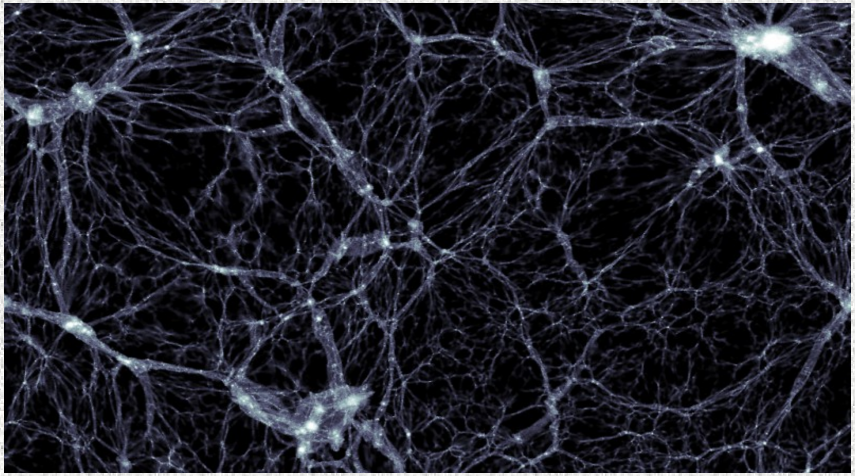
PGC2018-097585-B-C21

The large scale structure of the universe



Illustris simulation

Carlos Hernández-Monteagudo

Centro de **E**studios de **F**ísica del **C**osmos de **A**ragón

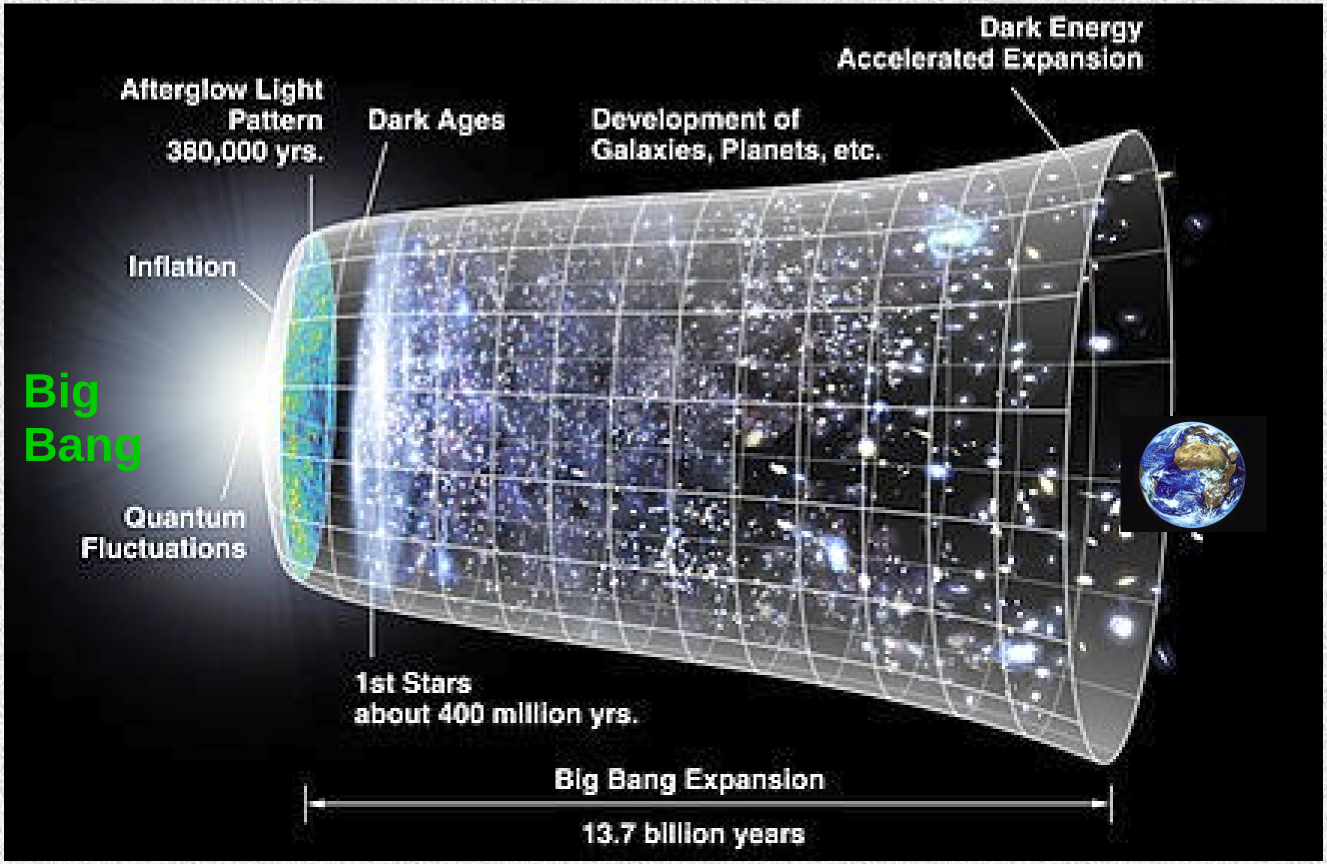
[CEFCA]

Benasque, September 2019

OUTLINE

- The information initally encoded in the clustering of *light*
- The imprint of gravity/growth of structure in the clustering of galaxies
- Other cosmological probes of the LSS: gravitational lensing and abundance of the most massive, collapsed objects in the universe (galaxy clusters)
- The epoch of Reionization and other open questions in cosmology/astro-particle physics

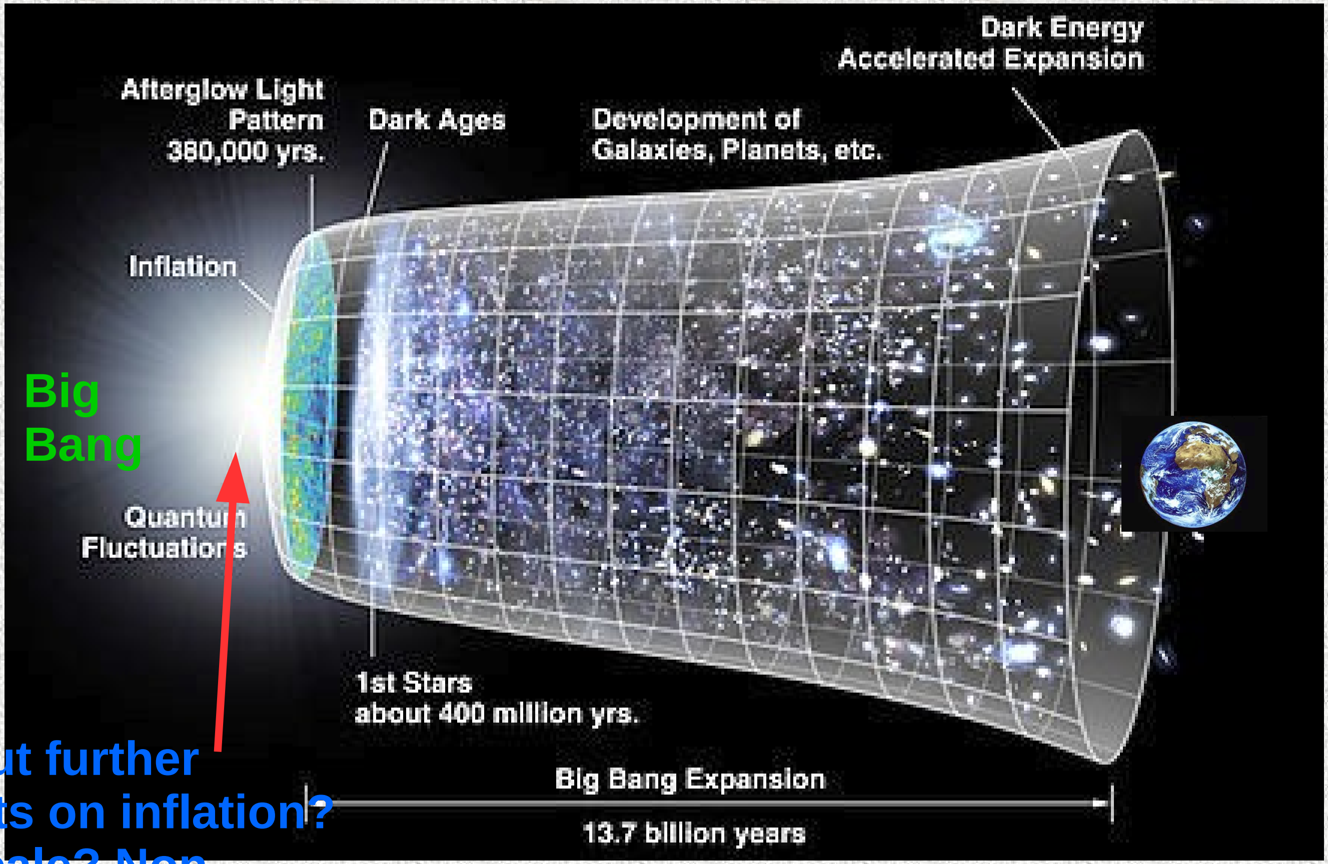
Big open questions in Cosmology ...



Present

Cosmological time →

Big open questions in Cosmology ...



