Measuring the speed of light with Baryon Acoustic Oscillations

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Vincenzo Salzano

Cosmology Group, Institute of Physics - University of Szczecin

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Baryon Acoustic Oscillations

- Potentially very powerful tool to constrain Universe dynamics
  - well known and controlled systematics errors
  - limited by statistical errors (need many observed galaxies)
  - link between early and late time epochs
- Primary objective of many future surveys
  - **SKA**, **Euclid**
  - now: precise, but not at its best

$$D_V = \left[(1+z)^2 c\, z \frac{D_A^2}{H} \right]^{1/3}, \; F = (1+z) D_A \, \frac{H}{c}$$

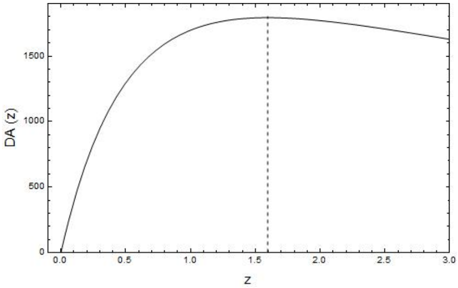
  - $> 10^7$ galaxies observed to have tenth of data points, but very precise
  - disentangling radial and tangential modes optimized:

$$y_t = \frac{D_A}{r_s} \quad ; \quad y_r = \frac{c}{H\, r_s}$$

with r_s sound horizon at decoupling (dragging) epoch

Method: let's start from this, to show what we want to do and how...

- D_A (tangential mode) has a maximum at z_M



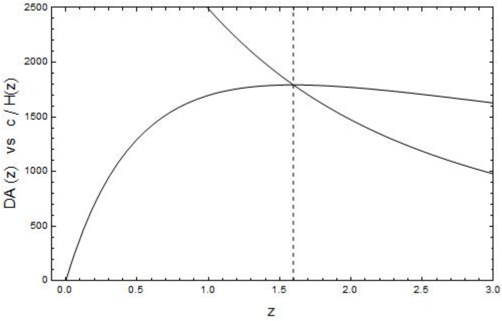
- How to find the maximum?
- Using only D_A is problematic:
  - very flat around z_M
  - binned data
  - observational errors and instrinsic dispersion
- All three combine to smear the maximum detection

Method: let's start from this, to show what we want to do and how...

- Condition for the maximum at z_M (provided FRW and $k = 0$):

$$\frac{\partial D_A}{\partial z} = 0 \quad \Rightarrow \quad D_A(z_M) = \frac{c}{H(z_M)} \quad \Leftrightarrow \quad y_t(z_M) = y_r(z_M)$$

- we can combine y_t and y_r to find the maximum



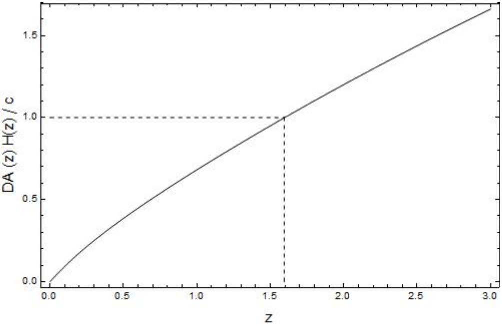
- **y_t and y_r are given by data, no model assumption!**

Method: let's start from this, to show what we want to do and how. . .

- once you have z_M you can try **measure** c:

$$D_A(z_M)\, H(z_M) = c \;\Leftrightarrow\; D_A(z_M)\,\frac{H(z_M)}{c} = 1 \;\Leftrightarrow\; y_t(z_M)\, y_r^{-1}(z_M) = 1$$

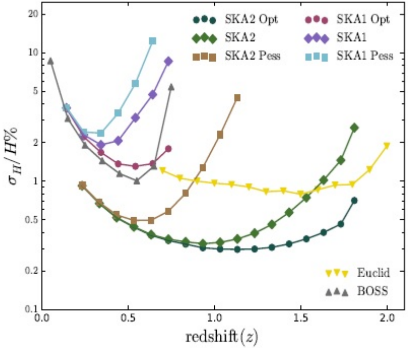
- **$D_A \cdot H$ at z_M is unequivocally equal to the speed of light c**

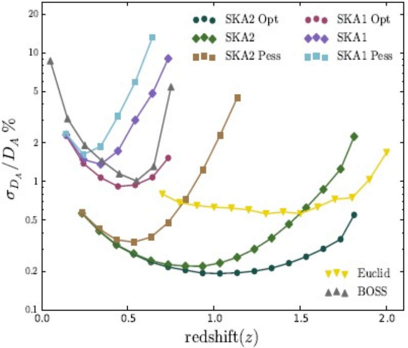


- Our method: data $\Rightarrow z_M \Rightarrow c$ - to be optimized!

