

“Universe in Fiore”

Cupola Fiore – Osservatorio Astronomico di Brera

Universe Primordiale e Inflazione

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INAF-IASF Milano

14 Febbraio 2018

Il cielo stellato



© Kiko Fairbairn

La Via Lattea: un fiume di stelle in cielo

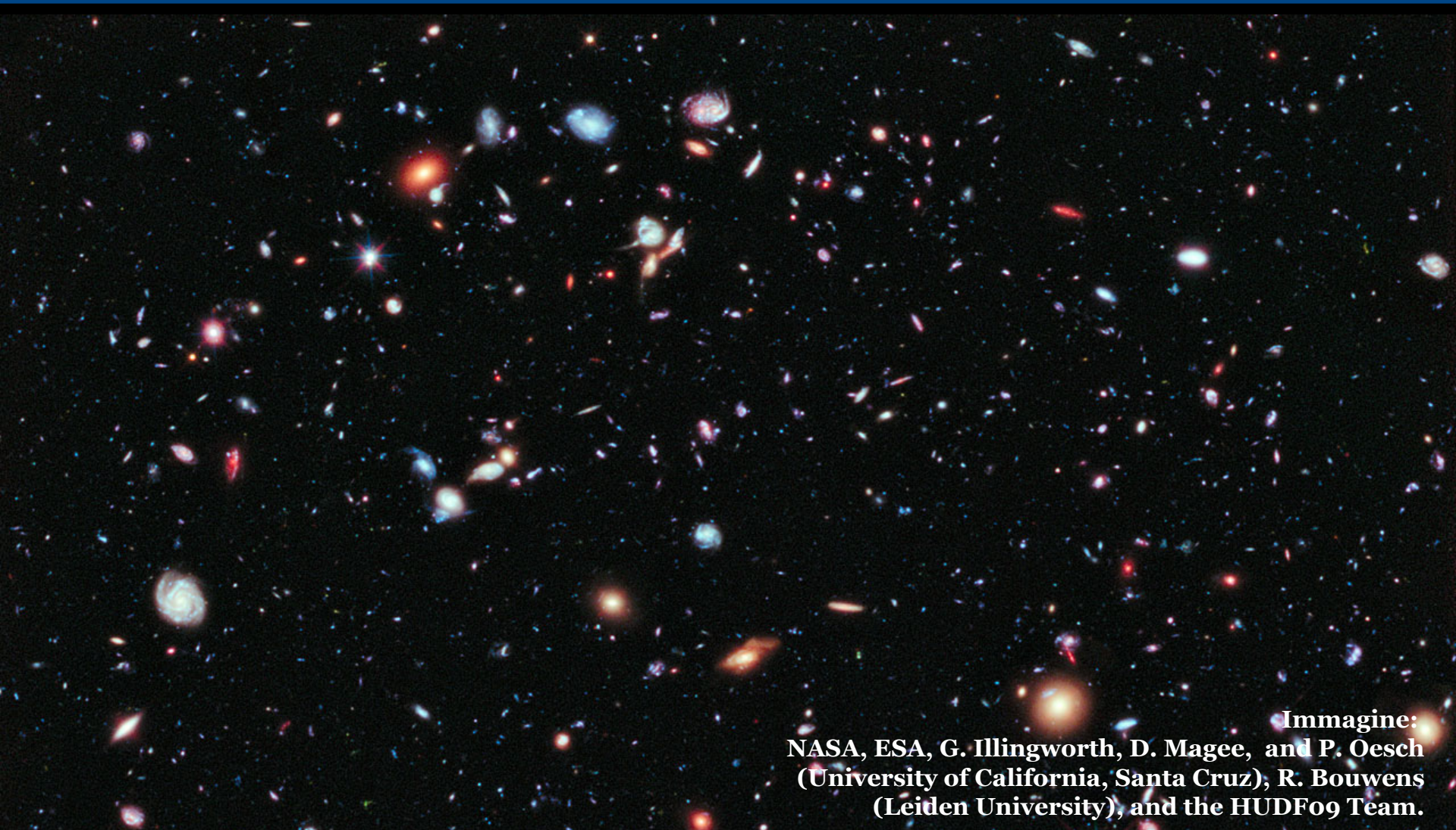
La galassia di Andromeda



Immagine: www.extremeinstability.com

M31 e la Via Lattea fanno parte di un gruppo di 35 galassie: il “Gruppo Locale”.

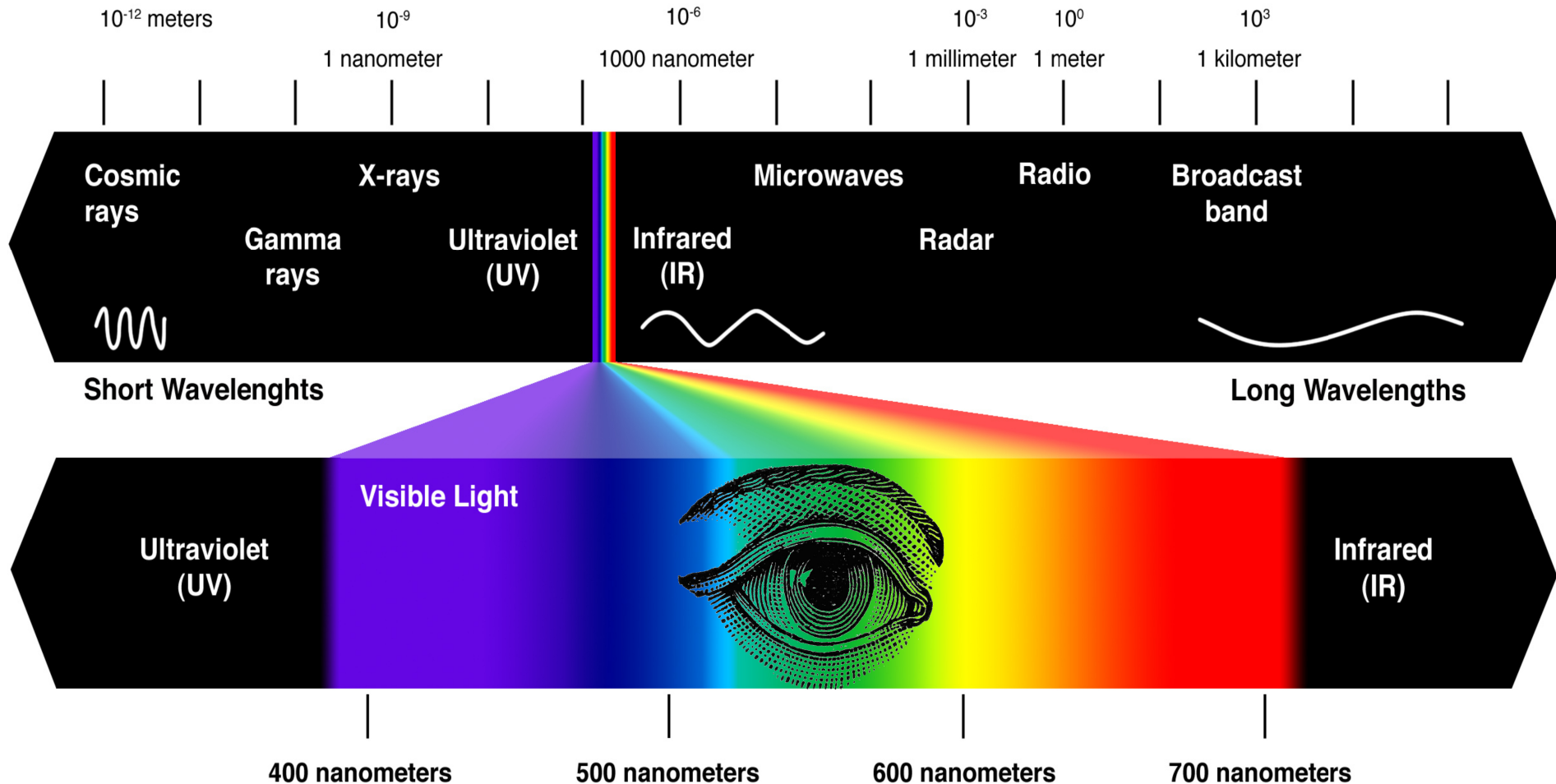
Miliardi di Galassie



Imagine:
NASA, ESA, G. Illingworth, D. Magee, and P. Oesch
(University of California, Santa Cruz), R. Bouwens
(Leiden University), and the HUDF09 Team.

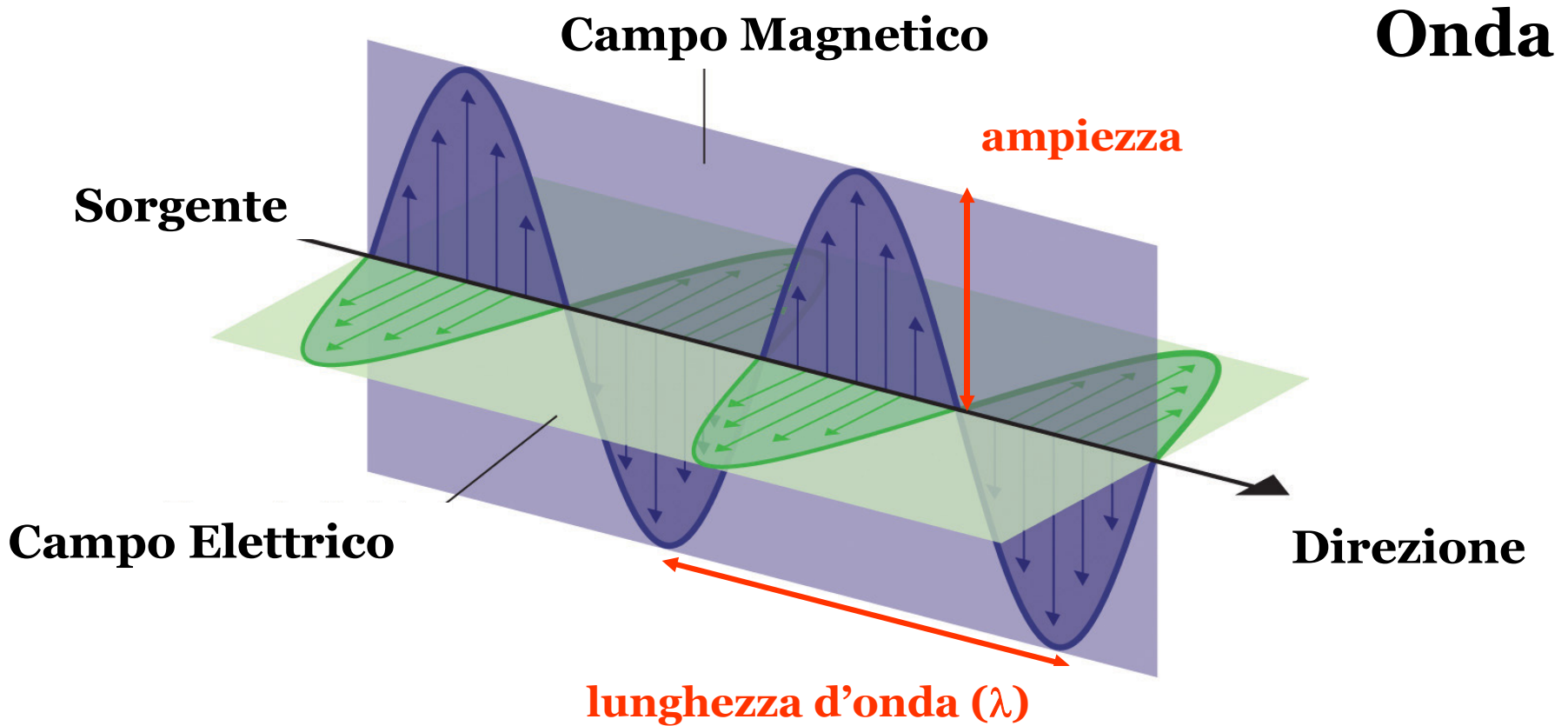
HST – eXtreme Deep Field

Spettro Elettromagnetico



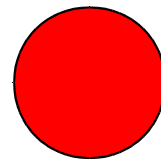
Tutti i “colori” della luce

Dualismo



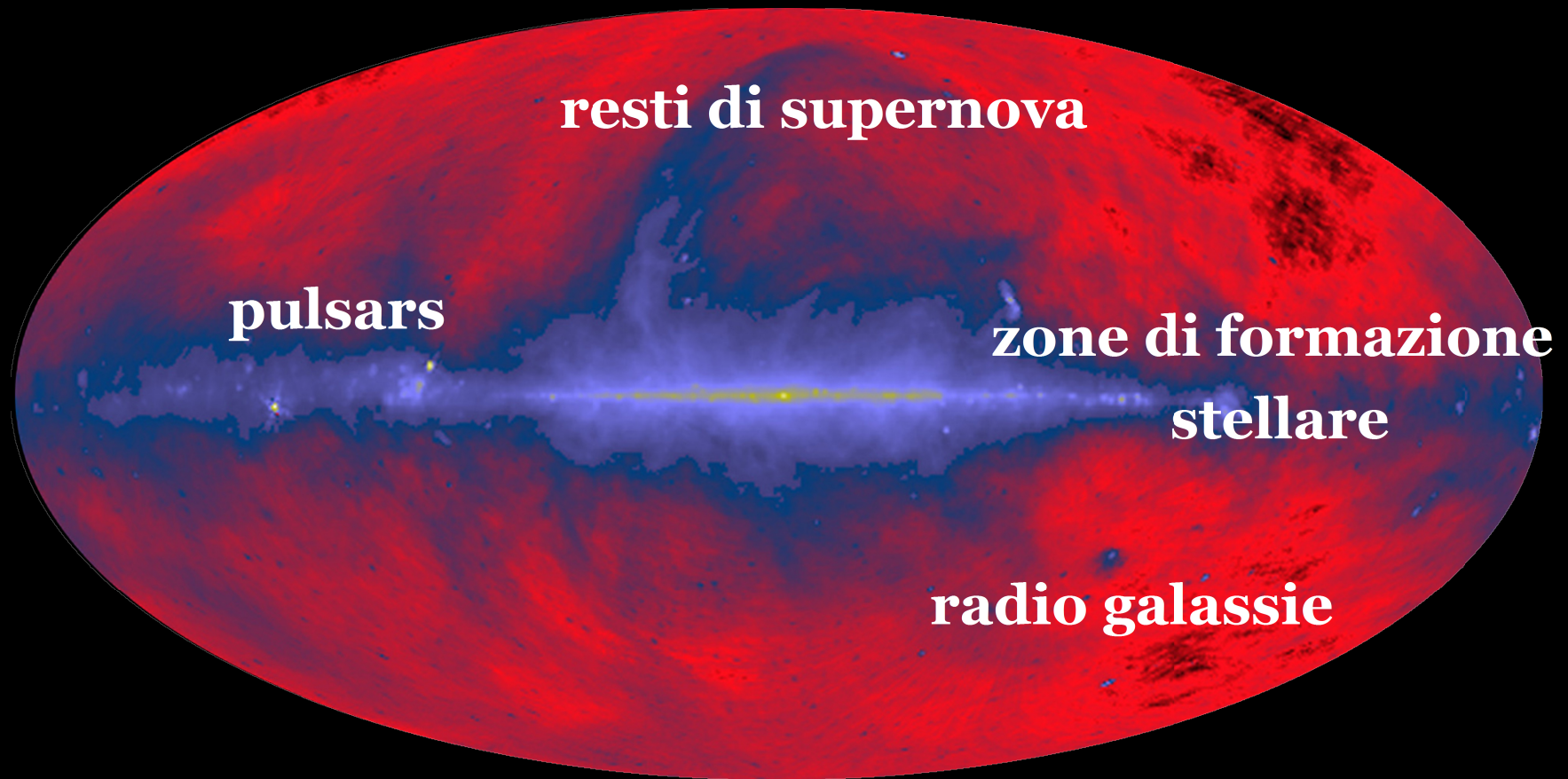
Particella (fotone)

- massa nulla
- $E = \text{costante } (h) \times \text{frequenza}$

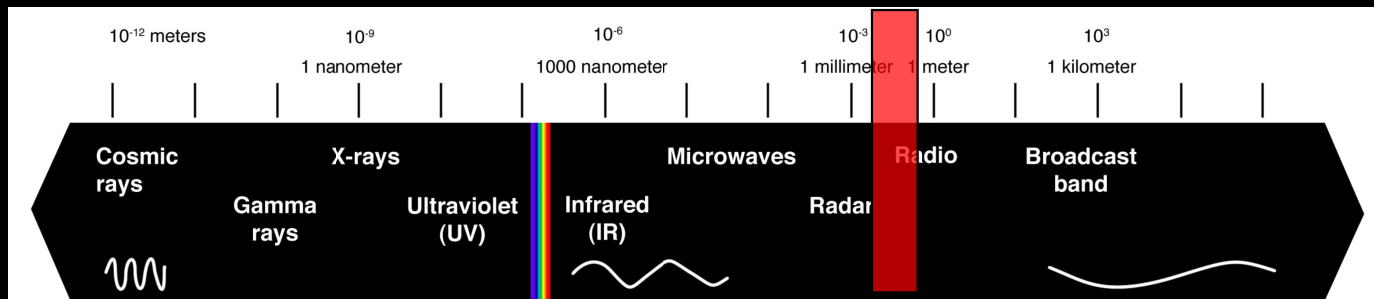


$$\begin{aligned}\lambda &\cong 700 \times 10^{-9} \text{ m} \\ \text{freq} &\cong 4 \times 10^{14} \text{ 1/sec (Hz)} \\ E &\cong 3 \times 10^{-19} \text{ Joule}\end{aligned}$$

Non solo galassie!



Il cielo a 408 MHz (408×10^6 Hz, 73 cm)



???

Come si sono formate le stelle, le galassie e tutto ciò che vediamo nell'Universo osservabile?

Qual è stata l'origine del tutto?

Quando?

L'Universo è nato così? Sarà così per sempre?

Le risposte dalla...“luce”

Velocità della luce [c] = $\sim 300.000 \text{ km} \cdot \text{s}^{-1}$ (vuoto)



Immagine: Johannes Schedler

Distanza Terra-Luna = 380.000 km = 1,2 s luce

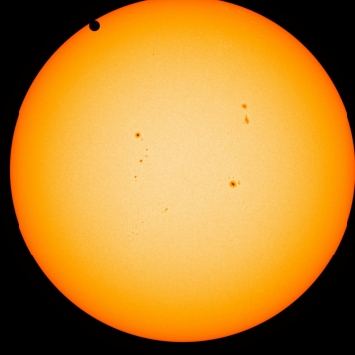


Immagine: NASA/SDO

Distanza Terra-Sole = $150 \cdot 10^6 \text{ km}$ = 8 minuti luce

Distanza Terra-M31 =
2,5 milioni di anni luce!!

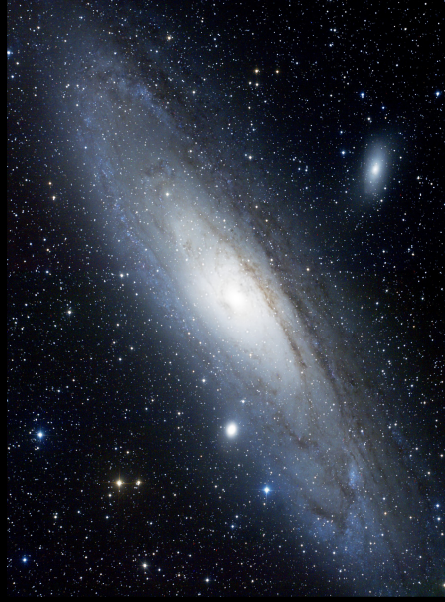


Immagine: P. Battaglia, F. Riccio

La Radiazione Cosmica di Fondo

L'Universo “bambino”...le strutture in divenire!

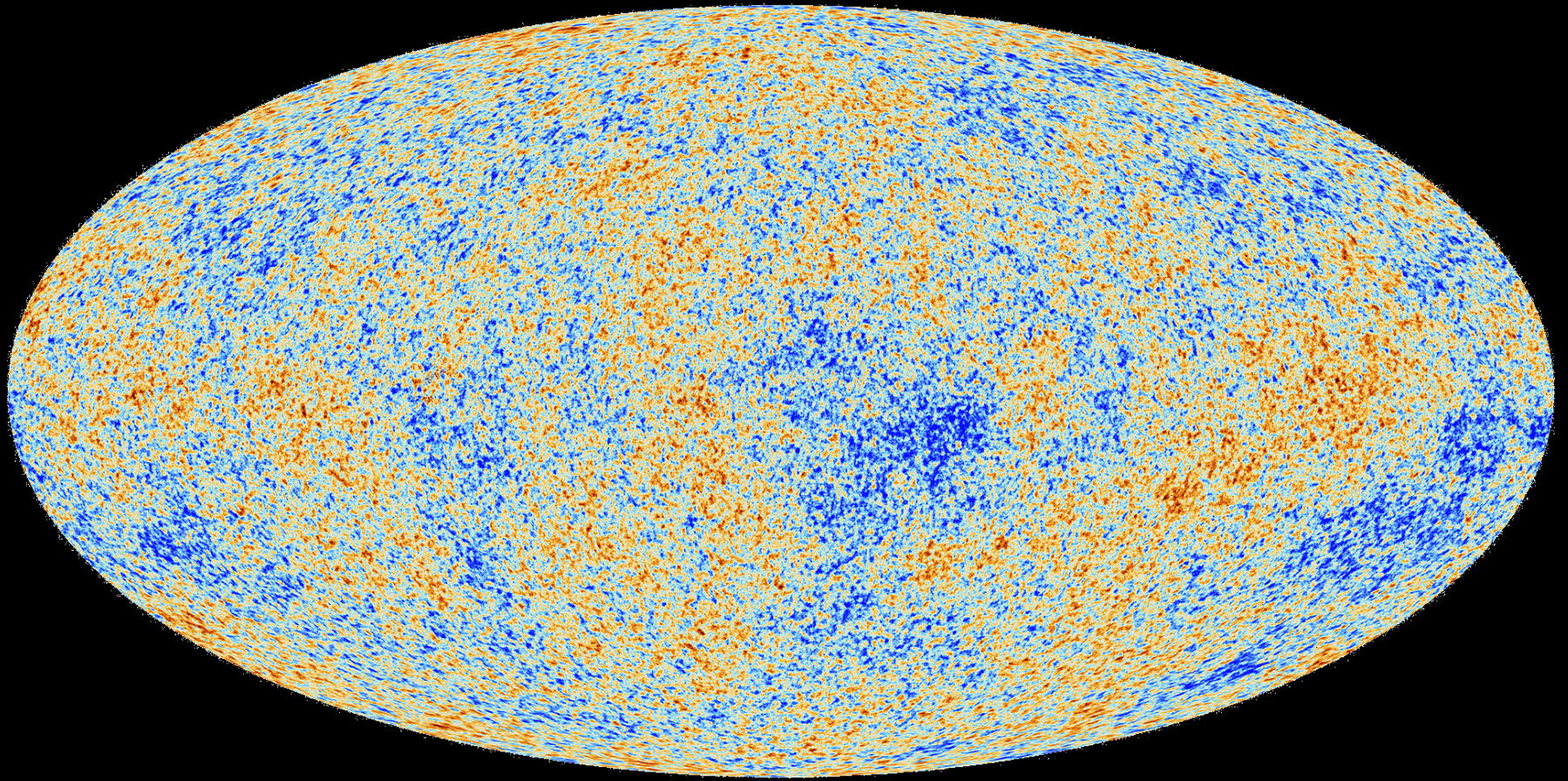
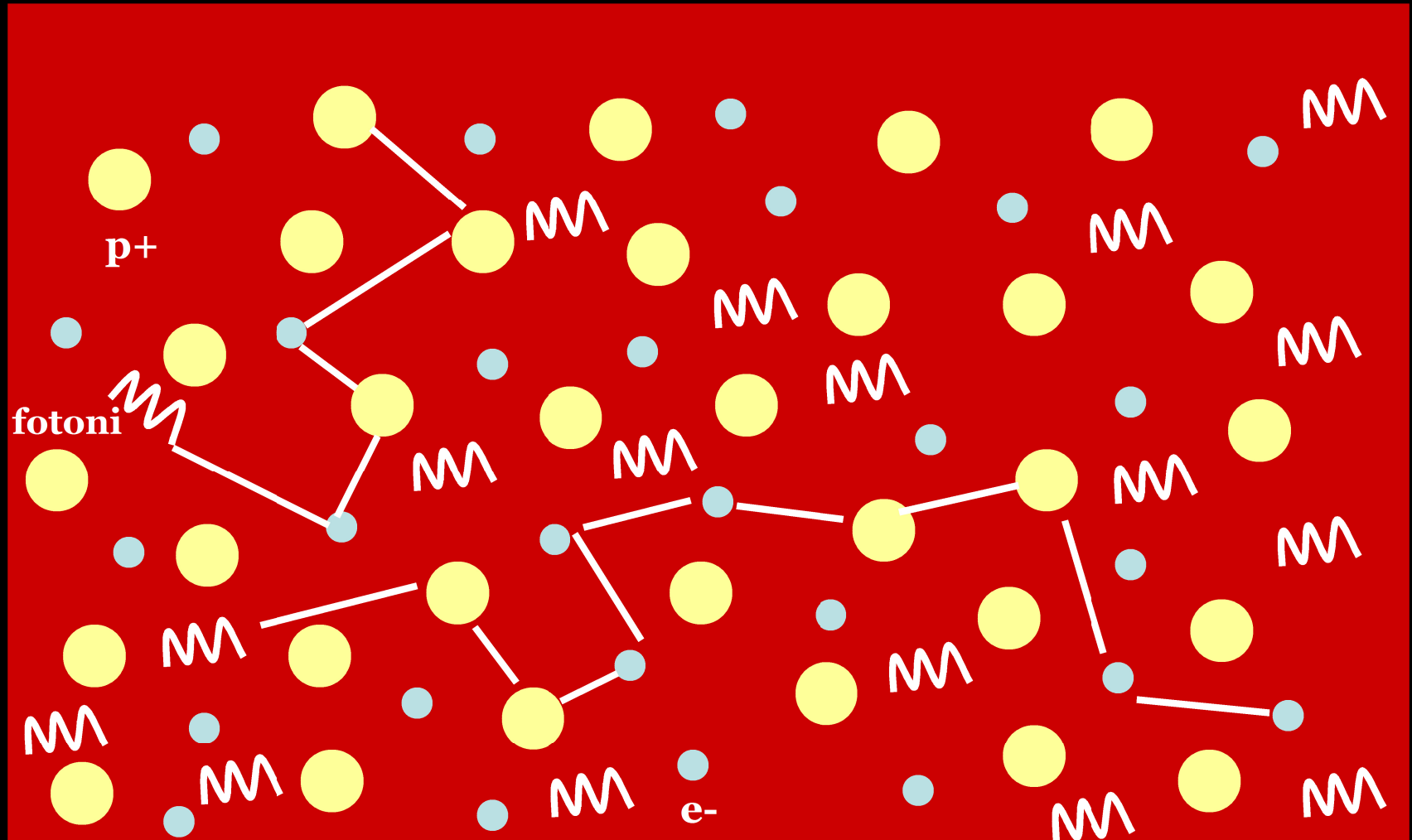


