Cosmological Tests with SN Ia and Galaxy Velocities

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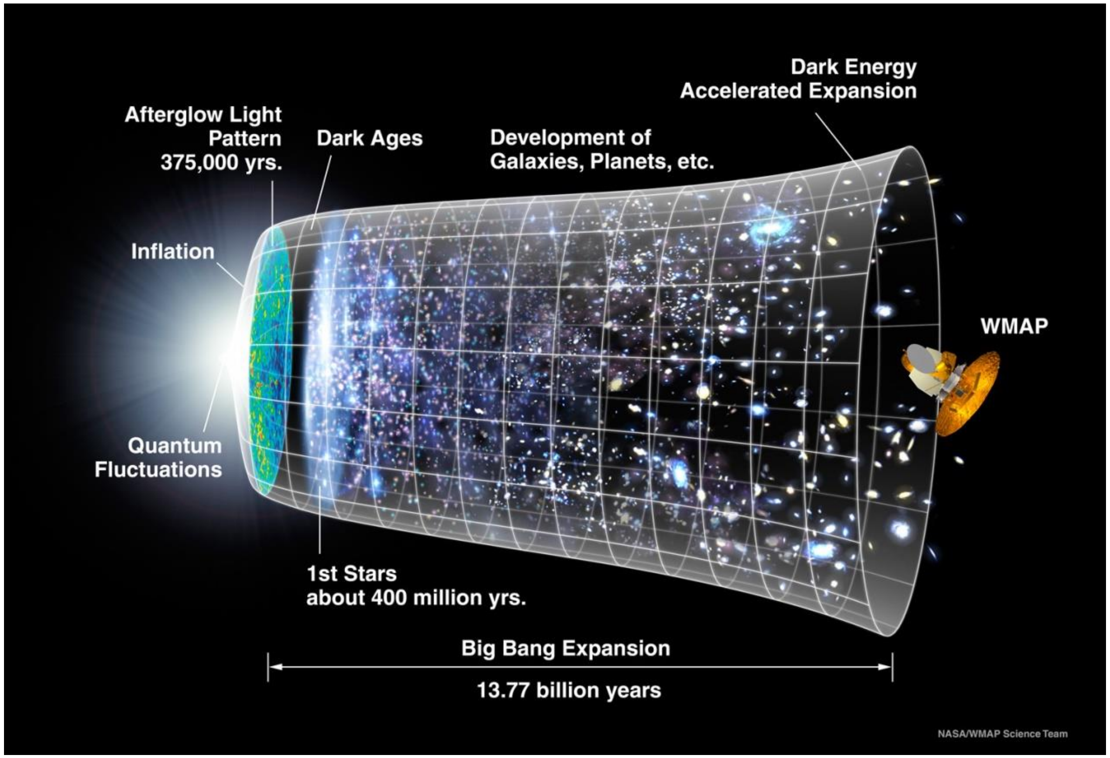
ΛCDM model: the whole story?



From *Planck* CMB power spectra only:

$\Omega_b h^2$ – 0.7 %
$\Omega_c h^2$ – 1.3 %
H_0 – 1 %
n_s – 0.5 %
A_s – 1.1 %
τ – 22 %

(Ade et al. 2015)

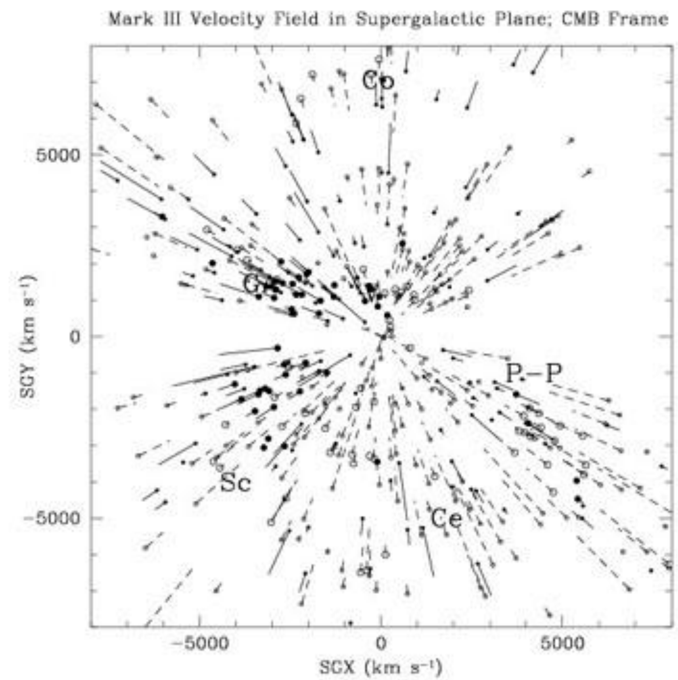
- Most other cosmological data is consistent with this picture, even if some tensions are arising (e.g. local Hubble constant, Ω_m- σ_8 plane)
- Have a robust model that's (almost) fully specified – Look for ways to break it!

