

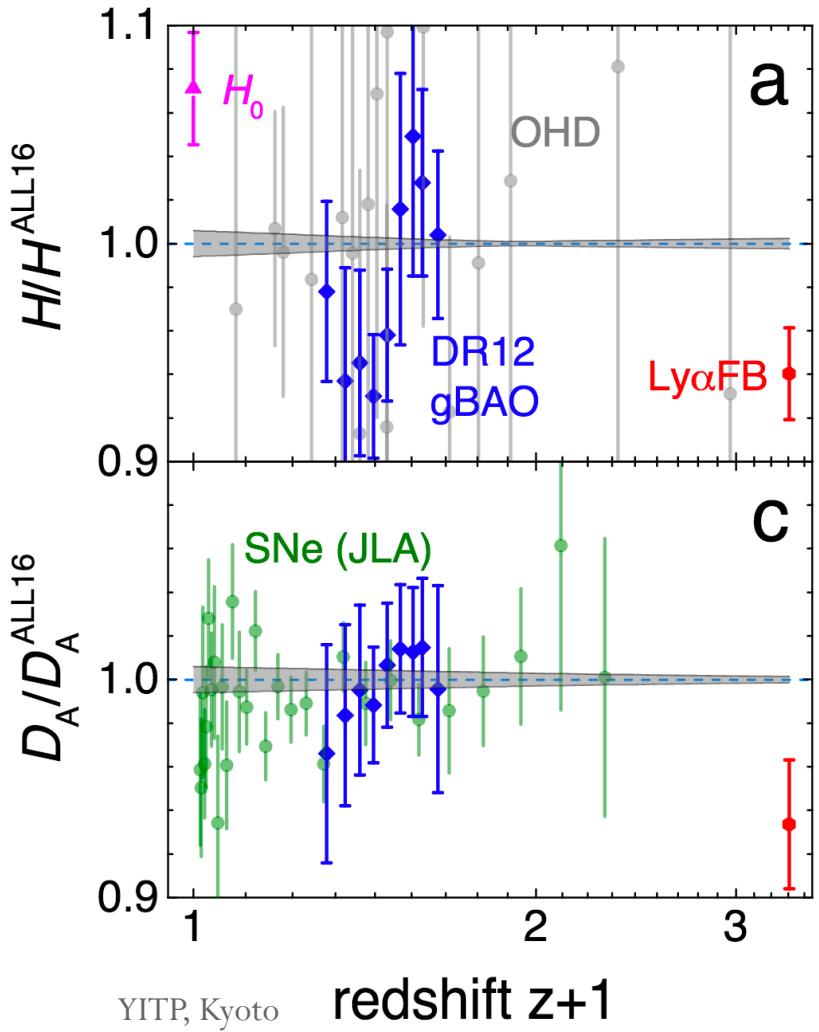
Dynamical dark energy in light of the latest observations

Gong-Bo Zhao

+25 co-authors including
Kazuya, Arman, Benjamin

Nature Astronomy 1, 627
arXiv: 1701.08165

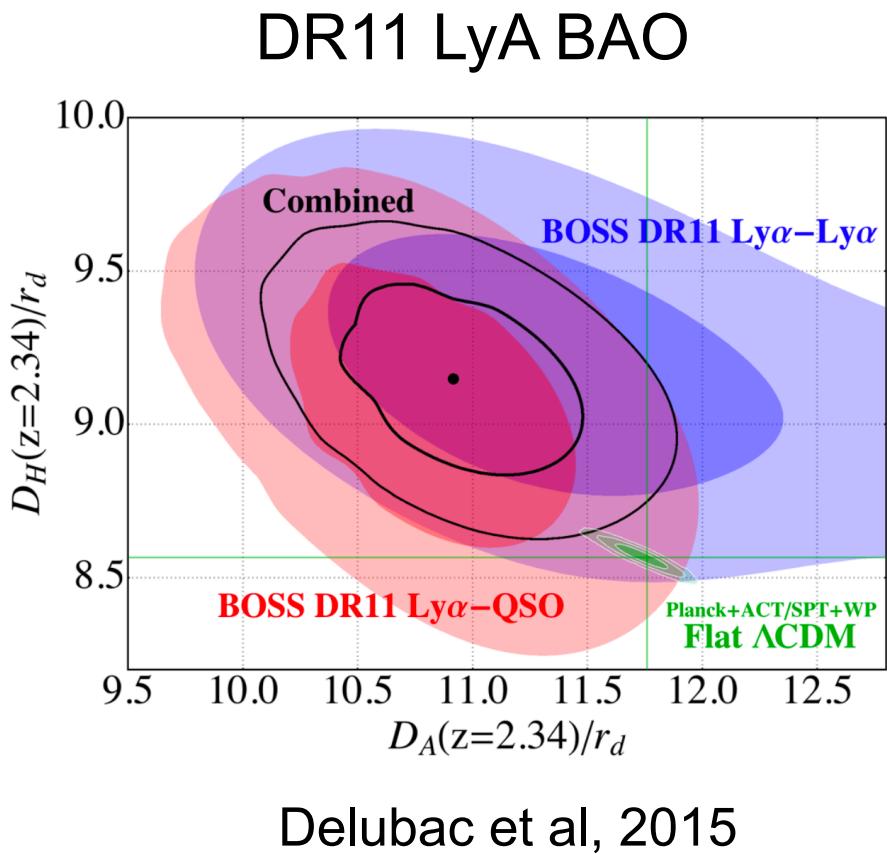
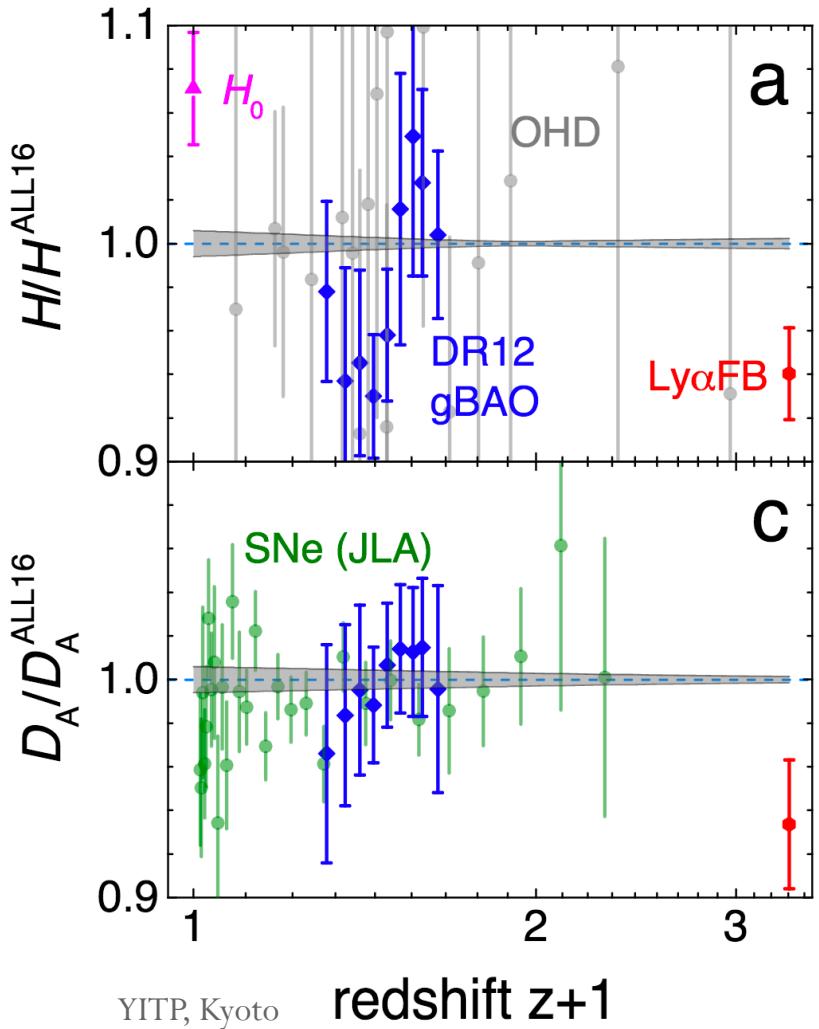
Tensions between data in LCDM



