The Large Scale Structure as a probe to go beyond The Standard Model of Cosmology

Shant Baghram
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In behalf of my Collaborators:
Saeed Tavasoli(IPM), Farhang Habibi(LAL),
Roya Mohayaee(IAP) and Joseph Silk (IAP-JH-Oxf)

The 2nd Topical Workshop on Theoretical Physics
Institute for Research in Fundamental Sciences(IPM)
October 7-8, 2015 (15-16 Mehr, 1394)
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Large Scale Structure of the Universe

Sloan Digital Sky Survey: 2.5 meter telescope operational since 2000

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In the Search of the sound of big bang

Wilkinson - 1935 - 2012

Dicke – 1916 - 1997

Peebles - 1935

Wilson and Penzias - 1965

~ 7°

~ 1°

~ 10°

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List of Questions for Cosmology in 80’s
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1) Is the gravitational instability picture basically correct?
2) Properties of Initial Condit. ? Where did they come from?
3) What is dark matter?
4) What is $\Omega$ ?

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Cosmology with correlation functions (LSS)

- **Density Contrast**

\[
\delta(x) = \frac{\rho(x) - \rho_b}{\rho_b}
\]

- **Correlation Function**

\[
\xi(\mathbf{r}) = \langle \delta(\mathbf{x}) \delta(\mathbf{x} + \mathbf{r}) \rangle
\]

- **Power Spectrum**

\[
\langle \delta(\mathbf{k}) \delta(\mathbf{k}') \rangle = (2\pi)^3 P(k) \delta^D(\mathbf{k} + \mathbf{k}')
\]
Matter Power Spectrum + Non Linear+ BAO
Cosmology with correlation functions (CMB)

✓ Temperature contrast

\[
\Delta \frac{T}{T}(\hat{n}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{n})
\]

✓ Two point function:

\[
\left\langle \frac{\delta T}{T}(\hat{n}) \frac{\delta T}{T}(\hat{n}') \right\rangle_{\mu=\hat{n},\hat{n}'} = \frac{1}{4\pi} \sum_{l} C_l P_l(\mu)
\]

\[
C_{\ell} = \frac{1}{2\ell + 1} \sum_{m} \langle |a_{\ell m}|^2 \rangle
\]
CMB – data and LCDM

\[ C_\ell = \frac{1}{2\ell + 1} \sum_m \left| a_{\ell m} \right|^2 \]
CMB Lensing – a level of 40\sigma detection

\[ \Theta(\hat{x}) = \Theta(\hat{x}') = \Theta(\hat{x} + \nabla \psi) \]

\[ \psi(\hat{n}) \equiv -2 \int_0^{\chi_\infty} d\chi \left( \frac{\chi_\infty - \chi}{\chi_\infty \chi} \right) \Psi(\vec{x}', \eta) \]

\[ \vec{x}' = \chi \hat{n}; \eta = \eta_0 - \chi \]
Standard model of Cosmology

- Cosmology with 6 parameters
  - baryons \( \Omega_b \sim 0.05 \pm 0.02 \)
  - Dark matter \( \Omega_c \sim 0.31 \pm 0.02 \)
  - Dark Energy \( \Omega_\Lambda \sim 0.68 \pm 0.02 \)
  - Dark baryons \( \tau \sim 0.097 \pm 0.038 \)
  - Amplitude of IC \( A \sim 10^{-10} + \ldots \)
  - Scale Dependence \( n_s \sim 0.9616 \pm 0.0094 \)

GR + IC+ Cosmological Principle
Distance Measurement in Universe

\[ H = \frac{\dot{a}}{a}, \quad q = -\frac{\ddot{a}}{a\dot{a}} \]

Alan Sandage (1926-2010)

Saul Perlmutter
Brian P. Schmidt
Adam G. Riess

The Nobel Prize in Physics 2011 was awarded “for the discovery of the accelerating expansion of the Universe through observations of distant supernovae” with one half to Saul Perlmutter and the other half jointly to Brian P. Schmidt and Adam G. Riess.


Approach these results not with your heart or head but with your eyes. We are observers after all!“
Adam Riess 1998: Email communication before publishing the results

\[ \ddot{a} = -\frac{4\pi G}{3} (\rho + 3p) \]
Union 2 – sample

\[ \mu = 5 \log(d_L) + 25 \]

\[ d_L = (1 + z) \chi \]
An idea to test the gravity!!