Where to look?

At $z \lesssim 0.1$, **peculiar velocity (PV)** measurements are clearly a test of the entire cosmological model.

This includes geometry, growth of structure, primordial power spectrum, and so on.

Peculiar velocities



- A mature subject
  (e.g. Gorski et al. 1989, Willick & Strauss 1995, Hui & Greene 2005, Johnson et al. 2014)
- How to measure velocities?

  Basic idea:

  We only observe one redshift per object,

$$(1 + z_{\rm obs}) = (1 + \bar{z})\,(1 + v_{{\rm pec},\parallel}/c)$$

  But if we can measure distance *d* independently,

$$c\,\bar{z} \approx H_0\,d \quad (z \ll 1)$$

- Signal-to-noise is typically less than unity – need many objects

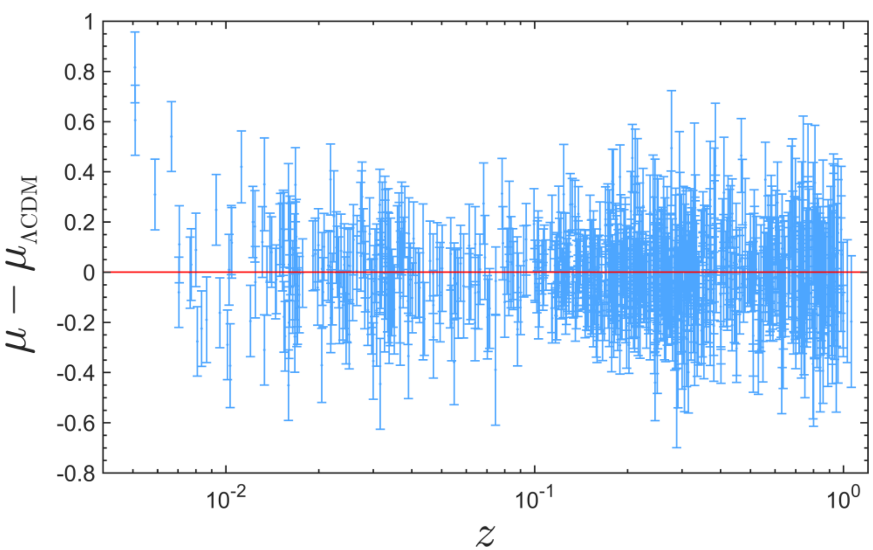
$$\mathrm{S/N} \approx v_\parallel/(cz\sigma_{\ln d})$$

"Supercal" compilation of SNe Ia

SNe Ia – standard(-izable) candles; distances with 7-10% precision, after correcting for light-curve width and color relations:

$$\mu \equiv 5\log_{10} d_L = m_{\rm obs} + \alpha s - \beta c - \mathcal{M}$$

- "Supercal" analysis: previous SN samples (PS1, SNLS, SDSS, CSP, CfA 1-4) recalibrated using the Pan-STARRS system (Scolnic et al. 2015)
  - 208 SNe at $z < 0.1$
  - The most careful treatment, especially of the low-z samples, to date