Big Bang

Present

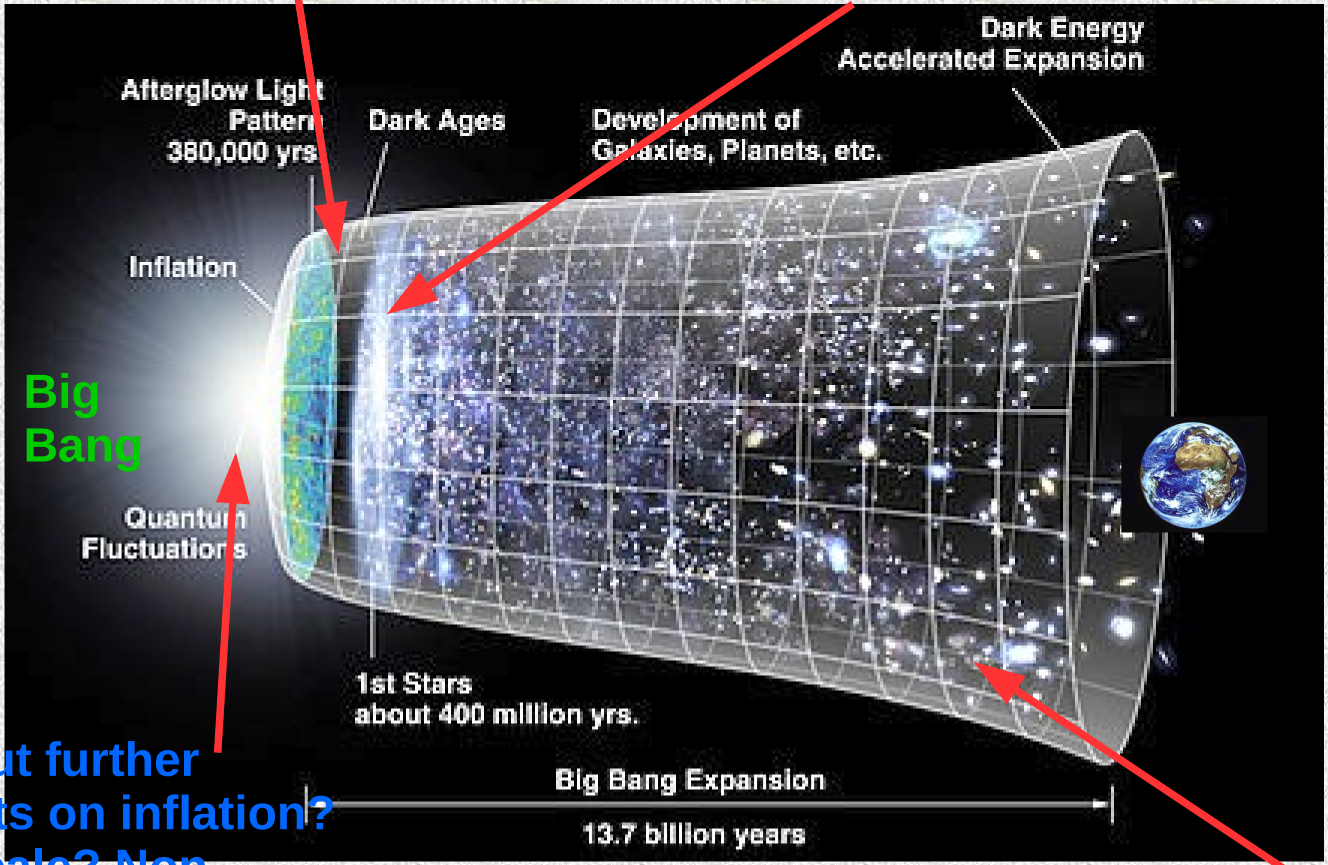
Can we put further constraints on inflation? Energy scale? Non-Gaussianity? Number of fields? How did reheating proceed?

Cosmological time →

Big open questions in Cosmology ...

How were the *dark ages?* How did the first stars form?

When and how did Reionization take place? How long did it last? Who caused this? Galaxies, QSOs? How were Pop III stars?



Present

Can we put further constraints on inflation? Energy scale? Non-Gaussianity? Number of fields? How did reheating proceed?

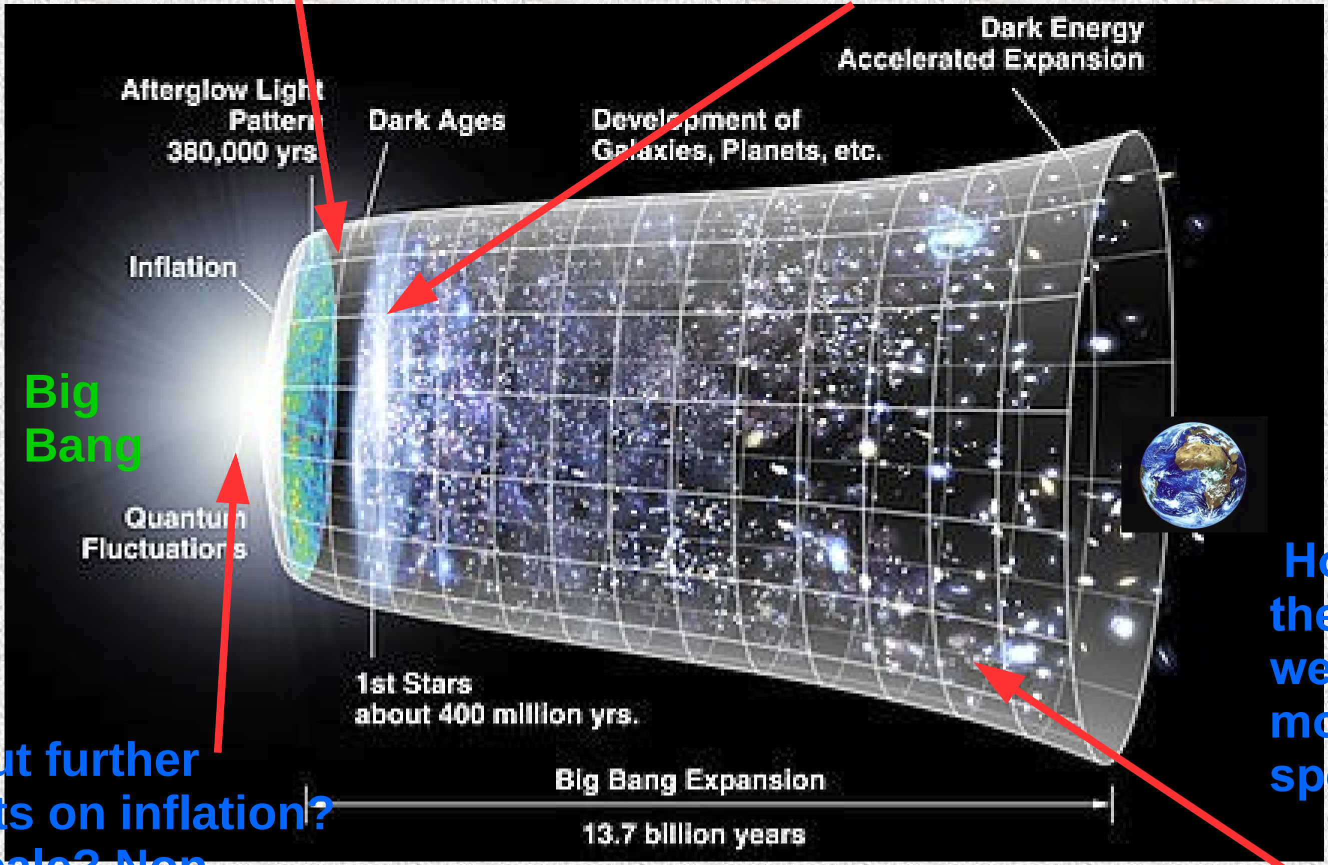
Cosmological time →

Big open questions in Cosmology ...

How were the *dark ages?* How did the first stars form?

When and how did Reionization take place? How long did it last? Who caused this? Galaxies, QSOs? How were Pop III stars?

Is there any interaction within the *Dark sector*?



Big Bang

Present

How much does the neutrinos weight? Are there more relativistic species?

Can we put further constraints on inflation? Energy scale? Non-Gaussianity? Number of fields? How did reheating proceed?

Cosmological time →

What is Dark Energy? Can we distinguish it from Modified Gravity?

The inflaton stretches quantum fluctuations to macroscopic scales ...

$$\phi_{\mathbf{k}}$$

… which are projected, after reheating, as curvature fluctuations ...

$$\phi_{\mathbf{k}} \rightarrow \zeta_{\mathbf{k}}$$

… which source the anisotropies in the (visible) energy and matter distribution in the universe ...

$$\zeta_{\mathbf{k}} \rightarrow \psi_{\mathbf{k}},\ \delta_{c,\mathbf{k}},\ \delta_{b,\mathbf{k}},\ \delta_{\gamma,\mathbf{k}}$$

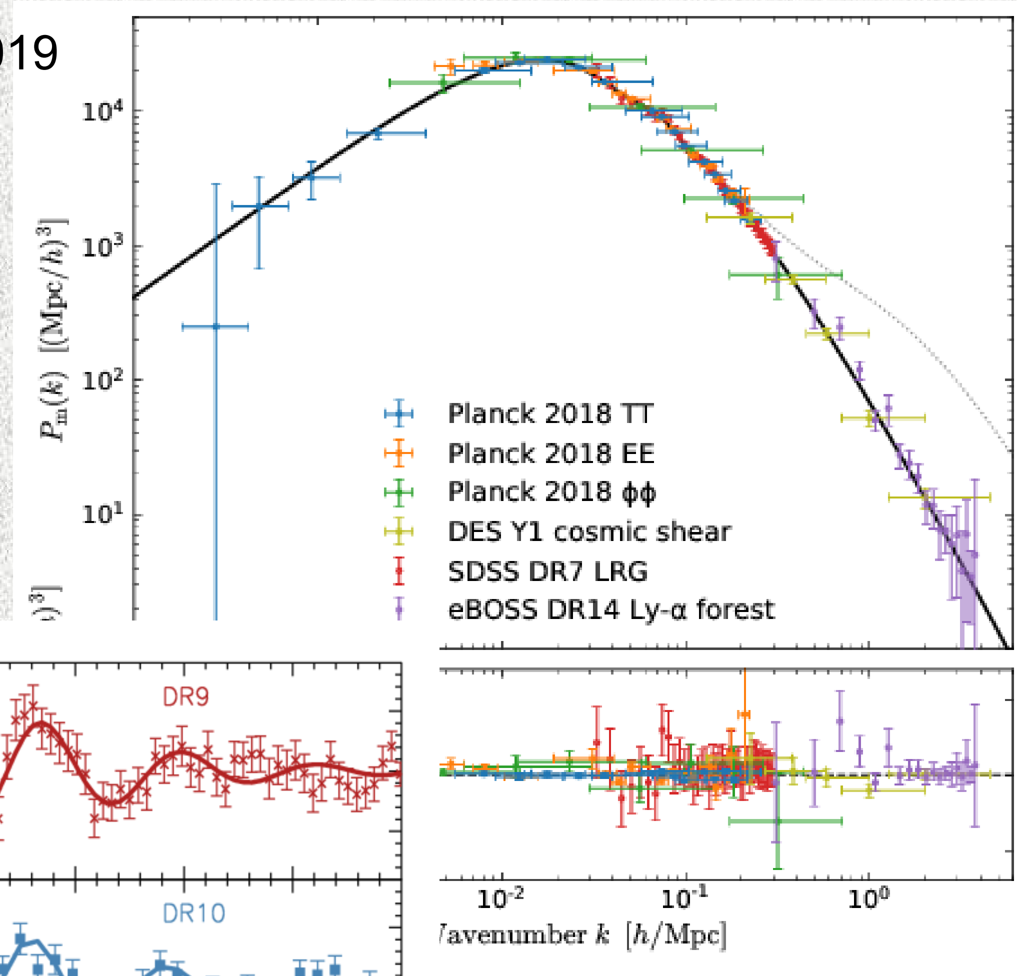
The impact of the transfer function can be seen in the matter power spectrum:

