Effects of Current SN Ia Systematics on Dark Energy Constraints

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Santa Fe Cosmology Workshop

July 5, 2013

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arXiv:1207.4781

Outline

Evidence for Dark Energy?

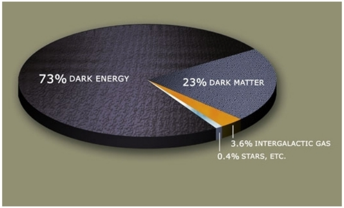
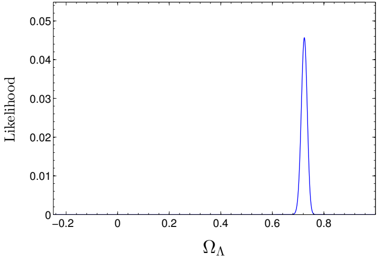


Image Credit: NASA



- Zero (or negative) Ω_Λ ruled out at 64-σ!

Why are SNe Ia so useful?

- Type Ia supernovae (SNe Ia) were used to discover DE (Riess, Schmidt, Perlmutter – late 1990s), and still provide the best constraints on DE parameters.
- SNe Ia are reliable, bright standard candles $\rightarrow$ useful for measuring cosmological distances and tracking expansion. *Each* SN provides a distance measurement.
- Rule of thumb: **b r o a d e r** is brighter, bluer is brighter.

Using SNe Ia to Constrain Cosmological Parameters

$$m_{\mathsf{mod}} = 5\log_{10}\left(\frac{H_0}{c}\, d_L(\mathbf{p})\right) - \alpha_s(s-1) + \beta_c\,\mathcal{C} + \mathcal{M}$$

$$\Downarrow$$

$$\chi^2 = \Delta\mathbf{m}^{\mathsf{T}}\mathbf{C}^{-1}\Delta\mathbf{m} \quad \rightarrow \quad \Delta\mathbf{m} = \mathbf{m}_{\mathsf{obs}} - \mathbf{m}_{\mathsf{mod}}(\mathbf{p})$$

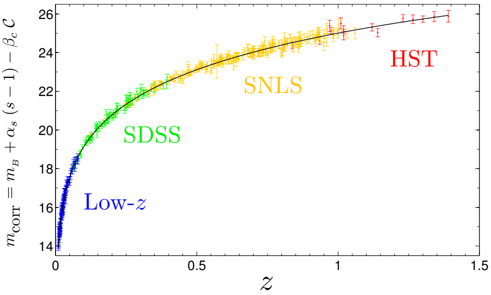
$$\mathbf{C} = \text{SN Covariance Matrix}$$

$$\Downarrow$$

$$\mathcal{L}(\mathbf{p}) \propto e^{-\chi^2/2}$$

In addition to $\mathbf{p}$, there are "nuisance" parameters to marginalize over: $\mathcal{M}$, α_s , β_c

SNLS Compilation



- Conley et al. [1]: 3-year SNLS compilation $\rightarrow$ **most comprehensive, rigorous analysis of SN systematics to date** $\rightarrow$ full covariance matrix
- 472 SNe, redshift coverage out to $z \approx 1.4$
- $\sim 1/2$ are from SNLS $\rightarrow$ better coverage at mid-to-high-z

Supernova Covariance

The complete covariance matrix $\mathbf{C}^{\text{full}}$ from Conley et al. [1] can be written as the sum of two parts:

- Diagonal part $\mathbf{D}^{\text{stat}}$ consisting of typical statistical errors (error propagation, intrinsic scatter):

$$D_{ii}^{\text{stat}} = \sigma_{m_B,i}^2 + \alpha_s^2\,\sigma_{s,i}^2 + \beta_c^2\,\sigma_{\mathcal{C},i}^2 + \sigma_{\text{int}}^2 + \left(\frac{5(1+z_i)}{z_i(1+z_i/2)\log 10}\right)^2 \sigma_{z,i}^2 + \sigma_{\text{lensing}}^2 + \sigma_{\text{host correction}}^2 + D_{ii}^{m_B\,s\,\mathcal{C}}(\alpha_s,\beta_c)\ ,$$

where $D_{ii}^{m_B\,s\,\mathcal{C}}(\alpha_s,\beta_c) = 2\alpha_s D_{ii}^{m_B\,s} - 2\beta_c D_{ii}^{m_B\,\mathcal{C}} - 2\alpha_s\beta_c D_{ii}^{s\,\mathcal{C}}$

- Off-diagonal part $\mathbf{C}^{\text{sys}}$ consisting primarily of systematic terms: Calibration (dominant), Malmquist bias, Milky Way dust, peculiar velocity, non-Ia contamination, evolution of α_s / β_c , light curve fitter differences, host relation.

