Lecture plan

Part 1: Deep large scale galaxy surveys

Part 2: The Universe on large scales

- Large scale structures observations
- Measuring clustering: the correlation function (and power spectrum)

Part 3: Baryon Acoustic Oscillations and Redshift space distortions

Part 4: The Euclid Surveys and galaxy clustering

Part 3

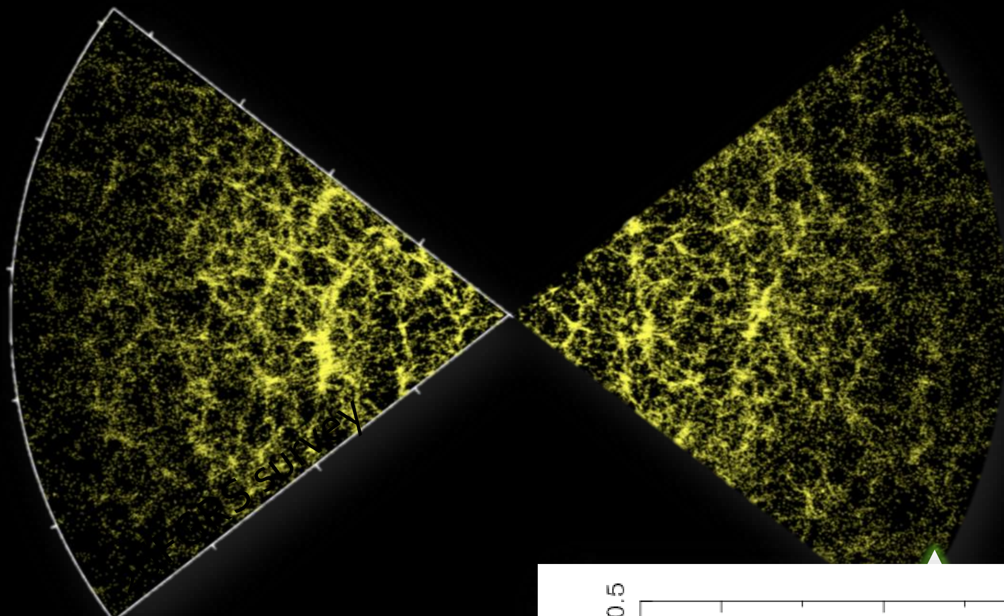
CLUSTERING: BARYON ACCOUSTIC OSCILLATIONS AND REDSHIFT SPACE DISTORTIONS

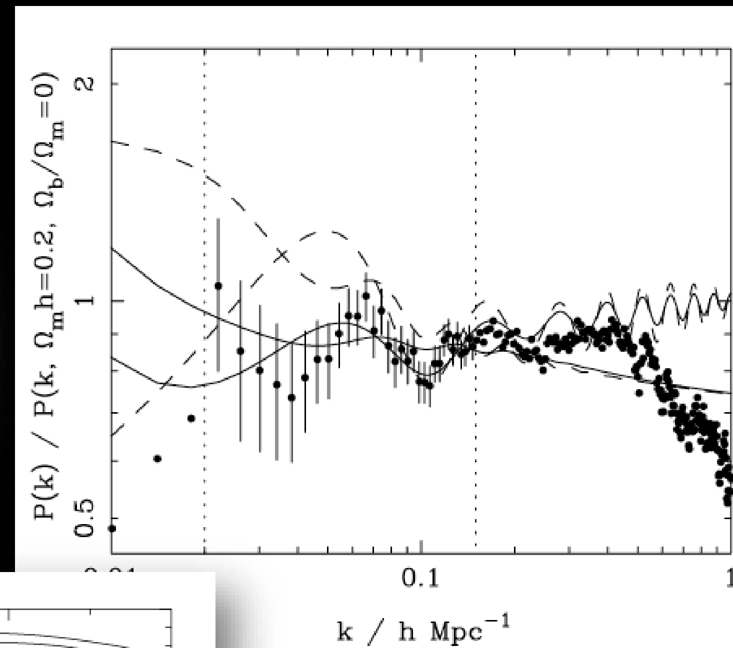
Olivier Le Fèvre – Cosmology Summer School 2016
With contribution from Sylvain de la Torre (Les Houches Cosmology School march 2016)

Outline

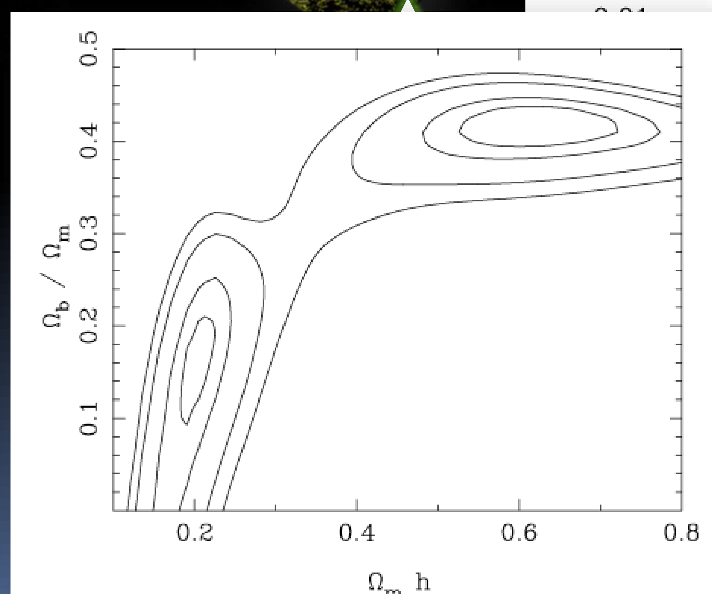
1. Cosmology from LSS
2. Baryon Accoustic Oscillations measurements
3. Redshift space distortions measurements
4. Constraints on cosmology from clustering

Cosmology from LSS





Galaxy power spectrum

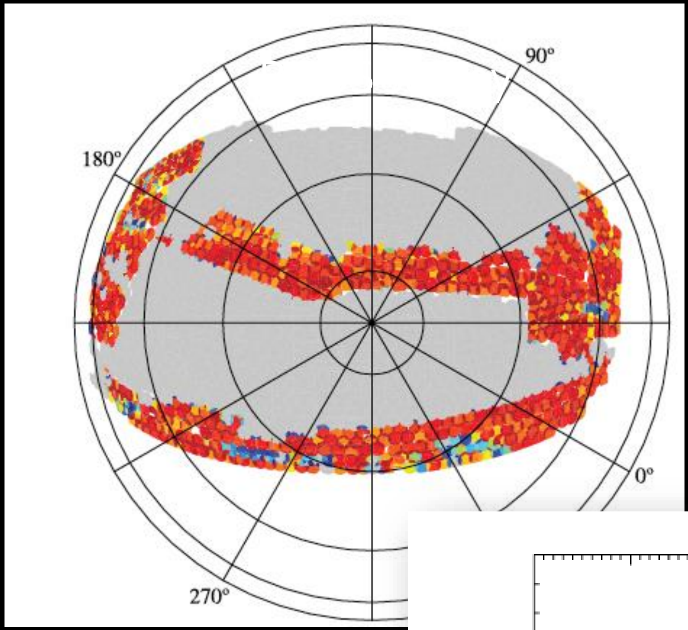


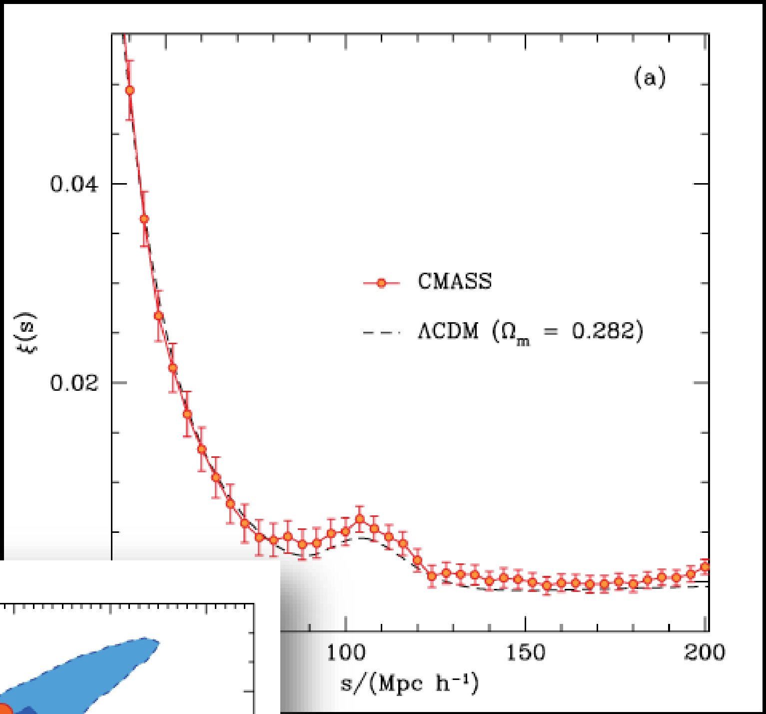
2dFGRS, Percival et al. 2001
SDSS, Tegmark et al. 2002

- Constraints from galaxy power spectrum full shape (linear scales)

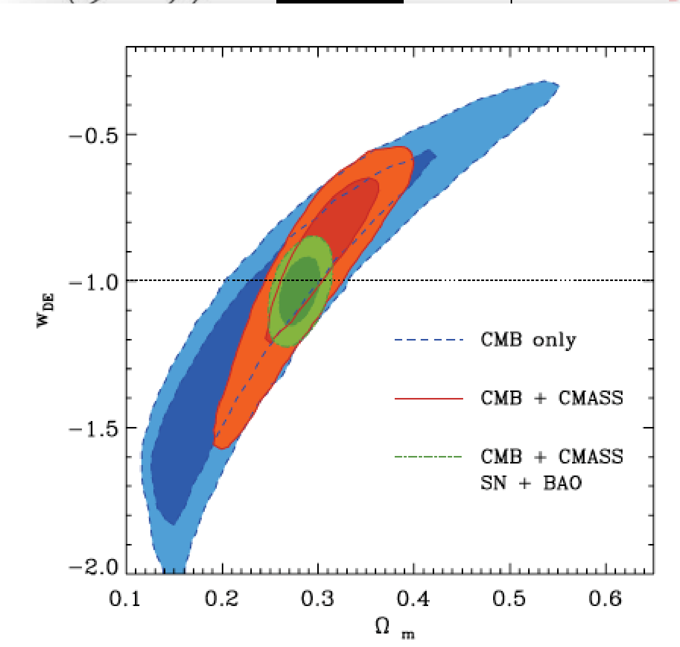
→ Sensitive to:
h, $\Omega_m h^2$, $\Omega_b h^2$, n_s, $(b\sigma_8)$

Cosmology from LSS





Galaxy correlation function

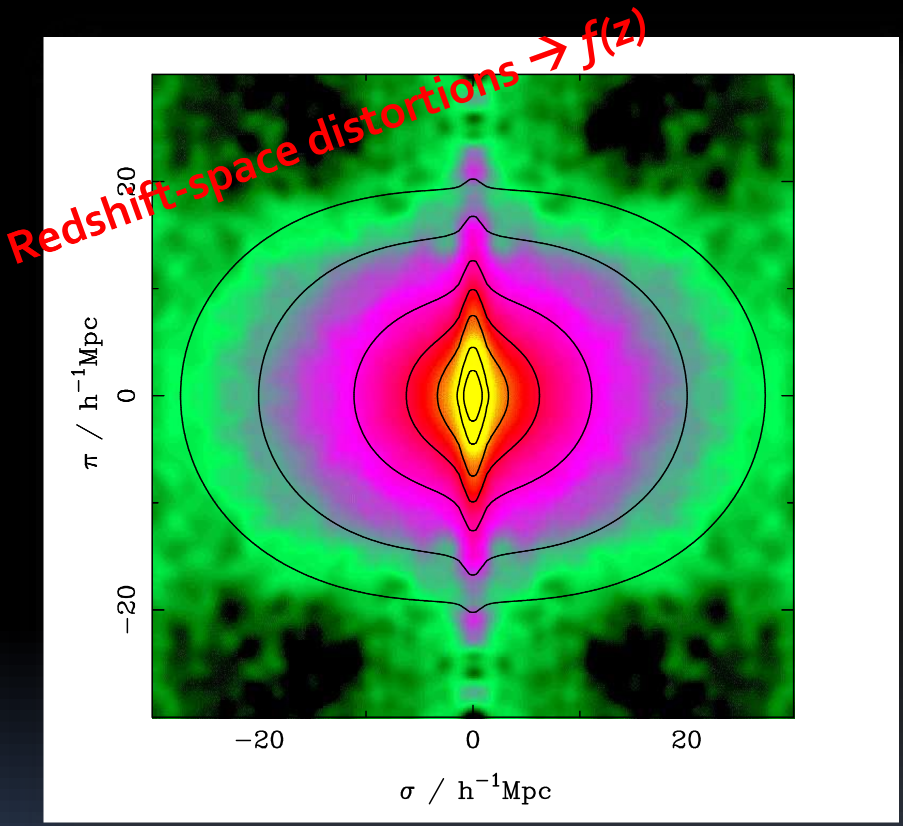


BOSS, Sanchez et al. 2012

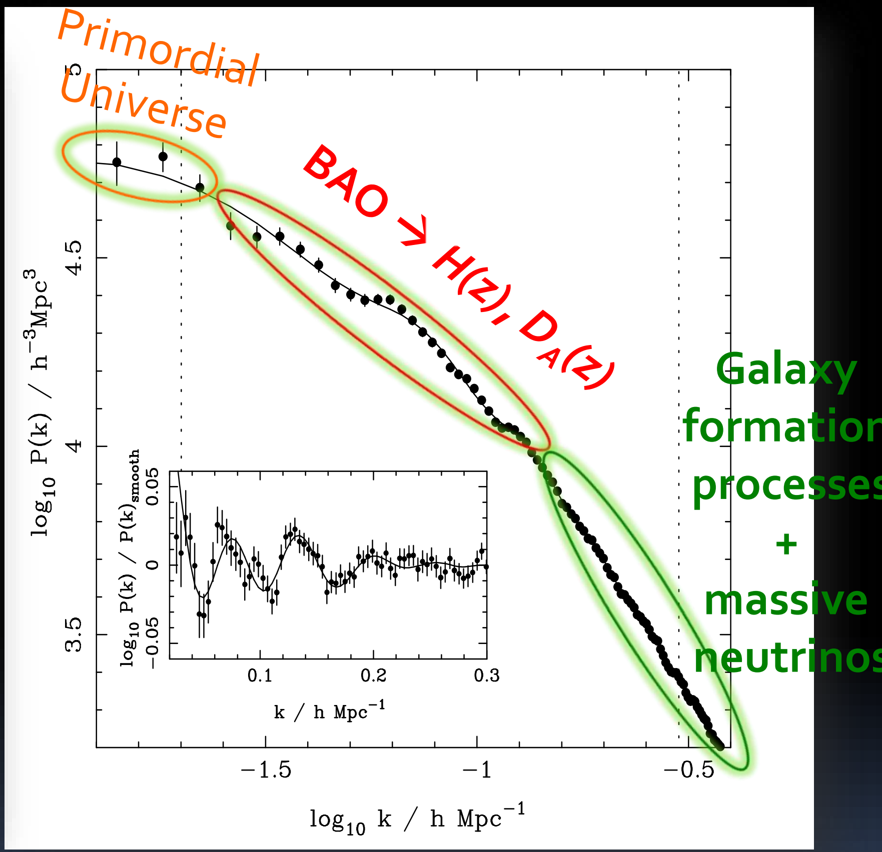
- Constraints from galaxy correlation function full shape

→ Sensitive to:
h, $\Omega_m h^2$, $\Omega_b h^2$, n_s, $(b\sigma_8)$

Cosmology from LSS



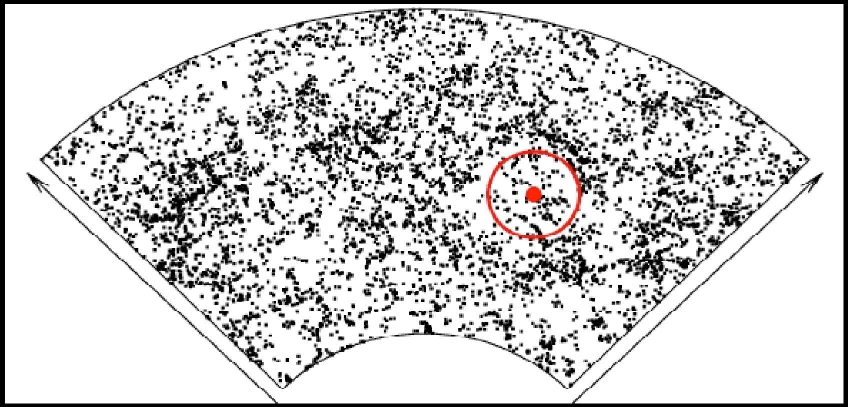
Galaxy anisotropic correlation function



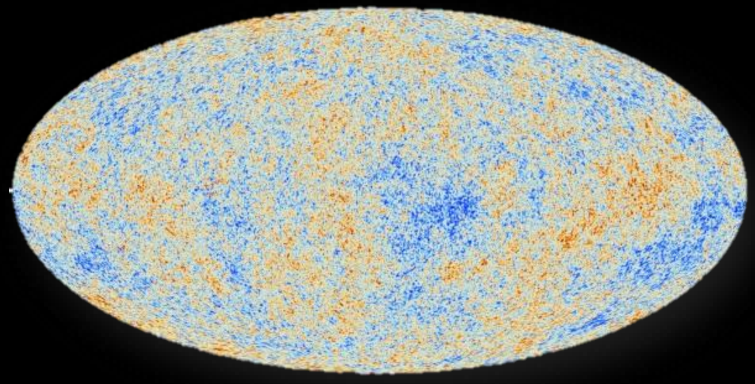
Galaxy Power spectrum

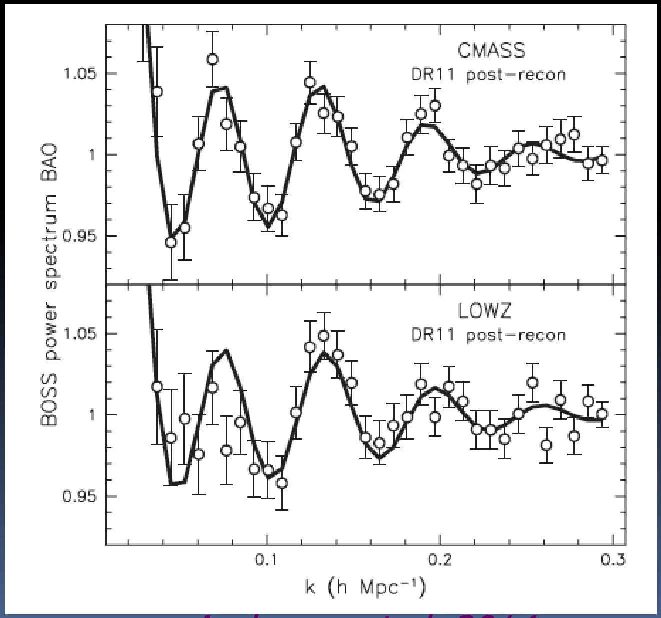
Baryon Acoustic Oscillations

Galaxies

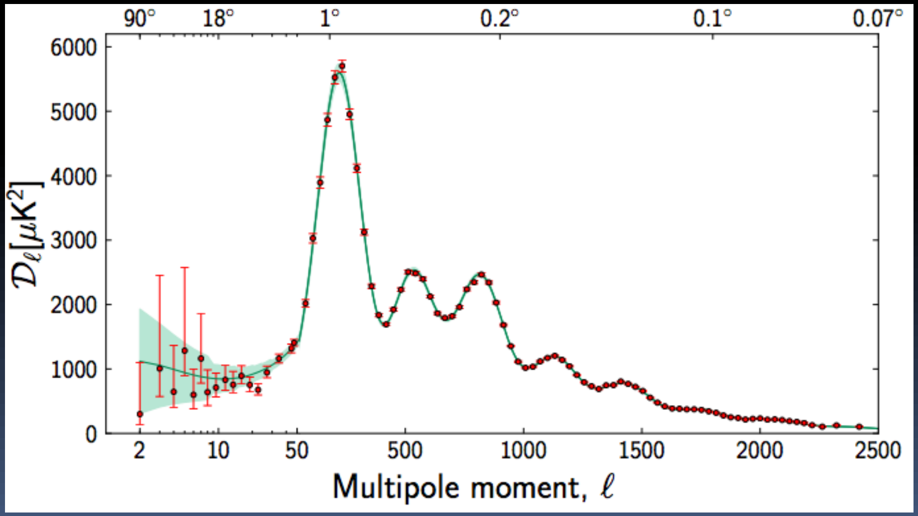


CMB





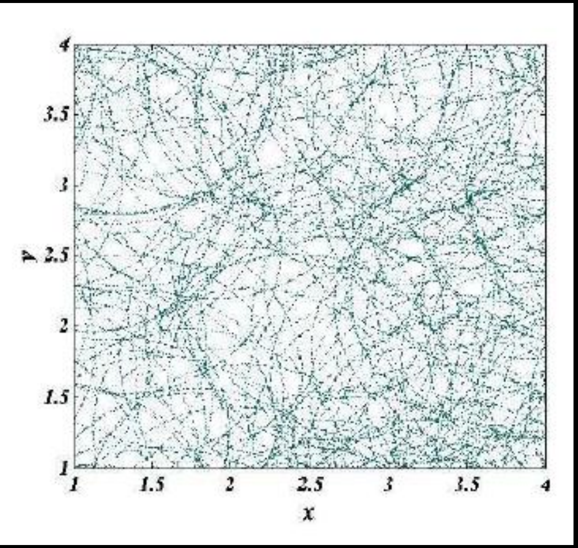
Anderson et al. 2014



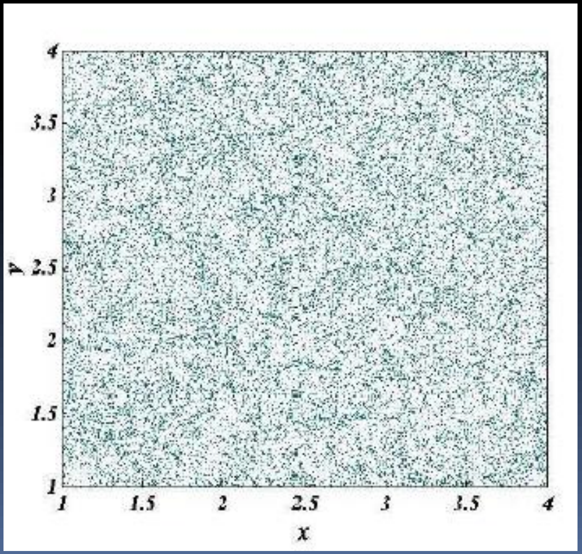
Planck Collaboration 2015

Clustering: Baryon Accoustic Oscillations

- Original hot, dense plasma of electrons and baryons
  - Short distances for photons as they interact via Thomson scattering
  - Oscillations from gravity and heat pressure of photon-matter interactions
- Recombination (z~1000): matter became neutral, photons propagate freely
  - Decoupling: pressure oscillations leave an imprint in the baryon distribution
- A standard ruler
  - Search for statistical imprint on galaxy distribution
- Compare to SNe: standard candel



