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&

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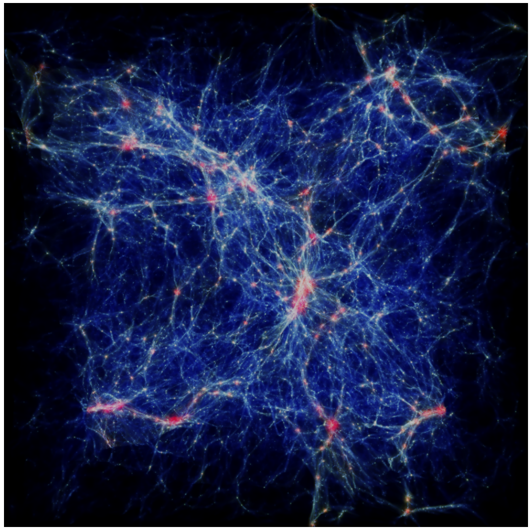
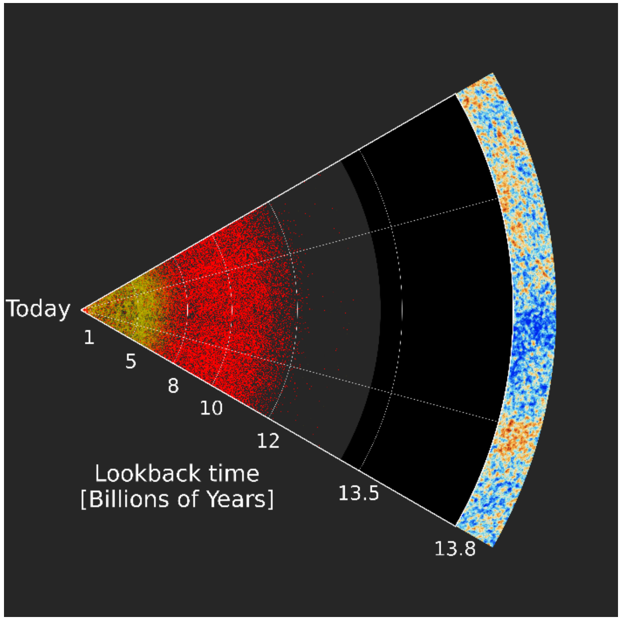
First measurement of the growth rate of structures with the SDSS-IV eBOSS DR14 quasar sample

PHENIICS FEST

May 31st

1. Structure formation within ΛCDM model

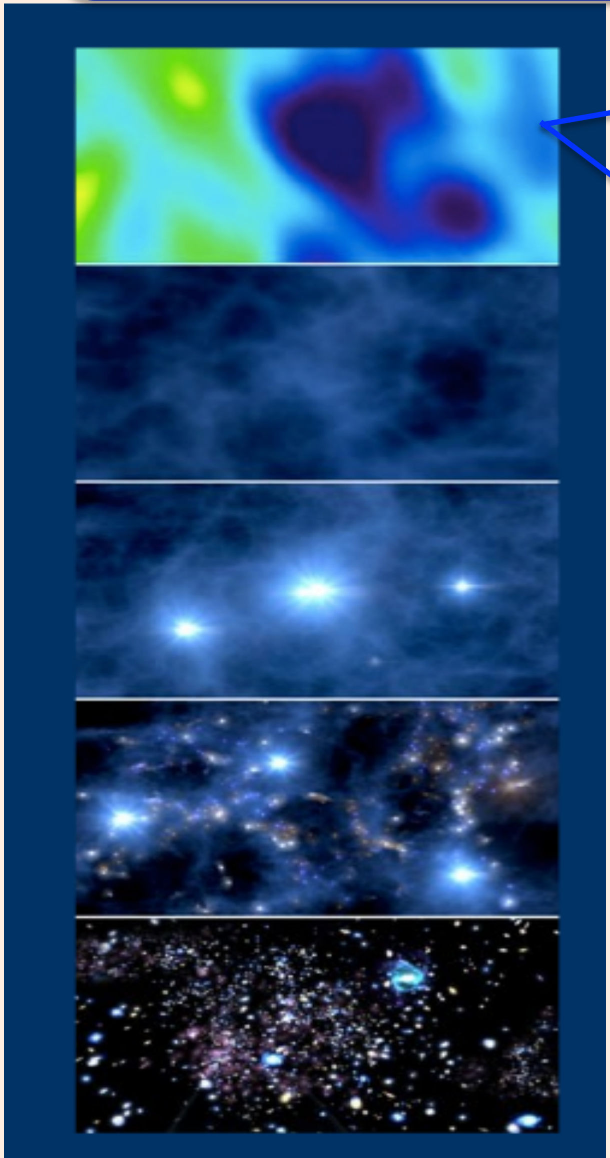


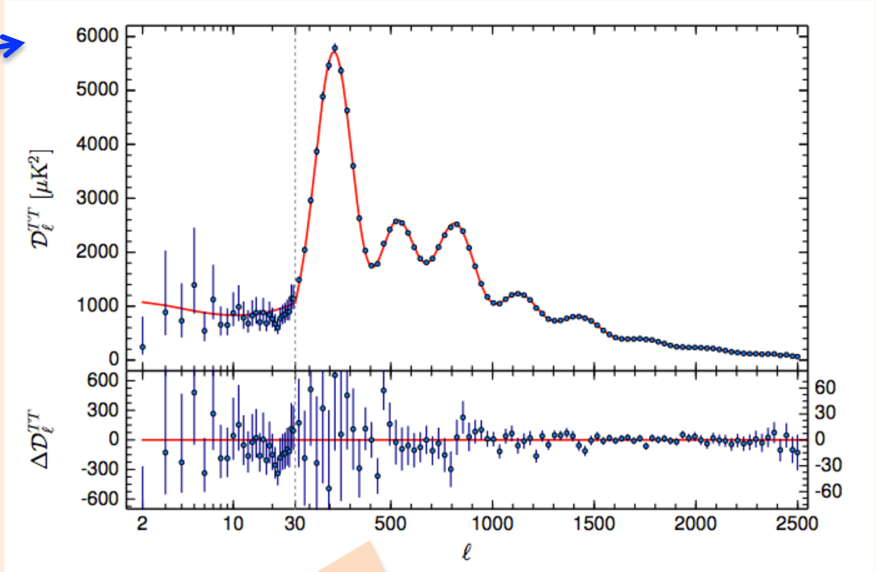


2. Using large-scale surveys like eBOSS

3. Extract the cosmological parameters

Structure formation within ΛCDM model



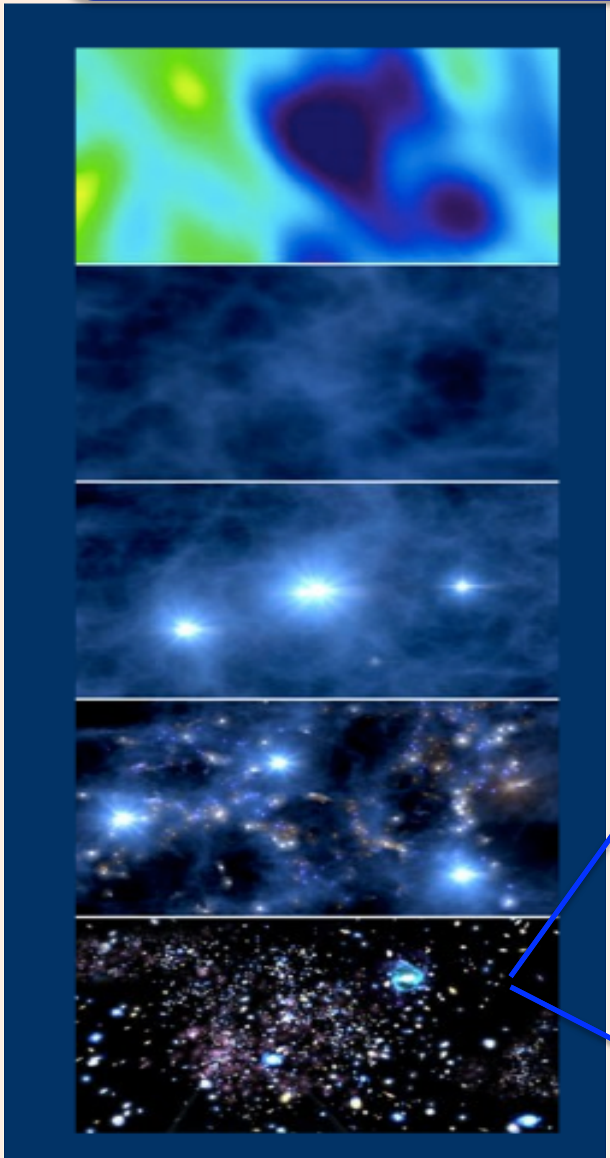


Primordial universe

- Very homogeneous $\Delta\rho / \rho \sim 10^{-3}$
- Hot and dense

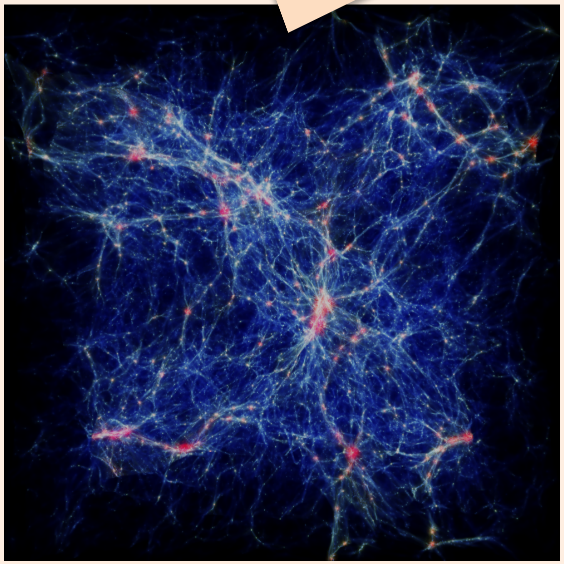
→ **Initial Gaussian fluctuations of matter**

Structure formation within ΛCDM model



The universe today

- Very inhomogeneous
- gravitationnaly-bound structures
- Ordinary matter falls into dark matter wells
- Late acceleration of the expansion of the universe



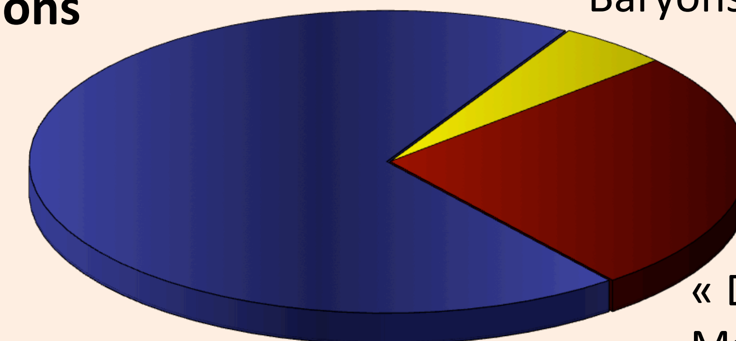
[Credit: Julien Baur, Nathalie Palanque-Delabrouille (Irfu/CEA)]

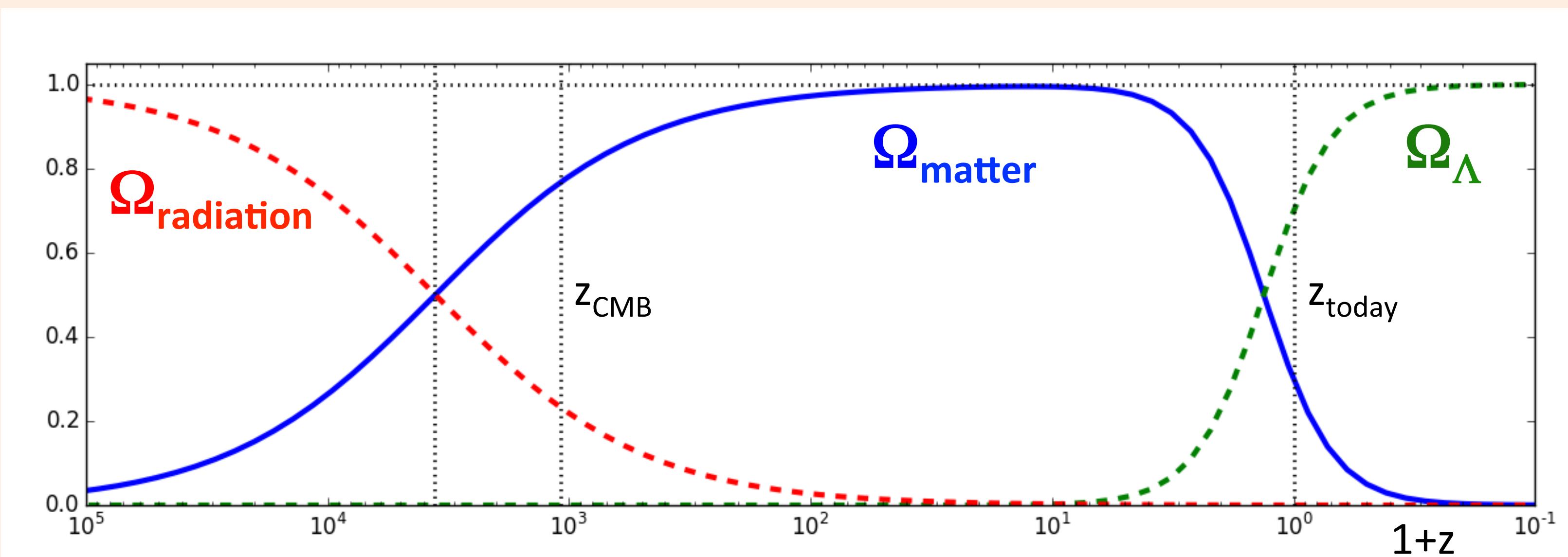
The concordance model – ΛCDM

Key ingredients (simplified) :

- Inflation produces a scale invariant perturbation spectrum : **initial Gaussian fluctuations**
- **Assumes General Relativity**
- Baryon density
- Cold dark mater (CDM) density
- Dark energy (Λ) density

→ Cosmological constant





Growth of structures in linear theory

Density perturbation : $\delta = \frac{\Delta\rho}{\rho} << 1$

Evolution of δ described by:

- Mass conservation (continuity equation)
- Momentum conservation (Euler equation)
- Matter-gravitational potential relation (Poisson equation)

$\Rightarrow$ Linearized equation gives :

