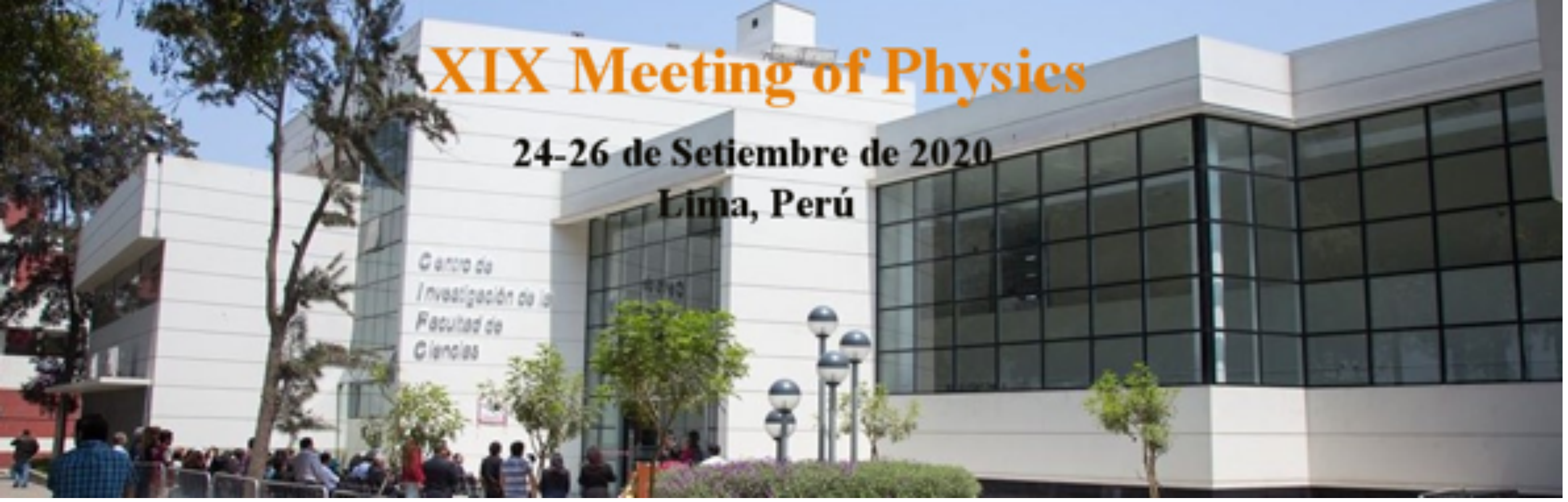
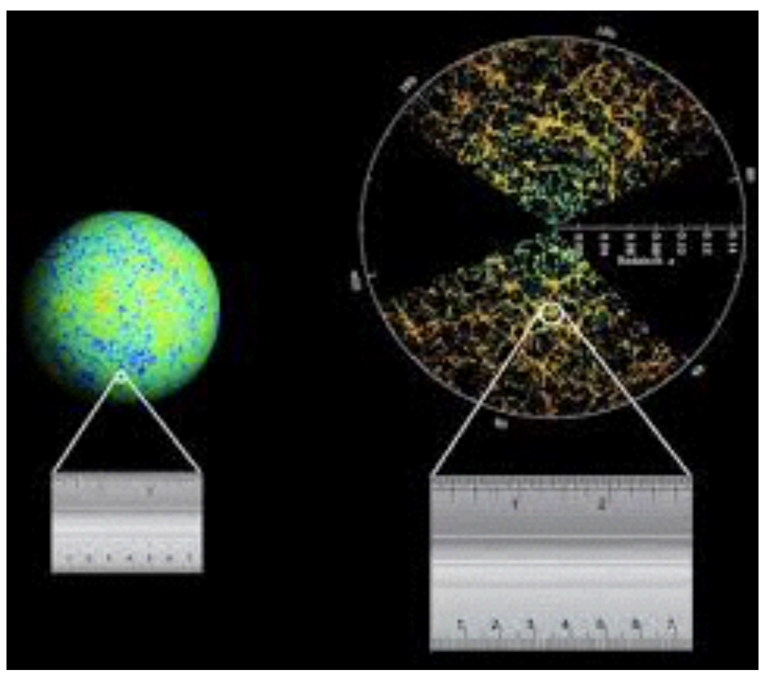


Observatório Nacional

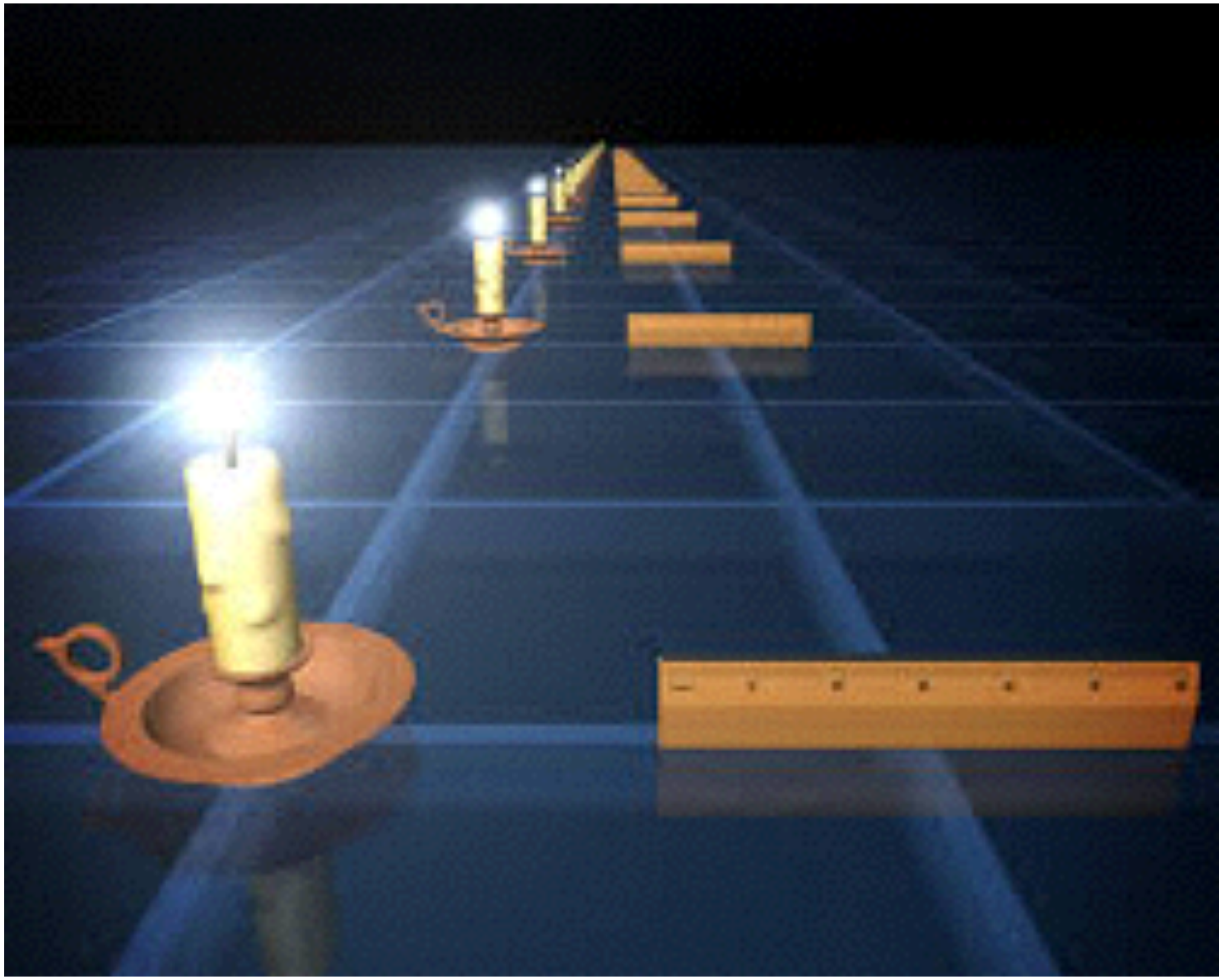
The sound horizon scale* at baryon drag epoch



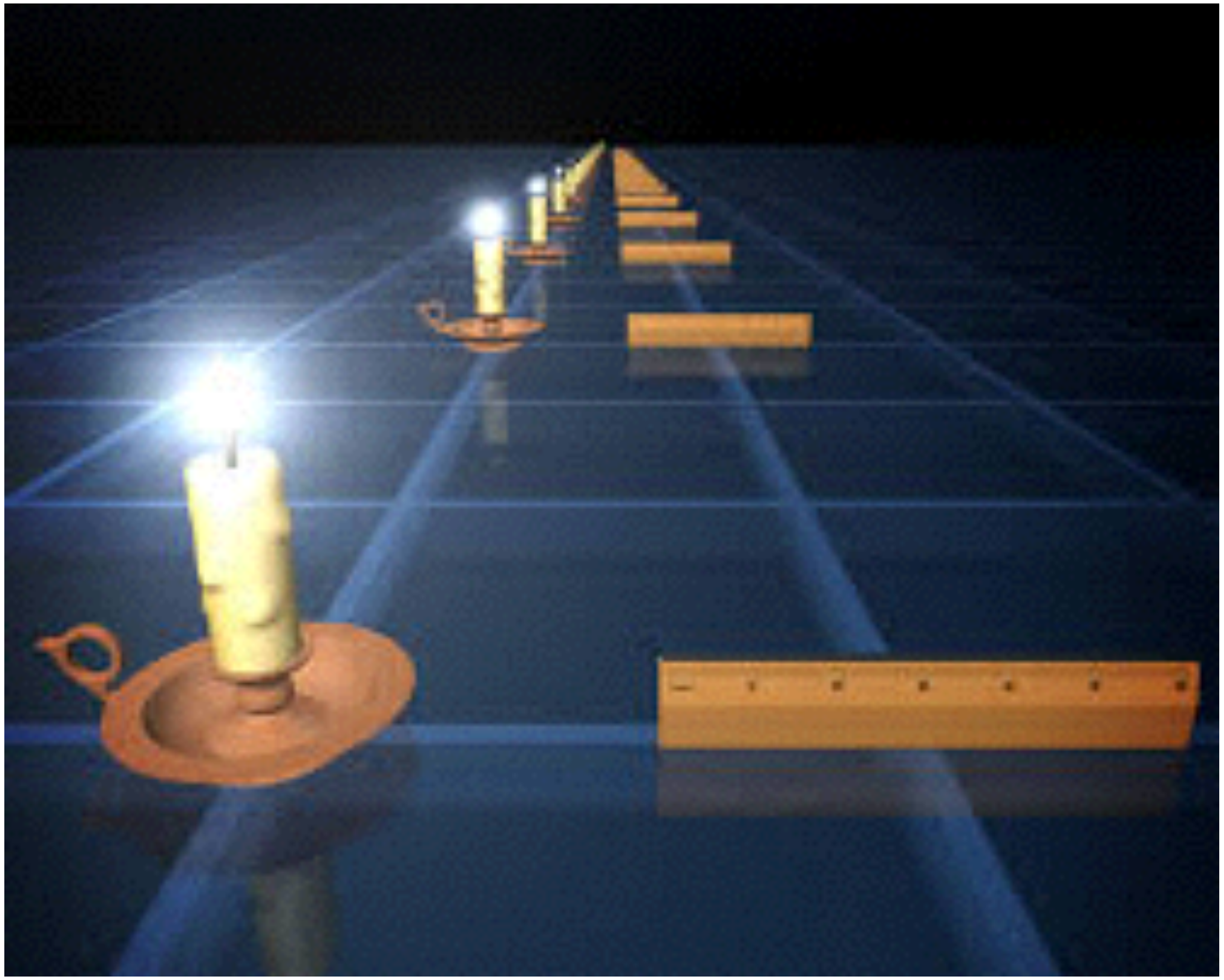
Armando Bernui

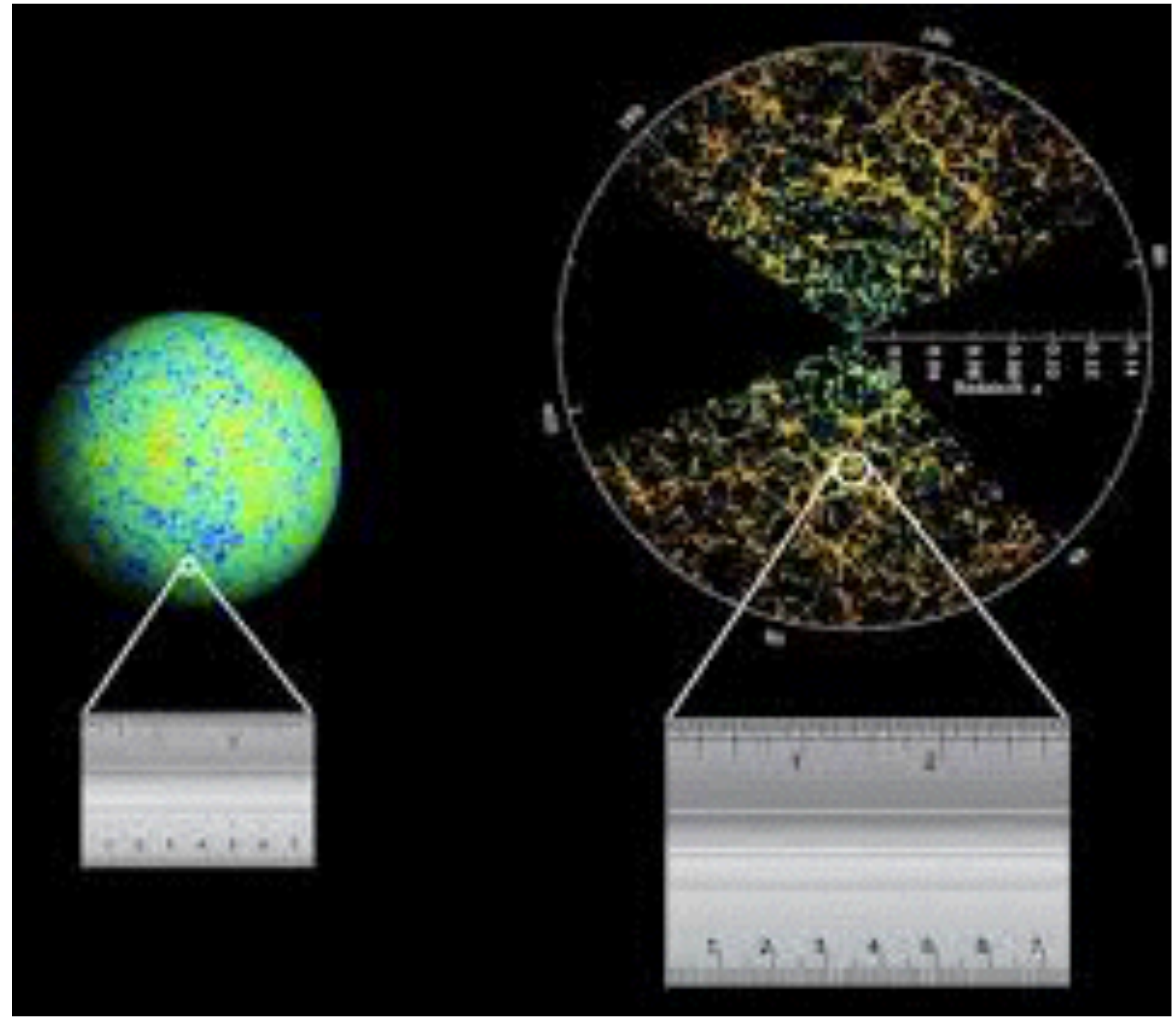
* work in collaboration with Edilson de Carvalho, Felipe Avila, Camila Novaes

