IRAFS-22. INTERNATIONAL SYMPOSIUM ON «SCIENCE & THEOLOGY»

PUL, October 20-21, 2022

Looking for
Quantum Gravity imprints in the Universe

SPECOLA VATICANA

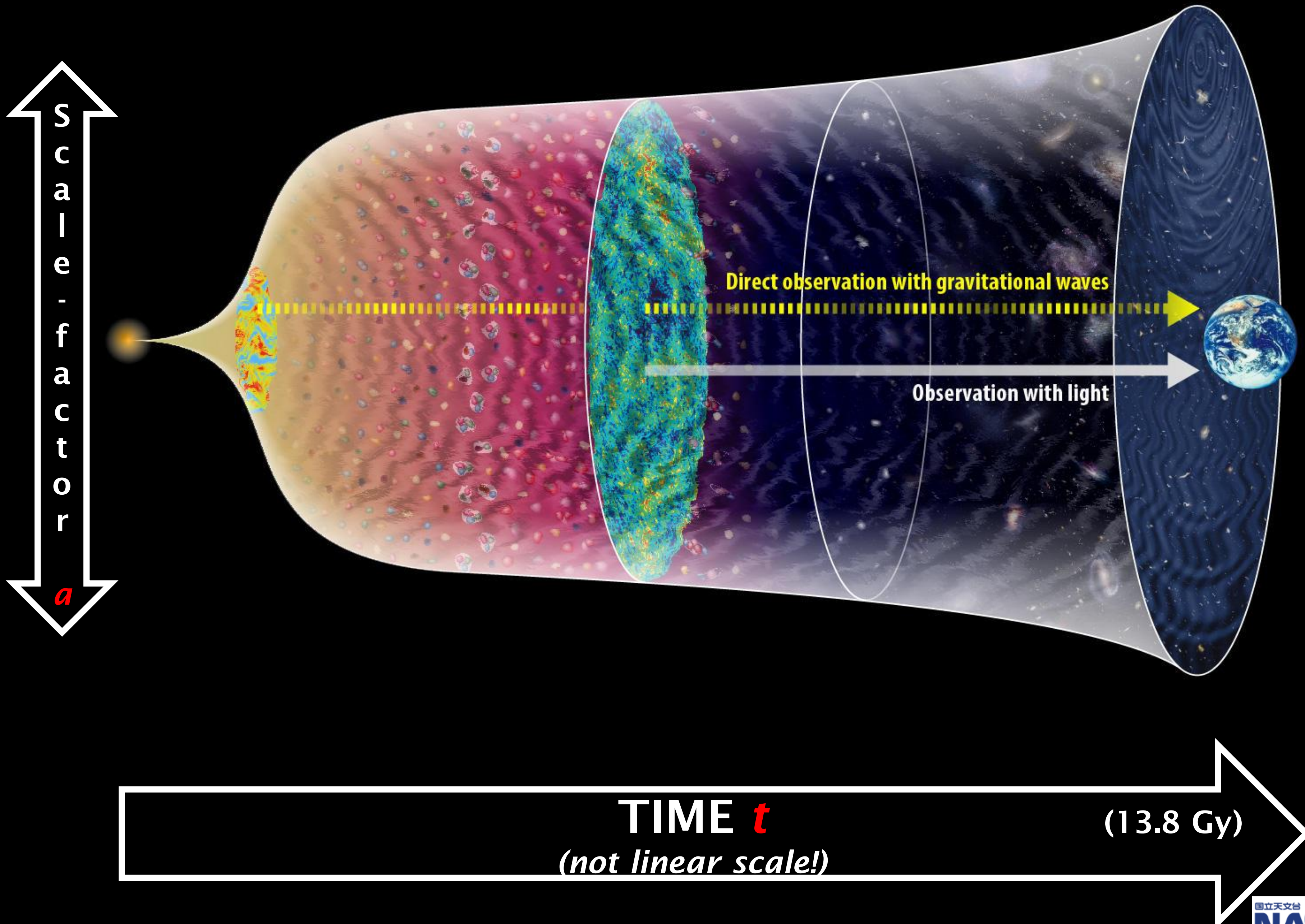
Vatican Observatory

INAF
ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS

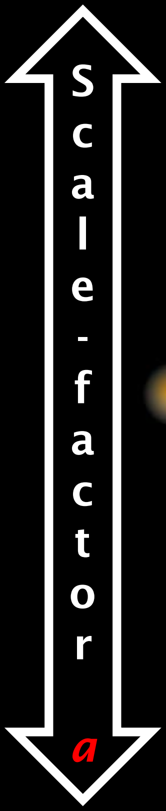
Matteo Galaverni

Looking for
Quantum Gravity imprints in the Universe

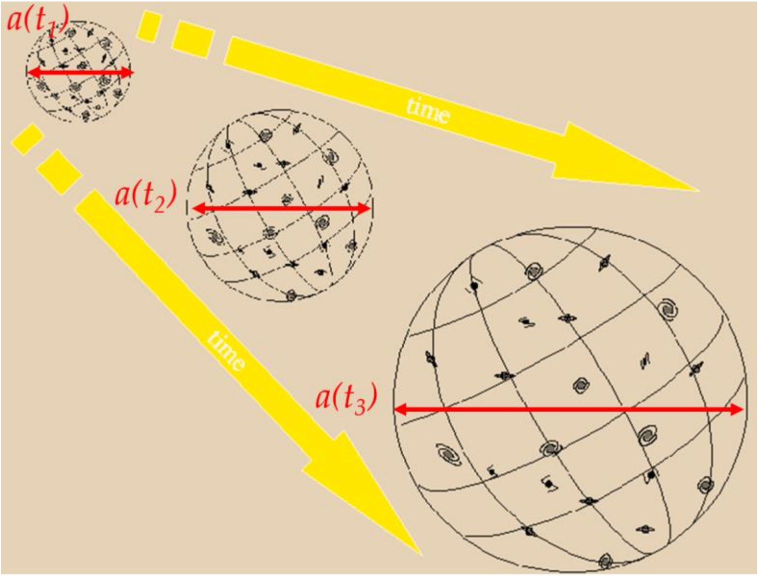
- Brief “history” of the universe
- Gravitational waves
- Cosmic Microwave Background Radiation (Temperature & Polarization)
- Conclusions



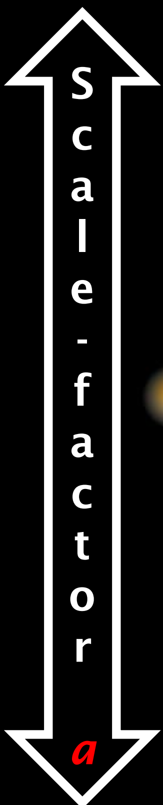
国立天文台 NAOJ National Astronomical Observatory of Japan



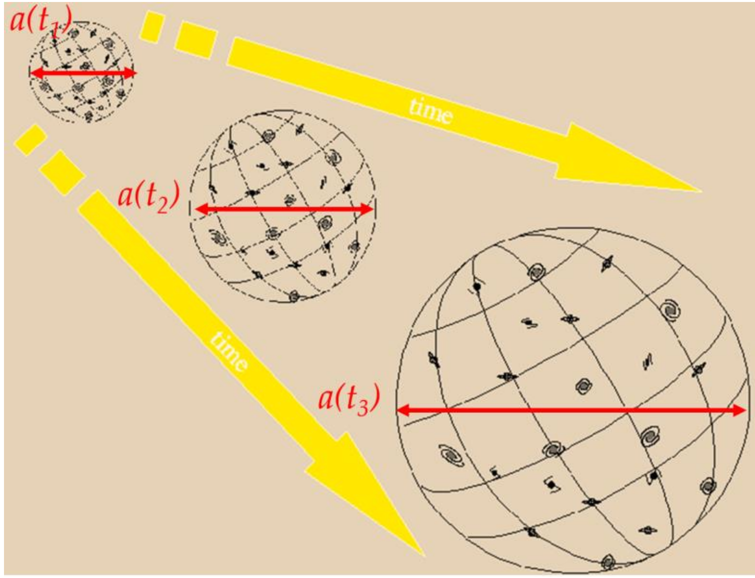
Universe expansion



$$ds^2 = a^2(t)(dx^2 + dy^2 + dz^2)$$



Universe expansion



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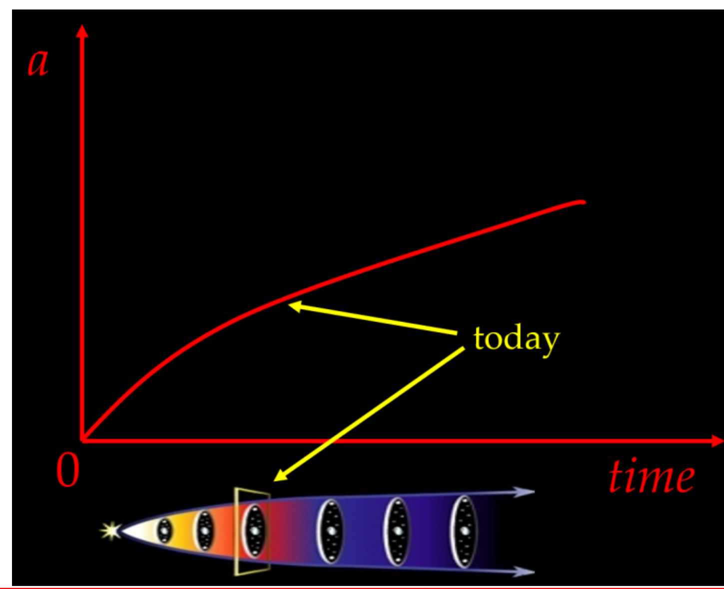
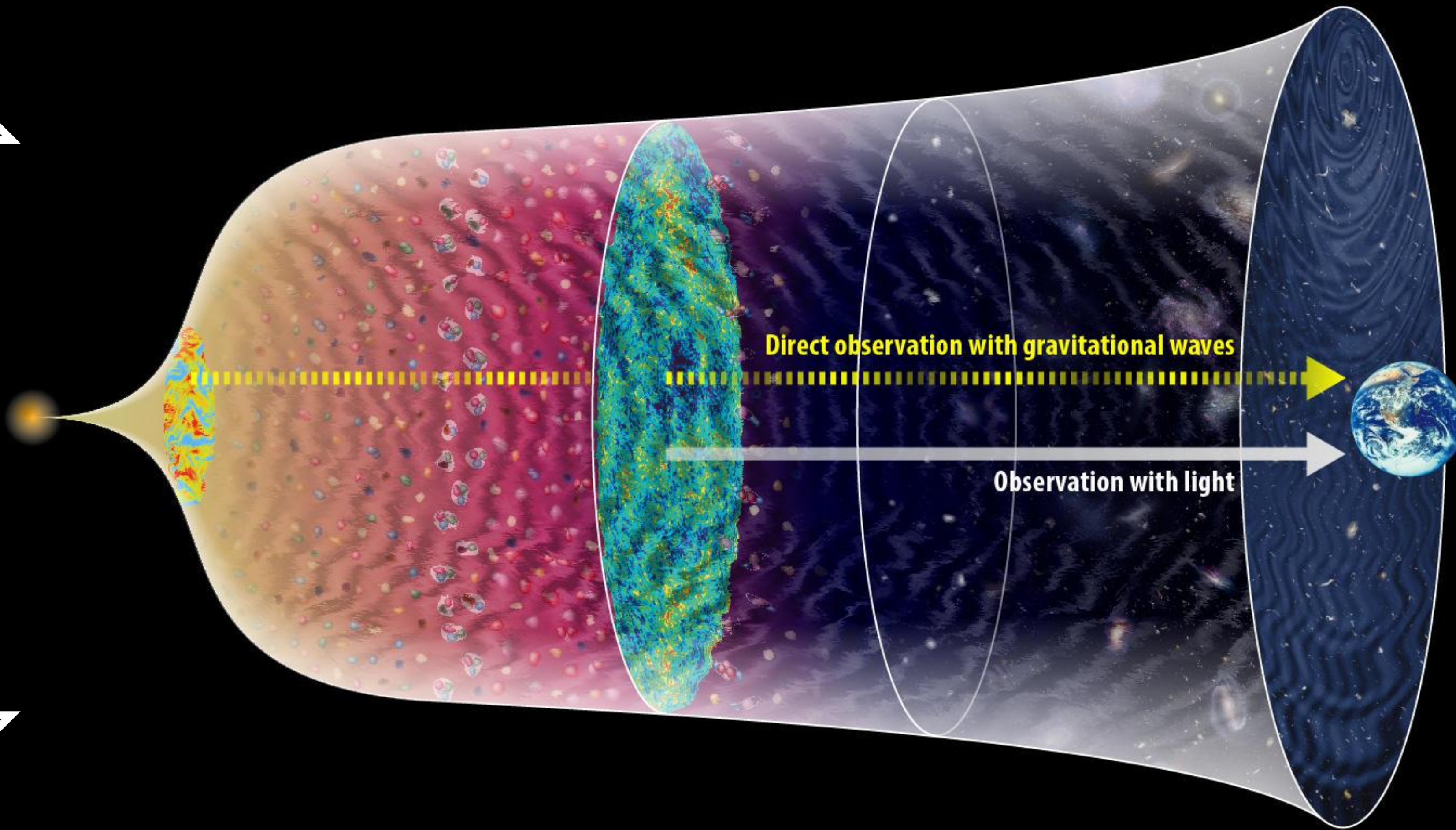


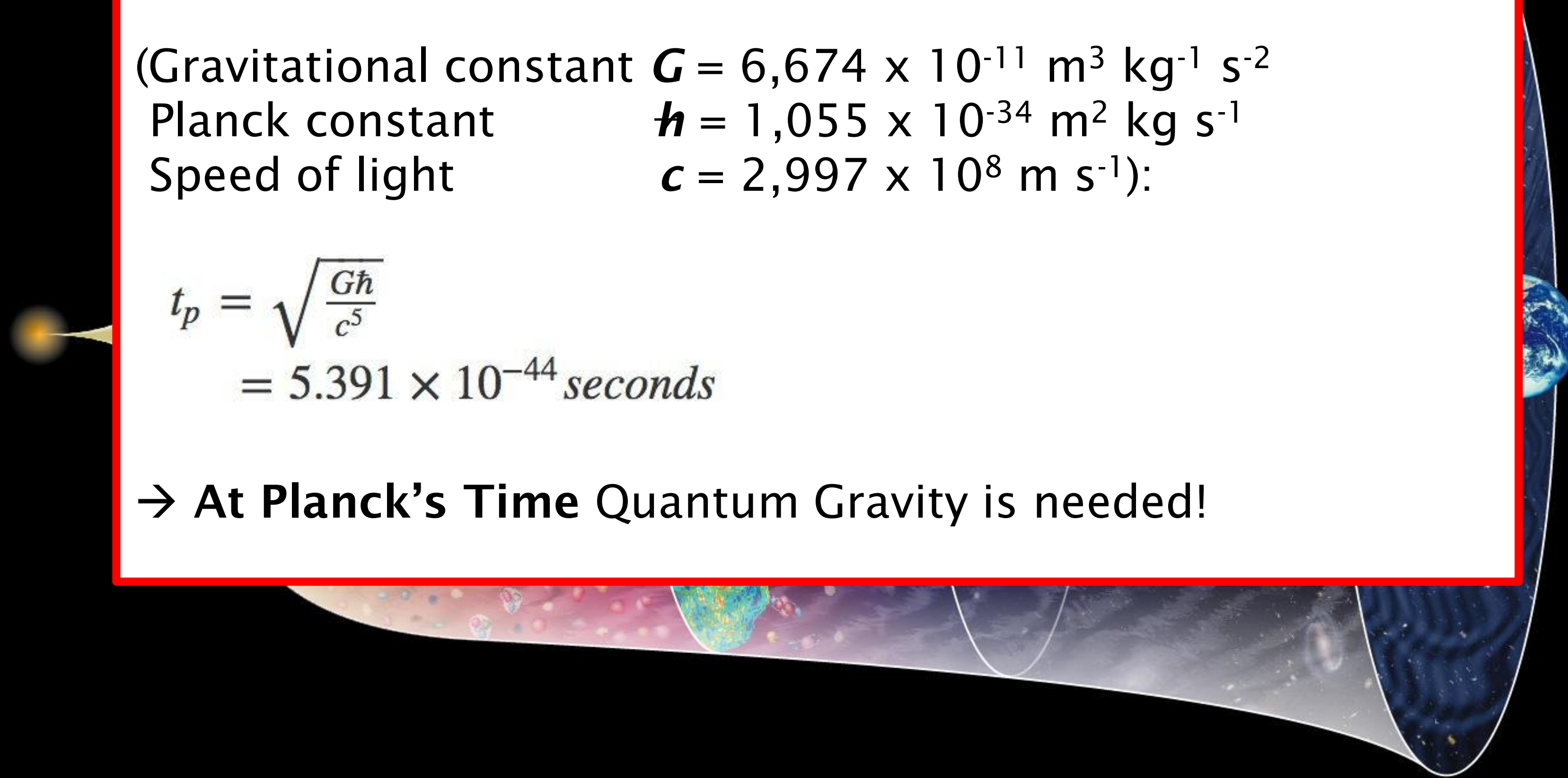
Scale-factor a



TIME t

(13.8 Gy)

(not linear scale!)

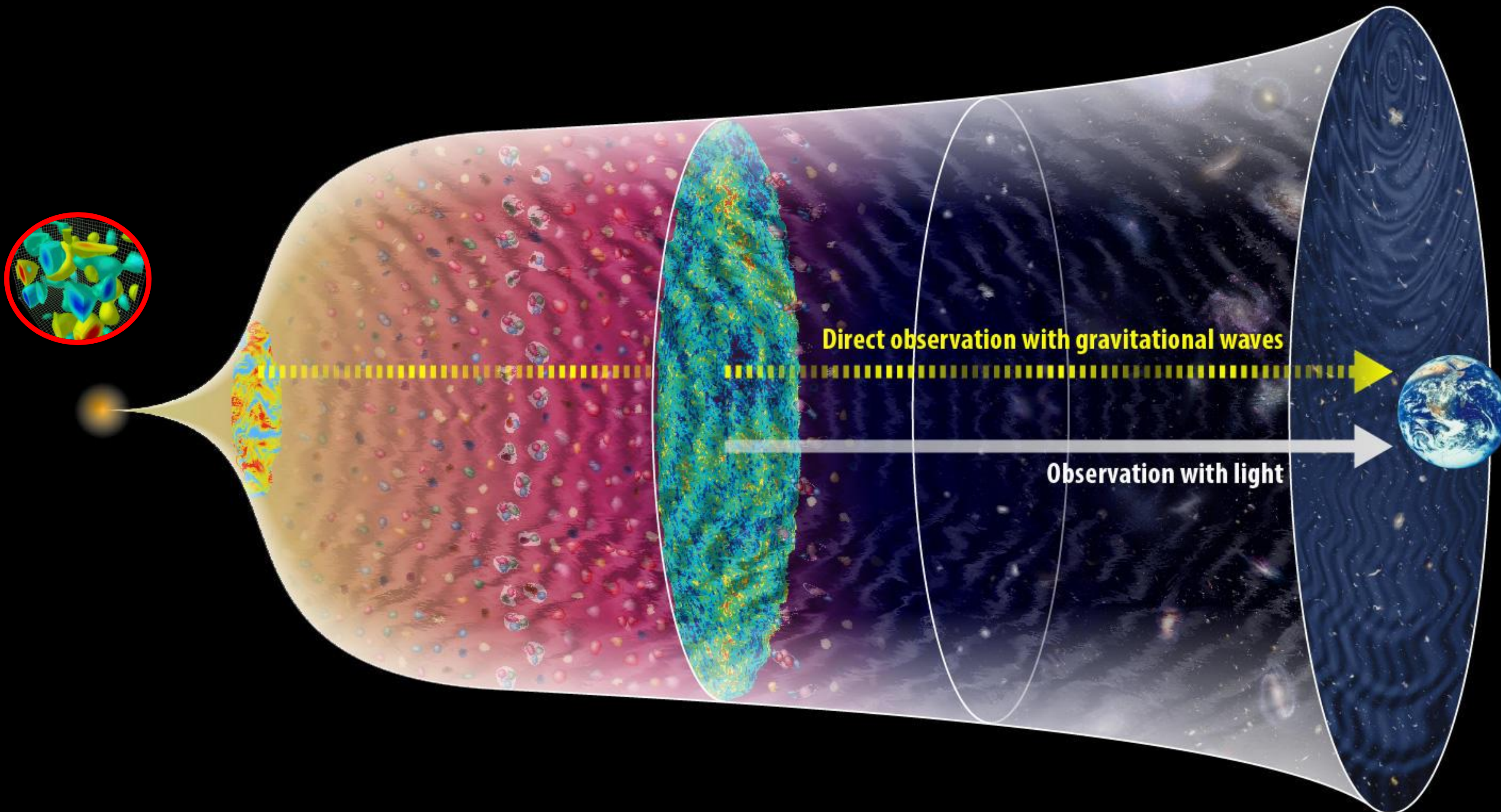


Time-scale defined using the fundamental constants of **Gravity** and **Quantum Mechanics**

(Gravitational constant $\boldsymbol{G}$ = 6,674 x 10^{-11} m^3 kg^{-1} s^{-2}
Planck constant $\boldsymbol{\hbar}$ = 1,055 x 10^{-34} m^2 kg s^{-1}
Speed of light $\boldsymbol{c}$ = 2,997 x 10^{8} m s^{-1}):

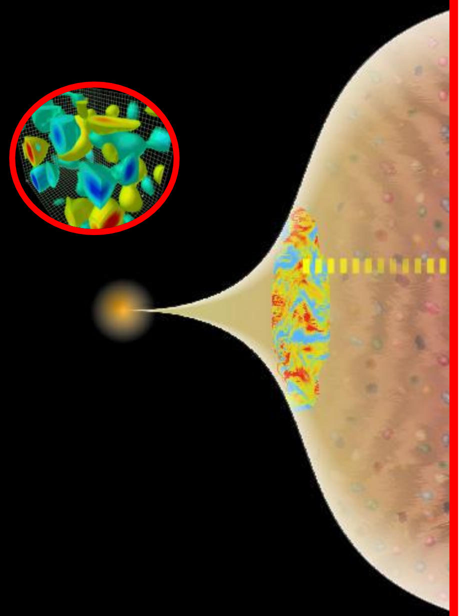
$$t_p = \sqrt{\frac{G\hbar}{c^5}}$$
$$= 5.391 \times 10^{-44} \, seconds$$

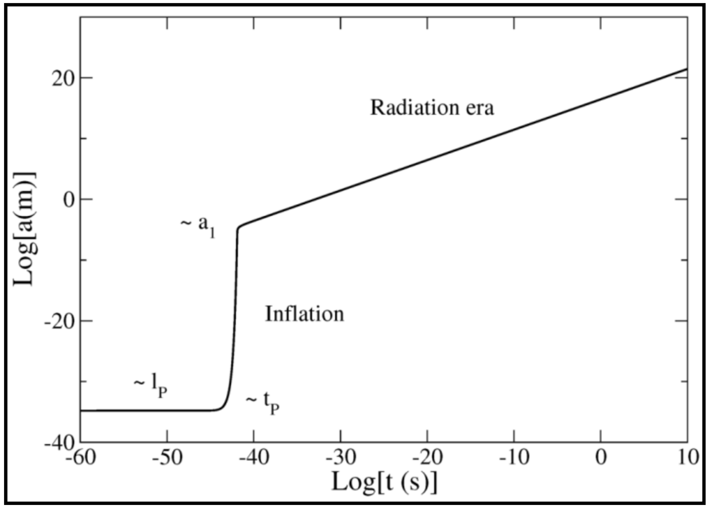
→ **At Planck's Time** Quantum Gravity is needed!



Direct observation with gravitational waves
Observation with light

Cosmic inflation: the universe underwent a phase of **exponential expansion** that sets up its very special initial conditions



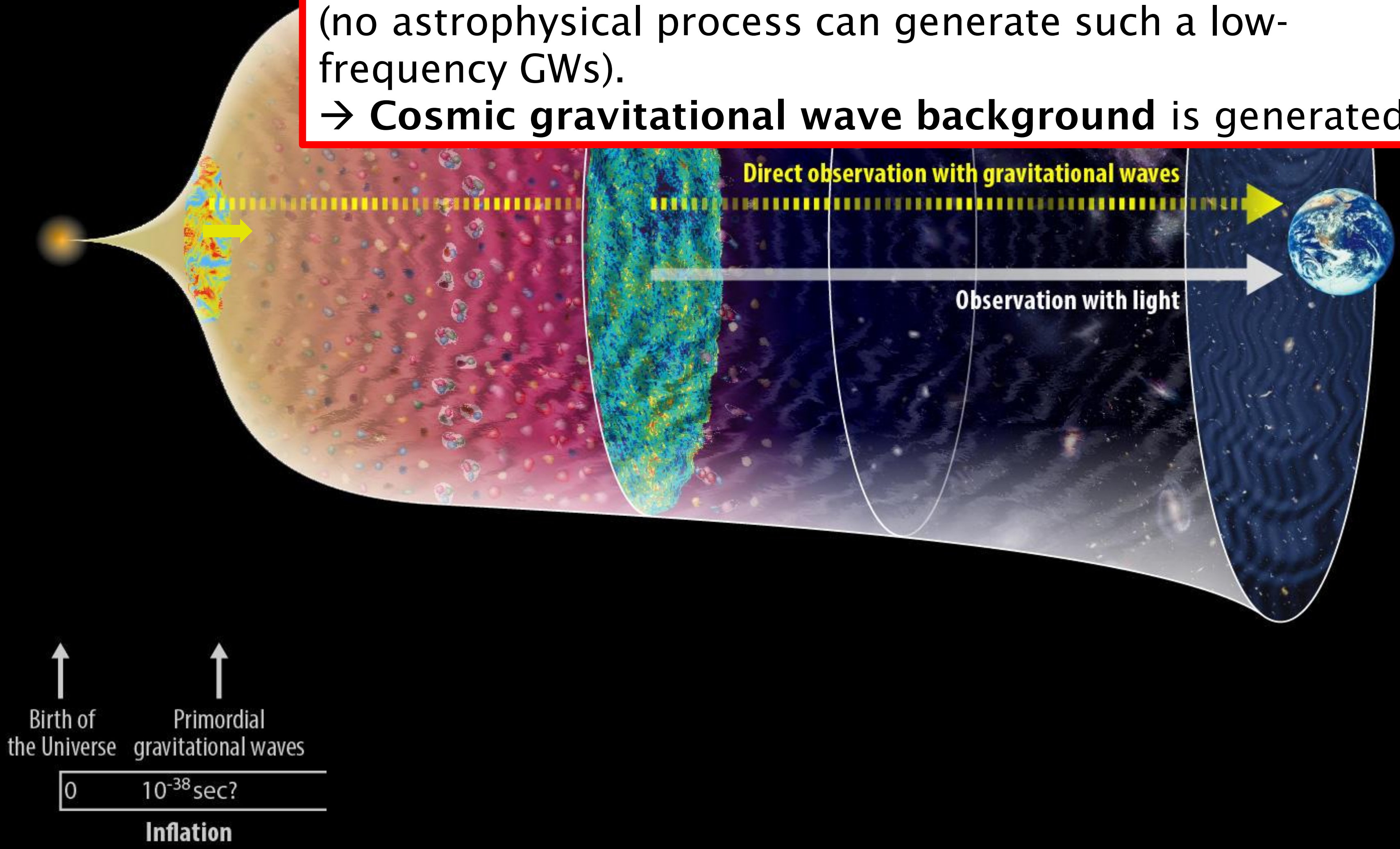


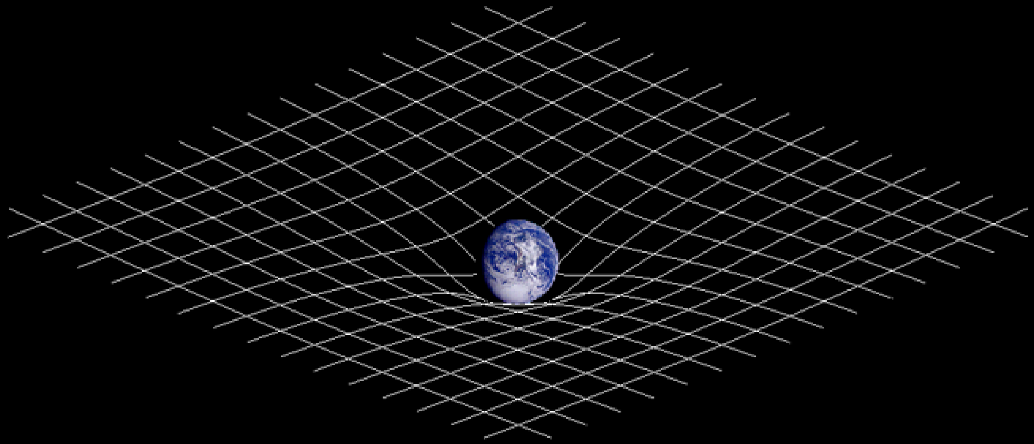
Quantum vacuum fluctuations during inflation turn out to play an important role. They give the initial condition for all the structures in the Universe.

