

# Is There Evidence for Phantom Dark Energy?

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Based on:

Shafer & Huterer (2014) | [arXiv:1312.1688](https://arxiv.org/abs/1312.1688)  
Ruiz, Shafer, Huterer, & Conley (2012) | [arXiv:1207.4781](https://arxiv.org/abs/1207.4781)



# Outline

- What do we mean by “phantom” dark energy?
- What do current data tell us about the equation of state?
- Is there anything more we can learn about the standard geometric probes of dark energy?
  - Planck vs. WMAP9
  - Measurements of the Hubble constant
  - Systematics in SN Ia observations
  - Significance of detections of the BAO feature

# What is “Phantom” Dark Energy?

Phantom



Dark Energy



(when the equation of state gives in to its anger)

# What is “Phantom” Dark Energy?

A phantom menace?

Cosmological consequences of a dark energy component with  
super-negative equation of state

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~2,000 citations!

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## Abstract

It is extraordinary that a number of observations indicate that we live in a spatially flat, low matter density Universe, which is currently undergoing a period of accelerating expansion. The effort to explain this current state has focused attention on cosmological models in which the dominant component of the cosmic energy density has negative pressure, with an equation of state  $w \geq -1$ . Remarking that most observations are consistent with models right up to the  $w = -1$  or cosmological constant ( $\Lambda$ ) limit, it is natural to ask what lies on the other side, at  $w < -1$ . In this regard, we construct a toy model of a “phantom” energy component which possesses an equation of state  $w < -1$ . Such a component is found to be compatible with most classical tests of cosmology based on current data, including the recent type Ia SNe data as well as the cosmic microwave background anisotropy and mass power spectrum. If the future observations continue to allow  $w < -1$ , then barring unanticipated systematic effects, the dominant component of the cosmic energy density may be stranger than anything expected.

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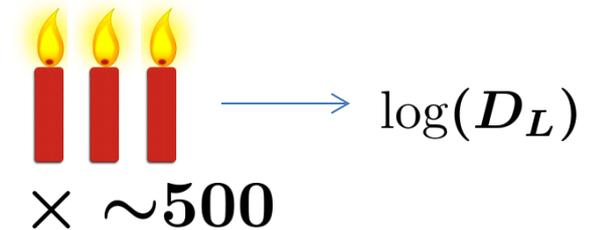
- Dark energy with  $w < -1$
- For example, negative kinetic term in the scalar field Lagrangian

# Tracking expansion history

## SNe Ia

Standard candles – measure luminosity distance to redshift of SN

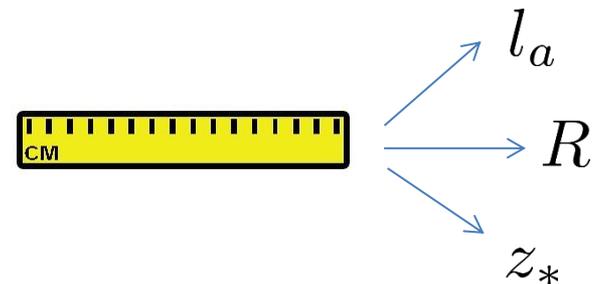
- Union2.1
- Supernova Legacy Survey (SNLS3)
- Pan-STARRS (PS1)