• How the light of standard candles reach us?

$$\mu \equiv m - M = 5 \log_{10} d_L(z_s) + 25$$

$$d_L(z_s) = d_L(\bar{z})(1 - \kappa)$$

arXiv:1412.8457,
arXiv:1411.7010,
In Preparation : ST, FH, SB

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Convergence & de-convergence

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

\[ k_g = \frac{1}{2} \int_0^{\chi_s} d\chi (\chi_s - \chi) \frac{\chi}{\chi_s} \nabla^2_\perp (\Phi(\bar{x}, t) + \Psi(\bar{x}, t)) \]

\[ \propto \delta_m \]
Data for structures and SNe
The surveying the Universe in 1 Mpc steps

\[ \delta_v = \frac{\rho_v - \bar{\rho}}{\bar{\rho}} \]

\[ \delta_g = \frac{\rho_g - \bar{\rho}}{\bar{\rho}} \]

\[ \delta = \delta_v + \delta_g \]
The Universe in the eyes of lensing
Here is Coma!!
The galaxies and their neighbors!!

\[ 1 + z_p = \frac{\lambda_c}{\lambda_e} \]
\[ 1 + z = \frac{\lambda_0}{\lambda_c} \]

\[ (1 + z) = \frac{\lambda_0}{\lambda_e} = (1 + \bar{z})(1 + z_p) \]

\[ \kappa_v = \frac{1 + z_s}{H \chi_s} \vec{v}_o \cdot \vec{n} + (1 - \frac{1 + z_s}{H \chi_s}) \vec{v}_s \cdot \vec{n} \]

Tamara M. Davis, Morag I. Scrimgeour - arXiv:1405.0105
Bacon et al. arXiv:1401.3694
The πασχω of peculiar velocities!

\[ r = a \chi \rightarrow v_{\text{obs}} (z_{\text{obs}}) = v_{\text{cos}} (z_{\text{cos}}) + v_{\text{pec}} \]

How to measure the peculiar velocity:
1) Standard candle!
2) Linear theory
3) Redshift space distortion

Bacon et al. arXiv:1401.3694
Hubble diagram in Perturbation

\[ D_L(z) = d_L(\bar{z}) \]

\[ \bar{d}_L(\bar{z}) \]

\[ \bar{d}_L(z) \]

observed (de)lensed object with peculiar velocity

observed (de)lensed object with no peculiar velocity

observed object with peculiar velocity in the absence of lensing
Why standard candle measurement of peculiar velocities are biased?

\[ \Delta \mu = \mu_{\text{obs}} - \mu_{\Lambda \text{CDM}} \]

\[ d_L(z_s) = \bar{d}_L(z_s)(1 - \kappa) \]

\[ \kappa = \kappa_g + \kappa_v \]
Relativistic Cosmology in one slide

\[
\kappa_g(z) = \int_0^{\chi(z)} d\chi' (\chi - \chi') \frac{\chi'}{\chi} \nabla_\perp^2 \Phi \\
\approx \frac{3}{2} \left( \frac{H_0}{c} \right)^2 \Omega_m^0 \int_0^\chi d\chi' (\chi - \chi') \frac{\chi'}{\chi} [1 + z(\chi')] \delta(\chi')
\]

\[
\kappa_v(z) = \frac{1+z}{H(z)\chi(z)} v_0 \cdot n + \left( 1 + \frac{c(1+z)}{H(z)\chi(z)} \right) \frac{z_p}{1+z_p},
\]

\[
\kappa_{SW}(z) = 2\Phi_z + \frac{c(1+z)}{H(z)\chi(z)} (\Phi_o - \Phi_z),
\]

\[
\kappa_{ISW}(z) = \frac{2}{\chi} \int_0^\chi d\chi' \Phi + \frac{2}{c} \left( 1 - \frac{c(1+z)}{H(z)\chi(z)} \right) \int_0^\chi d\chi' \Phi'.
\]
The 35 SNe:
(peculiar velocities from linear theory)
Where are they?
Still large uncertainties
Why we think this will tell us something?