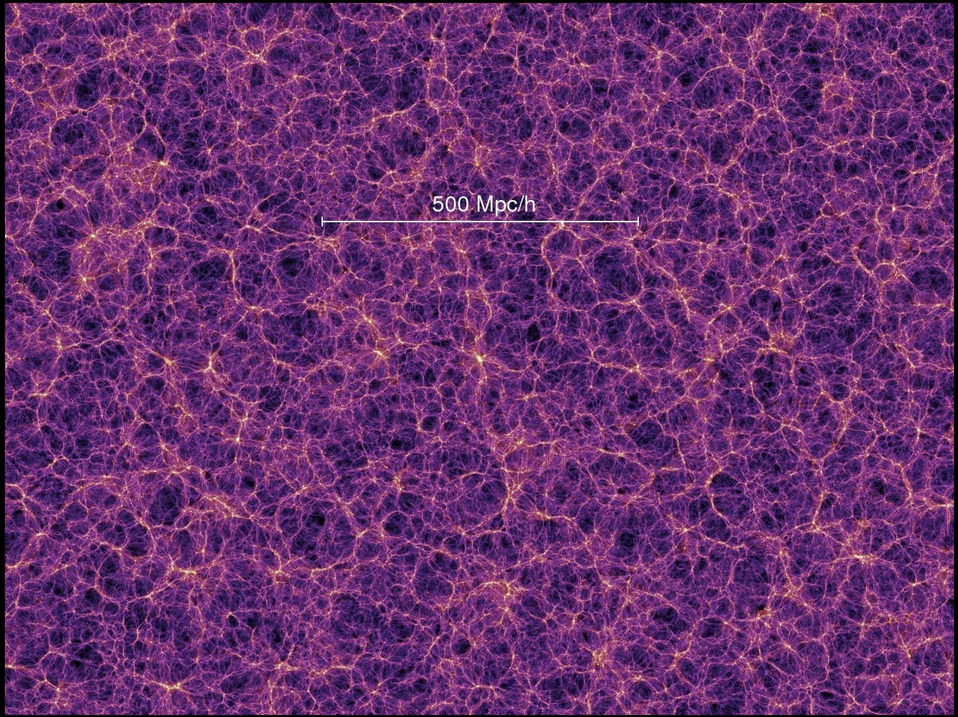
CMB lensing with TEReSiTA

Nicola Principi
Supervisor: Pawel Bielewicz

NCBJ PhD Seminar
30/10/2025

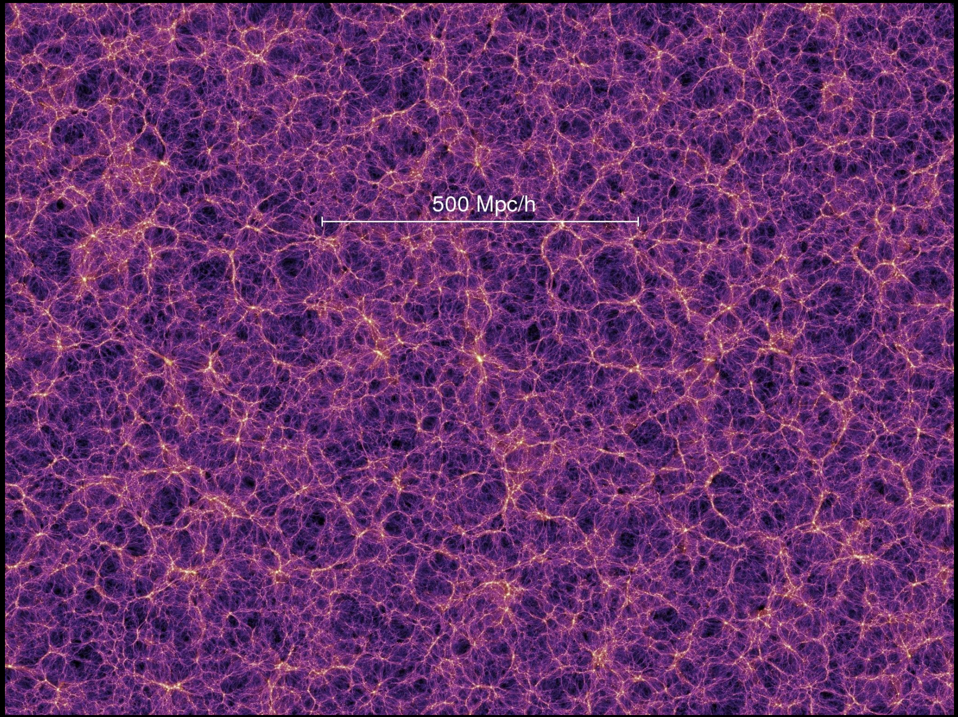
Cosmology

Study of the Universe on its larger scale



Credits: Millennium Simulation (Springel et al., 2005)

The Universe is homogeneous and isotropic



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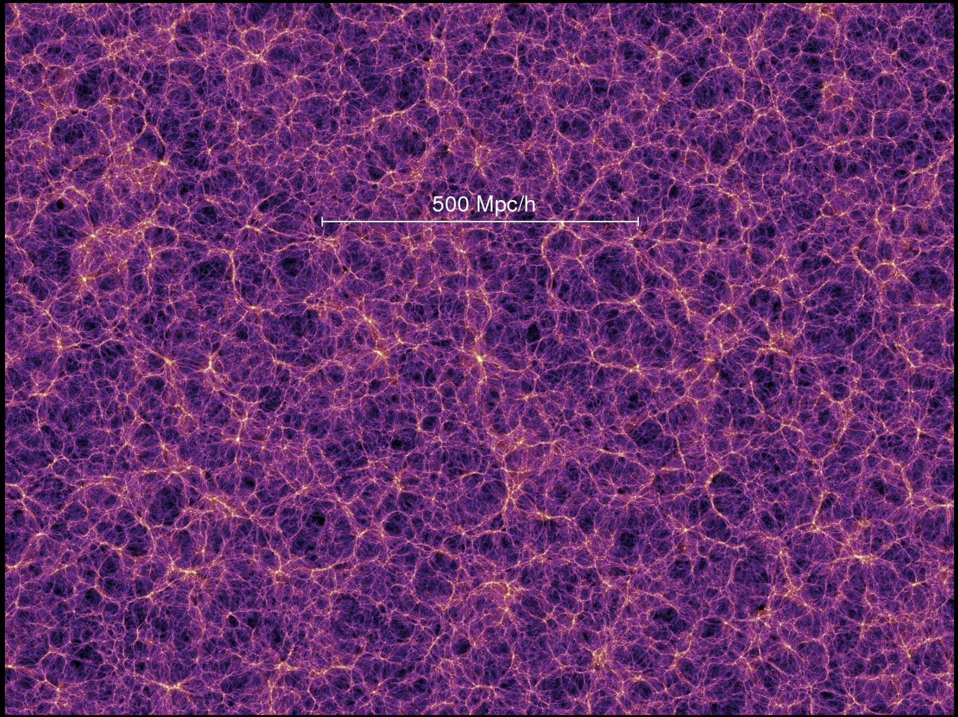
Cosmology

The Universe is homogeneous and isotropic

We are **not** privileged observers



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Cosmology

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Cosmology

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Content

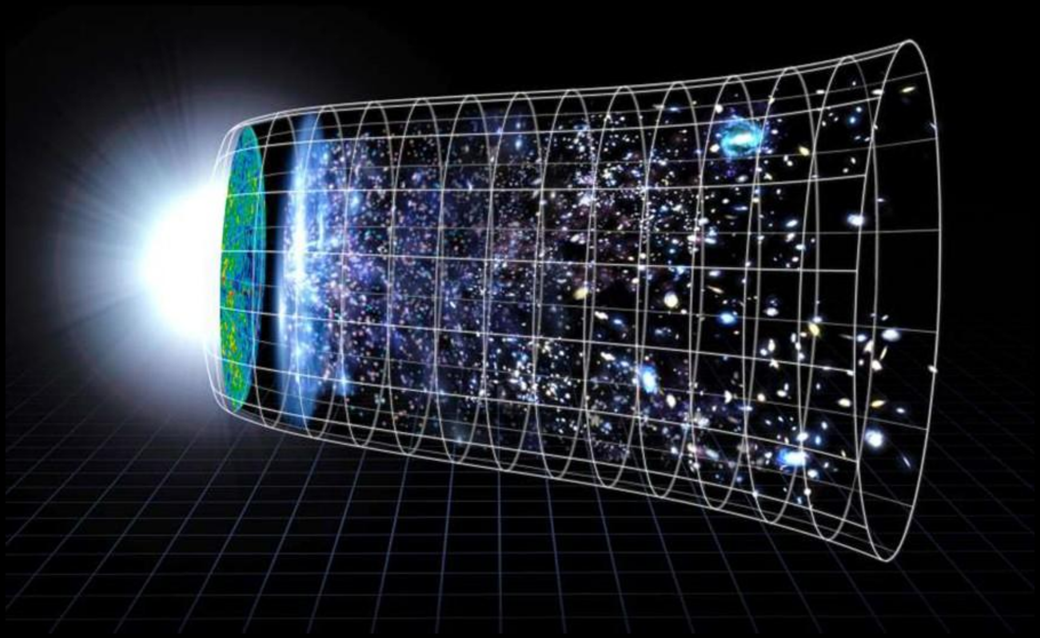
Cosmology

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Geometry

Content

$$\mathrm{d}s^2 = -c^2\mathrm{d}t^2 + a(t)^2 \left[\frac{\mathrm{d}r^2}{1 - kr^2} + r^2\mathrm{d}\Omega^2 \right]$$



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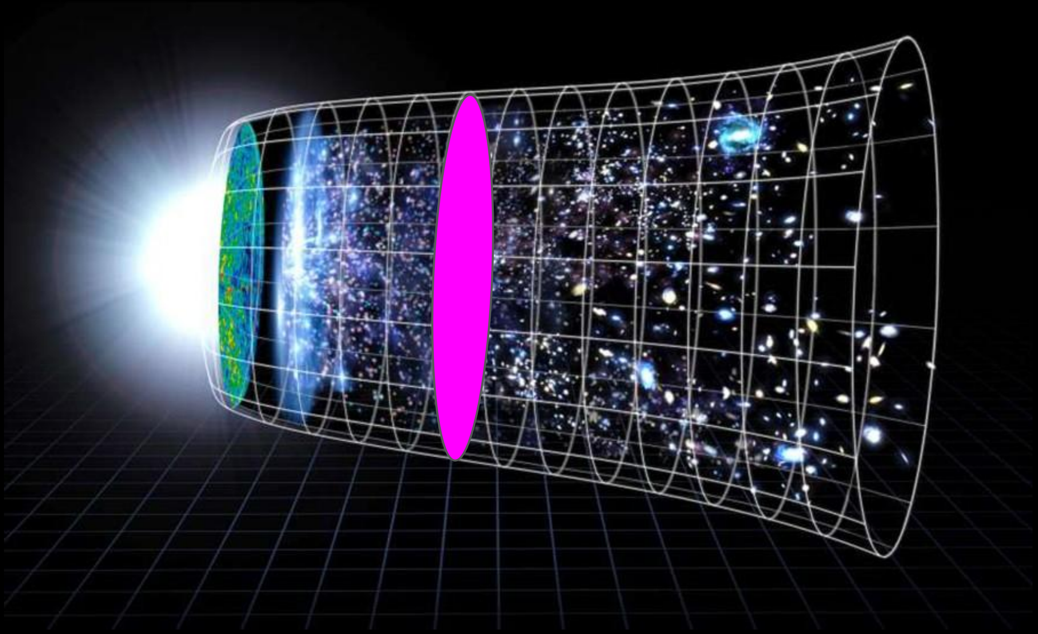