How to implement this?

- We need both observational y_t and y_r
- Font-Ribera et al. 2014: forecast percentage errors on y_t and y_r; best performance: *Euclid*
- Yahya et al. 2015: forecast percentage errors on y_t and y_r for SKA





How to implement this?

- Fiducial cosmological model - ΛCDM from *Planck 2015 (PLA)*: `base_plikHM_TTTEEE_lowTEB_lensing_post_BAO`

$$\{H_0 = 67.651,\ \Omega_m = 0.31,\ w_0 = -1,\ w_a = 0\} \quad \Rightarrow \quad \left\{y_t^{fid}(z),\ y_r^{fid}(z)\right\}$$

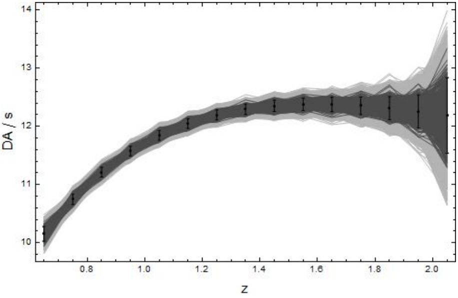
$$H(z) = H_0\,\sqrt{\Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_\Lambda}$$

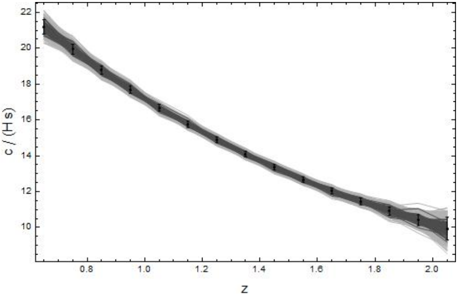
$$D_A(z) = \frac{1}{1+z}\int_0^z \frac{c}{H(z')}\,d\,z' \qquad\qquad r_s(z_{rec}) = \int_{z_{rec}}^{\infty} \frac{c\cdot c_s(z')}{H(z')}\,d\,z'$$

- Given y_t^{fid} and y_r^{fid} $\Rightarrow$ errors, σ_{y_t} and σ_{y_r}
- y_t and y_r have correlation coefficient $\rho \simeq 0.4$ (Seo & Eisenstein 2007)
- at each redshift z_i, we pick up $y_t(z_i)$ and $y_r(z_i)$ from a multivariate normal distribution centered on y_t^{fid} and y_r^{fid} and covariance matrix given by σ_{y_t}, σ_{y_r} and ρ

How to implement this?

- we cannot rely on only 1 simulation: 10^3 simulations
- our results will be on an ensemble of Universes (statistical)





We measure c but we are mainly interested in deviation from c

- Fiducial model plus varying speed of light (VSL) theory:
  - minimal coupling between VSL and matter (Barrow & Magueijo 1998)
  - if there is no curvature (*Planck 2015*: $\Omega_k = 0.000 \pm 0.005$ at 95%)

$$D_A = \int_0^z \frac{c(z')}{H(z')}\, d\, z' \qquad r_s(z_{rec}) = \int_{z_{rec}}^{\infty} \frac{c(z') \cdot c_s(z')}{H(z')}\, d\, z'$$

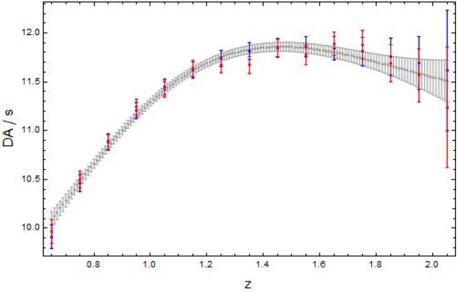
- $D_A(z_M)\; H(z_M) = c \quad \Rightarrow \quad D_A(z_M)\; H(z_M) = c(z_M)$
- Magueijo 2003:

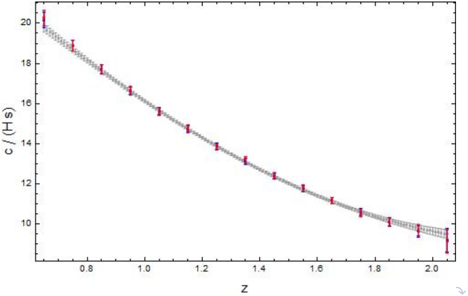
$$c(a) \propto c_0 \left(1 + \frac{a}{a_c}\right)^n \quad with \quad a = \frac{1}{1+z} \quad and \quad c_0 \equiv c$$

  - $a = 0.05,\ n = -0.001 \Rightarrow \Delta c / c_0 \approx 0.1\%$ at $z \approx 1.5 - 1.6$ ($\Omega_m = 0.314$)
  - $a = 0.05,\ n = -0.01 \Rightarrow \Delta c / c_0 \approx 1\%$ at $z \approx 1.5 - 1.6$ ($\Omega_m = 0.348$)
- no fit, but consistency check with ΛCDM using *Planck 2015* sound horizon, and WiggleZ and BOSS D_A and H

How to find z_M in a "cosmologically-independent" way?

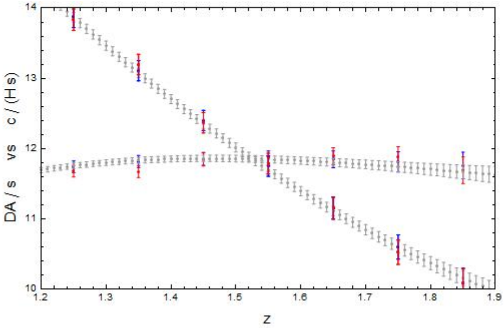
- reconstruction of D_A and H: Gaussian Processes (GP) (Seikel et al. 2012, Seikel & Clarkson 2013):
  - no preliminary information about D_A and H
  - basic but very general assumptions in some step
  - data are Gaussian distributed and Gaussian correlated (quite real)
- inputs: - only - data and errors
- output: smooth function (evaluated at whatever value one needs)





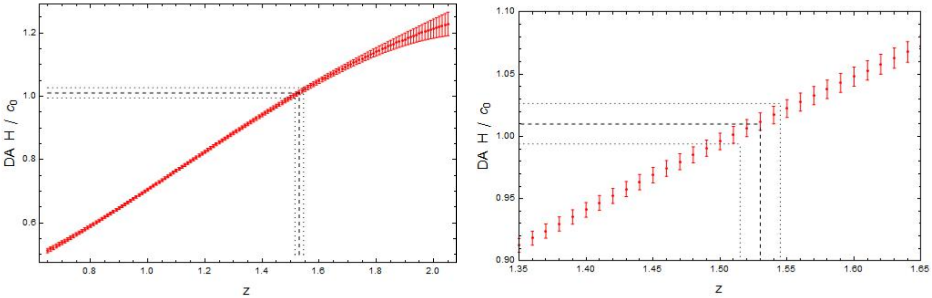
How to find z_M in a "cosmologically-independent" way?

- numerical methods to find z_M; polynomial interpolation of D_A and H



- how to determine the error on z_M:
  - pick up random values of D_A an H in the $[-4\sigma, 4\sigma]$ range
  - combine all the "trajectories" $\Rightarrow$ each one with its own z_M weighted by the multivariate normal distributions used to generate data
  - end up with a discrete distribution of $z_M \Rightarrow$ statistics: $z_M \pm \sigma_{z_M}$

Finally calculate the quantity $D_A(z_M) \cdot H(z_M)$ plot to calculate $c(z_M)$



The precision in constraining c depends on:

- mostly: error σ_{z_M}, which depends on observational errors on D_A and H
  - z_M lies in the redshift range $[1.3, 1.8]$ - checked varying "much-many" cosmological models
  - better results from surveys with better performance in this range
  - accomplished by SKA and *Euclid*
- slightly: the algorithm to find z_M (any suggestion is welcome)

Results: what can we tell about c from BAO?

