Detecting gravitational waves using Cosmic Microwave Background

Suvodip Mukherjee

Tata Institute of Fundamental Research

HEARING BEYOND THE STANDARD MODEL WITH COSMIC SOURCES OF GRAVITATIONAL WAVES

ICTS-TIFR,
January 6th, 2025

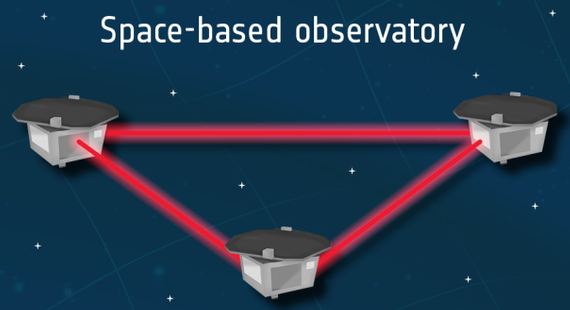
THE SPECTRUM OF GRAVITATIONAL WAVES

esa

Observatories & experiments

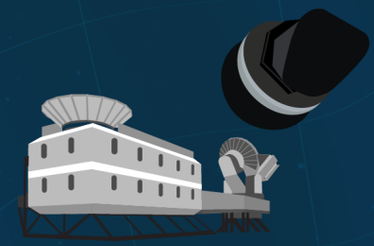
Ground-based experiment

Space-based observatory



Pulsar timing array

Cosmic microwave background polarisation



Timescales

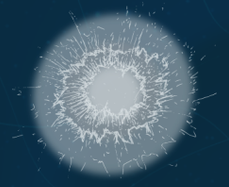
milliseconds — seconds — hours — years — billions of years

Frequency (Hz)

100 — 1 — 10^{-2} — 10^{-4} — 10^{-6} — 10^{-8} — 10^{-16}

Cosmic fluctuations in the early Universe

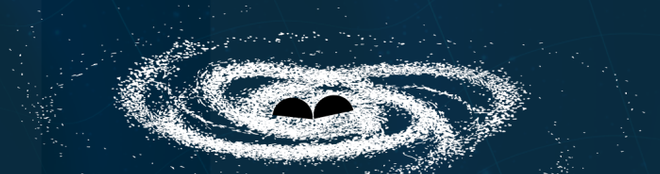
Cosmic sources



Supernova

Pulsar

Compact object falling onto a supermassive black hole



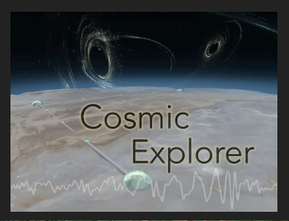
Merging supermassive black holes

Merging neutron stars in other galaxies

Merging stellar-mass black holes in other galaxies

Merging white dwarfs in our Galaxy

#lisa



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INTERNATIONAL PULSAR TIMING ARRAY IPTA

SIMONS OBSERVATORY

CMB-S4
Next Generation CMB Experiment

Suvodip Mukherjee, 2025

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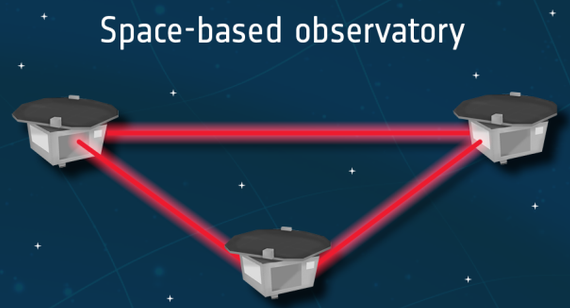

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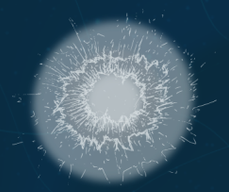

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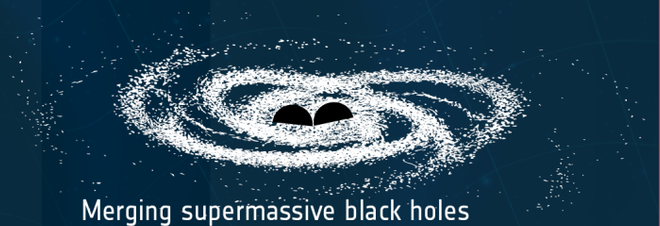

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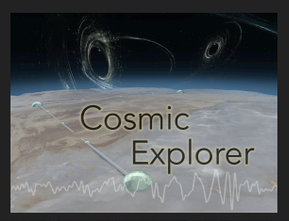

LISC
LIGO–India Scientific Collaboration

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INTERNATIONAL PULSAR TIMING ARRAY
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PARQUE ASTRONÓMICO ATACAMA, CHILE
SIMONS OBSERVATORY
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CMB-S4
Next Generation CMB Experiment

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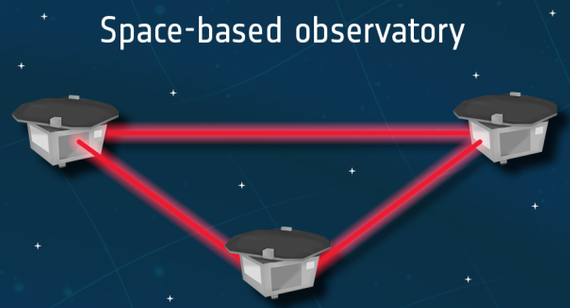

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Tomorrow's talk

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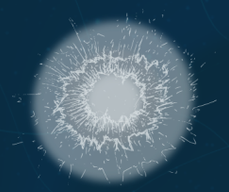

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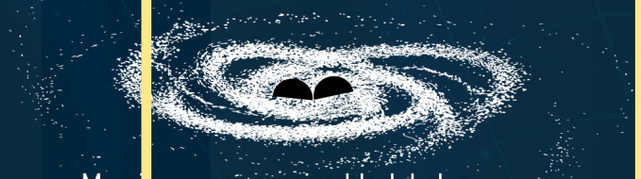

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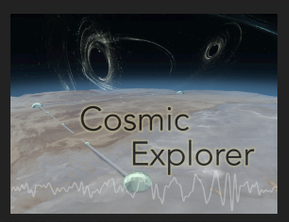

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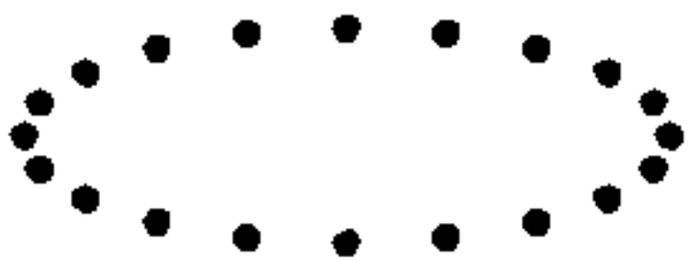
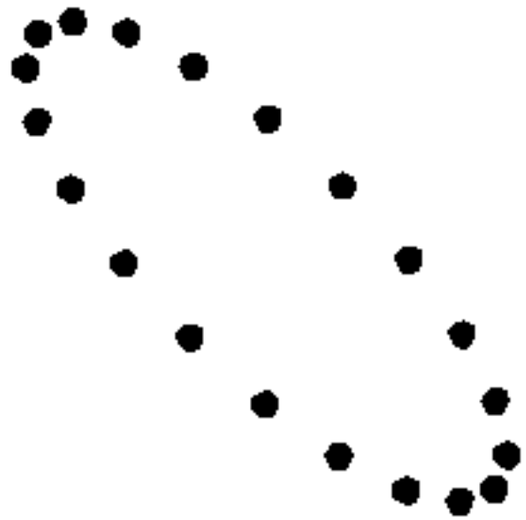
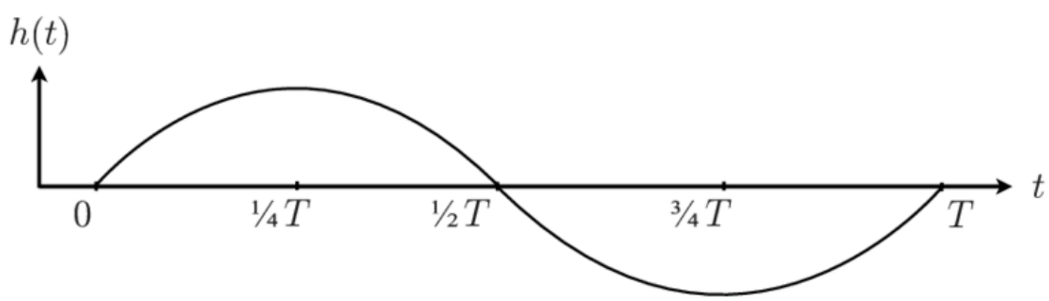
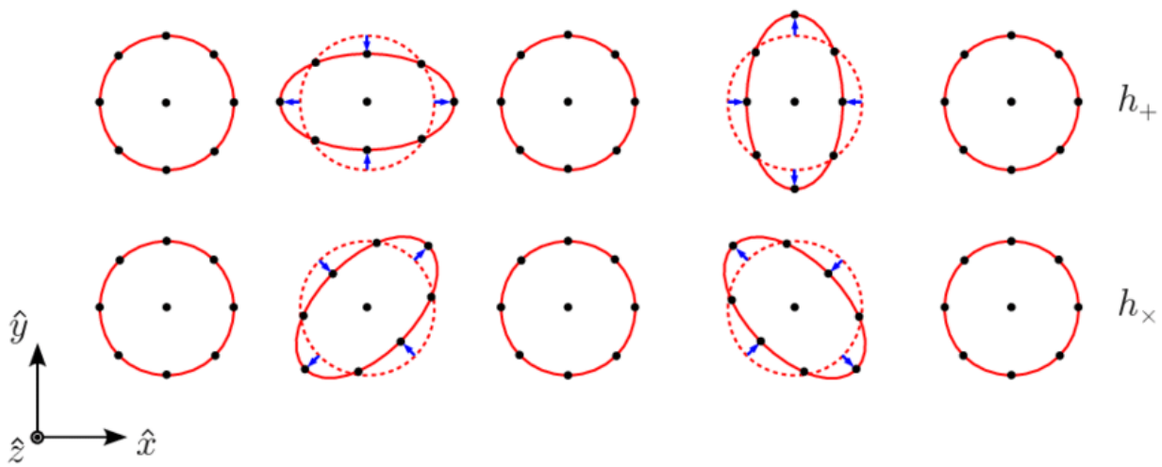
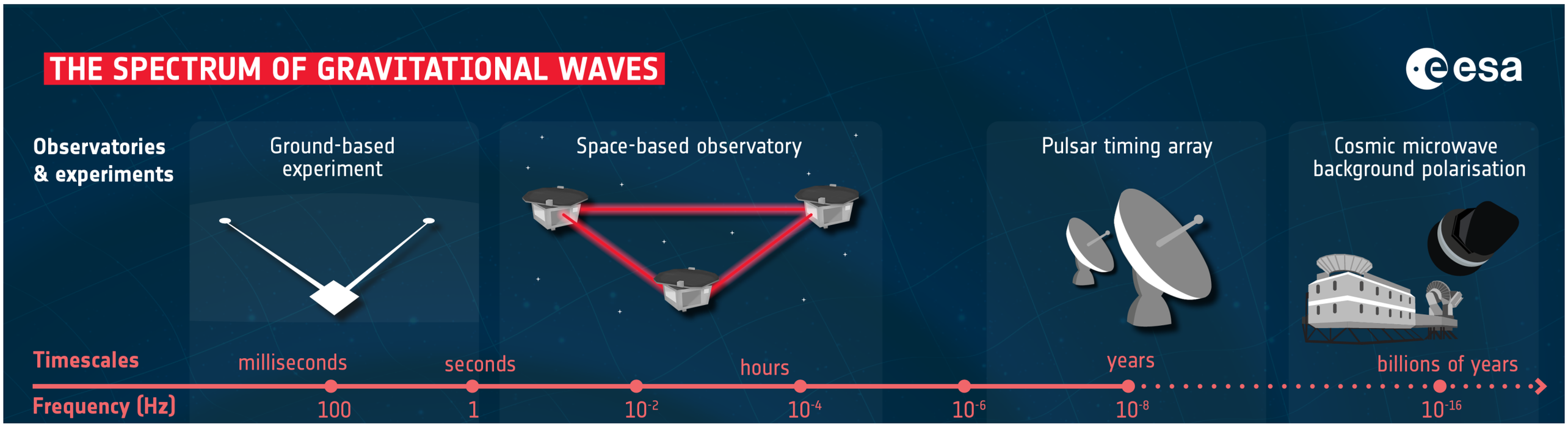








IMPRINTS OF GRAVITATIONAL WAVES CAN BE MEASURED BY A DIFFERENTIAL MEASUREMENT



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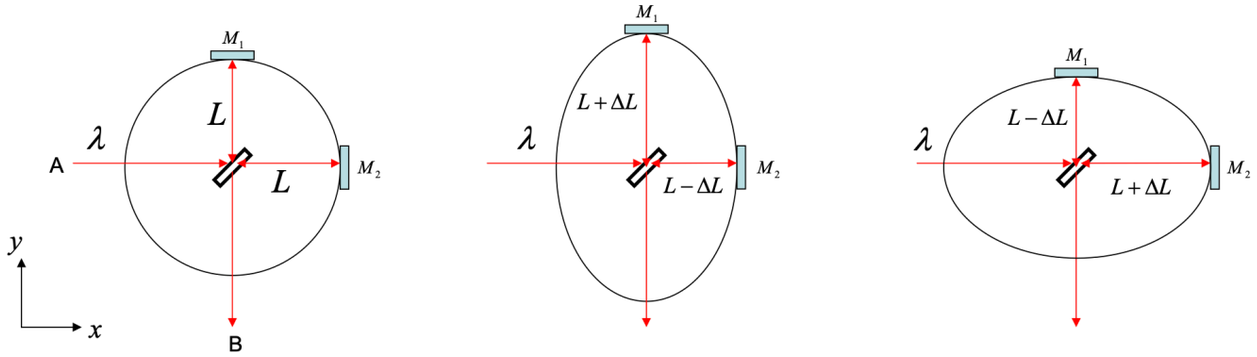

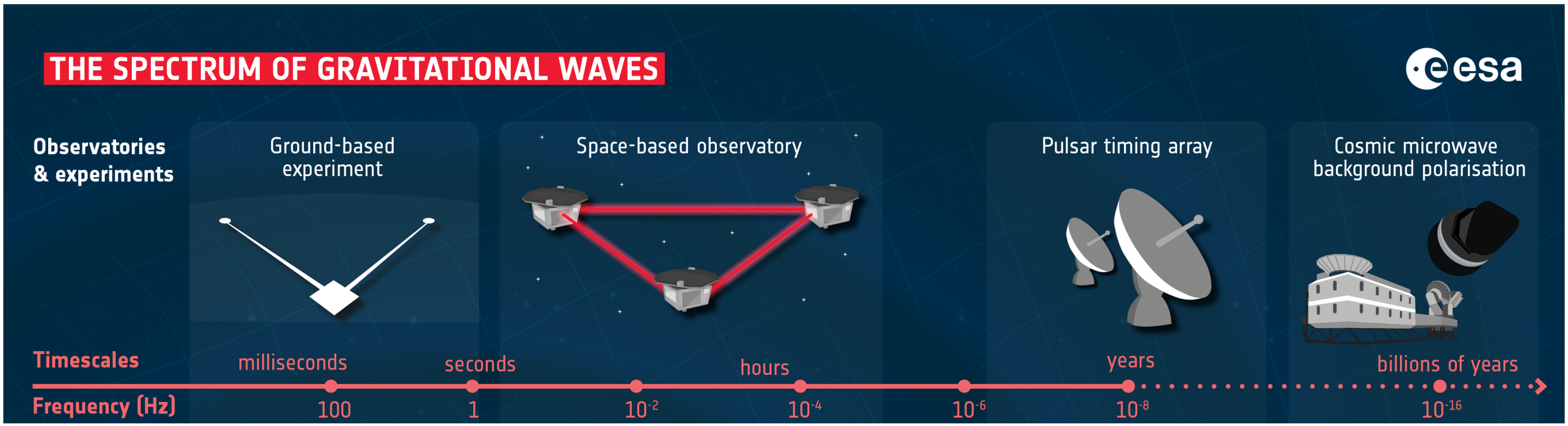

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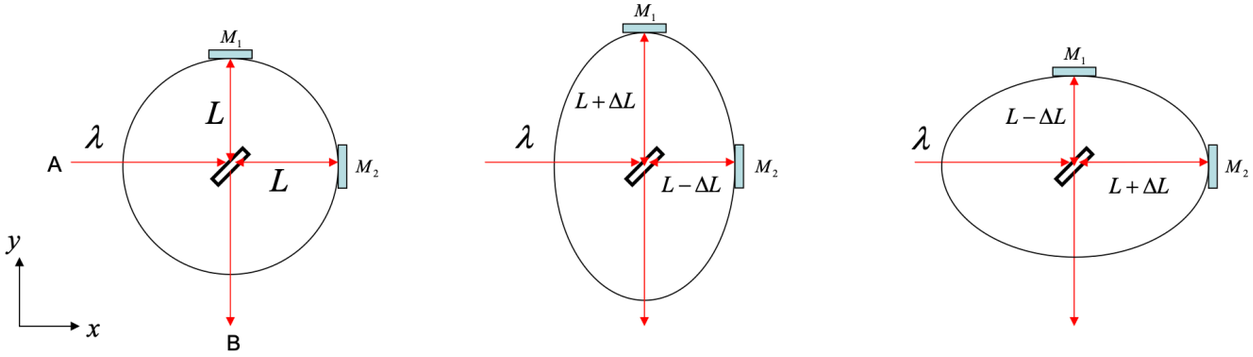

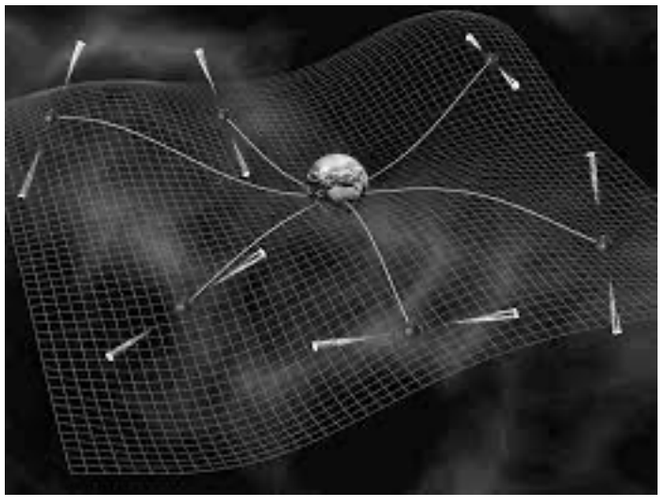

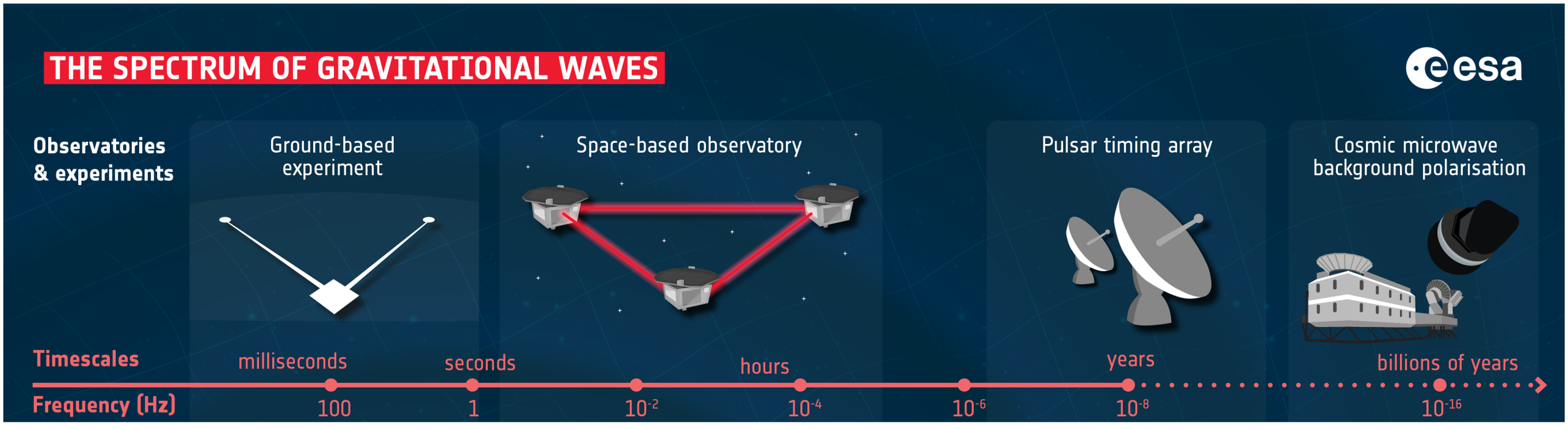

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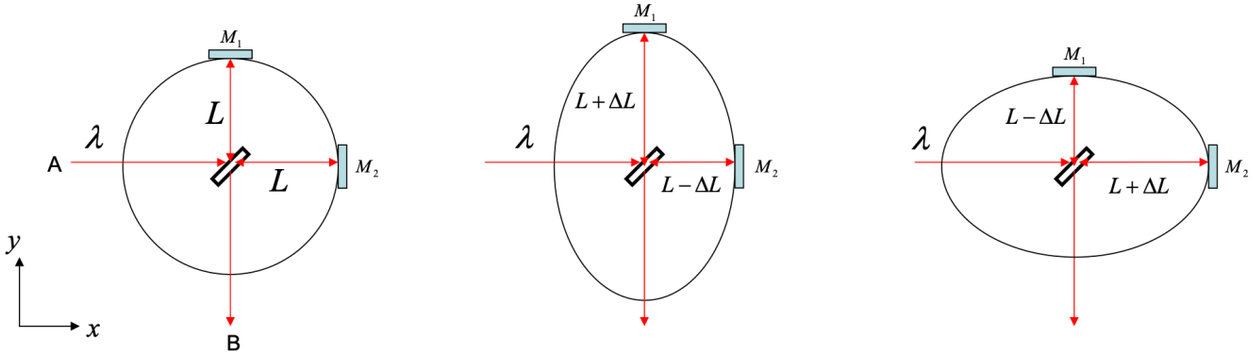
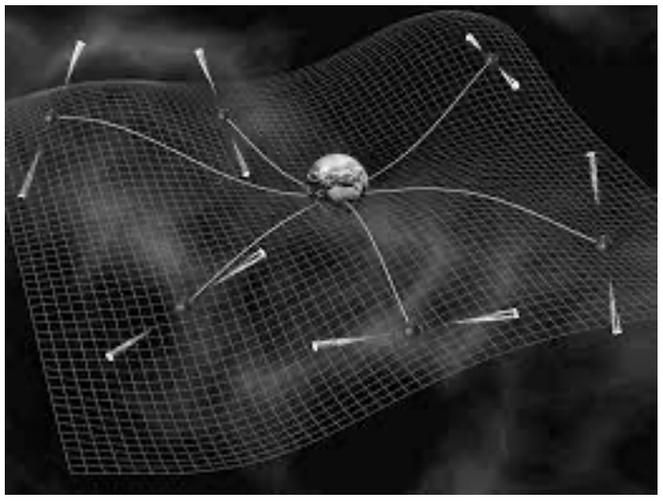
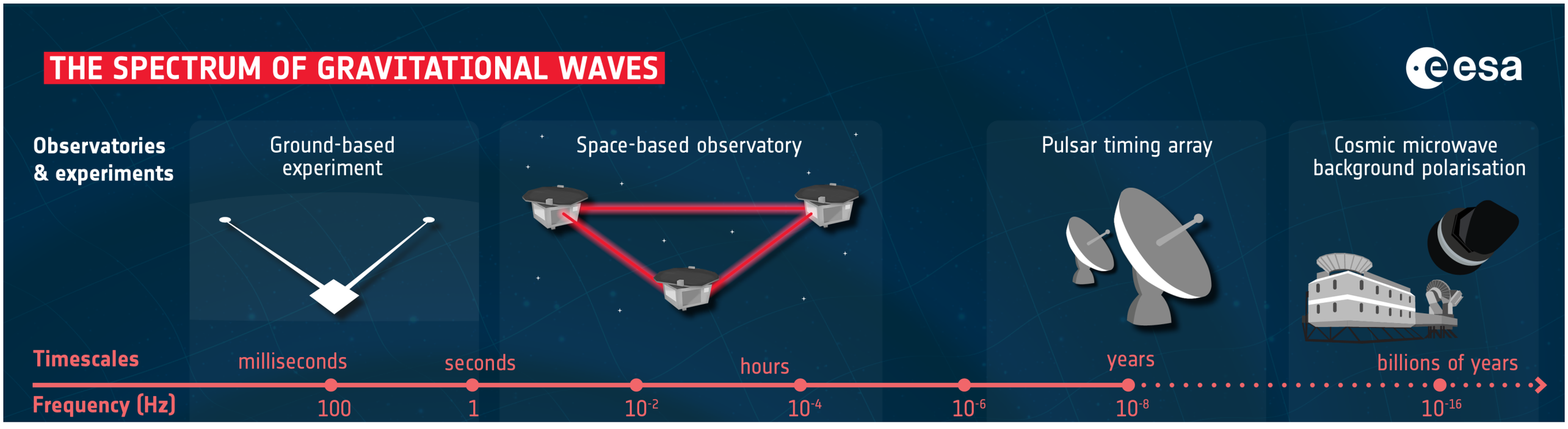




Using Cosmic Probes at the Largest Scales.



