Narrowing down the possible explanations of cosmic acceleration with geometric probes

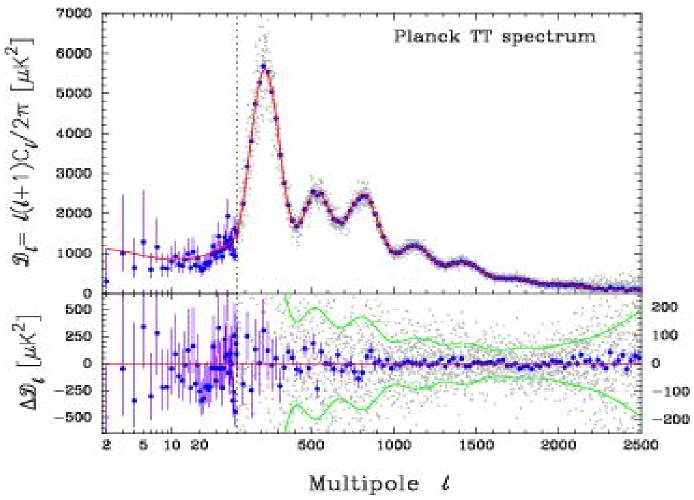
Suhail Dhawan (Oskar Klein Center, Stockholm University)
Collaborators: Ariel Goobar, Edvard Mortsell, Rahman Amanullah, Ulrich Feindt (OKC)

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



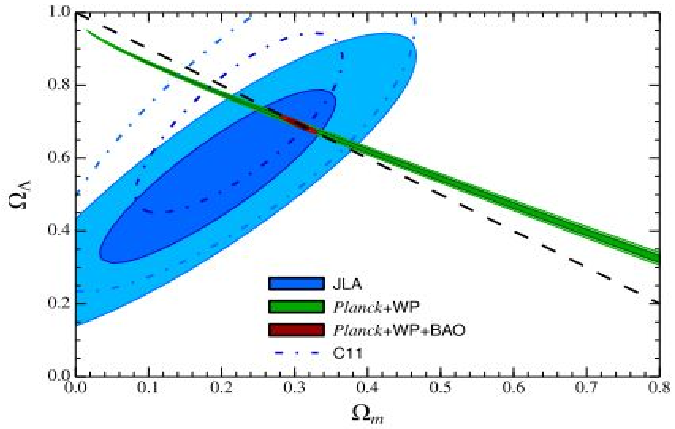


Fig: (Top): Fit to the Planck CMB power spectrum (Planck 2013). (Bottom): Combined fit for standard cosmology parameters to SNIa, CMB, BAO data (Betoule et al. 2014).

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)
- Bimetric Gravity (von Strauss et al. 2012; Comelli et al. 2012)
    - 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

