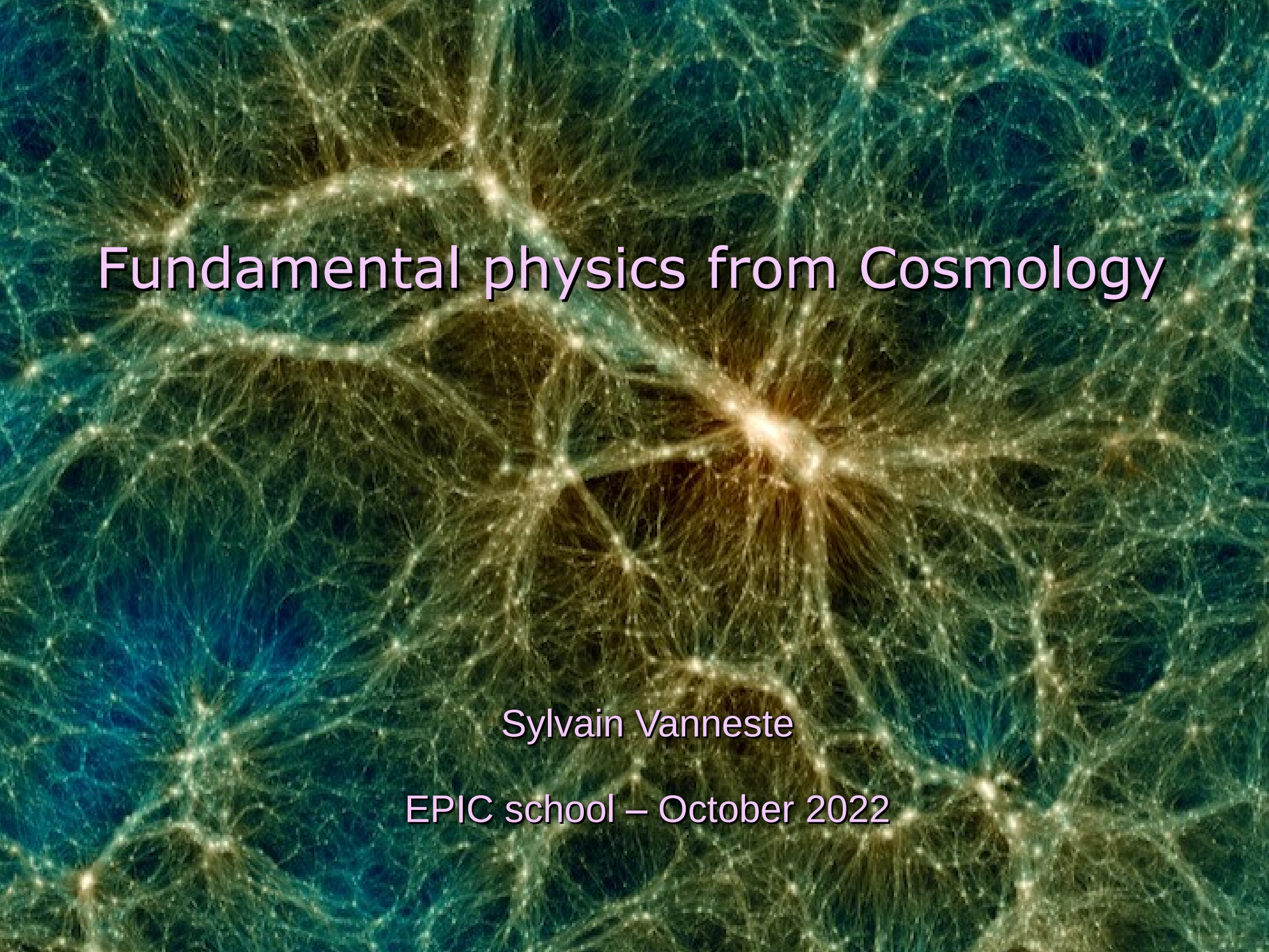


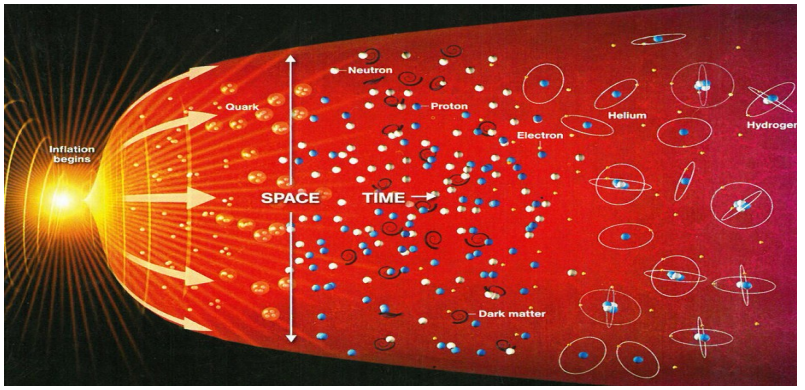
Fundamental physics from Cosmology

Sylvain Vanneste

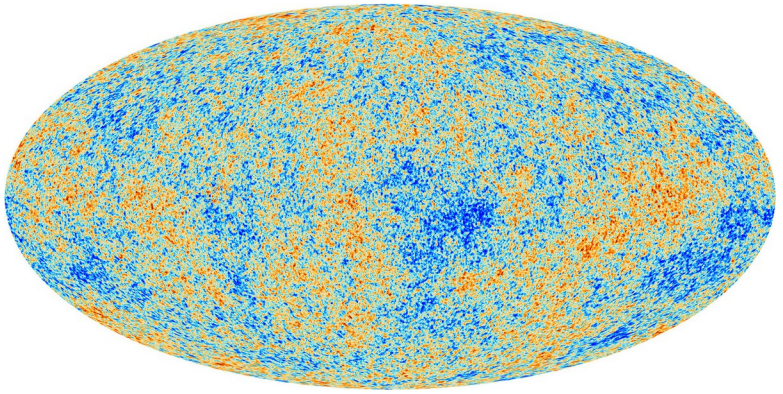
EPIC school – October 2022

Outline

- What is Cosmology ?
  - Brief history of the Universe
  - Big-bang theory
  - Cosmological Standard Model



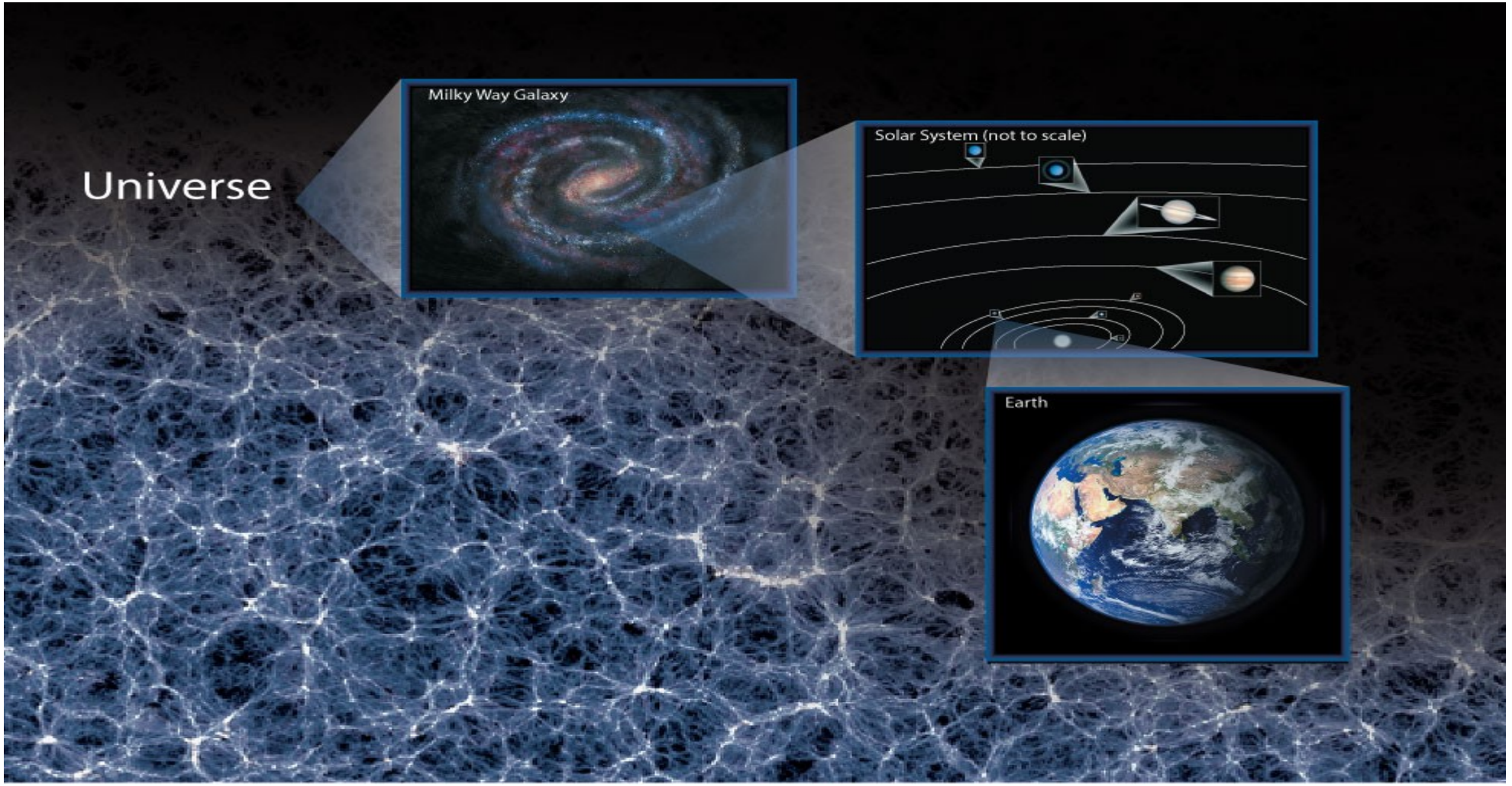
- Cosmic Microwave background
  - Measurement
  - Power spectrum
  - Constraints on physics