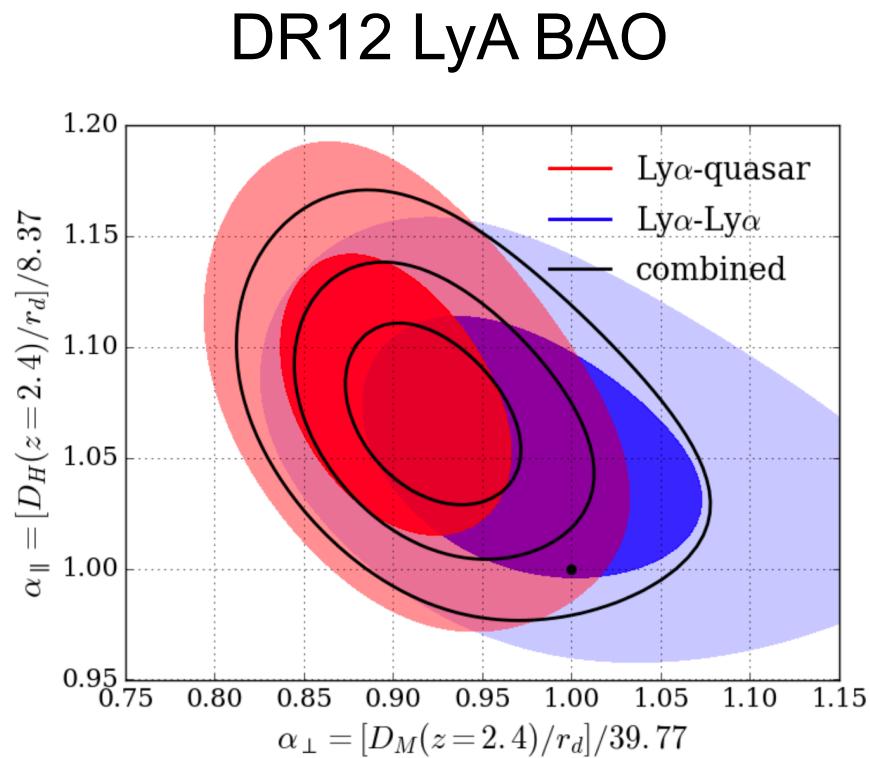
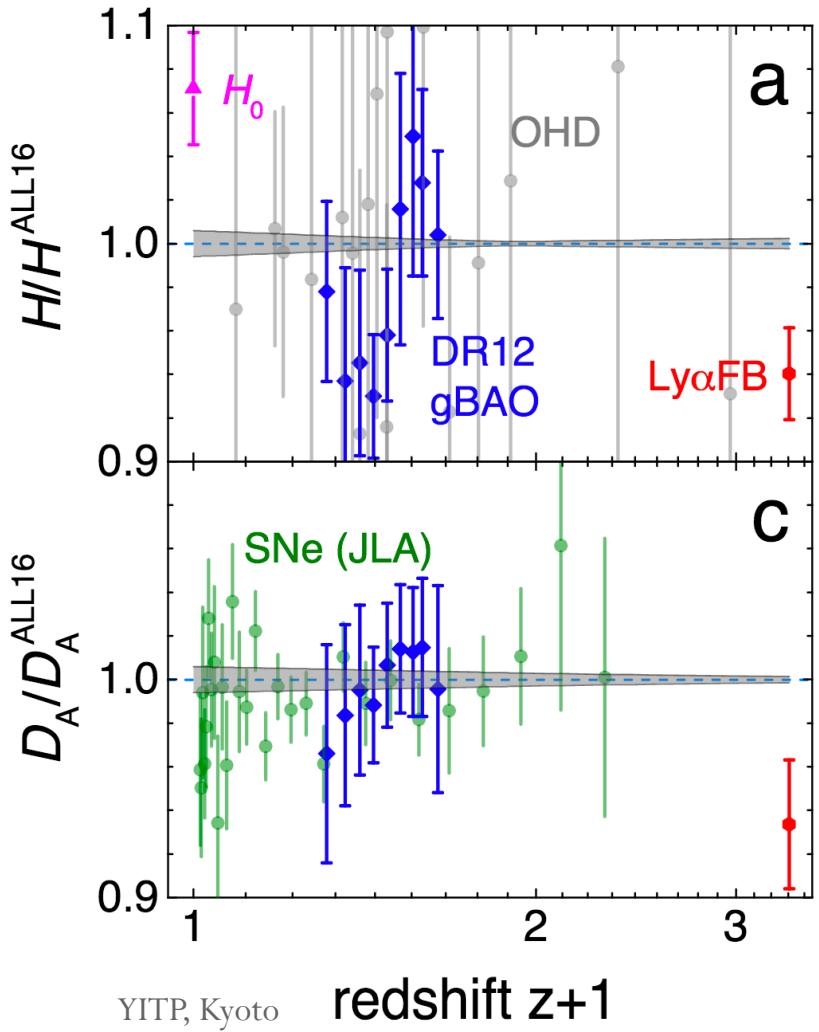
Riess et al, (2016):
 $H_0 = 73.24 \pm 1.74 \text{ (km s}^{-1} \text{ Mpc}^{-1}\text{)}$

Planck (2015):
 $H_0 = 66.93 \pm 0.62 \text{ (km s}^{-1} \text{ Mpc}^{-1}\text{)}$

Tensions between data in LCDM



Tensions between data in LCDM



du Mas des Bourboux et al, 2017

The information gain

The Kullback-Leibler (KL) divergence
(Kullback & Leibler, 1951)

$$D(P_2||P_1) \equiv \int P_2(\theta) \log_2 \left(\frac{P_2(\theta)}{P_1(\theta)} \right) d\theta = \frac{1}{\ln(2)} \int P_2(\theta) \ln \left(\frac{P_2(\theta)}{P_1(\theta)} \right) d\theta \quad [\text{ bits }]$$

- *Positive definite:* $D(P_2||P_1) \geq 0$ and $D(P_2||P_1) = 0$ iff $P_1 = P_2$;
- *Not symmetric:* $D(P_2||P_1) \neq D(P_1||P_2)$;
- *Invariant under re-parametrizations:* given $Y(X)$, a non-singular re-parametrization, $D(P_2(Y)||P_1(Y)) = D(P_2(X)||P_1(X))$.