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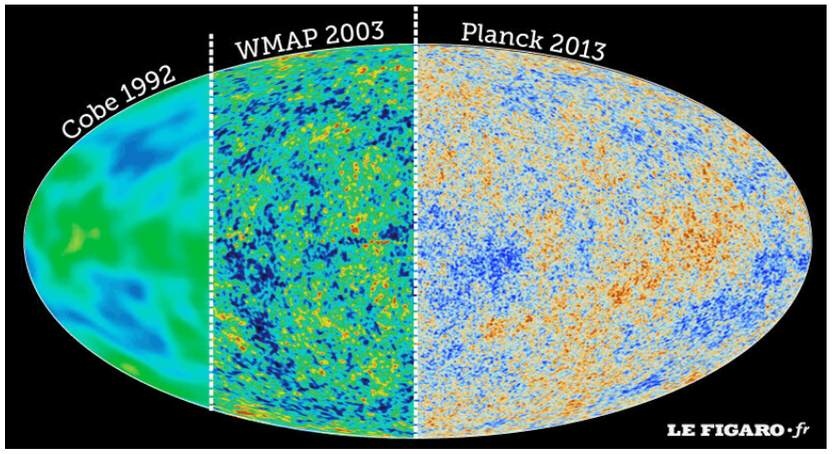
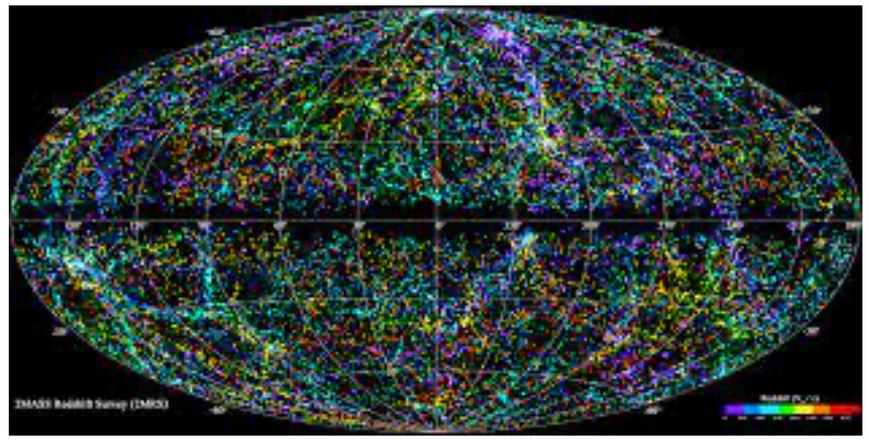
Cosmic Microwave Background

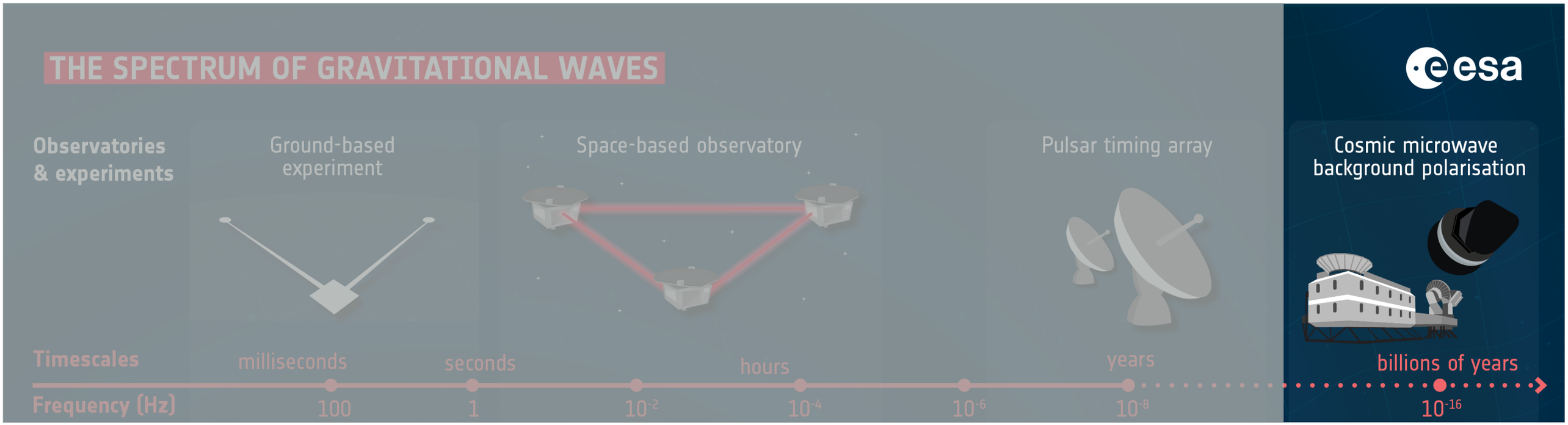


Feasible in interesting physics regime with existing technology

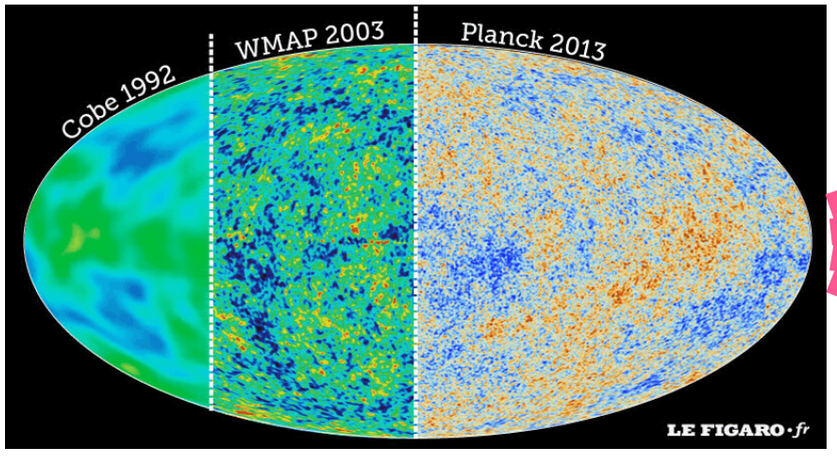
Galaxy Distribution



Feasible in-principle



CMB AS A PROBE TO GRAVITATIONAL WAVES

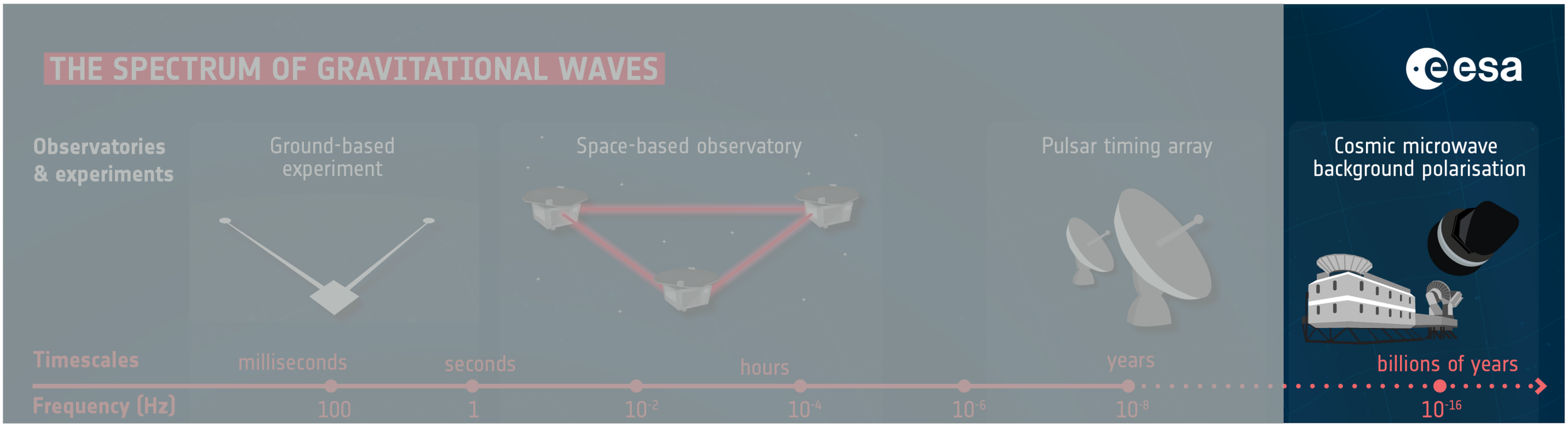


What is the interaction between CMB and GW?

What are the observables of this interaction?

What is the expected strength of the observables?

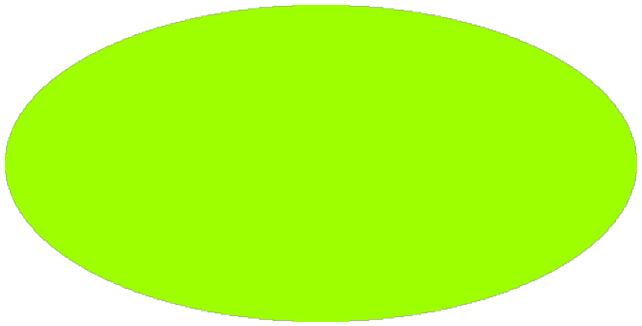
What is the prospect of detection?

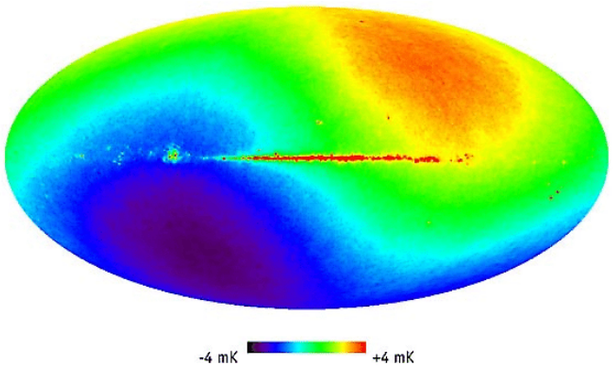


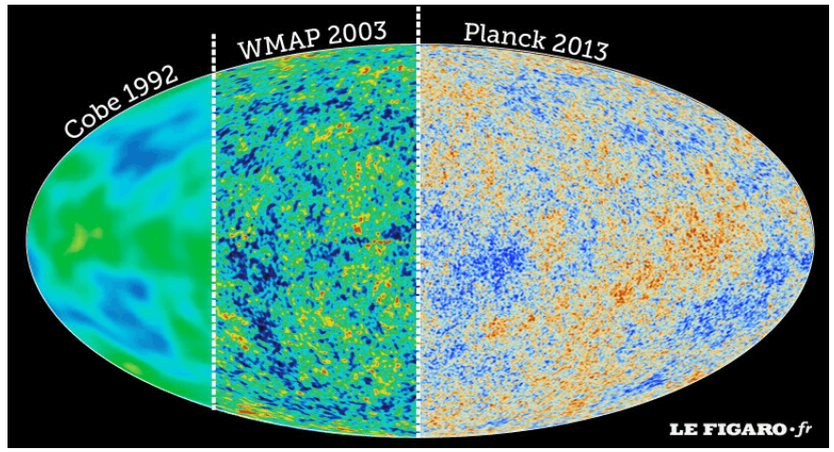
CMB as a Probe to Gravitational Waves

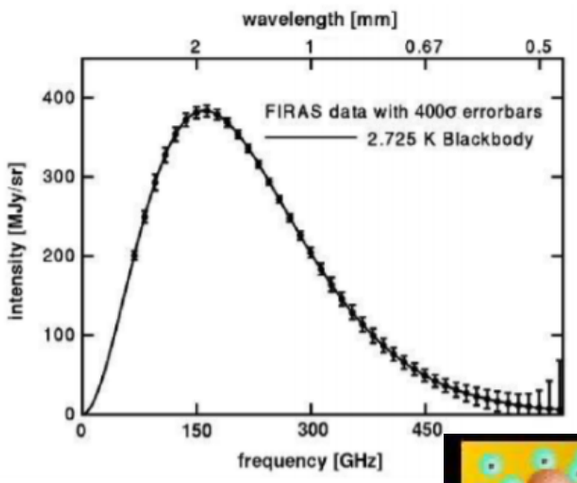
What is the interaction between CMB and GW?

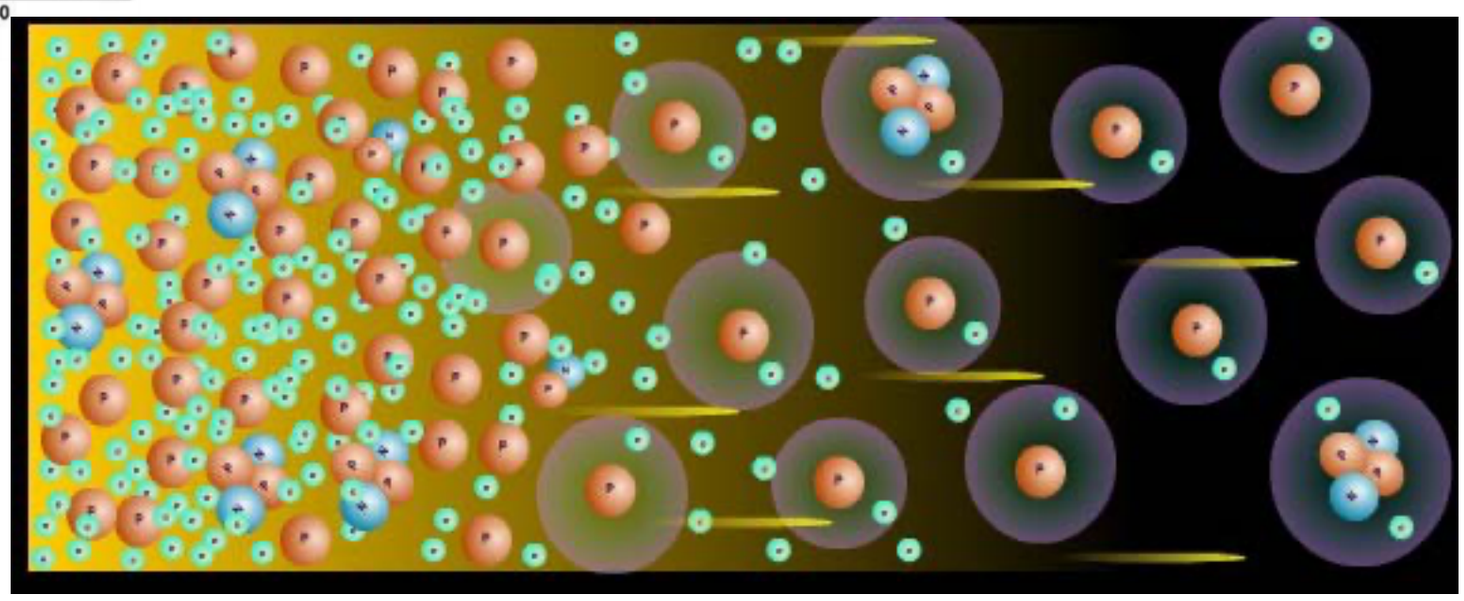
COSMIC MICROWAVE BACKGROUND TEMPERATURE AND ITS FLUCTUATIONS





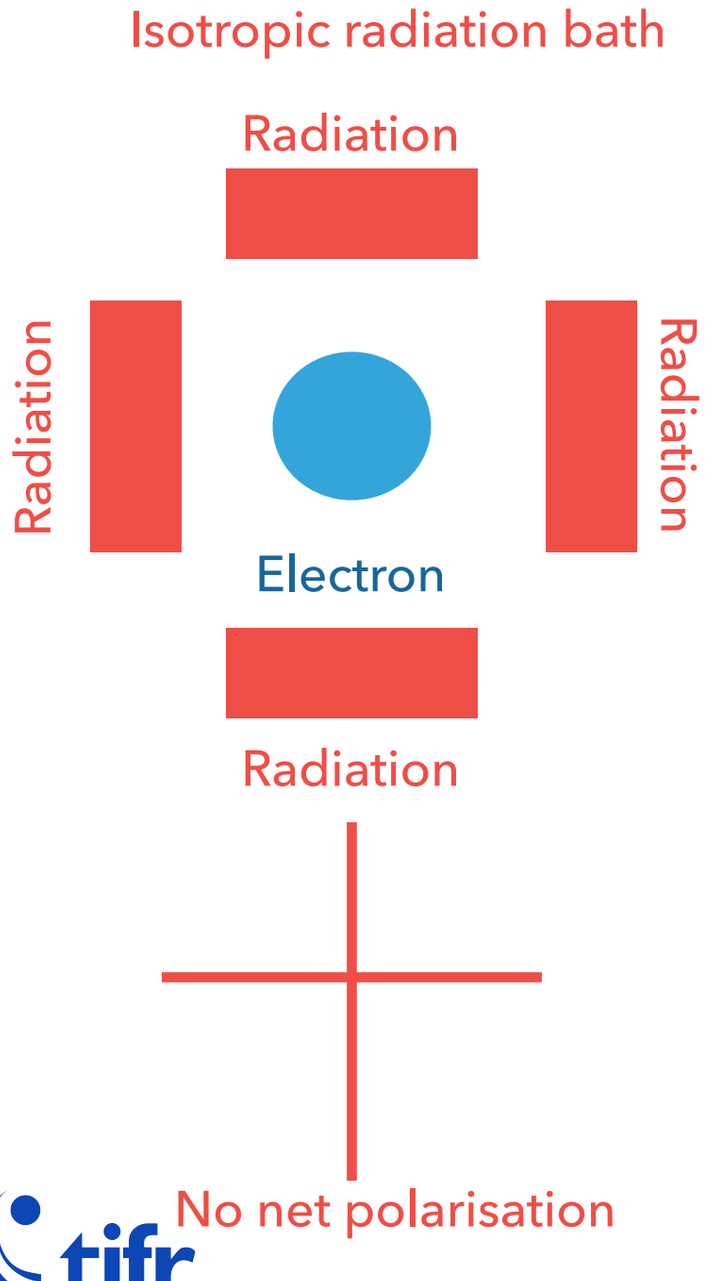






COSMIC MICROWAVE BACKGROUND POLARISATION

Can CMB be Polarised by Thomson scattering?



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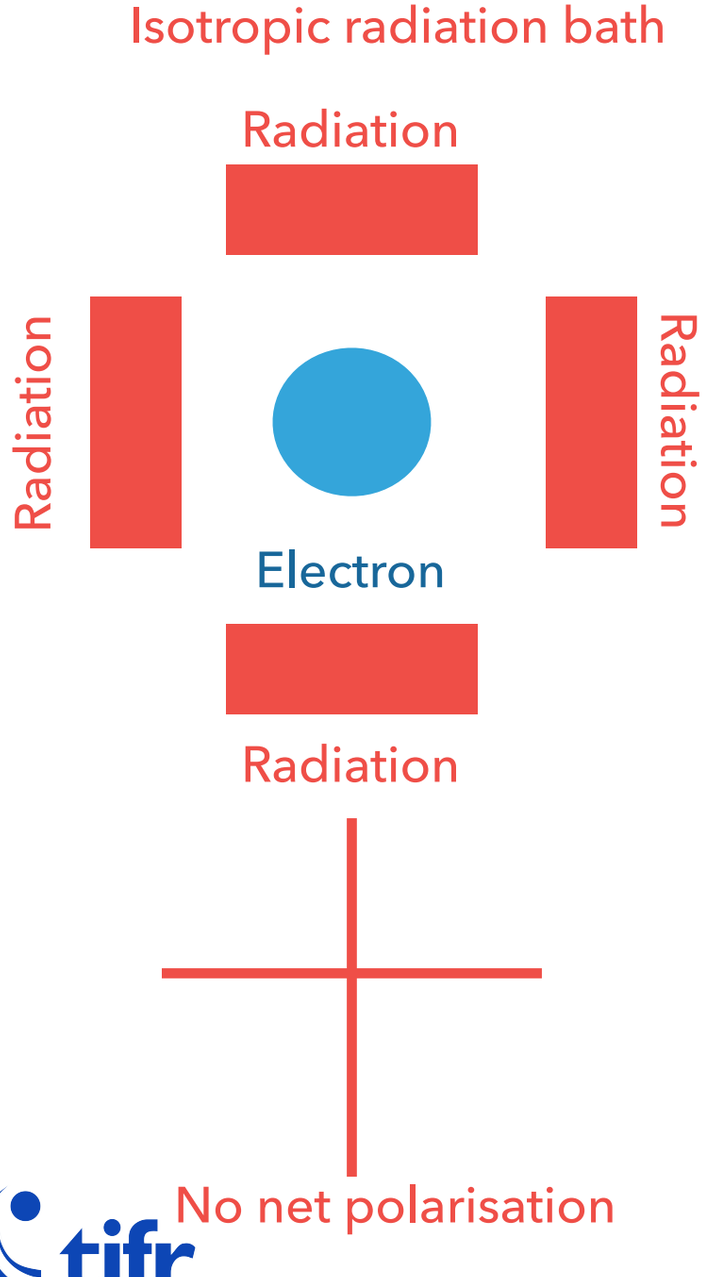

