Precision Cosmology in 2020 with PFS

PFS Meeting : July 9th, 2015

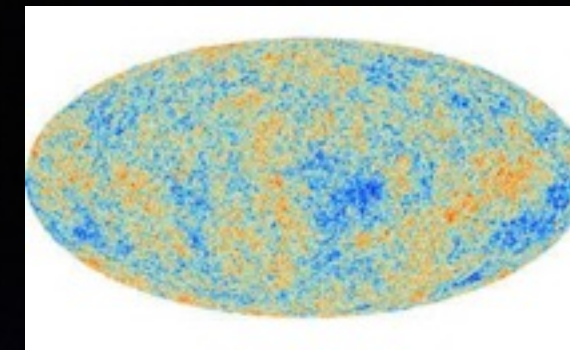
Nao Suzuki (Kavli IPMU)

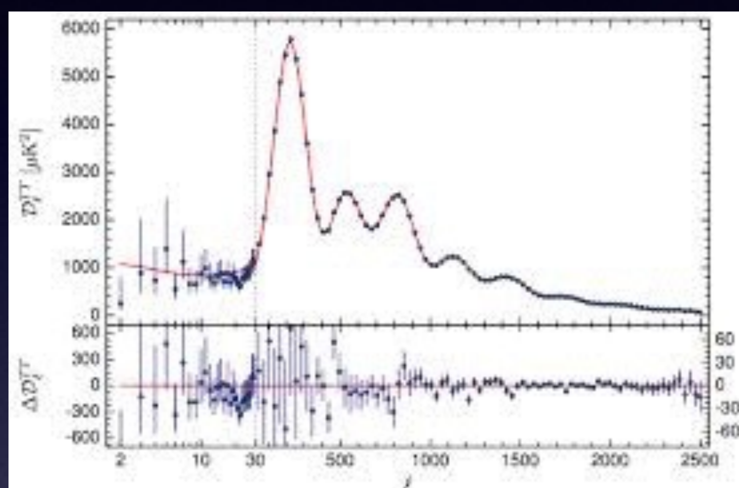
- Cosmology Today
- A Brief History of BAO
- BAO Measurement Today
- PFS & Future Experiments
- Tomography of the Universe
- Large Scale Structure => Shun Saito san

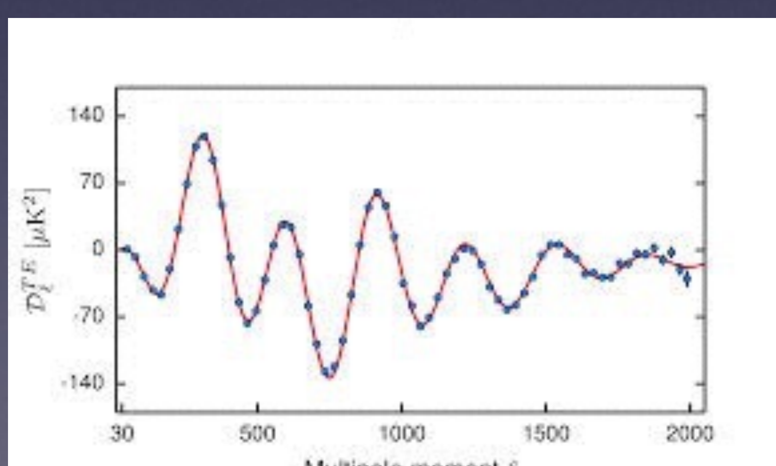
Cosmology Today

- CMB : Planck 2015, BICEP, SPT
- BAO : SDSS-III
- SNIa : Union2.1, JLA (SNLS-3, SDSS-II)

