Decrypting the Dark Energy with Spectroscopic Surveys.

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Dark Matter Days at CIFFU, 6 November 2017

Outline

- **Motivation: Dark Energy**
- **Cosmology with Large Scale Structure**
- **Dark Energy Experiments:**
  - **Extended Baryonic Oscillations Spectroscopic Survey**.
  - **Dark Energy Spectroscopic Instrument**.

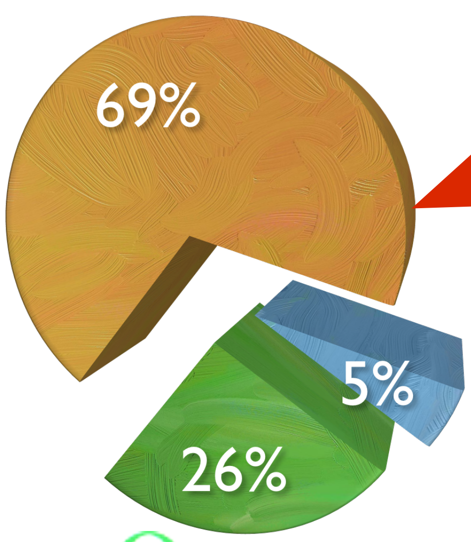
Status of Cosmology today

- Considers: Dark Energy, Cold Dark Matter. and Baryonic Matter

$$\Omega_i = \frac{\rho}{\rho_c}$$

Density value for a flat universe

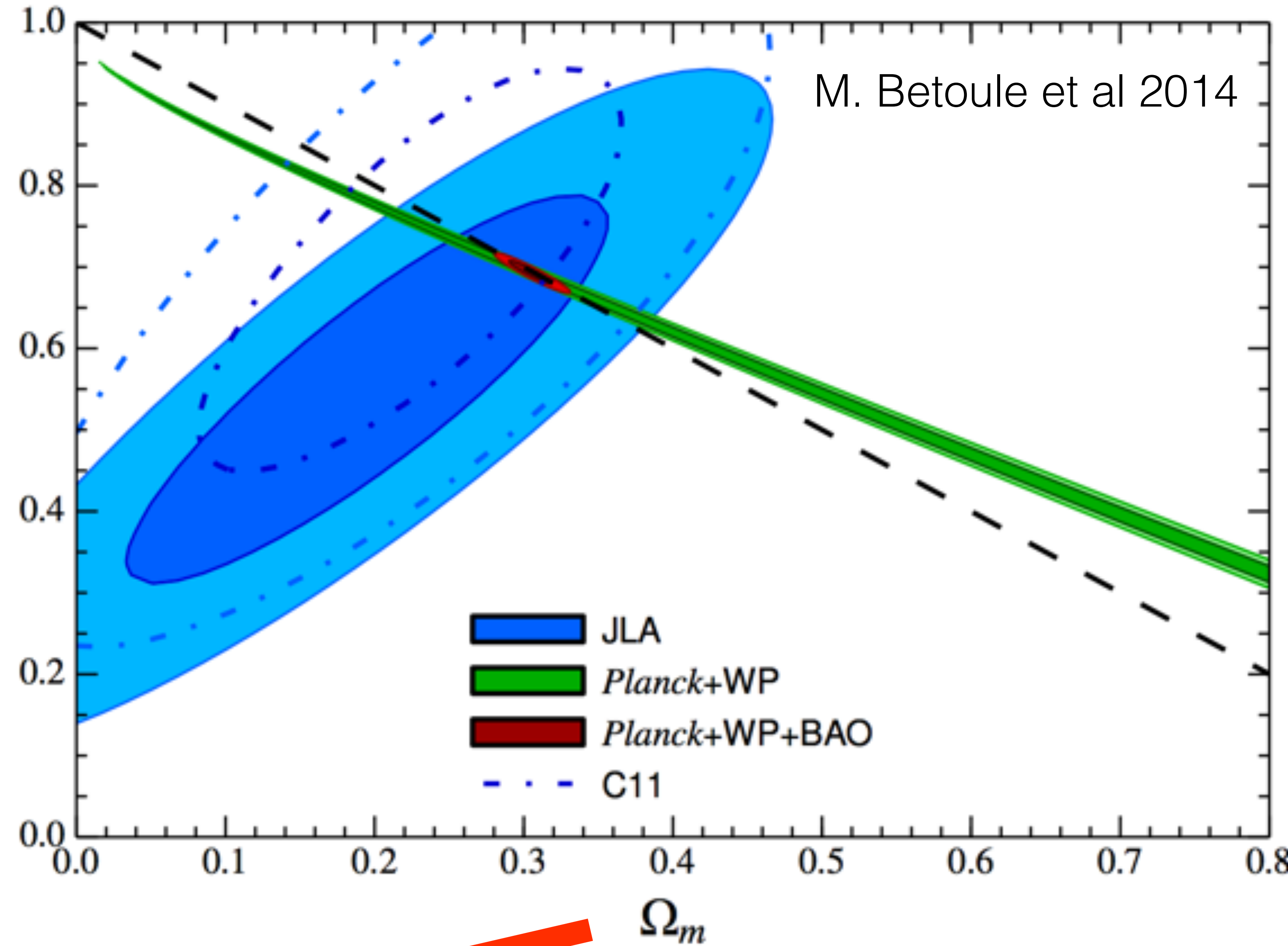
Dark Energy Density Ω_Λ



Ω_b

Dark Matter density Ω_c

Baryonic Matter Densit,



Energetic budget today

$$\Omega_m = \Omega_c + \Omega_b$$

Dark Energy (DE)= cosmic acceleration

Possible explanations:

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} - \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Geometry
Cosmological constant

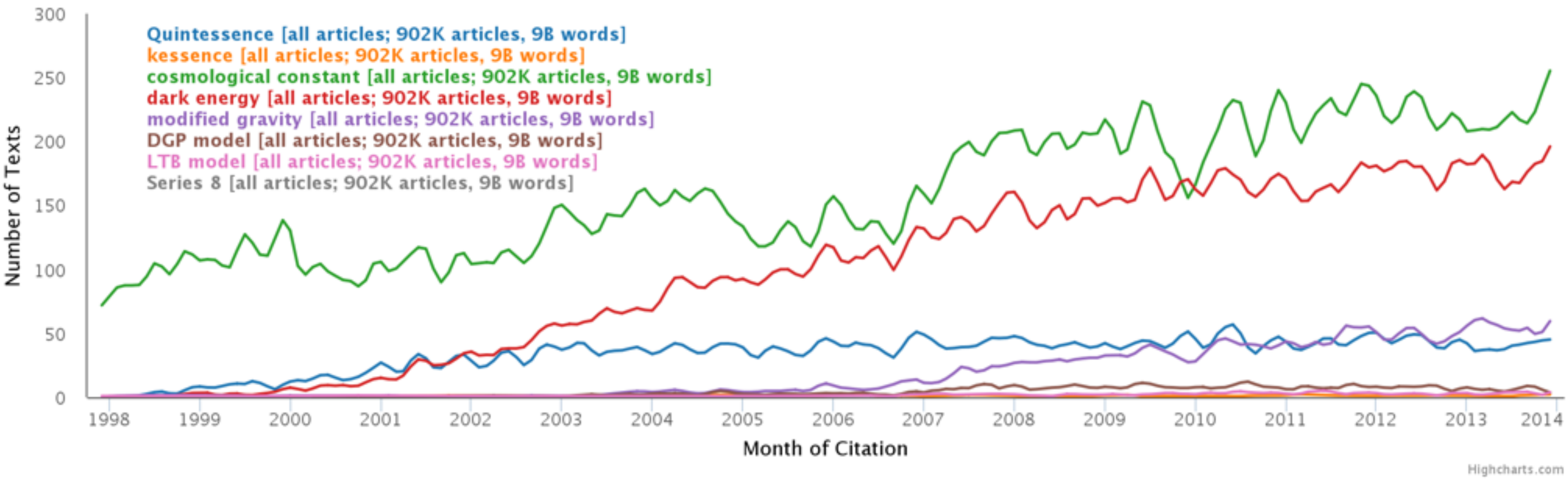
- f(R) gravity
- DGP model
- Inhomogeneous LTB model

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G T_{\mu\nu}$$
$$+T^{\Lambda}_{\mu\nu} = \frac{\Lambda}{8\pi G}$$

Energy Momentum Tensor
new component

Quintessence
K-essence
Coupled DE & DM
Unified DE & DM

Dark energy models



Phenomenological Approach to DE

Perfect Fluid $\rho = \omega p$

$$\frac{\ddot{a}}{a} = \frac{-4\pi G}{3}(\rho_\Lambda + 3p_\Lambda)$$

$p_\Lambda < 0$

$\omega < -1/3$ → Accelerated expansion

Cosmological constant $\omega = -1$

$\rho_\Lambda = cte$

$p_\Lambda = -\rho_\Lambda$

$\Omega_\Lambda = cte$

Constant Energy Density

More general equation for DE $w(z)$

Energy Density evolves with time

$$\Omega_X(z) = \Omega_{X_0} \times \exp\left(3\int_0^z \frac{1+\omega(z')}{1+z'}dz'\right)$$

$$\omega(z) = \omega_0 + \omega_a\left(\frac{z}{1+z}\right)$$

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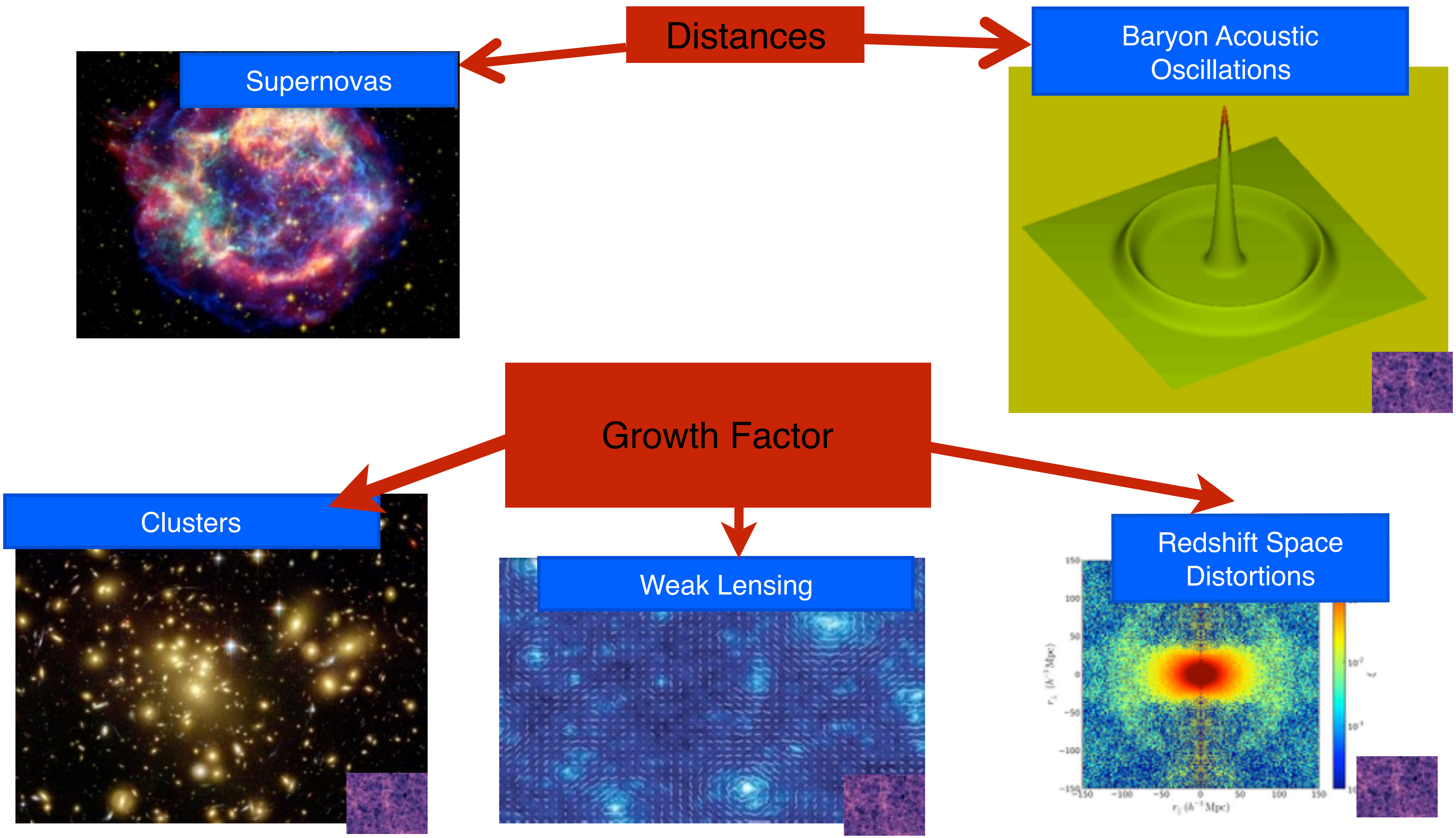
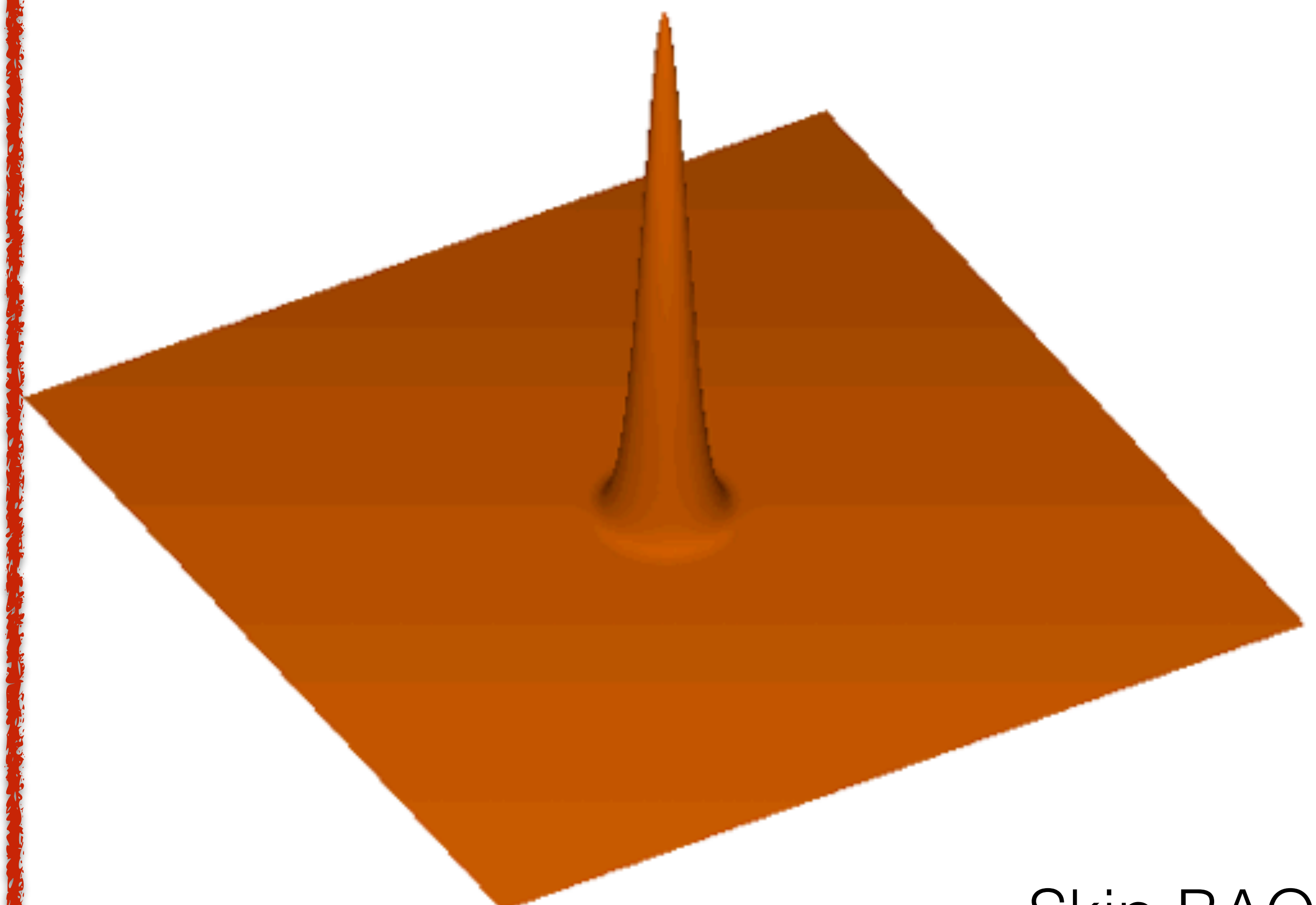
How we can study DE?