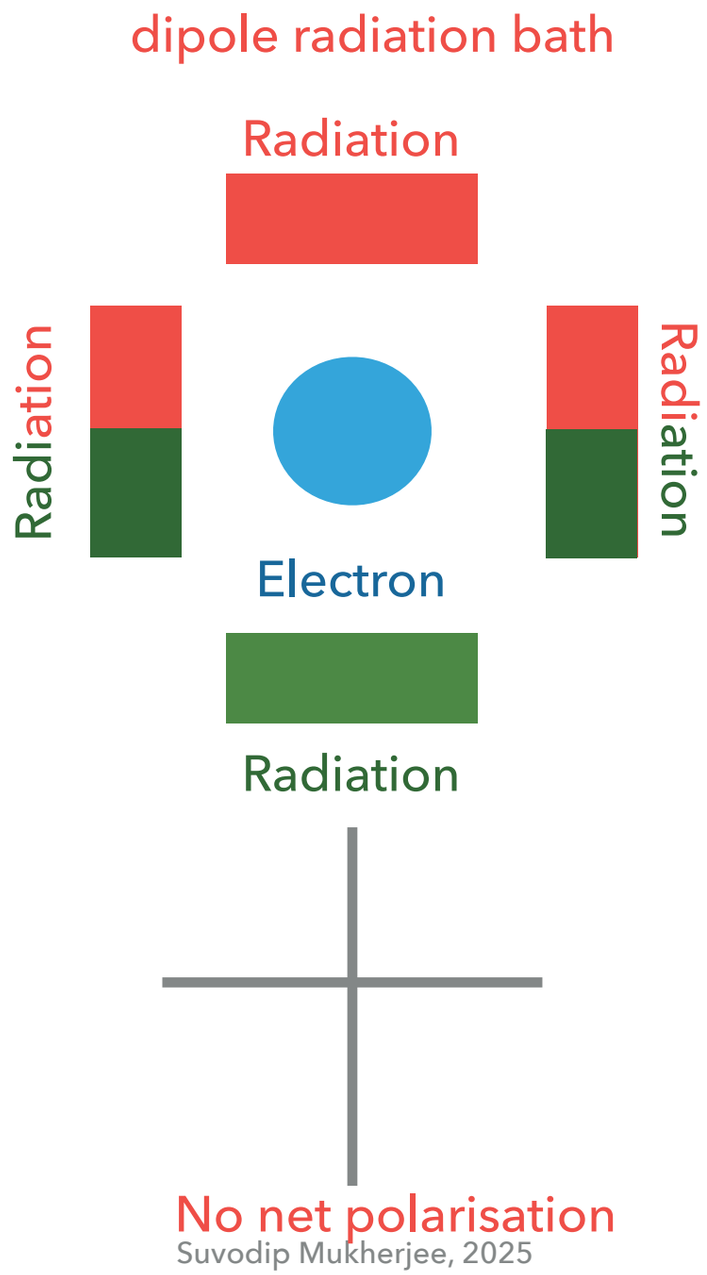

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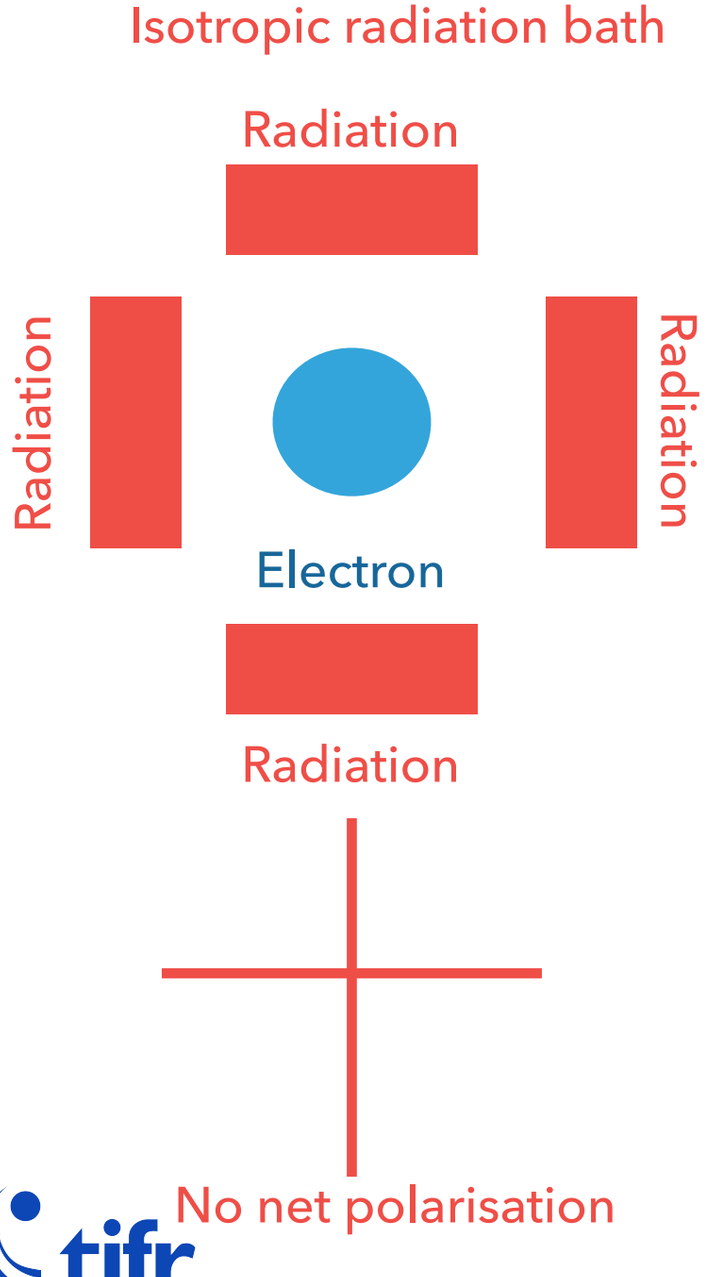
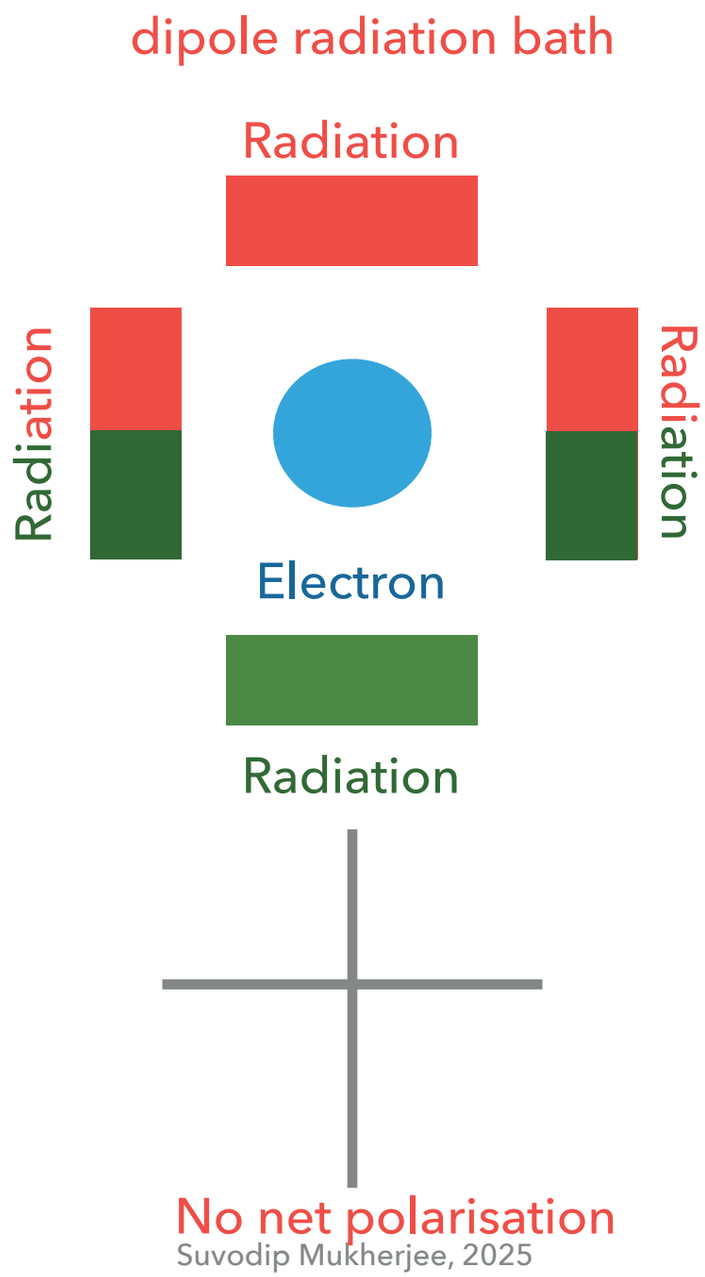
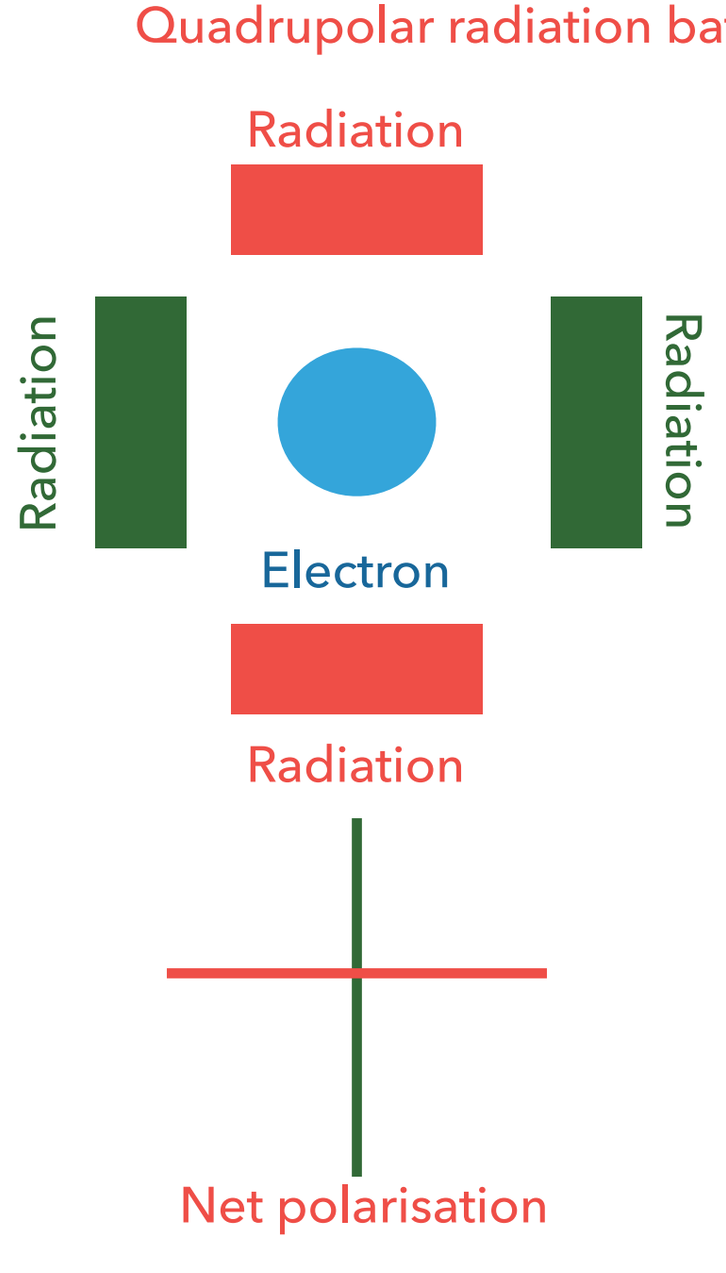
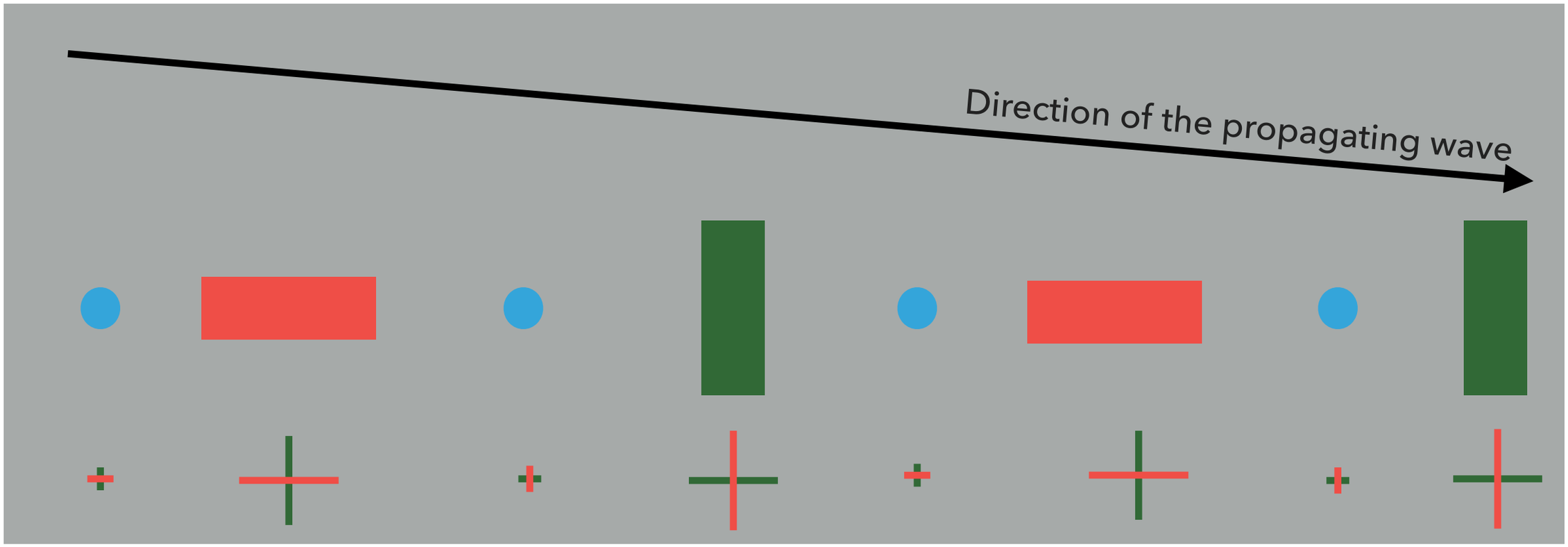


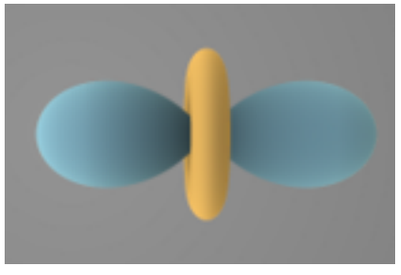




COSMIC MICROWAVE BACKGROUND POLARISATION

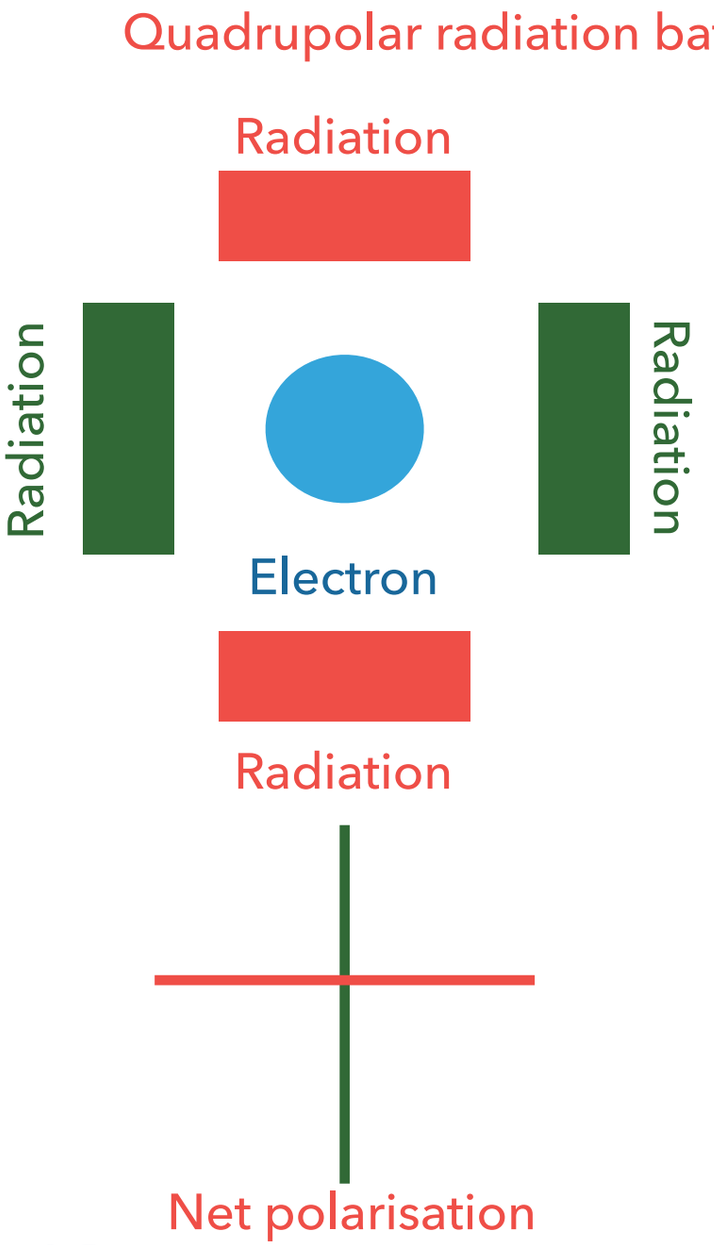
Projection of GW on the sky

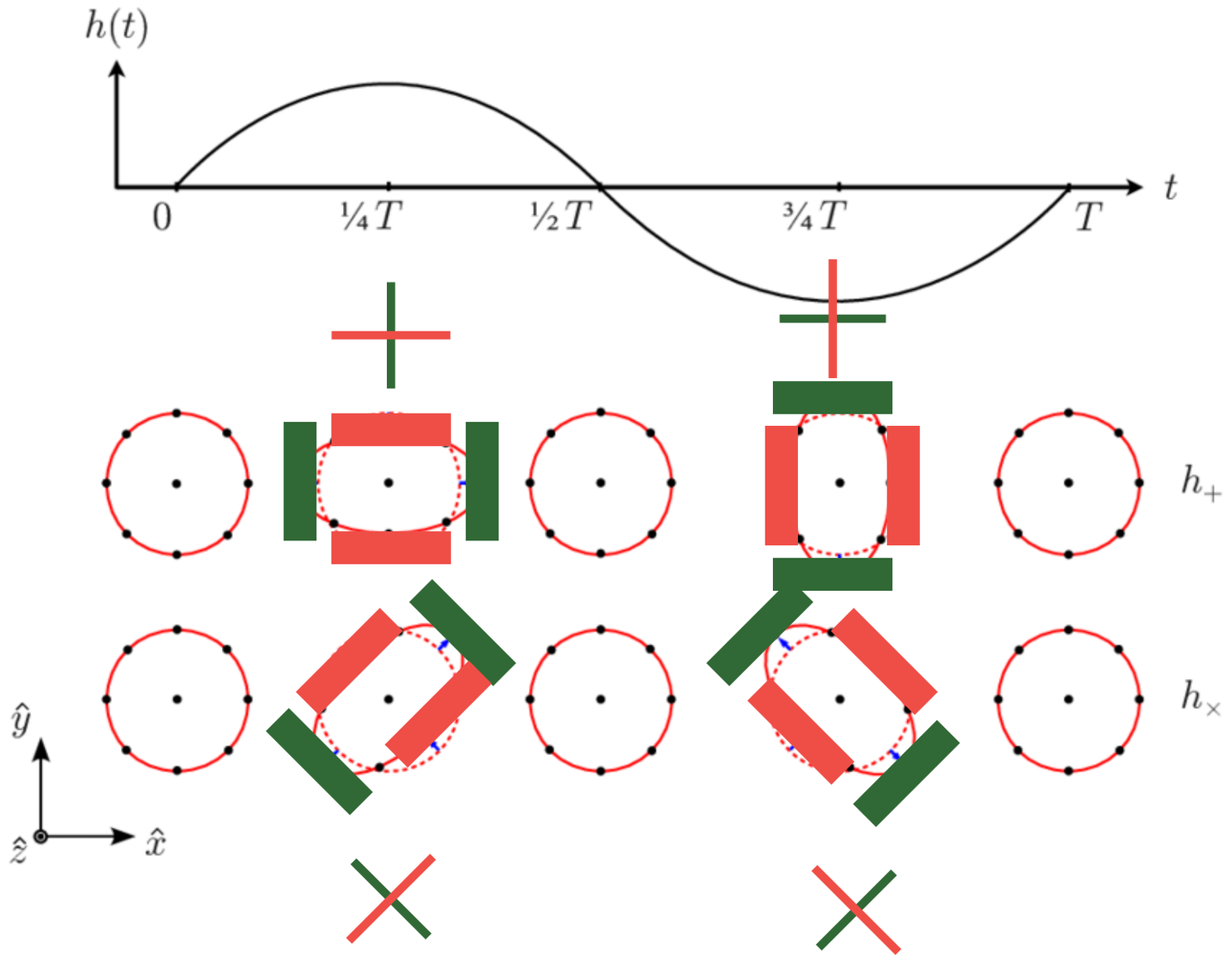




COSMIC MICROWAVE BACKGROUND POLARISATION

Can GW also generate quadrupolar fluctuation?





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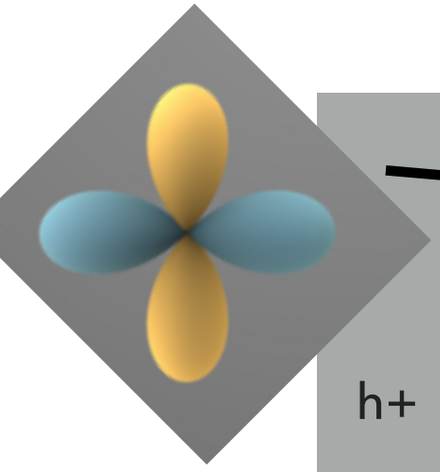

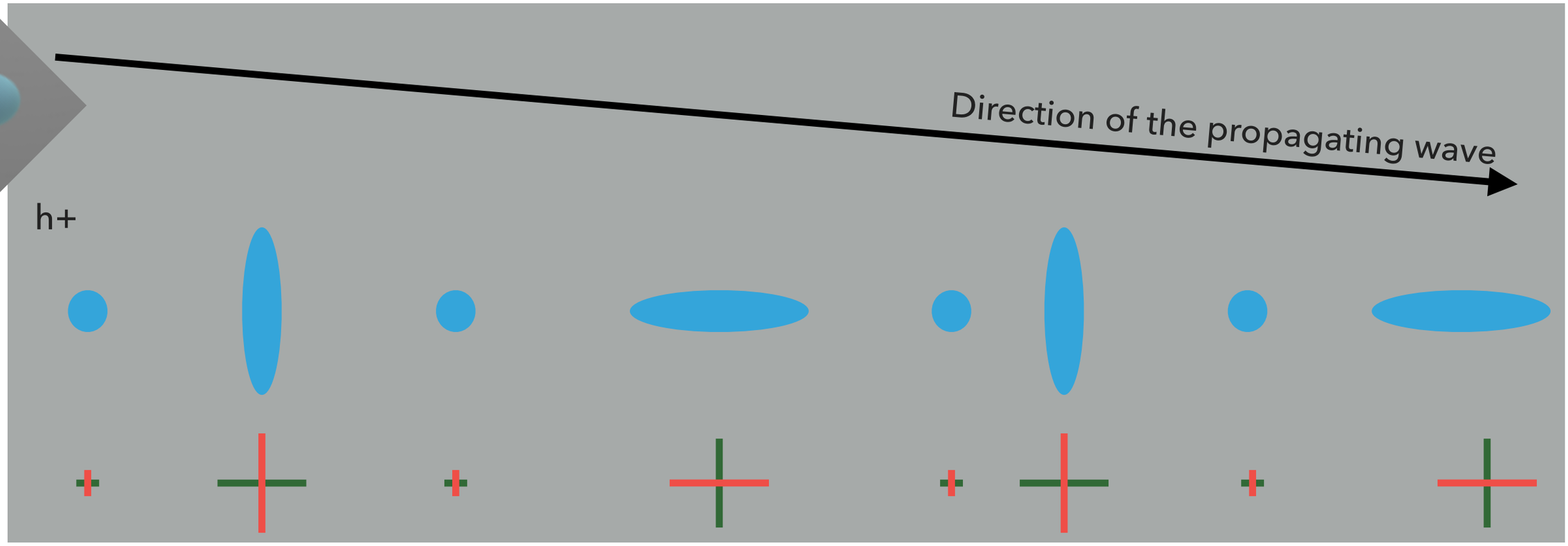

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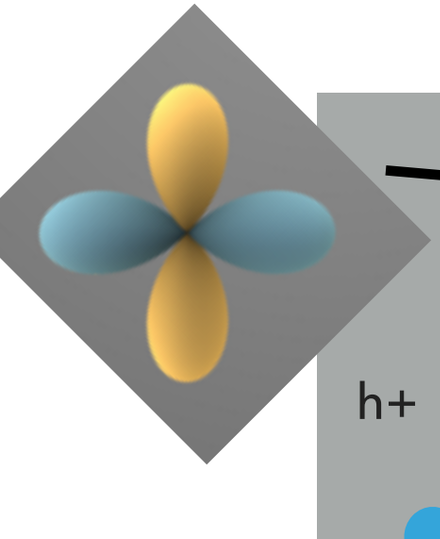
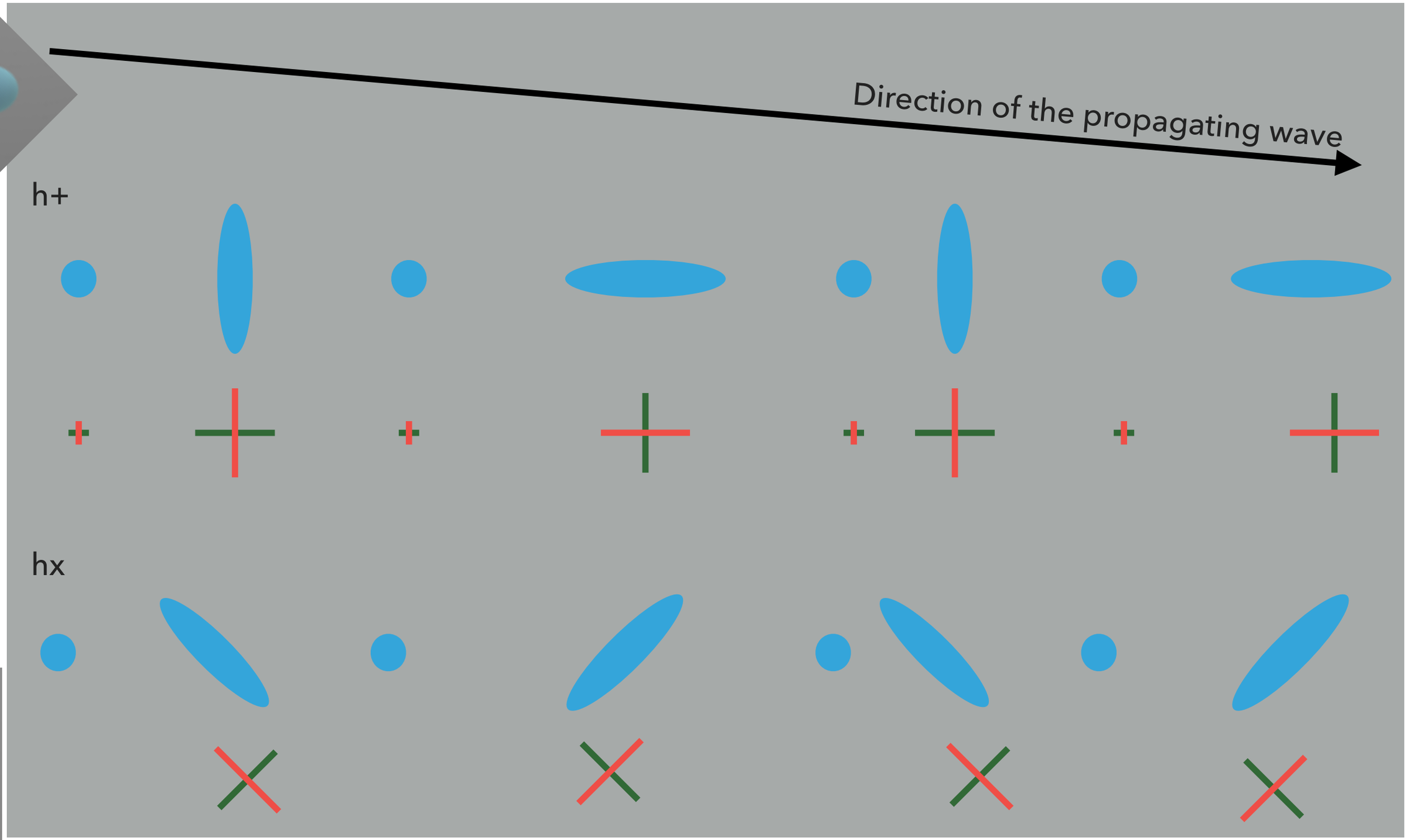
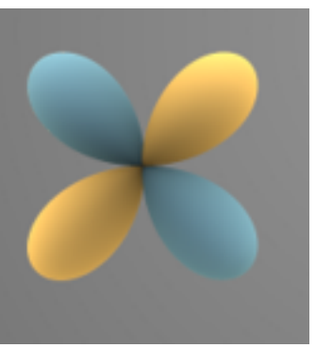