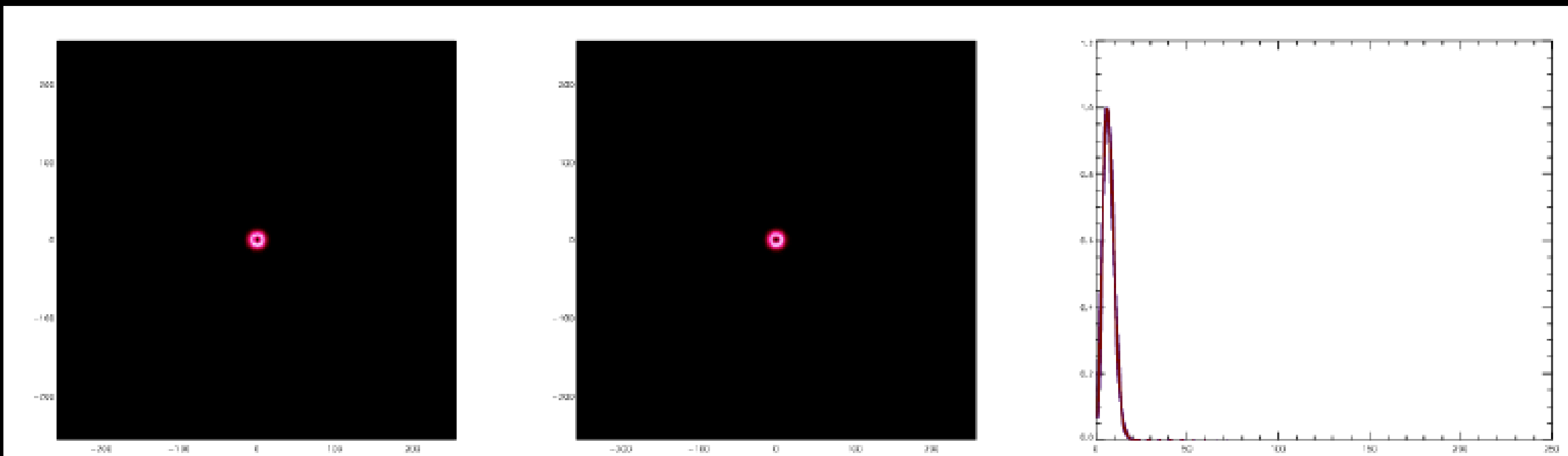
Idealized



Statistical

Baryon Acoustic Oscillations

Baryons | Photons | Mass profile

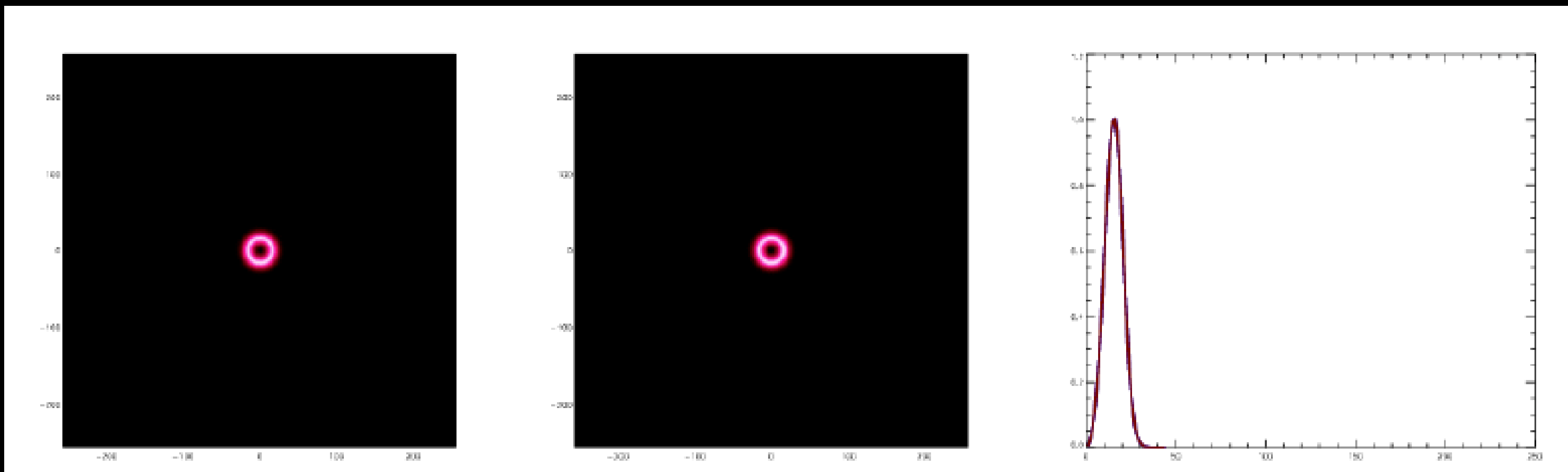


A single perturbation in an uniform plasma. Uniform except for an excess of matter at the origin.

Eisenstein, Seo, White 2006

Baryon Acoustic Oscillations

Baryons | Photons | Mass profile

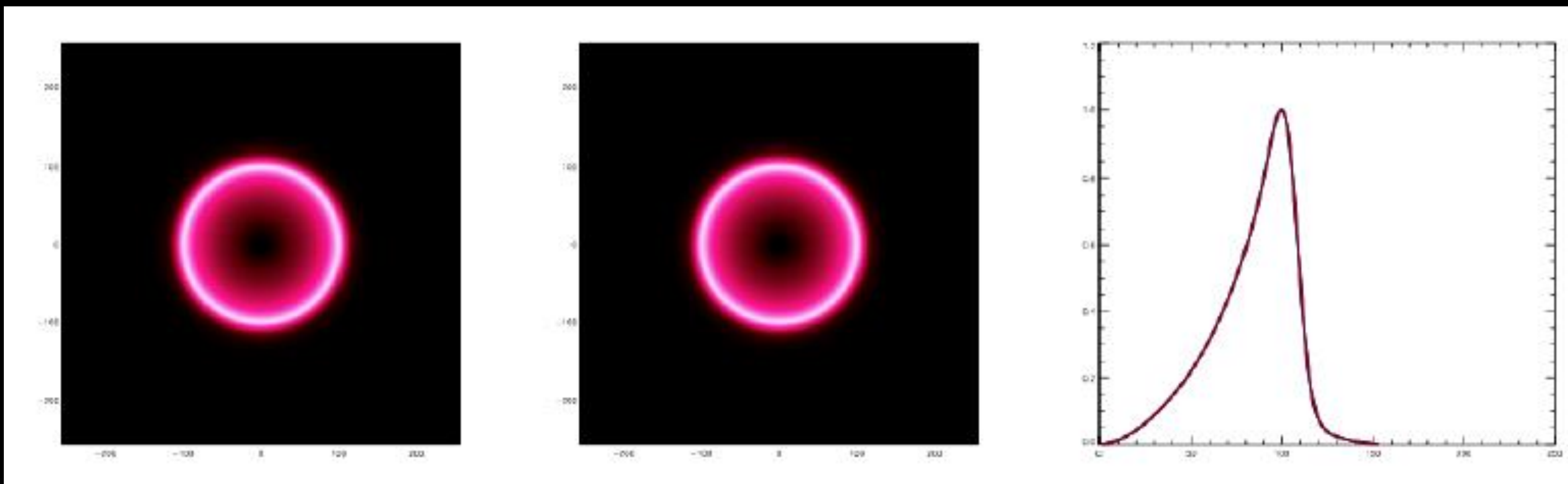


High pressure drives baryon-photon plasma outward at high speed. Baryons and photons move together.

Eisenstein, Seo, White 2006

Baryon Acoustic Oscillations

Baryons Photons Mass profile

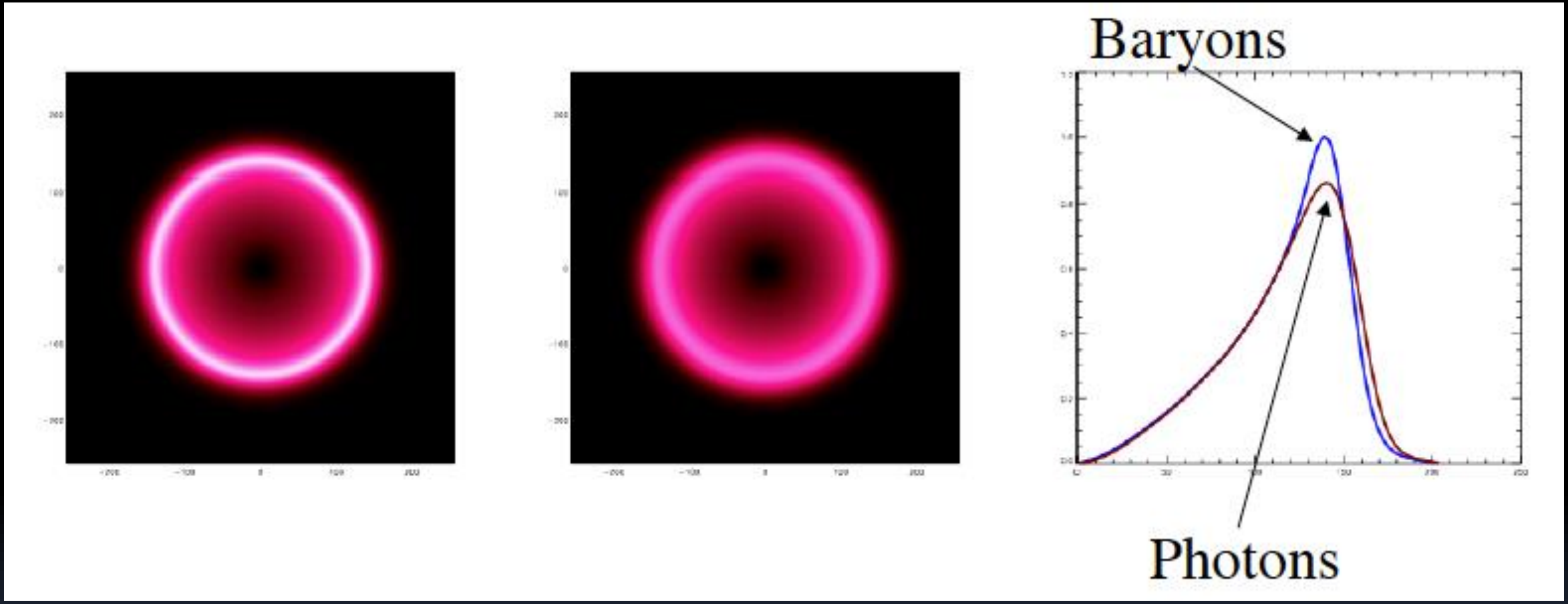


Expansion continues for about 10^5 years

Eisenstein, Seo, White 2006

Baryon Acoustic Oscillations

Baryons | Photons | Mass profile

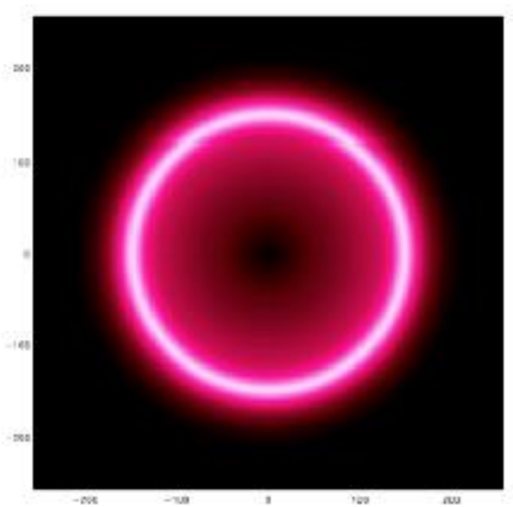


After 10^5 years, the Universe has cooled enough so that photons stop ionizing atoms. Photons decouple from baryons. The former quickly streams away.

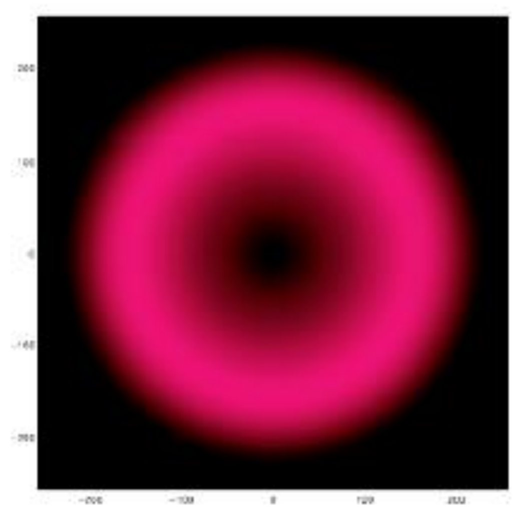
Eisenstein, Seo, White 2006

Baryon Acoustic Oscillations

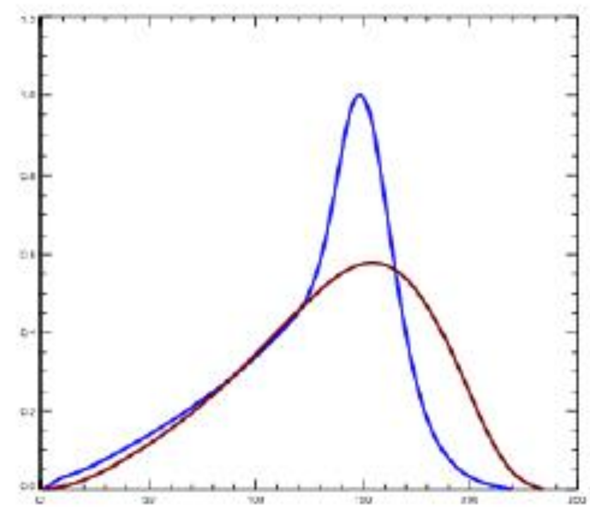
Baryons



Photons



Mass profile

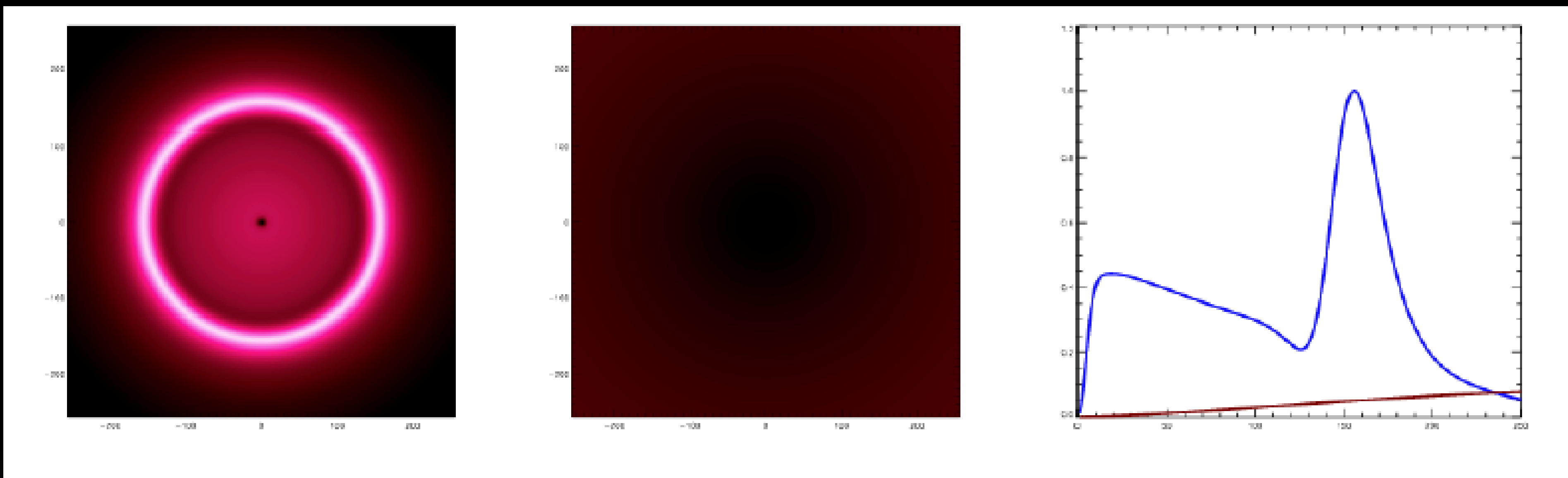


Baryons having lost their motive pressure remain in place, the baryon peak is stalled.

Eisenstein, Seo, White 2006

Baryon Acoustic Oscillations

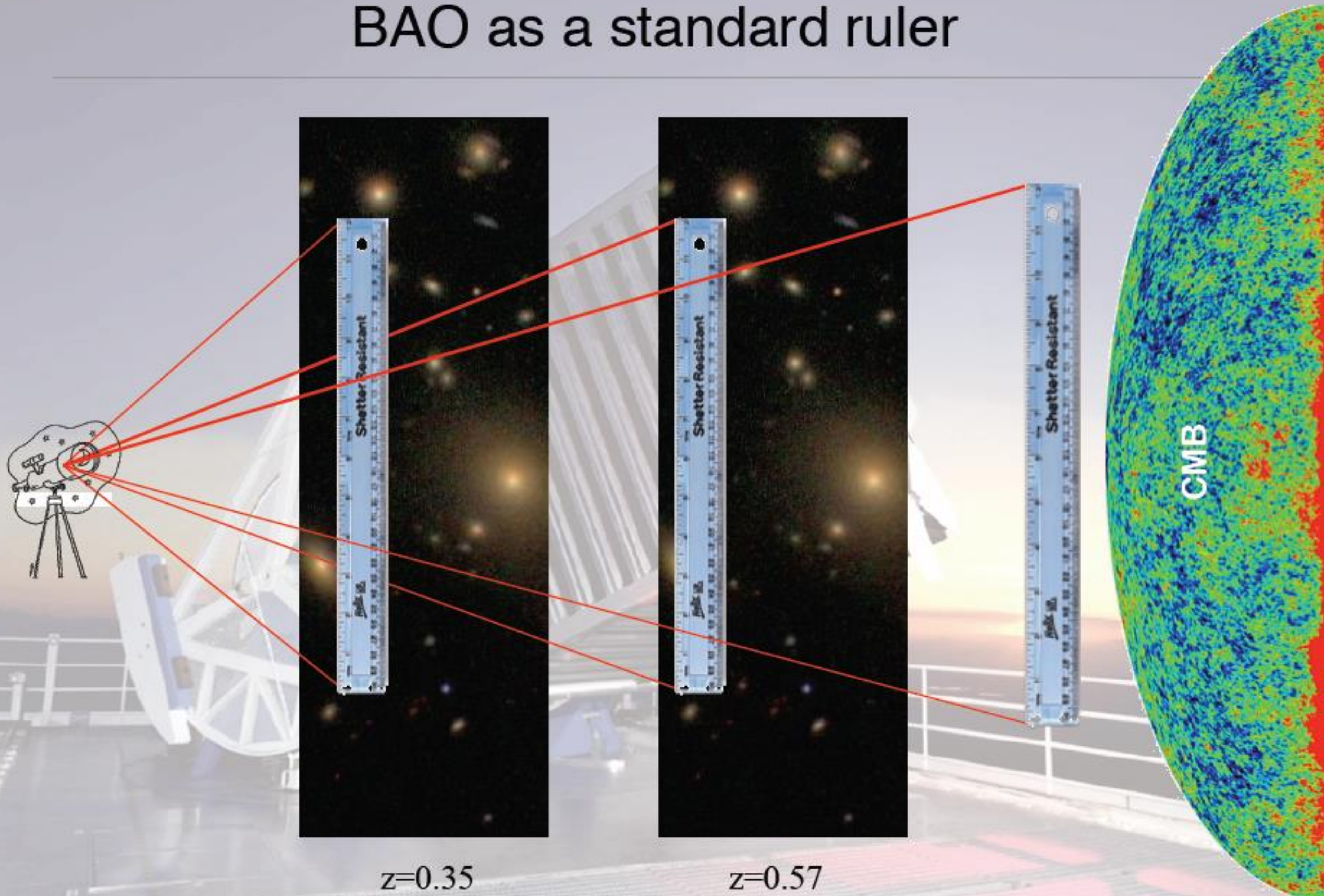
Baryons Photons Mass profile



Photons have become uniform, but baryons stay overdense in a shell of 150 Mpc in radius.

