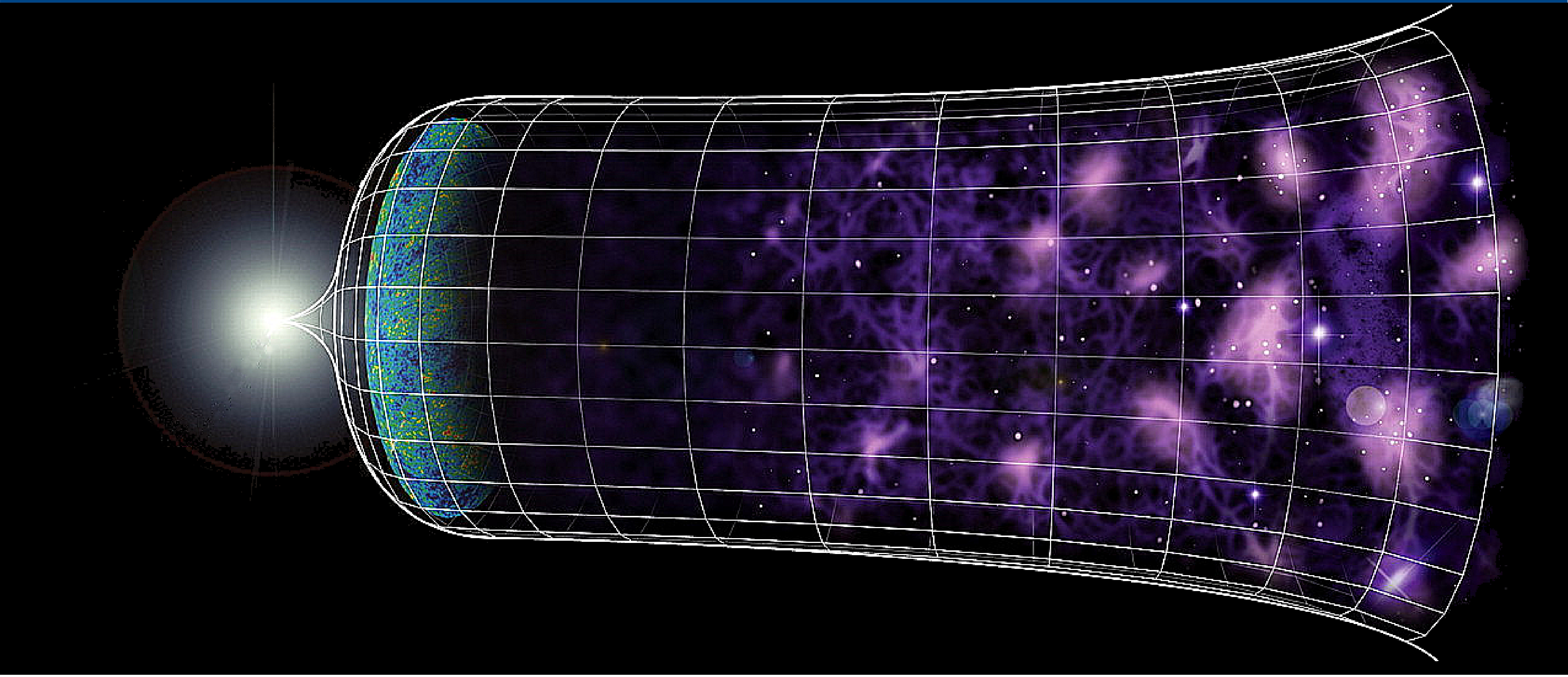
Les défis de la cosmologie

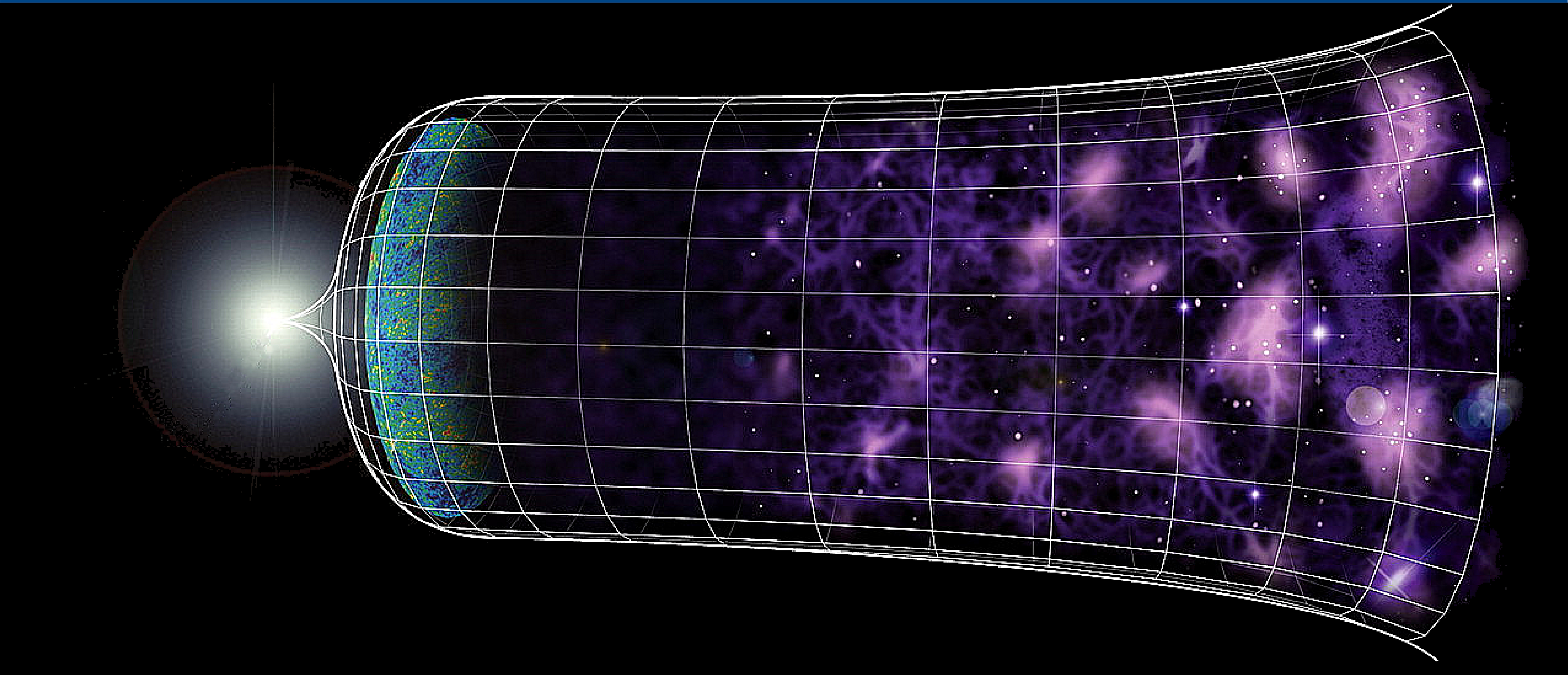


Mathieu Langer

Séminaire IAS

11 janvier 2018

The challenges facing cosmology



Mathieu Langer

Seminar IAS

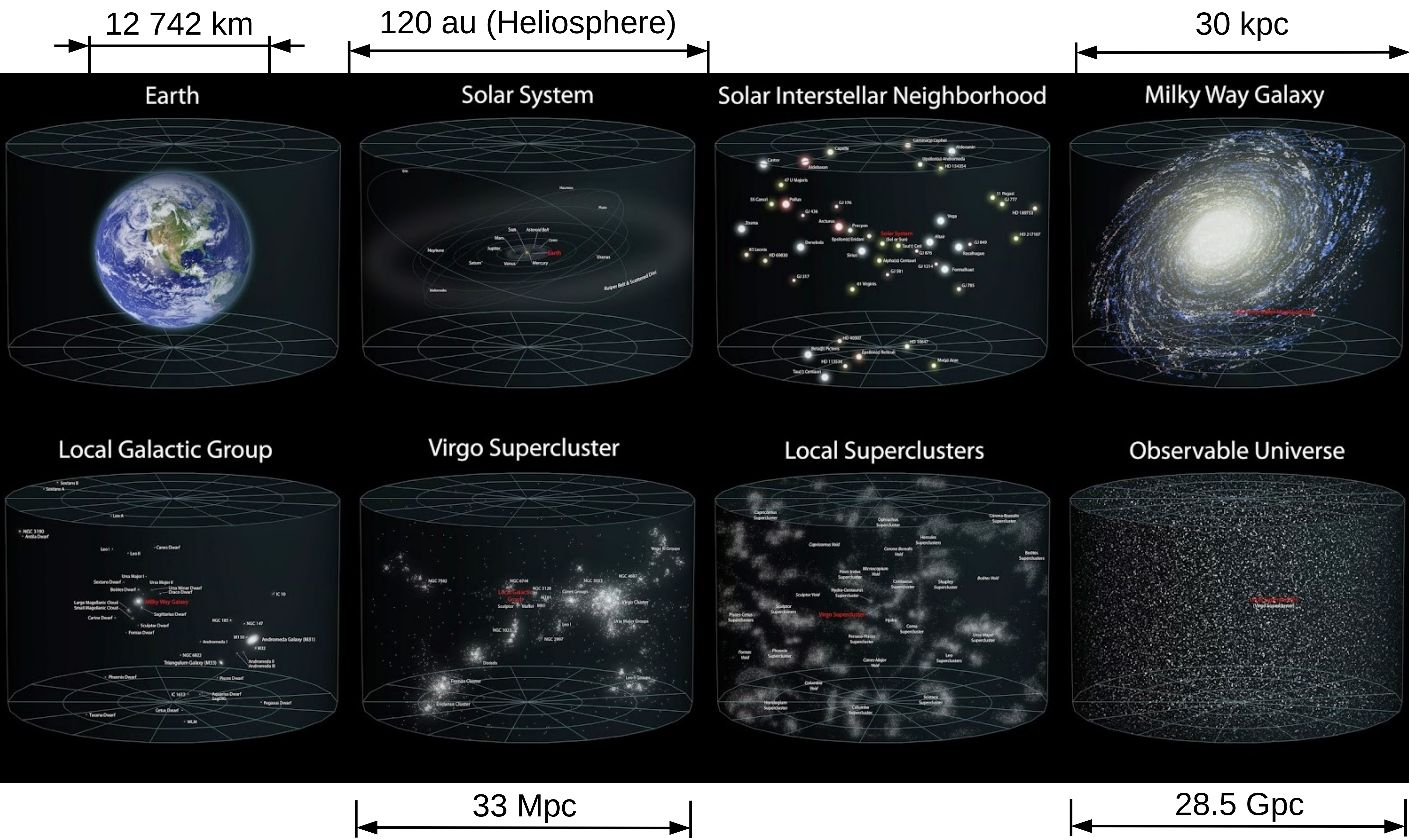
11 January 2018

IAS Institut d'Astrophysique Spatiale Orsay

Université Paris Sud

université Paris-Saclay

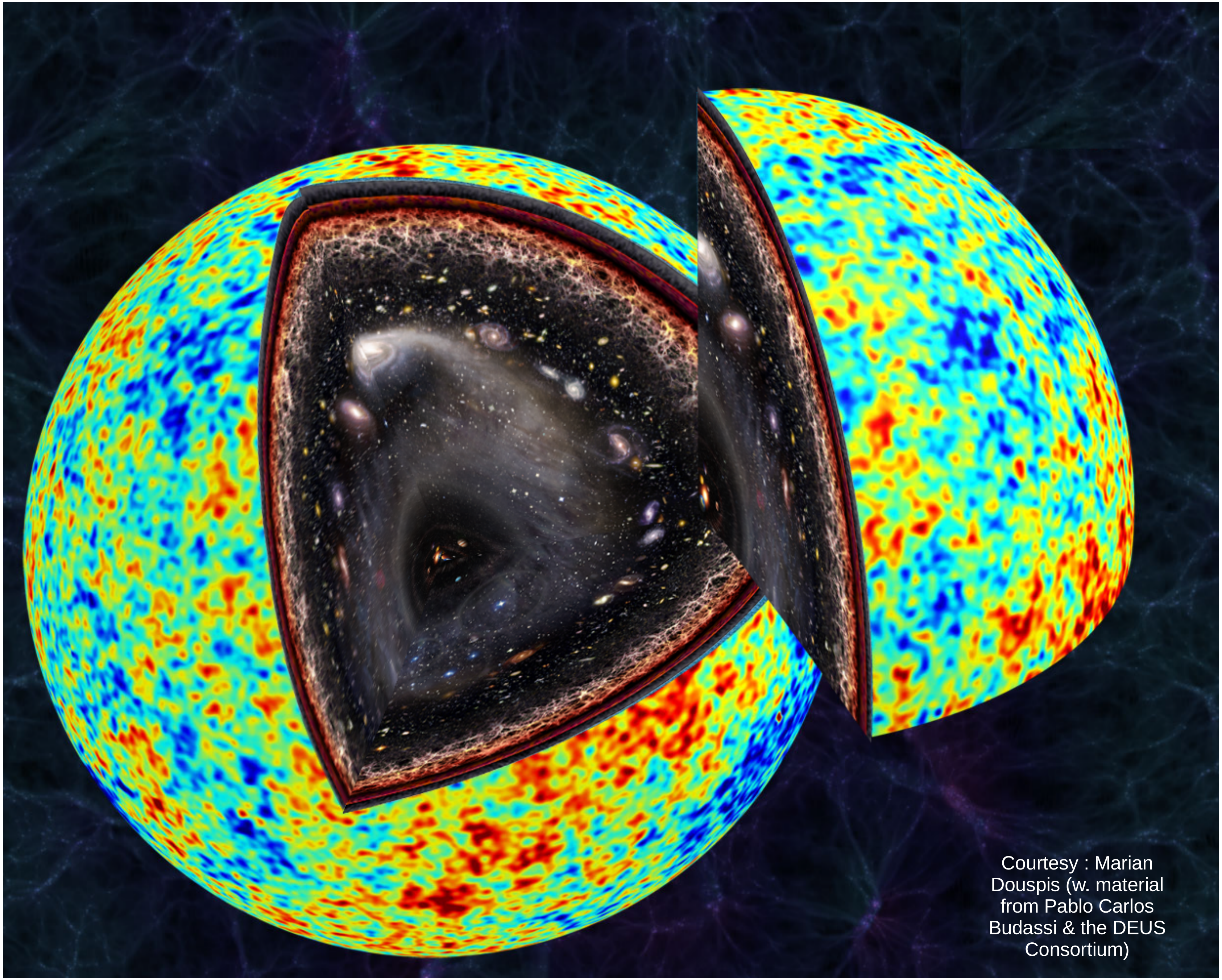
Where we are



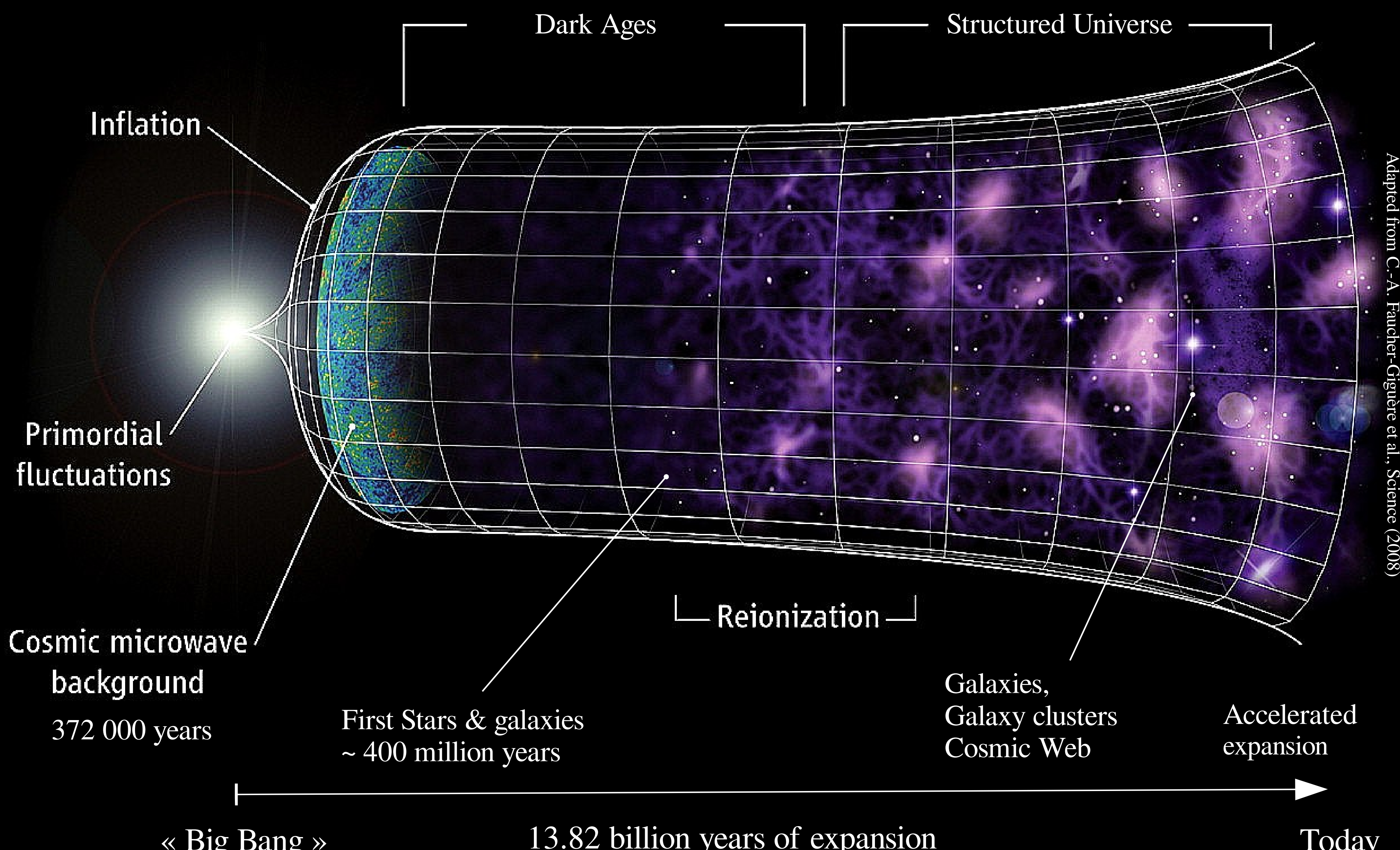
$$1 \text{ pc} = 2.06\ 10^5 \text{ au}$$

The observable universe (in logarithmic scale)