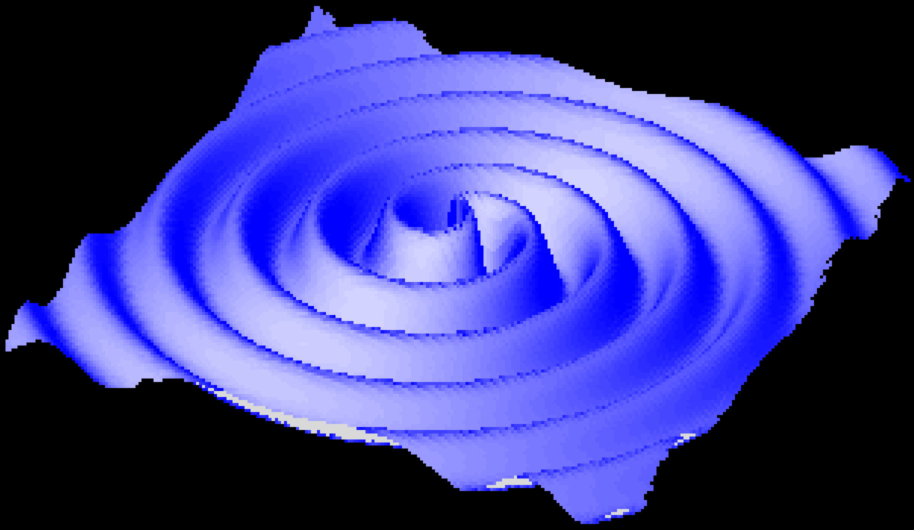
-A **microscopic wavelength** of quantum fluctuations is stretched by enormous expansion of space to became a **macroscopic** one.

-The **origin of cosmic structures** is explained by a combination of quantum mechanics and general relativity.

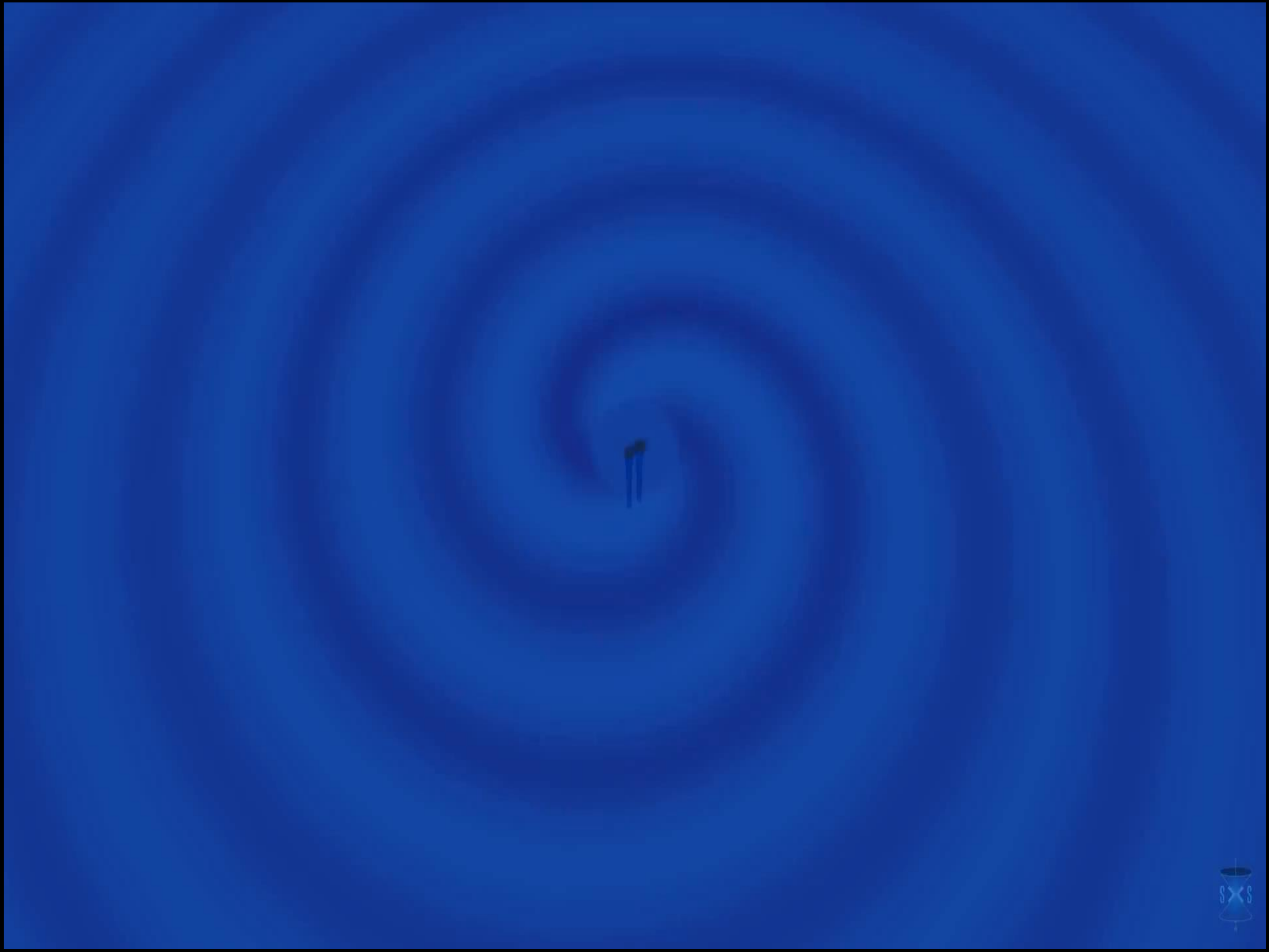
The simplest model of inflation (single energy component driving exponential inflation) predicts a **stochastic background of gravitational waves**
(no astrophysical process can generate such a low-frequency GWs).
→ **Cosmic gravitational wave background** is generated.







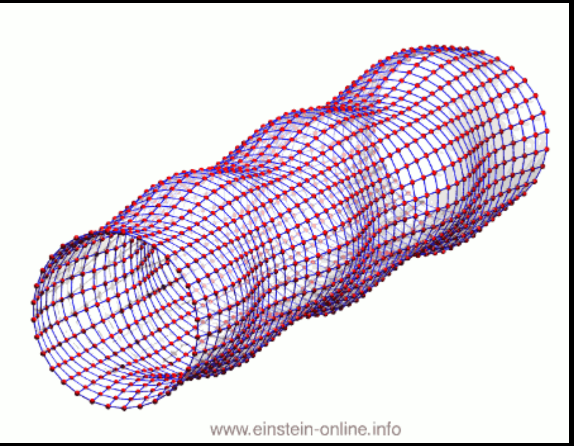
A computer **simulation of gravitational waves from merging black holes** [Simulating eXtreme Spacetimes (SXS) project]



If we consider a plane gravitational wave propagating in one direction:

- the gravitational wave shall be transverse (the direction of distortion is perpendicular to the propagation direction).
- the gravitational wave shall not change the area.

→ There are two degrees of freedom



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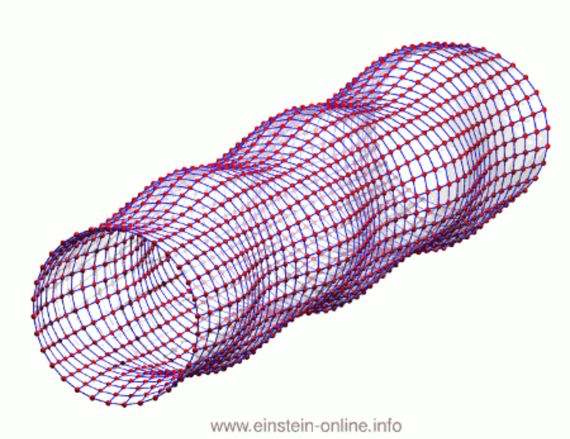
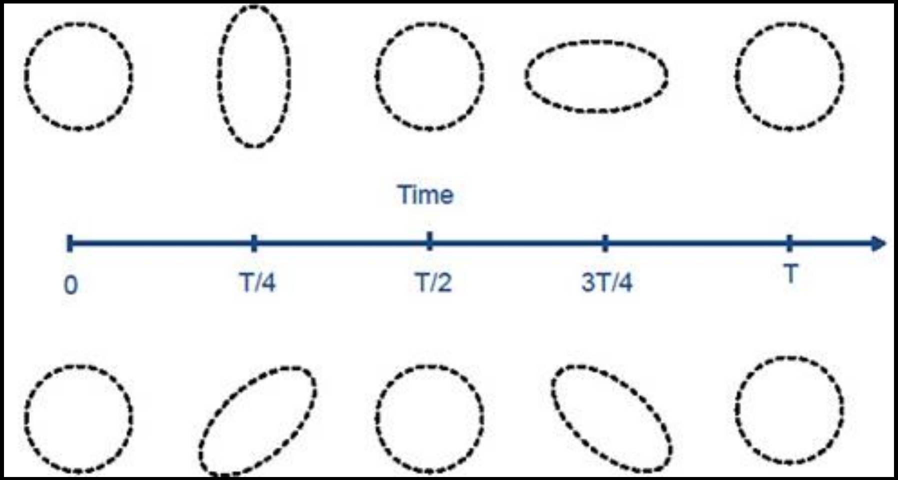
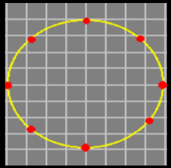
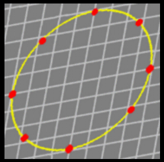






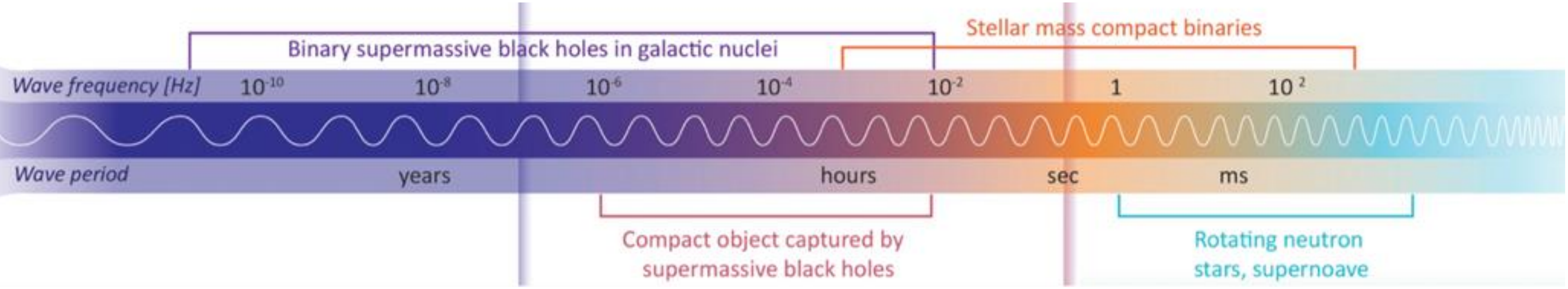
h_+ polarization



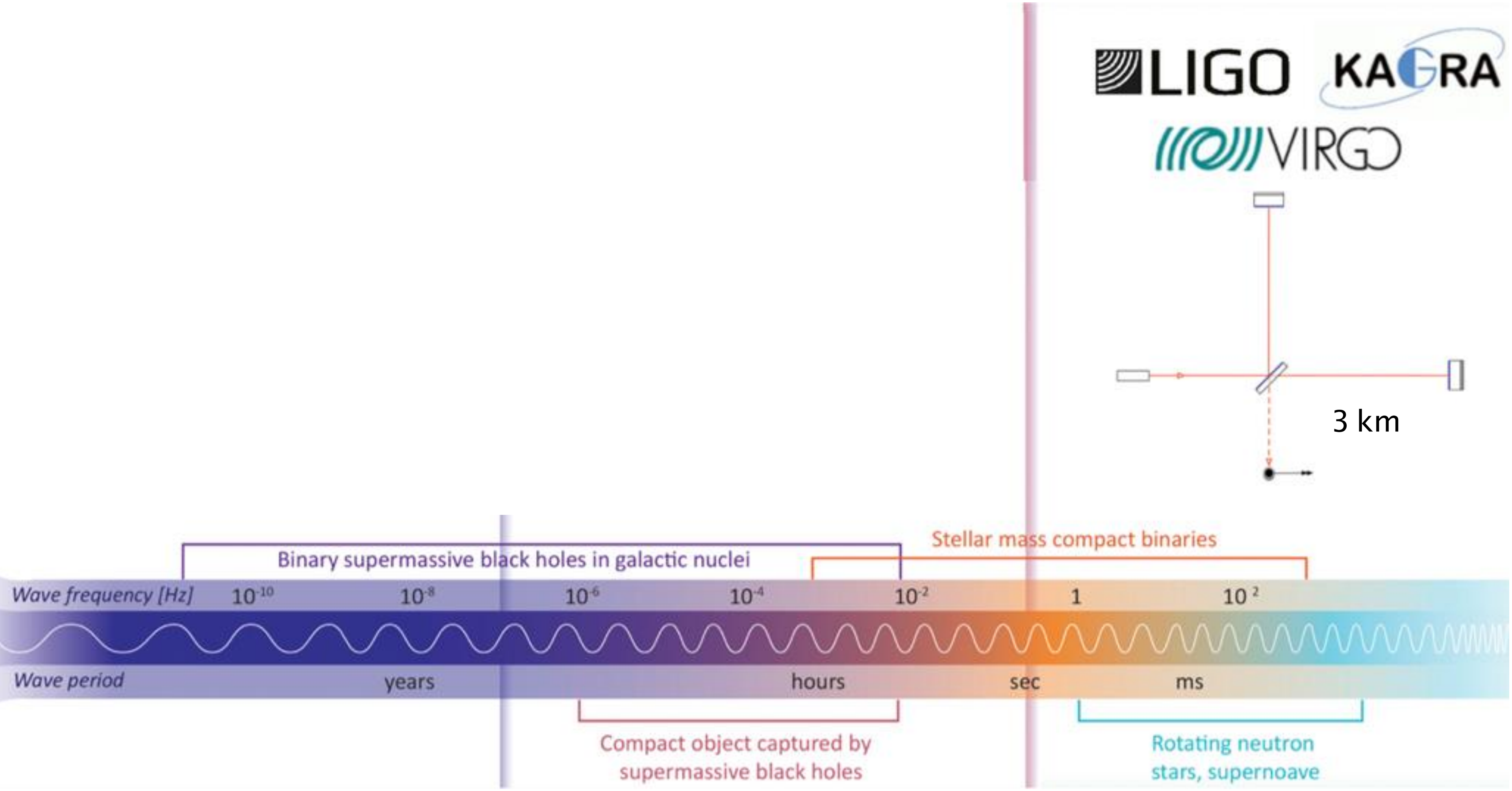
h_X polarization

$$h_{\mu\nu}^{\mathrm{TT}}(t,z) = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}_{\mu\nu} \cos[\omega(t - z/c)] \, ,$$