Immagine: Planck Collaboration, 2013

Universo opaco

tempo < 380.000 anni dopo il Big Bang



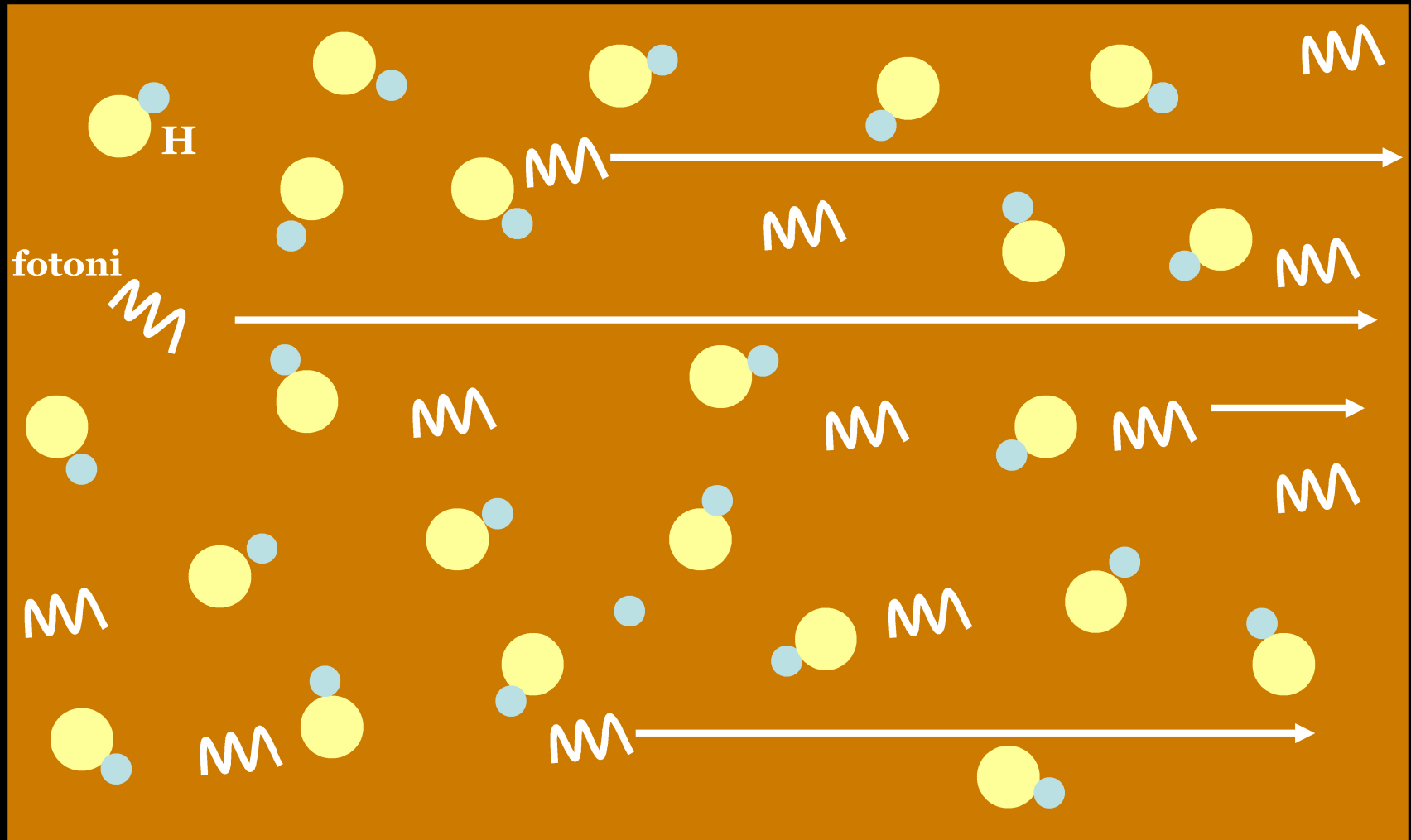
Temperatura > 3000 K

(kelvin = scala con zero posto a -273.15 °C)

...e luce fu!

tempo ≈ 380.000 anni dopo il Big Bang

RICOMBINAZIONE

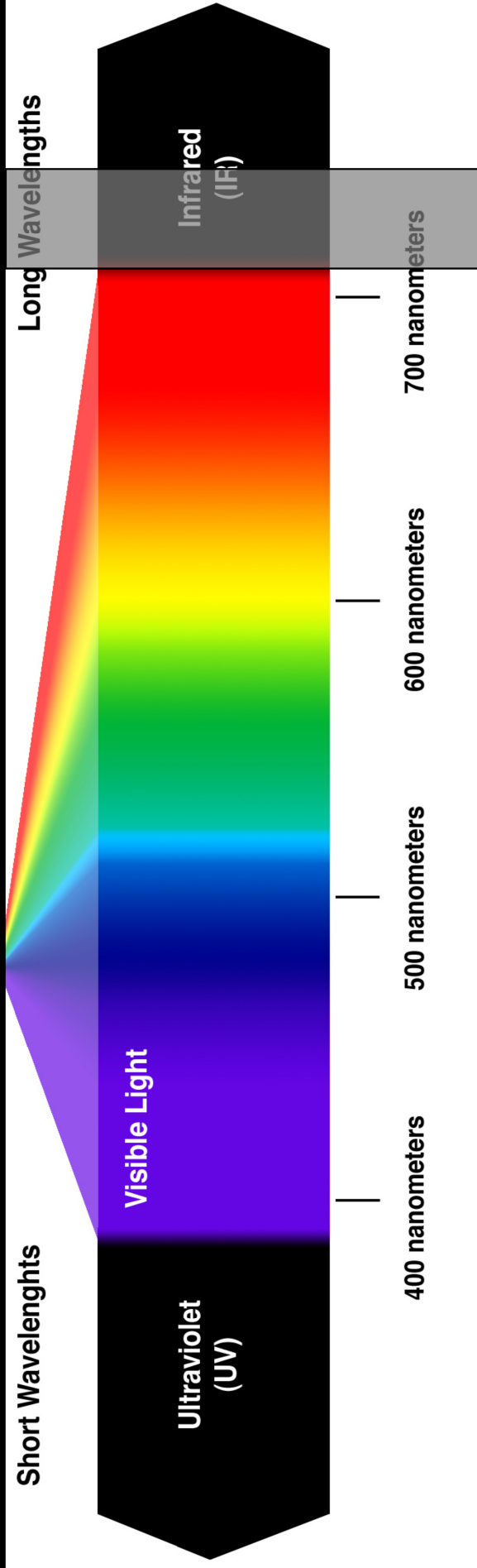


Temperatura ≈ 3000 K

Fondo infrarosso?

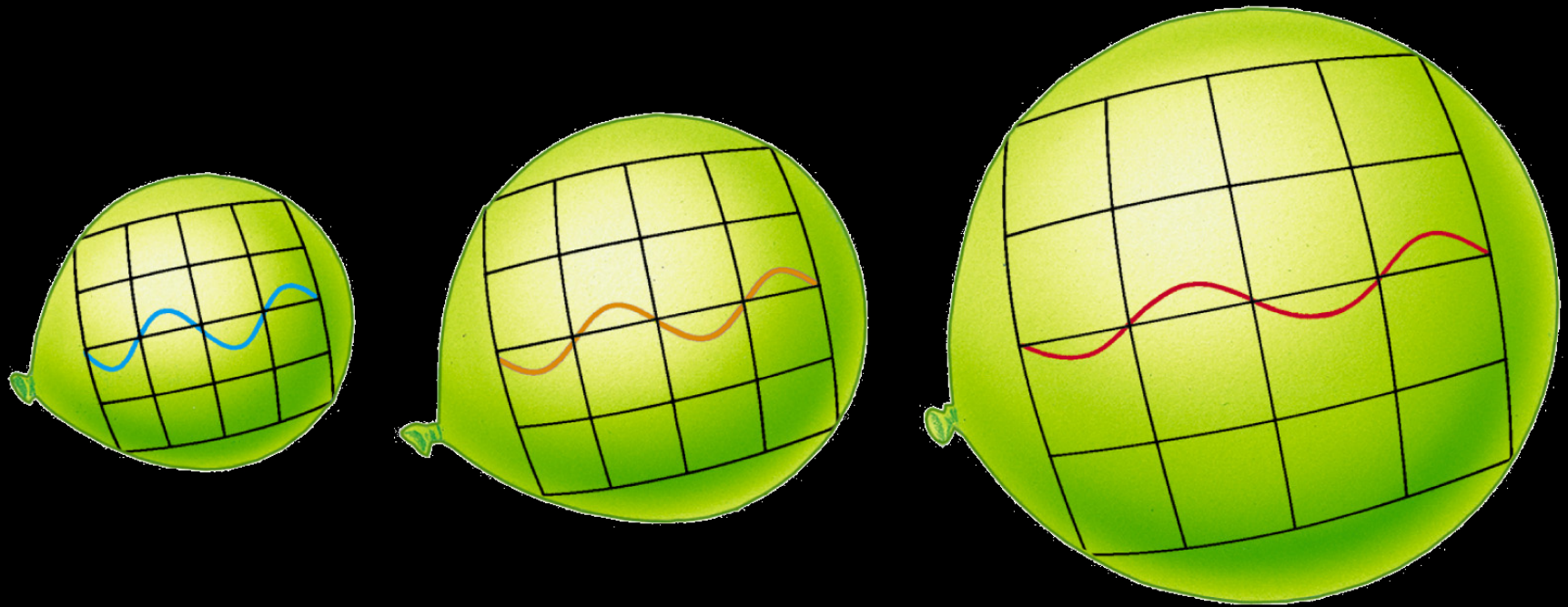
Temperatura ~ 3000 K

lunghezza d'onda = 966 nm (0,00000966 m)



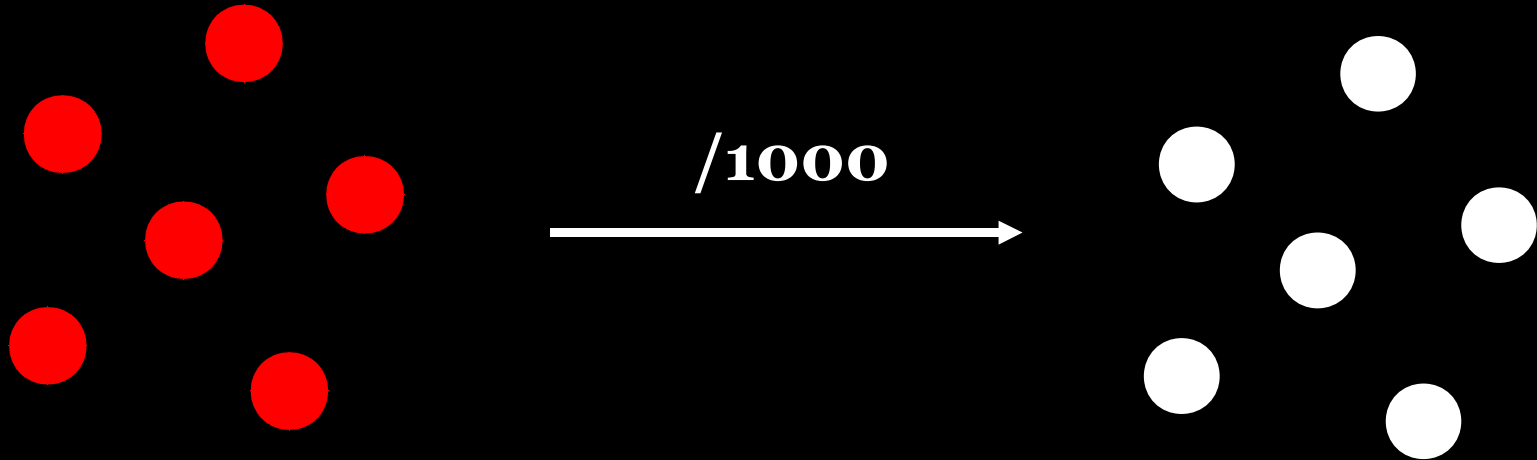
~~Densità = 400 milioni di fotoni $\text{infrarossi} \cdot \text{m}^{-3}$~~

L'Universo è in espansione



Radiazione di Fondo nelle “*Microonde*”

L'Universo, dalla ricombinazione si è espanso di un fattore 1000



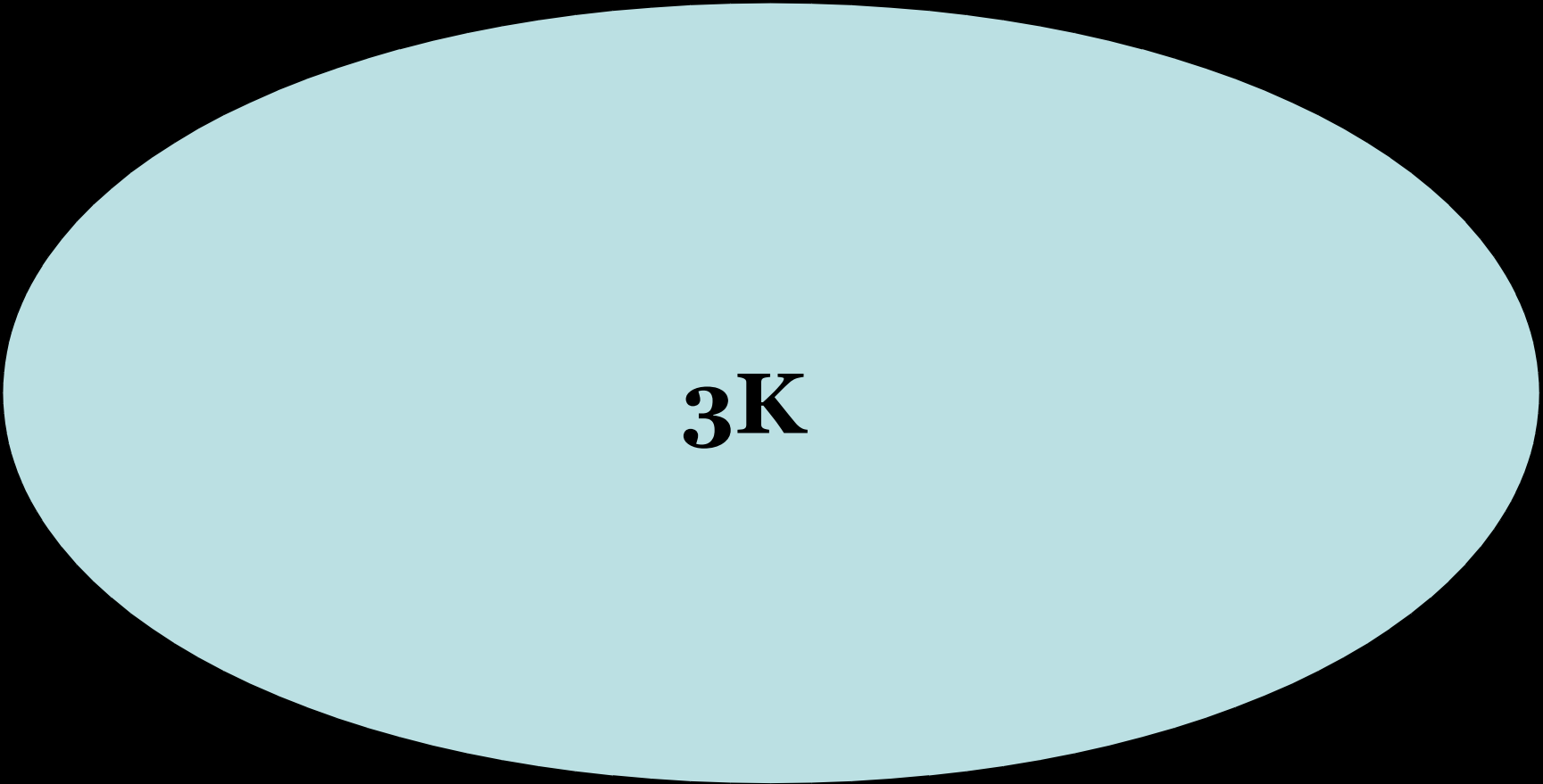
RICOMBINAZIONE

$t = 380.000$ anni dopo Big Bang
 $T = 3000\text{K}$
Fotoni infrarossi

OGGI

$t = 13,8$ mld anni dopo Big Bang
 $T = 3\text{K}$
Fotoni microonde

Un Universo “uniforme”...



3K

COBE

COBE (NASA)

Prime “*anisotropie*” (Nobel per la Fisica 2006)

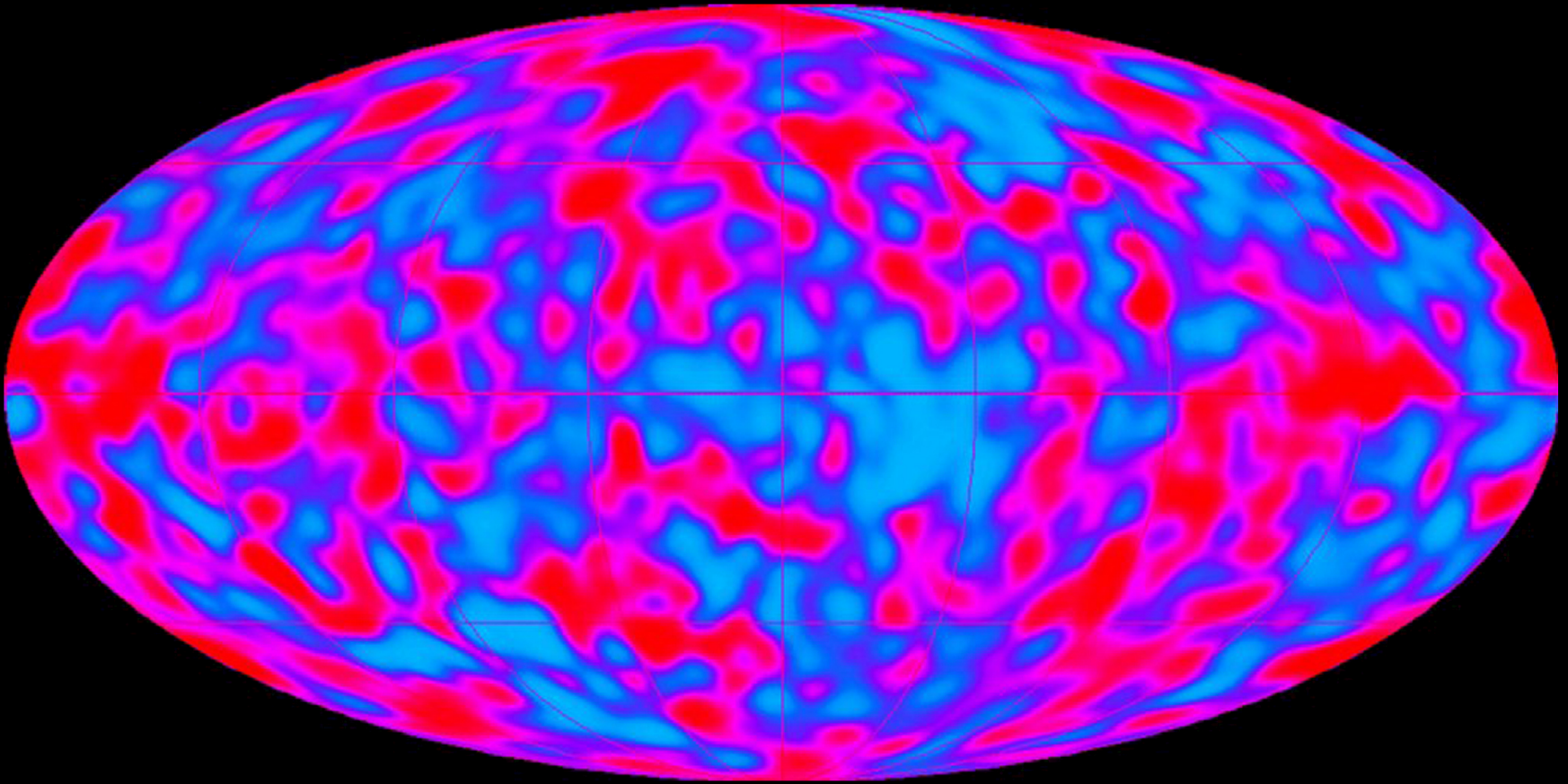
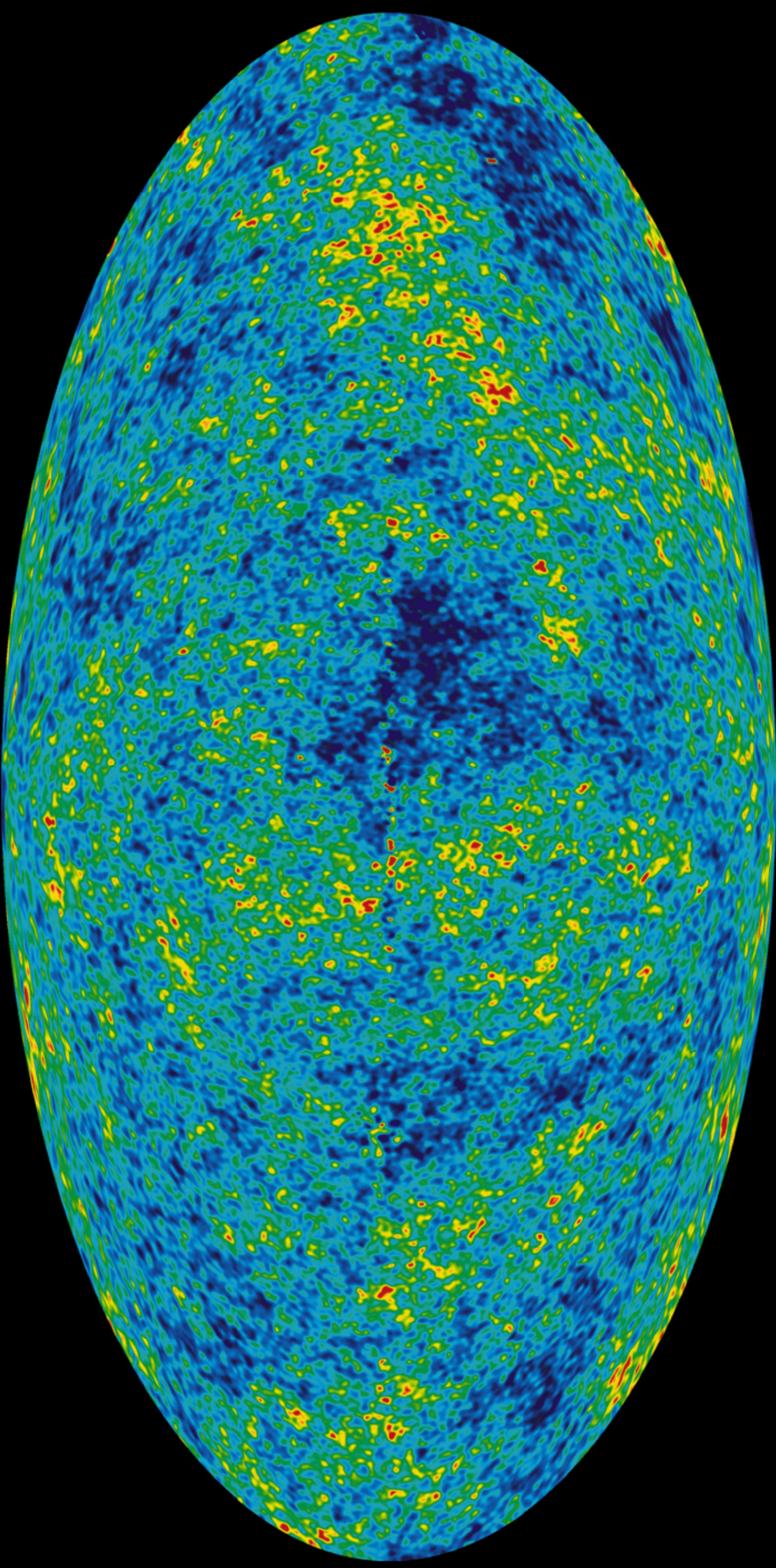


Immagine: NASA/COBE, 1992

WMAP

WMAP (NASA)



Imagine: NASA/WMAP Science Team, 2008

Planck

Planck (ESA)

Mappa più dettagliata della CMB

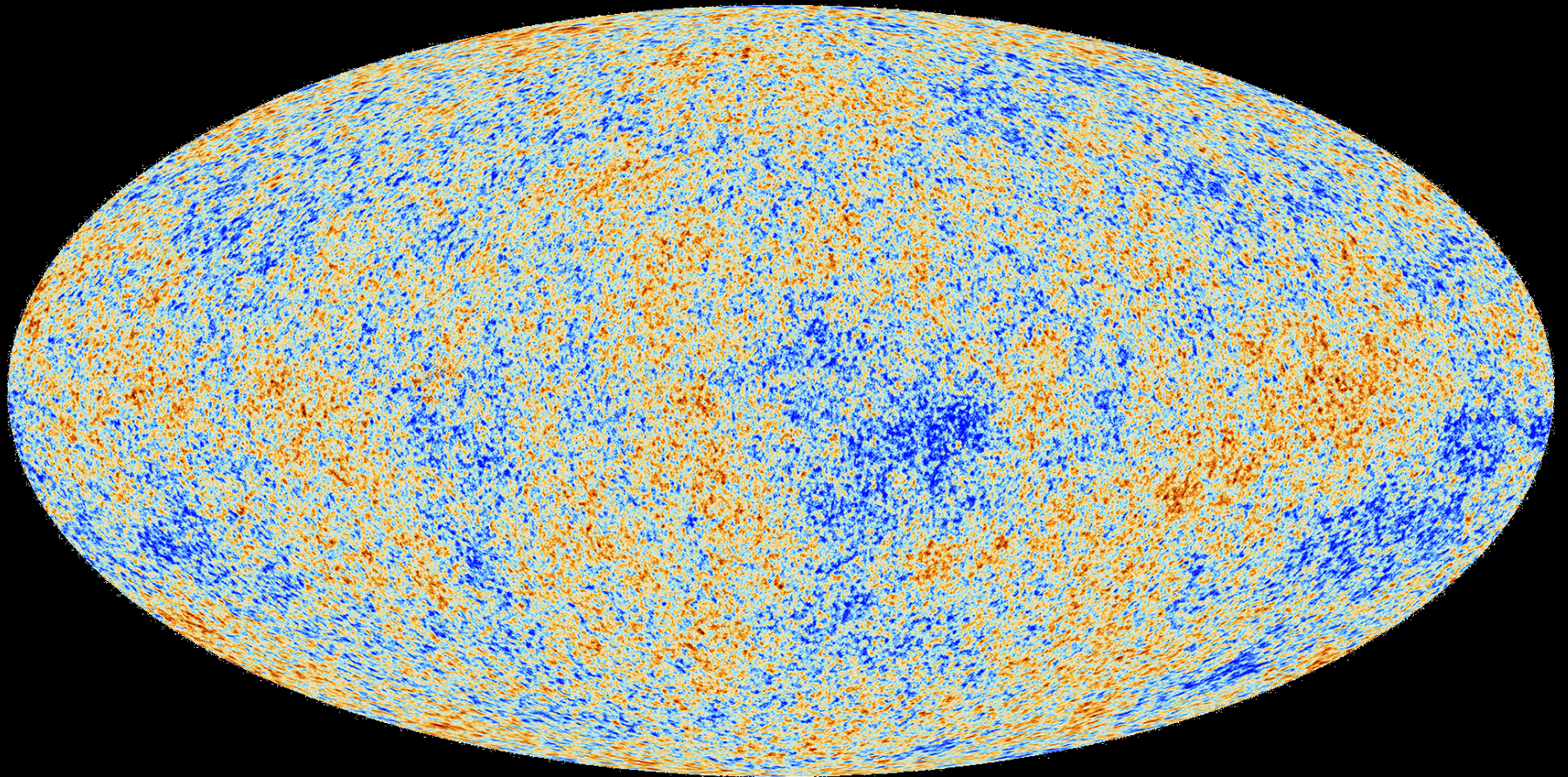
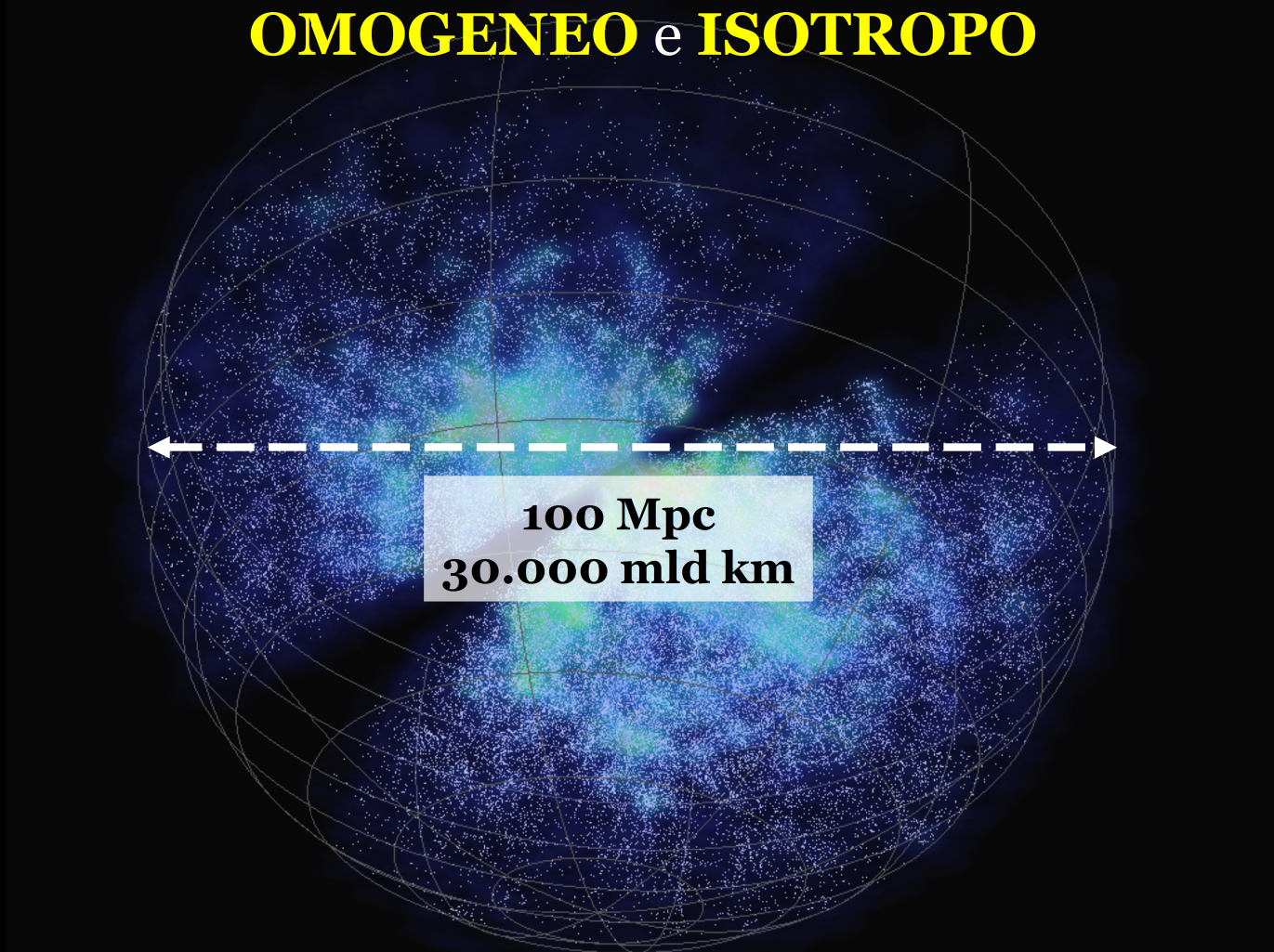