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G\bar{\rho}\delta = 0$$

$\Rightarrow$ 2 solutions

$$\delta(t) = \delta_+ D_+(t) + \delta\_D\_(t)$$

Linear growth rate of structures f

$$f(a) \equiv \frac{d\ln(D_+(a))}{d\ln(a)}$$

Linked to the divergence of the velocity field :

$$\nabla \cdot v = -f\delta$$

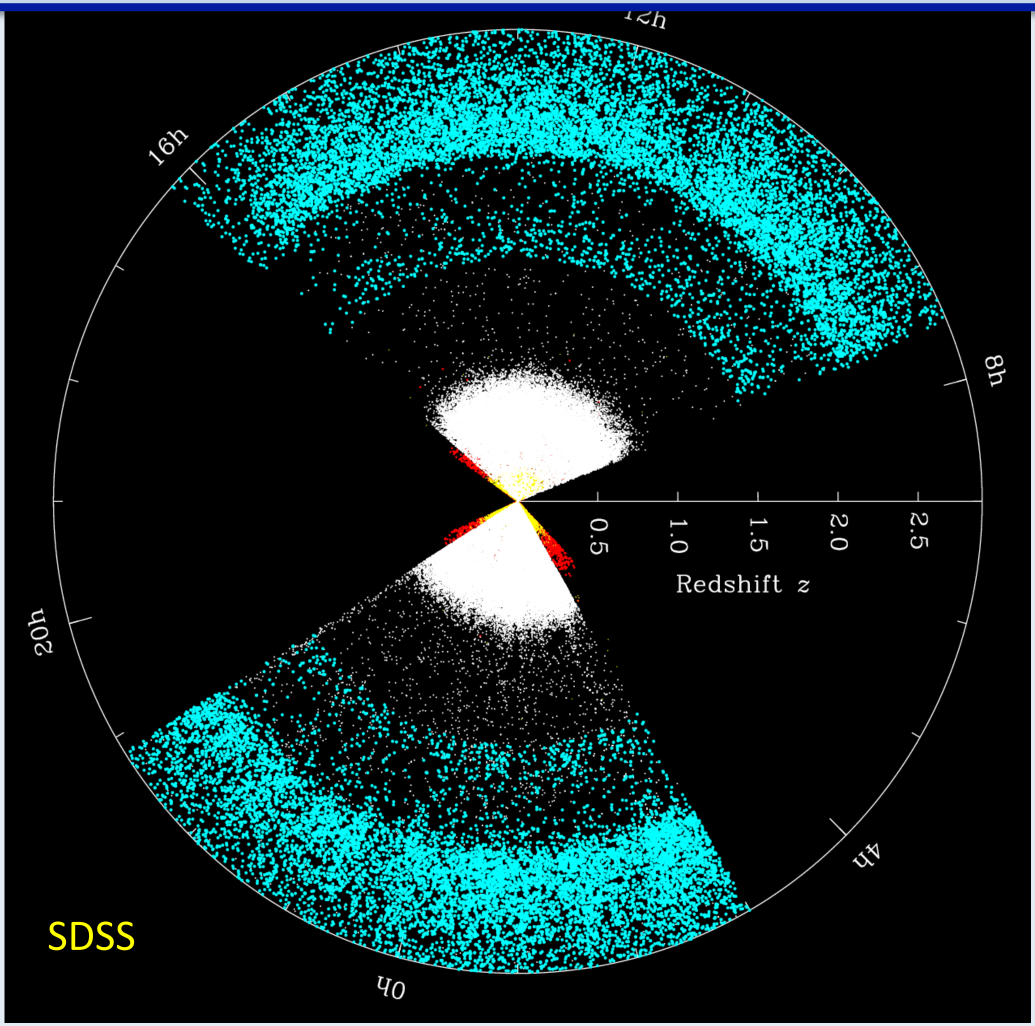
in General Relativity :

$$f(a) = \Omega_m(a)^{\gamma=0.55}$$

Redshift

$$1 + z = \frac{a(t_0)}{a(t)}$$

Using large-scale surveys like eBOSS



Baryon Oscillation Spectroscopic Survey

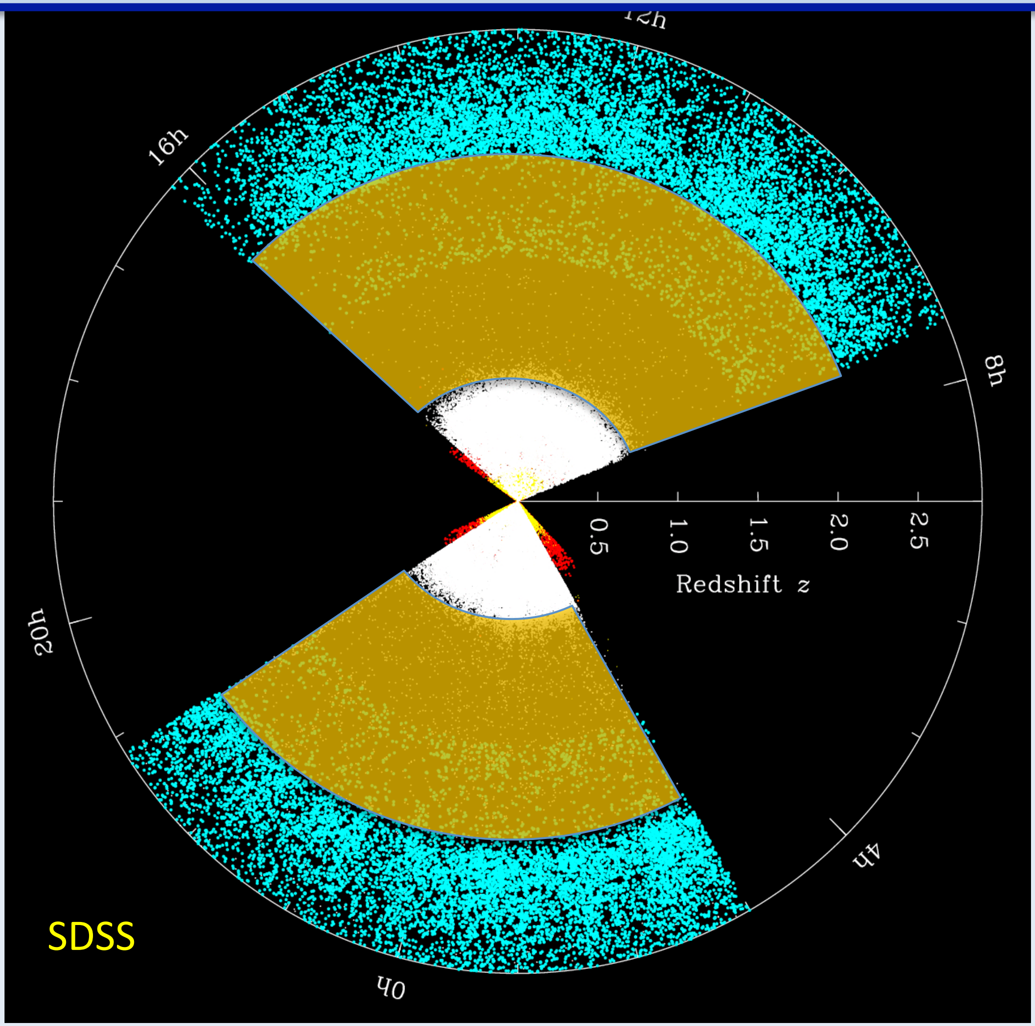
BOSS – SDSS 3

0.2 < z < 0.7 Luminous Red galaxies

Ly-α Quasars, 2.2 < z < 5

➢ Absorption by hydrogen along the line of sight

Using large-scale surveys like eBOSS



Baryon Oscillation Spectroscopic Survey

BOSS – SDSS 3

0.2 < z < 0.7 Luminous Red galaxies

Ly-α Quasars, 2.2 < z < 5

- Absorption by hydrogen along the line of sight

eBOSS – SDSS 4

0.9 < z < 2.2 Quasars*

- Tracers of cosmic structures
- Unexplored universe

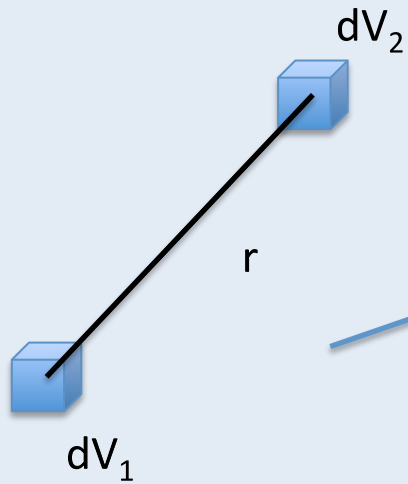
0.6 < z < 1.2 Emission Line Galaxies (stars forming)

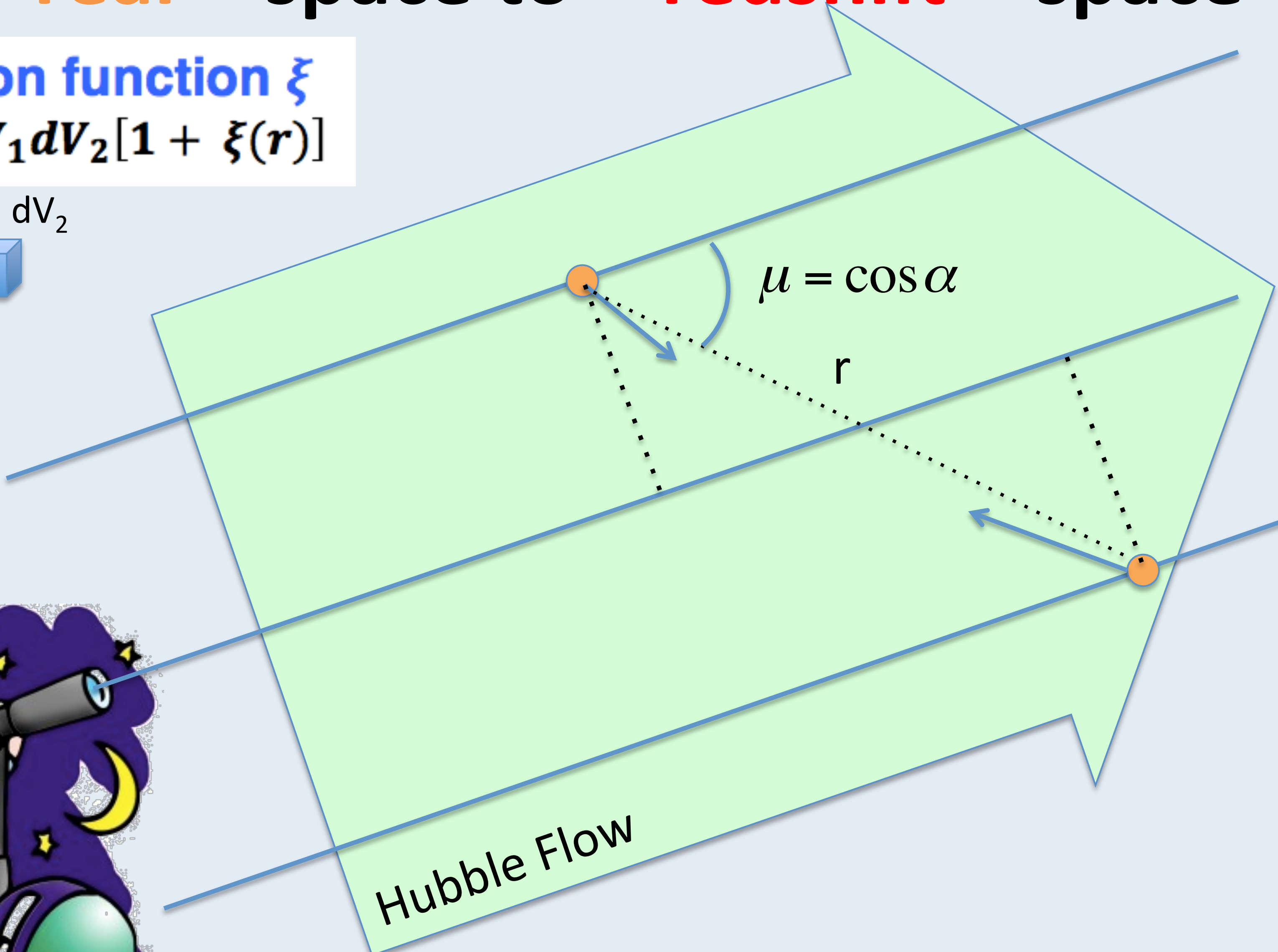
→ **Biased tracers of matter:** $\xi_{tr}(r) = b^2 \xi_m(r)$

From « real » space to « redshift » space

Correlation function ξ

$$dP = \overline{\rho}(r)dV_1dV_2[1 + \xi(r)]$$





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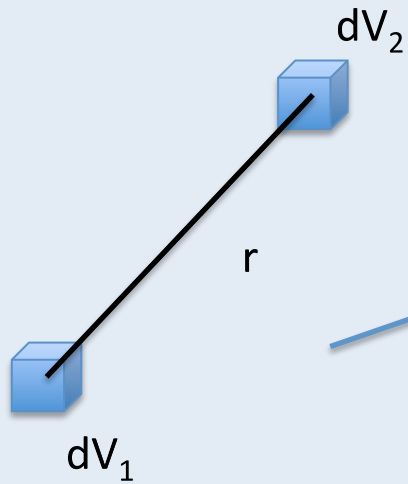

