Cosmic acceleration and large scale structure observations

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September 6, 2017

Cosmology: The scientific study of the **universe** and its **origin** and **development** (Oxford dictionary).

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Cosmology＝宇(space)宙(time)学(study)

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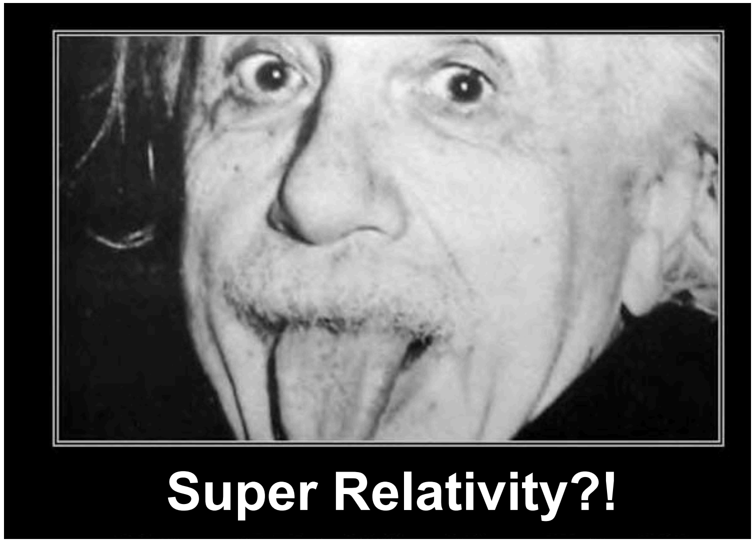

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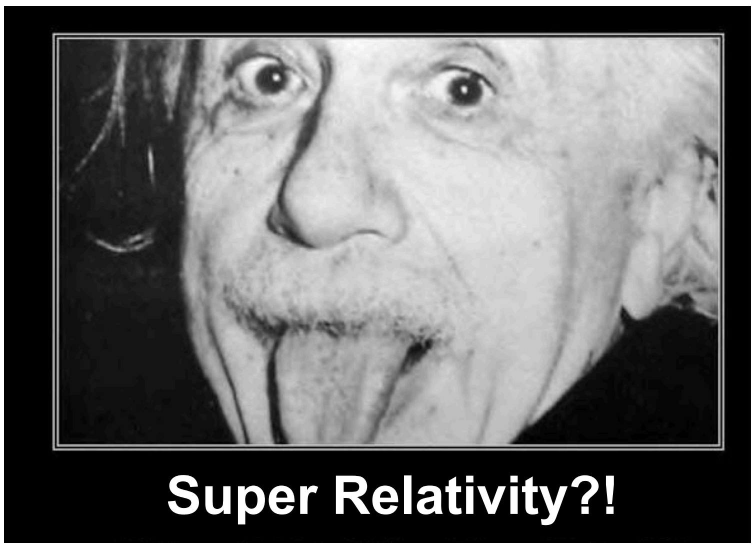
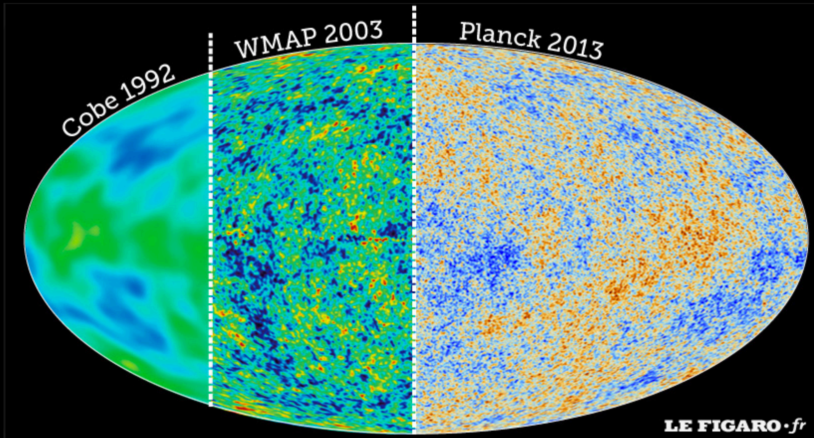
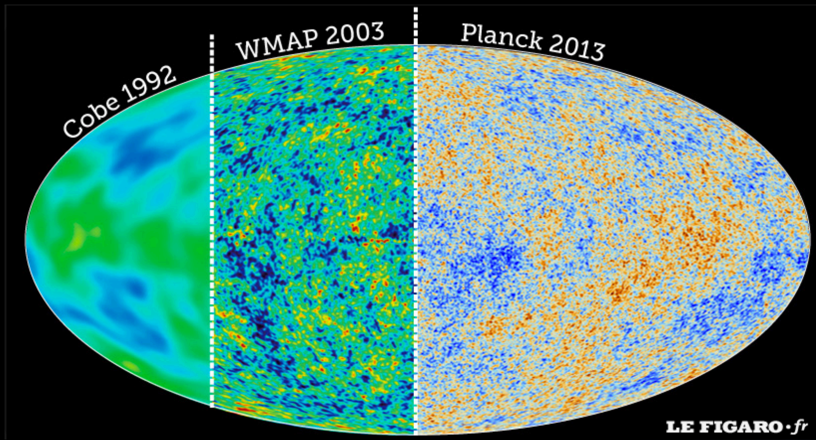


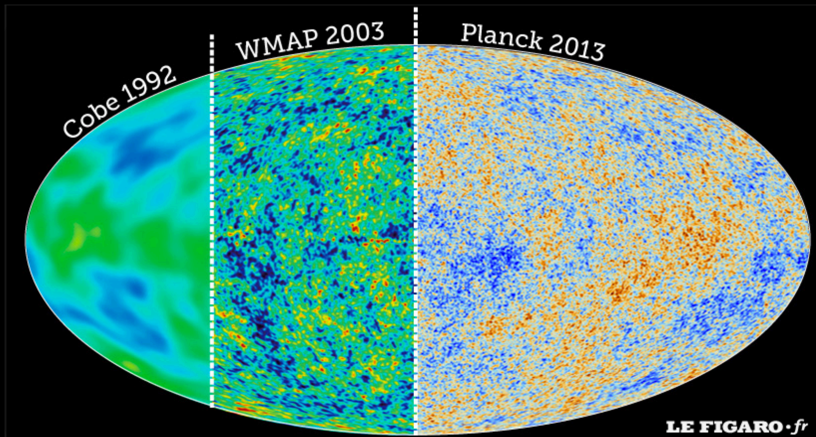


CMB



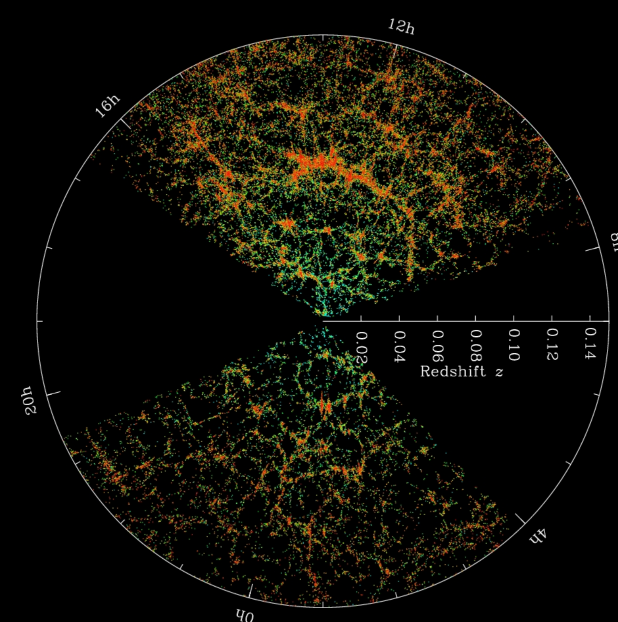
CMB

SNe

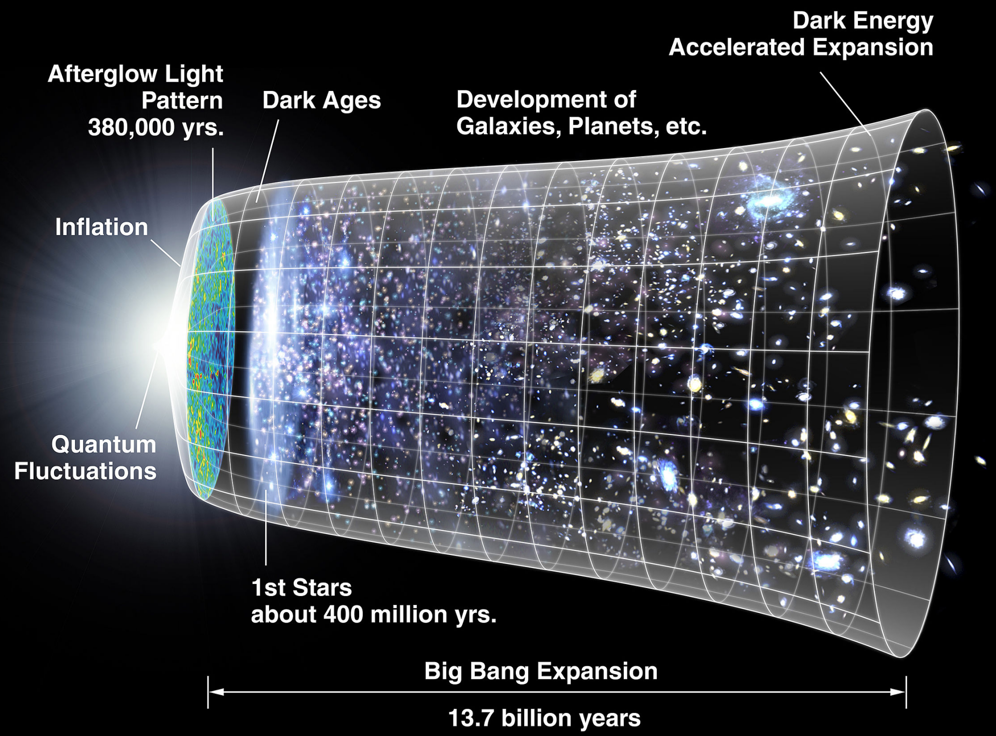


CMB

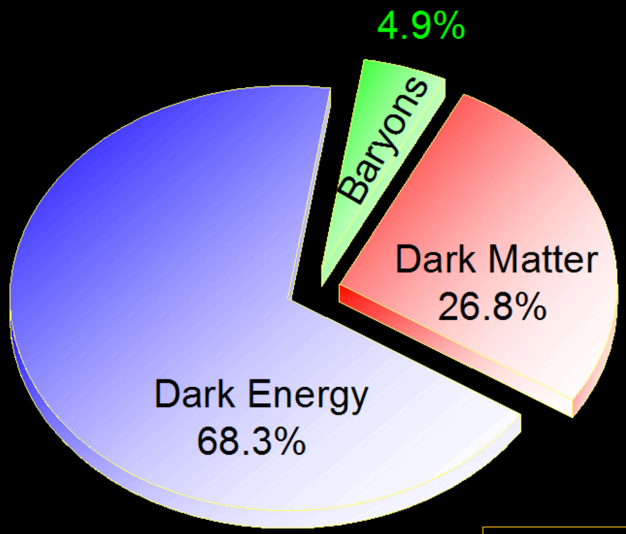
SNe

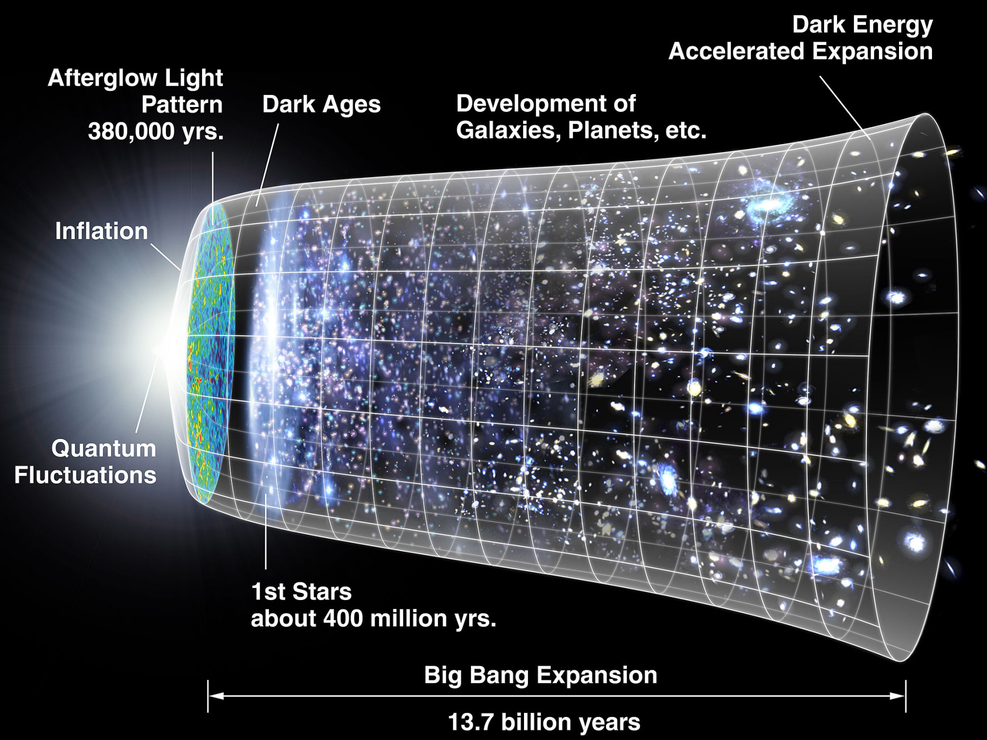


Redshift surveys (BAO,RSD)


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

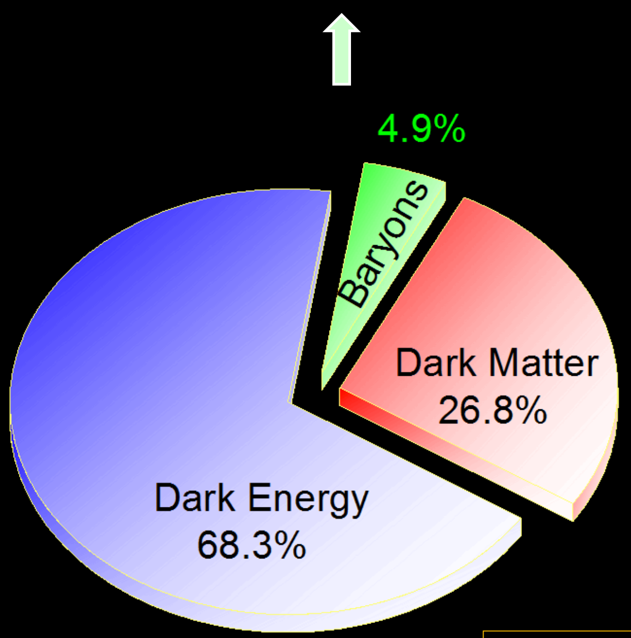
NASA

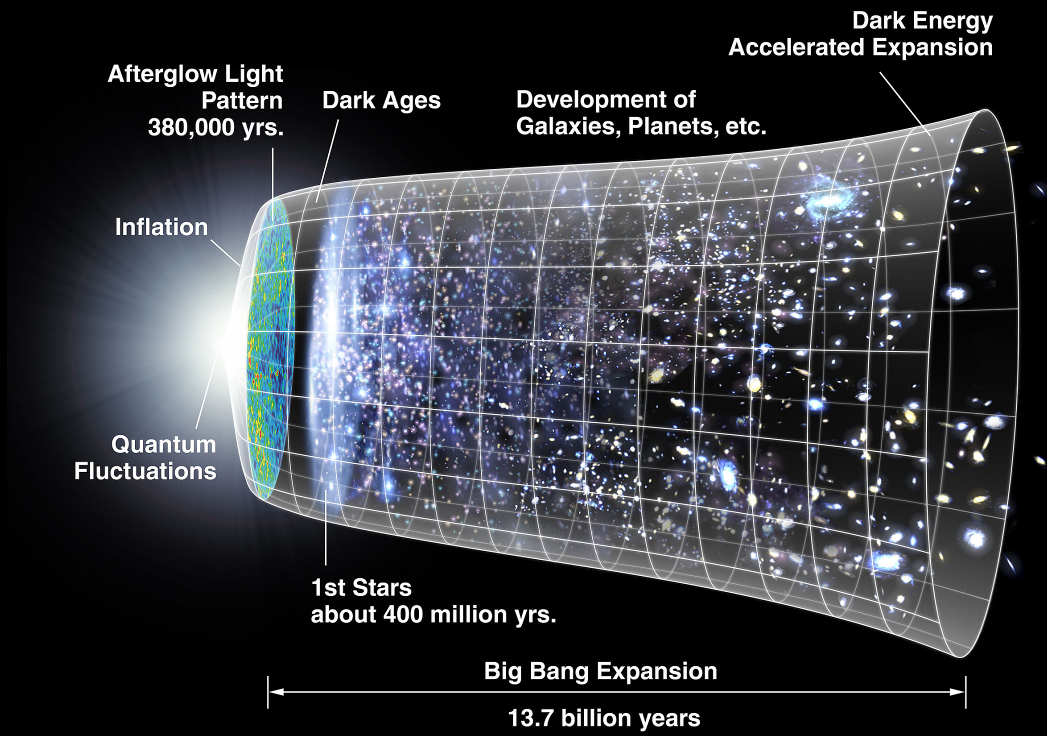

4.9%
Baryons
Dark Matter
26.8%
Dark Energy
68.3%



NASA

100+ Nobel Prizes since 1901!





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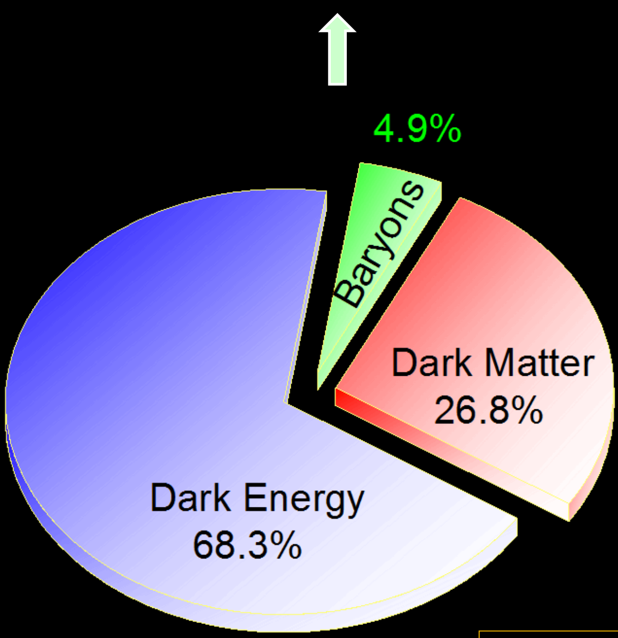
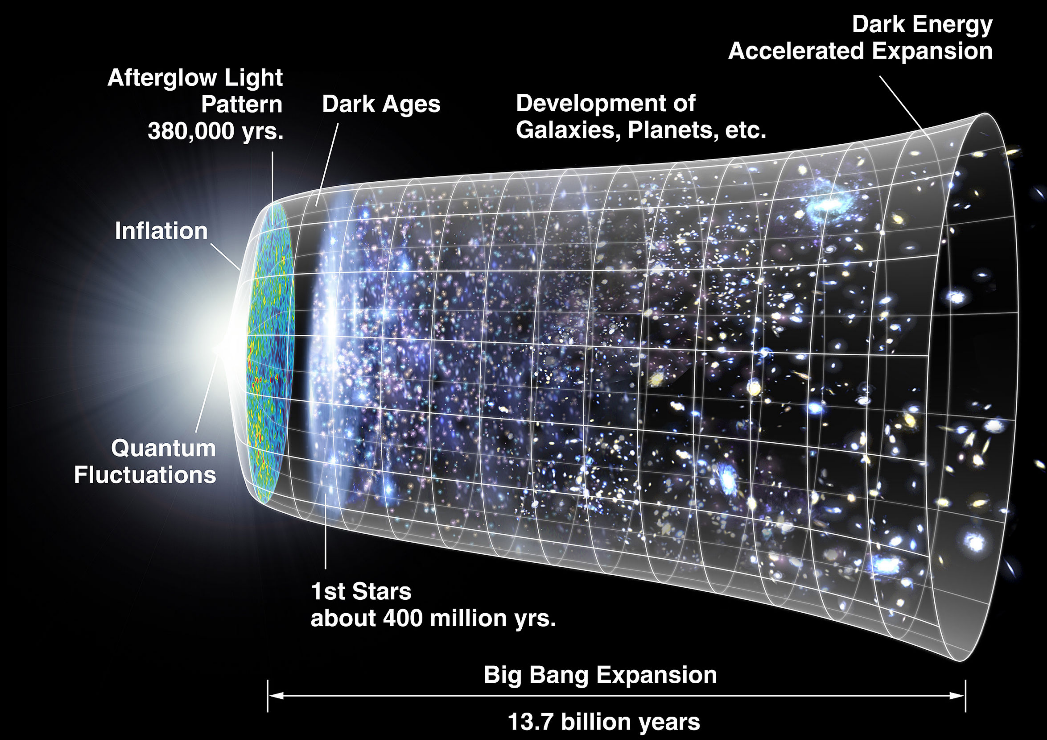


Huge discovery space in the dark sector!



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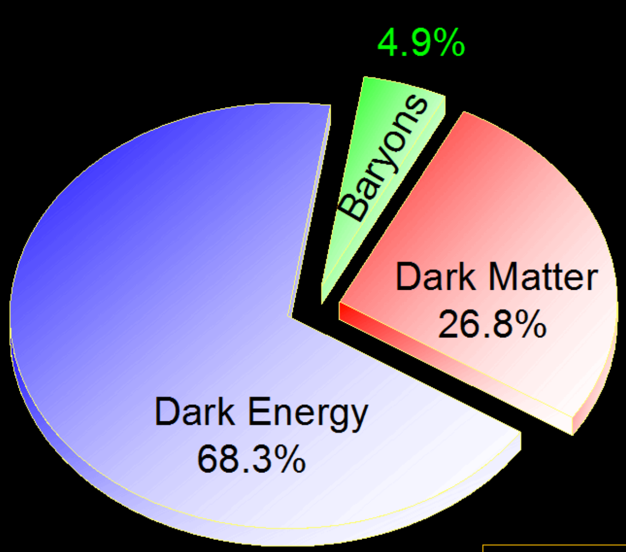


Huge discovery space in the dark sector!

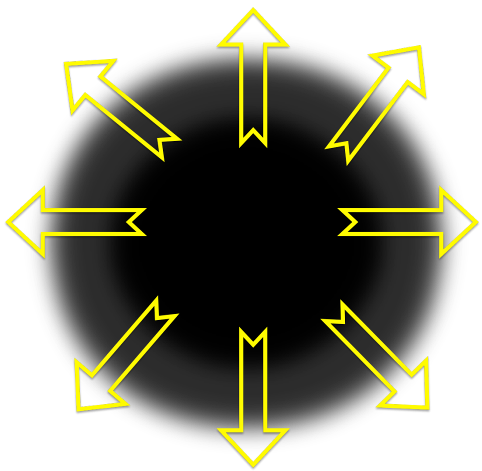
CMB (1978; 2006)

Cosmic Acceleration (2011)

The expansion of the Universe can **accelerate** if

In GR, to add new ‘repulsive matter’, which contributes 70% total energy

To modify General Relativity



Dark Energy

$$G_{\mu\nu} = 8\pi G \widetilde{T}_{\mu\nu}$$

Modified Gravity

$$\widetilde{G}_{\mu\nu} = 8\pi G T_{\mu\nu}$$

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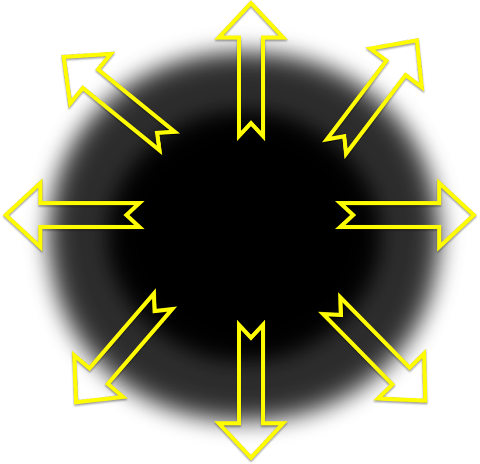

Dark Energy

Modified Gravity

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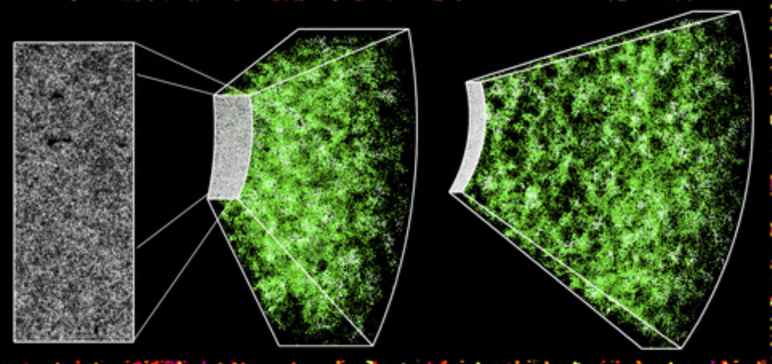
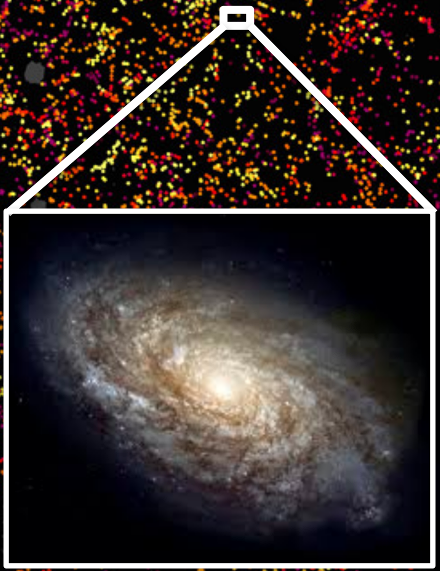
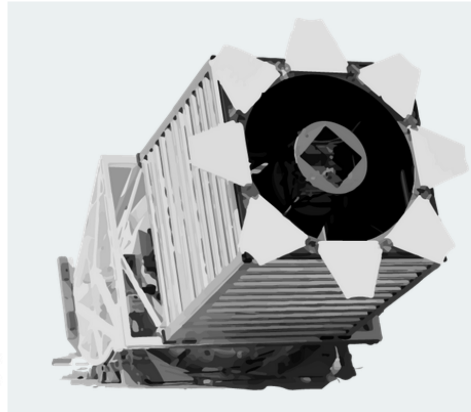
LSS surveys can help break the degeneracy

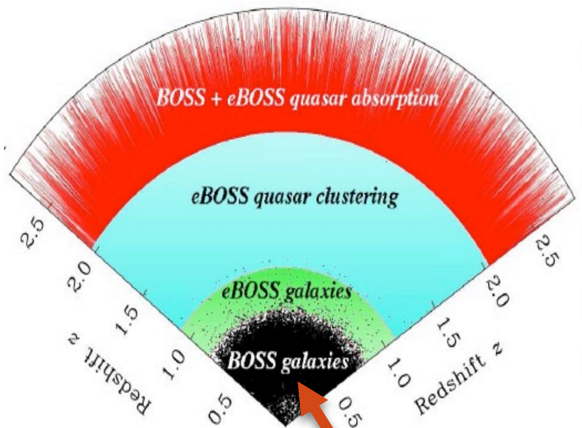


LSS surveys are census of galaxy polulations

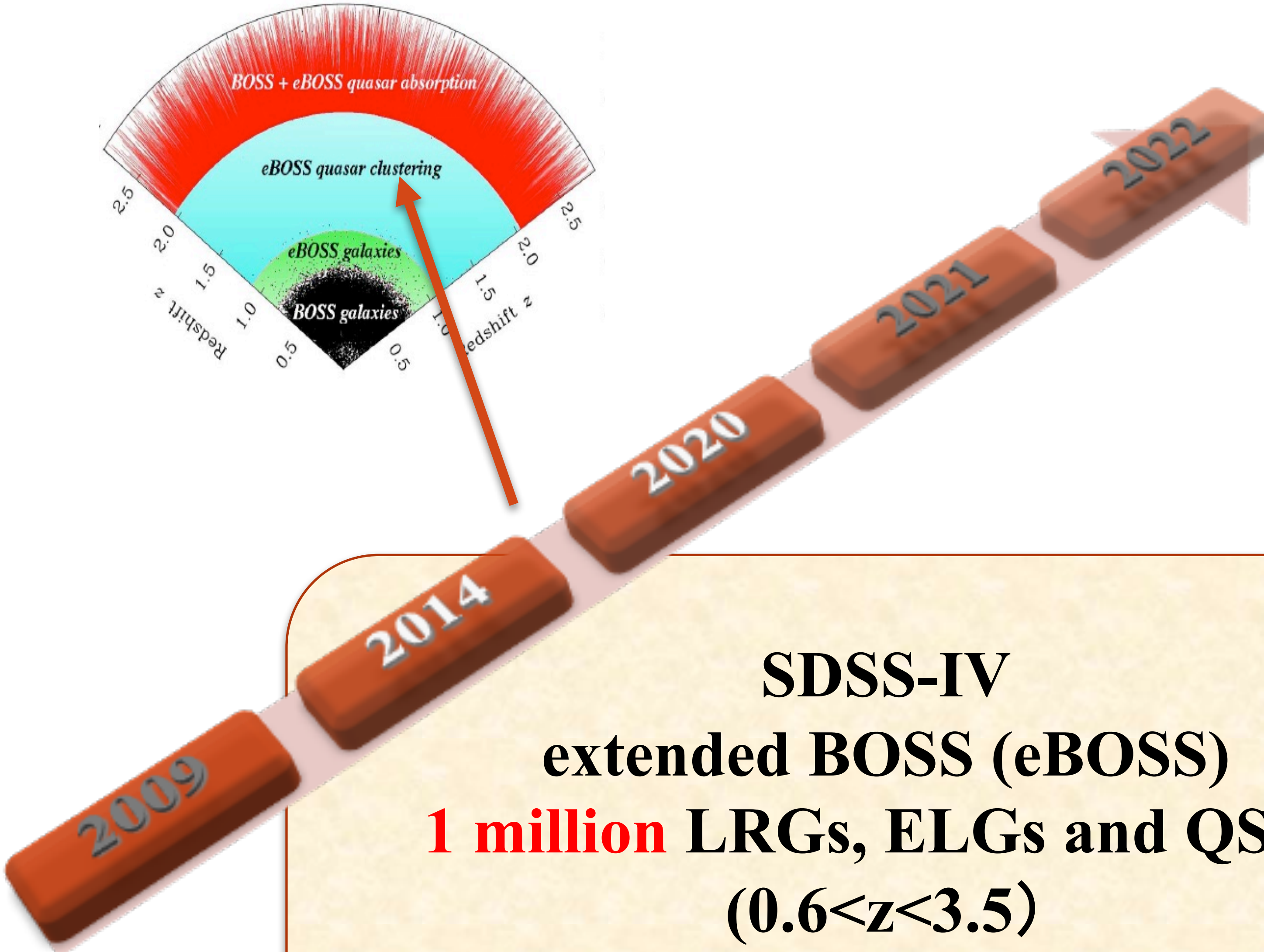




2.5 meter



SDSS-III
Baryon Oscillation Spectroscopic Survey (BOSS)
1.6 million LRGs
(z<0.6)
Largest in the world in the past 5 years



SDSS-IV

extended BOSS (eBOSS)

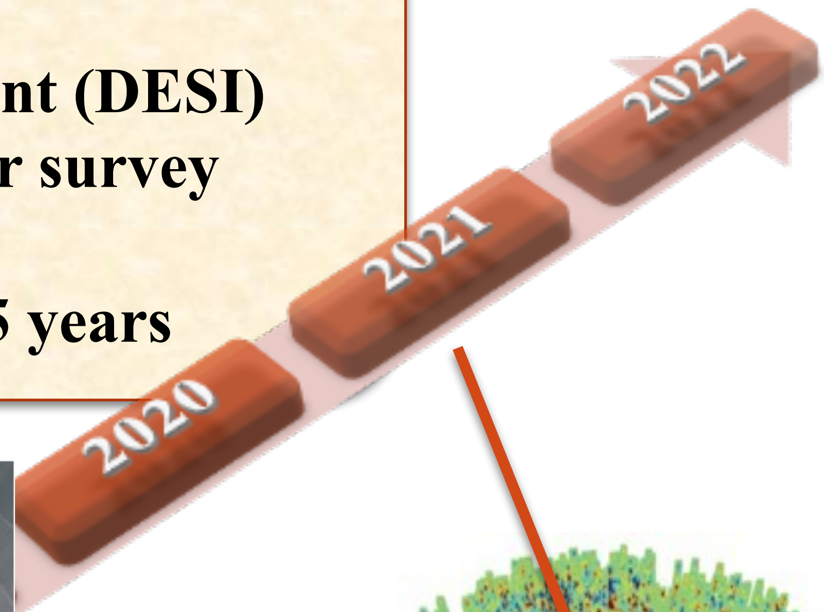
1 million LRGs, ELGs and QSOs

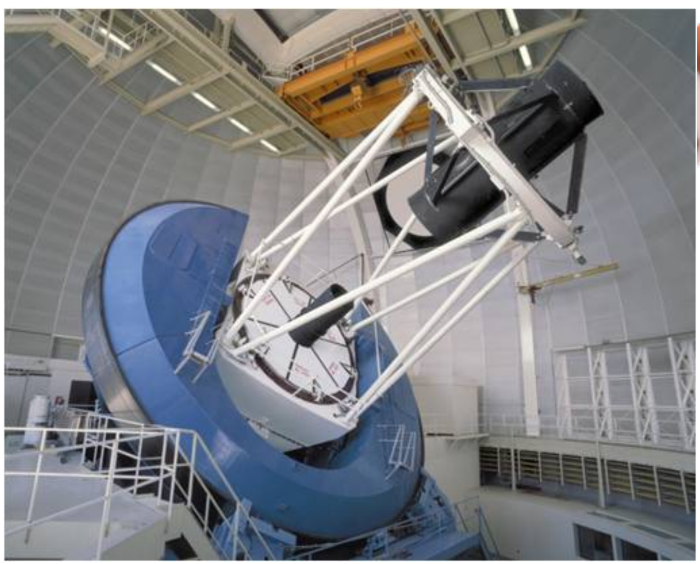
(0.6<z<3.5)

Largest ongoing survey

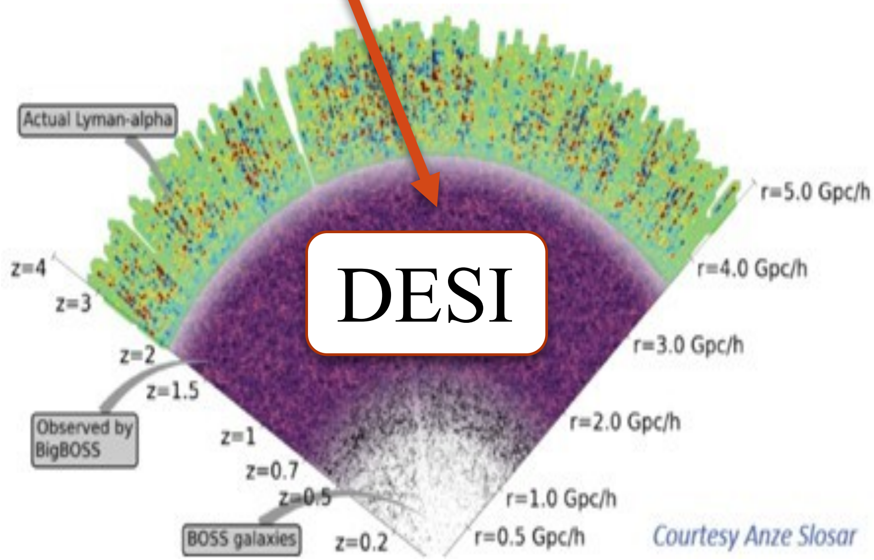
Stage-IV survey

Dark Energy
Spectroscopic Instrument (DESI)
20 million multi-tracer survey
(0<z<3.5)
Largest in the next 5 years

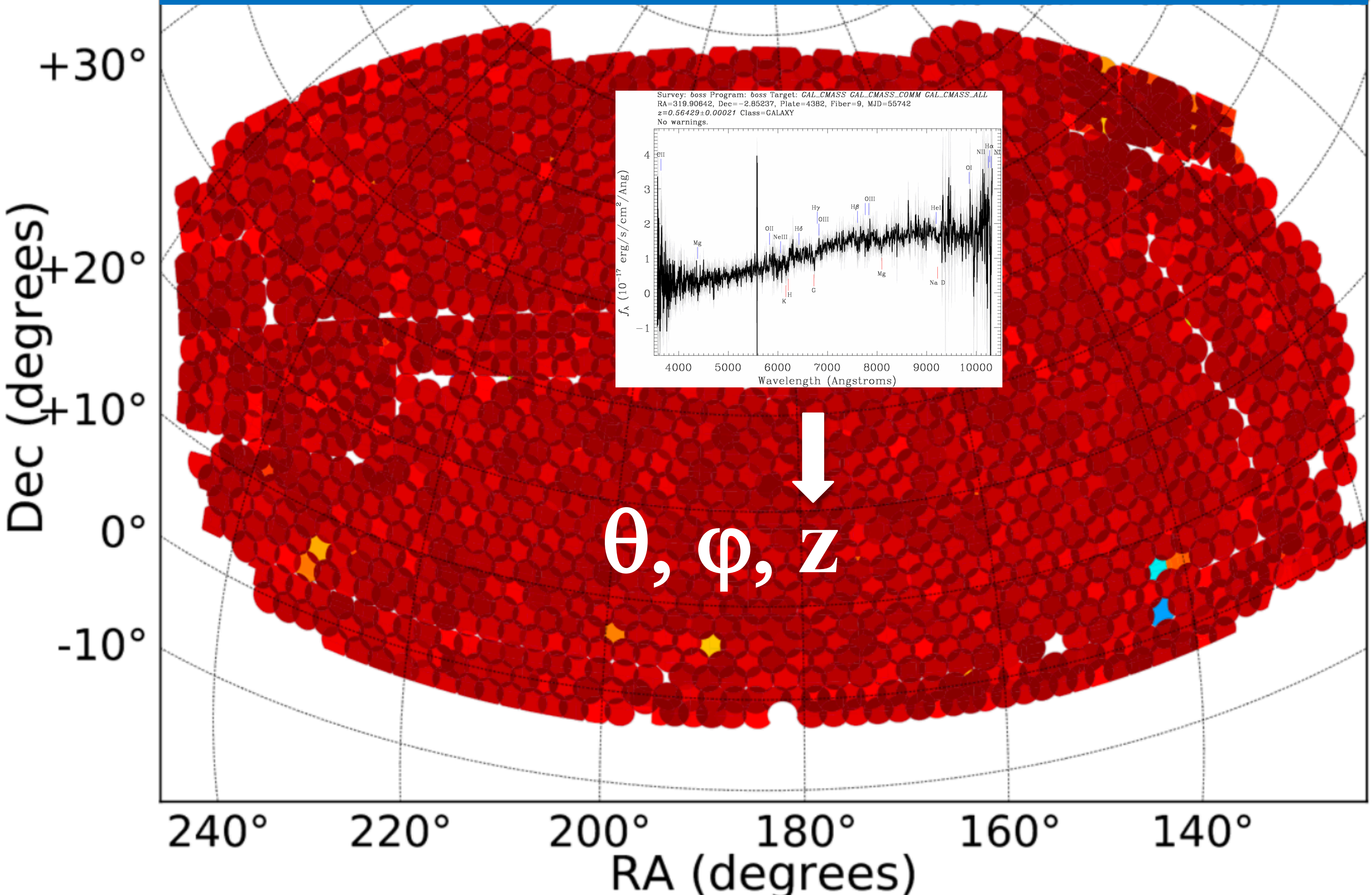




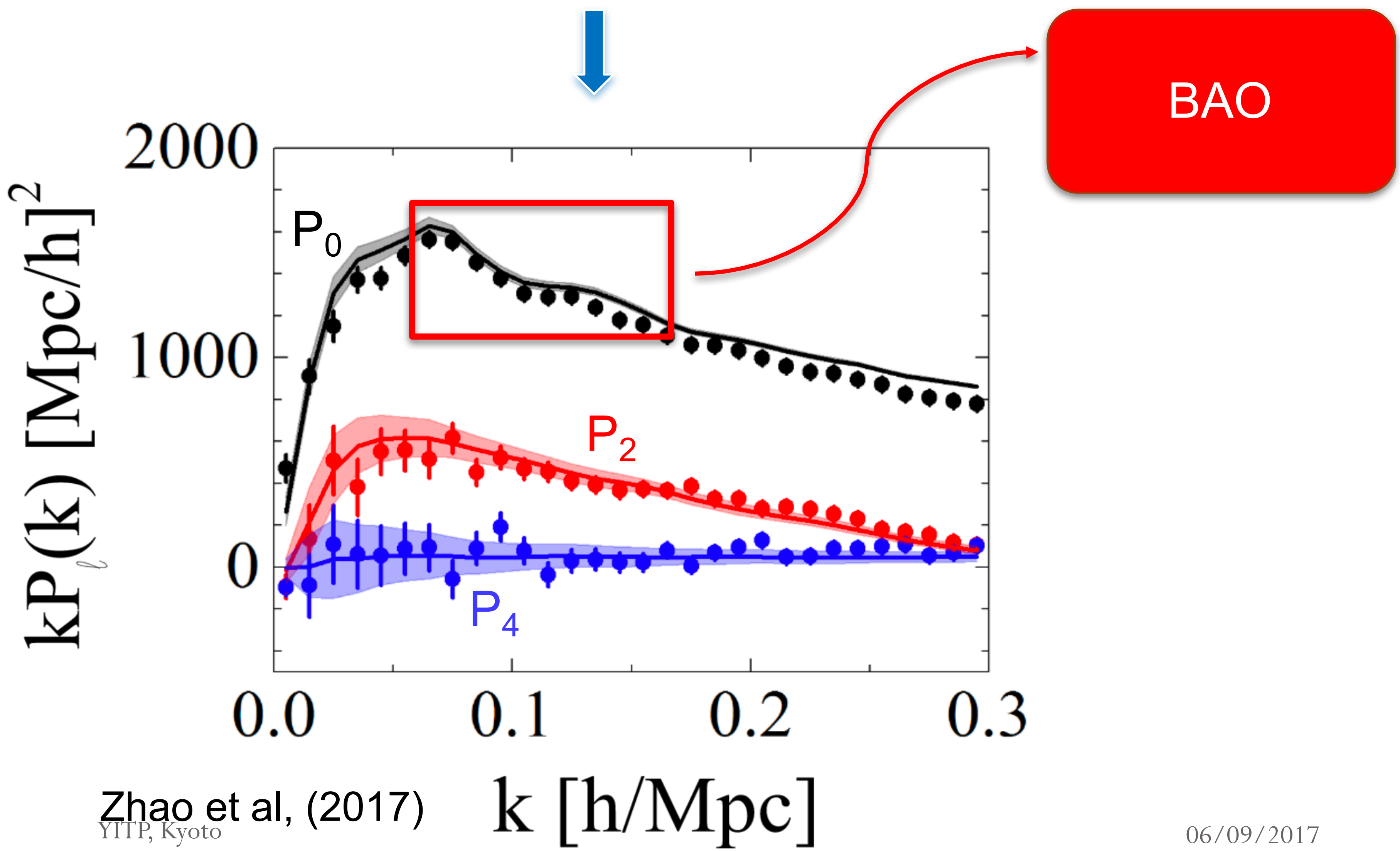
4 meter



What do redshift surveys measure?