Consolidate Observables

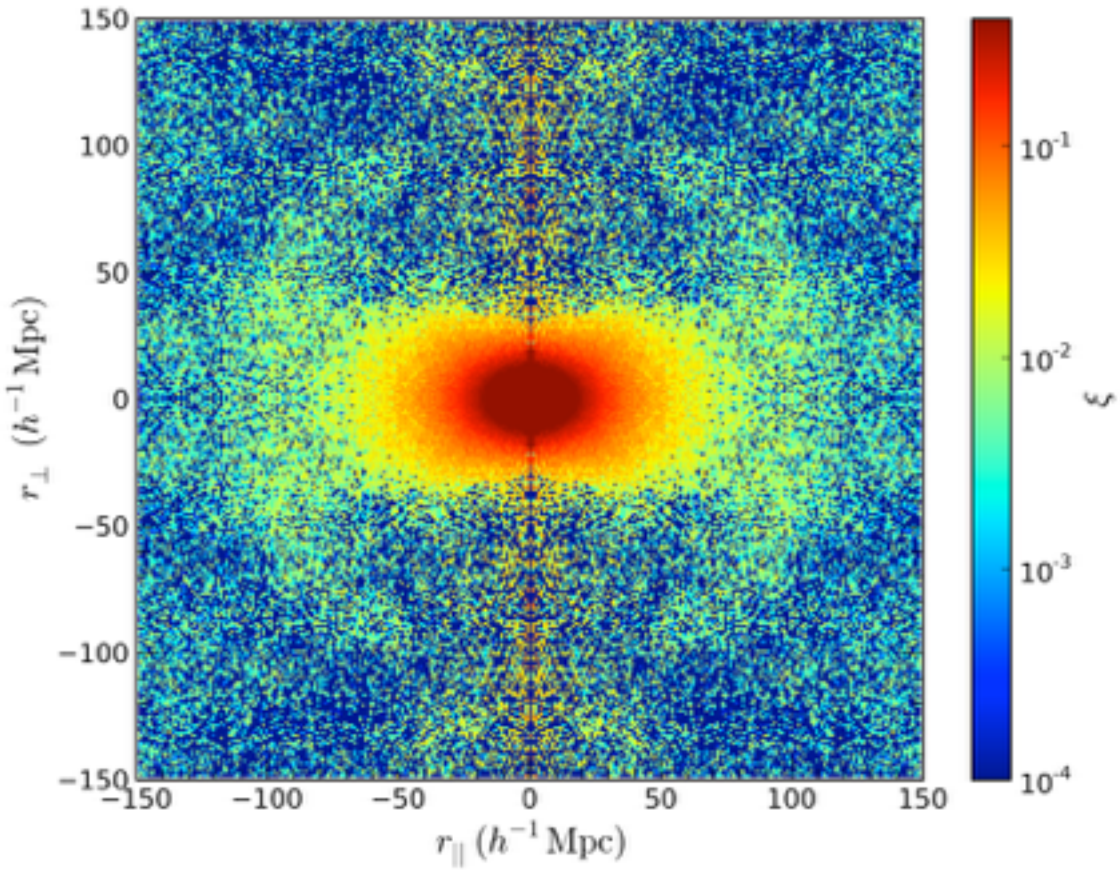
Distances



Skip BAO

BAO

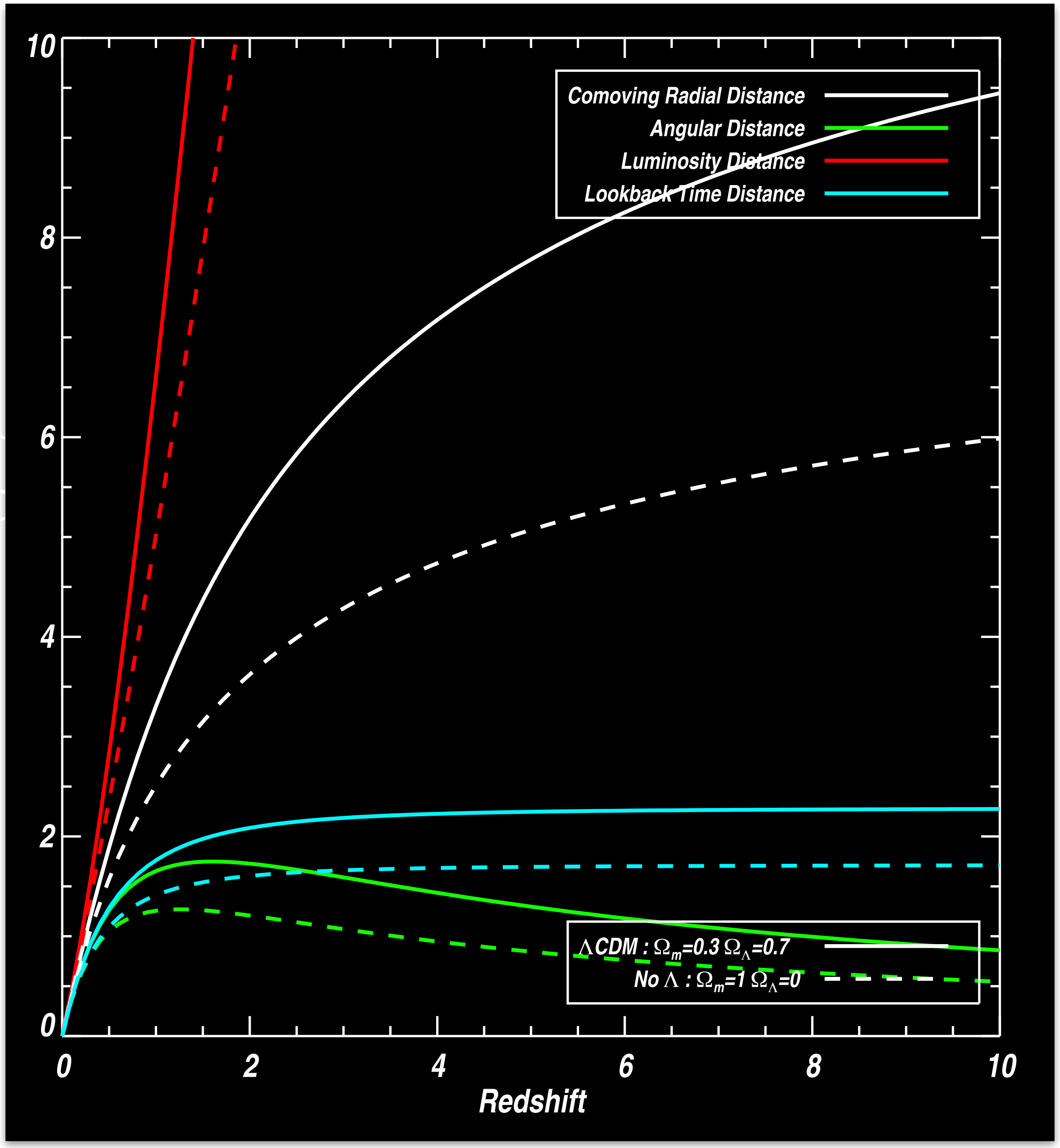
Growth Factor



Skip RSD

RSD

Distances



$$D_A(z) = \chi/(1+z)$$

$$D_L = \chi(1+z)$$

$$\chi = a_0 r(z) = \int_0^z \frac{dz'}{H(z')}$$

Hubble parameter=expansion rate universe

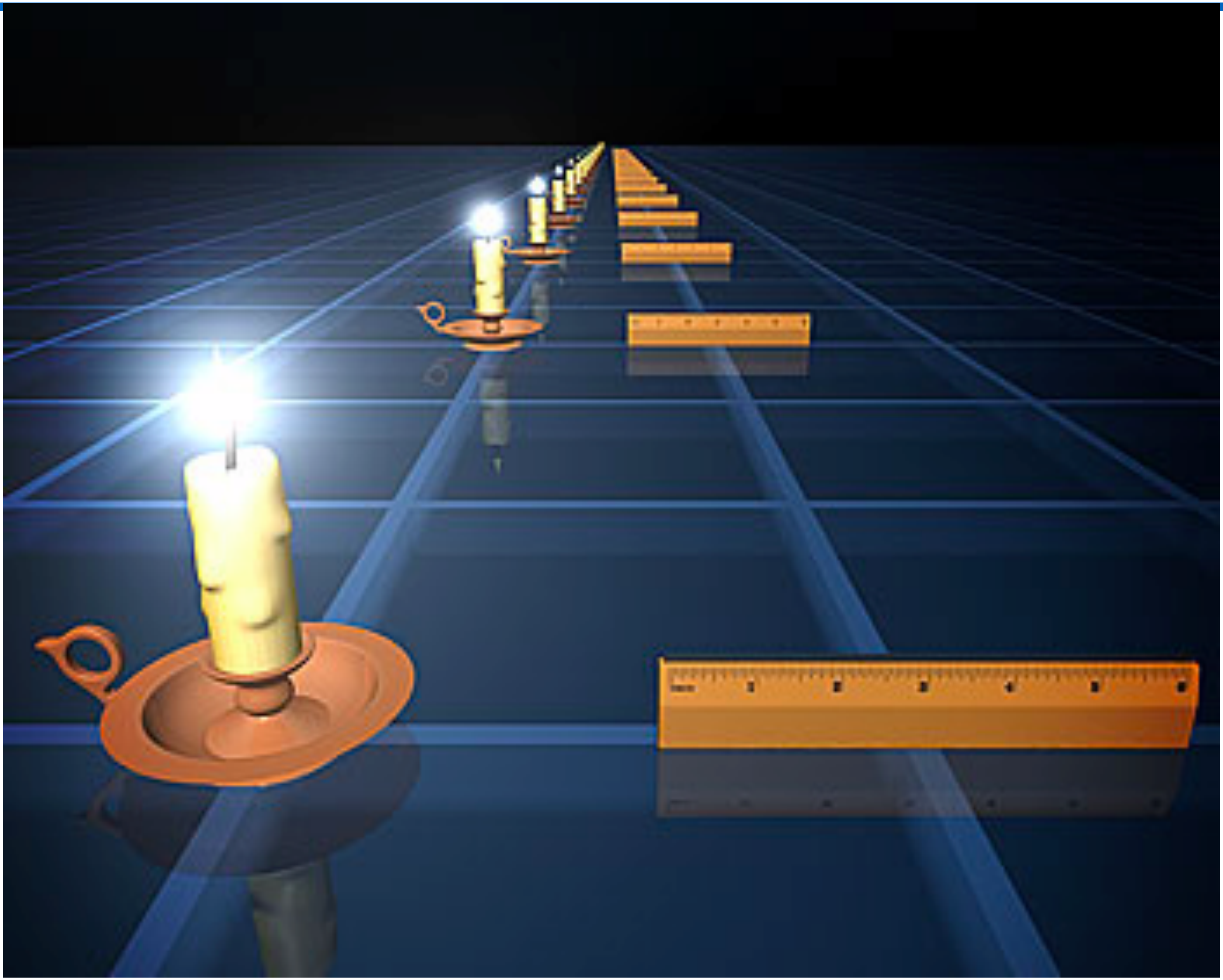
energetic content

$$H(z)^2 = (\tfrac{\dot{a}}{a})^2 = H_0(\Omega_m + \Omega_k + \Omega_\Lambda)$$

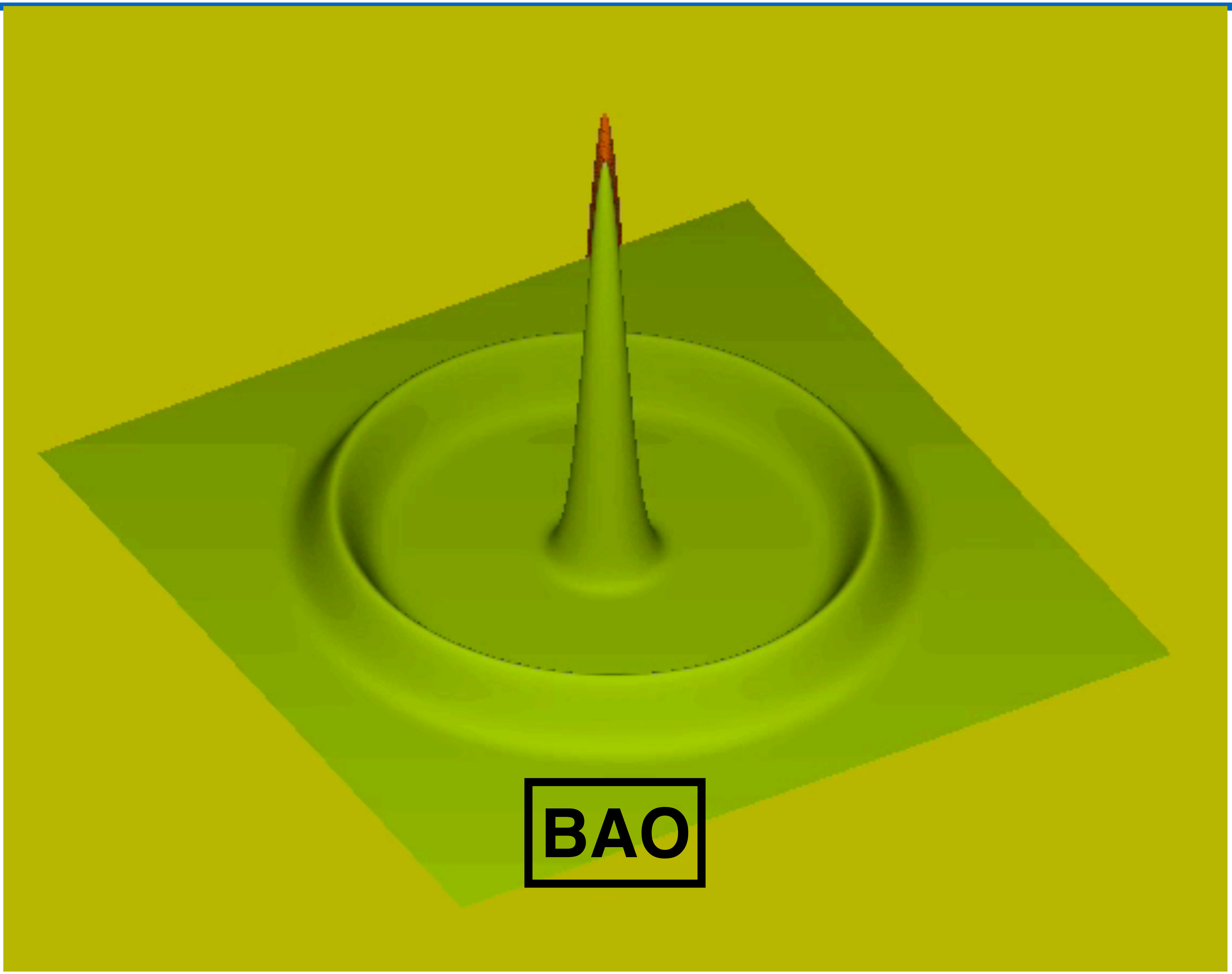
Dark Energy matter curvature DE

The relation between distance and redshift depends of cosmological parameters.

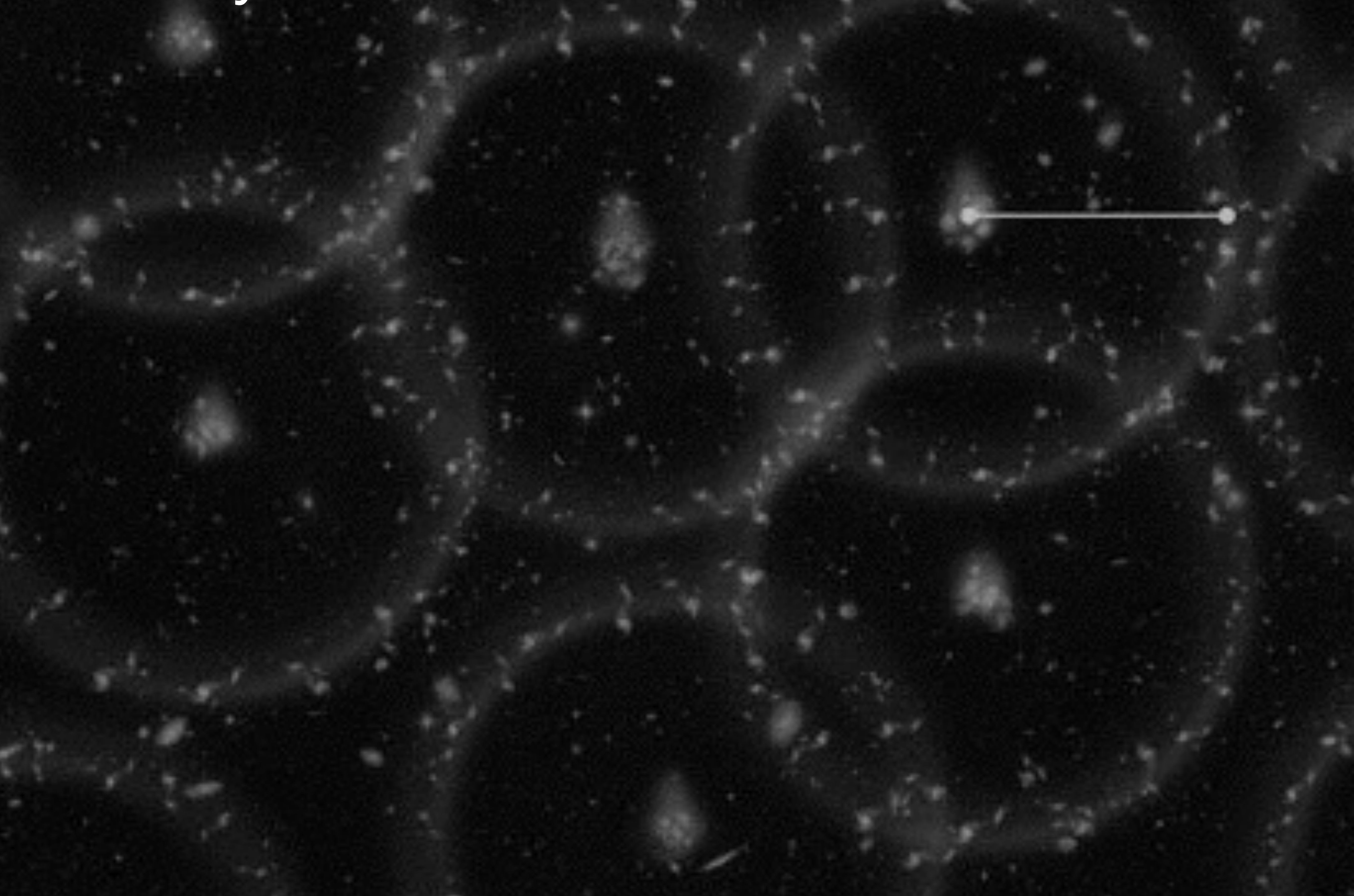
Standard Ruler



Baryonic Acoustic Oscillations (BAO) I

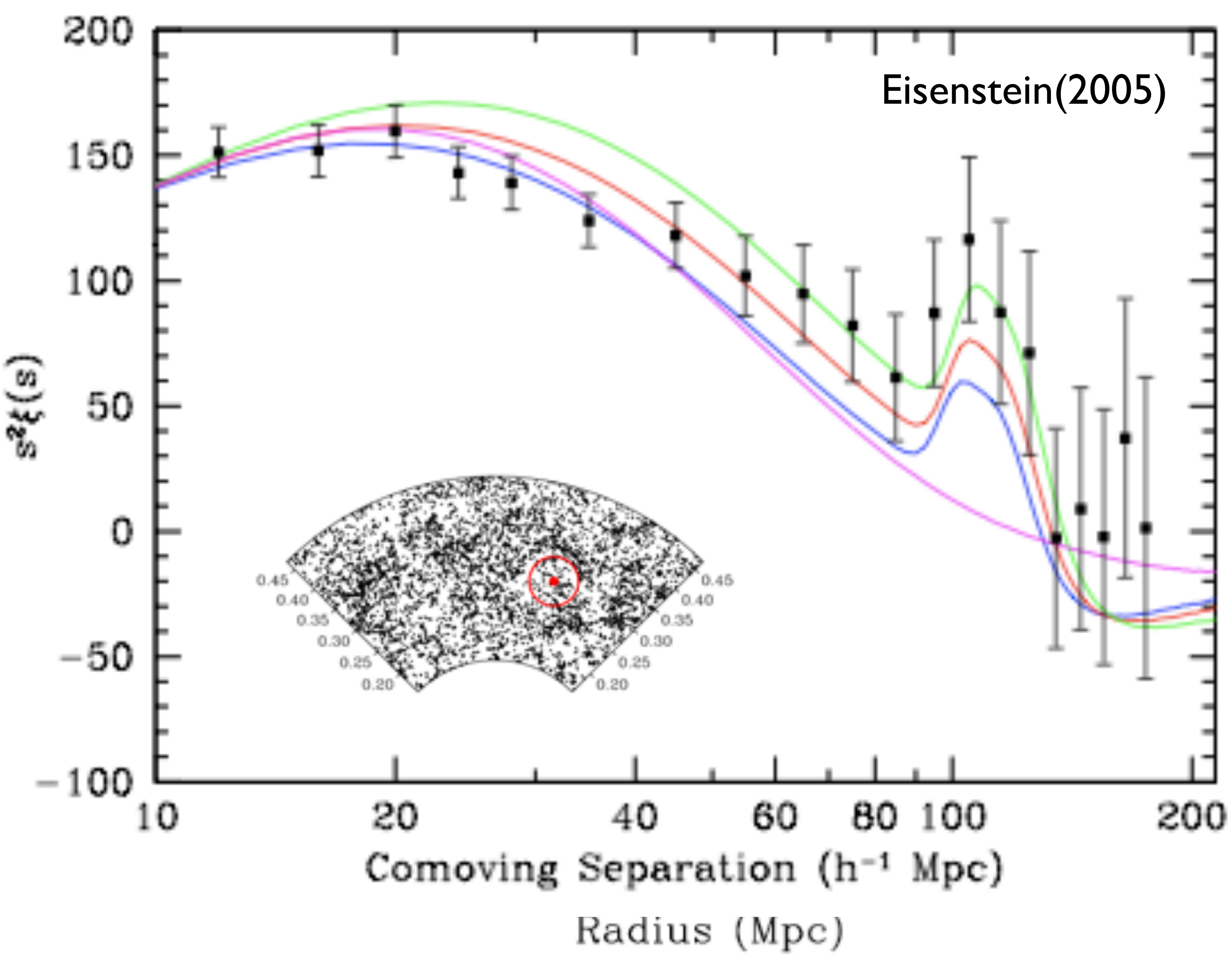


Baryonic Acoustic Oscillations III

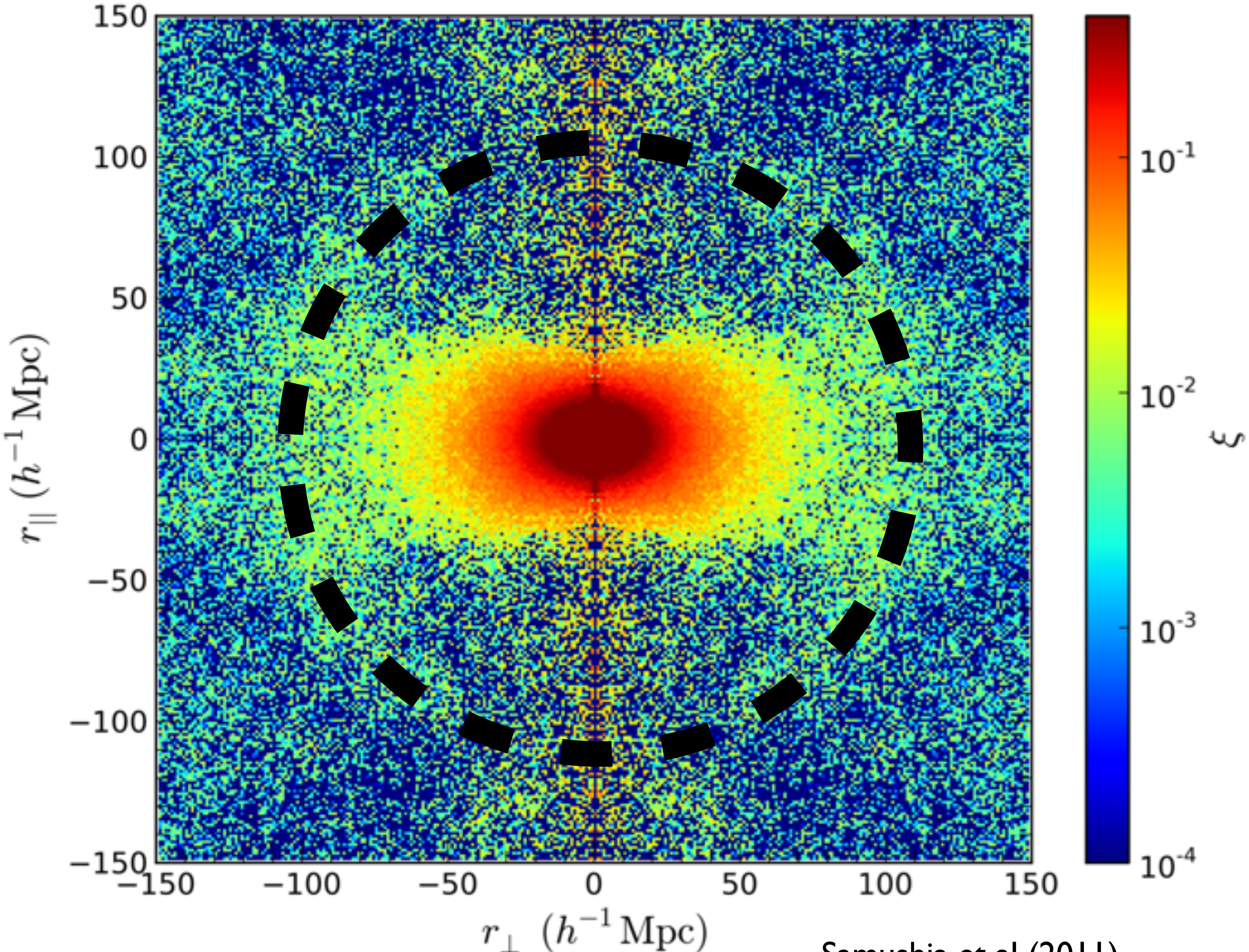


Baryonic Acoustic Oscillations (BAO) IV

BAO Detection in the correlation function of LRG Luminous Red Galaxies(2005)

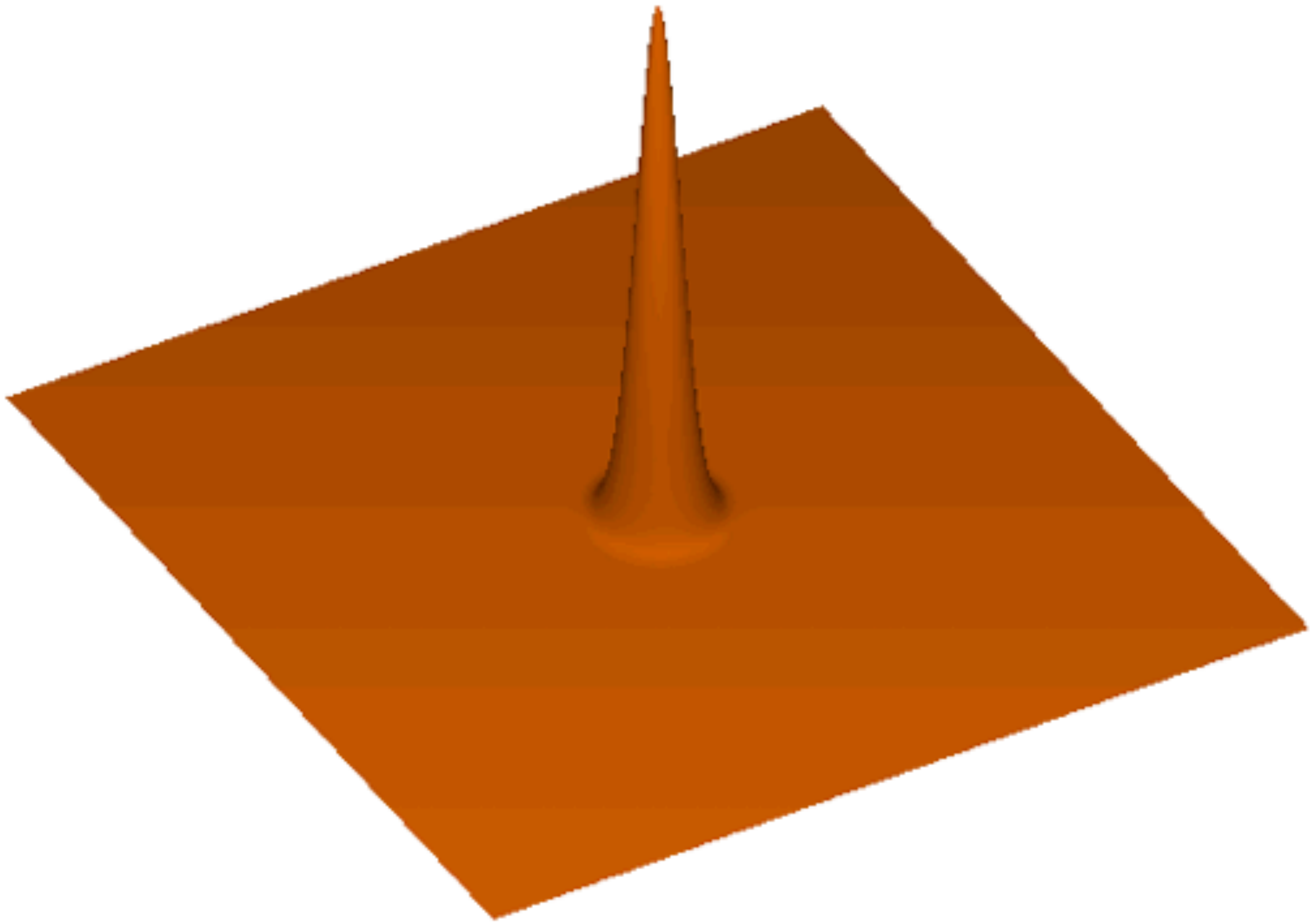


How we mesure BAO and RSD?