- Computer science and pipeline analysis

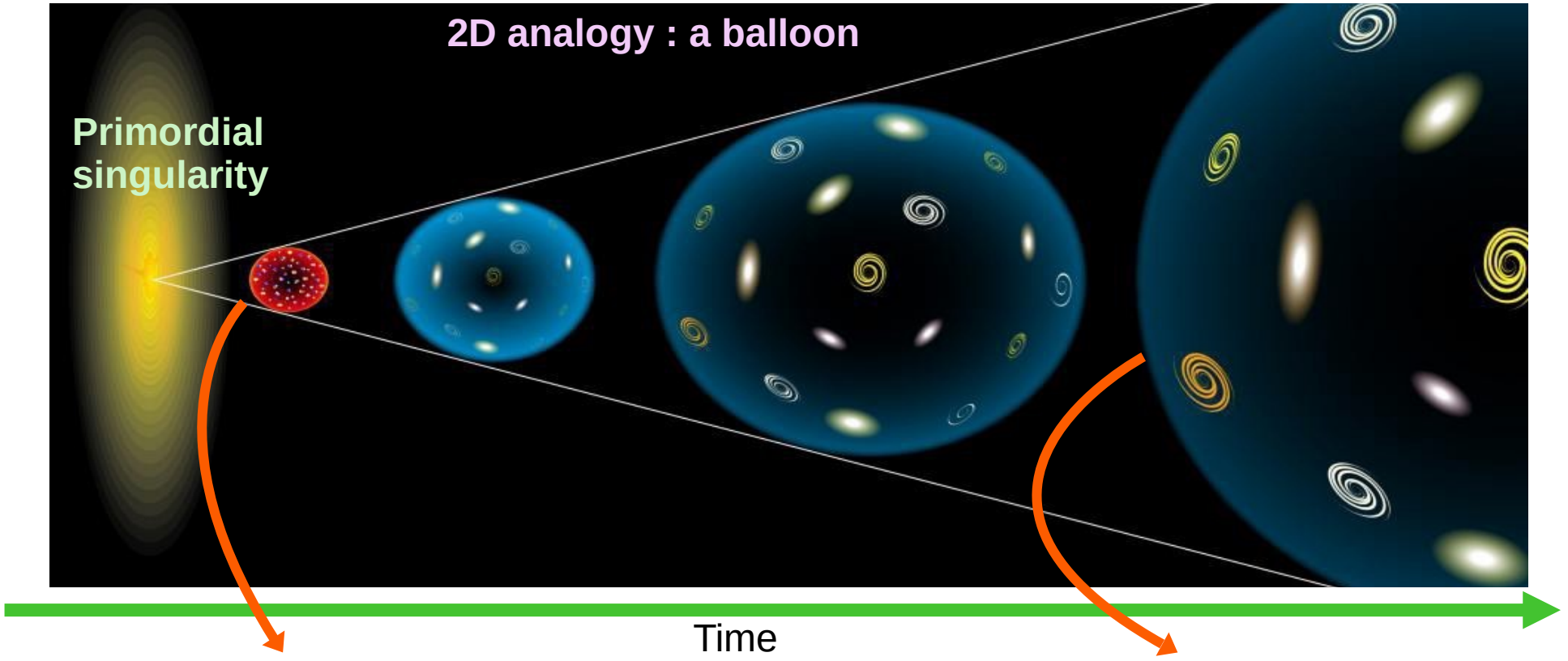
What is Cosmology?

- Today : physical cosmology :
  - origin, **history**, and fate of the **observable universe**
  - **composition** & **large-scale structures** (galaxies, dark matter …)
  - **dynamics** : shape, expansion, dark energy...



The Big-Bang theory

Galaxies *seems* to drift away from us.
→ The Universe is in **expansion** (thank you General Relativity !):



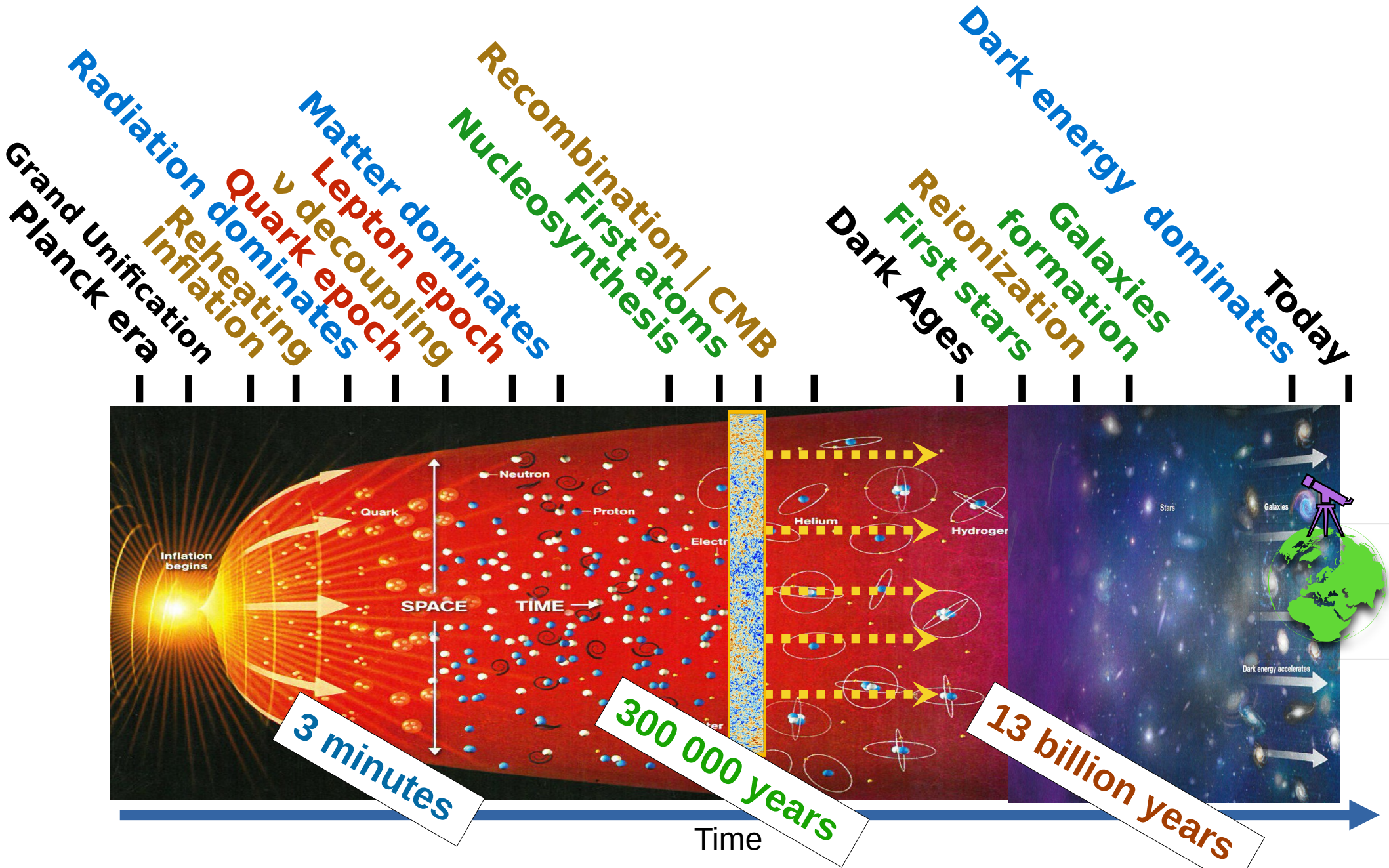
At some point, the Universe was very dense and hot, forming a primordial soup.

This is the **Big-Bang** theory.