The information gain

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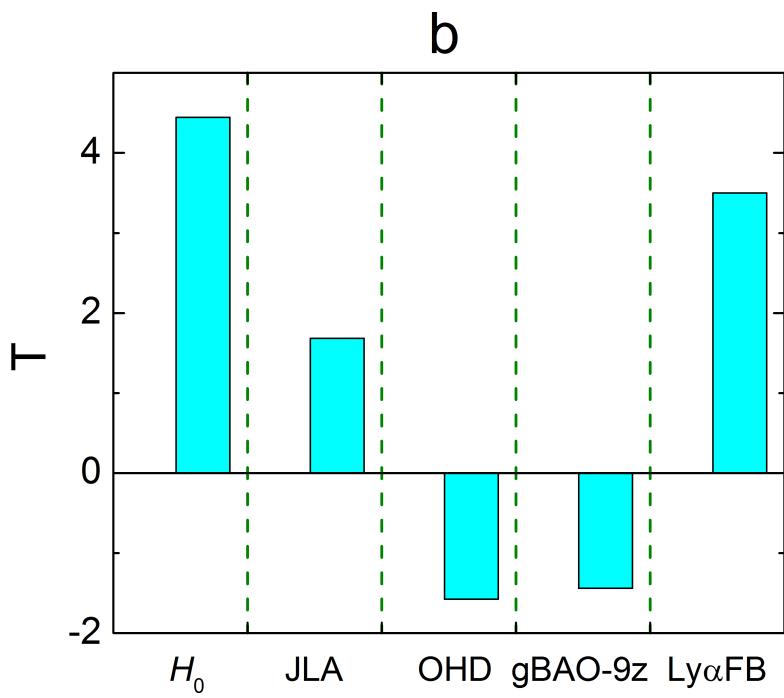
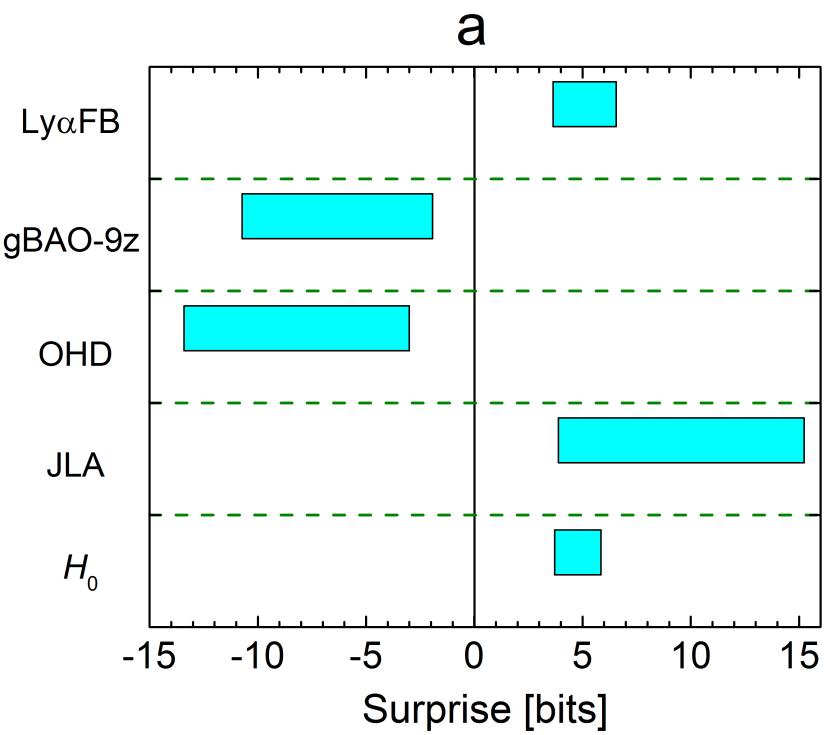
$$\langle D(P_2 || P_1) \rangle_{D_2} \equiv \int D(P_2 || P_1) \mathcal{L}(D_2) dD_2$$
$$\sigma^2(D) \equiv \int [D(P_2 || P_1) - \langle D(P_2 || P_1) \rangle]^2 \mathcal{L}(D_2) dD_2$$

To quantify the tension

$$S = \frac{1}{2\ln 2} \left[(\theta_1 - \theta_2)^{\textcolor{brown}{T}} \mathcal{C}_1^{-1} (\theta_1 - \theta_2) - \text{Tr} (\mathcal{C}_2 \mathcal{C}_1^{-1} + \mathbb{I}) \right]$$

$$\Sigma = \frac{1}{\sqrt{2\ln 2}} \sqrt{\text{Tr} (\mathcal{C}_2 \mathcal{C}_1^{-1} + \mathbb{I})^2}$$

$$T = S/\Sigma$$



Solving the tension using dynamics of dark energy

Crittenden, Pogosian, GBZ (JCAP 2009)

Crittenden, GBZ, Pogosian, Samushia, Zhang (JCAP 2012)

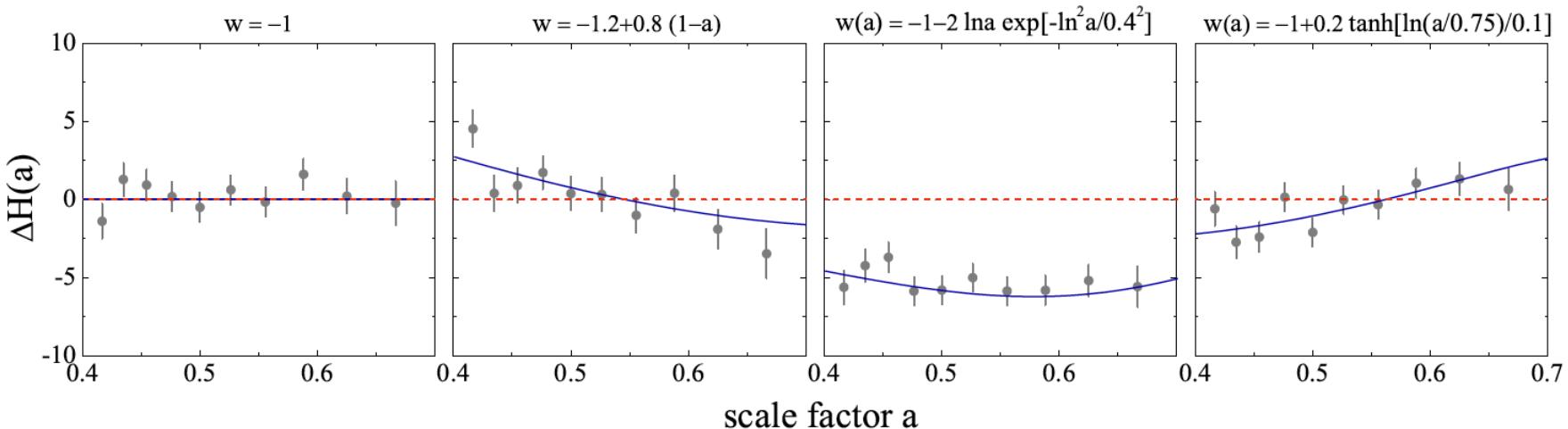
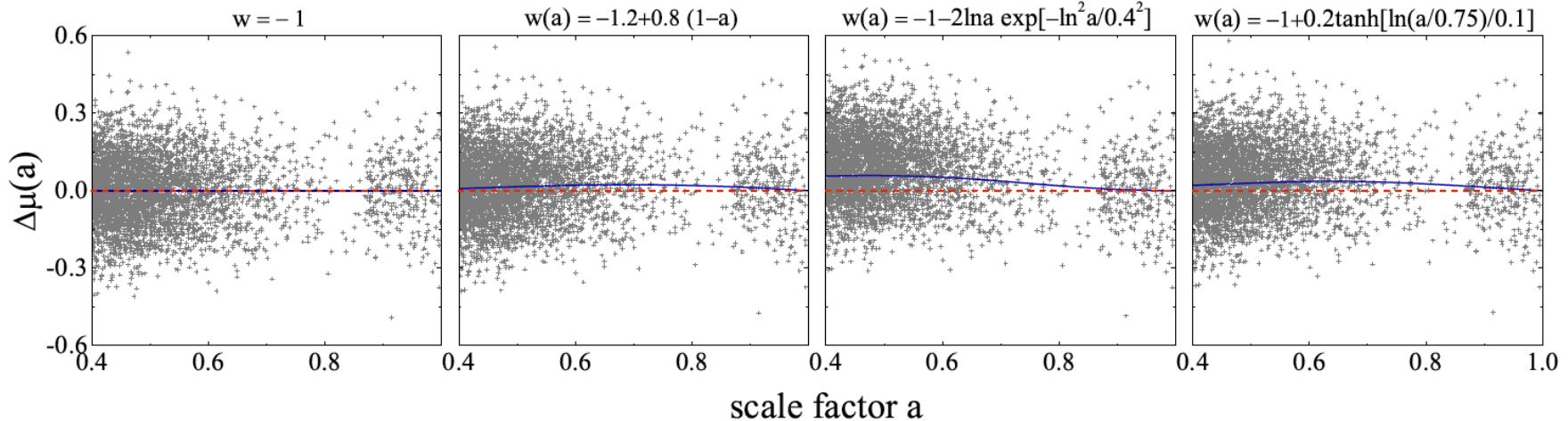
$$\xi_w(|a - a'|) \equiv \langle [w(a) - w^{\text{fid}}(a)][w(a') - w^{\text{fid}}(a')] \rangle$$