## CMB

Standard ruler – measure angular diameter distance to decoupling

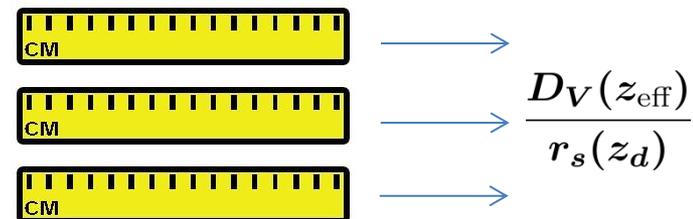
- Planck
- WMAP9



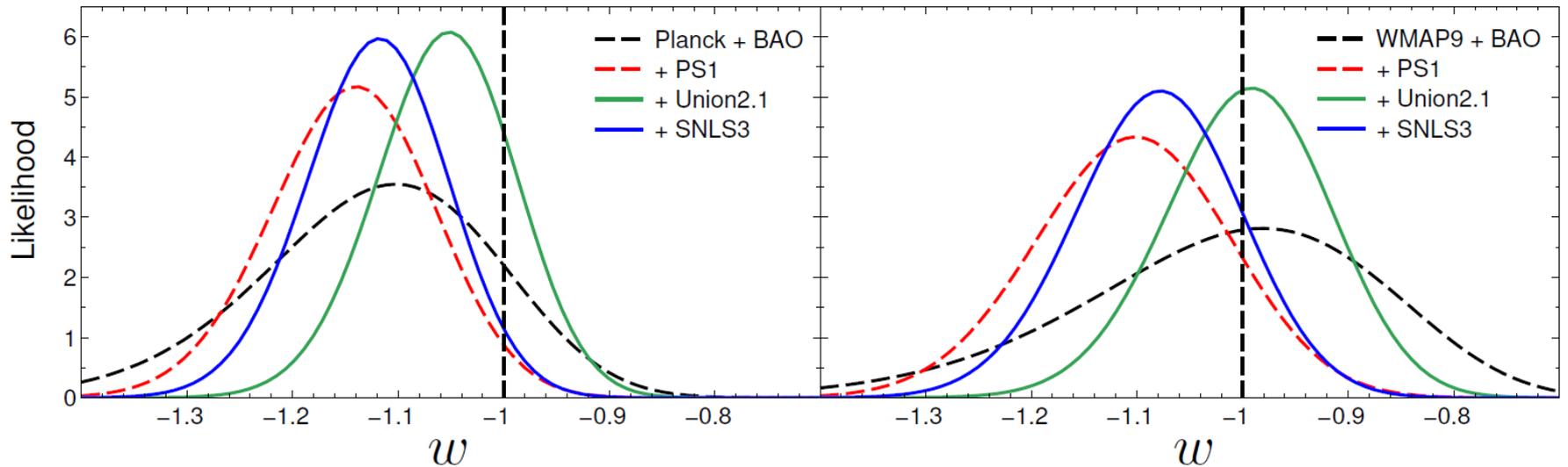
## BAO

Standard rulers – measure spherically averaged distance to effective redshift of galaxy survey

- 6dFGS –  $z_{\text{eff}} = 0.106$
- SDSS –  $z_{\text{eff}} = 0.35$
- BOSS –  $z_{\text{eff}} = 0.57$