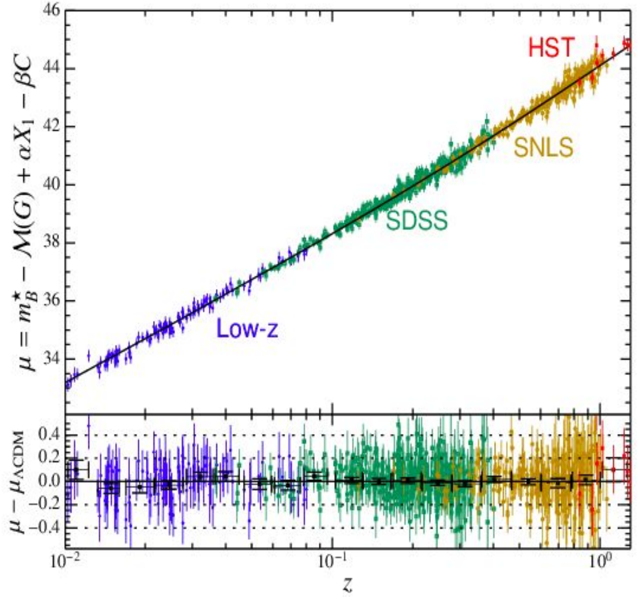


Figure 1: JLA Hubble diagram

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

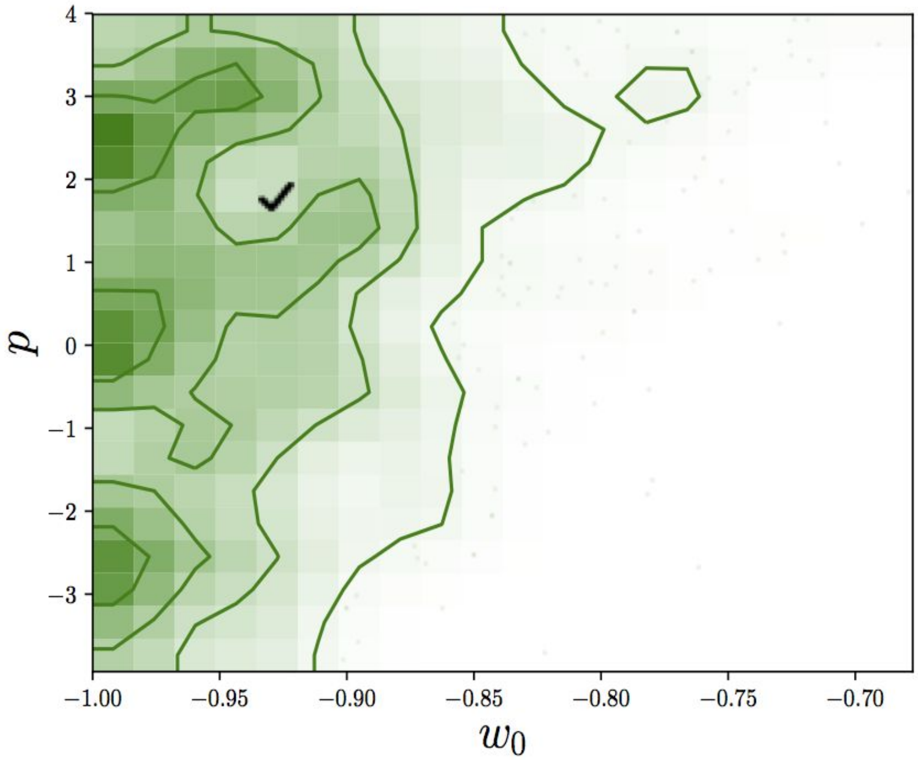


Fig: Constraints on the present day equation of state and the shape of the potential for the algebraic thawing model. The SNe and CMB/BAO ratio constrain w0 to < -0.78 at the 95% C.L. (Dhawan et al. submitted)

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

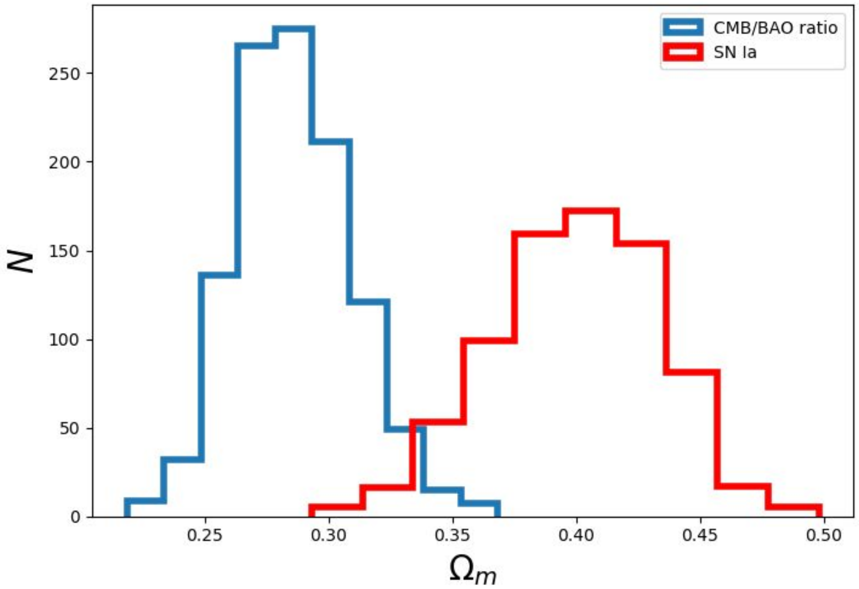


Fig: Bimetric gravity model with only linear interaction term (e.g. von Strauss et al. 2012, Comelli 2012) fitted to CMB/BAO (blue) and Supernova Ia (red) data. Although the fits to individual probes are satisfactory, there is an inconsistency in the resulting distributions (Dhawan et al. submitted)