$$w_i = \frac{1}{\Delta} \int_{a_i}^{a_i + \Delta} da w(a).$$

$$C_{ij} \equiv \langle \delta w_i \delta w_j \rangle = \frac{1}{\Delta^2} \int_{a_i}^{a_i + \Delta} da \int_{a_j}^{a_j + \Delta} da' \xi_w(|a - a'|)$$

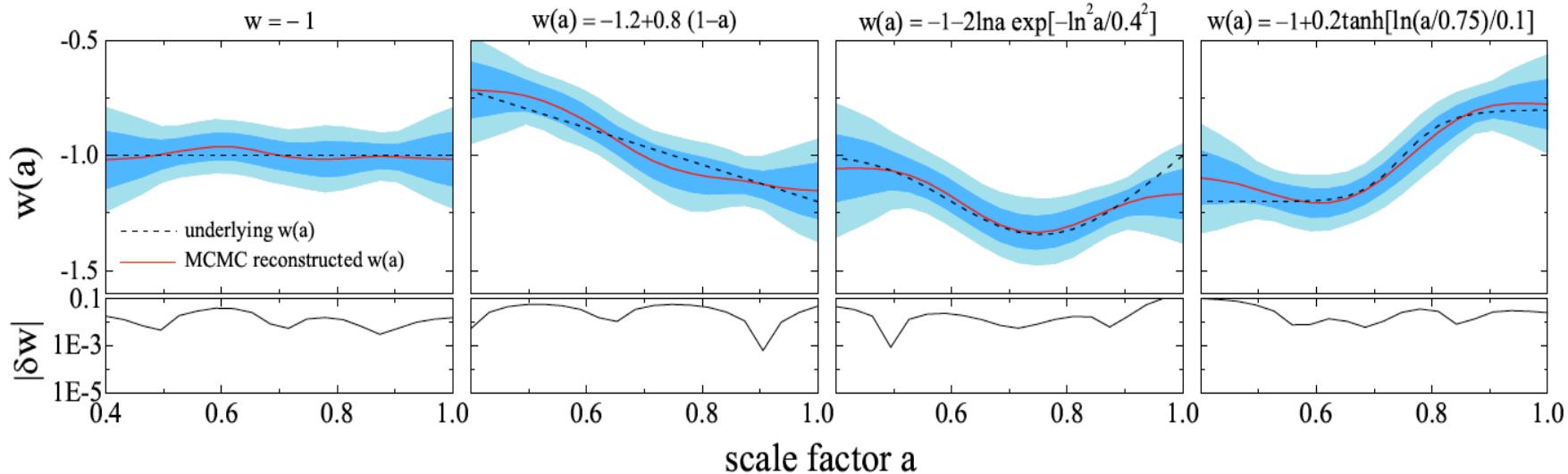
$$\chi_{\text{prior}}^2 = -2 \ln \mathcal{P}_{\text{prior}} = (\mathbf{w} - \mathbf{w}^{\text{fid}})^T \mathbf{C}^{-1} (\mathbf{w} - \mathbf{w}^{\text{fid}})$$

Hide $w(z)$ features in the mock data



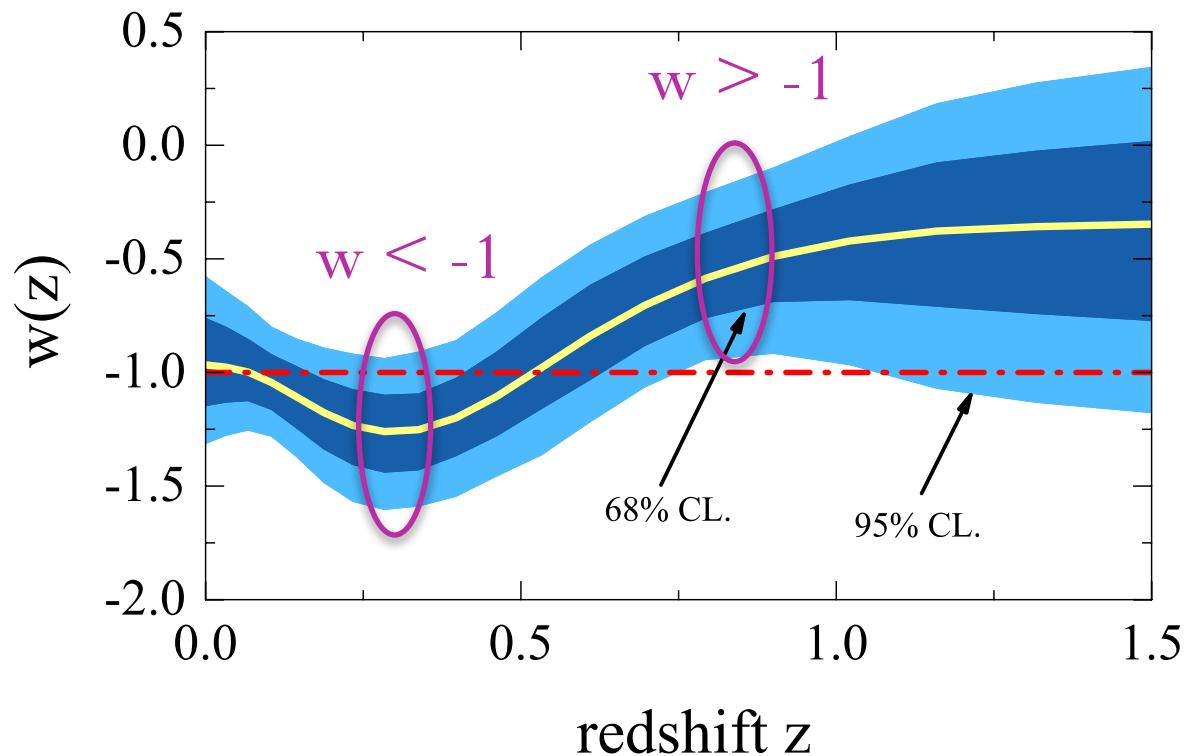
w reconstructed successfully

Crittenden, GBZ, Pogosian, Samushia, Zhang (JCAP 2012)