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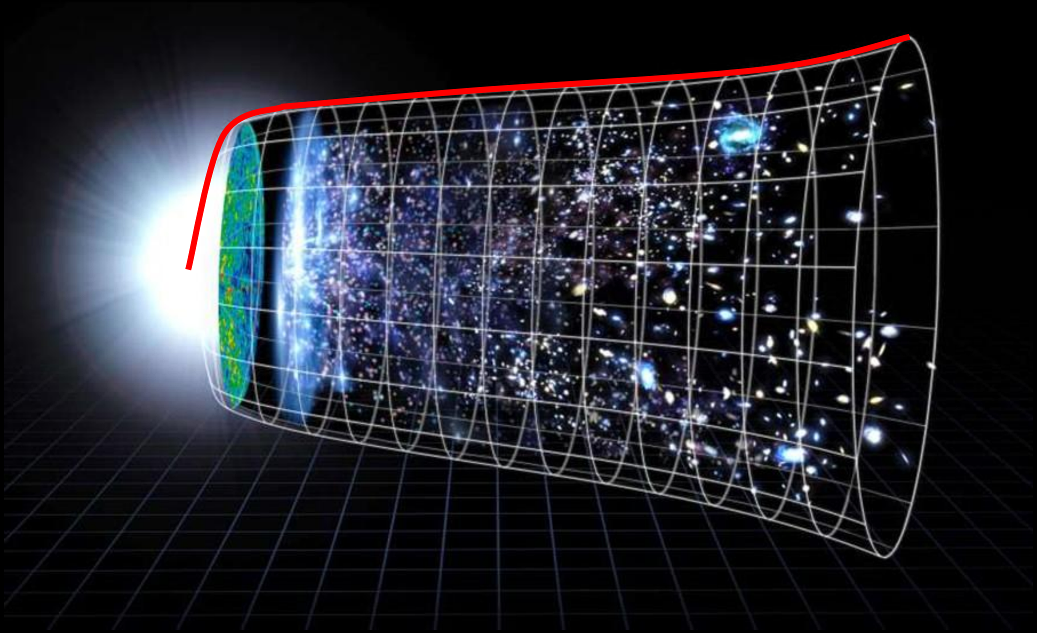
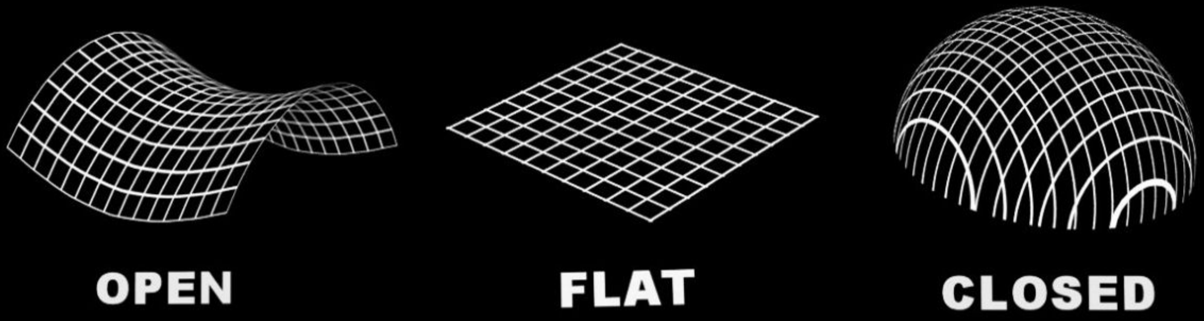


$$ds^2 = -c^2 dt^2 + a(t)^2 \left[\frac{dr^2}{1 - kr^2} + r^2 d\Omega^2 \right]$$

Depending on the value of k, spatial foliations in comoving coordinates can be...



$$\mathrm{d}s^2 = -c^2\mathrm{d}t^2 + a(t)^2\left[\frac{\mathrm{d}r^2}{1-kr^2} + r^2\mathrm{d}\Omega^2\right]$$

For a fiducial observer in comoving coordinates, the 3D spatial foliations of the Universe are consistent with being flat. In this particular reference frame, the **curvature of the 4D manifold** is seen as the expansion.

What do cosmologists do?

Constraining parameters

$$\boxed{a, k}$$

Constraining parameters

$\boxed{a,\ k}$

$\downarrow$

H_0, $\boldsymbol{\Omega}$□, A□, n□, $\boldsymbol{\tau}$, $\boldsymbol{\sigma}_8$, etc.

What do cosmologists do?

Try to answer the open questions

What do cosmologists do?

Try to answer the open questions

Why is the Universe accelerating?

What do cosmologists do?

Try to answer the open questions

How does inflation work?

Why is the Universe accelerating?

What do cosmologists do?

Try to answer the open questions

How does inflation work?

What is the geometry of space-time?

Why is the Universe accelerating?

What do cosmologists do?

Try to answer the open questions

How does inflation work?

What is the geometry of space-time?

Why is the Universe accelerating?

What is dark matter?

What do cosmologists do?

Try to answer the open questions

How does inflation work?

What is the geometry of space-time?

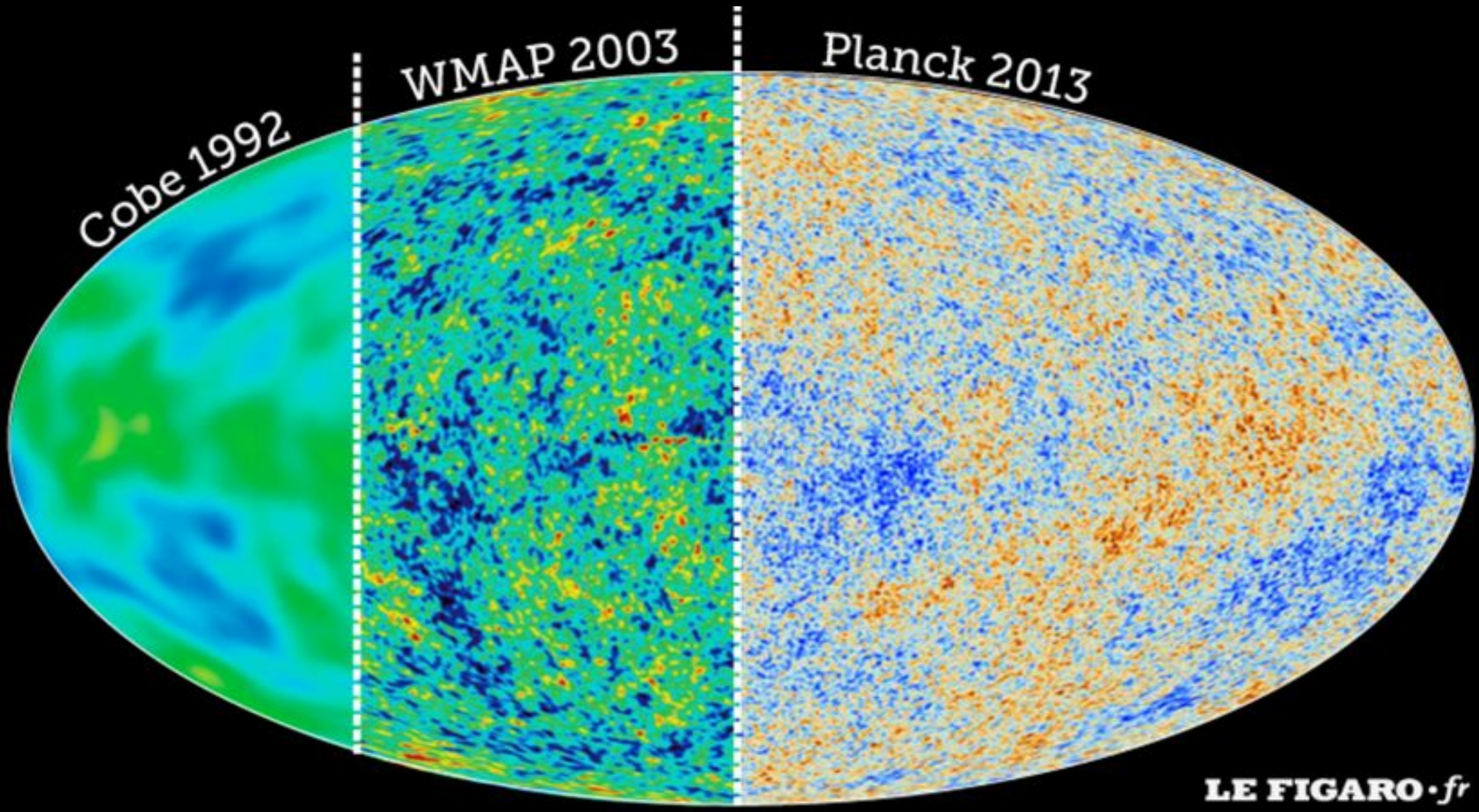
Why is the Universe accelerating?

What is dark matter?

But how?