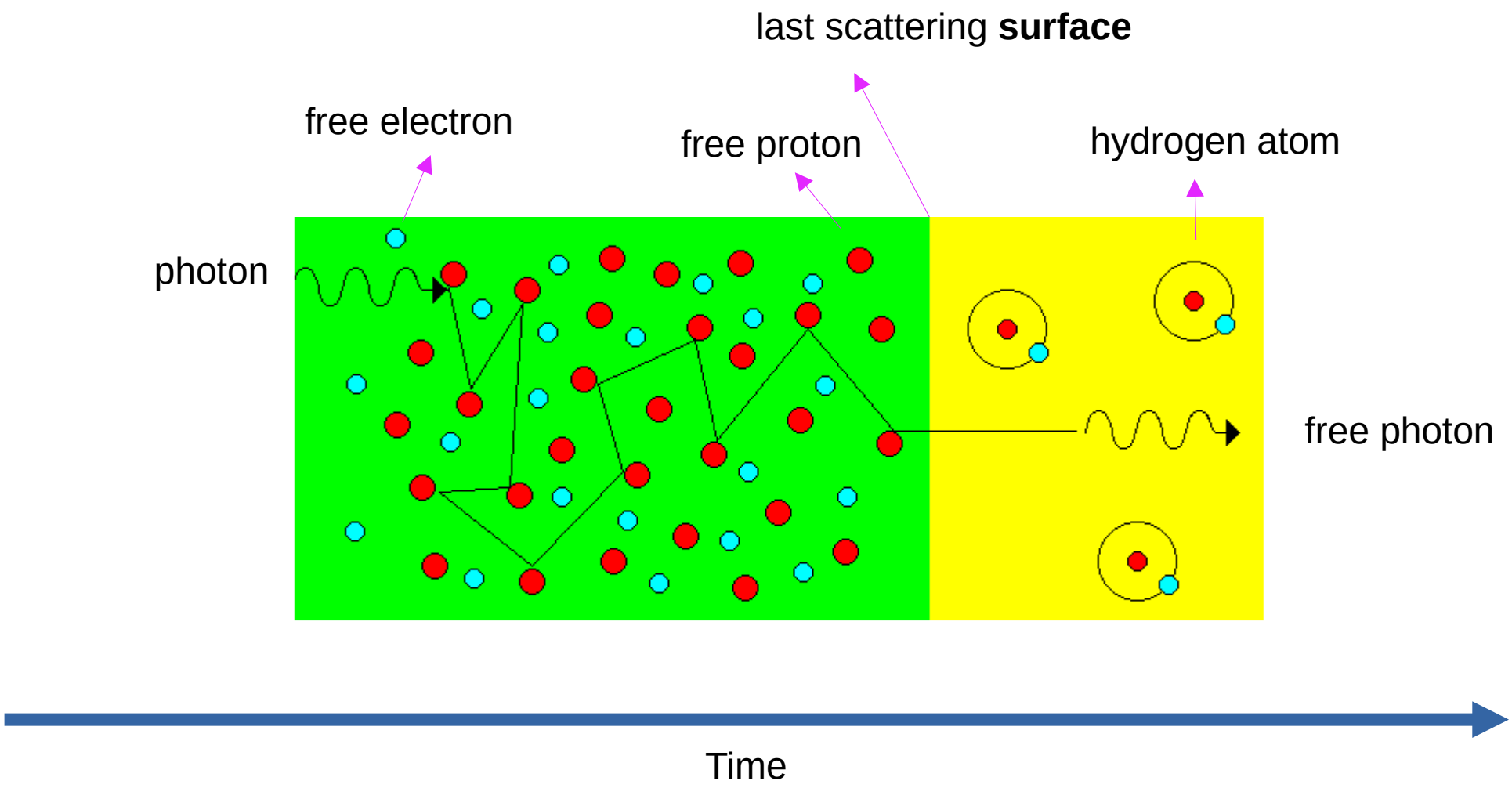
The whole Universe is the surface of the balloon.

It has no center. No location is more special than an other.

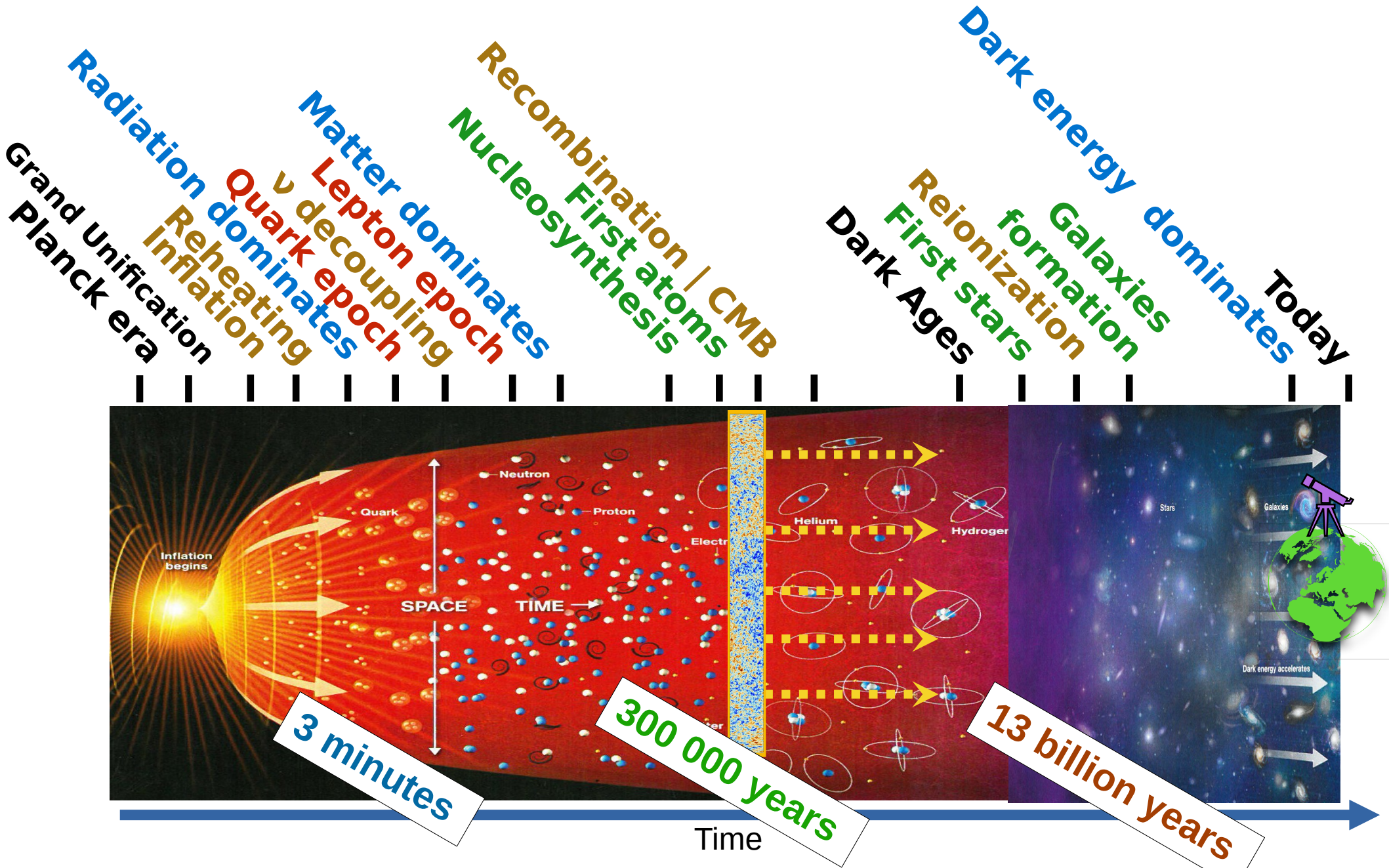
Universe epochs



Recombination



Universe epochs



Cosmological Standard Model

- **General Relativity +** Universe **isotropy & homogeneity +** fluids
  - Fluids : **dark matter** + **dark energy** + **baryons**, photons, neutrino,..

