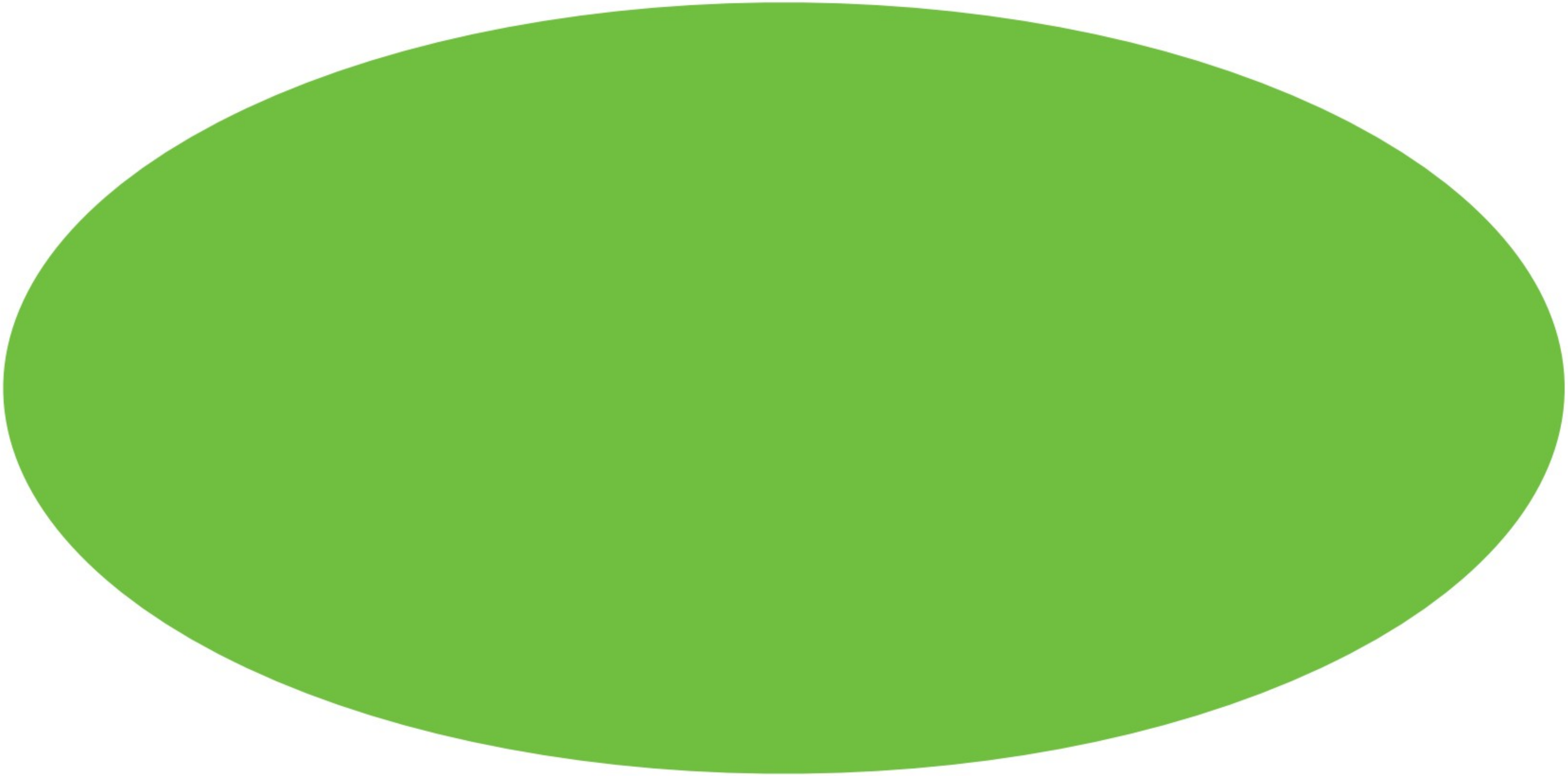
Cosmic Microwave Background: Foregrounds and Secondary Anisotropies

arXiv: 1811.02310
arXiv: 1112.1862
arXiv:1212.1075
arXiv:1511.04335
arXiv:1312.2462
arXiv:1303.5081

Cosmic Microwave Background

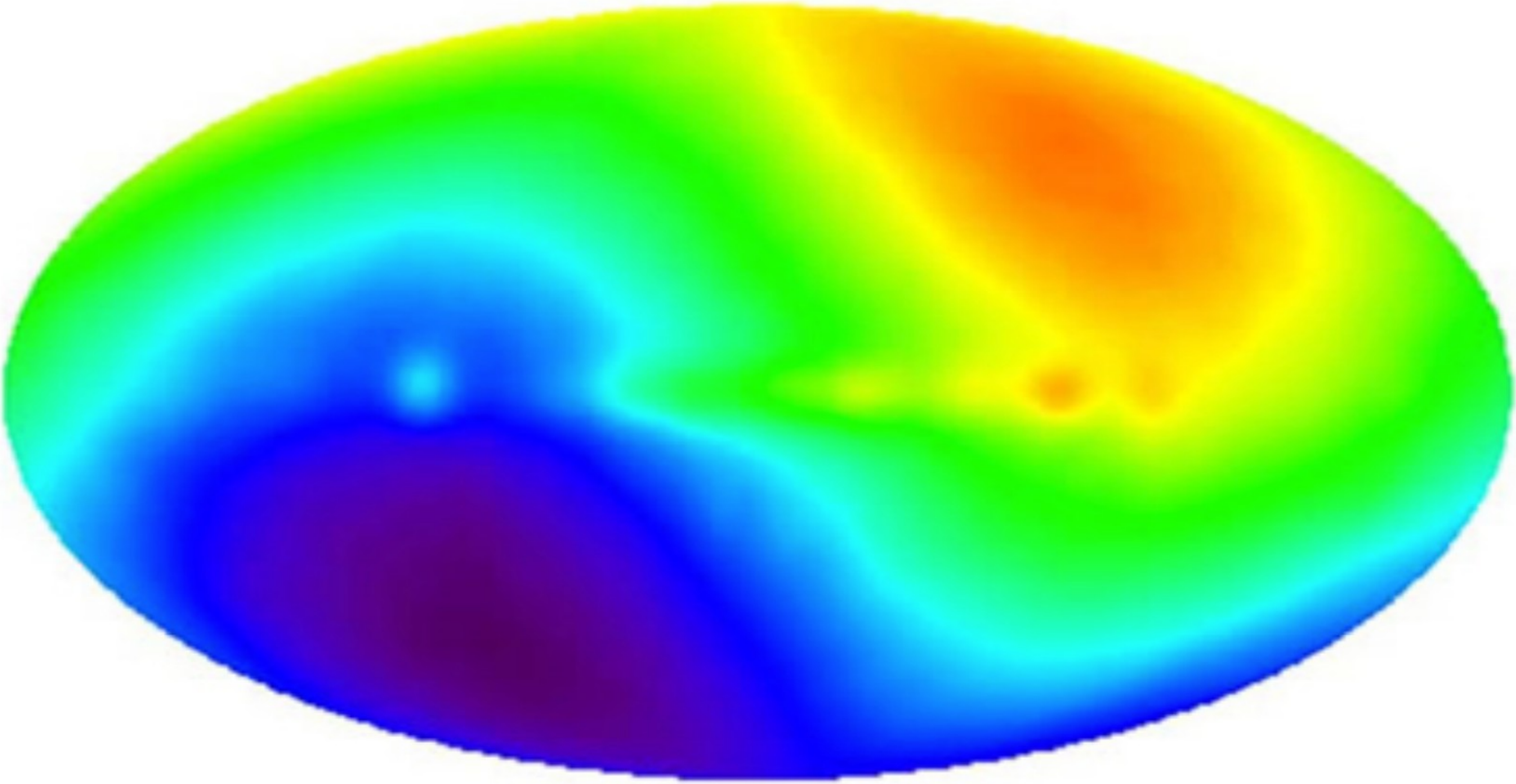
Uniform-temperature radiation bath…



$T = 2.725\,\mathrm{K}$

Cosmic Microwave Background

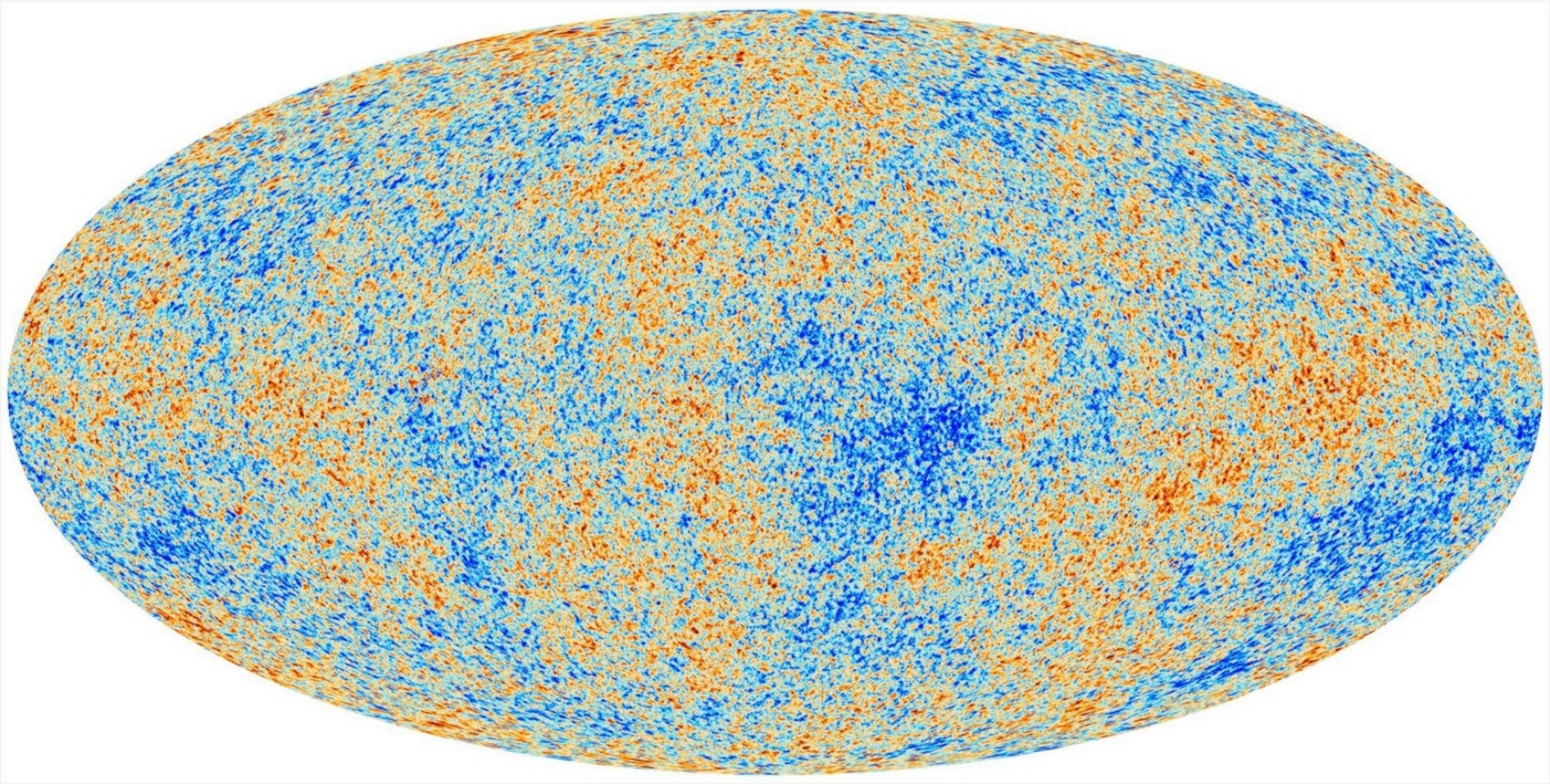
… with imprints of local motion…



$\Delta T/T \approx 10^{-3} \quad (v \sim 600\,\mathrm{km\,s^{-1}})$

Cosmic Microwave Background

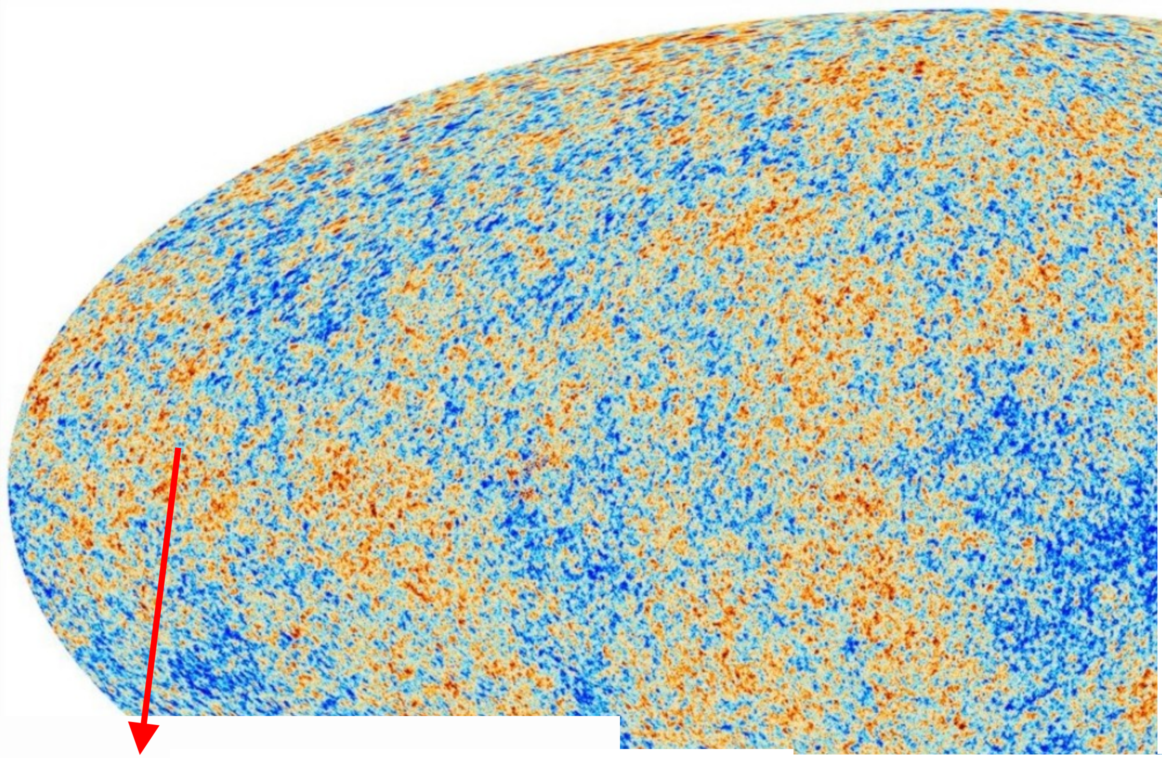
… and tiny primordial anisotropies

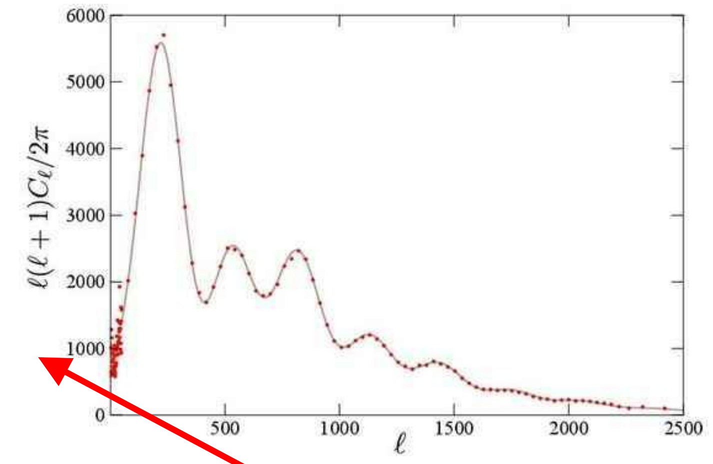


$\Delta T/T \approx 10^{-5}$

Cosmic Microwave Background

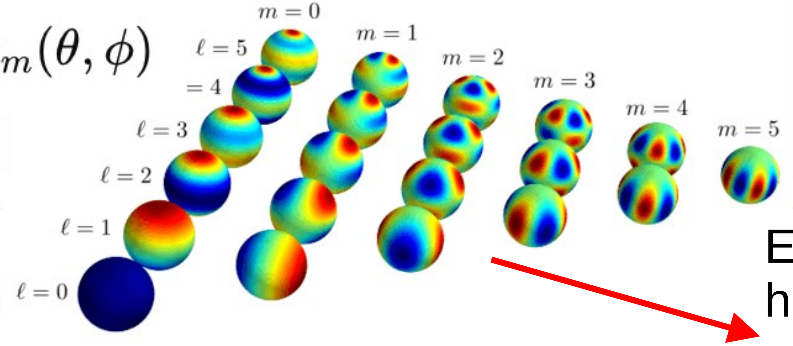
… and tiny primordial anisotropies





$$\frac{\Delta T}{T_0}(\theta,\phi) = \sum_{\ell=0}^{\infty}\sum_{m=-\ell}^{+\ell} a_{\ell m} Y_{\ell m}(\theta,\phi)$$

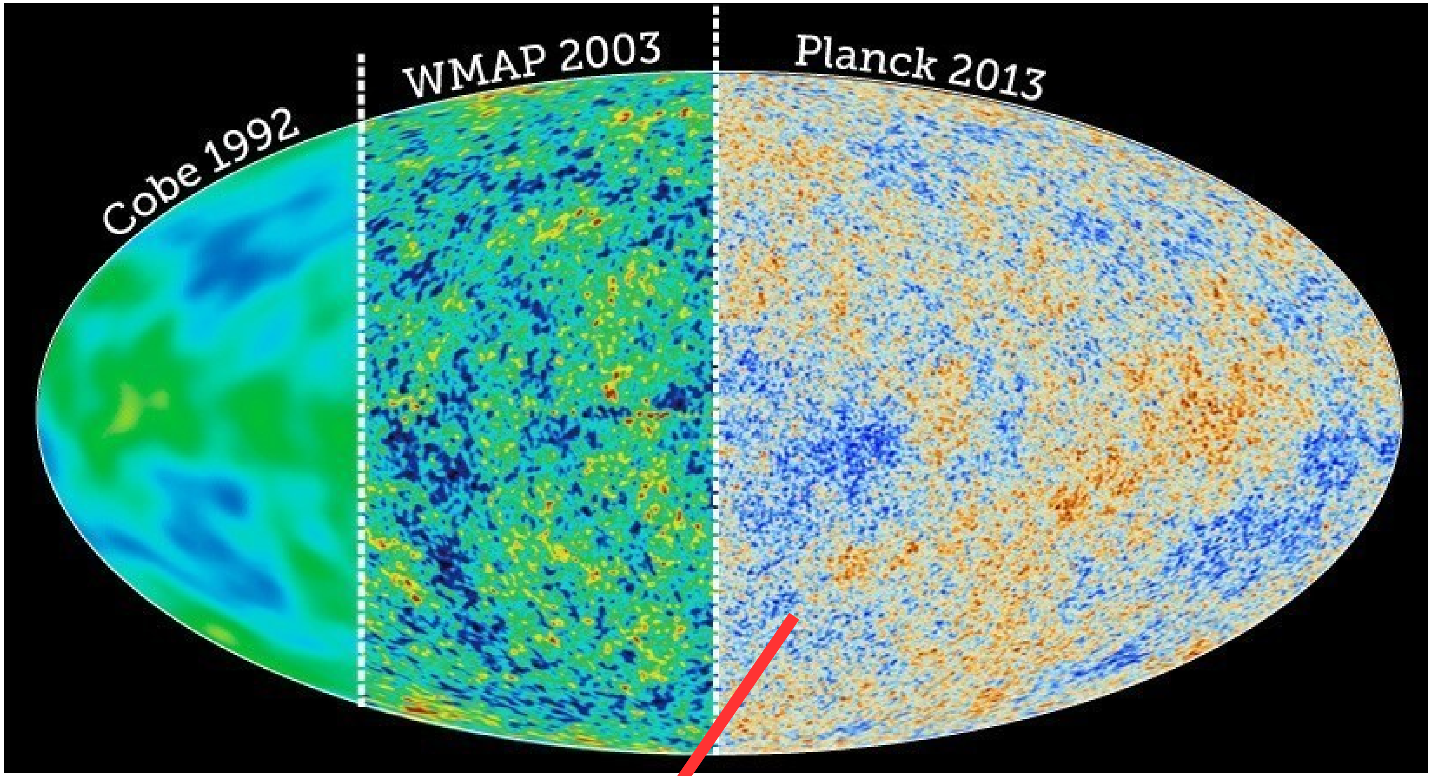
Expands in spherical harmonics



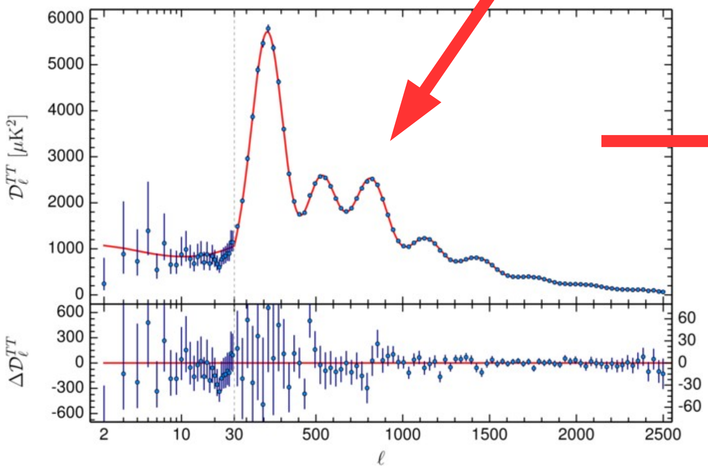
$$C_\ell = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell}\langle|a_{\ell m}|^2\rangle.$$

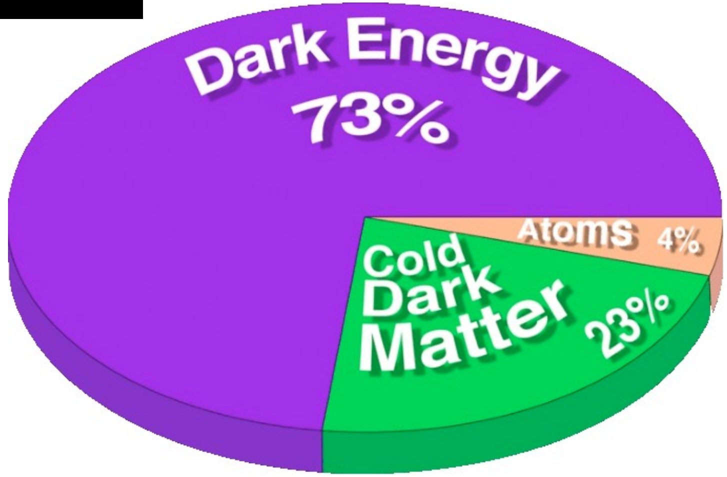
Expands in spherical harmonics

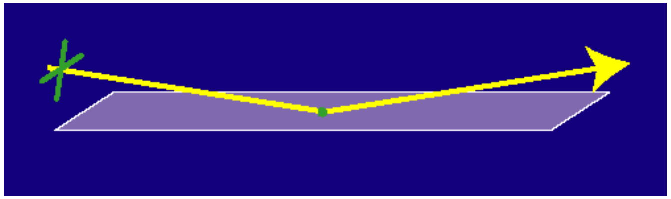
CMB



TT Power Spectrum information is sample-variance limited







Polarization

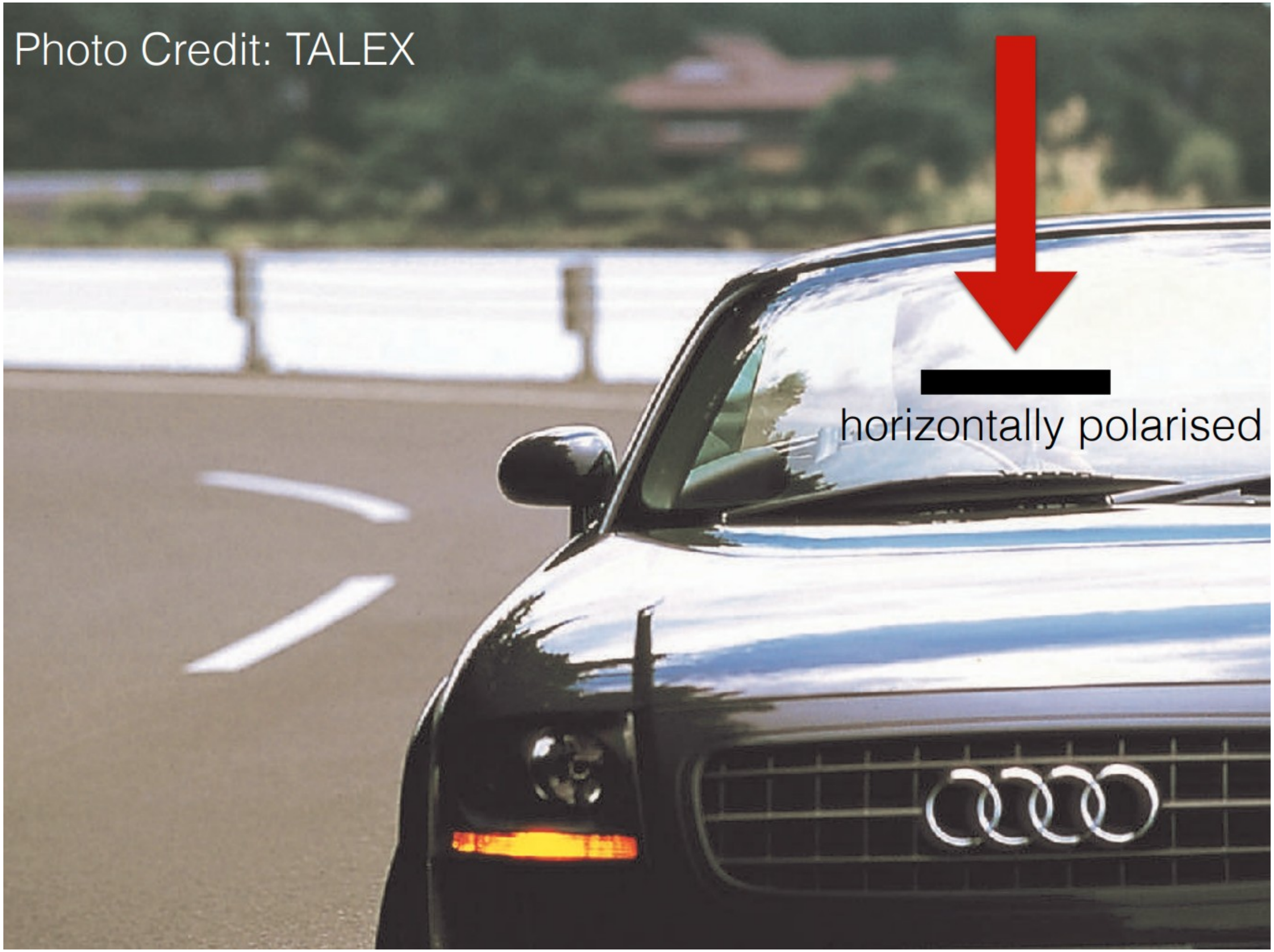
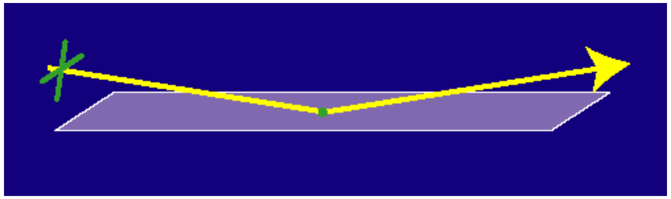
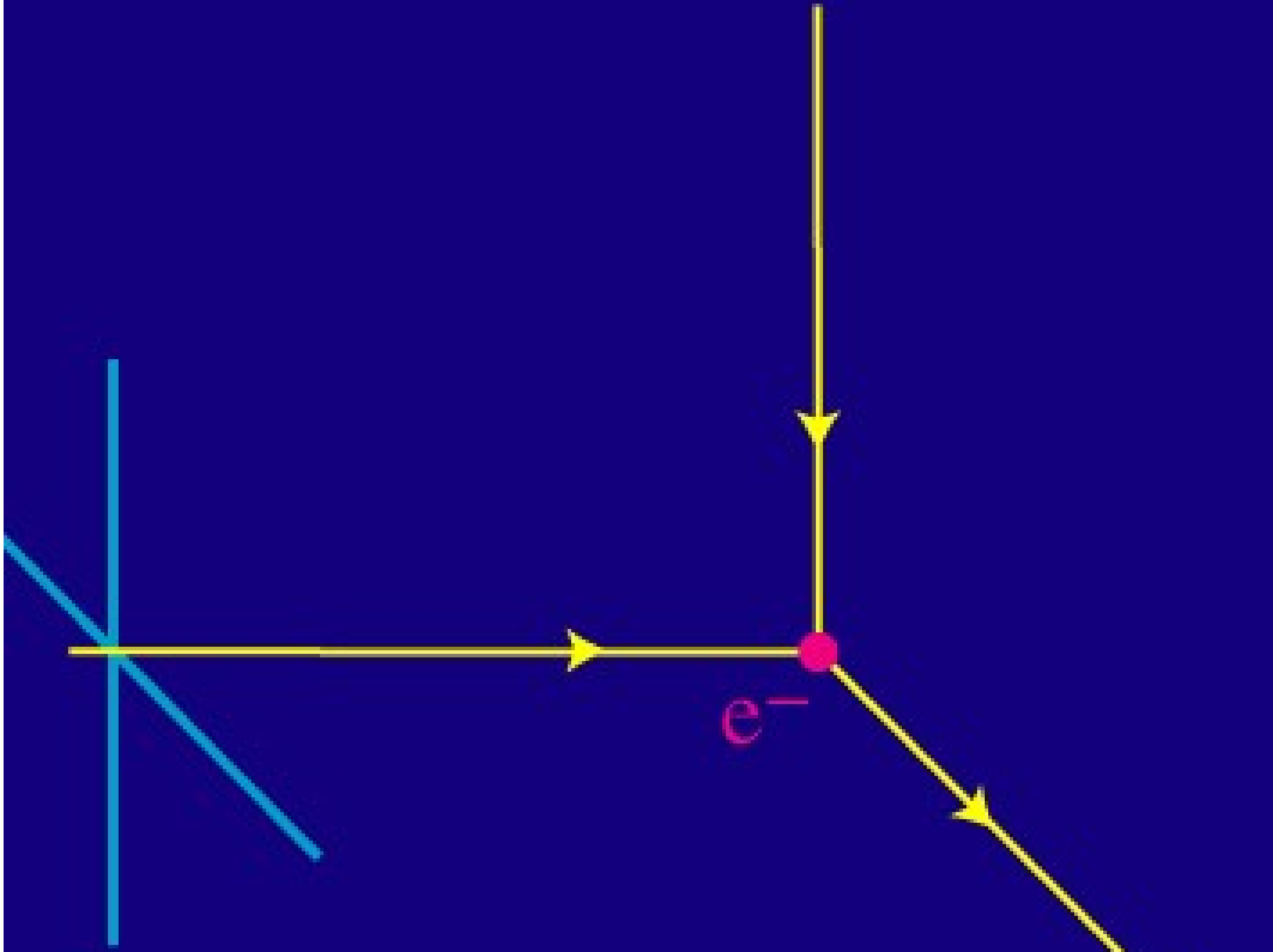