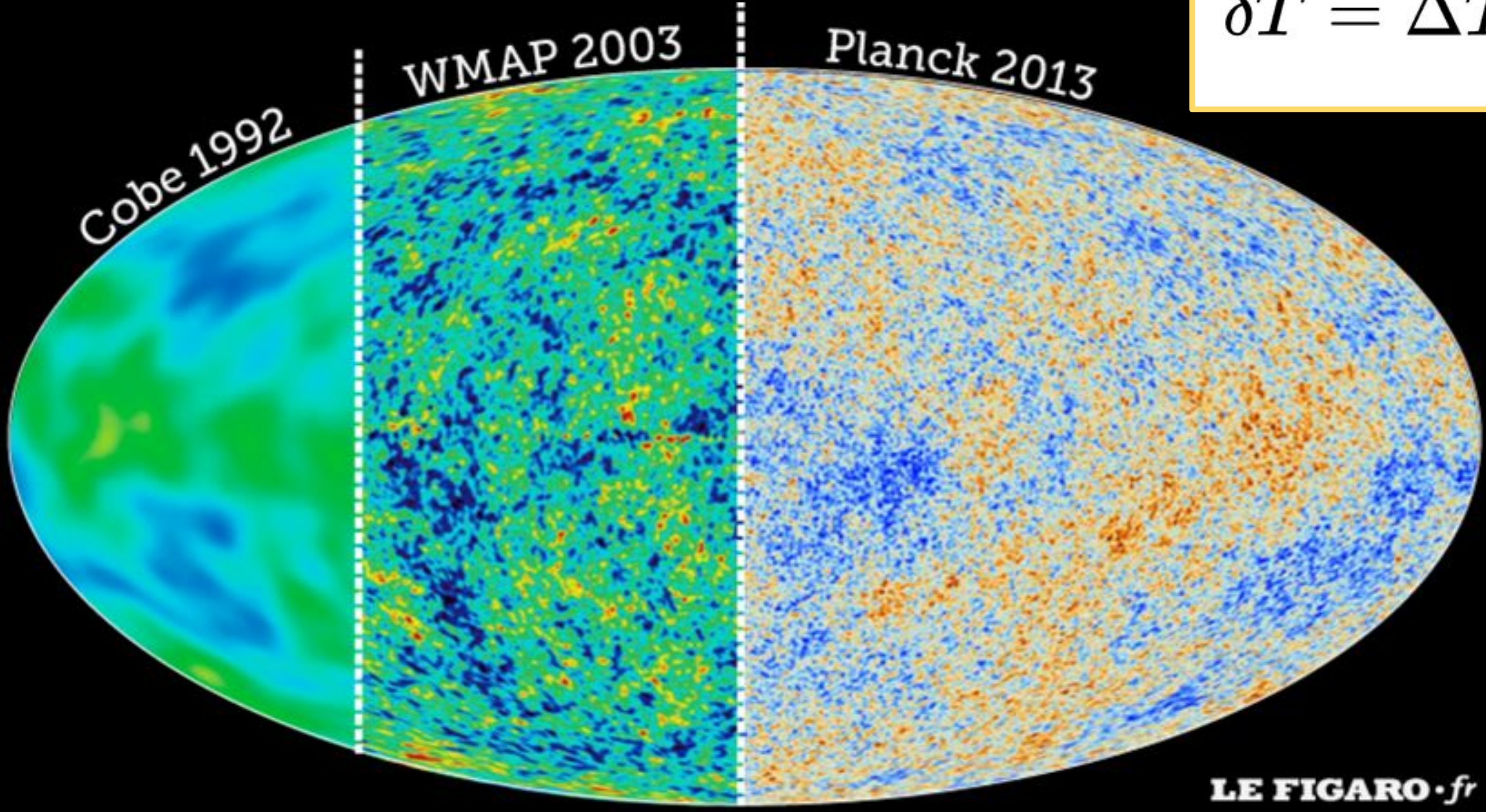
CMB

CMB



CMB

$$\delta T = \Delta T / \bar{T}$$



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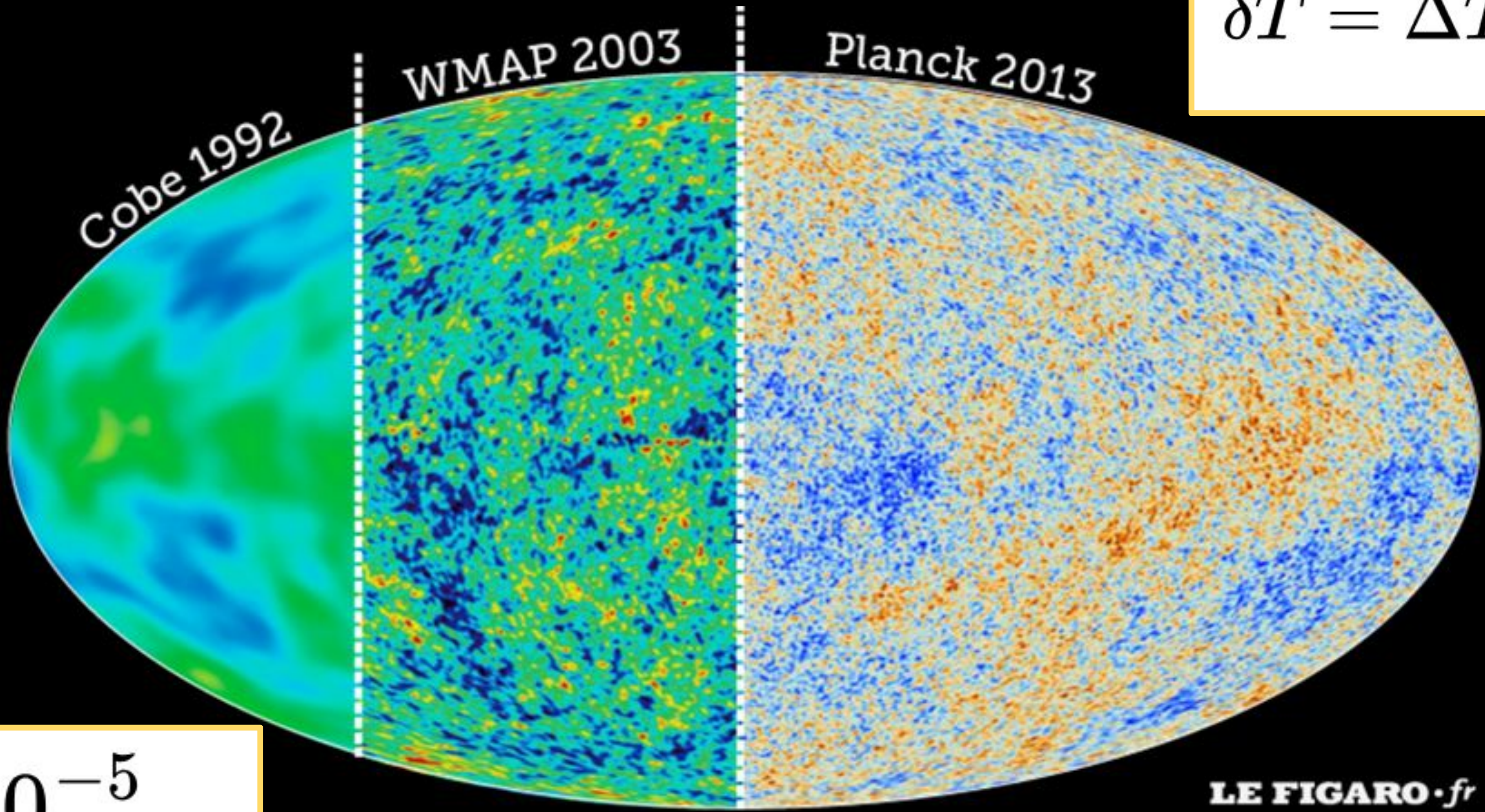


$$10^{-5}$$

Information in the CMB

Information in the CMB

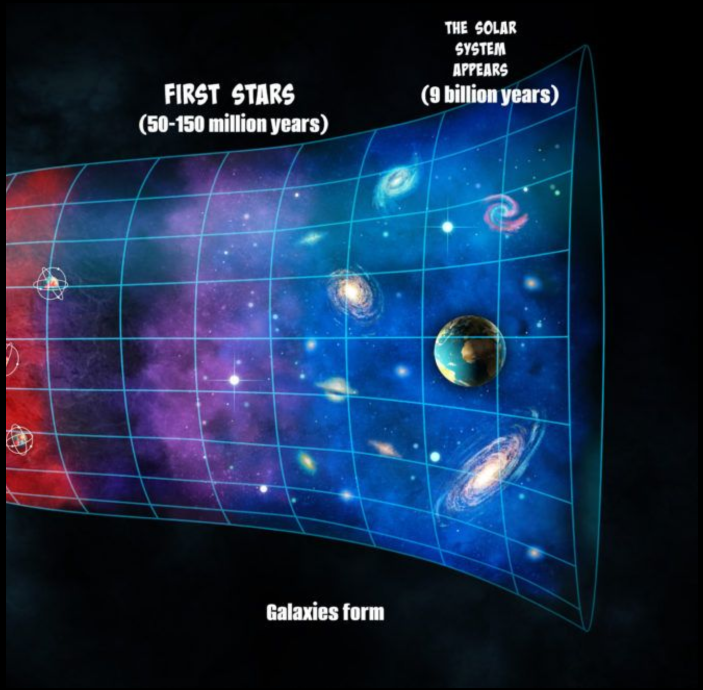
2.73

Information in the CMB

3000

Information in the CMB

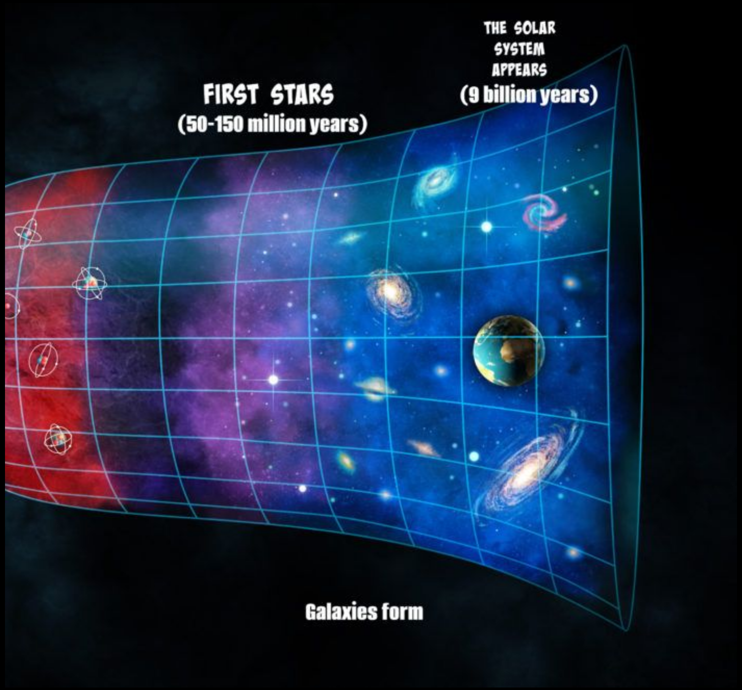
Thermal equilibrium



Credits: Emma Vastone, 2022

Information in the CMB

Thermal equilibrium



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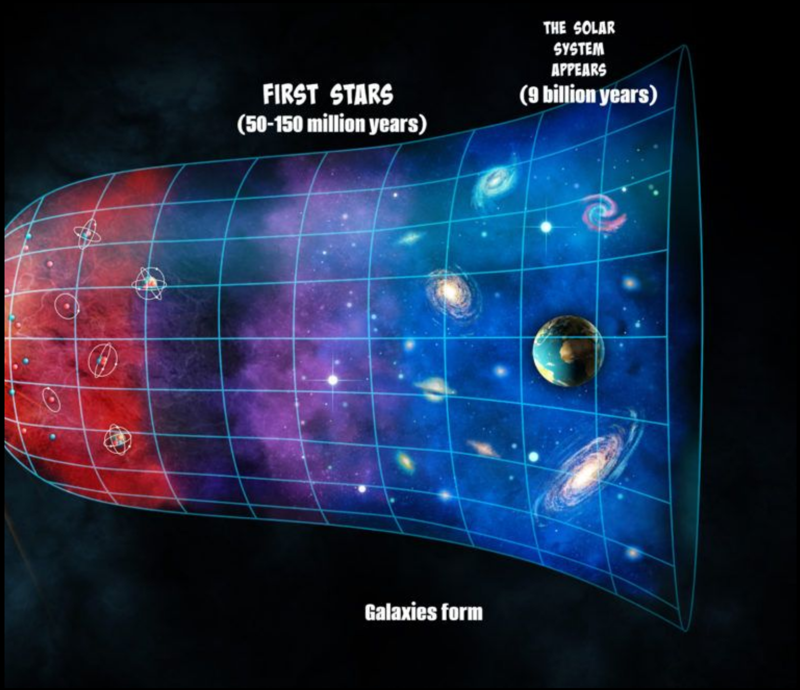

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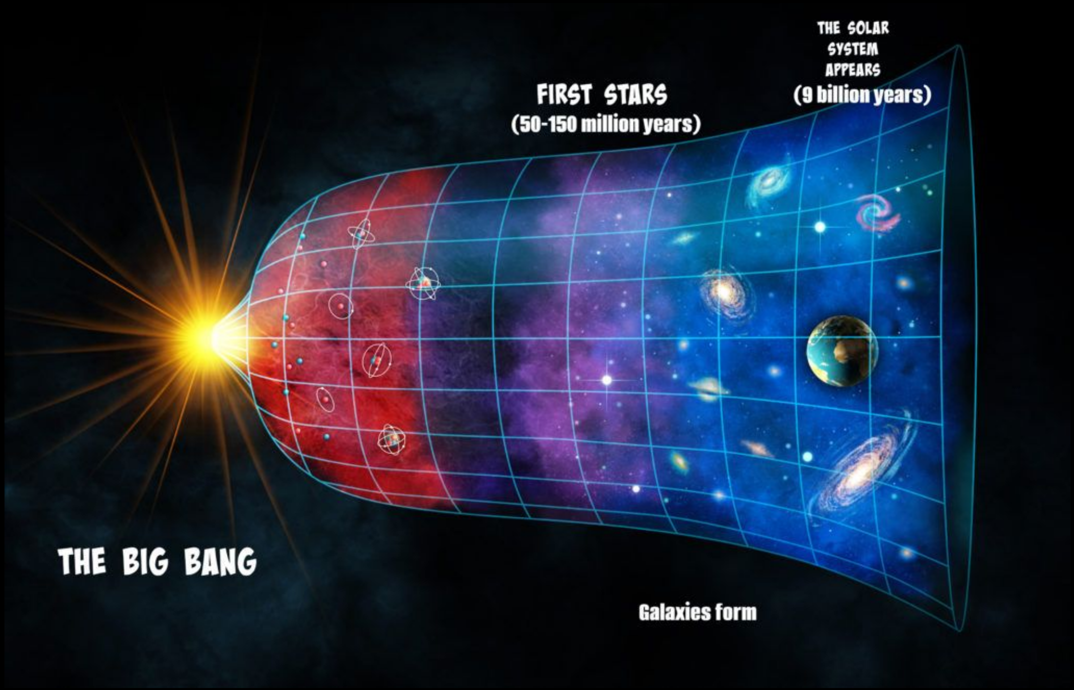

