Large scale structure of the Observed Universe

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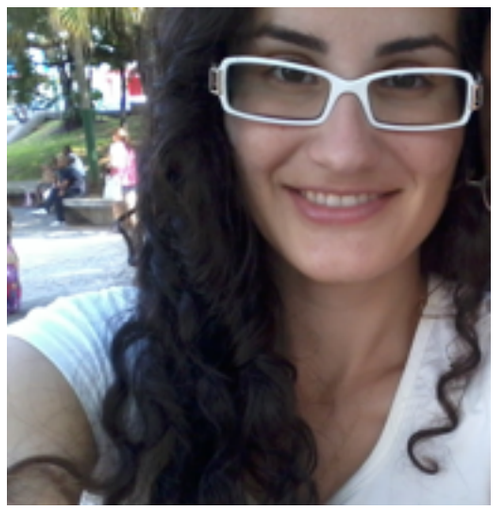
Observatório Nacional

Camila Novaes, Gabriela Marques, Edilson de Carvalho, Felipe Avila,...





(some) Fundamental Questions

- What is the shape of the Universe?
- Is the Universe homegeneous and isotropic?
- Is LCDM the `true' cosmology?
- Does the *dark energy* exist?
- Or: do we live in a void? How large it is?
- Is the Universe acceleration a data artifact?
- Did the Universe came from a singularity?

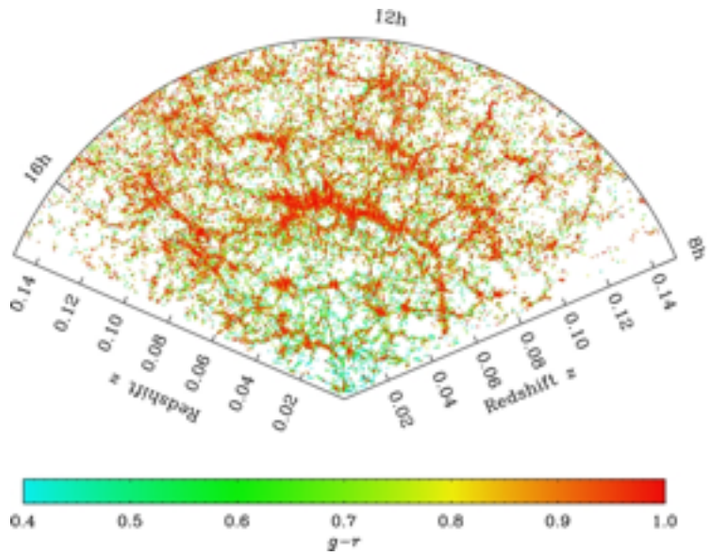
Cosmology precision era: 1990 $\longmapsto$ ...

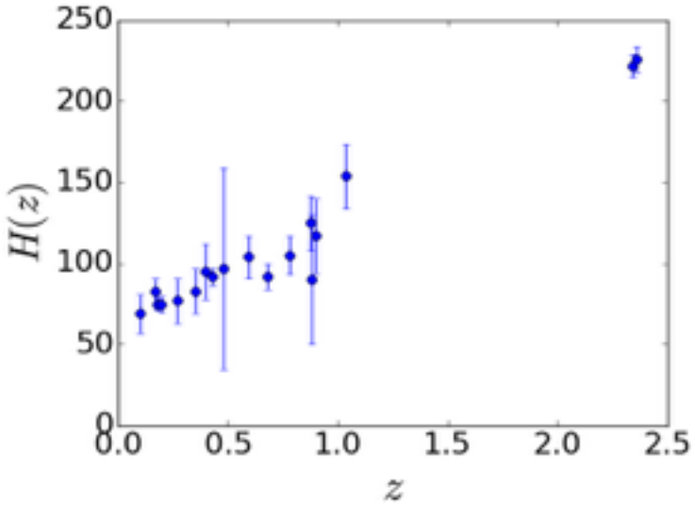
Observational Cosmology (OC)

or How to extract info from Peta-bytes of data

Multiple ways to do OC with public data:

- crude data
- intermed. data
- data products





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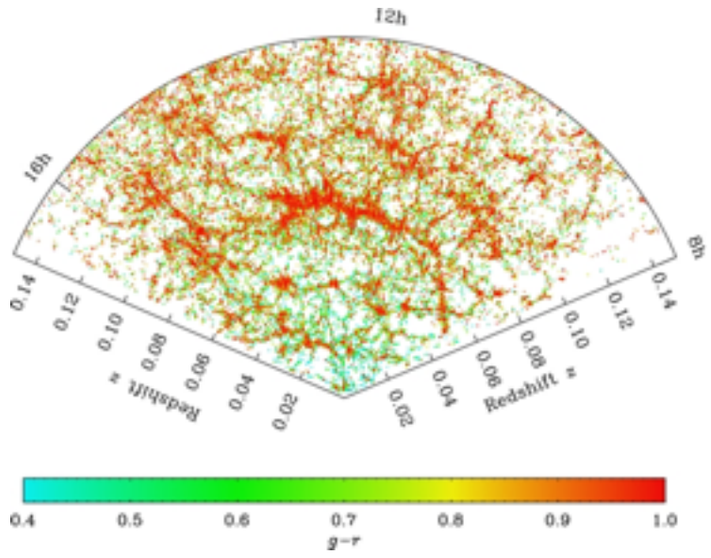
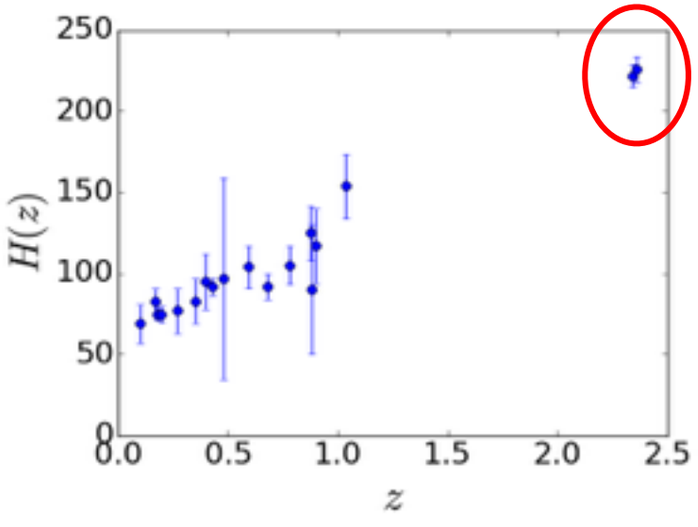
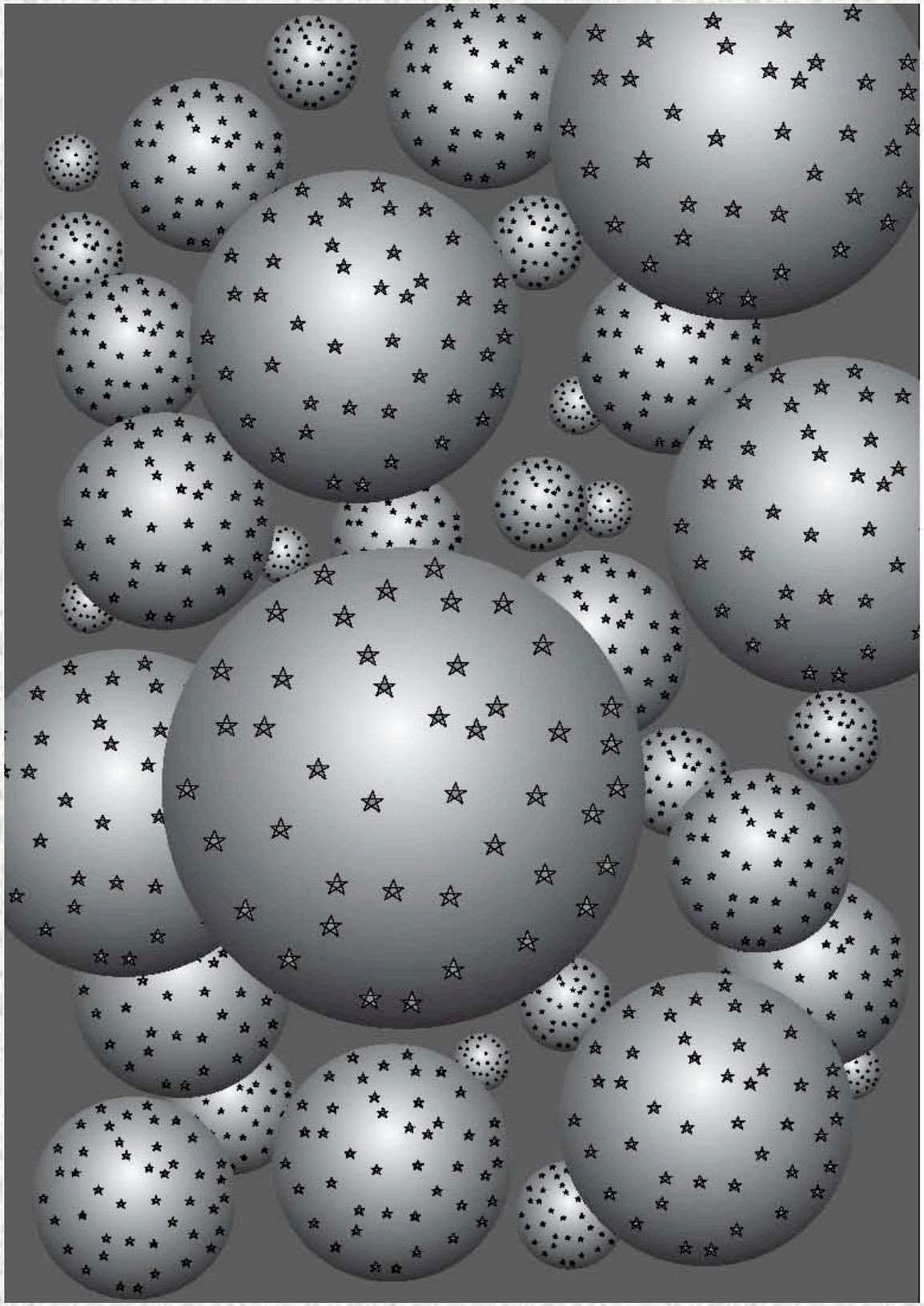
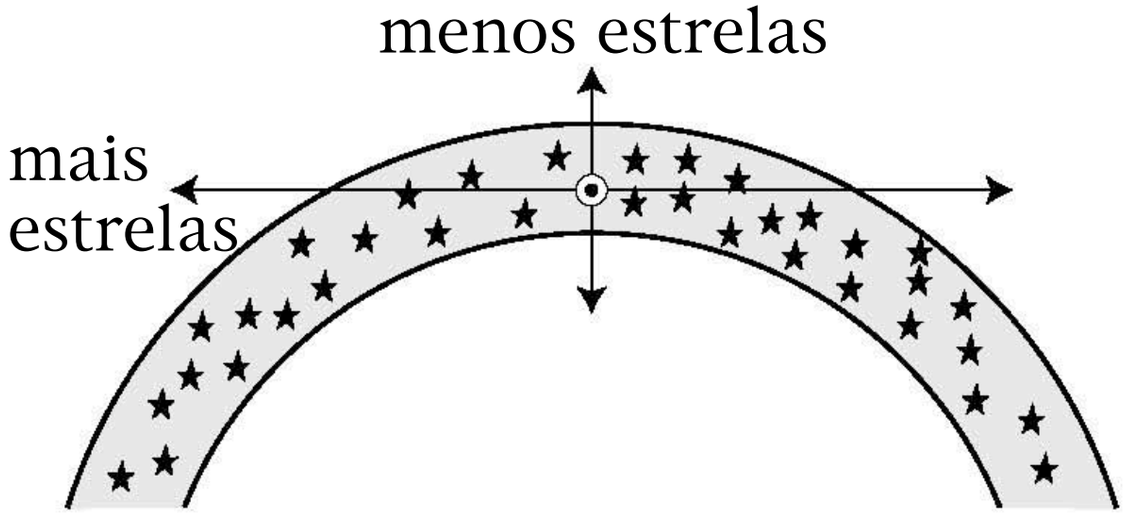




Universos-ilhas

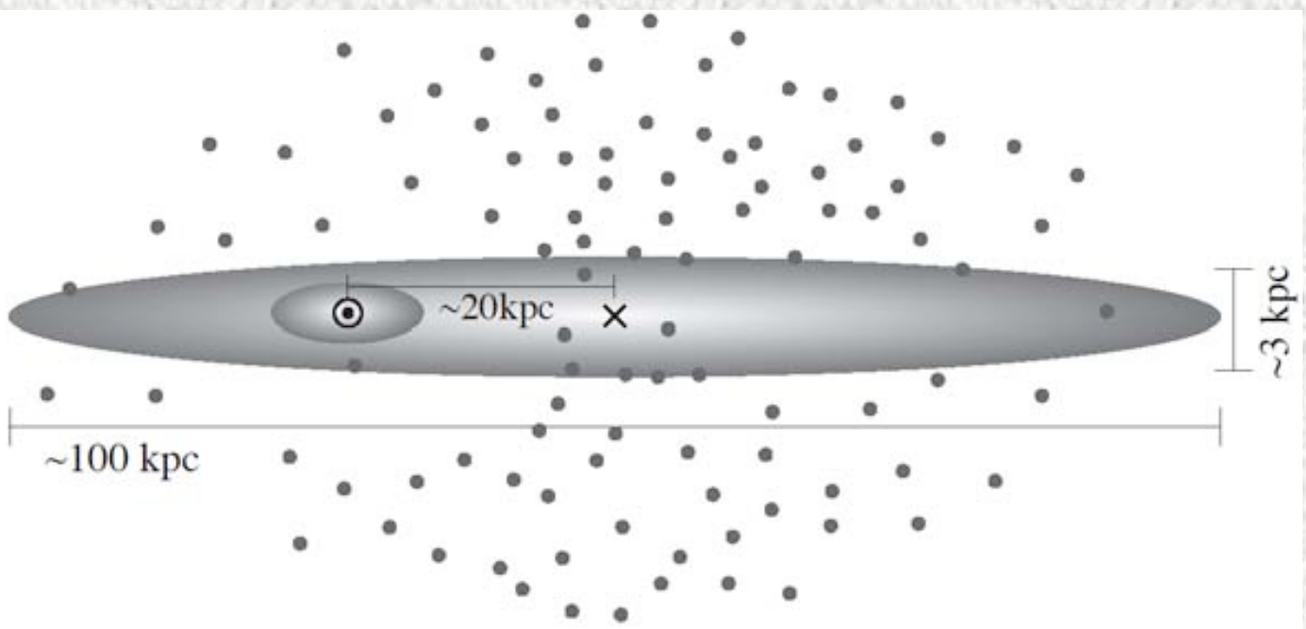




~1750, T. Wright, E. Kant e J. Lambert propõem que as nebulosas sejam "*Universos-Ilhas*"

“Grande debate de 1920”:
universo de estrelas x *universo de galáxias*

Harlow Shapley	Heber D. Curtis
Via Láctea muito grande Sol a 15 kpc do centro Nebulosas fazem parte da galáxia	Via Láctea pequena Sol está no centro Nebulosas são “universos ilhas”



modelo de Kapteyn (1901)

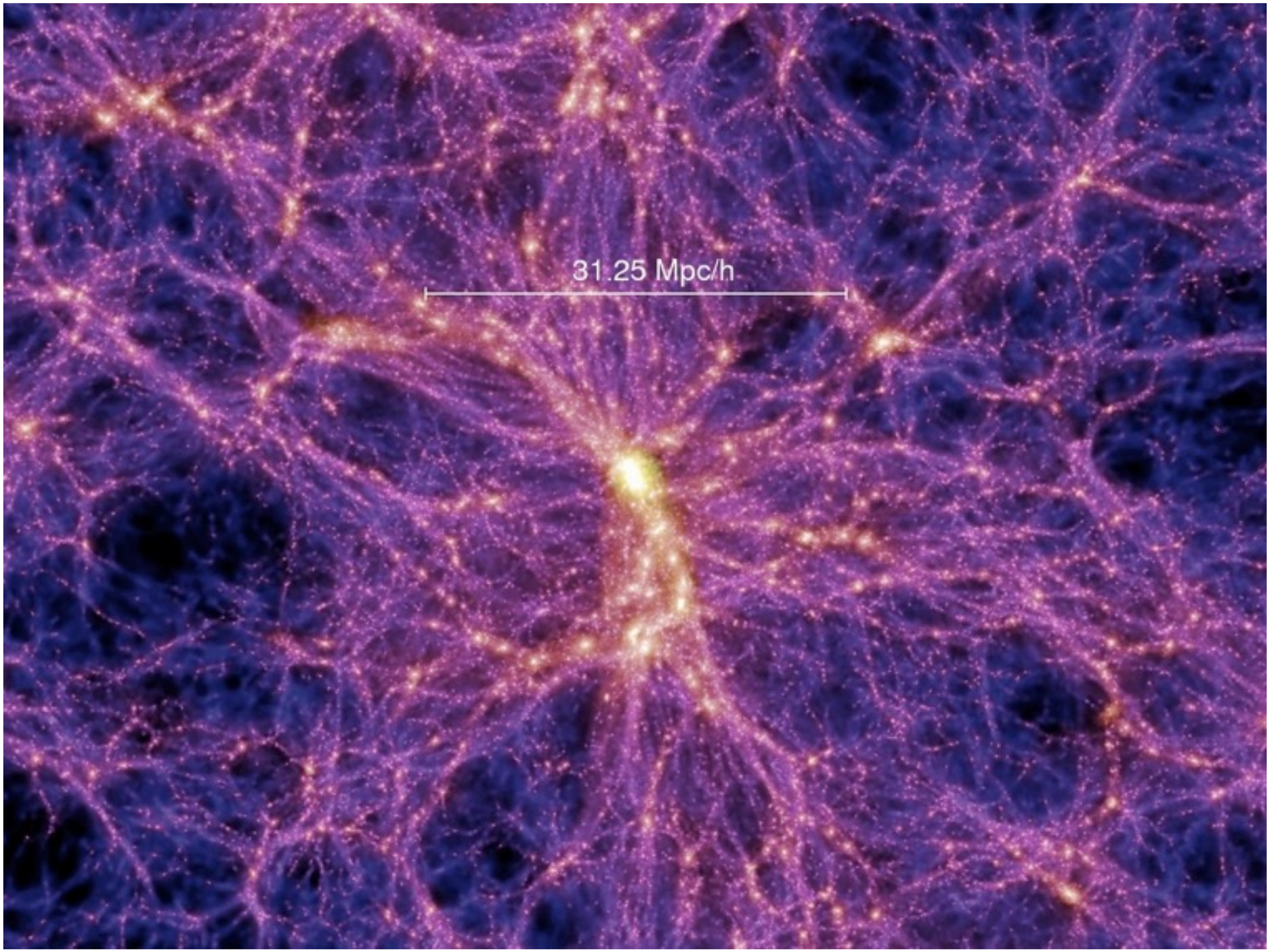
- O grande problema era a determinação de distâncias das nebulosas.

Descoberta da estrutura das galáxias

- 1786/1802: Catálogo de William Herschel e família.
- 1845: Lord Rosse descobre a estrutura espiral de algumas “nebulosas”.

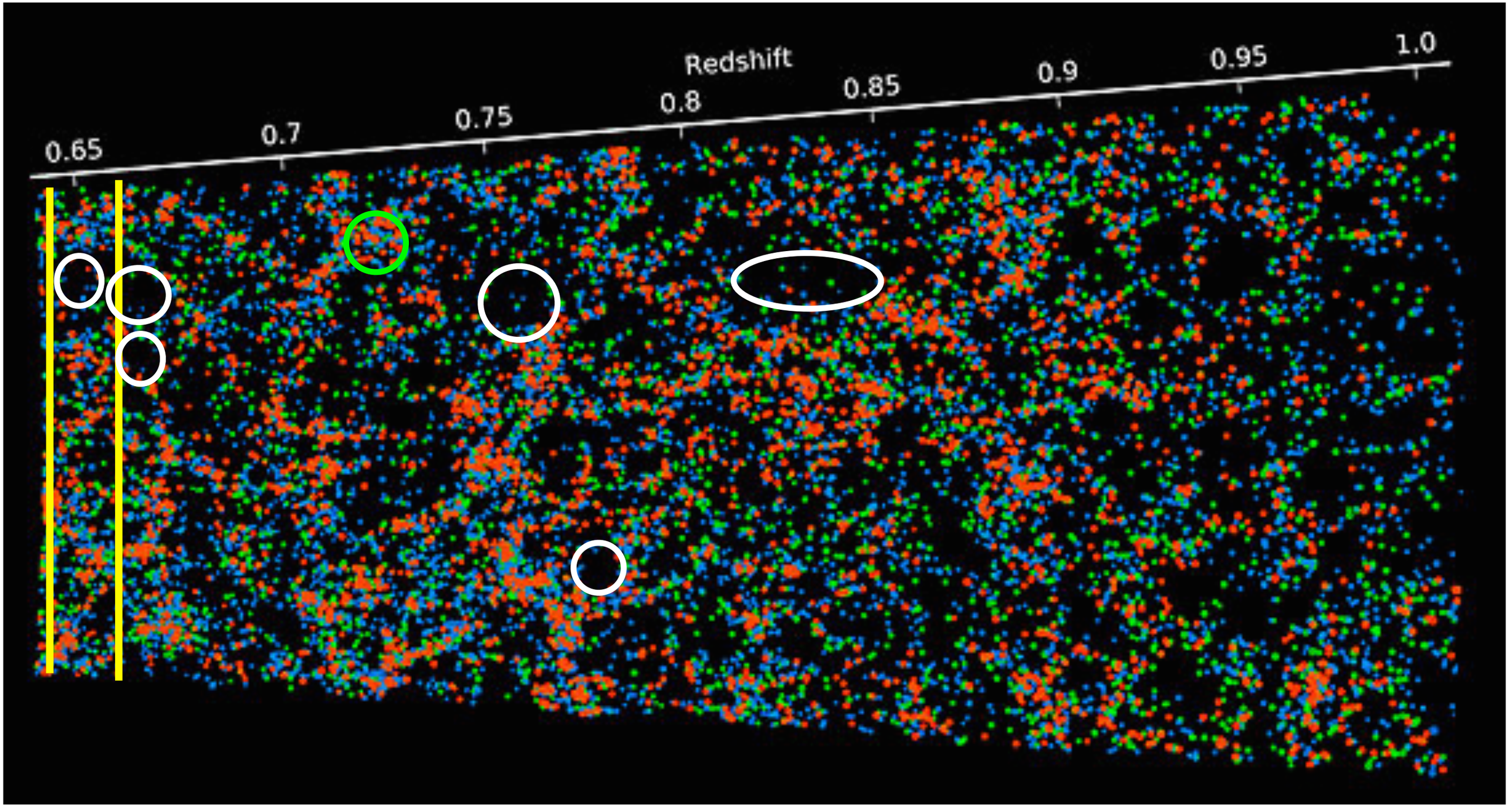
Montagem dos desenhos de Lord Rosse de 1845 e de imagens do SDSS

