Understanding the Accelerating Universe using the MSE

Gong-Bo Zhao
NAOC
Nobel Prize 2011

Saul Perlmutter

Brian P. Schmidt

Adam G. Riess
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**

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

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

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**Modified Gravity**

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LSS can help to break the degeneracy

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July 30, 2015
Redshift surveys (BAO,RSD)
Huge discovery space in the dark sector!

100+ Nobel Prizes since 1901!

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Huge discovery space in the dark sector!

CMB (1978; 2006)
Cosmic Acceleration (2011)

NASA

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‘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 (2018?)

EUCLID (2020), MSE (2025?)

credit: Jean-Paul KNEIB
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DESI
MSE
$i=24\ \text{mag}$
$\text{FoV: } 1.5\ \text{deg}^2$
$10,000\ \text{deg}^2$
$\sim2100\ \text{spectra / deg}^2$
credit: Alan
The graph shows the relationship between redshift $z$ and the quantity $dN/dz$. The quantity $dN/dz$ peaks at around $z = 0.5$, with a decrease as $z$ increases further.
DE: BAO/RSD
MG: Galaxy dynamics
DE as a solution to the accelerating universe problem

\[ G_{\mu\nu} = \frac{1}{M_p^2} \tilde{T}_{\mu\nu} \]
**Dark Energy**

- **Negative pressure:**
  \[
  \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) > 0
  \]
  \[\Rightarrow w \equiv \frac{p}{\rho} < -\frac{1}{3}\]

- **Candidates:**
  - Vacuum energy: \( w = -1 \)
  - Dynamical fields:
    - Quintessence \( w(a) > -1 \)
    - Phantom \( w(a) < -1 \)
    - Quintom \( w(a) \) across -1
σ(lnR) (%) vs. redshift z

- DESI
- Euclid
- MSE

credit: Yuting Wang
\[ \sigma(\ln \sigma_8) (\%) \]

- DESI
- Euclid
- MSE

credit: Yuting Wang
Reconstruct \( w(a) \) parametrically

\[
w(a) = w_0 + w_a (1-a)
\]

Planck (Ade et al), 2015
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+Λ

Cosmological scales

\[ R > \text{Gpc} \]

Small scales

Large scales

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Modified Gravity

Observationally testable feature

Structure formation scales
Mpc < R < Gpc

Resemble GR + Λ

Cosmological scales
R > Gpc

Small scales

Large scales

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Modified Gravity

Recover GR

Galactic scales
$R < \text{Mpc}$

Observationally testable feature

Structure formation scales
$\text{Mpc} < R < \text{Gpc}$

Resemble GR+$\Lambda$

Cosmological scales
$R > \text{Gpc}$

Small scales

Large scales

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Modified Gravity

- **Recover GR**
  - Galactic scales: $R < \text{Mpc}$

- **Observationally testable feature**
  - Structure formation scales: $\text{Mpc} < R < \text{Gpc}$

- **Resemble GR+Λ**
  - Cosmological scales: $R > \text{Gpc}$

Small scales

Large scales

f(R) gravity

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Modified Gravity

- **Recover GR**
  - Galaxy scales: $R < \text{Mpc}$
  - Structure formation scales: $\text{Mpc} < R < \text{Gpc}$

- **Observationally testable feature**
  - Cosmological scales: $R > \text{Gpc}$

- **Resemble GR+Λ**
  - SNe, CMB

Small scales

Large scales

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Numerical Simulations
GBZ, B.Li, K.Koyama, 2011

f(R)  GR
$f(R)$
GR TEST:

Compare the lensing mass to the dynamical mass
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 $f(R)$

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

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

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

$$= 4\pi G a^2 \delta \rho_{\text{eff}}$$
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

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

In GR, \( \Delta_M = 0 \)

In MG, \( \Delta_M \in [0, 1/3] \)
GBZ, Baojiu Li, Kazuya Koyama (2011)

Underdense Environment

Dense Environment

Small Halos

Large Halos

$\log_{10} A_M$

$\rho = -0.74$

$\rho = -0.20$

$\rho = +0.65$

$\rho = +0.67$

$\log_{10} [M_L/(M_{\odot}/h)]$

$\log_{10} D$

$|f_{R0}| = 10^{-6}$

$|f_{R0}| = 10^{-4}$

(A1) $\rho = -0.74$

(A2) $\rho = -0.20$

(B1) $\rho = +0.65$

(B2) $\rho = +0.67$

(A3) $\rho = +0.36$

(A4) $\rho = +0.16$

(B3) $\rho = -0.18$

(B4) $\rho = -0.08$
Clean mass dependence!

- Underdense Environment
  - (A1) $\rho = -0.74$
  - (A2) $\rho = -0.20$

- Dense Environment
  - (A3) $\rho = 0.36$
  - (A4) $\rho = 0.16$

- Small Halos
  - (B1) $\rho = 0.65$
  - (B2) $\rho = 0.67$

- Large Halos
  - (B3) $\rho = -0.18$
  - (B4) $\rho = -0.08$

\[
\log_{10} \left[ \frac{M_L}{(M_{\text{sun}}/h)} \right] \quad \log_{10} D
\]
Large scatter shows the environmental effect!!
Apparent environmental dependence!!
No screening!

- **Small Halos**
  - Underdense Environment

- **Large Halos**
  - Underdense Environment
  - Dense Environment

\[ \log_{10} \Delta M \]

\[ \frac{r}{r_{340}} \]
Maximum screening
Core is better screened

Small Halos
Underdense Environment

Large Halos
Underdense Environment

Small Halos
Dense Environment

Large Halos
Dense Environment

$r/r_{340}$

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Screened purely by environment

- Small Halos
  - Underdense Environment
- Large Halos
  - Underdense Environment
- Small Halos
  - Dense Environment
- Large Halos
  - Dense Environment
Screening on the edge shows environmental dependence!
Observationally...

**Lensing Mass:** TMT

**Dynamical Mass:** MSE

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• Measure lensing and dynamical mass profile for each cluster;
• Divide the sample using D;
• Compare!
Summary

- MSE can provide comparable DE constraints with Euclid/DESI, and complementary;

- A synergy between MSE and TMT can offer a high precision test of gravity on galactic scales!