standard candle



standard candle standard ruler



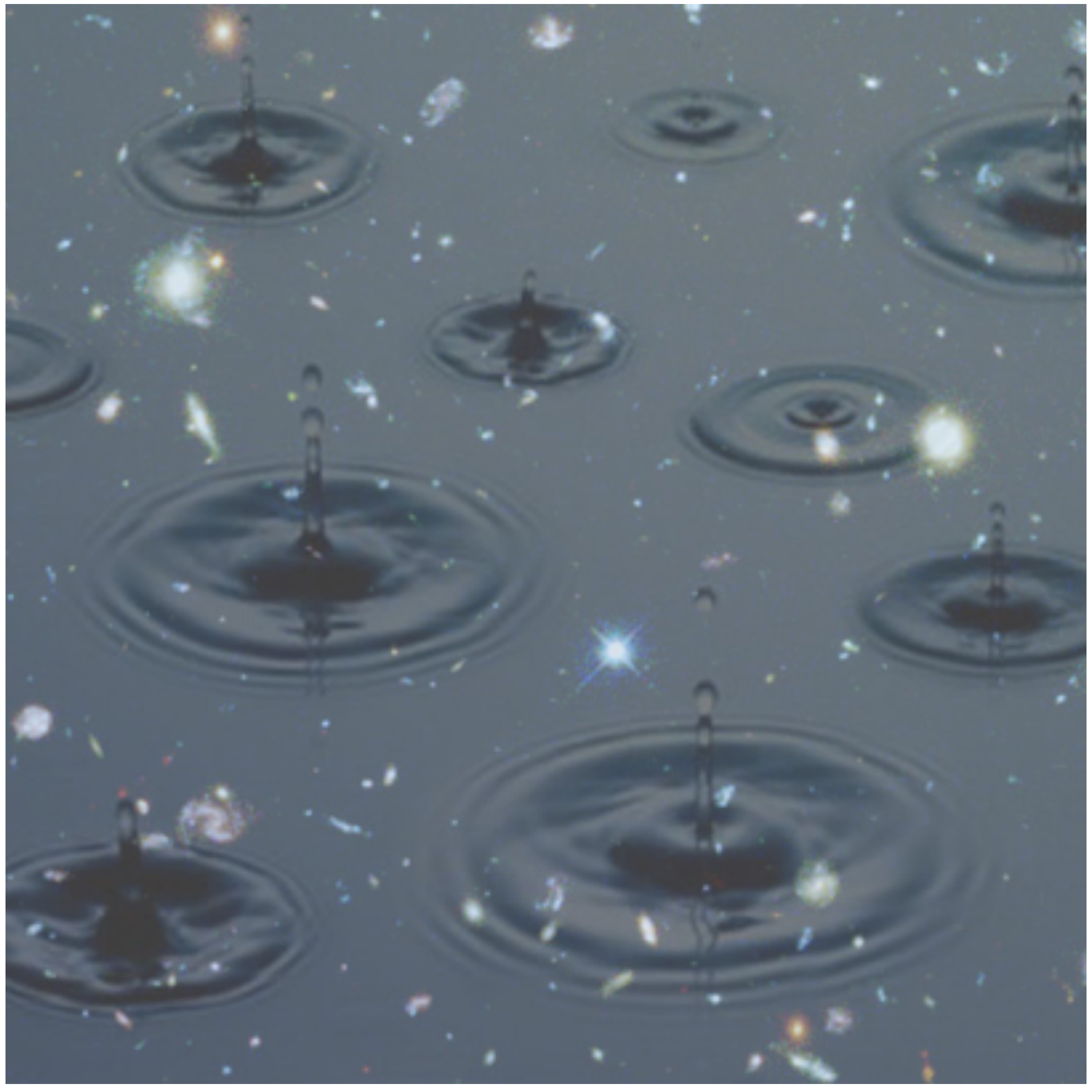


BAO: a cosmological ruler

Baryon Acoustic Oscillations (BAO)?

Are primordial sound waves propagating in a tightly coupling baryon +photon fluid

Exm: 2D waves in a medium



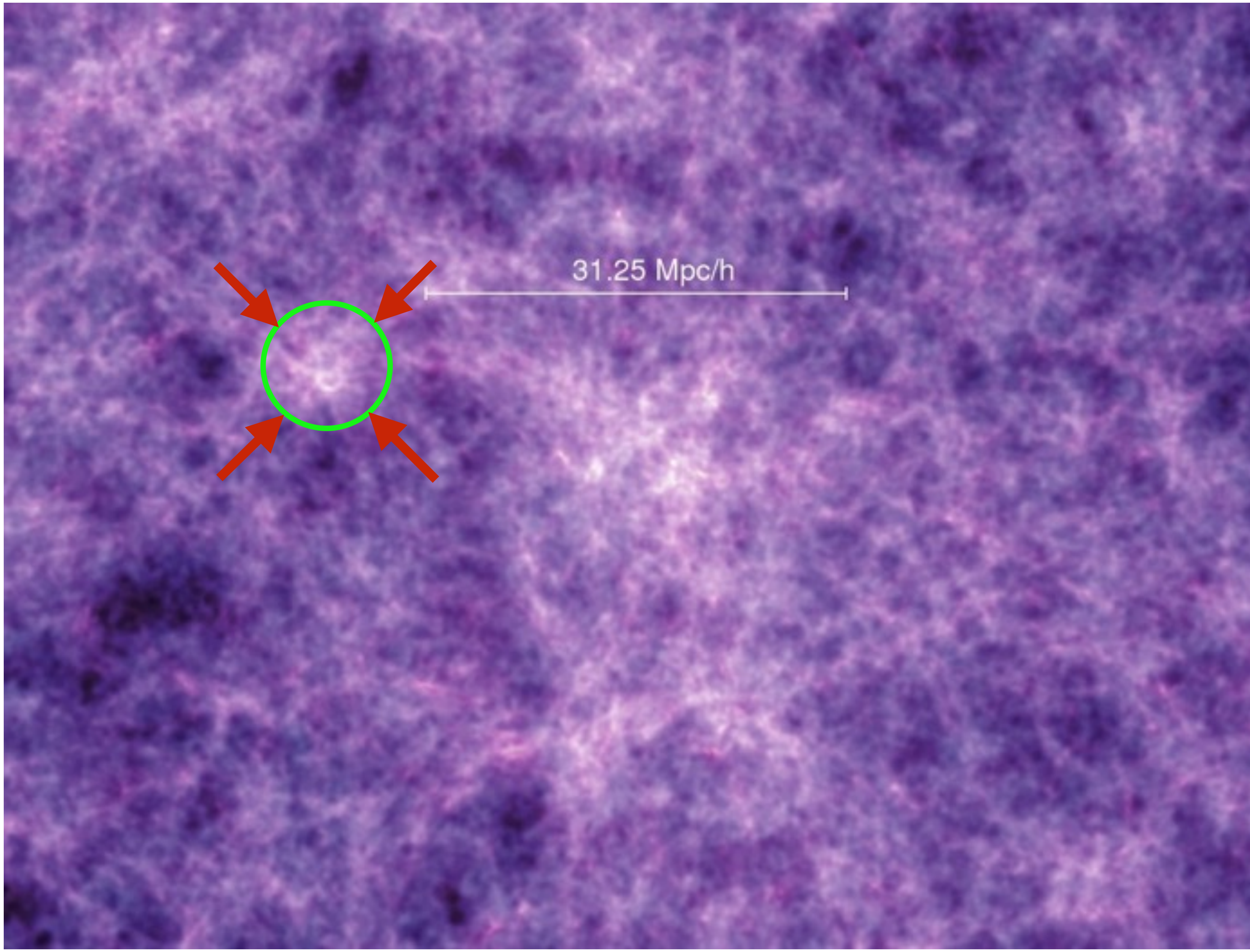
BAO: primordial origin

It was once...

BAO: primordial origin

Density fluctuations field: $\delta(t_0, \mathbf{r})$

$-4\pi G\bar{\rho}(t)\delta(t, \mathbf{r})$



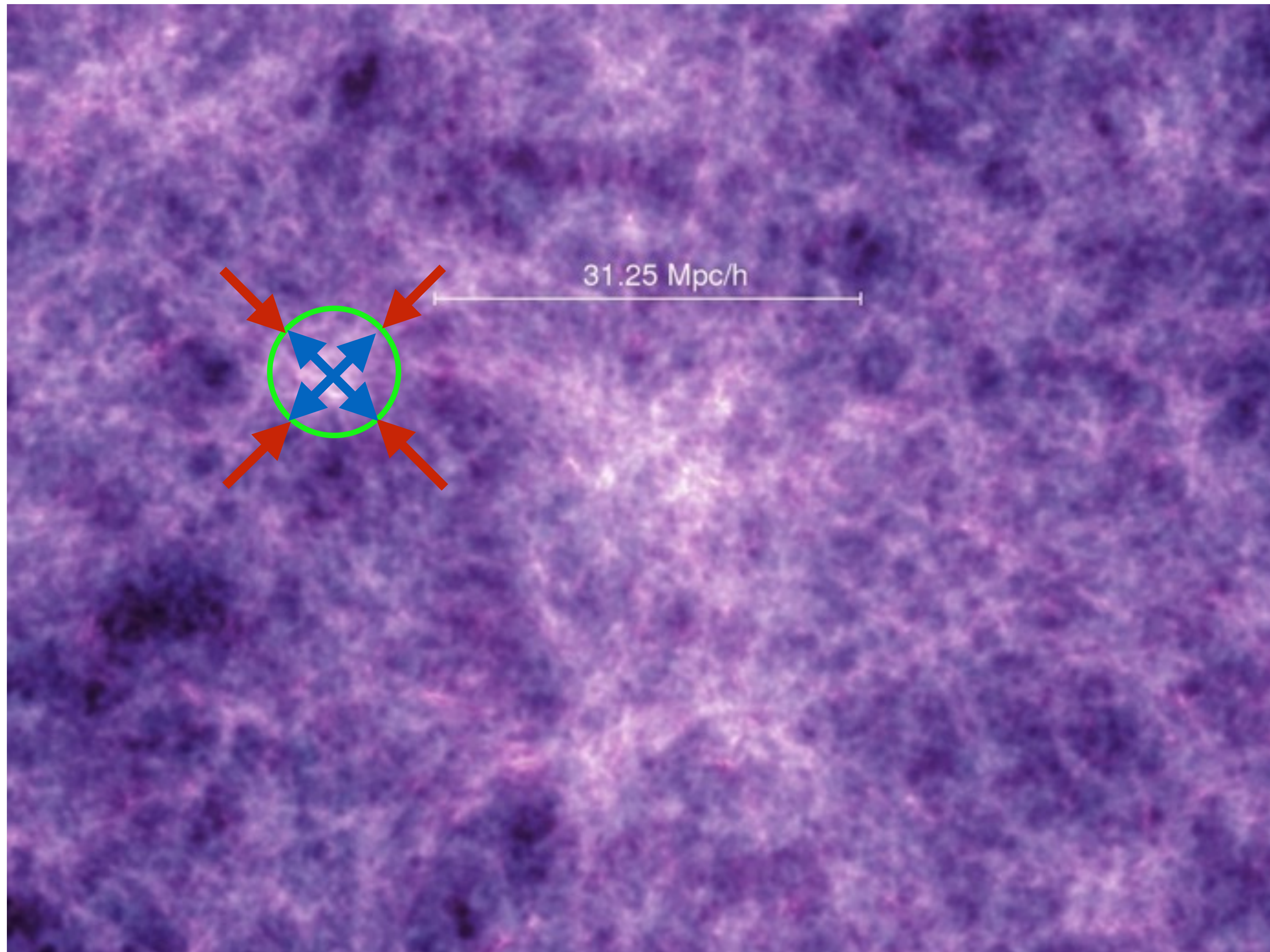
BAO: primordial origin

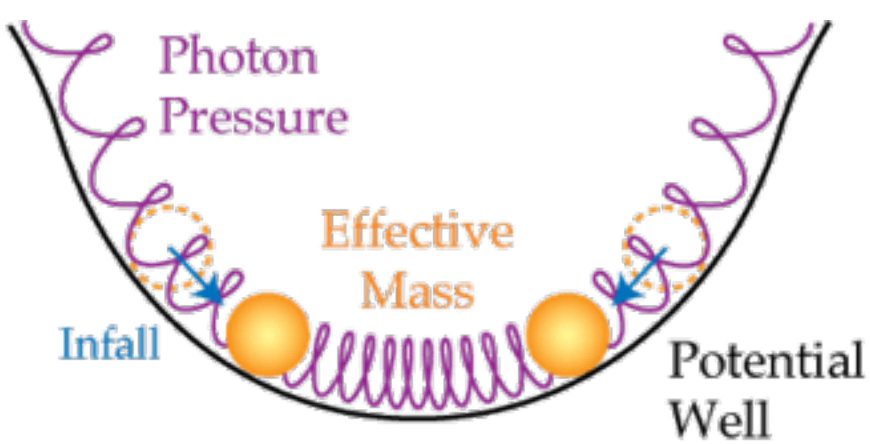
Density fluctuations field: $\delta(t_0, \mathbf{r})$