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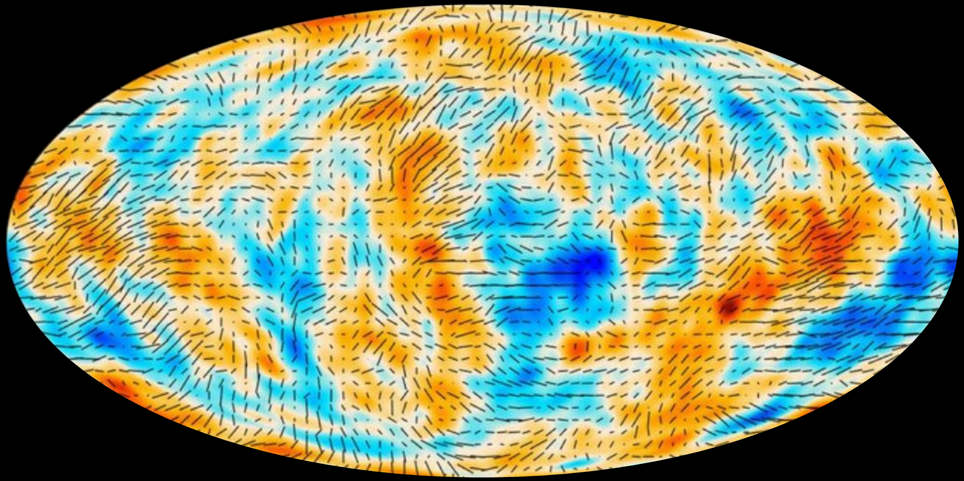
Information in the CMB

Thermal equilibrium

Polarisation



Credits: Julien Lesgourgues

CMB light is linearly polarized
via Thomson scattering

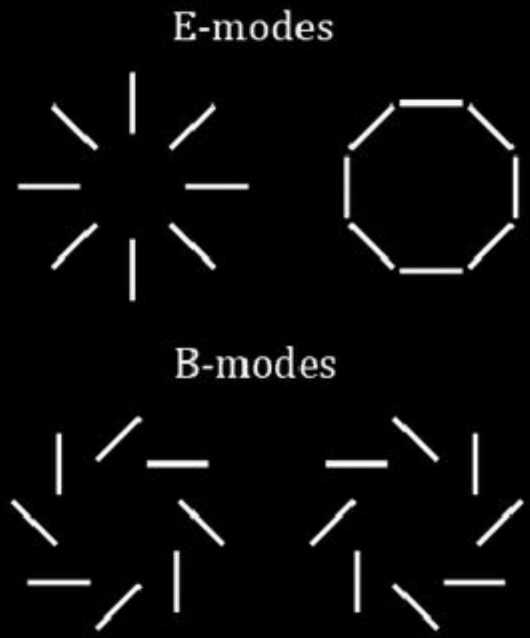
Information in the CMB

Thermal equilibrium

Polarisation

Spin-2 fields: Q and U

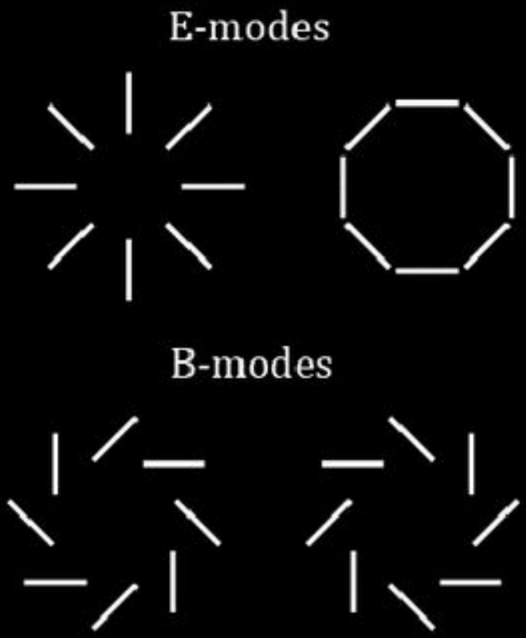
Information in the CMB



Spin-2 fields: Q and U

Scalar fields: E and B

Information in the CMB

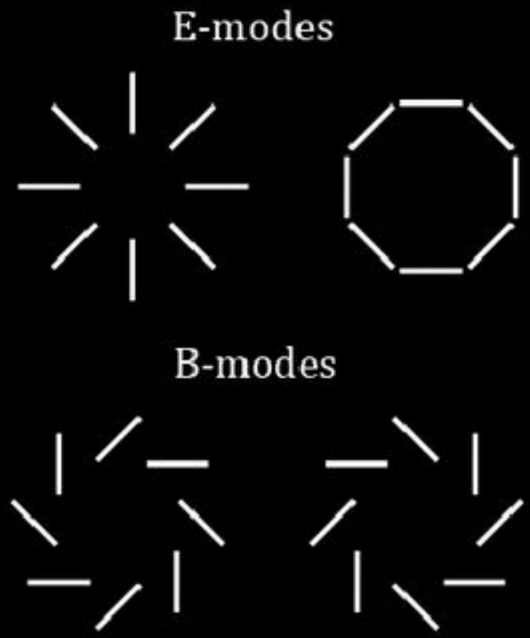


Spin-2 fields: Q and U

Scalar fields: E and B

E scalar perturbations

Information in the CMB



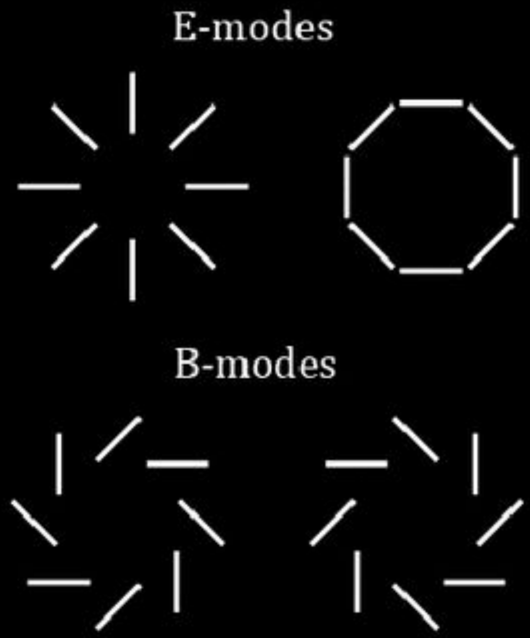
Spin-2 fields: Q and U

Scalar fields: E and B

E scalar perturbations

B tensor perturbations

Information in the CMB



Spin-2 fields: Q and U

Scalar fields: E and B

E scalar perturbations

B tensor perturbations

Tensor perturbations from primordial gravitational waves

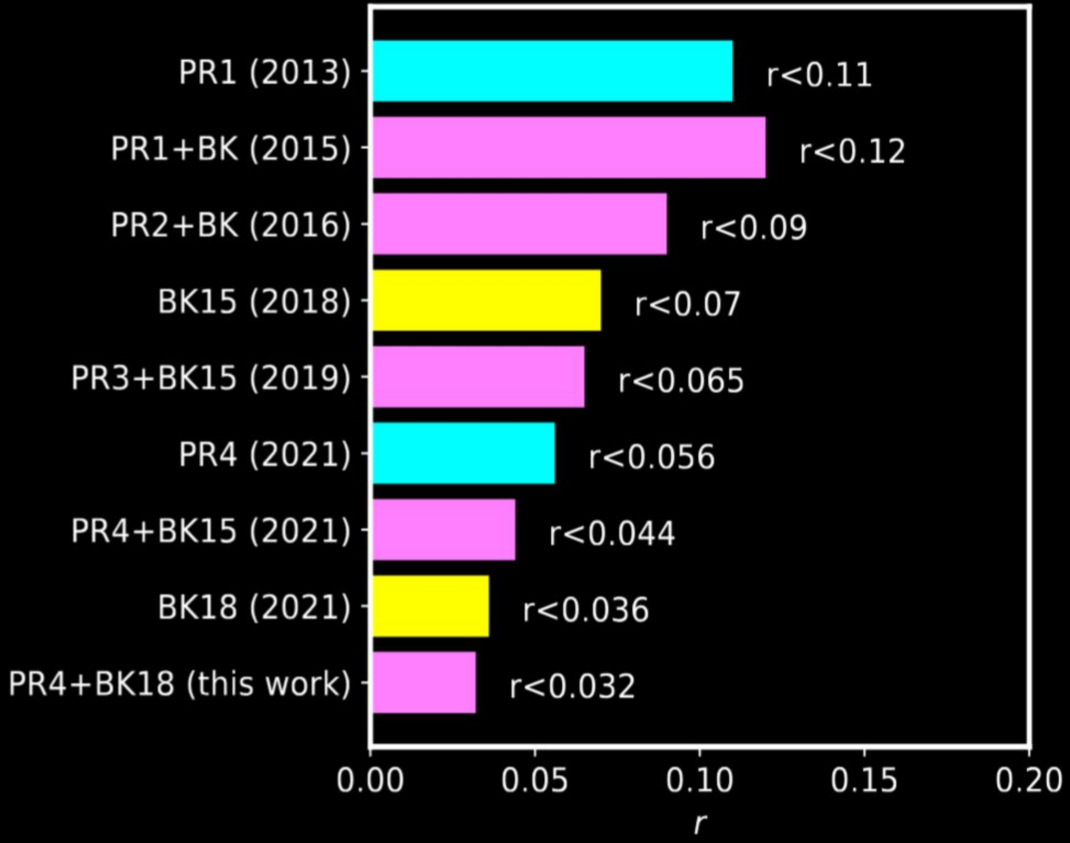
Tensor-to-scalar ratio

$$r = \frac{A_t}{A_s}$$

Information in the CMB

Tensor-to-scalar ratio

$$r = \frac{A_t}{A_s}$$



Credits: Tristam et al., 2022

Information in the CMB

Tensor-to-scalar ratio

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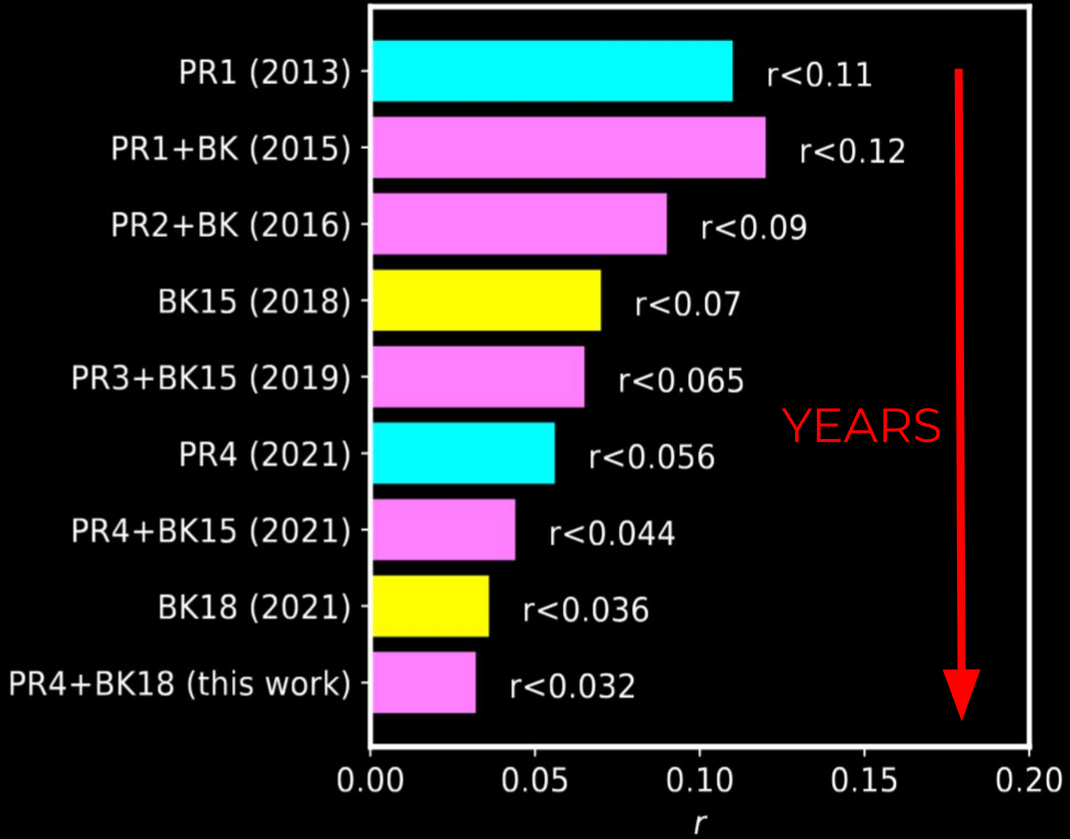