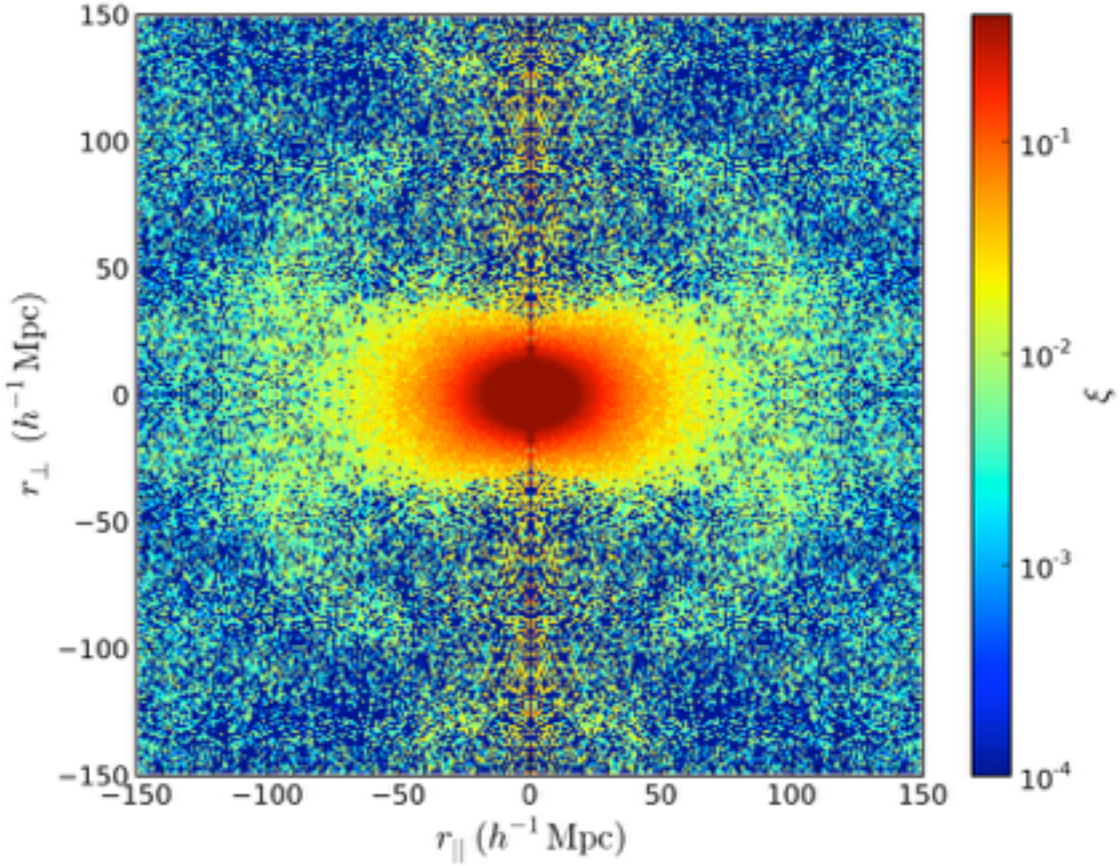


Samushia et al (2011)

Observables



BAO



Skip RSD

RSD

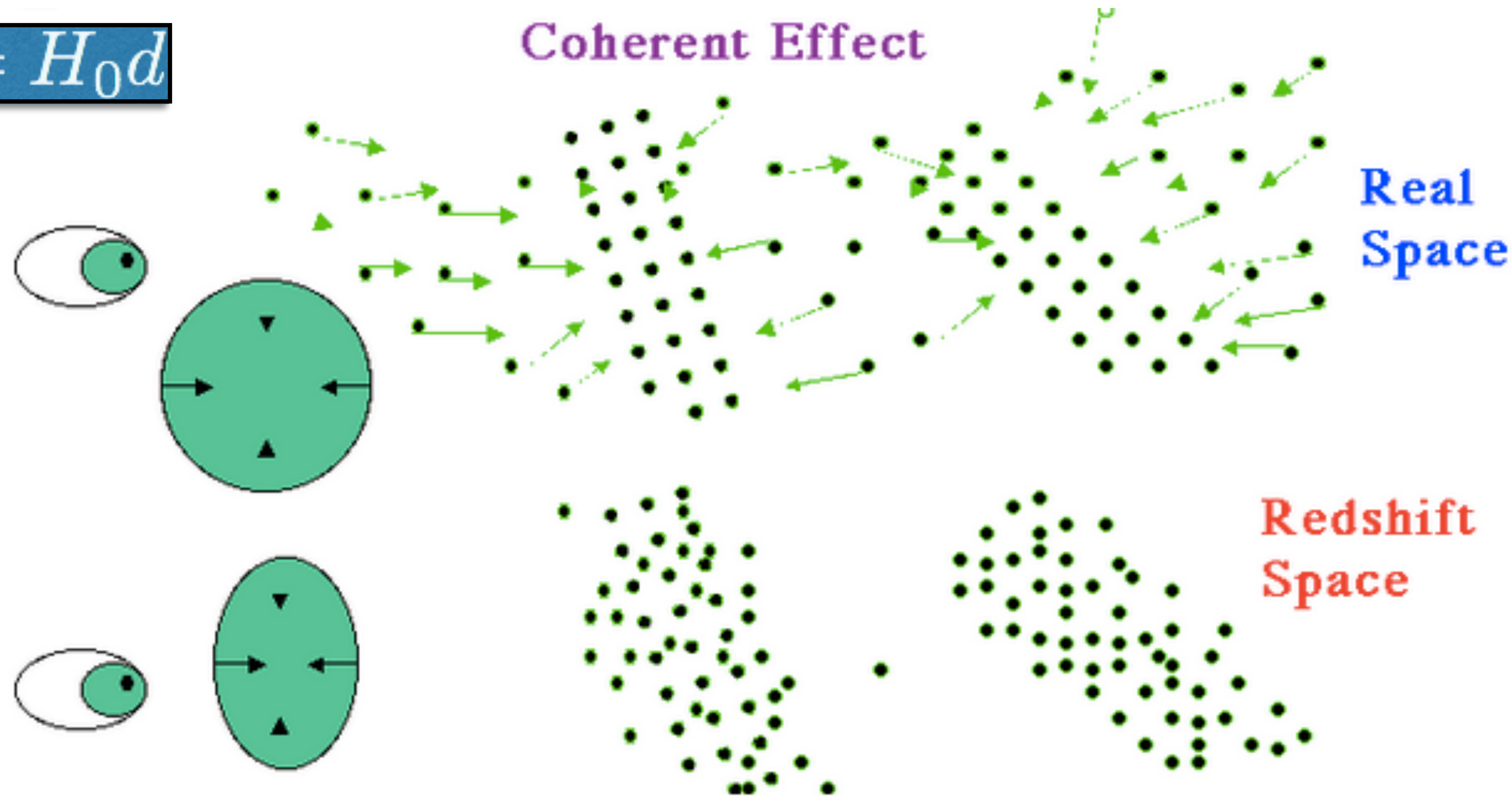
What are the RSD?

$s = cz$

$s = r + v$

Verdadera distancia

$r = H_0 d$



Redshift Space Distortions

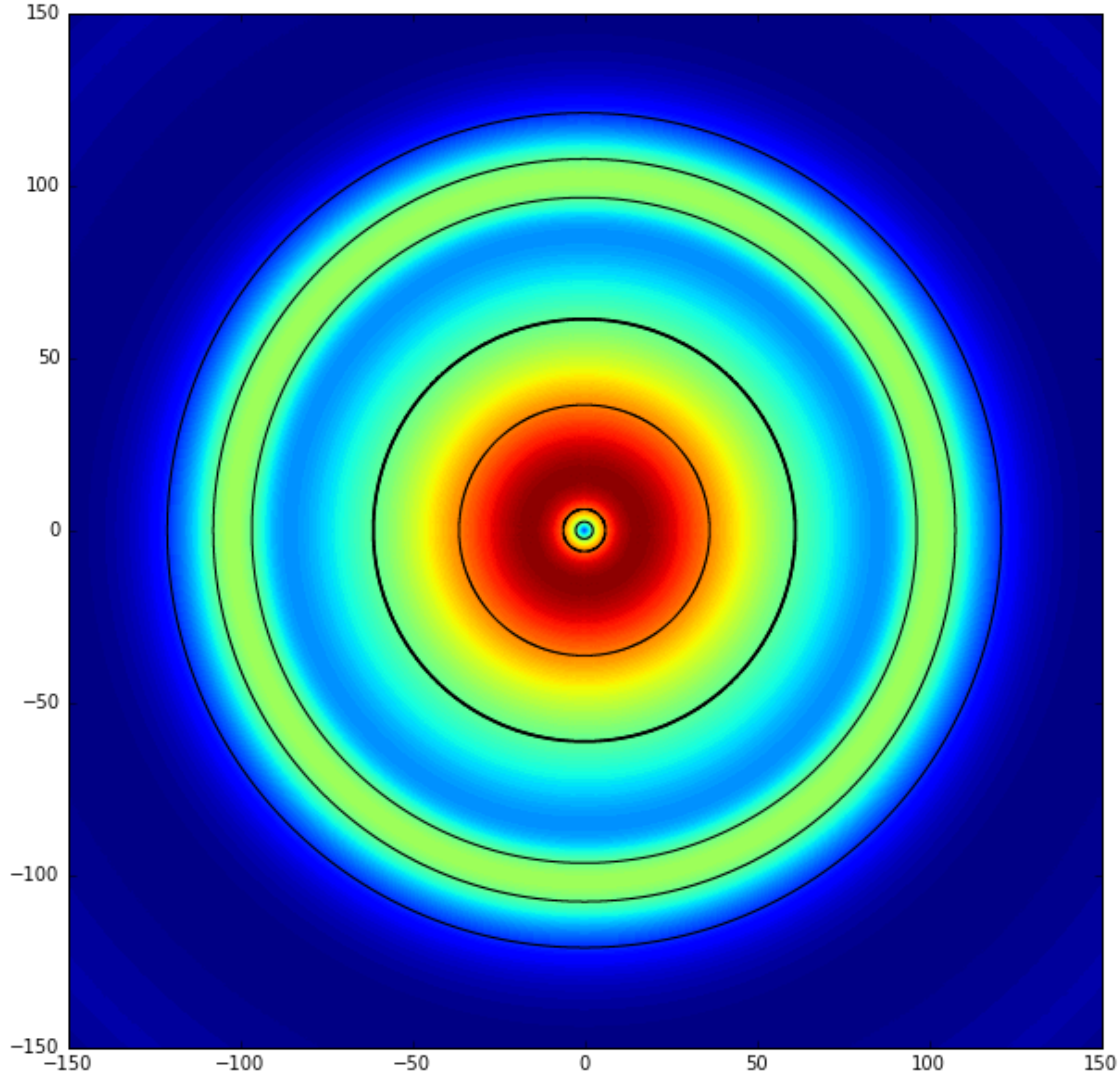
velocidad peculiar

$v = \hat{r} \cdot \vec{v}$

Real /Redshift space Correlation Functions

$$r = H_0 d$$

$$f(a) = \frac{d \ln D}{d \ln a}$$



Real /Redshift space Correlation Functions

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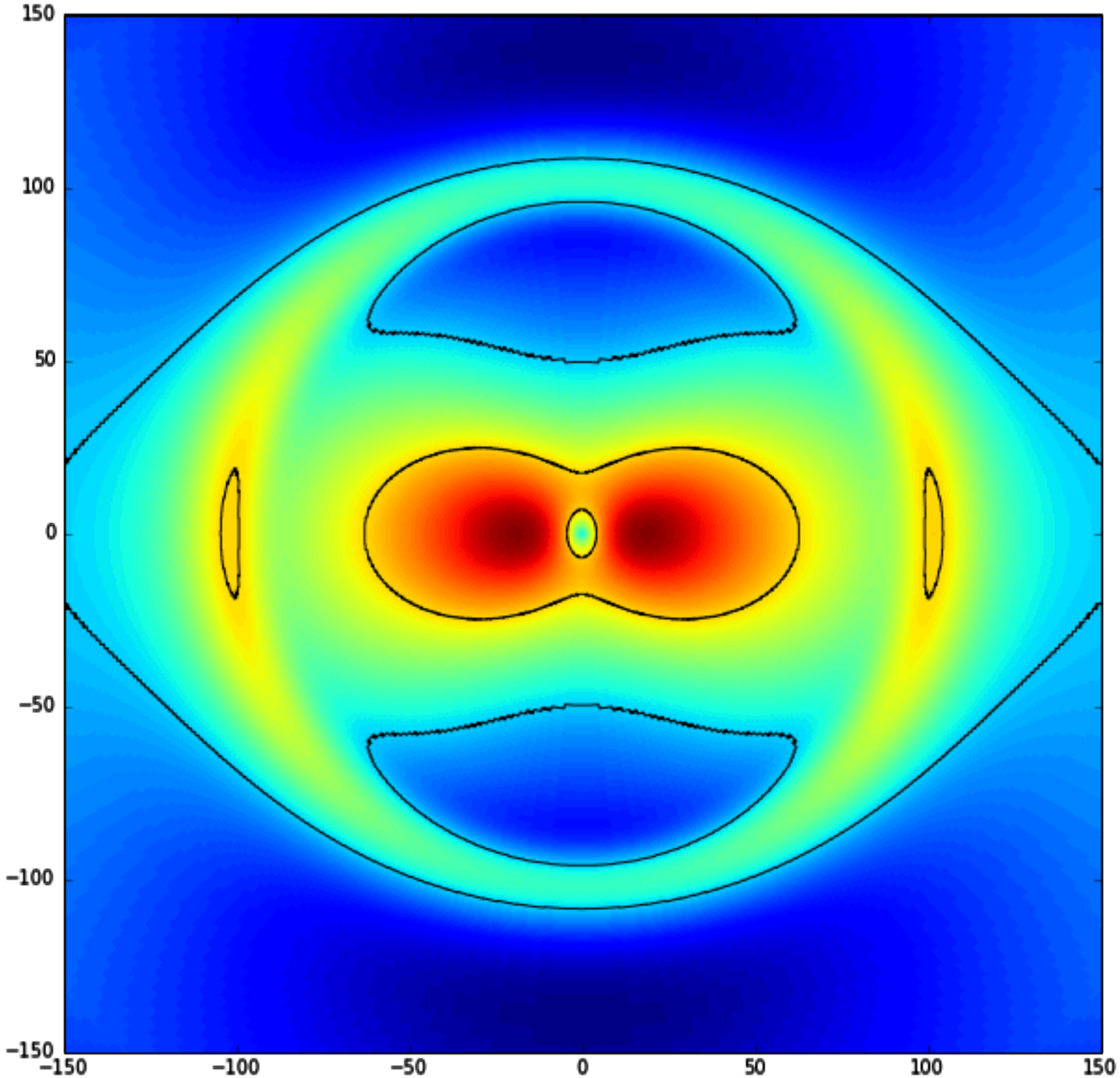
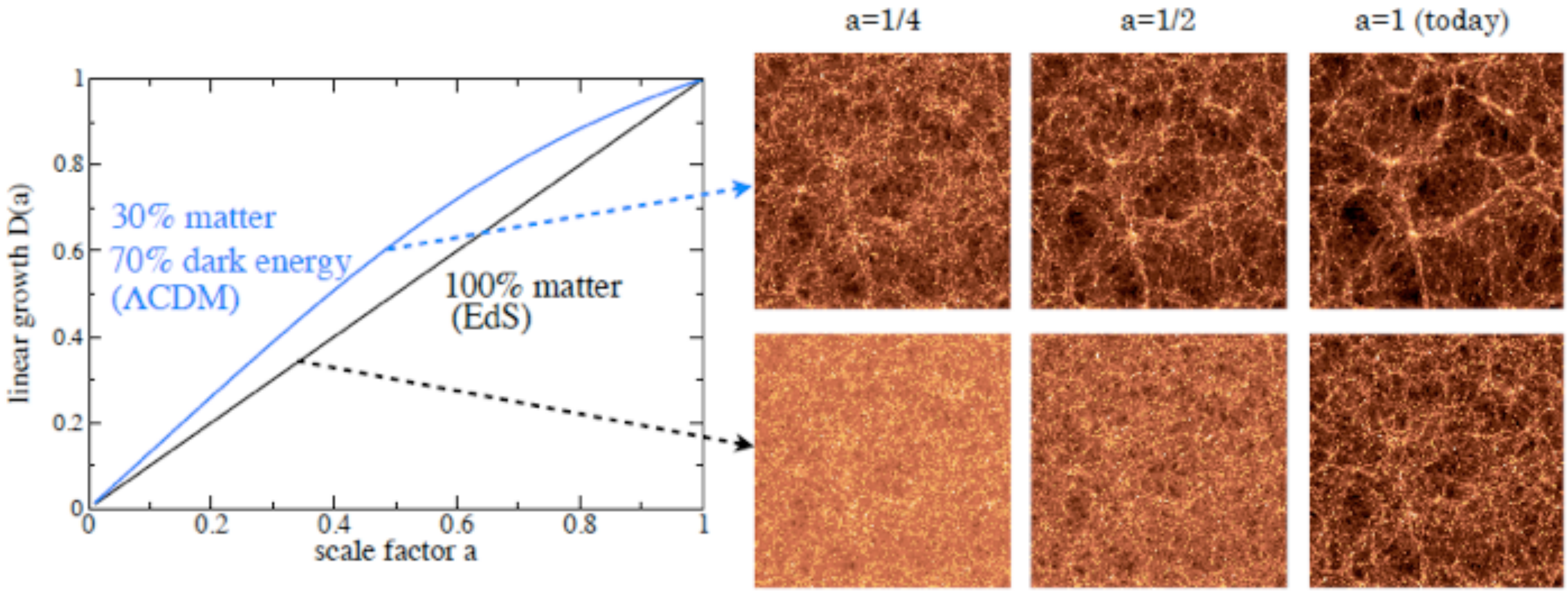


Structure Growth depends on cosmology

Structure formation at large scales

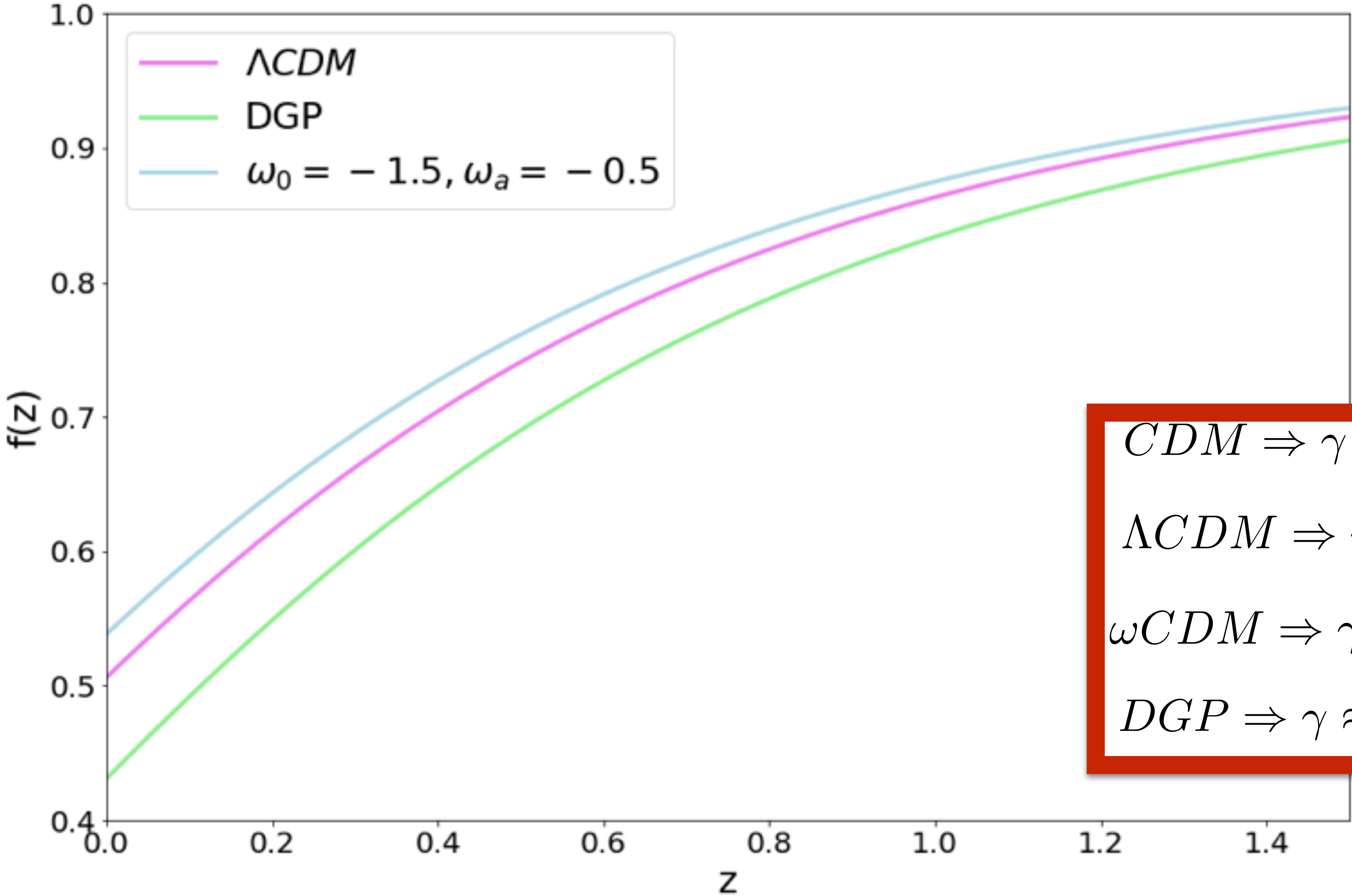


Community Planning Study: Snowmass 2013 ARXIV:1309.5385

Linear Growth D(a), D(a=1)=1

Snapshots de 2 N-body simulaciones a diferentes tiempos, muestra fluctuaciones de densidad mayores en un modelo **LCDM** comparado con un **universo dominado por materia (EdS).**