$$-4\pi G\bar{\rho}(t)\delta(t,\mathbf{r})$$

$$> \; = \; <$$

$$-\frac{c_s^2\,\nabla^2\delta(t,\mathbf{r})}{a(t)^2}$$

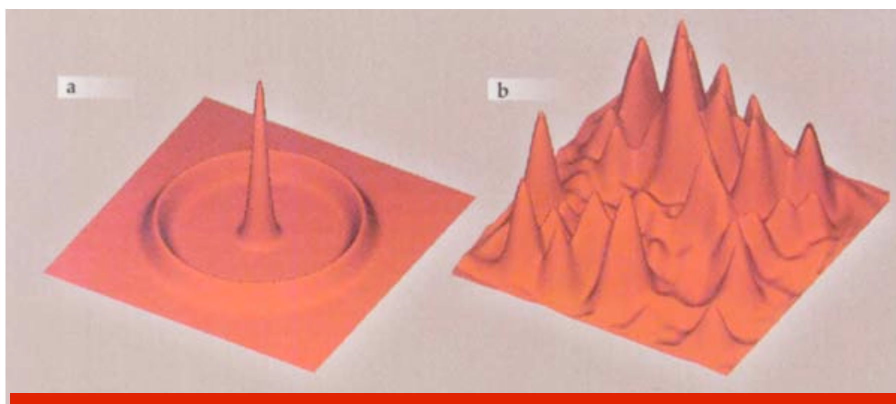




CMB Sound Waves in the Early Universe

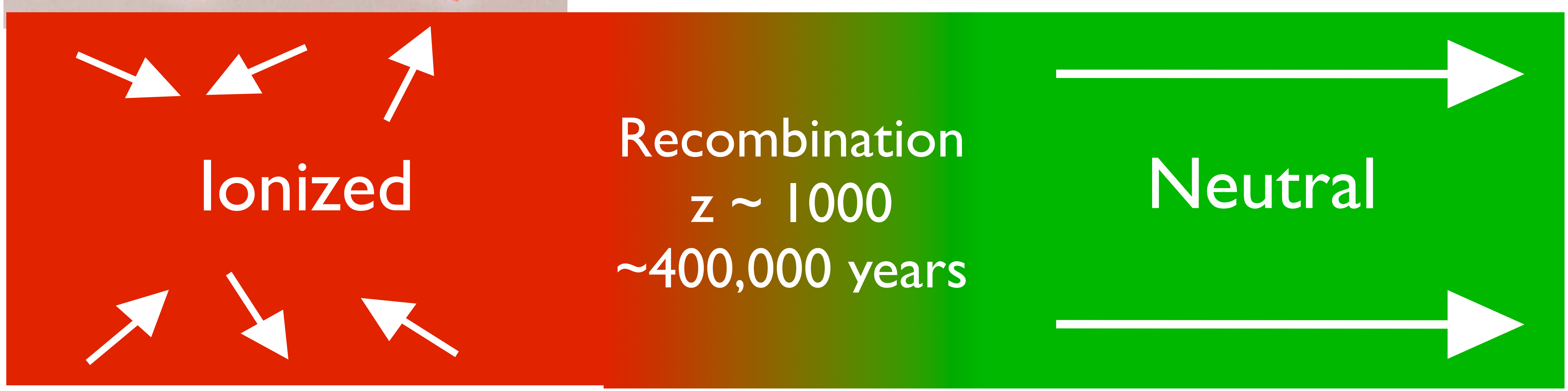
Before recombination:

- Universe is ionized
- Photons provide enormous pressure and restoring force
- Density perturbations oscillate as sound (or acoustic waves)



After recombination:

- Universe is neutral
- Photons travel freely; baryons form galaxies
- Each initial overdensity (DM & gas) is an overpressure that launched a spherical sound wave: shell of gas
- Overdensity in shell (gas) and in the original center (DM) both seed the formation of galaxies. Preferred separation: the shell radius!



Fluid evolution eqs.:
continuity, Euler, Poisson

$$\dot{\delta} + \frac{1}{a}\nabla\cdot\vec{v} = 0\,;\;\; \dot{\delta} \equiv \frac{\partial\delta}{\partial t}\,;\; \vec{v} \equiv \frac{d\vec{x}}{dt}$$

$$\frac{\partial\vec{v}}{\partial t} + \frac{\dot{a}}{a}\vec{v} = -\frac{1}{a}\nabla\phi - \frac{c_s^2}{a}\nabla\delta$$

$$\nabla^2\phi = 4\pi G\,\bar{\rho}\,a^2\delta$$

G.B.L.Neto (2010), Mukhanov, Padmanabhan,...

Excercise

$$\ddot{\delta} + 2\frac{\dot{a}}{a}\dot{\delta} - \underbrace{a^{-2}c_s^2\nabla^2\delta}_{\text{pressure repulsion}} - \underbrace{4\pi G\bar{\rho}\,\delta}_{\text{gravitational atraction}} = 0$$

$$\delta = \delta_{\mathbf{k}}(t)\,e^{i\vec{k}\cdot\vec{x}} \;\Rightarrow\; \ddot{\delta}_{\mathbf{k}} + 2\frac{\dot{a}}{a}\dot{\delta}_{\mathbf{k}} + \left(\frac{c_s^2k^2}{a^2} - 4\pi G\bar{\rho}\right)\,\delta_{\mathbf{k}} = 0$$

$$k \equiv 2\pi a/\lambda$$

Now large-scale modes enter the horizon

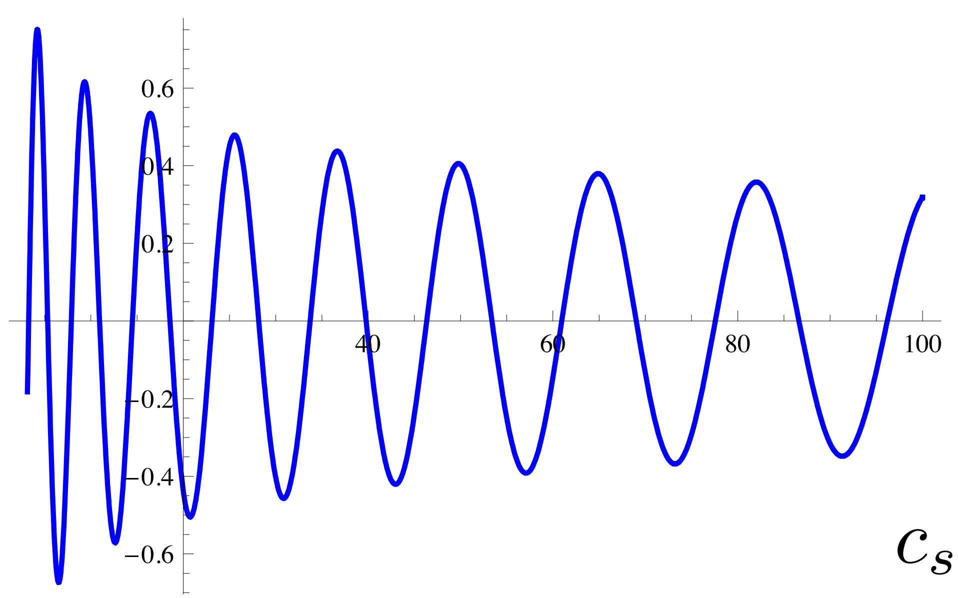
$$k > k_J \Leftrightarrow \lambda < \lambda_J \Rightarrow \delta(t) = ? \qquad k_J^2 \equiv \frac{4\pi G\,\bar{\rho}\,a^2}{c_s^2}$$

$$\ddot{\delta}_{\mathbf{k}} + 2\frac{\dot{a}}{a}\dot{\delta}_{\mathbf{k}} + (k^2 - k_J^2)c_s^2 a^{-2}\,\delta_{\mathbf{k}} = 0$$

Now, dm decouples from the γb fluid:

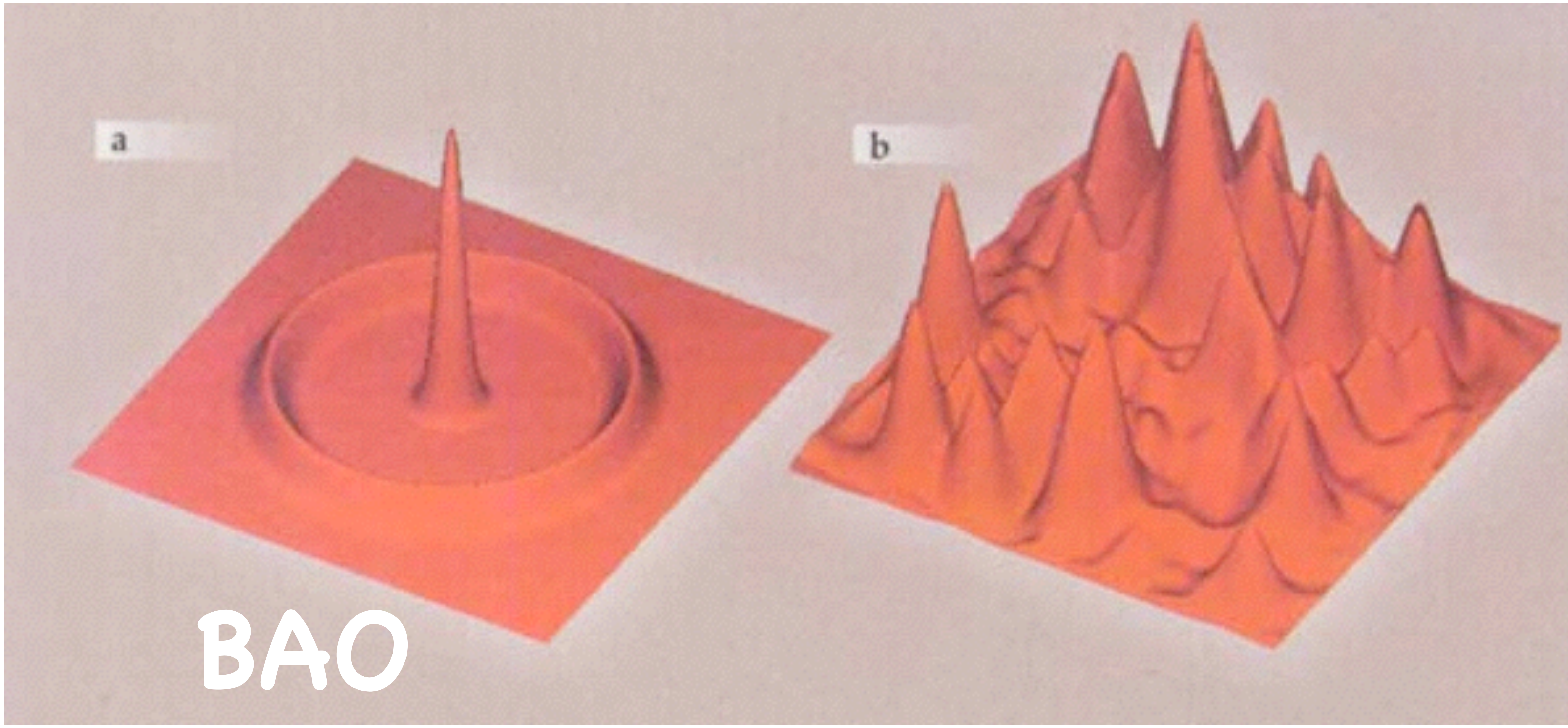
- baryon-photon:

$$\ddot{\delta}_{\gamma\mathrm{b}} + 2\frac{\dot{a}}{a}\dot{\delta}_{\gamma\mathrm{b}} + \omega_{\mathbf{k}}^2\,\delta_{\gamma\mathrm{b}} \simeq 0$$



