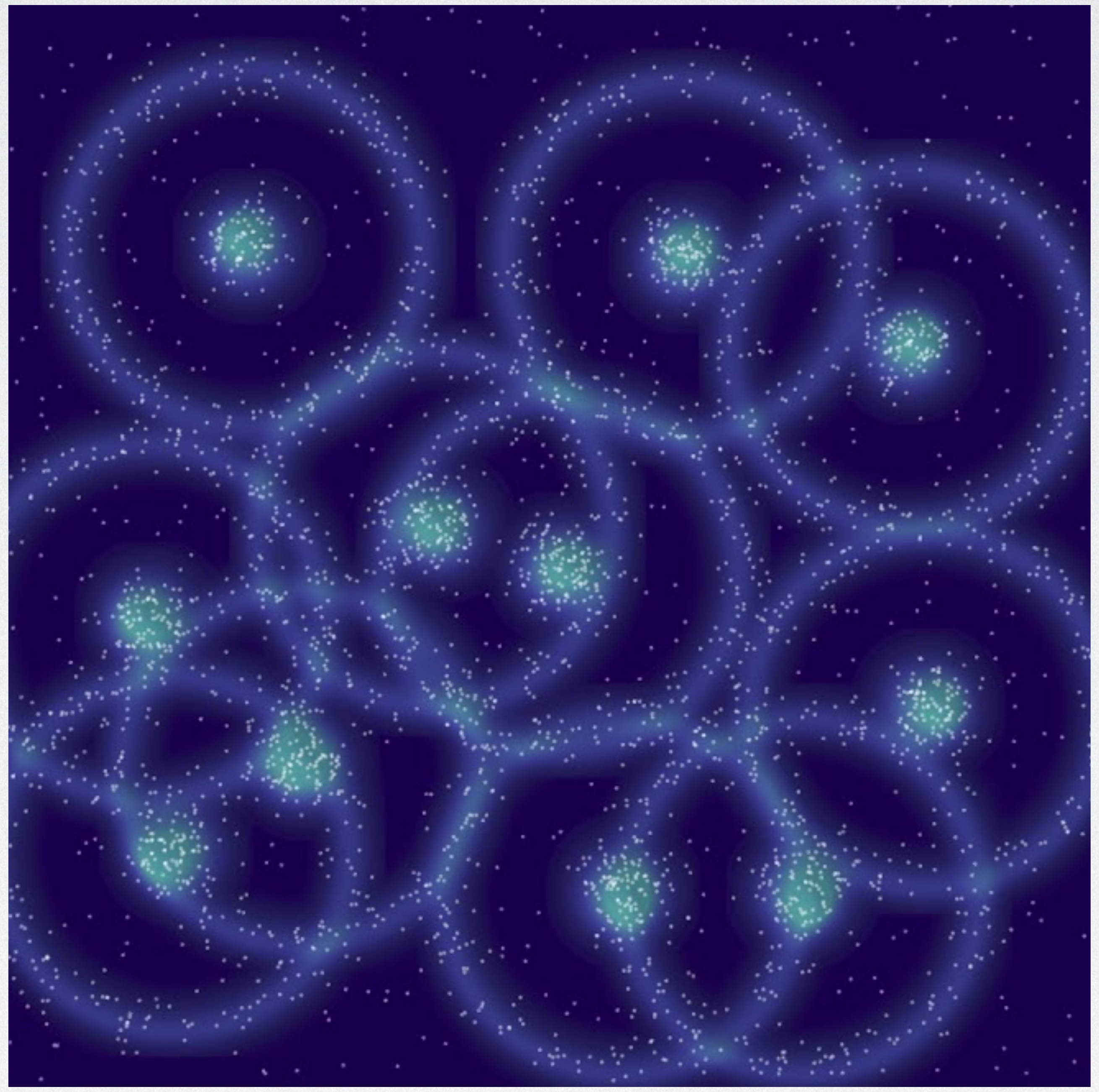
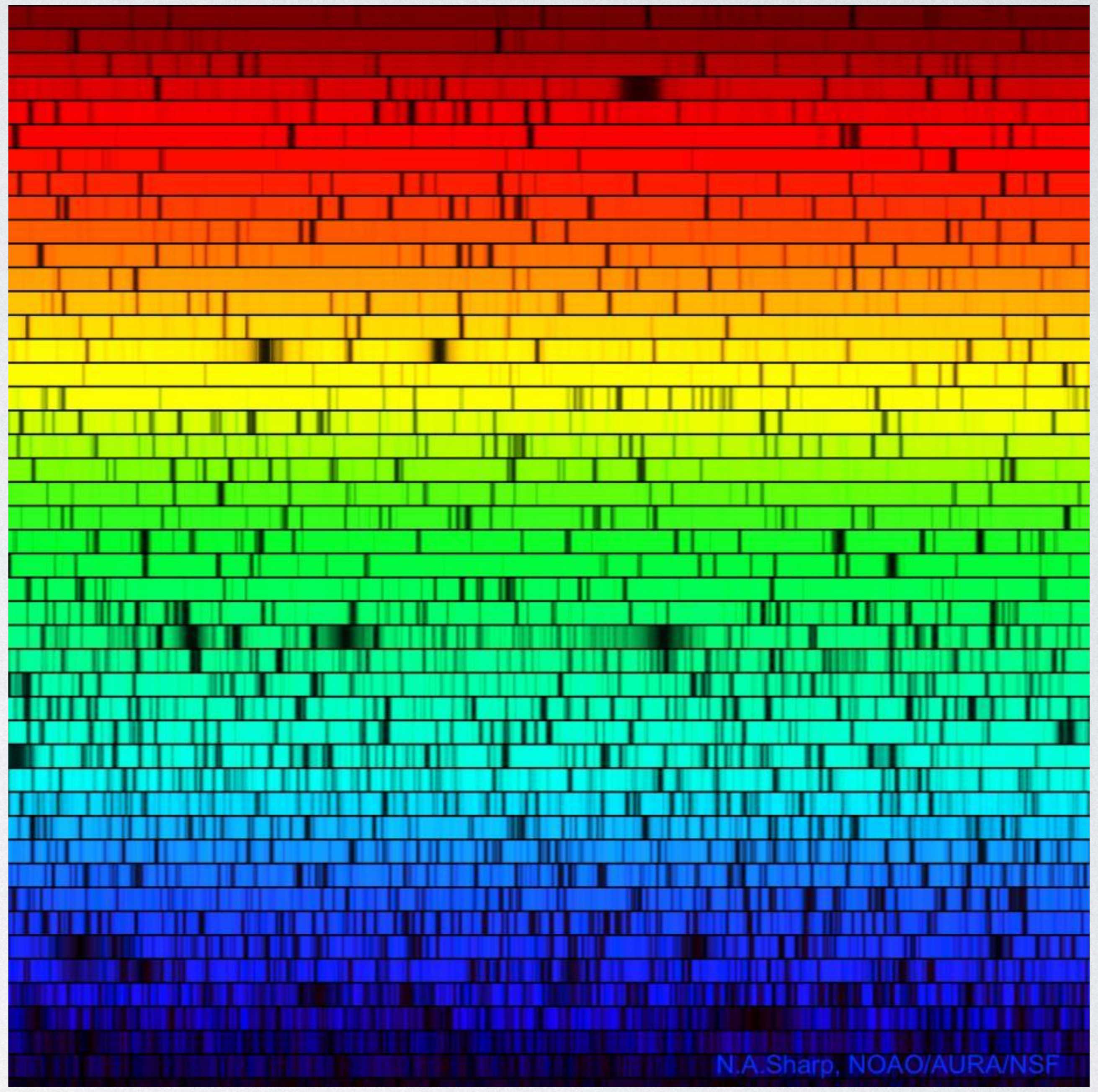
CANDLES, RULERS, AND REDSHIFTS





N.A.Sharp, NOAO/AURA/NSF

Tamara Davis, University of Queensland

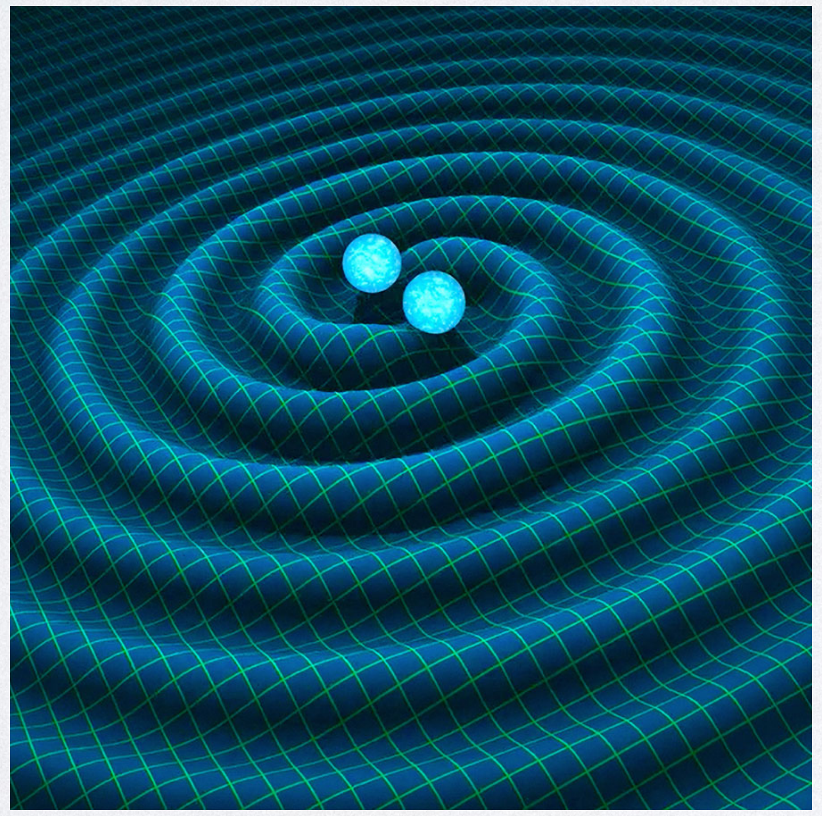
Tensions between the ~~early and late universe~~, July 2019

standard candles and standard rulers?

LOCAL / GLOBAL … OR … CANDLES / RULERS?

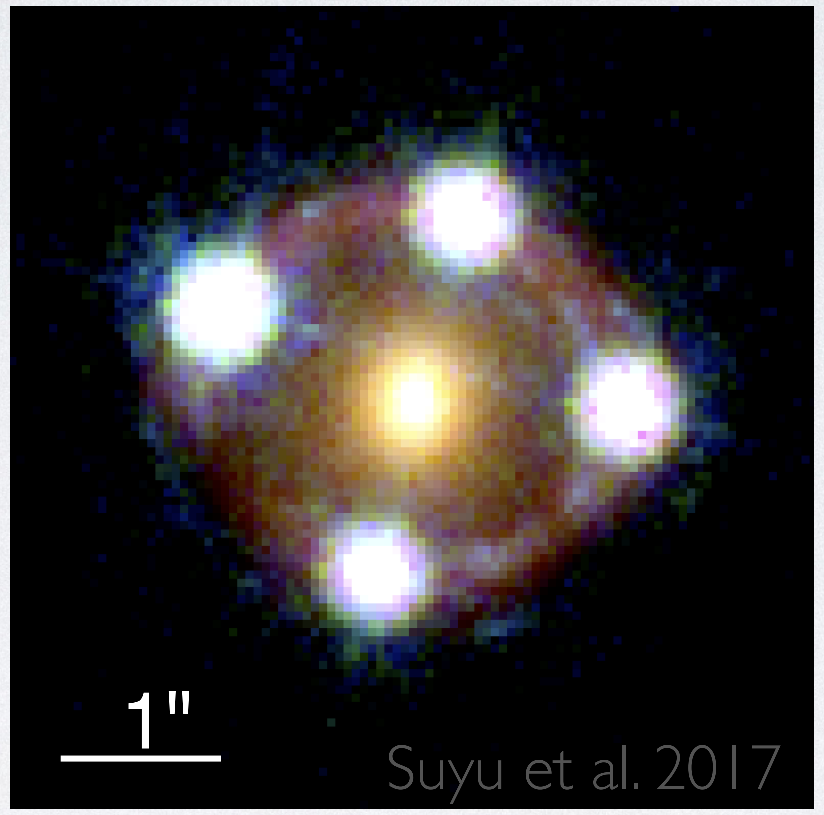
$$\tilde{D} = \begin{cases} R_0 \sin(\chi) & \text{closed} \\ R_0 \chi & \text{flat} \\ R_0 \sinh(\chi) & \text{open} \end{cases}$$

Candles



$$D_L = \tilde{D}(1+z)$$

Clocks/rulers



Suyu et al. 2017

angular diameter distances

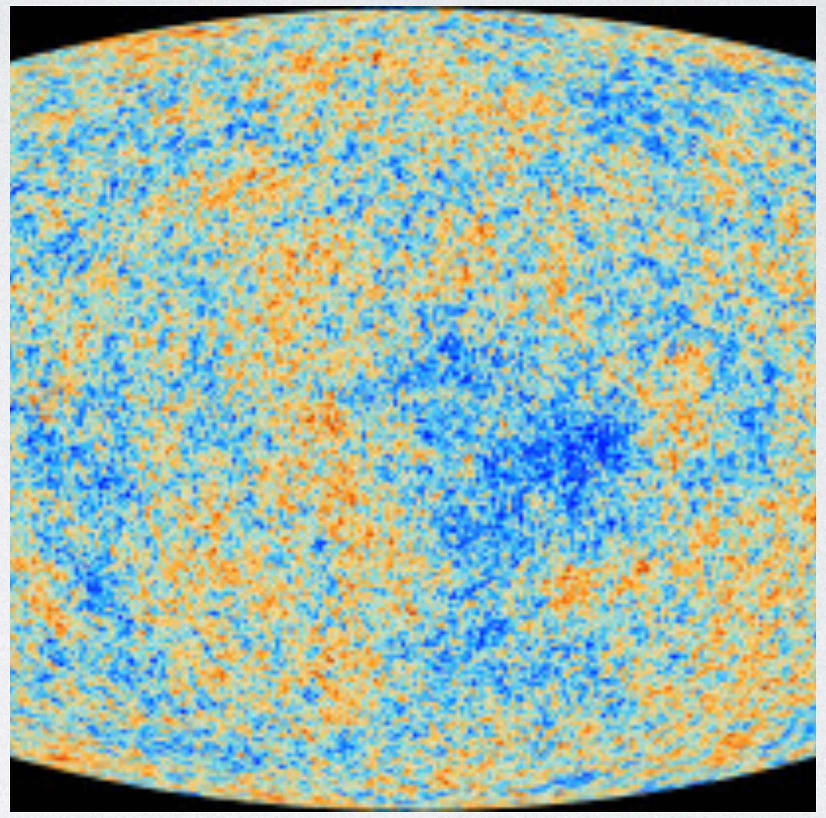
l = lens

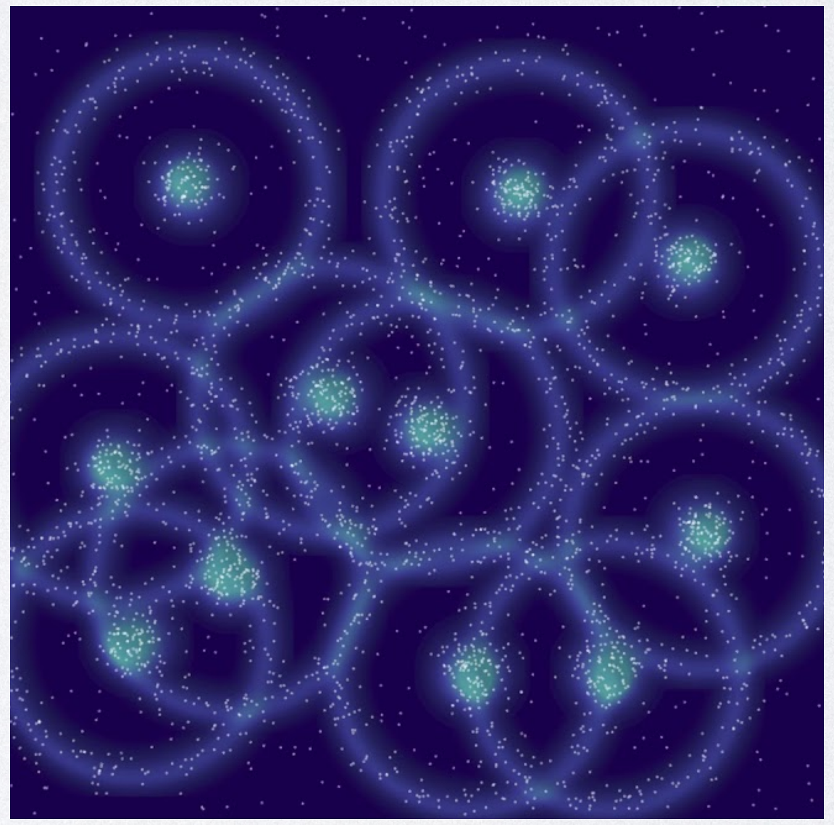
s = source

$$D_{\Delta t} = (1+z_{\mathrm{l}})\frac{D_{\mathrm{l}} D_{\mathrm{s}}}{D_{\mathrm{ls}}}$$

$$D_{\Delta t} = \frac{\tilde{D}_{\mathrm{l}} \tilde{D}_{\mathrm{s}}}{\tilde{D}_{\mathrm{ls}}} / (1+z_{\mathrm{l}})$$

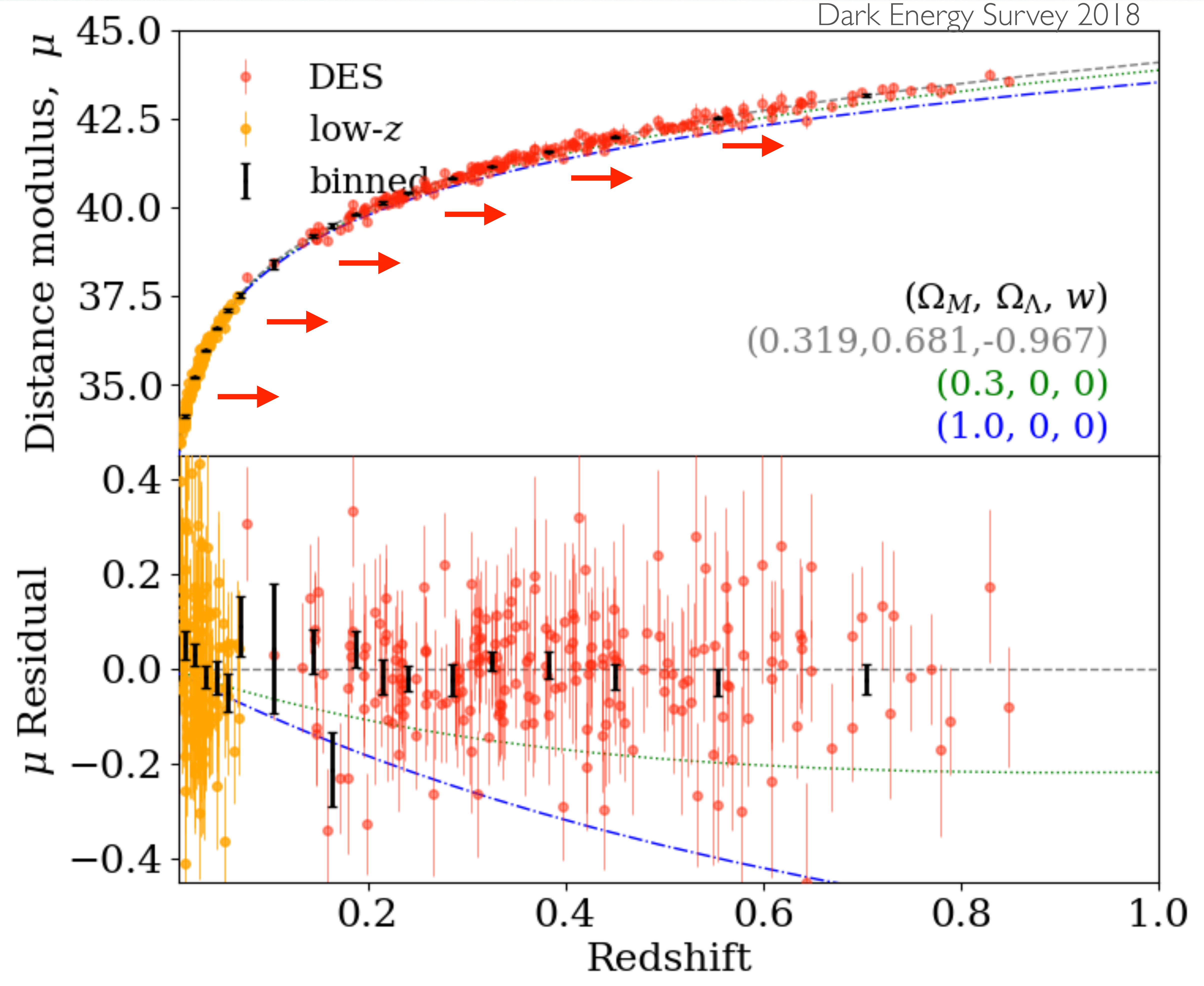
Rulers

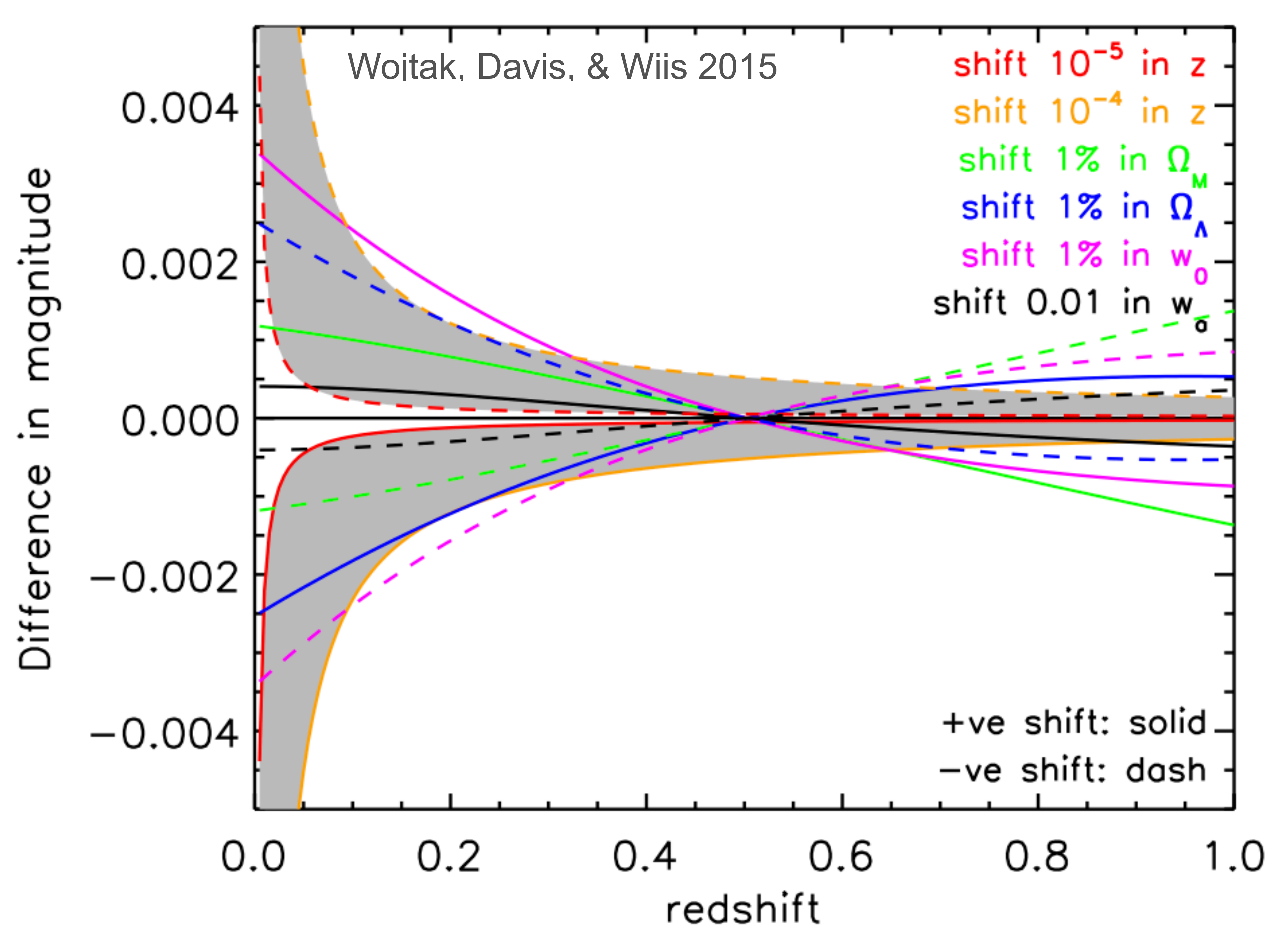




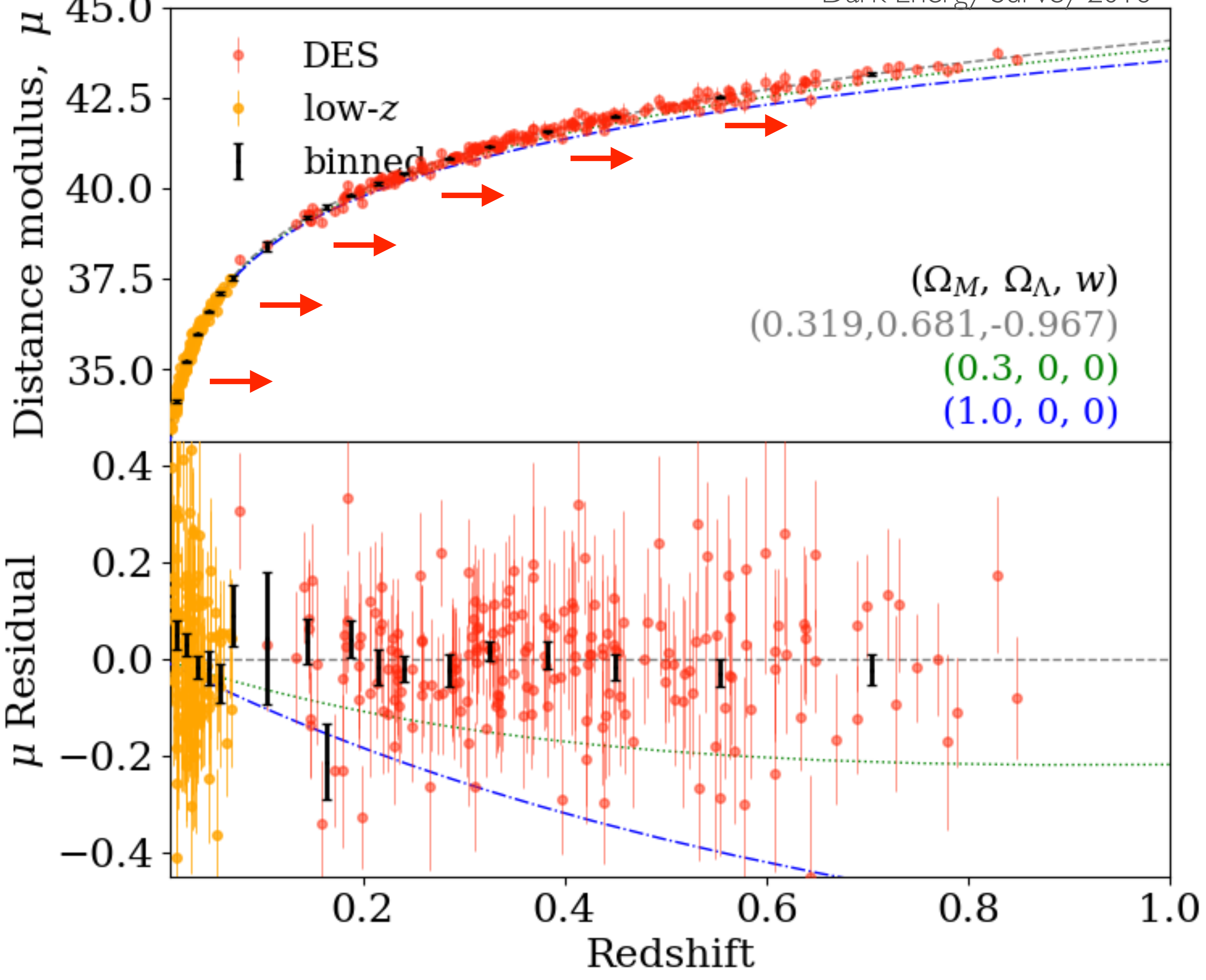
$$D_A = \tilde{D}/(1+z)$$

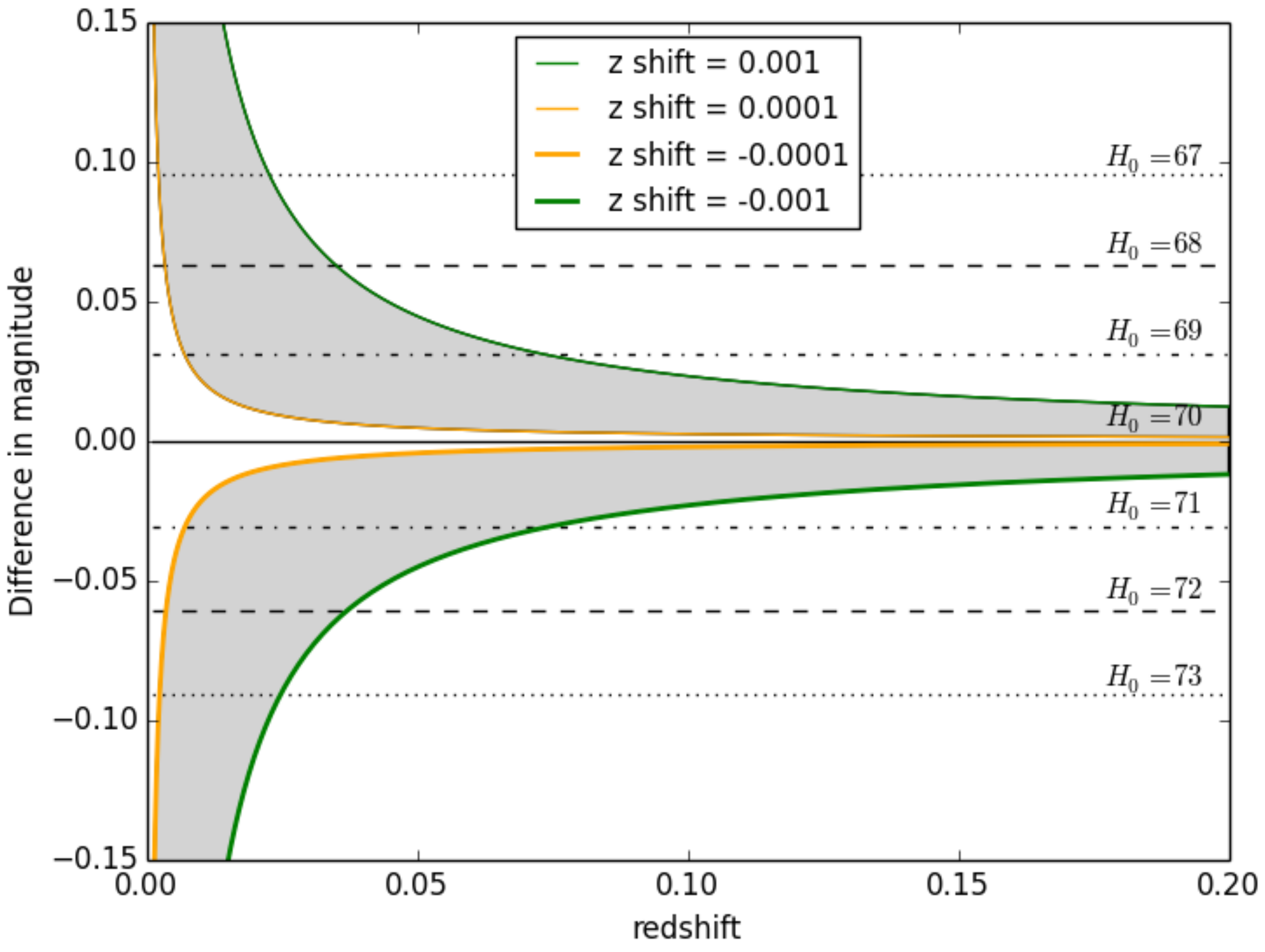
DO WE NEED TO WORRY ABOUT REDSHIFTS?





