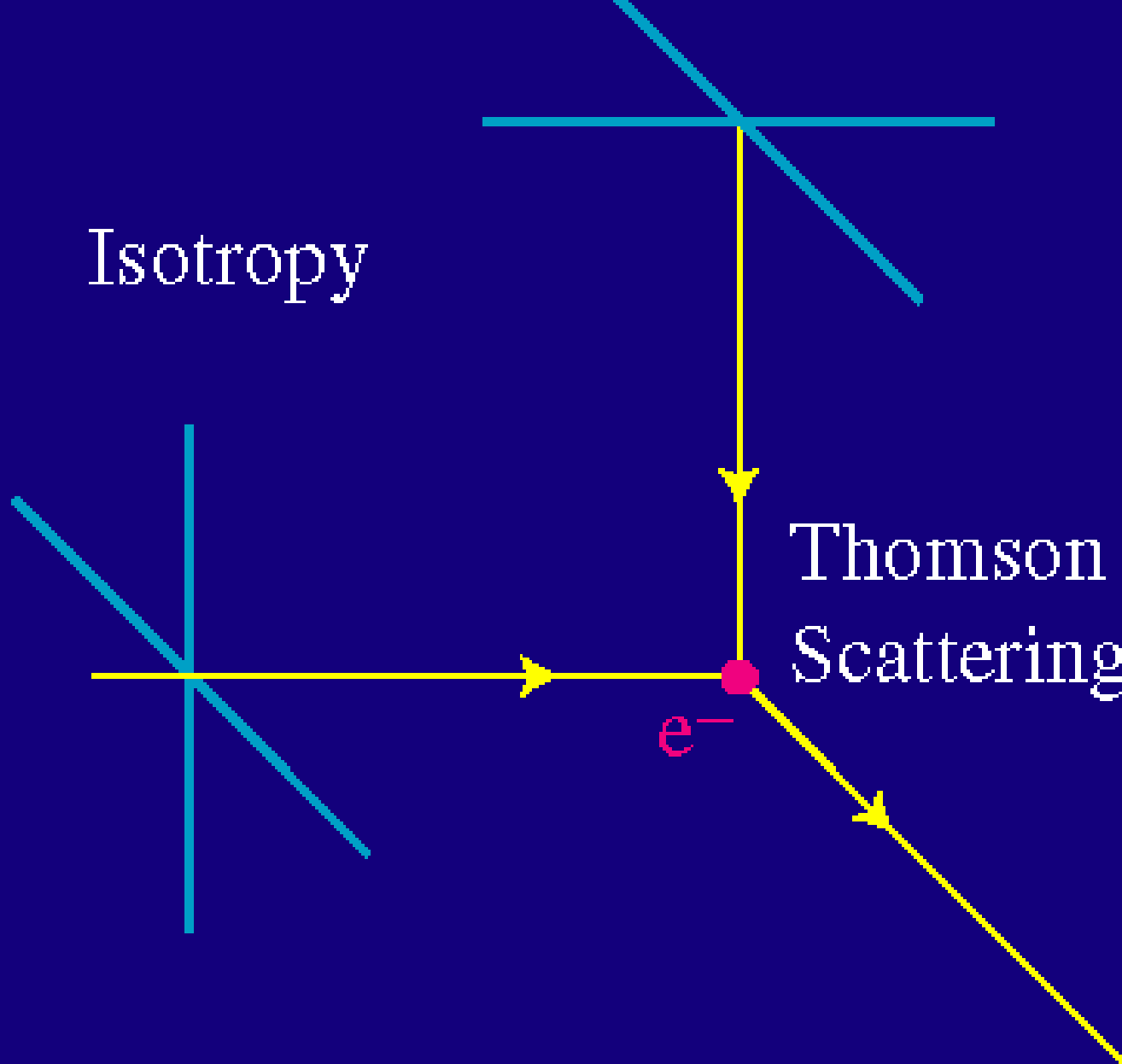


LENS : TALEX PPL75 HARD MULTI COAT
FRAME : NYLON





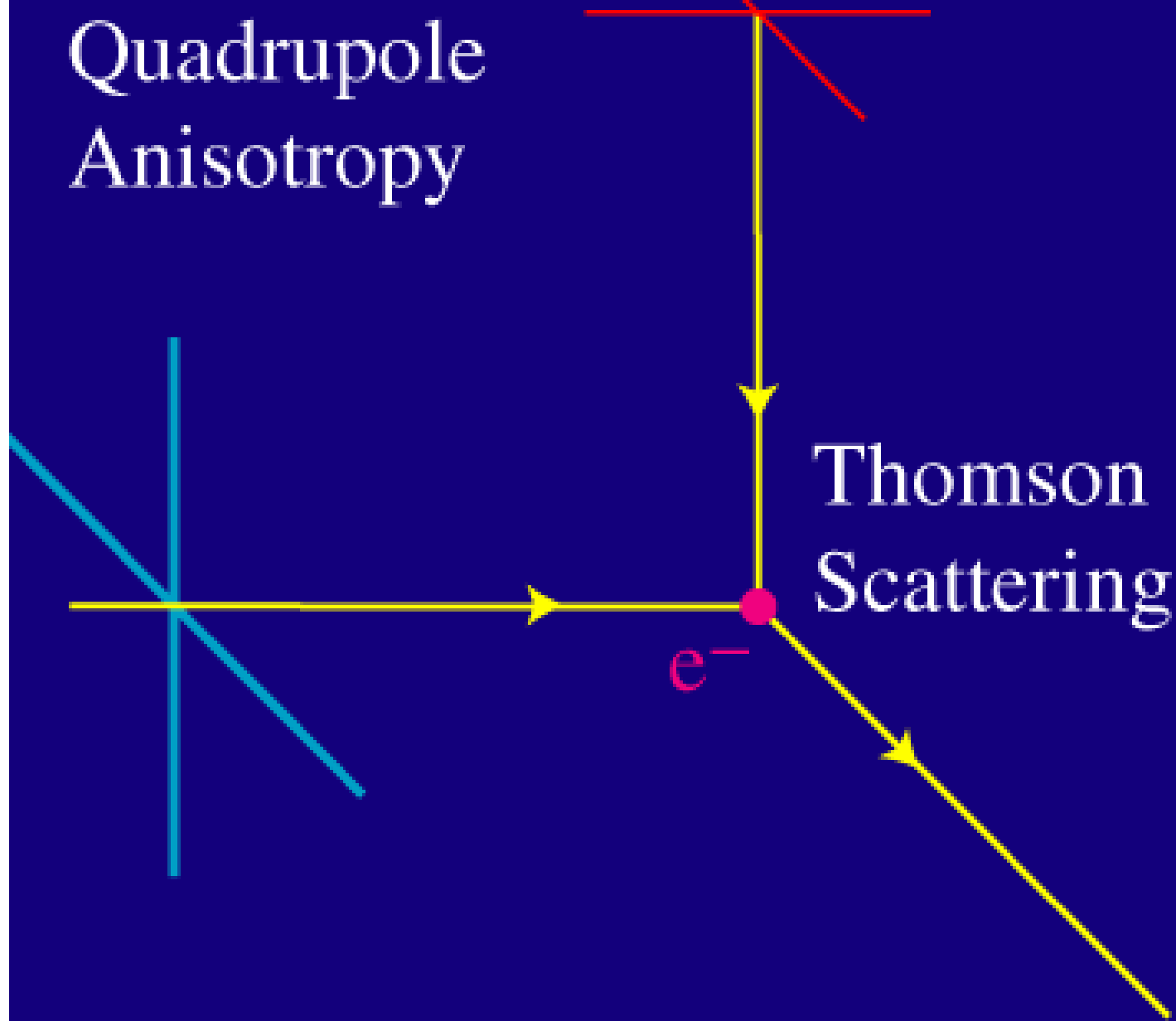
Isotropy



Thomson
Scattering

No Polarization

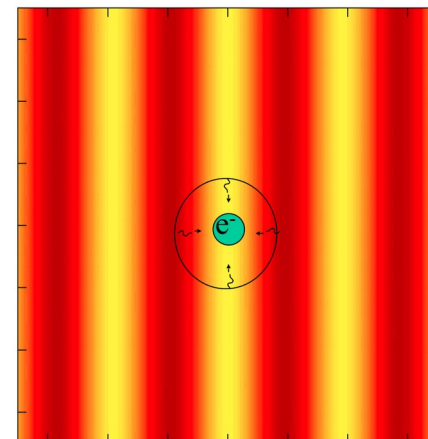
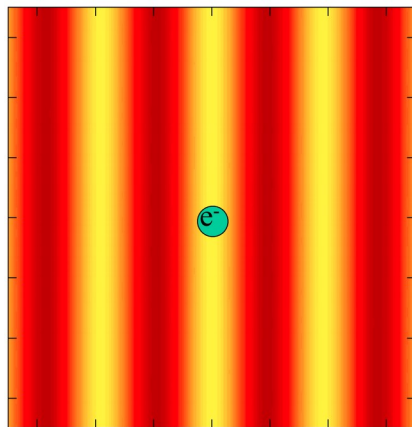
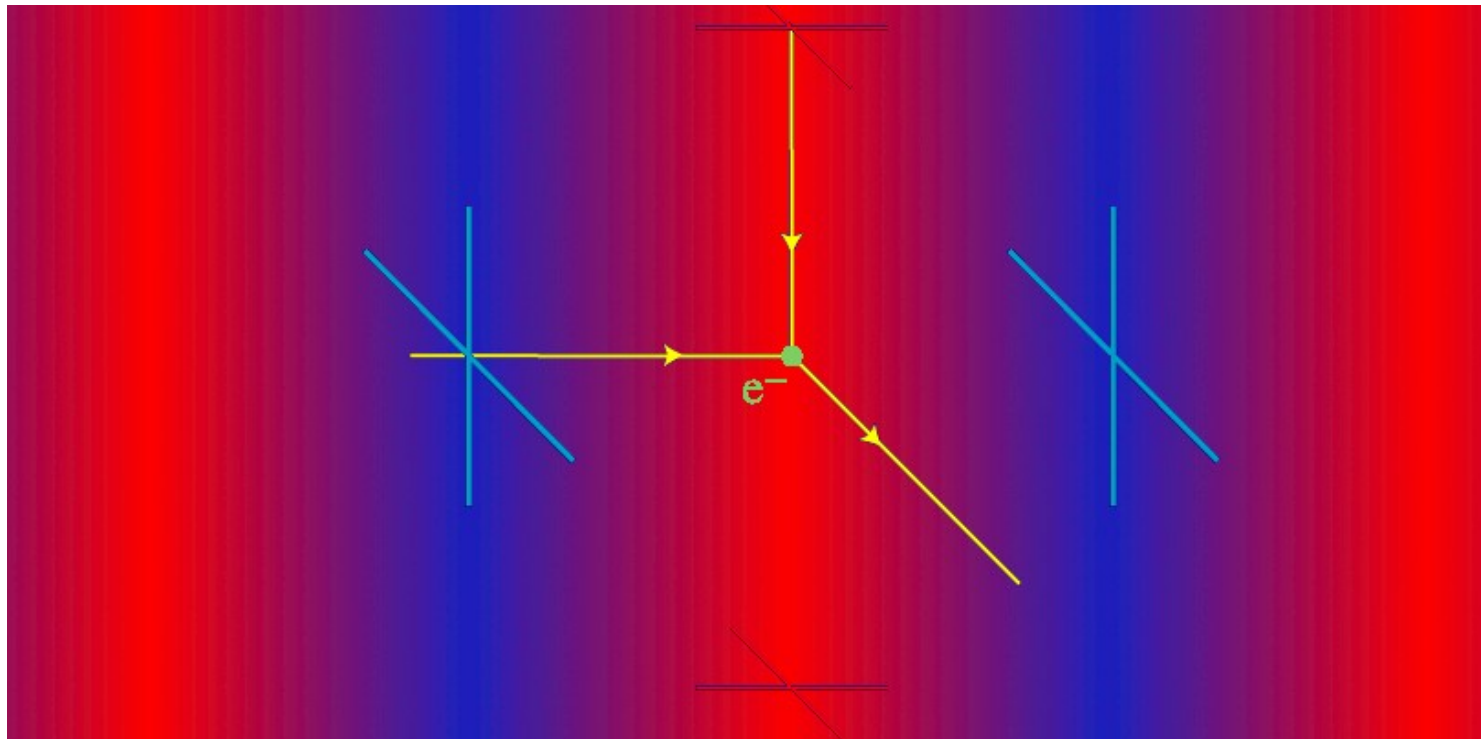
Quadrupole
Anisotropy