$$\delta_{\gamma\mathrm{b}} \sim \cos(c_s\,k\,t)$$

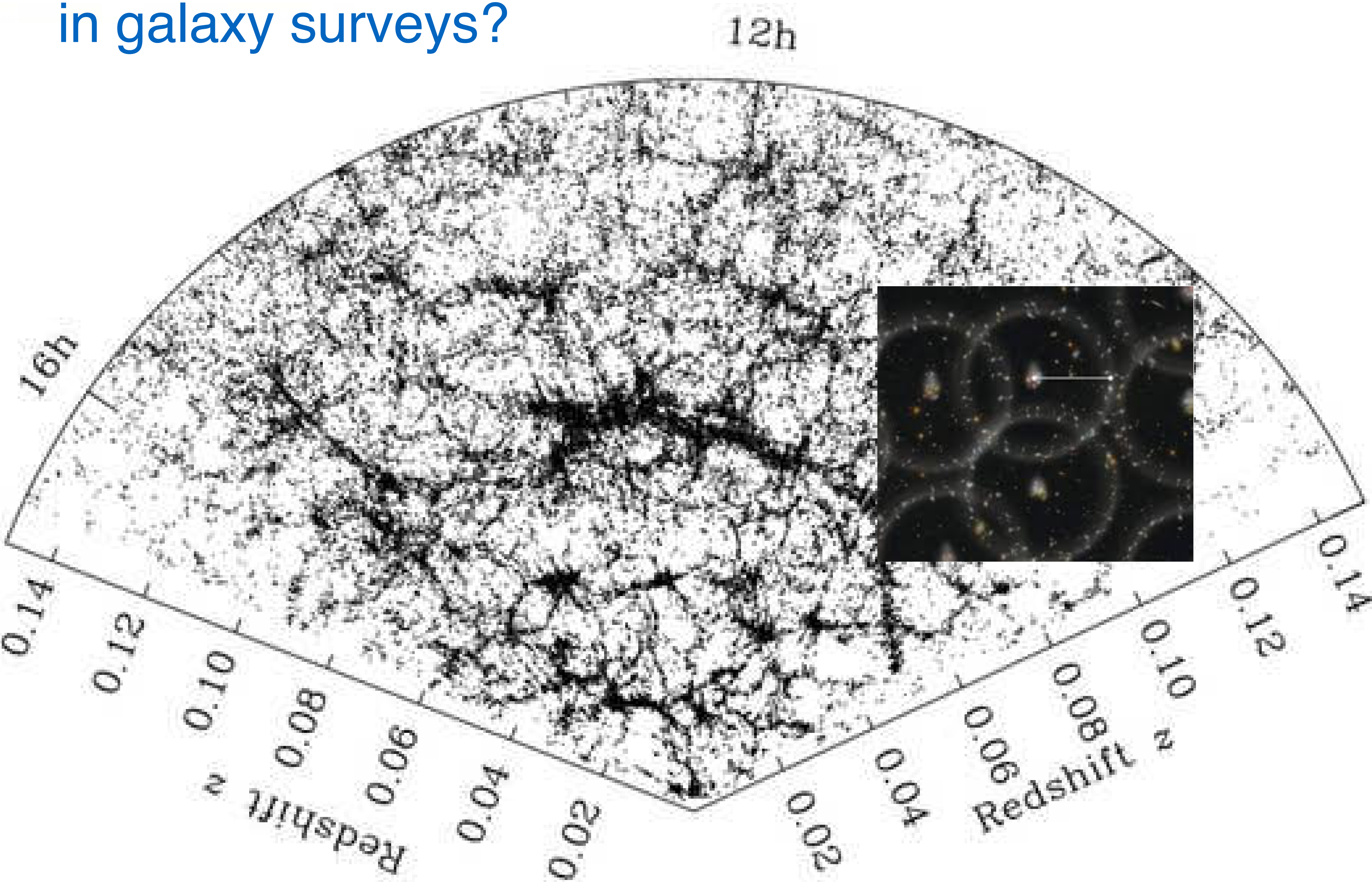
$$c_s = c/(1+R)^{1/2} \sim a^{-1/2}$$



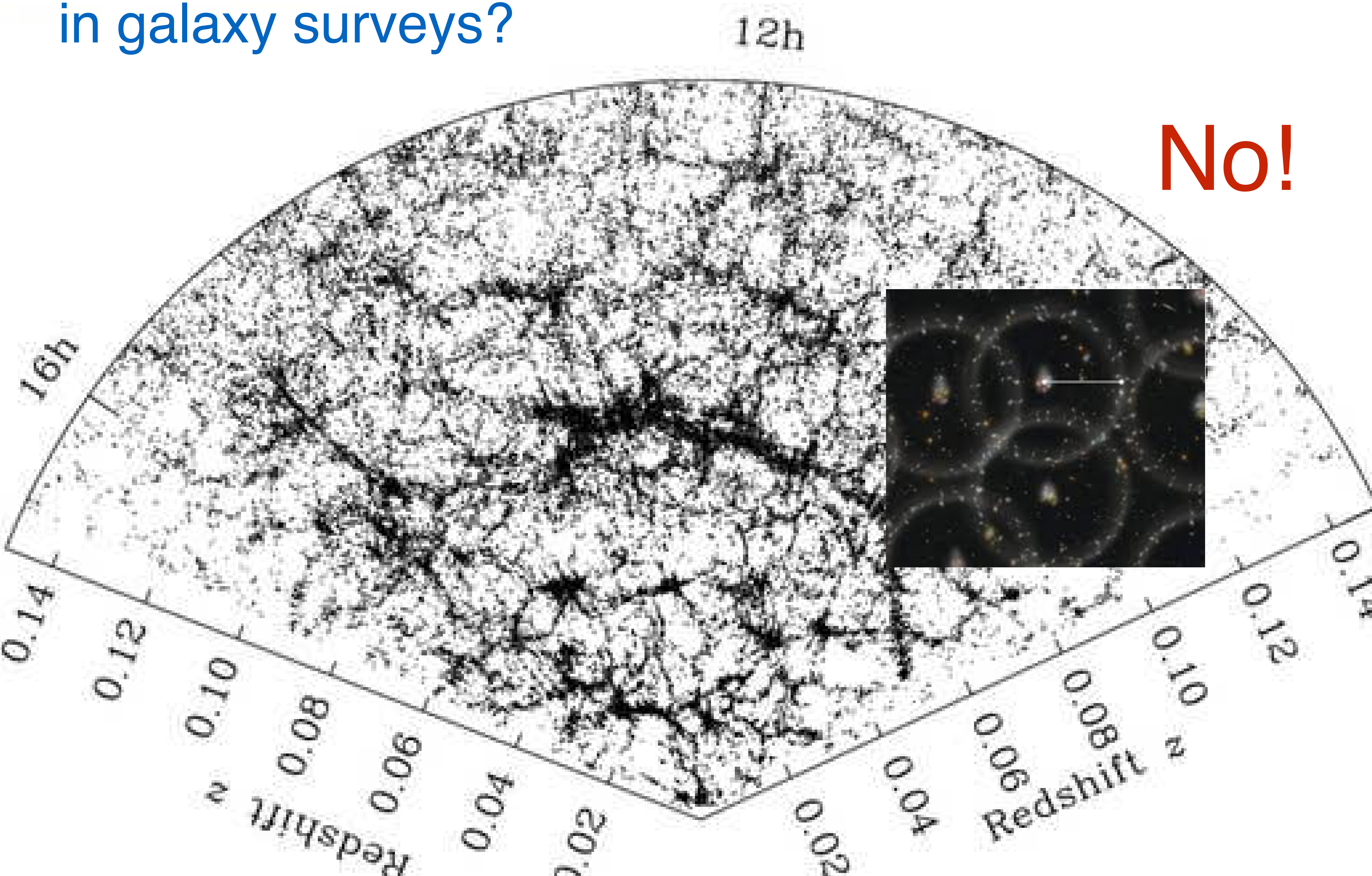
https://skyandtelescope.org/wp-content/uploads/anim.gif

https://skyandtelescope.org/wp-content/uploads/anim_many.gif

Does this mean one should “see” a BAO pattern in galaxy surveys?

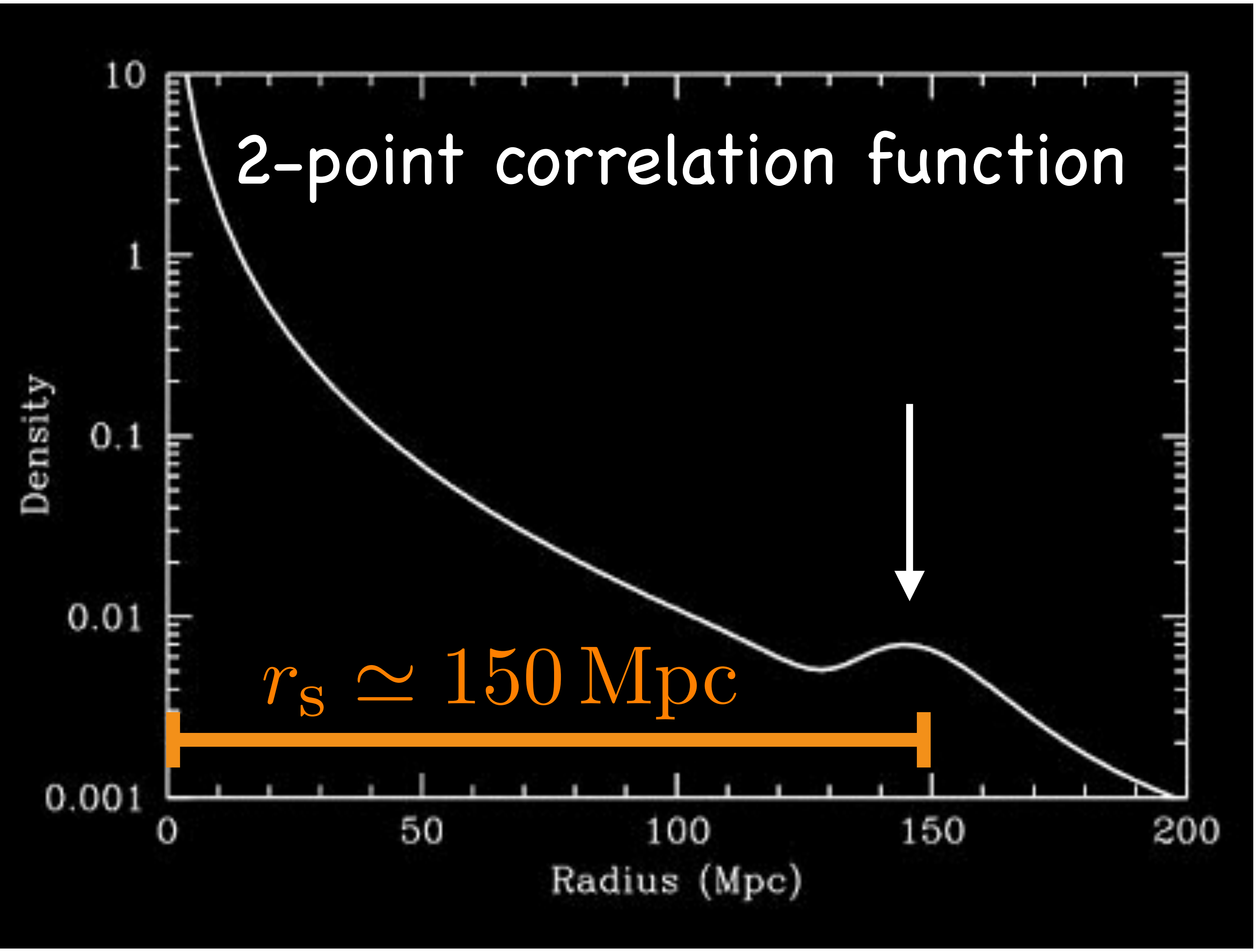


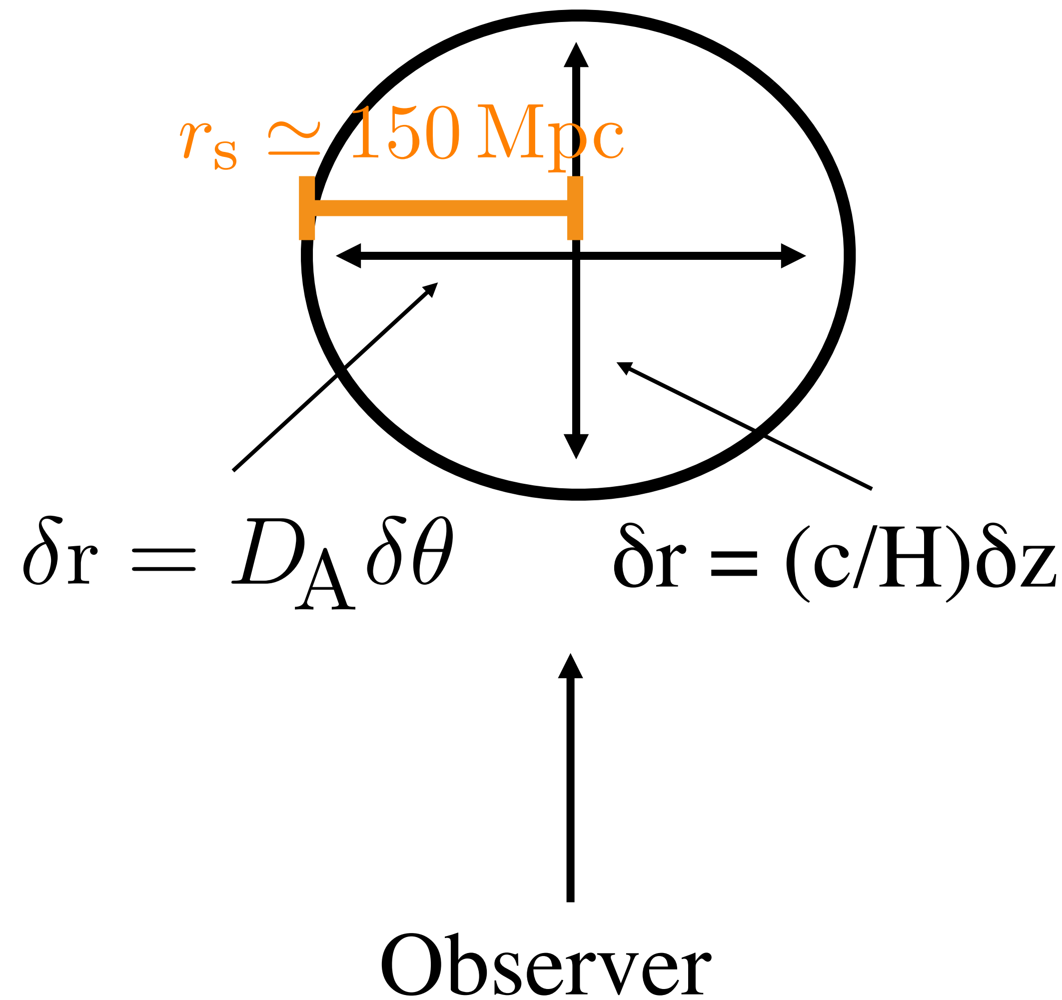
Does this mean one should "see" a BAO pattern in galaxy surveys?



No!

BAO: cosmological ruler



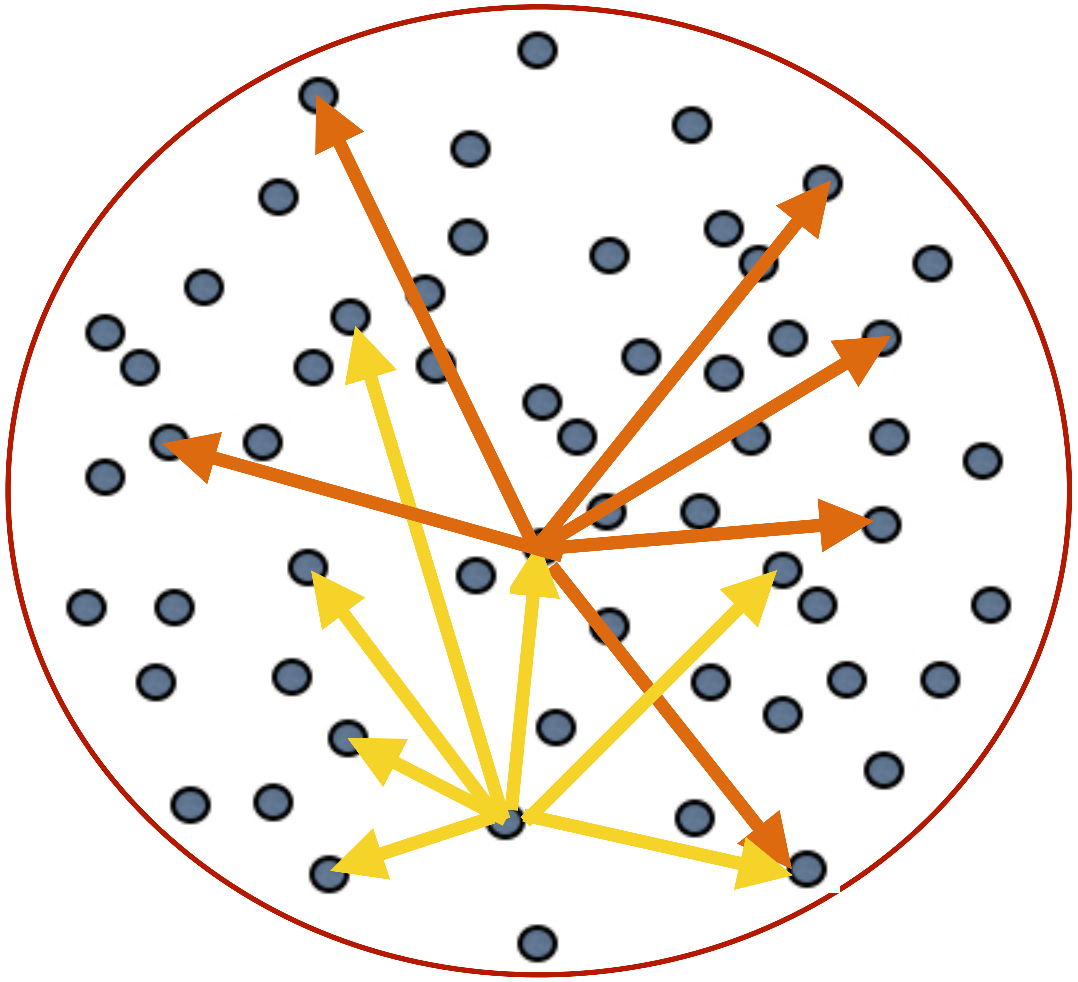


https://www.youtube.com/watch?v=jpXuYc-wzk4

In 3D BAO signature is find in spheres of radius 150 Mpc

BAO: how to extract the BAO signature from astronomical surveys?

a random distribution?