Large-scale structure



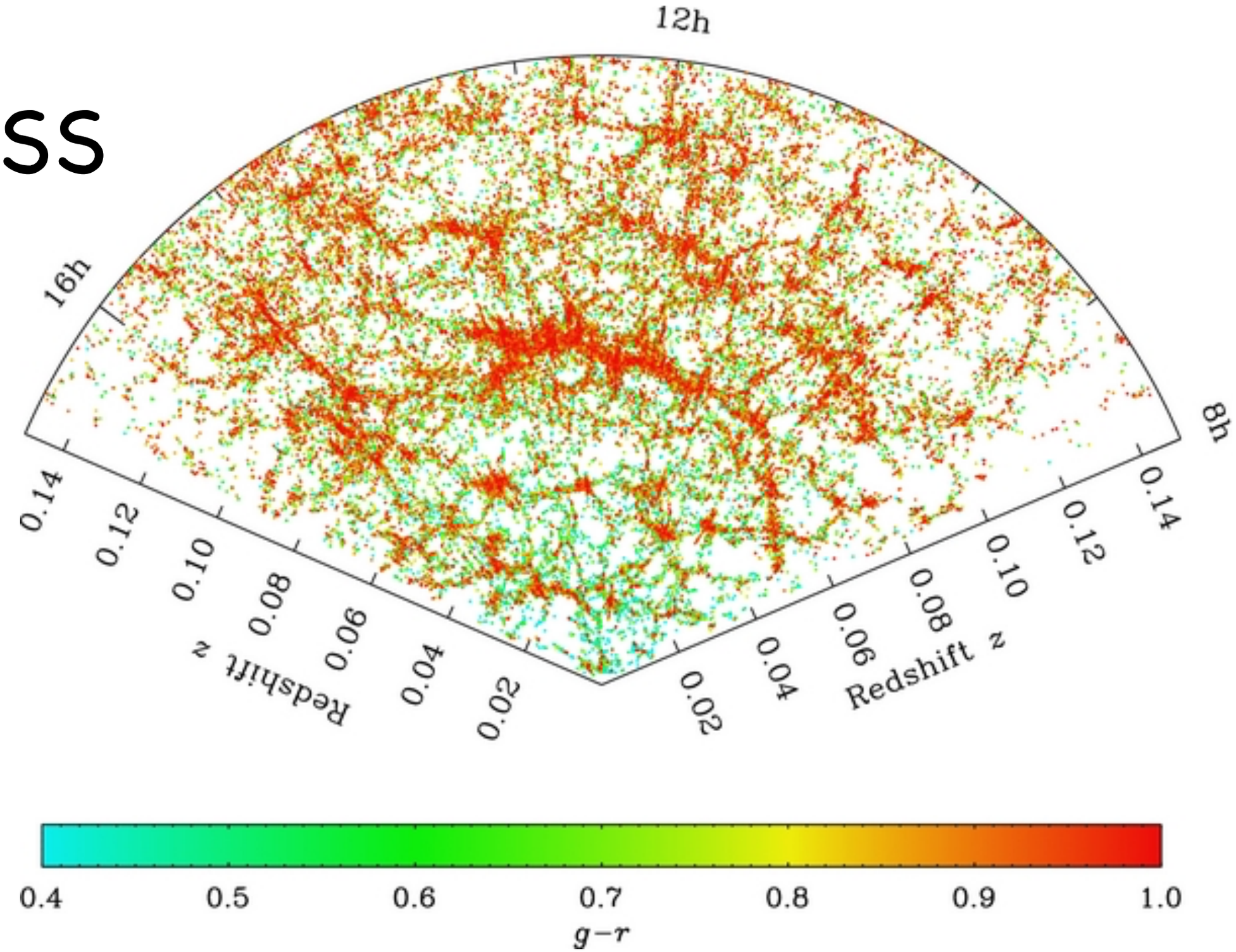
VIPERS survey catalog

exm. under- & over-densities: voids & bulks

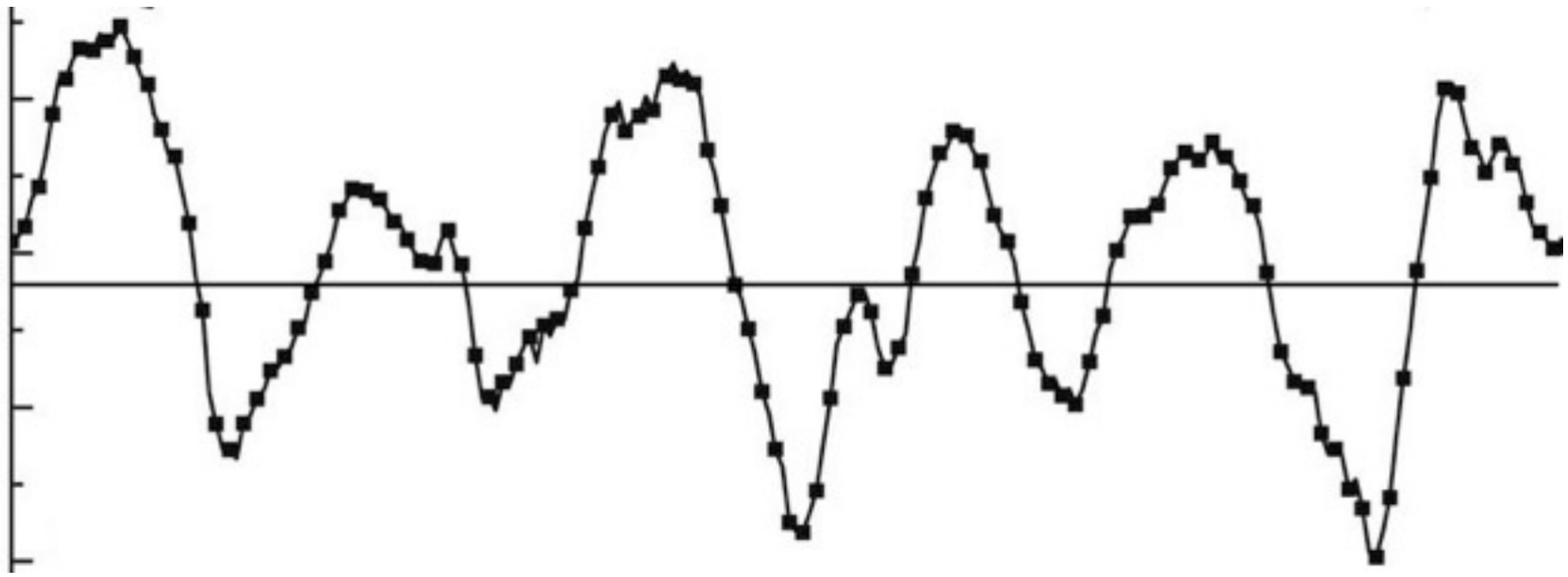


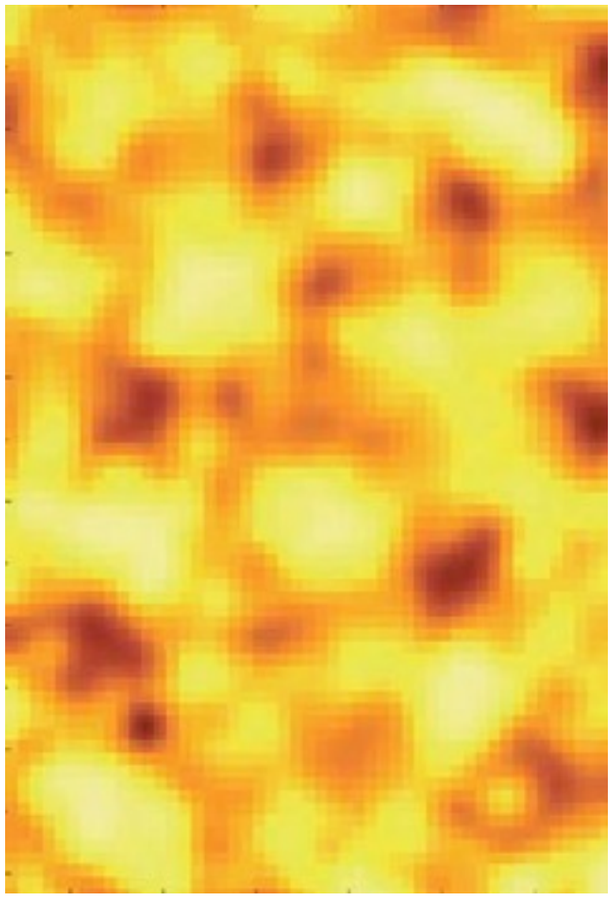
Large-scale structure: BAO

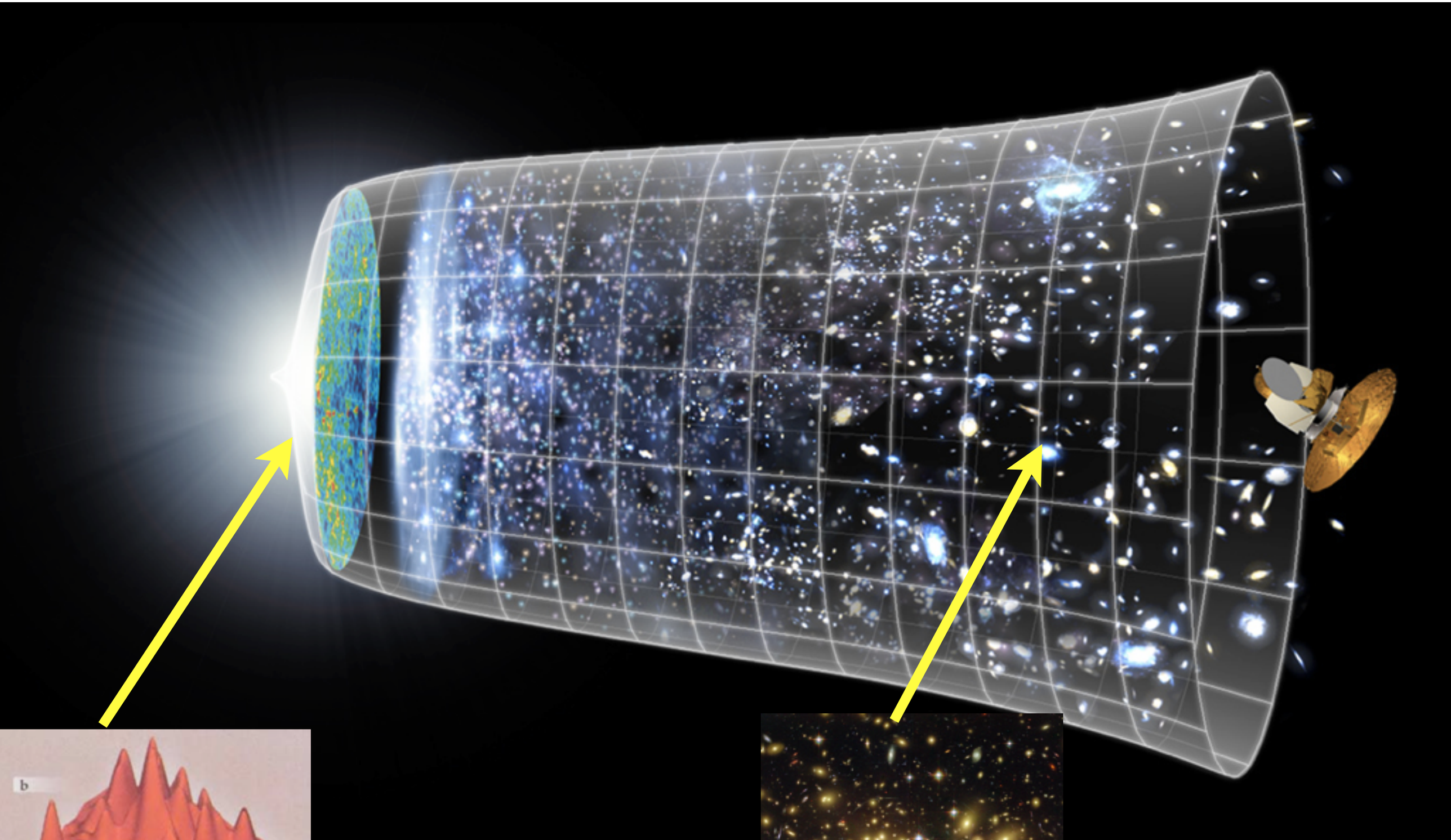
SDSS

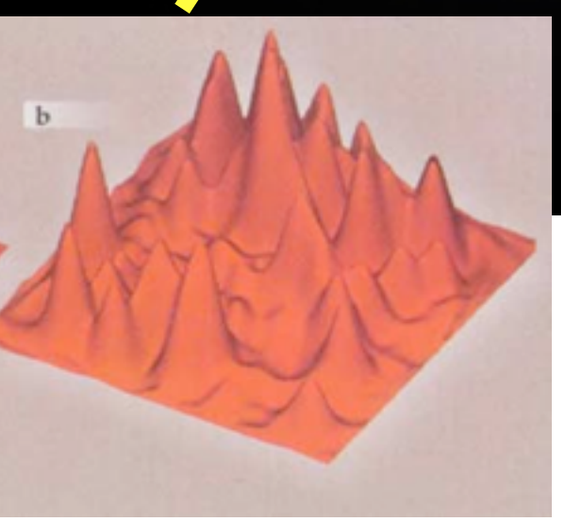


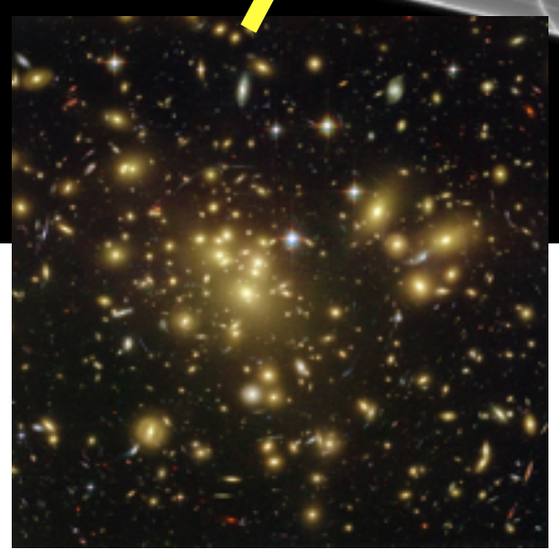
flutuações da Curvatura do espaço-tempo

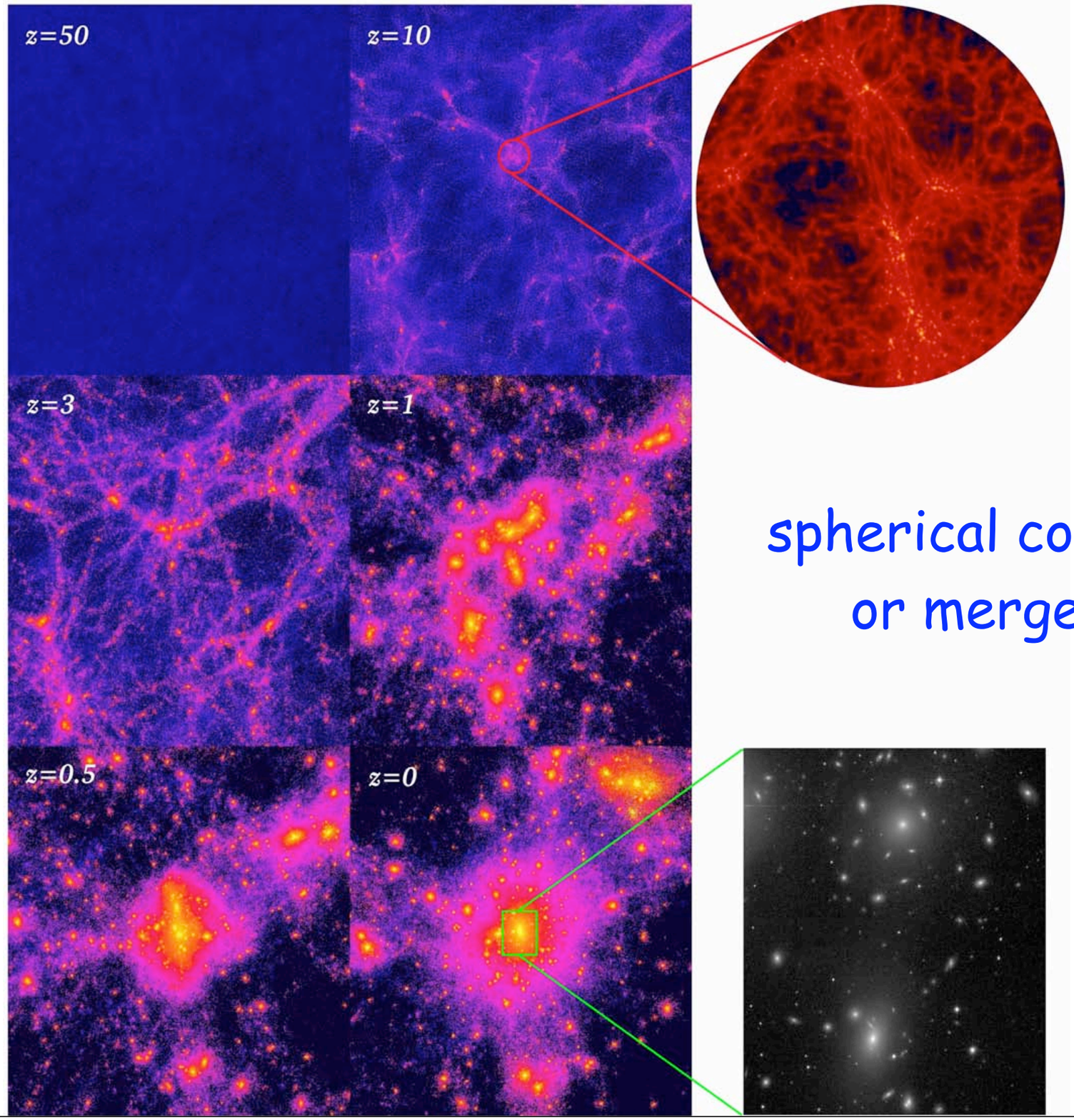






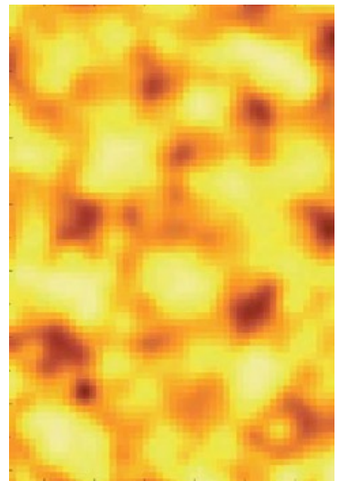

b

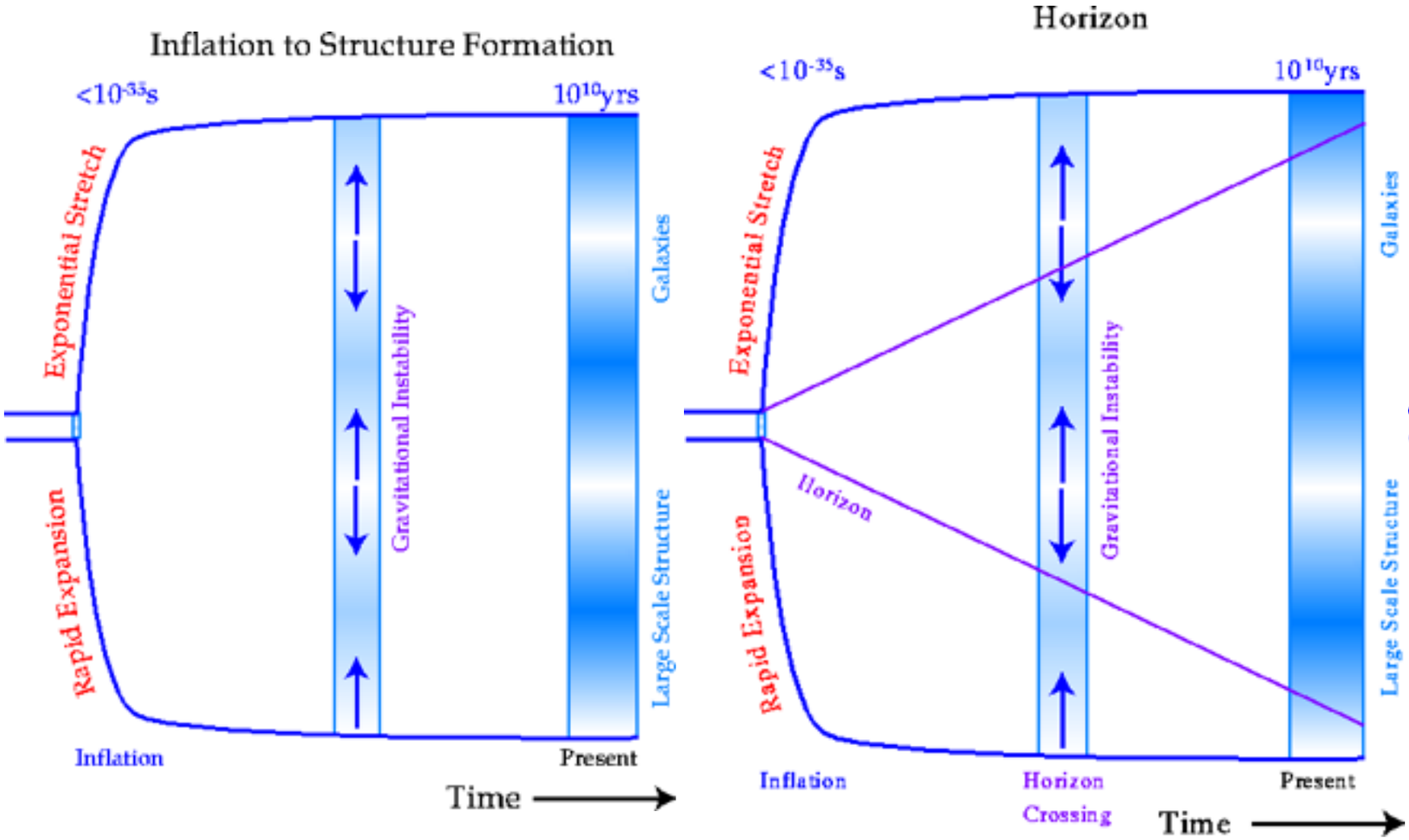


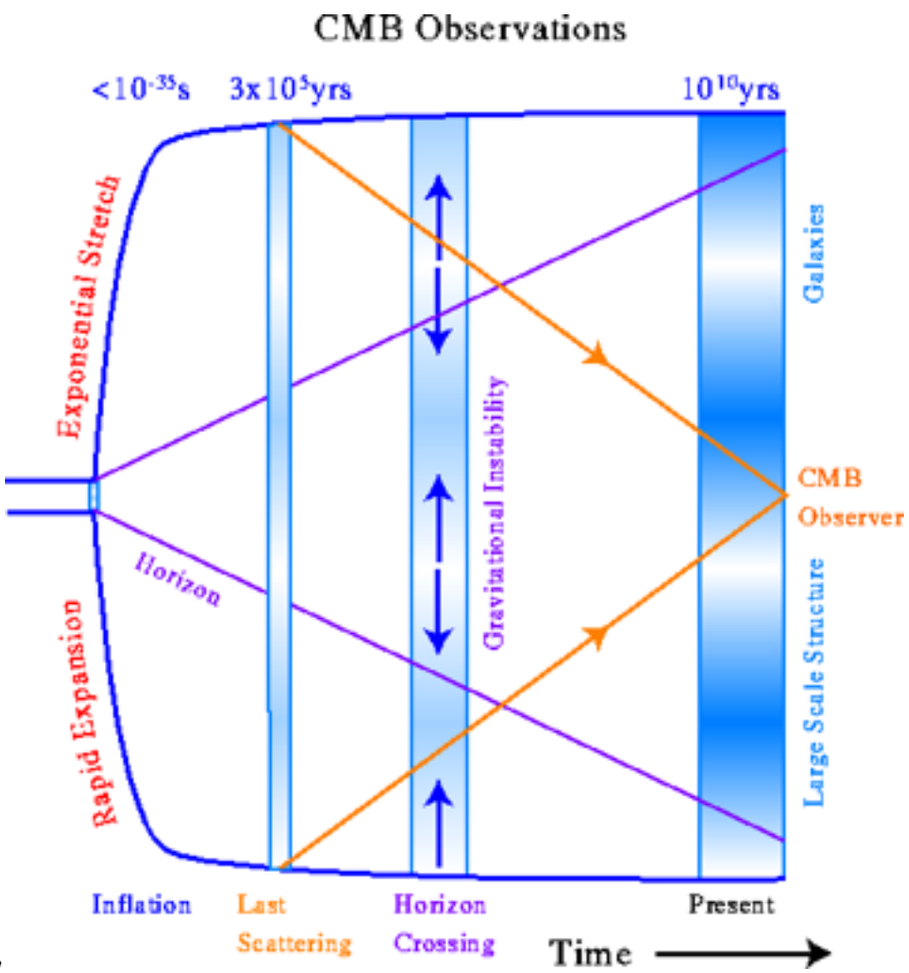


spherical collapse
or mergers

Formação de Estruturas







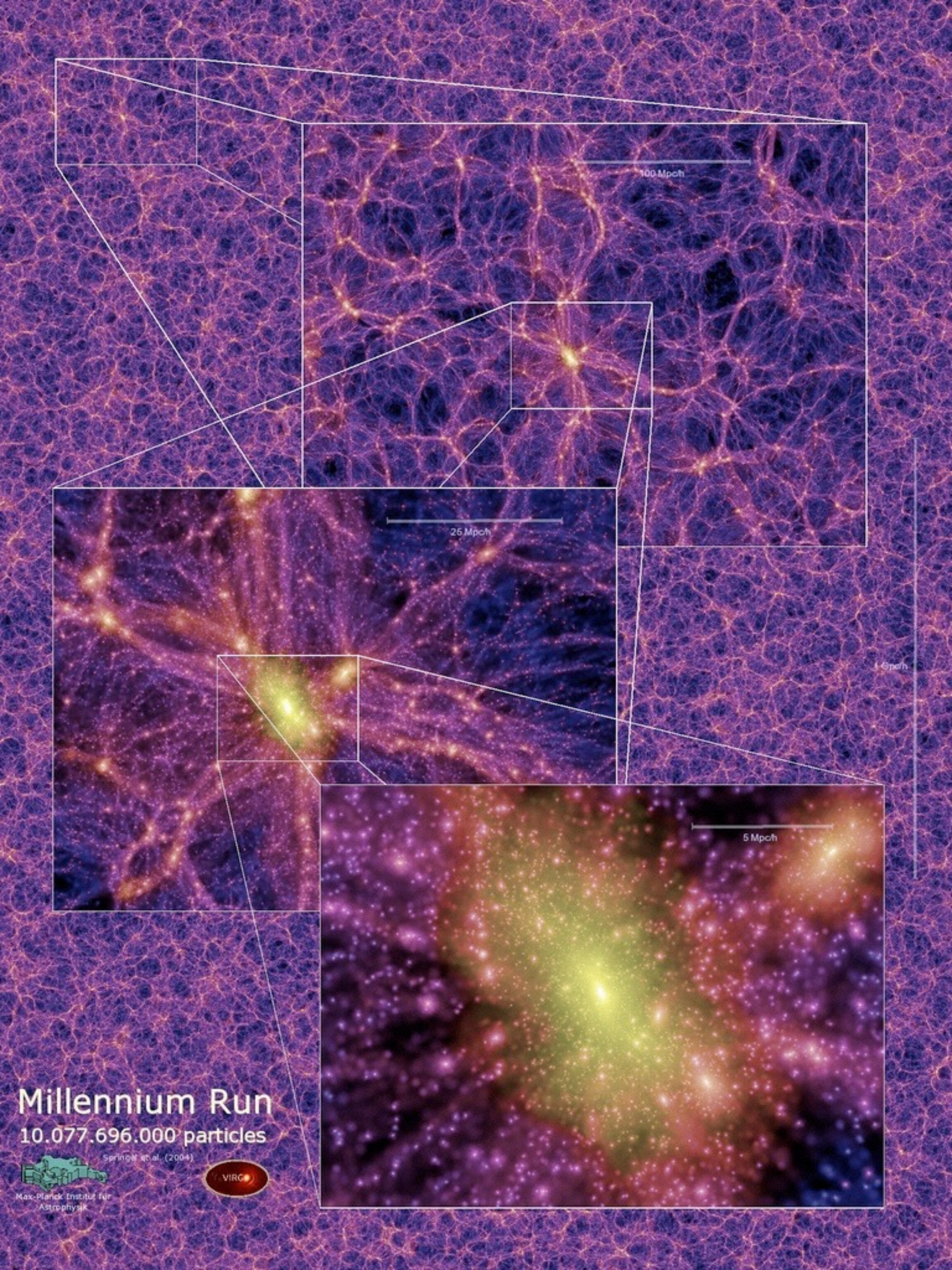
Perturbation Theory

- Begin from the basic equations for non-relativistic hydrodynamics.
  - Continuity, Euler, Poisson equations

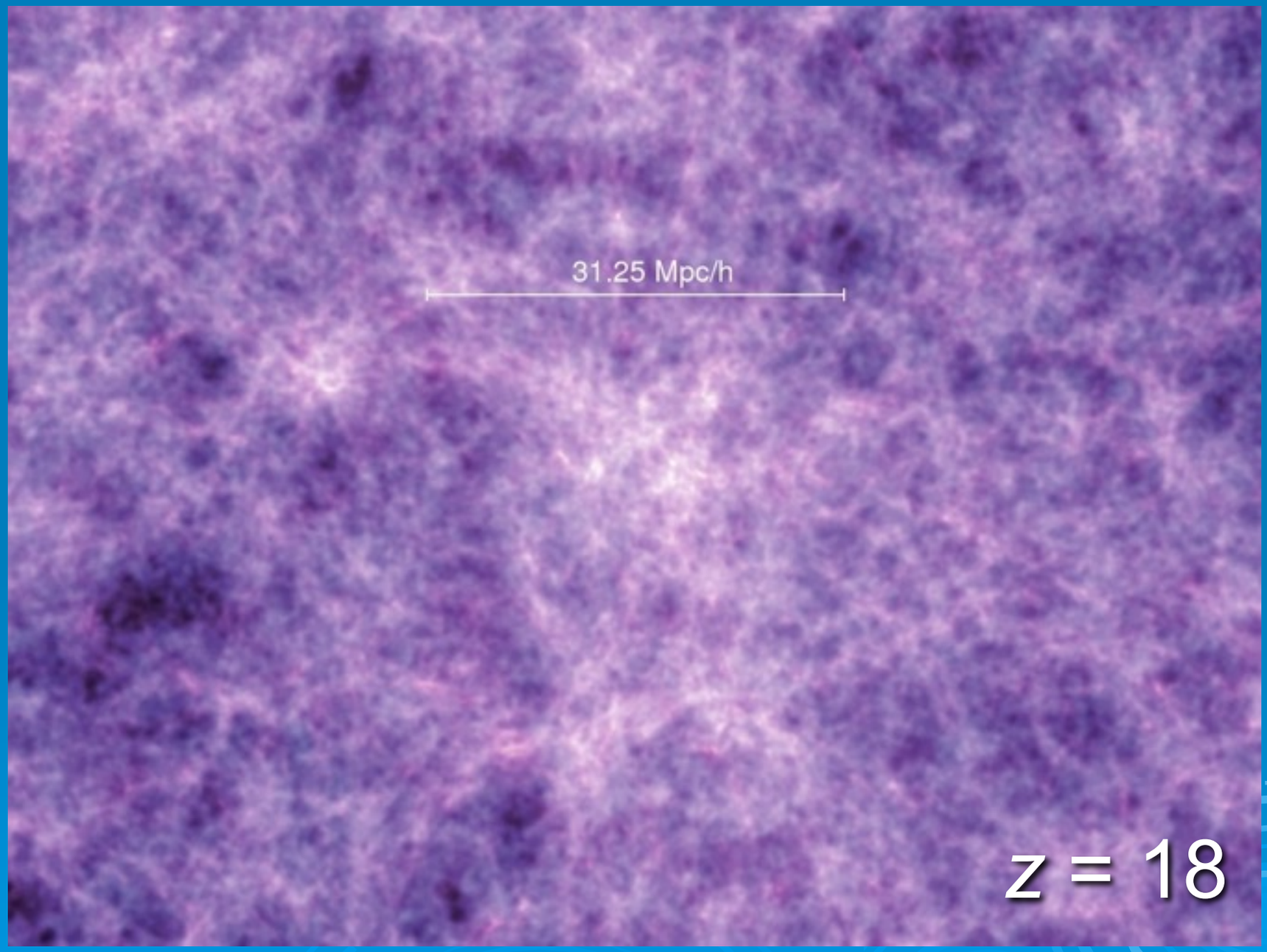
$$\frac{d_c\rho}{d_ct} + \rho\nabla_x \cdot \mathbf{v} = 0$$

$$\frac{d_c\mathbf{v}}{d_ct} = -\frac{1}{\rho}\nabla_x p - \nabla_x\Phi$$

$$\nabla_x^2\Phi = 4\pi G\rho$$


100 Mpc/h
25 Mpc/h
1 Gpc/h
5 Mpc/h
Millennium Run
10.077.696.000 particles
Springel et al. (2004)
VIRGO
Max-Planck Institut für Astrophysik