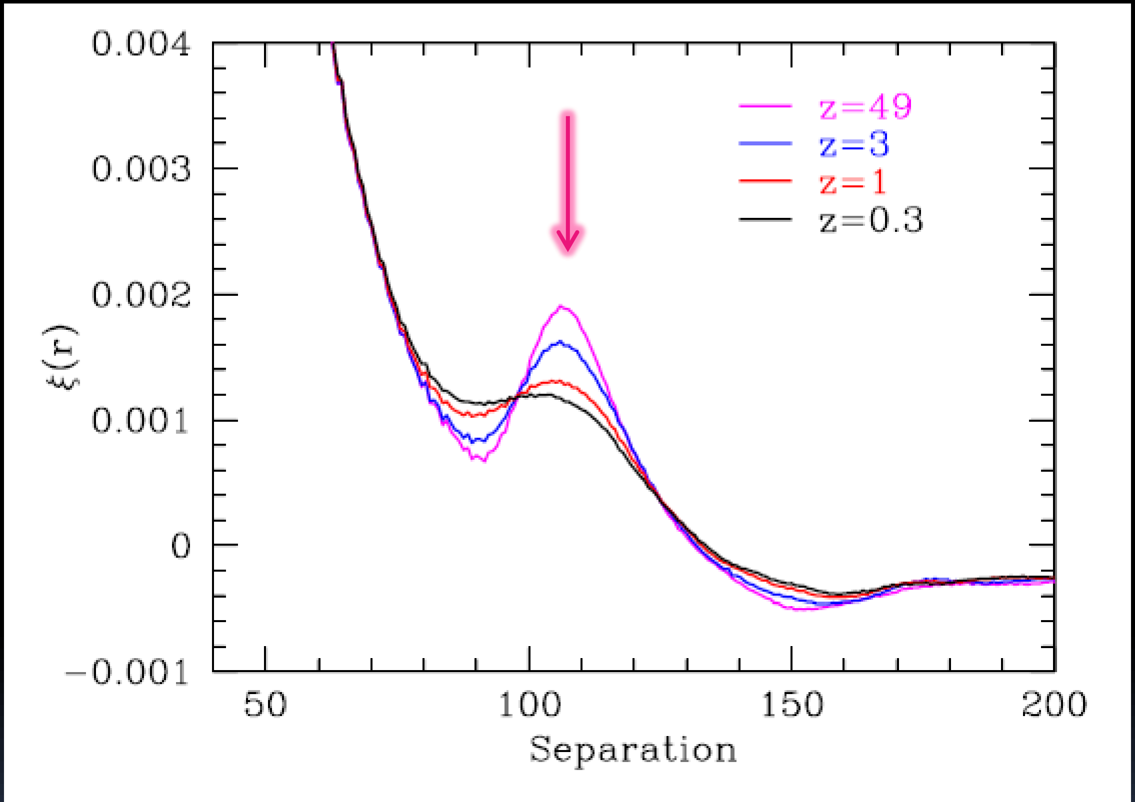
Further non-linear processes related to galaxy formation act to broaden and shift the peak on scales of 10-20 Mpc/h.

BAO as a standard ruler

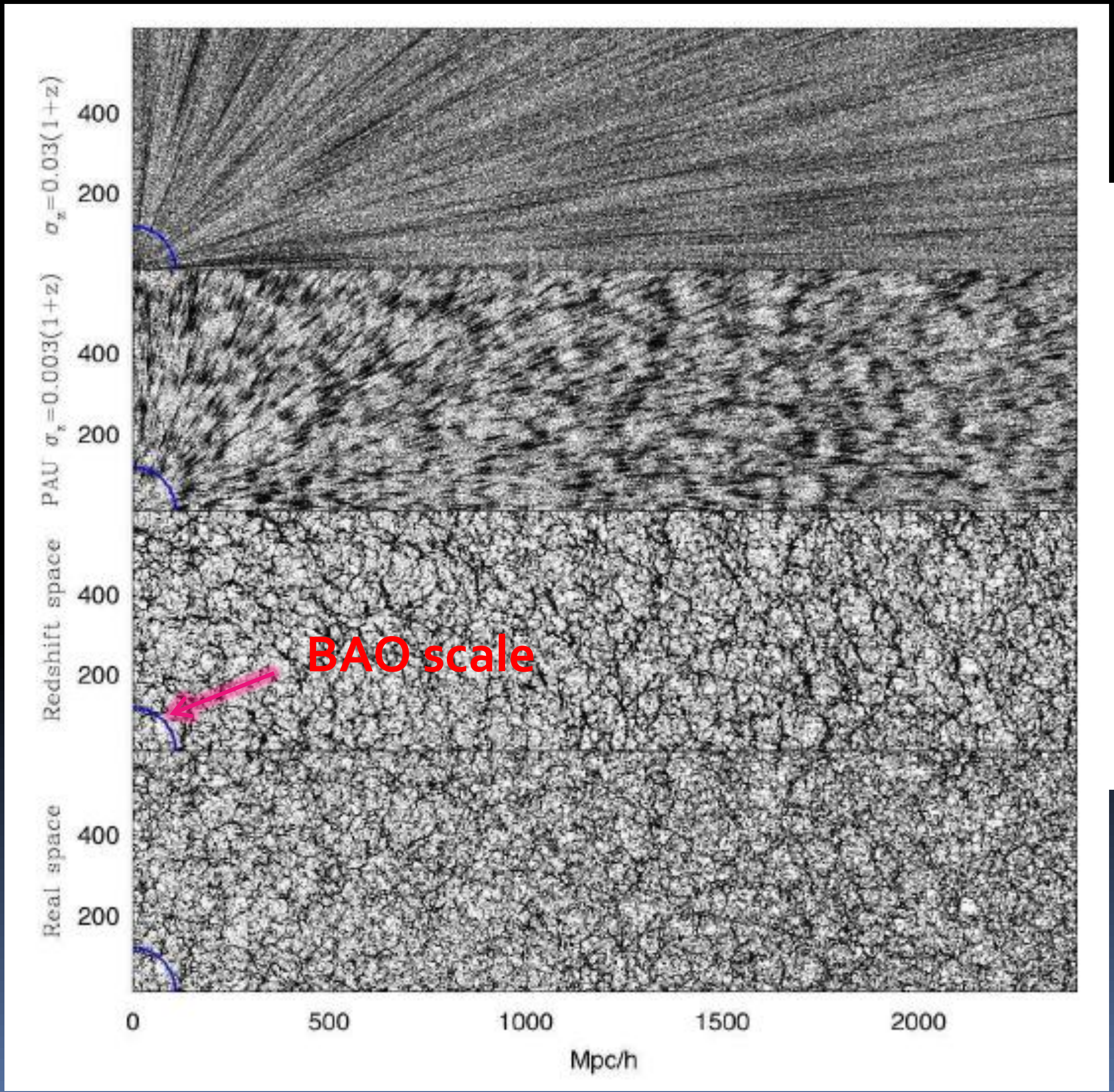


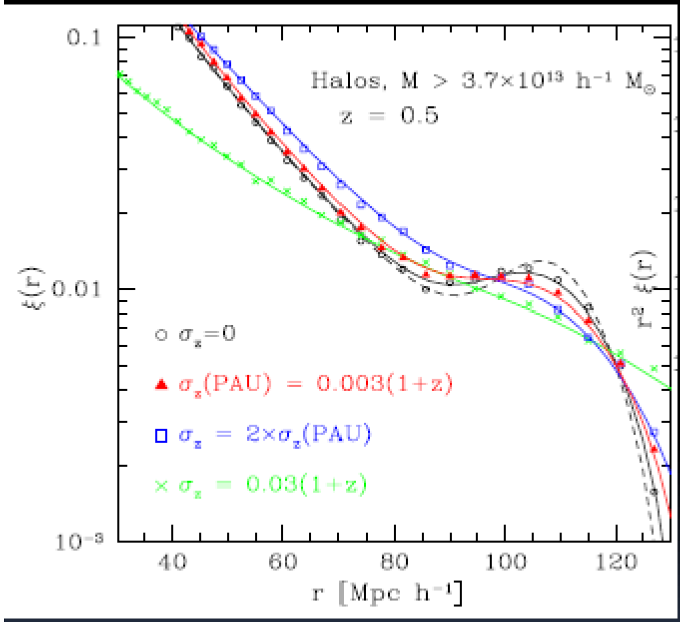
CREDIT: WMAP & SDSS websites

What is expected ?

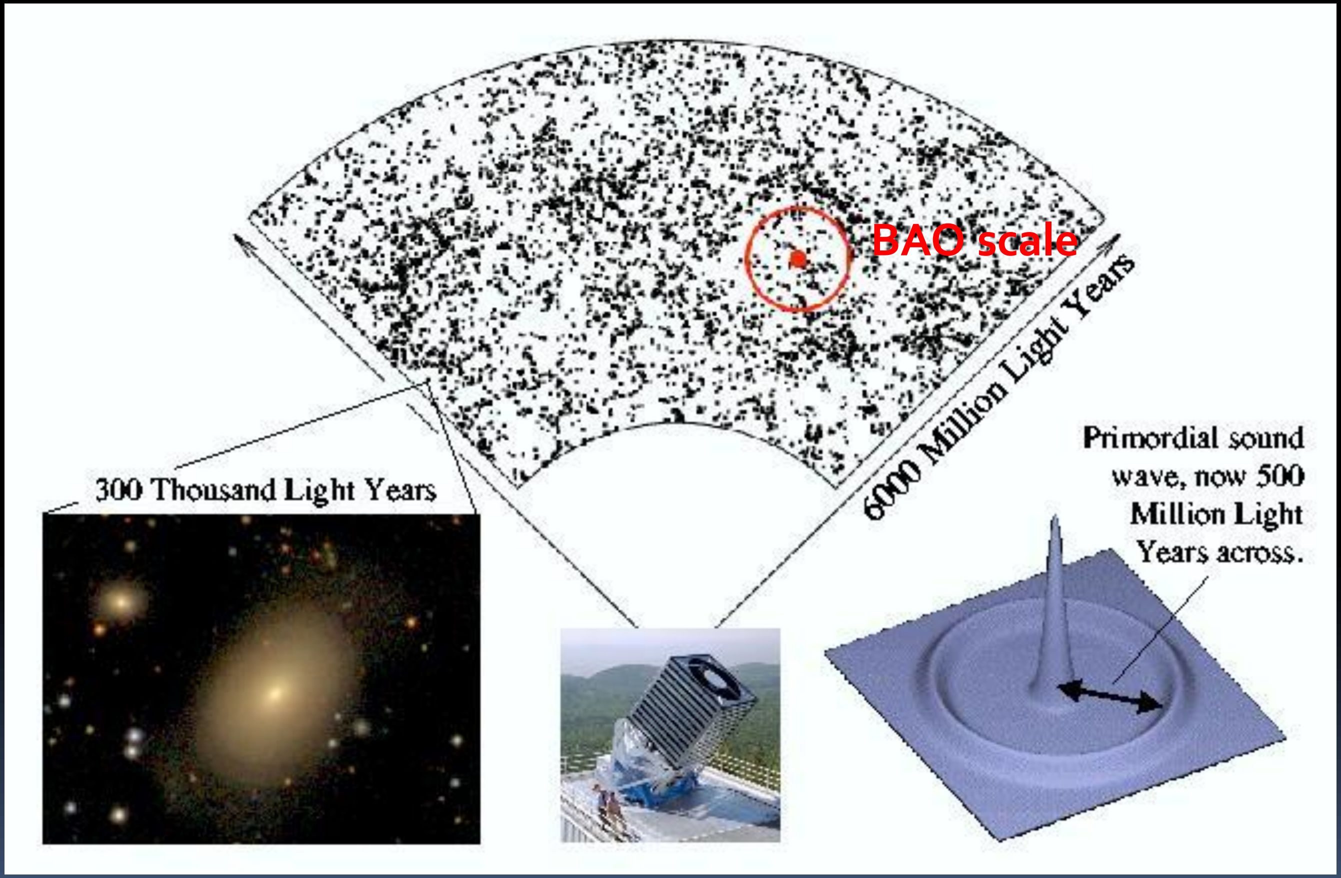


BAO measurements need spectral resolution





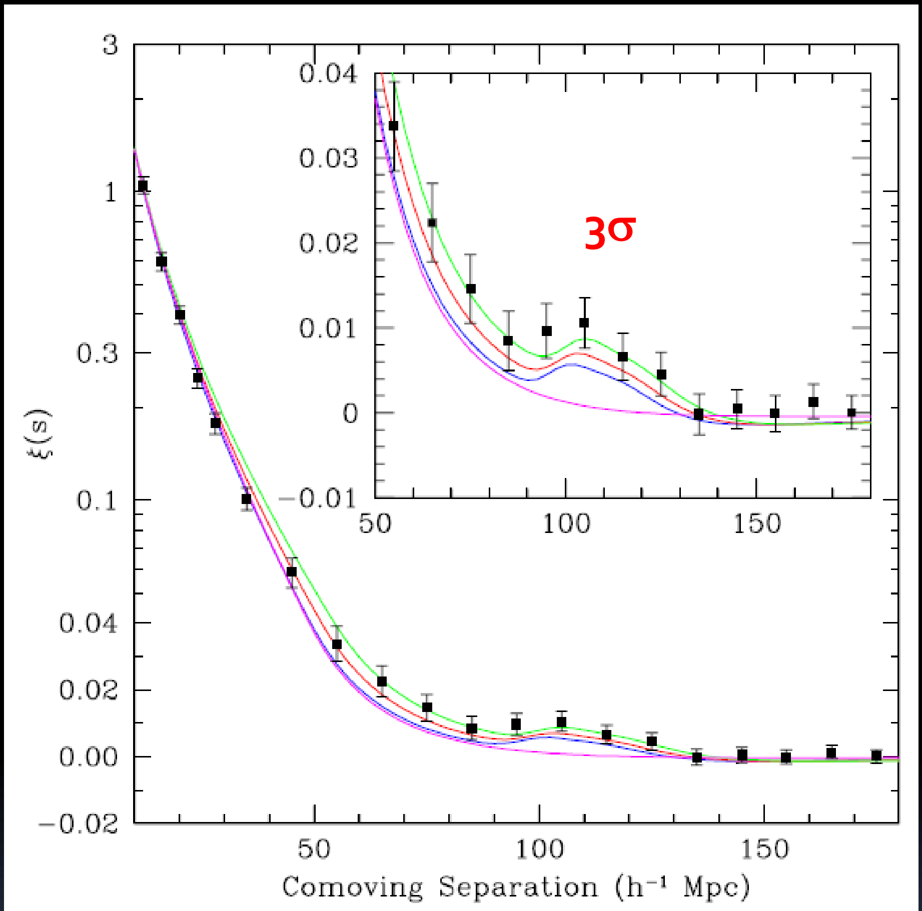
What has been found: SDSS

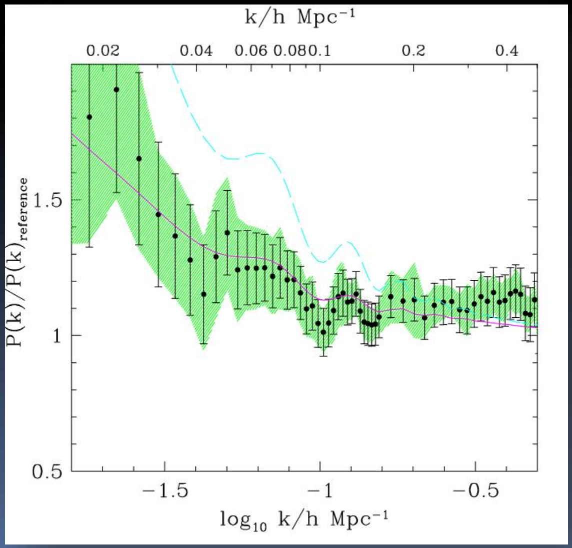


First detection in 2005

- ~46000 luminous red galaxies from SDSS-I
  - $\bar{z}{\sim}0.3$
- Red luminous galaxies have a larger bias, hence stronger correlation, easier to measure CF

Eisenstein et al. 2005

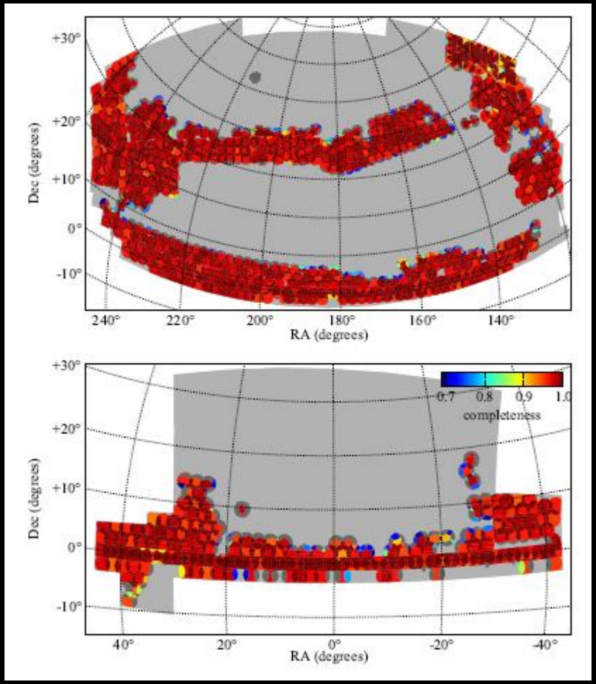


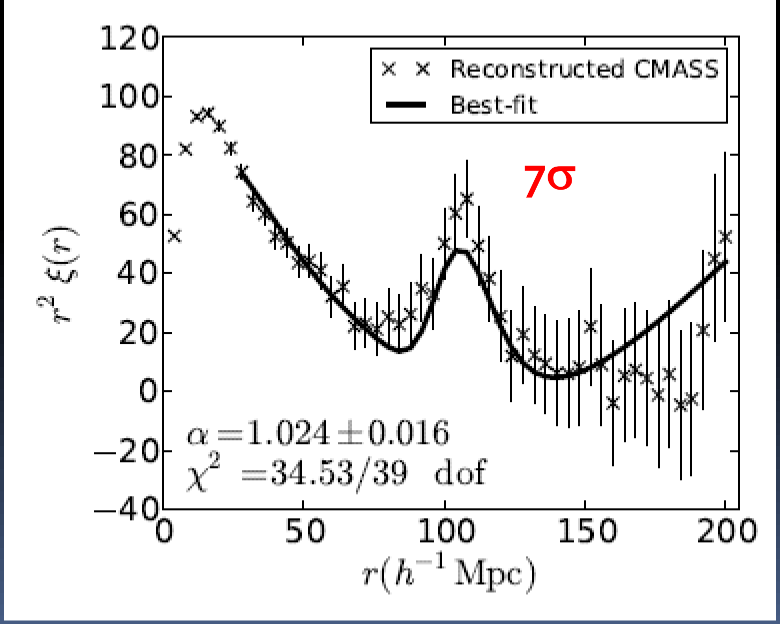


Also from 2DFGRS
Cole et al. 2005

2012: BOSS, SDSS-III/DR9

- ~260000 massive galaxies
- $\bar{z} \sim 0.57$



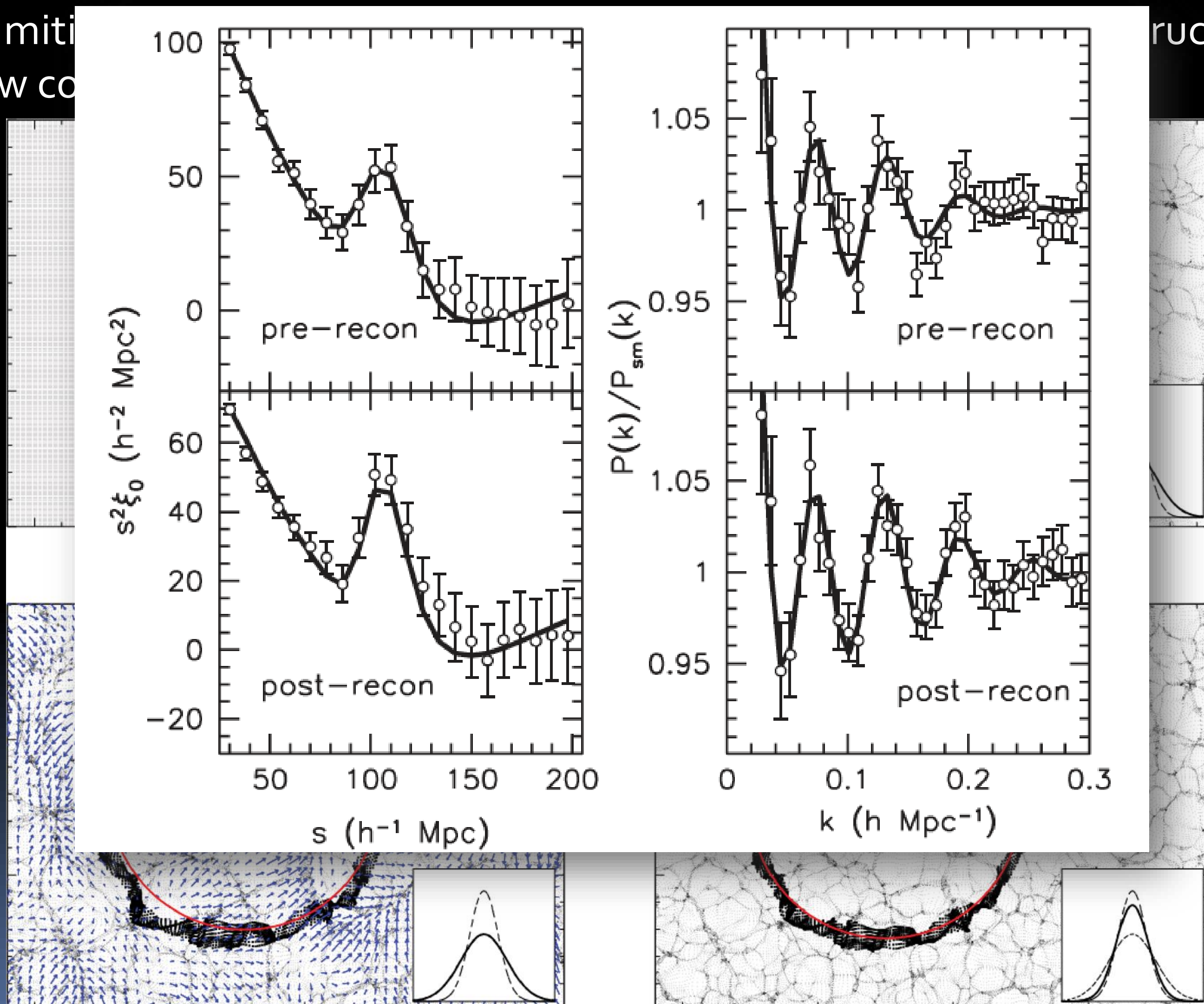


Anderson et al. 2012

Baryon Acoustic Oscillations

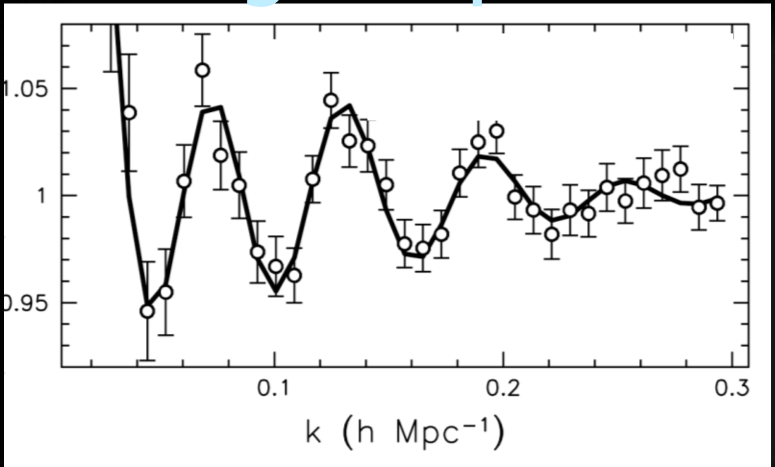
- Reconstruction
  - To miti … ruction is now co …