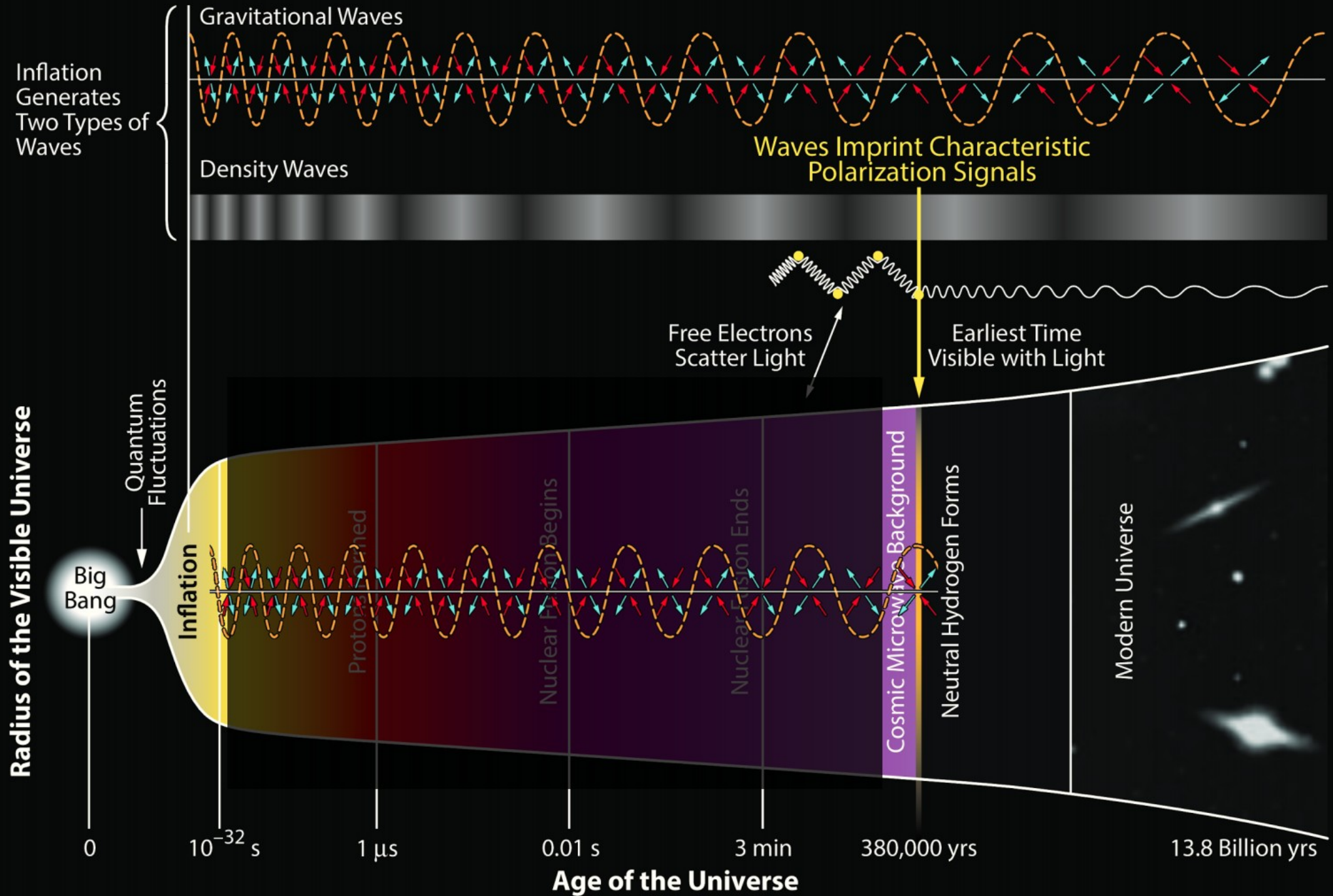
Thomson
Scattering

Linear
Polarization

CMB polarization: scattering from sound waves

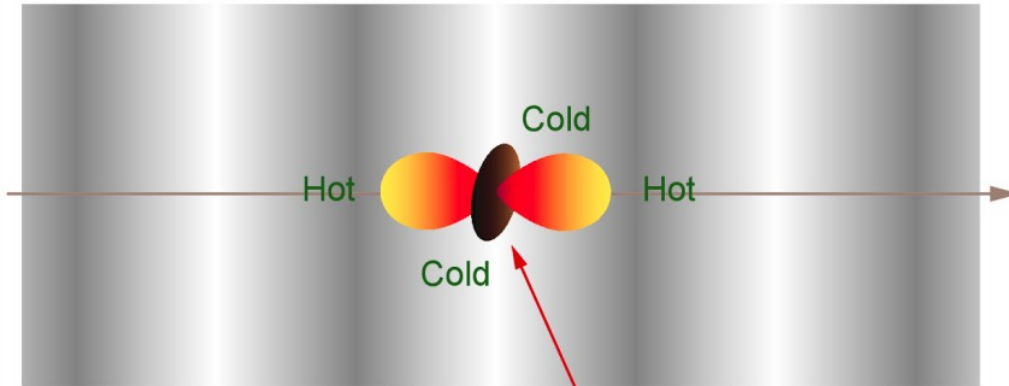


History of the Universe

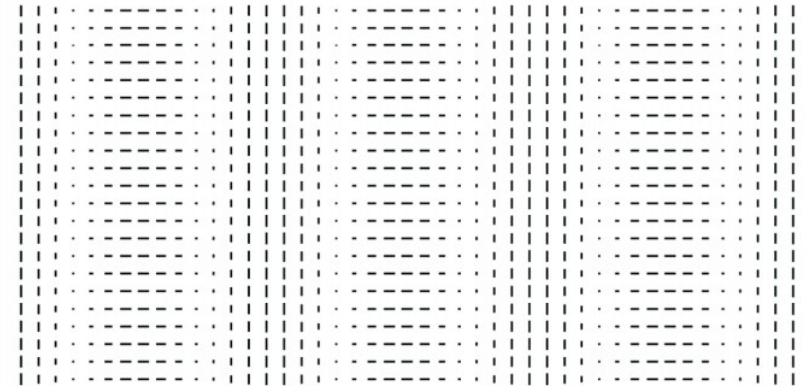


Polarization

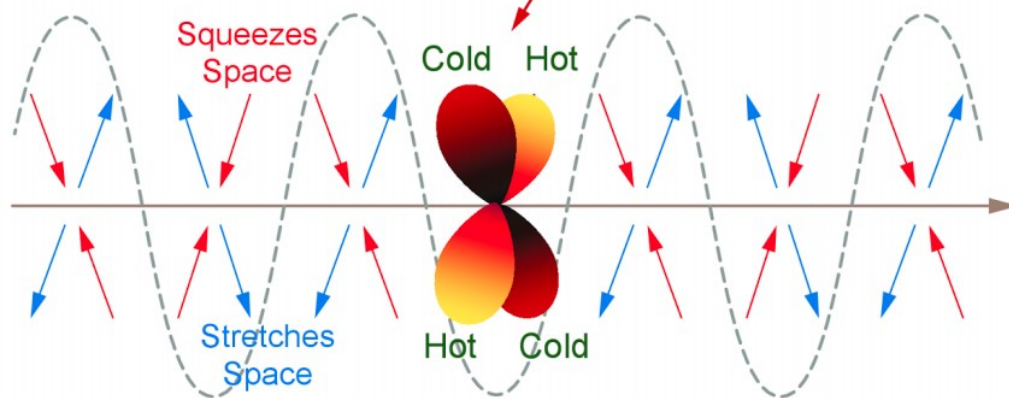
Density Wave



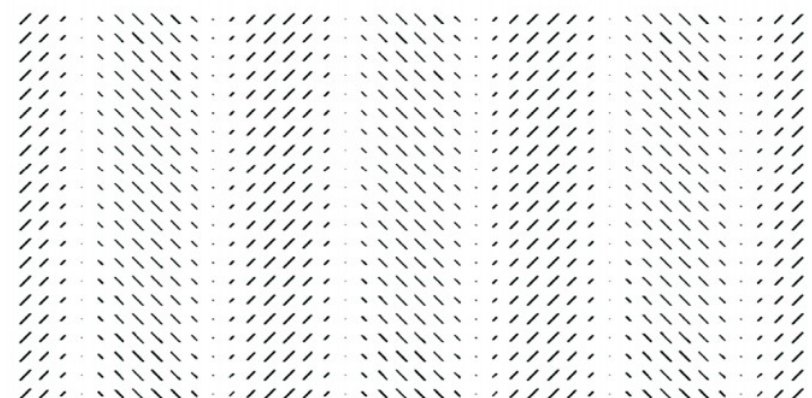
E-Mode Polarization Pattern



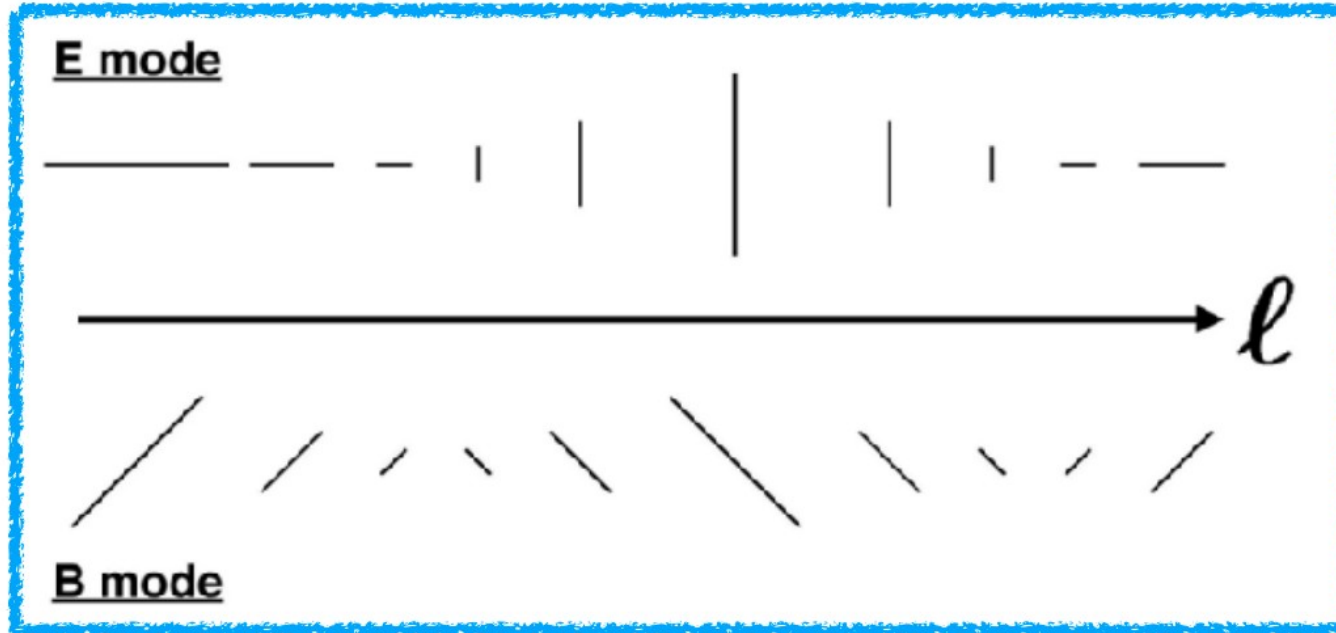
Gravitational Wave



B-Mode Polarization Pattern

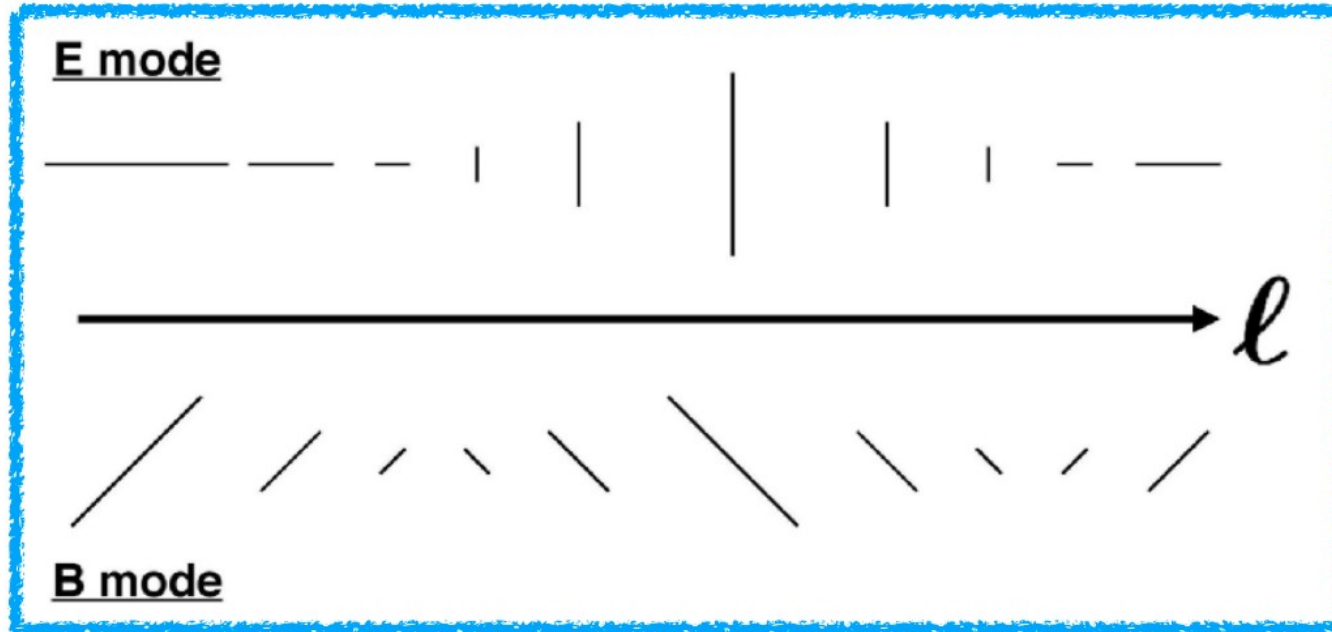


E and B mode



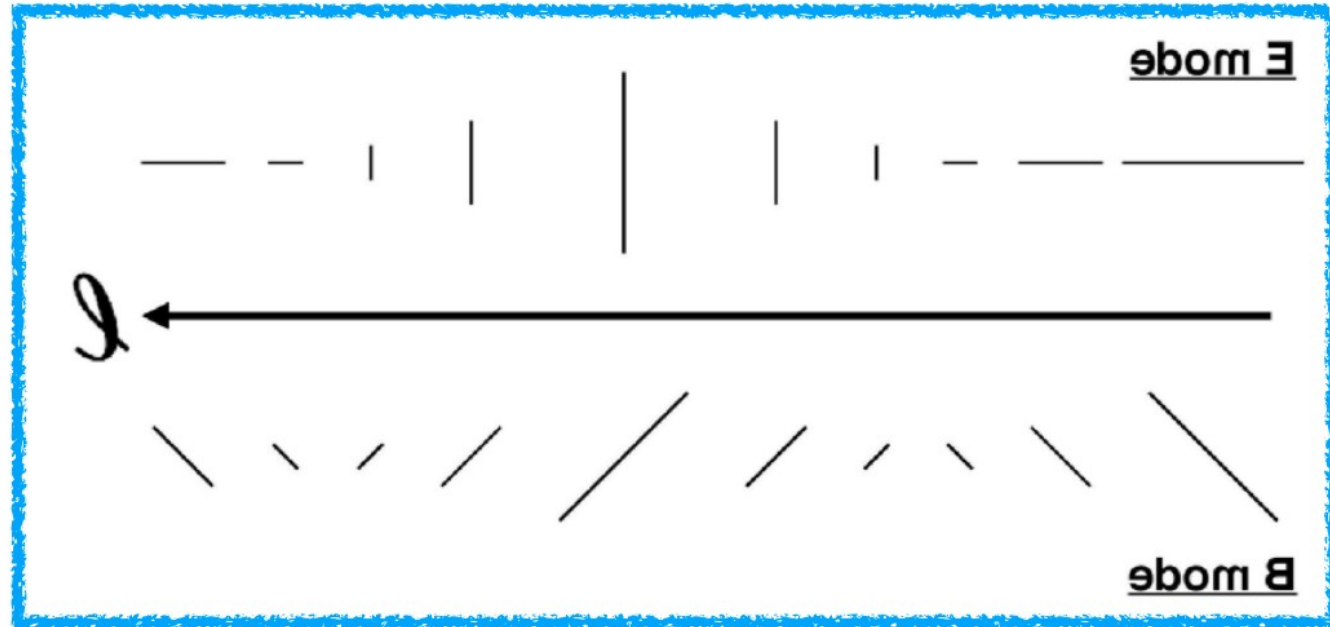
- **E mode**: Polarisation directions **parallel or perpendicular** to the wavevector
- **B mode**: Polarisation directions **45 degree tilted** with respect to the wavevector

Parity



- **E mode**: Parity even
- **B mode**: Parity odd

Parity



- E mode: Parity even
- B mode: Parity odd

Power Spectra

$$\langle E_{\ell} E_{\ell'}^* \rangle = (2\pi)^2 \delta_D^{(2)}(\ell - \ell') C_{\ell}^{EE}$$

$$\langle B_{\ell} B_{\ell'}^* \rangle = (2\pi)^2 \delta_D^{(2)}(\ell - \ell') C_{\ell}^{BB}$$

$$\langle T_{\ell} E_{\ell'}^* \rangle = \langle T_{\ell}^* E_{\ell'} \rangle = (2\pi)^2 \delta_D^{(2)}(\ell - \ell') C_{\ell}^{TE}$$

- However, $\langle EB \rangle$ and $\langle TB \rangle$ vanish for parity-preserving fluctuations because $\langle EB \rangle$ and $\langle TB \rangle$ change sign under parity flip

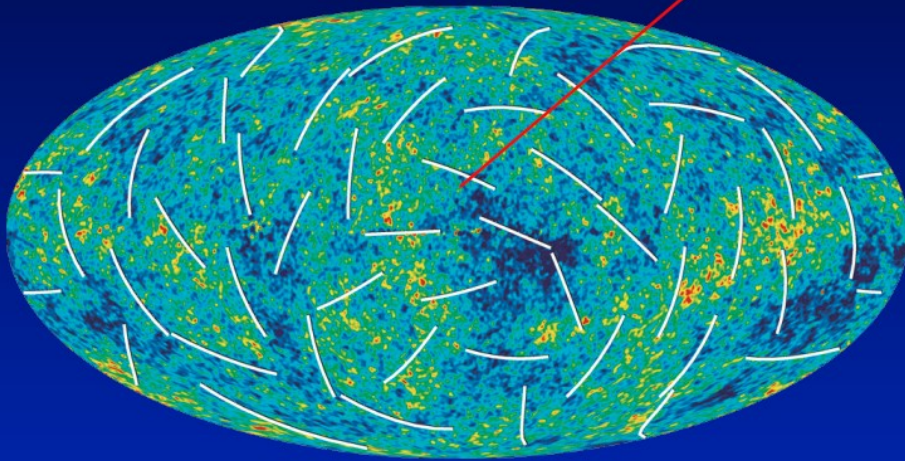
CMB Sky \rightarrow Cosmology

Compute $C_l \equiv \langle |a_{lm}|^2 \rangle$

Expand in
Spherical
Harmonics

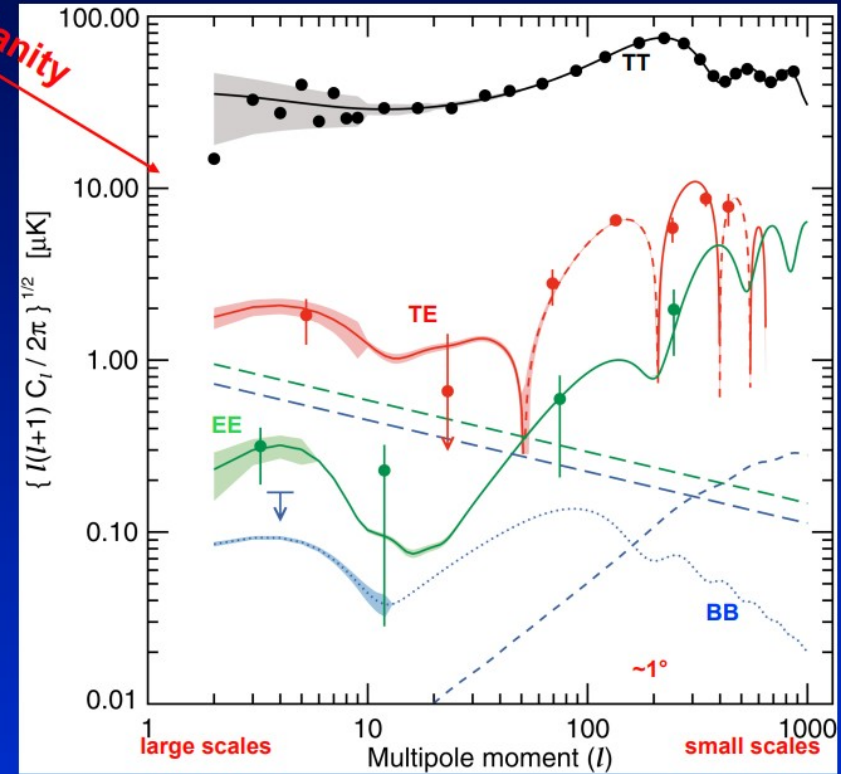
a_{lm}

WMAP CMB Sky

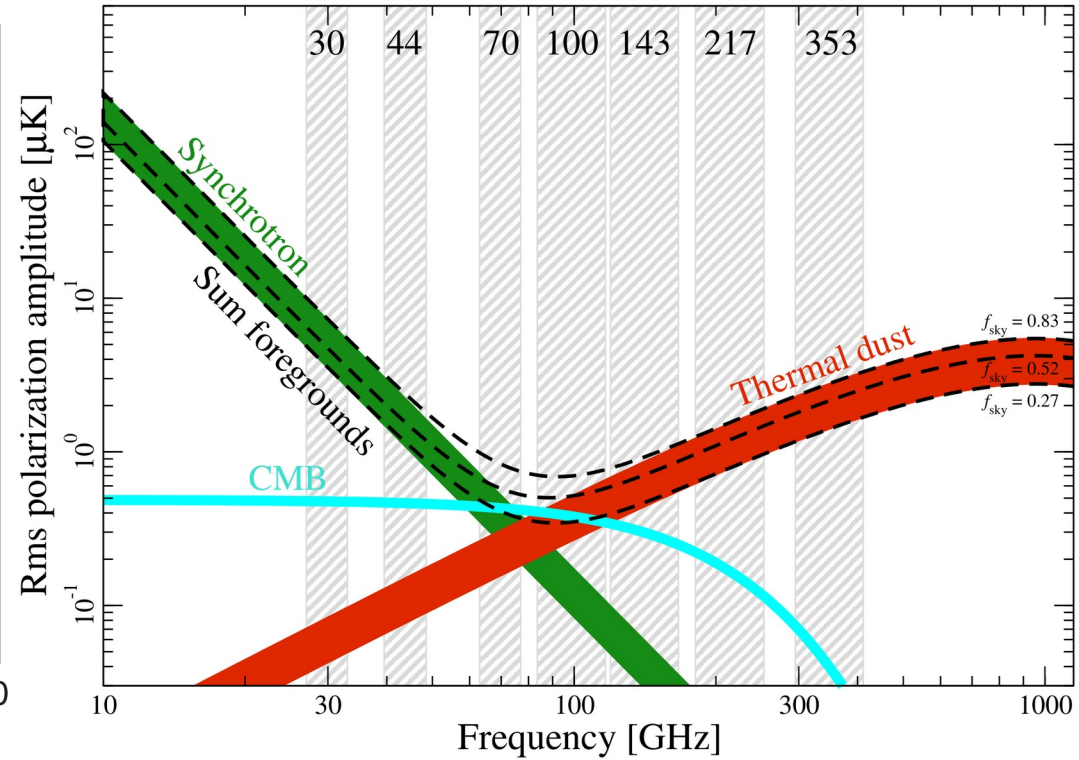
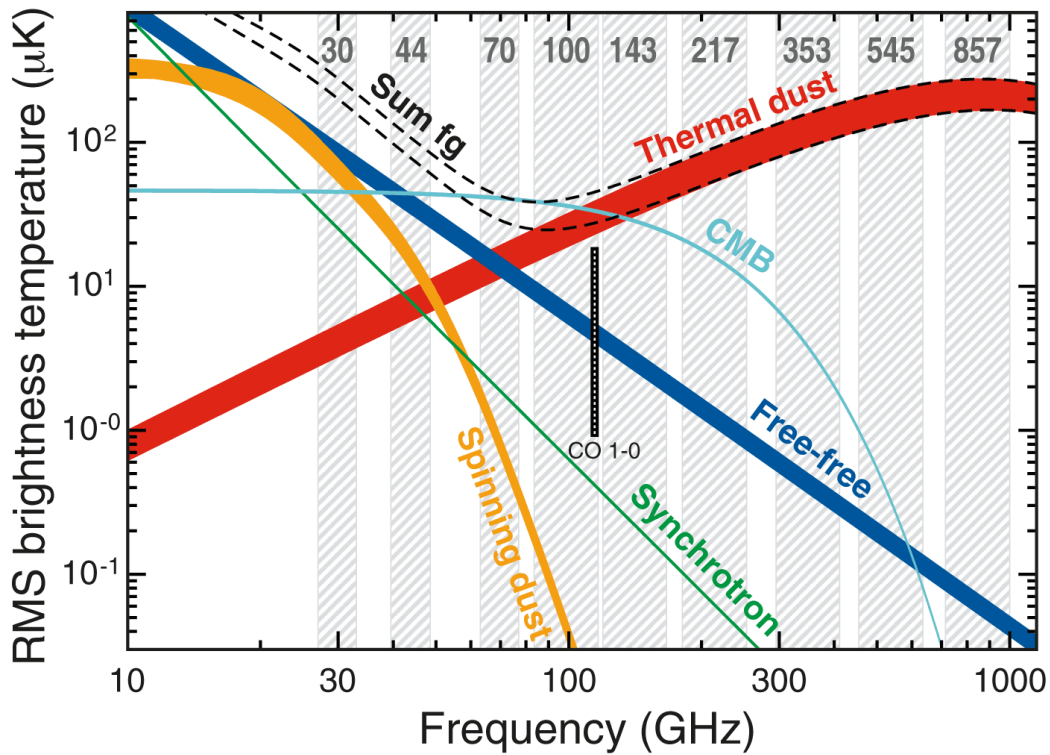


Gaussianity

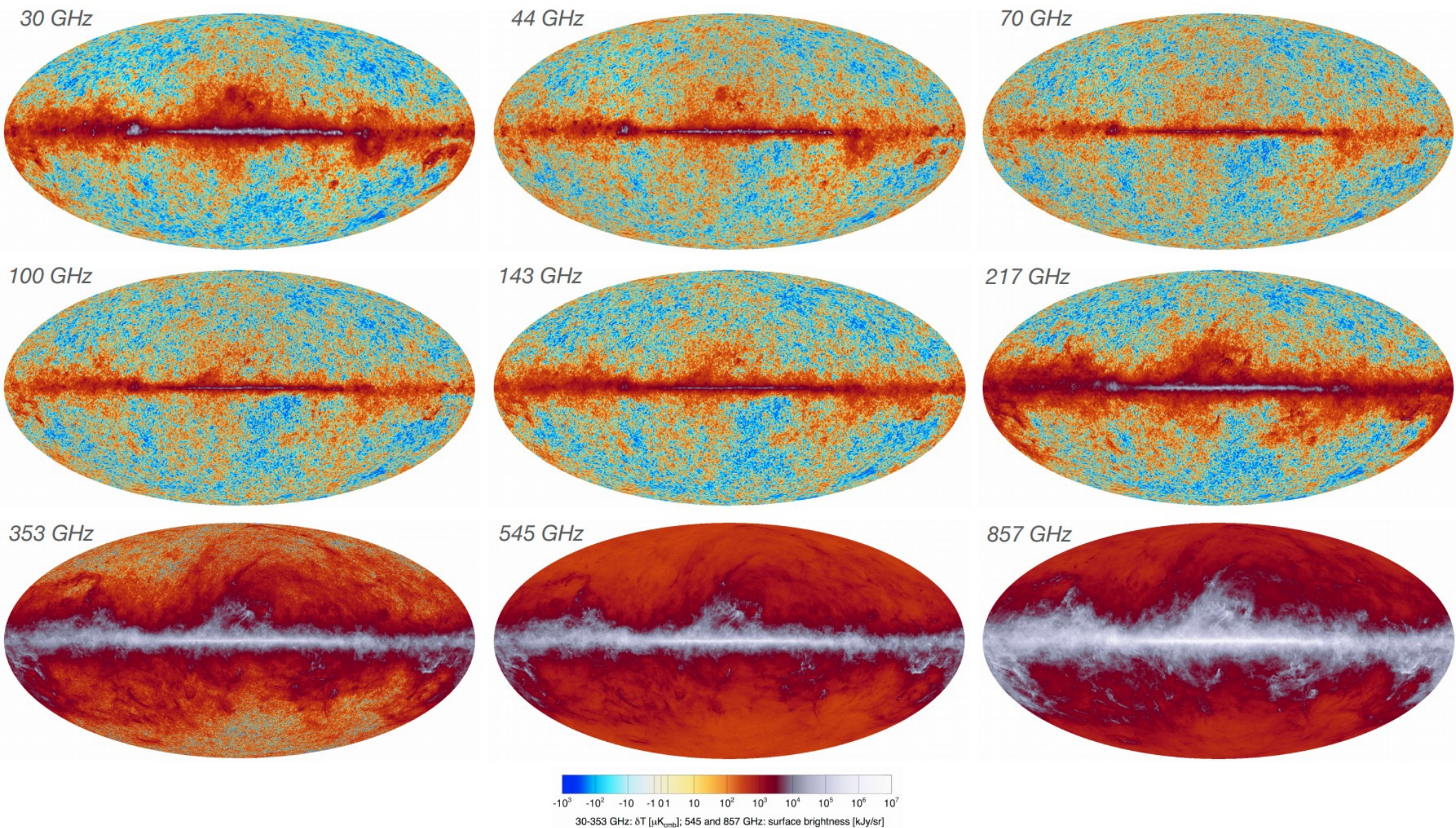
Power spectra



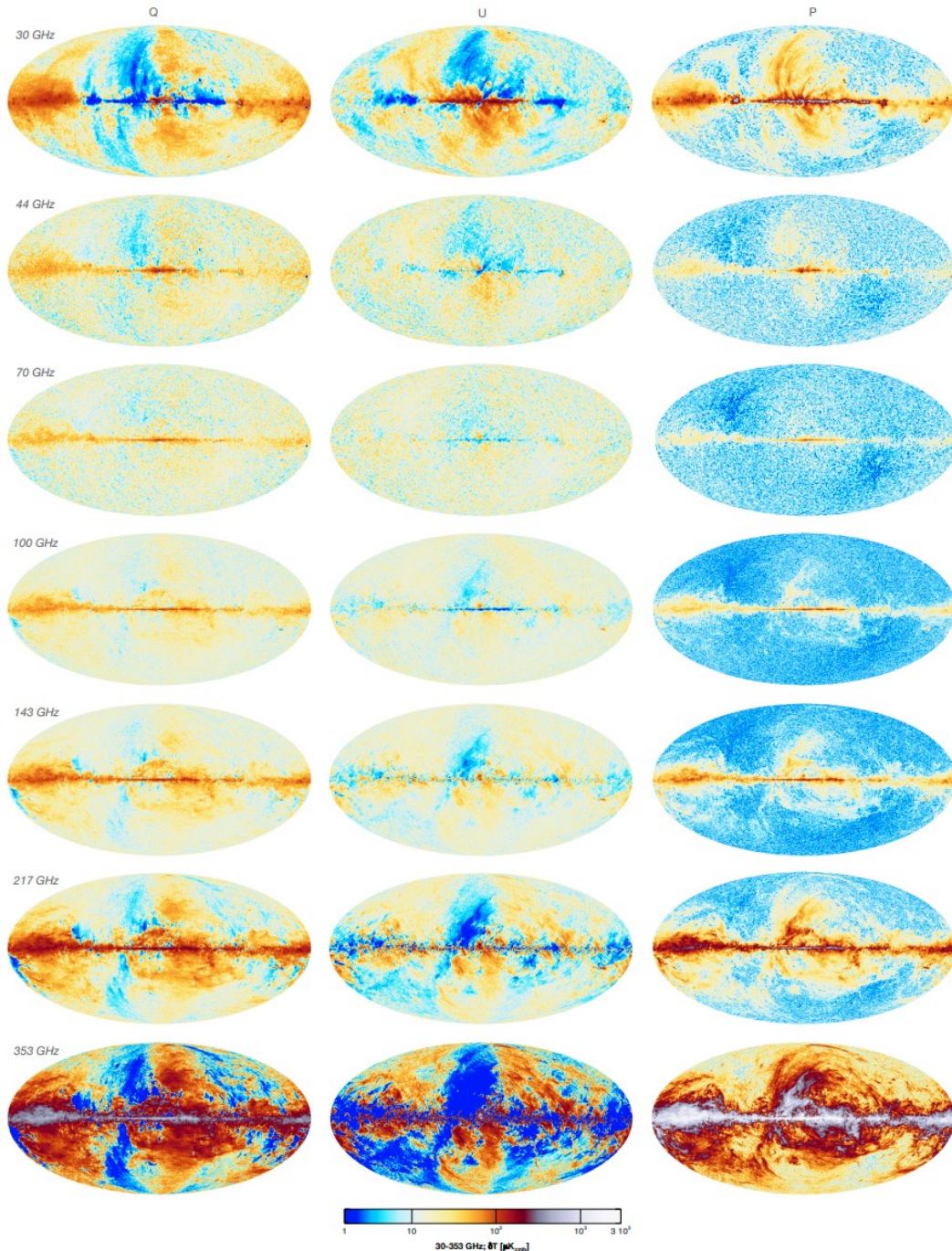
Measuring the CMB



Measuring the CMB



Measuring the CMB



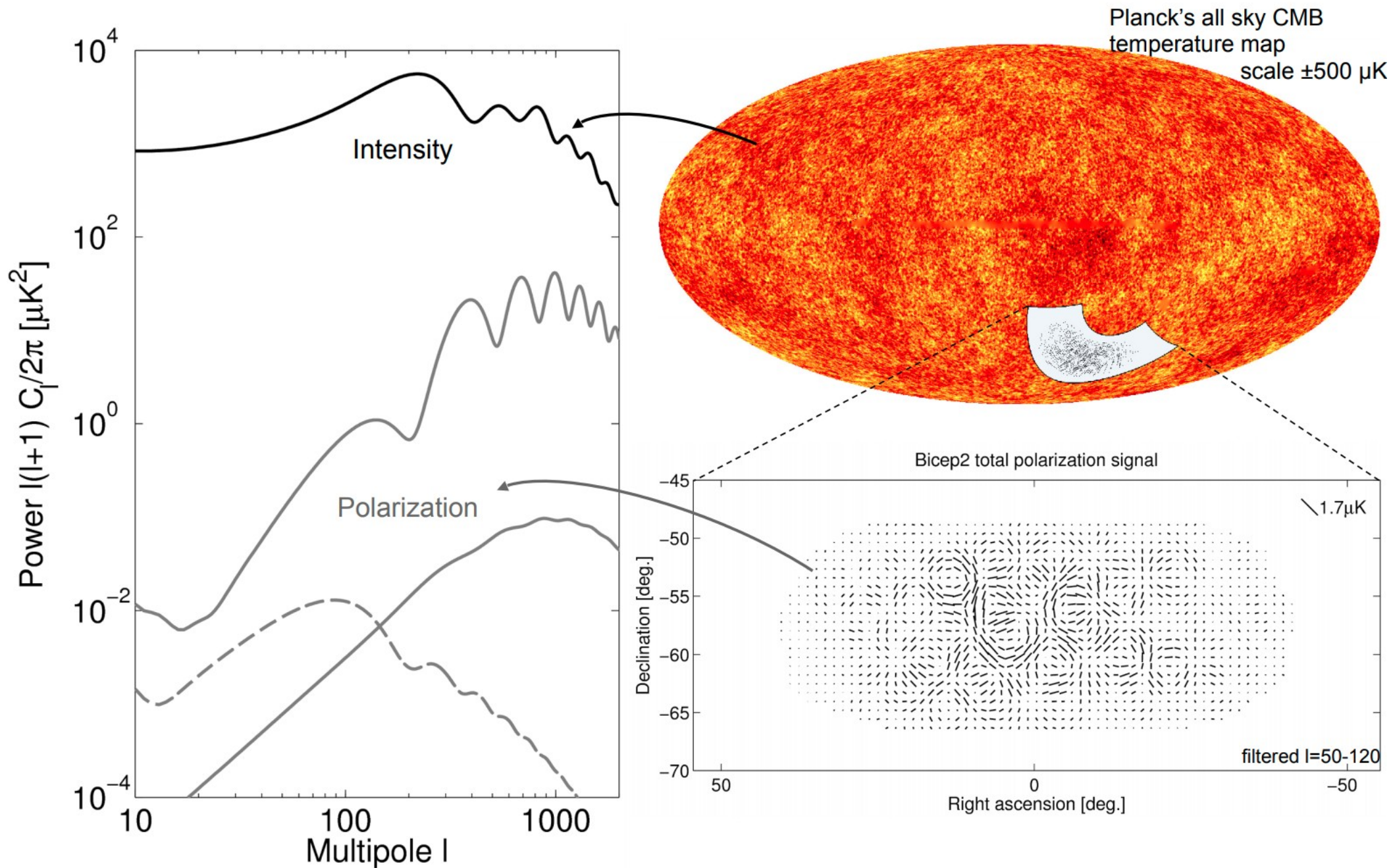
The 2018 Planck maps in polarization (Stokes Q, U, and polarized amplitude P)