2PCF:

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

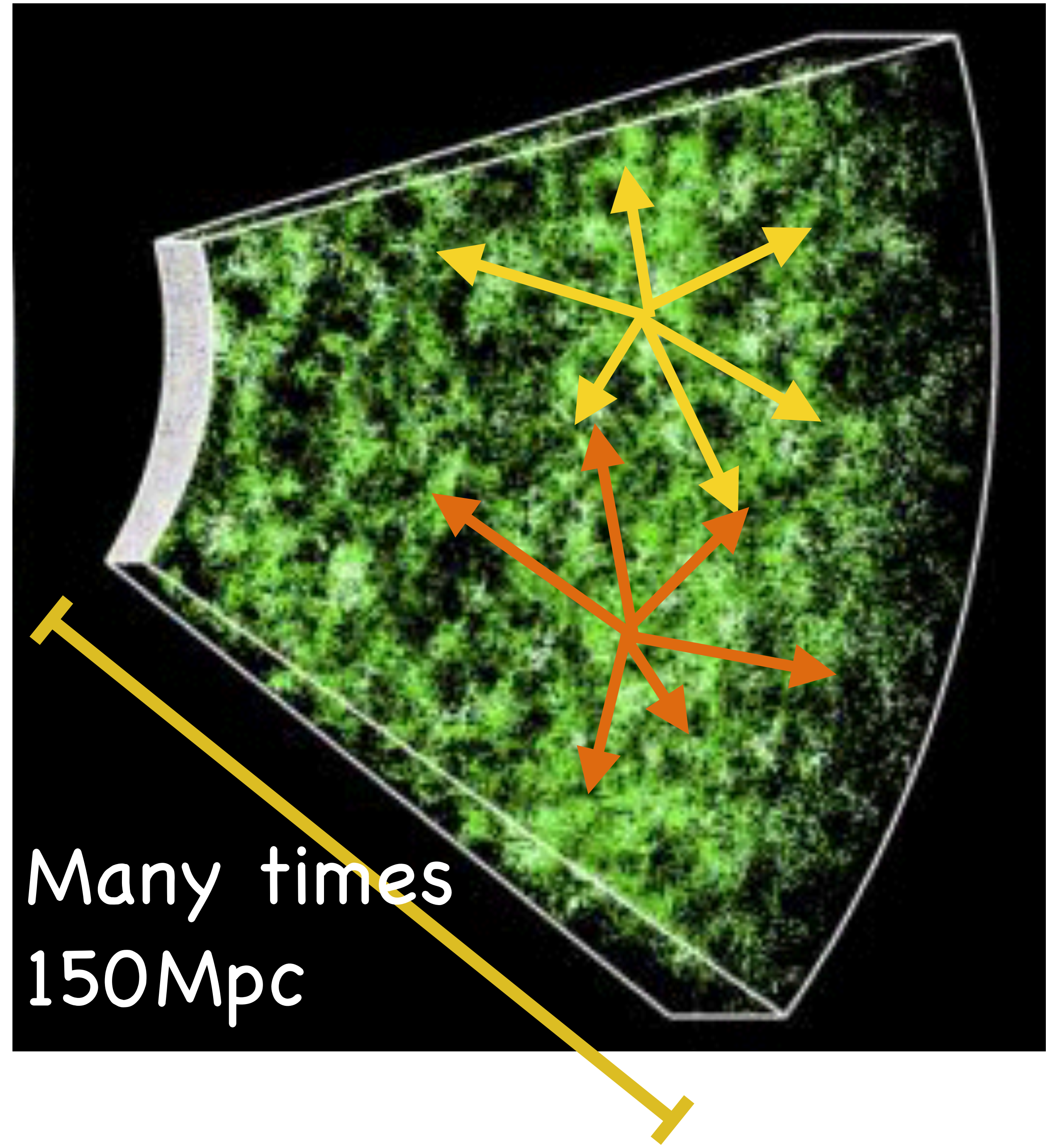
2PCF: a tool to explore BAO signature!

Large-scale structure in 3D

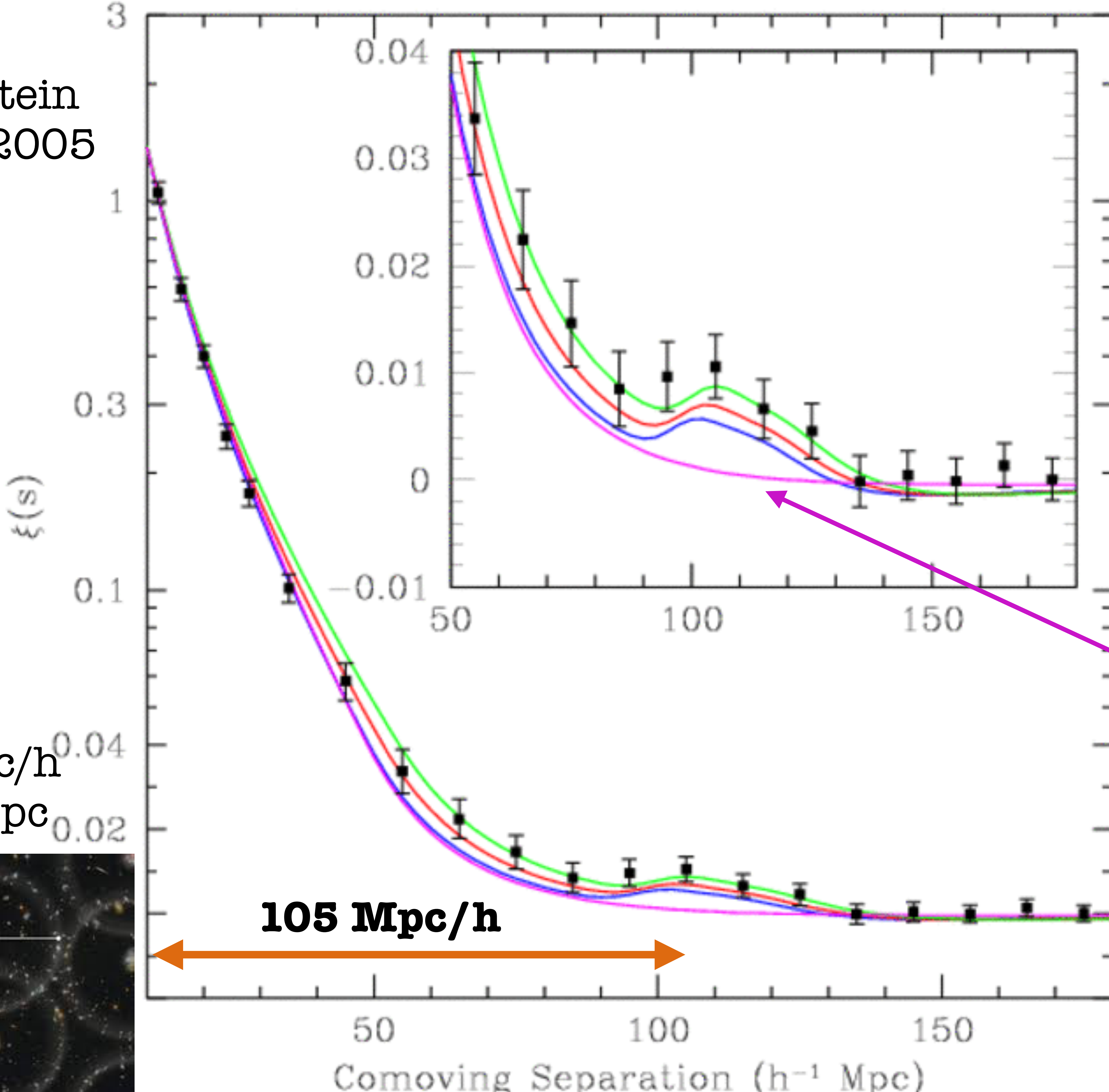
3D-2PCF

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

3D

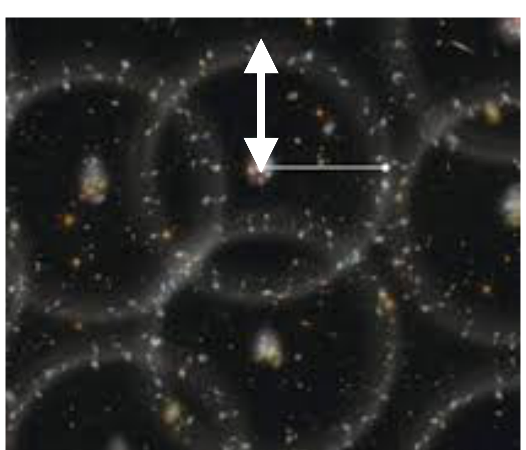


Eisenstein
et al., 2005



without
baryons

105 Mpc/h
= 150 Mpc



BAO: the data analyses

1: calculating the sound horizon scale

Sound horizon scale computations

Planck-18

arXiv:1807.06209

(multiplying r_s x h from Table 2)

$$r_{\rm drag} = 147.09 \pm 0.26\,{\rm Mpc}$$

$$H_0 = 67.36 \pm 0.54\,km/s/{\rm Mpc}$$

$$r_s \equiv r_{\rm drag} \in [98.11, 100.05]\,{\rm Mpc}\,h^{-1}$$

WMAP9

arXiv:1212.5226

(from the Cosmological parameters Table(s))

$$r_{\rm drag} = 152.3 \pm 1.3\,{\rm Mpc}$$

$$H_0 = 70.0 \pm 2.2\,km/s/{\rm Mpc}$$

$$r_s \equiv r_{\rm drag} \in [102.4, 110.9]\,{\rm Mpc}\,h^{-1}$$

Sound horizon scale computations

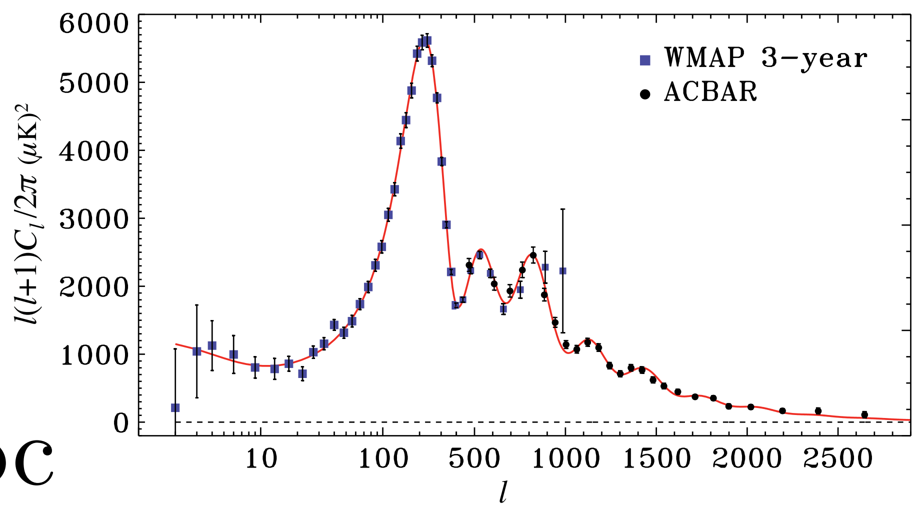
Planck-18

$$r_{\rm drag} = 147.09 \pm 0.26\,{\rm Mpc}$$

$$H_0 = 67.36 \pm 0.54\,km/s/{\rm Mpc}$$

$$r_s \equiv r_{\rm drag} \in [98.11, 100.05]\,{\rm Mpc}\,h^{-1}$$

WMAP9+SPT+ACT



$$r_{\rm drag} = 146.33 \pm 0.89\ {\rm Mpc}$$

$$H_0 = 70.5 \pm 1.6\,km/s/{\rm Mpc}$$

$$r_s \equiv r_{\rm drag} \in [100.2, 106.1]\,{\rm Mpc}\,h^{-1}$$

Sound horizon scale computations

1st form to calculate r_s

pag.13, arXiv:1807.06209

Planck-18

$$\left(\frac{r_{\mathrm{drag}}h}{\mathrm{Mpc}}\right)\left(\frac{\Omega_{\mathrm{m}}}{0.3}\right)^{0.4} = 101.056 \pm 0.036 \quad (68\,\%,\ \mathrm{TT,TE,EE}+\mathrm{lowE}). \tag{10}$$

from Table 1 pag.14, arXiv:1807.06209

$$\boxed{r_{\mathrm{drag}} \equiv r_s = 99.0988 \pm 0.0353\,\mathrm{Mpc}\,h^{-1}}$$

data from Table 2 pag.15, arXiv:1807.06209

$$r_s = (147.05 \pm 0.30) \times 0.6727 = 98.9205 \pm 0.2018\,\mathrm{Mpc}\,h^{-1}$$