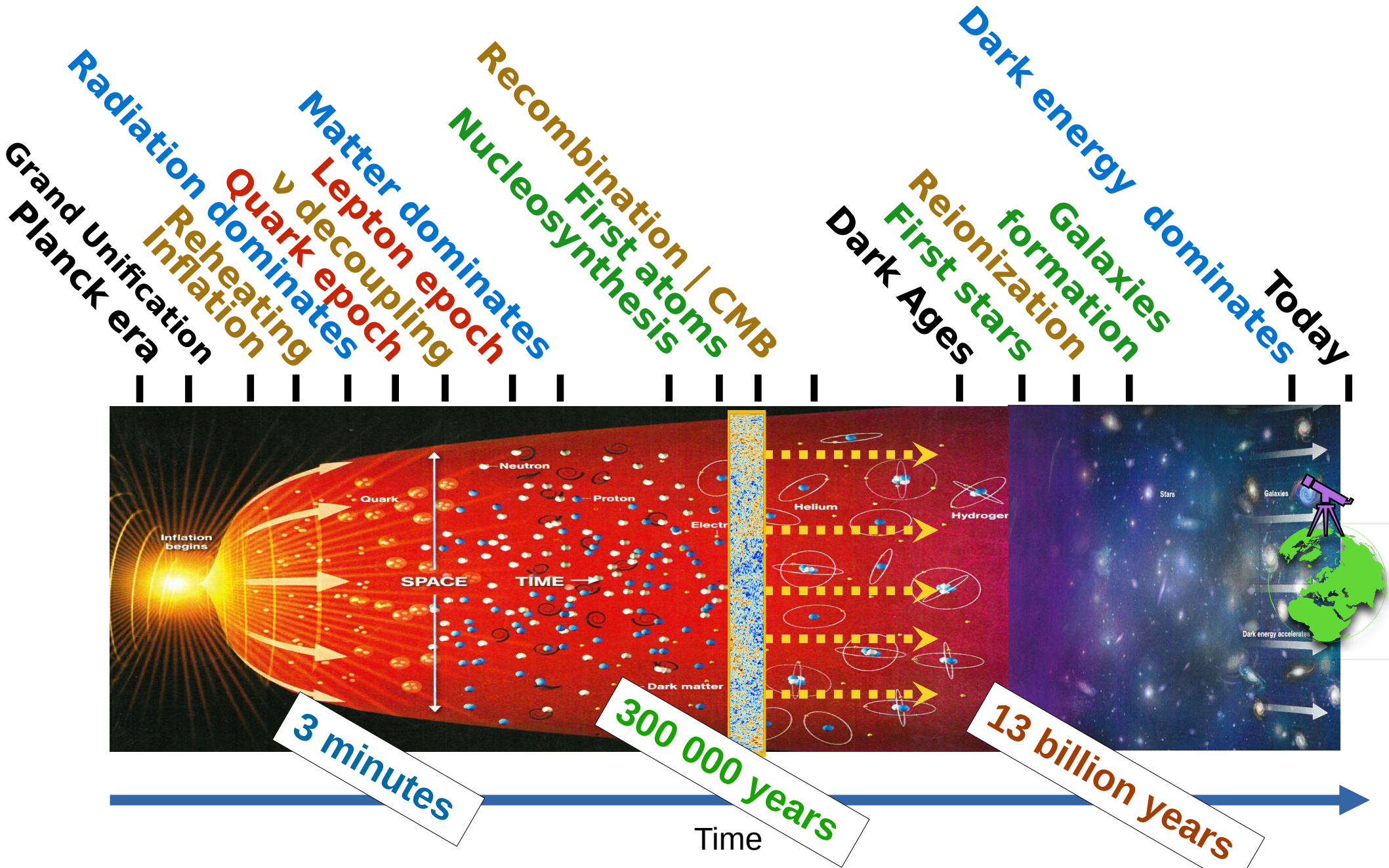
→ Cosmological Standard Model : **ΛCDM** = **Λ** (Dark energy) + **C**old **D**ark **M**atter

- <u>6 base parameters :</u>
  - The **Hubble-Lemaître expansion** parameter : H_0
  - **Baryonic** and **Dark Matter** densities : Ω_b , Ω_c
  - *+ 3 others...*

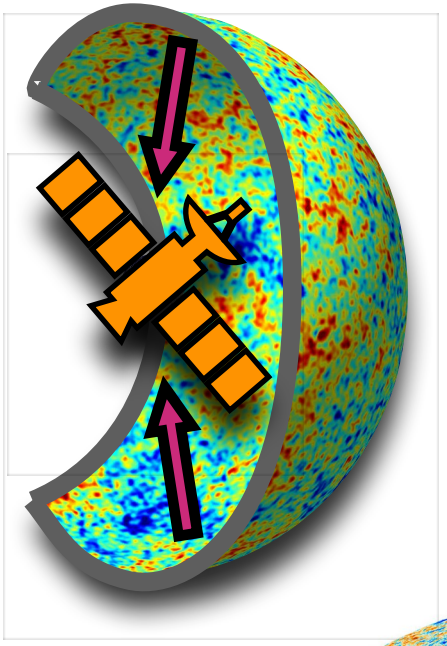
- <u>Probes :</u>
  - Galaxy clustering and distribution, gravitational lensing, supernovae, ...
  - **Cosmic Microwave Background (CMB)**

    → CMB photon energy (temperature) is related to matter density of the early Universe (13 billions years ago)

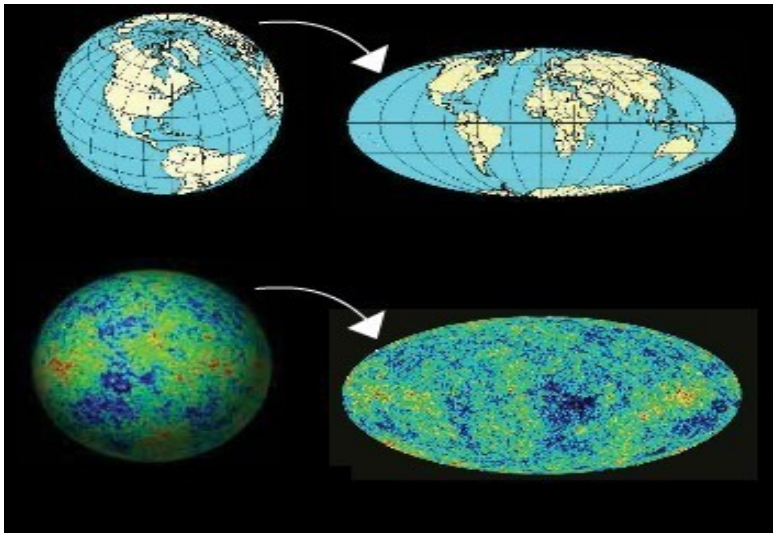
Universe epochs



Cosmic Microwave Background (CMB)