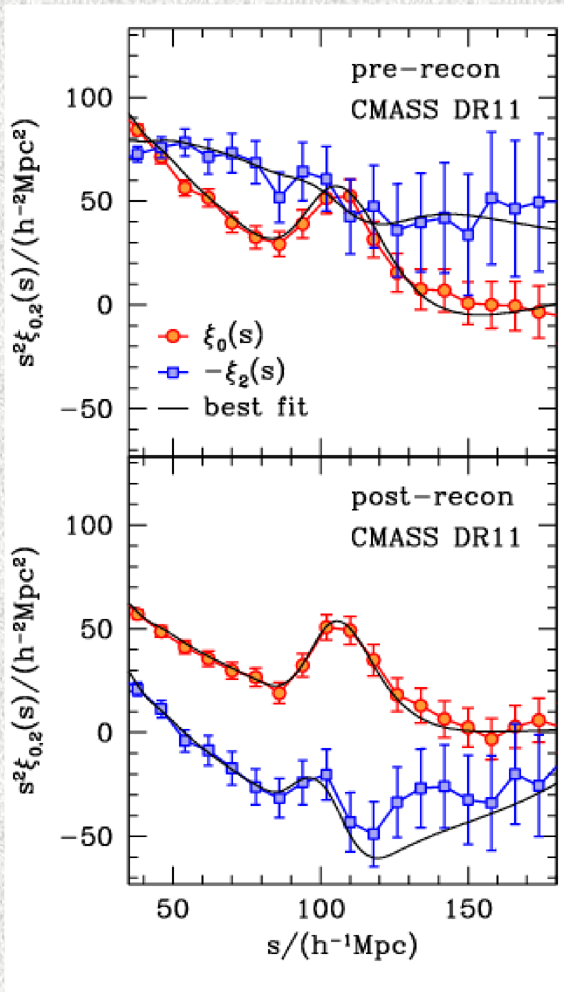
[**BLACKBOARD: derive scale invariant spectral index (Harrizon-Zeldovich)**]

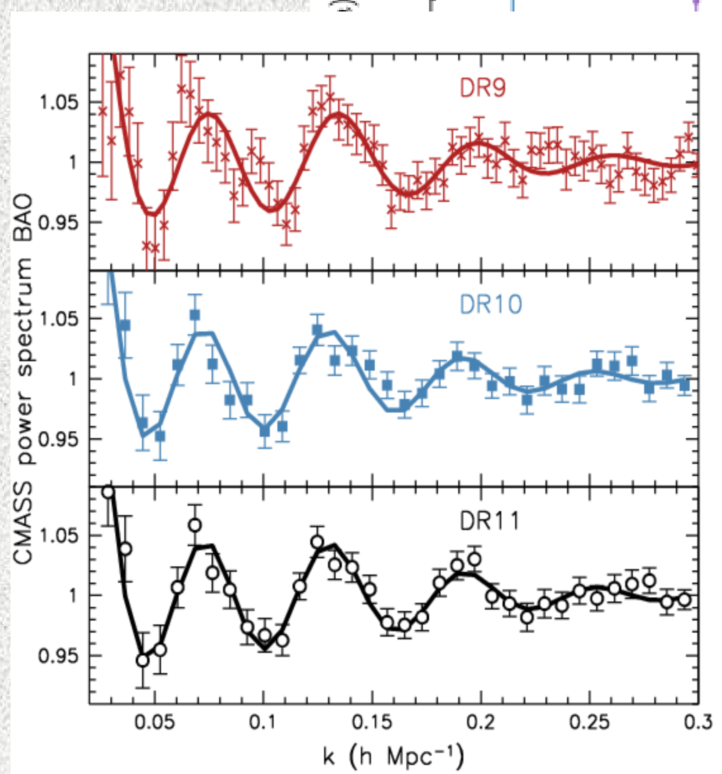
[BLACKBOARD: connect correlation function and power spectrum]

[BLACKBOARD: introduce impact of peculiar velocities on observed power spectrum]

Chabanier et al. 2019

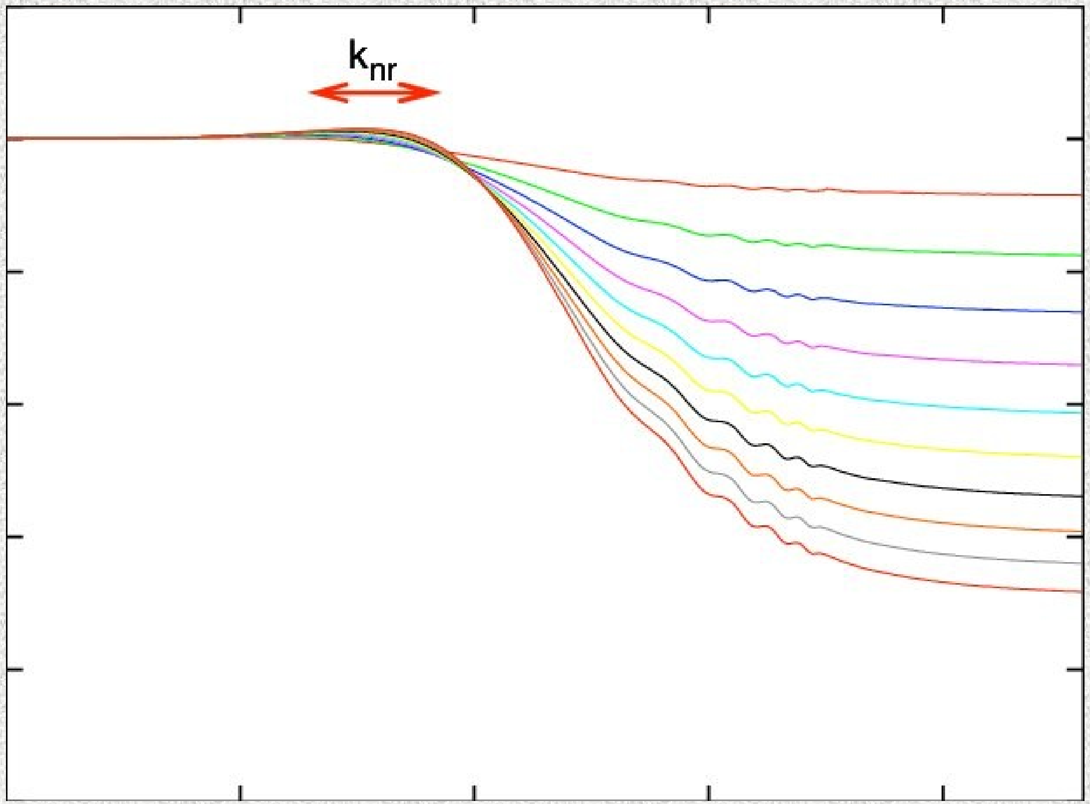






BOSS collab.

Impact of neutrinos and relativistic species on the LSS



Lesgourges & Pastor 2012

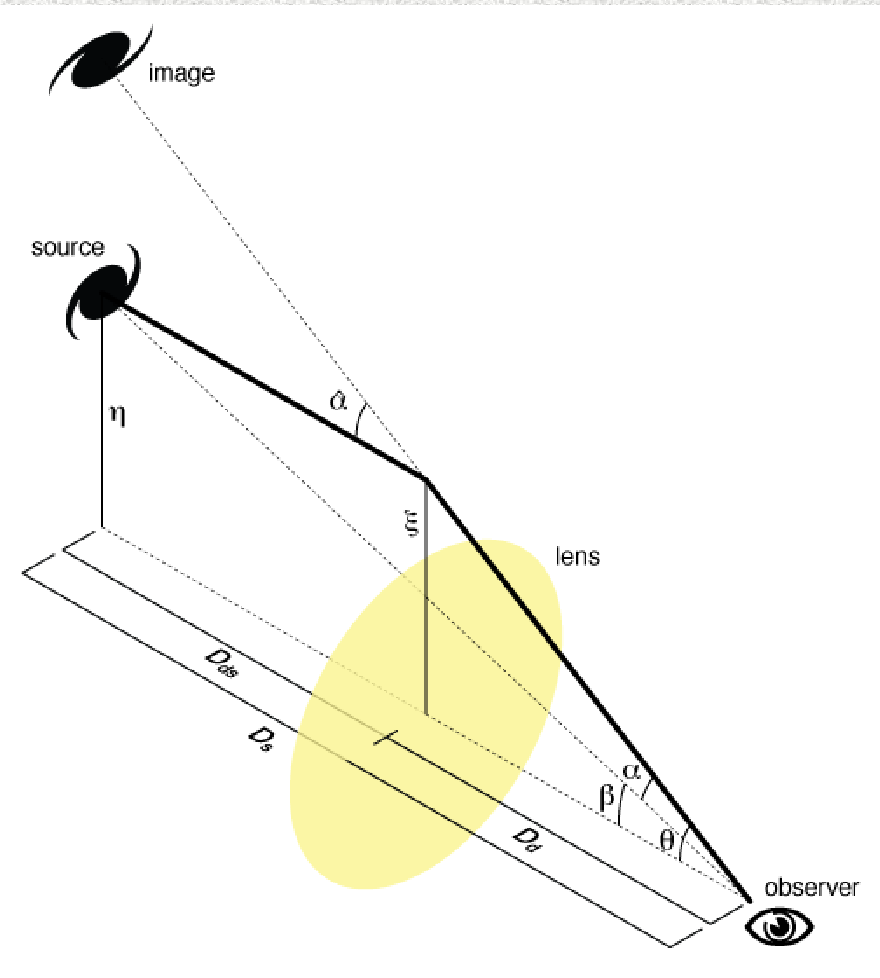
Transfer function of the power spectrum for different neutrino masses

