Narrowing down the possible explanations of cosmic acceleration with geometric probes

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Outline

● Motivation
  ○ Models tested
  ○ Input Data
● Parameter Estimation
● Model Selection
● Constraints from future surveys
● Conclusions
Motivation

- Standard Cosmology fits well
  - CMB power spectrum; $\Omega_k = 0$
  - SN Ia hubble diagram fitted well
- Significant Problems
  - Fine-tuning
  - Coincidence
- Possible extensions to solve problems
  - Dynamical Scalar Fields
  - Modifications to GR

Fig: (Top): Fit to the Planck CMB power spectrum (Planck 2013). (Bottom): Combined fit for standard cosmology parameters to SNIa, CMB, BAO data (Betoule et al. 2014).
Cosmological Models Tested

- Motivated by Scalar Fields and Modified Gravity
- Following “Beyond Lambda”: Rubin et al. 2009
- Thawing Quintessence (e.g. Linder 2015)
  - Algebraic
  - Linear Potential (Doomsday)
  - Pseudo-Nambu-Goldstone Boson (PNGB)
  - Slow-roll (motivated by inflation)
- Mass-varying neutrinos (Wetterich 2007; Amendola et al. 2008)
- Vacuum Phase Transition (Caldwell et al. 2006)
  - Linear Interaction
  - Linear and Quadratic Interaction
Geometric Probes

- SNe Ia; Hubble diagram (JLA; Betoule et al. 2014)
- CMB compressed likelihood (Planck 2015)
  - CMB shift, first acoustic peak position
  - Assumes $w$CDM; not suitable for modified gravity
  - Possibly used for thawing quintessence
- BAO angular scale (6dF, MGS, BOSS DR11)
- Create a CMB/BAO ratio; model independent

Fig: SN Ia hubble diagram from the “Joint Lightcurve Analysis” (Betoule et al. 2014)
Thawing Models

- Different potentials
  - Linear
  - Algebraic
  - PNGB
- Good fit to data
- Consistent with Λ
- Slow-roll also consistent
- $w_0 < -0.78$ (95%); some scope for dynamics

Fig: Constraints on the present day equation of state and the shape of the potential for the algebraic thawing model. The SNe and CMB/BAO ratio constrain $w_0$ to $< -0.78$ at the 95% C.L. (Dhawan et al. submitted)
Bimetric Gravity: Linear Interaction

- Two metrics with interaction terms
- We consider the simplest models
  - Linear Interaction
  - Linear and quadratic Interaction
- Linear model fits SN and CMB/BAO independently
- Combined constraints rule the model out

Fig: Bimetric gravity model with only linear interaction term (e.g. von Strauss et al. 2012, Comelli 2012) fitted to CMB/BAO (blue) and Supernova Ia (red) data. Although the fits to individual probes are satisfactory, there is an inconsistency in the resulting distributions (Dhawan et al. submitted)
Goodness of fit

- All models fit the data well
- Some fit by converging to standard model
- Metric to distinguish models

<table>
<thead>
<tr>
<th>Model</th>
<th>Parameters</th>
<th>$\ln Z_f$</th>
<th>$\Delta$</th>
<th>$\frac{Z_{\text{min}}}{Z_{f\Lambda}}$</th>
<th>$\chi^2_{\text{min}}$</th>
<th>Evidence Meaning</th>
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<tbody>
<tr>
<td>(flat) $\Lambda$CDM</td>
<td>$\Omega_M$</td>
<td>-359.6</td>
<td>...</td>
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<td>Doomsday</td>
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<td>Slow-Roll One parameter</td>
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<td>PNCB</td>
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<td>Algebraic Thawing</td>
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<td>Moderate/Strong</td>
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<tr>
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<td>Bimetric - Quadratic</td>
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</table>
Model Comparison

- Use Bayes Factor ($Z_i/Z_0$)
- Evidence Calculated via Nested Sampling
- Flat $\Lambda$ highest evidence
- Thawing models moderately disfavoured
- Bimetric: Linear poorly fit
- Bimetric: Quadratic fits well; approaches $\Lambda_{\text{CDM}}$
Figure: A comparison of the Bayesian evidences for each model tested, relative to the model with highest evidence (i.e. flat $\Lambda$). The green and red lines denote the region of moderate/strong and decisive exclusion respectively (based on the Jeffrey’s scale, Dhawan et al. submitted).
Forecasts for future surveys