6dFGS fundamental plane sample

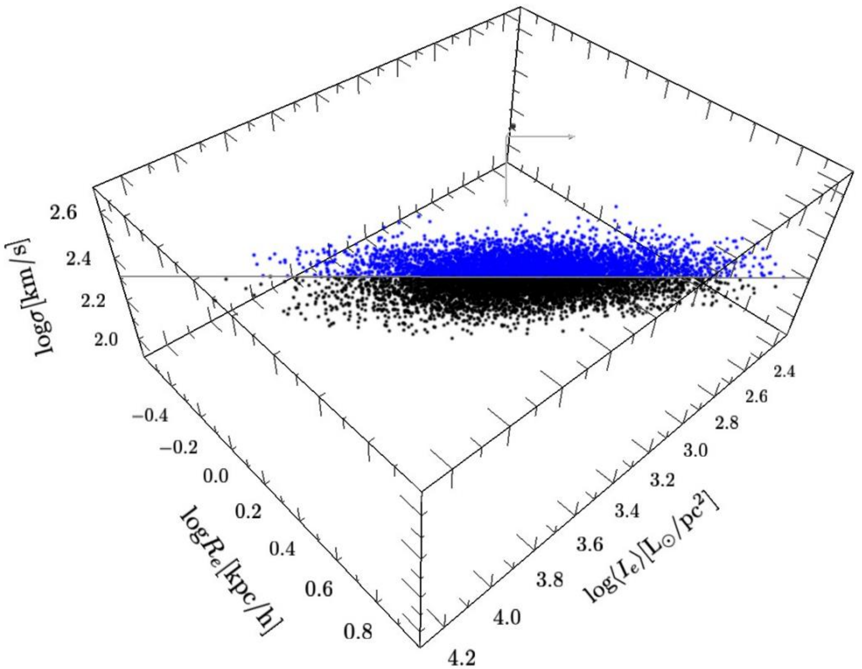
Fundamental plane (elliptical galaxies) – a relation between (logarithms of) physical radius, surface brightness, and central velocity dispersion:

$$r \equiv r_{\rm ang} + \log_{10} d_A = as + bi + c$$

(Distances to $\sim 25\%$)

6dFGS sample:

- 8885 galaxies ($z < 0.055$)
- Near-infrared photometry from 2MASS (*J*, *H*, *K* bands)
- Distances derived from a maximum-likelihood fit, using a 3D Gaussian model for the *J*-band FP (Springob et al. 2014)



(Magoulas et al. 2012)

A simple and direct approach…

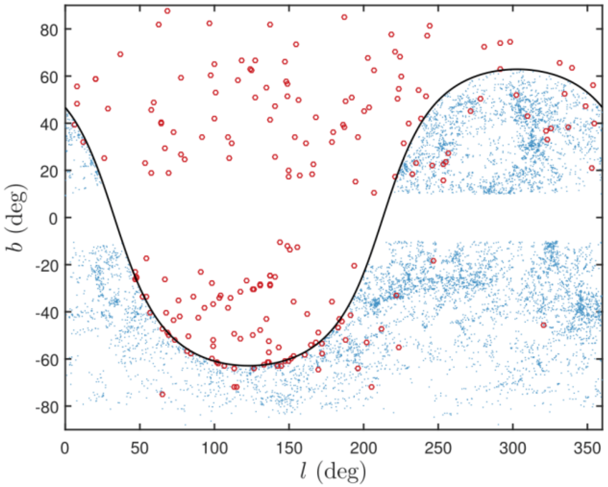
Define a "signal" contribution to the covariance matrix of distance residuals

$$S_{ij} \equiv \langle \Delta m_i \, \Delta m_j \rangle = \left[\frac{5}{\ln 10}\right]^2 \frac{(1+z_i)^2}{H(z_i) d_L(z_i)} \frac{(1+z_j)^2}{H(z_j) d_L(z_j)} \xi_{ij}^{\mathrm{vel}}$$

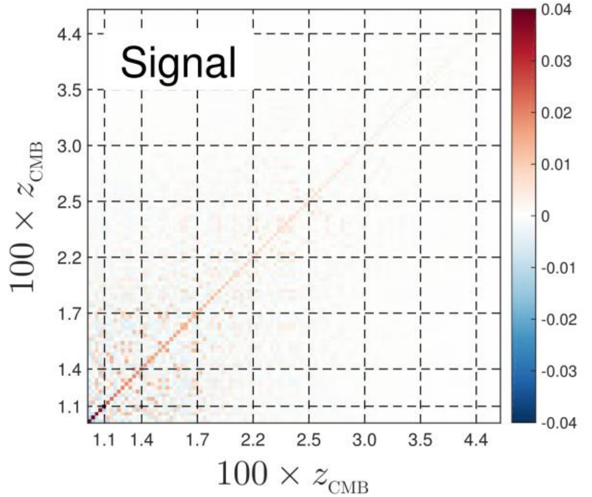
$$\mathcal{L}(A) \propto \frac{1}{\sqrt{|\mathbf{C}|}} \exp\left[-\frac{1}{2} \mathbf{\Delta m}^{\intercal} \mathbf{C}^{-1} \mathbf{\Delta m}\right]$$