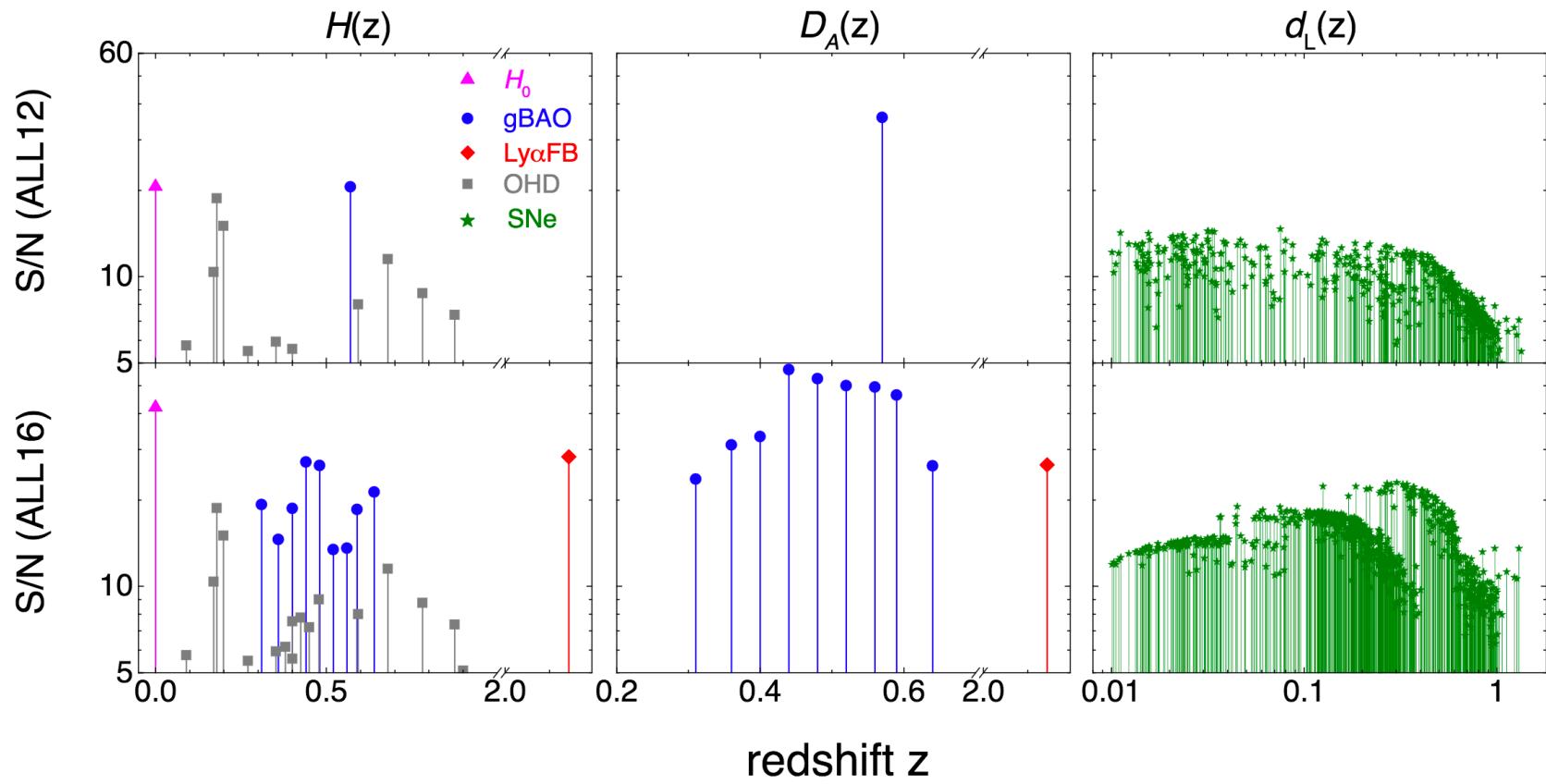


Reconstruct $w(a)$ non-parametrically

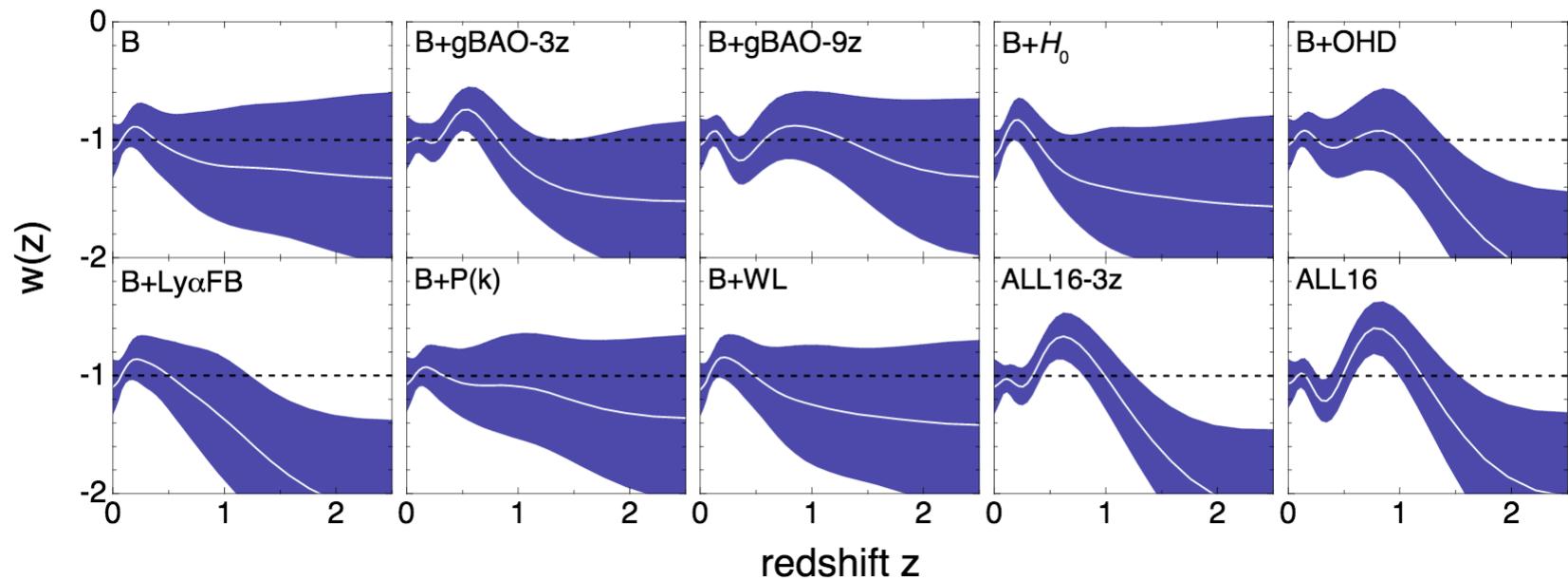
Real data circa 2012



GBZ, et al., 2012, PRL

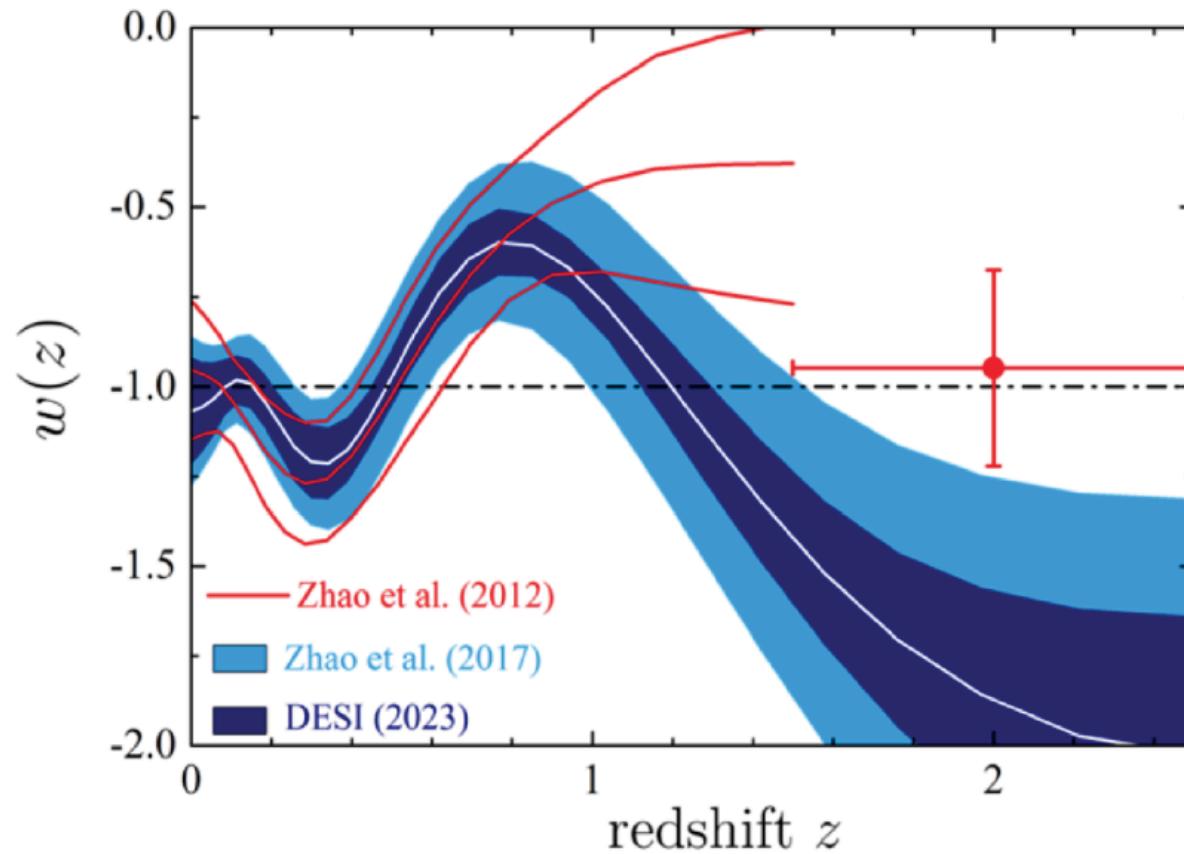


B=Planck15+SNe(JLA)