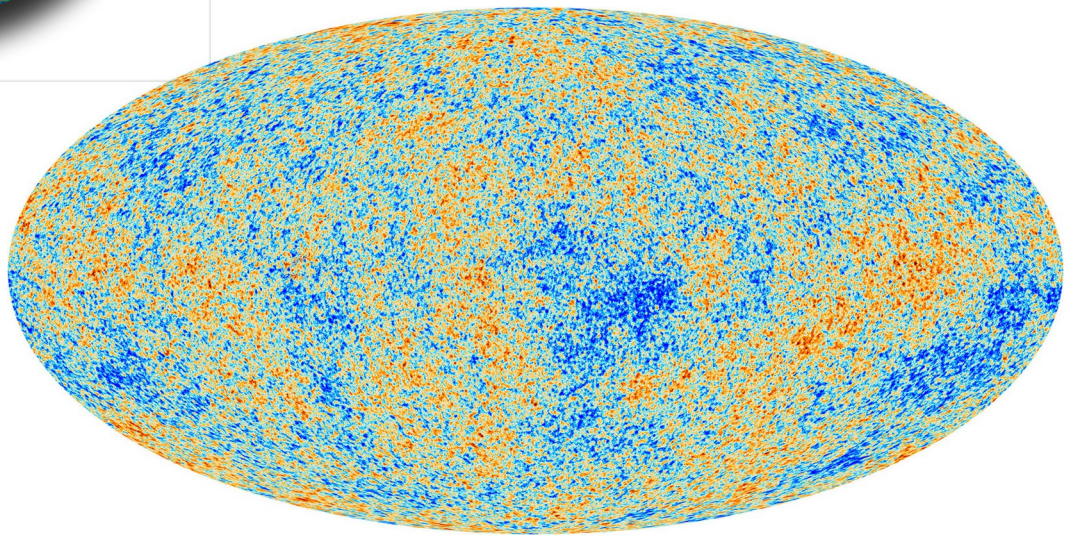


→



↙

$$\Delta T = T(\vec{n}) - \bar{T} =$$



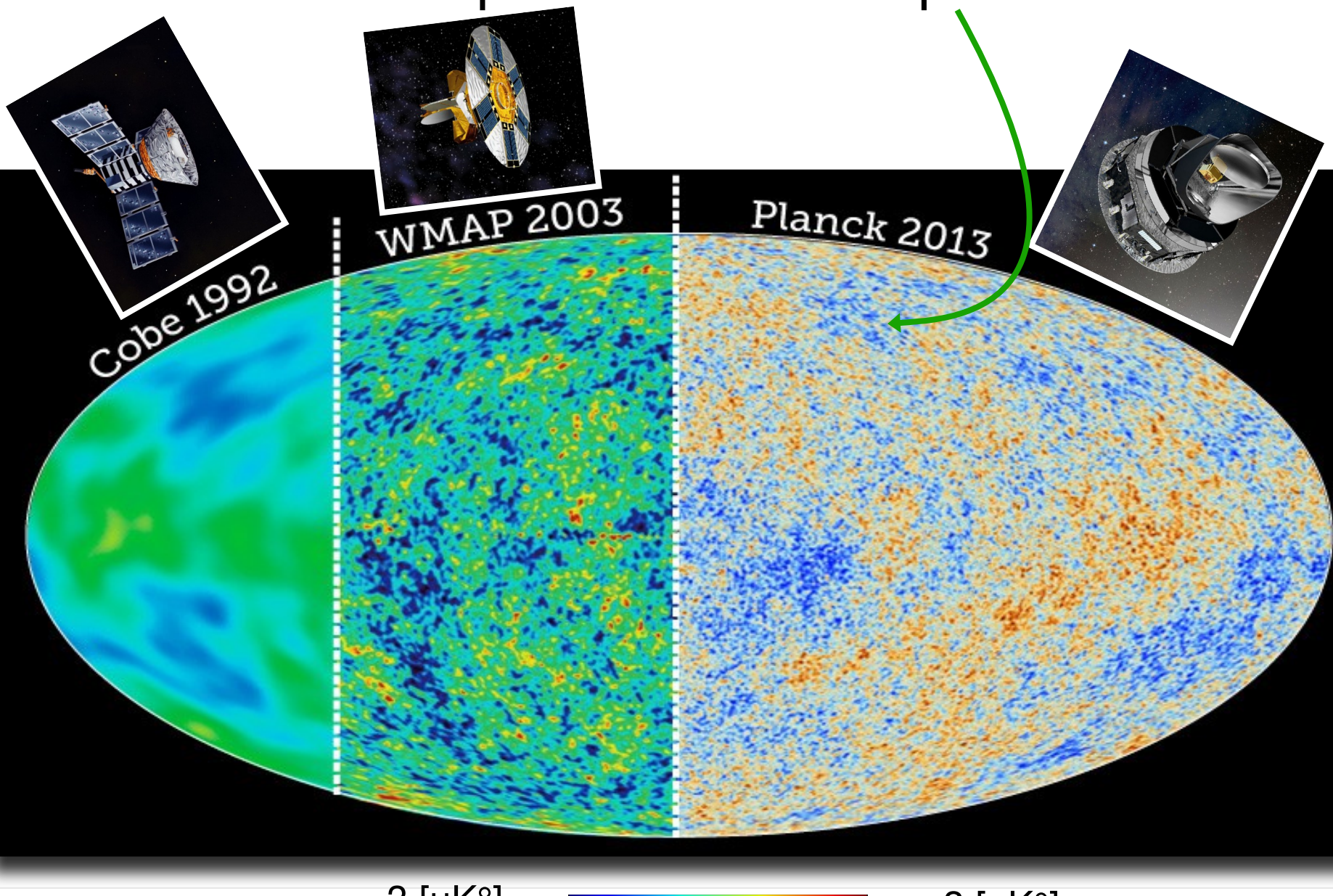
Each pixel color represents the **temperature** of the photons (their energy)

-3 [μK°] +3 [μK°]

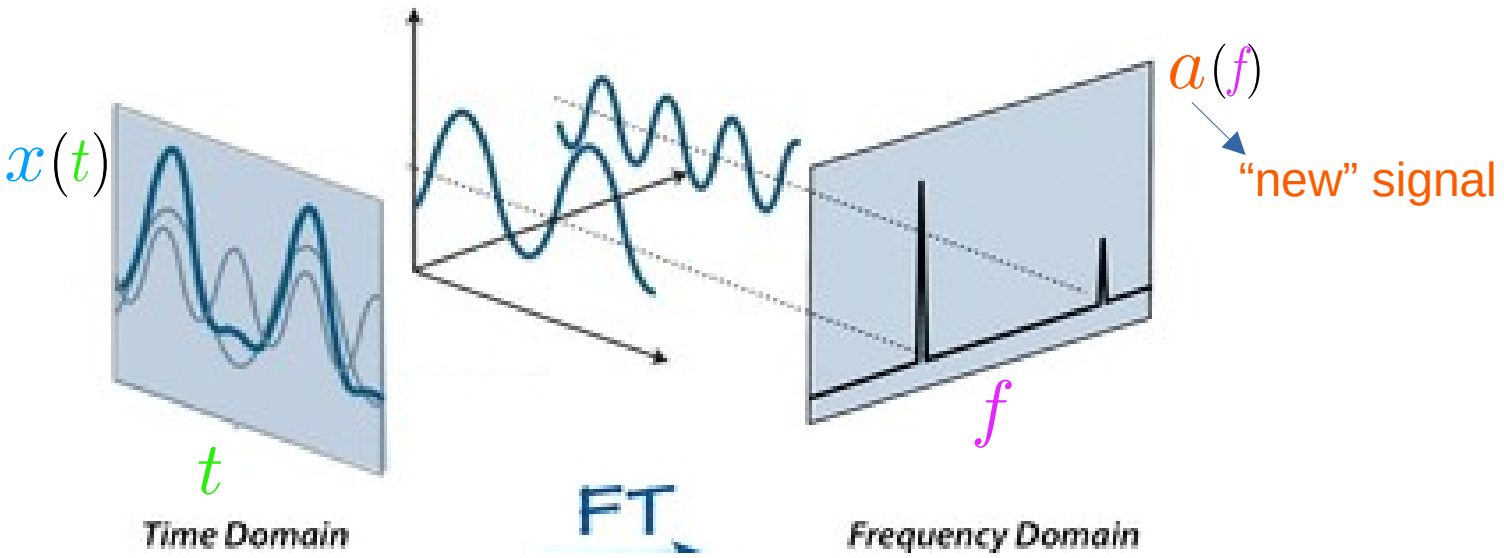
$\bar{T}$~2.7 [K°]

Temperature

CMB Temperature Anisotropies



Reminder : 1D - Fourier Decomposition



base function

phase

$$x(t) \simeq \sum_{f}^{f_{\max}} a(f) \sin(f\,t + \phi_f)$$

signal

amplitude
(new signal)

frequency

2D - Spherical Fourier Decomposition

- Temperatures anisotropy field is a function of observation direction

$$\Delta T(\vec{n}) = T(\vec{n}) - \bar{T}$$

- Spherical Fourier transform decomposition

$$\Delta T(\vec{n}) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\vec{n})$$