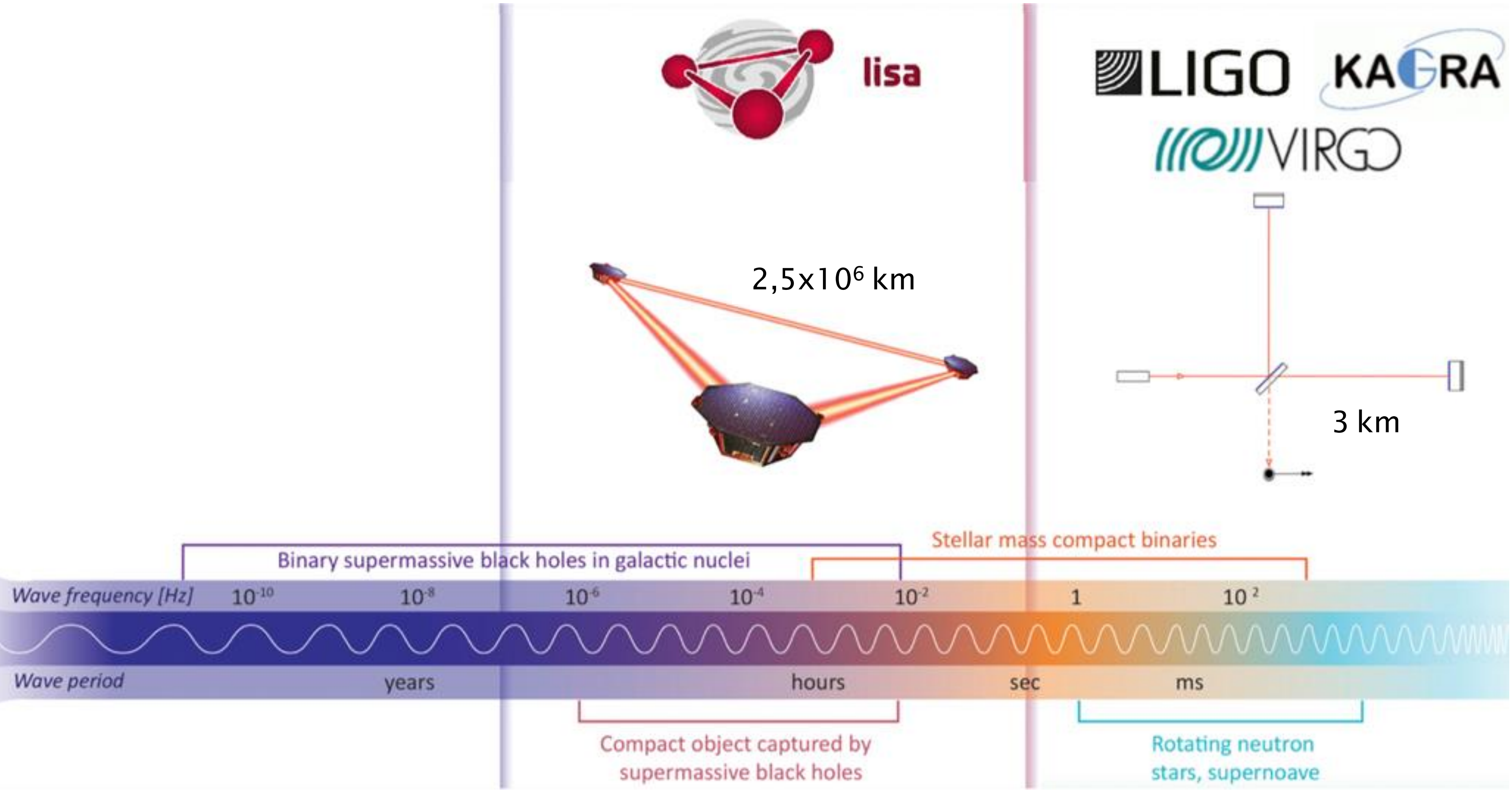
Gravitational waves spectrum



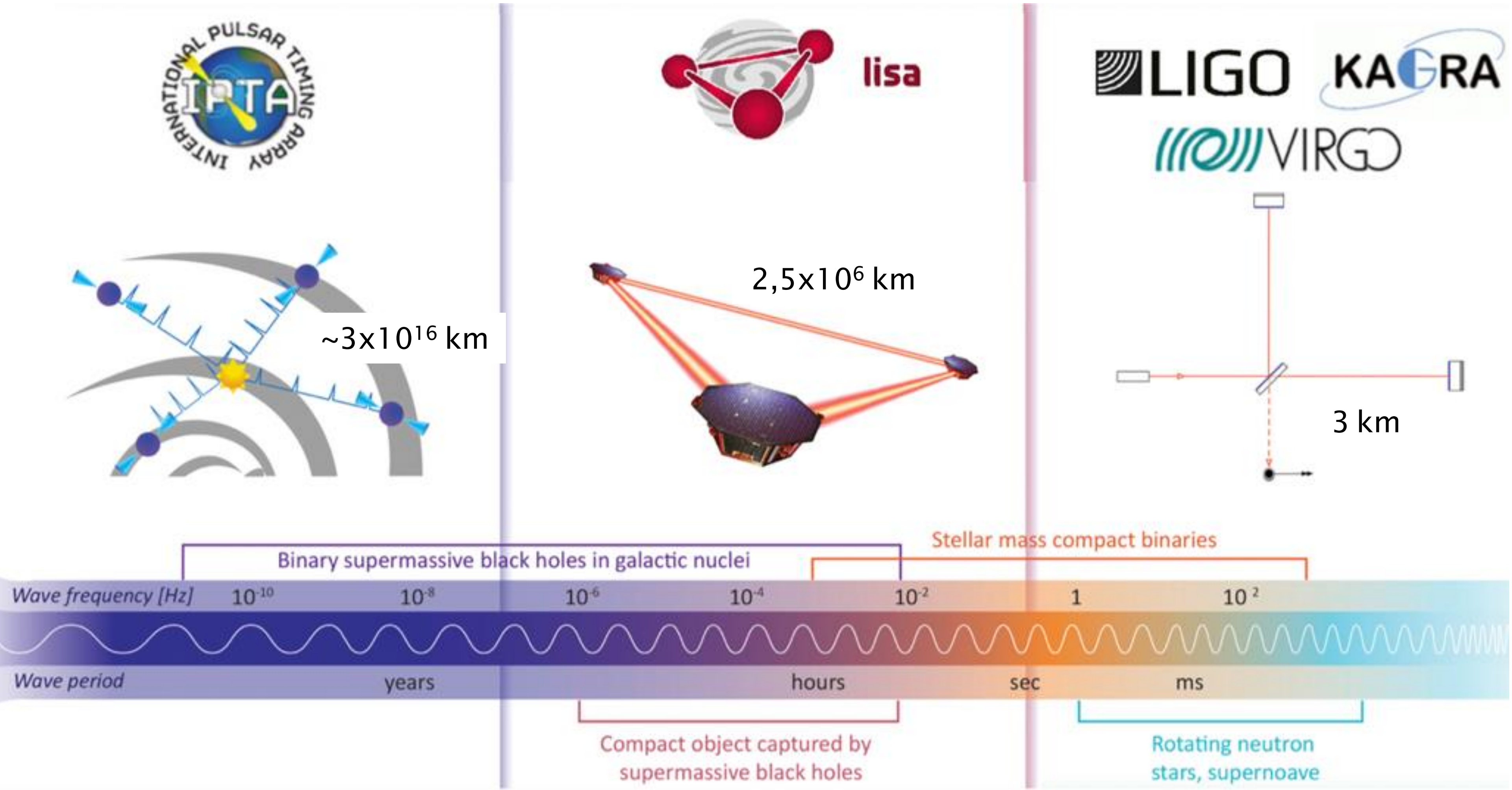
Gravitational waves spectrum



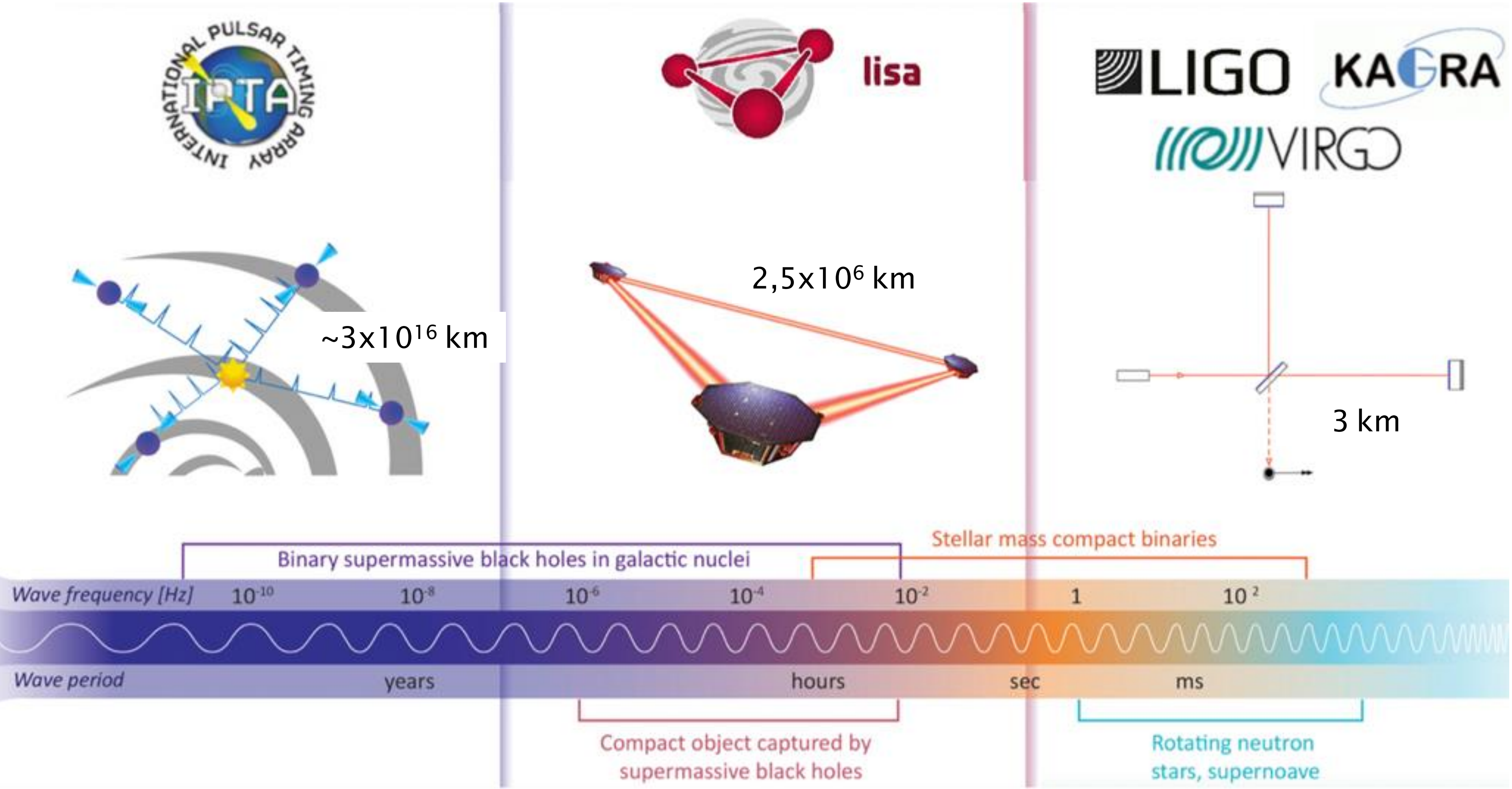
Gravitational waves spectrum



Gravitational waves spectrum

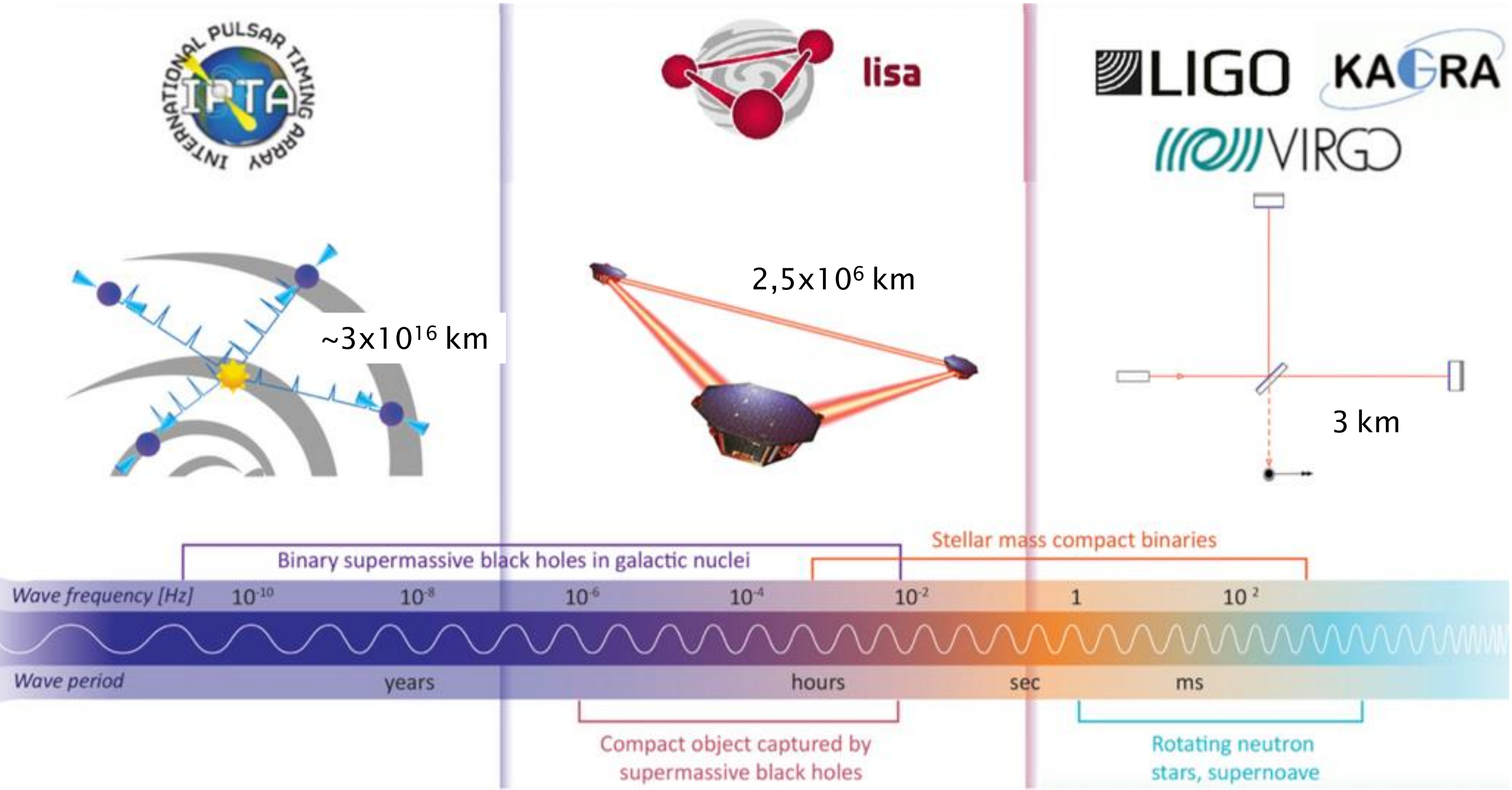


Gravitational waves spectrum



no astrophysical process can generate such a low-frequency GWs

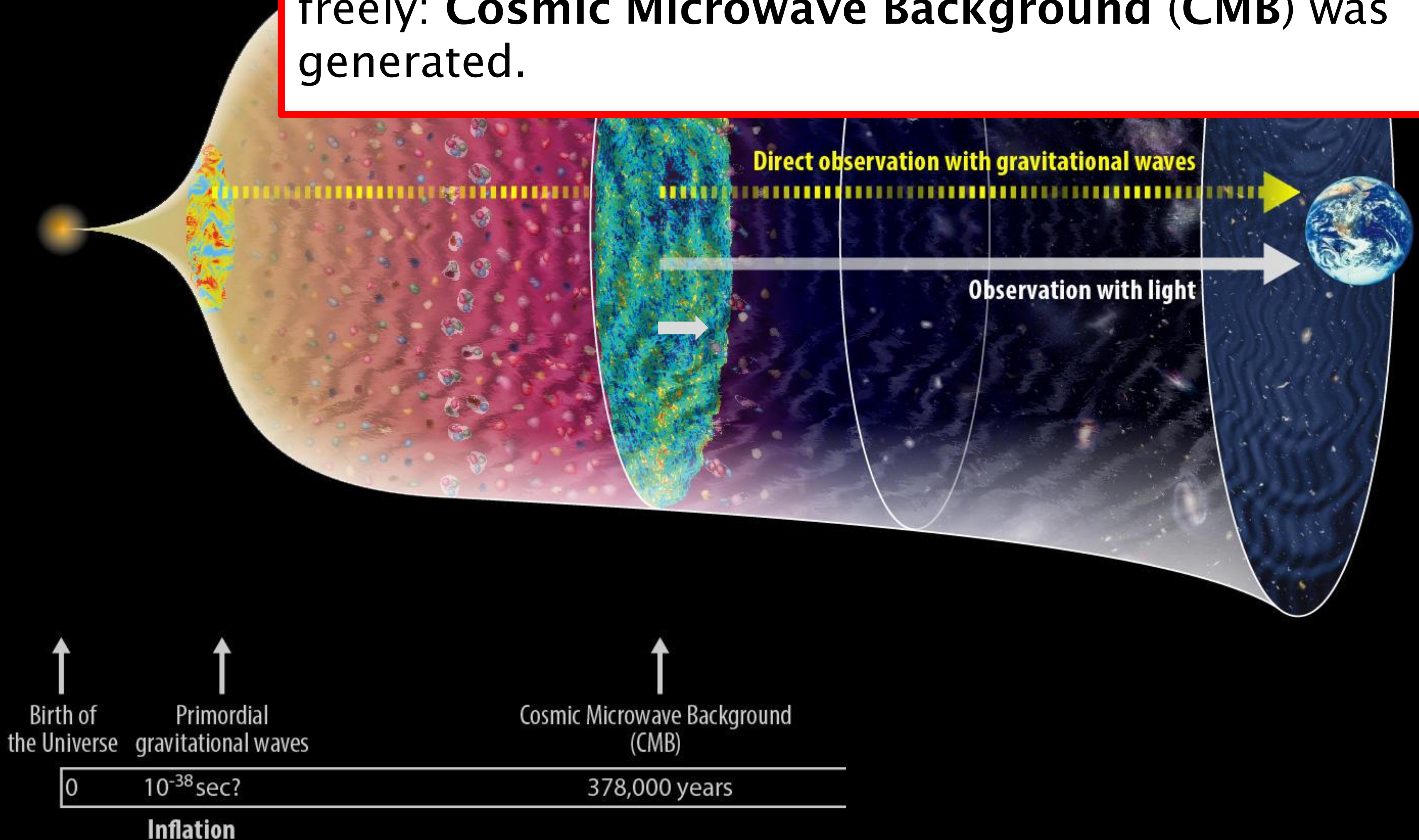
Gravitational waves spectrum



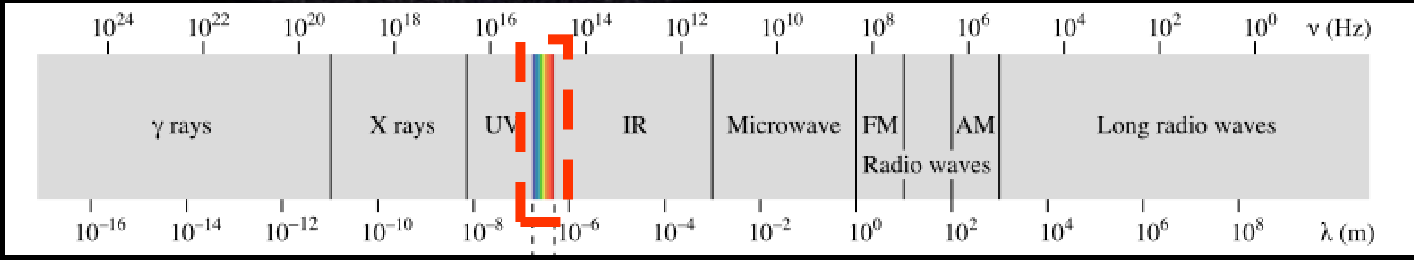
no astrophysical process can generate such a low-frequency GWs

…use the **entire Universe** as a detector (CMB).

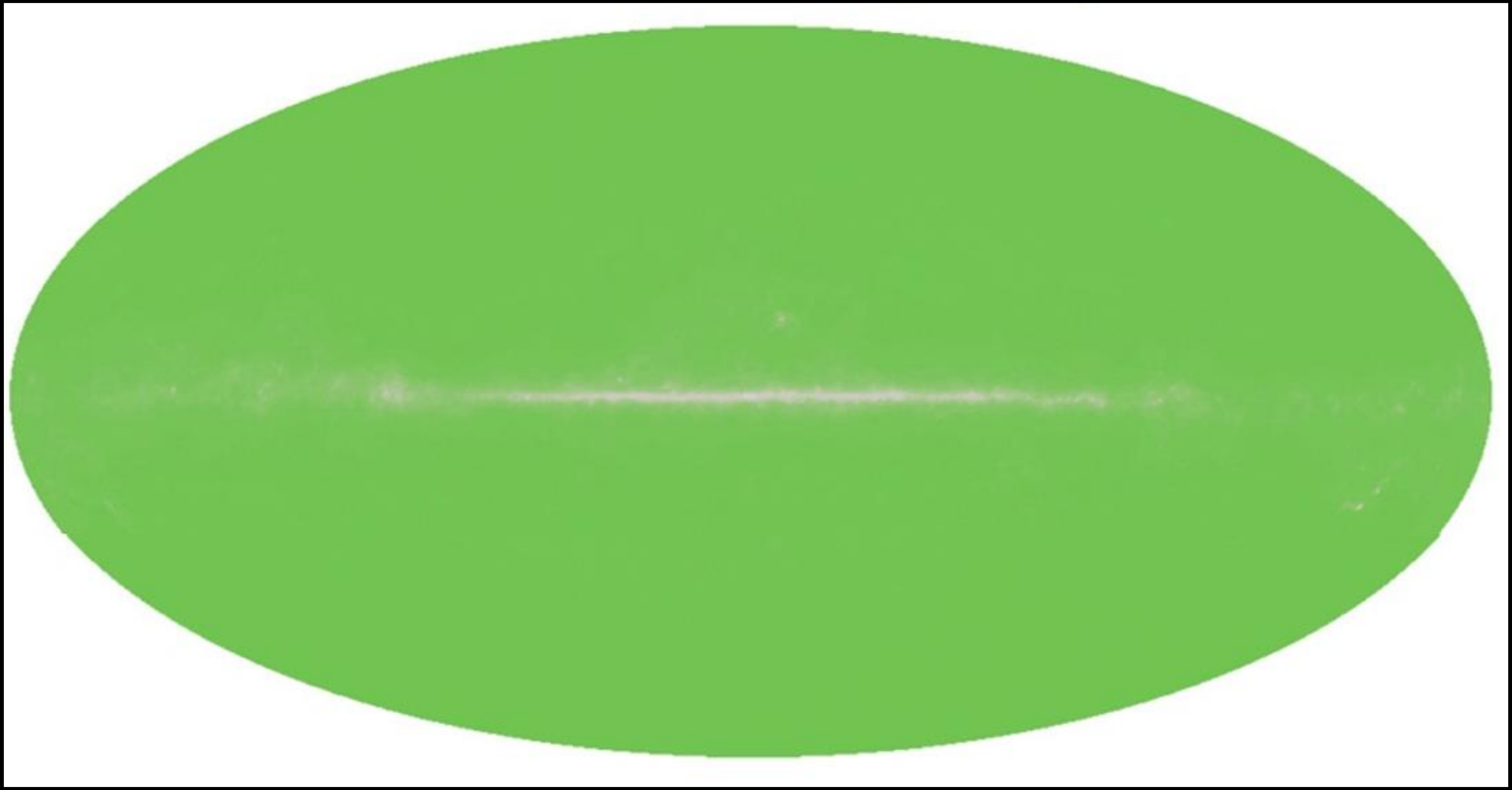
When the universe cooled down to a temperature at which atoms can form (about 3000°C), matter then became neutral, and allowed the light to travel freely: **Cosmic Microwave Background** (**CMB**) was generated.

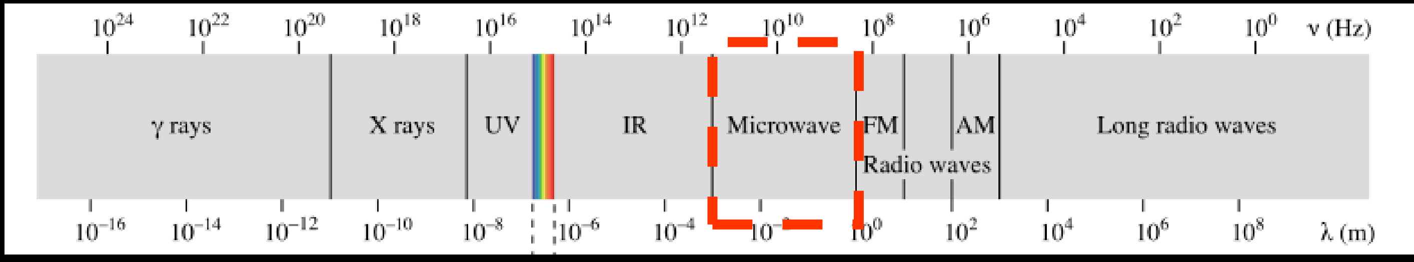


Visible



10^{24} 10^{22} 10^{20} 10^{18} 10^{16} 10^{14} 10^{12} 10^{10} 10^{8} 10^{6} 10^{4} 10^{2} 10^{0} ν (Hz)
γ rays
X rays
UV
IR
Microwave
FM
AM
Radio waves
Long radio waves
10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4} 10^{6} 10^{8} λ (m)





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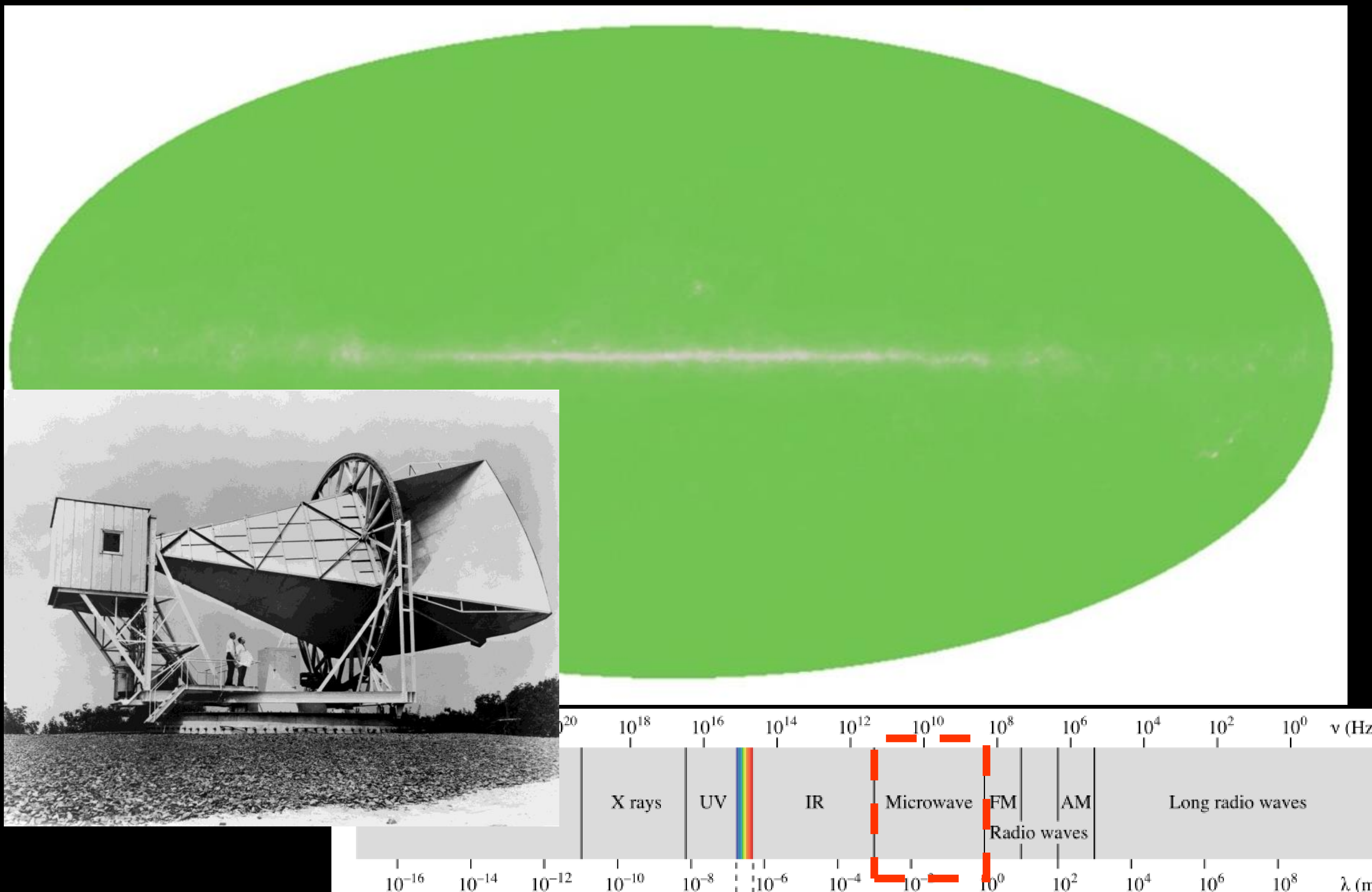
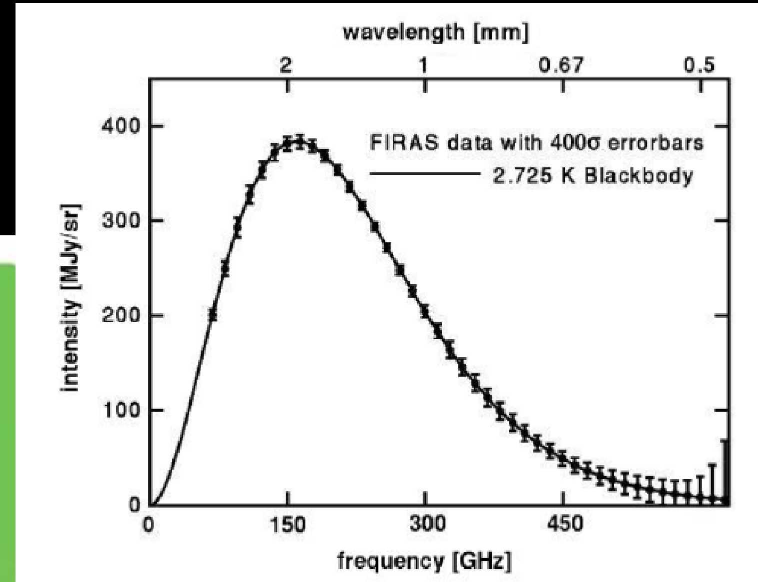
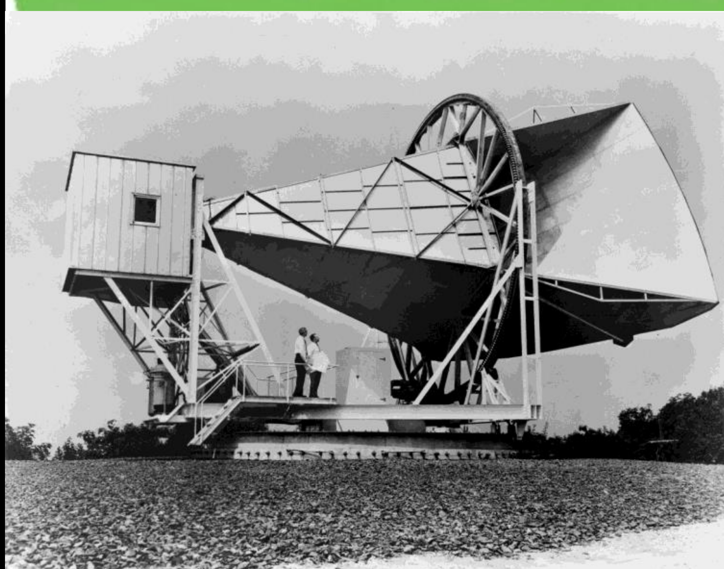
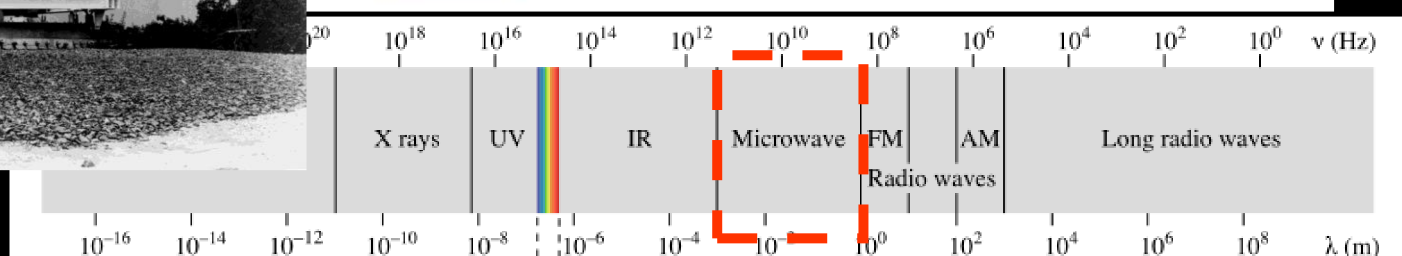


10^18 10^16 10^14 10^12 10^10 10^8 10^6 10^4 10^2 10^0 ν (Hz)
X rays
UV
IR
Microwave
FM
AM
Long radio waves
Radio waves
10^−16 10^−14 10^−12 10^−10 10^−8 10^−6 10^−4 10^0 10^2 10^4 10^6 10^8 λ (m)


wavelength [mm]
2
1
0.67
0.5
400
300
200
100
0
intensity [MJy/sr]
FIRAS data with 400σ errorbars
2.725 K Blackbody
0
150
300
450
frequency [GHz]




10^18 10^16 10^14 10^12 10^10 10^8 10^6 10^4 10^2 10^0 ν (Hz)
X rays
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10^-16 10^-14 10^-12 10^-10 10^-8 10^-6 10^-4 10^0 10^2 10^4 10^6 10^8 λ (m)

The Nobel Prize in Physics 1978

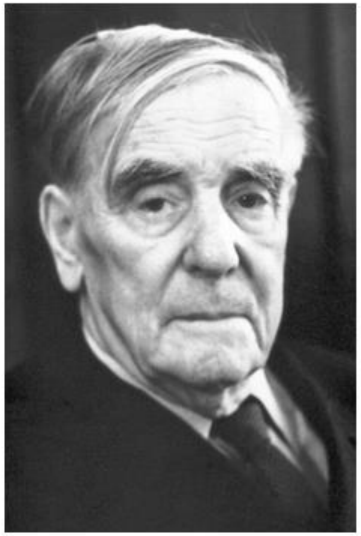


Photo from the Nobel Foundation archive.

Pyotr Leonidovich Kapitsa

Prize share: 1/2

Photo from the Nobel Foundation archive.

Arno Allan Penzias

Prize share: 1/4

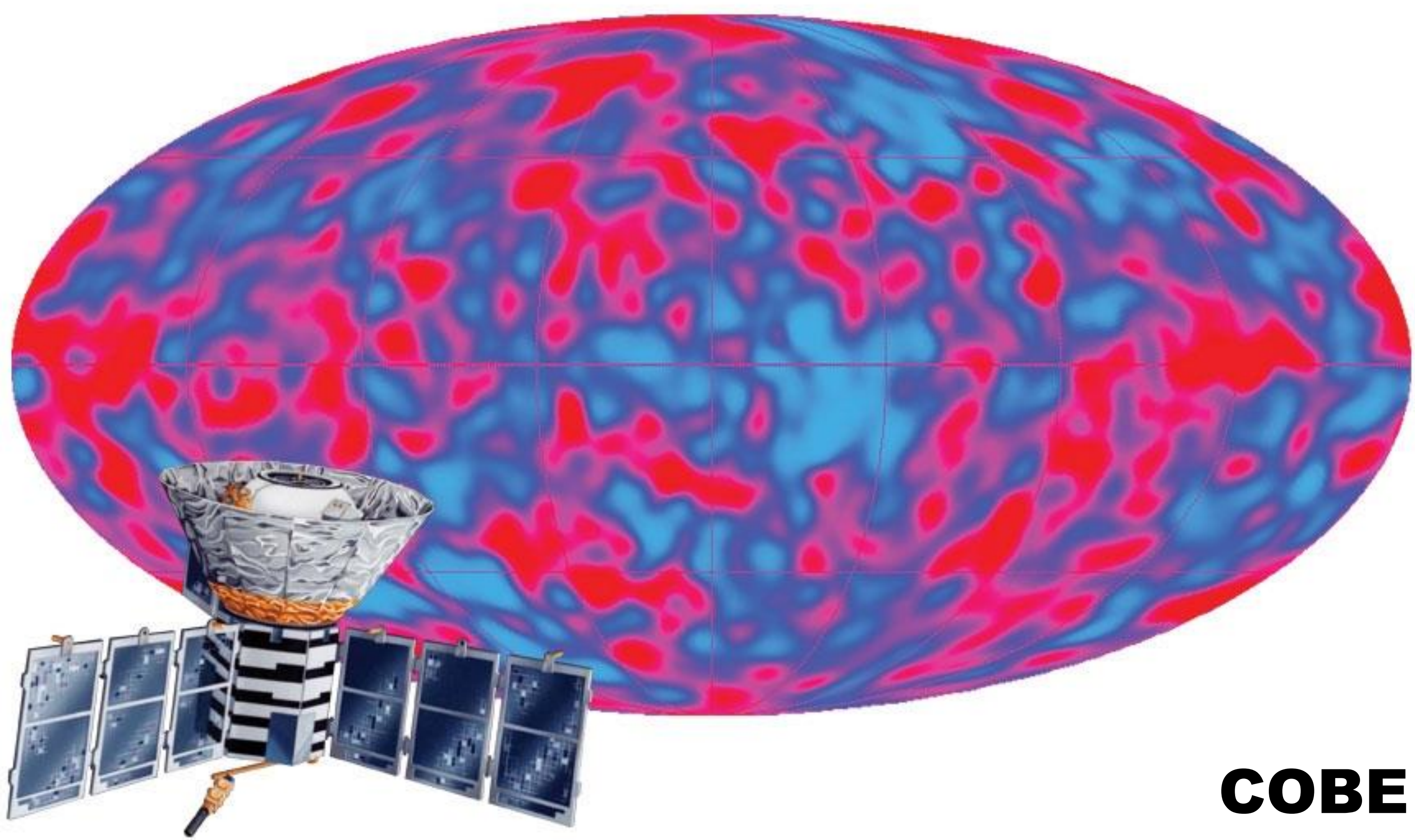
Photo from the Nobel Foundation archive.

Robert Woodrow Wilson

Prize share: 1/4

The Nobel Prize in Physics 1978 was divided, one half awarded to Pyotr Leonidovich Kapitsa "for his basic inventions and discoveries in the area of low-temperature physics", the other half jointly to Arno Allan Penzias and Robert Woodrow Wilson "for their discovery of cosmic microwave background radiation"