Planck 2015







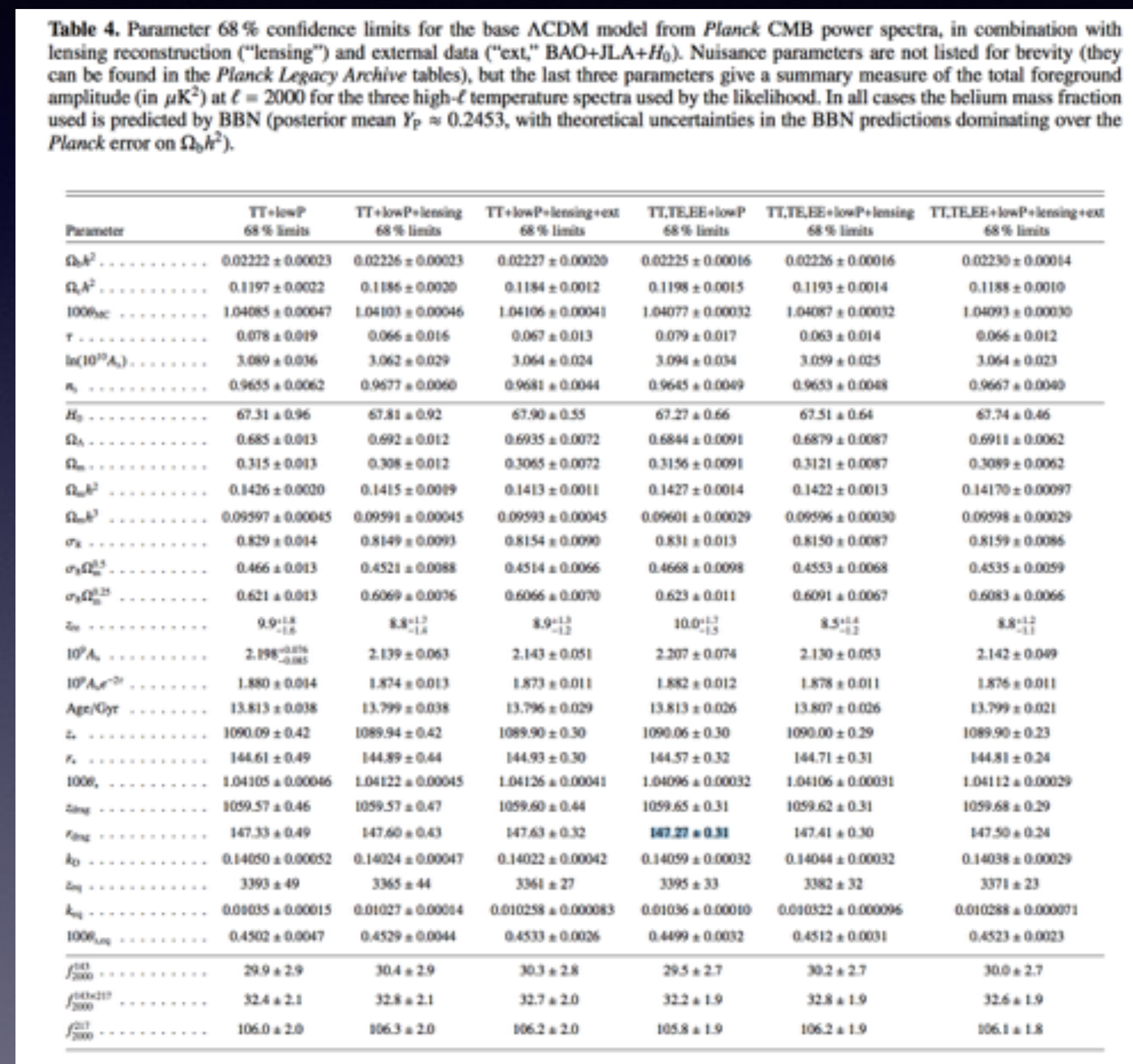


Table 4. Parameter 68 % confidence limits for the base ΛCDM model from *Planck* CMB power spectra, in combination with lensing reconstruction ("lensing") and external data ("ext," BAO+JLA+H_0). Nuisance parameters are not listed for brevity (they can be found in the *Planck Legacy Archive* tables), but the last three parameters give a summary measure of the total foreground amplitude (in μK^2) at $\ell = 2000$ for the three high-ℓ temperature spectra used by the likelihood. In all cases the helium mass fraction used is predicted by BBN (posterior mean $Y_P \approx 0.2453$, with theoretical uncertainties in the BBN predictions dominating over the *Planck* error on $\Omega_b h^2$).