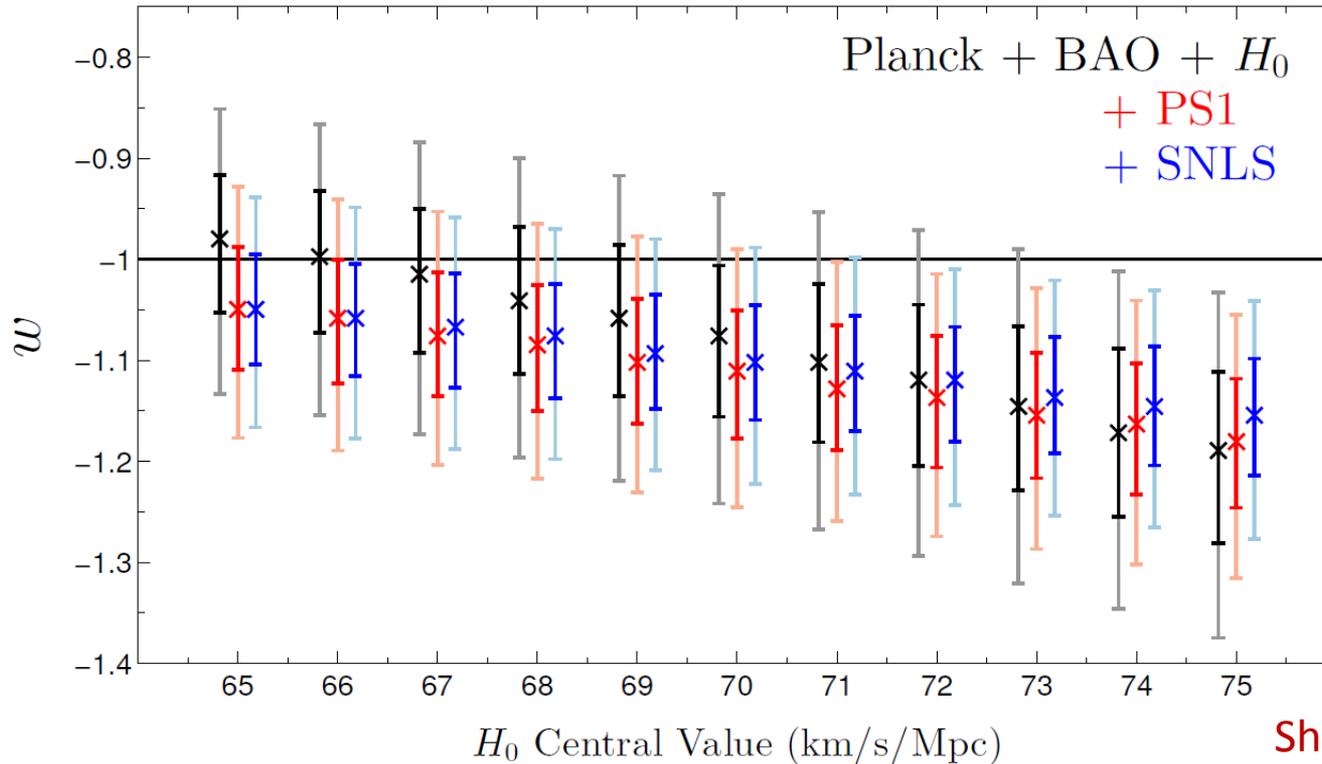
# Summary of current constraints



Shafer & Huterer (2014) | arXiv:1312.1688

- Planck visibly sharpens the likelihood peaks (the observables have errors 2–3 times smaller)
- Planck (mildly) prefers  $w < -1$
- $\sim 1.9\sigma$  with SNLS or PS1, no real preference with Union2.1