Power below the ***free-streaming scale*** is dumped/suppressed

Whenever we do **not** have **accurate** ***redshift*** measurements, we project on the sky → **angular** number densities → **angular** correlation function and power spectra

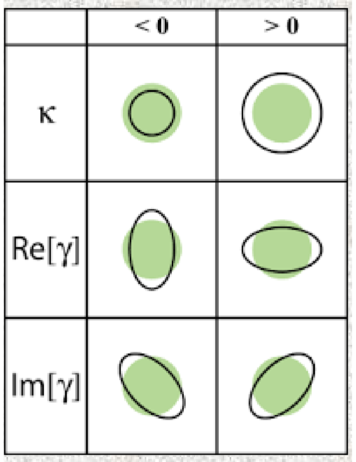
[**BLACKBOARD: derive angular quantities from 3D power spectrum]**

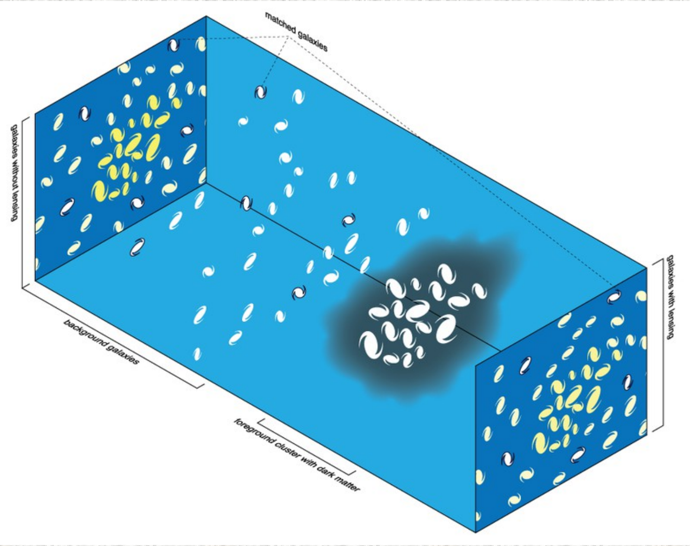
A few words about gravitational lensing

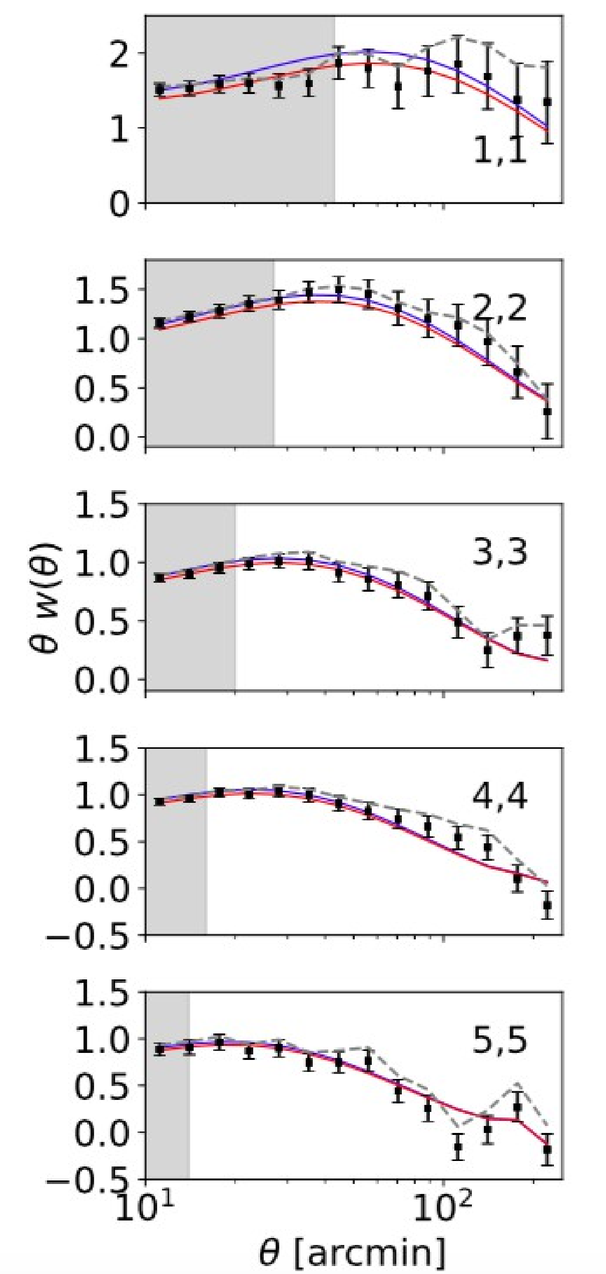


Wikipedia

One can work a **linear theory prediction** for this *shear* too …

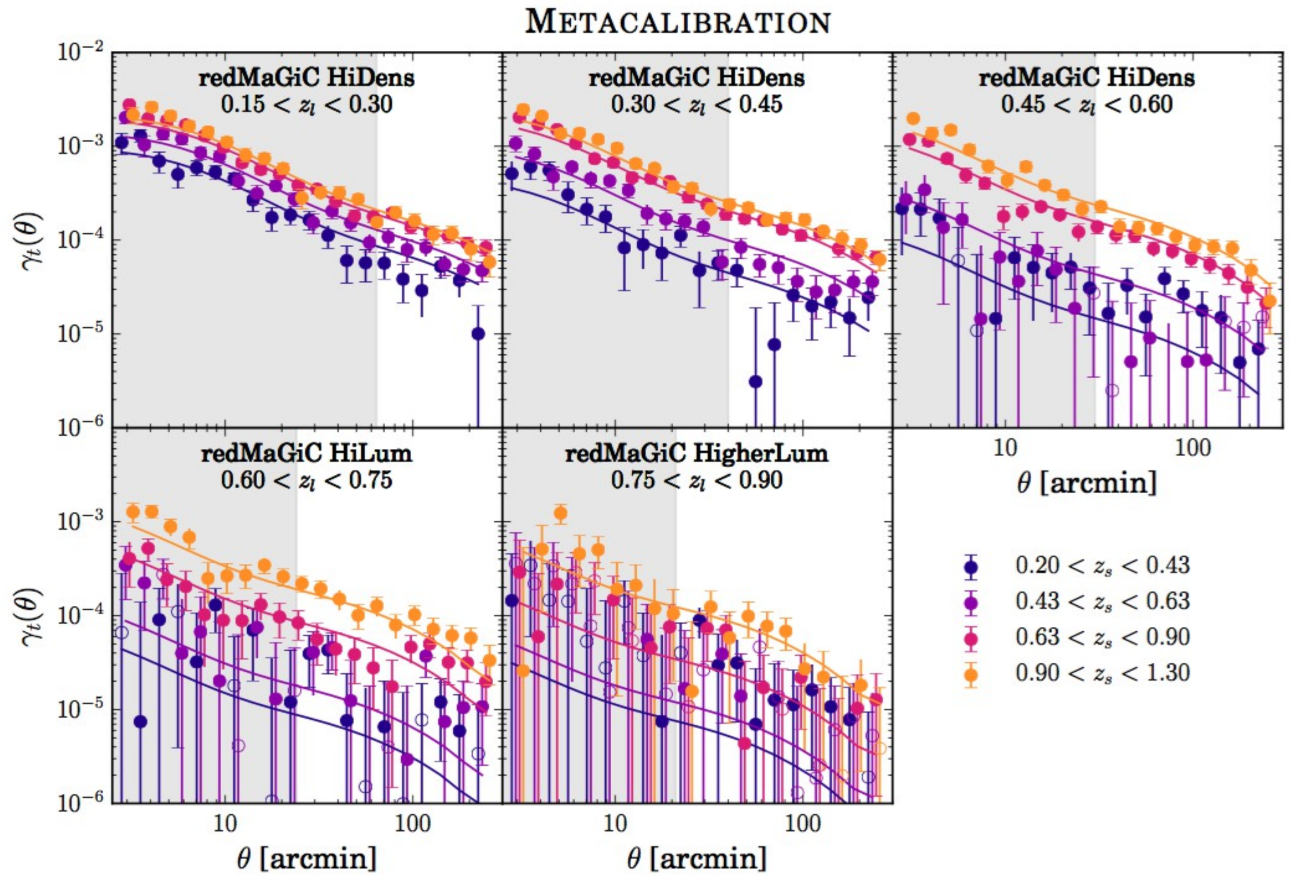


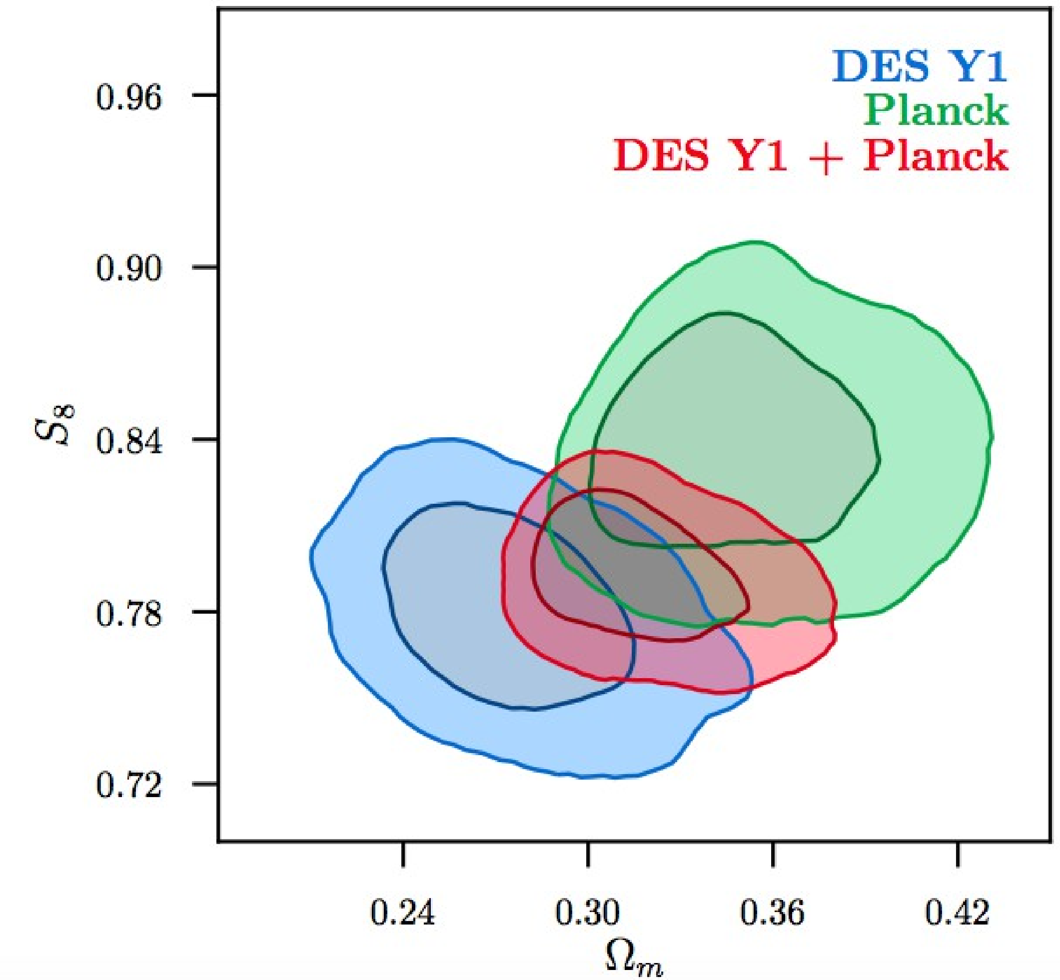




Dark Energy Survey Y1

Angular correlation function and Galaxy-galaxy shear

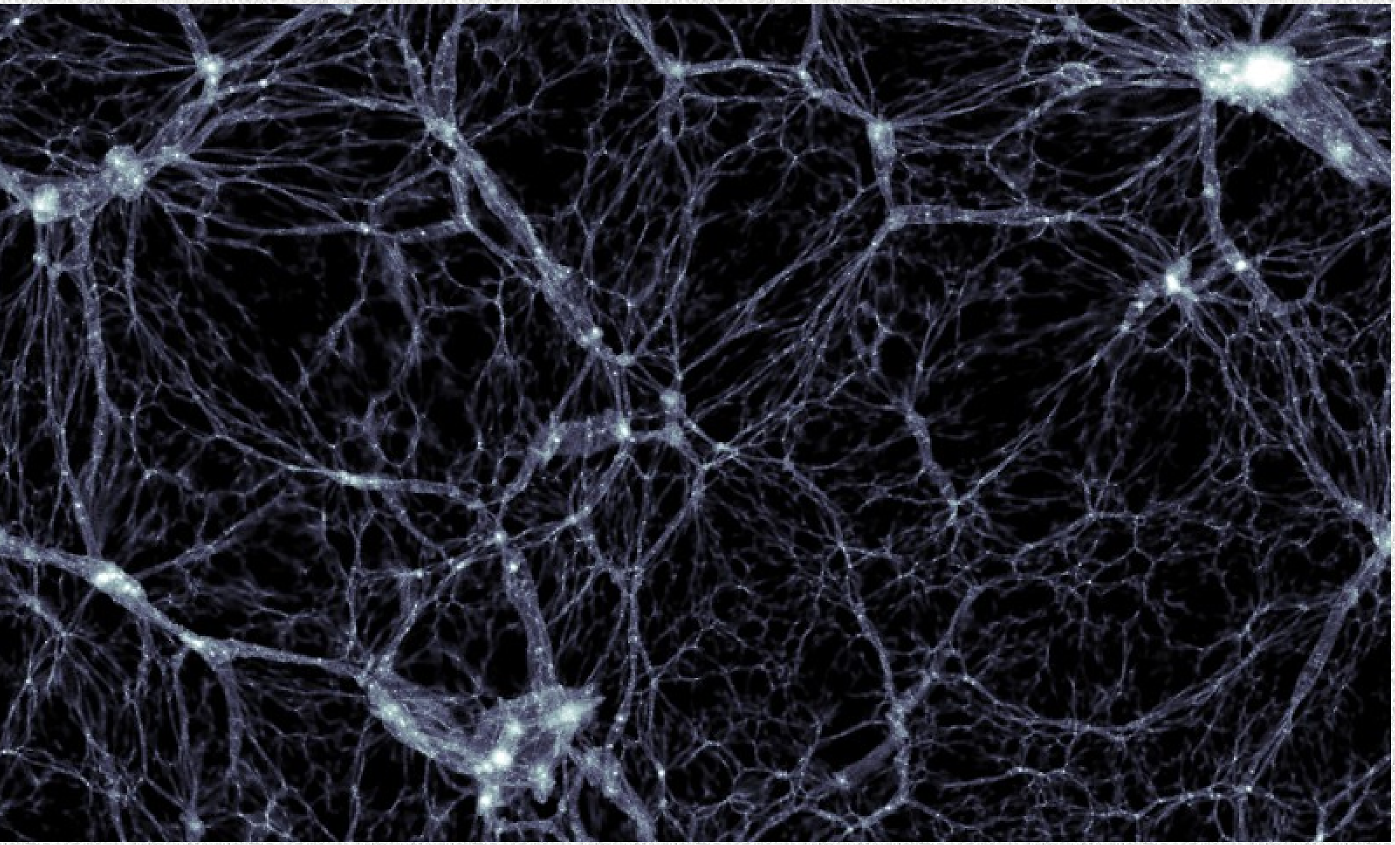




Dark Energy Survey Y1

“*Cosmic consistency*”

Other cosmological probes



Illustris simulation