DO WE NEED TO WORRY ABOUT REDSHIFTS?


Dark Energy Survey 2018



CHOOSE YOUR OWN ADVENTURE !

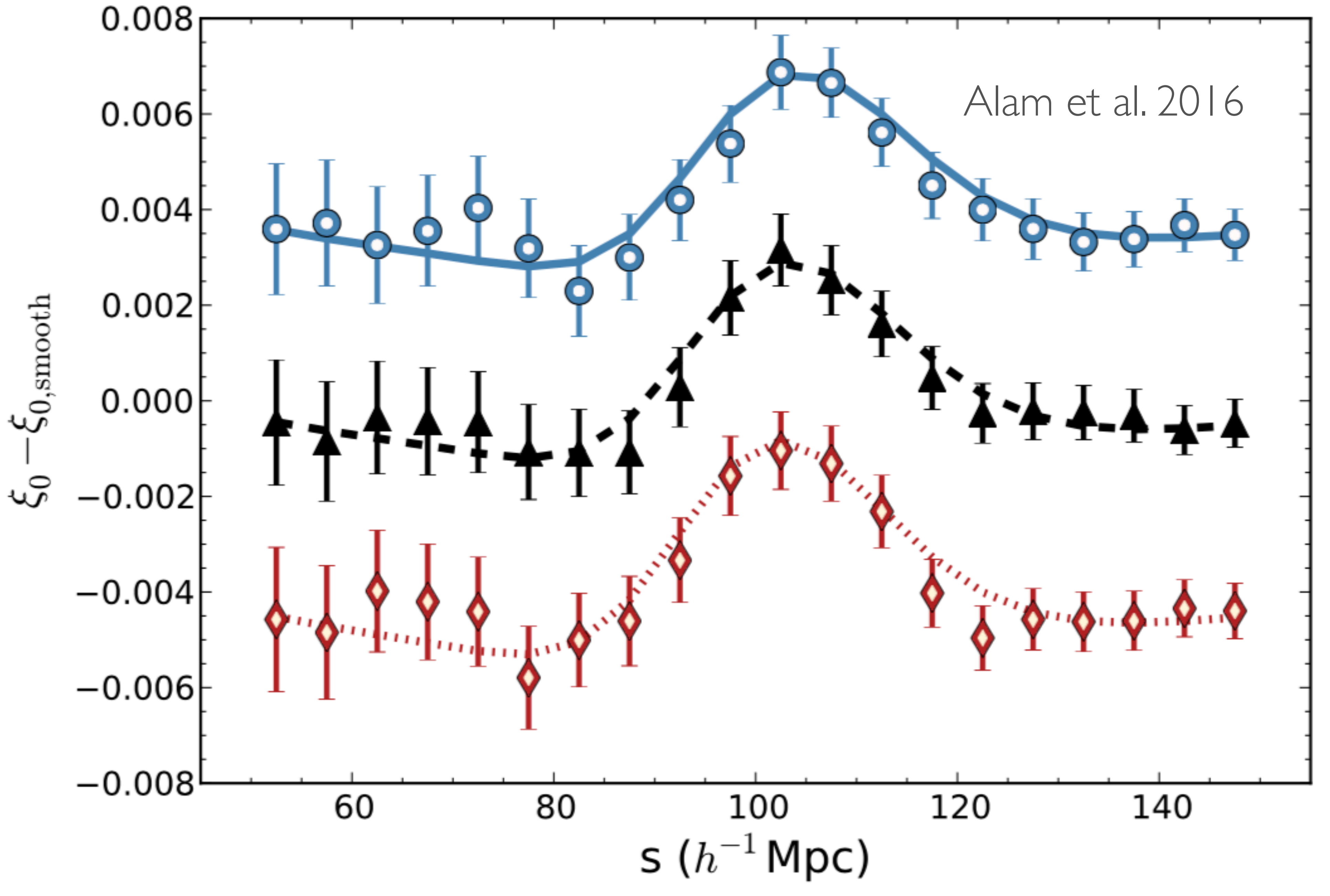
- More on how redshift errors could affect BAO
- More on how redshift errors could affect supernovae

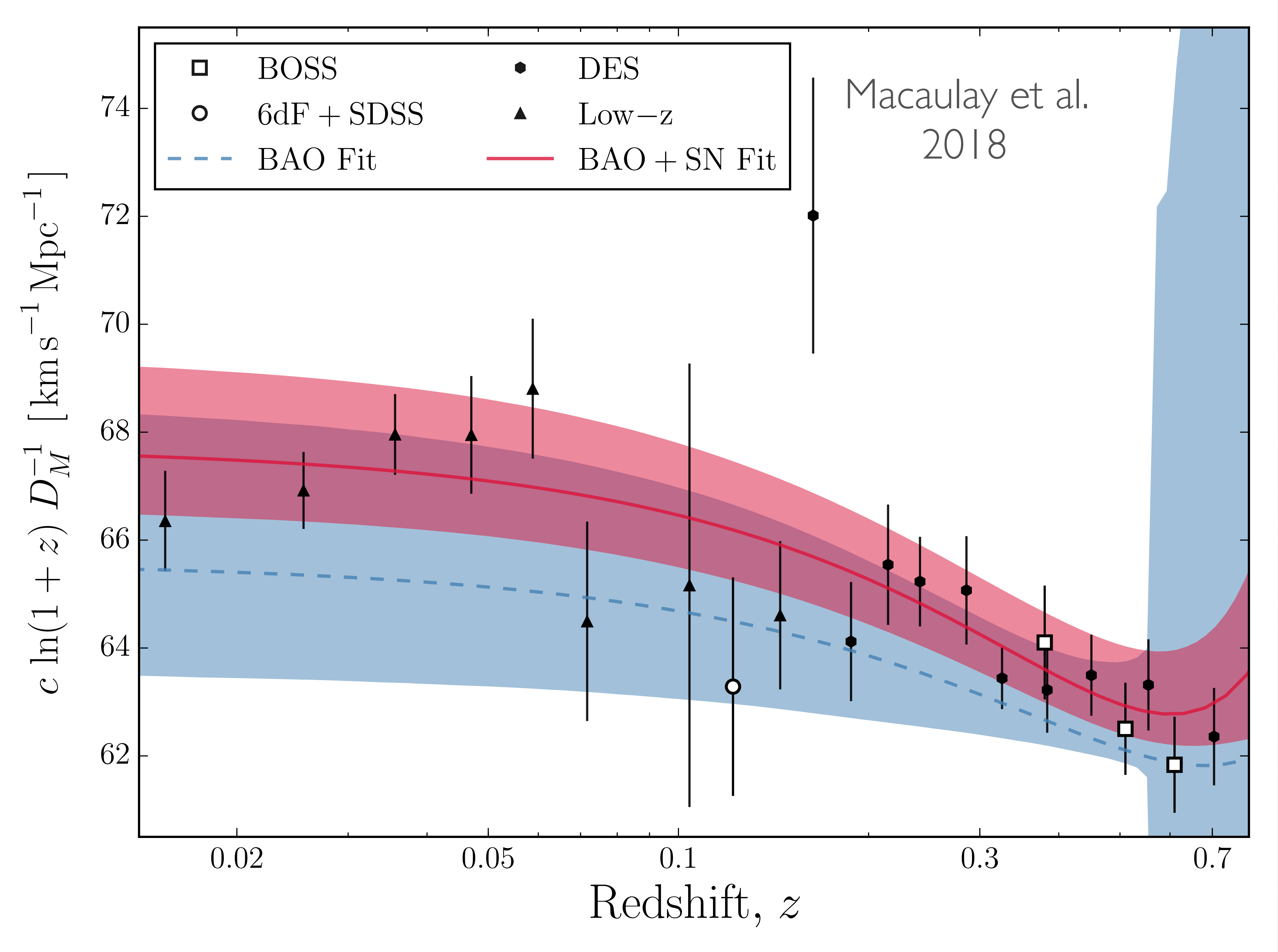
REDSHIFT EFFECTS IN BAO

Two main ways to infer H_0

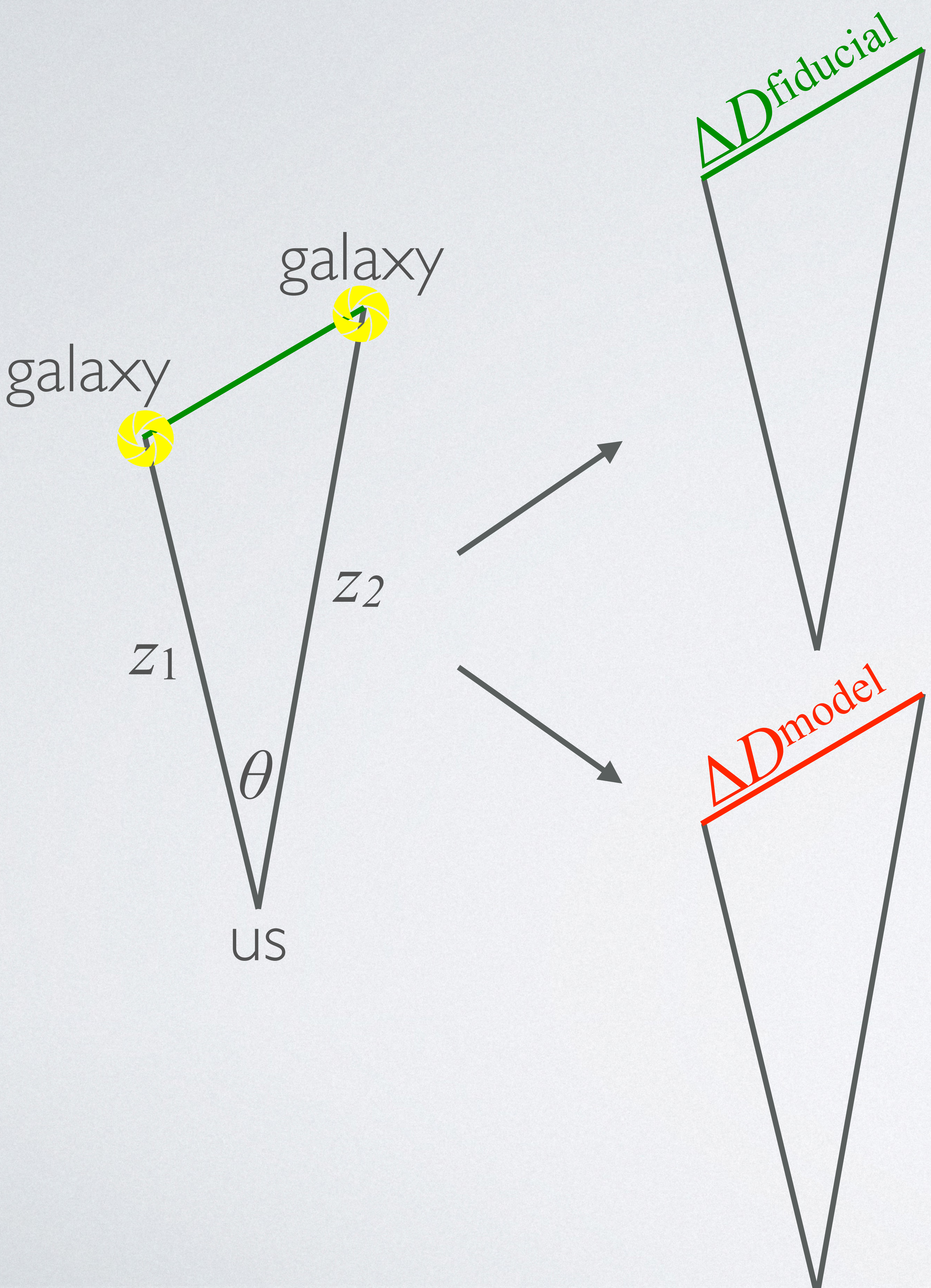
- Fit a cosmological model to the BAO
- Use an "inverse distance ladder"

(often shares ruler with CMB)

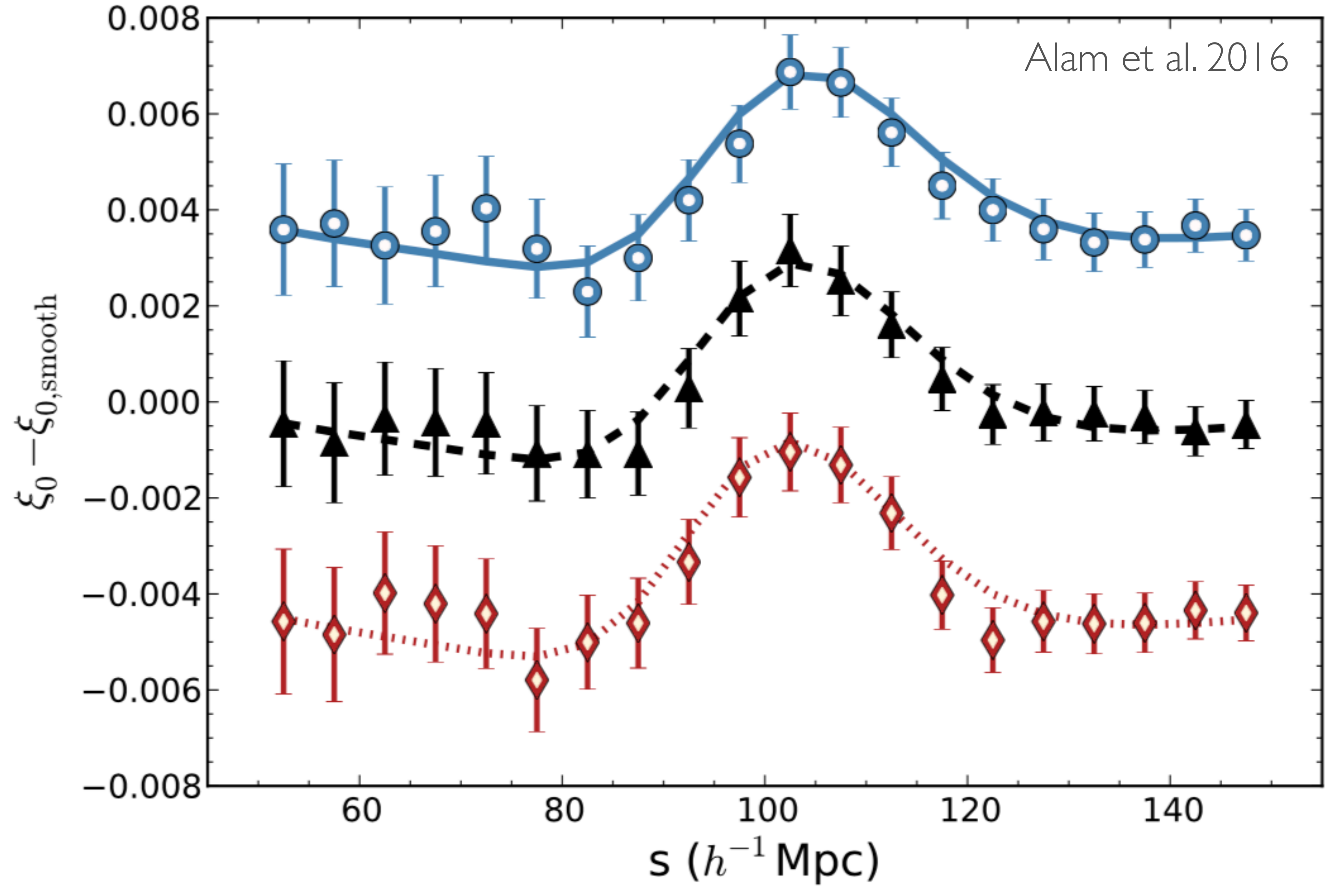


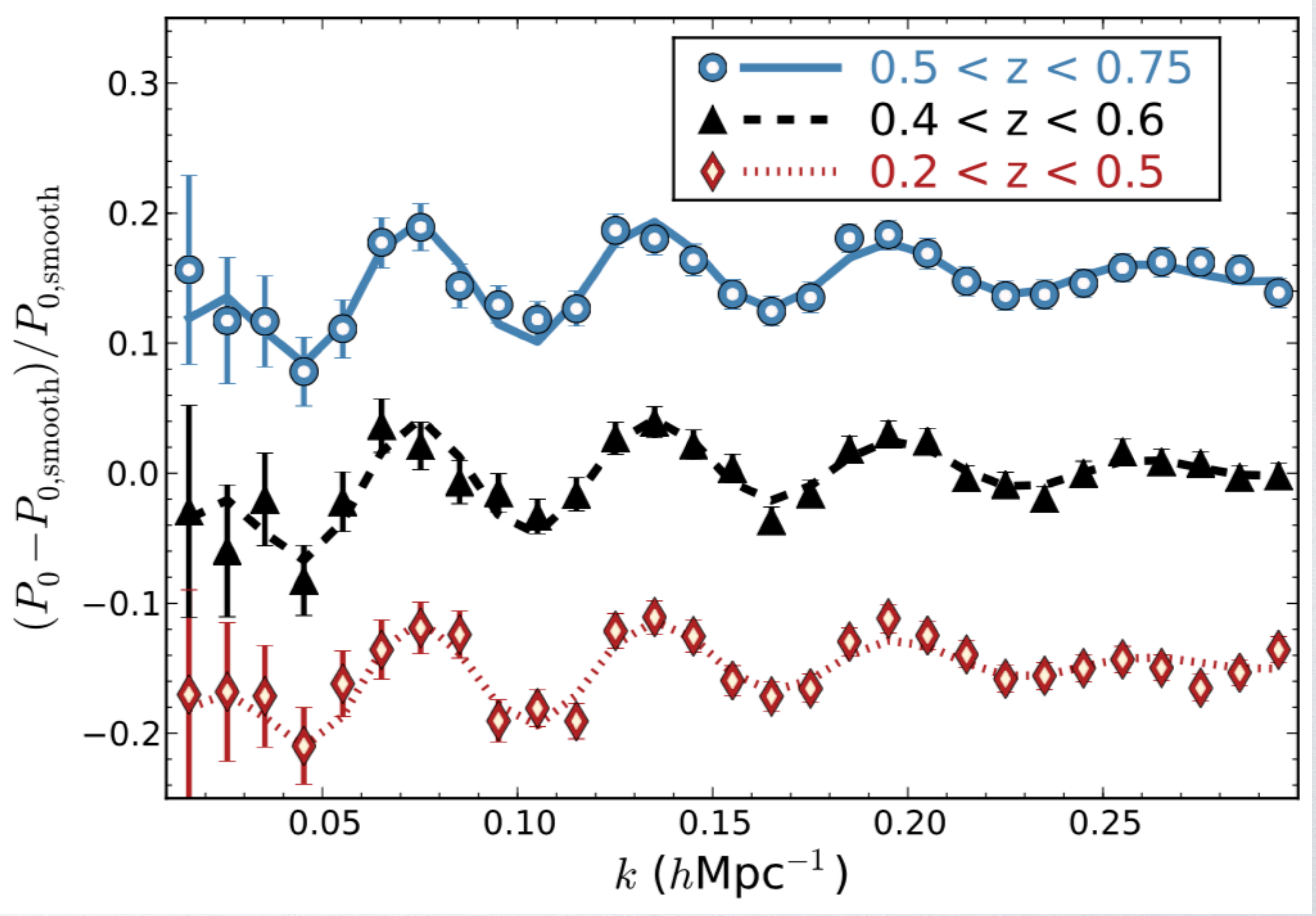


DERIVING H_0 FROM BAO



$$\alpha = \frac{\Delta D^{\text{fiducial}}}{\Delta D^{\text{model}}}$$

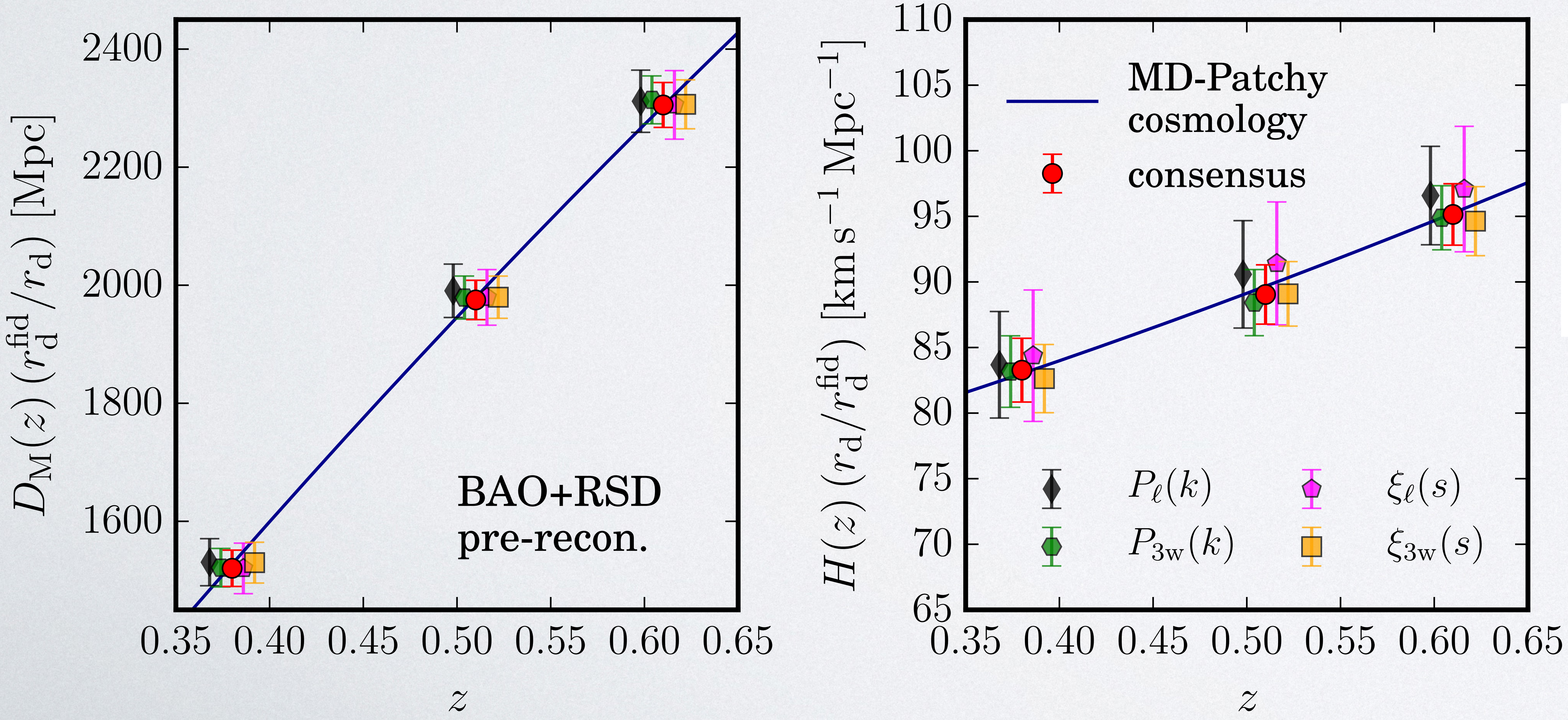




REDSHIFT EFFECTS IN BAO

- What is the **redshift** of the standard ruler?

$$0.2 < z < 0.5 \rightarrow z_{\rm eff} = 0.38,$$
$$0.4 < z < 0.6 \rightarrow z_{\rm eff} = 0.51,$$
$$0.5 < z < 0.75 \rightarrow z_{\rm eff} = 0.61.$$



$$w_i = \frac{1}{1 + n_i P_0},$$

$$\bar{z}_{\rm pair} = \frac{z_1 + z_2}{2}.$$

$$z_{\rm eff} = \frac{\sum_{i=1}^{n} \bar{z}_{{\rm pair},i} w_i}{\sum_{i=1}^{n} w_i}.$$

(Blake et al. 2011)

$$z_{\rm eff} = \frac{\sum_i^{N_{\rm gal}} w_{\rm FKP}(\vec{x}_i) z_i}{\sum_i^{N_{\rm gal}} w_{\rm FKP}(\vec{x}_i)},$$

$$w_{\rm FKP}(\vec{x}) = \frac{1}{1 + \frac{n'_g(\vec{x}) P_0}{w_{\rm sys}(\vec{x})}}.$$

(Beutler et al. 2017)

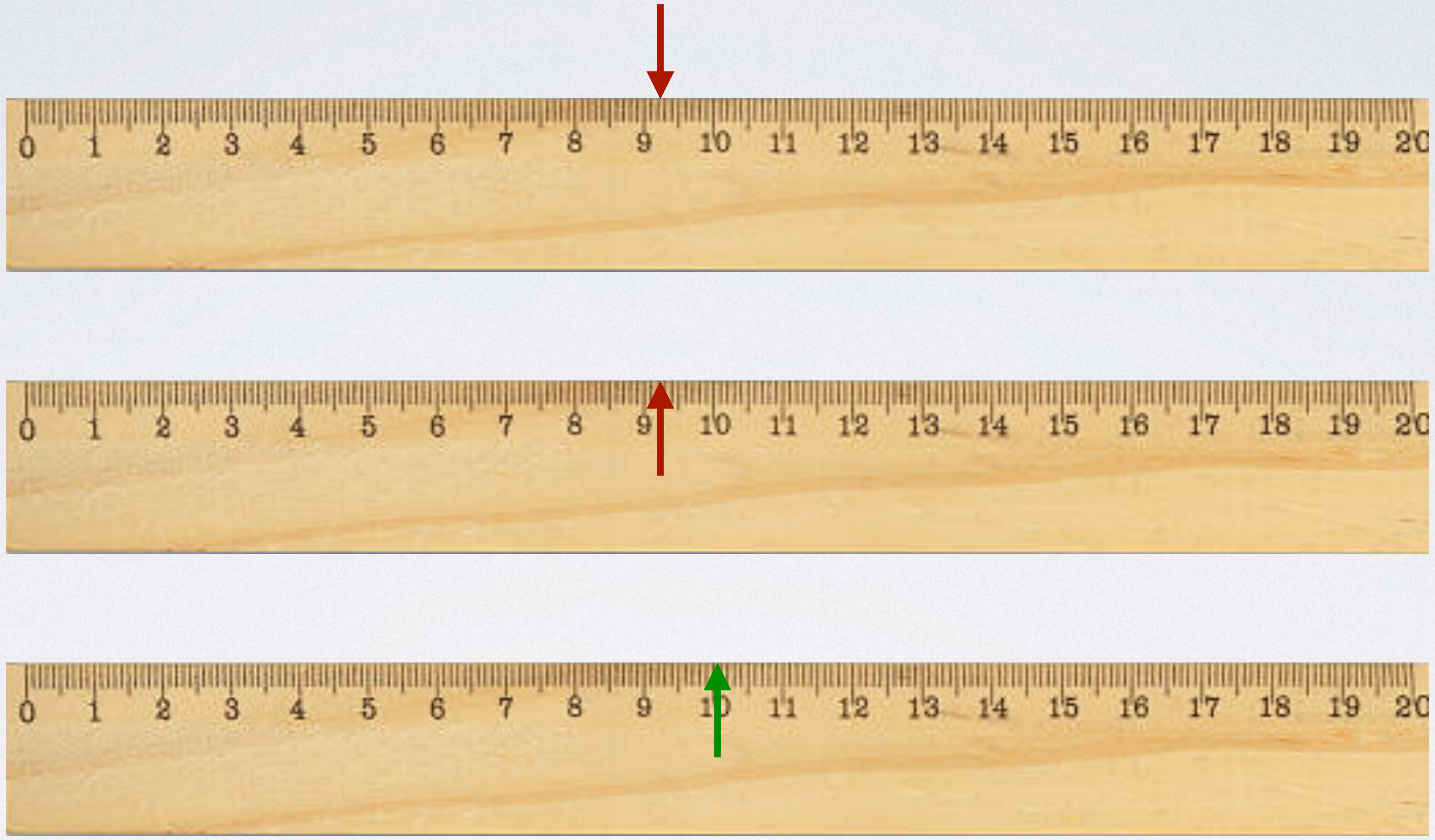
$P_0 = 5000\ h^{-3}\ {\rm Mpc}^3$ = characteristic power spectrum amplitude at scale of interest

n_i = survey number density at location of ith galaxy

But the average redshift
is not the average distance…

TWO WRONGS CAN MAKE A RIGHT

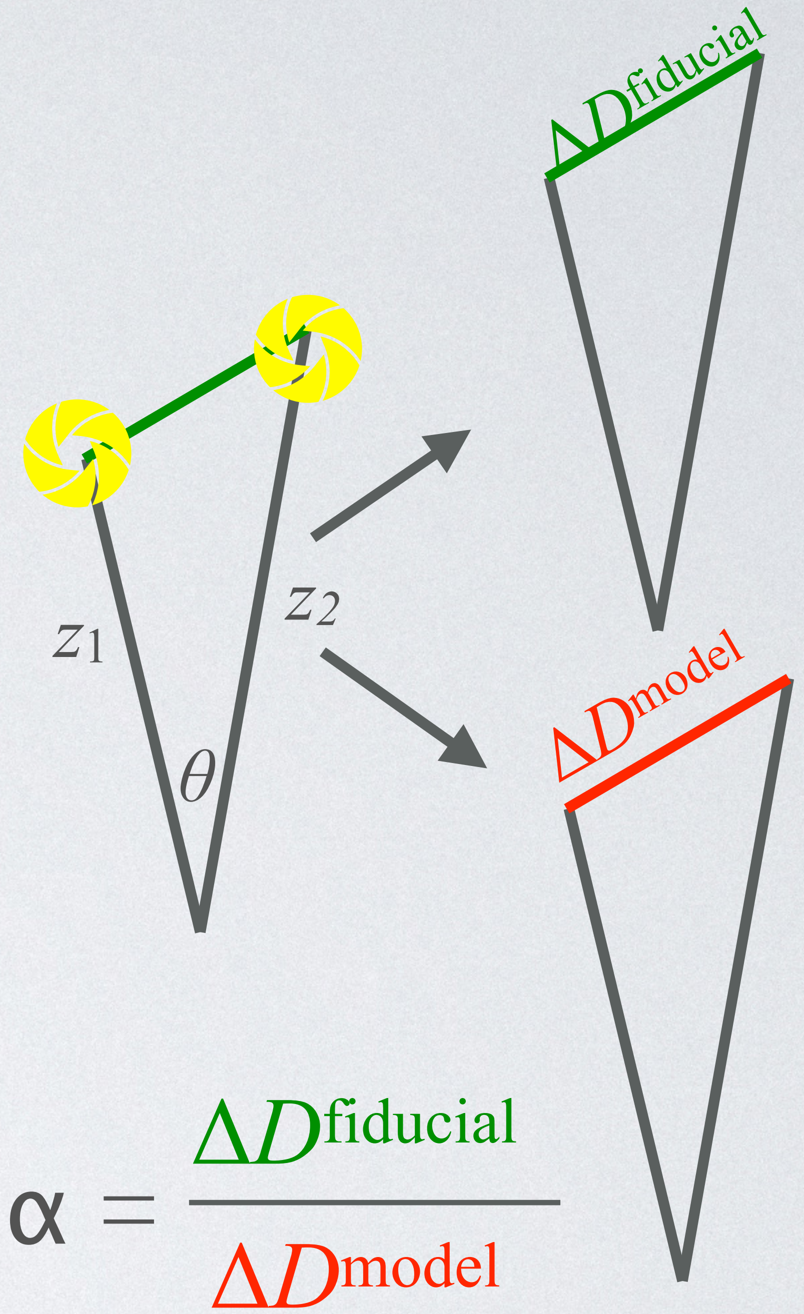
If you use the wrong calibration on both the data and the model, you're okay.