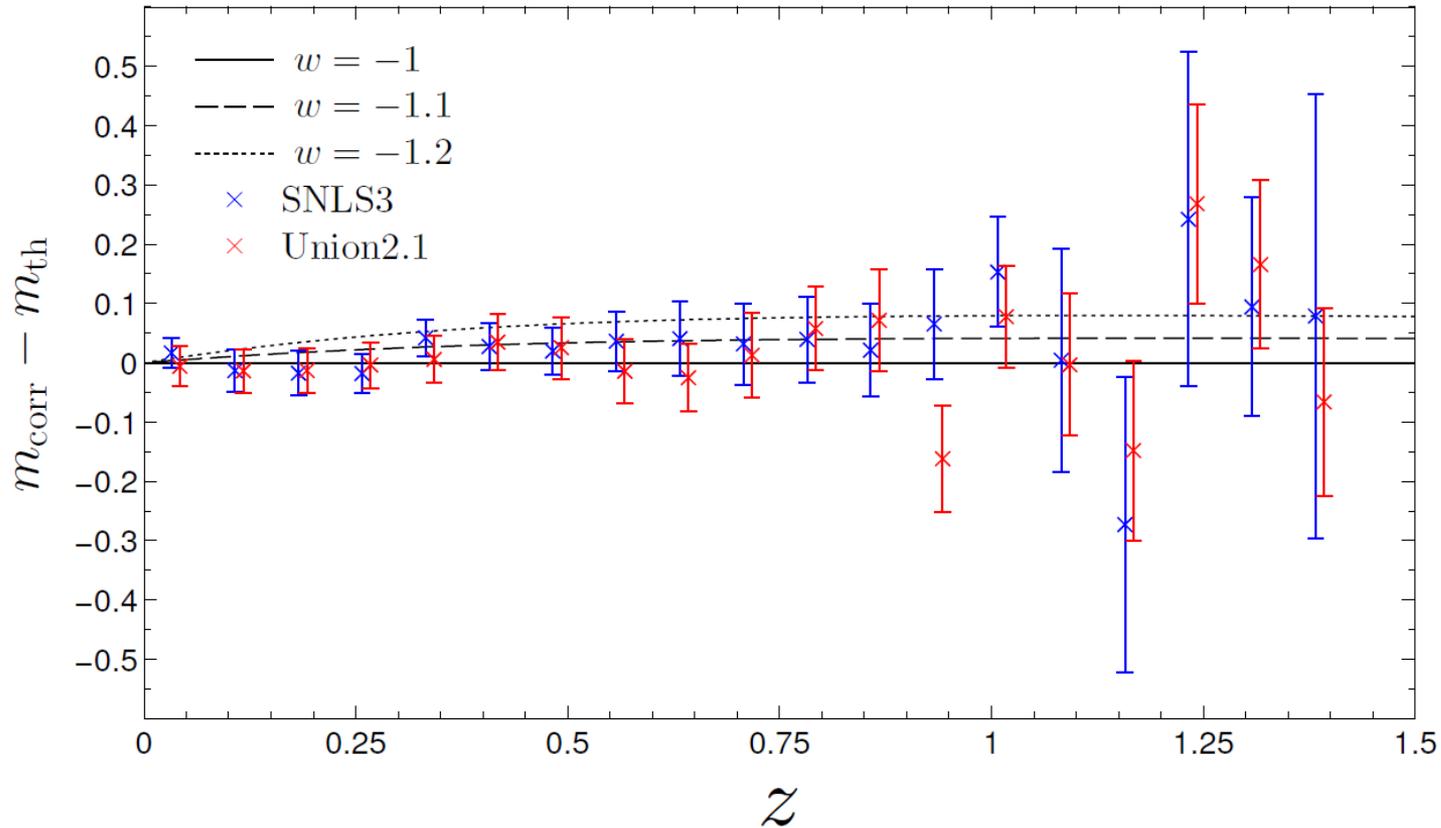
# Effect of an $H_0$ Prior



Shafer & Huterer (2014)  
arXiv:1312.1688

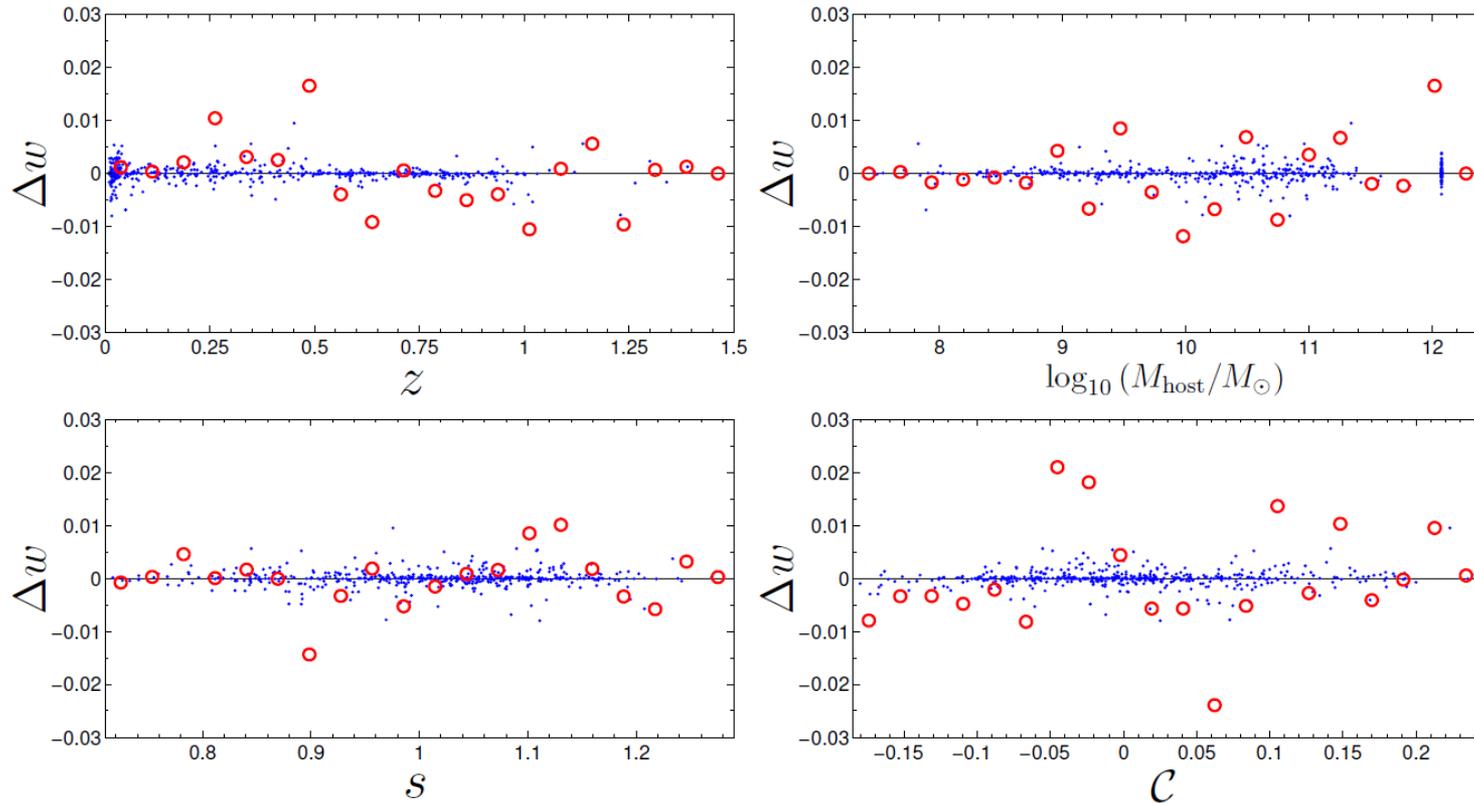
- Add a prior on  $H_0$  with the same uncertainty (2.4 km/s/Mpc) as Riess et al. (2011)
- Interesting ( $> 2\sigma$ ) only when prior is centered at  $\gtrsim 71$  km/s/Mpc