Growth factor



$$f(a) \approx \Omega_m^\gamma(a)$$

$$CDM \Rightarrow \gamma = 0.6$$

$$\Lambda CDM \Rightarrow \gamma = 0.55$$

$$\omega CDM \Rightarrow \gamma = 0.55 + 0.05[1 + \omega]$$

$$DGP \Rightarrow \gamma \approx 0.68$$

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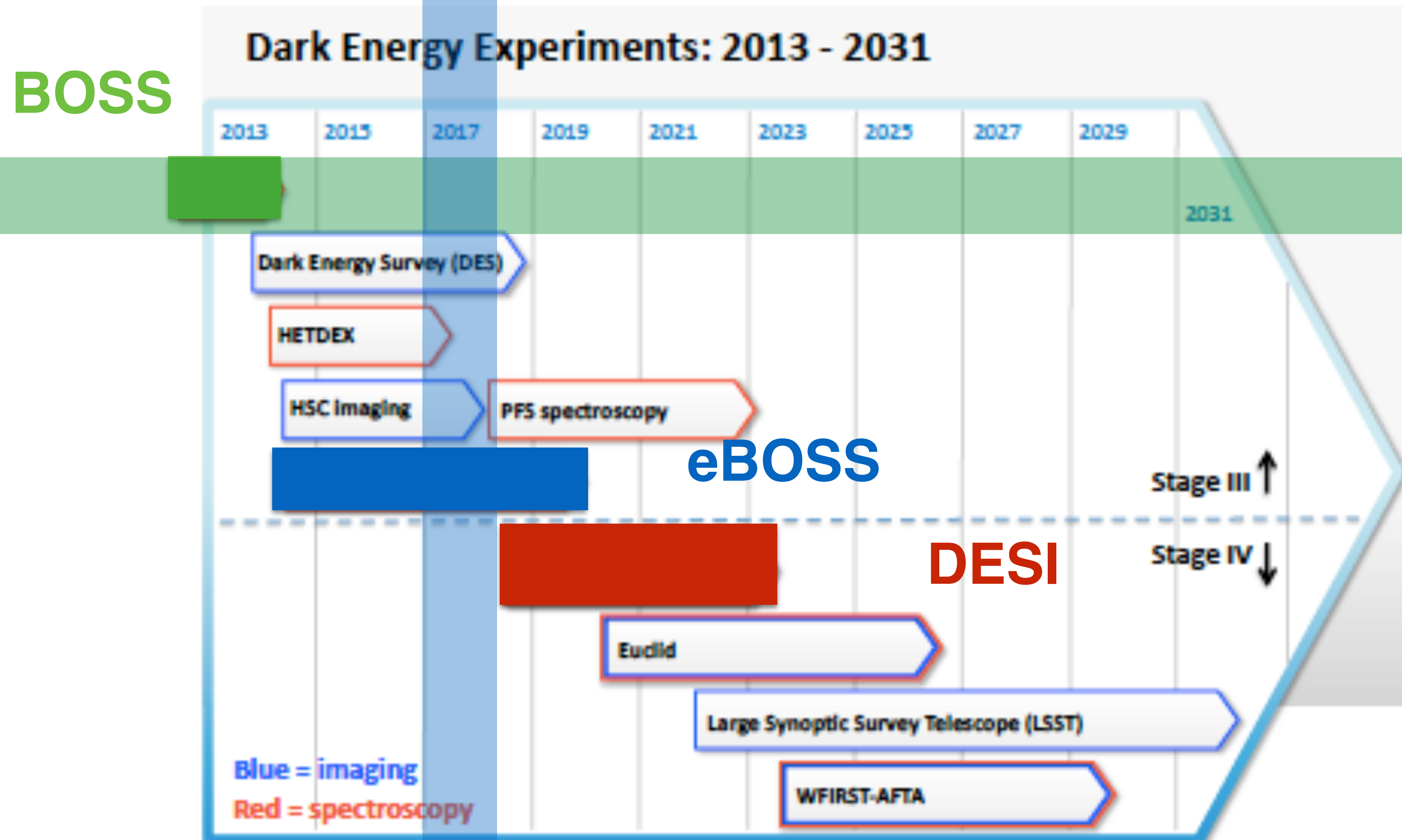
Dark Energy Experiments



Galaxy surveys

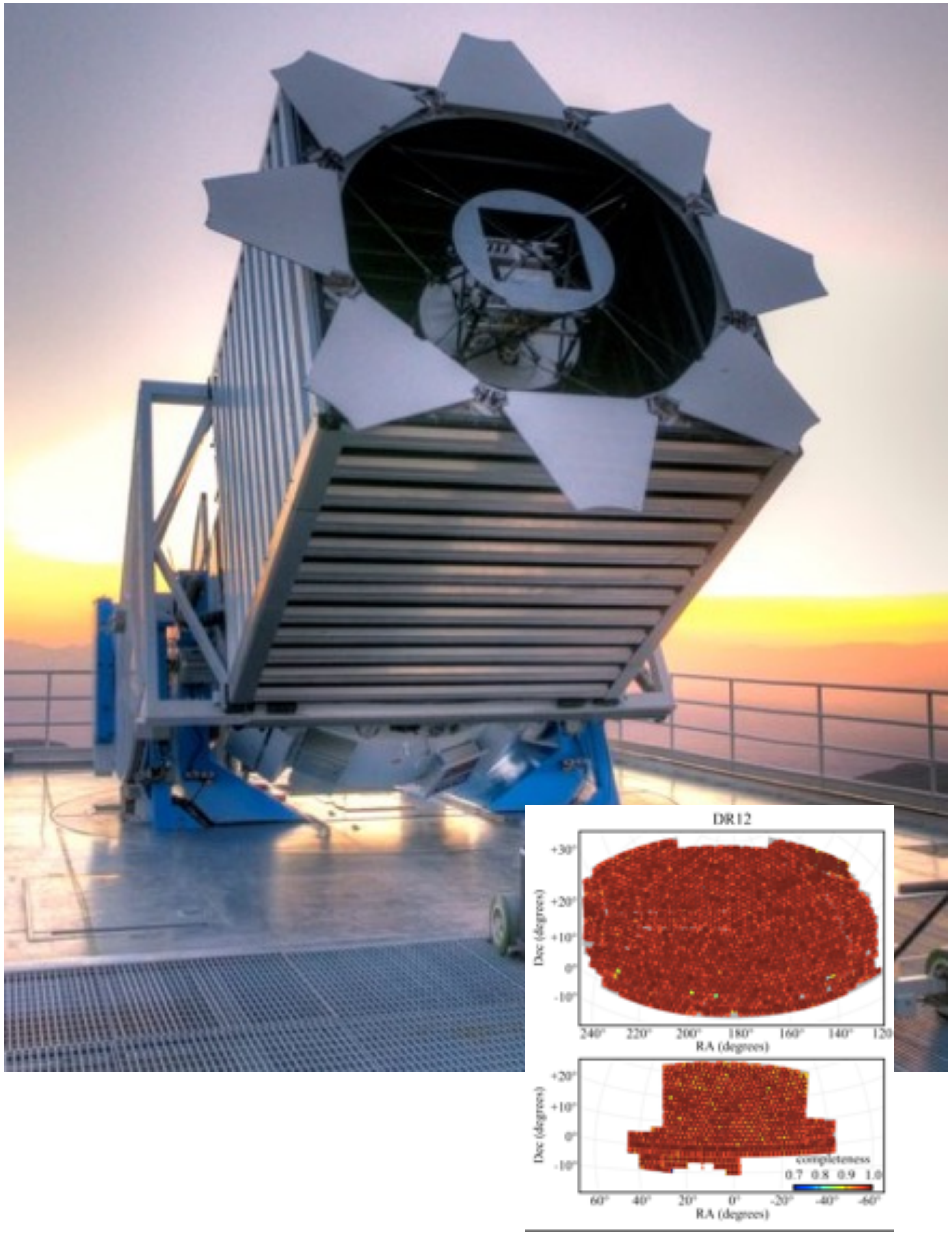
What is BOSS?

Description:

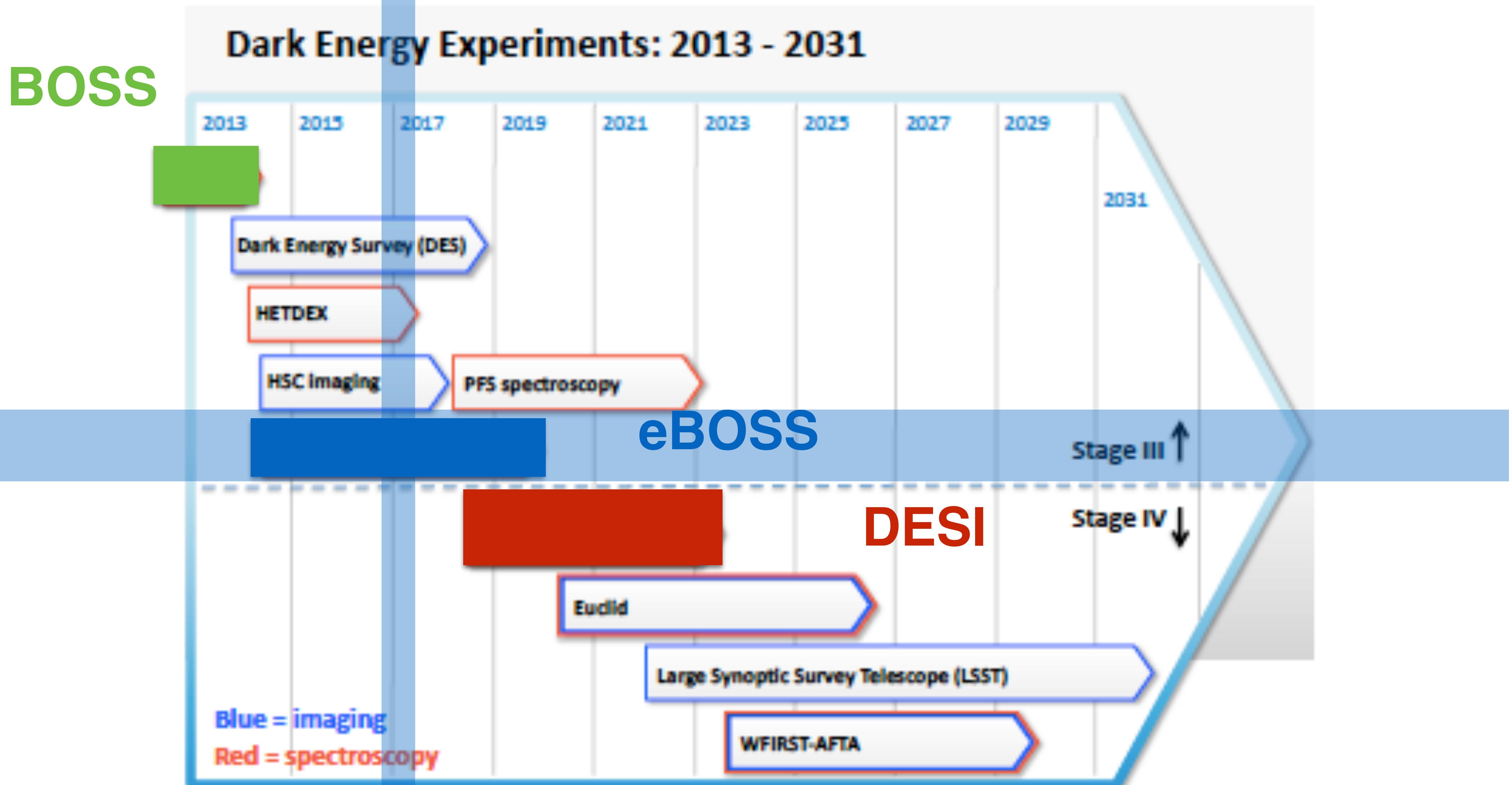
- Main SDSS-III project **(2008-2014)**
- APO telescope (New Mexico, USA), 2.5 m diameter
- Spectroscopic survey with SDSS-II photometry.
- 2 two-arms spectrographs: 1000 fibers
- 3600 Å < l < 10000 Å, $\lambda/\Delta\lambda \sim 3000$
- **1.5 Millions Luminous Red Galaxies at <z> ~ 0.6**
- **150 000 Quasars with Ly-a forests at <z> ~ 2.3**

Objectives:

- **BAO peak position 1%** at z=0.6 and 1.5% at z=2.3
- Best constraints on the Dark Energy equation of state before next generation



“Experimentos" de Energía Obscura



eBOSS

Fall 2014 - Spring 2020

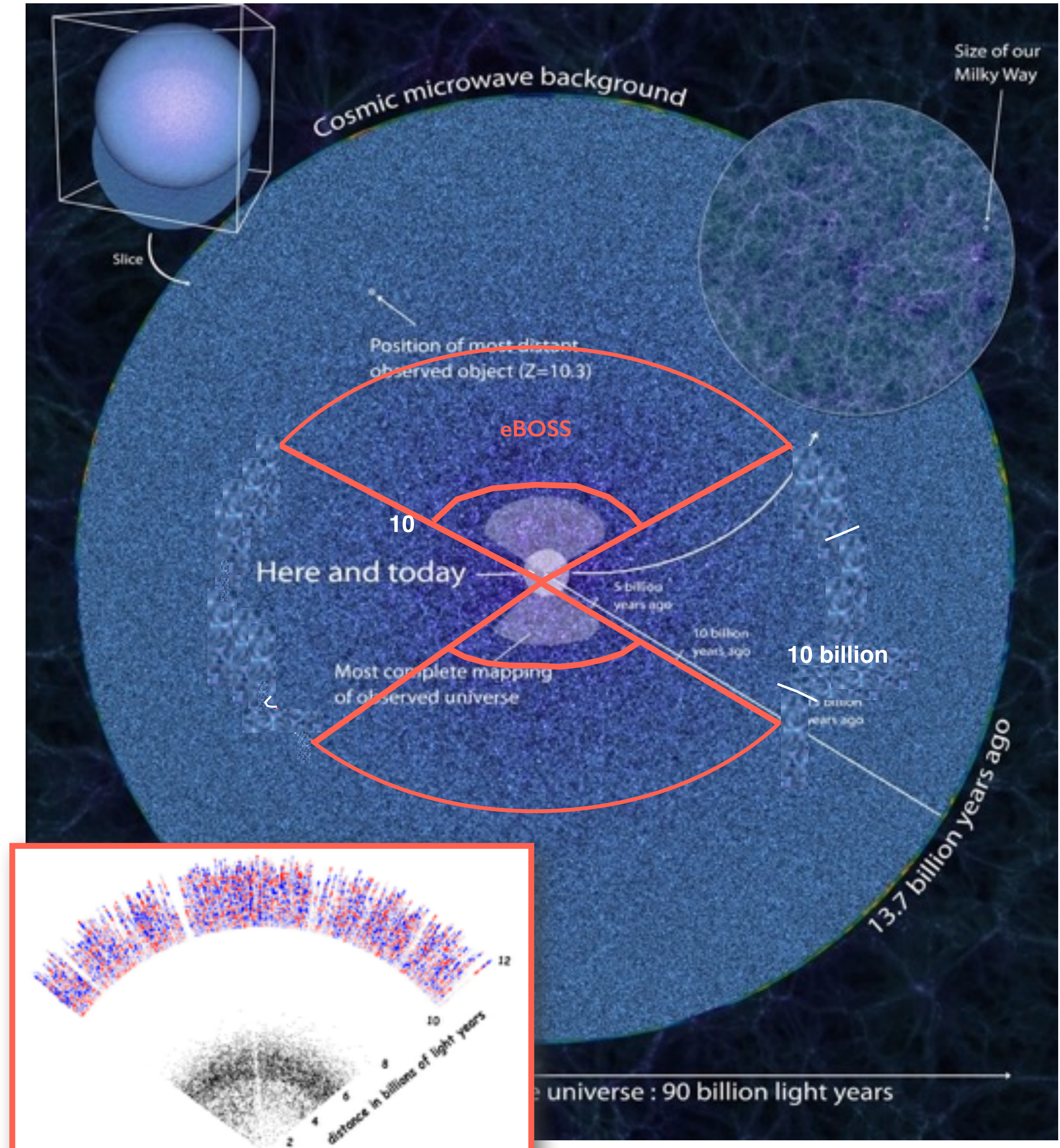
- Telescope APO 2.5m
- 1000 fibers per 7 deg2 plate, 7000 square degrees
- Wavelength: 360-1000 nm, resolution R~2000

4 different tracers within 0.6 < z < 2.2.

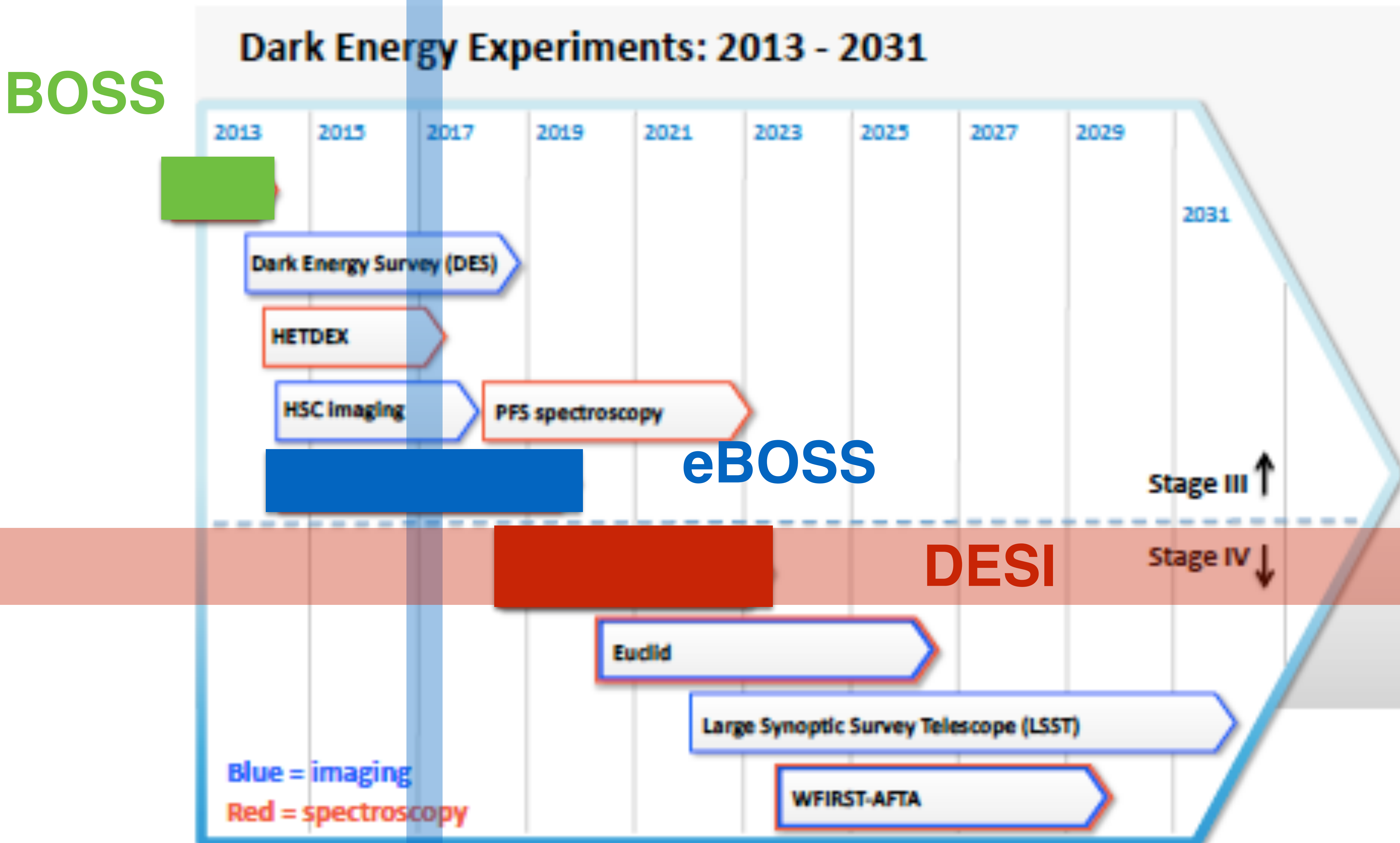
- 250,000 **LRG** over 7500 deg2, **0.6 < z < 0.8**
- **195,000 ELG over 1500 deg2, 0.6 < z < 1.0**
- **500,000 QSO over 7500 deg2, 0.9 < z < 3.5**

1-2% distance measurements from BAO between 0.6 < z < 2.5

- LRG's DA(z) 1.2% and H(z) to 2.1%
- **ELG's DA(z) 3.1% and H(z) to 4.7%.**
- **QSO DA(z) 2.8% and H(z) to 4.2%.**
- Lyα forest dA(z) and H(z) at z > 2.1 by a factor of 1.44 relative to BOSS.



