Cosmology: dark energy and beyond

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References: Snowmass reports
Kim et al, arXiv: 1309.5382
Huterer et al, arXiv: 1309.5358
BJ et al, arXiv:1309.5389

See talks by Kosowski, Kusenko, Pryke
Talk to Pitt Cosmologists!
Outline

• Cosmological observations: CMB to galaxy surveys

• Beyond dark energy

• Tests of gravity from mm to Gpc scales

• Discovery space for the future
Cosmology probes: geometry and growth

- Geometry: Distance-Redshift relation $D(z)$, Expansion rate $H(z)$
- **Growth:** Fluctuations in temperature, mass, gas and galaxies

- Features in the fluctuation power spectrum
  - Tilt (inflation), locations of peaks (geometry), damping tail (neutrinos)

- Low-z/late time universe has several probes of geometry and growth
  - Combining CMB with late time data provides huge lever arm in scale and time: tests of inflation, dark energy, massive neutrinos, dark sector interactions
Afterglow Light Pattern 375,000 yrs.

Dark Ages

Development of Galaxies, Planets, etc.

Dark Energy Accelerated Expansion

Inflation

Quantum Fluctuations

1st Stars about 400 million yrs.

Big Bang Expansion

13.77 billion years
### Cosmology probes: late times

<table>
<thead>
<tr>
<th>Probe</th>
<th>Physical Observable</th>
<th>Sensitivity to Dark Energy or Modified Gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak Lensing</td>
<td>Coherent distortions in galaxy shapes</td>
<td>Geometry and growth of structure (projected)</td>
</tr>
<tr>
<td>Large-Scale Structure (BAO)</td>
<td>Power spectrum of galaxy distribution</td>
<td>Geometry and Growth</td>
</tr>
<tr>
<td>Galaxy Clusters</td>
<td>Abundance of massive clusters</td>
<td>Geometry and Growth</td>
</tr>
<tr>
<td>Type Ia Supernovae</td>
<td>Fluxes of standard candles</td>
<td>Geometry: Distance-redshift relation</td>
</tr>
<tr>
<td>Strong lensing, Lyman-alpha, 21cm, and others</td>
<td>Time delays, power spectra</td>
<td>Geometry and growth</td>
</tr>
</tbody>
</table>
\[ \gamma \sim \frac{D_{LS}}{D_s b} 4GM \]

Gravity & Cosmology change the growth rate of mass structure

Cosmology changes geometric distance factors
Large-Scale Structure Lenses the CMB

- RMS deflection of $\sim 2.5'$
- Lensing efficiency peaks at $z \sim 2$
- Coherent on $\sim$degree ($\sim 300$ Mpc) scales
Current results: geometry

- Distance-redshift relation from SN and BAO
- Consistent with Lambda-CDM
Current results: growth of structure

- Growth of structure: BOSS, CFHLS, Planck and SPT data (also galaxy clusters)
- CMB+late universe: consistent with inflationary fluctuations
- But...amplitude at late times lower than inferred from CMB
Energy budget over cosmic time

TODAY

13.7 BILLION YEARS AGO
(Universe 380,000 years old)

WMAP web site
Neutrinos

\[ \sum m_\nu > 0 \]

Sum of the neutrino masses impacts growth of large scale structure, i.e., the matter power spectrum Probed by CMB lensing

\[ P(k) \rightarrow \]

\[ k \rightarrow \]

Matter Domination

Radiation Domination

graphic from NASA/WMAP

Carlstron
Multi-component dark matter and neutrinos

- Neutrinos as a known hot component of dark matter
- Changes matter-radiation equality: impact on CMB
- Suppress growth of structure in a scale dependent way
- Note: Data also sensitive to other features in primordial power spectrum.

1 Introduction

![Fractional change in the matter density power spectrum as a function of comoving wavenumber $k$ for different values of $\sum m_\nu$. Neutrino mass suppresses the power spectrum due to free streaming below the matter-radiation equality scale. The shape of the suppression is highly characteristic and precision observations over a range of scales can measure the sum of neutrino masses (here assumed all to be in a single mass eigenstate). Also shown are the approximate ranges of experimental sensitivity in the power spectrum for representative probes: the cosmic microwave background (CMB), galaxy surveys (Gal.), weak lensing of galaxies (WL), and the Lyman-alpha forest (Ly$\alpha$). The CMB lensing power spectrum involves (an integral over) this same power spectrum, and so is also sensitive to neutrino mass. The minimum sum of the masses must be greater than 100 meV. For the degenerate neutrino mass case where $m_1' = m_2' = m_3'$, the sum of neutrino masses is at least approximately 150 meV. As we will discuss below, future CMB-S4 and LSS experiments in the Cosmic Frontier have projected constraints to detect the minimum mass scale of 58 meV at $\sim 4$ confidence, a ground-breaking result.](image)
Multi-component dark matter and neutrinos

- Neutrinos as a known hot component of dark matter
- Changes matter-radiation equality: impact on CMB
- Suppress growth of structure in a scale dependent way
- Note: Data also sensitive to other features in primordial power spectrum.
(Mild) tension in cosmology data

Extrapolation from CMB to Present disagrees with low-z measurements
(Mild) tension in cosmology data

- BICEP2
- CMB vs low-z measurements of $H_0$
- Amplitude of fluctuations

Resolution?
- Tilt+running of primordial spectral index,
- evolving dark energy,
- sterile neutrinos,
- ??

2-3 theory papers per day since BICEP2 -> we need more data!
Dark Energy Survey: 150 sq deg mass map

- Convergence map from DES: largest mass map to date
- Overlaid with galaxy clusters
- Preliminary!