Immagine: Planck Collaboration, 2013

Modello del Big Bang

PRINCIPIO COSMOLOGICO

Universo, su scale di distanze opportunamente grandi, è
OMOGENEO e **ISOTROPO**



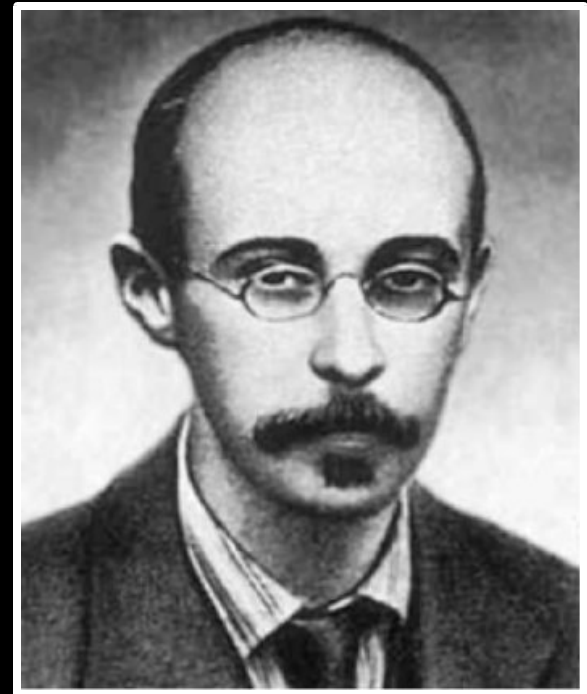
Evoluzione dell'Universo

1922

Friedmann scrive le equazioni del modello di Big Bang

$$\frac{\frac{d}{dt} a^2 + kc^2}{a^2} = \frac{8\pi\rho G}{3}$$

$$\frac{(\frac{d^2}{dt^2} a)}{a} = -\frac{4\pi G}{3}(\rho + \frac{3p}{c^2}) + \frac{\Lambda c^2}{3}$$

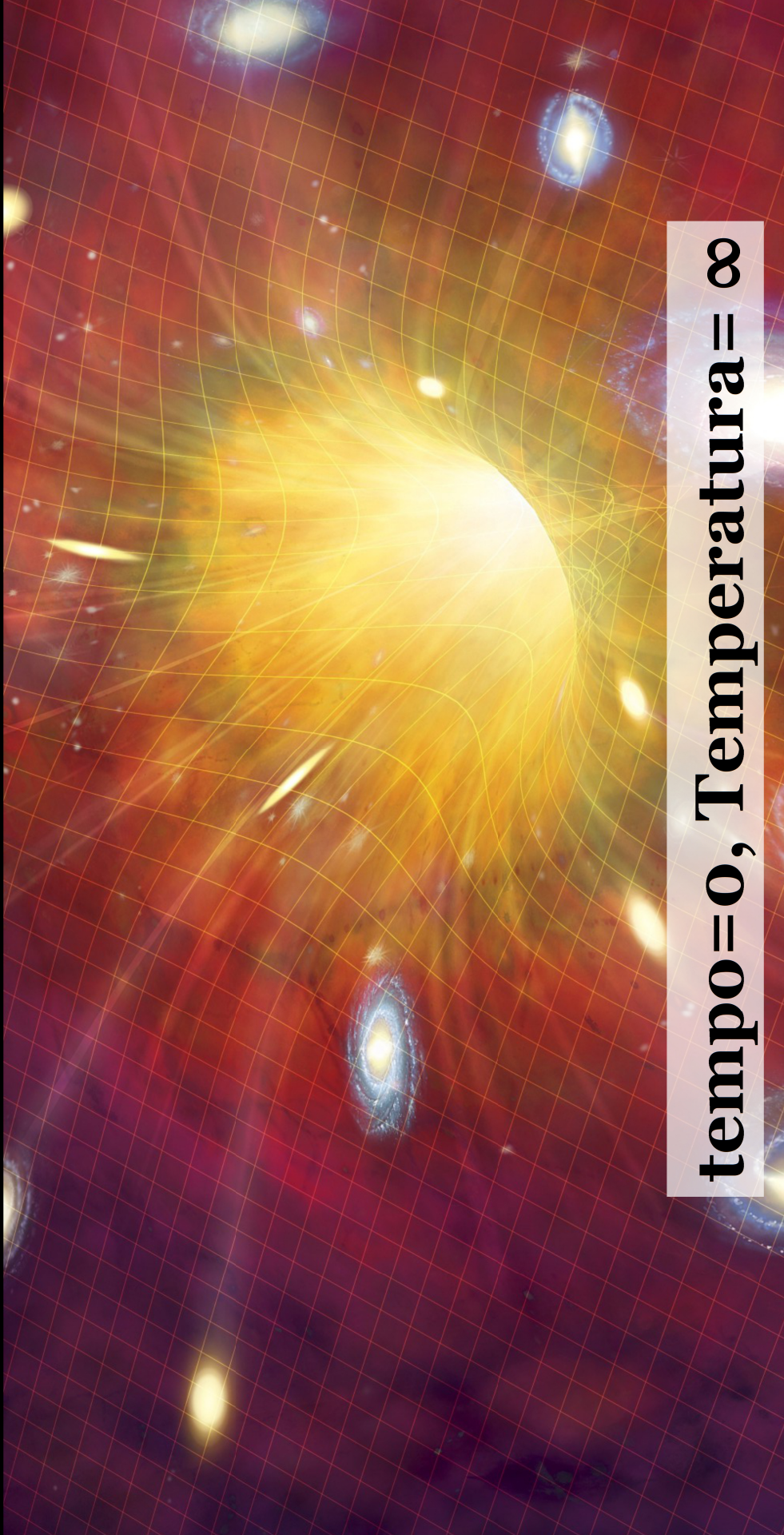


k = parametro di curvatura

Λ = costante cosmologica

1. Big Bang

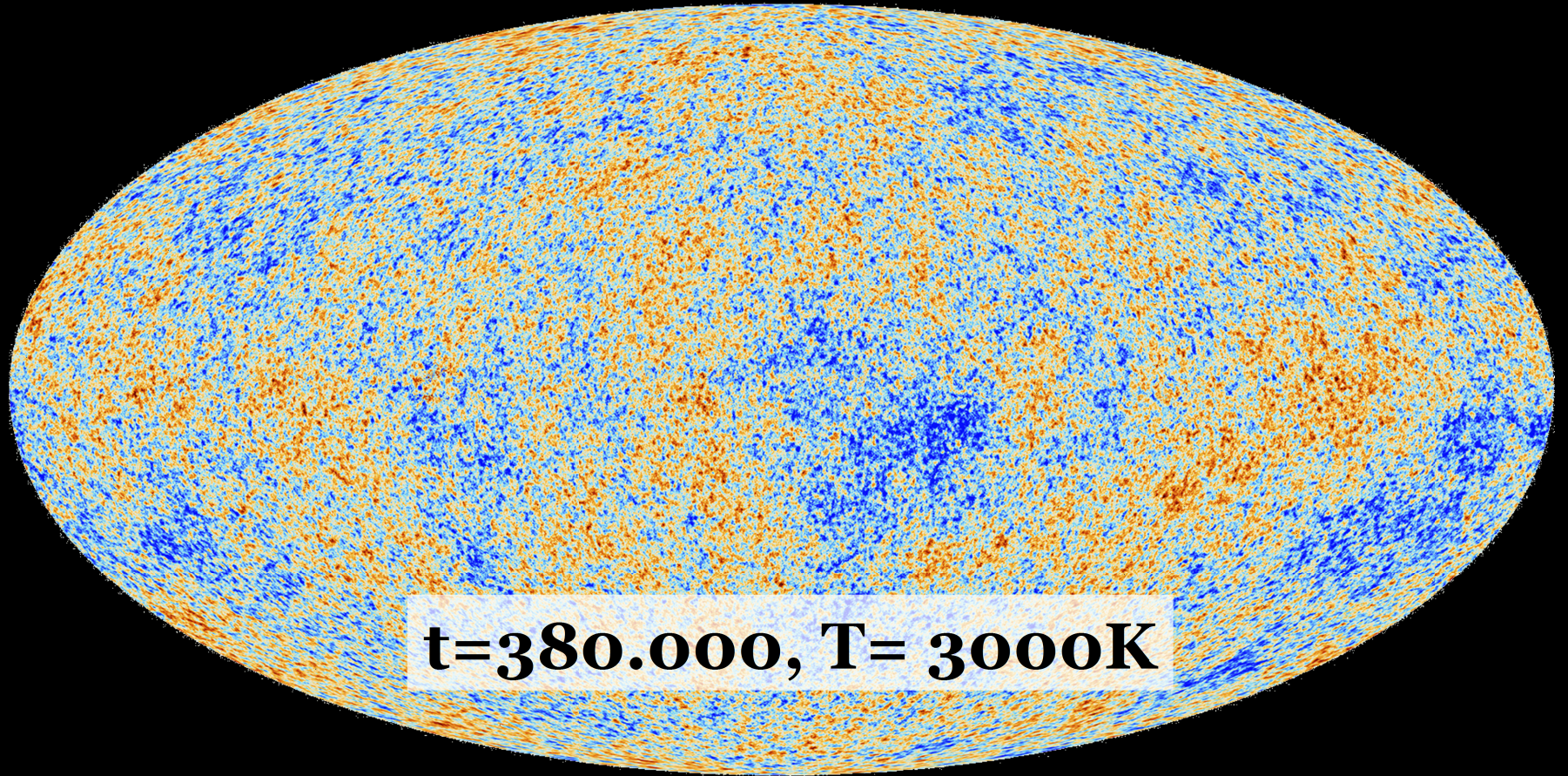
13,81 miliardi di anni fa nasce l'Universo



tempo=0, Temperatura= ∞

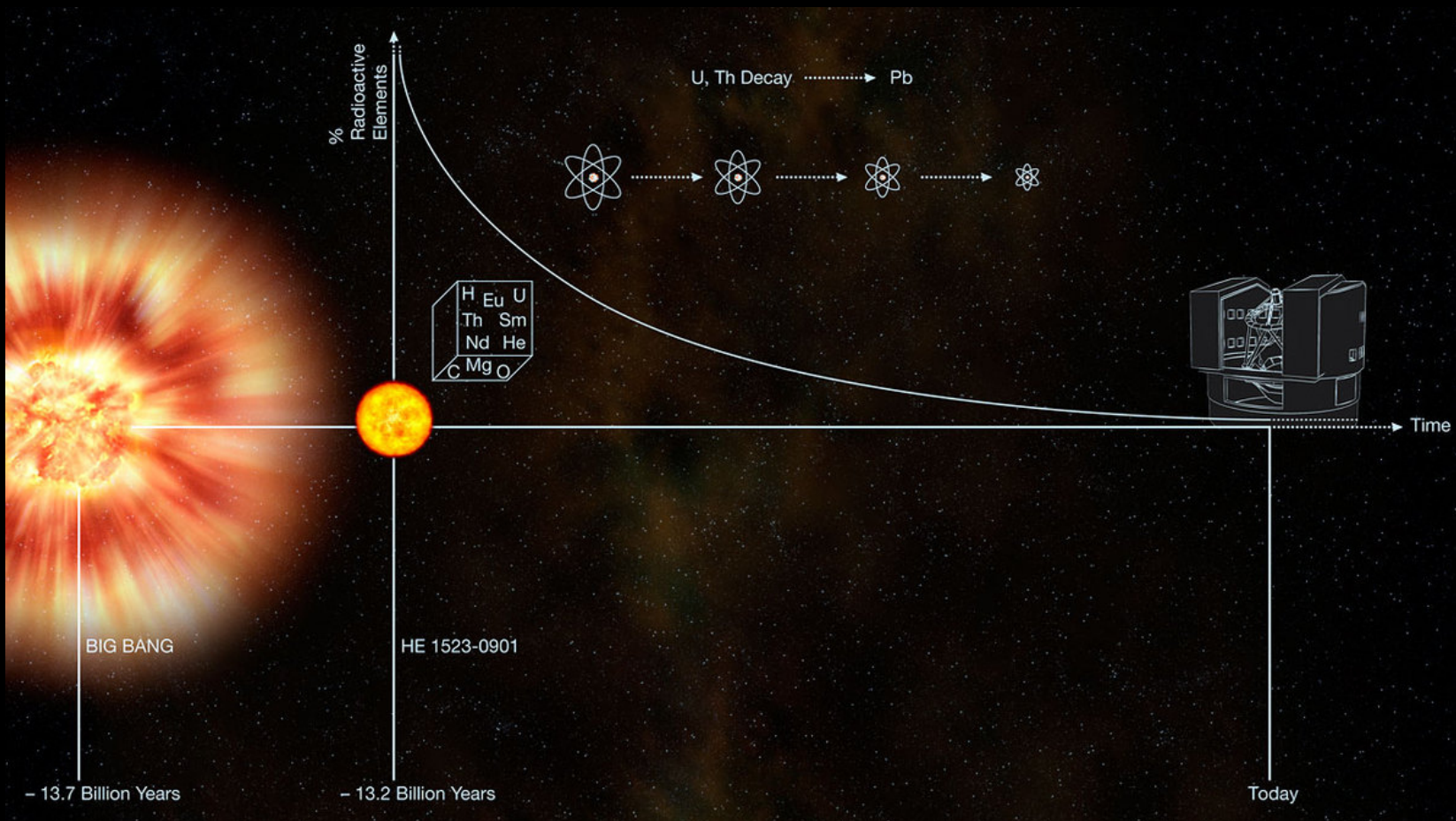
2. Ricombinazione

380.000 anni dopo il Big Bang l'Universo diventa “*trasparente*”

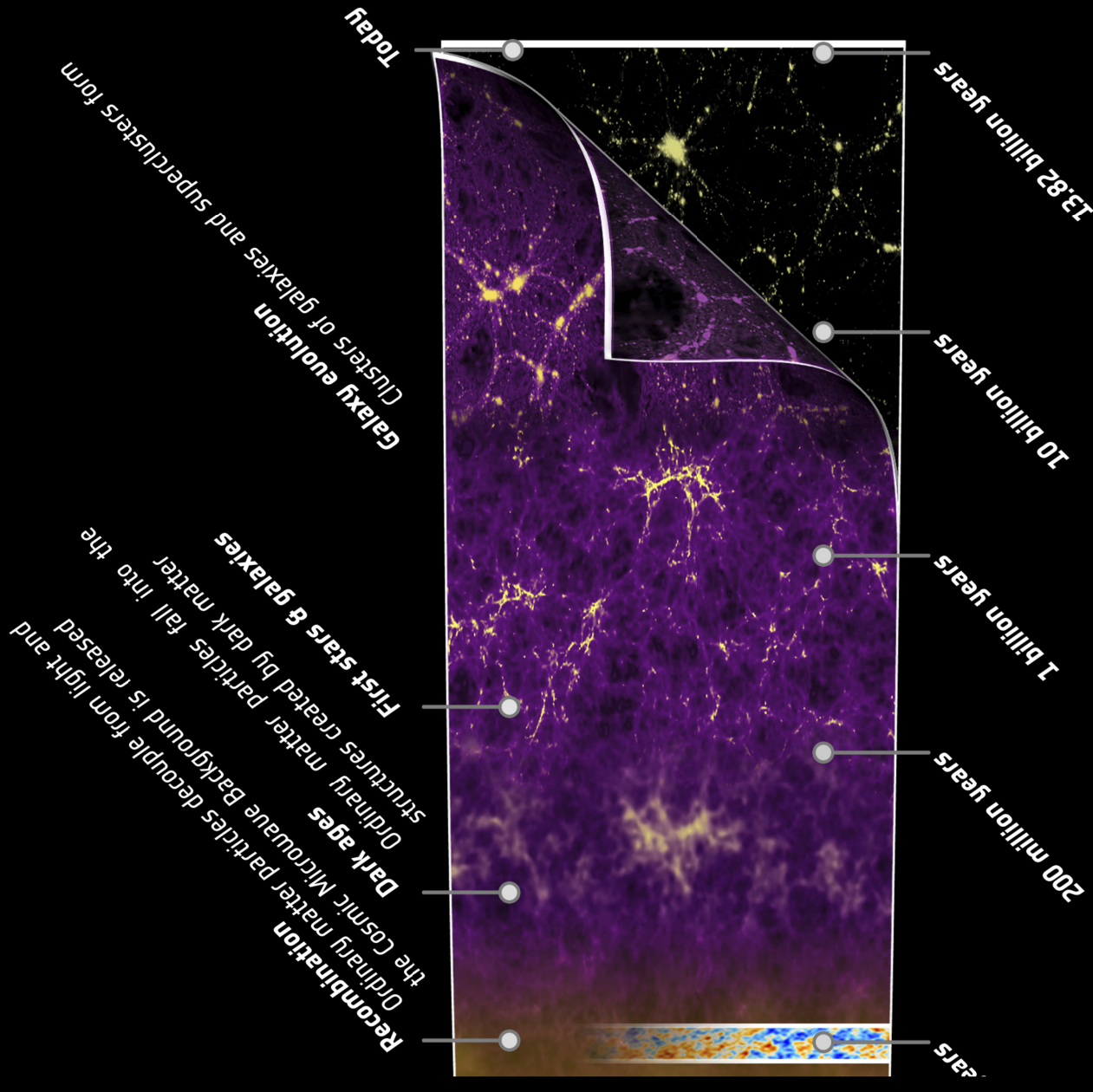


Evoluzione successiva

Nelle zone dove c'era una densità di materia superiore alla media la gravità richiama sempre più materia. Si accendono le prime stelle...

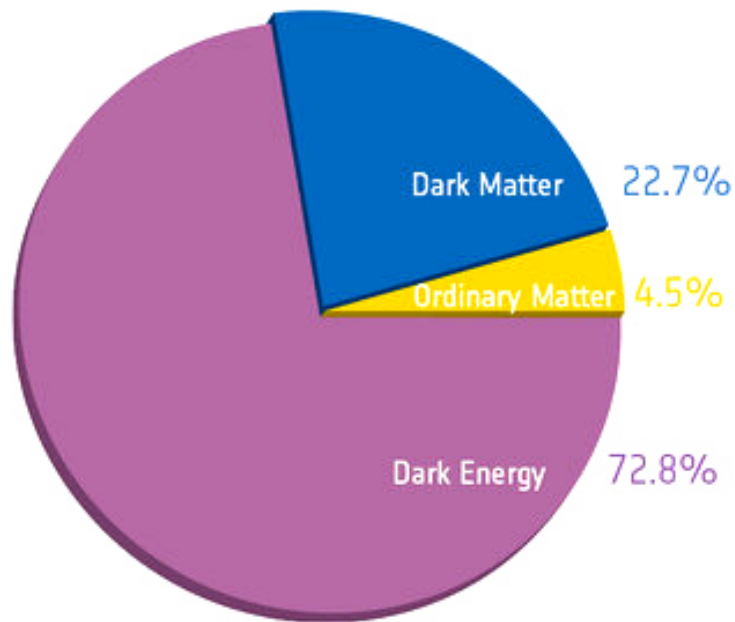


Evoluzione successiva

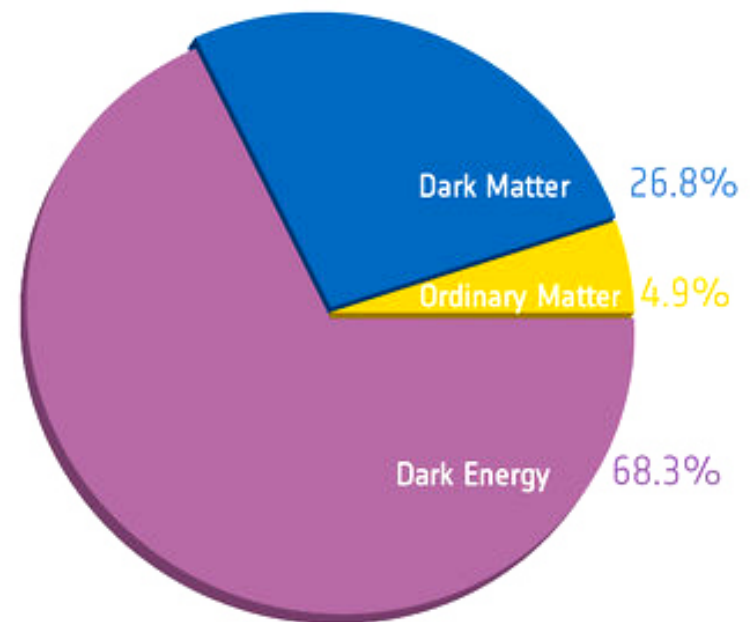


Dal Modello di Big Bang al Λ CDM

Sei parametri per descrivere l'Universo, tra cui densità di materia ordinaria, densità di materia oscura e densità di energia oscura



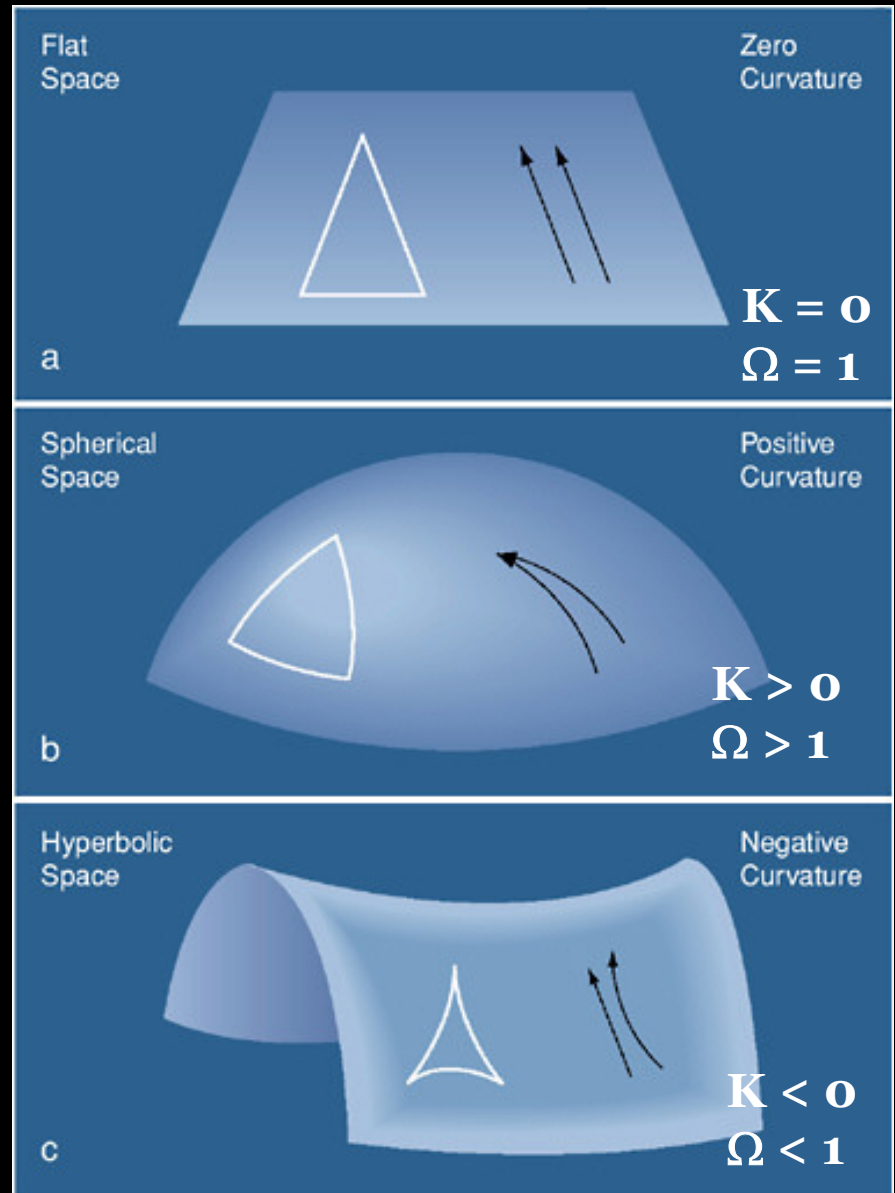
Before Planck



After Planck

Geometria dell'Universo

- **Densità critica** = $10^{-29} \text{ g cm}^{-3}$
- La geometria dell'Universo è legata alla densità di materia rispetto alla densità critica
- $\Omega = \text{densità} / \text{densità critica}$