$T = 2.7 \pm 0.00003$ K



COBE

The Nobel Prize in Physics 2006

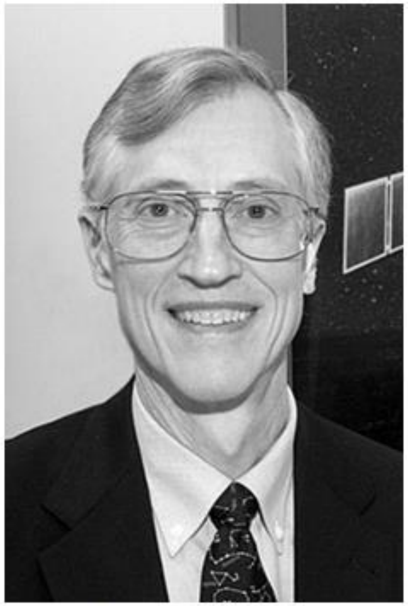


Photo: P. Izzo

John C. Mather

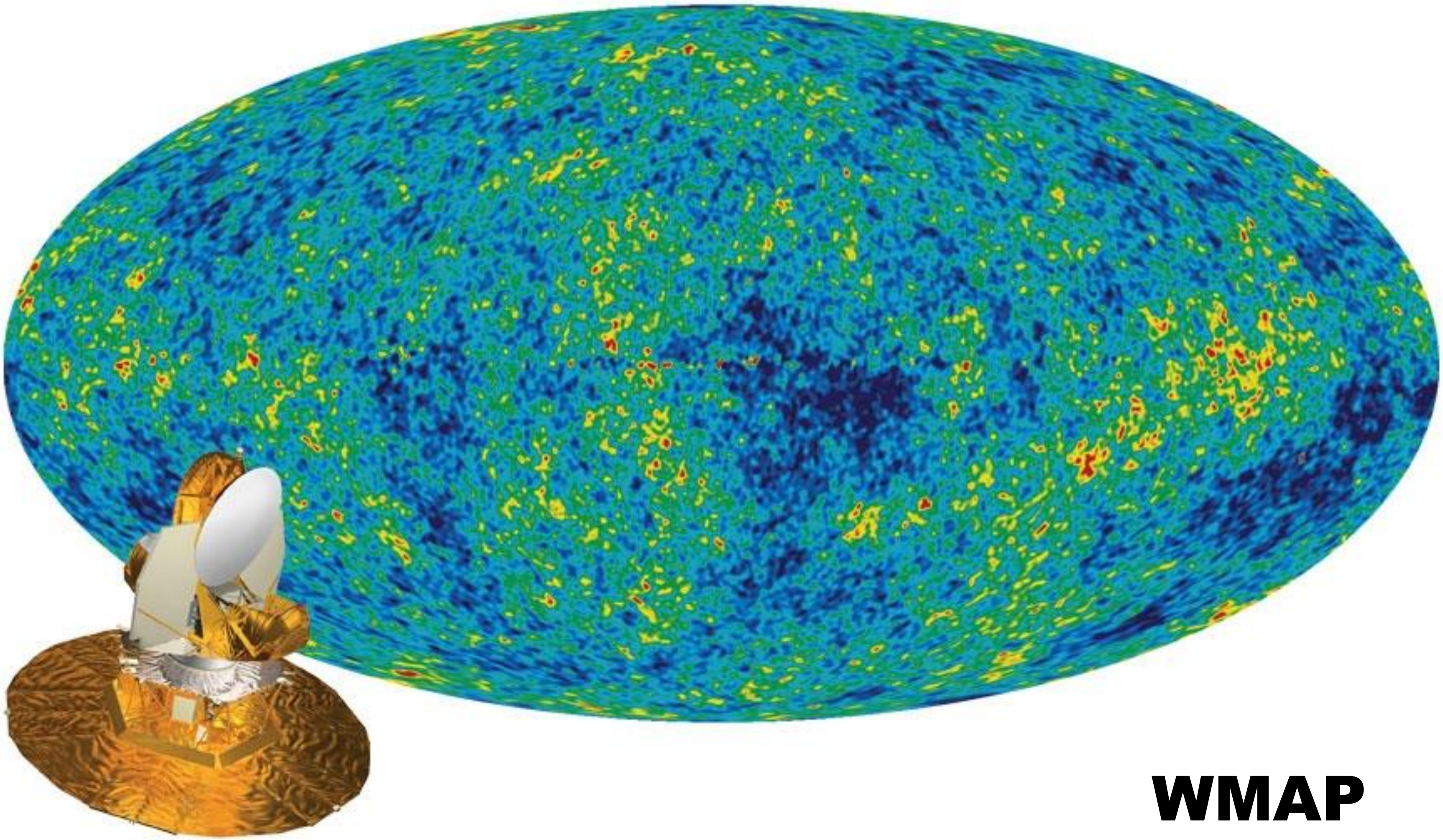
Prize share: 1/2

Photo: J. Bauer

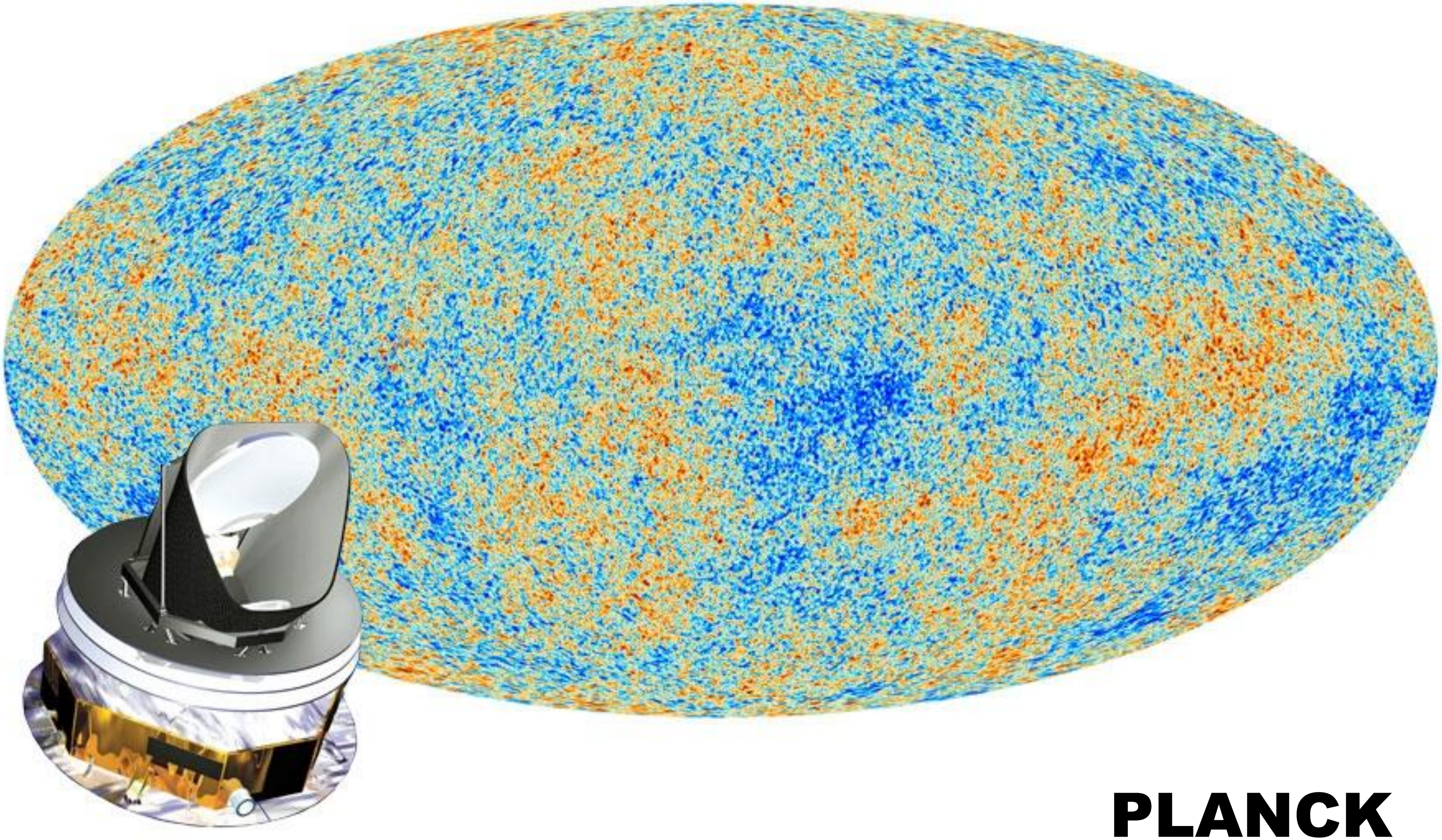
George F. Smoot

Prize share: 1/2

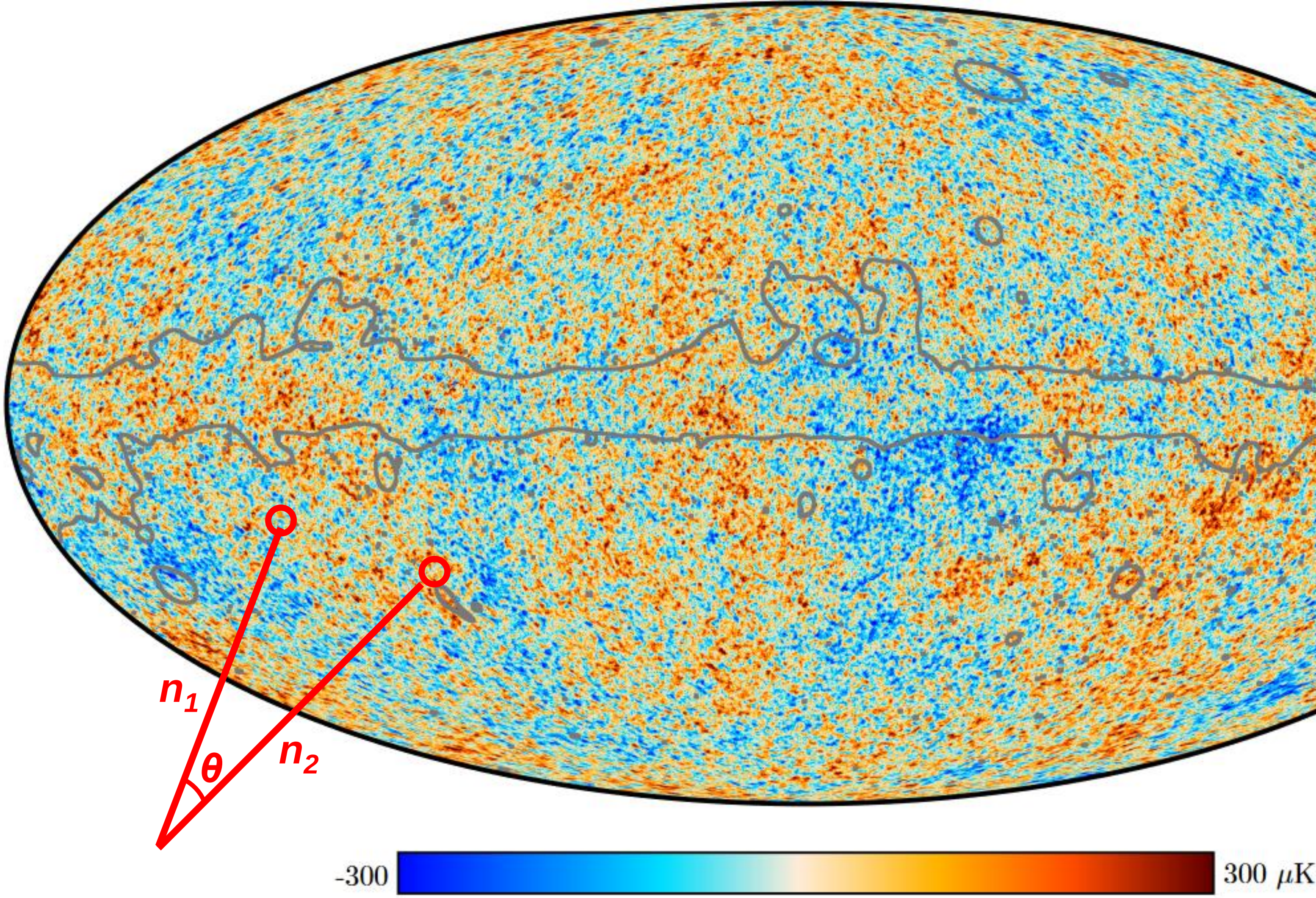
The Nobel Prize in Physics 2006 was awarded jointly to John C. Mather and George F. Smoot "for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"



WMAP



PLANCK



[Planck 2018]

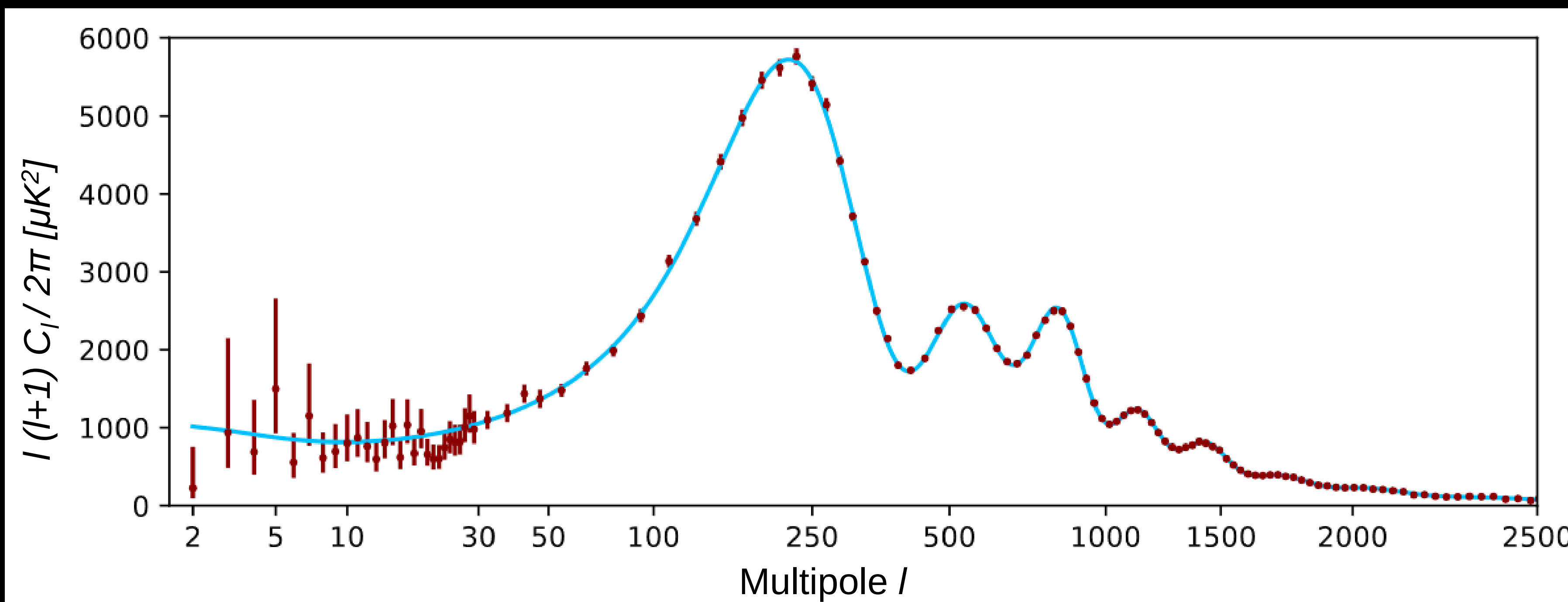
$$\frac{\Delta T(\theta,\phi)}{T} = \sum_{l=0}^{\infty}\sum_{m=-l}^{m=+l} a_{lm} Y_{lm}(\theta,\phi)$$

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

$$\theta \approx 60° / l$$

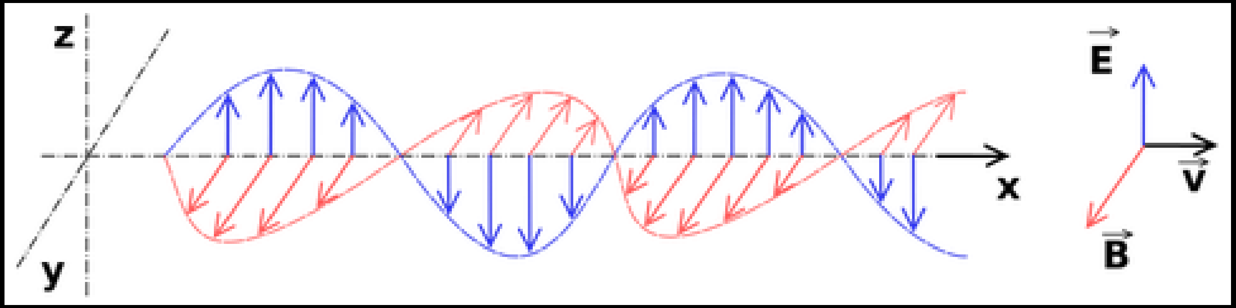
$\theta \approx 1°$

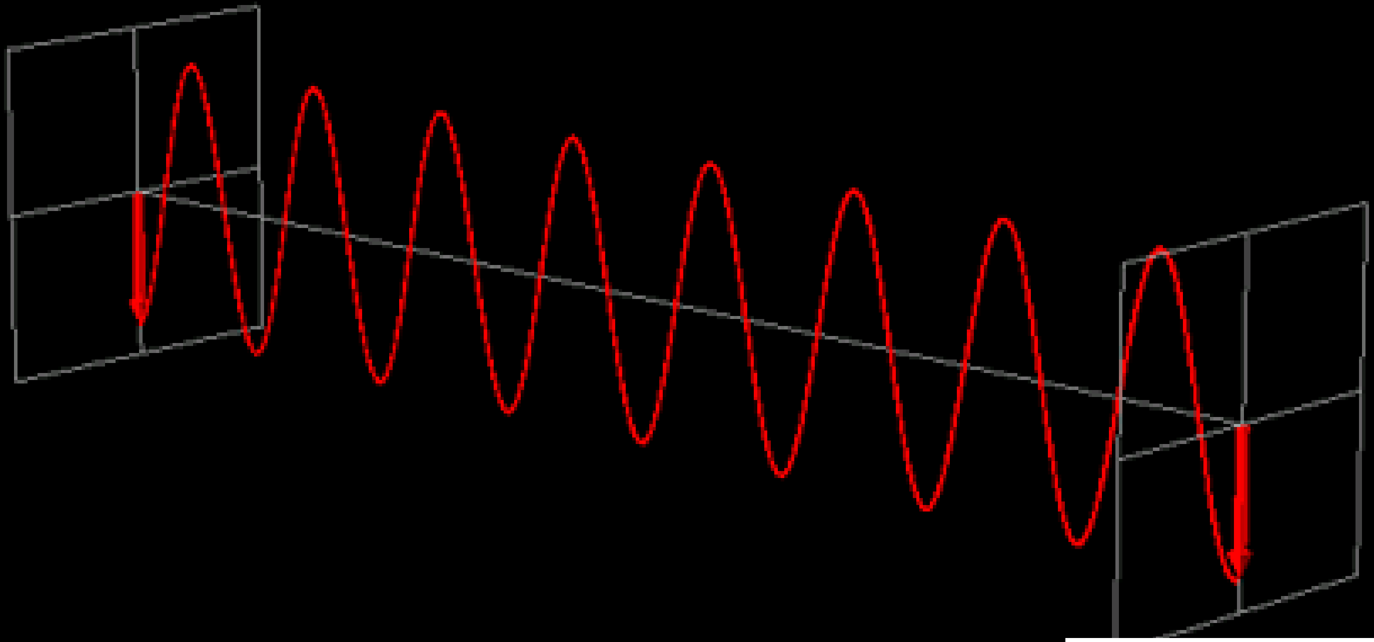
Size of the fluctuations



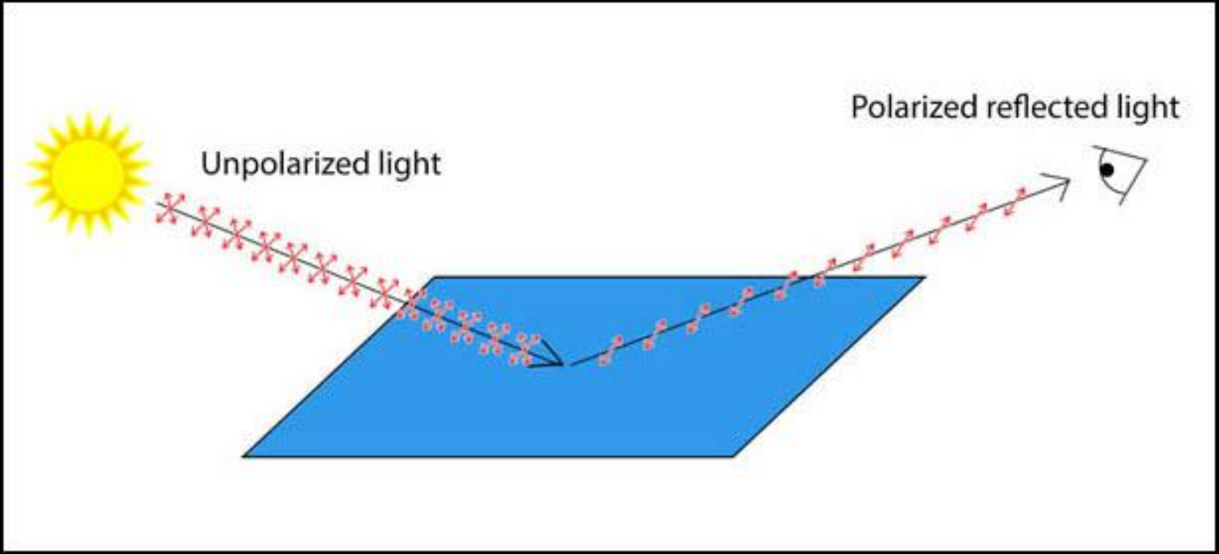
Angular scale

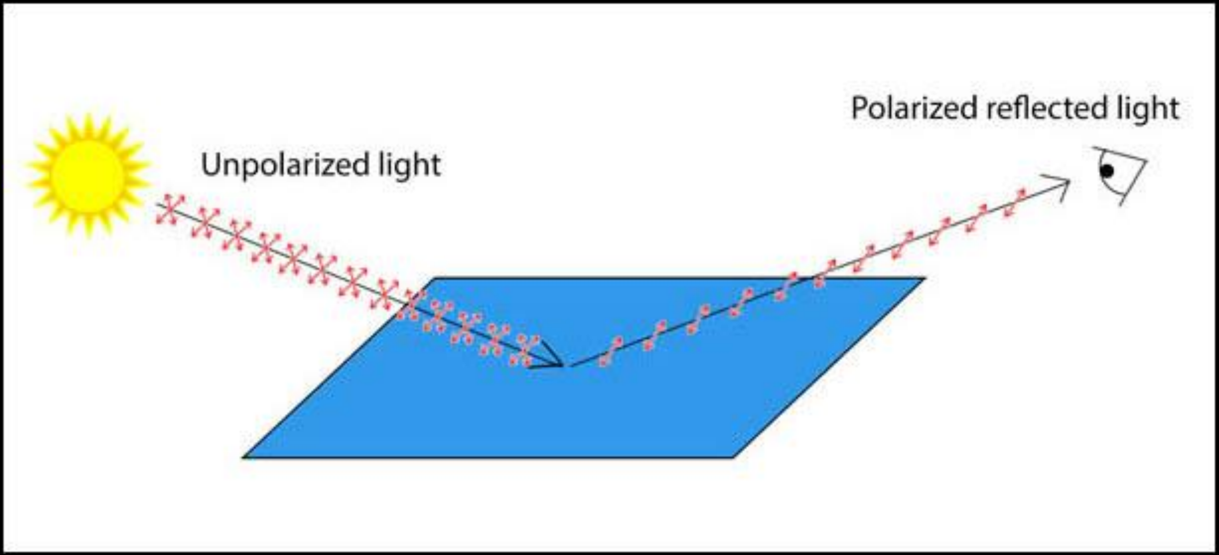
Polarization of light





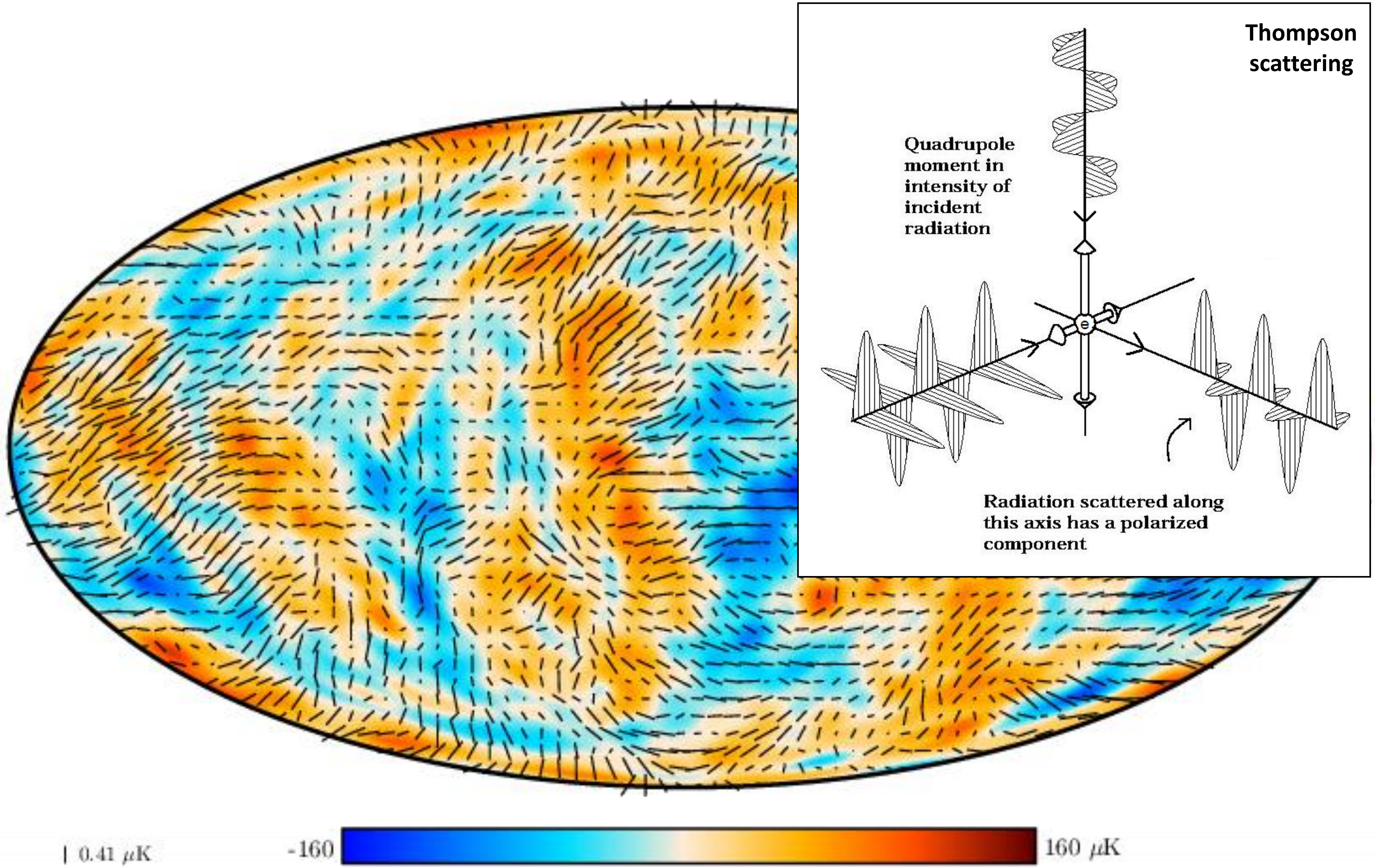
Linear polarization


Polarized reflected light
Unpolarized light



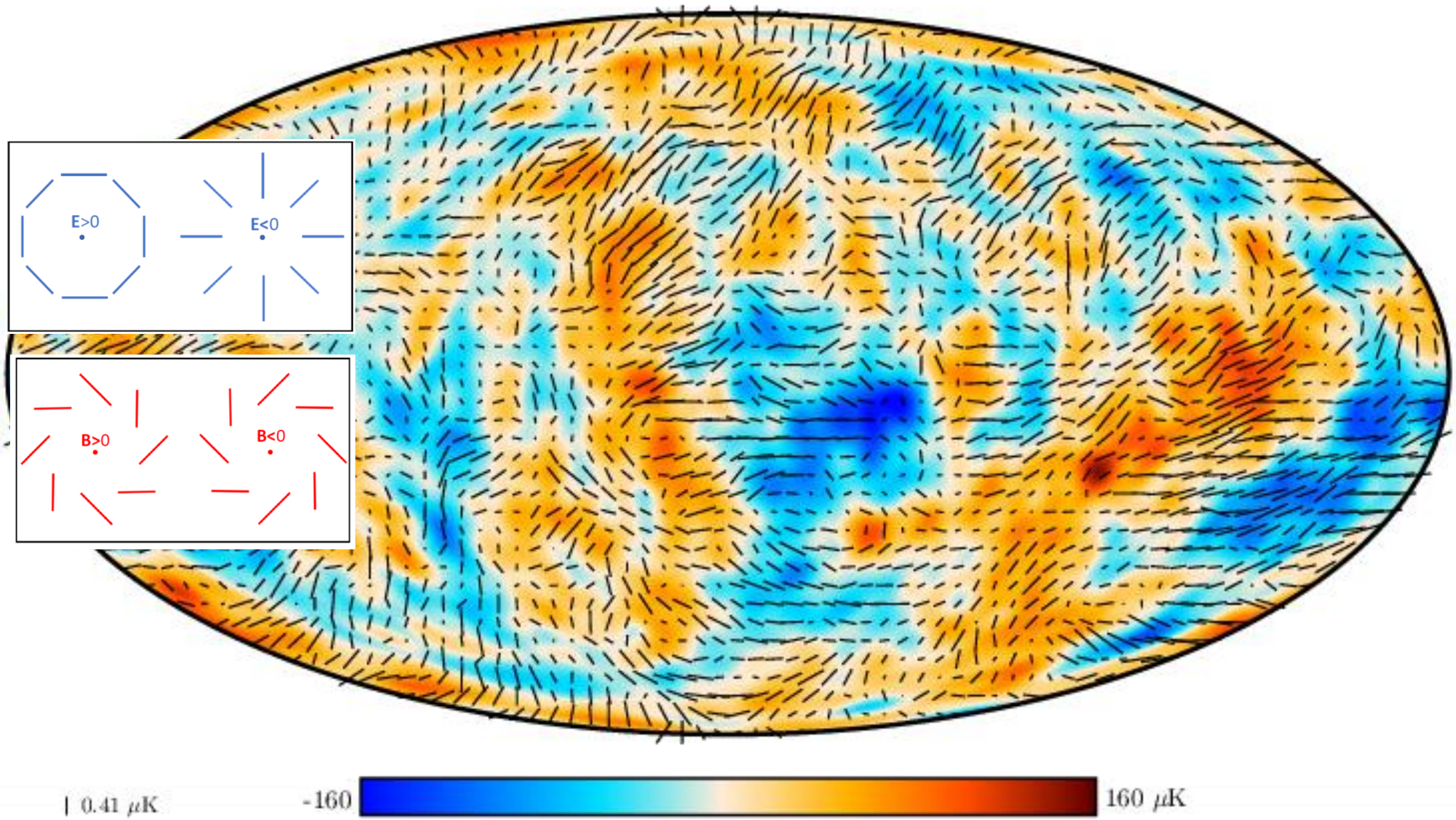
Polaroid
THE POLARIZED SUNGLASSES

CMB polarization anisotropies

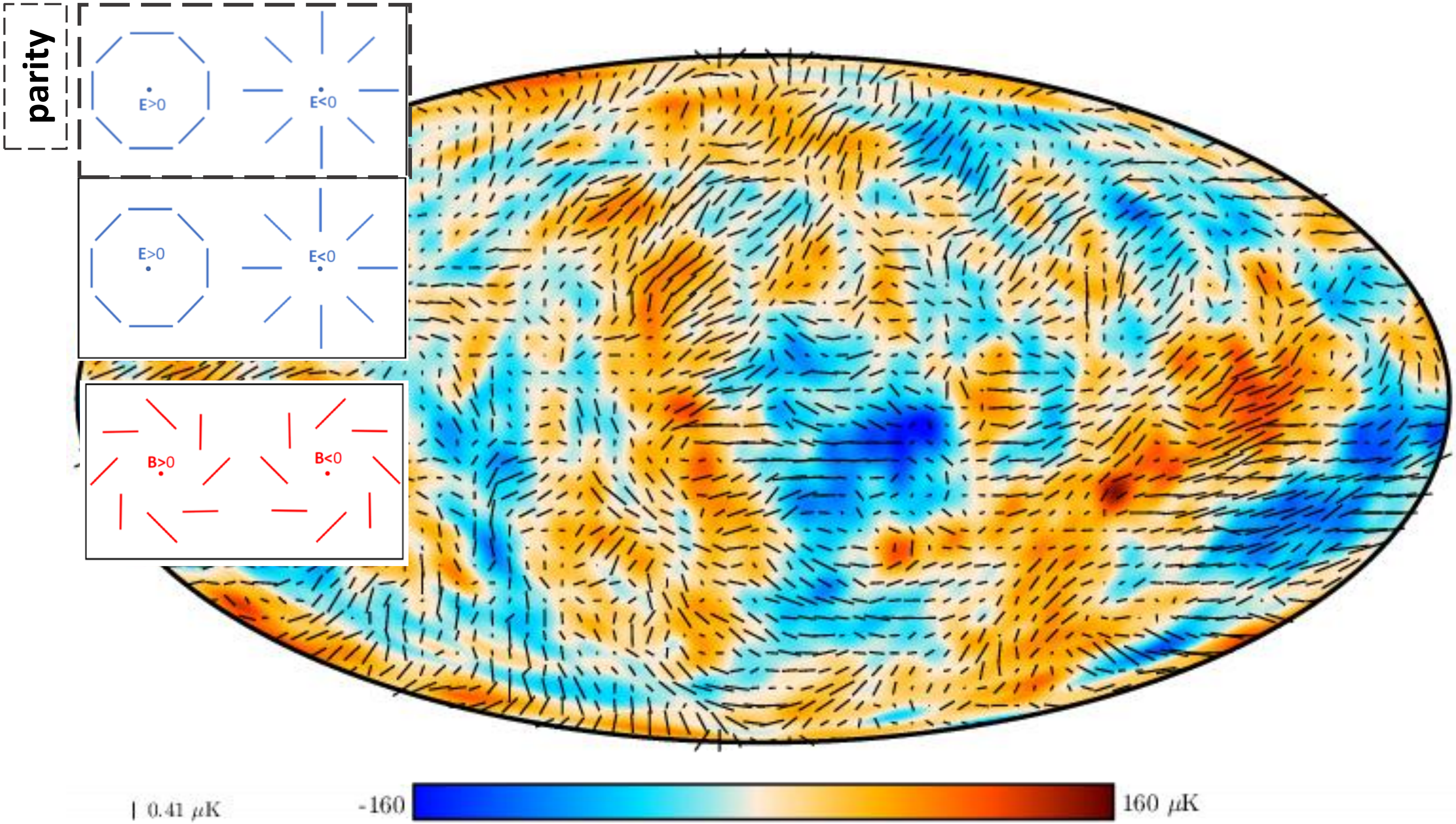


[2018 Planck map of the polarized CMB anisotropies]