The observable universe



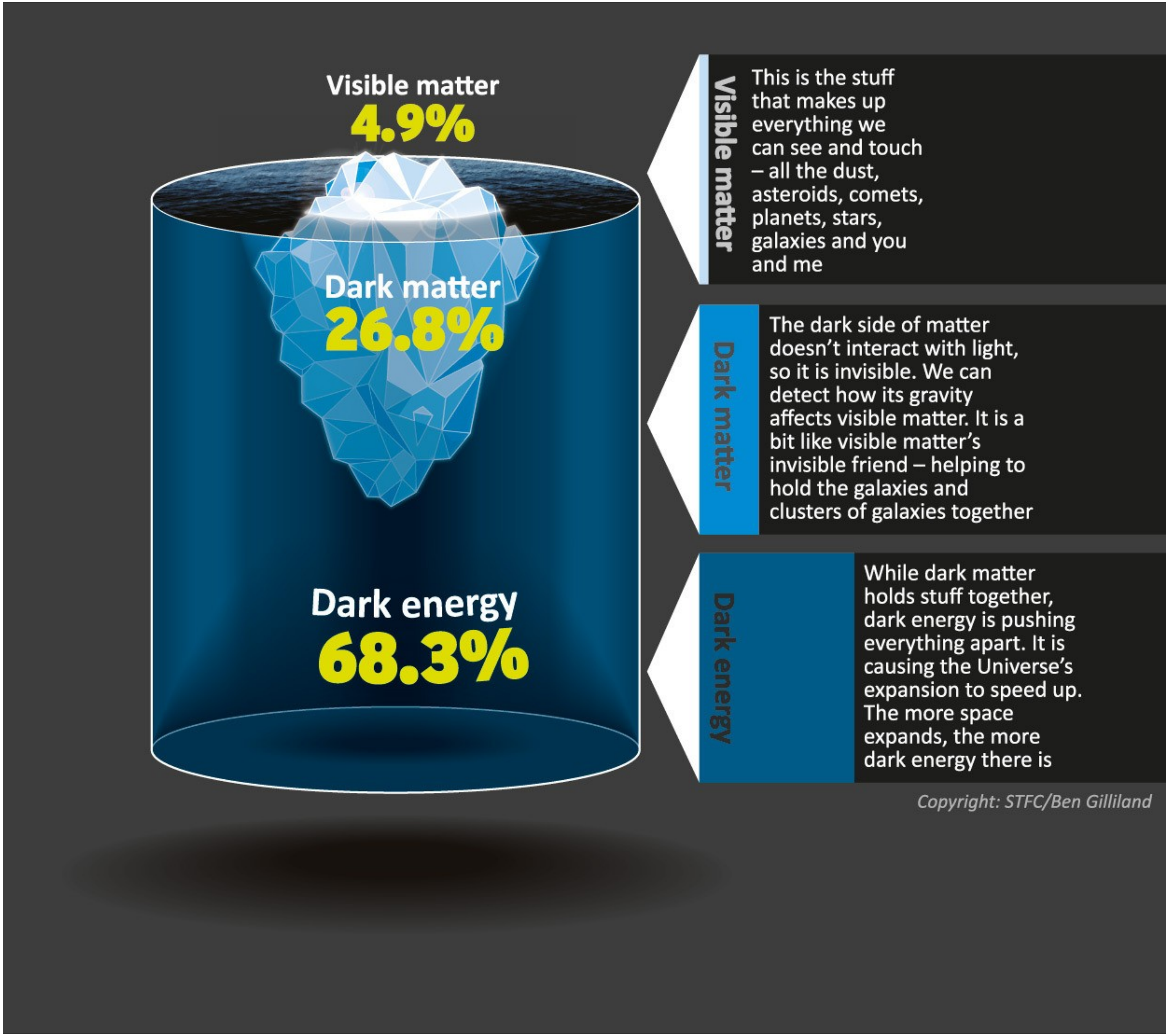
History of the Universe



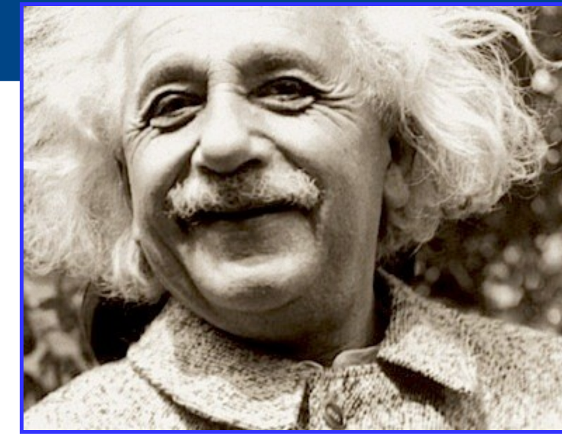
The Standard Cosmological Model : ΛCDM

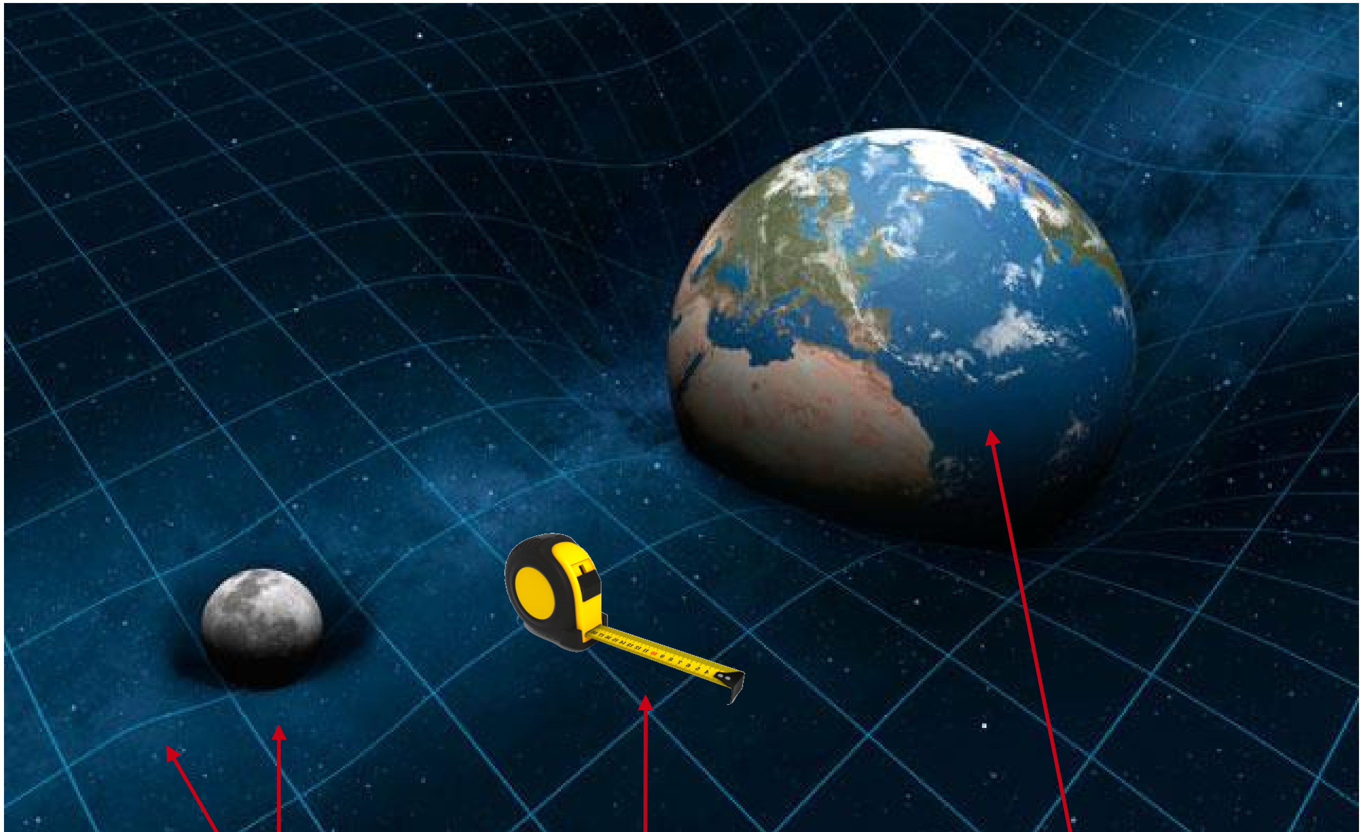
- Λ: agent responsible for the current accelerated expansion of the Universe
- Cold Dark Matter:
  - Massive particles
  - Set the expansion rate during most cosmic history
  - Shaped the landscape in which stars and galaxies form

Present day energy budget: exceedingly dark…



General Relativity





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

Die Feldgleichungen der Gravitation, 1915

Variation of curvature from place to place

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

Matter & Energy bend space

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 Λ with the opposite sign, and…

Which value for Λ?

- Measurements!

$$\rightarrow \quad \sim 6 \times 10^{-27} \text{ kilograms per cubic metre}$$

- Calculate: zero point energy (quantum fluctuations of empty space)

$$\rightarrow \sim 6 \times 10^{+96} \text{ kilograms per cubic metre}$$

123 orders of magnitude discrepancy…

"The worst 'prediction' of theoretical physics"

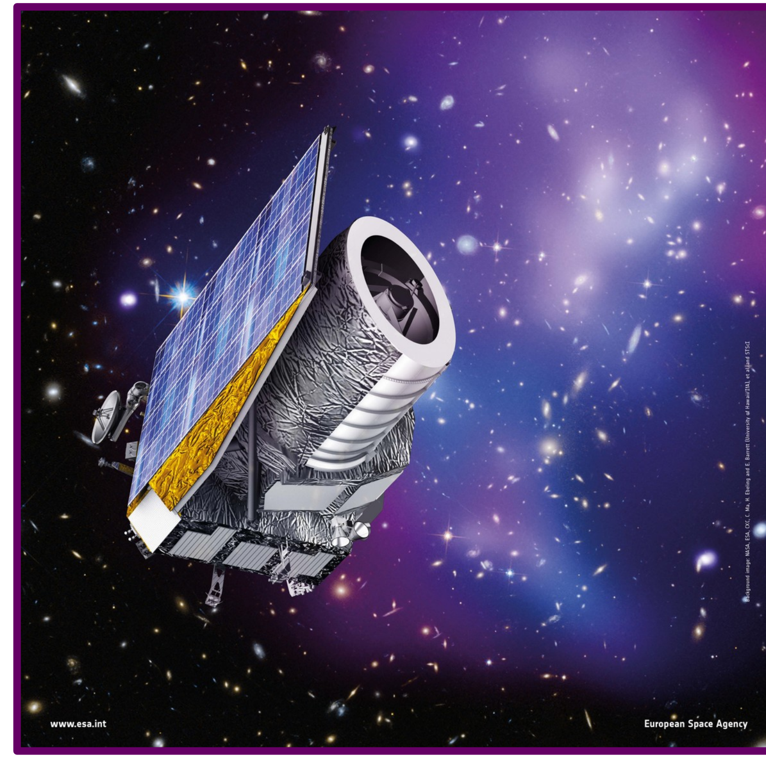
- Understand its nature:
  - Is it 'just' a fundamental constant?
  - Is it rather a quantum property of vacuum?
  - Both are **a priori** possible!

→ why **together** do they yield such a small value?

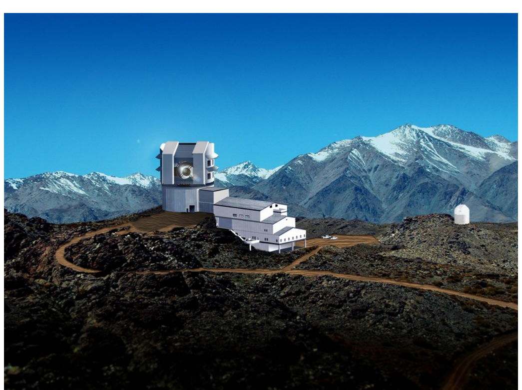
What is actually driving the accelerated expansion?