“Experimentos" de Energía Obscura



DESI (2018-2022)

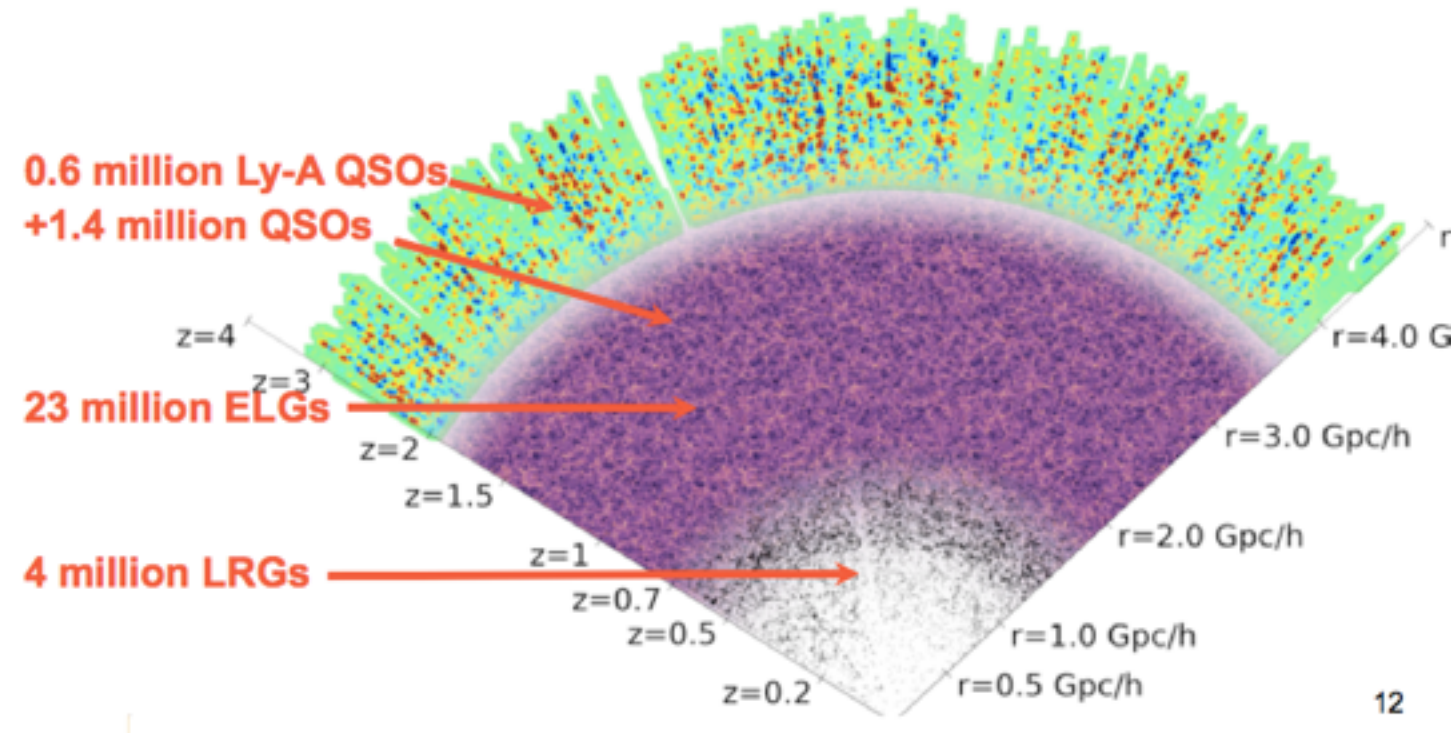
Stage-IV BAO experiment

4-m telescope Mayall Telescope, Tucson, Arizona.

14000 sq degrees.

5000 fiber-robot army

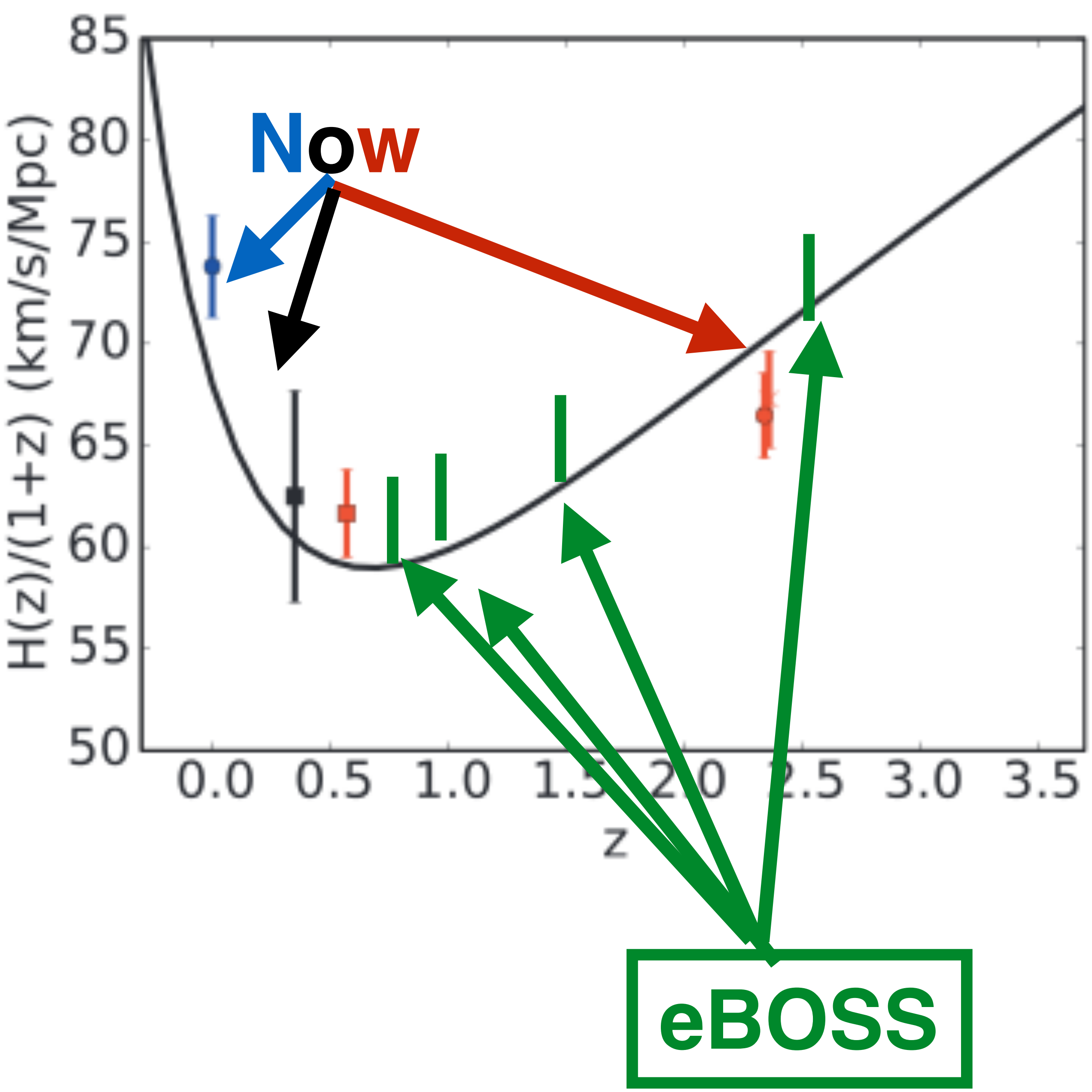
10 spectrographs x 3 cameras

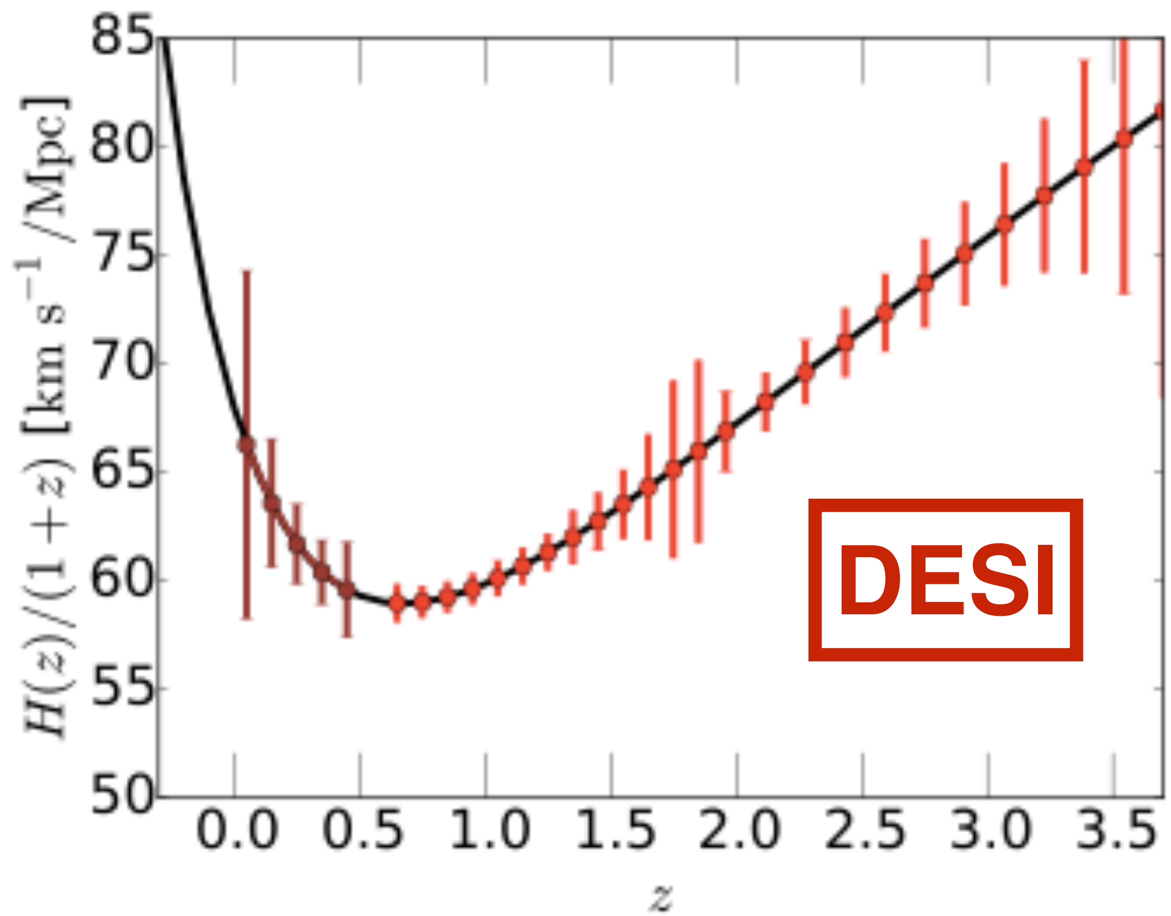


Object Class	Number of Spectra	Redshift Range
bright galaxies, $r < 19.5$	10 million	$0 < z < 0.4$
luminous red galaxies (LRGs)	4.2 million	$0.4 < z < 1.0$
emission line galaxies (ELGs)	18 million	$0.6 < z < 1.6$
quasars (QSOs)	2.4 million	$0.5 < z < 3.5$
Milky Way stars	10 million	---

- Survey Validation: July 2019-Nov 2019 Survey Start: Nov 2019

BAO constrains



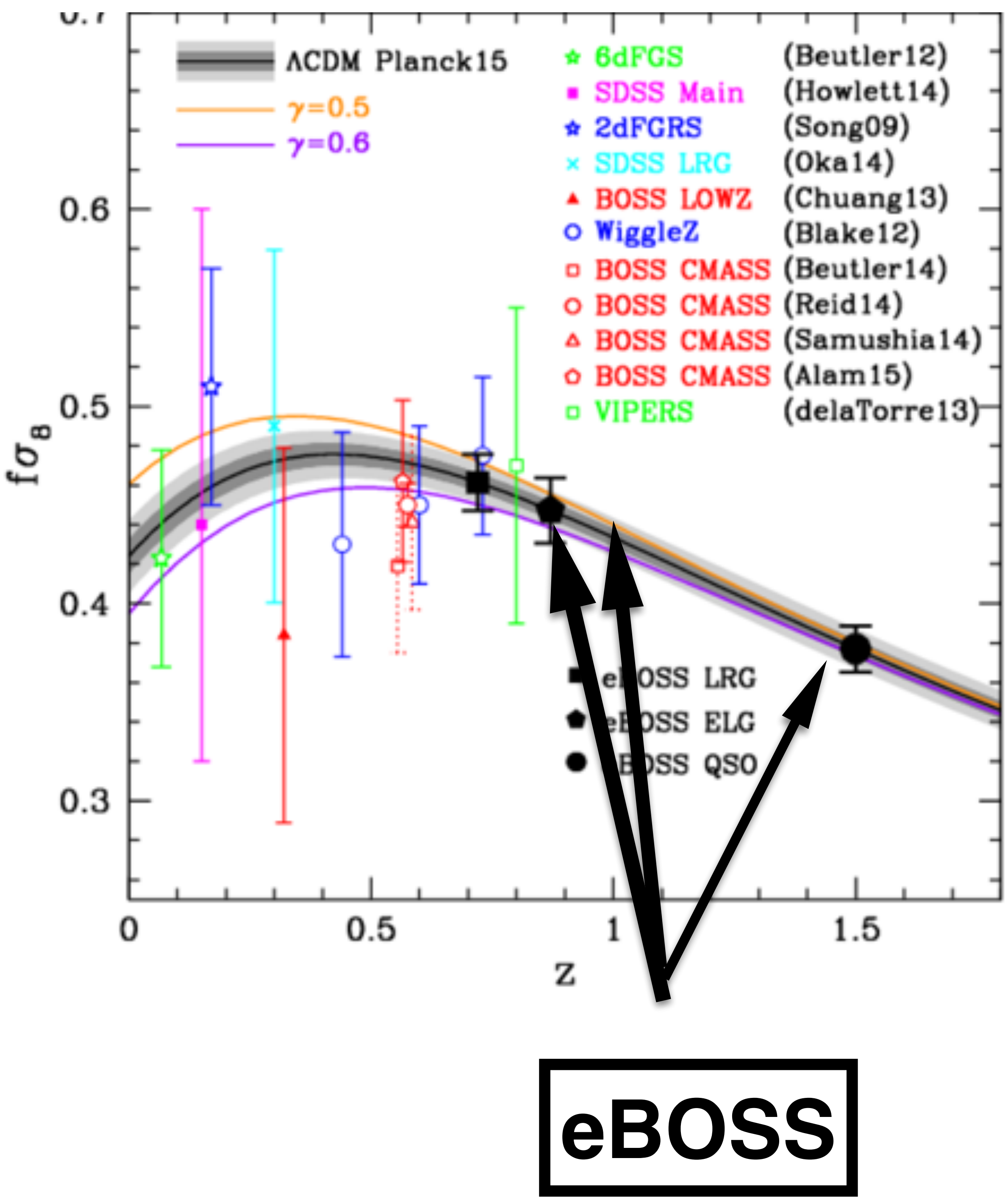


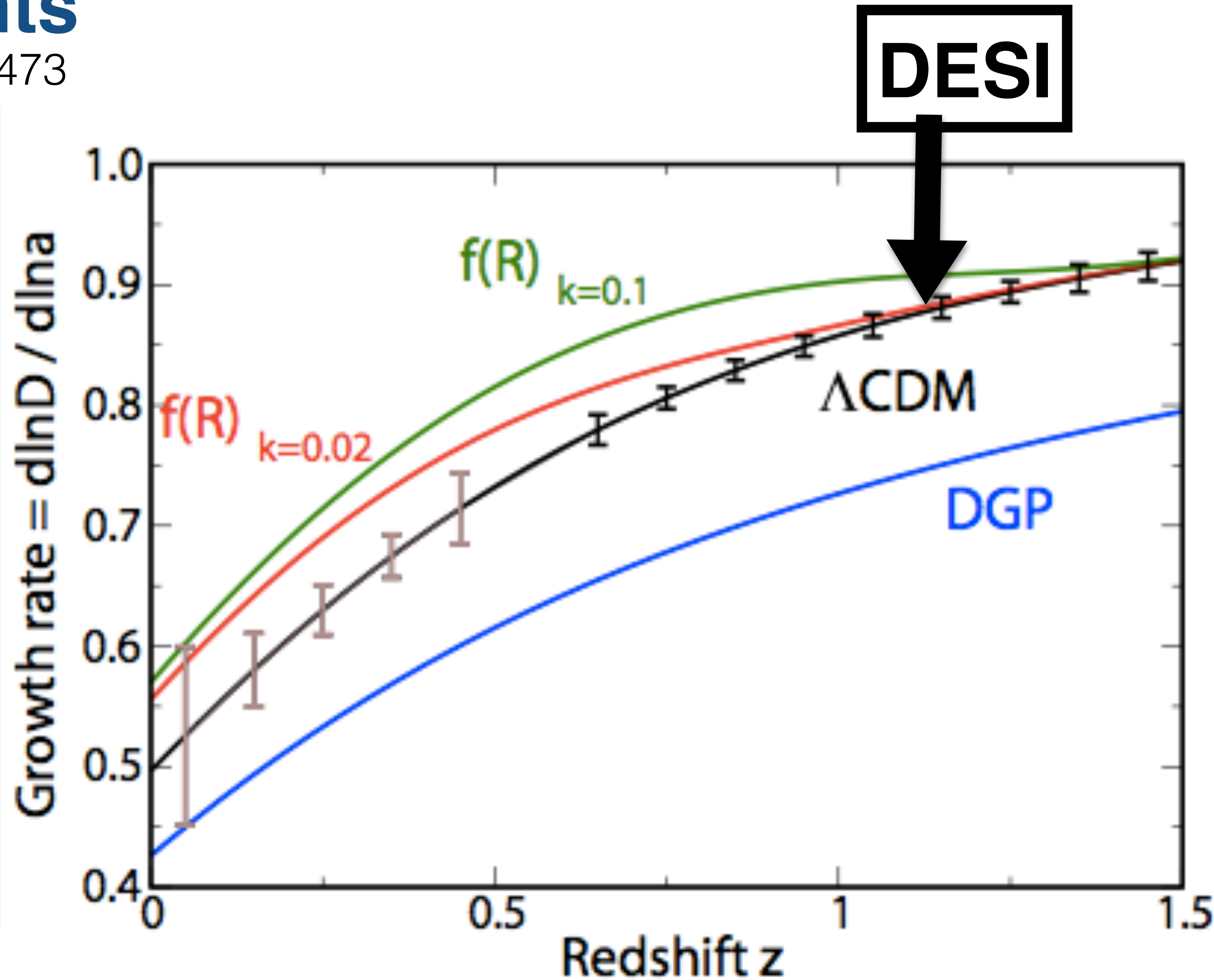
DESI, Conceptual Design Report (2014)

RSD constrains

Current Measurements

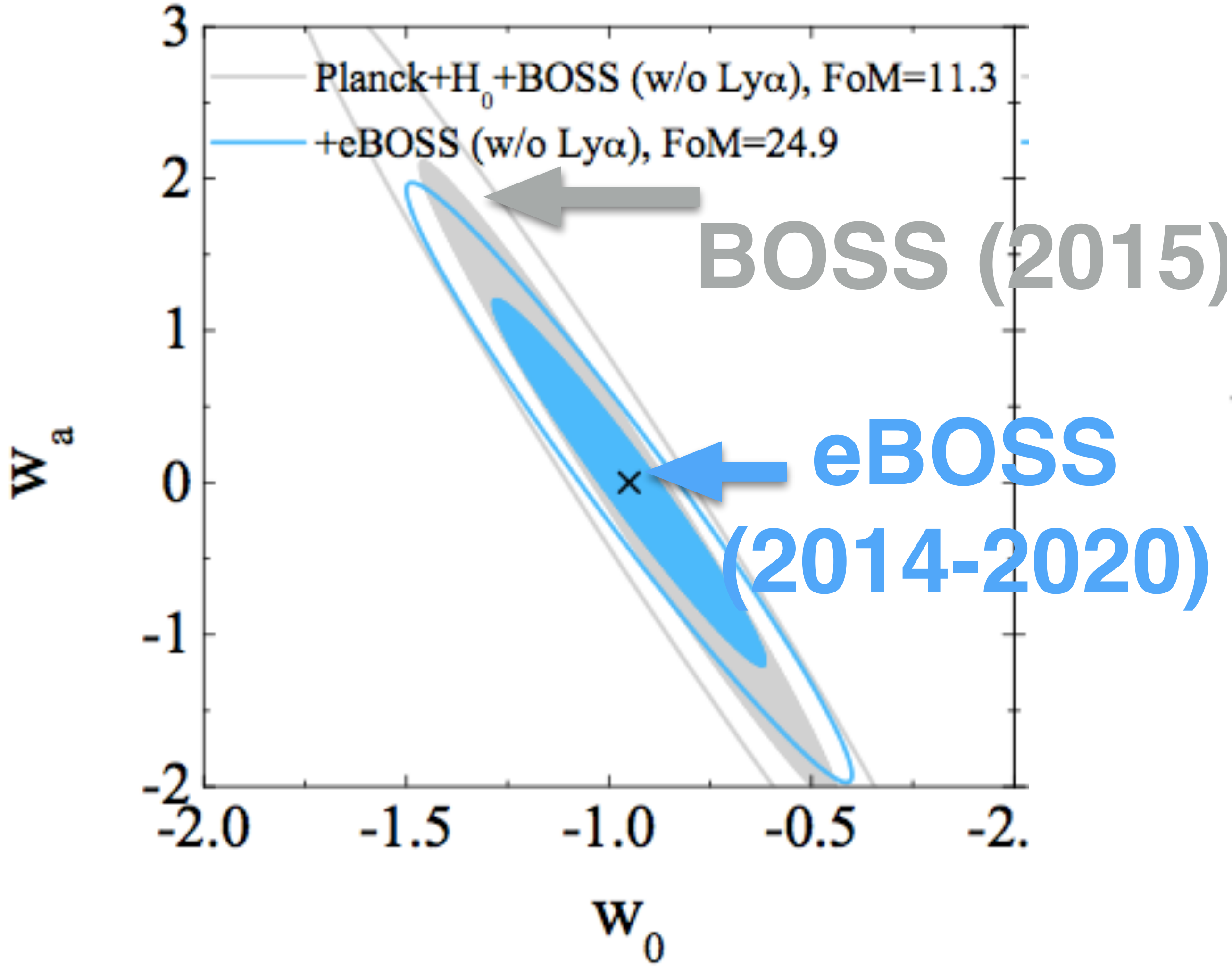
K.Dawson et al 2015, eBOSS arXiv:1508.04473





eBOSS Forecast on DE

DESI, Conceptual Design Report (2014)