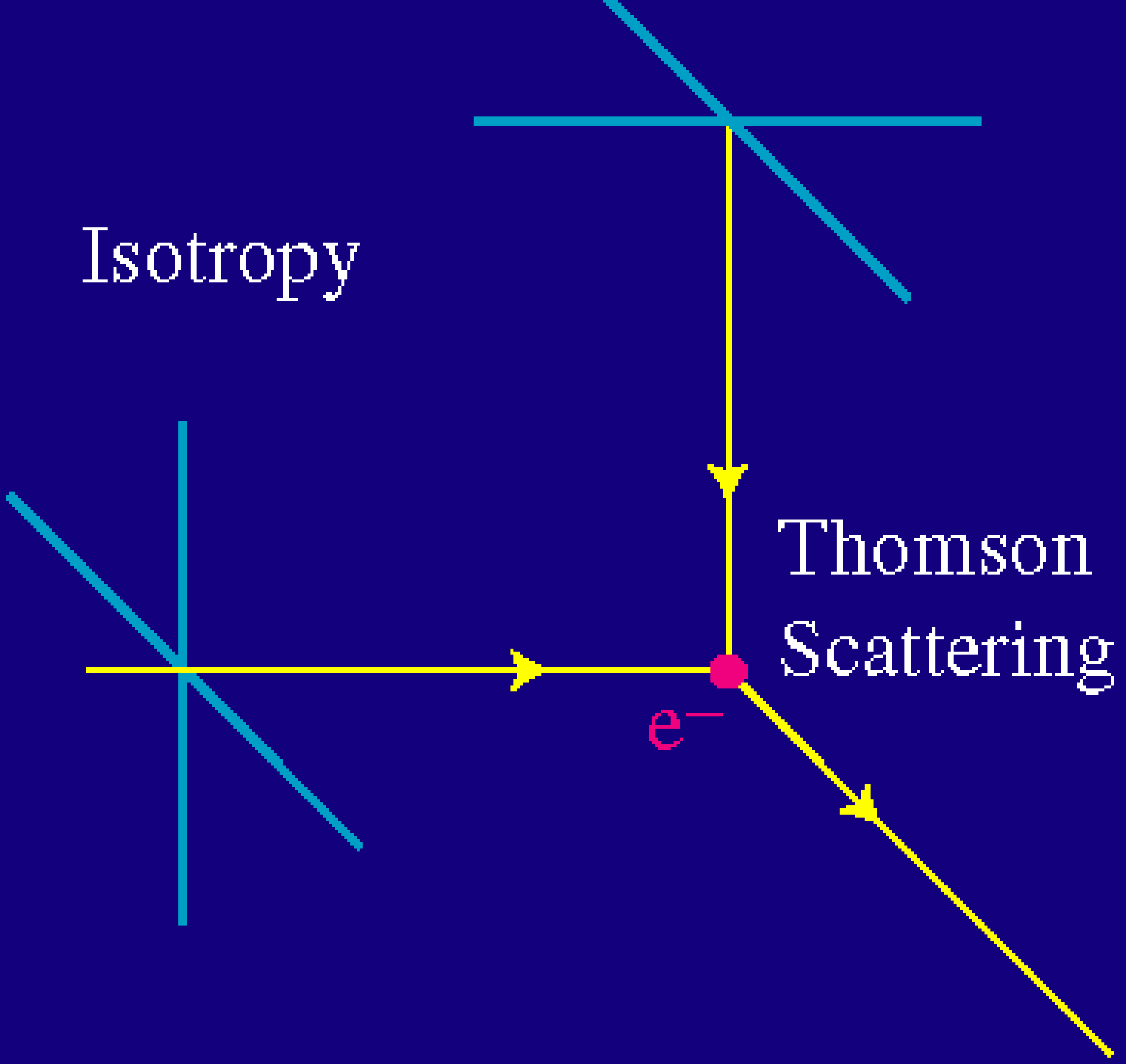
Photo Credit: TALEX



Polarization

Photo Credit: TALEX

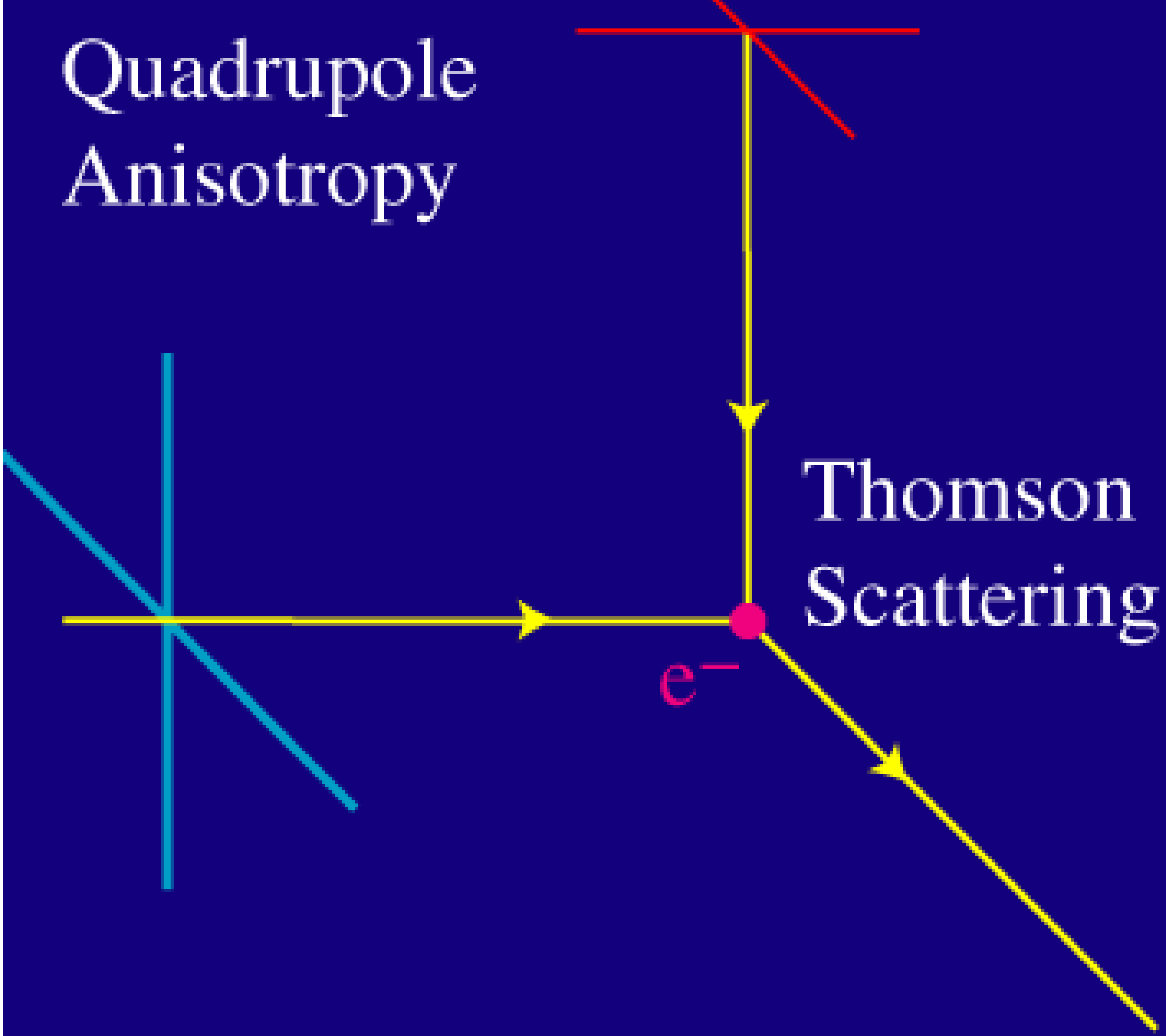

e^-



Isotropy

Thomson
Scattering

No Polarization

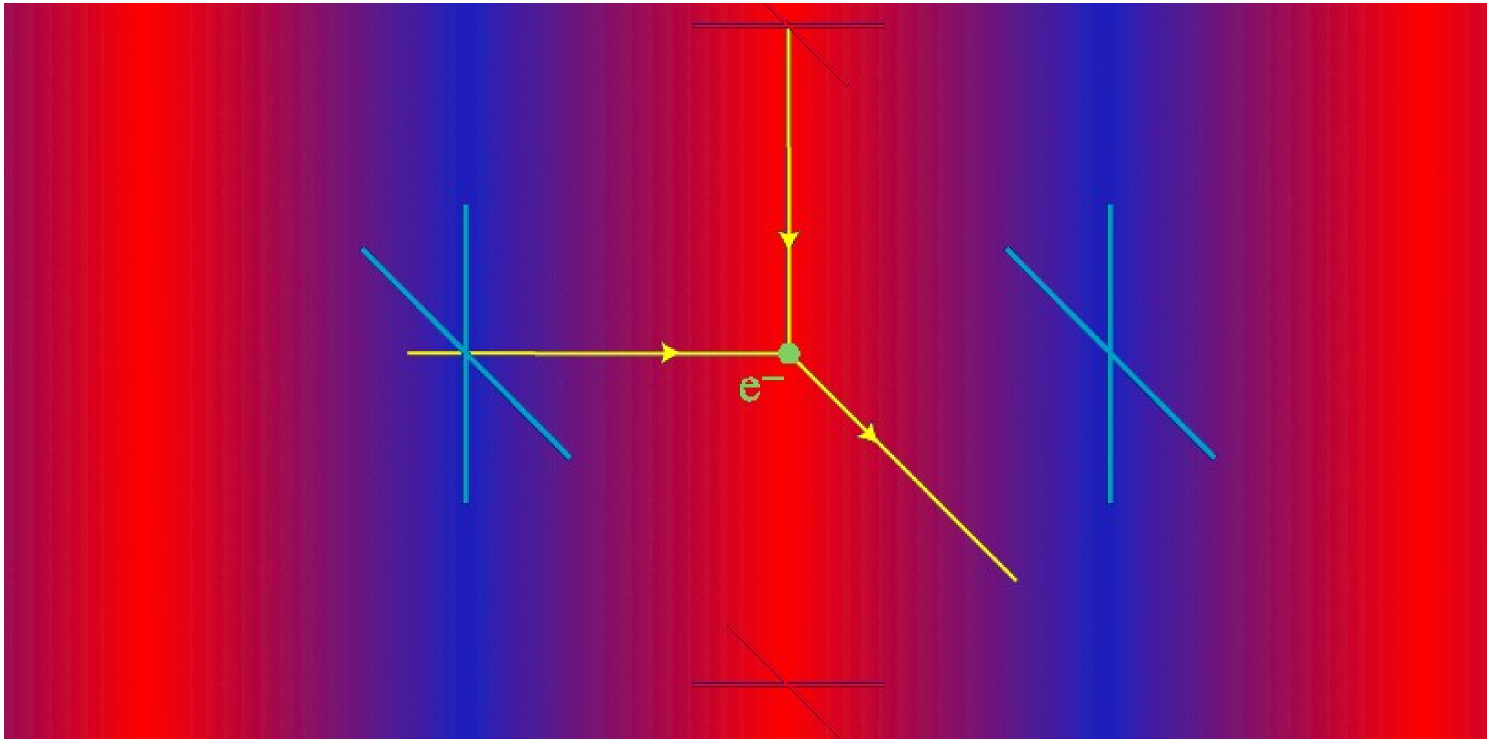


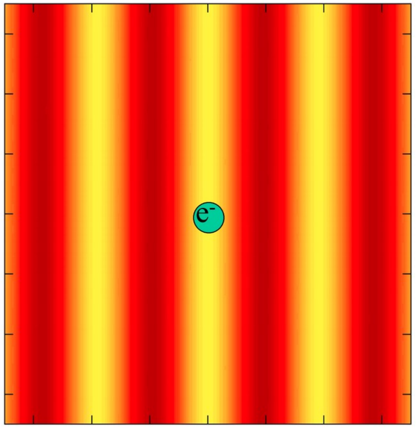
Quadrupole
Anisotropy

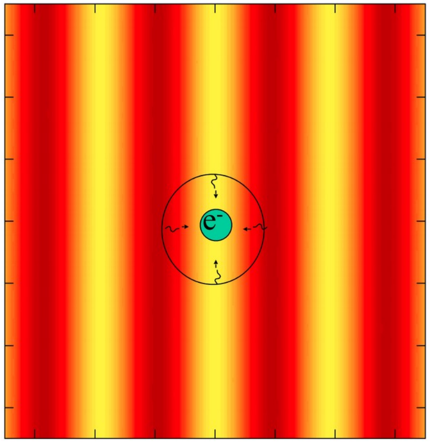
Thomson
Scattering

Linear
Polarization

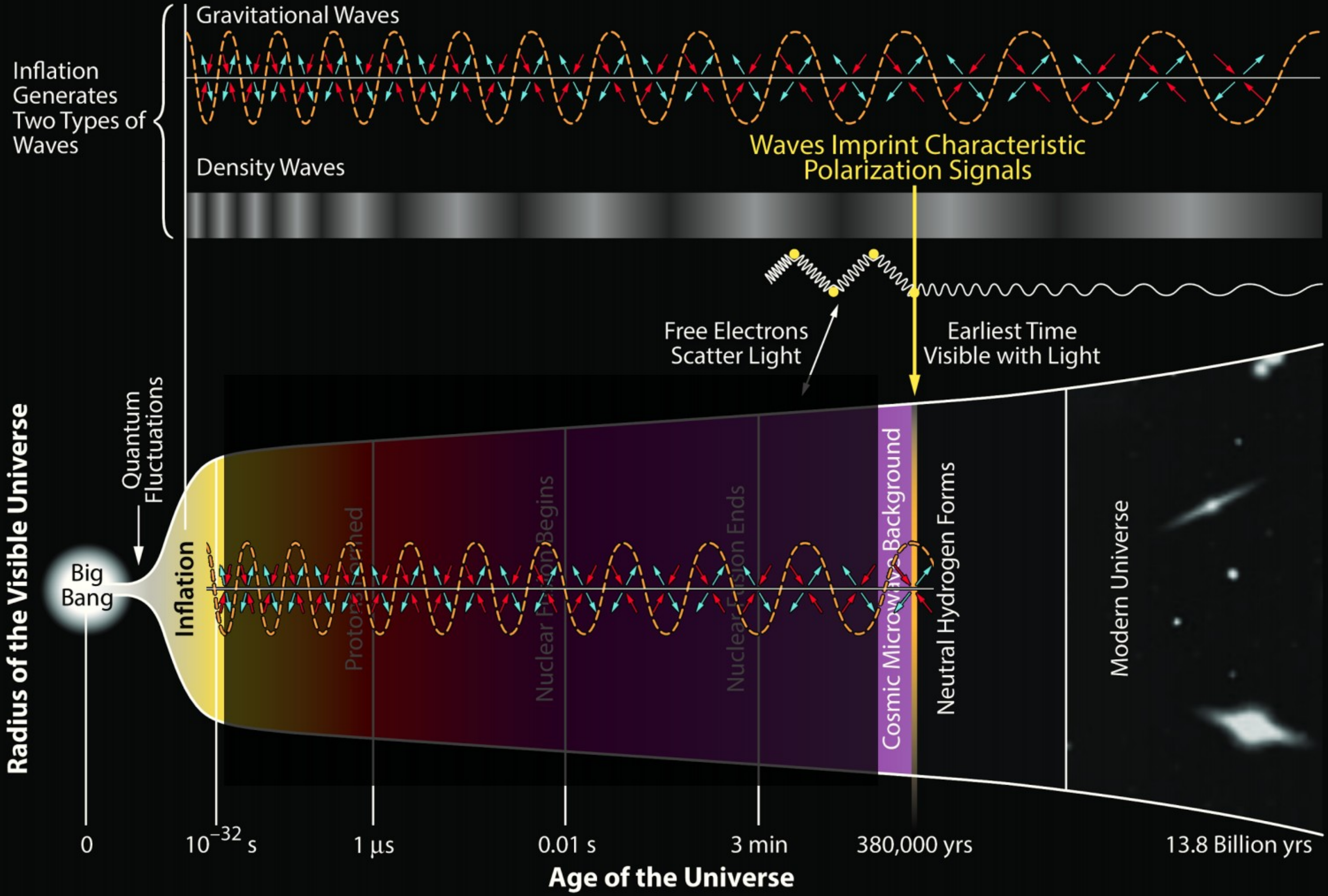
CMB polarization:
scattering from sound waves



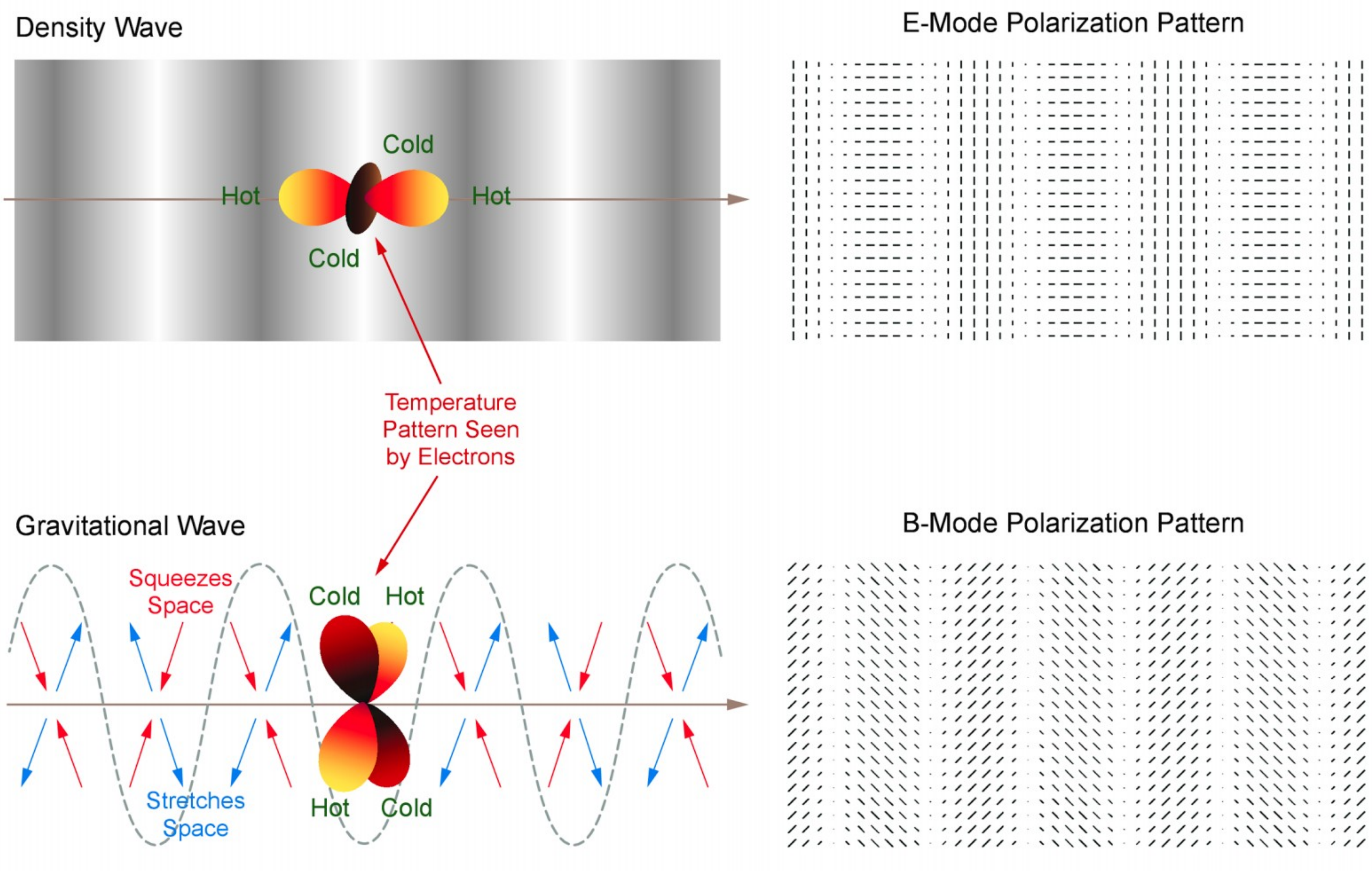




History of the Universe

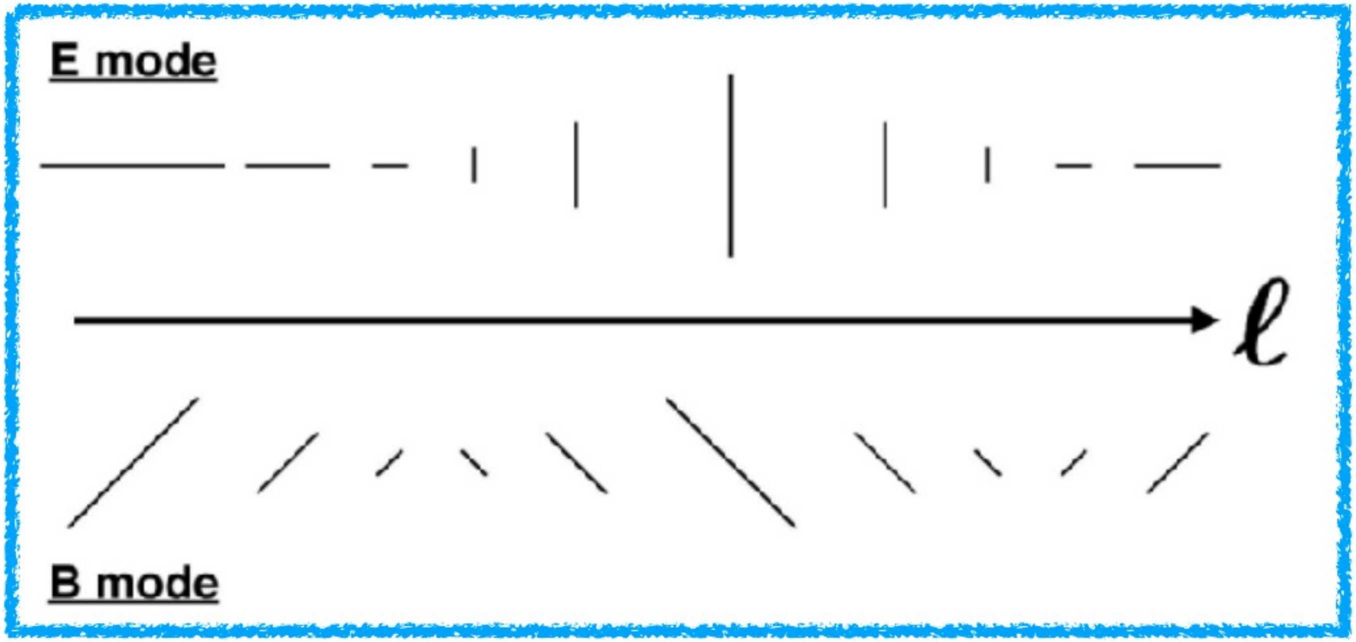


Polarization



Polnarev, A. G. 1985, Sov. Ast., 29, 607

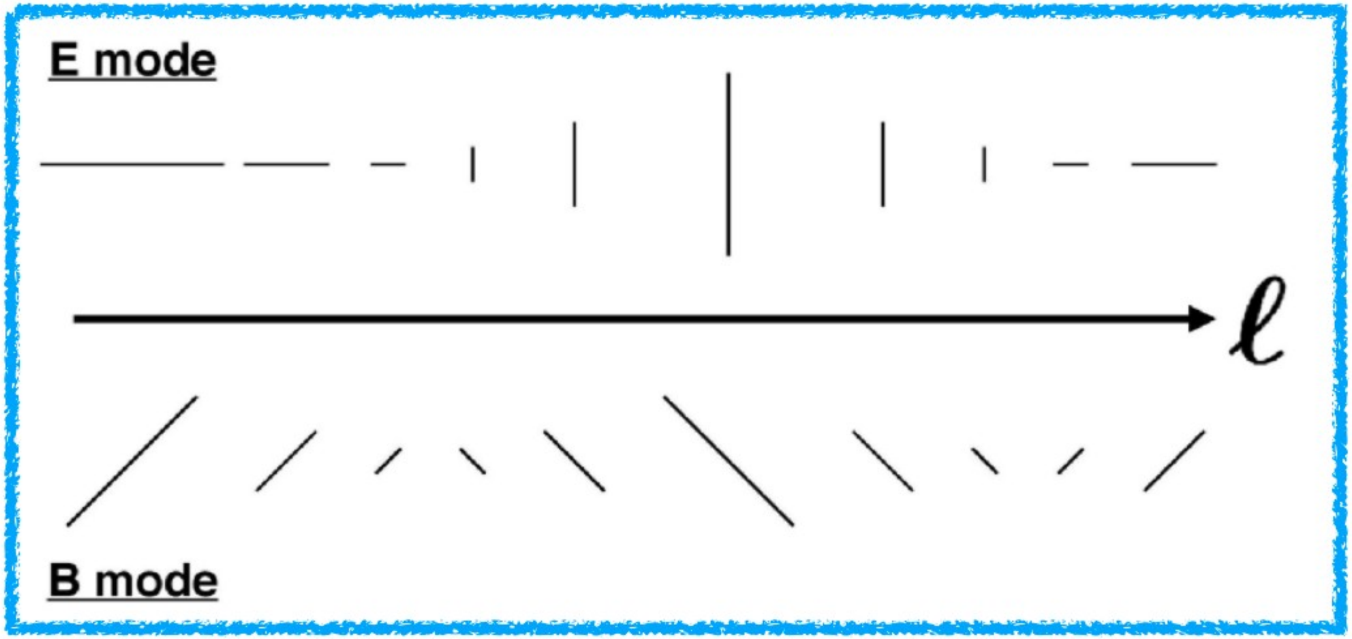
E and B mode



- **<u>E mode</u>**: Polarisation directions parallel or perpendicular to the wavevector