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

Euclid

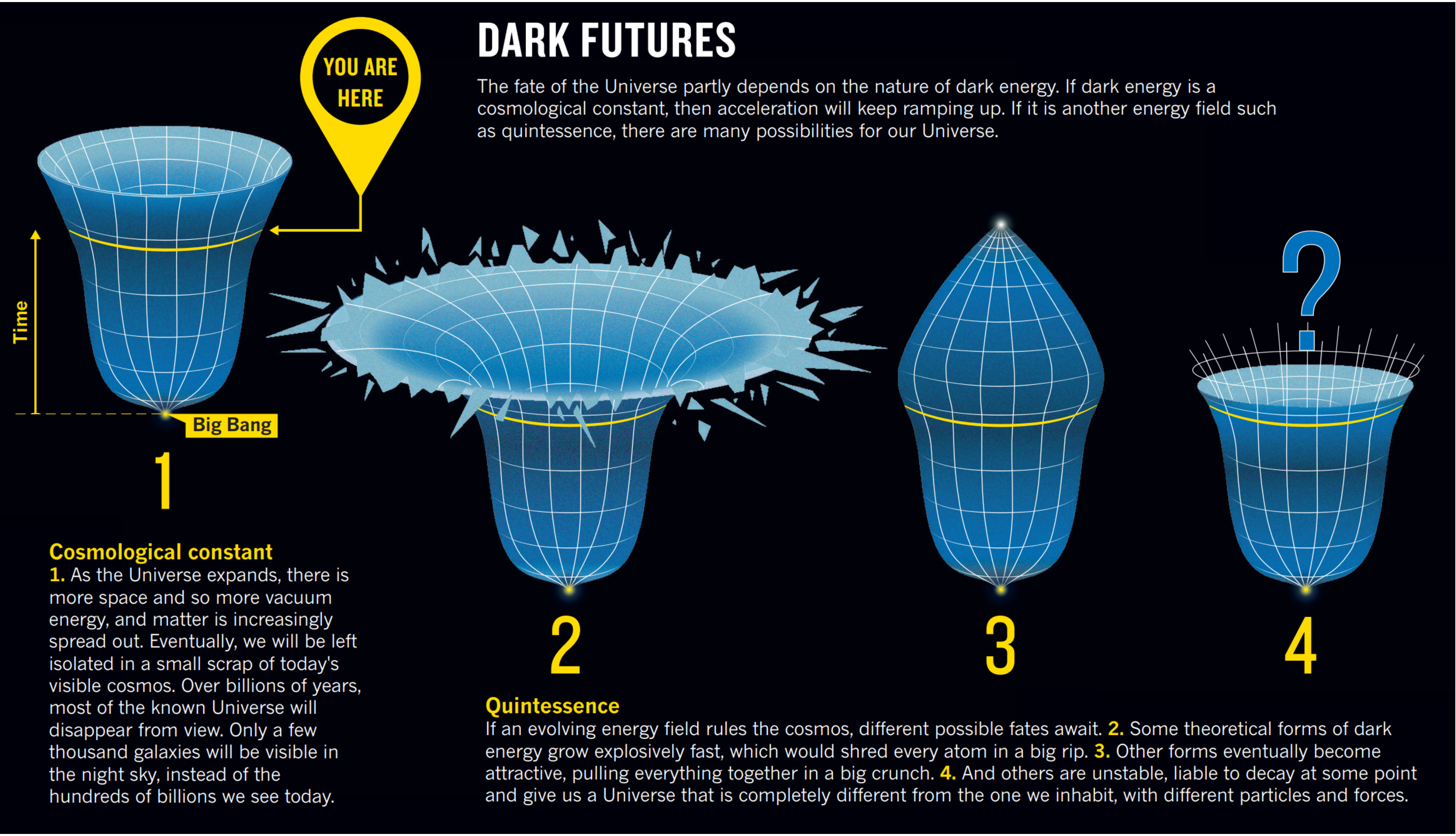


LSST



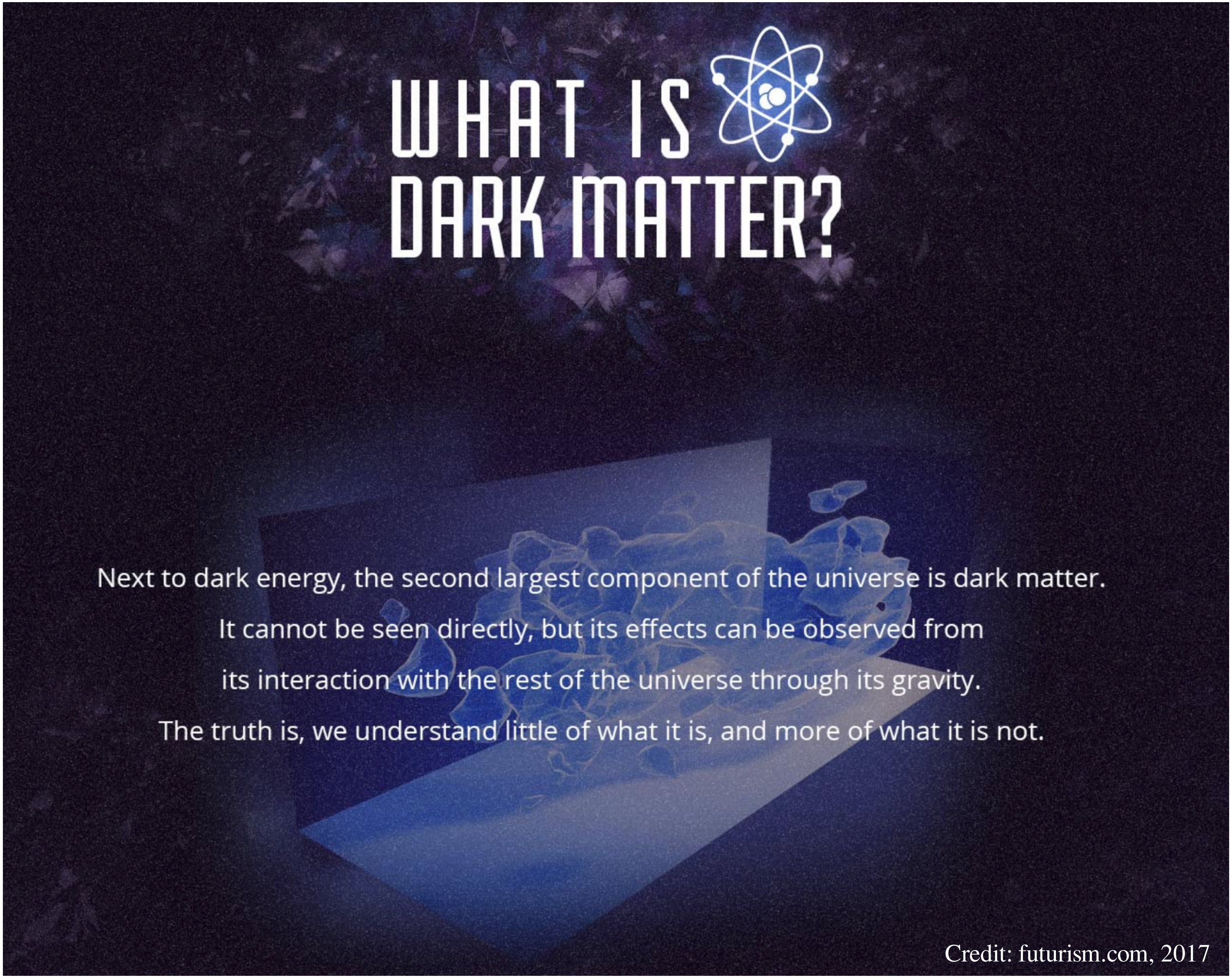
DES

The unknown fate of the Universe

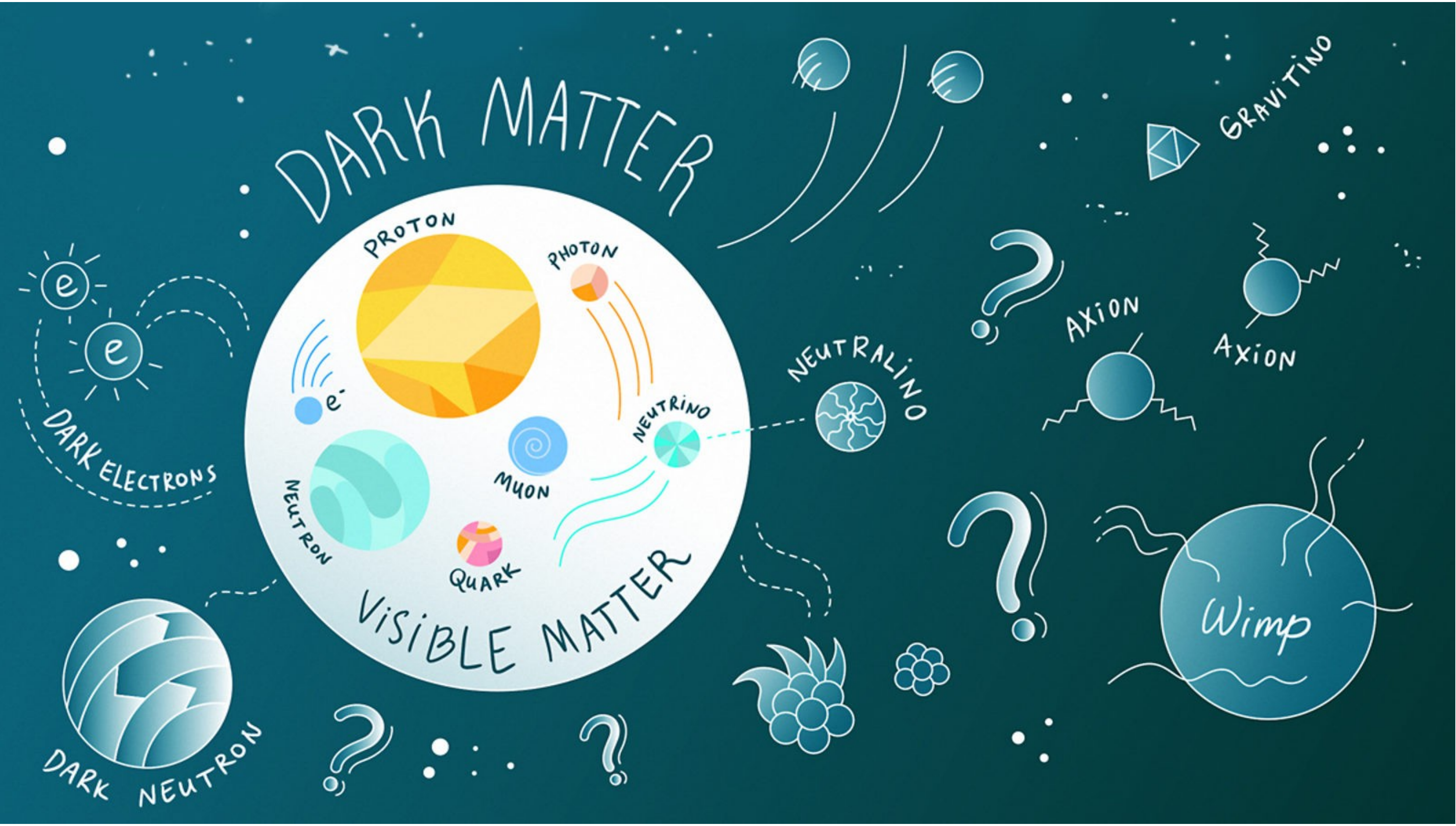


Credit: Nature, September 28, 2016

Dark Matter


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

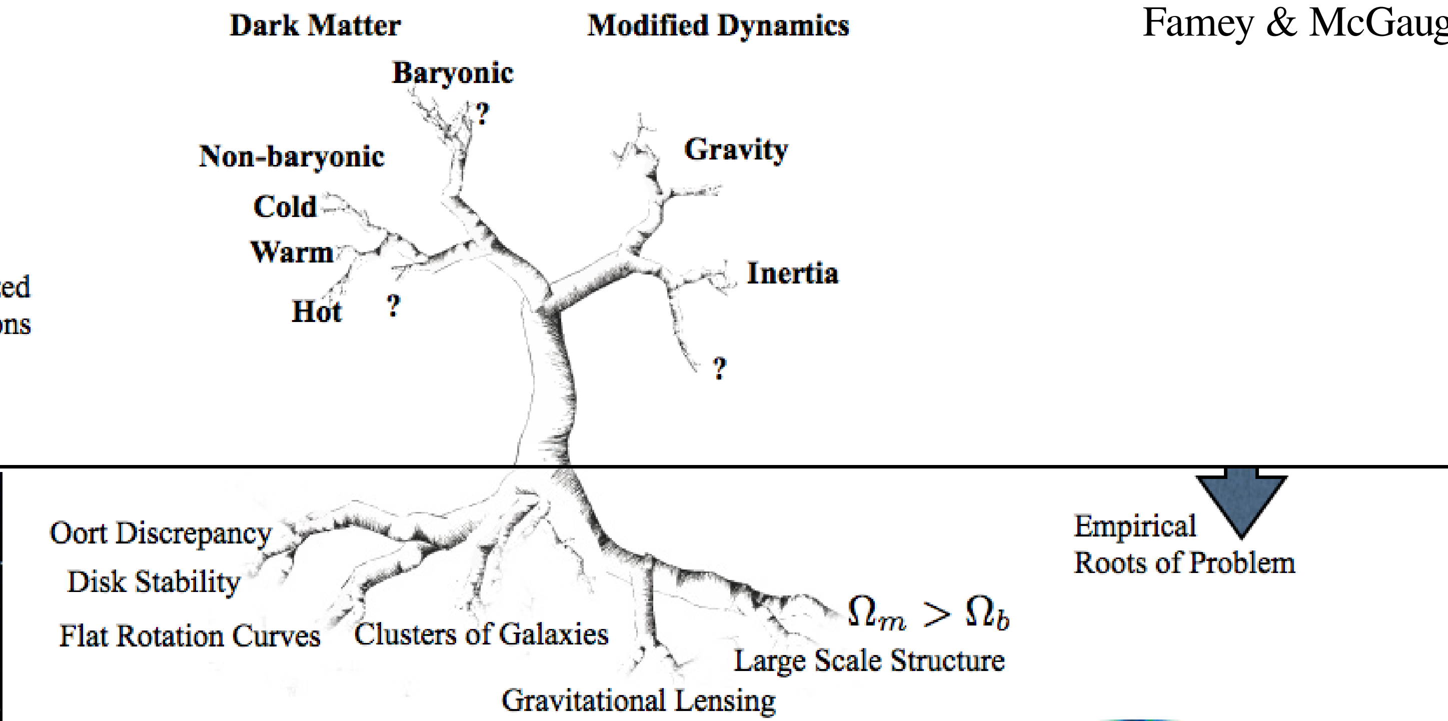
New Particles ?



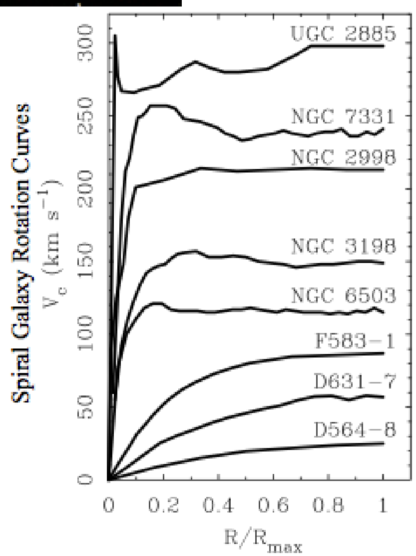
Credit: Symmetry Magazine, 2015

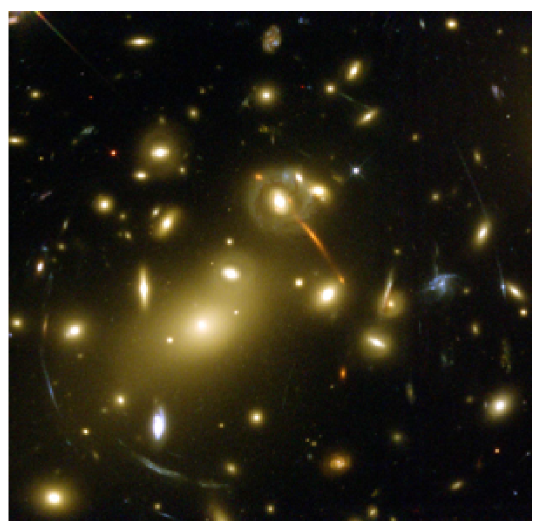
Mass Discrepancy Tree

Famey & McGaugh (2012)

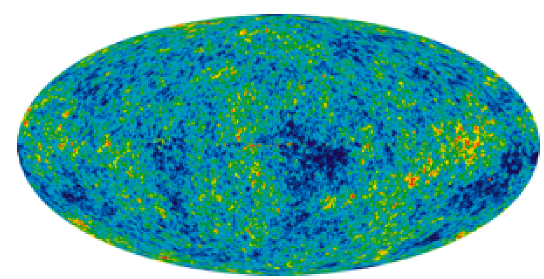


Spiral Galaxy UGC 2885 (Zagursky & McGaugh)

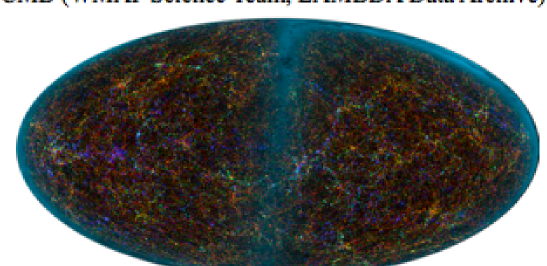




Galaxy Cluster Abell 2218
(NASA, Andrew Fruchter and the ERO Team)



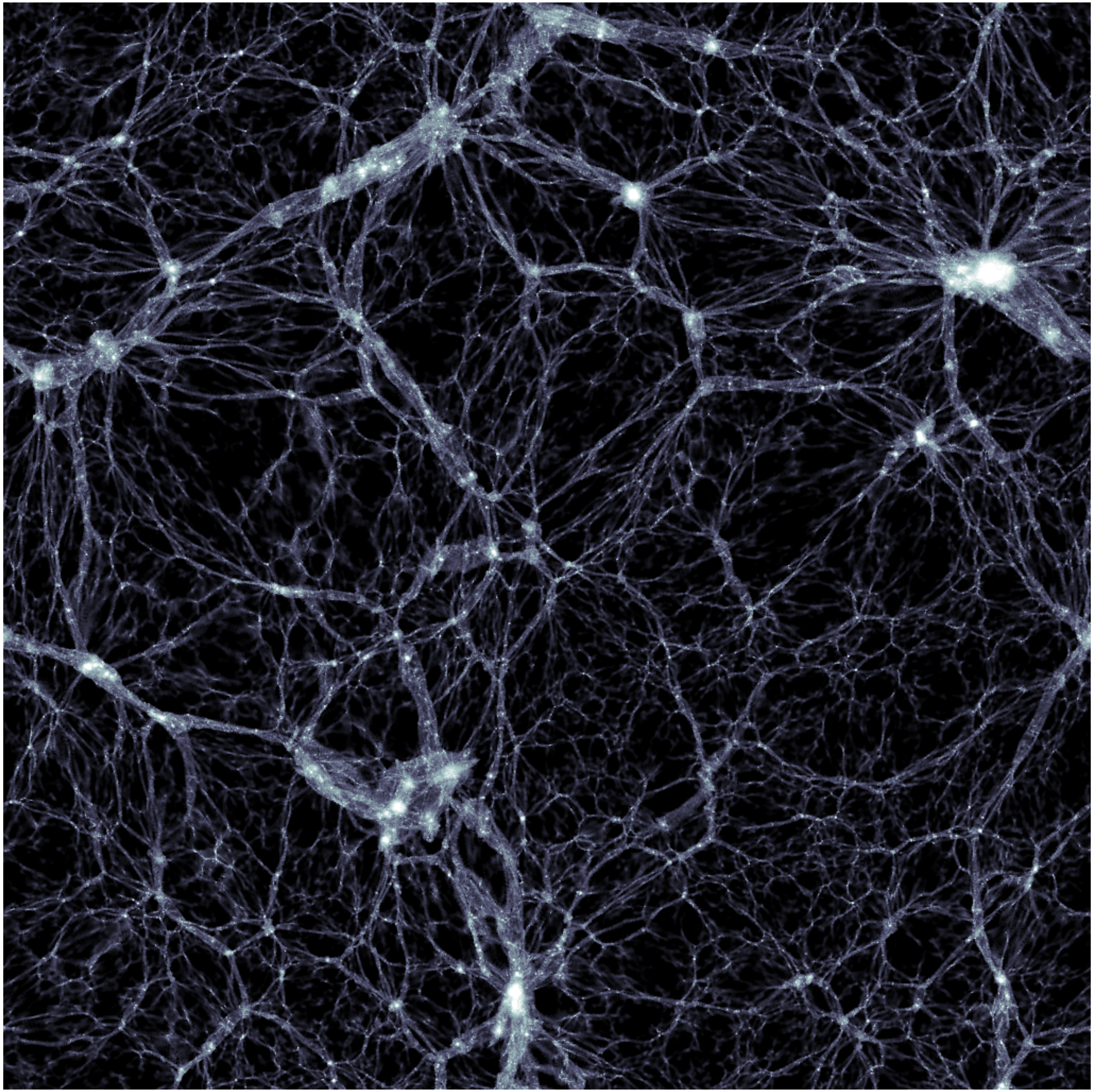
CMB (WMAP Science Team, LAMBDA Data Archive)



Large Scale Structure (2MASS, Jarrett et al. 2004)

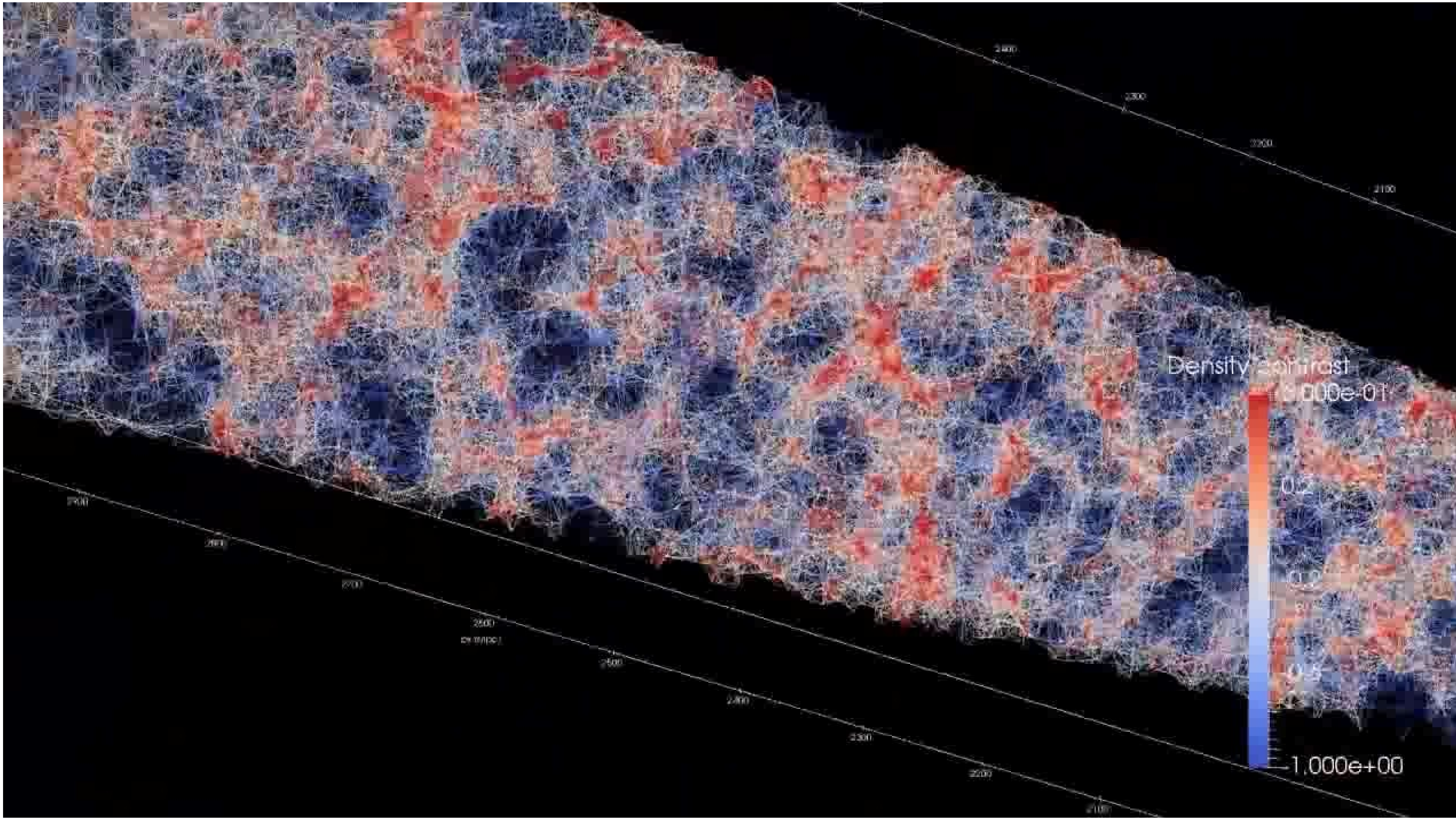
The Cosmic Web: simulated

Dark Matter only



Illustris simulation
Haider et al. (2016)