Data

Model

"True"

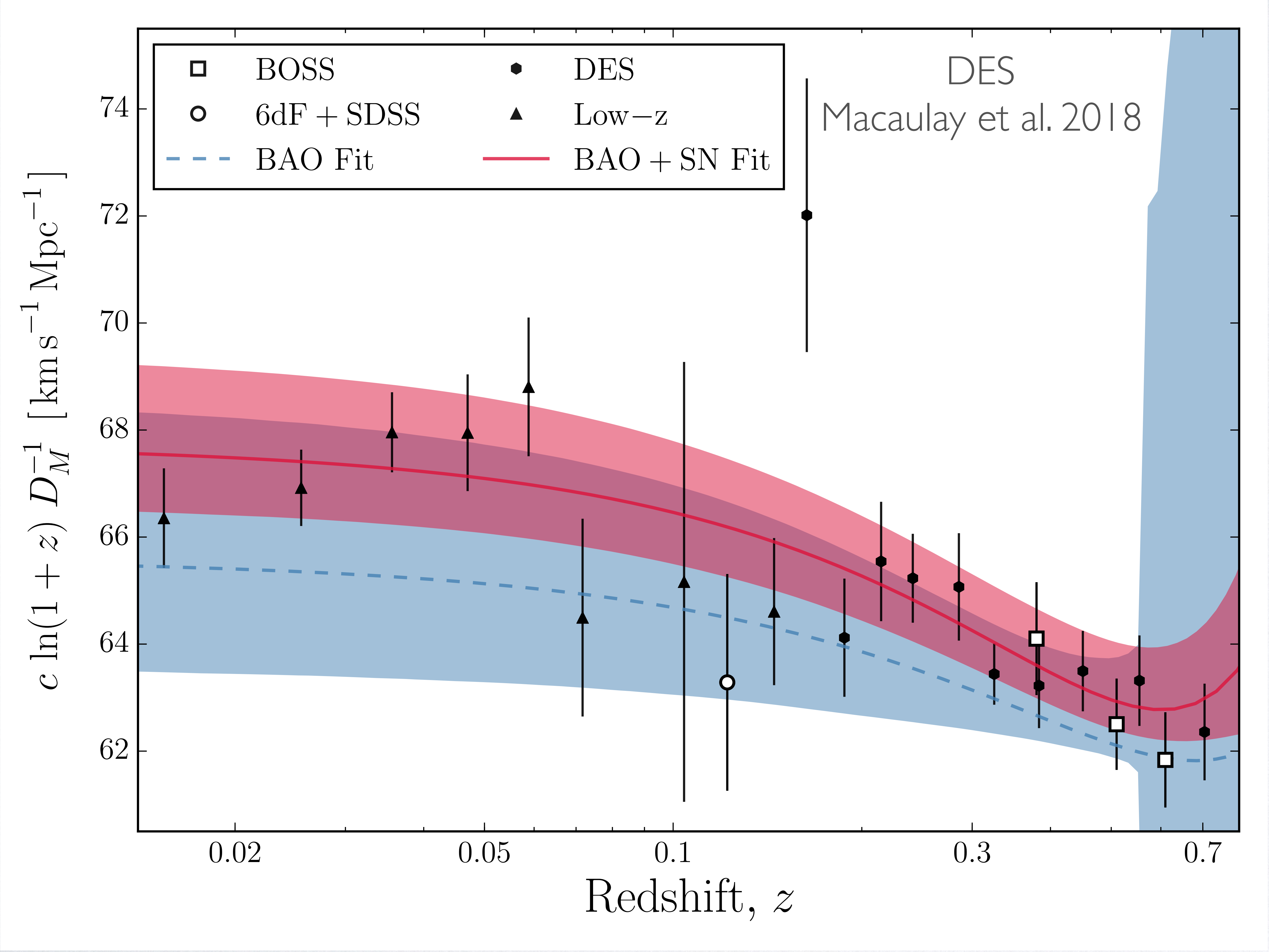


$$\alpha = \frac{\Delta D^{\text{fiducial}}}{\Delta D^{\text{model}}}$$

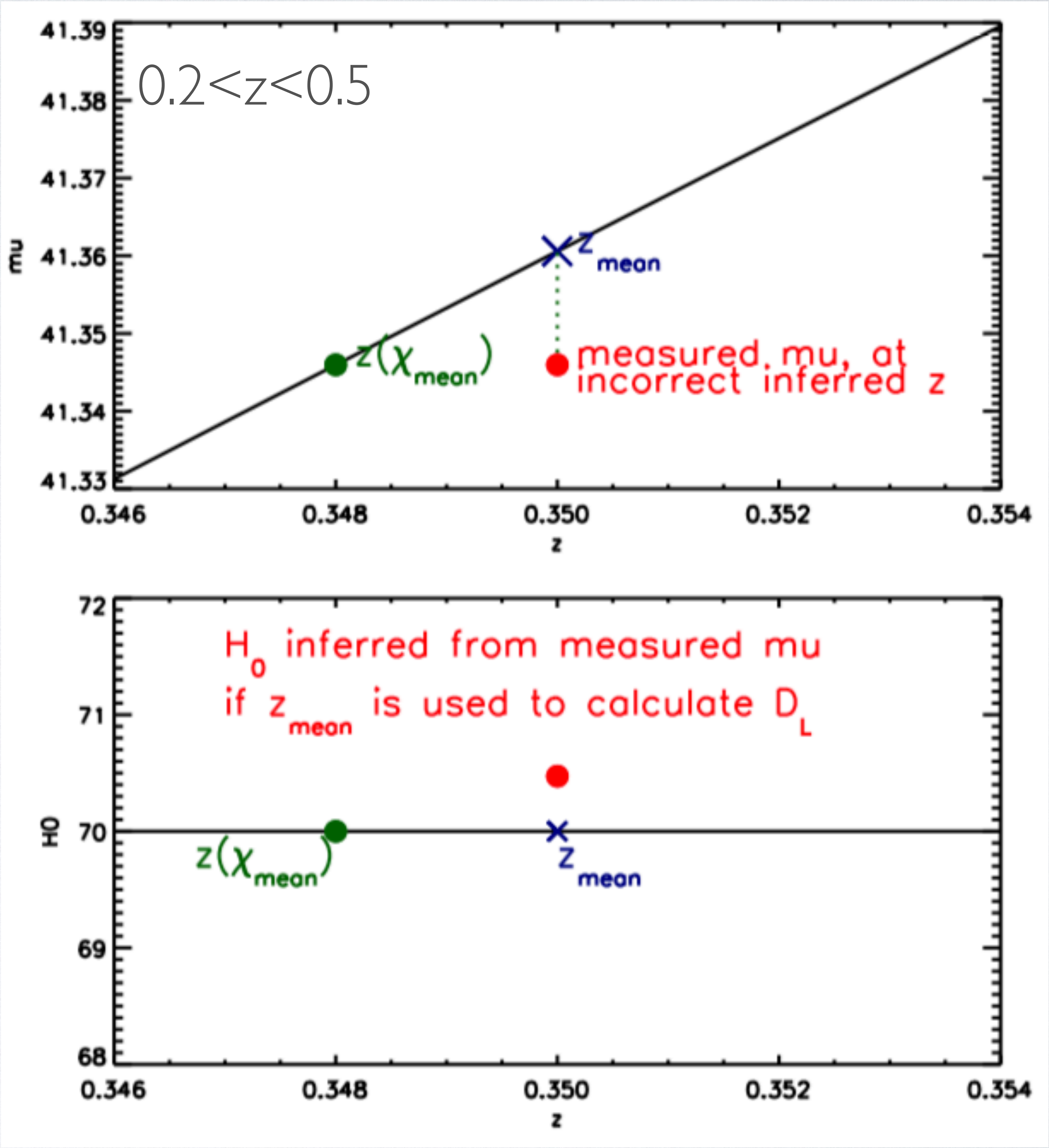
- But if you want an **absolute** distance, the correct z does matter.

HOW MUCH WILL H_0 SHIFT?

- Use an "inverse distance ladder"



$H_0 = 67.8 \pm 1.3$ km s^{-1} Mpc^{-1}



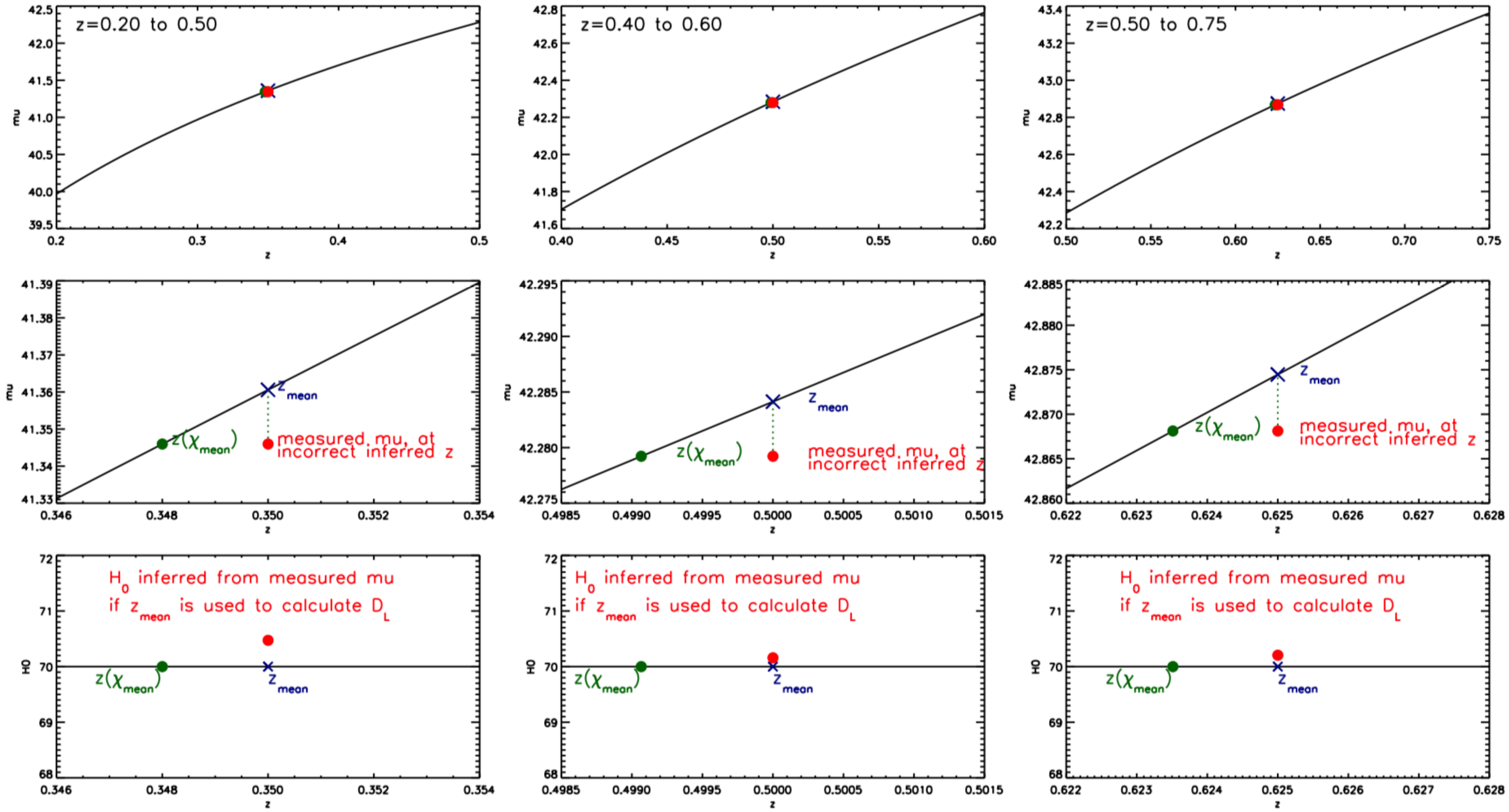
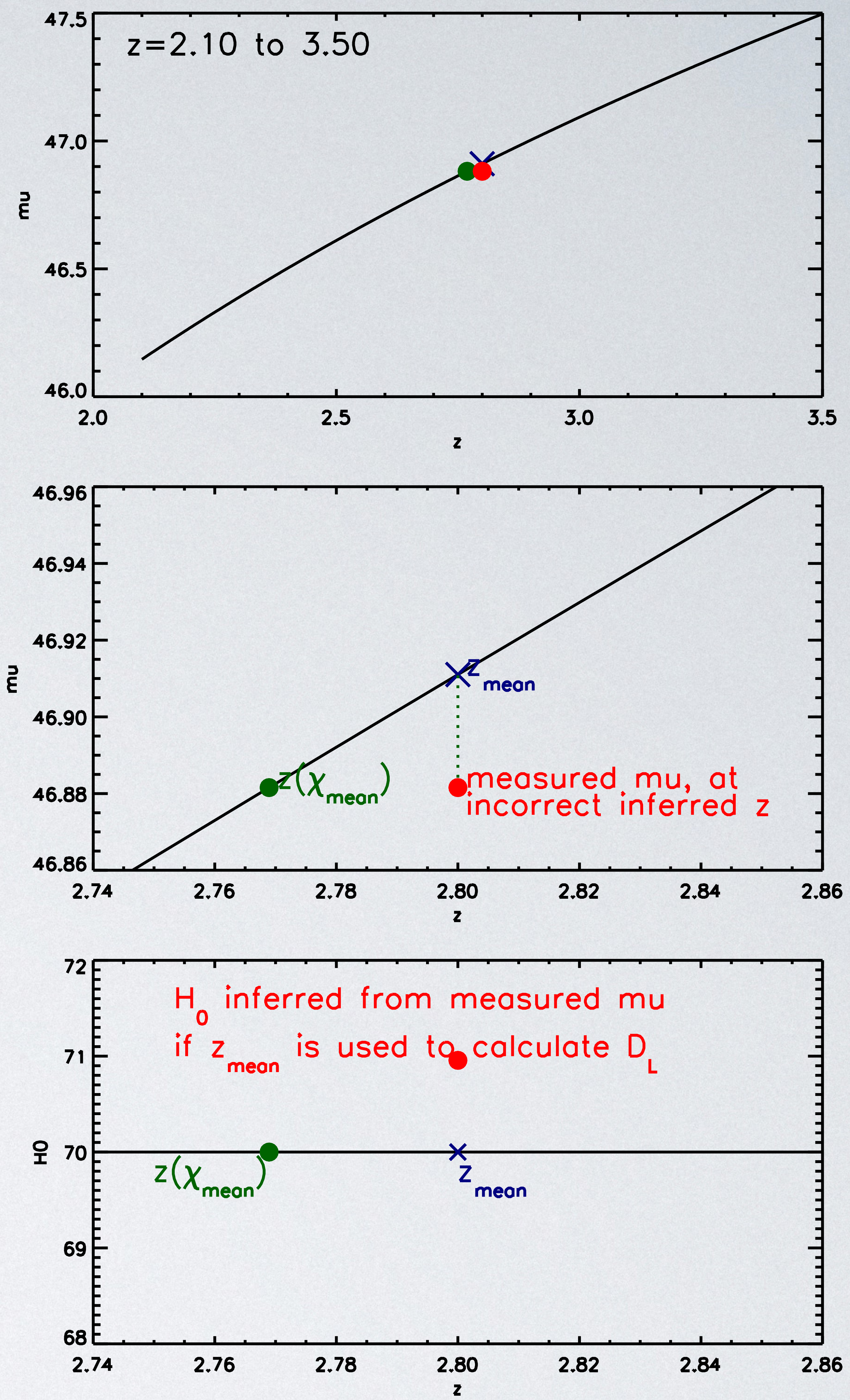
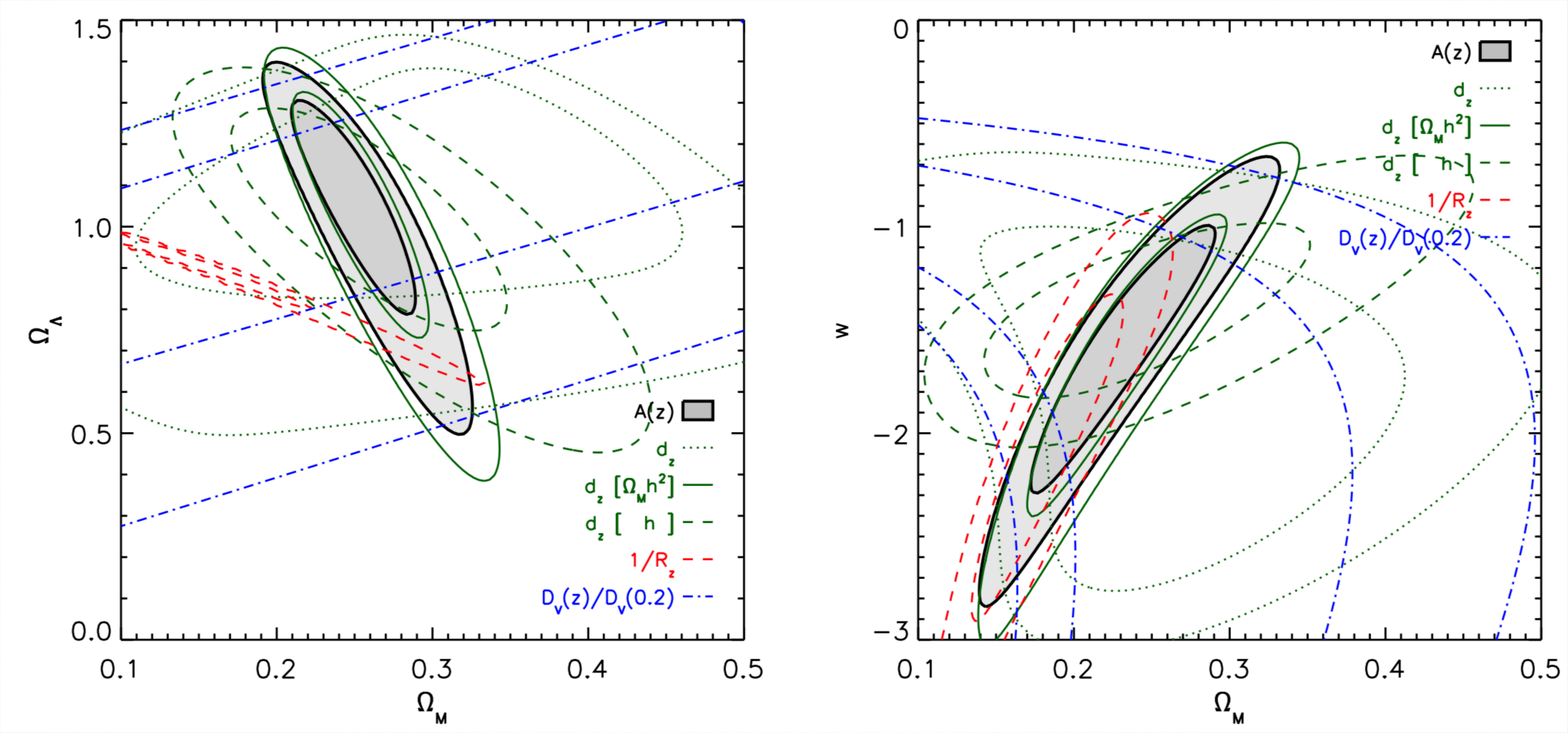


Figure 1: Each column shows a different redshift bin, as labelled at top left. The upper row shows the distance modulus vs redshift plot for each bin. The second row shows the same, but zoomed in on the central redshift region to show the difference between the mean redshift, $z_{\rm mean}$, and the redshift corresponding to the mean comoving distance, $z(\chi_{\rm mean})$. For this example each bin is evenly populated in redshift (this will not be the case in real data). In the lower panel I show the Hubble constant inferred from assuming the measurement was at $z_{\rm mean}$ when it was actually at $z(\chi_{\rm mean})$. The model used to generate the fake data was $(h, \Omega_m, \Omega_\Lambda) = (0.70, 0.27, 0.73)$ (to do the calculation of H_0 I used the same model, but without the $h = H_0/100{\rm km\,s^{-1}Mpc^{-1}}$ input).



This is an even z-distribution so proabably a worst-case scenario error.



1.5
1.0
0.5
0.0
Ω_Λ
0.1
0.2
0.3
0.4
0.5
Ω_M
A(z)
d_z
d_z [Ω_M h^2]
d_z [h]
1/R_z
D_V(z)/D_V(0.2)
0
−1
−2
−3
w
0.1
0.2
0.3
0.4
0.5
Ω_M
A(z)
d_z
d_z [Ω_M h^2]
d_z [h]
1/R_z
D_V(z)/D_V(0.2)

CHOOSE YOUR OWN ADVENTURE !

- More on how redshift errors could affect Supernovae
- What kinds of redshifts errors might we have in our data?

DERIVING H_0 FROM CANDLES

$$D_0(z) = \frac{c}{H_0}\int \frac{dz}{E(z)}$$

$$H_0 = \frac{v_0}{D_0}$$

$$H_0 = \frac{v_0(1+z)}{D_{L,0}}$$

$$v_0 = c\int \frac{dz}{E(z)} \qquad E(z) = H(z)/H_0$$

$$v_0 \approx \frac{cz}{1+z}\left(1 + \frac{1}{2}\left[1-q_0\right]z - \frac{1}{6}\left[1 - q_0 - 3q_0^2 + j_0\right]z^2\right)$$

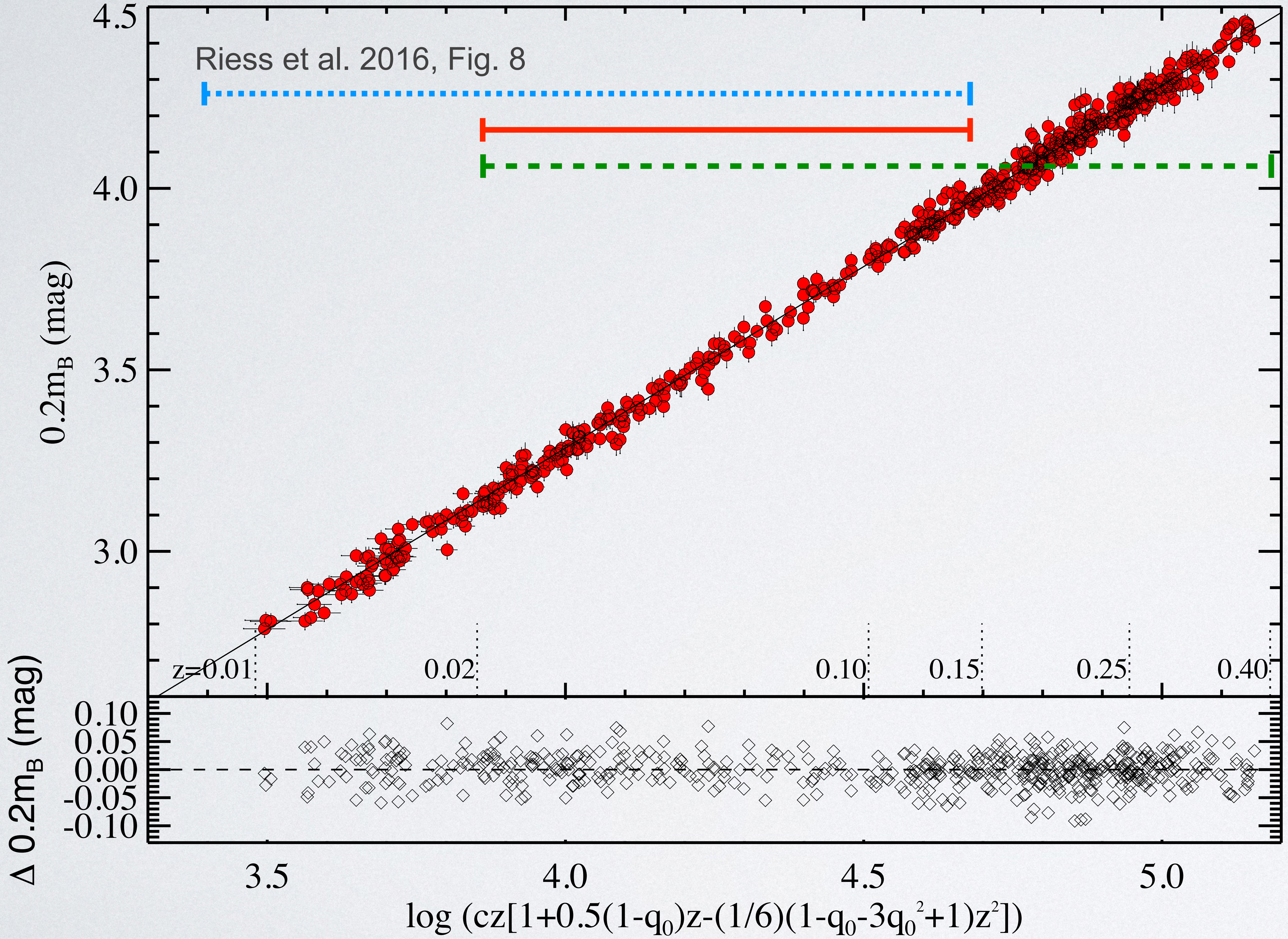
$$\begin{aligned}\log_{10} H_0 &= \log_{10}[v_0(1+z)] - \log_{10} D_{L,0}\\ &= \log_{10}[v_0(1+z)] - 0.2m + \frac{M+25}{5}\\ &= a_x + \frac{M+25}{5}\\ &= \frac{5a_x + M + 25}{5}\end{aligned}$$

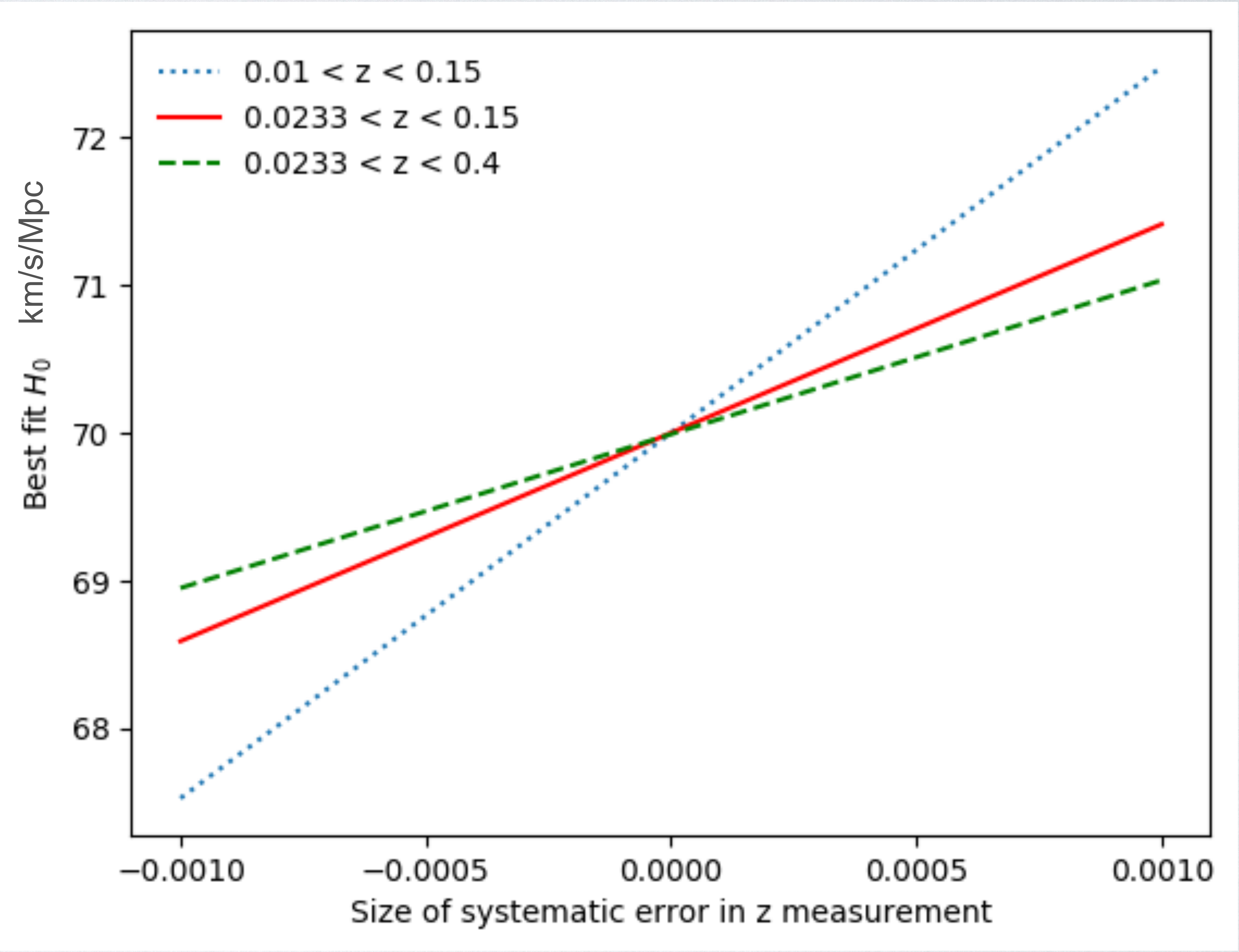
$$\mu = m - M = 5\log_{10} D_L(\mathrm{Mpc}) + 25$$

$$\log_{10} D_L = \frac{m - M - 25}{5} = 0.2m - \frac{M+25}{5}$$

$$a_x \equiv \log_{10}[v_0(1+z)] - 0.2m$$

HOW LARGE A REDSHIFT ERROR WOULD SIGNIFICANTLY CHANGE H_0?