# Comparing Union2.1 and SNLS3



- Overall, remarkable *agreement* between Union2.1 and SNLS3
- Largest discrepancy at  $z \simeq 0.9$

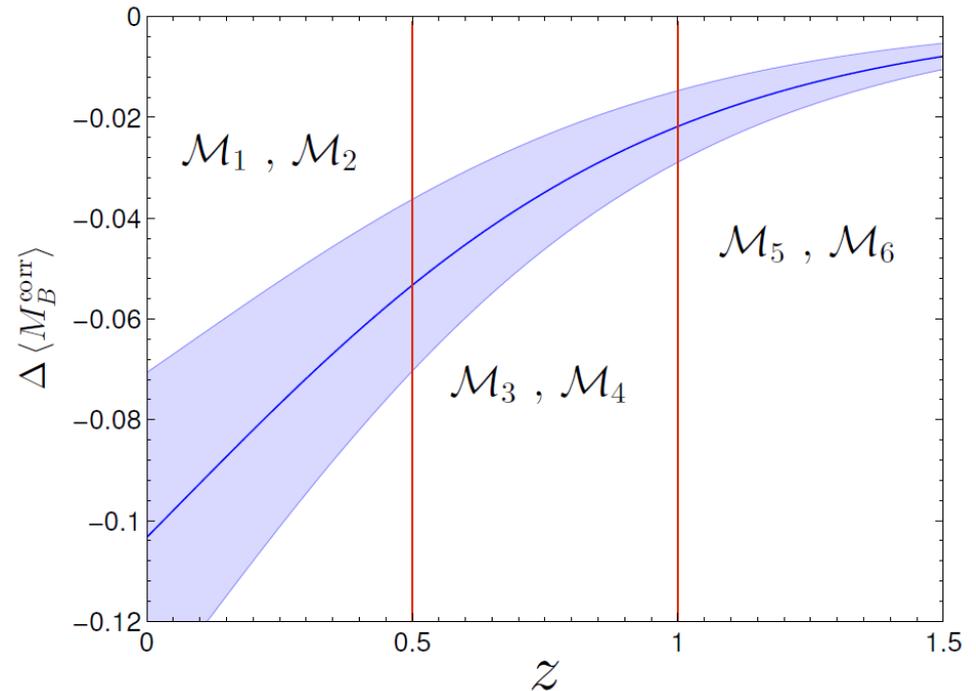
# SN Ia Scans



- Add each individual SN (from SNLS3) to the rest of the sample and compute mean equation of state from combined probes; plot as a function of SN observables
- Any trends, places of interest? Not really, but color ( $\mathcal{C}$ ) looks interesting