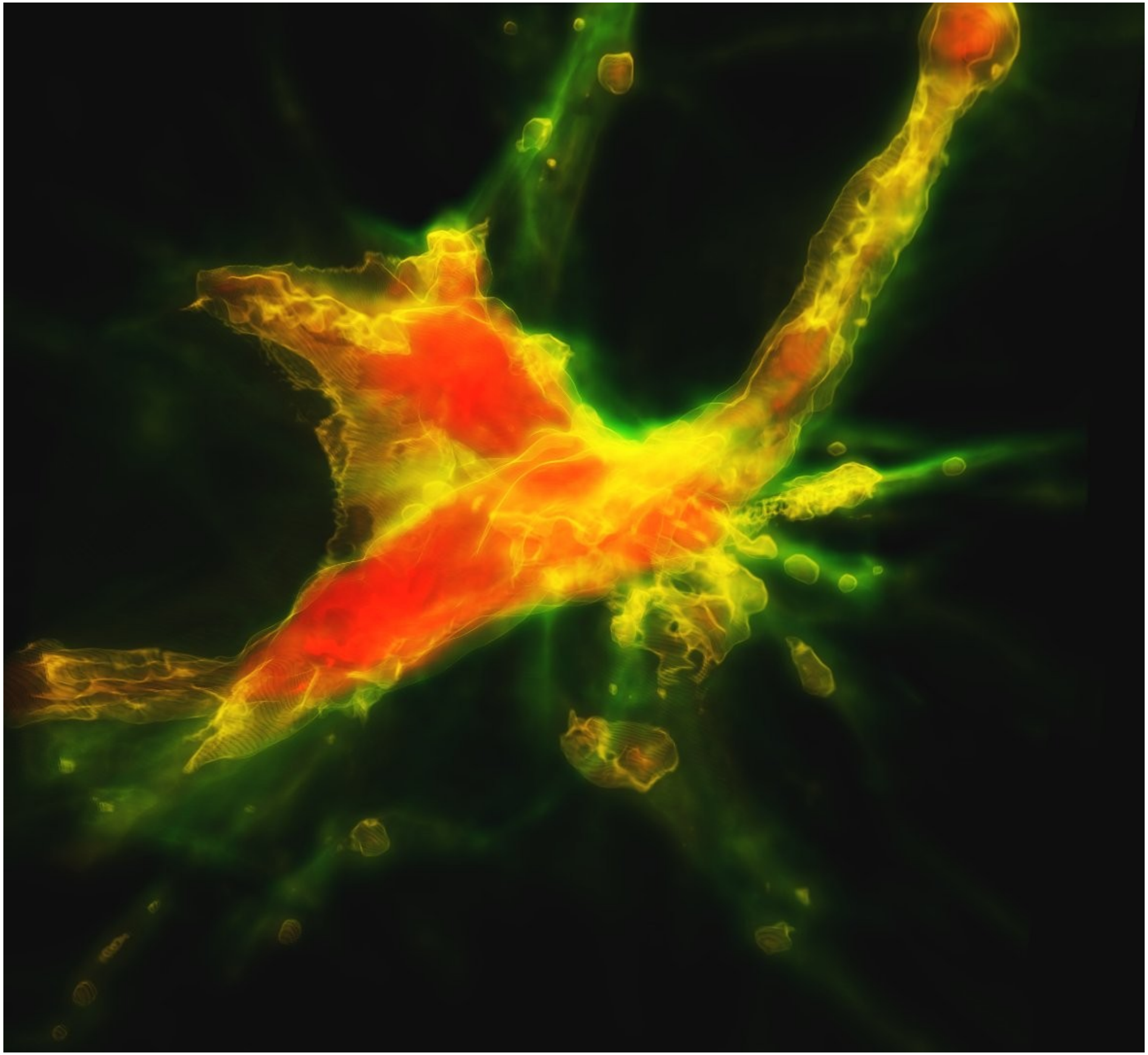
The Cosmic Web: observed



VIMOS Public Extragalactic Redshift Survey

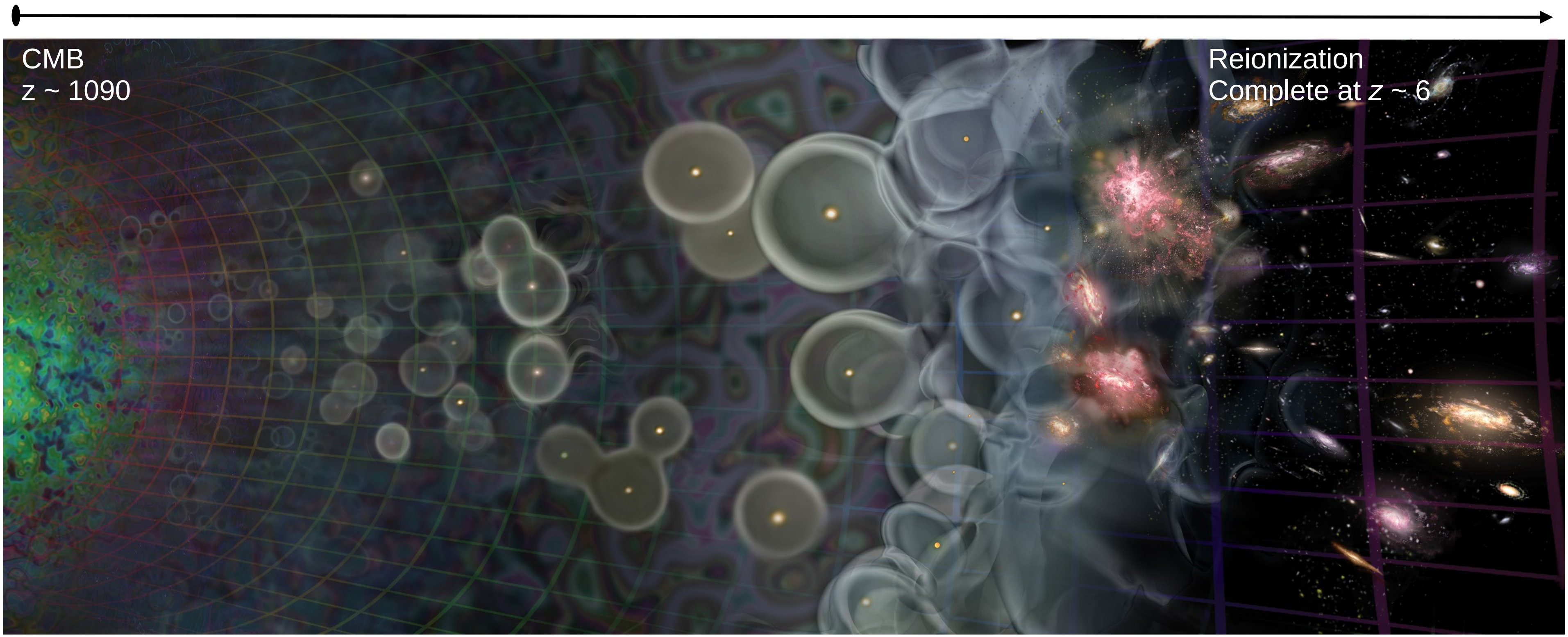
Credit: S. Arnouts, N. Malavasi & the VIPERS Collaboration

Multiscale filamentary structure: very early on!

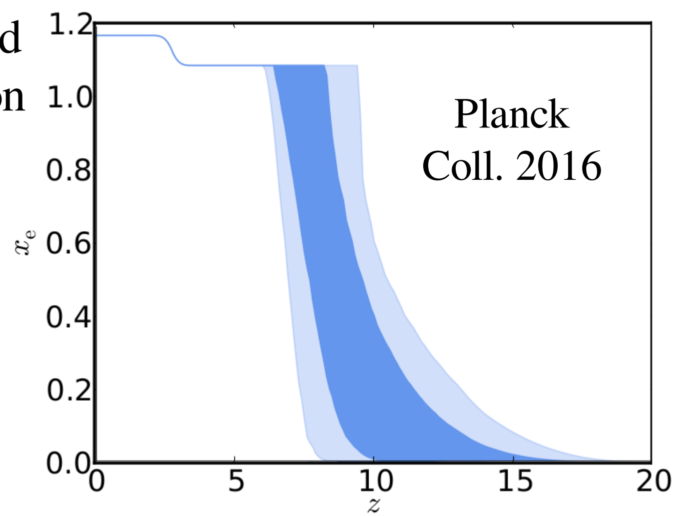


“First” galaxy in its filamentary environment at z ~10 (Greif et al., 2008)

Cosmological Reionization

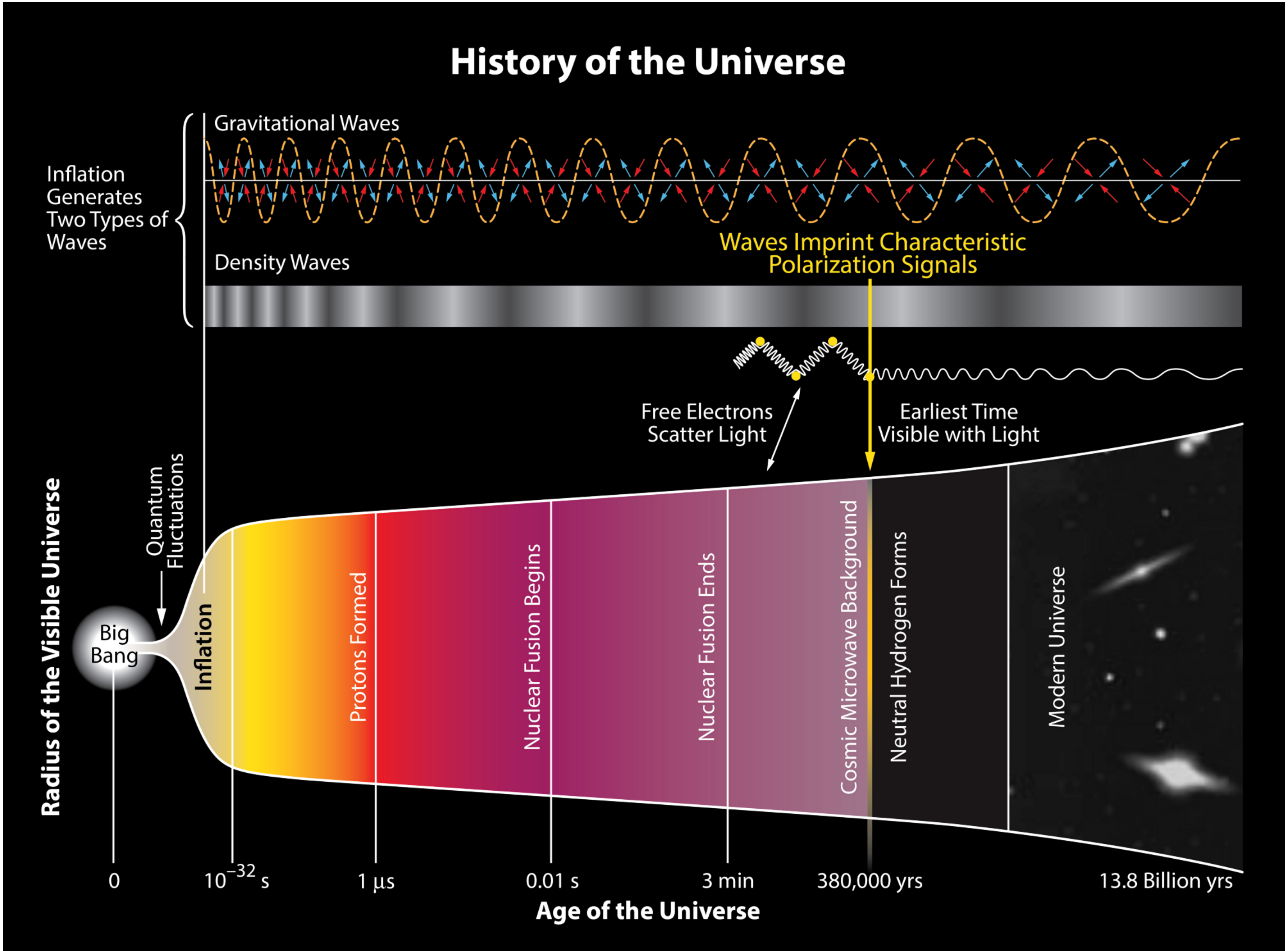


Credits :Sci. Am. & A. Loeb, 2006



- 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?

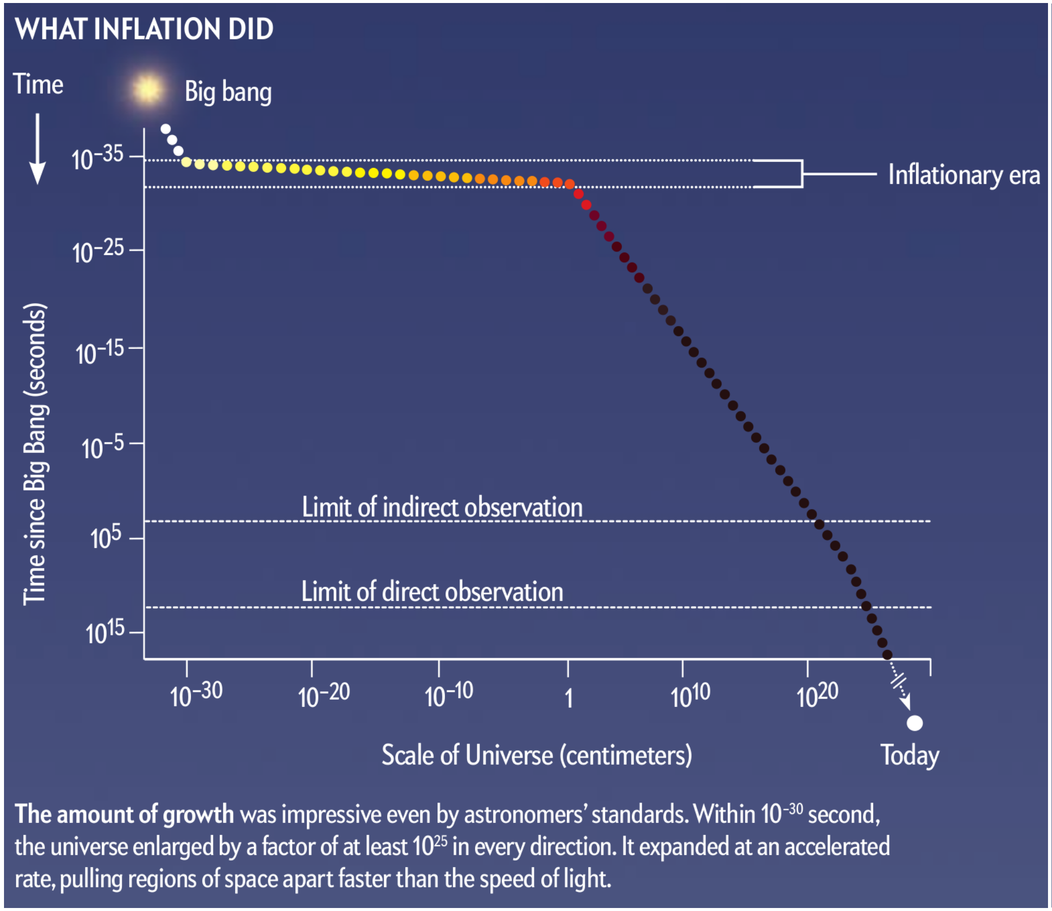
Inflation

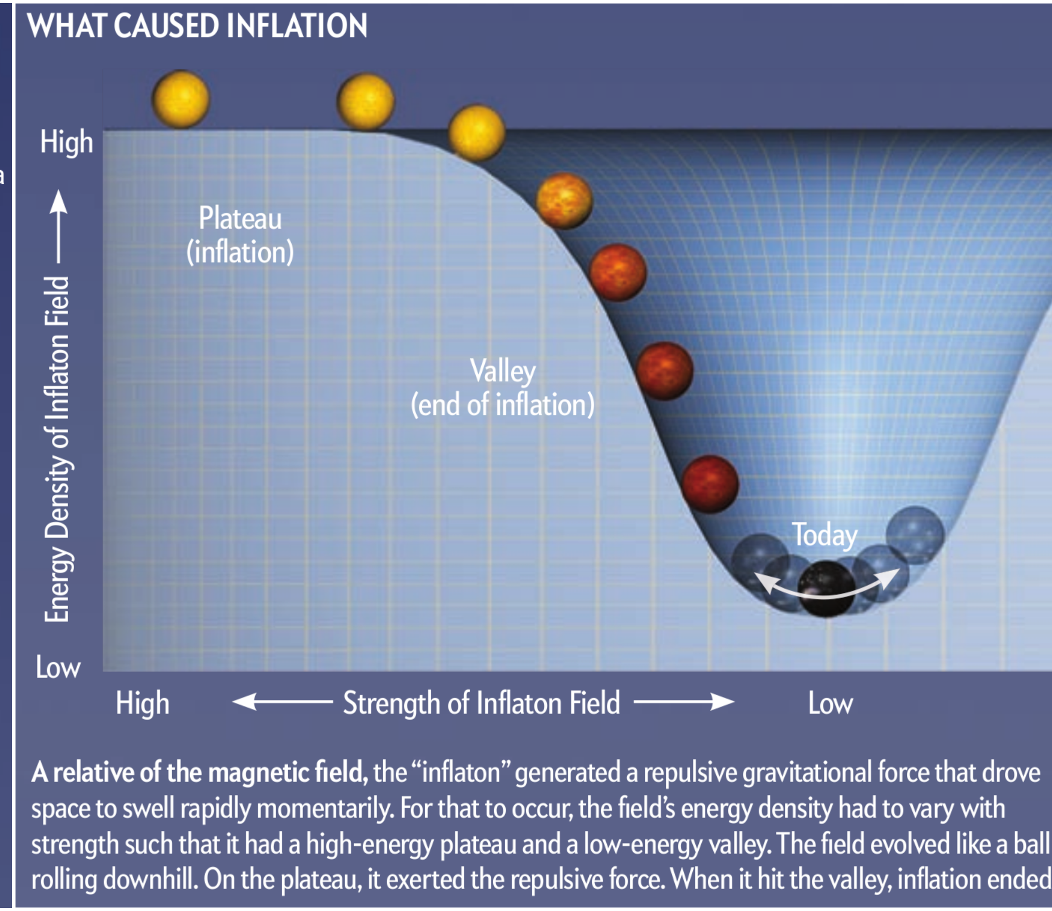


Credit: BICEP2 Collaboration

How does inflation work ?