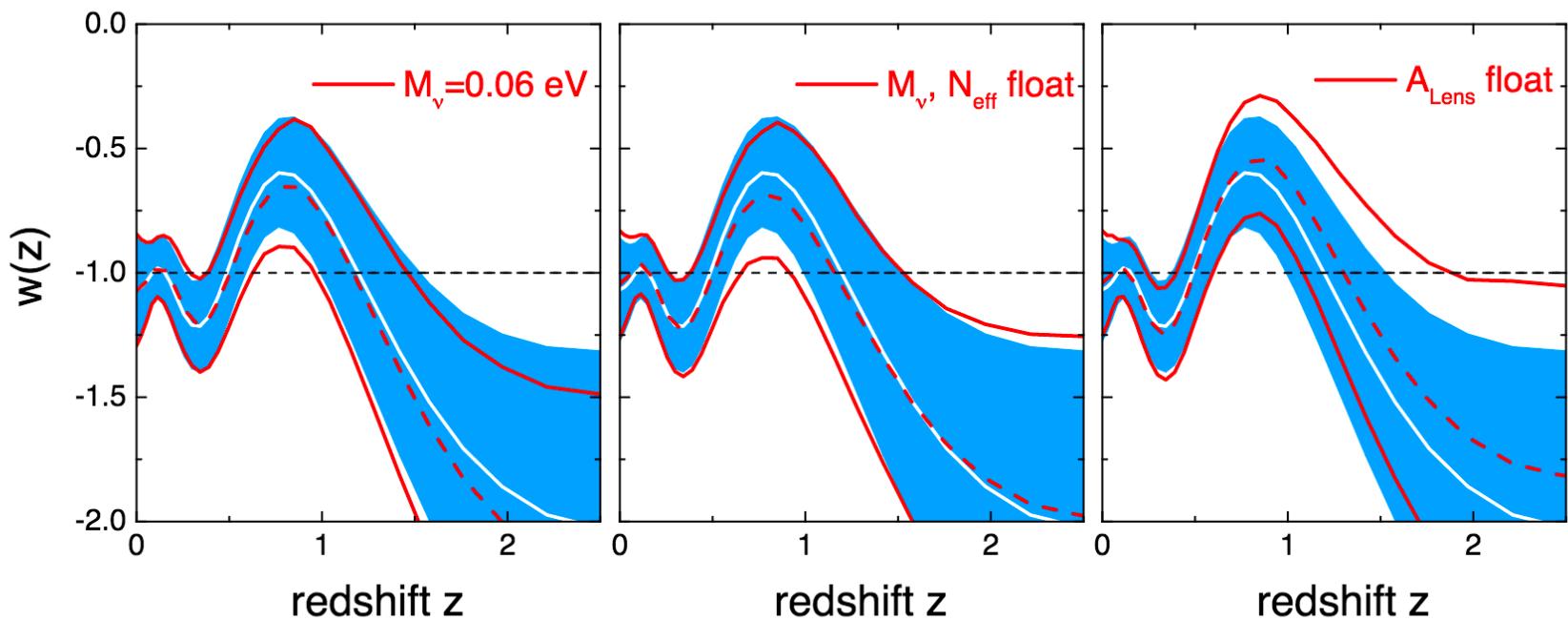


Zhao et al., (BOSS collaboration), 2017
Nature Astronomy 1, 627

Reconstruct $w(a)$ non-parametrically



Zhao et al., (BOSS collaboration), 2017
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Principal Component Analysis (PCA)