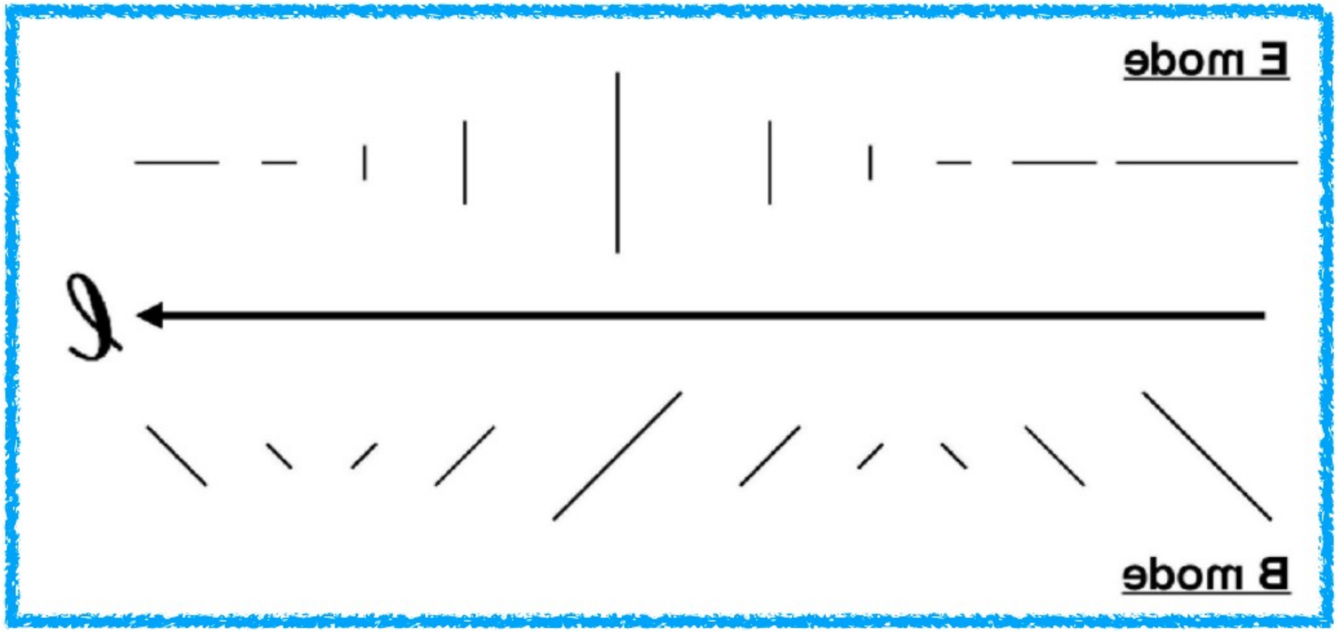
- **<u>B mode</u>**: Polarisation directions 45 degree tilted with respect to the wavevector

Parity



- **<u>E mode</u>**: Parity even
- **<u>B mode</u>**: Parity odd

Parity



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

Power Spectra

$$\langle E_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta^{(2)}_D(\boldsymbol{\ell} - \boldsymbol{\ell}') C^{EE}_\ell$$

$$\langle B_{\boldsymbol{\ell}} B^*_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta^{(2)}_D(\boldsymbol{\ell} - \boldsymbol{\ell}') C^{BB}_\ell$$

$$\langle T_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = \langle T^*_{\boldsymbol{\ell}} E_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta^{(2)}_D(\boldsymbol{\ell} - \boldsymbol{\ell}') C^{TE}_\ell$$

- However, <EB> and <TB> vanish for parity-preserving fluctuations because <EB> and <TB> change sign under parity flip

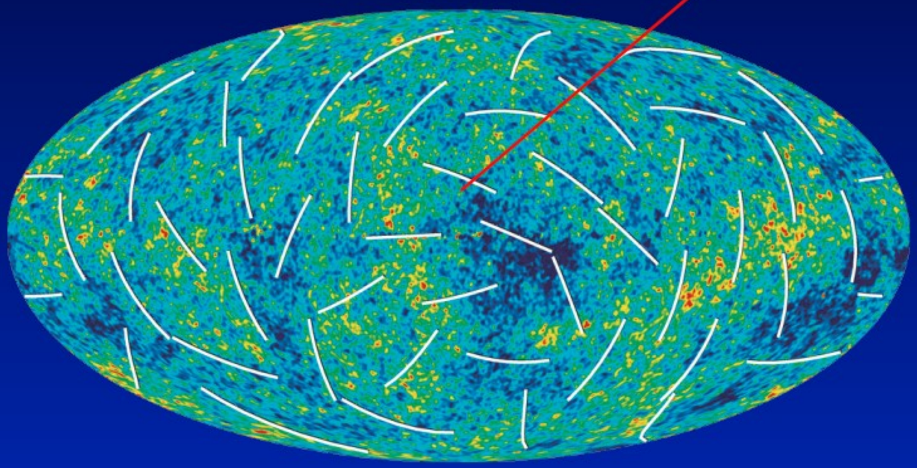
CMB Sky → Cosmology

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

Expand in Spherical Harmonics

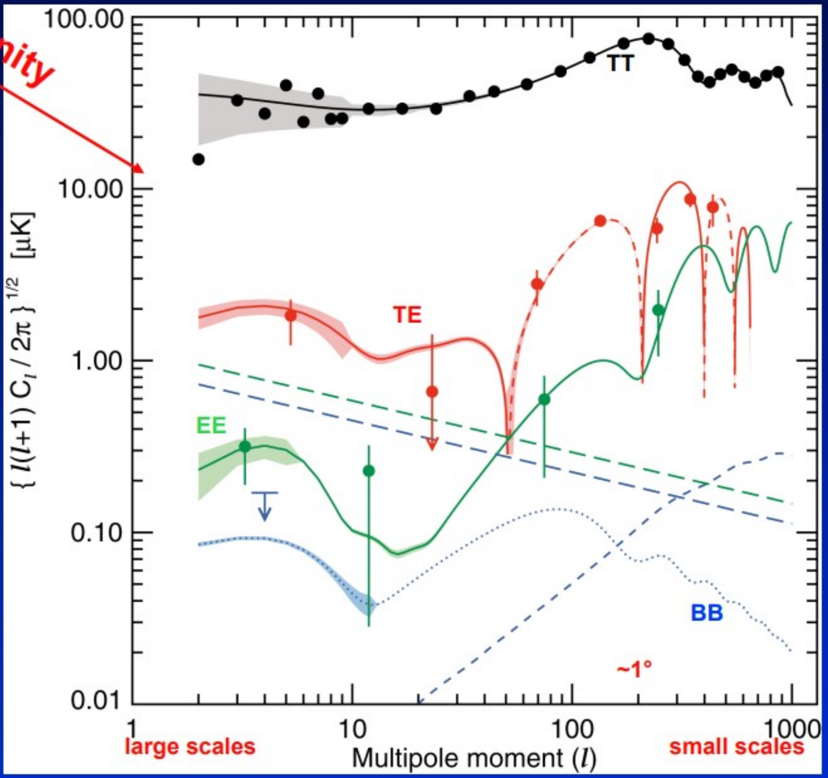
a_{lm}

WMAP CMB Sky

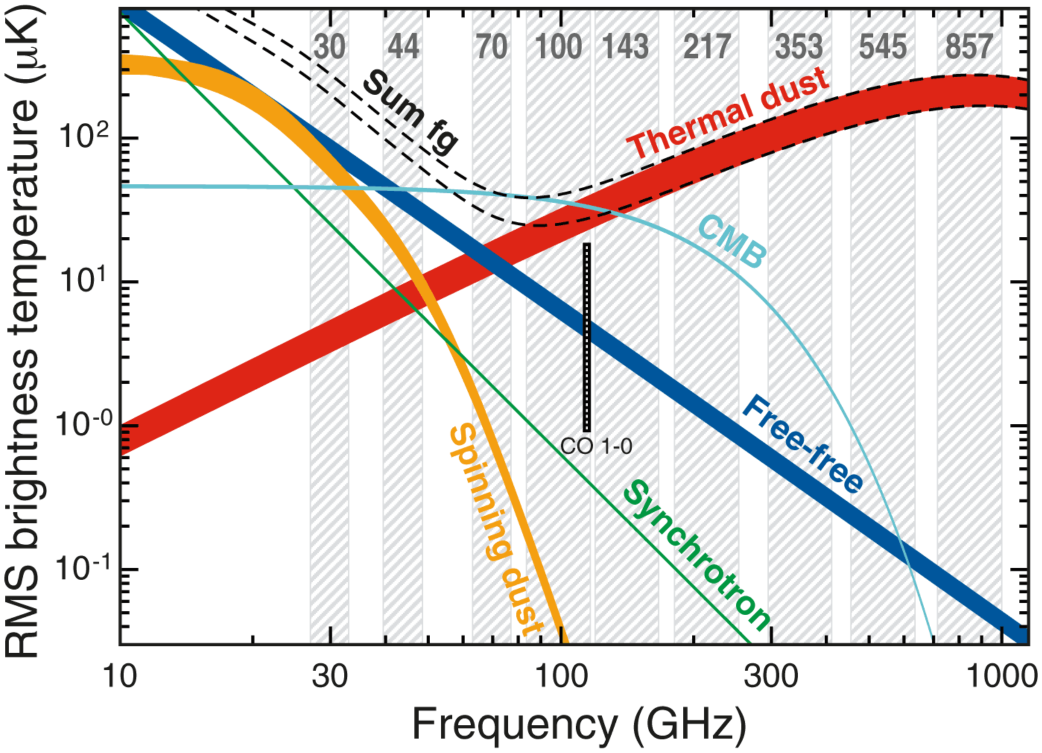


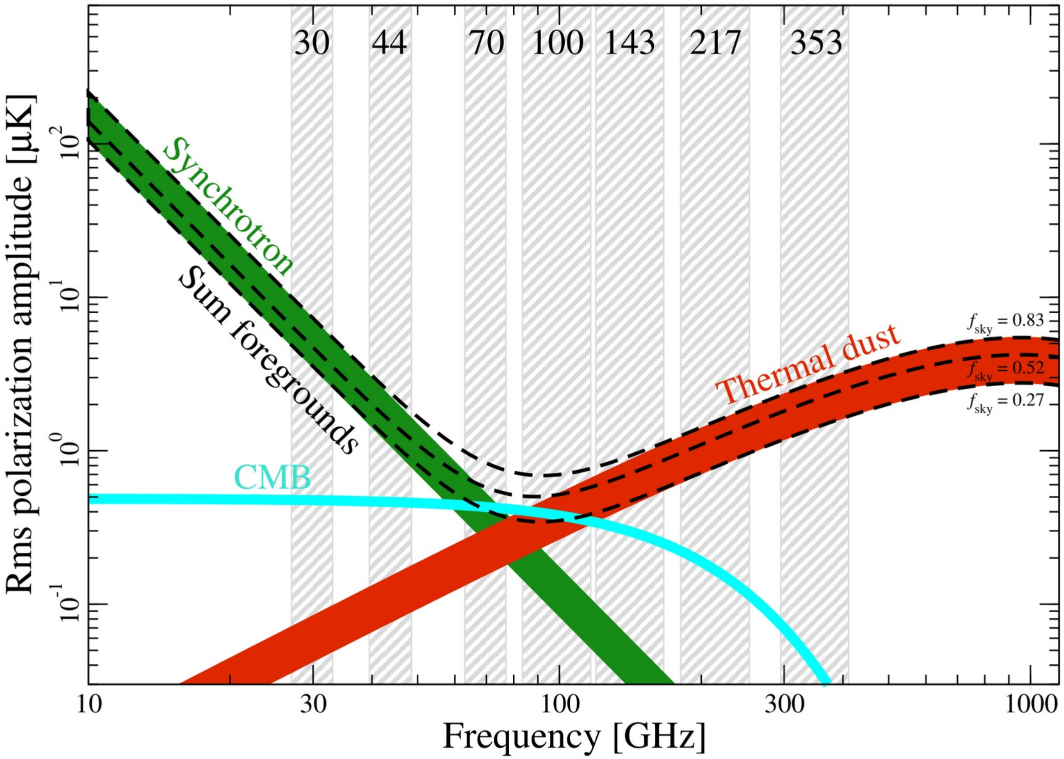
Gaussianity

Power spectra

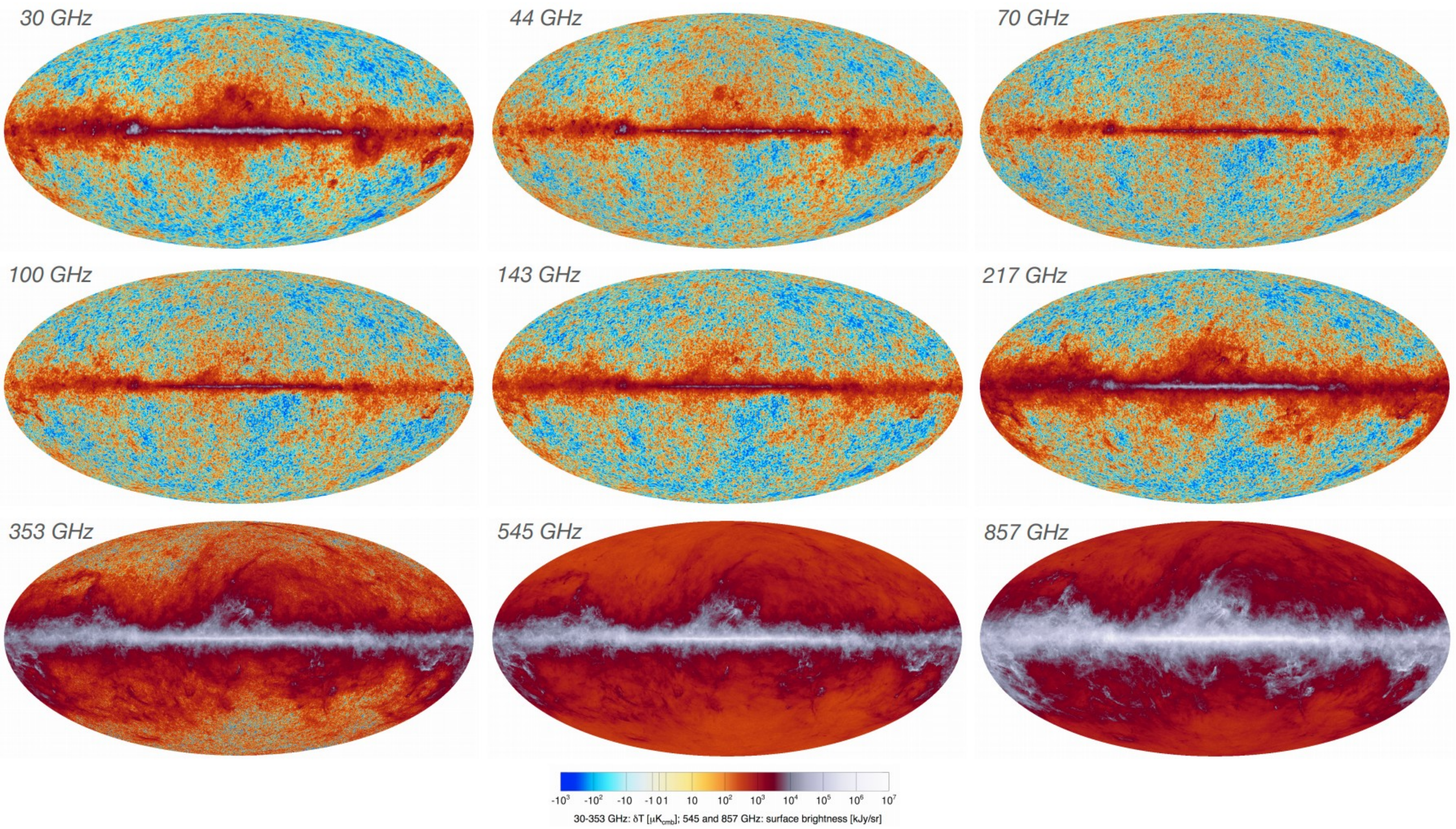


Measuring the CMB





Measuring the CMB



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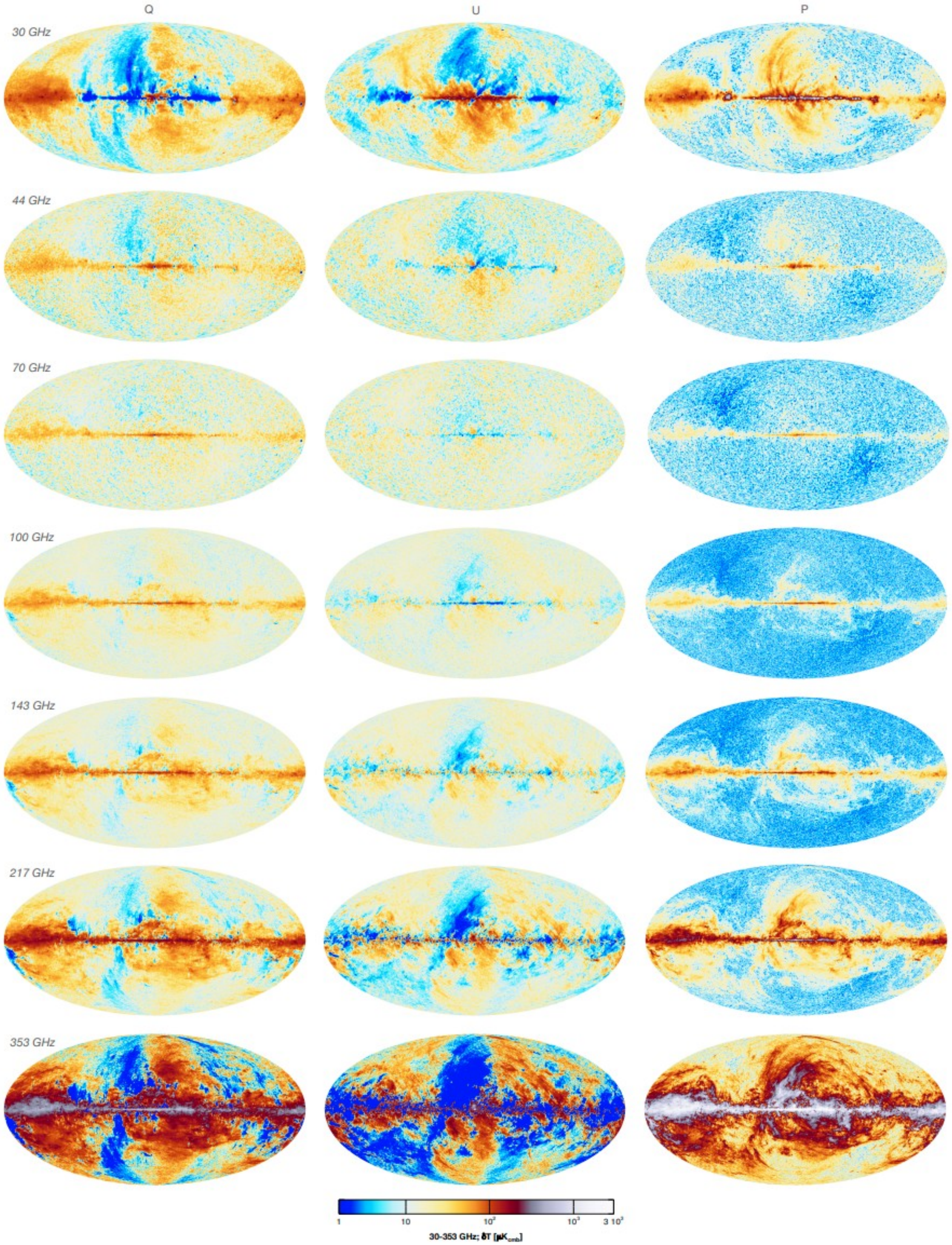


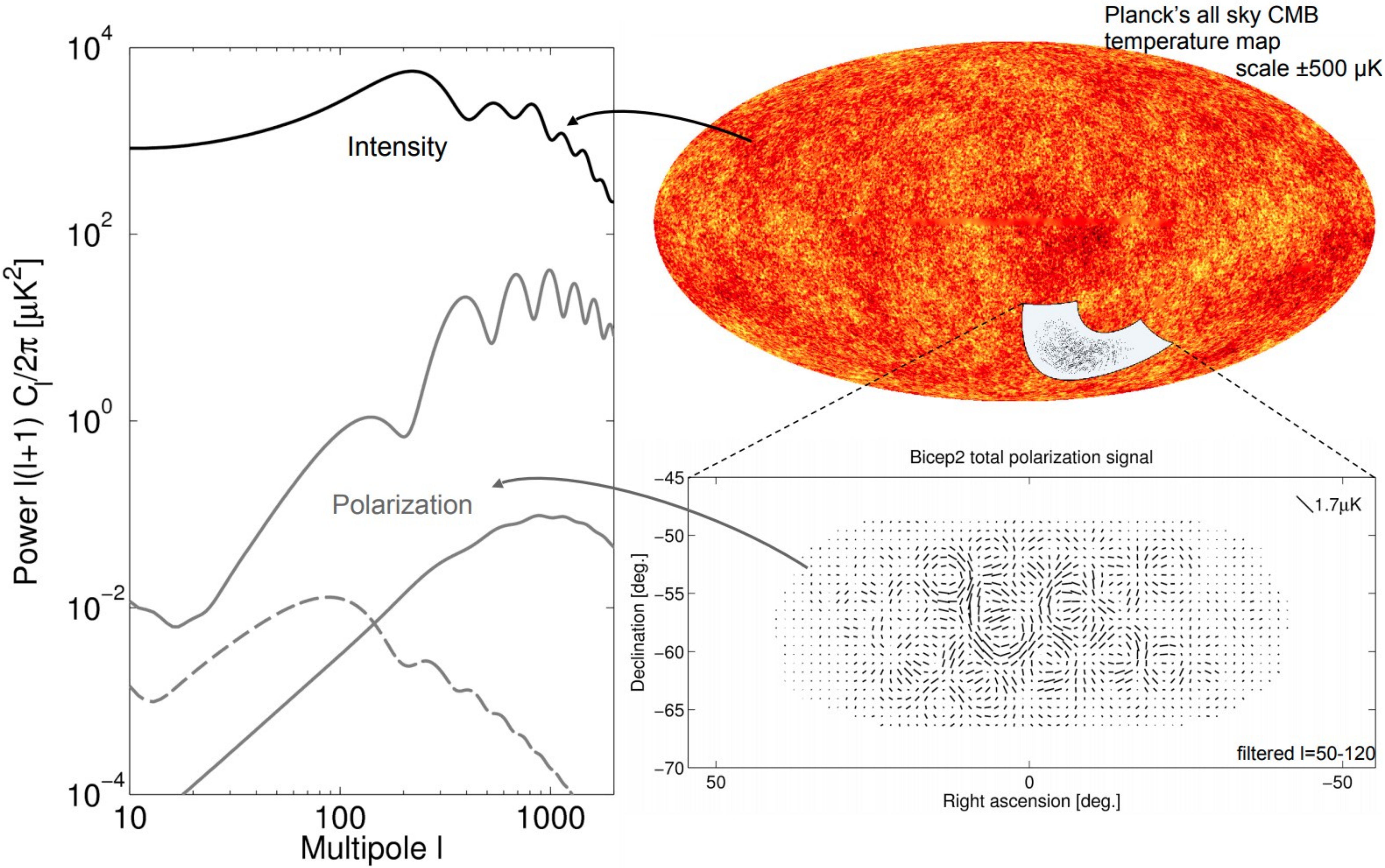
The 2018 Planck maps in polarization (Stokes Q, U, and polarized amplitude P)

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

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

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

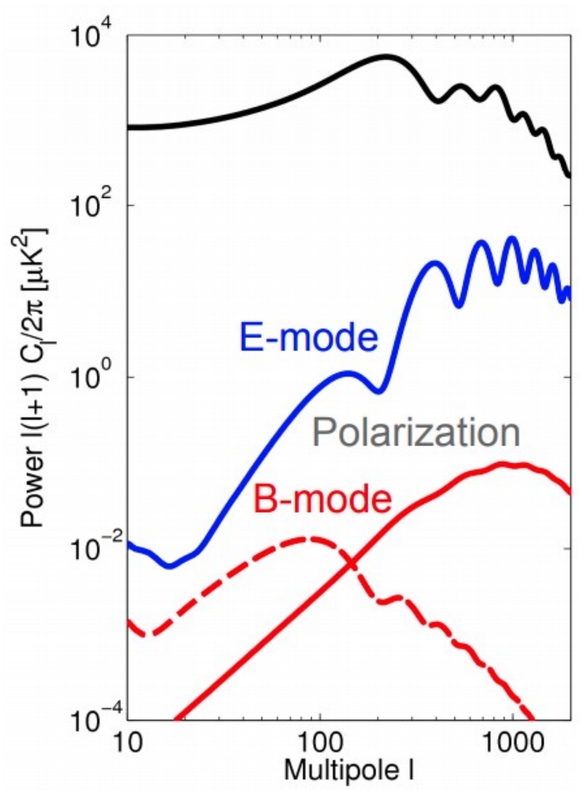
Cosmic Microwave Background



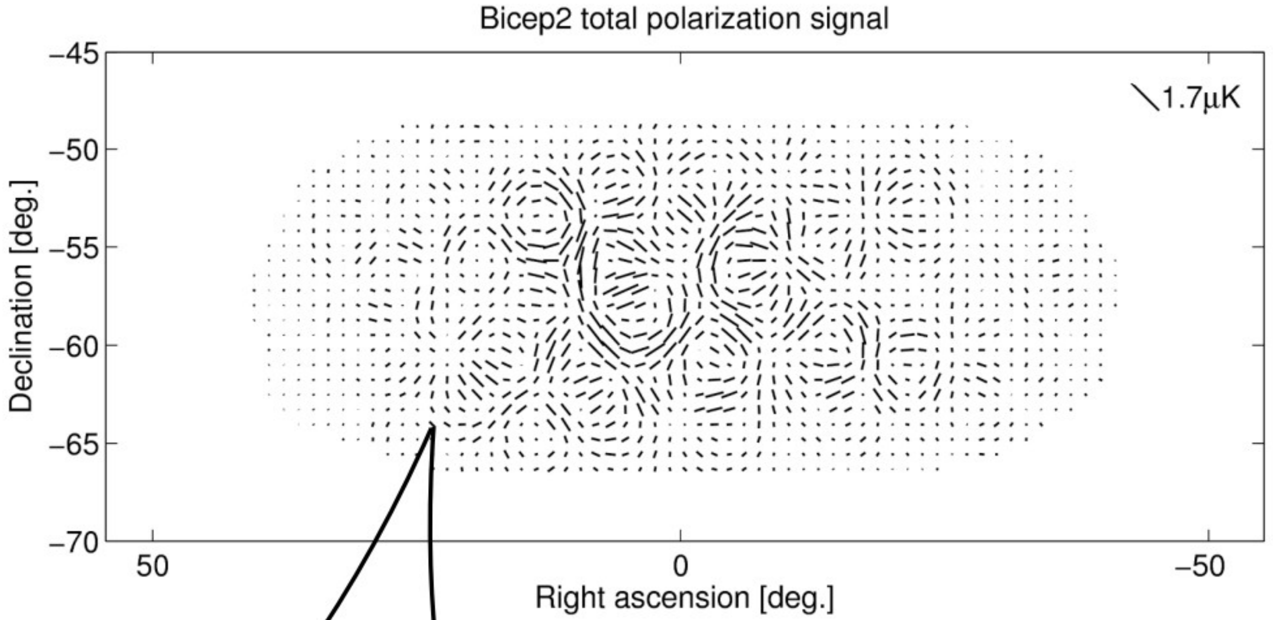
Planck's all sky CMB temperature map
scale ±500 μK

The Bicep2 Collaboration

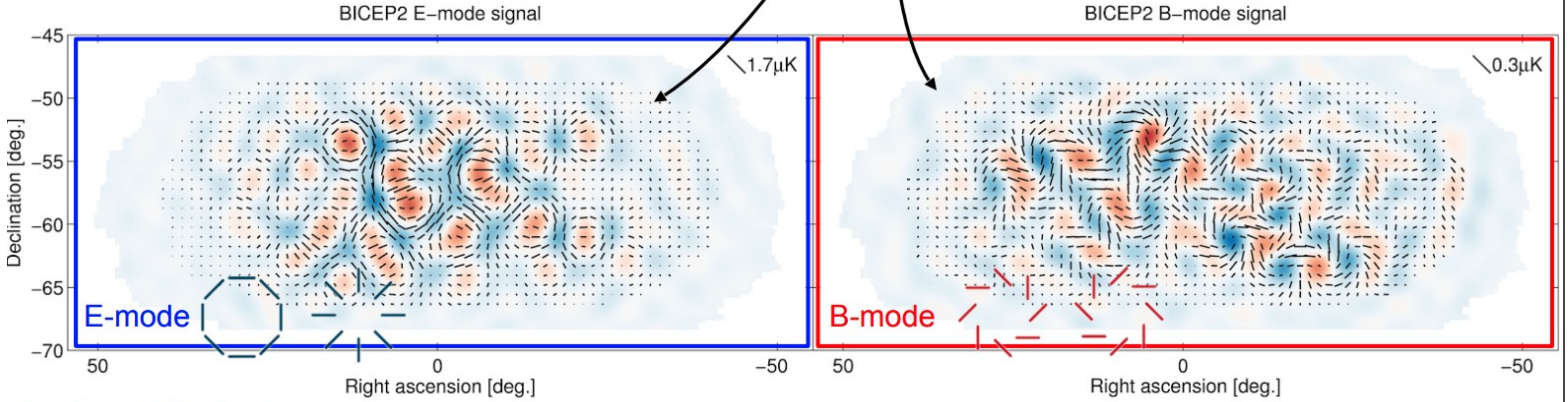
CMB Polarization



Need 2D basis to describe polarization map...