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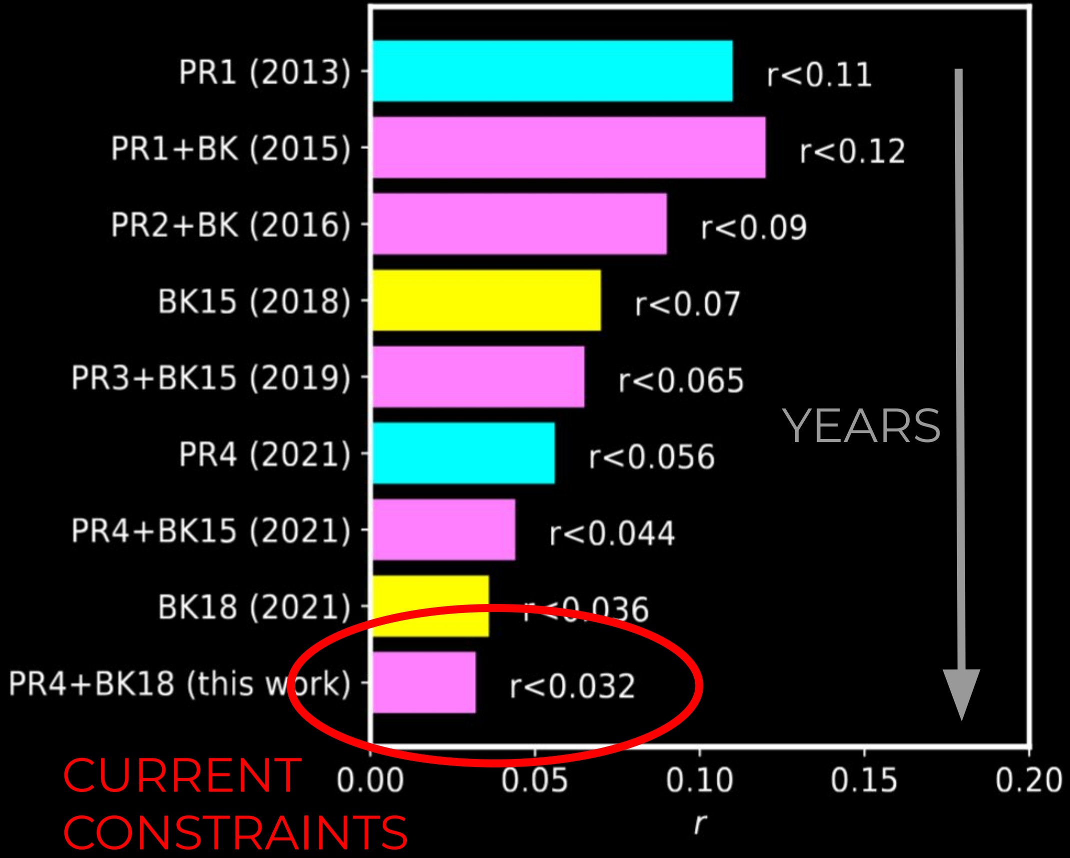

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Information in the CMB

$$\delta T = 0$$

Thermal equilibrium

Polarisation

Anisotropies

Information in the CMB

Thermal equilibrium

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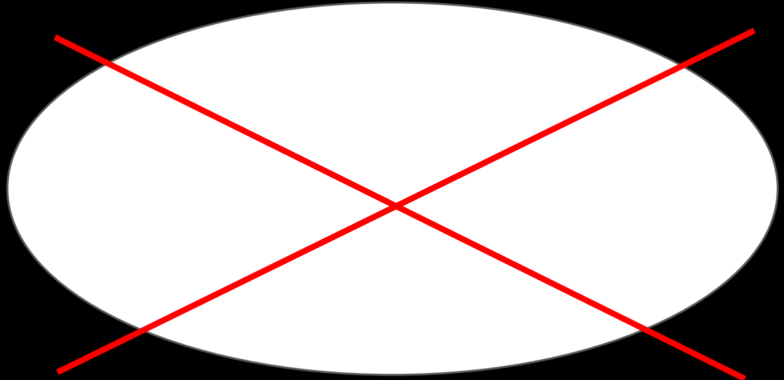
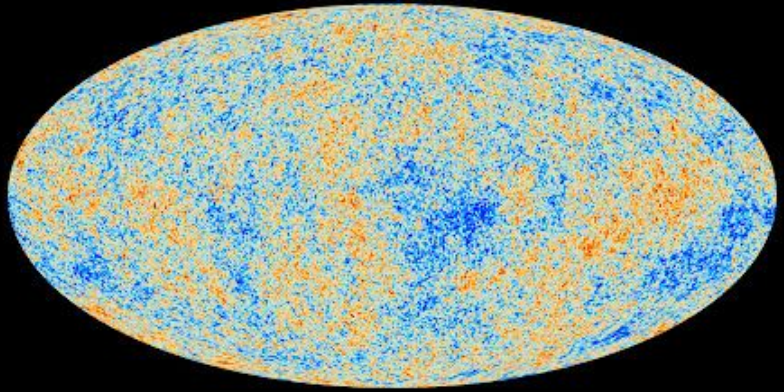
Anisotropies

$$\delta T = 0$$



$$\delta T \sim 10^{-5}$$



CMB anisotropies

Primary

Secondary

CMB anisotropies

Primary
Sachs-Wolfe effect (gravitational potential)

CMB anisotropies

Primary
Sachs-Wolfe
effect
(gravitational
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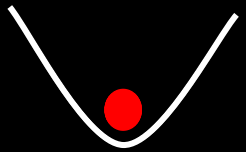
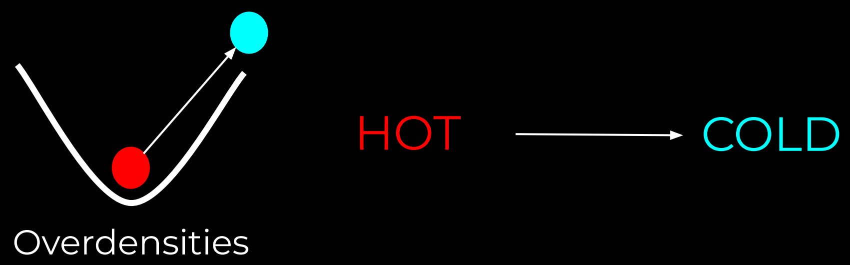


HOT

CMB anisotropies

Primary
Sachs-Wolfe effect (gravitational potential)



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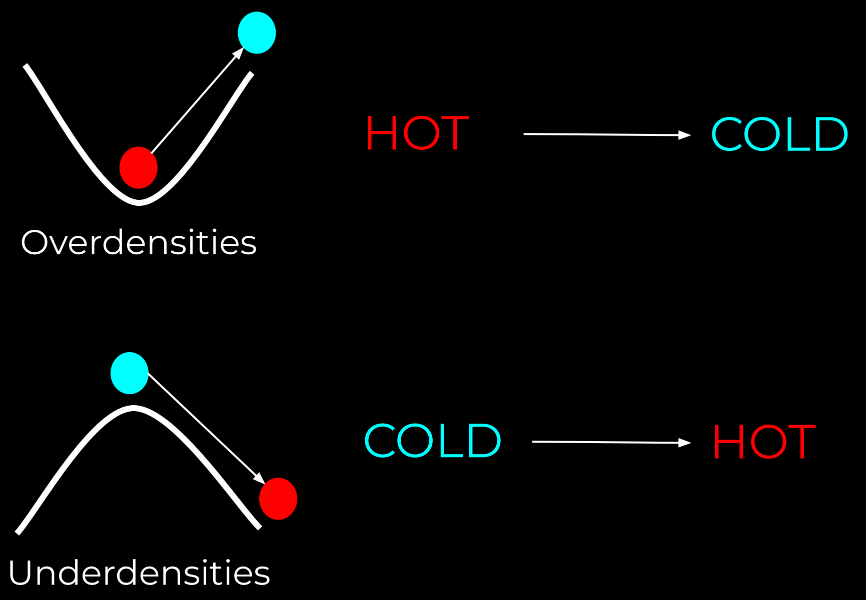

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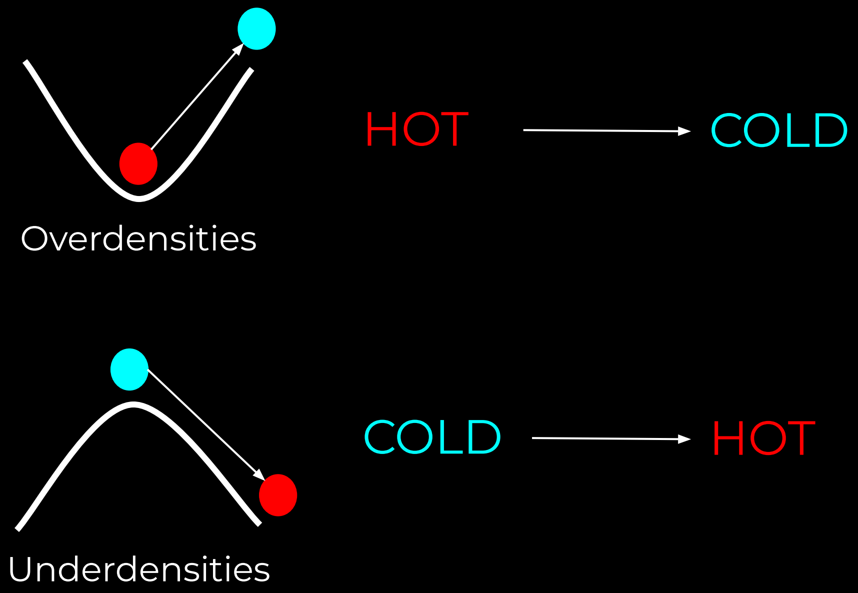


Information on the primordial gravitational potential field!