Riess et al. 2016, Fig. 8



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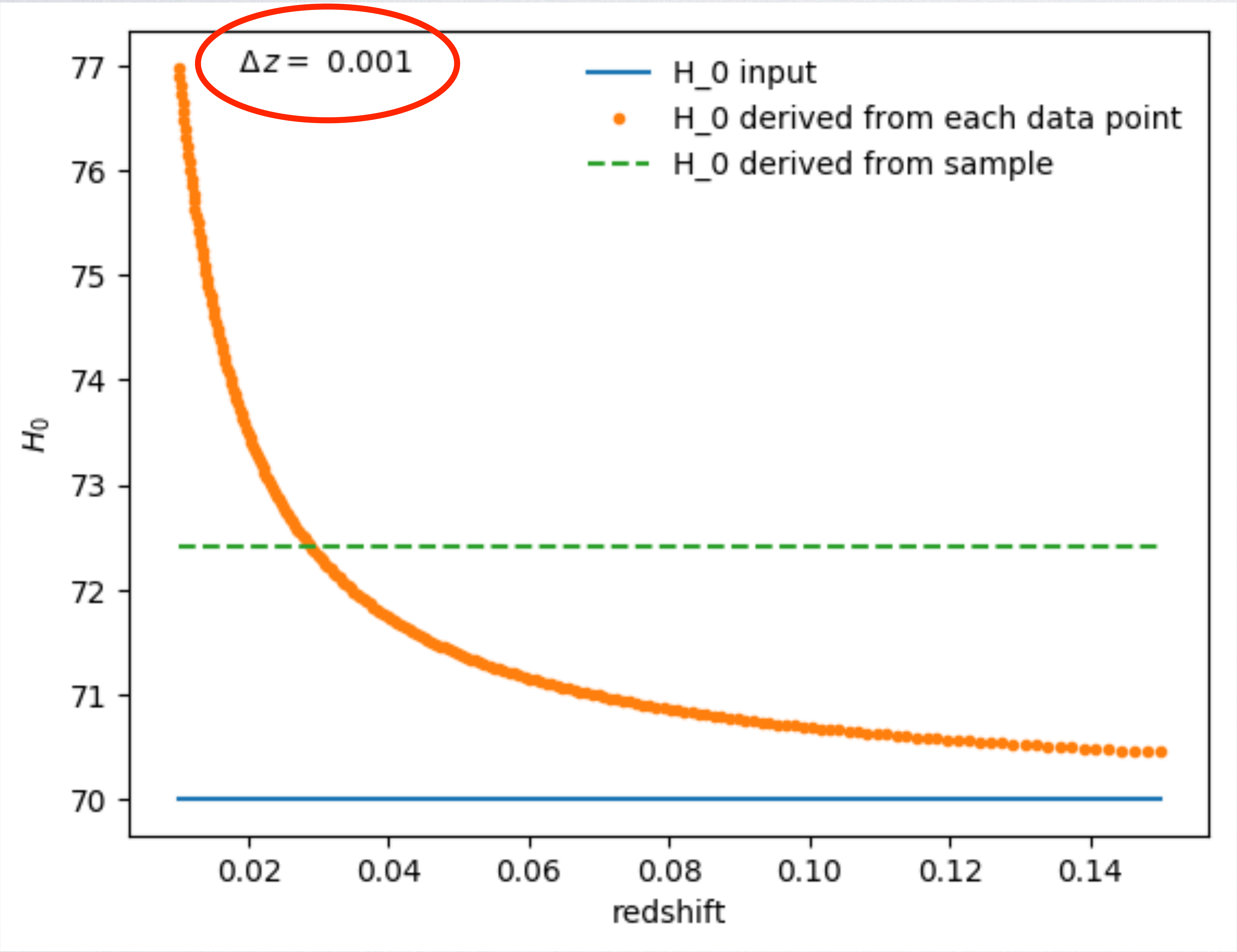
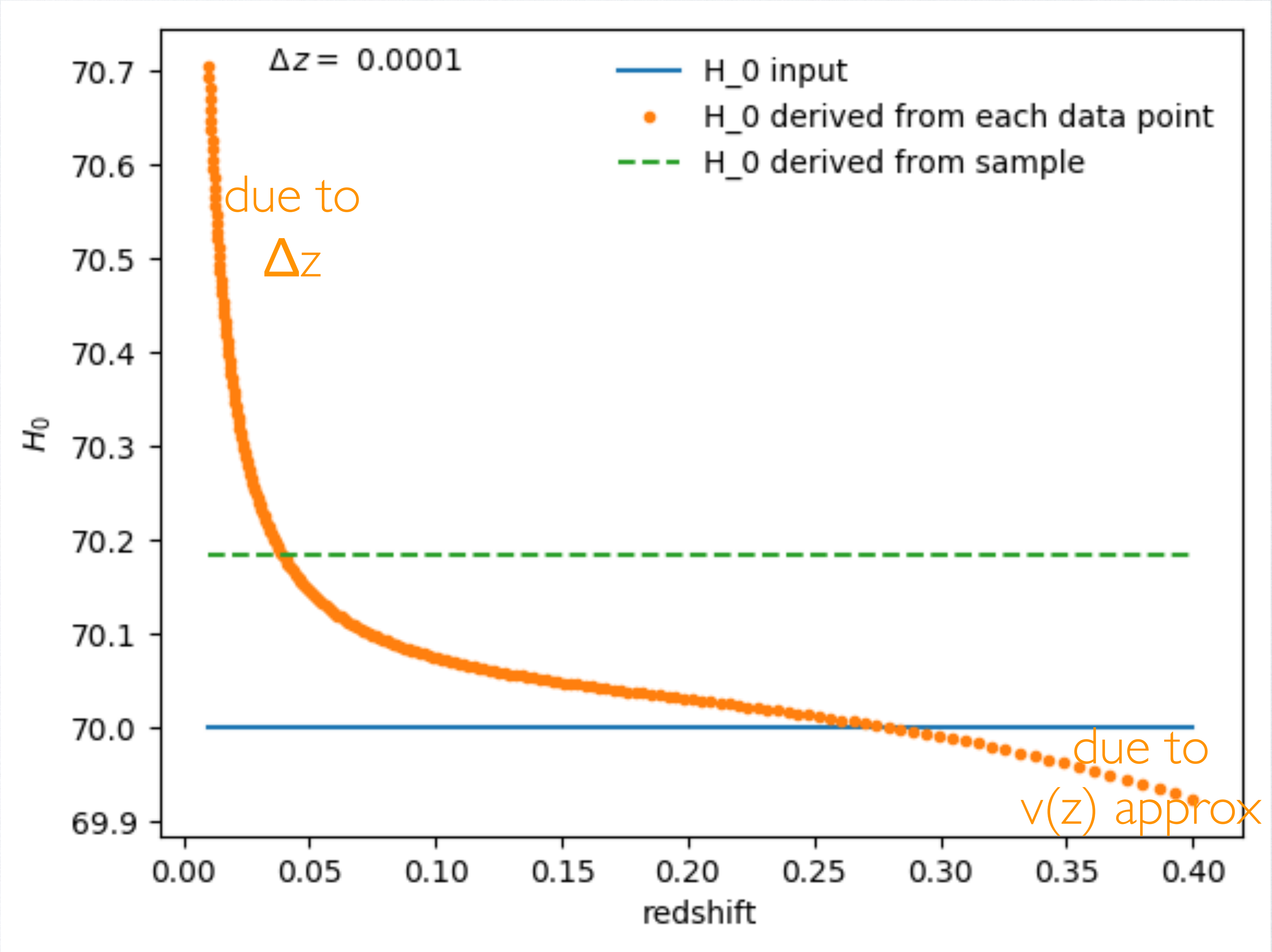
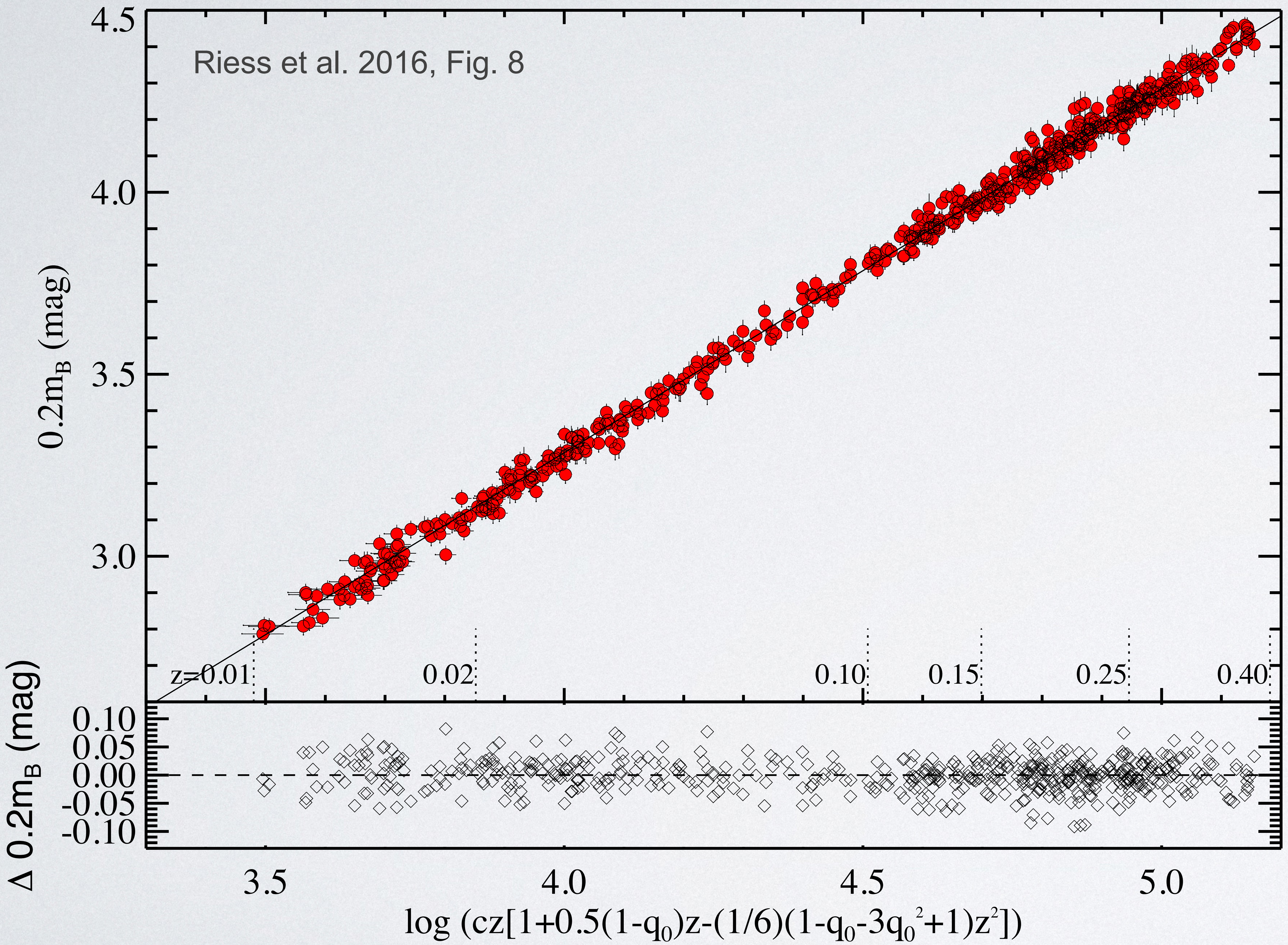


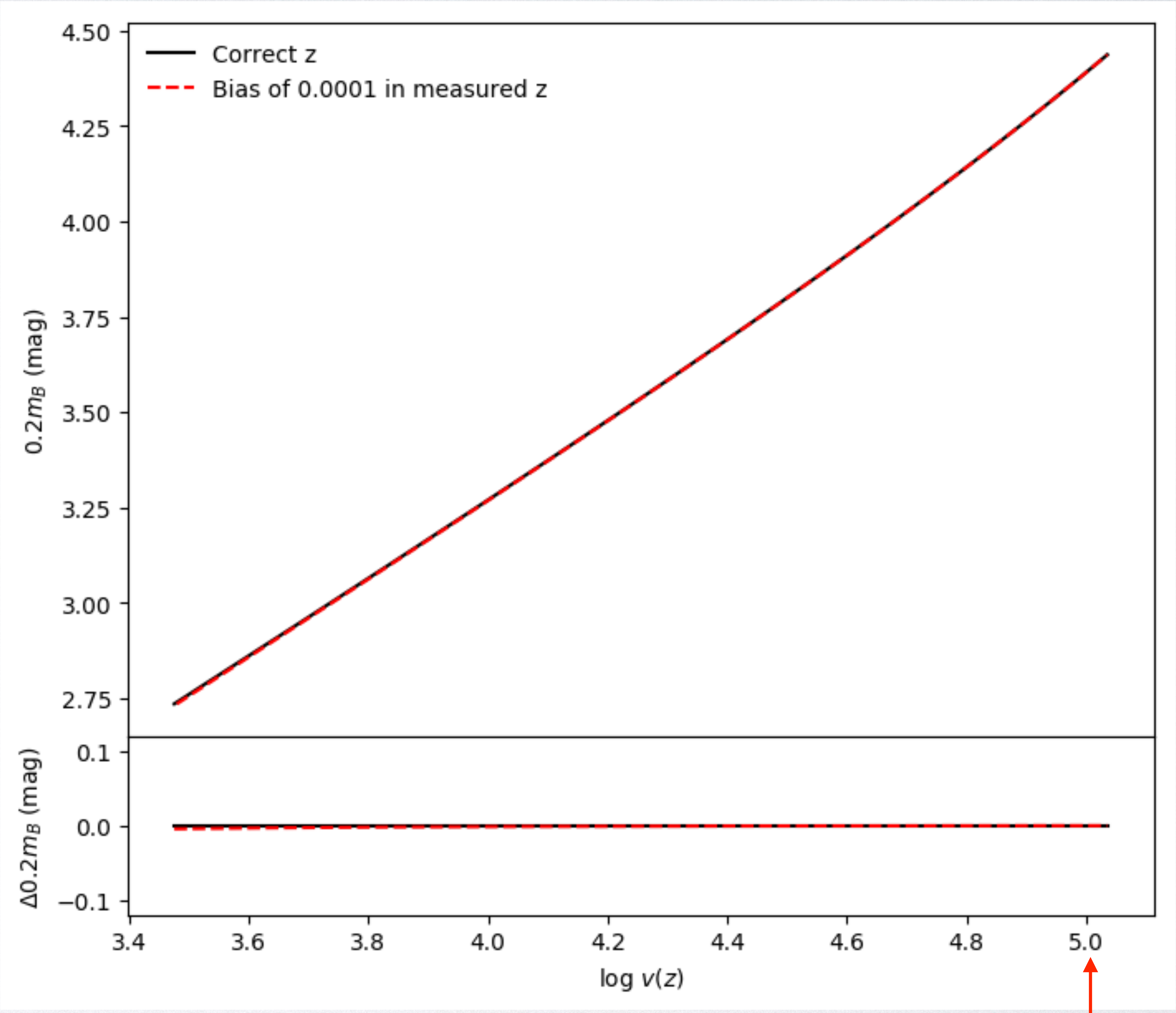


due to Δz

due to v(z) approx

SURELY WE'D HAVE NOTICED THAT, RIGHT?