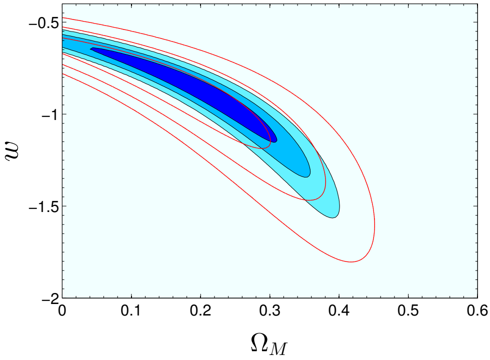
How to Parametrize the DE Equation of State?

- Constant w : Assume a flat universe ($\Omega_{\text{DE}} = 1 - \Omega_M$)
  $\rightarrow \quad p_i \in \{\Omega_M, w, \mathcal{M}, \alpha_s, \beta_c\}$
- w_0 and w_a : Let $w(a) = w_0 + w_a(1-a)$, also flat universe
  $\rightarrow \quad p_i \in \{\Omega_M, w_0, w_a, \mathcal{M}, \alpha_s, \beta_c\}$
- Principal Components (PCs) of $w(z)$: *Skip...*

Modest number of parameters $\rightarrow$ brute-force computation of likelihoods over an N-dimensional grid of parameter values

Effect of Systematics: Constant w

- $\Omega_K = 0$
- Marginalized over $\mathcal{M}$, α_s, β_c
- Systematics broaden the contours but do not significantly change best-fit values or the direction of degeneracy.
- Systematics increase σ_w by about 20% (from 0.17 to 0.20).



Constraints from CMB Anisotropies

- Hot and cold spots in the CMB $\rightarrow$ characteristic size scale in the angular power spectrum
- Measure the peak position $\rightarrow$ angular diameter distance to redshift of decoupling
- Effectively constrains the "CMB shift parameter" R:

$$R \equiv \frac{\sqrt{\Omega_M H_0^2}}{c} (1 + z_*) \, d_A(z_*)$$

- From WMAP7: $z_* = 1091.3$
  $R_0 = 1.725 \pm 0.0184$

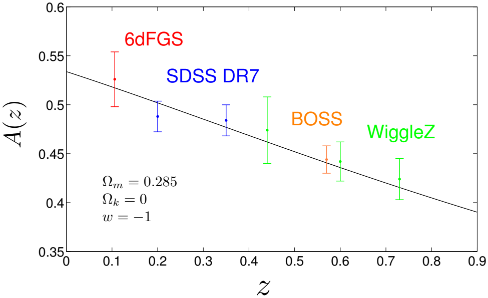
Komatsu et al. [2]

Constraints from Baryon Acoustic Oscillations

- Sound waves propagating in the early universe should leave behind matter over/under-densities $\rightarrow$ peak in LSS angular correlation function and power spectrum
- Can measure BAO peak position in one or more redshift bins $\rightarrow$ angular diameter distance to an effective (median) redshift.
- Effectively constrains the acoustic parameter $A(z)$:

$$\begin{aligned} A(z) &\equiv \frac{\sqrt{\Omega_M H_0^2}}{cz} \; D_V(z) \\ &= \frac{\sqrt{\Omega_M H_0^2}}{cz} \left[(1+z)^2 \, d_A^2(z) \, \frac{cz}{H(z)} \right]^{1/3} \end{aligned}$$

Combining BAO Measurements



- No significant tension between the various $A(z)$ measurements.

Sample	z_{eff}	$A_0(z_{\text{eff}})$
6dFGS	0.106	0.526 ± 0.028
SDSS DR7	0.20	0.488 ± 0.016
SDSS DR7	0.35	0.484 ± 0.016
WiggleZ	0.44	0.474 ± 0.034
BOSS	0.57	0.444 ± 0.014
WiggleZ	0.60	0.442 ± 0.020
WiggleZ	0.73	0.424 ± 0.021

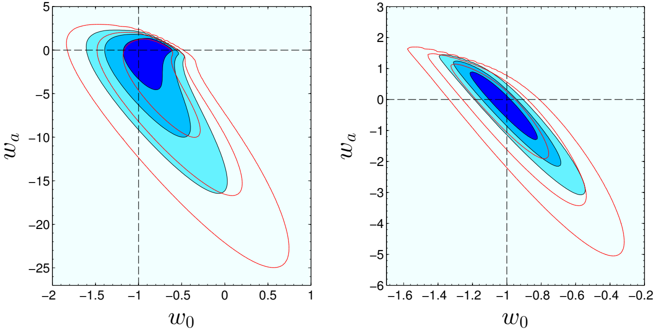
Beutler et al. [3], Percival et al. [4], Blake et al. [5], Blake et al. [6], Sanchez et al. [7], Anderson et al. [8]

Effect of Systematics: w_0 and w_a

Left: SN-only constraints

Right: Combined SN+BAO+CMB constraints

Very poor SN-only constraints – improve substantially with combined data



- Systematics expand the contours somewhat without changing the principal degeneracy direction. Contours elongate only toward more negative w_a.

