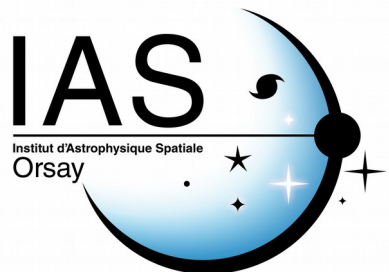
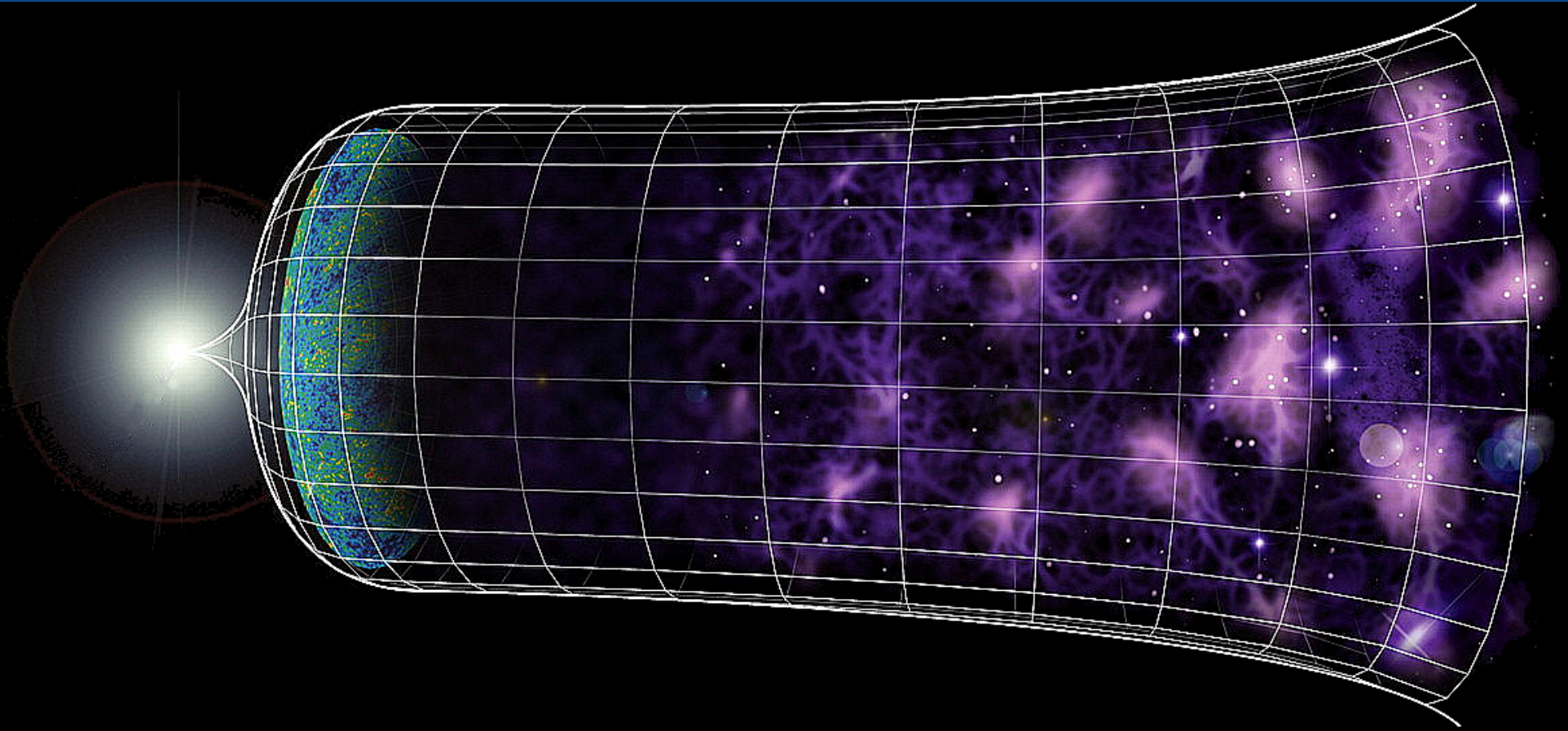


# Les défis de la cosmologie



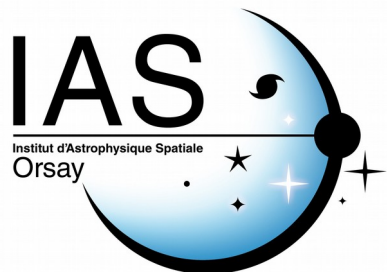
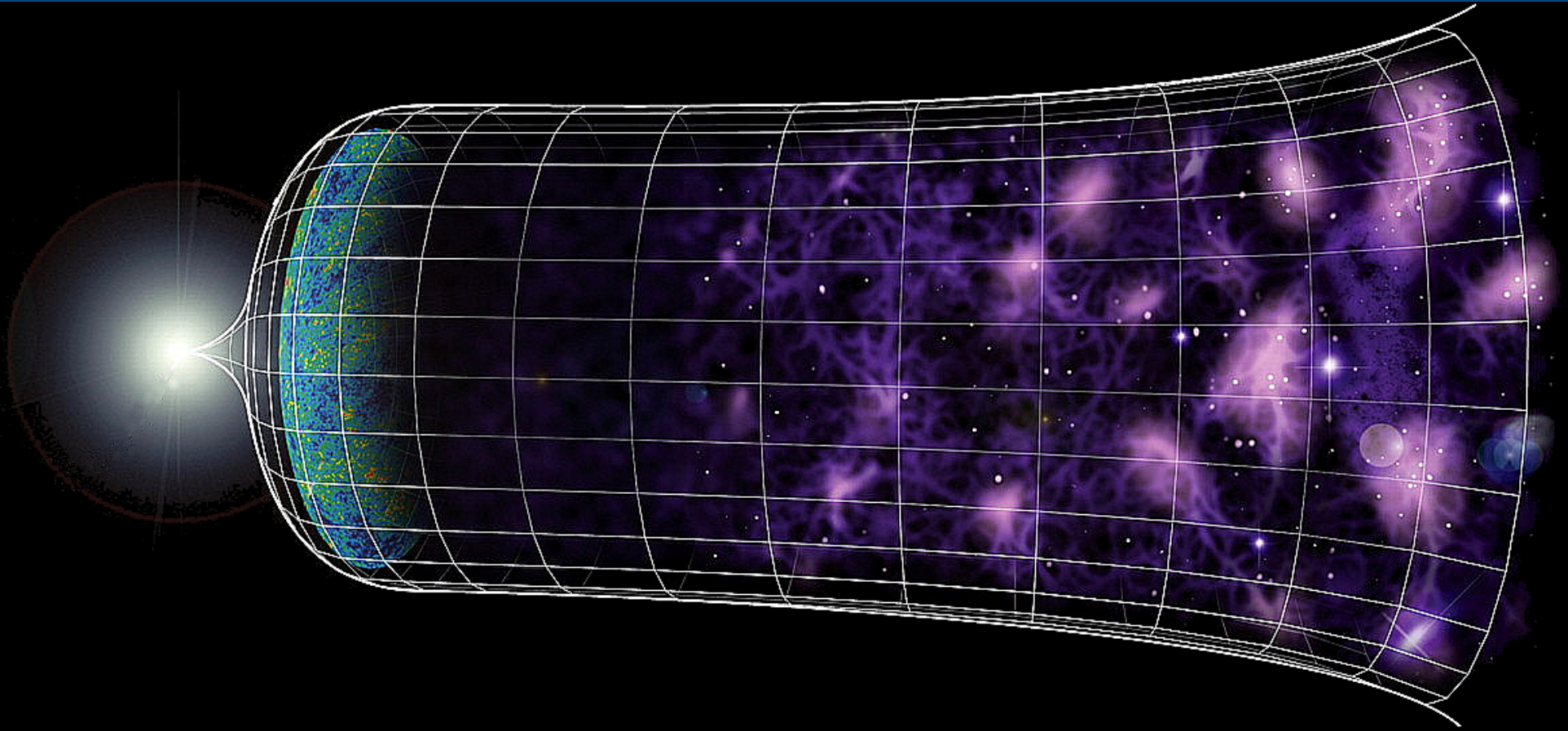
Mathieu Langer

Séminaire IAS

11 janvier 2018



# The challenges facing cosmology



Mathieu Langer

Seminar IAS

11 January 2018





# Where we are

12 742 km

120 au (Heliosphere)

30 kpc

Earth

Solar System

Solar Interstellar Neighborhood

Milky Way Galaxy

Local Galactic Group

Virgo Supercluster

Local Superclusters

Observable Universe

33 Mpc

28.5 Gpc

$$1 \text{ pc} = 2.06 \cdot 10^5 \text{ au}$$



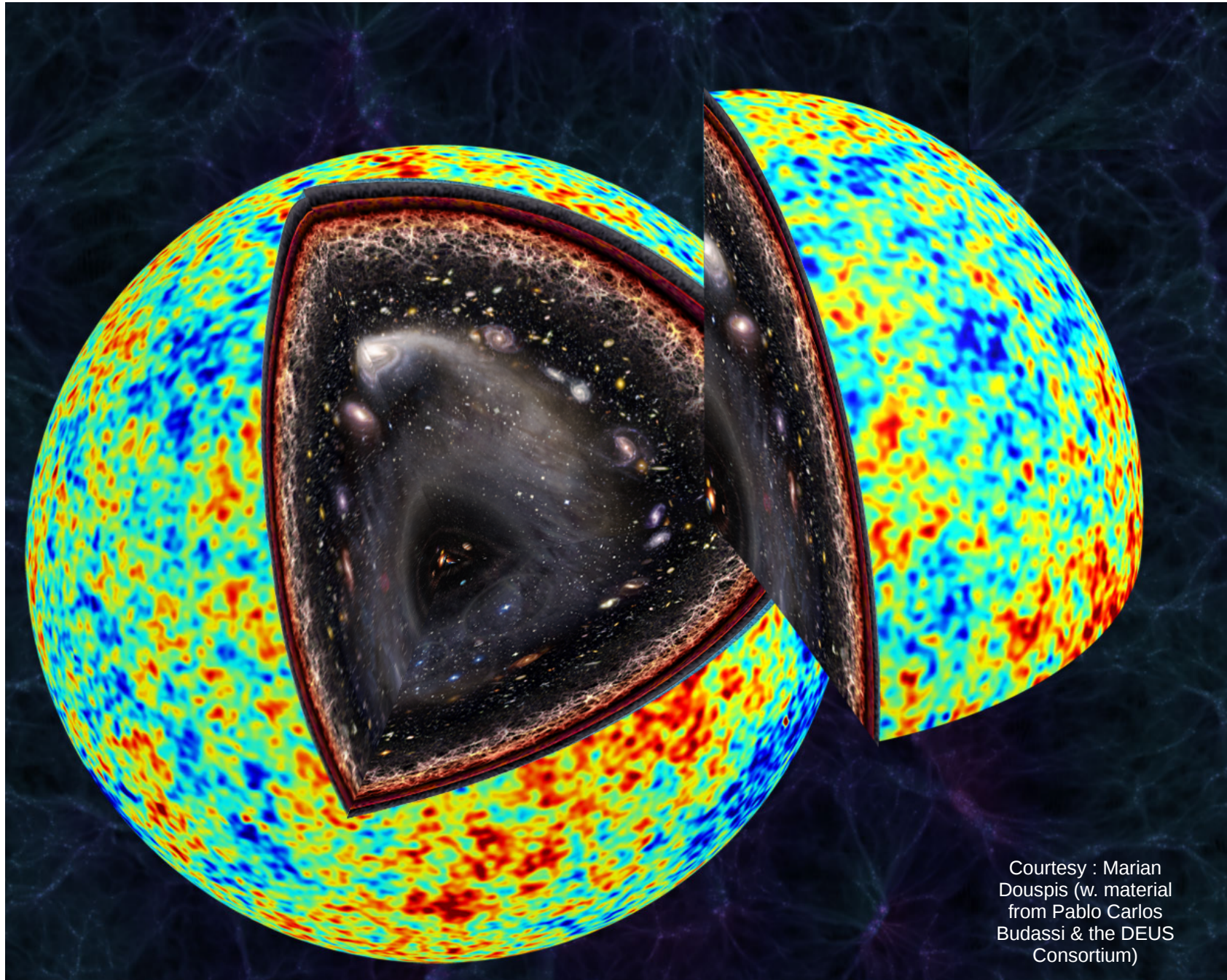
# The observable universe (in logarithmic scale)



© Pablo Carlos Budassi



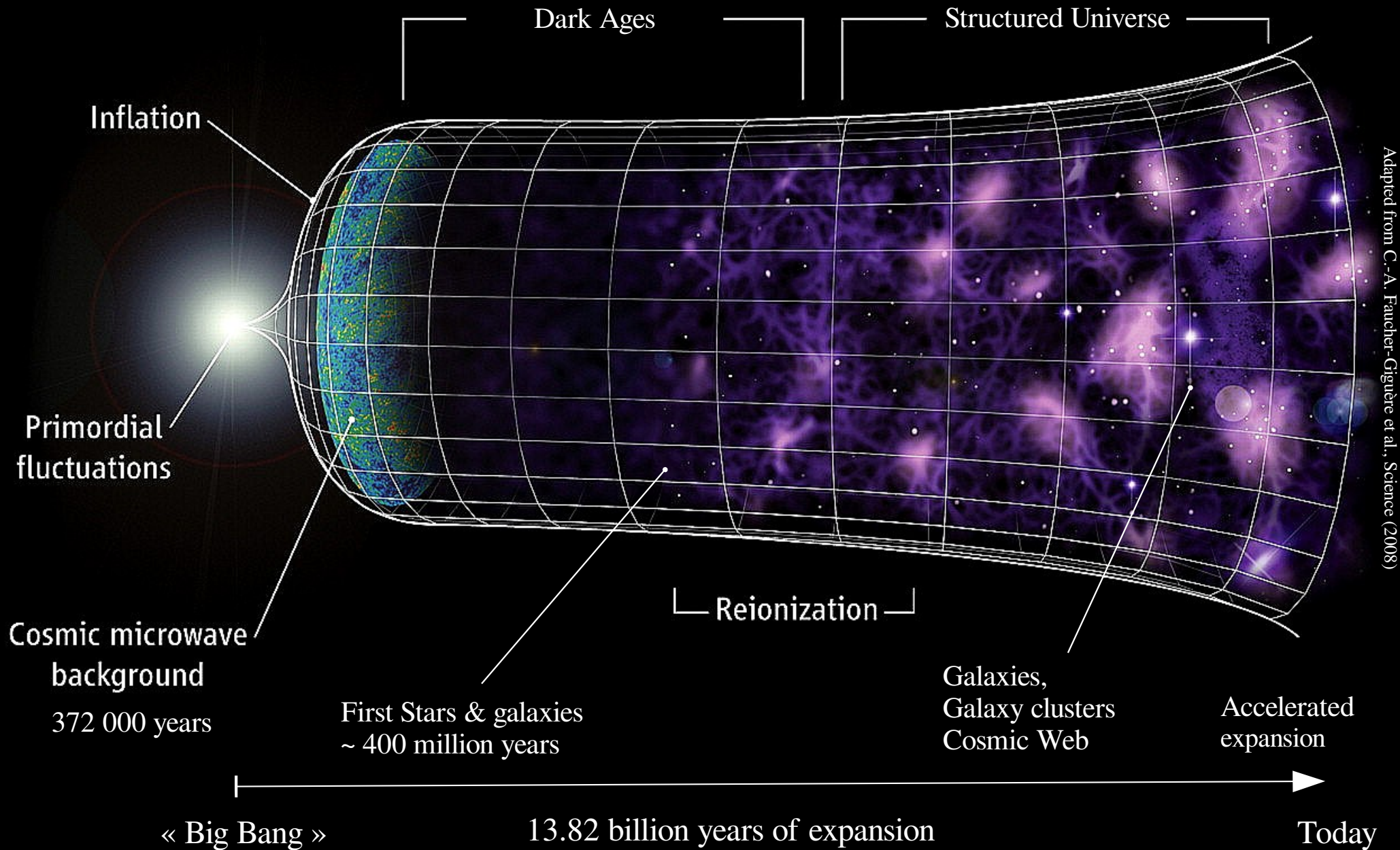
# The observable universe



Courtesy : Marian  
Douspis (w. material  
from Pablo Carlos  
Budassi & the DEUS  
Consortium)



# History of the Universe





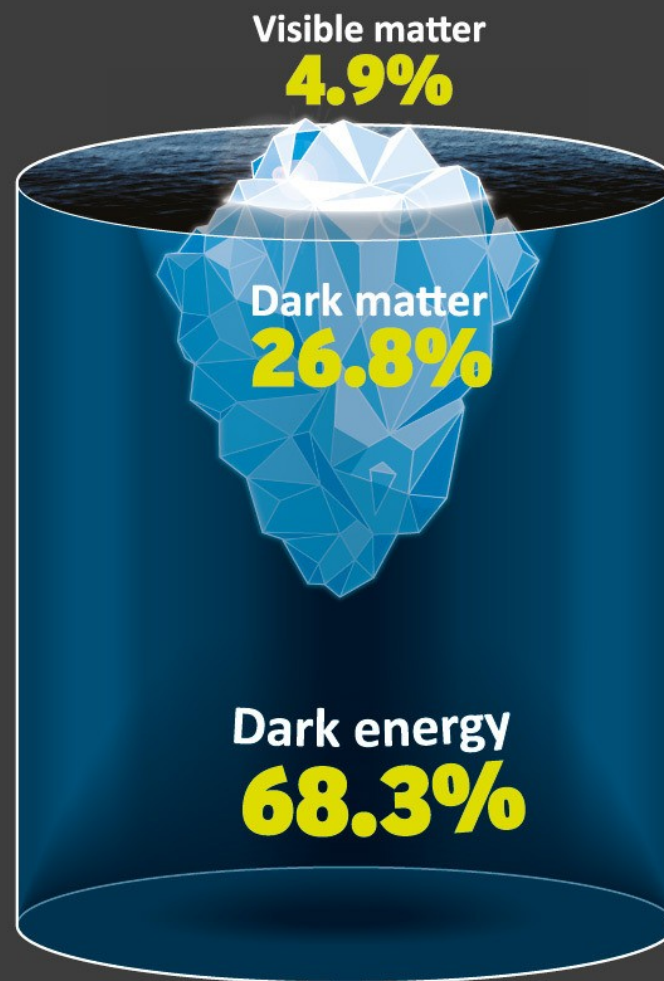
# The Standard Cosmological Model : $\Lambda$ CDM

