Bayesian Analysis of SNIa Cosmology

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BAHAMAS: new SNIa analysis reveals inconsistencies with standard cosmology

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We present results obtained by applying our BAyesian HierArchical Modeling for the Analysis of Supernova cosmology (BAHAMAS) software package to the 740 spectroscopically confirmed supernovae type Ia (SNIa) from the "Joint Light-curve Analysis" (JLA) dataset. We simultaneously determine cosmological parameters and standardization parameters, including host galaxy mass corrections, residual scatter and object-by-object intrinsic magnitudes. Combining JLA and Planck Cosmic Microwave Background data, we find significant discrepancies in cosmological parameter constraints with respect to the standard analysis: we find Omega_M = 0.399+/-0.027, 2.8\sigma\ higher than previously reported and w = -0.910+/-0.045, 1.6\sigma\ higher than the standard analysis. We determine the residual scatter to be sigma_res = 0.104+/-0.005.
We confirm (at the 95% probability level) the existence of two sub-populations segregated by host galaxy mass, separated at log_{10}(M/M_solar) = 10, differing in mean intrinsic magnitude by 0.055+/-0.022 mag, lower than previously reported. Cosmological parameter constraints are however unaffected by inclusion of host galaxy mass corrections. We find ~4\sigma\ evidence for a sharp drop in the value of the color correction parameter, beta(z), at a redshift z_trans = 0.662+/-0.055. We rule out some possible explanations for this behaviour, which remains unexplained.

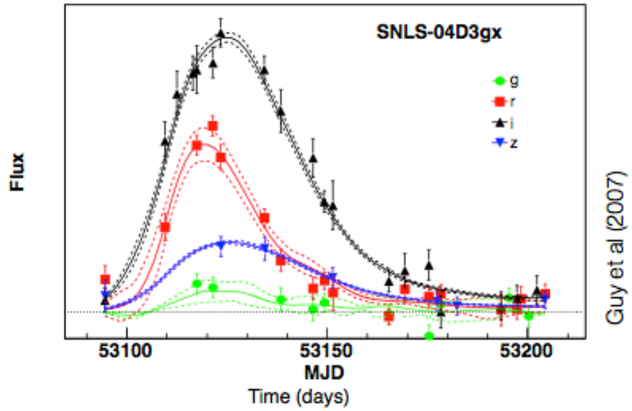
Summary

- SNIa Cosmology
- Classical Analysis and Related Issues
- Bayesian Analysis
- Results
- Phenomenological Extensions

SNIa Cosmology

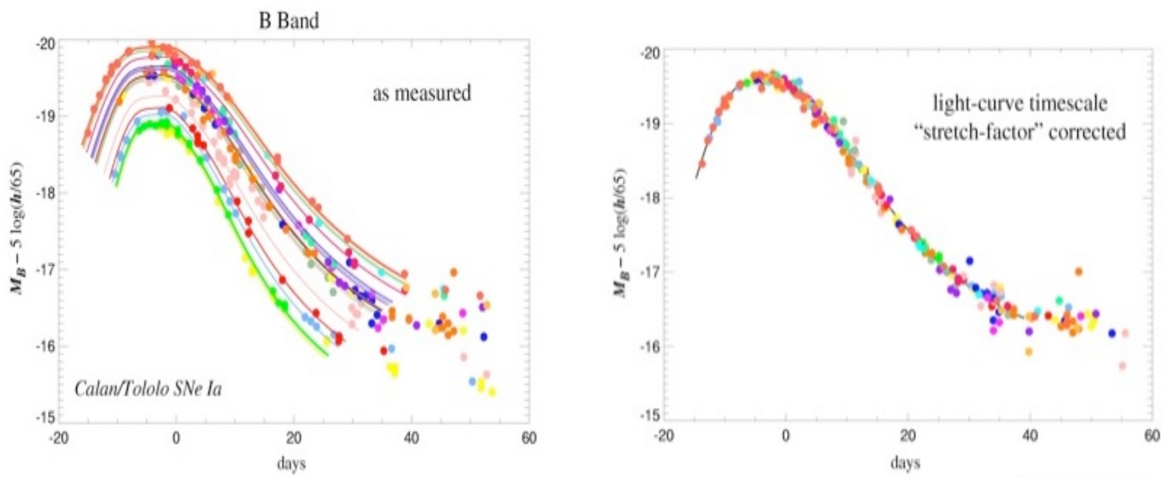
SNIa Background

- Supernovae are bright short lived explosions and can be observed to high redshifts ($z \approx 1$)
- Supernovae Type Ia (SNIa) are a subclass that do not have H-lines but do have Si lines
- SNIa are advantageous in cosmology as they are standardisable and can be used as standard candles
- SNIa sample used contains 740 observations used by Betoule et al, 2014 (JLA sample)
- Includes SNIa data as well as statistical and systematic matrices