Credits: Jen Christiansen, Scientific American, 2011

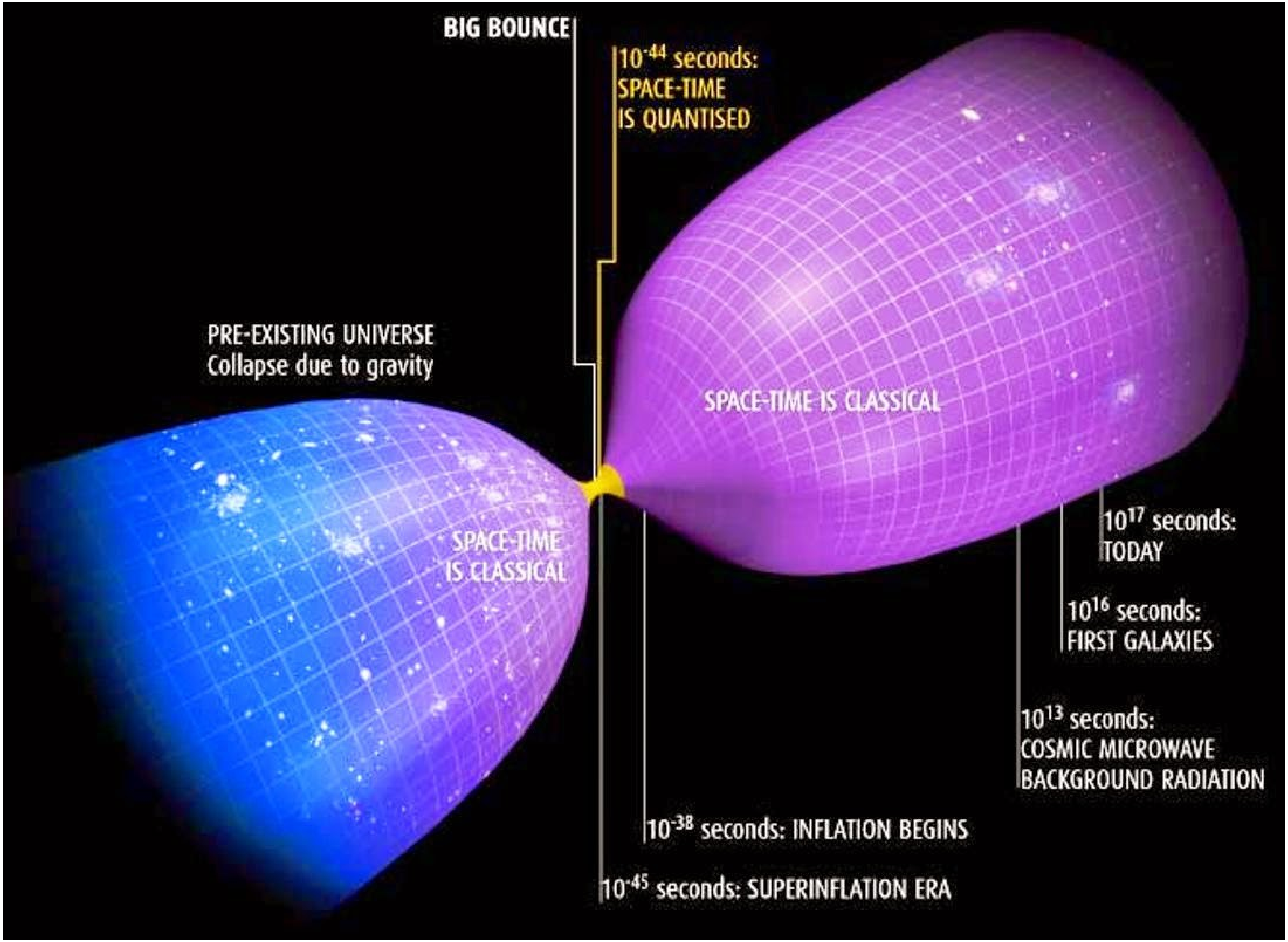




Time evolution
of the scale of the Universe

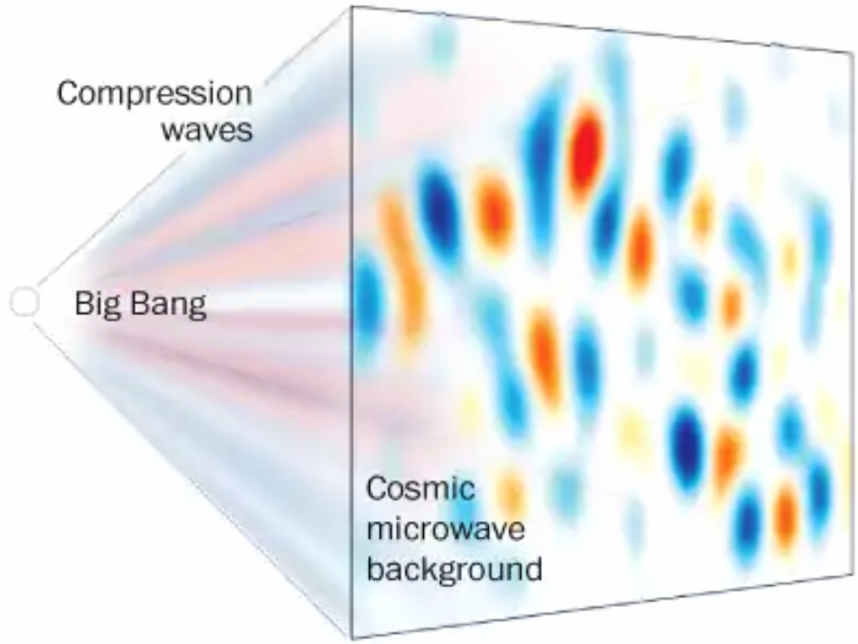
Energy density
of the Inflaton field

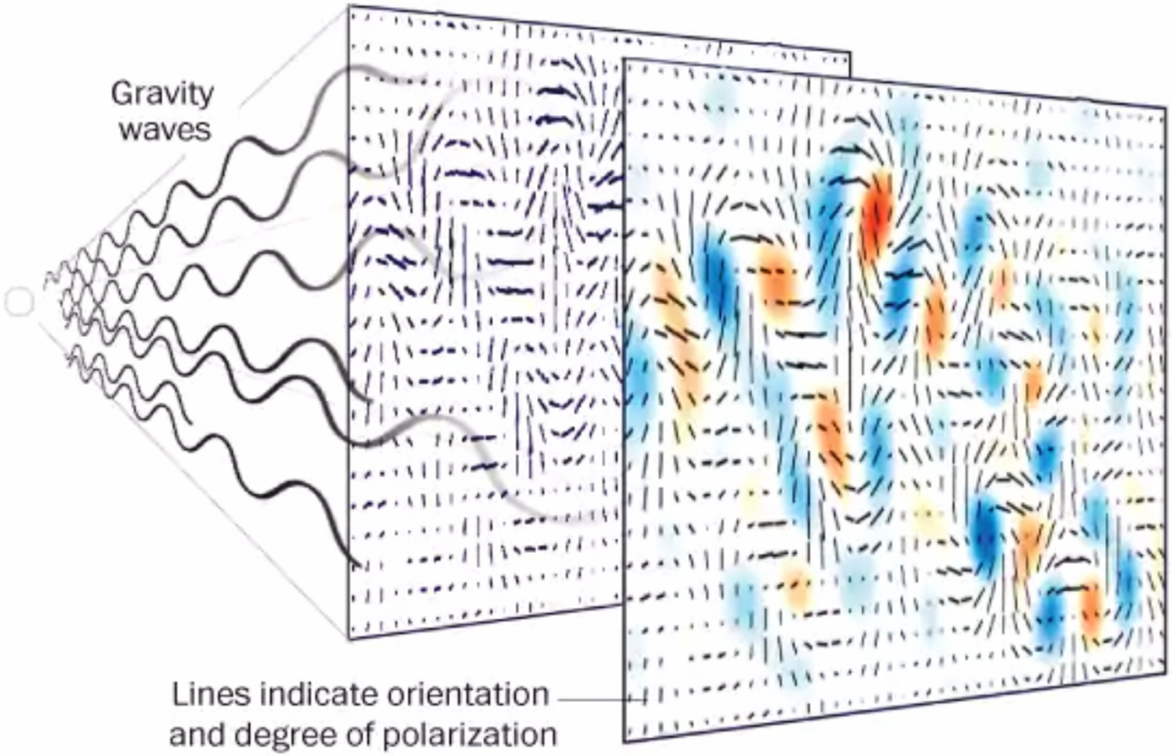
An alternative: bounce cosmology



Credit: New Scientist, Dec. 2008

Probing inflation: primordial gravity waves



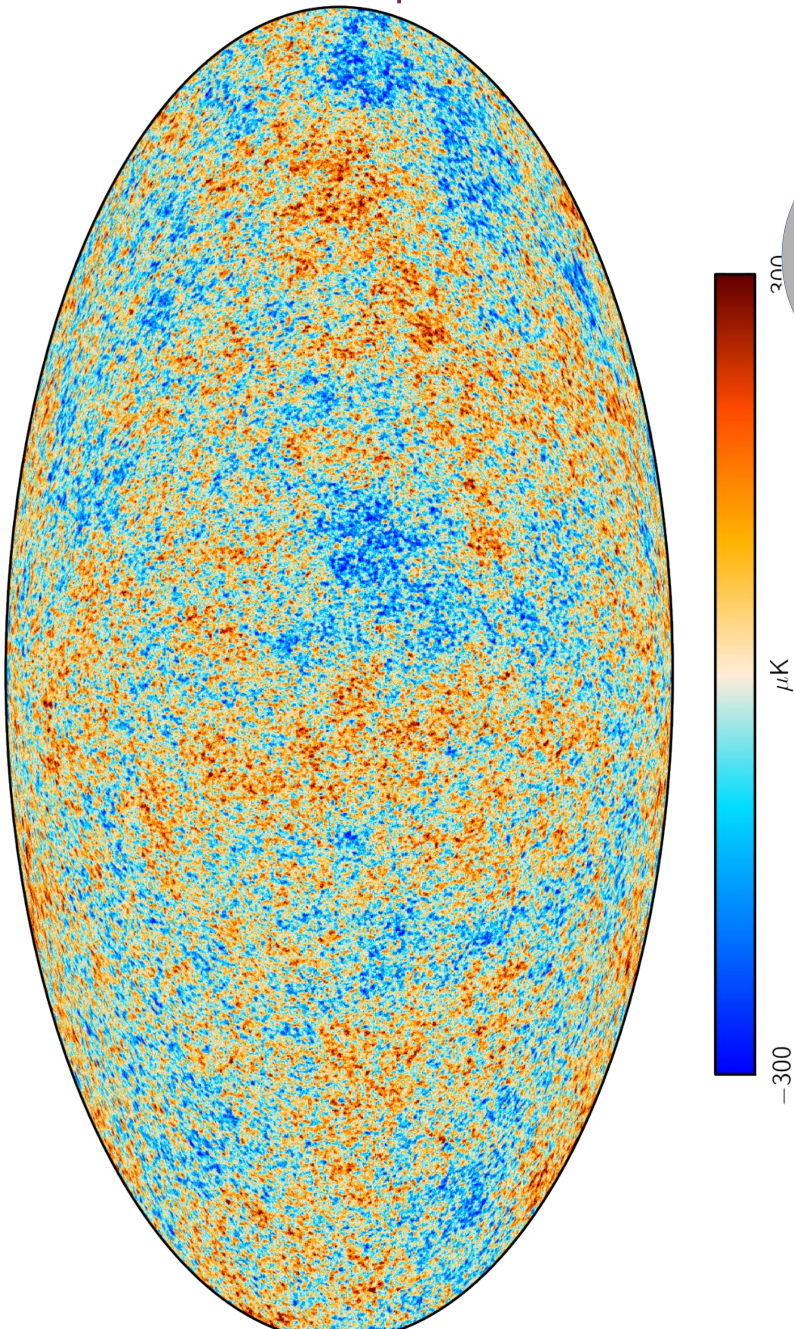


Within a tiny fraction of a second, the big bang inflated the universe. **Compression waves** created a pattern in the afterglow of the expansion, known as the **cosmic microwave background**.

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



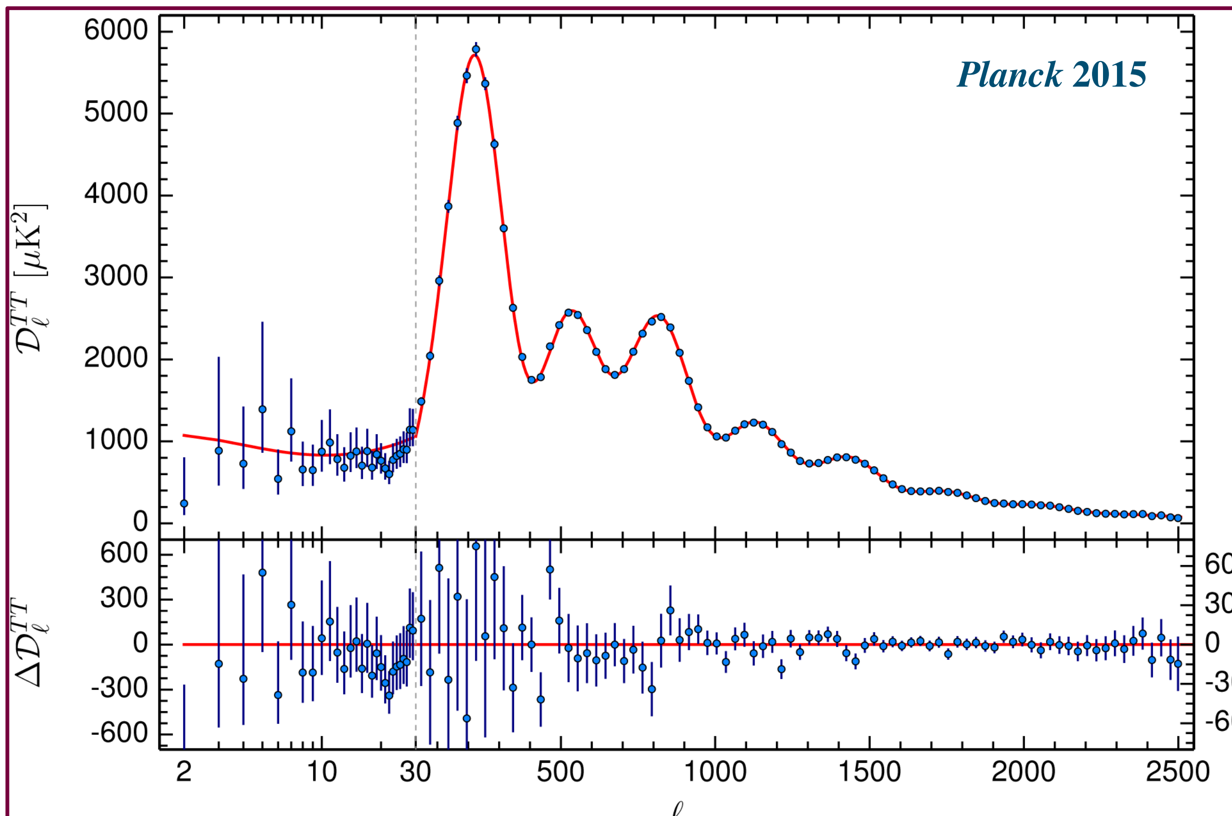
$$\frac{\Delta T}{T}(\theta,\phi)=\sum_{l=0}^{\infty}\sum_{m=-l}^{+l} a_{lm} Y_l^m(\theta,\phi)$$

"Frequency" of spots

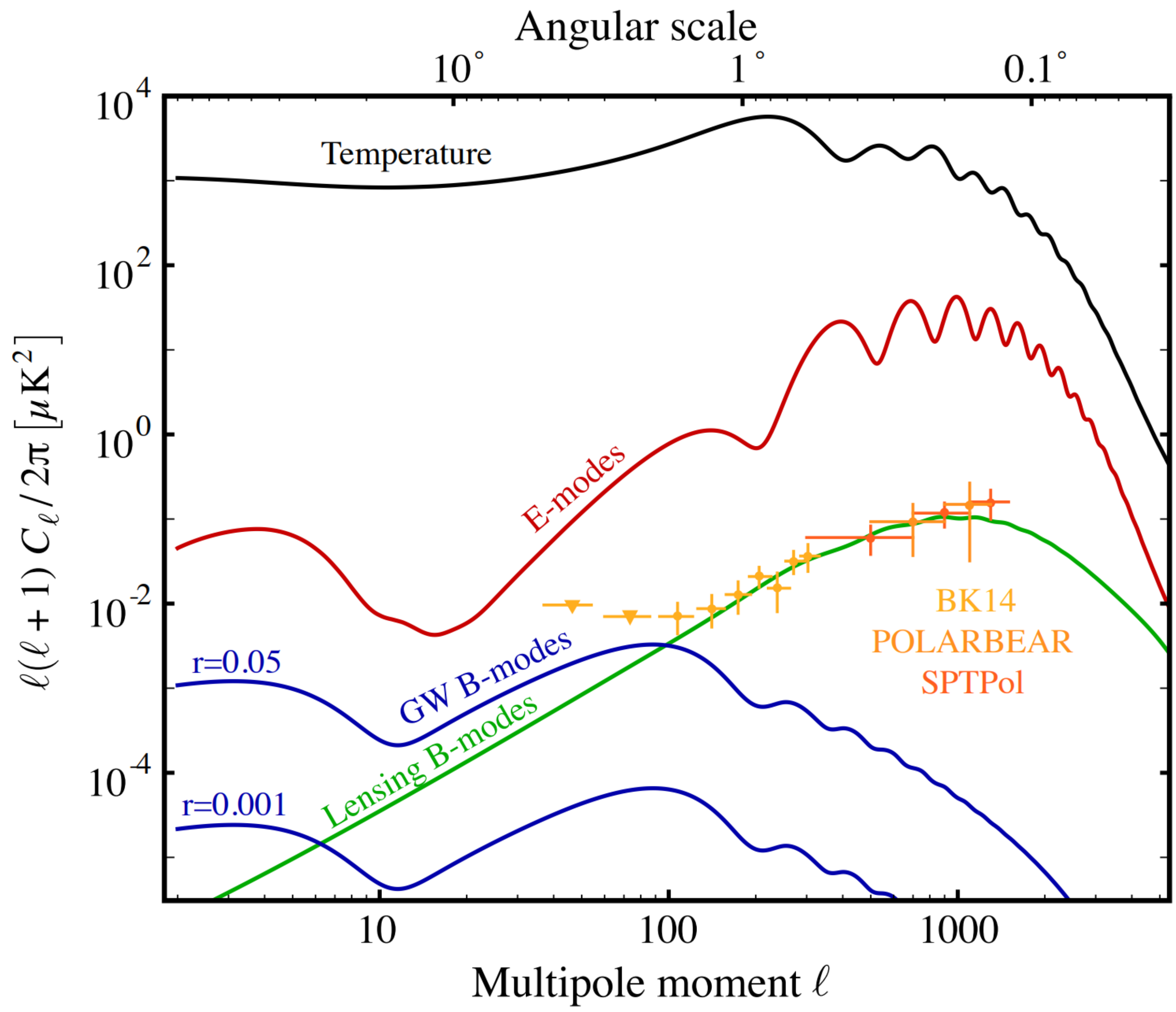
$$C_l \sim \mathrm{TF}\left\langle \frac{\Delta T}{T}(\vec{n})\frac{\Delta T}{T}(\vec{n}\,')\right\rangle$$

as function of their size

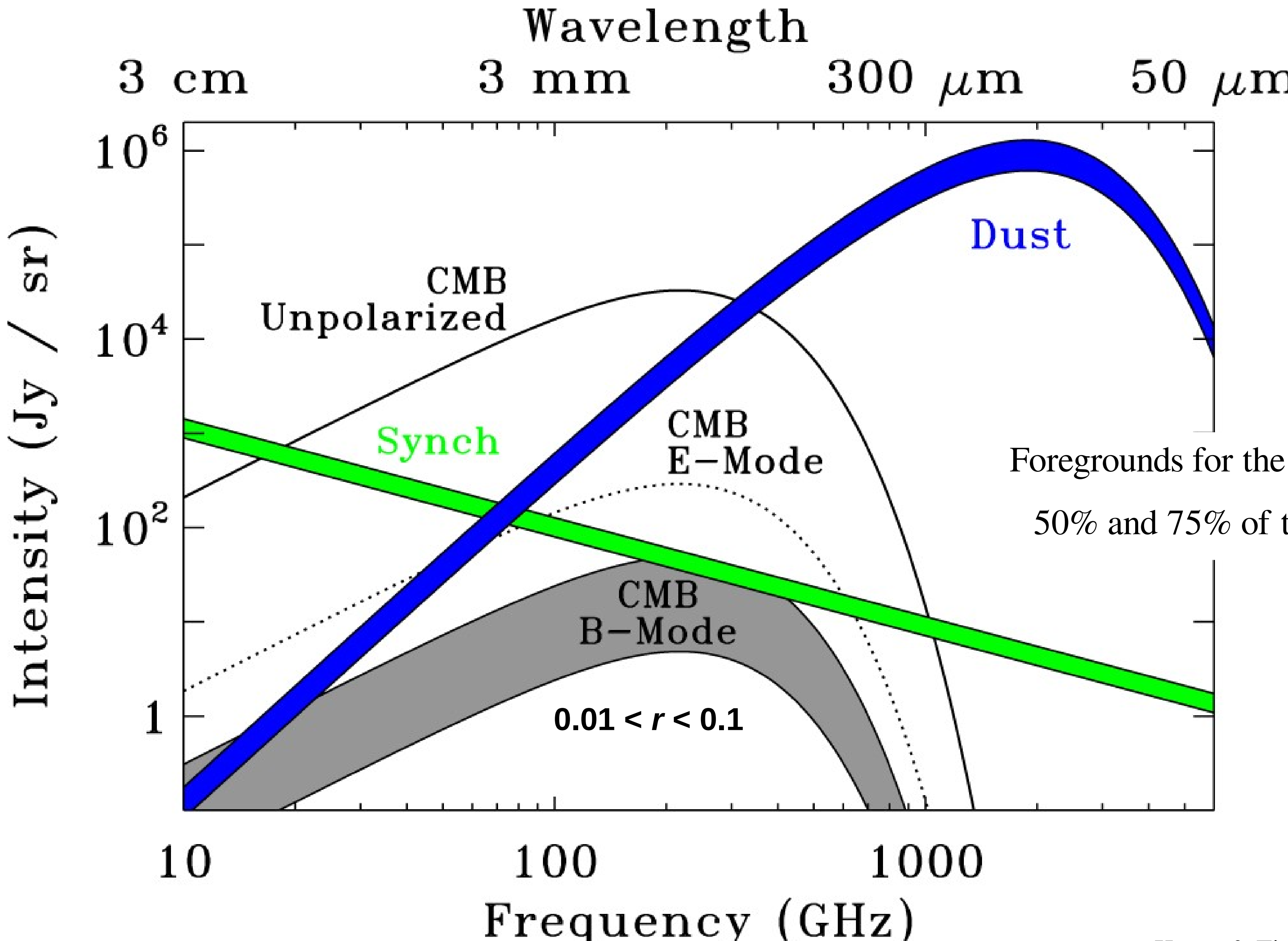
$$C_l=\left\langle \left|a_{lm}\right|^2\right\rangle$$