- Fiducial input: $z_M = 1.58912\,(\Delta c/c_0 = 0)$, $1.58996\,(\Delta c/c_0 = 0.1\%)$, $1.56143\,(\Delta c/c_0 = 1\%)$

Table I. Results.

$\Delta c/c_0$	z_M	$c\ (p_{>1})$	$c_{1\sigma}\ (p_{>1})$	$c_{2\sigma}\ (p_{>1})$	$c_{3\sigma}\ (p_{>1})$
	Euclid				
1%	$1.559^{+0.054}_{-0.051}$	$1.00872^{+0.00003}_{-0.00003}$ (1)	$0.99993^{+0.00013}_{-0.00024}$ (0.32)	$0.99436^{+0.00023}_{-0.00041}$ (0)	$0.98879^{+0.00032}_{-0.00056}$ (0)
0.1%	$1.587^{+0.058}_{-0.052}$	$1.000880^{+0.000006}_{-0.000006}$ (0.98)	$0.99199^{+0.00014}_{-0.00024}$ (0.001)	$0.98636^{+0.00024}_{-0.00038}$ (0)	$0.98072^{+0.00034}_{-0.00053}$ (0)
	SKA				
$\Delta c/c_0$	z_M	$c\ (p_{>1})$	$c_{1\sigma}\ (p_{>1})$	$c_{2\sigma}\ (p_{>1})$	$c_{3\sigma}\ (p_{>1})$
0%	$1.593^{+0.018}_{-0.017}$	$1.^{+3\cdot10^{-7}}_{-4\cdot10^{-7}}$	$0.99708^{+0.00003}_{-0.00004}$	$0.99524^{+0.00006}_{-0.00007}$	$0.99339^{+0.00008}_{-0.00008}$
1%	$1.561^{+0.017}_{-0.017}$	$1.00873^{+0.00001}_{-0.00001}$ (1)	$1.00585^{+0.00003}_{-0.00003}$ (1)	$1.004036^{+0.00005}_{-0.00005}$ (1)	$1.00221^{+0.00008}_{-0.00009}$ (1)
0.1%	$1.590^{+0.018}_{-0.017}$	$1.000880^{+0.000001}_{-0.000001}$ (1)	$0.99797^{+0.00003}_{-0.00003}$ (0)	$0.99612^{+0.00006}_{-0.00006}$ (0)	$0.99428^{+0.00008}_{-0.00008}$ (0)
0.1% ($err/3$)	$1.590^{+0.006}_{-0.006}$	$1.0008800^{+0.0000001}_{-0.0000001}$ (1)	$0.999834^{+0.000009}_{-0.000009}$ (0)	$0.99917^{+0.00001}_{-0.00001}$ (0)	$0.998510^{+0.00002}_{-0.00002}$ (0)
0.1% ($err/10$)	$1.590^{+0.003}_{-0.003}$	$1.0008800^{+0.0000003}_{-0.0000002}$ (1)	$1.00032^{+0.00014}_{-0.00018}$ (0.94)	$0.99996^{+0.00023}_{-0.00029}$ (0.44)	$0.99961^{+0.00032}_{-0.00040}$ (0.10)

Conclusions

- We have developed and tested a (highly-)model-independent method to detect VSL with BAO
- we only need observational data and erros (and nothing more)
- no need of other cosmological parameters (!!!)
    - CMB is generally better than BAO in "ordinary" cosmology
    - from *Planck 2013* CMB data: $\Delta\alpha/\alpha \sim 0.4\%$ ($\alpha = \frac{e^2}{\hbar\, c}$)
    - but varying all other cosmological parameters (!!!)
- **BAO will measure c directly**
- SKA is potentially able to detect 1% variation in c at 3σ
- Smaller variations (0.1%) to be detected (possibly):
    - *ad hoc*-built surveys, i.e. optimized in the right redshift range (?) - synergy between surveys (?)
    - future projects focussed in "testing gravity": our method might be a possible further element for proposal
    - BAO can be competitive with other cosmological probes (CMB)