Padmanabhan et al. 2012

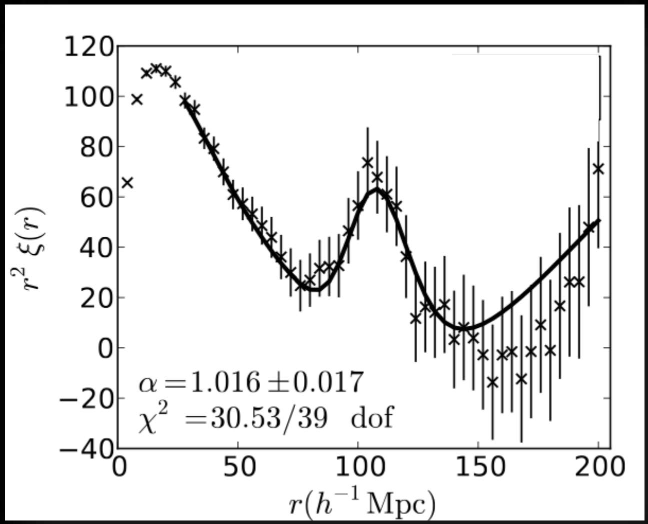


A major probe

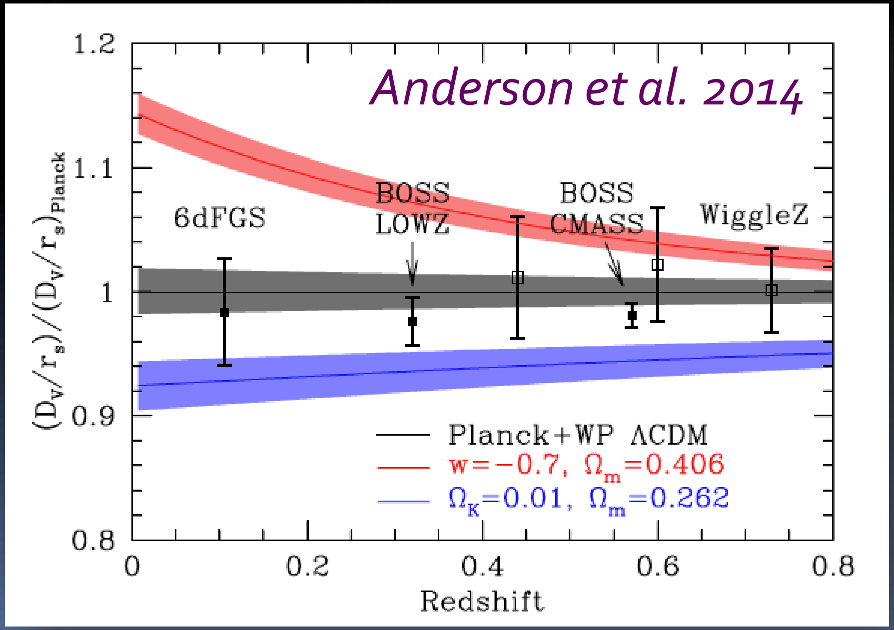
Galaxy power spectrum



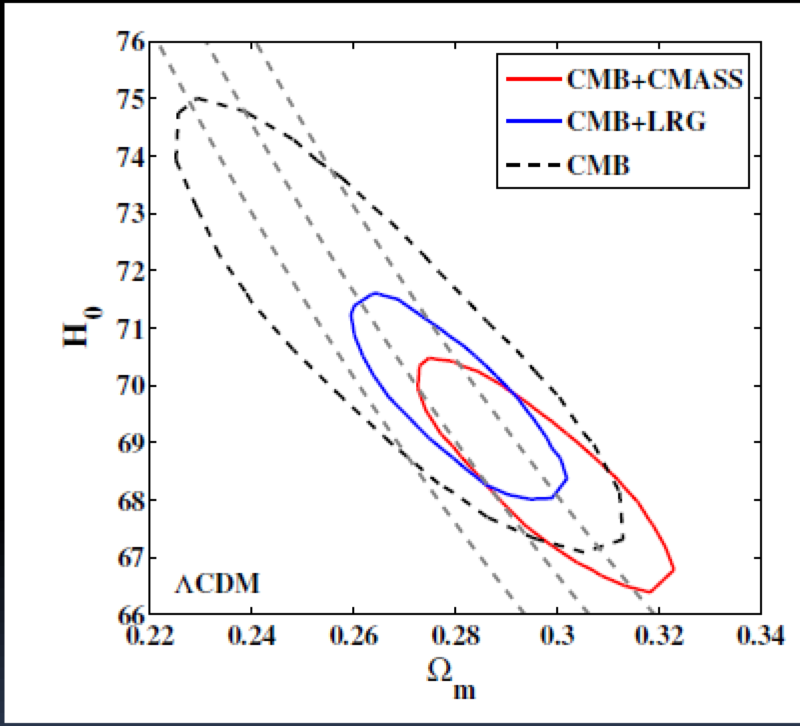
Galaxy correlation function

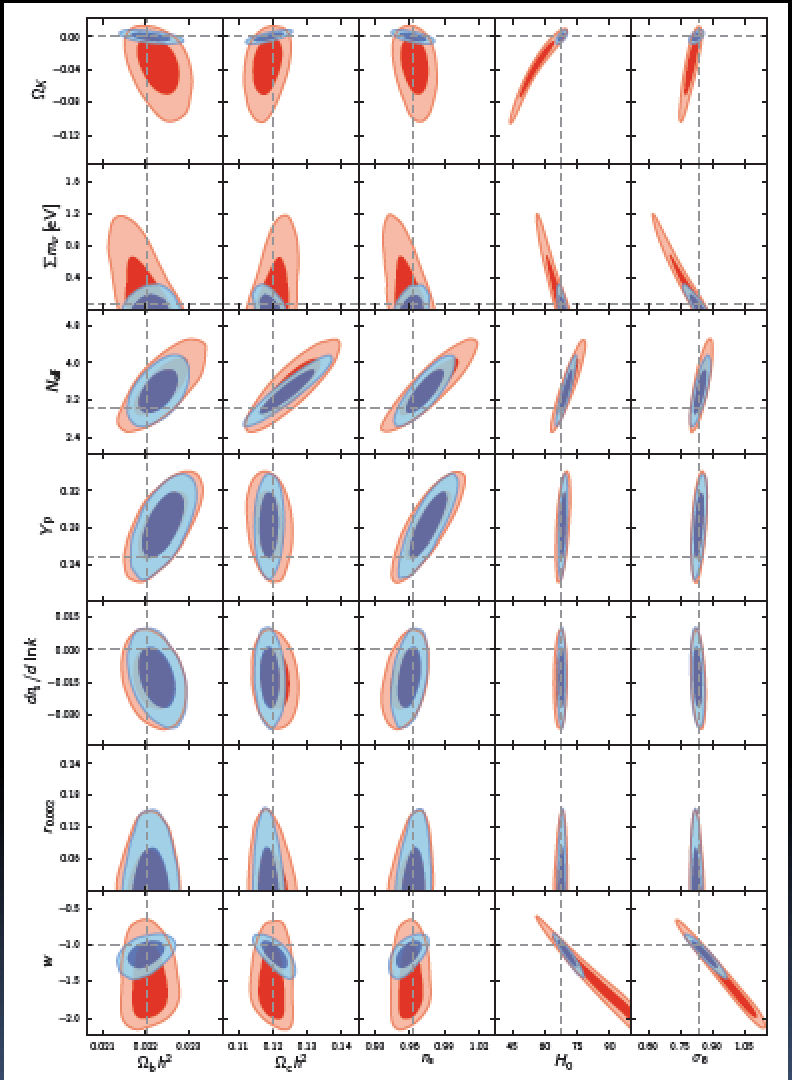


- BAO provides one of the most accurate geometrical constraints



Cosmological parameters: using BAO + Planck





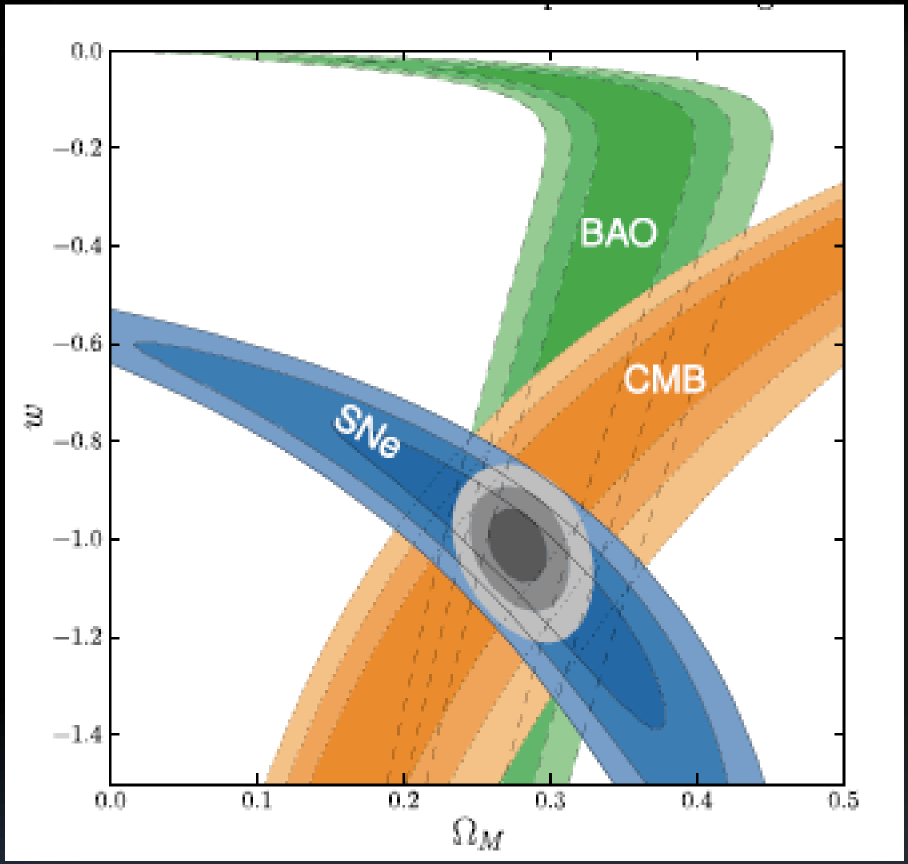
Red: Planck
Blue: Planck + BAO

Outline

1. Cosmology from LSS
2. Baryon Accoustic Oscillations measurements
3. Redshift space distortions measurements
4. Constraints on cosmology from clustering

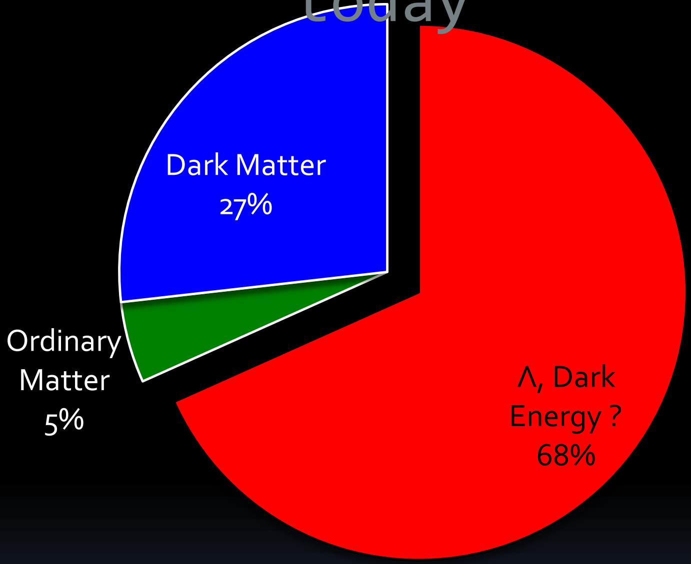
Concordance ΛCDM

Dark Energy EoS (w)



(e.g. Amanullah et al. 2010)

Universal content today



What is Dark Energy? What is the origin of cosmic acceleration?

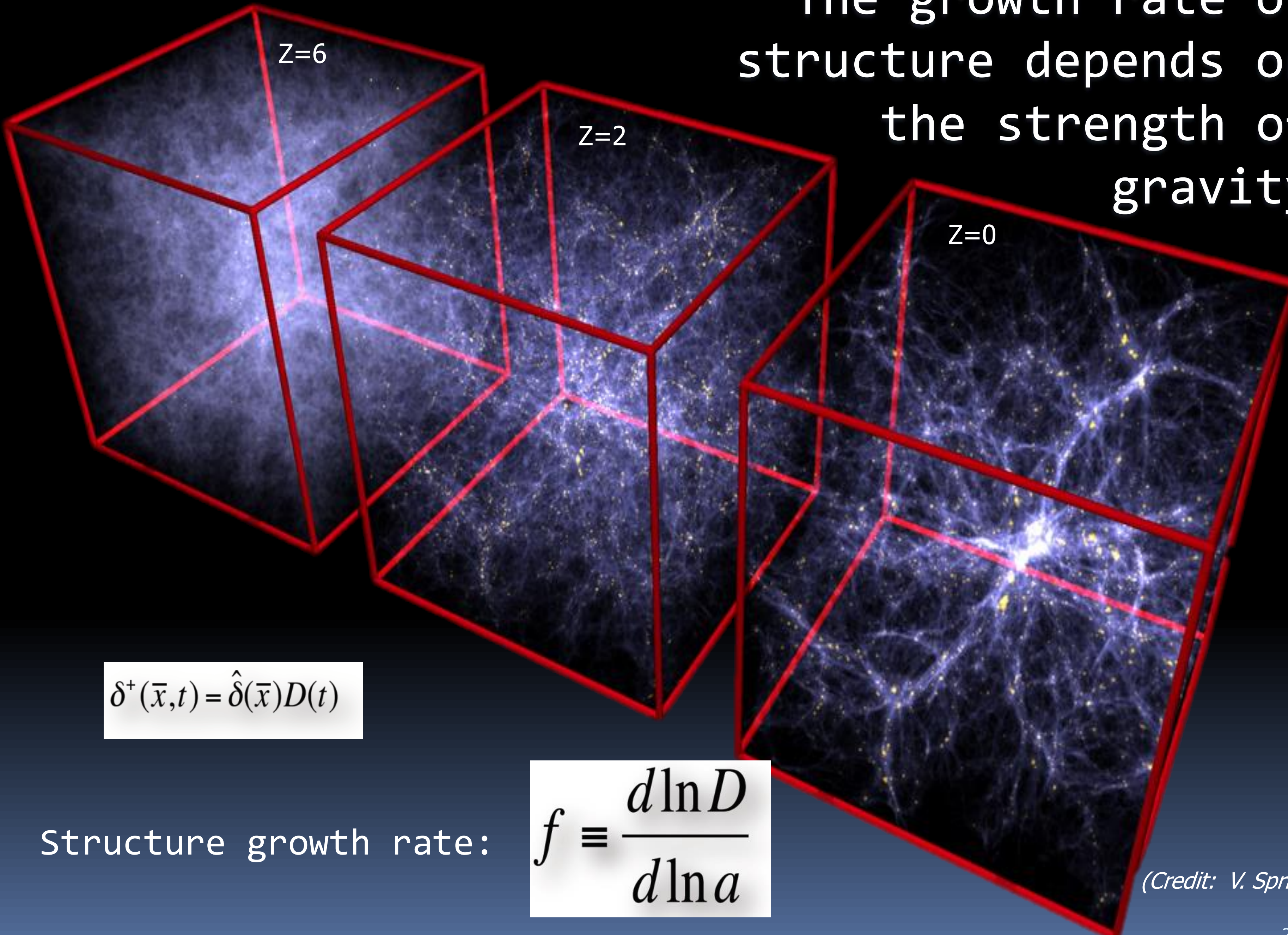
Cosmic acceleration

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

…or modify gravity theory? Add dark energy

To distinguish these two radically different options: **need to probe the dynamics of the Universe**

The growth rate of structure depends on the strength of gravity



(Credit: V. Springel)

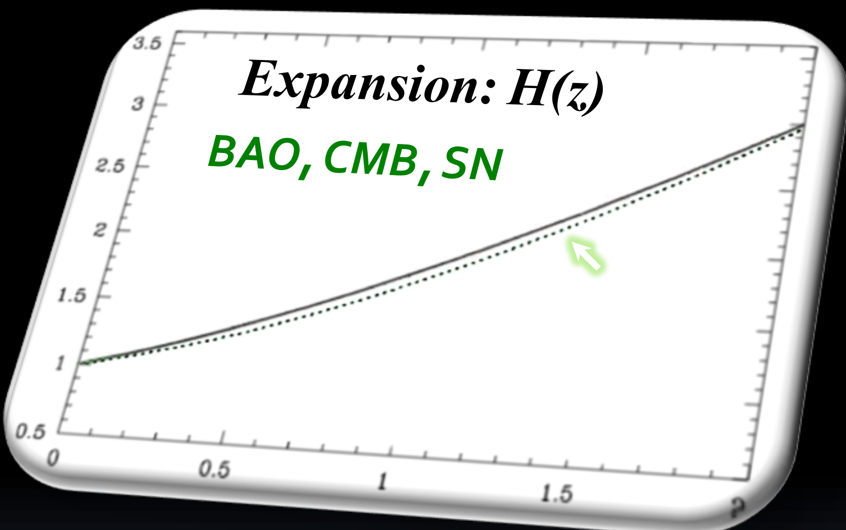
$$\delta^{+}(\bar{x},t) = \hat{\delta}(\bar{x})D(t)$$

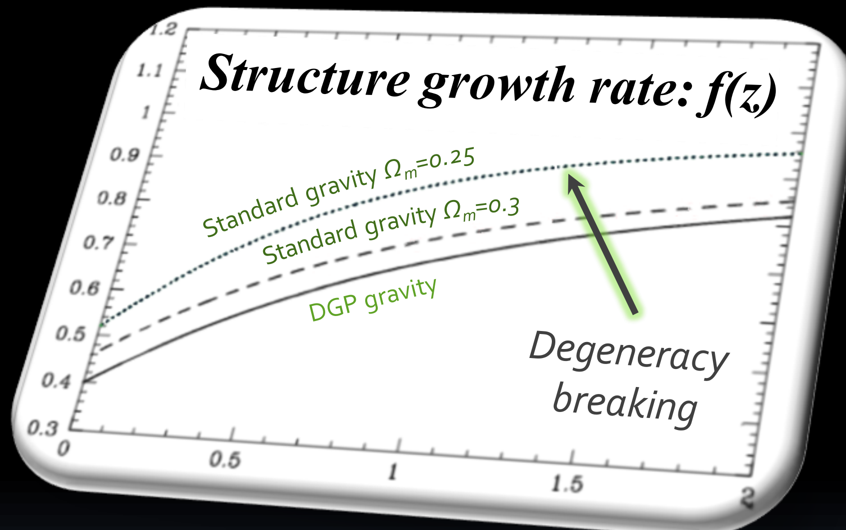
Structure growth rate: $f \equiv \dfrac{d\ln D}{d\ln a}$

Cosmic acceleration

The origin of cosmic acceleration is one the most important questions in cosmology today:

Dark Energy or a modification of standard gravity theory?