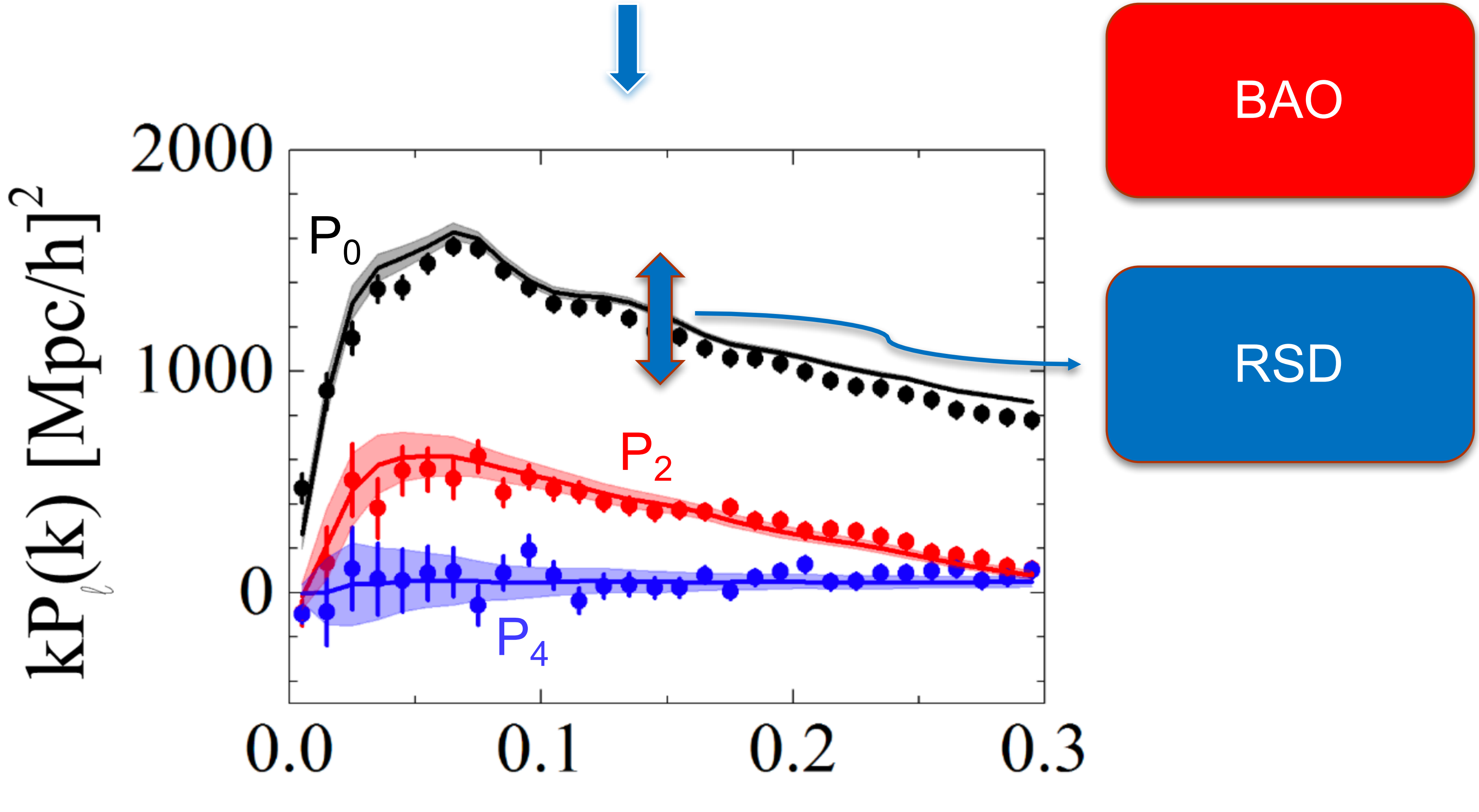


θ, φ, z



Zhao et al, (2017)

θ, φ, z



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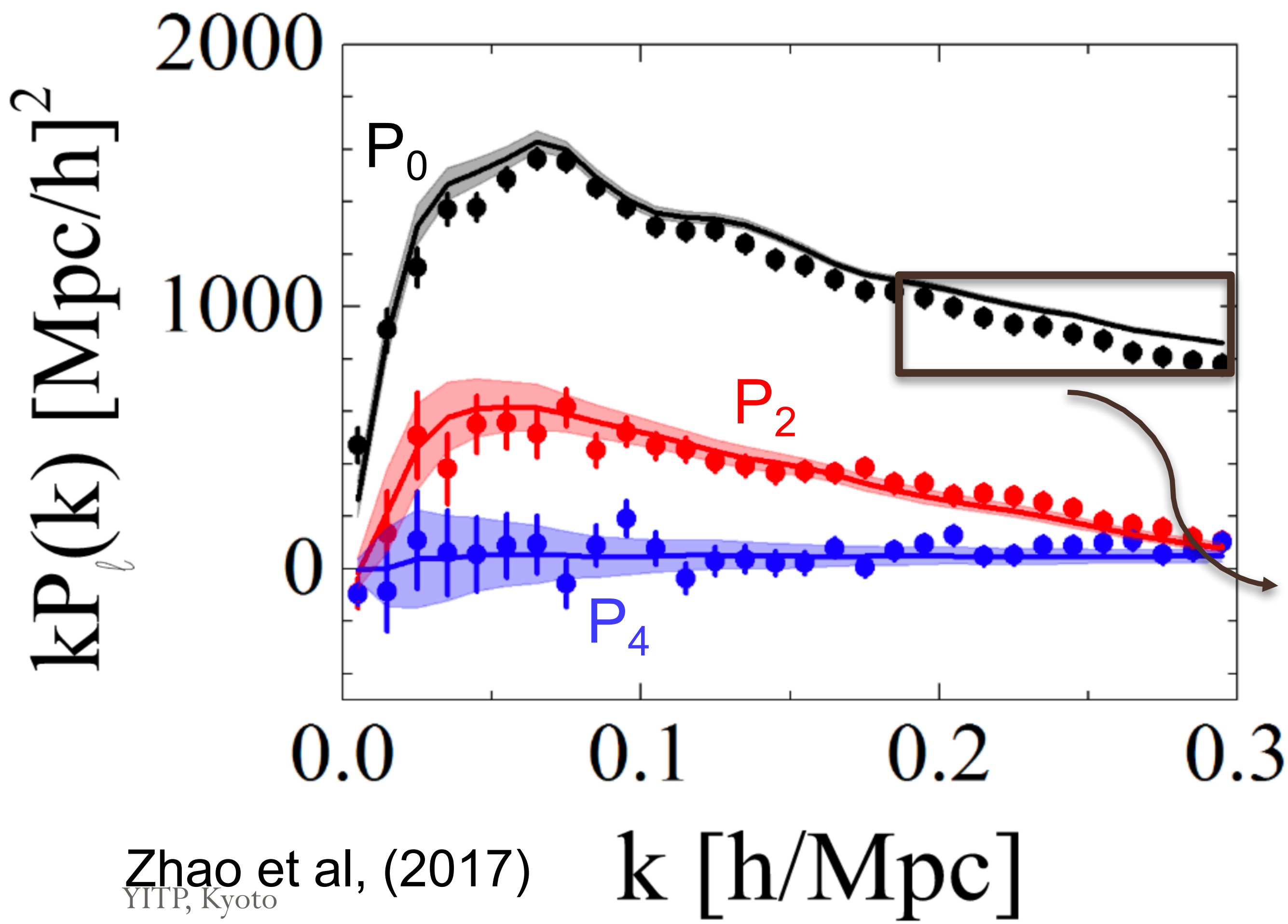


Zhao et al, (2017)

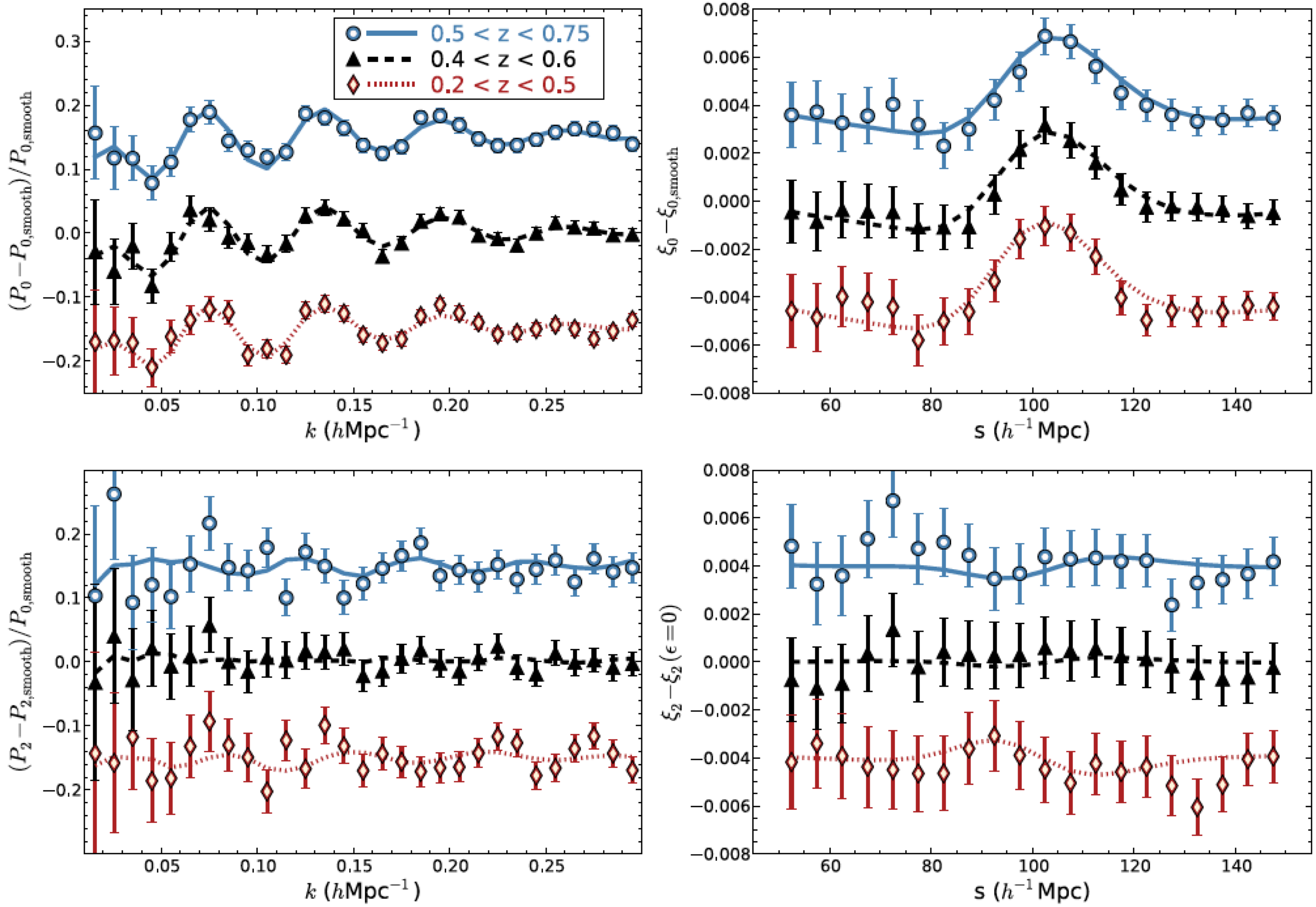
BAO

RSD

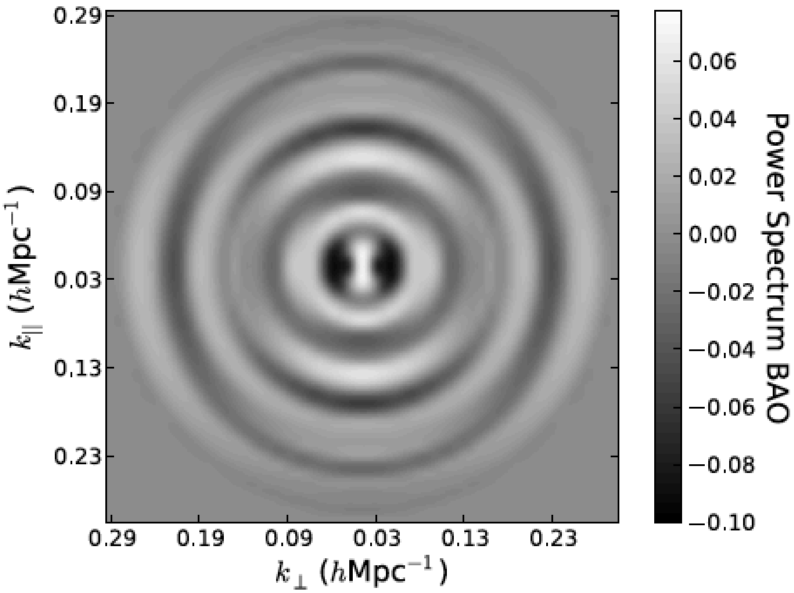
FS

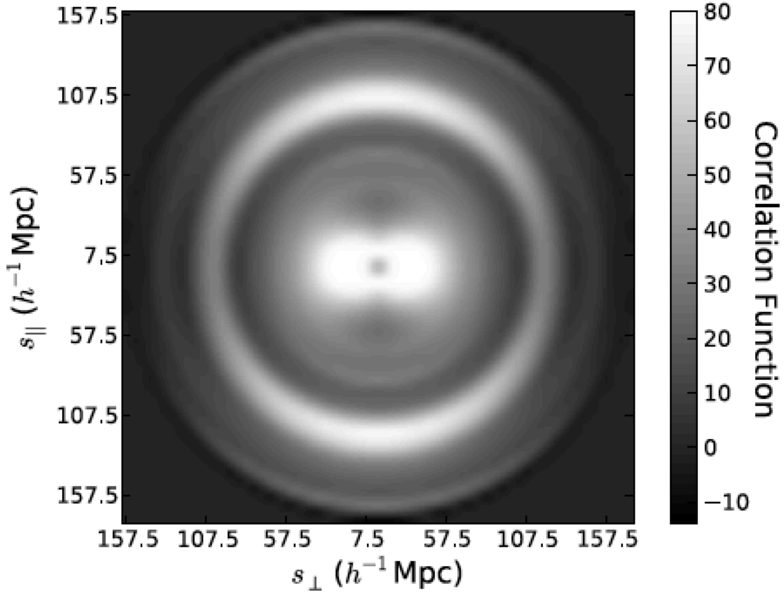
Latest BAO measurements

Fourier space | Configuration space



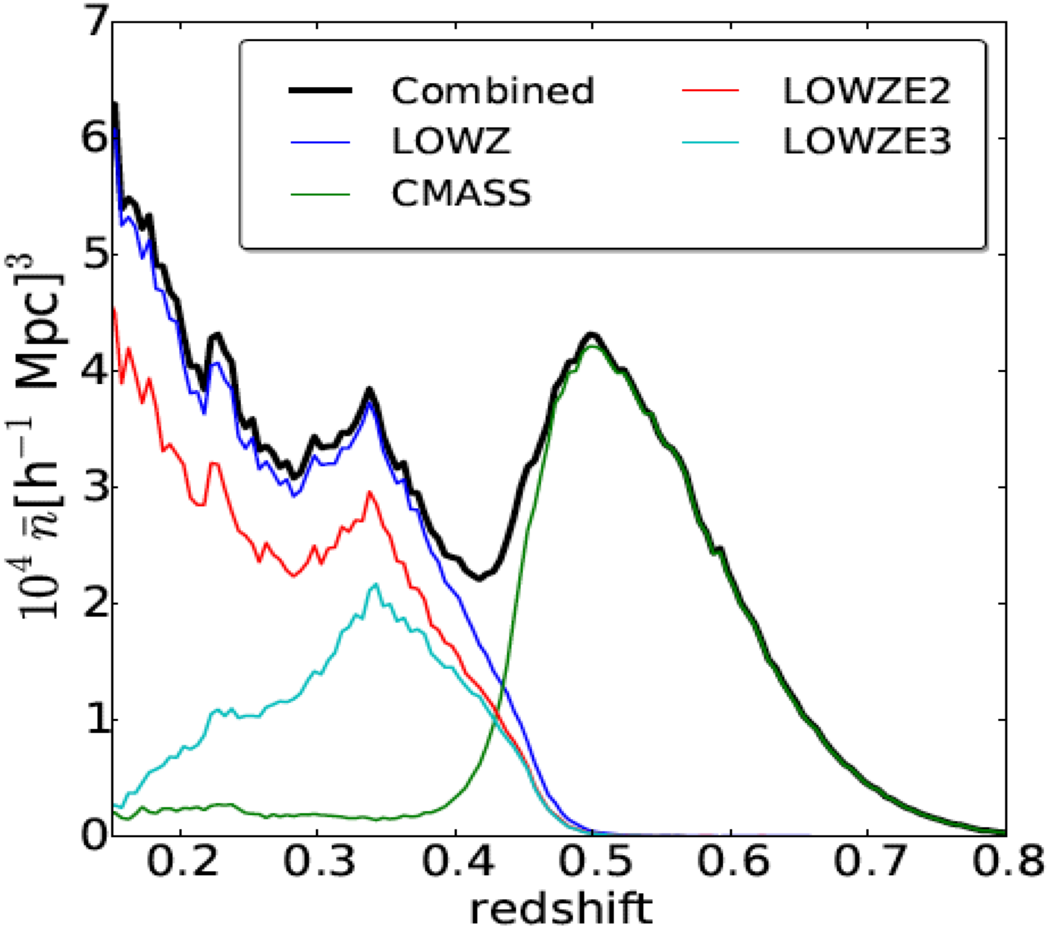
BOSS (Alam et al), 2016, 1607.03155





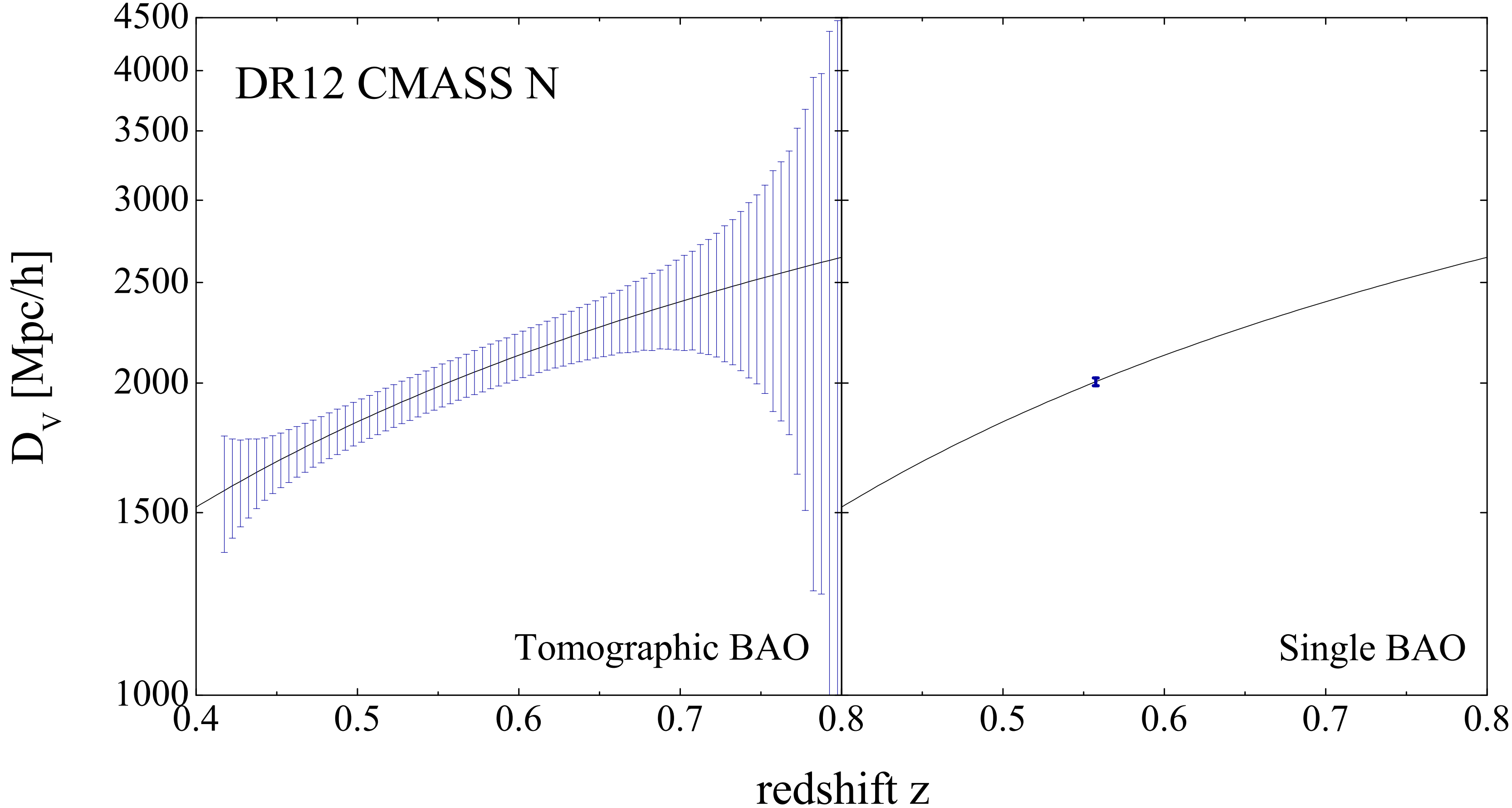
BOSS (Alam et al), 2016, 1607.03155

Explore the redshift data as much as possible

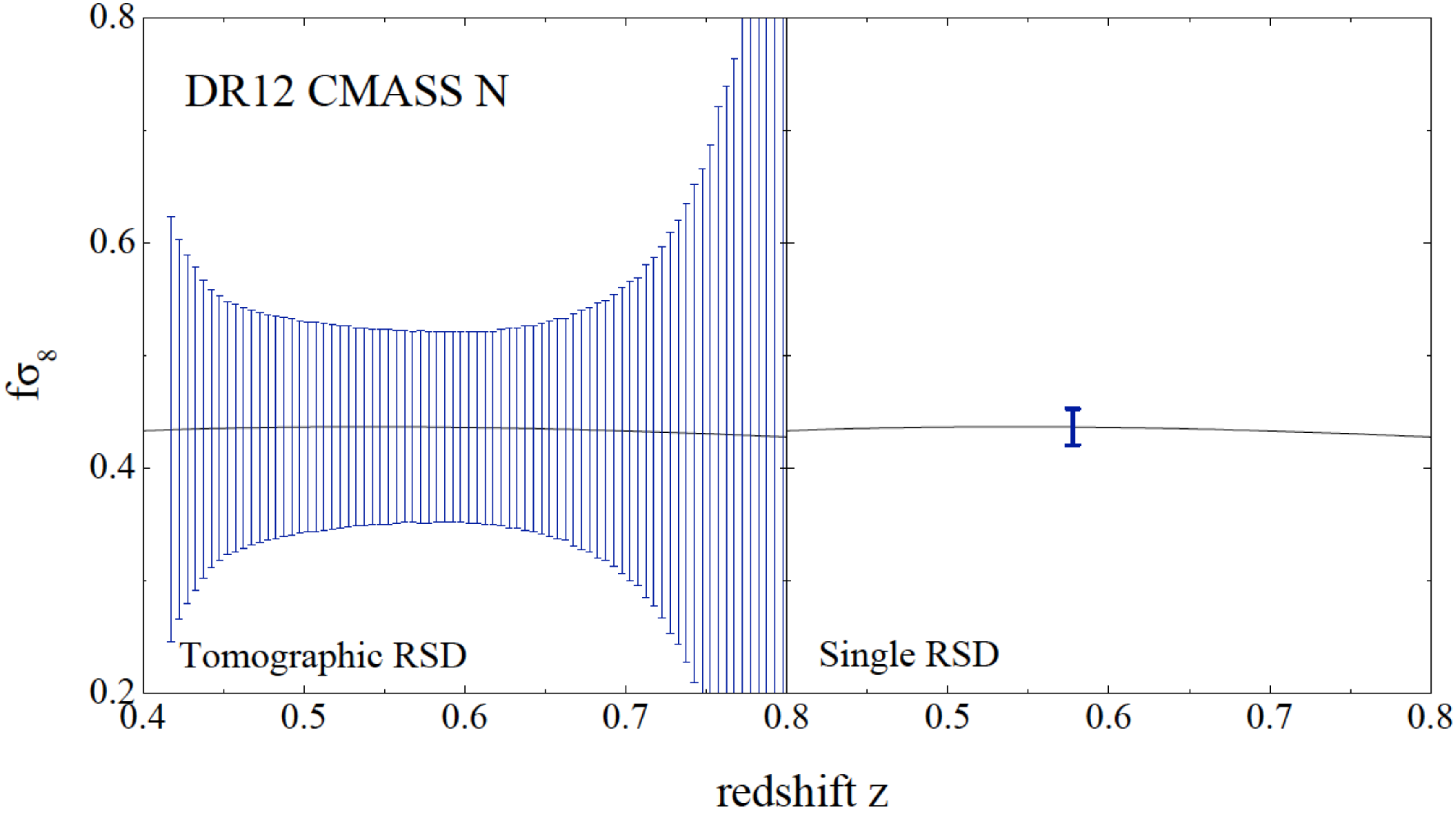


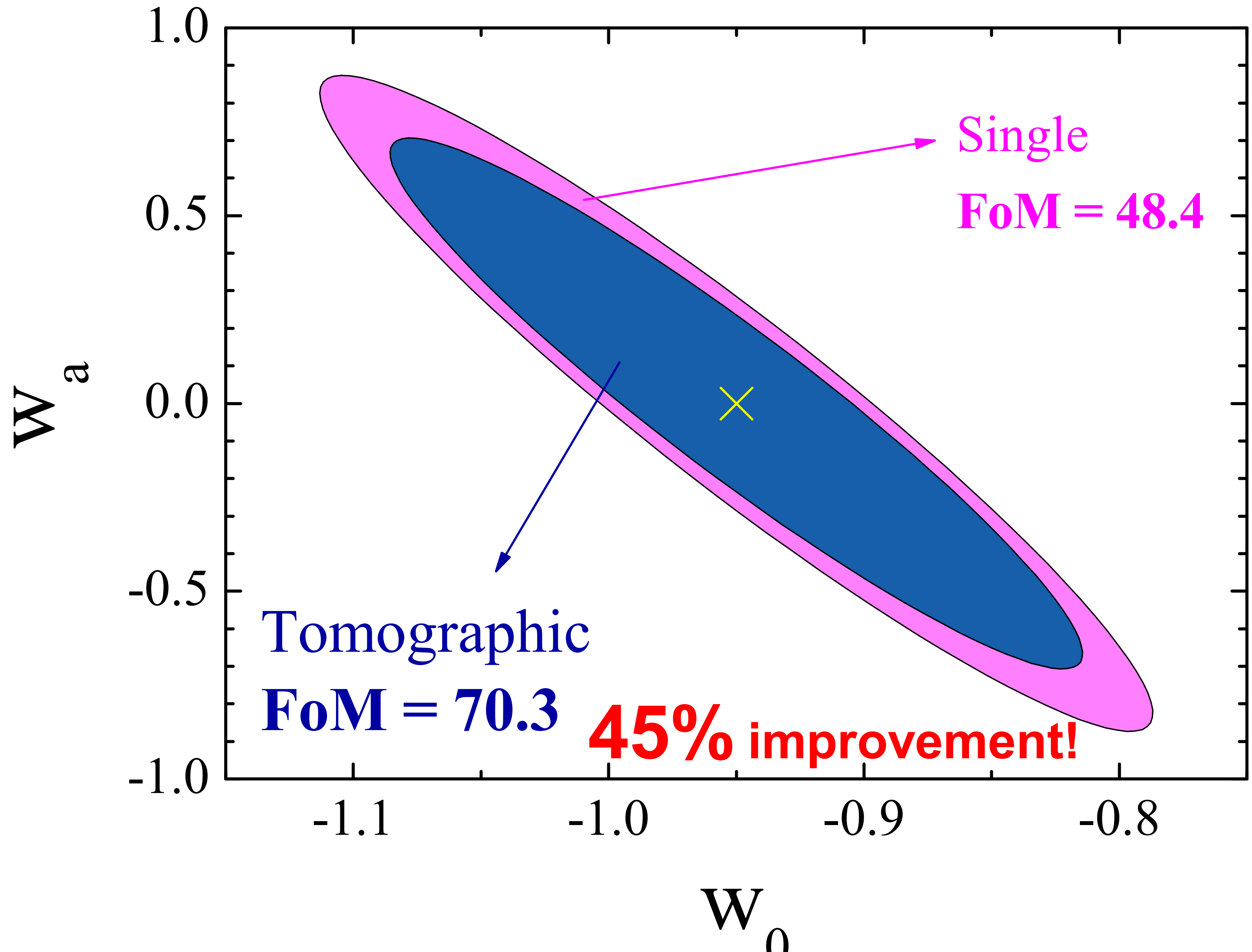
BOSS (Alam et al), 2016, 1607.03155

BOSS DR12 CMASS



BOSS DR12 CMASS

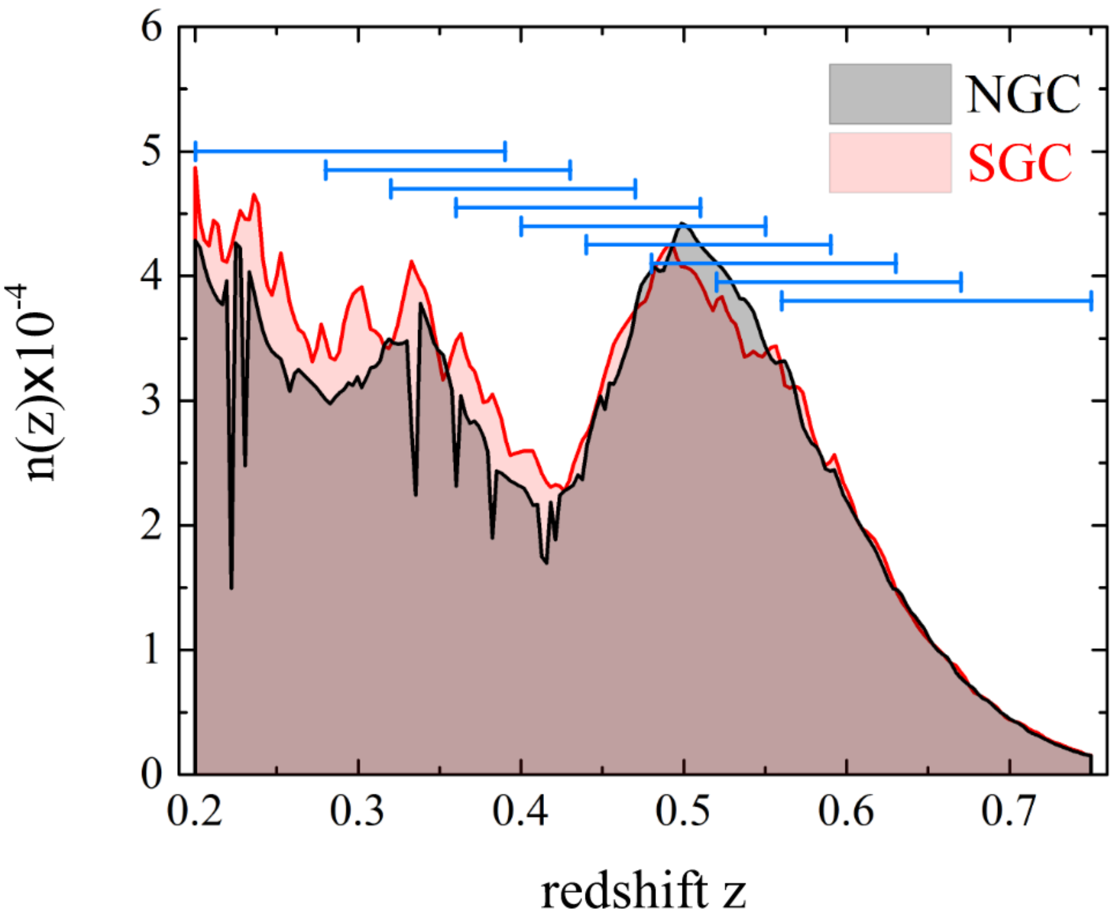




1.0
0.5
0.0
-0.5
-1.0
w
a
-1.1
-1.0
-0.9
-0.8
w
0
Single
FoM = 48.4
Tomographic
FoM = 70.3
45% improvement!

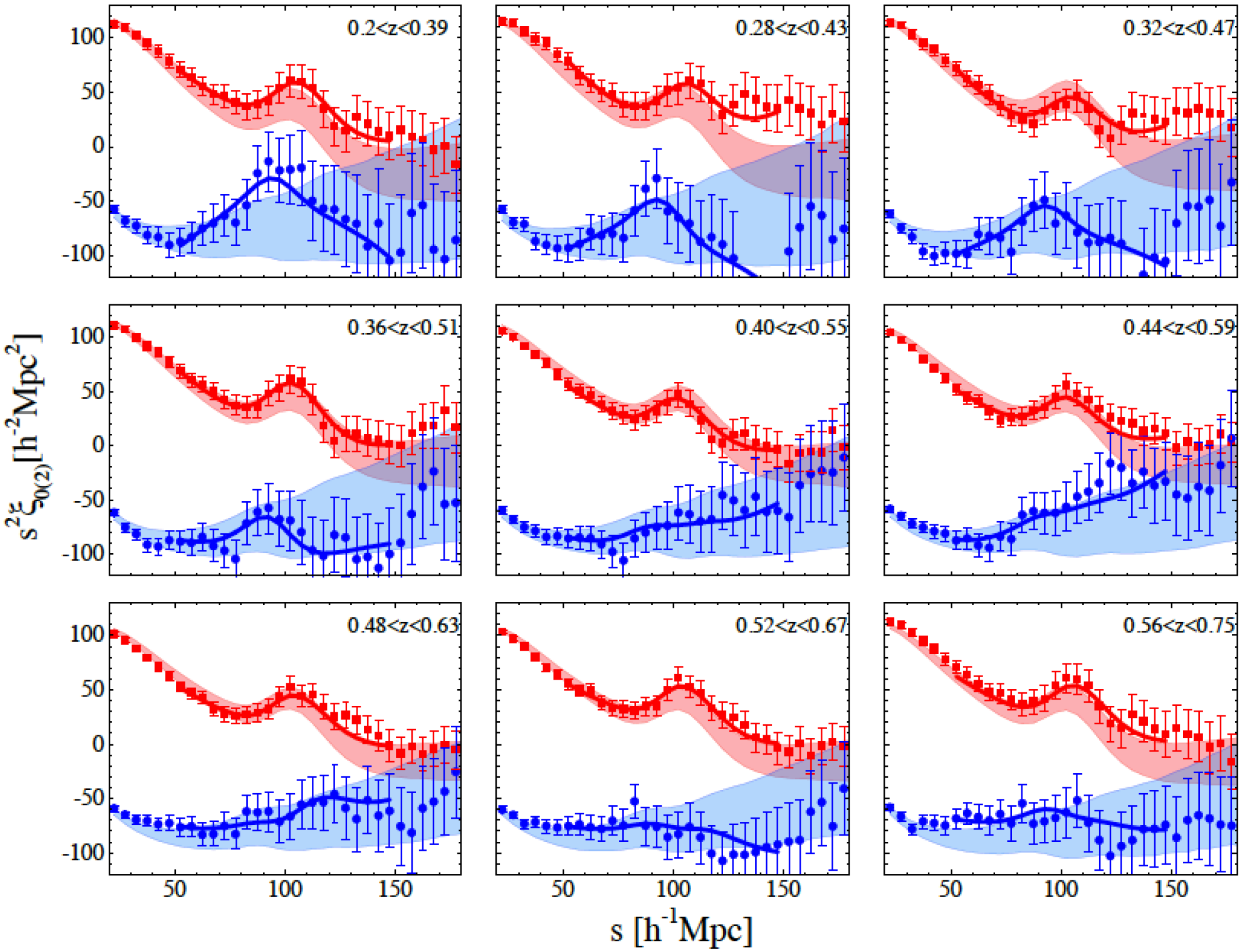
Tomographic BAO measurements from BOSS DR12

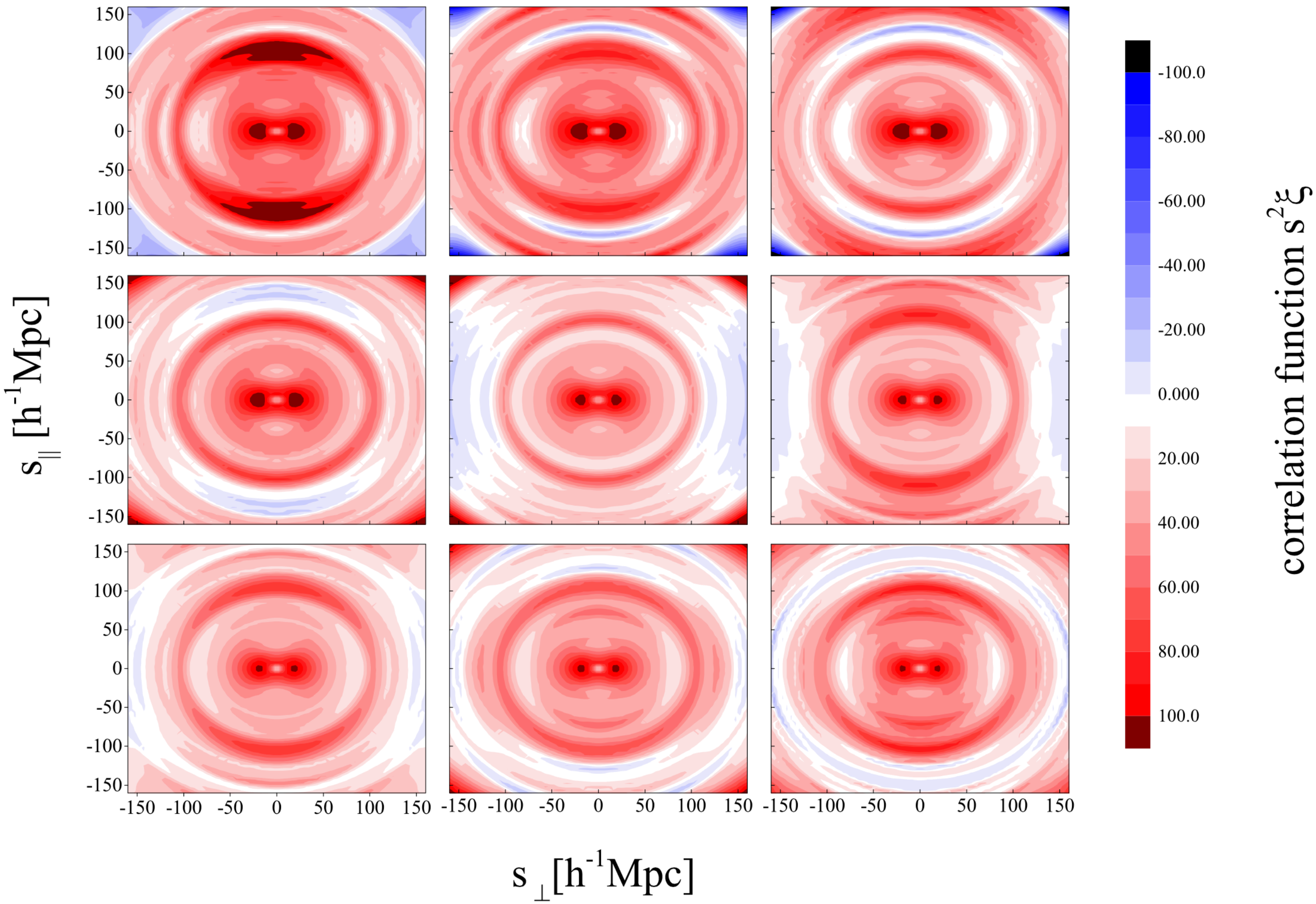
GBZ, Wang, et al, (BOSS team), 1607.03153, MNRAS, 2017
Wang, GBZ, et al, (BOSS team), 1607.03154



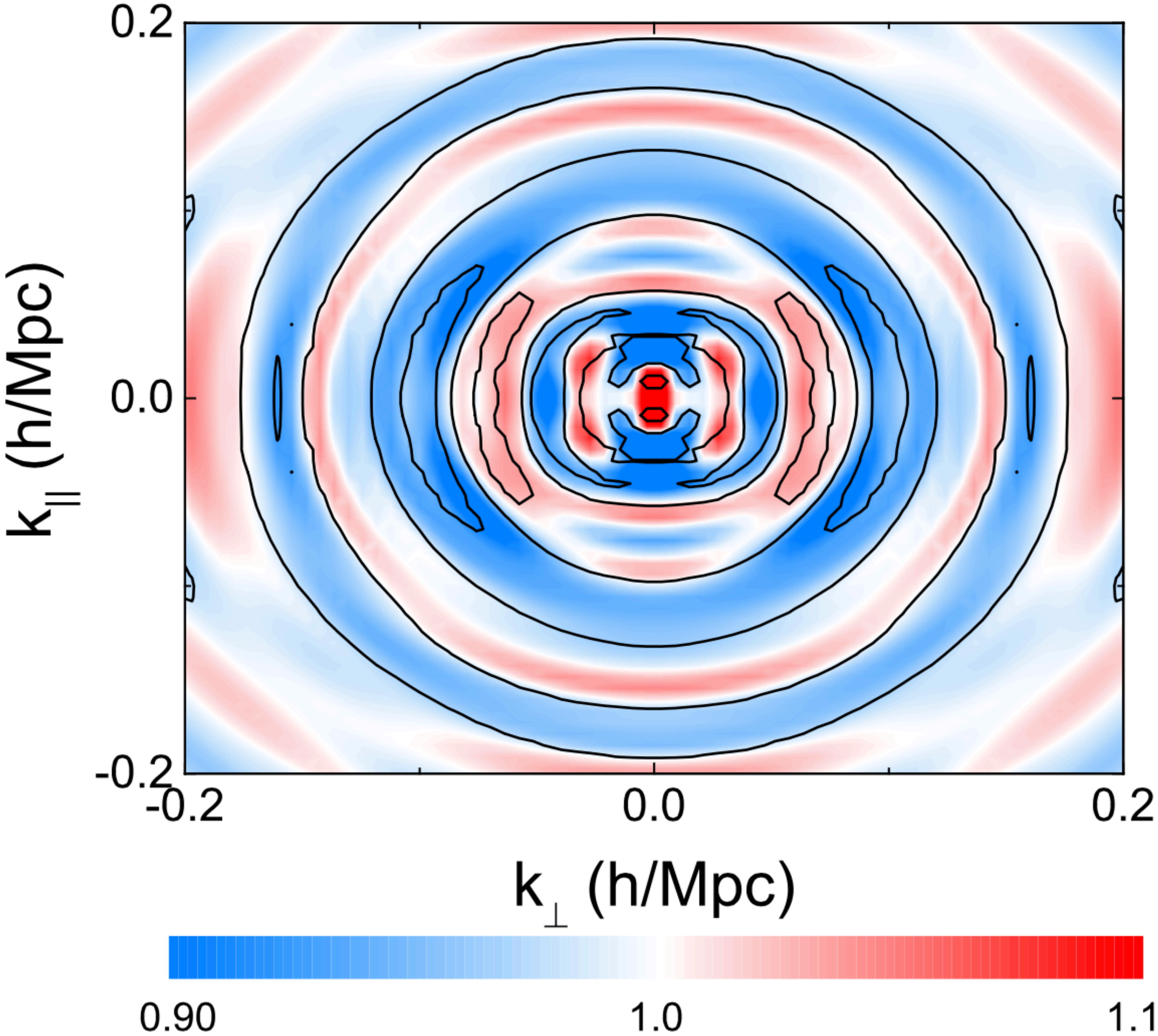
Tomographic galaxy correlation function measurement