Evolution of Structure



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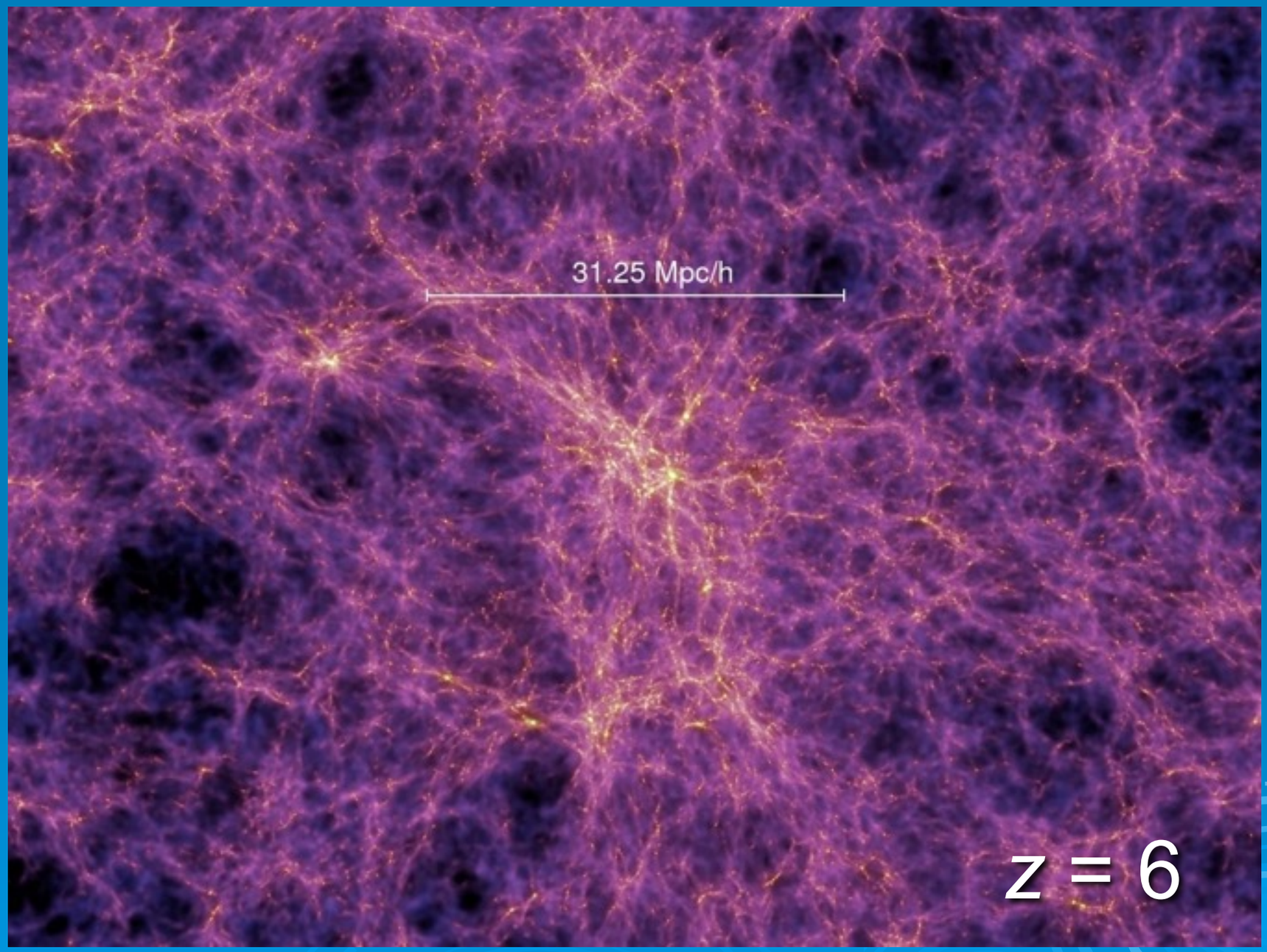

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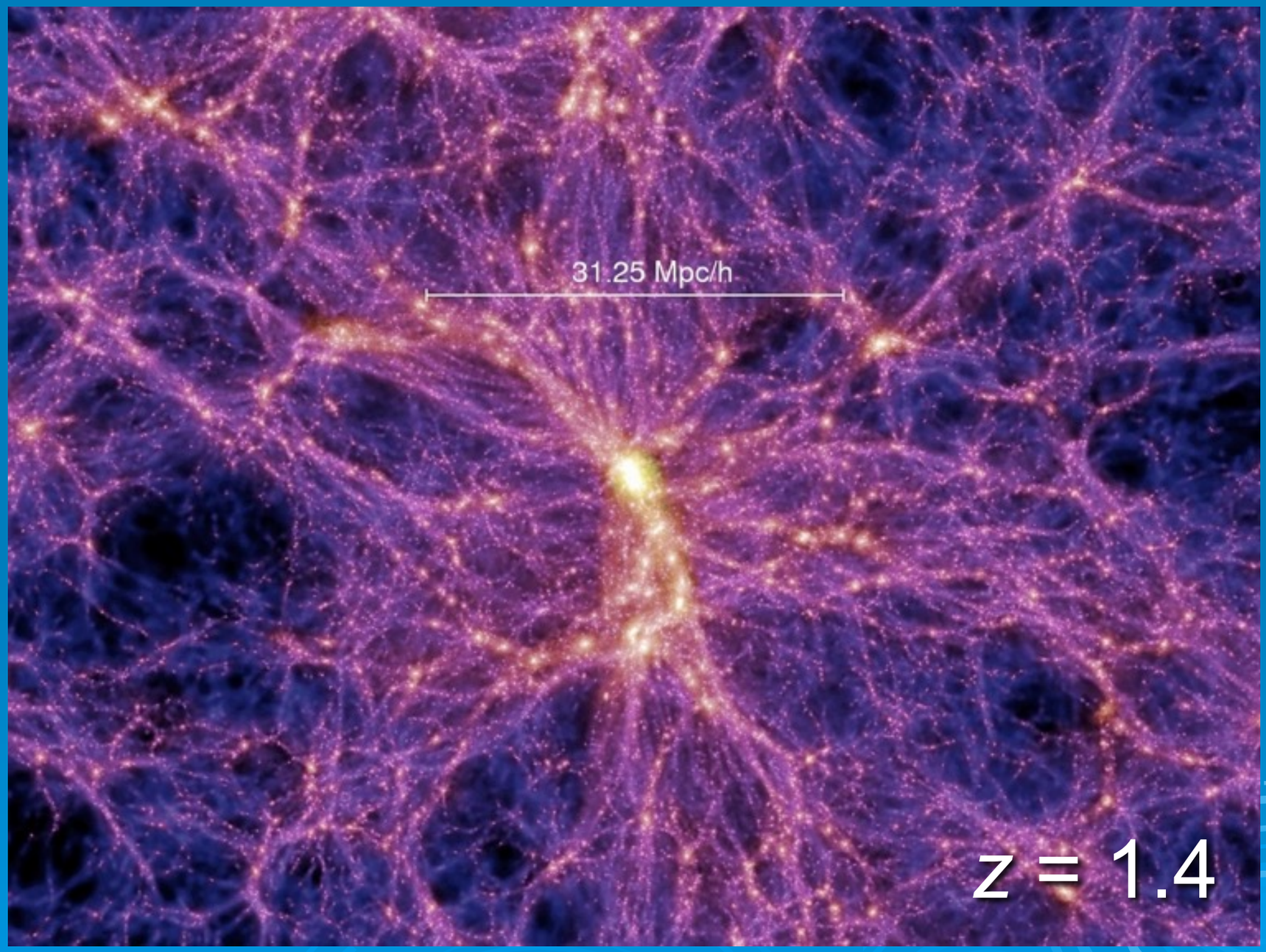

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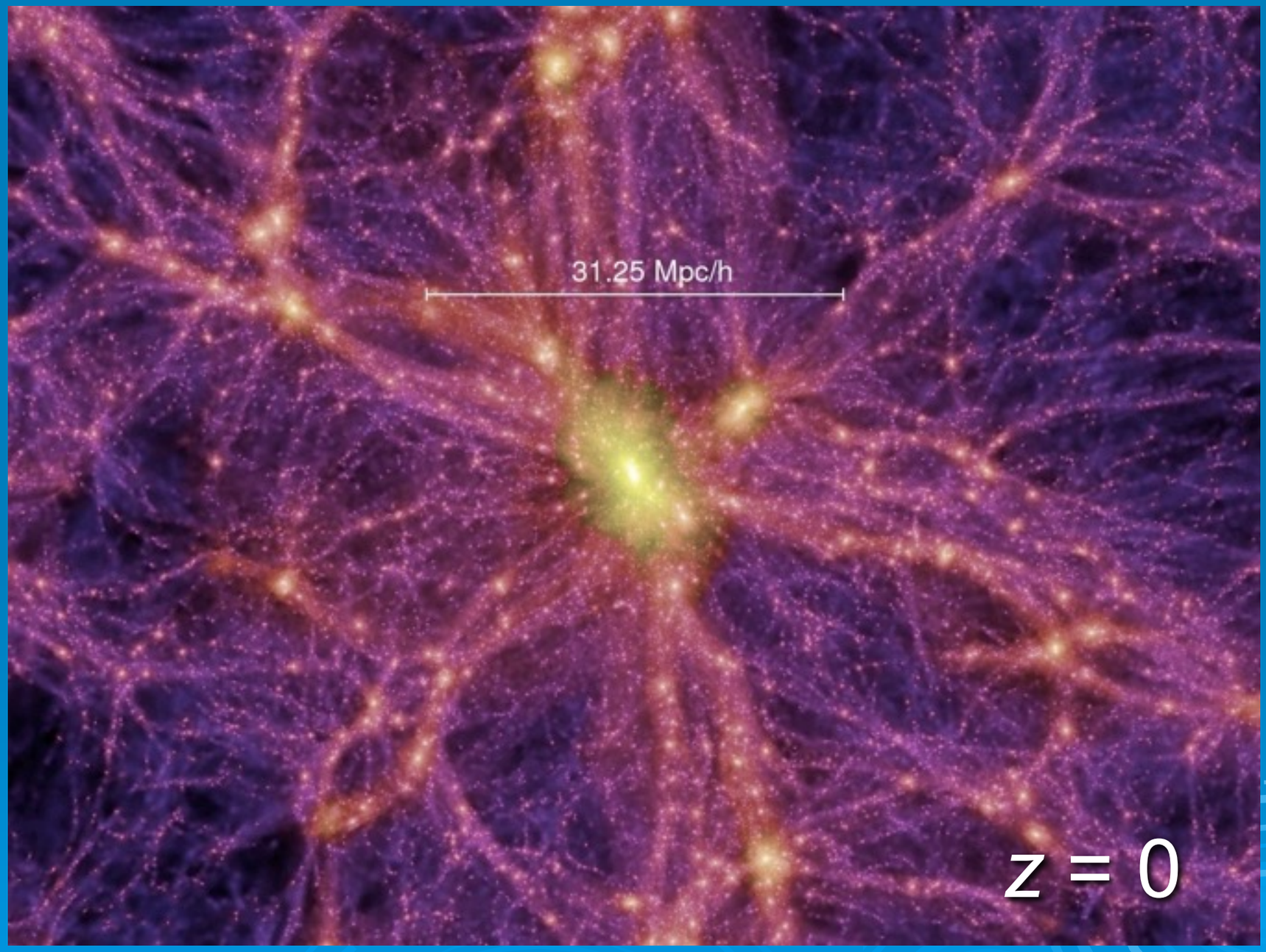
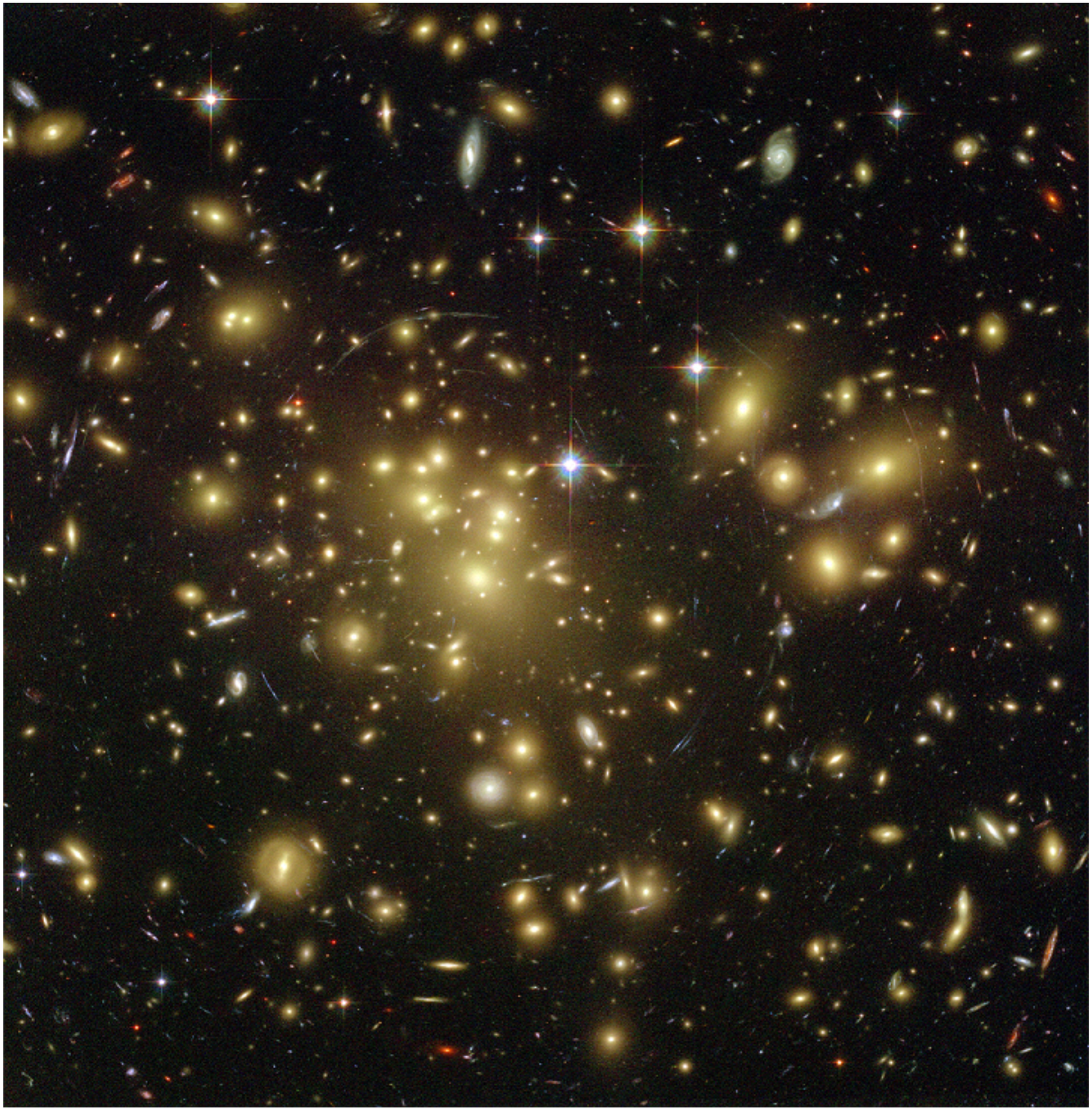
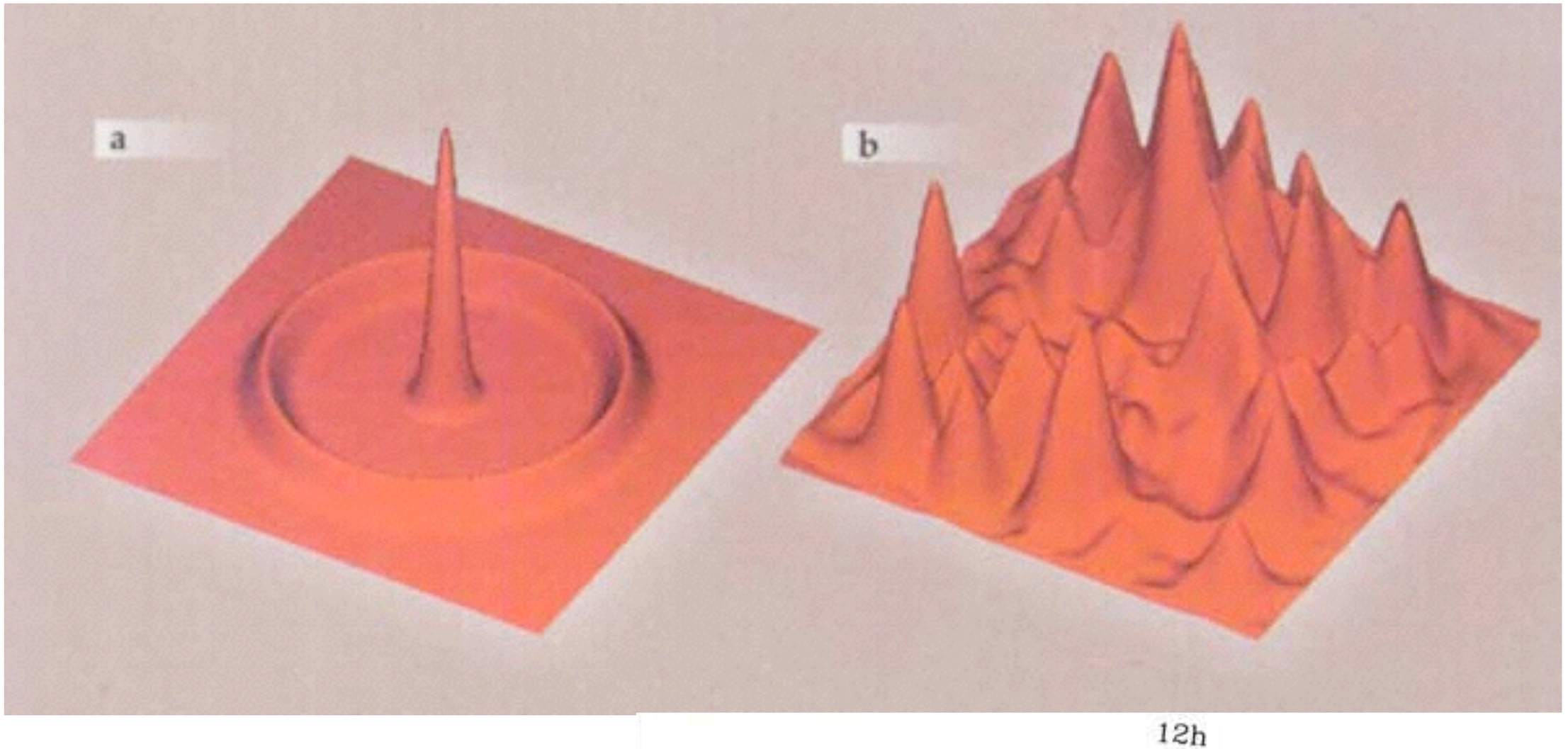


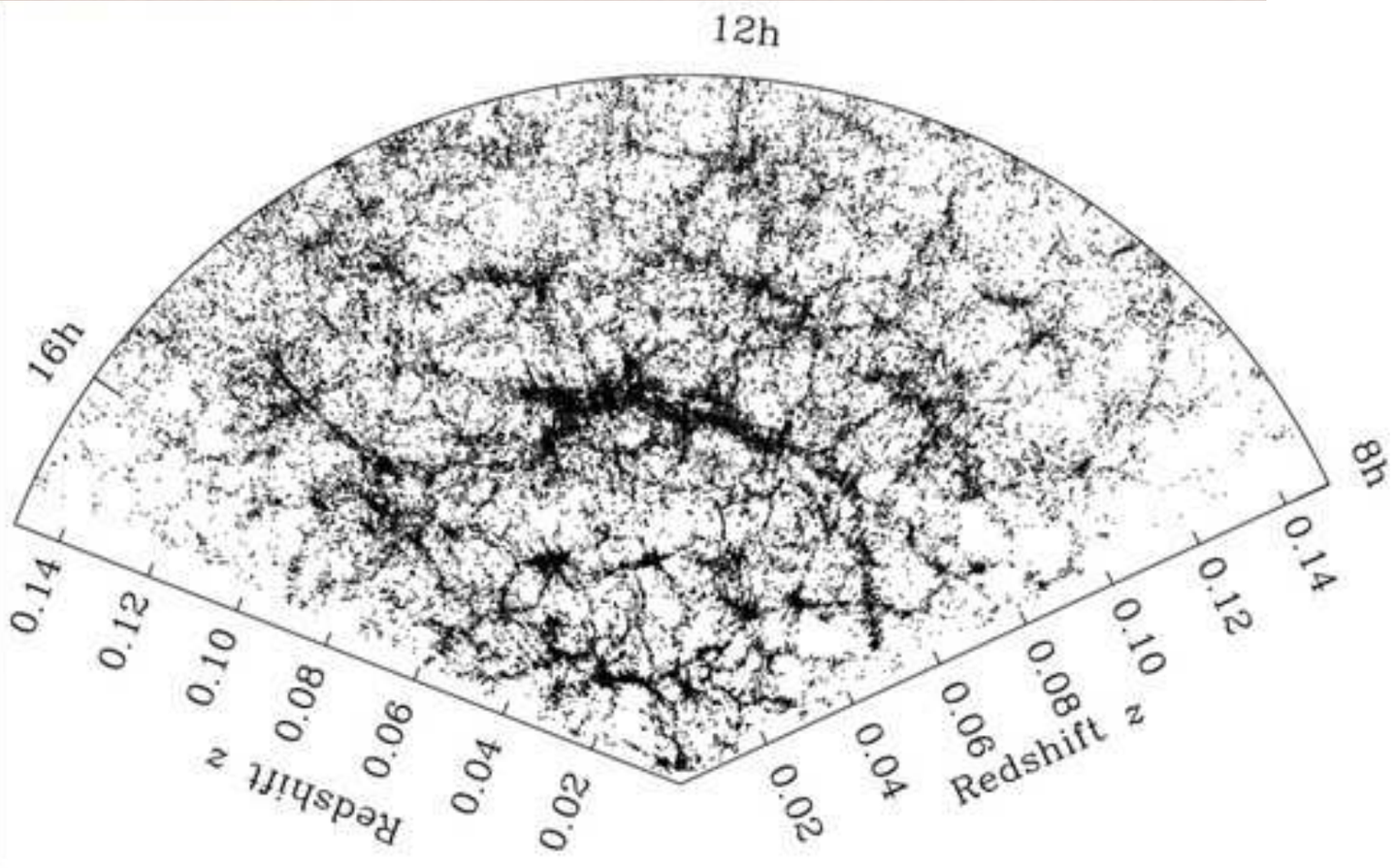
Subhalos within Halos



aglomerado
de galáxias

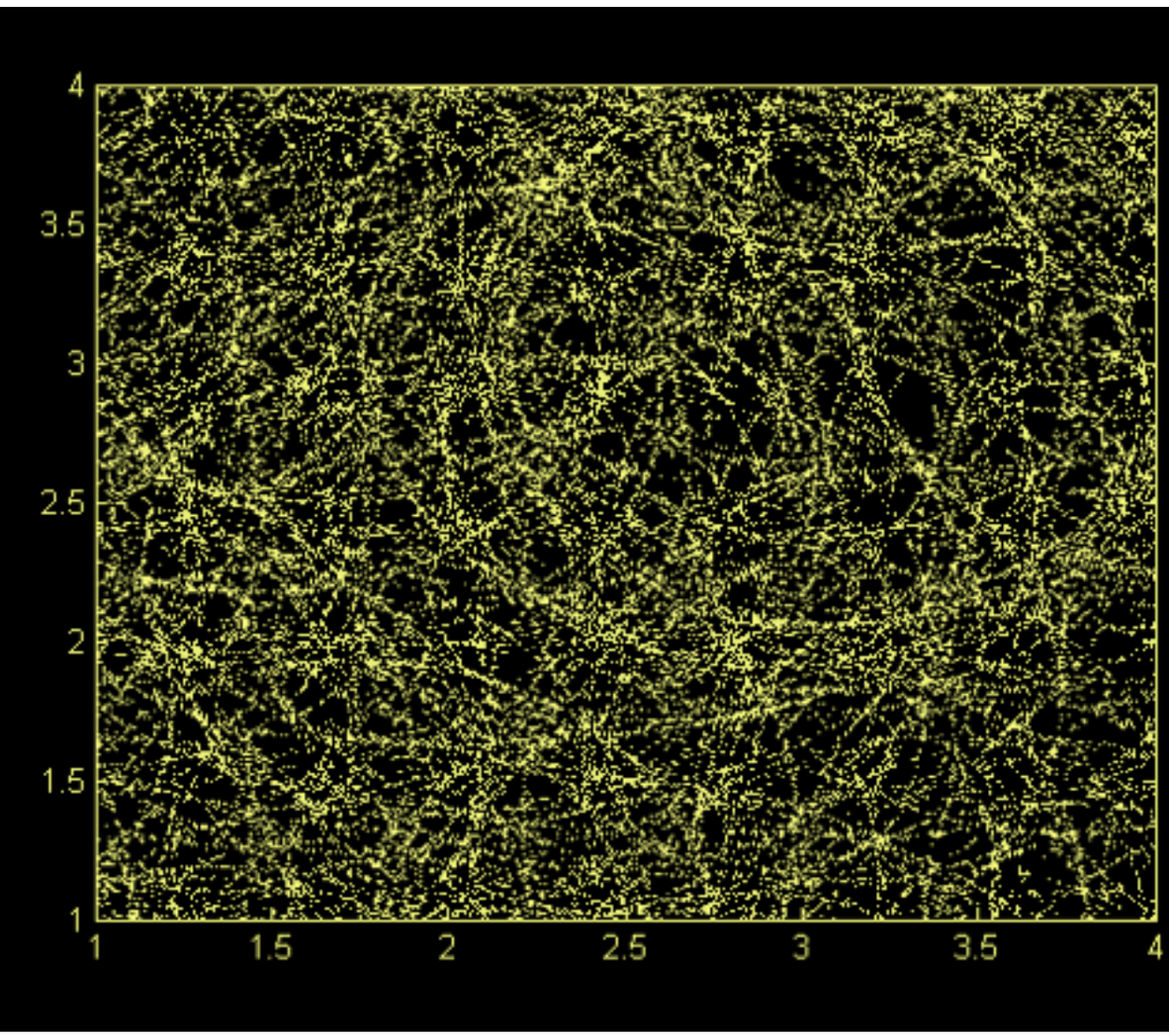


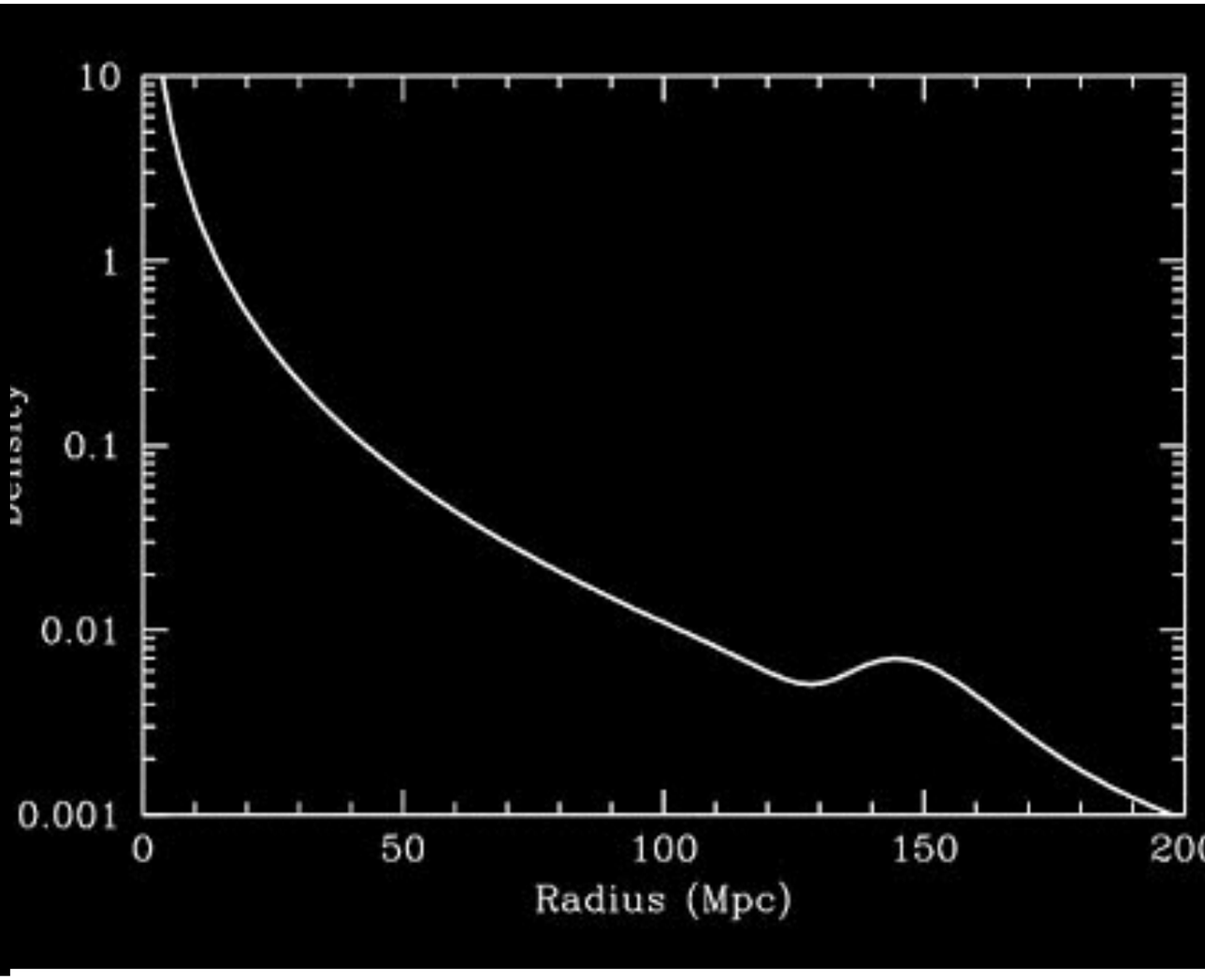
BAO is a signature imprinted in the distribution of cosmic objects.
Why is it important?



