Cosmic acceleration and large scale structure observations

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

Cosmology = 宇 (space) 宙 (time) 学 (study)
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Cosmology = 宇 (space) 宙 (time) 学 (study)
The diagram illustrates the cosmic timeline and components:

- **Big Bang Expansion**: 13.7 billion years

### Epochs of Cosmological Development

- **Inflation**
- **Quantum Fluctuations**
- **Afterglow Light Pattern 380,000 yrs.**
- **Dark Ages**
- **Development of Galaxies, Planets, etc.**
- **Dark Energy Accelerated Expansion**

### Dark Matter Distribution

- **Dark Matter**: 26.8%
- **Dark Energy**: 68.3%
- **Baryons**: 4.9%

The image is credited to NASA.
Huge discovery space in the dark sector!

100+ Nobel Prizes since 1901!

Dark Energy 68.3%
Dark Matter 26.8%
Baryons 4.9%
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

\[ G_{\mu\nu} = 8\pi G\tilde{T}_{\mu\nu} \]

Modified Gravity

\[ \tilde{G}_{\mu\nu} = 8\pi GT_{\mu\nu} \]
The expansion of the Universe can **accelerate** if

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To modify General Relativity

**Dark Energy**

\[ G_{\mu\nu} = 8\pi G \tilde{T}_{\mu\nu} \]

**Modified Gravity**

\[ \tilde{G}_{\mu\nu} = 8\pi G T_{\mu\nu} \]

LSS surveys can help break the degeneracy
Weak lensing

BAO, RSD

CMB

Radio surveys
‘Redshift-meters’

- **Hubble (1930):** expanding Universe
- **CfA Redshift Survey (1985):** first large scale structures (wall, filaments)
- **2dF (~2000):** 1500 sqdeg
- **SDSS (~2002):** 5700 sqdeg
- **VVDS/DEEP2 (~2004):** deep Universe ~ 1 sqdeg
- **WiggleZ (2008-2011):** 800 sqdeg BAO
- **VIPERS (2010-2014):** 25 sqdeg RSD
- **SDSS-III/BOSS (2009-2014):** 10,000 sqdeg BAO/LSS
- **e-BOSS (2014-2020)
- **DESI, PFS
- **EUCLID (2020), WFIRST (2025?)

credit: Jean-Paul KNEIB
‘Redshift-meters’

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e-BOSS (2014-2020)

DESI, PFS (2018?)

EUCLID (2020), WFIRST (2025?)

credit: Jean-Paul KNEIB
What do redshift surveys measure?

A 3D galaxy map in $z$-space

$\theta, \phi, z$
A 3D galaxy map in $z$-space

$P(k)$

BOSS (Beutler et al, 2014)

$\xi(s)$

BOSS (Samushia et al, 2014)

Feldman et al, 1994

Landy & Szalay, 1993

$\langle |F(k)|^2 \rangle = \int \frac{d^3 k'}{(2\pi)^3} |P(k') - P(0)\delta_D(k)||G(k-k')|^2 + \left(1 + \frac{1}{\alpha}\right) \int d^3 x \bar{n}(x)$

$\bar{\xi}(r) = \frac{DD(r) - 2DR(r) + RR(r)}{RR(r)}$

$\chi^2_{\text{fit}} = 18/27 \text{ dof}$
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

DR12 CMASS N

Tomographic RSD

Single RSD

redshift $z$

$\sigma_8$
Tomographic FoM = 70.3

45% improvement!

Single FoM = 48.4
Tomographic BAO measurements from BOSS DR12

GBZ, Wang, et al, (BOSS team), 1607.03153
Wang, GBZ, et al, (BOSS team), 1607.03154
Tomographic galaxy power spectrum measurement

BOSS (GBZ, Wang et al), 2016

- Tomographic multipole measurement (9 bins)
- Mass assignment: 4th order B-spline
- Anti-aliasing correction (Jing 2005)
- Cosmological implications using full \( P(k) \) shapes: dark energy reconstruction; gravity test; neutrino mass, etc
Tomographic galaxy correlation function measurement

BOSS (Wang, GBZ et al), 2016
BOSS (Yuting Wang, GBZ et al), 2016, 1607.03154
Latest BOSS tomographic BAO measurements

BOSS (GBZ, Yuting Wang et al), 2016, 1607.03153
BOSS (GBZ, Yuting Wang et al), 2016, 1607.03153
BAO: To bin or not to bin?