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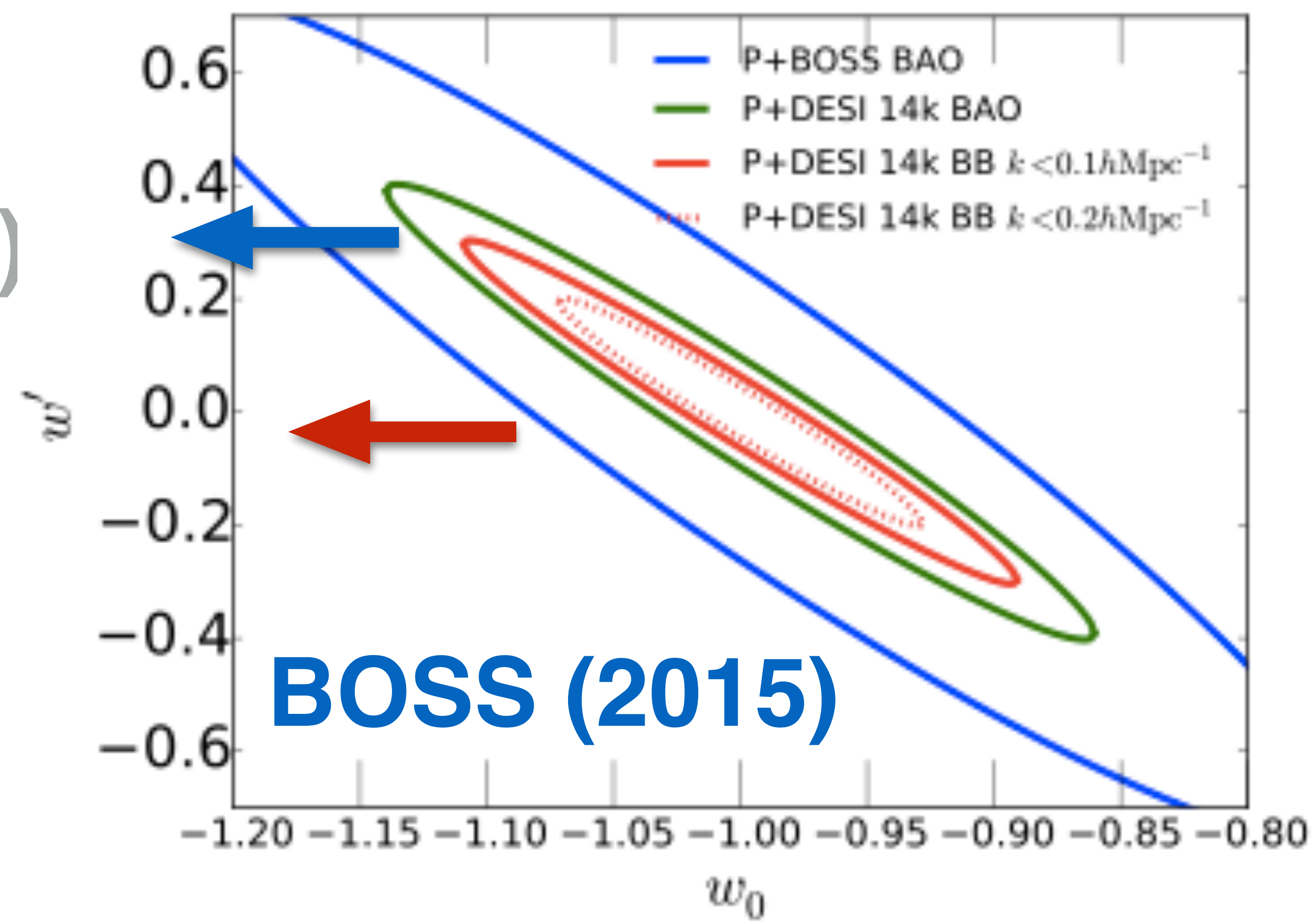
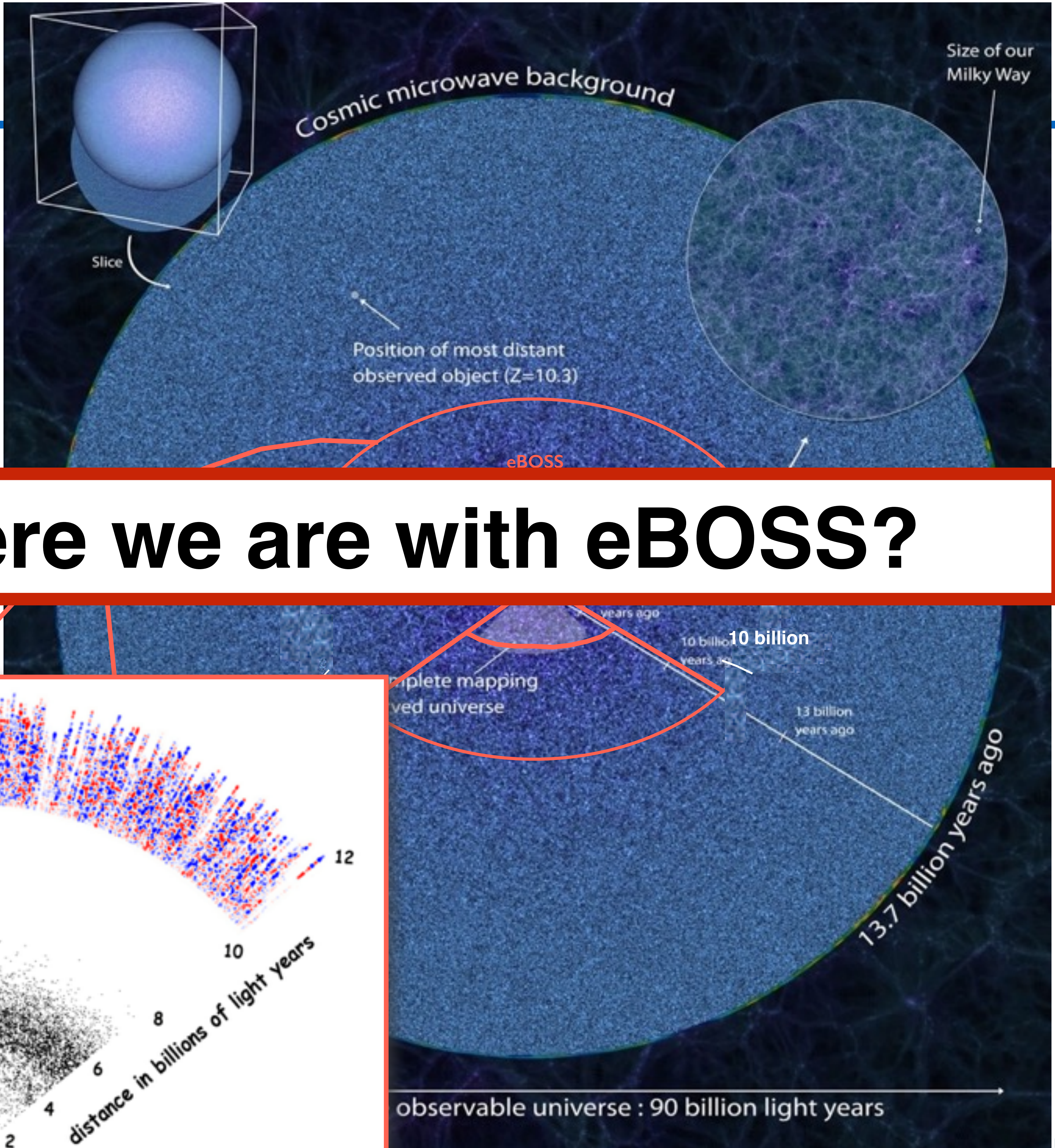
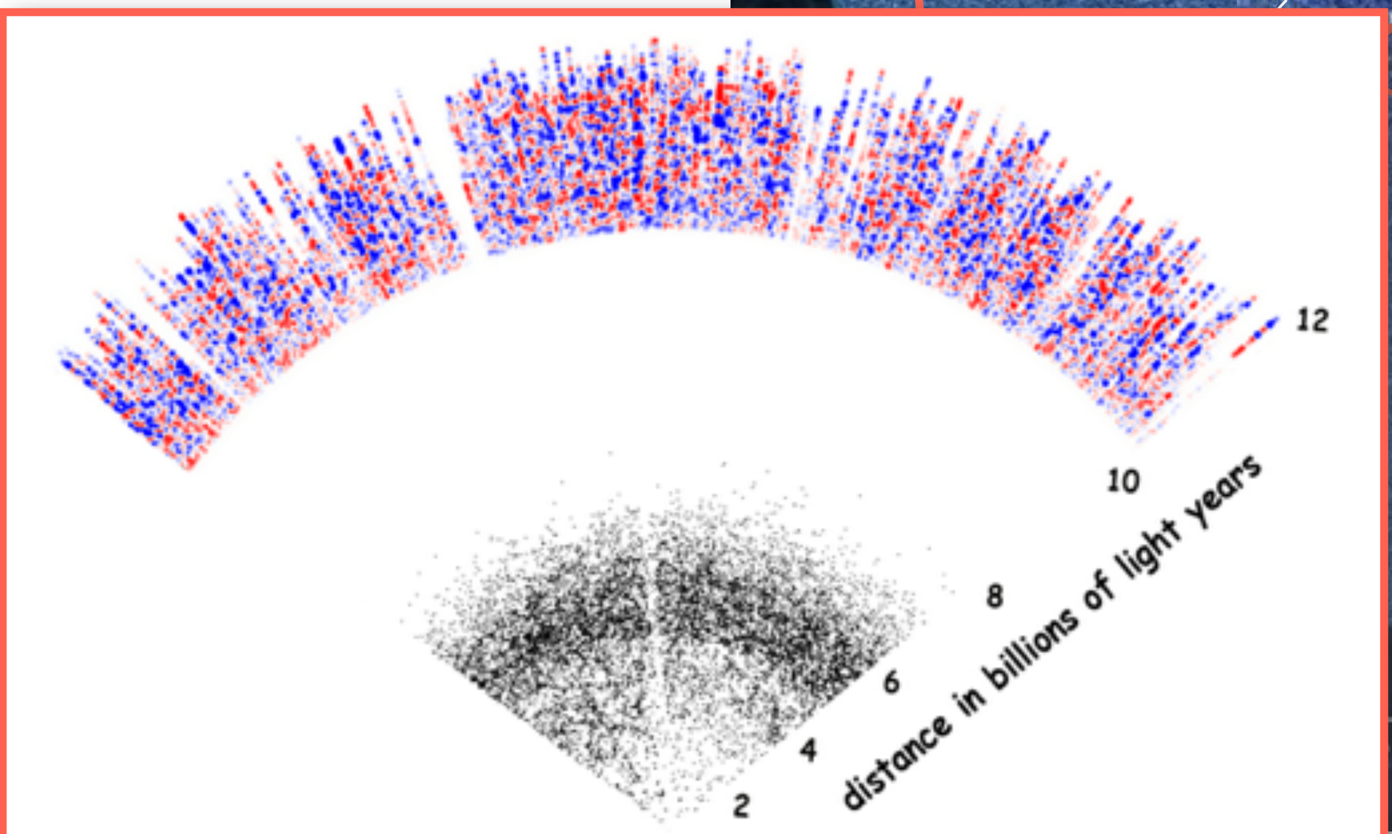


DESI (2018-2022)



Where we are with eBOSS?



Predictions for eBOSS

Table 9

expected for each eBOSS sample, together with predictions for the effective volumes and fractional const distance measurements and growth of structure.

Sample	Epoch	Area (deg^{-2})	σ_H/H	σ_{D_A}/D_A	σ_R/R	$\sigma_{f\sigma_8}/f\sigma_8$
LRG	year 2	2790	0.032	0.017	0.012	0.040
	year 4	4185	0.026	0.015	0.010	0.034
	year 6	6975	0.021	0.012	0.008	0.026
ELG (High Density DECam)	year 4	1100	0.047	0.031	0.020	0.038
Quasar	year 2	3000	0.066	0.043	0.028	0.050
	year 4	4500	0.054	0.036	0.023	0.041
	year 6	7500	0.042	0.028	0.018	0.032
BOSS Lyα Quasars		10,400	0.02	0.025	–	–
BOSS + eBOSS	year 2	3000	0.017	0.021	–	–
Lyα Quasars	year 4	4500	0.016	0.020	–	–
	year 6	7500	0.014	0.017	–	–

K.Dawson et al 2015, eBOSS arXiv:1508.04473

The third and fourth years will be split evenly between observations of ELG plates and observations of the LRG and quasar plates.

The final two years will be dedicated entirely to the LRG and quasar targets

Current status of eBOSS

Five distinct regions of sky (denoted ebossN, where N is a number ranging from 1 – 5) were tiled in the first year of eBOSS.

K.Dawson et al 2015, eBOSS arXiv:1508.04473

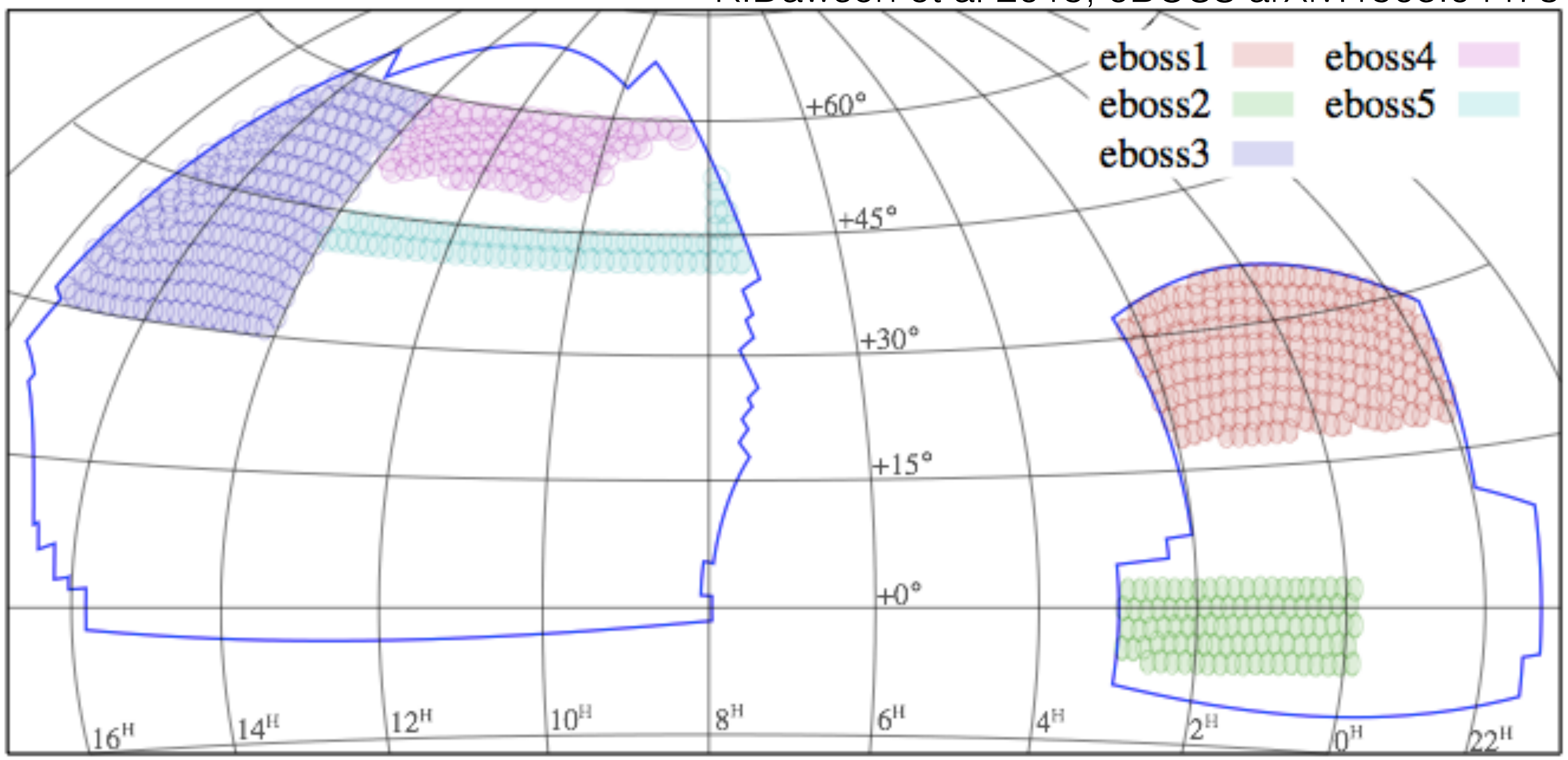


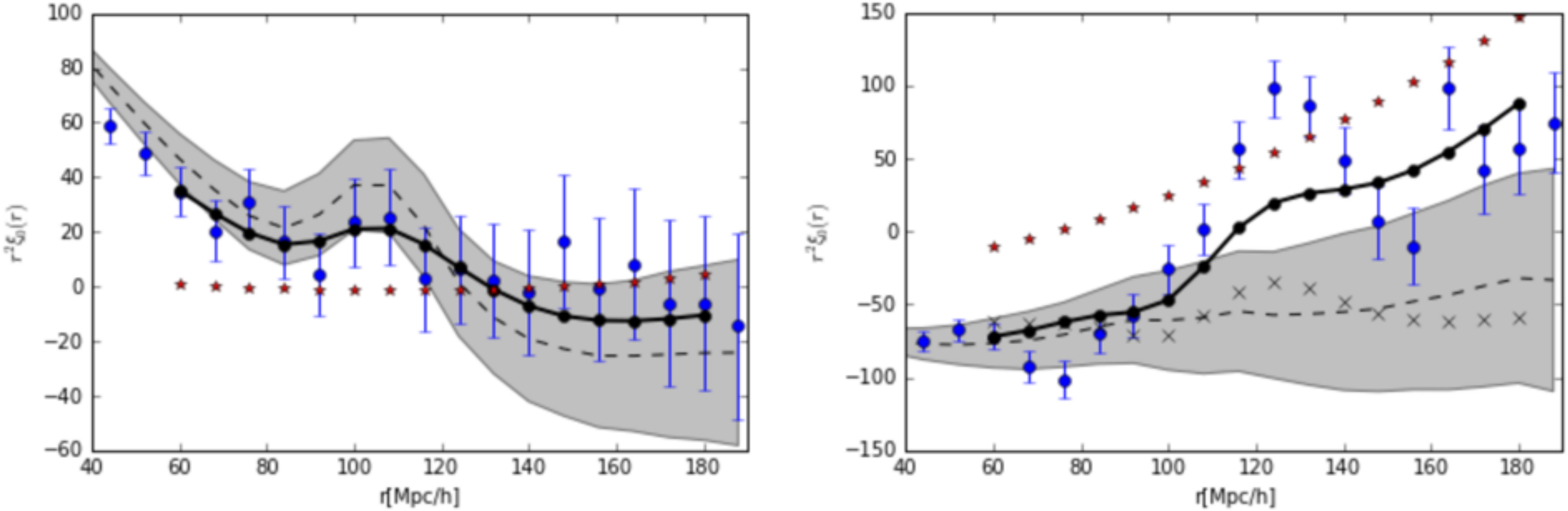
Figure 3. Field centers for eboss[1–5]. The SEQUELS area is clearly defined by white space between the boundaries of eboss4 and eboss5. The area covered here is the area that was tiled in the beginning of SDSS-IV and the approximate survey area expected to be completed in the first two years of observation.

Skip

The first two years of observation will be dedicated **almost exclusively to LRG and QSO.** After two years, approximately 600 plates should be completed for the LRG and quasar targets, producing a sample comparable in area to the DR9 CMASS cosmology sample.

LRG v1.8

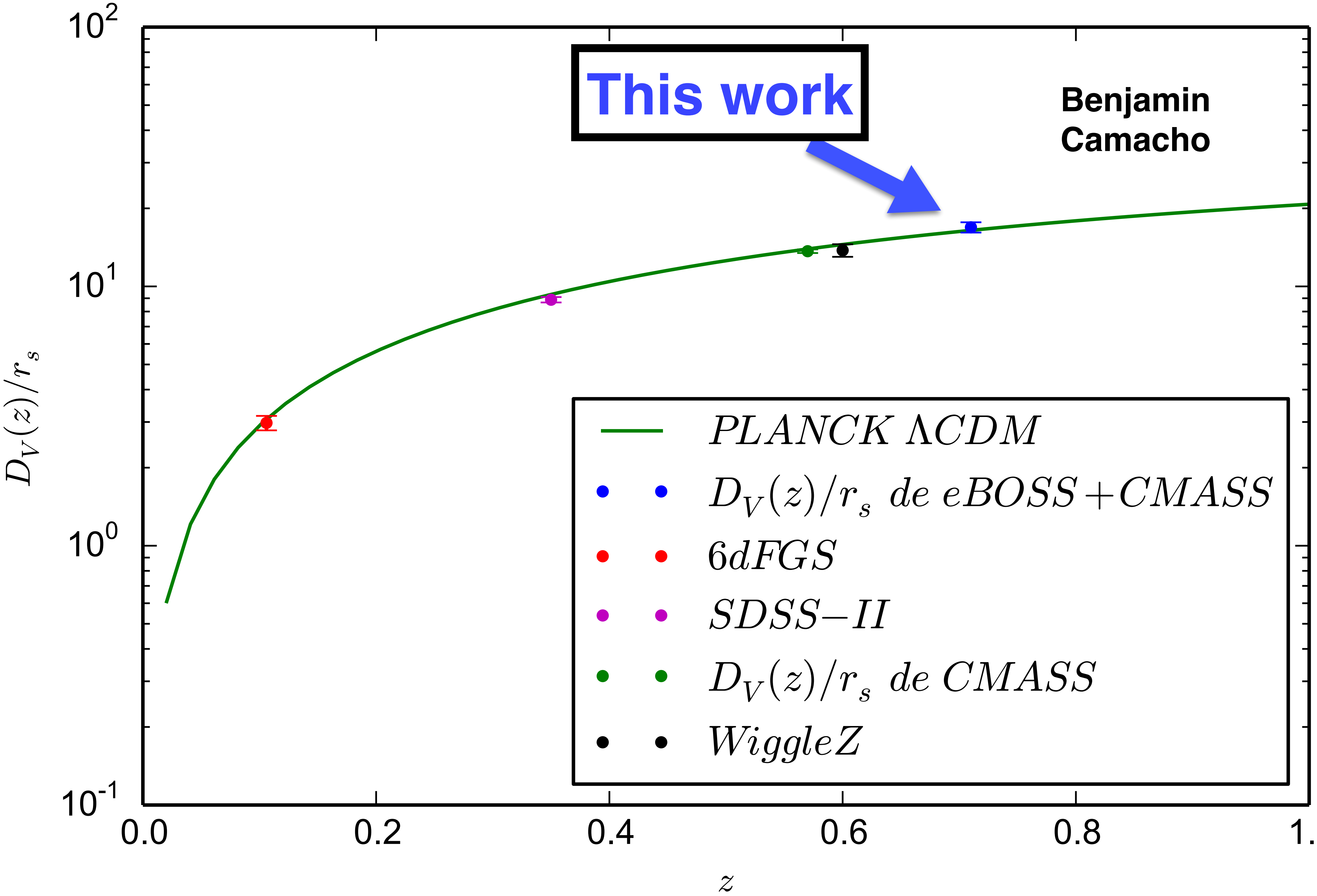
Pre-construction Anisotropic Results.