Planck-18, arXiv:1807.06209

Parameter	Plik best fit	Plik [1]
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031
τ	0.0543	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.0448	3.044 ± 0.014
n_s	0.96605	0.9649 ± 0.0042
$\Omega_m h^2$	0.14314	0.1430 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}] . . .	67.32	67.36 ± 0.54
Ω_m	0.3158	0.3153 ± 0.0073
Age [Gyr]	13.7971	13.797 ± 0.023
σ_8	0.8120	0.8111 ± 0.0060
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$ . .	0.8331	0.832 ± 0.013
z_{re}	7.68	7.67 ± 0.73
$100\theta_*$	1.041085	1.04110 ± 0.00031
r_{drag} [Mpc]	147.049	147.09 ± 0.26

primary

secondary

$$r_{\rm drag} = \int_{\eta_i}^{\eta_{\rm drag}} c_s(\eta)\, d\eta \;\; = \int_{z_{\rm drag}}^{\infty} \frac{c_s(z)}{H(z)}\, dz \equiv r_{\rm s}$$

$$c_s^2 = \frac{1}{3(1+R)} = \frac{1}{3}\,\frac{4\rho_\gamma}{(4\rho_\gamma + 3\rho_b)} \; = \frac{1}{3}\,\frac{4\Omega_\gamma}{(4\Omega_\gamma + 3\Omega_b)}$$

$$c_s = \sqrt{\frac{4\Omega_\gamma}{3(4\Omega_\gamma + 3\Omega_b)}}$$

$$\Omega_\gamma = 2.47\ 10^{-5}\, h^{-2}$$

$$\Omega_b = 0.0224\ h^{-2}$$

Sound horizon scale computations

$$r_{\rm drag} = \int_{\eta_i}^{\eta_{\rm drag}} c_s(\eta)\, d\eta \;=\; \int_{z_{\rm drag}}^{\infty} \frac{c_s(z)}{H(z)}\, dz \;\equiv\; r_{\rm s}$$

$$c_s^2 = \frac{1}{3(1+R)} = \frac{1}{3}\,\frac{4\rho_\gamma}{(4\rho_\gamma + 3\rho_b)} = \frac{1}{3}\,\frac{4\Omega_\gamma}{(4\Omega_\gamma + 3\Omega_b)}$$

$$c_s = \sqrt{\frac{4\Omega_\gamma}{3(4\Omega_\gamma + 3\Omega_b)}}$$

$$\Omega_\gamma = 2.47\ 10^{-5}\ h^{-2}$$

$$\Omega_b = 0.0224\ h^{-2}$$

$$\simeq 0$$

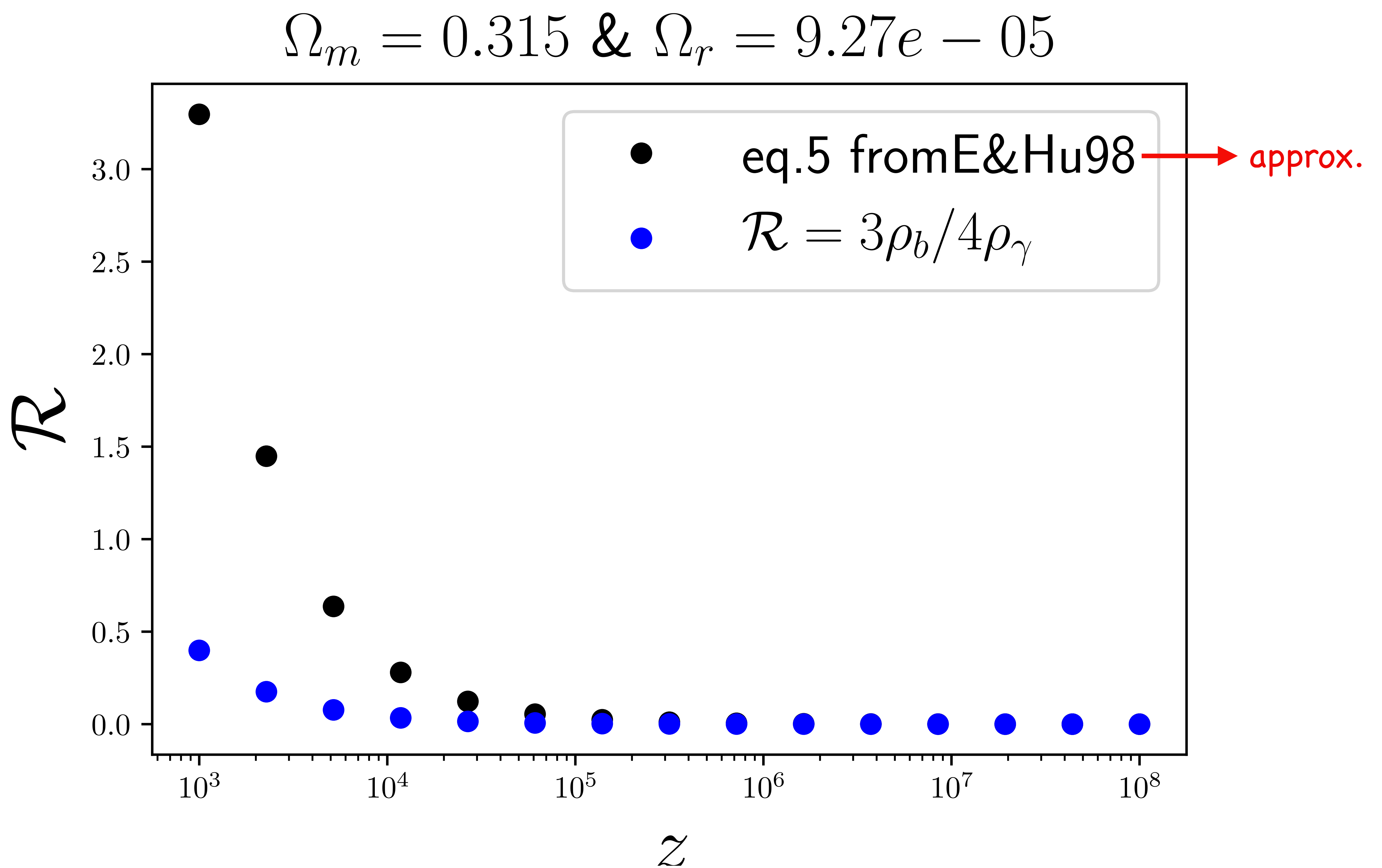
$$H(z) = H_0 \sqrt{(1+z)^4\,\Omega_r + (1+z)^3\,\Omega_m + (1+z)^2\,\cancel{\Omega_k} + \Omega_\Lambda}$$

$$= 0$$

$$\Omega_r = 4.18\ 10^{-5}\ h^{-2} \qquad \Omega_m = \Omega_b + \Omega_c$$

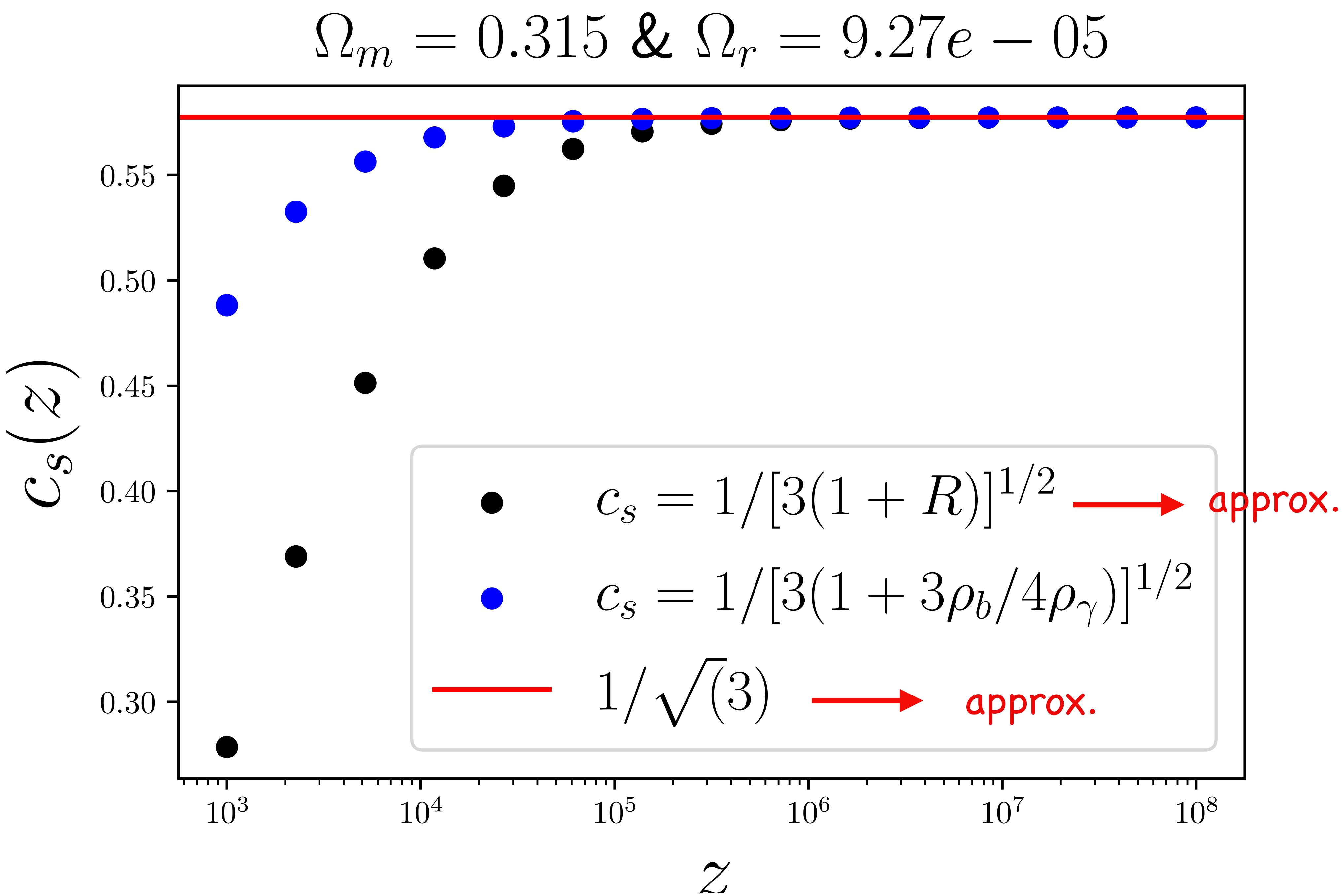
$$\Omega_\Lambda = 1 - \Omega_k - \Omega_m - \cancel{\Omega_r}$$

$$c_s^2 \equiv \frac{\partial p_{\gamma b}}{\partial \rho_{\gamma b}} = \frac{1}{3\,(1+R)} \;;\; R \;\equiv\; \frac{(\rho_b + p_b)v_b}{(\rho_\gamma + p_\gamma)v_\gamma} = \frac{\rho_b + p_b}{\rho_\gamma + p_\gamma} = \frac{3\rho_b}{4\rho_\gamma}$$



$$c_s^2 \equiv \frac{\partial p_{\gamma b}}{\partial \rho_{\gamma b}} = \frac{1}{3\,(1+R)}$$

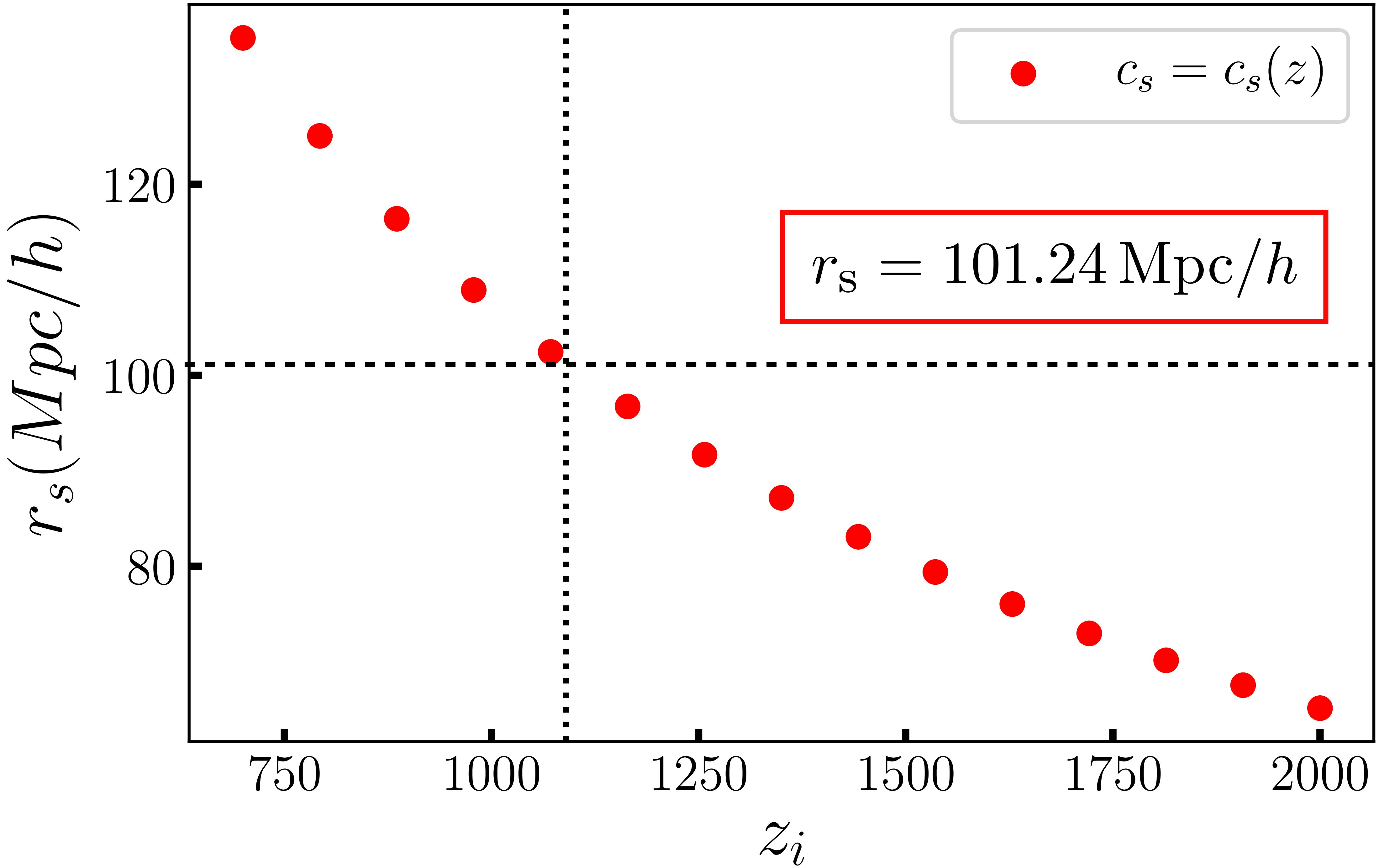
$$R \equiv \frac{(\rho_b + p_b)v_b}{(\rho_\gamma + p_\gamma)v_\gamma} = \frac{\rho_b + p_b}{\rho_\gamma + p_\gamma} = \frac{3\rho_b}{4\rho_\gamma}$$



Sound horizon scale computations

2nd form to calculate r_s

$$r_s = \int_{z_i}^{\infty} \frac{c_s(z)}{H(z)}\, dz$$



Notice that the sound horizon scale computation was done using cosmological model parameters and model hypotheses

$$\Omega_b, \; \Omega_m, \; \Omega_\gamma \qquad\qquad \Omega_k = 0, \; \exists\, \Omega_m, \text{ etc.}$$

Is there a form to calculate r_s in a model-independent approach?