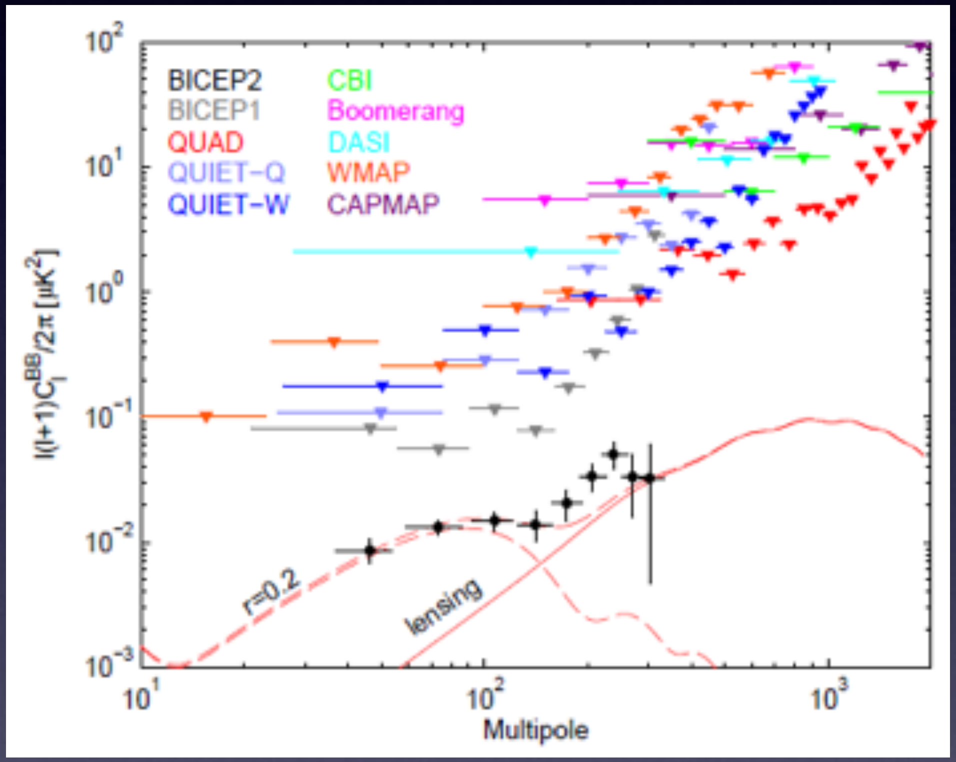
Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044	0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040
H_0	67.31 ± 0.96	67.81 ± 0.92	67.90 ± 0.55	67.27 ± 0.66	67.51 ± 0.64	67.74 ± 0.46
Ω_Λ	0.685 ± 0.013	0.692 ± 0.012	0.6935 ± 0.0072	0.6844 ± 0.0091	0.6879 ± 0.0087	0.6911 ± 0.0062
Ω_m	0.315 ± 0.013	0.308 ± 0.012	0.3065 ± 0.0072	0.3156 ± 0.0091	0.3121 ± 0.0087	0.3089 ± 0.0062
$\Omega_m h^2$	0.1426 ± 0.0020	0.1415 ± 0.0019	0.1413 ± 0.0011	0.1427 ± 0.0014	0.1422 ± 0.0013	0.14170 ± 0.00097
$\Omega_m h^3$	0.09597 ± 0.00045	0.09591 ± 0.00045	0.09593 ± 0.00045	0.09601 ± 0.00029	0.09596 ± 0.00030	0.09598 ± 0.00029
σ_8	0.829 ± 0.014	0.8149 ± 0.0093	0.8154 ± 0.0090	0.831 ± 0.013	0.8150 ± 0.0087	0.8159 ± 0.0086
$\sigma_8 \Omega_m^{0.5}$	0.466 ± 0.013	0.4521 ± 0.0088	0.4514 ± 0.0066	0.4668 ± 0.0098	0.4553 ± 0.0068	0.4535 ± 0.0059
$\sigma_8 \Omega_m^{0.25}$	0.621 ± 0.013	0.6069 ± 0.0076	0.6066 ± 0.0070	0.623 ± 0.011	0.6091 ± 0.0067	0.6083 ± 0.0066
z_{re}	$9.9^{+1.8}_{-1.6}$	$8.8^{+1.7}_{-1.4}$	$8.9^{+1.3}_{-1.2}$	$10.0^{+1.7}_{-1.5}$	$8.5^{+1.4}_{-1.2}$	$8.8^{+1.2}_{-1.1}$
$10^9 A_s$	$2.198^{+0.076}_{-0.085}$	2.139 ± 0.063	2.143 ± 0.051	2.207 ± 0.074	2.130 ± 0.053	2.142 ± 0.049
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.874 ± 0.013	1.873 ± 0.011	1.882 ± 0.012	1.878 ± 0.011	1.876 ± 0.011