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



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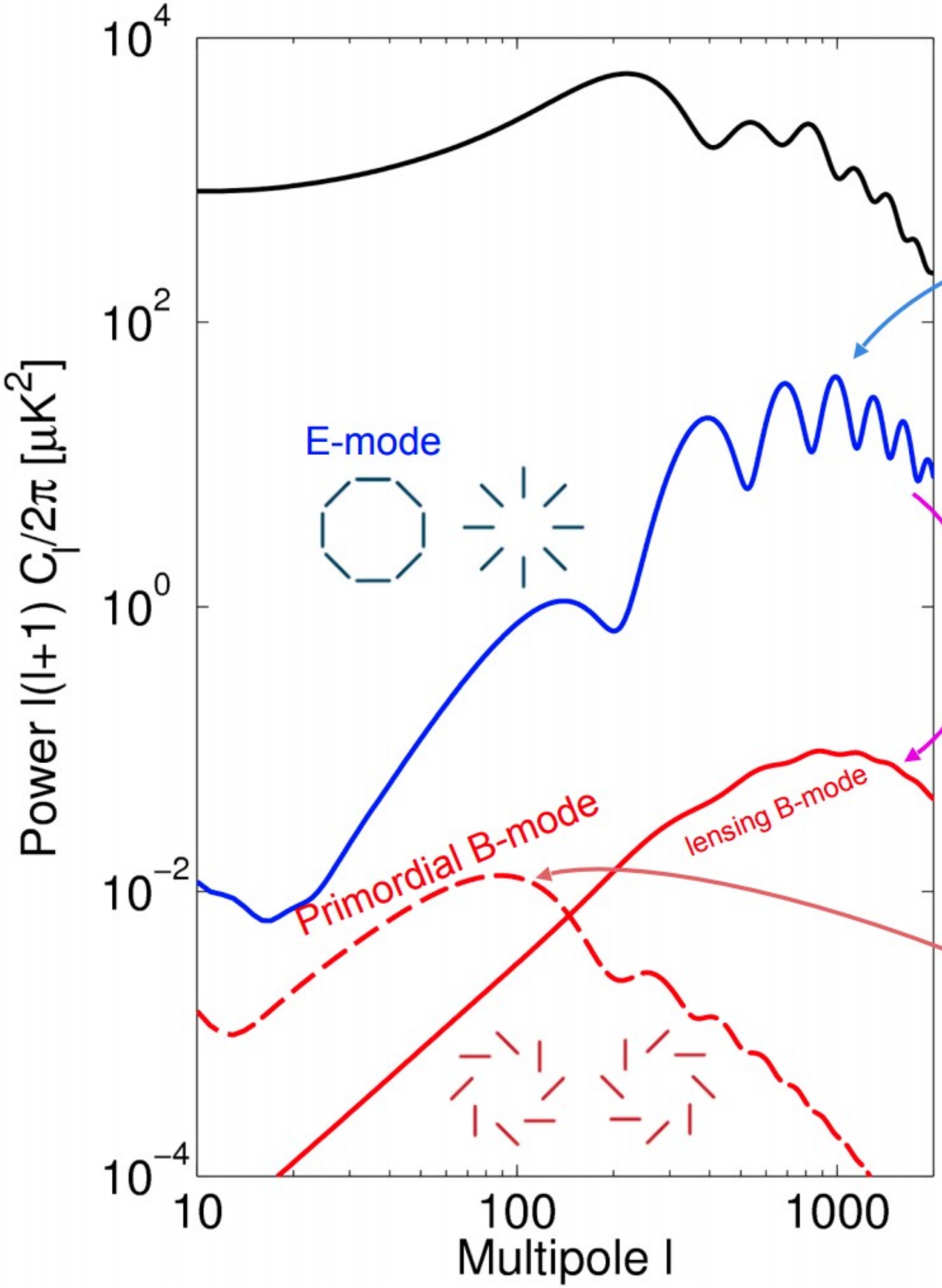
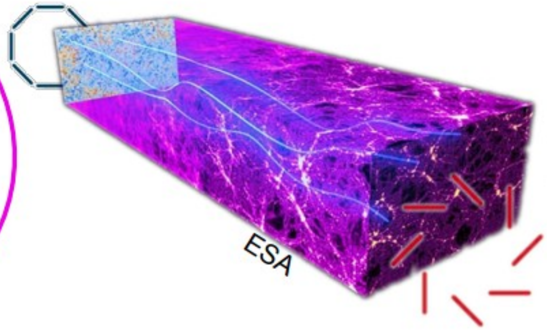
CMB Polarization



In standard ΛCDM only E-modes are present at last scattering

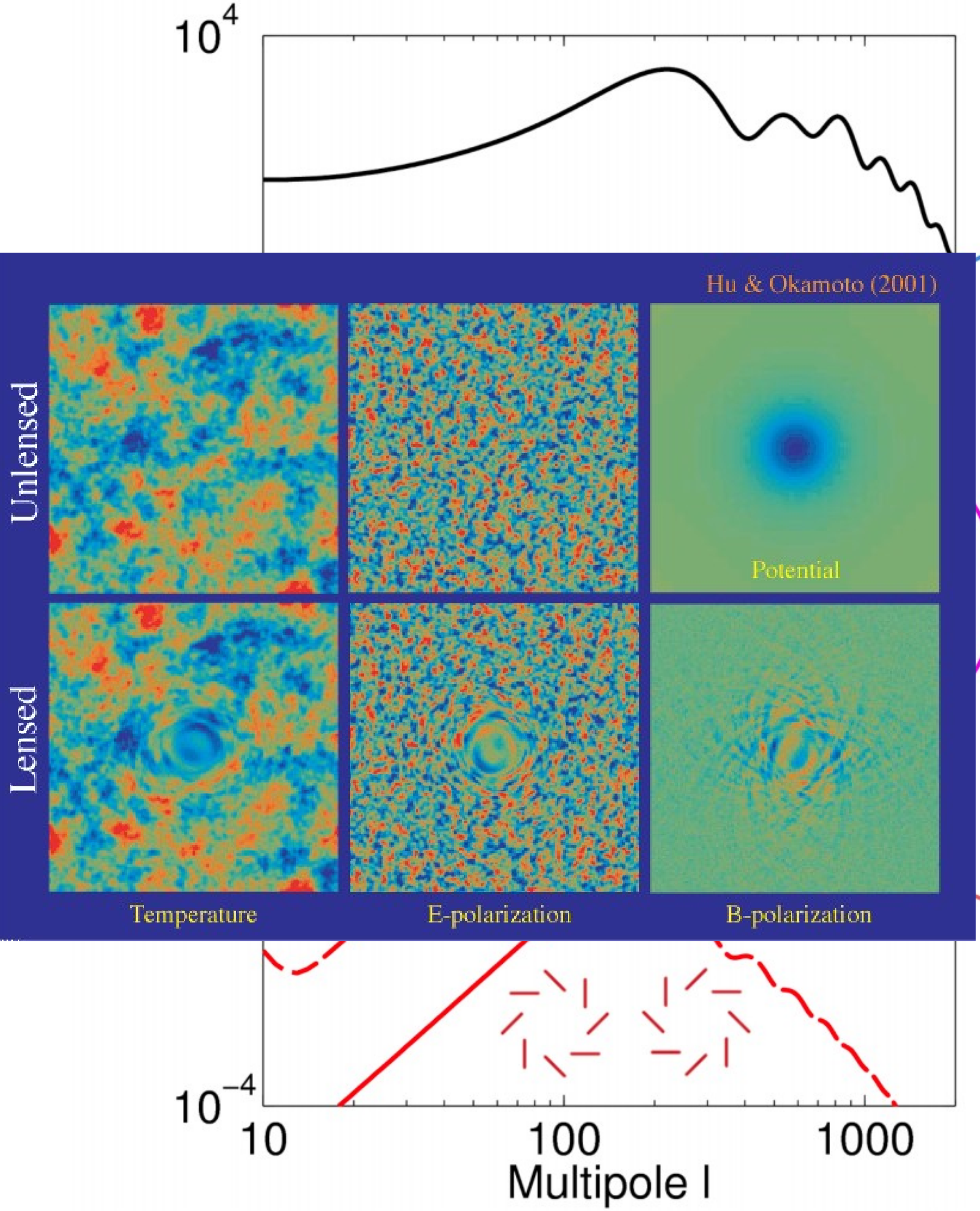


During propagation some of the E-modes are confused into B-modes by lensing

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

The Bicep2 Collaboration

CMB Polarization



The Bicep2 Collaboration

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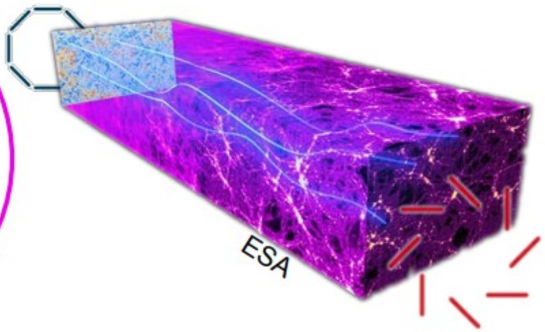

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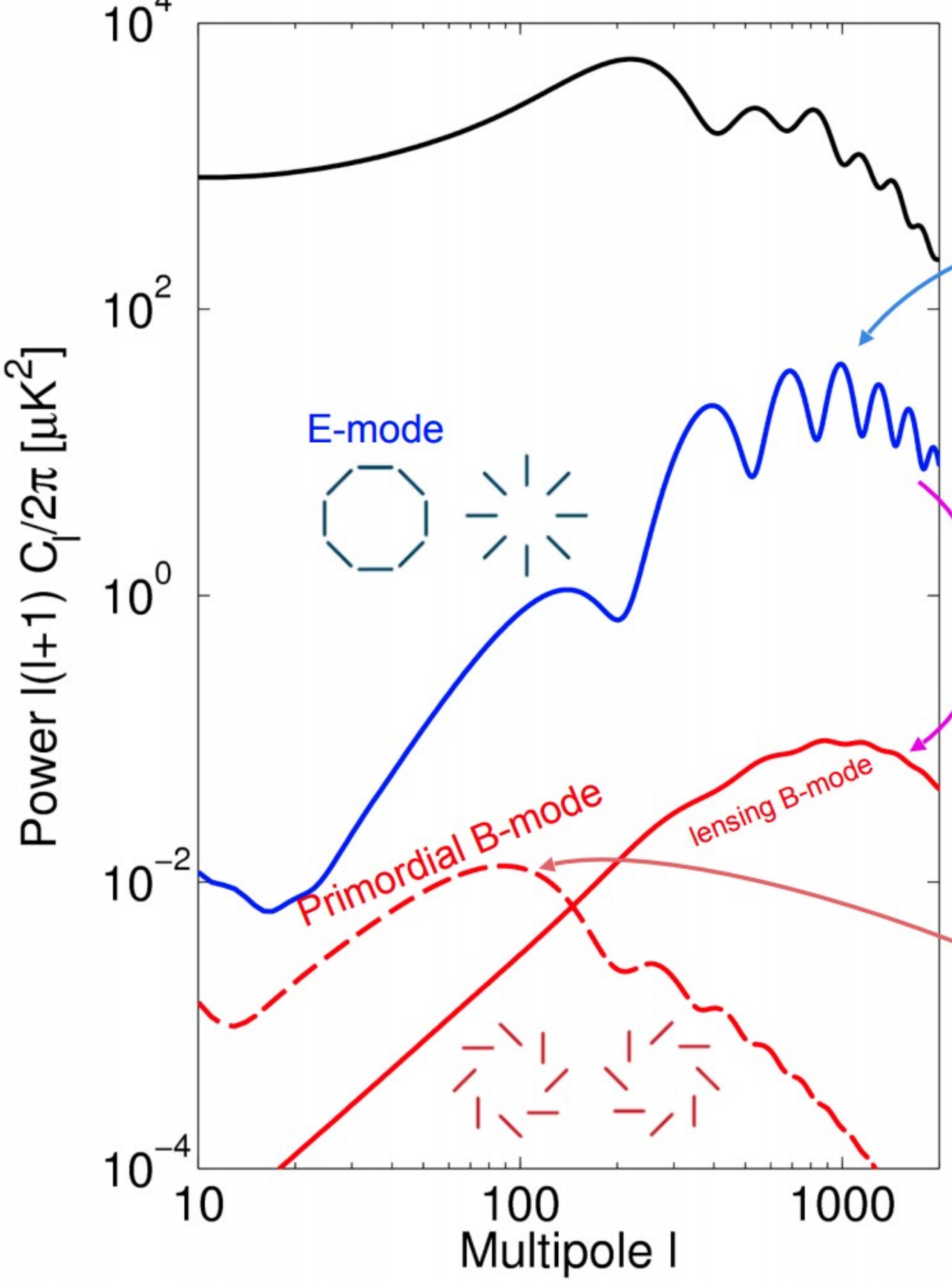

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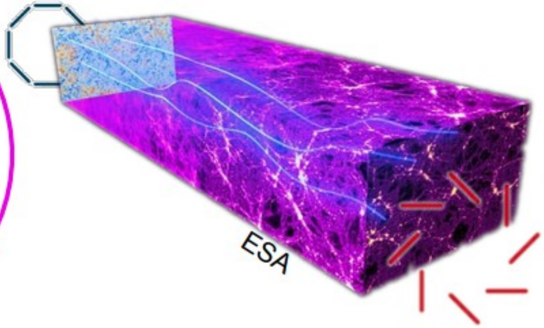

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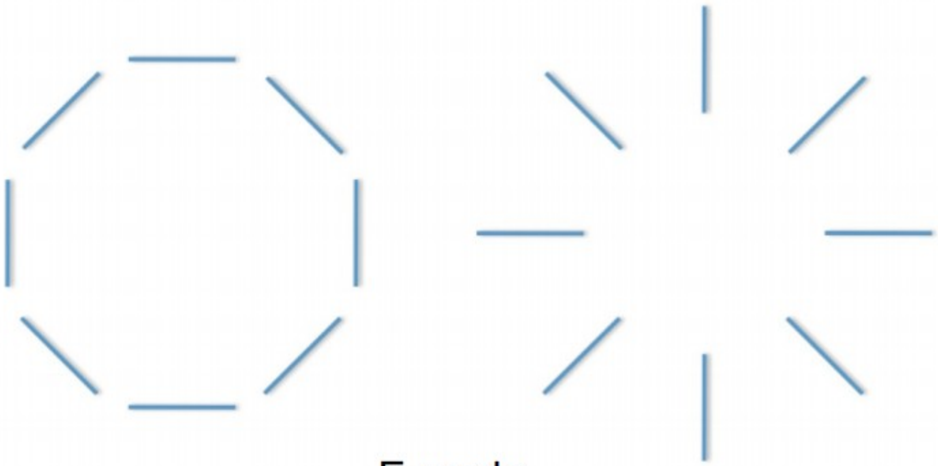
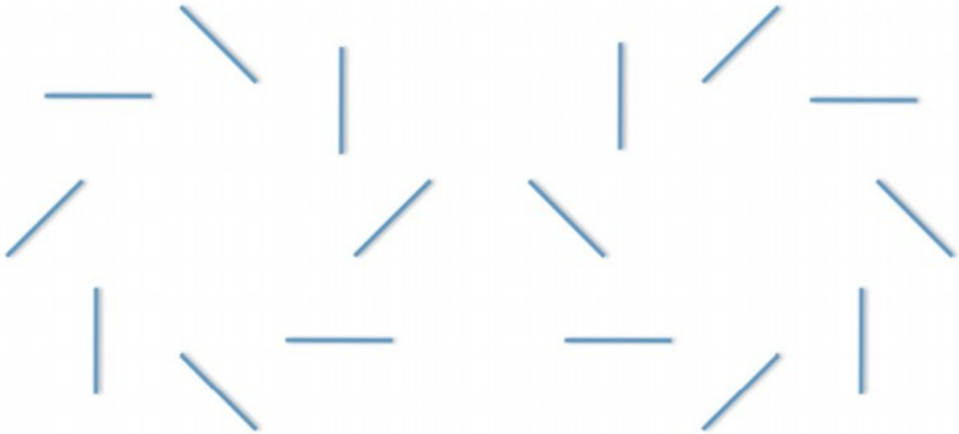


E-mode



B-mode

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

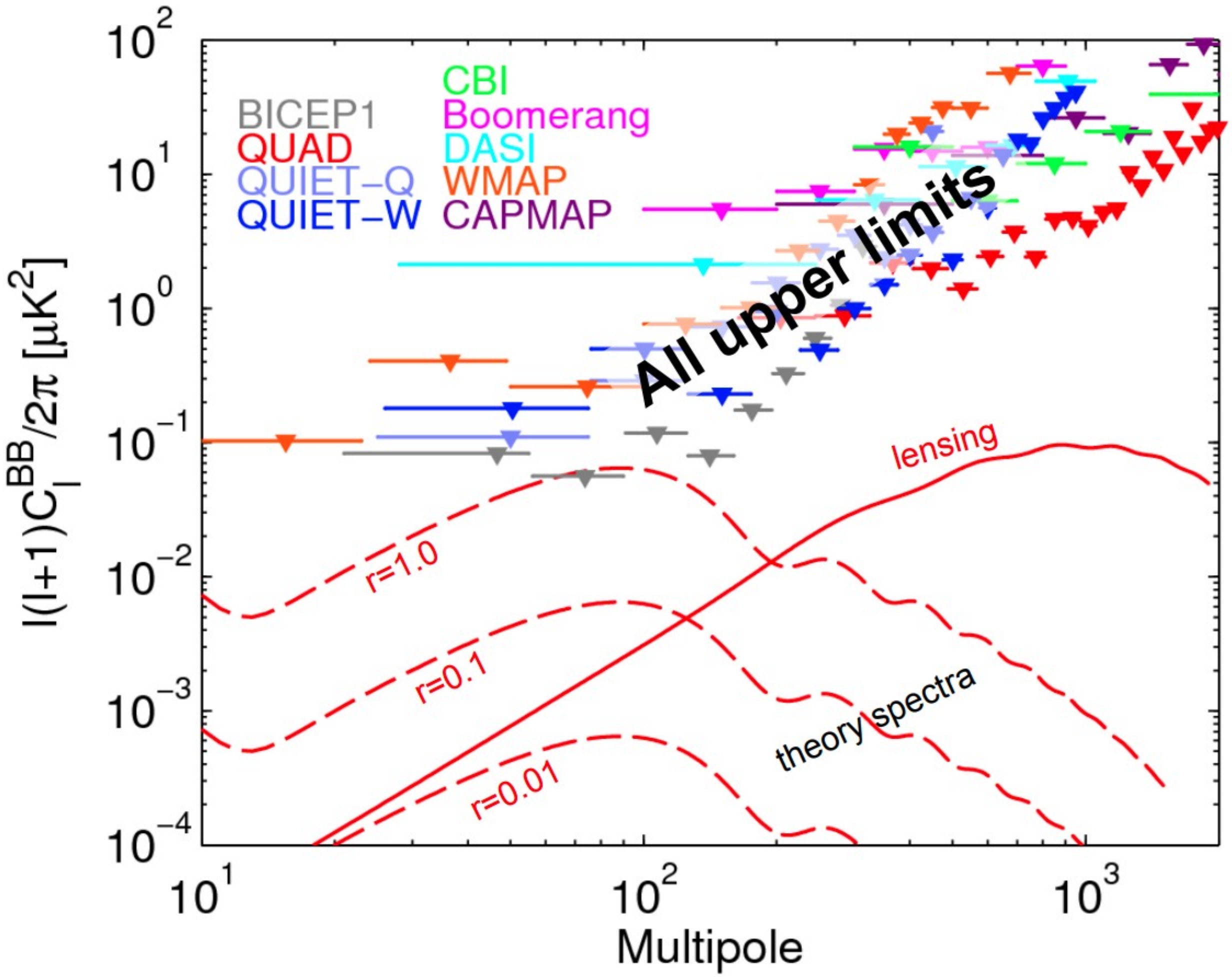
Polarization can be described as the sum of E-modes and B-modes.

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:

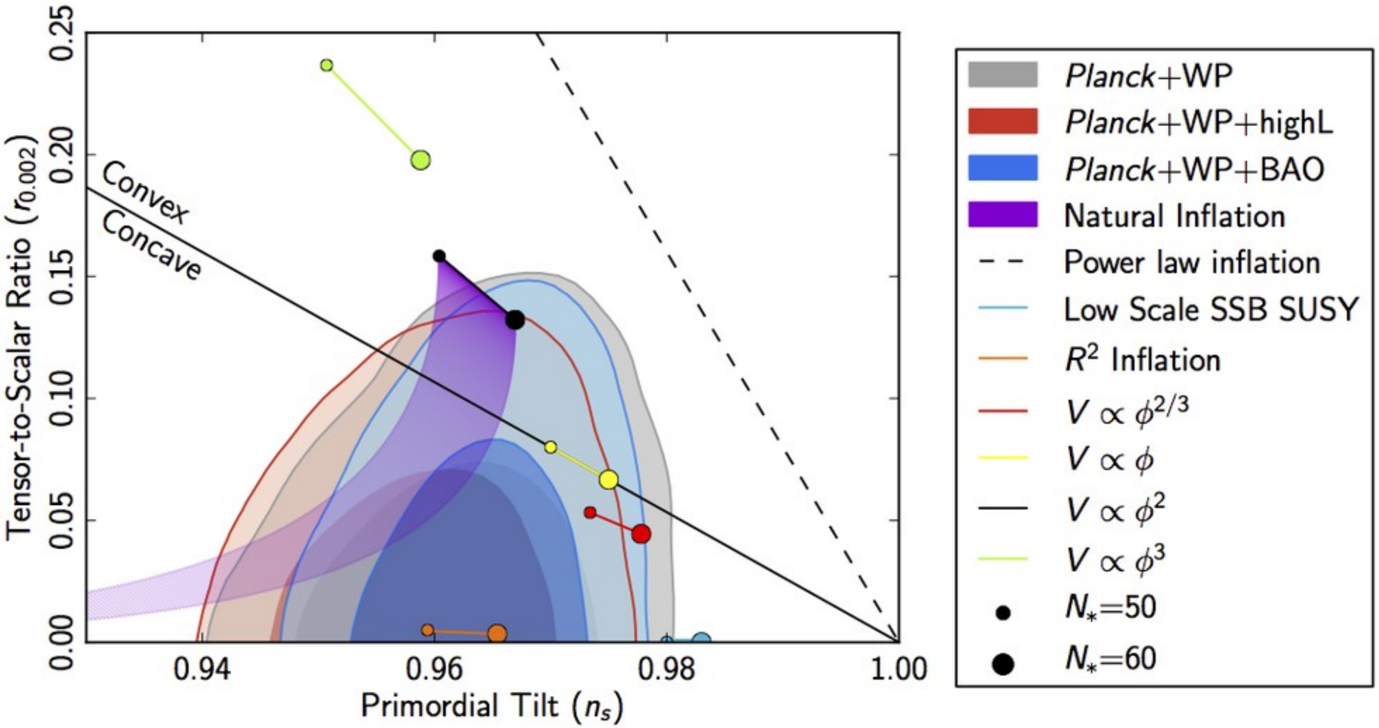
r < 0.7 (95% CL)

At high multipoles lensing B-mode dominant.

