Looking for evidences beyond the standard model of cosmology
Cosmological Observations

Cosmic Microwave Background (CMB)

Gravitational Lensing

Type Ia supernovae

Large-scale structure

Lyman Alpha Forest

Cosmology, from fiction to being science.
The Era of Precision Cosmology combines theoretical works with new measurements and uses statistical techniques to place sharp constraints on cosmological models and their parameters.

**Initial Conditions:**
- Form of the Primordial Spectrum and Model of Inflation and its Parameters
- Dark Energy: density, model and parameters
- Dark Matter: density and characteristics
- Neutrino species, mass and radiation density
- Baryon density
- Neutrino species, mass and radiation density
- Curvature of the Universe
- Hubble Parameter and the Rate of Expansion

**Epoch of reionization**
Standard Model of Cosmology

Using measurements and statistical techniques to place sharp constraints on parameters of the standard cosmological models.

Initial Conditions:

- Form of the Primordial Spectrum is **Power-law**
- Dark Energy is **Cosmological Constant**: density
- Dark Matter is **Cold** and **weakly Interacting**: density
- Neutrino mass and radiation density: assumptions and CMB temperature
- Baryon density
- Neutrino mass and radiation density: assumptions and CMB temperature
- Universe is **Flat**
- Hubble Parameter and the Rate of Expansion
- Epoch of reionization

**Power-law**
Standard Model of Cosmology

Using measurements and statistical techniques to place sharp constraints on parameters of the standard cosmological model.

**Initial Conditions:**
- Form of the Primordial Spectrum is **Power-law**
- Dark Energy is **Cosmological Constant**:
  \[ \Omega_\Lambda = 1 - \Omega_b - \Omega_{dm} \]
- Dark Matter is **Cold** and **weakly Interacting**: \( \Omega_{dm} \)
- Neutrino mass and radiation density: **fixed** by assumptions and CMB temperature

**Other Assumptions:**
- Baryon density
- Neutrino mass and radiation density:
  \[ \Omega_b + \Omega_{dm} + \Omega_\Lambda = 1 \]
- Universe is **Flat**
- Hubble Parameter and the Rate of Expansion
- Epoch of reionization

\[ n_s, A_s \]
\[ \tau \]
\[ H_0 \]
Standard Model of Cosmology

Using measurements and statistical techniques to place sharp constraints on parameters of the standard cosmological model.

Initial Conditions:
- Form of the Primordial Spectrum is Power-law
- Dark Energy is Cosmological Constant
- Dark Matter is Cold and weakly Interacting
- Baryon density
- Neutrino mass and radiation density:
- Combination of Assumptions

Universe is Flat

Hubble Parameter and the Rate of Expansion

Epoch of reionization

$$\Omega_\Lambda = 1 - \Omega_b - \Omega_{dm}$$
Standard Model of Cosmology

Using measurements and statistical techniques to place sharp constraints on parameters of the standard cosmological model.

- Initial Conditions:
  - Form of the Primordial Spectrum is Power-law
  - Dark Energy is Cosmological Constant
  - Dark Matter is Cold and weakly Interacting:
    - Baryon density
    - Neutrino mass and radiation density: assumptions and CMB temperature
  - Universe is Flat

\[ \Omega_{\Lambda} = 1 - \Omega_b - \Omega_{dm} \]

combination of reasonable assumptions, but.....
Beyond the Standard Model of Cosmology

• The universe might be more complicated than its current standard model (Vanilla Model).
• There might be some extensions to the standard model in defining the cosmological quantities.
• This needs proper investigation, using advanced statistical methods, high performance computational facilities and high quality observational data.
Standard Model of Cosmology

Universe is flat
Universe is isotropic
Universe is homogeneous (large scales)
Dark energy is Lambda ($w = -1$)
Power-law primordial spectrum ($n_s = \text{const}$)
Dark matter is cold
Almost 20 years after discovery of the acceleration of the universe:

Dark Energy in 2017

From 60 Supernovae Ia at cosmic distances, we now have ~800 published distances, with better precision, better accuracy, out to z=1.5.

Accelerating universe in proper concordance to the data.

JLA Compilation

L'Huillier & Shafieloo JCAP 2017
Almost 20 years after discovery of the acceleration of the universe:

Planck 2015
Almost 20 years after discovery of the acceleration of the universe:

BOSS collaboration (2016), arXiv: Alam et al, 1607.03155
Something seems to be there, but,

What is it?