Effect of Systematics: DETF Figure of Merit

- The w_0-w_a Figure of Merit (FoM) defined by the Dark Energy Task Force (DETF) is the inverse of the area of the 95.4% confidence level region A_{95} in the w_0-w_a plane. For simplicity, we define the FoM as

$$\text{FoM}^{(w_0\, w_a)} \equiv (\det \mathbf{C})^{-1/2} \approx \frac{6.17\pi}{A_{95}}.$$

$\text{FoM}^{(w_0\, w_a)}$	$\mathbf{D}^{\text{stat}}$	$\mathbf{C}^{\text{full}}$
SN	2.28	1.16
SN+BAO+CMB	32.9	11.8

Albrecht et al. [9]

- Including the systematic errors reduces the FoM by about a factor of two to three.

Accounting for Finite Detection Significance

- Bassett and Afshordi [10]: For marginal detections, a Gaussian likelihood is not a good approximation far from the peak. What if the feature was not actually detected?

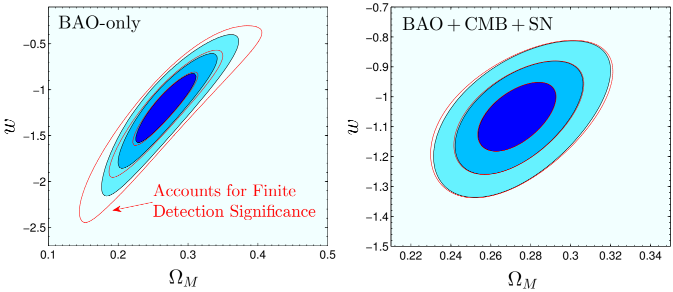
$$P(\mathbf{p}|\mathbf{d}) = P_{\text{detect}}\, P(\mathbf{p}|\mathbf{d}, \text{detect}) + (1 - P_{\text{detect}})\, P(\mathbf{p}|\mathbf{d}, \text{noise})$$

- A fitting function to approximate the correct likelihood:

$$\Delta\chi^2 = \frac{\Delta\chi^2_G}{\sqrt{1 + \left(\frac{\mathsf{S}}{\mathsf{N}}\right)^{-4} \Delta\chi^4_G}}$$

- Sensible limits: $\Delta\chi^2 = \Delta\chi^2_G$ for small (compared to signal-to-noise) departures from the best-fit model; asymptotes to a constant "tail" $(\mathsf{S}/\mathsf{N})^2$ when $\Delta\chi^2_G \gg (\mathsf{S}/\mathsf{N})^2$

Effect of Finite Detection Significance of BAO



- Significances of BAO feature detection: 2.4 σ (corresponding to S/N $= 2.4$) for 6dF, 2.8 σ for WiggleZ (combined for three redshift bins), 3.6 σ for SDSS (combined for two redshift bins), and 5.0 σ for BOSS
- Differences are modest in the BAO-only case and negligible in the combined case.

In Conclusion...

We have:

- Used *current* SN data combined with current BAO and CMB measurements to constrain DE parameters
- Adopted a rigorous systematic analysis (which included a fully off-diagonal SN covariance matrix) to study the effect of systematic errors on DE constraints
- Found that systematic errors weaken the constraints considerably $\rightarrow$ FoM$^{(w_0\, w_a)}$ decreased by a factor of two to three
- Looked at a "systematic" for BAO $\rightarrow$ accounting for finite detection of BAO feature leads to a significant effect only for BAO-only constraints

[1] A. Conley, J. Guy, M. Sullivan, N. Regnault, P. Astier, et al., Astrophys.J.Suppl. **192**, 1 (2011), 1104.1443.

[2] E. Komatsu et al. (WMAP), Astrophys. J. Suppl. **192**, 18 (2011), 1001.4538.

[3] F. Beutler, C. Blake, M. Colless, D. H. Jones, L. Staveley-Smith, et al., Mon.Not.Roy.Astron.Soc. **416**, 3017 (2011), 1106.3366.

[4] W. J. Percival et al. (SDSS Collaboration), Mon.Not.Roy.Astron.Soc. **401**, 2148 (2010), 0907.1660.

[5] C. Blake, S. Brough, M. Colless, C. Contreras, W. Couch, et al. (2012), 1204.3674.

[6] C. Blake, E. Kazin, F. Beutler, T. Davis, D. Parkinson, et al., Mon.Not.Roy.Astron.Soc. **418**, 1707 (2011), 1108.2635.

[7] A. G. Sanchez, C. Scoccola, A. Ross, W. Percival, M. Manera, et al. (2012), 1203.6616.

[8] L. Anderson, E. Aubourg, S. Bailey, D. Bizyaev, M. Blanton, et al. (2012), 1203.6594.

[9] A. Albrecht et al. (2006), astro-ph/0609591.

[10] B. A. Bassett and N. Afshordi (2010), 1005.1664.