Brian Keating for the Bicep2 Collaboration

B modes

Search for B-modes



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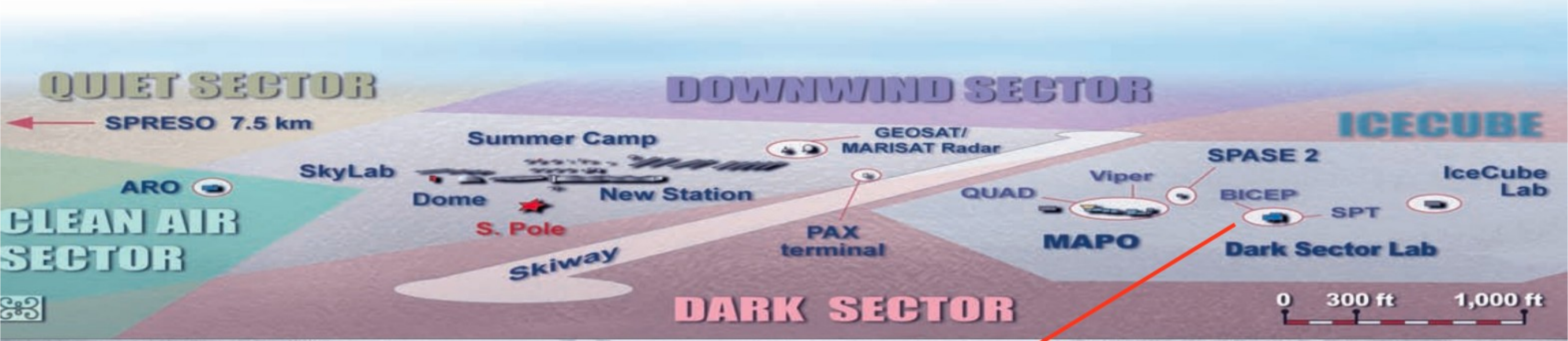
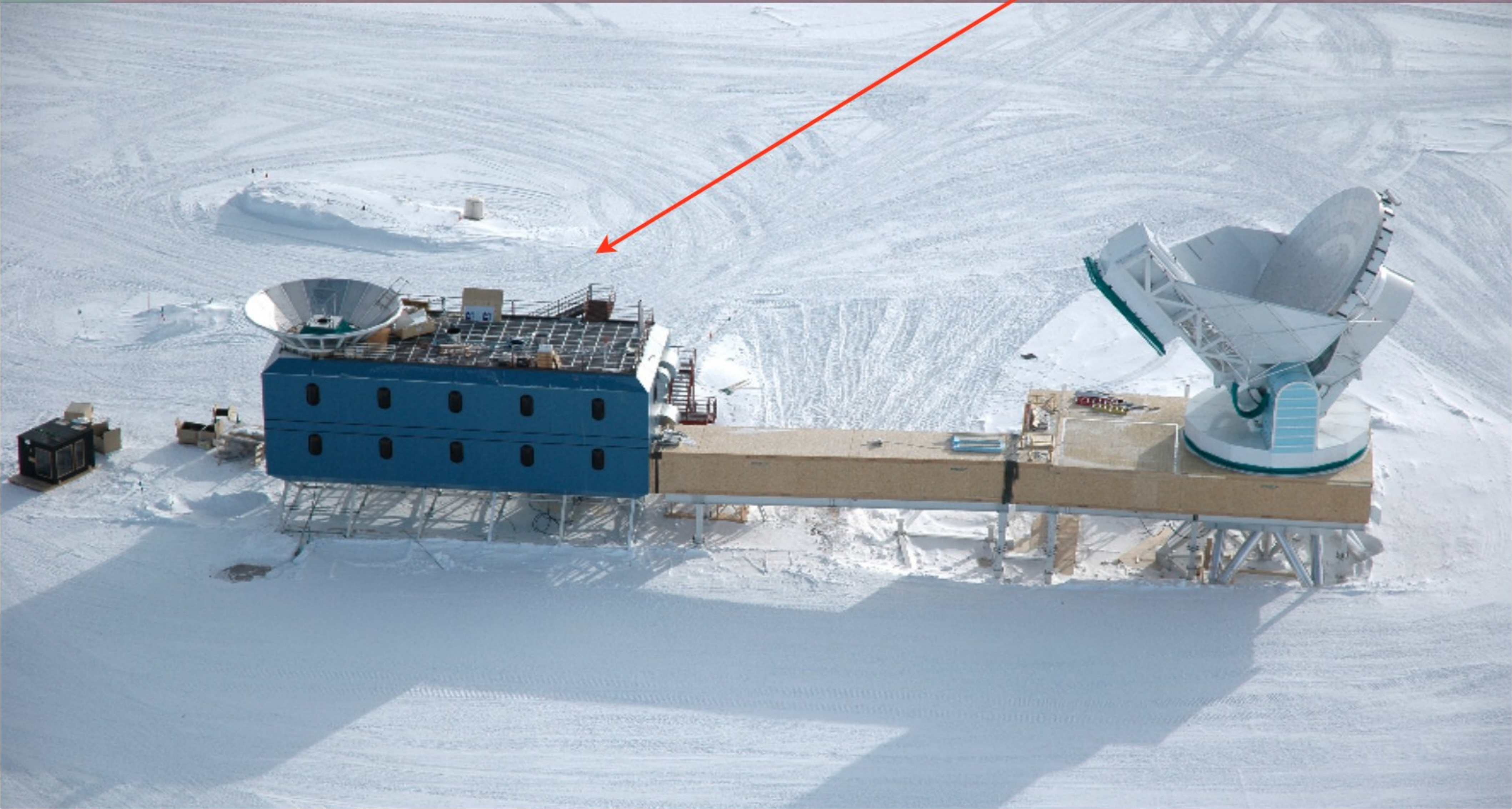
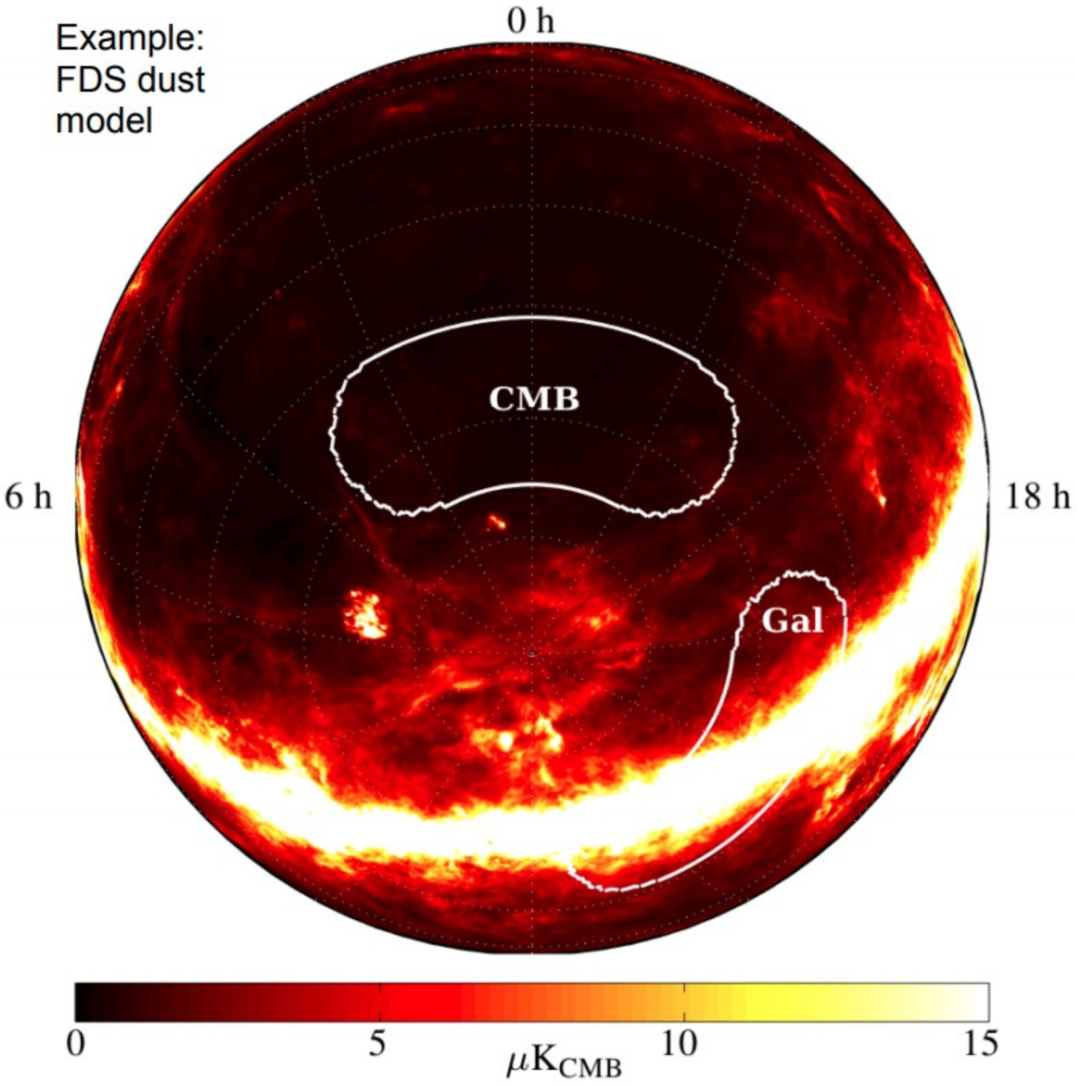

QUIET SECTOR
DOWNWIND SECTOR
ICECUBE
SPRESO 7.5 km
Summer Camp
GEOSAT/
MARISAT Radar
SPASE 2
IceCube
Lab
SkyLab
Viper
ARO
QUAD
BICEP
CLEAN AIR
SECTOR
Dome
New Station
SPT
S. Pole
PAX
terminal
MAPO
Dark Sector Lab
Skiway
DARK SECTOR
0
300 ft
1,000 ft



Observational Strategy



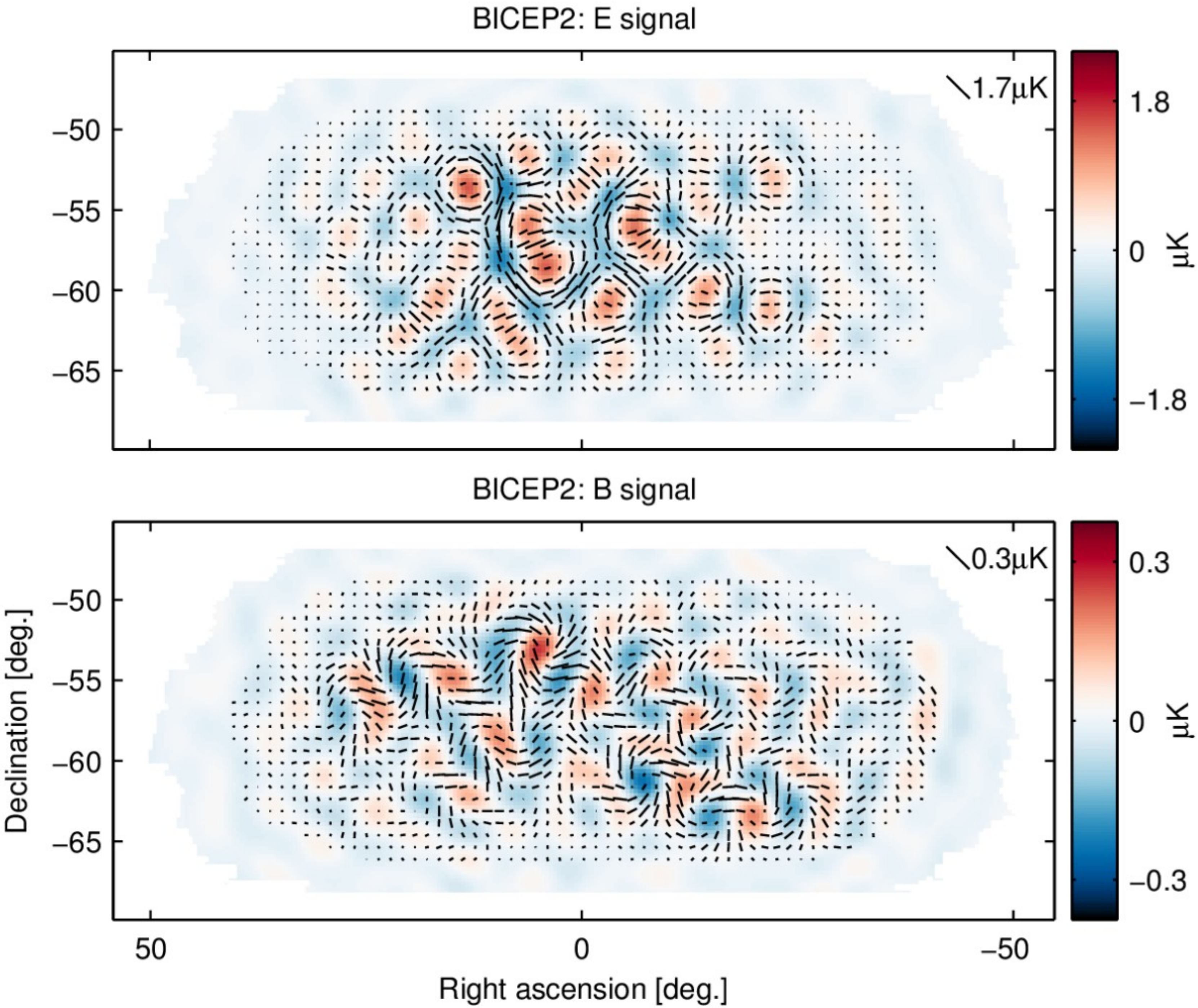
Target the “Southern Hole” - a region of the sky exceptionally free of dust and synchrotron foregrounds.

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

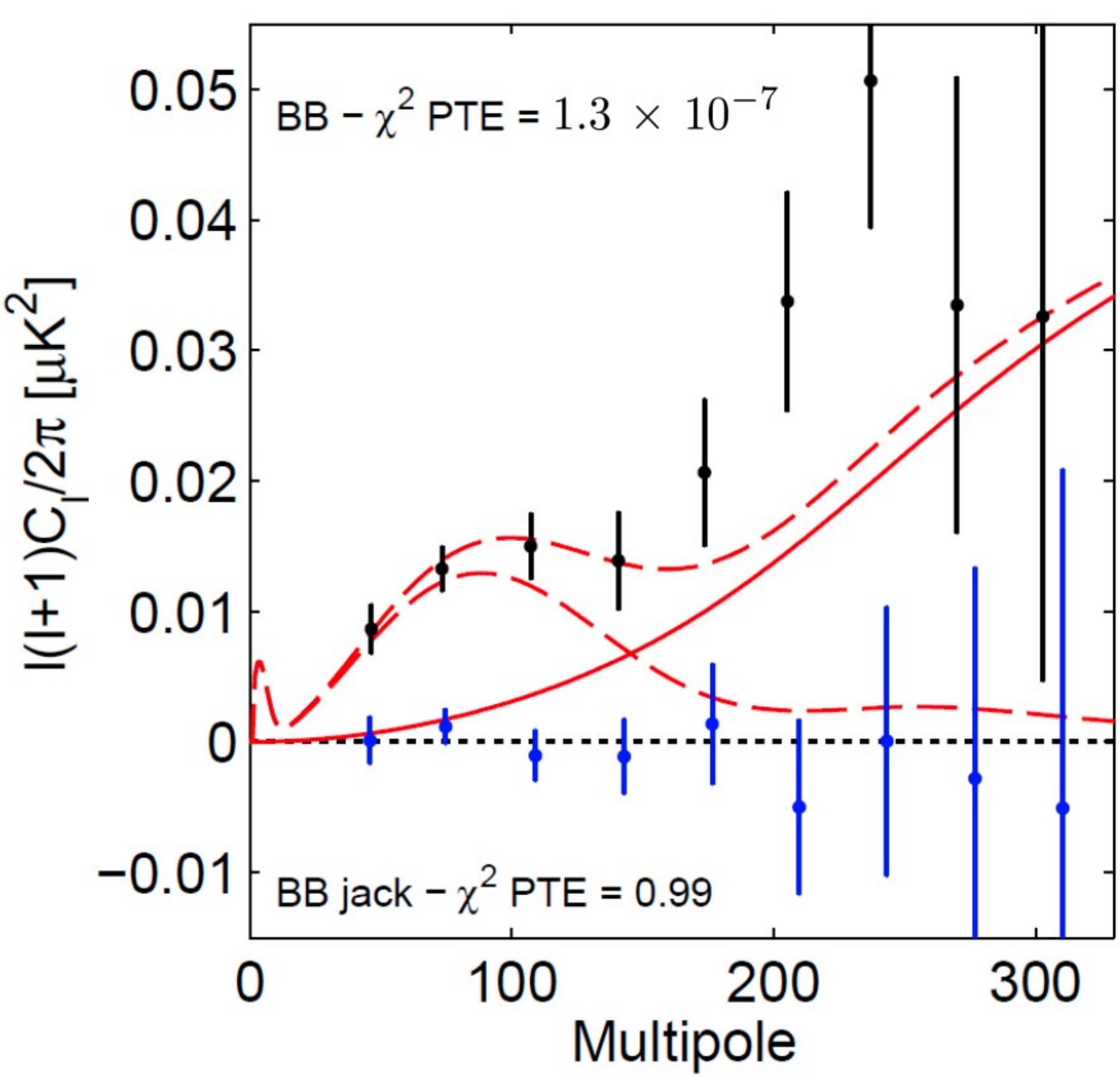
At 150 GHz the combined dust and synchrotron spectrum is predicted to be at a minimum in the Southern Hole.

Expected foreground contamination of the B-mode power: r ≤ ~0.01.

BICEP2 E- and B-mode Maps



BICEP2 B-mode Power Spectrum



B-mode power spectrum estimated directly from Q&U maps, including map based "purification" to avoid E→B mixing

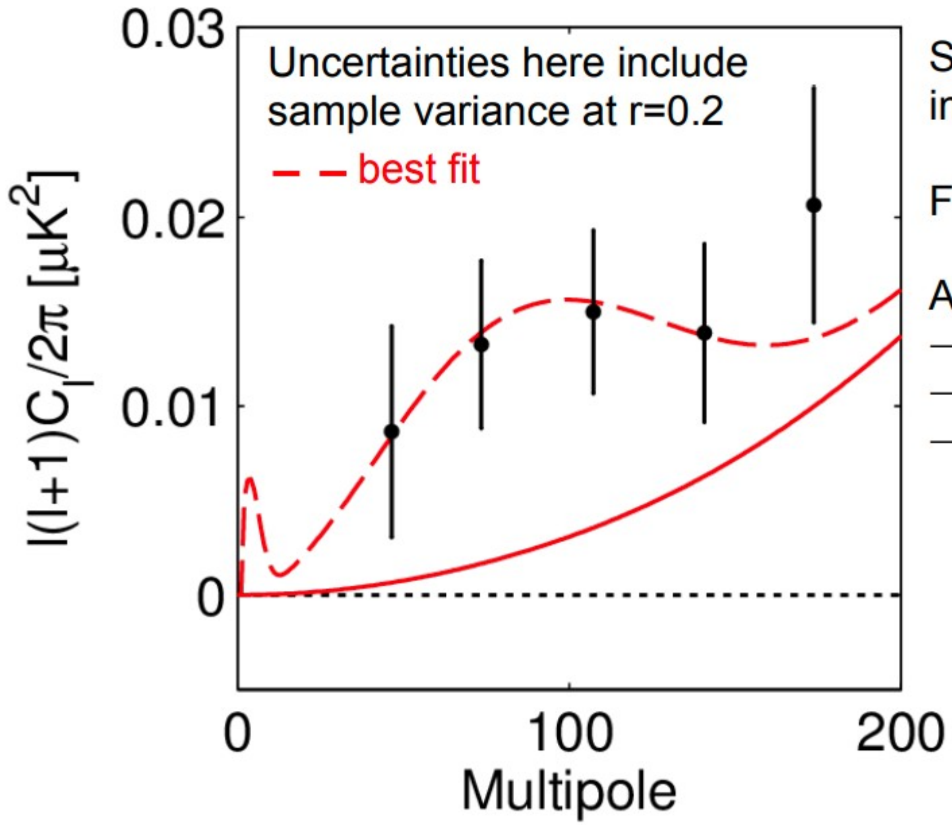
Consistent with lensing expectation at higher l…yes, two are a bit high…

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

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

χ^2PTE	1.3×10^{-7}
significance	$5.3\,\sigma$

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

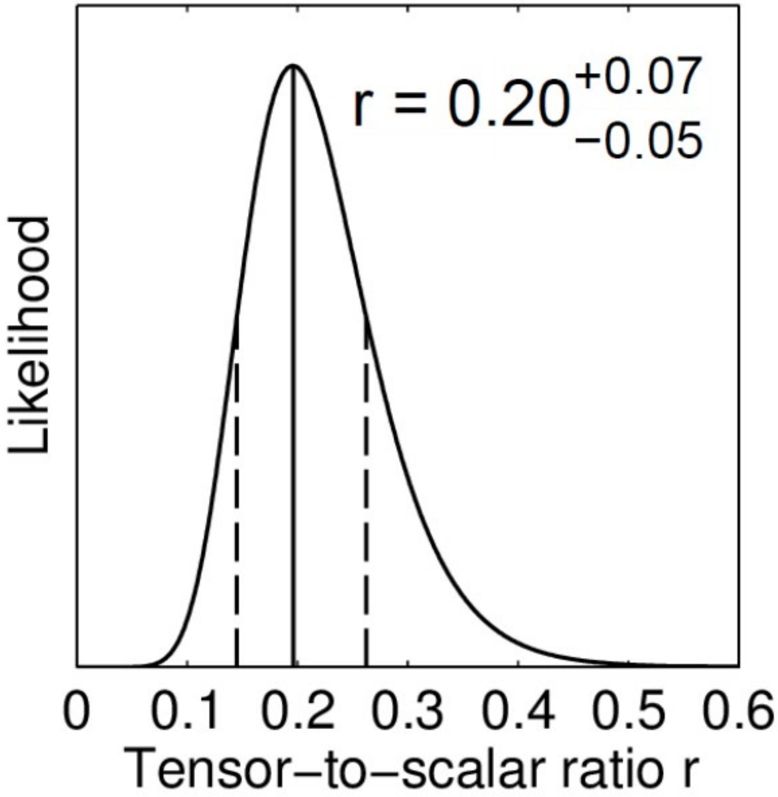
Apply “direct likelihood” method, uses:
→ lensed-ΛCDM + noise simulations
→ weighted version of the 5 bandpowers
→ B-mode sims scaled to various levels of r (n_T=0)

Within this simplistic model we find:

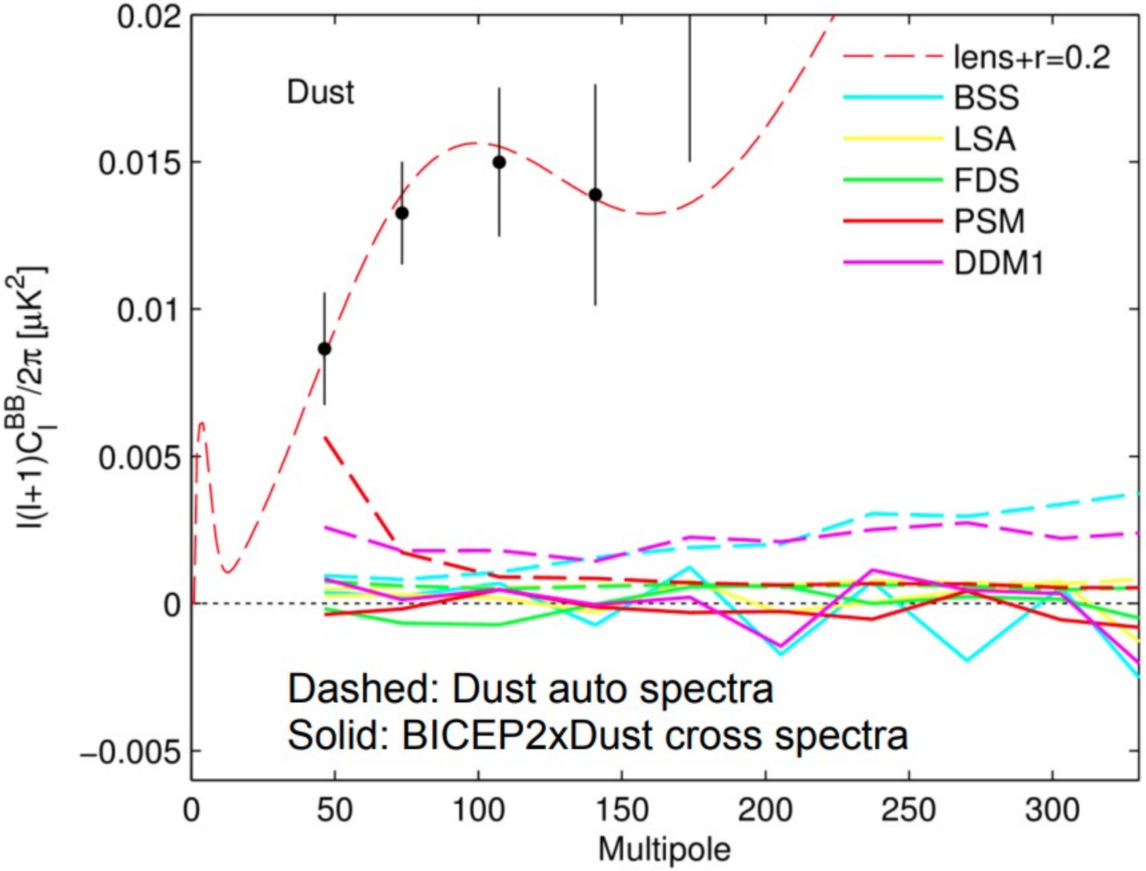
r = 0.2 with uncertainties dominated by sample variance

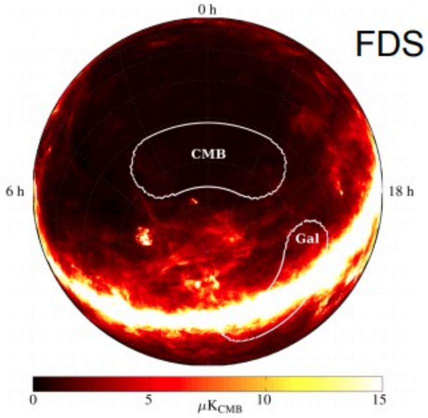
PTE of fit to data: 0.9
→ model is perfectly acceptable fit to the data

r = 0 ruled out at 7.0σ



Polarized Dust Foreground Projections





FDS Model

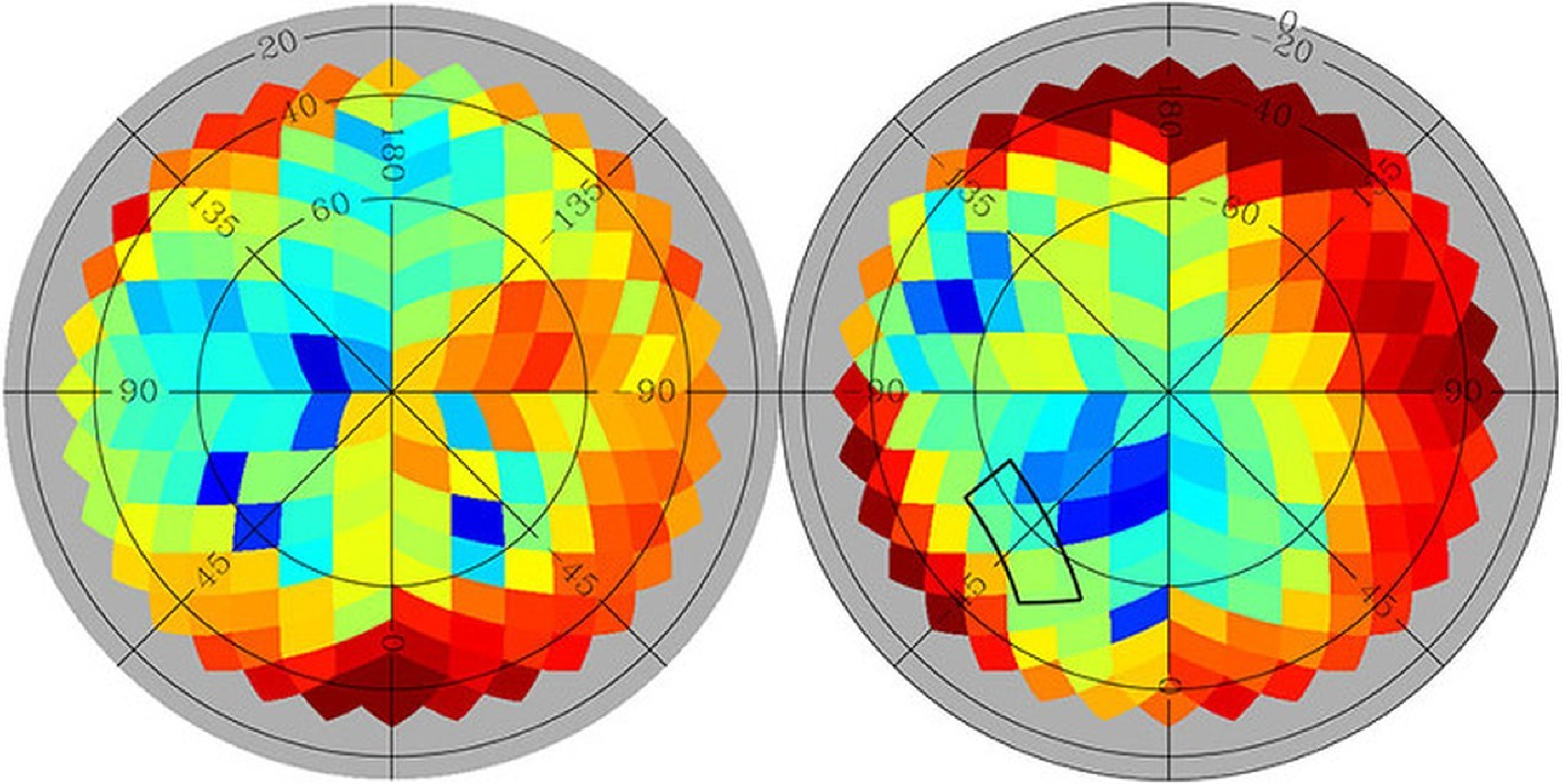
The BICEP2 region is chosen to have lowest foreground emission based on available pre-Planck models.

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.