Voids: empty or almost empty regions, their shapes, sizes and abundances could a priori constrain cosmological parameters (DE parameters, total matter density, etc)

It depends heavily on numerical simulations

Other cosmological probes

X-rays Optical sub-mm

Chandra Obs. / CFHT – von der Linden / Marrone

Galaxy clusters: the most massive, self gravitating entities in our universe, can be accessed in different wavelengths, and their abundance is a sensitive cosmological probe – the trick is to *weight those giants!!*

Their study also depends heavily on numerical simulations

Future of LSS studies

Dark Energy Spectroscopic Instrument

KiDS

HETDEX

Hobby-Eberly Telescope Dark Energy Experiment

Illuminating the Darkness

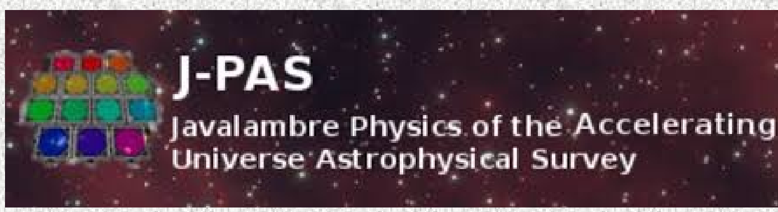
J-PAS

DARK ENERGY SURVEY

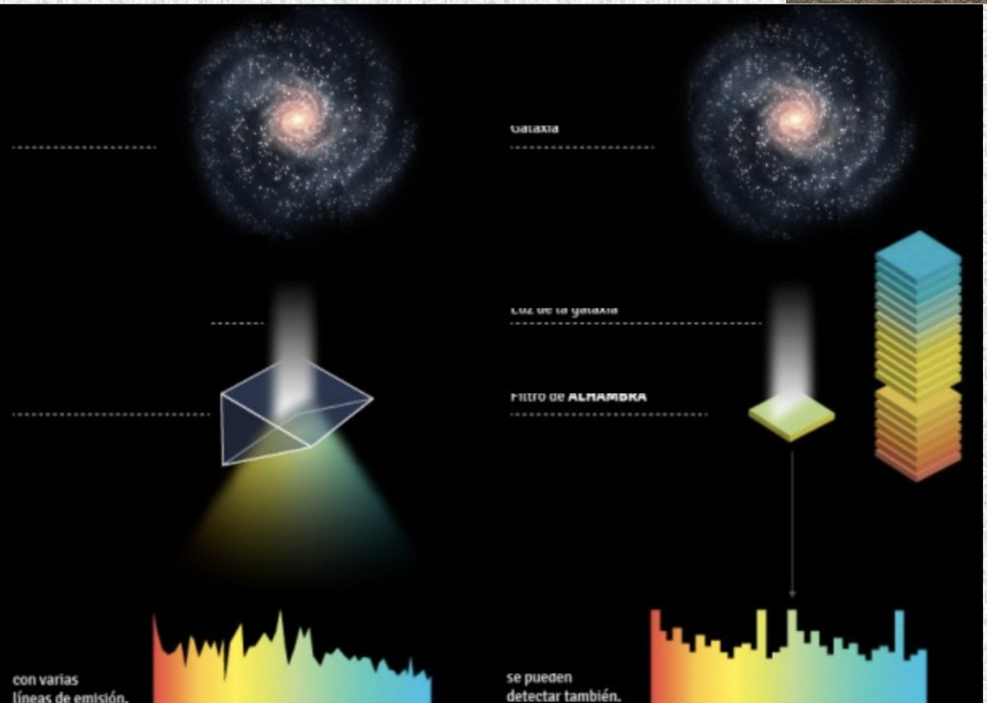
euclid

LSST

One slide on self-publicity:
The Javalambre PAU survey ...