Standardisation Procedure

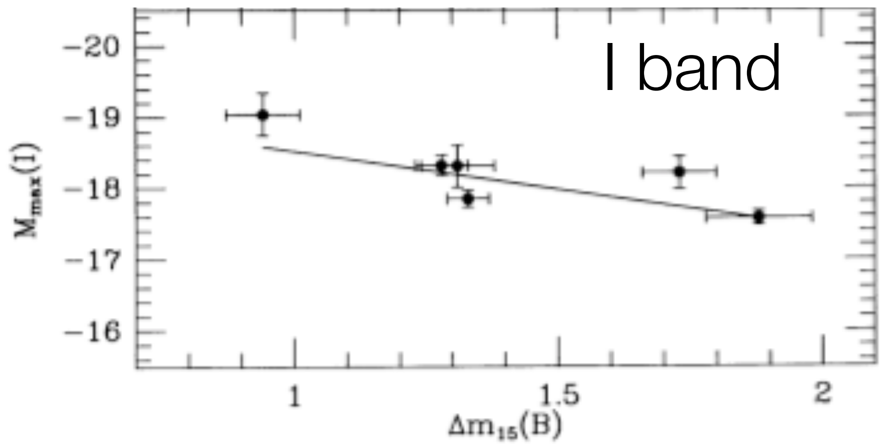
- First empirical correction was observed by Phillips (1993): Brighter SNIa last longer



Kim et al, 1997

Standardisation Procedure

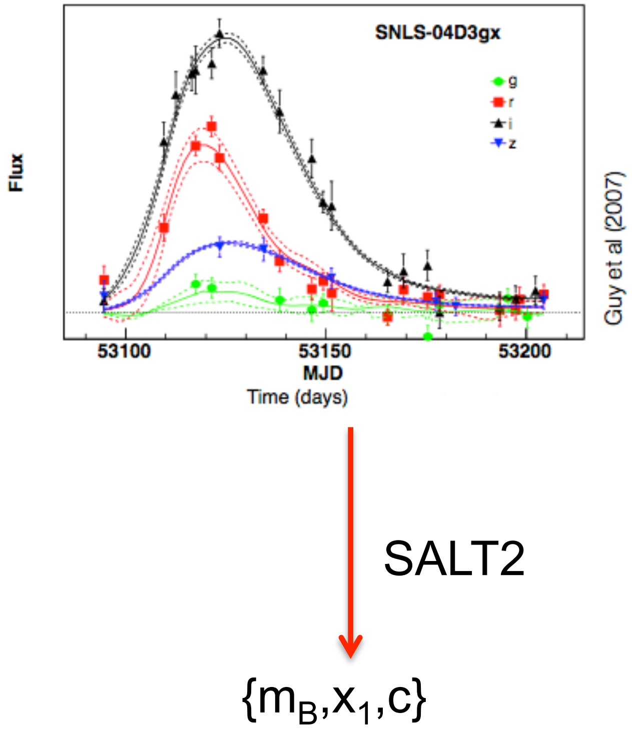
- First empirical correction was observed by Phillips (1993): Brighter SNIa last longer
- Negative correlation between M_B and $\Delta m_{15}(B)$



Phillip, 1993

Standardisation Procedure

- First empirical correction was observed by Phillips (1993): Brighter SNIa last longer
- Negative correlation between m_B and Δm_{15}
- Guy et al, 2007 developed an algorithm that employs two corrections: x1 (stretch correction) and c (color correction)



Application to Cosmology

$$\mu(z, C) = m_B - M_0 + \alpha x_1 - \beta c$$

SALT2 output for each SNIa

Application to Cosmology

$$\mu(z,C) = m_B - M_0 + \alpha x_1 - \beta c$$

Distance modulus: a function of luminosity distance. Which depends on redshift and cosmology

Application to Cosmology

$$\mu(z,C) = m_B - M_0 + \alpha x_1 - \beta c$$

Global parameters. Fitted simultaneously as C.
cf. Linear regression

Application to Cosmology

$$\mu(z,C) = m_B - M_0 + \alpha x_1 - \beta c$$

(Empirically corrected) Absolute magnitude. Assumed to constant

Classical Analysis and Related Issues

Standard χ^2 Procedure

Assuming a Gaussian likelihood

SALT2 Outputs for each SNIa

$$\chi^2 = \sum_i \frac{(\mu(z_i, C) - [\hat{m}_{B,i} - M_0 + \alpha \hat{x}_{1,i} - \beta \hat{c}_i])^2}{\sigma^2_{int} + \sigma^2_{fit}}$$