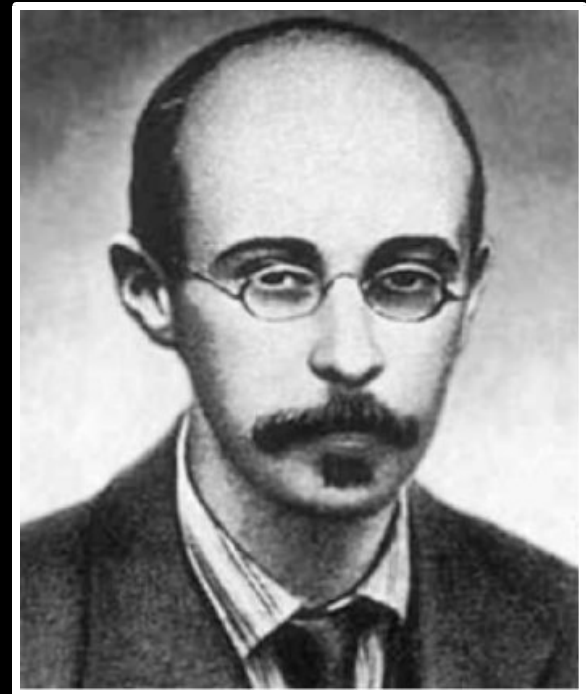
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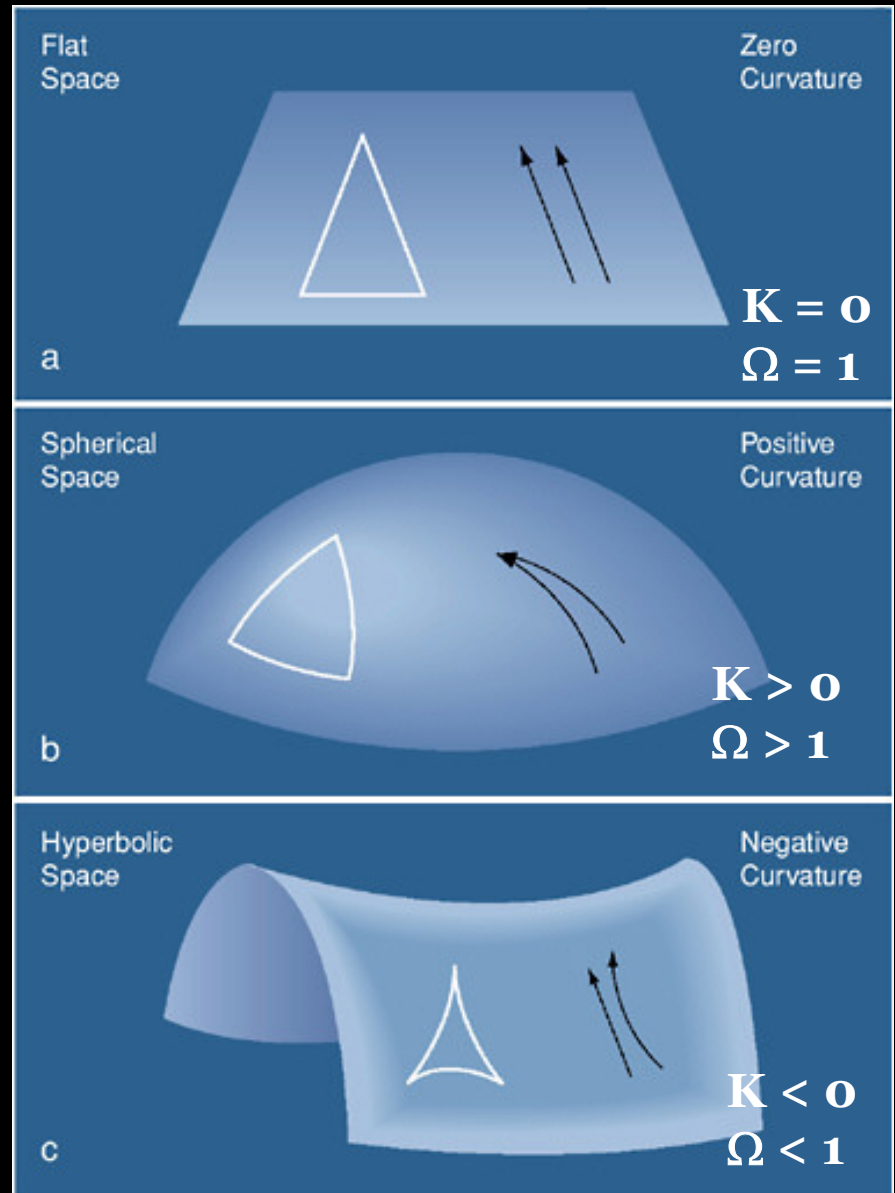


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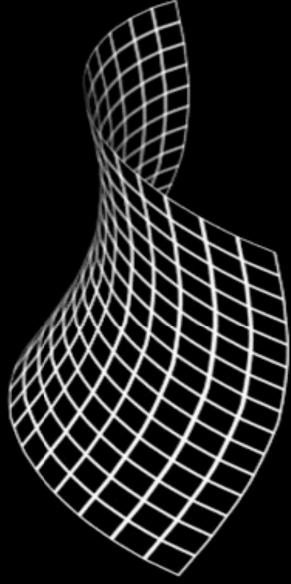
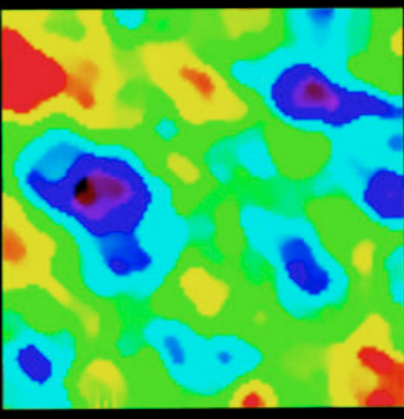
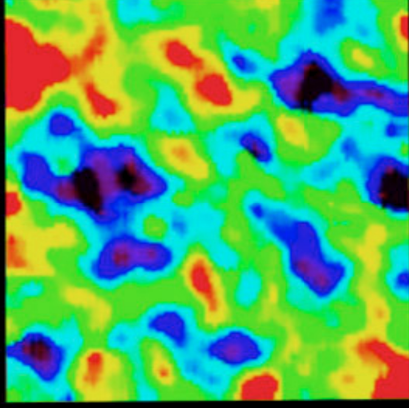
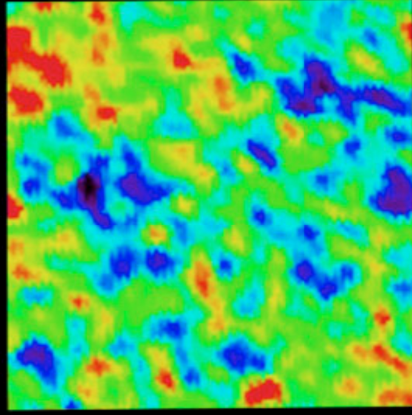
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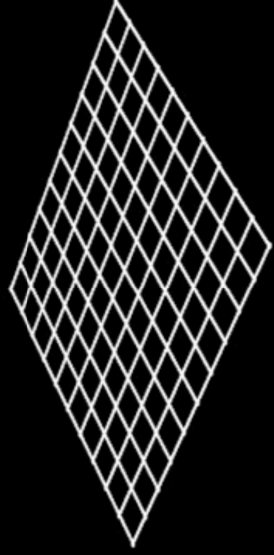


Un Universo Piatto

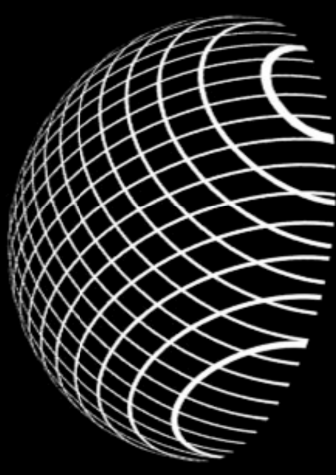
PLANCK, 2013



OPEN



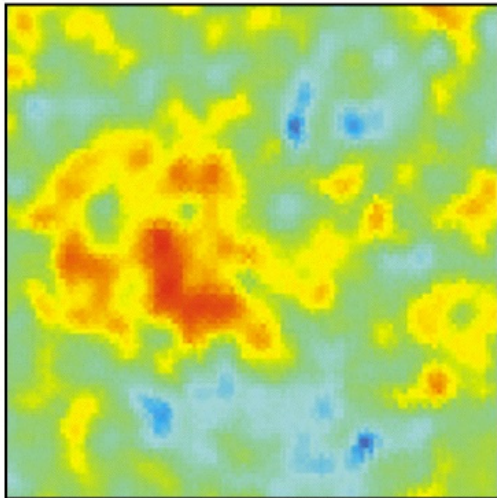
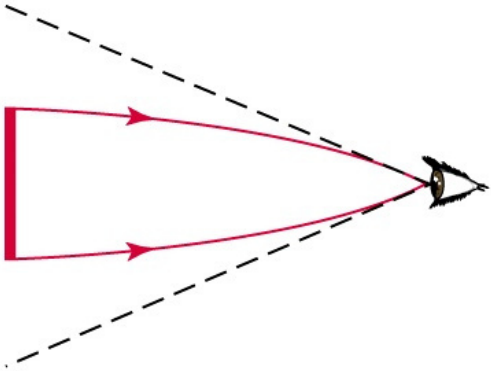
FLAT



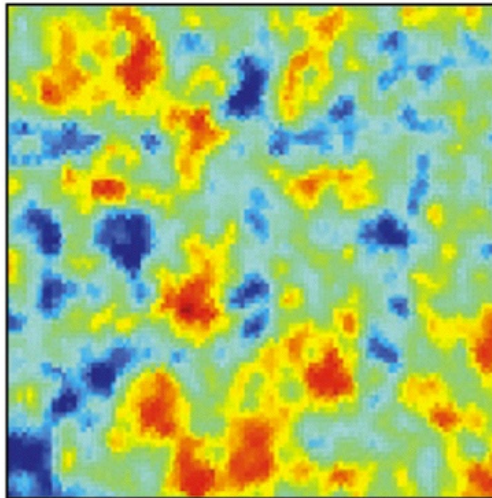
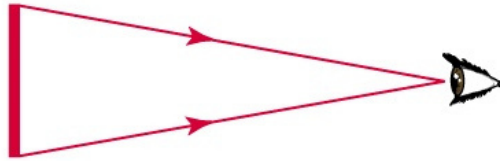
CLOSED

Geometria dell'Universo

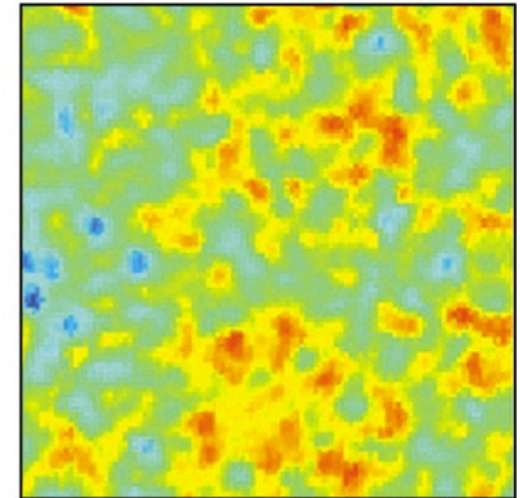
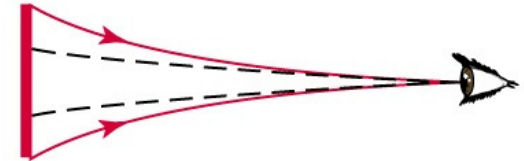
PLANCK, 2013



Universo chiuso:
le zone calde appaiono
più ampie del reale



CMB Simulator



Universo aperto:
le zone calde appaiono
meno ampie del reale

Modello di Big Bang: limiti

Le osservazioni condotte sulla CMB, sulle galassie e sulle supernovae lontane mostrano un Universo:

OMOGENEO e **ISOTROPO** (CMB)

PIATTO (CMB)

con **MATERIA OSCURA** (26,8 % del totale, galassie + CMB)

con **ENERGIA OSCURA** (68,3 % del totale, supernovae + CMB)

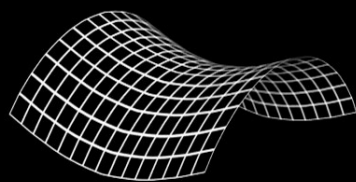
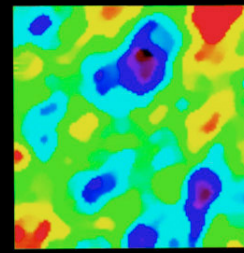
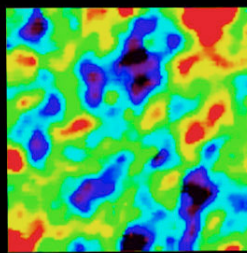
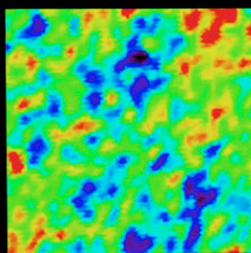
?? Il modello di Big Bang non spiega l' **OMOGENEITA'** dell'Universo.

In particolare, non spiega quali sono le condizioni iniziali che hanno portato alle fluttuazioni di densità nell'Universo primordiale.

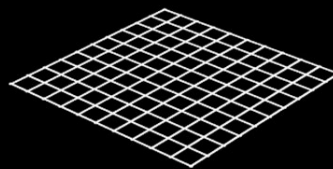
Modello di Big Bang: limiti

?? Il modello di Big Bang non spiega la **PIATTEZZA** dell'Universo.

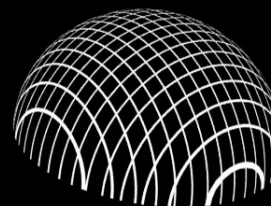
In questo modello sono necessarie delle condizioni iniziali molto particolari sulla curvatura dell'Universo per ottenere la piattezza che Planck ha osservato.



OPEN



FLAT

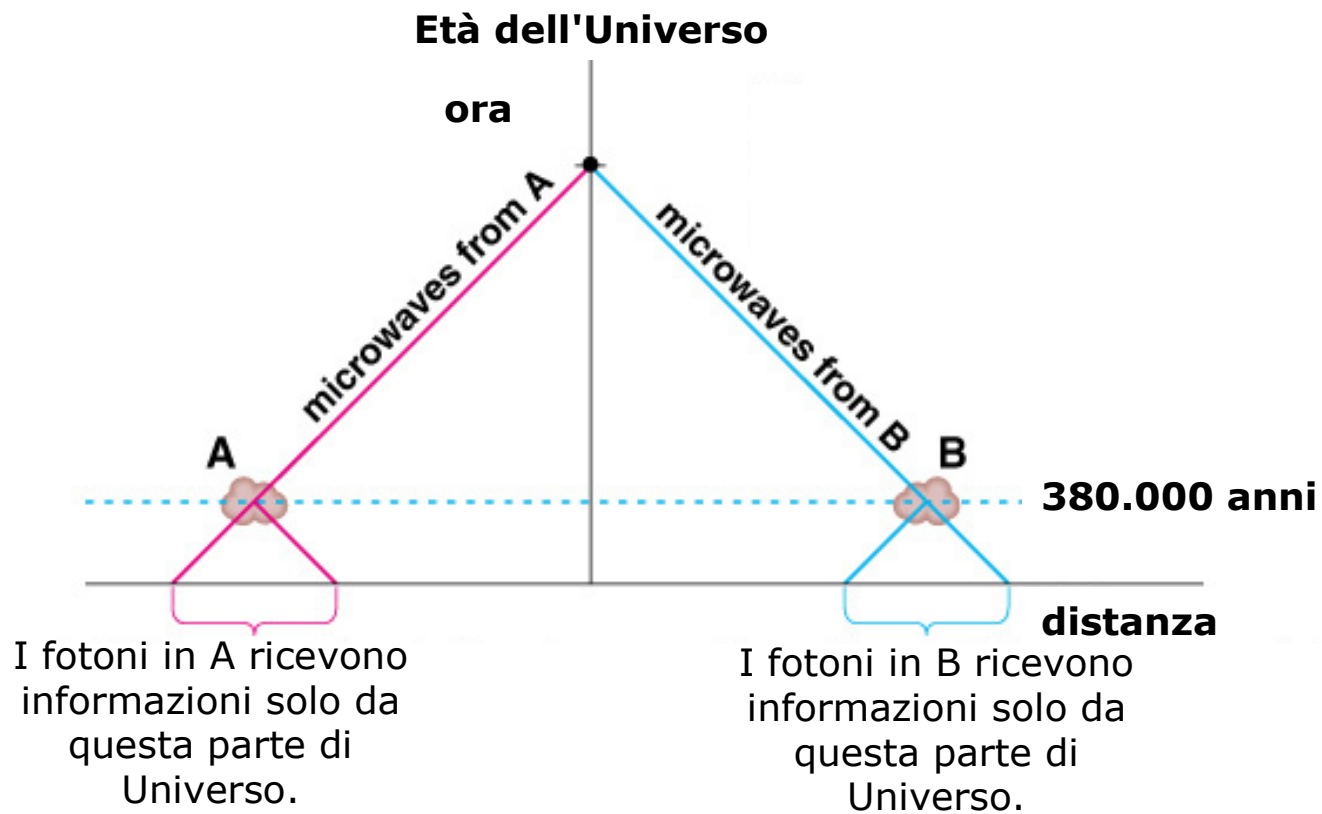


CLOSED

Modello di Big Bang: limiti

PROBLEMA DELL'ORIZZONTE

Se l'Universo si fosse espanso a ritmo costante, zone di cielo che adesso sono separate di 180° dovrebbero avere temperature molto diverse tra loro, perchè non sarebbero mai state in contatto.



Inflazione

1981

A. Guth, A. Linde propongono il **modello inflazionario** per spiegare le tre incongruenze del Modello di Big Bang.



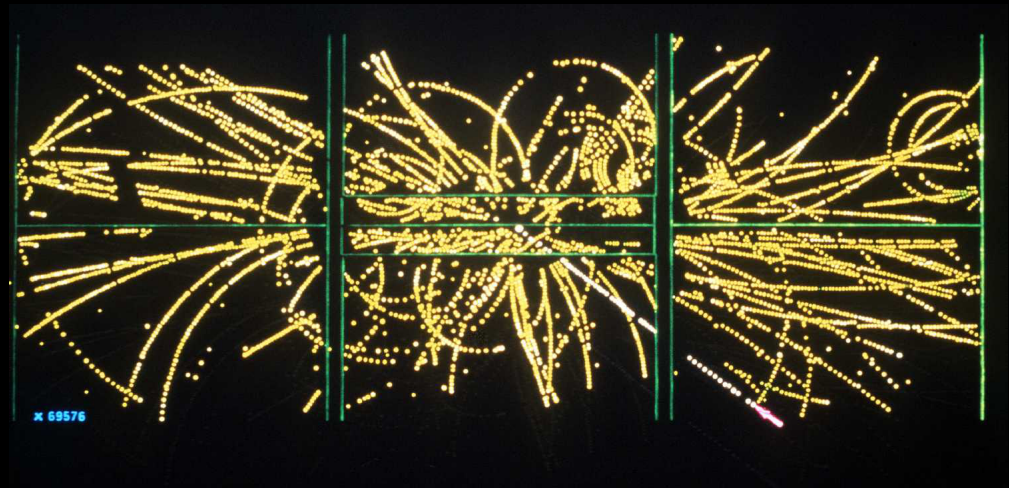
Inflazione

- Transizione di fase
- L'Universo si è riempito di energia di vuoto
- Gravità diviene repulsiva
- L'Universo aumenta le sue dimensioni di un fattore $10^{50} - 10^{60}$.



INFLATON??

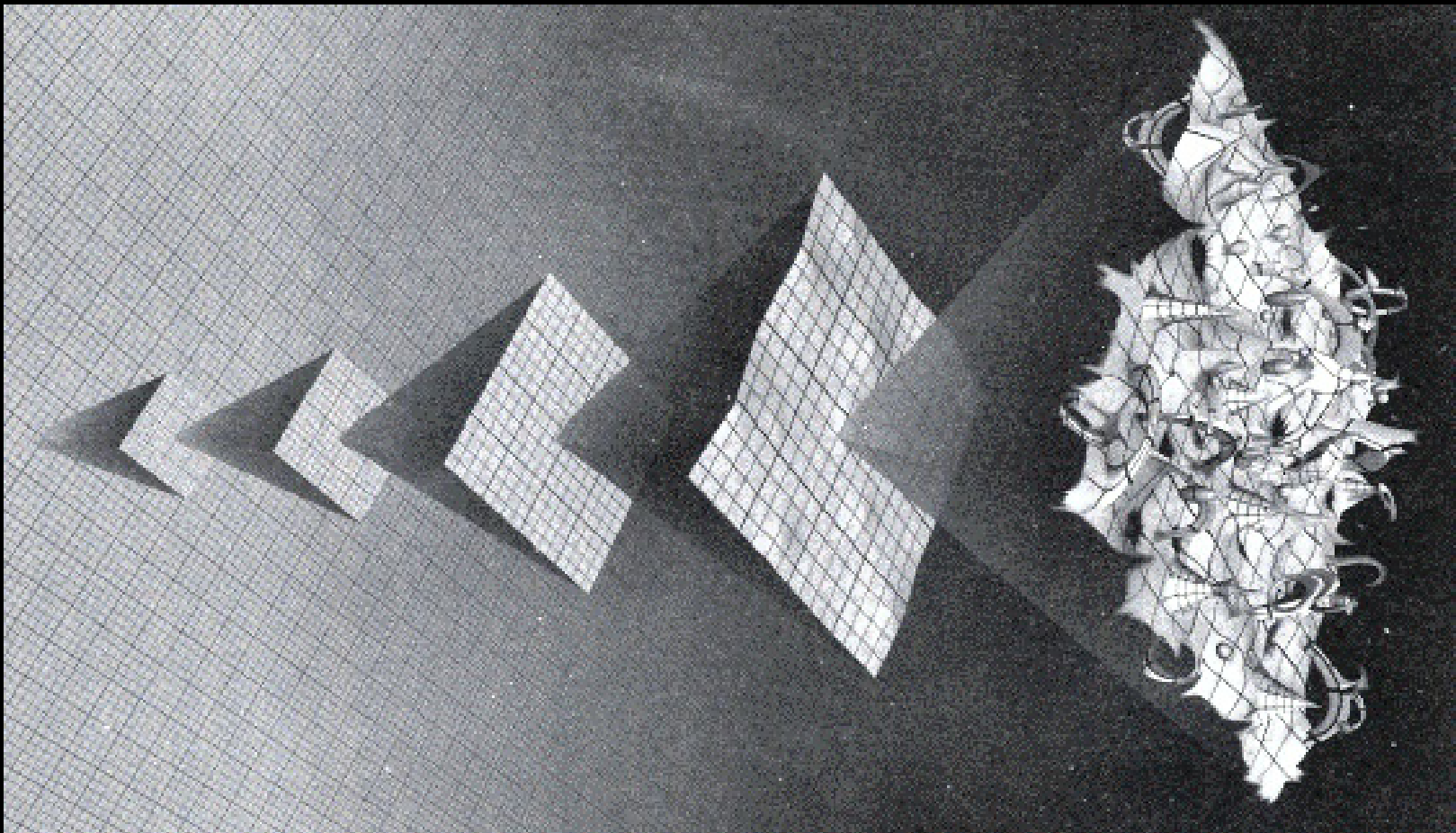
Bosone W e Z



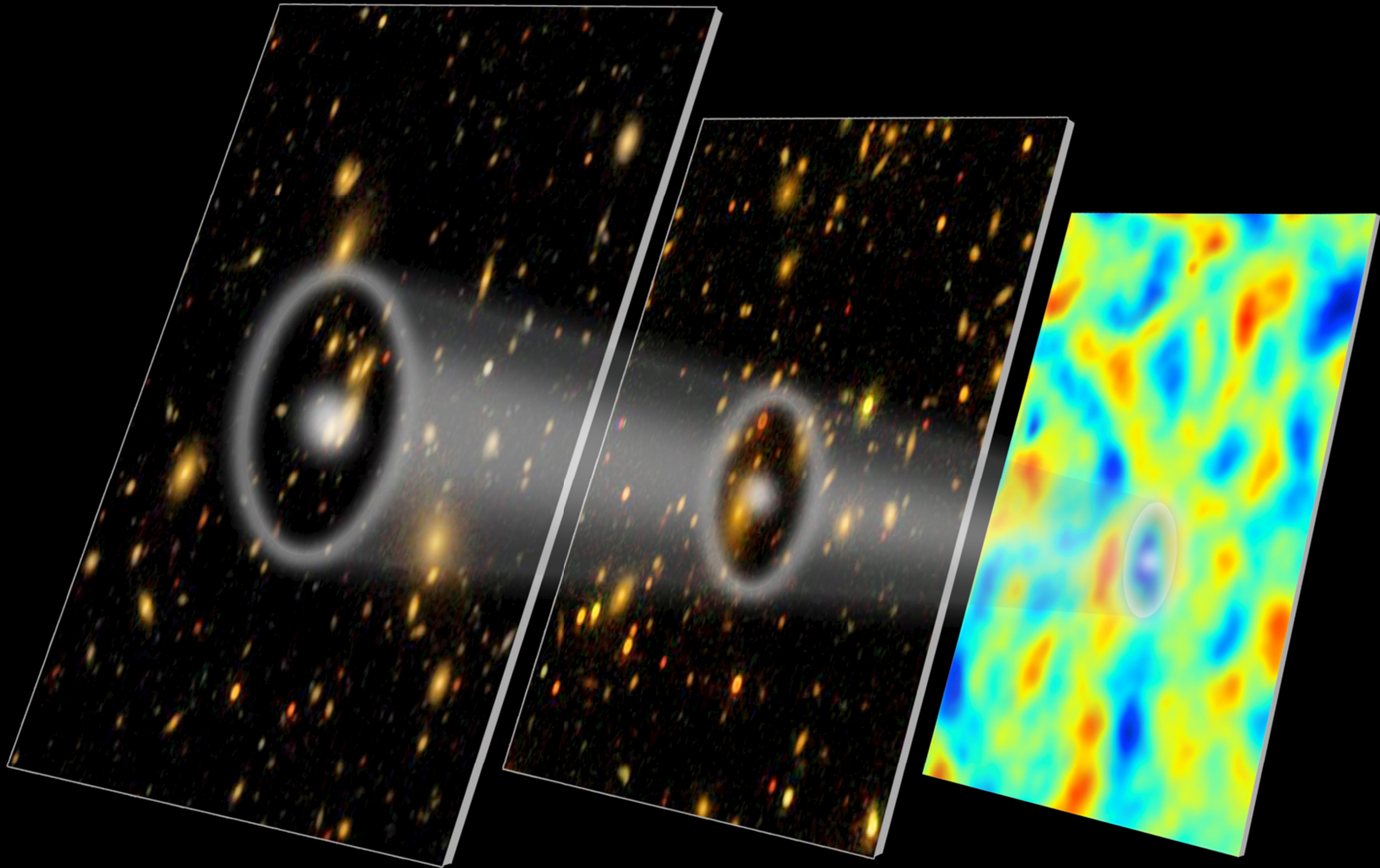
**Esperimento UA1, 1983, C. Rubbia
(Nobel per la Fisica 1984).**

Inflazione: disomogeneità

Le piccole disomogeneità che vediamo nella CMB si sarebbero originate da fluttuazioni quantistiche enfatizzate dall'Inflazione.