© National Geographic Society, Jan. 2015



- $\Lambda$ : agent responsible for the current accelerated expansion of the Universe
- Cold Dark Matter:
  - Massive particles
  - Set the expansion rate during most cosmic history
  - Shaped the landscape in which stars and galaxies form

# Present day energy budget: exceedingly dark...



## Visible matter

This is the stuff that makes up everything we can see and touch – all the dust, asteroids, comets, planets, stars, galaxies and you and me

## Dark matter

The dark side of matter doesn't interact with light, so it is invisible. We can detect how its gravity affects visible matter. It is a bit like visible matter's invisible friend – helping to hold the galaxies and clusters of galaxies together

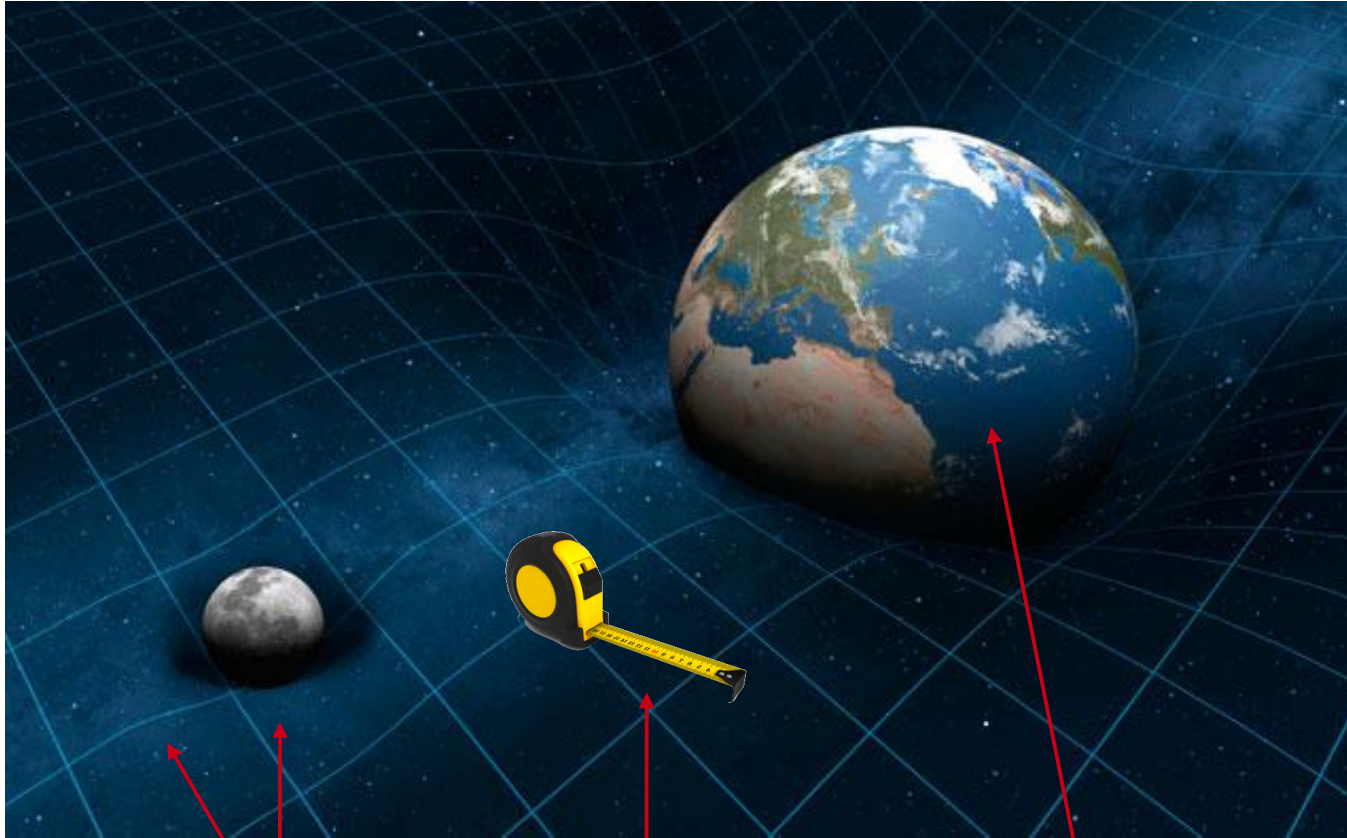
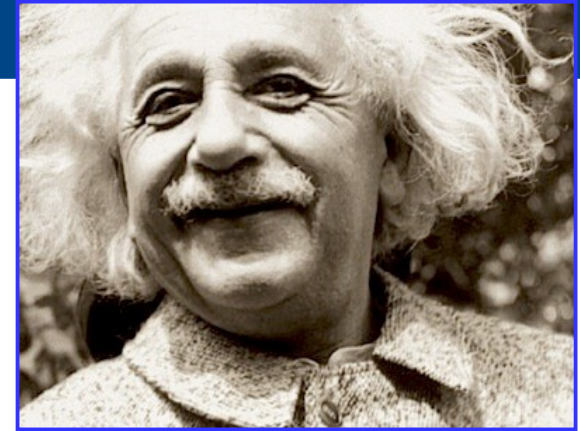
## Dark energy

While dark matter holds stuff together, dark energy is pushing everything apart. It is causing the Universe's expansion to speed up. The more space expands, the more dark energy there is

*Copyright: STFC/Ben Gilliland*



# General Relativity



$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Variation  
of curvature  
from place to place

Measure of distances  
given the curvature  $R$   
at each point

Matter & Energy  
bend space

*Die Feldgleichungen  
der Gravitation, 1915*

# The Cosmological Constant & Dark Energy

- First occurrence:

Einstein, 1917 → find a static solution to his equations

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- Disappearance:

Friedmann, Lemaître, Hubble, 1922 – 1929: the Universe is expanding!

- The comeback:

Perlmutter, Schmidt, Riess, 1998 – 1999 : expansion is accelerating!

(Nobel prize 2011)

→ reintroduce  $\Lambda$  with the opposite sign, and...



# Which value for $\Lambda$ ?

- Measurements!
  - $\sim 6 \times 10^{-27}$  kilograms per cubic metre
- Calculate: zero point energy (quantum fluctuations of empty space)
  - $\sim 6 \times 10^{+96}$  kilograms per cubic metre

**123** orders of magnitude discrepancy...

“The worst ‘prediction’ of theoretical physics”

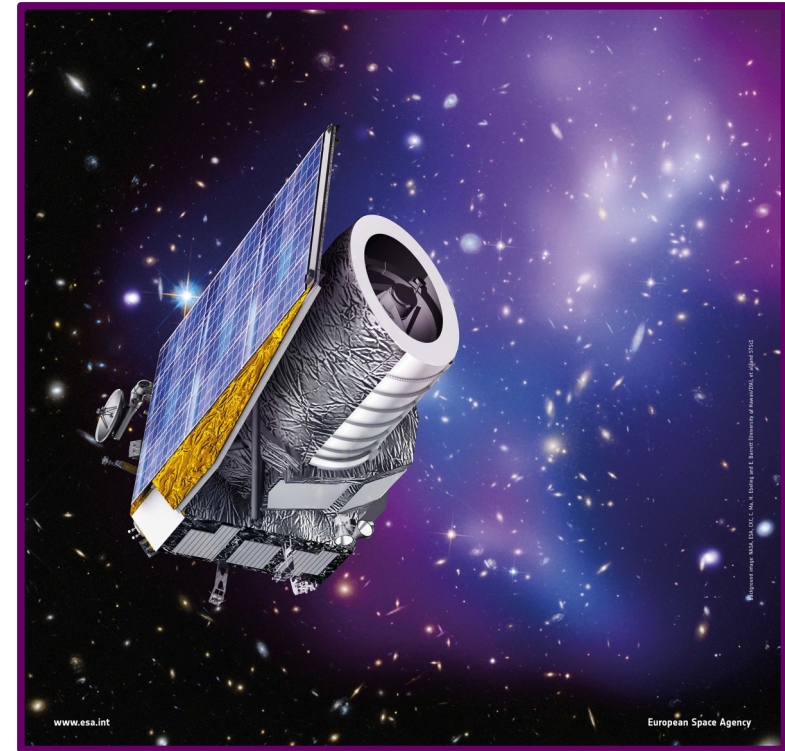
- Understand its nature:
  - Is it ‘just’ a fundamental constant?
  - Is it rather a quantum property of vacuum?
  - Both are **a priori** possible!
    - why **together** do they yield such a small value?



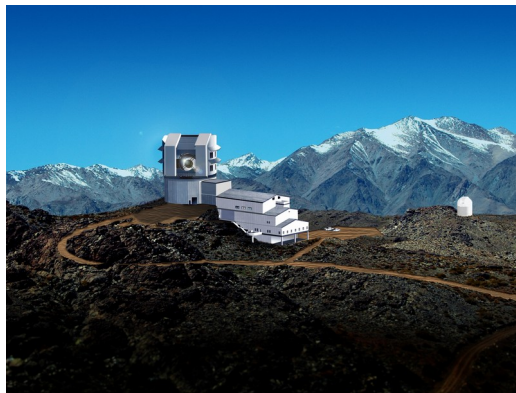
# What is actually driving the accelerated expansion?

- The cosmological constant?
- Something else (additional fields)?
- Incompleteness of General Relativity?
- Back reaction (non-linear) of structures?
- Acceleration: merely a mirage?

Euclid



LSST



DES

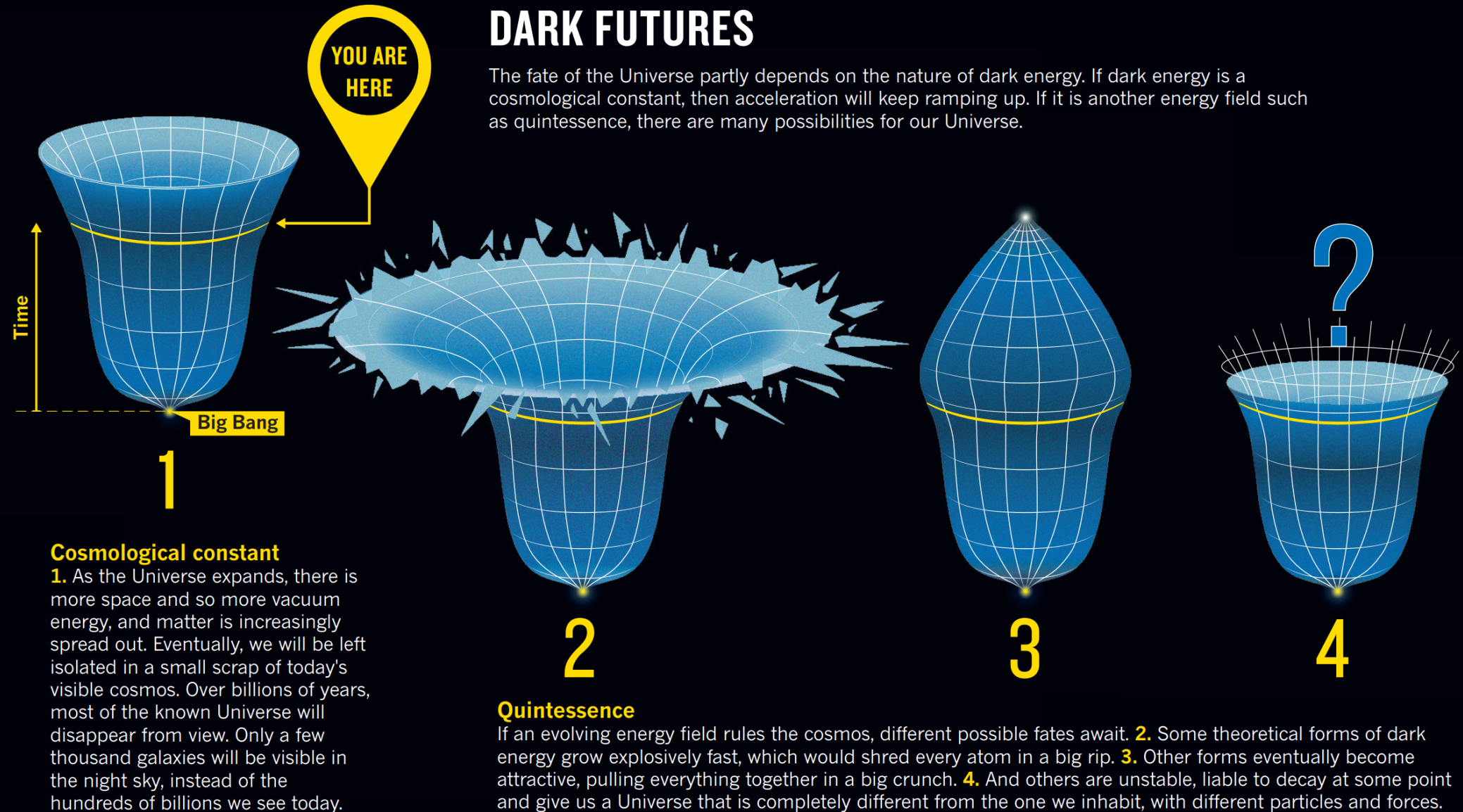




# The unknown fate of the Universe

## DARK FUTURES

The fate of the Universe partly depends on the nature of dark energy. If dark energy is a cosmological constant, then acceleration will keep ramping up. If it is another energy field such as quintessence, there are many possibilities for our Universe.



Credit: [Nature](#), September 28, 2016



## WHAT IS DARK MATTER?

Next to dark energy, the second largest component of the universe is dark matter.

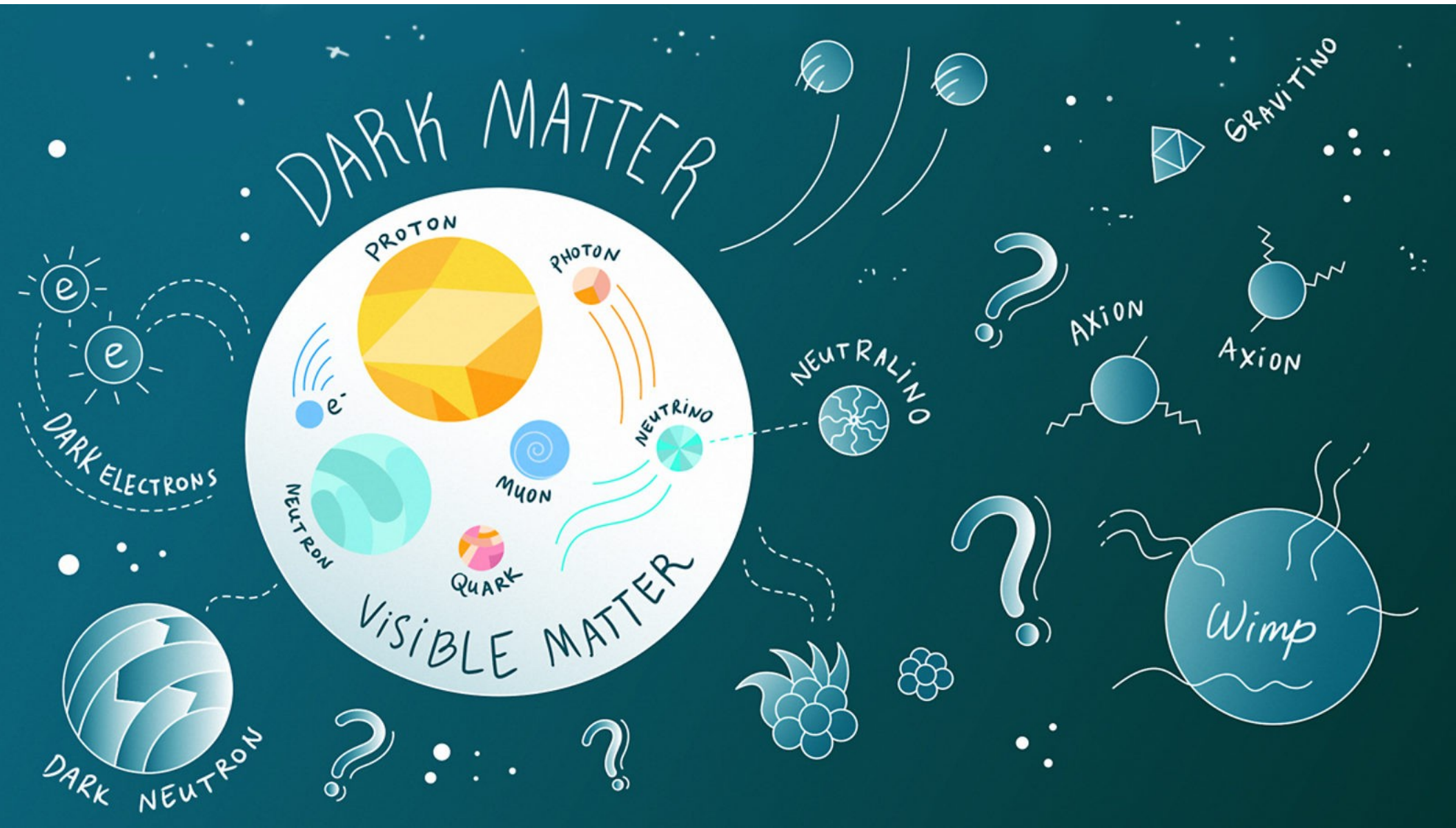
It cannot be seen directly, but its effects can be observed from its interaction with the rest of the universe through its gravity.

The truth is, we understand little of what it is, and more of what it is not.