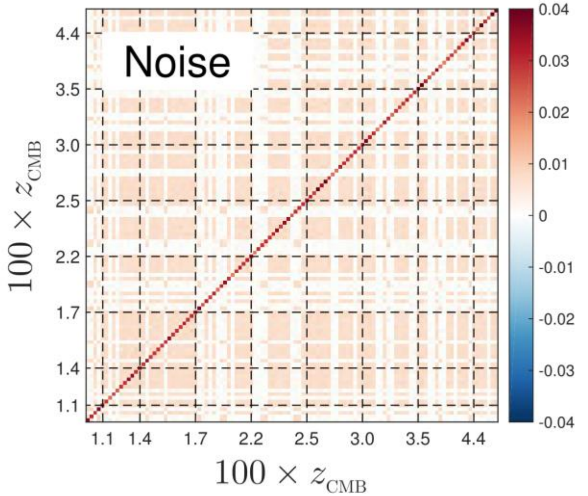
$$\mathbf{C} = A\,\mathbf{S} + \mathbf{N}$$

Constrain the amplitude *A* of the signal covariance in the presence of the noise contribution **N**. Is *A* consistent with one, different from zero?



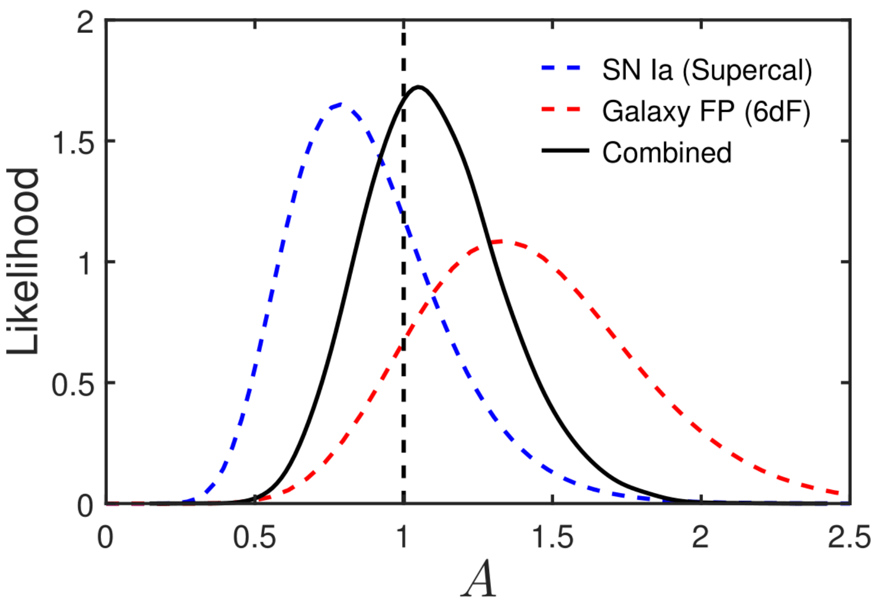
SNe (red), Galaxies (blue)





(Huterer, DLS, Schmidt | arXiv:1509.04708)

Results: constraints on the signal amplitude



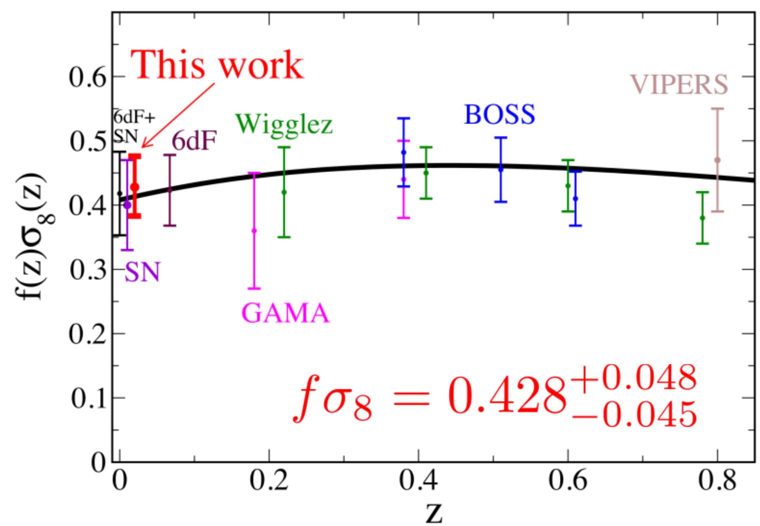
- Fiducial model $(A = 1)$

  $$\Omega_m = 0.3,\ \sigma_8 = 0.8$$

- Important: Always marginalize over intrinsic scatter(s) and distance offset(s).