D. Sherwin et al., PRL 2011

Hazra, Shafieloo, Souradeep, PRD 2013

Union 2.1 SN Ia Compilation
WiggleZ BAO

Non FLAT LCDM
Power-Law PPS

D. Sherwin et al, PRL 2011
Dark Energy Models
• Cosmological Constant
• Quintessence and k-essence (scalar fields)
• Exotic matter (Chaplygin gas, phantom, etc.)
• Braneworlds (higher-dimensional theories)
• Modified Gravity

But which one is really responsible for the acceleration of the expanding universe?!
To find cosmological quantities and parameters, there are two general approaches:

1. **Parametric methods**
   - Easy to confront with cosmological observations to put constraints on the parameters, but the results are highly biased by the assumed models and parametric forms.

2. **Non Parametric methods**
   - Difficult to apply properly on the raw data, but the results will be less biased and more reliable and independent of theoretical models or parametric forms.

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**Reconstructing Dark Energy**
Problems of Dark Energy Parameterizations

Holsclaw et al, PRD 2011


Chevallier-Polarski-Linder ansatz (CPL).

Brane Model

Quintessence DE?!

$w(z) = w_0 + w_a \frac{z}{1 + z}$.

Kink Model

Phantom DE?!
Model independent reconstruction of the expansion history

Crossing Statistic + Smoothing

Gaussian Processes

Shafieloo, JCAP (b) 2012
Shafieloo, Kim & Linder, PRD 2012
Dealing with observational uncertainties in matter density (and curvature)

- Small uncertainties in the value of matter density affect the reconstruction exercise dramatically.
- Uncertainties in matter density is in particular bound to affect the reconstructed $w(z)$.

\[ H(z) = \left[ \frac{d}{dz} \left( \frac{d_L(z)}{1+z} \right) \right]^{-1} \]

\[ \omega_{DE} = \frac{\left( \frac{2(1+z) \frac{H'}{H}}{3} \right) - 1}{1 - \left( \frac{H_0}{H} \right)^2 \Omega_{0M} (1+z)^3} \]
Cosmographic Degeneracy

\[ d_l(z) = \frac{1 + z}{\sqrt{1 - \Omega_m - \Omega_{de}}} \sinh \left( \sqrt{1 - \Omega_m - \Omega_{de}} \int_0^z \frac{dz'}{h(z')} \right) \]

\[ h(z)^2 \equiv \left[ \frac{H(z)}{H_0} \right]^2 \equiv \left( \frac{\dot{a}}{a} \right)^2 \]

\[ = \Omega_m (1 + z)^3 + (1 - \Omega_m - \Omega_{de})(1 + z)^2 \]

\[ + \Omega_{de} \exp \left[ 3 \int_0^z \frac{dz'}{1 + z'} \left[ 1 + w(z') \right] \right], \]
Cosmographic Degeneracy

Shafieloo & Linder, PRD 2011

Cosmographic Degeneracy

\[ \omega_{DE} = \frac{\left( \frac{2(1+z)}{H} \right)^{3/2}}{3 - \left( \frac{H}{H_0} \right)^3 \Omega_M (1+z)^3} \]

Indistinguishable from each other!
Reconstruction  Falsification

Falsification.

Yes-No to a hypothesis is easier than characterizing a phenomena.

We should look for special characteristics of the standard model and relate them to observables.

But, How?
Instead of looking for $w(z)$ and exact properties of dark energy at the current status of data, we can concentrate on a more reasonable problem:

Falsification of Cosmological Constant

Yes-No to a hypothesis is easier than characterizing a phenomena.
\[ w(z) = -0.7 \]

\[ w(z) = -1.3 \]

\[ H^2(z) = H_0^2 \left[ \Omega_{0m} (1+z)^3 + \Omega_{DE} \right] \]

\[ \Omega_{DE} = (1 - \Omega_{0m}) \exp \left\{ 3 \int_0^z \frac{1 + w(z')}{1 + z'} \, dz' \right\} \]
$\Omega_m(z) = \frac{h^2(z) - 1}{(1 + z)^3 - 1}$

