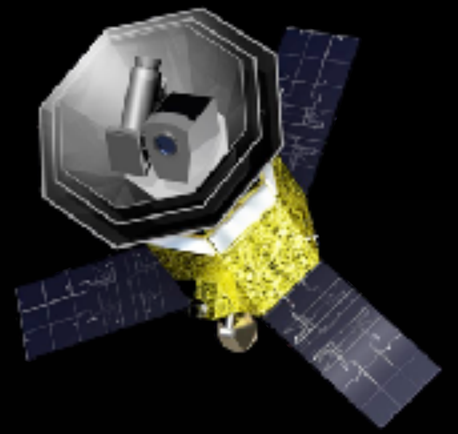
CMB B-modes observations

Status and perspectives



Benjamin Beringue
Postdoc @ APC-CNRS
June, 6th 2024

SciPol
Science from the large scale cosmic microwave background polarization structure

Exploring the Dark Side of the Universe - Tools

Cosmic Evolution

10^{-32} seconds | 1 second | 100 seconds | 380 000 years | 300–500 million years | Billions of years | 13.8 billion years

Inflation
Accelerated expansion of the Universe

Formation of light and matter

Light and matter are coupled
Dark matter evolves independently: it starts clumping and forming a web of structures

Light and matter separate
- Protons and electrons form atoms
- Light starts travelling freely: it will become the Cosmic Microwave Background (CMB)

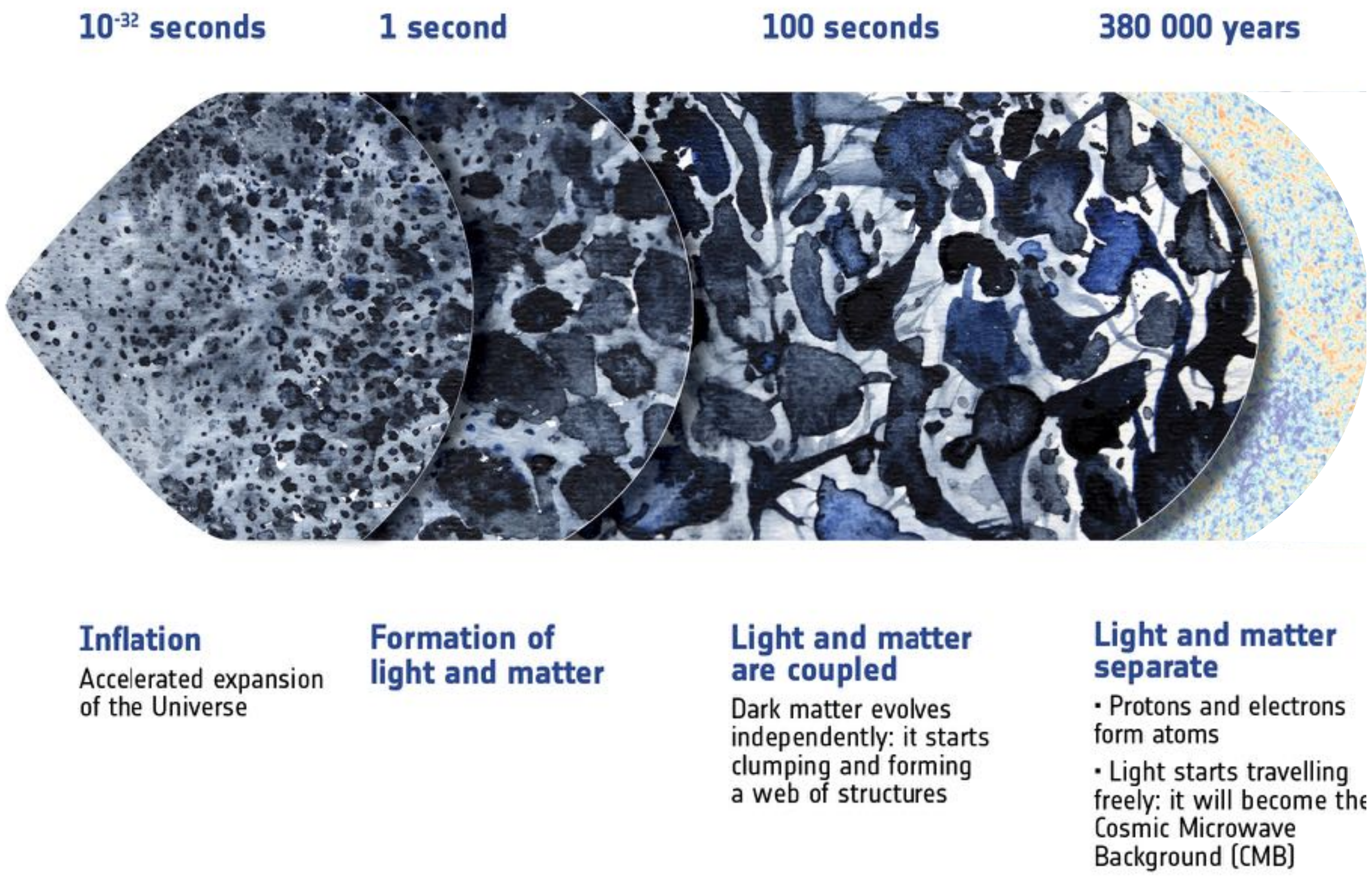
Dark ages
Atoms start feeling the gravity of the cosmic web of dark matter

First stars
The first stars and galaxies form in the densest knots of the cosmic web

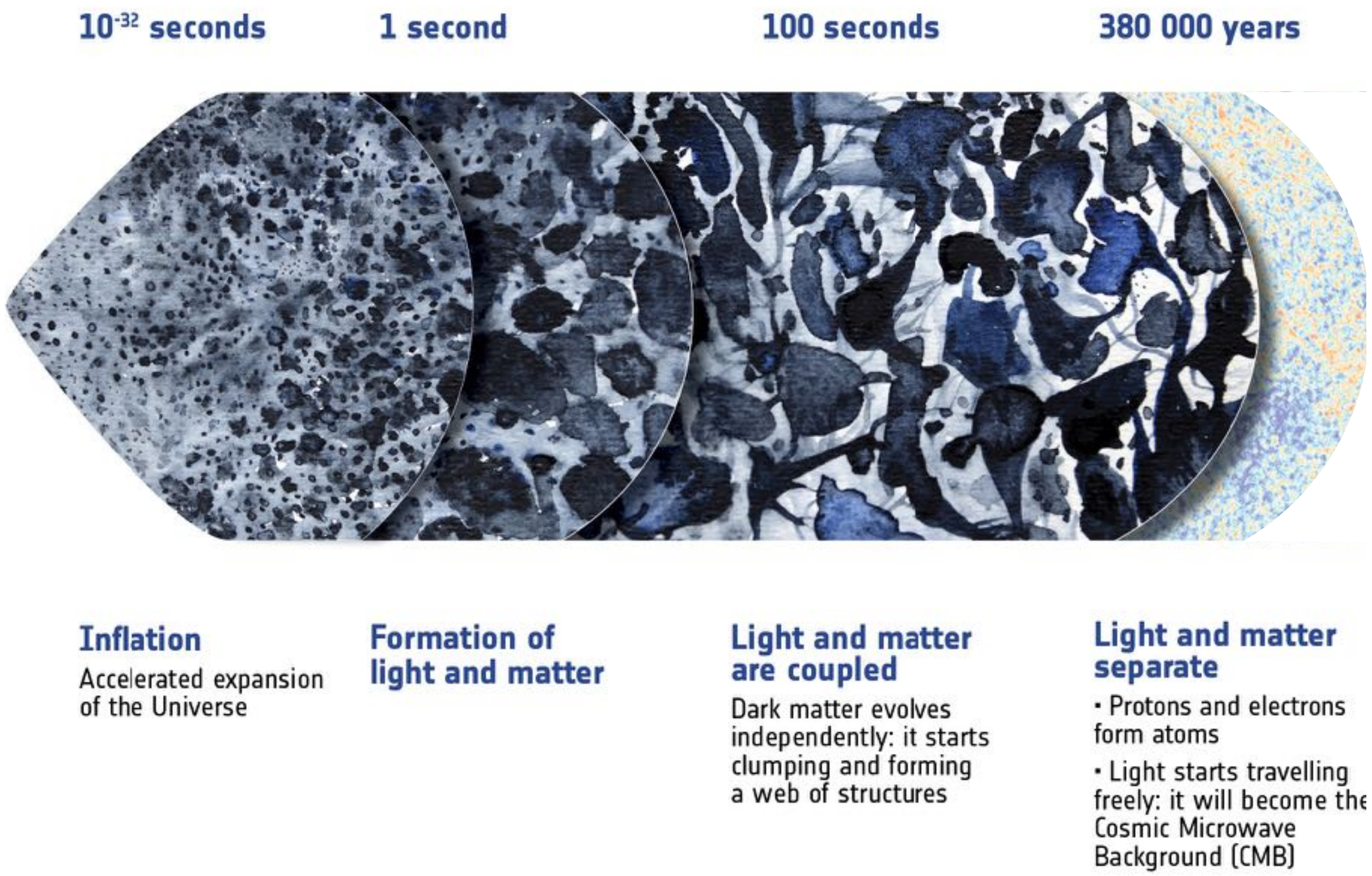
Galaxy evolution

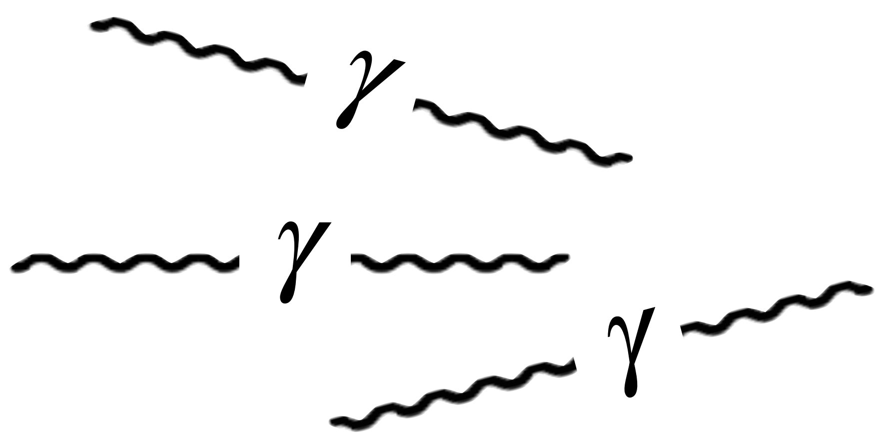
The present Universe

Cosmic Microwave Background



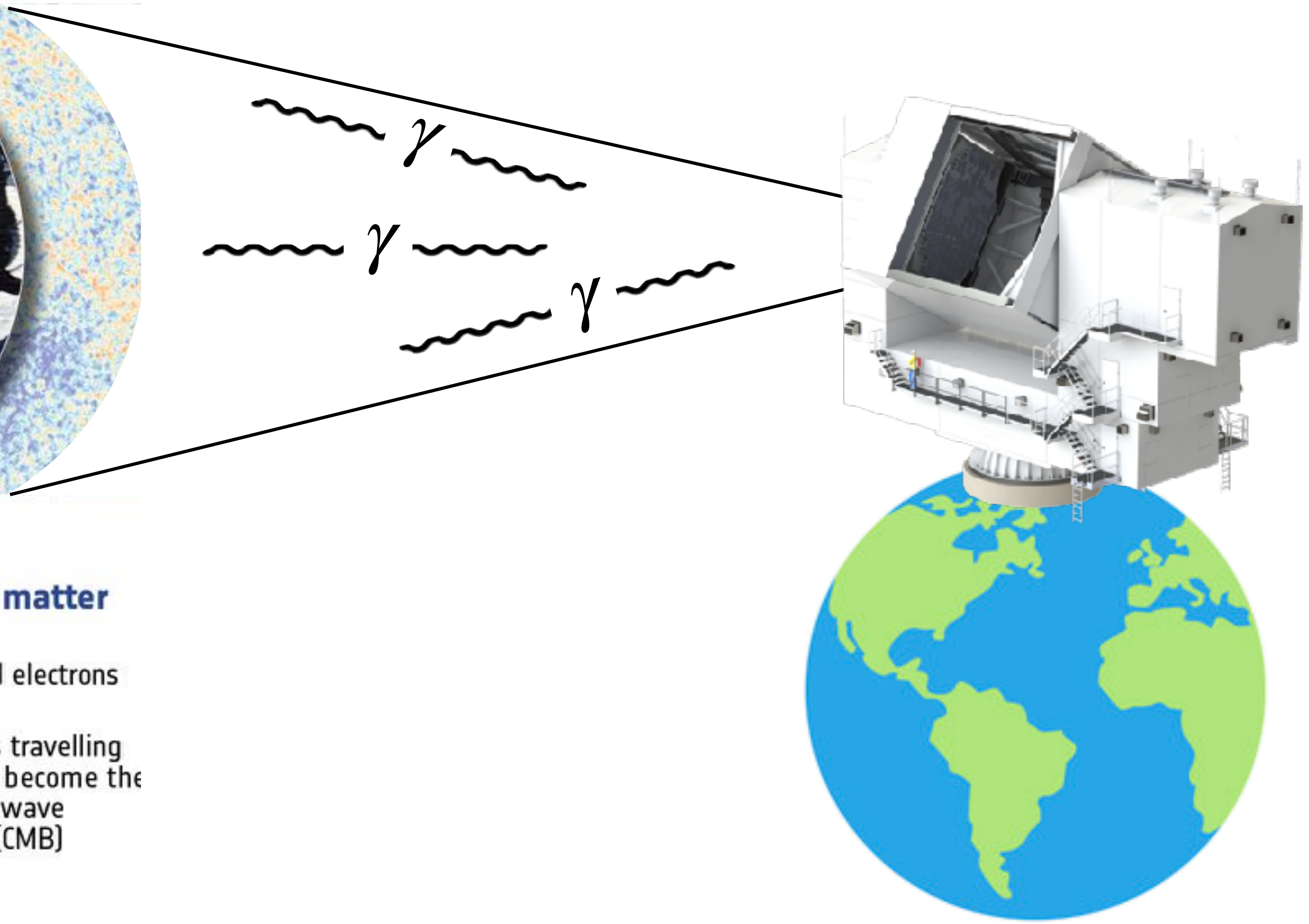
Cosmic Microwave Background





Cosmic Microwave Background

10^{-32} seconds	1 second	100 seconds	380 000 years



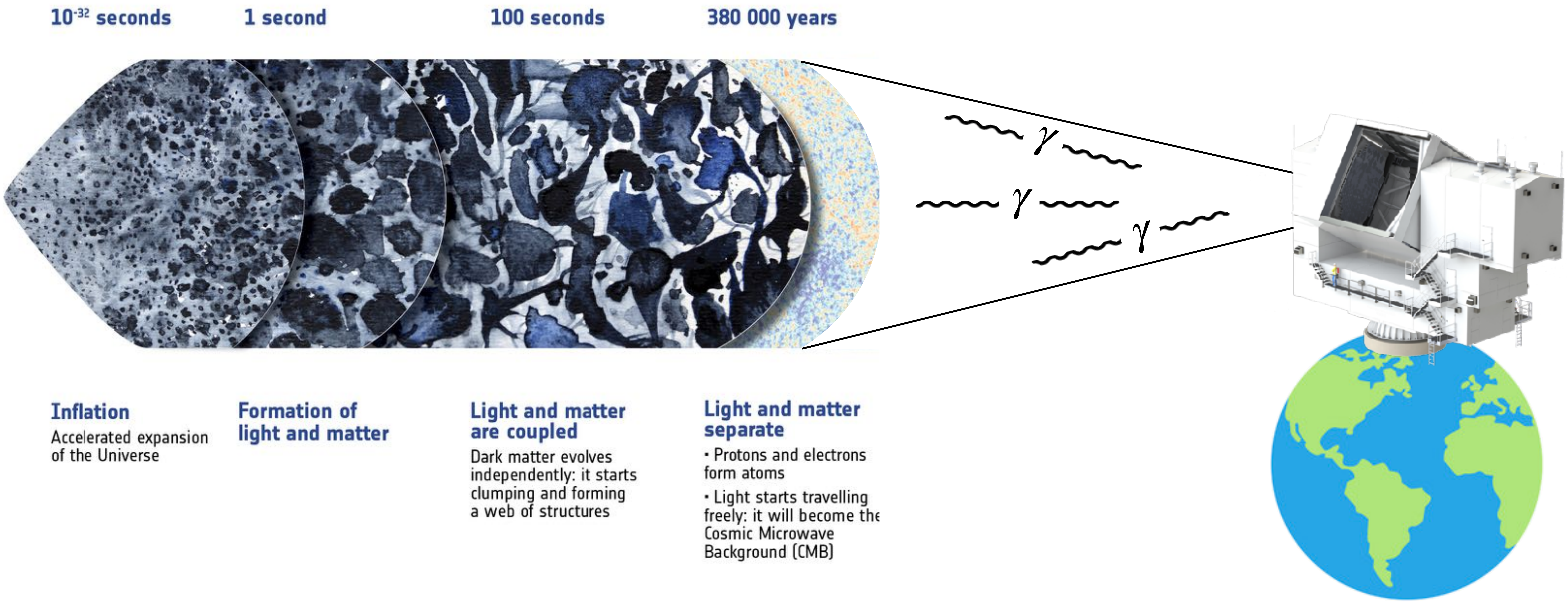
Inflation
Accelerated expansion of the Universe

Formation of light and matter

Light and matter are coupled
Dark matter evolves independently: it starts clumping and forming a web of structures

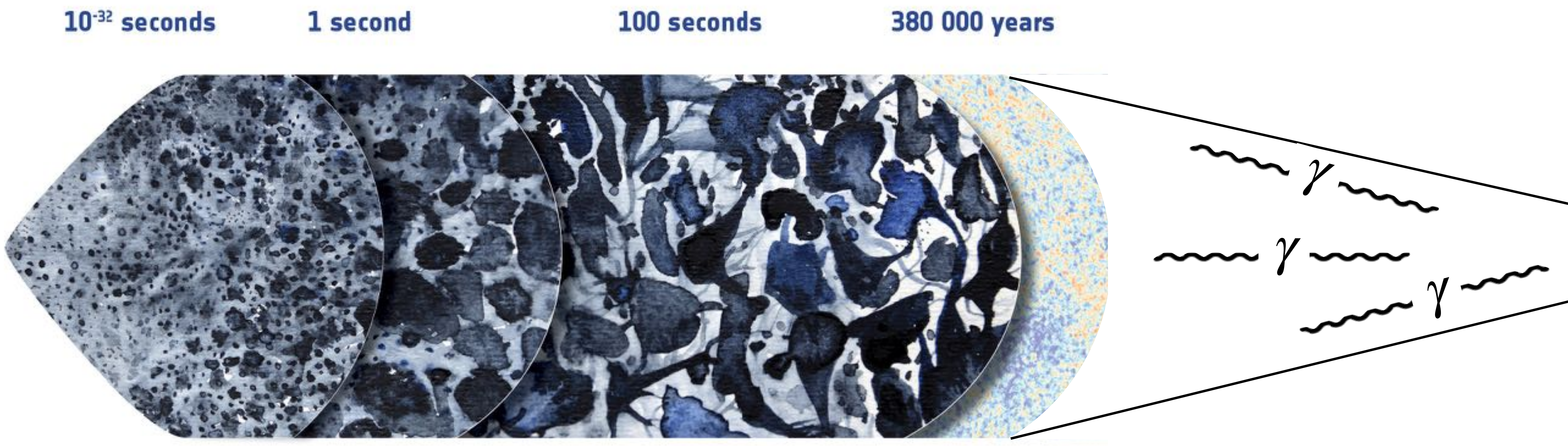
Light and matter separate
- Protons and electrons form atoms
- Light starts travelling freely: it will become the Cosmic Microwave Background (CMB)