Inflazione: disomogeneità



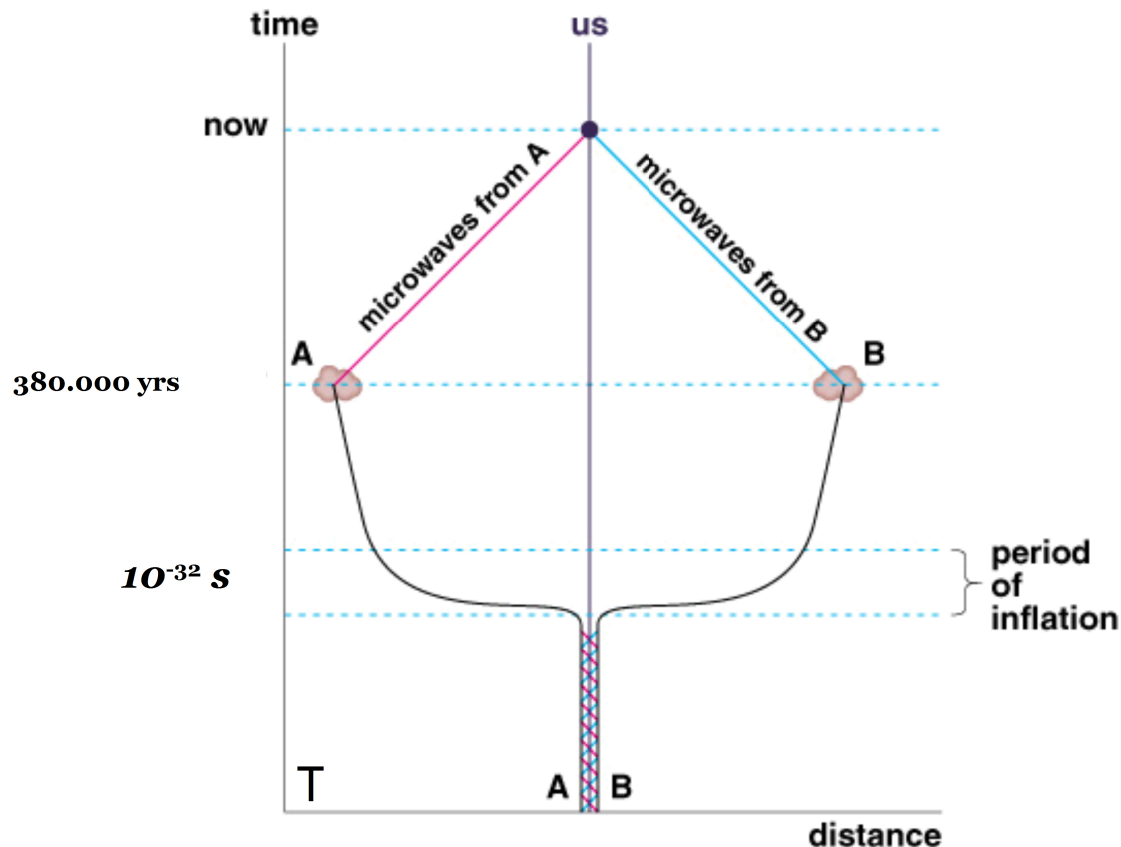
Galaxy map 3.8 billion years ago

Galaxy map 5.5 billion years ago

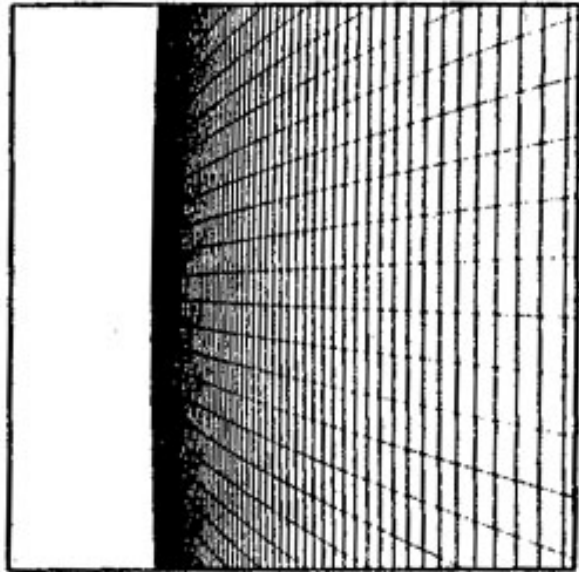
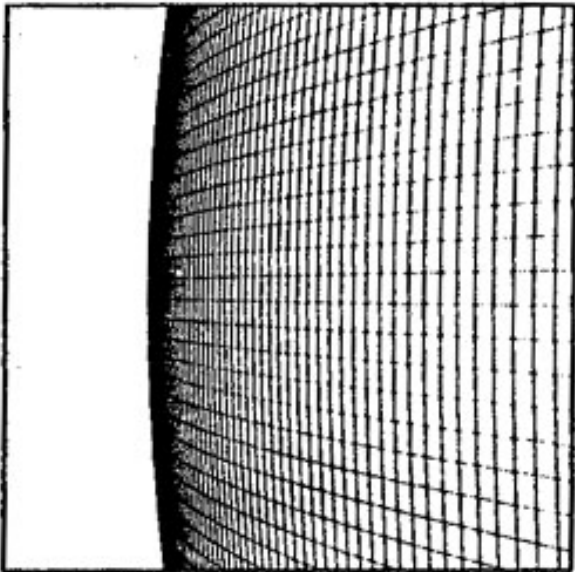
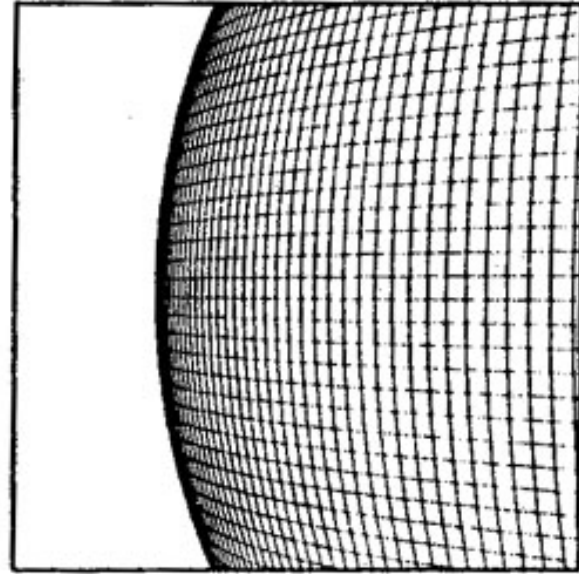
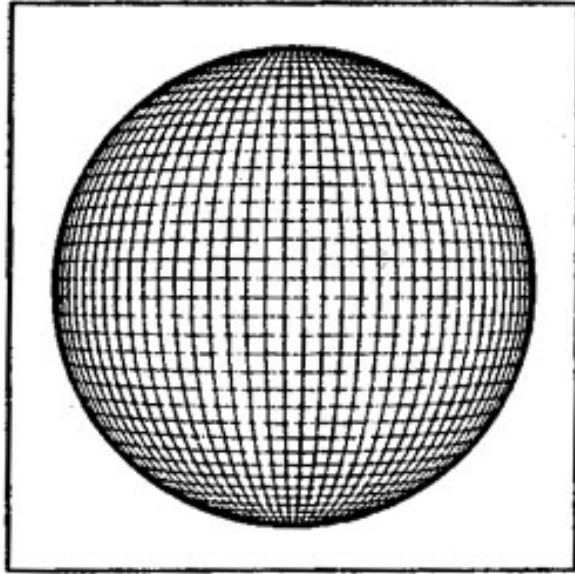
CMB 13.7 billion years ago

Inflazione: orizzonte

- Le regioni di cielo che oggi vediamo molto distanti, a causa dell'enorme espansione, erano in contatto prima dell'Inflazione
- Oggi hanno la stessa temperatura

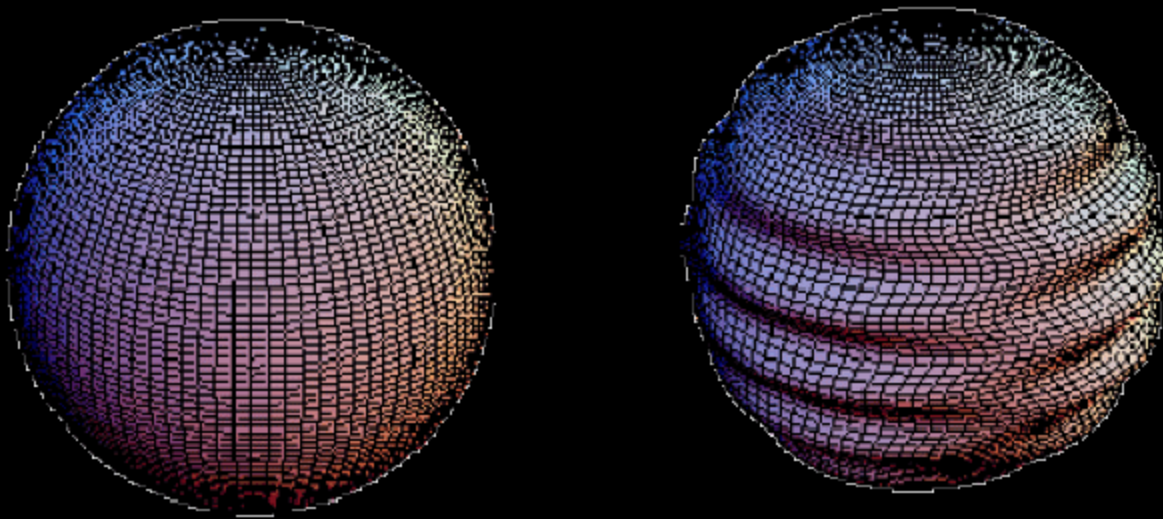


Inflazione: piattezza

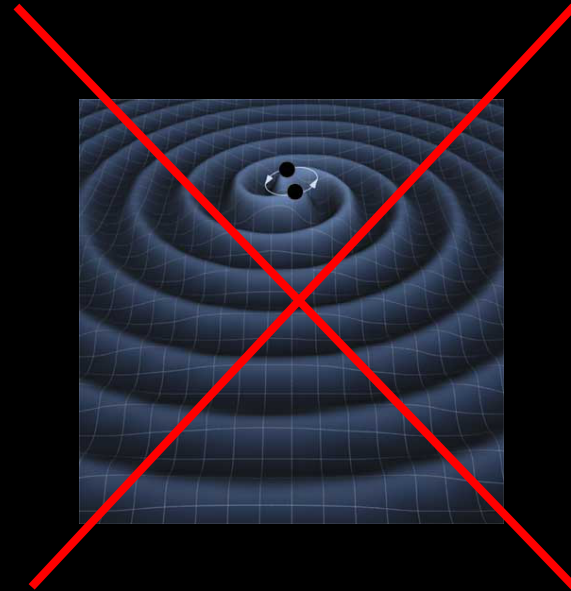


Inflazione: ?

- L'Inflazione spiega efficacemente alcune caratteristiche dell'Universo osservabile che il modello di Big Bang non spiega
- Il fatto che si sia verificata non è ancora confermato
- E' possibile provare che l'Inflazione si è verificata?

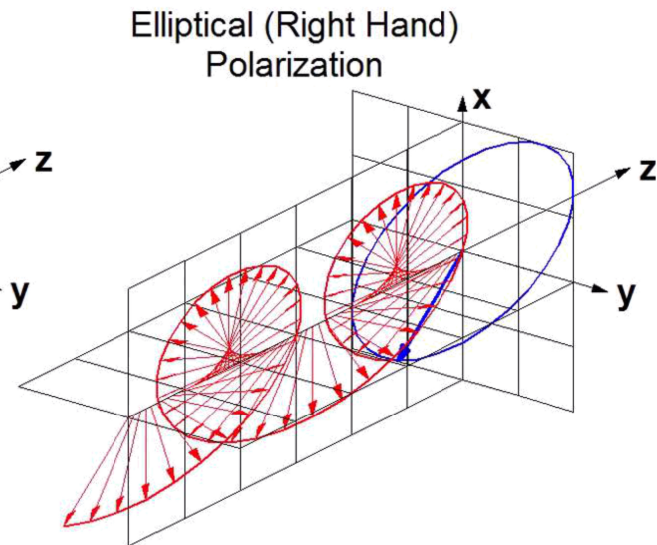
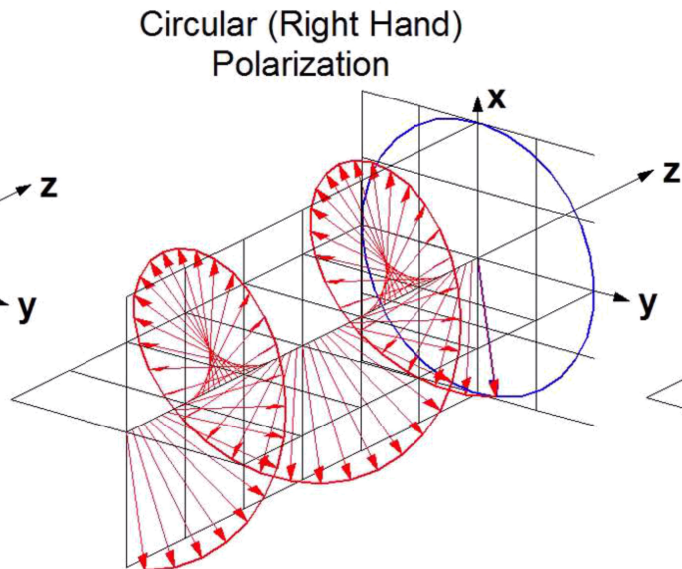
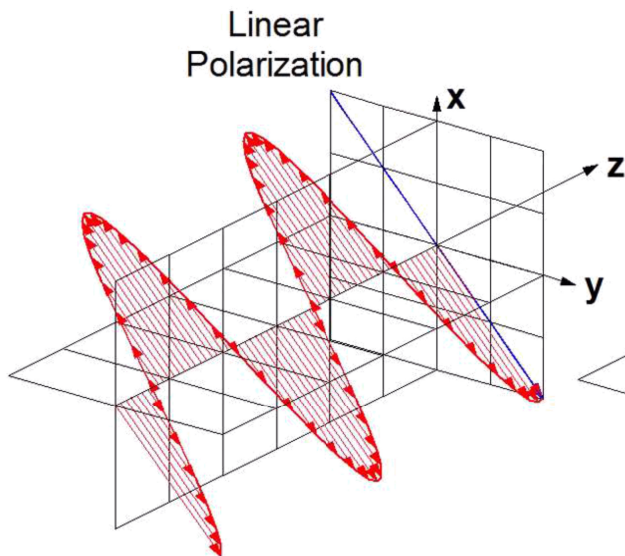


**ONDE GRAVITAZIONALI
PRIMORDIALI**



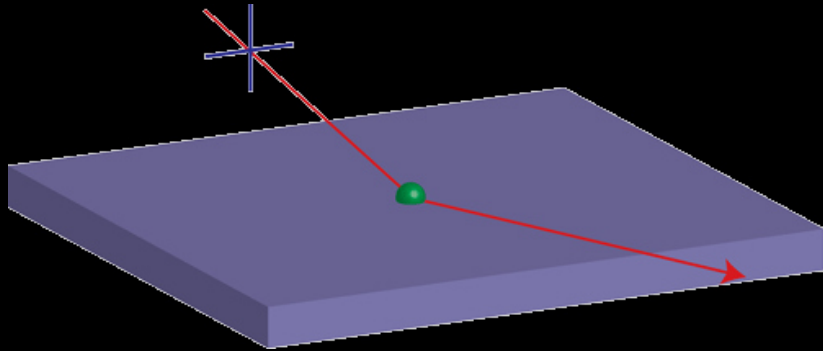
Polarizzazione della Radiazione di Fondo

- La Radiazione di Fondo è polarizzata
- Analogia con la luce solare
- Riflessione della luce solare da parte di acqua o metalli

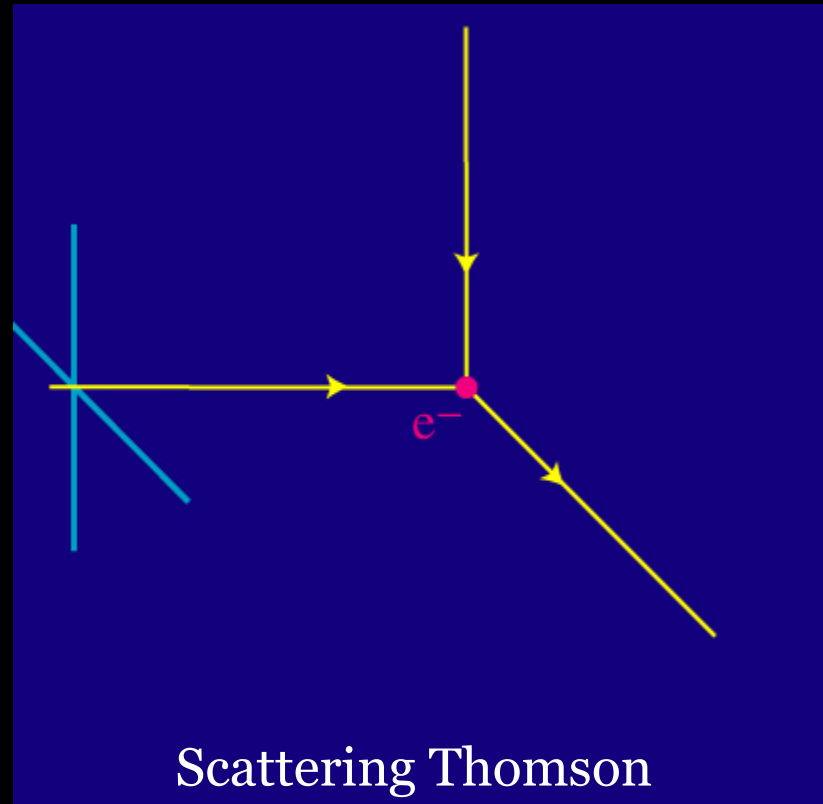


Polarizzazione della Radiazione di Fondo

- Radiazione di fondo polarizzata per il 10%
- Riflessione dei fotoni da parte di elettroni liberi (Scattering Thomson)

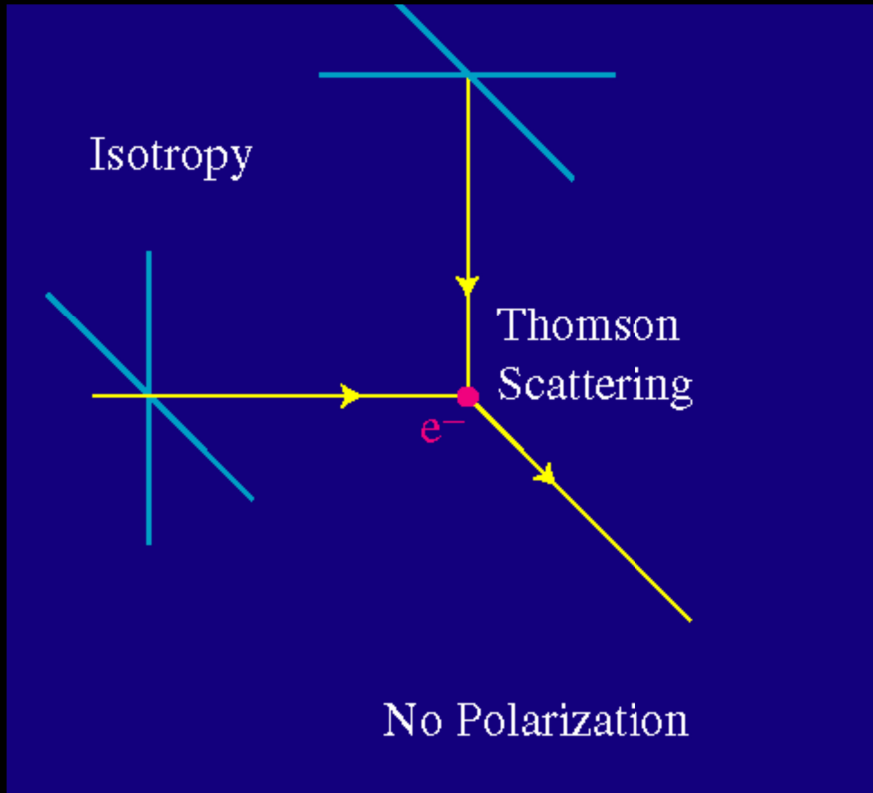


Polarizzazione per riflessione
da materia

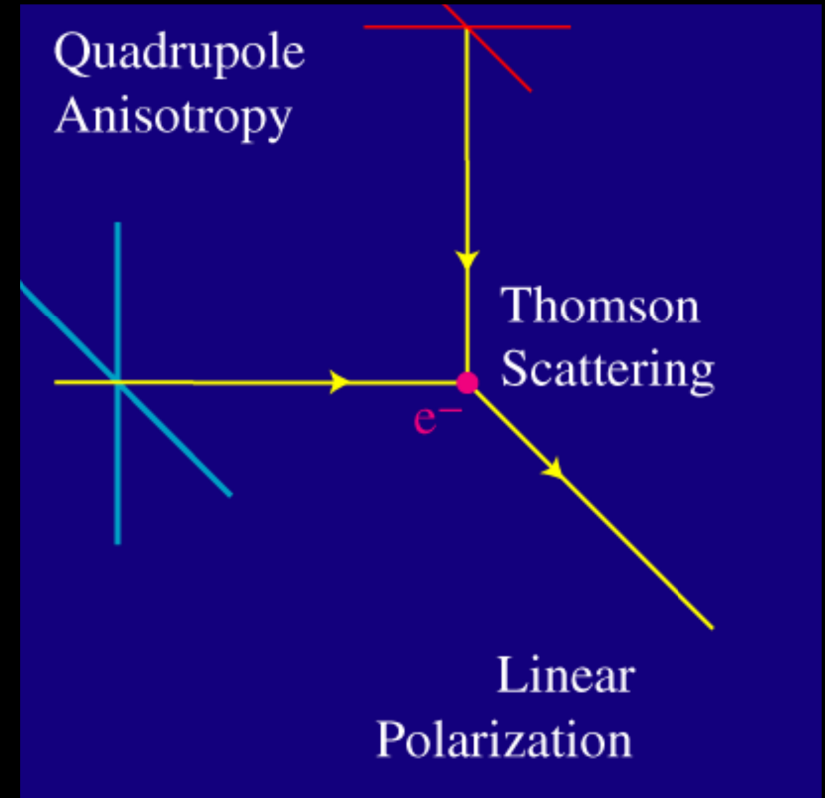


Scattering Thomson

Polarizzazione della Radiazione di Fondo



Nessuna Polarizzazione

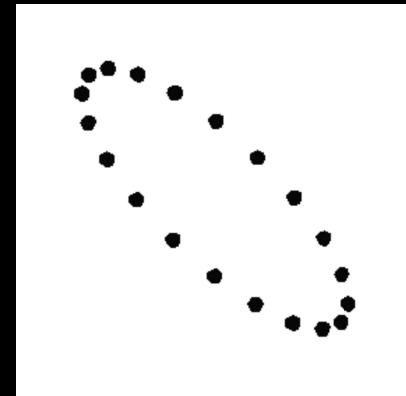
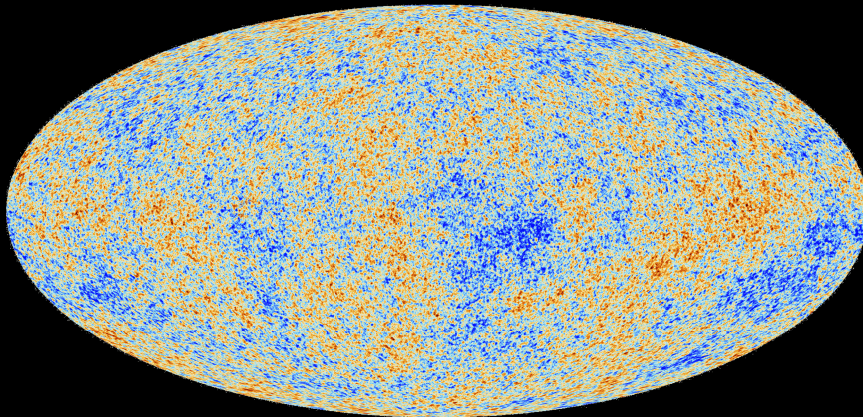


Polarizzazione

Modi E, Modi B

L'inflazione ha agito su:

1. **materia e radiazione**, producendo variazioni locali di temperatura/densità (**modi E**, in analogia con il campo Elettrico). La polarizzazione è circolare.
2. **campo gravitazionale**, producendo onde gravitazionali (**modi B**, in analogia con il campo magnetico). La polarizzazione è “vorticiosa”.



Modi E, Modi B

FINDINGS

From Inflation to Gravitational Waves to Polarized Light

If a period of inflation rapidly stretched the universe just after it was born, we might be able to find proof in some of the oldest light we see: the cosmic microwave background (CMB), which was emitted just 380,000 years after the big bang. During inflation, quantum fluctuations in the universe's gravitational field would have been amplified into gravitational waves, or ripples in the fabric of spacetime. Such waves could polarize the CMB, and the BICEP2 experiment seems to have identified such polarization.

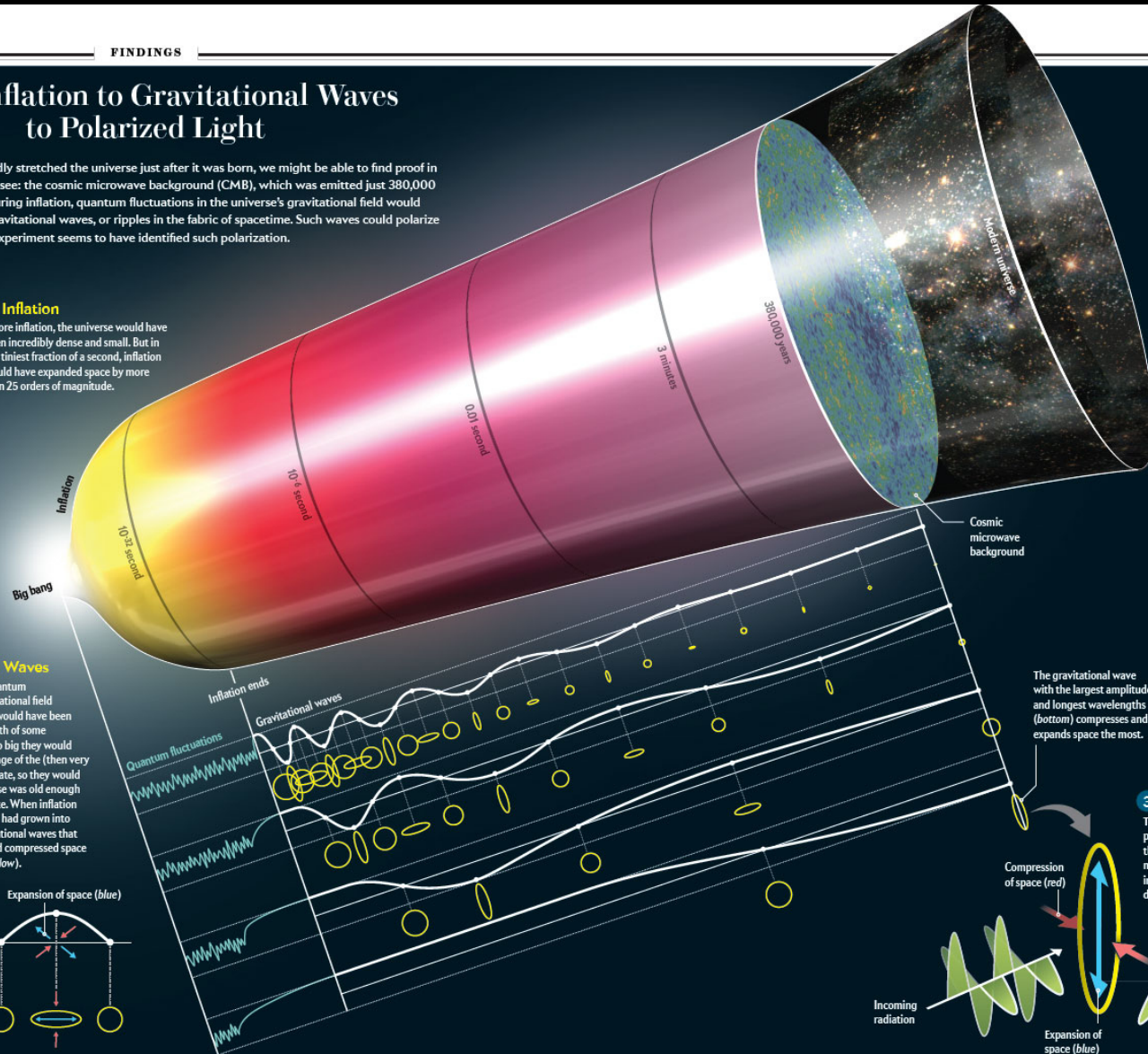
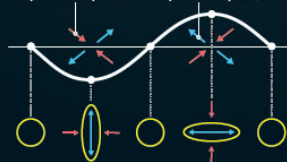
1 Inflation

Before inflation, the universe would have been incredibly dense and small. But in the tiniest fraction of a second, inflation would have expanded space by more than 25 orders of magnitude.