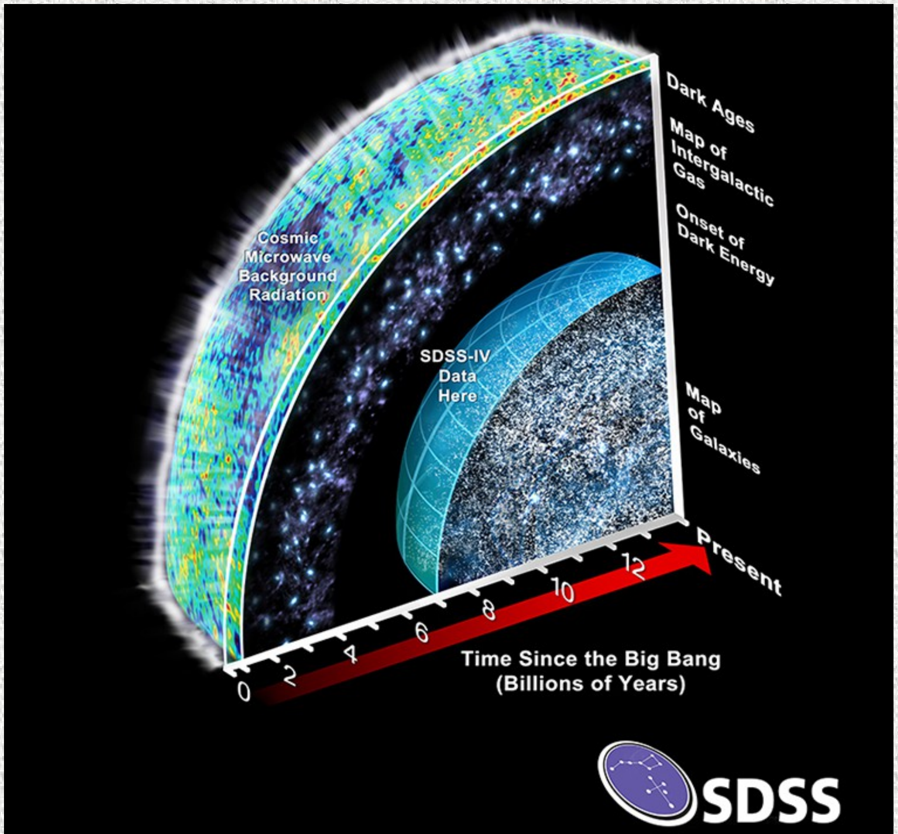


Astrophysical Observatory
of Javalambre (OAJ)

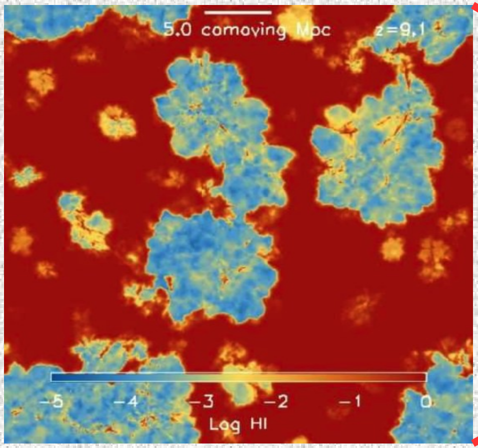


A cheap way to get a *low-resolution spectrum* in ***every*** pixel of the sky – worse redshift qualities, but **way better statistics**!