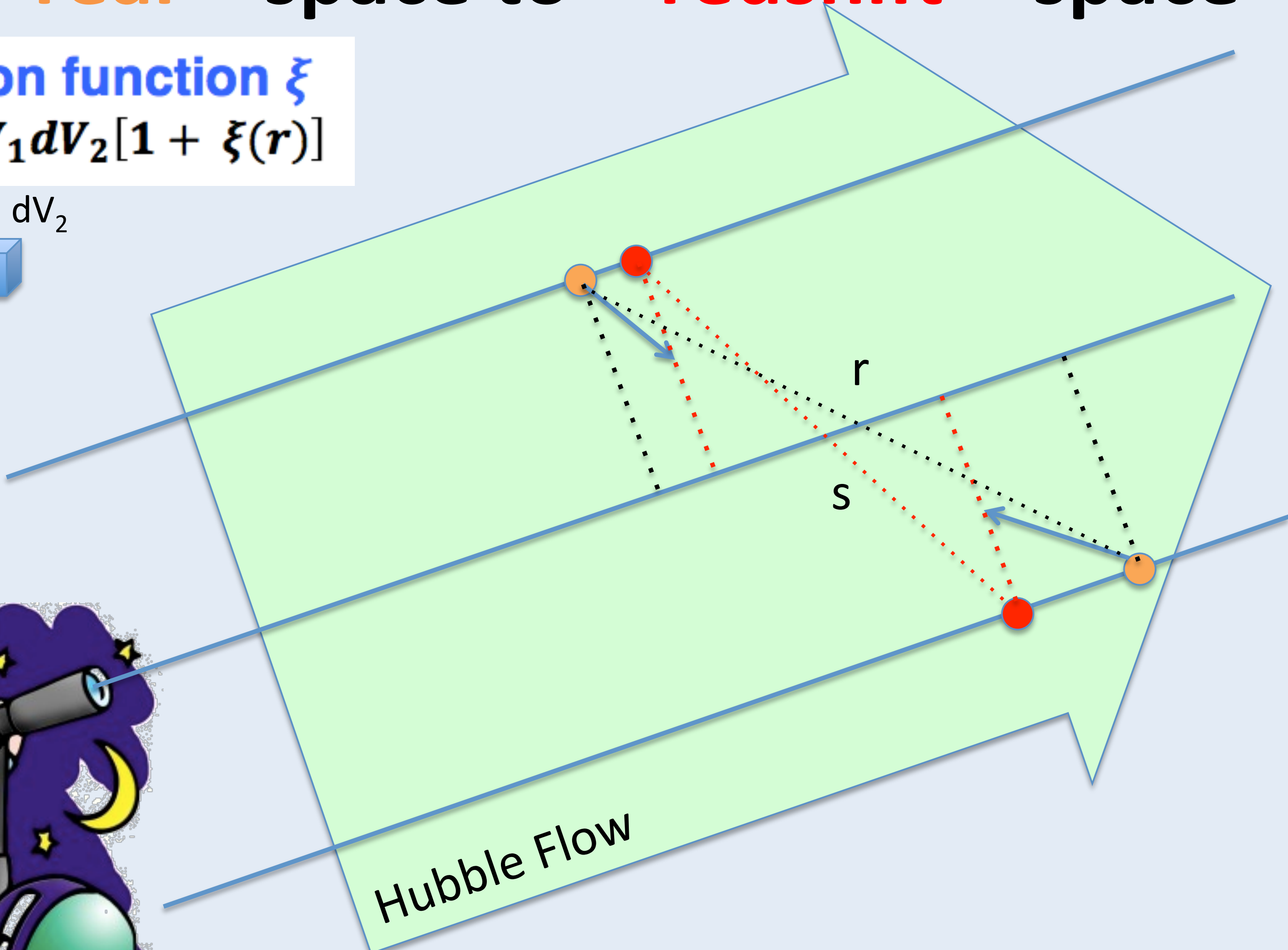

From « real » space to « redshift » space

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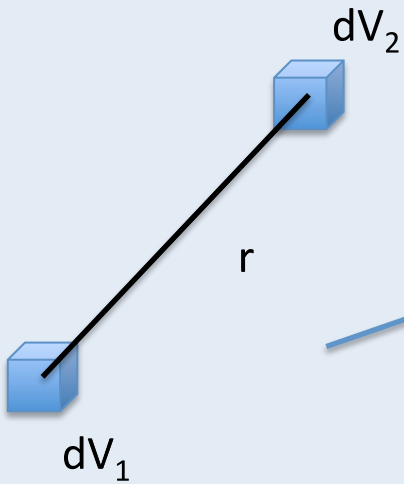
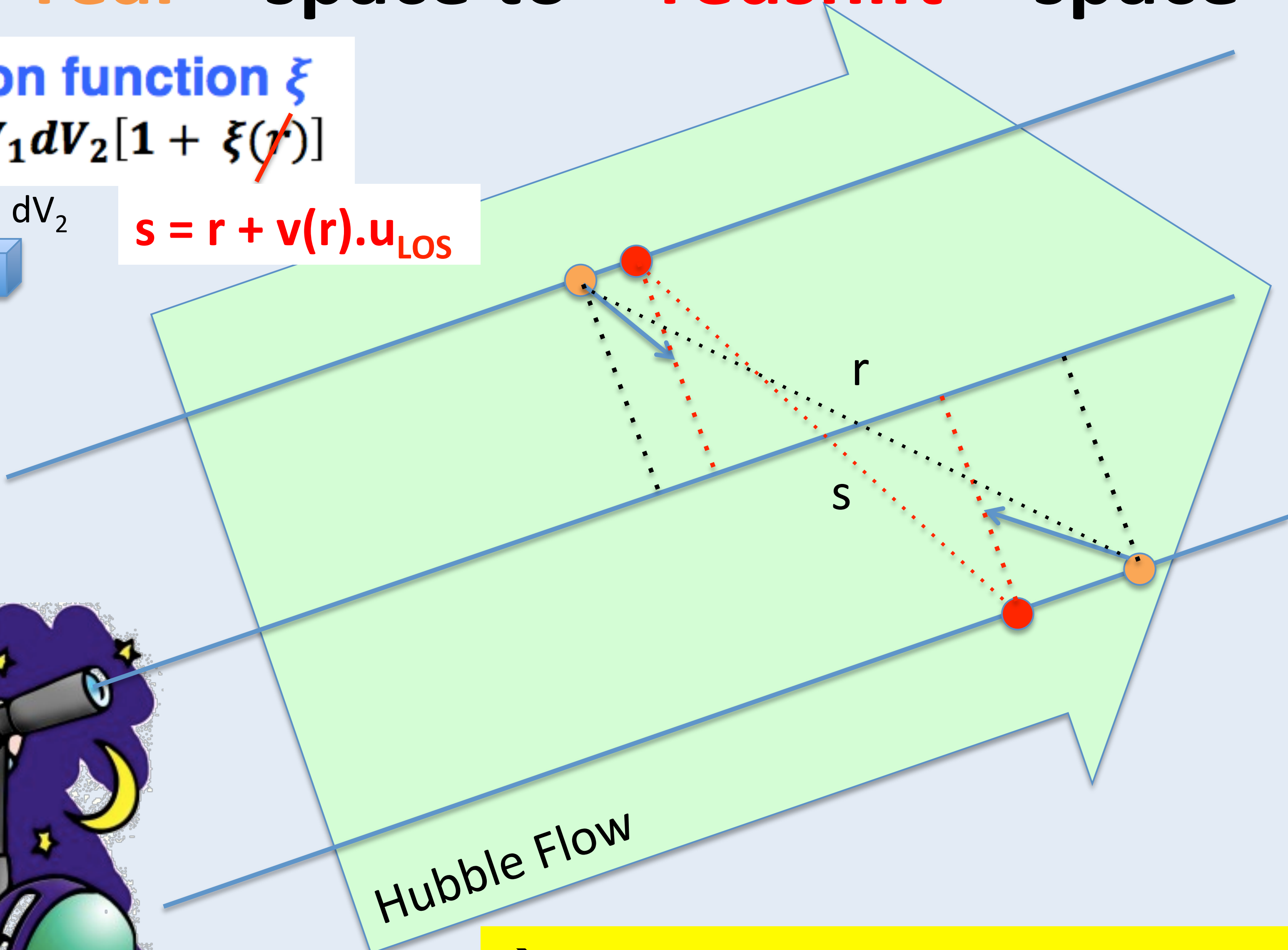
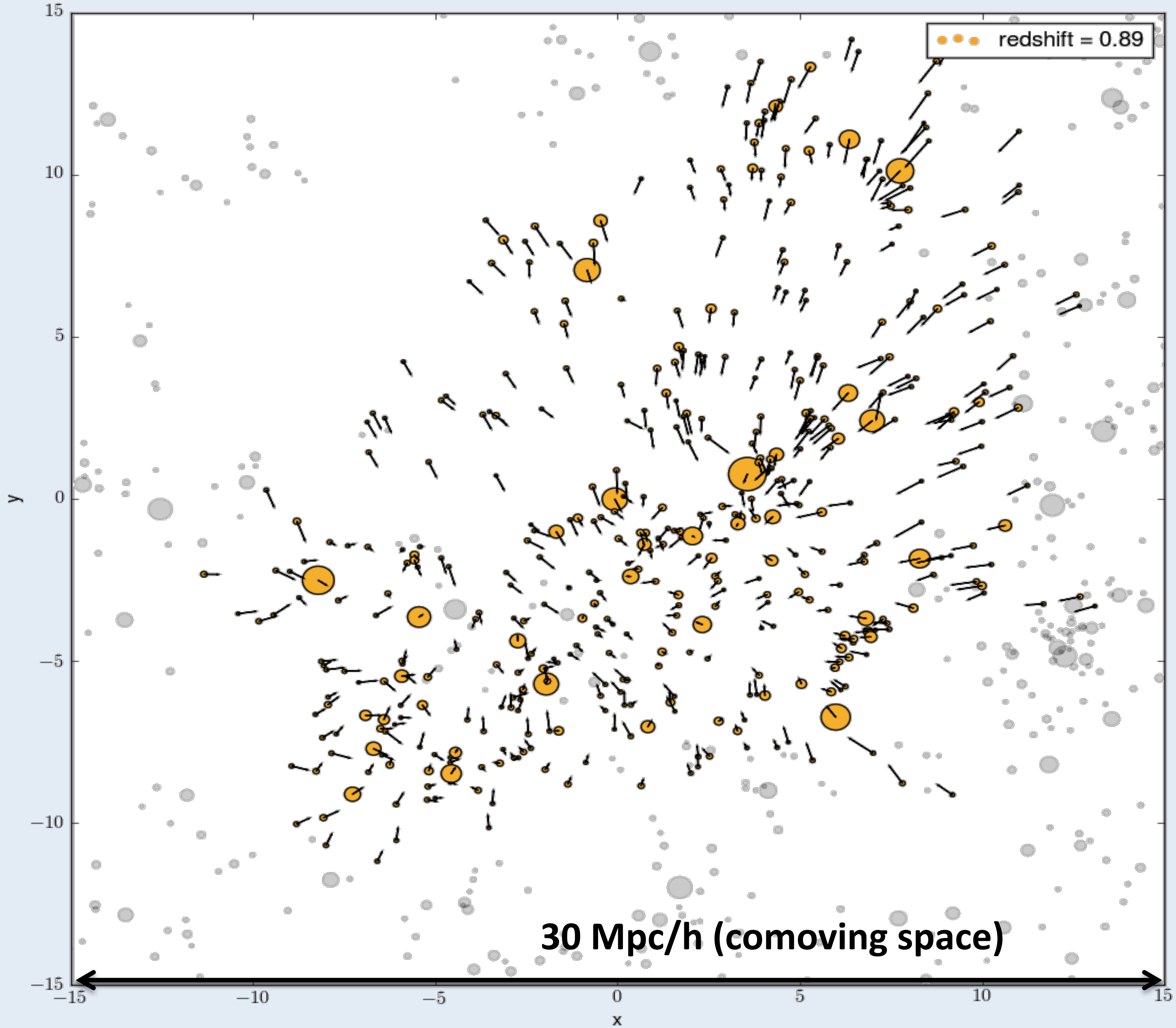


$s = r + v(r).u_{LOS}$



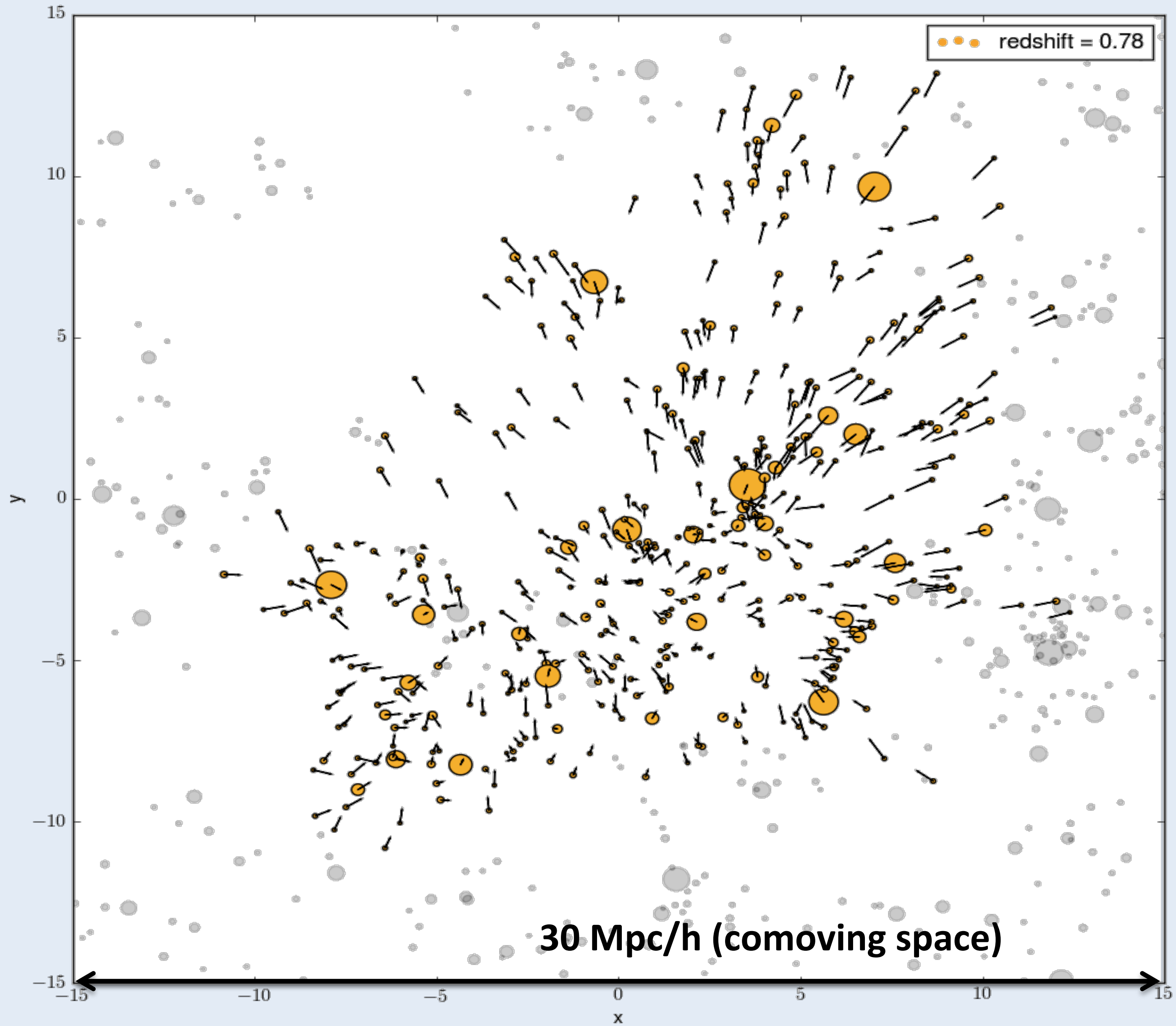
→ Redshift space distortions (RSD)

Coherent Infall



From MultiDark
N-Body simulation
Dark Matter only
$M_{halo} > 10^{12} M_{sun}$
Klypin et al. (2014)