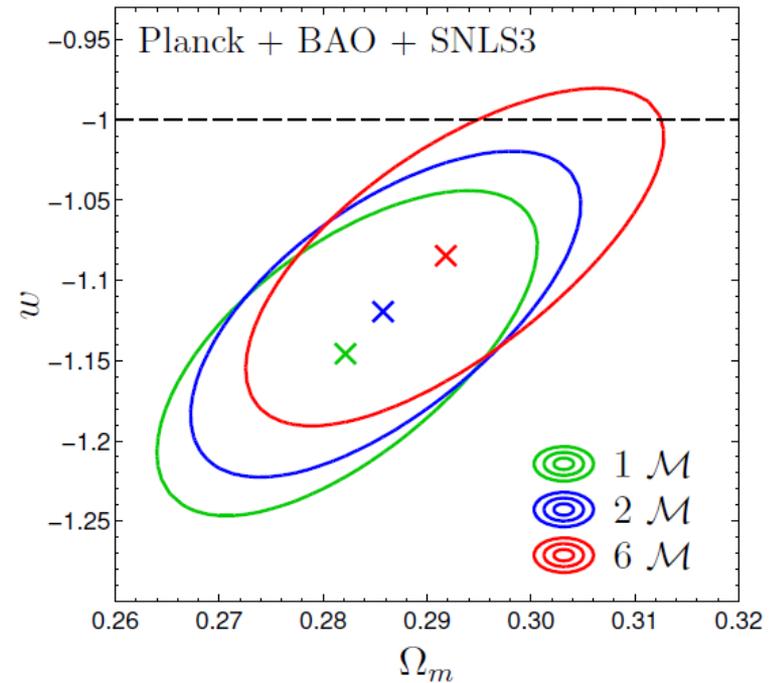
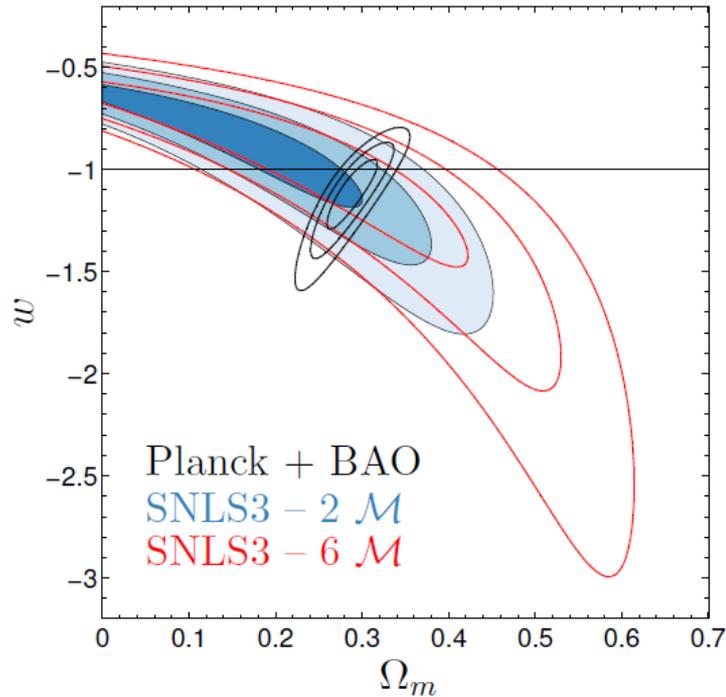
# SN Ia “Mass Step”

- Well known that peak magnitudes correlate with lightcurve properties (stretch / color)
- Strong evidence that peak magnitudes also correlate with host properties *after* lightcurve correction
- Clearest effect is a “mass step” where SNe Ia in high-mass hosts are brighter, on average



- Rigault et al. (2013): evidence that local star formation rate is responsible for mass step
- Bad news, since SFR surely evolves with redshift! Can we protect ourselves from this systematic?

# SN Ia “Mass Step”



Shafer & Huterer (2014) | arXiv:1312.1688

- Simply allowing some freedom for redshift evolution of the absolute magnitude and mass step shifts constraints on the equation of state
- Surprisingly small increase in error for combined probes!

# BAO Finite Detection Significance

- Bassett & Afshordi (2010): For marginal detections, a Gaussian likelihood is not a good approximation far from the peak. What if the feature was not actually detected?