Credit: futurism.com, 2017



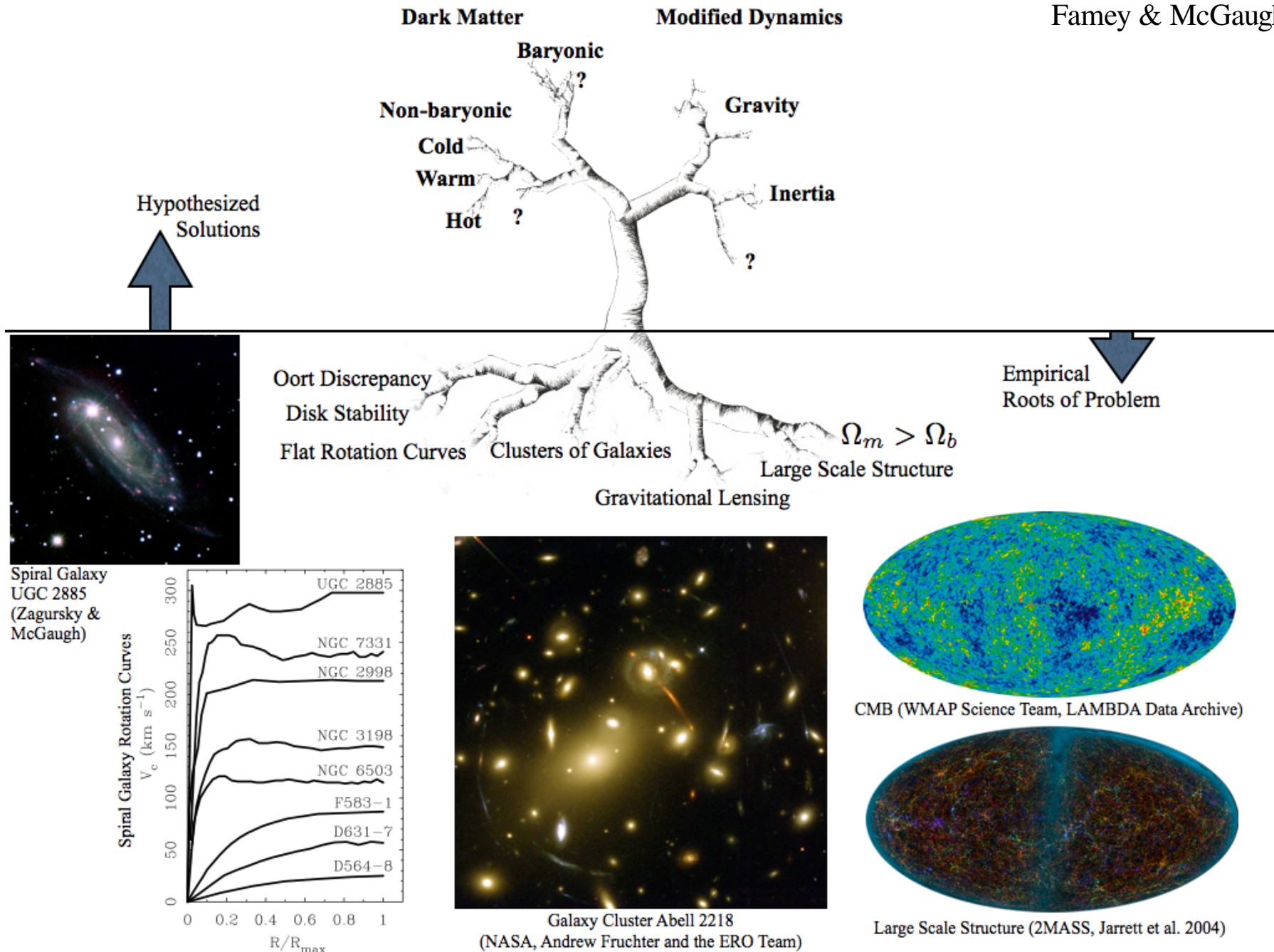
# New Particles ?



Credit: Symmetry Magazine, 2015

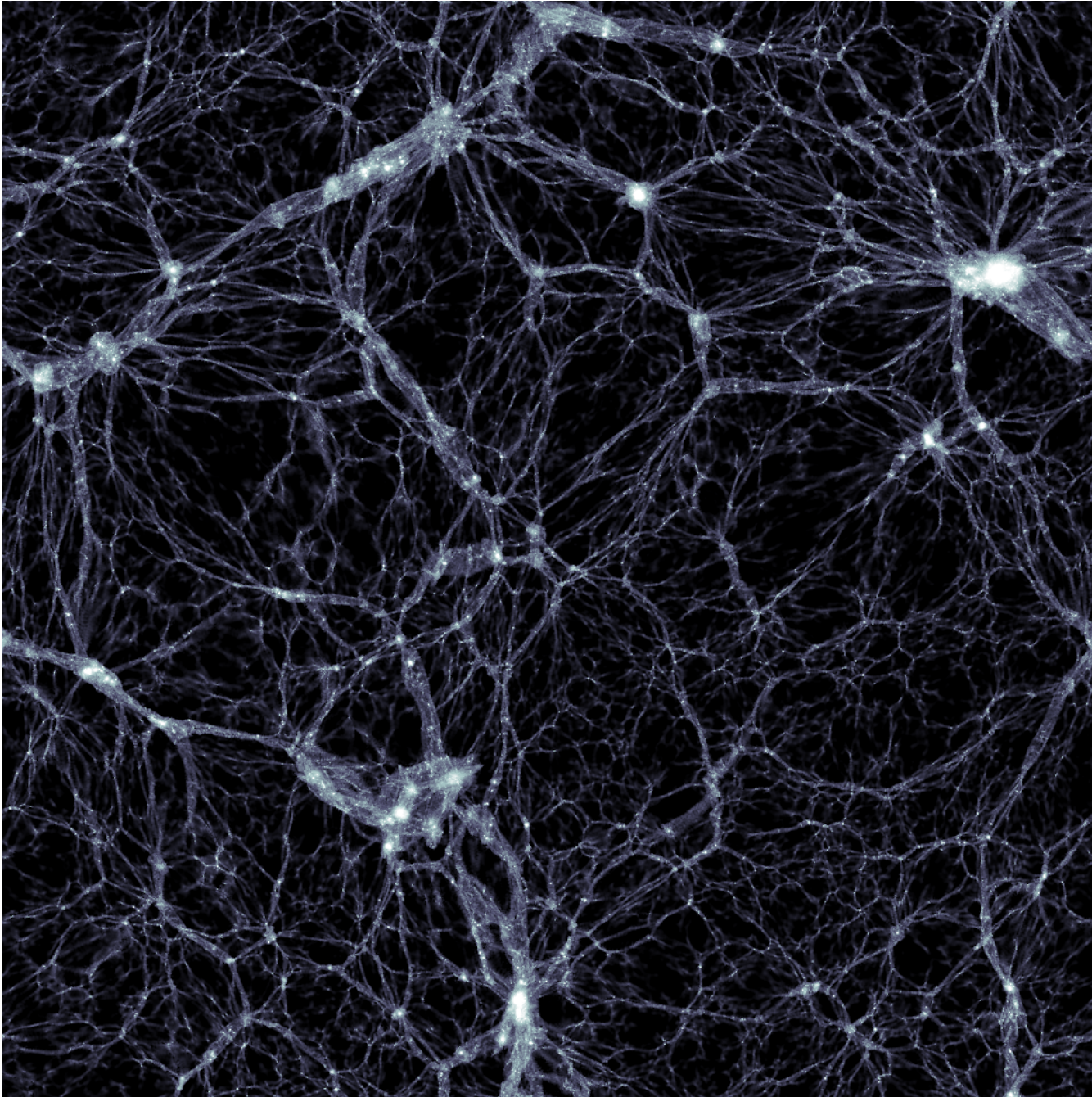
# Mass Discrepancy Tree

Famey & McGaugh (2012)





# The Cosmic Web: simulated

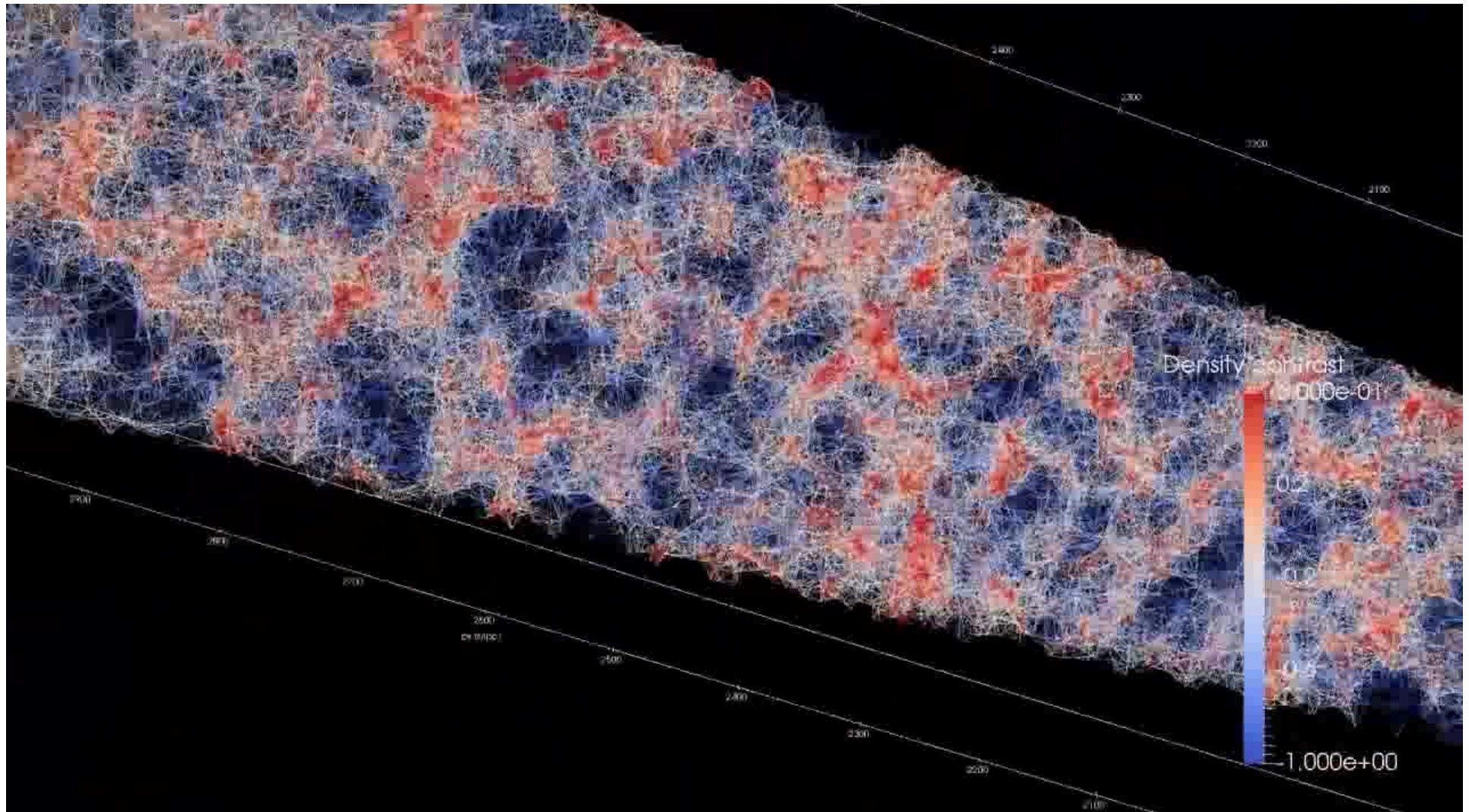


Dark Matter only

*Illustris* simulation  
Haider et al. (2016)



# The Cosmic Web: observed

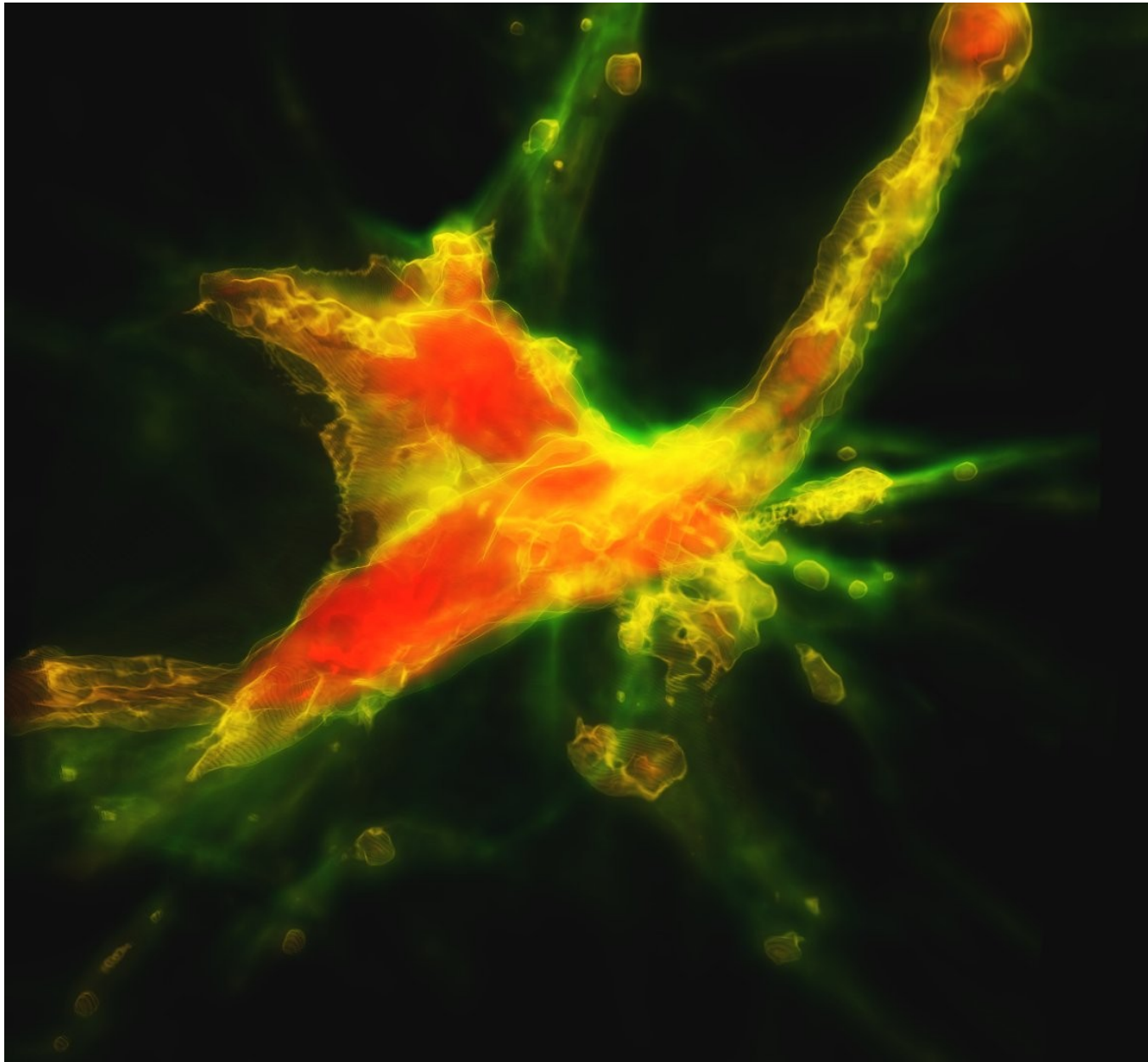


## VIMOS Public Extragalactic Redshift Survey

Credit: S. Arnouts, N. Malavasi & the VIPERS Collaboration

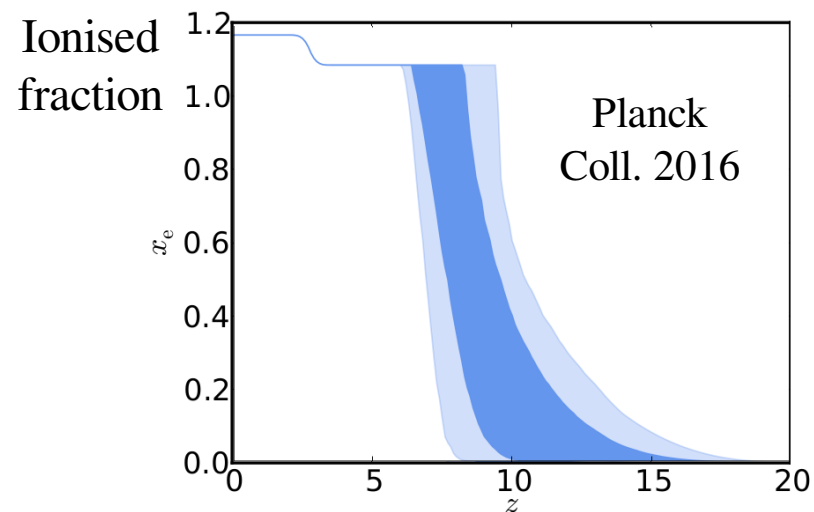
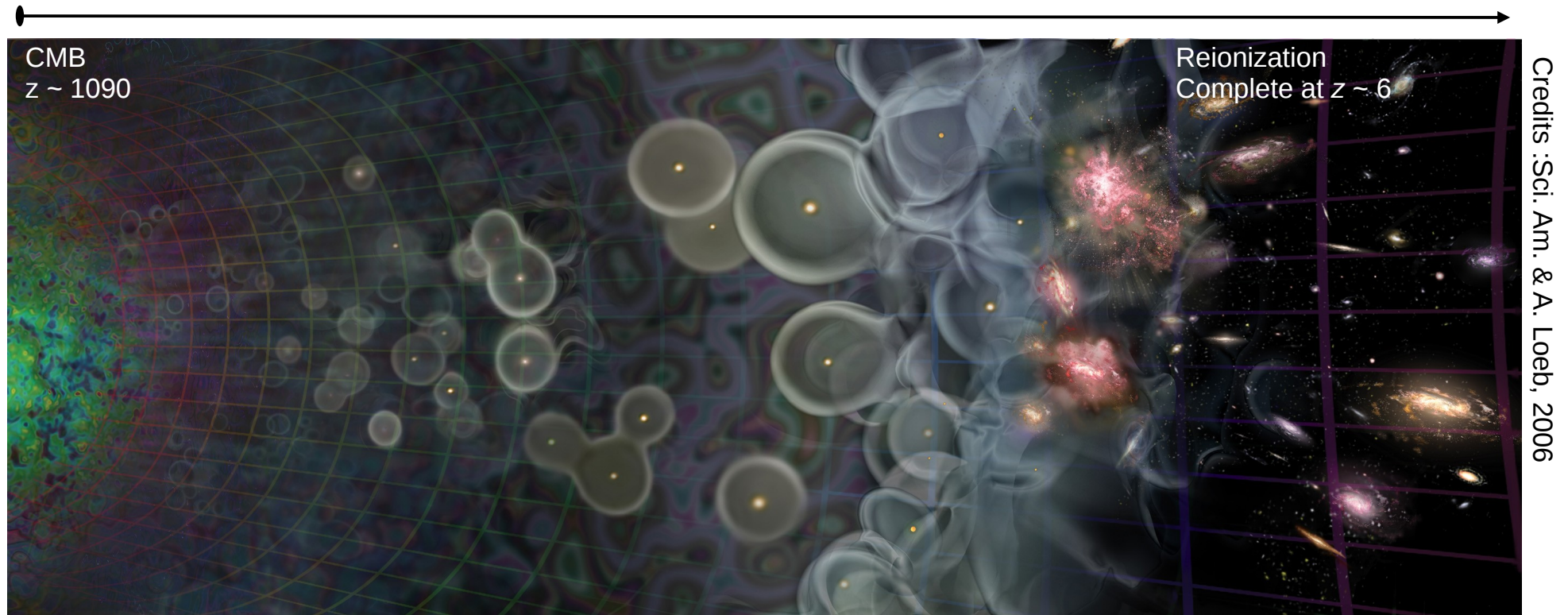