Coherent Infall



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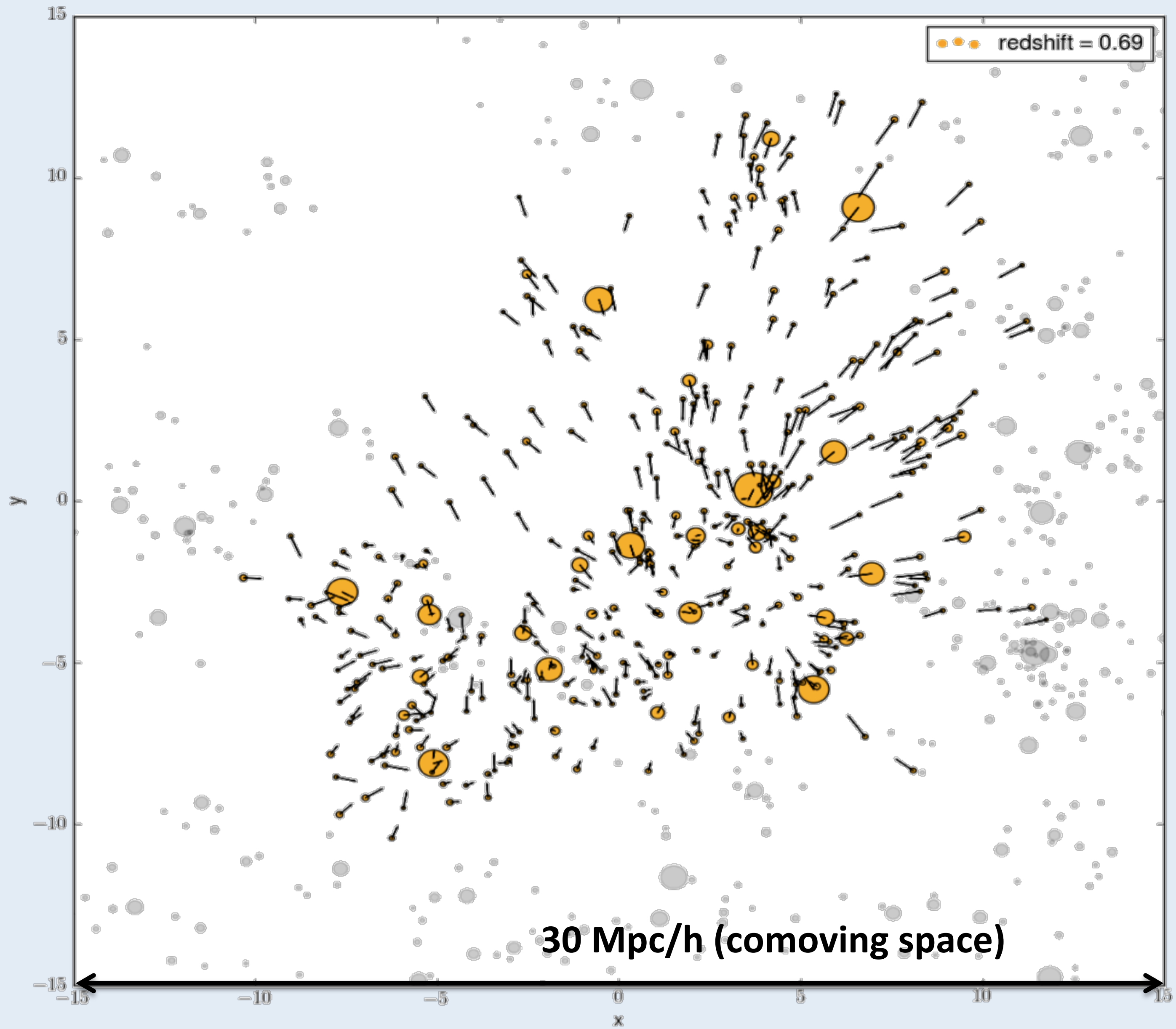

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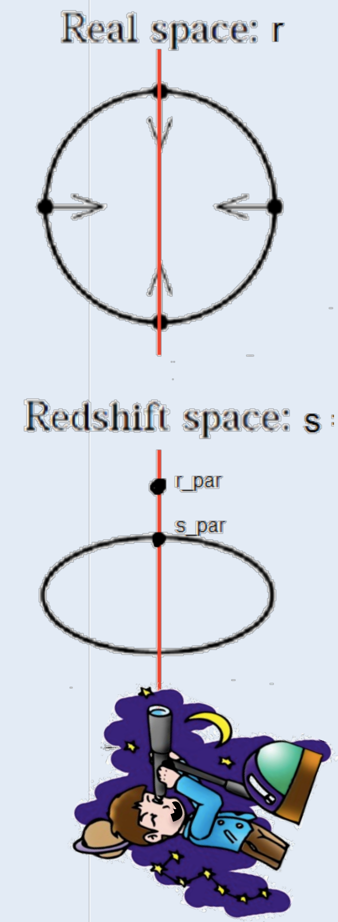
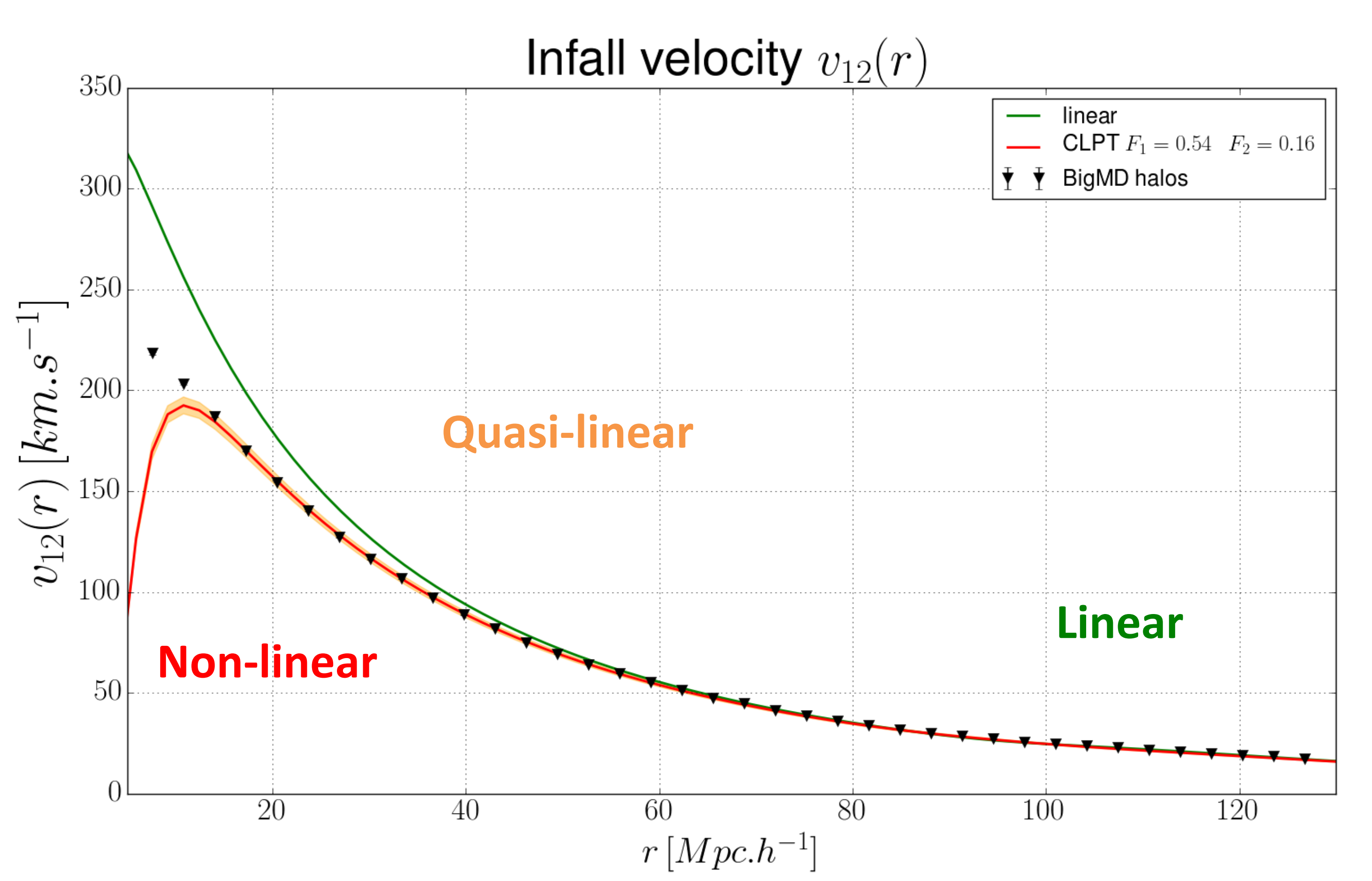


Pair-wise velocity distribution



1. To form dark matter halos in a N-body simulation for a given set of cosmological parameters

2. To apply mass selection to select halos which can host the astrophysical objects of interest

3. To calculate velocity and clustering statistics of these «fictive » population to test RSD models

Model : Convolution Lagrangian Perturbation Theory, Carlson et al. (2013), Wang et al. (2014)

Anisotropic 2-point correlation function

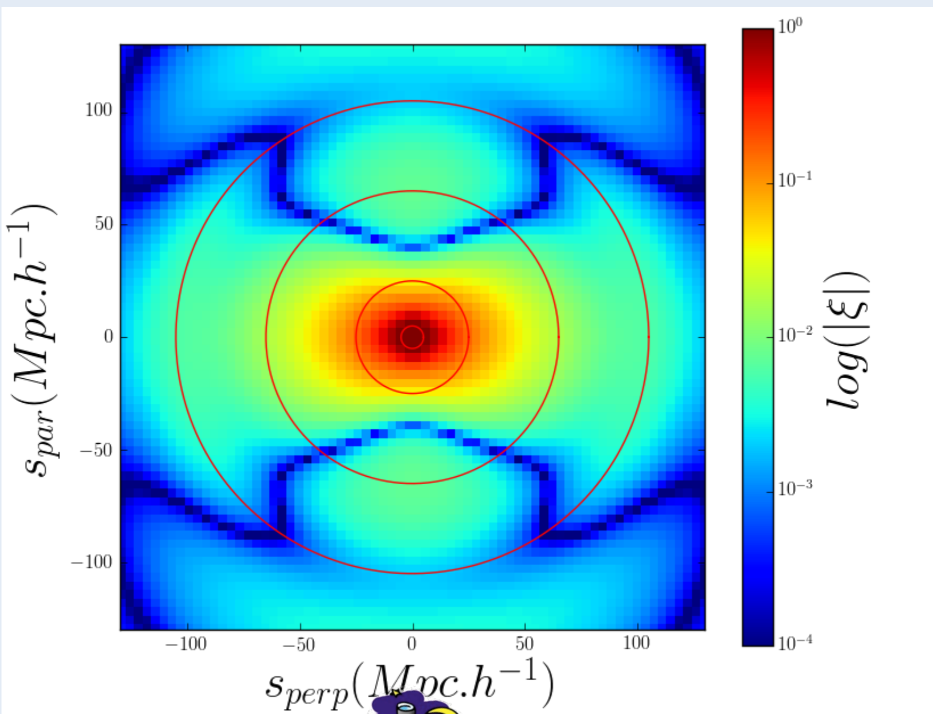
Gaussian Streaming model :

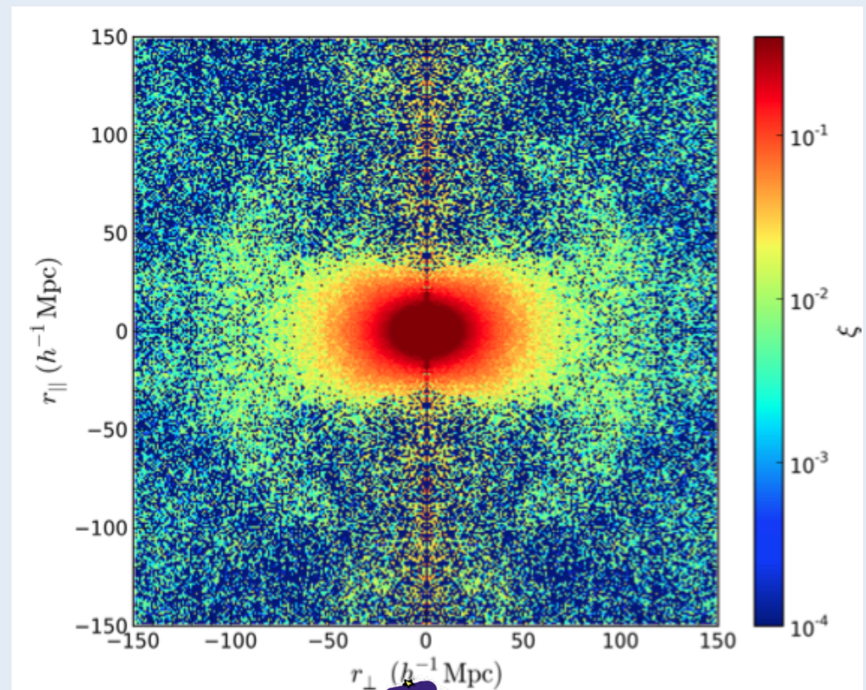
Real space (model)

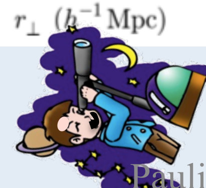
Redshift space

$$1+\xi(s_{\parallel},s_{\perp}) = \int dr_{\parallel}\left[1+\xi(r)\right]G(s_{\parallel}-r_{\parallel},\mu\cdot v_{12}(r),\sigma_{12}(r,\mu))$$

From 3D distribution of quasars







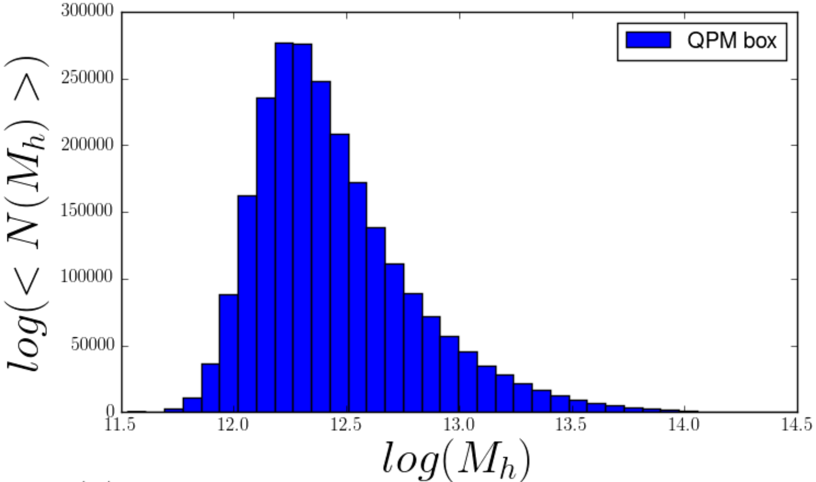
BOSS – LRG

Samushia et al. 2014

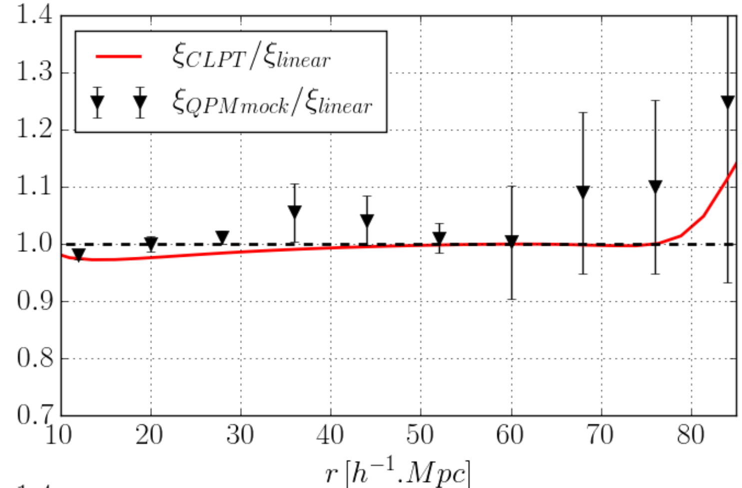
Test of the validity of the model

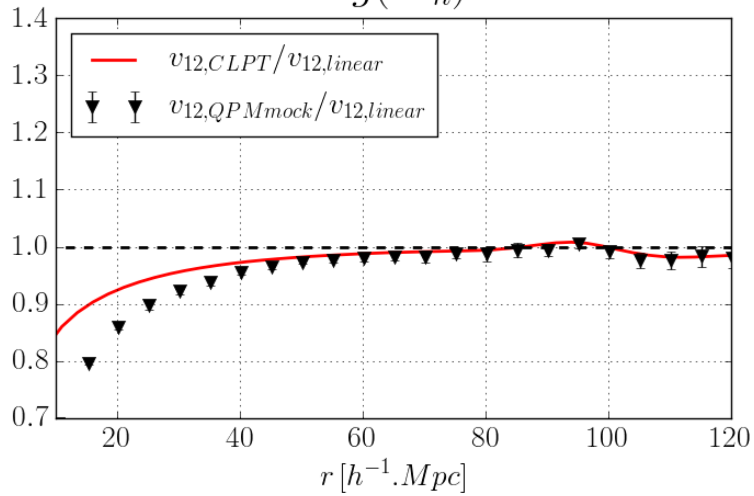
QPM boxes (White, Tinker & McBride 2013)