- Q and U produced by E and B modes are given by

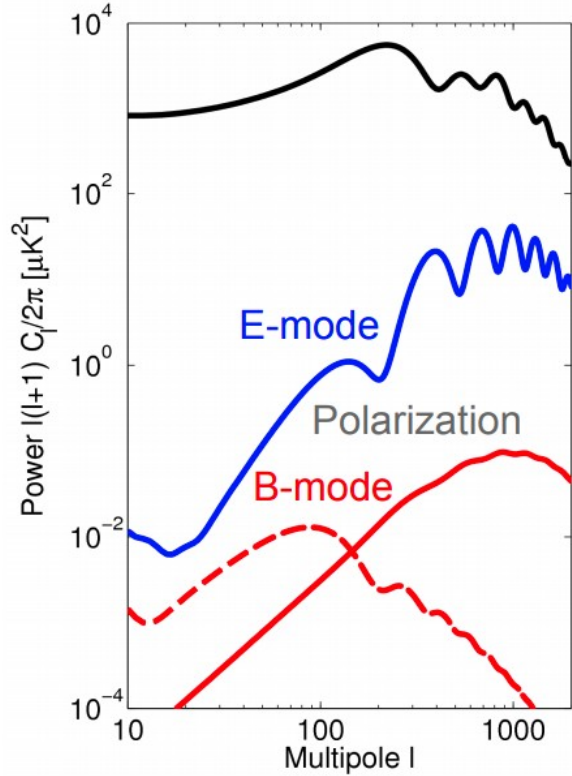
$$Q(\boldsymbol{\theta}) = \int \frac{d^2\ell}{(2\pi)^2} (E_\ell \cos 2\phi_\ell - B_\ell \sin 2\phi_\ell) \exp(i\boldsymbol{\ell} \cdot \boldsymbol{\theta})$$

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

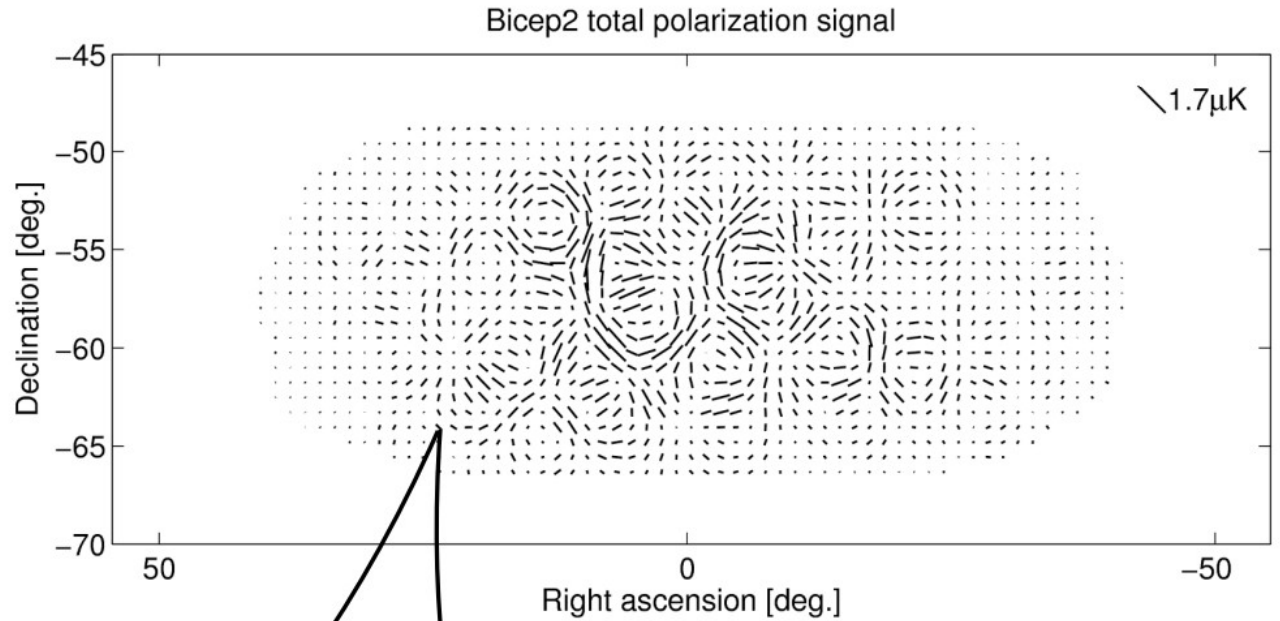
Cosmic Microwave Background



CMB Polarization



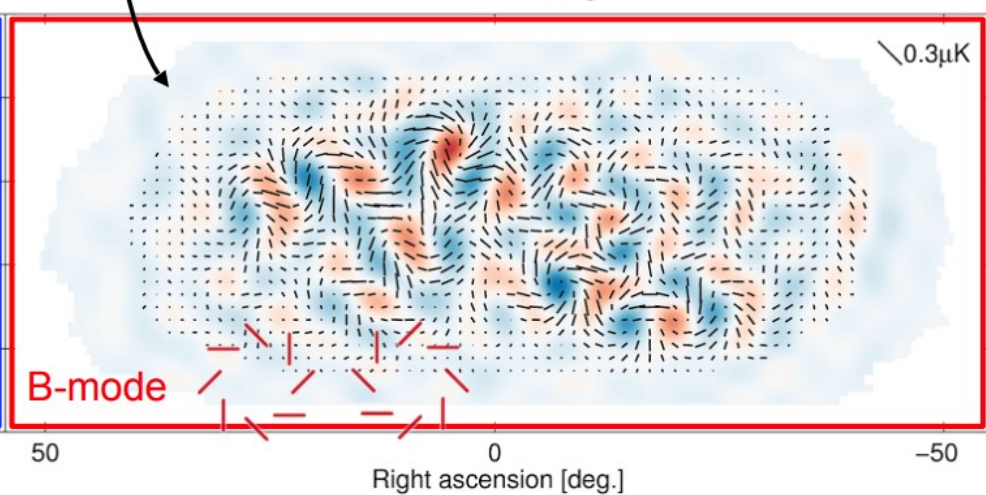
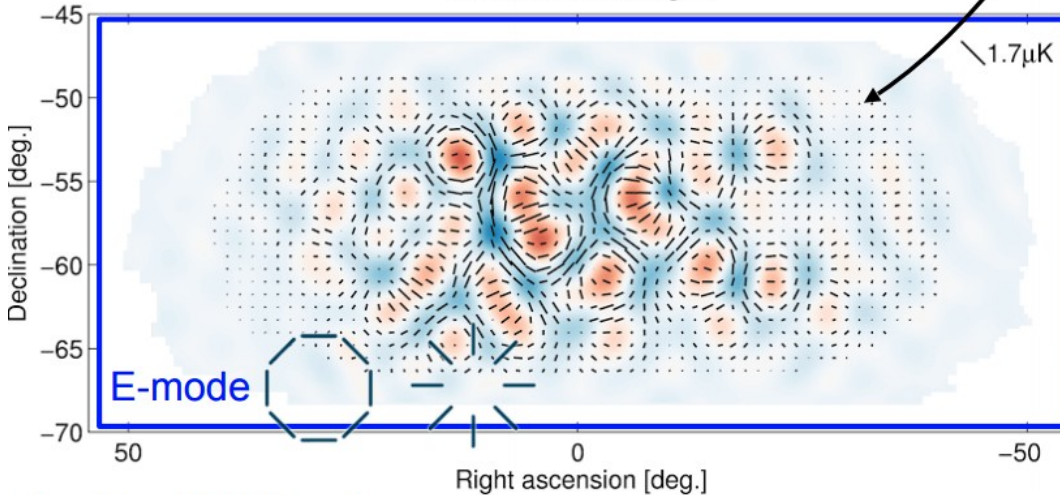
Need 2D basis to describe polarization map...



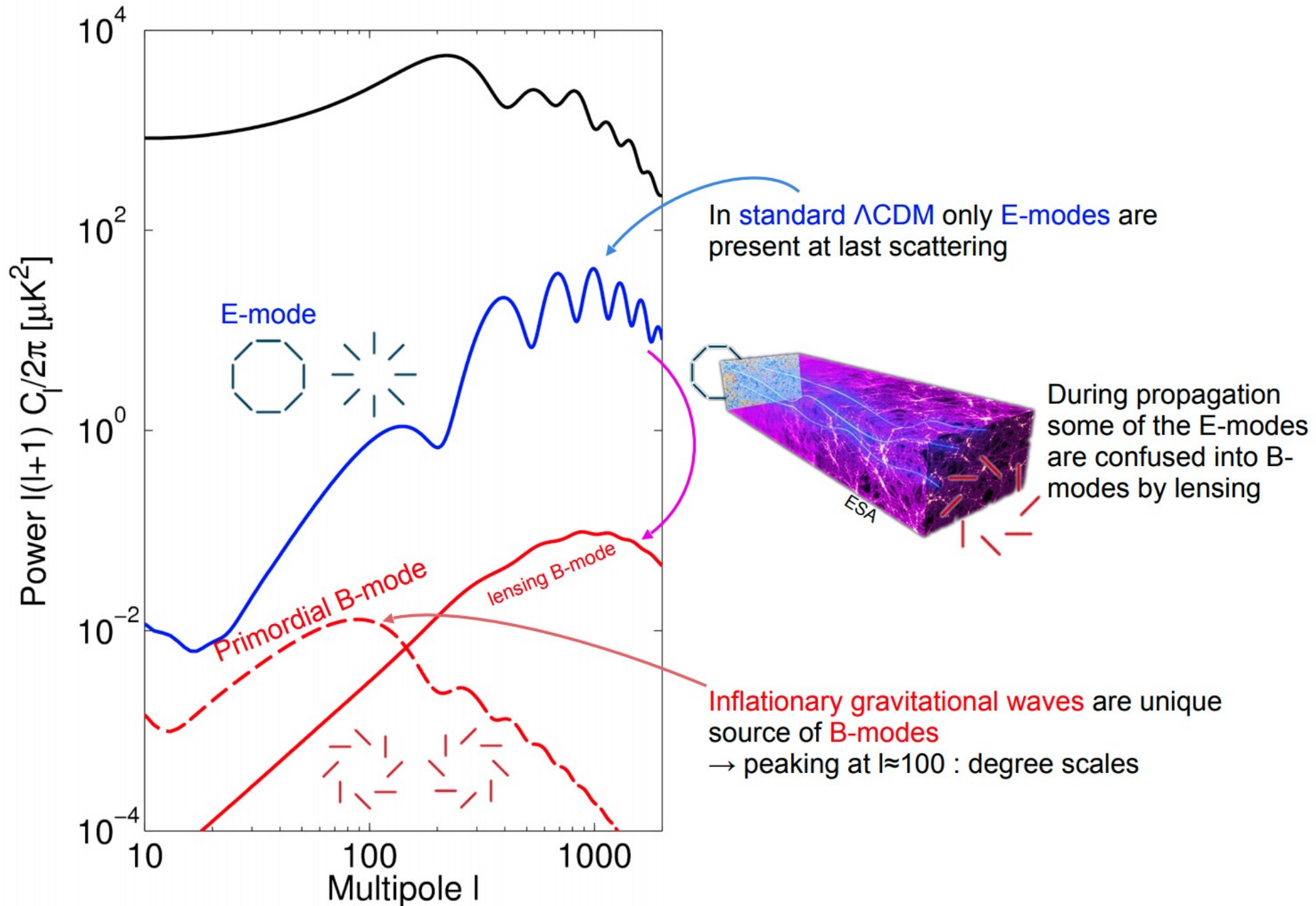
...clever choice for cosmology: E&B-modes

BICEP2 E-mode signal

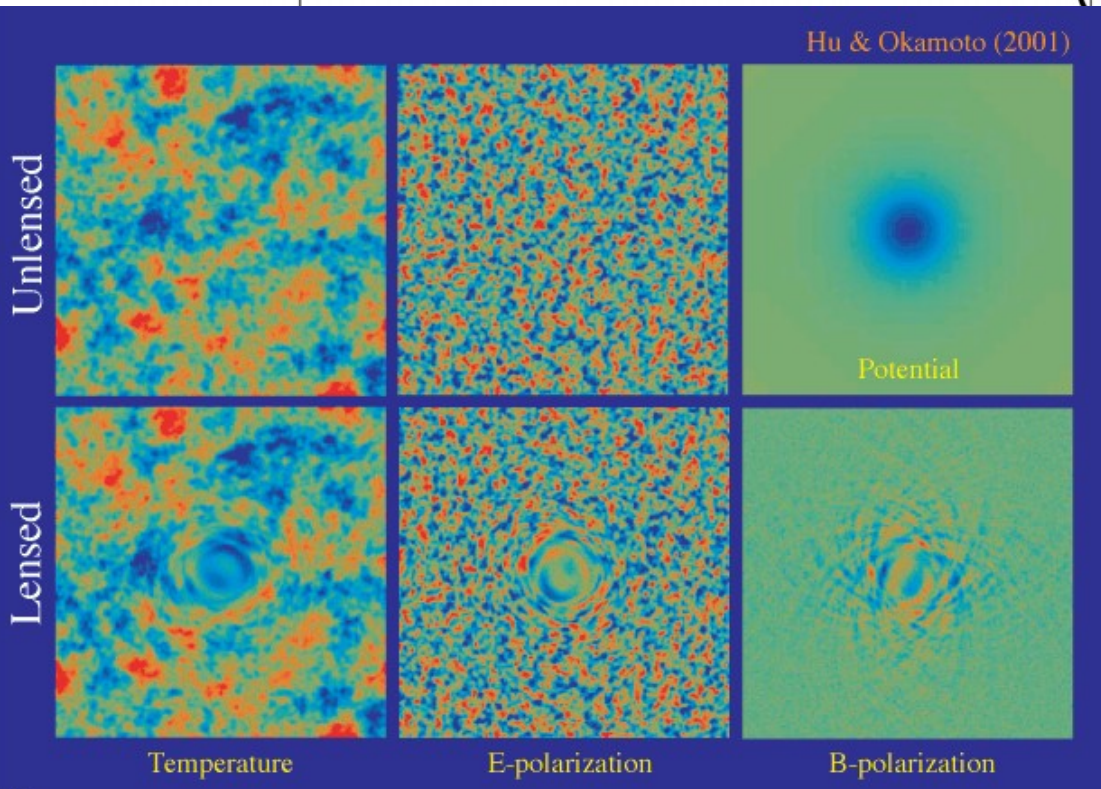
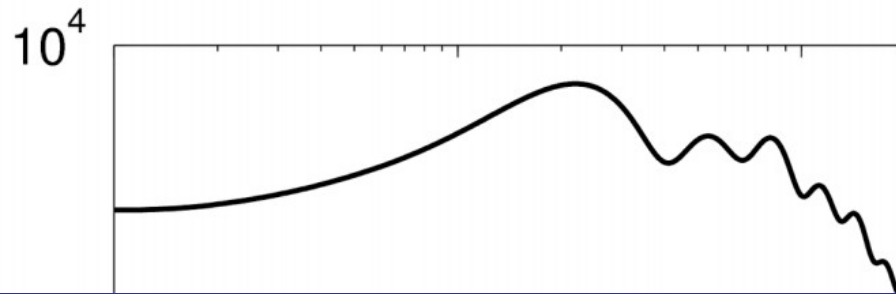
BICEP2 B-mode signal



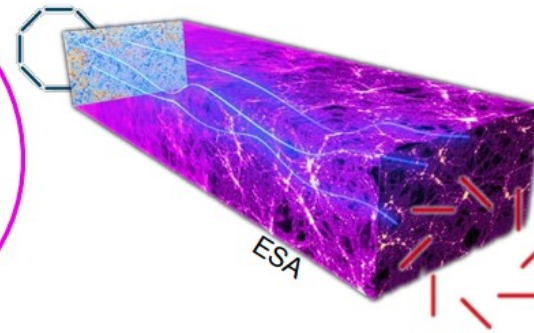
CMB Polarization



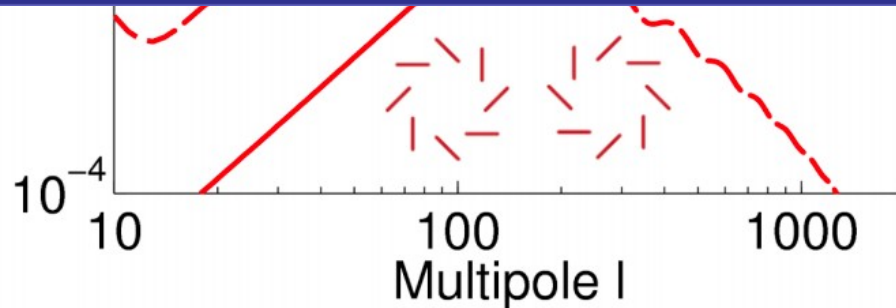
CMB Polarization



In **standard Λ CDM** only **E-modes** are present at last scattering



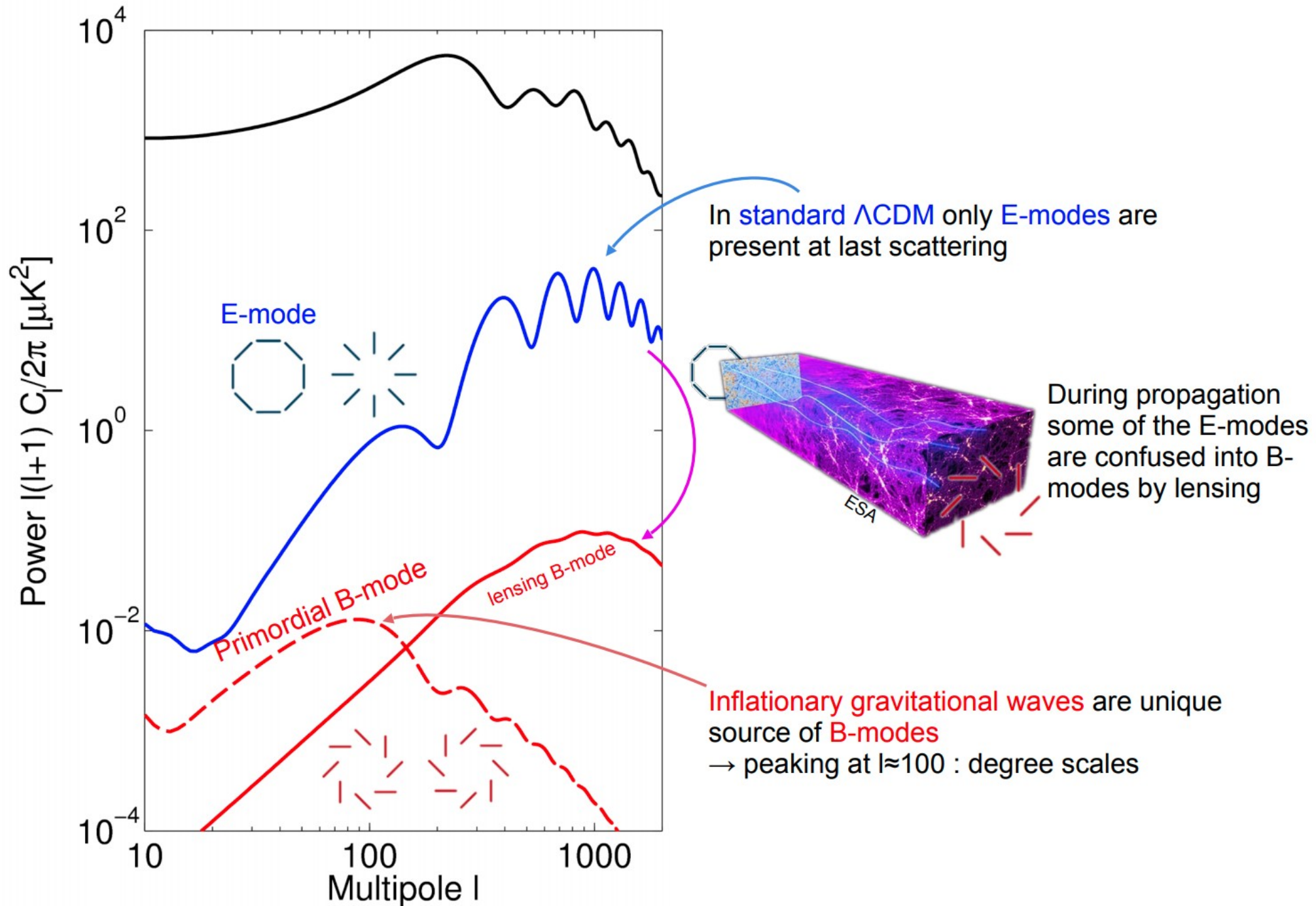
During propagation some of the E-modes are confused into B-modes by lensing



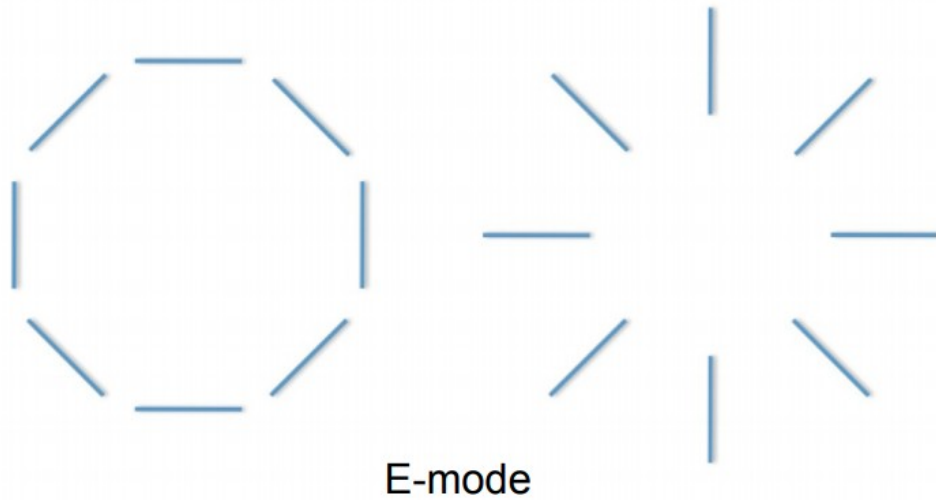
Inflationary gravitational waves are unique source of **B-modes**

→ peaking at $l \approx 100$: degree scales

CMB Polarization



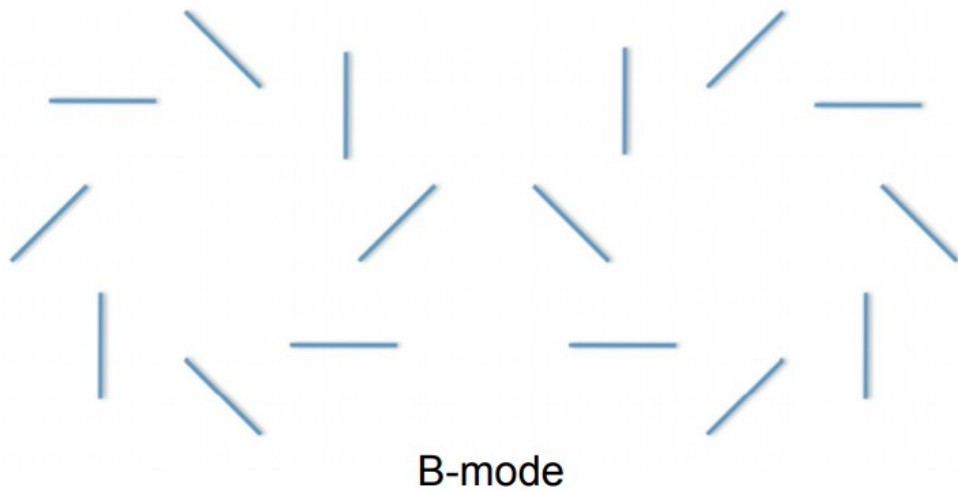
CMB Polarization



The plasma physics of the early universe causes the CMB to become slightly polarized.

Polarization can be described as the sum of E-modes and B-modes.