Goodness of fit

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

Model	Parameters	$\ln Z_f$	Δ	$\frac{Z_m}{Z_{f\Lambda}}$	χ^2_{min}	Evidence Meaning
(flat) ΛCDM	Ω_M	-359.6	$\cdots$	1.000	685.7	$\cdots$
ΛCDM	Ω_M, Ω_K	-362.2	-2.6	0.074	684.9	Moderate/Strong
Vacuum Metamorphosis[a]	Ω_M, Ω_*	-361.1	-1.5	0.223	683.0	Inconclusive/Weak
Doomsday	Ω_M, w_0	-362.7	-3.1	0.045	684.8	Moderate/Strong
Slow-Roll One parameter	Ω_M, δw_0	-361.4	-1.8	0.150	684.9	Weak/Moderate
PNGB	Ω_ϕ, w_0, K	-363.3	-3.7	0.024	682.9	Moderate/Strong
Algebraic Thawing	Ω_M, w_0, p	-362.8	-3.2	0.040	684.7	Moderate/Strong
Algebraic Thawing (p=1)	Ω_M, w_0	-362.8	-3.2	0.040	684.7	Moderate/Strong
Growing ν mass	Ω_e, Ω_ν	-360.5	-0.9	0.405	684.5	Inconclusive
Bimetric - Linear	Ω_M	-363.6	-4.0	0.024	691.8	Moderate/Strong
Bimetric - Quadratic	Ω_M, B_2	-360.1	-0.5	0.606	685.6	Inconclusive

Model Comparison

- Use Bayes Factor (Z_i/Z_0)
- Evidence Calculated via Nested Sampling
- Flat Λ highest evidence
- Thawing models moderately disfavoured
- Bimetric: Linear poorly fit
- Bimetric: Quadratic fits well; approaches ΛCDM