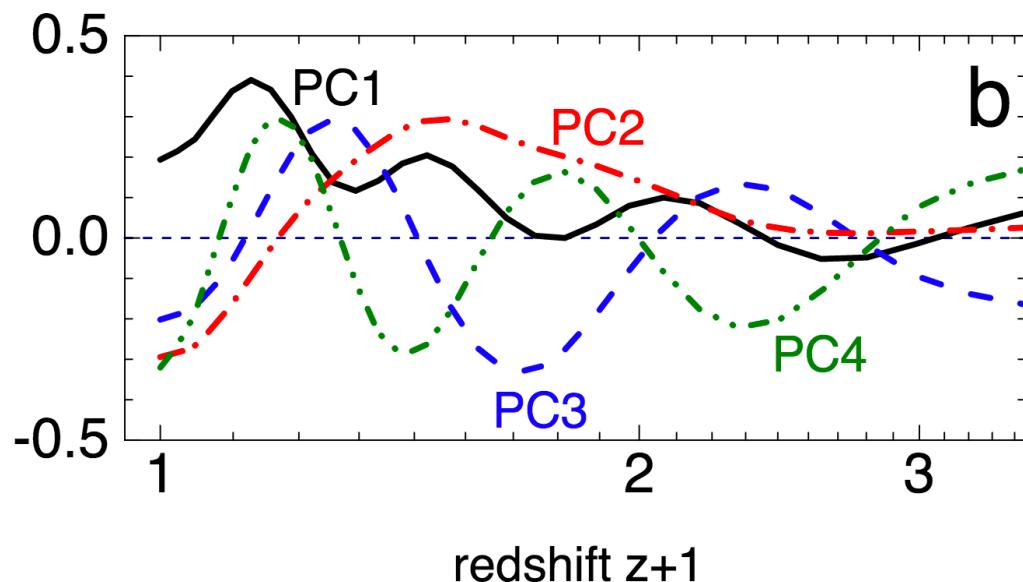
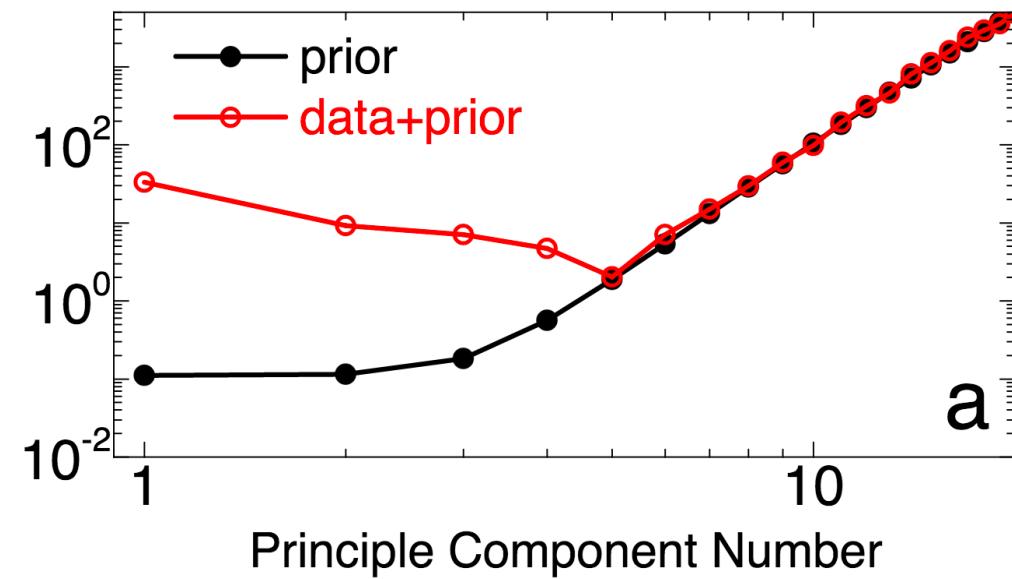
Hamilton & Tegmark 1999, Huterer & Starkman 2002

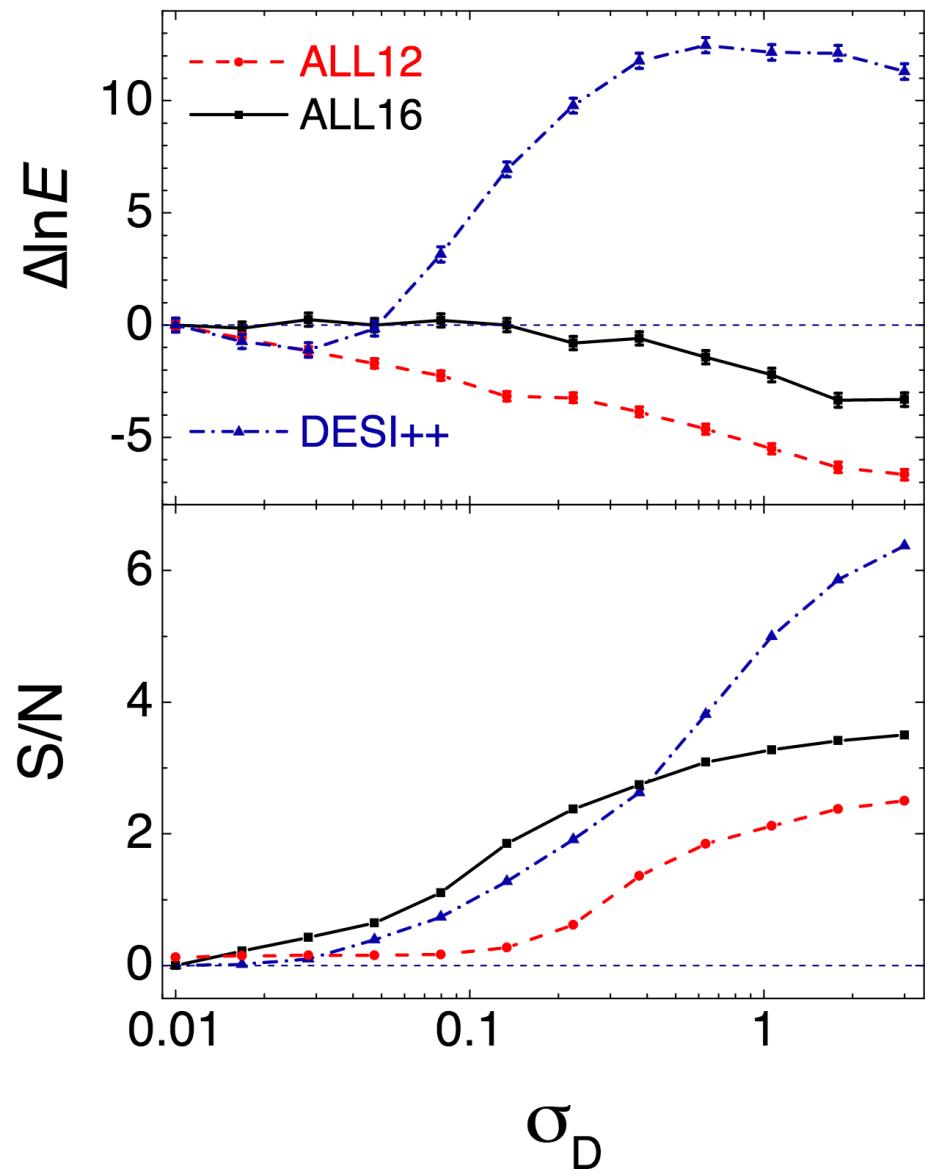
Diagonalise the w block of the Fisher matrix
to find the orthonormal basis, on which we can
expand $w(z) + 1$,