# Multiscale filamentary structure: very early on!



“First” galaxy in its filamentary environment at  $z \sim 10$  (Greif et al., 2008)

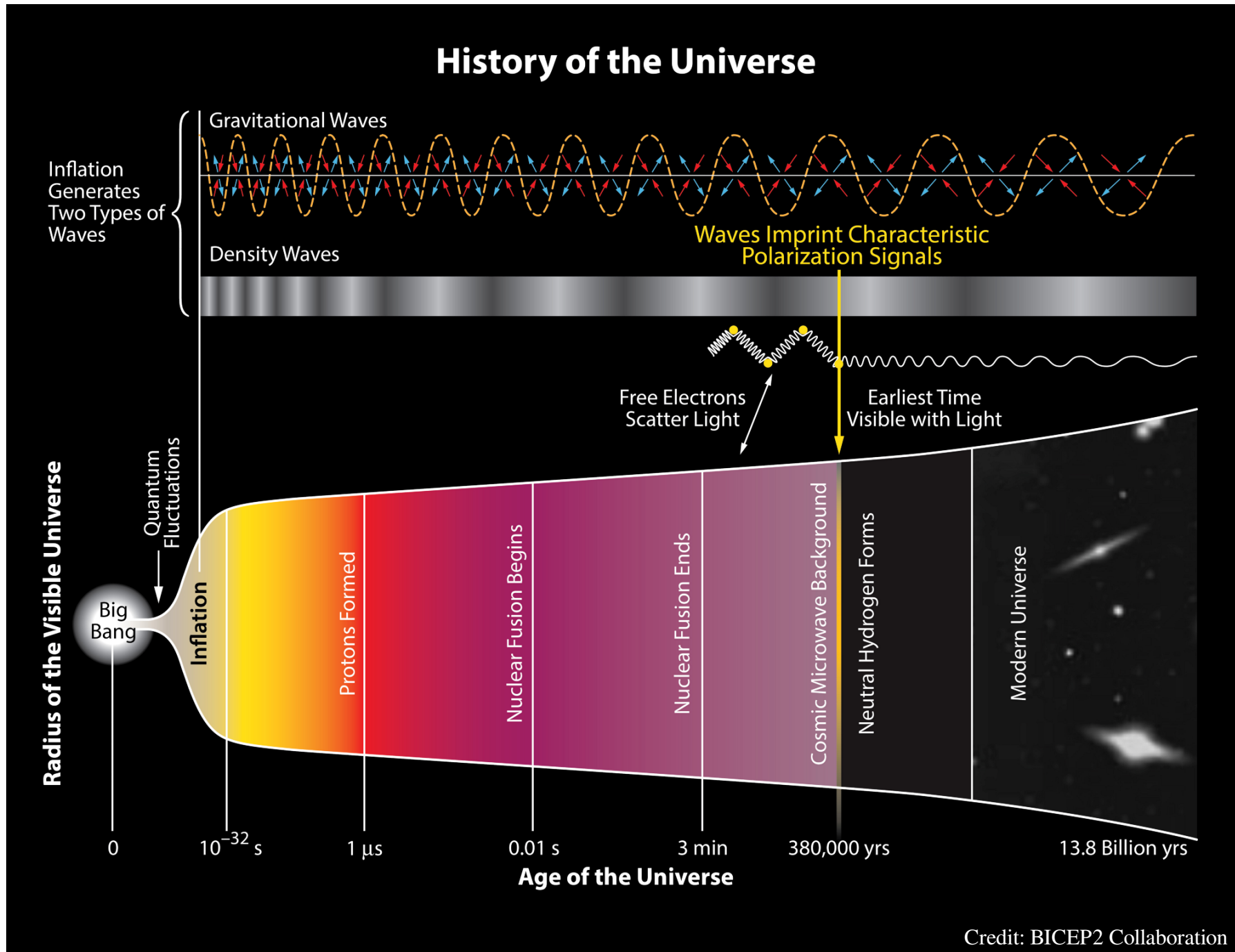
# Cosmological Reionization



- When did it begin?
- How much did first stars contribute?
- How much did first quasars contribute?
- Exotic sources of ionising radiation?
- Impact on subsequent structure formation?

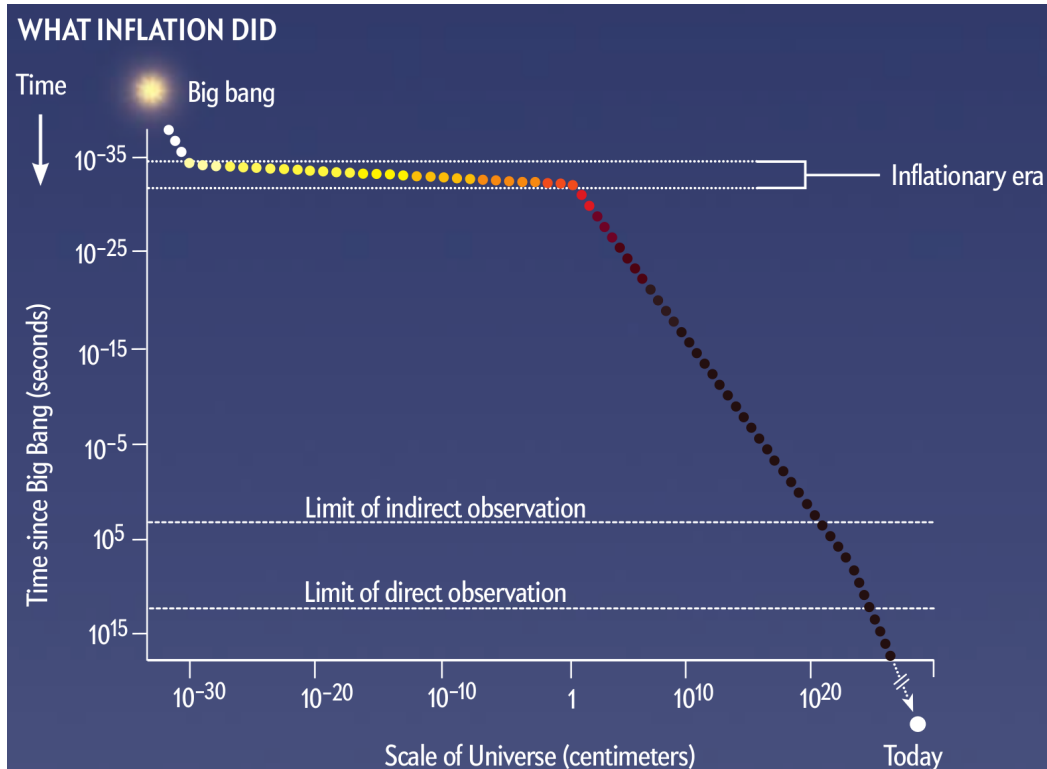


# Inflation



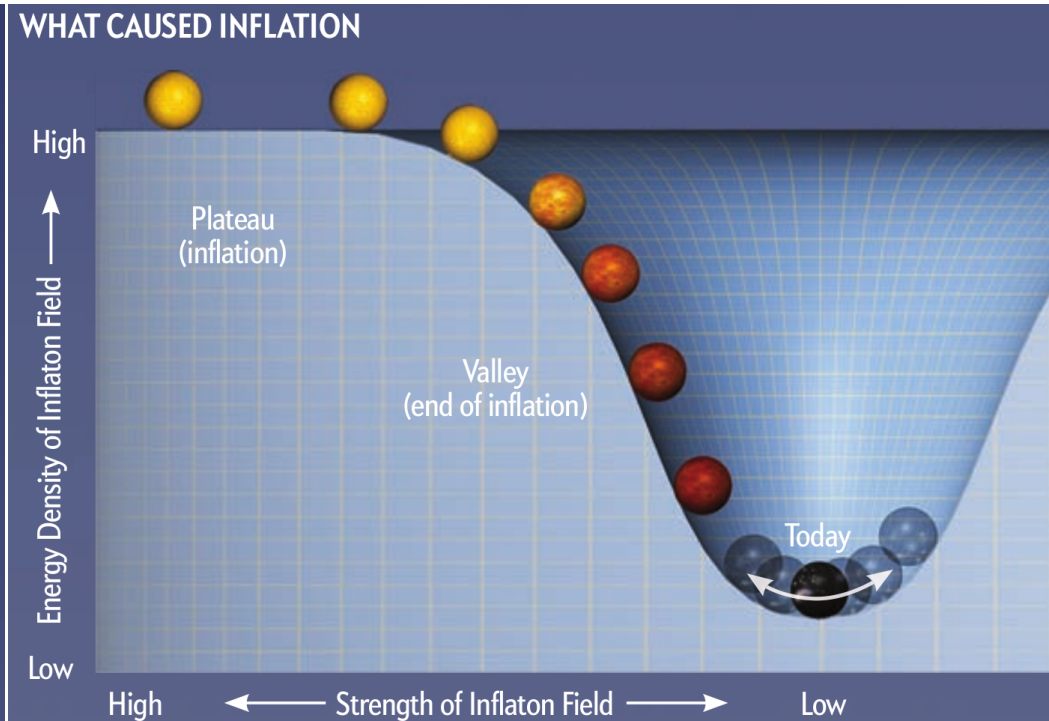
# How does inflation work ?

Credits: Jen Christiansen, Scientific American, 2011



The amount of growth was impressive even by astronomers' standards. Within  $10^{-30}$  second, the universe enlarged by a factor of at least  $10^{25}$  in every direction. It expanded at an accelerated rate, pulling regions of space apart faster than the speed of light.

Time evolution  
of the scale of the Universe

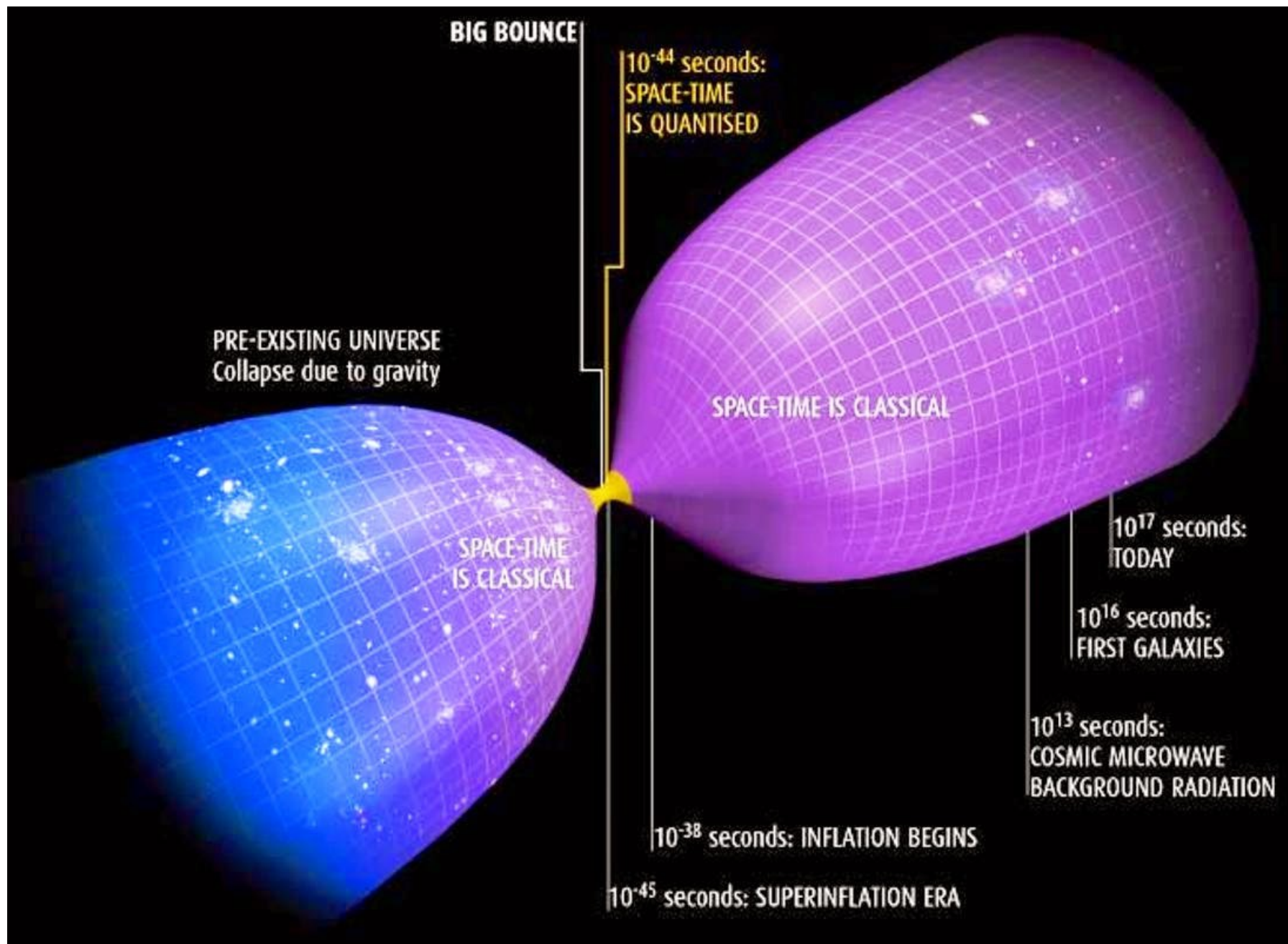


A relative of the magnetic field, the “inflaton” generated a repulsive gravitational force that drove space to swell rapidly momentarily. For that to occur, the field’s energy density had to vary with strength such that it had a high-energy plateau and a low-energy valley. The field evolved like a ball rolling downhill. On the plateau, it exerted the repulsive force. When it hit the valley, inflation ended.

Energy density  
of the Inflaton field

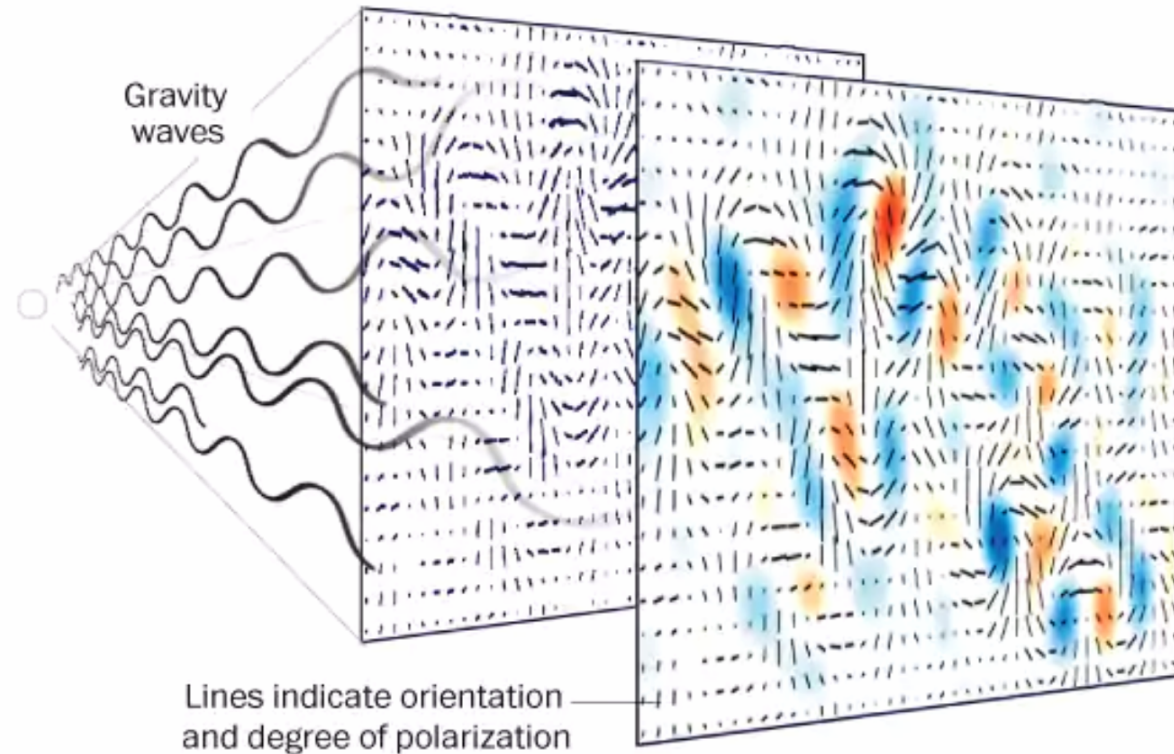
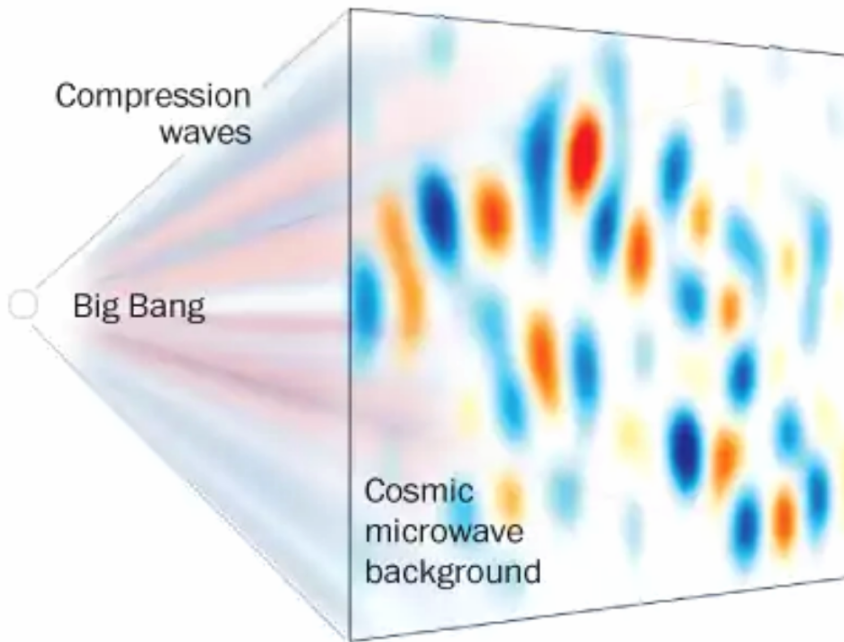