2 Gravitational Waves

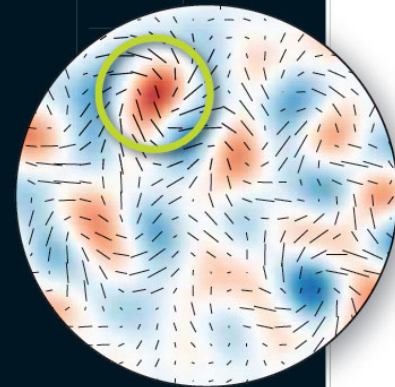
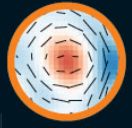
During inflation, tiny quantum fluctuations in the gravitational field pervading the universe would have been stretched. The wavelength of some fluctuations would get so big they would require longer than the age of the (then very young) universe to oscillate, so they would "freeze" until the universe was old enough for them to again oscillate. When inflation ended, these oscillations had grown into long-wavelength gravitational waves that alternately stretched and compressed space around them (ellipses below).

Compression of space (red) Expansion of space (blue)



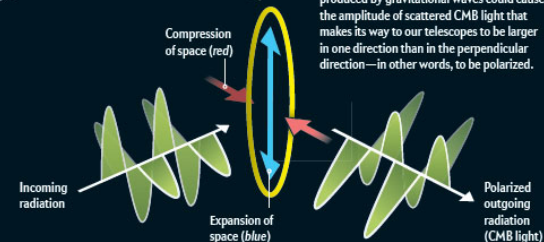
4 Pinwheels

Polarization can take several forms. Normal local temperature and density fluctuations in space produce a radial or circular pattern of polarization (orange circle). Gravitational waves, however, produce a striking pinwheel pattern (below). Red spots here are where space has been compressed, so photons are packed tighter together and the radiation is hotter. Blue areas are cooler.



3 Polarization

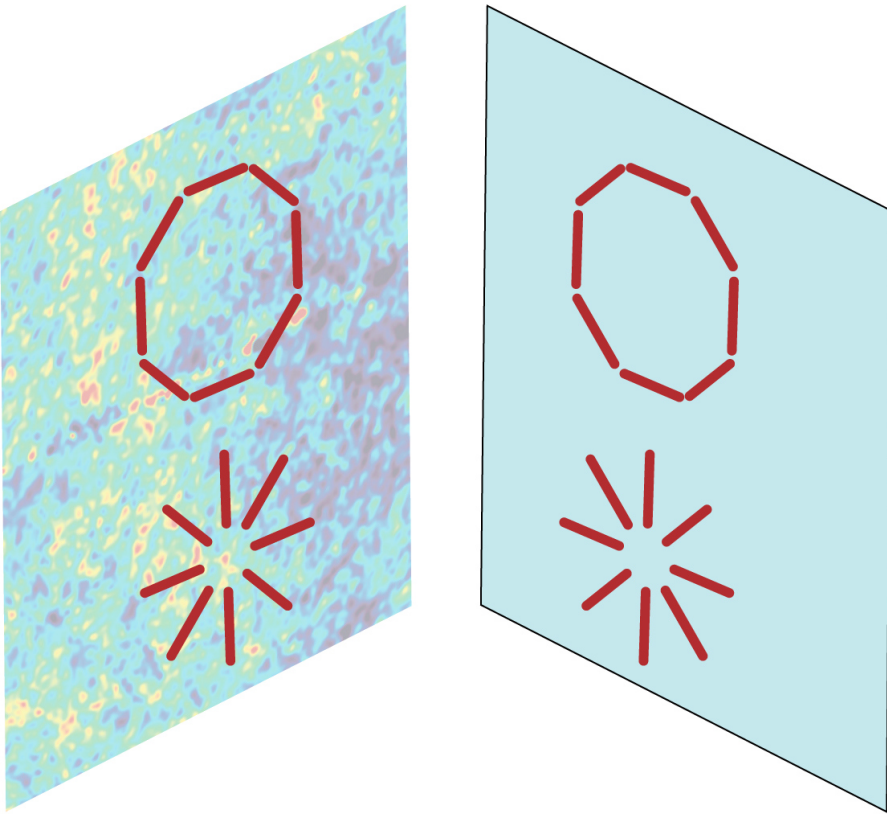
The compression and expansion of space produced by gravitational waves could cause the amplitude of scattered CMB light that makes its way to our telescopes to be larger in one direction than in the perpendicular direction—in other words, to be polarized.



Polarizzazione della Radiazione di Fondo

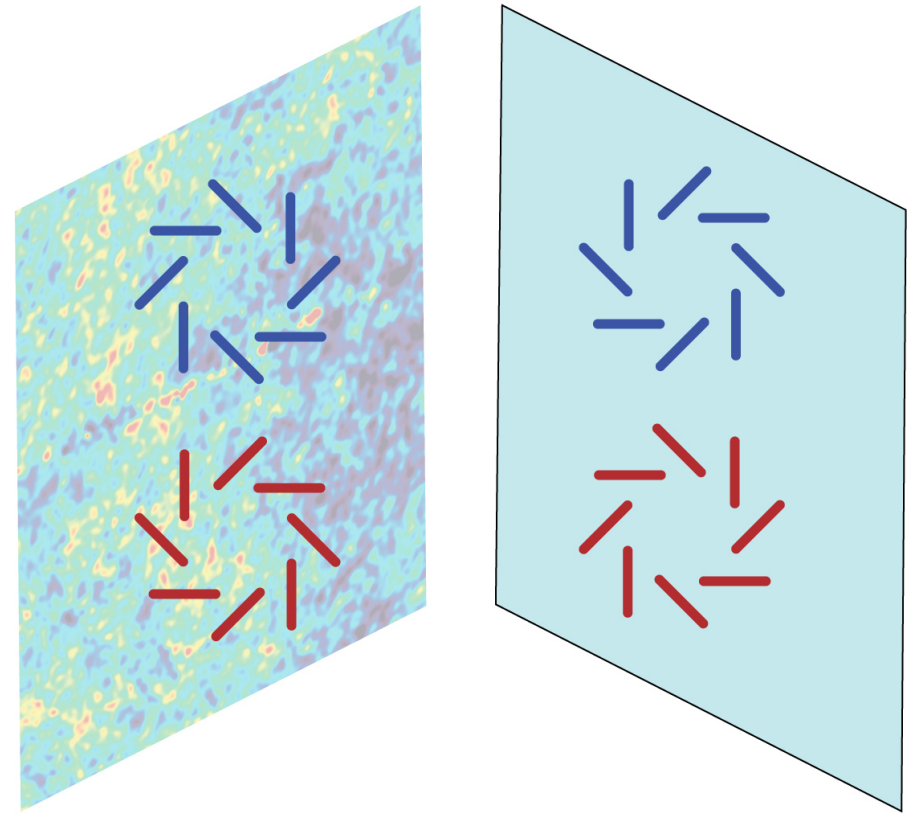
10^{-5} K

$r = ?$



MODI E

Anisotropie T



MODI B

Onde Gravitazionali
Primordiali

Radiometro



Sensibilità di un radiometro

Il più piccolo segnale rilevabile da un radiometro è dato dall'espressione

$$\Delta T = K \frac{T_A + T_N}{\sqrt{B \cdot \tau}}$$

T_N rumore che disturba l'acquisizione

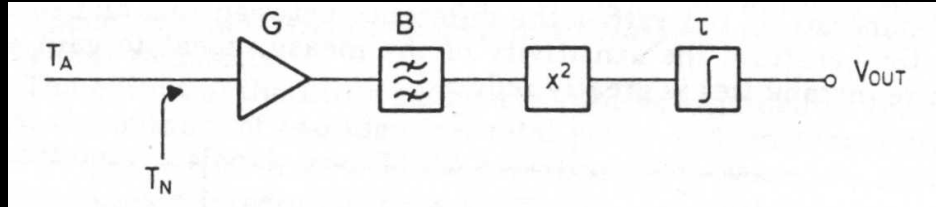
1. **Sorgenti esterne** di rumore: interferenze locali, effetti atmosferici, sorgenti galattiche (nel caso di osservazioni dallo spazio)
2. **Sorgenti interne** di rumore: effetti quantistici elettroni conduzione (**rumore termico – non termico**)

Rumore termico: moto termico elettroni in una resistenza produce corrente casuale (white noise)

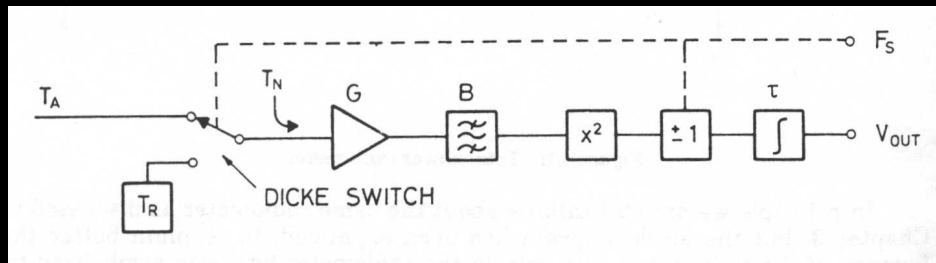
Rumore non-termico: difetti superficiali materiali (rumore $1/f$, aumenta a bassa frequenza)

Diverse architetture

Total Power, Dicke, correlazione



Total Power

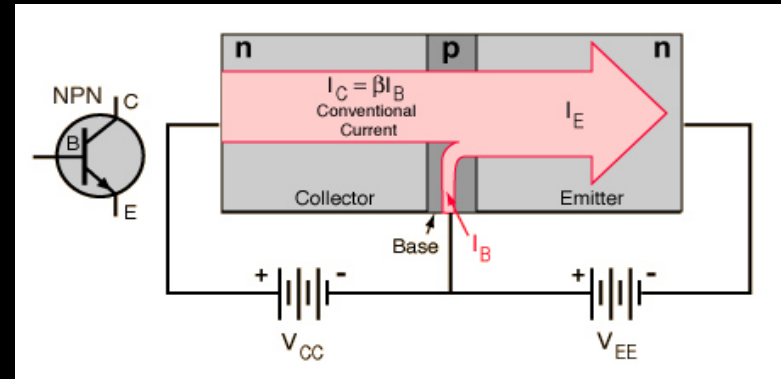


Dicke

Differenza tra input e riferimento
> meno sensibile a fluttuazioni
di guadagno e rumore

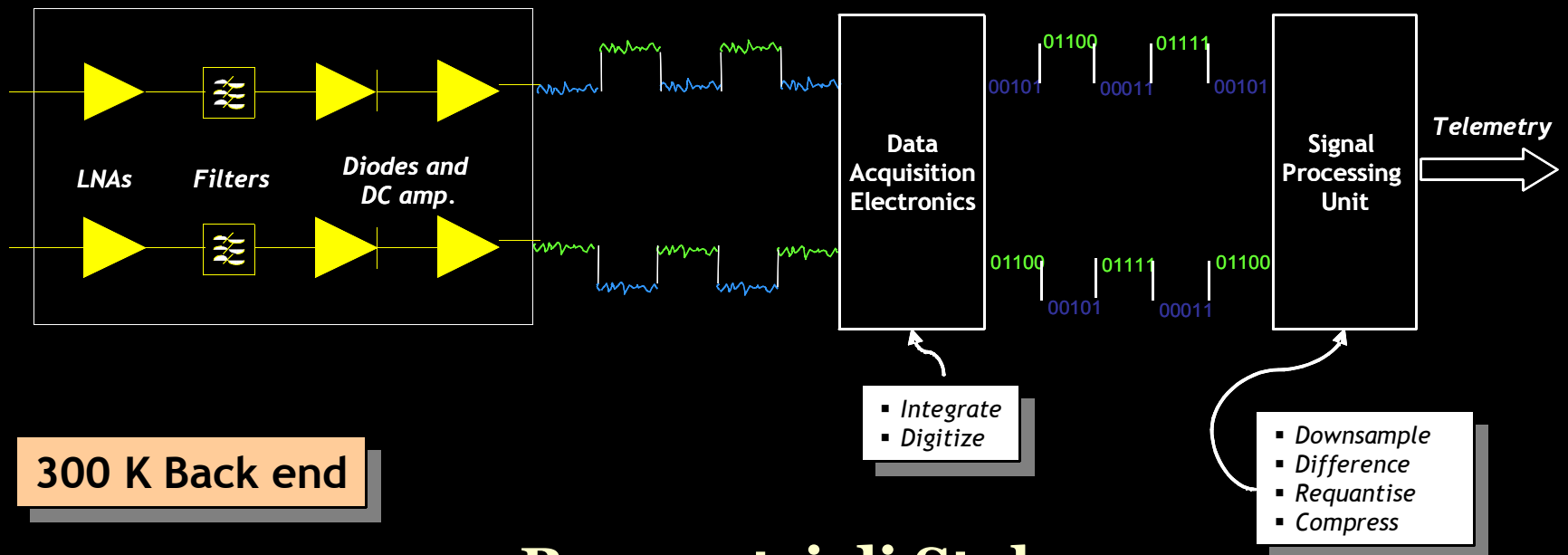
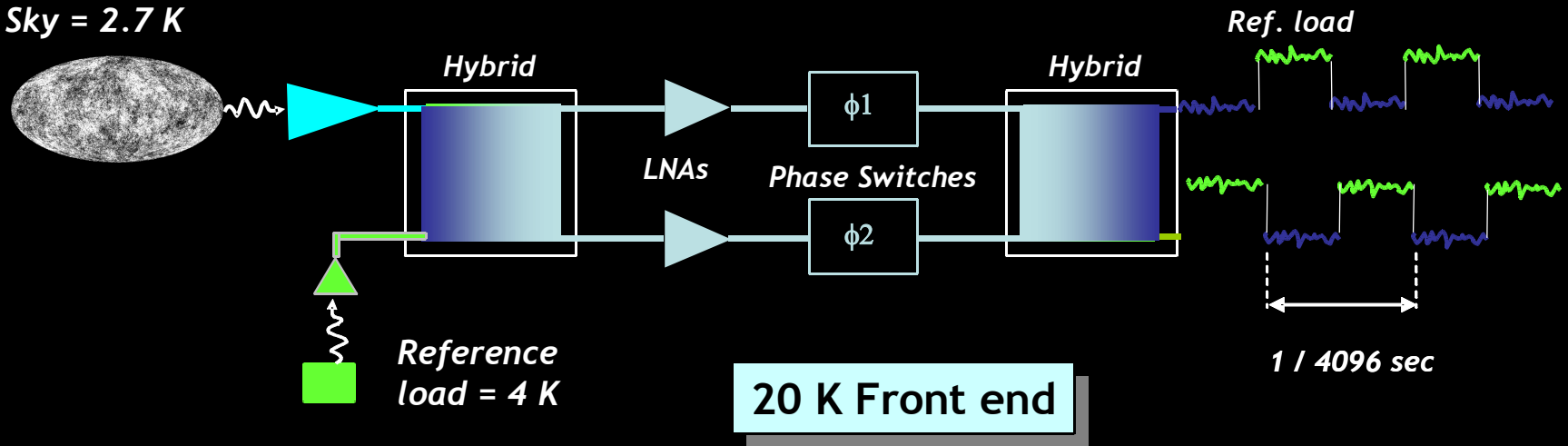
Composti da:

1. filtro (limitare la risposta in frequenza)
2. stadi di amplificazione (HEMT, $G=10^6$)
3. diodi conversione segnale R.F. in corrente continua proporzionale a intensità della radiazione incidente



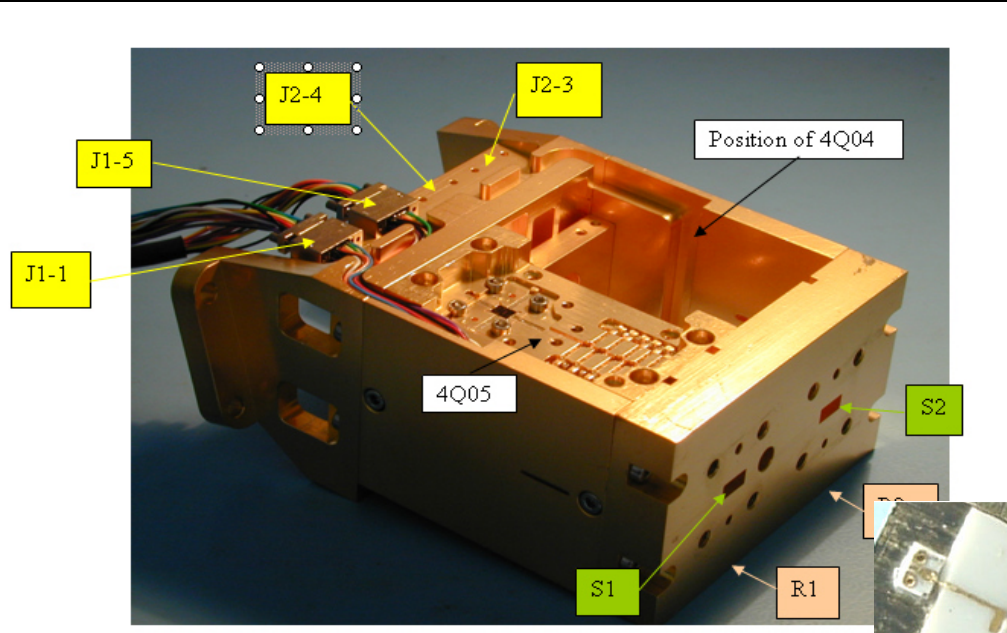
Radiometro a correlazione

Sky = 2.7 K



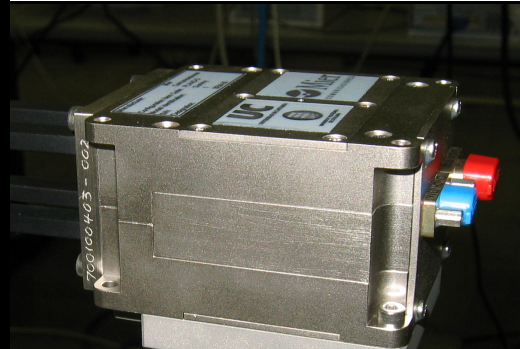
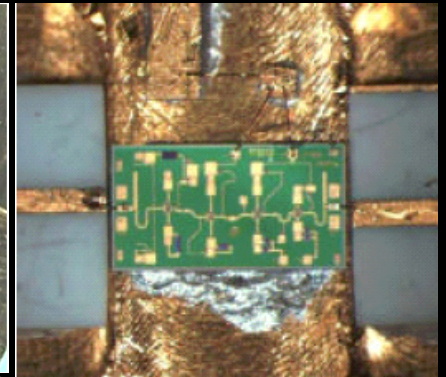
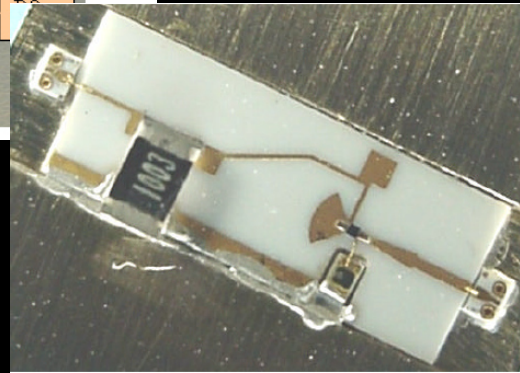
Parametri di Stokes

Amplificatori, filtri, etc.

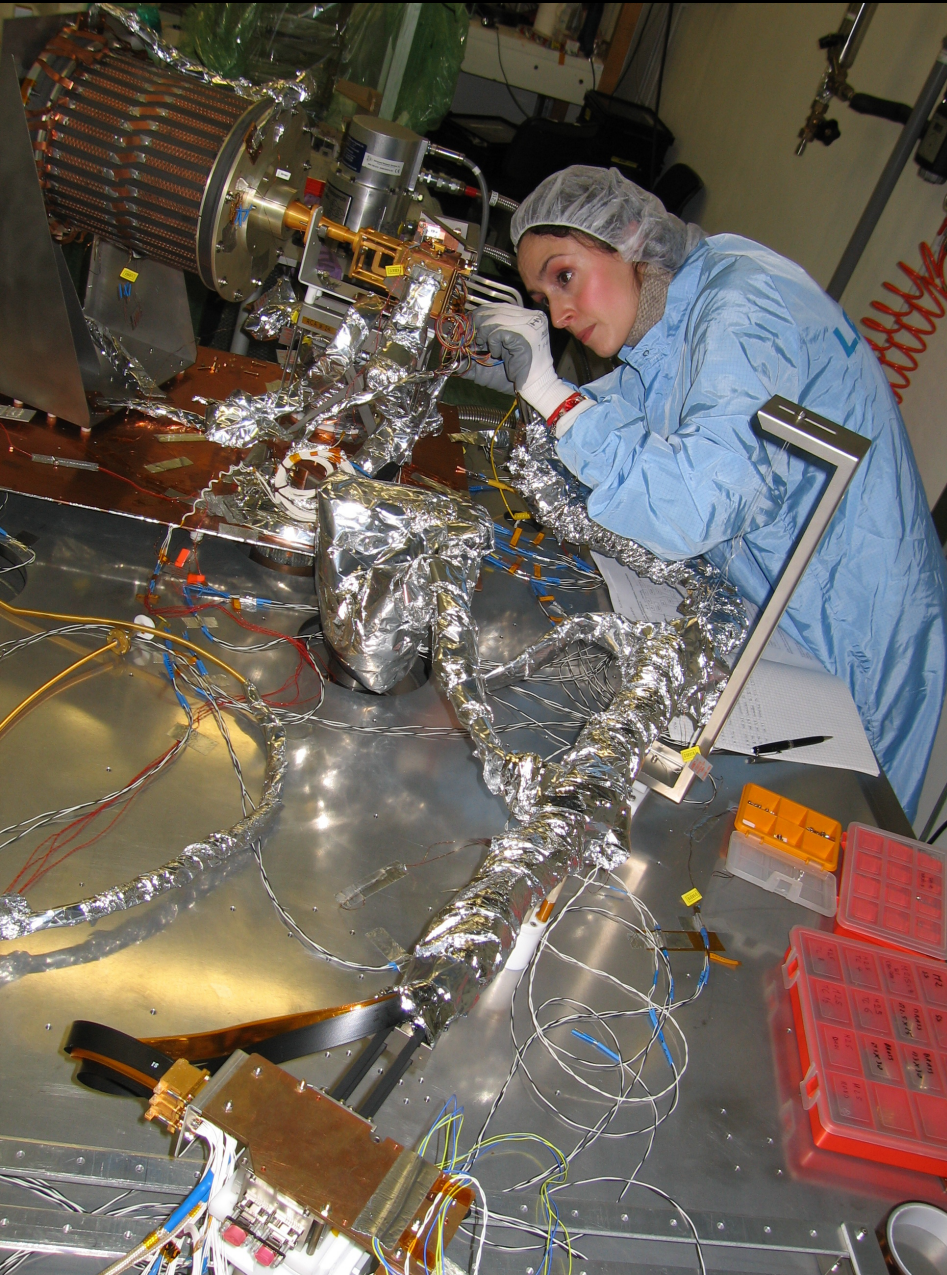


Planck LFI FEM

Planck LFI BEM



Test...complicati!



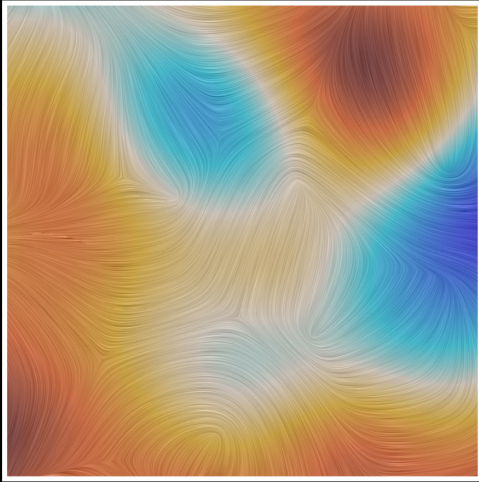
Riprodurre le condizioni operative durante la fase di caratterizzazione e calibrazione:

1. camere criogeniche
2. possibilità di fare il “vuoto” (10^{-6} mbar)
3. acquisizione e registrazione dei test
4. protezione da ESD (electrostatic Discharge)
5. protezioni da disturbi condotti lungo le linee di alimentazione

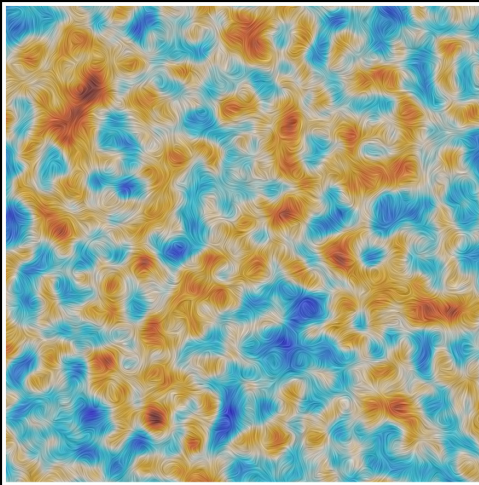
...e molto altro ancora!