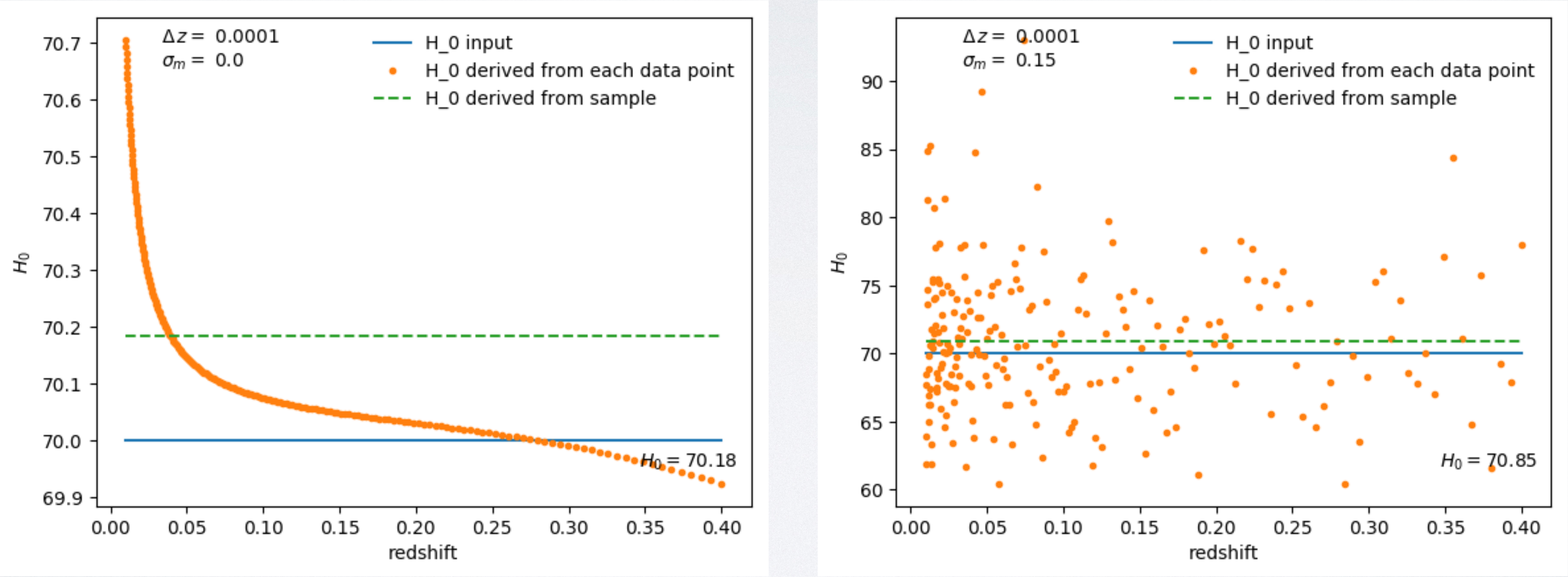




10^5 km/s

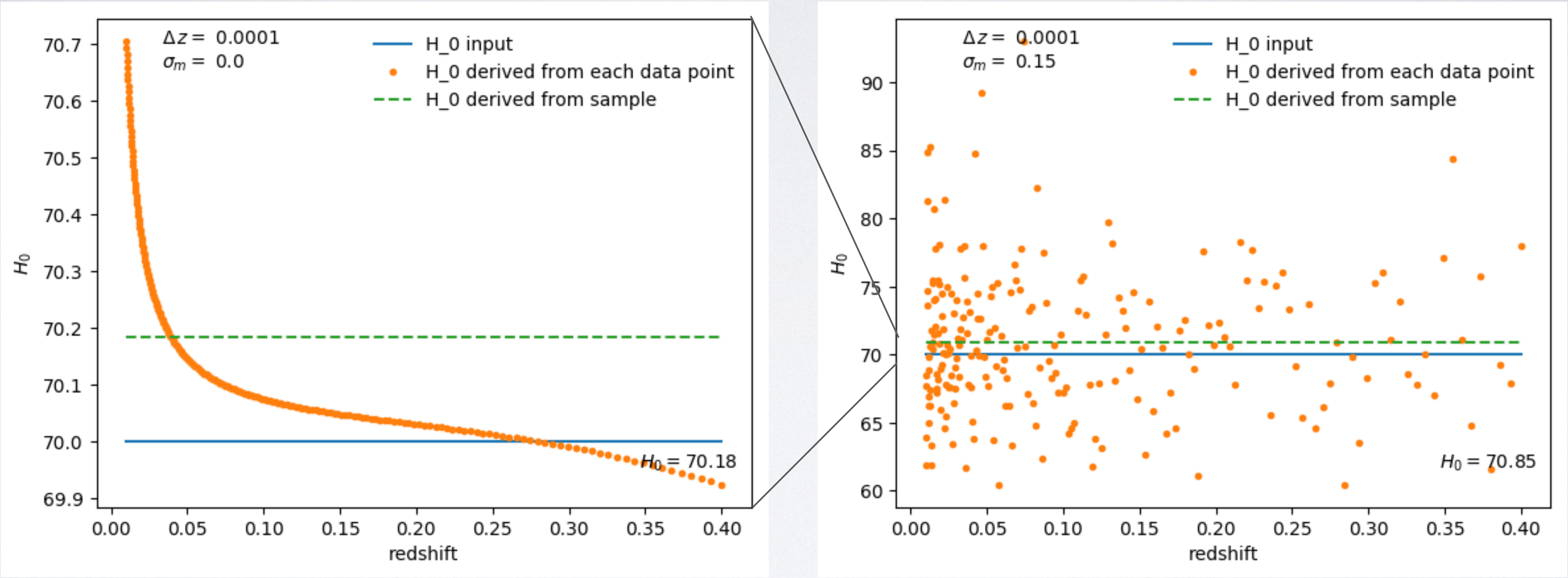
∴ small % errors in velocity matter

SCATTER VERSION OF H_0 VS Z



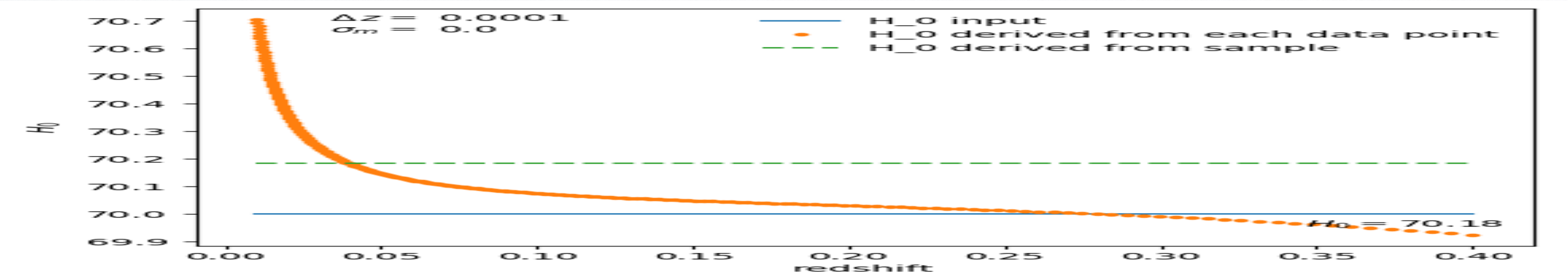
magnitude error of 0.15 mag

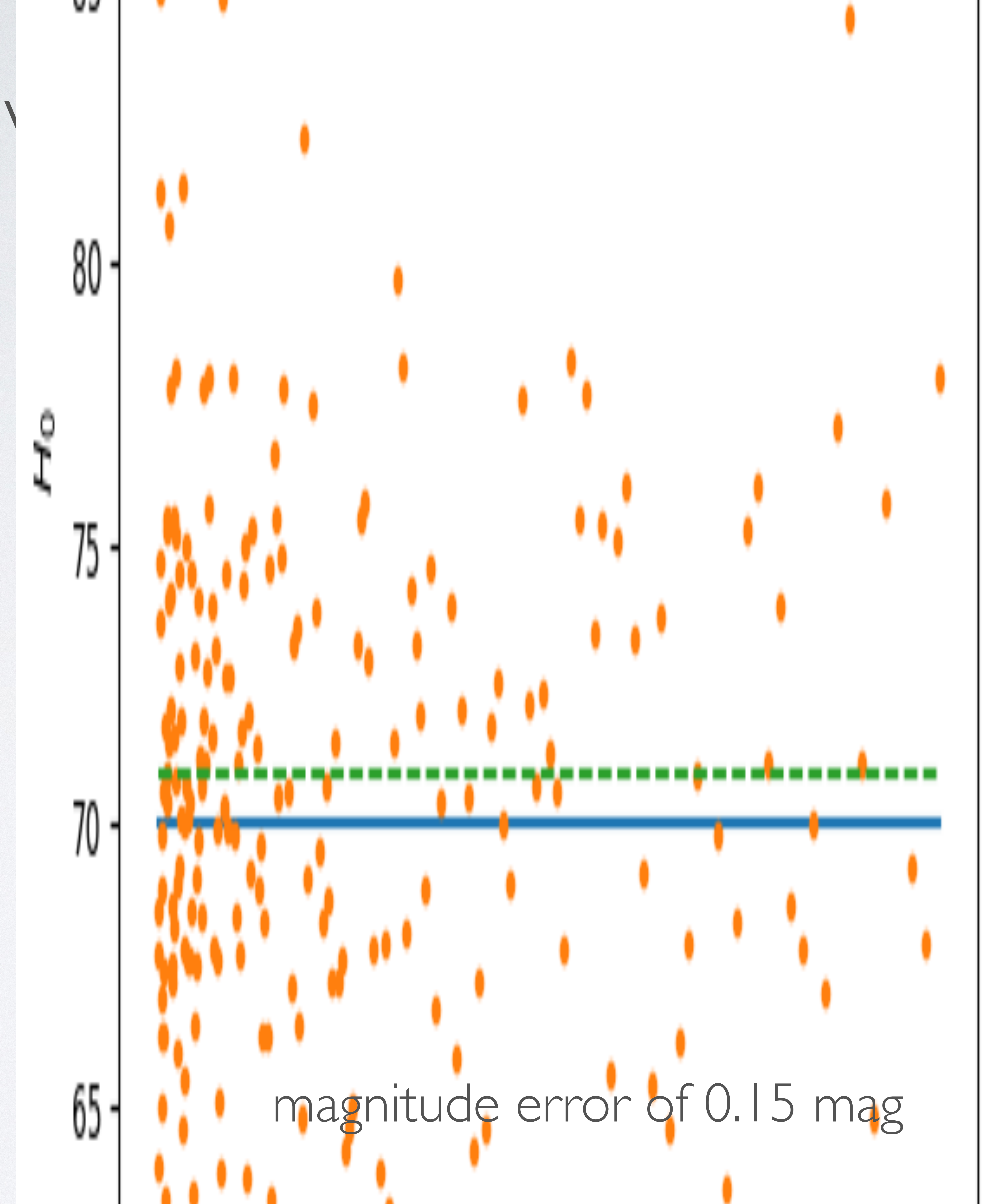
SCATTER VERSION OF H_0 VS Z



magnitude error of 0.15 mag

SCATTER VERSION OF H_0

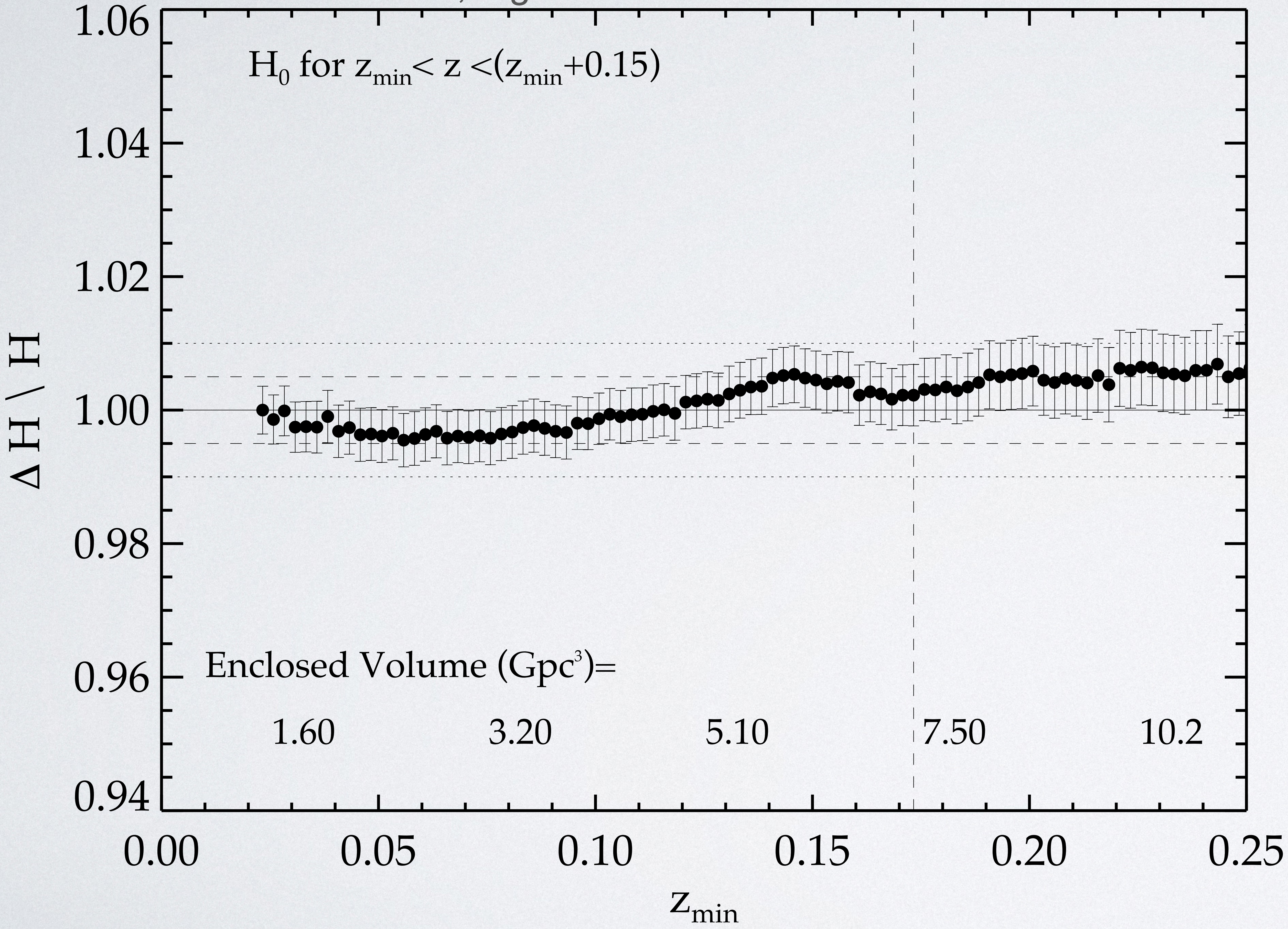




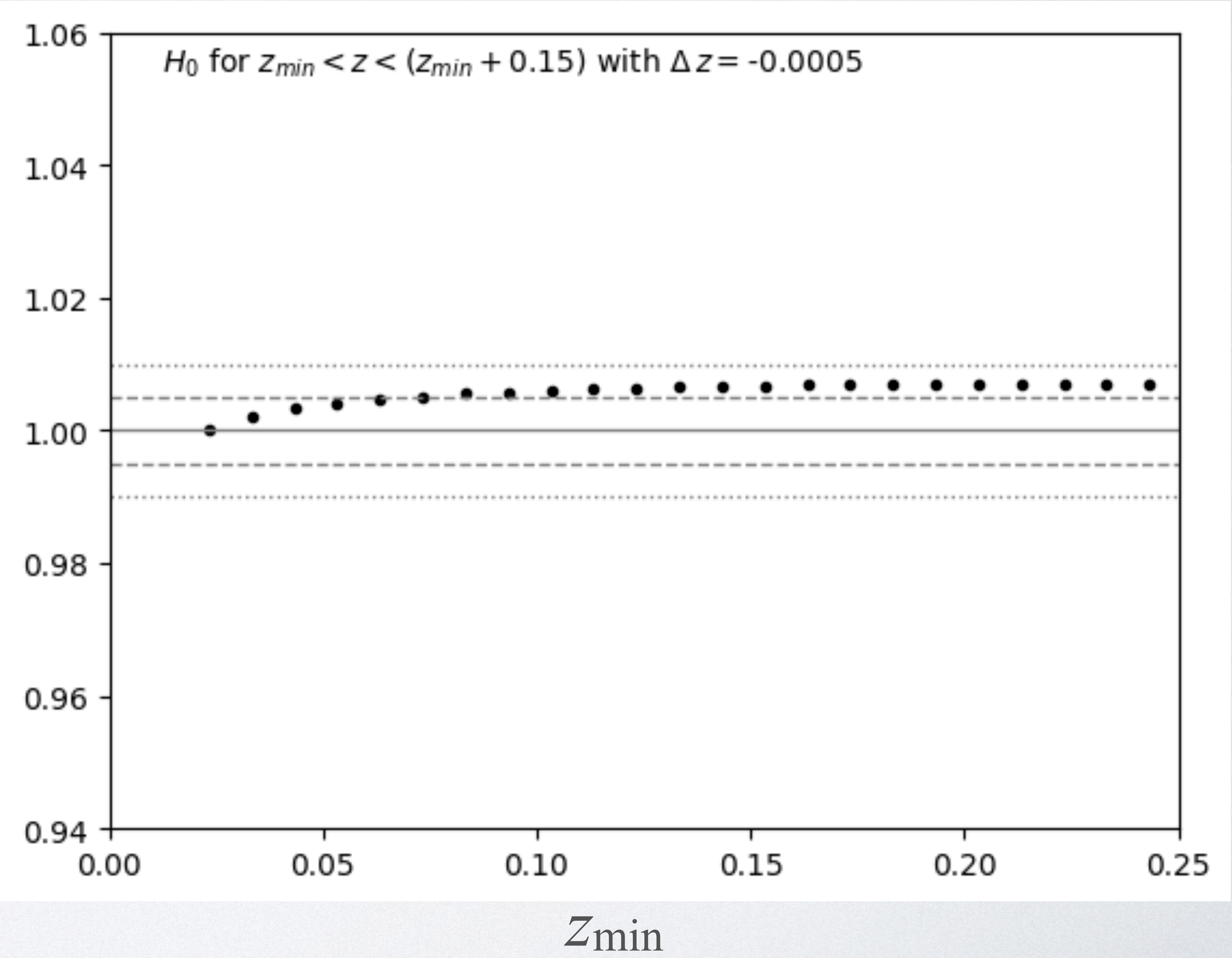
magnitude error of 0.15 mag

HOW LARGE A REDSHIFT ERROR WOULD SIGNIFICANTLY CHANGE H_0?

Riess et al. 2016, Figure 12



See also Calcino et al. 2016, Fig. 3



CHOOSE YOUR OWN ADVENTURE !

- More on how redshift errors could affect BAO
- What kinds of redshifts errors might we have in our data?

HOW LARGE COULD A REDSHIFT BIAS BE?

Observational error

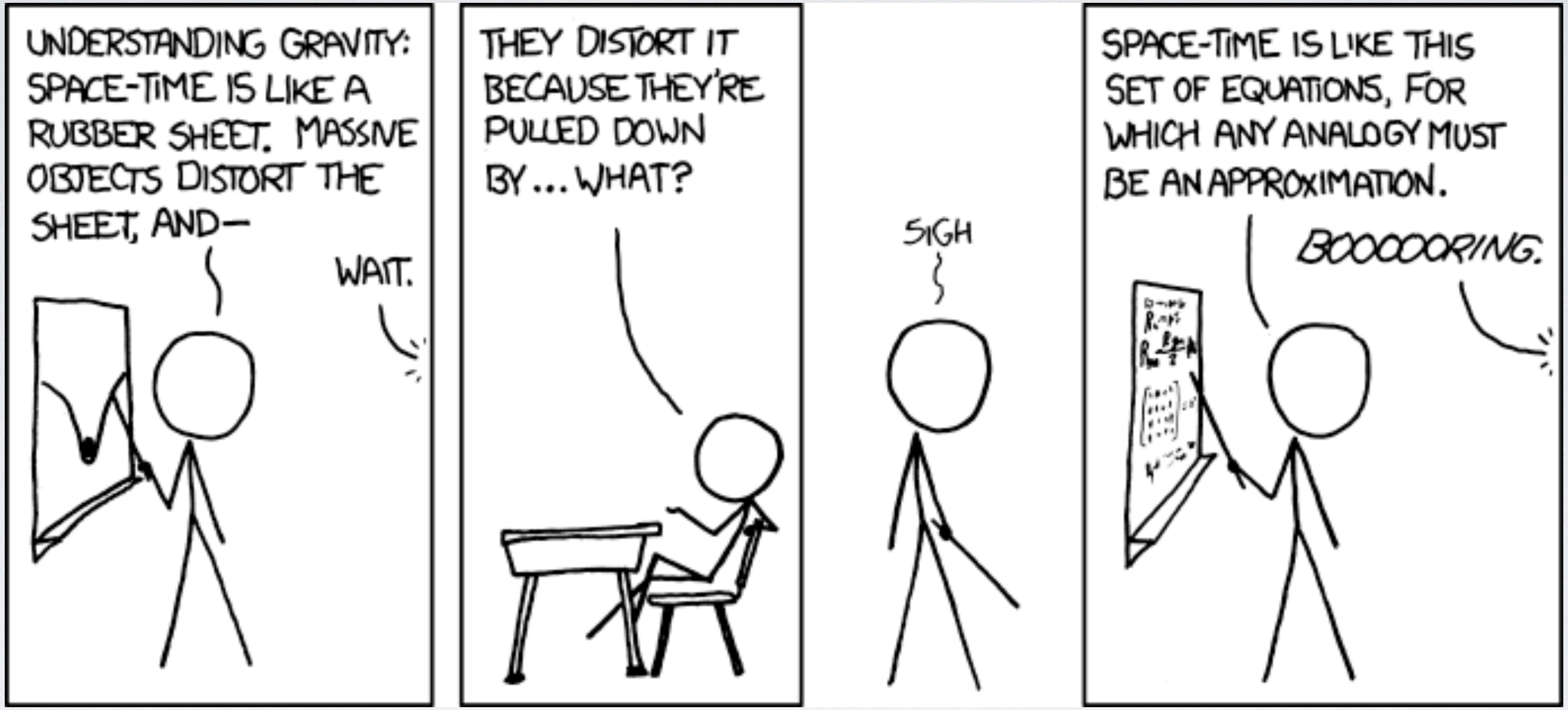
- Measurement uncertainty
- Local peculiar velocity corrections (spin, orbit, helio)
- Rest frame wavelength precision
- Air to vacuum conversion
- Spectrograph wavelength calibration
- Continuum tilt

Physical effects

- Gravitational z (local density fluct.)
- Peculiar velocities
- Bulk flows
- Internal velocities

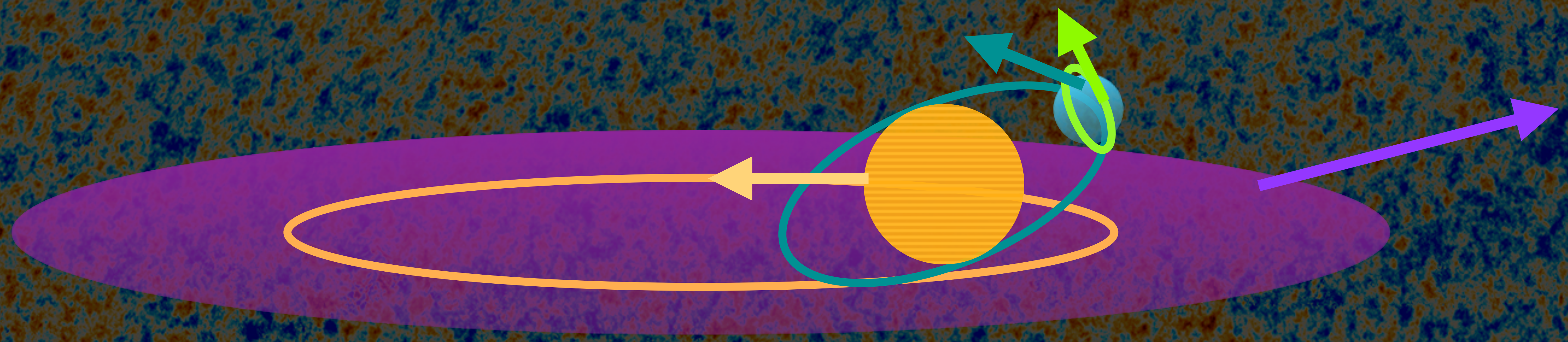
Theoretical error

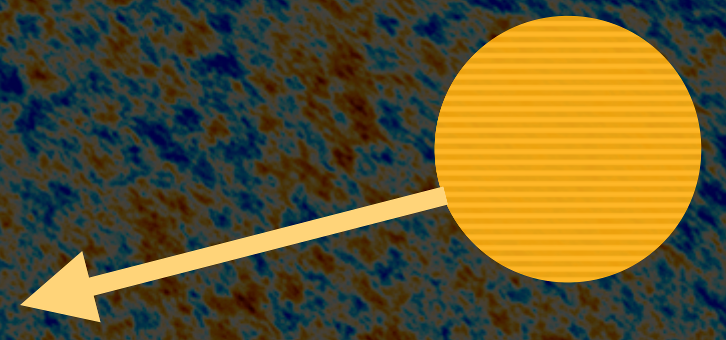
- Using (1+z) factors incorrectly
  - D_L and D_A
  - Redshift addition
- NED peculiar velocity correction



THEORETICAL EFFECTS

PECULIAR VELOCITIES





$$z_{10} \equiv \frac{\lambda_1 - \lambda_0}{\lambda_0}$$

$$1 + z_{10} \equiv \frac{\lambda_1}{\lambda_0}$$

Earth's spin

Earth about Sun (30km/s, z~10^{-4})

Sun about Galaxy (~260km/s, z~10^{-3})

Galaxy w.r.t. CMB (627km/s, z~$2\text{x}10^{-3}$)

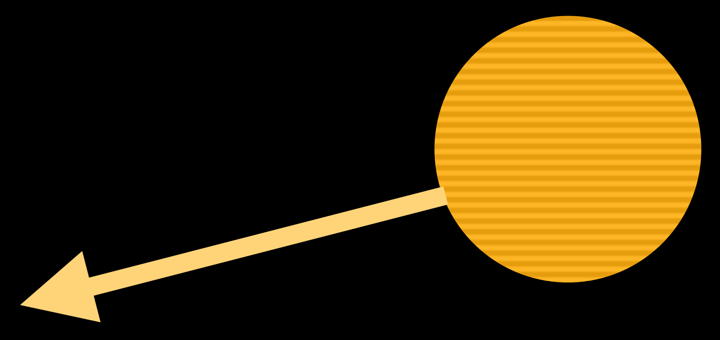
$$1 + z_{20} \equiv \frac{\lambda_2}{\lambda_0} = \frac{\lambda_2}{\lambda_1}\frac{\lambda_1}{\lambda_0} = (1 + z_{21})(1 + z_{10})$$

Sun + Galaxy (368±2 km/s , z~10^{-3})

$$1 + z_{\text{obs}} = (1 + z_{\text{rec}})(1 + z_{\text{pec}})$$

(not to scale)

PECULIAR VELOCITIES



FLRW metric

$$ds^2 = -c^2\cancel{dt^2} + R^2(t)[d\chi^2 + S_k^2(\chi)(\cancel{d\theta^2} + \sin^2(\theta)\cancel{d\phi^2})]$$

$$\boxed{ds^2 = R^2(t)\, d\chi^2}$$

along $dt = d\theta = d\phi = 0$

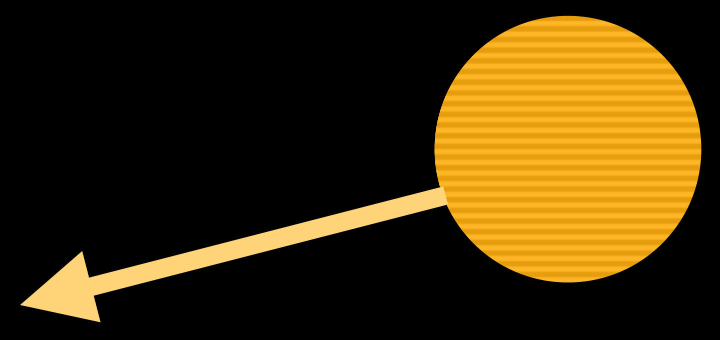
$$D = R\chi$$

$$v_{\rm tot} = \dot{R}\chi + R\dot{\chi}$$

$$v_{\rm tot} = \frac{\dot{R}}{R}R\chi + R\dot{\chi}$$

$$v_{\rm tot} = HD + v_{\rm pec}$$

PECULIAR VELOCITIES



FLRW metric

$$\cancel{ds^2} = -c^2dt^2 + R^2(t)[d\chi^2 + S_k^2(\chi)(\cancel{d\theta^2} + \sin^2(\theta)\cancel{d\phi^2})]$$

$$\boxed{0 = -c^2dt^2 + R^2(t)\; d\chi^2}$$

along $ds = d\theta = d\phi = 0$

$$D = R\chi$$

$$\boxed{c = R\frac{d\chi}{dt}}$$

$$v_{\text{tot}} = \dot{R}\chi + R\dot{\chi}$$

$$v_{\text{tot}} = \frac{\dot{R}}{R}R\chi + R\dot{\chi}$$

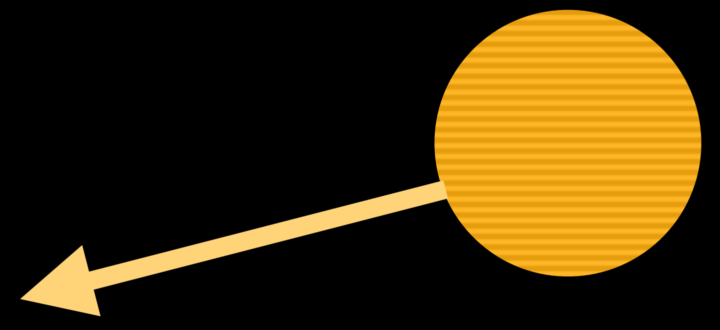
$$v_{\text{tot}} = HD + v_{\text{pec}}$$

(Why recession velocities can exceed the speed of light without violating relativity.)

PECULIAR VELOCITIES

FLRW metric

$$ds^2 = -\, c^2\cancel{dt^2} + R^2(t)[d\chi^2 + S_k^2(\chi)(\cancel{d\theta^2} + \sin^2(\theta)\cancel{d\phi^2})]$$



$$\boxed{ds^2 = \qquad R^2(t)\; d\chi^2}$$

along $dt = d\theta = d\phi = 0$

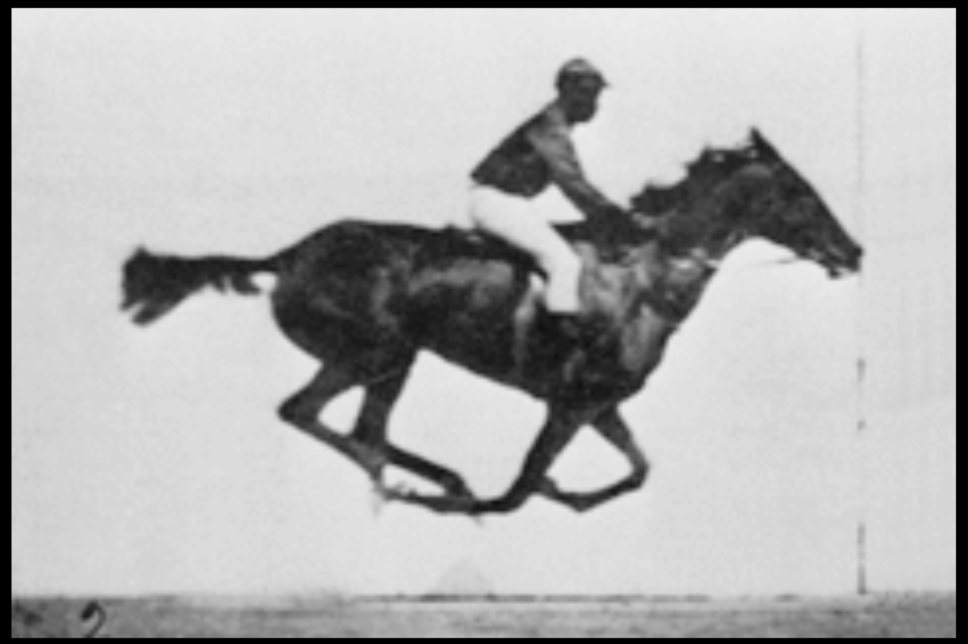
$$D = R\chi$$

$$v_{\text{tot}} = \dot{R}\chi + R\dot{\chi}$$

$$v_{\text{tot}} = \frac{\dot{R}}{R}R\chi + R\dot{\chi}$$

$$v_{\text{tot}} = HD + v_{\text{pec}} \quad \sim cz_{\text{obs}}$$

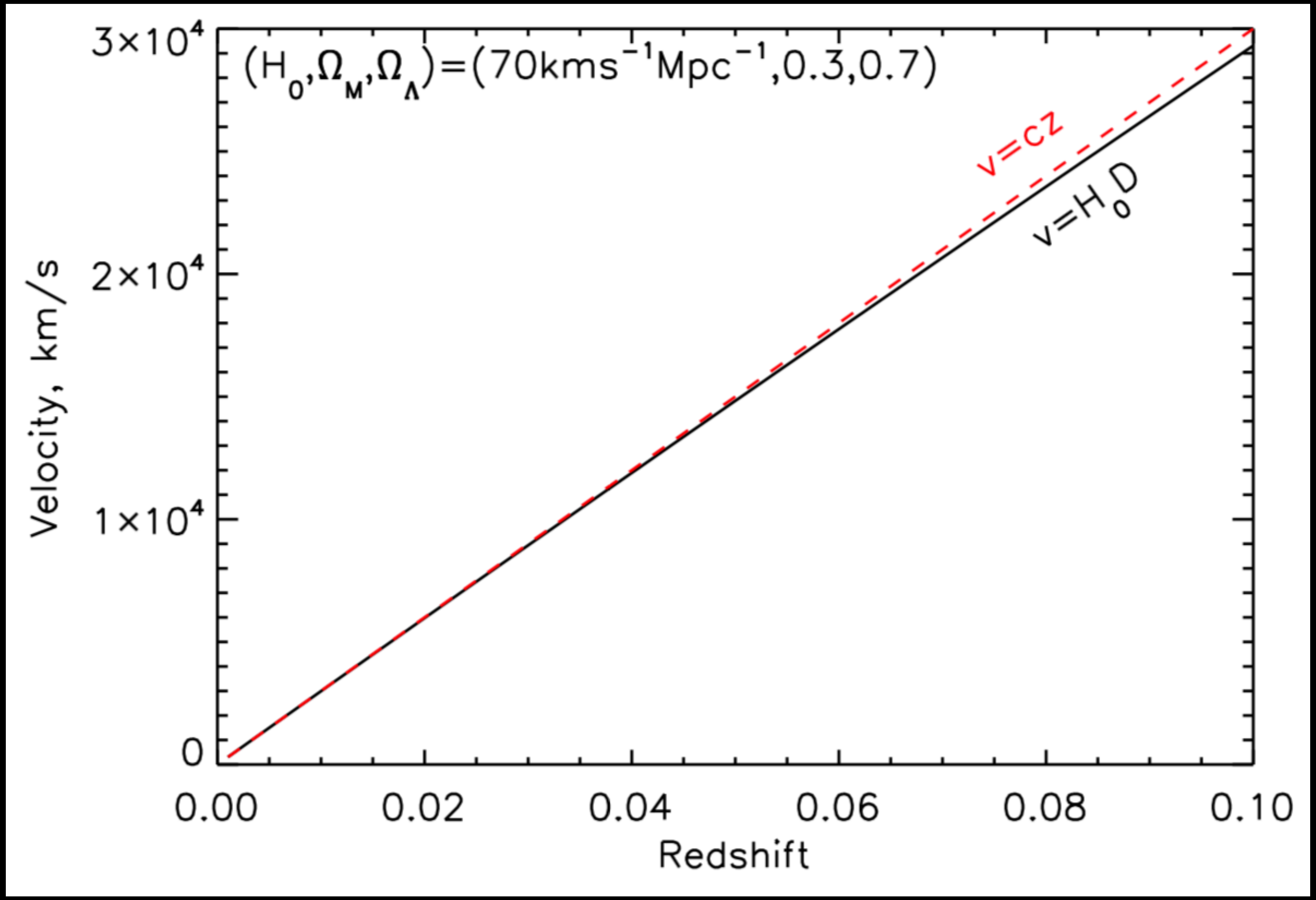
at $z \ll 1$

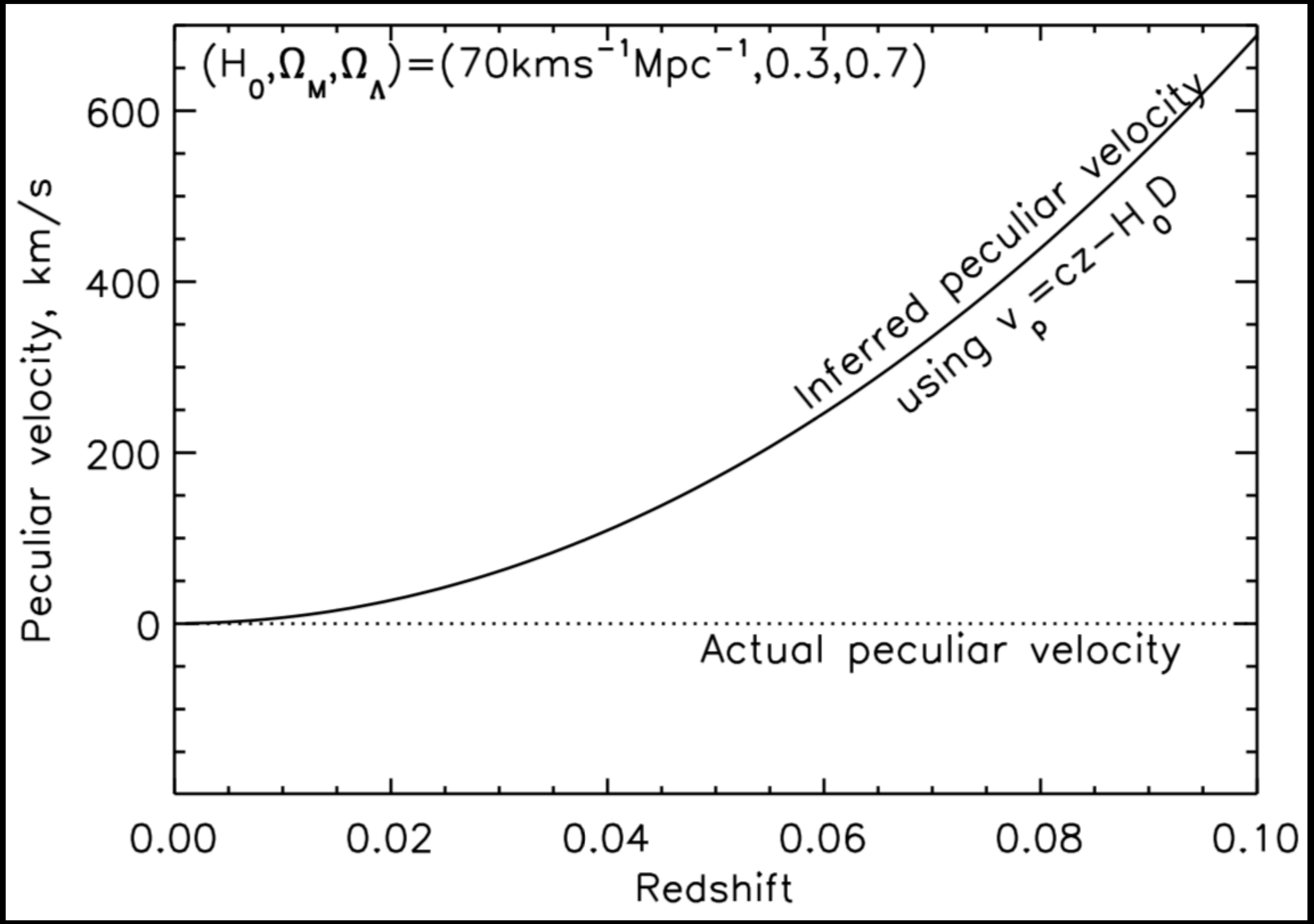


$$\cancel{v_{\text{pec}} = cz = H_0 D}$$

Davis and Scrimgeour 2014

Imagine $v_{\mathrm{pec}}=0$ and you use $v_{\mathrm{tot}}=cz$



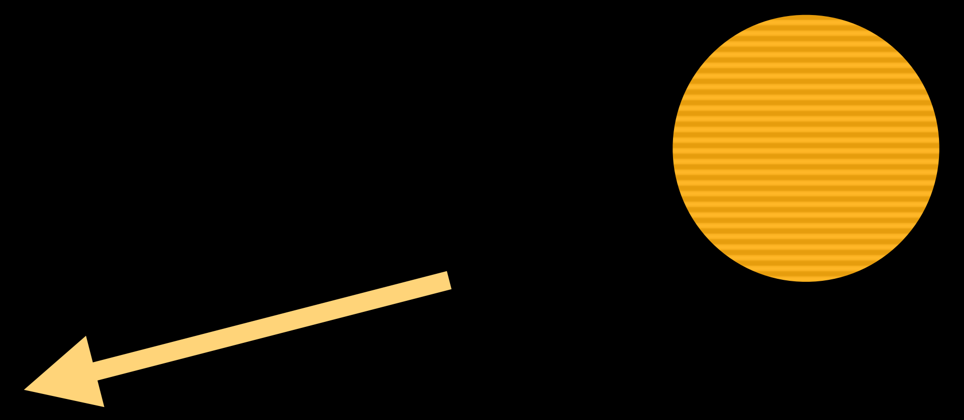


Looks like a small deviation…
… but look at the scale on the y-axis

Error of **700km/s** at $z \sim 0.1$!!!