Standard χ^2 Procedure

Global parameters: need to be fitted
Done iteratively

$$\chi^2 = \sum_i \frac{(\mu(z_i, C) - [\hat{m}_{B,i} - M_0 + \alpha \hat{x}_{1,i} - \beta \hat{c}_i])^2}{\sigma^2_{int} + \sigma^2_{fit}}$$

Standard χ^2 Procedure

$$\chi^2 = \sum_i \frac{(\mu(z_i, C) - [\hat{m}_{B,i} - M_0 + \alpha \hat{x}_{1,i} - \beta \hat{c}_i])^2}{\sigma_{int}^2 + \sigma_{fit}^2}$$

Intrinsic scatter, since SNIa are not completely standardisable
Determined by requiring χ^2/dof ≈ 1

Statistical and systematics errors. But depends on α and β

Issues

- Even after empirical corrections, SNIa are not exactly standard candles
- Empirical corrections are not exact: model uncertainty needs to be incorporated into analysis
- Observed quantities are not the same as real quantities due measurement noise
- Standard analysis leads to biased results. March et al. (2011) showed that the bias is 2-3 larger (than a Bayesian analysis)
- The likelihood is not a principled approach; The treatment of σ_{int} and systematics is at best an approximation

Bayesian Analysis

Bayesian Hierarchical Analysis

- Based on Bayes' Theorem
- For each observed variable, there is a latent (real but unobserved) variable – a hierarchy
- Originally developed by March et al., 2011; but extended in this latest analysis