BOSS (Wang, GBZ et al), 2016



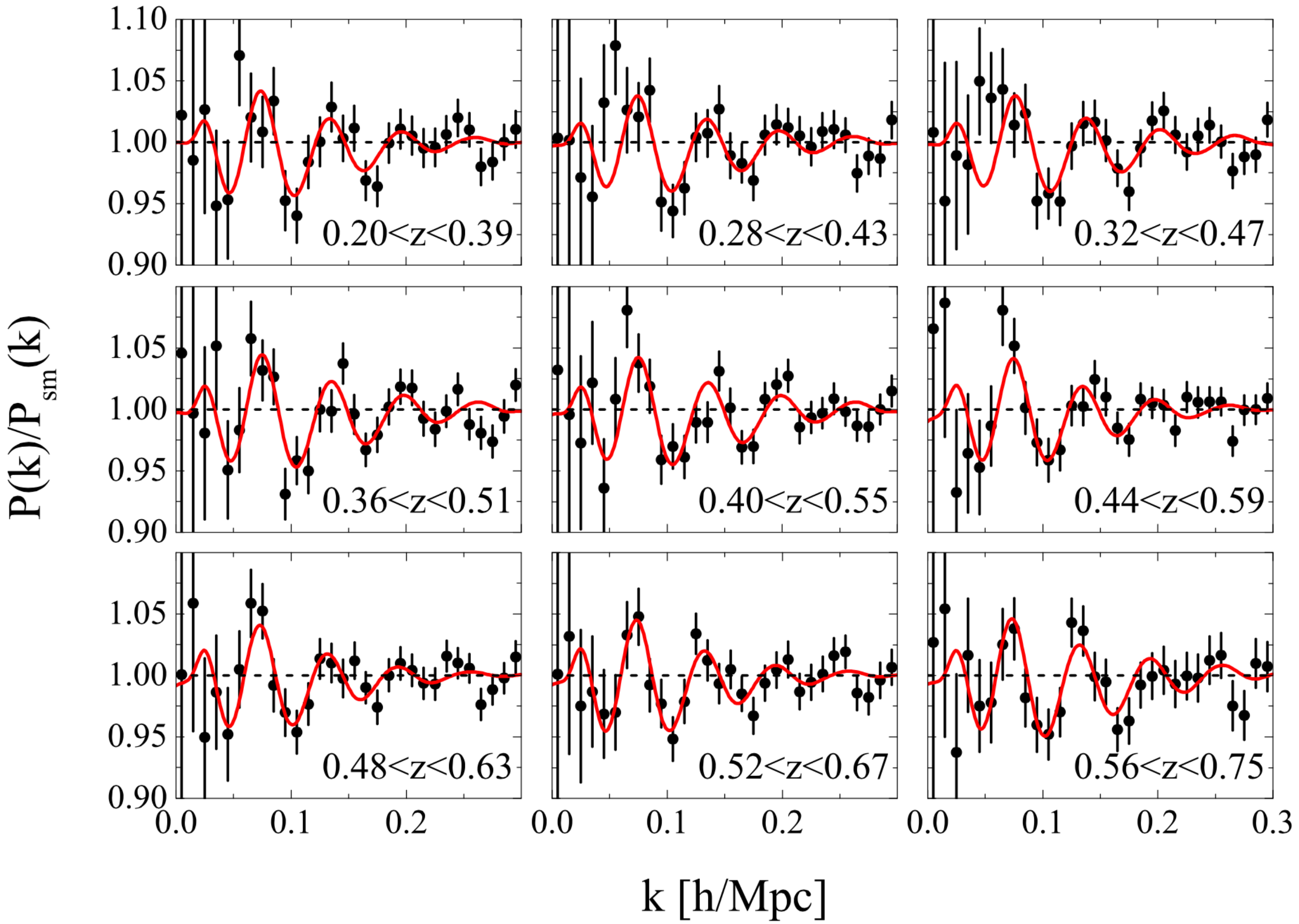


BOSS (Yuting Wang, GBZ et al), 2016, 1607.03154

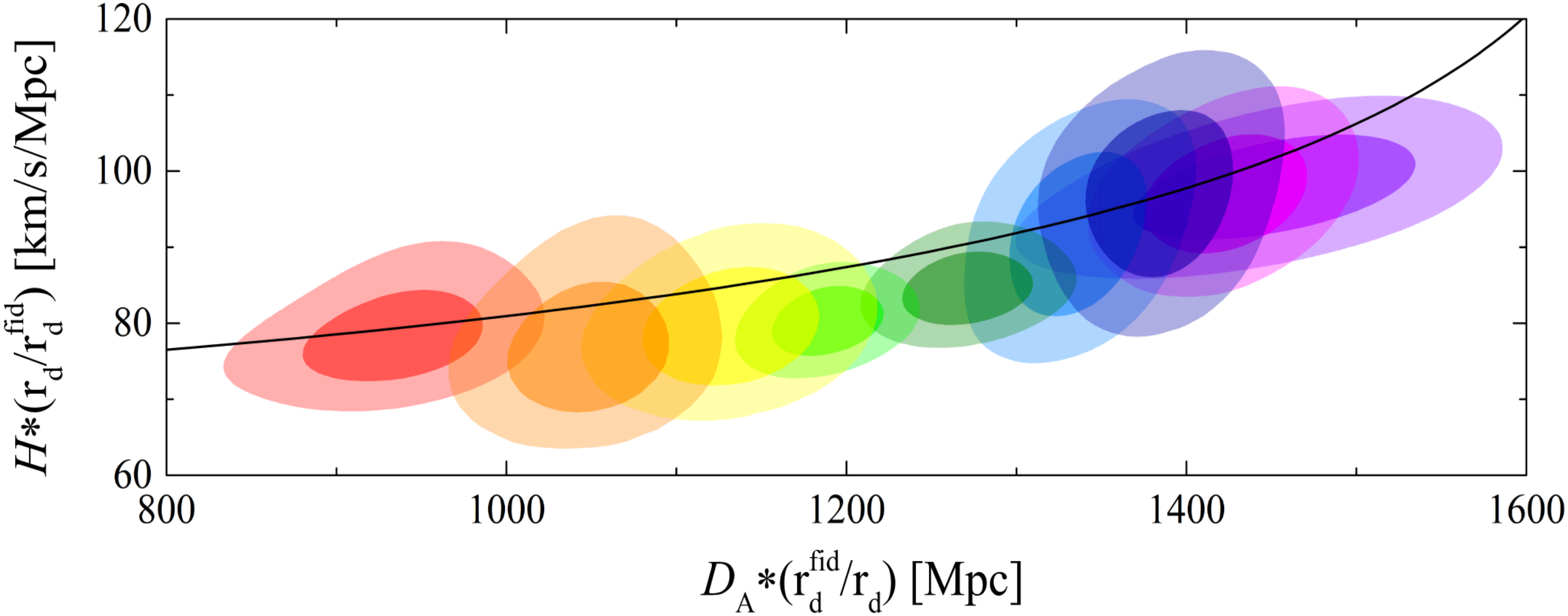


BOSS (GBZ, Yuting Wang et al), 2016, 1607.03153

Latest BOSS tomographic BAO measurements

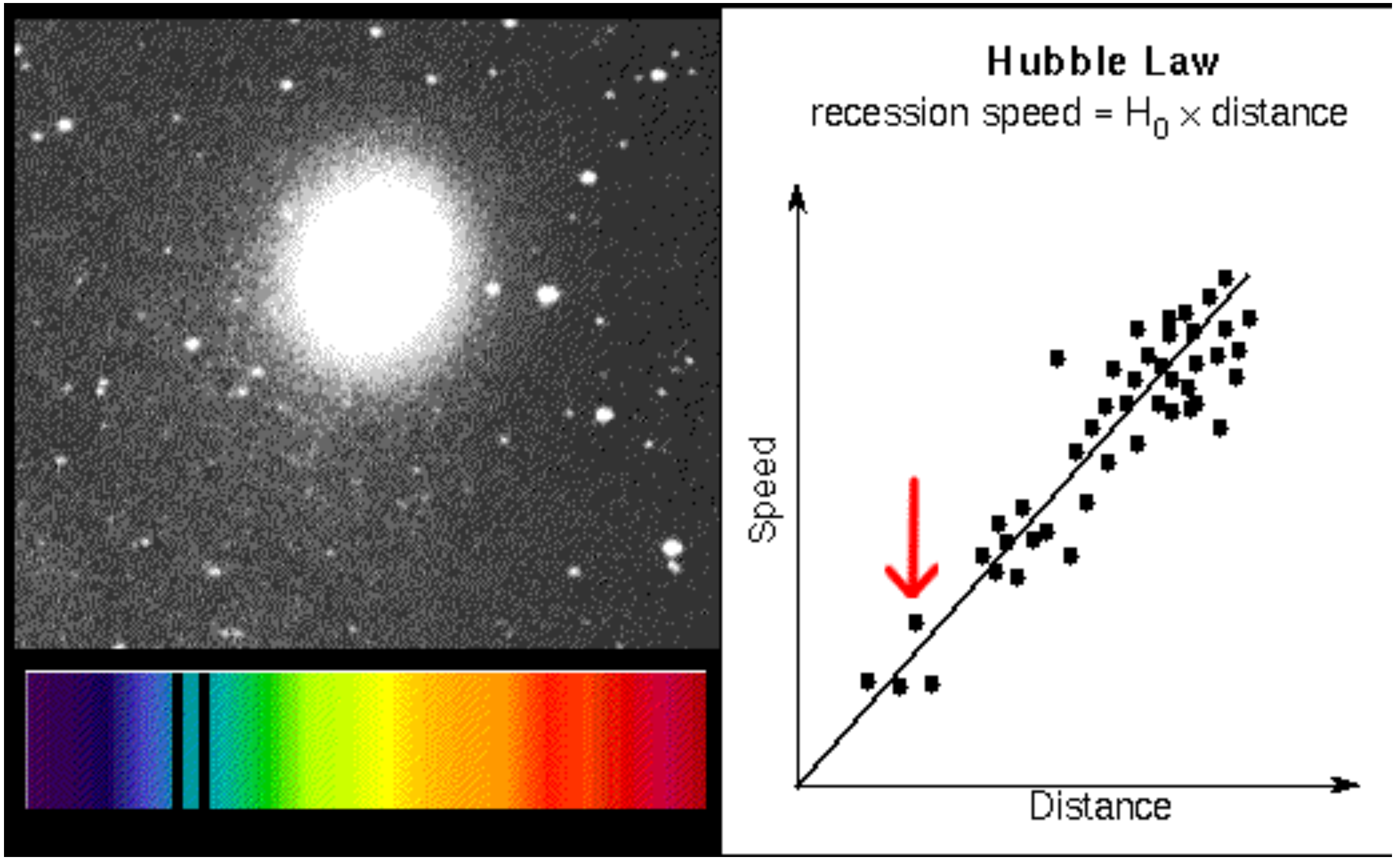


BOSS (GBZ, Yuting Wang et al), 2016, 1607.03153



BOSS (GBZ, Yuting Wang et al), 2016, 1607.03153

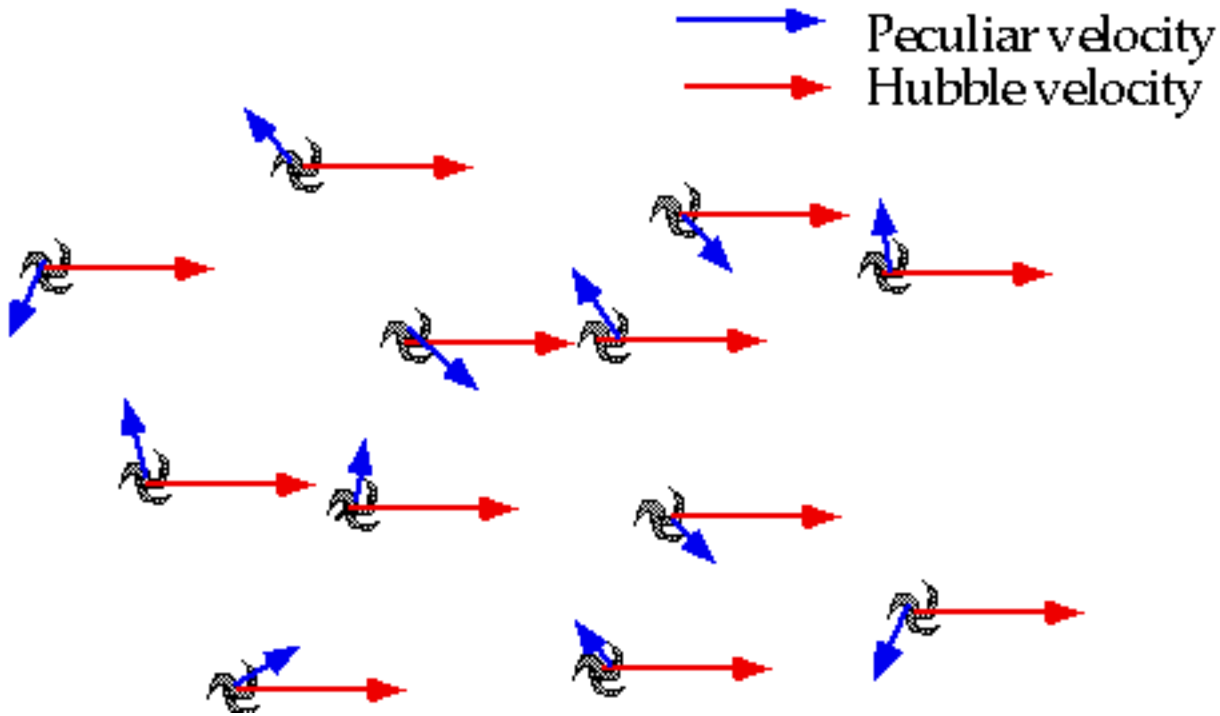
The Redshift Space Distortion (RSD)



We use redshift *z* to infer distance *d* in redshift surveys!

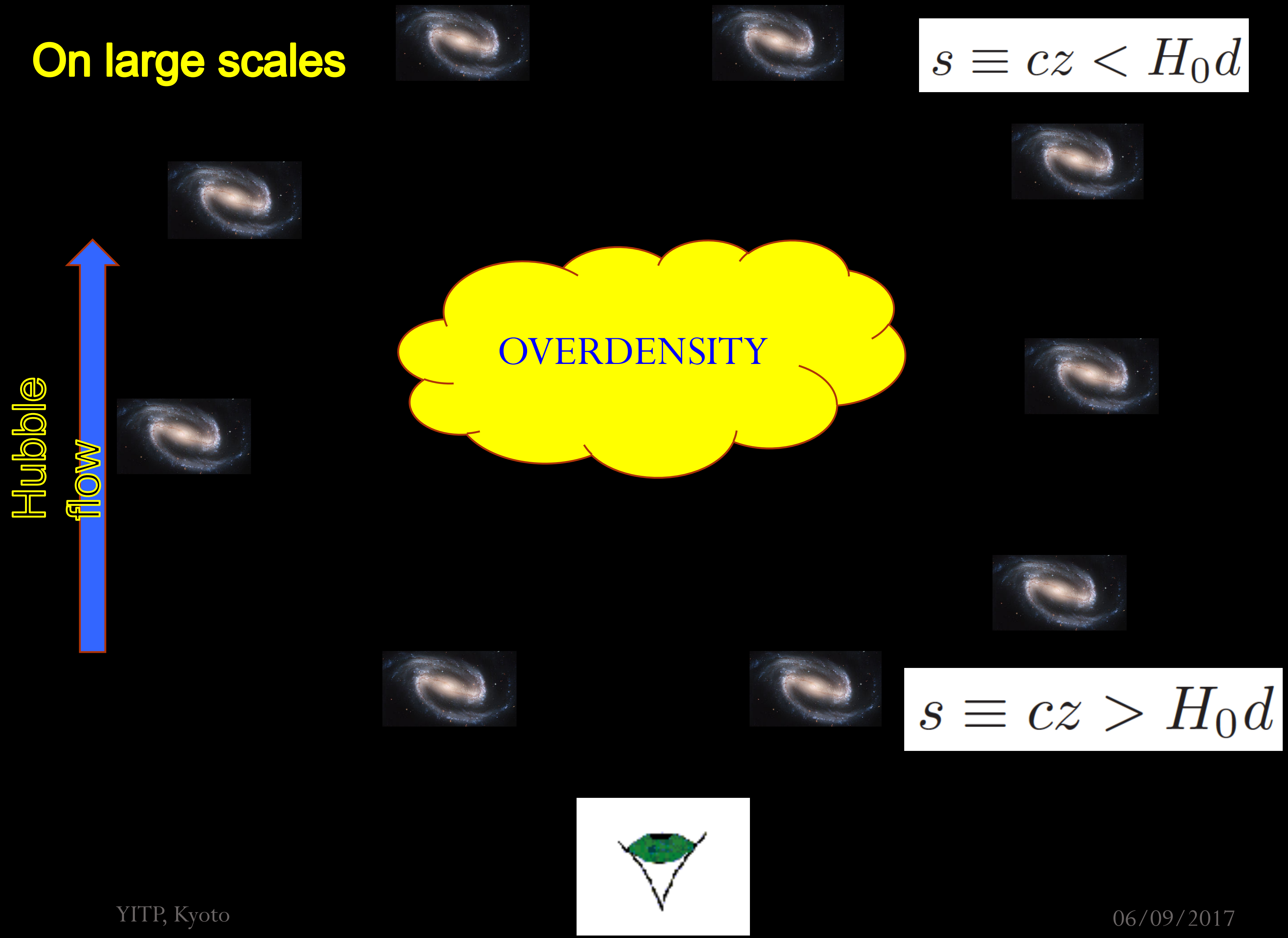
$$cz = H_0 d$$

Galaxies have *peculiar motions* due to the local overdensity on top of the Hubble velocity



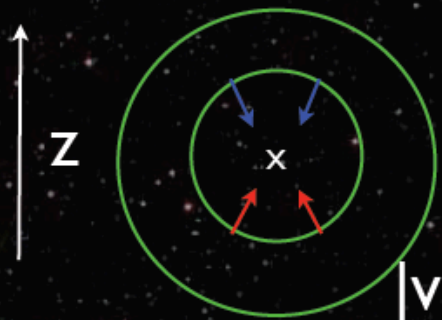
$$cz = H_0 d \boxed{+ \hat{\mathbf{r}} \cdot \mathbf{v}}$$

On large scales



Redshift Space Distortions (RSD)

real to redshift space separations



$$\nabla \cdot \mathbf{v_p} = -aHf\, \delta_m$$

$$|v_p| \sim d\, \sigma_8 / d \ln a = \sigma_8 * f$$

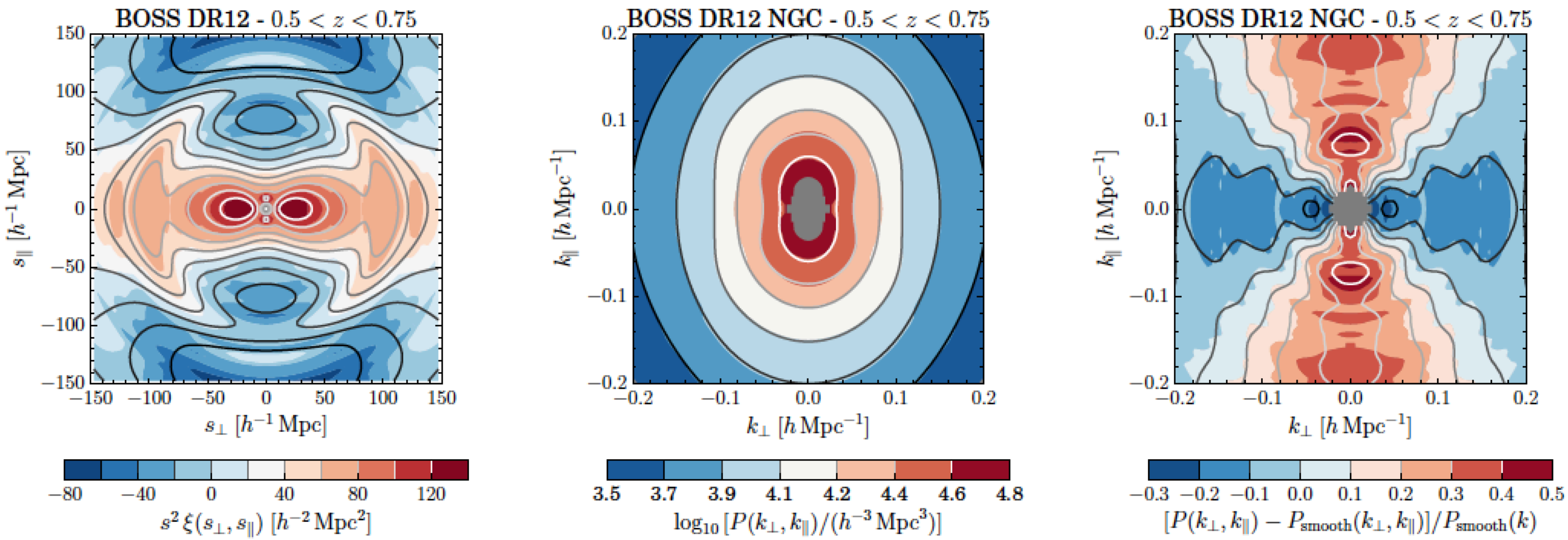
isotropic

squashed along line of sight

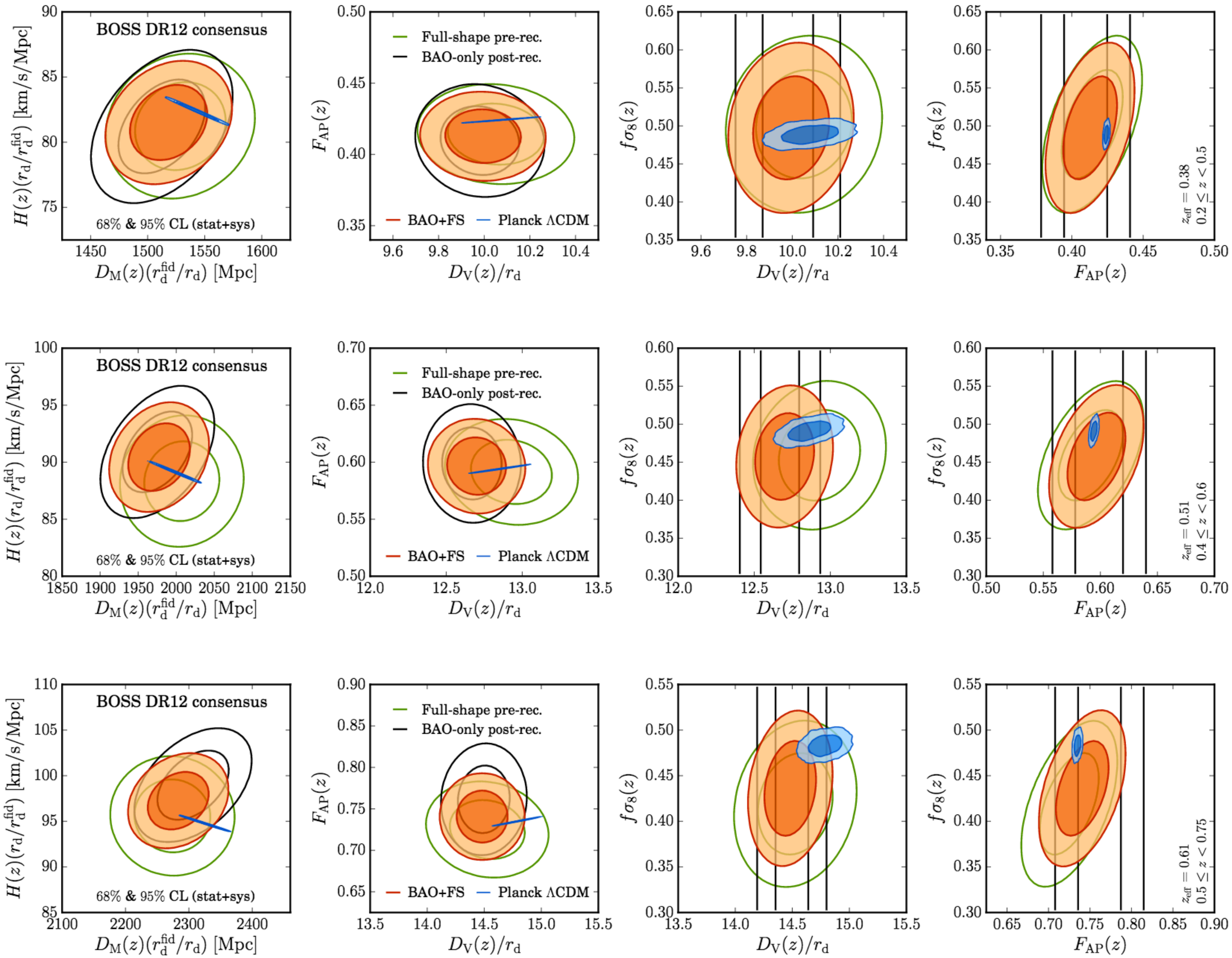
$$f = d \ln \sigma_8 / d \ln a$$

Kaiser, 1987

Latest BOSS DR12 RSD measurements

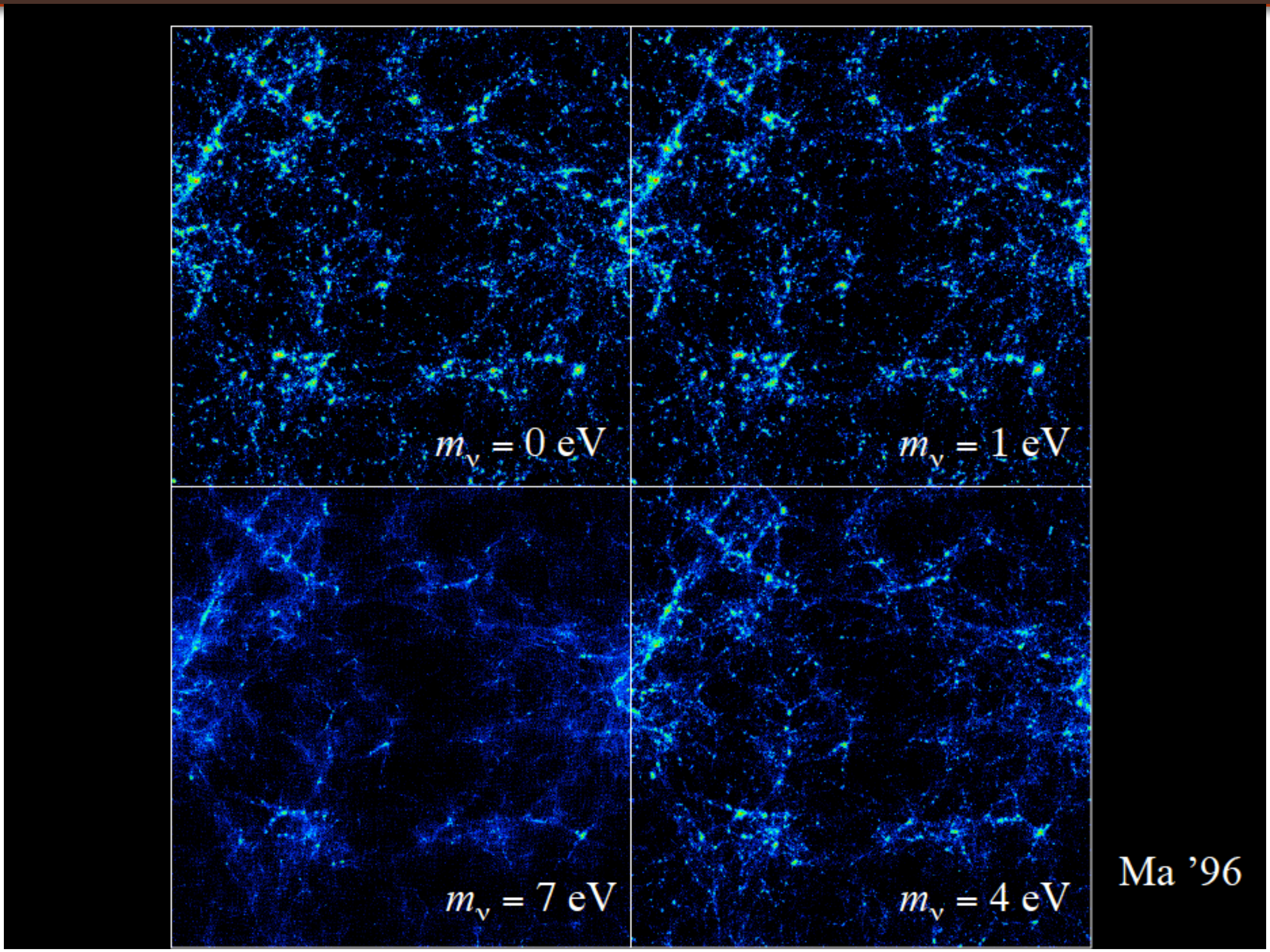


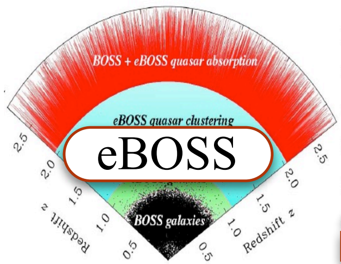
BOSS (Alam et al), 2016, 1607.03155

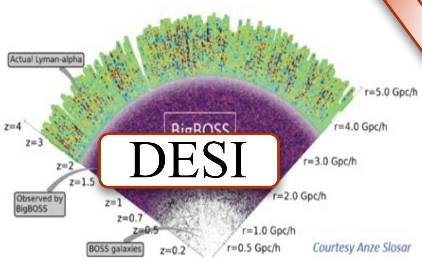


BOSS (Alam et al), 2016, 1607.03155

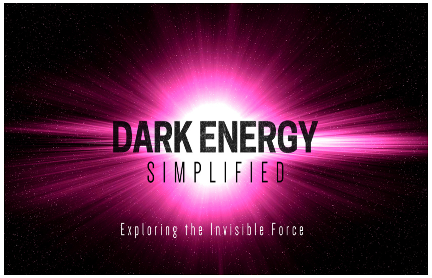
Free streaming effect: a probe for neutrinos




BOSS + eBOSS quasar absorption
eBOSS quasar clustering
eBOSS
BOSS galaxies
Redshift z
Redshift z


Actual Lyman-alpha
DESI
Observed by BigBOSS
BOSS galaxies
z=4
z=3
z=2
z=1.5
z=1
z=0.7
z=0.5
z=0.2
r=5.0 Gpc/h
r=4.0 Gpc/h
r=3.0 Gpc/h
r=2.0 Gpc/h
r=1.0 Gpc/h
r=0.5 Gpc/h
Courtesy Anze Slosar

BAO

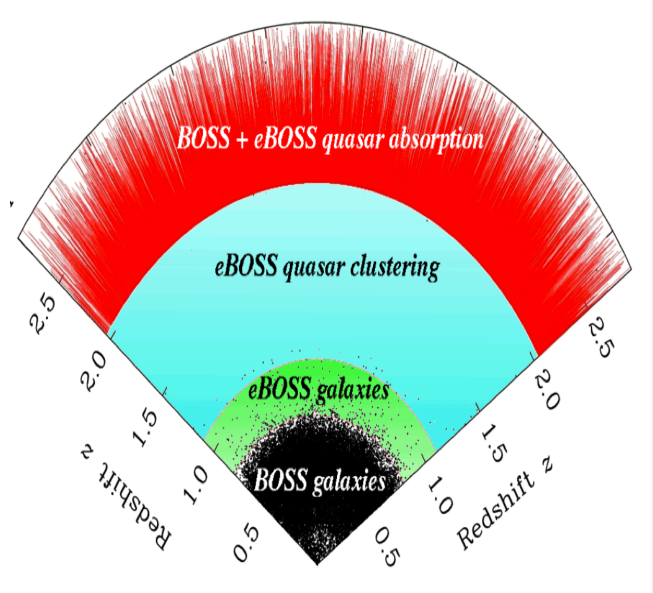

DARK ENERGY
SIMPLIFIED
Exploring the Invisible Force

RSD


GRAVITY

FS

eBOSS Survey (started summer 2014)



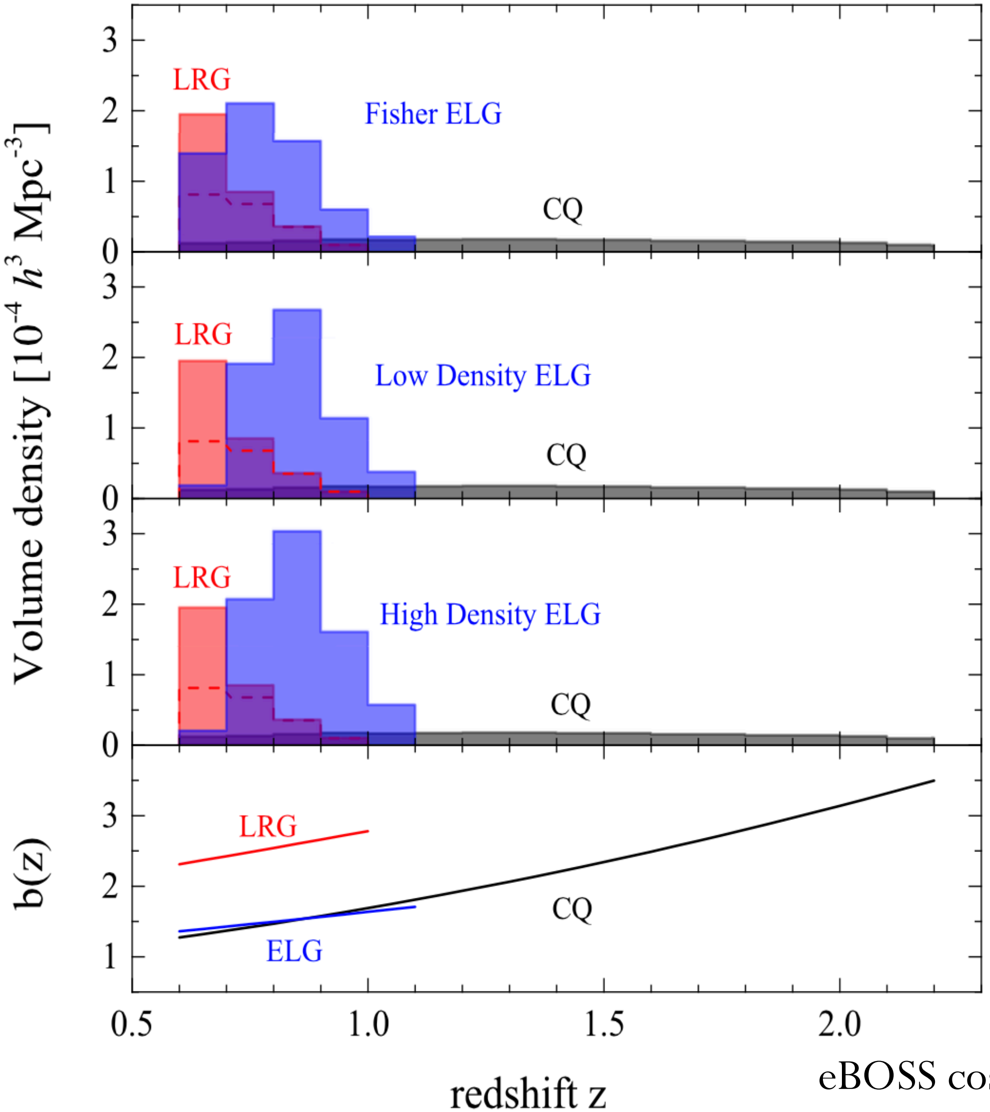
Planned eBOSS coverage of the universe

- ✧ Dark-time observations
- ✧ Fall 2014 – Spring 2020
- ✧ 1000 fibers per 7 deg2 plate
- ✧ Wavelength: 360-1000 nm, resolution R~2000

- ✧ 1–2% distance measurements from baryon acoustic oscillations between $0.6 < z < 2.5$

http://www.sdss.org

eBOSS specification



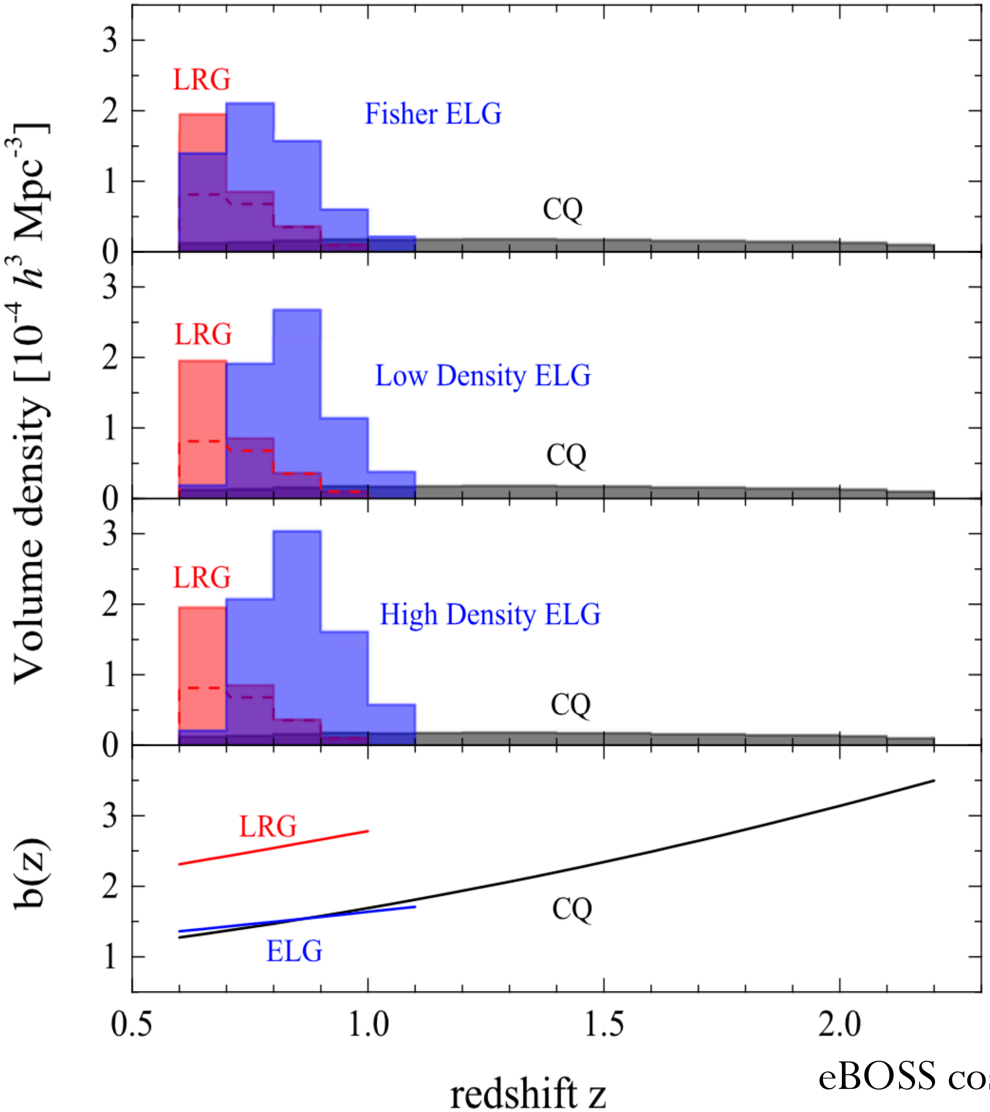
LRG: 375k, 7500 deg^2

ELG: 260k, 1100-1500 deg^2

QSO: 740k, 7500 deg^2

eBOSS cosmological forecast (GBZ et al, 1510. 08216)

eBOSS specification



LRG: 375k, 7500 deg^2

ELG: 260k, 1100-1500 deg^2

QSO: 740k, 7500 deg^2

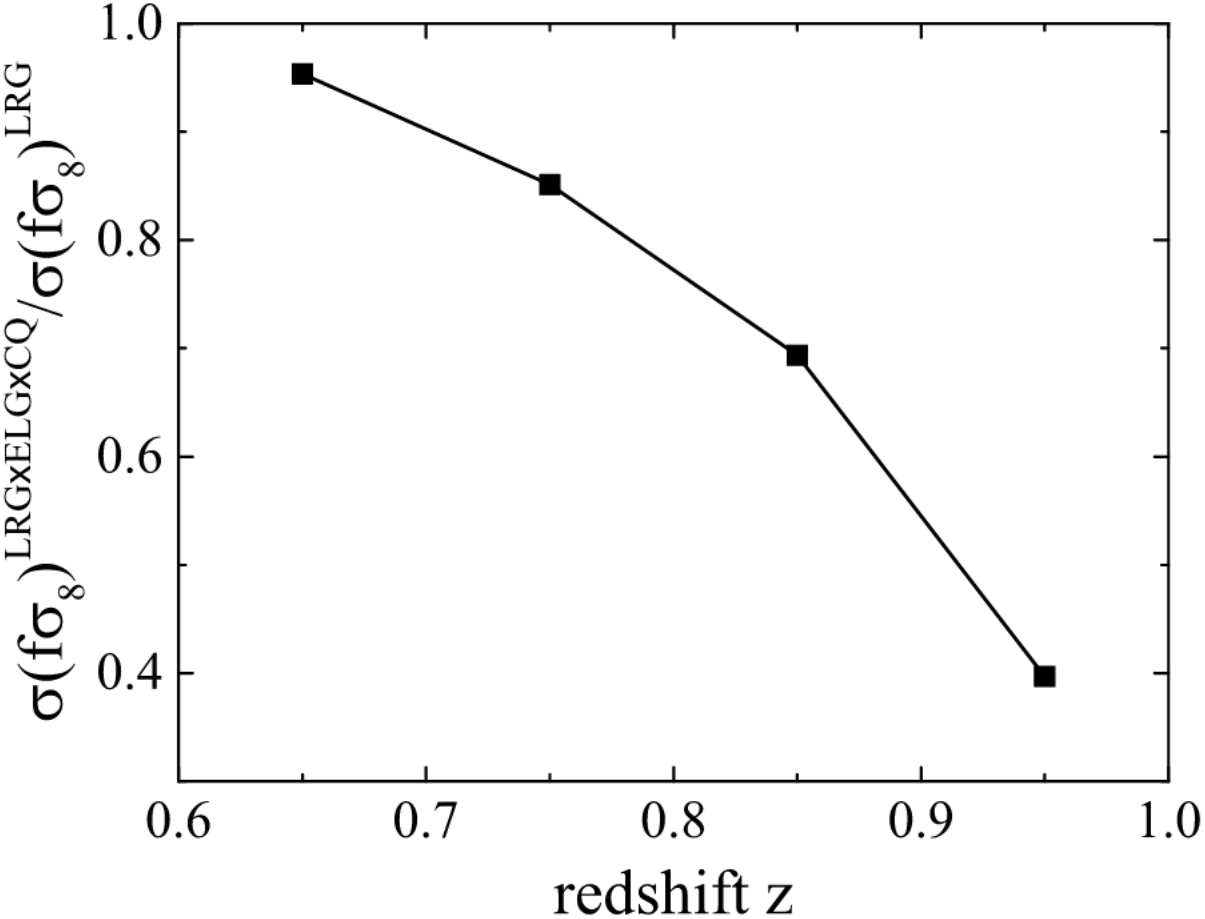
Additional gain by x-correlating LRG with ELG