BOSS (Yuting Wang, GBZ et al), 2016, 1607.03153
Optimal redshift weighting scheme
BOSS/eBOSS applications (GBZ et al, Dandan Wang et al, in prep.)

Poor man’s method:
\[ F = D^T C^{-1} D \]
\[ D = \left( \frac{\partial P}{\partial p_1}, \frac{\partial P}{\partial p_2}, ..., \frac{\partial P}{\partial p_M} \right) \]
\[ P = [\ln P(z_1), \ln P(z_2), ..., \ln P(z_N)]^T \]

A smart method:
\[ F_w = D_w^T C_w^{-1} D_w \]
\[ D_w = \left( \frac{\partial P_w}{\partial p_1}, \frac{\partial P_w}{\partial p_2}, ..., \frac{\partial P_w}{\partial p_M} \right) = W^T D \]
\[ P_w = W^T P \]

\[ W = \begin{pmatrix} W_{p_1}(z_1) & W_{p_2}(z_1) & ... & W_{p_M}(z_1) \\
W_{p_1}(z_2) & W_{p_2}(z_2) & ... & W_{p_M}(z_2) \\
... & ... & ... & ... \\
W_{p_1}(z_N) & W_{p_2}(z_N) & ... & W_{p_M}(z_N) \end{pmatrix} \]
\[ C_w = W^T C W \]

The optimal weight:
\[ W = C^{-1} D \]

\[ D_w^T = C_w = D_w = F_w = D^T C^{-1} D = F \]
Reconstruct $w(a)$ non-parametrically

Real data circa 2012

GBZ, et al., 2012
Reconstruct \( w(a) \) non-parametrically

BOSS (GBZ, et al.), to appear soon
The Redshift Space Distortion (RSD)

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

$$cz = H_0d$$
Galaxies have *peculiar motions* due to the local overdensity on top of the Hubble velocity.

\[ cz = H_0 d + \hat{r} \cdot \mathbf{v} \]
On large scales

\[ s \equiv cz < H_0d \]

\[ s \equiv cz > H_0d \]
Redshift Space Distortions (RSD)

Real to redshift space separations

\[ \nabla \cdot \mathbf{v}_p = -aHf \delta_m \]

\[ |\mathbf{v}_p| \sim \frac{d}{d \ln a} \frac{\sigma_8}{\ln a} = \sigma_8 \cdot f \]

Isotropic \hspace{1cm} Squashed along line of sight

\[ f = \frac{d \ln \sigma_8}{d \ln a} \]

Kaiser, 1987
Latest BOSS DR12 RSD measurements

BOSS (Alam et al), 2016, 1607.03155
BOSS (Alam et al), 2016, 1607.03155
eBOSS Survey (started summer 2014)

- 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$^2$

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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)
PFS parameters taken from Takada et al, 2014
See Naoyuki Tamura’s talk on PFS
eBOSS forecast (GBZ et al, 2015)
eBOSS forecast (GBZ et al, 2015)
PFS parameters taken from Takada et al, 2014
eBOSS ability to constrain MG

\[ \Delta \chi^2 (\text{nDGP}) = 23 \]
\[ \Delta \chi^2 (\gamma = 0.5) = 1.3 \]
\[ \Delta \chi^2 (\gamma = 0.6) = 1.1 \]
PFS ability to constrain MG

\[ \Delta \chi^2(\text{nDGP}) = 105 \]
\[ \Delta \chi^2(\gamma = 0.5) = 3.3 \]
\[ \Delta \chi^2(\gamma = 0.6) = 2.7 \]
eBOSS status

- First 2 years’ observation successfully finished
- DR14 data ready internally (QSO and LRG) and being analysed
- A 4% BAO has been detected using QSO; multiple collaboration papers to release in summer 2016
Observational tests on multi-scales