Large-scale structure: BAO

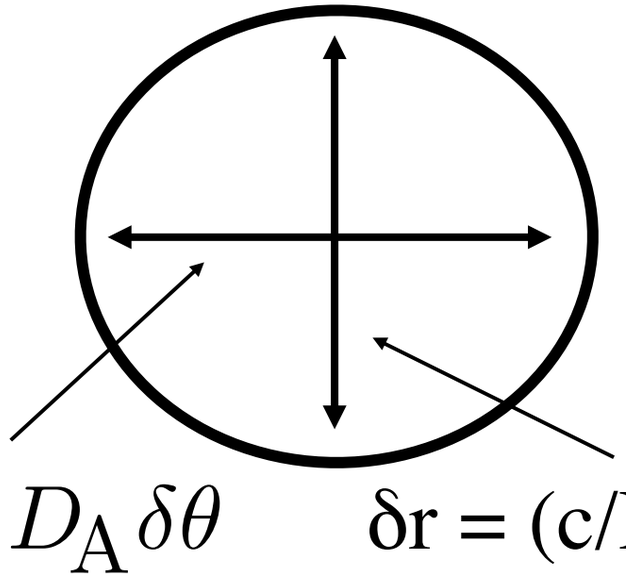
BAO: cosmological ruler





2-point correlation function

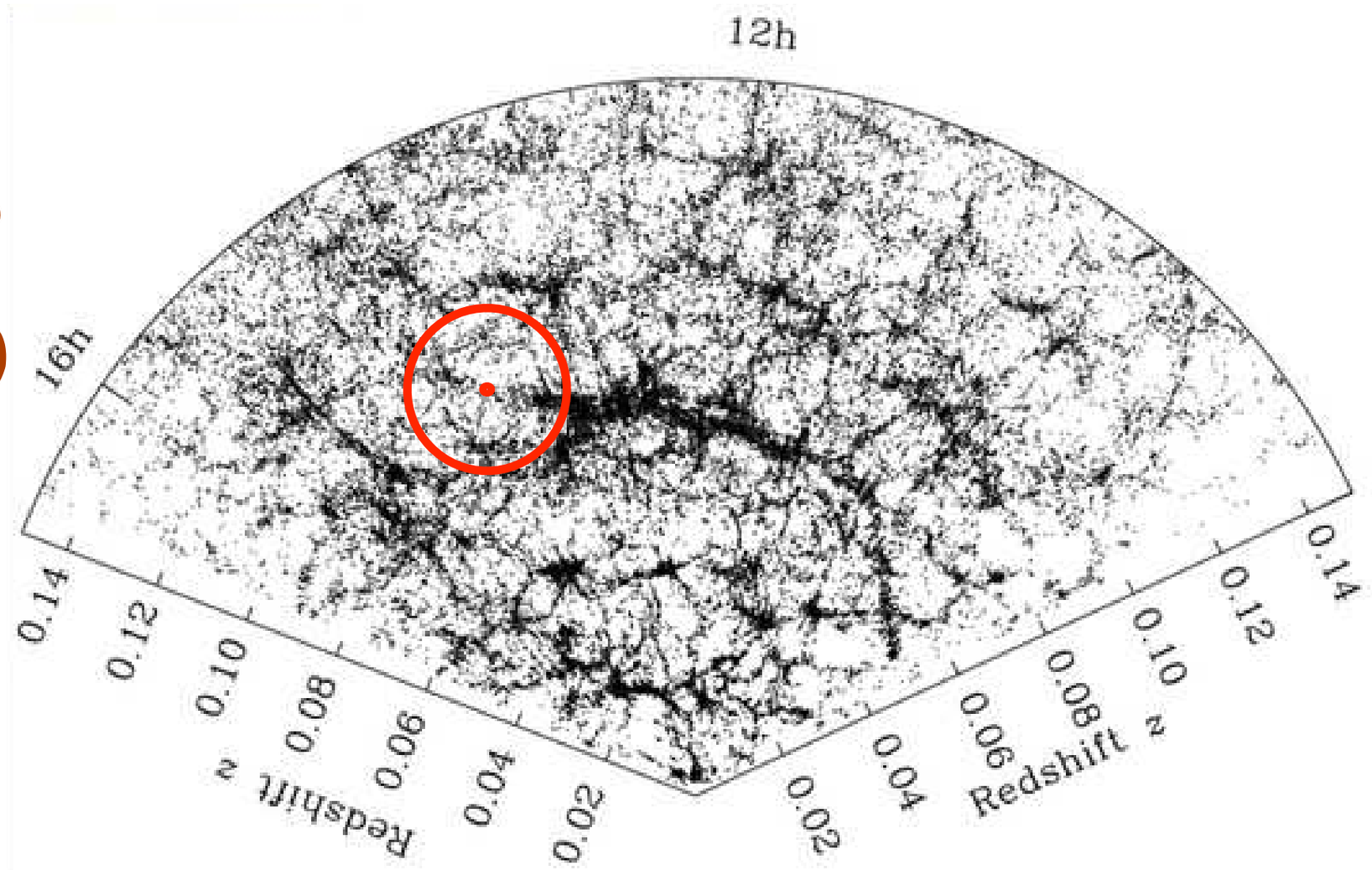
BAO: cosmological ruler



2PACF*: a tool to explore transversal-BAO signature

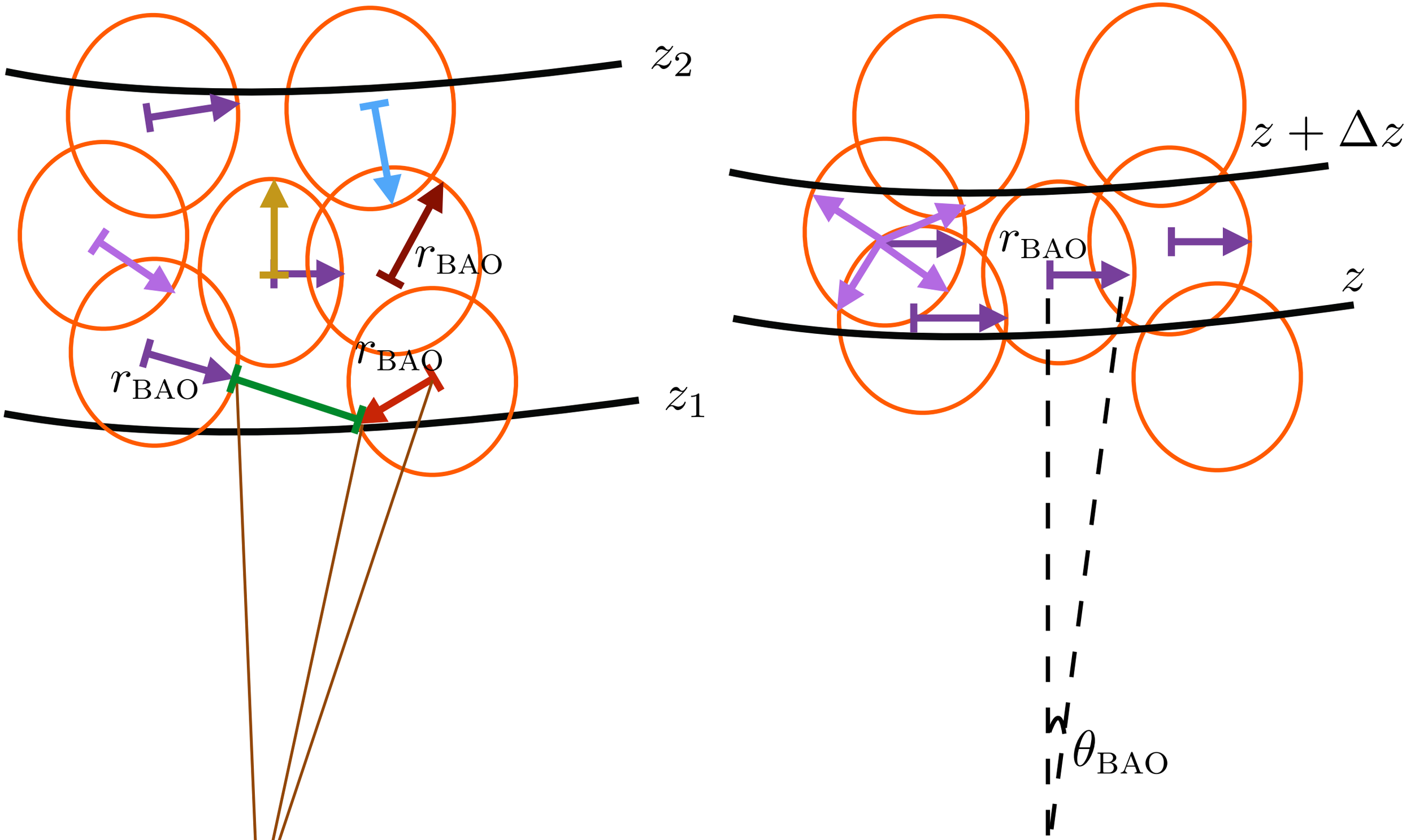
*2-point angular correlation function

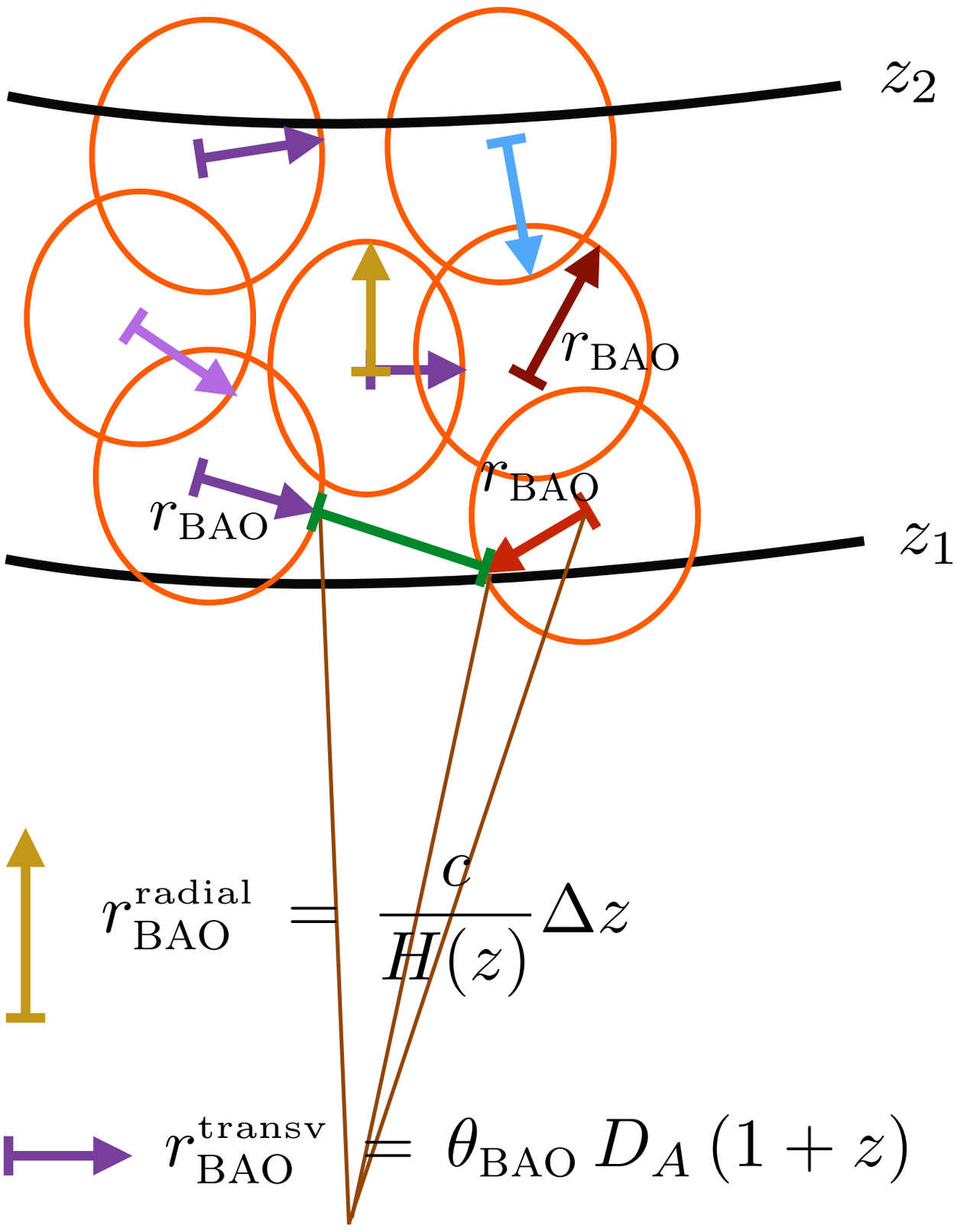
Analyses with galaxy surveys e.g.,SDSS-DR10

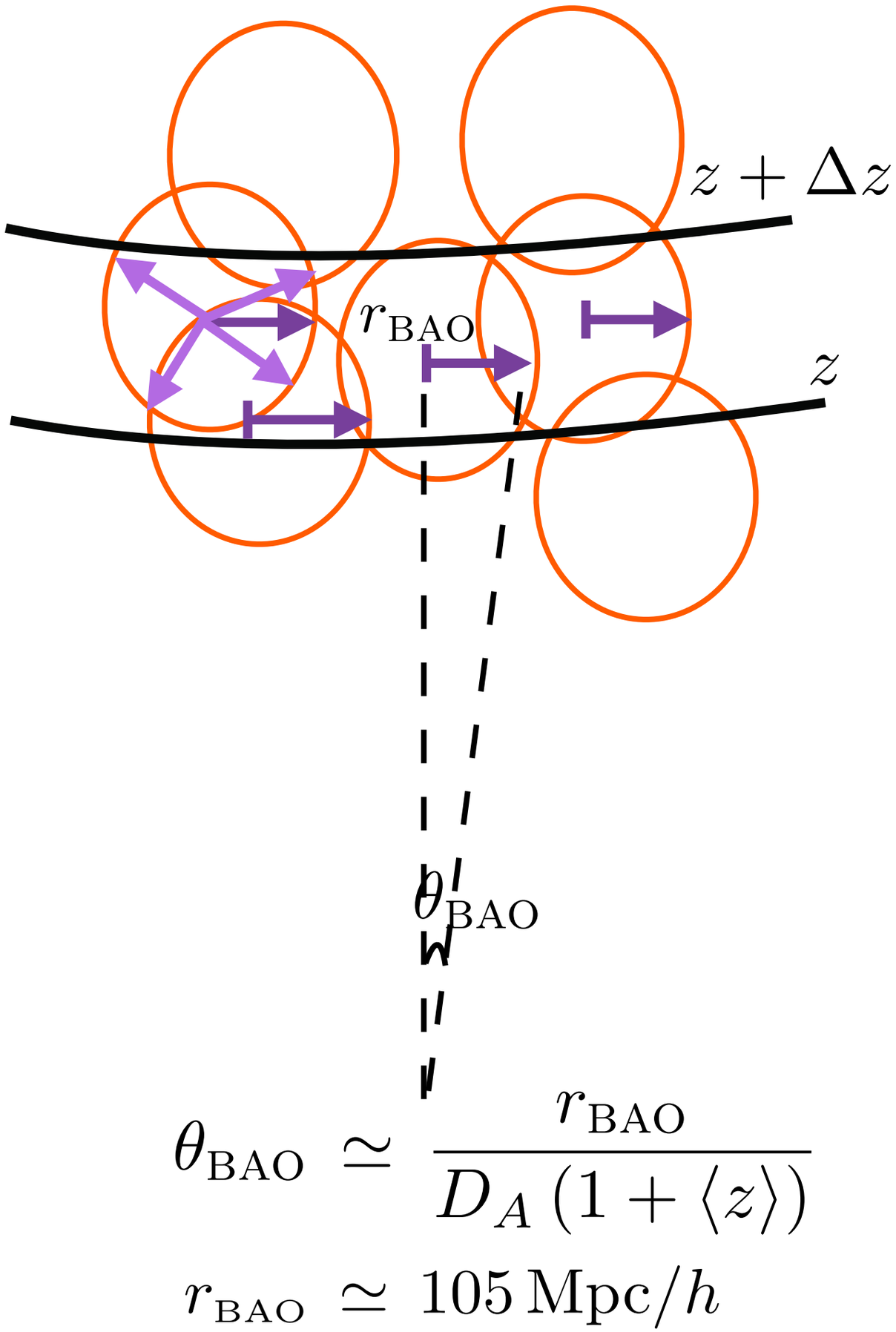


- Motivation: To restrict cosmological models and parameters in a model independent way

- What do we do: Precise measurements of $D_A(z)$ without assuming a fiducial cosmology.


z_2
z_1
$r_{\rm BAO}$
$r_{\rm BAO}$
$r_{\rm BAO}$
$z + \Delta z$
z
$r_{\rm BAO}$
$\theta_{\rm BAO}$



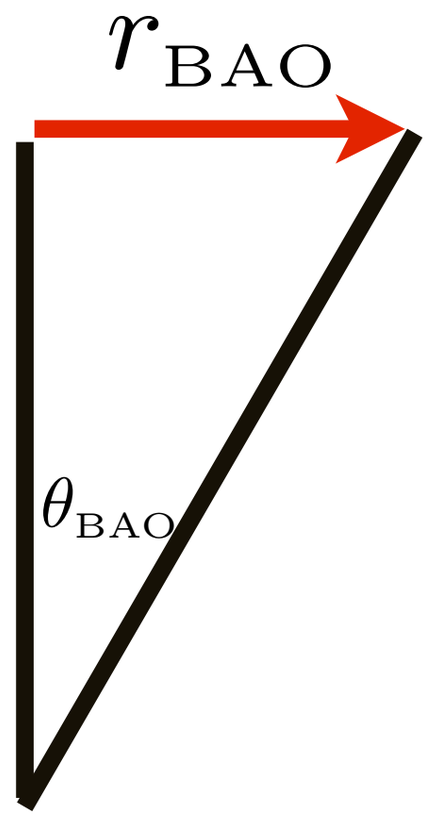


$$\theta_{\rm BAO} \simeq \frac{r_{\rm BAO}}{D_A\,(1+\langle z\rangle)}$$

$$r_{\rm BAO} \simeq 105\,{\rm Mpc}/h$$

$$D_A = \frac{r_{\rm BAO}}{(1+z)\,\theta_{\rm BAO}}$$

$$r_{\rm BAO} \simeq 105\,{\rm Mpc}/h$$



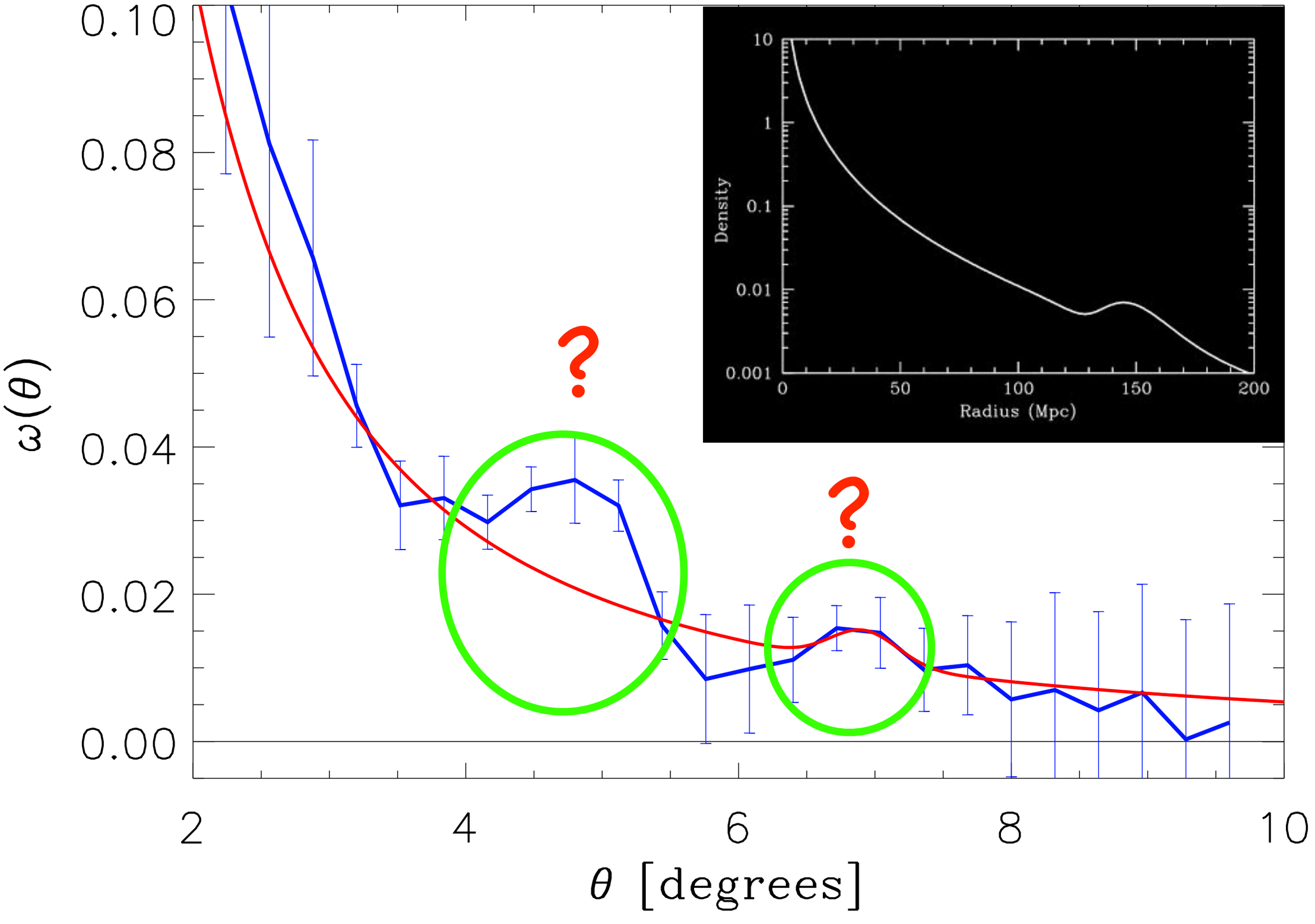
$$\theta_{\rm BAO} = \frac{r_{\rm BAO}}{(1+z)\,D_A}$$

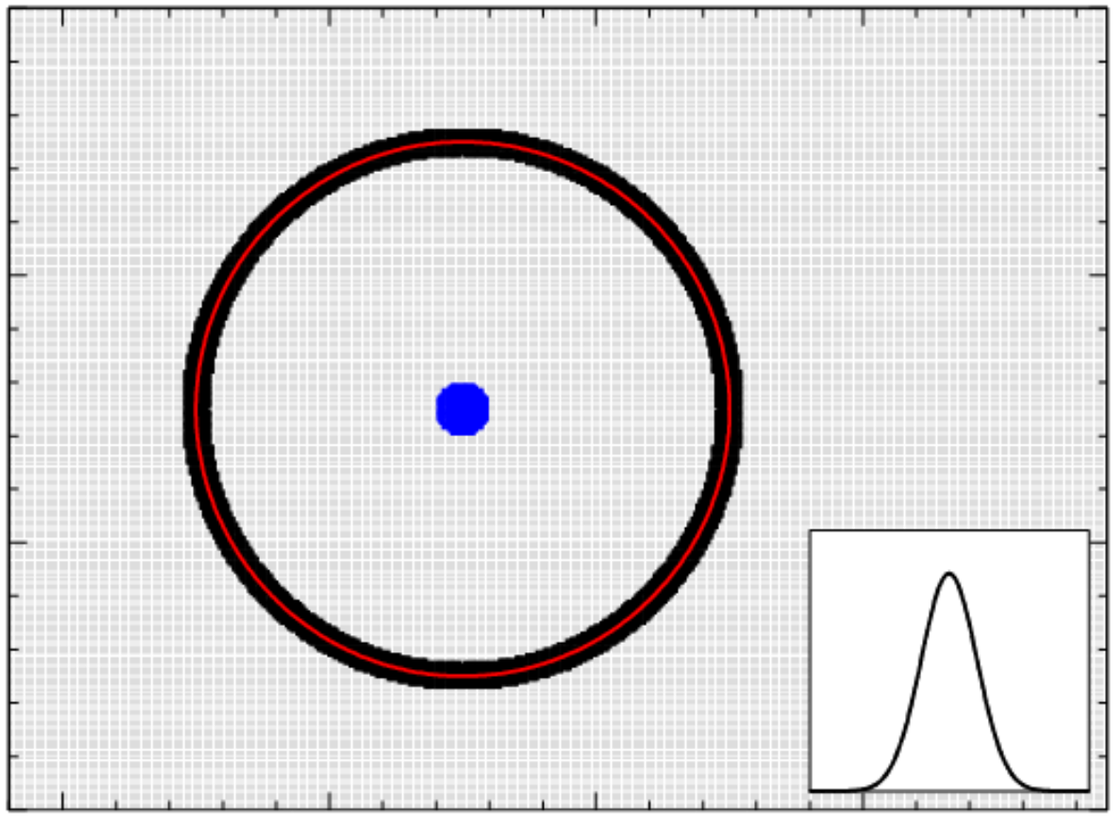
Finding θ_{BAO} in the 2PACF in thin bin-redshift shells $\Delta z \simeq 0.01$