The Multi-tracer technique

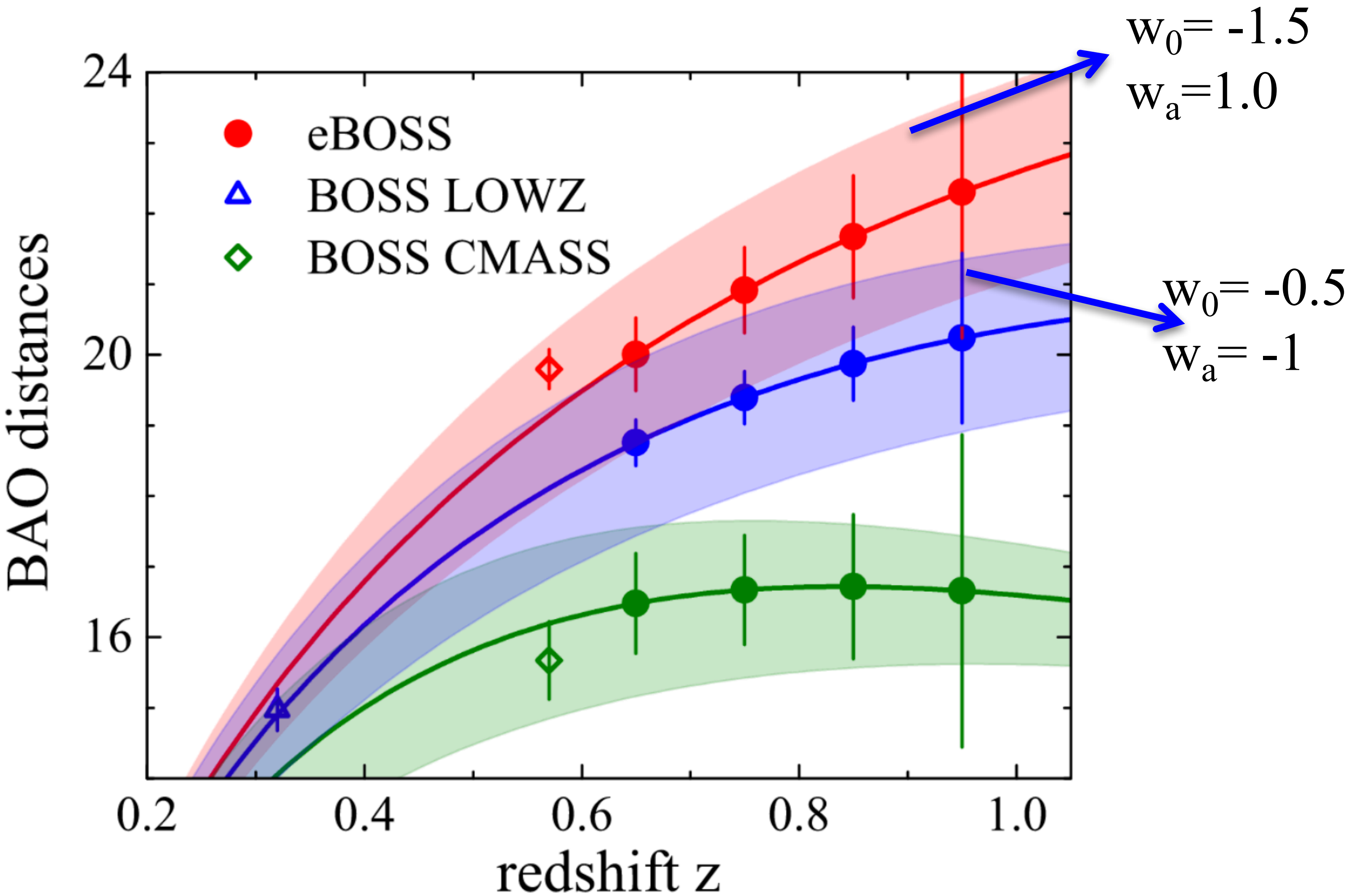
McDonald & Seljak 08

Seljak 09

eBOSS cosmological forecast (GBZ et al, 1510. 08216)

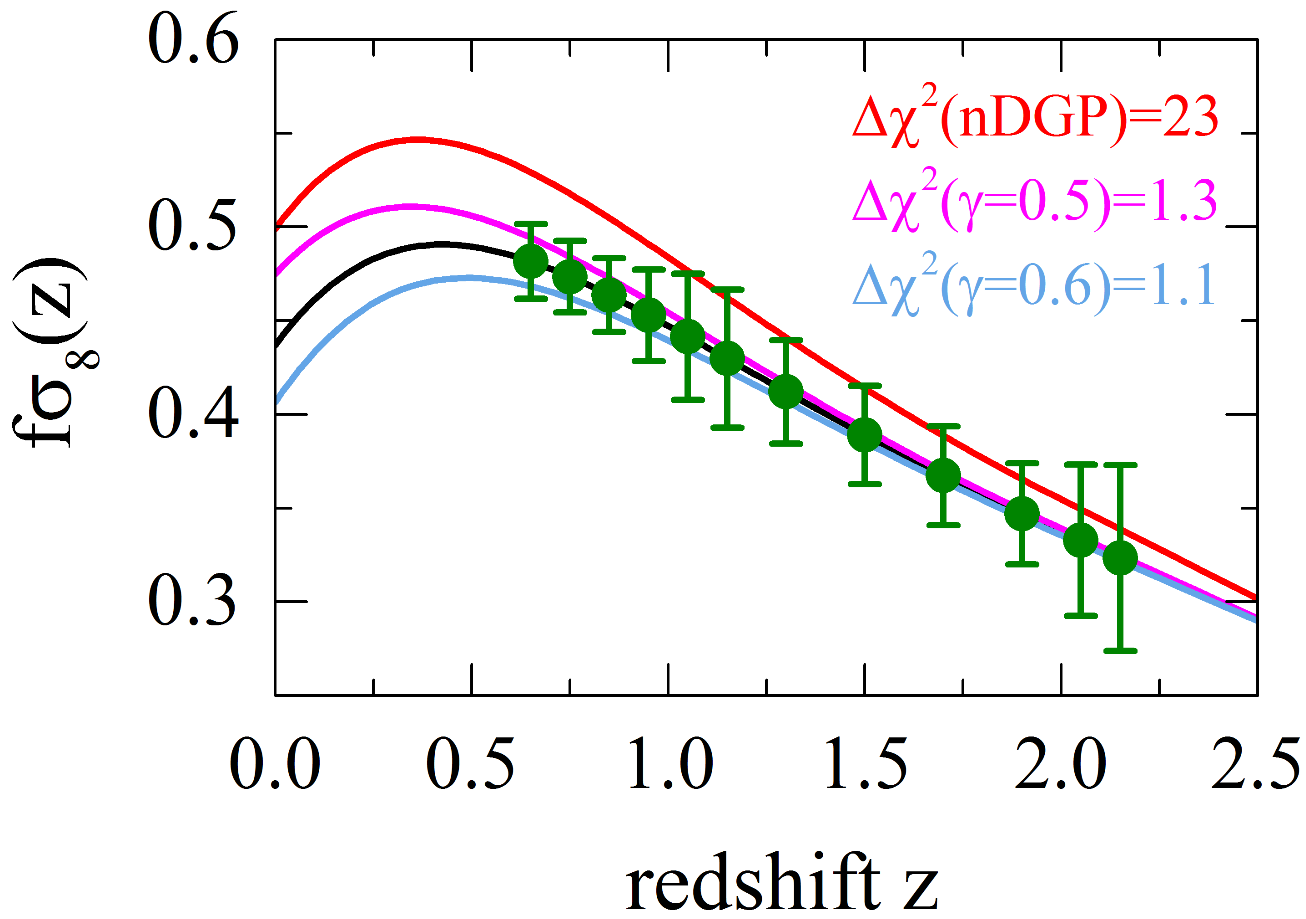


eBOSS cosmological forecast (GBZ et al, 1510. 08216)

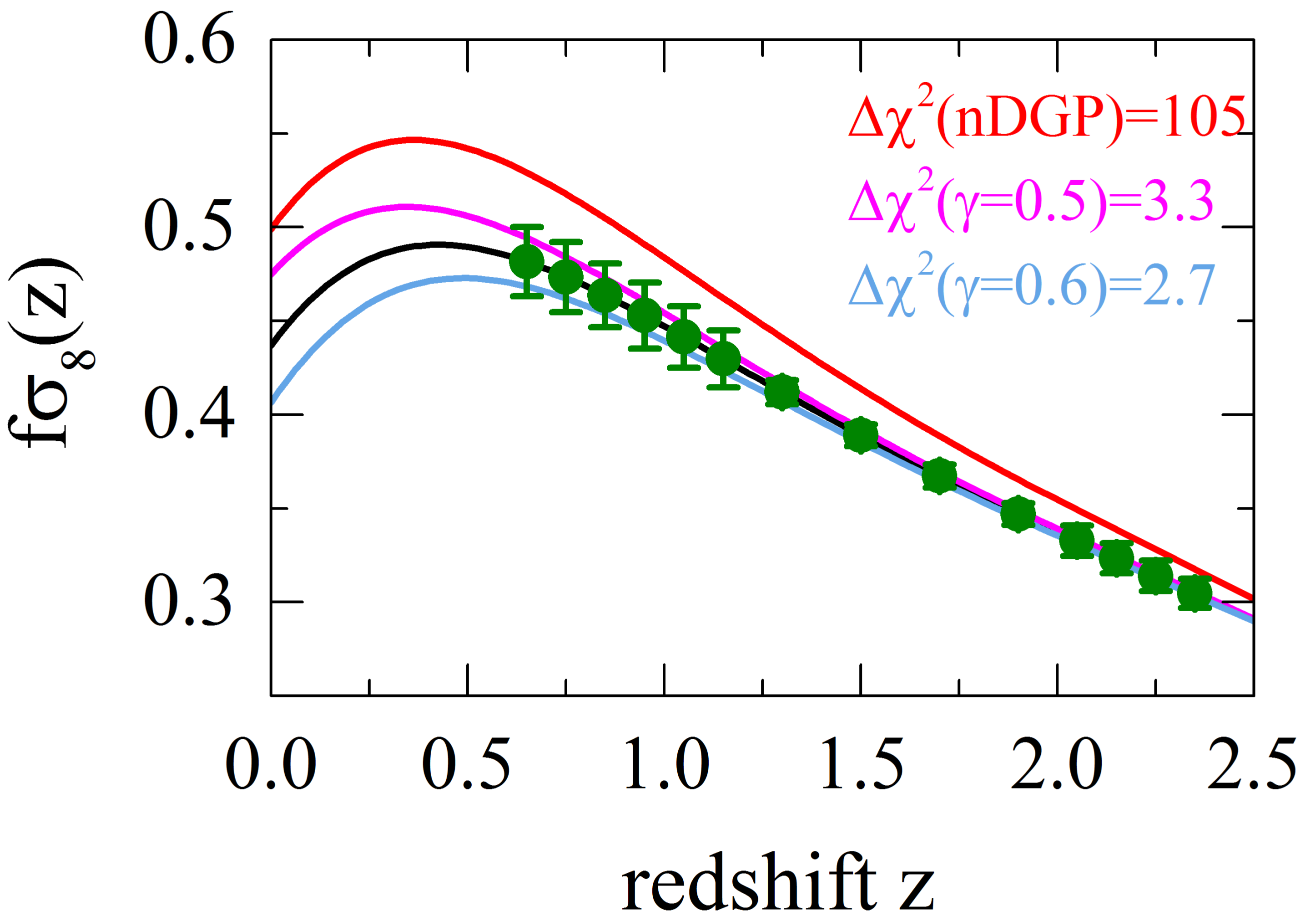


eBOSS cosmological forecast (GBZ et al, 1510. 08216)

eBOSS ability to constrain MG



PFS ability to constrain MG

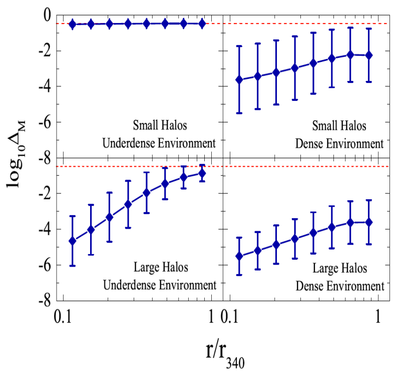


eBOSS status

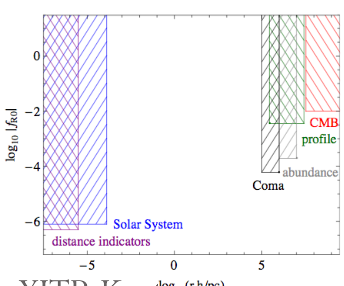
- Year 2 observation (till 2016 summer shutdown) successfully finished
- DR14 data ready internally (QSO and LRG)
- Year 2 data being analysed
- A 4% BAO has been detected using QSO (Ata et al); multiple collaboration papers to release in the fall of 2017

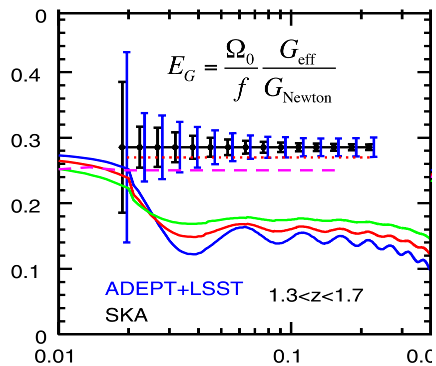
Observational tests on multi-scales

$R <$ Mpc	Mpc $< R <$ Gpc	$R >$ Gpc
Cluster profiles	Galaxy clustering, WL	Reconstructing w(z) using BAO, SN

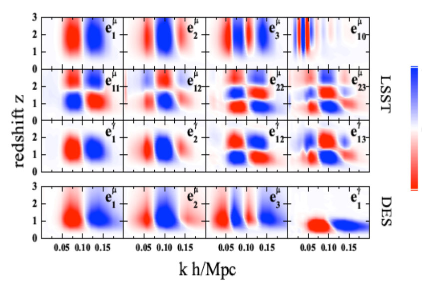


GBZ et al., 2011, PRL

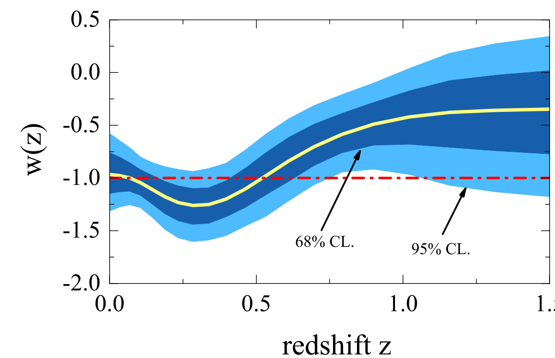




Pengjie Zhang et al., 2007, PRL



GBZ et al., 2009, PRL

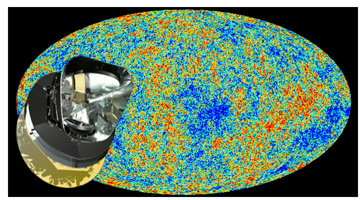


GBZ et al., 2012, PRL

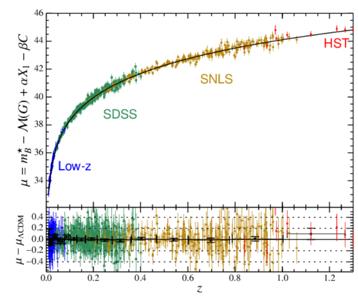
Terukina et al., 2014, JCAP

Current surveys

$R <$ Mpc	Mpc $< R <$ Gpc	$R >$ Gpc
Cluster profiles	Galaxy clustering, WL	Reconstructing w(z) using BAO, SN



Planck



740 SNe from SNLS

BOSS
z<0.6

~50 clusters

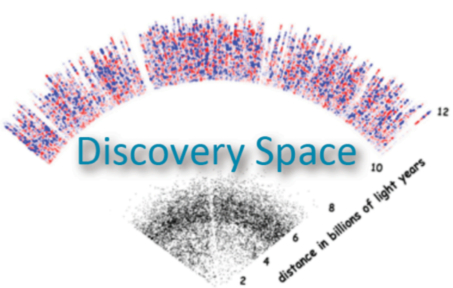
Surveys in 5 years

$R <$ Mpc	Mpc $< R <$ Gpc	$R >$ Gpc
Cluster profiles	Galaxy clustering, WL	Reconstructing w(z) using BAO, SN

IFU
~10000 spectra

~2000 clusters

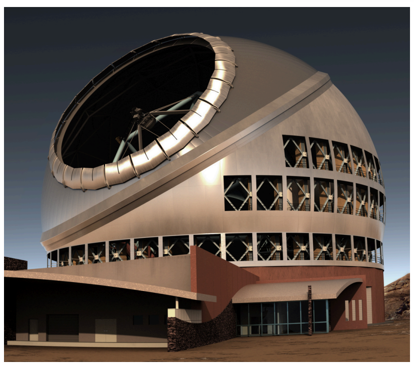
DES
~1000 SNe
5000 deg^2

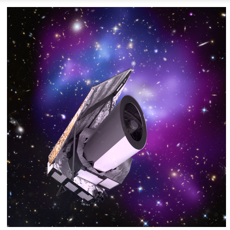


eBOSS
$0.6<z<2.5$

Surveys in 10 years

R < Mpc	Mpc < *R* < Gpc	*R* > Gpc
Cluster profiles	Galaxy clustering, WL	Reconstructing w(z) using BAO, SN





TMT: 30 meter imaging

~20000 clusters

DESIRE (Euclid)+LSST ~18k SNe

LSST: 8.4 m, **20000 deg² imaging**

Euclid: 15000 deg² imaging + spectroscopic

DESI: 4 m, **14000 deg² spectroscopic**

PFS: 8 m spectroscopic

SKA: full sky radio

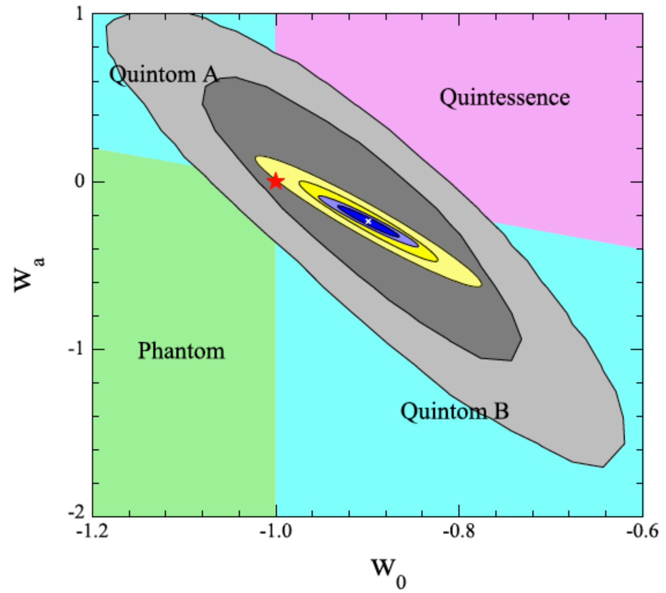
DE as a solution to the accelerating universe problem

$$G_{\mu\nu} = \frac{1}{M_p^2}\widetilde{T}_{\mu\nu}$$

Dark Energy

- Negative pressure:

$$\ddot{a}/a = -\frac{4\pi G}{3}(\rho + 3p) > 0$$
$$\Rightarrow w \equiv p/\rho < -1/3$$



GBZ & Zhang, 2010

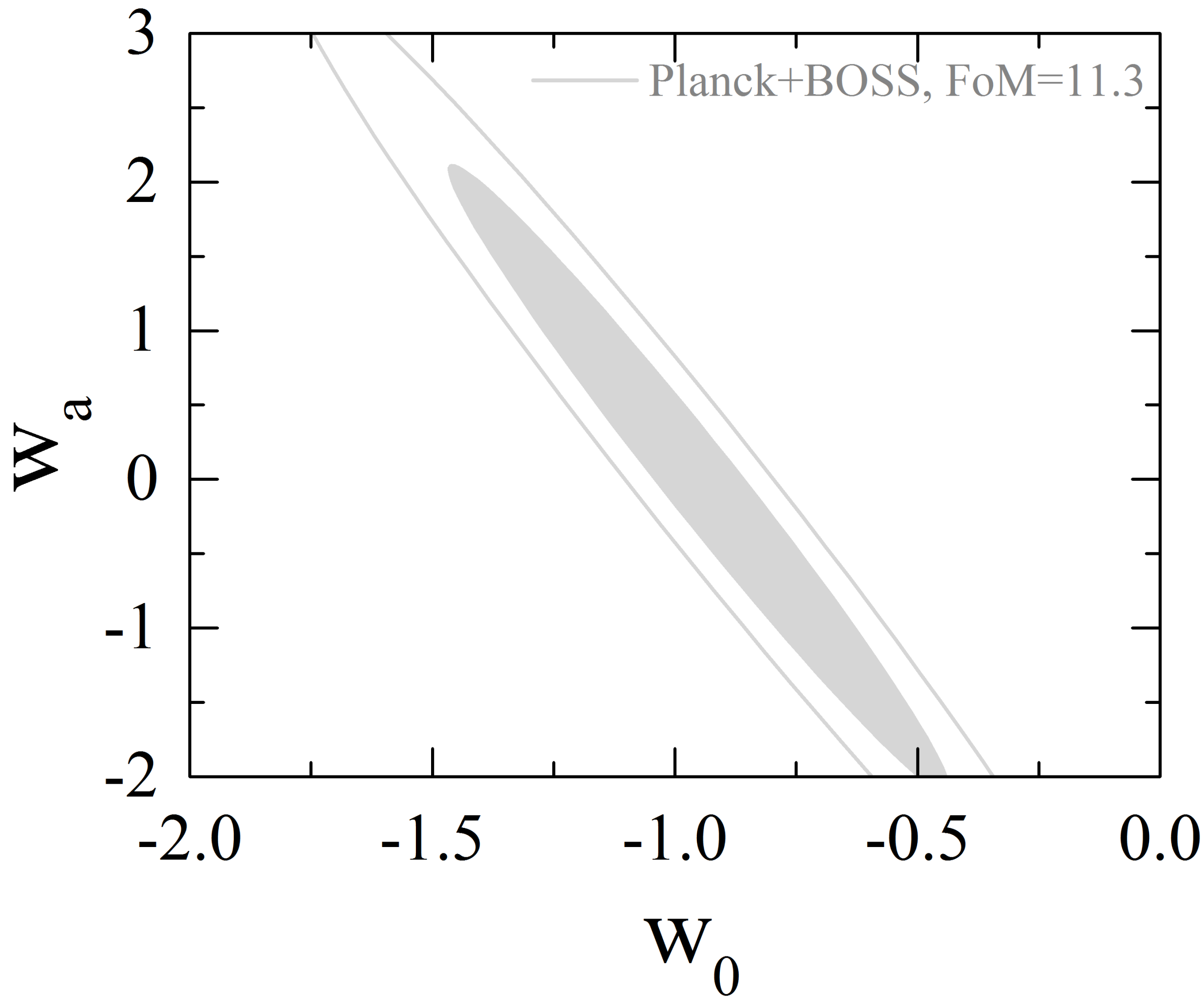
- Candidates: Vacuum energy : $w = -1$

  Dynamical fields:

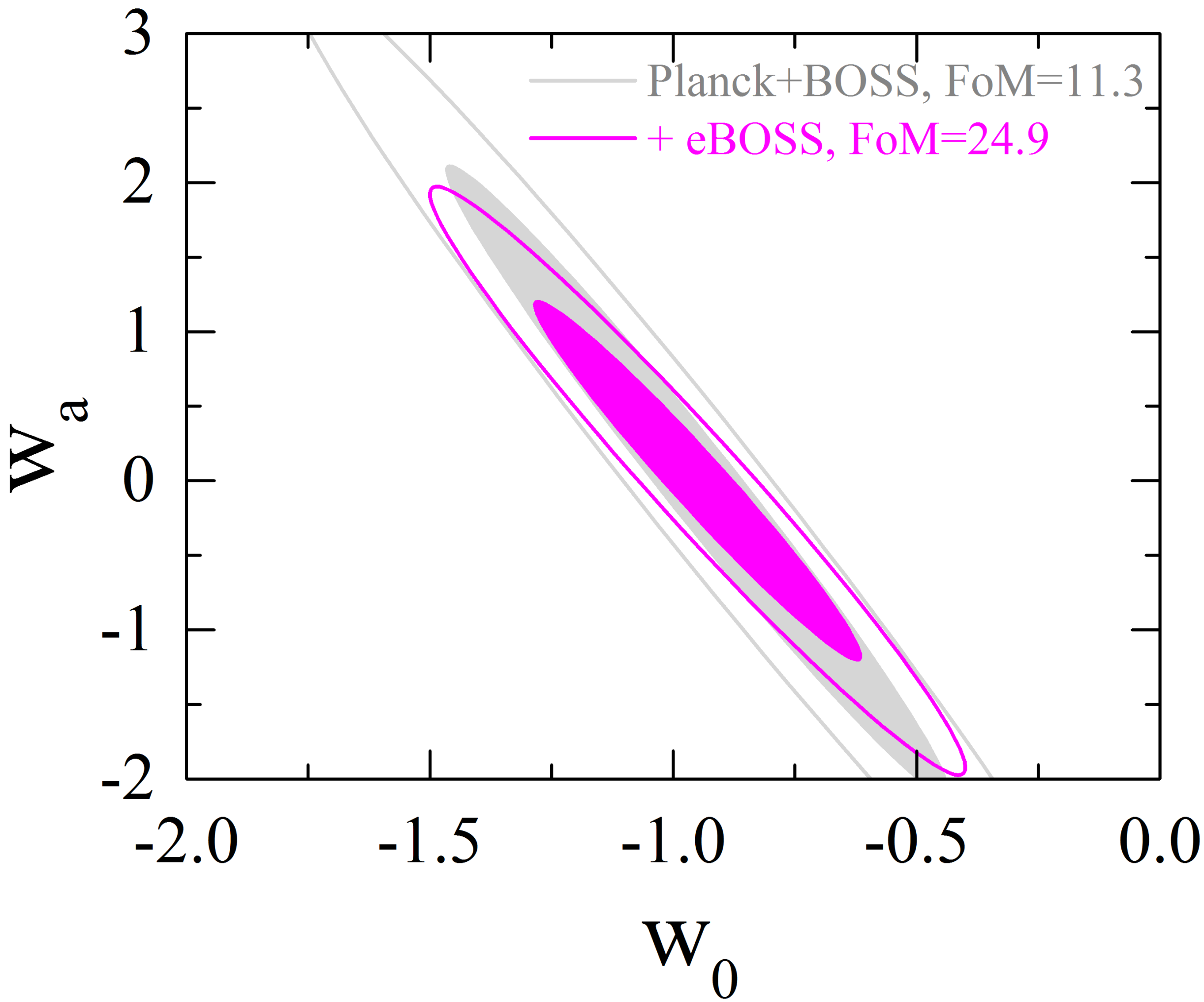
  Quintessence (Ratra & Peebles, 1988): $w(a) > -1$

  Phantom (Caldwell, 2002): $w(a) < -1$

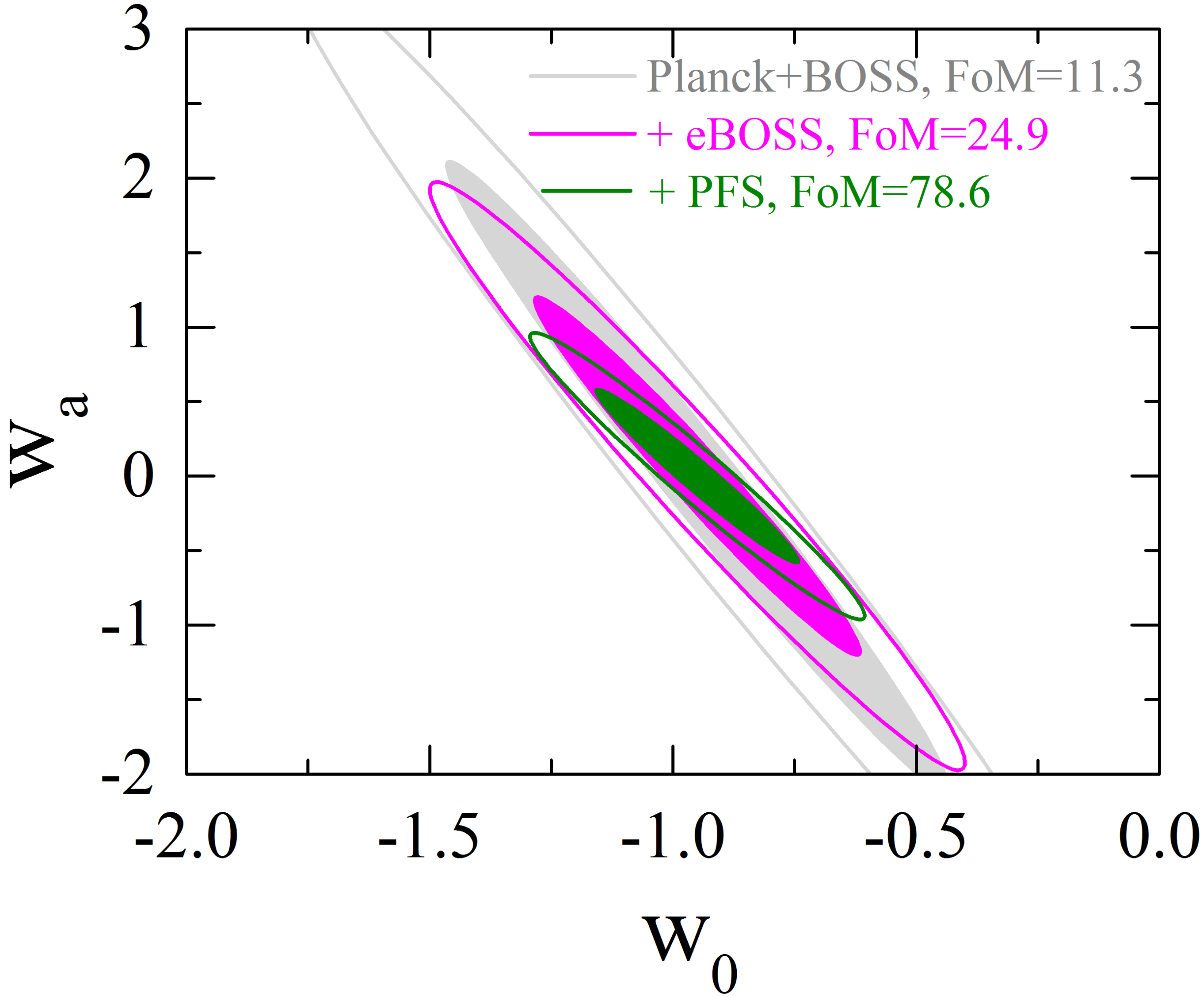
  Quintom (Feng, Wang and Zhang 2004): w (a) across -1



eBOSS forecast (GBZ et al, 2015)



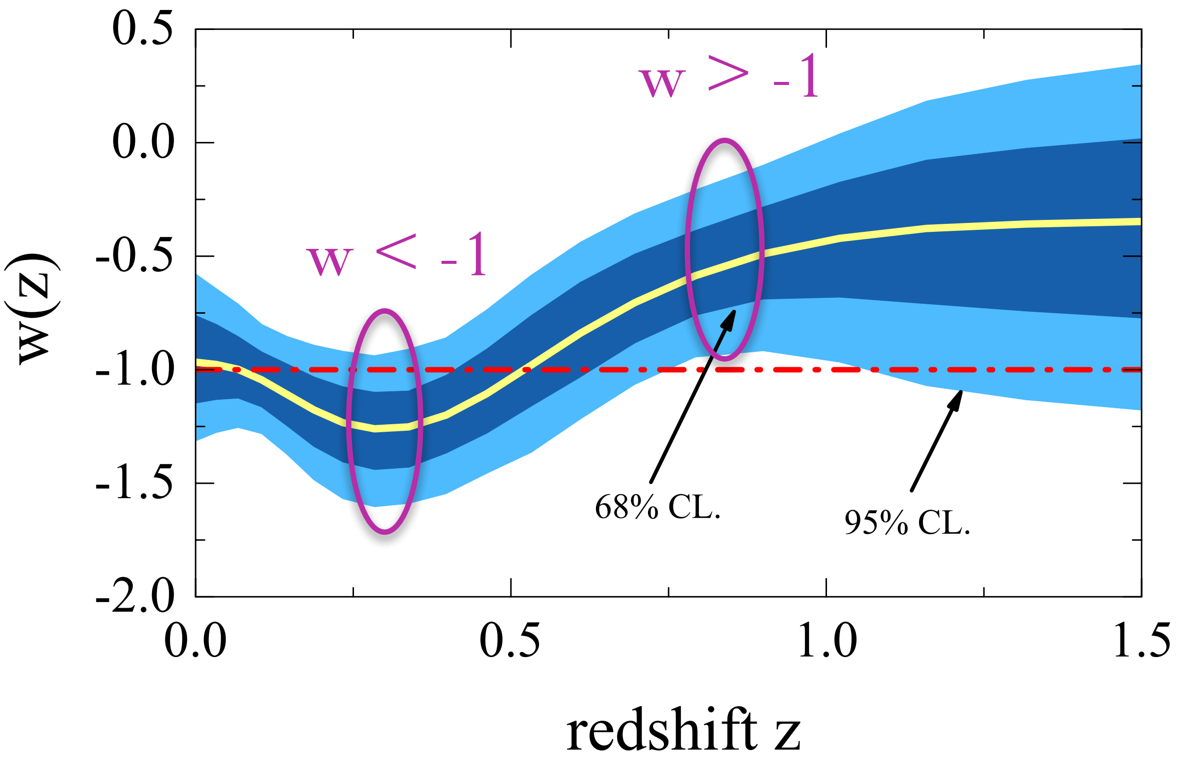
eBOSS forecast (GBZ et al, 2015)



PFS parameters taken from Takada et al, 2014

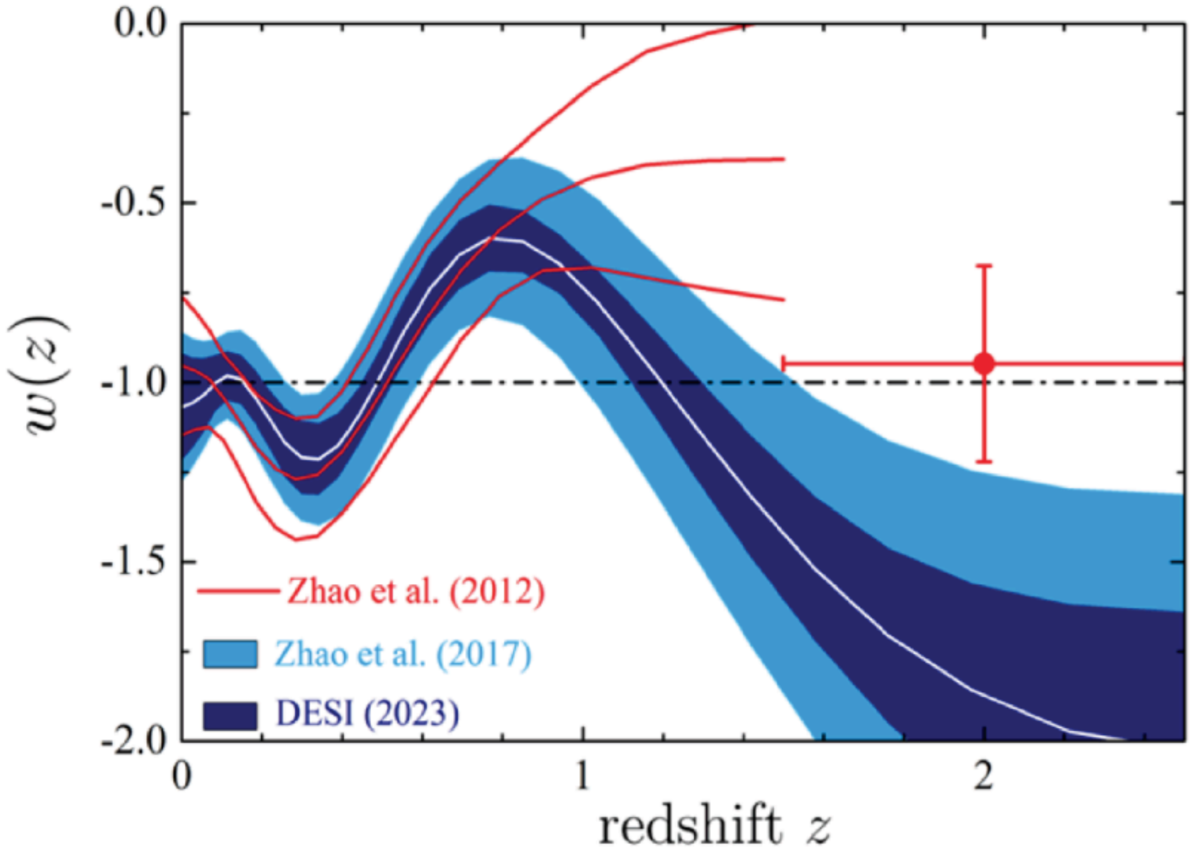
Reconstruct w(a) non-parametrically

Real data circa 2012



GBZ, et al., 2012, PRL

Reconstruct w(a) non-parametrically



Zhao et al., (BOSS collaboration), 2017
Nature Astronomy, 1, 627-632

Principal Component Analysis (PCA)

Hamilton & Tegmark 1999, Huterer & Starkman 2002

Diagonalise the w block of the Fisher matrix to find the orthonormal basis, on which we can expand $w(z)+1$,

$$F = W^T \Lambda W$$

$$w(z)+1 = \sum_m \alpha_m e_m(z)$$

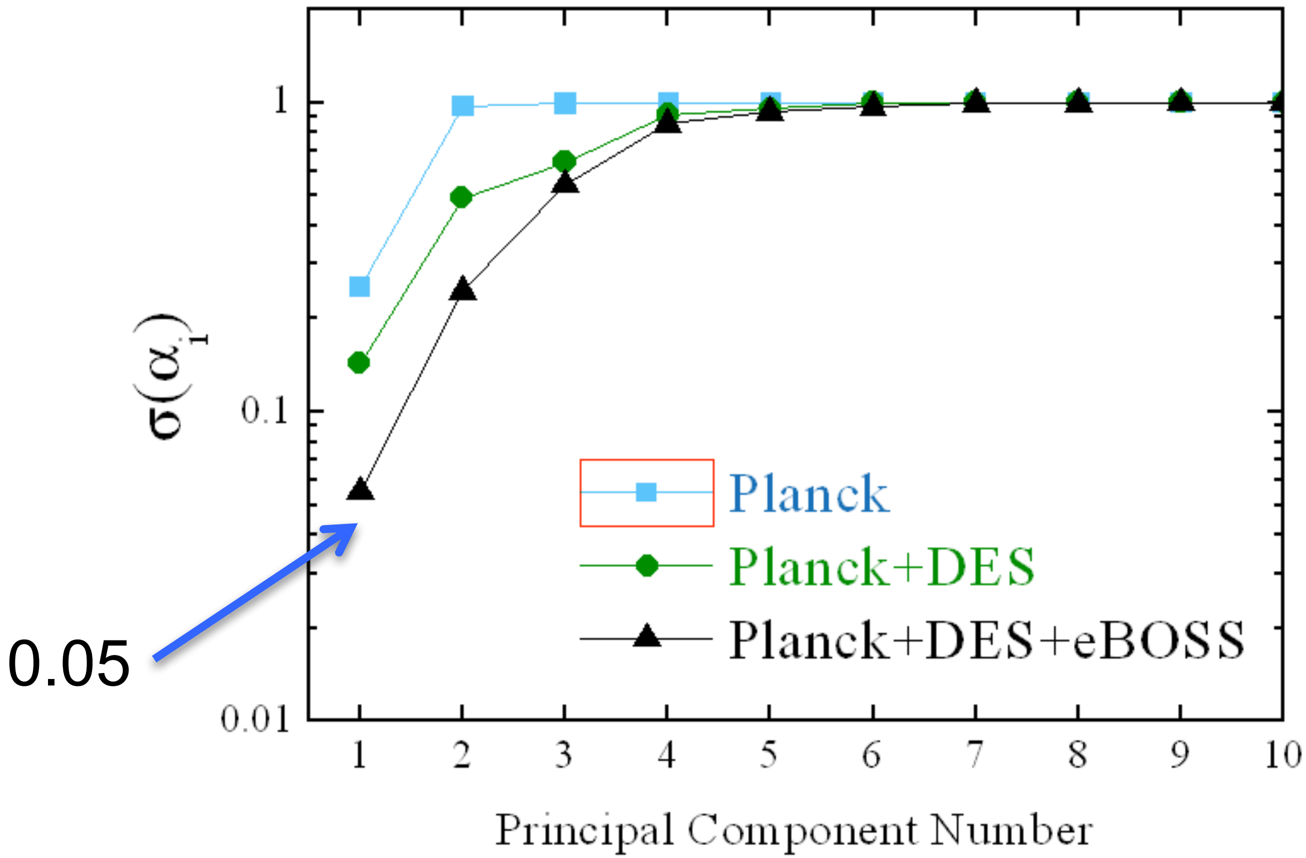
⇒ **Where are the 'sweet spots'?**

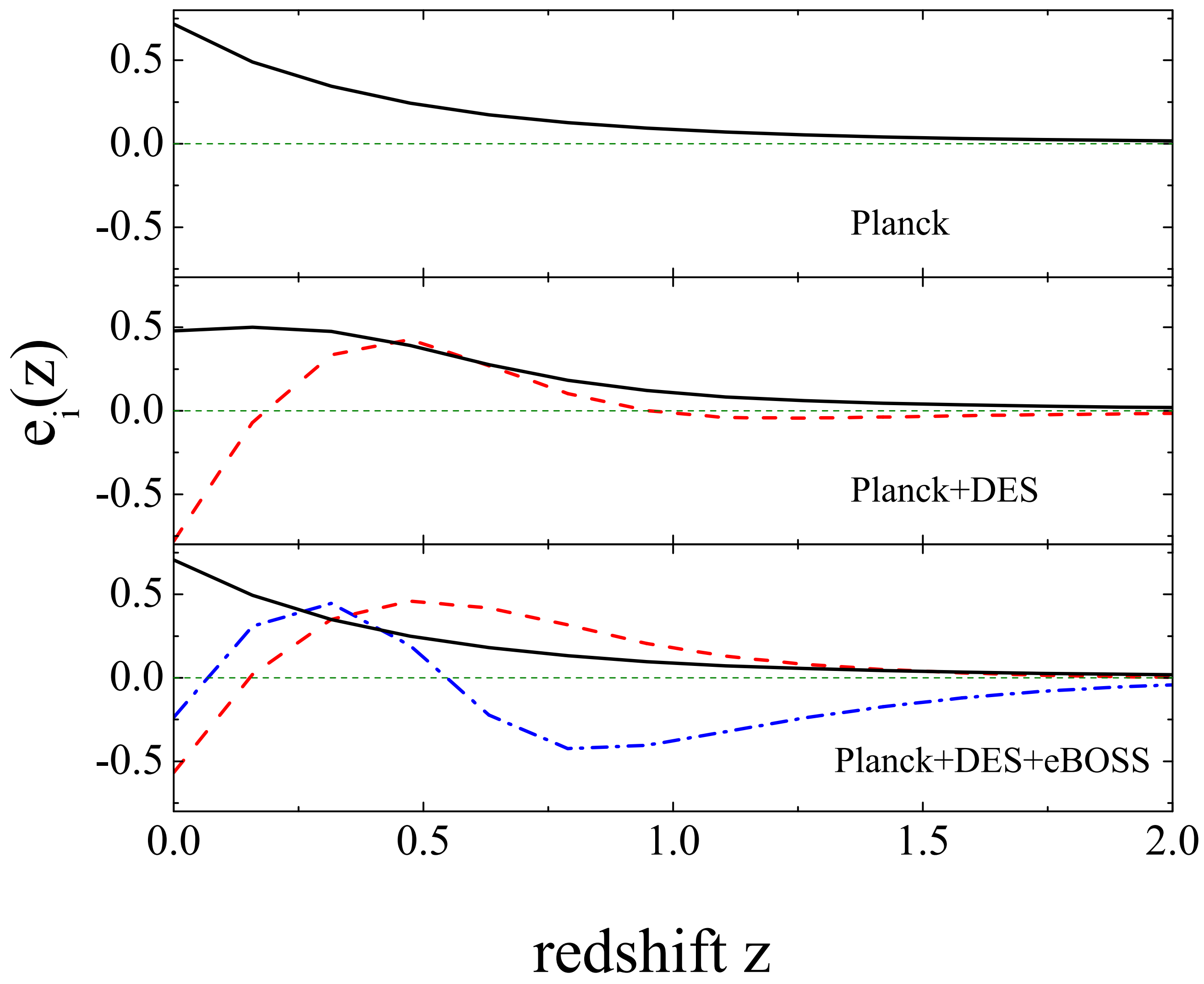
⇓

How 'sweet' they are?