CMB powerspectra



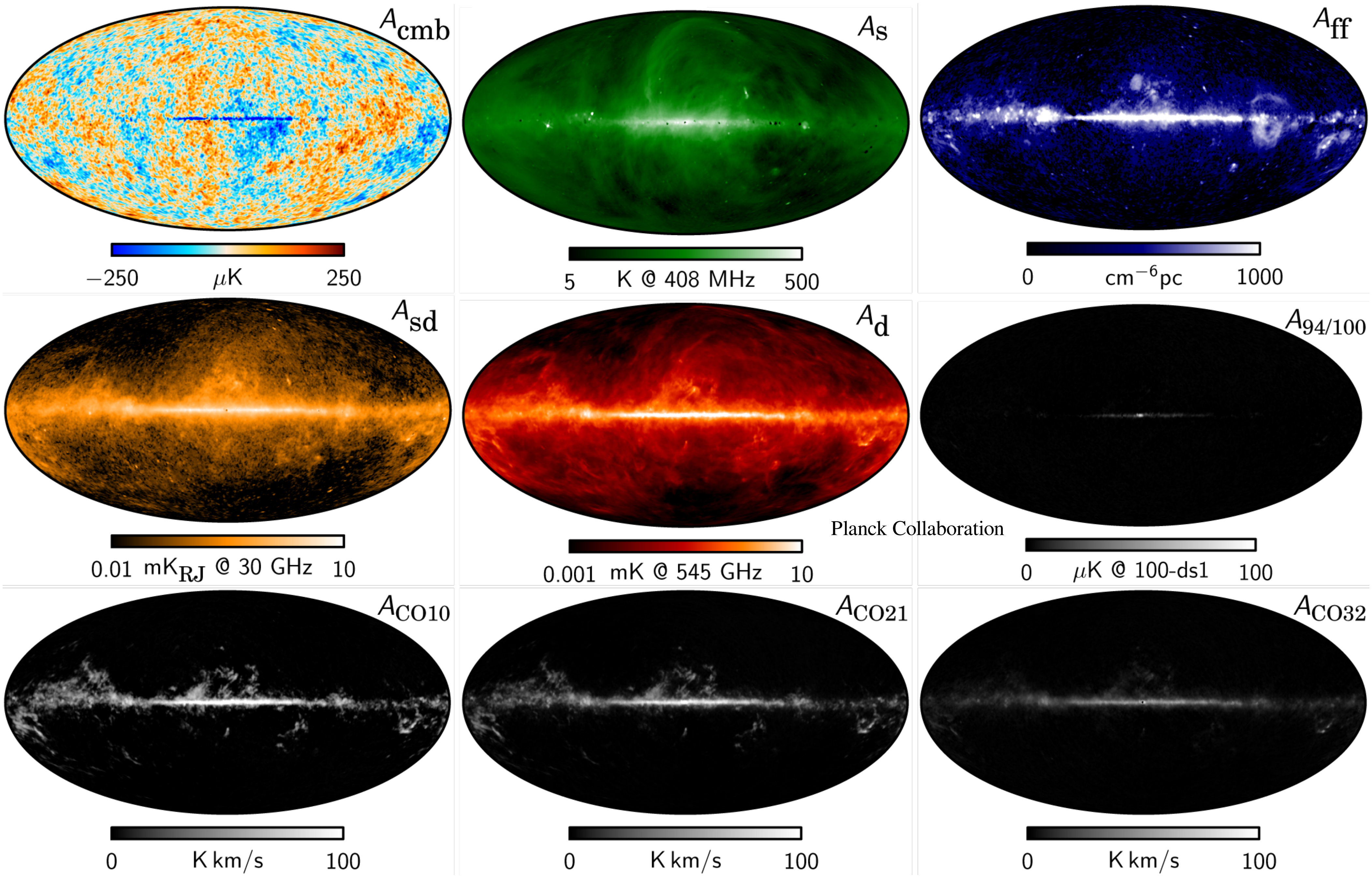
The signal: a tiny needle in a haystack of foregrounds & noise



Foregrounds for the cleanest 50% and 75% of the sky

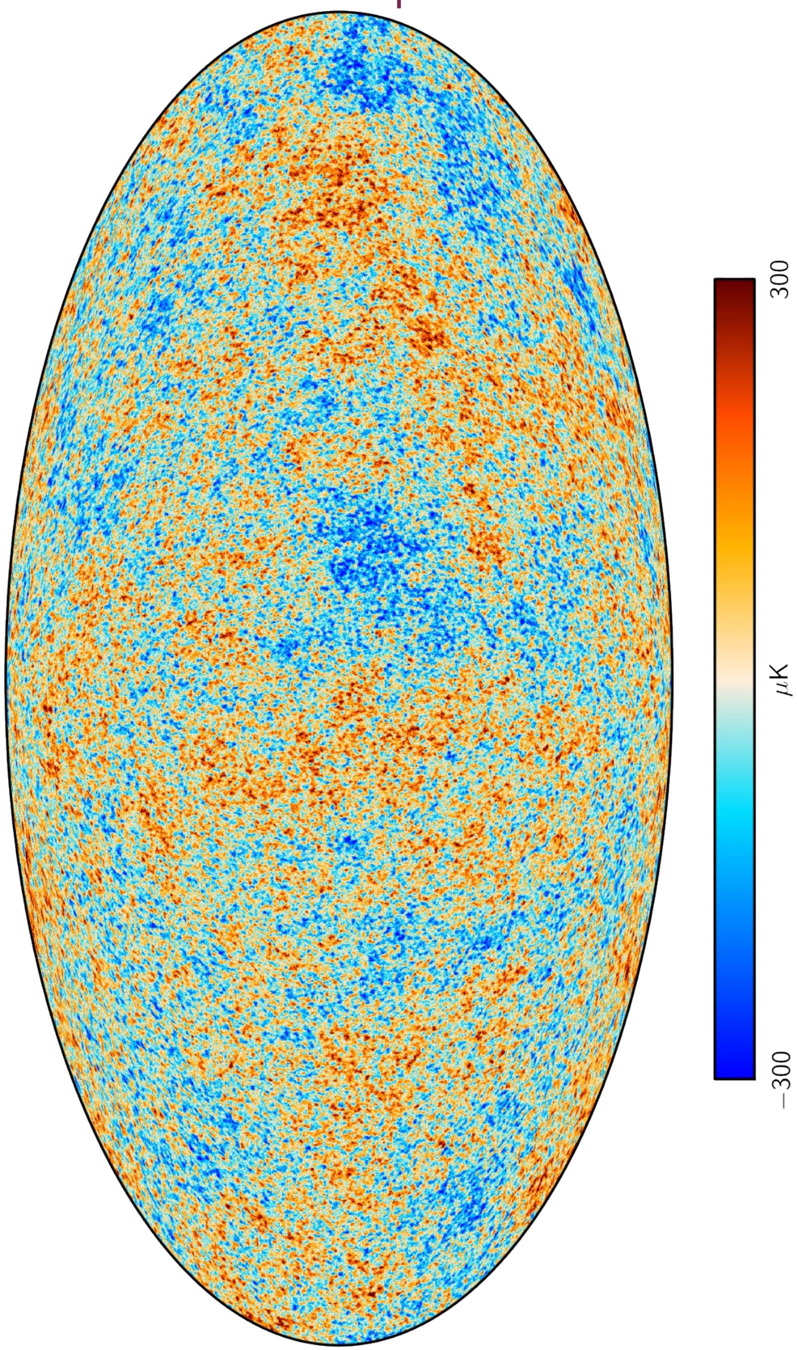
Kogut & Fixsen 2016

Some of the Temperature foregrounds



Planck Collaboration

The CMB: statistical analysis



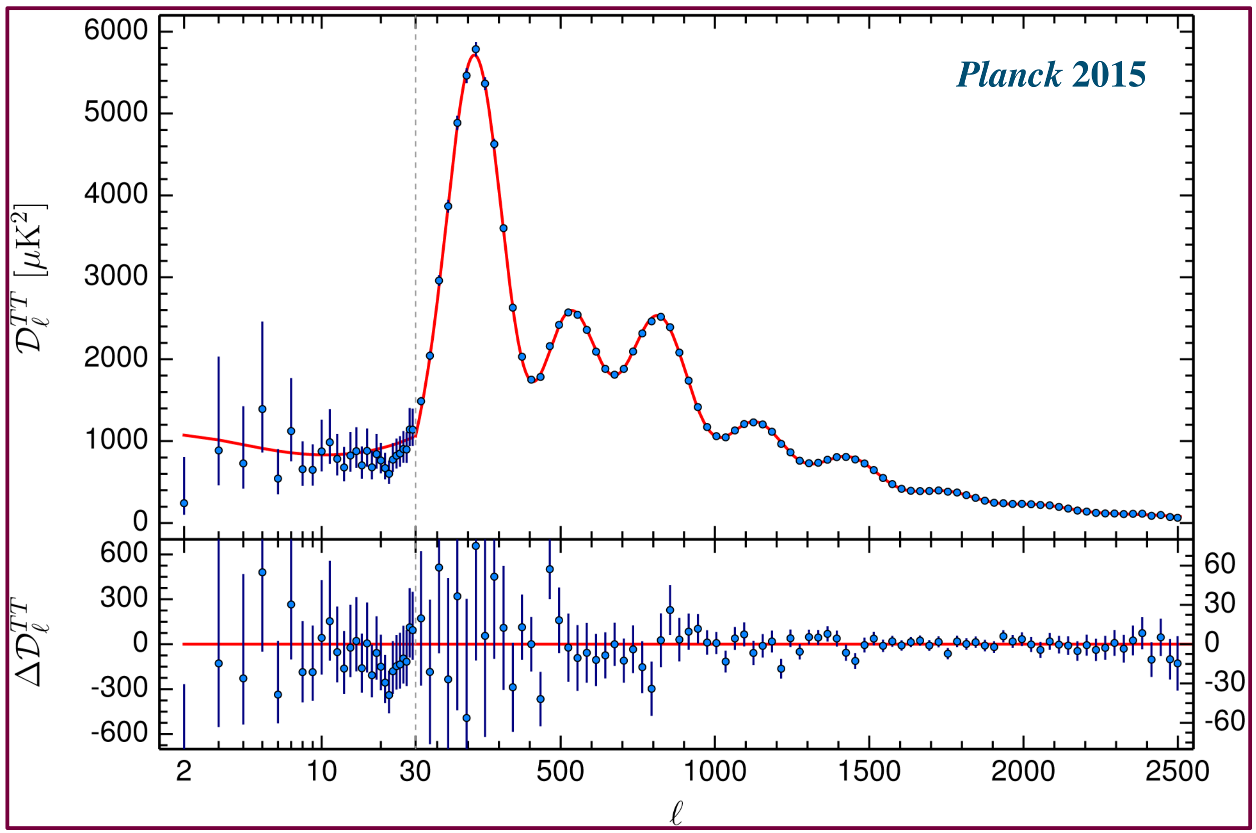
$$\frac{\Delta T}{\bar{T}}(\theta,\phi)=\sum_{l=0}^{\infty}\sum_{m=-l}^{+l} a_{lm} Y_l^m(\theta,\phi)$$

“Frequency” of spots

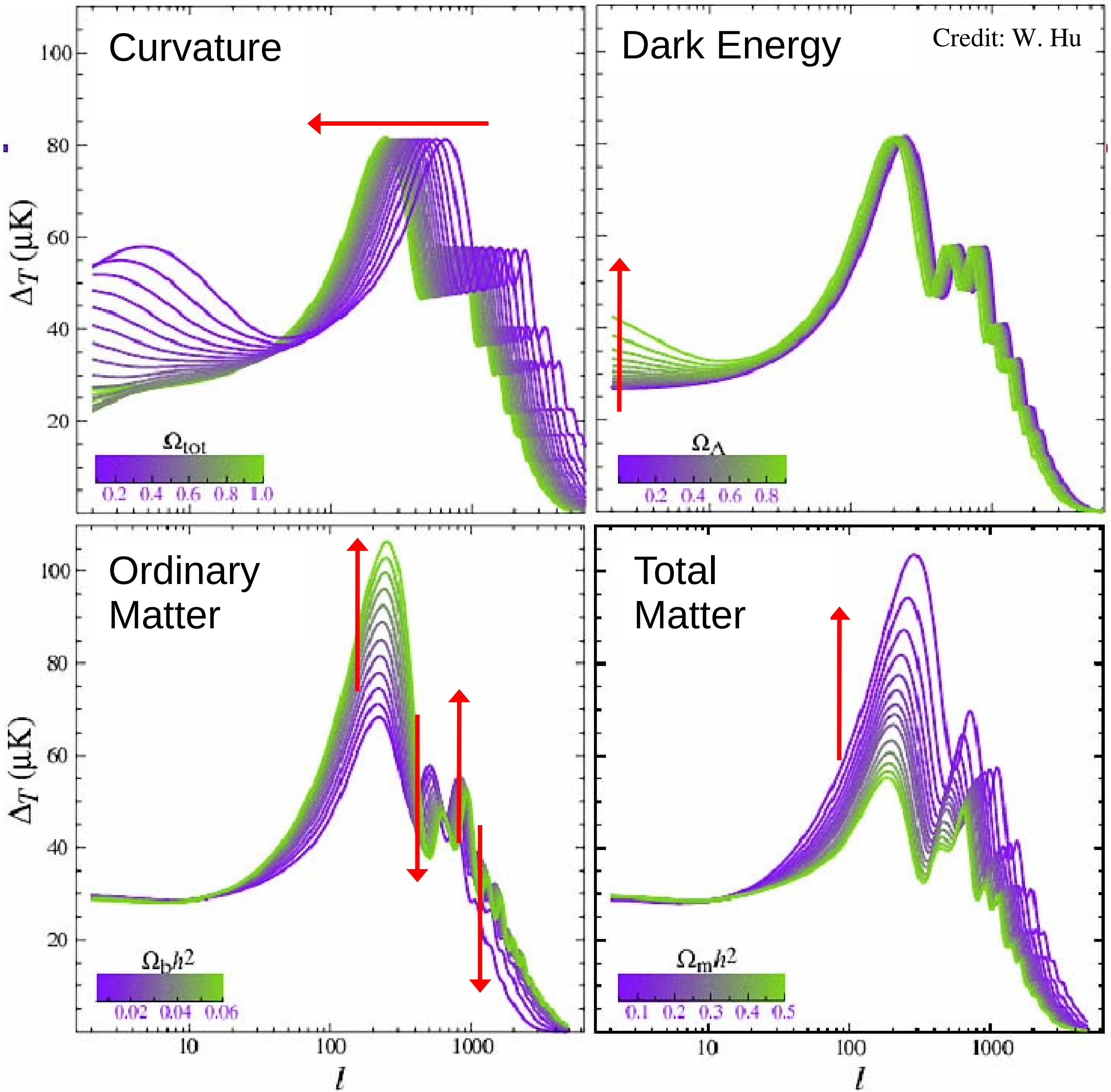
$$C_l \sim \mathrm{TF}\left\langle \frac{\Delta T}{\bar{T}}(\vec{n})\frac{\Delta T}{\bar{T}}(\vec{n}\,')\right\rangle$$

as function of their size

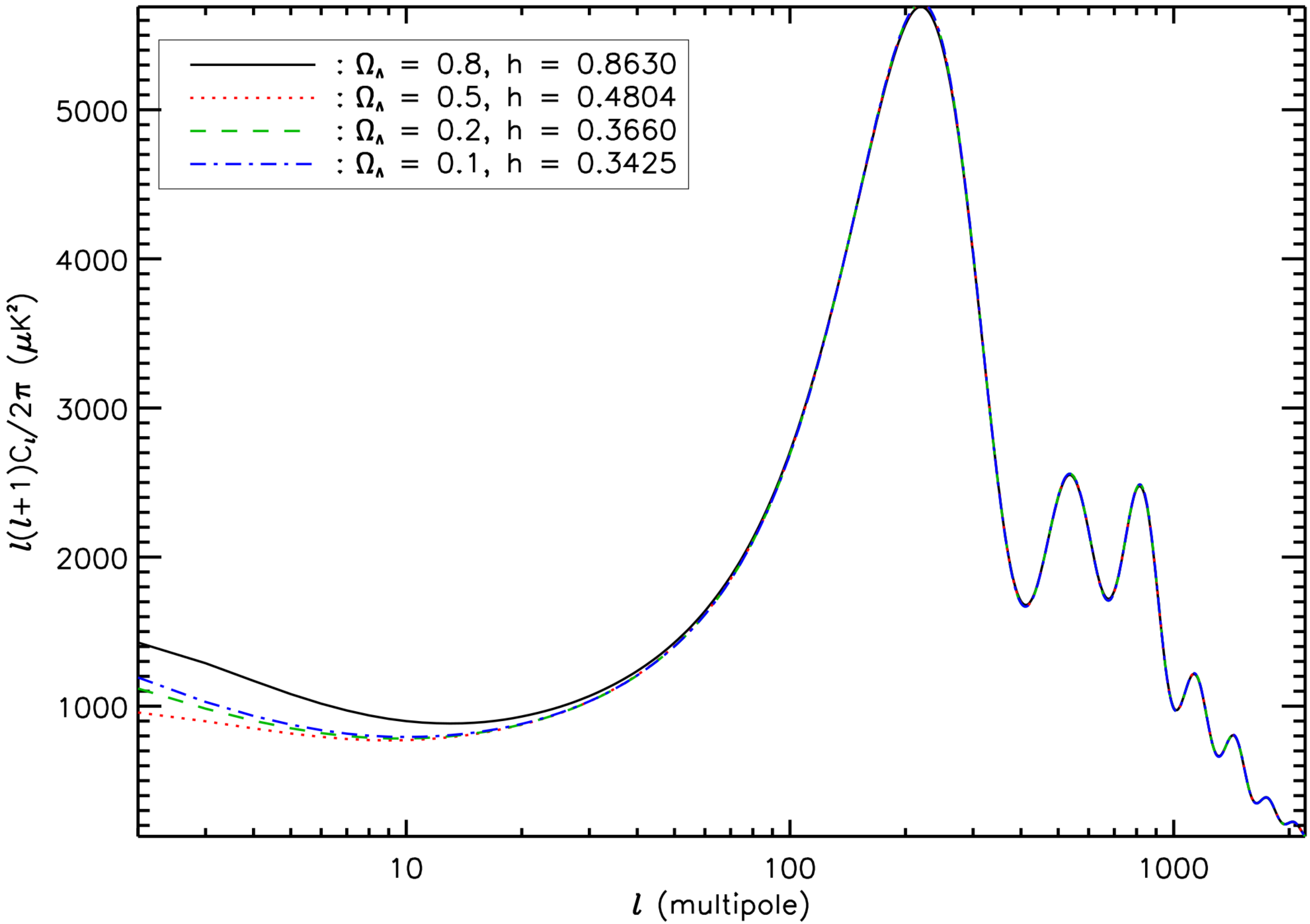
$$C_l=\left\langle |a_{lm}|^2 \right\rangle$$



