Dark Energy
The Push, Pull, and Wiggle of Gravity

COSPA 2016
Sydney

Eric Linder
UC Berkeley/Berkeley Lab/ECL
Dark Energy and Gravity

The Push of Gravity –
Cosmic Acceleration and Dark Energy

The Pull of Gravity –
Growth of Structure and Lensing

The Wiggle of Gravity –
The Tensor Sector and Gravitational Waves

Future Cosmic Surveys
The Push of Gravity

“This is not dark energy.”

Rene Magritte
The Treachery of Images
Physics of Dark Energy

There is no equivalent of the Standard Model of particle physics to guide us for dark energy.

But if there was, should we expect it to be less complicated, i.e. just a single, canonical, minimally coupled scalar field?

Early approach – choose a model

Standard approach – phenomenological

New approach – Effective Field Theory

Gubitosi, Piazza, Vernizzi 1210.0201
Bloomfield, Flanagan, Park, Watson 1211.7054
Gleyzes, Langlois, Piazza, Vernizzi 1304.4840
Bellini & Sawicki 1404.3713
Linder, Sengor, Watson 1512.06180
Very little motivation. Highly arbitrary. Lots of fine tuning, subject to quantum corrections.

Observations rule out (push to $\Lambda$) tracker models that relieve initial fine tuning.

One model I still have some fondness for:

**PNGB (pseudo-Nambu Goldstone boson)**

$$V(\phi) = M^4 \left[ 1 + \cos \left( \frac{\phi}{f} \right) \right]$$

Has a shift symmetry giving technical naturalness. Connections with axion physics. In excellent agreement with observations.

Frieman, Hill, Stebbins, Waga 1995

Smer-Barreto & Liddle 2015
Phenomenological Approach

Handles on dark energy:

Expansion history $\rightarrow$ eq of state $w(z)$

Clustering $\rightarrow$ sound speed $c_s(z)$

Growth vs expansion $\rightarrow$ modified gravity, DE clustering, DE coupling, neutrinos

These help determine whether dark energy is a physical (scalar) field, or a modification of gravity.
Cosmic Expansion History

Expansion history $a(t)$ is completely equivalent to an (effective) dark energy equation of state $w(z)$.

The phase space $w-w'$ has distinct regions corresponding to different physics.

Entire “thawing” region looks like $\langle w \rangle \sim -1 \pm 0.05$.

Need experiments sensitive to $\sigma(w') \approx 2(1+w)$. 

Caldwell & Linder 2005
Models have a diversity of behavior, within thawing and freezing regions. But we can calibrate $w'$ by “stretching” it: $w' \rightarrow w'(a_*)/a_*$. Calibrated parameters $w_0, w_a$. 

deputter & Linder 2008
All You Need to Know About: Cosmic Acceleration

The two parameters $w_0$, $w_a$ achieve $10^{-3}$ level accuracy on observables $d(z)$, $H(z)$.

$$w(a)=w_0+w_a(1-a)$$

They are wholly sufficient for Stage 4 data.

They are calibration parameters arising from the physics (Klein-Gordon equations), having nothing to do with a Taylor expansion [Linder 2003].
The Pull of Gravity

In general relativity, (linear) growth of structure and expansion are tied together – one predicts the other. Cosmic growth tests GR.

Is growth suppressed? Or is beyond linear modeling insufficient?
Cosmic Growth vs Expansion

Growth vs expansion can be tested in a model independent way.

Beyond linear clustering must treat modGR consistently (perturbation theory).

Song+ 1507.01592
The Wiggle of Gravity

How do we parametrize the modGR time dependence and how do we capture the general physics?

A relatively new approach is the Effective Field Theory of dark energy.

This writes the most general theory possible, subject to symmetries – **model independent**!

One does not have to impose by hand limitations such as “no more than two derivatives”. It encompasses theories beyond Horndeski.