- Distinguish exotic models from flat

- Example case: Algebraic Thawing

- For $w_0 = -0.92$ and higher: positively
  - For $w_0 = -0.94$ and higher: moderately

- $\sigma(w_0) \sim 0.02$
  - BAO and SN Ia extremely constraining
  - $H(z)$ helps distinguish models

Fig: Posterior distribution for $w_0$ in the algebraic thawing model with different combinations of input datasets
Conclusions

- Use a model independent geometric probe
- Non-standard cosmologies fit data well
- Thawing quintessence approaches ΛCDM
- Moderate Evidence against thawing models
- Bimetric gravity: linear interaction excluded
- Complementarity of probes: powerful discriminant
CMB/BAO distance ratio

- CMB compressed likelihood: model dependent
- Ratio is model independent
- Requires three measurements
  - CMB first peak
  - BAO angular scale
  - Ratio of drag and decoupling sound horizons
- Only depends on baryon and photo density

\[ f = \frac{d_A(z_*)}{D_V(z)} = \frac{l_A}{\pi d_z} \cdot \frac{r_s(z_d)}{r_s(z_*)}, \]

Forecasts for Future Surveys

- DESIRE, WFIRST: low-z, LSST, Euclid SN survey
- BAO:
  - LSST (Ivezic et al. 2009)
  - DESI (Aghamousa et al. 2016)
  - HETDEX (Font-Ribera et al. 2014)
- H(z) cosmic chronometers:
  - HETDEX (Font-Ribera et al. 2014)
  - DESI (Aghamousa et al. 2016)
  - WFIRST (Green et al. 2016)
  - Euclid (Refriger et al. 2010)
- CMB (Planck 2015)

Fig: Combined statistical and systematic uncertainties for the WFIRST SN survey (Spergel et al. 2013).
Bimetric Gravity: Linear and Quadratic Interaction

- Next order interaction term
- $B_2$ describes the interaction
- $r$ is the ratio of the scale factor
- $B_2$ and $r$ describe effective DE density
- Model approaches $\Lambda$CDM
- Fits as well as standard cosmology

Fig: Constraints on the parameter describing the quadratic interaction term for bimetric gravity (Dhawan et al. submitted.)
Growing $\nu$ mass

- Cosmon field coupled to matter (neutrinos)
- Free parameters: $\Omega_e$, $\Omega_\nu$
- Strong Degeneracy
- Can be broken by growth information
- More precise with CMB compressed likelihood

Fig: Constraints on the growing neutrino quintessence. The model is appealing since dark energy has cosmological constant behaviour when the neutrinos become non-relativistic and decouple from the scalar field. A strong degeneracy between the parameters gives a loose constraint of $\Omega_\nu < 2$ eV (Dhawan et al. submitted)
Curvature

- Extending $\Lambda$CDM
  - $\Omega_k$ is free
- Single curvature term
  - No distinction between expansion and geometric
- Consistent with flatness ($\Omega_k = -0.004 +/- 0.021$)
- Bayesian Evidence penalises the model

Fig: Extension of LCDM to curvature density as a free parameter. The data constrain it to $\Omega_k = -0.004 +/- 0.021$. Bayesian evidence for this model moderately disfavours this scenario.
CMB compressed likelihood

- CMB shift ($R$); first acoustic peak ($I_A$)
- Assumes wCDM cosmology
- Inadequate for modified gravity
  - “Dark Degeneracy”: interacting DE models
  - Bimetric Gravity
- More precise than CMB/BAO ratio
- Thawing Models are decisively excluded ($\Delta \ln Z > 5.$)
Vacuum Metamorphosis

- Sudden Vacuum Transition
- Two parameter model
  - $\Omega_M$ (present day matter density)
  - $\Omega_*$ (matter density at transition)
- Zero transition redshift $\Rightarrow$ $\Lambda$CDM
- Non-zero transition at 1.5$\sigma$

Fig: Constraints on the present-day, and transition, matter density from SN-Ia and the CMB/BAO ratio for the vacuum metamorphosis model (Dhawan et al. submitted).