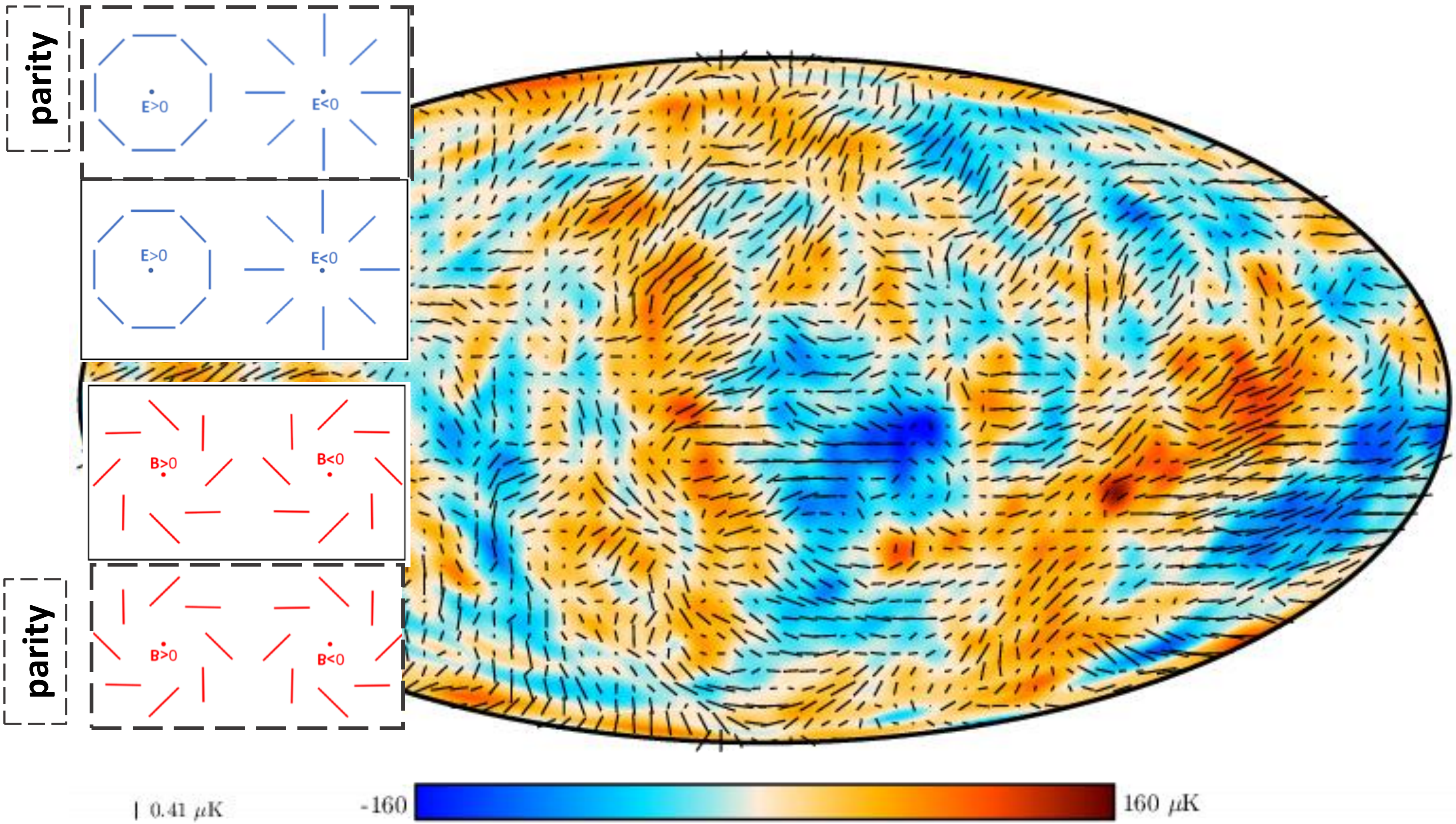
CMB polarization anisotropies

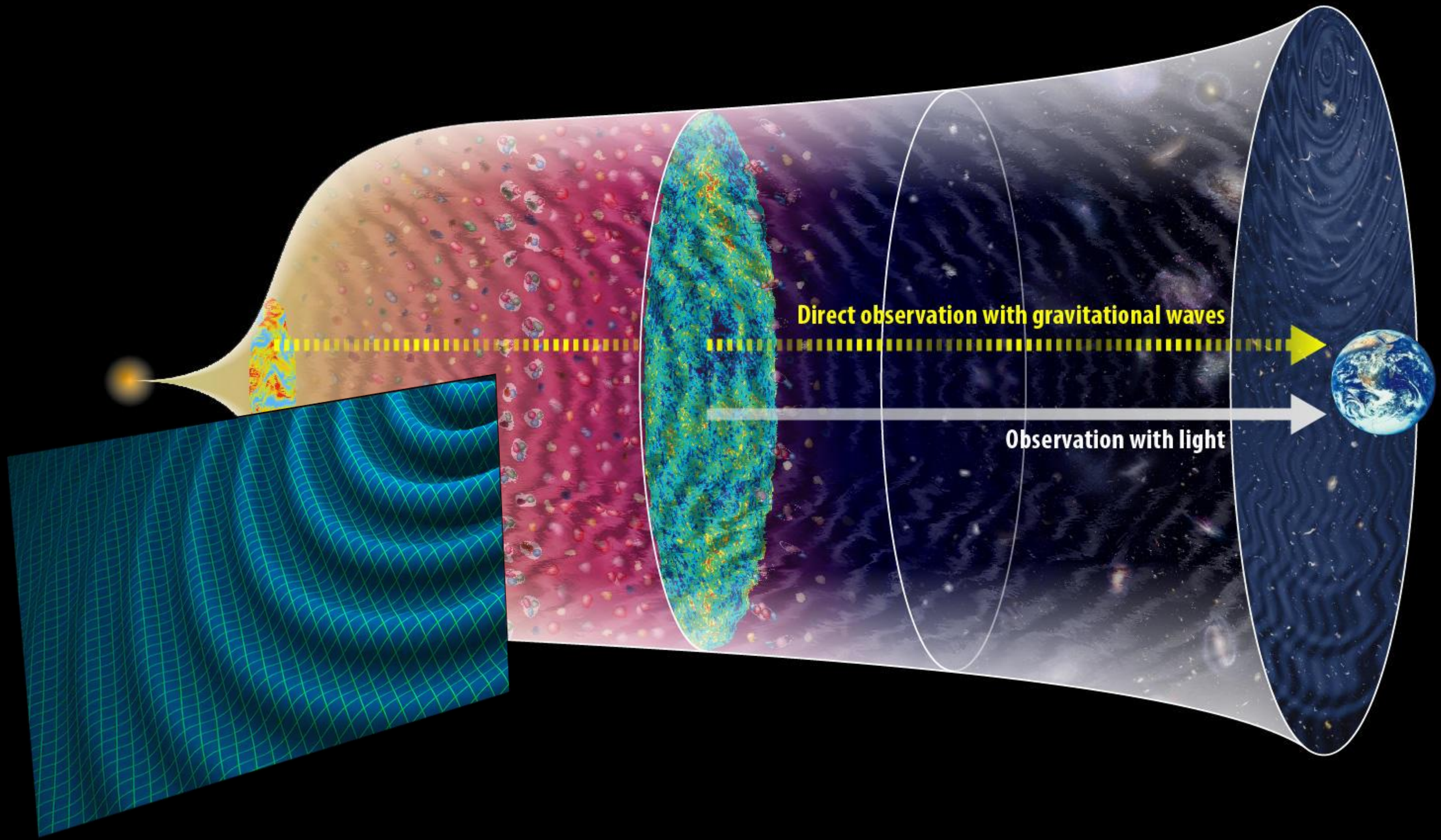


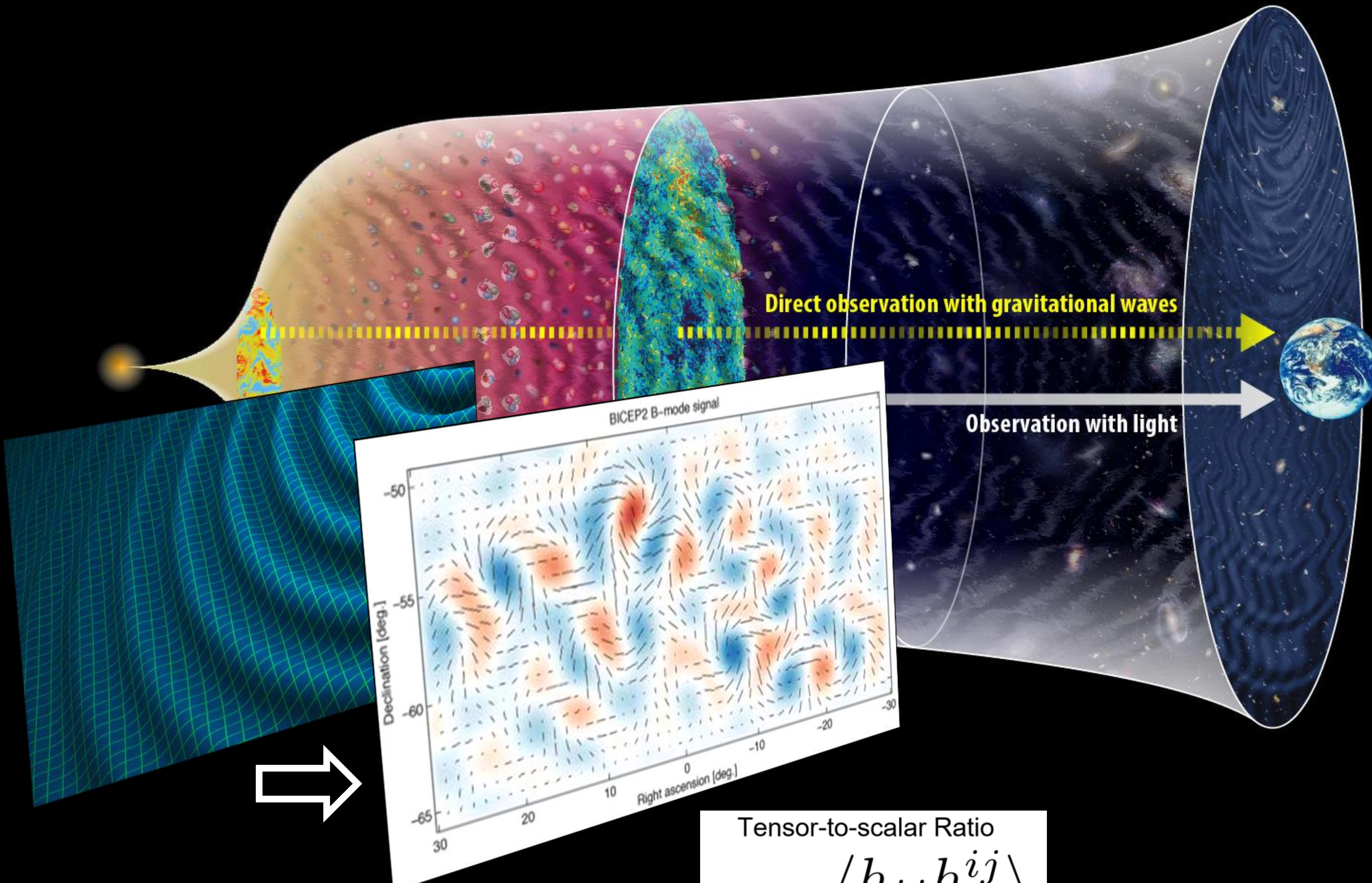
CMB polarization anisotropies



CMB polarization anisotropies




Direct observation with gravitational waves
Observation with light



Tensor-to-scalar Ratio

$$r \equiv \frac{\langle h_{ij} h^{ij} \rangle}{\langle \zeta^2 \rangle}$$

Scalar mode

PRL **112,** 241101 (2014) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 20 JUNE 2014

Detection of *B*-Mode Polarization at Degree Angular Scales by BICEP2

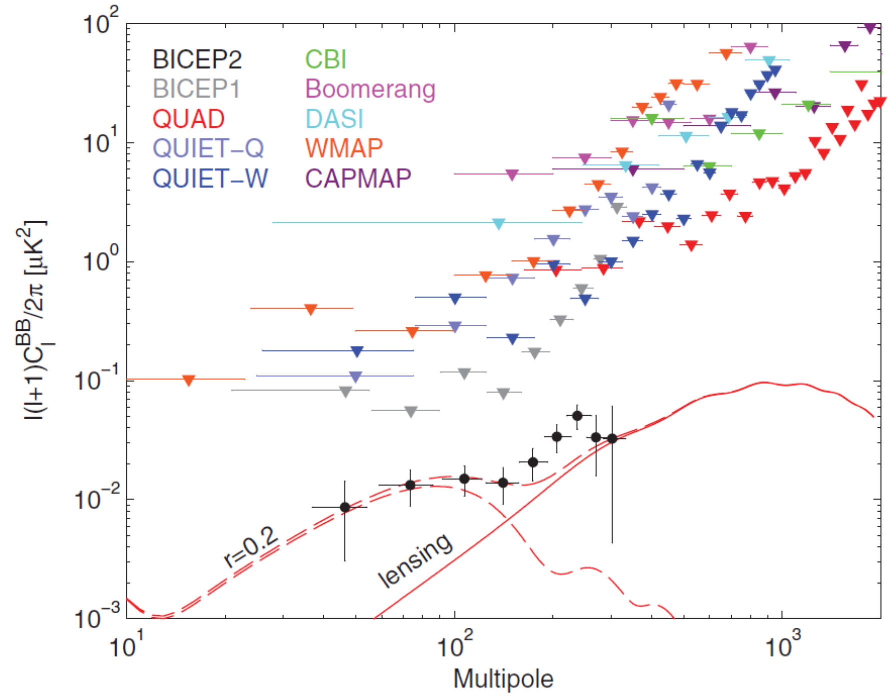


FIG. 14 (color). BICEP2 *BB* auto spectra and 95% upper limits from several previous experiments [2,40,42,43,47,49–51,107]. The curves show the theory expectations for $r = 0.2$ and lensed ΛCDM. The BICEP2 uncertainties include sample variance on an $r = 0.2$ contribution.

BICEP
(Background Imaging of Cosmic Extragalactic Polarization)

PRL **112,** 241101 (2014)

Selected for a Viewpoint in *Physics*

PHYSICAL REVIEW LETTERS

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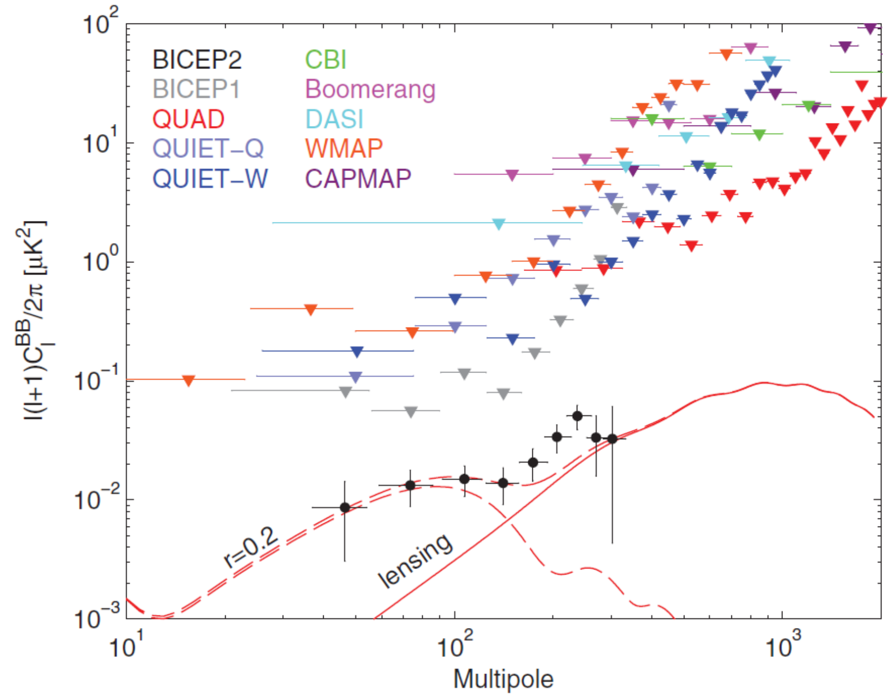

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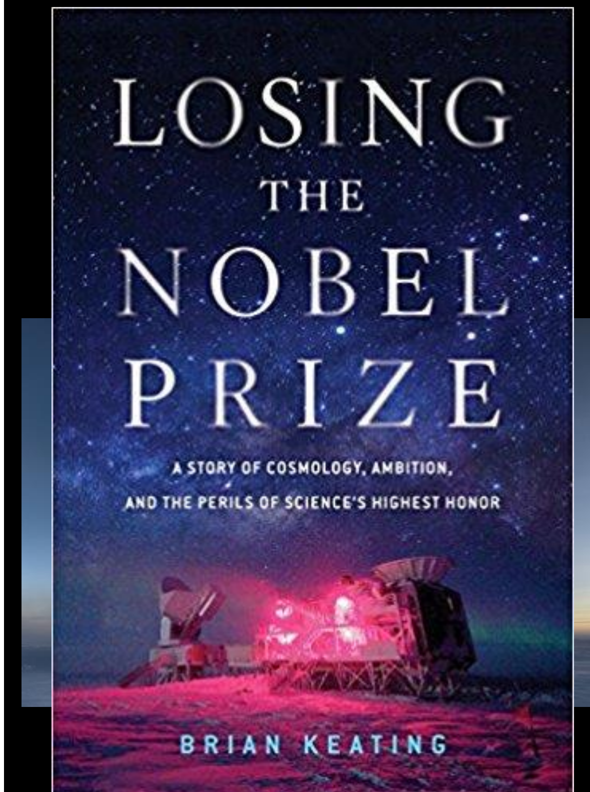
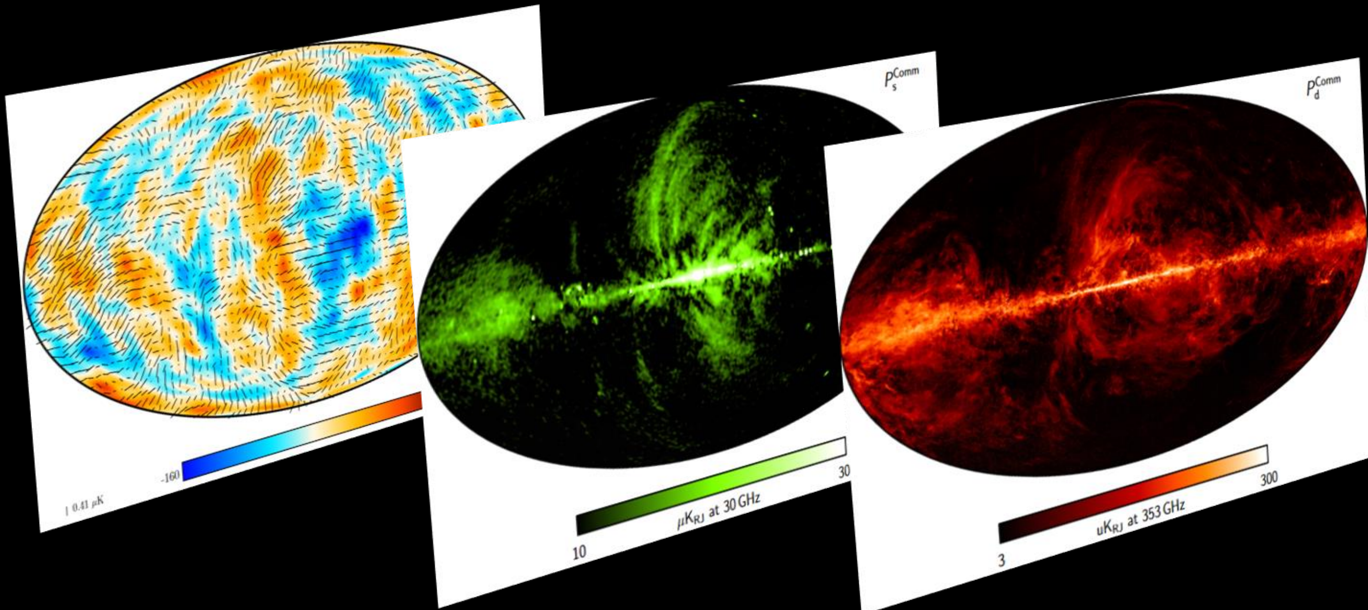
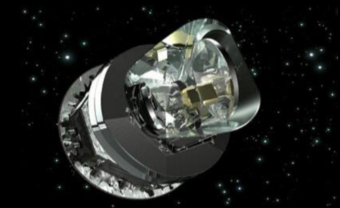


CMB **Synchrotron** **Dust**

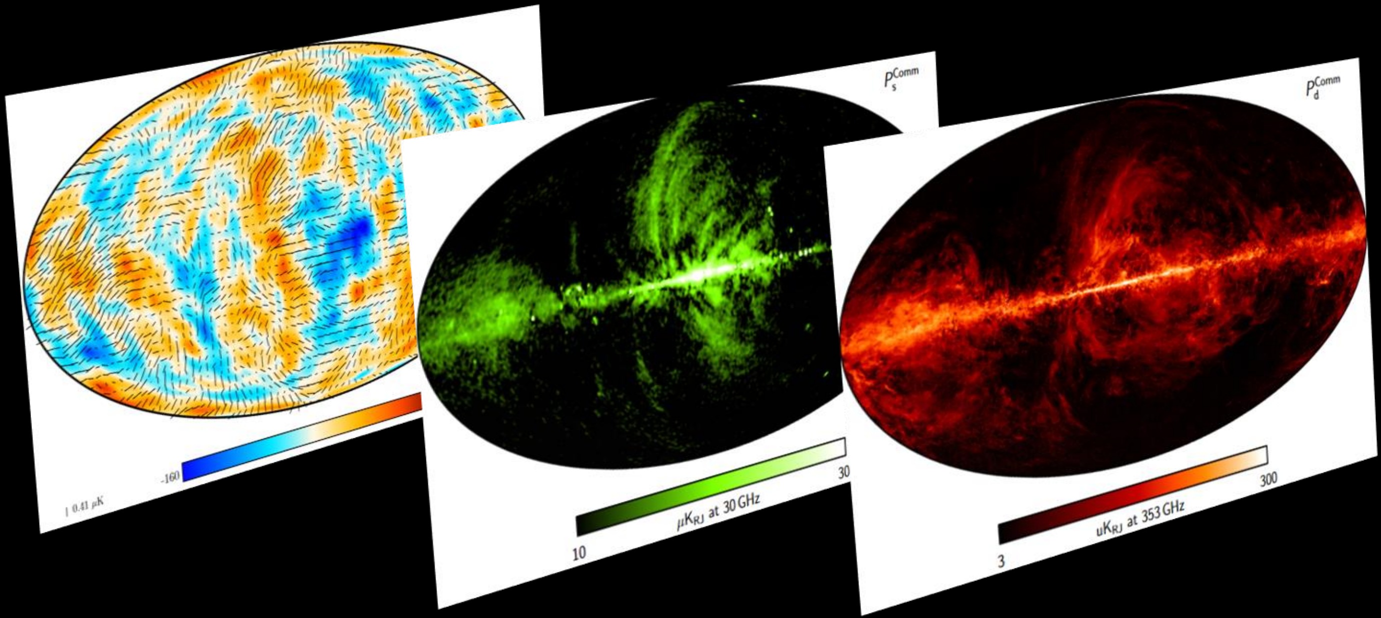


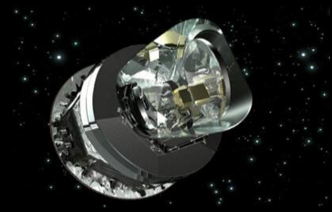


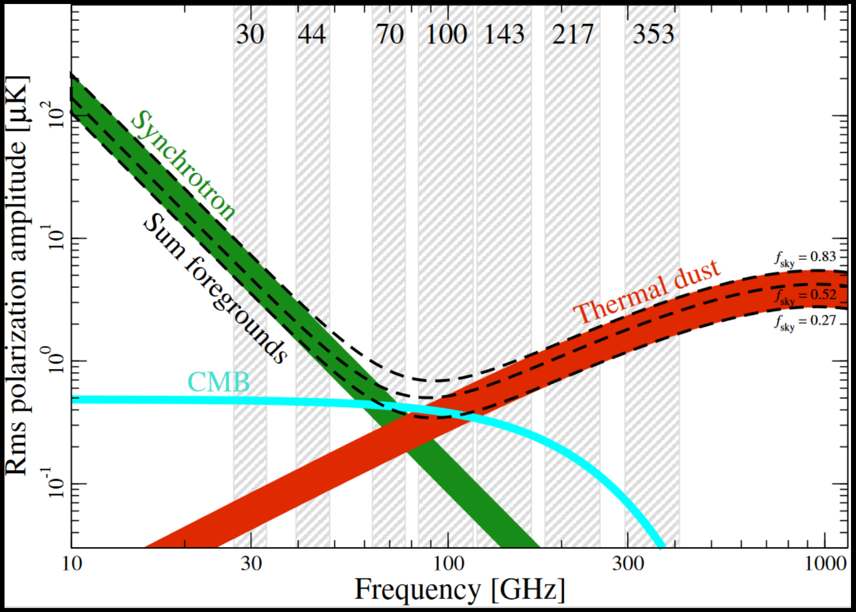
CMB

Synchrotron

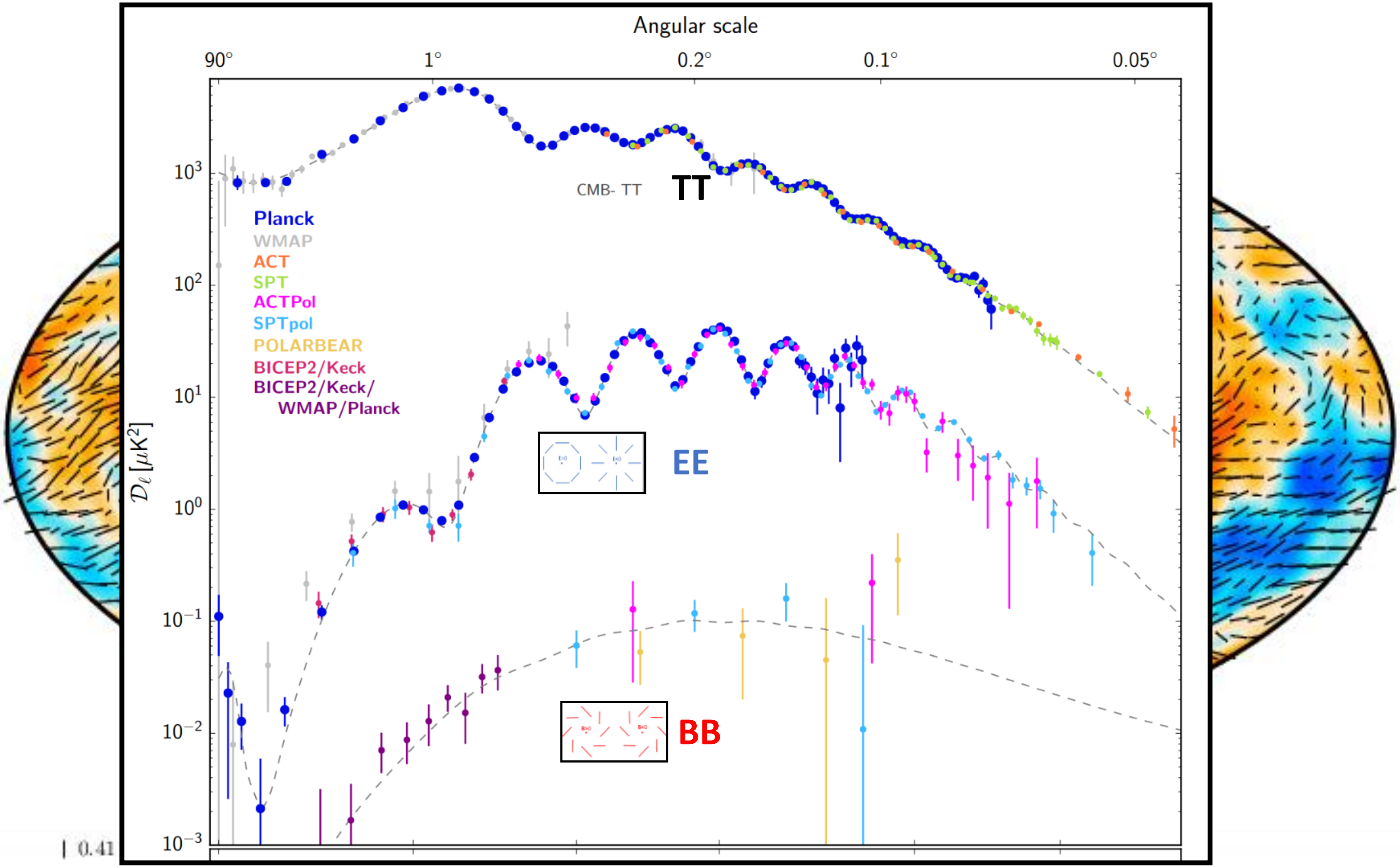
Dust







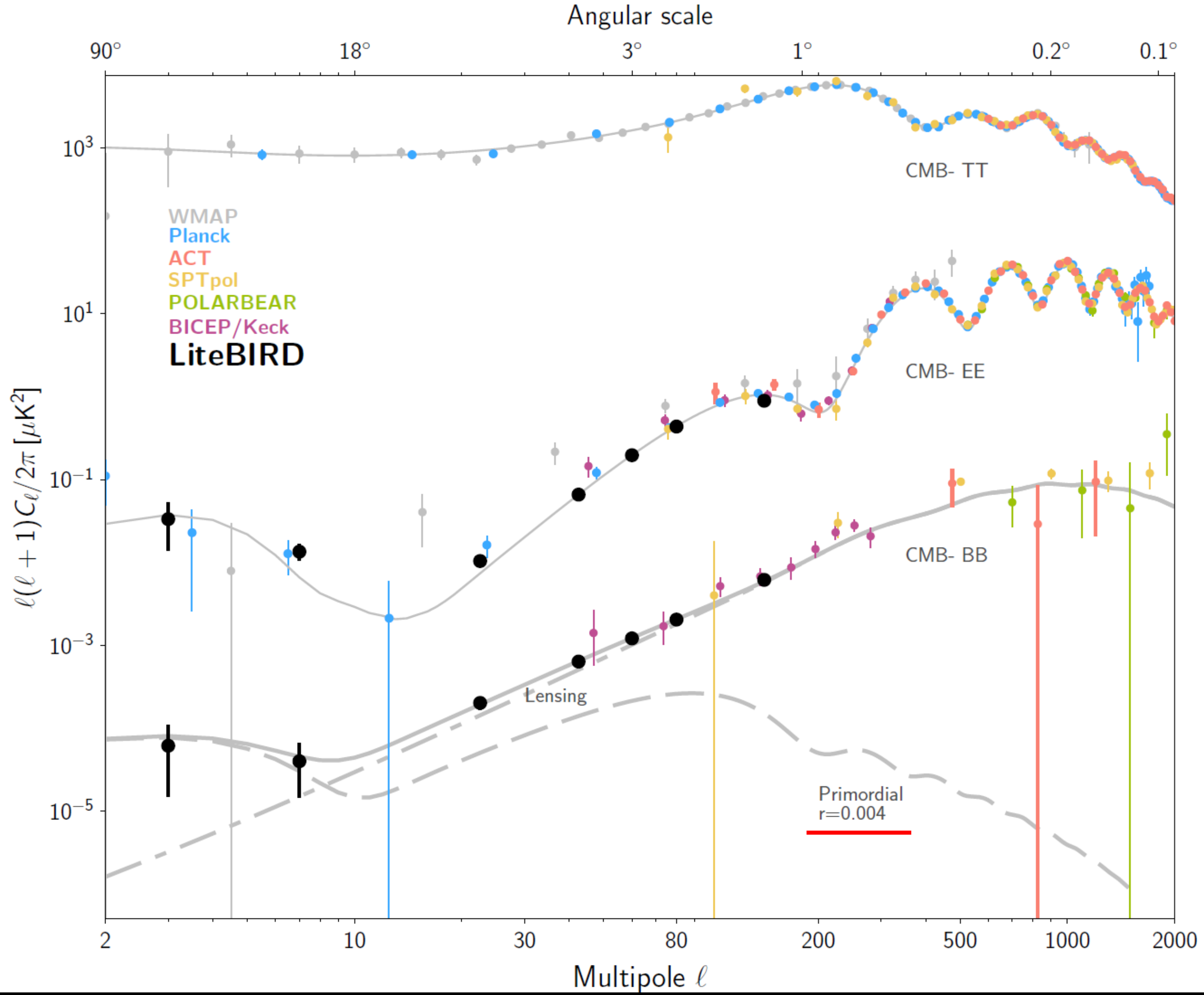
CMB polarization anisotropies



[Planck 2018 results I, A&A 641, A1 (2020)]