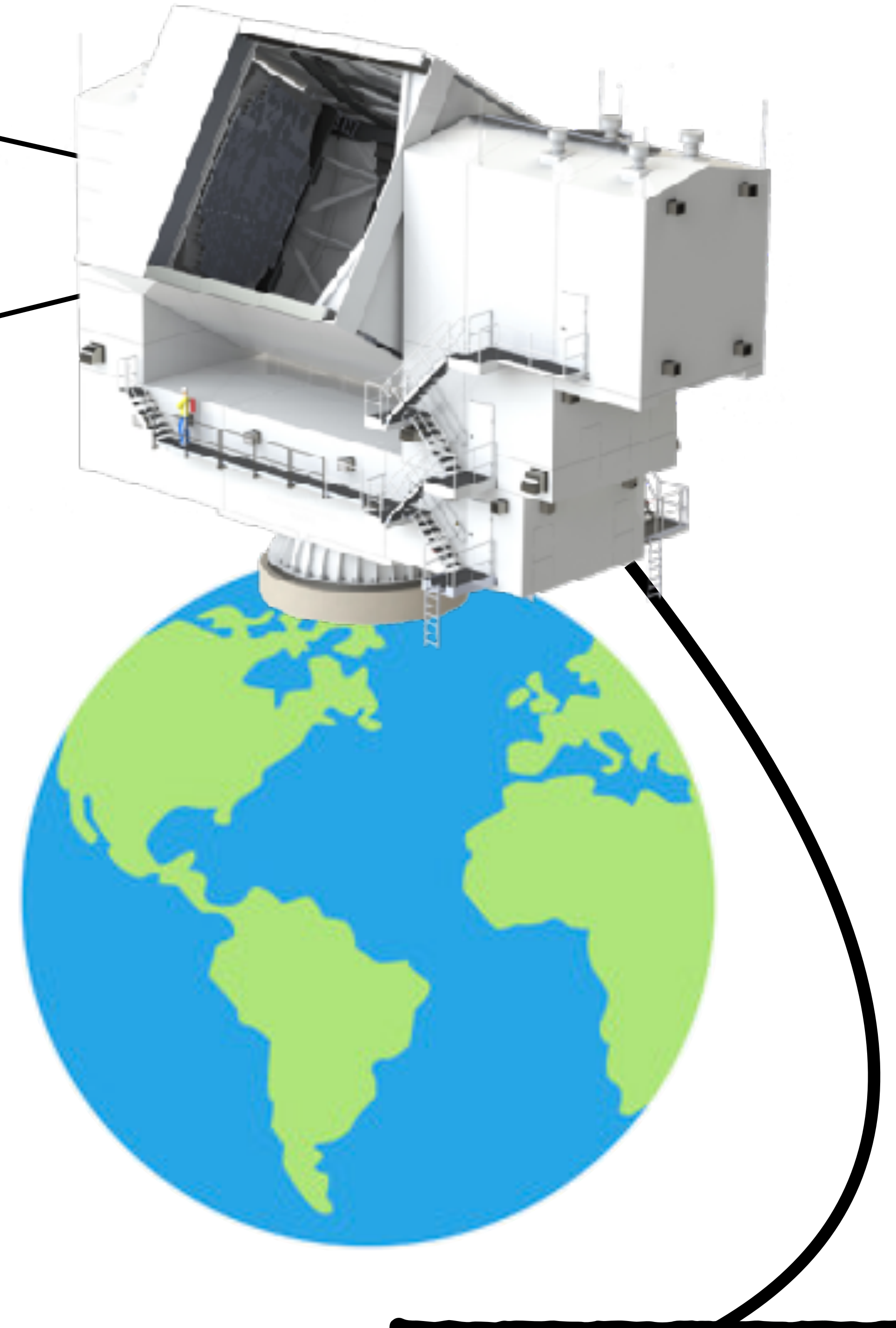
Cosmic Microwave Background

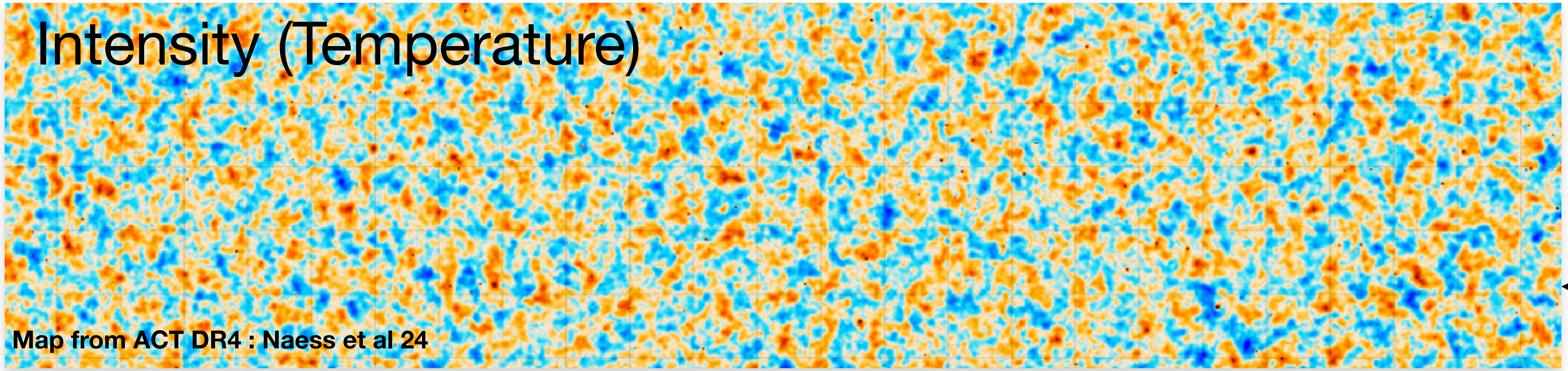


- Preprocessing
- MapMaking
- **Component separation**

Cosmic Microwave Background

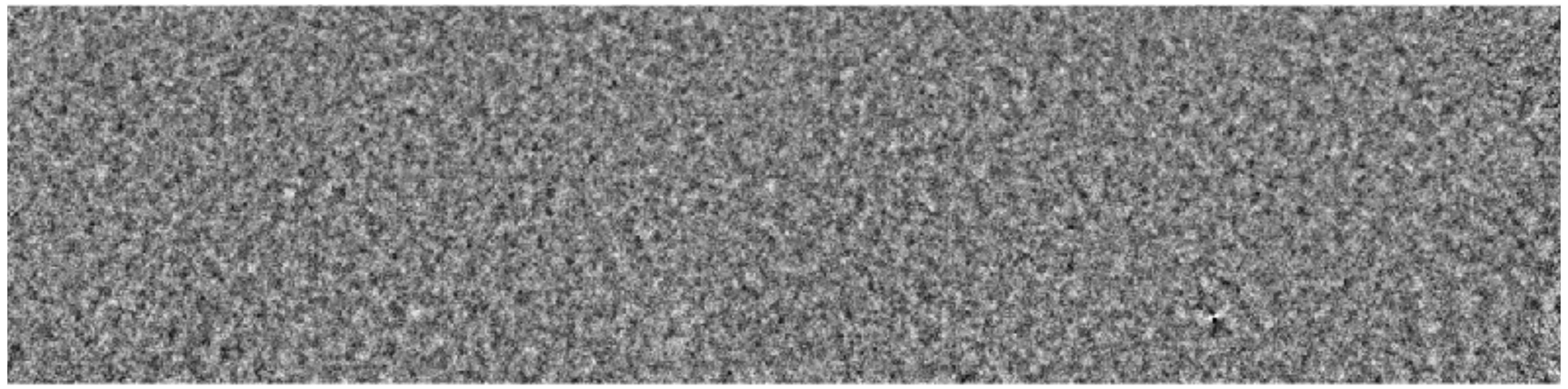


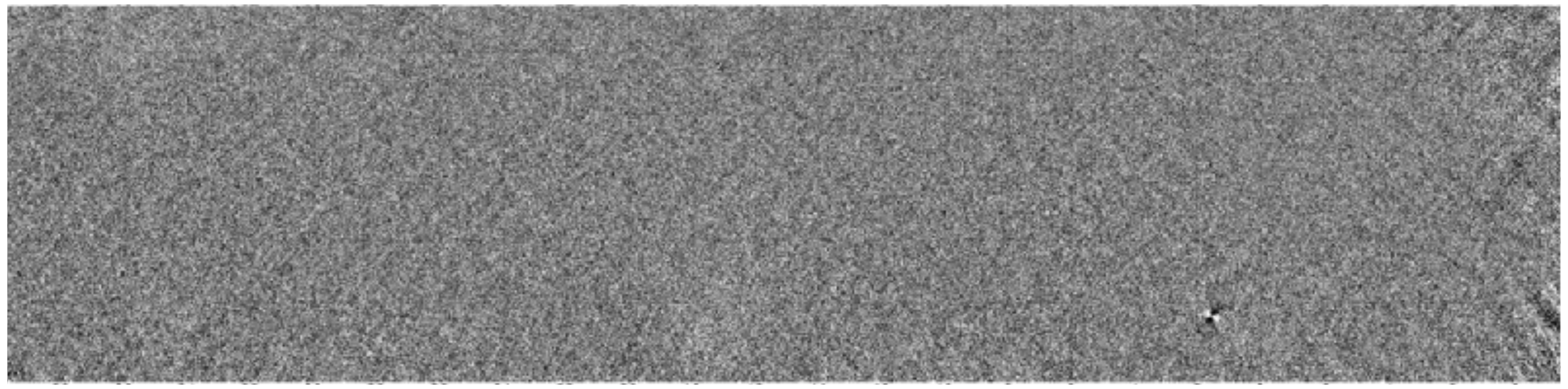


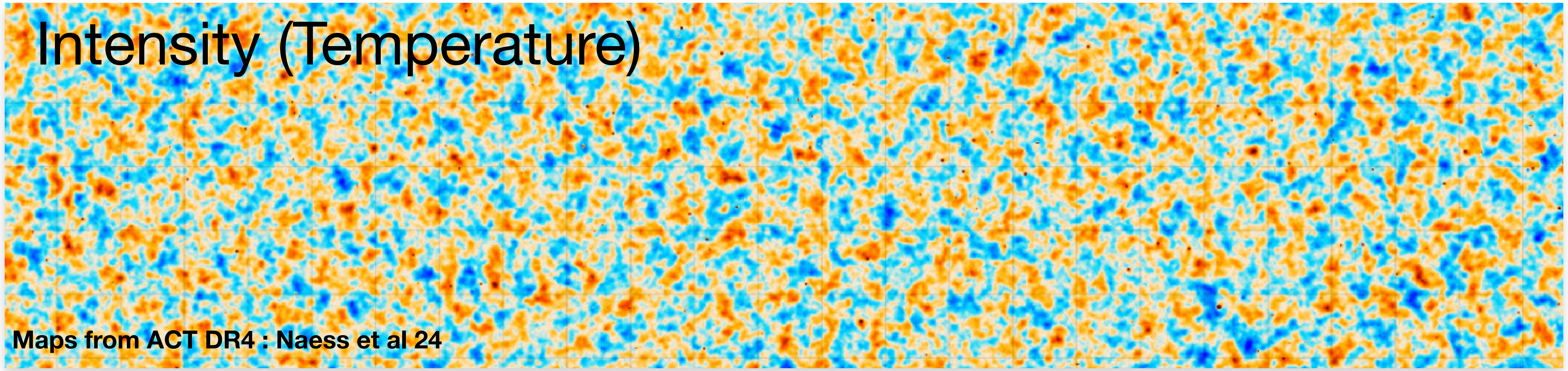


- Preprocessing
- MapMaking
- **Component separation**

Cosmic Microwave Background

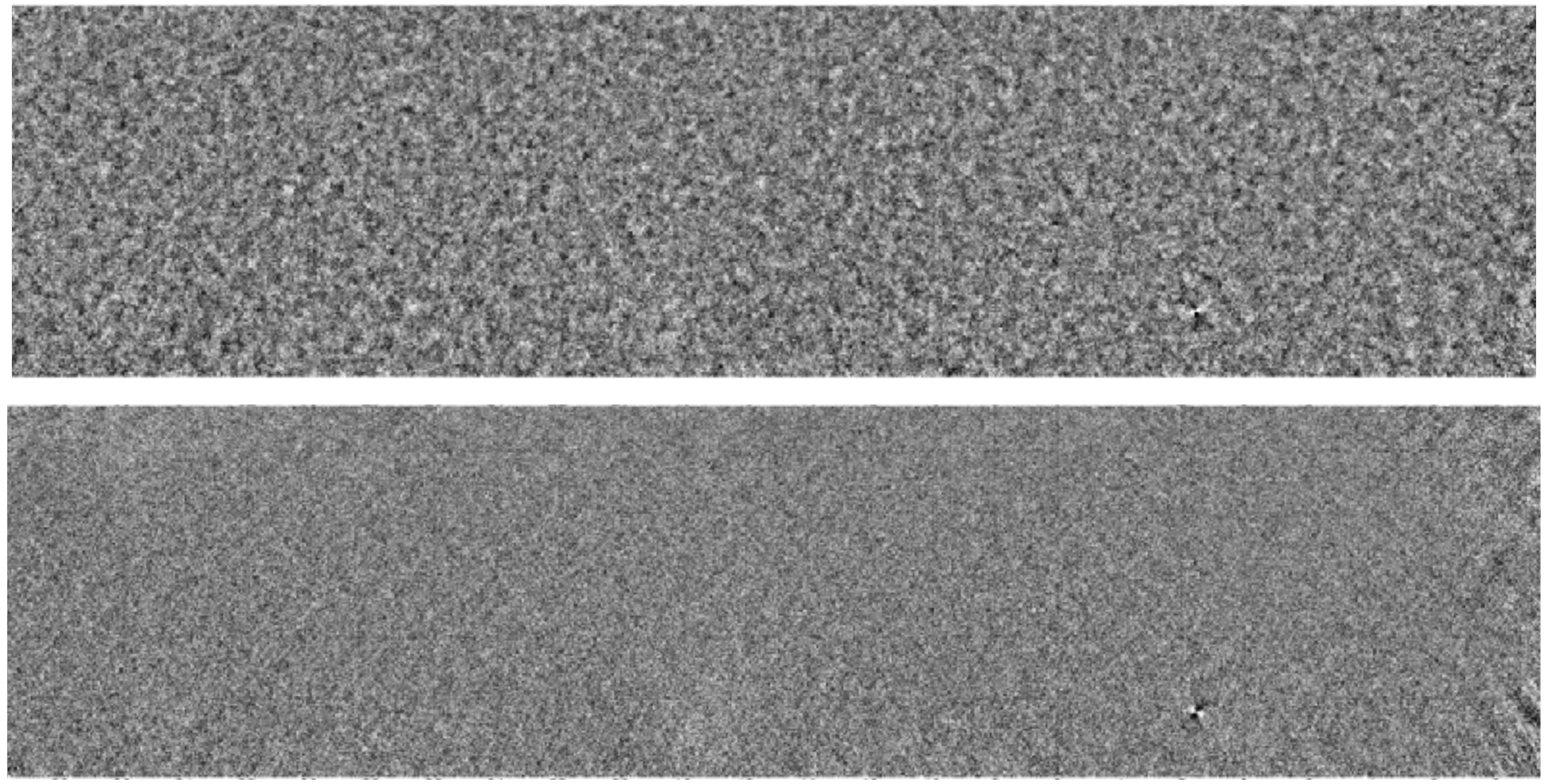


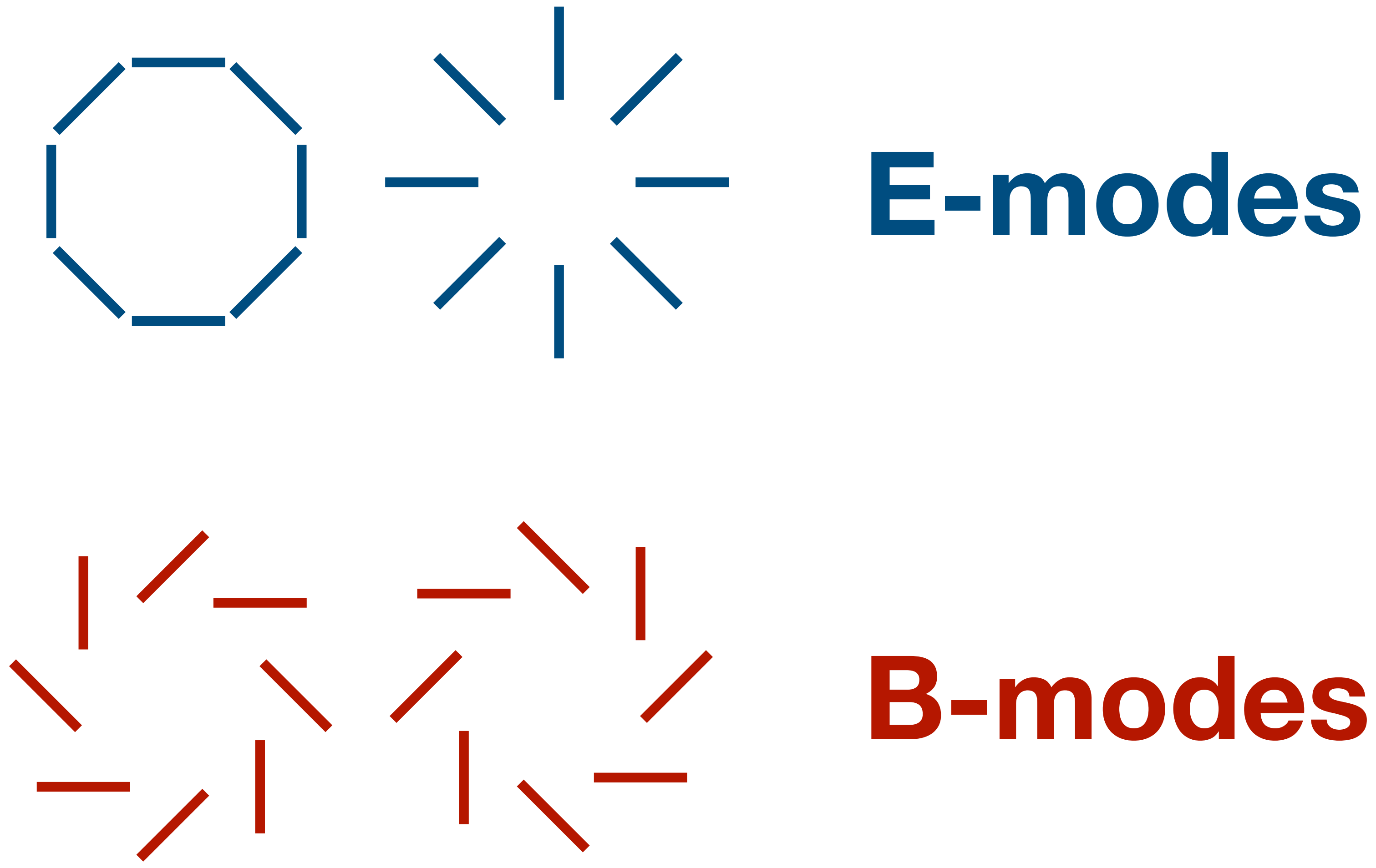


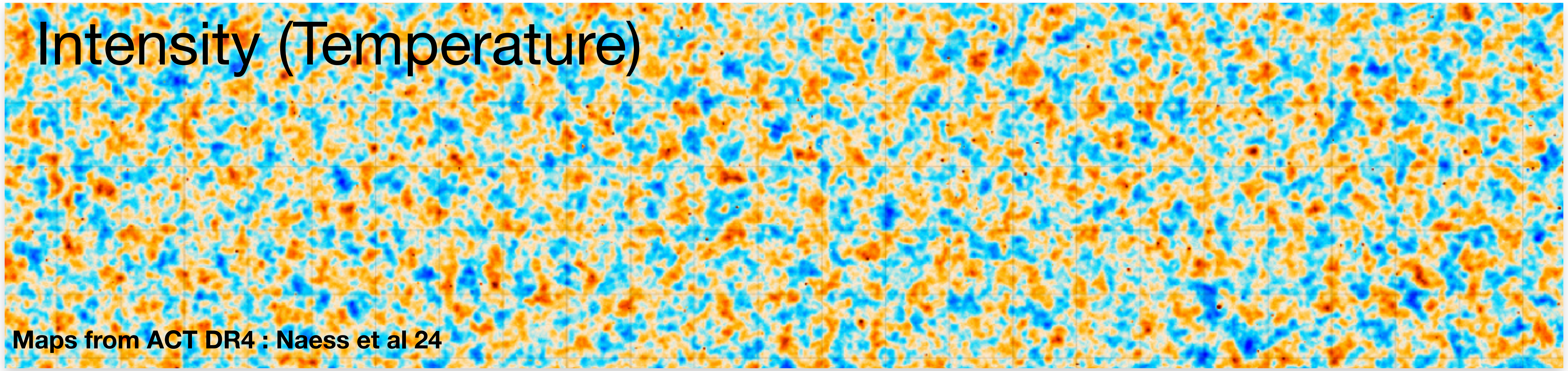


The CMB is also polarised !

Cosmic Microwave Background

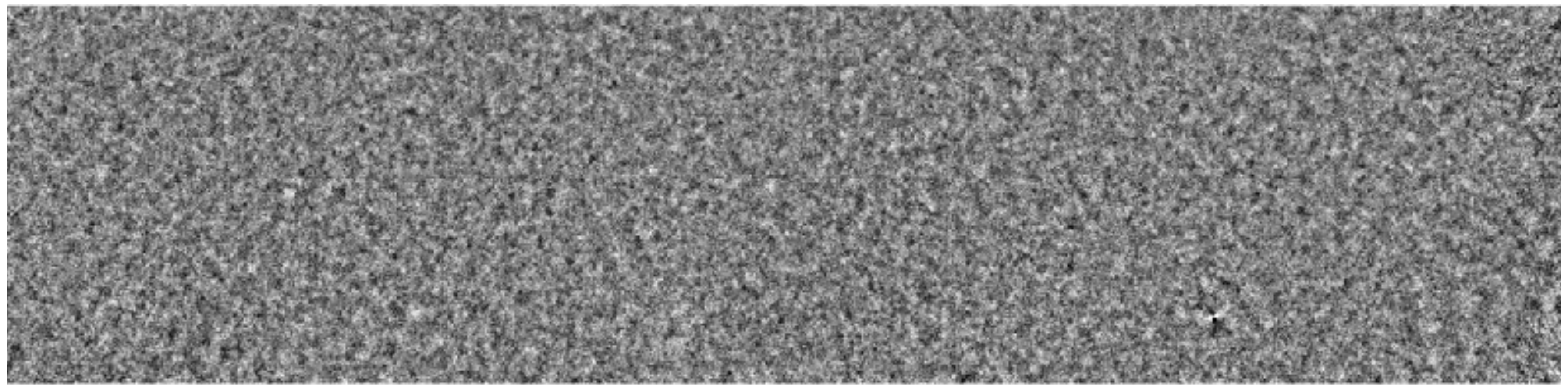


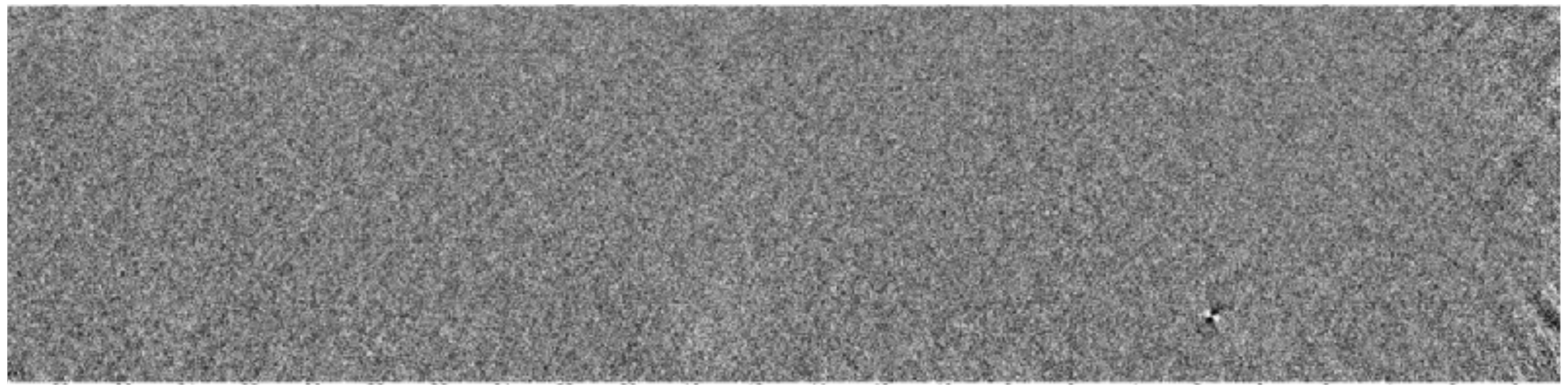


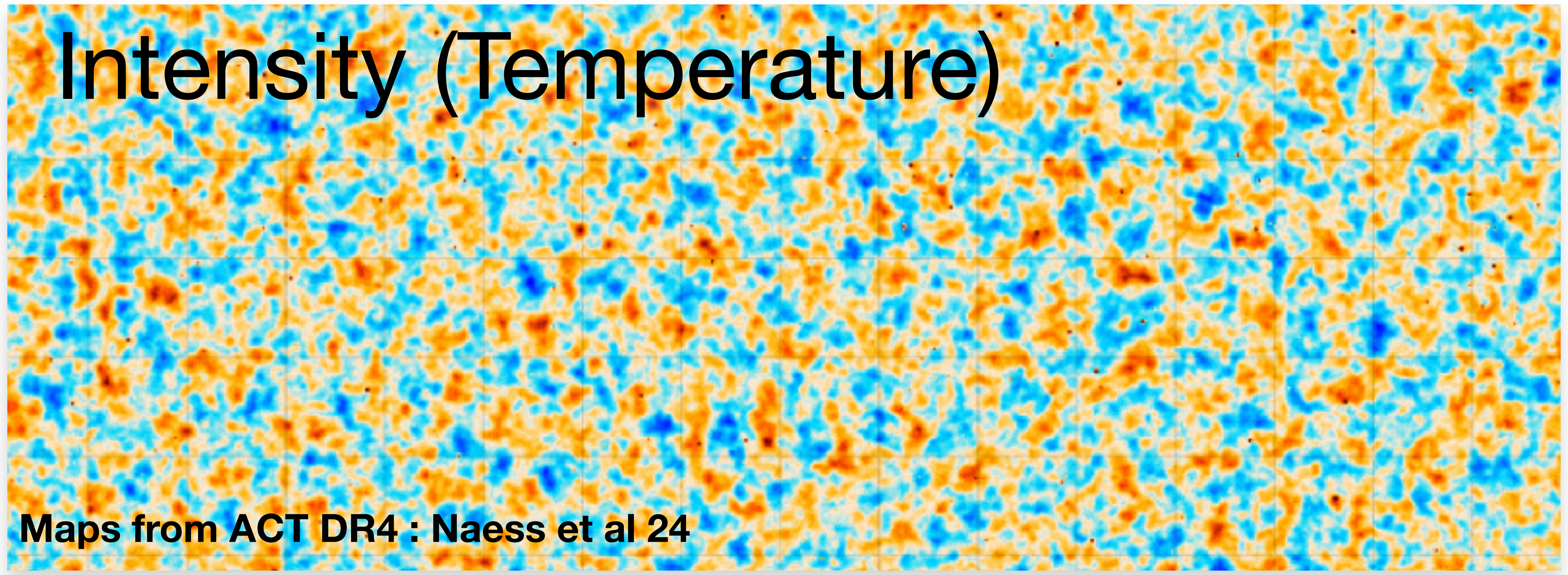


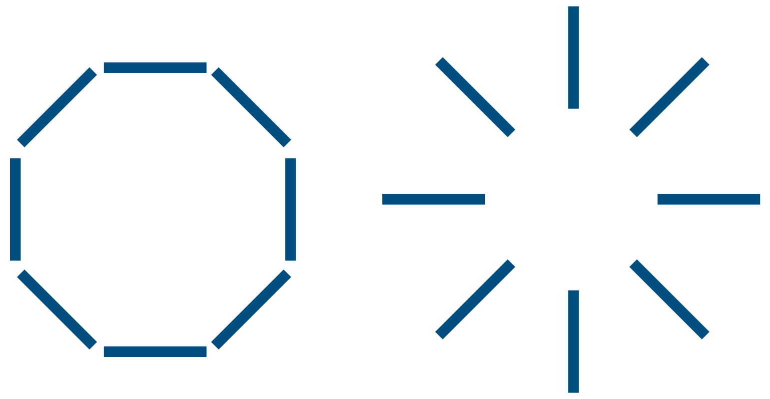
The CMB is also polarised !

