Model-independant test of the FLRW metric, the curvature, and non-local measurement of $H_0$

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Introduction

Metric of the Universe and flatness

- Cosmological model: flat-$\Lambda$CDM Universe
- Assumption: Homogeneity, isotropy, GR
- Solution to the Einstein equations: Friedmann-Lemaître-Robertson-Walker (FRLW) metric
- Necessary to test the metric

$H_0$

- Fundamental cosmological parameter
- Disagreement:
  - $H_0 \approx 67$ km/s/Mpc (Planck, 6dFGS)
  - $H_0 \approx 73$ km/s/Mpc (WMAP, Cepheids (Riess))
FRLW metric

In a FLRW Universe, the luminosity distance is defined as

\[ d_L(z) = \frac{c}{H_0} \frac{(1+z)}{\sqrt{-\Omega_k}} \sin \left( \sqrt{-\Omega_k} \int_0^z \frac{dz'}{h(z')} \right), \tag{1} \]

where

\[ h^2(z) = \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_{DE} \exp \left( 3 \int_0^z \frac{1+w(z')}{1+z'} dz' \right) \tag{2} \]

for a FLRW universe where the equation of state of dark energy is \( w(z) = P/\rho \).

Relations between distances:

\[ d_L(z) = (1+z) \frac{c}{H_0} D(z) = (1+z)^2 d_A(z) \tag{3} \]
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   - Iterative smoothing

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Testing the metric and flatness

Metric test: the $O_k$ parameter (Clarkson et al. 2008)

\[ O_k(z) = \left( \frac{\left( \frac{H(z)D'(z)}{H_0} \right)^2}{D^2(z)} \right) - 1 \]  

- $O_k(z) = \text{Cst}$ for FLRW Universe
- $O_k(z) = 0$ for flat-FLRW Universe
- Need $H(z), H_0, D(z),$ and $D'(z)$
- $H(z)$ from BAO
- $DD, DD'(z)$ from supernovae
Iterative smoothing (Shafieloo et al. 2006, Shafieloo 2007)

- Distance modulus $\mu(z_i)$
- Non-parametric, model-independent method
- Iterative smoothing with log-normal kernel
- Start with initial (parametric) guess: (for instance best-fit flat-$\Lambda$CDM) $\hat{\mu}_0(z)$

\[
\hat{\mu}_{n+1}(z) = \hat{\mu}_n(z) + N(z) \sum_i \left( \frac{\mu(z_i) - \hat{\mu}_n(z_i)}{\sigma_i^2} \exp \left( - \frac{\ln^2 \left( \frac{1+z_i}{1+z} \right)}{2\Delta^2} \right) \right), \tag{5}
\]

- Keep all reconstructions with $\chi^2 < \chi^2_{\text{flat } \Lambda\text{CDM}}$

where $N^{-1}(z) = \sum_i (1/\sigma_i^2 \exp (-\ln^2 ((1 + z_i)/(1 + z))/2\Delta^2))$, is a normalisation factor, and

$z_i$: input redshift  
$z$: any redshift

We obtain $\frac{H_0}{c} d_L(z) = (1 + z) \mathcal{D}(z)$

$\mathcal{D}'(z)$: Numerical derivation

$\Delta = 0.3$: smoothing scale
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   - Metric test
   - Measurement of $H_0$
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Distance reconstruction

All lines have a better $\chi^2$ to the JLA $\mu(z_i)$ than the best-fit flat-\Lambda CDM model
Metric test

\[ \Theta(z) = \frac{H(z)D'(z)}{H_0} \]

\[ O_k(z) = \left( \frac{\left(\frac{H(z)D'(z)}{H_0}\right)^2 - 1}{D^2(z)} \right) \]

- \( H(z) \) from BAO (Cuesta et al 2016)
- \( D(z), D'(z) \) from JLA supernovae (Betoule et al. 2014)
- Two different (local) \( H_0 \): Rigault et al (2015), Riess et al. (2016)
- **Consistent with a flat Universe!**
Model-independent measurement of $H_0$

L’Huillier & Shafieloo, arXiv:1606.06832

- $H(z), d_A(z)$ from BAO (BOSS, Cuesta et al 2016)
- $h(z) = 1/D'(z), D(z)$: model-independently reconstructed from supernovae (JLA, Betoule et al 2014)
- $H_0 r_d = (10077.64 \pm 347.41) \, \text{km s}^{-1}$
- Assuming $r_d = 147.1 \, \text{Mpc}$, we find $H_0 = (68.51 \pm 2.36) \, \text{km s}^{-1} \, \text{Mpc}^{-1}$. 
Summary

- Model-independent test of the FLRW metric and the flatness of the Universe: Compatible with a flat-FLRW metric
- Model-independent measurement of $H_0 r_d = (10,077.64 \pm 347.41) \text{ km s}^{-1}$
- Assuming $r_d = 147.1 \text{ Mpc}$, we find $H_0 = (68.51 \pm 2.36) \text{ km s}^{-1} \text{ km}^{-1}$.
- Compatible with Planck and 6dFGS *without using CMB data*
- Future surveys (like DESI) will bring down the error-bars