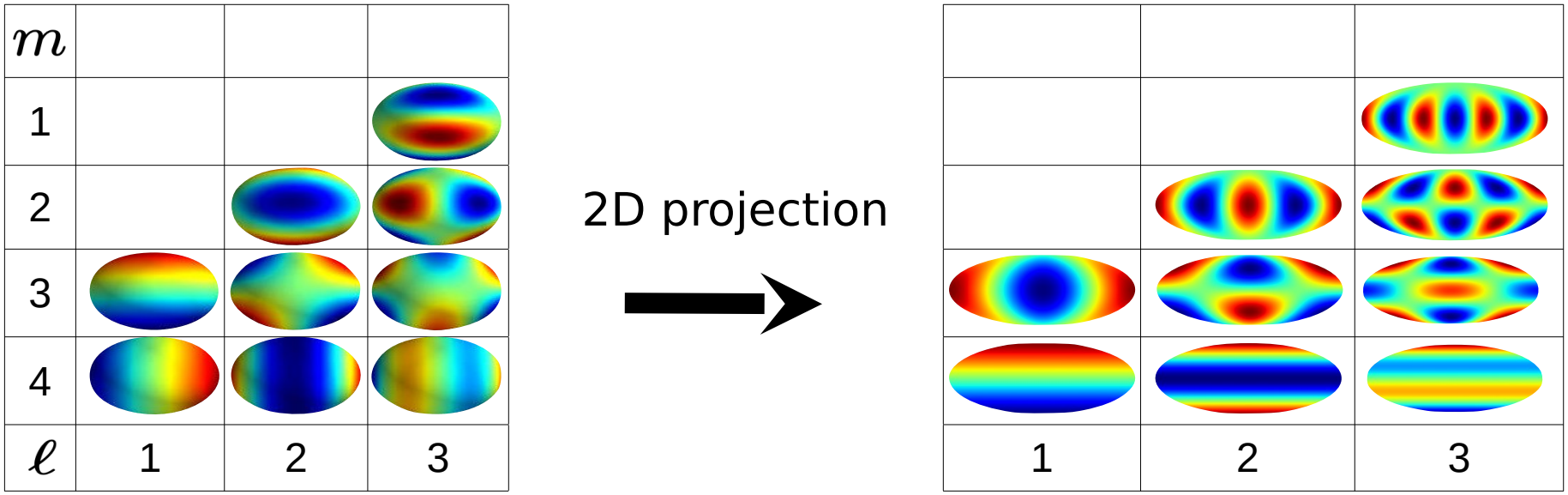
amplitude

base function

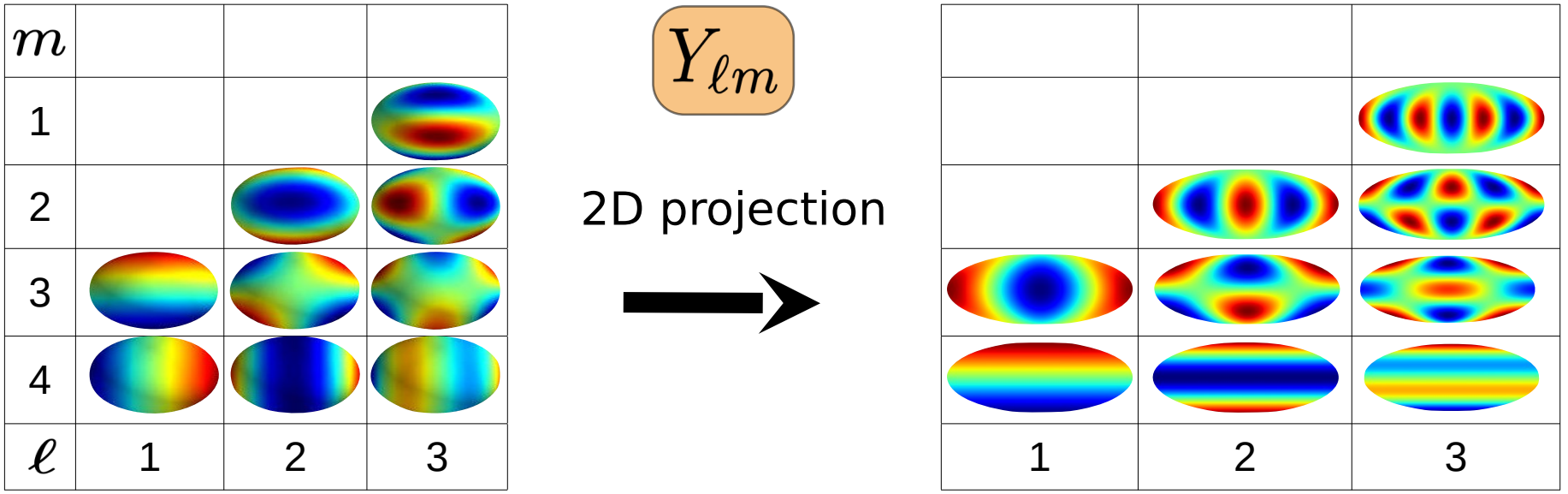
"frequency"

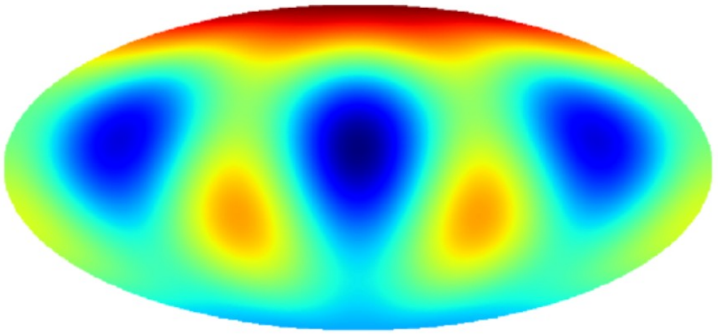
- Representation of spherical harmonics functions:

$Y_{\ell m}$



2D - Spherical Fourier Decomposition





$$\Delta T(\vec{n}) = \sum_{\ell m} a_{\ell m} Y_{\ell m} = 0.5\, Y_{1,0} + 1\, Y_{2,0} + 1.2\, Y_{3,0} - 0.3\, Y_{2,2} + 0.1\, Y_{3,2}$$

spherical harmonics

harmonics coefficients

Anisotropies power spectrum

- Temperatures anisotropy field is a function of observation direction $\Delta T(\vec{n}) = T(\vec{n}) - \bar{T}$

- Spherical Fourier transform decomposition $\Delta T(\vec{n}) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}$

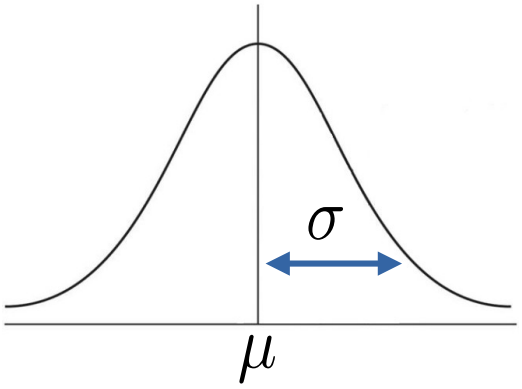
amplitude

- Temperature anisotropies **power spectrum** $C_\ell = \langle a_{\ell m} a^*_{\ell' m'} \rangle$

  → **Compresses** CMB anisotropies statistics into a "variance" function.

  → **Retains** all the cosmological informations (*CMB assumed Gaussian*).

Similar to



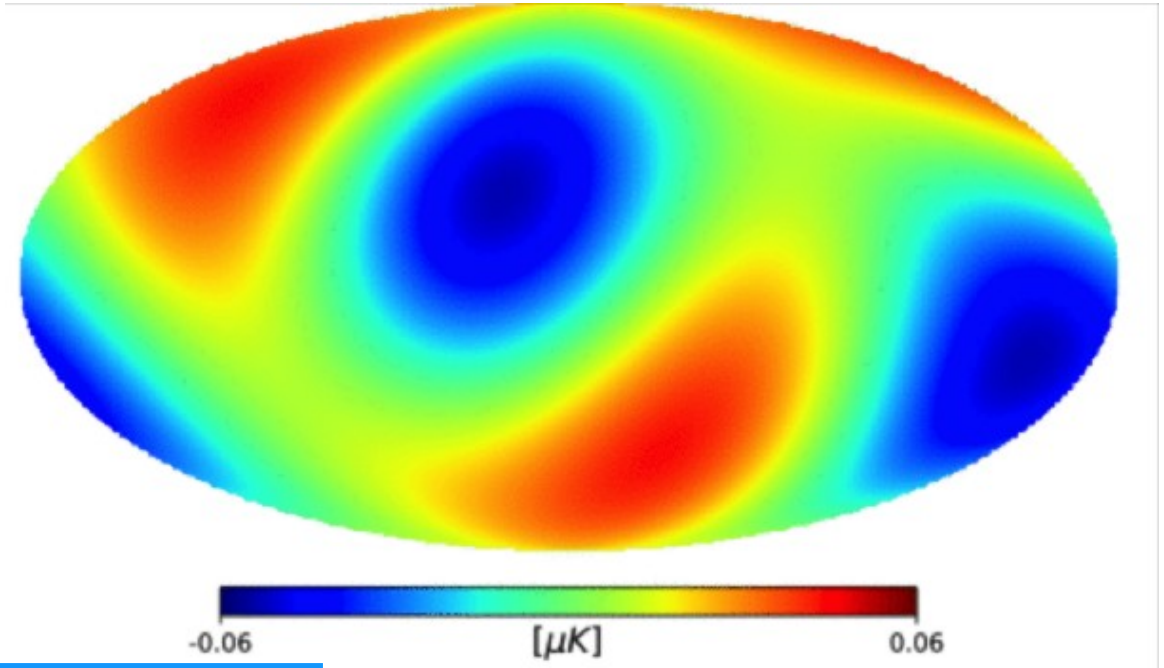
compression

$\mathcal{N}(\mu, \sigma)$

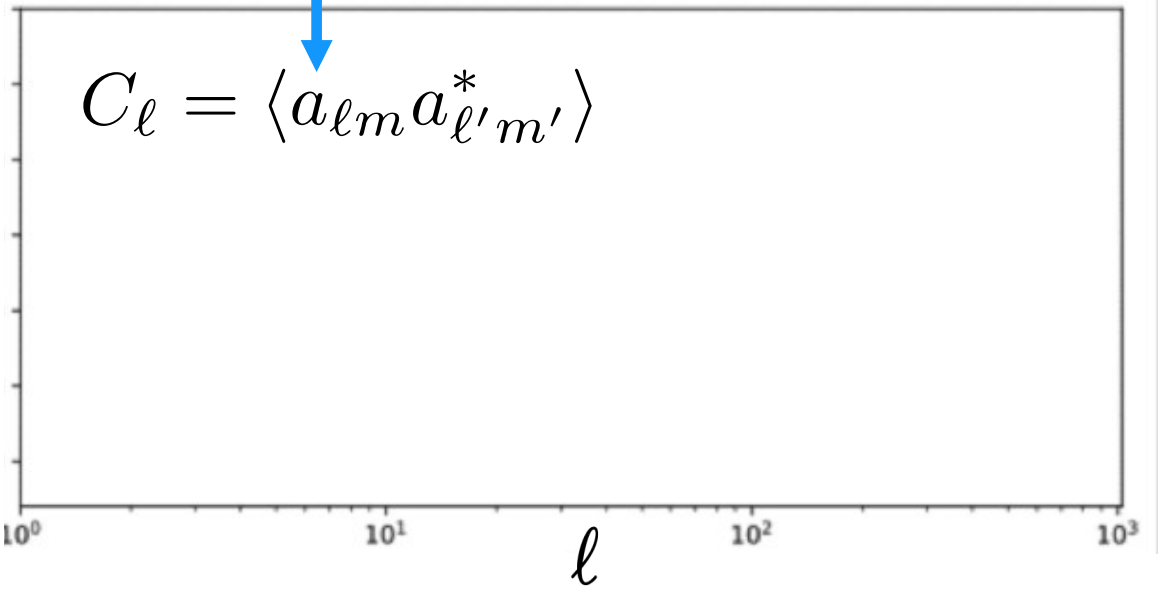
mean variance

Anisotropies power spectrum

$$\Delta T(\vec{n}) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m}^{T} Y_{\ell m} \quad =$$