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

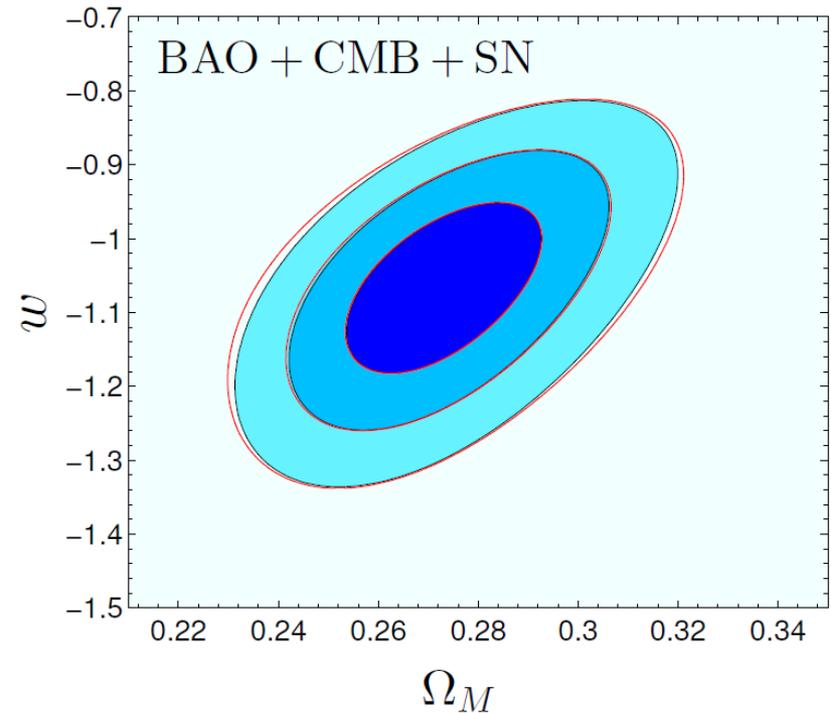
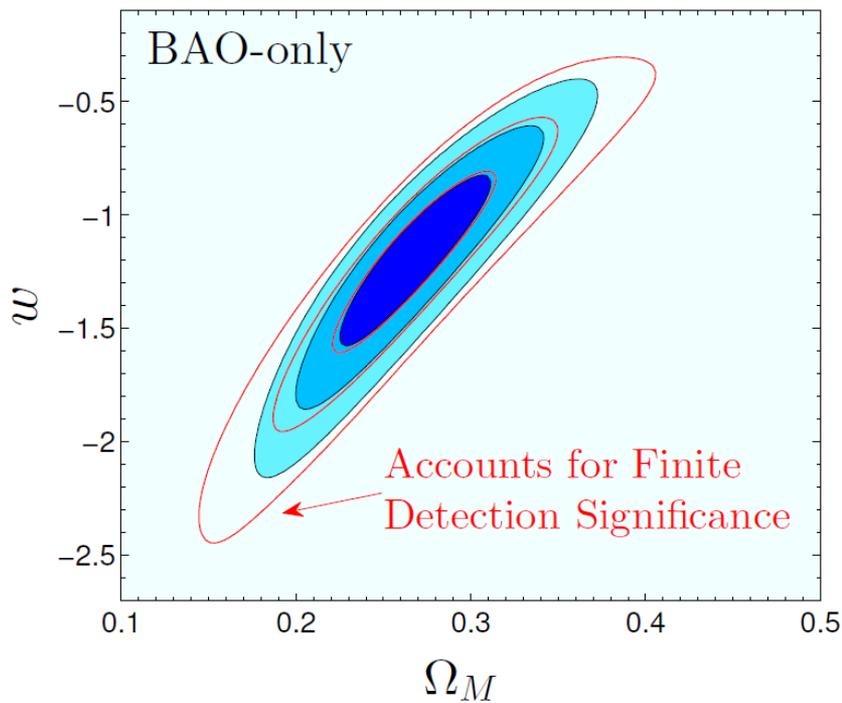
- Fitting function to approximate the correct likelihood:

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

Sensible limits:

- $\Delta\chi^2 = \Delta\chi_G^2$  for small (compared to signal-to-noise) departures from the best-fit model
- Asymptotes to a constant “tail”  $(S/N)^2$  when  $\Delta\chi_G^2 \gg (S/N)^2$