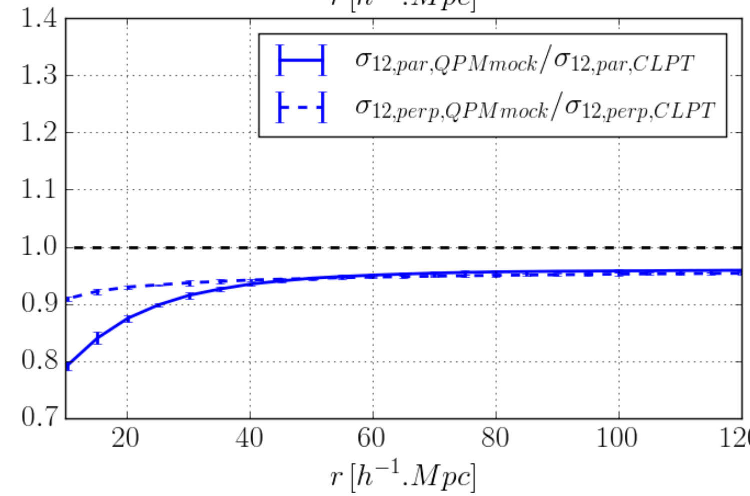
DM halo mass distribution



Correlation function in real space







Infall velocity

Dispersion velocity

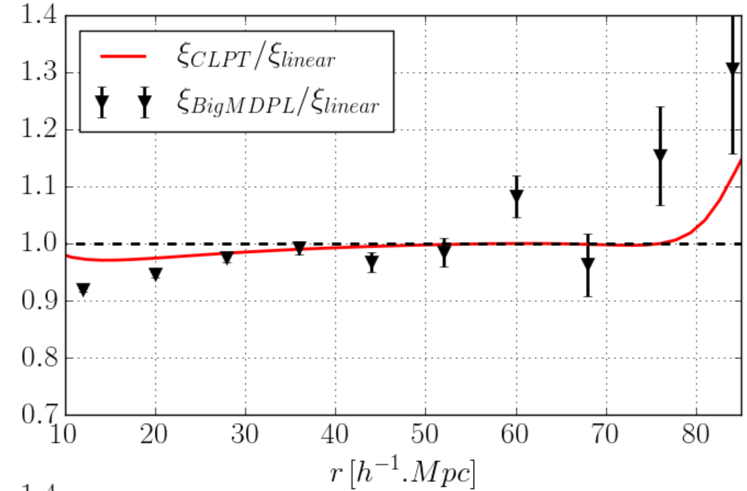
P. Zarrouk, E. Burtin et al. (2017a in prep)

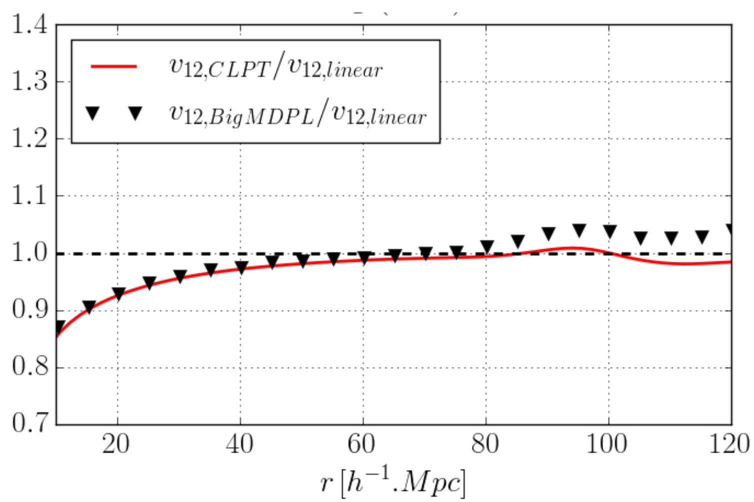
Test of the validity of the model

<u>BigMDPL simulation</u> (Klypin et al. 2014)

- **We select central halos only with log (M/h^{-1}M $_{sun}$) in [12.3,12.7]** (mass distribution similar to the one in QPM boxes)

Correlation function in real space





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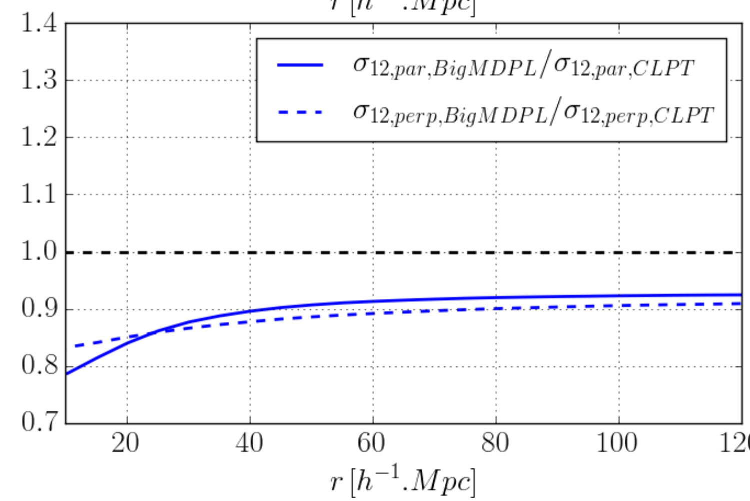


Dispersion velocity

Extract the cosmological parameters

$\xi_0^{Data}(s)$

$\xi_2^{Data}(s)$

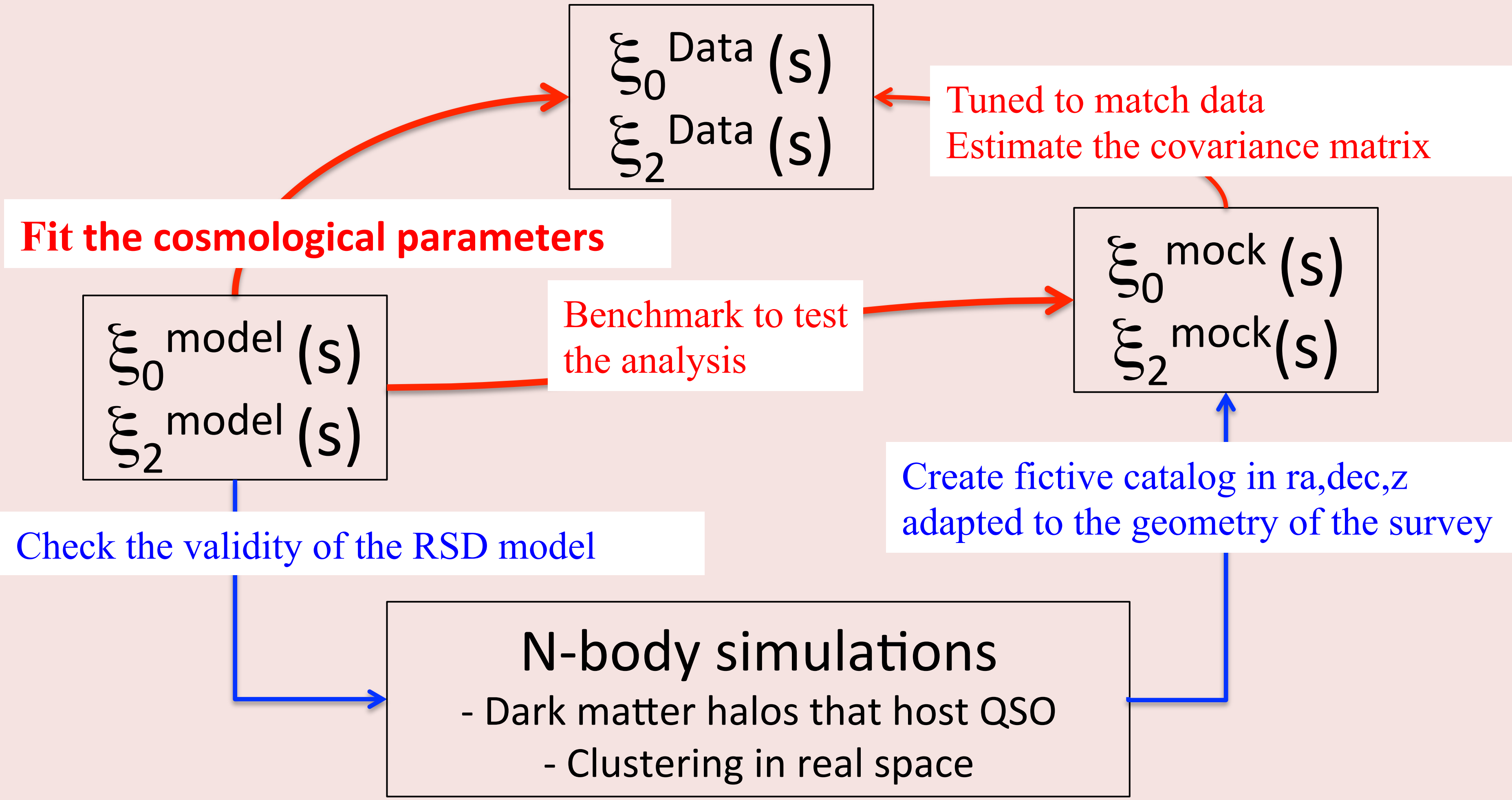
➢ **Multipoles:** $\xi_l(s) = \frac{2l+1}{2} \int_{-1}^{1} d\mu \, \xi(s,\mu) P_l(\mu)$

Where $P_0(\mu) = 1$ and $P_2(\mu) = \frac{1}{2}(3\mu^2 - 1)$: Legendre decomposition

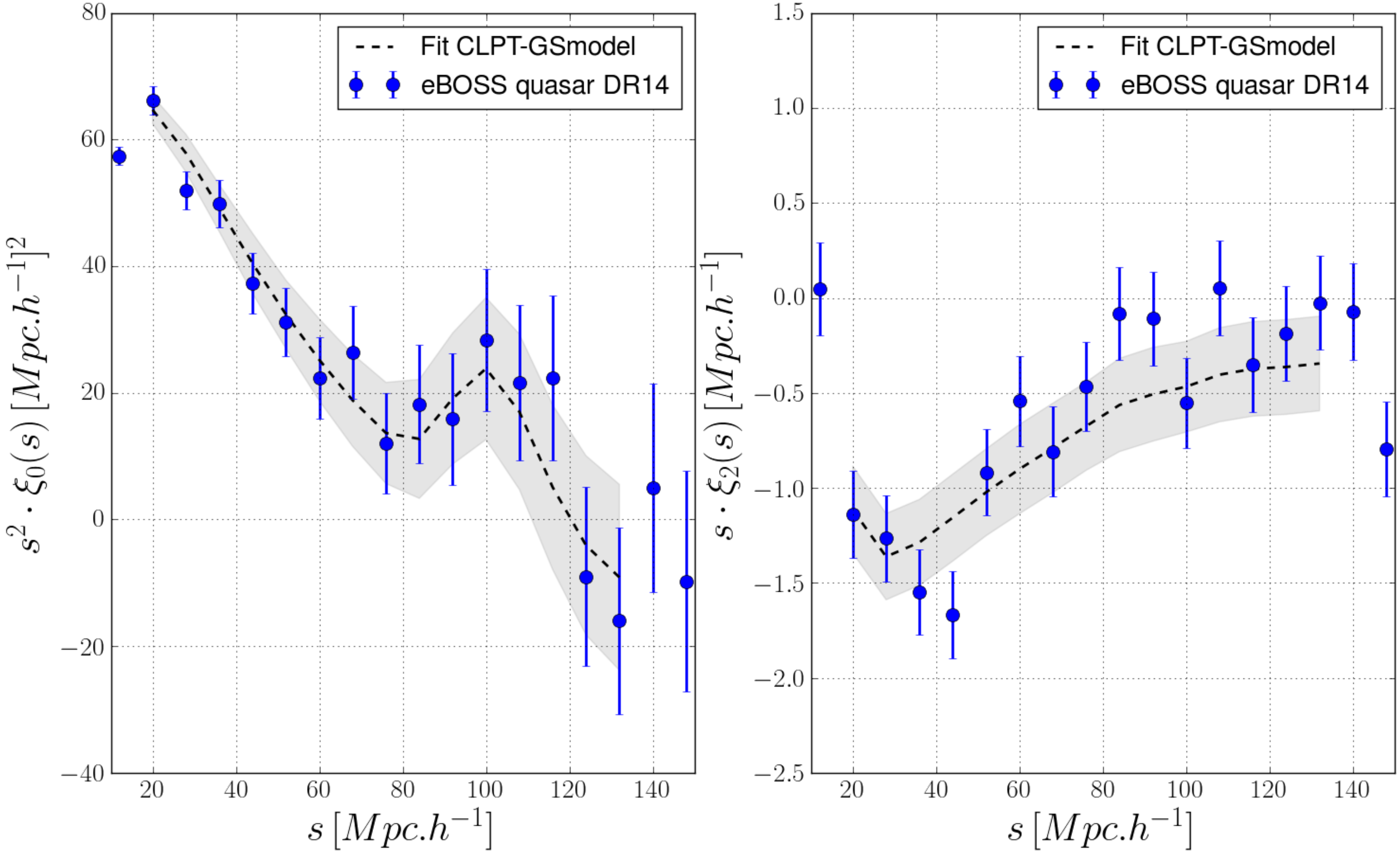
→ Monopole ξ_0 mostly related to $b\sigma_8$