$R < \text{Mpc}$
Cluster profiles

$\text{Mpc} < R < \text{Gpc}$
Galaxy clustering, WL

$R > \text{Gpc}$
Reconstructing $w(z)$ using BAO, SN

GBZ et al., 2011, PRL

GBZ et al., 2009, PRL

GBZ et al., 2012, PRL

Pengjie Zhang et al., 2007, PRL

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Terukina et al., 2014, JCAP

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KIAS

Terukina et al., 2014, JCAP
Current surveys

$R < \text{Mpc}$
Cluster profiles

$\text{Mpc} < R < \text{Gpc}$
Galaxy clustering, WL

$R > \text{Gpc}$
Reconstructing $w(z)$ using BAO, SN

740 SNe from SNLS

Planck

CFHTLenS

SDSS

BOSS

~50 clusters

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02/11/2016
Surveys in 5 years

$R < \text{Mpc}$
Cluster profiles

$\text{Mpc} < R < \text{Gpc}$
Galaxy clustering, WL

$R > \text{Gpc}$
Reconstructing $w(z)$ using BAO, SN

**DES**
$\sim 1000$ SNe
$5000$ deg$^2$

**eBOSS**
$0.6 < z < 2.5$

- $R < \text{Mpc}$
- Mpc $< R < \text{Gpc}$
- $R > \text{Gpc}$

Cluster profiles

Galaxy clustering, WL

Reconstructing $w(z)$ using BAO, SN

- DES
  - $\sim 1000$ SNe
  - $5000$ deg$^2$

- eBOSS
  - $0.6 < z < 2.5$
Surveys in 10 years

\[ R < \text{Mpc} \]
Cluster profiles

\[ \text{Mpc} < R < \text{Gpc} \]
Galaxy clustering, WL

\[ R > \text{Gpc} \]
Reconstructing \( w(z) \) using BAO, SN

TMT: 30 meter imaging

\(~20000\) clusters

**DESIRE (Euclid)+LSST** \(~18k\) SNe

**LSST:** 8.4 m, **20000** deg\(^2\) imaging

**Euclid:** 15000 deg\(^2\) imaging + spectroscopic

**DESI:** 4 m, **14000** deg\(^2\) spectroscopic

**PFS:** 8 m spectroscopic

**SKA:** full sky radio
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

Observationally testable feature
Structure formation scales
Mpc < R < Gpc

Resemble GR + L
Cosmological scales
R > Gpc

Small scales

Large scales
Modified Gravity

Recover GR
Galactic scales \( R < \text{Mpc} \)

Observationally testable feature
Structure formation scales \( \text{Mpc} < R < \text{Gpc} \)

Resemble GR+L
Cosmological scales \( R > \text{Gpc} \)

Small scales

Large scales

KIAS

02/11/2016
Modified Gravity

Recover GR

Galactic scales
\( R < \text{Mpc} \)

Observationally testable feature

Structure formation scales
\( \text{Mpc} < R < \text{Gpc} \)

Resemble GR + L

Cosmological scales
\( R > \text{Gpc} \)

Small scales

f(R) gravity

Large scales
Cosmological tests of GR on **linear** scales

Galaxy scales \[\rightarrow\] Structure formation scales \[\rightarrow\] Cosmological scales

Small scales

Large scales

The deviation from GR is encoded in

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

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

In GR, \(\mu = \gamma = 1\)

A smoking gun of modified gravity:

\(\mu\) and/or \(\gamma\) deviating from 1

\[F_1 = F_2 = \mu G \frac{m_1 \times m_2}{r^2}\]
Cosmological tests of GR on linear scales

Galaxy scales  Structure formation scales  Cosmological 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

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The error of the principal components of $\mu(k,z)$

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

5 modes within 10%

2%
High-resolution numerical simulations are needed!
f(R) Gravity

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

- 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**:

\[
f(R) = -m^2 \frac{c_1 (R/m^2)^n}{c_2 (R/m^2)^n + 1}
\]

\[
m^2 = \frac{8\pi G \bar{\rho}_{M,0}}{3} = H_0^2 \Omega_M
\]

- **Model parameters**:

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

- **Cosmological parameters**: WMAP7
Equations to solve in the code

\[
\frac{ac^2}{(H_0B)^2} \nabla^2 f_R = \frac{1}{3} \left( n \frac{c_1}{c_2} \right)^{\frac{1}{n+1}} f_R^{-\frac{1}{n+1}} \Omega_M a^3 - \Omega_M \rho_c - 4\Omega_\Lambda a^3
\]

\[
\nabla^2 \Phi_c = \frac{3}{2} \Omega_M (\rho_c - 1)
\]

\[+ \left[ \frac{1}{2} \Omega_M \rho_c + 2\Omega_\Lambda a^3 - \frac{1}{6} \Omega_M a^3 \left( n \frac{c_1}{c_2} \right)^{\frac{1}{n+1}} f_R^{-\frac{1}{n+1}} \right]
\]
Get some sense…

f(R)  