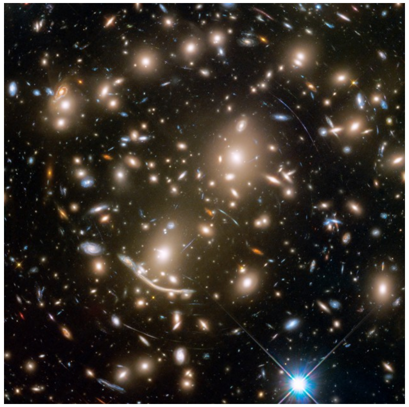
The CMB: a developer of the Universe

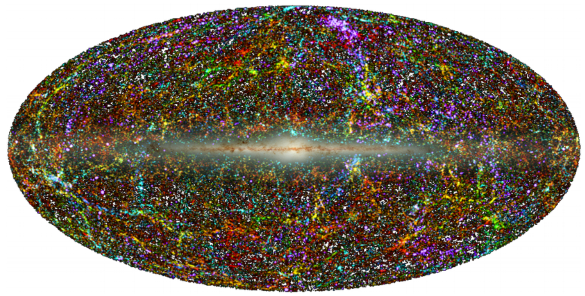


The CMB & “degeneracies”

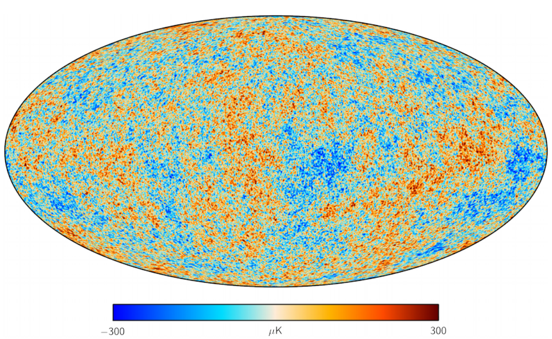


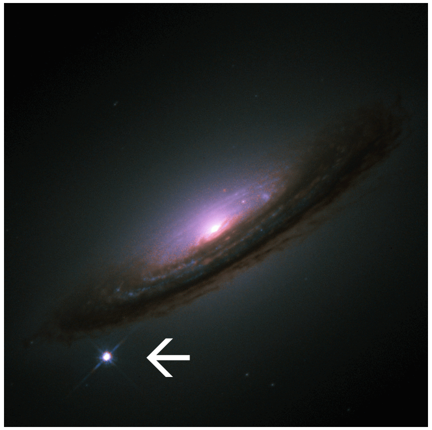
Breaking degeneracies?

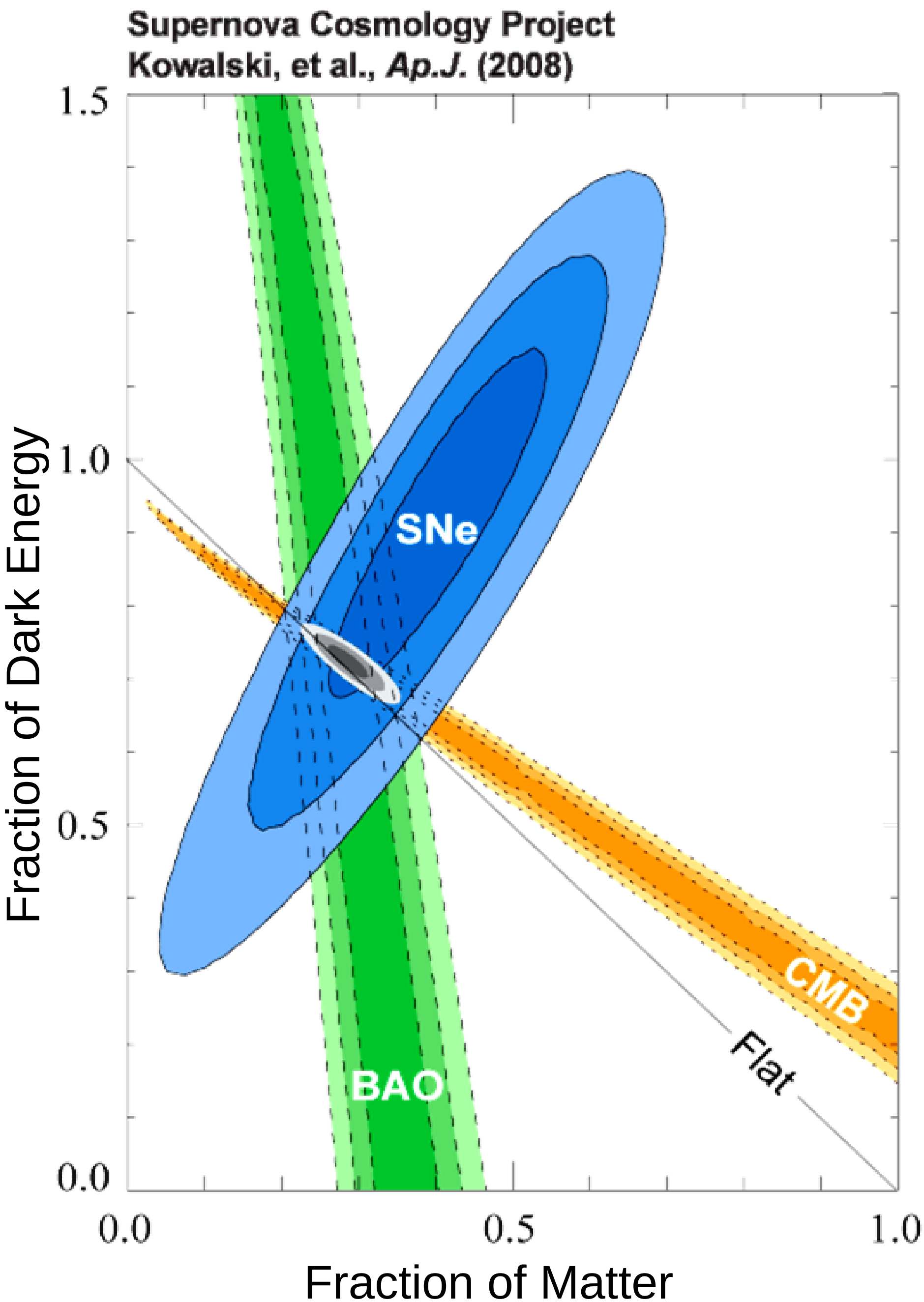




Combining independent data!

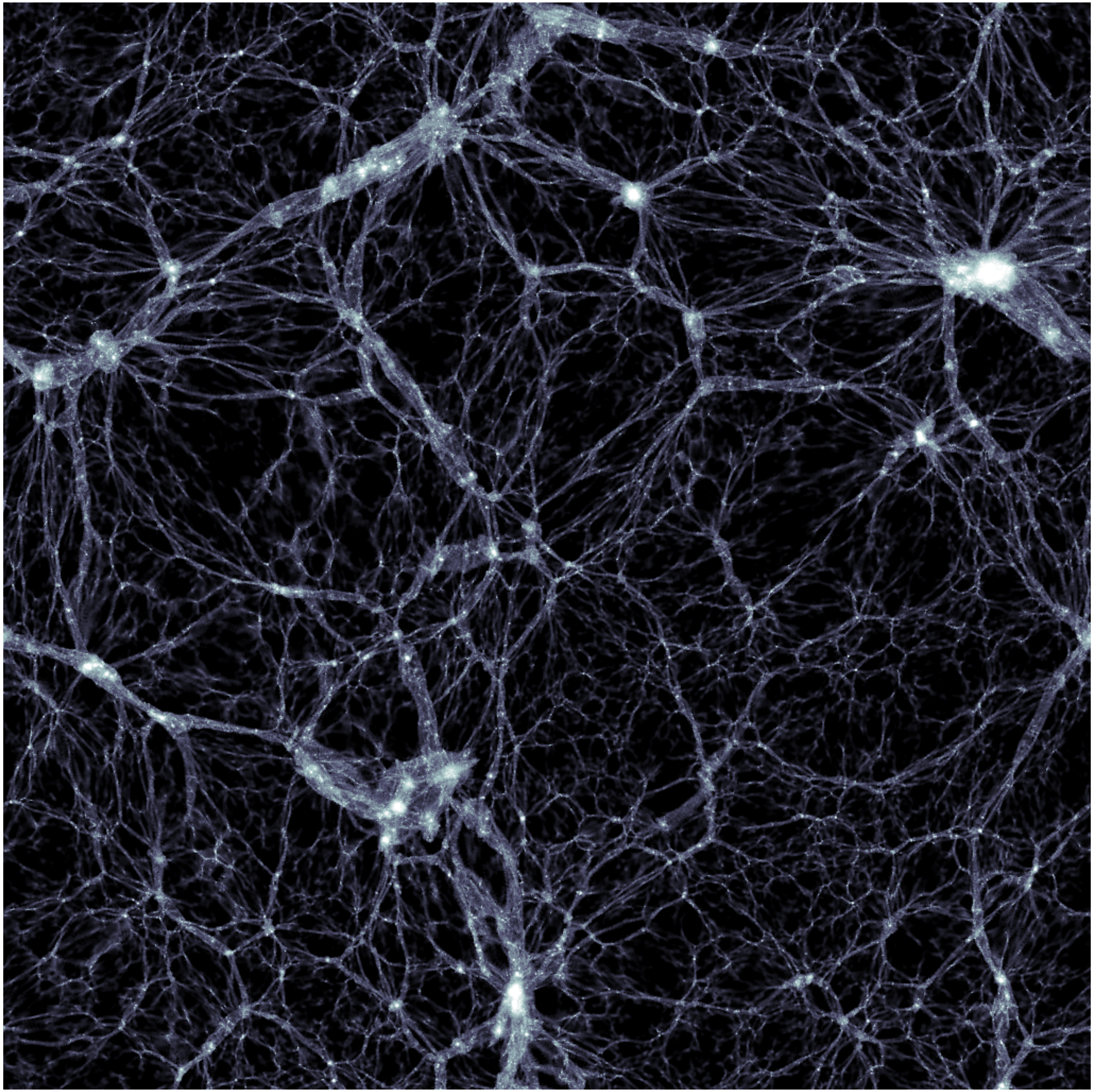






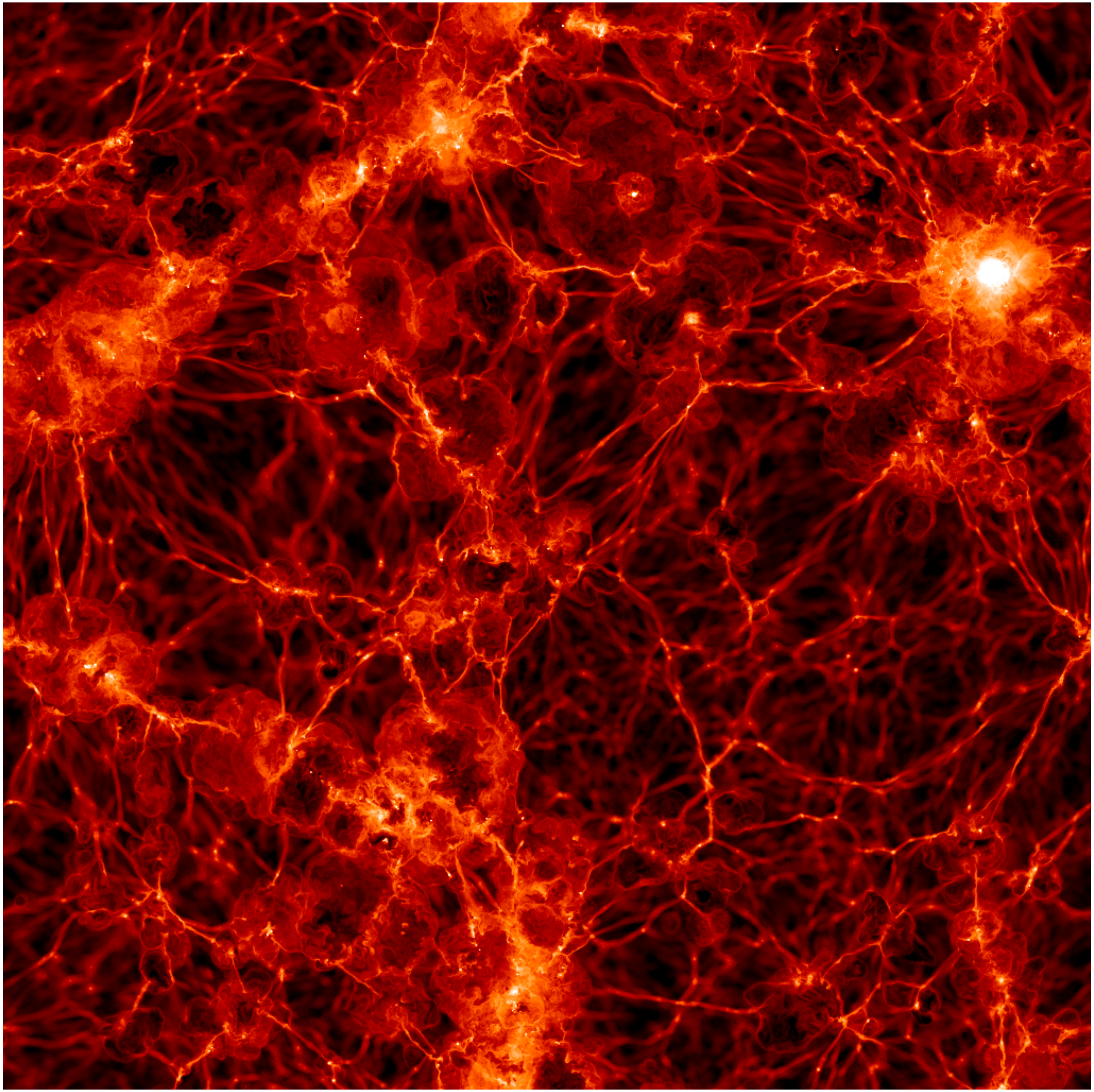
The Cosmic Web: the Dark Matter distribution

Dark Matter only



Illustris simulation
Haider et al. (2016)

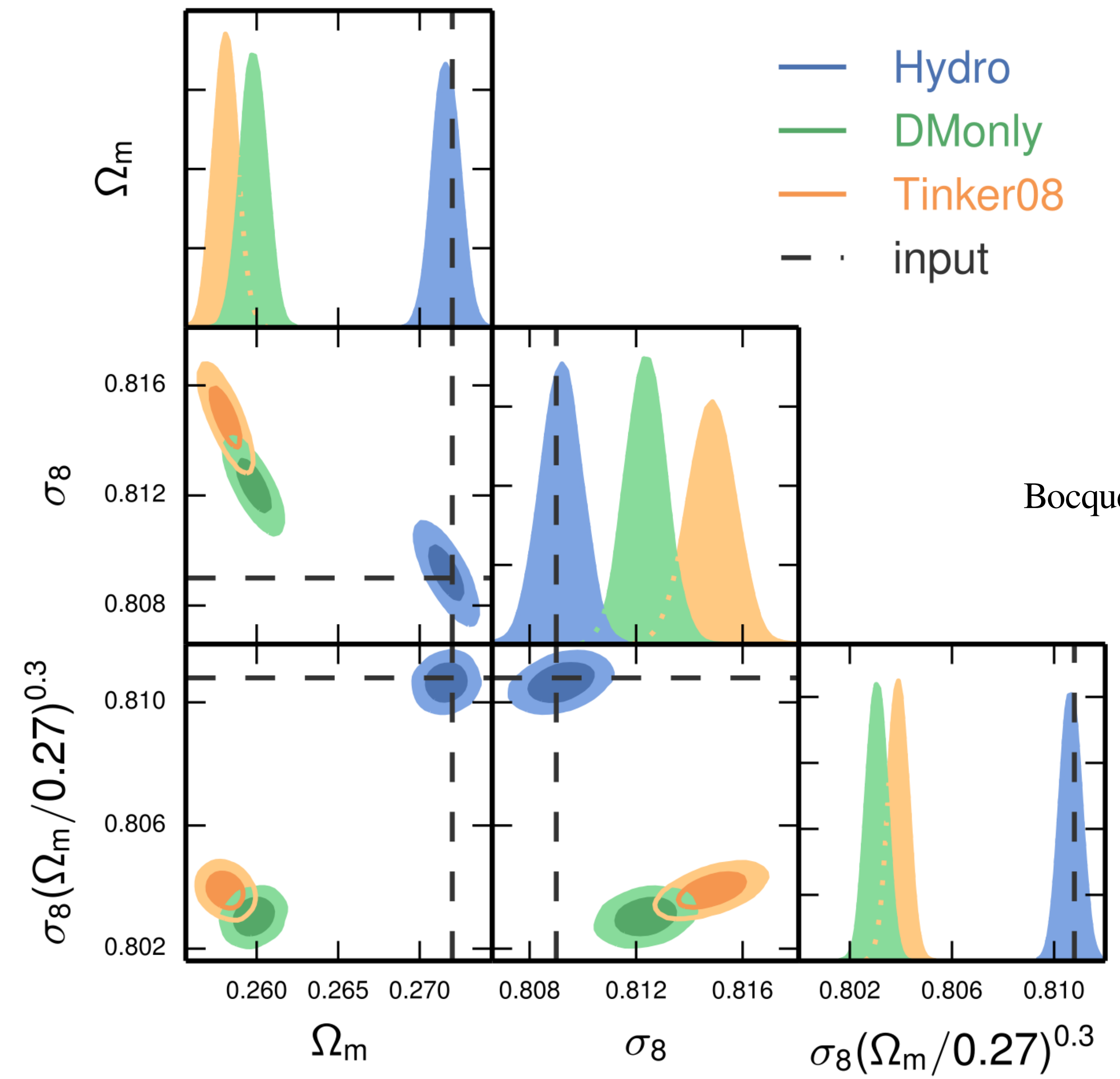
The Cosmic Web: the baryonic gas



Baryons
+ heating
+ cooling

Illustris simulation
Haider et al. (2016)