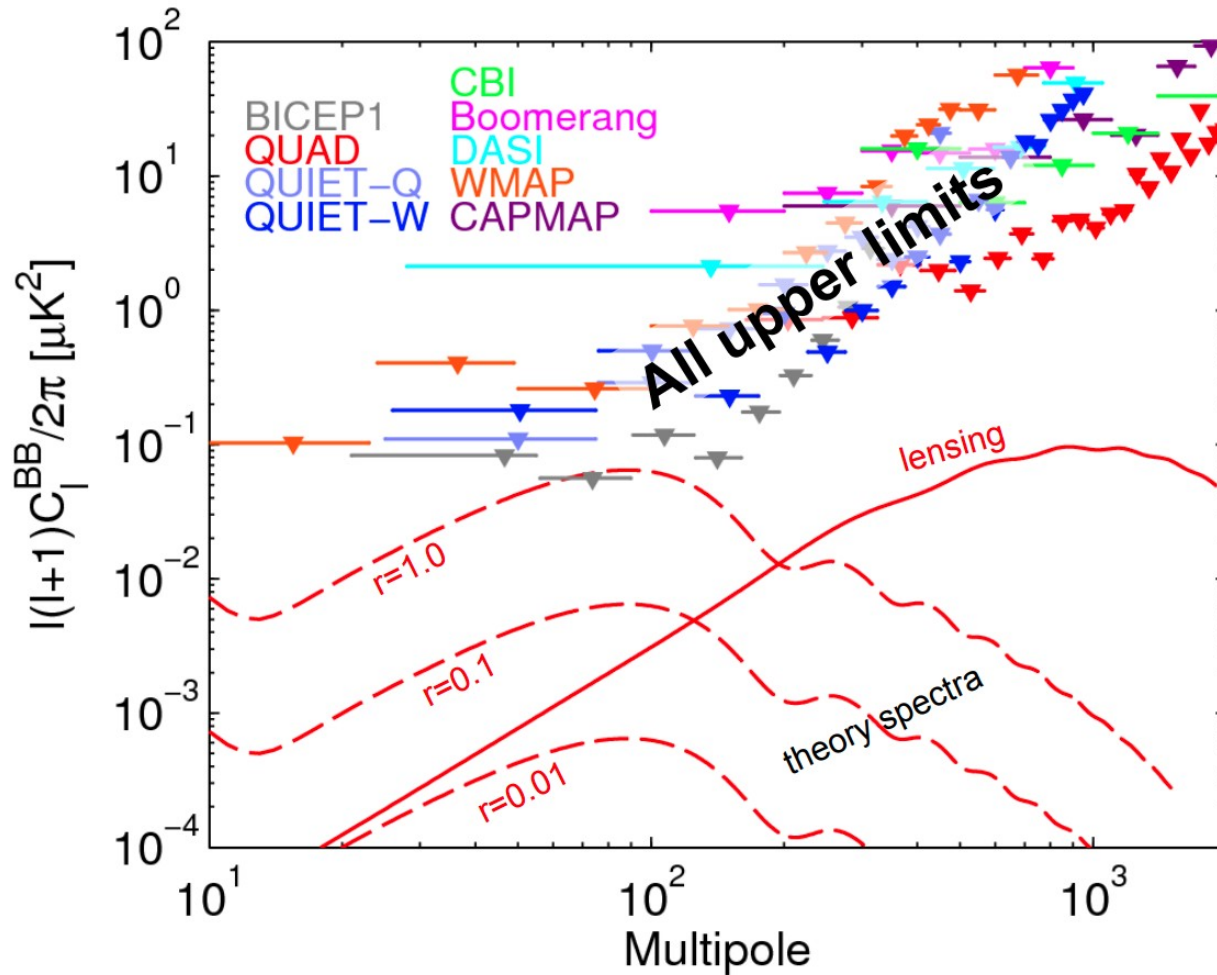
Only inflationary gravitational waves can induce significant B-mode polarization on degree angular scales.



A measurement of degree-scale B-modes would be direct evidence for the gravitational wave background, free of the parameter degeneracies and cosmic variance inherent to temperature measurements.

B modes until 2014

Search for B-modes



In simple inflationary gravitational wave models the

tensor-to-scalar ratio r

is the only parameter to the B-mode spectrum.

Up to now: just upper limits from searches for B-modes in the CMB polarization

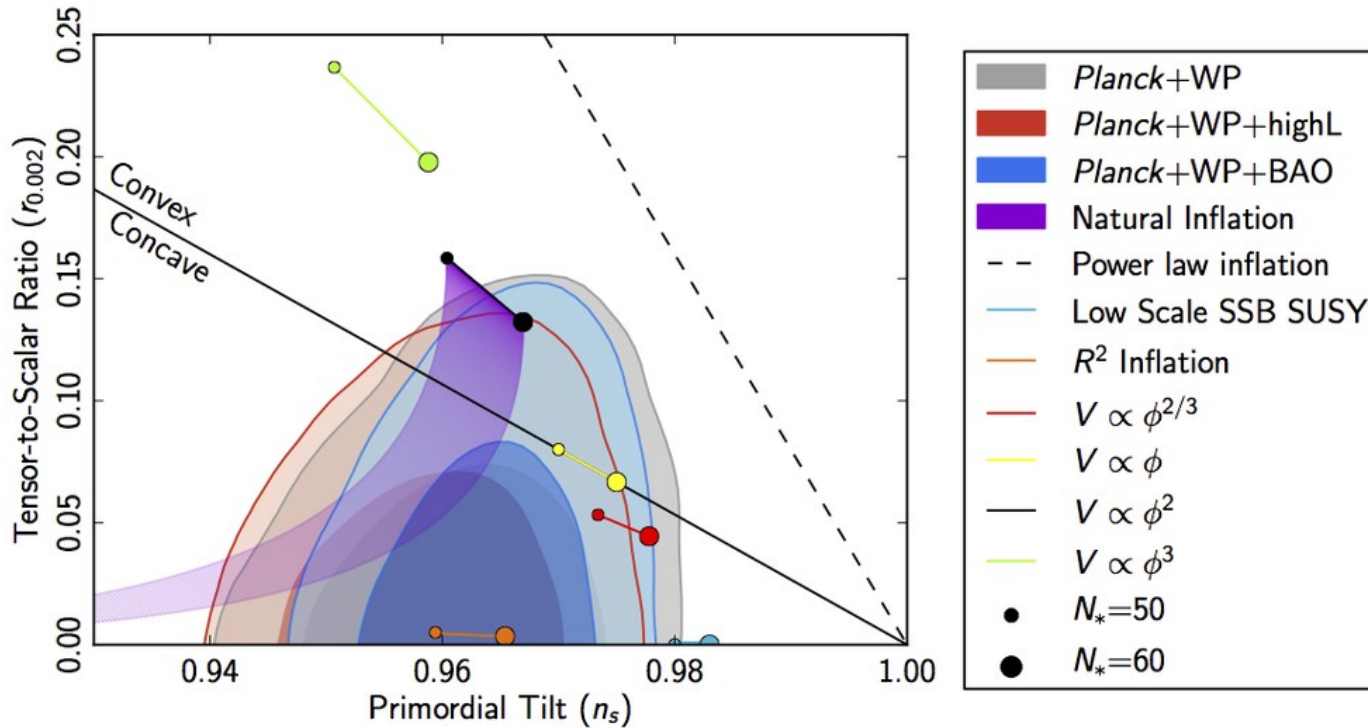
Best limit on r from BICEP1:

$r < 0.7$ (95% CL)

At high multipoles lensing B-mode dominant.

B modes

Search for B-modes



In simple inflationary gravitational wave models the

tensor-to-scalar ratio r

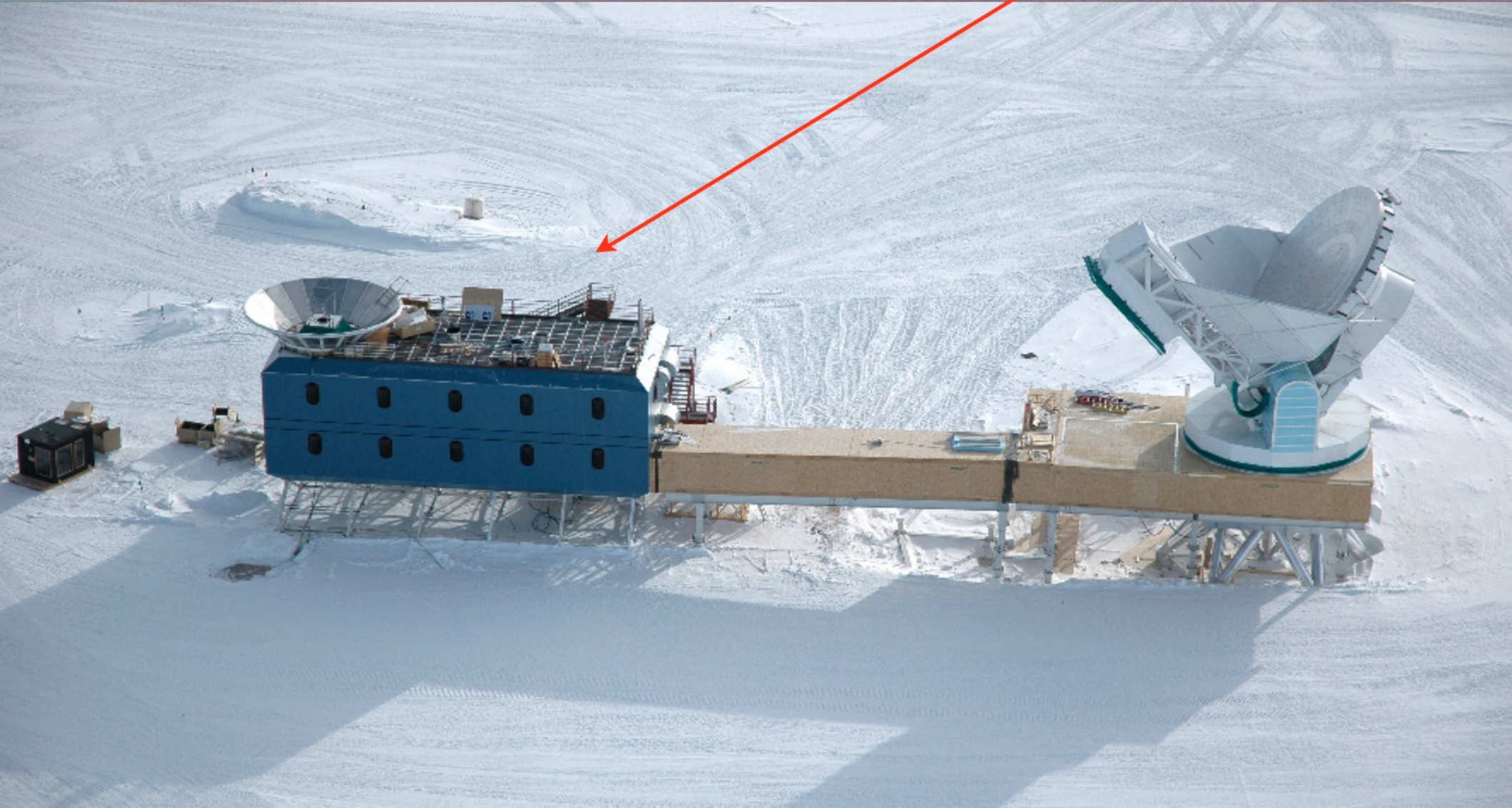
is the only parameter to the B-mode spectrum.

Up to now: just upper limits from searches for B-modes in the CMB polarization

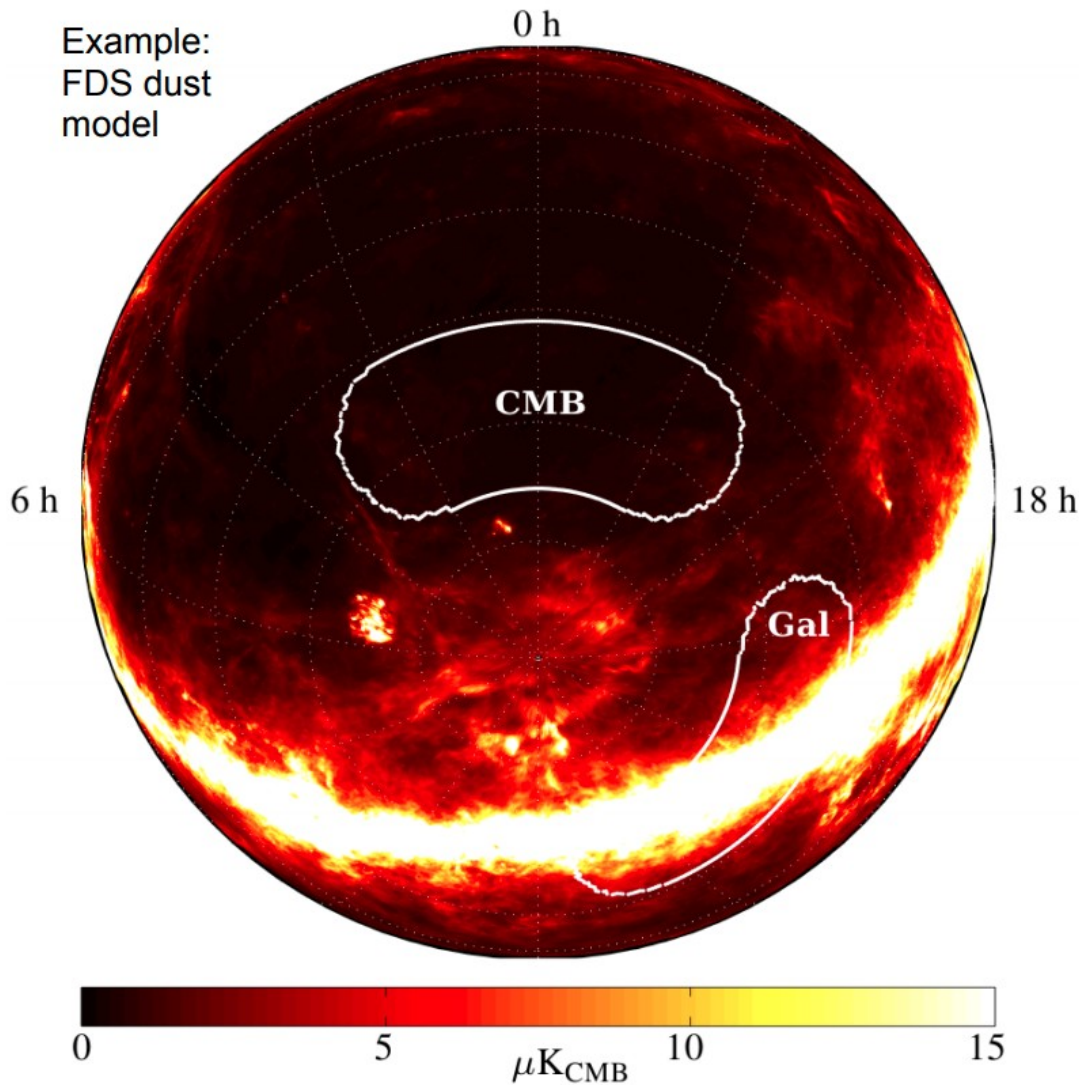
Best limit on r from BICEP1:

$r < 0.7$ (95% CL)

At high multipoles lensing B-mode dominant.



Observational Strategy



Target the “Southern Hole” - a region of the sky exceptionally free of dust and synchrotron foregrounds.

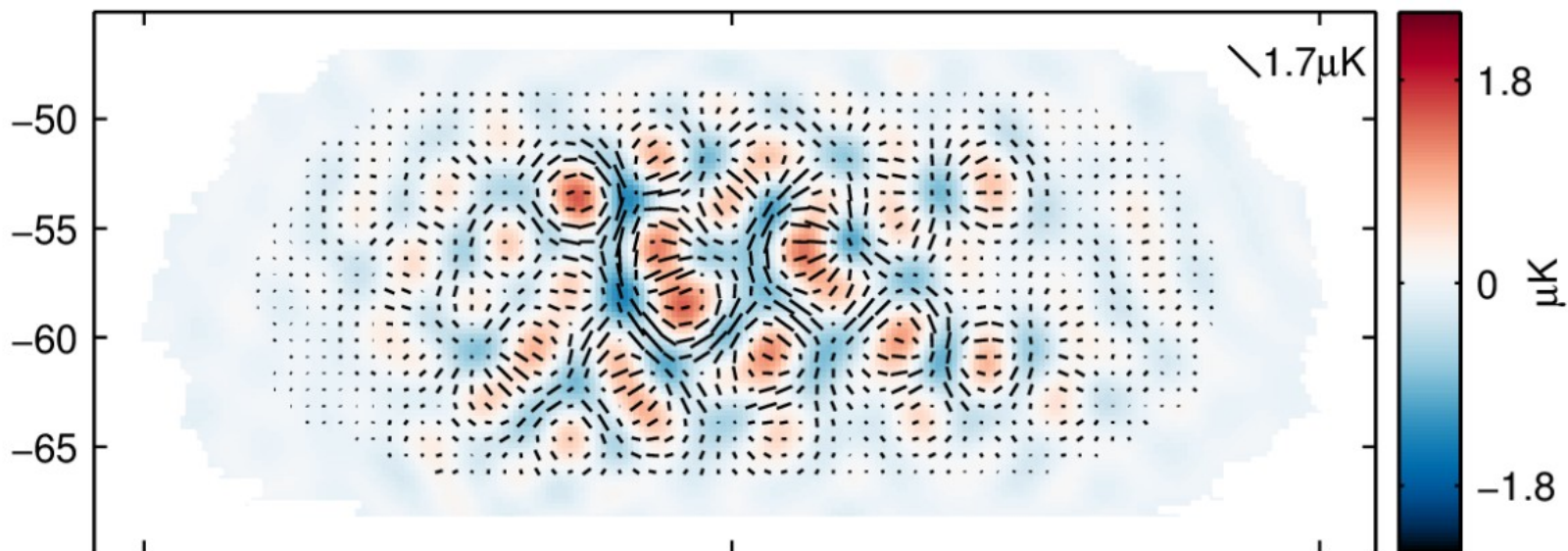
Detectors tuned to 150 GHz, near the peak of the CMB’s 2.7 K blackbody spectrum.

At 150 GHz the combined dust and synchrotron spectrum is predicted to be at a minimum in the Southern Hole.

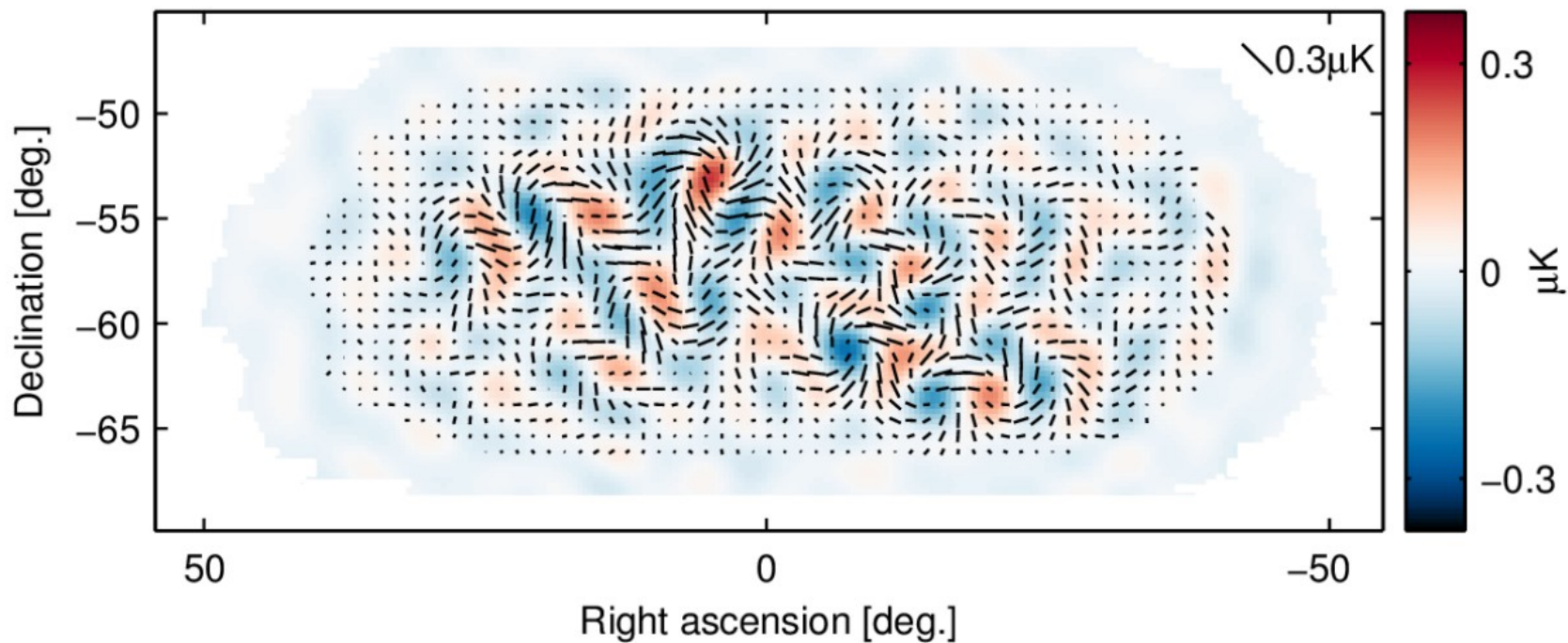
Expected foreground contamination of the B-mode power: $r \leq \sim 0.01$.

BICEP2 E- and B-mode Maps

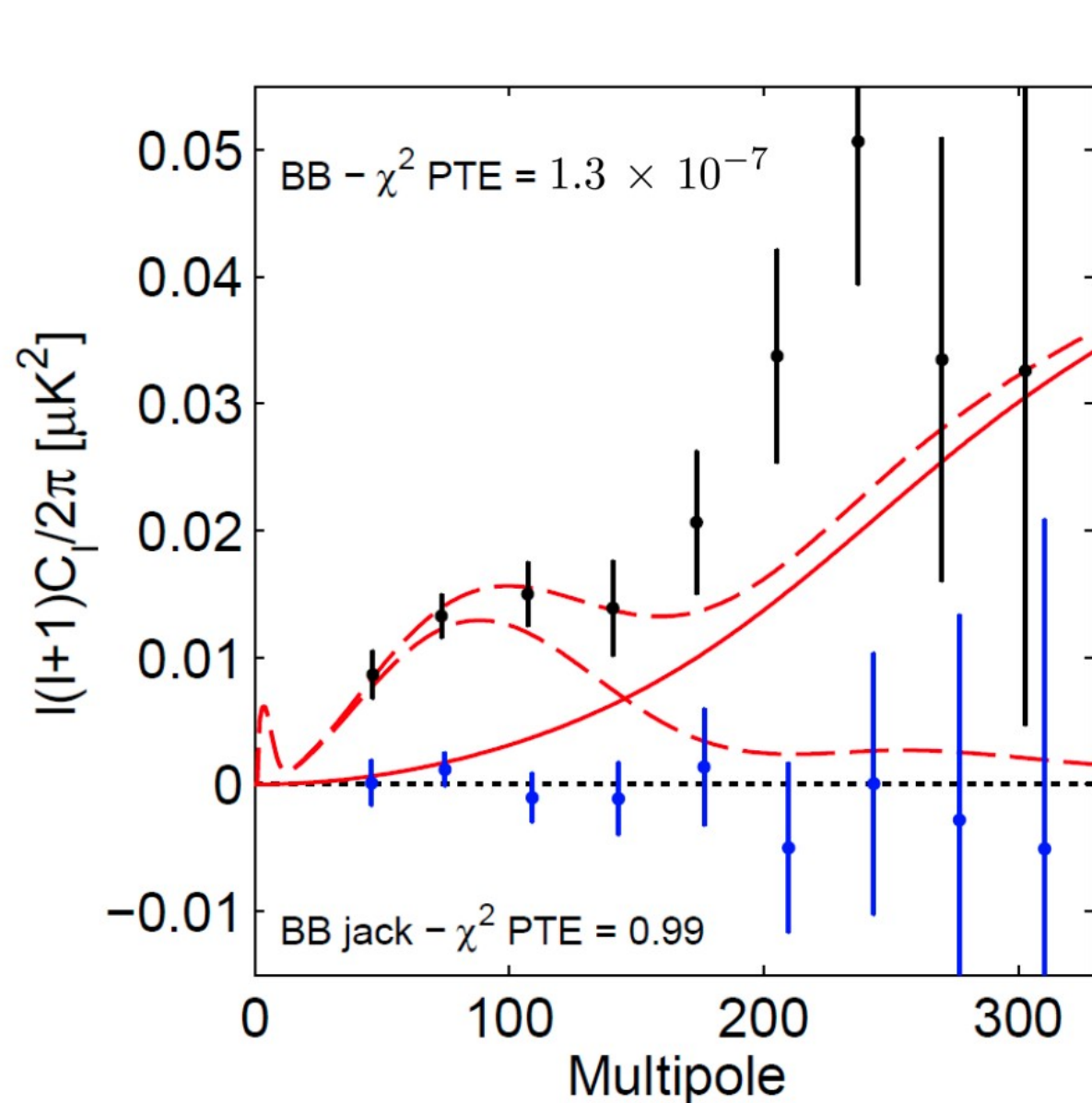
BICEP2: E signal



BICEP2: B signal



BICEP2 B-mode Power Spectrum



- B-mode power spectrum
- temporal split jackknife
- lensed- Λ CDM
- - - $r=0.2$

B-mode power spectrum estimated directly from Q&U maps, including map based “purification” to avoid $E \rightarrow B$ mixing

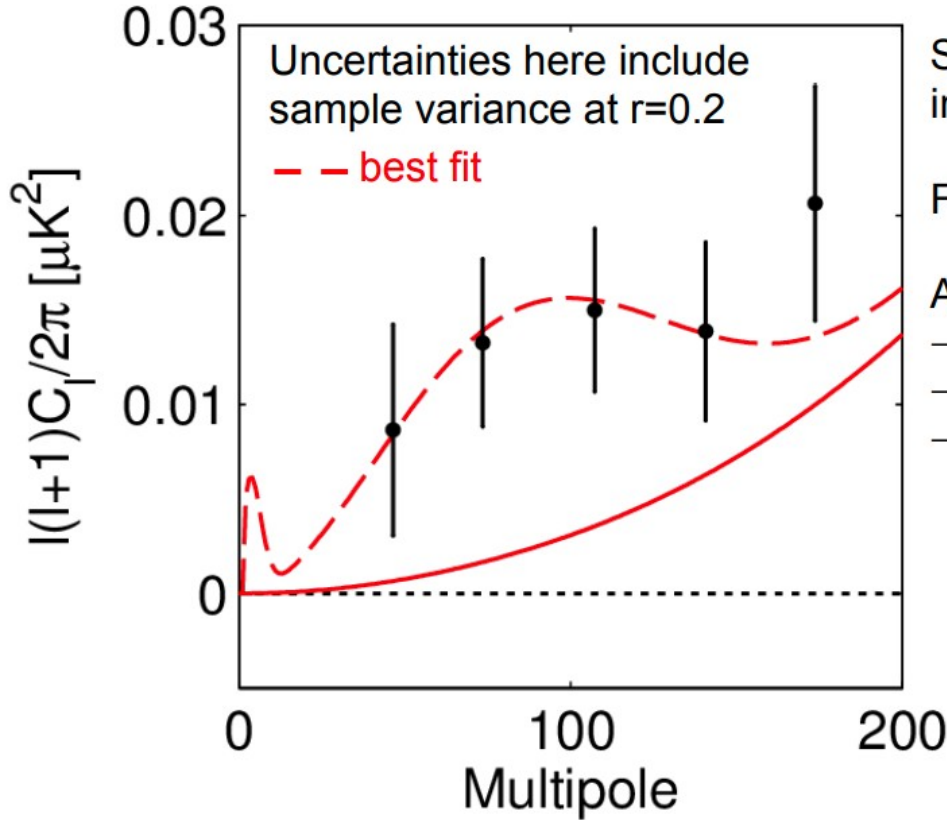
Consistent with lensing expectation at higher l ...yes, two are a bit high...