I modi E di Planck

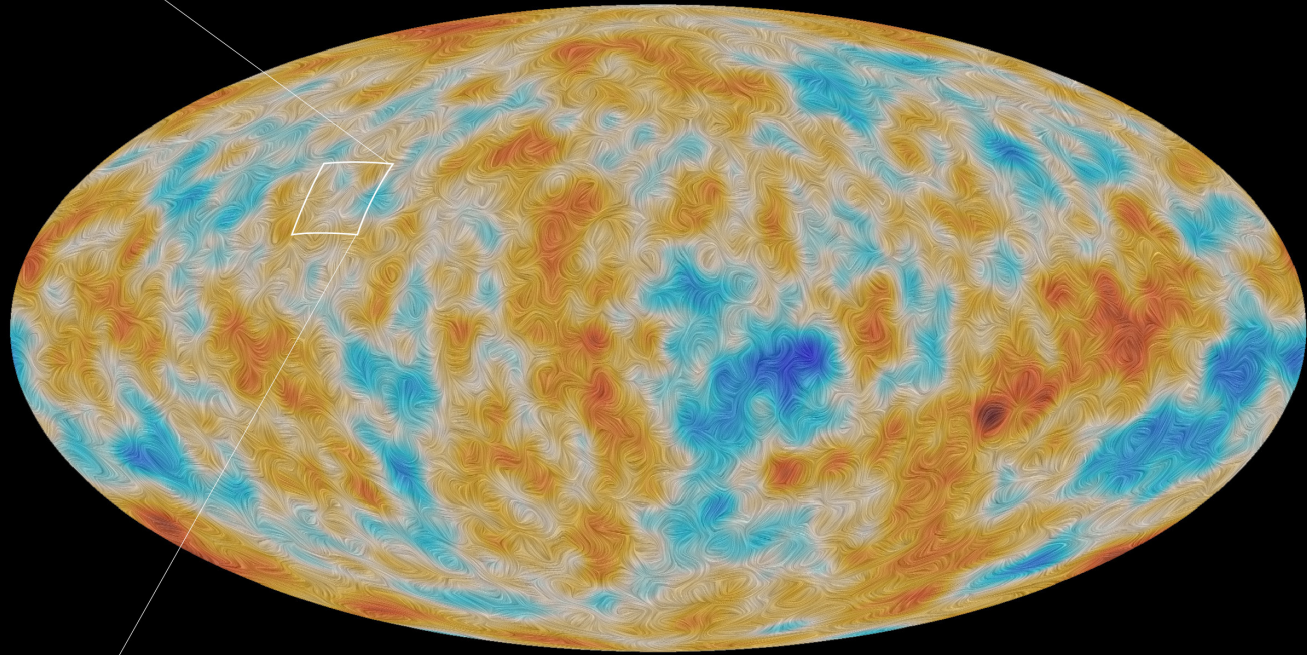
→ PLANCK'S POLARISATION OF THE COSMIC MICROWAVE BACKGROUND



Filtered at 5 degrees



Filtered at 20 arcminutes



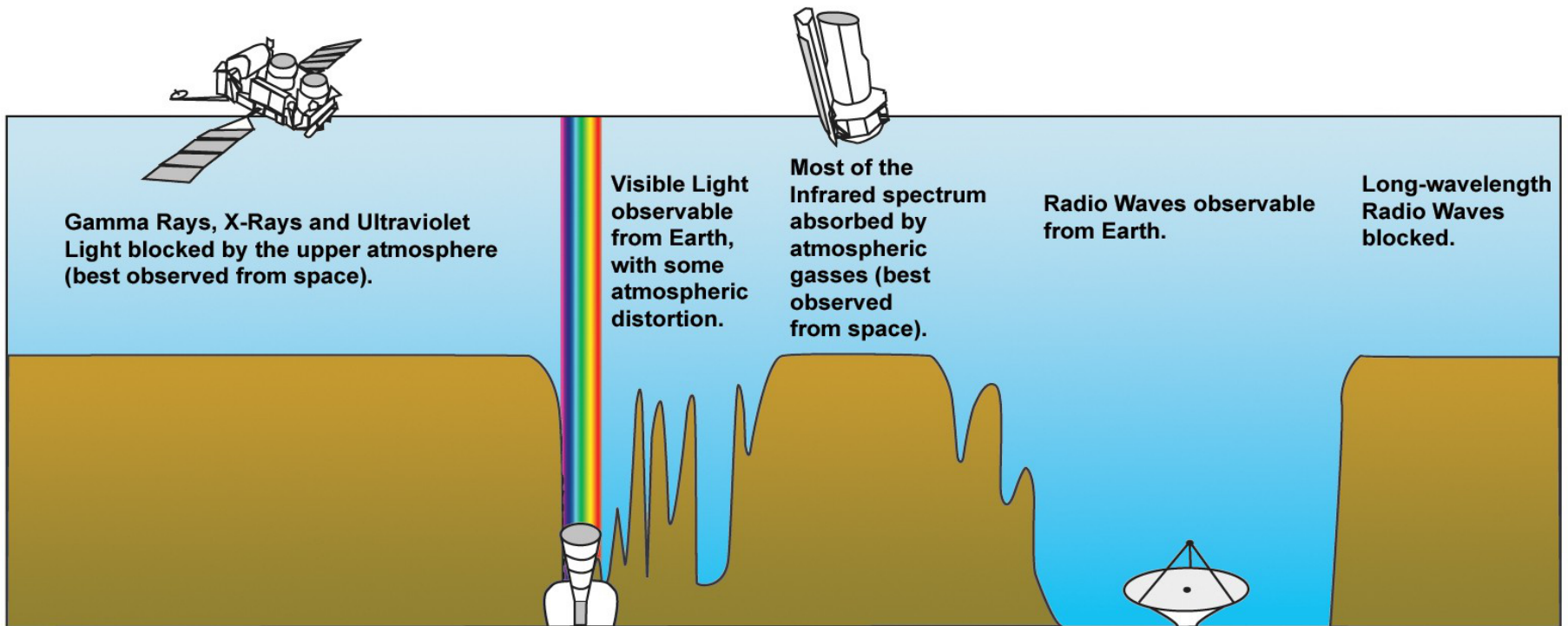
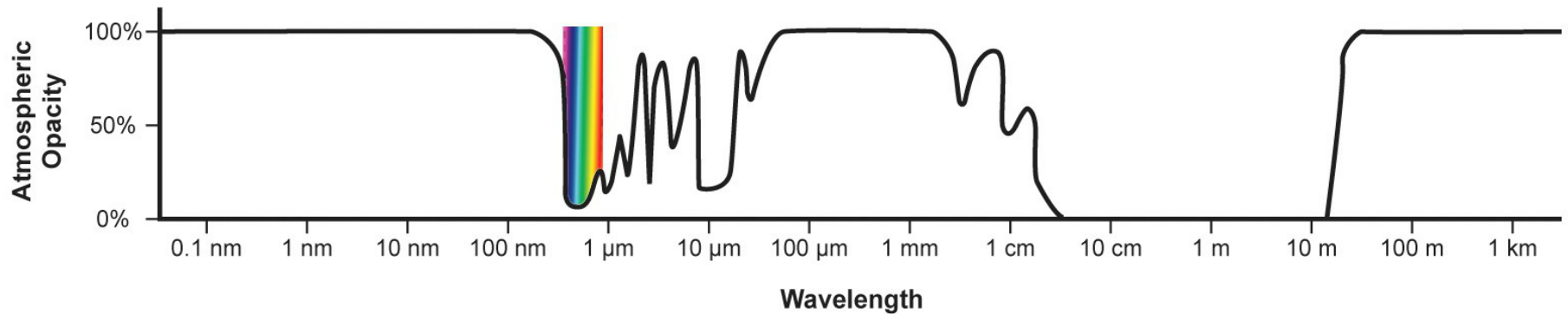
Full sky map
Filtered at 5 degrees

I modi B di Planck?

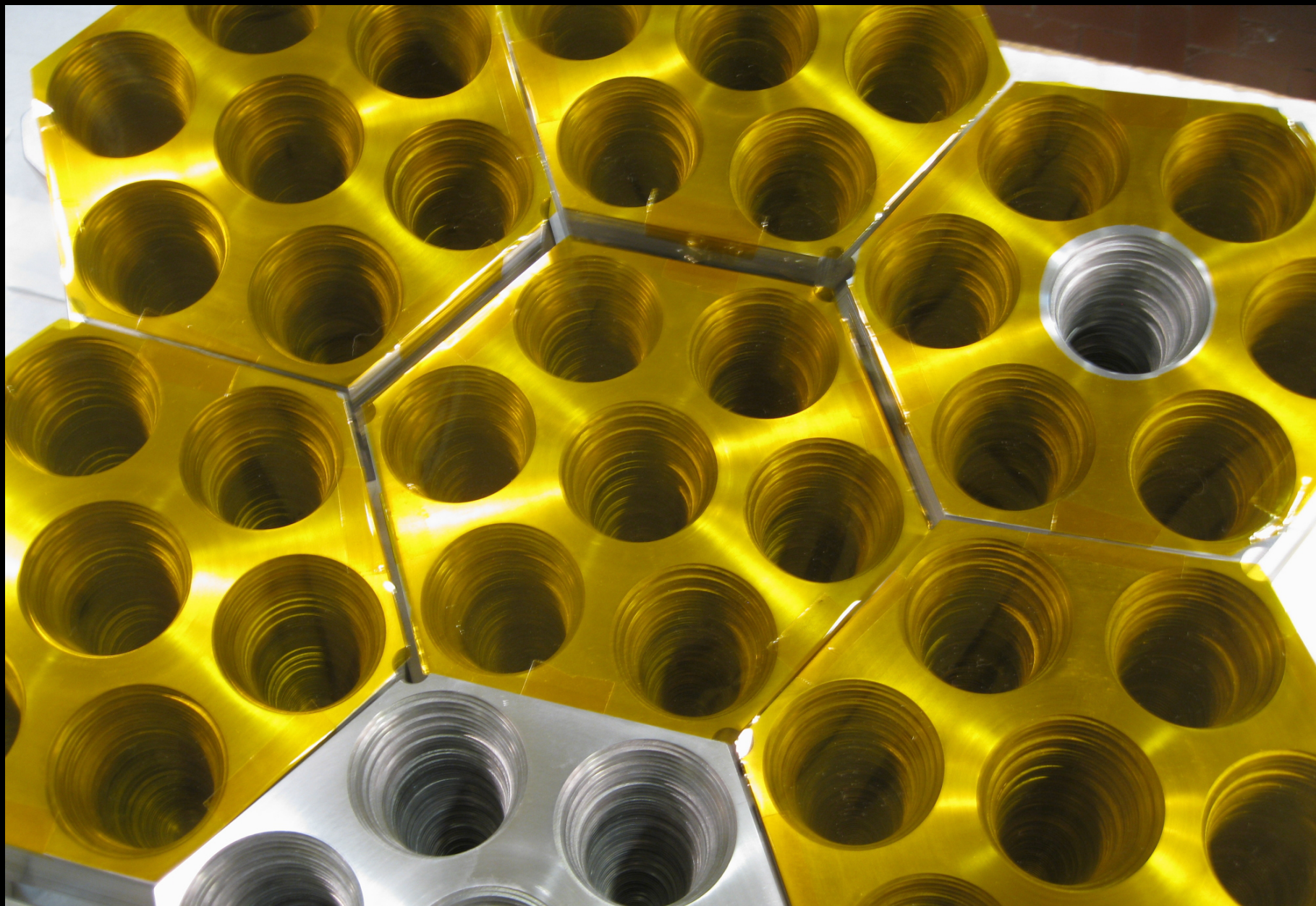
- Planck non aveva abbastanza sensibilità per vedere i modi B
- Planck ha posto un limite superiore per l'intensità dei modi B che ha permesso di escludere molti modelli inflazionari
- Sono previste future missioni da terra (palloni stratosferici e telescopi da terra): QUBIC, LSPE.



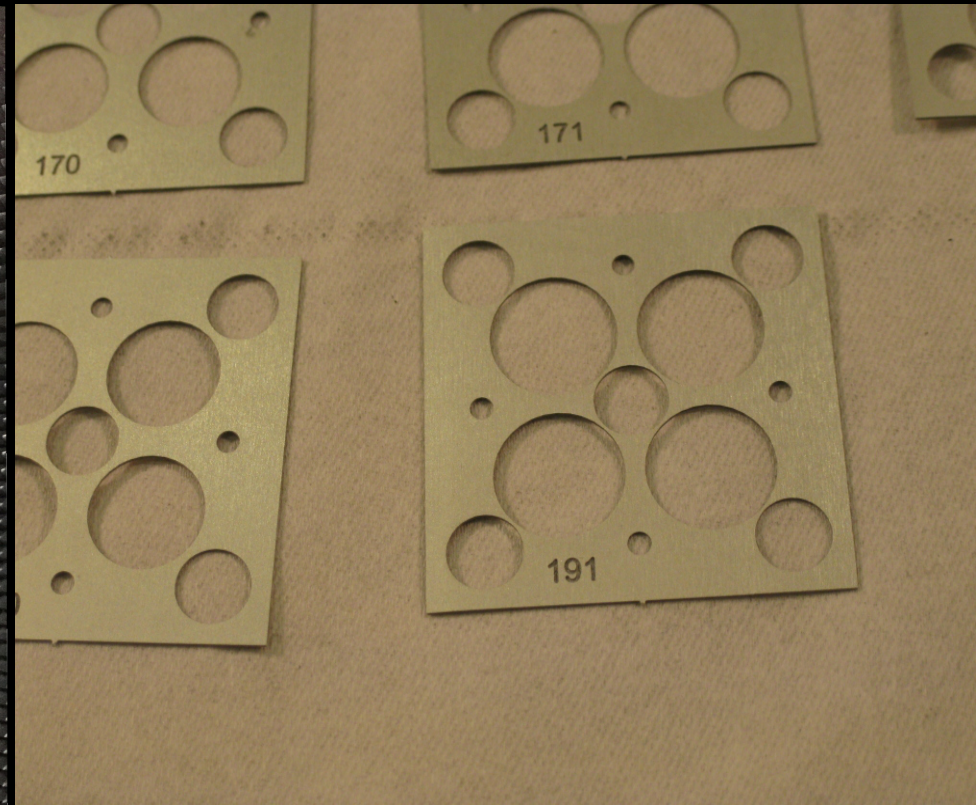
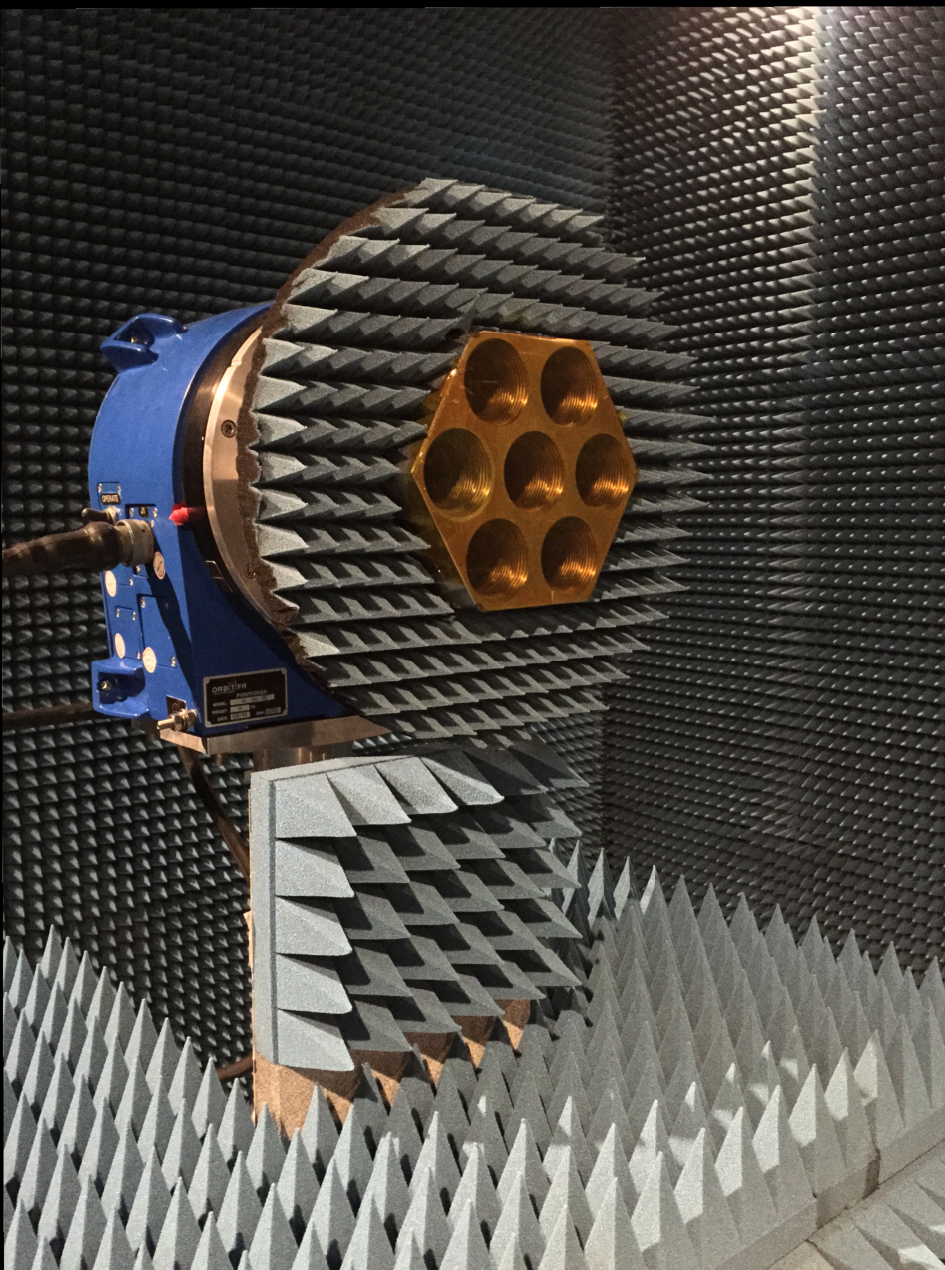
Trasparenza atmosferica



Antenne “platelet”



Camera anecoica



**Tecnica “platelet”
(Dip. Di Fisica, UniMI)**

**Modulo di LSPE in camera anecoica
(Dip. Di Fisica, UniMI)**

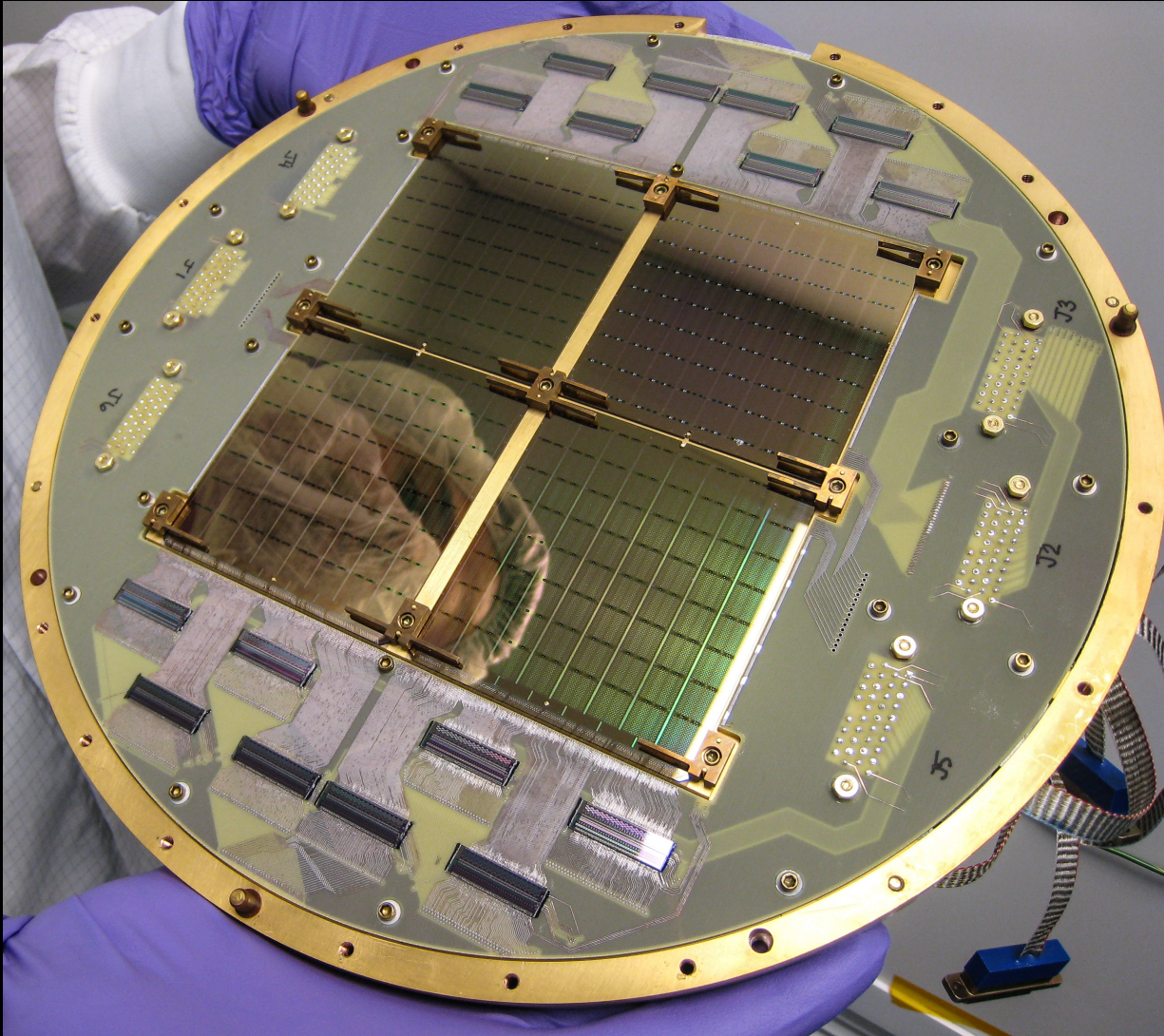
Bicep 2

17 Marzo 2014

L'esperimento Bicep2 annuncia di aver osservato i modi B nella polarizzazione della Radiazione di Fondo.



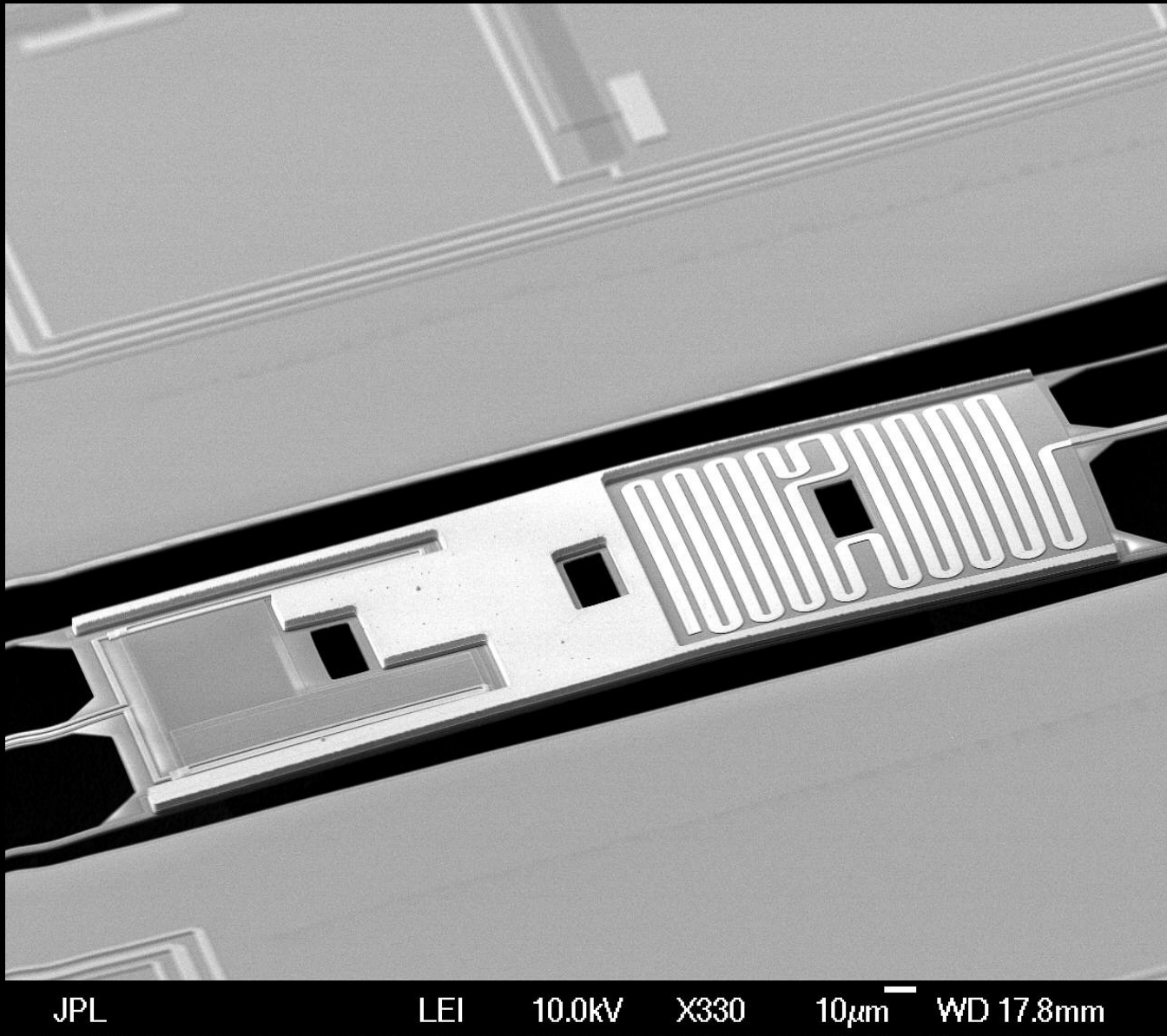
Bicep 2



512 bolometri

**T operativa:
0.25 K**

Bicep 2



Bicep 2

nature

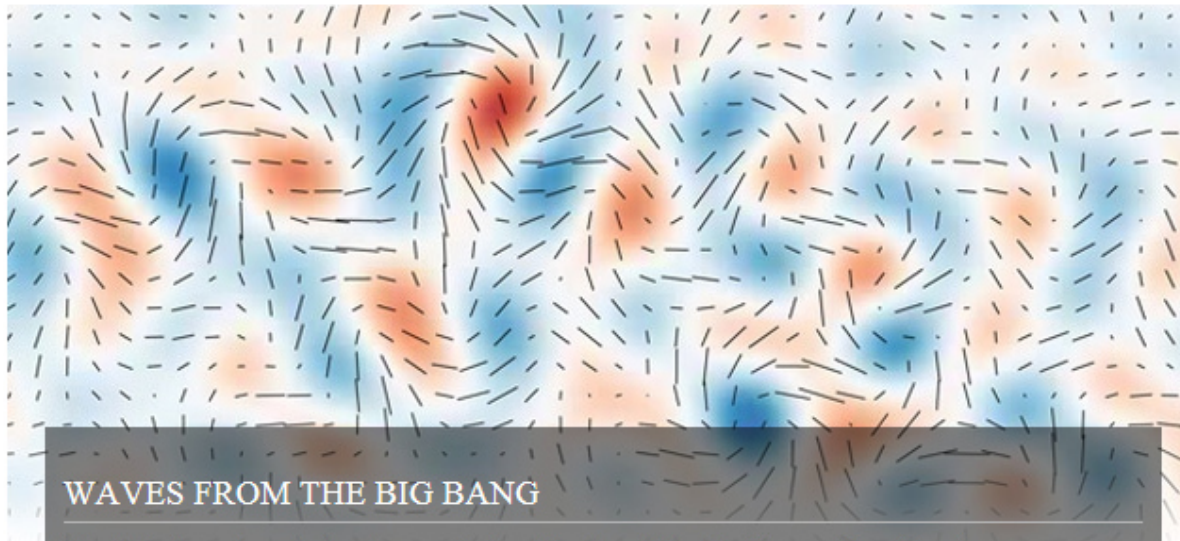
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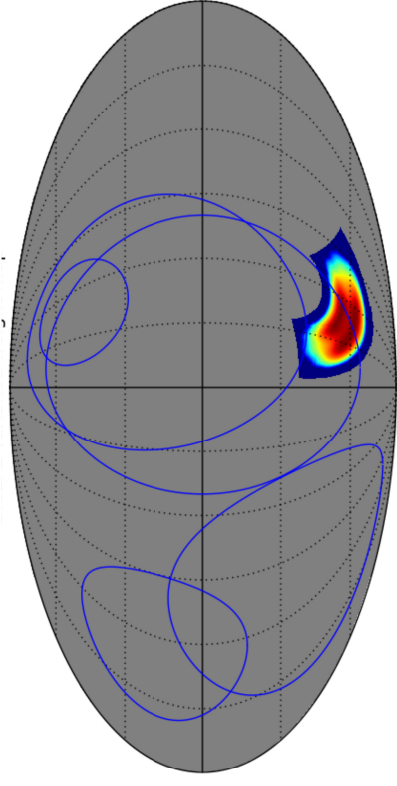
WAVES FROM THE BIG BANG

The detection of gravitational waves in the afterglow of the Big Bang — if confirmed — opens a new chapter in astronomy, cosmology and physics. The signature, seen by the BICEP2 radio telescope at the South Pole, packs at least three discoveries into one: It provides the most direct evidence for the existence of the waves predicted by Einstein; it is the proof of 'cosmic inflation' that physicists had been eagerly awaiting; and it opens a window into the unification of the fundamental forces of nature and into quantum gravity. In this special collection, *Nature News* has the most comprehensive and up-to-date coverage of the breakthrough and its aftermath.