GR
\( f(R) \)
Application I: A novel GR test on galactic scales
Structure formation in GR

\[ ds^2 = a^2 (1 + 2\Phi) d\eta^2 - (1 - 2\Psi) d\bar{x}^2 \]

\[ \delta R = -8\pi G \delta \rho \]

\[ \nabla^2 \Phi = 4\pi G a^2 \delta \rho \]
Structure formation in $f(R)$

$$ds^2 = a^2 (1 + 2\Phi) d\eta^2 - (1 - 2\Psi) d\bar{x}^2$$

$$\delta R = -8\pi G \delta \rho - \frac{3\nabla^2 \delta f_R}{a^2}$$

$$\nabla^2 \Phi = 4\pi Ga^2 \delta \rho + \left( \frac{4\pi Ga^2 \delta \rho}{3} + \frac{a^2}{6} \delta R \right)$$

$$= 4\pi Ga^2 \delta \rho_{\text{eff}}$$
Dynamical Mass

\[ M_D \equiv \int a^2 \delta \rho_{\text{eff}} \, dV \]

\[ \nabla^2 \Phi = 4\pi G a^2 \delta \rho_{\text{eff}} \]

Spherical symmetry

\[ M_D(r) = r^2 \frac{d \Phi}{dr} \]
Lensing Mass

\[ M_L \equiv \int a^2 \delta \rho dV \]

\[ \nabla^2 \Phi_+ = 4\pi G a^2 \delta \rho \]

\[ \Phi_+ \equiv (\Phi + \Psi)/2 \]

Spherical symmetry

\[ M_L(r) = r^2 \frac{d\Phi_+}{dr} \]
Mass Difference

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

For f(R), \( 0 \leq \Delta_M \leq 1/3 \)

depending on local density
GBZ et al, 2011

Underdense Environment

<table>
<thead>
<tr>
<th>(A1)</th>
<th>( \rho = -0.74 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A2)</td>
<td>( \rho = -0.20 )</td>
</tr>
</tbody>
</table>

Dense Environment

<table>
<thead>
<tr>
<th>(A3)</th>
<th>( \rho = +0.36 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A4)</td>
<td>( \rho = +0.16 )</td>
</tr>
</tbody>
</table>

Small Halos

<table>
<thead>
<tr>
<th>(B1)</th>
<th>( \rho = +0.65 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B2)</td>
<td>( \rho = +0.67 )</td>
</tr>
</tbody>
</table>

Large Halos

<table>
<thead>
<tr>
<th>(B3)</th>
<th>( \rho = -0.18 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B4)</td>
<td>( \rho = -0.08 )</td>
</tr>
</tbody>
</table>

\( \log_{10} A_M \)

\( \log_{10} [M_L/(M_{\text{sun}}/\text{h})] \)

\( \log_{10} D \)
Clean mass dependence!

GBZ et al, 2011
GBZ et al., 2011

Underdense Environment

Dense Environment

Small Halos

Large Halos

GBZ et al., 2011
Large scatter shows the environmental effect!!

GBZ et al, 2011
Apparent environmental dependence!!

GBZ et al, 2011
No screening!

GBZ et al, 2011
GBZ et al., 2011

$\log_{10} \Delta M$

Small Halos
Underdense Environment

Small Halos
Dense Environment

Large Halos
Underdense Environment

Large Halos
Dense Environment

$\frac{r}{r_{340}}$

GBZ et al., 2011
Screened purely by environment

$\log_{10} \Delta M$

Small Halos
Underdense Environment

Small Halos
Dense Environment

Large Halos
Underdense Environment

Large Halos
Dense Environment

$r/r_{340}$

GBZ et al, 2011
GBZ et al, 2011

![Graph showing the relationship between log10 Δ_M, r/r_340, and the environment of halos.](image)
Screening on the edge shows environmental dependence!
Observationally...