Principle Component Analysis

$$w(z)+1=\Sigma_i \alpha_i e_i(z)$$




0.5
0.0
-0.5
Planck
Planck+DES
Planck+DES+eBOSS
$e_i(z)$
0.0
0.5
1.0
1.5
2.0
redshift z

Modified Gravity as a solution to the accelerating universe problem

$$\tilde{G}_{\mu\nu} = \frac{1}{M_p^2} T_{\mu\nu}$$

Modified Gravity

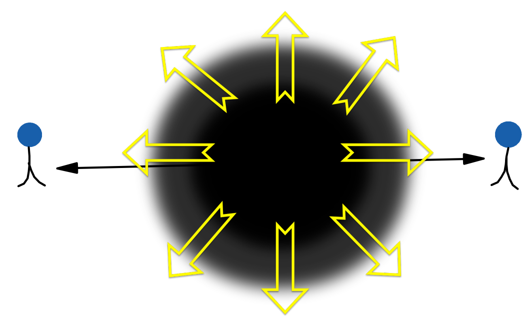
Resemble GR+L

Cosmological scales

R>Gpc

Small scales

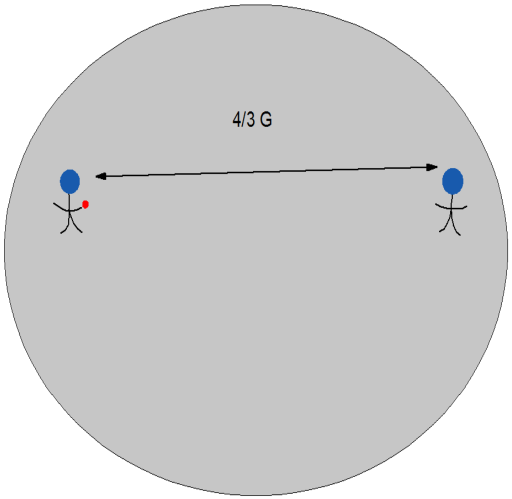
Large scales

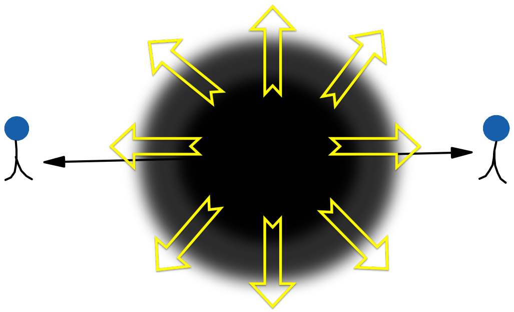


Modified Gravity

Small scales	Observationally testable feature	Resemble GR+L
	Structure formation scales Mpc<R<Gpc	Cosmological scales R>Gpc

Small scales → Large scales

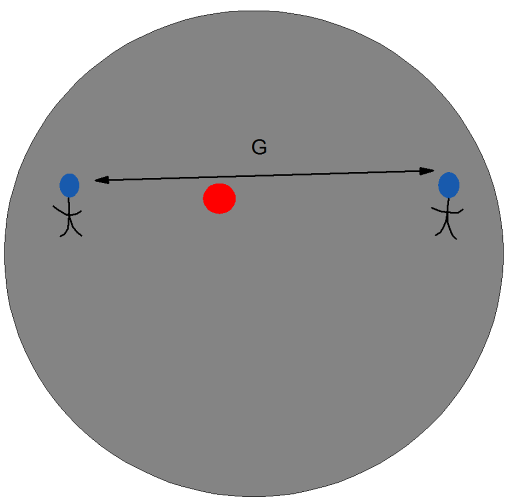


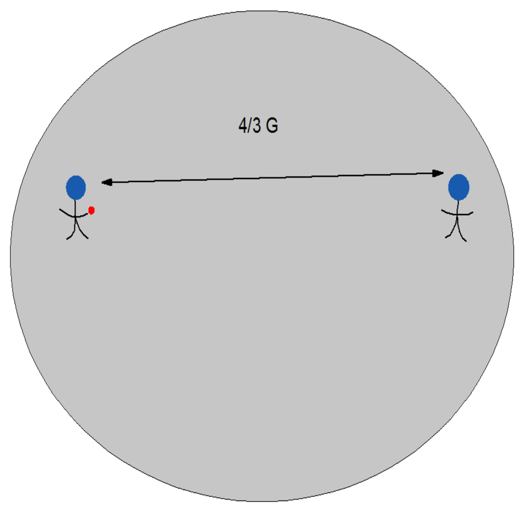


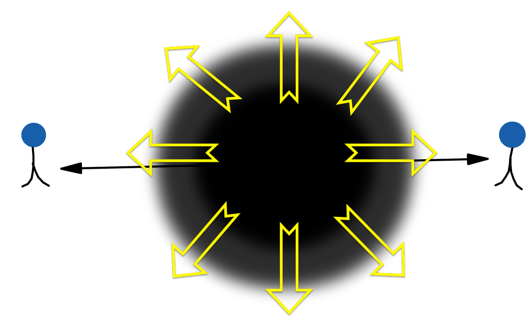
Modified Gravity

Recover GR	Observationally testable feature	Resemble GR+L
Galactic scales R<Mpc	Structure formation scales Mpc<R<Gpc	Cosmological scales R>Gpc

Small scales → Large scales



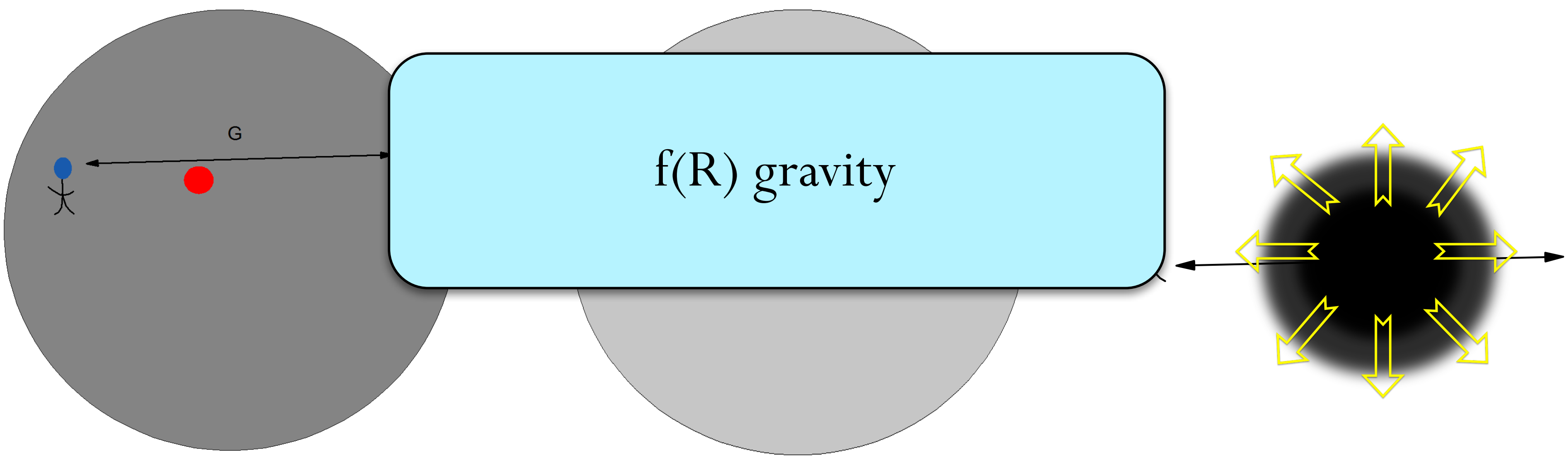




Modified Gravity

Recover GR	Observationally testable feature	Resemble GR+L
Galactic scales R<Mpc	Structure formation scales Mpc<R<Gpc	Cosmological scales R>Gpc

Small scales → Large scales



Cosmological tests of GR on **linear** scales

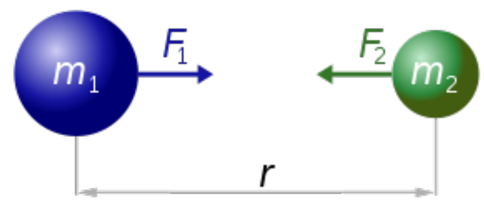
Galaxy scales | Structure formation scales | Cosmological scales

Small scales → Large scales

The deviation from GR is encoded in

$$k^2\Phi = -\mu(a,k)4\pi G a^2\rho\delta$$

$$\frac{\Phi}{\Psi} = \gamma(a,k)$$

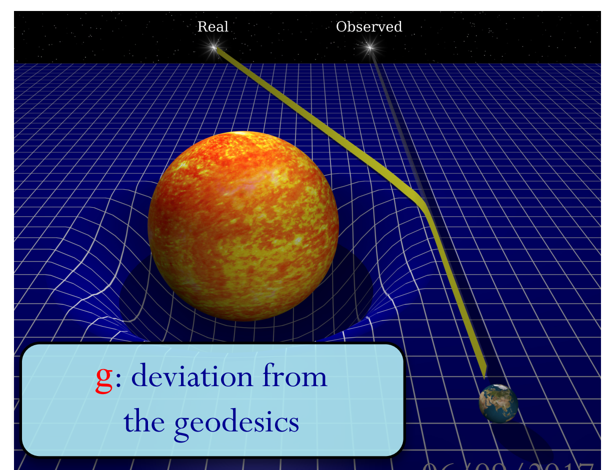


$$F_1 = F_2 = \mu G\frac{m_1 \times m_2}{r^2}$$

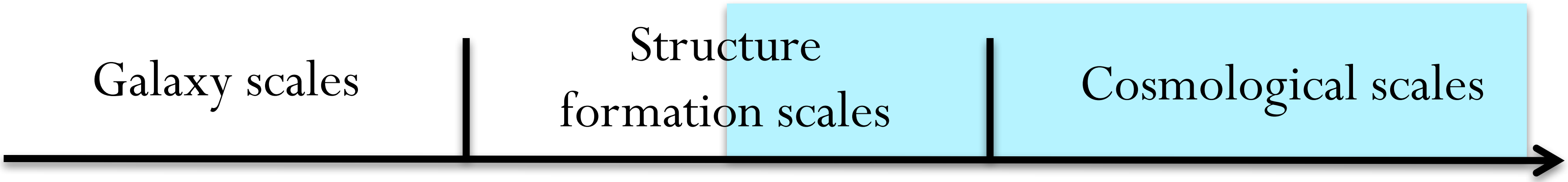
In GR, μ=γ=1

A smoking gun of modified gravity:

μ and/or γ deviating from 1



Cosmological tests of GR on **linear** scales



Constraints from current data

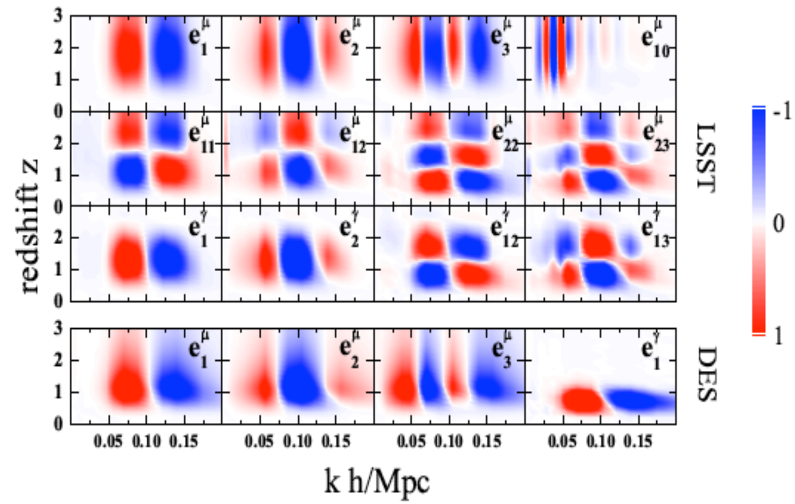
$$\mu_0 = 0.90 \pm 0.21$$
$$\gamma_0 = 1.30 \pm 0.56$$

GR ($\mu_0 = \gamma_0 = 1$) is OK, but errors are too large to draw any conclusion.

GBZ et al, 2009, 2010

From Forecast

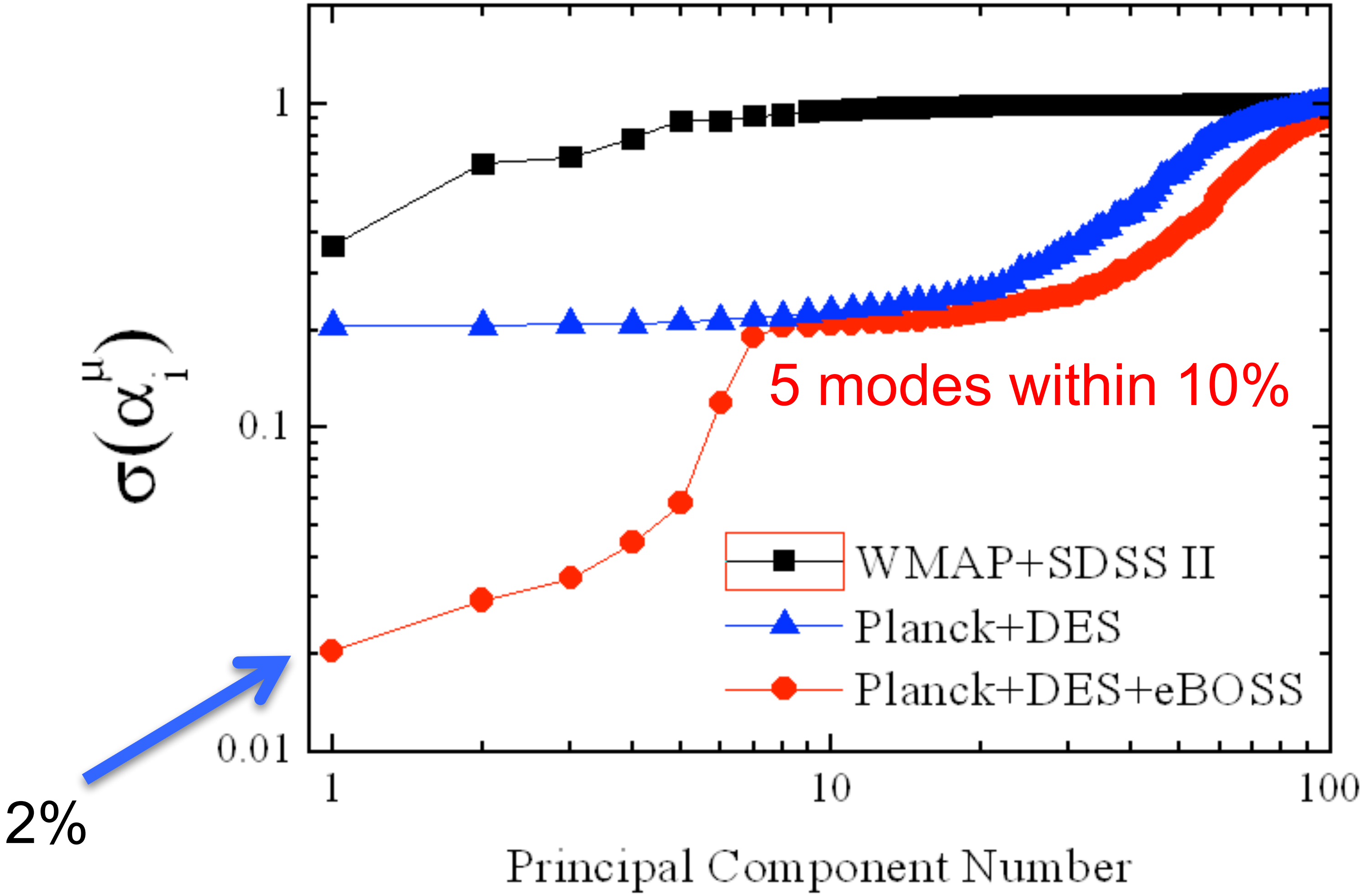
2DPCA for $\mu(k,z),\gamma(k,z)$

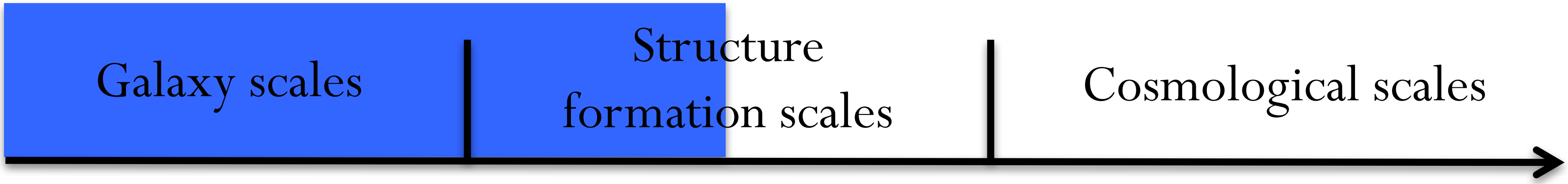


GBZ et al, 2009

The error of the principal components of μ(k,z)

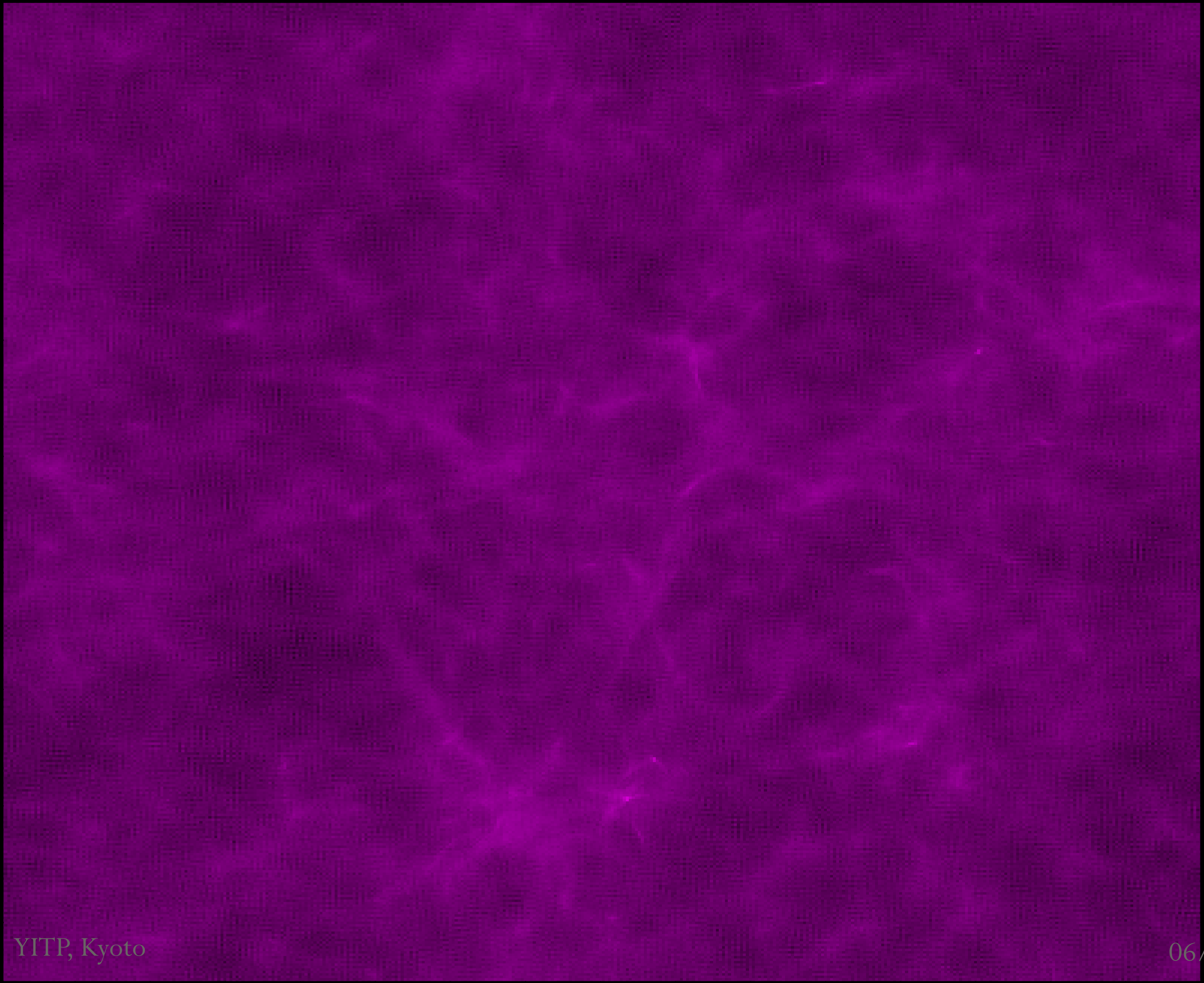
$$\mu(k,z)-1=\sum_m \alpha_m \, e_m(k,z)$$



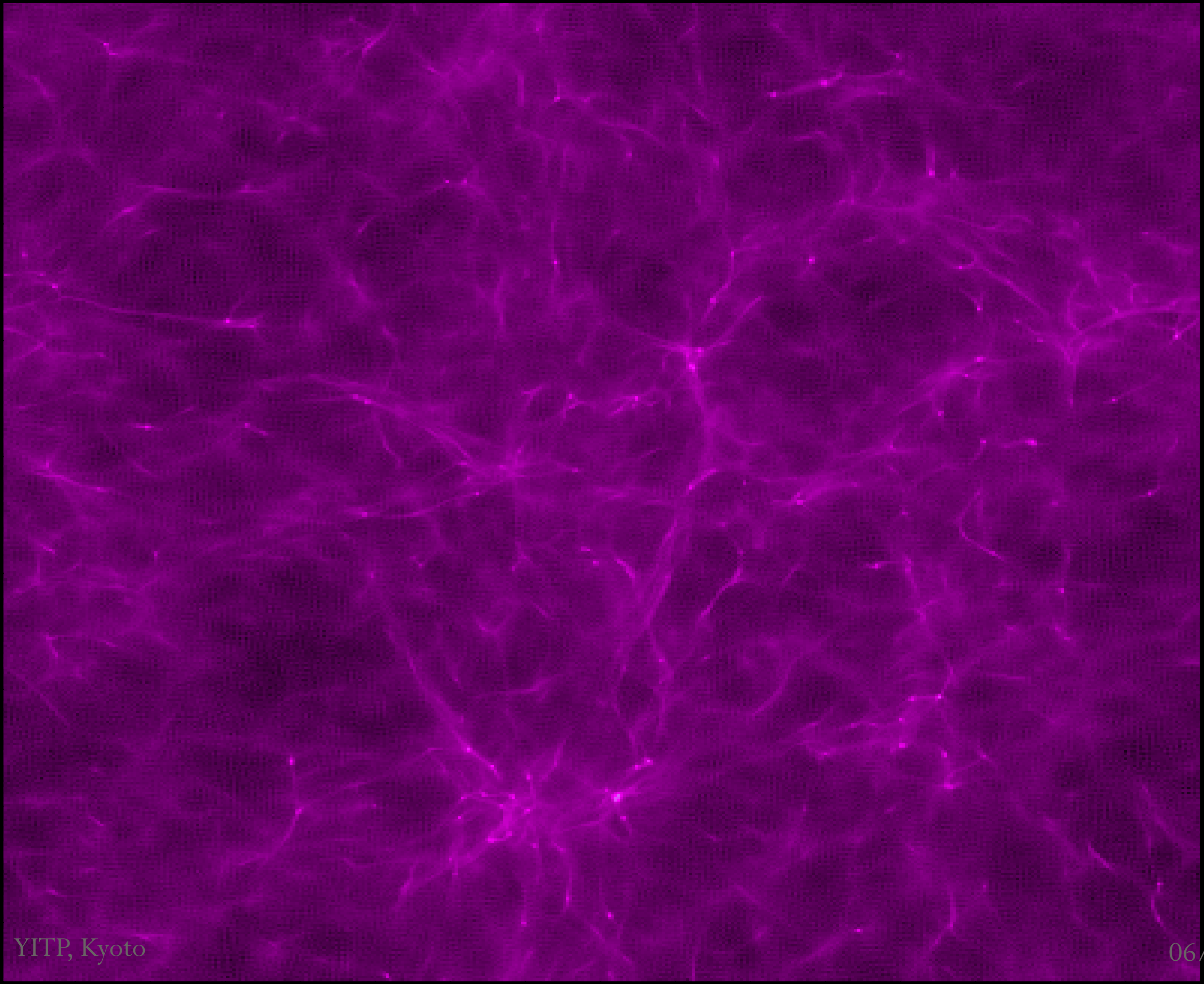


High-resolution numerical simulations are needed!

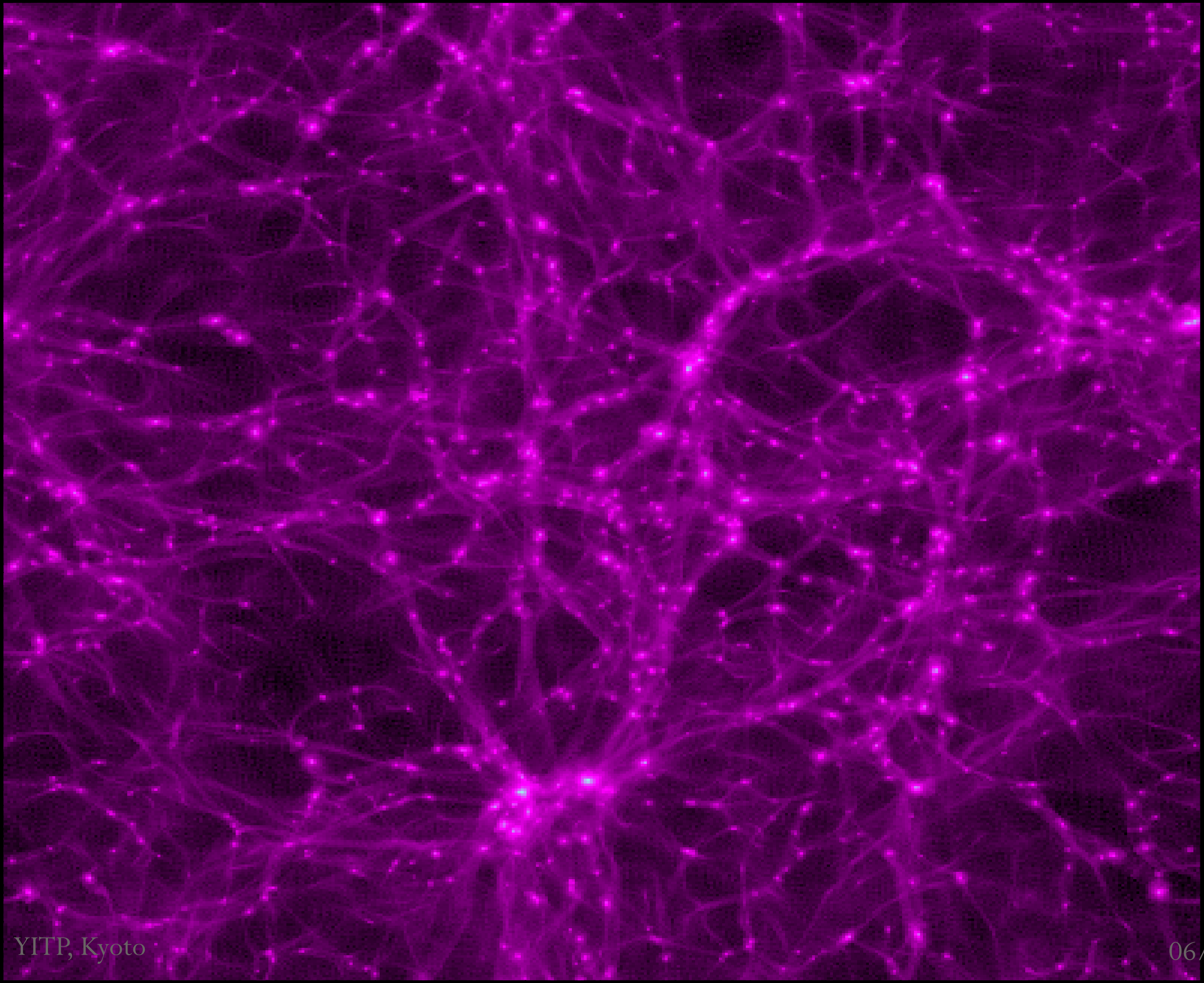
12 billion years ago



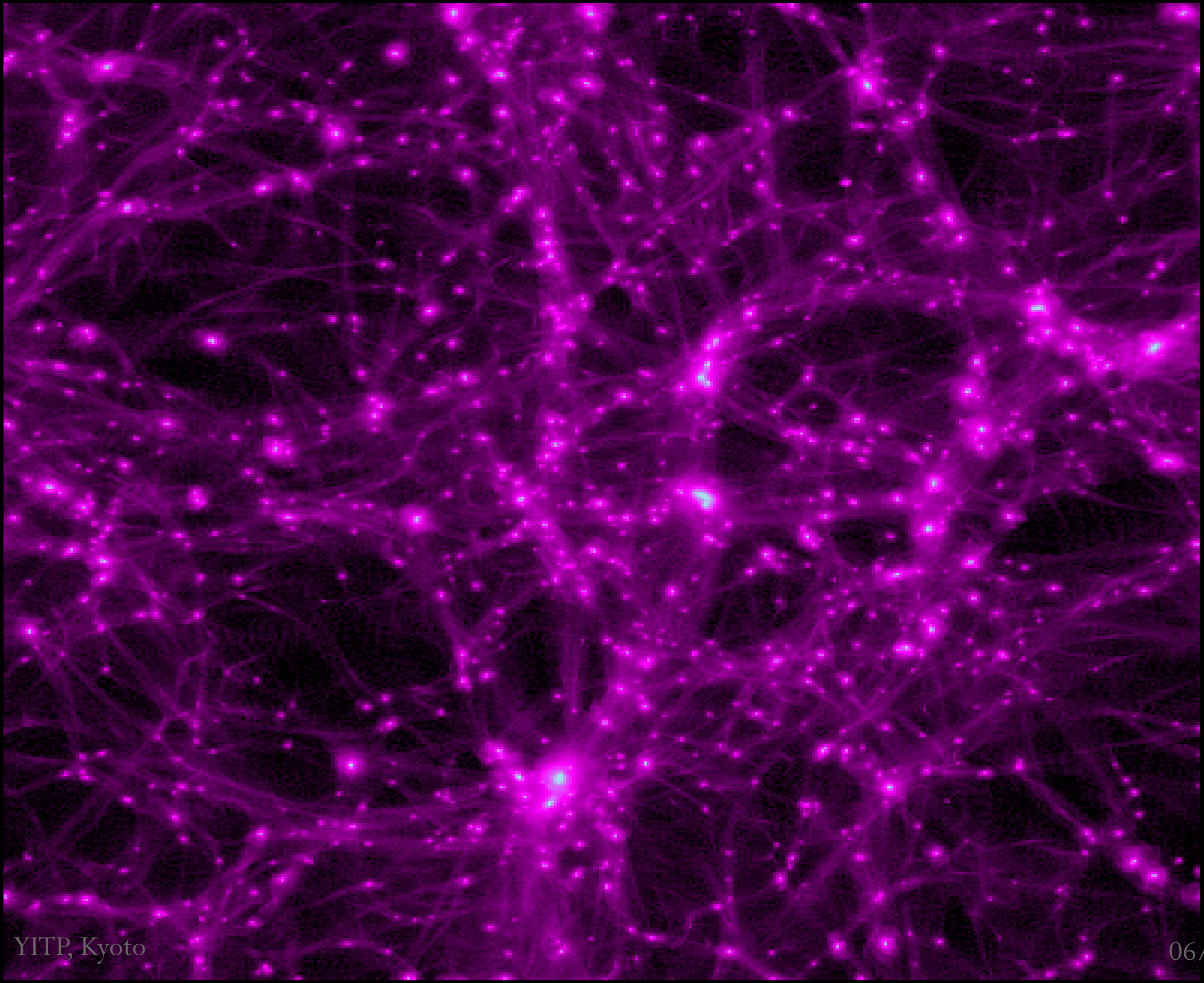
10 billion years ago



8 billion years ago



Today



f(R) Gravity

$$S = \int d^4x\sqrt{-g}\left[\frac{R+f(R)}{16\pi G}+L_m\right]$$

- ☺ Mimic GR at high z;
- ☺ Accelerate the expansion at low z;
- ☺ Recover GR locally to pass solar system test.

Numerical Simulations
1011.1257 GBZ, B.Li, K.Koyama, PRD 11

- Code: Modified MLAPM
- f(R) model:

$$f(R) = -m^2 \frac{c_1 (R/m^2)^n}{c_2 (R/m^2)^n + 1} \qquad m^2 \equiv \frac{8\pi G \bar{\rho}_{M,0}}{3} = H_0^2 \Omega_M$$

- Model parameters:

$$n = 1, \quad |f_{R0}| = \frac{n c_1}{c_2^2} \left[3\left(1 + 4\frac{\Omega_\Lambda}{\Omega_M}\right)\right]^{-n-1} = 10^{-4}, 10^{-5}, 10^{-6}$$

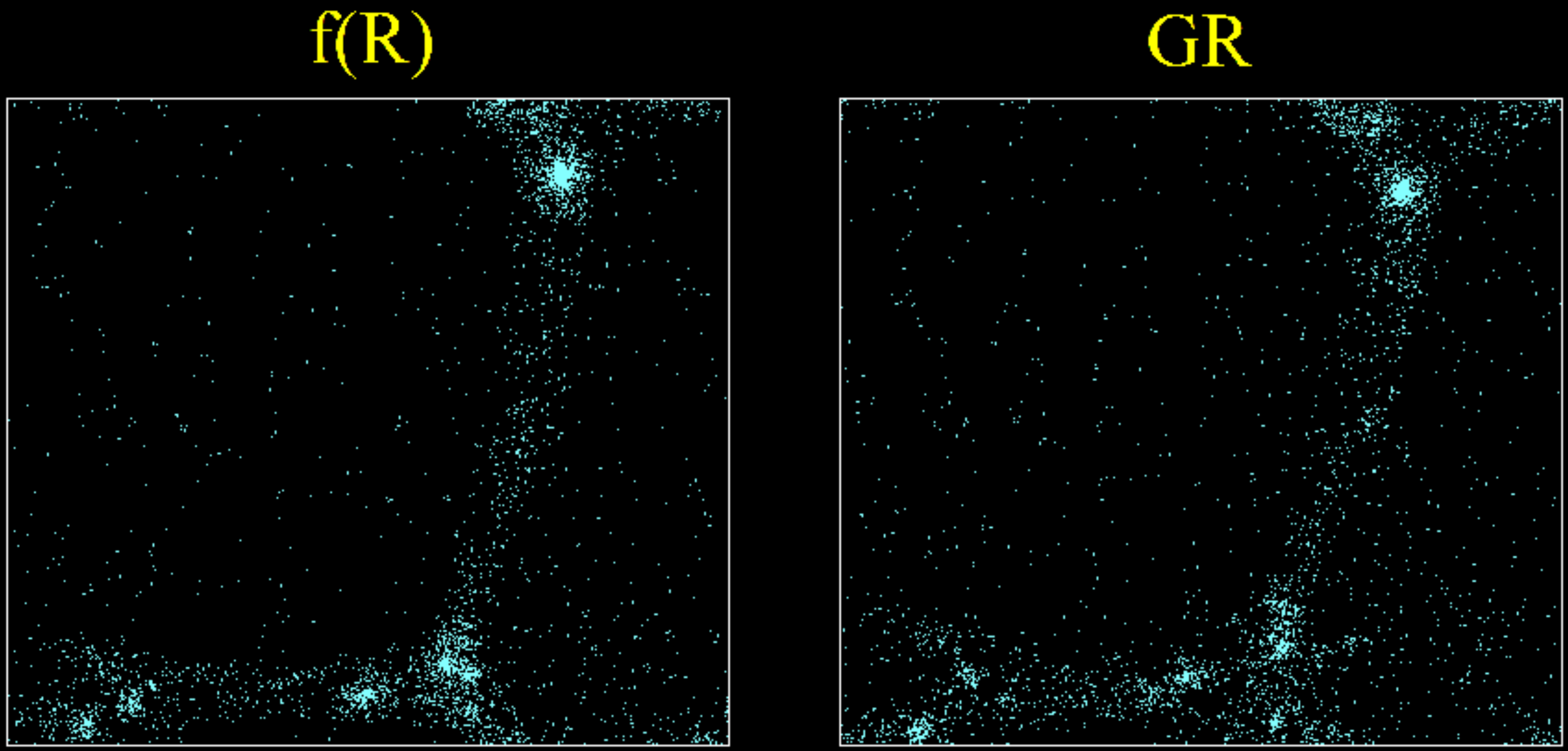
- Cosmological parameters: WMAP7

Equations to solve in the code

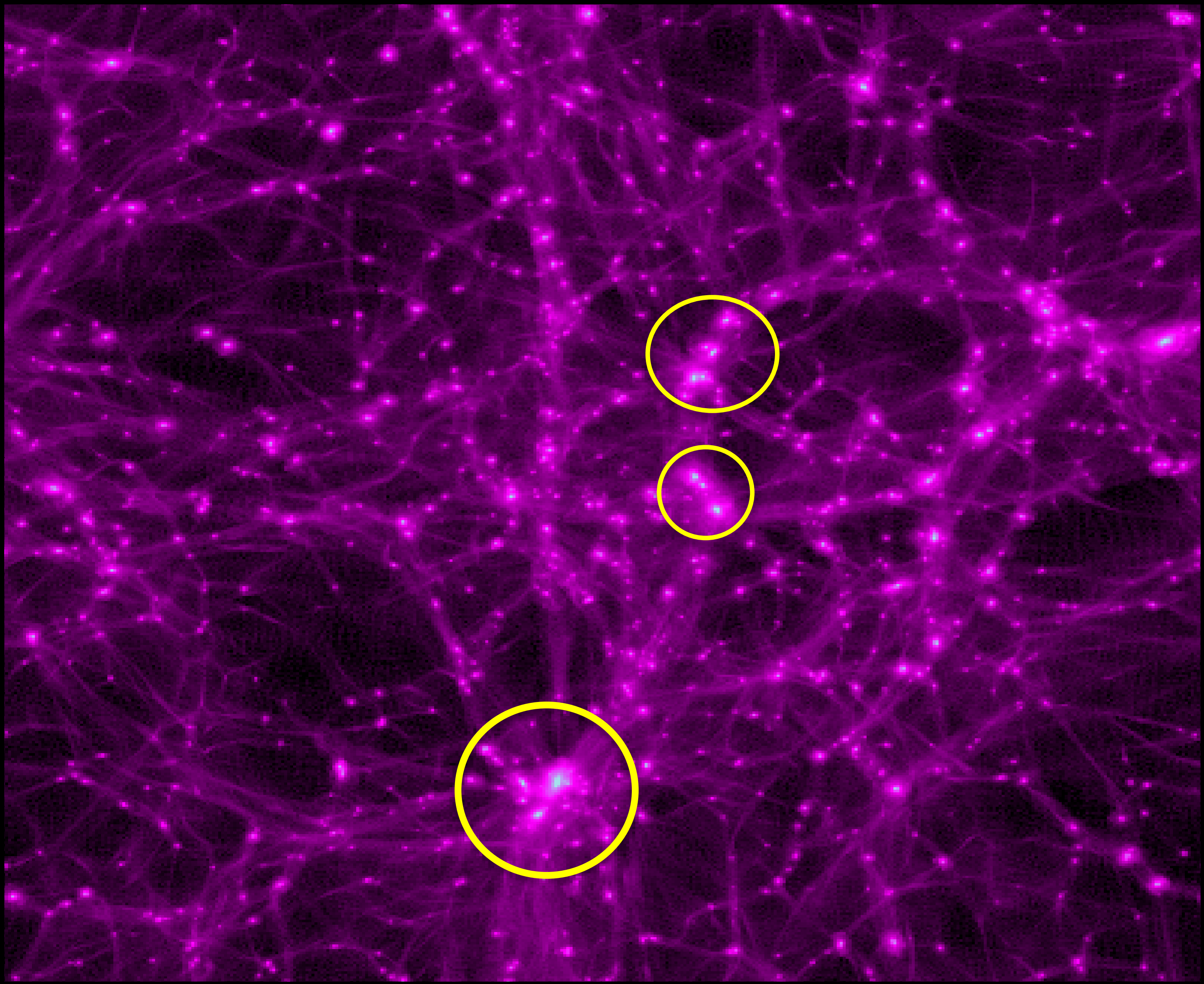
$$\frac{ac^2}{(H_0B)^2}\nabla_c^2 f_R = \frac{1}{3}\left(n\frac{c_1}{c_2^2}\right)^{\frac{1}{n+1}} f_R^{-\frac{1}{n+1}}\Omega_{\rm M}a^3 - \Omega_{\rm M}\rho_c - 4\Omega_\Lambda a^3$$

$$\nabla_c^2\Phi_c = \frac{3}{2}\Omega_{\rm M}(\rho_c - 1)$$
$$+\left[\frac{1}{2}\Omega_{\rm M}\rho_c + 2\Omega_\Lambda a^3 - \frac{1}{6}\Omega_{\rm M}a^3\left(n\frac{c_1}{c_2^2}\right)^{\frac{1}{n+1}} f_R^{-\frac{1}{n+1}}\right]$$