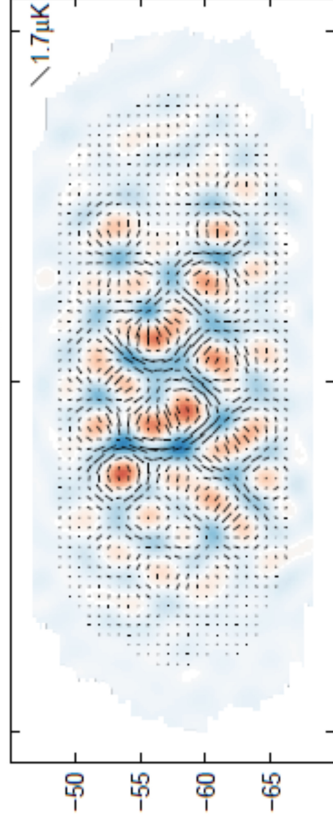
Image credit: BICEP2 Collaboration

Bicep 2

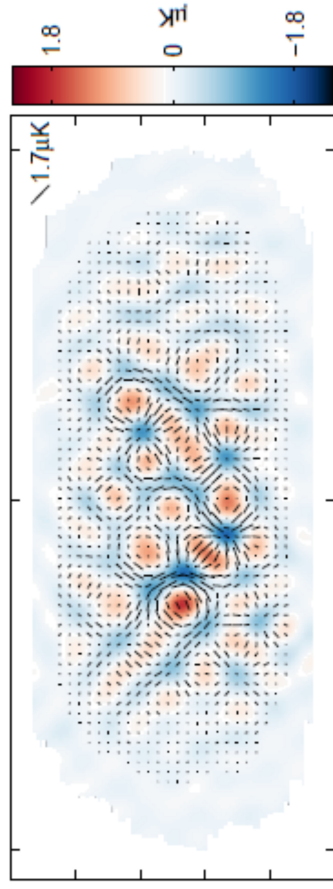
Mappa in polarizzazione
(modi E, modi B) @150
GHz (150 miliardi di Hz)
prodotta da BICEP 2.



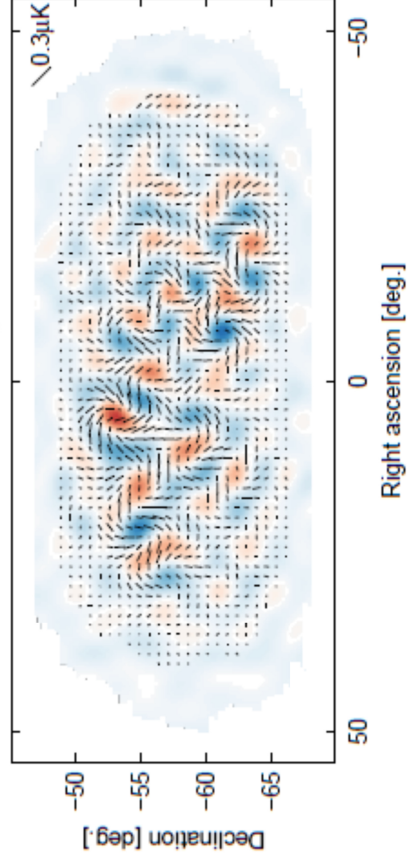
BICEP2: E signal



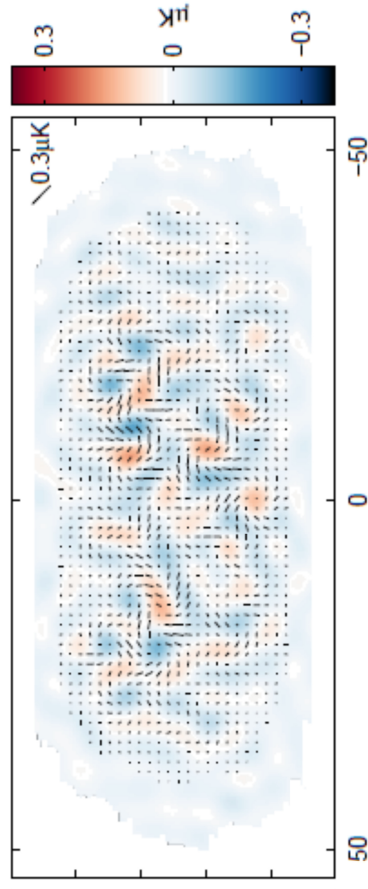
Simulation: E from lensed- Λ CDM+noise



BICEP2: B signal



Simulation: B from lensed- Λ CDM+noise



Polvere Galattica

- L'intensità dei modi B vista da Bicep2 non è compatibile con il limite superiore calcolato dai dati di Planck.
- Il segnale visto da Bicep2 è quello emesso dalla polvere interstellare della nostra galassia polarizzata dal campo magnetico galattico.

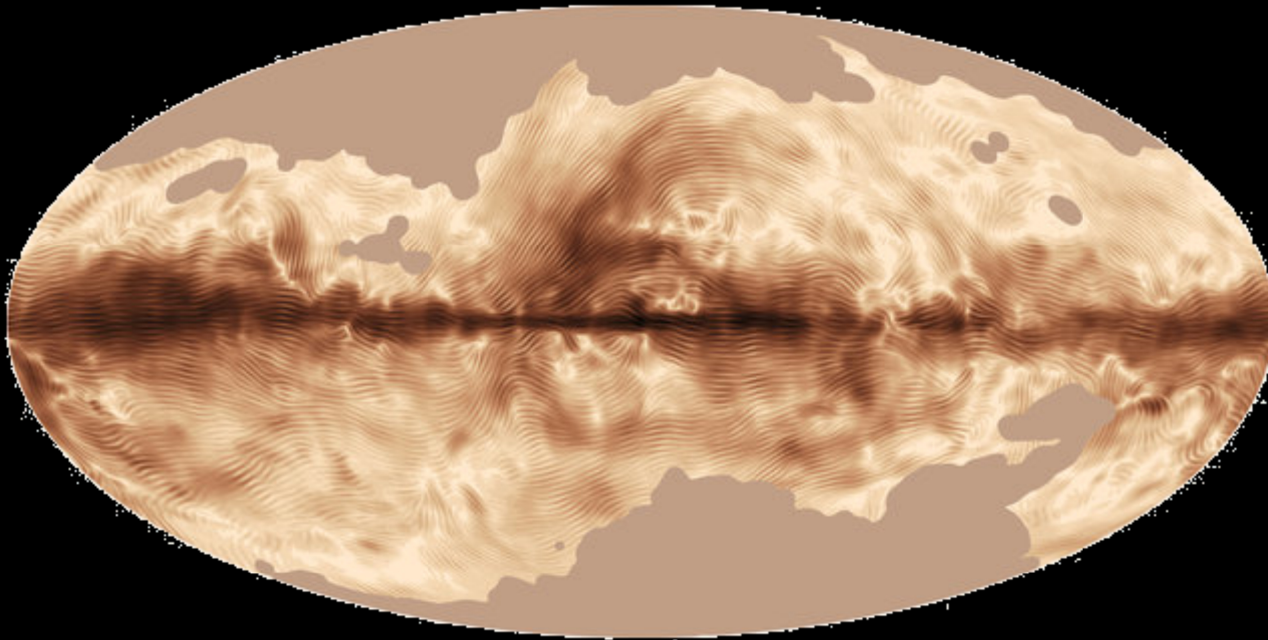
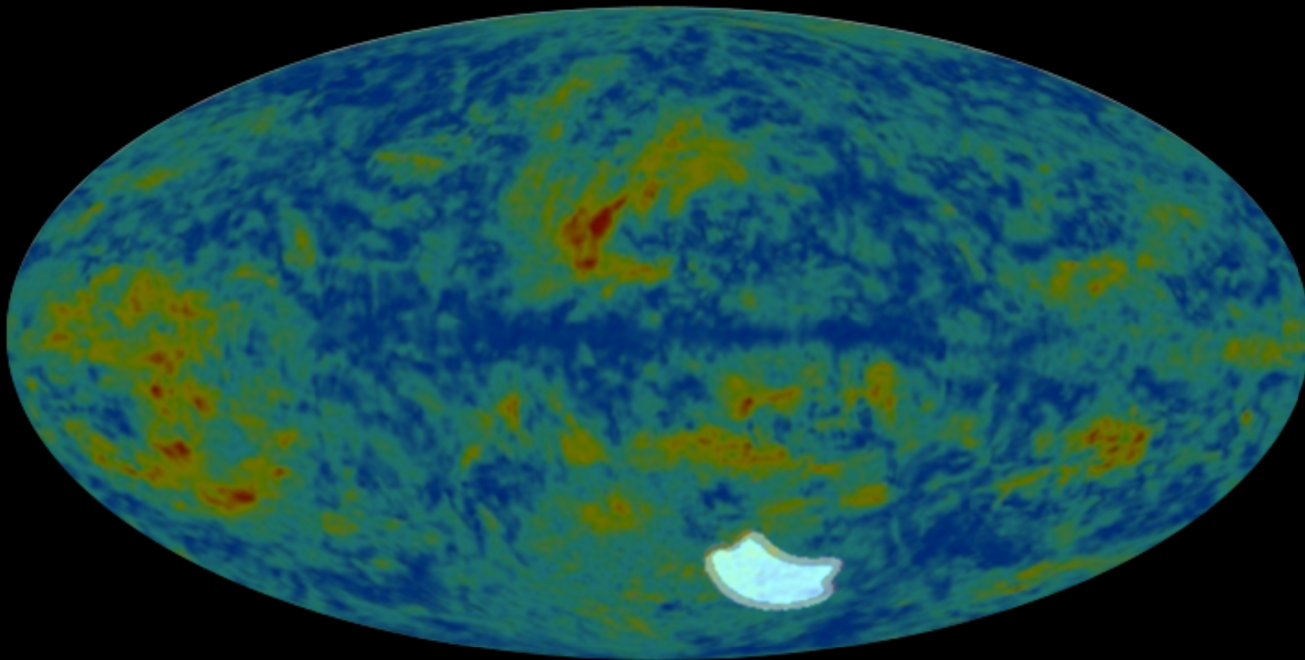


Immagine: ESA/PLANCK Collaboration

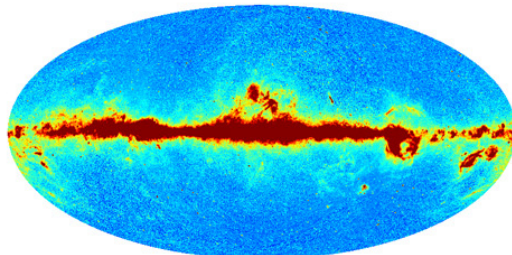
Bicep 2: limiti

- Bicep 2 può osservare il cielo solo in una frequenza (150 GHz).
- Ha usato un modello per il segnale polarizzato della polvere galattica sbagliato: pensavano di guardare in una zona ...meno polverosa!

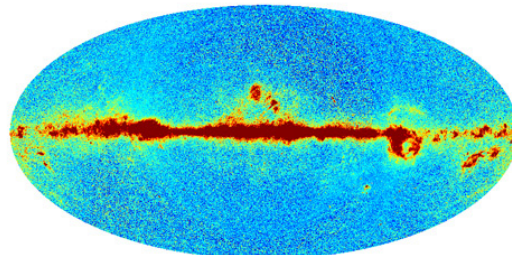


Bicep 2: limiti

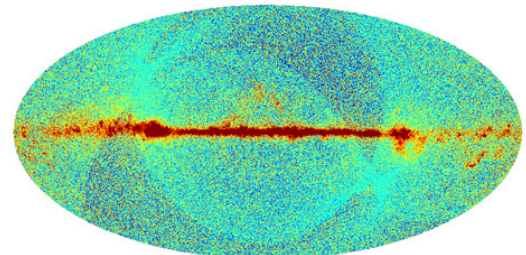
Il segnale polarizzato emesso dalla nostra galassia raggiunge la massima intensità a frequenze più alte.



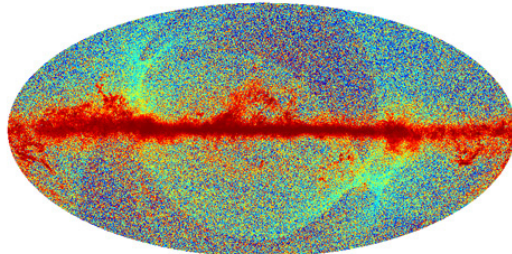
LFI 30 GHz



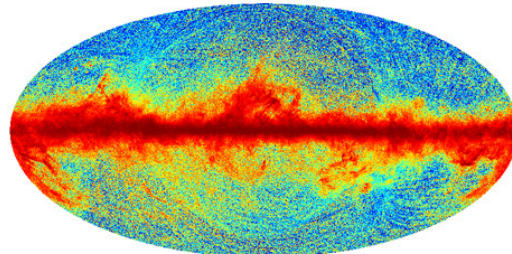
LFI 44 GHz



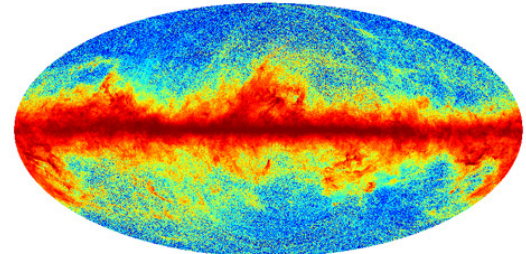
LFI 70 GHz



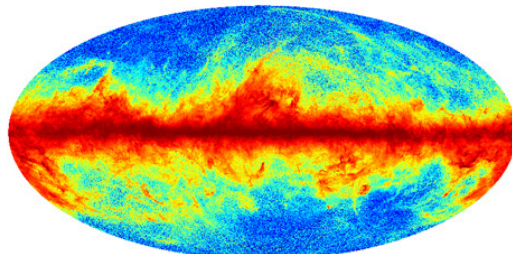
HFI 100 GHz



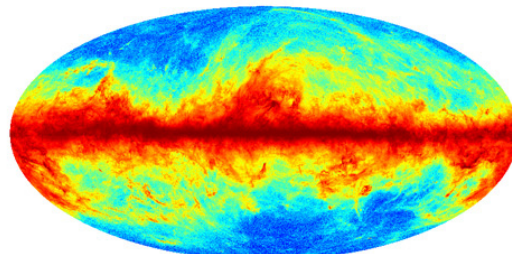
HFI 143 GHz



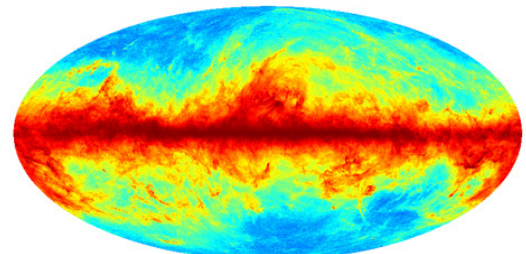
HFI 217 GHz



HFI 353 GHz



HFI 545 GHz



HFI 857 GHz

Immagine: ESA e PLANCK

Luce polarizzata della nostra galassia

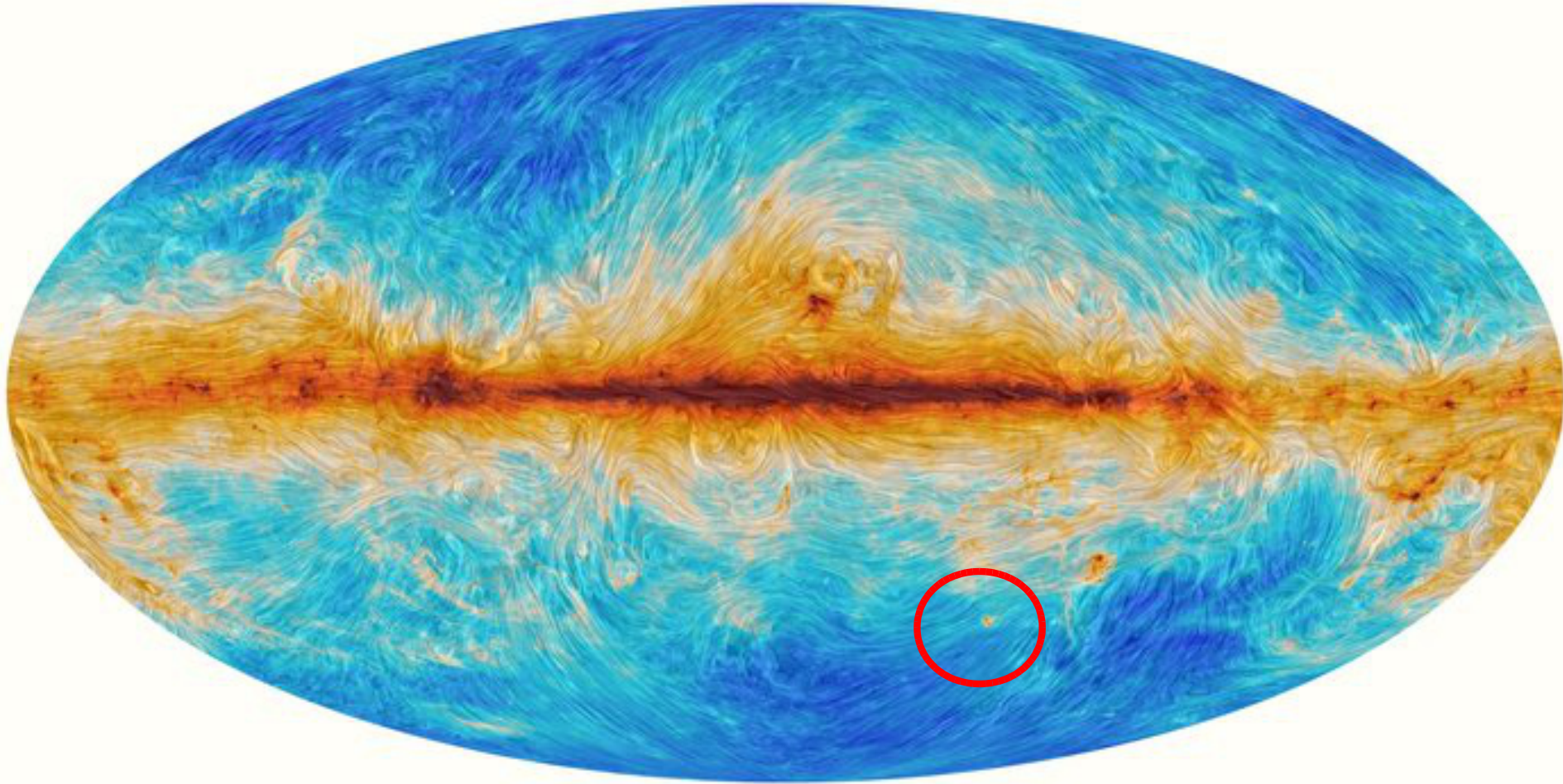


Immagine: ESA e PLANCK

Luce polarizzata della nostra galassia

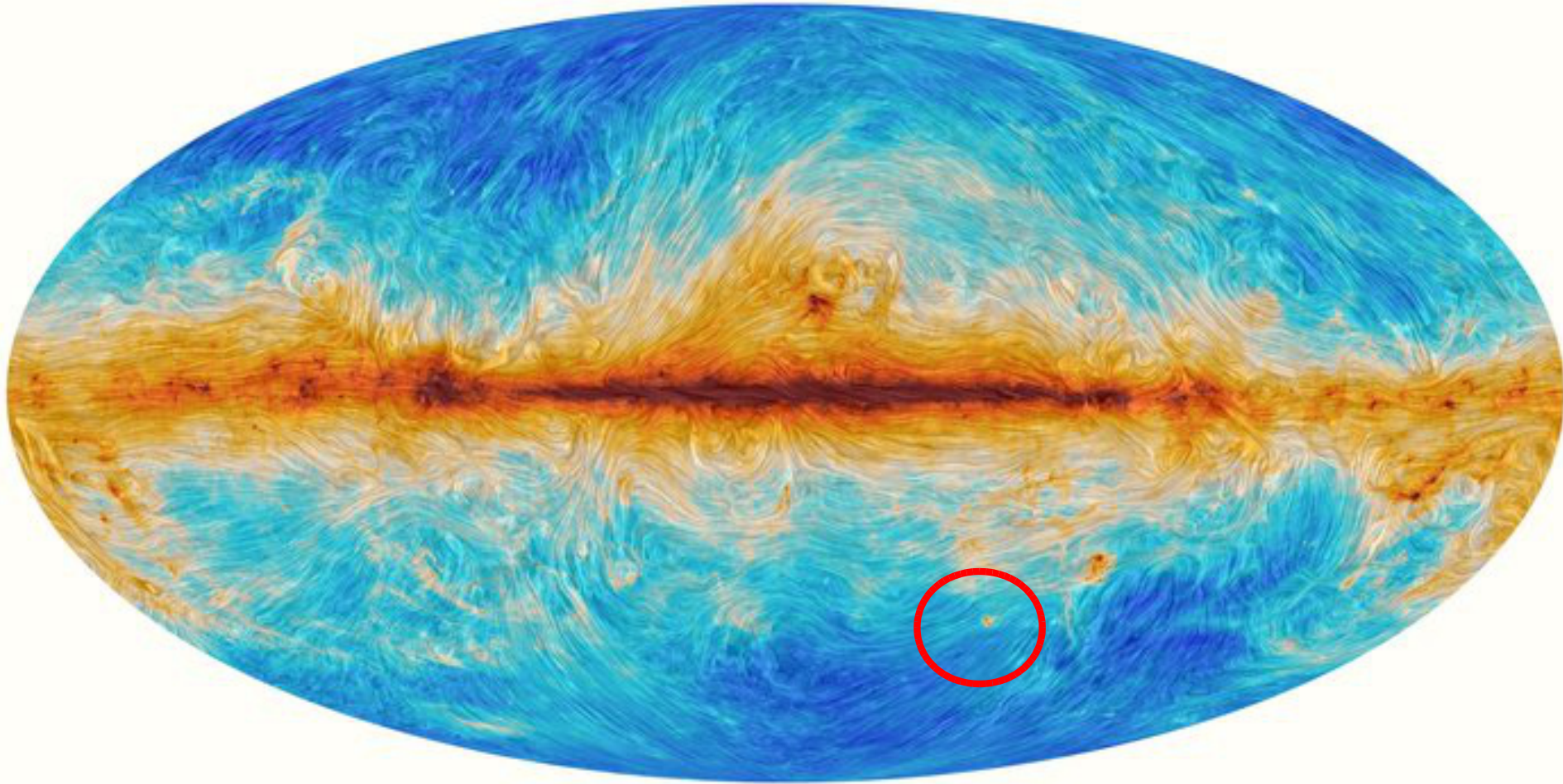
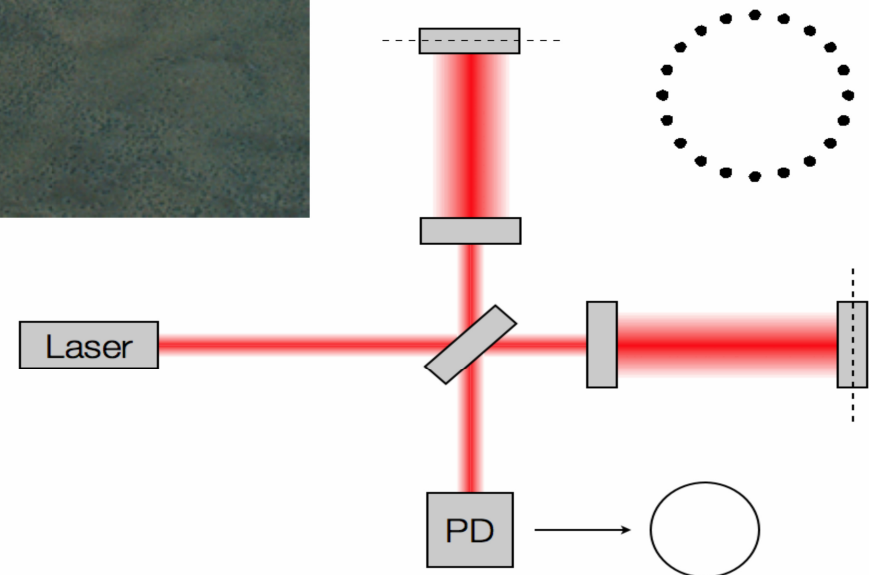


Immagine: ESA e PLANCK

Virgo e LIGO?



Gravitational waves from oscillons after inflation

Stefan Antusch,^{1,2} Francesco Cefalà,¹ and Stefano Orani¹

¹*Department of Physics, University of Basel, Klingelbergstr. 82, CH-4056 Basel, Switzerland*
²*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, D-80805 München, Germany*
 (Dated: December 21, 2016)

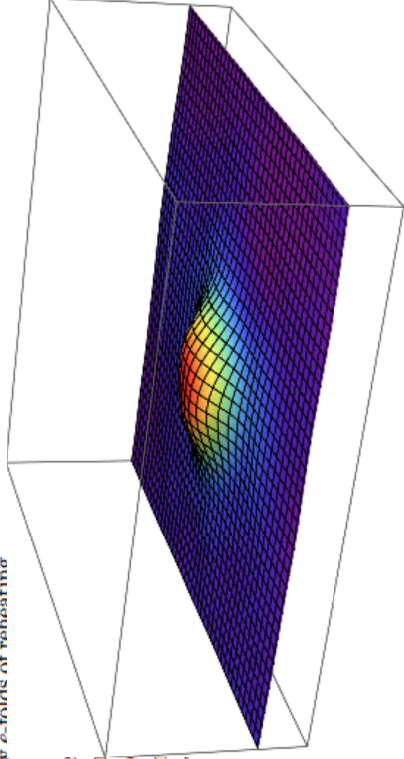
We investigate the production of gravitational waves during preheating after inflation in the common case of field potentials that are asymmetric around the minimum. In particular, we study the impact of oscillons, comparatively long lived and spatially localized regions where a scalar field (e.g. the inflaton) oscillates with large amplitude. Contrary to a previous study, which considered a symmetric potential, we find that oscillons in asymmetric potentials associated with a phase transition can generate a pronounced peak in the spectrum of gravitational waves, that largely exceeds the linear preheating spectrum. We discuss the possible implications of this enhanced amplitude of gravitational waves. For instance, for low scale inflation models, the contribution from the oscillons can strongly enhance the observation prospects at current and future gravitational wave detectors.

Introduction: Inflation is a very successful paradigm for early universe cosmology. The accelerated expansion can solve the horizon and flatness problems, while the quantum fluctuations of the inflaton field provide the seed for structure in the universe. After inflation, the potential energy of the inflaton is transferred to a thermal bath of the matter species present in the universe today in a process called reheating. The early stage of reheating, referred to as preheating, is often governed by non-linear dynamics of the inflaton field and other fields coupled to it, typically resulting in inhomogeneous field configurations. A generic consequence of preheating is the production of a stochastic background of gravitational waves (GW) [1, 2].

Observations of the CMB [3] point to adiabatic, nearly

the other side they are steeper. Nevertheless, oscillons are a characteristic feature of the reheating dynamics of this class of models. Despite the fact that the potential is steeper than quadratic on one side, the oscillons are “long-lived” and can survive at least several e -folds after the end of inflation [21, 22], potentially contributing to the production of GW. Interactions with other fields can affect the oscillons in some cases, e.g. when a parametric resonance occurs, however in general they do not have a significant impact during the first few e -folds of reheating (see e.g. [22]).

So far, effects of oscillons on the have been studied in [23] in the context of anisotropic inflation [24], a large-field model around the minimum. It was found that the production of GW is enhanced when there



Conclusioni

1. L'Inflazione venne introdotta nel modello cosmologico Λ CDM per giustificare alcune incongruenze osservative (omogeneità, piattezza, “orizzonte”)
2. l'Inflazione ha prodotto una piccola percentuale (10%) di segnale polarizzato nella Radiazione di Fondo Cosmico
3. La polarizzazione viene studiata ricavando i “parametri di Stokes”, ottenuti combinando la tensione in uscita da radiometri o bolometri posti nel fuoco di telescopi a microonde ubicati a Terra (in posti secchi) o, preferibilmente, nello spazio
4. E' in corso di valutazione la possibilità di usare interferometri a Terra (se confermati i risultati in corso sulla forma del segnale delle onde gravitazionali primordiali)

GRAZIE!