**EFTDE** includes LCDM, quintessence, f(R), DGP, k-essence, Galileons, kinetic braiding, Horndeski, ghost condensate, Horava-Lifshitz, ...
Parametrizing Gravity

Property functions give phenomenological combinations of EFT functions. Bellini & Sawicki 2014

\[ \alpha^B \] – braiding: mixing scalar and tensor sectors

\[ \alpha^K \] – kineticity: kinetic structure

\[ \alpha^M \] – running Planck mass (coupling)

\[ \alpha^T \] – tensor wave speed deviation \((c_T^2 - 1)\)

All are functions of time, and 0 within GR.

Note that now the tensor sector (GW) is as important as the scalar (matter) sector!
In GR, expansion determines growth.

Note the expansion history $H(z)$ is merely one free function of time.

For cosmic structure and growth we find that we have 5 times as many!

Cosmology much richer. Plus the tensor sector!

We have learned to fit $H(z)$ with just a few parameters: $\Omega_m$, $w_0$, $w_a$.

Can we do the same with gravity functions?

Need close connection between theory, computation, and data to test/interpret the results.
Testing Gravity

Very difficult to fit these modified gravity functions of time to observations with just a few parameters, even for simple theories.

To reveal gravity, must also look at:

1) Nonlinear regime and screening mechanisms
2) Tensor sector (gravitational waves)
3) Strong gravity systems (black holes)

Planck mass running 1 parameter f(R) gravity

Today Cosmic scale factor ➔
Linder 1607.03113
Understanding Gravity

Unexpected synergies!

Plus, cosmology in the linear regime can’t do it all.

The tensor sector is accessible through gravitational waves: CMB B-modes, pulsar timing arrays, interferometers.

Galaxy surveys have deep complementarity with CMB surveys (and PTA, LISA).
The study of cosmic acceleration is far richer than realized even a few years ago:

- The background, i.e. expansion $H(z)$, has 1/5 or less of the functional information!

- The tensor sector has equal information to the scalar sector (2 functions each)!

Don’t despair! Be clever in looking for new theoretical principles and new observational regimes.
We will have sub% distance measurements over most of the cosmic expansion history.
CMB – Stage 4

CMB-S4: a distributed array of telescopes with 0.5M detectors (Chile, South Pole,...).

Goes beyond Stage 3 (AdvACT, Simons Array, SPT-3G). S4 test bed: Simons Observatory ($45M grant).

220 page Science Book arXiv:1610.02743
CMB-S4 Science

Inflation

BSM

Neutrinos

Dark Energy

<table>
<thead>
<tr>
<th>Year</th>
<th>Stage</th>
<th>Detectors</th>
<th>Sensitivity ($\mu K^2$)</th>
<th>$\sigma(r)$</th>
<th>$\sigma(N_{\text{eff}})$</th>
<th>$\sigma(\Sigma m_\nu)$</th>
<th>Dark Energy F.O.M</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>Stage 2</td>
<td>1000</td>
<td>$\approx 10^{-5}$</td>
<td>0.035</td>
<td>0.14</td>
<td>0.15eV</td>
<td>Boss BAO prior</td>
</tr>
<tr>
<td>2016</td>
<td>Stage 3</td>
<td>10,000</td>
<td>$10^{-5}$</td>
<td>0.006</td>
<td>0.06</td>
<td>0.06eV</td>
<td>SPT clusters</td>
</tr>
<tr>
<td>2017</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2018</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2019</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td>Stage 4</td>
<td>CMB-S4</td>
<td>$10^{-8}$</td>
<td>0.0005</td>
<td>0.027</td>
<td>0.015eV</td>
<td>DESI BAO + $T_\text{e}$ prior</td>
</tr>
<tr>
<td>2021</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2022</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2023</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2023 Target

DES + DESI SZ Clusters

DES + LSST S4 Clusters

~300-600

~180

1250
Beyond DESI/LSST/etc., there are already thoughts about **Stage 5** Dark Energy experiments.
DESI, Euclid, LSST, WFIRST, etc. will have exciting next generation surveys. CMB polarization and lensing plays a critical role too.

Will map the expansion and growth, also need to understand them!

$H(z) + 4$ growth functions (including tensors). Gravity tests (CMB B-modes, PTA, interferometers).

Cosmologists are thinking now of further future surveys that can explore fundamental physics. Technology and theory developments are critical to enable these future cosmic surveys.

Your ideas are wanted!