(+ parameters-independent)

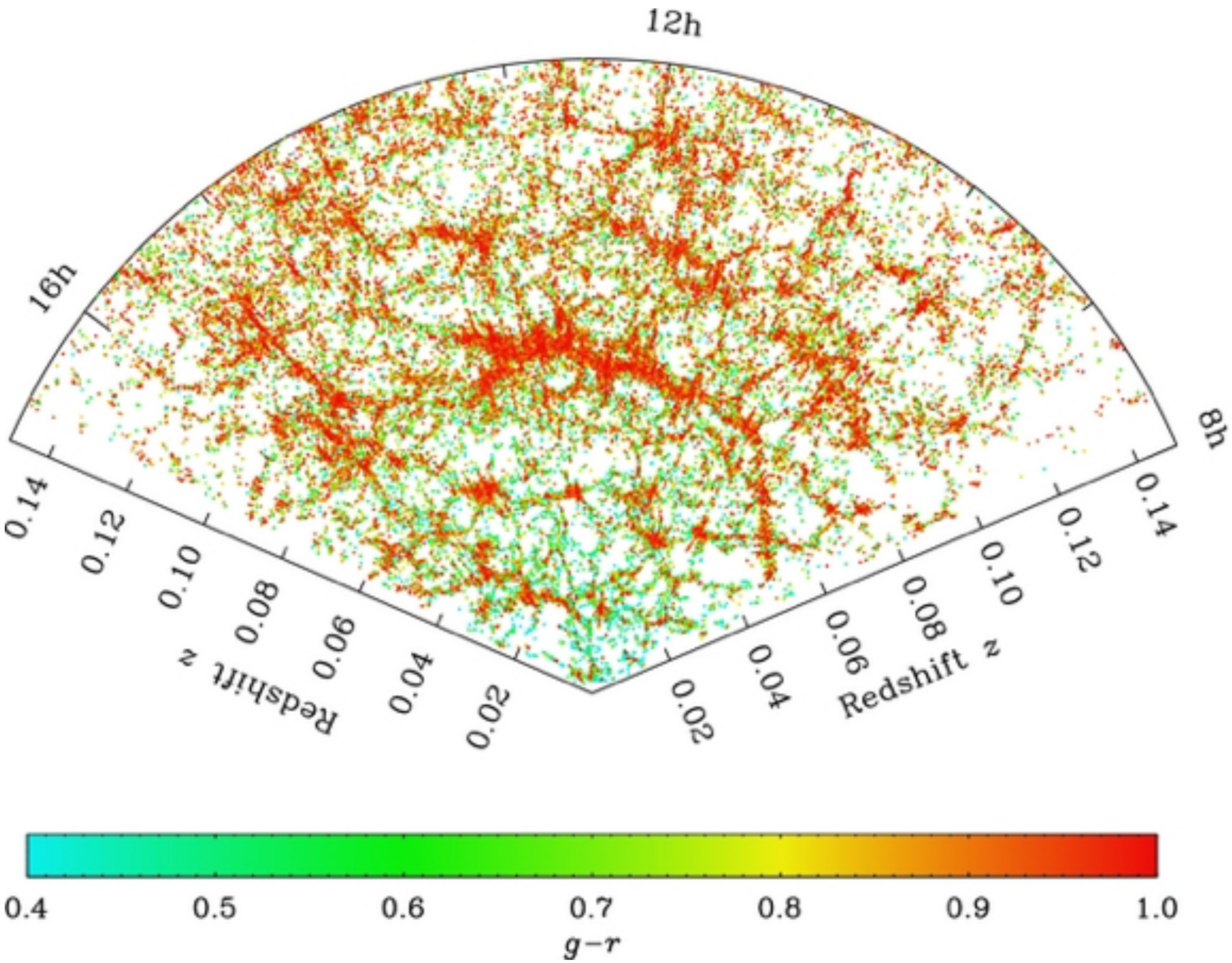
Sound horizon scale measurements

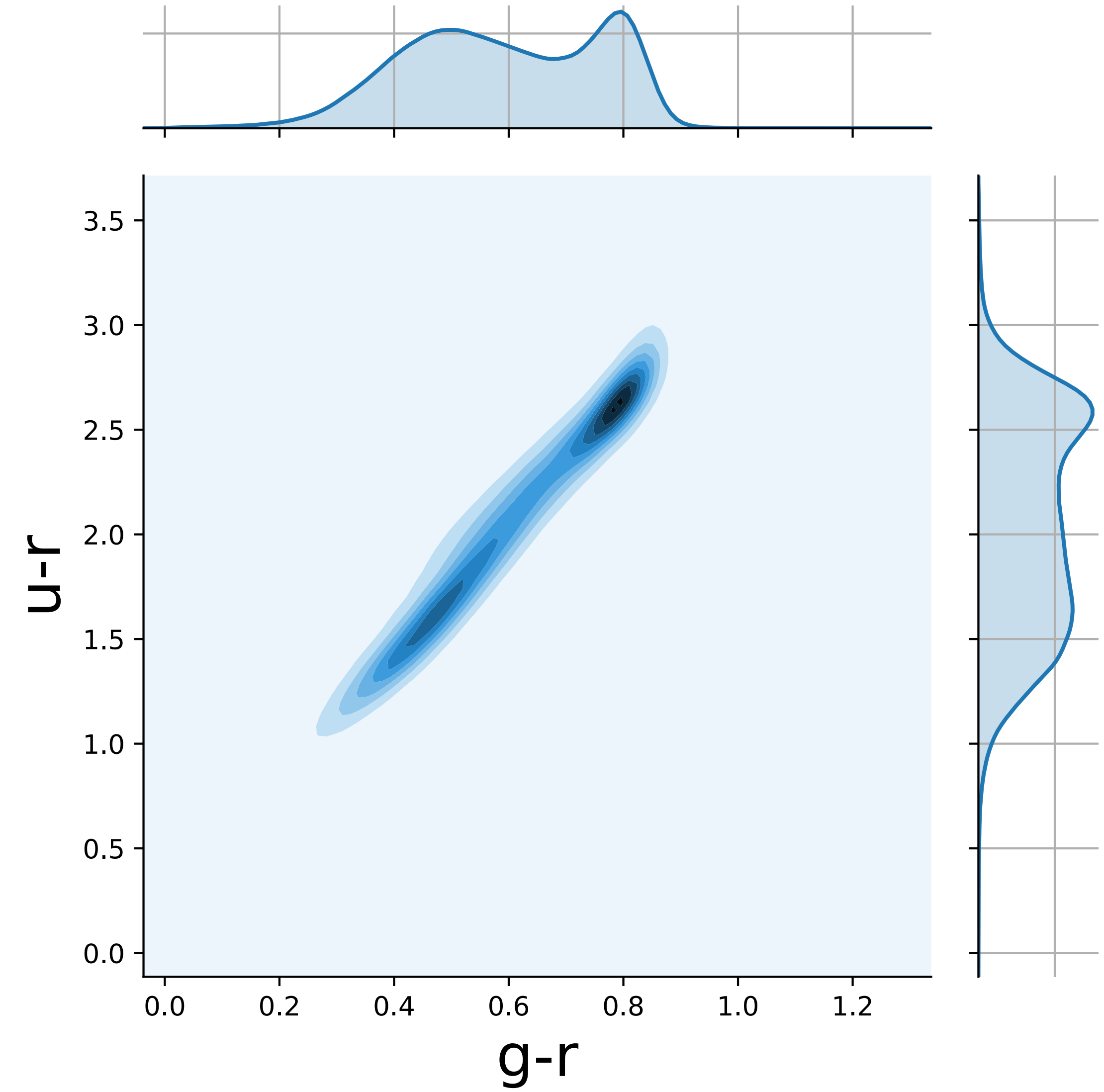
BAO: the data analyses

2: choose the cosmic tracer and perform the measurement analyses

* to calculate $\neq$ to measure

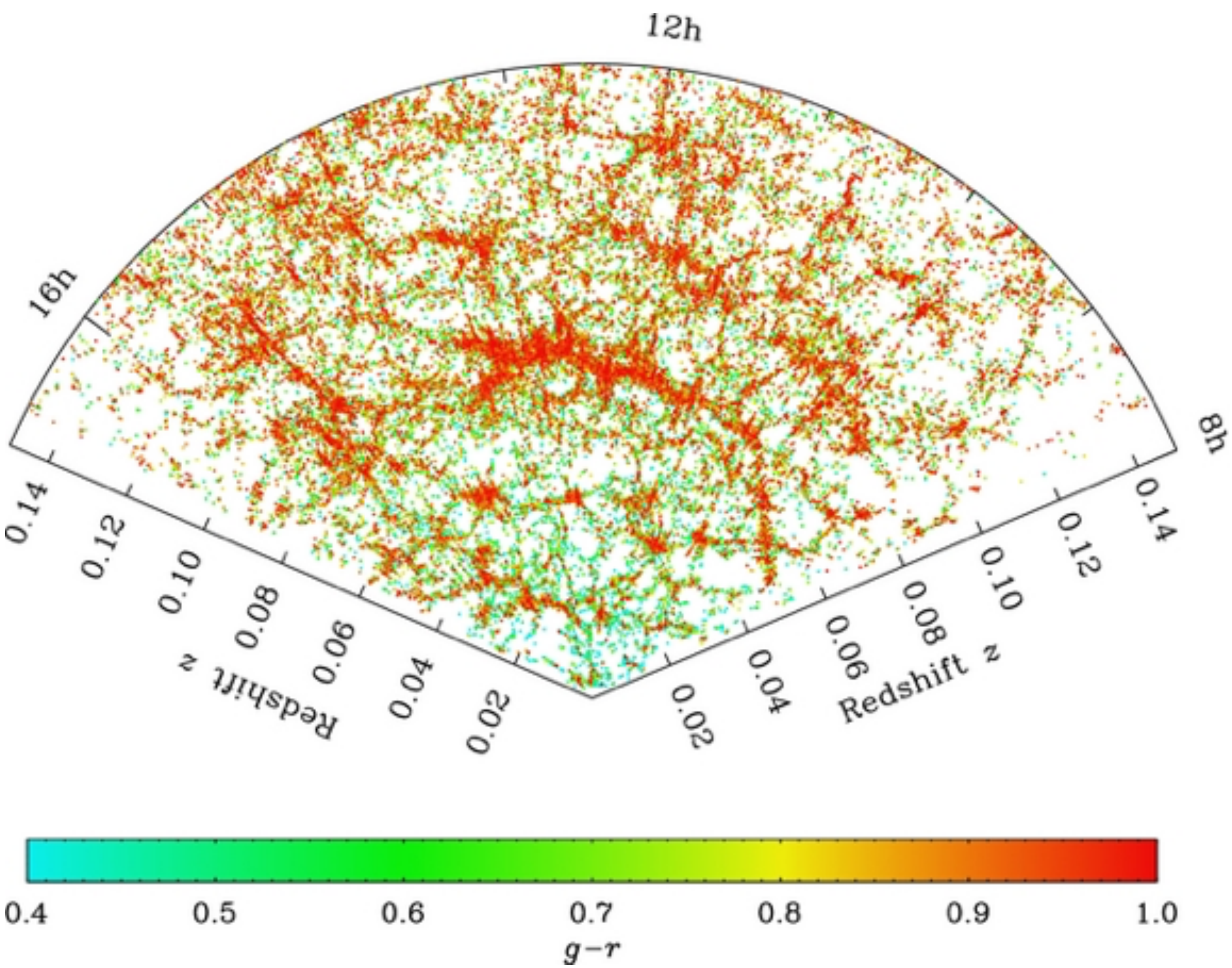
SDSS Main Galaxy Sample (MGS)