BAHAMAS

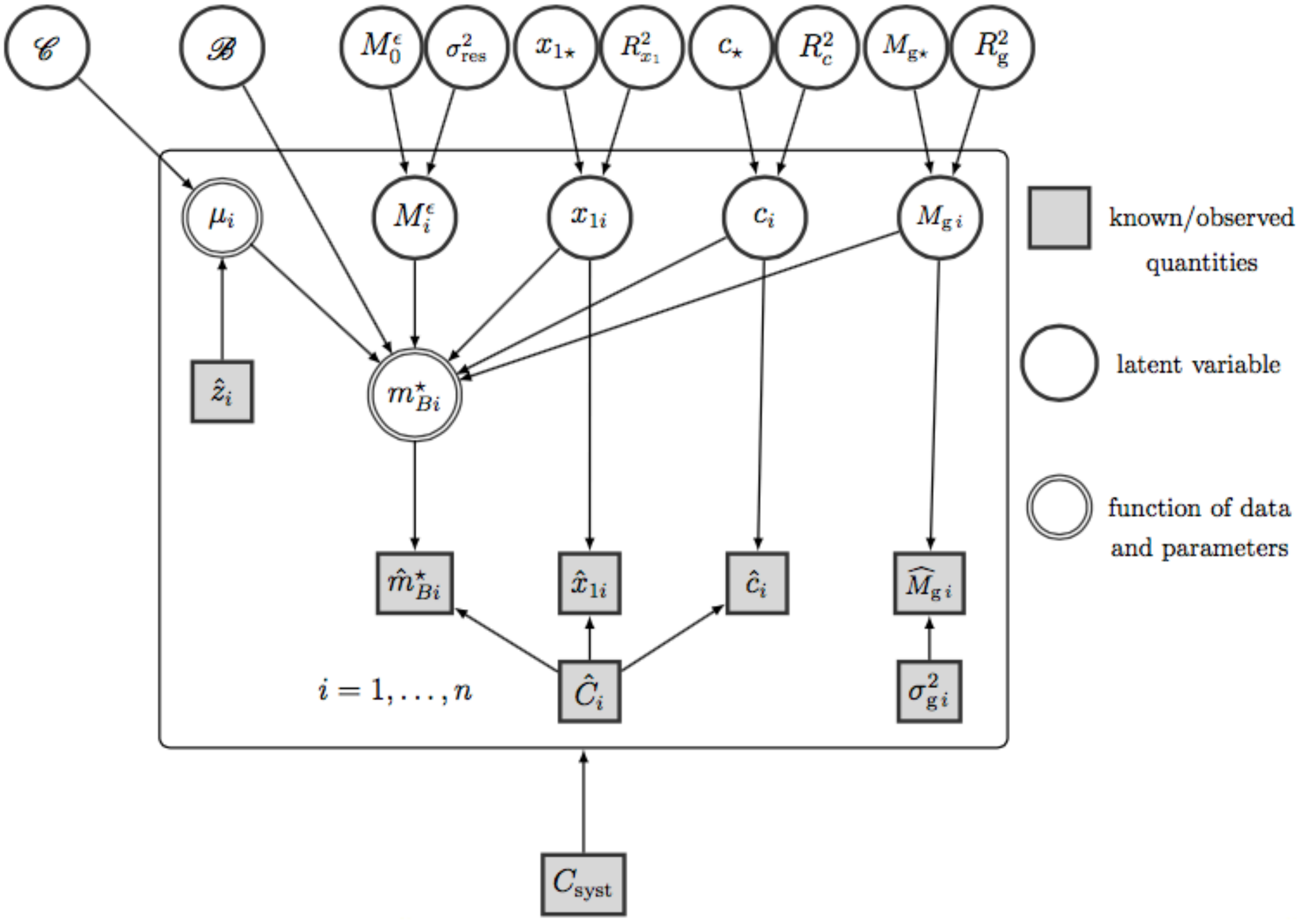
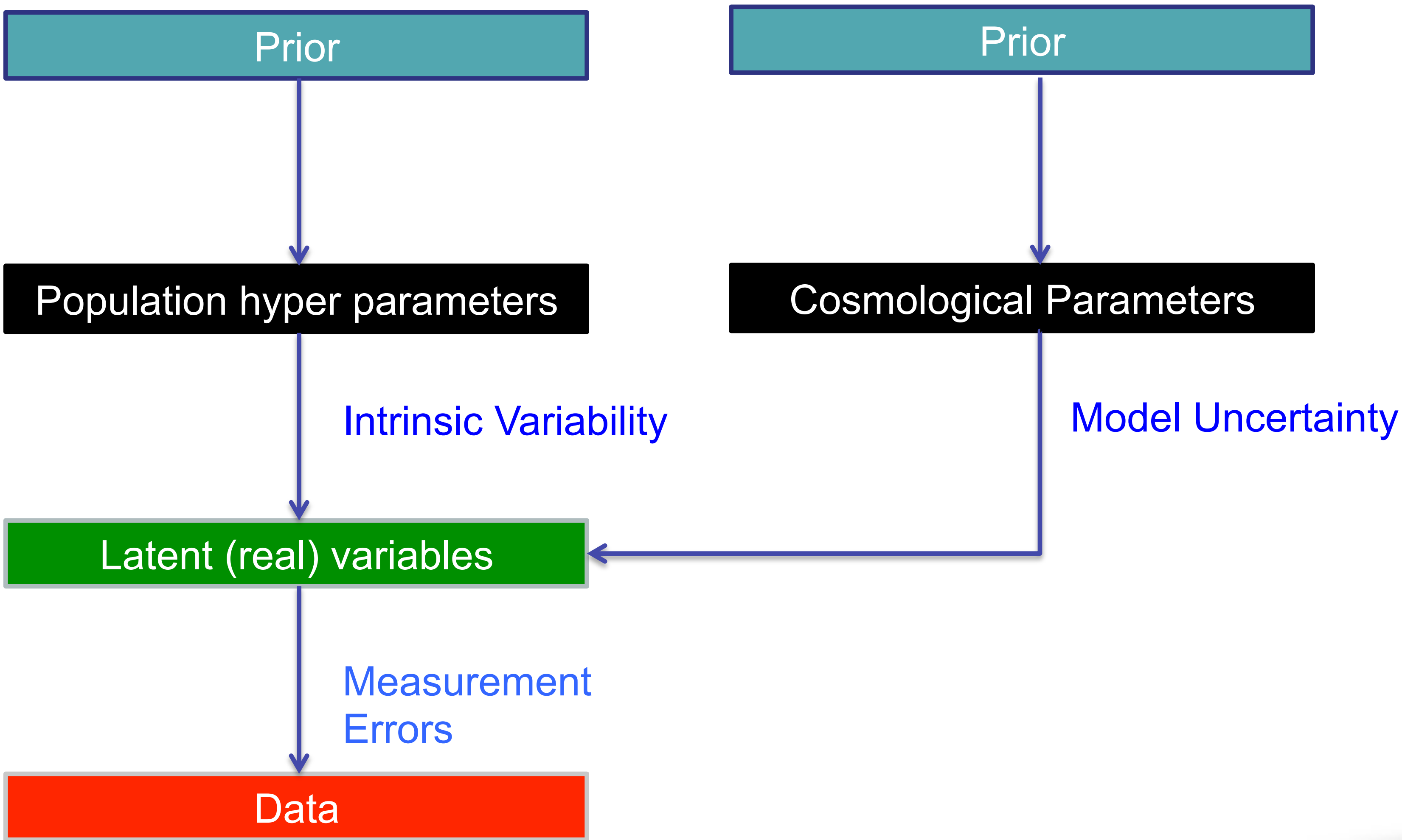


Fig. 1.— Graphical representation of *BAHAMAS*. The meaning of the symbols is given in Table 1.