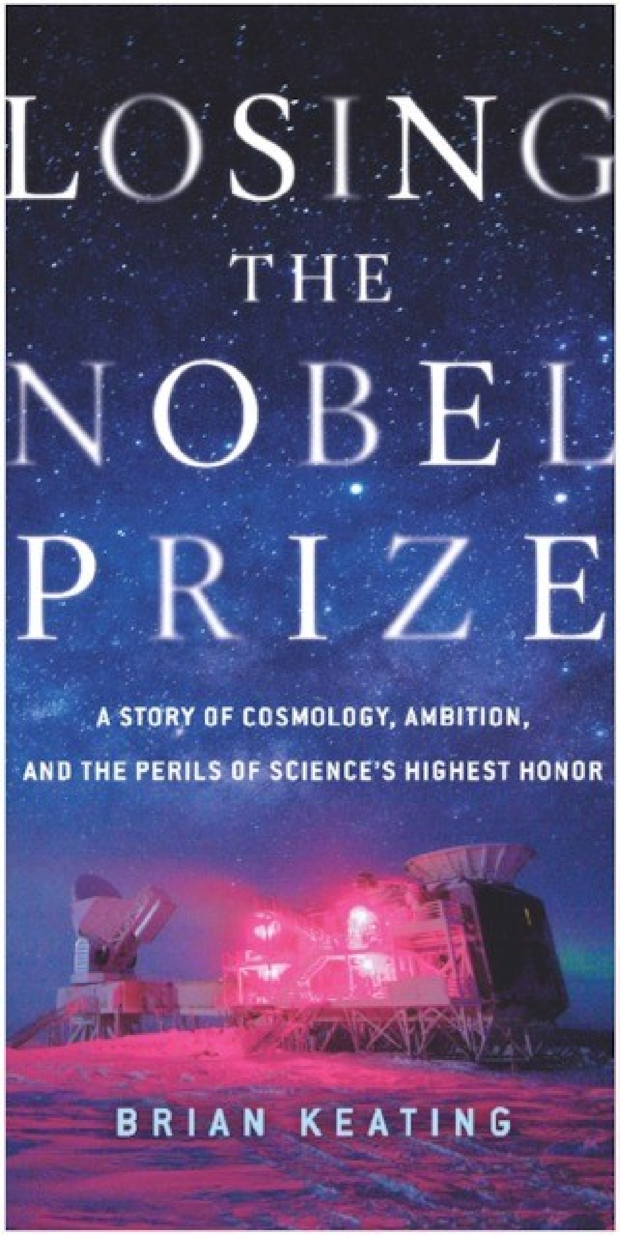
Polarized Dust Foreground Measurements



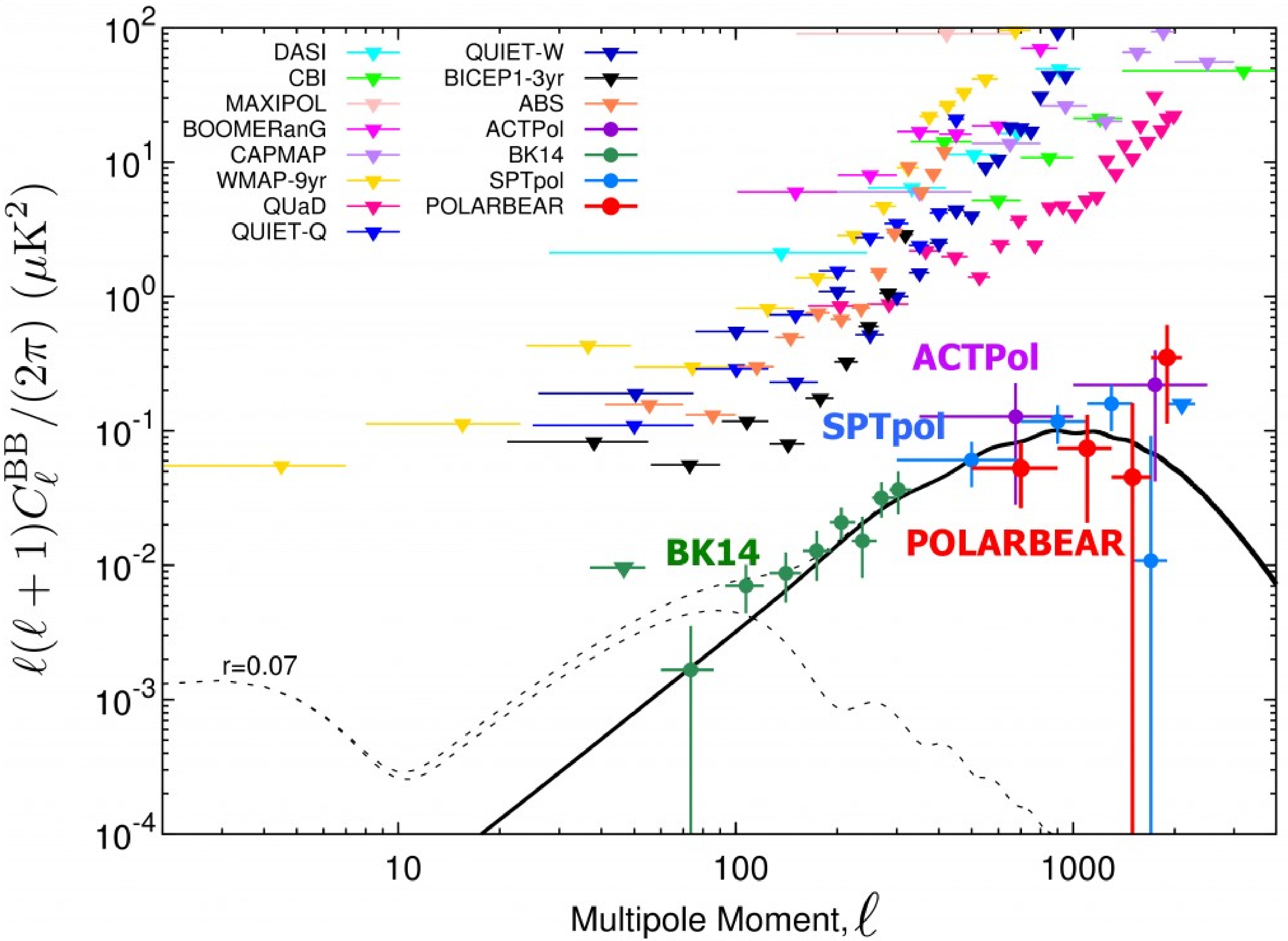
Map of the dust B-mode polarization, as estimated from the Planck data, in units of the signal expected from primordial gravitational waves. The green color corresponds to a Galactic signal comparable to the signal detected by the BICEP2 experiment over the sky patch marked with a black contour. Blue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


LOSING
THE
NOBEL
PRIZE
A STORY OF COSMOLOGY, AMBITION,
AND THE PERILS OF SCIENCE'S HIGHEST HONOR
BRIAN KEATING

B-modes Power Spectrum



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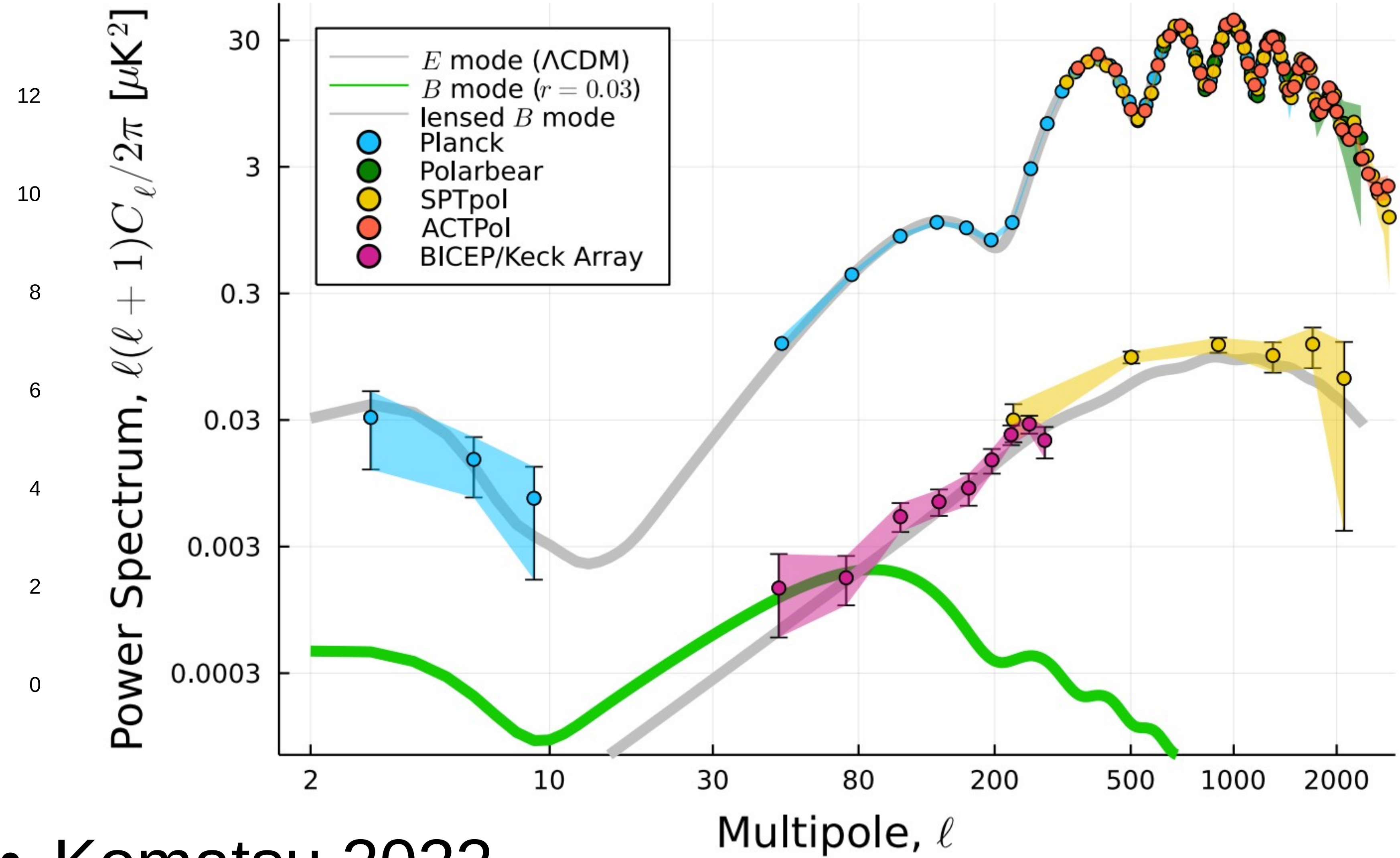
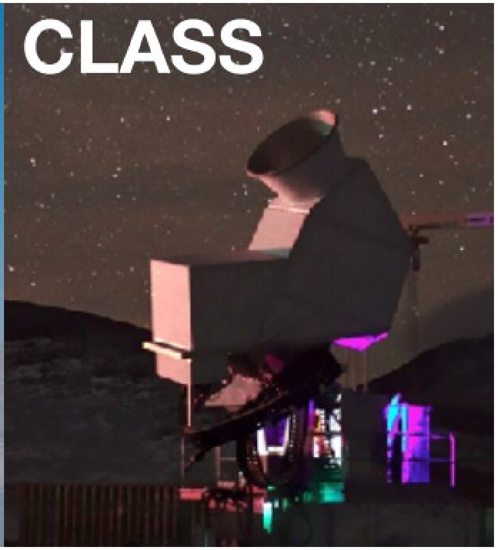


- Komatsu 2022

What comes next?

The Simons Array

BICEP/Keck Array



CLASS

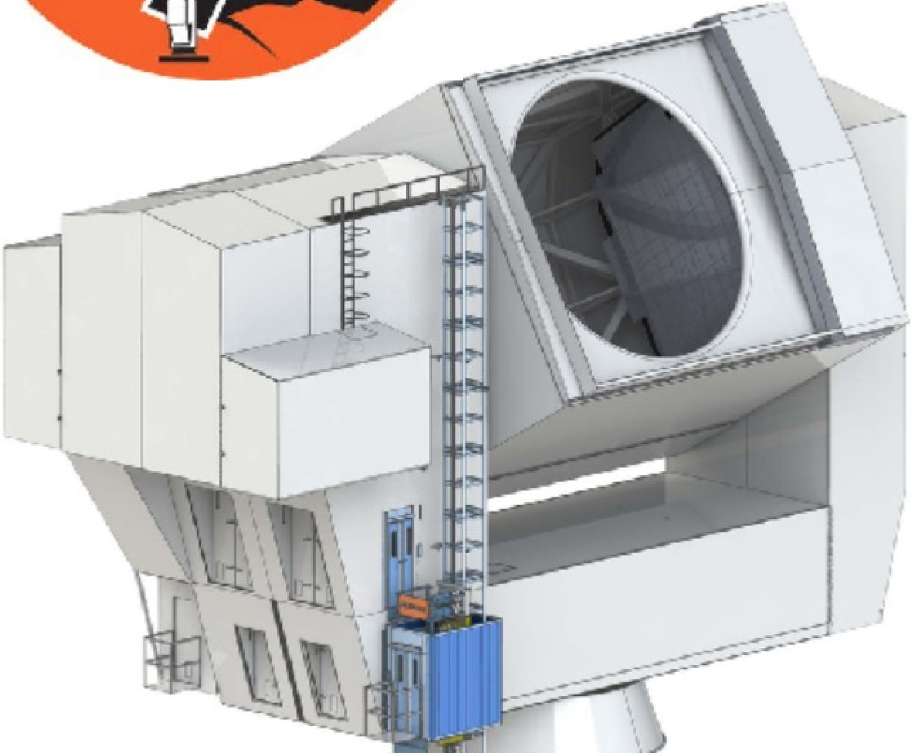
Advanced Atacama Cosmology Telescope

+

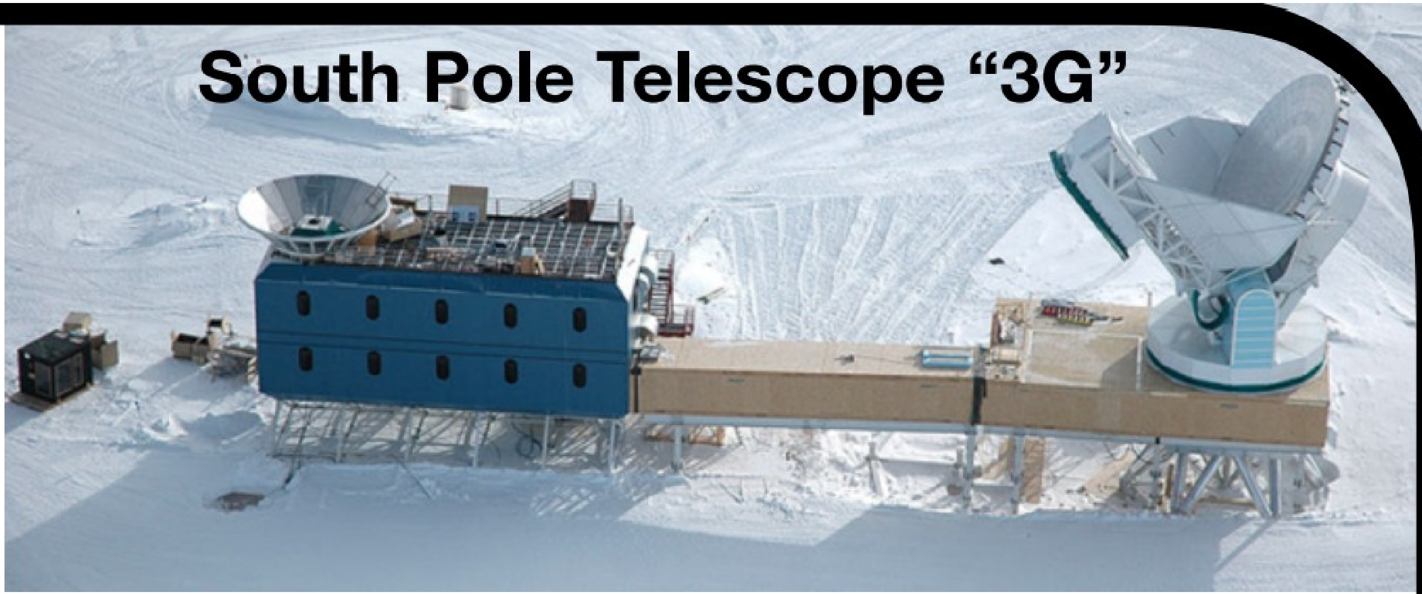
The Simons Array

=

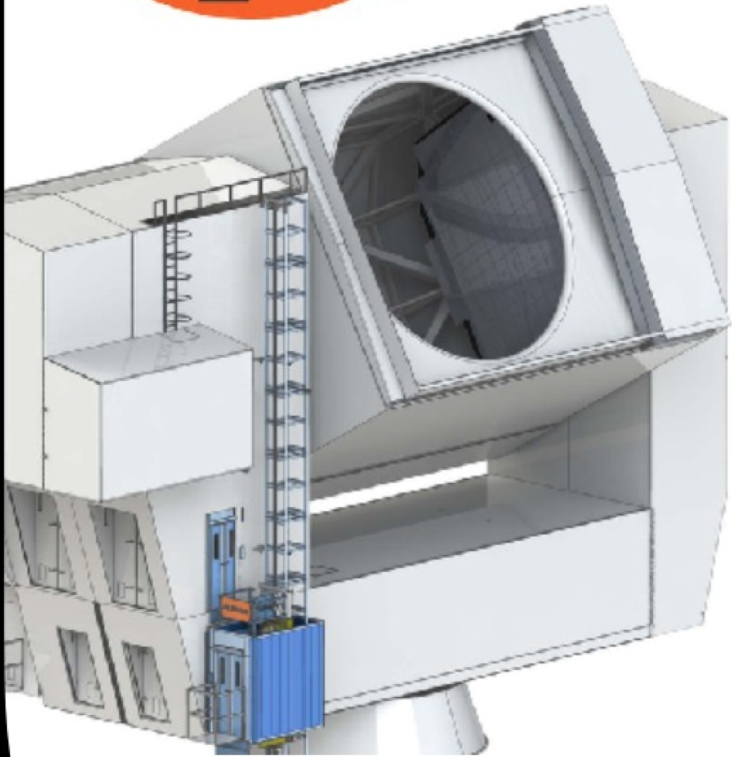
SIMONS OBSERVATORY

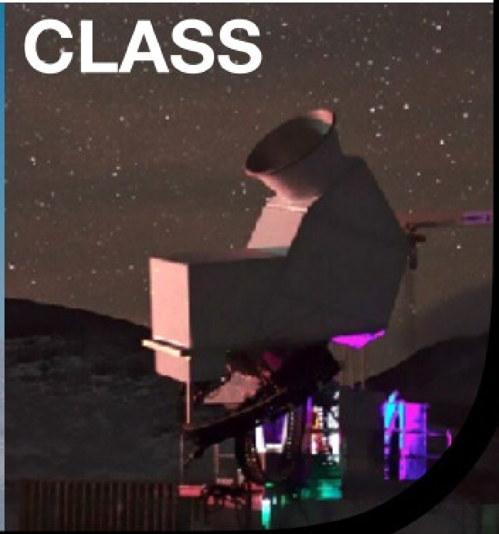


SIMONS
OBSERVATORY



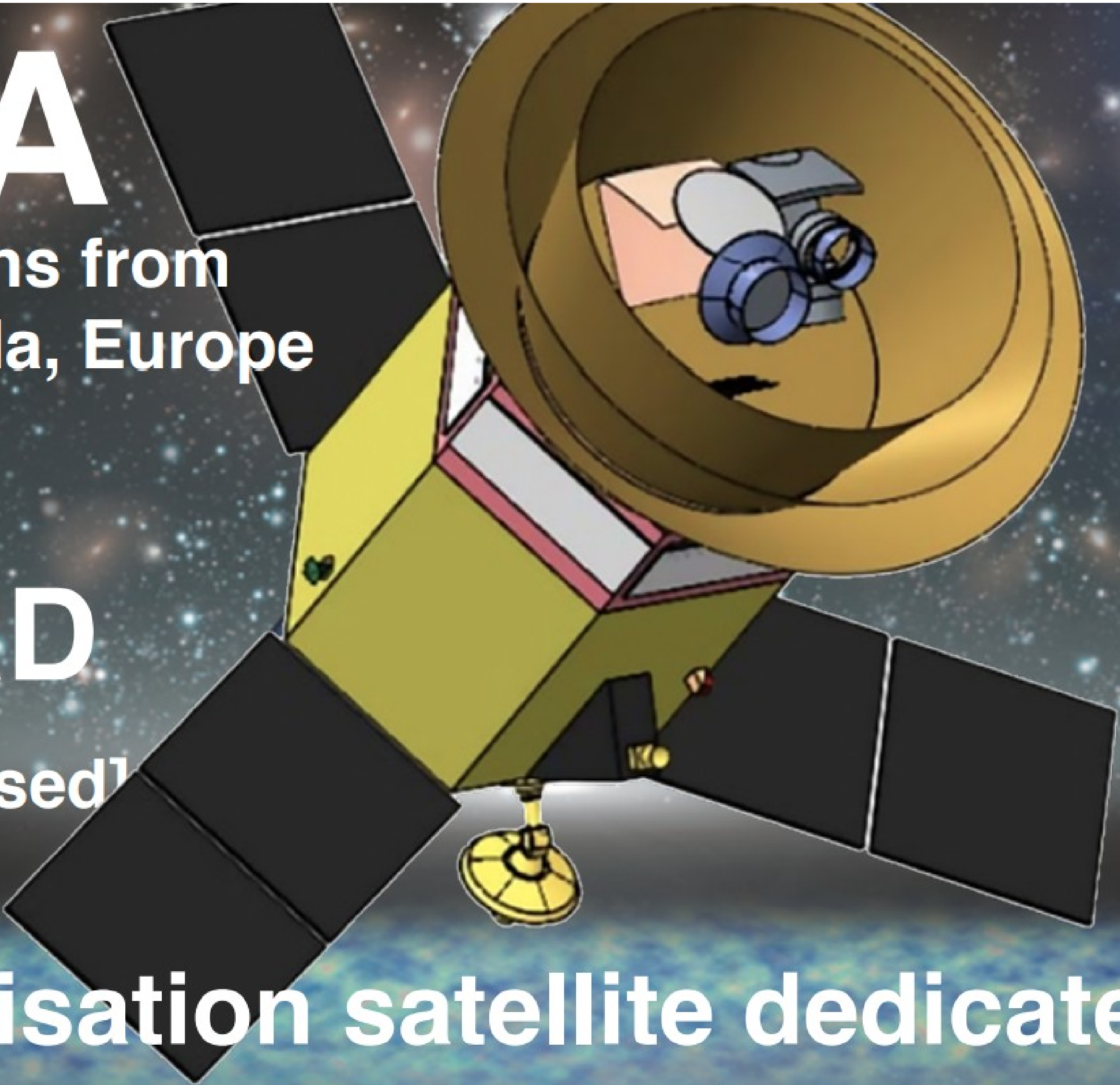
CMB-S4(?)





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

+ participations from
USA, Canada, Europe

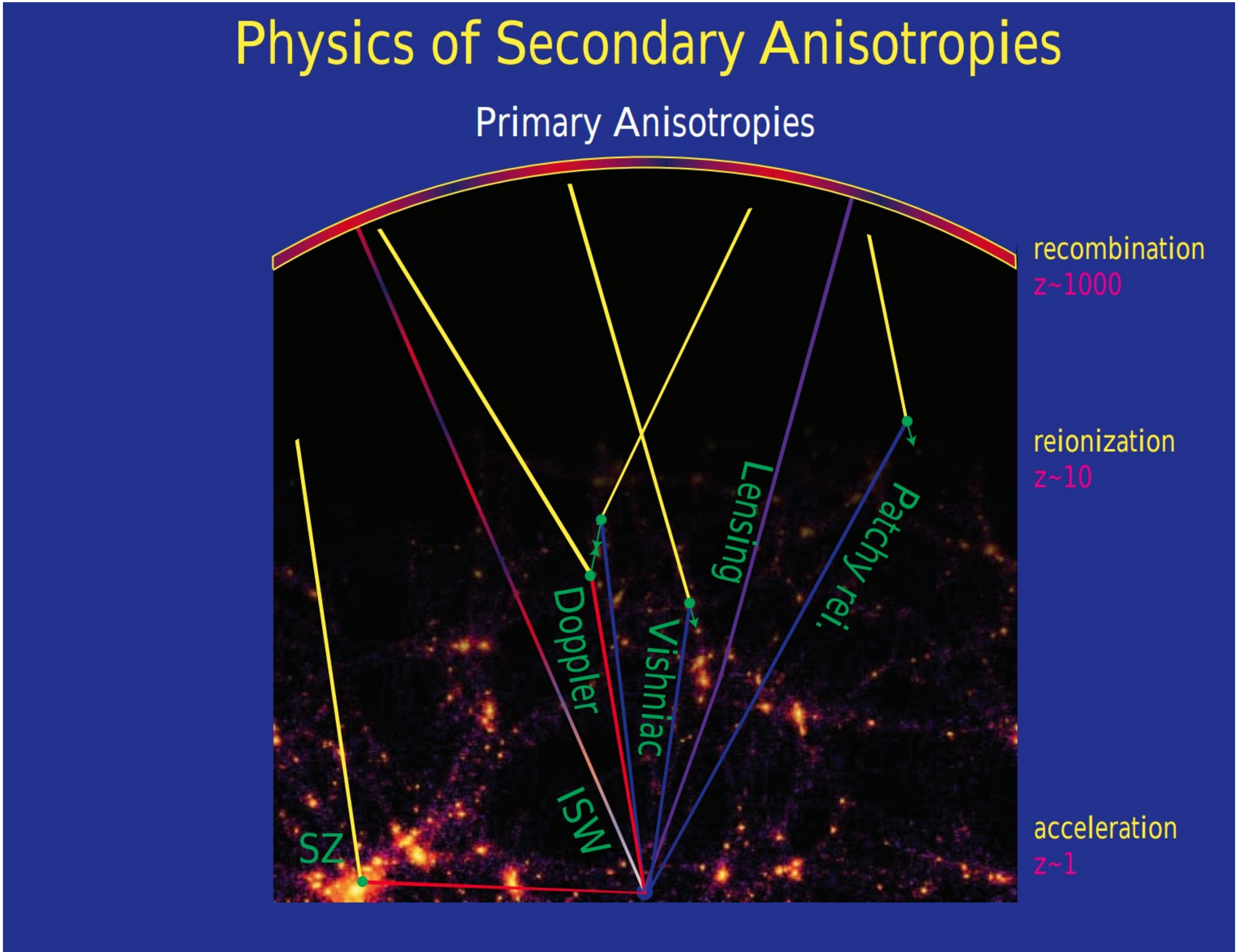
LiteBIRD

2027– **Selected!**

<u>May 21</u>: **JAXA has chosen LiteBIRD as the strategic large-class mission.**

We will go to L2!