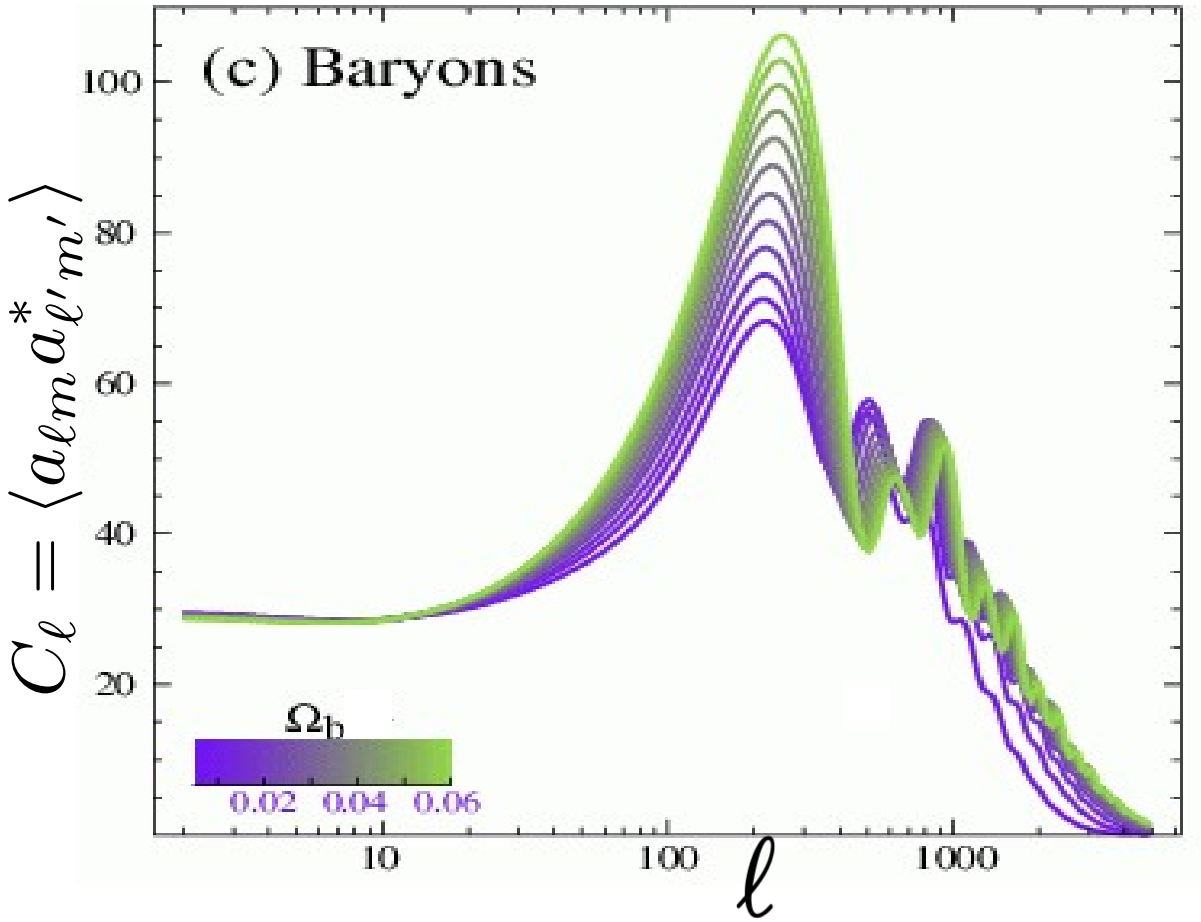


$$C_\ell = \langle a_{\ell m} a^*_{\ell' m'} \rangle$$

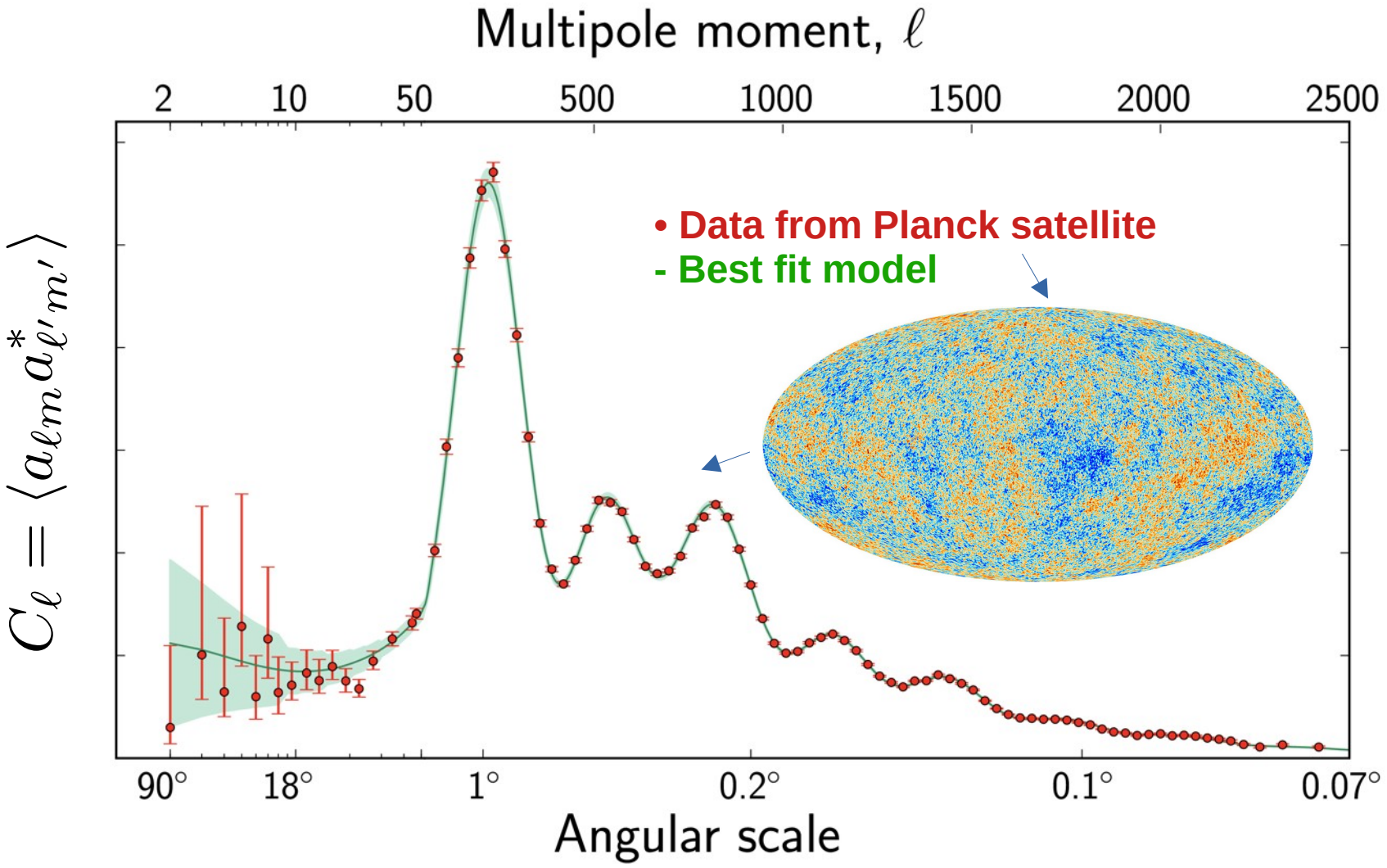


Model parameters dependence

- From the cosmological standard model ΛCDM , we can **predict** the shape of the power spectrum, depending on the value of the parameters:
  - The Hubble-Lemaître expansion parameter : H_0
  - Baryonic and Dark Matter densities : Ω_b , Ω_c
  - + *others ...*