Shariff et al, 2015

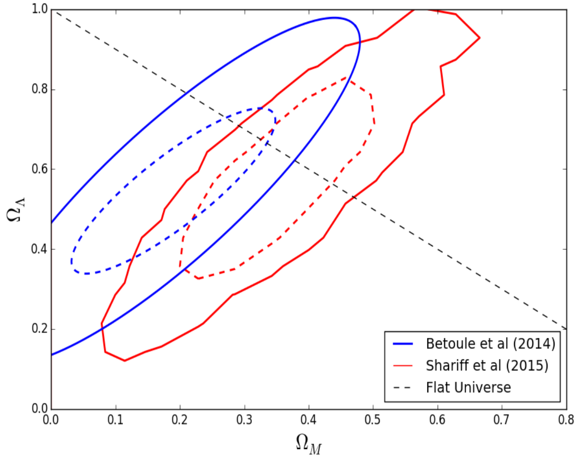
Bayesian Hierarchical Analysis



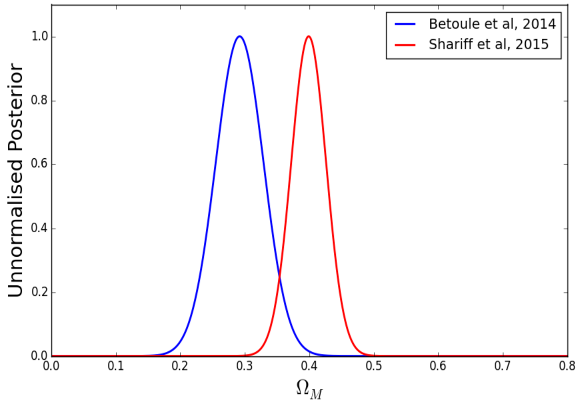
Results

ΛCDM Results

SNIa alone



SNIa + Planck



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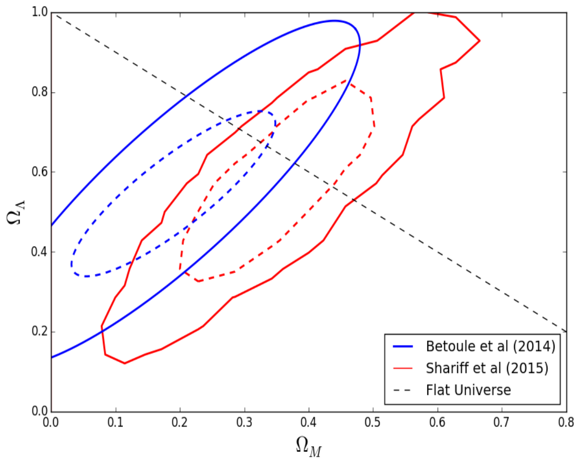
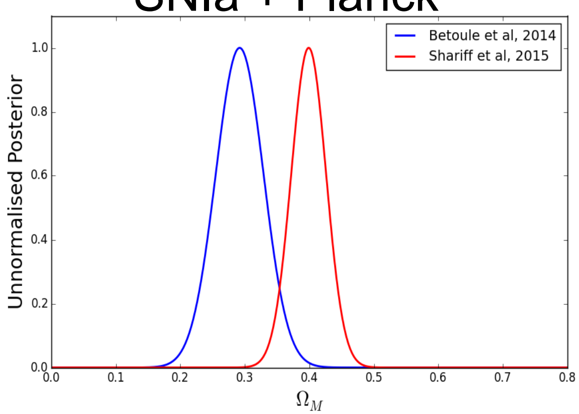
ΛCDM Results

SNIa alone



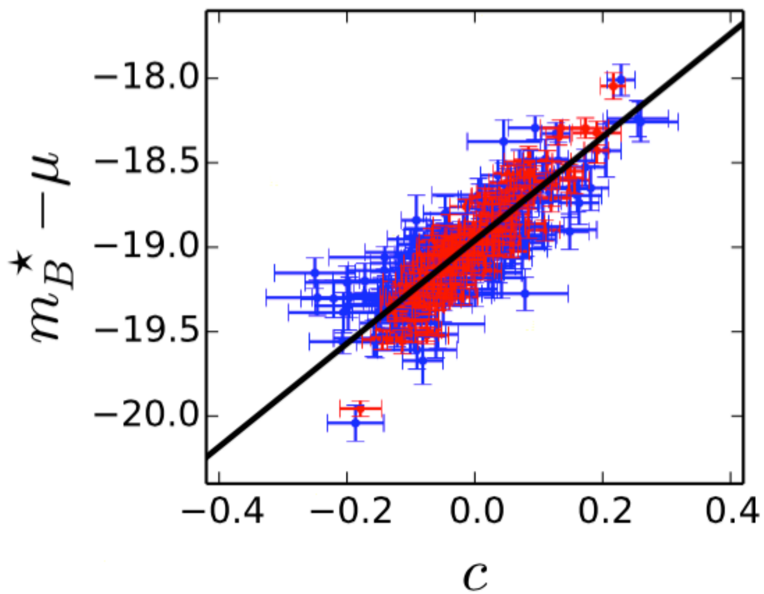
SNIa + Planck



Using SNIa and Planck:

$\Omega_m = 0.399 \pm 0.027$

$\Omega_\kappa = -0.024 \pm 0.008$



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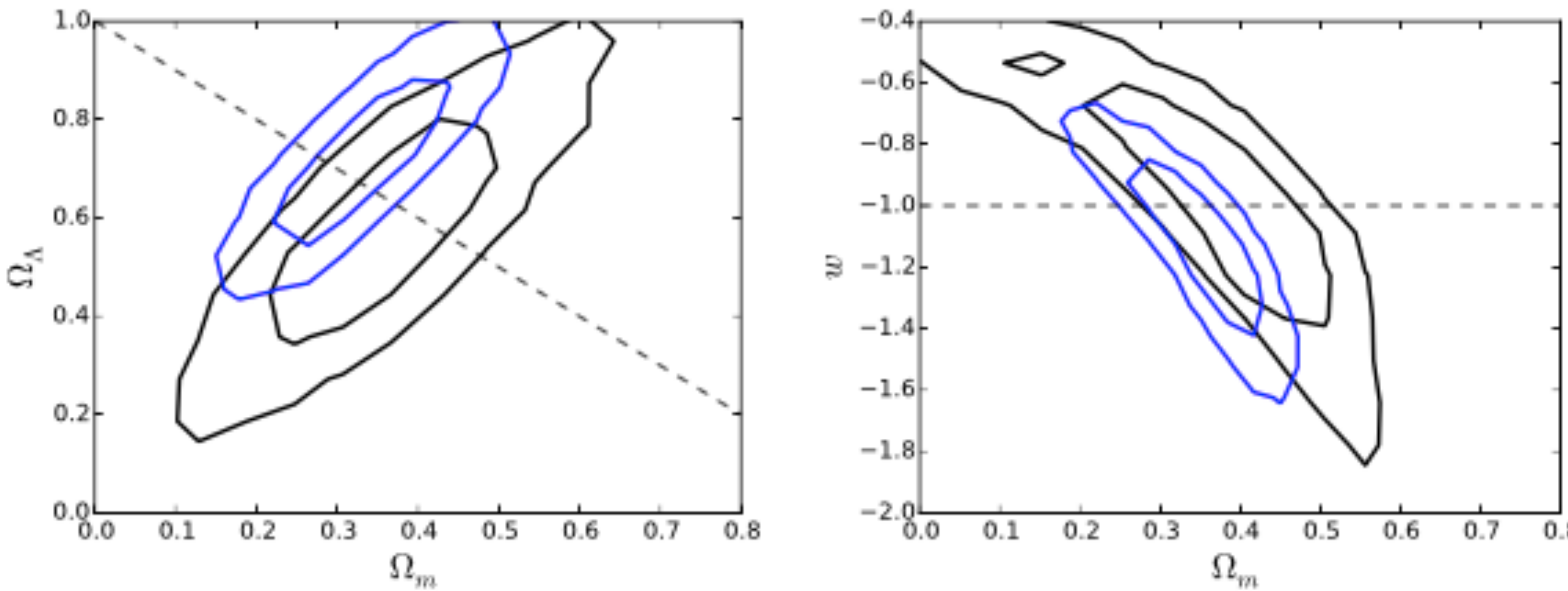
Pinpointing the issue