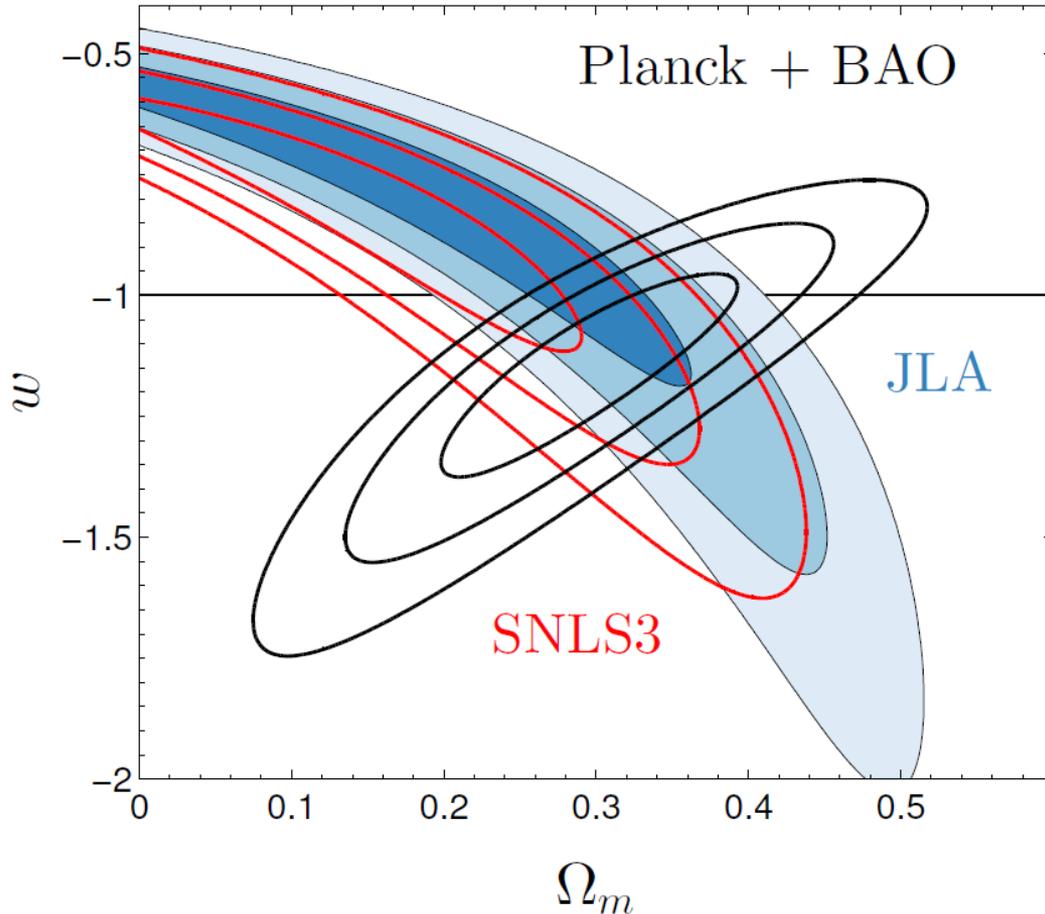
# BAO Finite Detection Significance



Ruiz, Shafer, Huterer, & Conley (2012) | arXiv:1207.4781

- Significance of BAO feature detection (units of  $\sigma$ , or S/N):  
6dFGS = 2.4 | WiggleZ = 2.8 | SDSS = 3.6 | BOSS = 5.0
- Correction is modest for BAO-only constraints but negligible for combined

# Updated SNLS/SDSS sample



- Newer SN Ia data from Betoule et al. (2014)
- Joint Likelihood Analysis (JLA) with final SDSS sample and recalibrated SNLS3 sample
- JLA + Planck + BAO yields:

$$w = -1.032^{+0.048}_{-0.055}$$

# Take Home

- Some current observations provide modest ( $\sim 2-2.5\sigma$ ) evidence for a phantom equation of state with  $w < -1$ 
  - Newest SNLS/SDSS analysis is consistent with  $\Lambda$
  - Tension remains for Planck + BAO + PS1 +  $H_0$
- Even the mature geometric probes of dark energy, particularly SNe Ia, have potential systematics that are very important at current levels of precision
- Work in the near future should help clear things up:
  - SN Ia calibration and other systematics control
  - Updated data and analysis from Planck
  - 1% local measurements of the Hubble constant