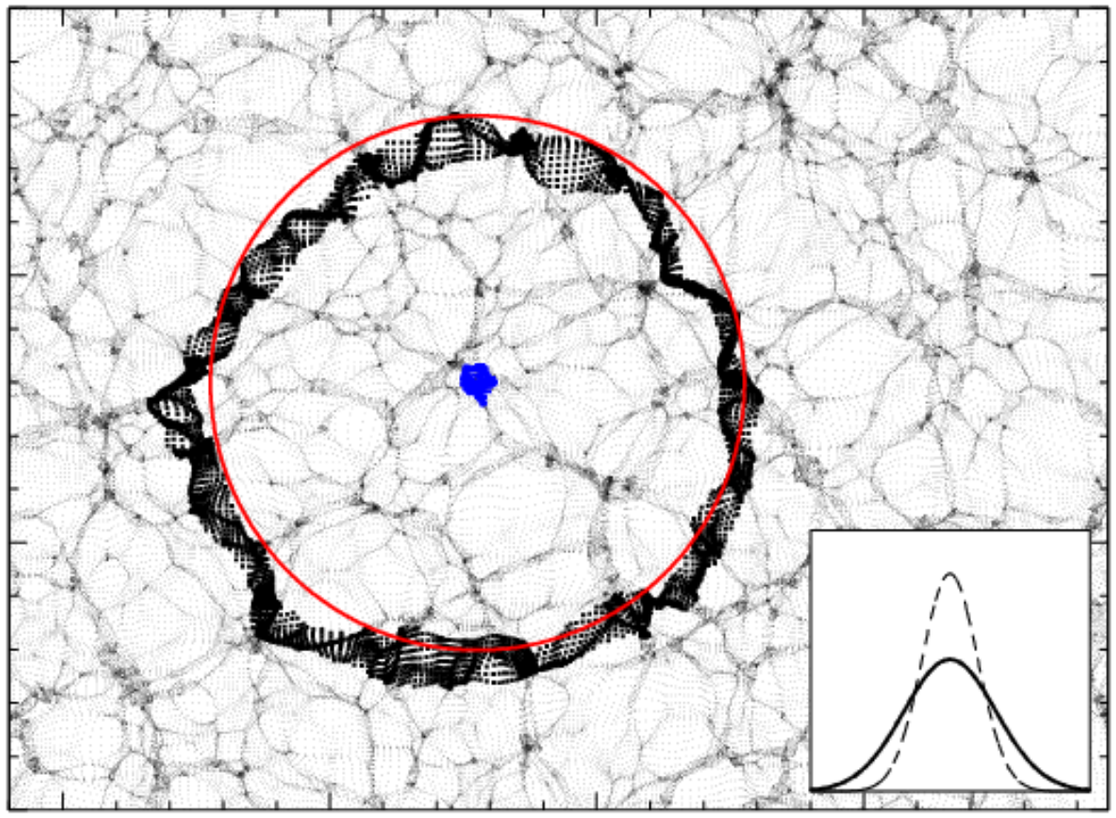
SDSS-DR10

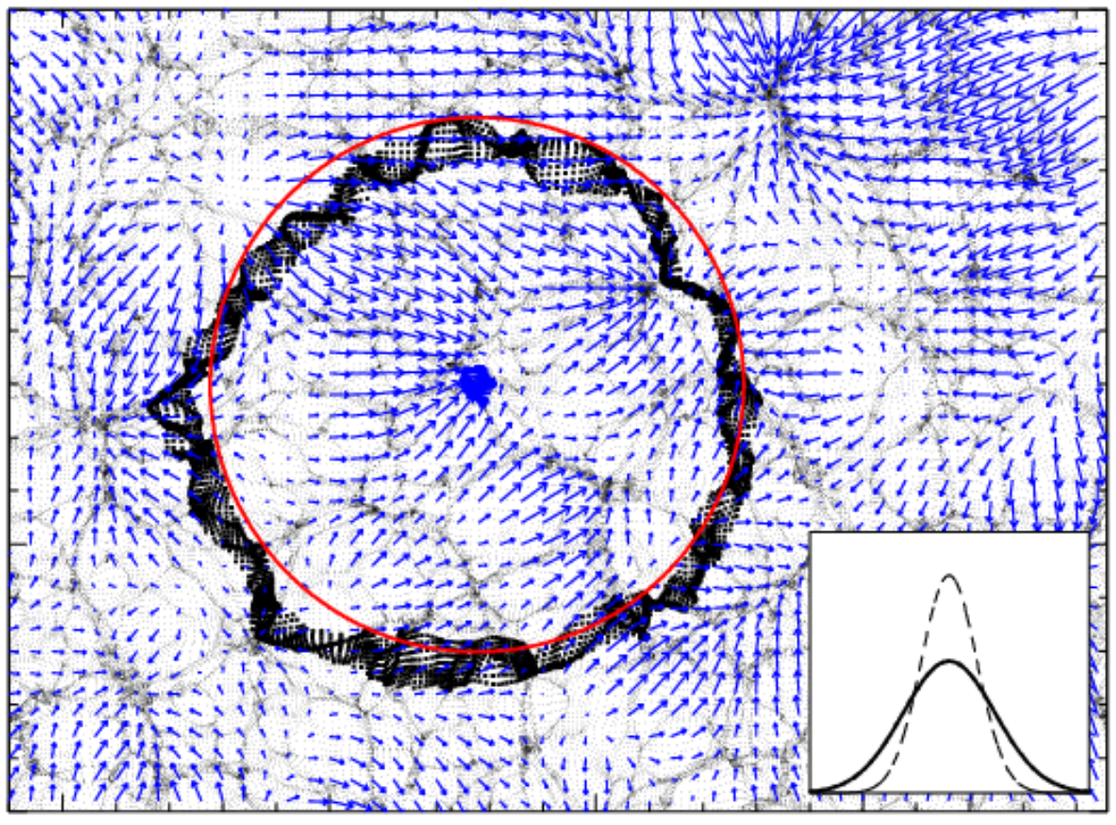
redshift intervals	number of LRGs	$\bar{z}$	δz
0.440 - 0.460	21,862	0.45	0.02
0.465 - 0.475	17,536	0.47	0.01
0.480 - 0.500	40,957	0.49	0.02
0.505 - 0.515	21,046	0.51	0.01
0.525 - 0.535	22,147	0.53	0.01
0.545 - 0.555	21,048	0.55	0.01

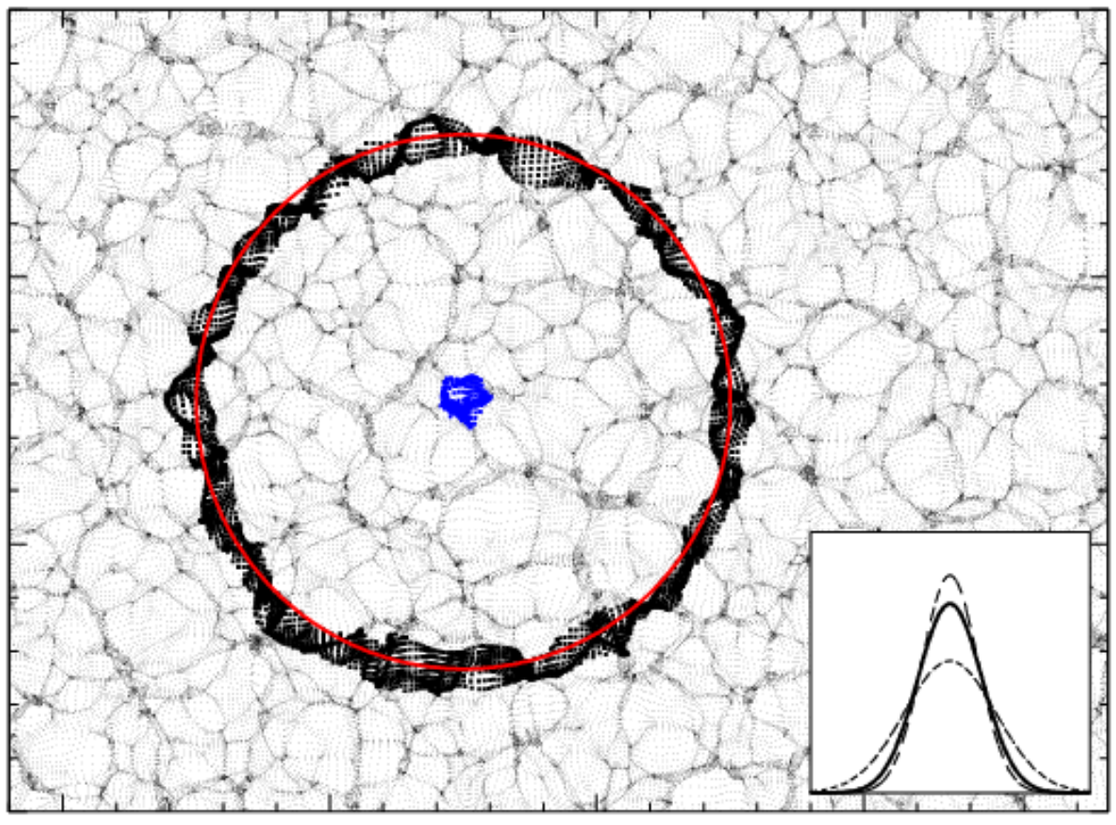
Finding θ_{BAO} in the 2PACF









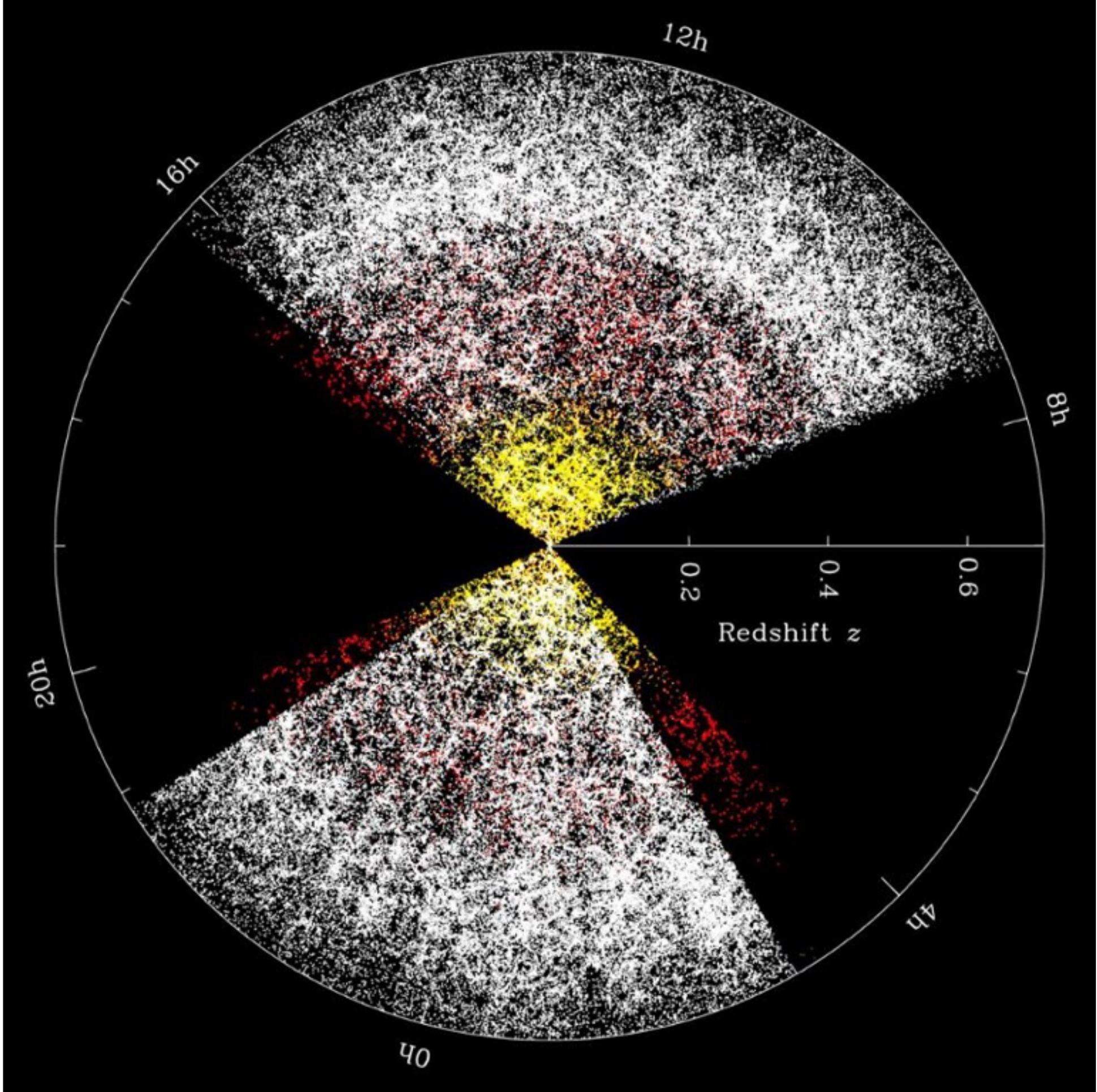


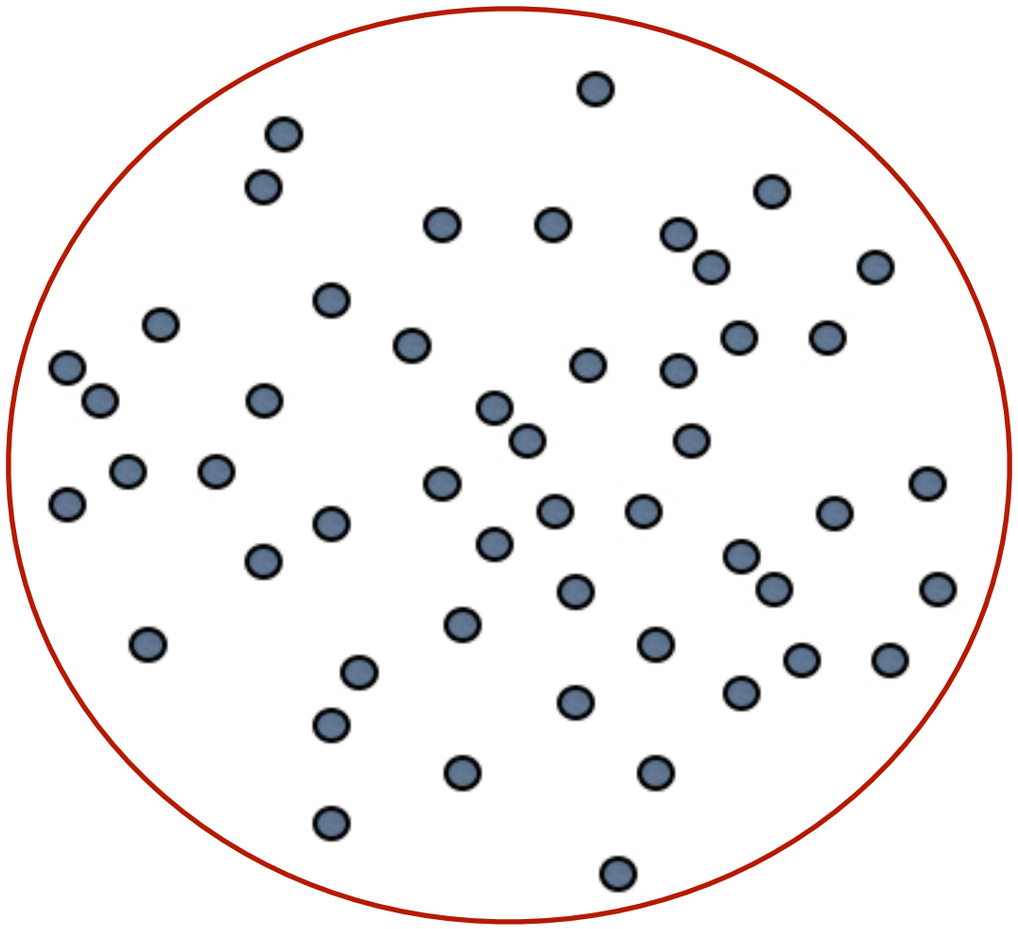
after understanding systematics,... results

Gabriela

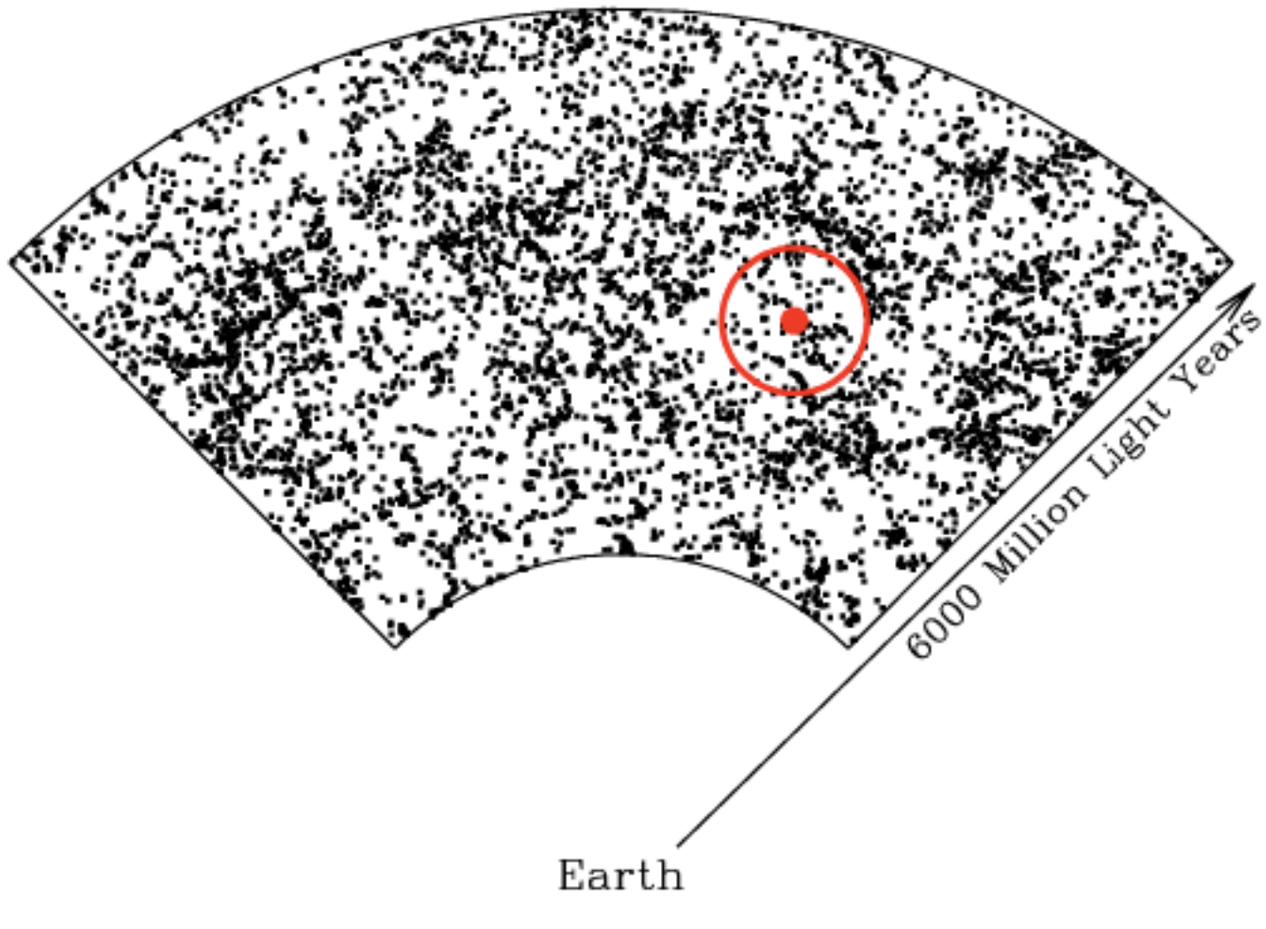
SDSS

Edilson





uniform distribution?



isotropy -> 2d: 2PACF

homogeneity -> 2d, 3d: 2PACF, 2PCF

can be tested with astronomical data

3PCF

$$\xi(s) = \frac{DD(s) - RR(s)}{RR(s)}$$

2PACF

$$\omega(\theta) = \frac{DD(\theta) - RR(\theta)}{RR(\theta)}$$

An example: 2PACF in a CMB map

Função de correlação angular de dois pontos

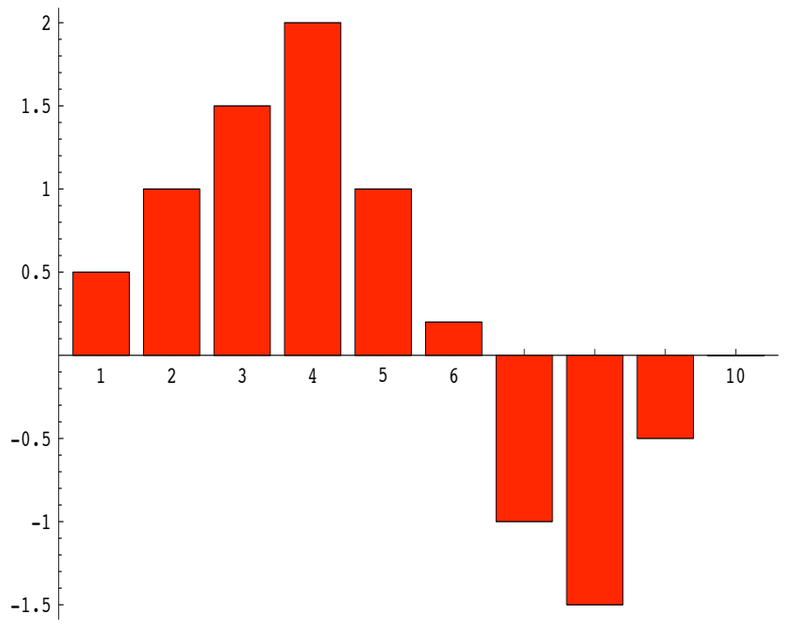
Seja um mapa de flut. de temperaturas $\Delta T_i = \Delta T(\theta_i, \phi_i)$ com N pixels: $\Delta T_1, \Delta T_2, ..., \Delta T_N$. A pixelização da esfera determina que as distâncias angulares são discretas: entre o centro do pixel i com coordenadas (θ_i, ϕ_i) e o centro do pixel j com coordenadas (θ_j, ϕ_j).

A função de correlação angular de dois pontos (2PACF , em inglês) é

$$C(\gamma_{ij}) \equiv \langle\, \Delta T(\theta_i, \phi_i) \Delta T(\theta_j, \phi_j) \,\rangle\,,$$

$$\gamma_{ij} \equiv \cos^{-1}[\cos(\theta_i)\,\cos(\theta_j) + \sin(\theta_i)\,\sin(\theta_j)\,\cos(\phi_i - \phi_j)]\,,$$

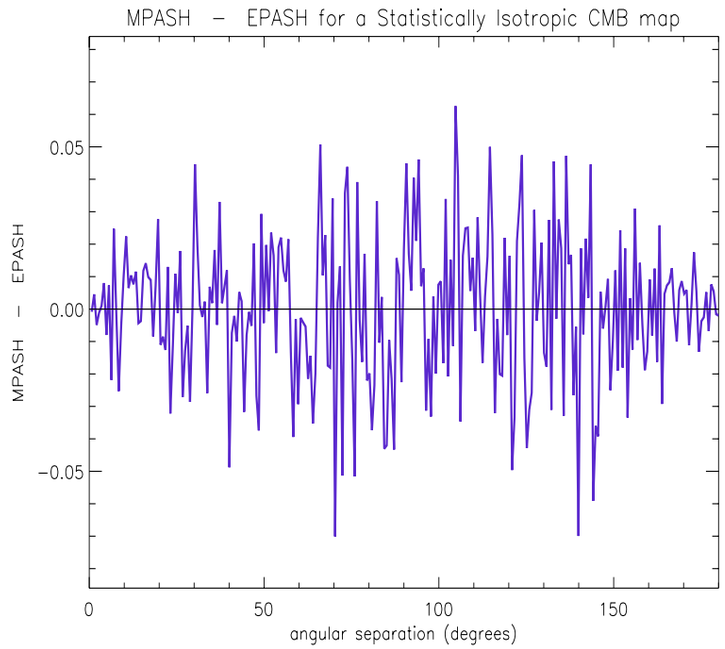
a média $\langle\ \rangle$ é obtida usando todos os valores t.q. $\gamma_{ij} \in [(k-1)\delta, k\delta]$, $\forall k = 1, ..., N_{\text{bins}}$; tal média dá o valor de C no $k-$ésimo bin:

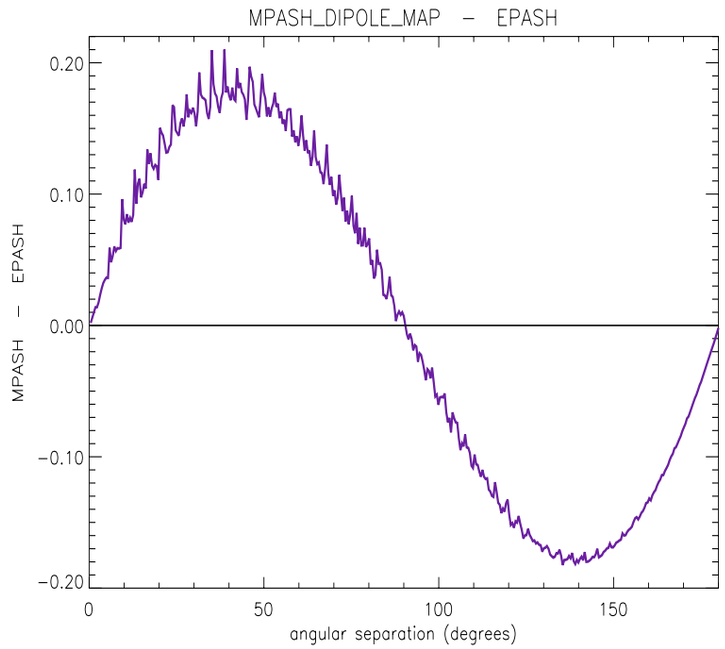


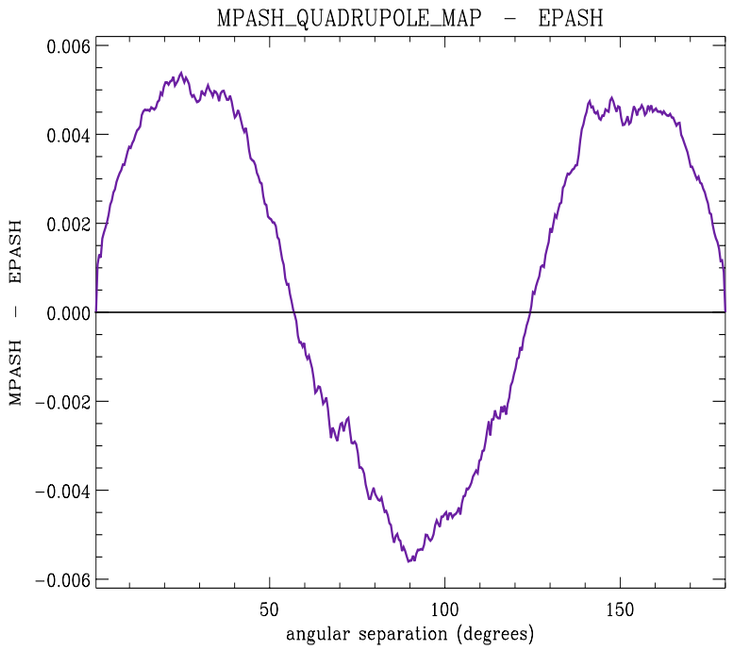
δ é o tamanho do bin

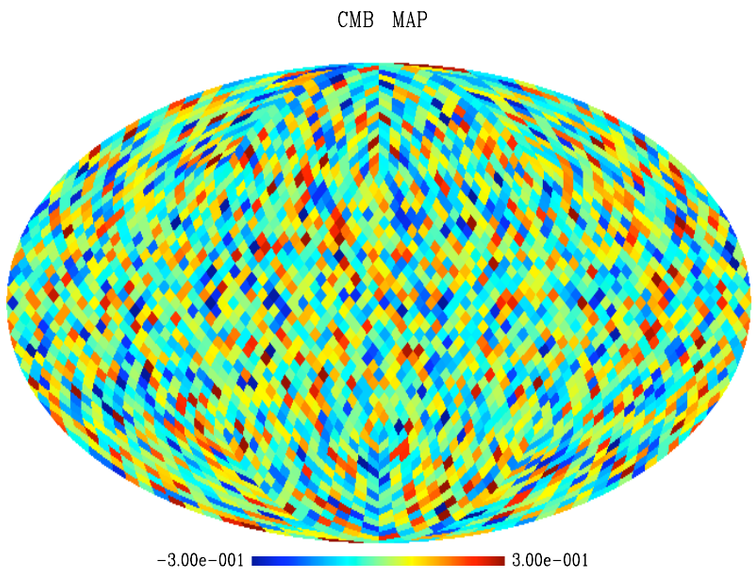
Revelando assinaturas nas curvas 2PACF

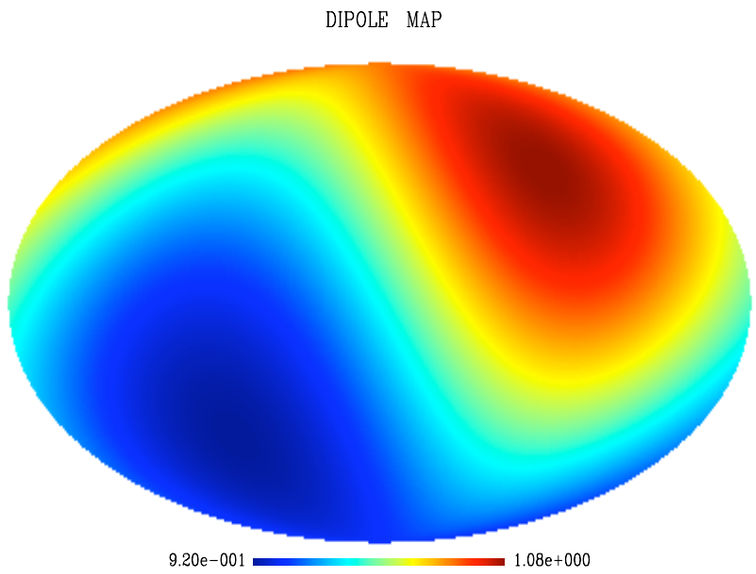
assinatura-zero, assinatura-dipolar, assinatura-quadrupolar,..