$z_{\mathrm{error}} = 2.3\mathrm{x}10^{-3}$

PECULIAR VELOCITIES



Solution: Don't convert to velocities!! Just use the (1+z) redshift formula.

$$\cancel{v_{\rm pec} = \underset{v_{\rm tot}}{\boxed{cz}} = H_0 D}$$

observed redshift

redshift inferred from distance (magnitude)

$$v_{\rm pec} = c\,\frac{\boxed{z_{\rm obs}} - \boxed{\bar{z}}}{1 + \bar{z}}$$

$$R_0 \chi = c \int_0^{\bar{z}} \frac{dz}{H(z)}$$

If you absolutely must convert to velocities, use the observed redshift in:

$$v_{\rm tot}(z) = \frac{cz}{1+z}\left[1 + \frac{1}{2}(1-q_0)z - \frac{1}{6}(1 - q_0 - 3q_0^2 + j_0)z^2\right]$$

Distance inferred from redshift

$$\Delta d = \log \frac{\boxed{D_z}}{\boxed{D_H}}$$

Distance inferred from magnitude

Even better: converting your theory to a log distance ratio allows better comparison to observables because it gives more Gaussian uncertainties

THEORY - PECULIAR VELOCITIES

- **NED velocity calculator**

- Uses: $v_{\text{converted}} = v_{\text{original}} + v_{\text{pec}}$ (https://ned.ipac.caltech.edu/Documents/Guides/Calculators#notes)

- Common use: $v_{\text{cmb}} = v_{\text{tot}} + v_{\text{pec}}$

  Which is fine as long as you get the peculiar velocity sign correct (e.g. +ve for the direction of our sun's motion w.r.t. CMB)

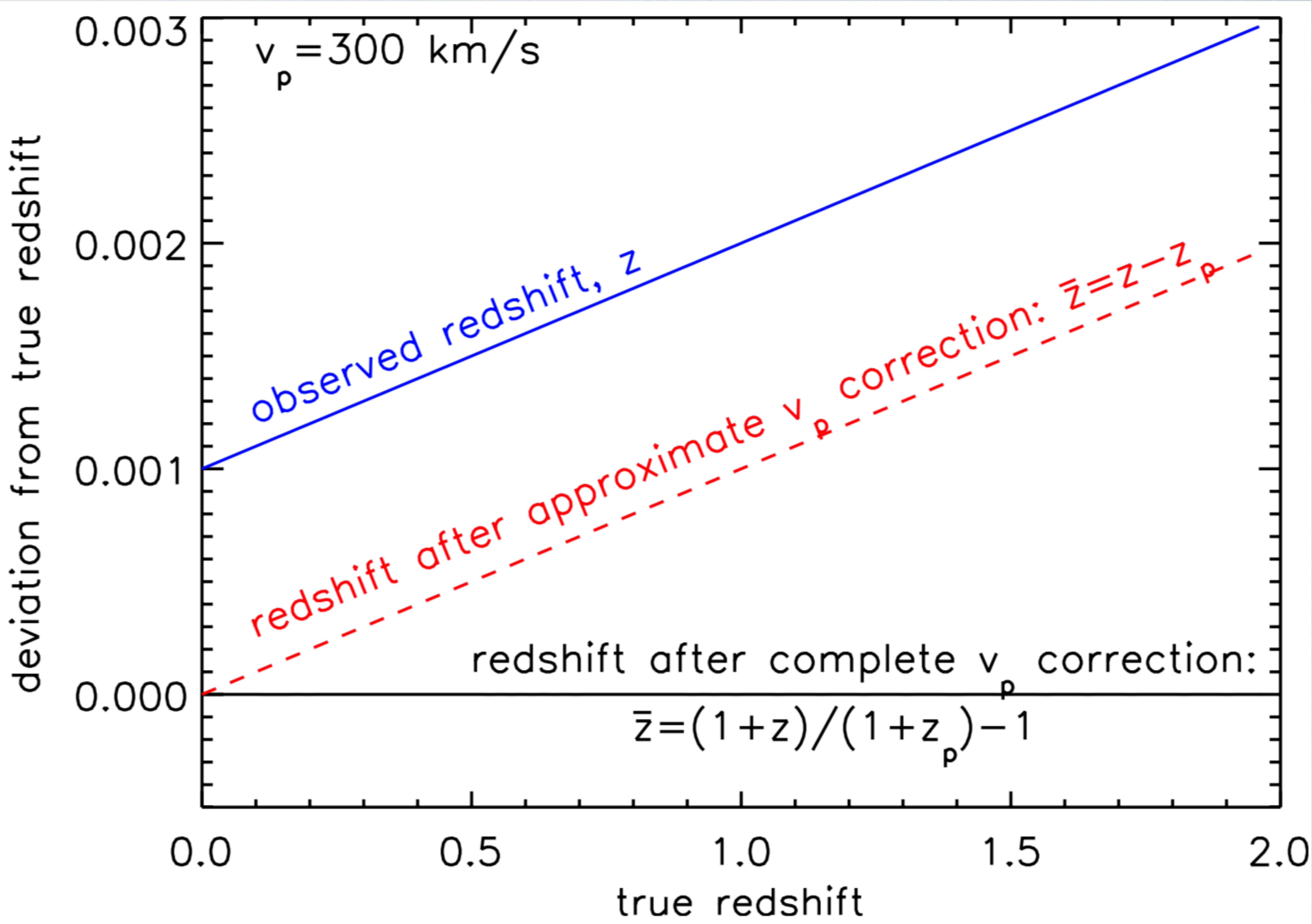
- Potentially common error: $v_{\text{tot}} = cz_{\text{obs}}$

  Which is fine at low redshifts

- Common error encouraged by explanatory notes: (https://ned.ipac.caltech.edu/Documents/References/zdef)
  - Which say: $z_{\text{tot}} = z_{\text{grav}} + z_{\text{pec}} + \bar{z}$ and $D_P = \dfrac{cz}{H_0}$

  Which are not in principle correct, and only okay at z <0.01

THEORY - PECULIAR VELC



- **NED velocity calculator**
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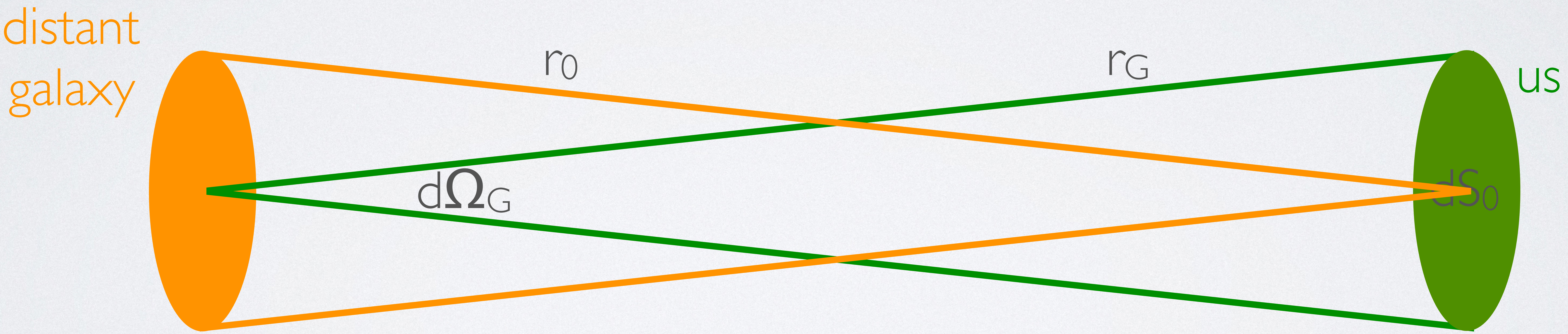
Which are not in principle correct, and only okay at z <0.01

THEORETICAL ERROR - WHICH Z?

Reciprocity relation (distance duality)
Etherington 1933

$$D_L = \tilde{D}(1+z)$$
$$D_A = \tilde{D}/(1+z)$$

$$\tilde{D} = \begin{cases} R_0 \sin(\chi) & \text{closed} \\ R_0 \chi & \text{flat} \\ R_0 \sinh(\chi) & \text{open} \end{cases}$$



But which redshifts should we use?

Ellis, G.F.R.: Relativistic Cosmology. In: Sachs, R.K. [illegible] School of Physics "Enrico Fermi" (Varenna), Course XLVII, pp. 104–179(1971)

Weinberg, S.W.: Gravitation and Cosmology:Principles and applications [illegible]

Etherington 1933
[illegible]

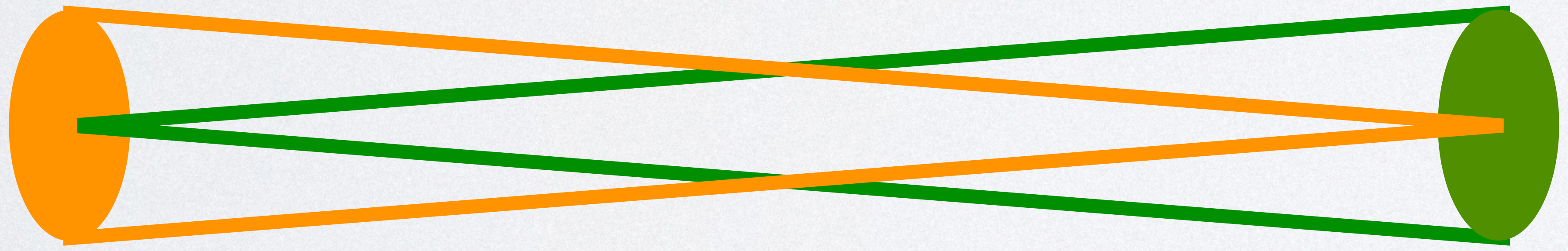
THEORETICAL ERROR - WHICH Z?

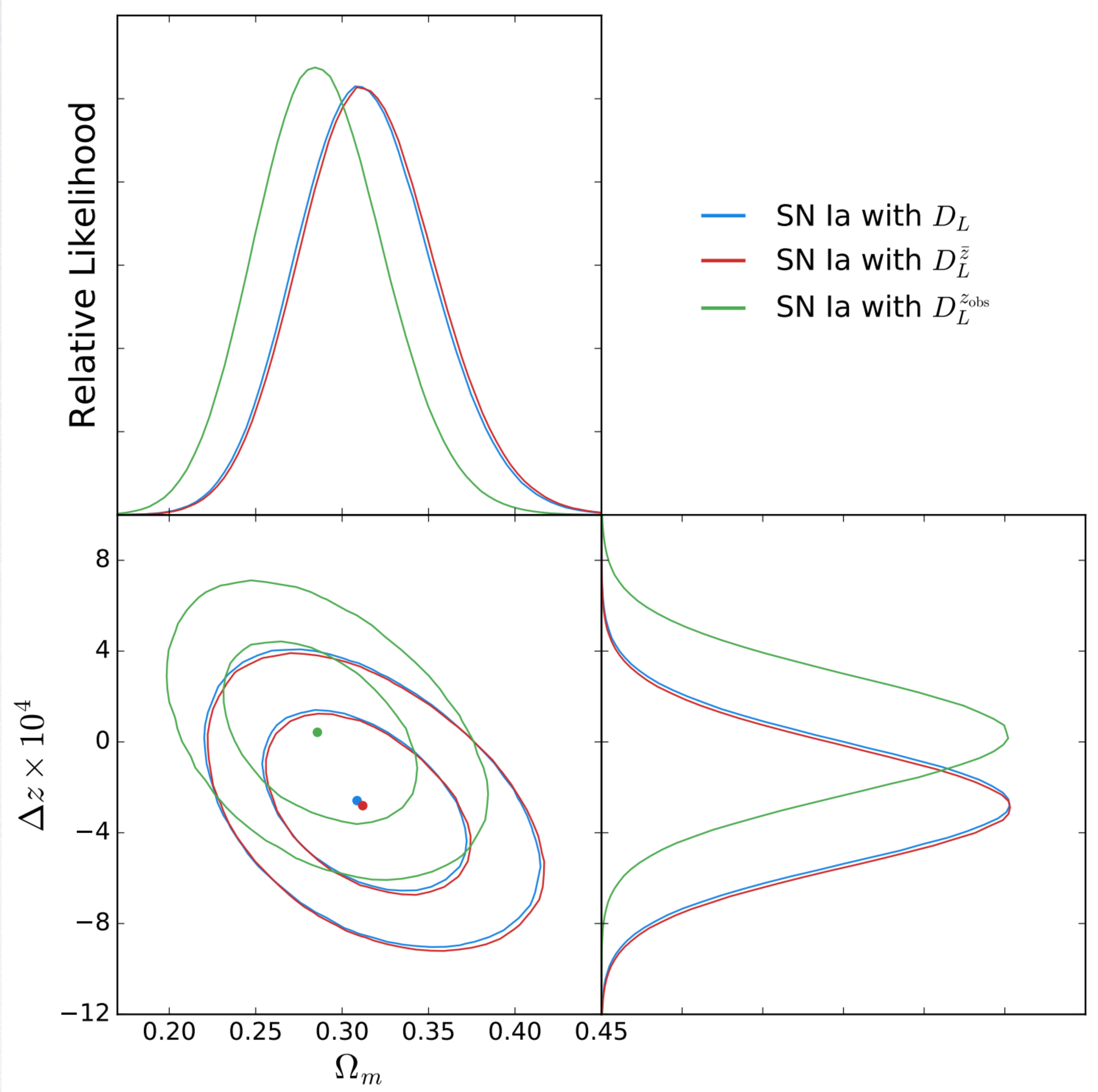
Which redshifts should we use in angular diameter and luminosity distances?

$$D_L(\bar{z}, z_{\rm obs}) = \tilde{D}(\bar{z})(1 + z_{\rm obs})$$
$$D_A(\bar{z}, z_{\rm obs}) = \tilde{D}(\bar{z})/(1 + z_{\rm obs})$$

CMB frame (cosmological) redshift

observed redshift





Calcino et al. 2017 (arXiv:1610.07695) + honours thesis

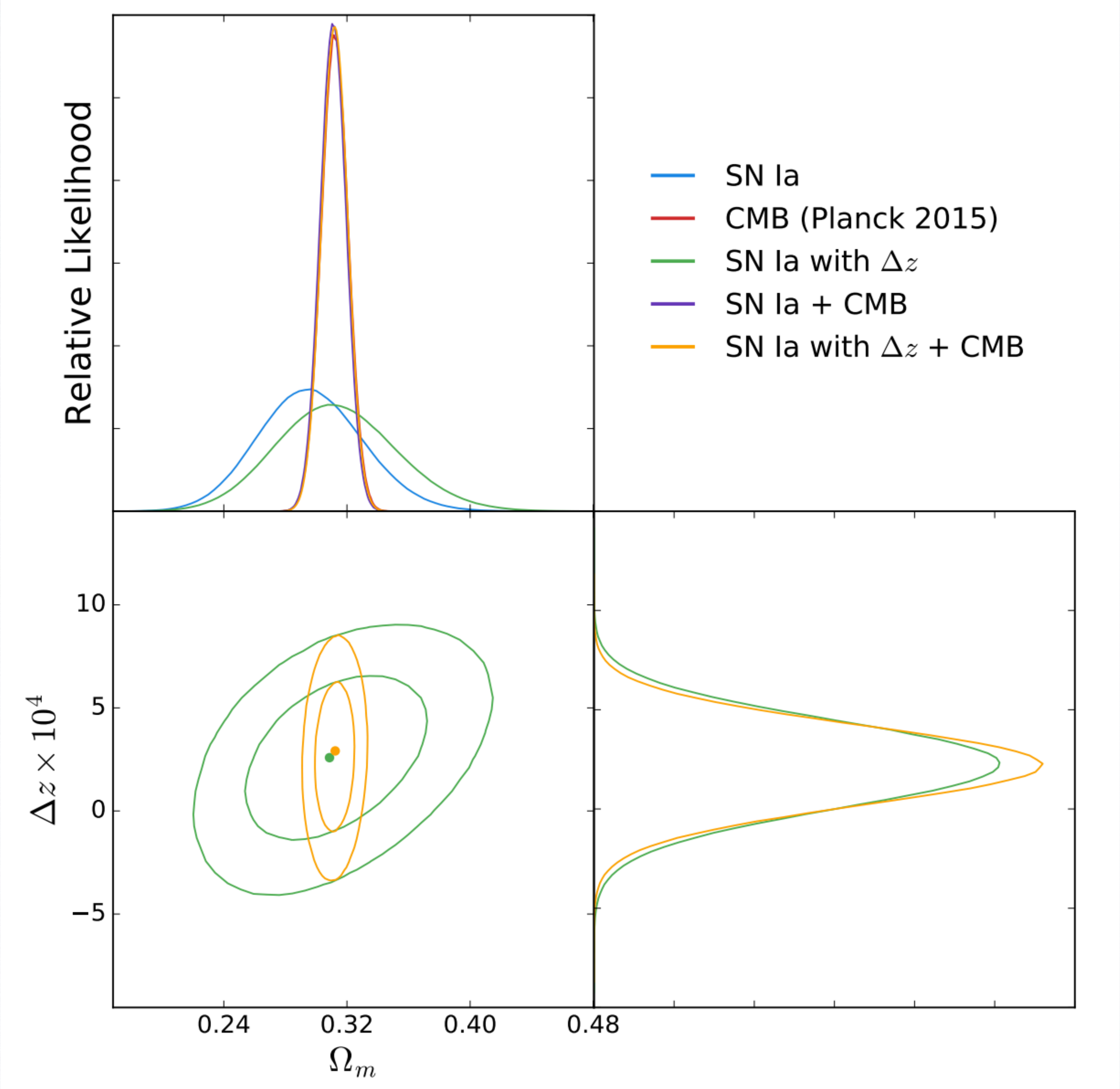
1. Ellis, G.F.R.: Relativistic Cosmology. In: Sachs, R.K. (ed.) General Relativity and Cosmology, Proc Int School of Physics “Enrico Fermi” (Varenna), Course XLVII, pp. 104–179. Academic Press, New York (1971)

2. Weinberg, S.W.: Gravitation and Cosmology:Principles and applications of the general theory of relativity. Wiley, New York (1972)

IS THERE EVIDENCE FOR A REDSHIFT SHIFT?

Allow **Δ**z as a free parameter

$$d_L = \begin{cases} (1 + z_{\text{hel}})d(z_{\text{cmb}}) \\ (1 + z_{\text{hel}} + \Delta z)d(z_{\text{cmb}} + \Delta z) \end{cases}$$



HOW LARGE COULD A REDSHIFT BIAS BE?

Observational error

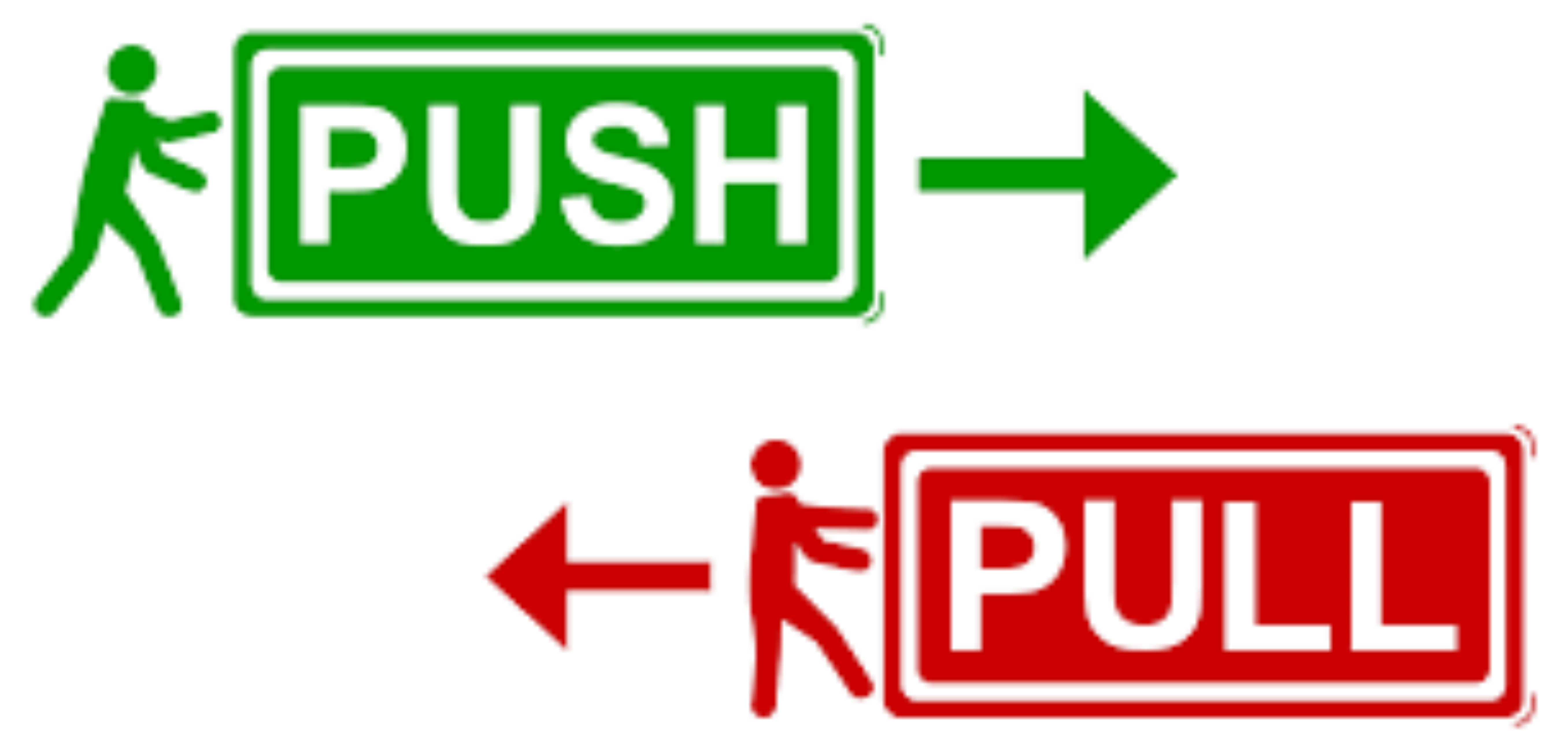
- Measurement uncertainty
- Local peculiar velocity corrections (spin, orbit, helio)
- Rest frame wavelength precision
- Air to vacuum conversion
- Spectrograph wavelength calibration
- Continuum tilt

Physical effects

- Gravitational z (local density fluct.)
- Peculiar velocities
- Bulk flows
- Internal velocities

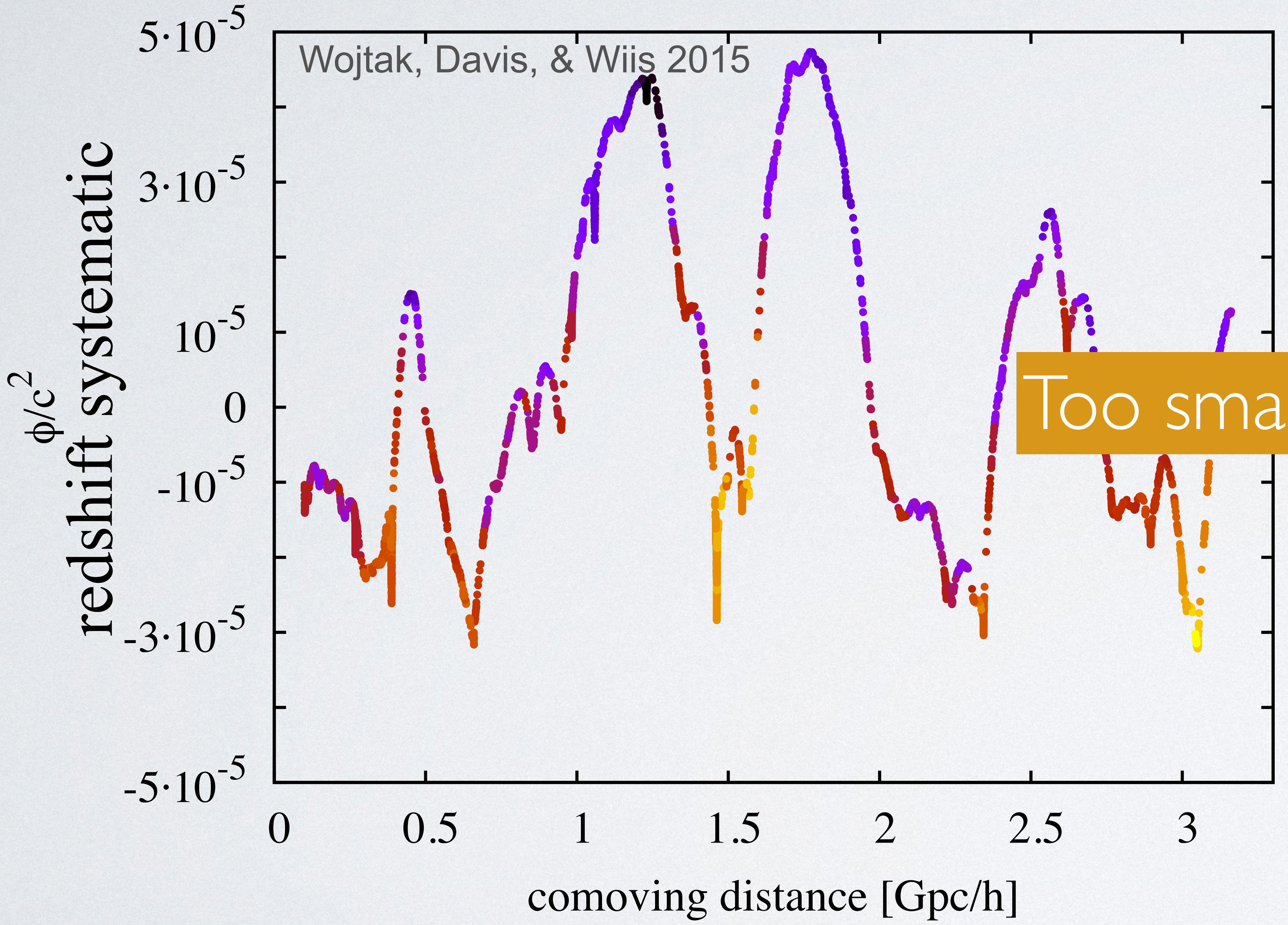
~~Theoretical error~~

- ~~Using (1+z) factors incorrectly~~
  - ~~D_L and D_A~~
  - ~~Redshift addition~~
- ~~NED peculiar velocity correction~~



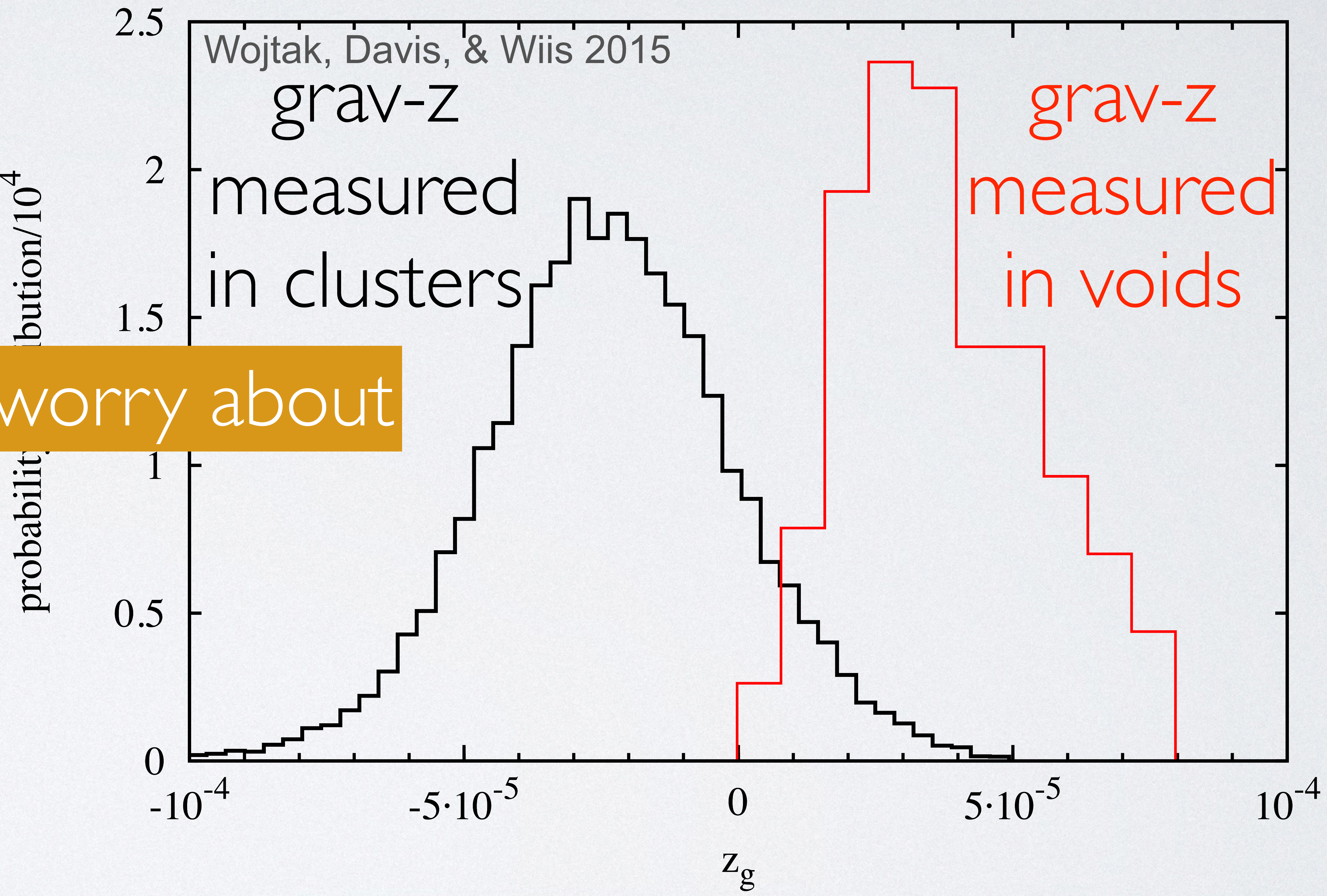
PHYSICAL EFFECTS

PHYSICAL EFFECTS - GRAVITATIONAL REDSHIFTS



Sim from MultiDark database:
$\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$, $\sigma_8 = 0.82$

Probability distribution of the gravitational redshift measured by observers in clusters or voids at z = 0.