# An alternative: bounce cosmology



Credit: New Scientist, Dec. 2008

# Probing inflation: primordial gravity waves



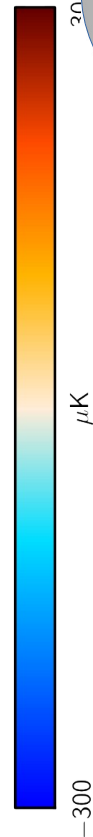
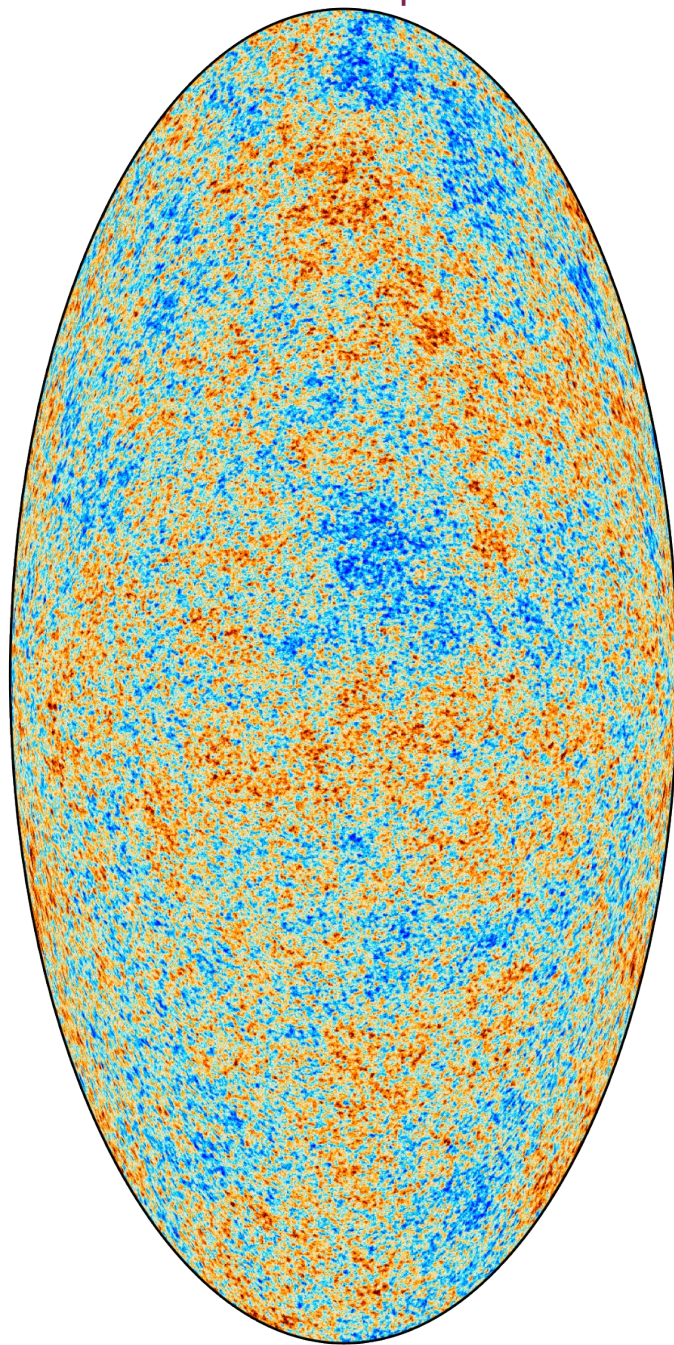
Within a tiny fraction of a second, the big bang inflated the universe. **Compression waves** created a pattern in the afterglow of the expansion, known as the **cosmic microwave background**.

In the 1990s, physicists theorized that rapid inflation during the big bang would also generate **gravity waves**, which would leave their mark by polarizing light in the cosmic afterglow.

SOURCE: Harvard-Smithsonian Center for Astrophysics



# The CMB: statistical analysis

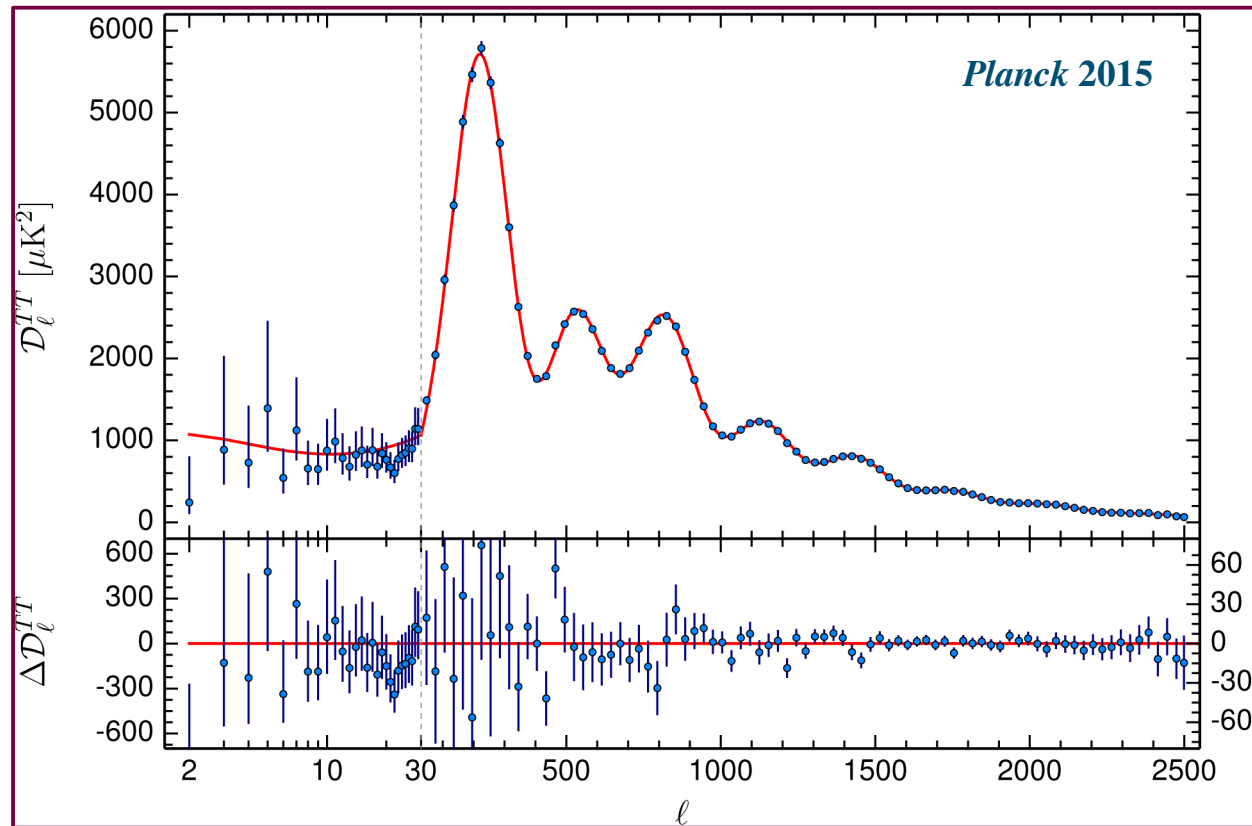


$$\frac{\Delta T}{\bar{T}}(\theta, \phi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{+l} a_{lm} Y_l^m(\theta, \phi)$$

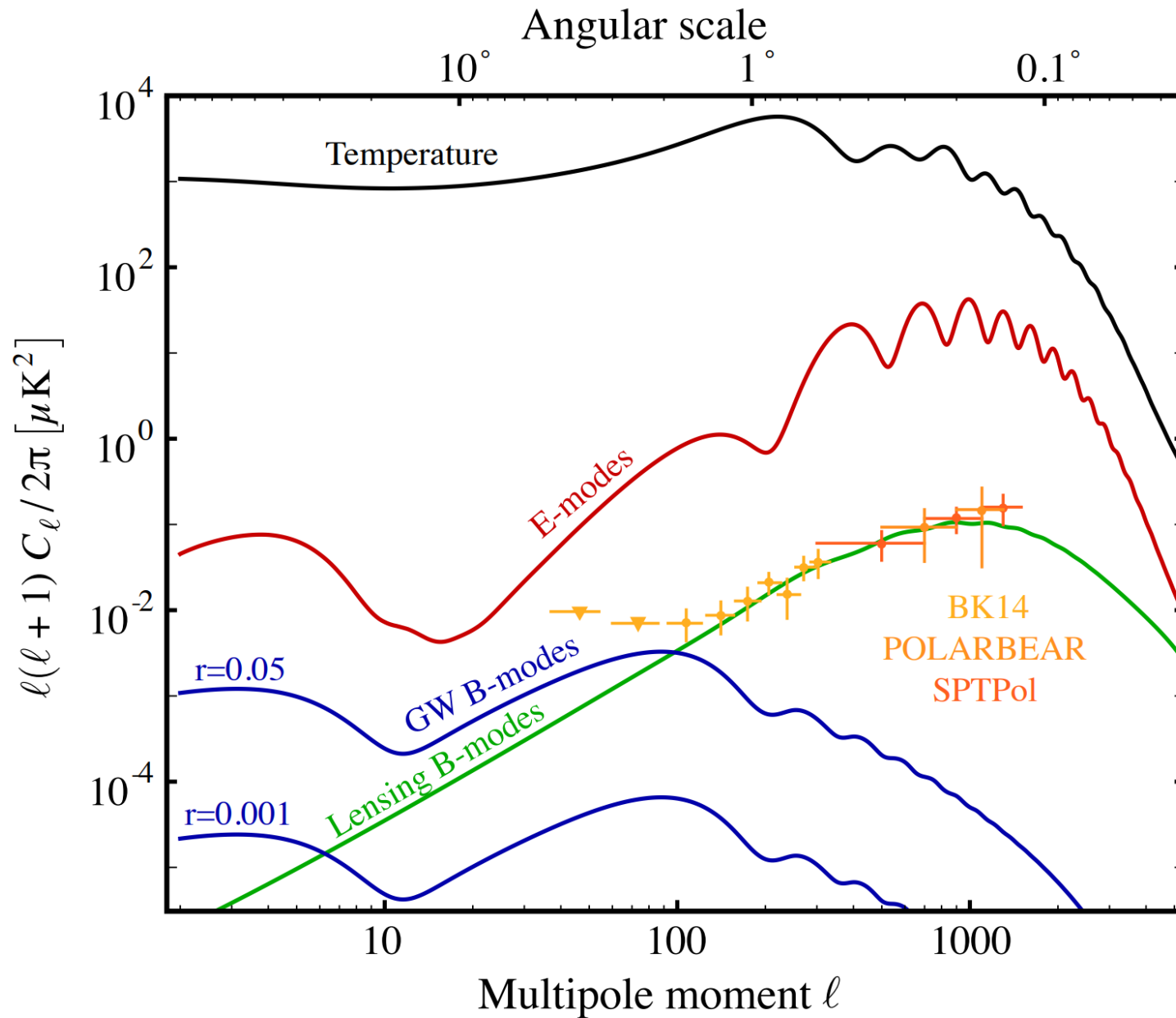
**“Frequency” of spots  
as function of their size**

$$C_l \sim \text{TF} \left\langle \frac{\Delta T}{\bar{T}}(\vec{n}) \frac{\Delta T}{\bar{T}}(\vec{n}') \right\rangle$$