Cosmic Microwave Background

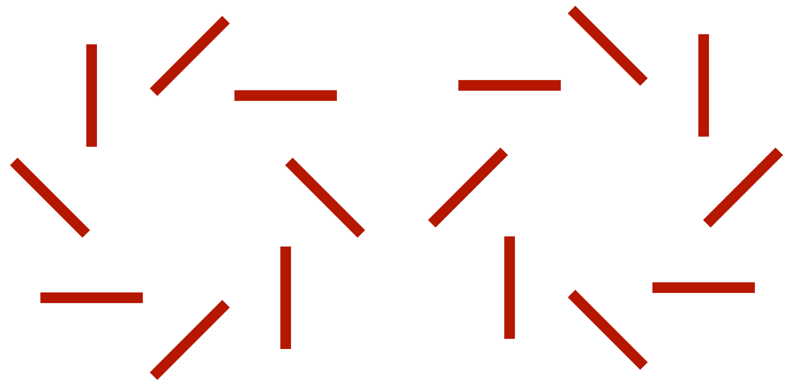








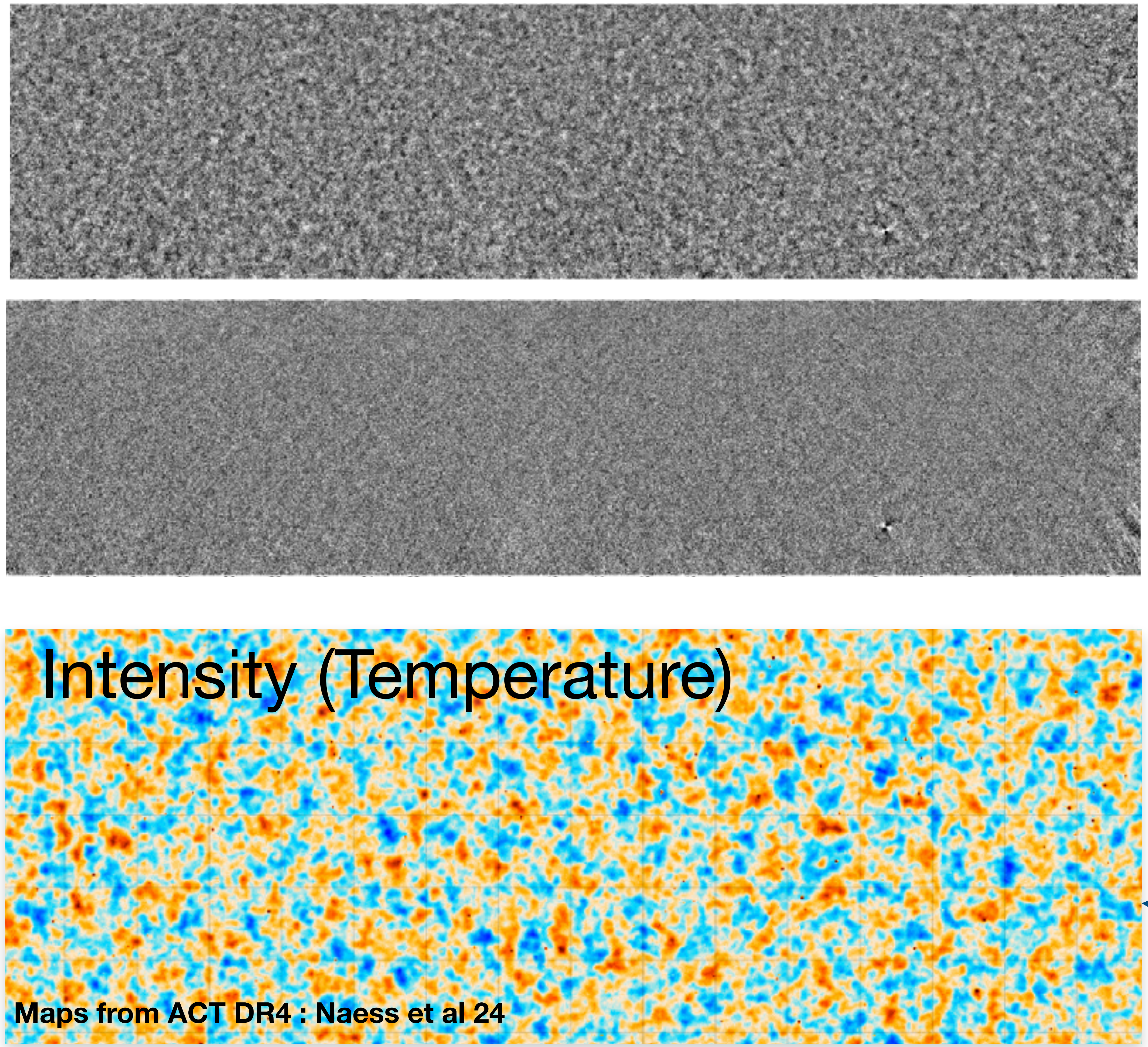
E-modes

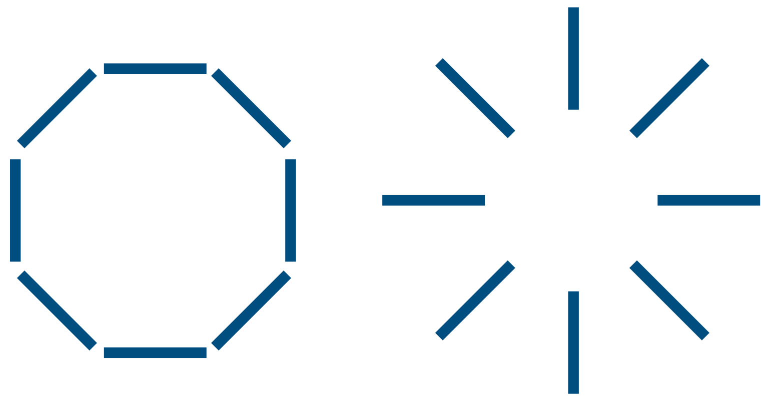


B-modes

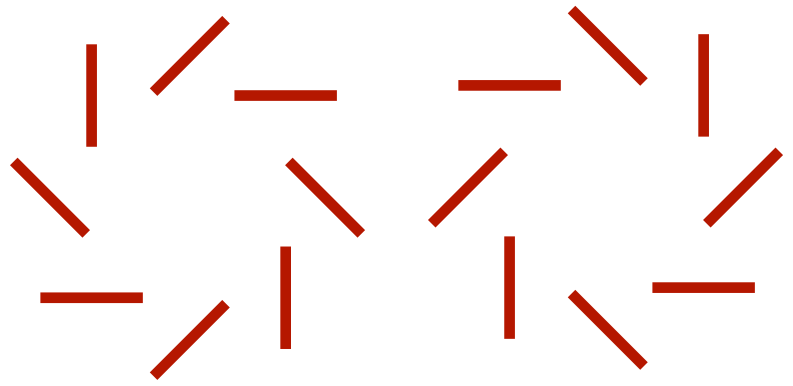
$$dl^2 = a^2(t)\left[1 + 2\zeta(\mathbf{x}, t)\right] \left[\delta_{ij} + h_{ij}(\mathbf{x}, t)\right] dx^i dx^j$$

Cosmic Microwave Background





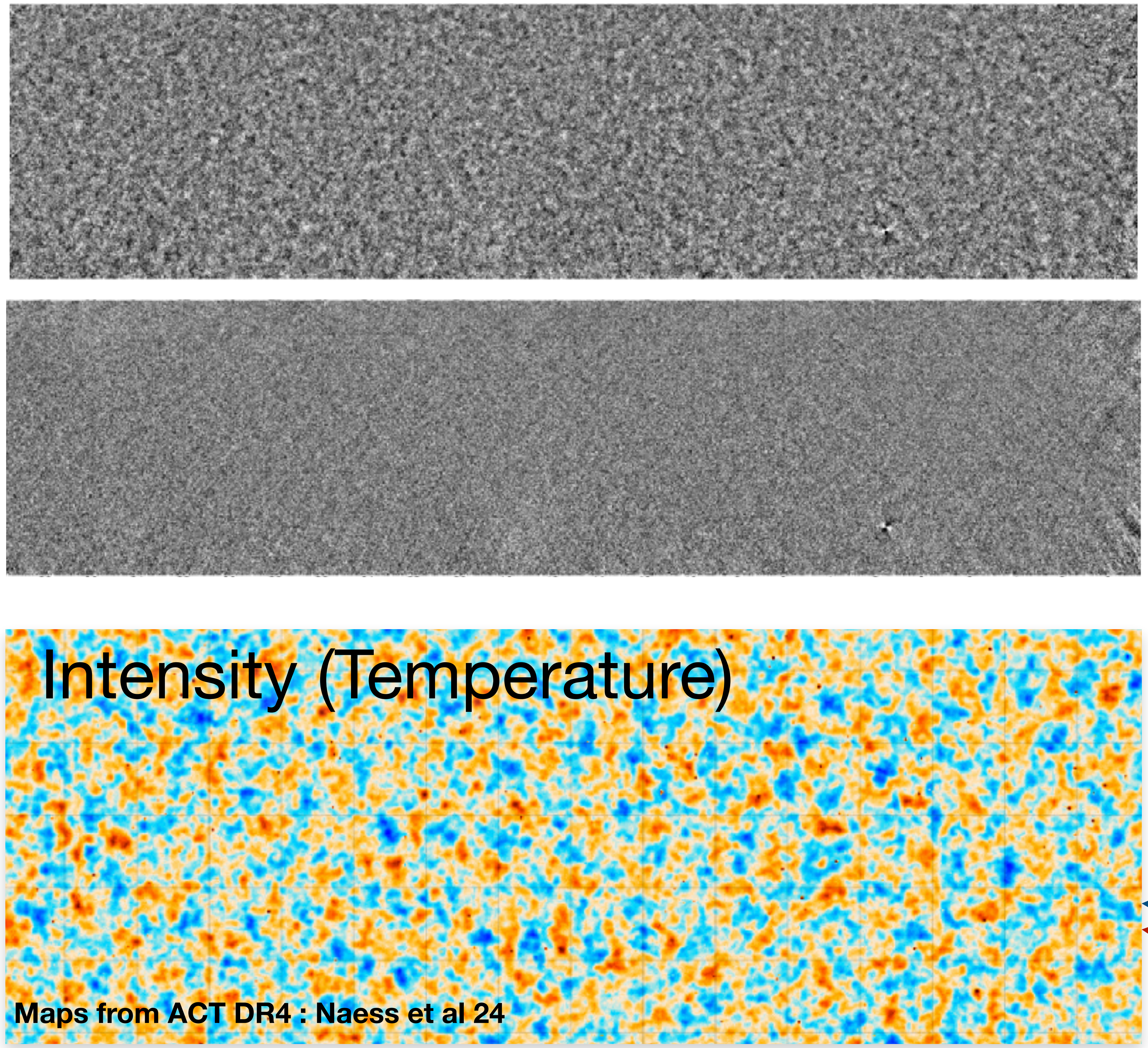
E-modes

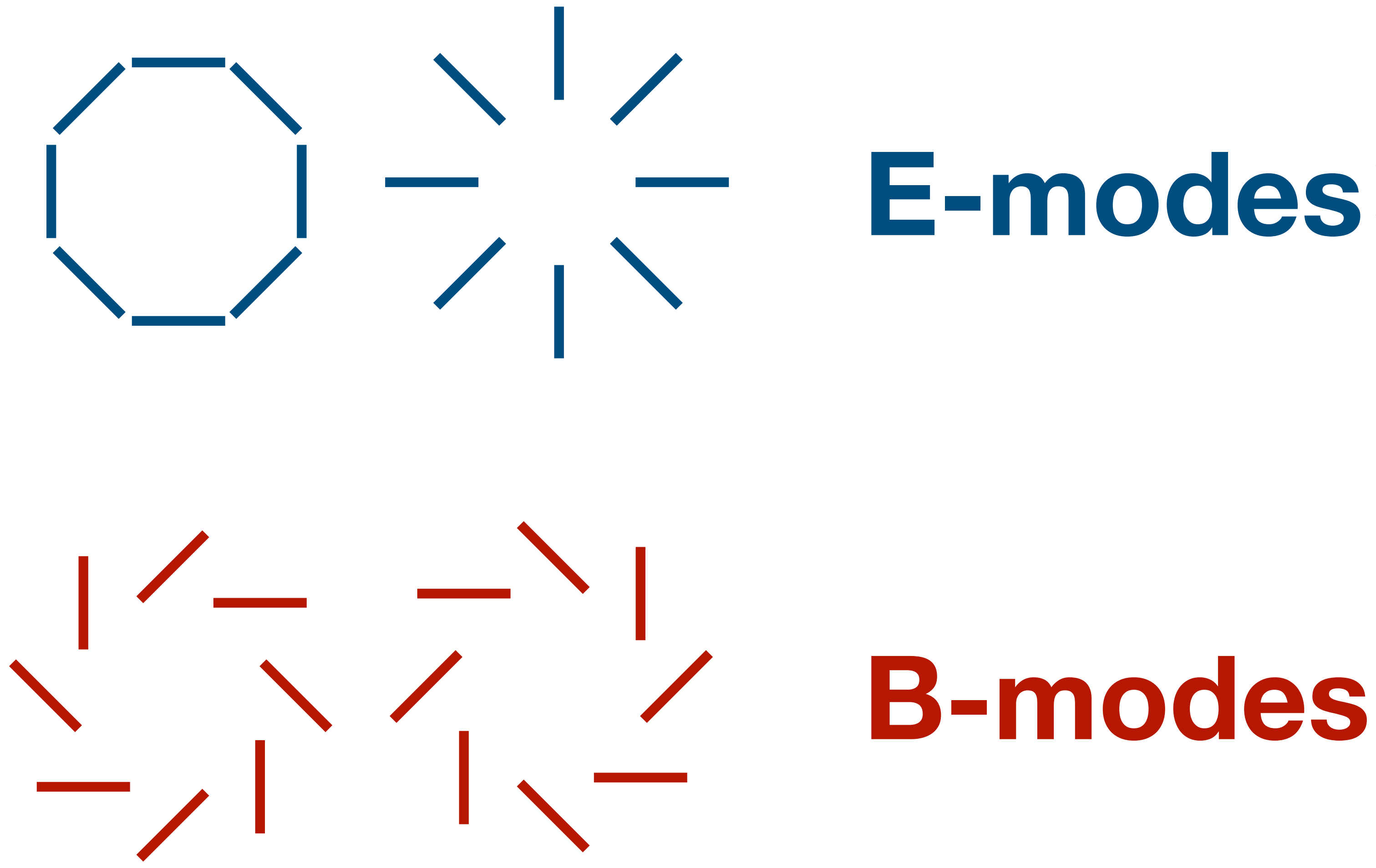


B-modes

$$dl^2 = a^2(t)\left[1 + 2\zeta(\mathbf{x}, t)\right]\left[\delta_{ij} + h_{ij}(\mathbf{x}, t)\right] dx^i dx^j$$

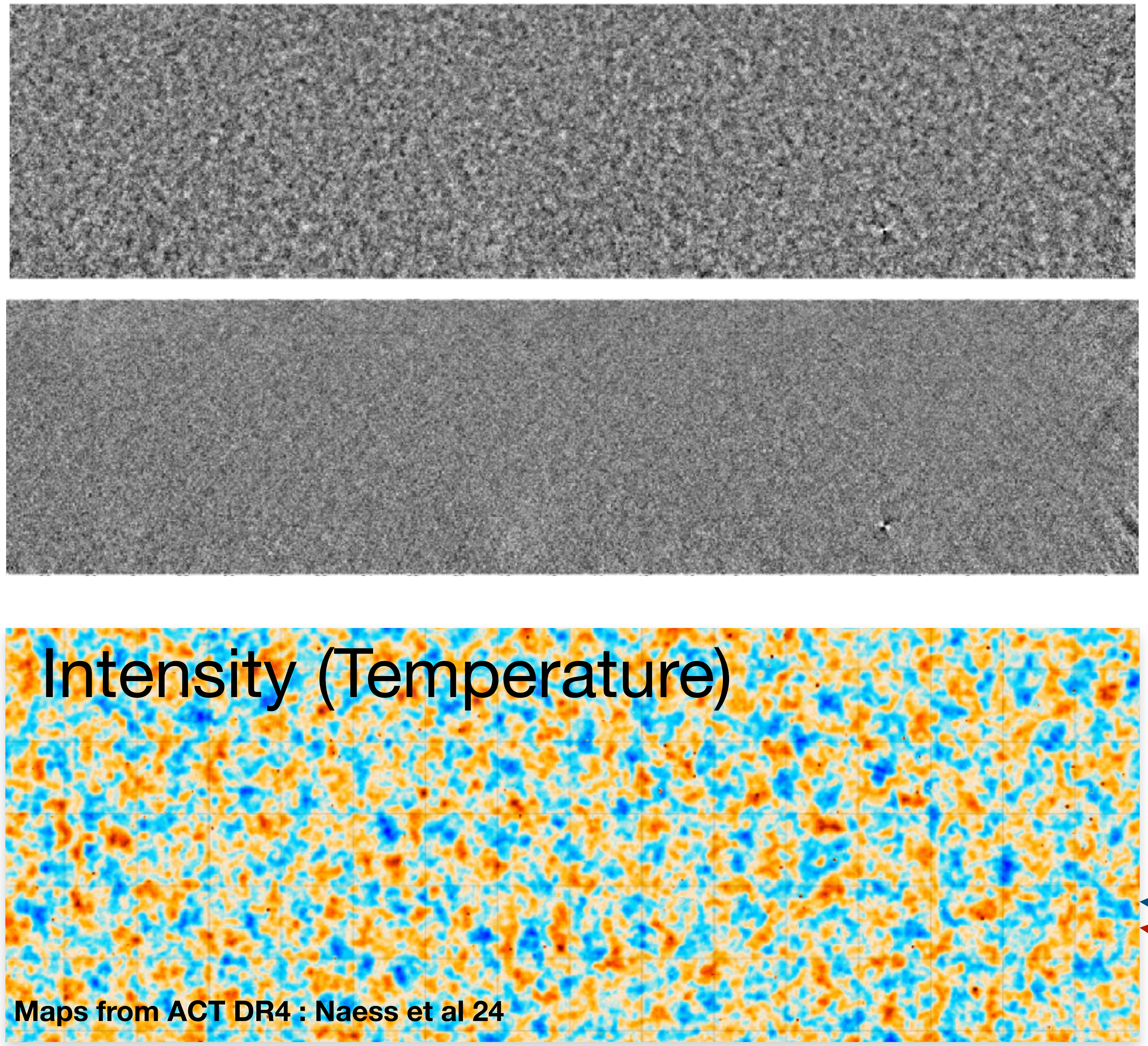
Cosmic Microwave Background

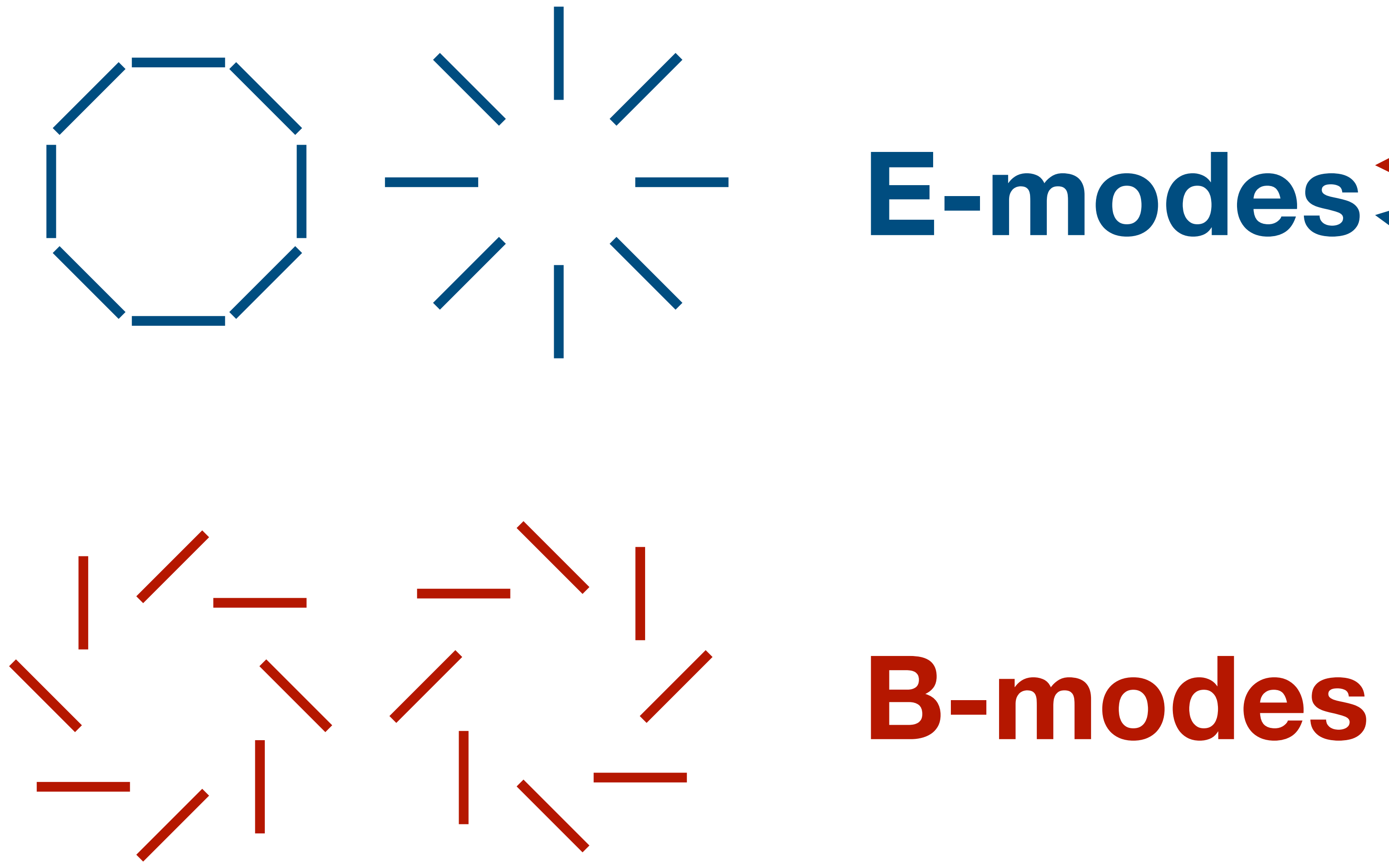




$$dl^2 = a^2(t)\left[1 + 2\zeta(\mathbf{x}, t)\right]\left[\delta_{ij} + h_{ij}(\mathbf{x}, t)\right] dx^i dx^j$$

Cosmic Microwave Background

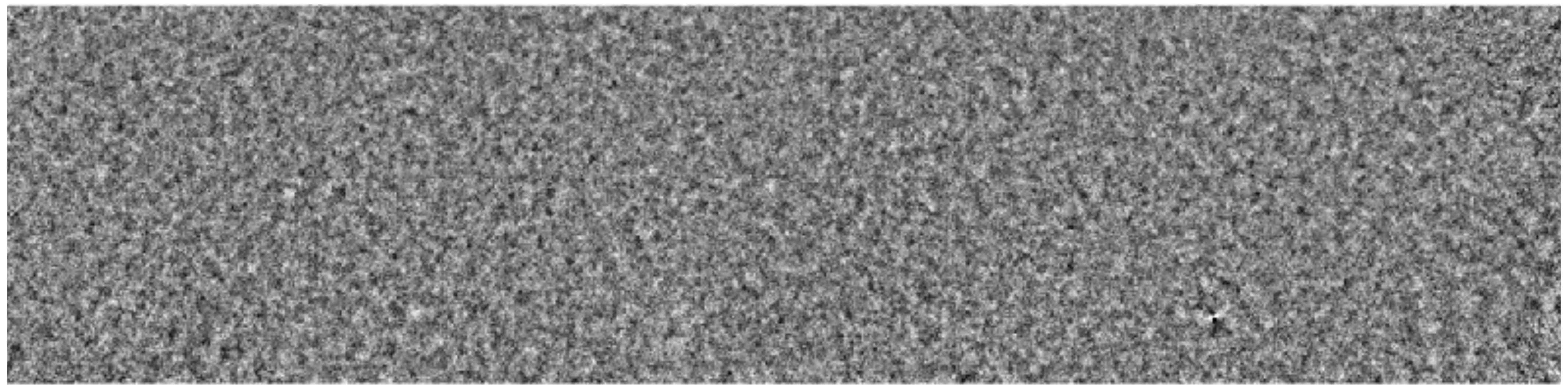


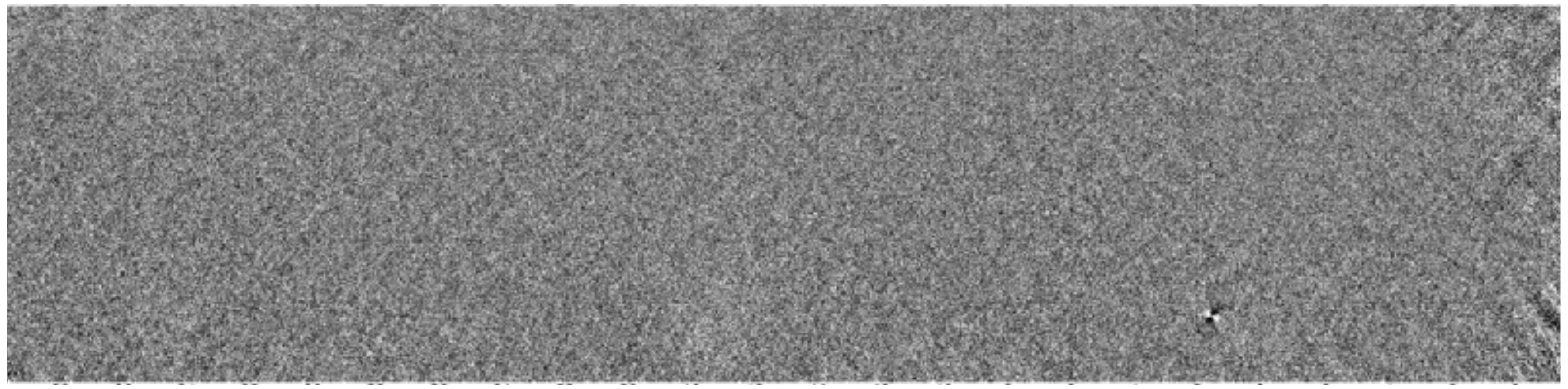


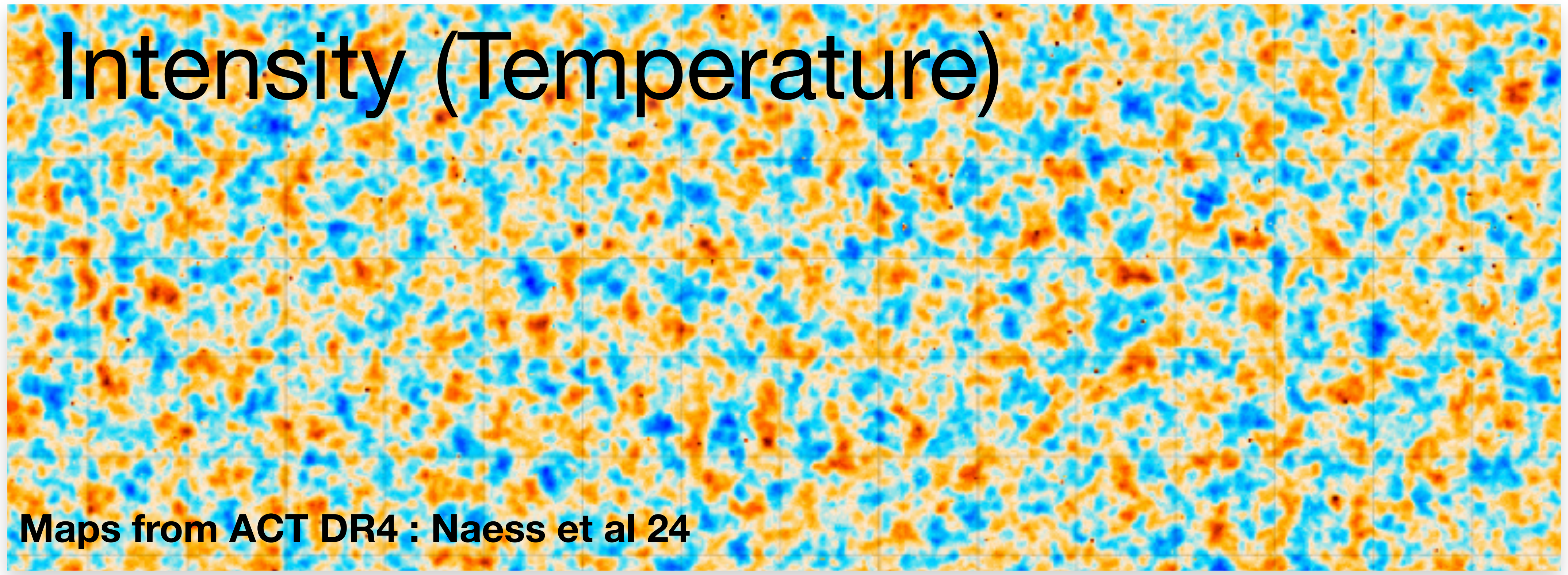
$$dl^2 = a^2(t)\left[1 + 2\zeta(\mathbf{x}, t)\right]\left[\delta_{ij} + h_{ij}(\mathbf{x}, t)\right] dx^i dx^j$$