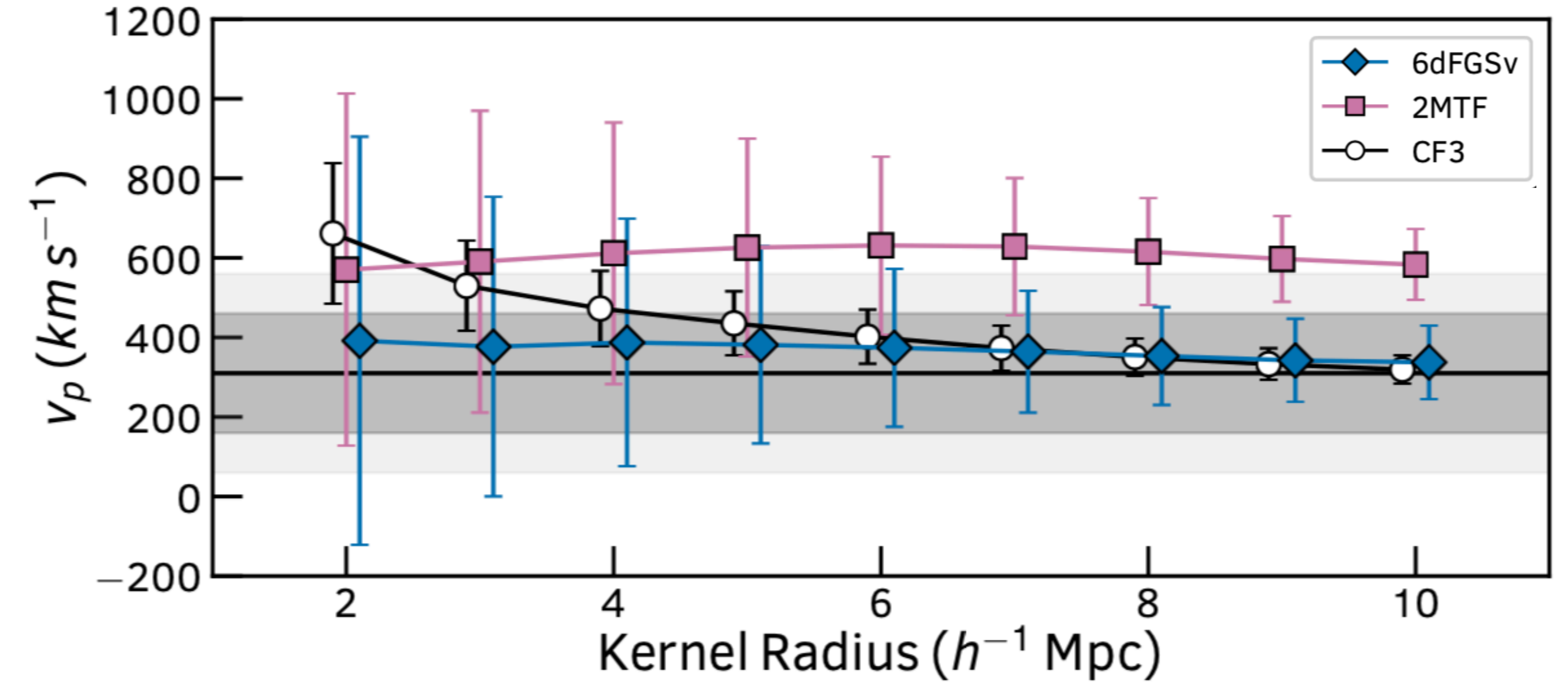
Too small to worry about

Observers in **underdense** env. tend to measure a + signal (gravitational **redshift**),
whereas those in galaxy **clusters** tend to observe a - signal (gravitational **blueshift**).

PHYSICAL EFFECTS - PECULIAR VELOCITIES

- The peculiar velocity correction is uncertain:
  - Small scale velocities
  - Bulk flows

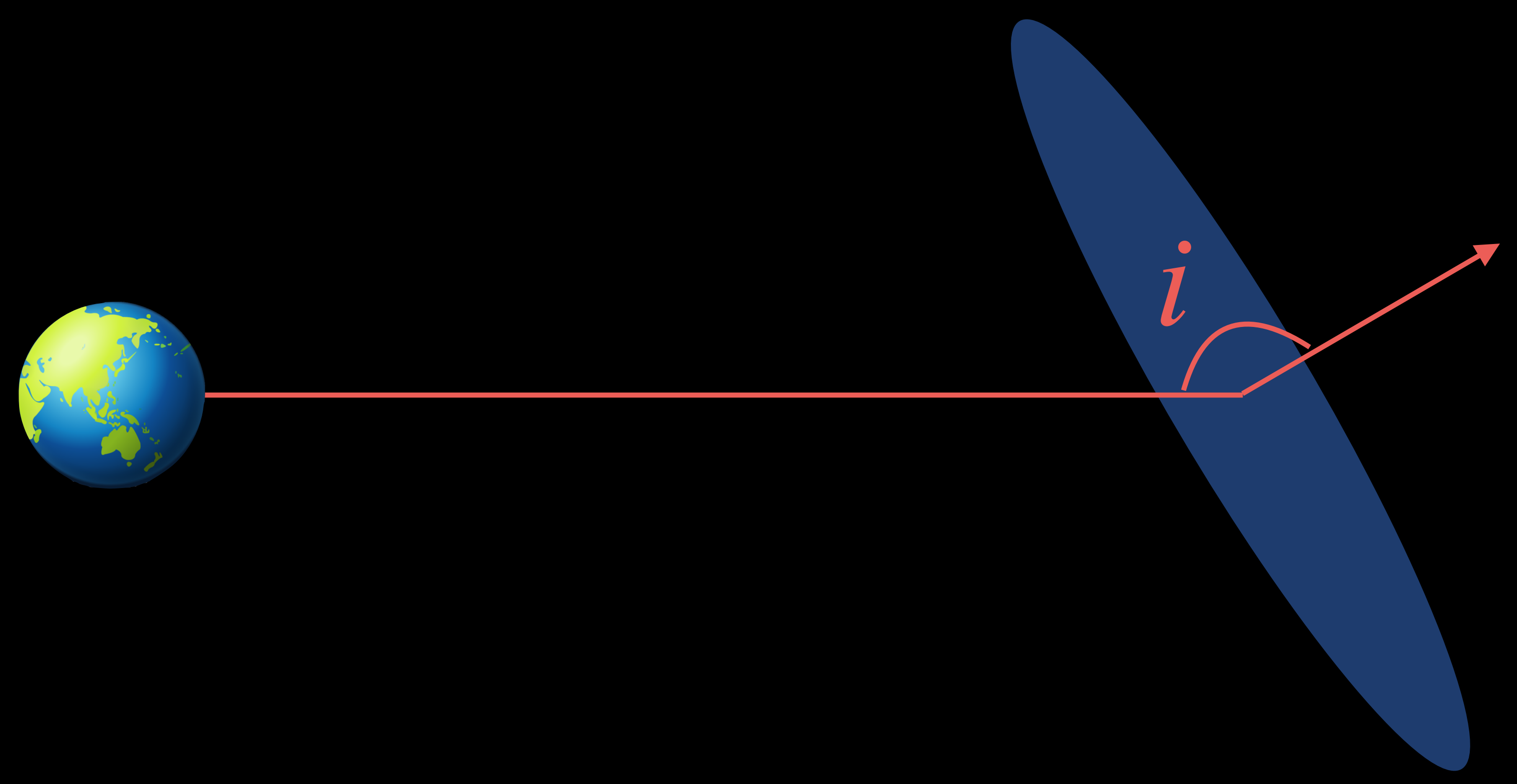
Howlett et al. (in prep)



Various peculiar velocity predictions in the literature for the group hosting GW170817
(Black line + shaded is the peculiar velocity used in the calculation of H_0.)

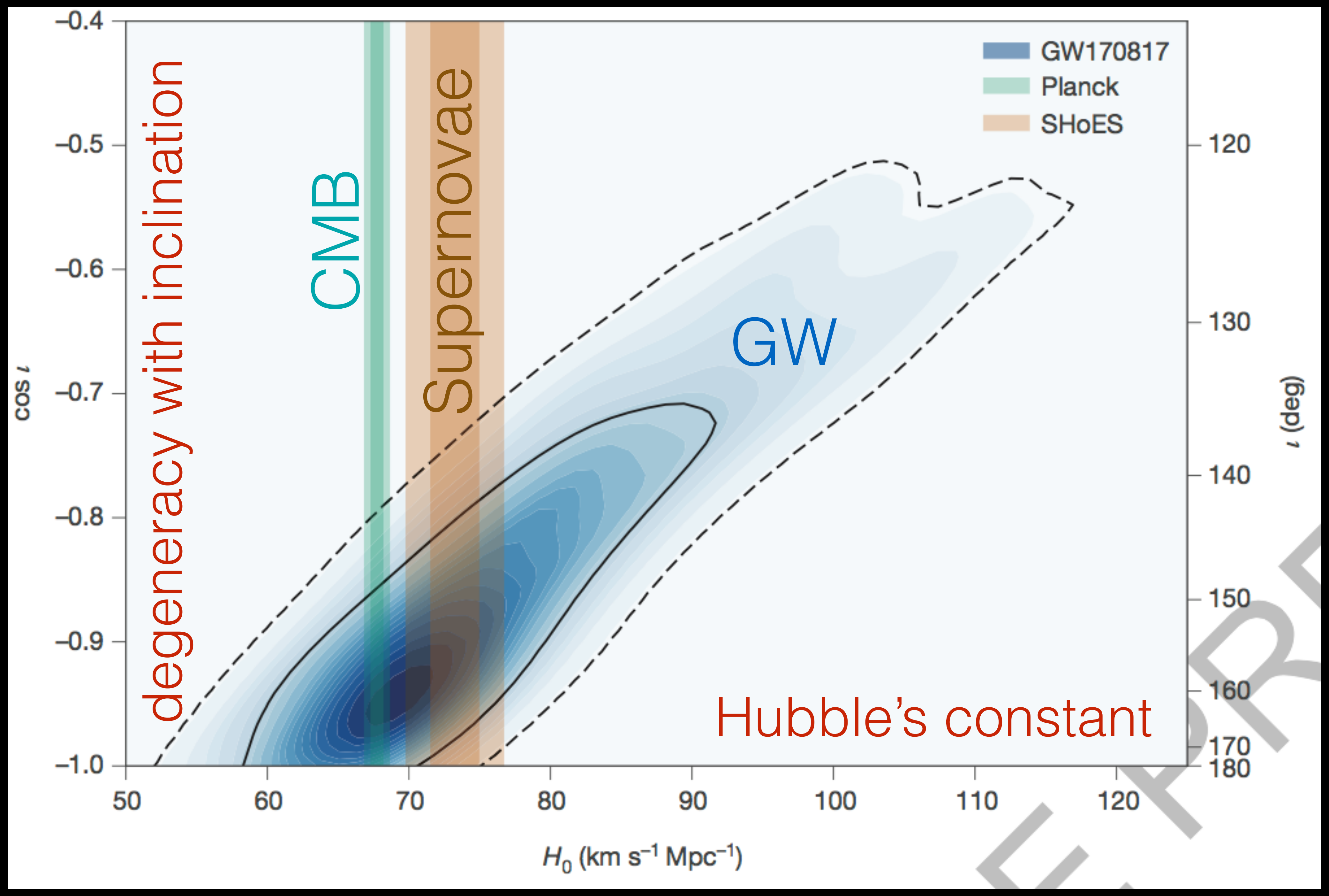
H_0 FROM GRAV WAVES

$d = 43.8^{+2.9}_{-6.9}$ Mpc (z~0.01)



$H_0 = 70.0^{+12.0}_{-8.0}$ Mpc

1710.05835.pdf



Peculiar velocity correction:

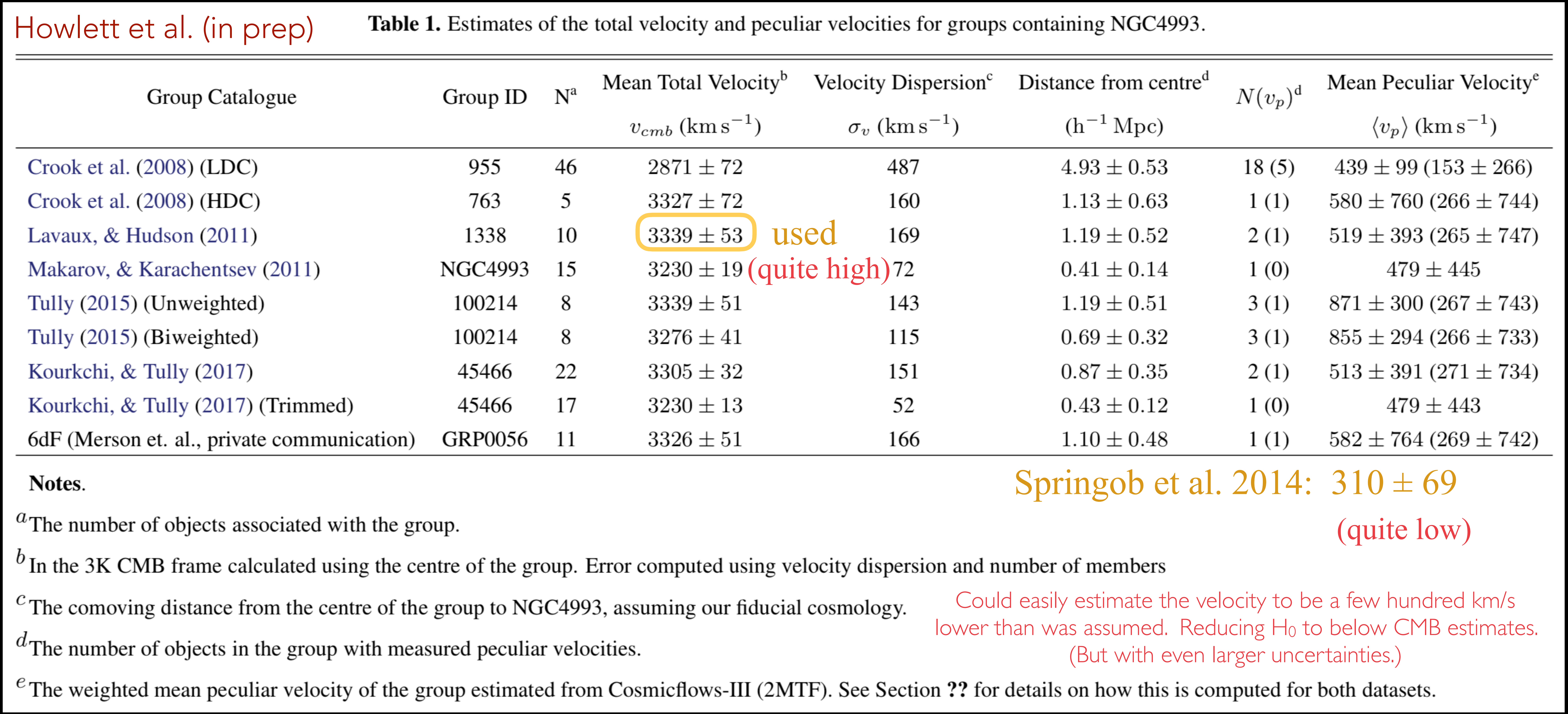
1. Assume it has the v_{tot} of the group 3327 ± 72 km/s
2. Measure $v_{pec} = 310 \pm 69$ km/s by mapping the velocity field (6dF; Springob et al. 2014)
3. Subtract from v_{pec} to get $v_{rec} = 3017 \pm 166$ km s^{-1} (error increased due to other uncertainties)

Using this gives peak H_0=76km/s/Mpc

Using this gives peak H_0=69km/s/Mpc

pec. vel. correction is ~7km/s

PECULIAR VELOCITIES AND H_0 FROM GRAV WAVES



Howlett et al. (in prep)

Table 1. Estimates of the total velocity and peculiar velocities for groups containing NGC4993.

Group Catalogue	Group ID	N[a]	Mean Total Velocity[b] v_{cmb} ($\mathrm{km\,s^{-1}}$)	Velocity Dispersion[c] σ_v ($\mathrm{km\,s^{-1}}$)	Distance from centre[d] (h^{-1} Mpc)	$N(v_p)$[d]	Mean Peculiar Velocity[e] $\langle v_p \rangle$ ($\mathrm{km\,s^{-1}}$)
Crook et al. (2008) (LDC)	955	46	2871 ± 72	487	4.93 ± 0.53	18 (5)	439 ± 99 (153 ± 266)
Crook et al. (2008) (HDC)	763	5	3327 ± 72	160	1.13 ± 0.63	1 (1)	580 ± 760 (266 ± 744)
Lavaux, & Hudson (2011)	1338	10	3339 ± 53	169	1.19 ± 0.52	2 (1)	519 ± 393 (265 ± 747)
Makarov, & Karachentsev (2011)	NGC4993	15	3230 ± 19	72	0.41 ± 0.14	1 (0)	479 ± 445
Tully (2015) (Unweighted)	100214	8	3339 ± 51	143	1.19 ± 0.51	3 (1)	871 ± 300 (267 ± 743)
Tully (2015) (Biweighted)	100214	8	3276 ± 41	115	0.69 ± 0.32	3 (1)	855 ± 294 (266 ± 733)
Kourkchi, & Tully (2017)	45466	22	3305 ± 32	151	0.87 ± 0.35	2 (1)	513 ± 391 (271 ± 734)
Kourkchi, & Tully (2017) (Trimmed)	45466	17	3230 ± 13	52	0.43 ± 0.12	1 (0)	479 ± 443
6dF (Merson et. al., private communication)	GRP0056	11	3326 ± 51	166	1.10 ± 0.48	1 (1)	582 ± 764 (269 ± 742)

used

(quite high)

Springob et al. 2014: 310 ± 69

(quite low)

Notes.

[a] The number of objects associated with the group.

[b] In the 3K CMB frame calculated using the centre of the group. Error computed using velocity dispersion and number of members

[c] The comoving distance from the centre of the group to NGC4993, assuming our fiducial cosmology.

[d] The number of objects in the group with measured peculiar velocities.

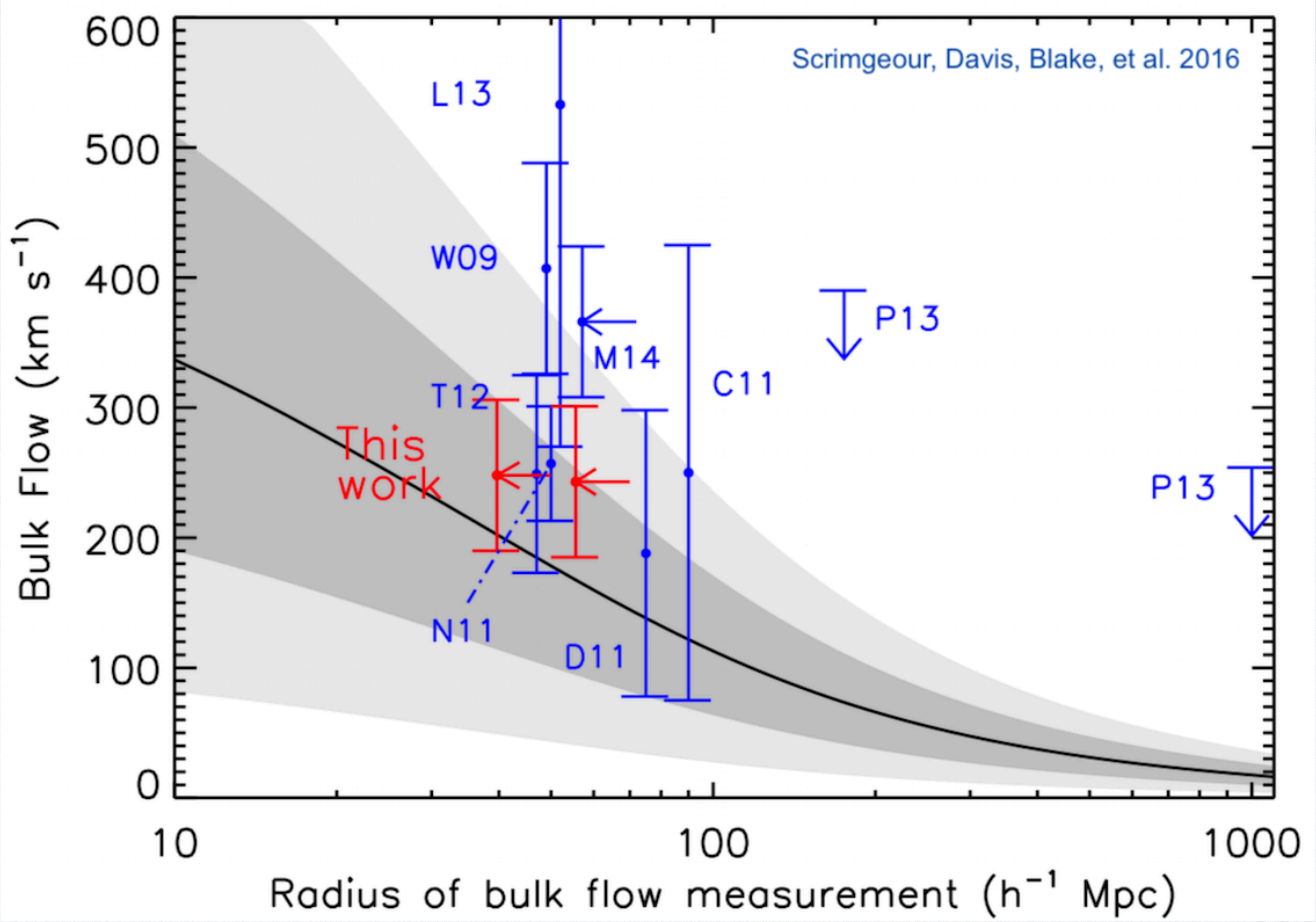
[e] The weighted mean peculiar velocity of the group estimated from Cosmicflows-III (2MTF). See Section **??** for details on how this is computed for both datasets.

Could easily estimate the velocity to be a few hundred km/s lower than was assumed. Reducing H_0 to below CMB estimates. (But with even larger uncertainties.)

This systematic will reduce with more objects because the peculiar velocities will average out, and will also have a smaller impact for more distant objects.

PHYSICAL EFFECTS - PECULIAR VELOCITIES

- The peculiar velocity correction is uncertain:
  - Small scale velocities
  - Bulk flows



Correcting nearby galaxies to the CMB frame over-corrects the velocity (since they share some of our bulk flow)

HOW LARGE COULD A REDSHIFT BIAS BE?

Observational error

- Measurement uncertainty
- Local peculiar velocity corrections (spin, orbit, helio)
- Rest frame wavelength precision
- Air to vacuum conversion
- Spectrograph wavelength calibration
- Continuum tilt

~~**Physical effects**~~

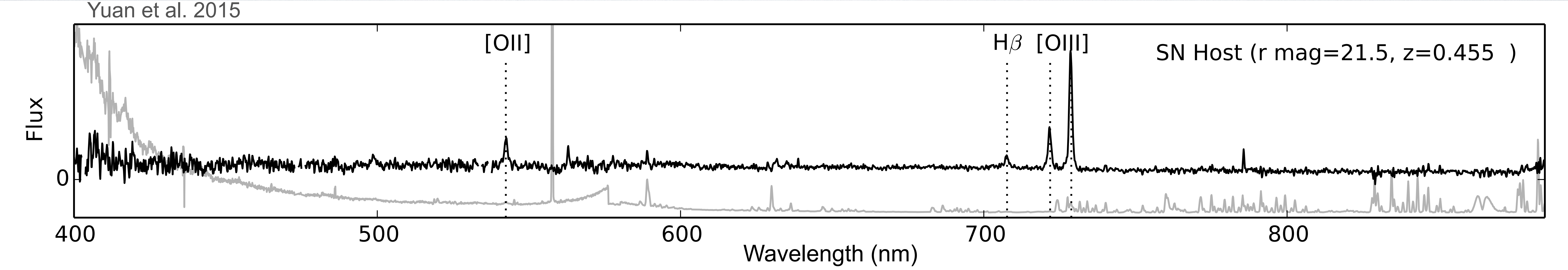
- ~~Gravitational z (local density fluct.)~~
- ~~Peculiar velocities~~
- ~~Bulk flows~~
- ~~Internal velocities~~

Theoretical error

- Using (1+z) factors incorrectly
  - D_L and D_A
  - Redshift addition
- NED peculiar velocity correction

OBSERVATIONAL EFFECTS

OBSERVATIONAL ERROR

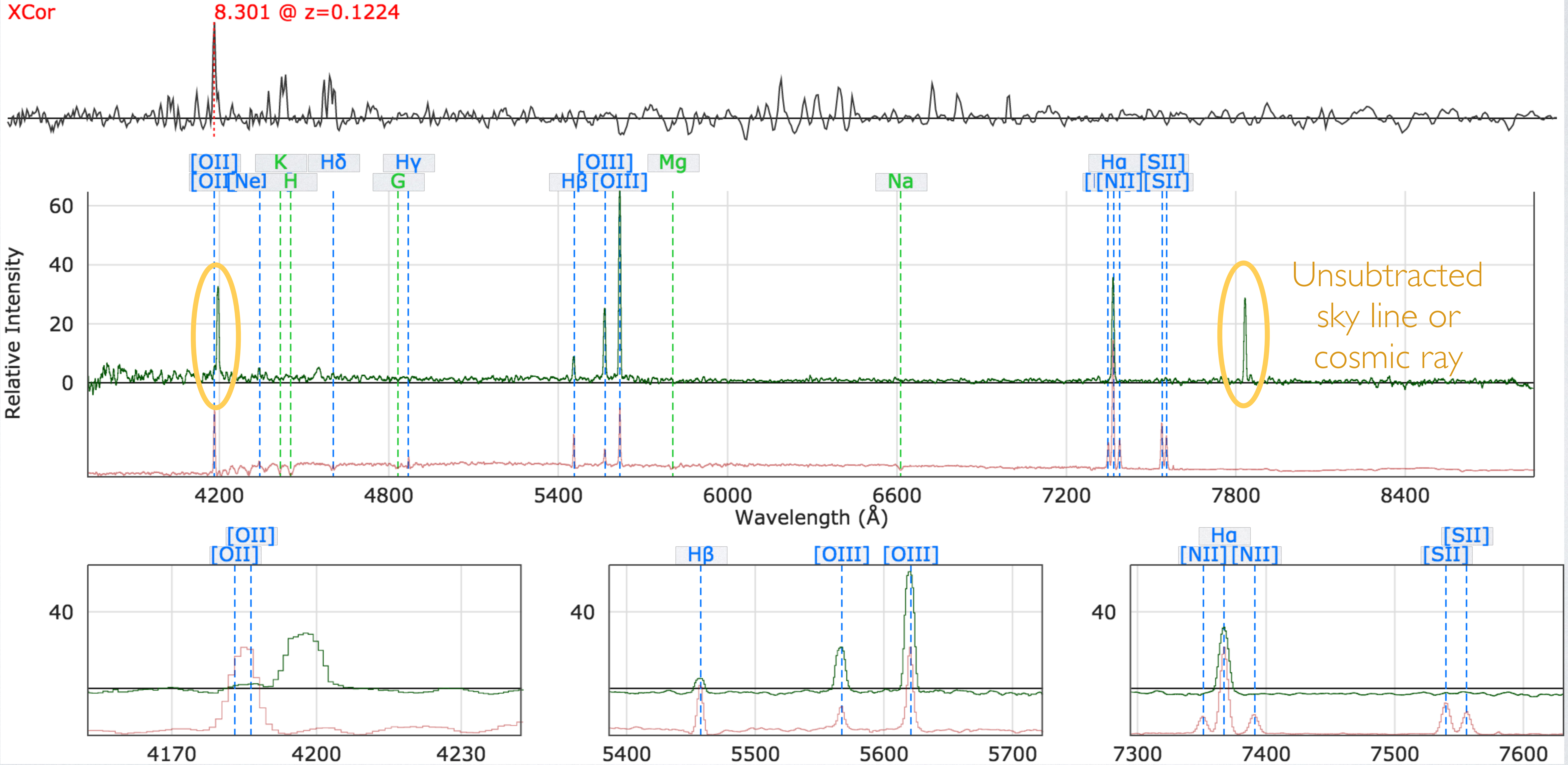

Yuan et al. 2015

OzDES spectrum of a supernova host galaxy (an extremely pretty one)