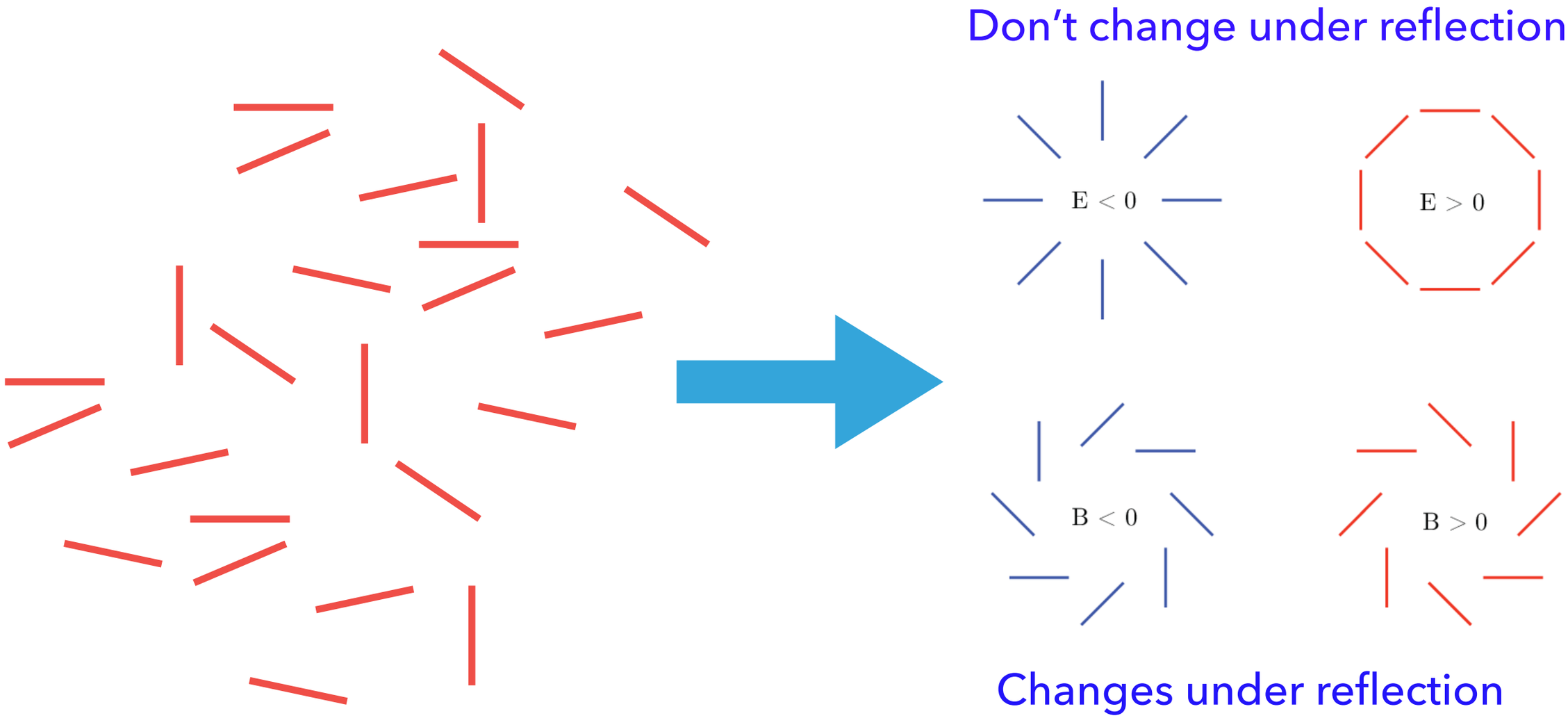




COSMIC MICROWAVE BACKGROUND POLARISATION

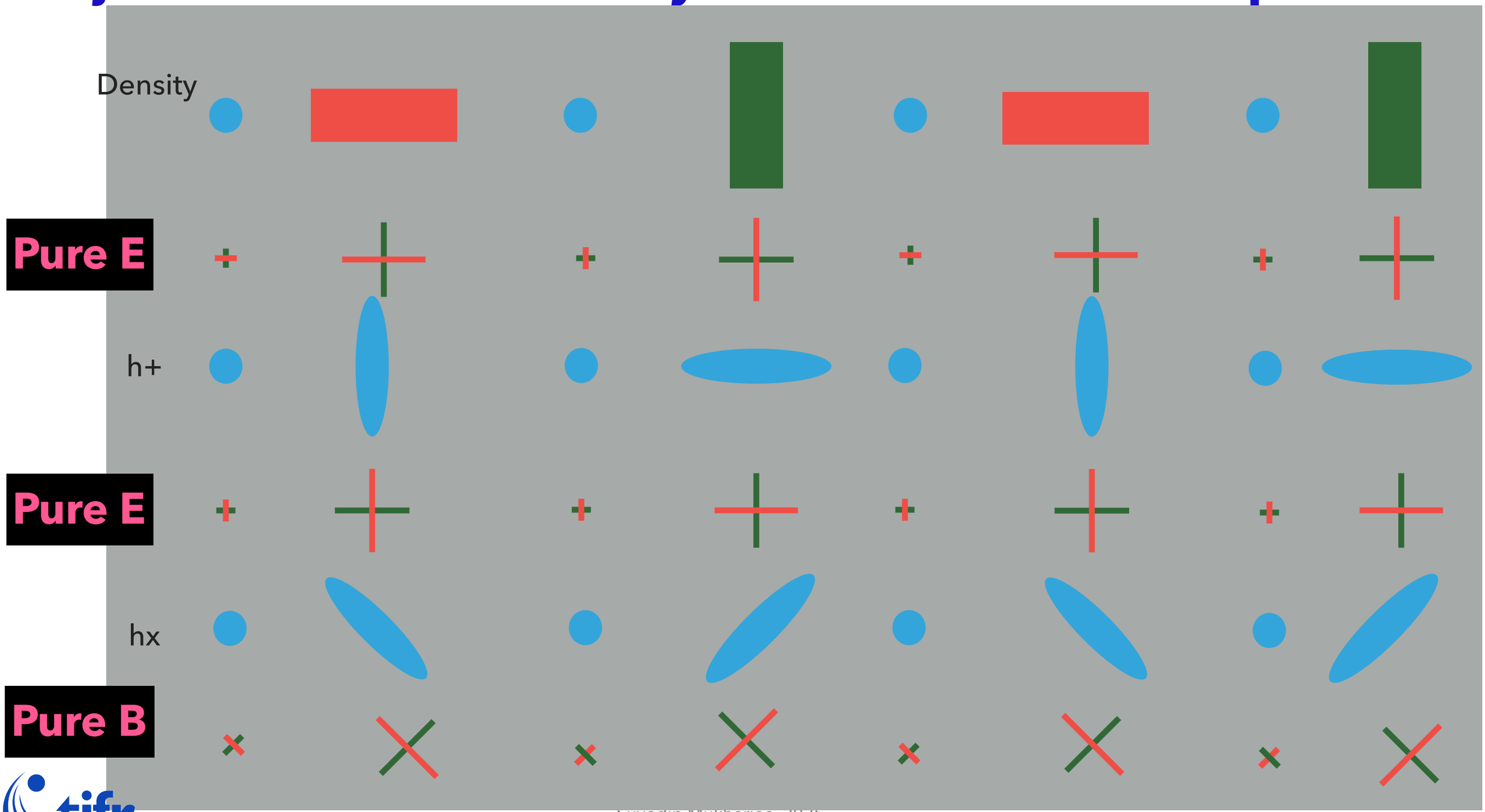
Identifying polarisation pattern on the sky

(In a coordinate independent way)



COSMIC MICROWAVE BACKGROUND POLARISATION

Projection of GW on the sky: E-mode and B-mode patterns



CMB as a Probe to Gravitational Waves

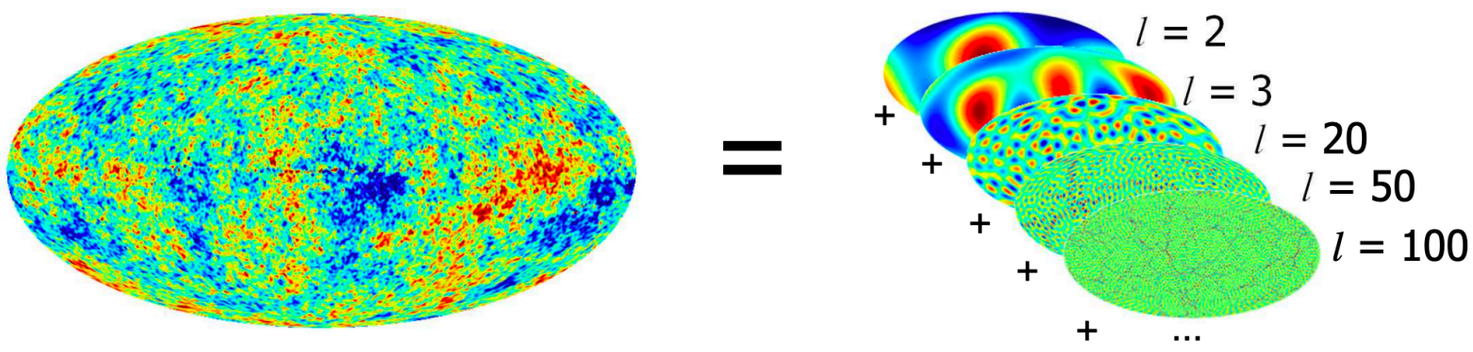
What are the observables of this interaction?

OBSERVABLES OF GW PERTURBATIONS ON B-MODE

CMB fluctuations are zero mean (nearly) Gaussian random field on the sky

$$T(\hat{n}) = \sum_{lm} a_{T,lm} Y_{lm}(\hat{n})$$

$$(Q \pm iU)(\hat{n}) = \sum_{lm} a_{\pm 2,lm}\, {}_{\pm 2}Y_{lm}(\hat{n})$$



$$a_{E,lm} = -(a_{2,lm} + a_{-2,lm})/2$$

$$a_{B,lm} = i(a_{2,lm} - a_{-2,lm})/2$$

$$\ell \propto k$$

Angular Modes ⟷ Fourier Modes

tifr

OBSERVABLES OF GW PERTURBATIONS ON B-MODE

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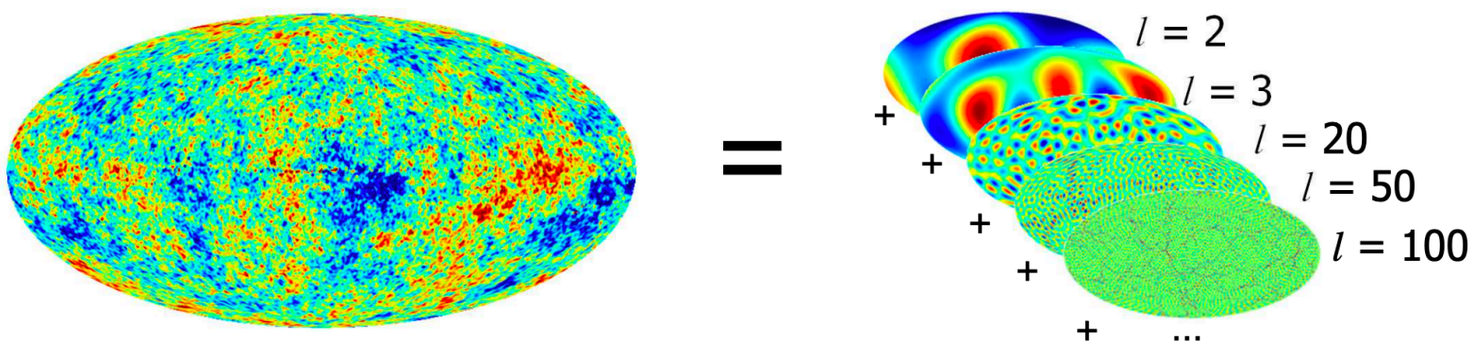

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Angular Modes ⟷ Fourier Modes

Harmonic coefficients

Power spectra

$$C_{XX'l} = \frac{1}{2l+1} \sum_m \langle a^*_{X,lm} a_{X',lm} \rangle$$

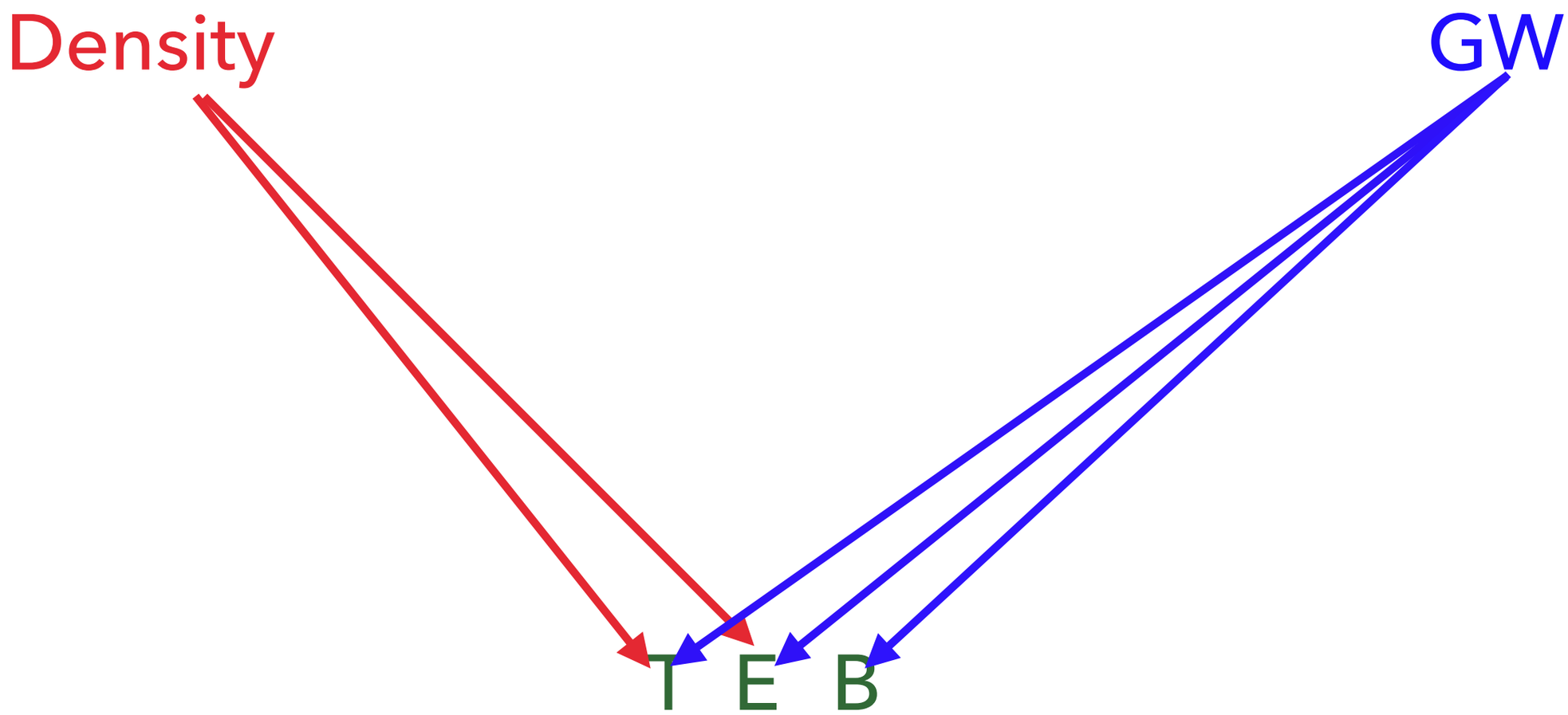
TT, EE, BB, TE are non-zero in absence of non-parity violating physics in early Universe

tifr

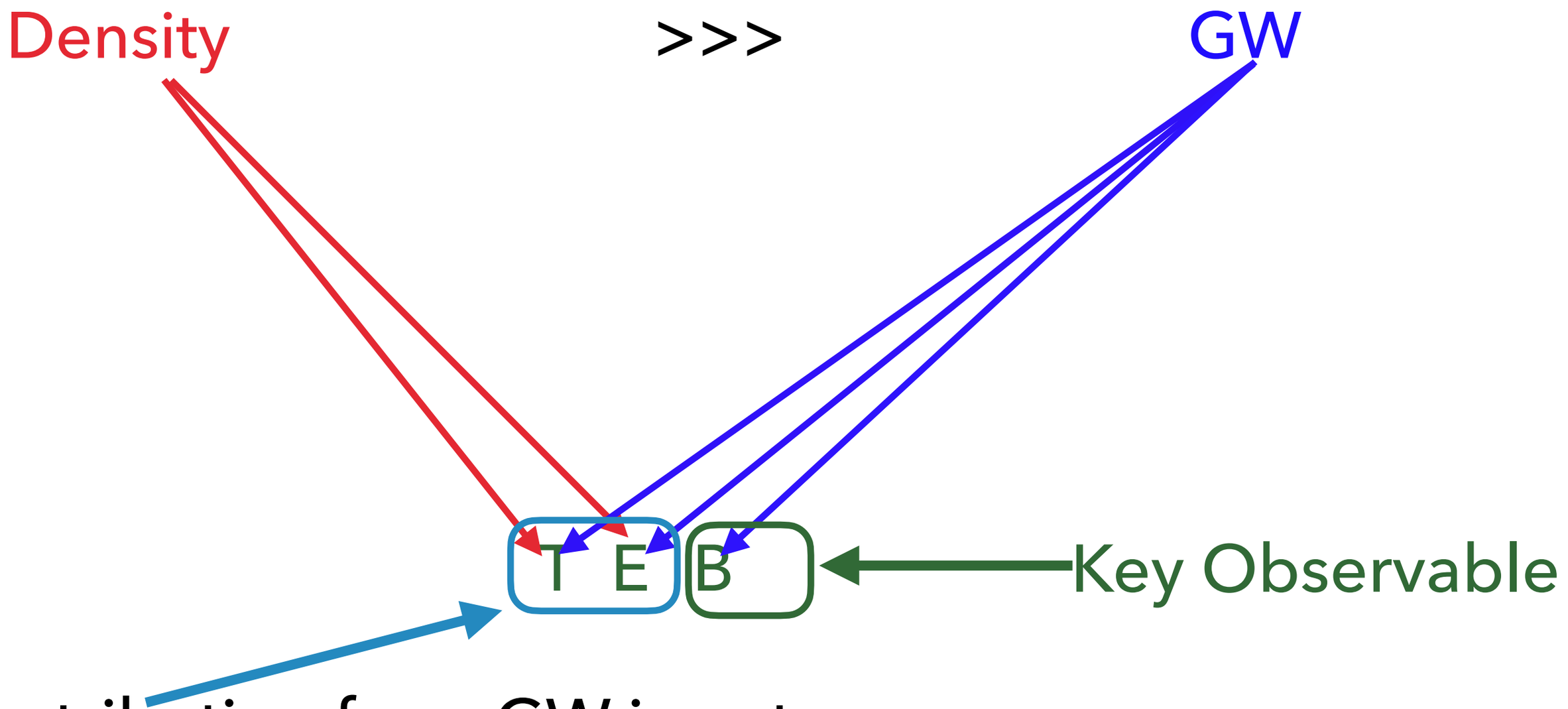
CMB as a Probe to Gravitational Waves

What is the expected strength of the observables?