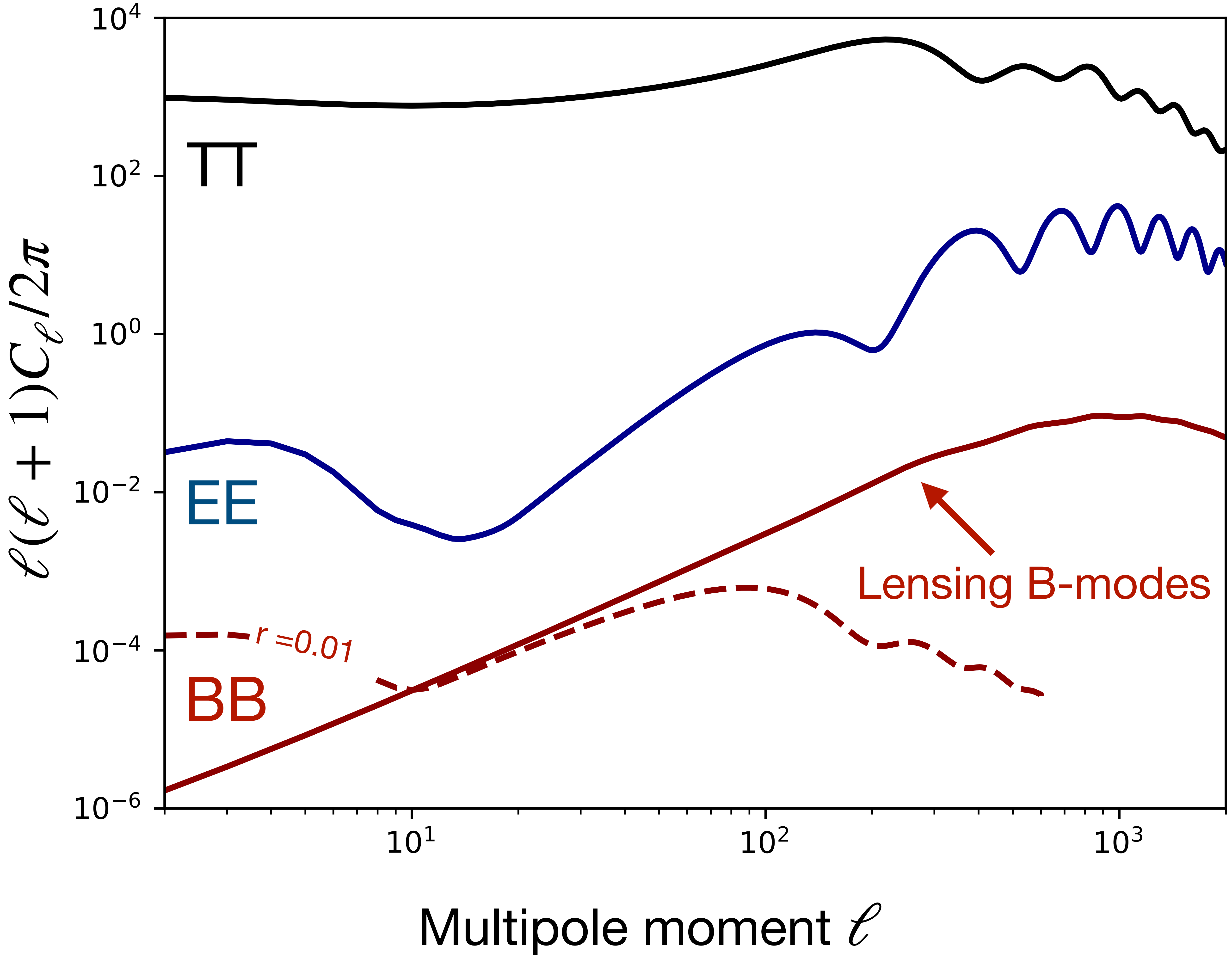
B-modes are only sourced by tensor perturbations, ie primordial grav. waves

Cosmic Microwave Background



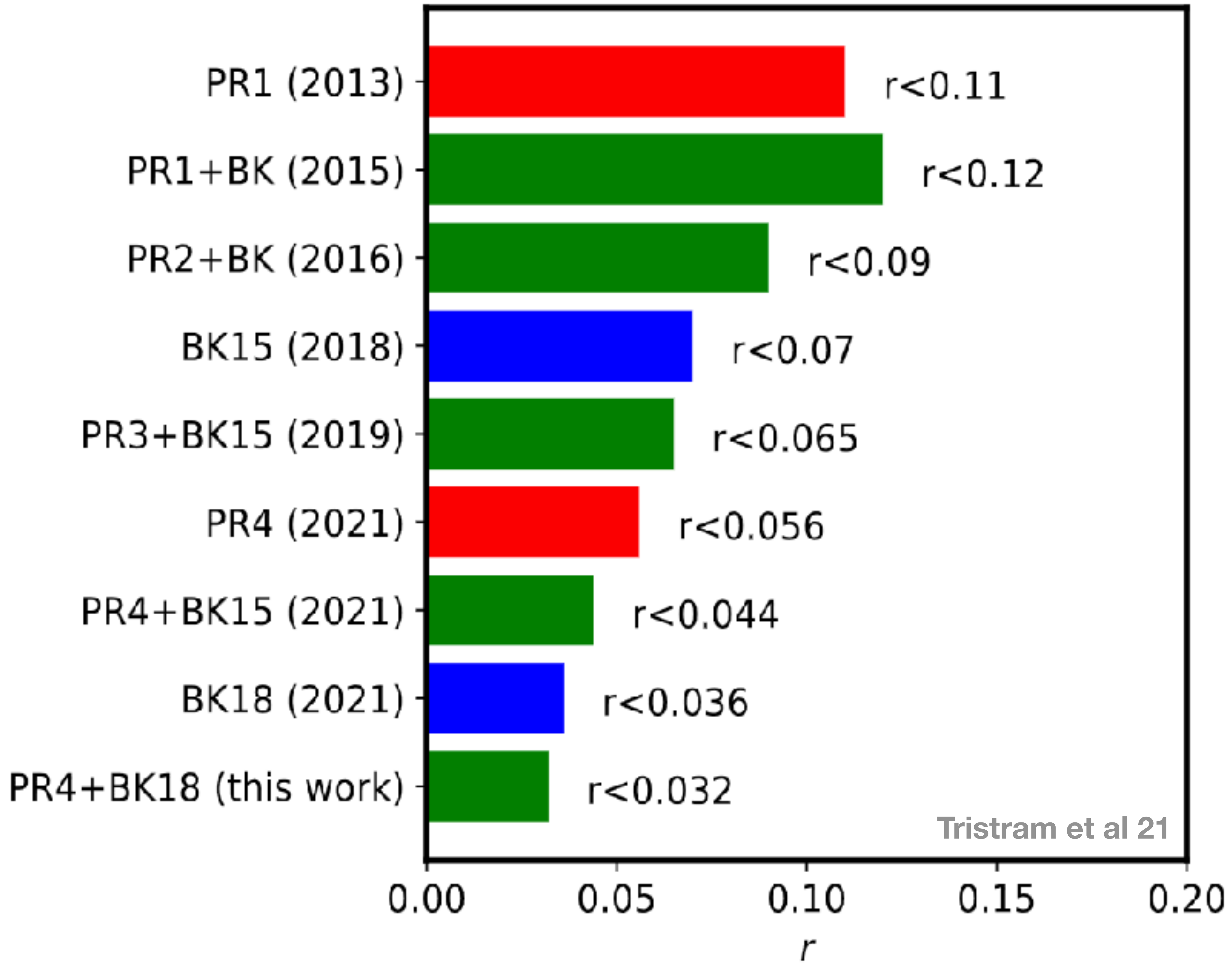


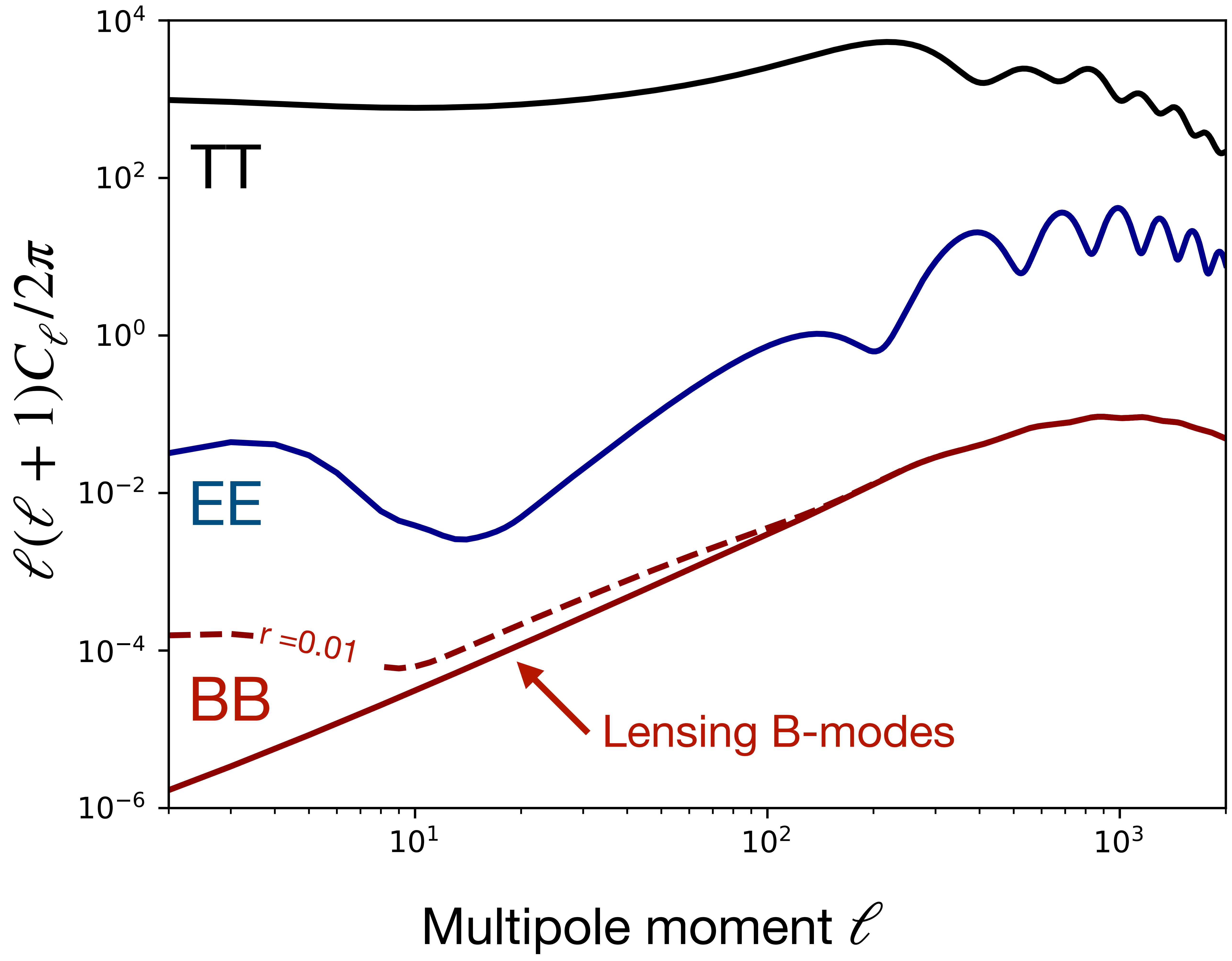




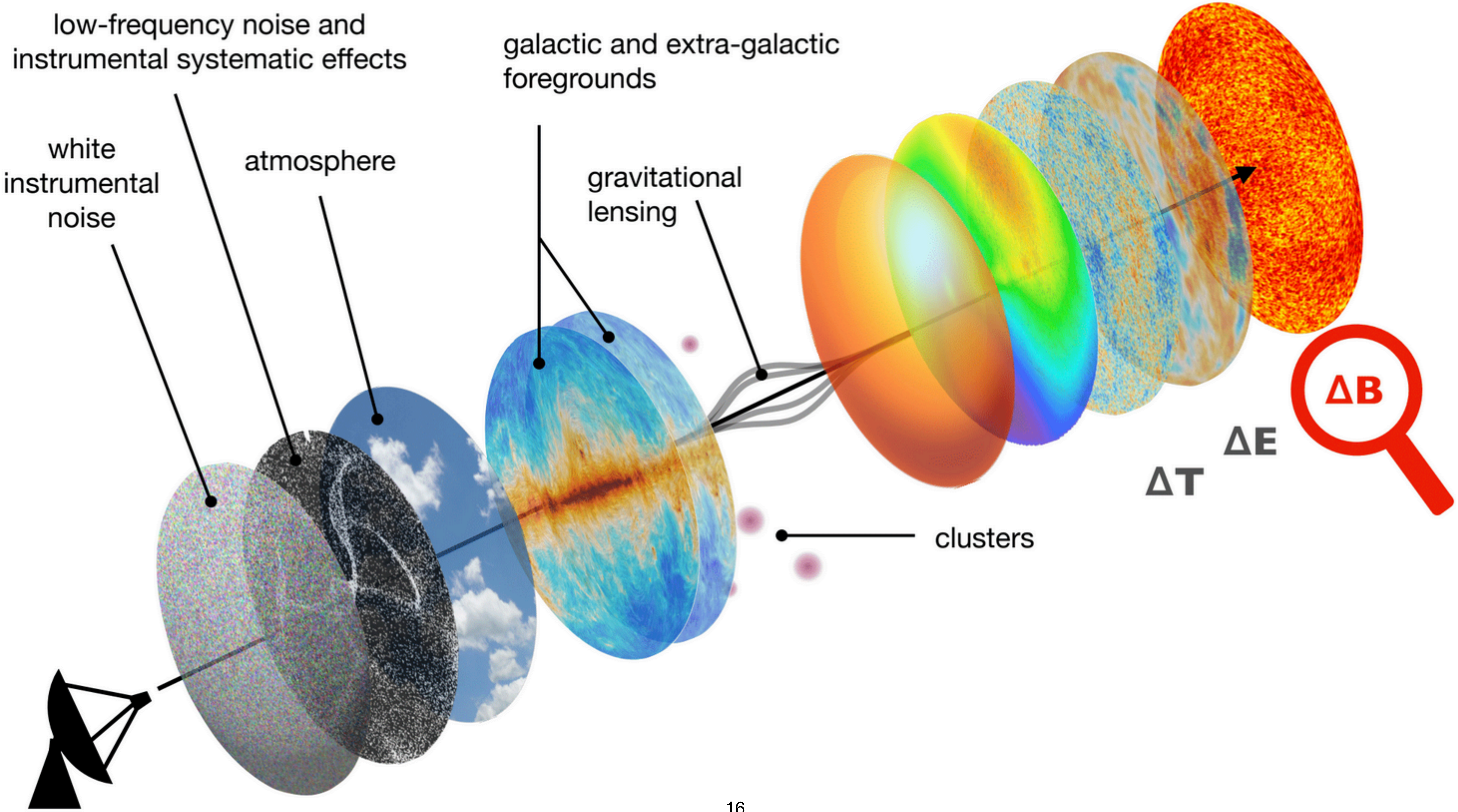
Cosmic Microwave Background

Current constraints on r



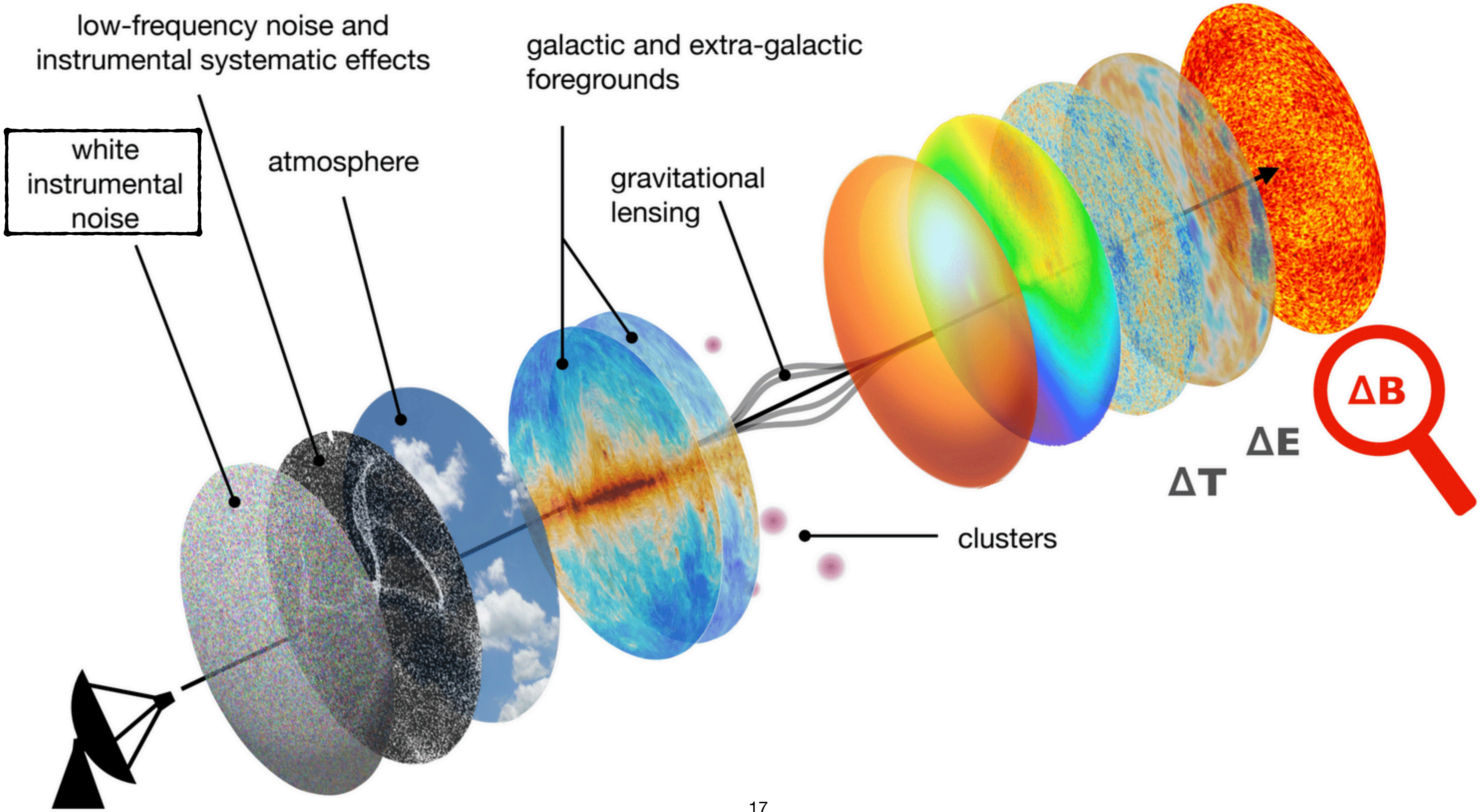


CMB B-modes observations



Credit: J. Errard

CMB B-modes observations



Credit: J. Errard

CMB B-modes observations

Improving sensitivity of future experiments

Noise per detector

Fraction of the sky observed

$$s[\mu\mathrm{K}\,.\,\mathrm{arcmin}] = \frac{\mathrm{NET}[\mu\mathrm{K}\,.\,\sqrt{\mathrm{s}}] \times \sqrt{f_{sky}[\mathrm{arcmin}^2]}}{\sqrt{N_{\mathrm{det}} \times Y \times \Delta t[s]}}$$

Number of detectors

Efficiency

Integration time

CMB B-modes observations

Improving sensitivity of future experiments

$$s[\mu\mathrm{K}\,.\,\mathrm{arcmin}] = \frac{\mathrm{NET}[\mu\mathrm{K}\,.\,\sqrt{\mathrm{s}}] \times \sqrt{f_{sky}[\mathrm{arcmin}^2]}}{\sqrt{N_{\mathrm{det}} \times Y \times \Delta t[s]}}$$

Noise per detector

Fraction of the sky observed

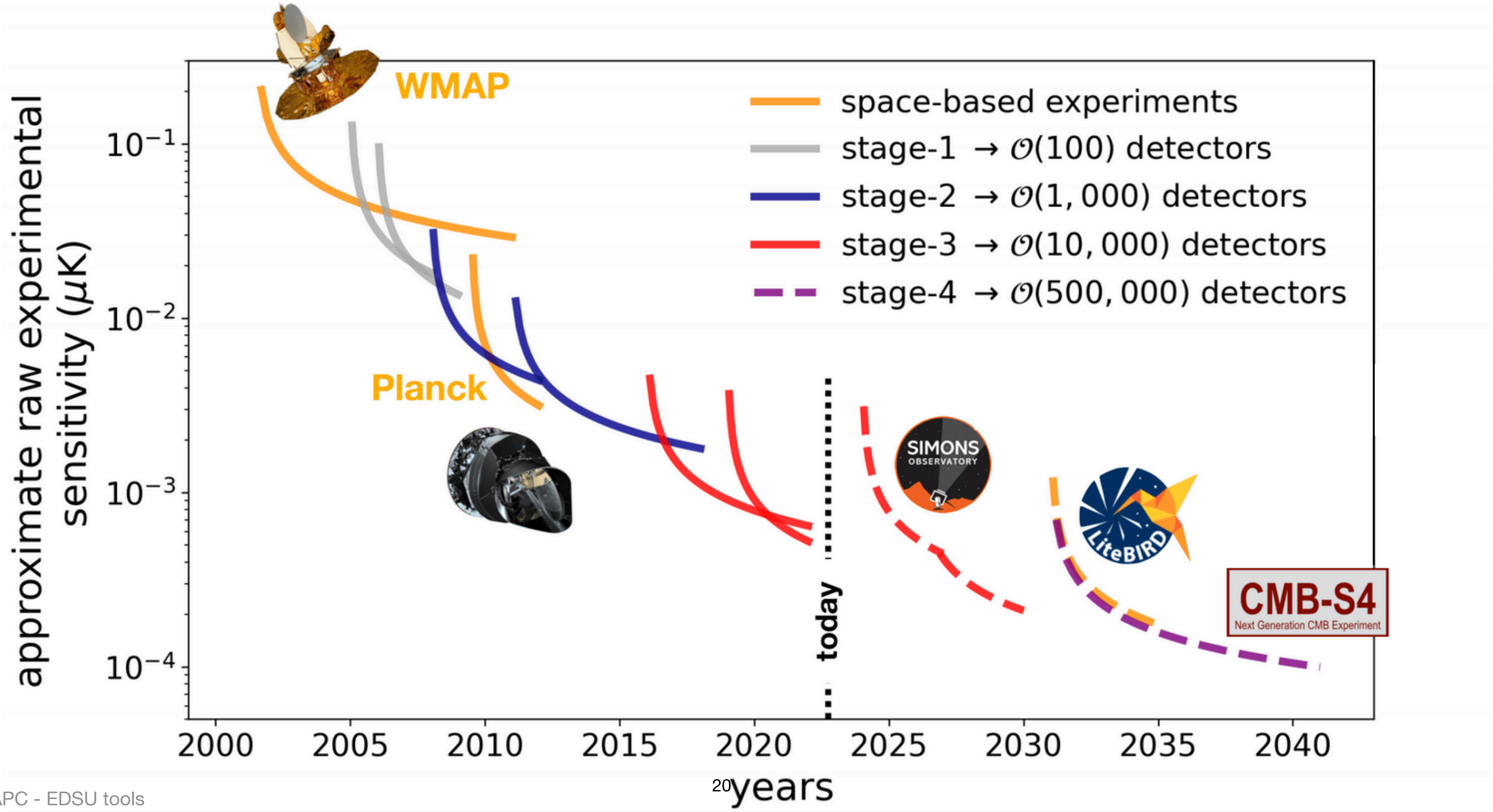
Number of detectors

Efficiency

Integration time

CMB B-modes observations

Improving sensitivity of future experiments

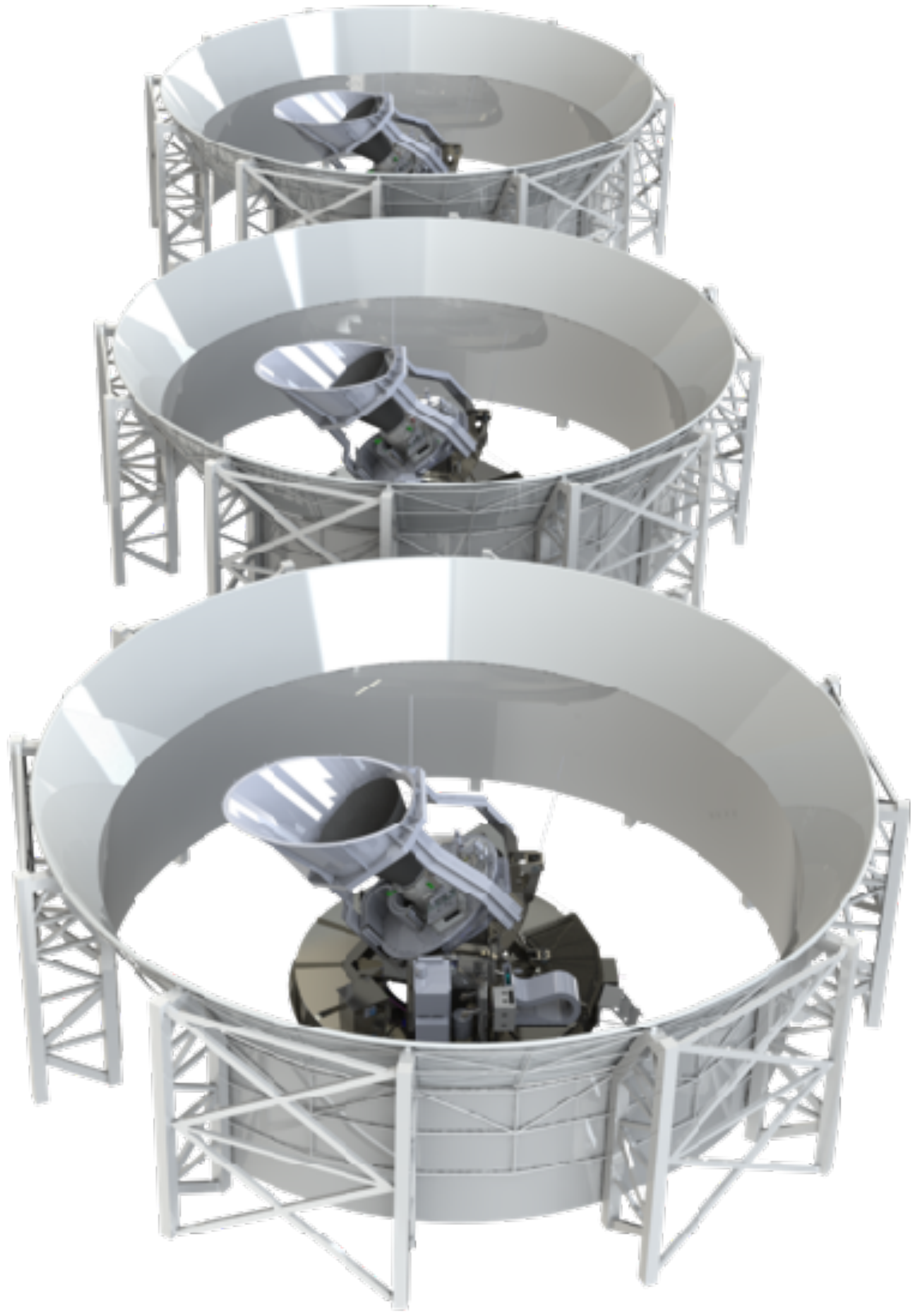


CMB B-modes observations

Simons Observatory

SO Small Aperture Telescopes (SATs)