Vikram, Chang, BJ, Bacon and the DES collaboration, in prep.
Beyond dark energy
Beyond Lambda

- Is dark energy constant in redshift?
- Is dark energy spatially clustered or anisotropic?
- Are there couplings between dark energy, dark matter, baryons?
- Is it dark energy or modified gravity?
New degrees of freedom in the universe

• Theorem: Cosmological constant is the ‘unique’ large distance modification to GR that does not introduce any new degrees of freedom

• Dynamical models of Dark Energy or Modified Gravity invoke new degrees of freedom (also arise in string theory, higher dimension theories...).

• Modified gravity (MG) theories typically invoke a scalar field coupled non-minimally to gravity. The scalar enhances the gravitational potential observable effects on all scales, mm to Gpc!

• Dark energy and dark matter can also directly couple to standard model particles, leading to other 5th force-like effects.
Consider a scalar $\phi = \phi_b + \delta \phi$ coupled to the energy density $\rho$.

Since it is light, the long range, scalar force inside the solar system must be suppressed to satisfy tests of the equivalence principle and GR.

In the last decade, some natural ways to achieve this have been realized by theories designed to produce cosmic acceleration.

The generic form of the equation of motion for $\delta \phi$ is:

$$Z(\phi_b, \rho_b) \left[ \frac{d^2 \delta \phi}{dt^2} - c_s^2 \frac{d^2 \delta \phi}{dx^2} \right] + m^2(\phi_b, \rho_b)\delta \phi = \beta(\phi_b, \rho_b) G_{\text{Newton}} \delta \rho$$

**Modified gravity and scalar fields**

A. Tolley
Screening: how to hide enhanced gravity

\[ \delta F \approx \frac{M_a M_b G}{r^2} \frac{\beta^2(\phi_b, \rho_b)}{\sqrt{Z(\phi_b, \rho_b) c_s(\phi_b, \rho_b)}} \exp(-m(\phi_b, \rho_b)r) \]

To keep force enhancement small, this term must be small.

Only 3 options!

(a) Coupling \( \beta \) is small (Symmetron)
(b) Mass \( m \) is large (Chameleon)
(c) Kinetic term \( Z \) is large (Vainshtein)

- The three mechanisms of screening lead to distinct observable effects as one transitions from MG on large scales to GR well inside galaxies.
- **A successful MG theory must incorporate a screening mechanism** we can pursue observable effects even before theorists agree on a theory!
- The parameters that observations constrain:
  - coupling \( \beta \) & mass \( m \) (the range of the scalar force \( \lambda \))
Signatures of modified gravity

how cosmological effects show up in galaxies

• Unscreened environments in the universe will show these signatures of gravity: from cosmological scales to nearby galaxies

\[ ds^2 = -(1 + 2\psi)dt^2 + (1 - 2\phi)a^2(t)d\mathbf{x}^2 \]

• GR: \( \psi = \Phi \). MG: \( \psi \neq \Phi \).

• Generically extra scalar field enhances forces on stars and galaxies

  – acceleration = -\( \nabla \psi = -\nabla (\psi_s + \psi_N) \)

  – This enhances effective G & velocities by \( \sim 10\% \)

• Photons respond to the sum \( (\psi + \Phi) \) which is typically unaltered

  – Dynamical masses are larger than Lensing (true) masses
Modified Gravity
Stars, gas and dark matter

• Enhanced forces can alter the luminosities, colors and ages of stars in unscreened galaxies.
  - Pulsating giant stars may feel higher $G_{\text{eff}}$: faster pulsations are detectable
    *Chang & Hui 2010; Davis et al 2011; BJ, Vikram, Cabre 2012*

• Dark matter and gas clouds are diffuse -> should feel the fifth/scalar force if their host galaxy is unscreened.
  - Stars rotate slower and separate from gas due to external forces
  - Black holes and stars may also separate in some scenarios
    *Hui, Nicolis & Stubbs 2009; BJ & VanderPlas 2011; Hui & Nicolis 2012*
Astrophysical and cosmological probes of gravity

**Dynamical probes** (blue) measure Newtonian potential $\psi$

**Lensing and ISW** (red) measures $\phi + \psi$  

*Jain & Khoury 2010*
Cosmological tests with nearby galaxies
Pulsating stars and nearby distances

• Cepheids are 3-10 $M_\odot$ giant stars that pulsate over days to weeks. The period $P$ and luminosity $L$ are tightly related -> distance indicator
  - Newtonian potential in oscillating envelope of star ~ $10^{-7}$
  - $P \sim 1/\sqrt{G \rho}$
  - Scalar force enhances $G$ -> lowers $P$ -> underestimate distance.

• The peak luminosity at the TRGB (tip of the red giant branch) is nearly universal for 1-2 $M_\odot$ stars -> distance indicator
  - Distance estimate is insensitive to gravity theory, and has the opposite change from cepheid distance

• Water masers around SMBHs provide a geometric method: independent of $G$!
Disk Galaxy Tests

• Enhanced forces between dwarf galaxies can displace stellar disk from halo center
• The gas disk tracks the dark matter halo -> observable offsets

BJ & VanderPlas 2011
Current limits on gravity theories

- Nearly all these limits have been obtained in the last 5 years.
- A broad class of gravity theories ``ruled out''
Einstein ring test of gravity

\[ \psi / \phi = 1.01 \pm 0.05 \] from Einstein Rings + velocity dispersion

*Bolton et al 2006; Schwab, Bolton, Rappaport 2010*

*A suite of tests on large scales will be carried out with upcoming surveys*
Discovery Space

- Cosmic acceleration and fundamental physics motivations ➔ multi-scale tests of dark energy, gravity and dark sector couplings.

- The "discovery space" spans:
  - Early universe
  - Evolution of the universe at late times
  - Dark sector interactions