**Lensing** Mass

**Dynamical** Mass

![Diagram of lensing and dynamical mass](image_url)
• 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
A SDSS exercise

2016 = 1.005 ± 0.025 (65 galaxies)
2010 = 1.01 ± 0.05 (53 galaxies)
2009 = 0.88 ± 0.05 (53 galaxies)
2006 = 0.98 ± 0.07 (15 galaxies)

Wei Du, Yiping Shu, GBZ, Cheng Li, Yipeng Jing, in prep.
Application II: A $P(k)$ fitting formula for $f(R)$ model
$\Lambda$CDM: Smith et al vs. simulation

![Graph showing $P(k)$ versus $k\, h$/Mpc with data points for different velocities: 256, 128, and 64 Mpc/h, and a comparison to Smith et al.](image)
LCDM: Takahashi et al vs. simulation
Hu-Sawicki: Smith et al vs. simulation

GBZ et al, 2010
In default Halofit

\[ \Delta^2 \equiv \frac{k^3 P(k)}{2\pi^2} = \Delta^2_Q + \Delta^2_H \]

\[ \Delta^2_Q(k) = \Delta^2_L(k) \frac{1 + \Delta^2_L(k)}{1 + \alpha(n_{\text{eff}}, C)\Delta^2_L(k)} \exp \left[ - \left( \frac{y}{4} + \frac{y^2}{8} \right) \right] \]

\[ \Delta^2_H(k) = \frac{\Delta^2_H(k)}{1 + \mu(n_{\text{eff}}, C)/y + \nu(n_{\text{eff}}, C)/y^2} \]

\[ \Delta^2_H'(k) = \frac{a(n_{\text{eff}}, C)y^3 f_1(\Omega_M)}{1 + b(n_{\text{eff}}, C)y^2 f_2(\Omega_M) + [c(n_{\text{eff}}, C)f_3(\Omega_M)y]^{3-\gamma(n_{\text{eff}}, C)}} \]

\[ \sigma^2(R, z) = \int \Delta^2_L(k, z) \exp(-k^2 R^2) d\ln k \]

\[ n_{\text{eff}} \equiv \frac{d\ln \frac{\sigma^2(R)}{d\ln R}}{d\ln R} \bigg|_{\sigma=1} - 3; \quad C \equiv \frac{d^2 \ln \sigma^2(R)}{d\ln R^2} \bigg|_{\sigma=1}, \quad y \equiv \frac{k}{k_{\text{NL}}}, \quad \sigma(k_{\text{NL}}^{-1}, z) = 1 \]
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 $\Delta_P$ should not exceed the linear prediction;

(G) On all scales, $\Delta_P$ should be positive definite.
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)

Void

Halo

F6
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 $f(R)$ \cite{Lee: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)
Morphology-dependent screening

Falck, Koyama, GBZ, Li (2014)
The next step
Adding baryons into the simulation

2.5-degree thick wedge of the redshift distribution of galaxies
MAIN galaxy sample has median redshift \( z = 0.1 \)

Real galaxy map from SDSS
KIAS

Blue: dark matter
Green: galaxies

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
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, in prep

- Code: MGENZ0 (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**

\[ A\Theta = F(\Theta) \]

\[ A\tilde{\Theta} \geq F(\tilde{\Theta}), \quad A\hat{\Theta} \leq F(\hat{\Theta}), \quad \tilde{\Theta} \geq \hat{\Theta} \]

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

\[ C^{(m)} \equiv \text{diag}\left(c_{1}^{(m)}, ..., c_{N}^{(m)}\right), \quad c_{i}^{(m)} = \left[\gamma_{i}^{(m)} + \text{abs}(\gamma_{i}^{(m)})\right]/2 \]

\[ \gamma_{i}^{(m)} \equiv \max\left\{-\frac{\partial F_{i}}{\partial \theta_{i}}(\theta_{i}); \quad \theta_{i}^{(m)} \leq \theta_{i} \leq \bar{\theta}_{i}^{(m)}\right\} \]

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GBZ, in prep

KIAS

02/11/2016
$f(R)$

Preliminary

$z = 0.400 \quad t = 9.417 \text{ Gyr}$
$z = 0.400 \quad t = 9.417 \text{ Gyr}$
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 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.