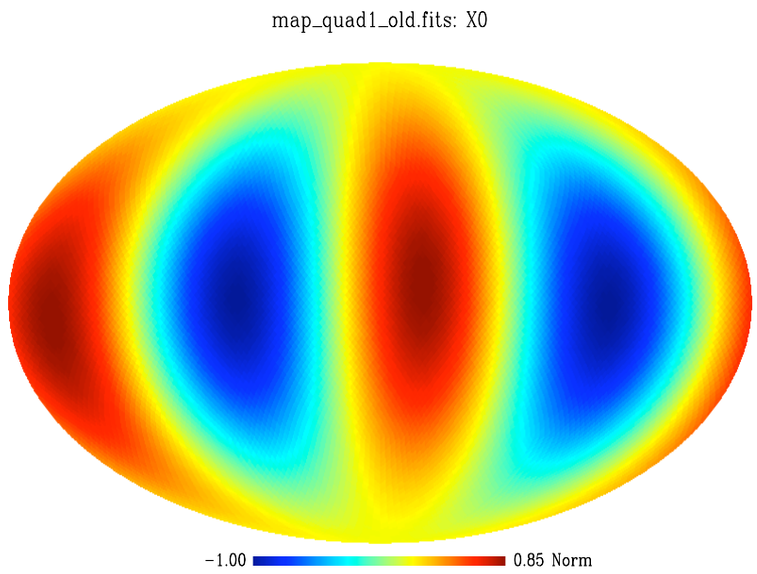






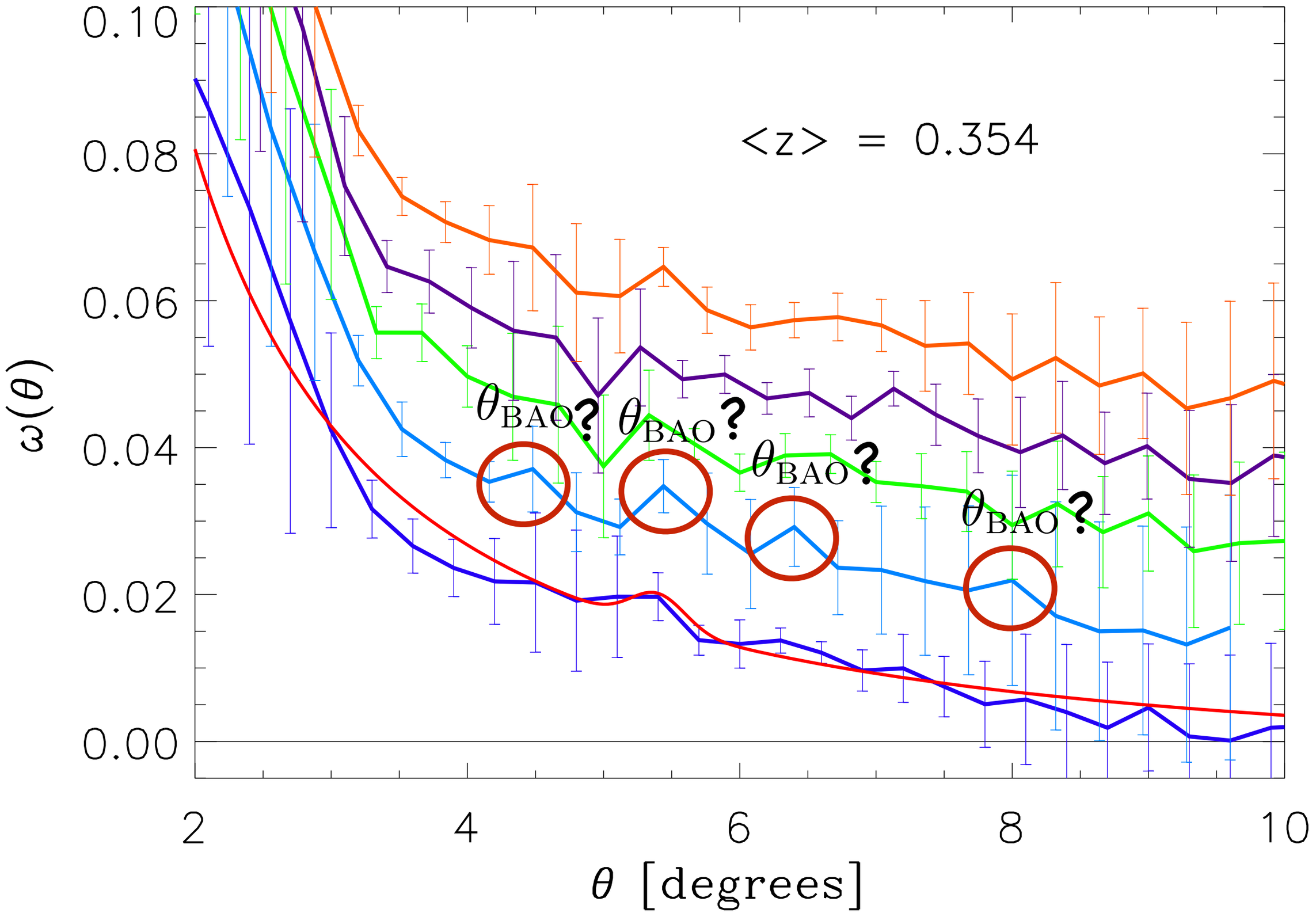




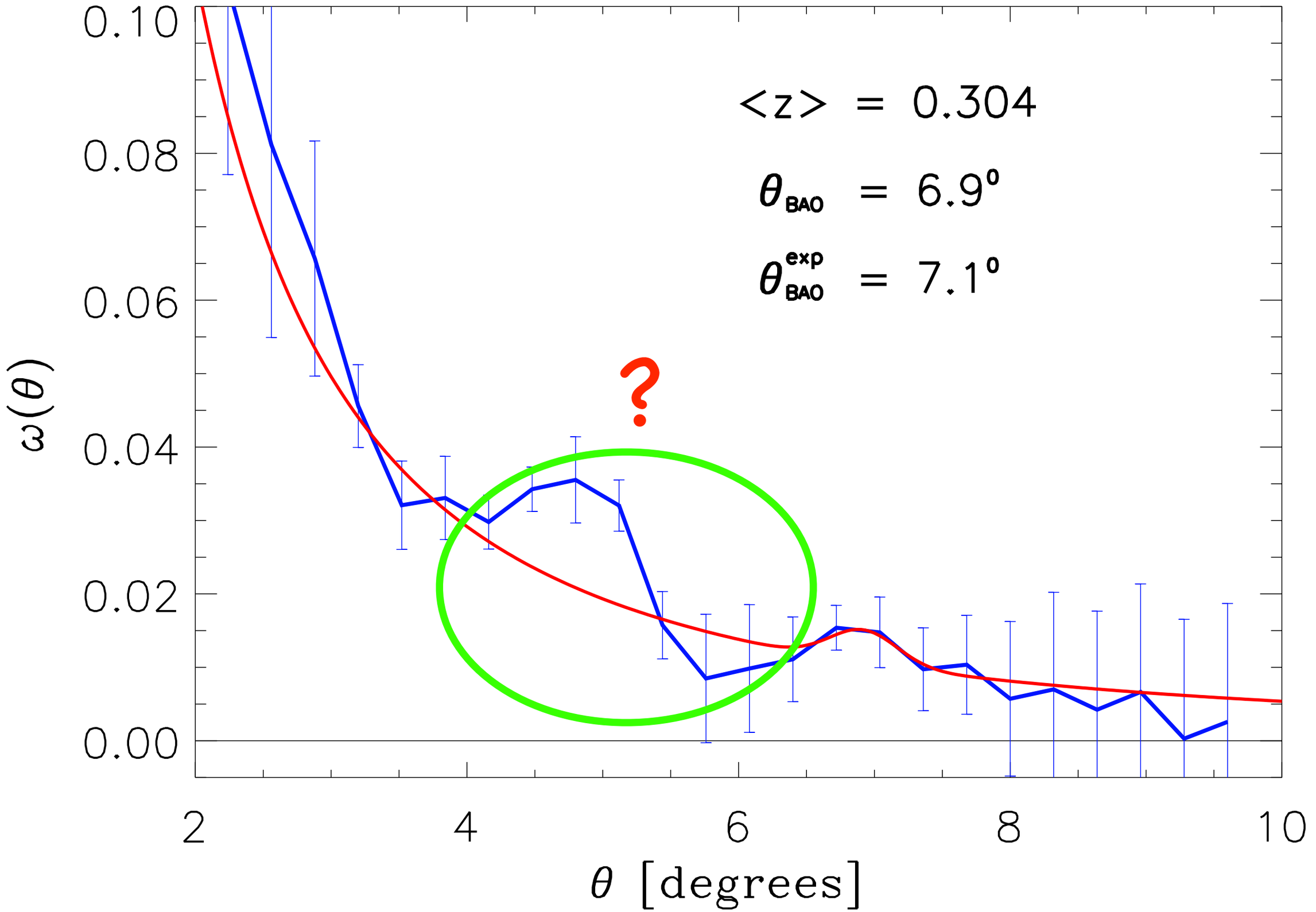


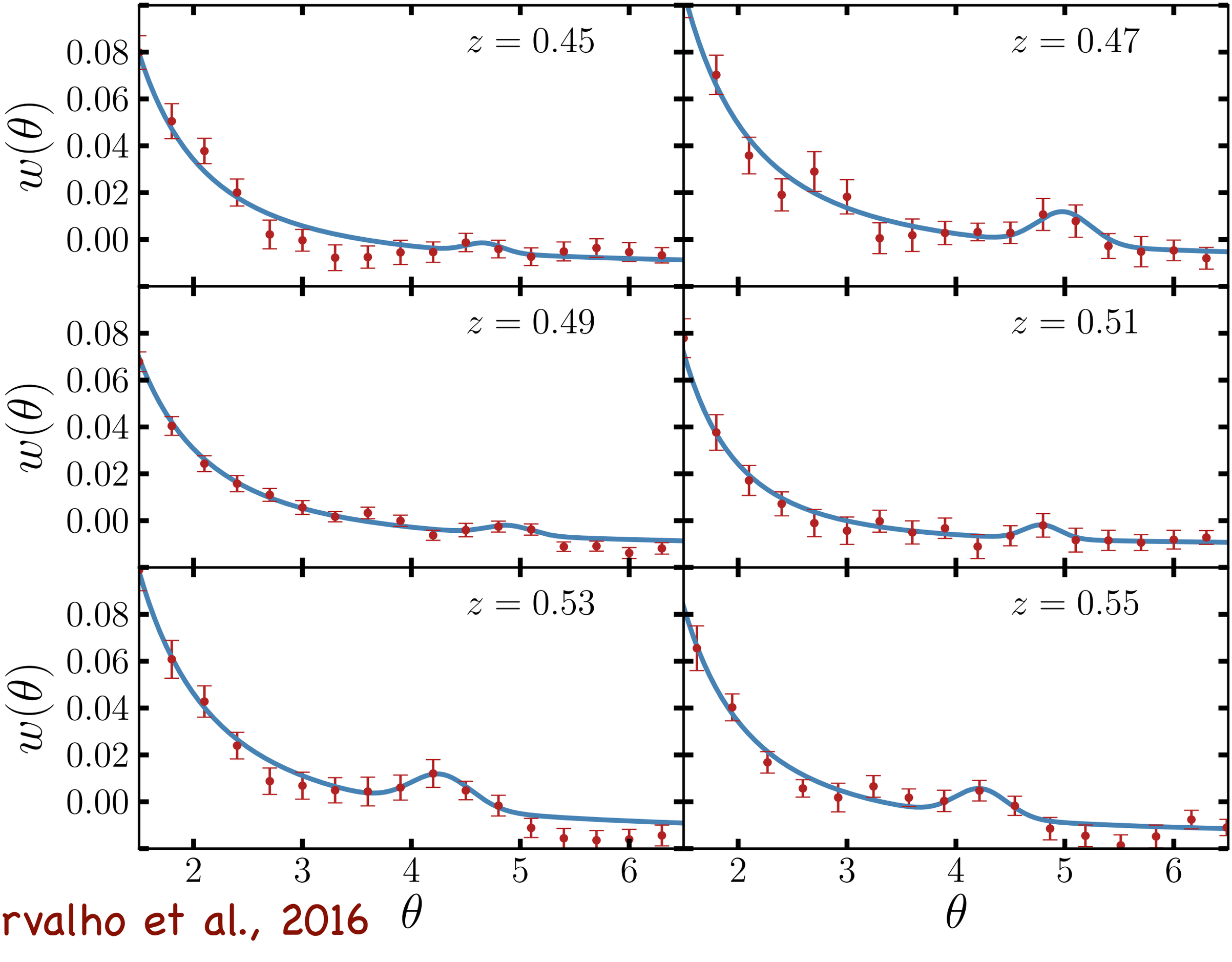
Finally: 2PACF in a galaxies catalog!

Where is the angular-BAO signal?

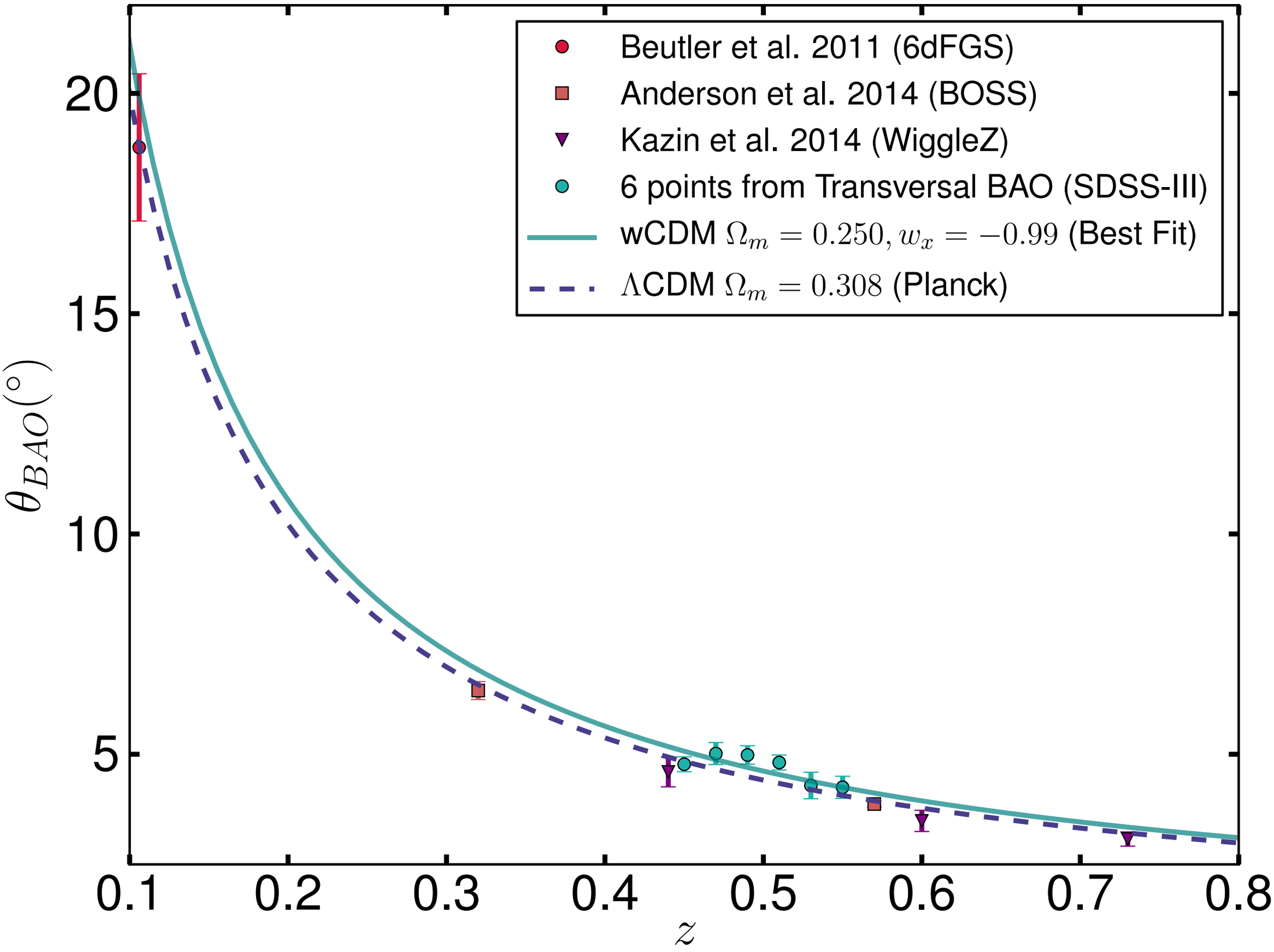


Systematics: Problems or Opportunities?

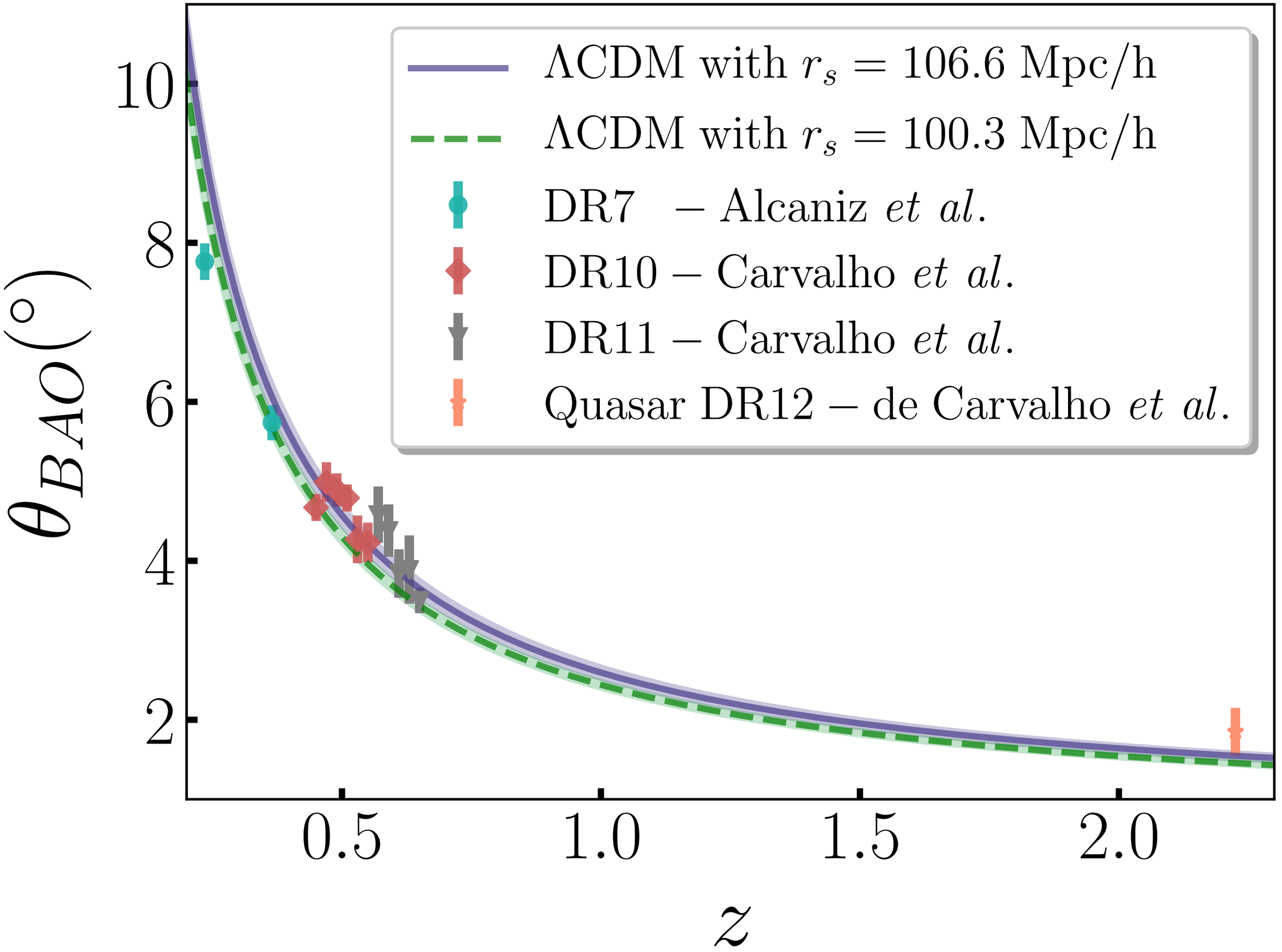


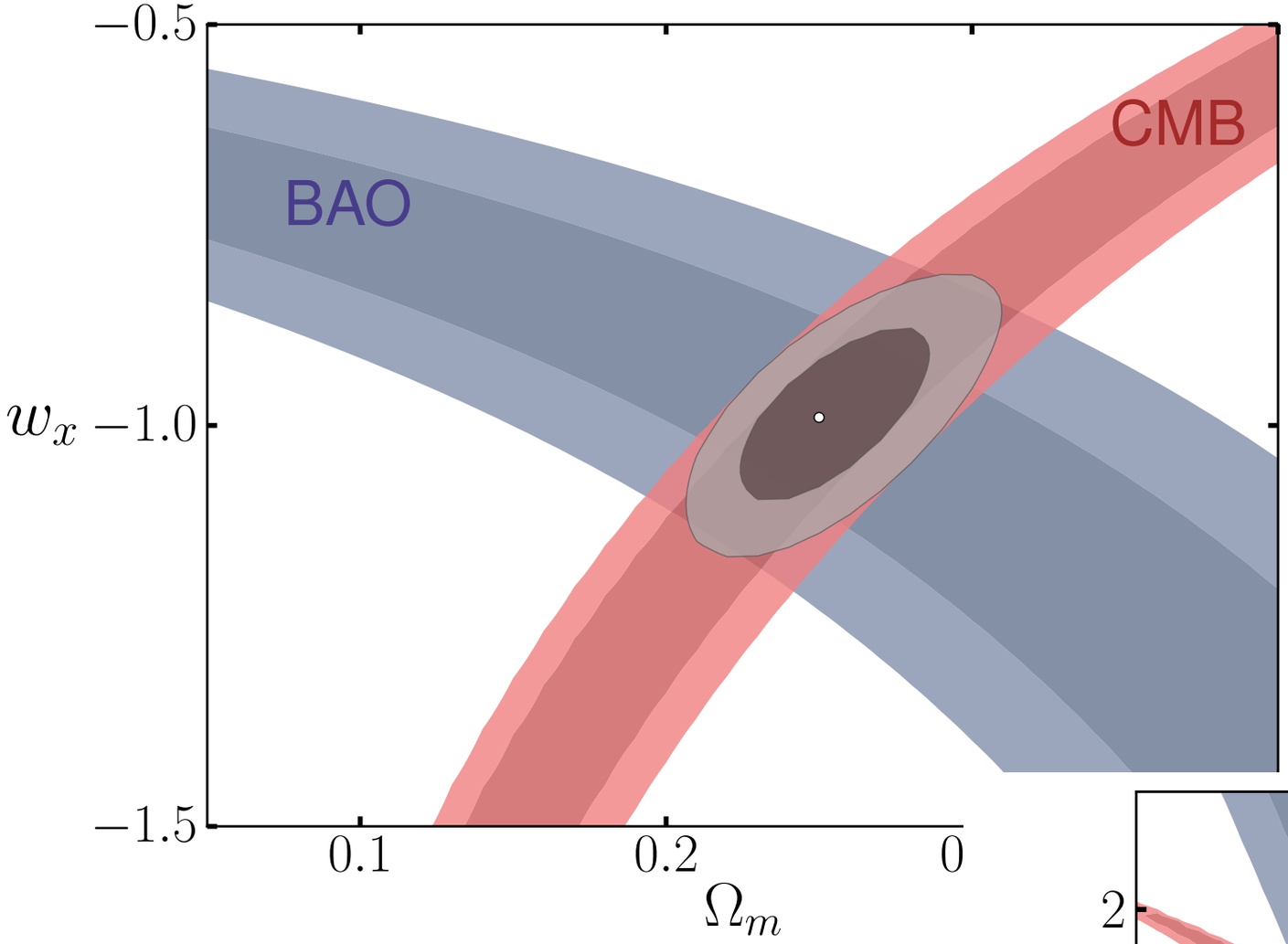


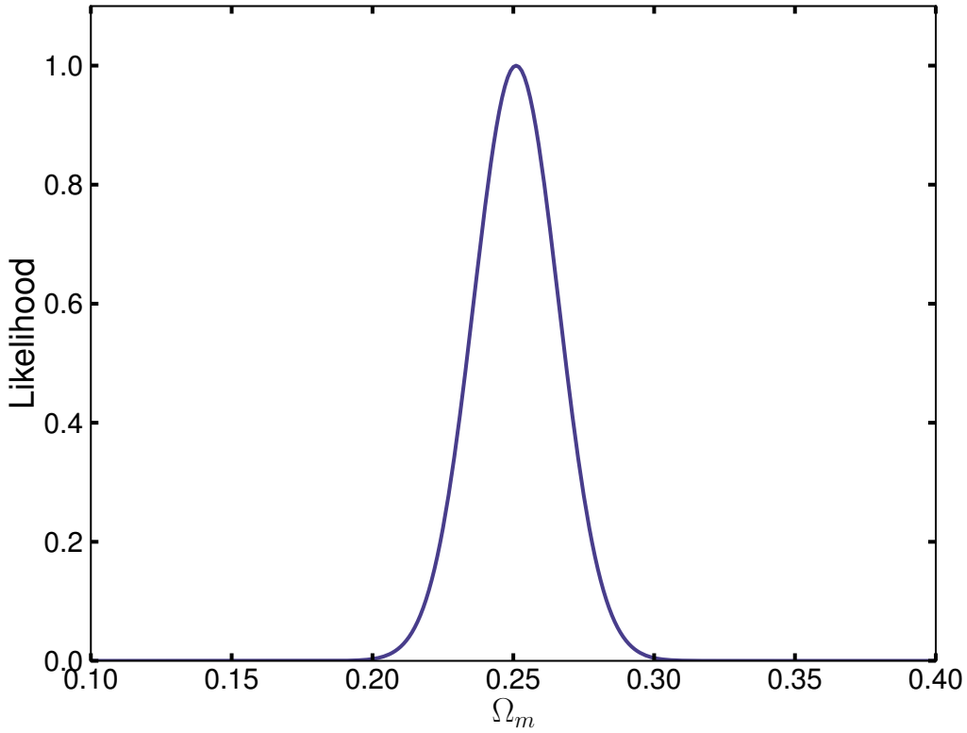
Carvalho et al., 2016

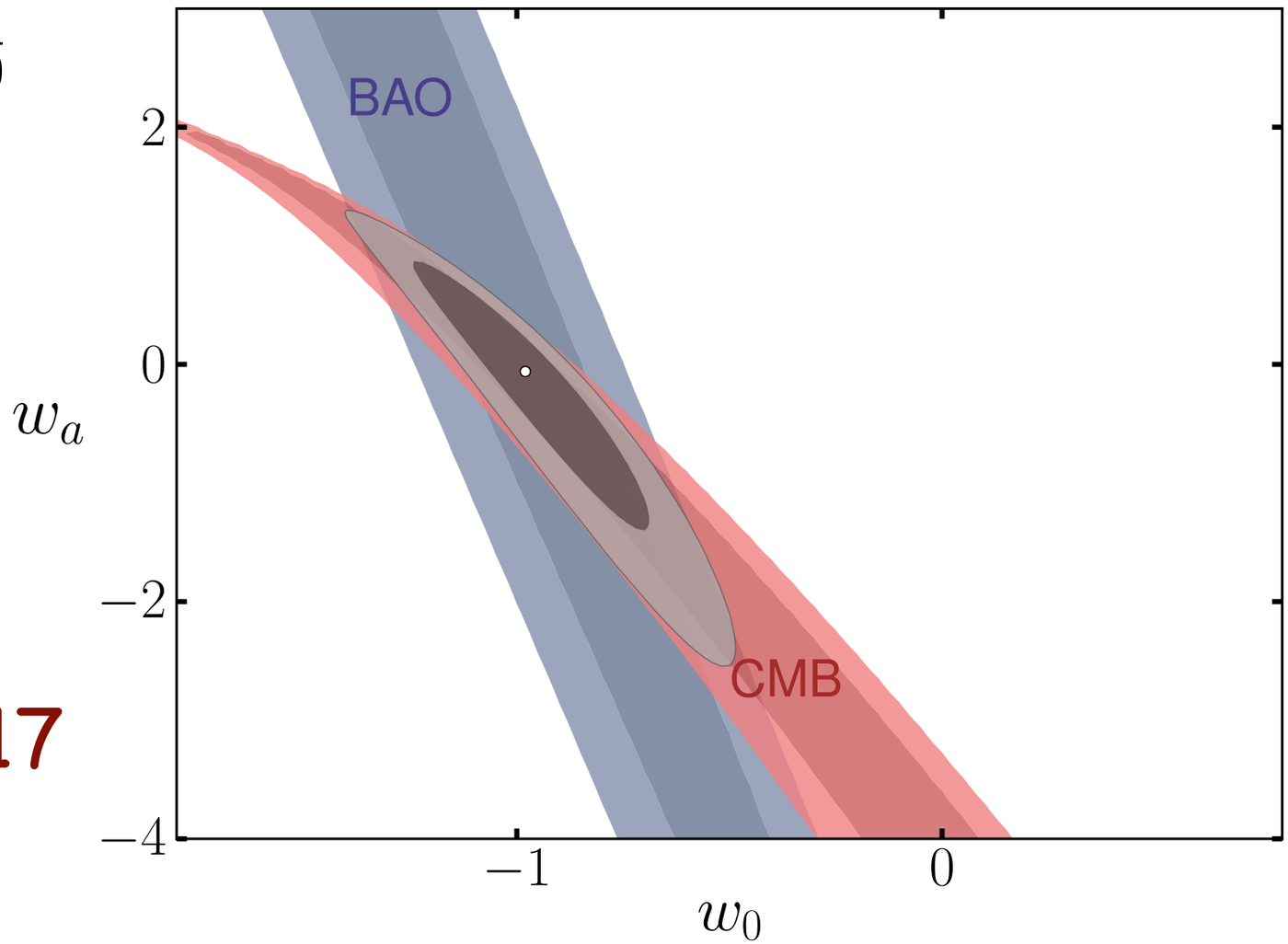


Carvalho et al., 2015


ΛCDM with $r_s = 106.6$ Mpc/h
ΛCDM with $r_s = 100.3$ Mpc/h
DR7 – Alcaniz *et al.*
DR10 – Carvalho *et al.*
DR11 – Carvalho *et al.*
Quasar DR12 – de Carvalho *et al.*
$\theta_{BAO}(°)$
z
10
8
6
4
2
0.5
1.0
1.5
2.0