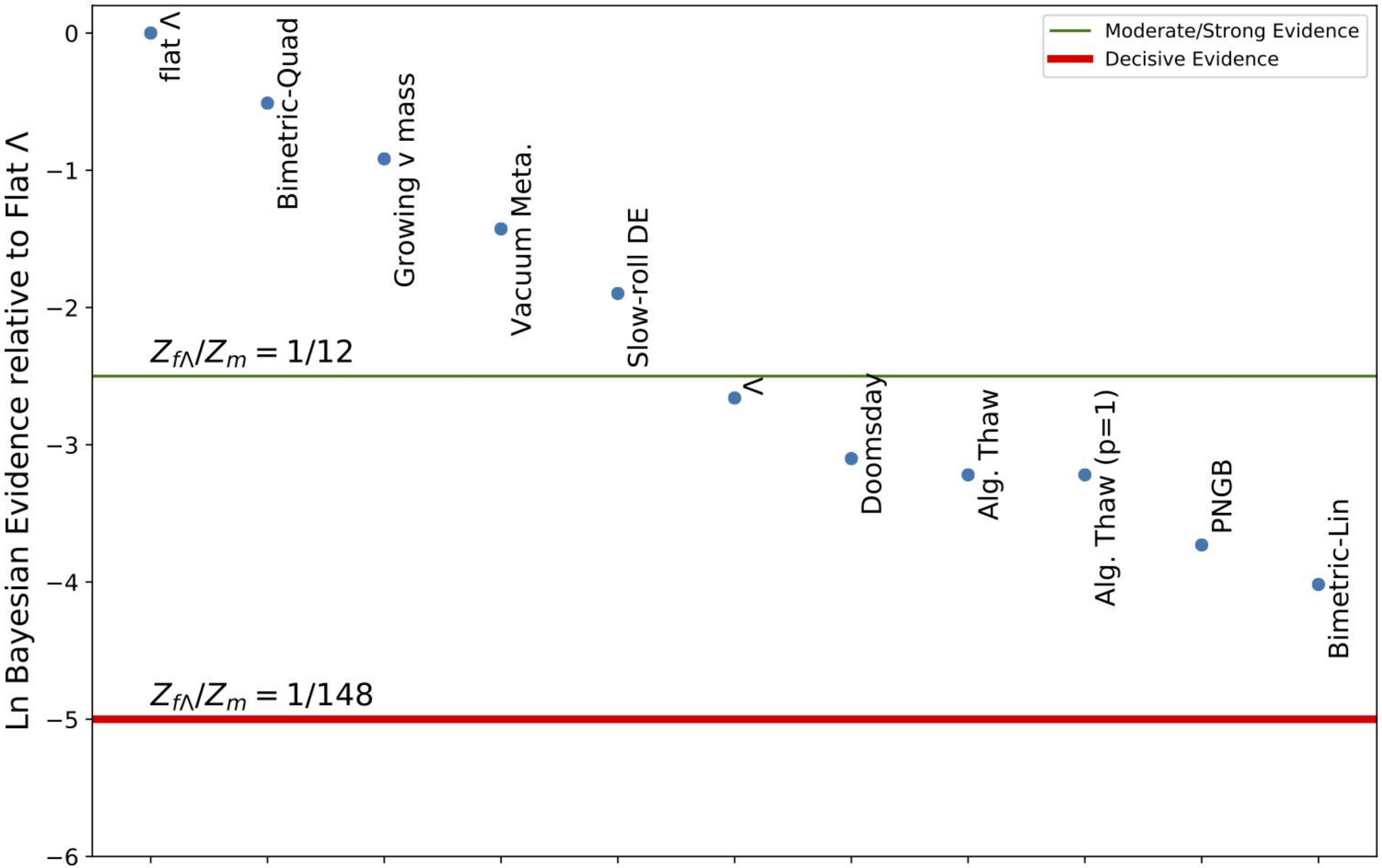


Figure: A comparison of the Bayesian evidences for each model tested, relative to the model with highest evidence (i.e. flat Λ). The green and red lines denote the region of moderate/strong and decisive exclusion respectively (based on the Jeffrey's scale, Dhawan et al. submitted)

Forecasts for future surveys

- Distinguish exotic models from flat Λ
- 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

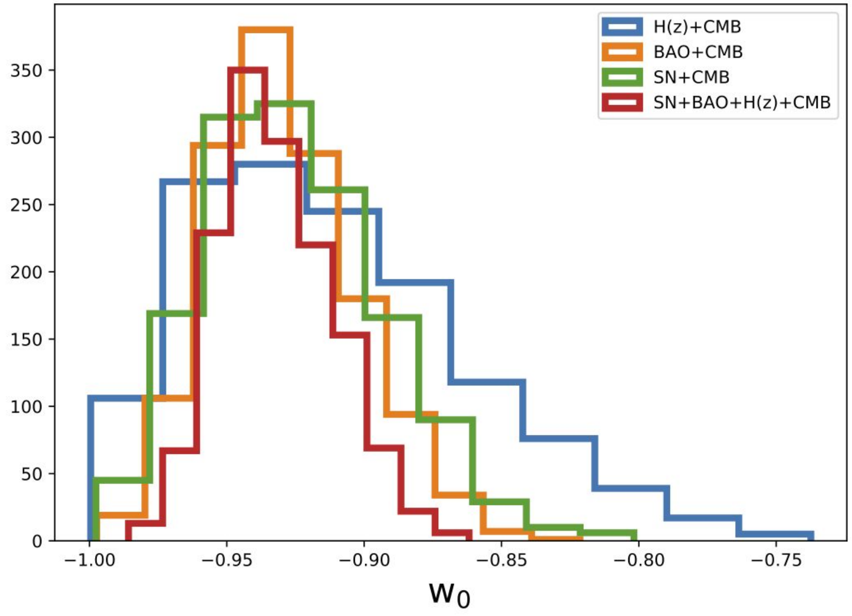


Fig: Posterior distribution for w_0 in the algebraic thawing model with different combinations of input datasets

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

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

Equation reference: Sollerman et al. 2009, Enander et al. 2014, Dhawan et al. submitted

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. 2012)
  - Euclid (Refreiger et al. 2010)
- CMB (Planck 2015)

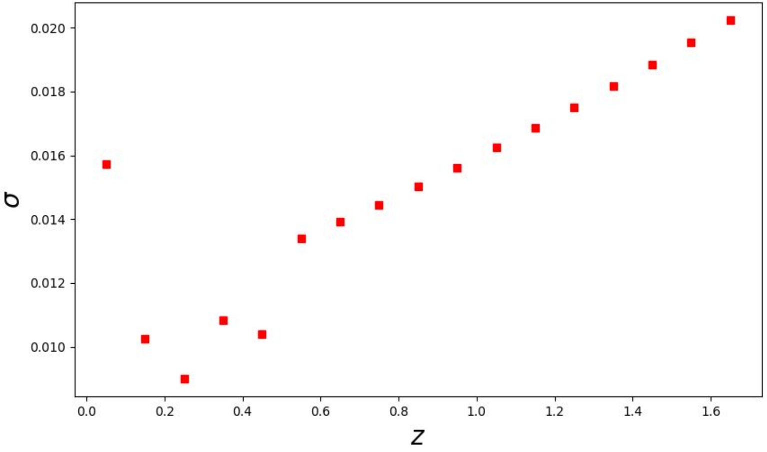


Fig: Combined statistical and systematic uncertainties for the WFIRST SN survey (Spergel et al. 2013).