- Nominally 3 telescopes
- **30.000** TES detectors
- **6 frequency** bands
- Focusing on **large scale polarisation modes**

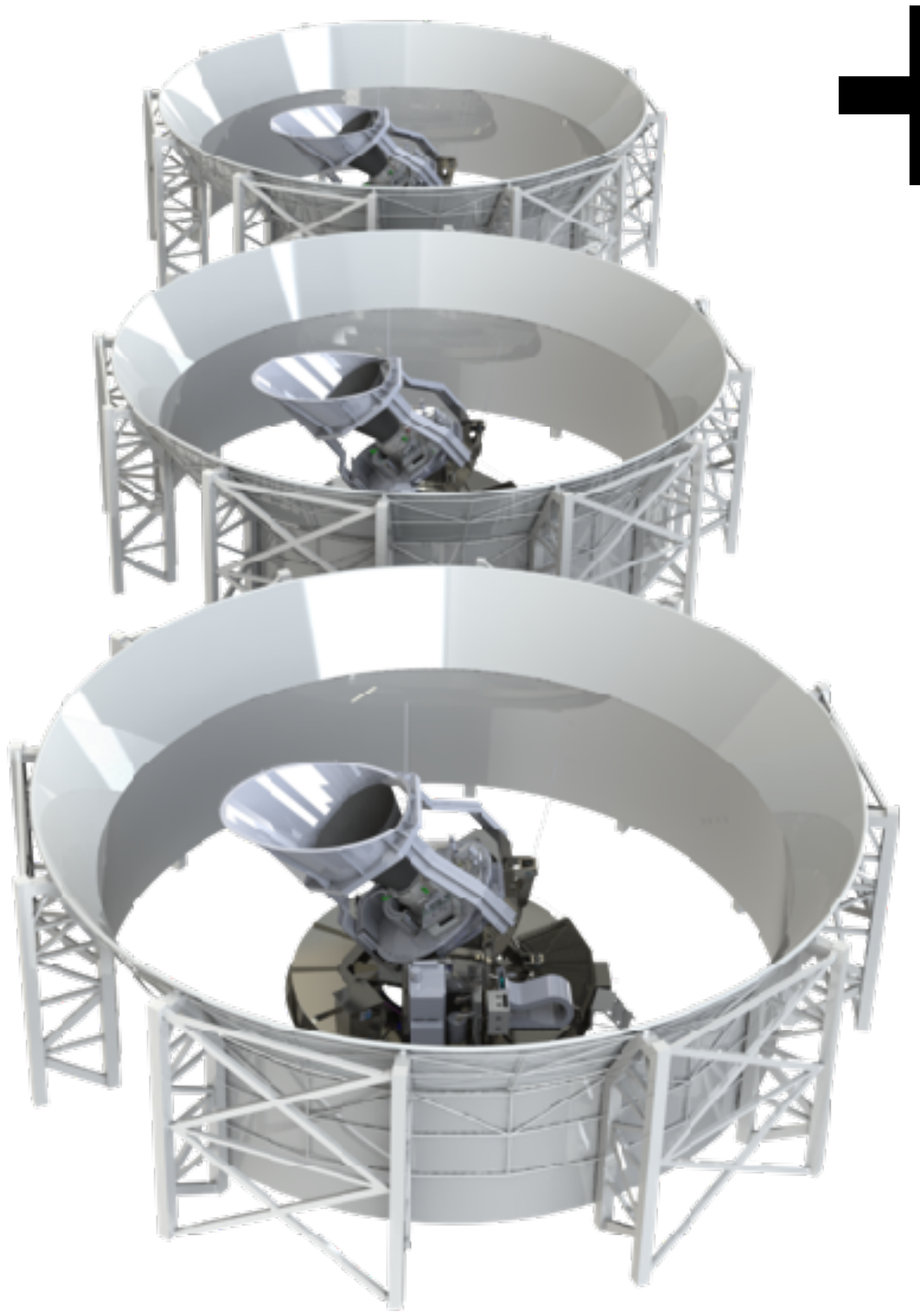


CMB B-modes observations

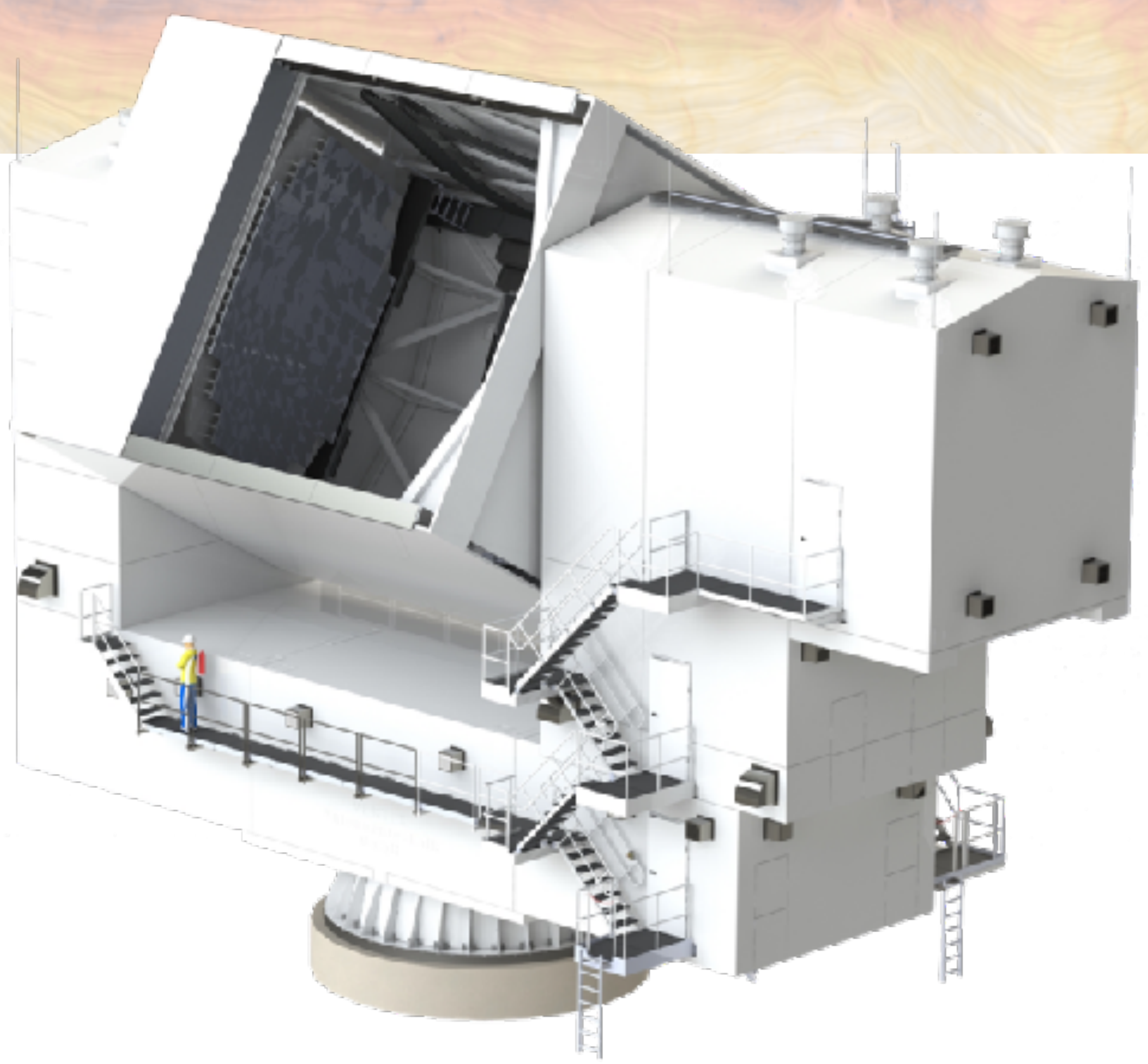
Simons Observatory

SO Small Aperture Telescopes (SATs)

- Nominally 3 telescopes
- **30.000** TES detectors
- **6 frequency** bands
- Focusing on **large scale polarisation modes**



+



SO Large Aperture Telescope (LAT)

- **6m cross-Dragone** telescope
- **30.000** TES detectors
- **6 frequency** bands
- Observing **small scale anisotropies** over a large fraction of the sky

CMB B-modes observations

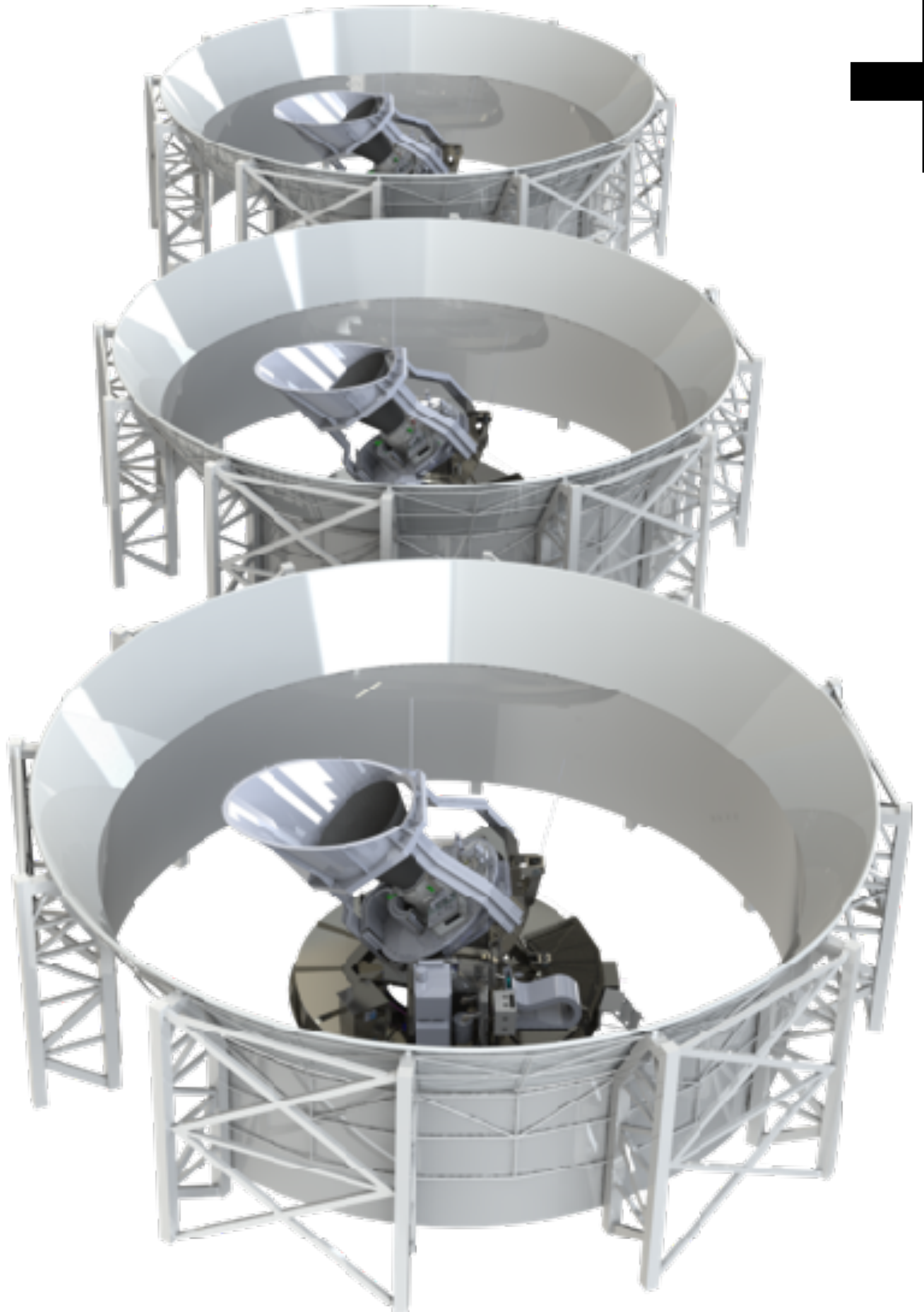
Simons Observatory

SO Small Aperture Telescopes (SATs)

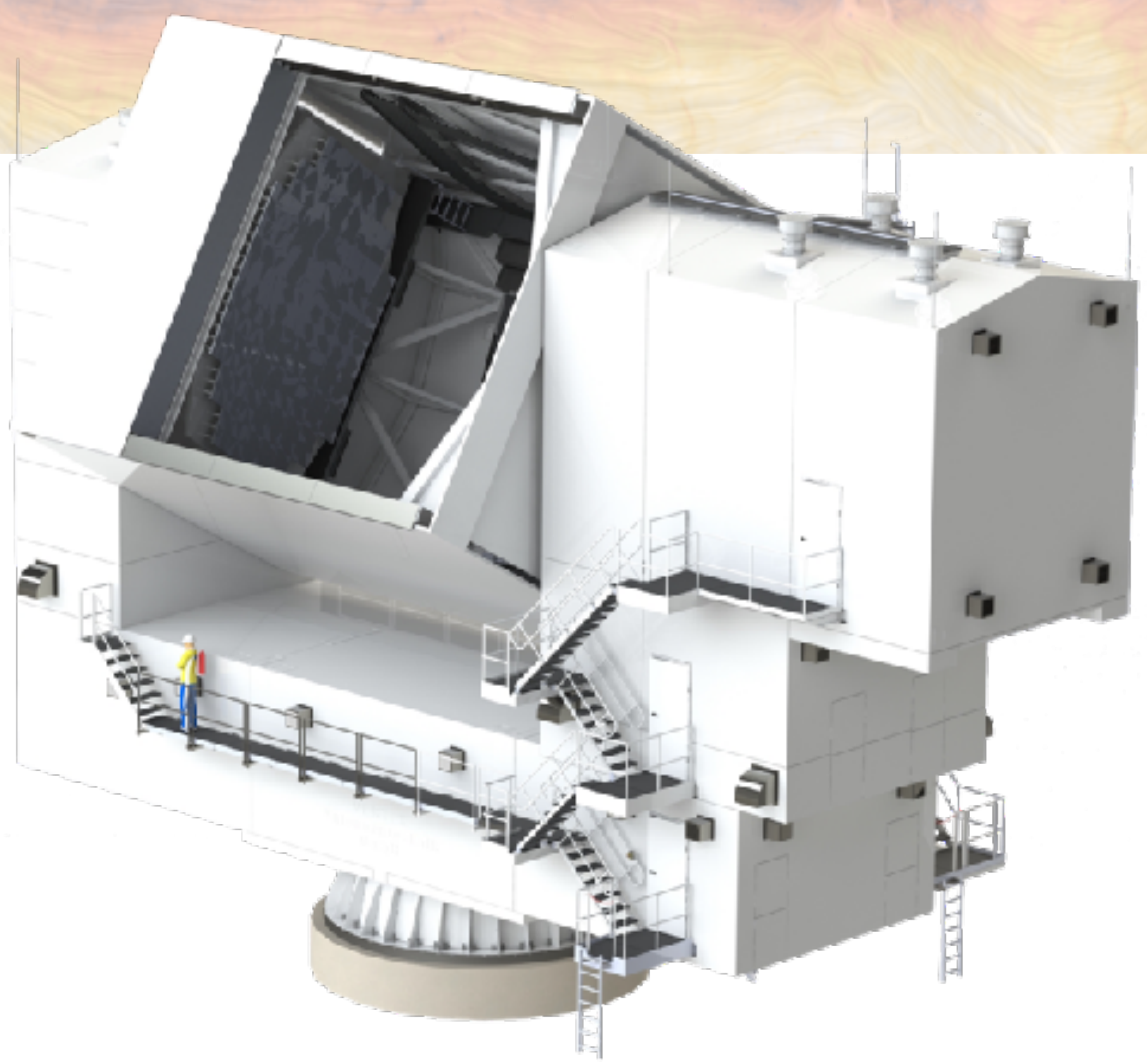
- Nominally 3 telescopes
- **30.000** TES detectors
- **6 frequency** bands
- Focusing on **large scale polarisation modes**

SO:UK + SO:JP

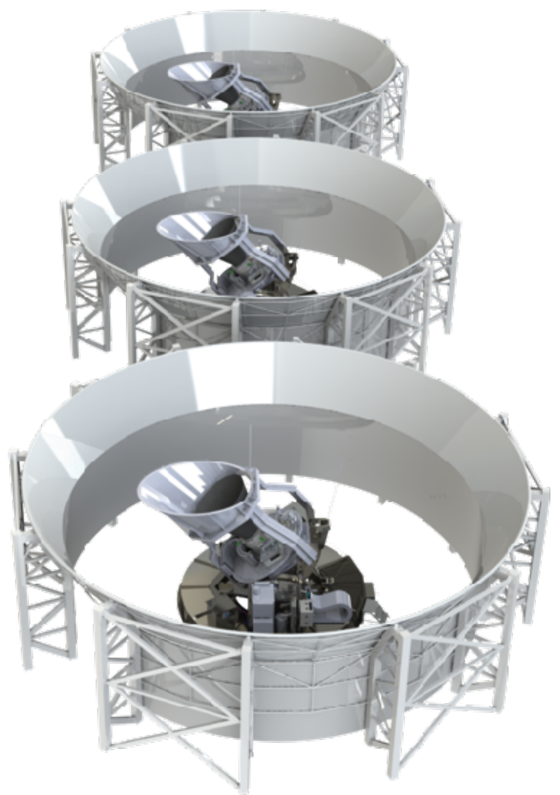
- 3 additional telescopes
- **30.000** TES detectors
- **Extended frequency range**



+



+



SO Large Aperture Telescope (LAT)

- **6m cross-Dragone** telescope
- **30.000** TES detectors
- **6 frequency** bands
- Observing **small scale anisotropies** over a large fraction of the sky

CMB B-modes observations

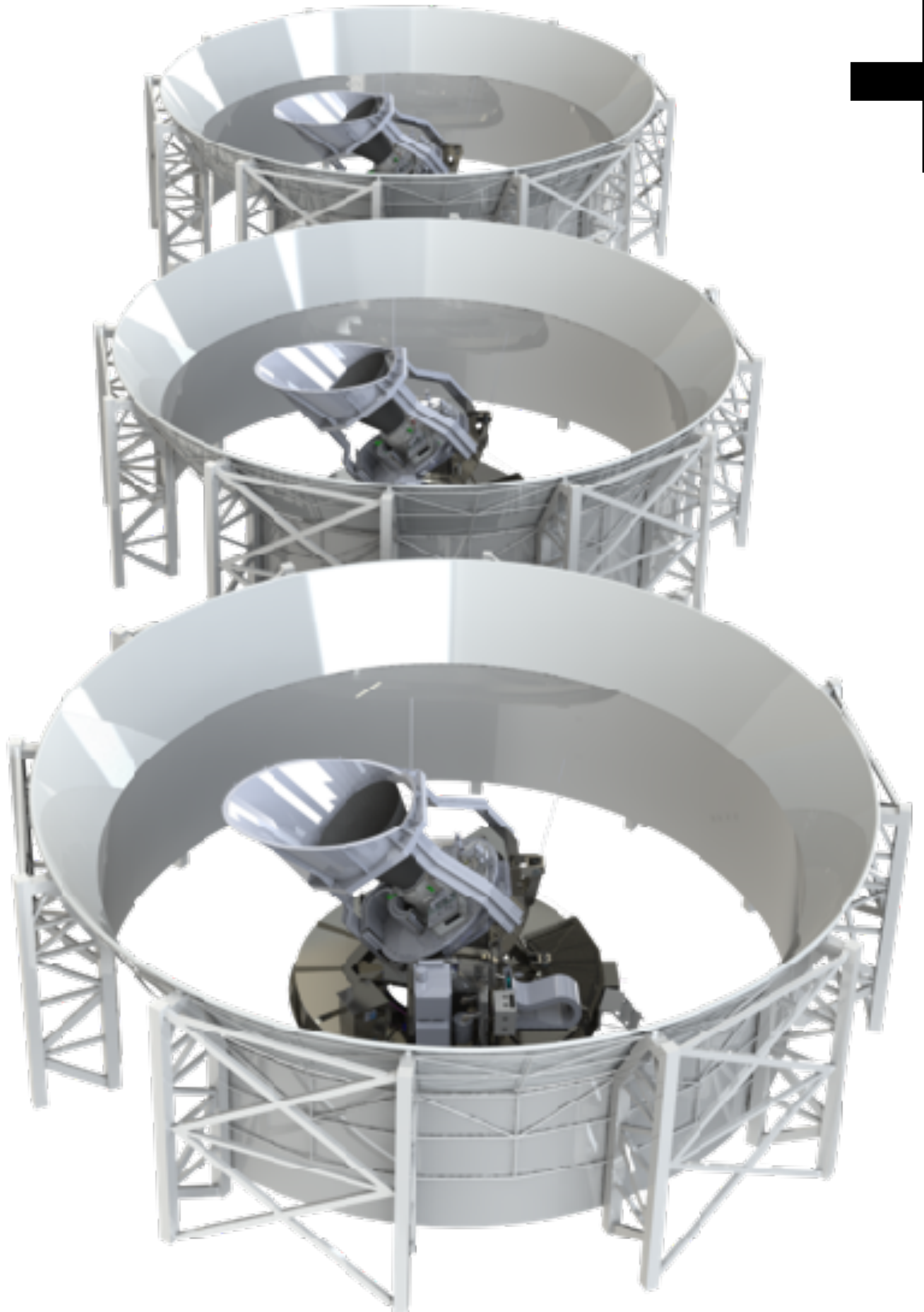
Simons Observatory

SO Small Aperture Telescopes (SATs)

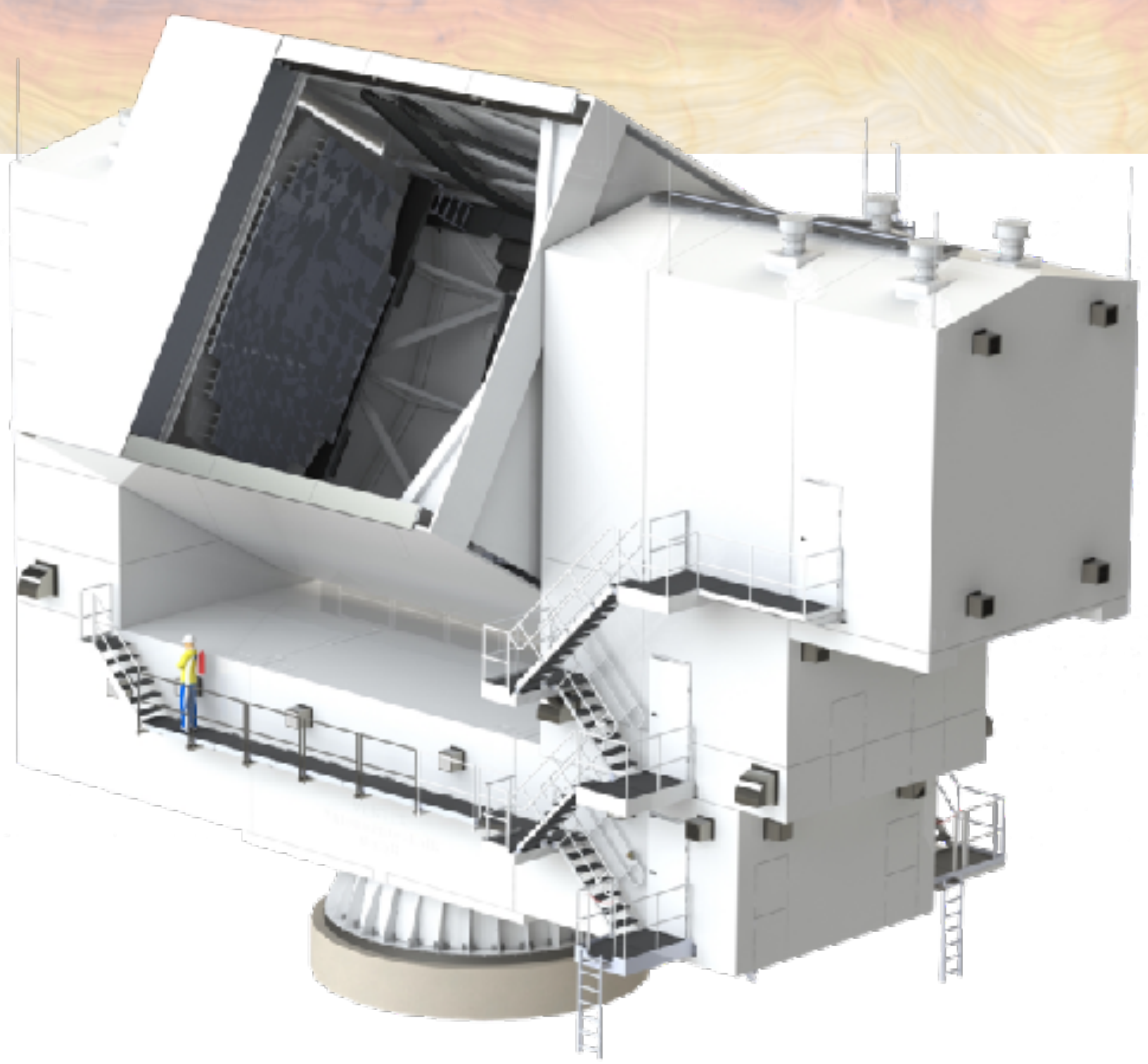
- Nominally 3 telescopes
- **30.000** TES detectors
- **6 frequency** bands
- Focusing on **large scale polarisation modes**

SO:UK + SO:JP + SO:FR ?