CMB anisotropies

Secondary

CMB anisotropies

Secondary

Integrated Sachs-Wolfe

Secondary

Integrated Sachs-Wolfe

Sunyaev-Zel’dovich

CMB anisotropies

Secondary

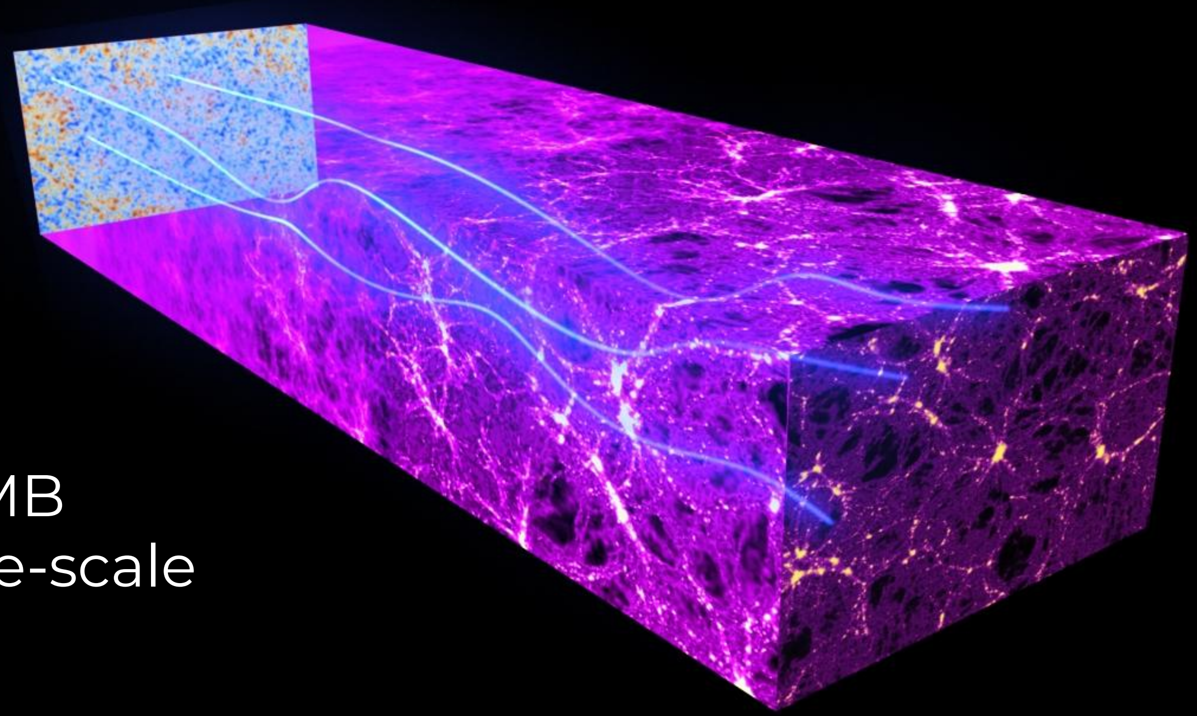
Integrated Sachs-Wolfe

Sunyaev-Zel’dovich

Gravitational lensing

CMB lensing

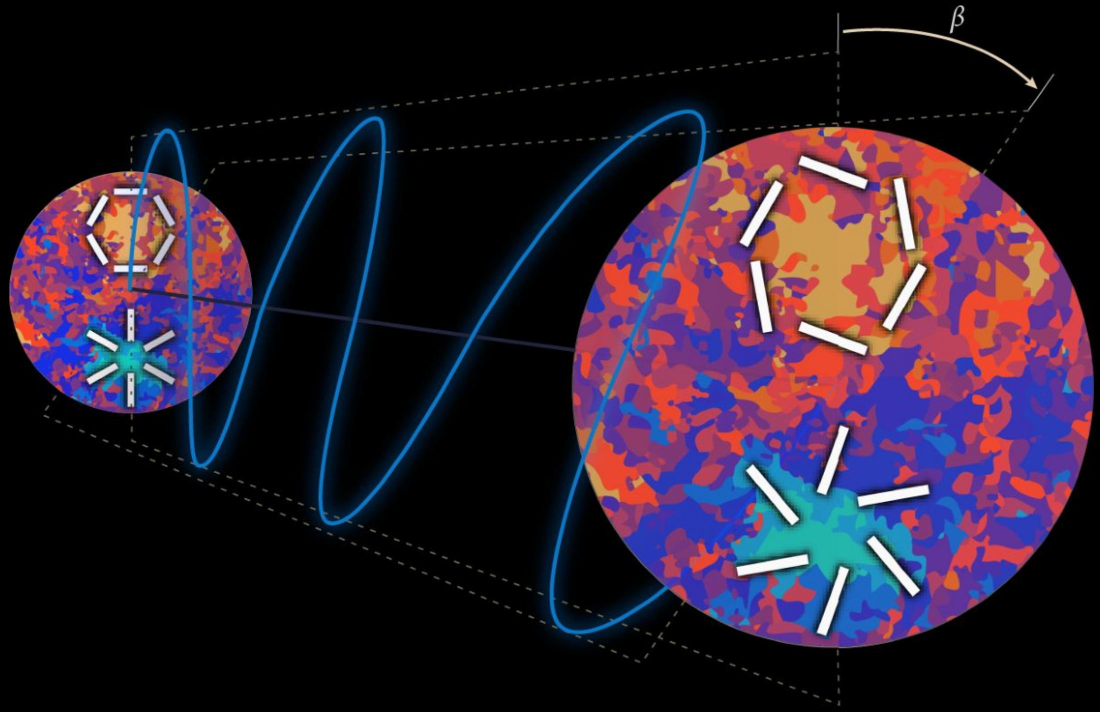
CMB lensing



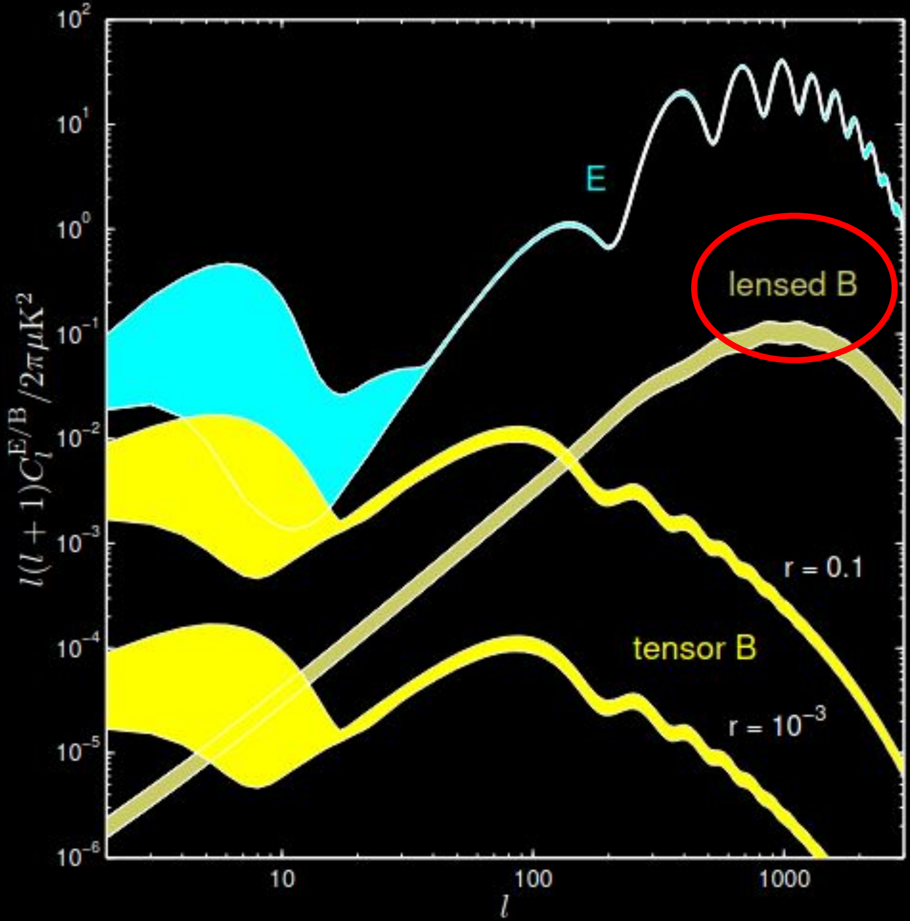
Deflection of CMB photons by large-scale structure

Credits: Planck (ESA)

CMB lensing



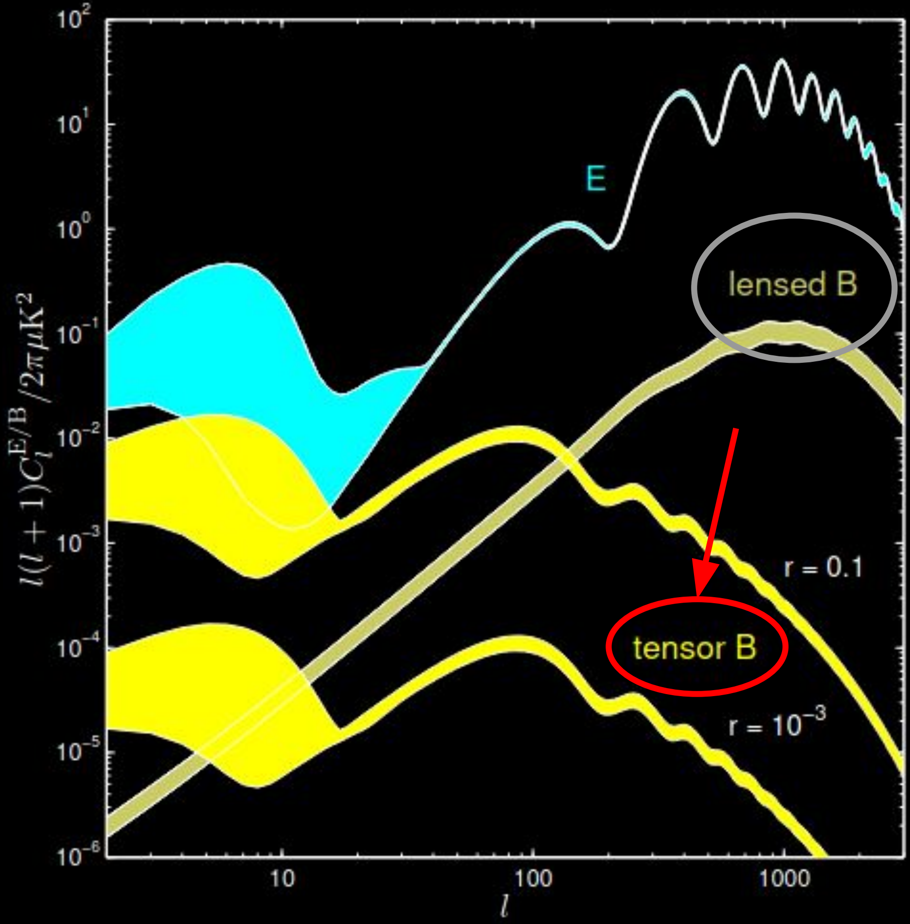
Turns E-modes
into B-modes
and vice versa



Credits: Lewis & Challinor, 2006

What we observe, with lensing effect

Turns E-modes into B-modes and vice versa



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What we observe, with lensing effect

Turns E-modes into B-modes and vice versa

Primordial B-modes

"The observed CMB is thus a distorted image of the last-scattering surface, containing information about the intervening mass distribution."

-Wayne Hu, 2000

Quantities

Quantities

Lensing
Potential

$$\phi$$

Quantities

$$\underbrace{\boxed{\phi}}_{\text{Lensing Potential}} \propto \int \underbrace{\boxed{\psi}}_{\text{Gravitational Potential}} \, d\chi$$

Quantities

Convergence		Lensing Potential		Gravitational Potential	
κ	$\propto \nabla^2$	ϕ	$\propto \int$	ψ	$d\chi$

Why CMB lensing?

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Using quadratic estimators (Hu & Okamoto, 2001) we can reconstruct lensing potential just from the CMB maps

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Double treat: large-scale structure & cleaned CMB

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Using quadratic estimators (Hu & Okamoto, 2001) we can reconstruct lensing potential just from the CMB maps

Double treat: large-scale structure & cleaned CMB

It would be amazing to have a tool for testing de-lensing algorithms and studying cross-correlations between CMB and large-scale structure...

Here is where my work begins…

TEReSiTA

Tomographic

Ensemble of

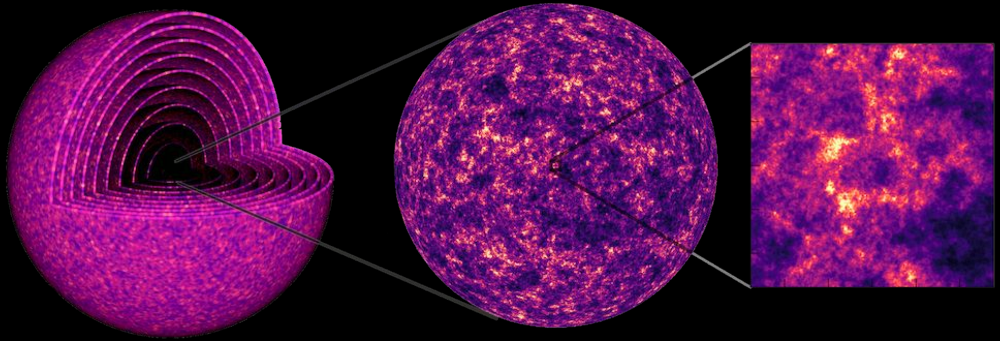
Realistic

Simulations of

Tracers and

Anisotropies

Galaxy catalogue



TEReSiTA

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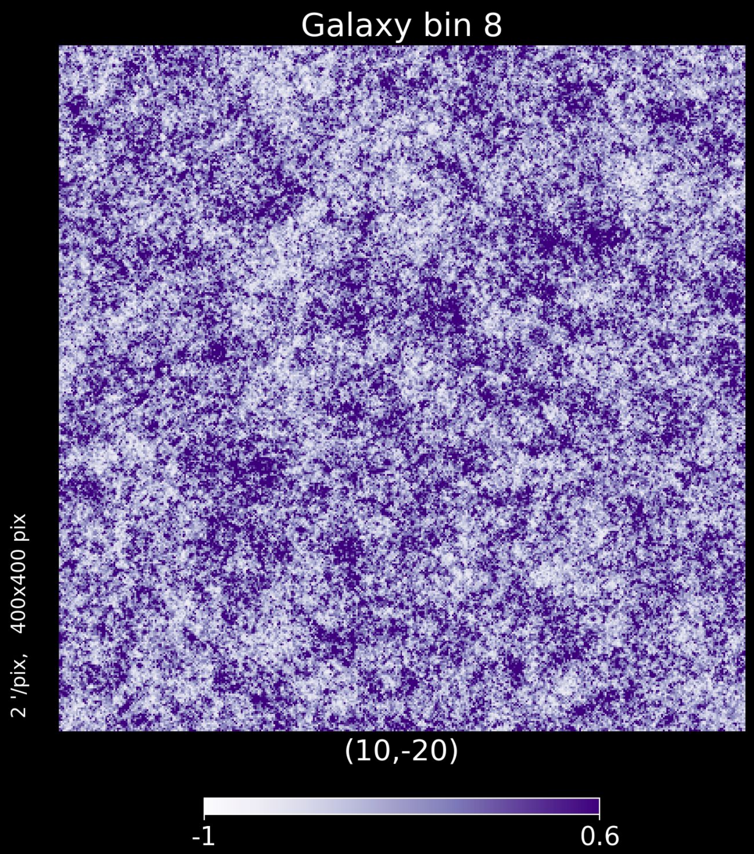