At low l excesses over lensed- Λ CDM at high signal-to-noise.

For the hypothesis that the measured band powers come from lensed- Λ CDM we find:

χ^2 PTE	1.3×10^{-7}
significance	5.3σ

Constraint on Tensor-to-scalar Ratio r



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

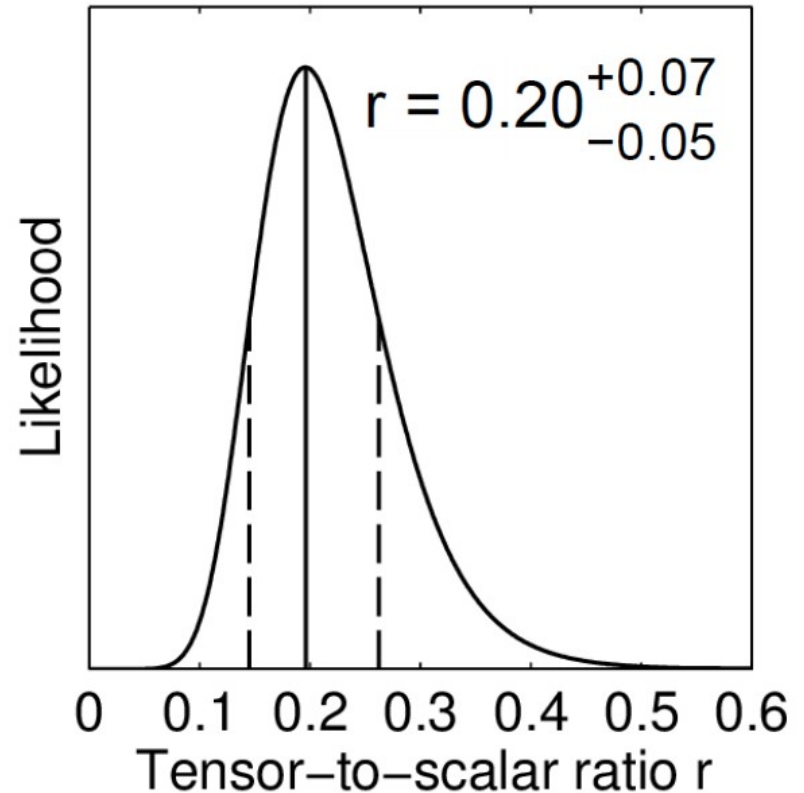
Within this simplistic model we find:

$r = 0.2$ with uncertainties dominated by sample variance

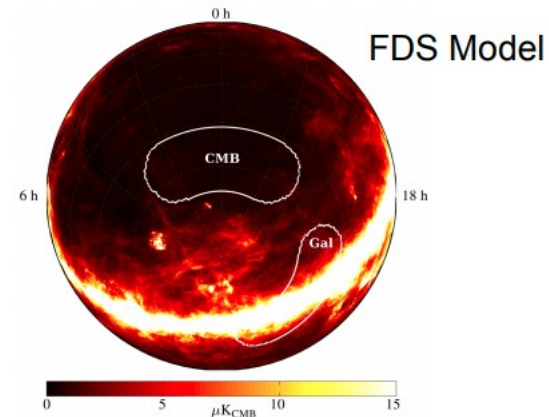
PTE of fit to data: 0.9

→ model is perfectly acceptable fit to the data

$r = 0$ ruled out at 7.0σ



Polarized Dust Foreground Projections

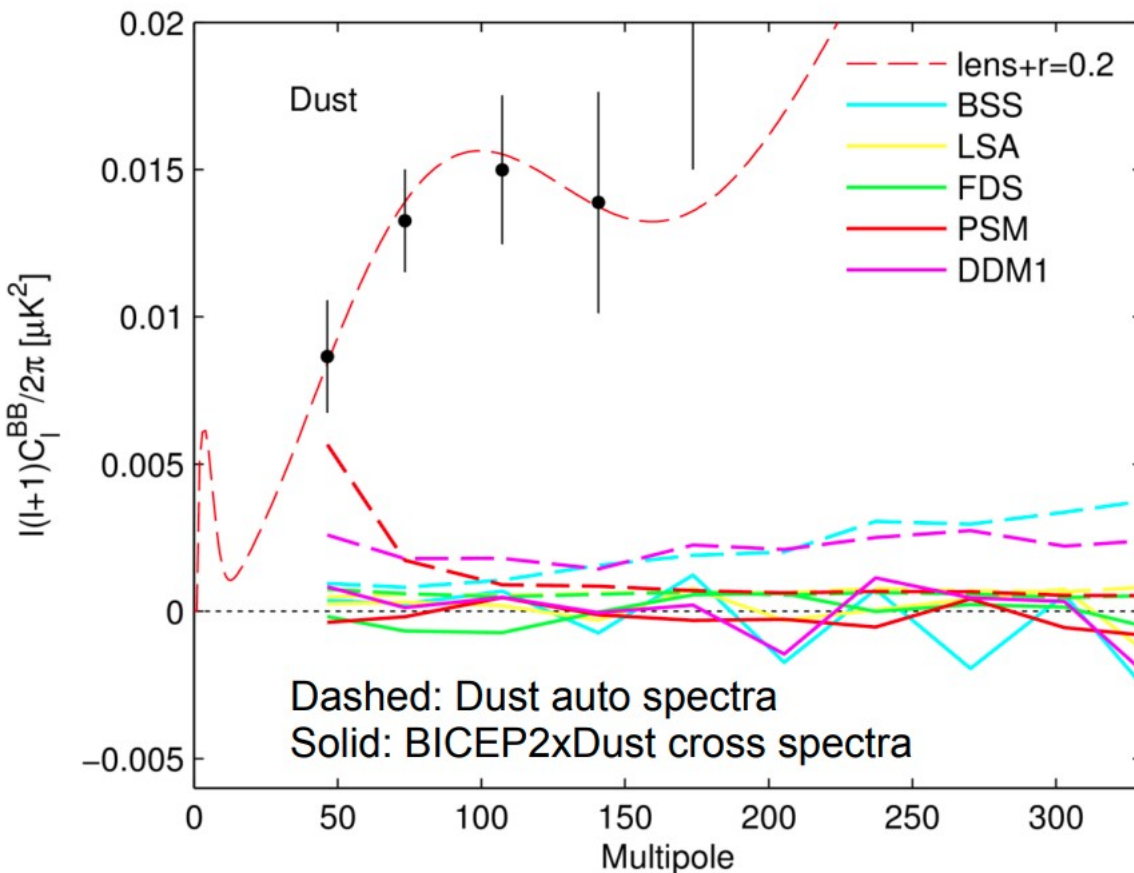


The BICEP2 region is chosen to have lowest foreground emission based on available pre-Planck models.

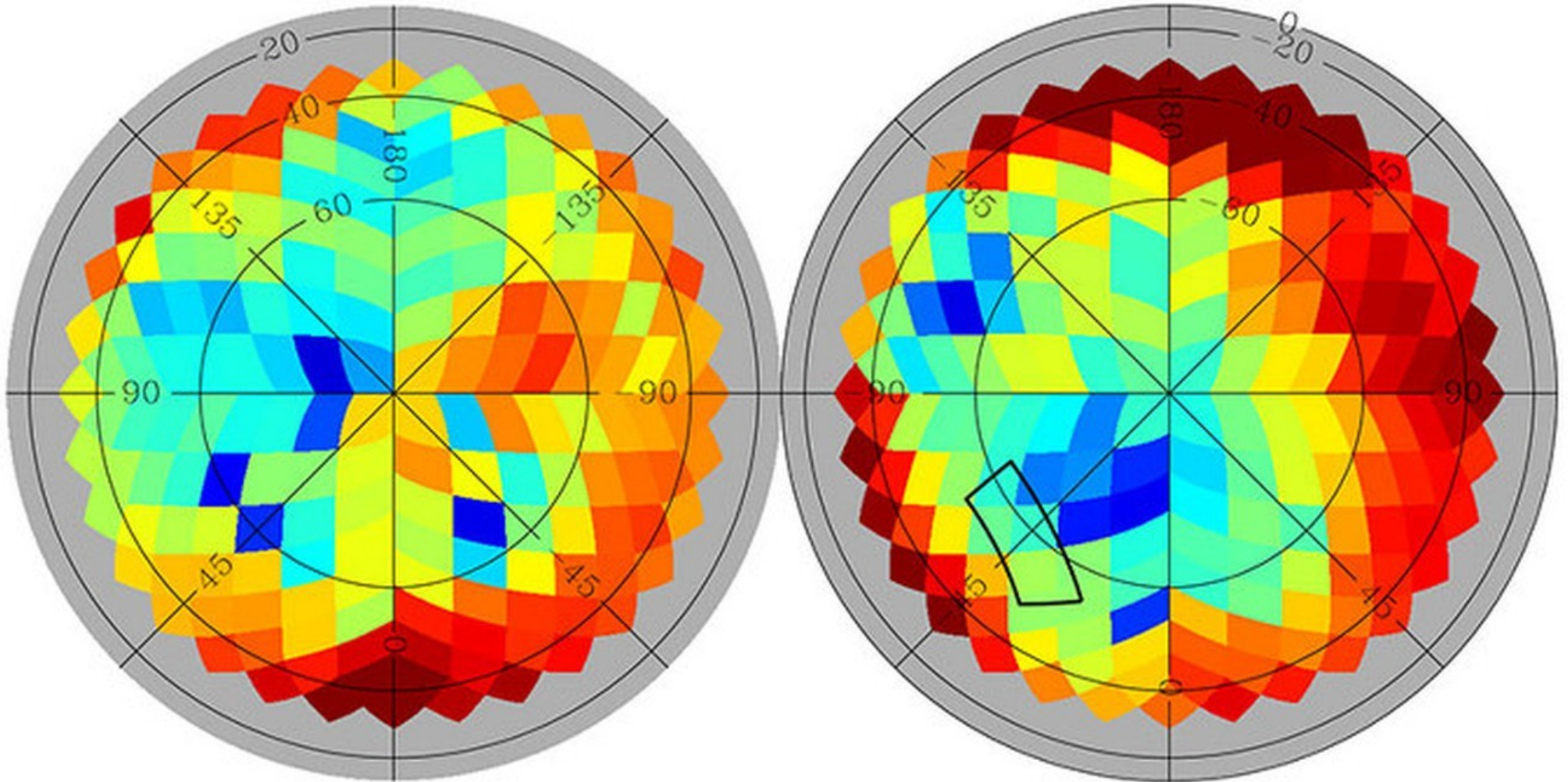
Use models of polarized dust emission to estimate foregrounds. **(default parameter values)**

Dust model auto spectra are well below observed signal level.

Cross spectra are lower, though this could indicate limitations of models.



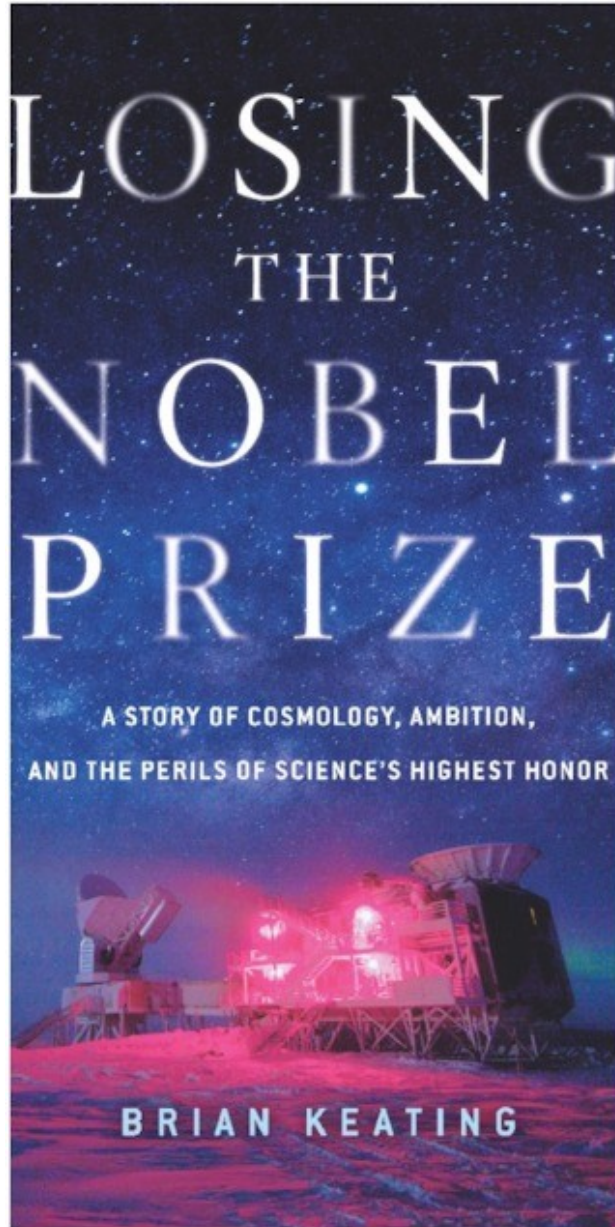
Polarized Dust Foreground Measurements



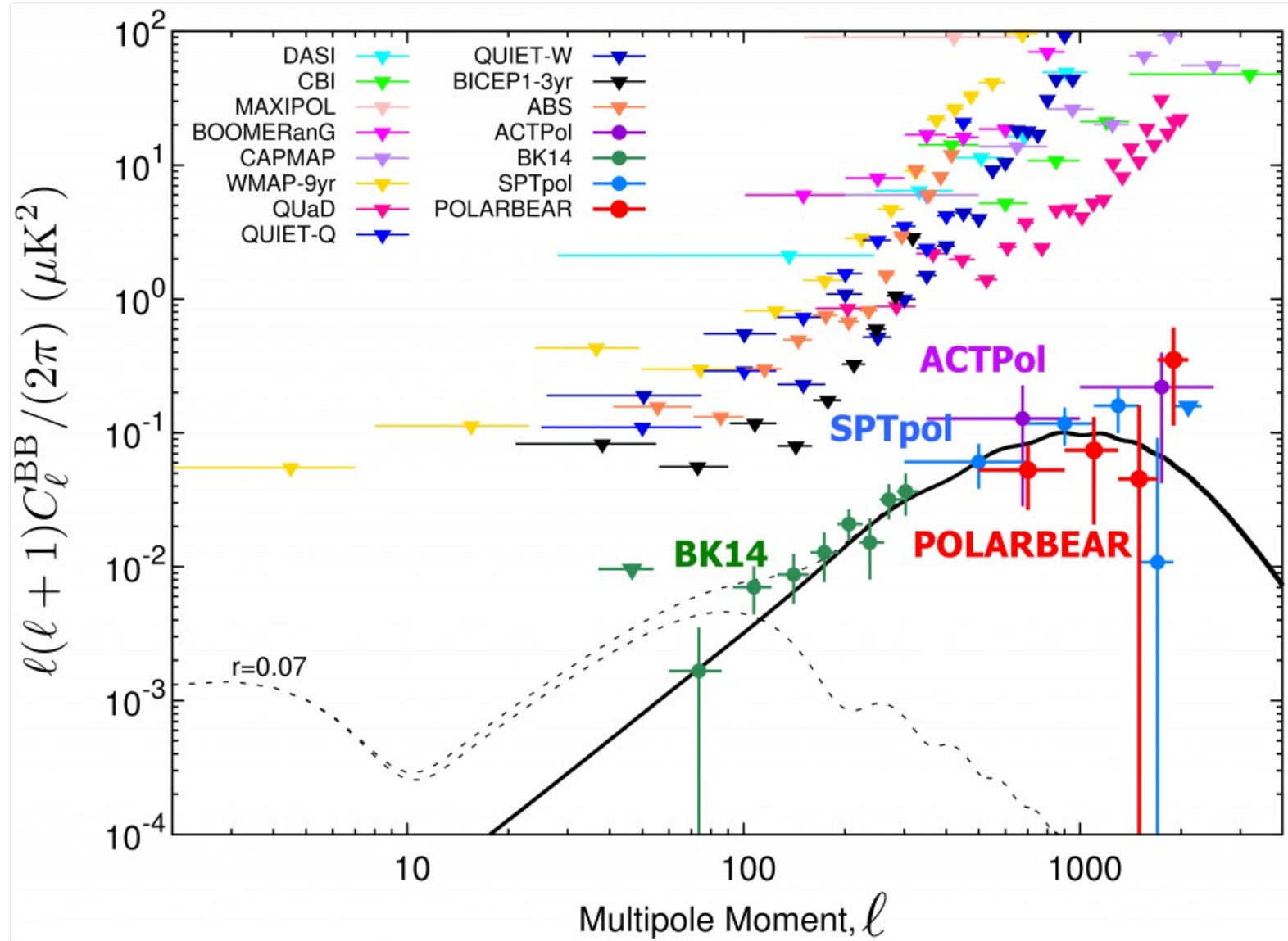
Map of the dust B-mode polarization, as estimated from the Planck data, in units of the signal expected from primordial gravitational waves. The green color corresponds to a Galactic signal comparable to the signal detected by the BICEP2 experiment over the sky patch marked with a black contour. Blue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

Dust to dust



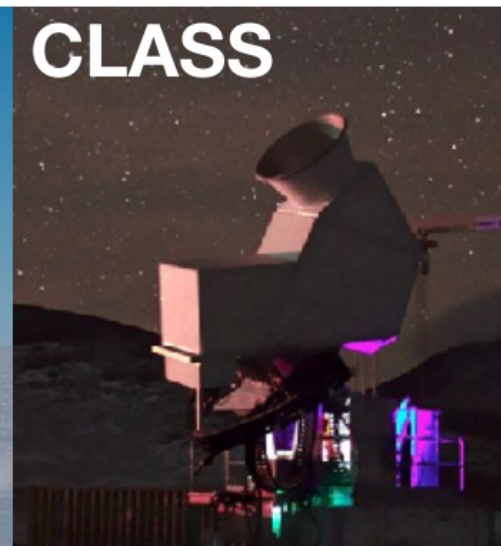
B-modes Power Spectrum





What comes next?