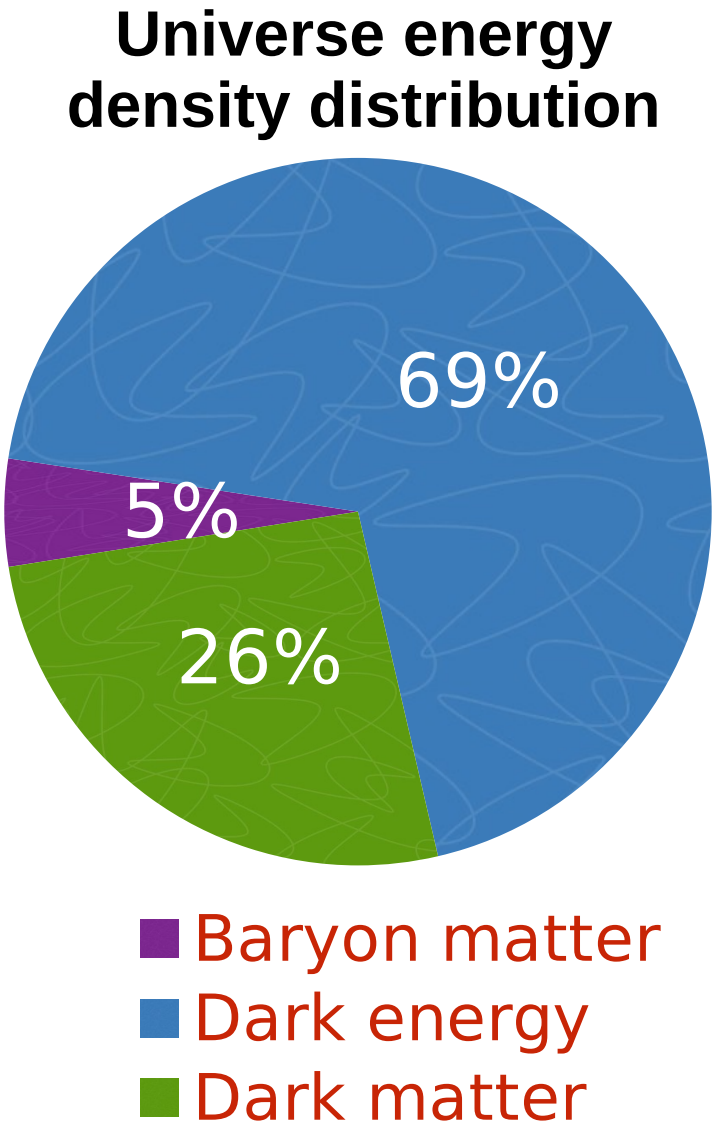


Data VS model



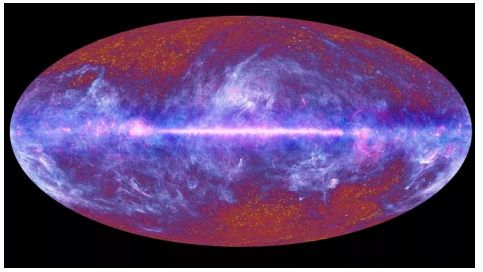
Model parameters dependence

Ω_b	0.0486 ± 0.0010
Ω_c	0.2589 ± 0.0057
H_0	67.3 ± 1.20
...	...



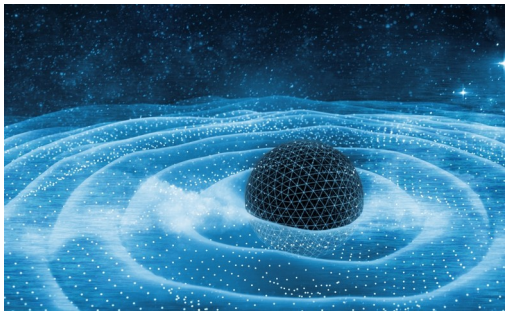
Open the parameter space

- The Cosmic Microwaves Background is "contaminated" by astrophysical sources:
  - Solar system, milky way, other galaxies, …
  - Allows for constrains in astrophysical models.



- We can add more parameters to the Standard Cosmological Model ΛCDM:
  - More complex dark energy and dark matter nature
  - Constrains on neutrino physics, sum of mass, hierarchy, ... (see previous talk)
  - Super string theory, cosmic strings, brane, multiverse collision, …
  - Gravitational waves physics
  - Primordial inflation (10^{-36} to 10^{-33} sec. after Big Bang), distances multiplied by $\sim 10^{26}$.
    - Primordial inflates effects from quantum scale to macroscopic scale.
    - Seed of (Gaussian) matter anisotropies, flatten the Universe, …

      → Possible window toward **Quantum Gravity physics !**



A few figures

Raw dataset from Planck Satellite : 30 TB

↓

Dozen of maps ~1 billions pixels each

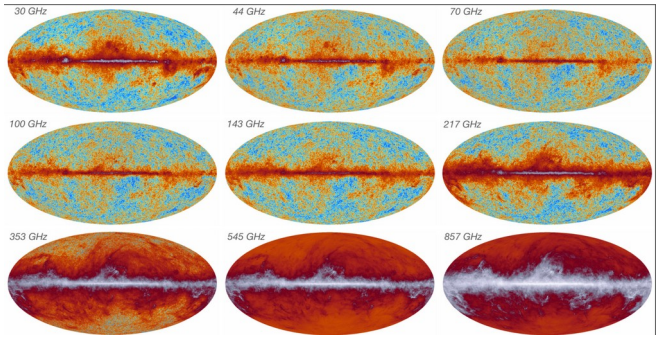
↓

Power spectrum : ~ 2000 data points

↓

Dozen of cosmological and astrophysical parameters

↓



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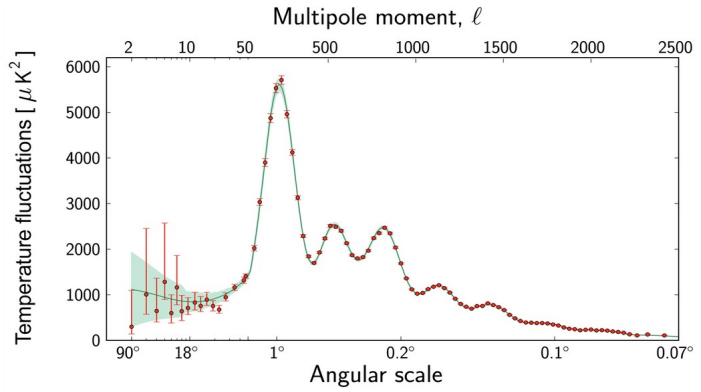


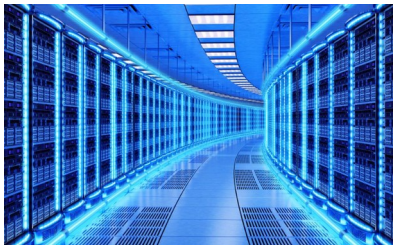
↓

Ω_b	0.0486 ± 0.0010
Ω_c	0.2589 ± 0.0057
H_0	67.3 ± 1.20
...	...

In practice : my experience

- **Python** : quick scripts, tests, plot, ideas …
- **C/C++** : efficiency, speed, parallelism, ...
- Work on **computer farms**: Bash

  - Need **terminal**, connect remotely using **SSH**


↔


  - Learn how to coordinate thousands of **threads**

```
# HELP squeue_jobs hold info on current squeue slurm jobs
# TYPE squeue_jobs gauge
squeue_jobs{job_type="RUNNING",slurm_group="lofar"} 3.0
squeue_jobs{job_type="COMPLETED",slurm_group="spexone"} 2.0
squeue_jobs{job_type="PENDING",slurm_group="projectmine"} 1.0
squeue_jobs{job_type="COMPLETED",slurm_group="sksp"} 2.0
squeue_jobs{job_type="PENDING",slurm_group="allegro"} 1.0
squeue_jobs{job_type="RUNNING",slurm_group="allegro"} 3.0
squeue_jobs{job_type="COMPLETING",slurm_group="allegro"} 2.0
squeue_jobs{job_type="SUSPENDED",slurm_group="allegro"} 1.0
squeue_jobs{job_type="COMPLETED",slurm_group="allegro"} 1.0
squeue_jobs{job_type="SUSPENDED",slurm_group="lofar"} 2.0
squeue_jobs{job_type="PENDING",slurm_group="lofar"} 1.0
squeue_jobs{job_type="COMPLETING",slurm_group="lofar"} 2.0
squeue_jobs{job_type="COMPLETED",slurm_group="lofar"} 1.0
squeue_jobs{job_type="SUSPENDED",slurm_group="projectmine"} 2.0
squeue_jobs{job_type="COMPLETED",slurm_group="projectmine"} 2.0
squeue_jobs{job_type="RUNNING",slurm_group="projectmine"} 1.0
squeue_jobs{job_type="COMPLETING",slurm_group="projectmine"} 4.0
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squeue_jobs{job_type="COMPLETING",slurm_group="sksp"} 1.0
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squeue_jobs{job_type="RUNNING",slurm_group="sksp"} 1.0
squeue_jobs{job_type="SUSPENDED",slurm_group="spexone"} 2.0
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squeue_jobs{job_type="RUNNING",slurm_group="spexone"} 1.0
squeue_jobs{job_type="PENDING",slurm_group="tropomi"} 1.0
squeue_jobs{job_type="COMPLETED",slurm_group="tropomi"} 1.0
```

  - **Store** data, **organize**, sort, edit, reuse, ...

Example of code for computing the CMB power spectrum on GitLab