LiteBIRD

"Lite satellite for the study of B-mode polarization and Inflation from cosmic background Radiation Detection"



[LiteBIRD Coll PTEP-arXiv:2202.02773]

Looking for **Quantum Gravity imprints in the Universe**

Brief introduction to the current search for Quantum Gravity imprints in the early Universe:

- Primordial Gravitational waves
- Cosmic Microwave Background Polarization

Looking for Quantum Gravity imprints in the Universe

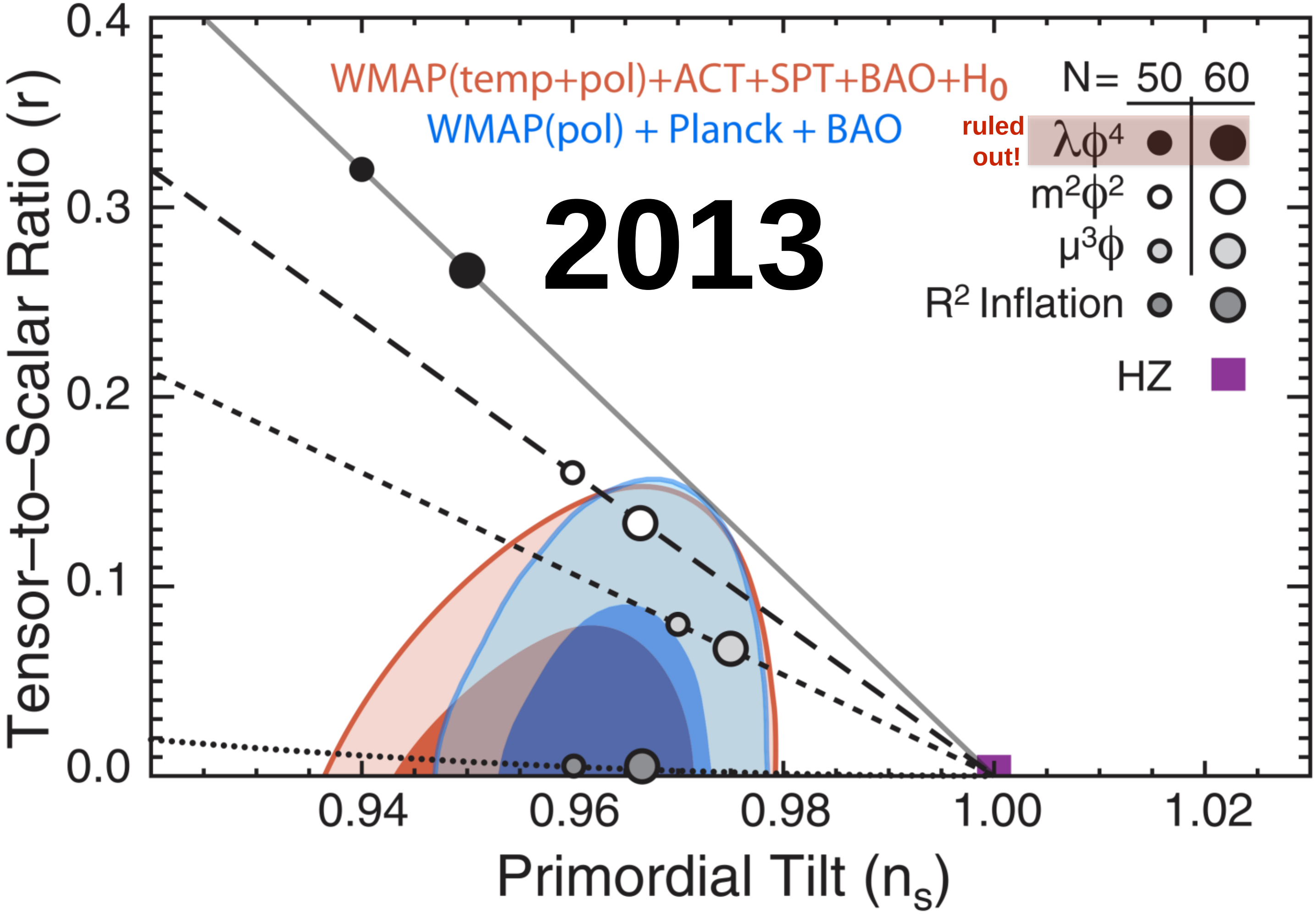
Brief introduction to the current search for Quantum Gravity imprints in the early Universe:

- Primordial Gravitational waves
- Cosmic Microwave Background Polarization

Detection of **CMB primordial B modes** induced by **primordial gravitational waves** would constitute a glimpse of **Quantum Gravity at work** (10^{-38} seconds after the singularity).

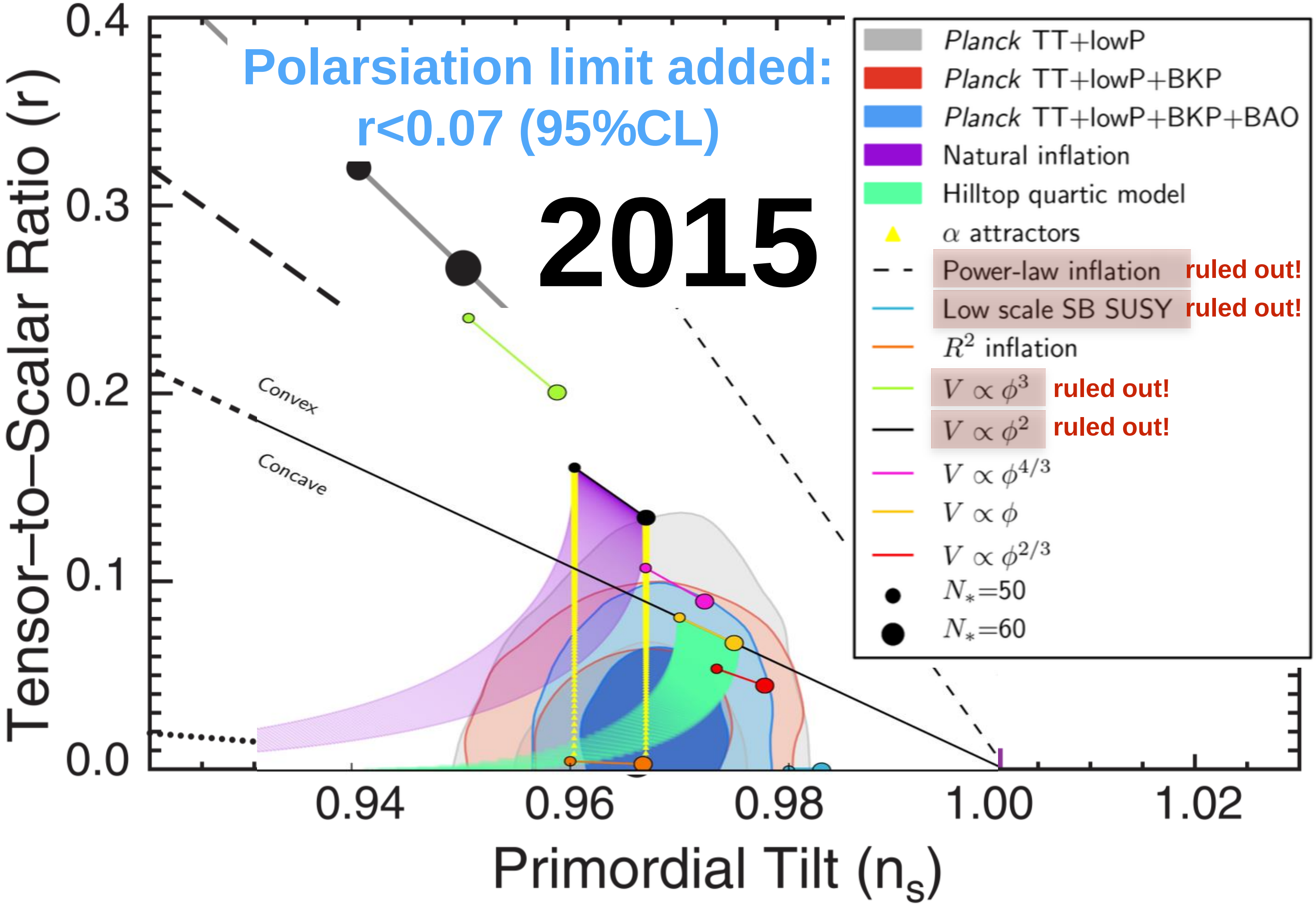
- [*II part →* *A short theoretical introduction to QG*
  Gabriele Gionti, SJ]

WMAP Collaboration



[Eiichiro Komatsu (Max-Planck-Institut für Astrophysik)
Guest lecture, Univ. Bonn, January 17, 2022]

Planck Collaboration (2015); BICEP2/Keck Array Collaboration (2016)



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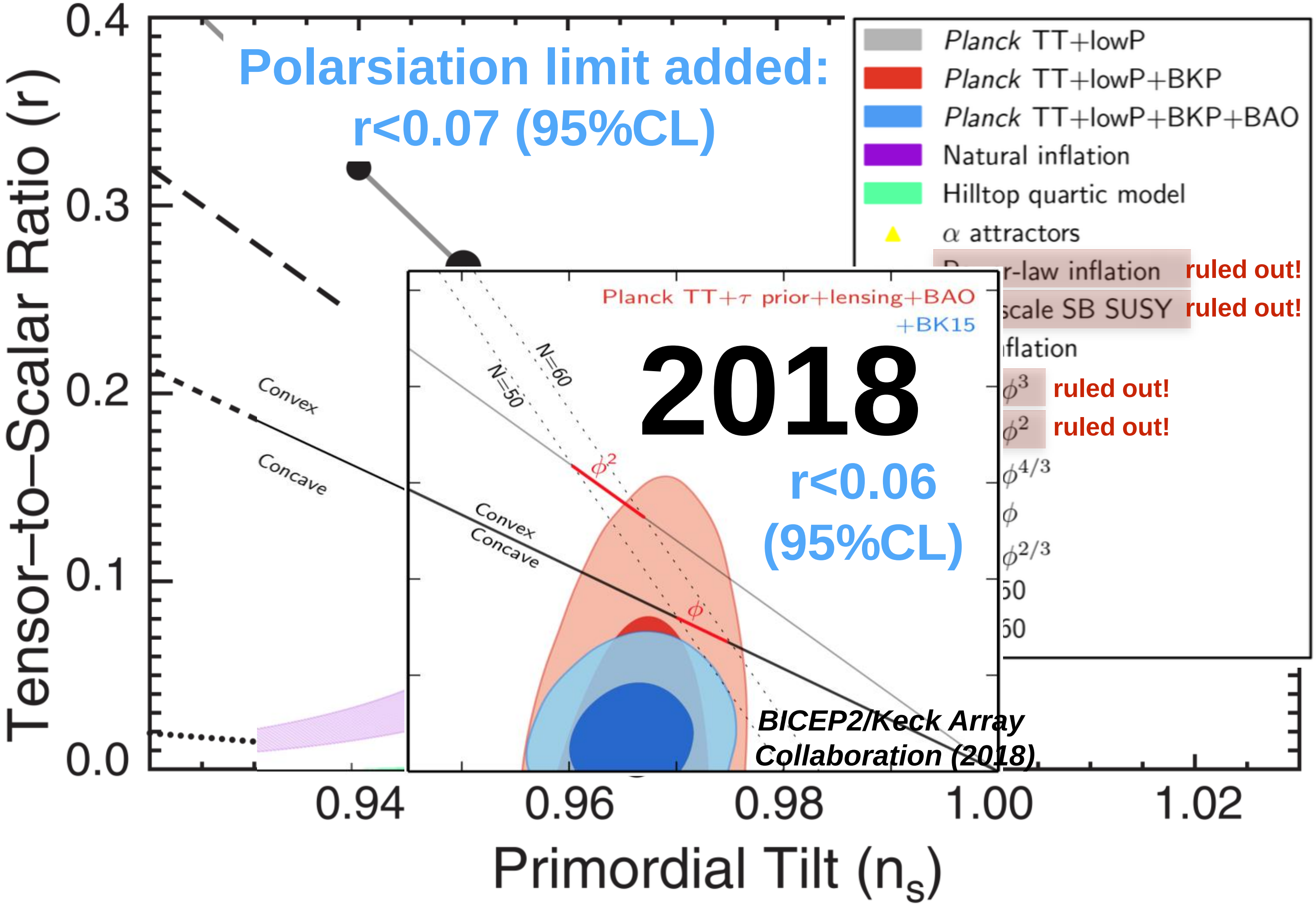

[Eiichiro Komatsu (Max-Planck-Institut für Astrophysik)
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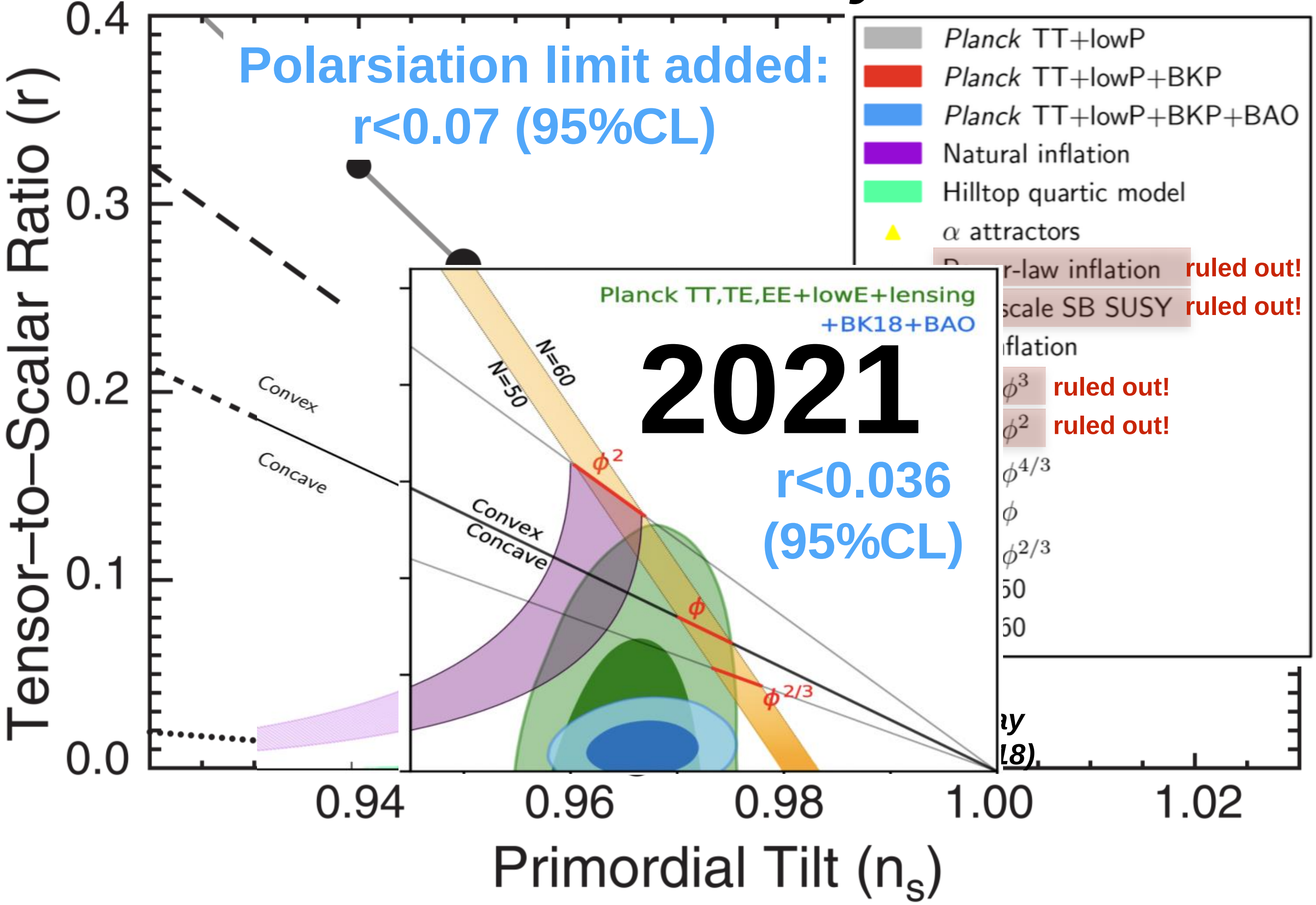
BICEP2/Keck Array Collaboration (2021)



[Eiichiro Komatsu (Max-Planck-Institut für Astrophysik)
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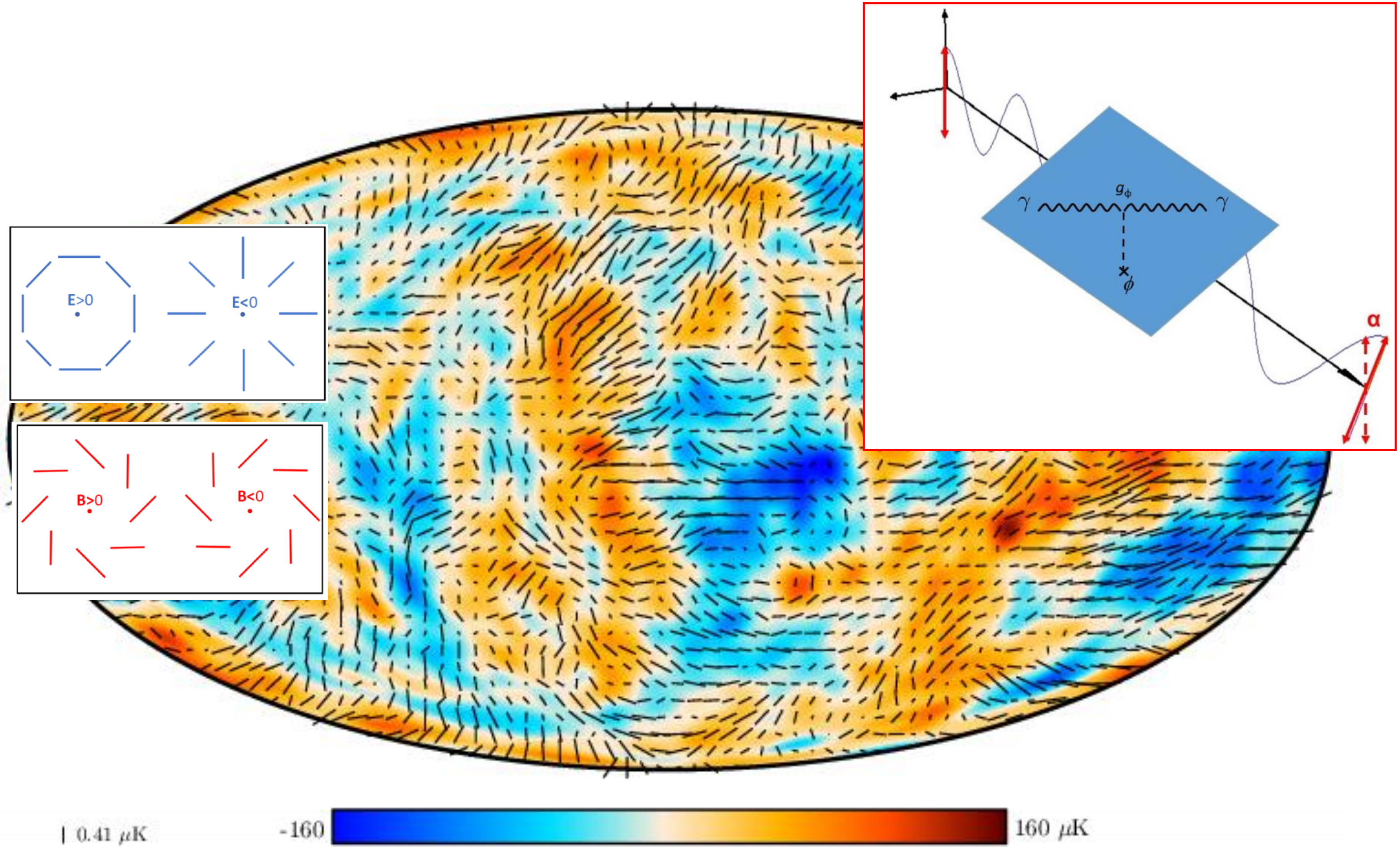
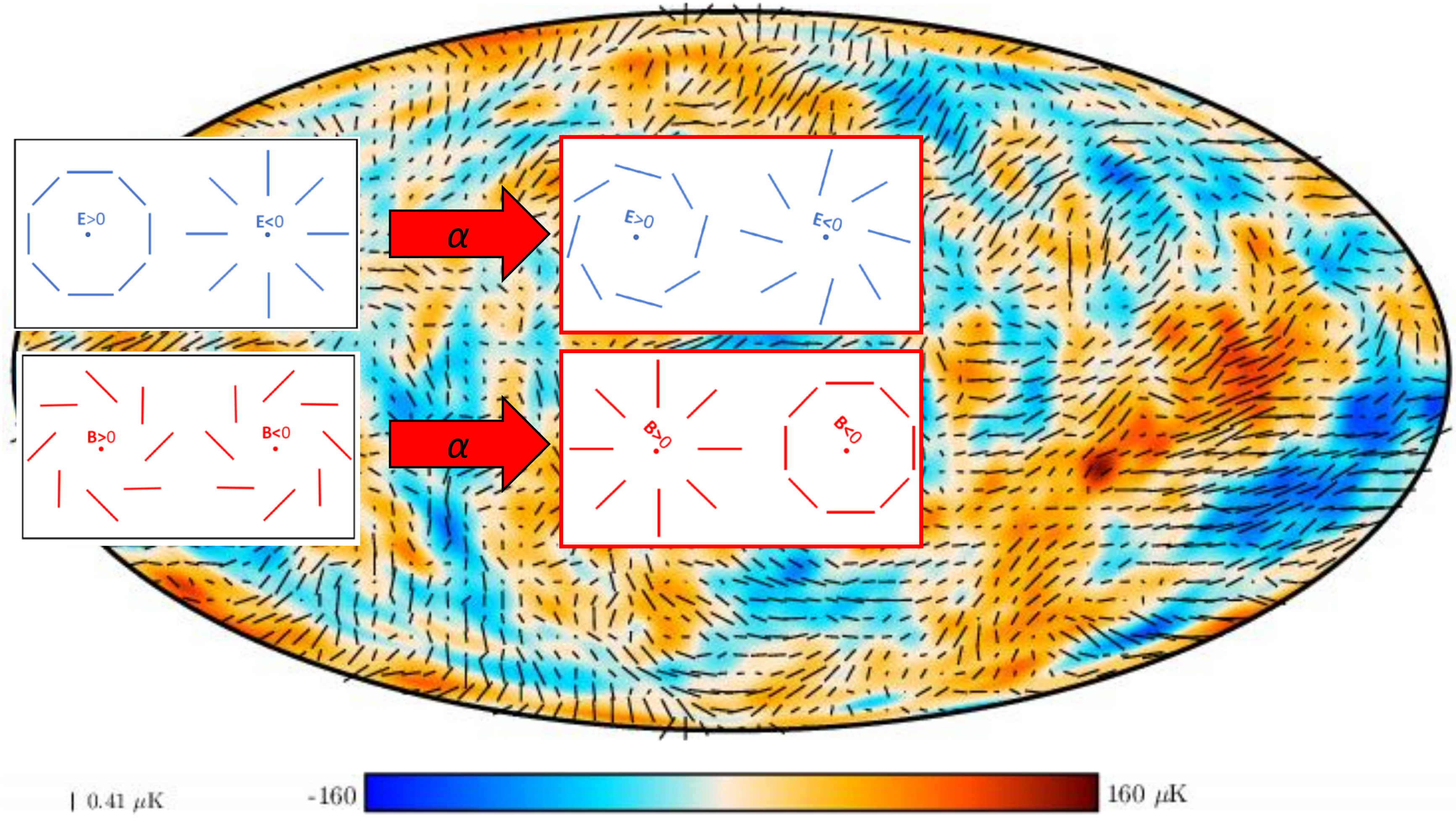
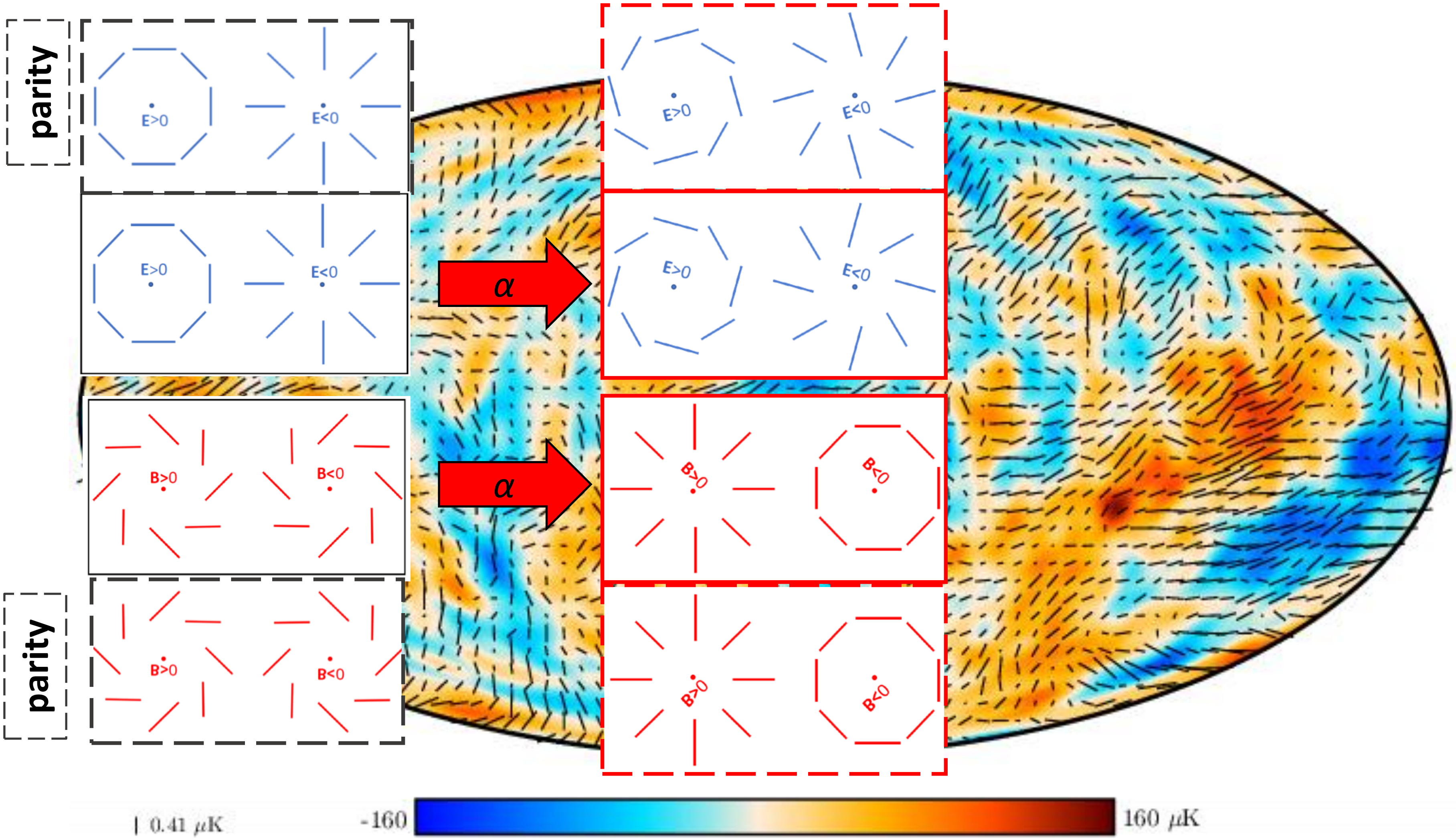
Cosmological birefringence