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

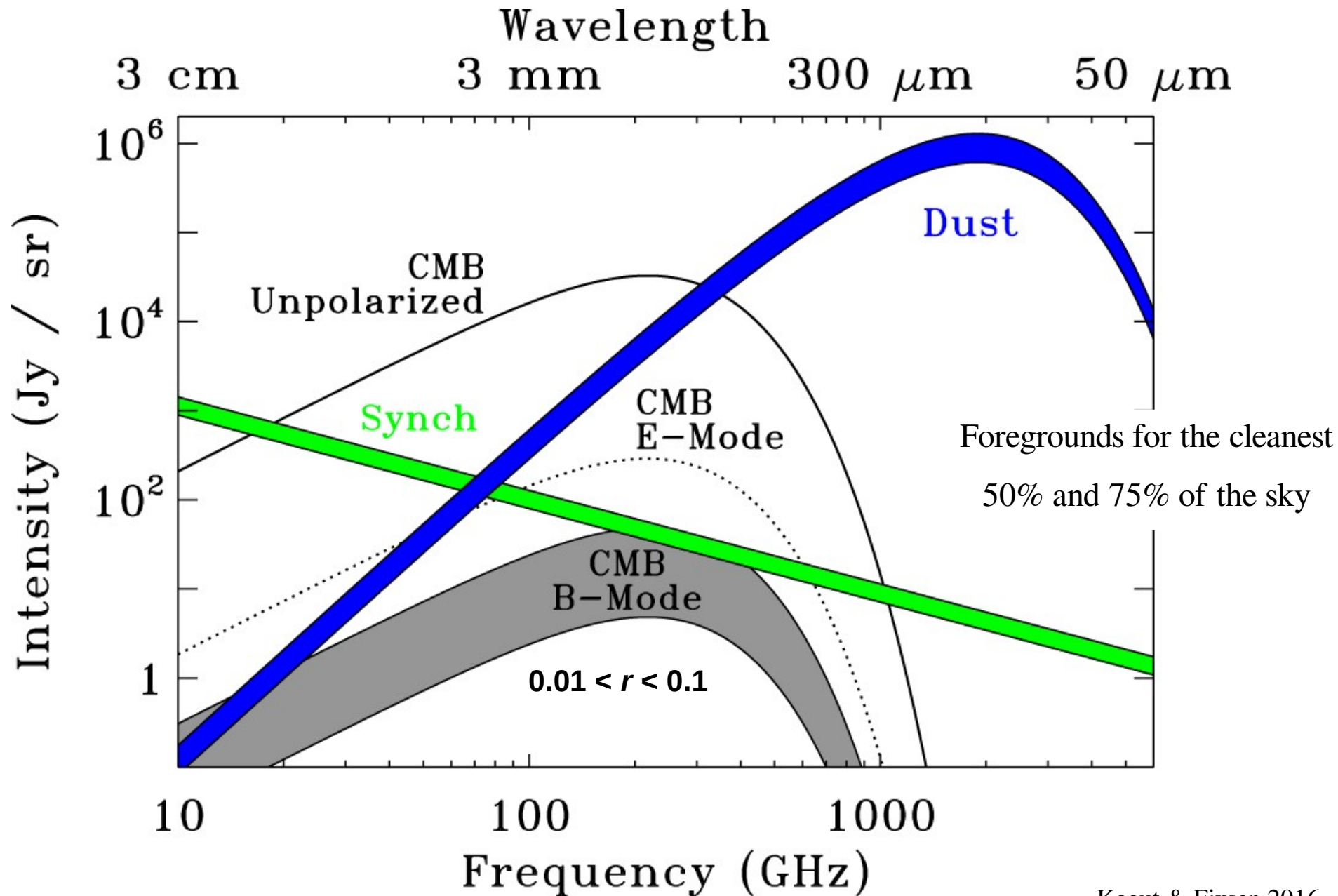


# CMB powerspectra



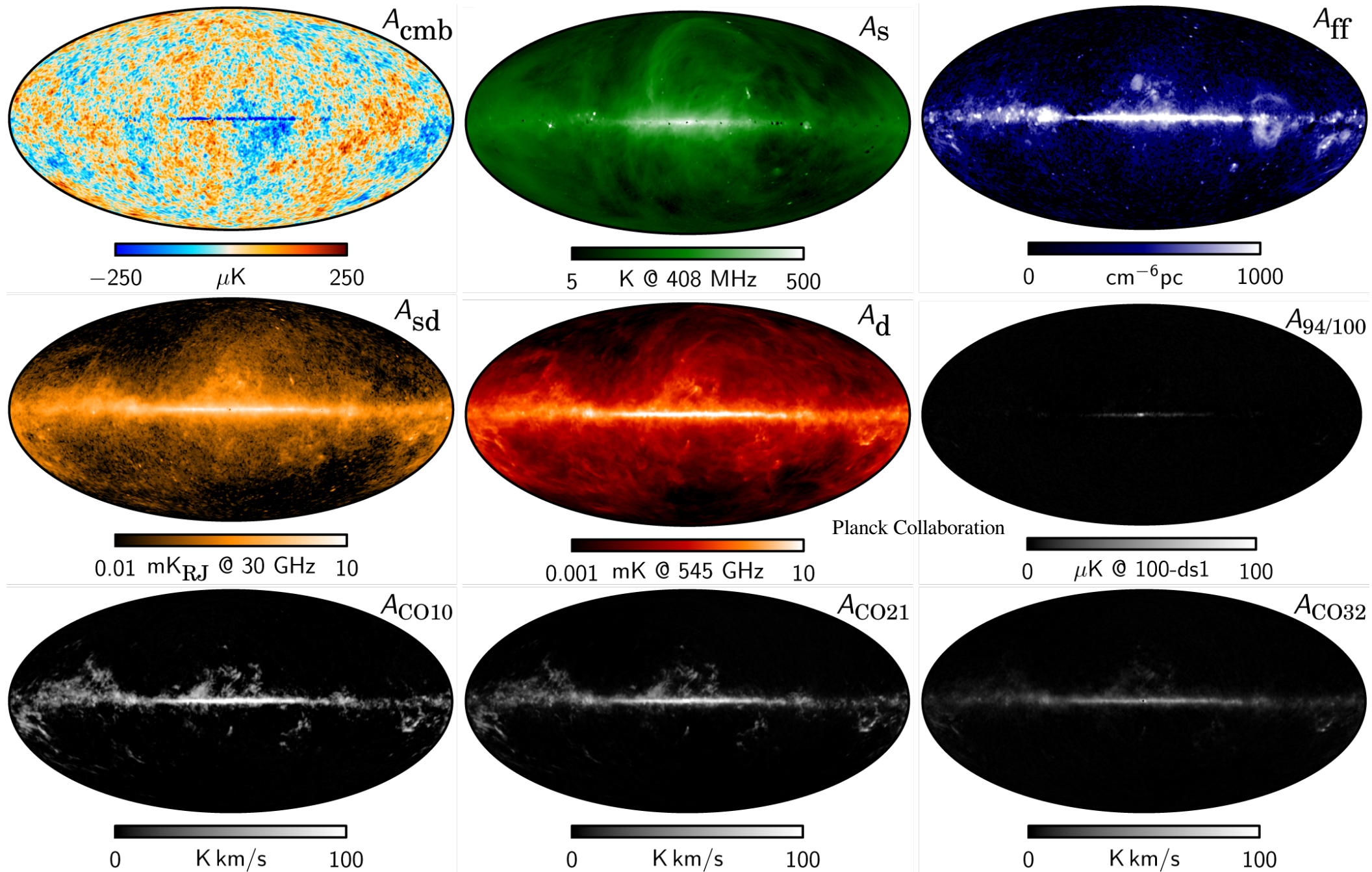


# The signal: a tiny needle in a haystack of foregrounds & noise



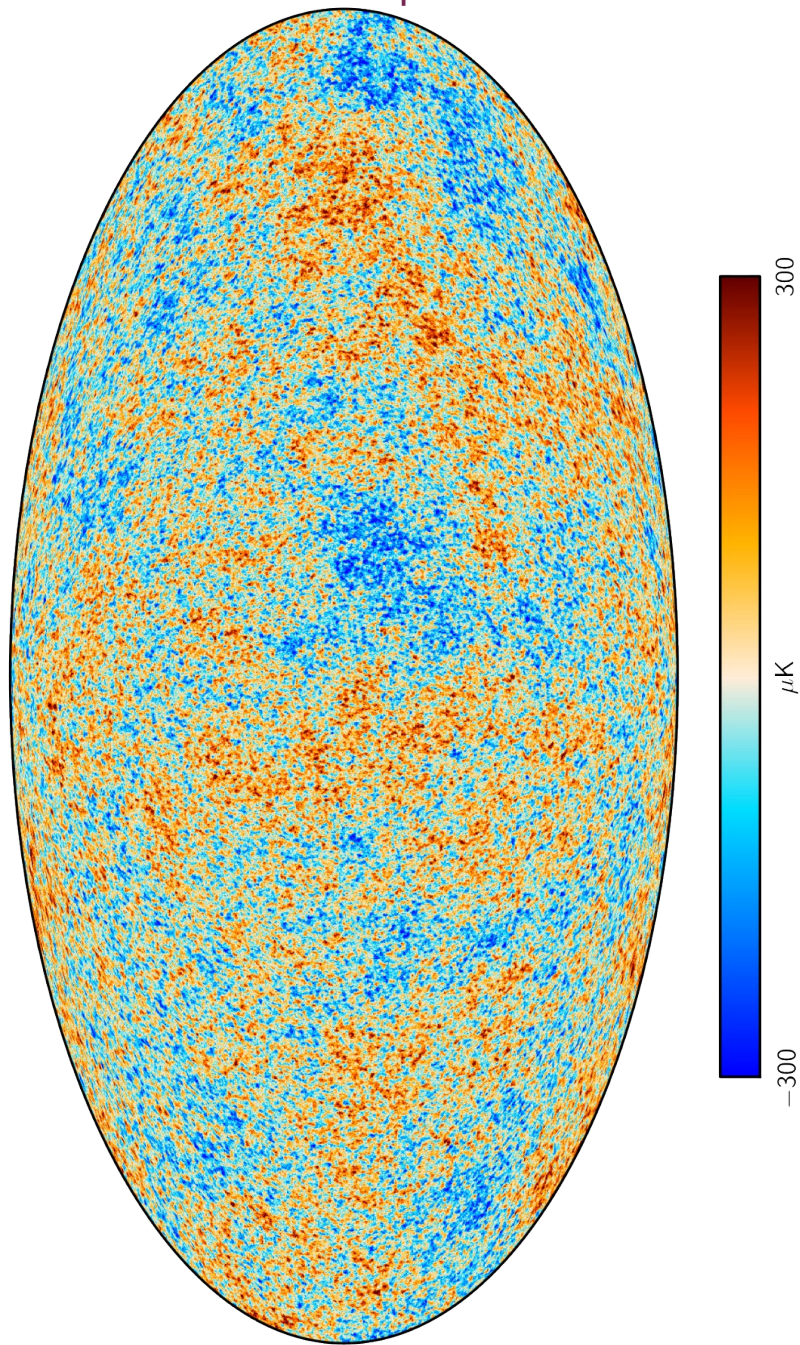
Kogut & Fixsen 2016

# Some of the Temperature foregrounds





# The CMB: statistical analysis

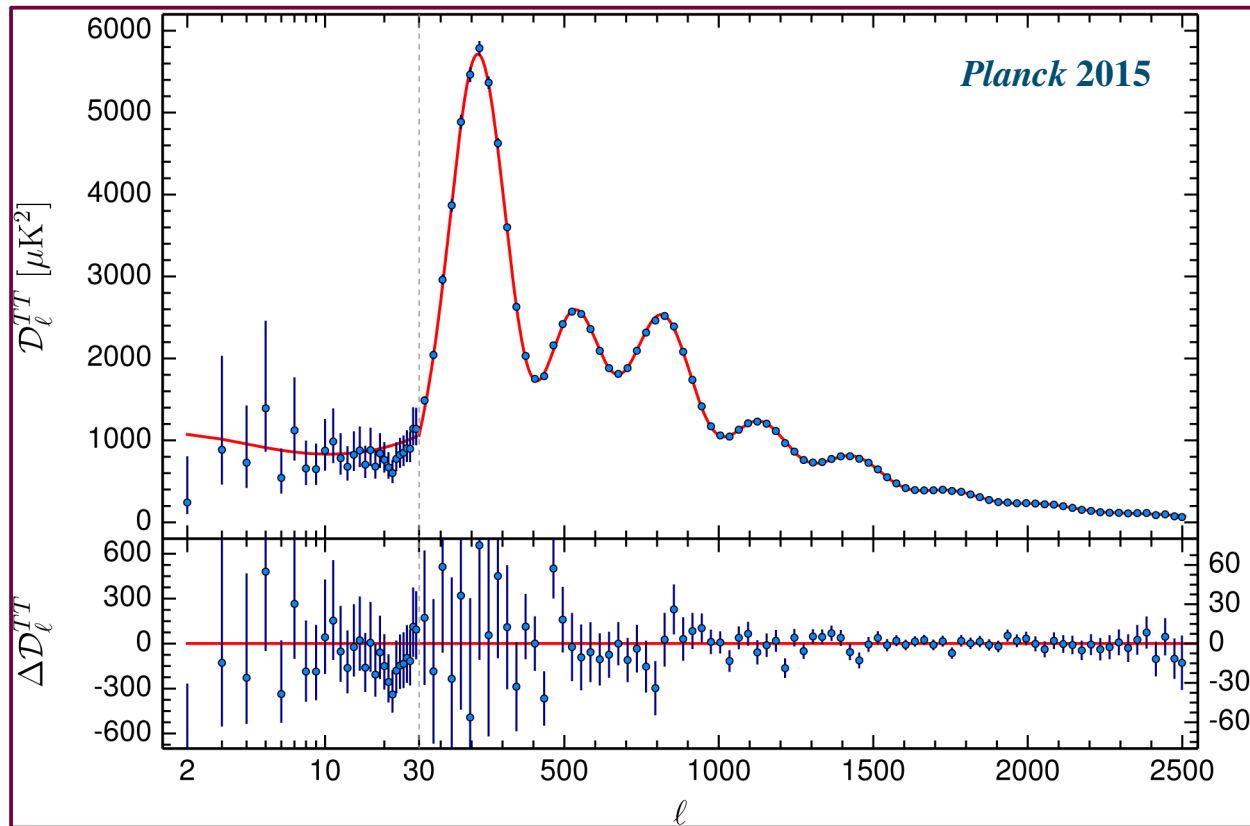


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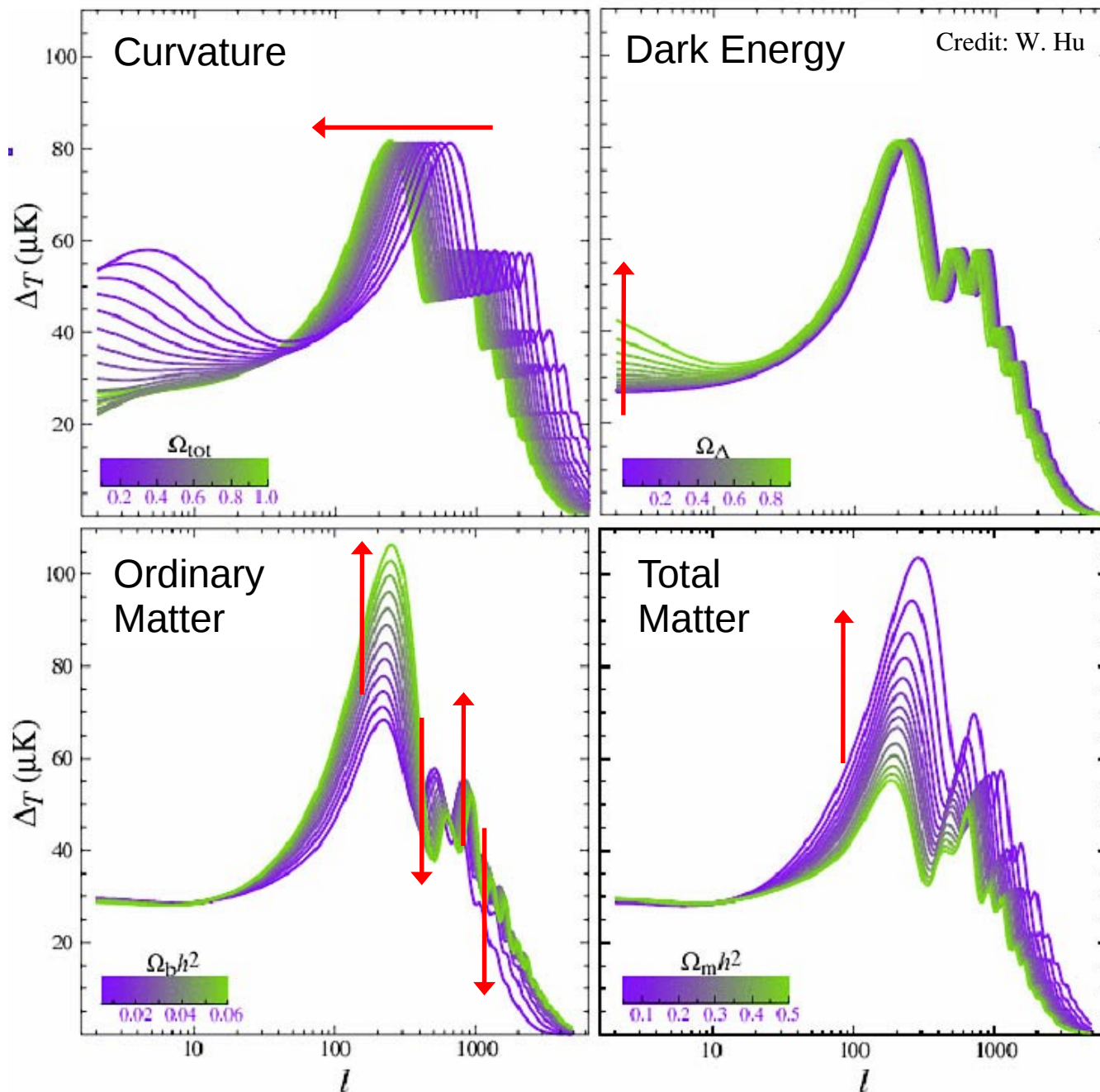
**“Frequency” of spots  
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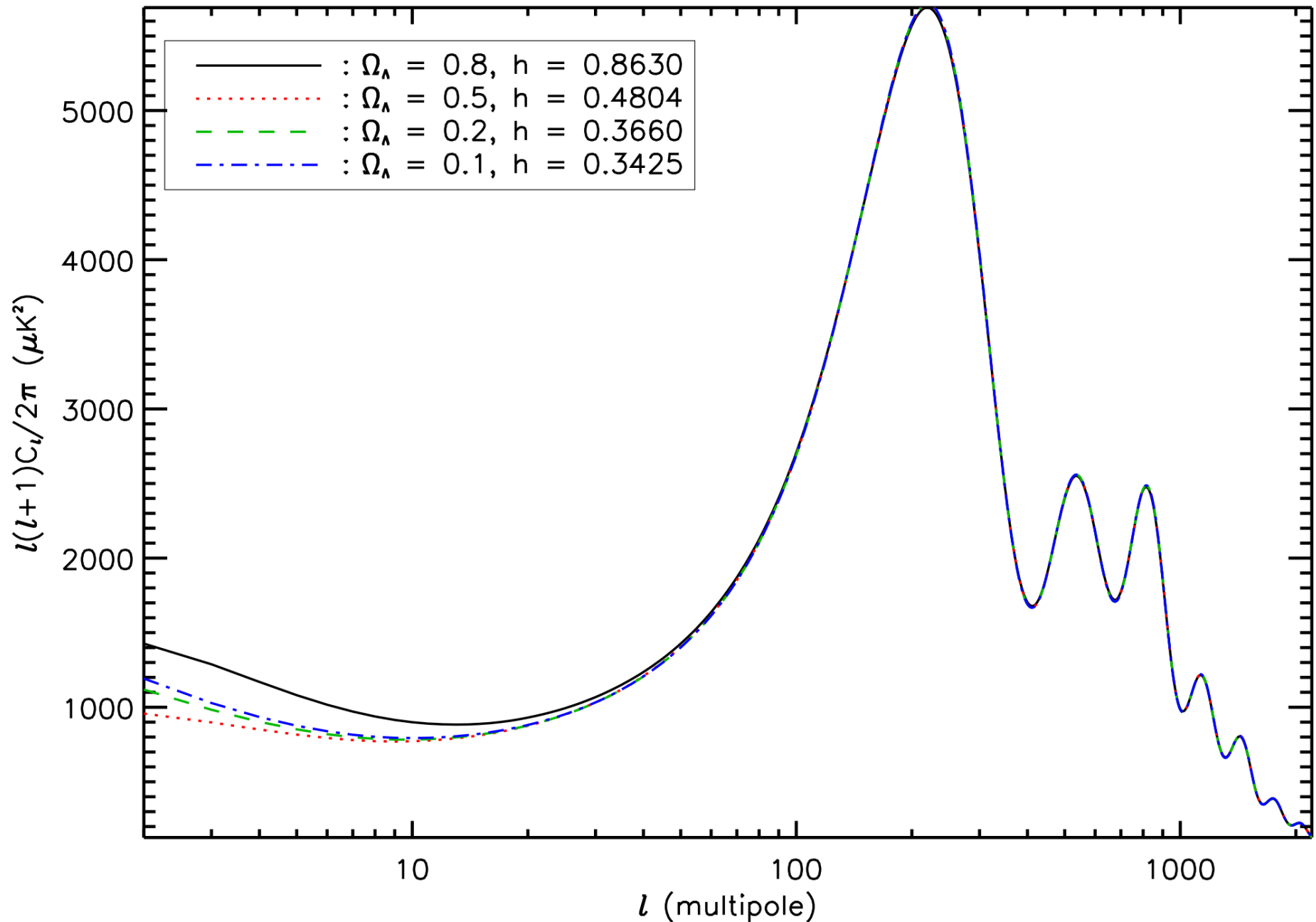