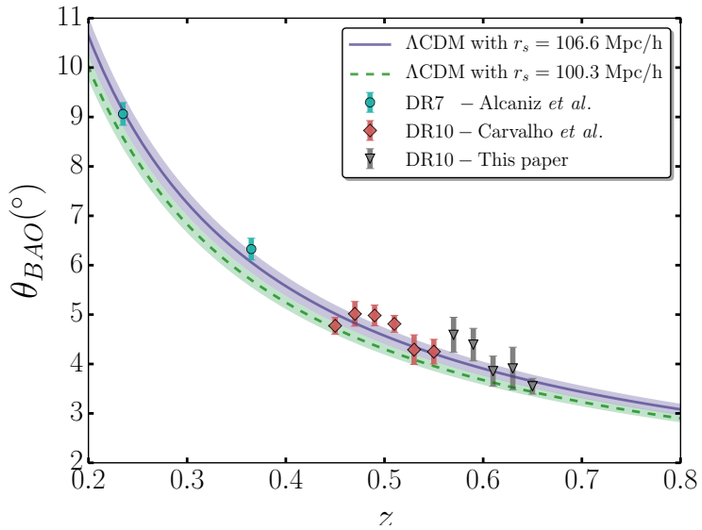
Carvalho et al., 2016,2017

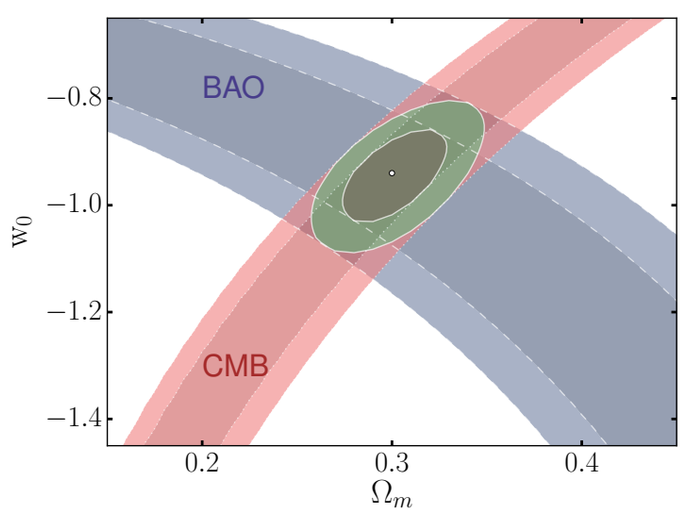
(some) Fundamental Questions

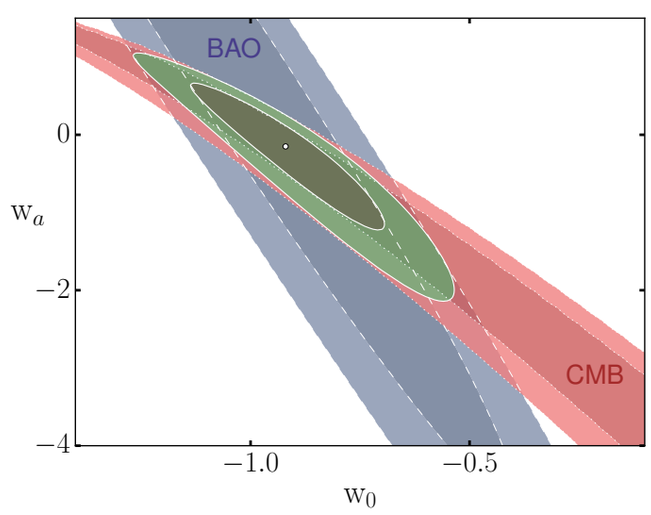
- What is the shape of the Universe? R^3 ⟼ sure?
- Is the Universe homegeneous and isotropic? yes! ⟼ hdyki?
- Is LCDM the `true' cosmology? maybe! ⟼ f(R,G),..
- Does the *dark energy* exist? Is it necessary?
- Or: do we live in a void? How large it is?
- Is the Universe acceleration a data artifact?
- Did the Universe came from a singularity?

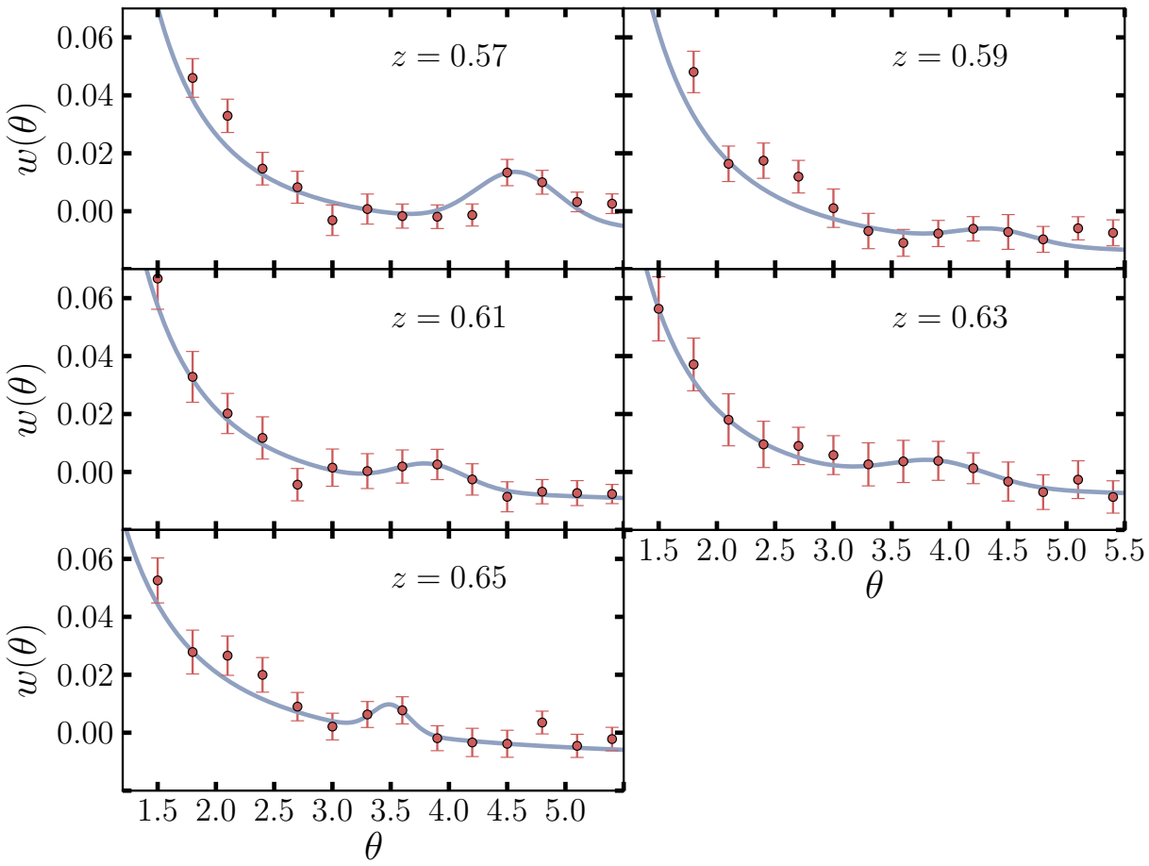
Transversal Scale from Baryon Acoustic Oscillations using SDSS DR11 galaxies angular correlation function [arXiv:1709.00271]

Gabriela C. Carvalho, Armando Bernui, Micol Benetti, Joel C. Carvalho e Jailson Alcaniz









Principais Resultados

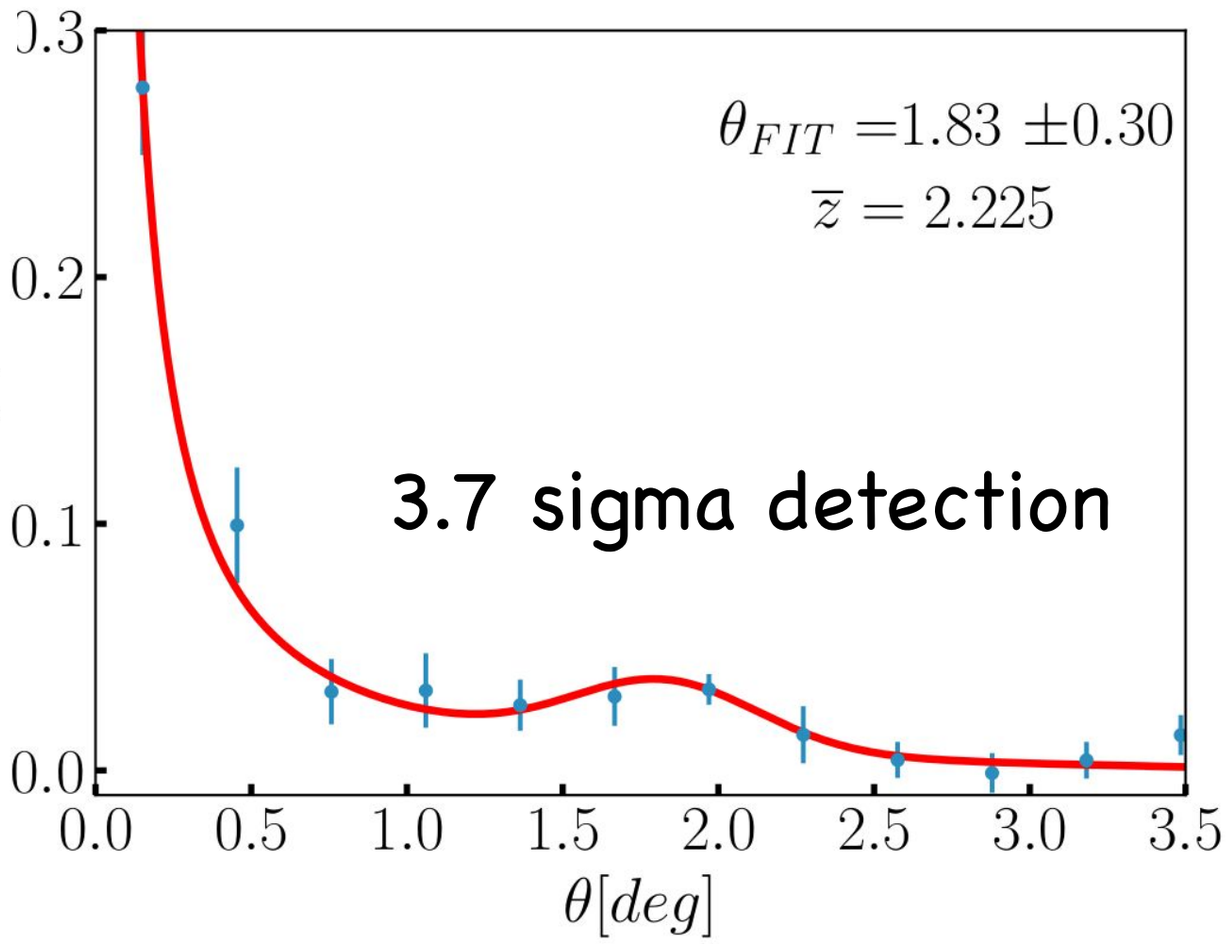
Ampliamos o número de medidas de BAO transversal (quase independente de modelo) para os redshifts médios z =0.57,0.59,0.61,0.63 e 0.65 utilizando o DR11 do Sloan Digital Sky Survey. Tais dados possibilitam obter bons vínculos para o modelo wCDM e w(a)CDM e para o horizonte acústico na época de arraste.

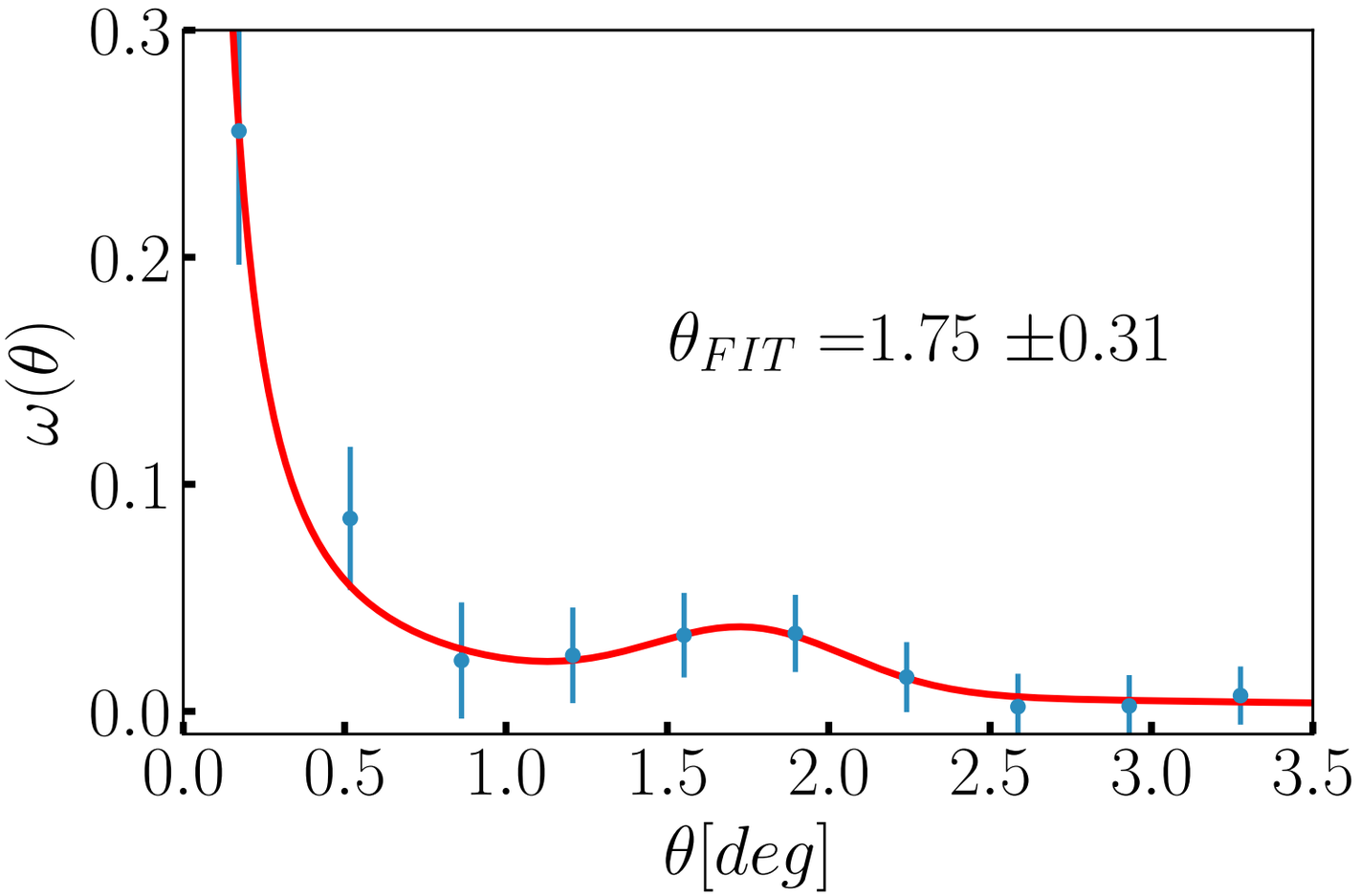
Angular Baryon Acoustic Oscillation measure at z=2.225 from the SDSS quasar survey

E. de Carvalho, A. Bernui, G. C. Carvalho and C. P. Novaes

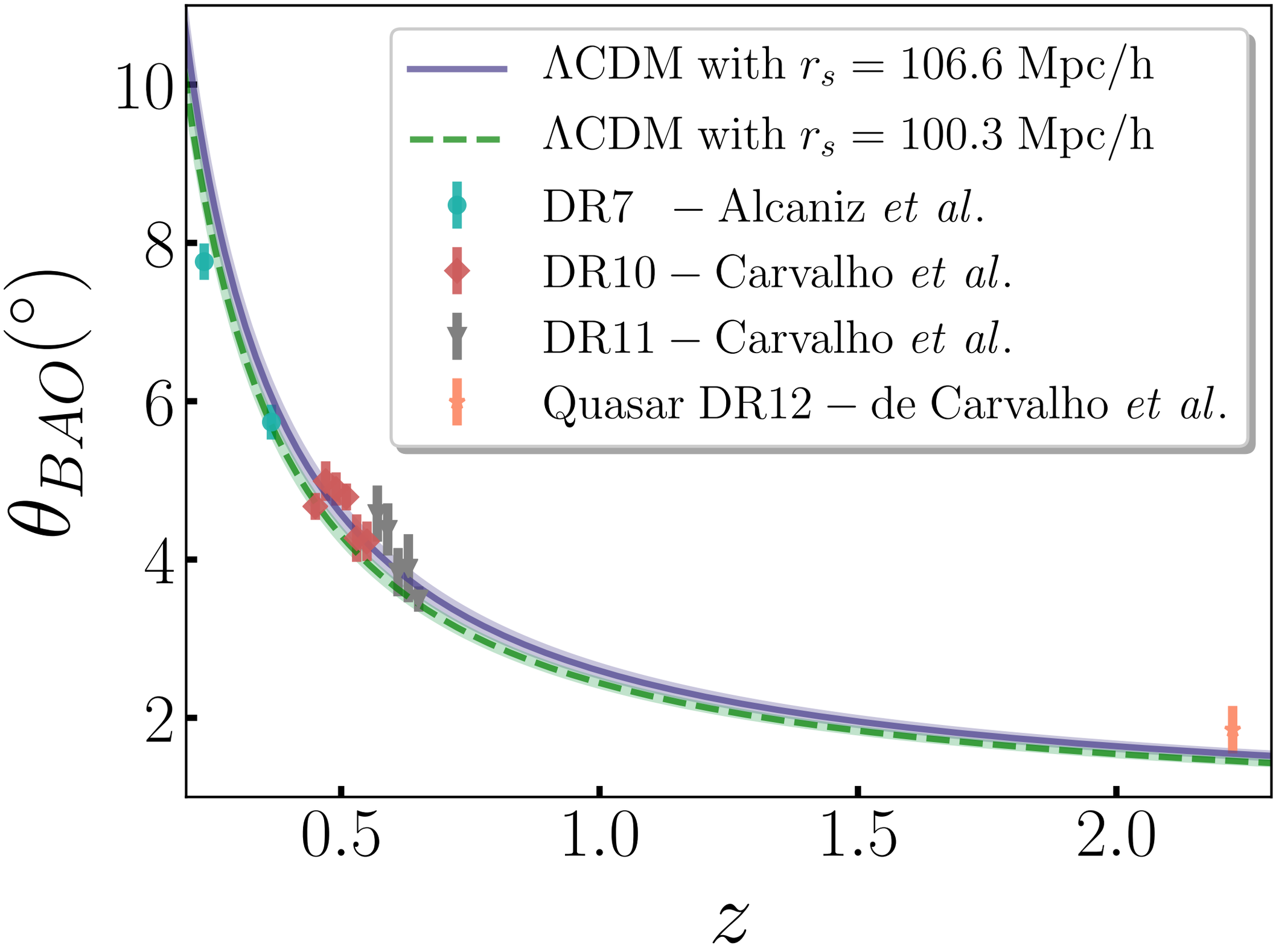
Edilson

arXiv: 1709.00113v2

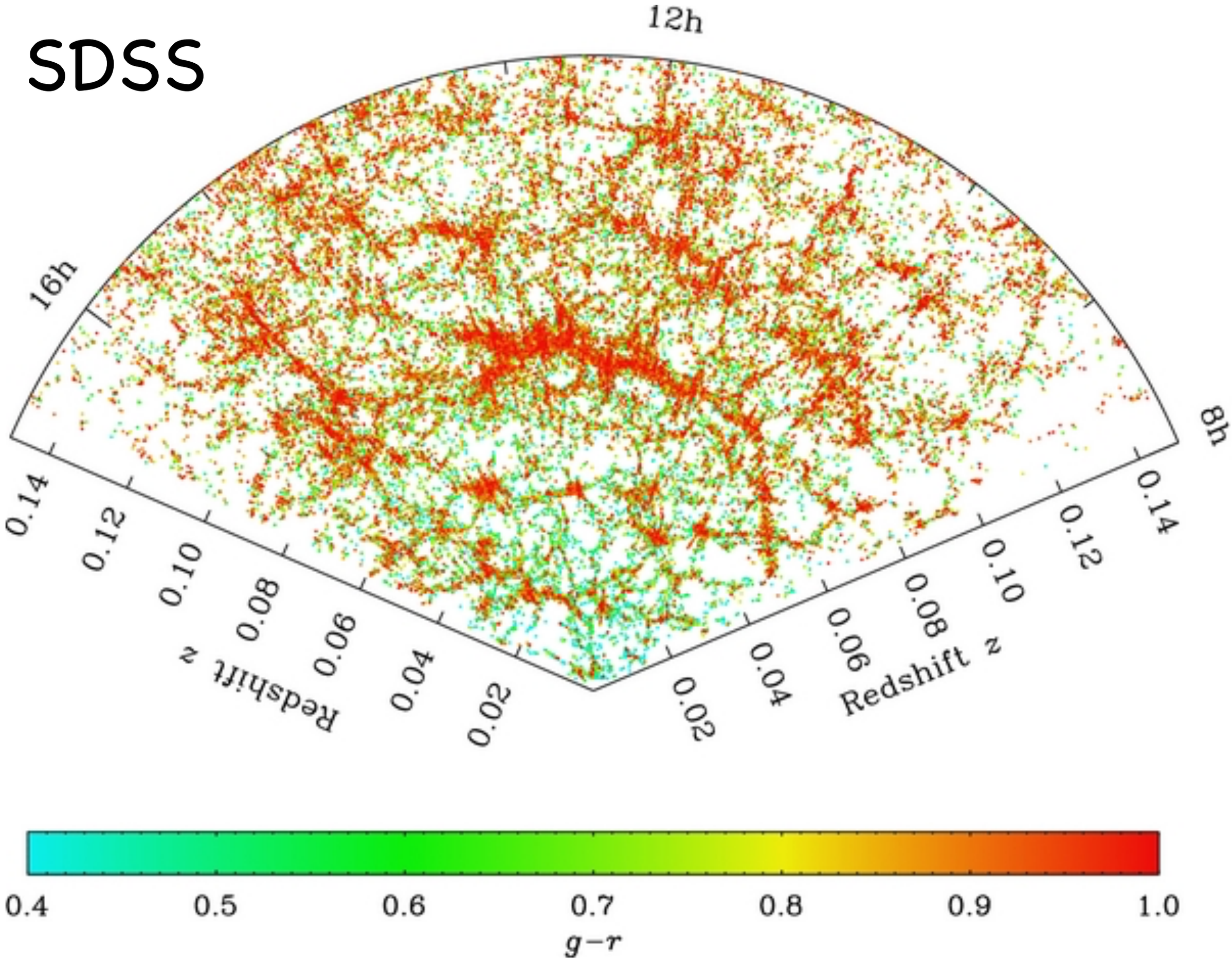



0.3
0.2
0.1
0.0
$\omega(\theta)$
θ_{FIT} =1.75 ±0.31
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
$\theta[deg]$

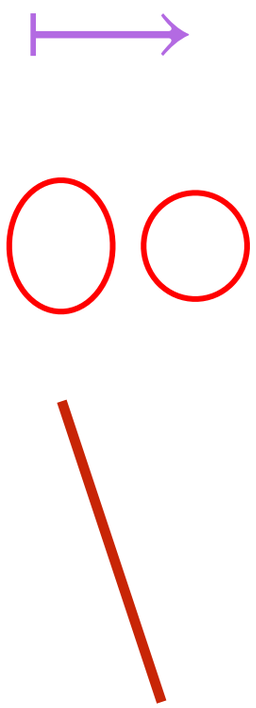
14 model independent measurements

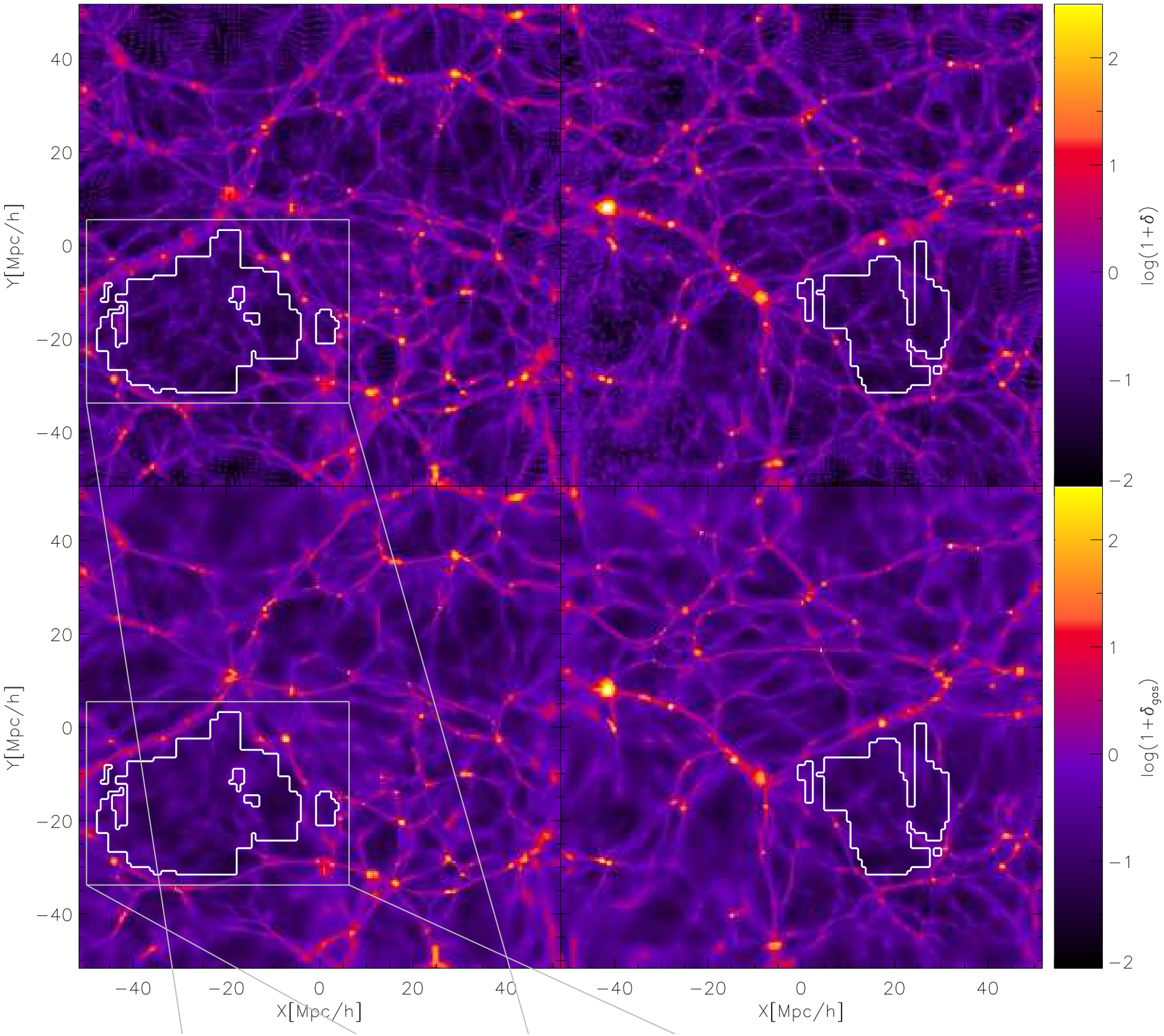


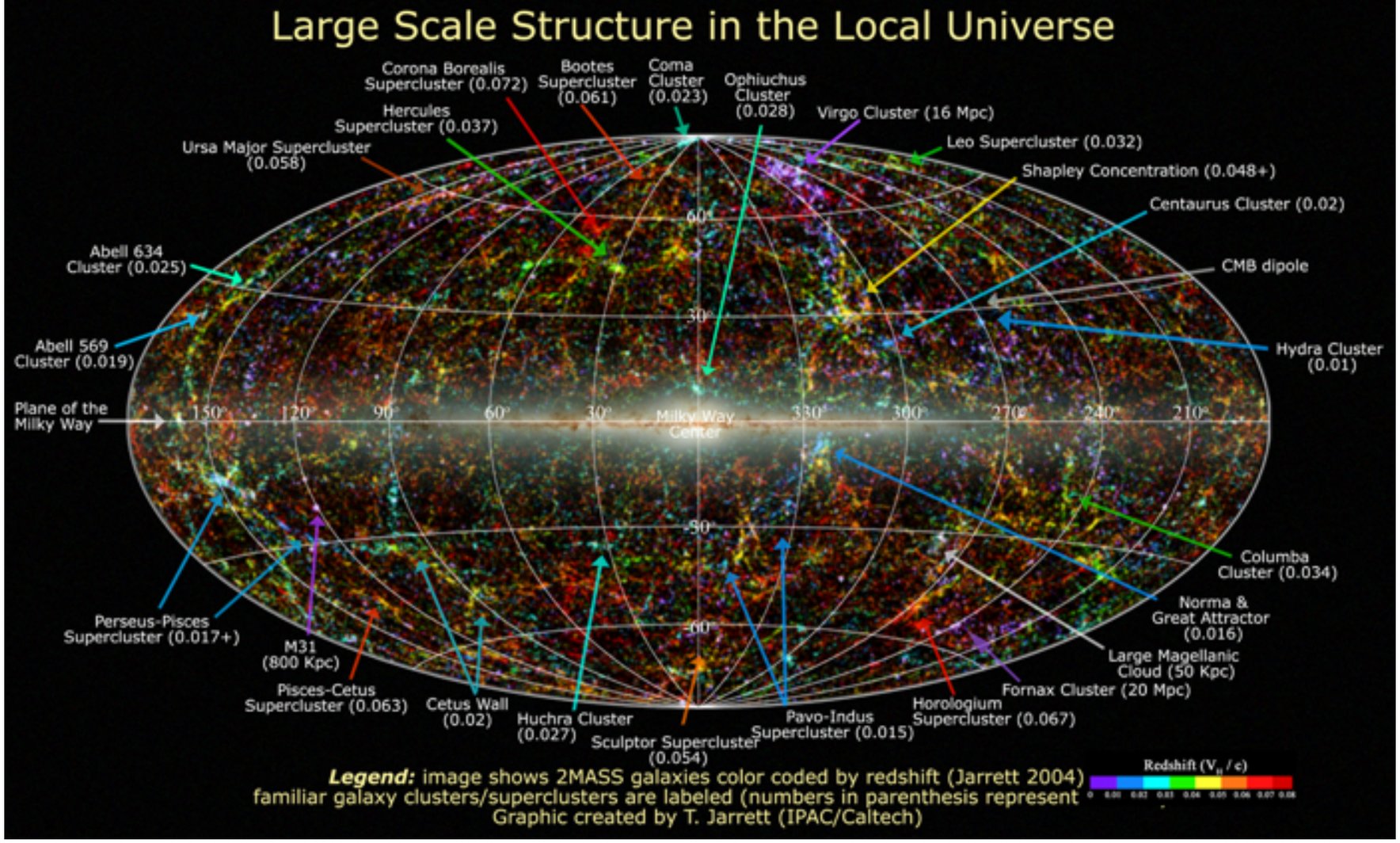
SDSS


12h
16h
8h
0.14
0.12
0.10
0.08
0.06
0.04
0.02
Redshift z
Redshift z
0.4
0.5
0.6
0.7
0.8
0.9
1.0
g−r