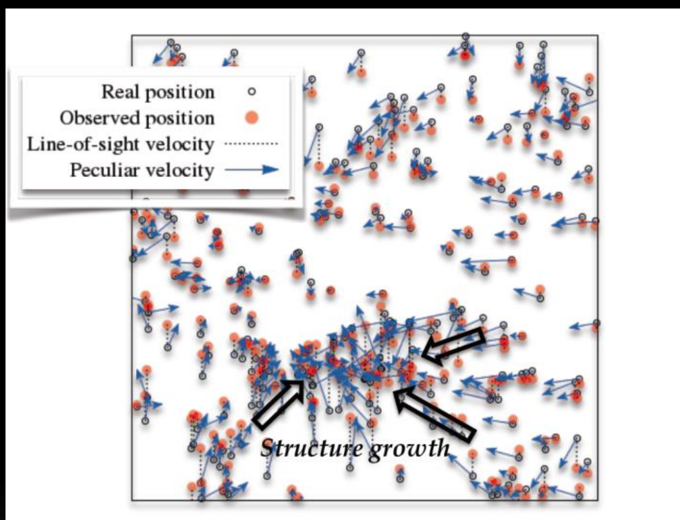




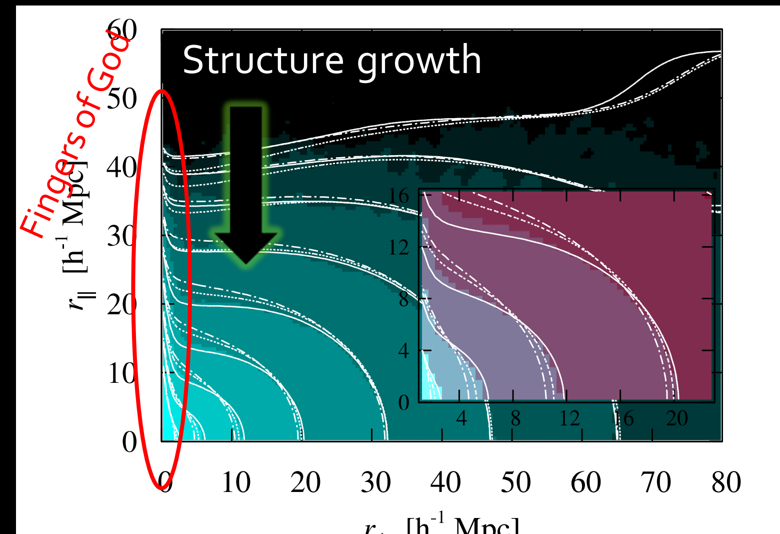
→ Growth rate of structure *f(z)* crucial to break the degeneracy between cosmological models

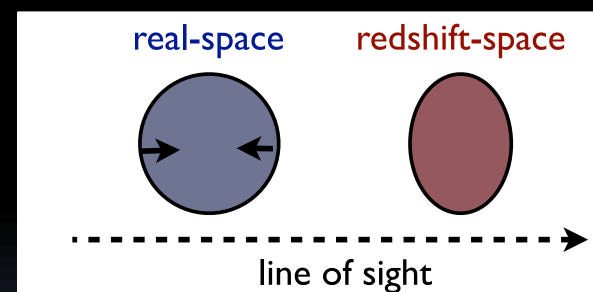
Redshift-space distortions

- Large-scale peculiar velocities, gravity-driven coherent motions in velocity space
- Galaxy spatial distribution observed in galaxy redshift surveys, i.e. in redshift-space:



Distance in redshift-space: $s = r + \frac{v_{los}}{aH}$





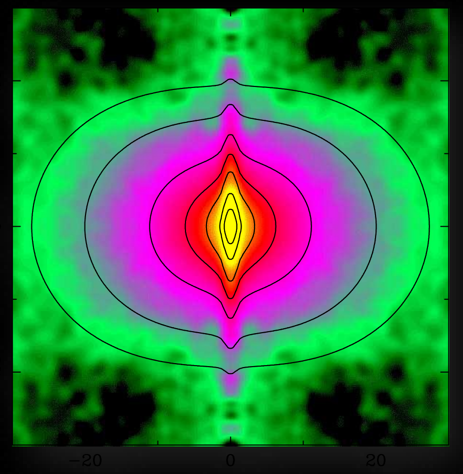
$$f = \frac{d \ln D}{d \ln a} \approx \Omega_m(z)^{\gamma}$$

Growth rate of structure

- Because of peculiar motions, redshift is not strictly a distance
- Observed in redshift-space the correlation function is “squashed” by structure growth hence sentivite to Gravity

Redshift-space distortions

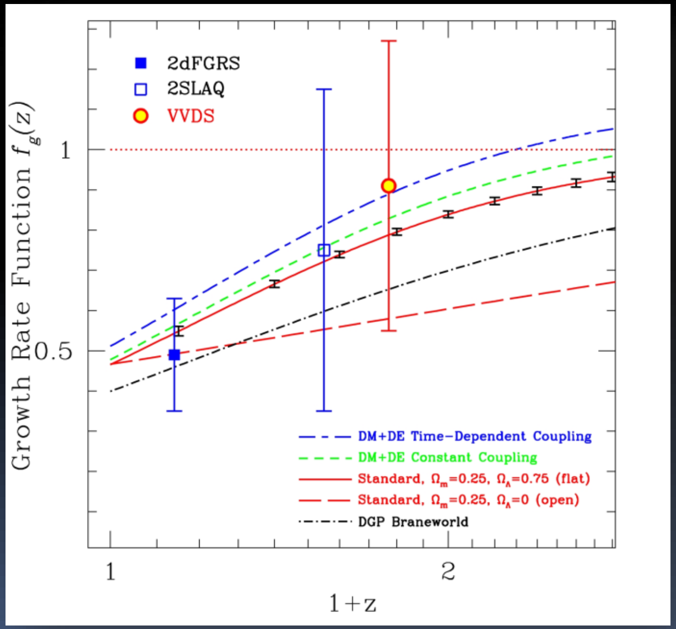
- RSD are known for about 30 years… (Kaiser 1987)



Peacock et al. (2001), Nature
RSD to measure Ω_m:

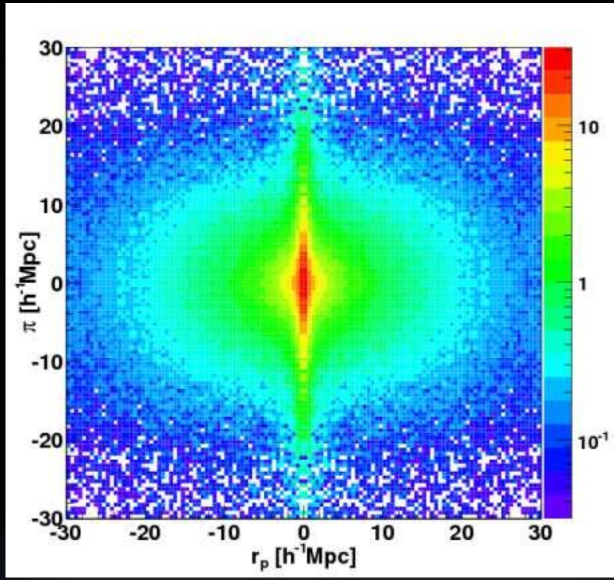
$$\beta = f/b = \Omega_m{}^{\gamma}/b$$

- … but we realised its usefulness for probing gravity only less than 10 years ago!

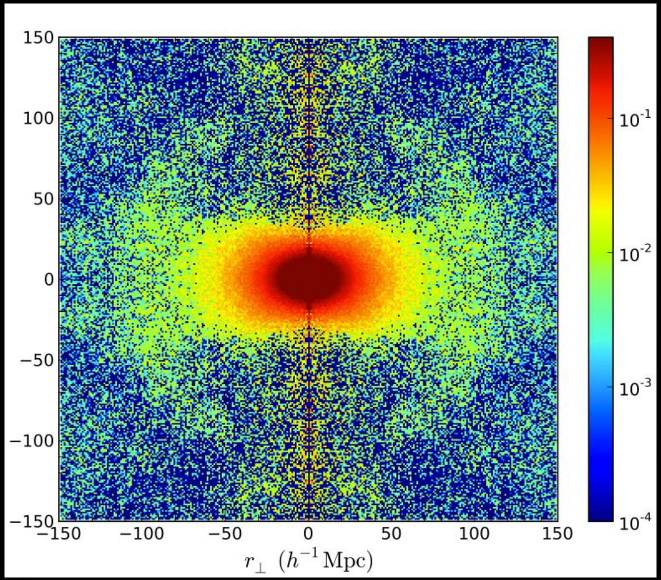


VVDS, Guzzo et al. (2008), Nature
RSD to probe gravity : $\beta = f/b = \Omega_m{}^{\gamma}/b_L$

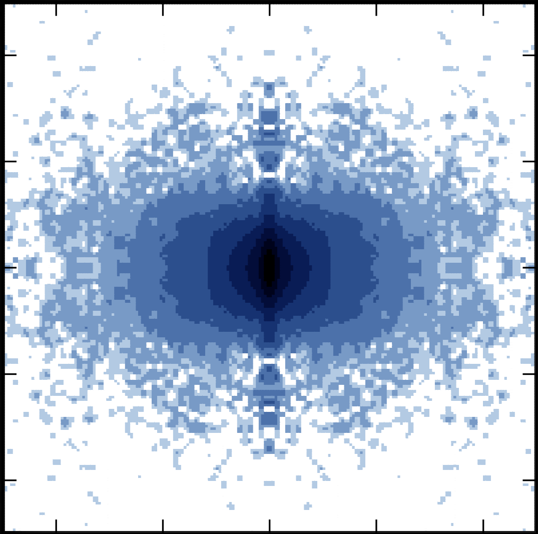
Recent RSD measurements



6dFGS
Beutler et al. 2012
z=0.06

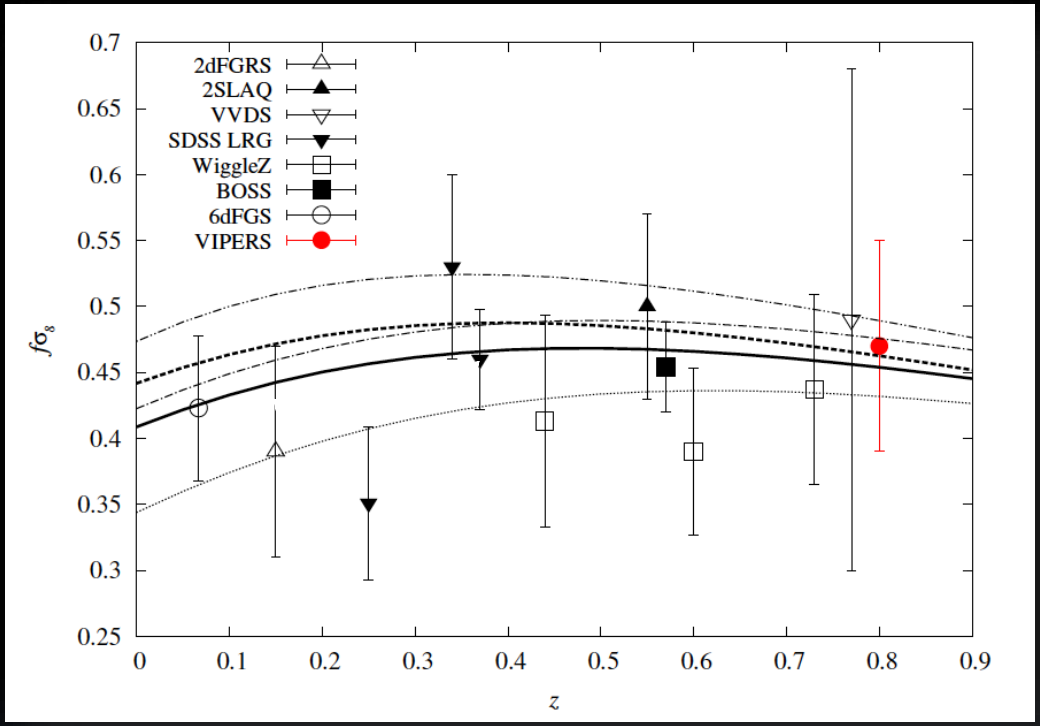


SDSS-III/BOSS
Samushia et al. 2014
z=0.57



VIPERS
de la Torre et al. 2013
z=0.8

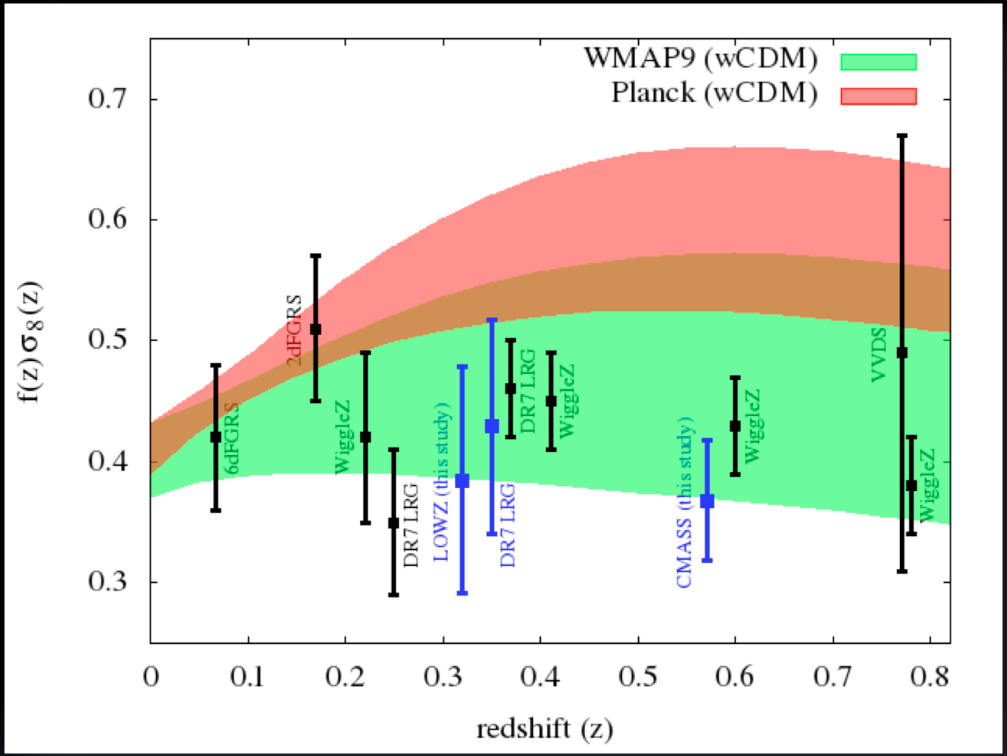
Constraints on growth rate



VIPERS, de la Torre et al. 2013

- Current constraints in agreement with ΛCDM and Einstein gravity

Constraints on growth rate

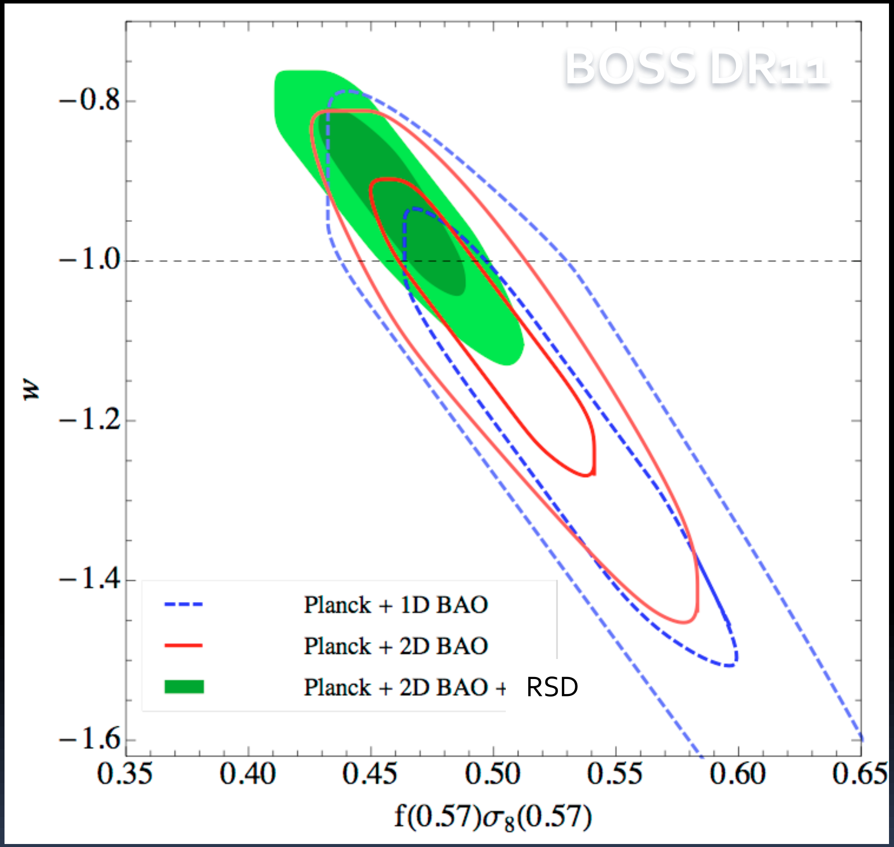


Samushia et al. 2014

Current constraints in agreement with ΛCDM and *Einstein gravity*

Combined BAO and RSD

Combined BAO and RSD constraints on Dark Energy EoS

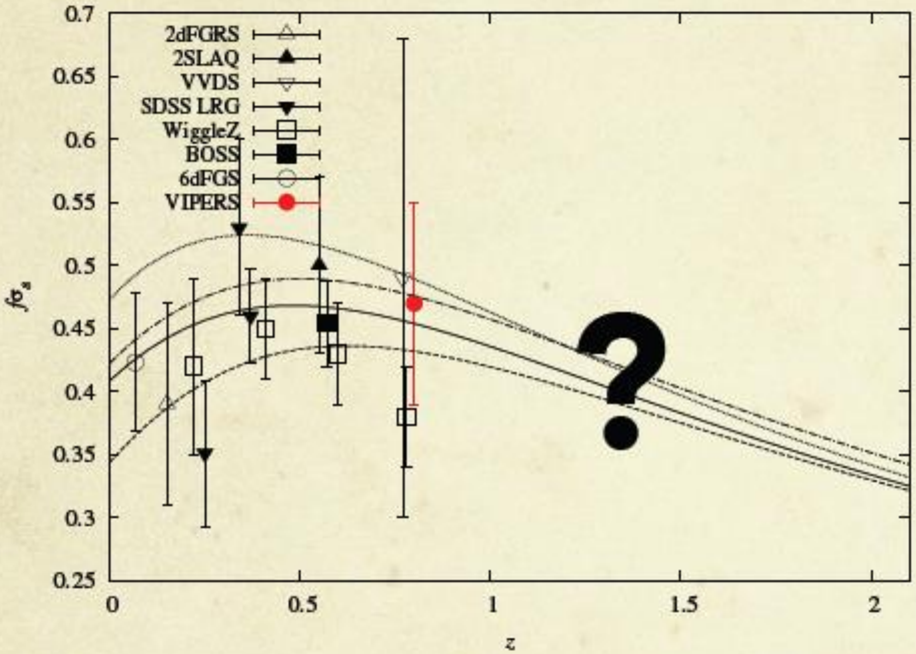


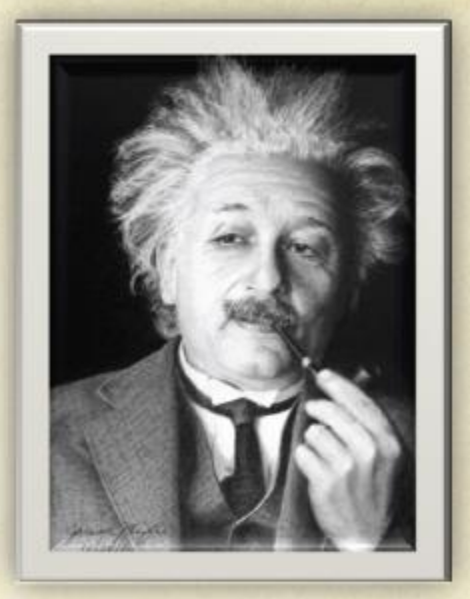
Chuang et al. 2014

The future of clustering analysis

- Correlation function: a powerful tool to probe galaxy (halo) evolution and cosmology
- CF with BAO and RSD has become a major tool to constrain the cosmological world model

Growth rate from next generation surveys



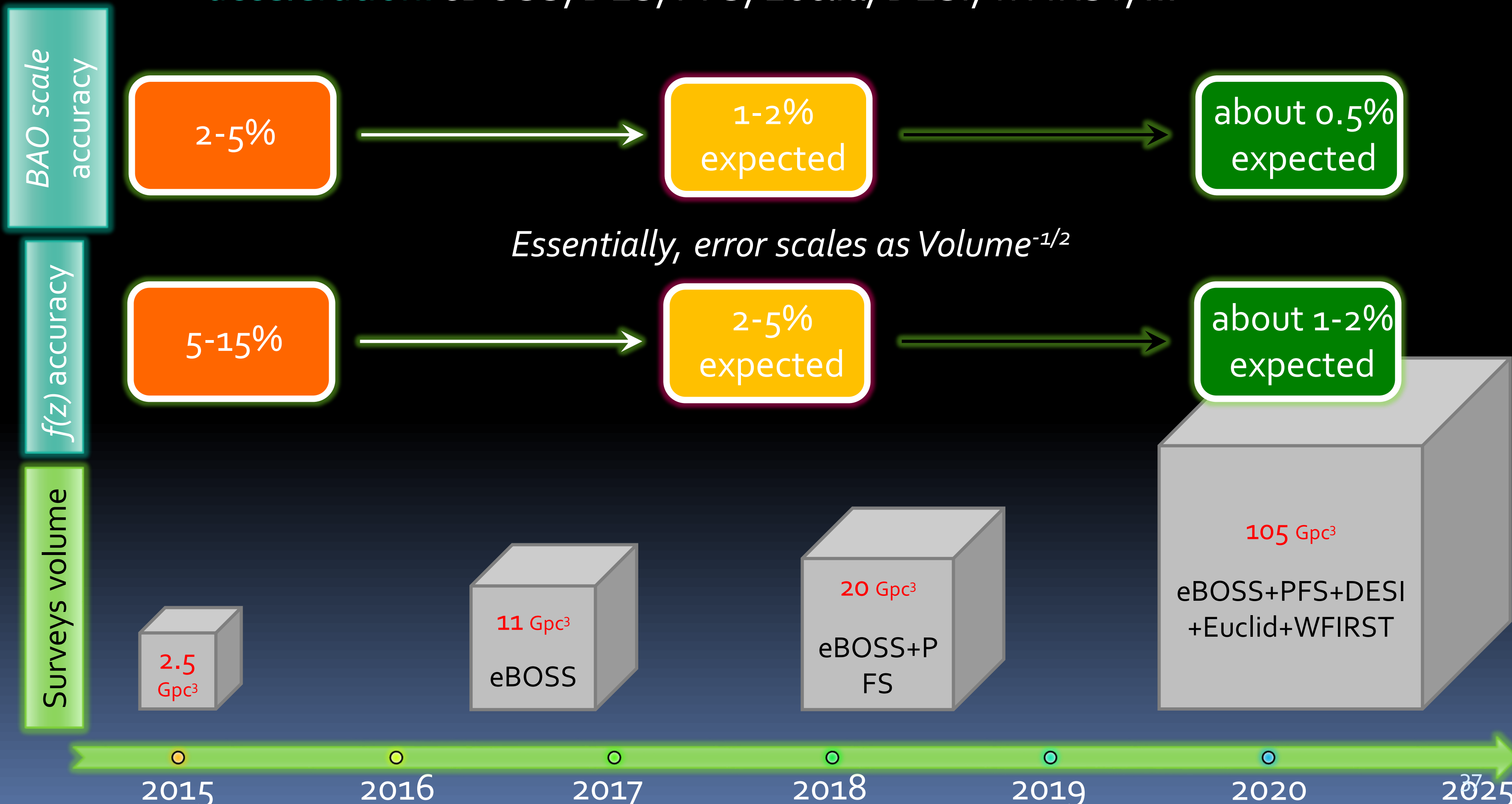


- Current measurements:
  - Not accurate enough to distinguish between GR and modified gravity
  - Restricted to z<0.8, low redshifts intrinsically limited by volume

→ Need redshift surveys probing largest volumes at high redshift

Future Dark Energy surveys

- Massive effort today to prepare massive galaxy/quasar surveys to solve the problem of Dark Energy and the origin of late cosmic acceleration: *eBOSS, DES, PFS, Euclid, DESI, WFIRST, …*



Future spectroscopic surveys

Spectroscopic Survey	Instrument	redshift	Field # galaxies	Start/end dates
eBOSS	Sloan 2.5m	0.5-1.5	10^6	2014-2017
PFS	Subaru 8m	0.5-2.7	1400 deg^2 3×10^6	2019-2022
DESI	KPNO 4m	0.5-1.5 Gal.	12000 deg^2 50×10^6	2019-2024
EUCLID	1.2m	0.5-2	15000 deg^2 50×10^6	2021-2027
WFIRST	2.4m	1-3	2200 deg^2 16×10^6	2024-

Lecture plan

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Part 2: The Universe on large scales

- Large scale structures observations
- Measuring clustering: the correlation function (and power spectrum)