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 ΛCDM
- Fits as well as standard cosmology

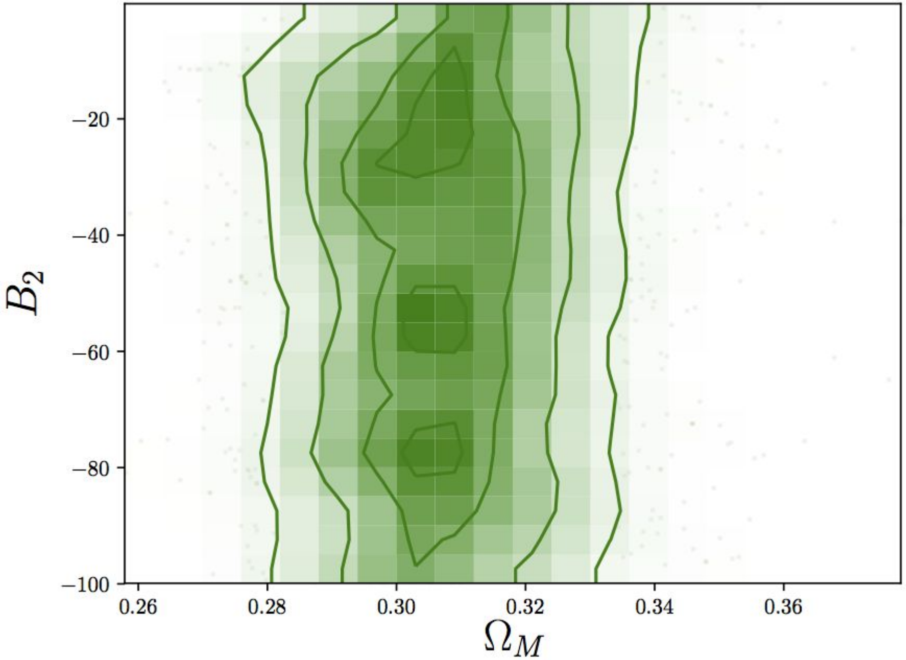


Fig: Constraints on the parameter describing the quadratic interaction term for bimetric gravity (Dhawan et al. submitted.)

Growing ν mass

- Cosmon field coupled to matter (neutrinos)
- Free parameters: Ω_e, Ω_ν
- Strong Degeneracy
- Can be broken by growth information
- More precise with CMB compressed likelihood

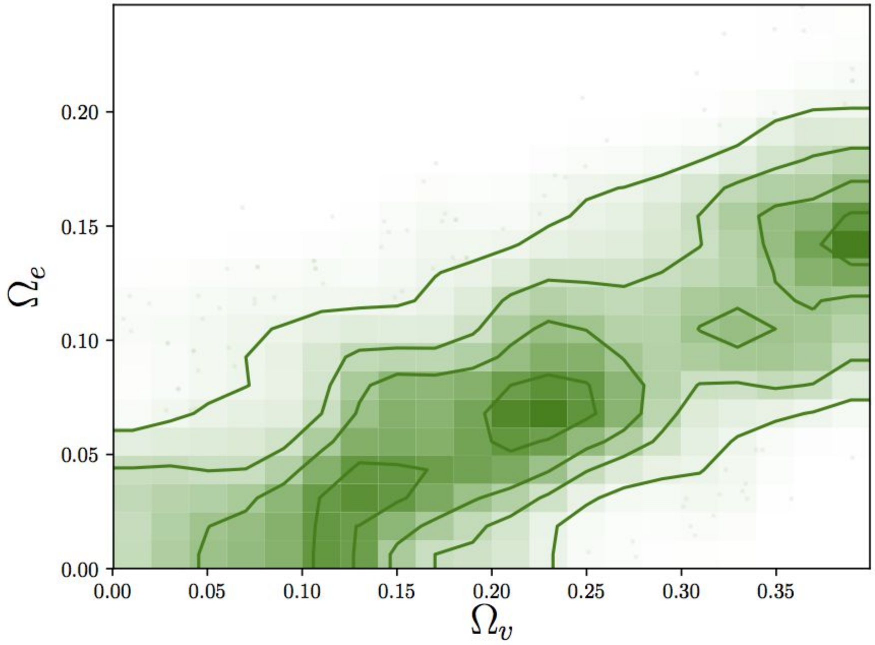


Fig: Constraints on the growing neutrino quintessence. The model is appealing since dark energy has cosmological constant behaviour when the neutrinos become non-relativistic and decouple from the scalar field. A strong degeneracy between the parameters gives a loose constraint of Ω_ν < 2 eV (Dhawan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