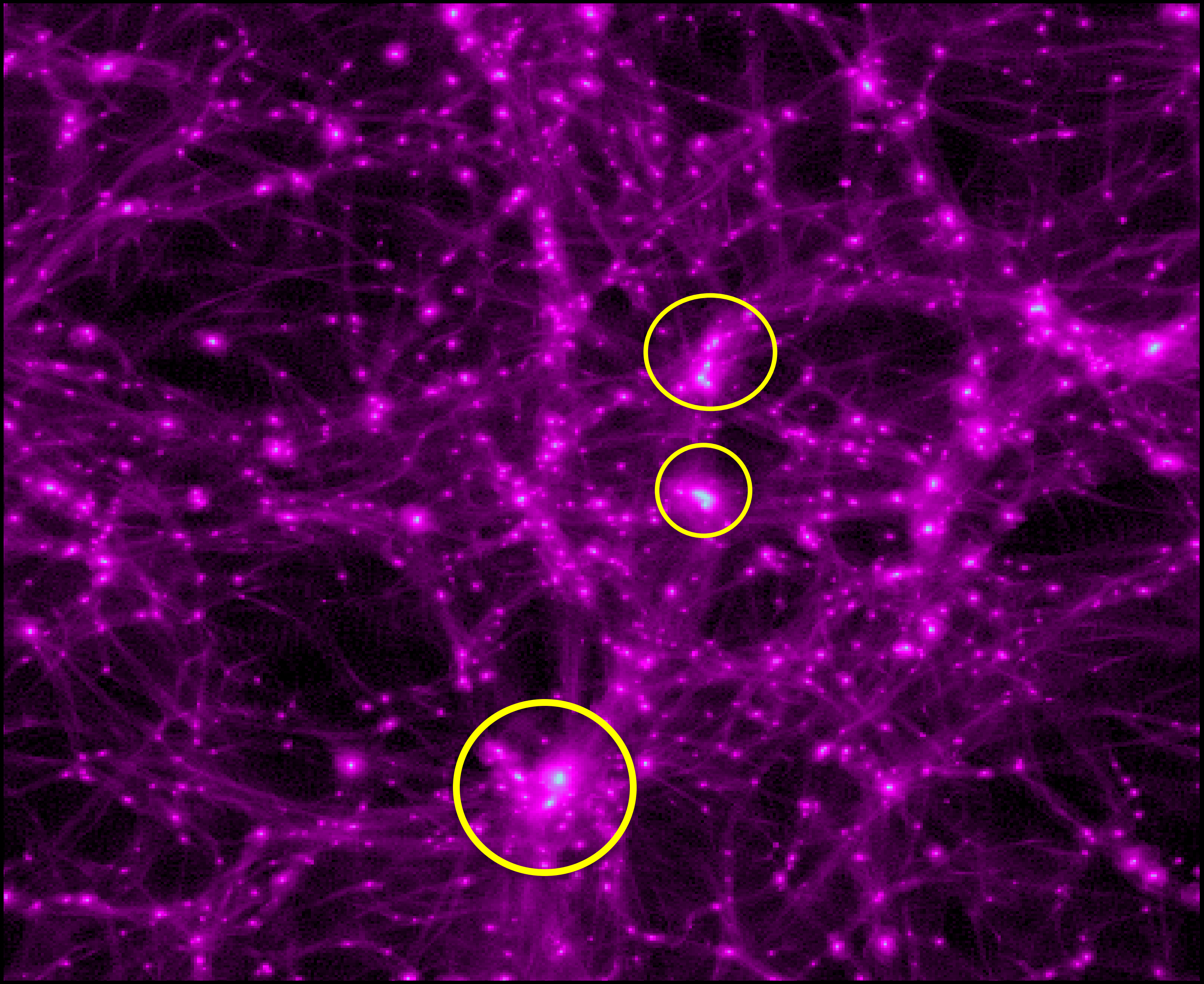
Gongbo Zhao et al, Phys. Rev. Lett. 2011



GR



f(R)

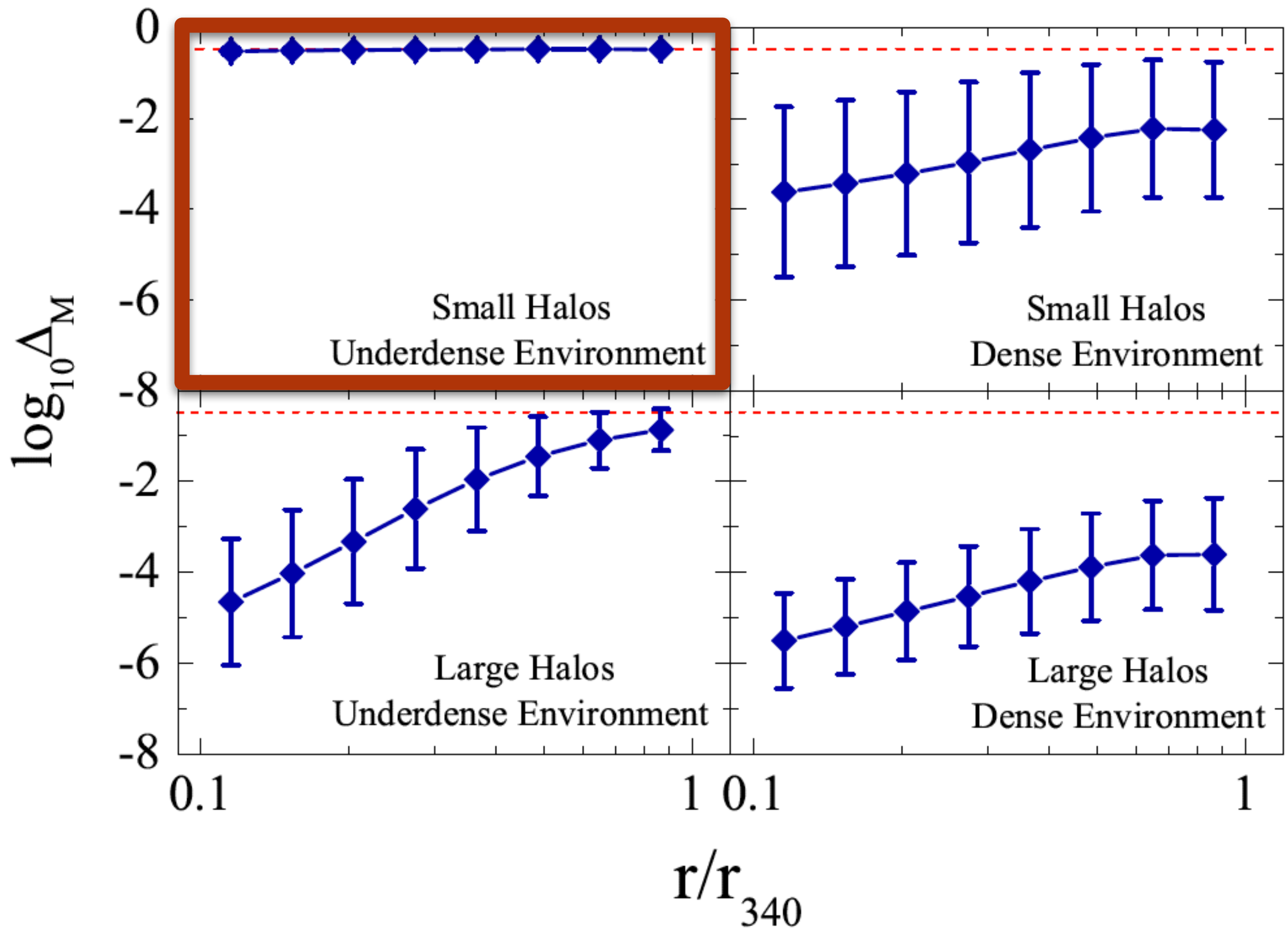


Halo, galaxy scales | Structure formation scales | Cosmological scales

Application I: A novel GR test on galactic scales

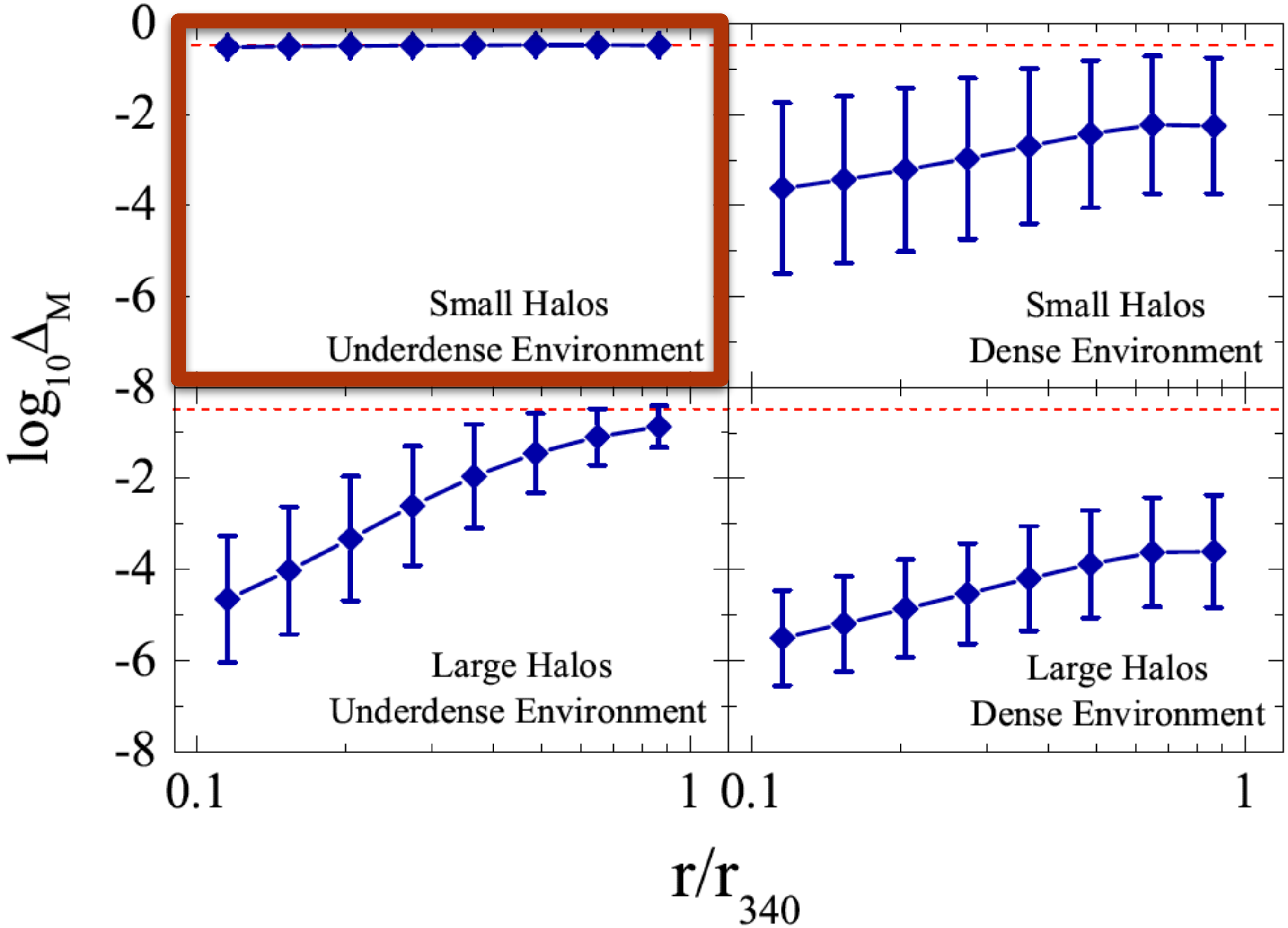
Mass Difference

$$\Delta_M \equiv M_D/M_L - 1 \;= \frac{d\Phi(r)/dr}{d\Phi_+(r)/dr} - 1$$

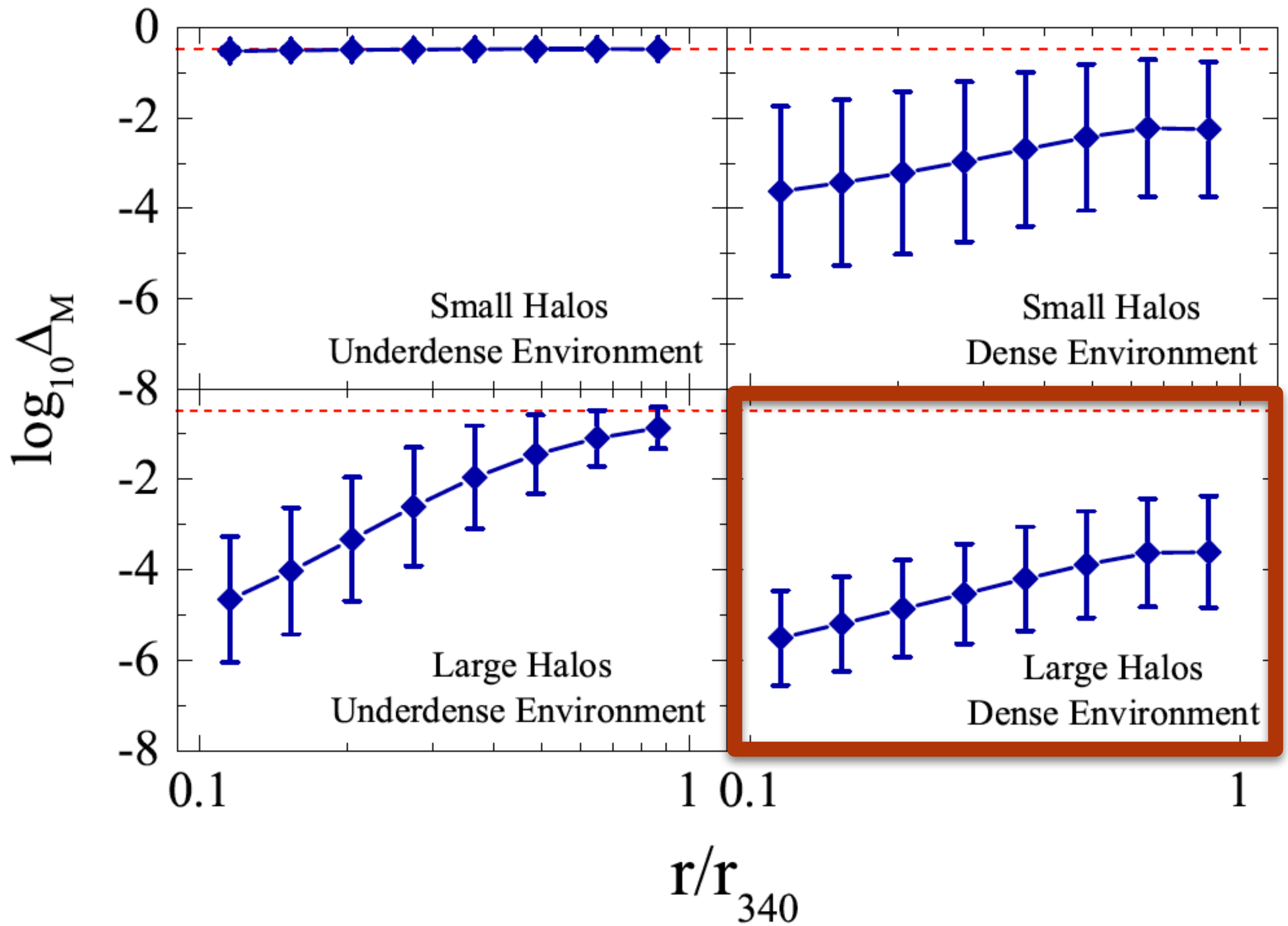


GBZ et al, 2011

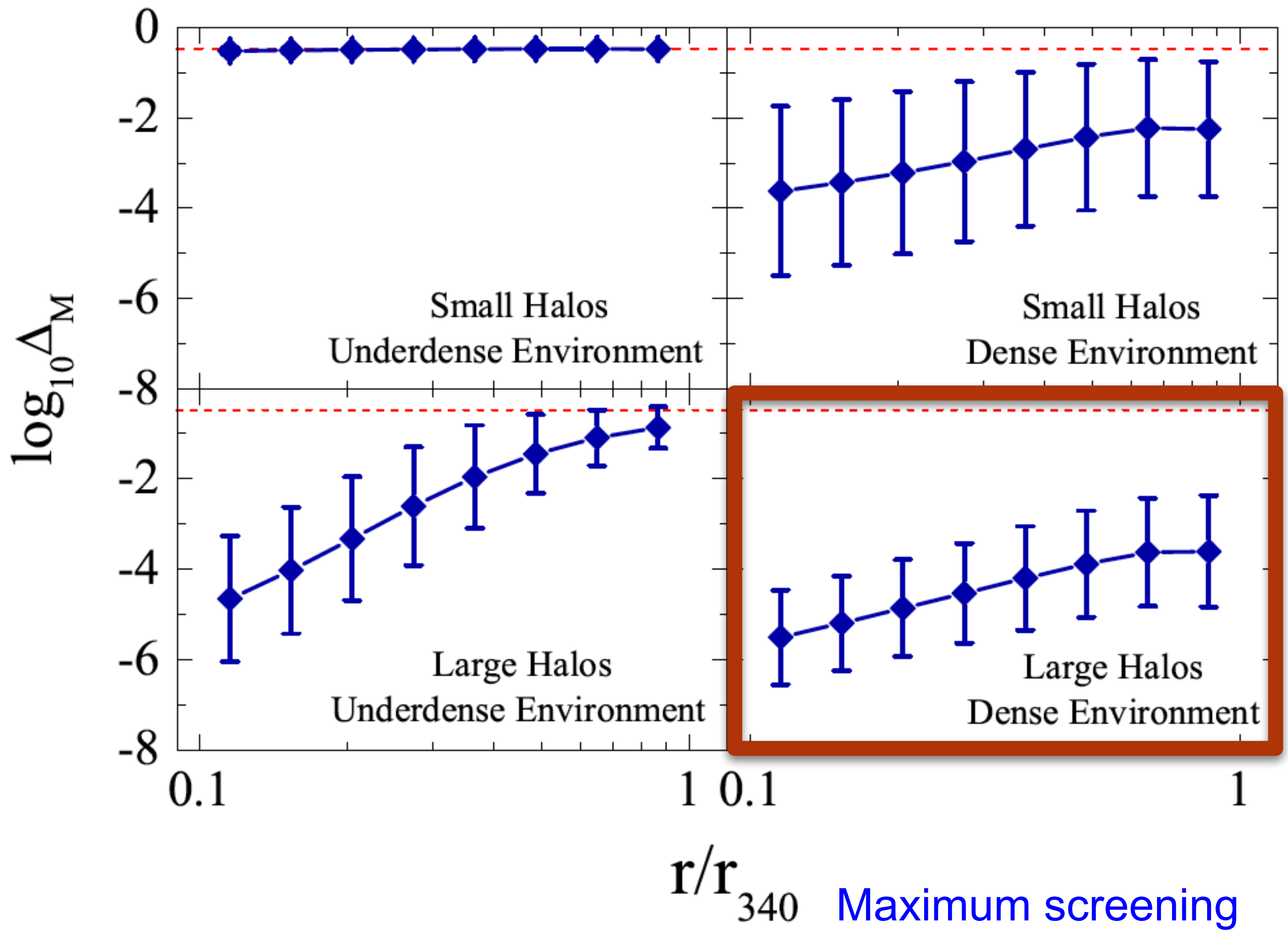
No screening!



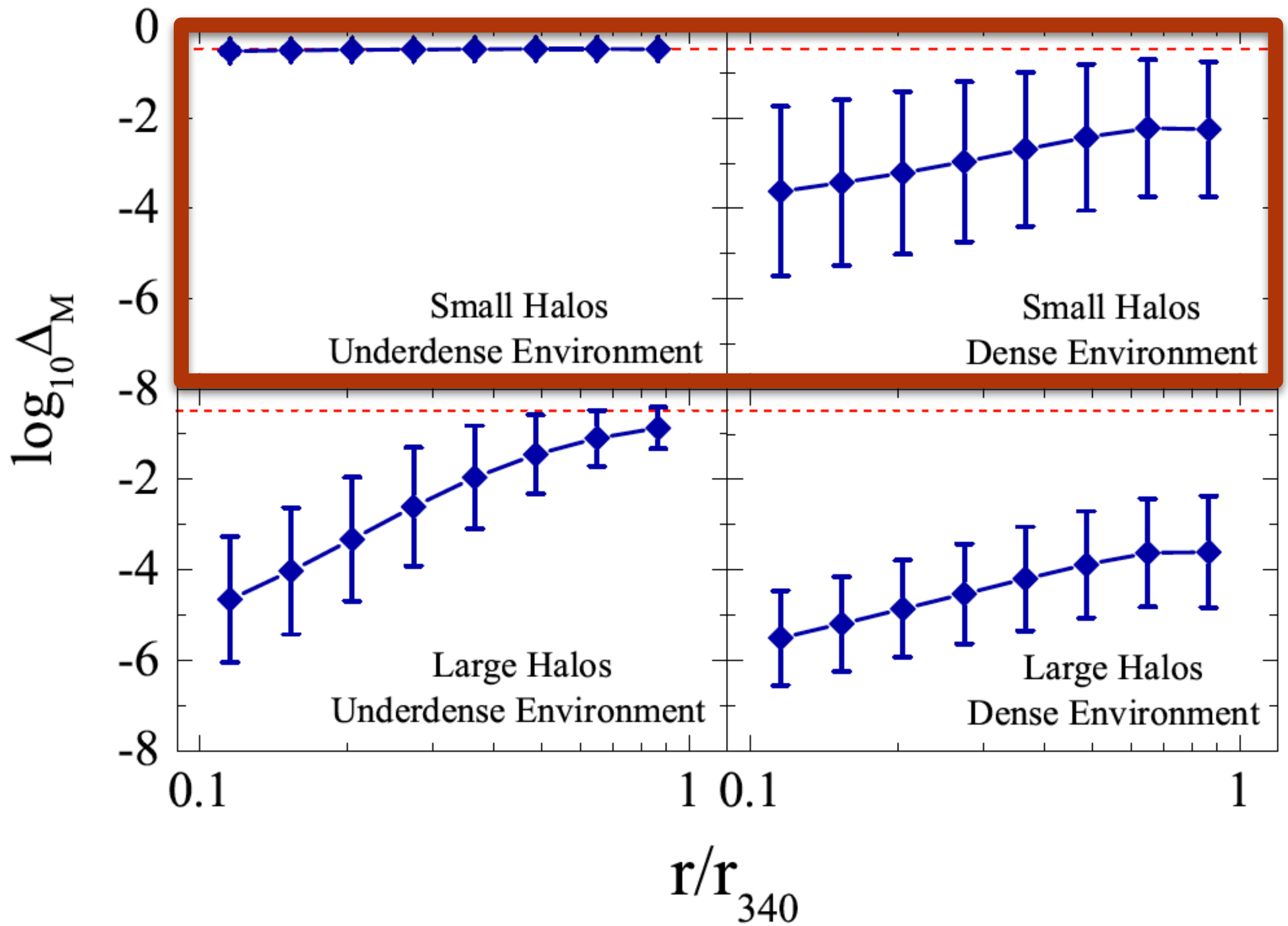
GBZ et al, 2011



GBZ et al, 2011

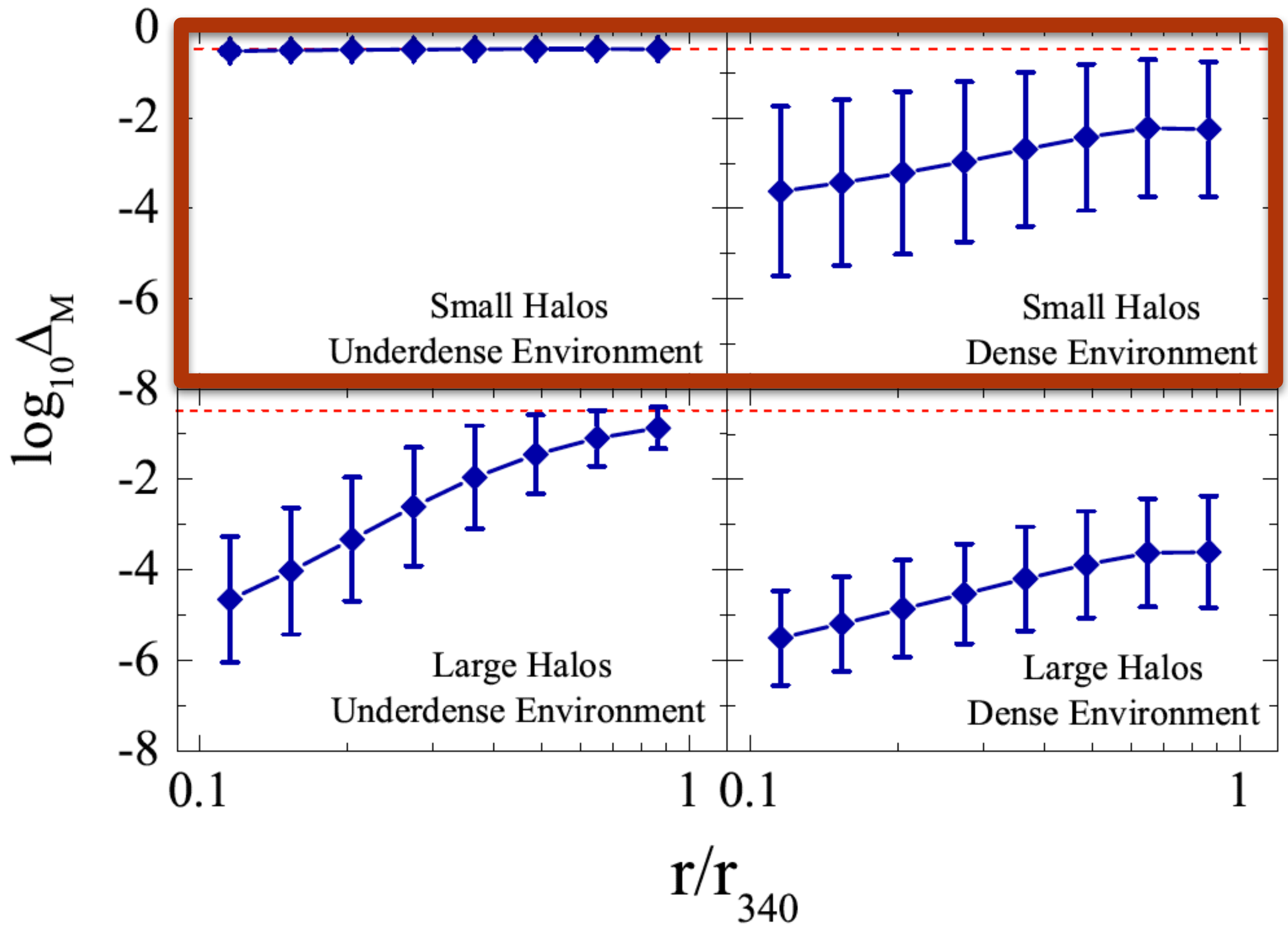


Maximum screening
Core is better screened

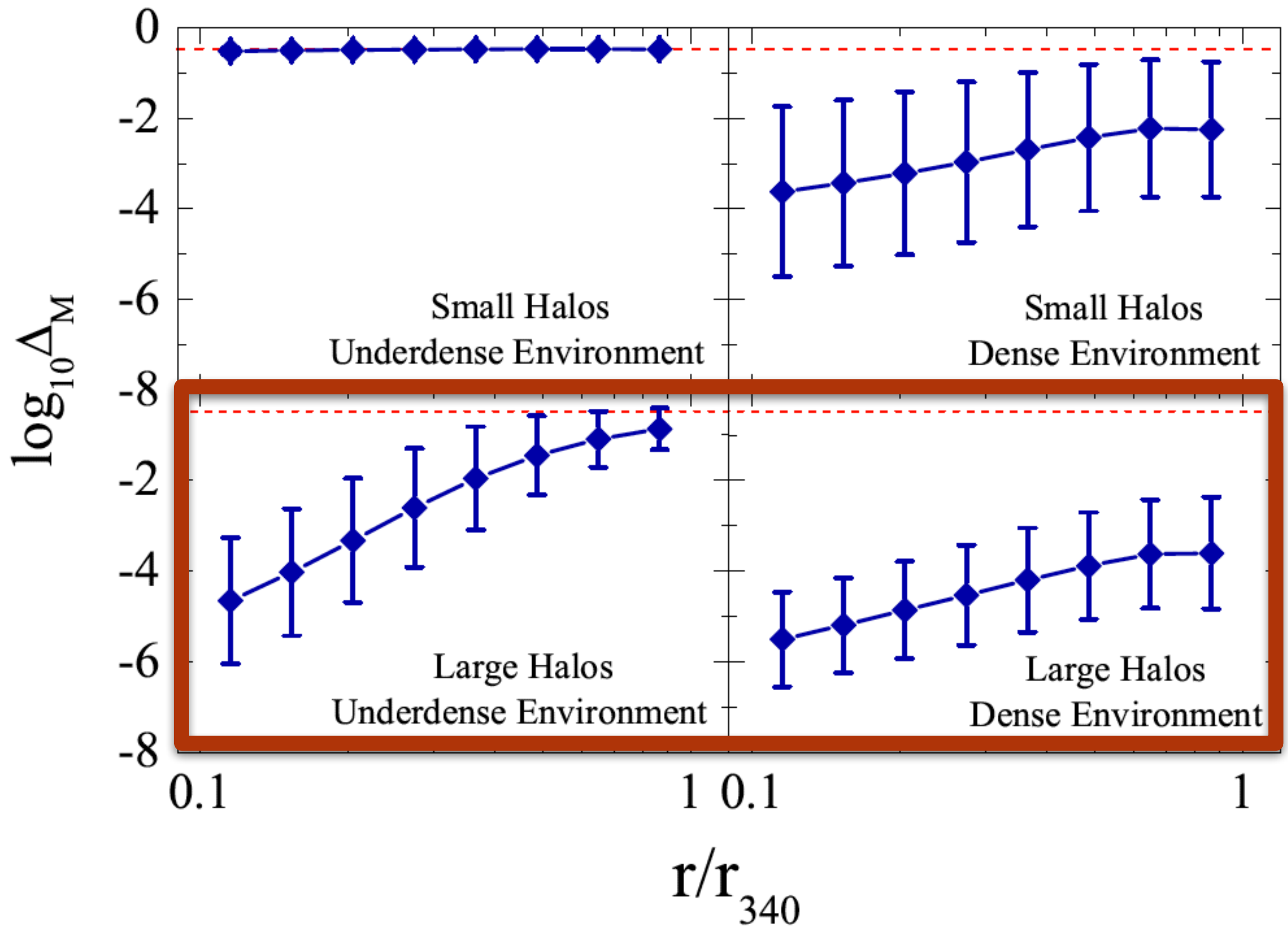


GBZ et al, 2011

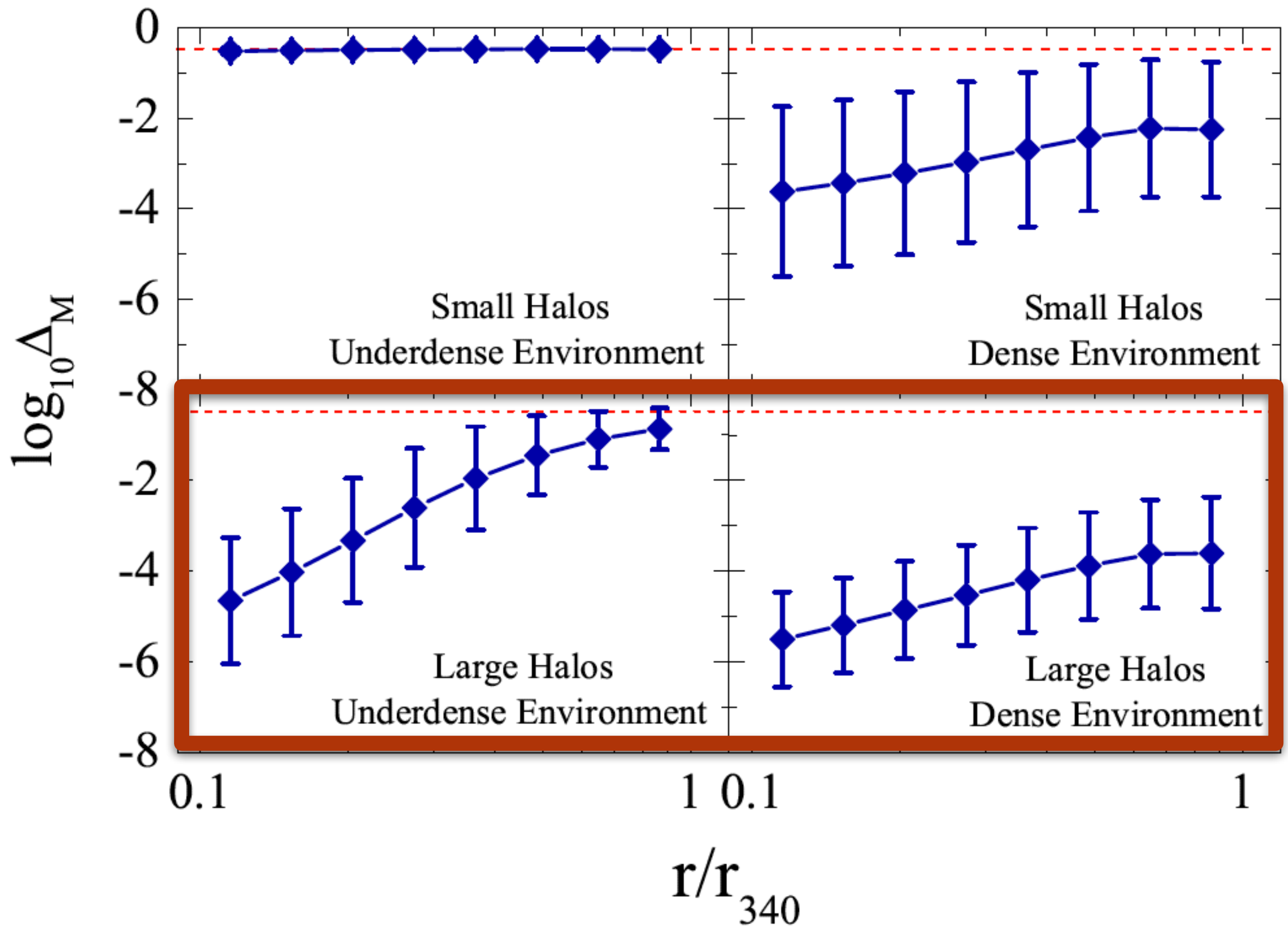
Screened purely by environment



GBZ et al, 2011



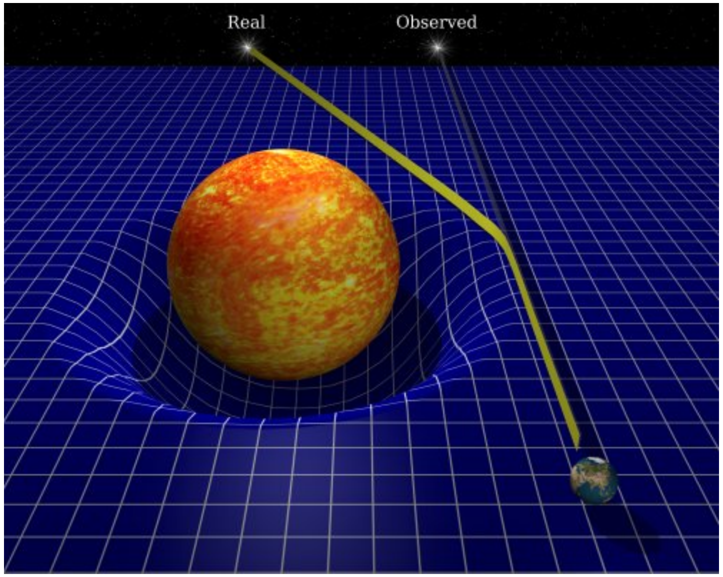
GBZ et al, 2011



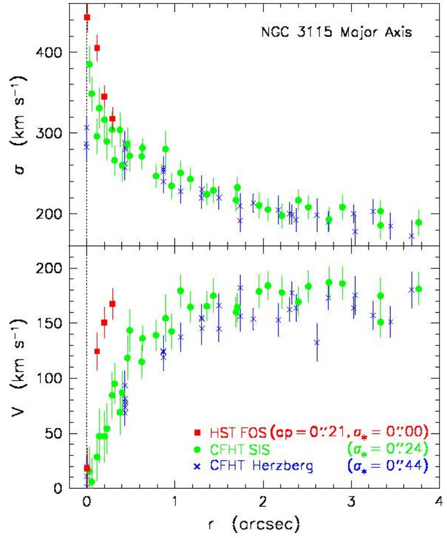
Screening on the edge shows environmental dependence!

Observationally…

Lensing Mass



Dynamical Mass



- Measure lensing and dynamical mass for each halo;
- Divide the sample using D;
- Compare!

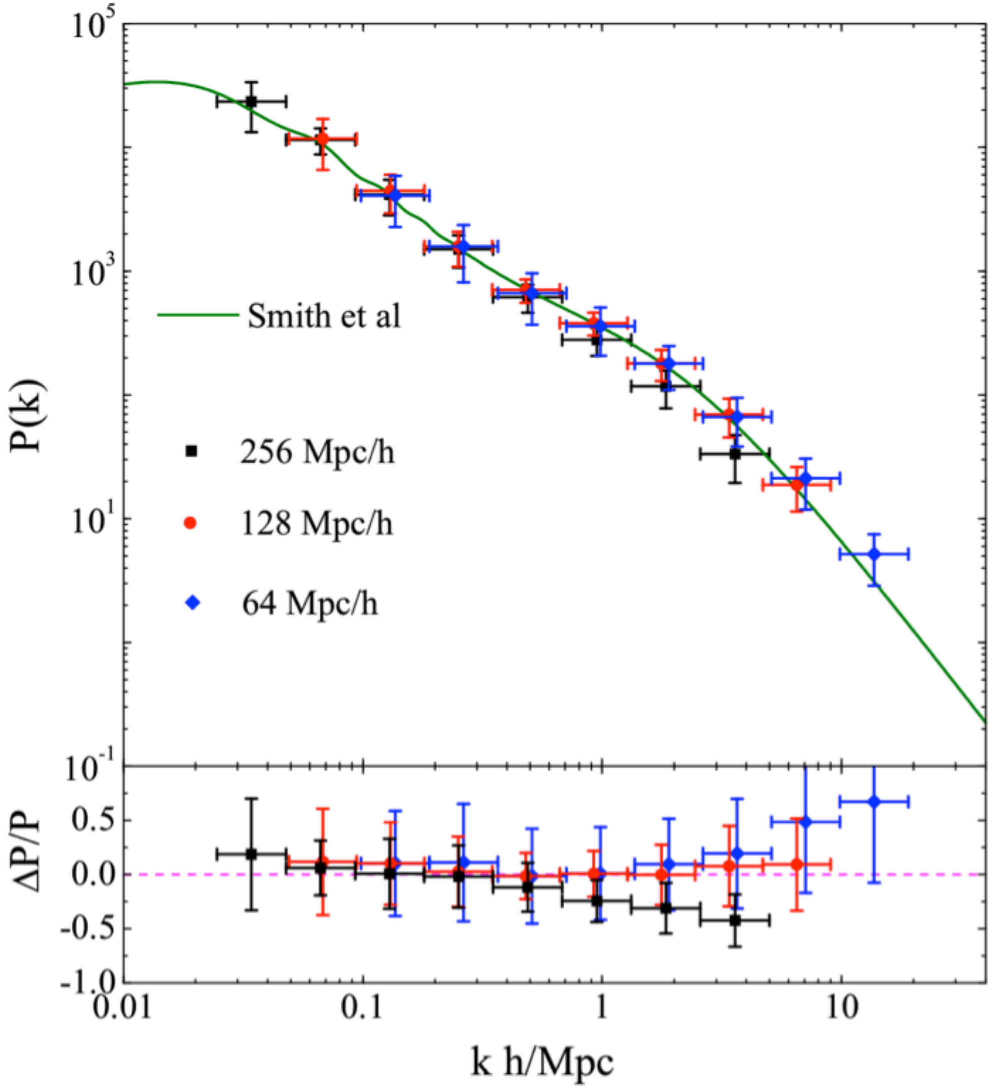
- Measure lensing and dynamical mass for each halo;
- Divide the sample using D;
- Compare!