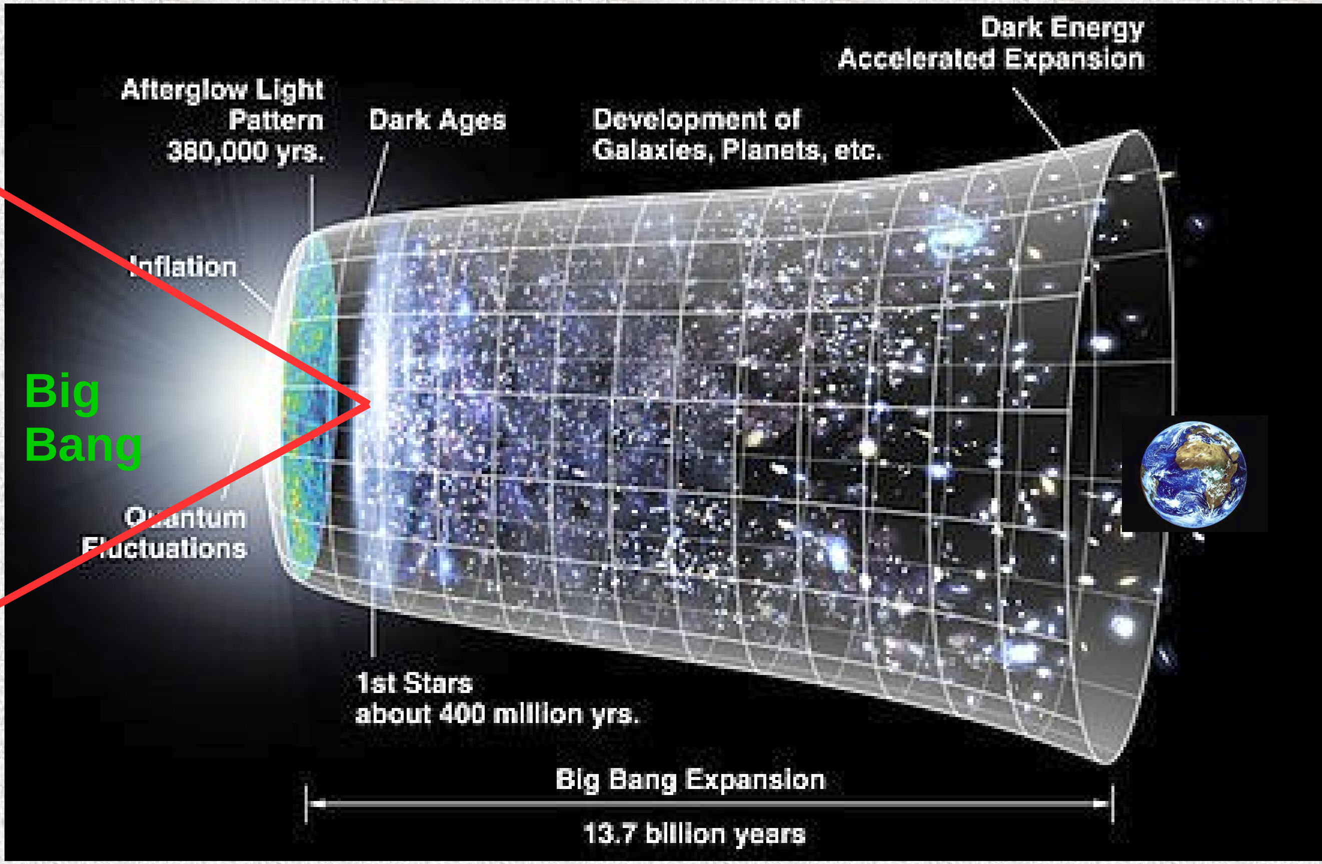
Changing gears …



Cosmological Reionization

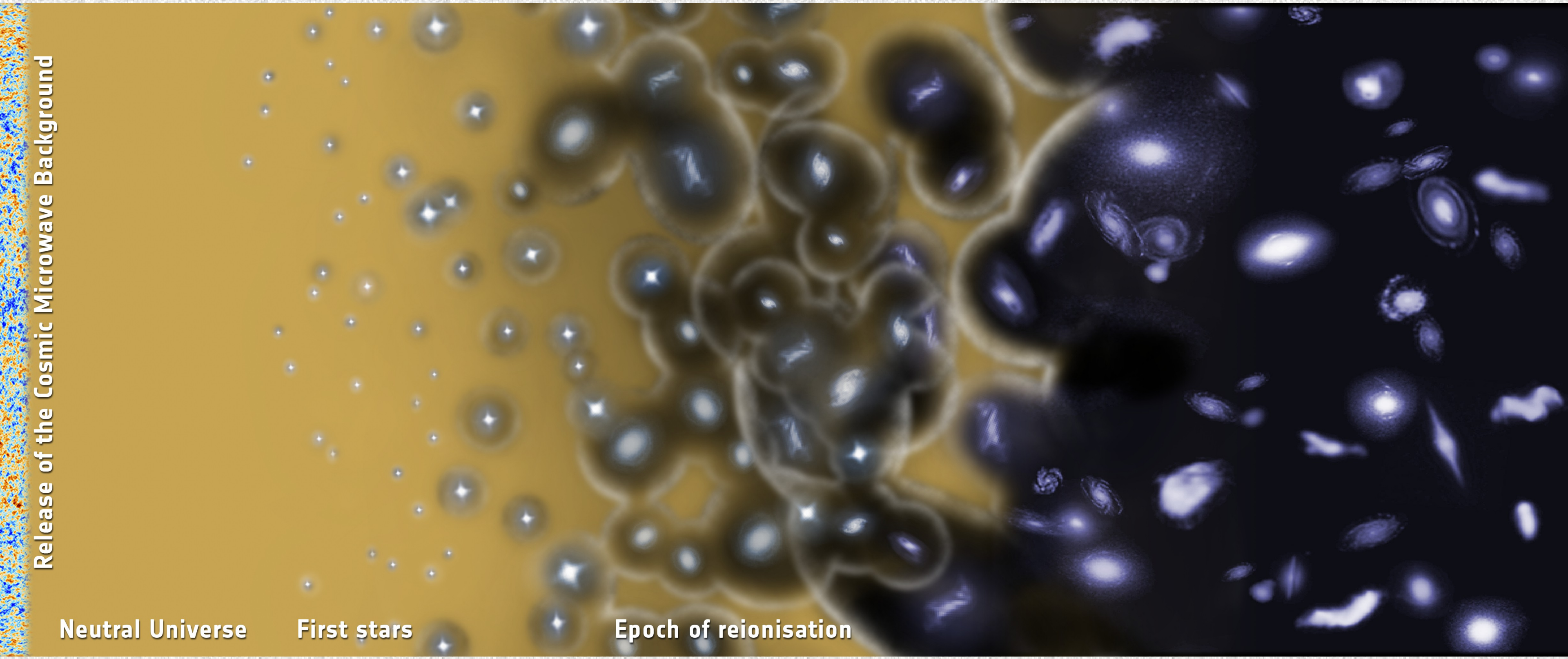


Pawlik et al 2015



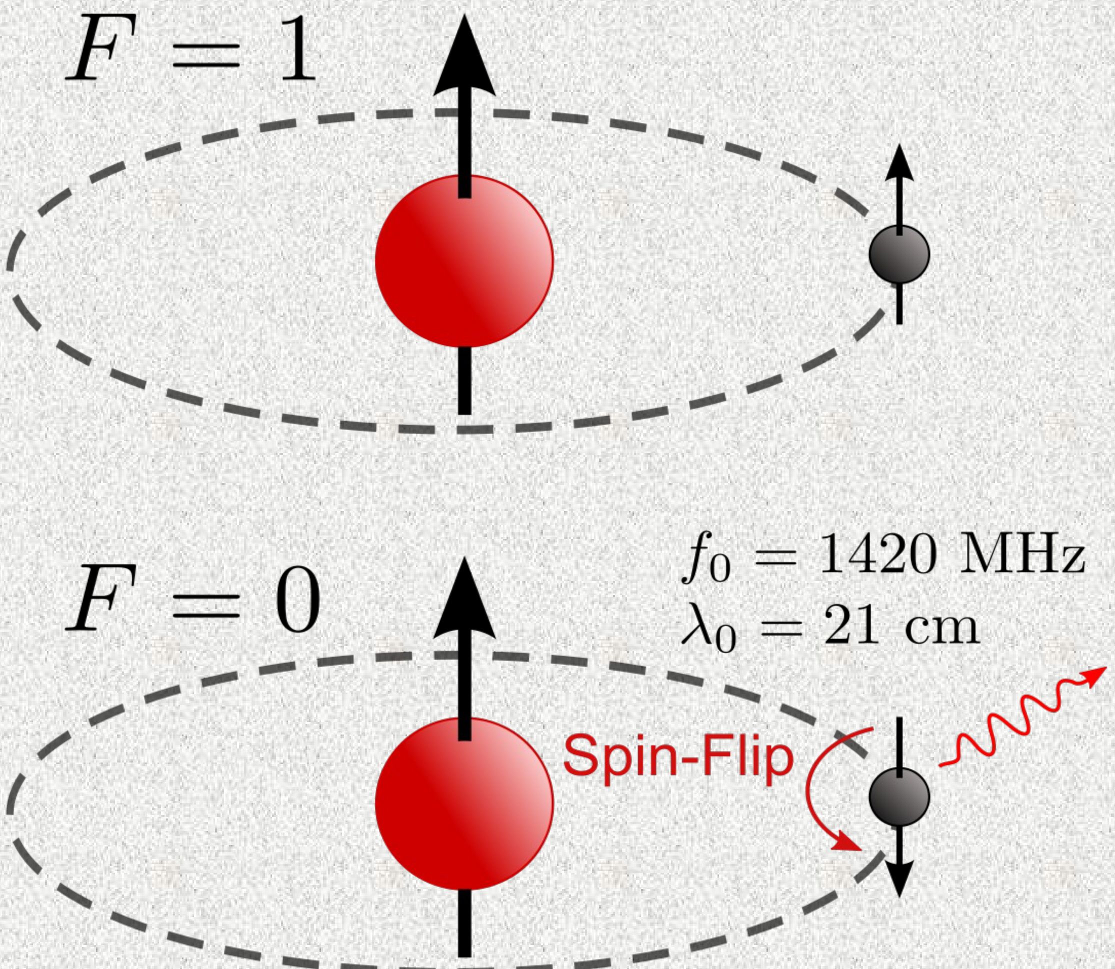
Cosmological time →

Cosmological Reionization



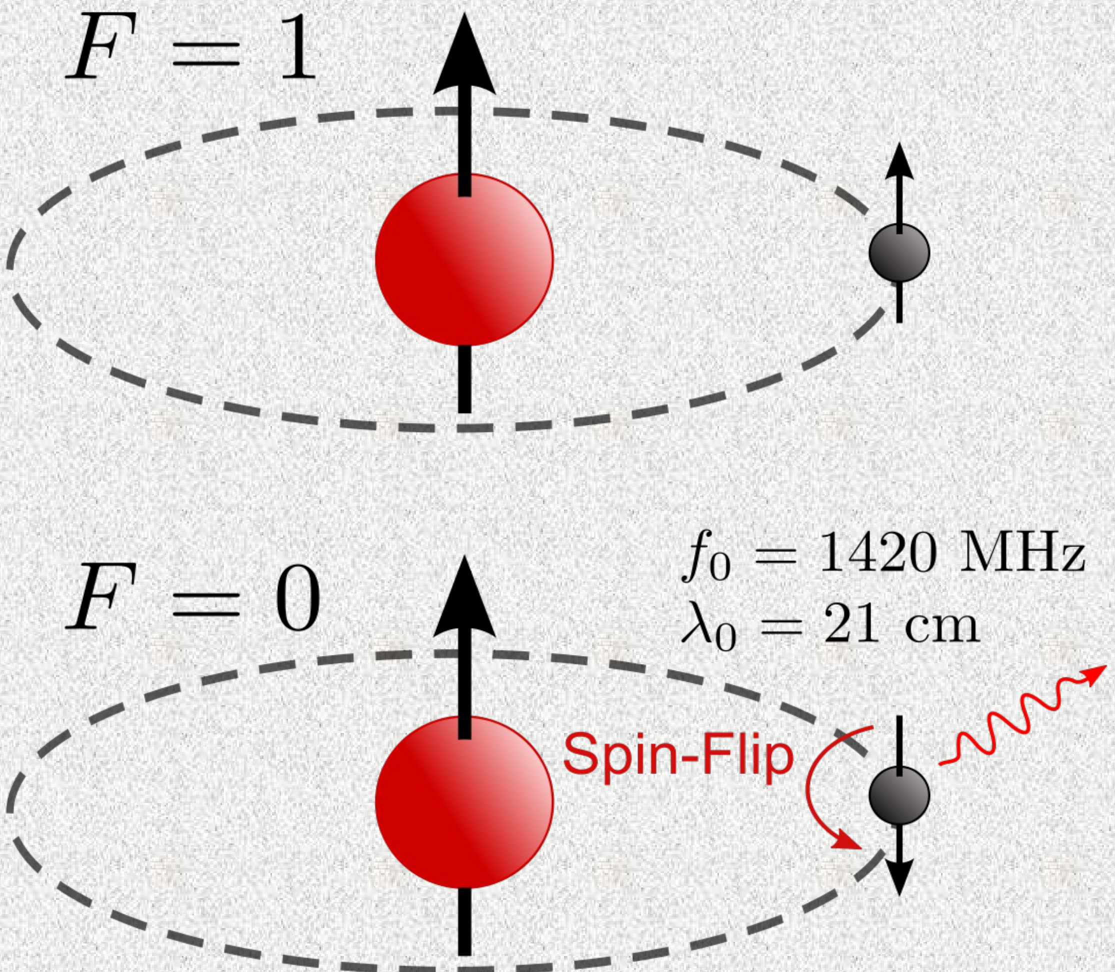
Courtesy NASA/JPL-Caltech

Cosmological Reionization



Neutral hydrogen is visible through the 21 cm hyperfine transition that **couples the electron's and the proton's spins...**

Cosmological Reionization



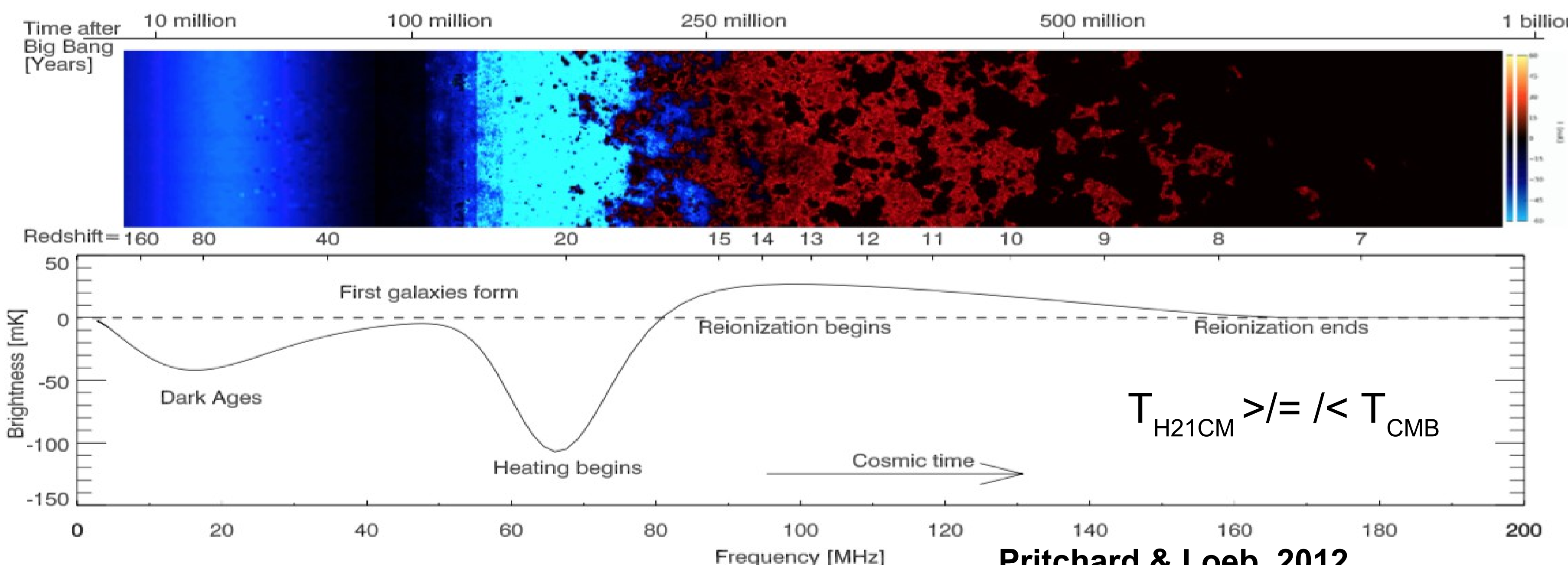
This 21 cm transition will be seen with the CMB as a background, and thus its observability will depend on