OBSERVABLES OF DIFFERENT PERTURBATIONS



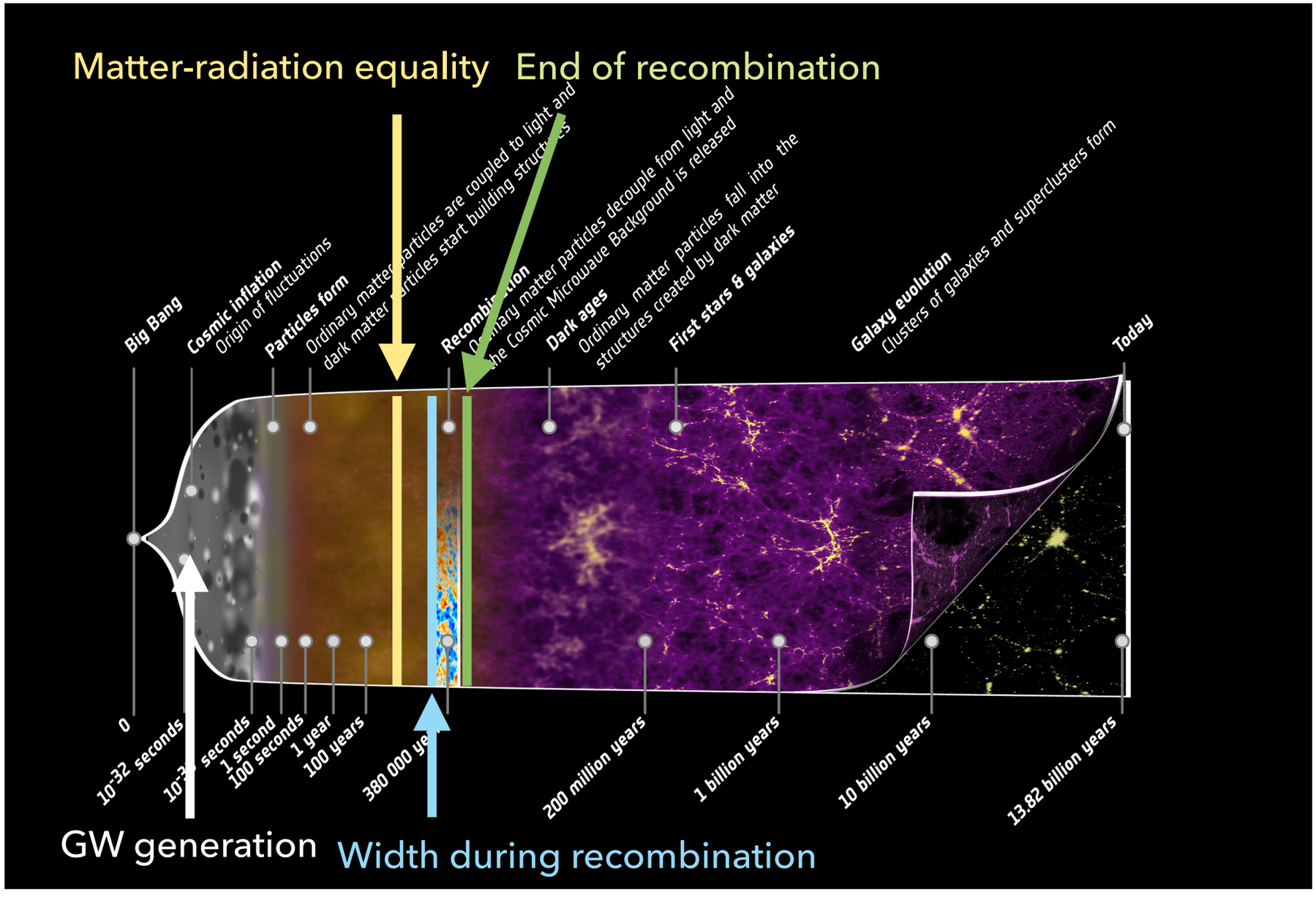
OBSERVABLES OF DIFFERENT PERTURBATIONS



Contribution from GW is not pronounced than density fluctuations

OBSERVABLES OF GW PERTURBATIONS ON B-MODE

Different Cosmic stages



OBSERVABLES OF GW PERTURBATIONS ON B-MODE

Evolution of GW signal in an expanding Universe

$$\ddot{h}_{ij} + 2\frac{\dot{a}}{a}\dot{h}_{ij} + k^2 h_{ij} = 0$$

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tifr

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For modes at horizon entry:

$$a_{\text{enter}} H_{\text{enter}} \propto k \quad \Rightarrow \quad a_{\text{enter}} \propto k^{-2}$$ **for matter-dominated Universe**

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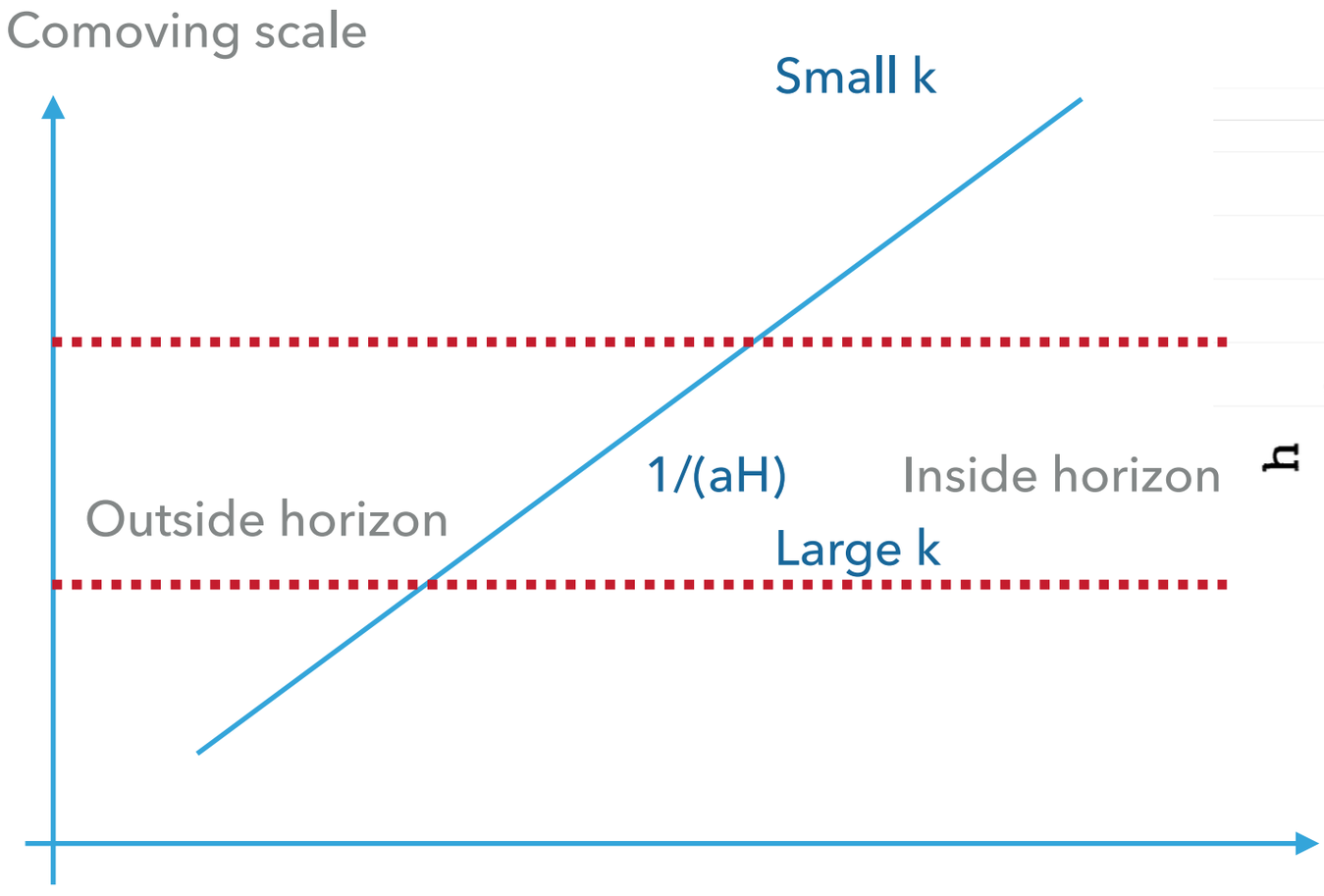
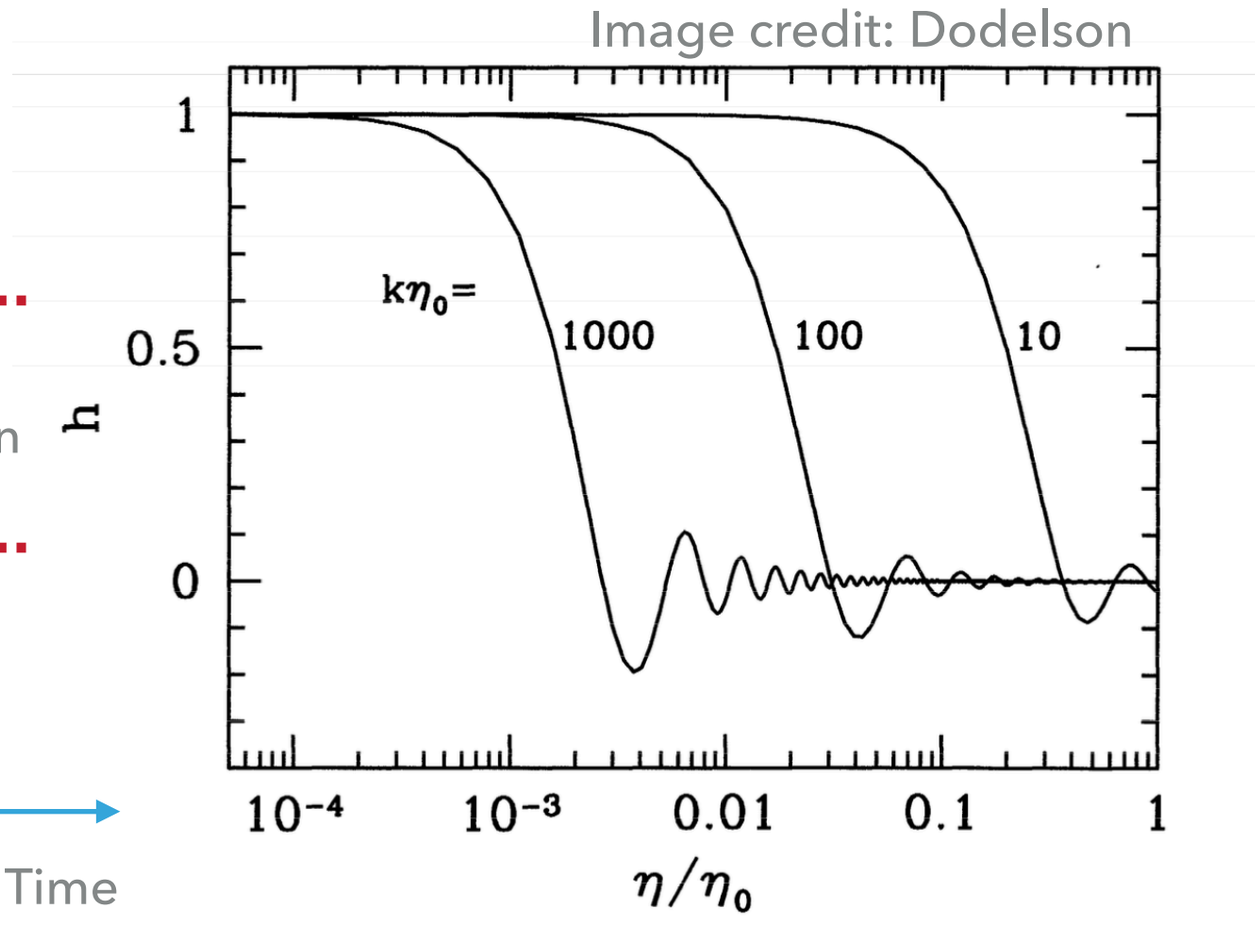
OBSERVABLES OF GW PERTURBATIONS ON B-MODE

Evolution of GW signal in an expanding Universe





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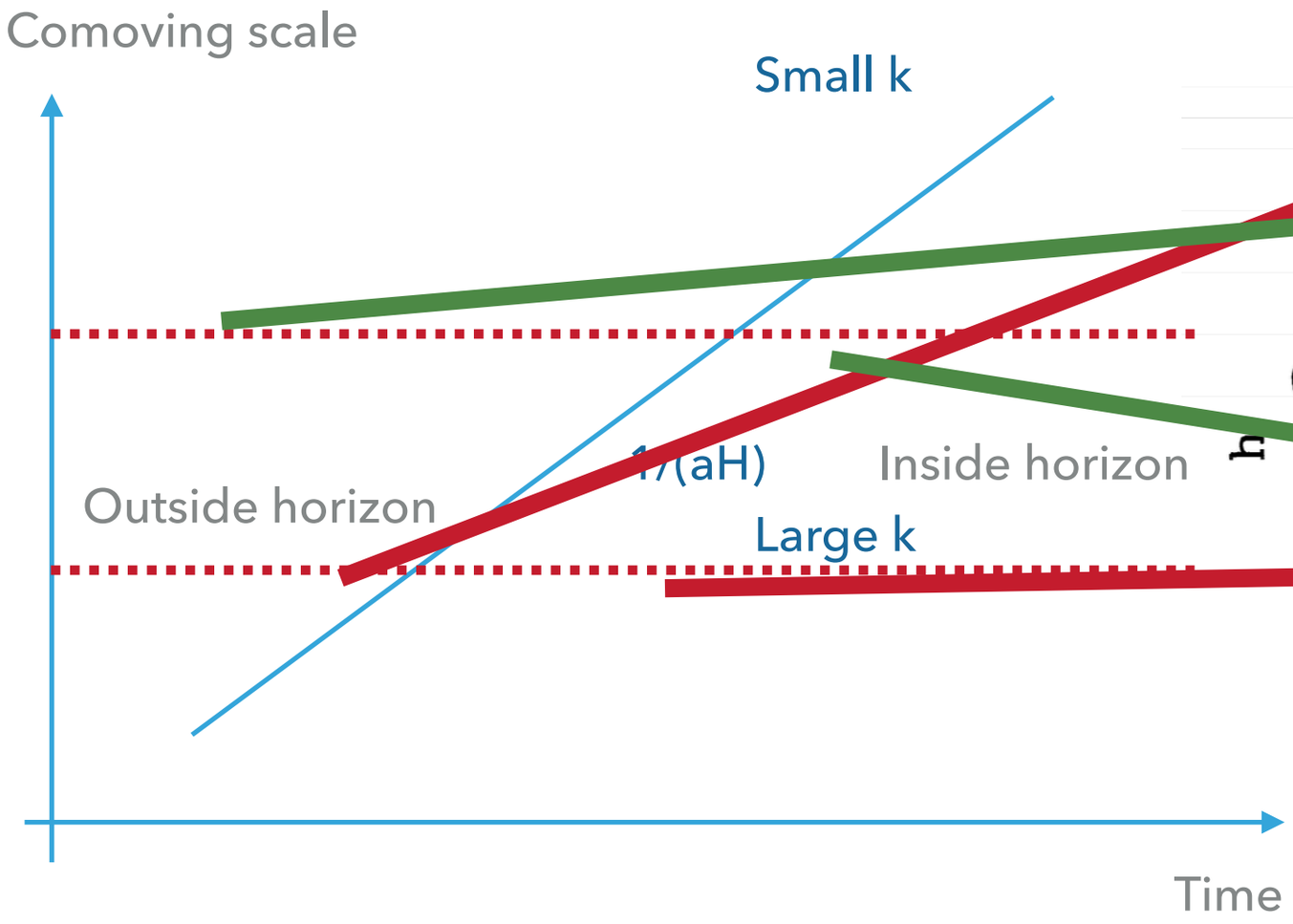
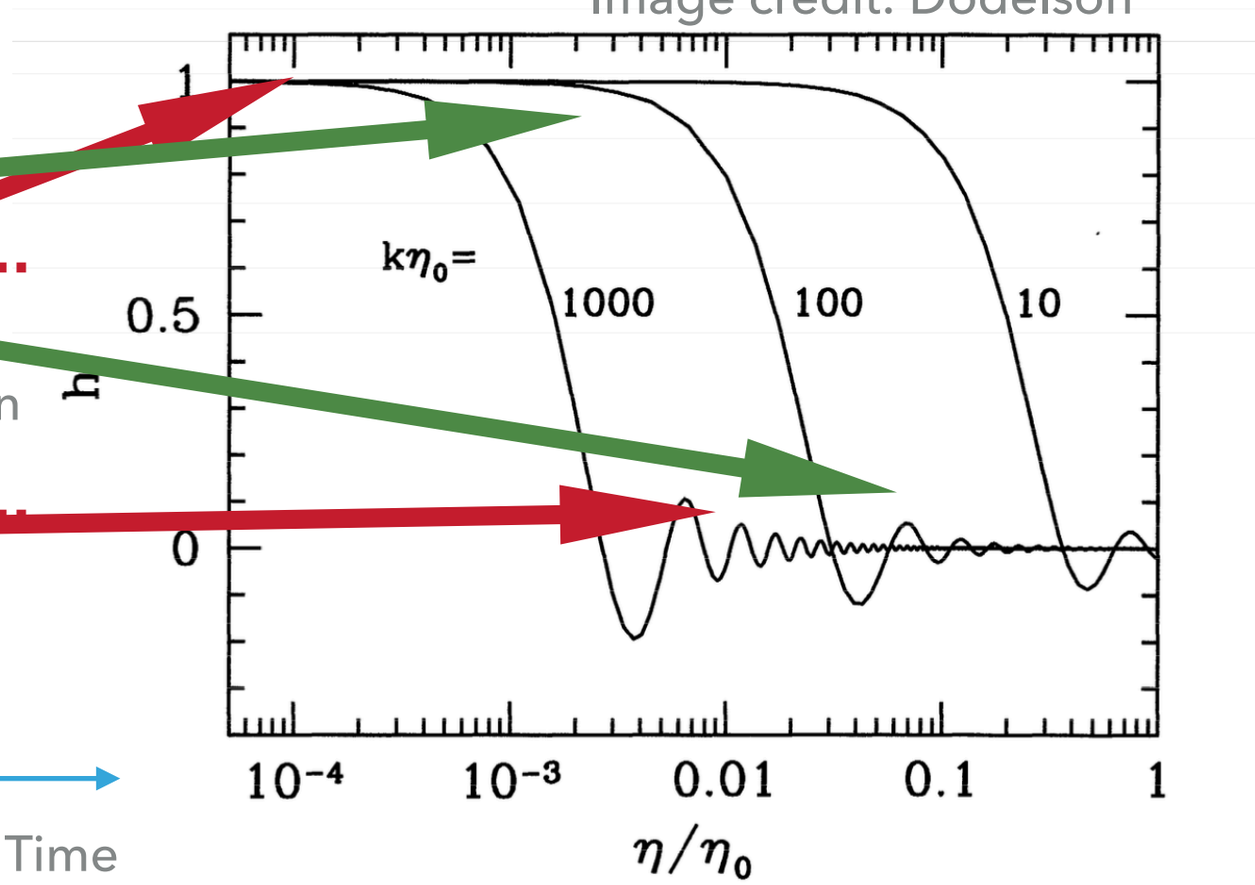


Image credit: Dodelson



OBSERVABLES OF GW PERTURBATIONS ON B-MODE

Signature of evolution on the power spectrum

$$C_{XX'l} = (4\pi)^2 \int k^2 \, \mathrm{d}k \, P_h(k) \, \Delta_{Xl}(k) \, \Delta_{X'l}(k)$$

Evolution of the modes

Initial GW fluctuation

$$\ell \propto k$$

Angular Modes ⟷ Fourier Modes

tifr

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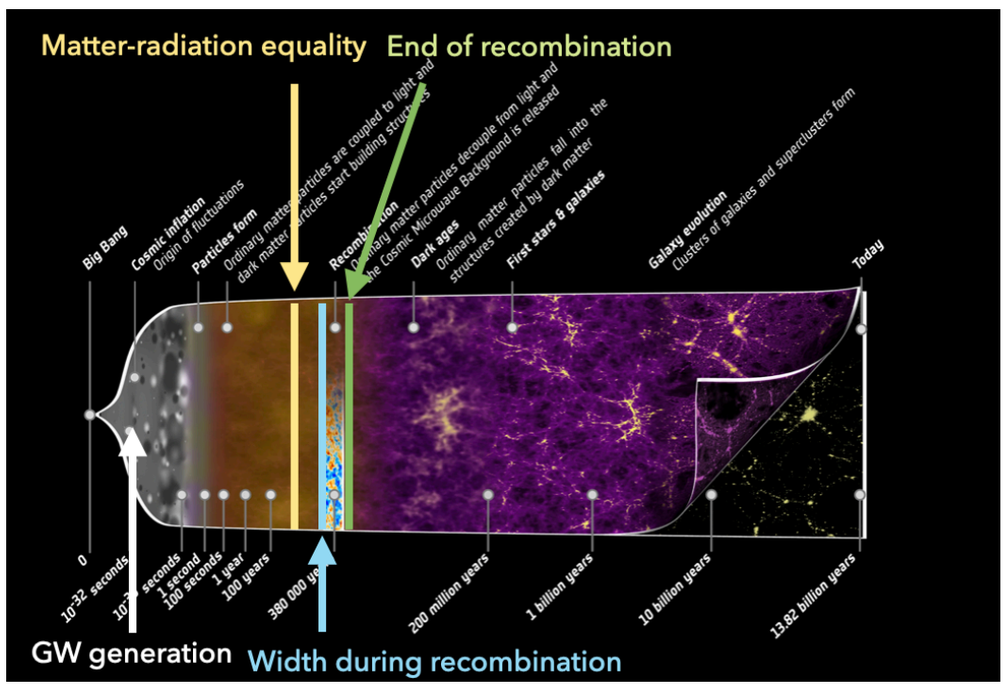

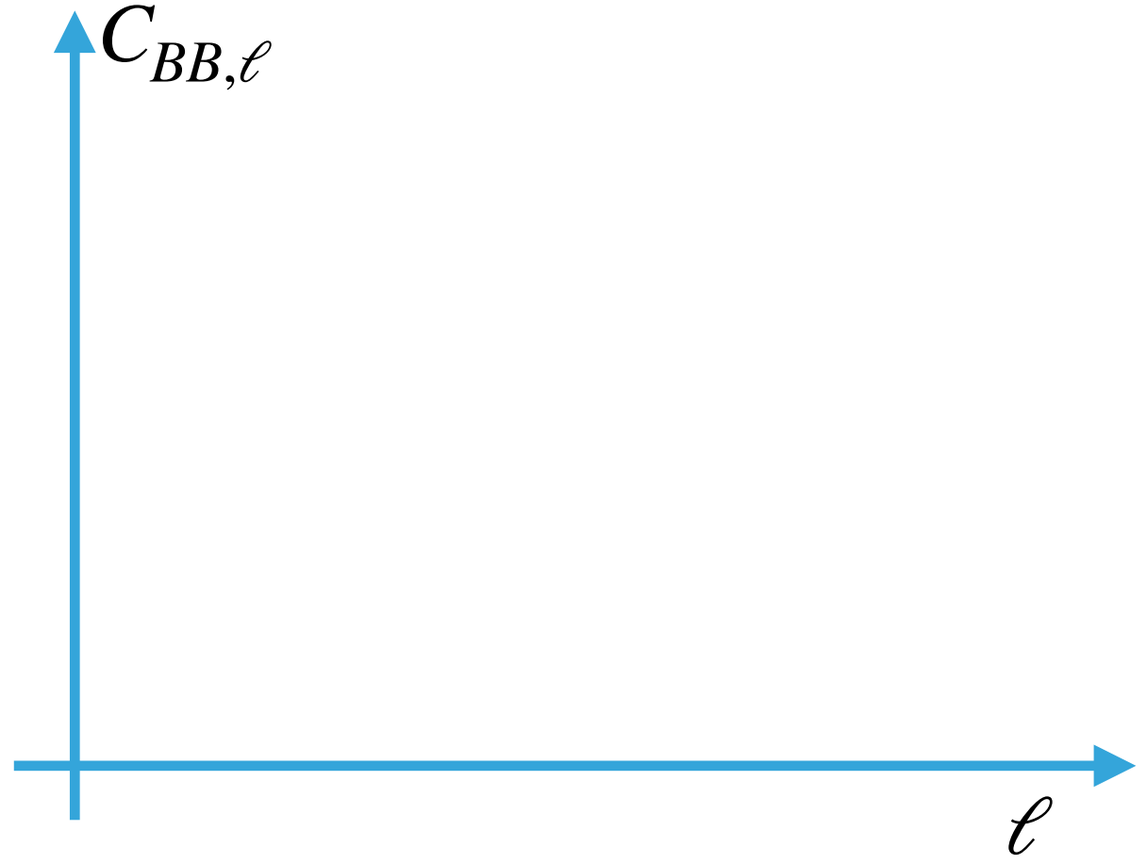

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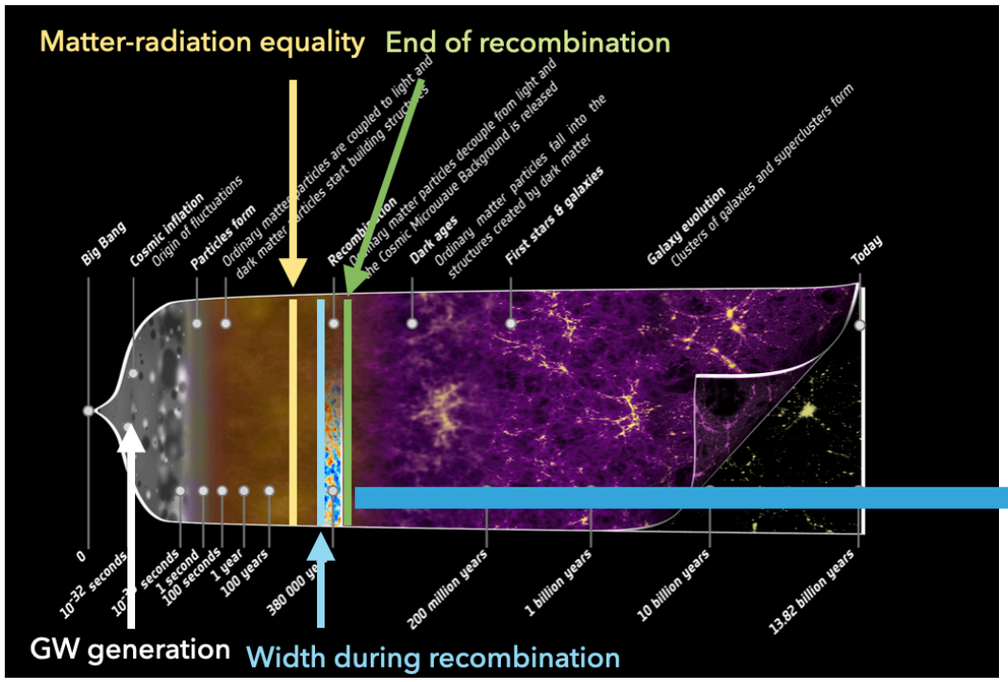