Statistical errors alone

Statistical + Systematics errors

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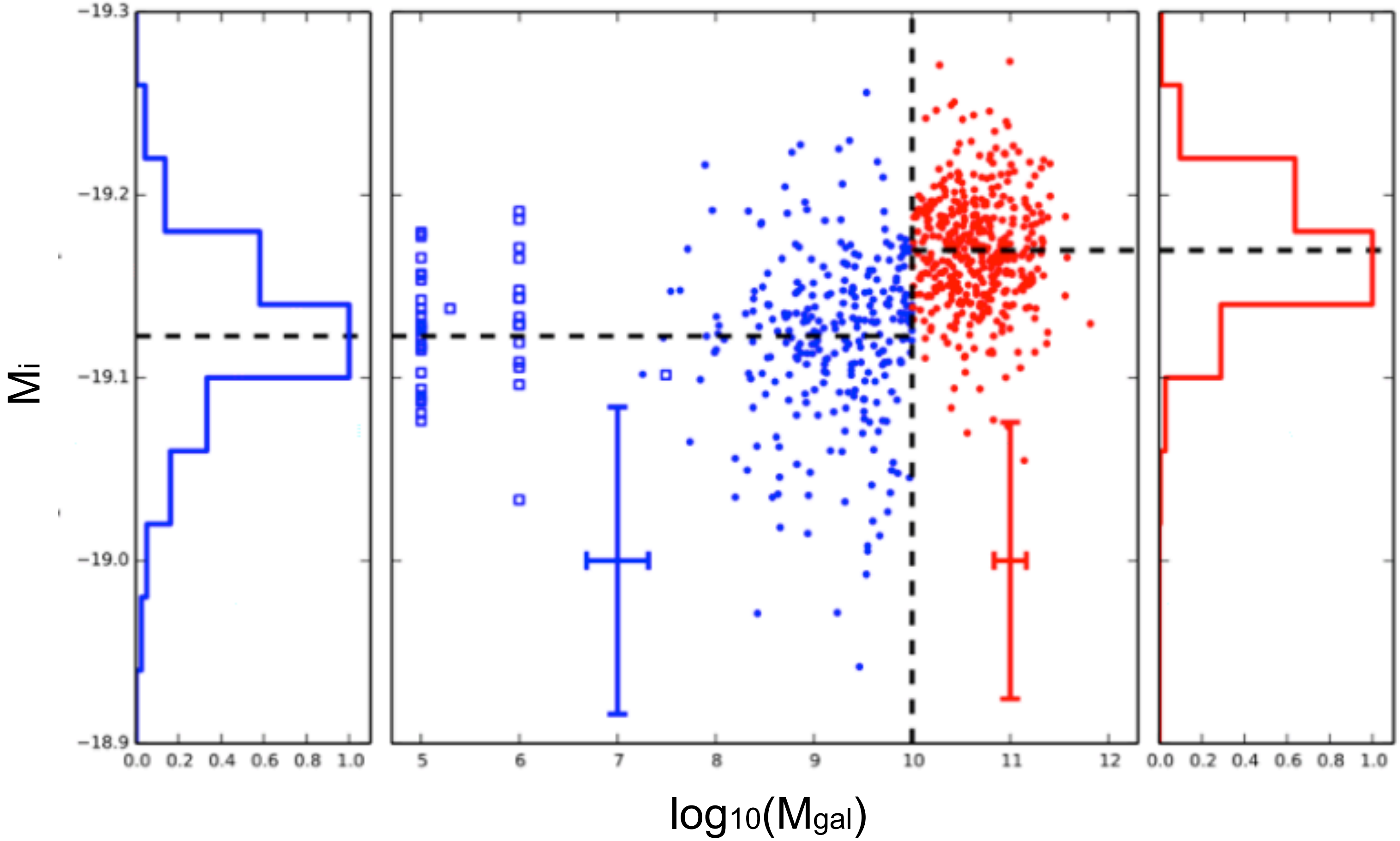
Phenomenological Extensions

I. Host Galaxy Mass

- Sullivan et al (2006) suggested using host galaxy mass as a predictor of underlying differences in the host environment (like metalicity)
- Then could use host galaxy mass as an additional empirical correction to SNIa

$$M_0 = \begin{cases} M_0 & \text{if } M_{gal} \leq 10^{10} \\ M_0 + \Delta M_0 & \text{if } M_{gal} > 10^{10} \end{cases}$$

I. Host Galaxy Mass



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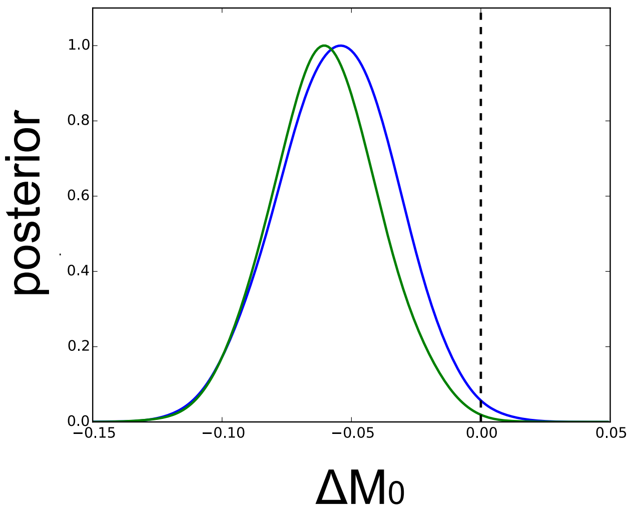
I. Host Galaxy Mass

$\Delta M_0 = -0.055 \pm 0.022$

2σ deviation from 0
Similar to previous results (eg. Rigault et al, 2015)
But cosmological posterior distributions remain the same



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II. Redshift dependence on colour

- Assume β is dependent on redshift. Assume one colour correction for low redshift data and a second for high redshift data
- A simplified equation for this evolution would be a step function