$T_{\text{spin H21CM}}$ > /=/ < T_{CMB}

For that,one has to account for the interaction of HI with electrons, protons, UV photons from the first stars and the CMB …

Cosmological Reionization

- Experiments thus target the redshifted 21 cm line (thus looking at the ~1e2 MHz radio regime)
- These experiments typically sweep the ***redshift range*** **[0.5 – 50]**
- The main limitation to overcome is the presence of contaminants at these radio-frequencies, which lie **several orders of magnitude** above the targetted signal
- The **anisotropy reionization signal** at HI 21 cm has **not** been yet isolated



T_{H21CM} >/= /< T_{CMB}

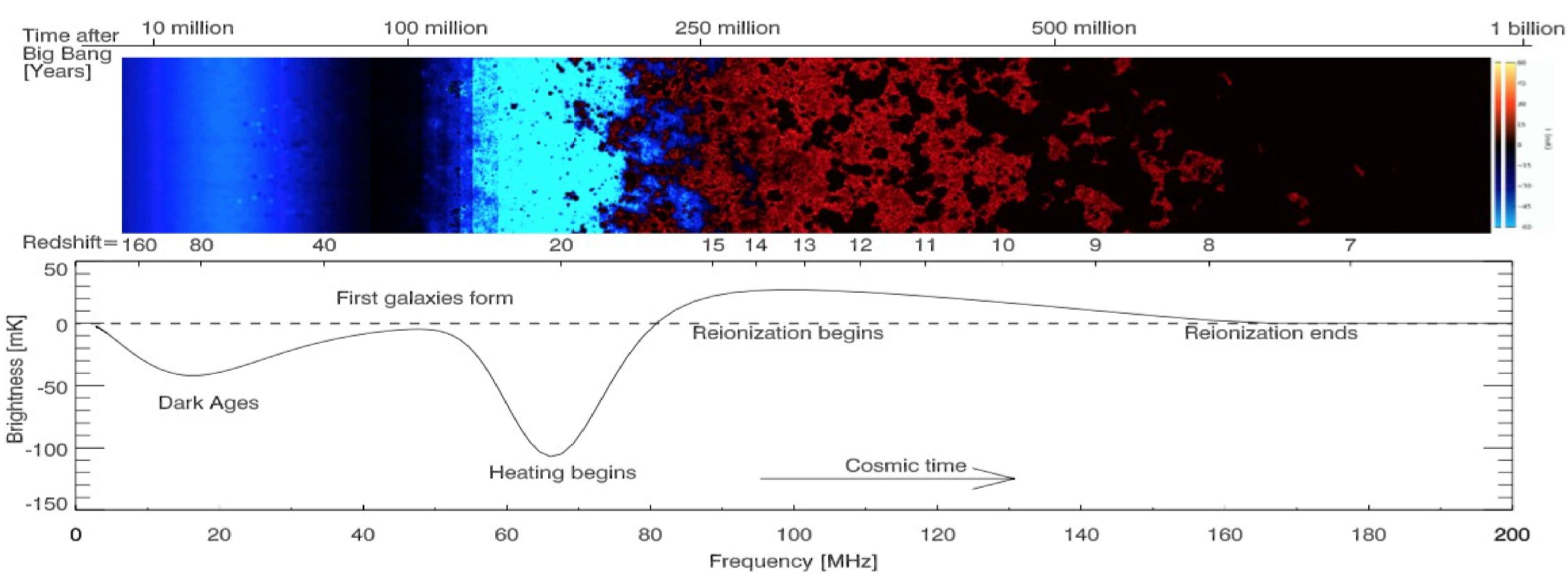
Pritchard & Loeb, 2012

El estudio de la época de reionización

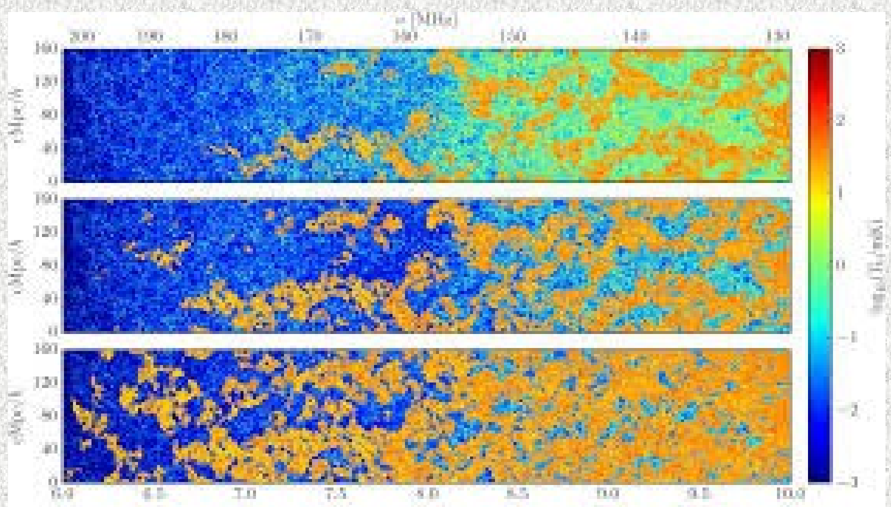
LOFAR consists on 20,000 antennas in a region of ~1,500 km diameter centred in Holland, it has been operating since 2012, in a frequency range from 10 MHz up to 240 MHz – as of a year ago, they were limited by the Earth's ionosphere ...

MWA is placed in an isolated region of Australia, and mounts 128 antenna clusters, extending 3 km apart, and operating from 80 up to 300 MHz. Its construction finished in 2012.

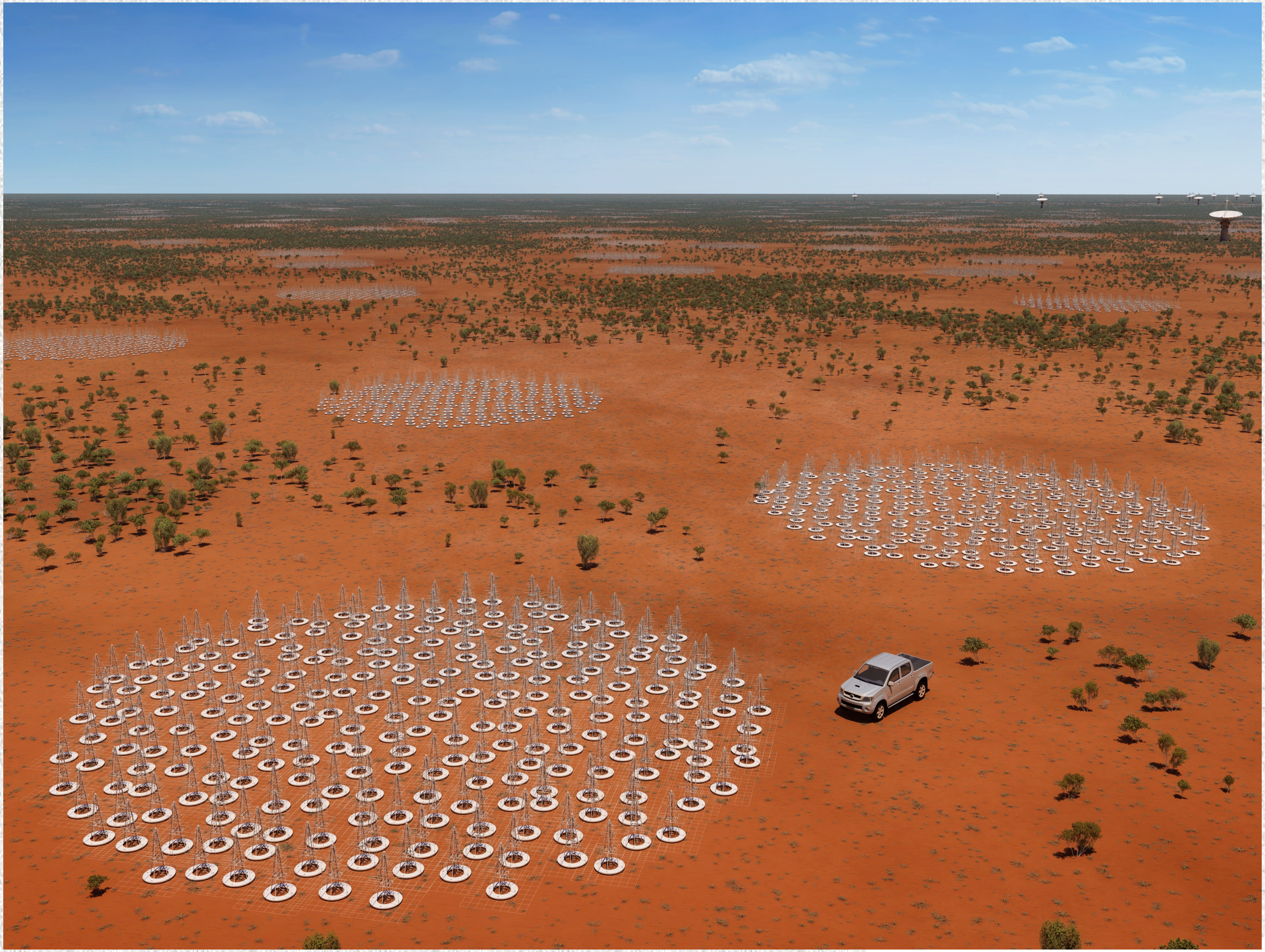
SKA will extend in South-Africa and Australia, with an effective collective area of **one squared km**. Its construction has been divided in 3 phases, ranging from 2018 up to 2023, with phase 1 ending in 2023.



Average antenna temperature



Spatial fluctuations of antenna temperature



SKA
SQUARE KILOMETRE ARRAY

The EDGES experiment has provided measurements of average antenna temperature of the HI 21 cm absorption feature at ***z~17***, whose amplitude is significantly **higher** (~x 3 – 4) than expected, raising some controversy in the community ...