# The CMB: a developer of the Universe

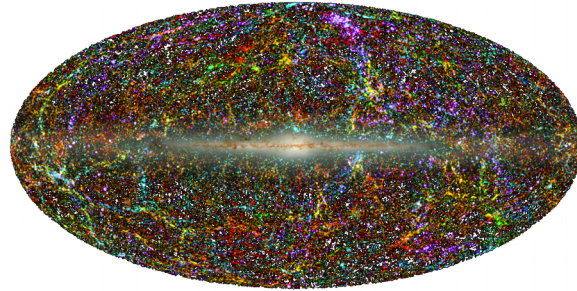




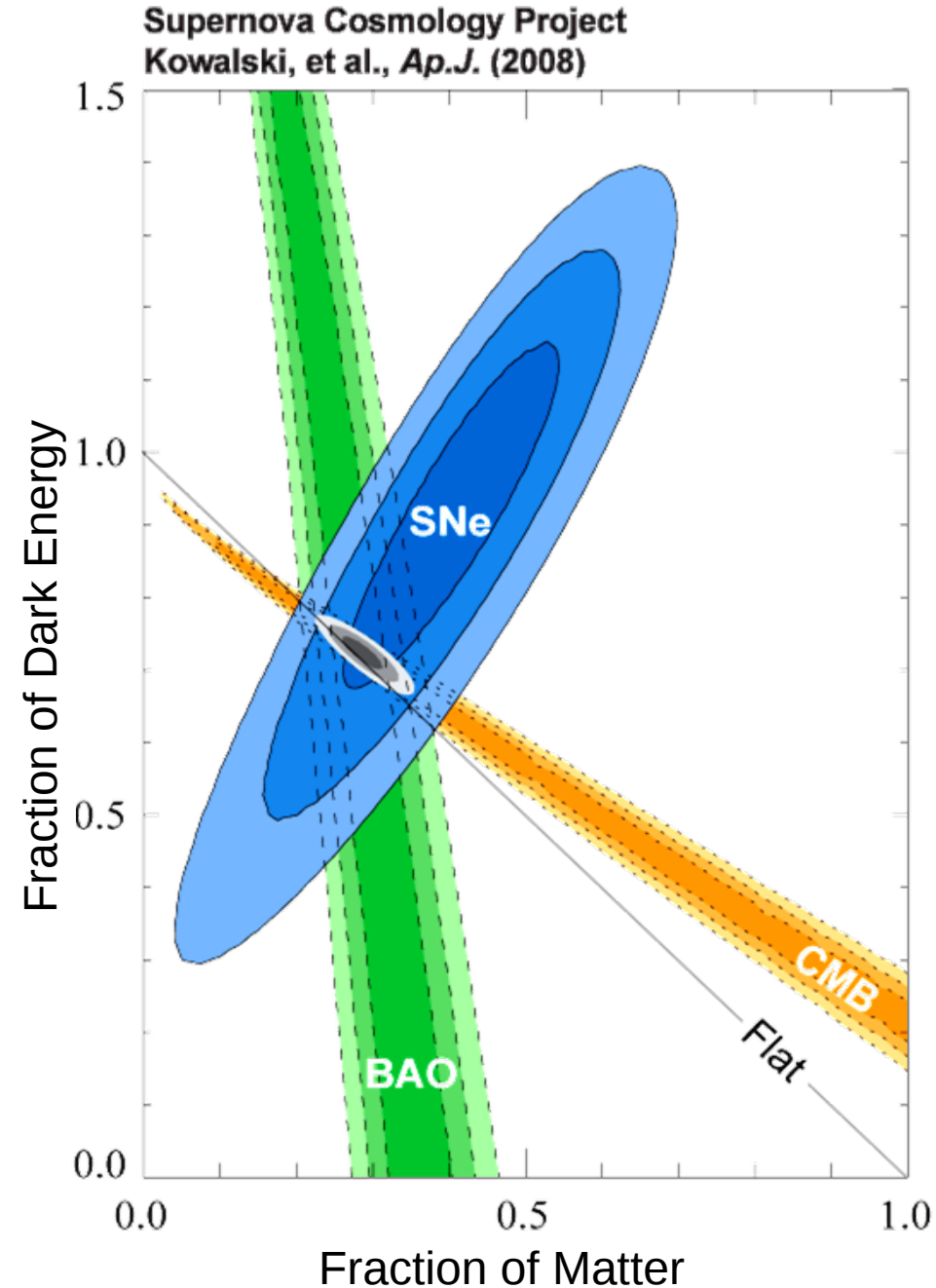
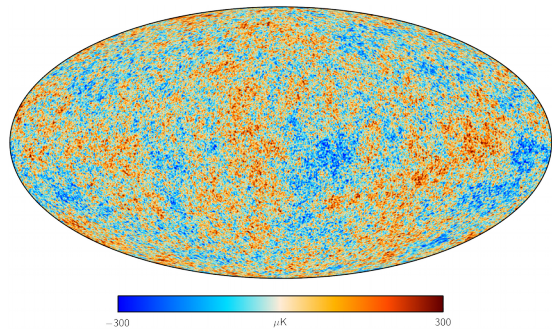
# The CMB & “degeneracies”



# Breaking degeneracies?

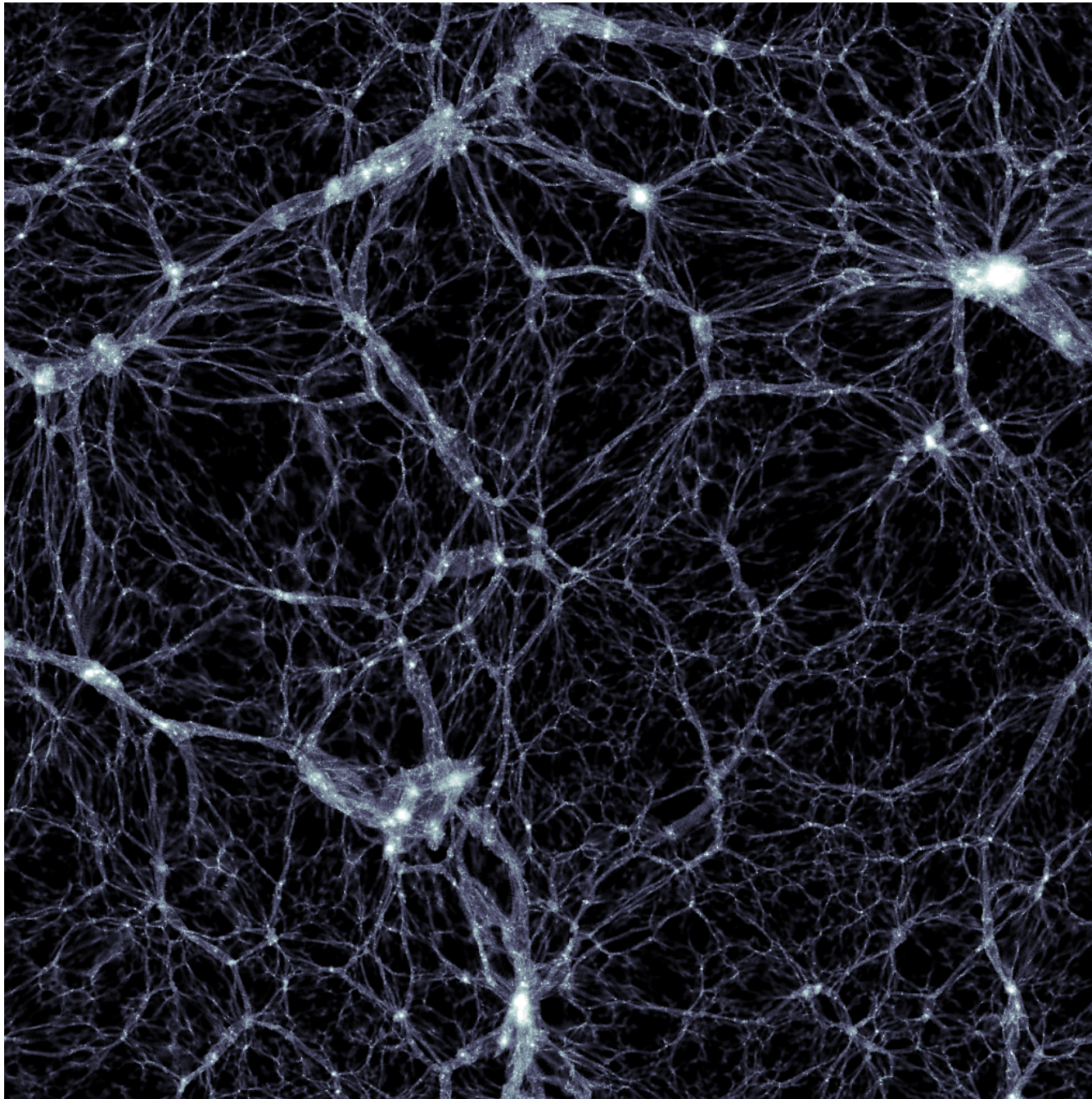


Combining  
independent  
data!





# The Cosmic Web: the Dark Matter distribution

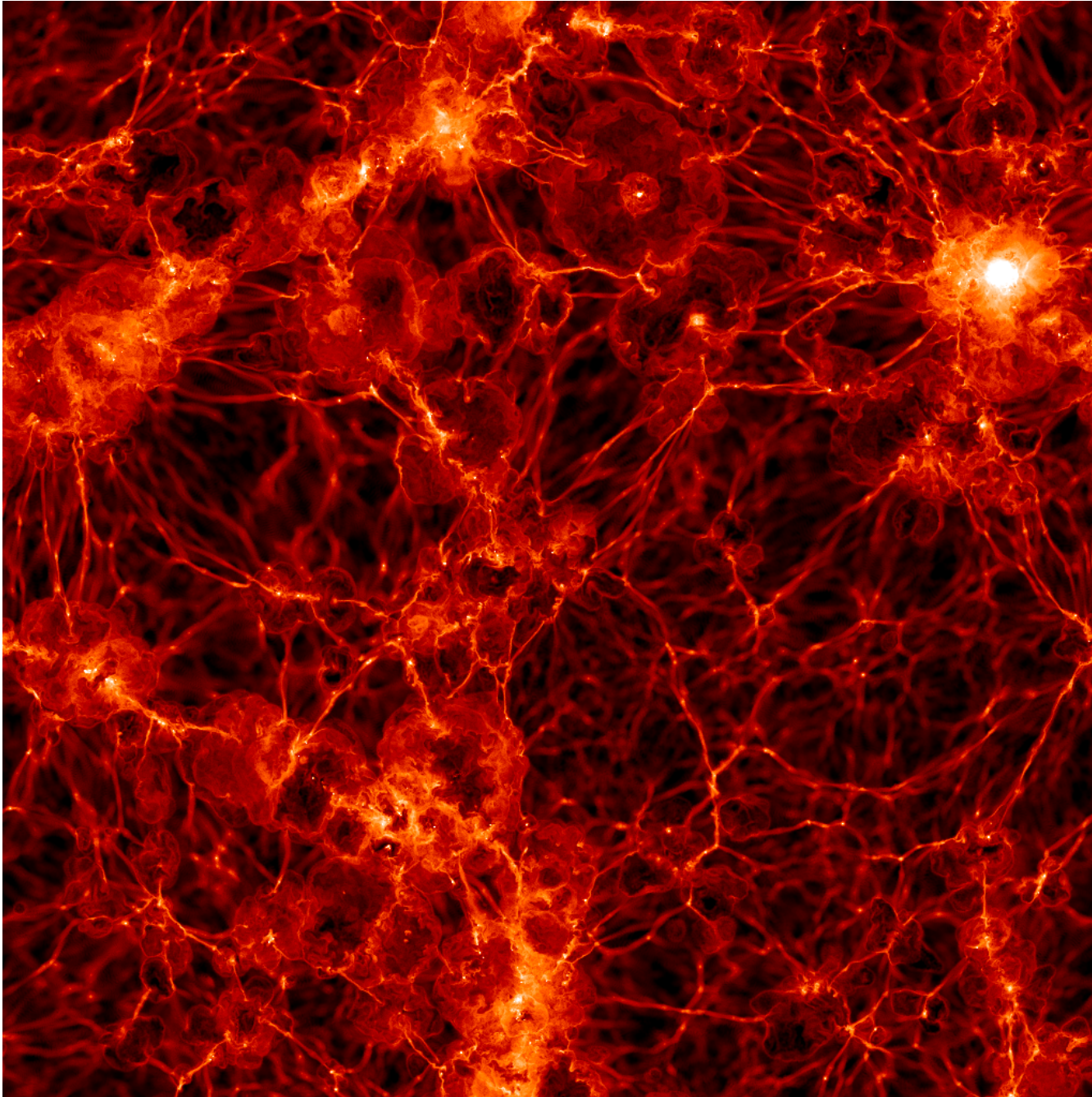


Dark Matter only

*Illustris* simulation  
Haider et al. (2016)



# The Cosmic Web: the baryonic gas

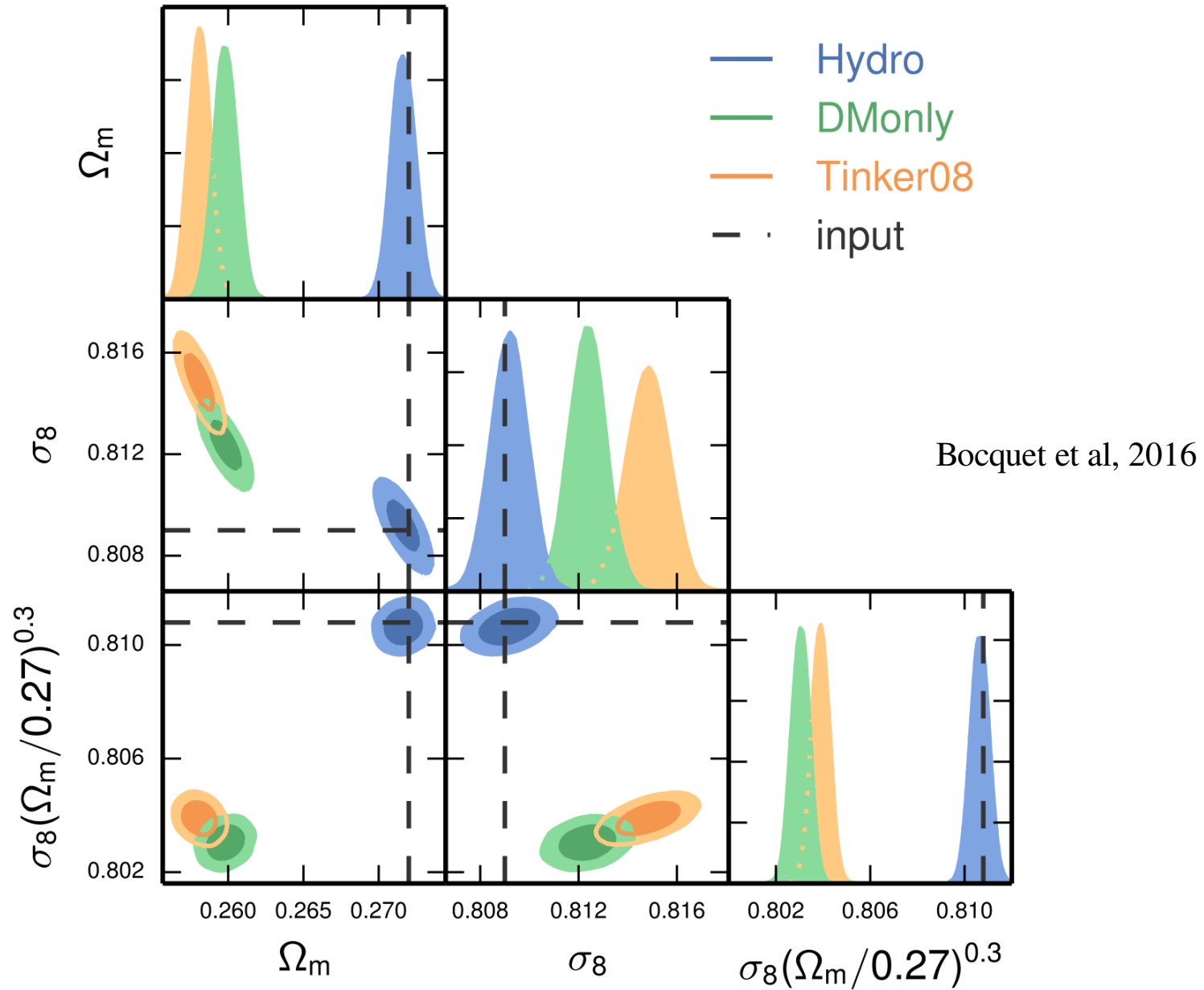


Baryons  
+ heating  
+ cooling

*Illustris* simulation  
Haider et al. (2016)

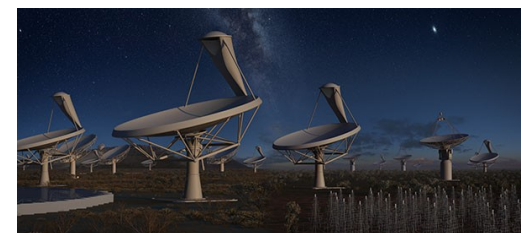
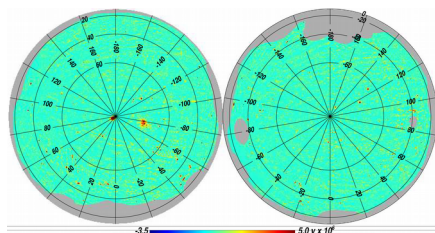
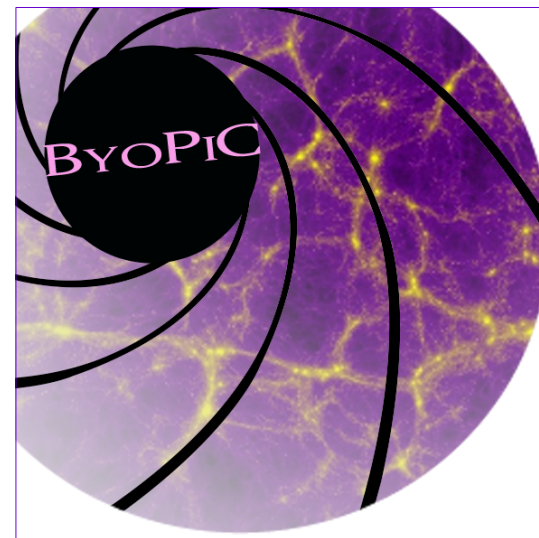
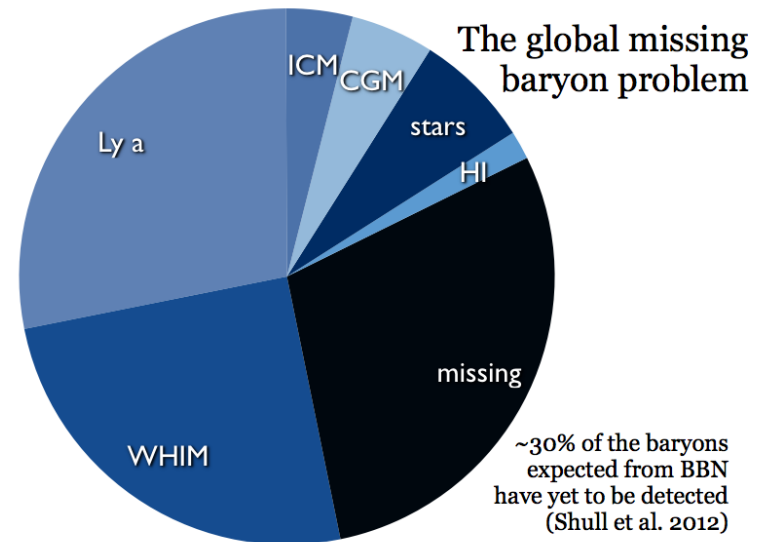