$$\chi^2 = 34.9,\ \alpha = 0.961,\ \epsilon = -0.065$$

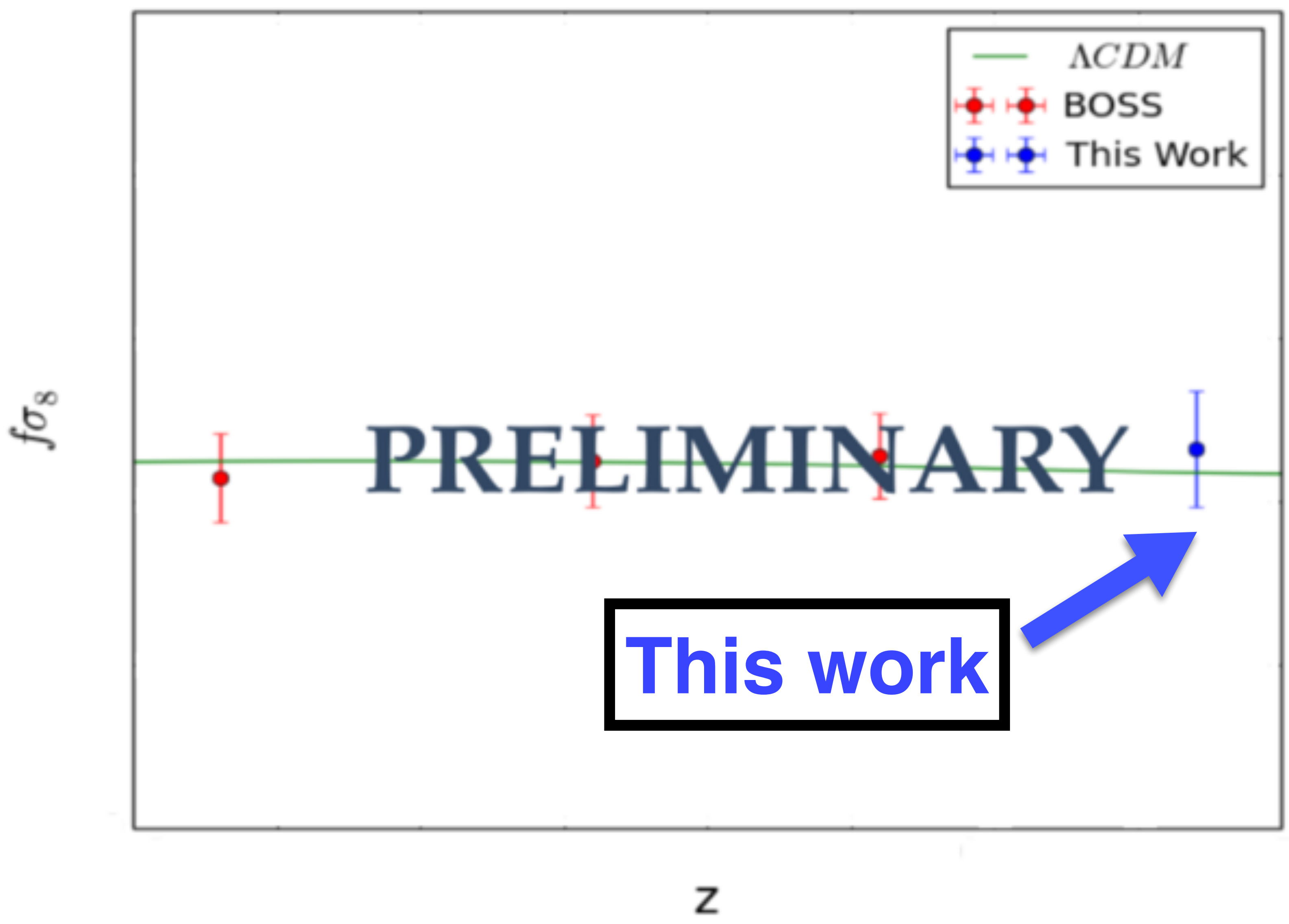
Fitting range =[60,185], (16x2)32 bins-10 parameters=22 d.o. f.

Dv(z)

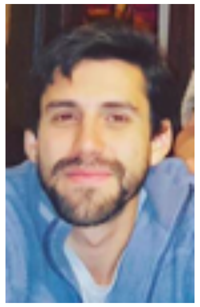


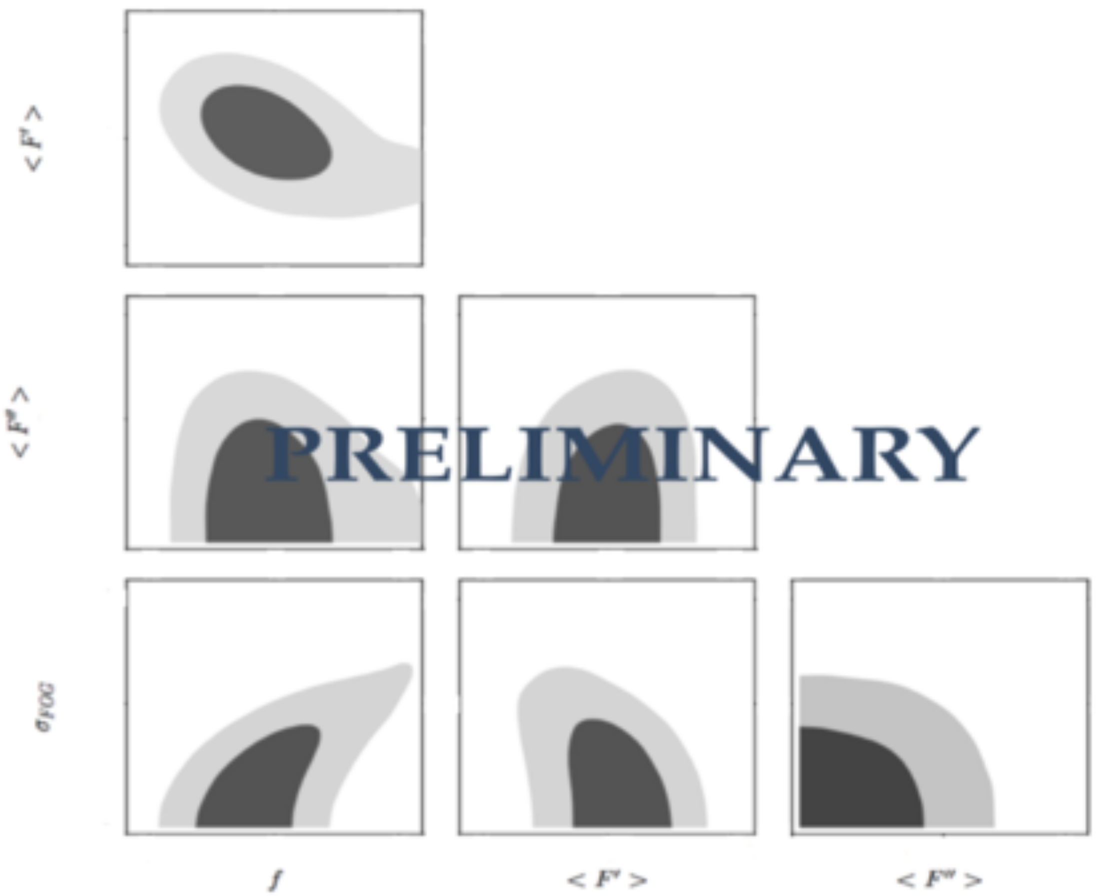
This work
Benjamin Camacho
$D_V(z)/r_s$
z
10^2
10^1
10^0
10^{-1}
0.0
0.2
0.4
0.6
0.8
1.0
$PLANCK\ \Lambda CDM$
$D_V(z)/r_s$ de $eBOSS+CMASS$
$6dFGS$
$SDSS-II$
$D_V(z)/r_s$ de $CMASS$
$WiggleZ$

RSD Project with LRG´s

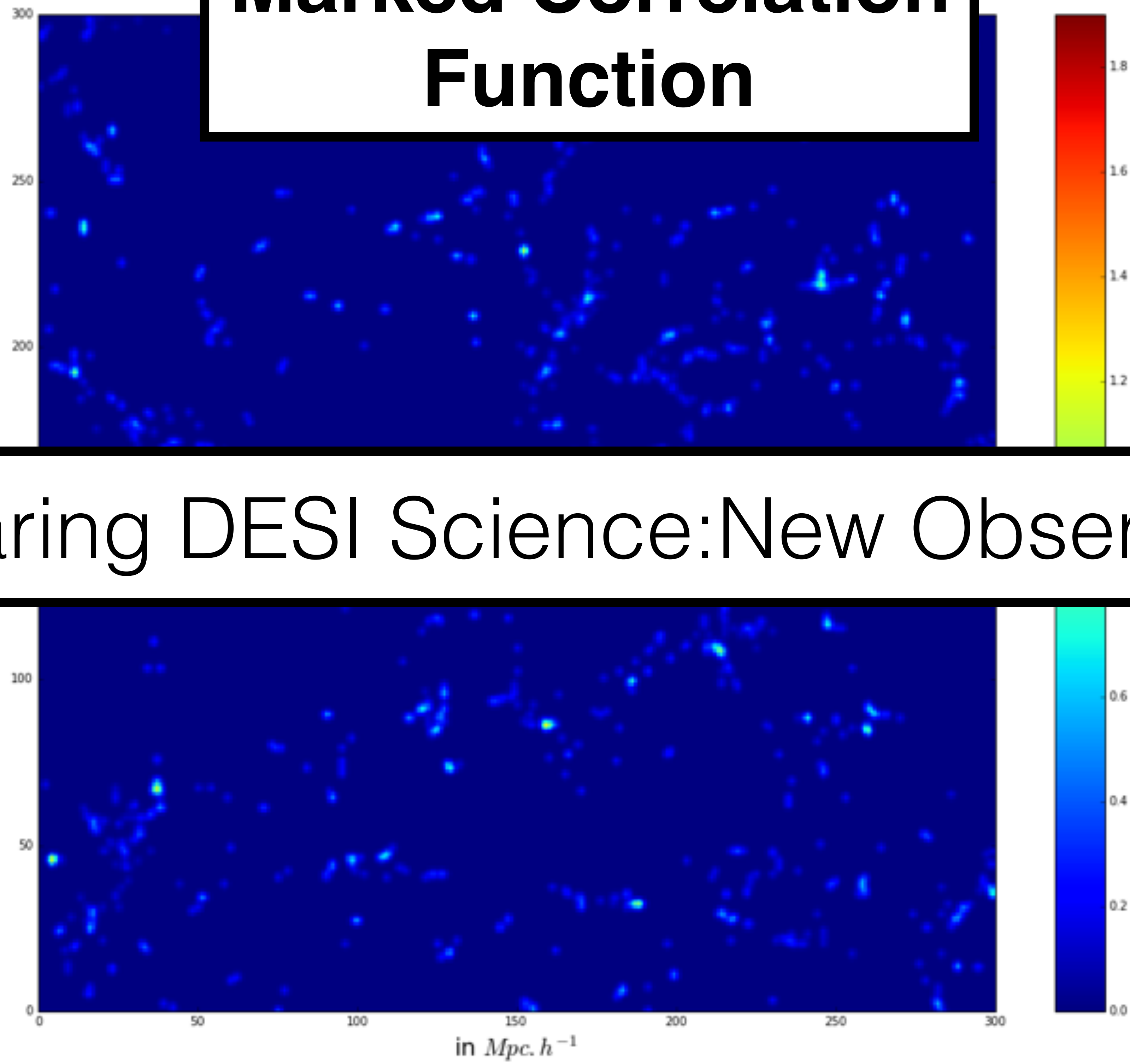


Miguel Angel de Icaza





Marked Correlation Function



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Preparing DESI Science:New Observables

Why Marked Correlation Functions are interestir

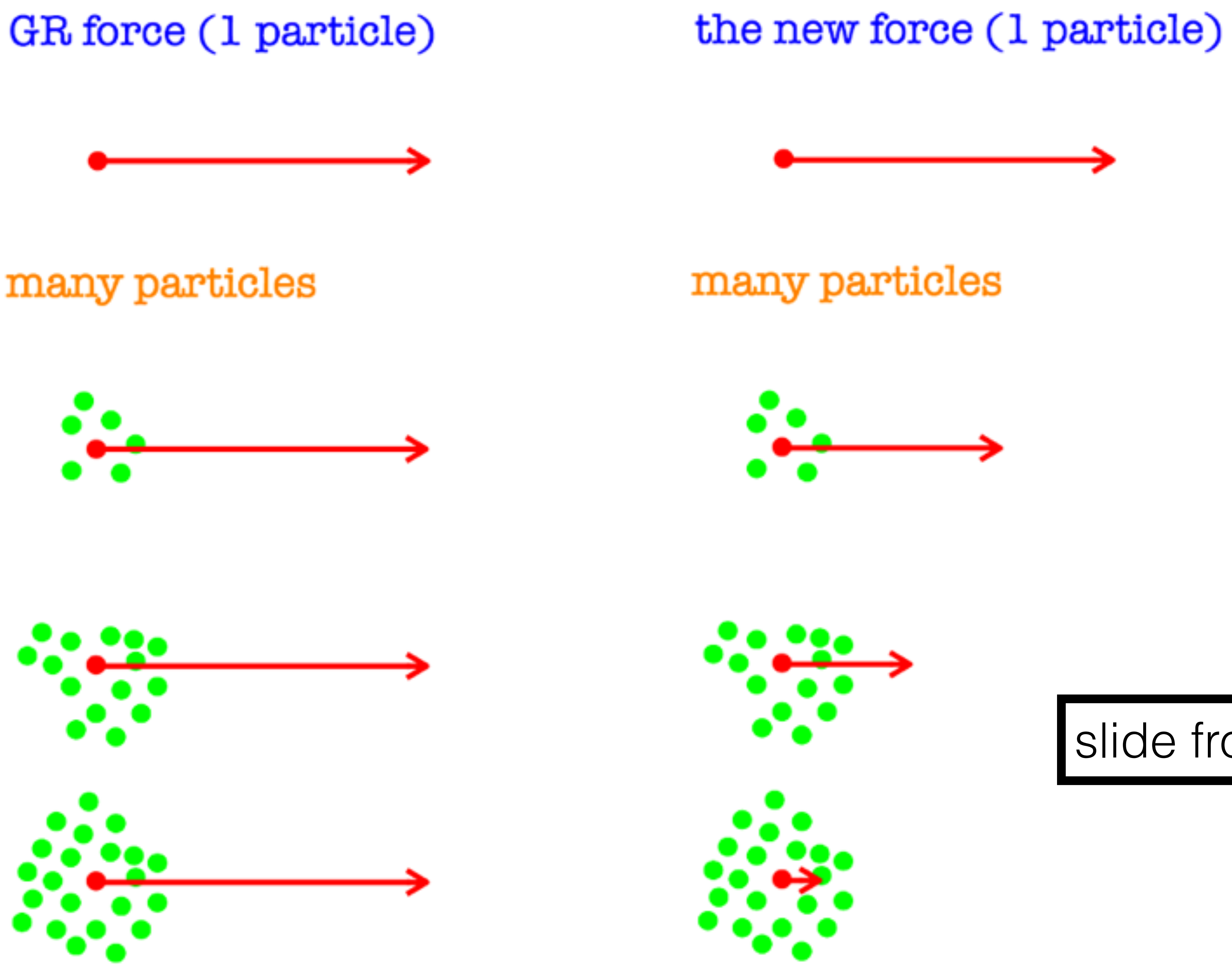
- We would like to have more observables to maximize the cosmological information extraction.

- **Marked Correlations functions provide us a *new window* for exploring MG models using clustering statists at low cost** (M.White 2017).

What are MCF?

- Marked correlations functions measure the **clustering of marks**
- Models which aim to explain the accelerated expansion rate of the Universe by modifications to GR often invoke **screening mechanisms** which can imprint a **non-standard density dependence on their predictions**

Model f(R)



slide from Baijo Li

Modify Gravity Models

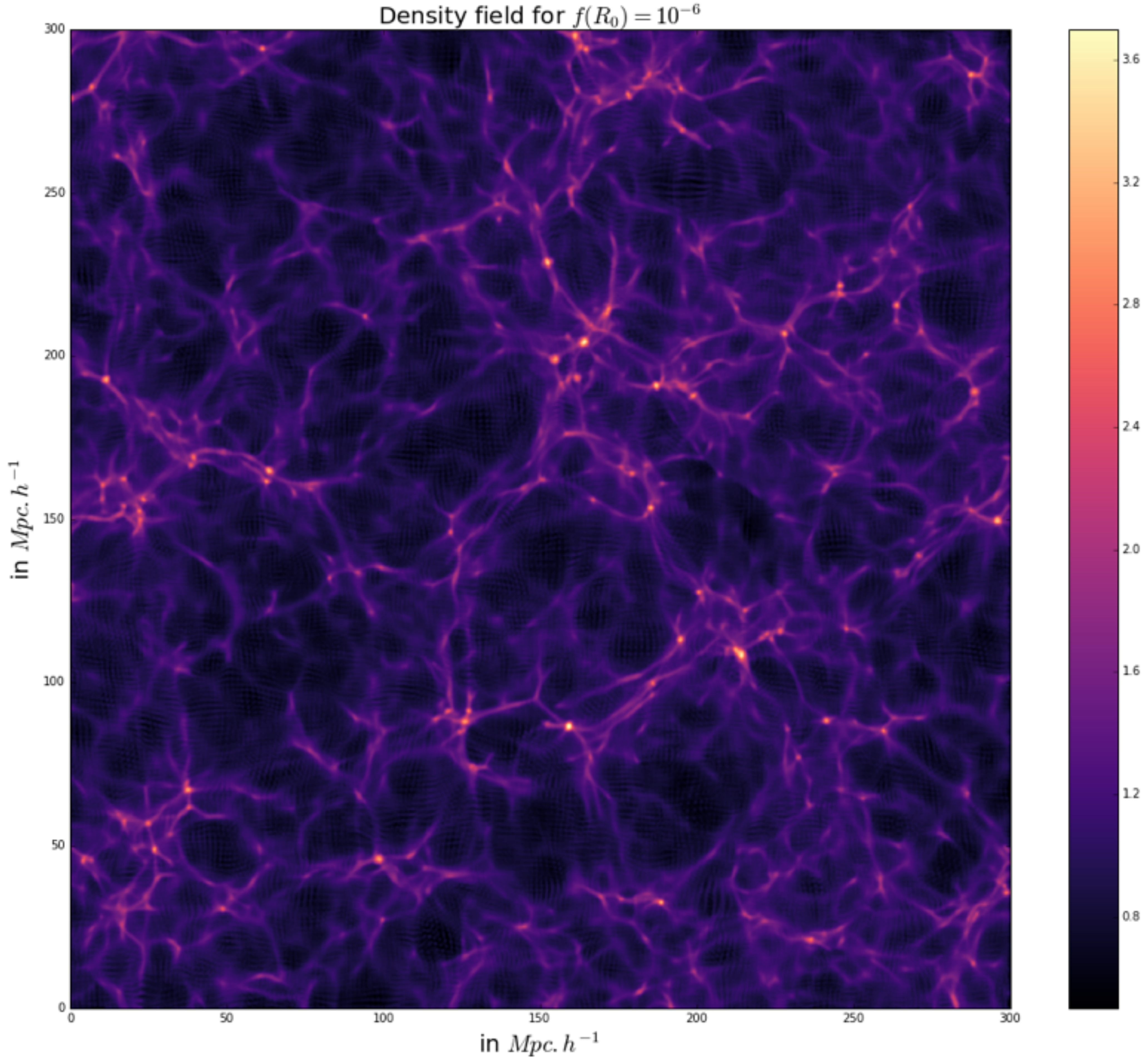
Model f(R)

$$S_{RG}[g] = \frac{c^4}{16\pi G}\int R\sqrt{-|g_{\mu\nu}|} \rightarrow S_{f(R)}[g] = \frac{c^4}{16\pi G}\int f(R)\sqrt{-|g_{\mu\nu}|}$$

Model DGP

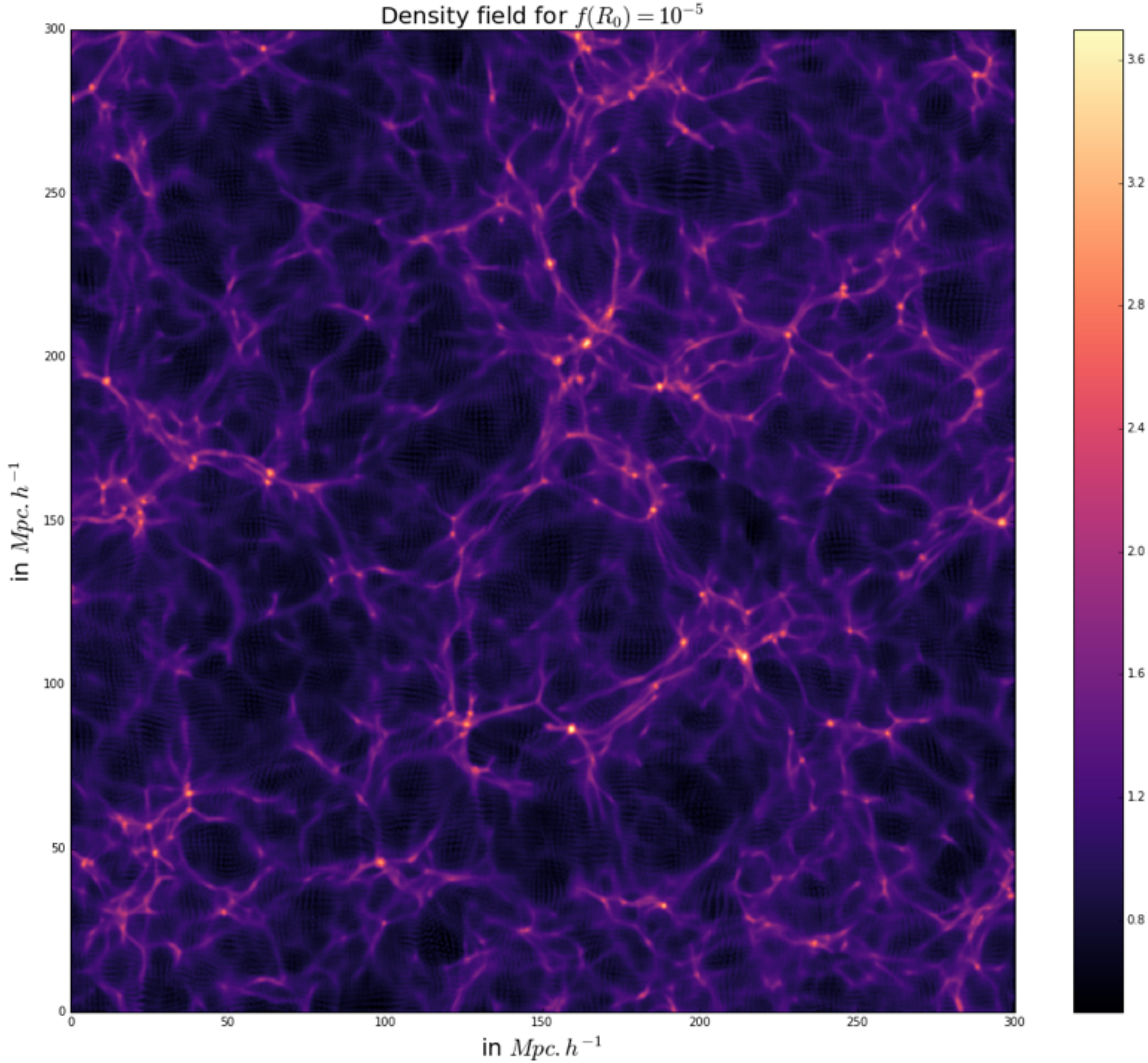
$$S = M_5^3 \int_{5D} d^5x\sqrt{-\gamma}R + \int_{4D} d^4x\sqrt{-g} \times f(M_4, M_5)$$