→ Quadrupole ξ_2 related to $b\sigma_8$ and $f\sigma_8$

Extract the cosmological parameters

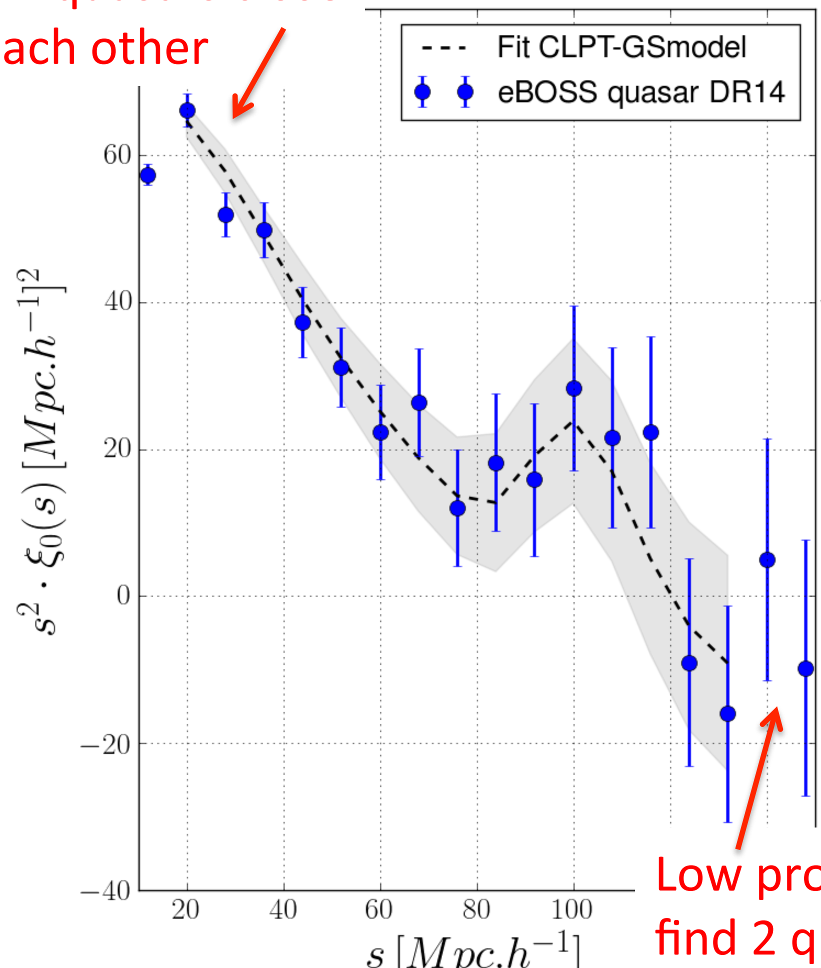


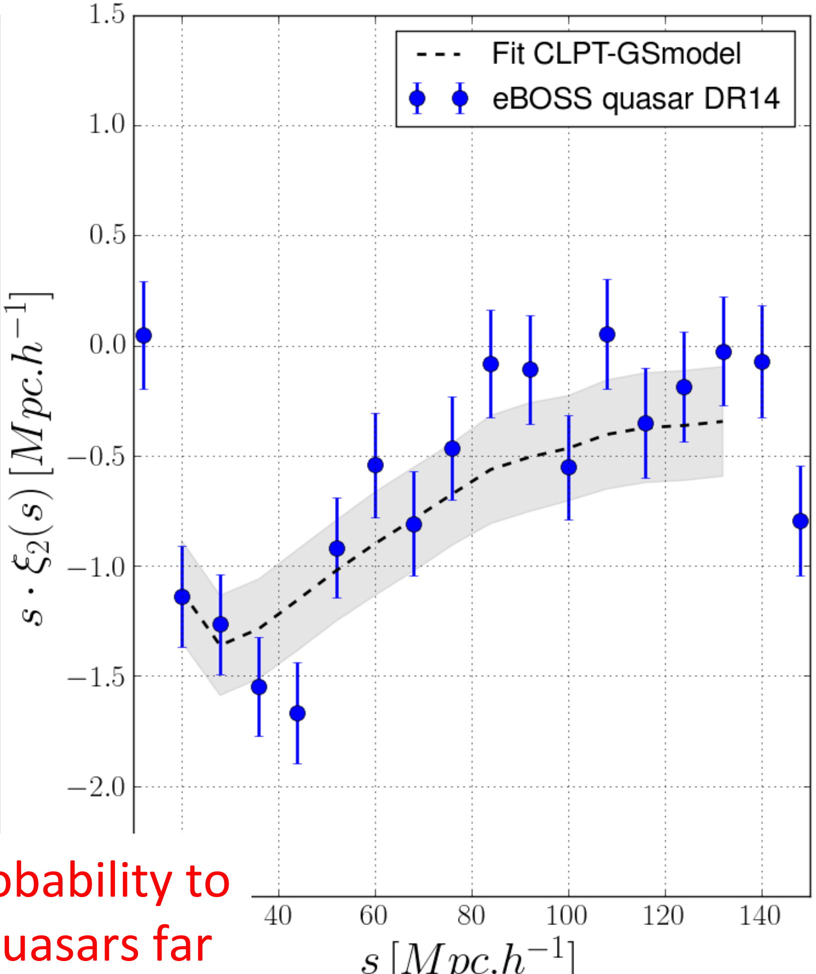
Monopole and quadrupole of the 2-point correlation function



Monopole and quadrupole of the 2-point correlation function

High probability to find 2 quasars close to each other

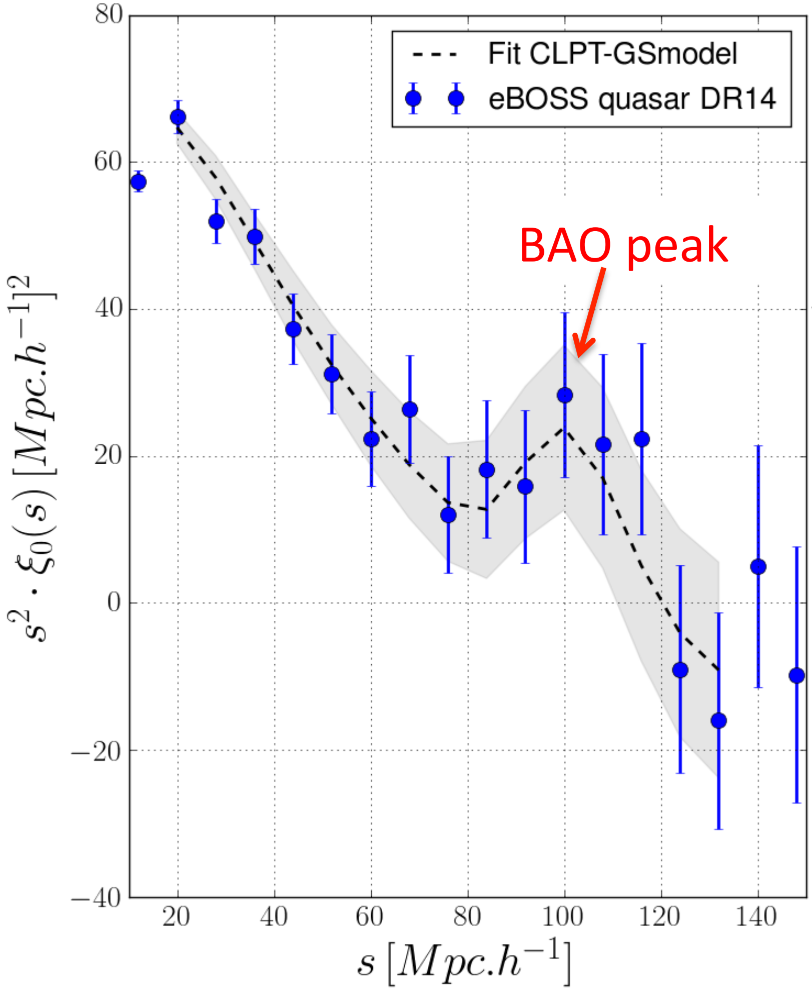


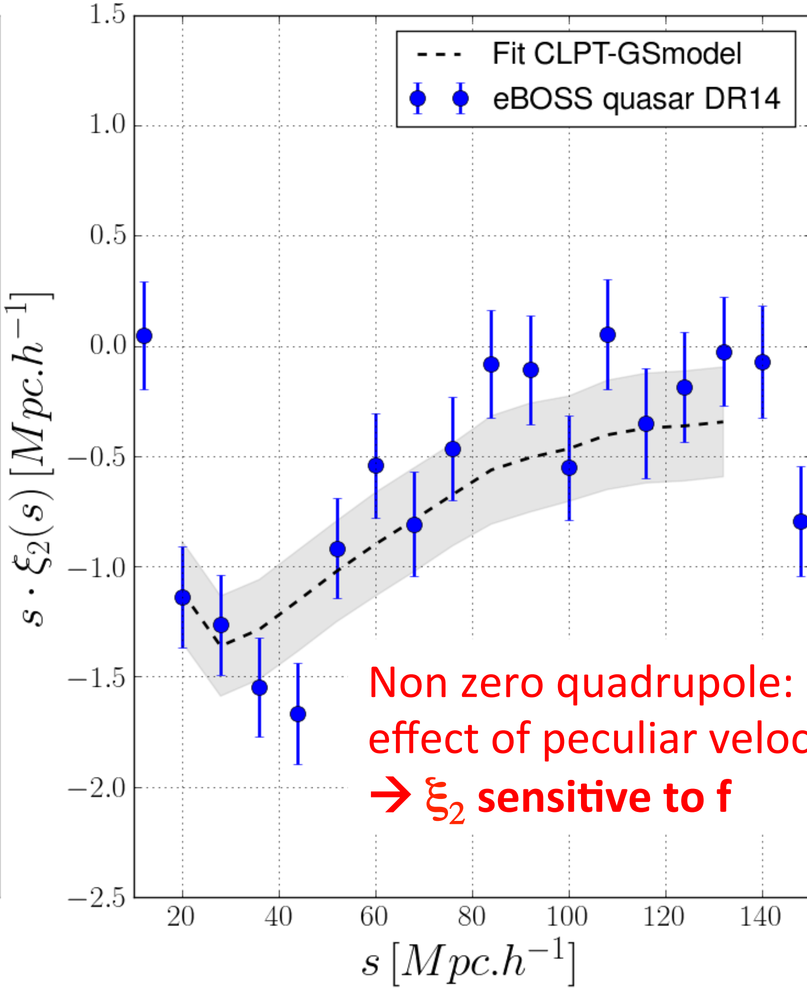


Low probability to find 2 quasars far from each other

Monopole and quadrupole of the 2-point correlation function

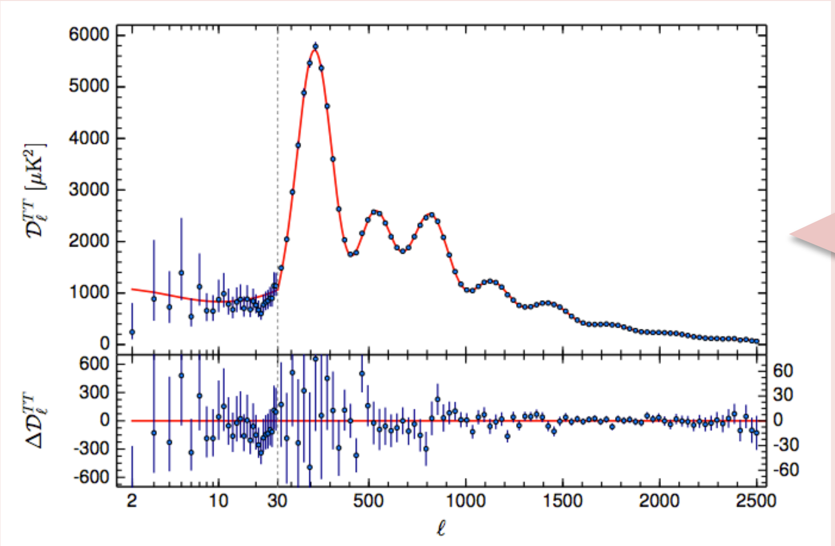
→ 3 physical parameters : $b\sigma_8$, $f\sigma_8$, α





Non zero quadrupole: sizeable effect of peculiar velocities
→ **ξ_2 sensitive to f**