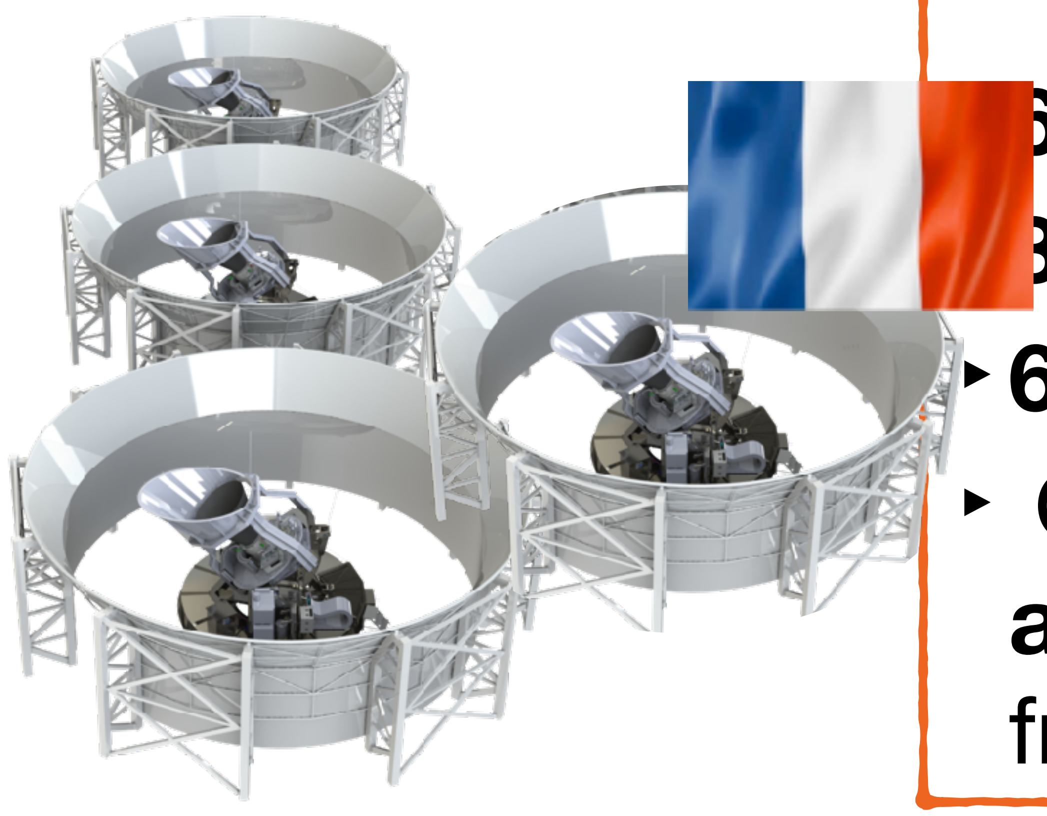
- 3 additional telescopes
- **30.000** TES detectors
- **Extended frequency range**



+



+

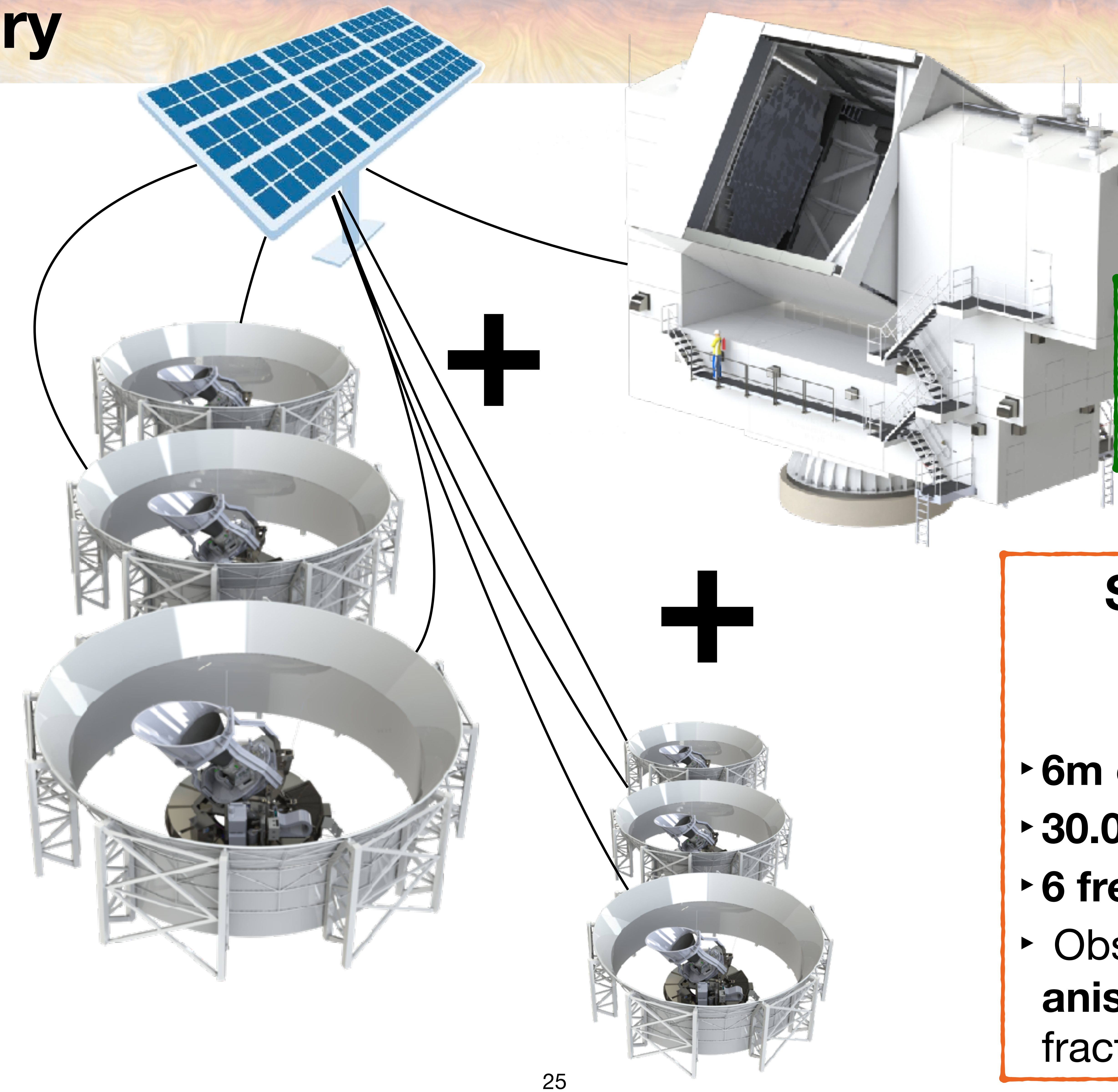


SO Large Aperture Telescope (LAT)

- **6m cross-Dragone** telescope
- **30.000** TES detectors
- **6 frequency** bands
- Observing **small scale anisotropies** over a large fraction of the sky

CMB B-modes observations

Simons Observatory



SO Small Aperture Telescopes (SATs)

- Nominally 3 telescopes
- **30.000** TES detectors
- **6 frequency** bands
- Focusing on **large scale polarisation modes**

SO:UK + SO:JP

- 3 additional telescopes
- **30.000** TES detectors
- **Extended frequency range**

SO PV array

- **-70% diesel consumption**
- **+9% efficiency**

SO Large Aperture Telescope (LAT)

- **6m cross-Dragone** telescope
- **30.000** TES detectors
- **6 frequency** bands
- Observing **small scale anisotropies** over a large fraction of the sky

CMB B-r

Simons Obse

PARQUE ASTRONÓMICO ATACAMA, CHILE
SIMONS OBSERVATORY
22°57' S, 67°47' W
ELEVATION: 5190m
www.simonsobservatory.org

SO Small Aper
Telescopes (S

- Nominally 3 telesc
- **30.000** TES detect
- **6 frequency** band
- Focusing on **large**
polarisation mod

SO:UK + SO:

- 3 additional telesc
- **30.000** TES detect
- **Extended frequen**
range

SO PV array

- diesel consumption
- efficiency

rge Aperture
cope (LAT)

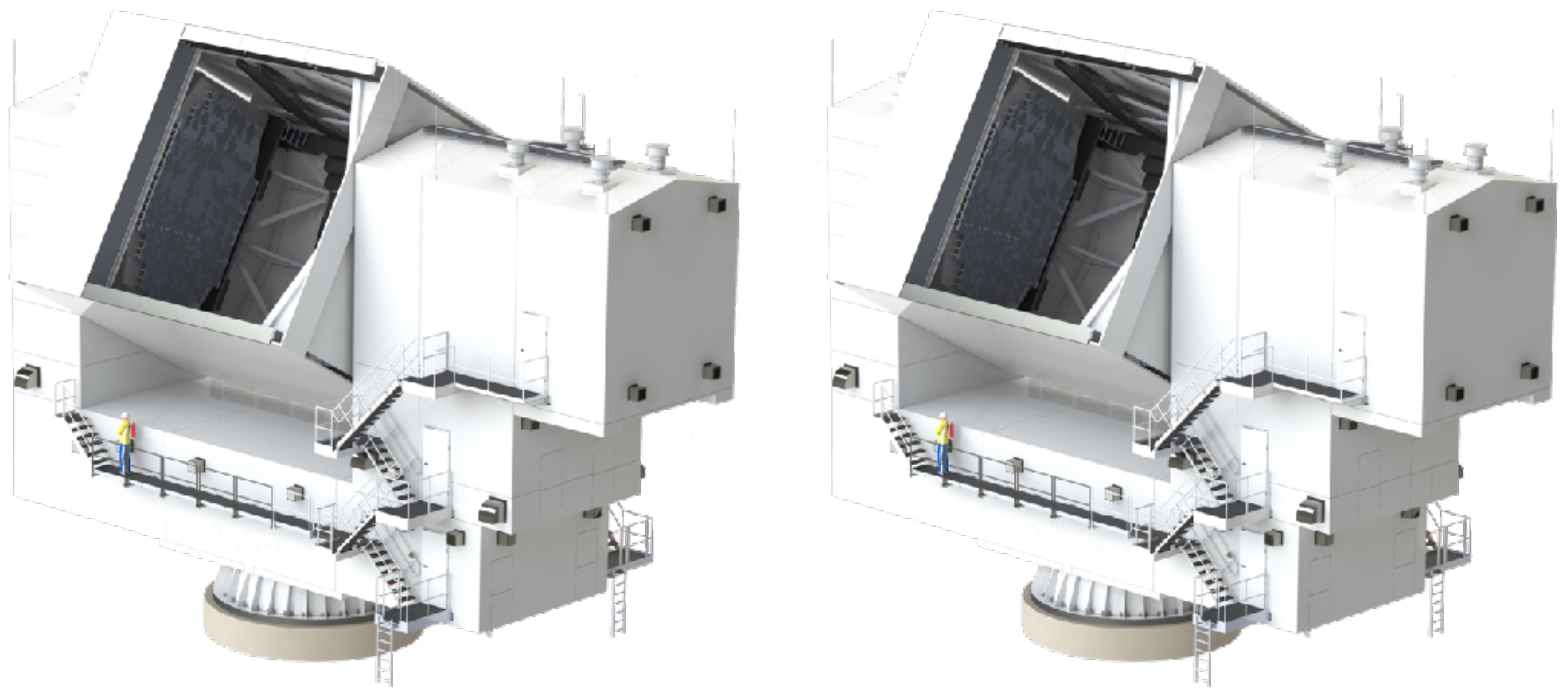
- **Dragone** telescope
- detectors
- **y** bands
- **small scale**
es over a large
the sky

CMB B-modes observations

CMB Stage 4

Nominal configuration (until a few weeks ago)

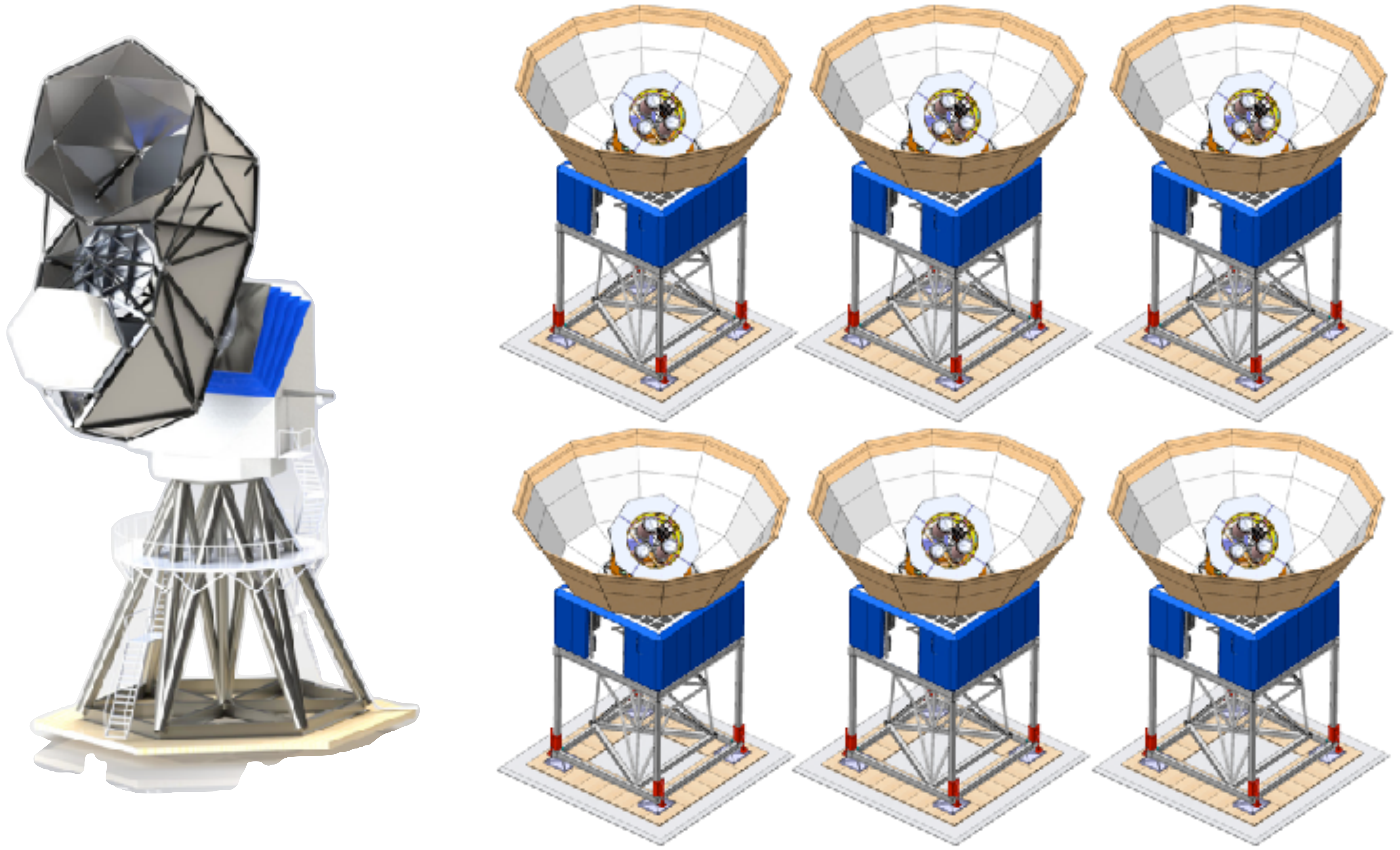
Chilean Observatory



- Deep & wide survey
- Two LATs, ~60% of the sky
- 240,000 detectors

+

South Pole Observatory



- Delensing LAT, 120,000 detectors
- SATs, 150,000 detectors
- 3% of the sky

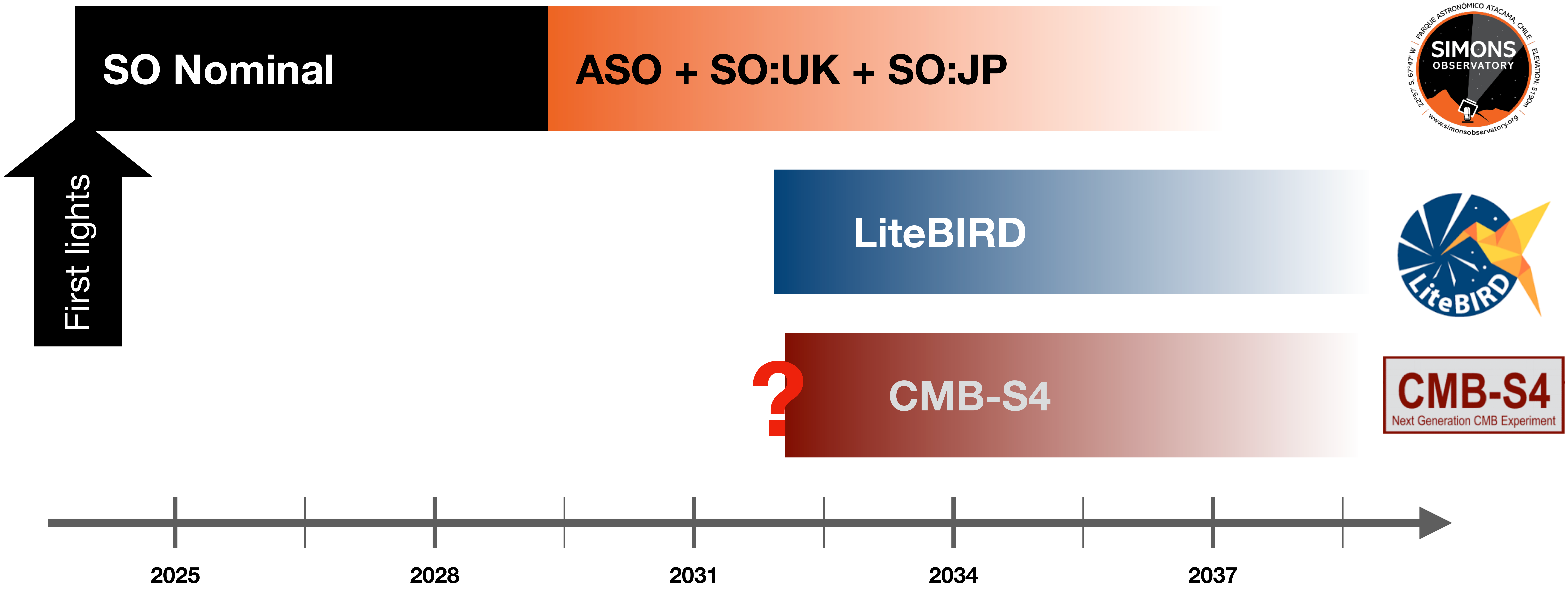
CMB B-modes observations

LiteBIRD

See next talk by Gilles Weymann-Despres !