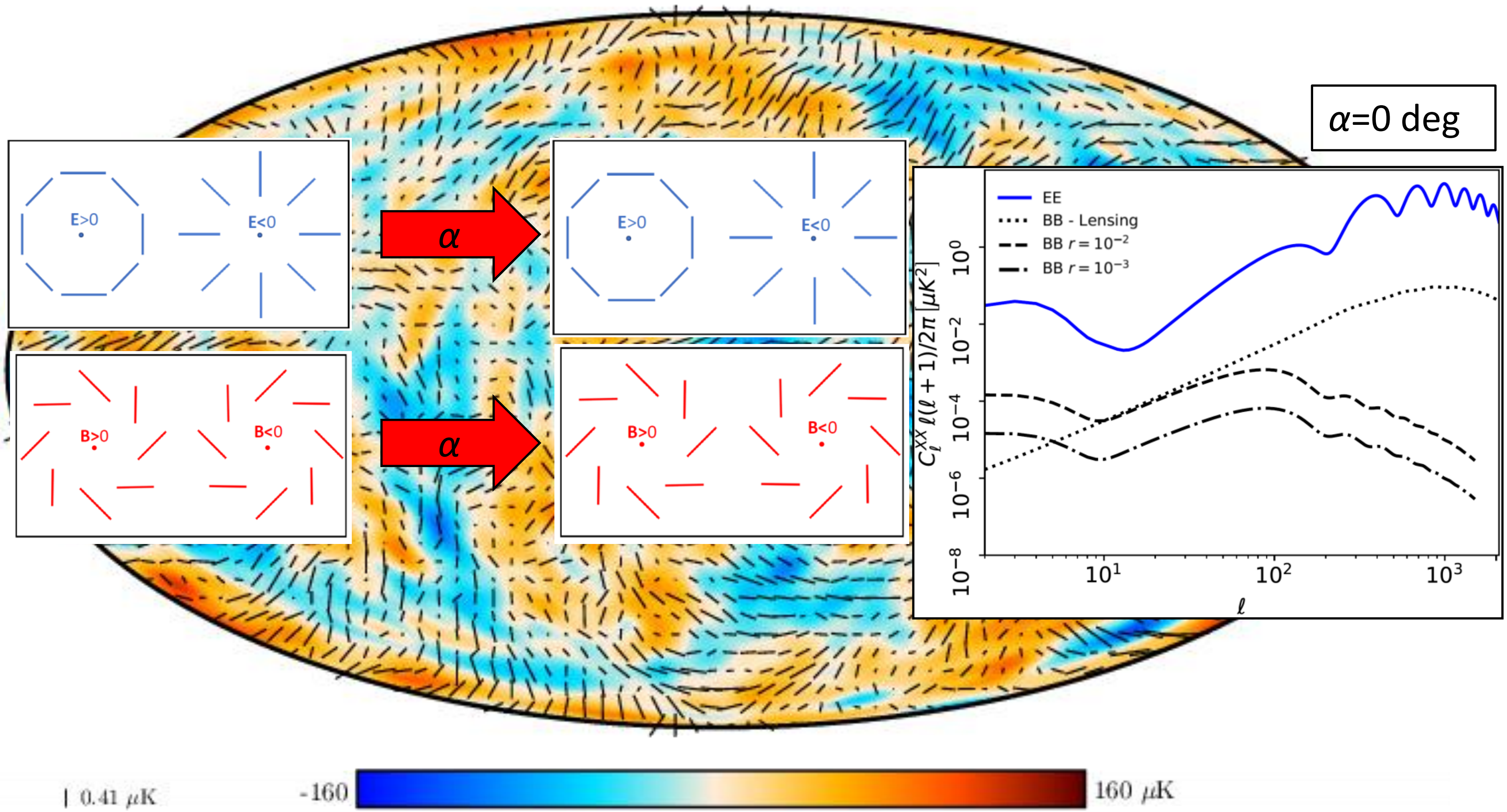
Cosmological birefringence



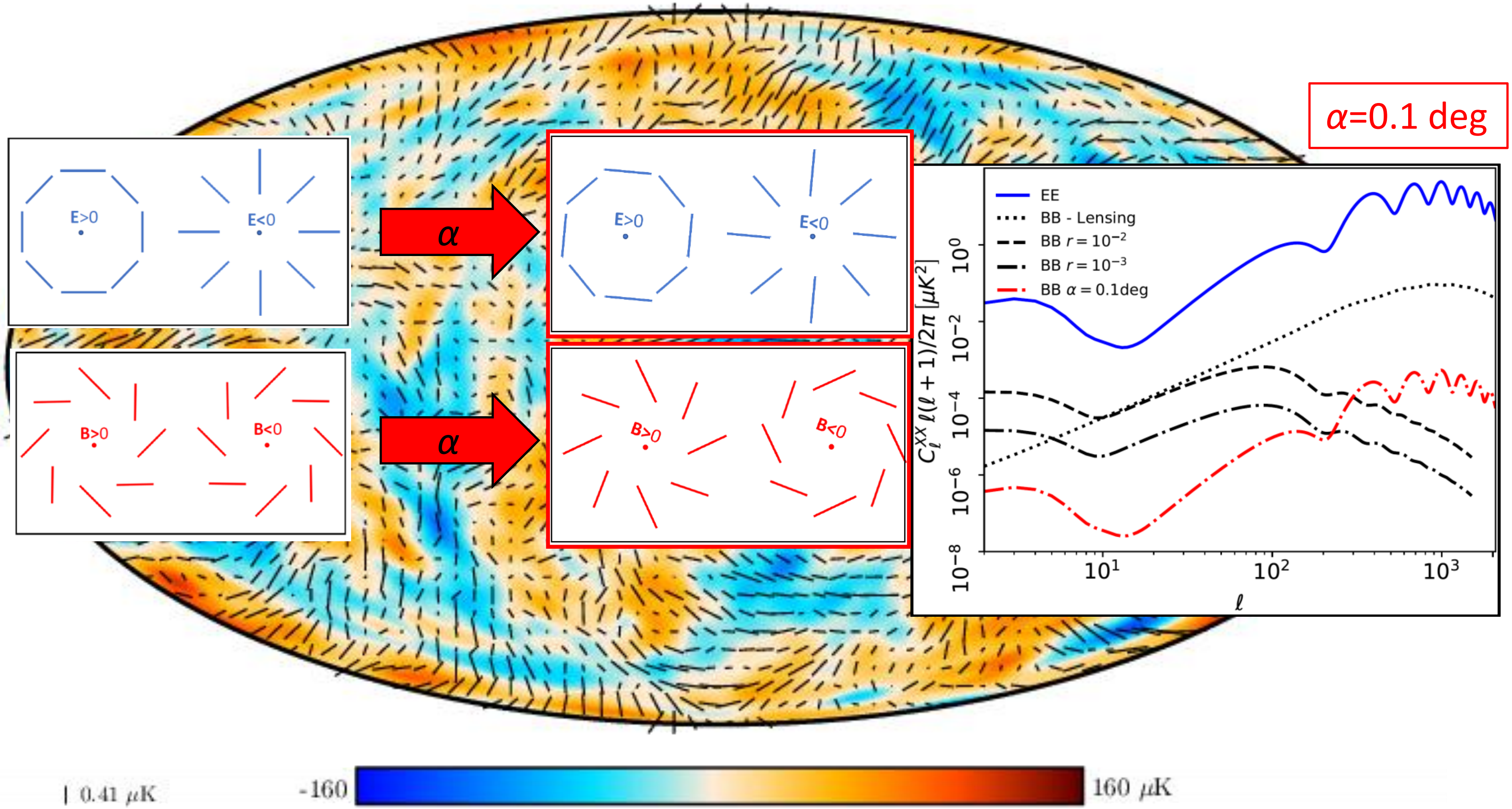
Cosmological birefringence



CMB polarization anisotropies



CMB polarization anisotropies



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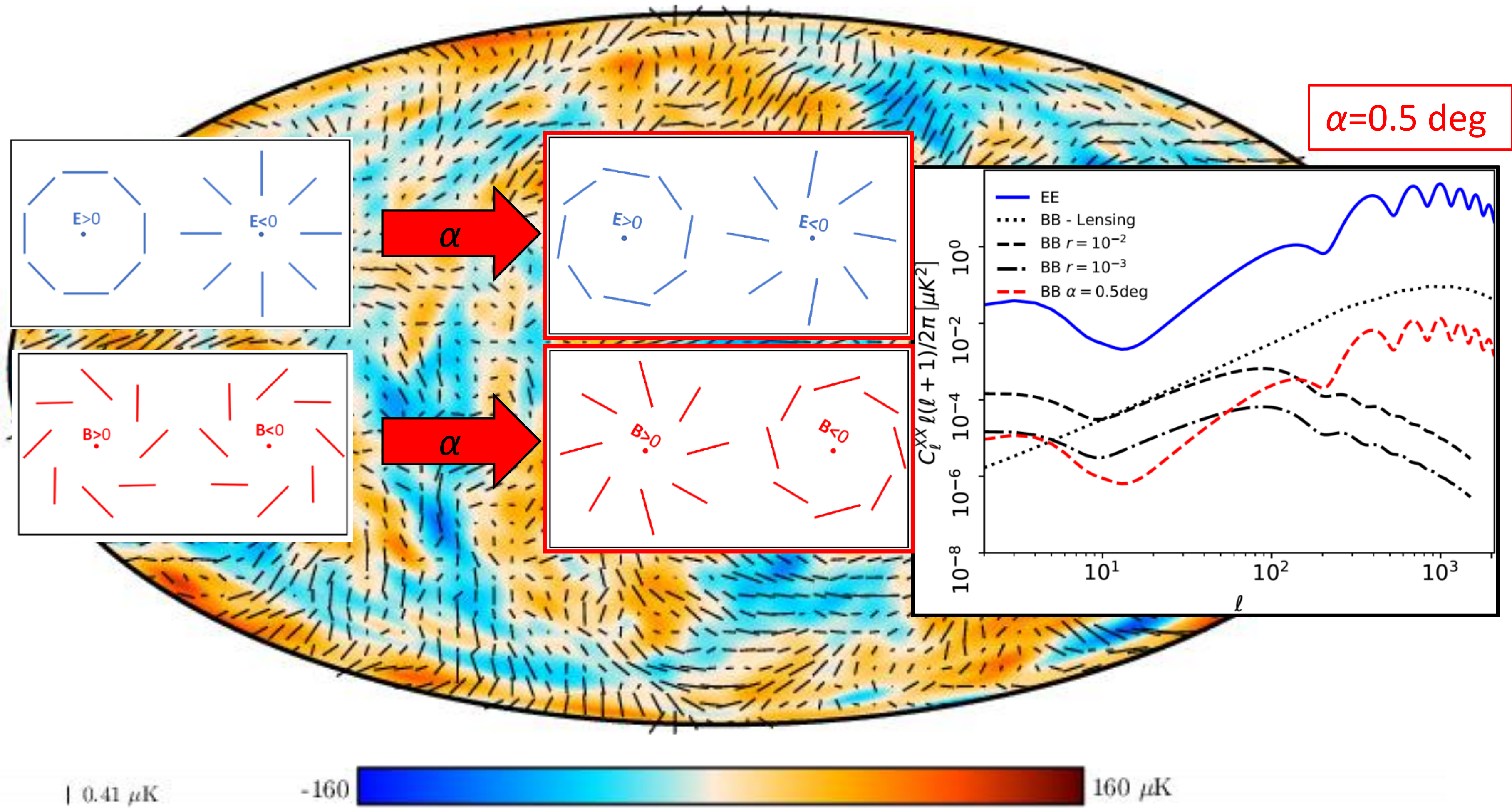

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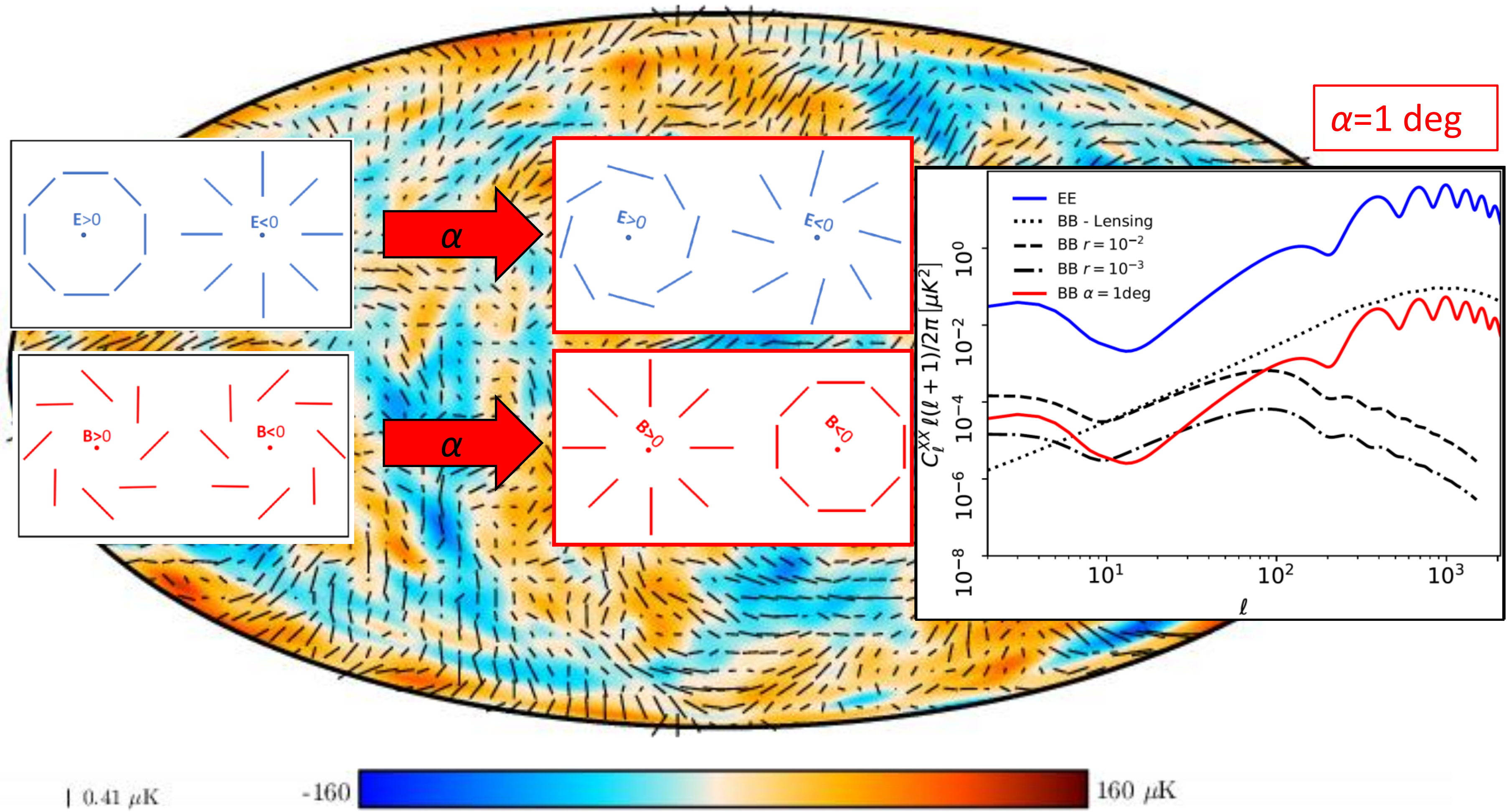


A SHORT INTRODUCTION TO QUANTUM GRAVITY

Gabriele Gionti, S.J.

SPECOLA VATICANA

INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

SCIENCE AN THEOLOGY

-A STUDY PROGRAM FOR FUTURE THEOLOGIAN-

The Quantum Gravitational Challenge in Modern Cosmology

Pontifical Lateran University Rome, October 21 2022.

OUTLINE

- Brief introduction to Einstein's Theory of General Relativity.
- Canonical Quantum Gravity and Loop Quantum Gravity.
- String Theory
- Asymptotically Safe Approach to Quantum Gravity
- Conclusions

1915

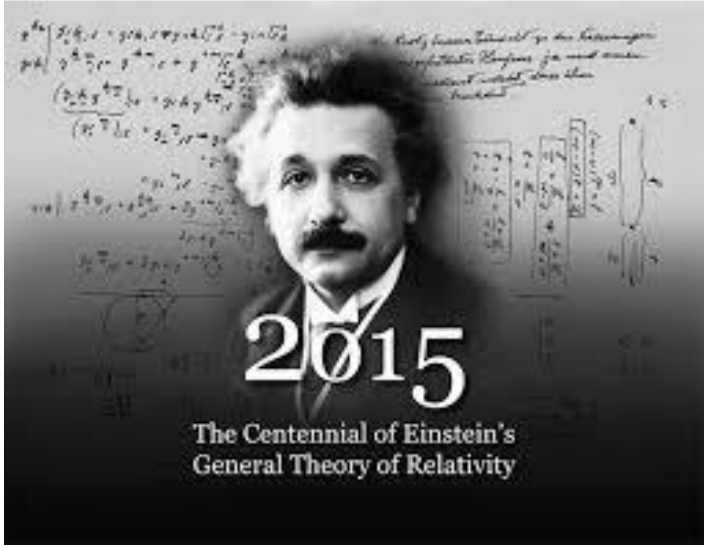
"Annus Mirabilis" !

Albert Einstein:
Equations of the Gravitational Field

David Hilbert:
Action of the Gravitational Field

Emmy Noether:
Conservations Laws

GENERAL RELATIVITY



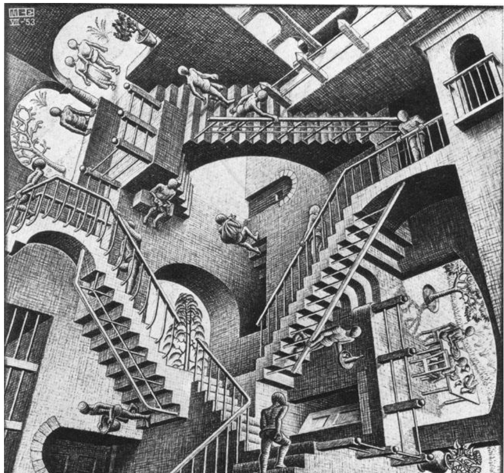
- "Extension" of Special Relativity.

- Deal with "non-inertial frames"
  (case in which the frame "relative" velocity
  is not constant).

- One fundamental principle:

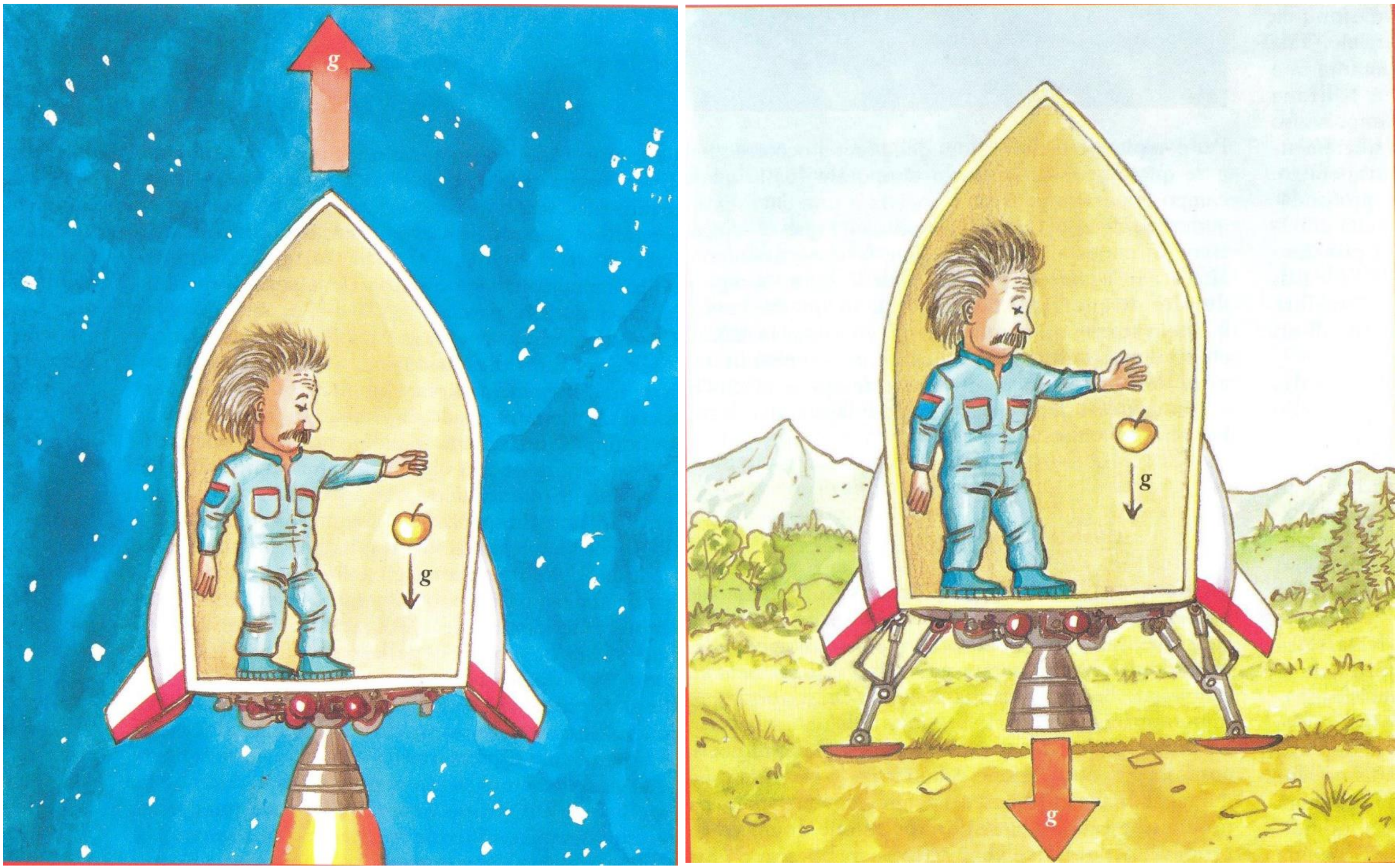
The principle of equivalence "the mass equivalence"

$$m_g = m_i$$

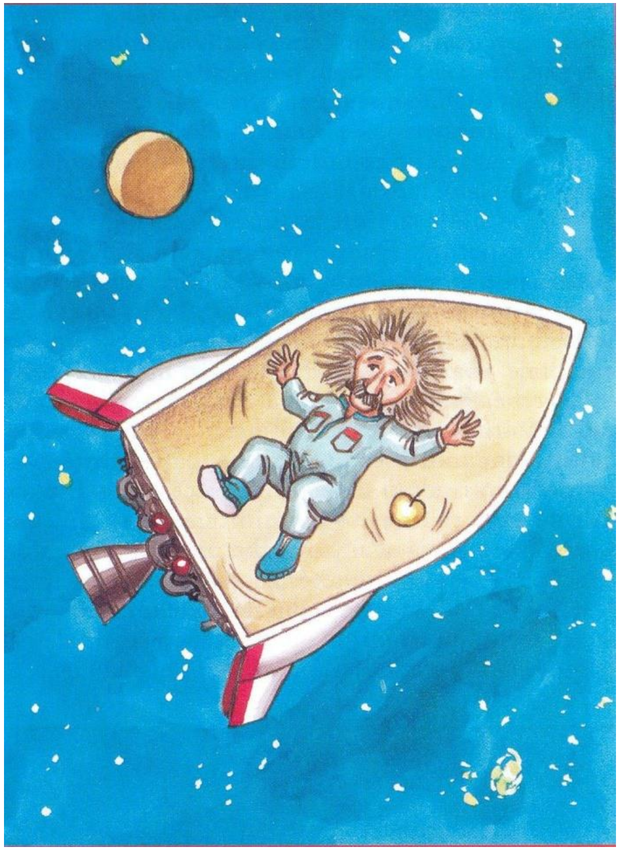


- The gravitational effects are locally indistinguishable from the acceleration effects.

Gravity and Acceleration



Gravity and Acceleration



An astronaut will experience no weight in a free-falling starship in the empty space. The free-fallisng starship cancels the gravitational effects.

GENERAL RELATIVITY

- Alternative version of the Principle of Equivalence

- The "Covariance Principle": the Laws of Physics are the same (covariant) in every reference frame! (therefore also non inertial..)

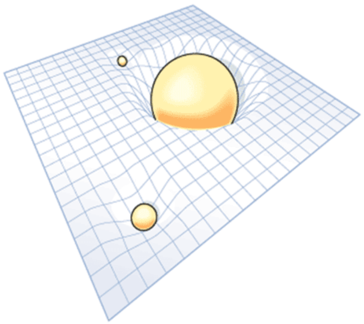
1) The physical laws agrees with Special Relavity in the absence of gravitation

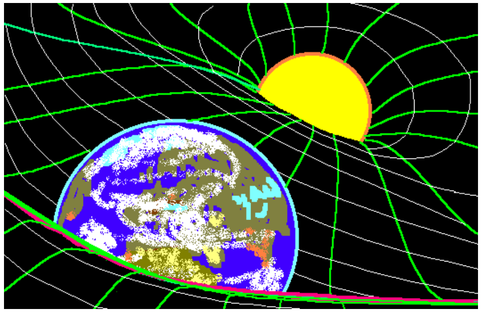
2) The equations are generally covariant; the are preserved, in form, under arbitrary transformations of coordinates.

GENERAL RELATIVITY

- The Space-Time is a "physical entity"; it is a dynamical entity that is modified by the presence of massive bodies (as well as Energy).

- The massive bodies modify Space-Time, which gains curvature.

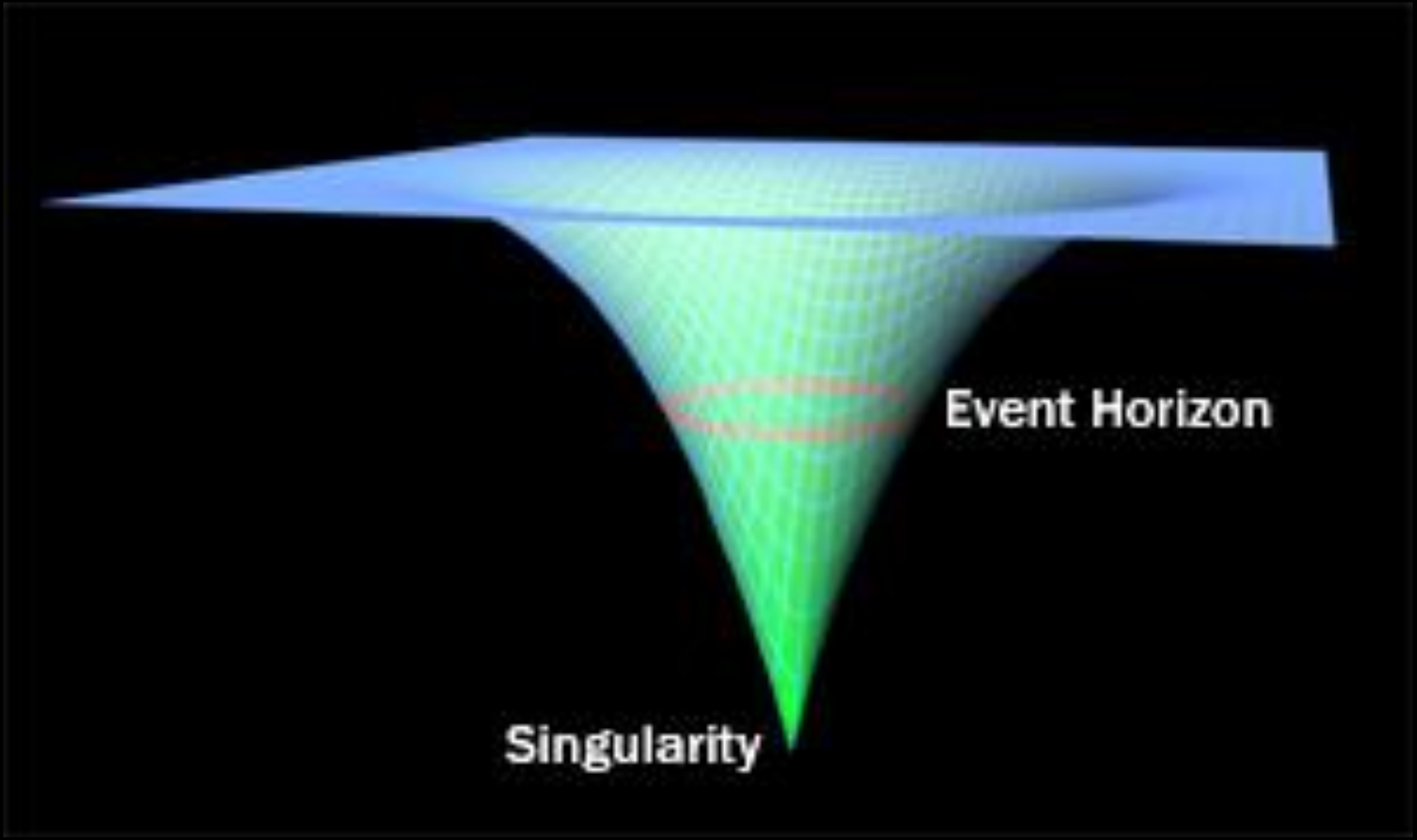




- Free falling bodies moves on the analogous of straight line, in inertial reference frames, which are called geodesic lines.