Part 3: Baryon Acoustic Oscillations and Redshift space distortions

Part 4: The Euclid Surveys and galaxy clustering

Part 4

THE EUCLID MISSION AND CLUSTERING

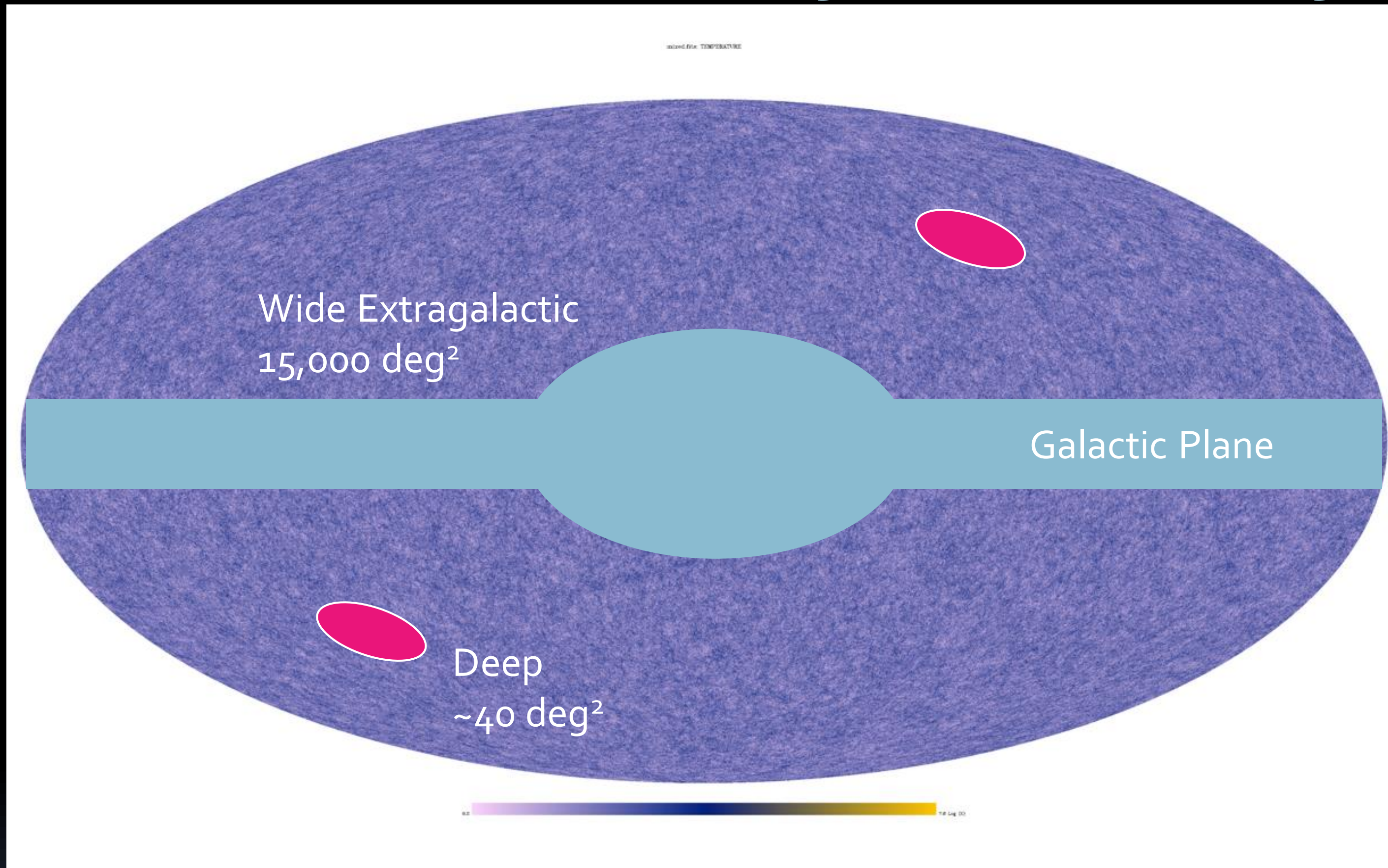
Outline

1. The Euclid mission and NISP spectrograph for clustering
2. The NISP spectroscopic survey
3. Forecasts for BAO and RSD

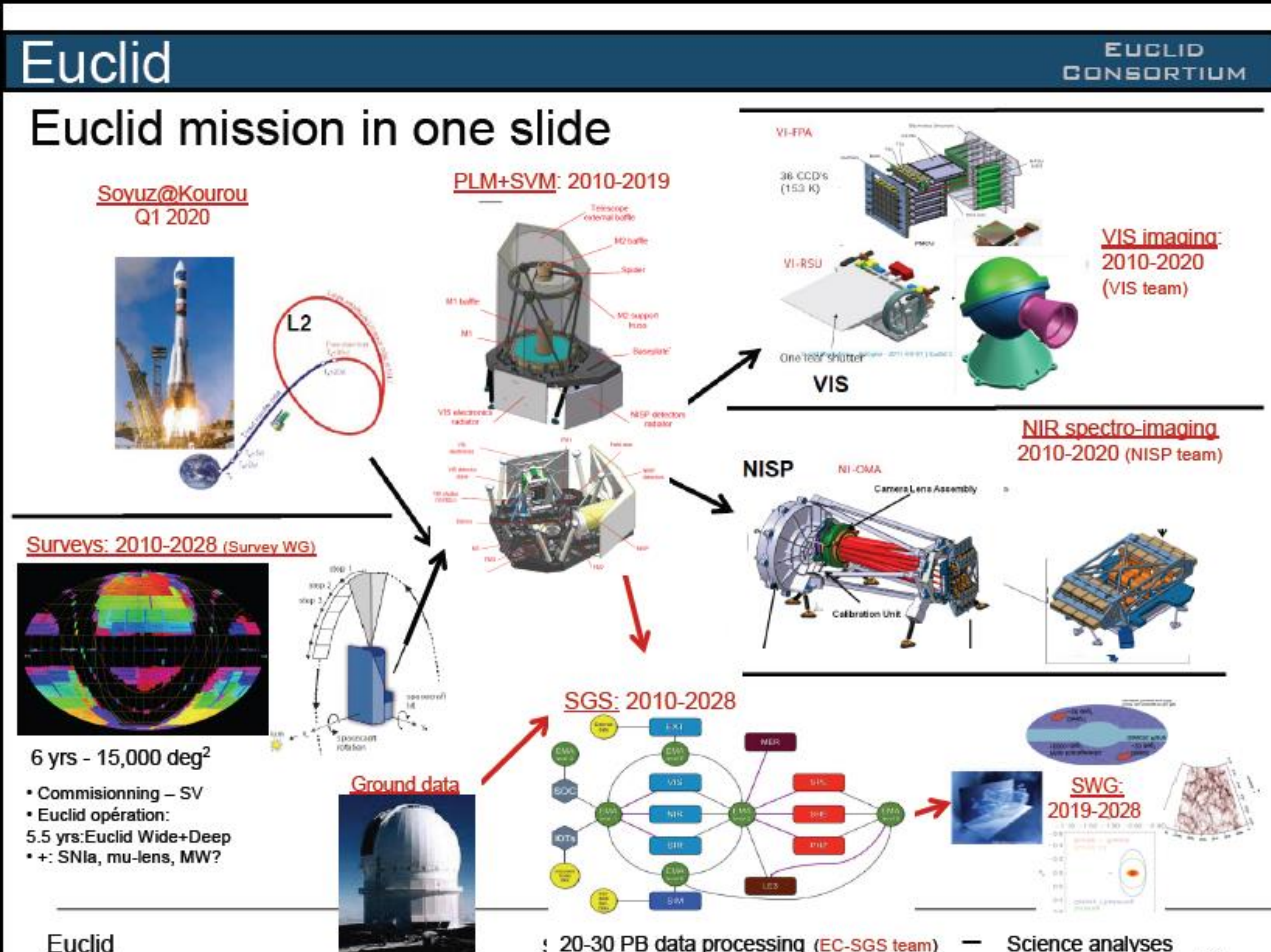
The ESA-Euclid space mission

- A space mission dedicated to dark energy and dark matter
- A 1.2m diameter telescope, visible + IR, low background (Lagrange L2 point)
- 2 survey instruments
  - VIS: the VISible imager
  - NISP: the near Infrared Spectrograph and Photometer
- An integrated survey
  - Wide survey: 15000 deg^2 in imaging (2G galaxies) and spectroscopy (50M spectra)
  - Deep survey: 40 deg^2 in imaging and spectroscopy

Euclid « All sky » survey

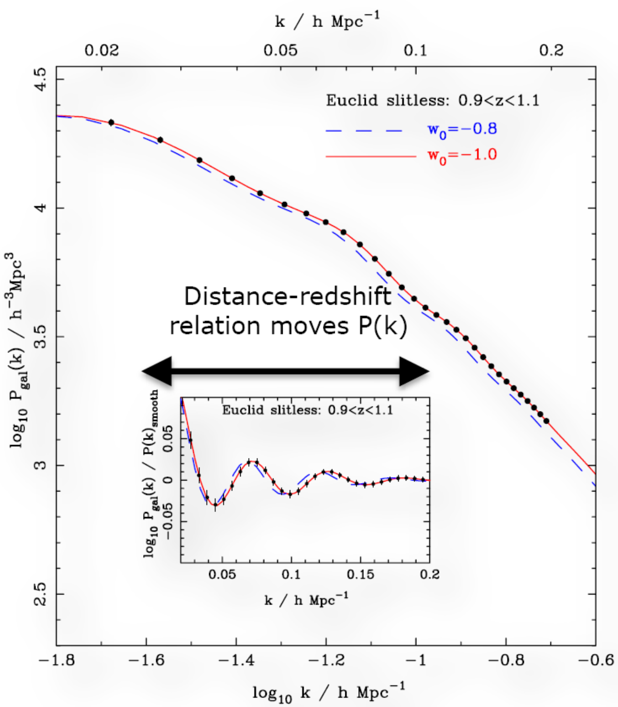


All the extragalactic sky (away from the Milky Way)
2 billion galaxy images
50 million galaxy redshifts
To z~2: 10 billion years back

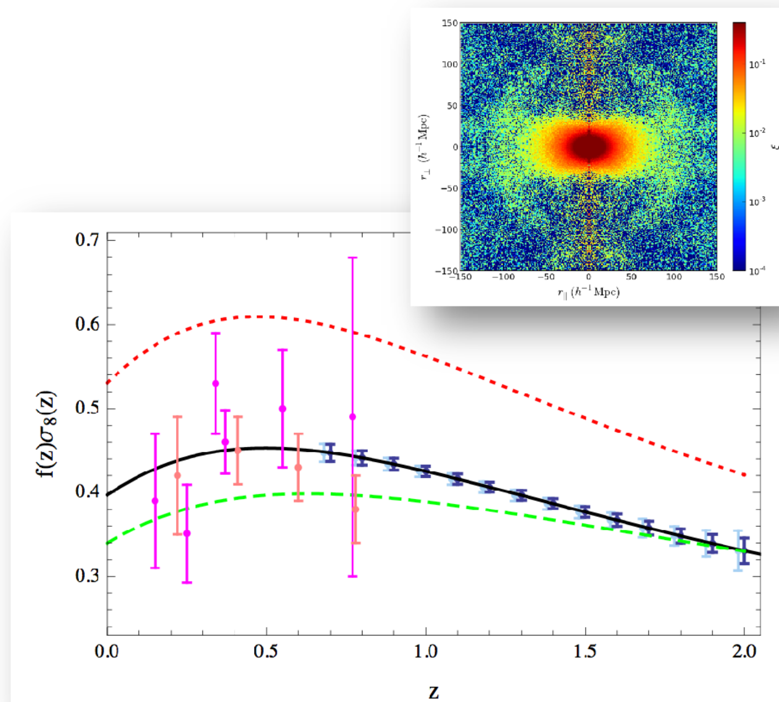


From Y. Mellier, EC-Lead

Measuring clustering with Euclid



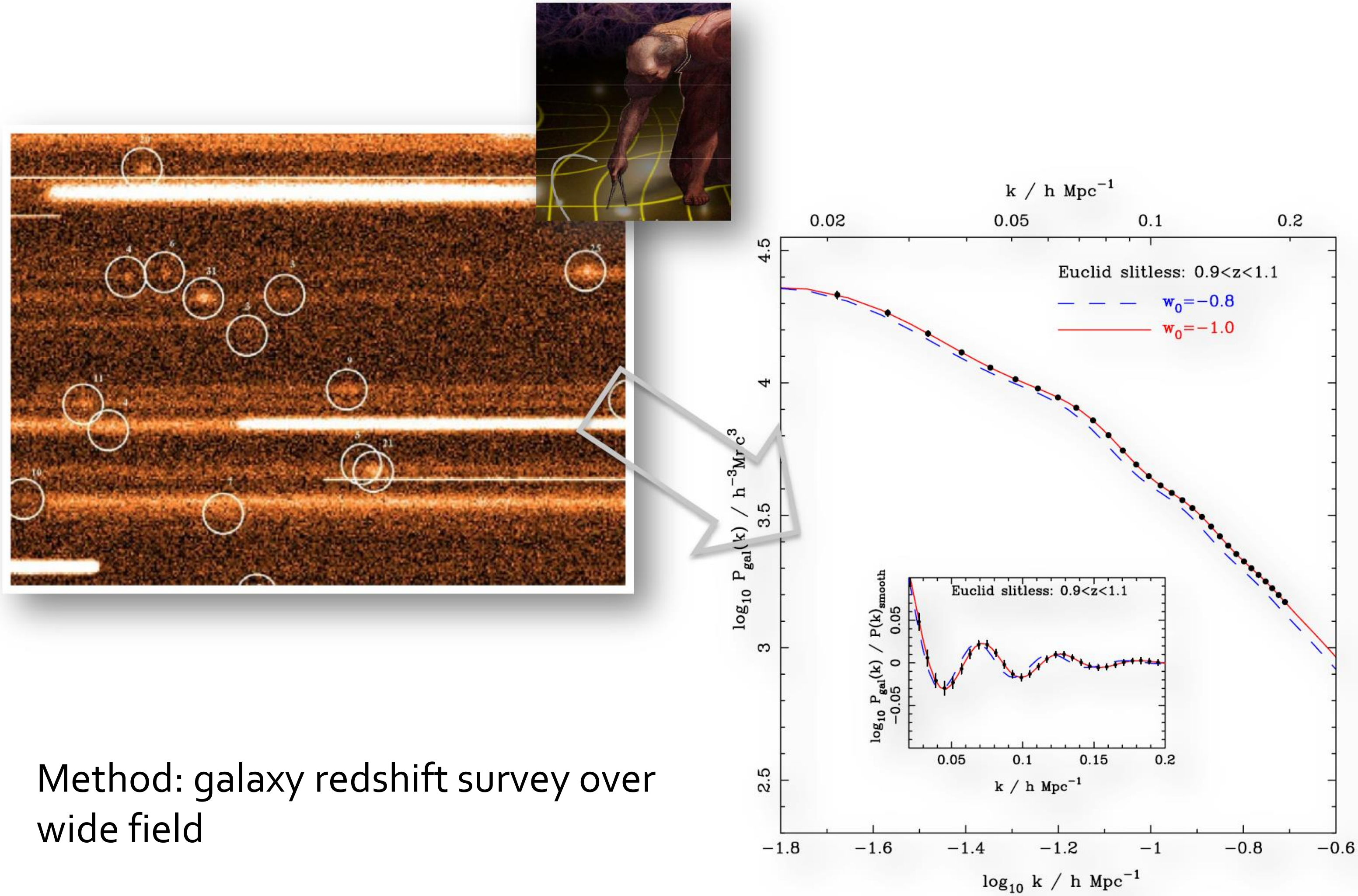
Baryonic Acoustic Oscillations in the galaxy power spectrum as a standard ruler (one Δz=0.2 redshift slice)



Anisotropy of the correlation function or power spectrum (RSD) as a measure of the growth of structure

From Guzzo Euclid-Marseille 2014

Measuring clustering with Euclid



Method: galaxy redshift survey over wide field

From Guzzo Euclid-Marseille 2014

From science goals to experiment

Putting it all together

Science: Galaxy clustering

- RSD: Probe of structure growth
- BAO

Survey Parameter Space

- All sky (15000 deg^2)
- R~300
- z~0.7-2
- Hα selected

Instrument Concept

- Slitless spectroscopy & imaging
- Wide field 0.5 deg^2
- 0.9-1.8 microns

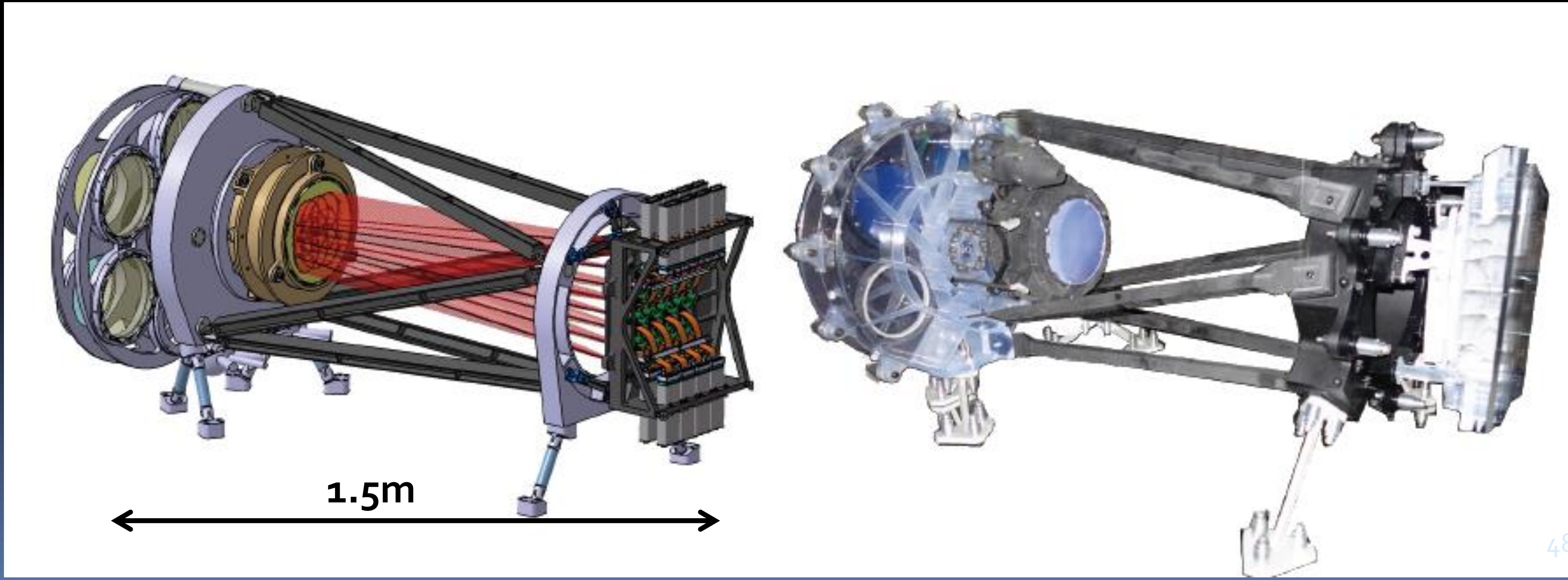
Survey Implementation

NISP: infrared spectrograph & camera

Technical specifications:

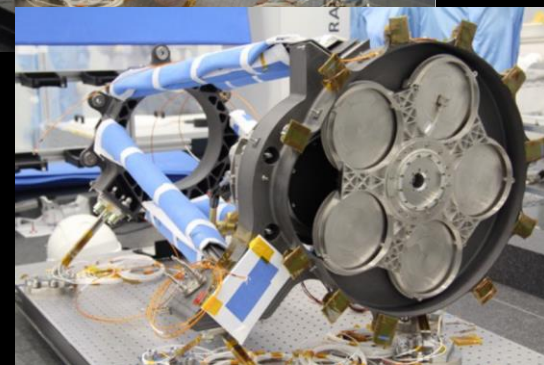
- Field of view: 0.54 deg^2 (2.7x the full moon)
- Infrared: 0.8 to 2 microns
- Spectrograph designed to get the Hα line up to z~2

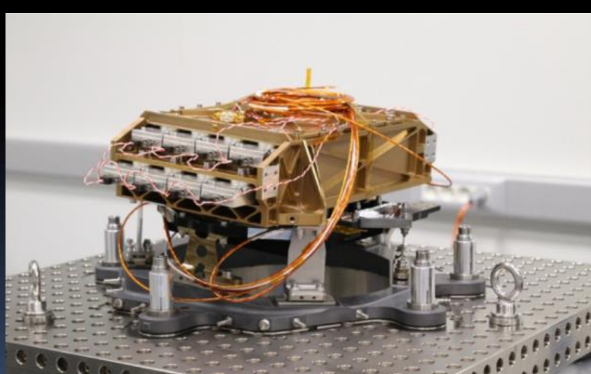
Build in Marseille, LAM-AMU leadership, with CPPM, under CNES overall agency responsibility

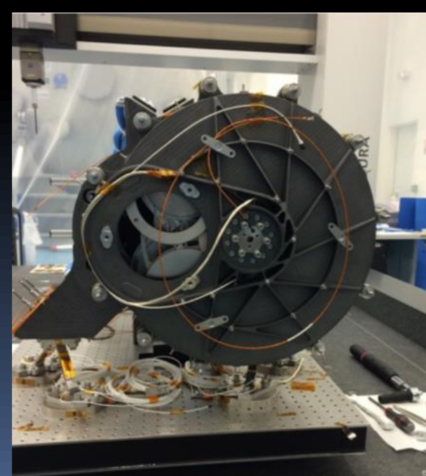


Euclid-NISP:
in full development

- First design 2010
- Critical Design Review (CDR): Sept.
  - Existing models, tested
- Delivered to ESA: 2018
- In flight: 2020