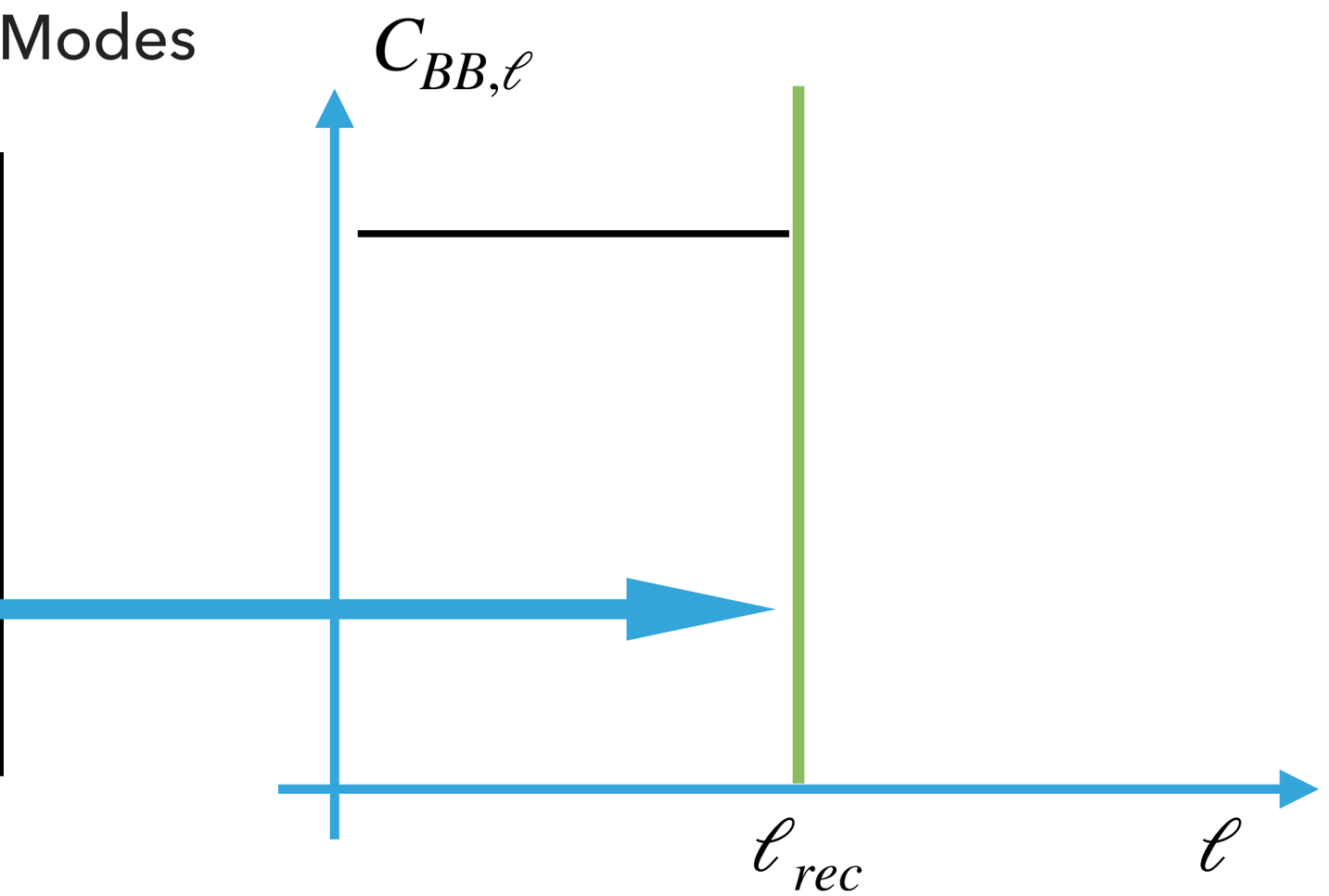

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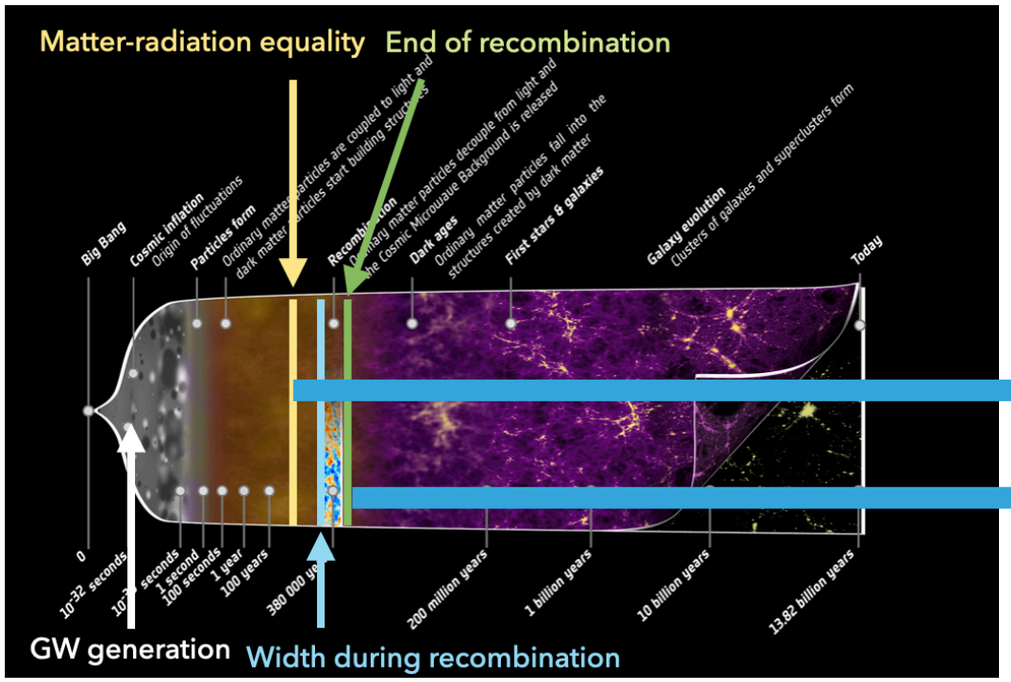

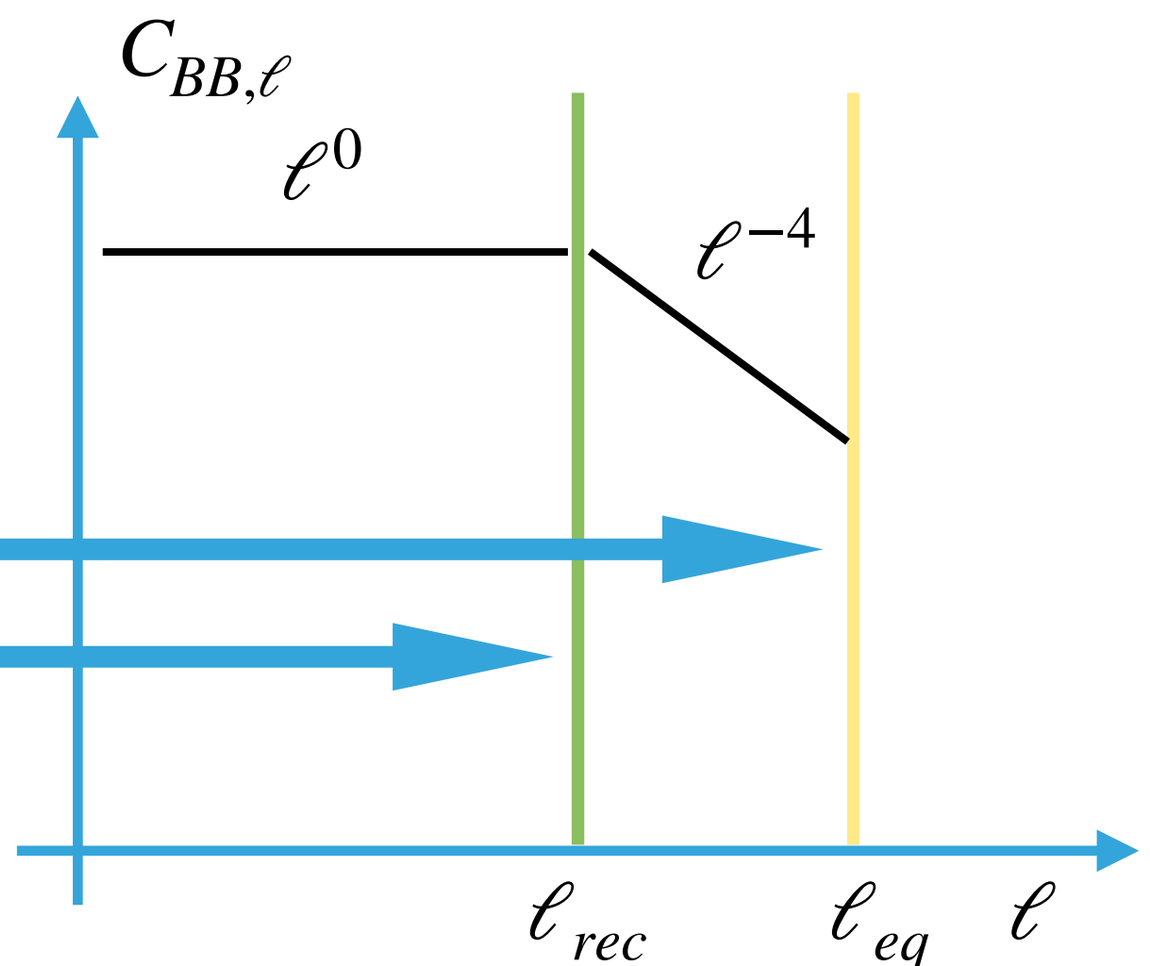

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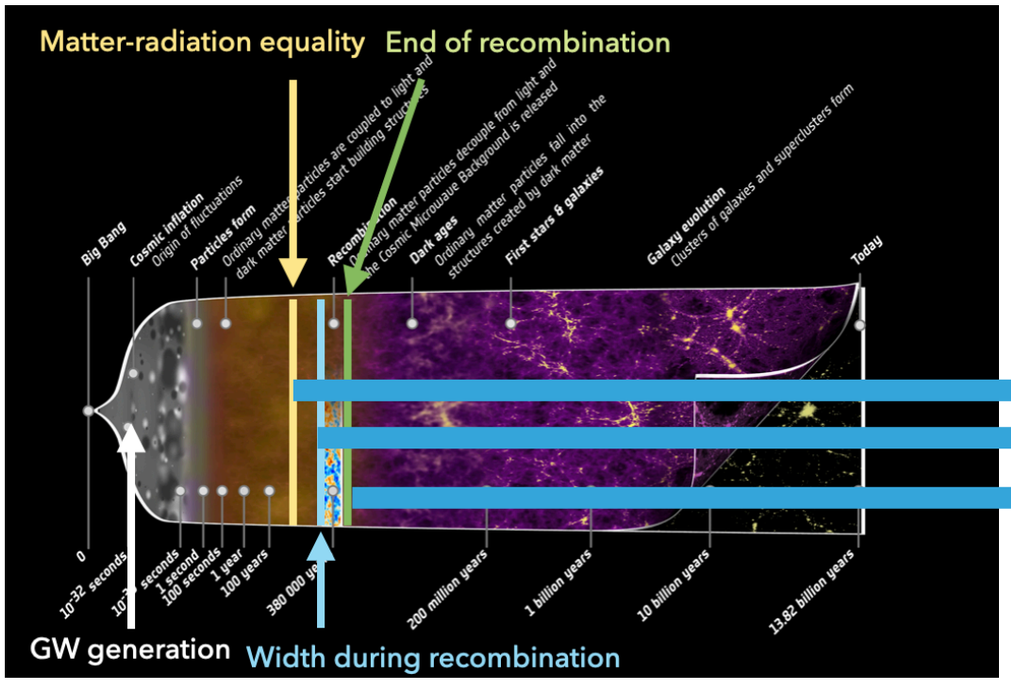

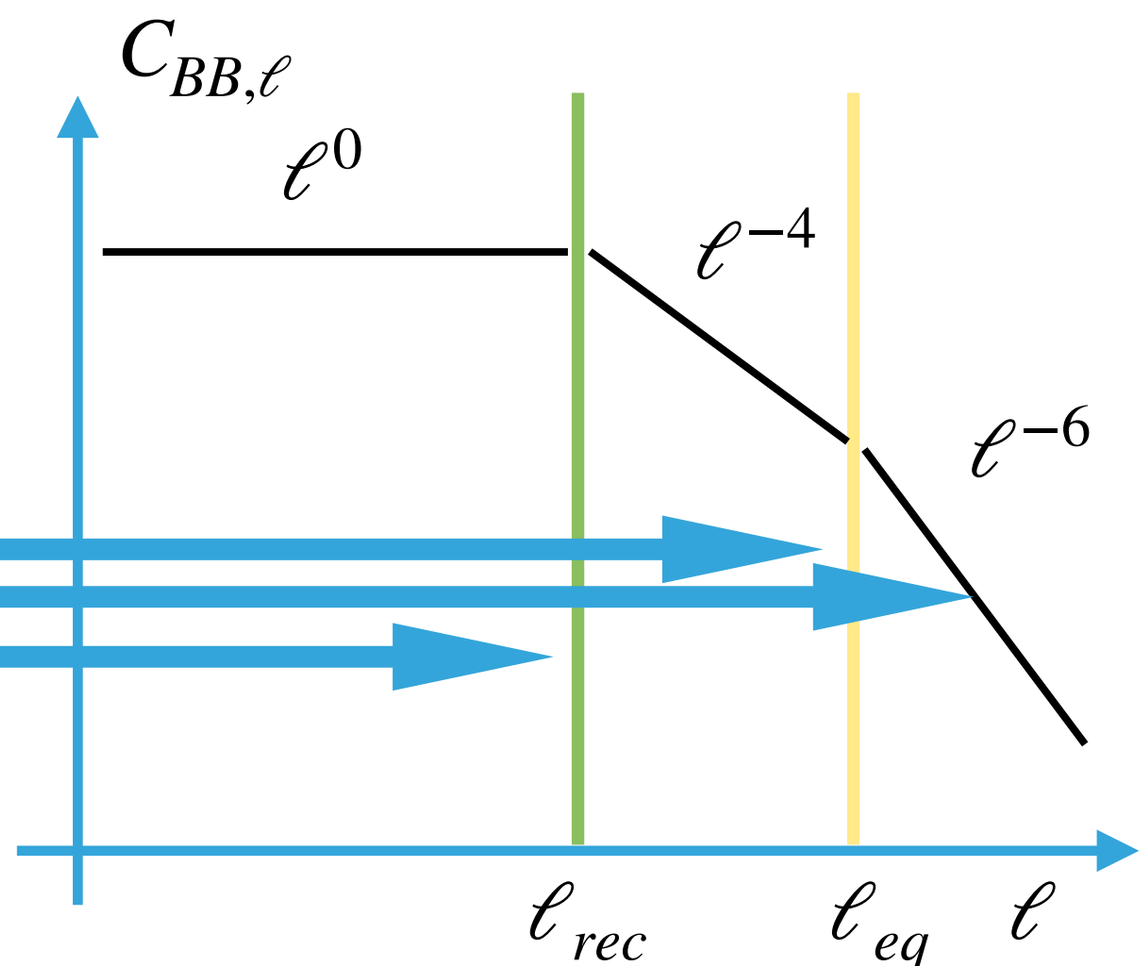

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OBSERVABLES OF GW PERTURBATIONS ON B-MODE

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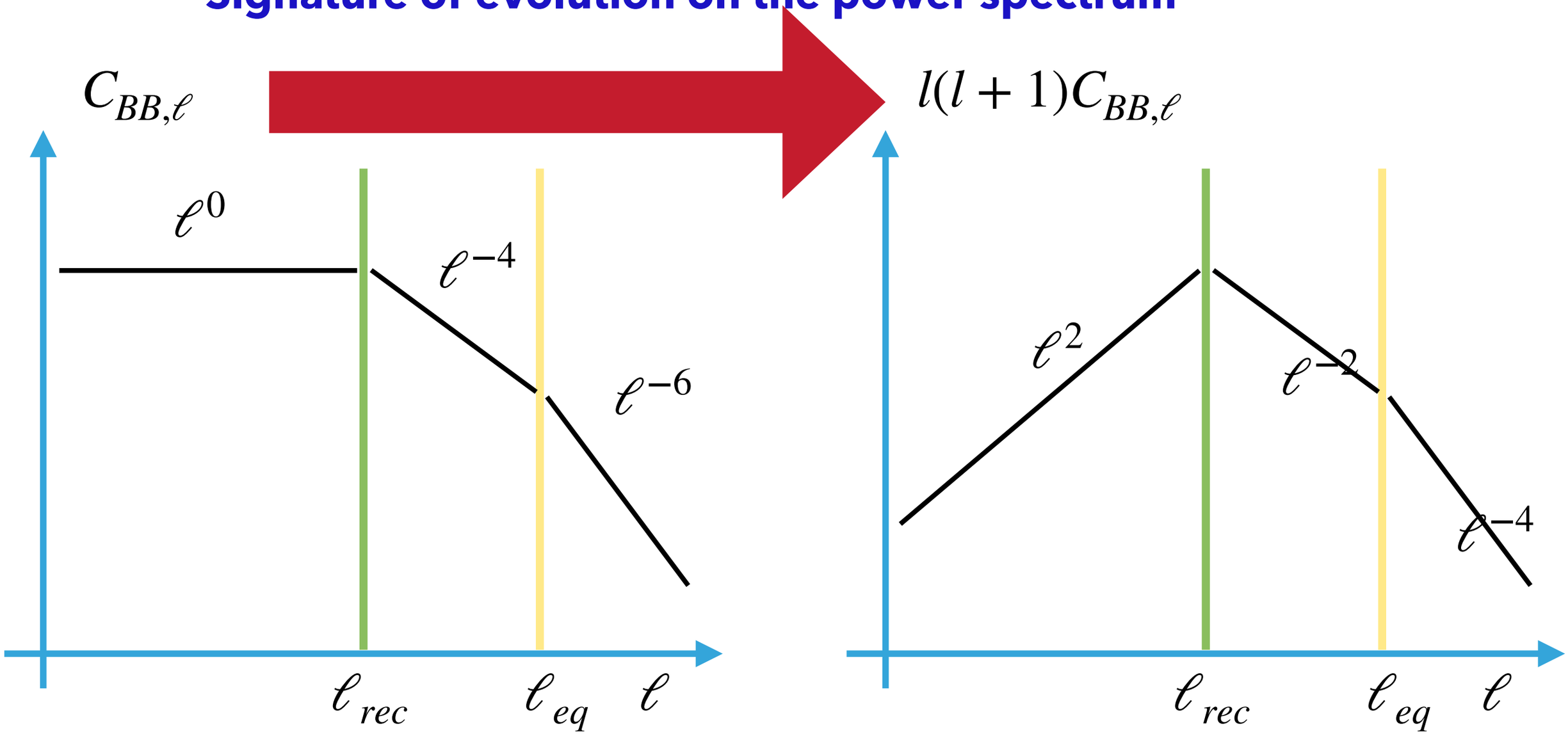

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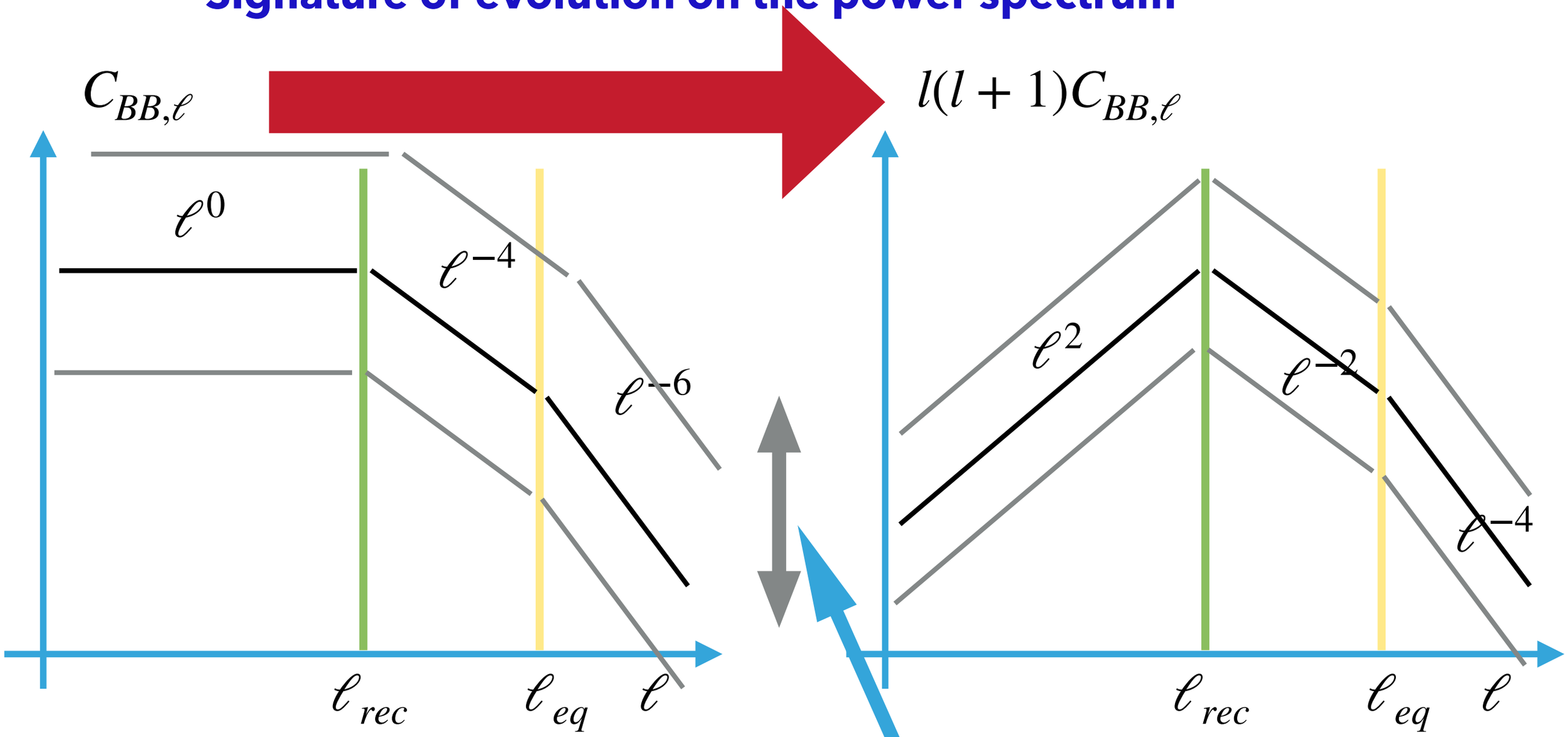

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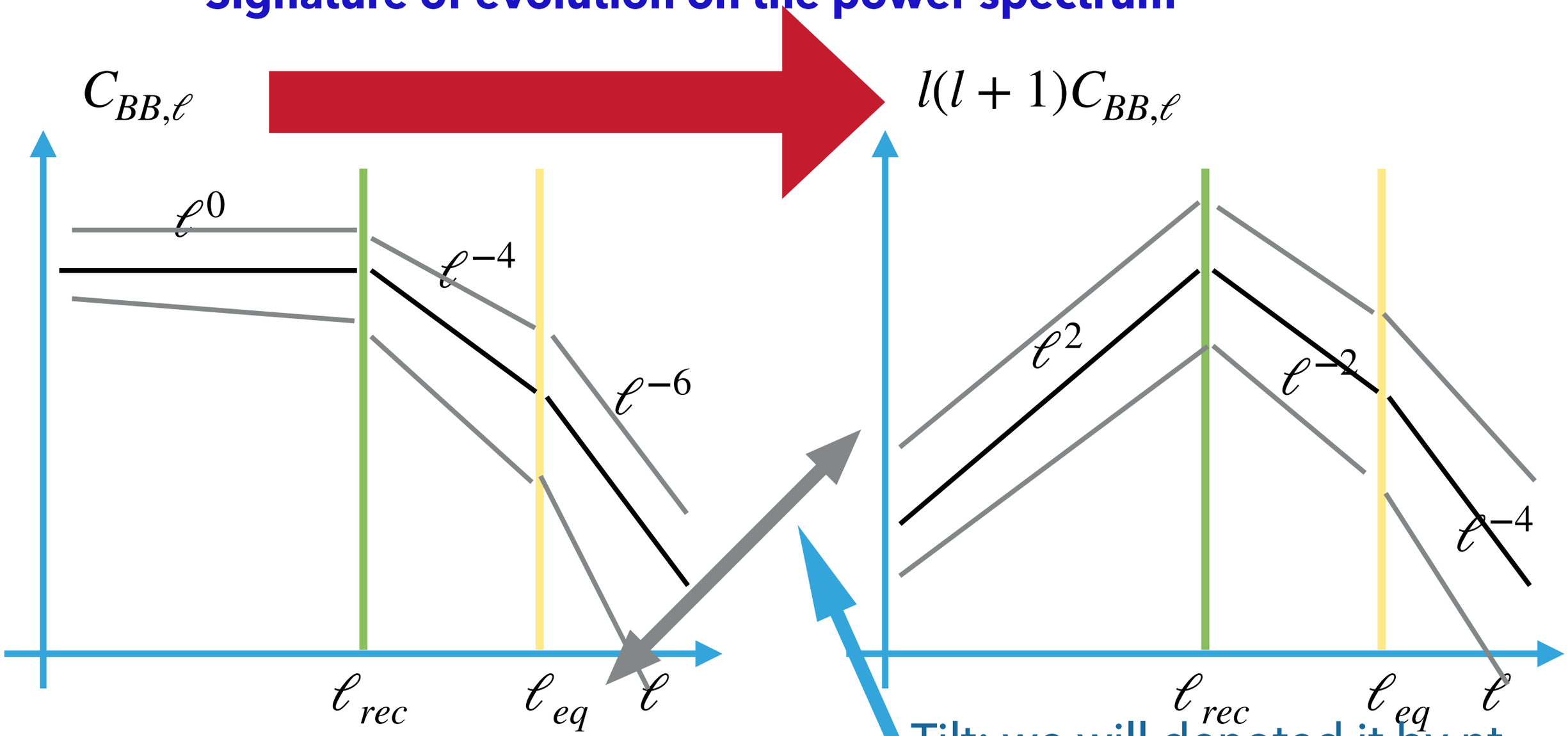