OzDES spectrum of a supernova host galaxy (an extremely ugly one)

REAL SPECTRUM (HIGH QUALITY)

- **Wavelength calibration issue**

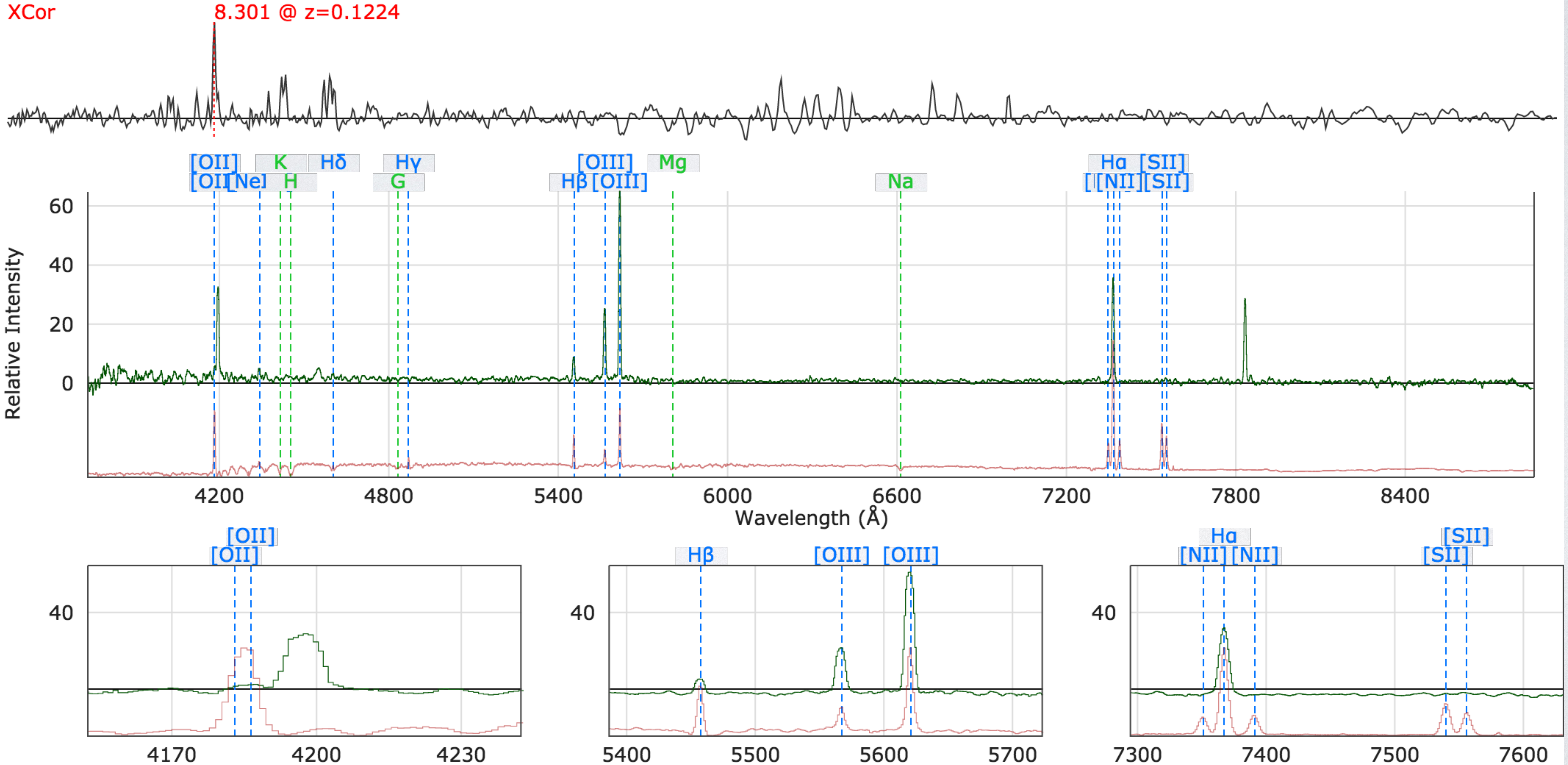


Unsubtracted sky line or cosmic ray

Bad wavelength calibration

REAL SPECTRUM (HIGH QUALITY)

- **Wavelength calibration issue**



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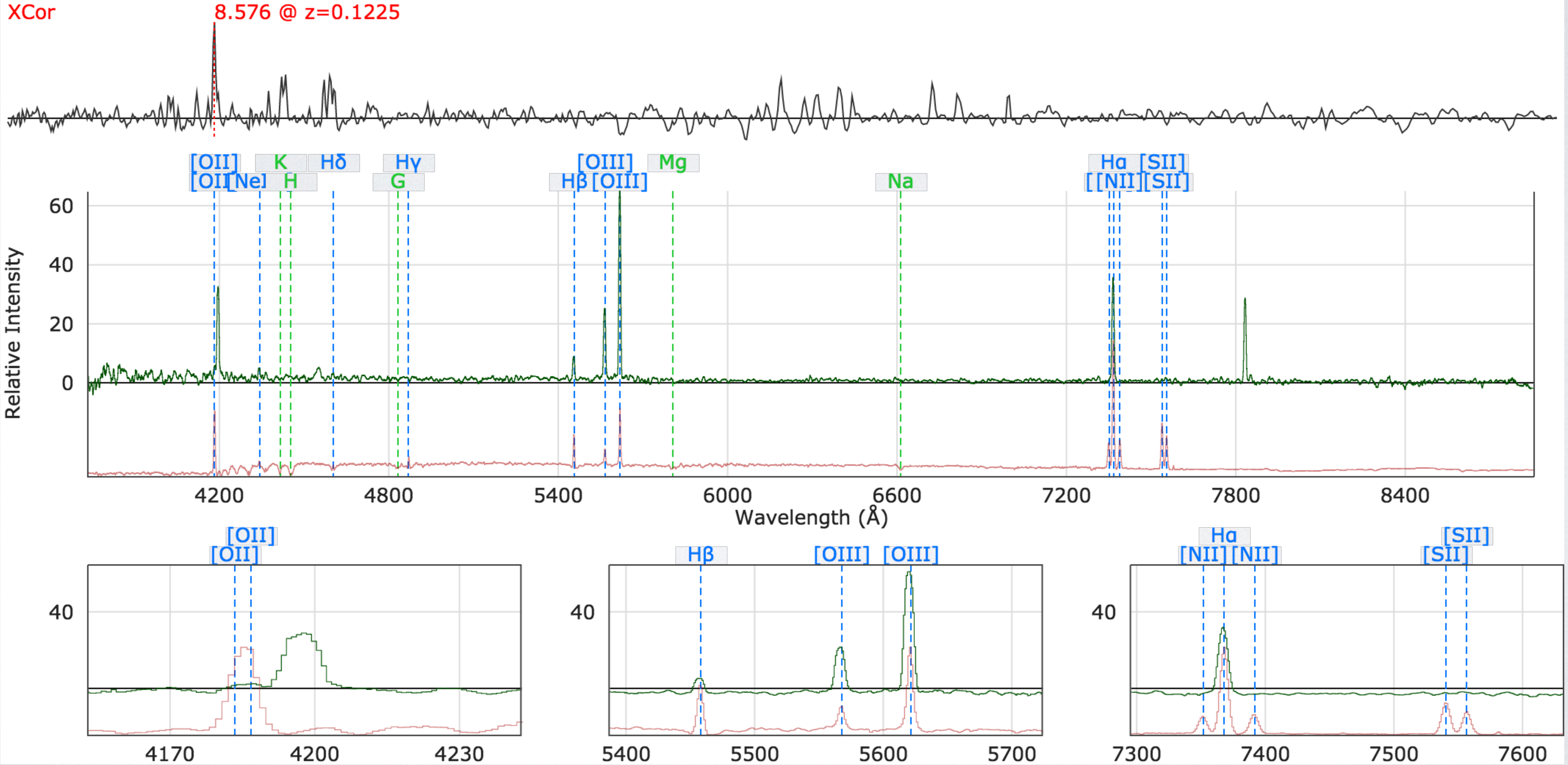

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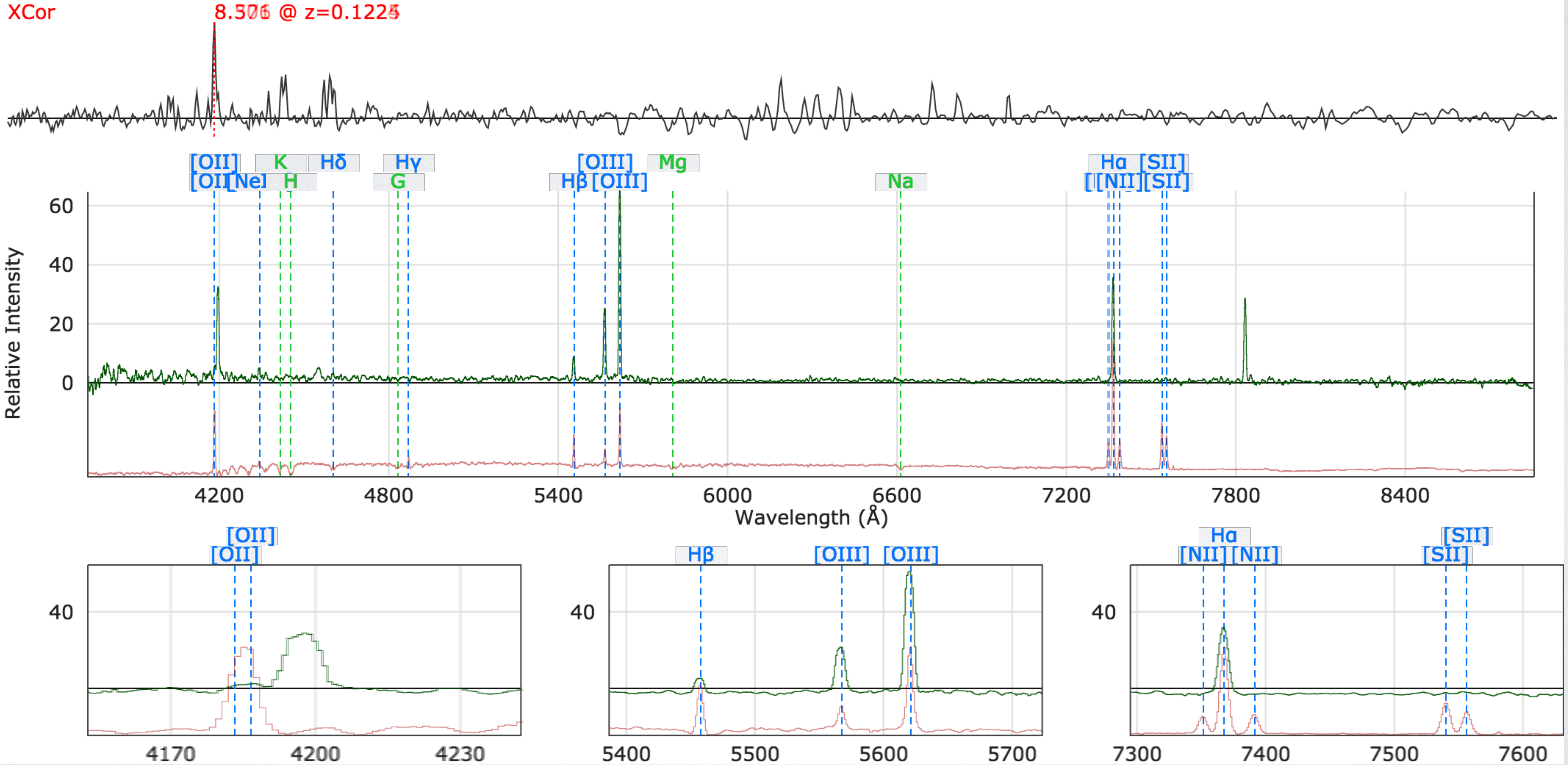
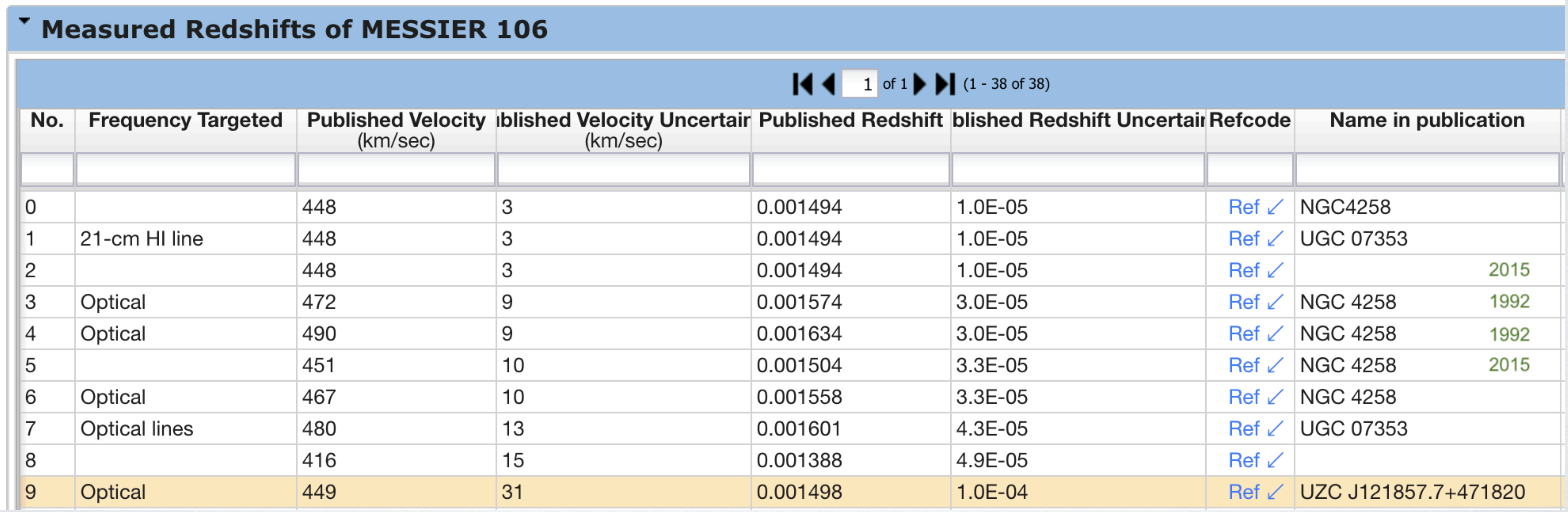


OBSERVATIONAL EFFECTS

- Observers tend to be overoptimistic about their uncertainties…

From NED:



Measured Redshifts of MESSIER 106

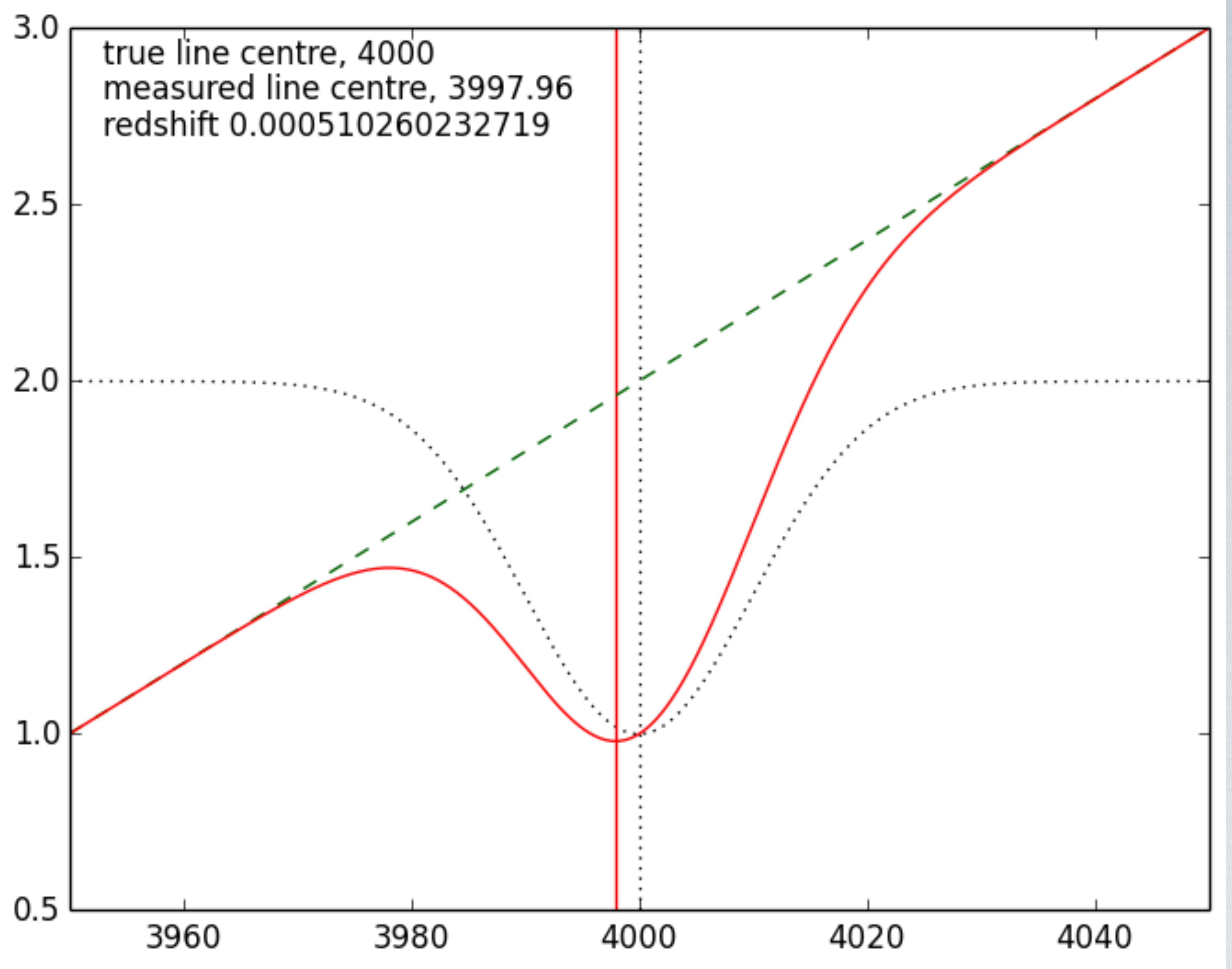
1 of 1 (1 - 38 of 38)

No.	Frequency Targeted	Published Velocity (km/sec)	blished Velocity Uncertai (km/sec)	Published Redshift	blished Redshift Uncertai	Refcode	Name in publication
0		448	3	0.001494	1.0E-05	Ref ↙	NGC4258
1	21-cm HI line	448	3	0.001494	1.0E-05	Ref ↙	UGC 07353
2		448	3	0.001494	1.0E-05	Ref ↙	2015
3	Optical	472	9	0.001574	3.0E-05	Ref ↙	NGC 4258 1992
4	Optical	490	9	0.001634	3.0E-05	Ref ↙	NGC 4258 1992
5		451	10	0.001504	3.3E-05	Ref ↙	NGC 4258 2015
6	Optical	467	10	0.001558	3.3E-05	Ref ↙	NGC 4258
7	Optical lines	480	13	0.001601	4.3E-05	Ref ↙	UGC 07353
8		416	15	0.001388	4.9E-05	Ref ↙	
9	Optical	449	31	0.001498	1.0E-04	Ref ↙	UZC J121857.7+471820

OBSERVATIONAL ERRORS

Source of error	Potential magnitude	Explanation
Rest frame wavelength precision	5×10^{-6}	Wavelengths calibrated to 0.01Å. z error of 5e+06 at z~1 for OII (3727.09Å), slighly less for higher wavelengths and at lower redshifts
Air to vacuum conversion $n_{\mathrm{air}} \equiv \lambda_{\mathrm{vac}}/\lambda_{\mathrm{air}} \sim 1.00028$	10^{-4}	n_{air}~1.00028 at 500nm in 15C, 101325 Pa, 450ppm CO_2, and 0% humidity. At 3000m and 0C the air pressure is approximately 69000 Pa, and n_{air}~1.00020. Thus using a standard temperature and pressure refractive index when cold and at altitude, would result in a redshift error of ~10^{-4}
Spectrograph wavelength calibration	10^{-4}	Can be done extremely well if using e.g. frequency combs. Not always done that carefully. May be wavelength dependent.
Redshift measurement	rand: 5×10^{-4}	Different for different surveys, but for SDSS and OzDES galaxies z uncertainty~5×10^{-4}, larger for AGN at ~10^{-3}
Internal velocities, outflows	rand?: 10^{-3}	If redshifts not made from centre of galaxy, then unaccounted for v_{pec}; if galaxy has outflow then systematic blueshift.
Line smoothing	a few 10^{-4}	If a line is on a sloped continuum, peak may be shifted, and smoothing may also shift the peak.

OBSERVATIONAL ERRORS



Source of error	Potential magnitude	
Rest frame wavelength precision	5x10^{-6}	Wavelengths calibrated (3727.09Å), slighly
Air to vacuum conversion $n_{\mathrm{air}} \equiv \lambda_{\mathrm{vac}}/\lambda_{\mathrm{air}} \sim 1.00028$	10^{-4}	n$_{\mathrm{air}}$~1.00028 at 500nm humidity. At 3000m 69000 Pa, and n$_{\mathrm{air}}$~1.00020. Thus using a standard temperature and pressure refractive index when cold and at altitude, would result in a redshift error of ~10^{-4}
Spectrograph wavelength calibration	10^{-4}	Can be done extremely well if using e.g. frequency combs. Not always done that carefully. May be wavelength dependent.
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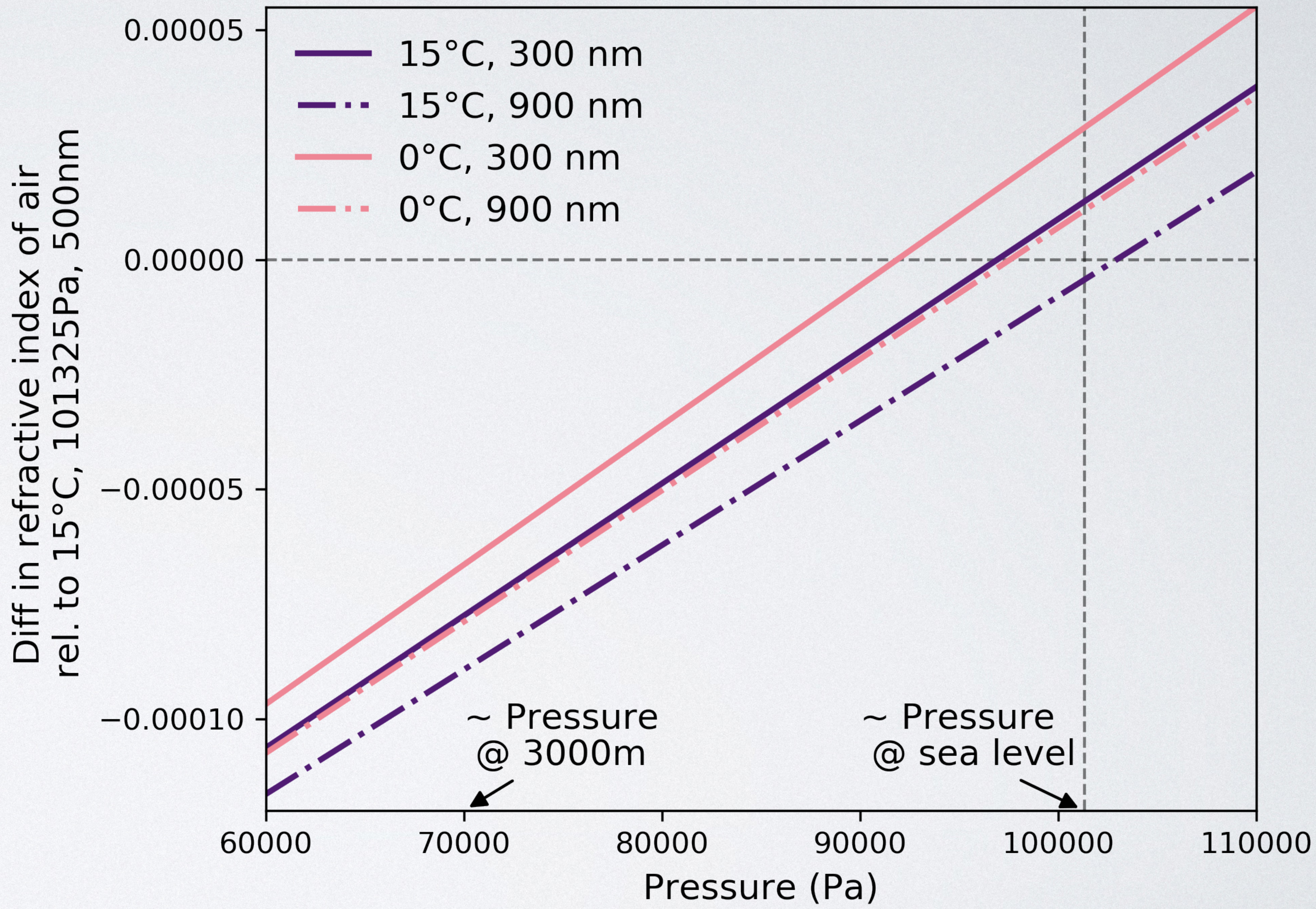
OBSERVATIONAL ERRORS - AIR TO VACUUM

$$n_{\mathrm{air}} \equiv \lambda_{\mathrm{vac}}/\lambda_{\mathrm{air}} \sim 1.00028$$

n_{air}~1.00028 at 500nm in 15C, 101325 Pa, 450ppm CO_2, and 0% humidity. At 3000m and 0C the air pressure is approximately 69000 Pa, and n_{air}~1.00020. Thus using a standard temperature and pressure refractive index when cold and at altitude, would result in a redshift error of ~10^{-4}



HOW LARGE COULD A REDSHIFT BIAS BE?

~~Observational error~~

- ~~Measurement uncertainty~~
- ~~Local peculiar velocity corrections (spin, orbit, helio)~~
- ~~Rest frame wavelength precision~~
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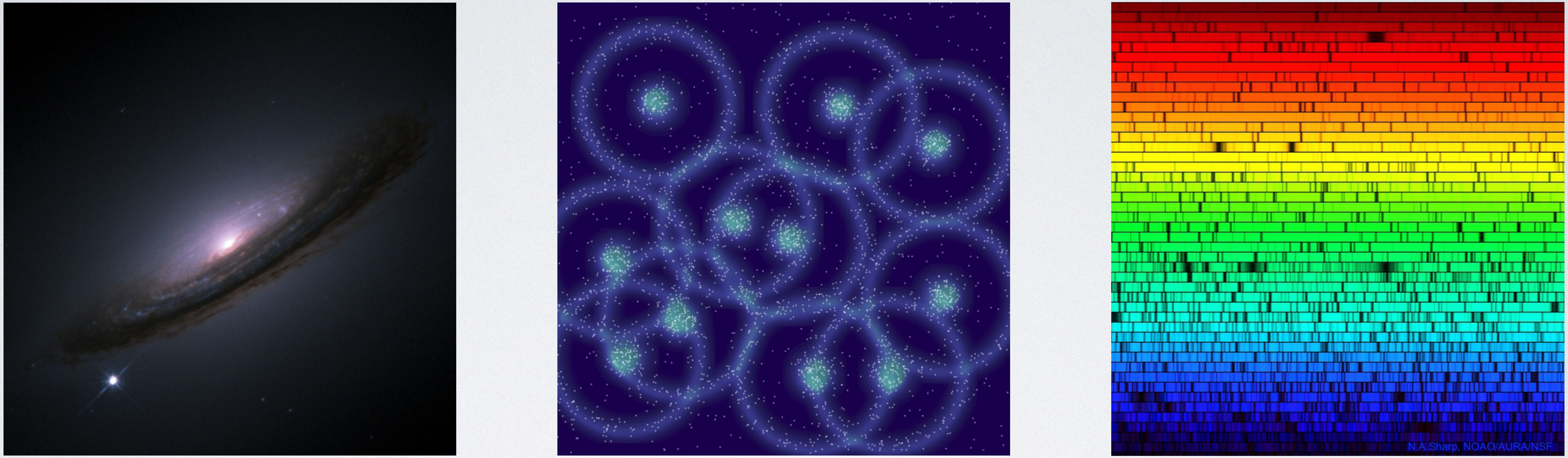
- Internal velocities

Theoretical error

- Using (1+z) factors incorrectly
  - D_L and D_A
  - Redshift addition
- NED peculiar velocity correction

CANDLES, RULERS, AND REDSHIFTS



N.A.Sharp, NOAO/AURA/NSF

Maybe the H_0 tension arises between standard candles and standard rulers, rather than local vs global measurements.

Small redshift errors matter (if systematic), and there are lots of ways to make small errors.