Impact of baryonic physics on the Cosmological Model

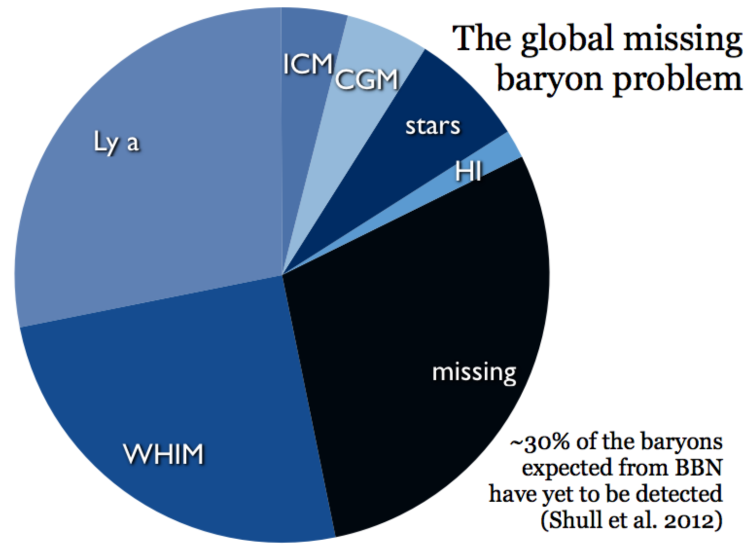


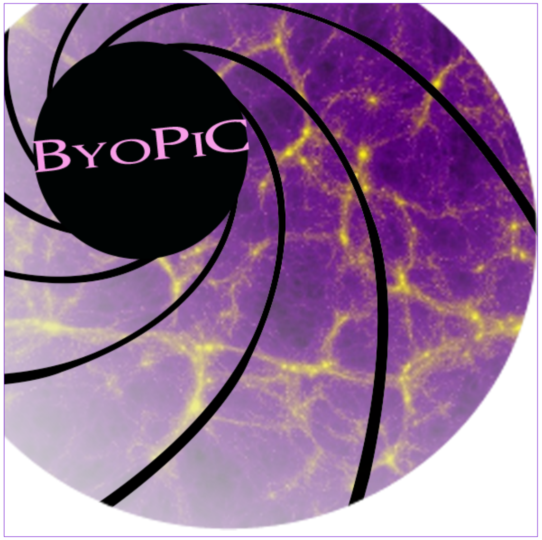
Bocquet et al, 2016

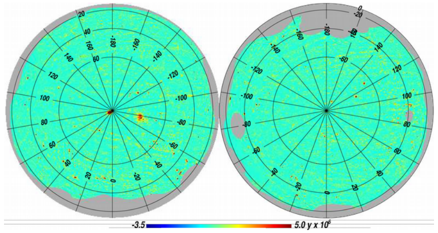
Problems with baryons

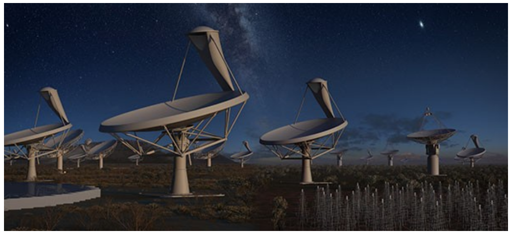
- Complex physics :
  - Non-linear
  - Instabilities
  - Dissipative
  - Multi-scale
  - Chemistry
  - Magnetic Fields
  - Not well understood
  - …

- On the global scale:
  - 30% – 50% are missing!

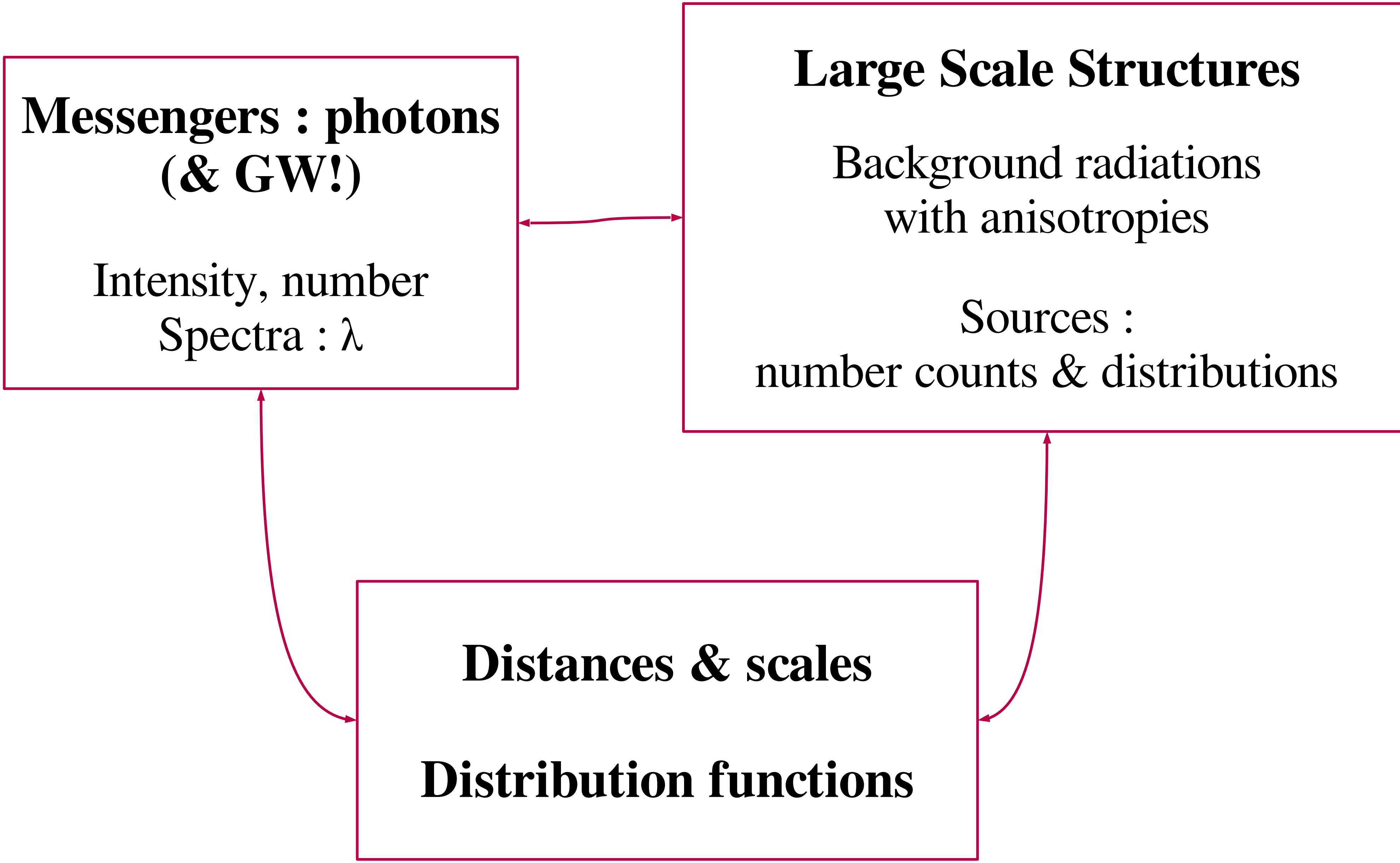






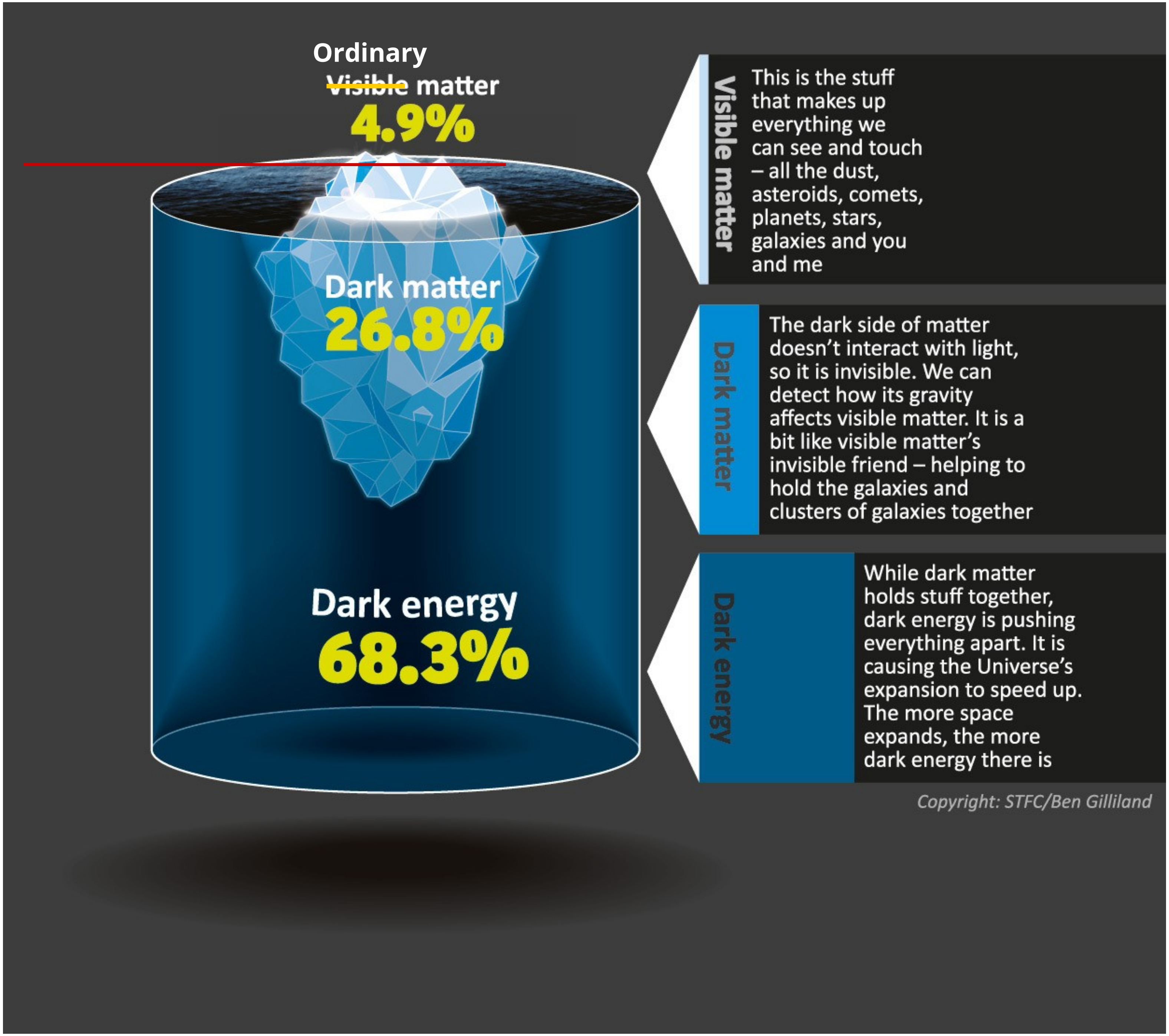


Modern cosmology: measurements



Visible matter < Ordinary matter

Visible ≃ stars = 0.4%



Messengers : photons (& GW!)

Intensit

Spe

Large Scale Structures

Background radiations with anisotropies

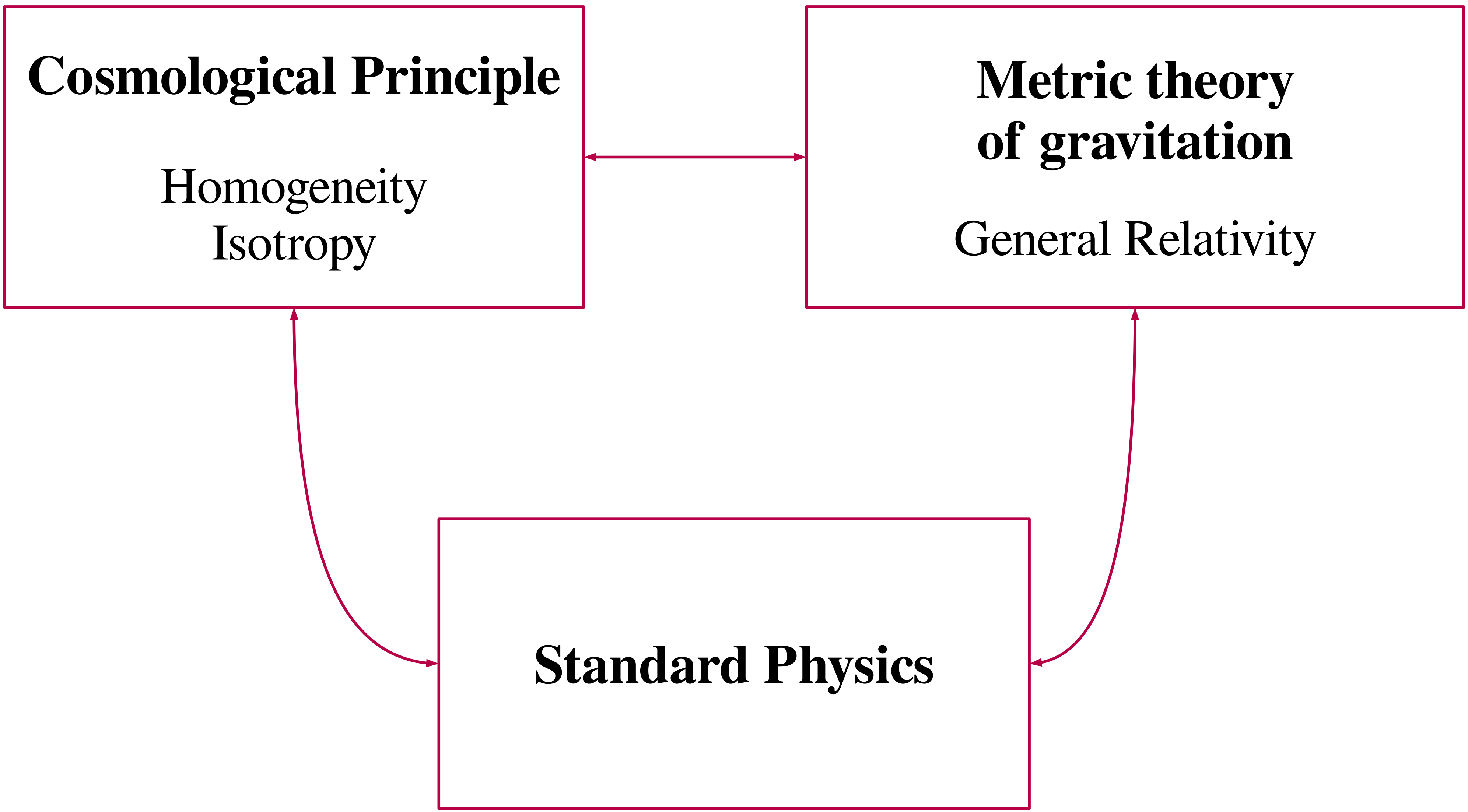
tributions

Framework for interpretations?

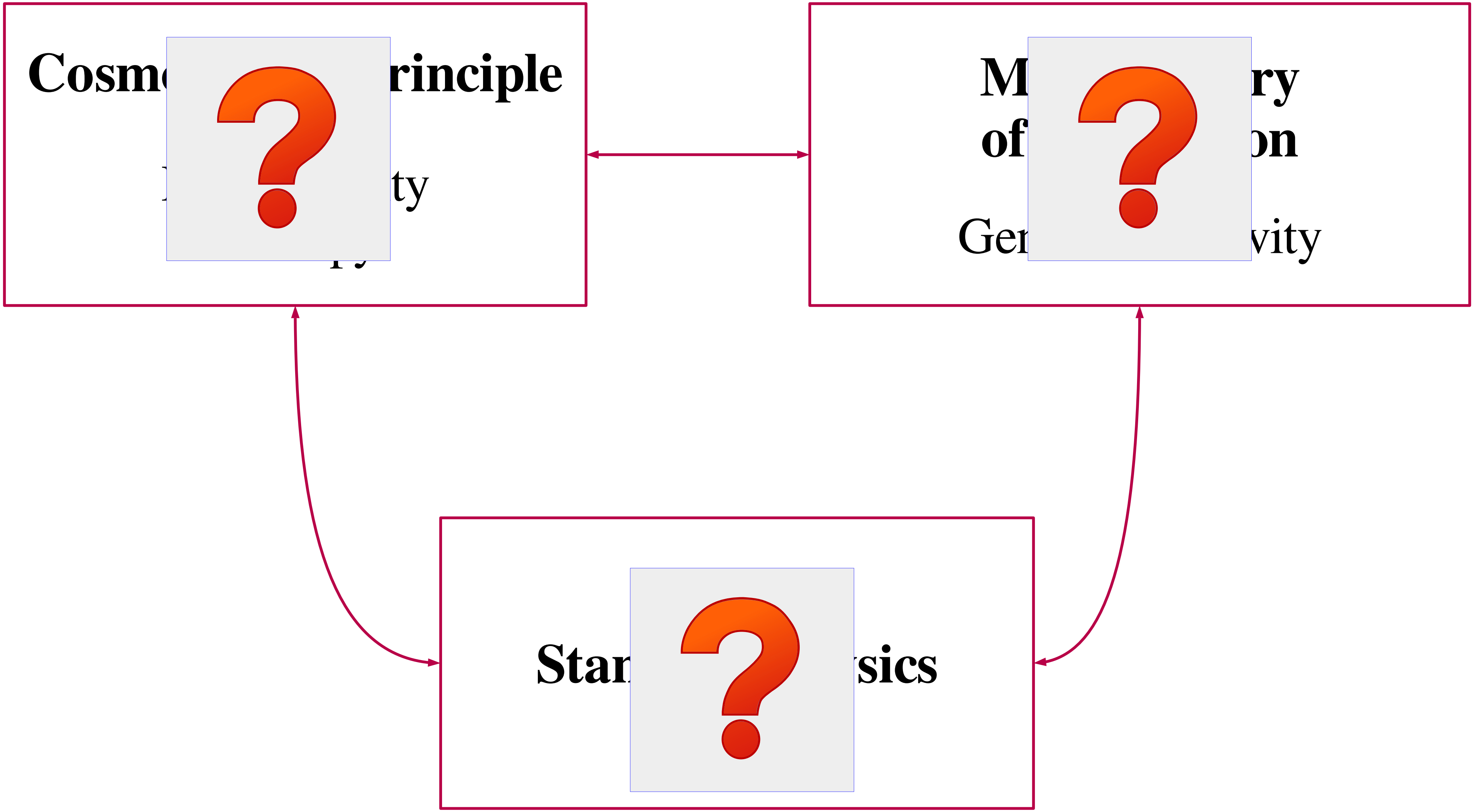
Distances & scales

Distribution functions

Modern Cosmology : theory



Modern Cosmology : theory



Challenges facing Cosmology