- The gravitational force is not, anymore, an action at distance; it is a field theory like in electromagnetism.

SINGULARITY IN EINSTEIN'S GENERAL RELATIVITY



Why Quantum Gravity?

$$\text{Planck Temperature} = \sqrt{\frac{\hbar c^5}{G k_B^2}} = 1.42 \times 10^{32}\,\text{K}$$

$$\text{Planck Mass} = \sqrt{\frac{\hbar c}{G}} = 2.2 \times 10^{-8}\,\text{kg}$$

$$\text{Planck Time} = \sqrt{\frac{G \hbar}{c^5}} = 5.4 \times 10^{-44}\,\text{s}$$

$$\text{Planck Length} = \sqrt{\frac{G \hbar}{c^3}} = 1.6 \times 10^{-35}\,\text{m}$$

$$\text{Planck Energy} = \sqrt{\frac{\hbar c^5}{G}} = 1.22 \times 10^{19}\,\text{GeV}$$

$$\text{Planck Density} = \frac{c^5}{G^2 \hbar} = 5.16 \times 10^{93}\,\text{g/cm}^2$$

- **All fundamental interactions have a quantum field theory behavior, then there could emerge a contradiction when we couple them to Gravity**

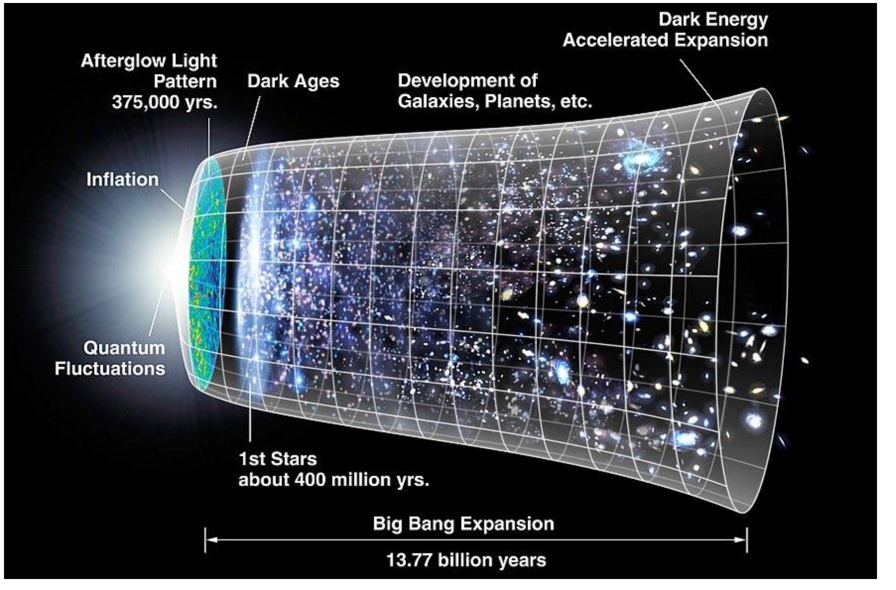
QUANTUM GRAVITY

- Einstein General Relativity is considered succesful phenomenological theory at laboratory, solar system, galatic, for lenght scales $l \gg l_{Pl}$ (=Planck lenght)$\equiv {}^{1}/_{\sqrt{G}} \approx 10^{-33}$cm

- Singularity problem and the quantum mechanical behavour of matter-energy at small distance suggest a quantum mechanical behavour of the gravitational field (Quantum Gravity) at small distances (High Energy).

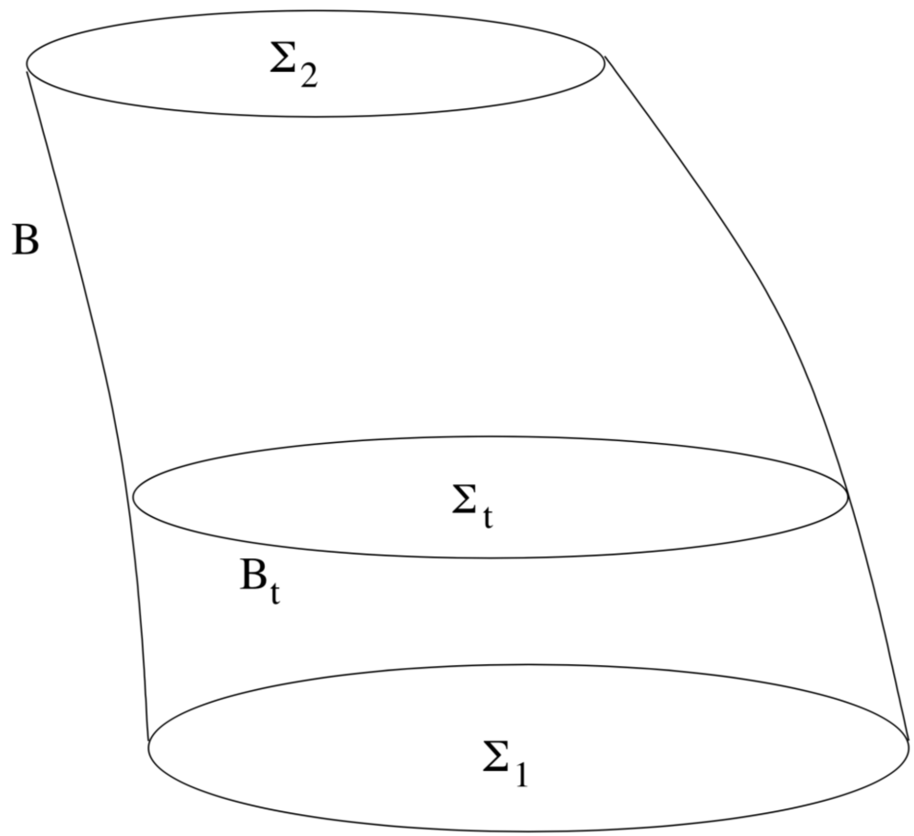
- Many different approaches to Quantum Gravity: String Theory, Loop Quantum Gravity, Non-commutative Geometry, Causal Dynamical Triangulations, Asymptotic Safety etc.

- General Relativity is considered an effective theory. It is not pertubatively renormalizable (the Newton constant G has a (lenght)$^{-2}$ dimension)



CANONICAL QUANTUM GRAVITY

(non-perturbative)



CANONICAL QUANTUM GRAVITY

It is one of the oldest approach in Quantum Gravity

It is based on ADM (Arnowit, Deser and Misner) technique: a three-dimensional space-like surface evolving in time.

The goal is to write a Hamiltonian density functional of the gravitational field.

This can be done and one can write the Wheeler-DeWitt equation for the wave-function of the Universe.

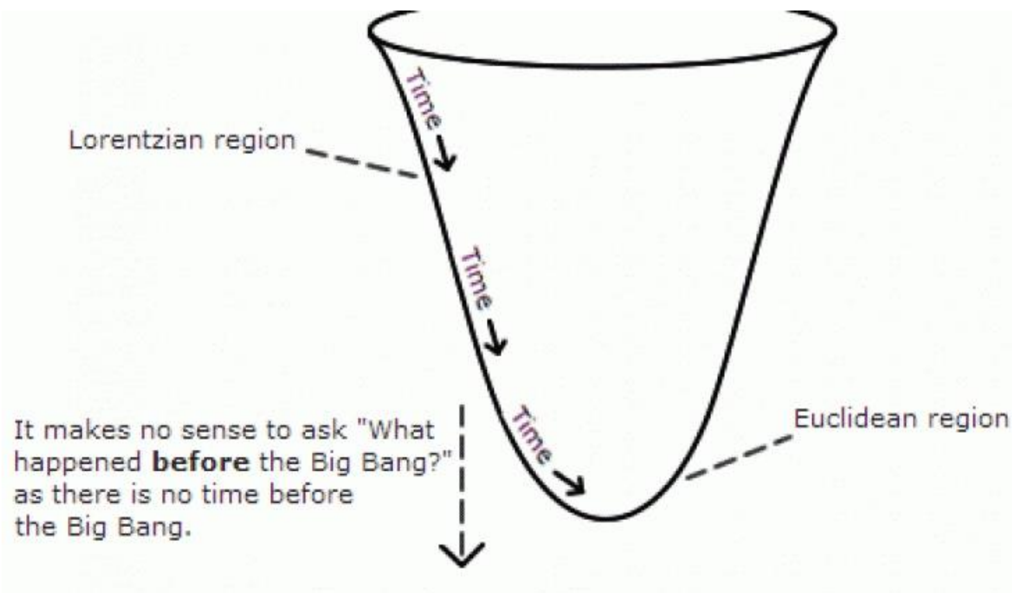
It is difficult to solve except in very particular cases called "mini-superspace" models of Quantum Cosmology.

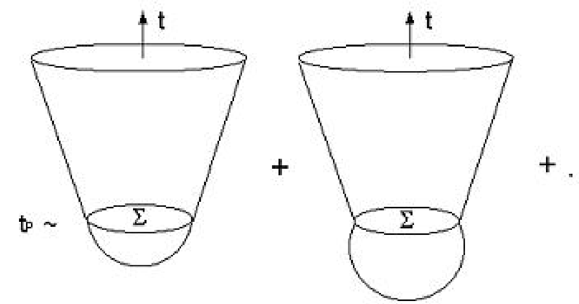
$$\hat{H}\Psi = 0$$

The wave function of the Universe gives a probability distribution for a certain stage of our universe, e.g., a probability before inflation.

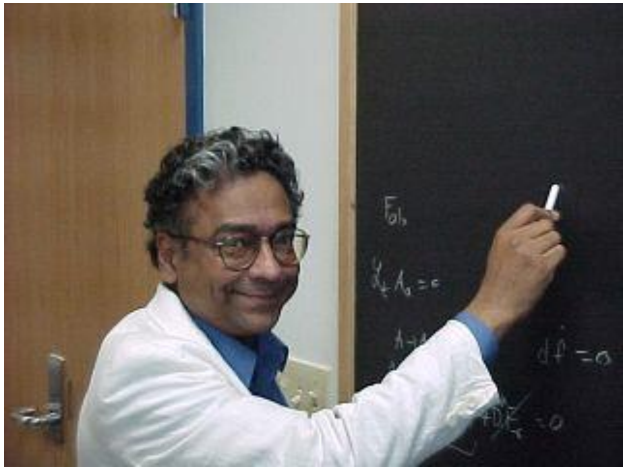
CANONICAL QUANTUM GRAVITY

- Hartle-Hawking proposal: no-boundary-boundary proposal. Solution of Wheeler-DeWitt equation for FLRW minusuperspace model





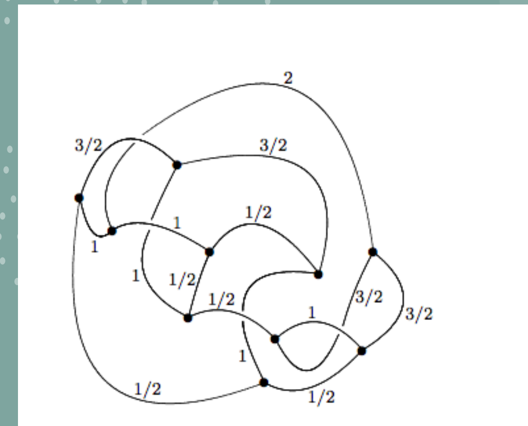
LOOP QUANTUM GRAVITY



Abhay Ashtekar

Lee Smolin

Carlo Rovelli



SPIN NETWORK

- A VERSION OF CANONICAL QUANTUM GRAVITY IN THE ASHTEKAR'S VARIABLES

For any curve $\gamma : [0,1] \to \Sigma$, consider the holonomy

$$U_\gamma(s_1, s_2) = P \exp\left\{ - \int_{s_1}^{s_2} ds \frac{dx^i(s)}{ds} A_i{}^{\hat{I}} \tau_{\hat{I}} \right\},$$

where P denotes path ordering. Then for a closed curve, the "Wilson loop" $\mathrm{Tr}\, U_\gamma(0,1)$ is gauge invariant. More generally, let Γ be a graph, and define a "coloring" as follows:

The area operator, for example, has eigenvalues of the form

$$A = 8\pi\gamma G \sum_i \sqrt{j_i(j_i+1)},$$

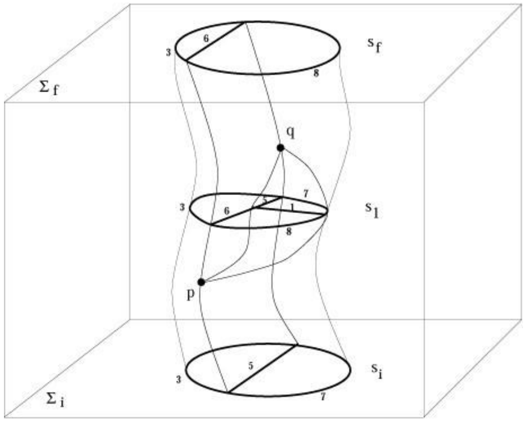
BLACK HOLE ENTROPY

- Bekestein-Hawking formula:

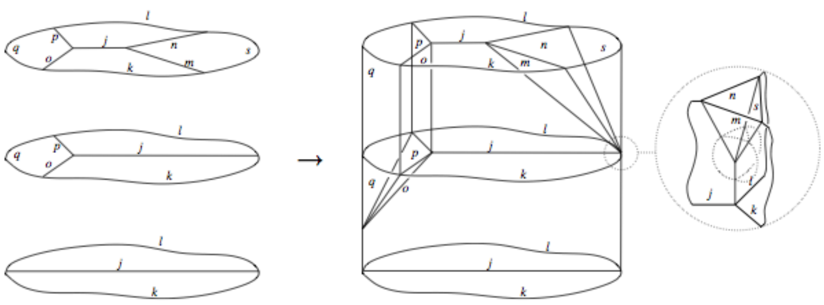
$$S_{BH} = \frac{A}{4L_P^2} = \frac{c^3 A}{4G\hbar}$$

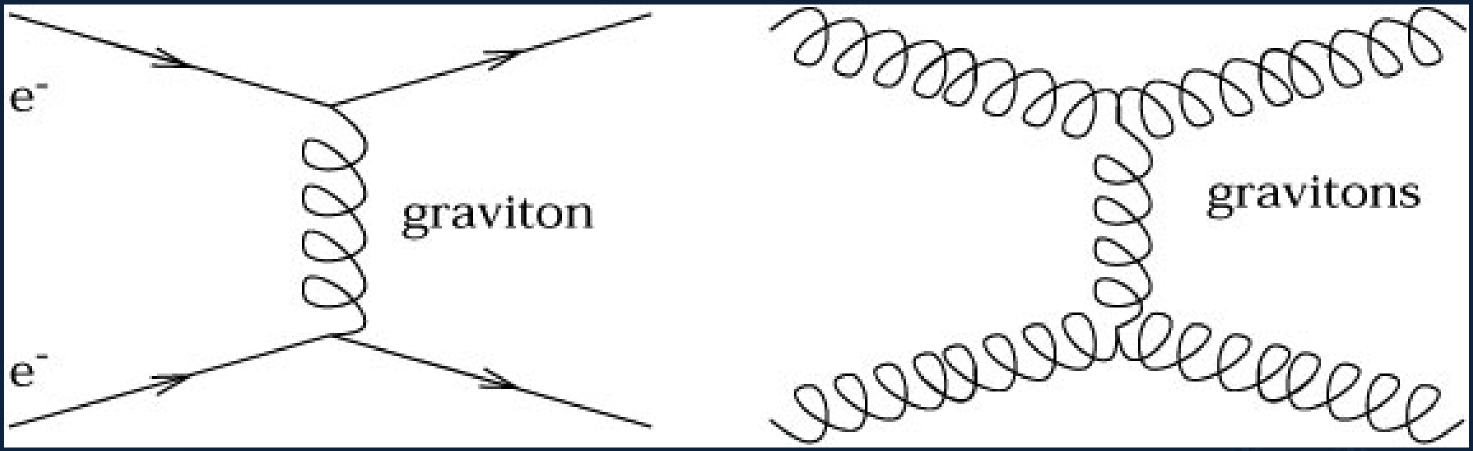
- The same formula can be derived from Loop Quantum Gravity starting with

  S=k ln N(A), and the microstates are Spin networks intersecting the surface A



- Spin Foam (time evolution of Spin Networks)



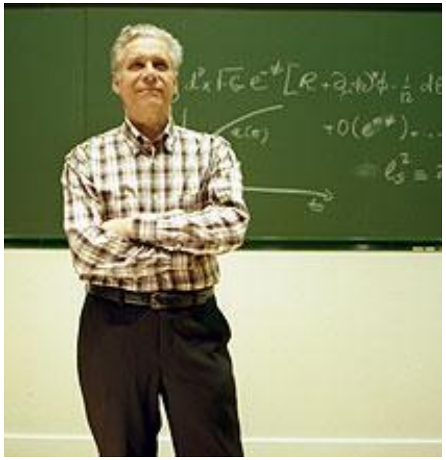


QUANTUM GRAVITY (via Path Integral)

- Quantized G.R. is perturbative non renormalizable. It is believed it is an effective theory valid for $l \gg l_{Pl}$, rather than a fundamental (microscopic) theory valid at arbitrary small distances.
- In general, theories are fundamental if they are perturbatively renormalizable, if their infinities can be absorbed by re-definining only finitely many parameters (m, e, …)
- Perturbative non-renormalizable theories: increasing number of conter terms as the loop order increases. Infinite many parameters, no predictive power

STRING THEORY

- Gabriele Veneziano's formula in dual Model for Strong interactions:
Duality in s and t channel interchange of strong interactions



- Generalizations of Veneziano Model (Nielsen, Nambu, Susskind) and Relativistic String first appearance.

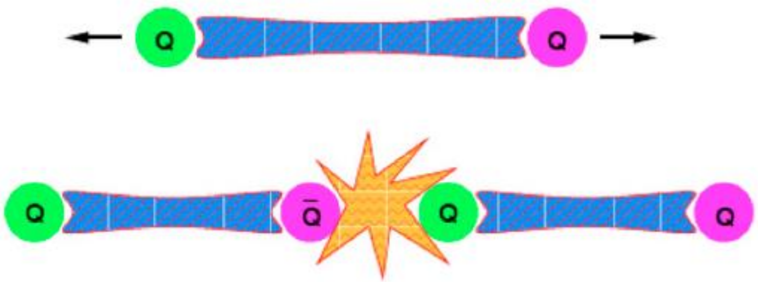
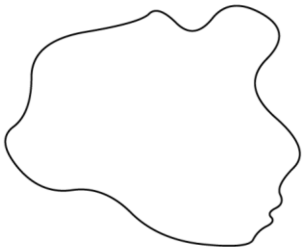
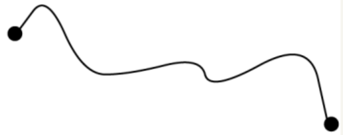


Figure 6: As quarks are pulled apart, eventually new quarks appear.

- Some problem with the model: needed 26 dimensions, states with negative energy(tachyons), massless spin-2 unknown states (later identified as gravitons)

- A SU(3) Gauge theory (QCD) described better strong interactions



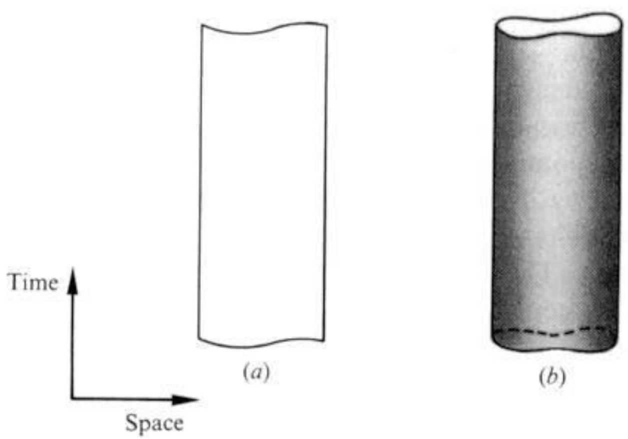


STRING THEORY

Polyakov action for Bosonic strings

$$I_{\rm str} = \frac{1}{4\pi\alpha'} \int_S d^2\sigma \sqrt{g} g^{ab} \partial_a X^\mu \partial_b X^\nu \eta_{\mu\nu} .$$

World-sheets for (*a*) open and (*b*) closed strings.

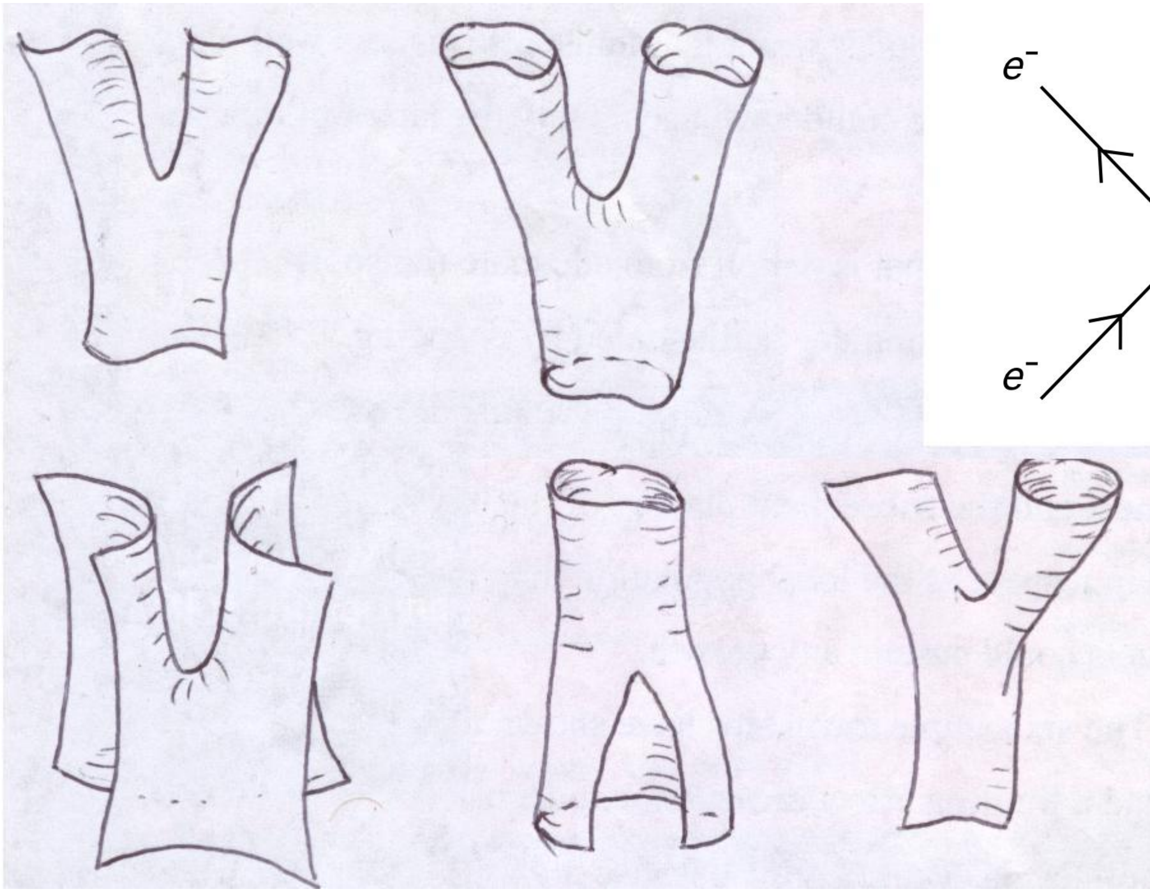


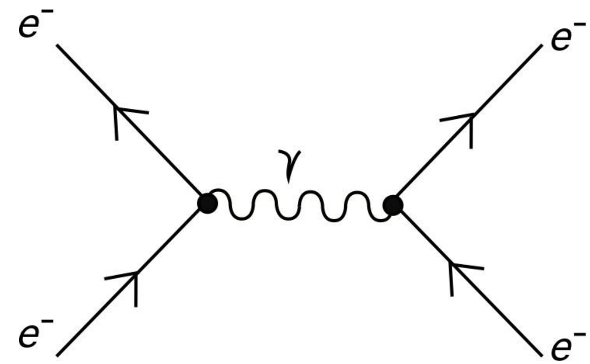
QUANTIZATION OF BOSONIC STRINGS

- One quantizes Bosonic String like any vector field in Quantum Field Theory (Expand the field in a Fourier base and impose commutation relations among the coefficients like the harmonic oscillator).
- Open and Closed Strings both have a tachyon (negative mass) in their quantum spectrum
- Closed Strings have a spin-two massless excited state and a massless scalar field called dilaton
- d=26 for consistency conditions
- The presence of tachyon makes Bosonic String Theory unstable

INTERACTIONS OF BOSONIC STRINGS

- Feynman diagrams of Bosonic String interactions





- Bosonic String Theory expansion is finite (one loop… really), no divergences…so perturbative Quantum Gravity looks renormalizable

SUPERSTRING THEORY

- Bosonic String Theory is un-stable (tachyons)
- It is possible to introduce a new String Theory such that for every Bosonic degree of freedom $X^m(t,s)$ there corresponds a Fermionic (anti-commuting) degree of freedom $\psi^m(t,s)$.
- The theory does not have tachyons in its spectrum.
- In order to be consistent, it needs ten (9+1) dimensions
- There are five non-equivalent Superstring Theories
- One of the important result in String Theory is that they reproduce Bekestein-Hawking formula for Black-hole Entropy in the Quantum regime

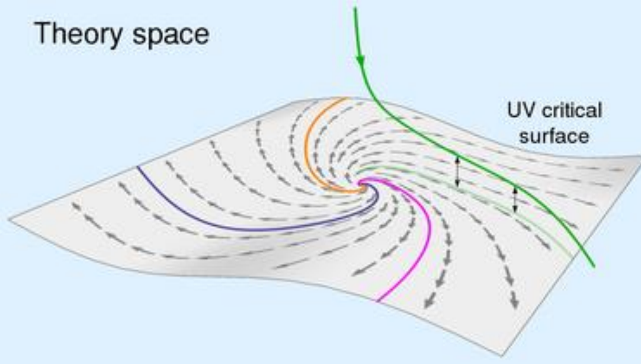
ASYMPTOTIC SAFETY APPROACH TO QUANTUM GRAVITY

- The “Asymptotic safety approach to Quantum Gravity” is based on “Weinberg conjecture” (1979). He suggested to run the coupling constant as function of a cut-off. Find a Non Gaussian Fixed Point (NGFP) in this space of parameters, define the Quantum Theory of Gravity at this point.

- $d=2+\epsilon$: F. P. exists (Weinberg); d=4 NGFP in the Einstein-Hilbert truncation exists (Reuter and Sauressing 2002).

- There exist fundamental theories which are not perturbatively renormalaizable (along the line of K. Wilson’s general principles of renormalization)

- They are constructed by performing the infinite-cutoff limit at a non-Gaussian fixed point ($u_* \neq 0$) (pert.theory: trivial (Gaussian) $u_* = 0$)



ASYMPTOTIC SAFETY APPROACH TO QUANTUM GRAVITY

The effective average action is used in modern Asymptotic Safety approach to Quantum Gravity.

The effective average action contains all momenta p>k (=cut off) and not yet those momenta p<k.

The effective average action should provide the dependence by k of the fundamental constant.

The Einstein-Hilbert truncation is implemented.

CONCLUSIONS

- A well established theory of Quantum Gravity does not exist yet. Lack of experimental tests

- We have analyzed some approaches to Quantum Gravity

1. Loop Quantum Gravity (Mathematical problems)
2. String Theory (no supersymmetry found..)
3. Asymptotic Safety (quite young…evidence for the existence of the Non-Gaussian Fixed Point, no final proofs).

- More work appears needed to define a final theory of Quantum Gravity. This theory should reproduce all semi-classical results (e.g. Black Hole entropy) and it should have classical Einstein General Relativity as a limit when $\hbar \longrightarrow 0$.