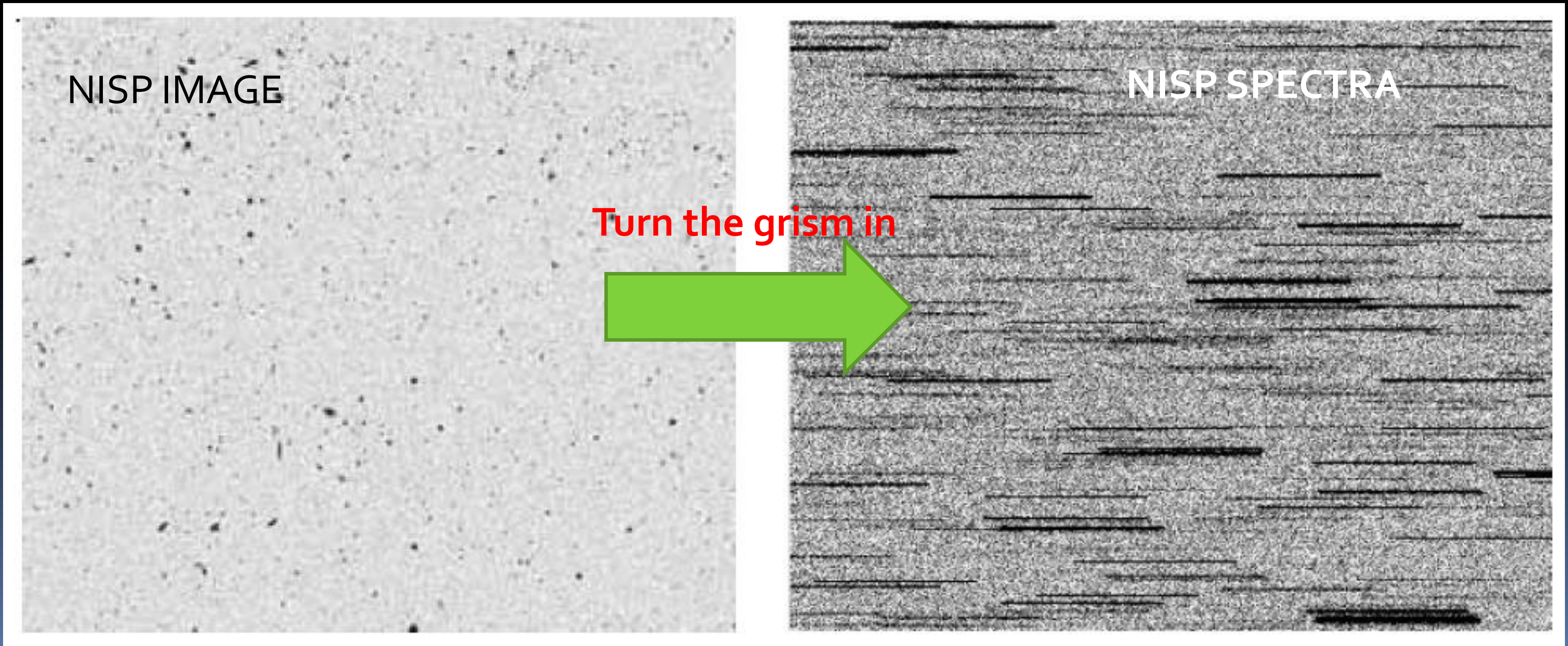






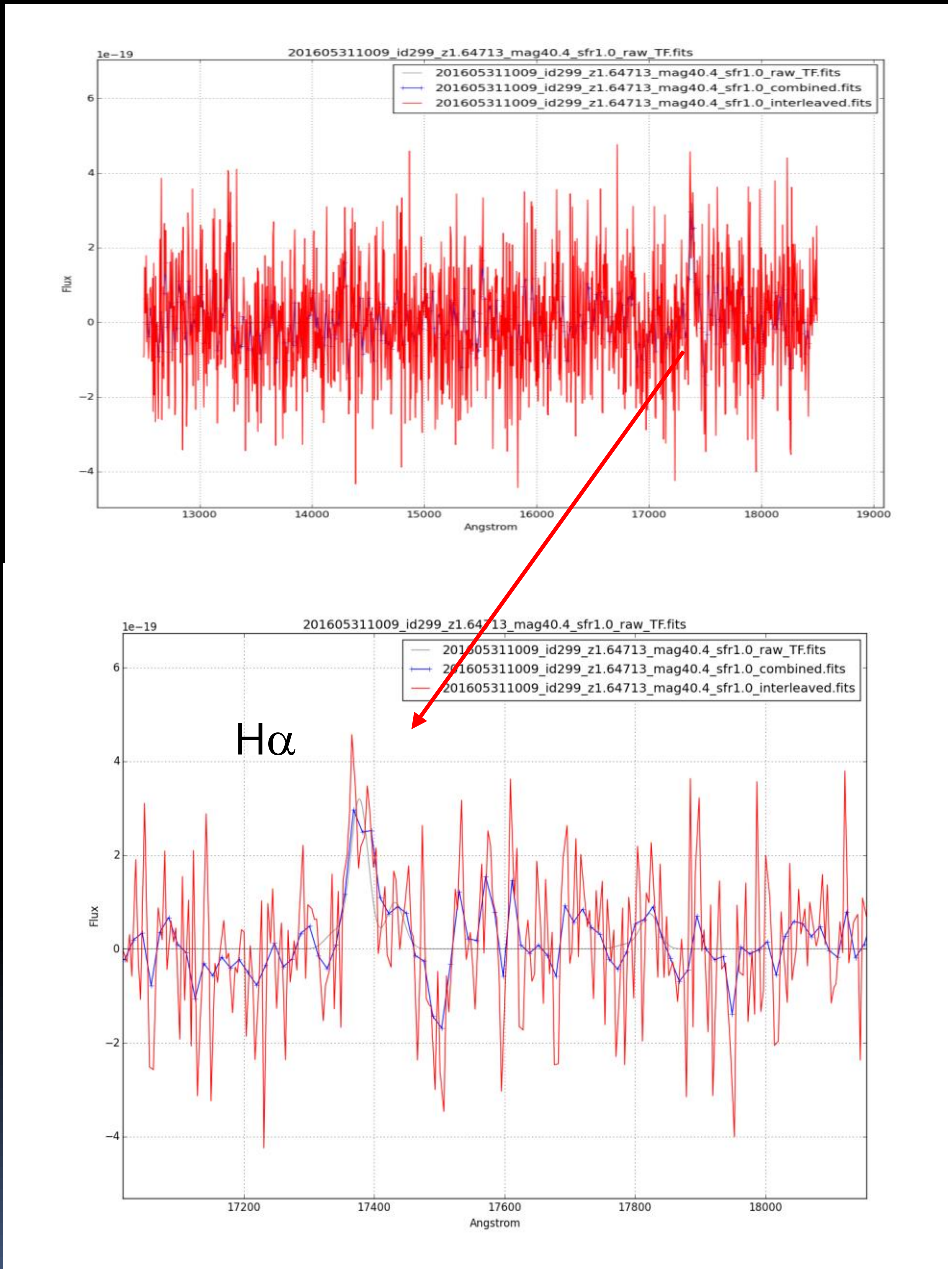
Measuring clustering with Euclid

- NISP will produce slitless spectroscopy
- This implies superimposition of spectra from different objects (at different redshifts…).
- The challenge is to get rid of this contamination and ensure a robust redshift measurement
- Evaluate the reliability of the redshift measurement per object
- Do all this automatically for ~50 million objects



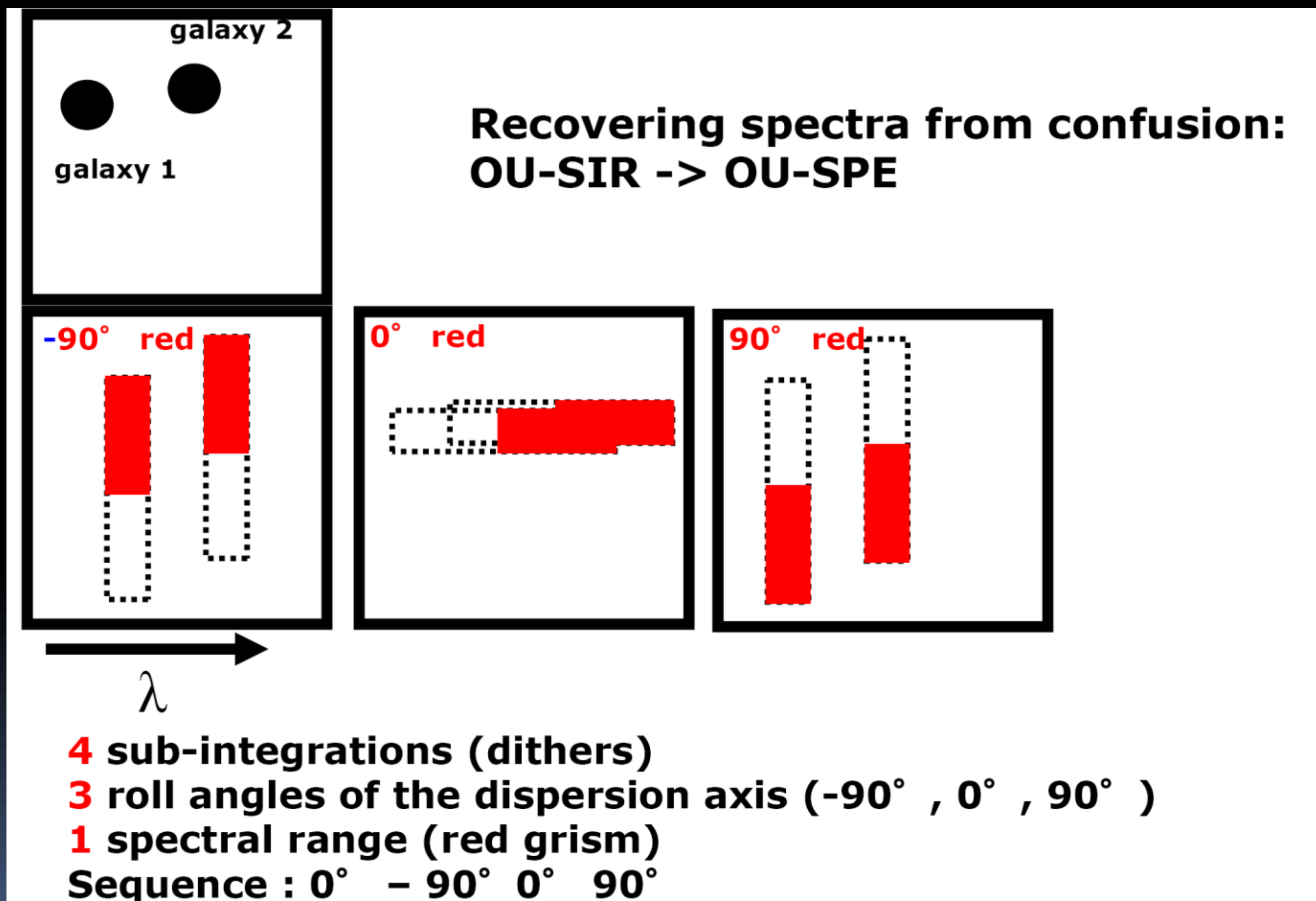
Extracting the spectra and redshifts

- Extract all galaxy spectra
  - Measure redshifts <u>automatically</u>
- Find 50M Hα emitters $0.8<z<2$
- Accurately measure line flux
- Estimate uncertainties

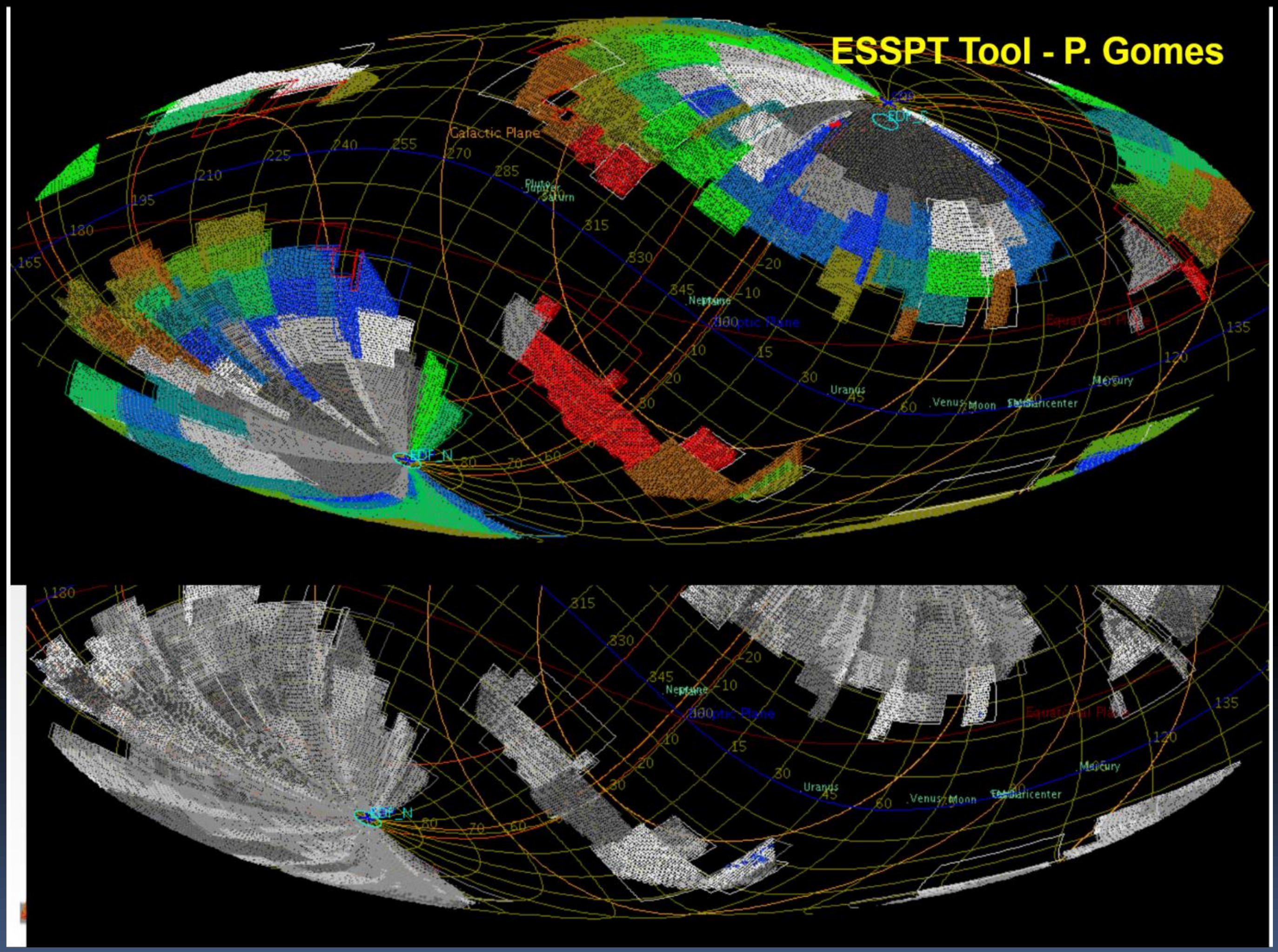


Simulated galaxy at z=1.647

Extracting spectra: contamination

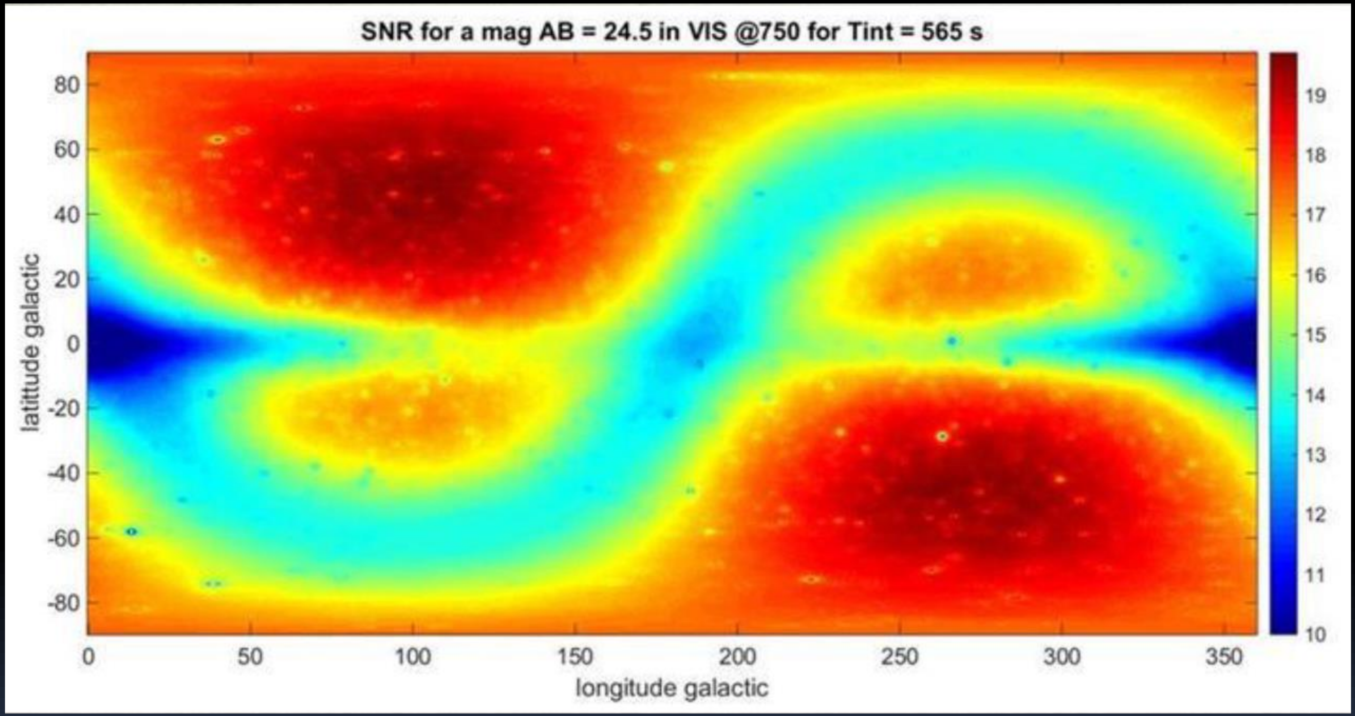


Paving the sky



from Scaramella Euclid-Lisbon 2016

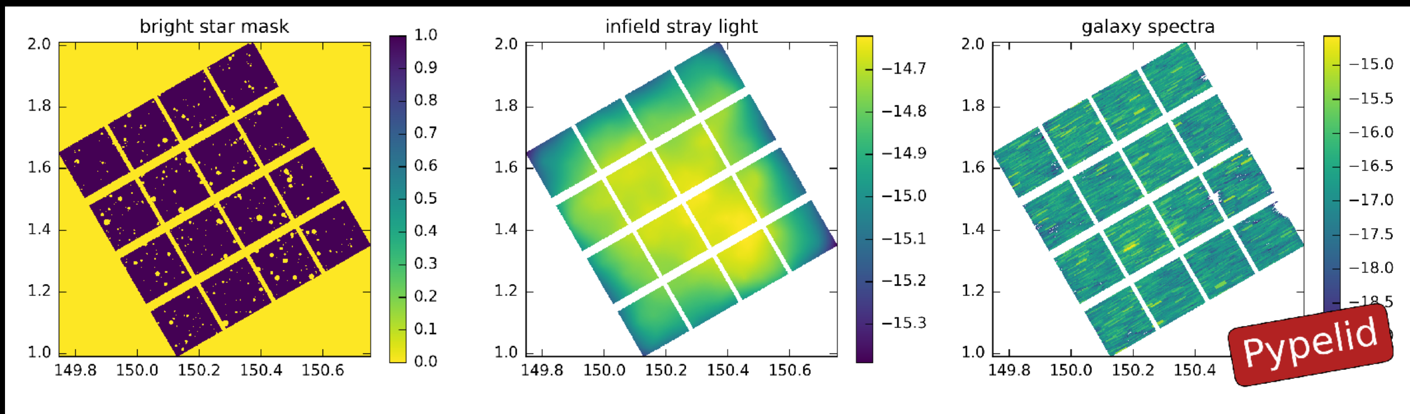
Know the background and instrument: predict the SNR