Apply to (e)BOSS, DES, Euclid data

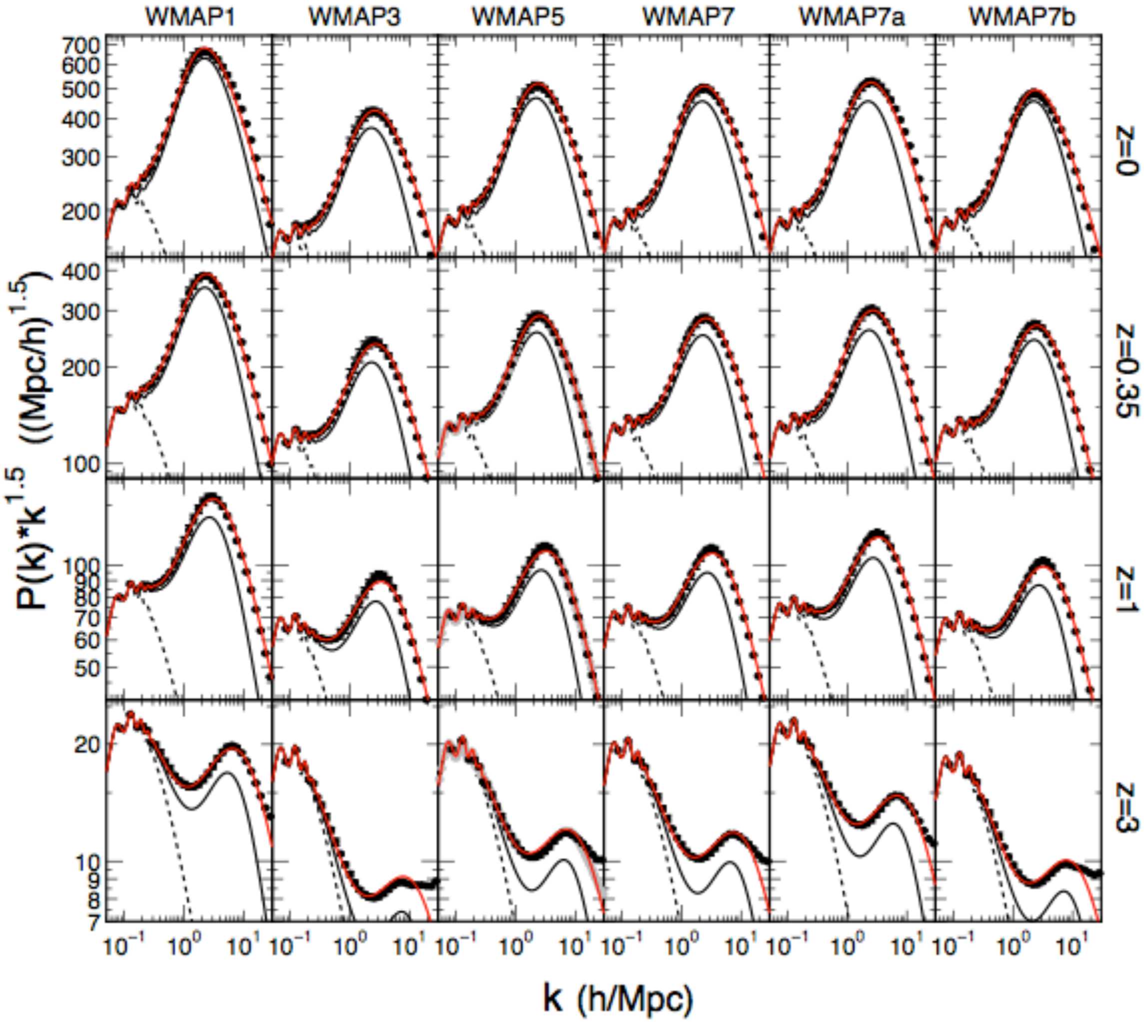
Halo, galaxy scales | Structure formation scales | Cosmological scales

Application II: A P(k) fitting formula for f(R) model

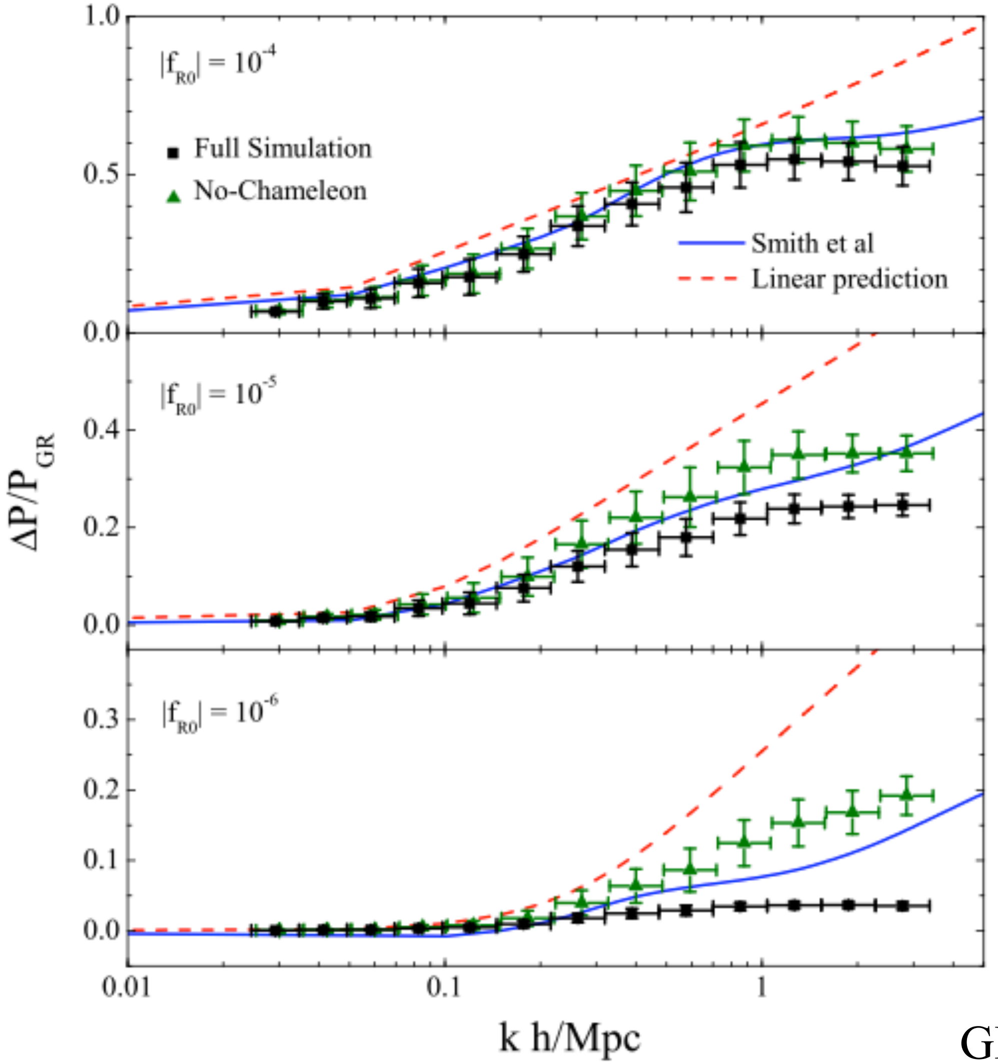
LCDM: Smith et al vs. simulation



LCDM: Takahashi et al vs. simulation



Hu-Sawicki: Smith et al vs. simulation



GBZ et al, 2010

In default Halofit

$$\Delta^2 \equiv \frac{k^3 P(k)}{2\pi^2} = \Delta_Q^2 + \Delta_H^2$$

$$\begin{aligned}
\Delta_Q^2(k) &= \Delta_L^2(k) \frac{[1+\Delta_L^2(k)]^{\beta(n_{\rm eff},\mathcal{C})}}{1+\alpha(n_{\rm eff},\mathcal{C})\Delta_L^2(k)} \exp\left[-\left(y/4+y^2/8\right)\right] \\
\Delta_H^2(k) &= \frac{\Delta_H^{2\prime}(k)}{1+\mu(n_{\rm eff},\mathcal{C})/y+\nu(n_{\rm eff},\mathcal{C})/y^2} \\
\Delta_H^{2\prime}(k) &= \frac{a(n_{\rm eff},\mathcal{C})y^{3f_1(\Omega_M)}}{1+b(n_{\rm eff},\mathcal{C})y^{f_2(\Omega_M)}+[c(n_{\rm eff},\mathcal{C})f_3(\Omega_M)y]^{3-\gamma(n_{\rm eff},\mathcal{C})}}
\end{aligned}$$

$$\begin{aligned}
\sigma^2(R,z) &= \int \Delta_L^2(k,z)\exp(-k^2R^2)\mathrm{d}\ln k \\
n_{\rm eff} &\equiv \left.\frac{\mathrm{d}\ln\sigma^2(R)}{\mathrm{d}\ln R}\right|_{\sigma=1} - 3; \quad \mathcal{C} \equiv \left.\frac{\mathrm{d}^2\ln\sigma^2(R)}{\mathrm{d}\ln R^2}\right|_{\sigma=1}, \quad y \equiv \frac{k}{k_{\rm NL}}, \quad \sigma(k_{\rm NL}^{-1},z) = 1
\end{aligned}$$

Generalising Halofit

(A) It should well predict the power spectrum for a wide range of HS model parameter f_{R0} and for various background cosmologies at various redshifts;

(B) When $|f_{R0}| \to 0$, it should recover **`Halofit`**;

(C) The screening effect must be included, *i.e.*, for small field models ($|f_{R0}| \ll 10^{-4}$), or at higher redshifts, the power should be suppressed compared to the **`Halofit`** prediction on small scales;

(D) The suppression should decrease when $|f_{R0}|$ increases, or z increases;

(E) On large scale, the prediction should agree with the linear prediction;

(F) On all scales, the prediction of Δ_P should not exceed the linear prediction;

(G) On all scales, Δ_P should be positive definite.

$$\tilde{\Delta}^2 \equiv \frac{k^3 P(k)^{\texttt{MGHalofit}}_{\rm HS}}{2\pi^2} = \tilde{\Delta}^2_{\rm Q} + \tilde{\Delta}^2_{\rm H}$$

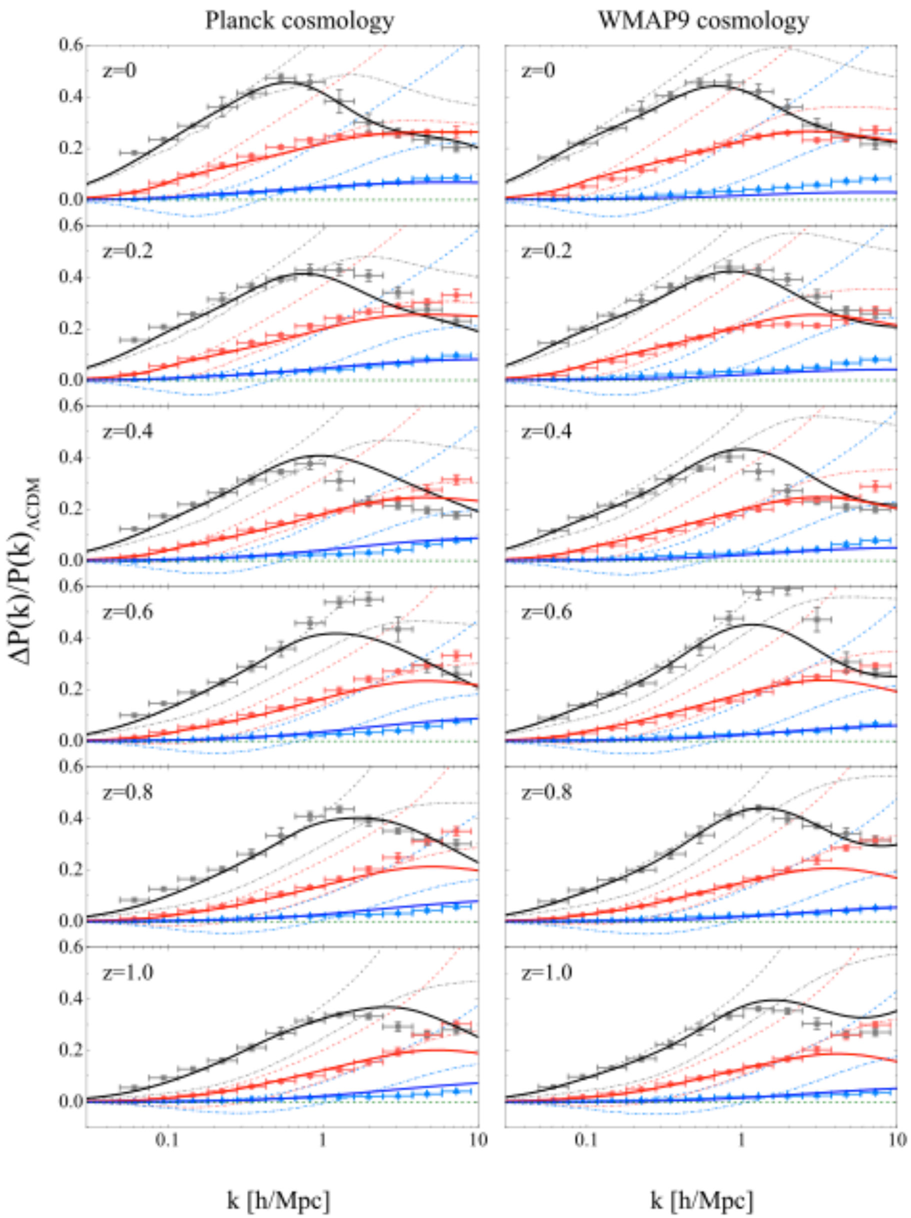
$$\tilde{\Delta}^2_{\rm Q}(k) = \Delta^2_{\rm L}(k) \frac{[1+\tilde{\Delta}^2_{\rm L}(k)]^{\tilde{\beta}(n_{\rm eff},\mathcal{C},\mathcal{F})}}{1+\tilde{\alpha}(n_{\rm eff},\mathcal{C},\mathcal{F})\tilde{\Delta}^2_{\rm L}(k)} \exp[-f(y)]$$

$$\tilde{\Delta}^2_{\rm H}(k) = \frac{\tilde{\Delta}^{2\prime}_{\rm H}(k)\xi(n_{\rm eff},\mathcal{C},\mathcal{F})}{1+\tilde{\mu}(n_{\rm eff},\mathcal{C},\mathcal{F})/y+\tilde{\nu}(n_{\rm eff},\mathcal{C},\mathcal{F})/y^2}$$

$$\tilde{\Delta}^{2\prime}_{\rm H}(k) = \frac{\tilde{a}(n_{\rm eff},\mathcal{C},\mathcal{F})y^{3f_1(\Omega)}}{1+\tilde{b}(n_{\rm eff},\mathcal{C},\mathcal{F})y^{f_2(\Omega)}+[\tilde{c}(n_{\rm eff},\mathcal{C},\mathcal{F})f_3(\Omega)y]^{3-\tilde{\gamma}(n_{\rm eff},\mathcal{C},\mathcal{F})}}$$

$$
\begin{aligned}
\tilde{\Delta}^2_{\rm L}(k) &= \Delta^2_{\rm L}(k)\left[1+\mathcal{F}\left(x_1+x_2 n_{\rm eff}+x_3\mathcal{C}\right)\right] \\
\tilde{\alpha} &= \alpha+\mathcal{F}\left(x_4+x_5 n_{\rm eff}+x_6 n^2_{\rm eff}+x_7\mathcal{C}\right) \\
\tilde{\beta} &= \beta+\mathcal{F}\left(x_8+x_9 n_{\rm eff}+x_{10} n^2_{\rm eff}+x_{11}\mathcal{C}\right) \\
\tilde{\gamma} &= \gamma+\mathcal{F}\left(x_{12}+x_{13} n_{\rm eff}+x_{14} n^2_{\rm eff}+x_{15}\mathcal{C}\right) \\
\log_{10}\tilde{a} &= \log_{10}\left[a+\mathcal{F}\left(x_{16}+x_{17} n_{\rm eff}+x_{18} n^2_{\rm eff}+x_{19}\mathcal{C}\right)\right] \\
\log_{10}\tilde{b} &= \log_{10}\left[b+\mathcal{F}\left(x_{20}+x_{21} n_{\rm eff}+x_{22} n^2_{\rm eff}+x_{23}\mathcal{C}\right)\right] \\
\log_{10}\tilde{c} &= \log_{10}\left[c+\mathcal{F}\left(x_{24}+x_{25} n_{\rm eff}+x_{26} n^2_{\rm eff}+x_{27}\mathcal{C}\right)\right] \\
\log_{10}\tilde{\mu} &= \log_{10}\left[\mu+\mathcal{F}\left(x_{28}+x_{29} n_{\rm eff}+x_{30} n^2_{\rm eff}+x_{31}\mathcal{C}\right)\right] \\
\log_{10}\tilde{\nu} &= \log_{10}\left[\nu+\mathcal{F}\left(x_{32}+x_{33} n_{\rm eff}+x_{34} n^2_{\rm eff}+x_{35}\mathcal{C}\right)\right] \\
\xi &= \exp\left[\mathcal{D}\left(x_{36}+x_{37} n_{\rm eff}+x_{38} n^2_{\rm eff}+x_{39}\mathcal{C}\right)\right]
\end{aligned}
$$

$$
\mathcal{F}\equiv|f_{R0}|/(3\times10^{-5}) \qquad \mathcal{D}\equiv\left|\frac{P(k)^{\rm lin.}_{\rm HS}}{P(k)^{\rm lin.}_{\Lambda{\rm CDM}}}-\max\left[\frac{P(k)^{\tt Halofit}_{\rm HS}}{P(k)^{\tt Halofit}_{\Lambda{\rm CDM}}},1\right]\right|
$$



GBZ, ApJS 2014

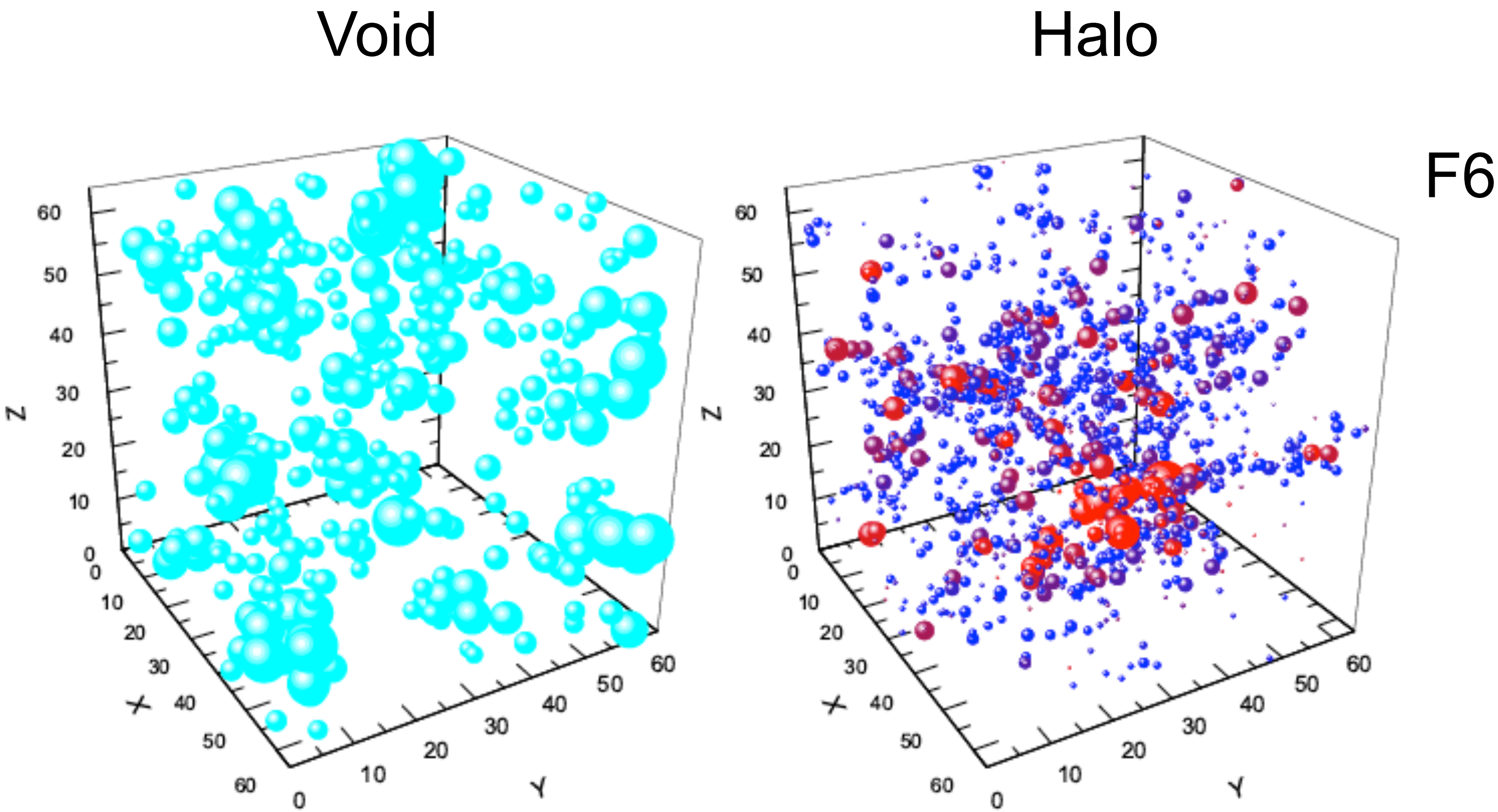
A upgrade: the ECOSMOG code

B.Li, GBZ, R.Teyssier, K.Koyama, JCAP 2012

- Code: Modified RAMSES (AMR code, **MPI**)
- $N_p=1024^3$
- Models: f(R), DGP, symmetron, dilaton, general chameleon, and Galileon.
- Data analysis: RSD, ISW, matter and velocity power spectrum, halo spin, halo morphology,

Halos and Voids in f(R)

Li, GBZ and Koyama (2012)



Halos and Voids in f(R)

Li, GBZ and Koyama (2012)

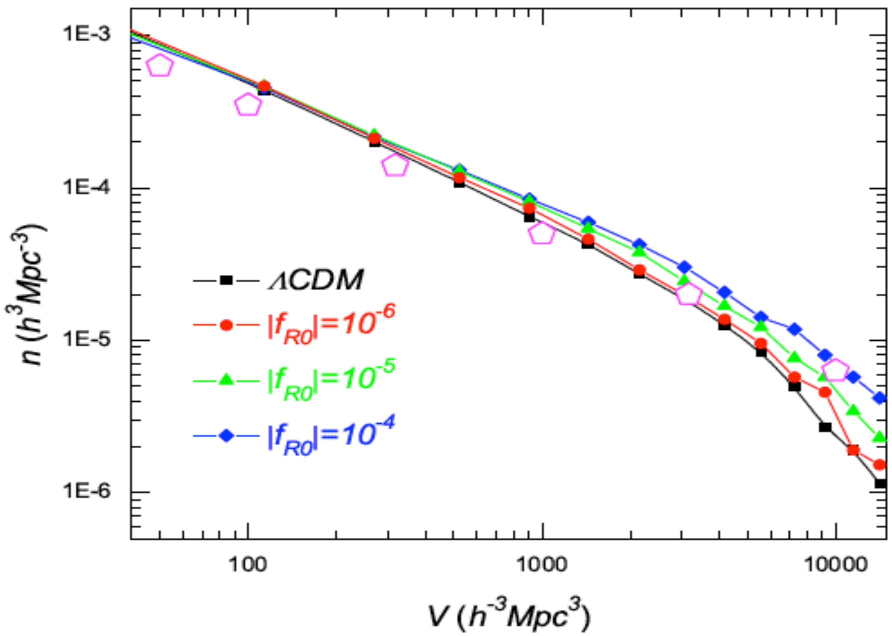
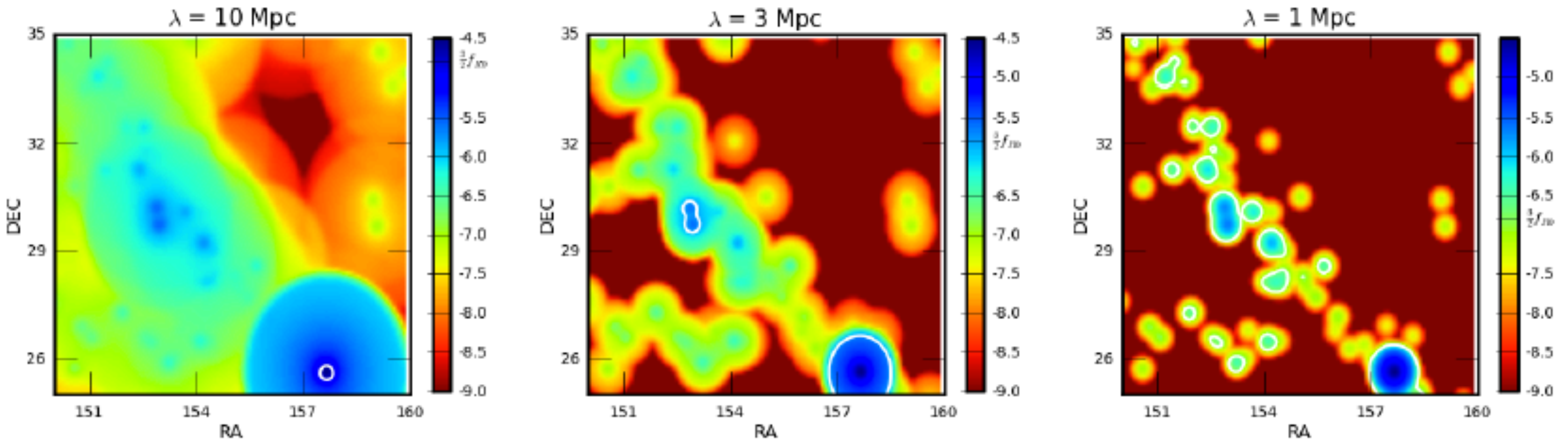


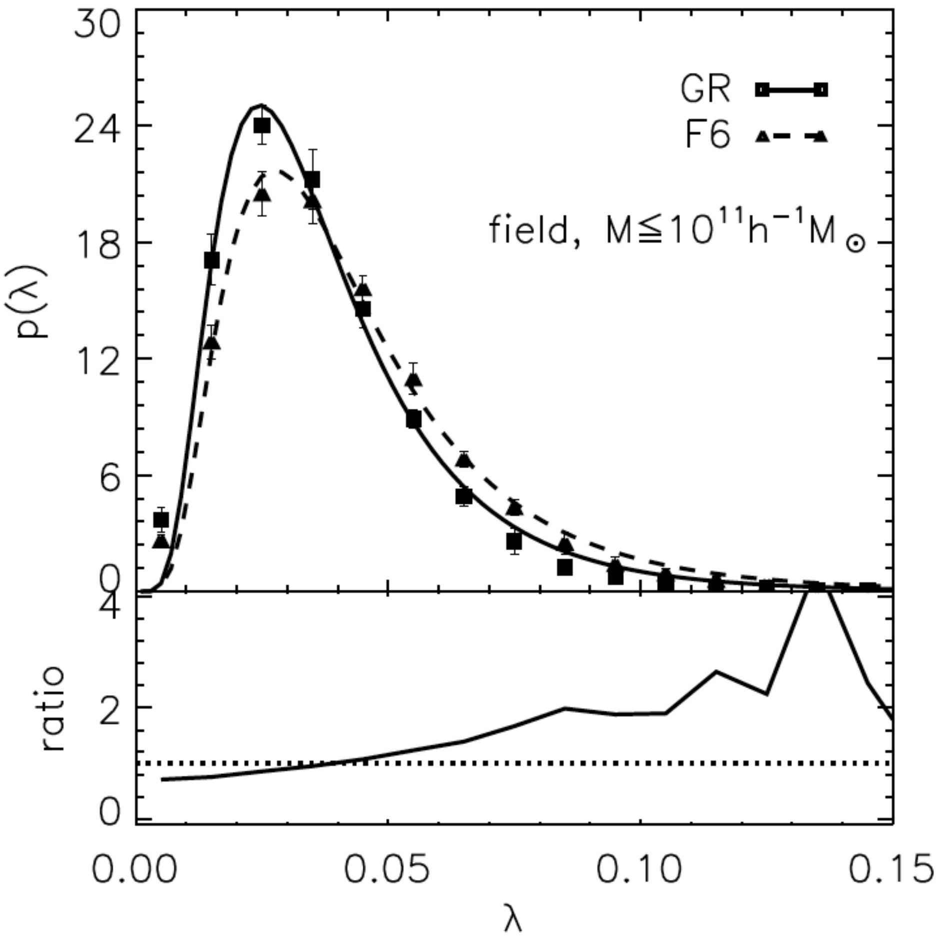
Figure 6. (Colour Online) The void number density as a function of a volume. The black squares, red circles, green triangles and blue diamonds are from the ΛCDM simulation and $f(R)$ simulations with $|f_{R0}| = 10^{-6}, 10^{-5}, 10^{-4}$ respectively. Each curve is the averaged result of ten realisations. The magenta pentagons are results for ΛCDM from Colberg et al. (2005) for consistency check. All results are at $a = 1$.

3D screening map in the SDSS region

Cabre, Vikram, GBZ, Jain and Koyama (2012)

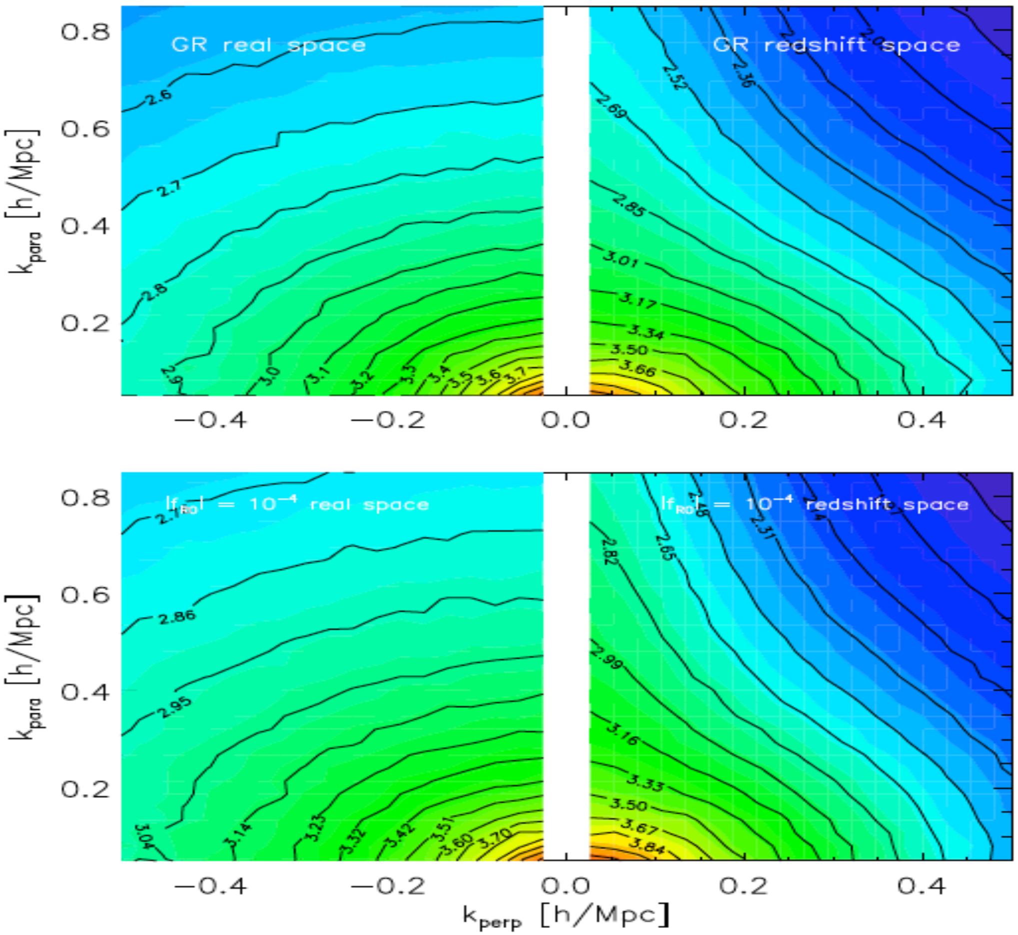


Halos spin faster in f(R) Lee, GBZ, Li and Koyama (2013)



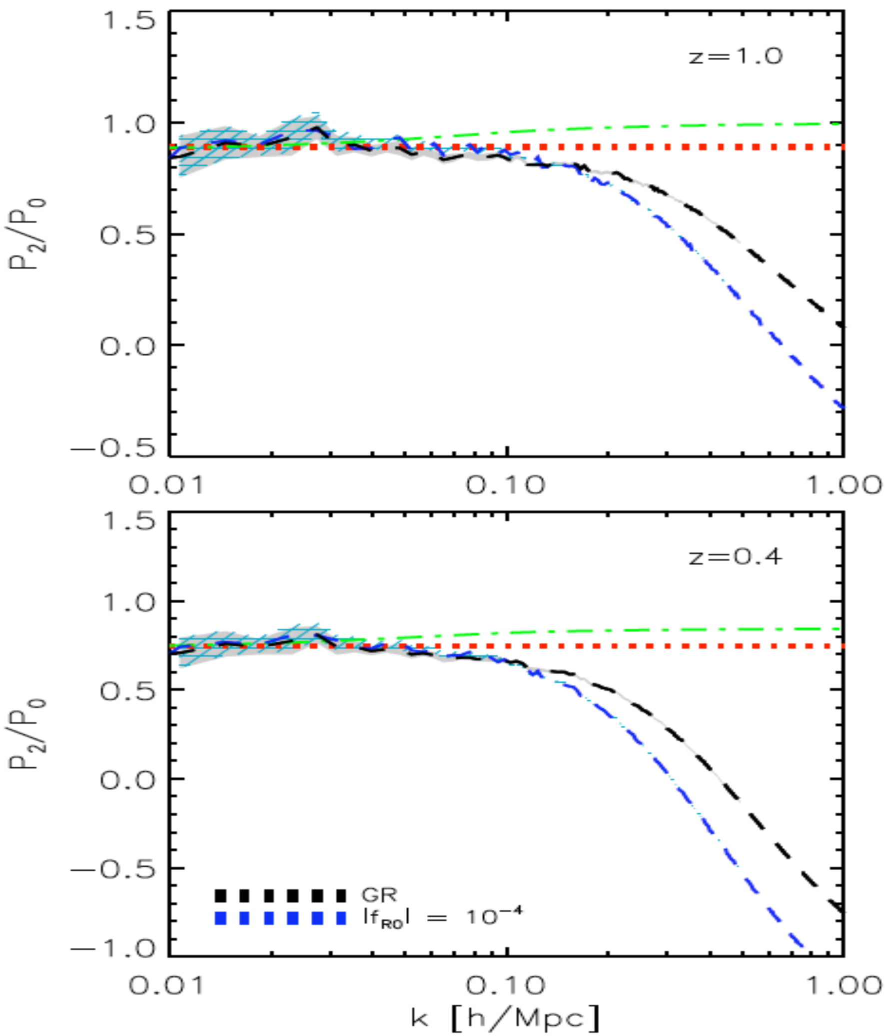
RSD in f(R)

Jennings, Baugh, Li, GBZ and Koyama (2012)



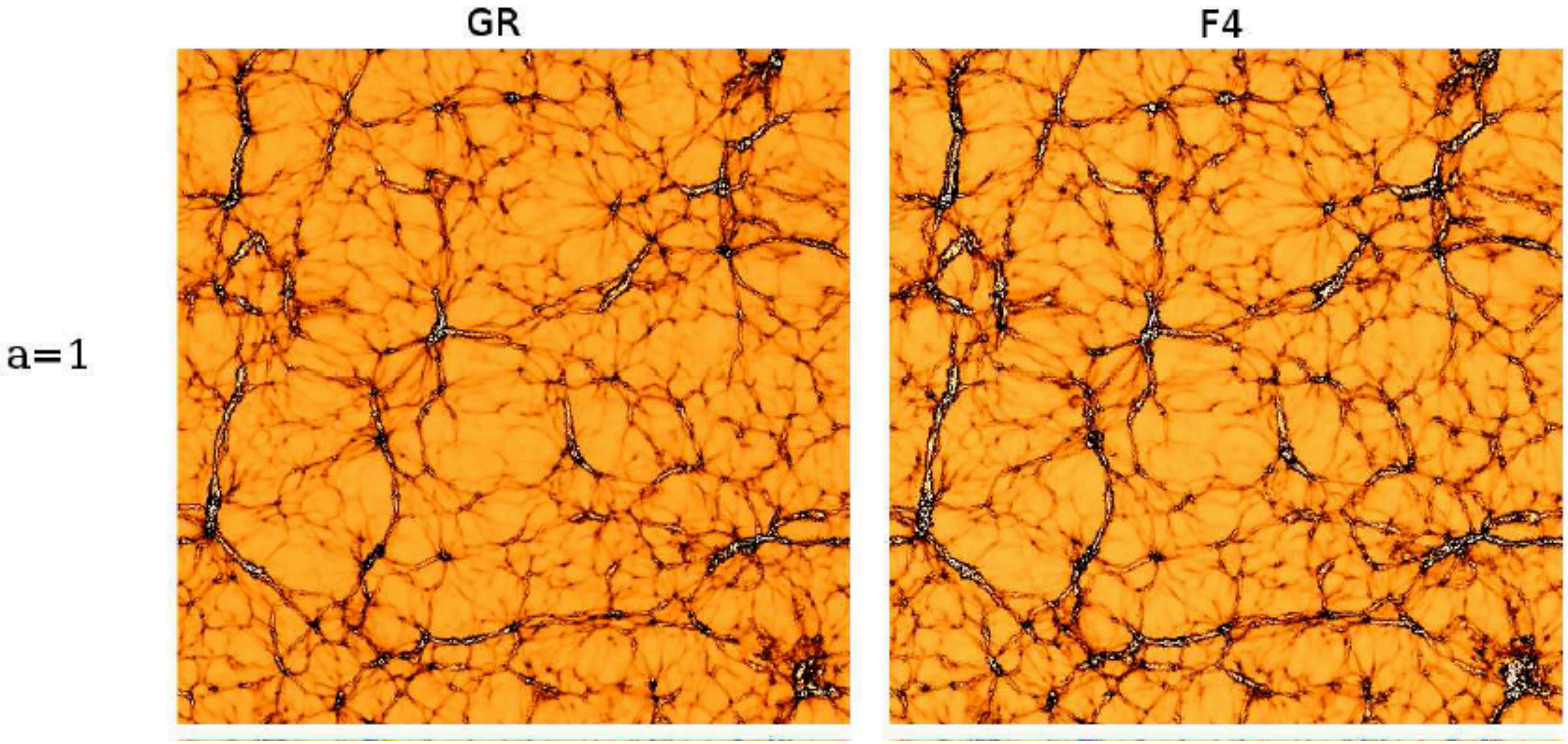
RSD in f(R)

Jennings, Baugh, Li, GBZ and Koyama (2012)



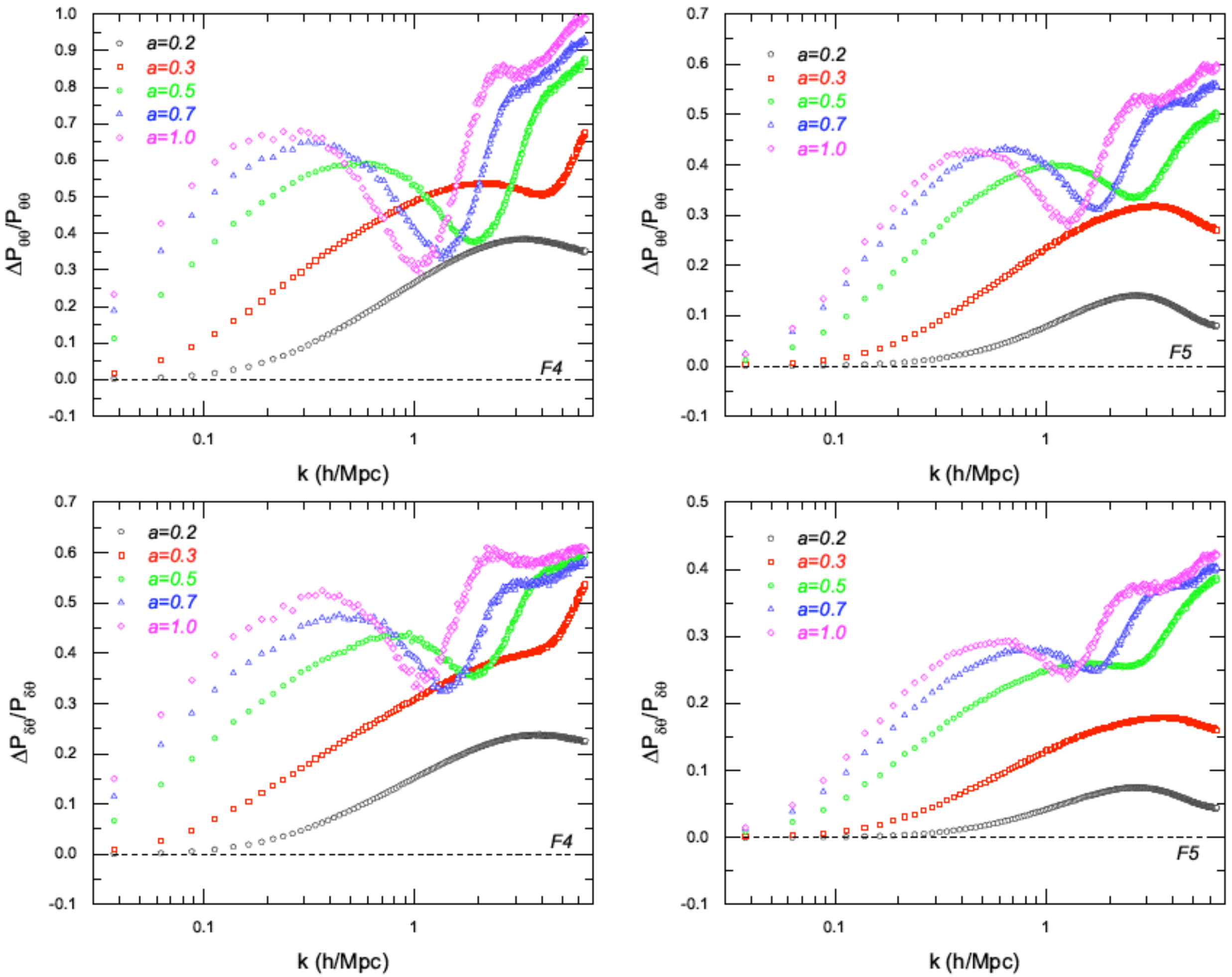
Nonlinear matter/velocity power spectra

Li, Hellwing, Koyama, GBZ, Jennings, Baugh (2013)



Nonlinear matter/velocity power spectra

Li, Hellwing, Koyama, GBZ, Jennings, Baugh (2013)



DGP model simulations

Li, GBZ, Koyama (2013)

$$\nabla^2\varphi + \frac{r_c^2}{3\beta(a)a^2}[(\nabla^2\varphi)^2 - (\nabla_i\nabla_j\varphi)(\nabla^i\nabla^j\varphi)] = \frac{8\pi G a^2}{3\beta(a)}\rho\delta, \tag{4}$$

and

$$\nabla^2\Psi = 4\pi G a^2\rho\delta + \frac{1}{2}\nabla^2\varphi, \tag{5}$$

$$\tilde{\nabla}^2\tilde{\varphi} + \frac{R_c^2}{3\beta a^4}\left[\left(\tilde{\nabla}^2\tilde{\varphi}\right)^2 - \left(\tilde{\nabla}_i\tilde{\nabla}_j\tilde{\varphi}\right)^2\right] = \frac{\Omega_m a}{\beta}(\tilde{\rho} - 1)$$