We Only Need $h(z)$

$h(z) = \frac{H(z)}{H_0}$

$\Omega_m(z)$ is constant only for FLAT LCDM model

$w = -1 \rightarrow \Omega_m(z) = \Omega_{0m}$

$w < -1 \rightarrow \Omega_m(z) < \Omega_{0m}$

$w > -1 \rightarrow \Omega_m(z) > \Omega_{0m}$

Quintessence
$w = -0.9$

Phantom
$w = -1.1$
Om diagnostic is very well established
Model Independent Evidence for Dark Energy Evolution from Baryon Acoustic Oscillation

\[ Omh^2(z_1, z_2) = \frac{H^2(z_2) - H^2(z_1)}{(1 + z_2)^3 - (1 + z_1)^3} = \Omega_{0m} H_0^2 \]


Only for LCDM

\[ Omh^2 = 0.1426 \pm 0.0025 \]

\[ Omh^2(z_1; z_2) = 0.124 \pm 0.045 \]

\[ Omh^2(z_1; z_3) = 0.122 \pm 0.010 \]

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Important discovery if no systematic in the SDSS Quasar BAO data

\[ Omh^2 = 0.1426 \pm 0.0025 \]

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\]

Only for LCDM


No systematic yet found,

Measurement of BAO correlations at \( z = 2.3 \) with SDSS DR12 Ly-forests

Bautista et al, arXiv:1702.00176

\[
Omh^2 = 0.1426 \pm 0.0025
\]

\[
Omh^2(z_1; z_2) = 0.124 \pm 0.045
\]

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\]

\[
Omh^2(z_2; z_3) = 0.122 \pm 0.012
\]
$Omh^2(z_1, z_2) = \frac{H^2(z_2) - H^2(z_1)}{(1 + z_2)^3 - (1 + z_1)^3} = \Omega_0 m H_0^2$

Model Independent Evidence for Dark Energy Evolution from Baryon Acoustic Oscillation


No systematic yet found, Results Persistent!

Measurement of BAO correlations at $z=2.3$ with SDSS DR12 Ly-Forests

Bautista et al, arXiv:1702.00176

$Omh^2 = 0.1426 \pm 0.0025$

$Omh^2(z_1; z_2) = 0.124 \pm 0.045$

$Omh^2(z_1; z_3) = 0.122 \pm 0.010$

$Omh^2(z_2; z_3) = 0.122 \pm 0.012$
Do we still see evidence for dark energy evolution?

\[
O_{mh}^2(z_1, z_2) = \frac{H^2(z_2) - H^2(z_1)}{(1 + z_2)^3 - (1 + z_1)^3} = \Omega_{0m} H_0^2
\]

Only for LCDM


Measurement of BAO correlations at \( z=2.3 \) with SDSS DR12 Ly-Forests

Bautista et al, arXiv:1702.00176

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\[ O_{mh}^2(z_2; z_3) = 0.122 \pm 0.012 \]
For LCDM; H0, LyFB and JLA measurements are in tension with the combined dataset, with tension values of T = 4.4, 3.5, 1.7. LCDM

Kullback-Leibler (KL) divergence to quantify the degree of tension between different datasets assuming a model.

\[
T \equiv \frac{S}{\Sigma} = \frac{(\theta_1 - \theta_2)^T C^{-1}_1 (\theta_1 - \theta_2) - \text{Tr} \left( C_2 C_1^{-1} + I \right)}{\sqrt{\text{Tr} \left( C_2 C_1^{-1} + I \right)^2}}
\]
The clustering of galaxies in the completed SDSS-III Baryon Oscillation Spectroscopic Survey: Examining the observational evidence for dynamical dark energy


\[ T \equiv \frac{S}{\Sigma} = \frac{(\theta_1 - \theta_2)^T C_1^{-1}(\theta_1 - \theta_2) - \text{Tr} \left( C_2 C_1^{-1} + I \right)}{\sqrt{\text{Tr} \left( C_2 C_1^{-1} + I \right)^2}} \]

<table>
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<tr>
<th>( \Delta \chi^2 )</th>
<th>P15</th>
<th>JLA</th>
<th>gBAO-9z</th>
<th>( P(k) )</th>
<th>WL</th>
<th>( H_0 )</th>
<th>LyαFB</th>
<th>OHD</th>
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<tbody>
<tr>
<td>( \Delta \chi^2 )</td>
<td>-0.7</td>
<td>-1.6</td>
<td>-2.8</td>
<td>+1.1</td>
<td>-0.1</td>
<td>-2.9</td>
<td>-3.7</td>
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<tr>
<td>S/N</td>
<td>2.5( \sigma )</td>
<td>3.5( \sigma )</td>
<td>6.4( \sigma )</td>
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<tr>
<td>( \Delta AIC )</td>
<td>-0.3</td>
<td>-4.3</td>
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<tr>
<td>( \Delta \ln E )</td>
<td>-6.7 ( \pm 0.3 )</td>
<td>-3.3 ( \pm 0.3 )</td>
<td>11.3 ( \pm 0.3 )</td>
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</tbody>
</table>
A null diagnostic customized for reconstructing the properties of dark energy directly from BAO data