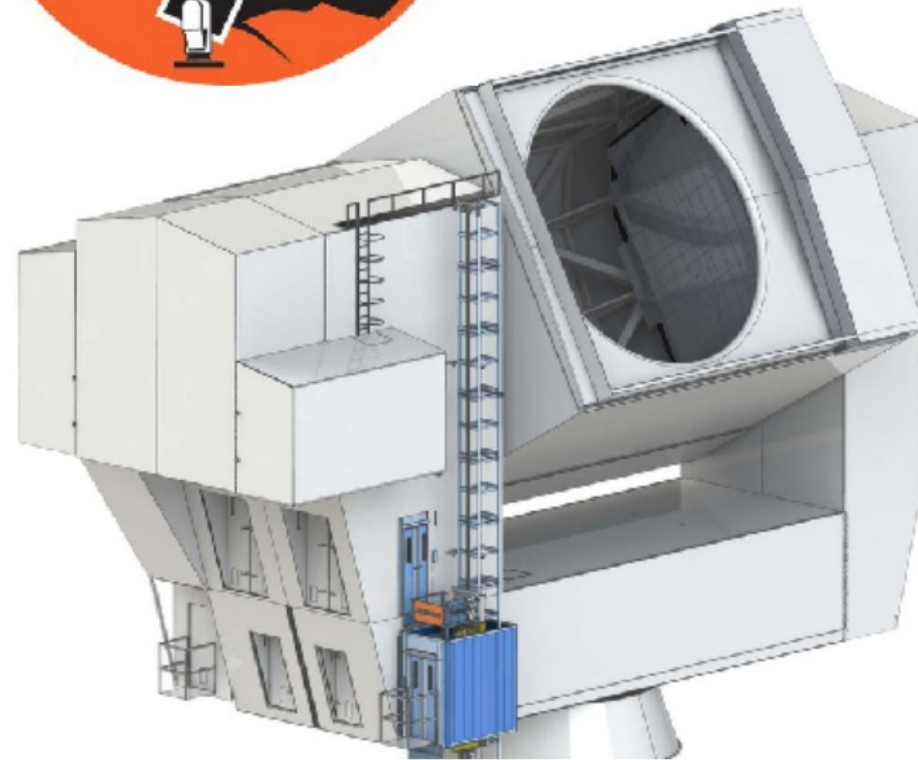
The Simons Array

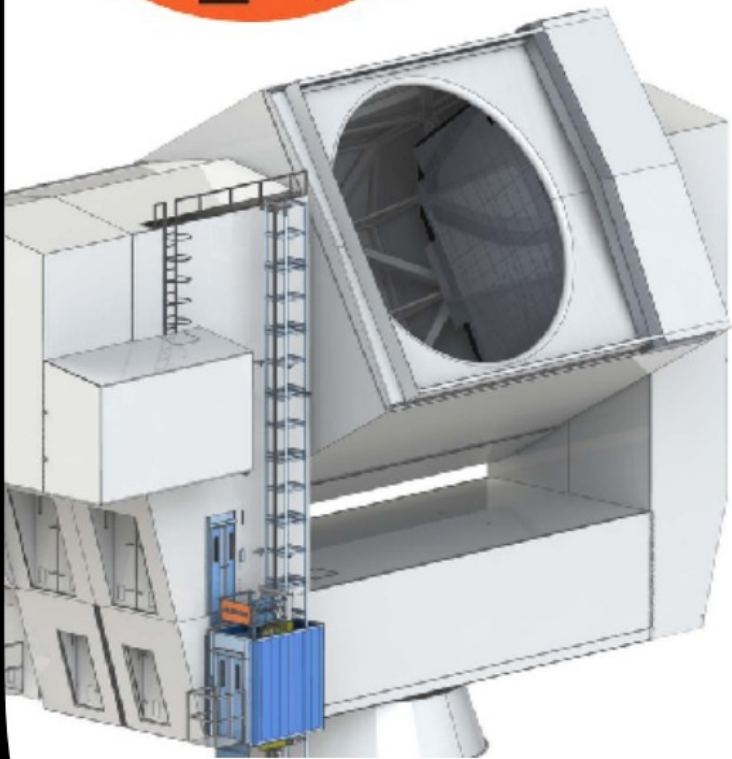
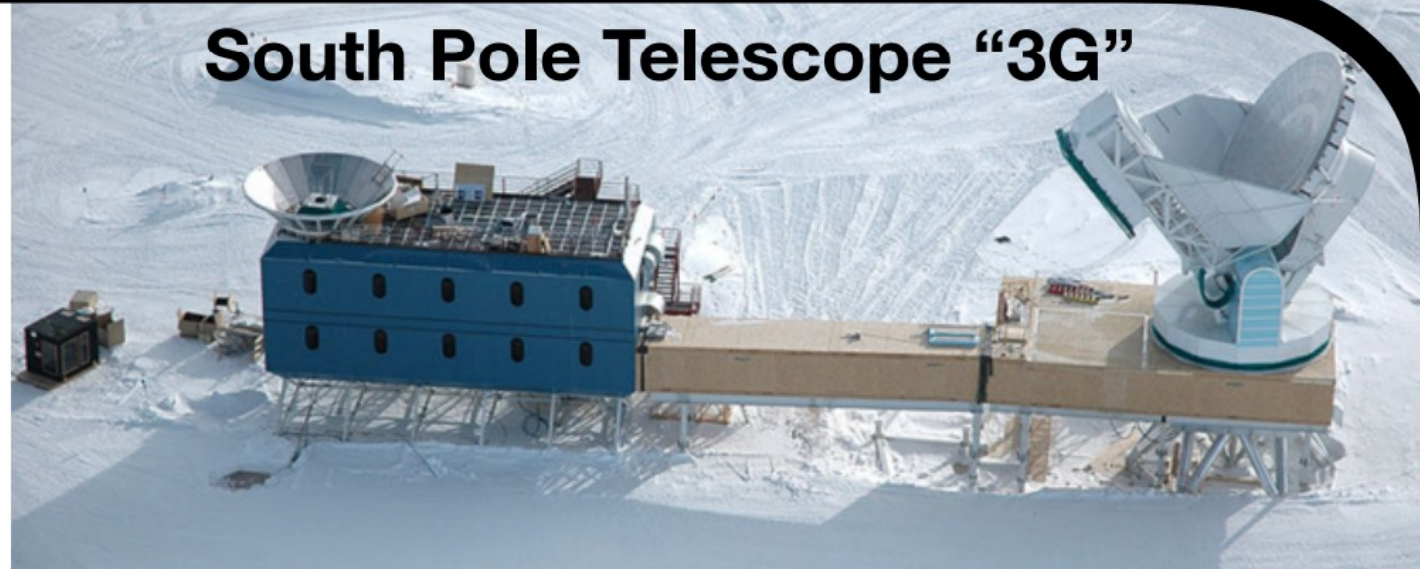


Advanced Atacama Cosmology Telescope

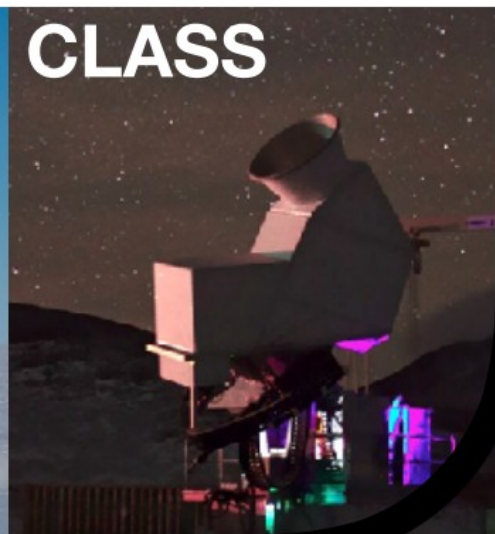


The Simons Array





CMB-S4(?)

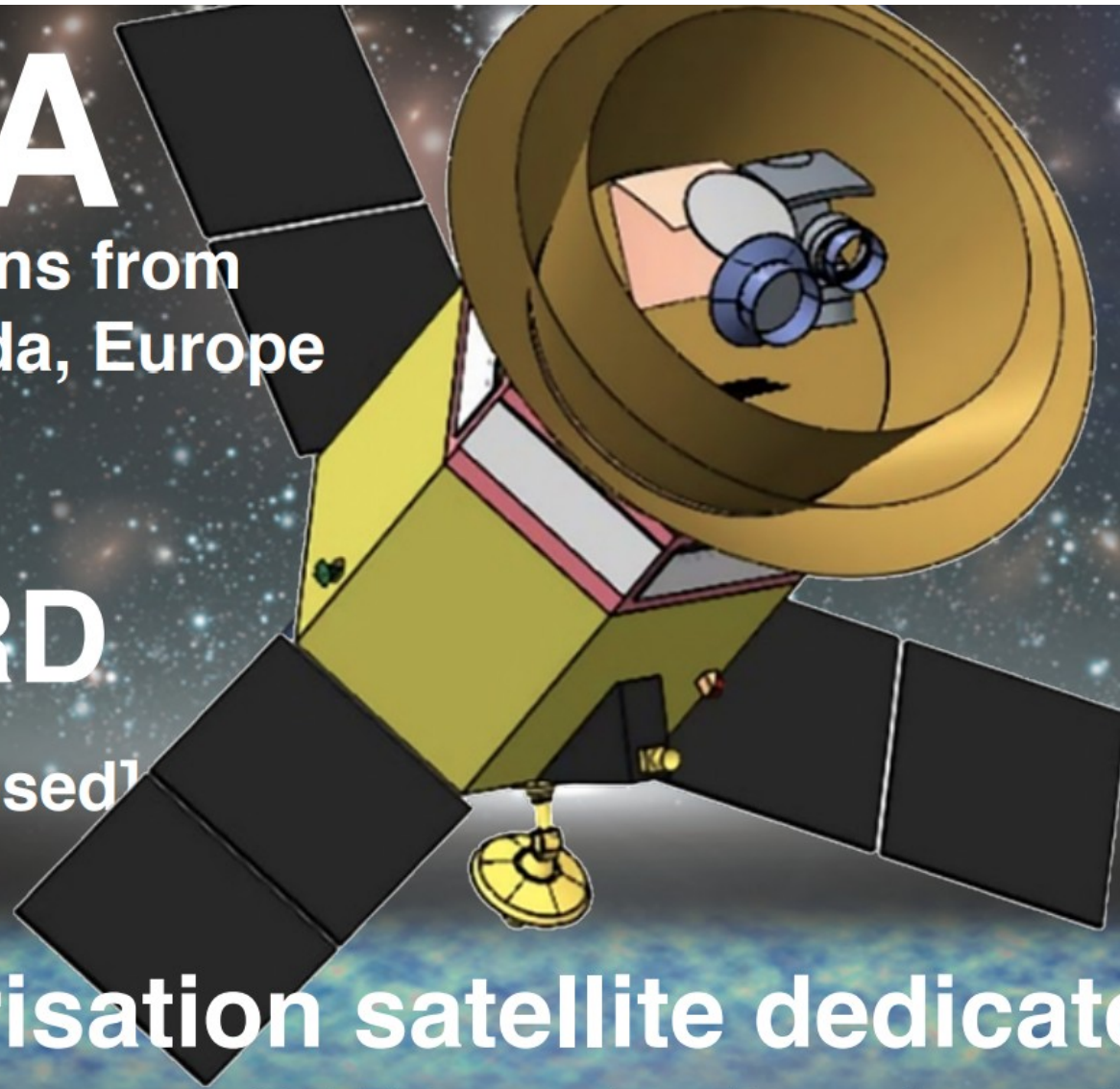


JAXA

+ participations from
USA, Canada, Europe

LiteBIRD

2027– [proposed]



**Polarisation satellite dedicated to
measure CMB polarisation from
primordial GW, with a few thousand
TES bolometers in space**

JAXA

The image features a detailed illustration of the LiteBIRD satellite. The satellite is shown from a perspective that highlights its large, gold-colored parabolic dish antenna, which is the central feature. The dish is mounted on a complex structure of yellow and white panels. Two large, black rectangular solar panels are extended from the sides of the satellite. Below the main body, a smaller yellow dish antenna is visible. The satellite is set against a background of a starry space sky with a curved horizon line of Earth's surface at the bottom, showing blue oceans and green landmasses.

+ participations from
USA, Canada, Europe

LiteBIRD

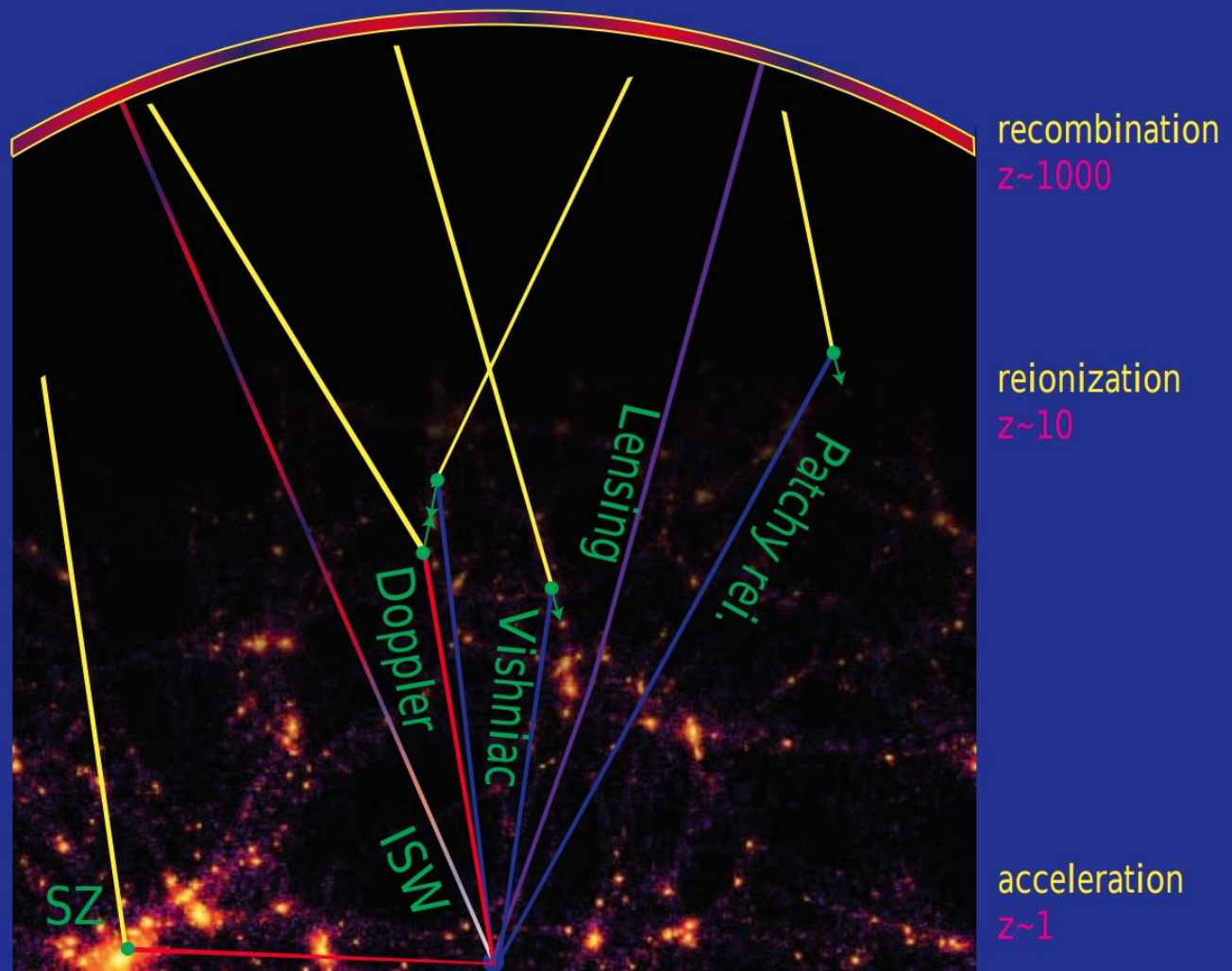
2027– **Selected!**

May 21: JAXA has chosen LiteBIRD
as the strategic large-class mission.
We will go to L2!

CMB Secondary Anisotropies

Physics of Secondary Anisotropies

Primary Anisotropies



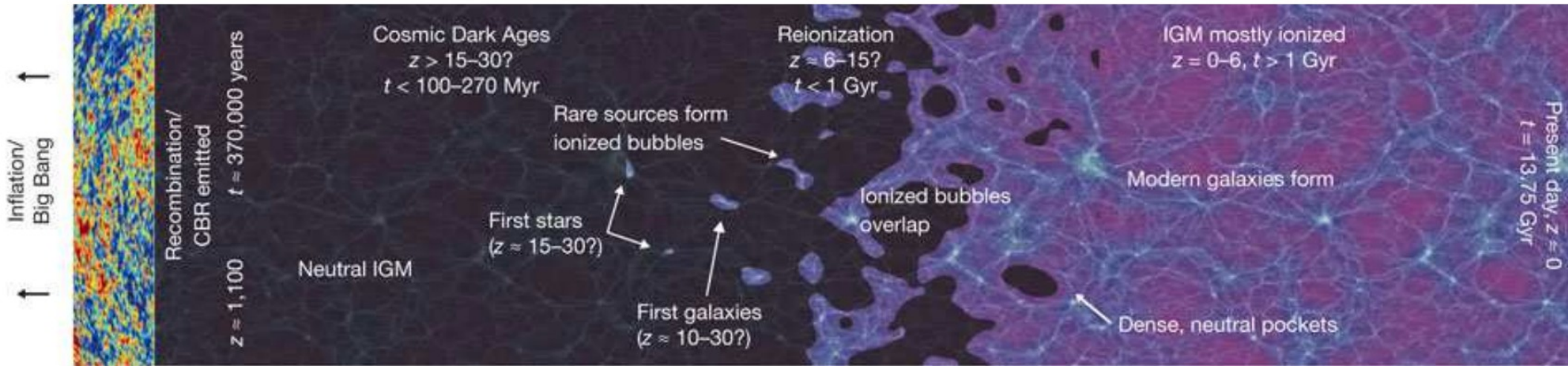
Epoch of Reionization

Epoch of reionization

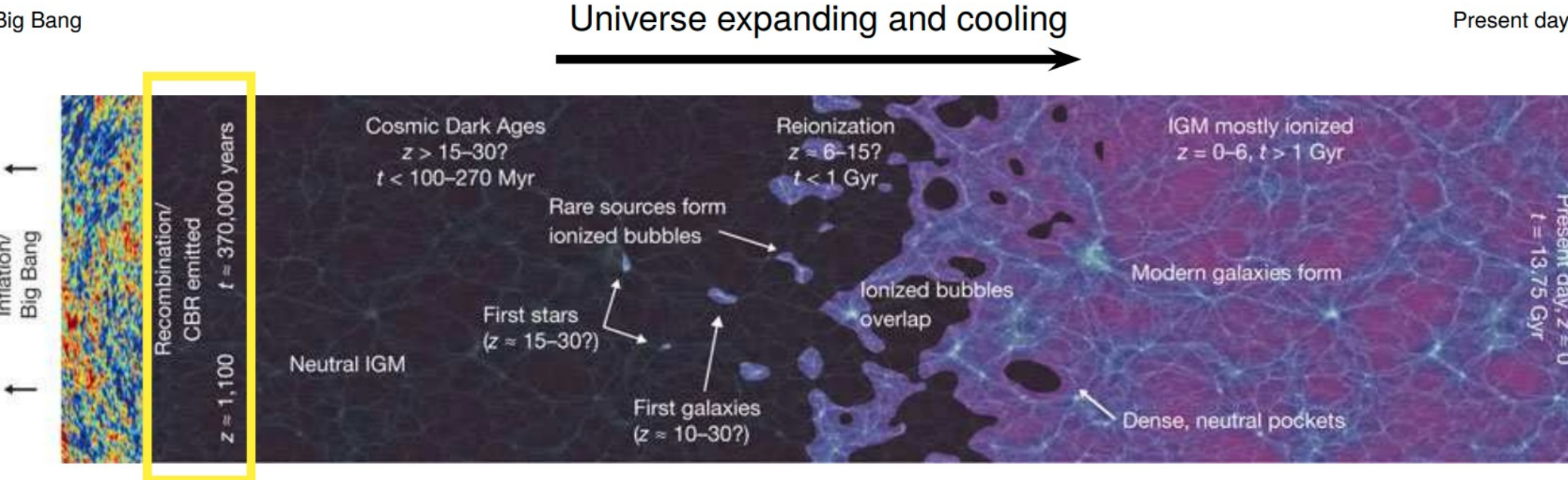
Big Bang

Universe expanding and cooling

Present day



Epoch of reionization



Last scattering epoch
First hydrogen atoms form

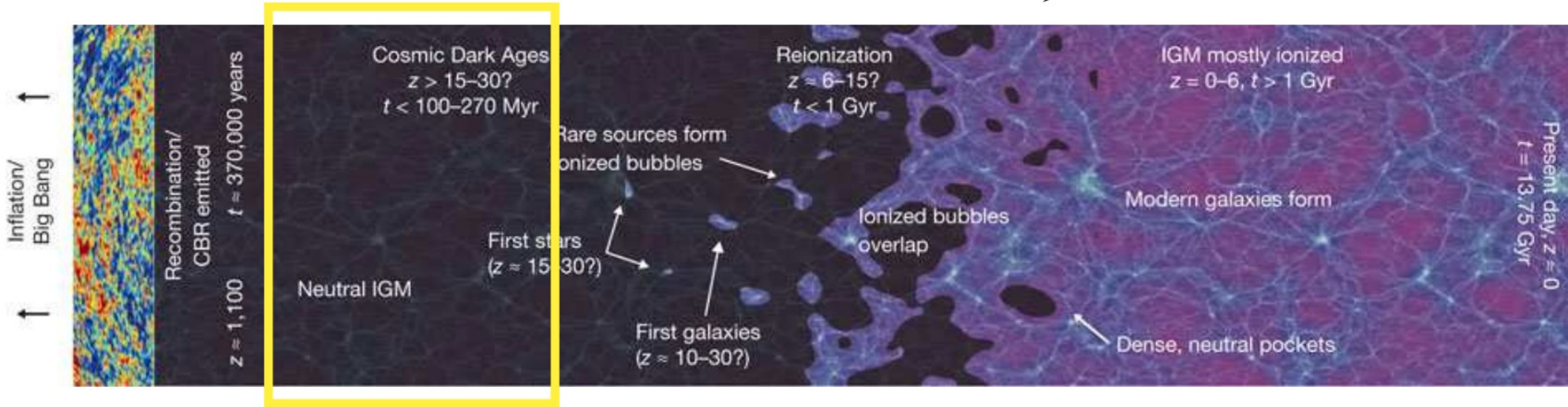
Figure courtesy: http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html