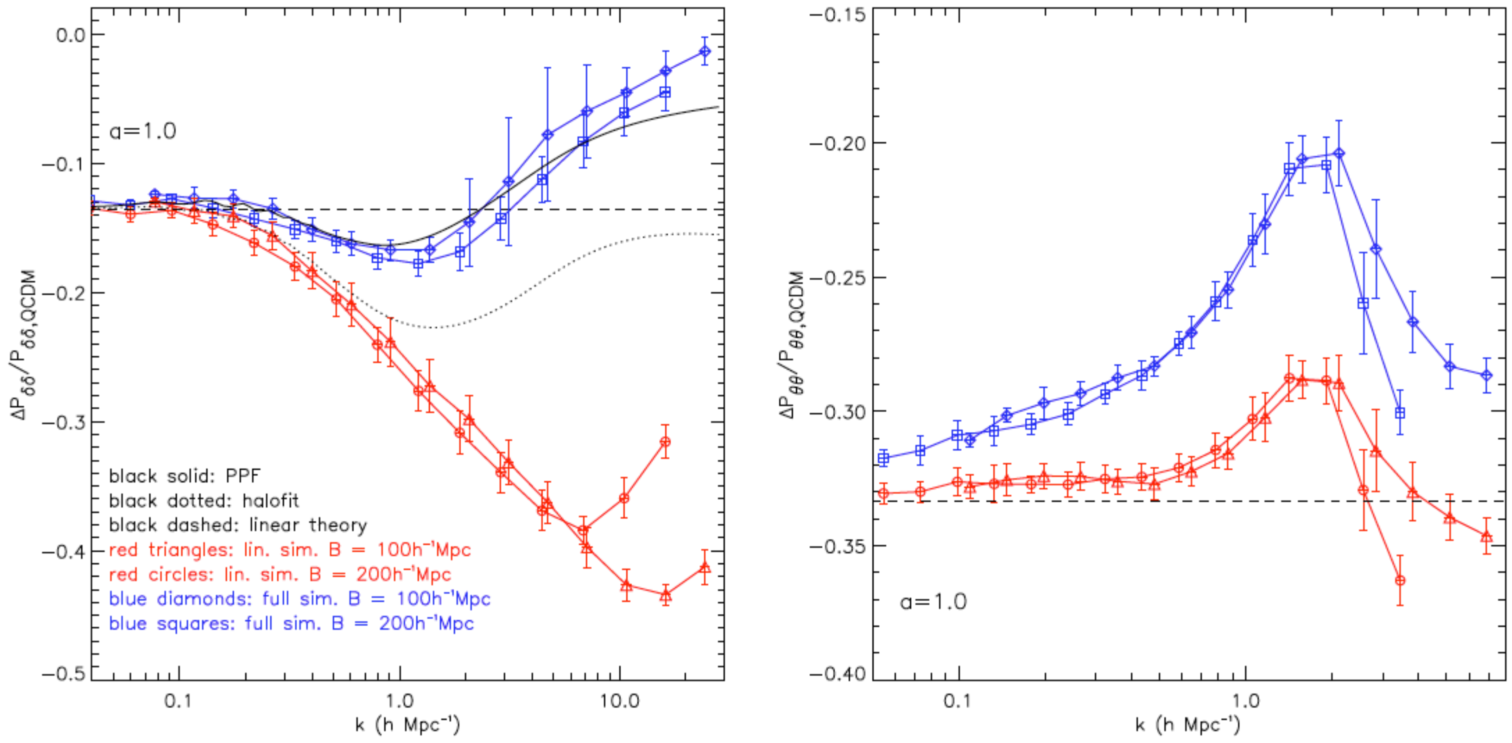
$$\nabla^2\varphi = \frac{1}{2(1-w)}\left[-\alpha \pm \sqrt{\alpha^2 + 4(1-w)\Sigma}\right]$$

$$\alpha \equiv \frac{3\beta a^4}{R_c^2},$$

$$\Sigma \equiv (\nabla_i\nabla_j\varphi)^2 - w\left(\nabla^2\varphi\right)^2 + \frac{\alpha}{\beta}\Omega_m a\,(\rho - 1)\,,$$

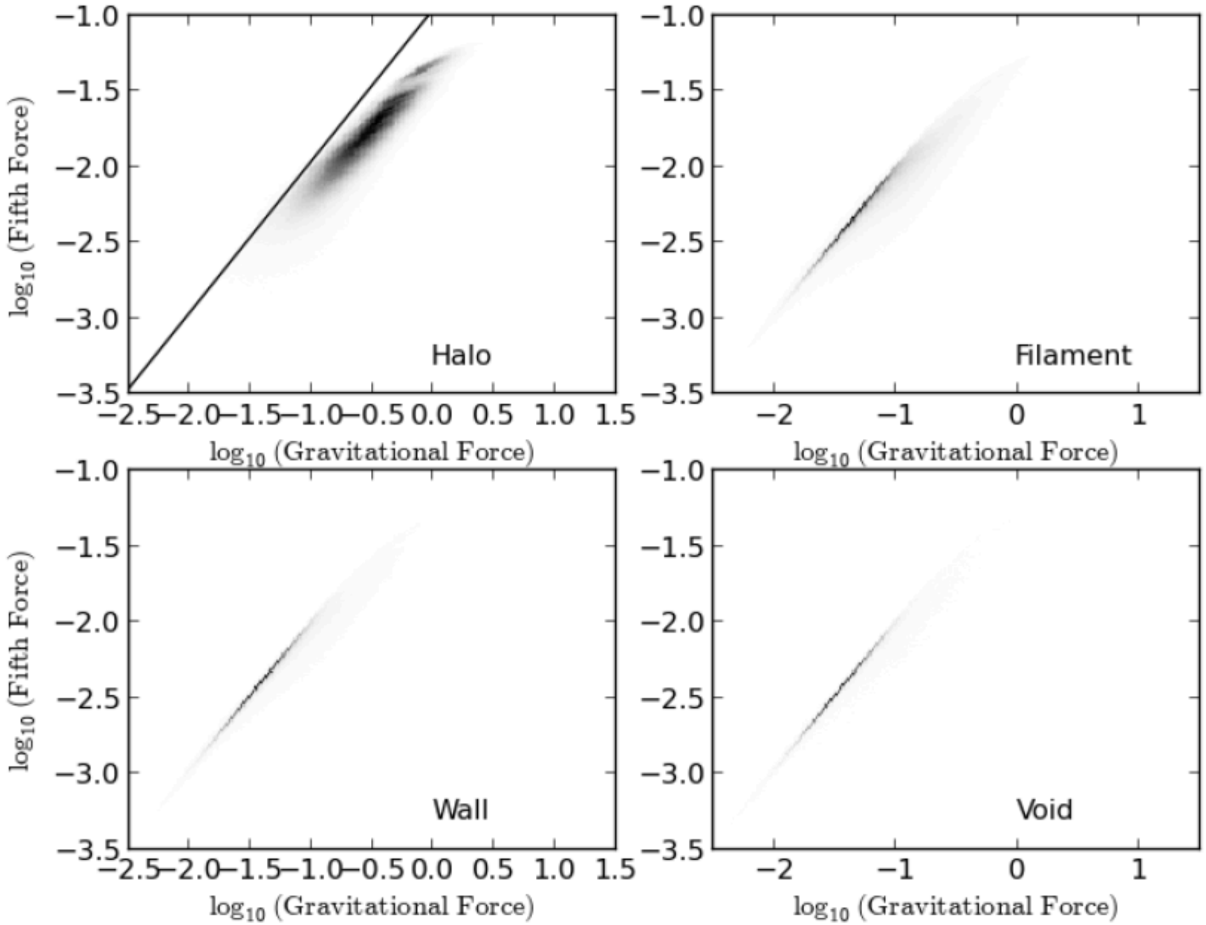
DGP model simulations

Li, GBZ, Koyama (2013)



Morphology-dependent screening

Falck, Koyama, GBZ, Li (2014)



A new gravity probe using Minkowski functionals

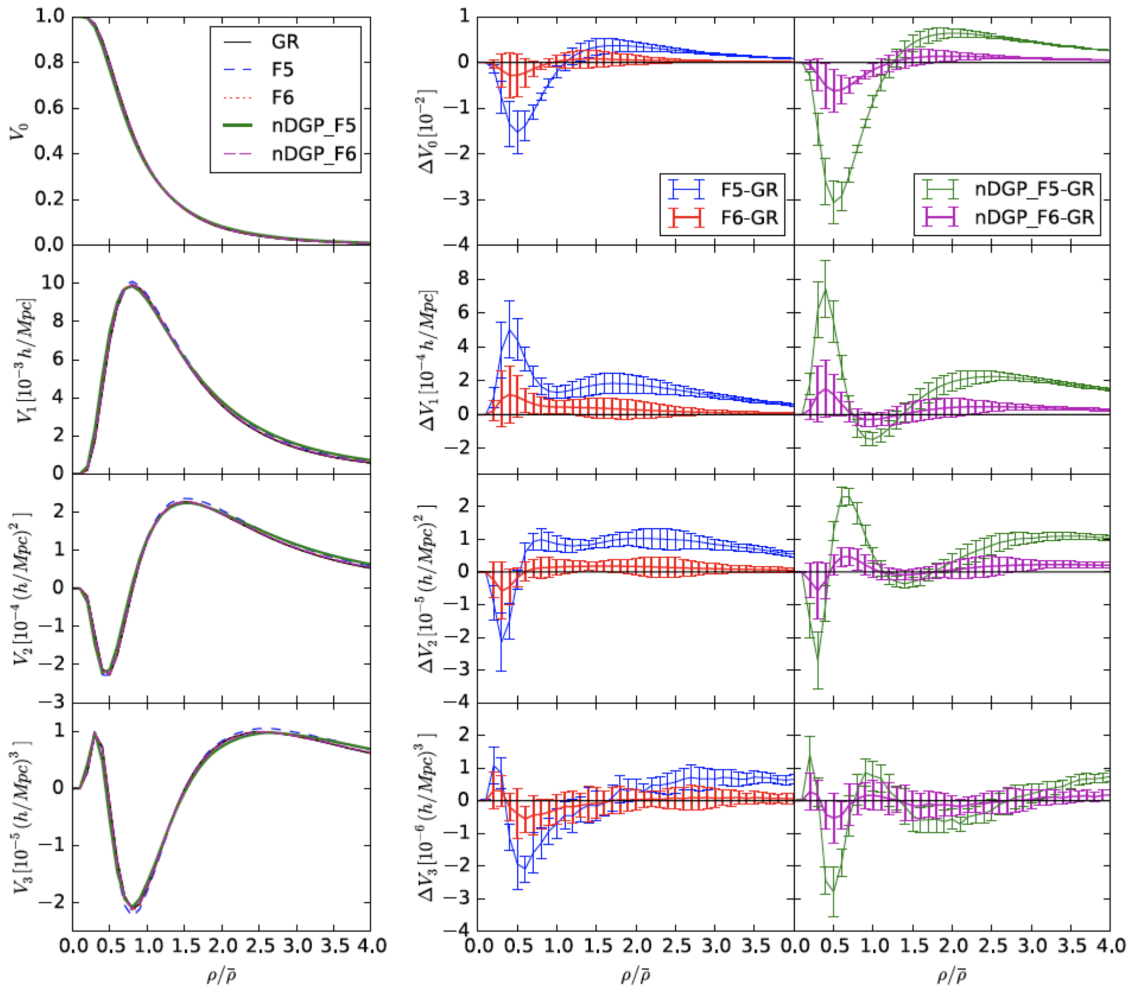
Fang, Li & GBZ, PRL (2017)

Volume

Surface area

curvature

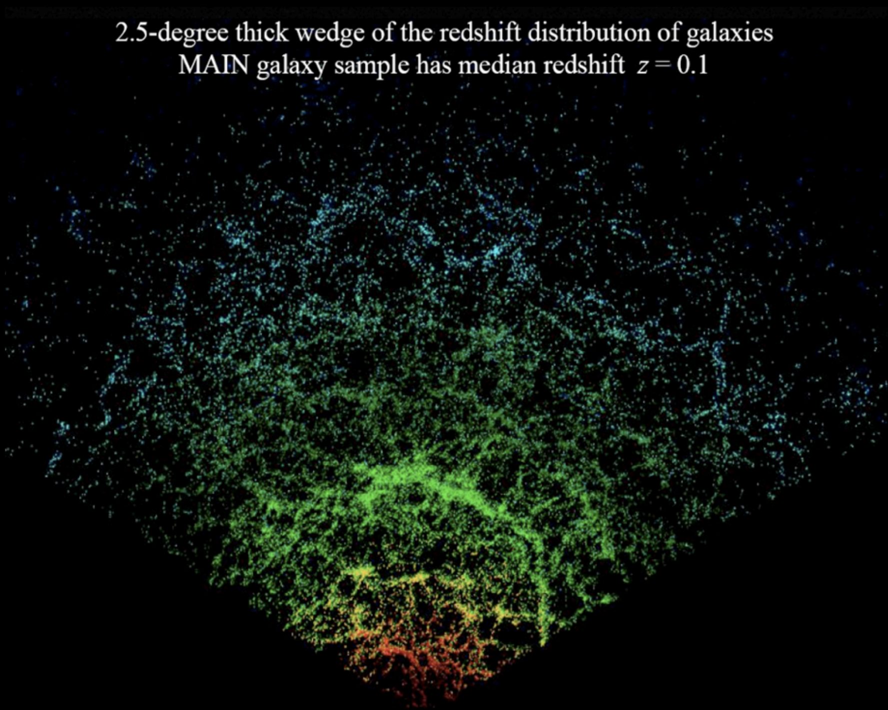
genus



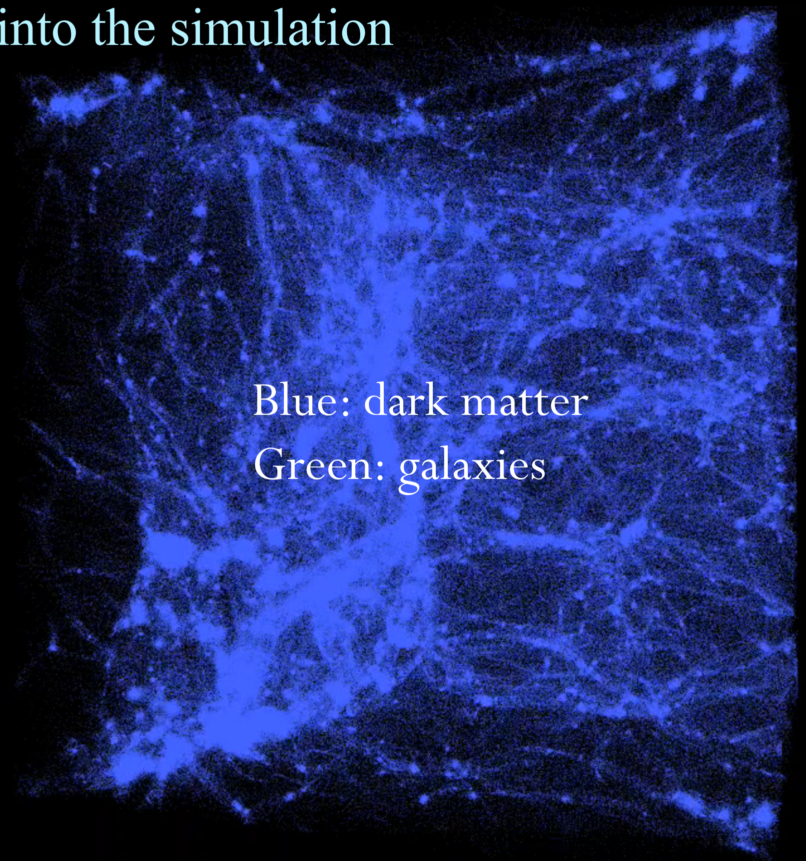
Halo, galaxy scales | Structure formation scales | Cosmological scales

The next step

Adding baryons into the simulation

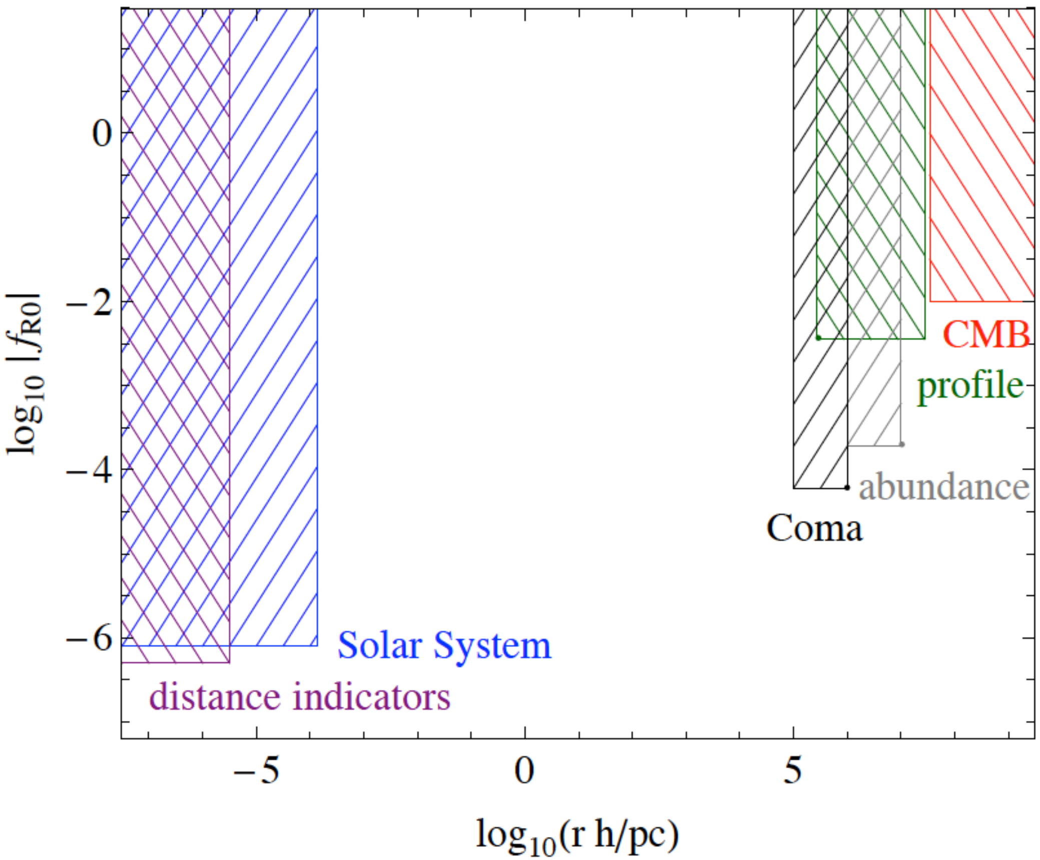


Real galaxy map from SDSS



Preliminary hydrodynamical f(R) simulations
GBZ, in prep

Gravity tests using clusters



Lensing mass: CFHTLS

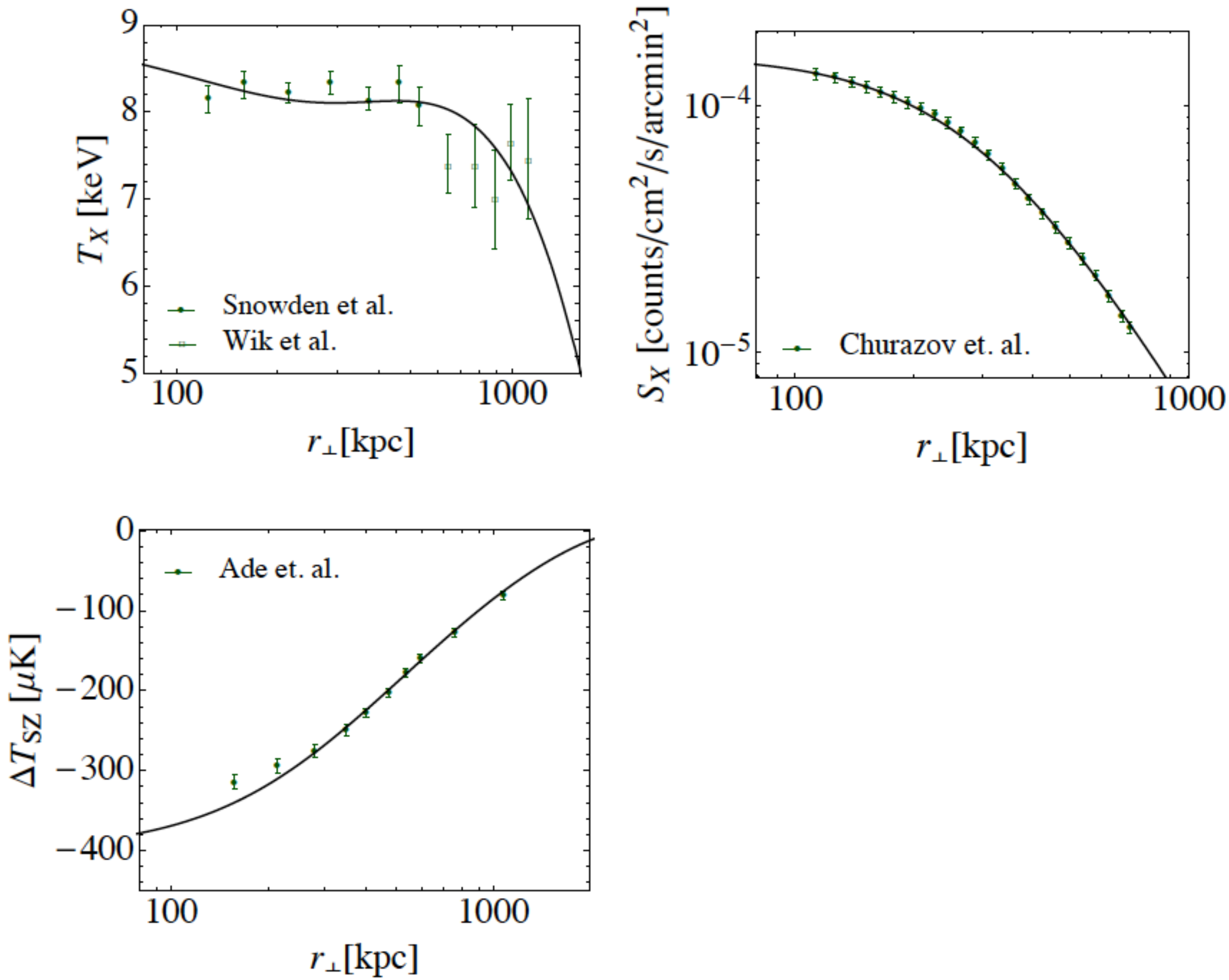
Dynamical (hydrostatic) mass:

1. X-ray temperature (XMM-Newton+Suzaku);

2. X-ray surface brightness (XMM-Newton)

3. SZ (Planck)

Terukina et al, JCAP 2014



9
8
7
6
5
T_X [keV]
Snowden et al.
Wik et al.
100
1000
$r_\perp$[kpc]
S_X [counts/cm^2/s/arcmin^2]
10^{-4}
10^{-5}
Churazov et. al.
100
1000
$r_\perp$[kpc]
0
−100
−200
−300
−400
ΔT_{SZ} [μK]
Ade et. al.
100
1000
$r_\perp$[kpc]

Caveats

- The Hydrostaticity (to be verified)
- The non-thermal pressure is negligible (probably not true in MG)
- The NFW profile (?)
- A few fitting formulae calibrated using LCDM hydro-simulations

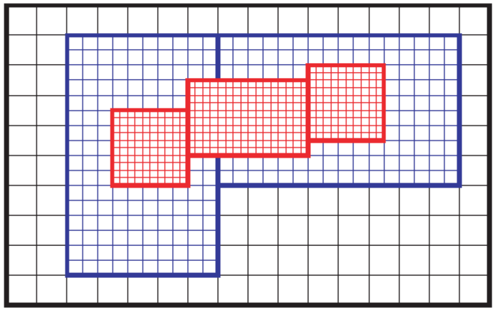
THE MISSING LINK

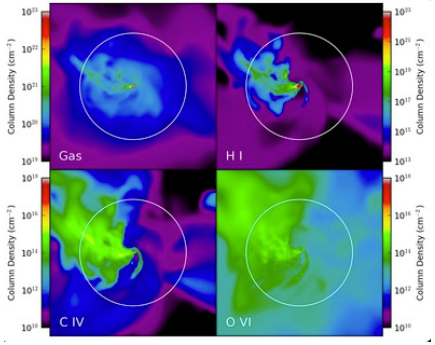
High-resolution MG hydro-simulations

Hydro-simulation of MG

GBZ & Shiming Gu, in prep

- Code: MGENZO (block AMR, MPI, full hydro, excellent data analysis support using yt)





- An improved algorithm: Monotone-Gauss-Seidal instead of NGS. More stable for complicated MG models
- Plan: Full zoom-in hydro-simulations for MG

Monotone-Gauss-Seidal Method

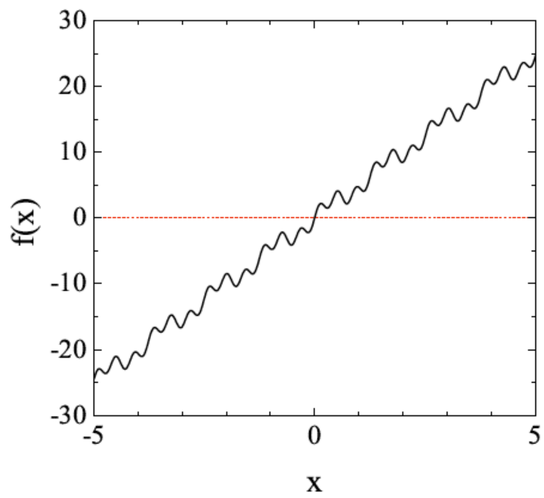
$$A\Theta = F(\Theta)$$

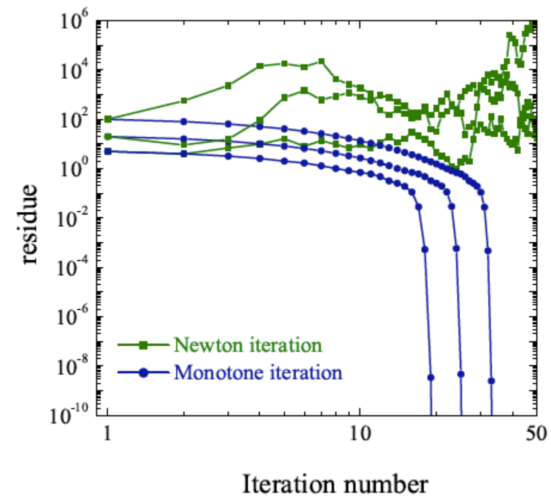
$$A\widetilde{\Theta} \geq F(\widetilde{\Theta}), \quad A\widehat{\Theta} \leq F(\widehat{\Theta}), \quad \widetilde{\Theta} \geq \widehat{\Theta}$$

$$\left(A + C^{(m)}\right)\Theta^{(m+1)} = C^{(m)}\Theta^{(m)} + F\left(\Theta^{(m)}\right)$$

$$C^{(m)} \equiv \mathrm{diag}\left(c_1^{(m)}, ..., c_N^{(m)}\right), \quad c_i^{(m)} = \left[\gamma_i^{(m)} + \mathrm{abs}(\gamma_i^{(m)})\right]/2$$

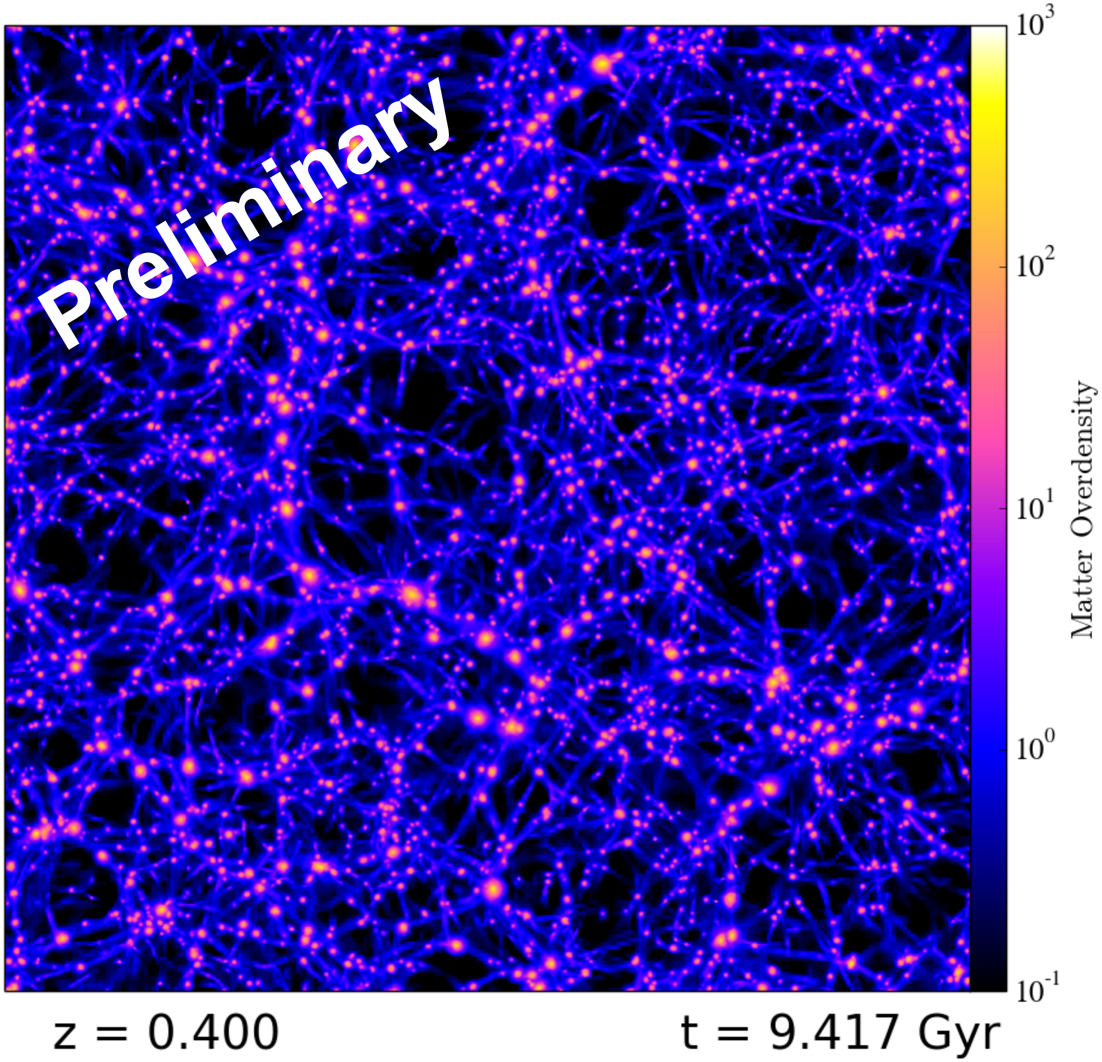
$$\gamma_i^{(m)} \equiv \max\left\{-\frac{\partial F_i}{\partial \theta_i}(\theta_i); \quad \underline{\theta}_i^{(m)} \leq \theta_i \leq \bar{\theta}_i^{(m)}\right\}$$



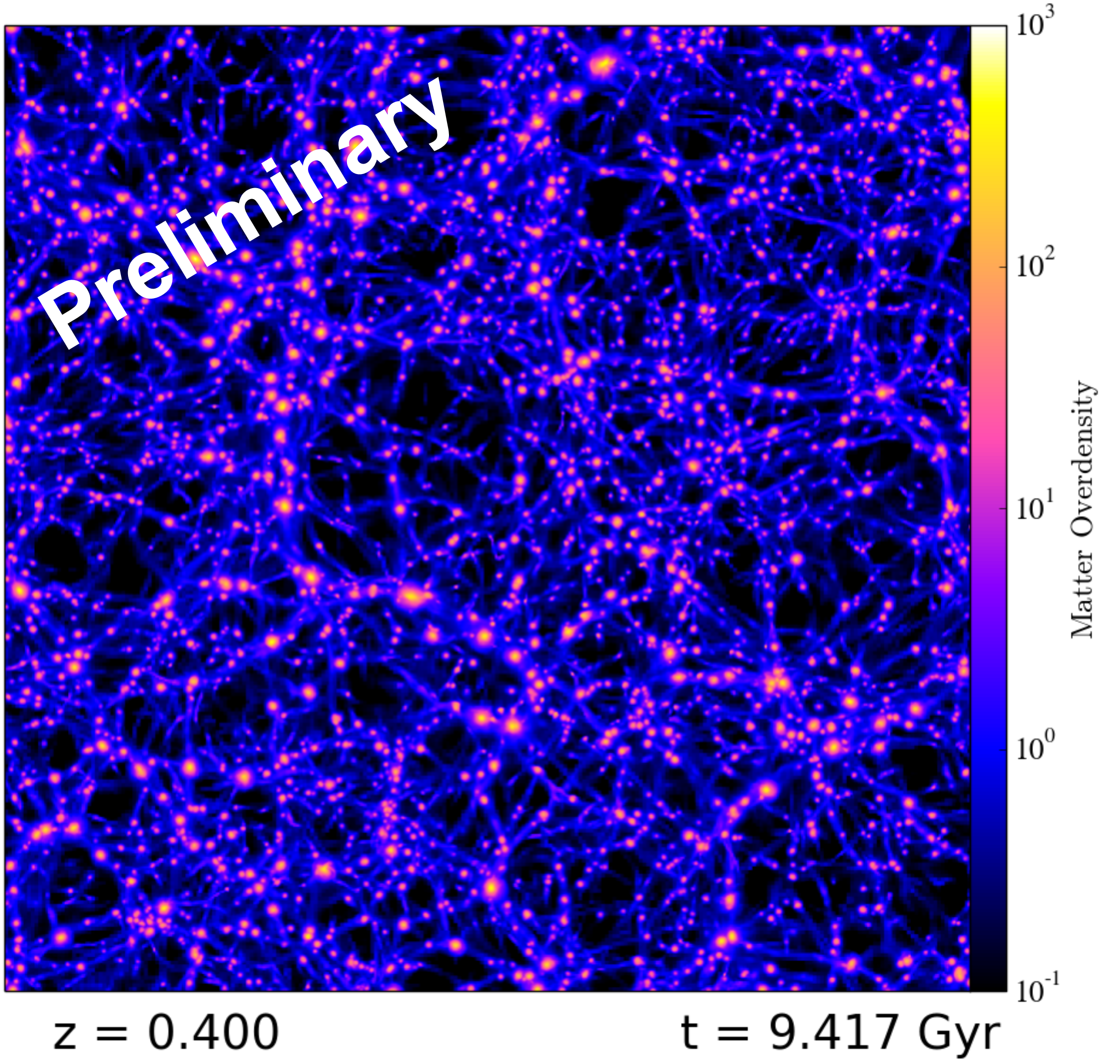


GBZ, in prep

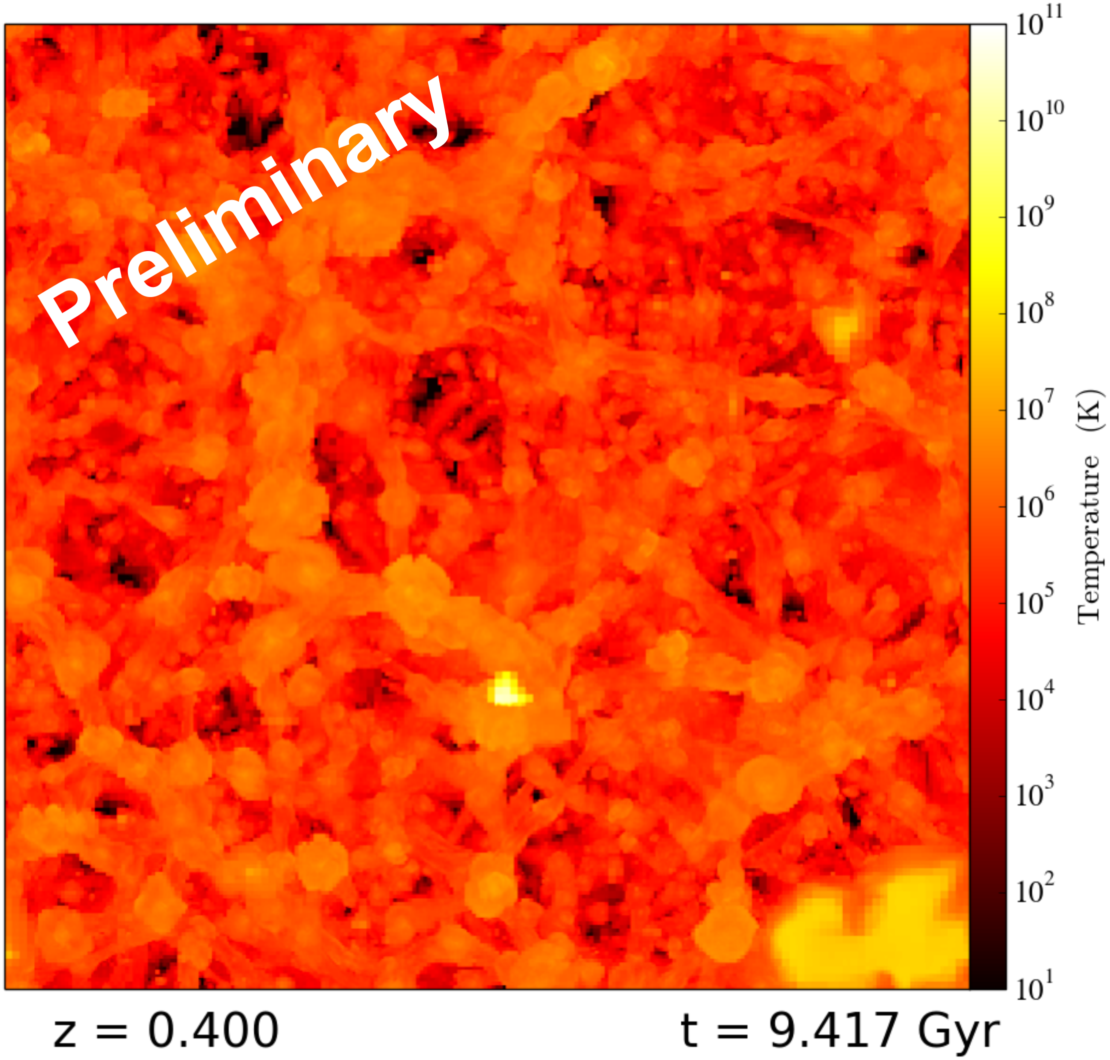
GR


Preliminary
10^3
10^2
10^1
10^0
10^{-1}
Matter Overdensity
z = 0.400
t = 9.417 Gyr

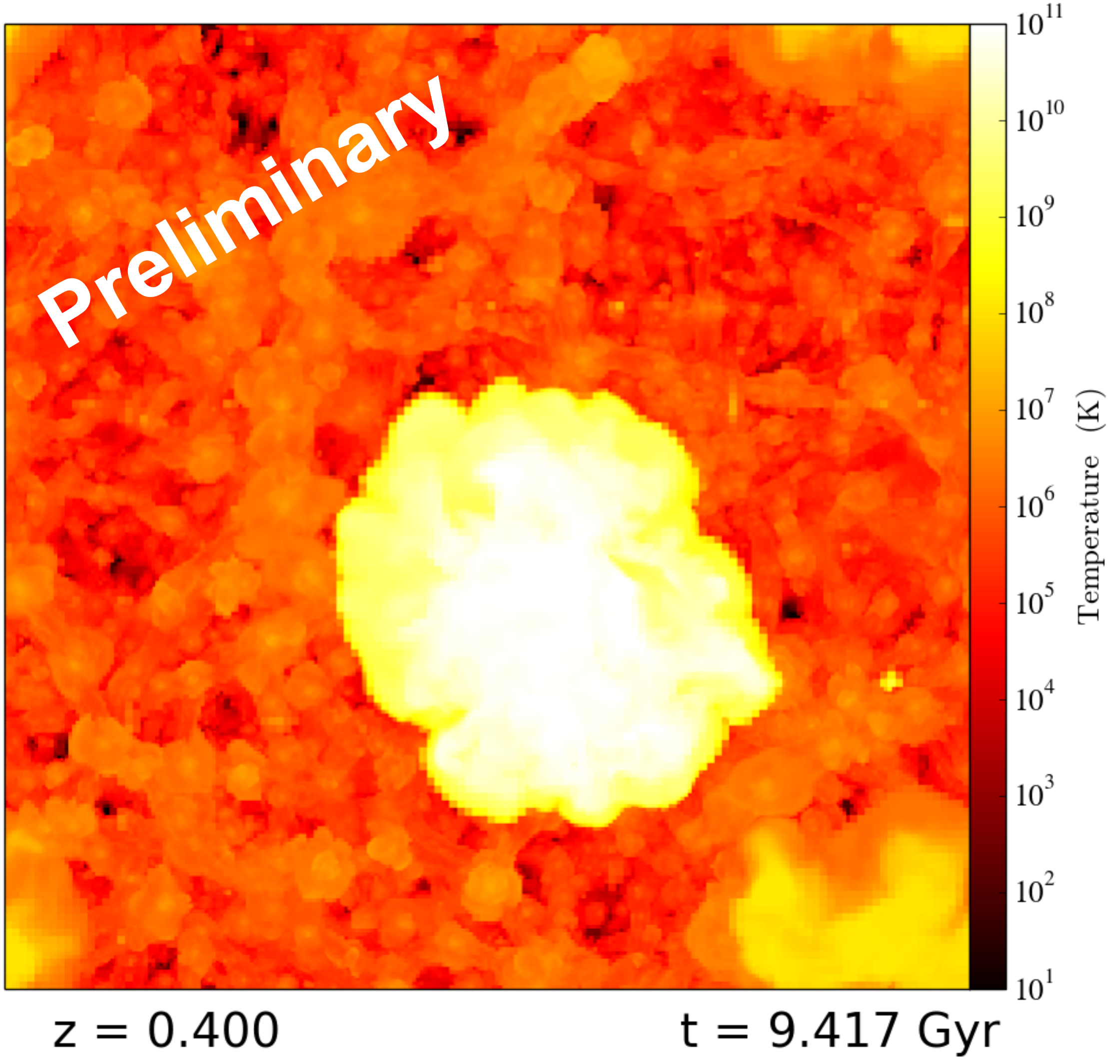
f(R)


Preliminary
10^3
10^2
10^1
10^0
10^{-1}
Matter Overdensity
z = 0.400
t = 9.417 Gyr

GR


Preliminary
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
Temperature (K)
z = 0.400
t = 9.417 Gyr

f(R)


Preliminary
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
Temperature (K)
z = 0.400
t = 9.417 Gyr

Summary

- Galaxy surveys can provide key information for cosmology, and tomographic BAO/RSD analyses are crucial for DE and MG;
- Data/likelihood of our BOSS measurements available at https://sdss3.org/science/boss_publications.php
- BOSS DR12 data (combined with others) show a hint of DE dynamics at 3.5 sigma level;
- There is rich information on nonlinear scales for gravity test, but we need high-resolution hydro-simulations in order to use the excellent observational data (eBOSS, DES, DESI, LSST, Euclid,PFS etc) in the next few years.