# Impact of baryonic physics on the Cosmological Model



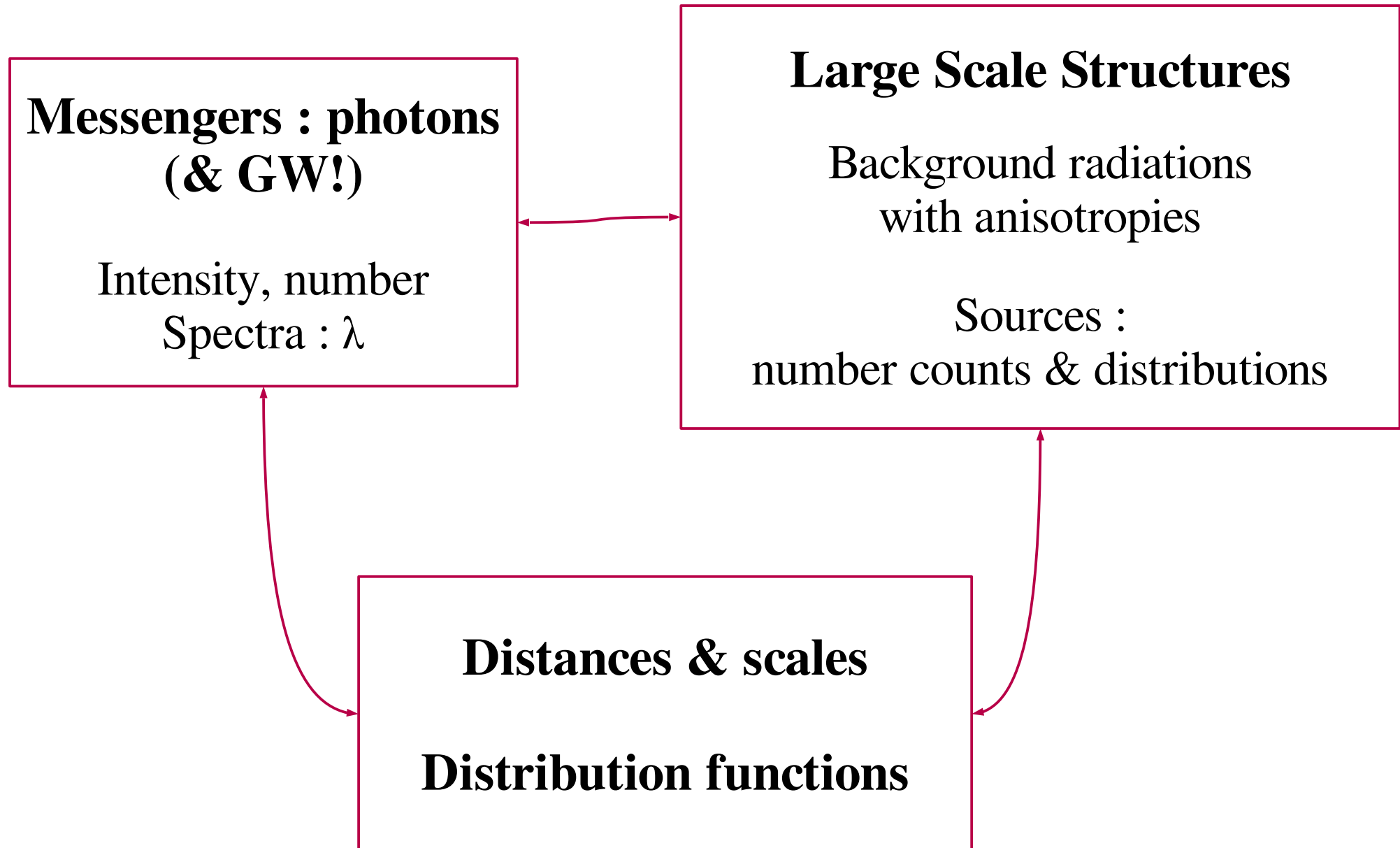
# Problems with baryons

- Complex physics :
  - Non-linear
  - Instabilities
  - Dissipative
  - Multi-scale
  - Chemistry
  - Magnetic Fields
  - Not well understood
  - ...
- On the global scale:
  - 30% – 50% are missing!



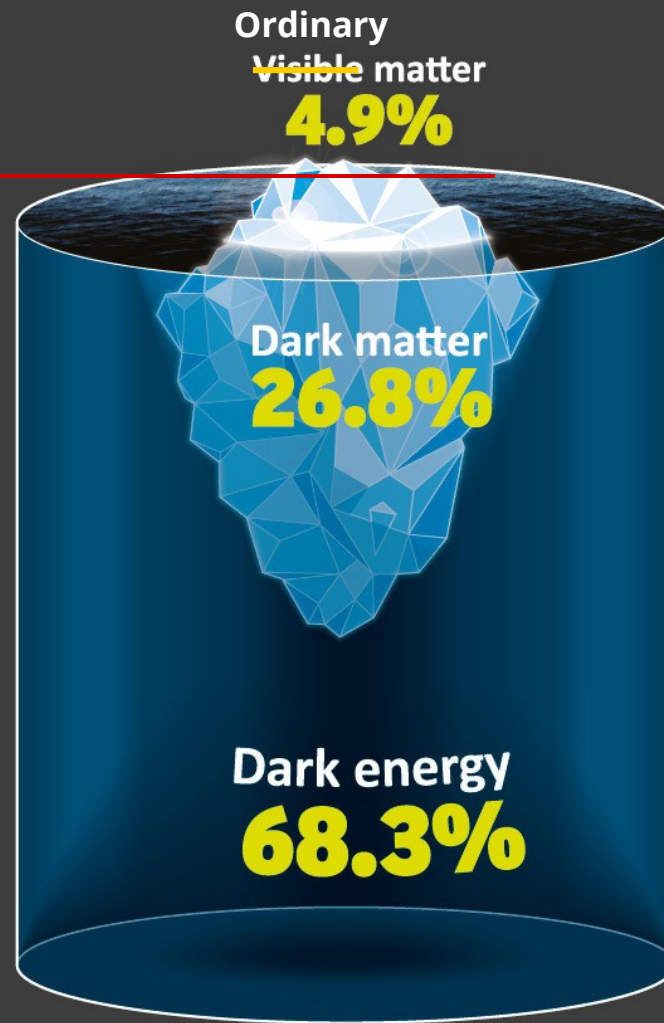


# Modern cosmology: measurements



# Visible matter < Ordinary matter

Visible  $\approx$   
stars =  
0.4%



## Visible matter

This is the stuff that makes up everything we can see and touch – all the dust, asteroids, comets, planets, stars, galaxies and you and me

## Dark matter

The dark side of matter doesn't interact with light, so it is invisible. We can detect how its gravity affects visible matter. It is a bit like visible matter's invisible friend – helping to hold the galaxies and clusters of galaxies together

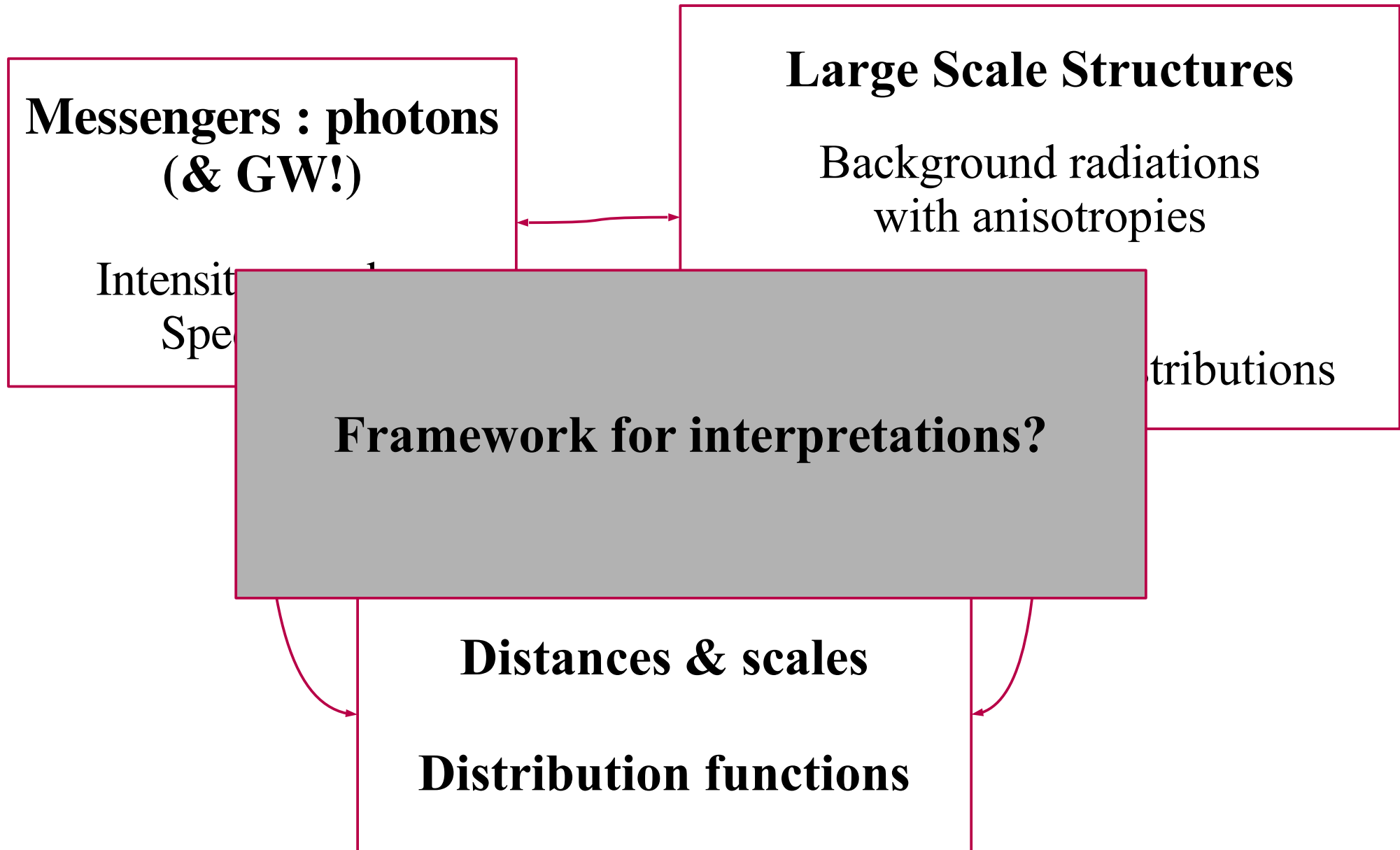
## Dark energy

While dark matter holds stuff together, dark energy is pushing everything apart. It is causing the Universe's expansion to speed up. The more space expands, the more dark energy there is

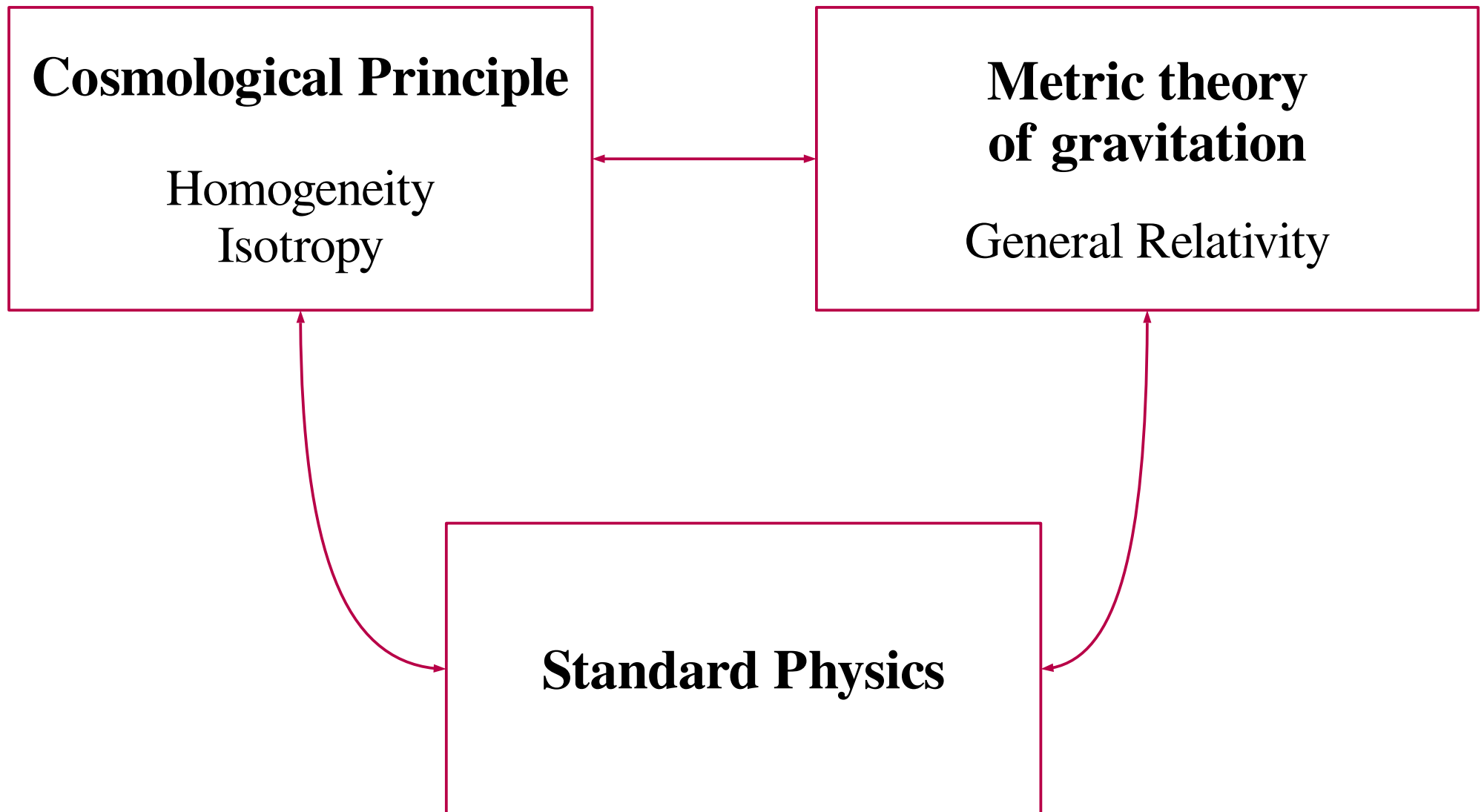
*Copyright: STFC/Ben Gilliland*



# Modern cosmology: measurements

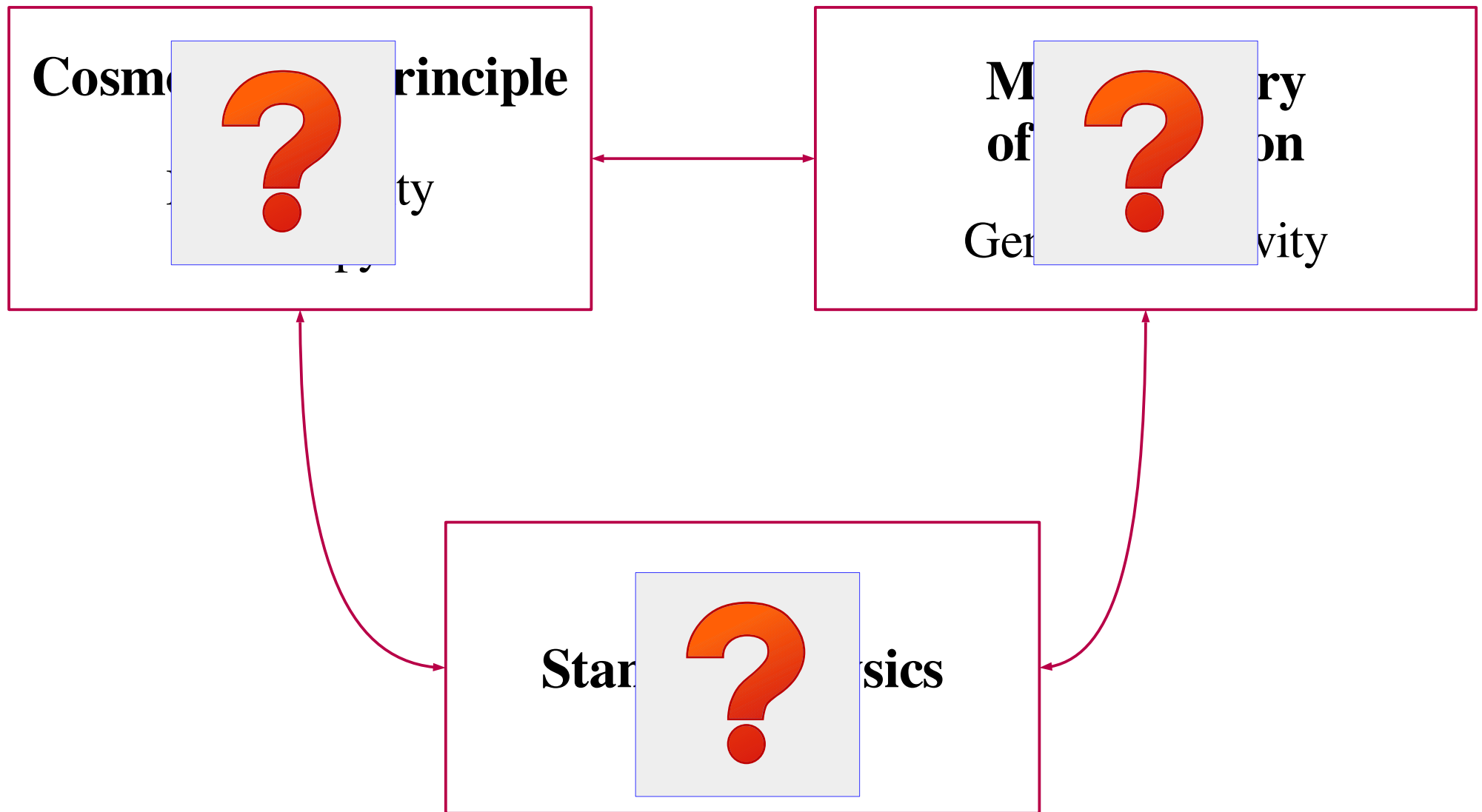


# Modern Cosmology : theory





# Modern Cosmology : theory



# Challenges facing Cosmology