Curvature

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

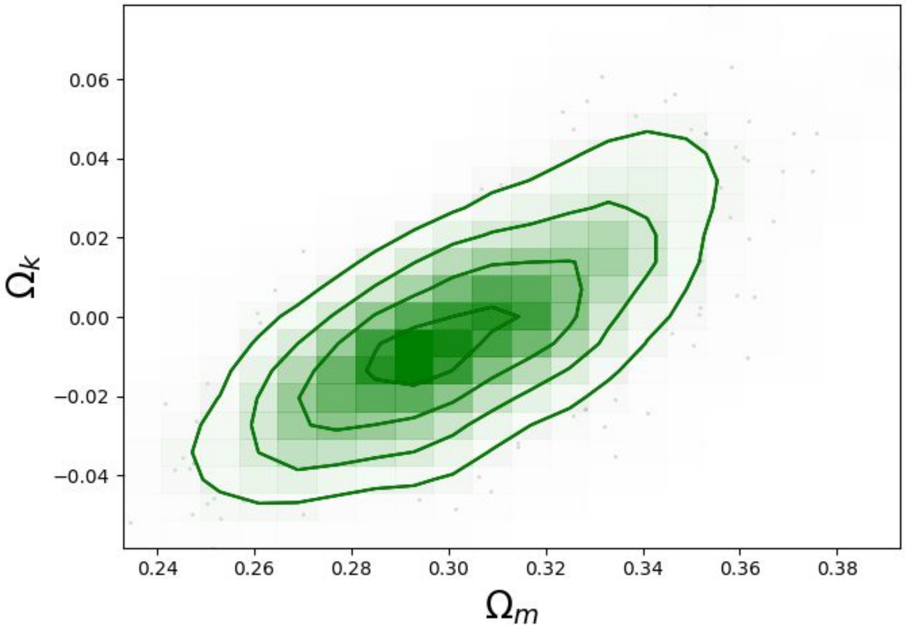


Fig: Extension of LCDM to curvature density as a free parameter. The data constrain it to Ω_k = -0.004 +/- 0.021. Bayesian evidence for this model moderately disfavours this scenario.

CMB compressed likelihood

- CMB shift (R); first acoustic peak (l_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
    - Ω_M (present day matter density)
    - Ω_* (matter density at transition)
- Zero transition redshift => ΛCDM
- Non-zero transition at 1.5σ

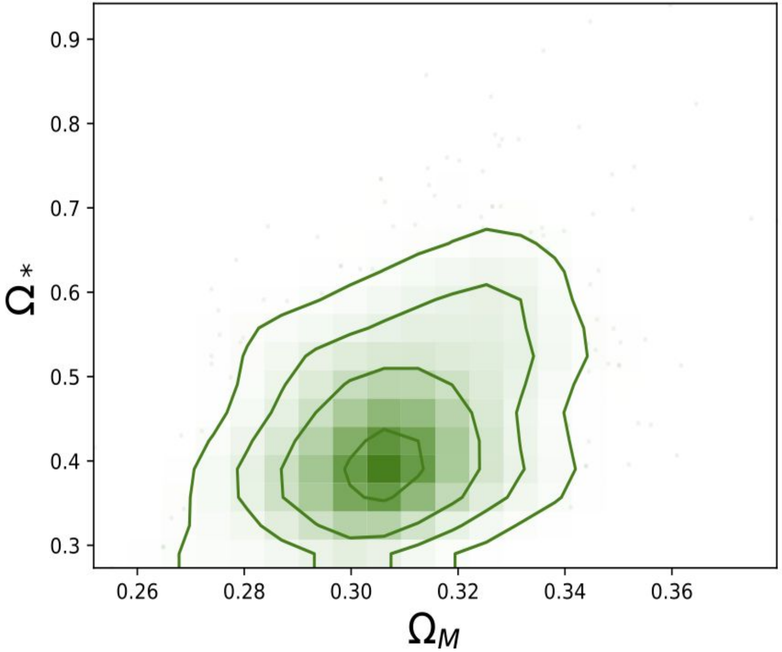


Fig: Constraints on the present-day, and transition, matter density from SN~Ia and the CMB/BAO ratio for the vacuum metamorphosis model (Dhawan et al. submitted).