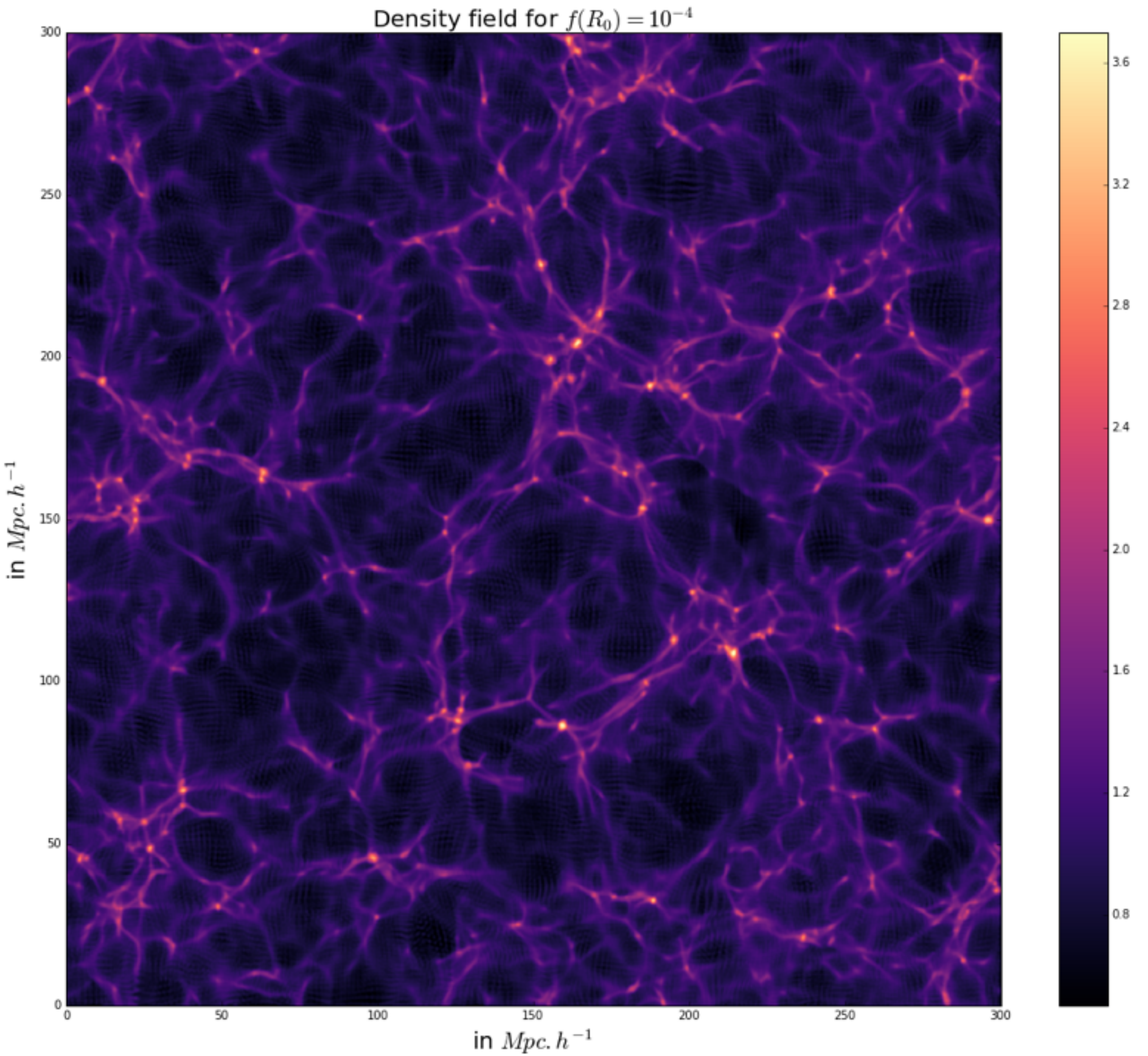
....

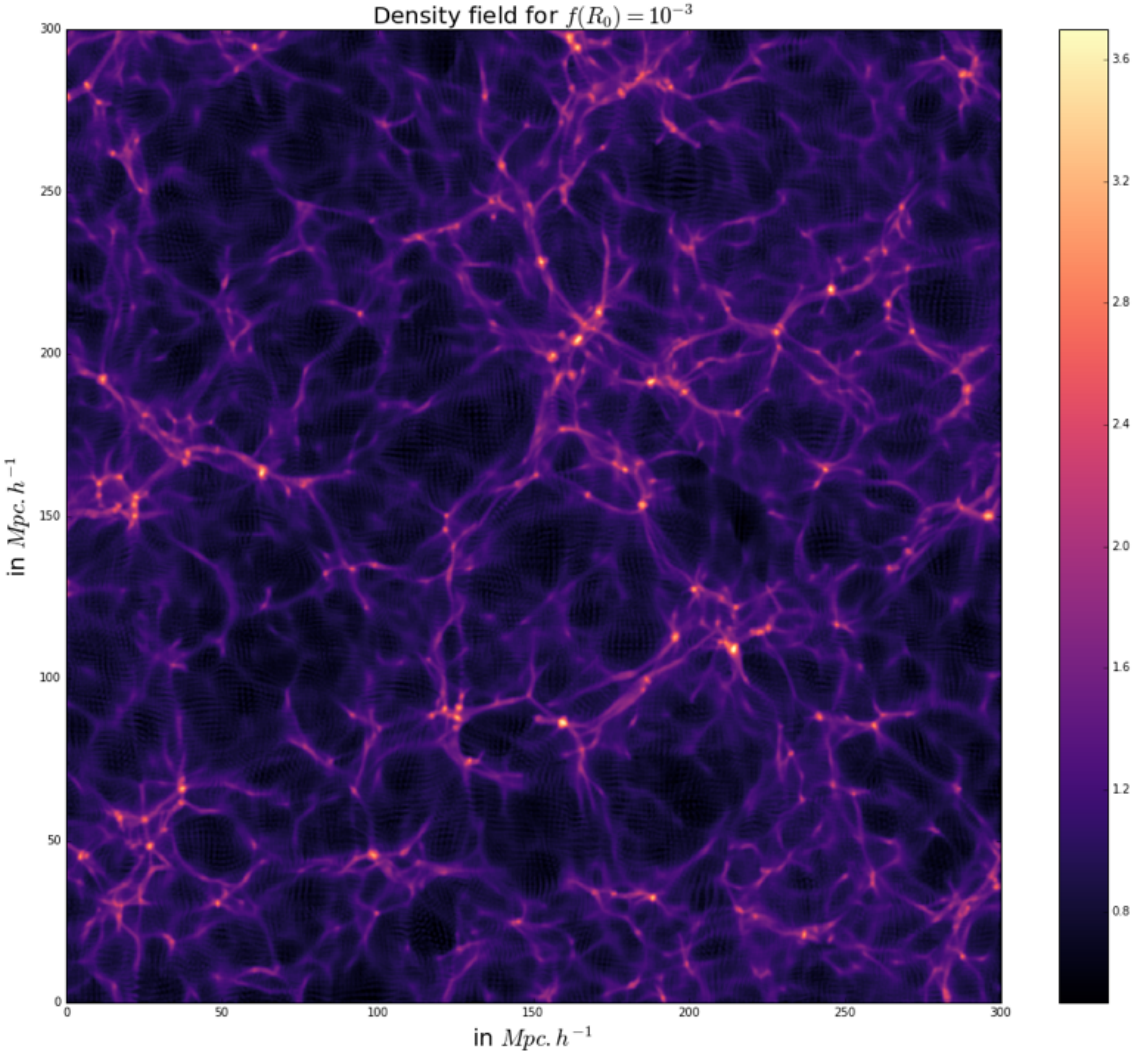


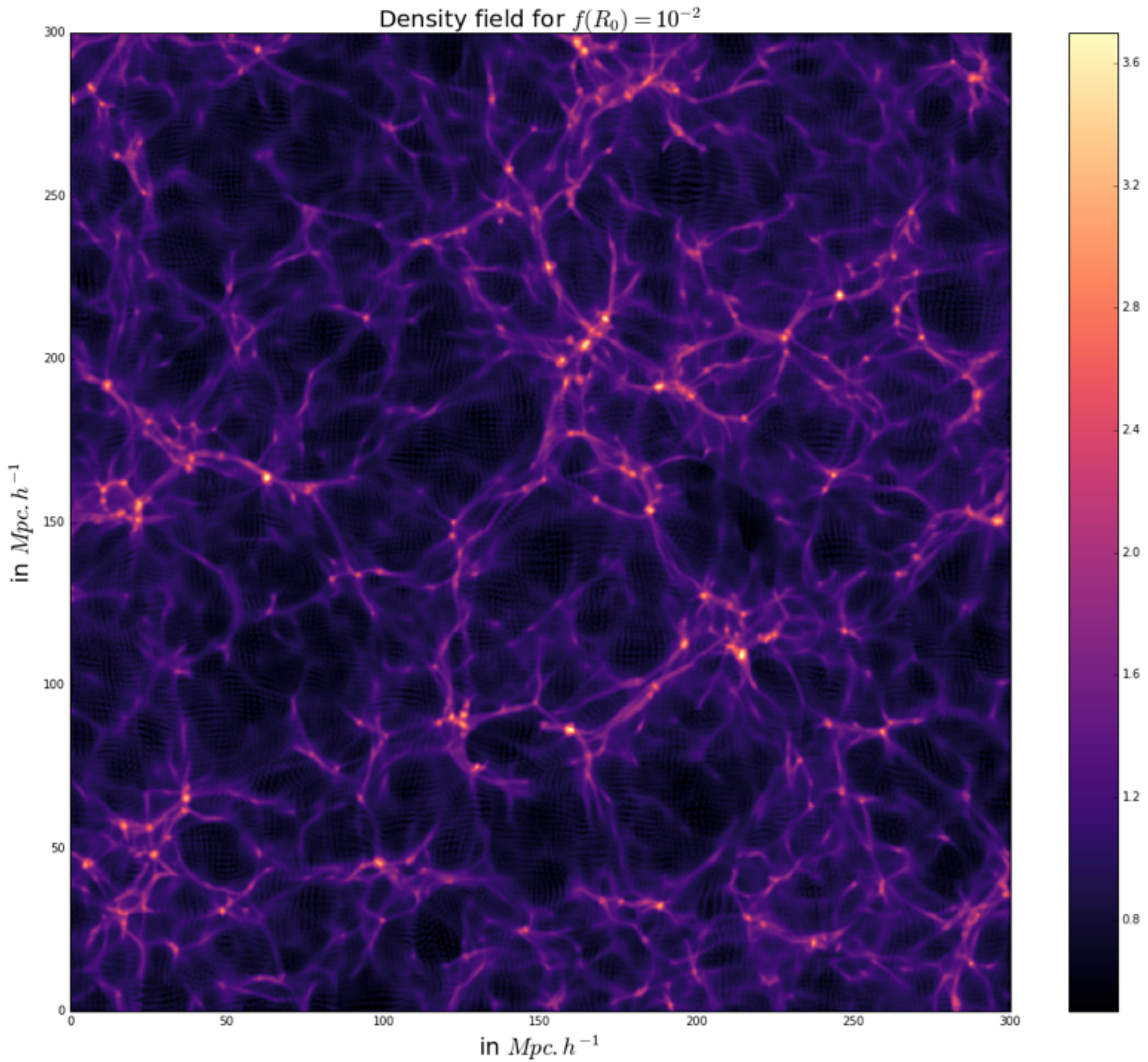
Density field for $f(R_0) = 10^{-6}$
in $Mpc.h^{-1}$
in $Mpc.h^{-1}$
0
50
100
150
200
250
300
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6

Mar

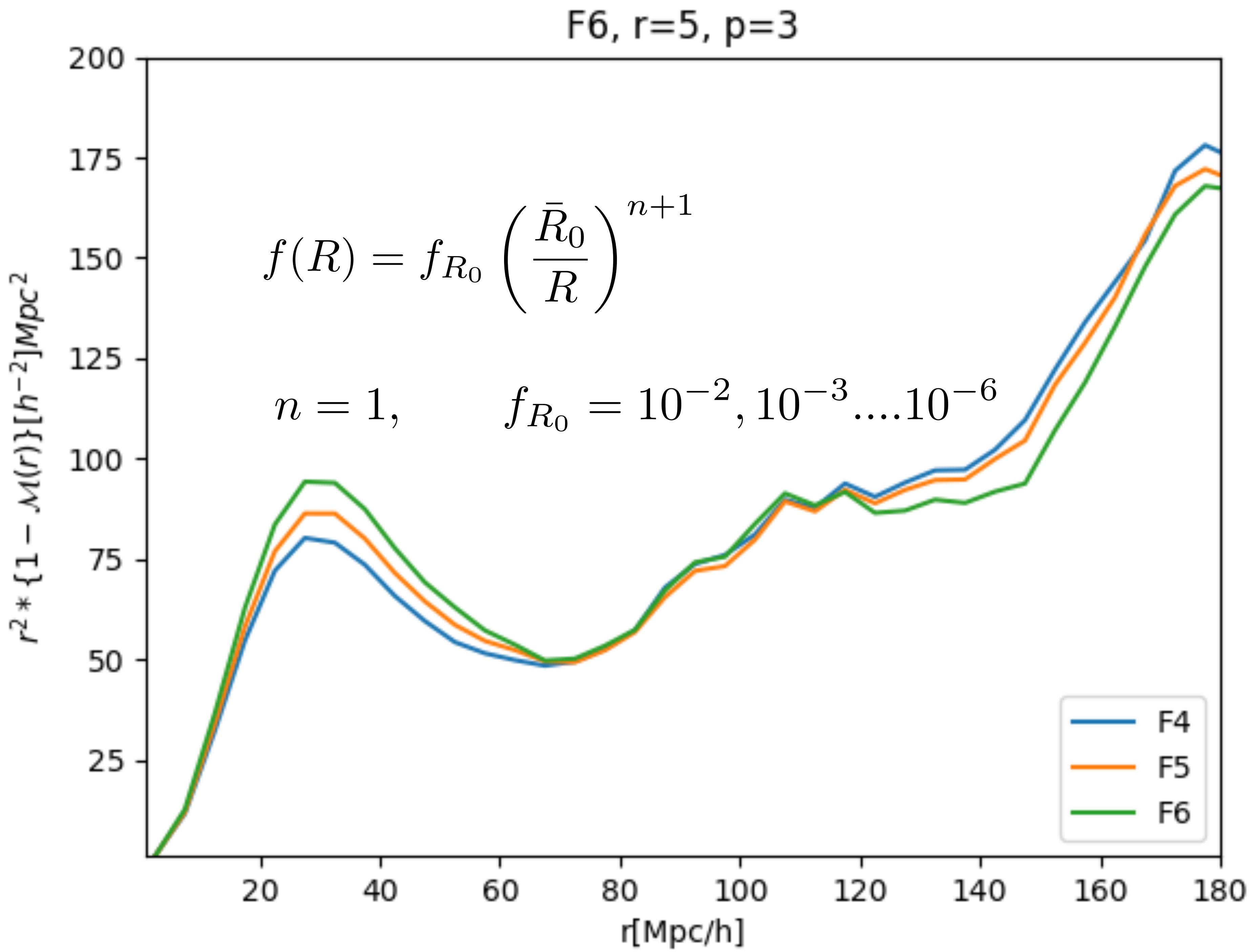

Density field for $f(R_0) = 10^{-5}$
in $Mpc.h^{-1}$
in $Mpc.h^{-1}$
0
50
100
150
200
250
300
0
50
100
150
200
250
300
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6


Density field for $f(R_0) = 10^{-4}$
in $Mpc.h^{-1}$
in $Mpc.h^{-1}$
0
50
100
150
200
250
300
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6


Density field for $f(R_0) = 10^{-3}$
in $Mpc.h^{-1}$
in $Mpc.h^{-1}$
0
50
100
150
200
250
300
0
50
100
150
200
250
300
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8


Density field for $f(R_0) = 10^{-2}$
in $Mpc.h^{-1}$
in $Mpc.h^{-1}$
0
50
100
150
200
250
300
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6

Marked correlations for different f(R) models



$$f(R) = f_{R_0}\left(\frac{\bar{R}_0}{R}\right)^{n+1}$$

$$n = 1, \qquad f_{R_0} = 10^{-2}, 10^{-3} \ldots .10^{-6}$$

Conclusions

- BAO is a robust probe for constraining DE. Ongoing and future experiments use this observable as the baseline for the investigations of dark energy. Preliminary results shown of current analysis in preparation using the latest data from eBOSS for LRG sample.

- RSD is currently a powerful tool for constraining DE and in particular to test the gravity theory. RSD analysis using CLPT-GSRSD model is currently in preparation for analyzing eBOSS LRG sample. Preliminary results shown of current analysis .

- First steps towards new observable MCF, potentially useful for future surveys as the infrastructure required for using is similar to current chain of analysis. We are exploring MCF with MG simulations produced using MG-Picola..

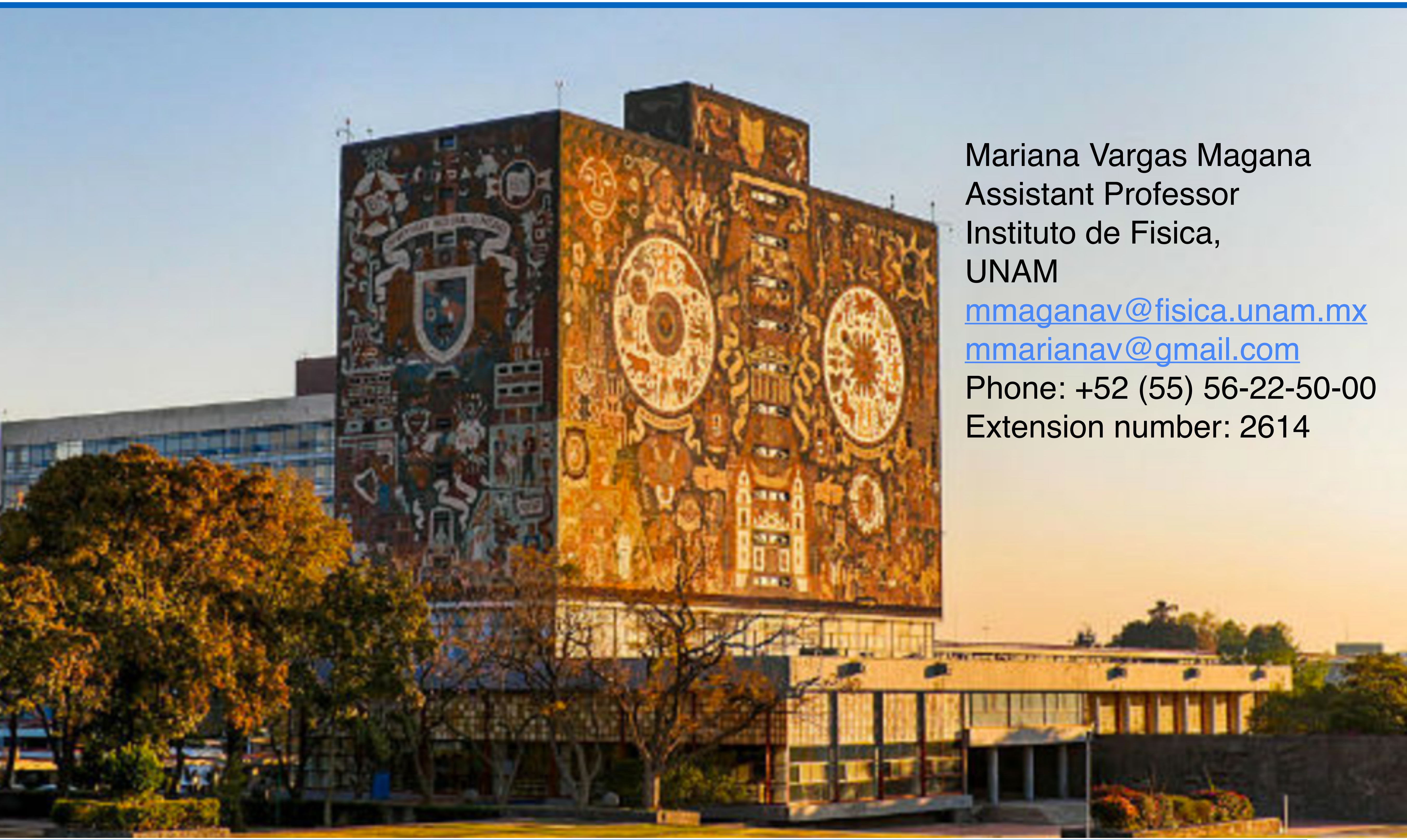
Conclusions

“For the past 13 years, we've had a simple model of how dark energy works. But the truth is, we only have a little bit of data, and we're just beginning to explore the times when dark energy turned on. If there are surprises lurking out there, we expect to find them.”

–DAVID SCHLEGEL*

*PI for the BOSS, co-PI of the DECals, Project scientist of DESI

Contact



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BACKUP SLIDES