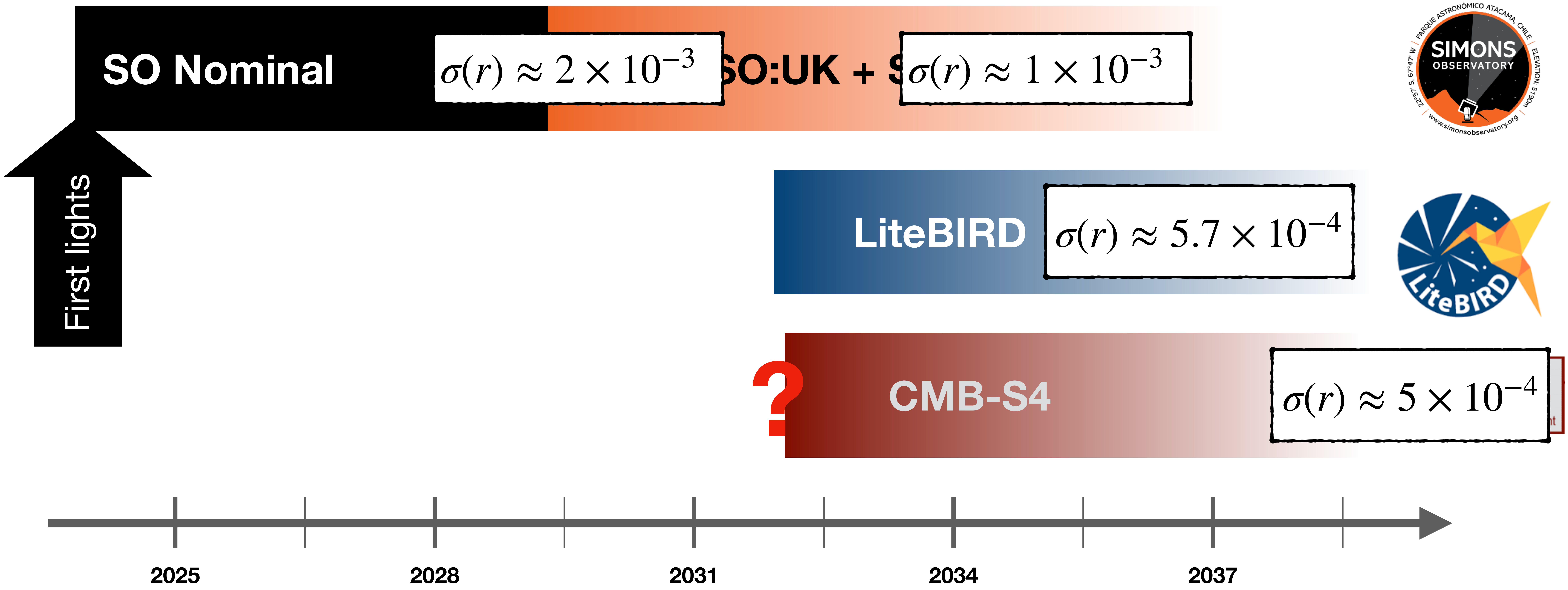
CMB B-modes observations

Future Observatories

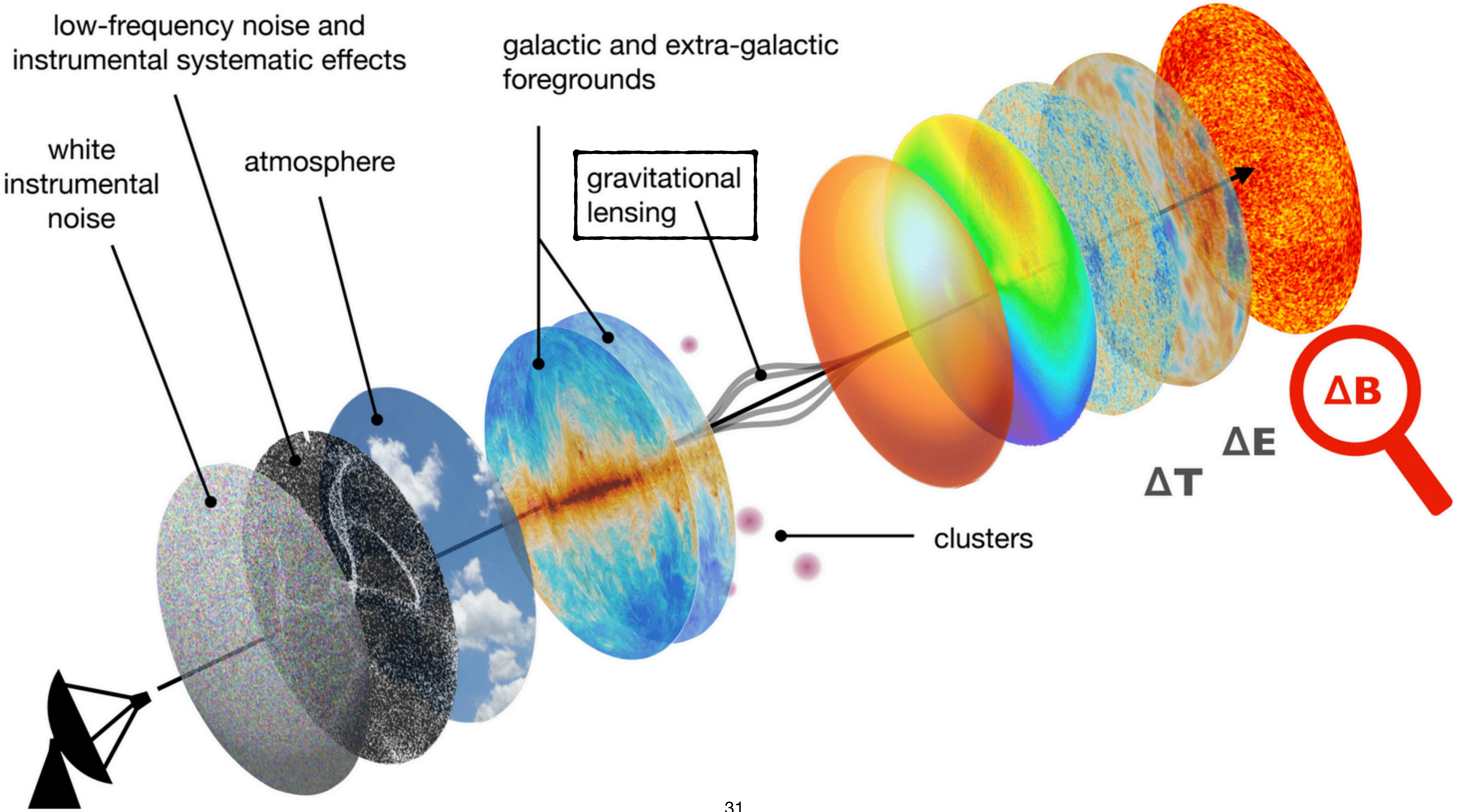


CMB B-modes observations

Future Observatories



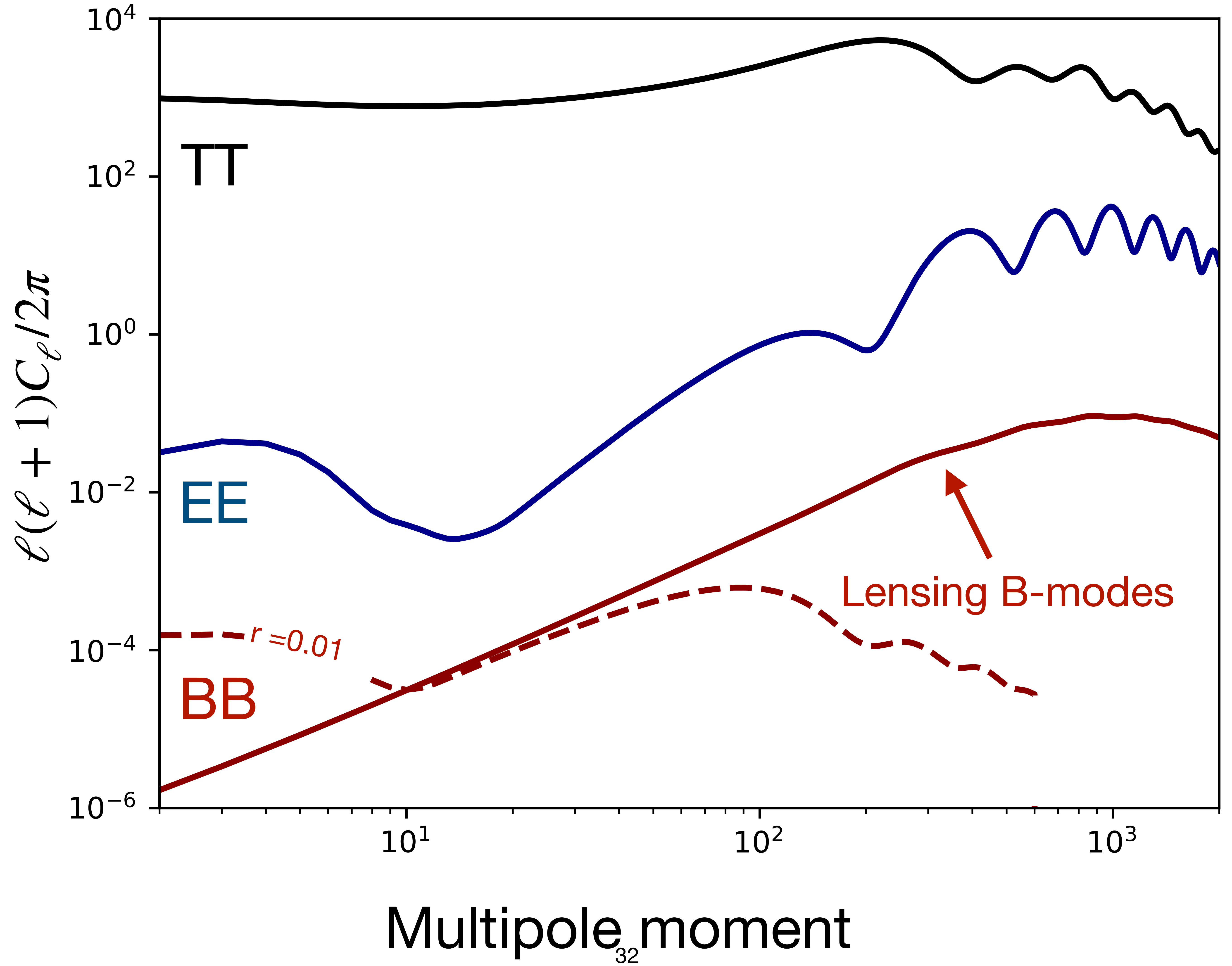
CMB B-modes observations



Credit: J. Errard

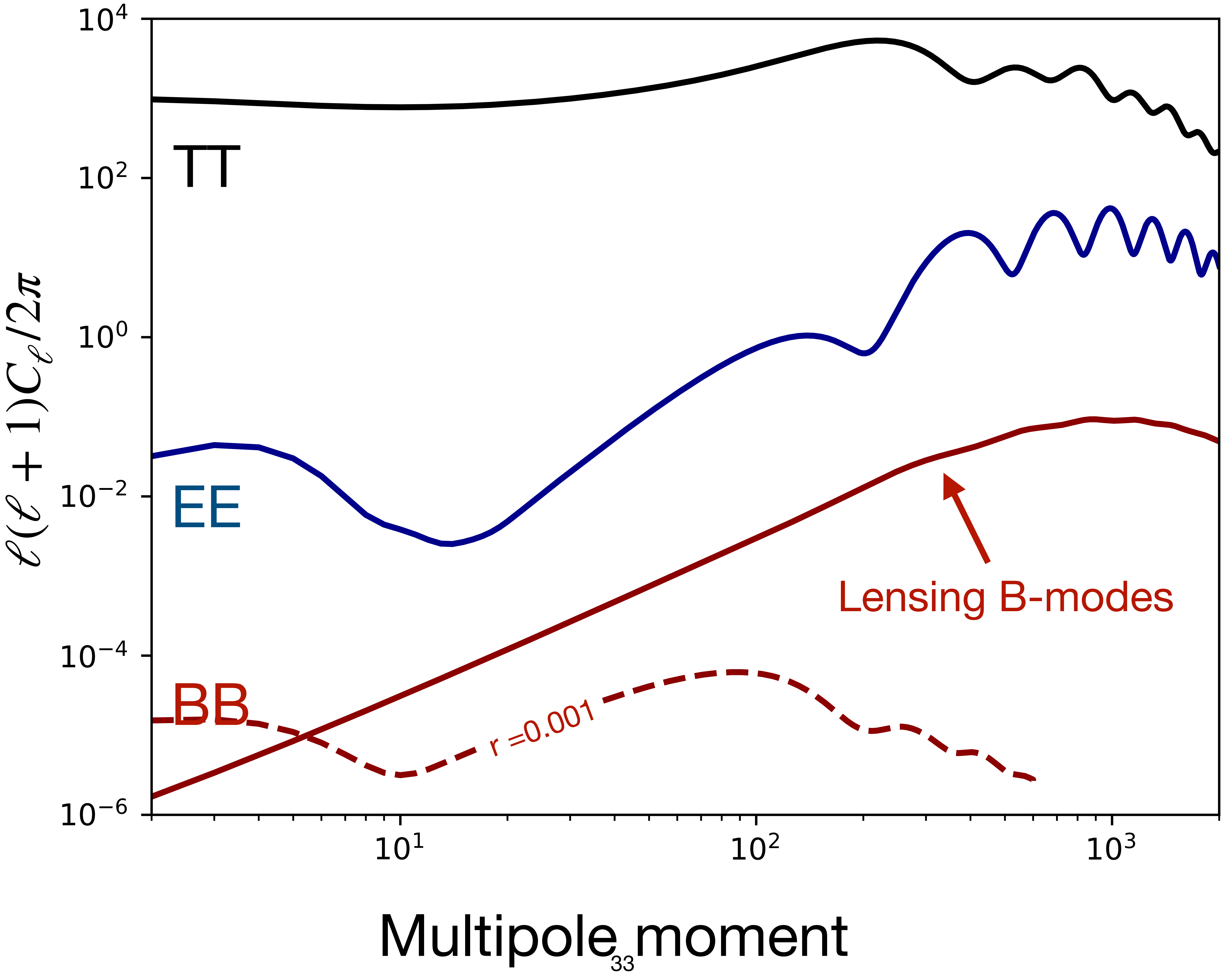
CMB B-modes observations

Delensing



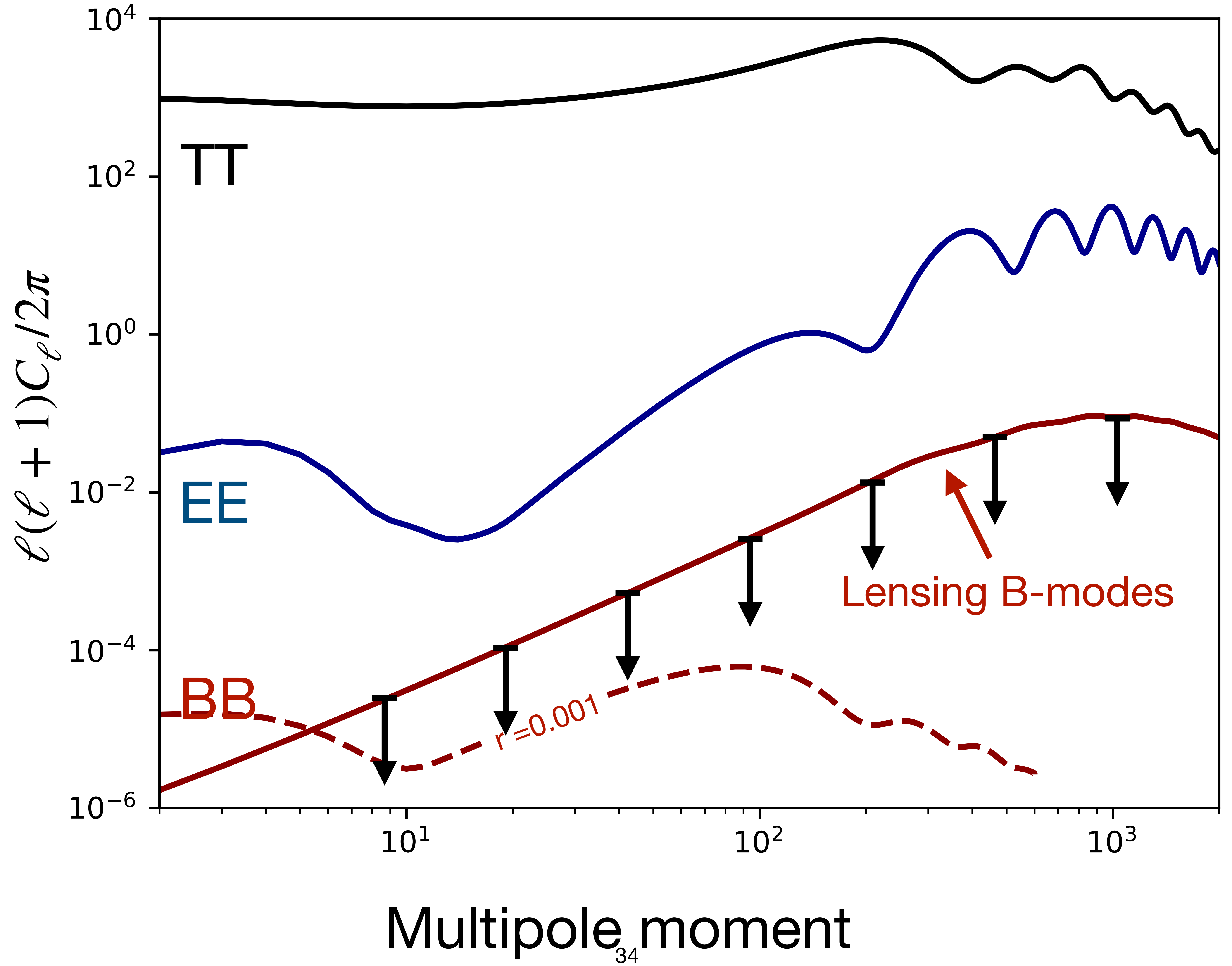
CMB B-modes observations

Delensing



CMB B-modes observations

Delensing

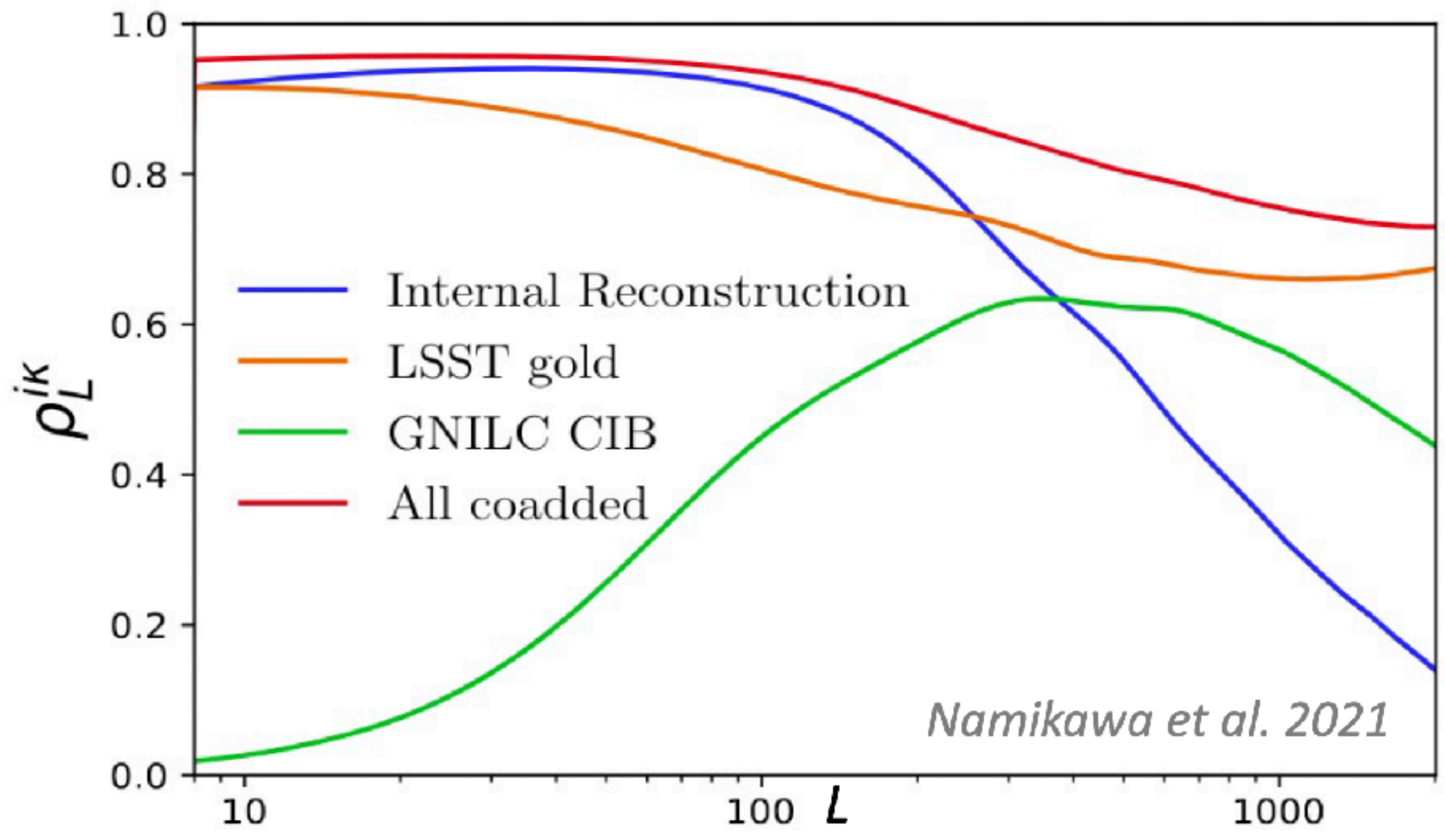


CMB B-modes observations

Delensing

Delensing steps

1. Need to reconstruct the gravitational potential
2. Estimate the lensing B-modes
3. Subtract from the observed B-modes

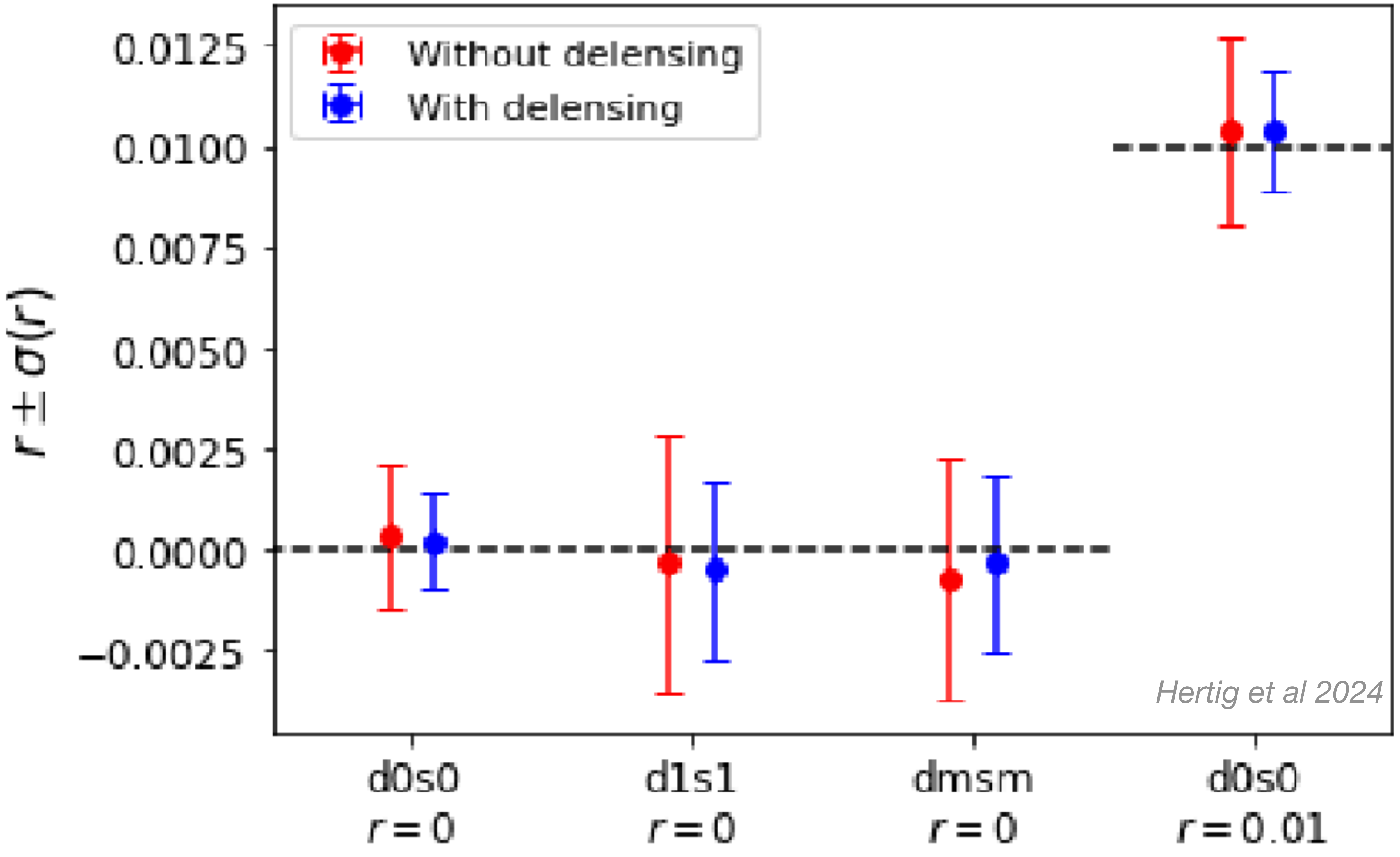


CMB B-modes observations

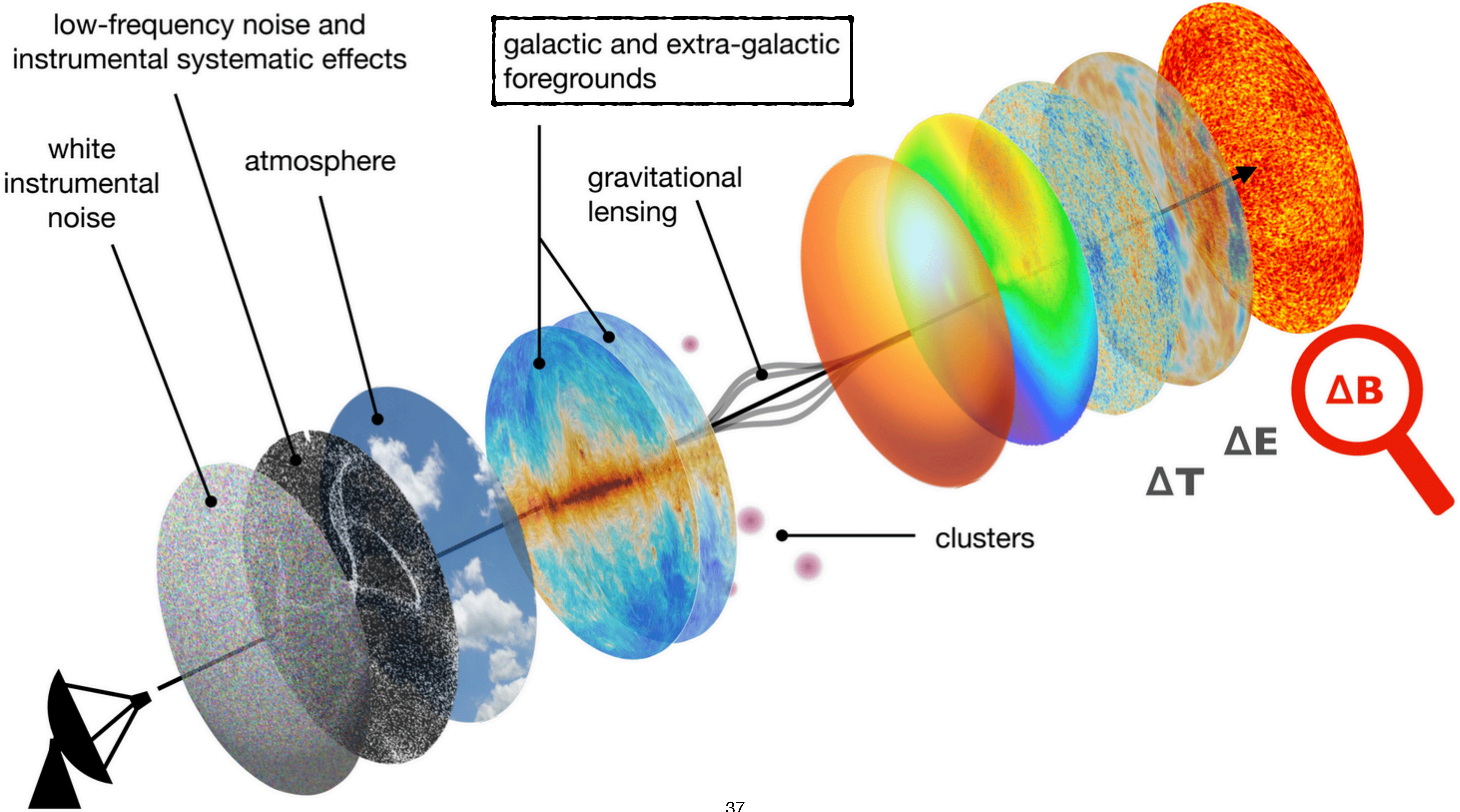
Delensing

Delensing steps

1. Need to reconstruct the gravitational potential
2. Estimate the lensing B-modes
3. Subtract from the observed B-modes



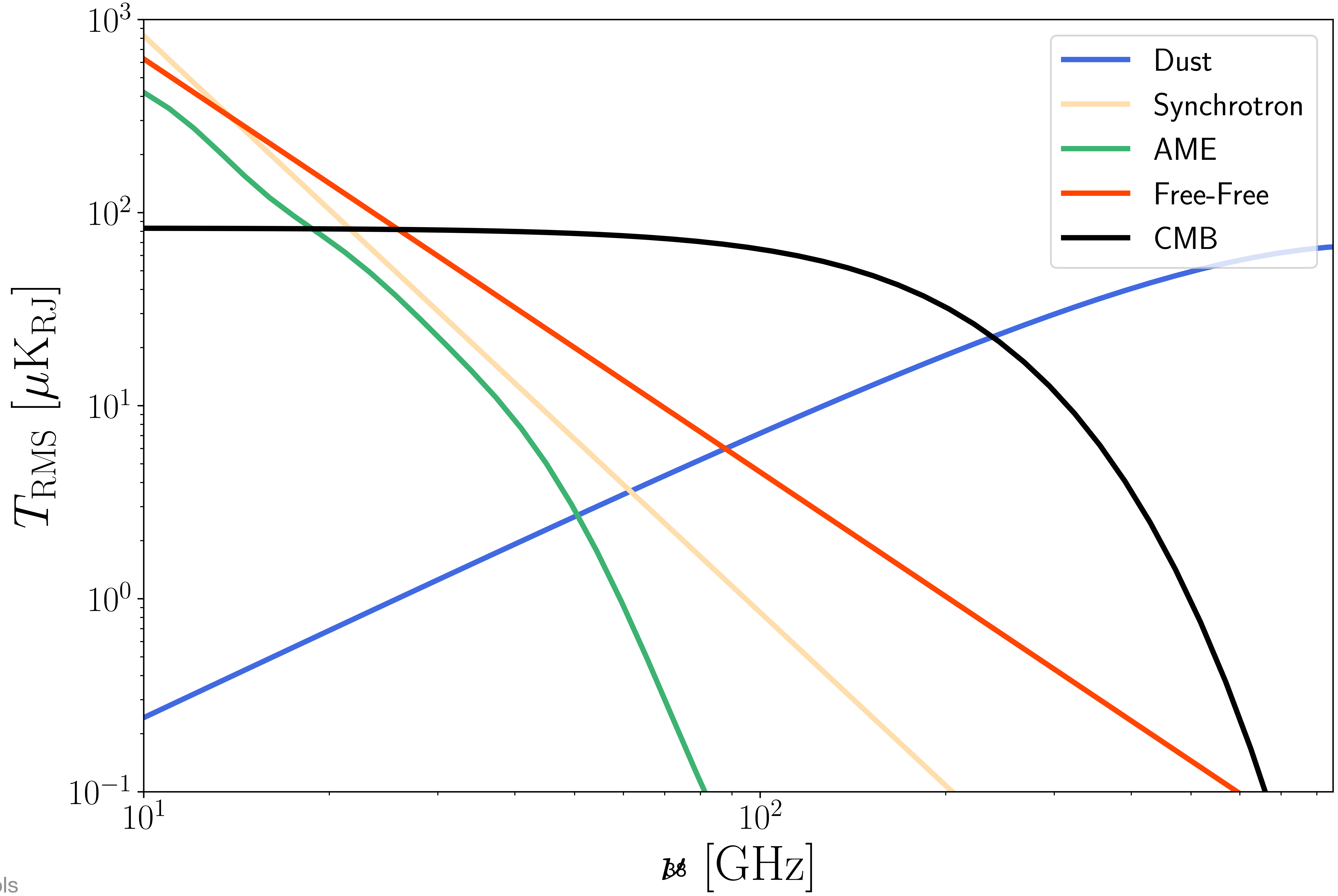
CMB B-modes observations



Credit: J. Errard

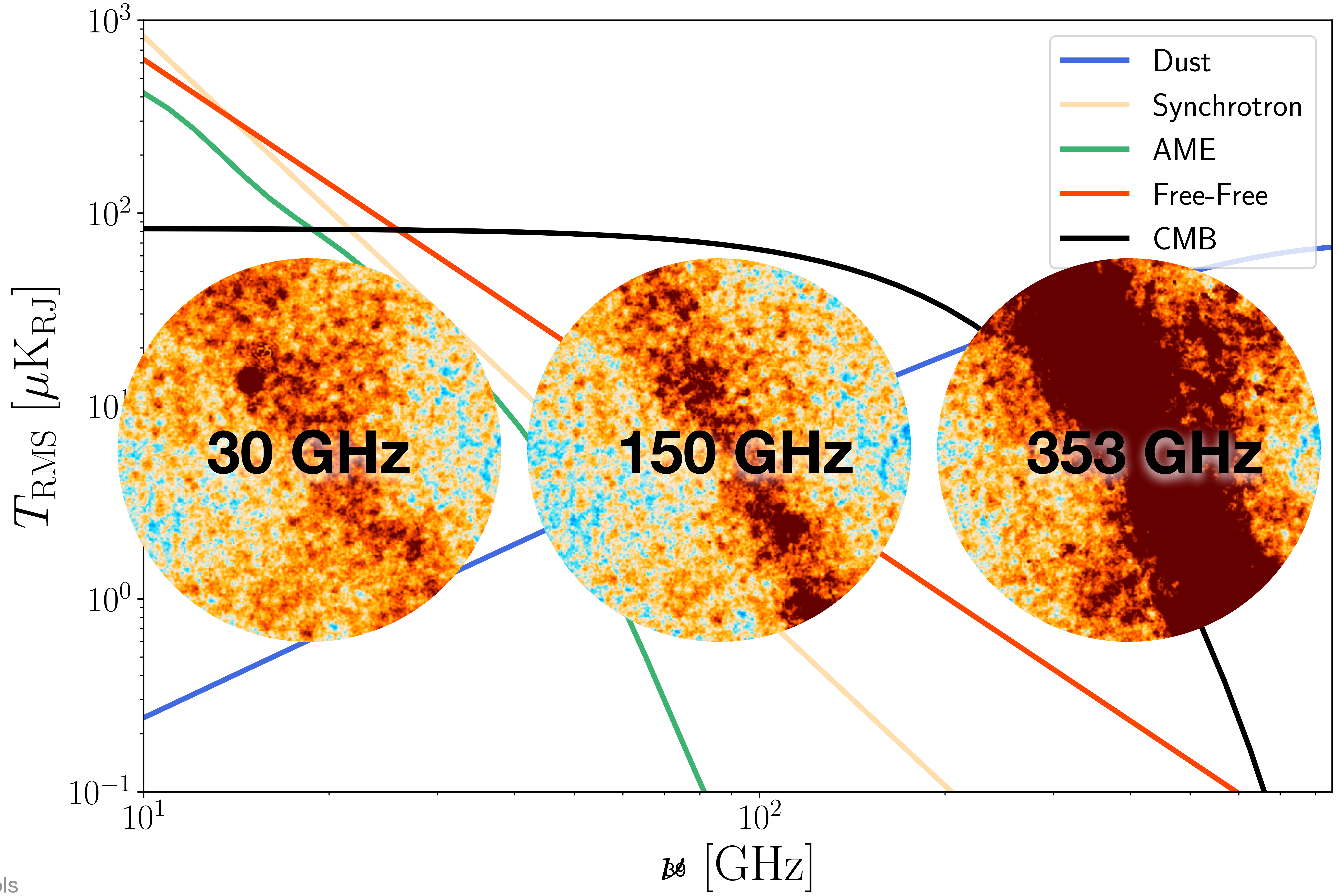
CMB B-modes observations

The mm/sub-mm sky



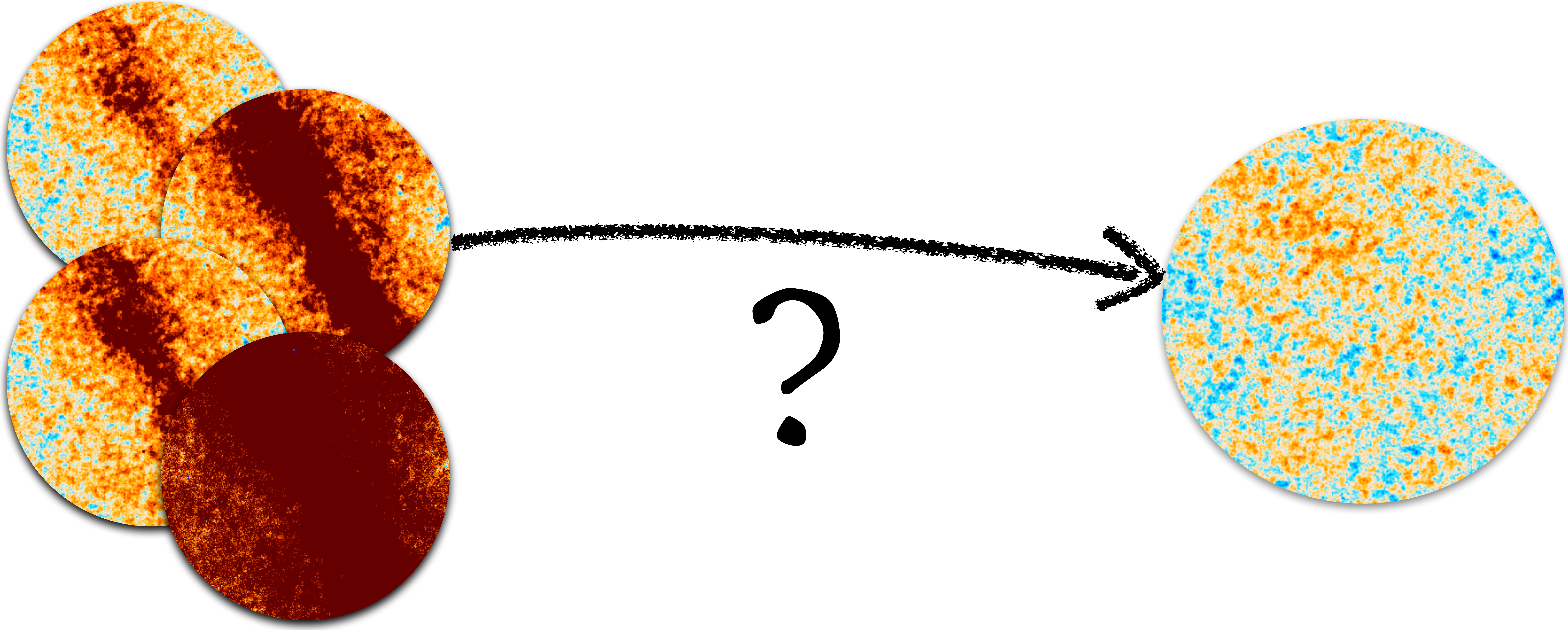
CMB B-modes observations

The mm/sub-mm sky



CMB B-modes observations

Component separation



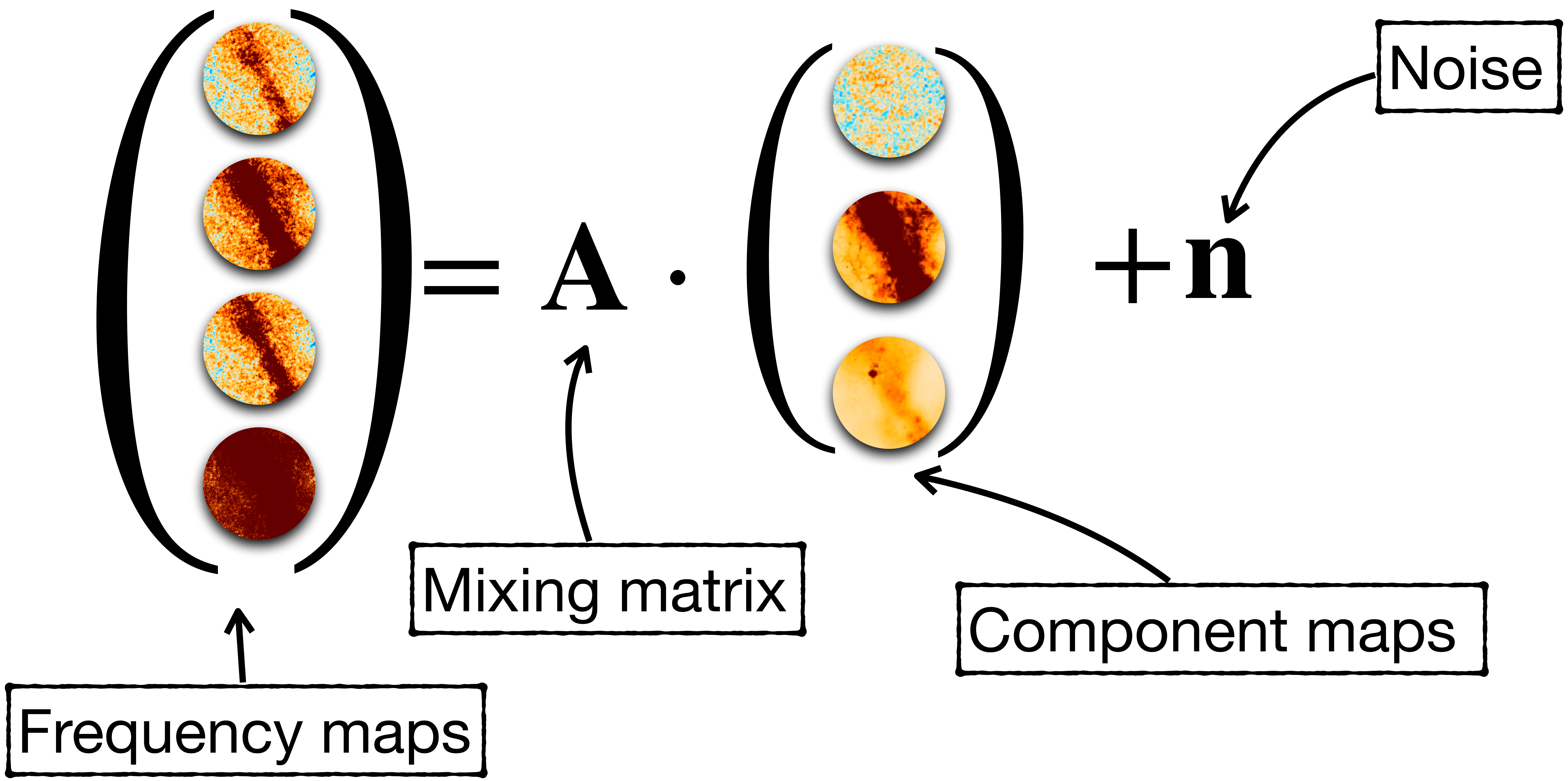
CMB B-modes observations

Component separation

$$\mathbf{d} = \mathbf{A} \cdot \mathbf{s} + \mathbf{n}$$

CMB B-modes observations

Component separation



CMB B-modes observations

Component separation

Blind Methods:

- Minimum assumptions
- **Example**: ILC
  - Assume **one column of A** is known
  - **Compute weights** such that $w \cdot a = 1$ and $\hat{s} \equiv w \cdot d$ has **minimum variance**
  - $w = \dfrac{a^{\mathrm{T}}\hat{R}^{-1}}{a^{\mathrm{T}}\hat{R}^{-1}a}$

CMB B-modes observations

Component separation

Blind Methods:

- Minimum assumptions
- **Example**: ILC
  - Assume **one column of A** is known
  - **Compute weights** such that $w \cdot a = 1$ and $\hat{s} \equiv w \cdot d$ has **minimum variance**
  - $w = \dfrac{a^{\mathrm{T}}\hat{R}^{-1}}{a^{\mathrm{T}}\hat{R}^{-1}a}$

- **Example**: SMICA [Cardoso et al 2008]
  - **Provide structure of A** and s
  - Fit model to the data
  - Wiener filtering of the input maps with best-fit model

CMB B-modes observations

Component separation

Blind Methods:

- Minimum assumptions
- **Example**: ILC
  - Assume **one column of A** is known
  - **Compute weights** such that $w \cdot a = 1$ and $\hat{s} \equiv w \cdot d$ has **minimum variance**
  - $w = \dfrac{a^{\mathrm{T}}\hat{R}^{-1}}{a^{\mathrm{T}}\hat{R}^{-1}a}$

- **Example**: SMICA [Cardoso et al 2008]
  - **Provide structure of A** and s
  - Fit model to the data