The physics behind the BAO peak

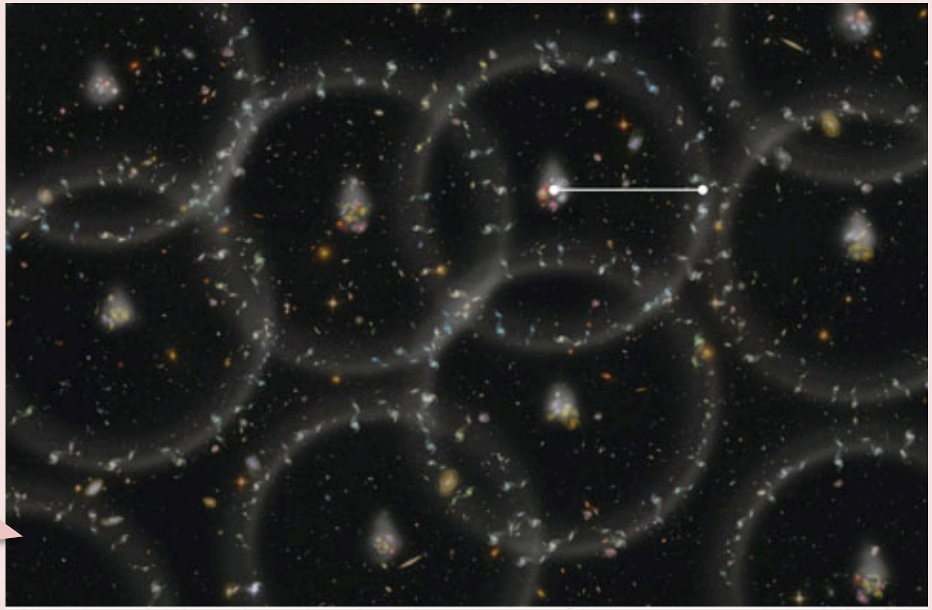


Plasma matter-light at the thermal equilibrium until decoupling

→ **Sound waves: Baryon Acoustic Oscillations**

When the Universe was 380,000 years old

Now



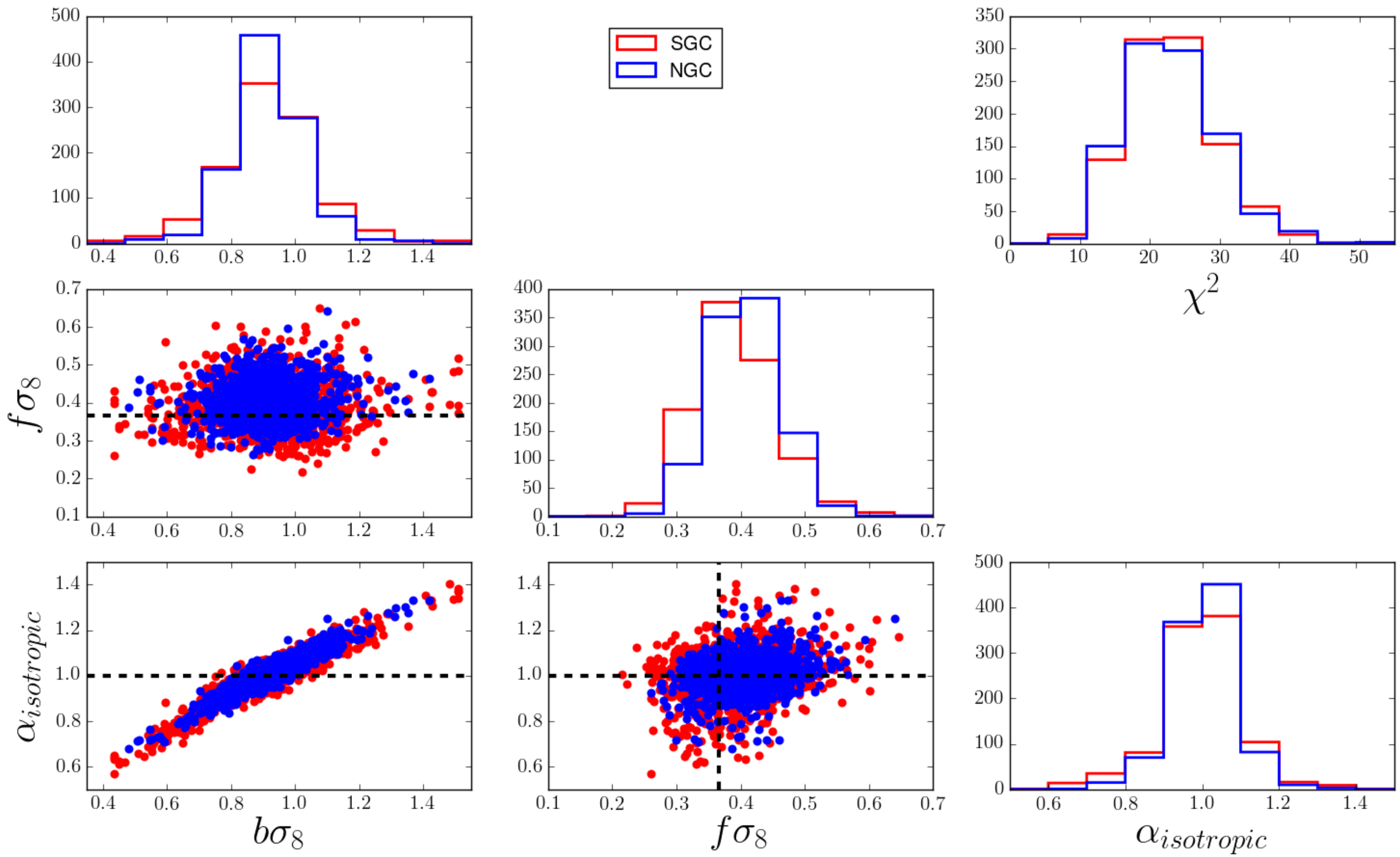
Imprint left by the BAO on the matter clustering: pairs of tracers are preferentially separated by **500 million light-years**

→ **« Standard ruler »**

Source of systematics

1. Theoretical systematics

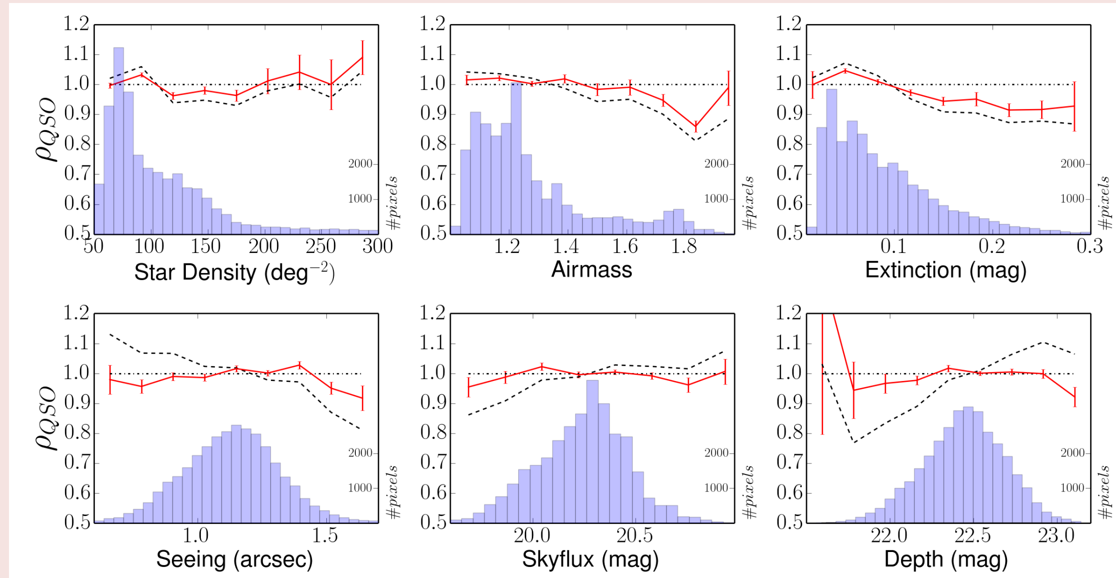
→ Can be estimated using mocks since we know the input cosmology

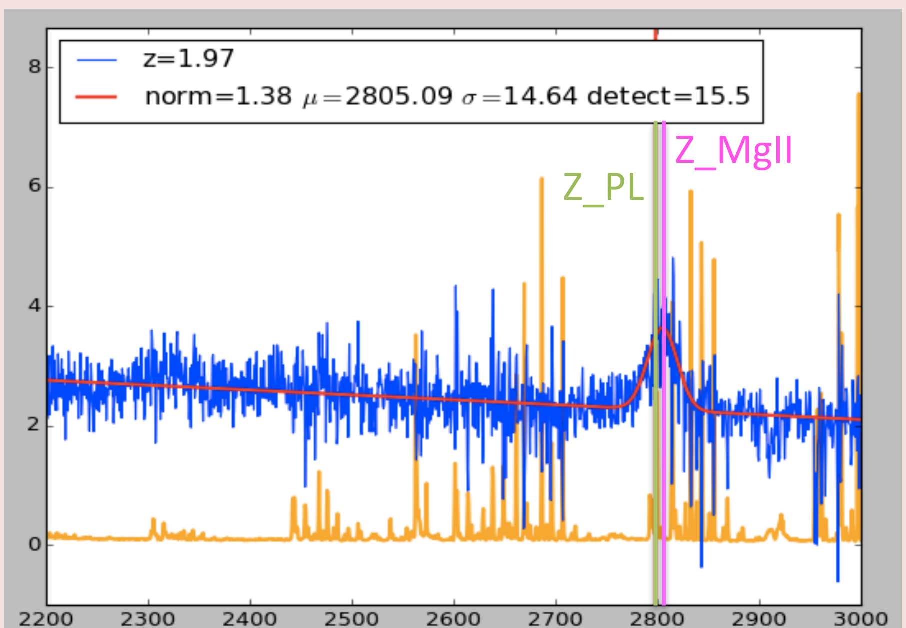


Source of systematics

2. Observational systematics

→ Weight the objects according to « depth » and correct from galactic extinction (P. Laurent et al. 2017)



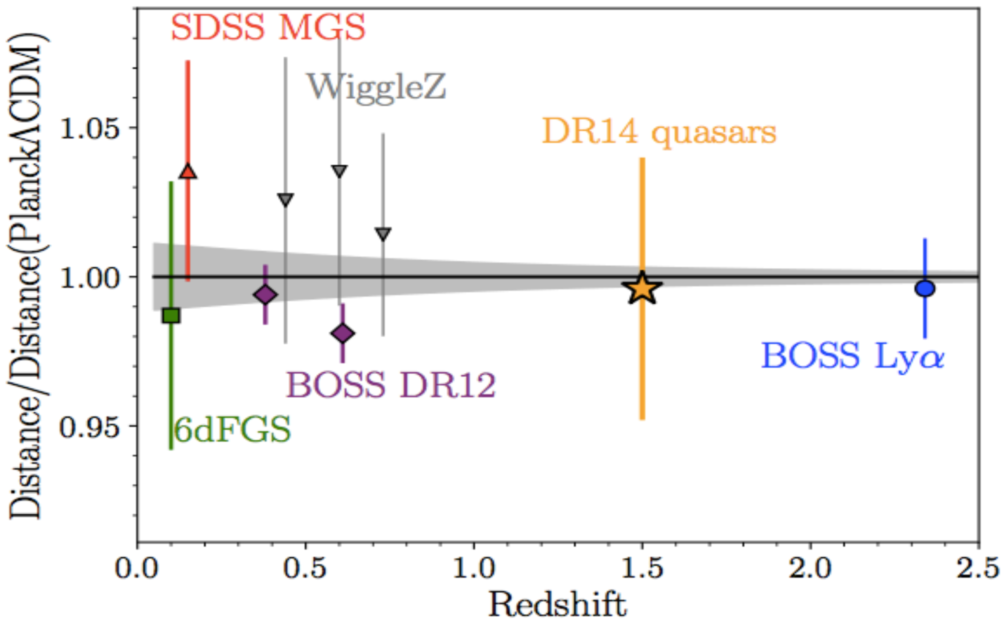


3. Redshift estimate

- Pipeline Z_PL
- MgII-based redshit Z_MgII
- Automatic redshift Z_PCA

→ Has been tested by applying different redshift errors on the mocks and looking at the impact on clustering and cosmological parameters

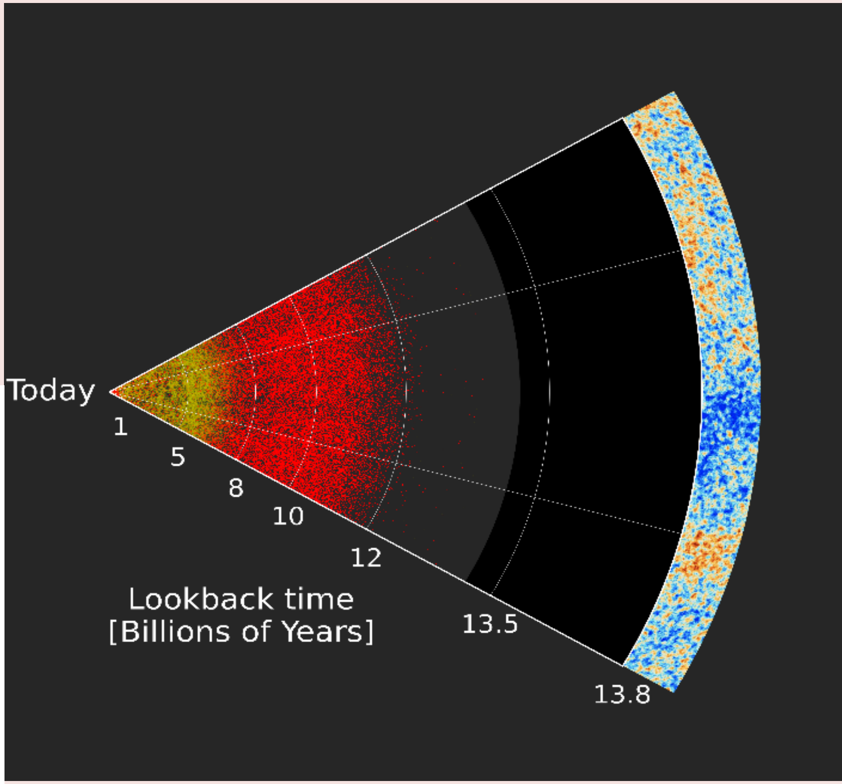
Testing Λ-CDM on cosmological scales



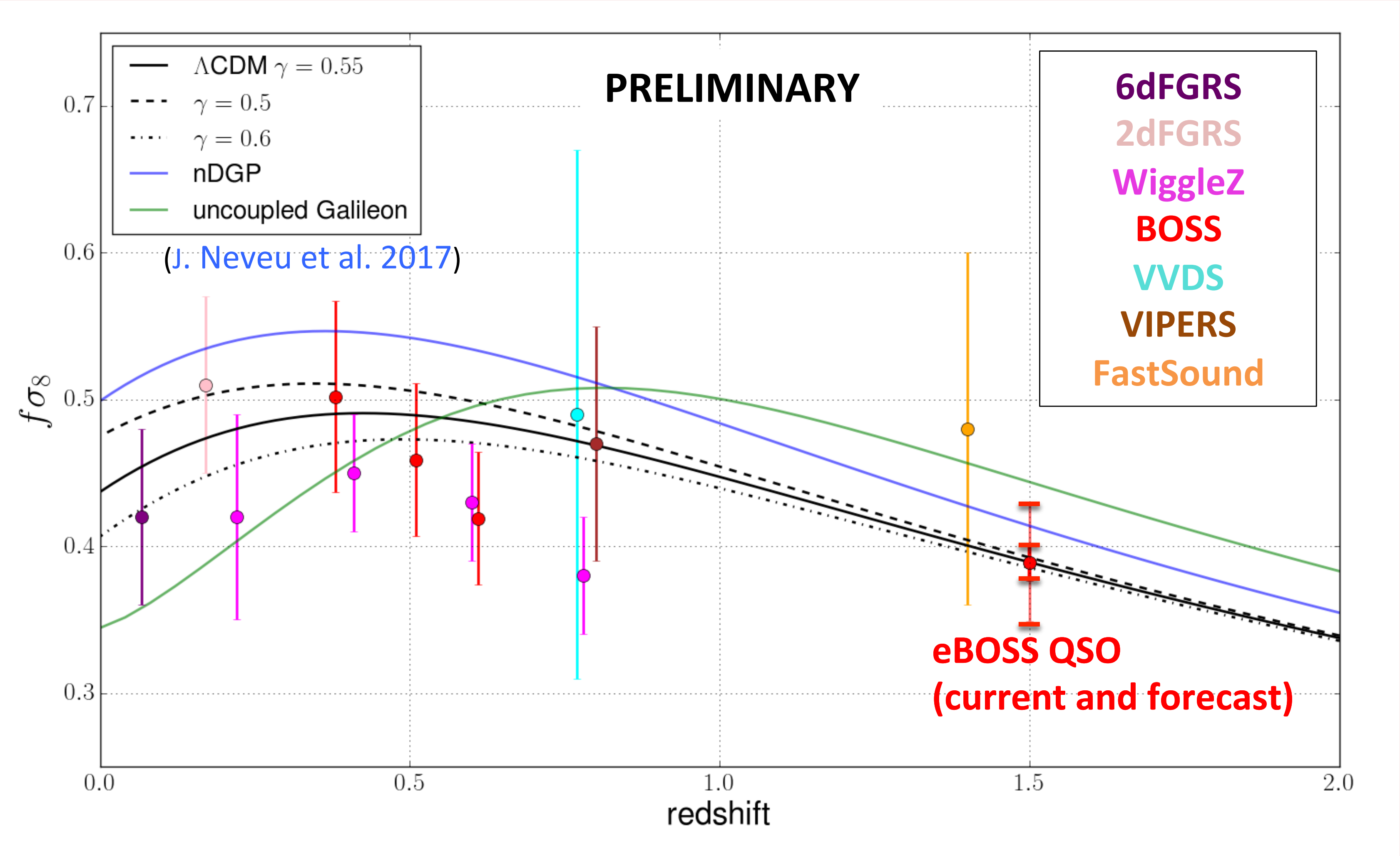
M. Ata et al. 2017 (submitted)