For the VIS instrument

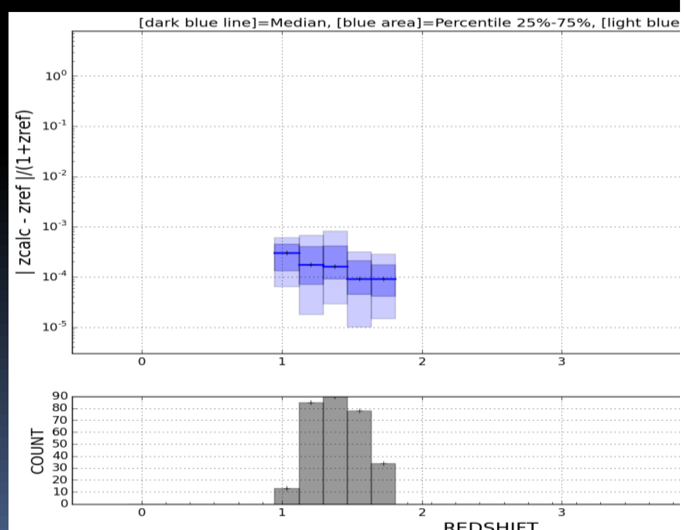
from Scaramella Euclid-Lisbon 2016

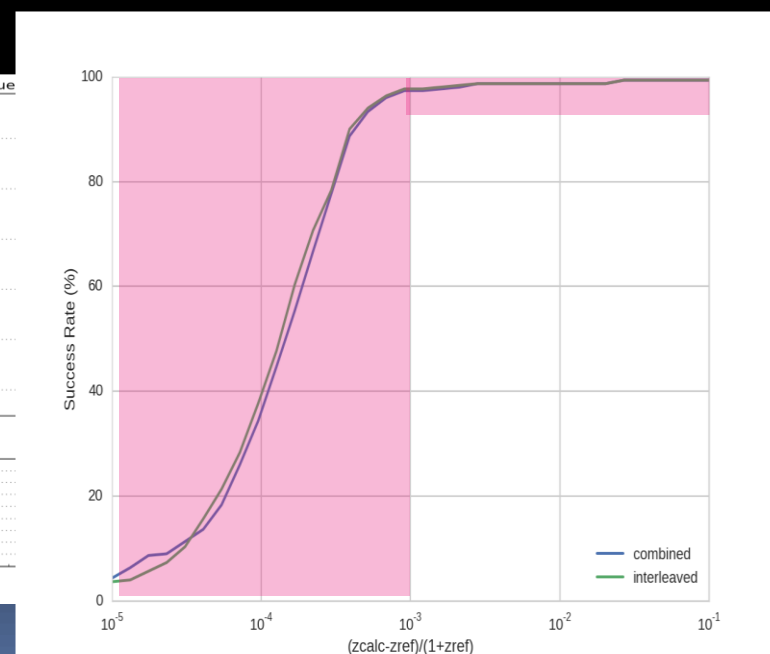
Understanding the selection function



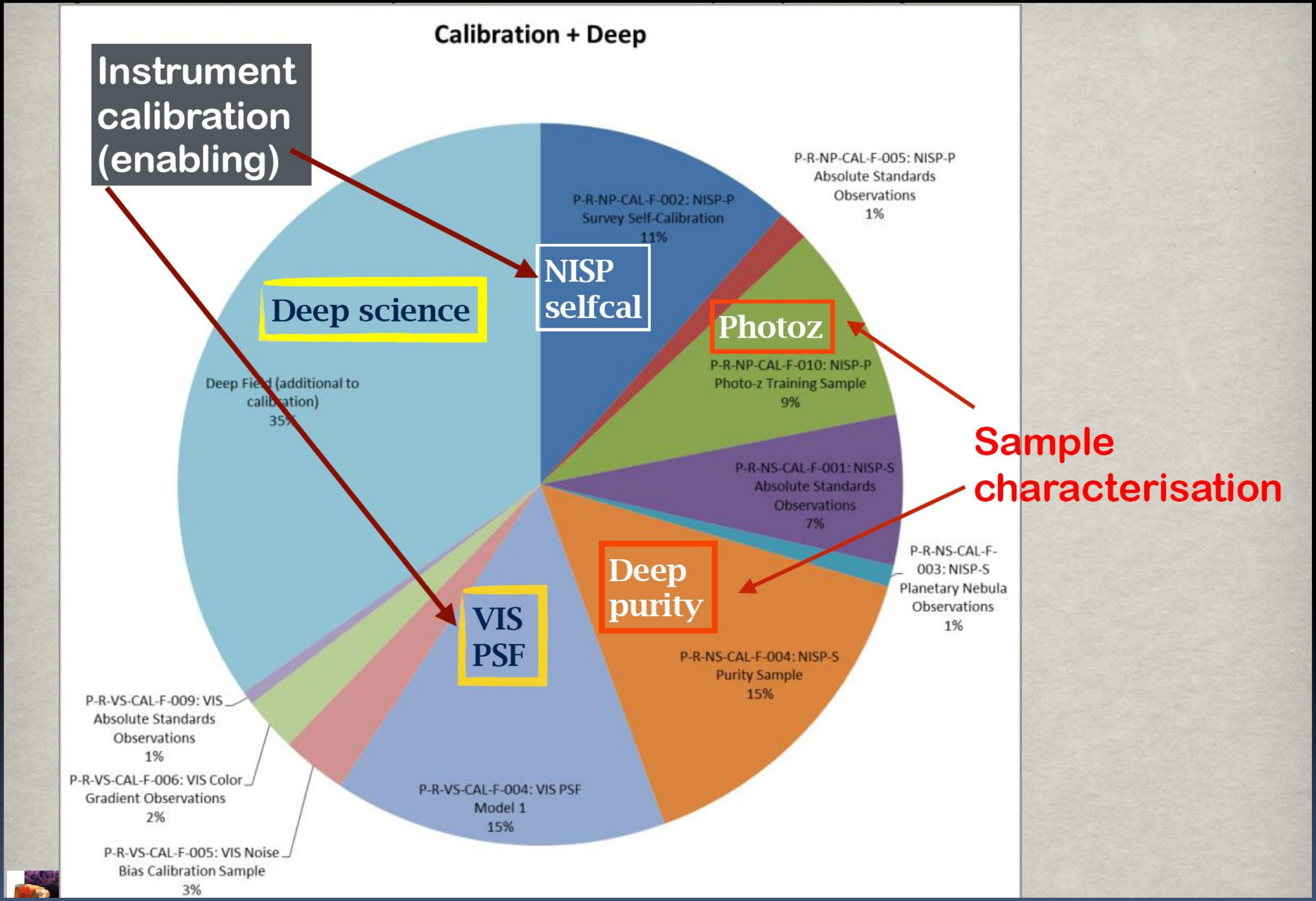
Target
Sampling Rate

Spectroscopic
Success Rate





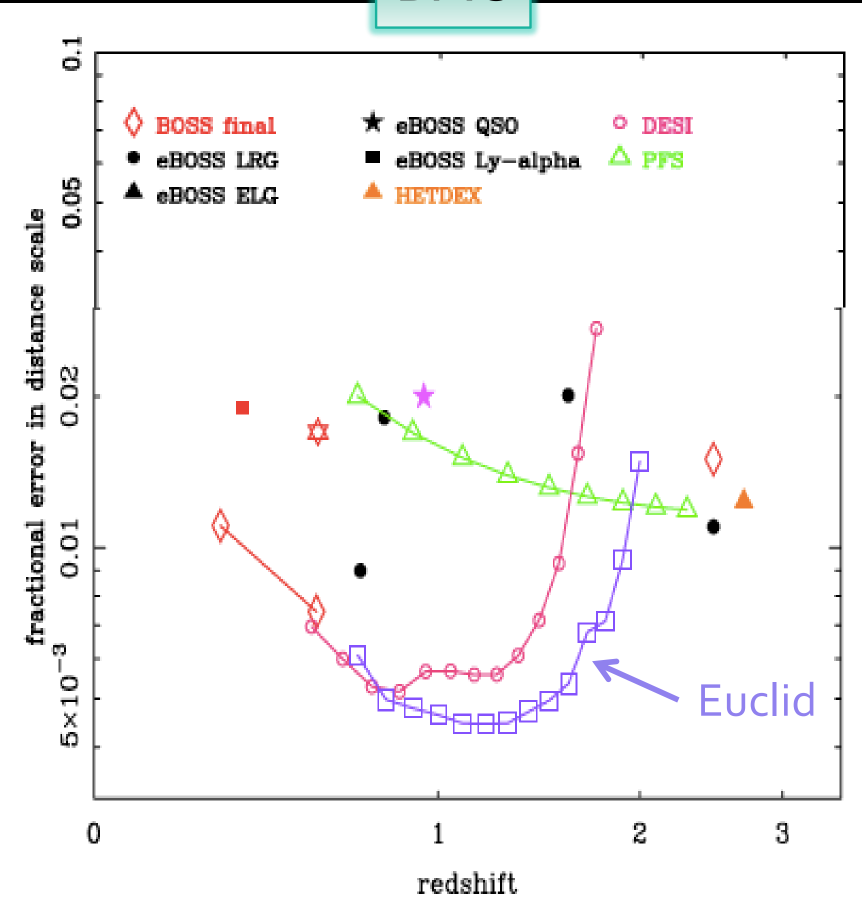
Survey timing



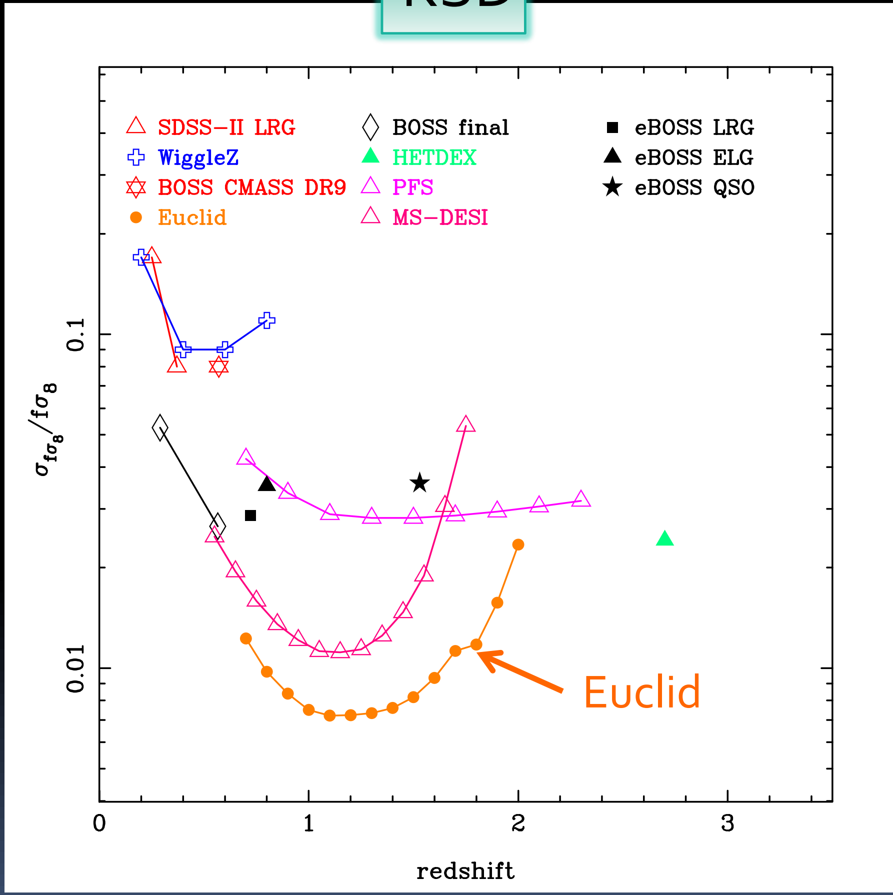
From Scaramella Euclid-Lisbon 2016

Future surveys forecast

BAO

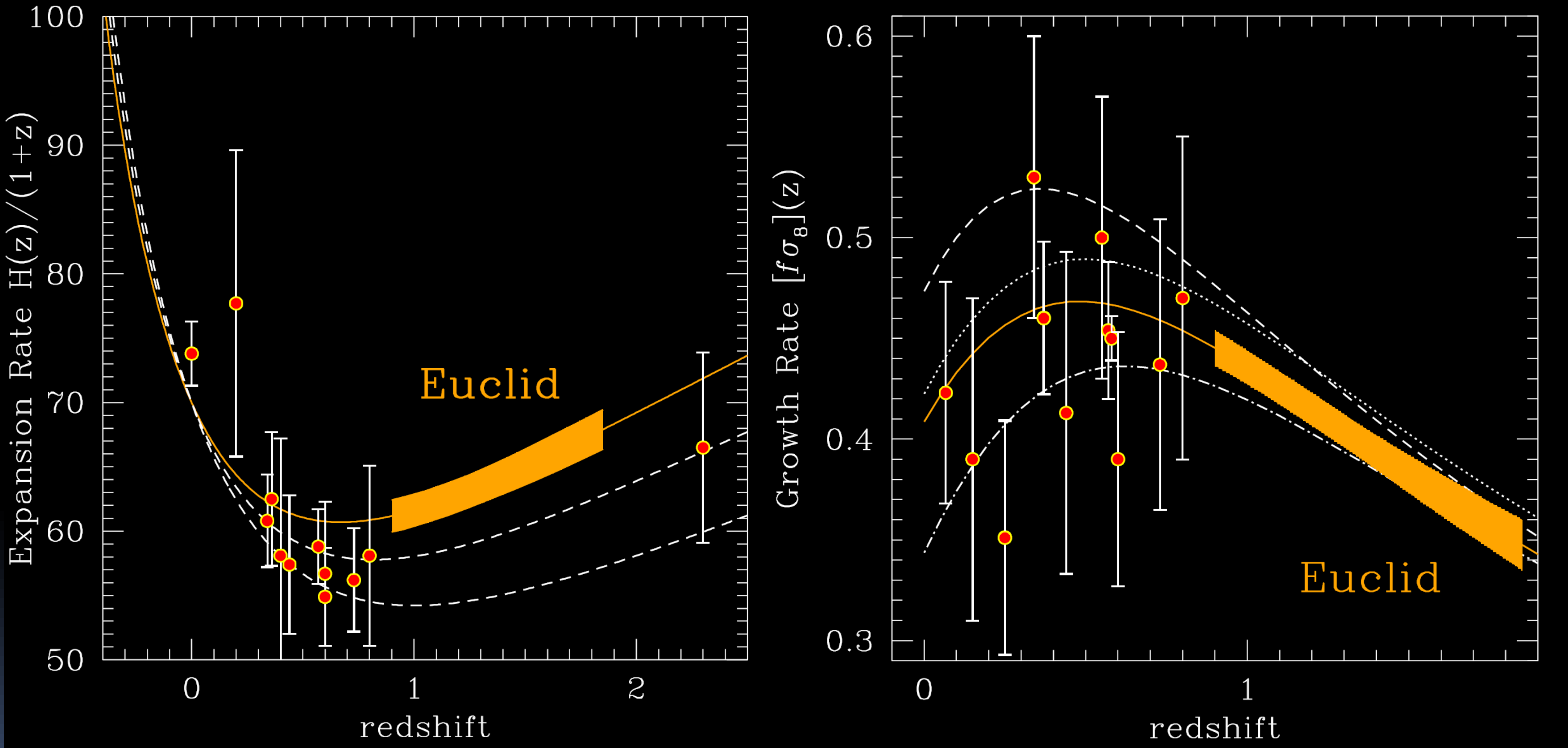


RSD



Credit: W. Percival

Euclid: forecast on H(z) and growth rate



From Guzzo, Euclid-Lisbon 2016

A word on WFIRST

- New kid on the bloc
- Refurbished 2.4m "star wars" telescope
- Wide field + depth combination
- Will be very competitive

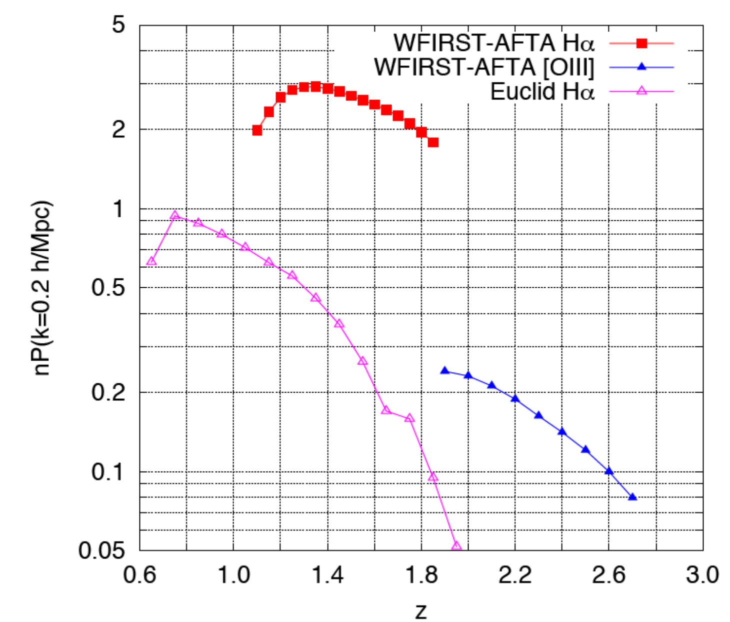
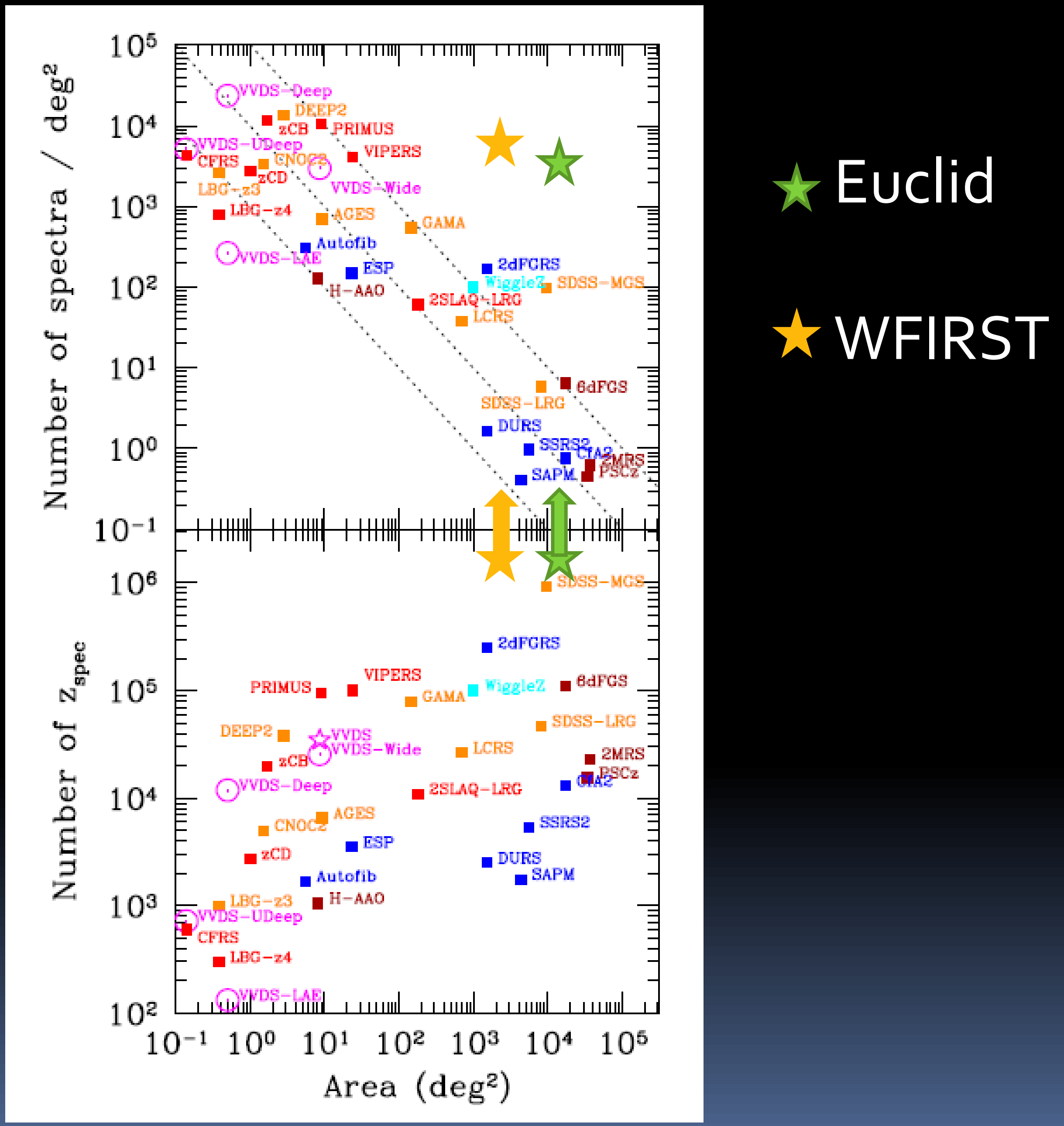


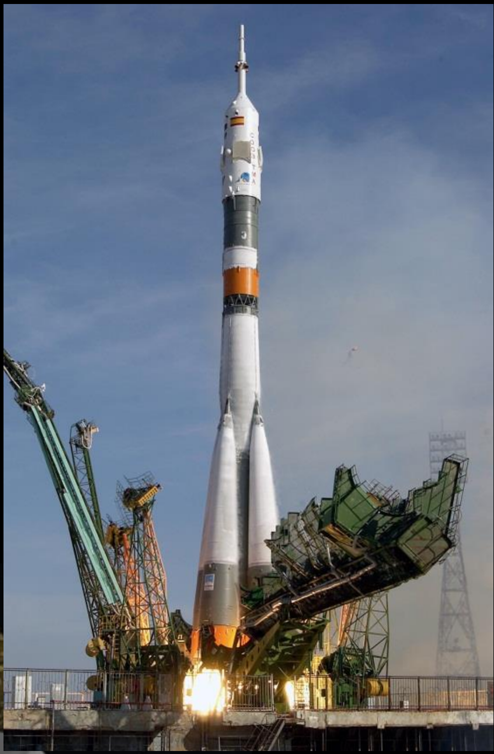
Figure 2-17: Product nP_{BAO} of the mean galaxy space density and the amplitude of the galaxy power spectrum at the BAO scale as a function of redshift for the

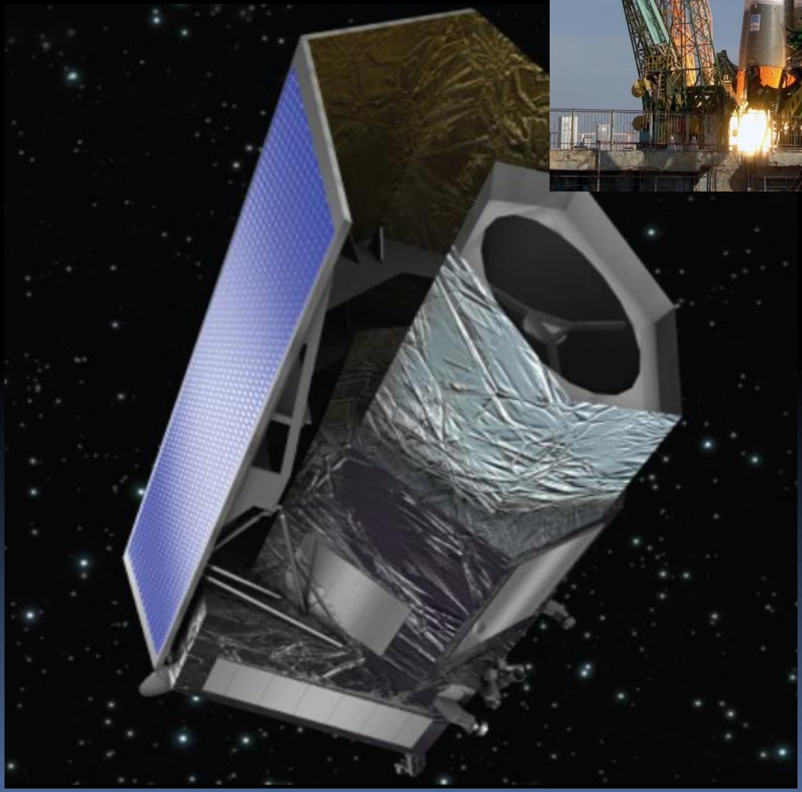

Euclid
WFIRST
Number of spectra / deg²
Number of z_spec
Area (deg²)
VVDS−Deep
DEEP2
zCB
PRIMUS
VVDS−UDeep
CFRS
CNOC2
VIPERS
zCD
LBG−z3
VVDS−Wide
LBG−z4
AGES
GAMA
Autofib
VVDS−LAE
ESP
2dFGRS
H−AAO
WiggleZ
SDSS−MGS
2SLAQ−LRG
LCRS
6dFGS
SDSS−LRG
DURS
SSRS2
CfA2
2MRS
SAPM
PSCz
VVDS

Wait and see !

- Launch 2020
- 7 years nominal survey

- Lots of opportunities for participation





THANK YOU !