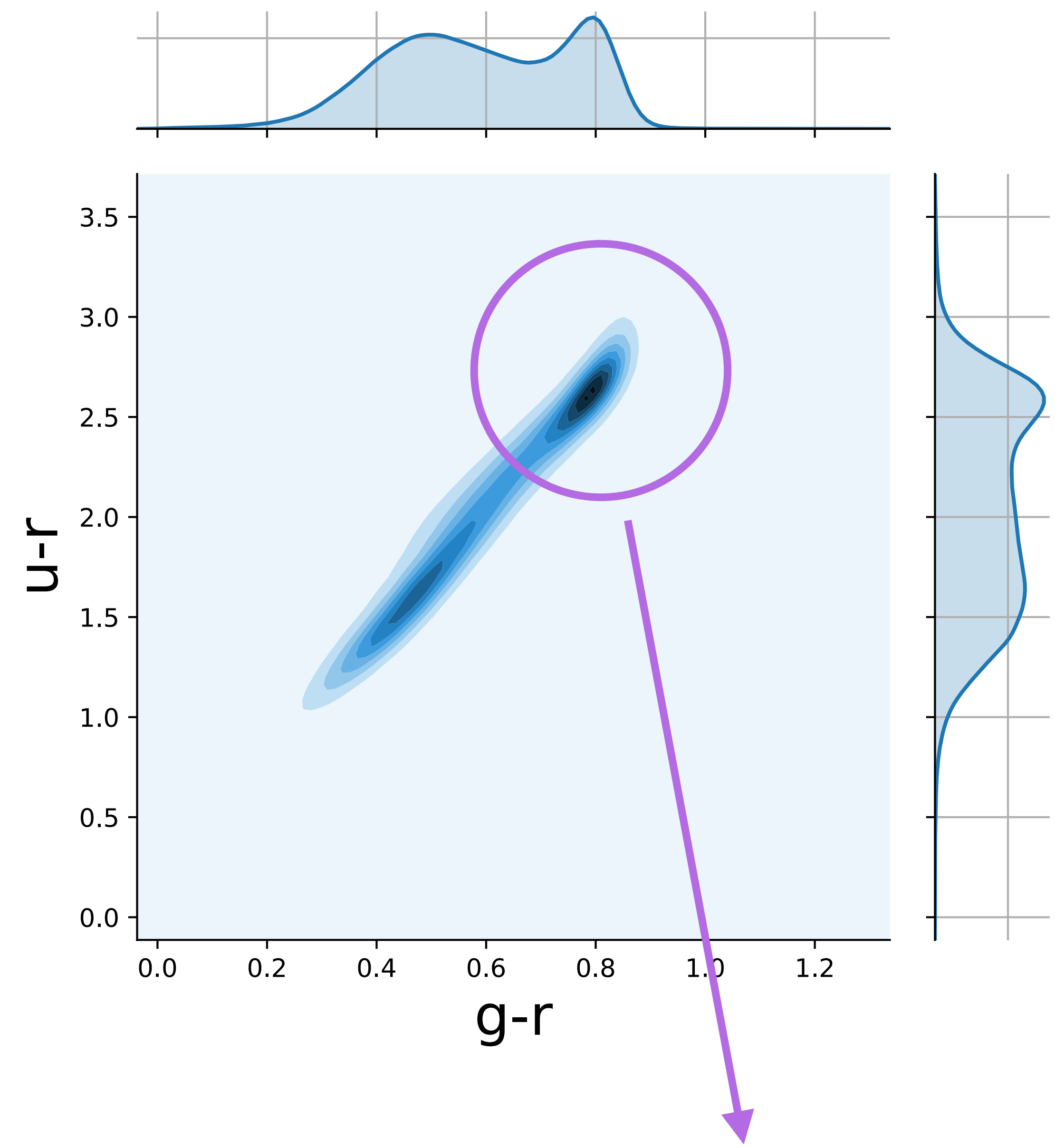


Different colors = diferent cosmic tracers

SDSS MGS

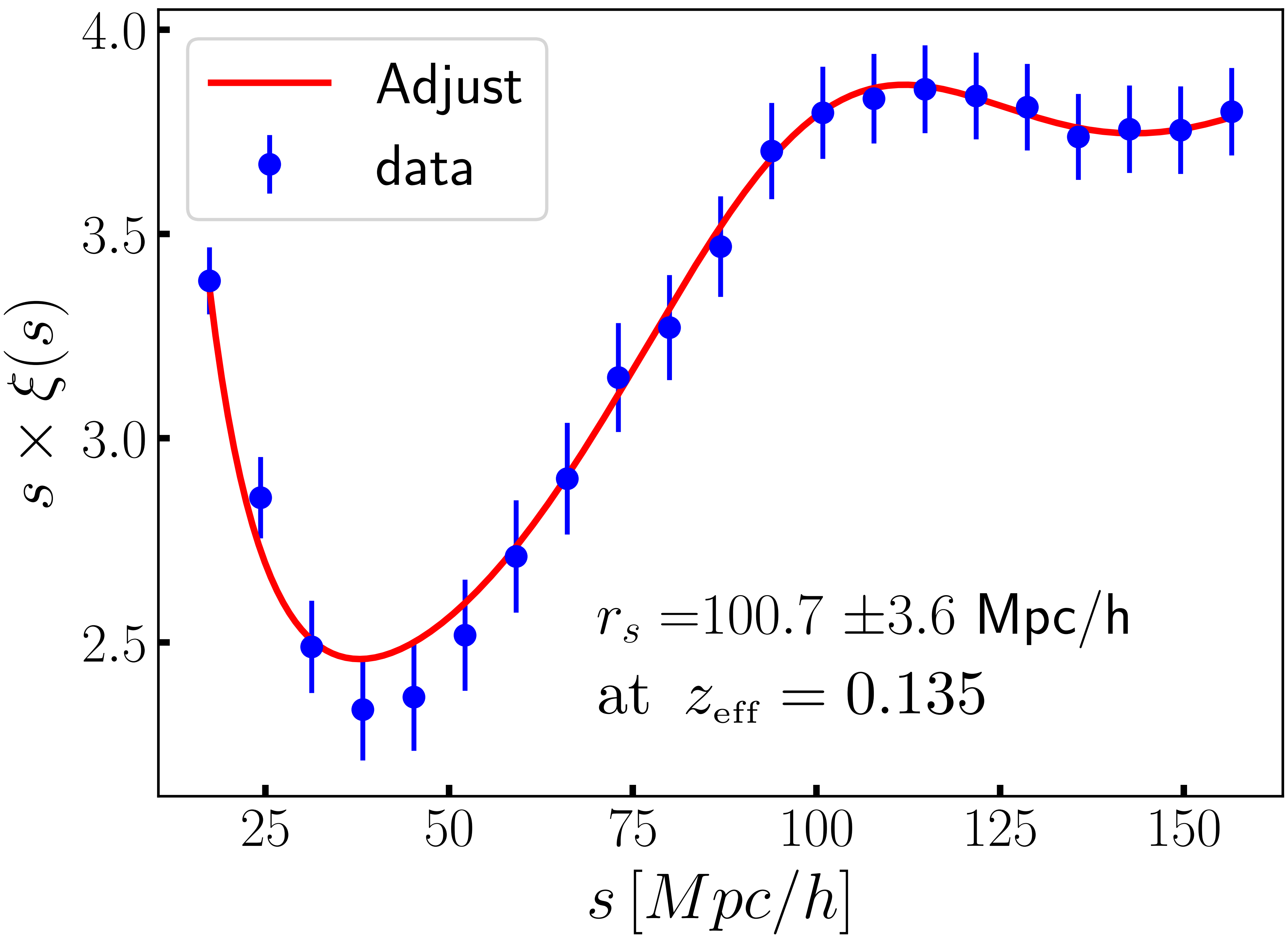


color-color diagram



blue galaxies

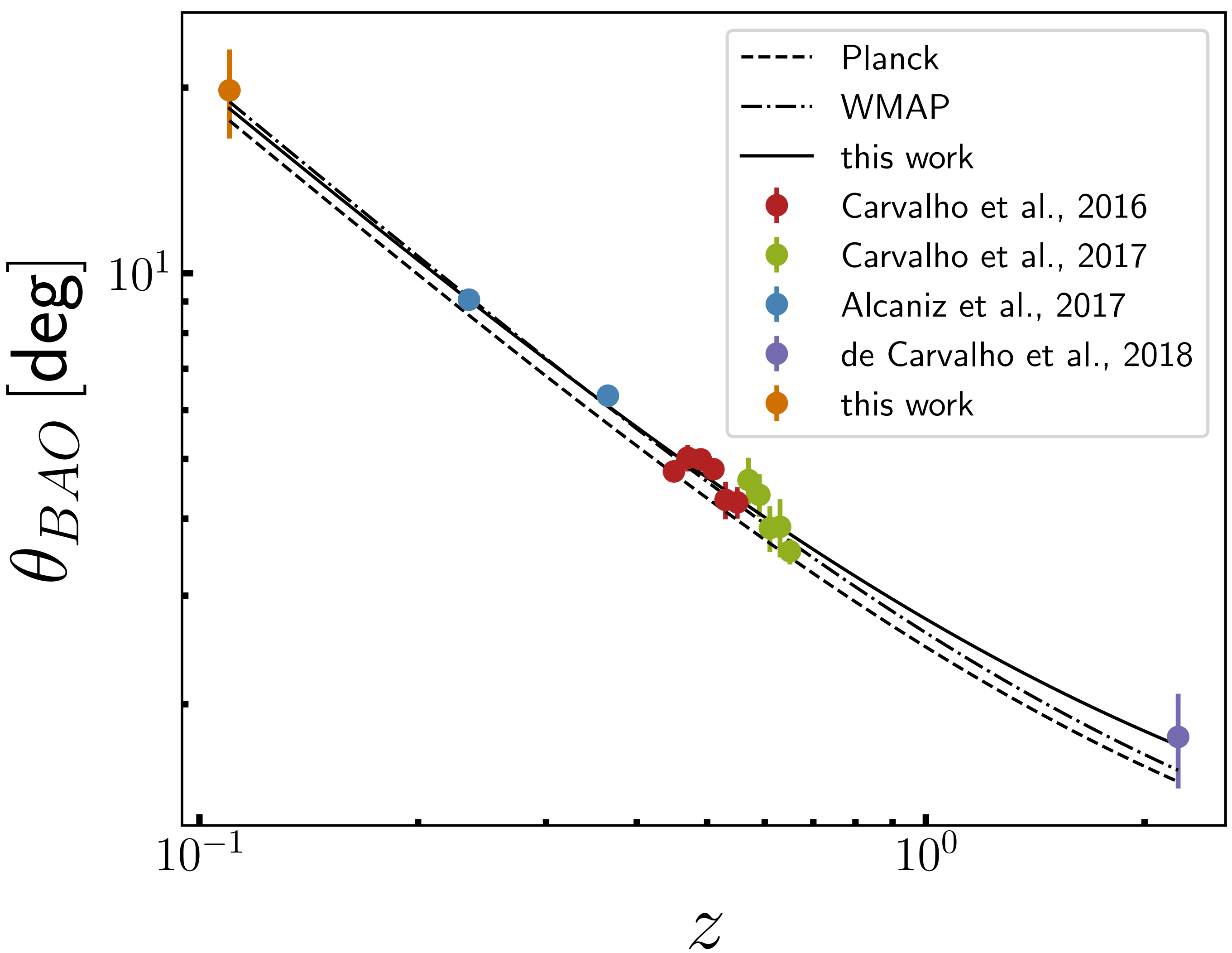
Using Cosmography one calculates the 2PCF: $\xi = \xi(s)$ and measures the sound scale horizon



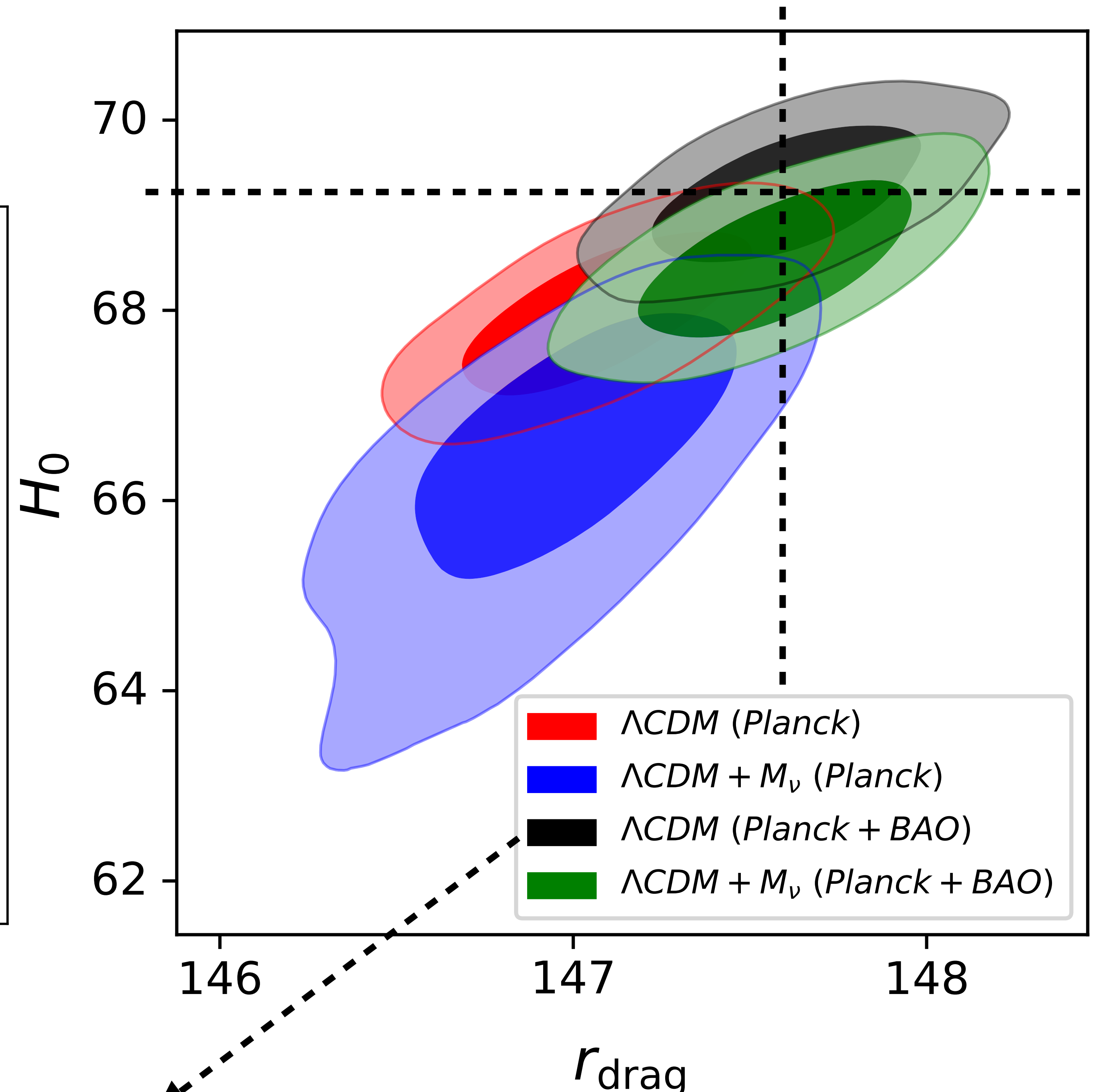
E. de Carvalho et al., 2020

3rd form to calculate r_s

$15 \; \{\theta_{\rm BAO}\}$ values



E. de Carvalho et al., 2020



$$r_s \simeq 102 \ {\rm Mpc}/h$$

R.C. Nunes et al., arXiv:2002.09293

Conclusions

- Accurate measurements of the sound horizon scale are extremely important to study LSS of the Universe
- The BAO measurement is a statistical procedure, a good S/N depends on suitable number density of cosmic objects
- The sound horizon scale can also be obtained by Bayesian analyses with other data sets

Collaborators and scientific Collaborations

Maybe, the most important thing one can do for young scientists is to promote an ambient to motivate them to develope their scientific curiosity, creativity, mutual discussions, ... where people use their skills to solve challenging problems.
In this collaborative ambience to learn and to teach are pleasant activities.

Eisenstein et al., 2005