Spherically-averaged BAO distance measured from the position of the BAO
→ If the cosmology we assume to fit the data is correct, the ratio should be 1

Astronomers map the universe with the brightest objects in the sky
http://www.sdss.org/press-releases/astronomers-make-the-largest-map-of-the-universe-yet/
Yellow: BOSS galaxies
Red: eBOSS quasars (2 years data taking)

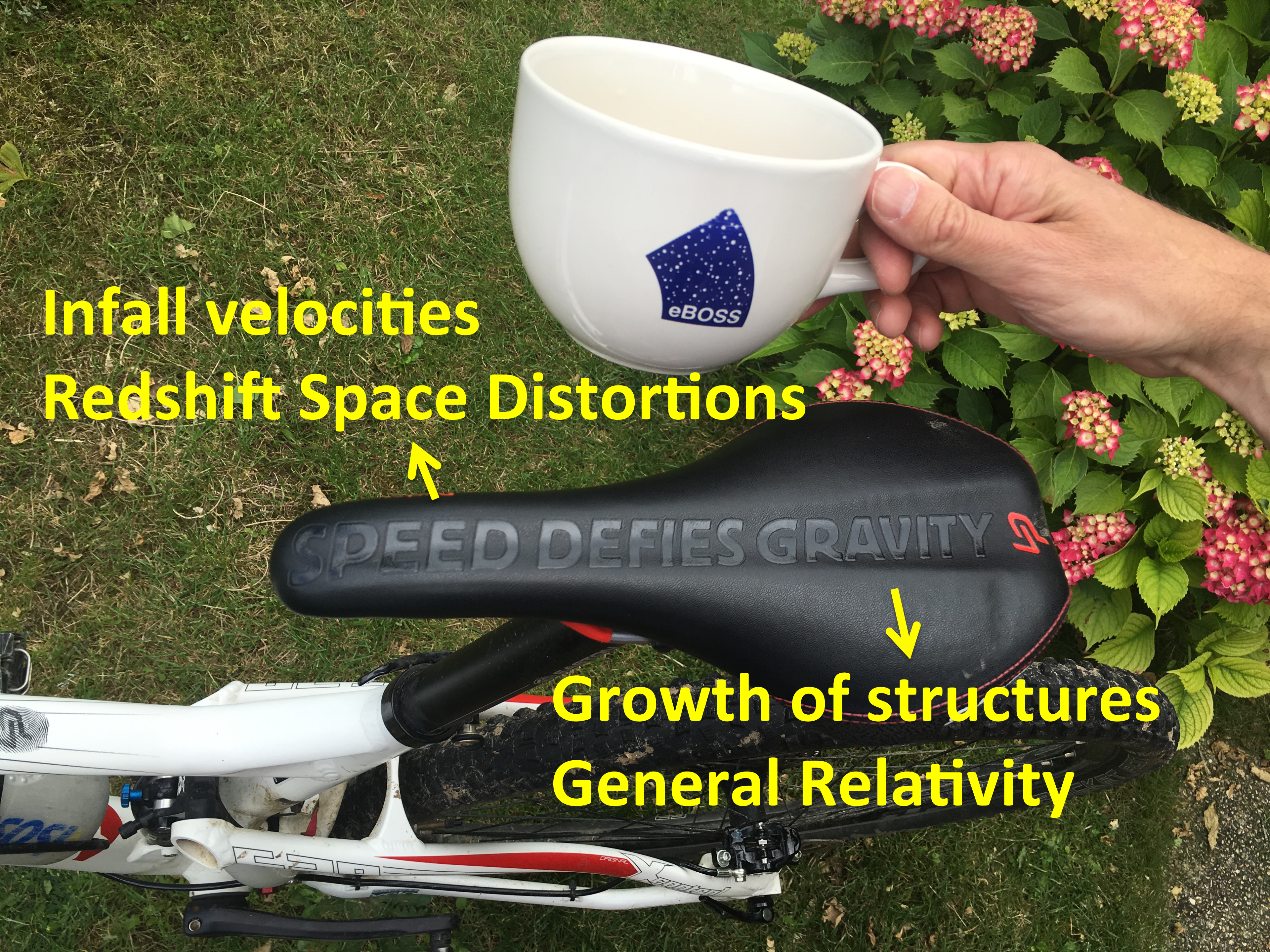


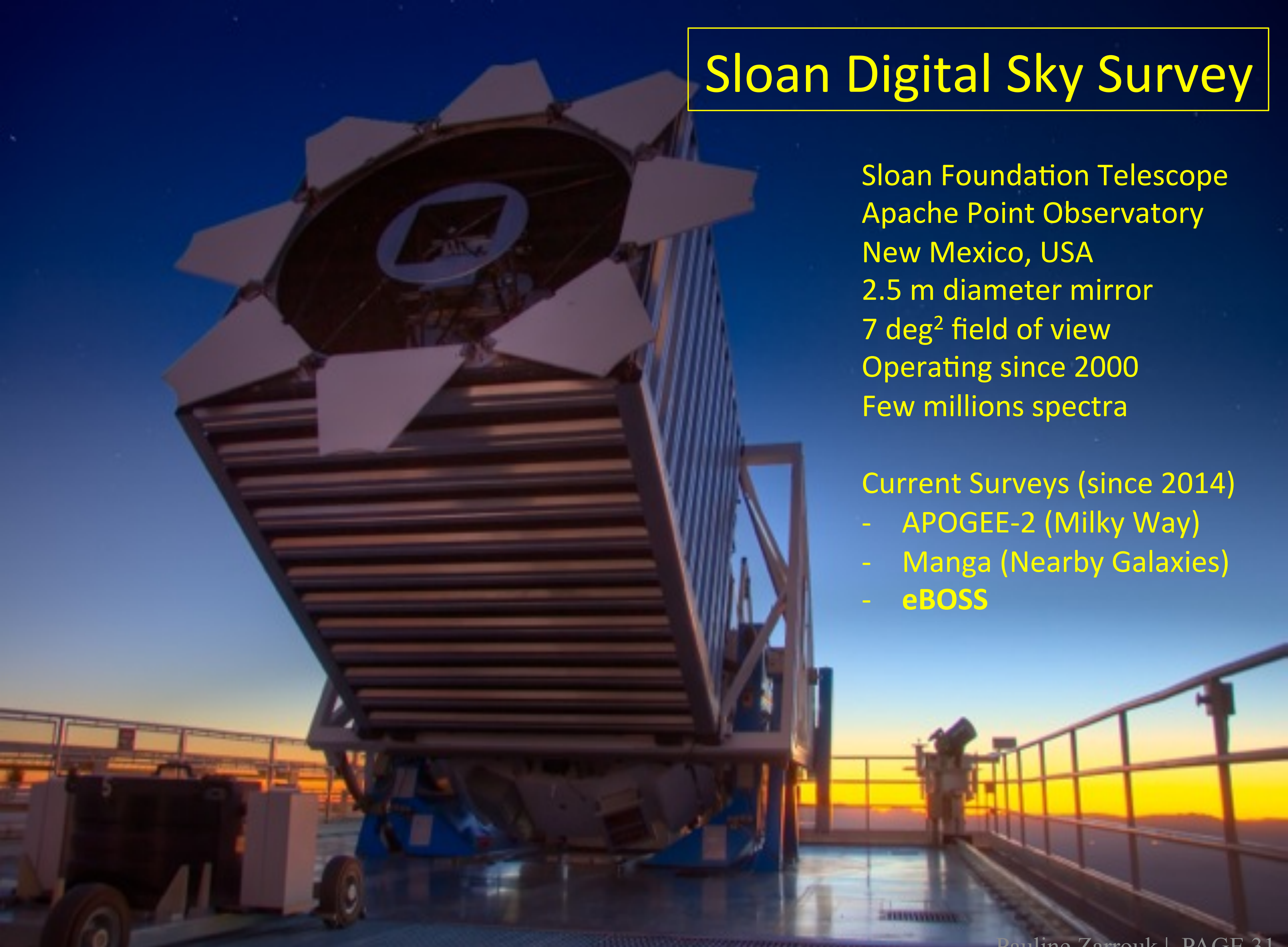
Testing Λ-CDM on cosmological scales



P. Zarrouk, E. Burtin et al. (2017b in prep)


eBOSS
SPEED DEFIES GRAVITY


eBOSS
Infall velocities
Redshift Space Distortions
SPEED DEFIES GRAVITY
Growth of structures
General Relativity



Sloan Digital Sky Survey

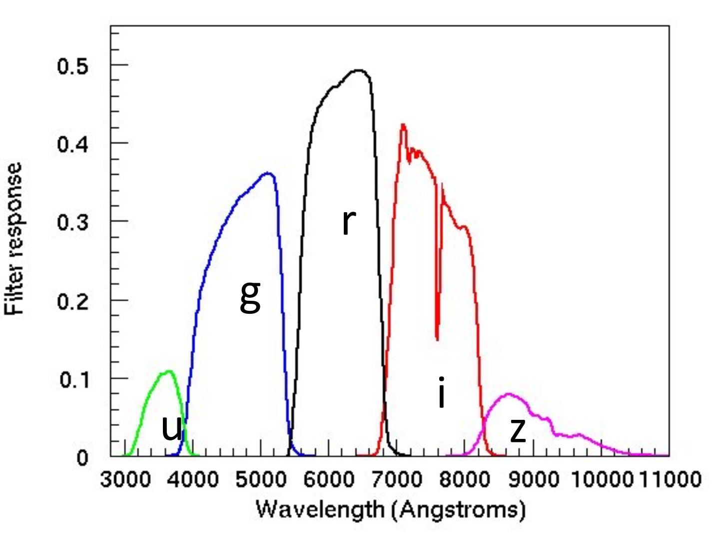
Sloan Foundation Telescope
Apache Point Observatory
New Mexico, USA
2.5 m diameter mirror
7 deg^2 field of view
Operating since 2000
Few millions spectra

Current Surveys (since 2014)

- APOGEE-2 (Milky Way)
- Manga (Nearby Galaxies)
- **eBOSS**

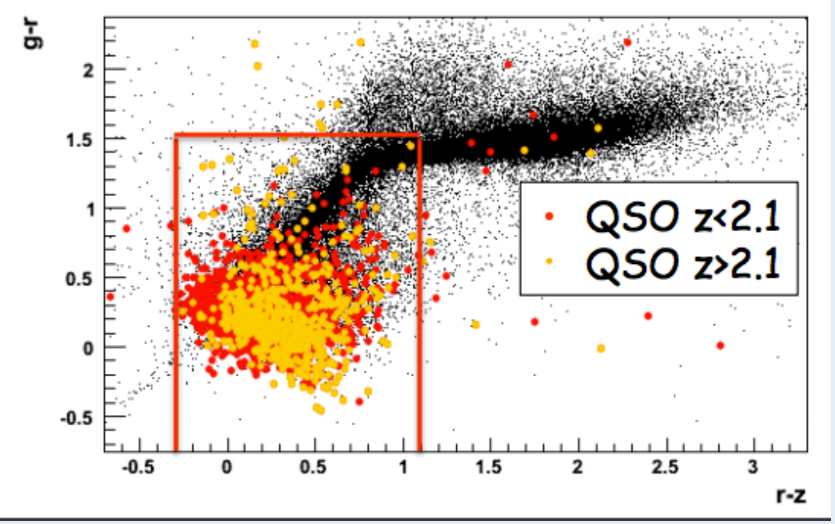
Data taking with SDSS-eBOSS

Stage 1 : Photometric survey-Imaging

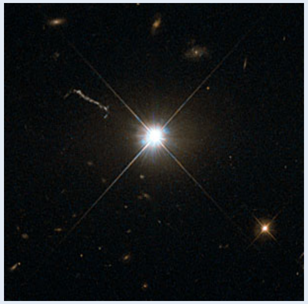


Stage 2 : Target selection

Color cuts

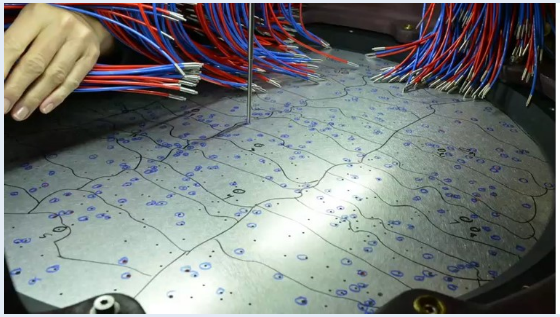


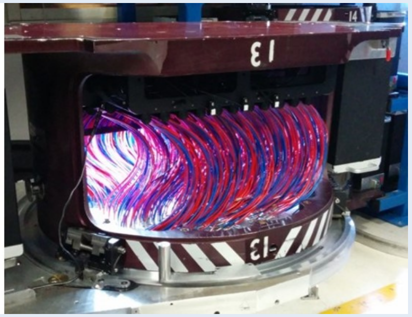
Morphology



VS

Stage 3 : Tiling
+ Plugging

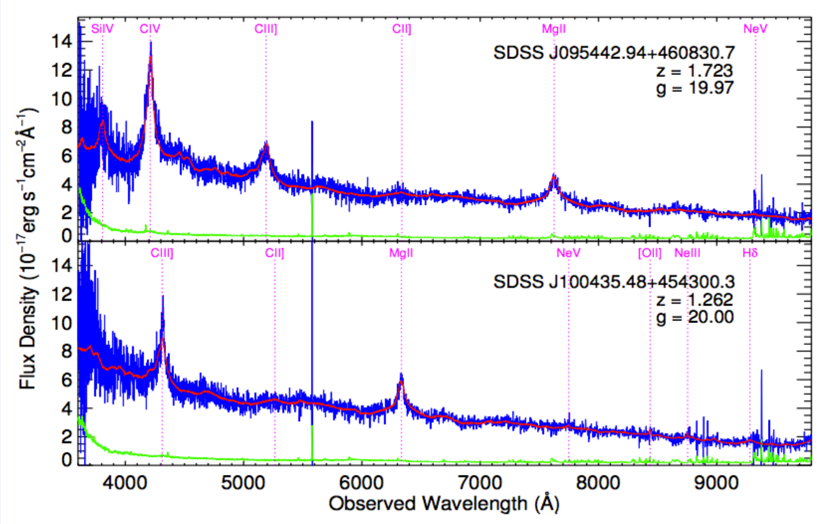




Data taking with SDSS-eBOSS

Stage 4 : Spectroscopy

To measure redshift



Stage 5 : eBOSS DR14 footprint