Tilt: we will denoted it by nt

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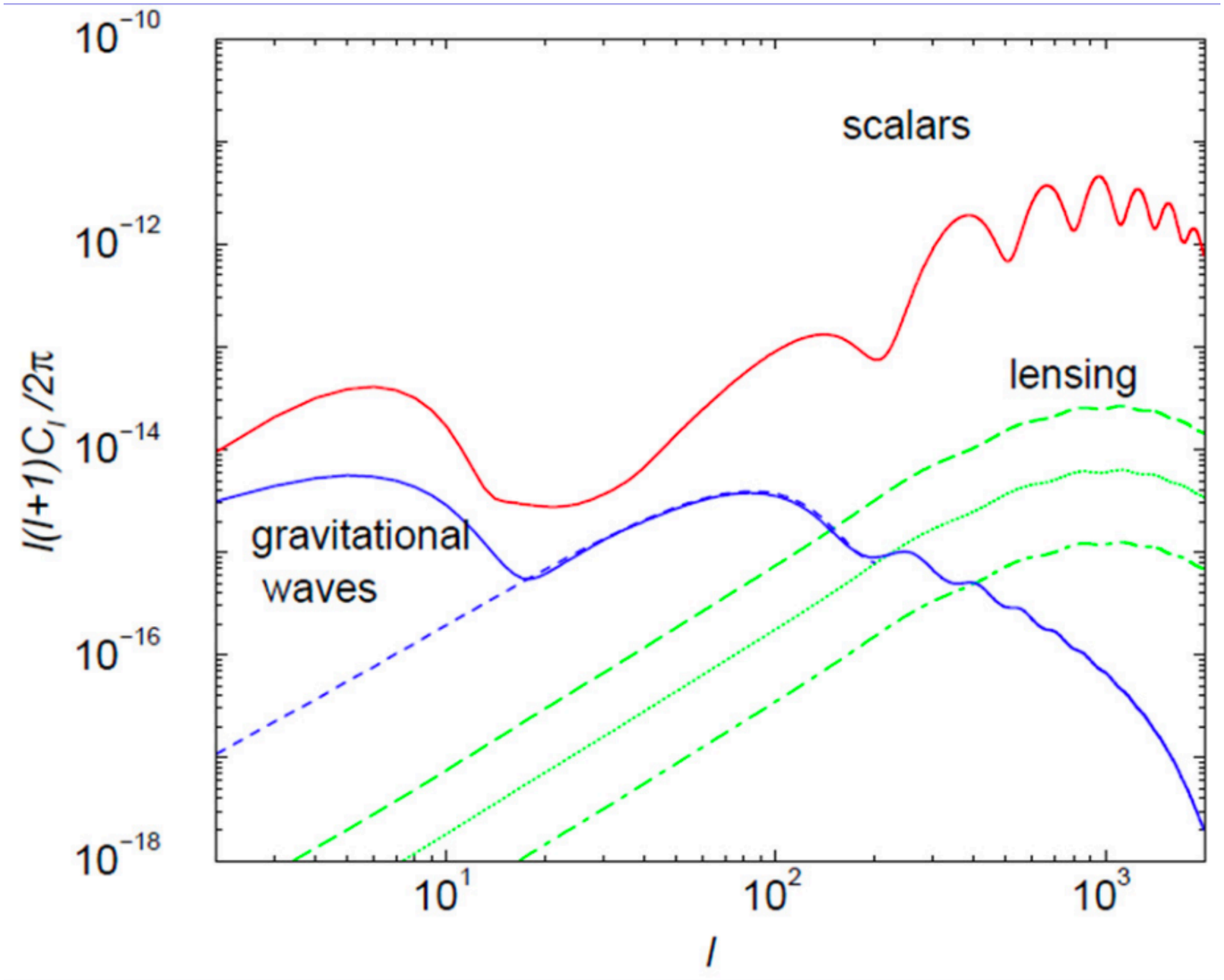
OBSERVABLES OF GW PERTURBATIONS ON B-MODE

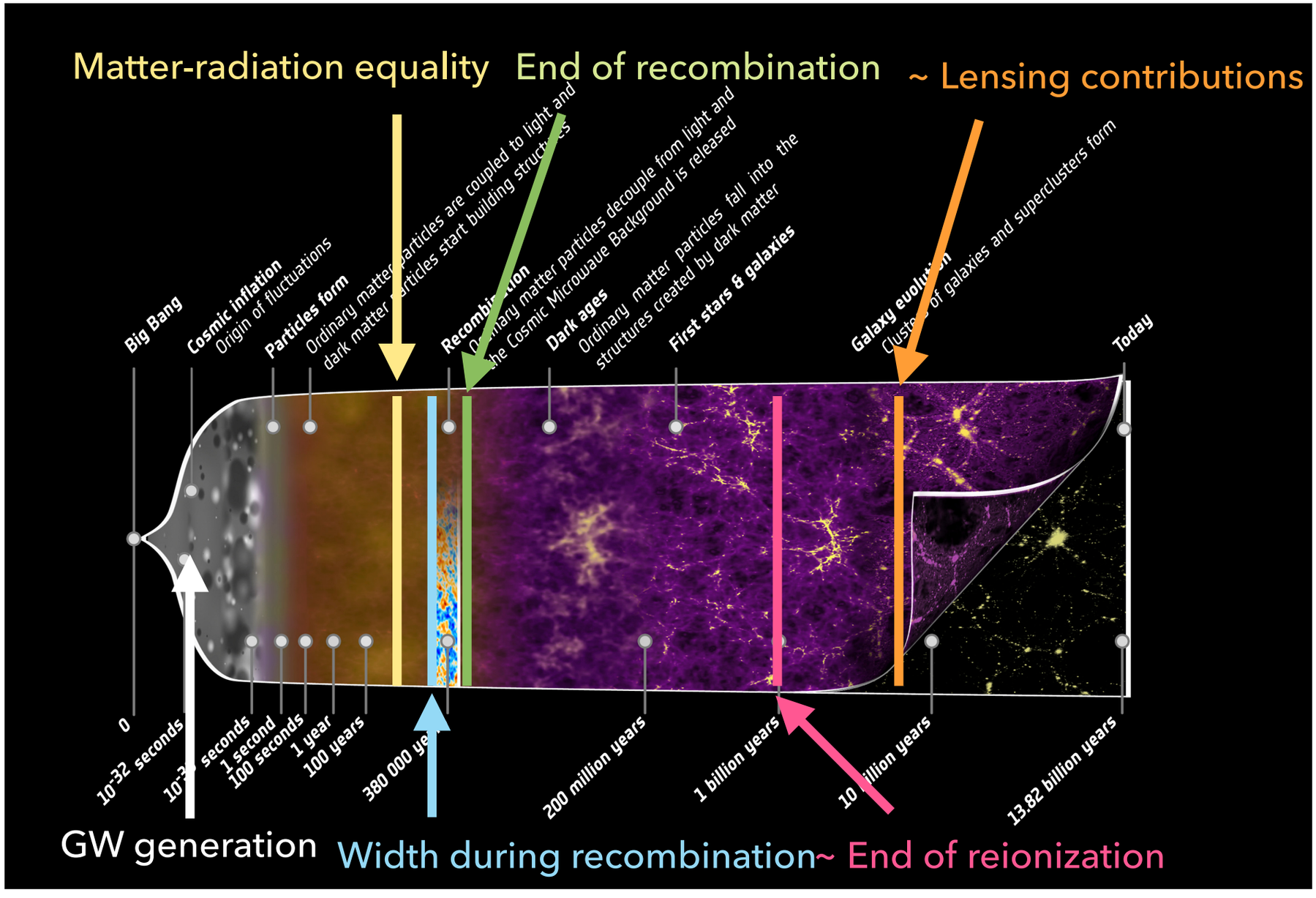
From numerical code

Lewis and Challinor 2006



OBSERVABLES OF GW PERTURBATIONS ON B-MODE

Different Cosmic stages



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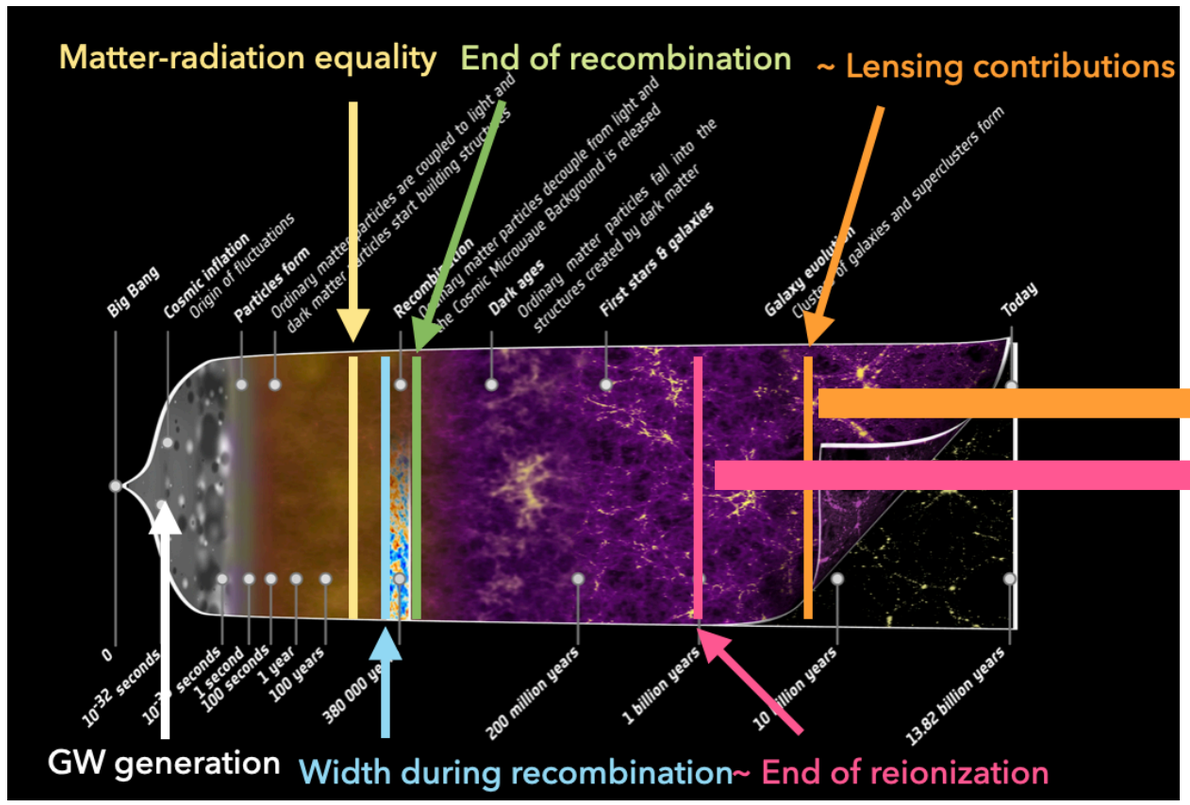

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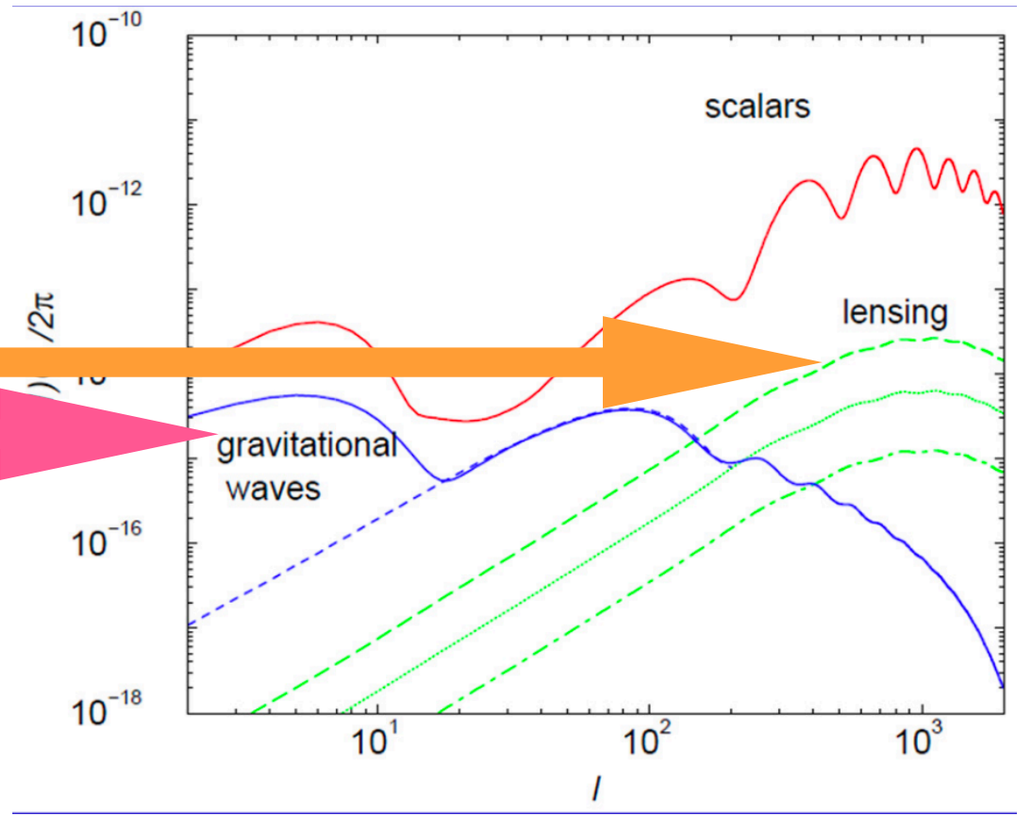
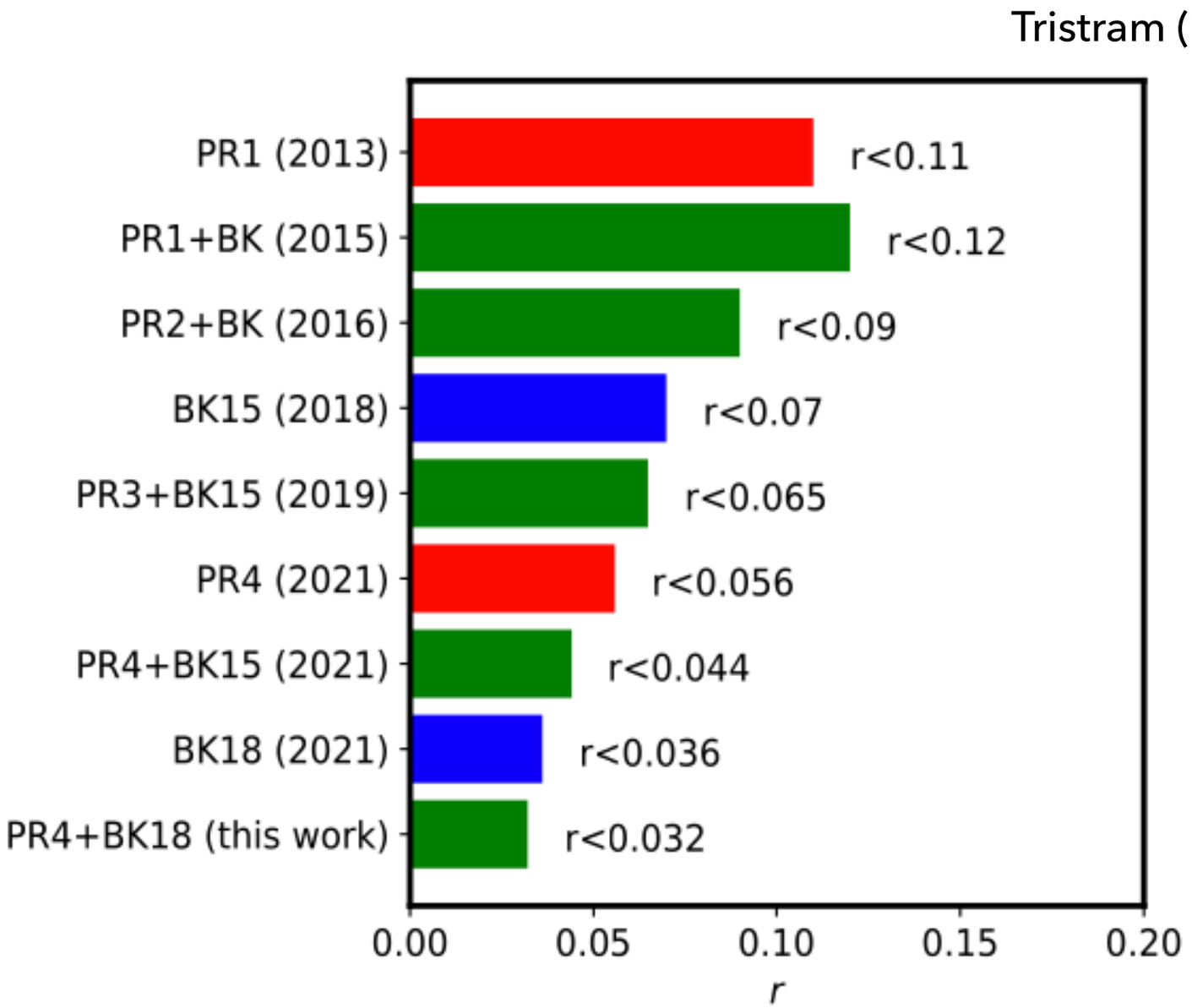


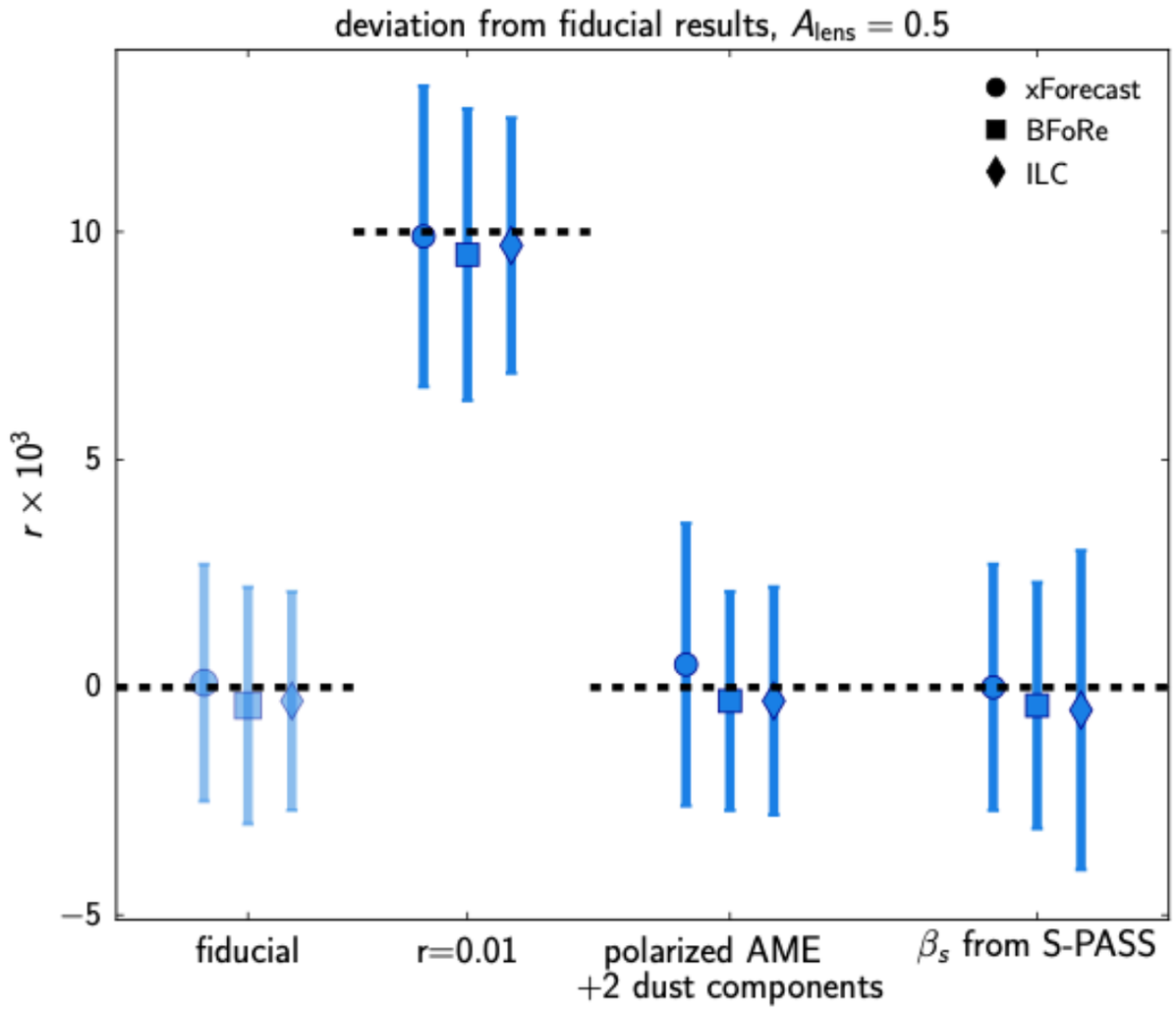
CMB as a Probe to Gravitational Waves

What is the prospect of detection?