- With other parameters fixed, $A \propto (f\sigma_8)^2$

- The effective redshift of the constraint is $z \approx 0.02$, the $\left({}^{S}/_{N}\right)^2$-weighted mean

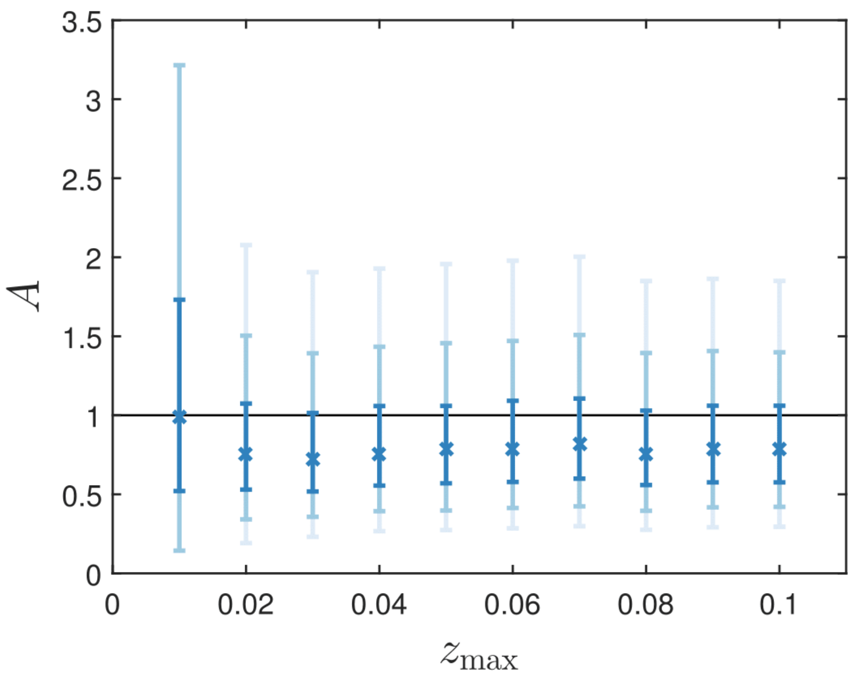


(Huterer, DLS, Scolnic, Schmidt |arXiv:1611.09862)

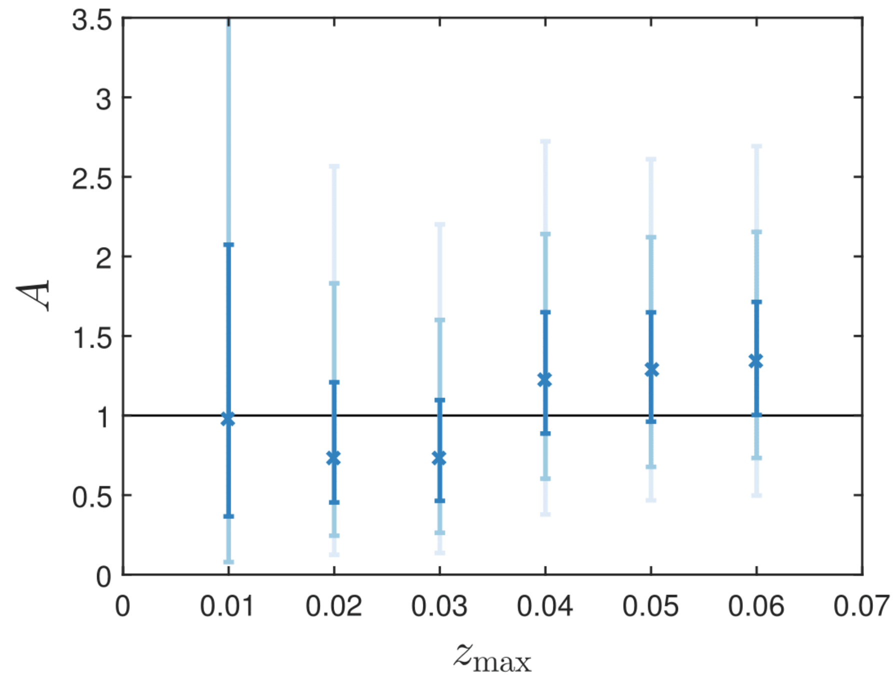
Systematics?