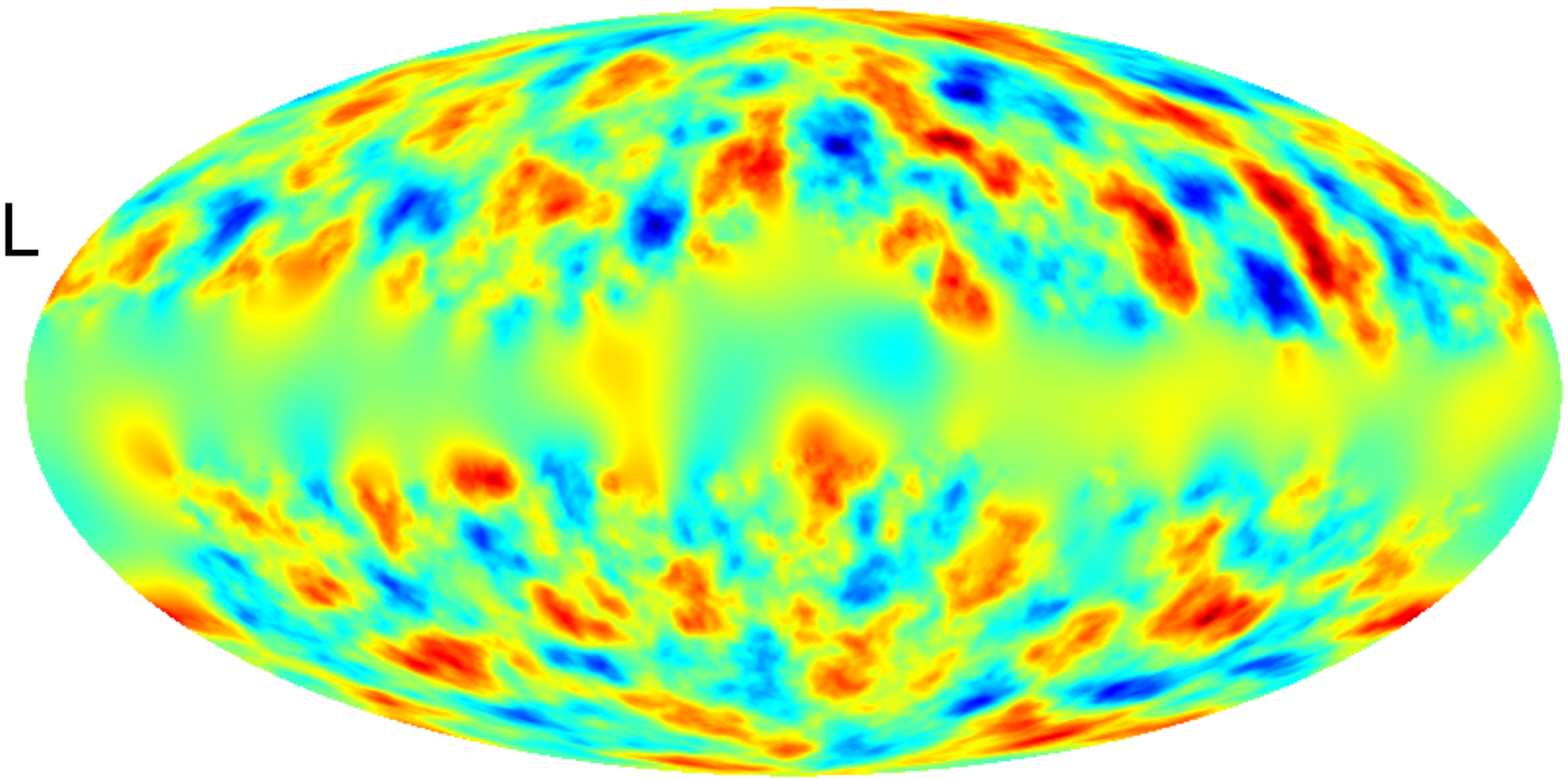
Voids







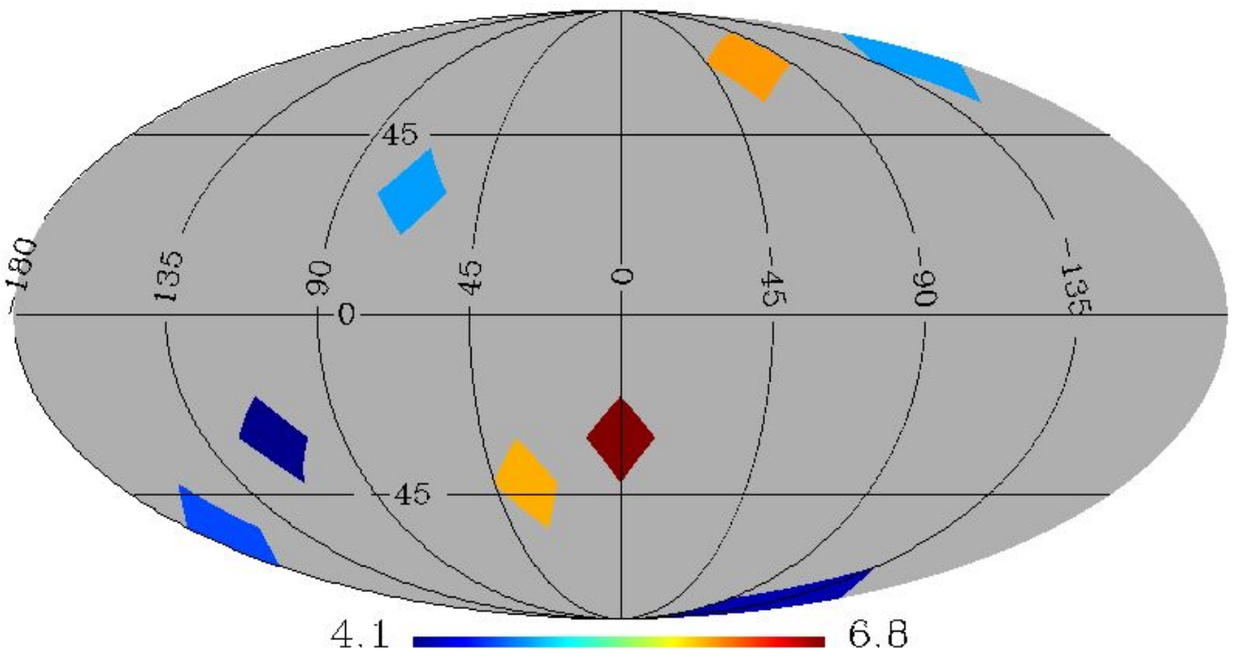
LENSING POTENTIAL MAP



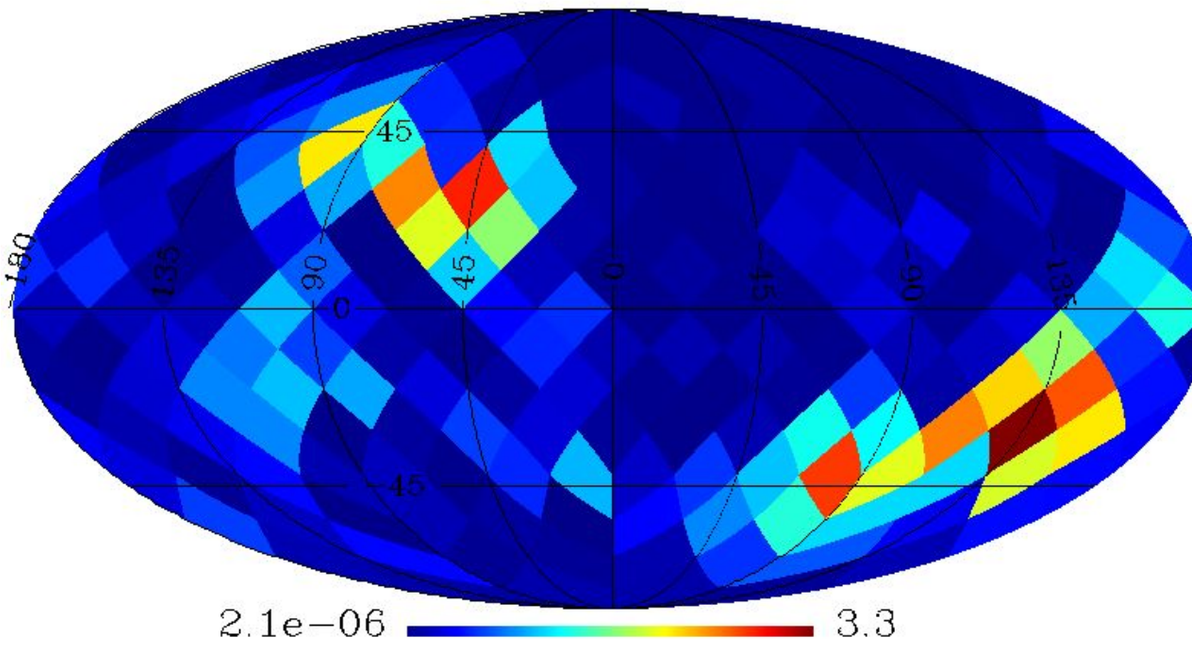
Isotropy analysis of the Planck Convergence map

Monthly Notices of the Royal Astronomical Society **473**, 165 (2018)

Patch Analysis

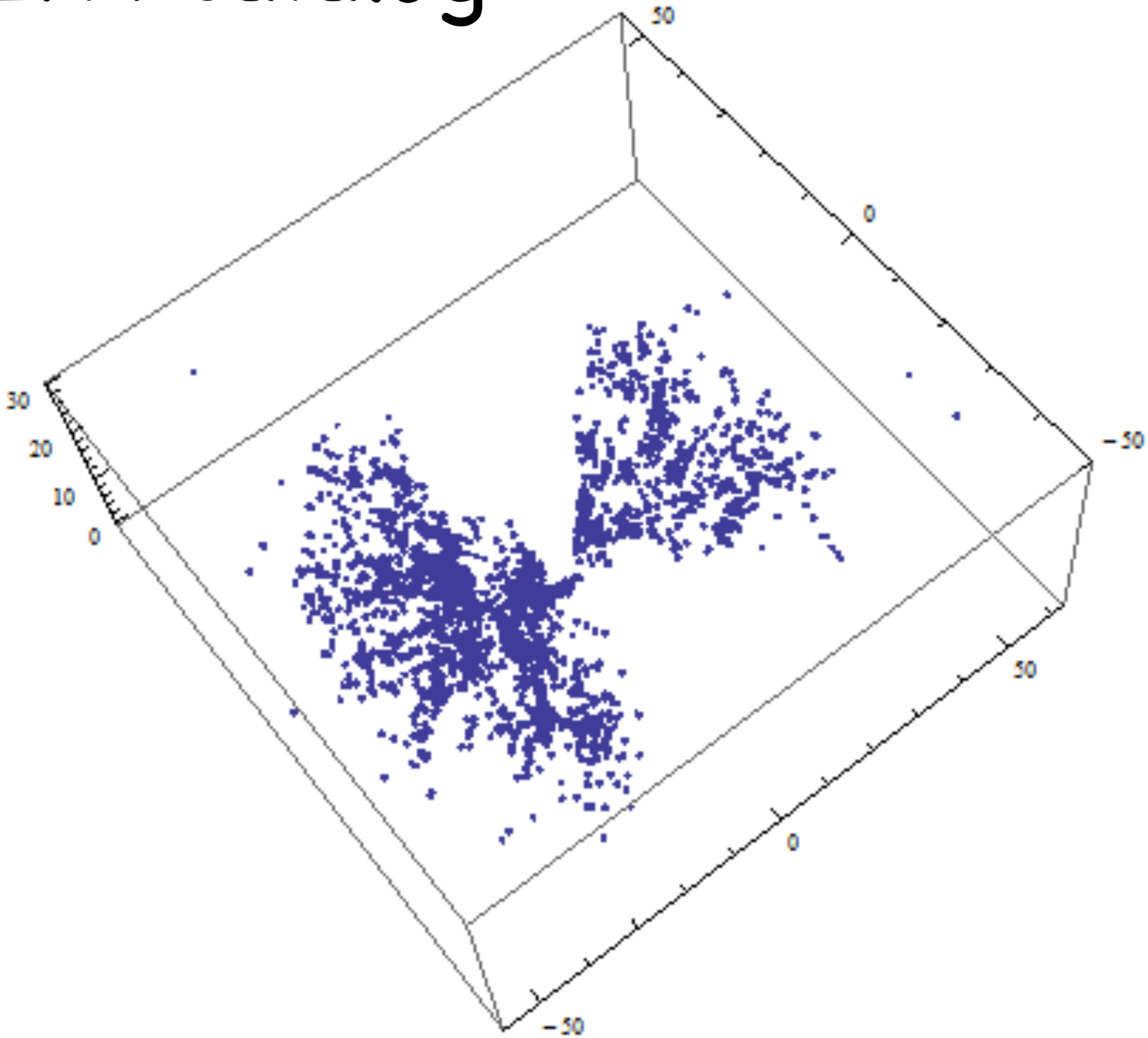


Hemispherical Analysis

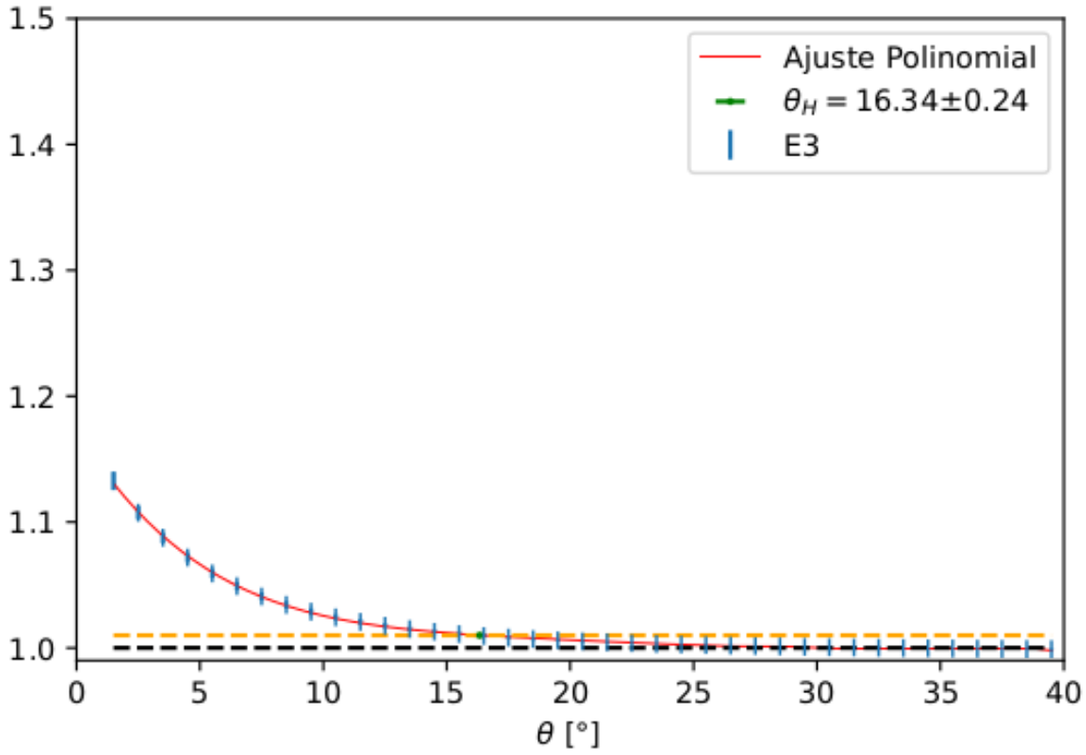


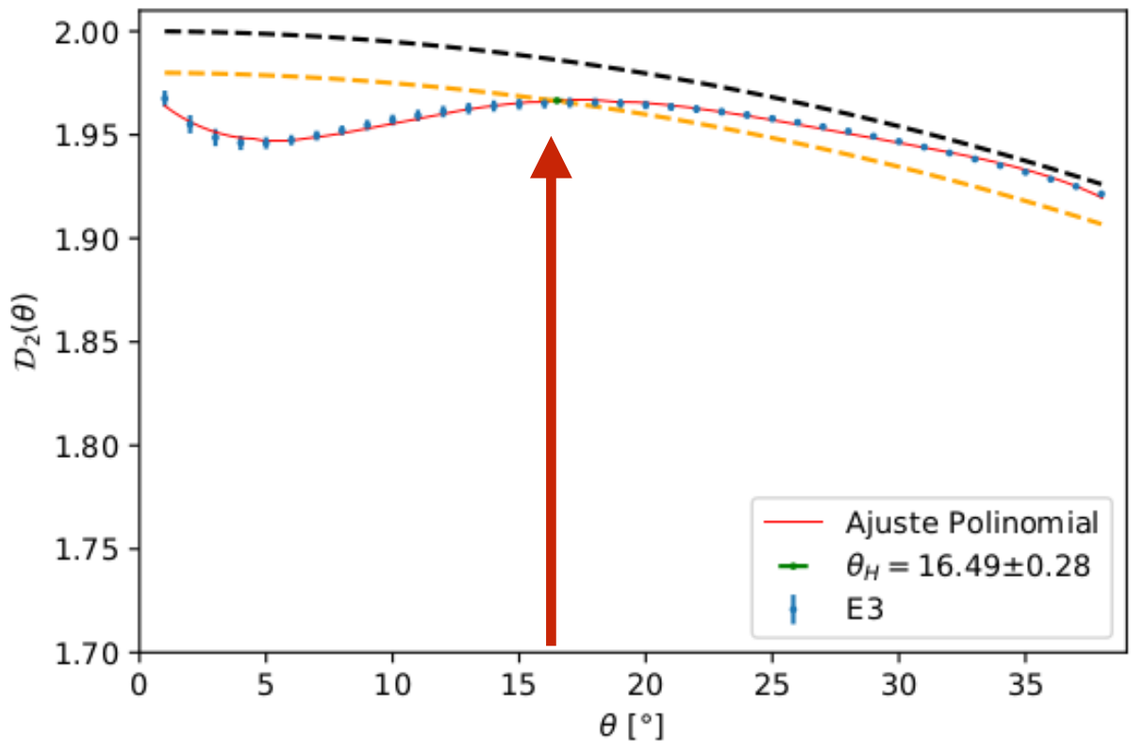
G. A. Marques; C. P. Novaes; A. Bernui; I. S. Ferreira.

ALFALFA catalog



Escala de homogeneidade do Universo local





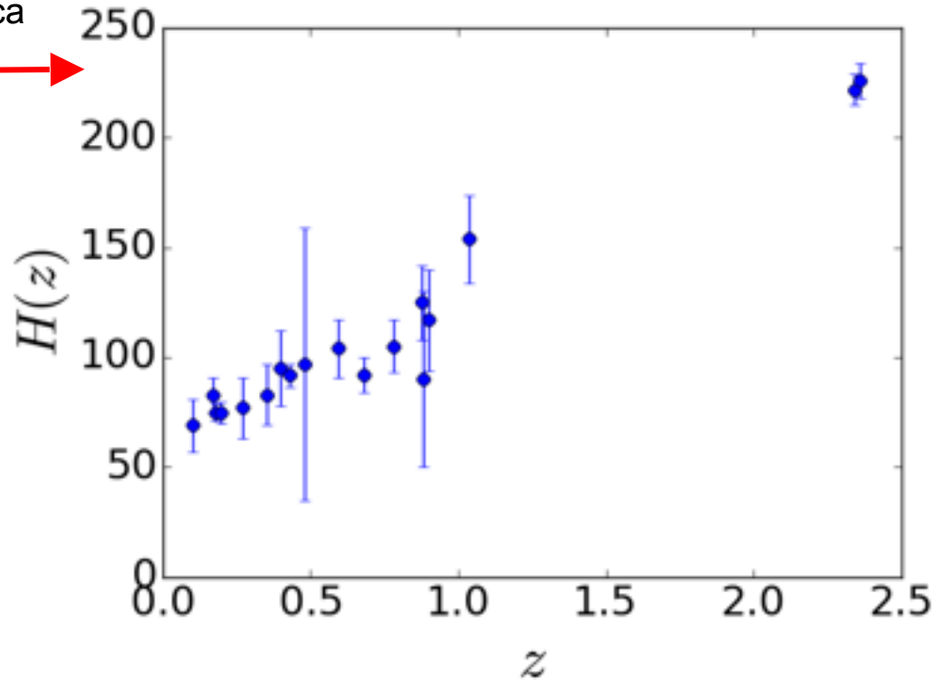
$$\mathcal{N}(<\theta) \equiv \frac{N_{gal}(<\theta)}{N_{ale}(<\theta)}$$

$$\mathcal{D}_2(\theta) = \frac{d\log\mathcal{N}(<\theta)}{d\log\theta} + \frac{\theta\ \mathrm{sen}\,\theta}{1-\cos\theta}$$

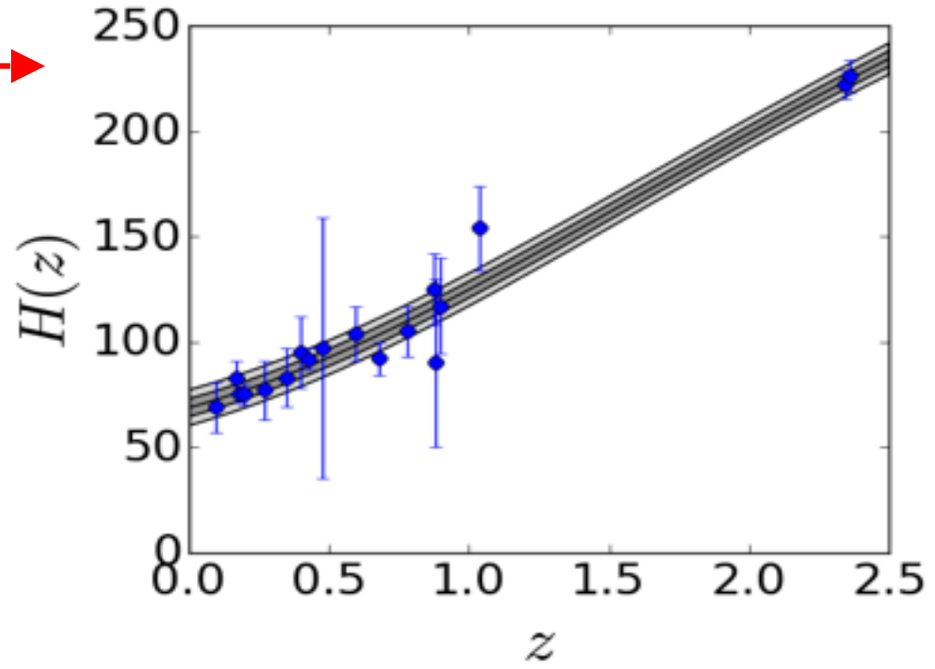
Felipe Avila et al.

Reconstrução de Perturbações Cosmológicas de Matéria

Dados da expansão cósmica

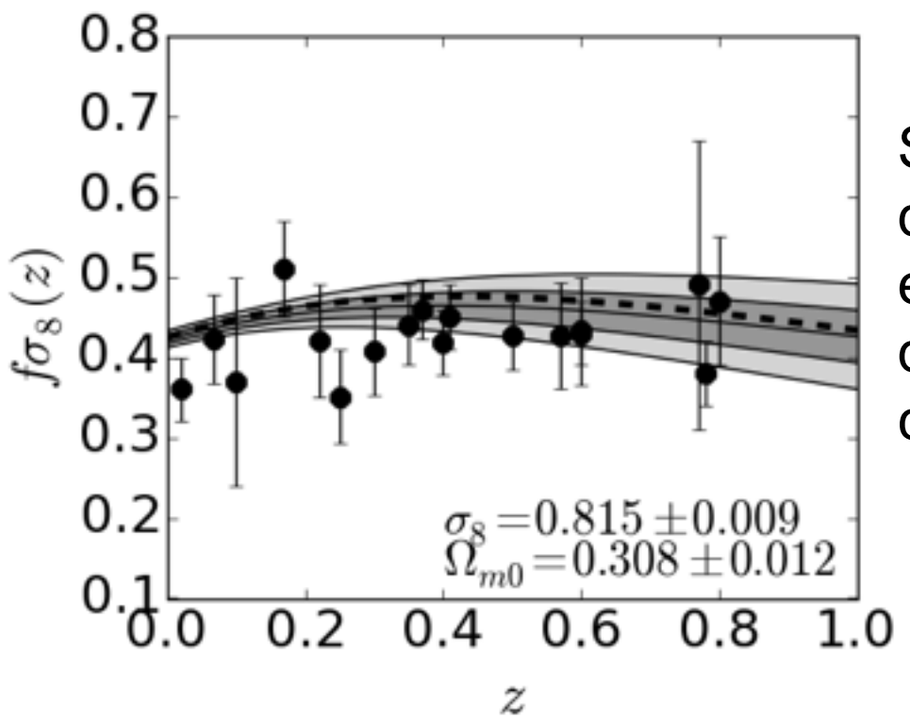


Reconstrução não paramétrica



Hipóteses testadas:

- Universo homogêneo, isotrópico e espacialmente plano;
- Matéria covariantemente conservada;
- Teoria da Relatividade Geral descreve corretamente a gravidade.



Solução da equação do contraste

Javier González Sánchez et al.

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

What is the shape of the Universe?

AB, C. Novaes, T. Pereira, G. Starkman