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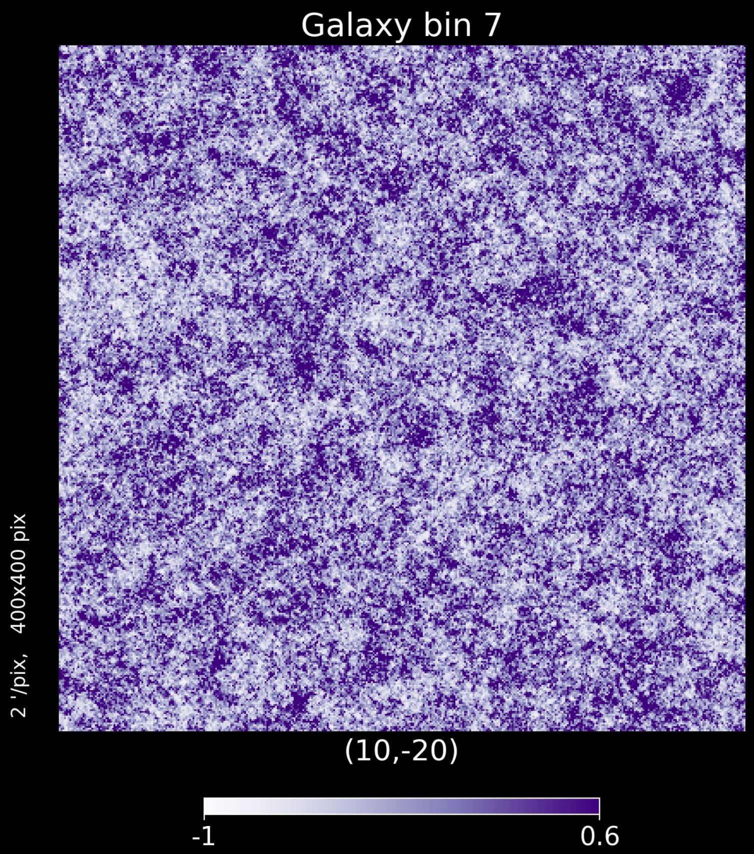

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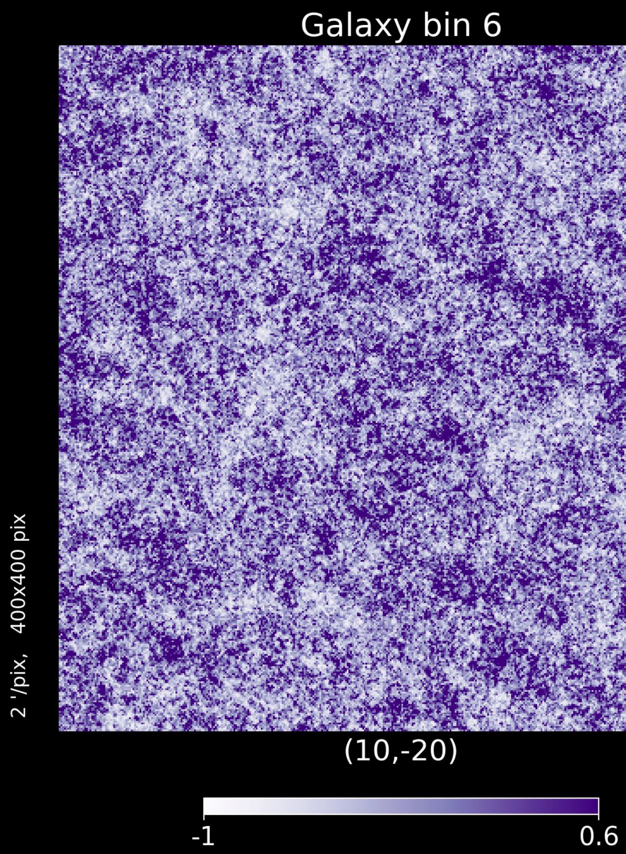

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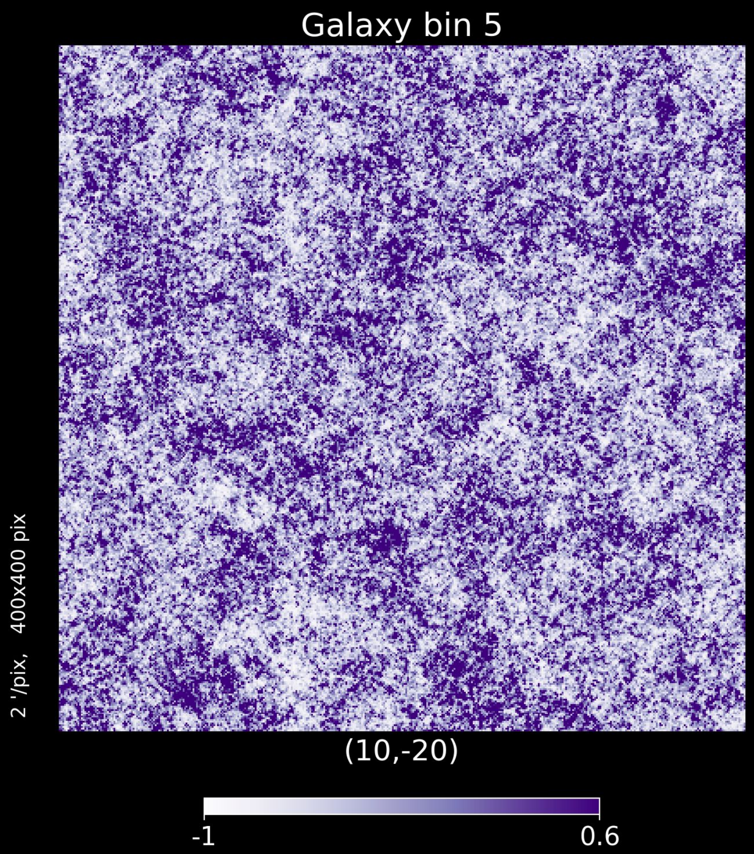

TEReSiTA

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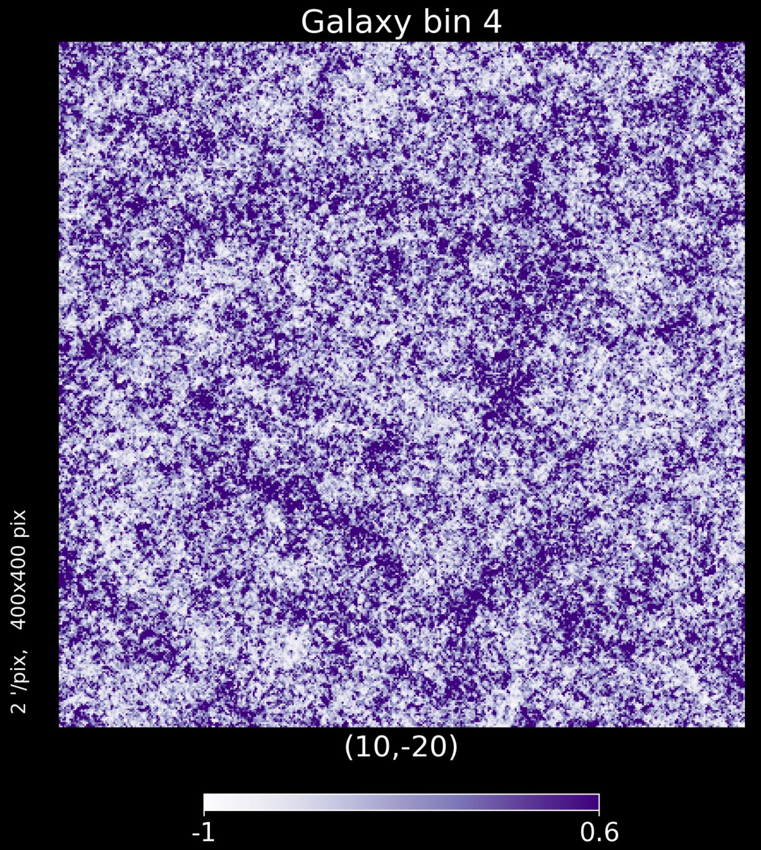

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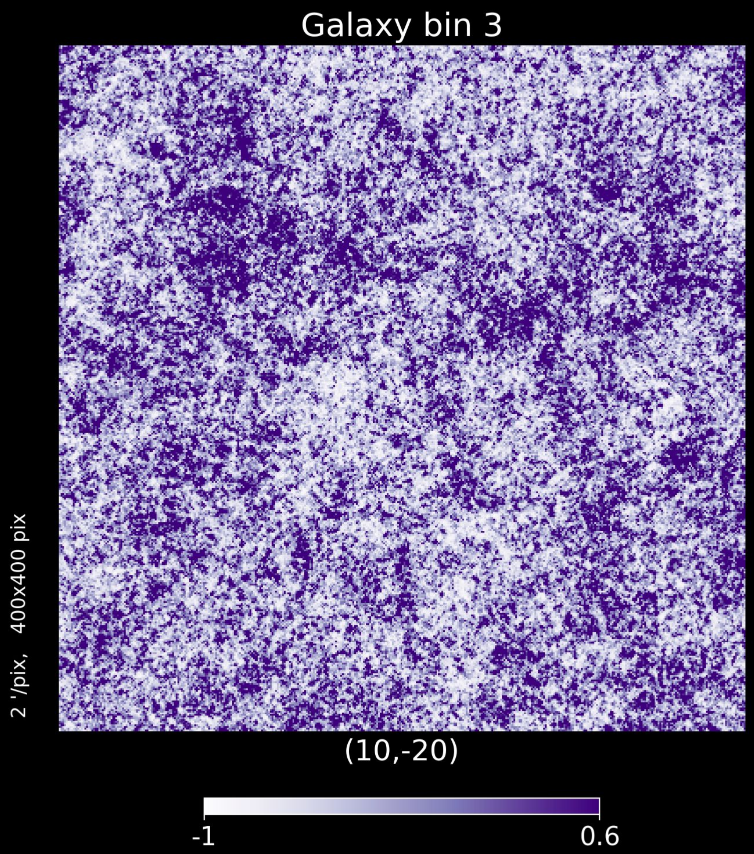

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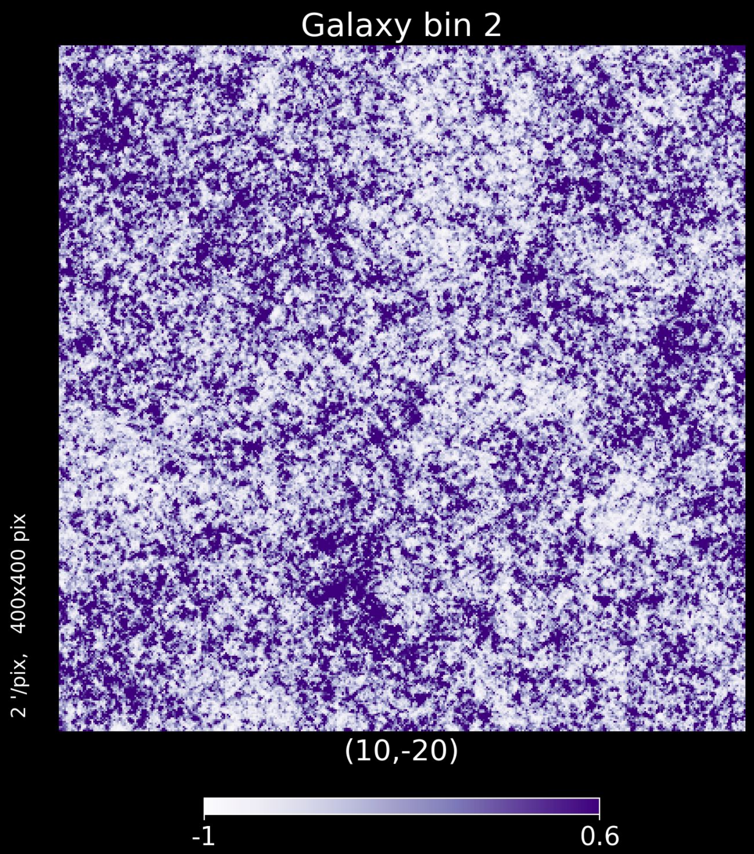