Epoch of reionization

Big Bang

Universe expanding and cooling

Present day



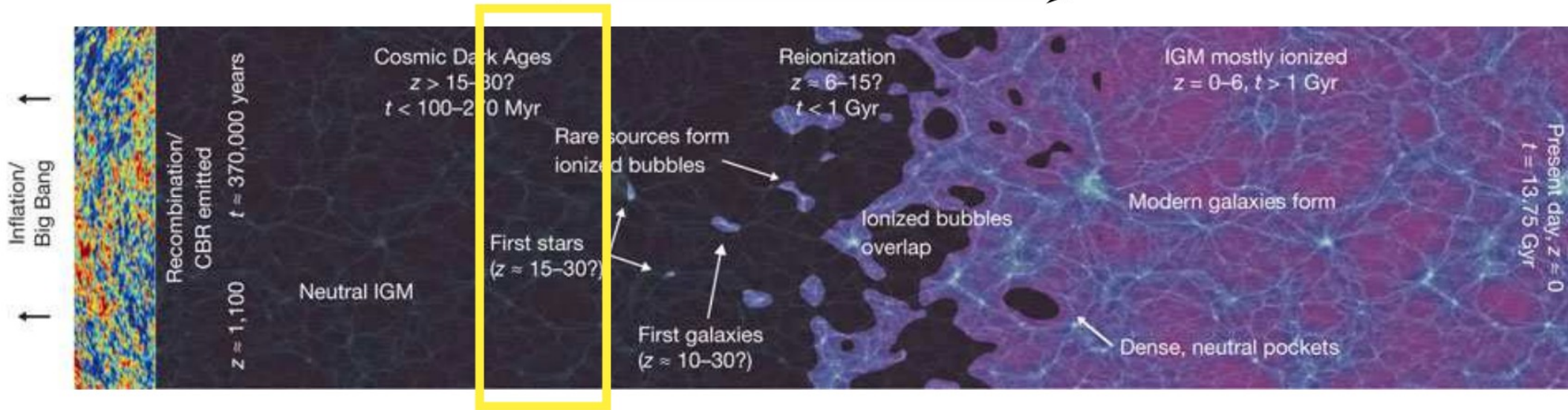
Dark ages

Epoch of reionization

Big Bang

Universe expanding and cooling

Present day



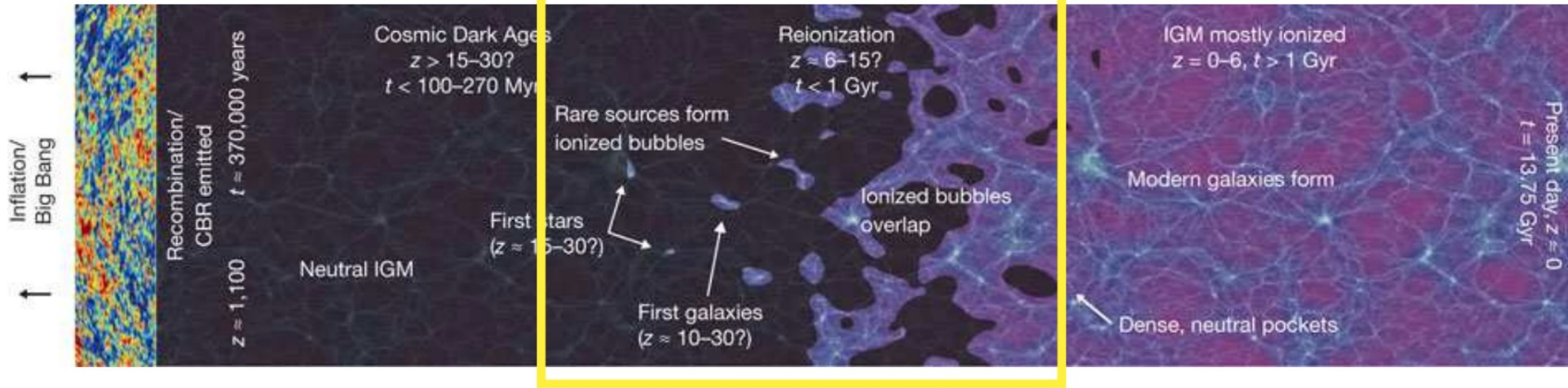
First stars form

Epoch of reionization

Big Bang

Universe expanding and cooling

Present day



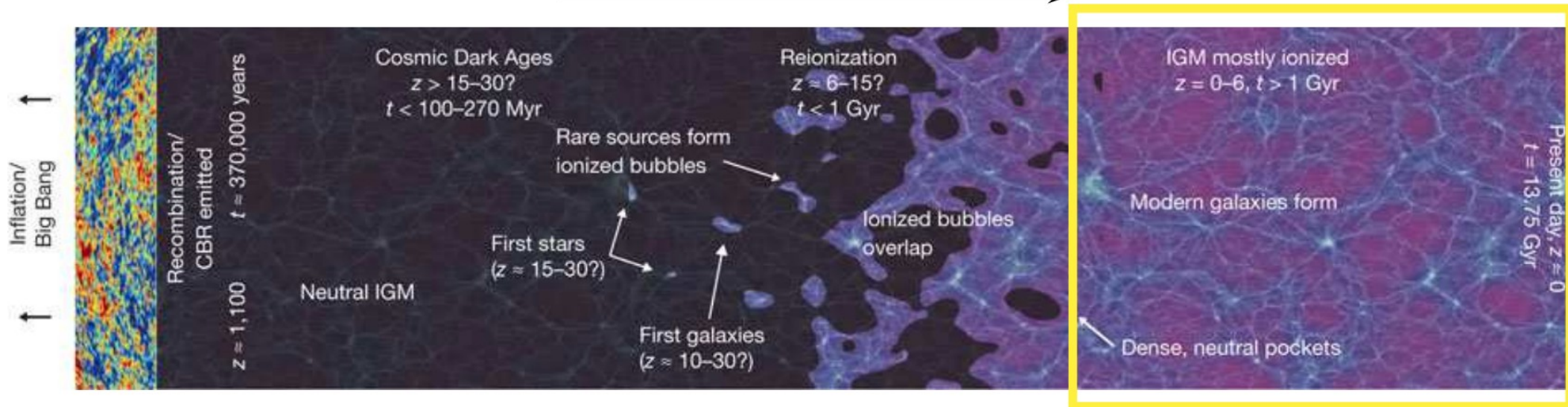
Reionization

Epoch of reionization

Big Bang

Universe expanding and cooling

Present day



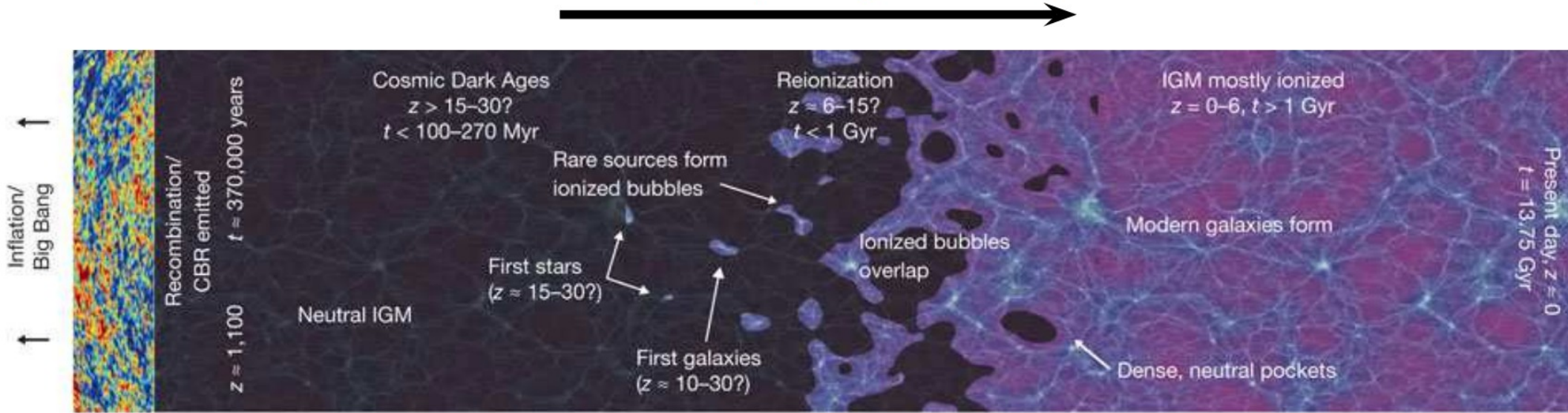
Post-reionization

Epoch of reionization

Big Bang

Universe expanding and cooling

Present day



Dark ages

Strong probe of cosmology



Reionization

1. First stars
2. Cosmology

Post-reionization

1. Galaxy formation
2. Cosmology

Evidence for reionization of the Inter-Galactic Medium

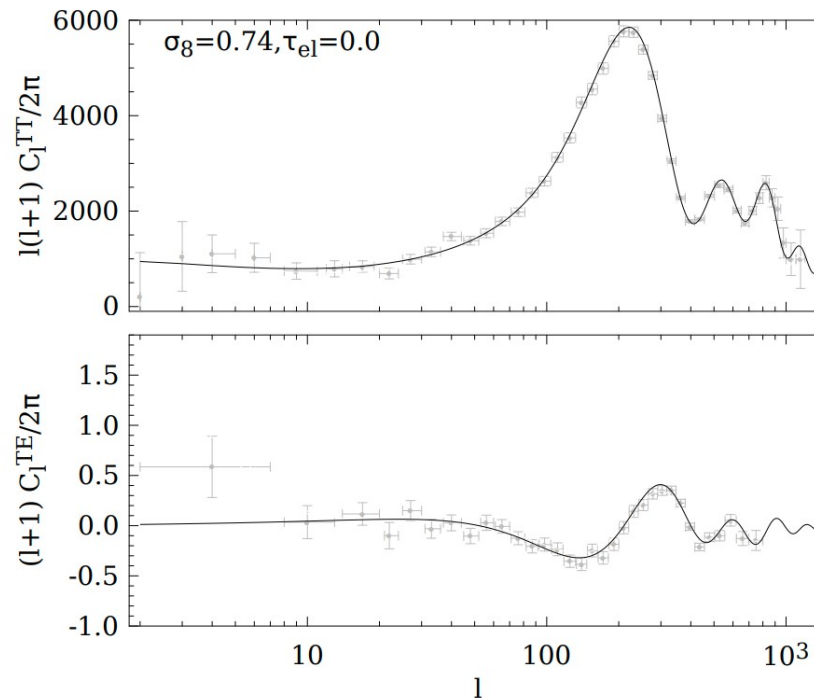
- CMB
- Lyman alpha Forest

CMB angular Power Spectrum

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

$$\tau_{\text{el}} = \sigma_T C \int_{t_{\text{LSS}}}^{t_0} dt n_e (1+z)^3$$

Provided by reionization

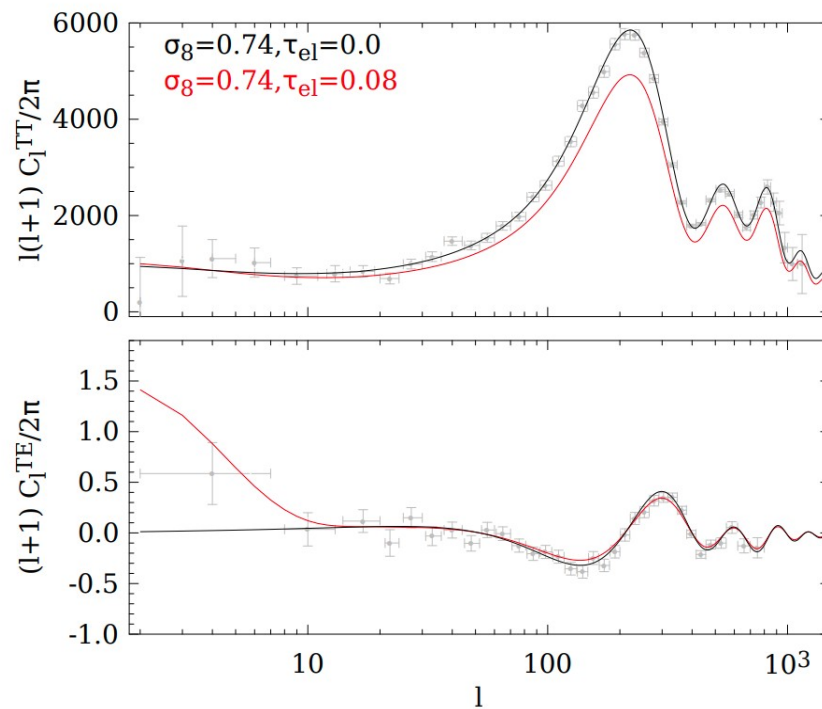


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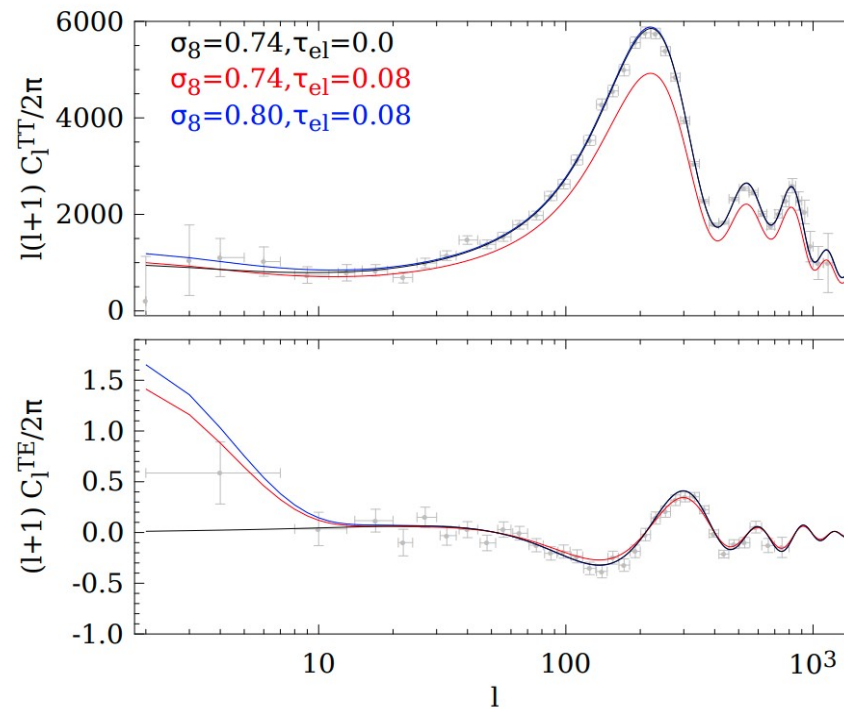


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CMB angular Power Spectrum

- Current constraints on reionization come from polarization signal at large angular scales
(weak signal, can be confused with polarized foregrounds, e.g., WMAP, Planck)
- dampening of anisotropies at (almost) all angular scales
(effect is degenerate with amplitude of density power spectrum)
- Planck and high resolution ground based experiments can break the degeneracy through lensing of the CMB
- The value of τ_{el} can be related to a reionization redshift z_{re} . Assume $n_e = n_H$ for $z < z_{\text{re}}$ and $n_e = 0$ for $z > z_{\text{re}}$, then

$$\tau_{\text{el}} = \sigma_T c n_H \int_0^{z_{\text{re}}} dz \left| \frac{dt}{dz} \right| (1+z)^3$$

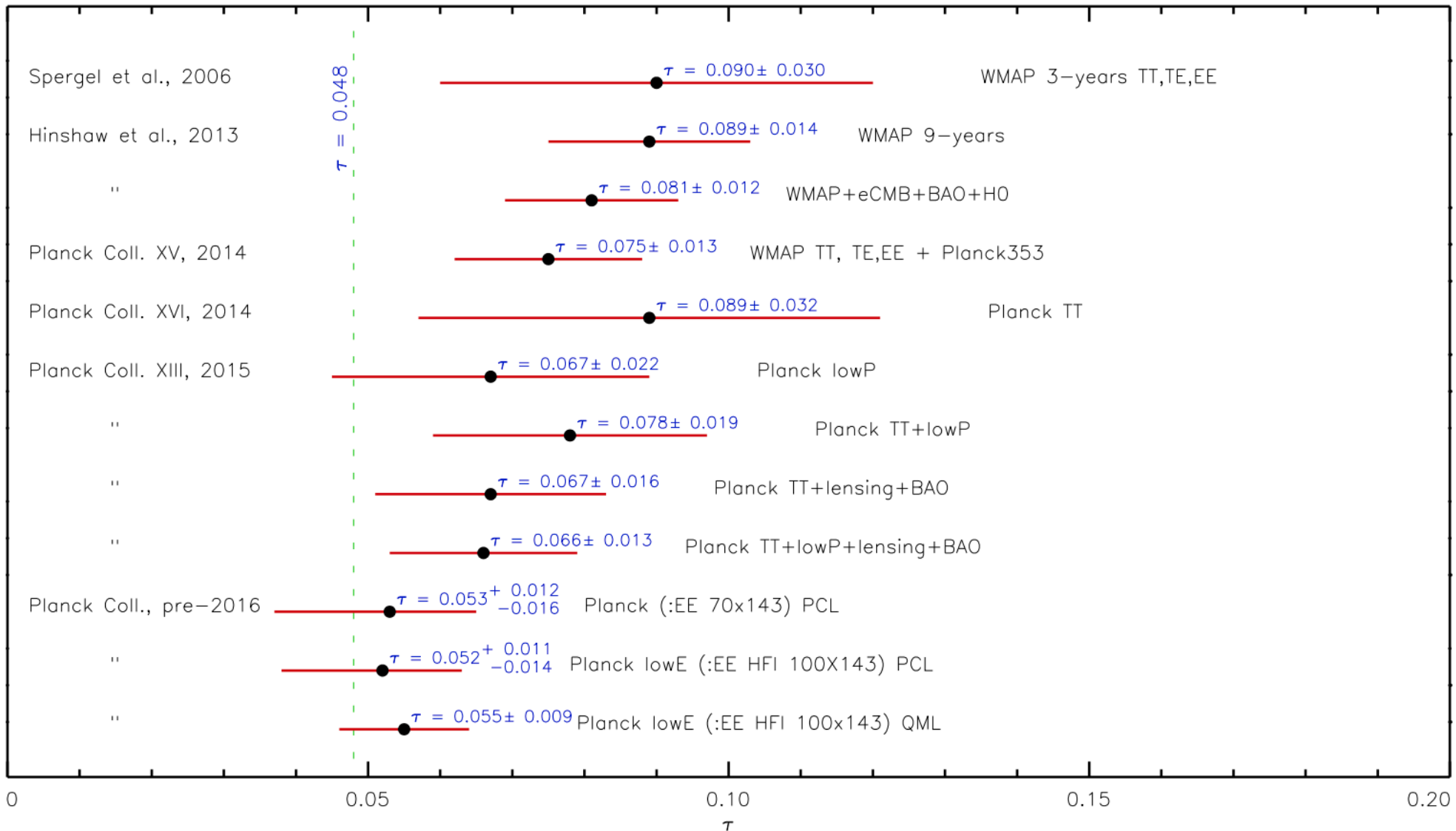
(Usually a slightly generalised tanh form is incorporated in CMB data analysis)

- Current constraints imply $z_{\text{re}} \approx 7.5 - 8$

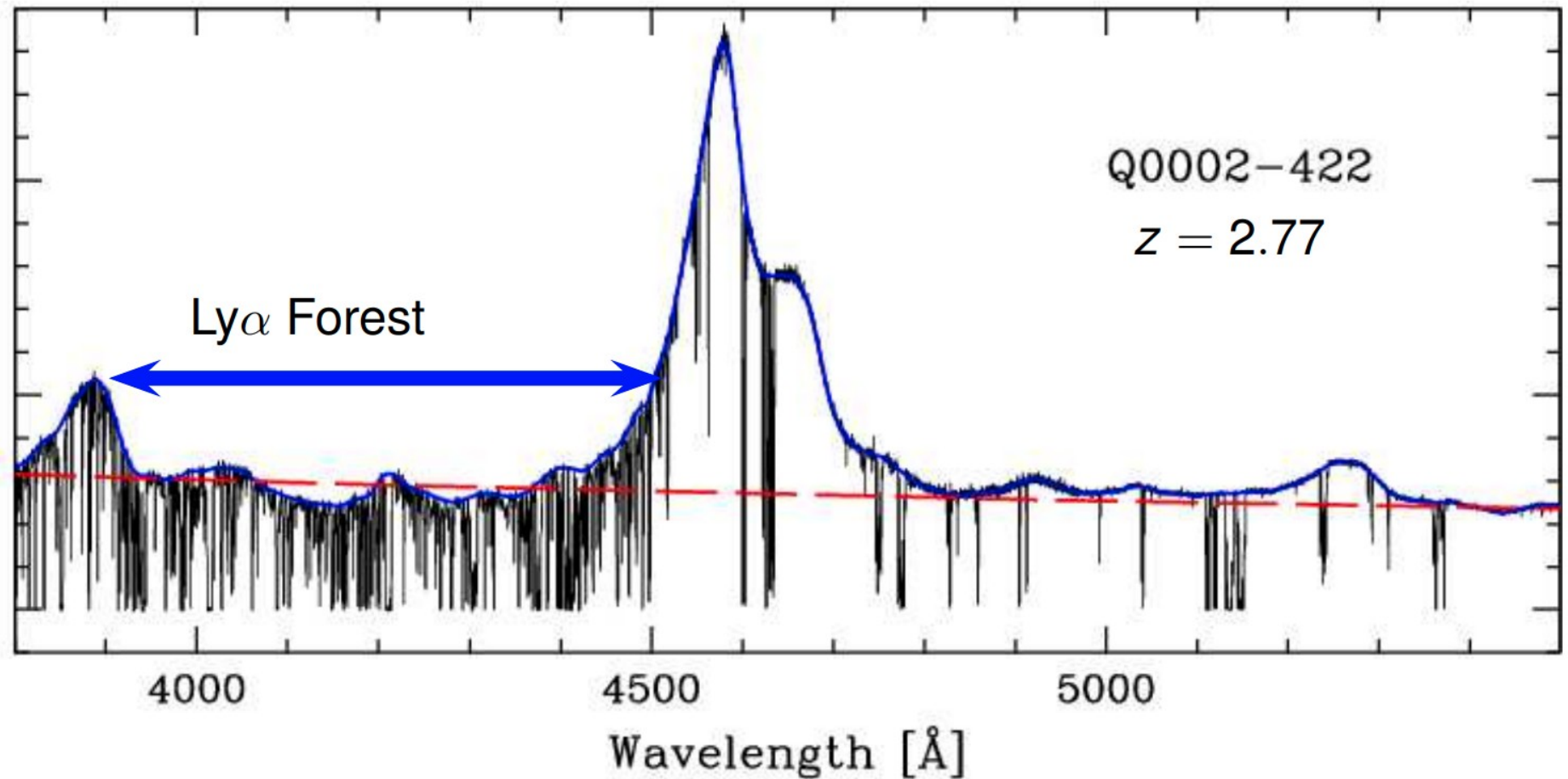
Thomson scattering τ_{e1} from CMB

$$\tau_{e1} = \sigma_T c \int_0^{z[t]} dt n_e (1+z)^3$$

Planck Collaboration (2016)



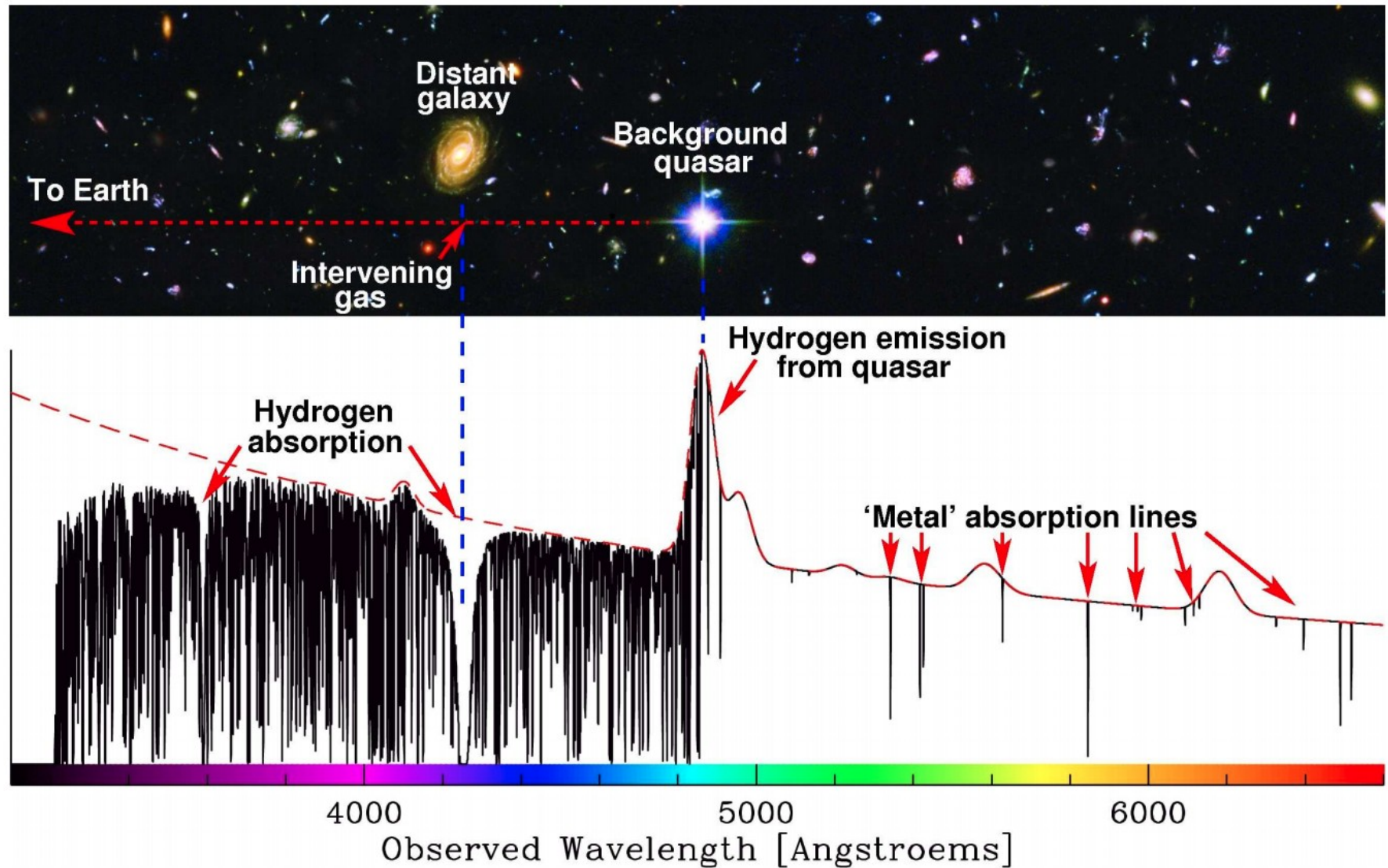
Evidence for reionization: Lyman- α forest



The absorption lines **blueward** of the emission line arise from Ly α transition ($n = 1$ to $n = 2$) of neutral hydrogen (HI) present between the quasar and us.

Absorption lines

- The IGM is detected through the absorption features it produces in the spectrum of a background bright source of light (typically a QSO).