\[
\frac{\text{Om3}(z_1, z_2, z_3)}{\text{Om}(z_1, z_2)} = \frac{h^2(z_2) - h^2(z_1)}{(1 + z_2)^3 - (1 + z_1)^3} = \frac{h^2(z_3) - h^2(z_1)}{(1 + z_3)^3 - (1 + z_1)^3} = \frac{H^2(z_2)}{H_0^2} - 1 = \frac{H^2(z_3)}{H_0^2} - 1
\]

\[
d(z) = \frac{r_s(z_{\text{CMB}})}{D_V(z)}
\]

\[
H(z_i; z_j) = \frac{H(z_i)}{H(z_j)} = \frac{z_i}{z_j} \left[ \frac{D(z_i)}{D(z_j)} \right]^2 \left[ \frac{D_V(z_j)}{D_V(z_i)} \right] = \frac{z_i}{z_j} \left[ \frac{D(z_i)}{D(z_j)} \right]^2 \left[ \frac{d(z_i)}{d(z_j)} \right] \]

Observables

Shafieloo, Sahni, Starobinsky, PRD 2013
Om is constant only for Flat LCDM model
Om3 is equal to one for Flat LCDM model

\[ Om3(z_1; z_2; z_3) = \frac{H(z_2; z_1)^2 - 1}{x_2^3 - x_1^3} \sqrt{\frac{H(z_3; z_1)^2 - 1}{x_3^3 - x_1^3}}, \quad \text{where} \quad x = 1 + z, \]

\[ H(z_i; z_j) = \left( \frac{z_j}{z_i} \right)^2 \left[ \frac{D(z_i)}{D(z_j)} \right]^2 \left[ \frac{A(z_j)}{A(z_i)} \right]^3 = \frac{z_i}{z_j} \left[ \frac{D(z_i)}{D(z_j)} \right]^2 \left[ \frac{d(z_i)}{d(z_j)} \right]^3, \]

Om3 is independent of $H_0$ and the early universe models and can be derived directly using BAO observables.

Shafieloo, Sahni, Starobinsky, PRD 2013
Future perspective

P. Bull et al,

1501.04088
Om3 will show its power as it can be measured very precisely and used as a powerful litmus test of Lambda.

\[ \sigma_{Om3} \approx 1.0 \times 10^0 \text{[WiggleZ]} \]
\[ \sigma_{Om3} \approx 2.0 \times 10^{-1} \text{[DESI]} \]
\[ \sigma_{Om3} \approx 5.7 \times 10^{-1} \text{[SKA1 – SUR(Gal)]} \]
\[ \sigma_{Om3} \approx 5.6 \times 10^{-1} \text{[SKA1 – MID(Gal)]} \]
\[ \sigma_{Om3} \approx 4.0 \times 10^{-2} \text{[SKA1 – MID(IM)]} \]
\[ \sigma_{Om3} \approx 2.5 \times 10^{-2} \text{[SKA1 – SUR(IM)]} \]
\[ \sigma_{Om3} \approx 1.4 \times 10^{-2} \text{[Euclid]} \]
\[ \sigma_{Om3} \approx 9.3 \times 10^{-3} \text{[SKA2(Gal)]} \]
The current standard model of cosmology seems to work fine but this does not mean all the other models are wrong. Data is not yet good enough to distinguish between various models.

Using parametric methods and model fitting is tricky and we may miss features in the data. Non-parametric methods of reconstruction can guide theorist to model special features.

First target can be testing different aspects of the standard ‘Vanilla’ model. If it is not ‘Lambda’ dark energy or power-law primordial spectrum then we can look further. It is possible to focus the power of the data for the purpose of the falsification. Next generation of astronomical/cosmological observations, (DESI, Euclid, SKA, LSST, WFIRST etc) will make it clear about the status of the concordance model.

Combination of different cosmological data hints towards some tension with LCDM model. If future data continues the current trend, we may have some exciting times ahead!
• We can (will) describe the constituents and pattern of the universe (soon). But still we do not understand it. Next challenge is to move from inventory to understanding, by the help of the new generation of experiments.