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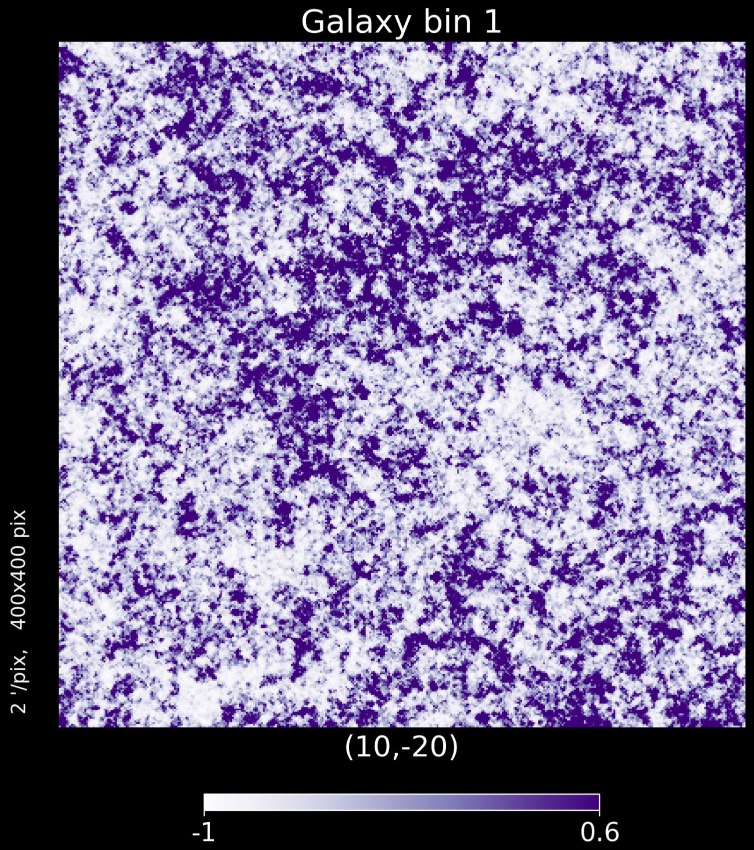
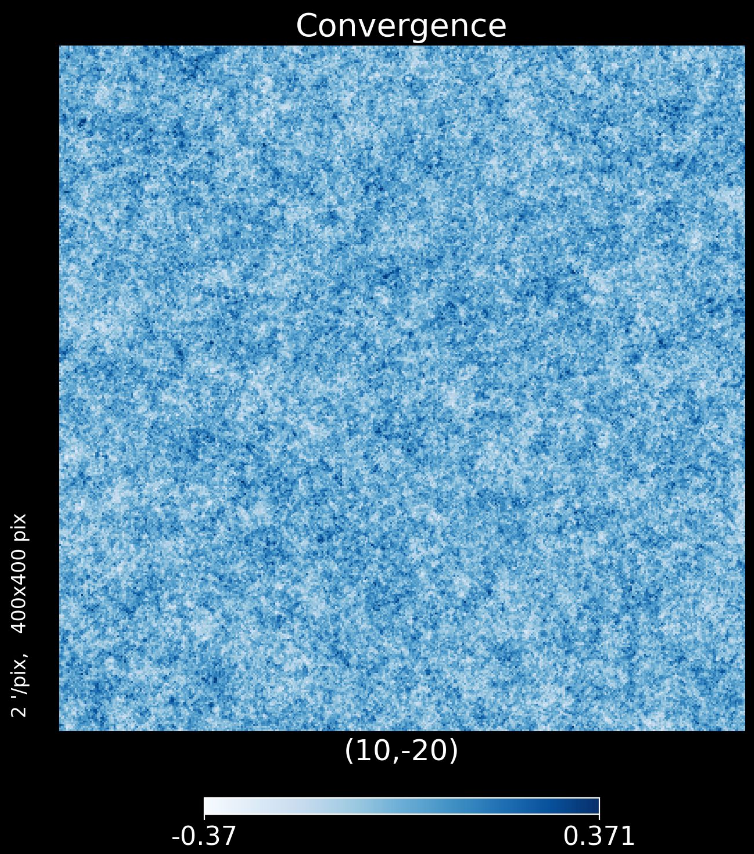


Galaxy catalogue

Convergence map

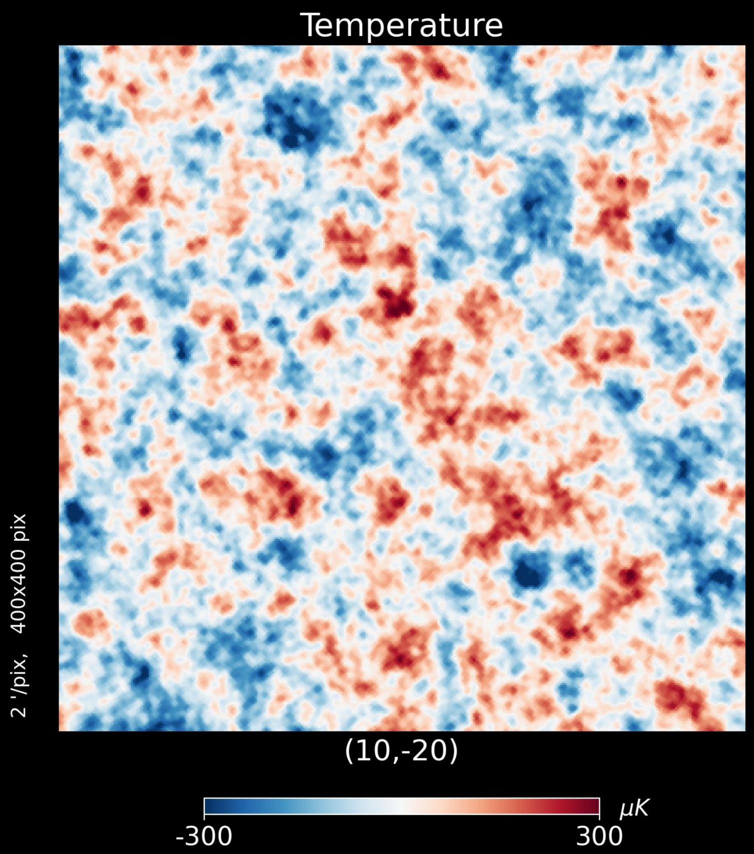


TEReSiTA

Galaxy catalogue

Convergence map

Unlensed CMB



TEReSiTA

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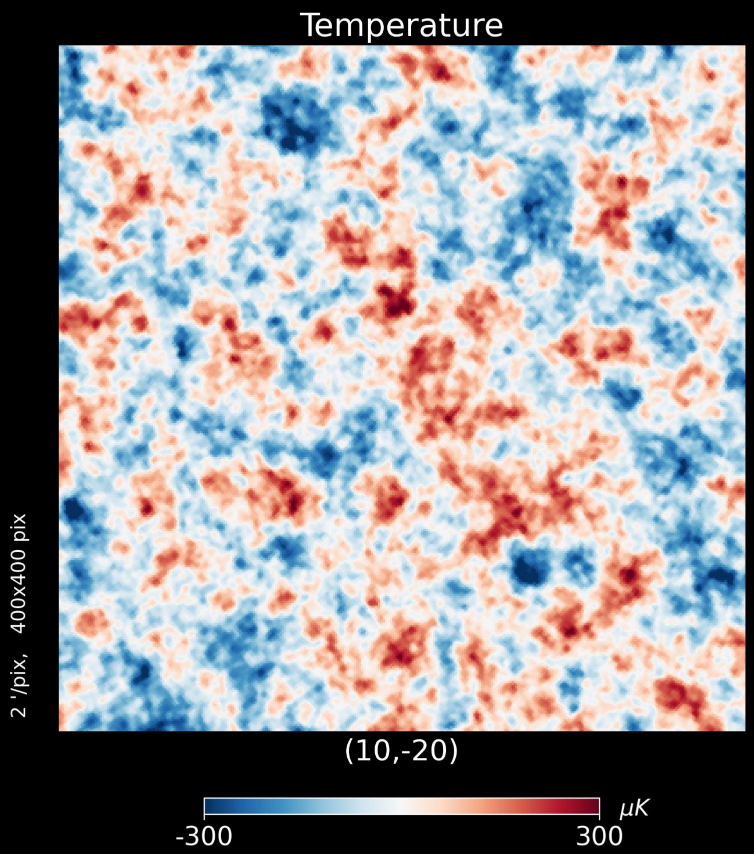
Lensed CMB



TEReSiTA applications

Testing de-lensing

TEReSiTA applications

Testing de-lensing

LSS-CMB cross-correlations

TEReSiTA applications

Testing de-lensing

LSS-CMB cross-correlations

Cosmic shear

TEReSiTA applications

Testing de-lensing

LSS-CMB cross-correlations

Cosmic shear

Photometric redshift errors

TEReSiTA applications

Testing de-lensing

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Other systematics

TEReSiTA applications

Everything is aiming to achieve tighter constraints on cosmological parameters

TEReSiTA applications

$\boxed{\text{Everything is aiming to achieve tighter constraints on cosmological parameters}}$

Study of systematics

TEReSiTA applications

Everything is aiming to achieve tighter constraints on cosmological parameters

Study of systematics

Info on large-scale structure

TEReSiTA applications

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Study of systematics

Info on large-scale structure

Clearer view of primordial CMB

TEReSiTA applications

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Tensor-to-scalar ratio

TEReSiTA applications

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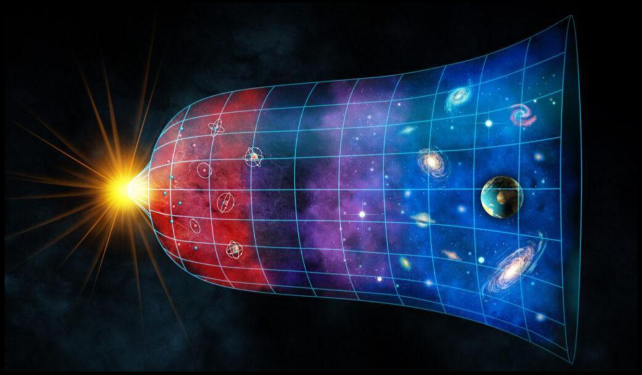


Study of systematics

Info on large-scale structure

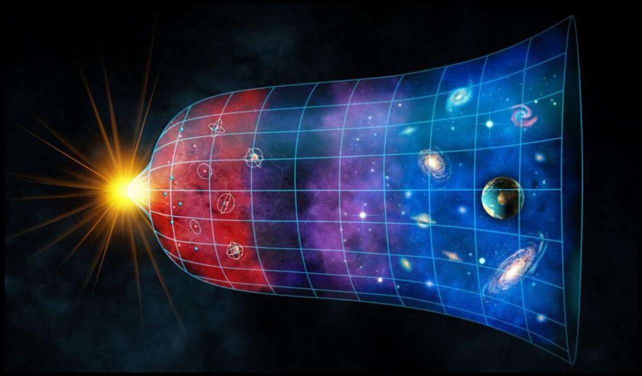
Clearer view of primordial CMB

Tensor-to-scalar ratio

Constraining the geometry of the Universe (scale factor)

TEReSiTA applications

Everything is aiming to achieve tighter constraints on cosmological parameters



Study of systematics

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nicola.principi@ncbj.gov.pl