  - Wiener filtering of the input maps with best-fit model

- sps4lat, for SIMONS OBSERVATORY on GitHub
- SMICAX, for LiteBIRD using JAX

CMB B-modes observations

Component separation

Parametric Methods:

- Build a complete model
- Fit it to the data
- **Example**: fgbuster [Errard and Stompor 2012]
  - Model the mixing matrix
  - Maximise the spectral likelihood
  - Use the best-fit maxing matrix to derive the component maps

CMB B-modes observations

Component separation

Parametric Methods:

- Build a complete model
- Fit it to the data
- **Example**: fgbuster [Errard and Stompor 2012]
  - Model the mixing matrix
  - Maximise the spectral likelihood
  - Use the best-fit mixing matrix to derive the component maps

MEGATOP pipeline for SIMONS OBSERVATORY

CMB B-modes observations

Component separation

Parametric Methods:

- Build a complete model
- Fit it to the data
- **Example**: fgbuster [Errard and Stompor 2012]
  - Model the mixing matrix
  - Maximise the spectral likelihood
  - Use the best-fit mixing matrix to derive the component maps

MEGATOP pipeline for SIMONS OBSERVATORY

- **Example**: Cosmo analysis
  - Construct noiseless power spectra from splits
  - Model foreground and systematics at the power spectrum level
  - Maximise (gaussian) likelihood

CMB B-modes observations

Component separation

Parametric Methods:

- Build a complete model
- Fit it to the data
- **Example**: fgbuster [Errard and Stompor 2012]
  - Model the mixing matrix
  - Maximise the spectral likelihood
  - Use the best-fit mixing matrix to derive the component maps

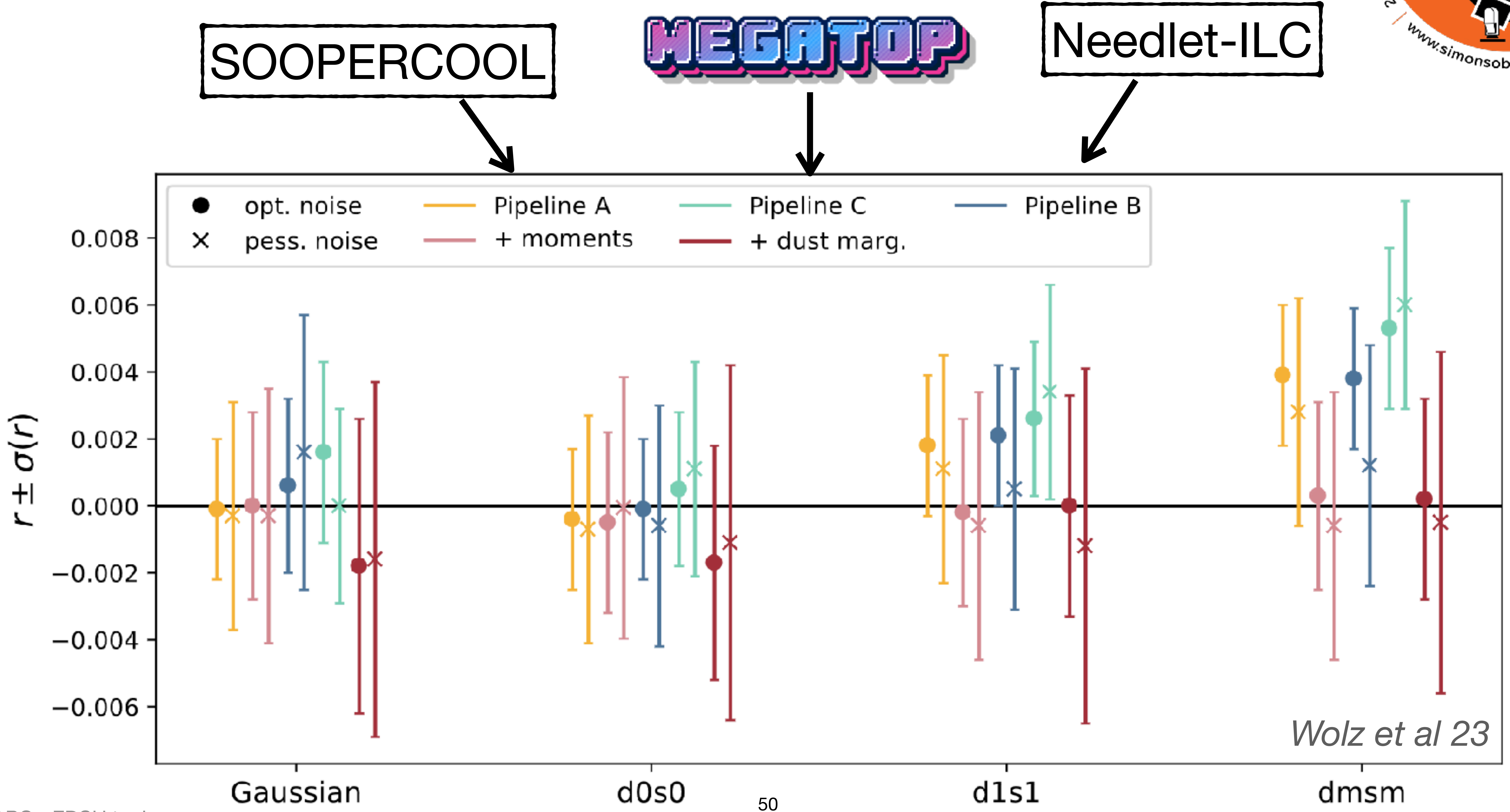
MEGATOP pipeline for SIMONS OBSERVATORY

- **Example**: Cosmo analysis
  - Construct noiseless power spectra from splits
  - Model foreground and systematics at the power spectrum level
  - Maximise (gaussian) likelihood

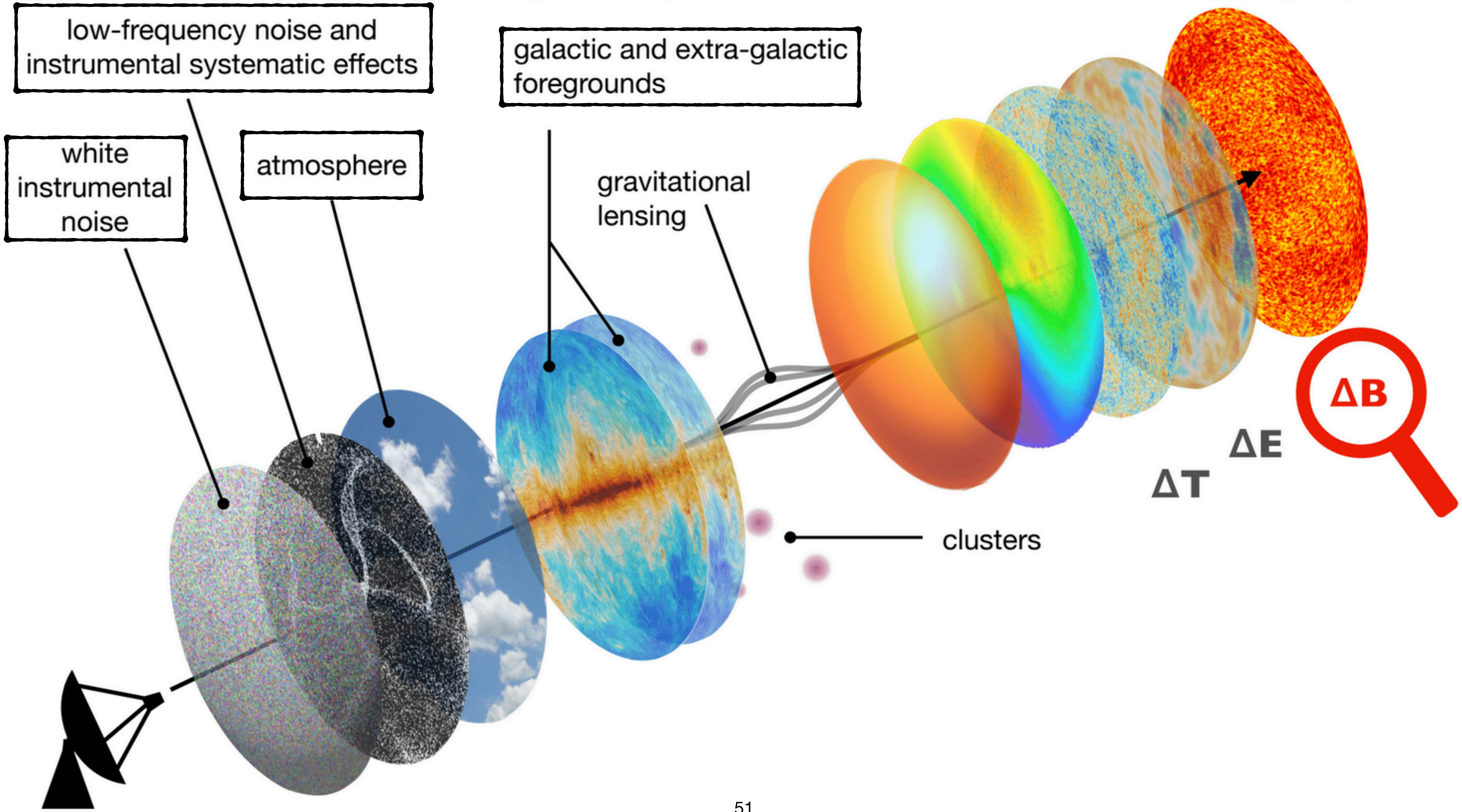
- SOOPERCOOL pipeline for SIMONS OBSERVATORY
- ACT DR6 cosmological analysis (coming this summer 🤞)

CMB B-modes observations

Component separation



CMB B-modes observations

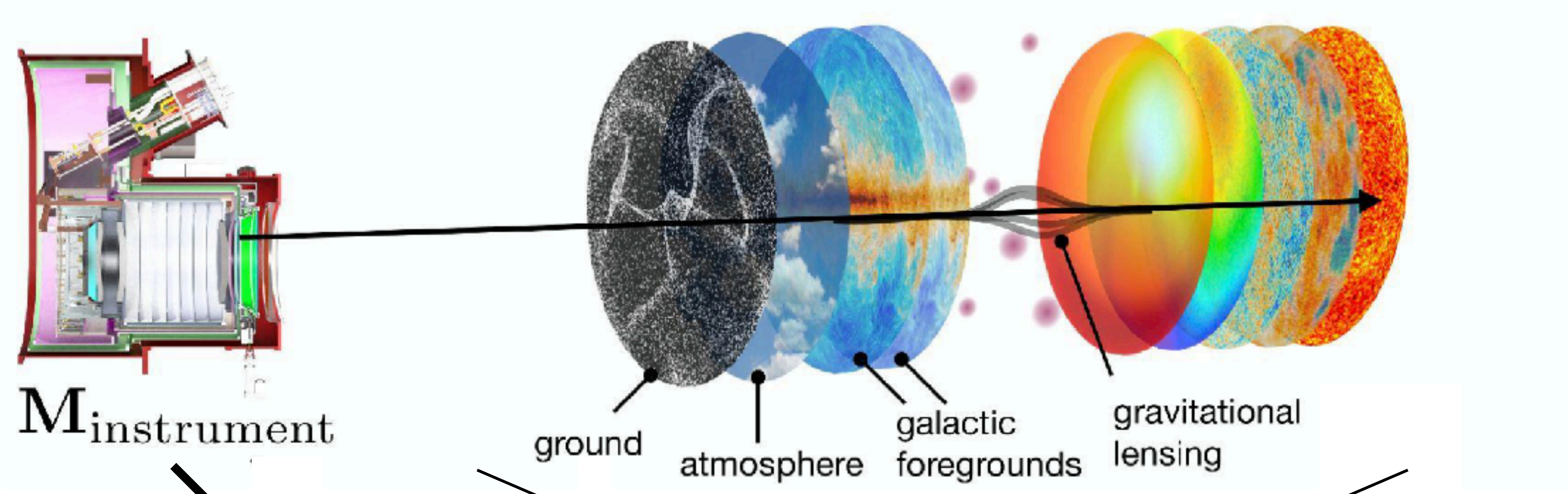


CMB B-modes observations

Mitigation of systematics

SciPol

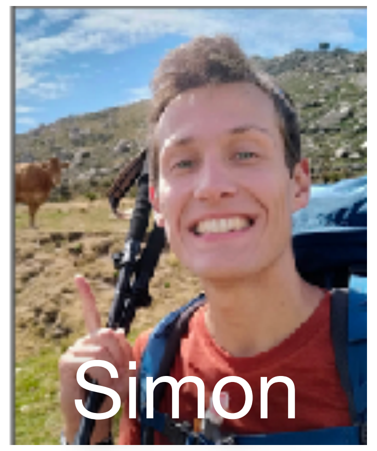
Science from the Large Scale
Cosmic Microwave Background
Polarisation Structure



$$\mathbf{d} = \mathbf{M}(\gamma) \cdot \mathbf{A}(\beta) \cdot \mathbf{s} + \mathbf{n}(\sigma)$$

- Gains
- Beam properties
- Passbands
- HWP parameters

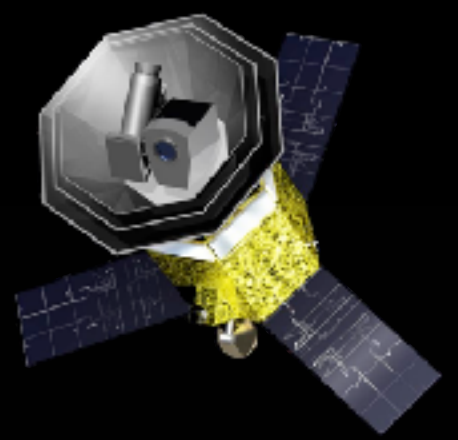
- Foregrounds SED
- Atmosphere SED
- Ground SED



+ Amalia, Binh, Andrea, Alice, Charles

Thanks a lot !

beringue@apc.in2p3.fr
beringueb



SciPol
Science from the large scale cosmic microwave background polarization structure