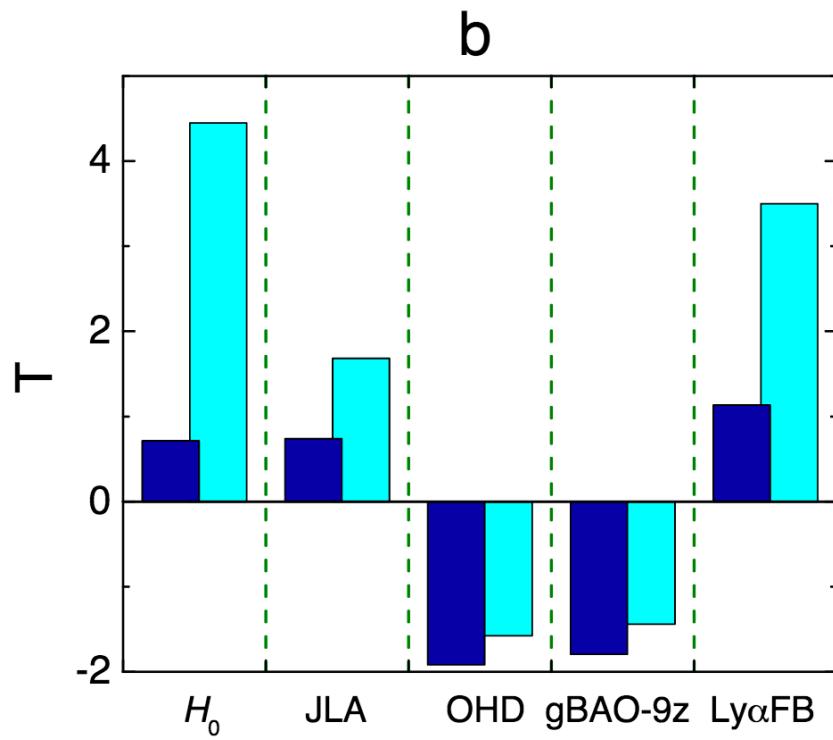
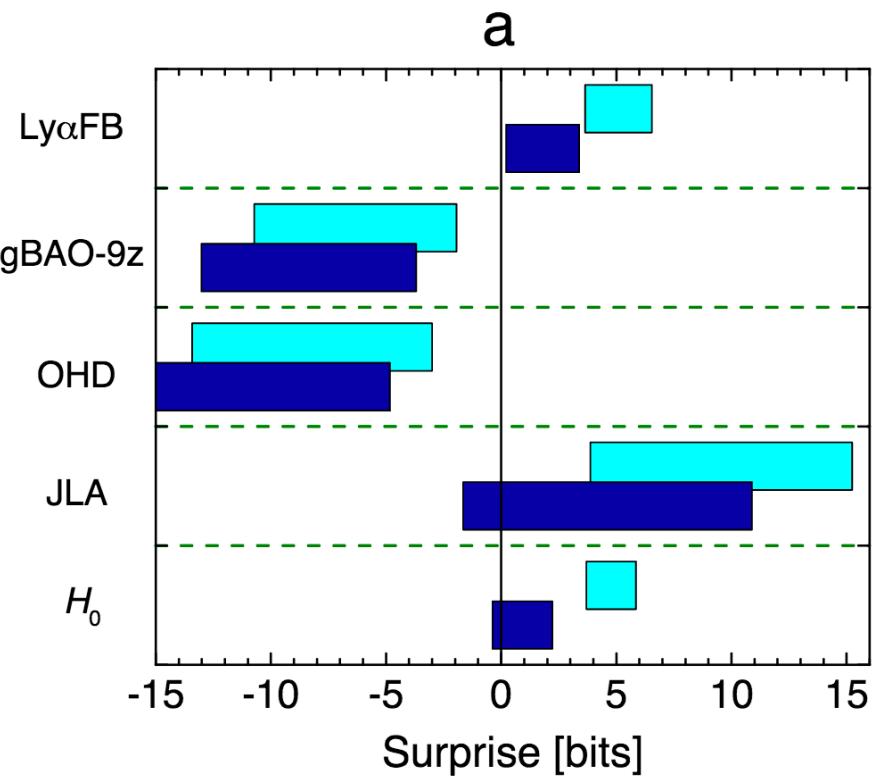
$$F = W^T \begin{pmatrix} \Lambda \\ \alpha_m \\ e_m(z) \end{pmatrix} W$$

Where are the ‘sweet spots’?

How ‘sweet’ they are?

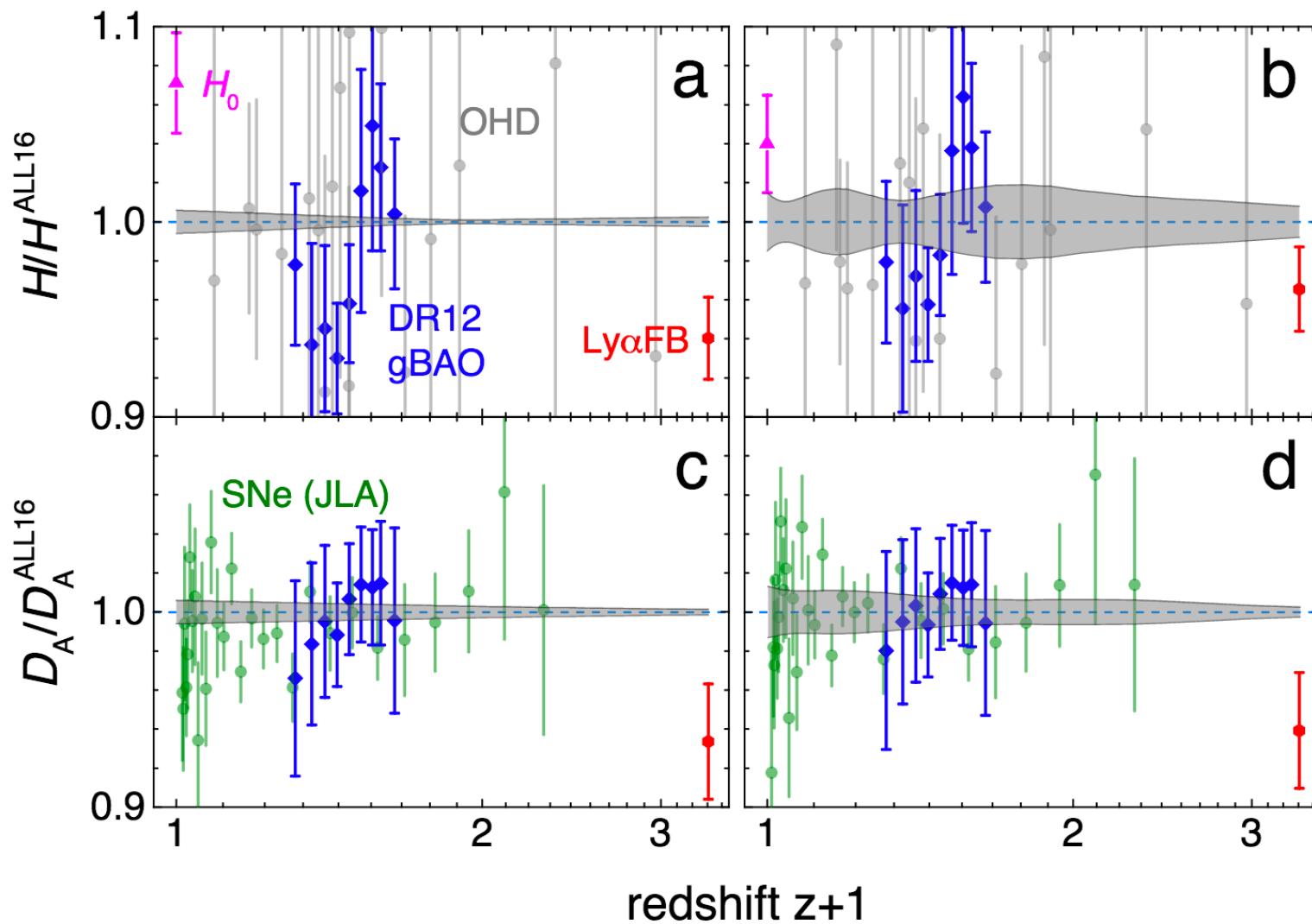






LCDM

w(z)CDM



Summary

- There is a high level of tension among datasets in LCDM;
- BOSS DR12 data (combined with others) show a hint of DE dynamics at 3.5 sigma level, which releases the tension;
- Given the best-fit model from current data, DESI will be able to discover it decisively.