What is the current status?: Upper Bound



Future Prospects: Simons Observatory



Simons Observatory Collaboration

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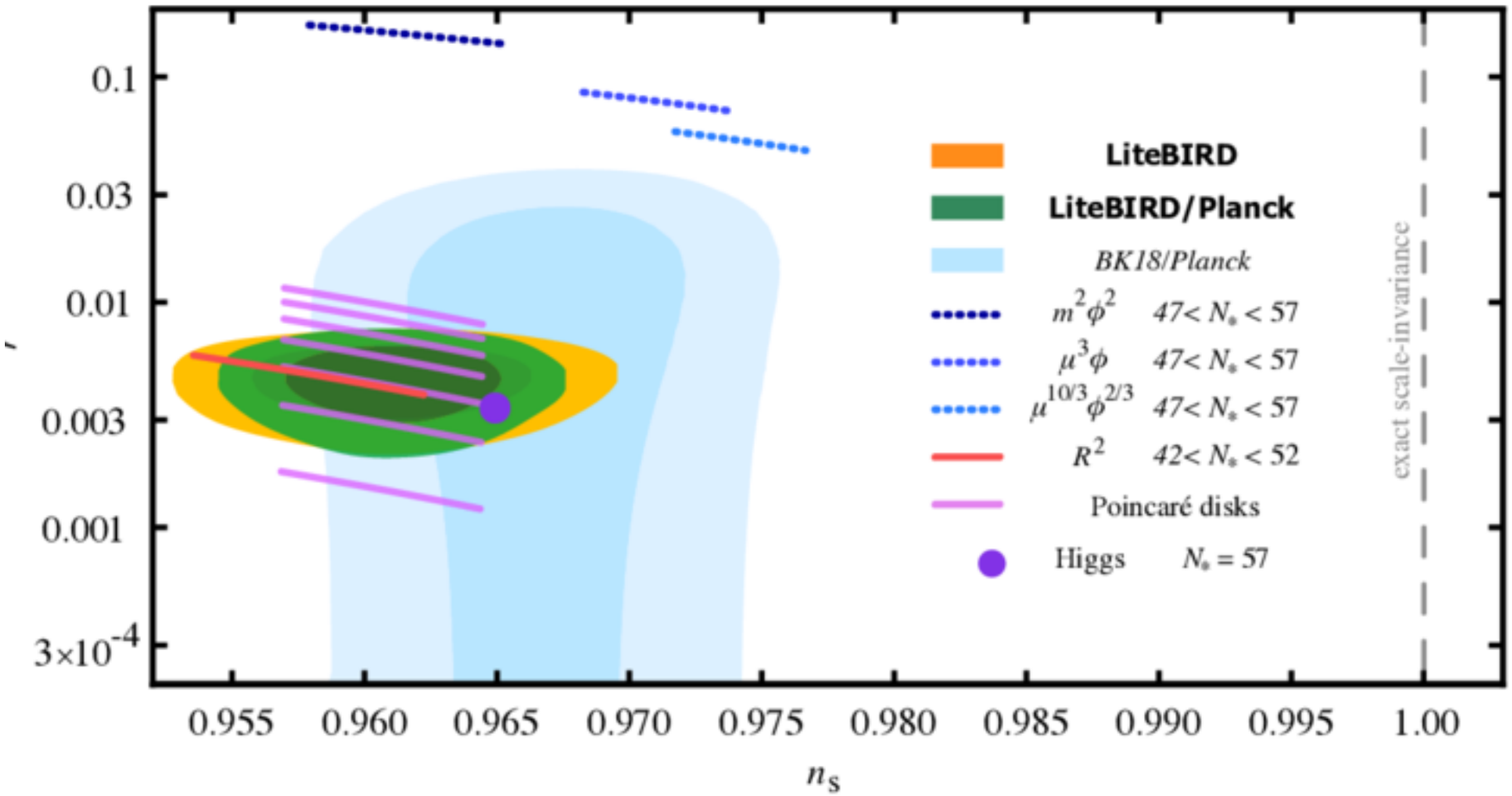
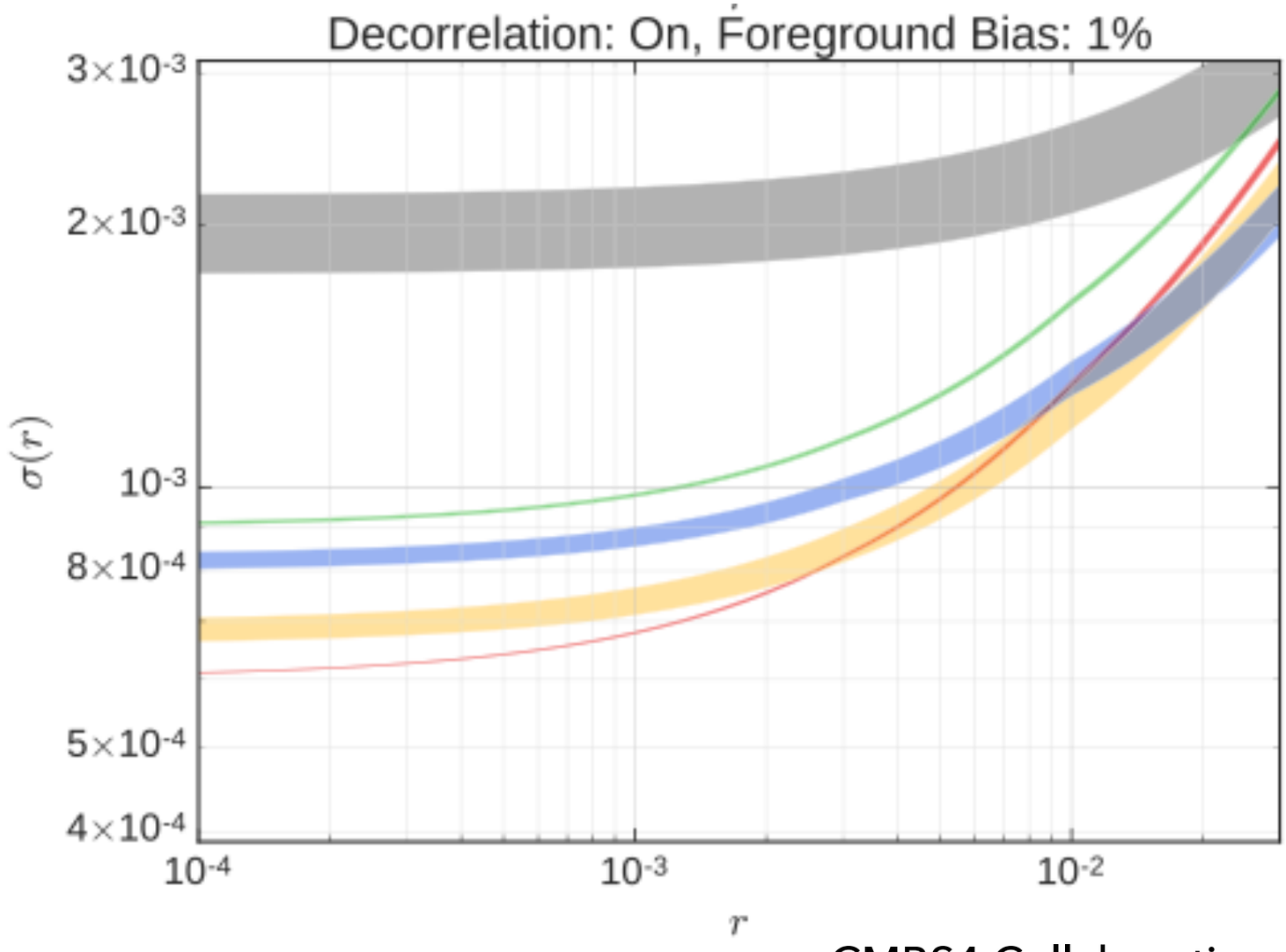
Future Prospects: LiteBIRD



LiteBIRD Collaboration

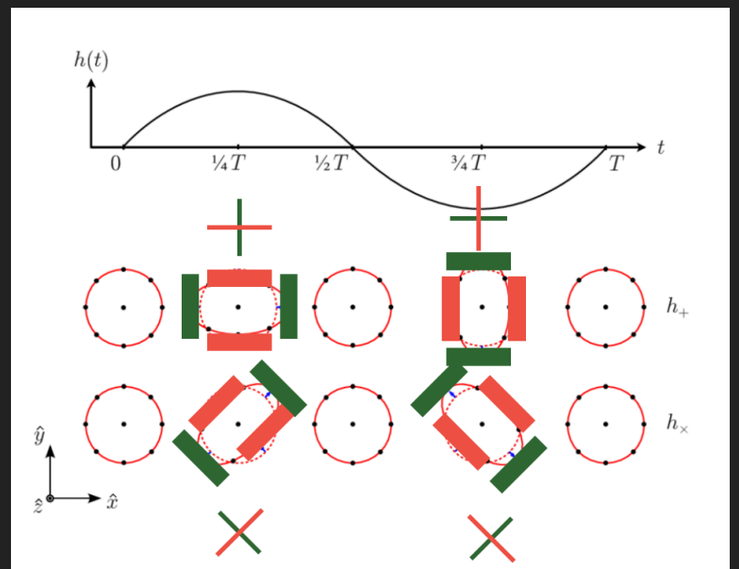
Future Prospects: CMB-S4



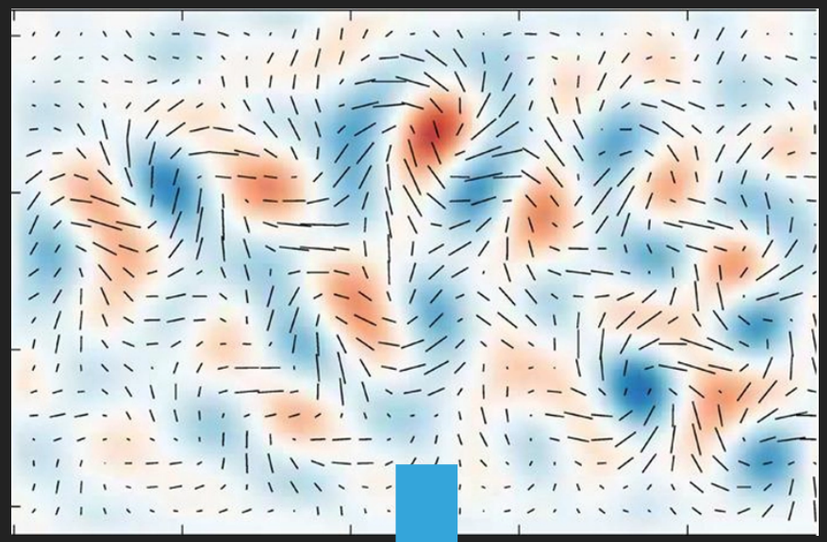
CMBS4 Collaboration

CMB B-MODE TO DETECT LOW FREQUENCY GW SIGNAL

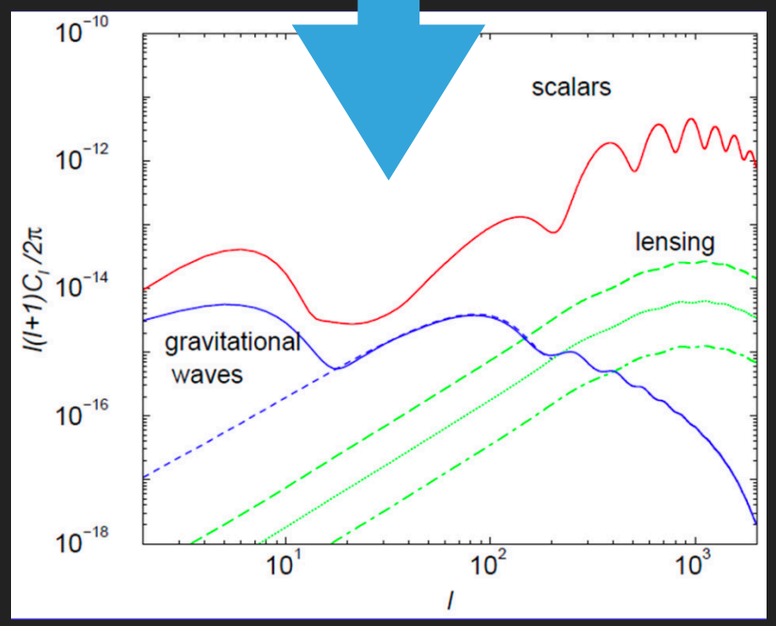
Interaction



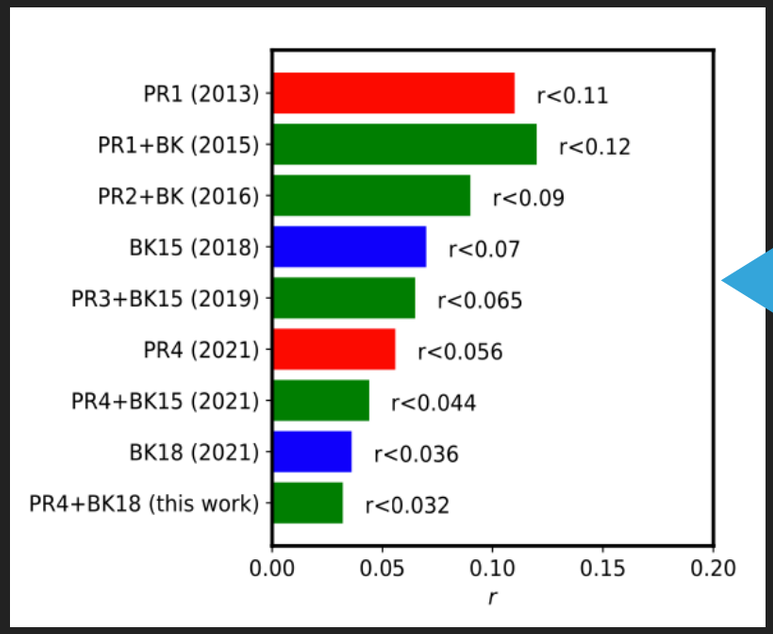
Observable



Expected strength



Prospects



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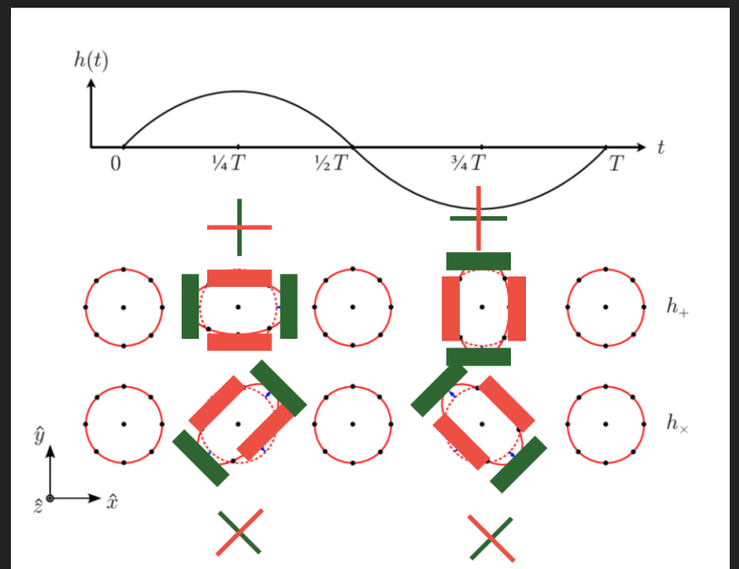

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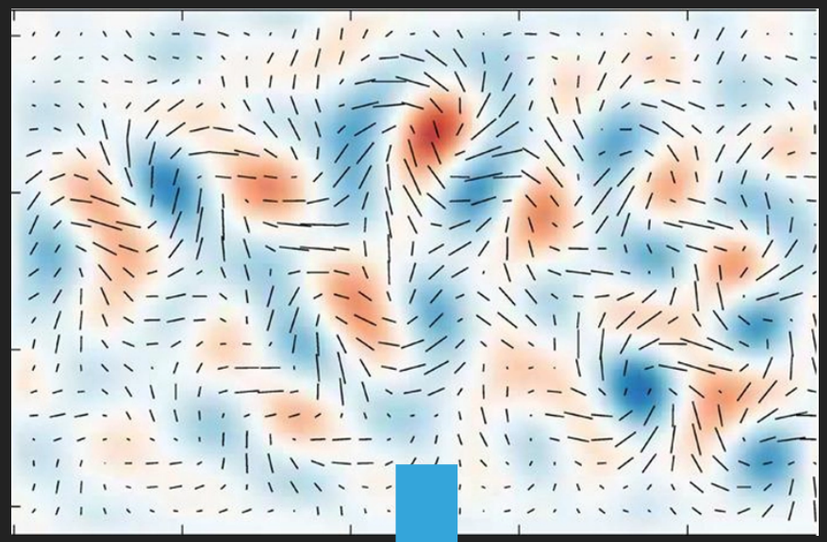

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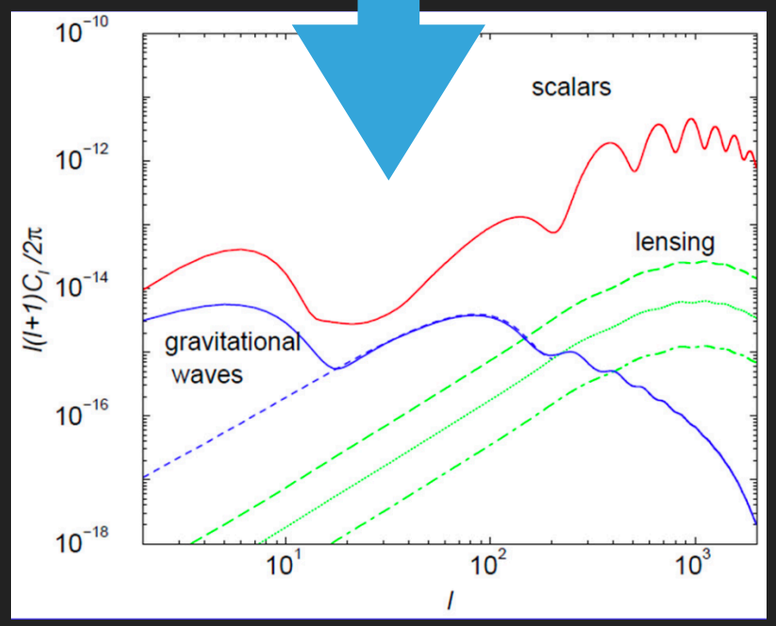
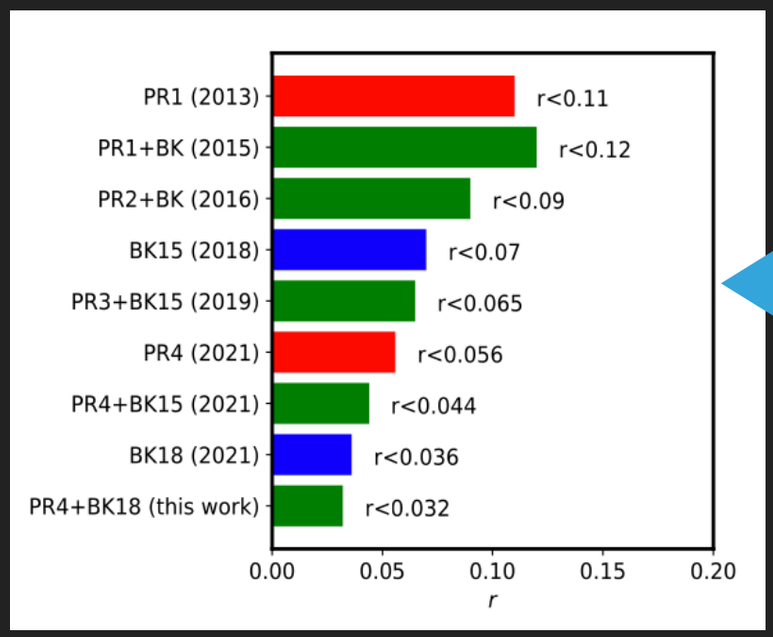


Challenges

Prospects



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CMB B-MODE TO DETECT LOW FREQUENCY GW SIGNAL

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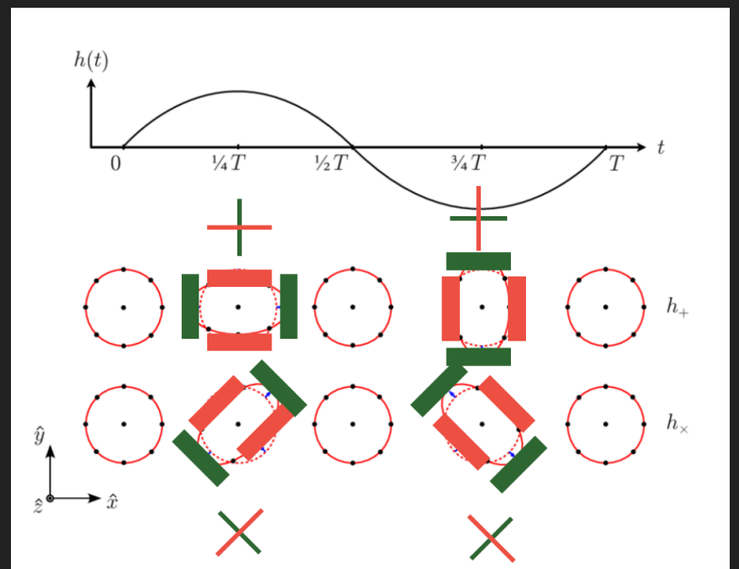
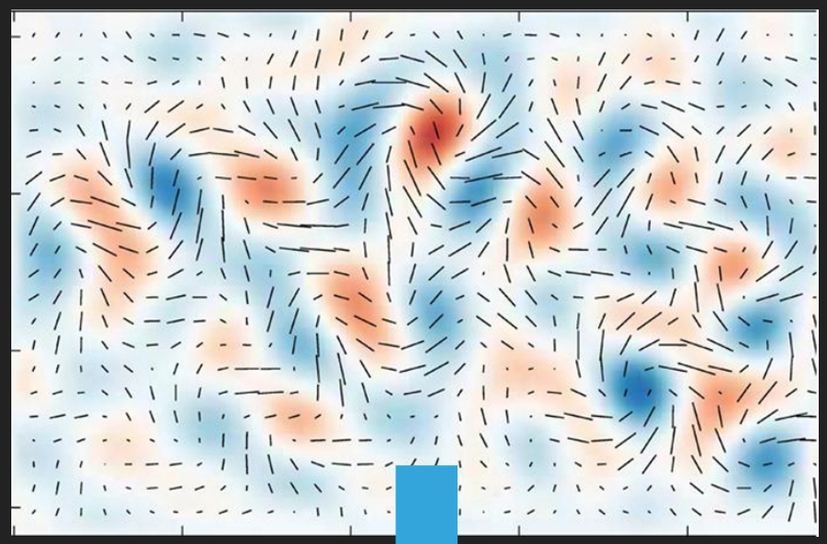
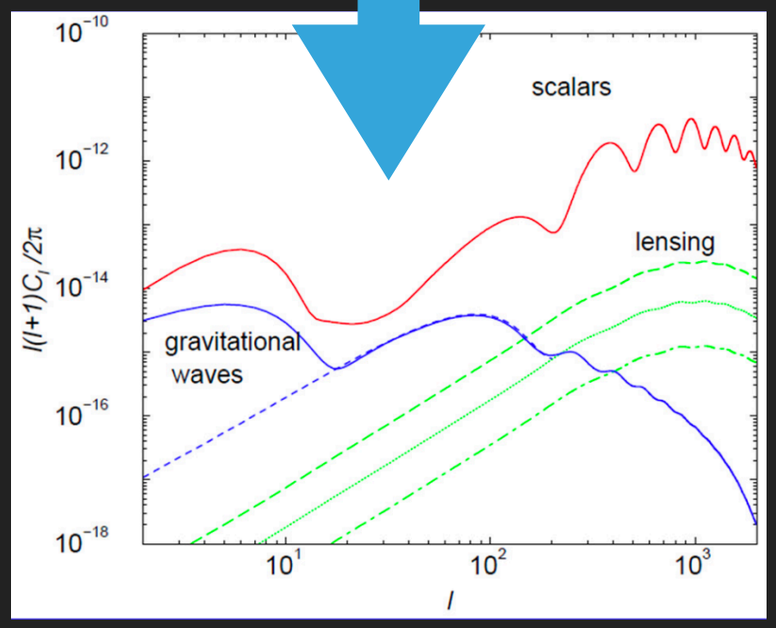


Observable



Expected strength



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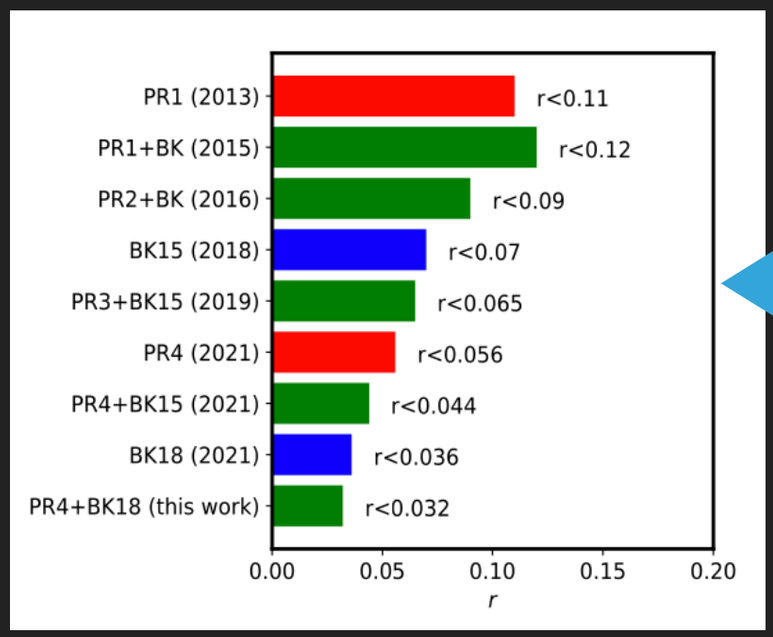

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REFERENCES (A PARTIAL LIST)

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2. Crittenden, Davis, Steinhardt, 1993
3. Atrio-Barandela and Silk, 1993
4. Pritchard and Kamionkowski, 2005
5. Modern Cosmology, Dodelson
6. Cosmology, Weinberg