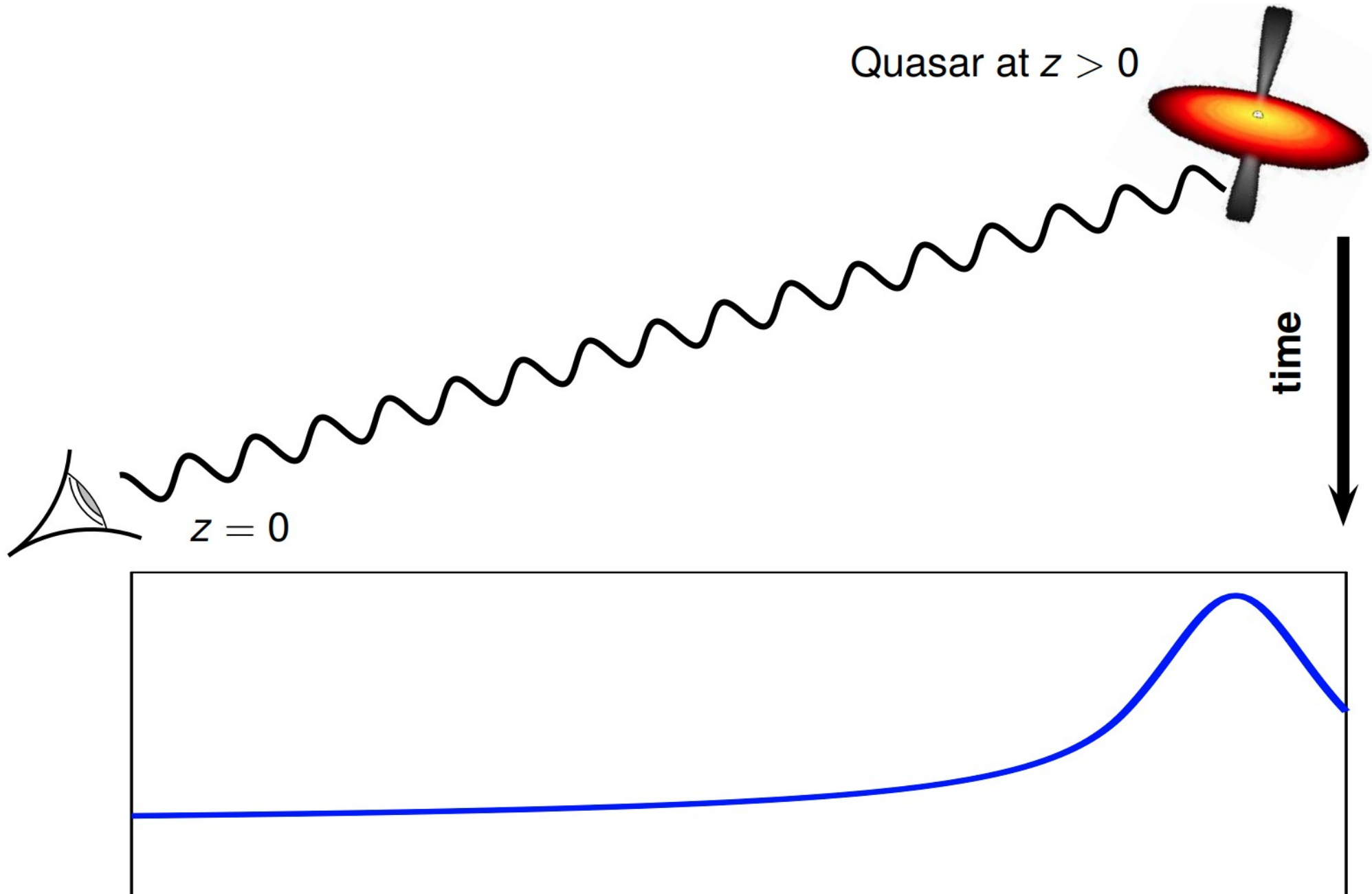
Absorption lines

- ▶ Consider radiation (photons) emitted at the QSO (at $z = z_Q$) rest frame frequency $\nu_Q > \nu_{fi}$. As the universe expands, the frequency will decrease and will reach ν_{fi} at a redshift z given by

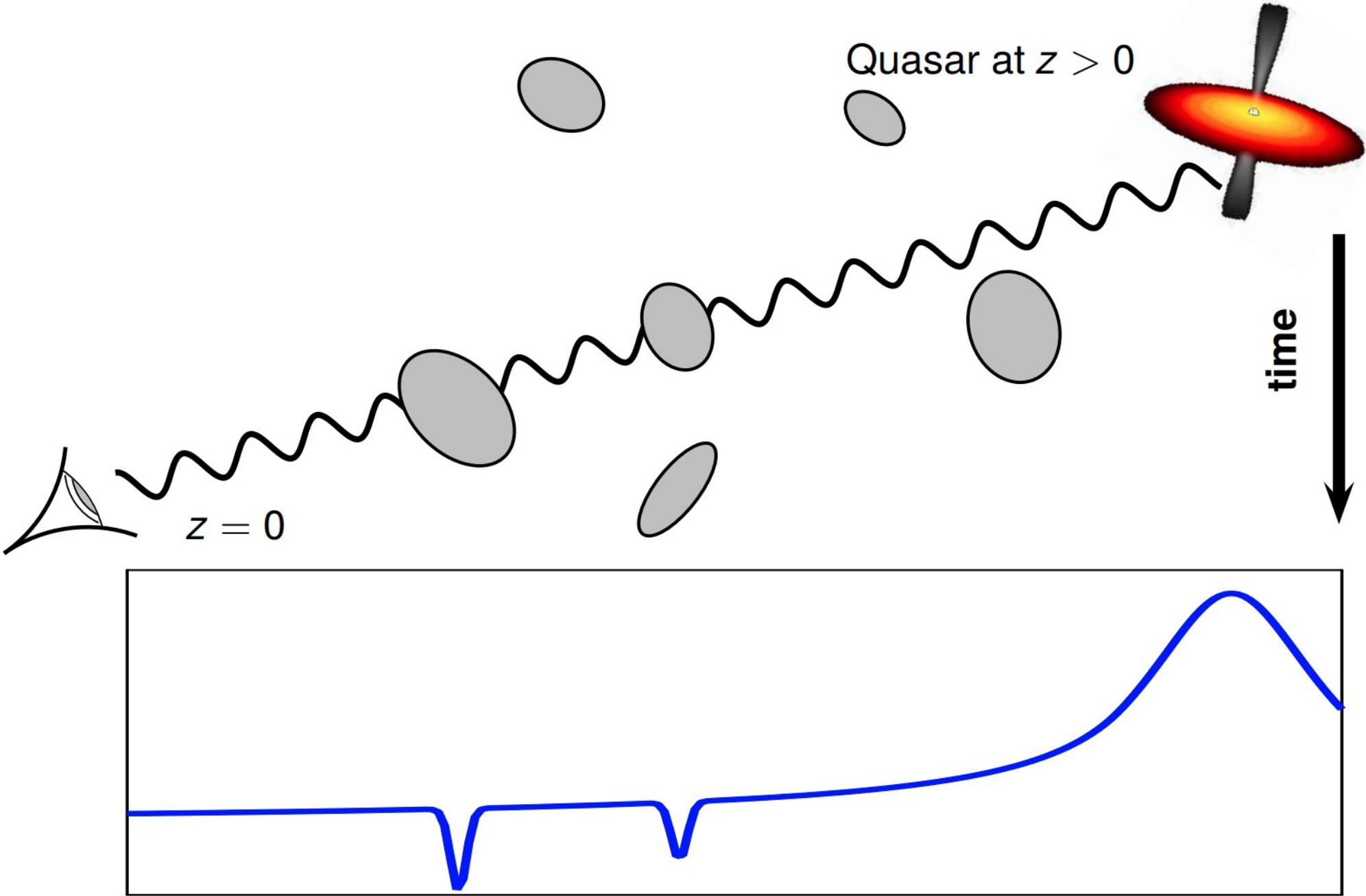
$$\frac{\nu_Q}{1 + z_Q} = \frac{\nu_{fi}}{1 + z} \implies \lambda_Q(1 + z_Q) = \lambda_{fi}(1 + z)$$

- ▶ Example: Consider a QSO at $z_Q = 3$. Consider a photon emitted at wavelength $\lambda_Q = 1187 \text{ \AA}$, then it would reach the Ly α wavelength 1216 \AA at $z \approx 1187 \times 4/1216 - 1 \approx 2.9$. If there is neutral hydrogen at that position, it will produce an absorption signature.
- ▶ We will observe the feature at $\lambda = \lambda_Q(1 + z_Q) \approx 4742 \text{ \AA}$. Thus any absorption arising at a redshift z will show up at $\lambda = \lambda_{fi}(1 + z)$.

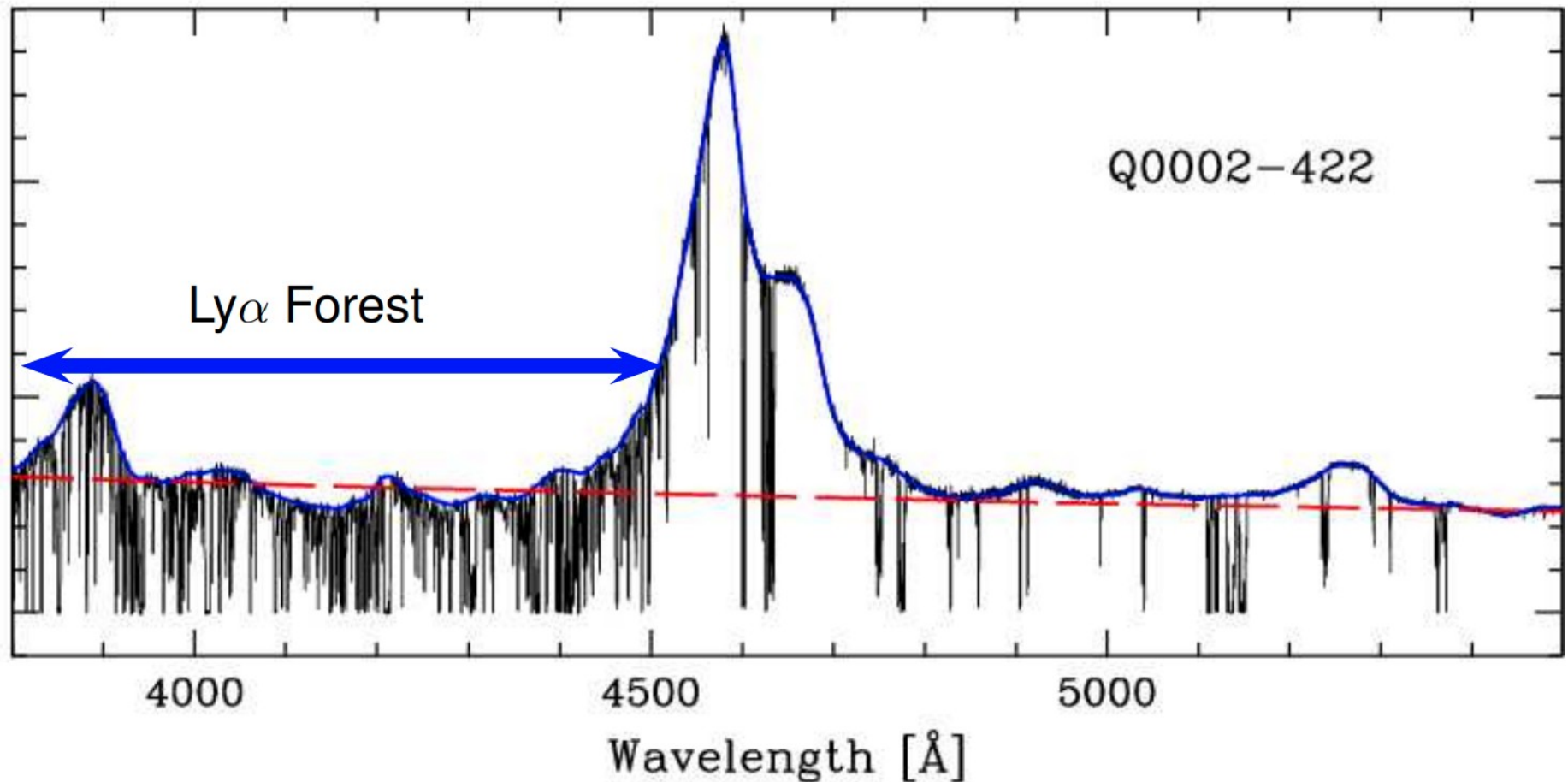
Absorption signatures



Absorption signatures

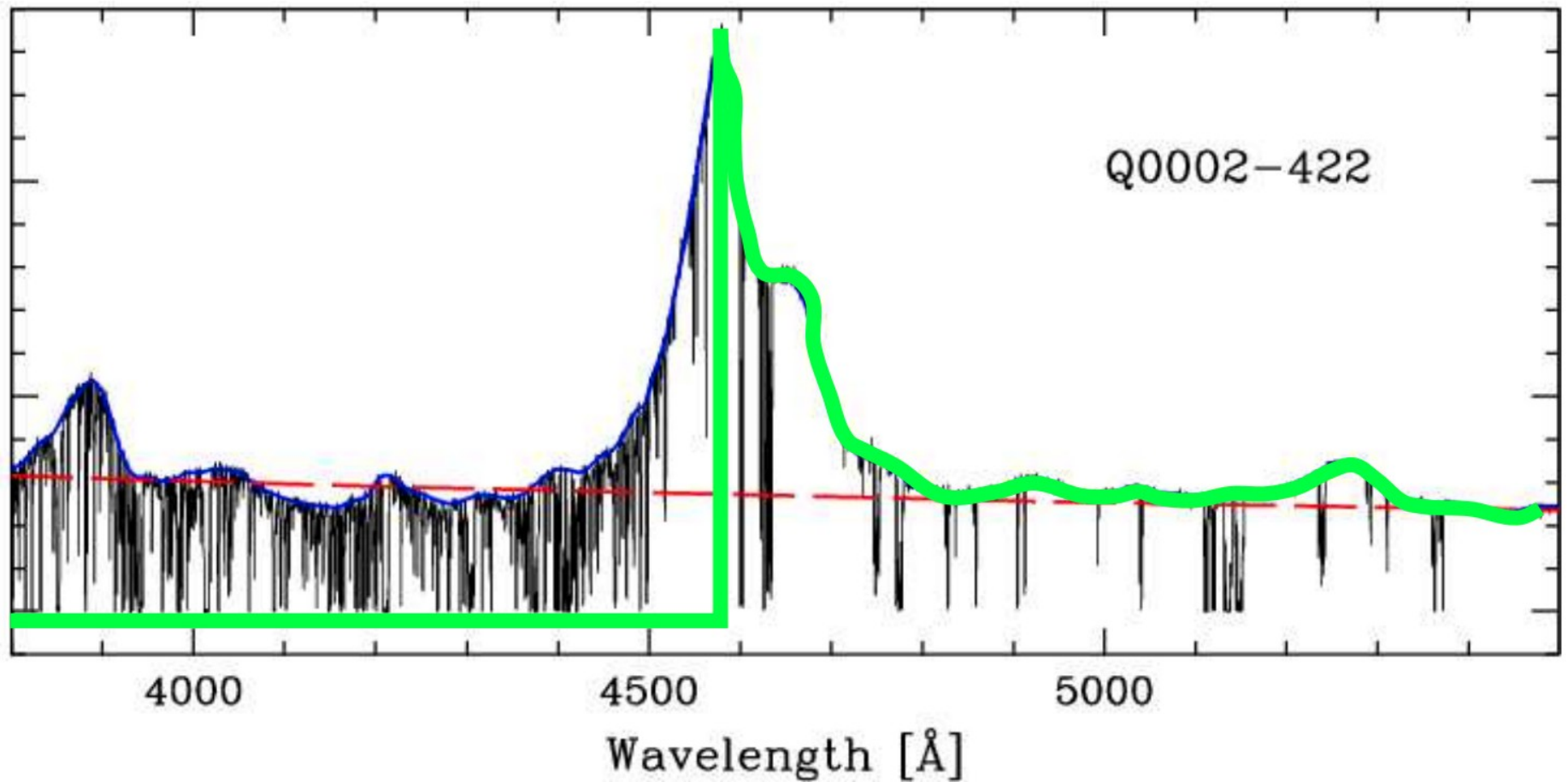


Absorption spectra



- ▶ The absorption lines **blueward** of the emission line arise from Ly α transition of neutral hydrogen (HI) present between the QSO and us.
- ▶ The unabsorbed regions correspond to either **ionized regions** or **no matter at all**.

Gunn-Peterson effect



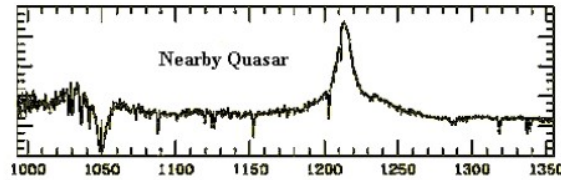
Observed flux \sim Unabsorbed flux $\times \exp(-10^5 x_{\text{HI}})$, where $x_{\text{HI}} = \rho_{\text{HI}}/\rho_{\text{H}}$.

The fact that there is non-zero flux implies that $x_{\text{HI}} \simeq 10^{-5}$

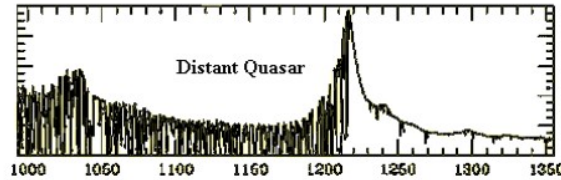
Non-zero flux observed till $z \sim 5.5$

QSO absorption lines at $z \sim 6$

$z \approx 0$

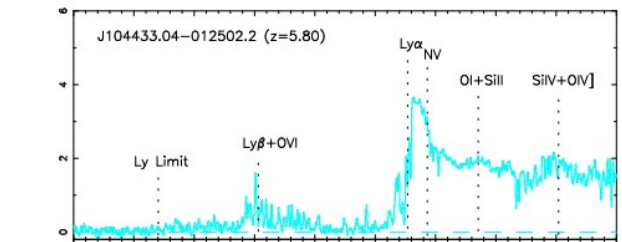


$z \approx 3$

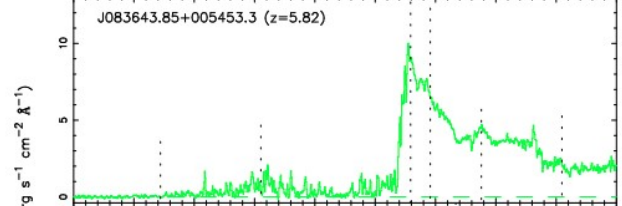


$$X_{\text{HI}} \lesssim 10^{-5}$$

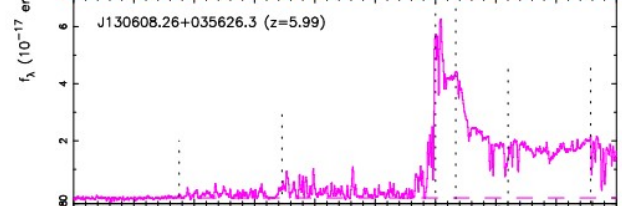
$z = 5.80$



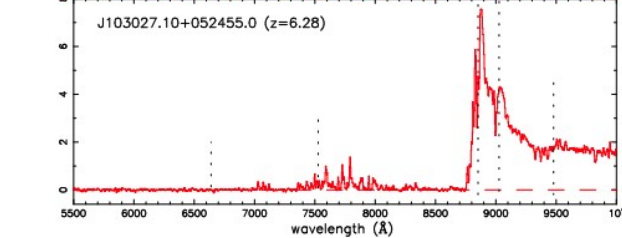
$z = 5.82$



$z = 5.99$



$z = 6.28$

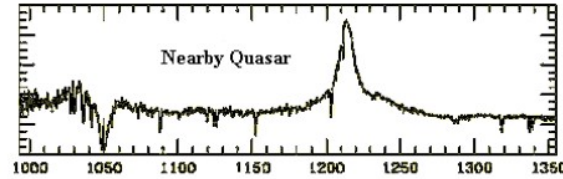


f_{λ} (10^{-17} erg s^{-1} cm^{-2} \AA^{-1})

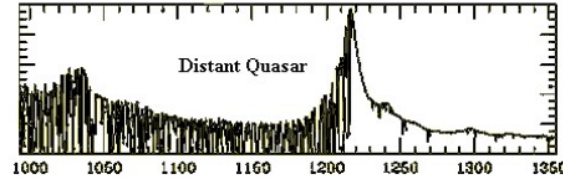
wavelength (\AA)

QSO absorption lines at $z \sim 6$

$z \approx 0$

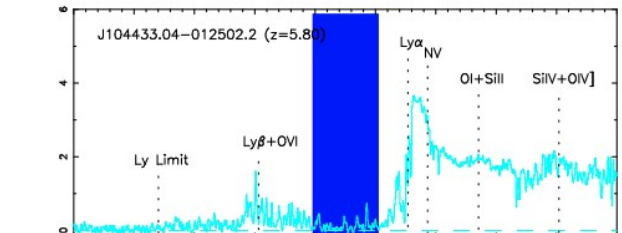


$z \approx 3$

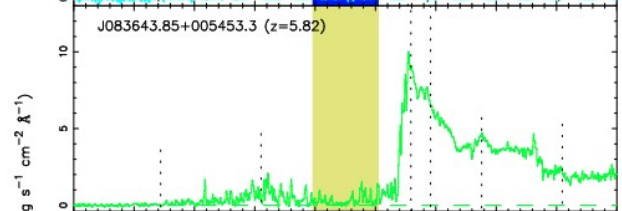


$$X_{\text{HI}} \lesssim 10^{-5}$$

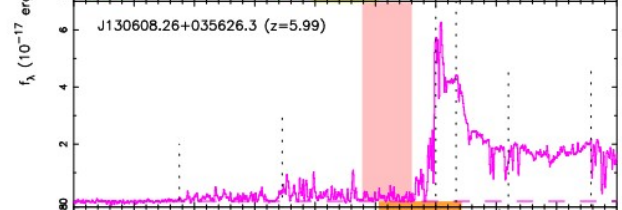
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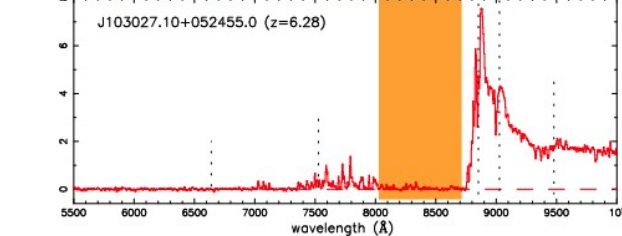
$z = 5.82$



$z = 5.99$



$z = 6.28$



Does this absorption mean
high neutrality?

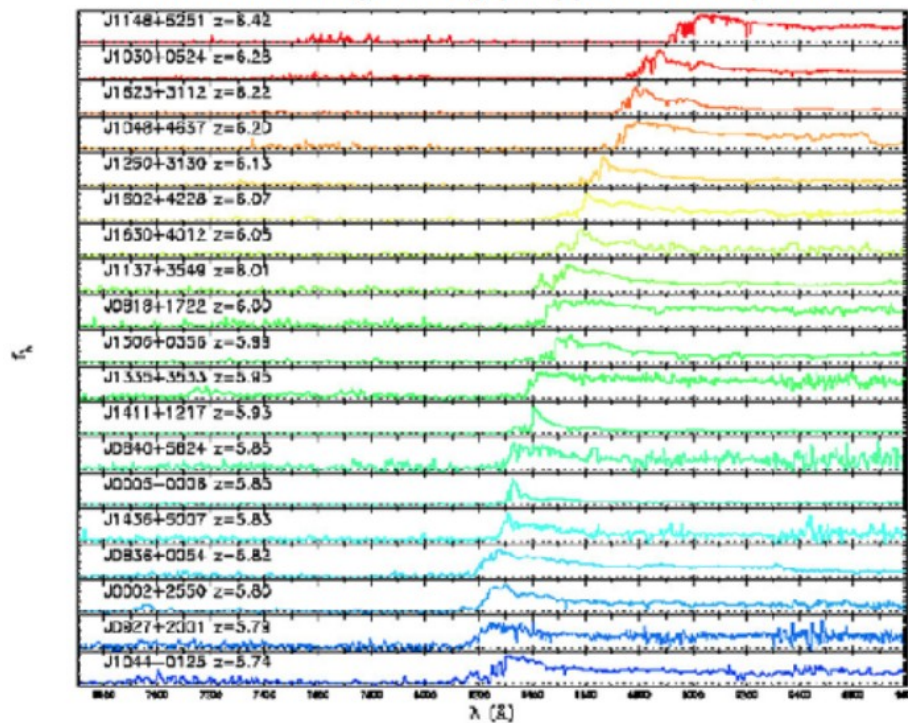
QSO absorption lines at $z \sim 6$

- ▶ Gunn-Peterson optical depth:

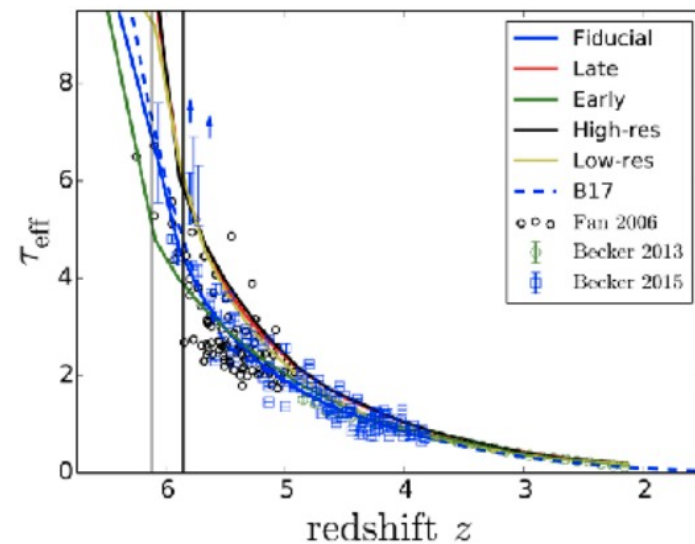
$$\tau_{\text{GP}} \approx \left(\frac{\bar{x}_{\text{HI}}}{10^{-5}} \right)$$

- ▶ So, even a neutral fraction $x_{\text{HI}} \approx 10^{-4}$ would produce **complete absorption!**
- ▶ Ly α transition “too strong”, saturates too easily....

Around $z \sim 6$ large dark gaps appear in the spectrum



Fan et al. 2006



Barnett et al. 2017

Observations of low- z quasars show a clear Gunn-Peterson effects, suggesting that reionization ended around $z \sim 6$ (rapid increase in optical depth at $z > 6$).

Perspectives

- **Epoch of reionization?** When did the sources produce enough photons to ionize the Universe? $z = 20$ or $z = 6$?
- **Nature of reionization?** Sudden or Gradual? Homogeneous or Inhomogeneous?
- **What are the sources responsible?** Stars, quasars, Exotic Particles?
- Confusing statements while interpreting the data:
 - Quasar absorption spectra imply that “redshift of reionization” is $z \sim 6$?
 - No, they only imply that $x_{\text{HI}} > 10^{-4}$ at $z \sim 6$!
 - CMB experiments imply that “redshift of reionization” is $z \sim 8$?
 - But they assume an instantaneous reionization (or a tanh model) which is clearly too simplistic!
 - There is a tension between quasar and CMB data?
 - The data only imply that reionization is an extended process, starting at $z > 8$ and completing at $z \sim 6$.
- Challenge is to build a reionization model that matches all the data sets simultaneously, i.e.,
 - reionization should start early enough to give a sufficiently (but not too) high τ_{el}
 - reionization must end before $z \sim 6$
 - the model should produce the right number of photons such that $x_{\text{HI}} > 10^{-4}$ at $z \sim 6$

**Extremely active field of research in Trieste!!
(Fontanot, Cristiani, Dodorico, Feruglio,..)**