CMB Secondary Anisotropies



Epoch of Reionization

Epoch of reionization

Big Bang

Universe expanding and cooling

Present day

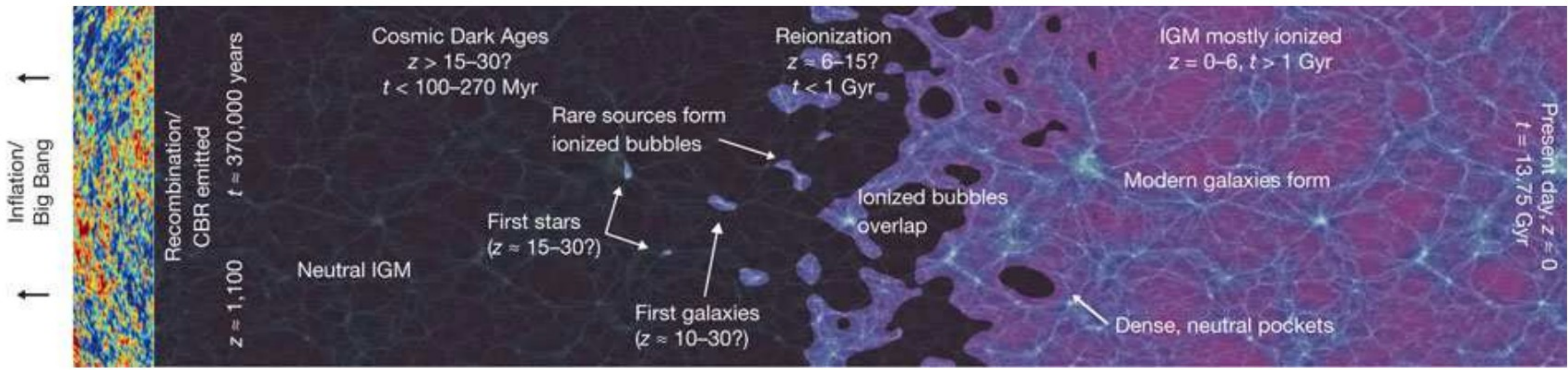


Figure courtesy: `http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html`

Epoch of reionization

Big Bang

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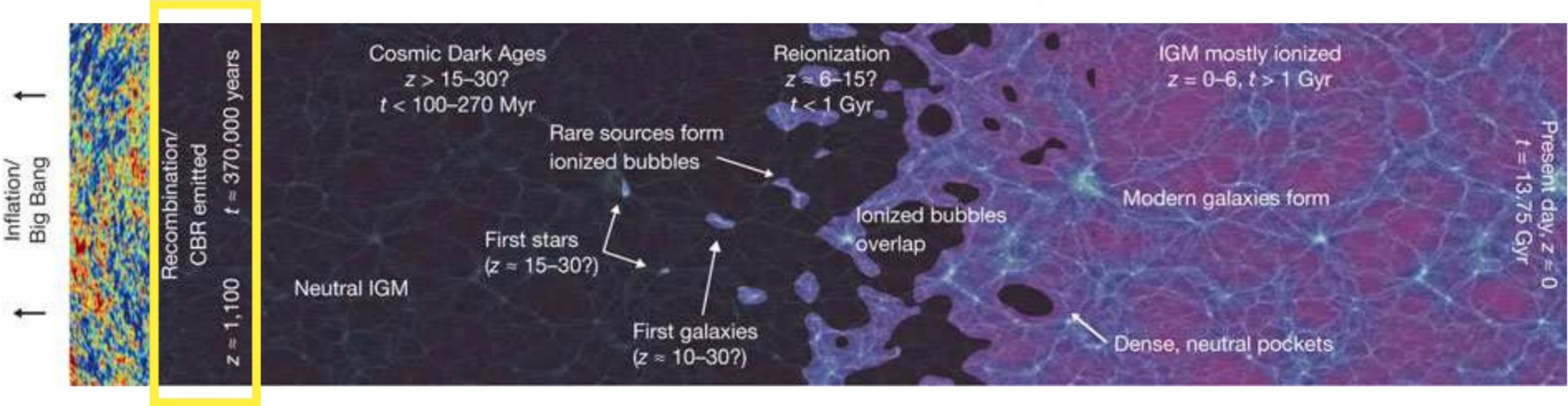

Last scattering epoch
First hydrogen atoms form

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

Epoch of reionization

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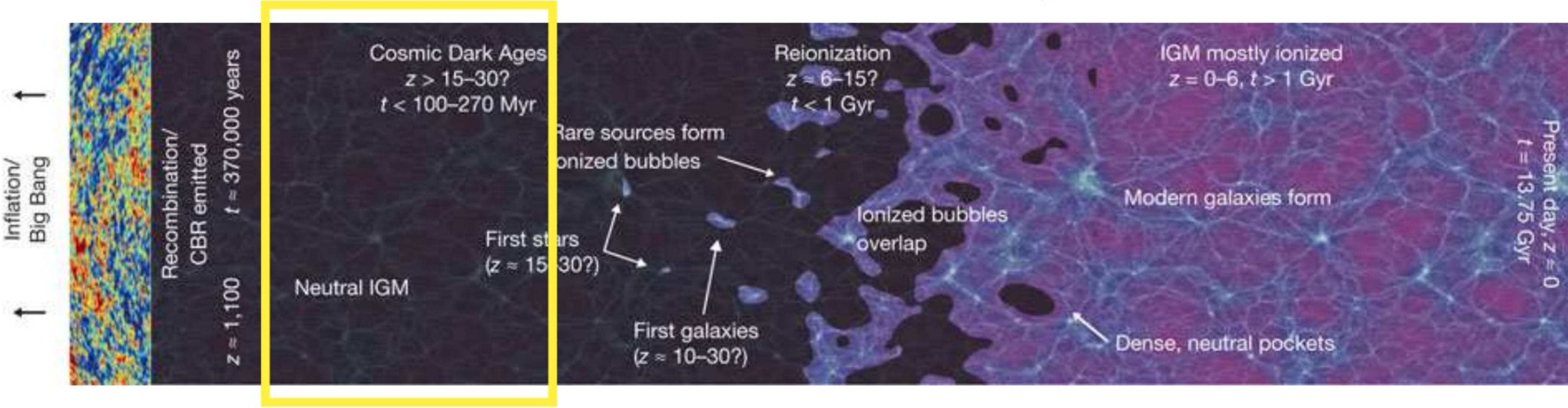

Dark ages

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

Epoch of reionization

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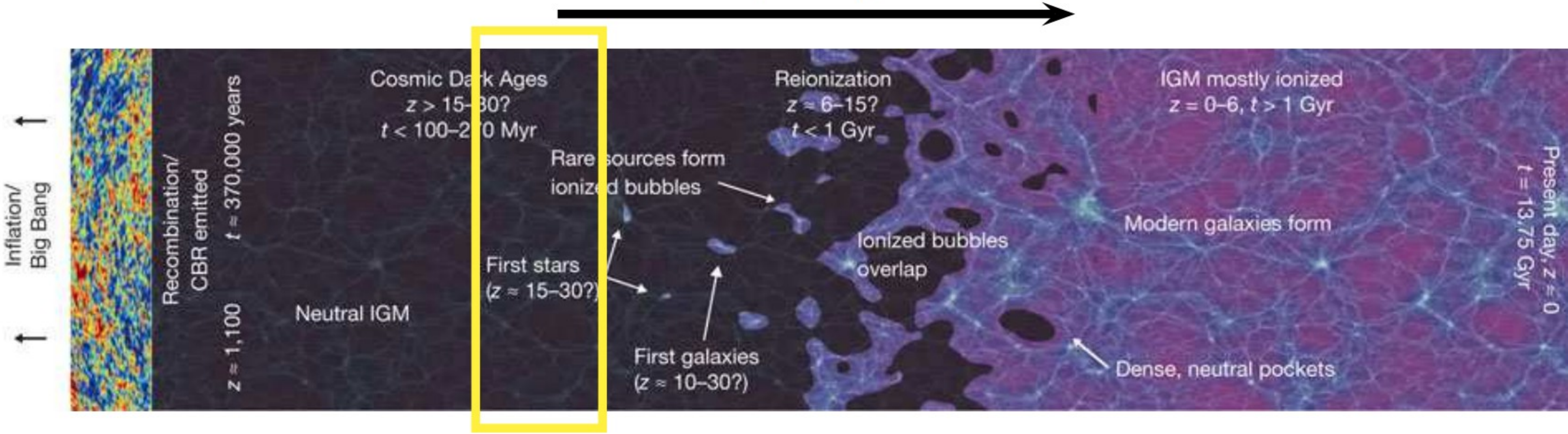


First stars form

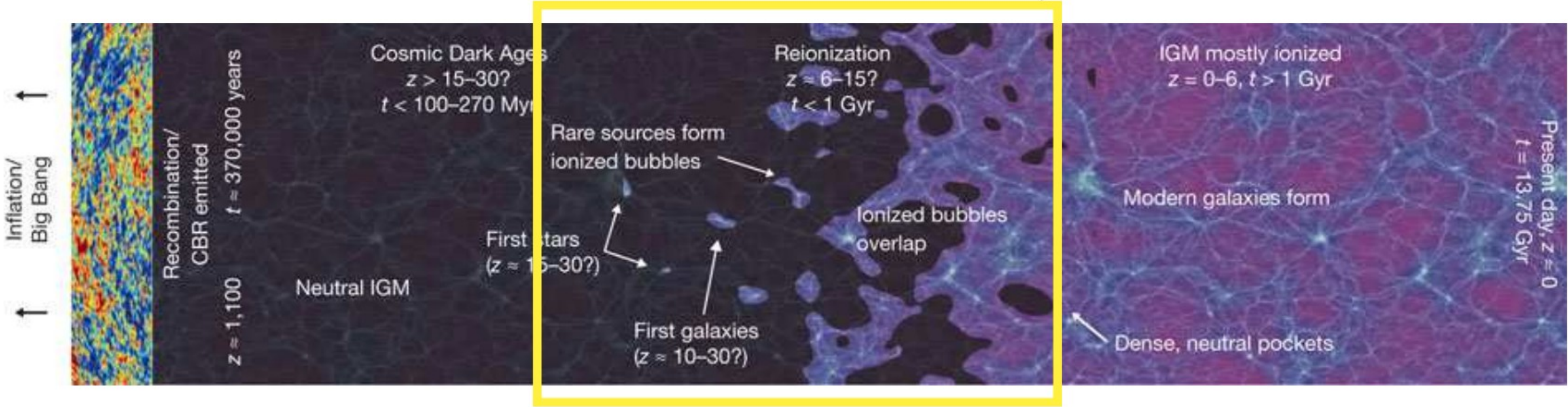
Figure courtesy: `http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html`

Epoch of reionization

Big Bang

Universe expanding and cooling

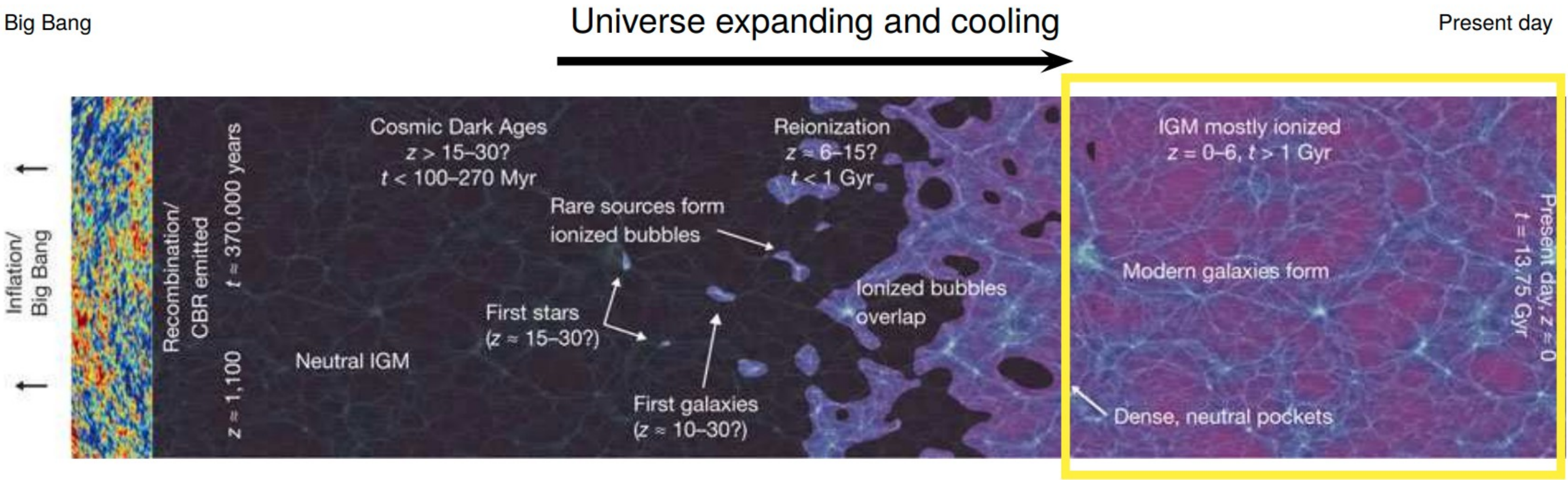
Present day



Reionization

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

Epoch of reionization



Post-reionization

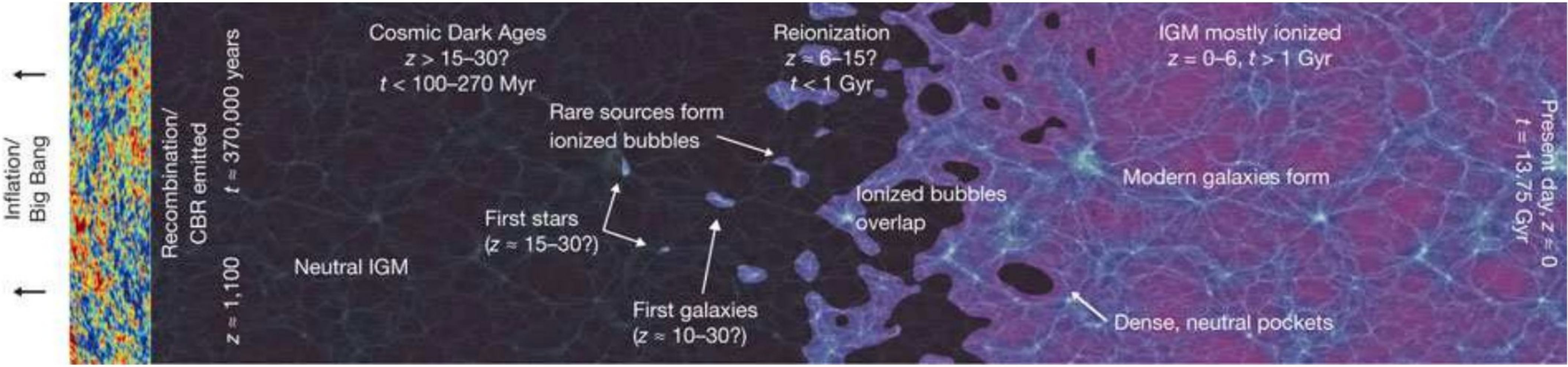
Figure courtesy: `http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html`

Epoch of reionization

Big Bang

Universe expanding and cooling

Present day



Dark ages

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

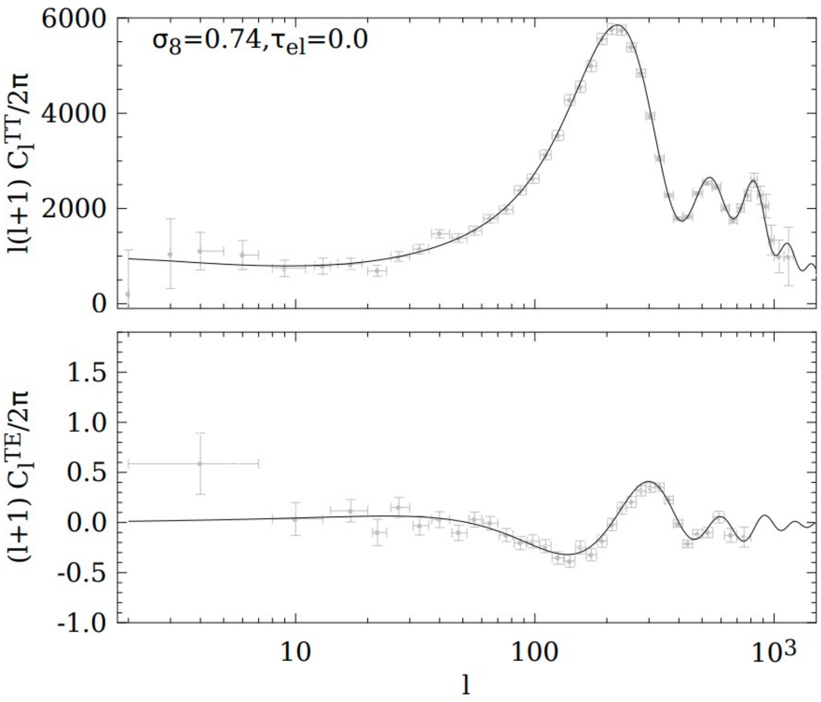
- Lyman alpha Forest

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:

$$\tau_{\rm el} = \sigma_T c \int_{t_{\rm LSS}}^{t_0} {\rm d}t \; n_e \; (1+z)^3$$

Provided by reionization



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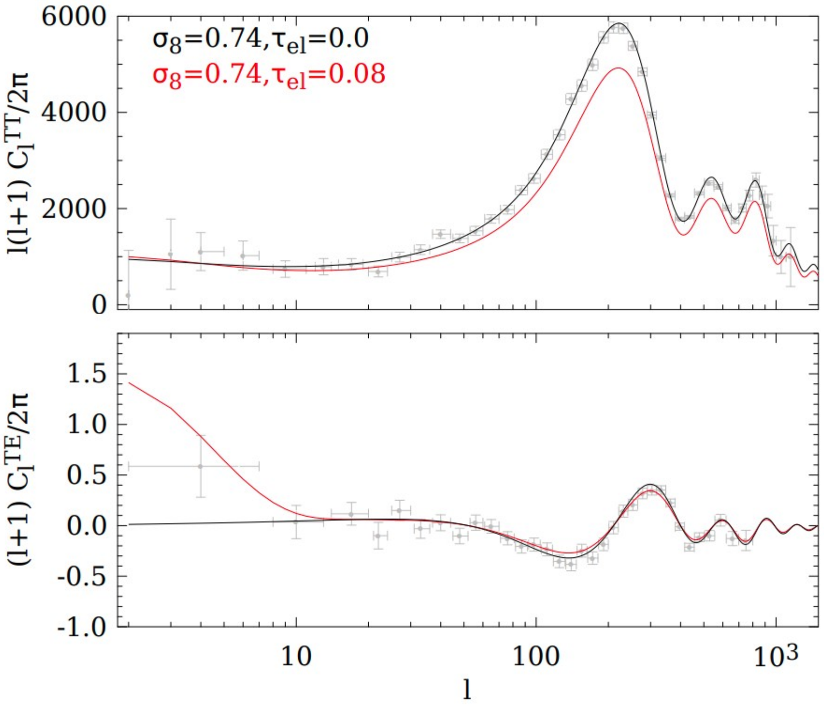

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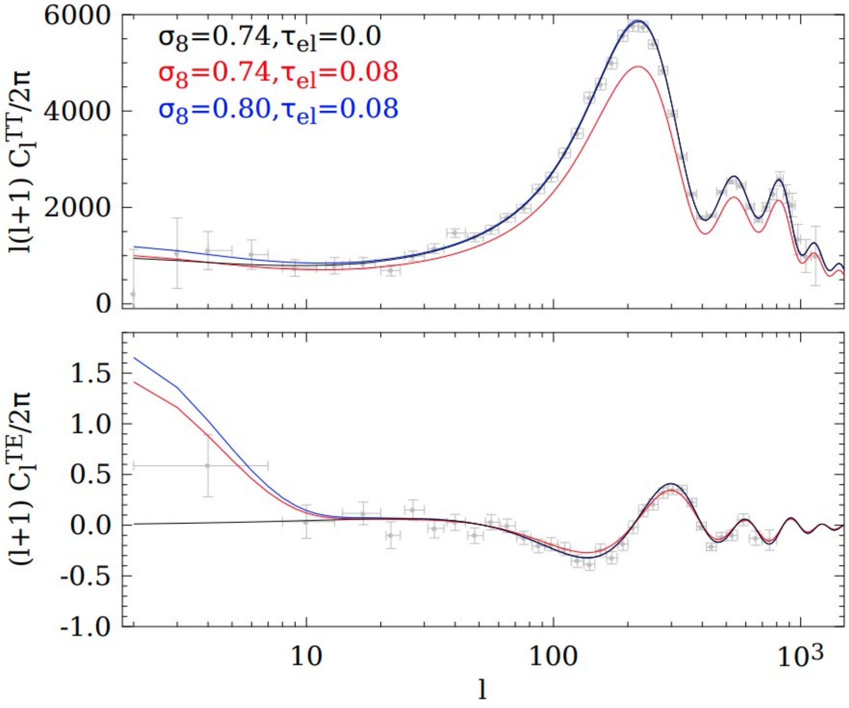


CMB angular Power Spectrum

- 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 related to a reionization redshift z_{re}. Assume $n_e = n_H$ for $z < z_{re}$ and $n_e = 0$ for $z > z_{re}$, then

$$\tau_{\rm el} = \sigma_T \, c \, n_H \int_0^{z_{\rm re}} {\rm d}z \left| \frac{{\rm d}t}{{\rm d}z} \right| (1+z)^3$$

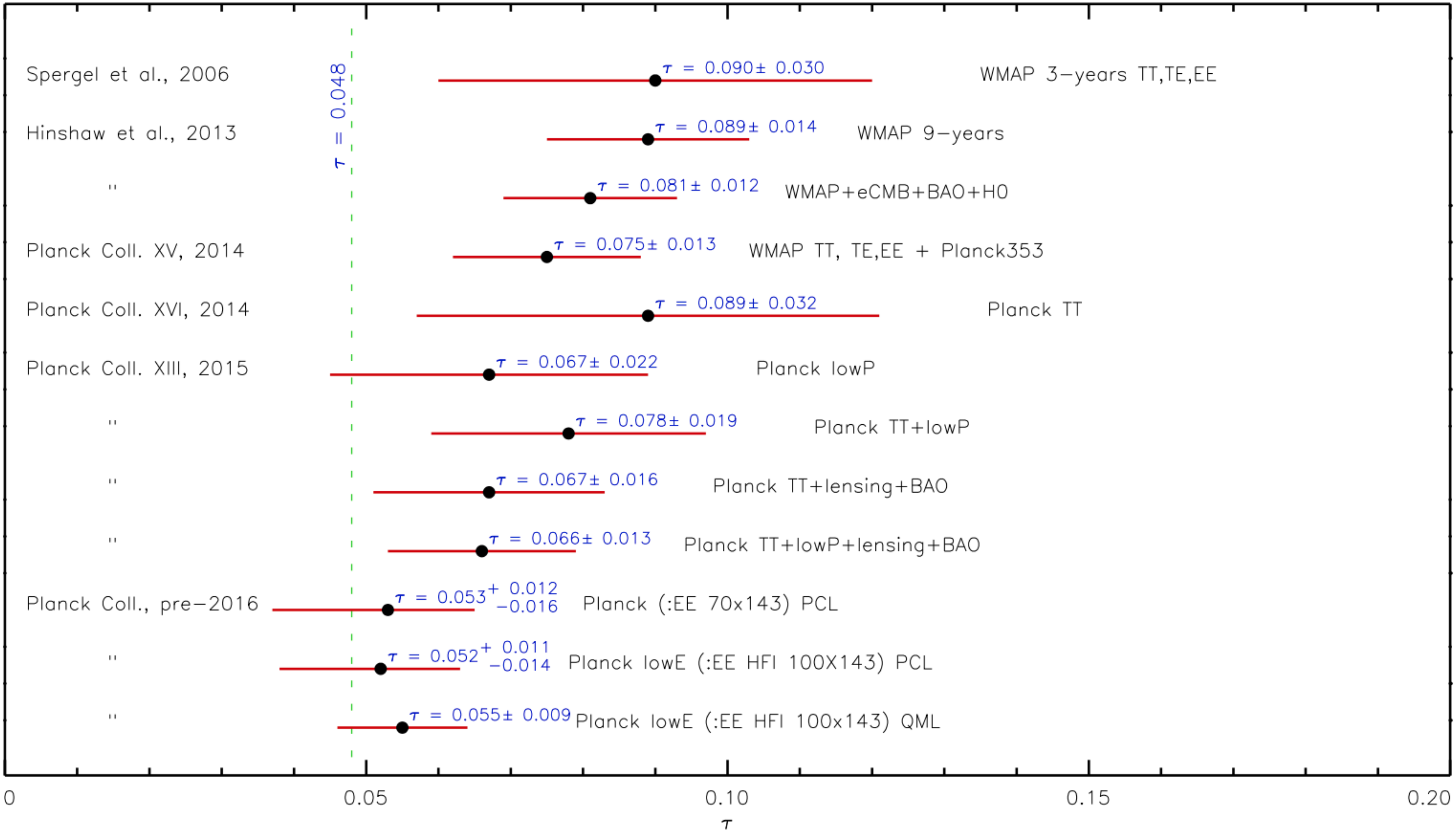
  (Usually a slightly generalised tanh form is incorporated in CMB data analysis)

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

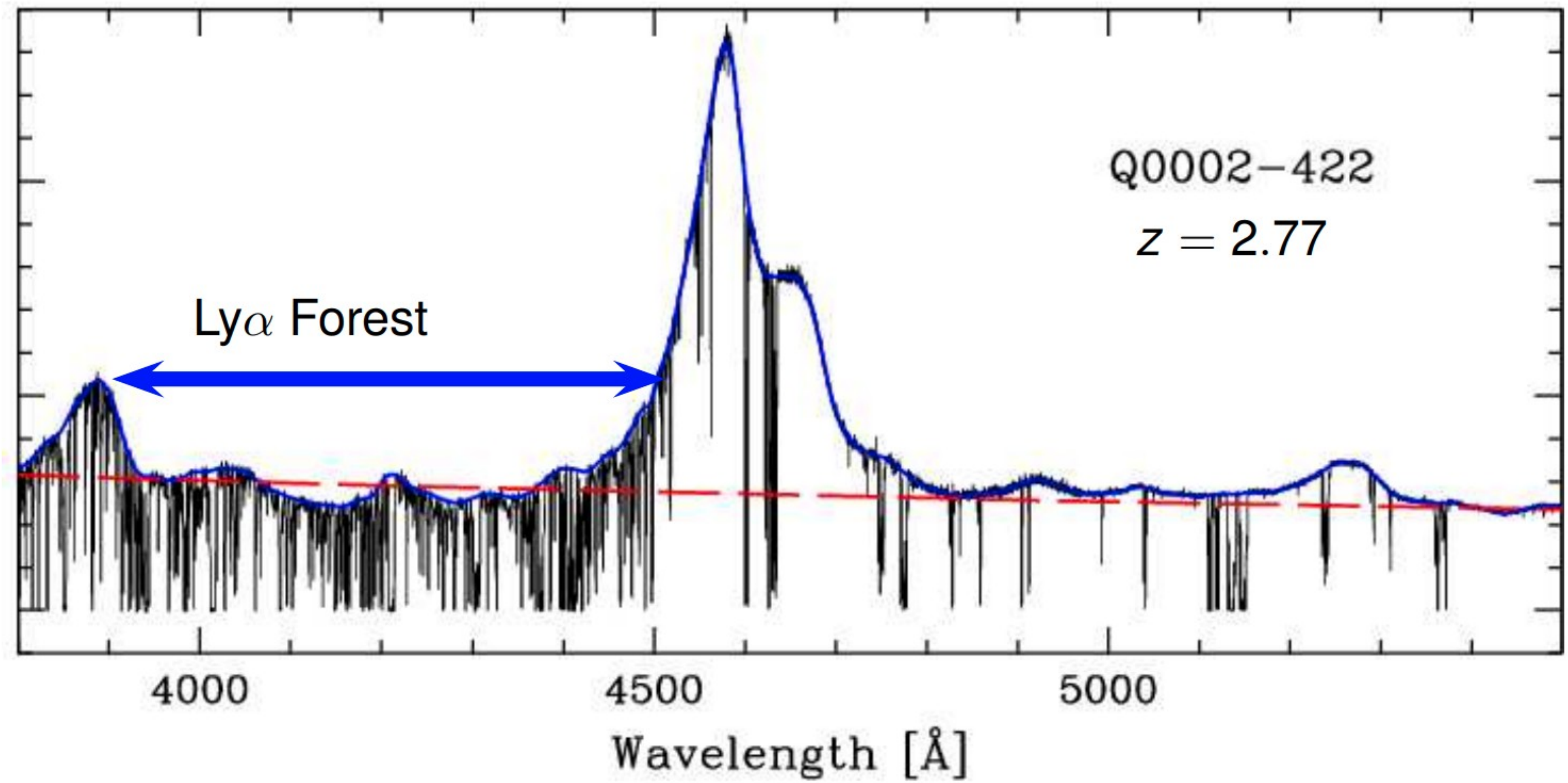
Thomson scattering $\tau_{\rm el}$ from CMB

$$\tau_{\rm el} = \sigma_T c \int_0^{z[t]} \mathrm{d}t \; n_e \; (1+z)^3$$

Planck Collaboration (2016)