Does varying the maximum redshift shift the constraint on *A* significantly?

SNe Ia



Galaxies



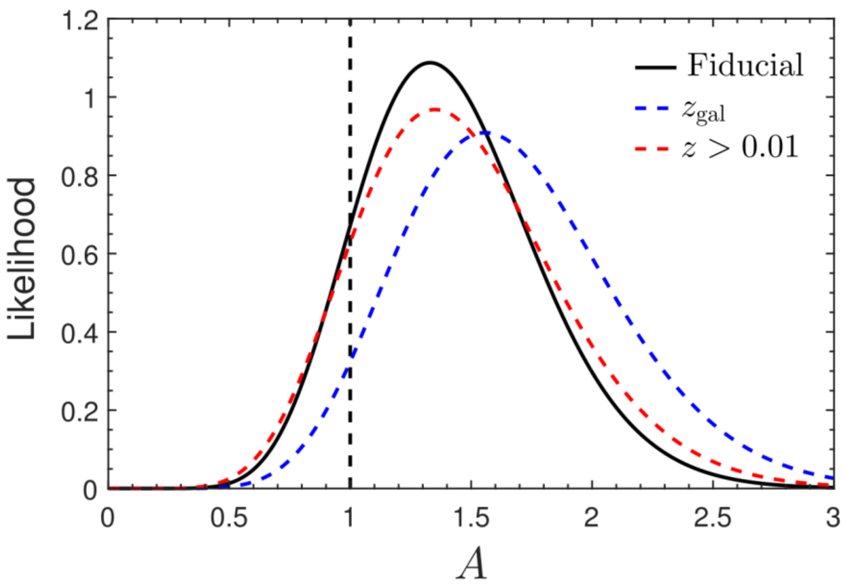
…and more Systematics!

Does removing the $z < 0.01$ objects affect the constraint?

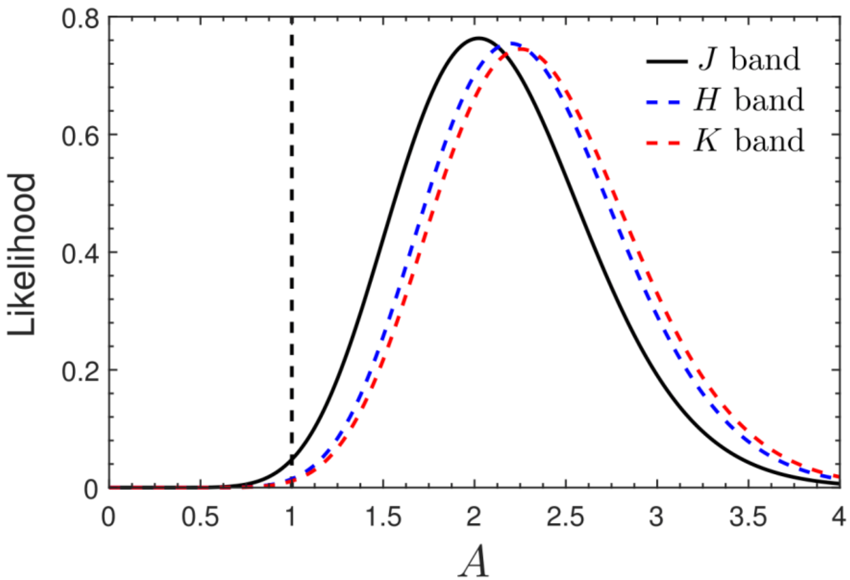
What about using galaxy redshifts instead of group redshifts?

Does it matter which photometric band is used to define the FP?

Galaxies



Galaxies



Summary

- Constraints on the amplitude A of the PV signal covariance matrix serve as a test of the full cosmological model.
- Results for SNe, galaxies, and their combination are consistent with the fiducial ΛCDM model (effectively constrain $f\sigma_8$ to 11%).
- Results are fairly robust to variations in the analysis, though one could still worry about systematic effects (e.g. modeling of FP).
- Upcoming surveys (e.g. LSST, new low-*z* SN surveys) should facilitate a much more stringent test.