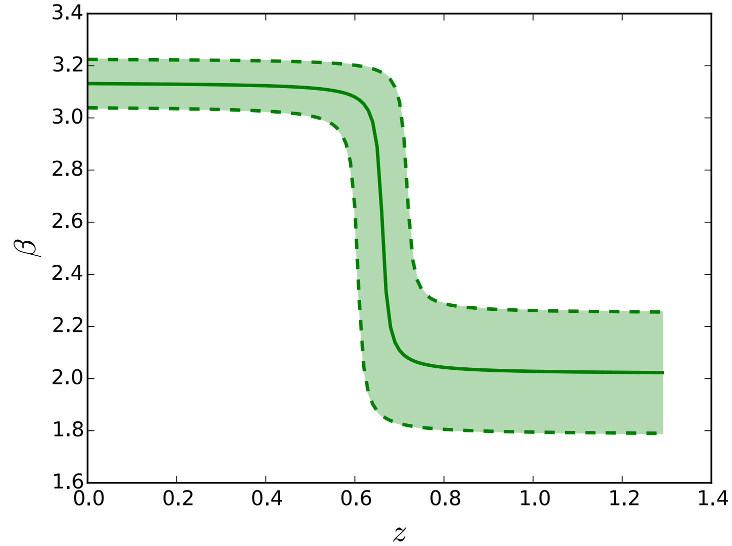
$$\beta = \begin{cases} \beta & \text{if } z \leq z_t \\ \beta + \Delta\beta & \text{if } z > z_t \end{cases}$$

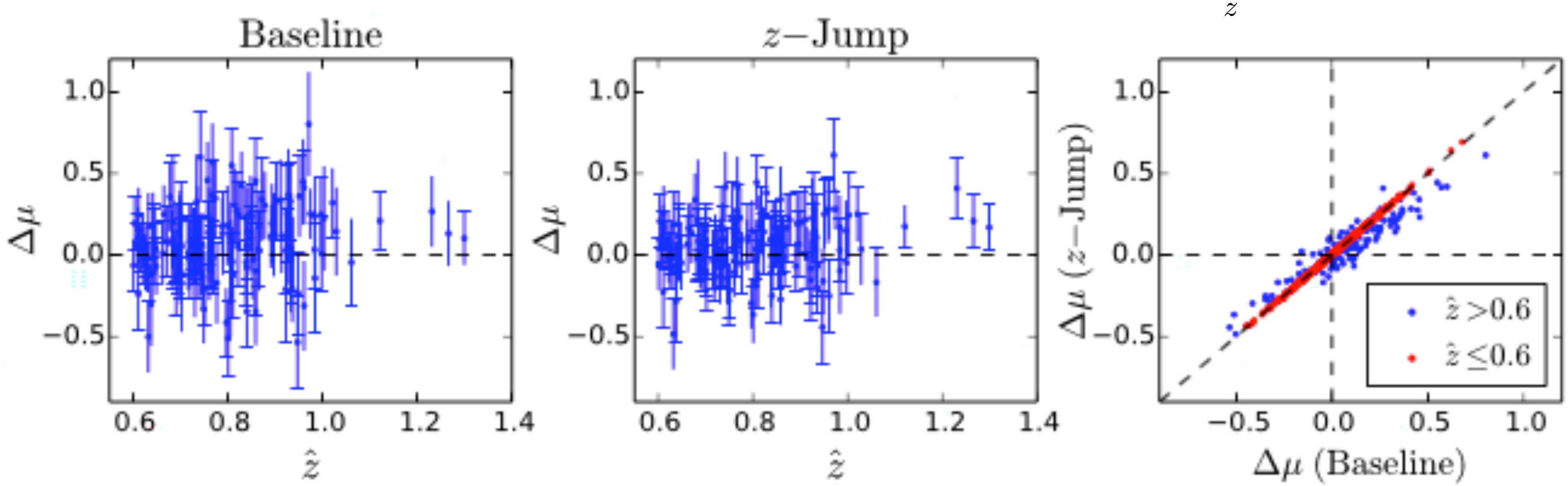
- 2 extra parameters: Δβ and z_t

II. Redshift dependence on colour

$\Delta\beta = -1.116 \pm 0.240$

4σ drop in β(z)
However, yet again, no change in cosmological parameters





Shariff et al, 2015

Conclusion

- Bayesian technique is a statistically principled approach to SNIa cosmology
- We can use this approach to find the latent distributions of the observed SNIa, for example absolute magnitude
- We find 2σ deviation with standard χ^2 analysis in cosmological parameters (Ω_m, Ω_κ and w)
- We find evidence for both host galaxy mass affecting the absolute magnitude (2σ) as well as a colour evolution with redshift (4σ)

Questions