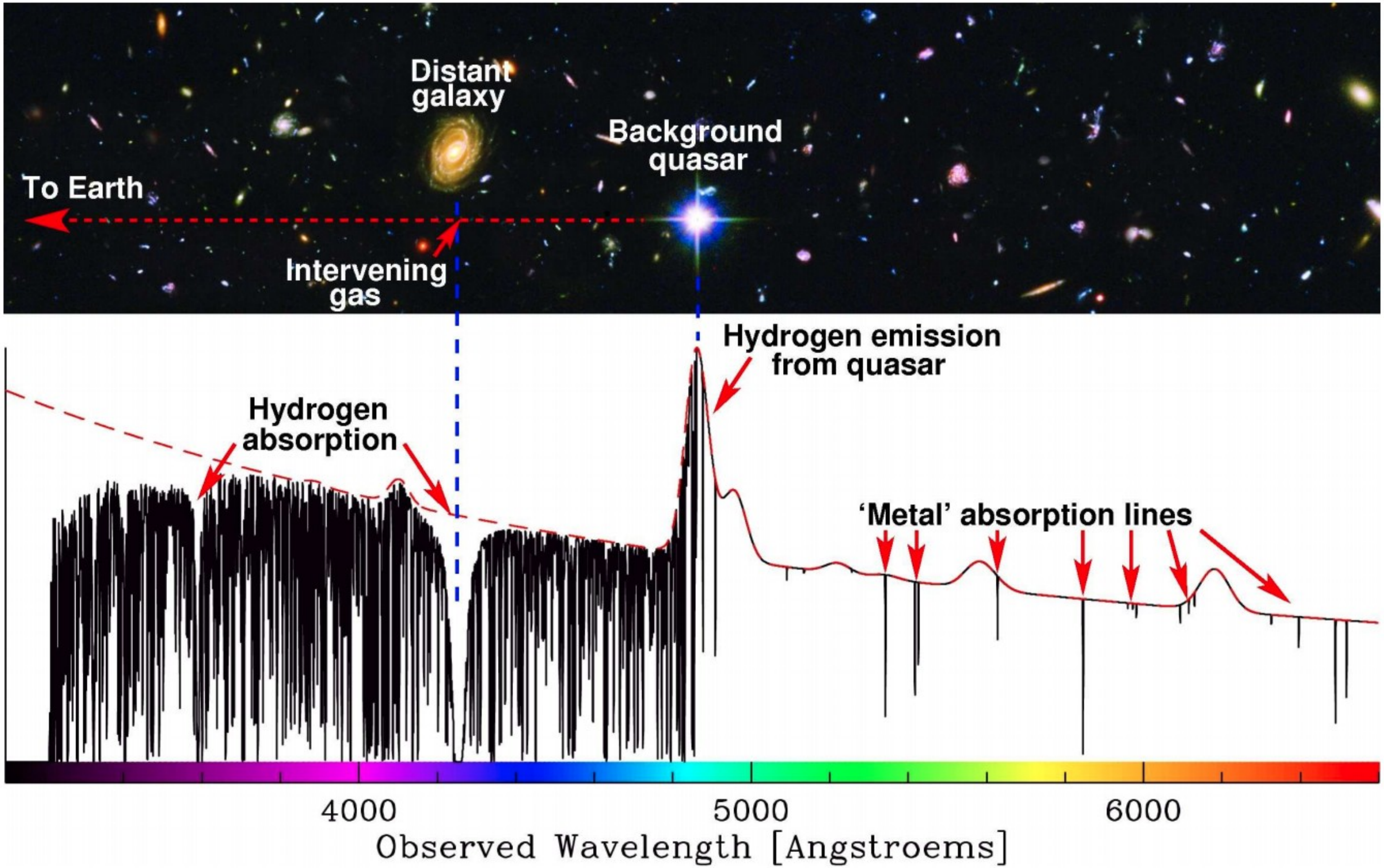
Evidence for reionization: Lyman-α forest



The absorption lines blueward of the emission line arise from Lyα 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).



http://www.eso.org/~jliske/qsoal/

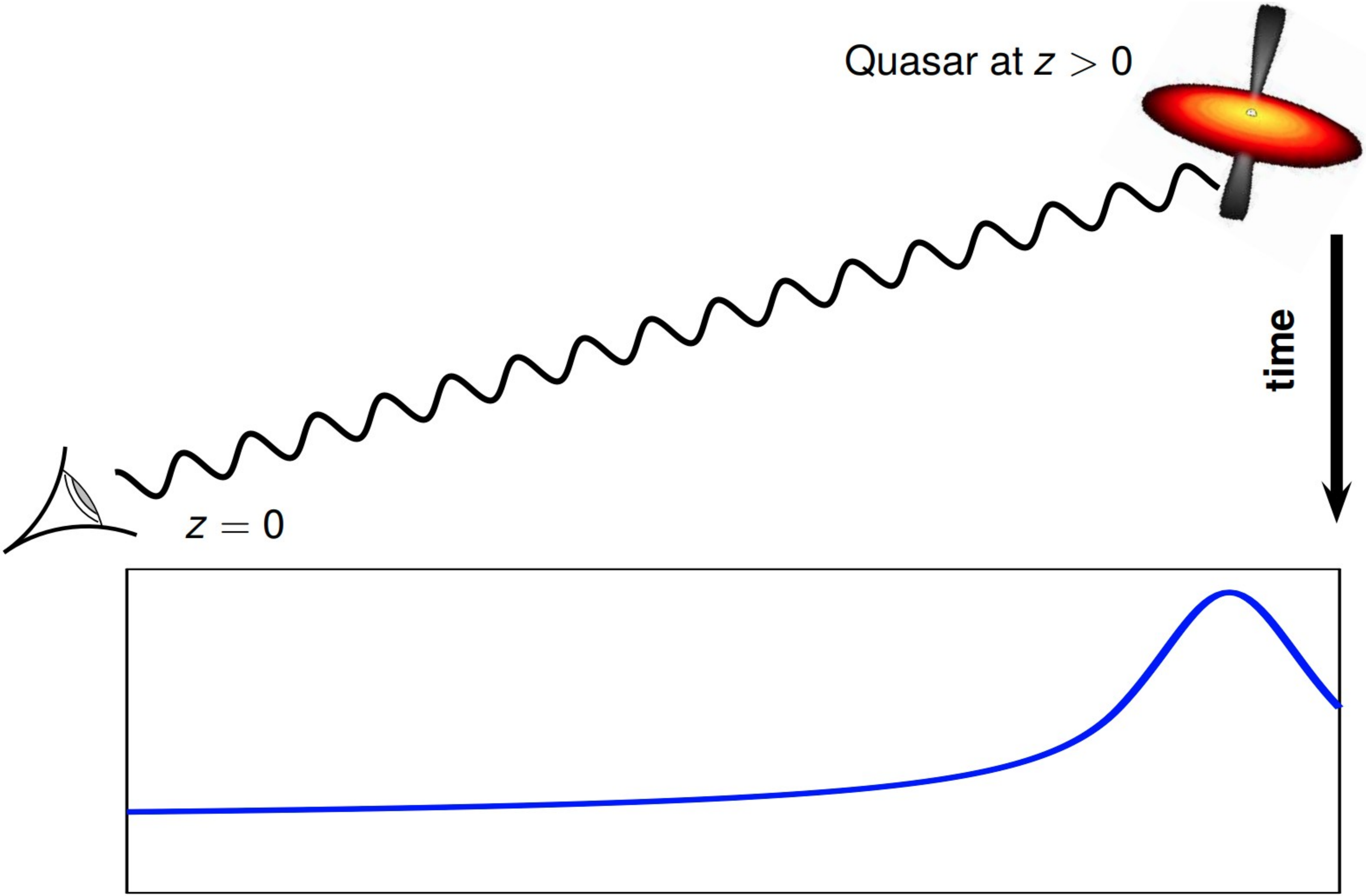
Absorption lines

- 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

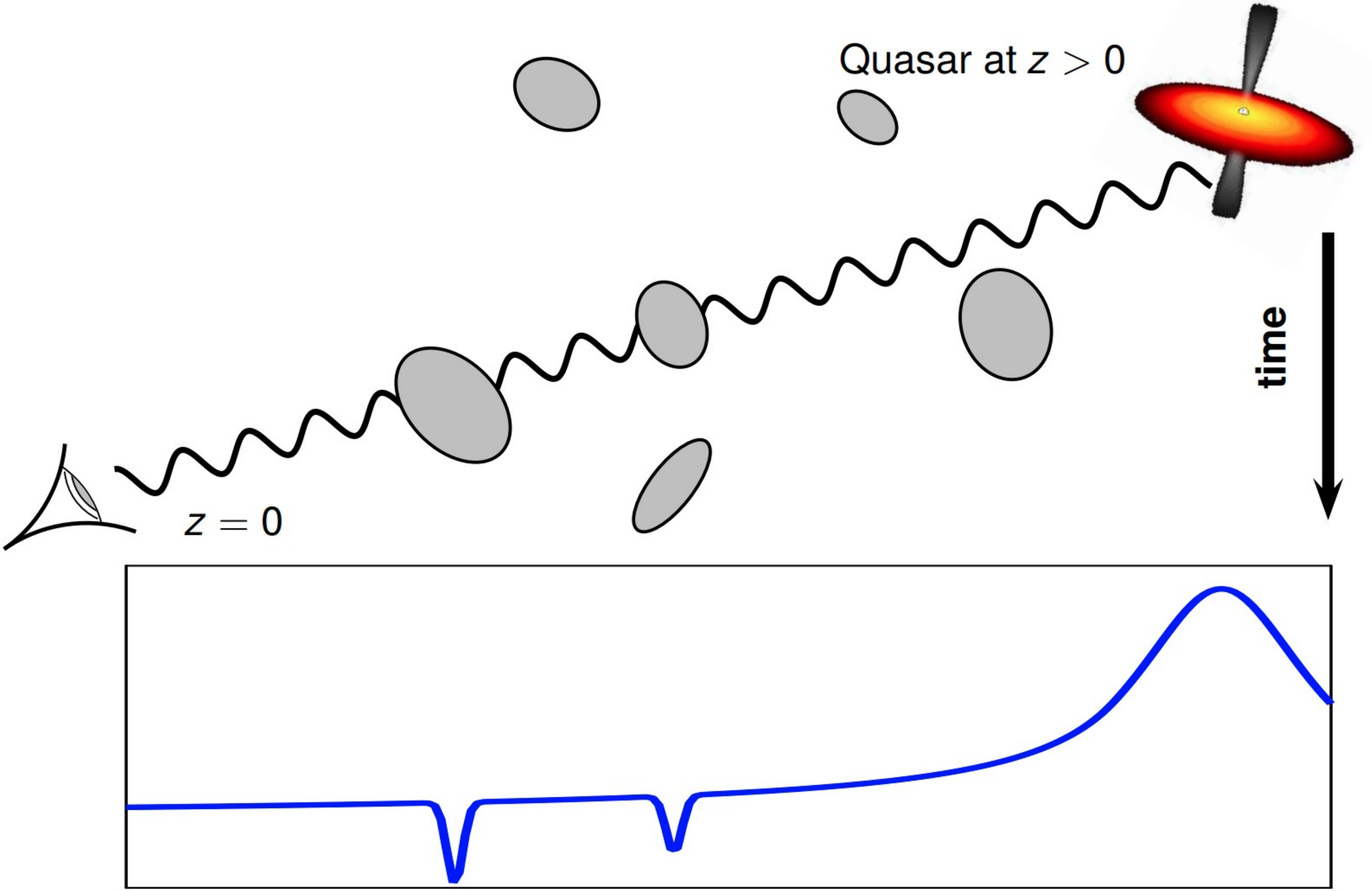
$$\frac{\nu_Q}{1+z_Q} = \frac{\nu_{fi}}{1+z} \Longrightarrow \lambda_Q(1+z_Q) = \lambda_{fi}(1+z)$$

- Example: Consider a QSO at $z_Q = 3$. Consider a photon emitted at wavelength $\lambda_Q = 1187$ Å, then it would reach the Lyα wavelength 1216 Å 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 $\lambda = \lambda_Q(1+z_Q) \approx 4742$ Å. Thus any absorption arising at a redshift z will show up at $\lambda = \lambda_{fi}(1+z)$.

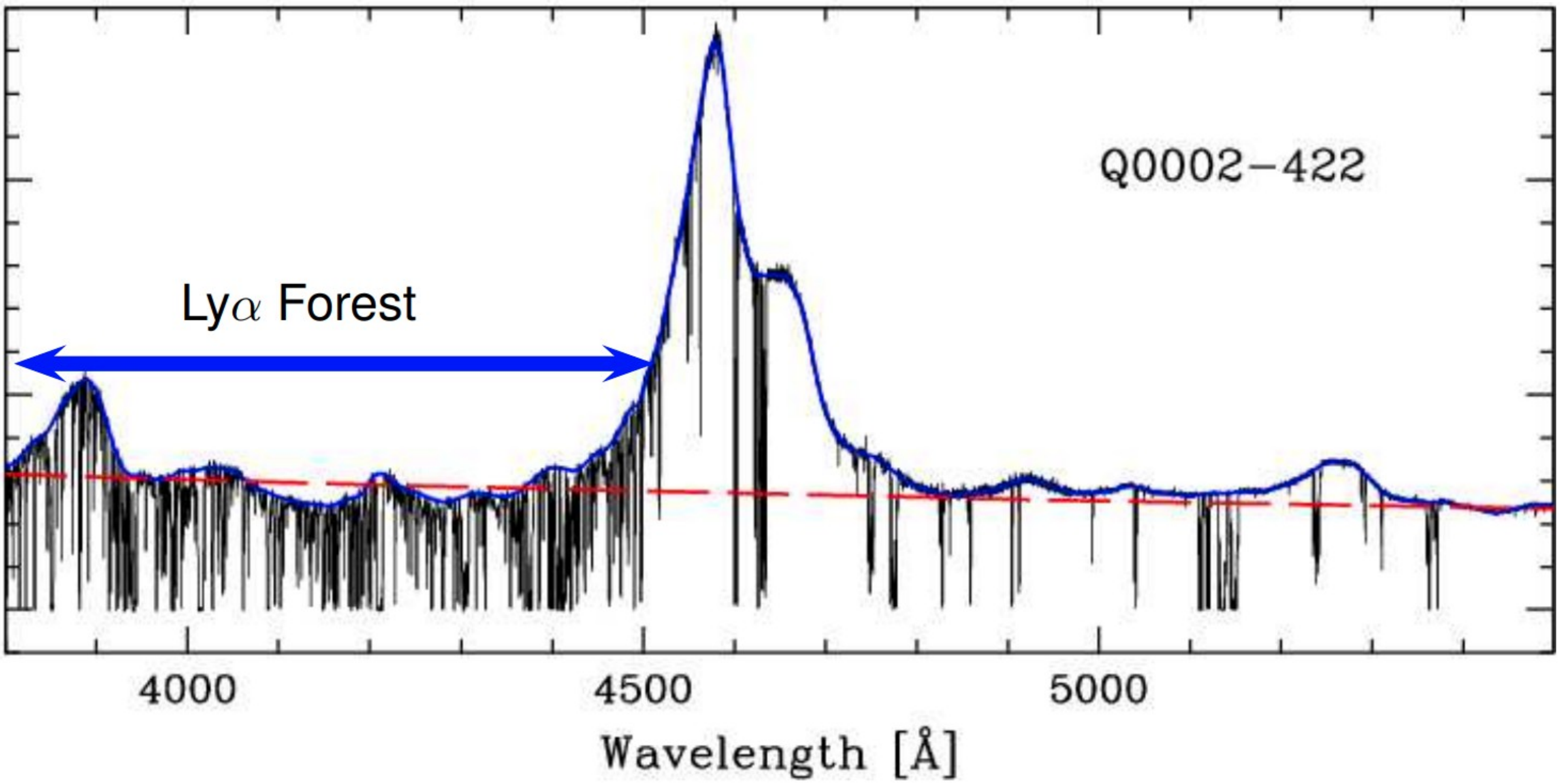
Absorption signatures



Absorption signatures

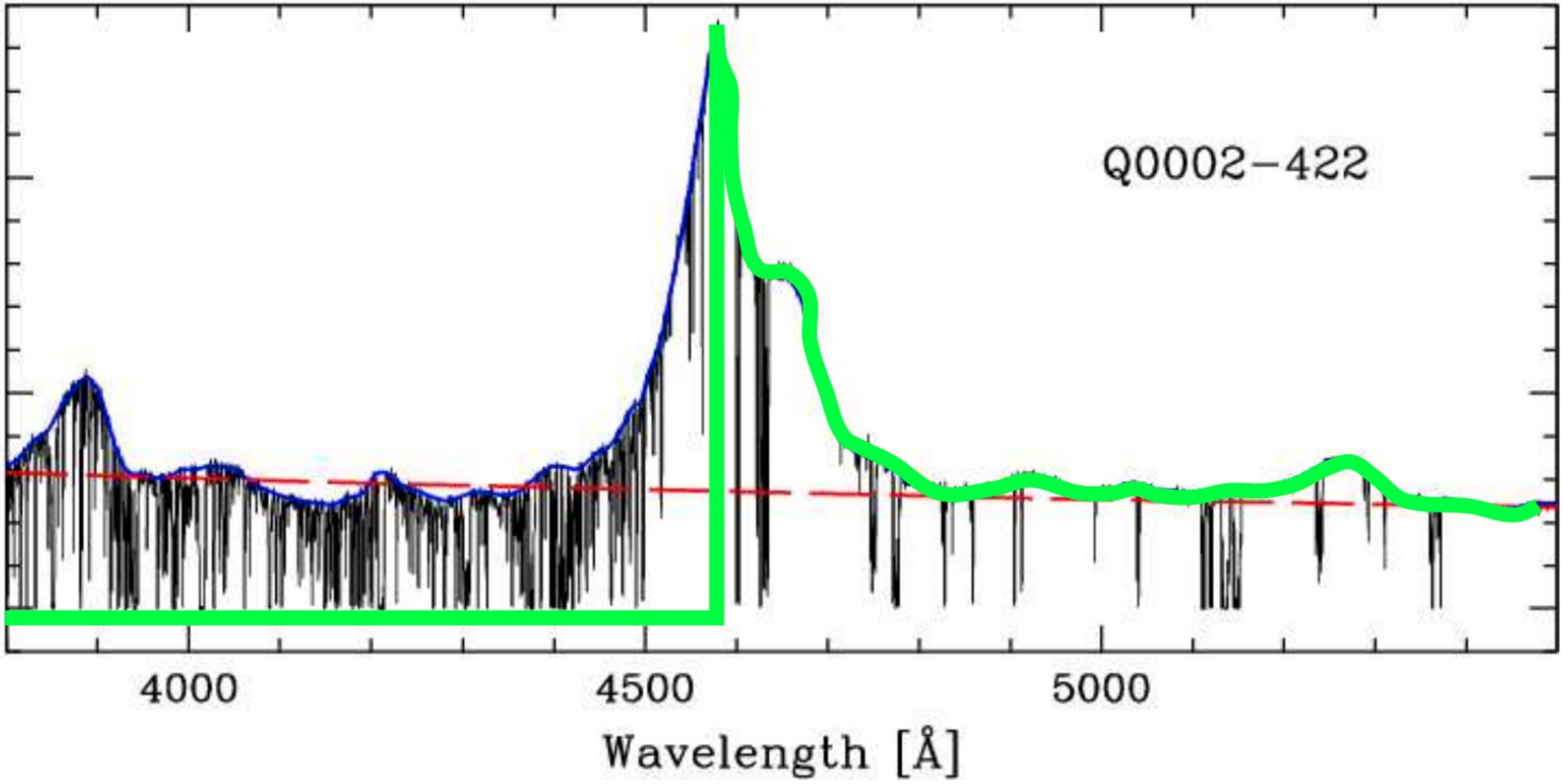


Absorption spectra



- The absorption lines blueward of the emission line arise from Lyα 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



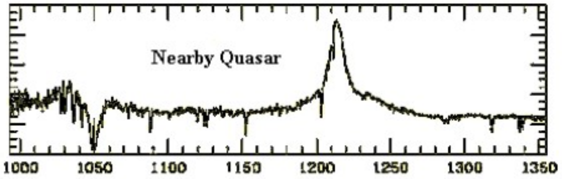
Observed flux $\sim$ Unabsorbed flux $\times\ \exp\left(-10^5\, x_{\rm HI}\right)$, where $x_{\rm HI} = \rho_{\rm HI}/\rho_H$.

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

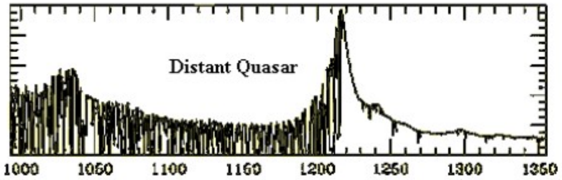
Non-zero flux observed till $z \sim 5.5$

QSO absorption lines at $z \sim 6$

$z \approx 0$



$z \approx 3$



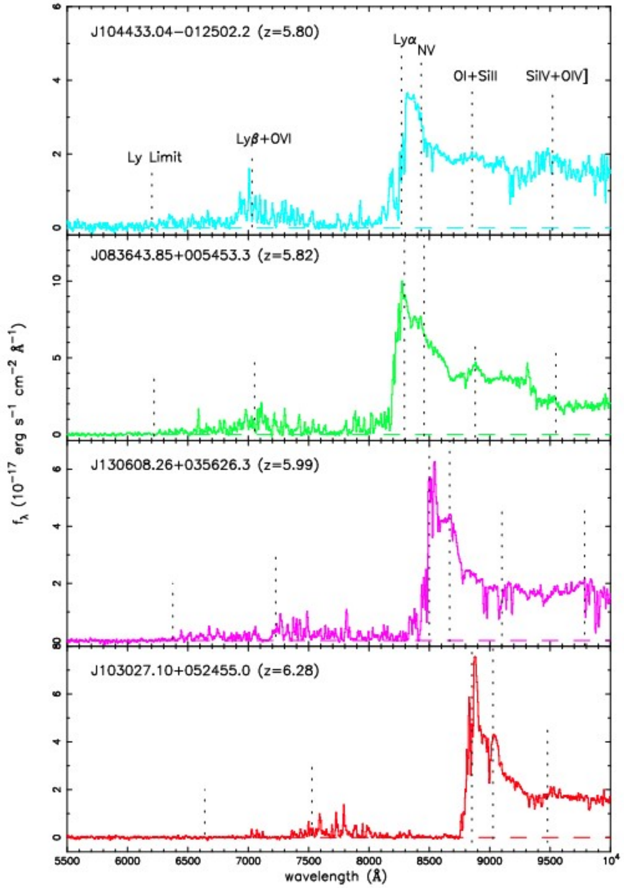
$x_{\rm HI} \lesssim 10^{-5}$

$z = 5.80$

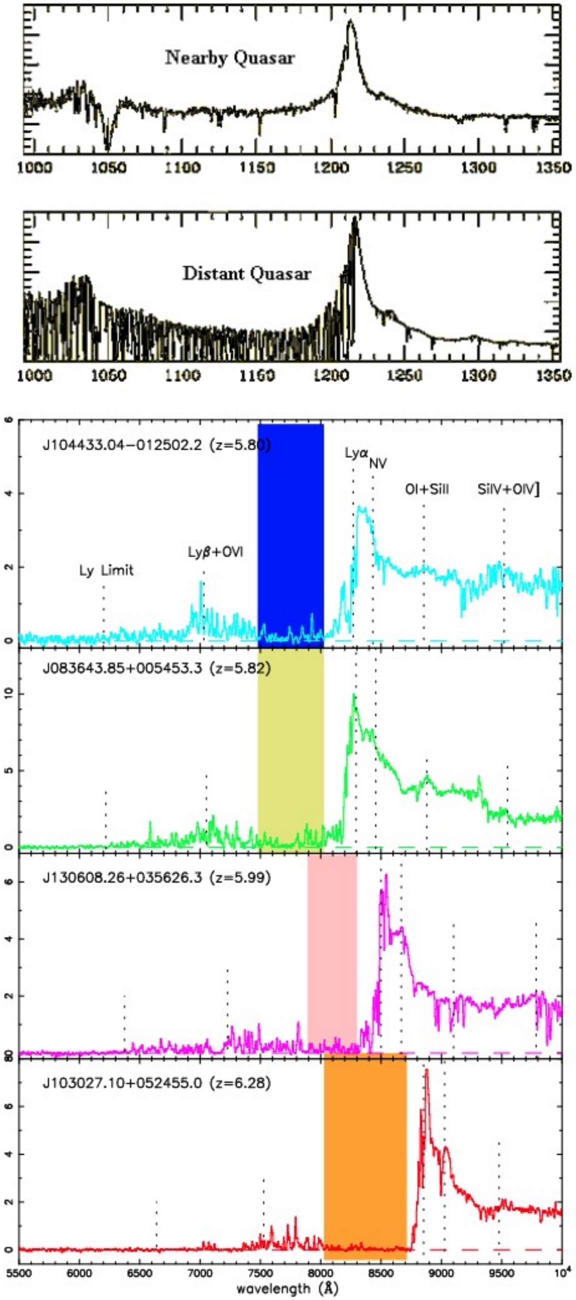
$z = 5.82$

$z = 5.99$

$z = 6.28$



QSO absorption lines at $z \sim 6$



$z \approx 0$

$z \approx 3$

$x_{\mathrm{HI}} \lesssim 10^{-5}$

$z = 5.80$

Does this absorption mean

high neutrality?

$z = 5.82$

$z = 5.99$

$z = 6.28$

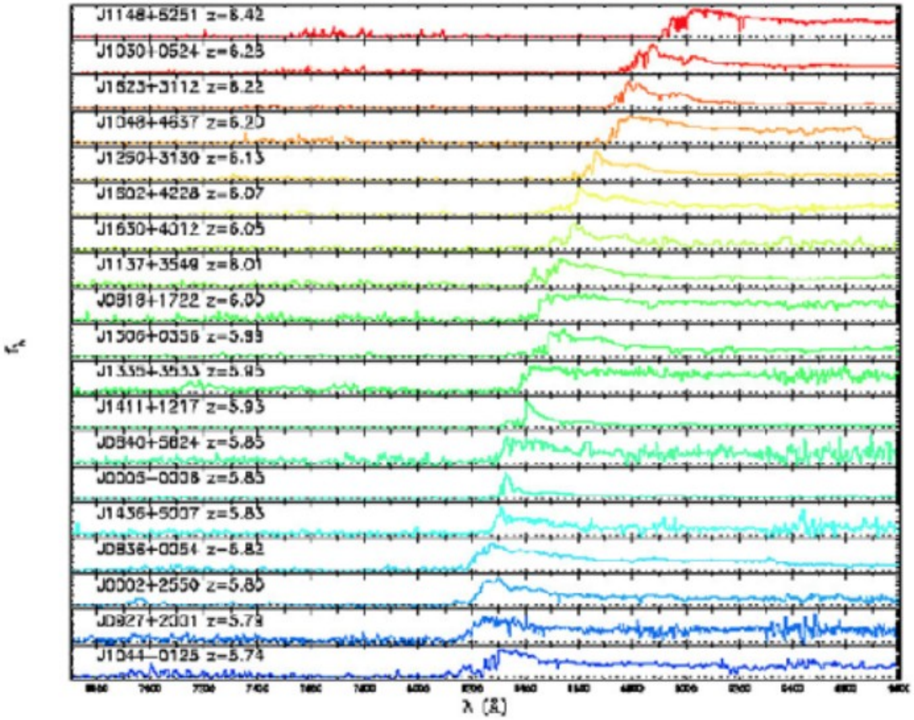
QSO absorption lines at $z \sim 6$

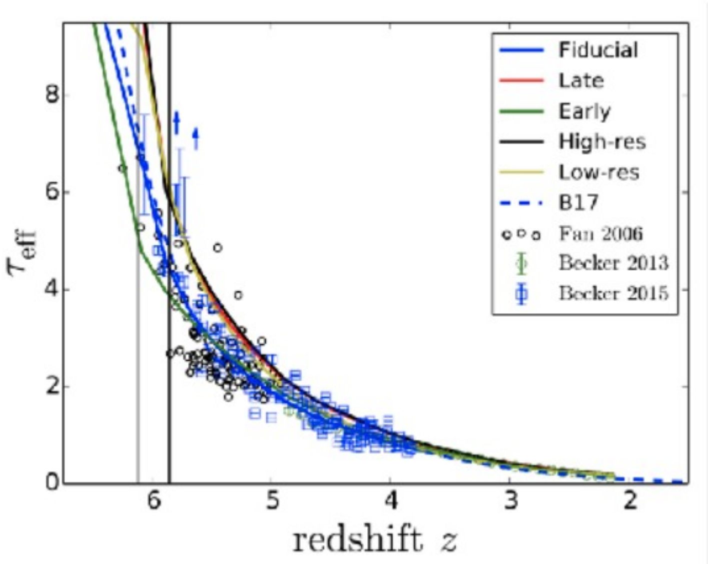
- Gunn-Peterson optical depth:

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

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

Around z~6 large dark gaps appear in the spectrum





Barnett et al. 2017

Fan et al. 2006

Observations of low-z quasars show a clear Gunn-Peterson effects, suggesting that reionization ended around z~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 $x_{HI} > 10^{-4}$ 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 $x_{HI} > 10^{-4}$ at $z \sim 6$

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