Age/Gyr	13.813 ± 0.038	13.799 ± 0.038	13.796 ± 0.029	13.813 ± 0.026	13.807 ± 0.026	13.799 ± 0.021
z_*	1090.09 ± 0.42	1089.94 ± 0.42	1089.90 ± 0.30	1090.06 ± 0.30	1090.00 ± 0.29	1089.90 ± 0.23
r_*	144.61 ± 0.49	144.89 ± 0.44	144.93 ± 0.30	144.57 ± 0.32	144.71 ± 0.31	144.81 ± 0.24
$100\theta_*$	1.04105 ± 0.00046	1.04122 ± 0.00045	1.04126 ± 0.00041	1.04096 ± 0.00032	1.04106 ± 0.00031	1.04112 ± 0.00029
z_{drag}	1059.57 ± 0.46	1059.57 ± 0.47	1059.60 ± 0.44	1059.65 ± 0.31	1059.62 ± 0.31	1059.68 ± 0.29
r_{drag}	147.33 ± 0.49	147.60 ± 0.43	147.63 ± 0.32	147.27 ± 0.31	147.41 ± 0.30	147.50 ± 0.24
k_D	0.14050 ± 0.00052	0.14024 ± 0.00047	0.14022 ± 0.00042	0.14059 ± 0.00032	0.14044 ± 0.00032	0.14038 ± 0.00029
z_{eq}	3393 ± 49	3365 ± 44	3361 ± 27	3395 ± 33	3382 ± 32	3371 ± 23
k_{eq}	0.01035 ± 0.00015	0.01027 ± 0.00014	0.010258 ± 0.000083	0.01036 ± 0.00010	0.010322 ± 0.000096	0.010288 ± 0.000071
$100\theta_{s,eq}$	0.4502 ± 0.0047	0.4529 ± 0.0044	0.4533 ± 0.0026	0.4499 ± 0.0032	0.4512 ± 0.0031	0.4523 ± 0.0023
f_{2000}^{143}	29.9 ± 2.9	30.4 ± 2.9	30.3 ± 2.8	29.5 ± 2.7	30.2 ± 2.7	30.0 ± 2.7
$f_{2000}^{143\times217}$	32.4 ± 2.1	32.8 ± 2.1	32.7 ± 2.0	32.2 ± 1.9	32.8 ± 1.9	32.6 ± 1.9
f_{2000}^{217}	106.0 ± 2.0	106.3 ± 2.0	106.2 ± 2.0	105.8 ± 1.9	106.2 ± 1.9	106.1 ± 1.8

Planck 2015 Best Estimate

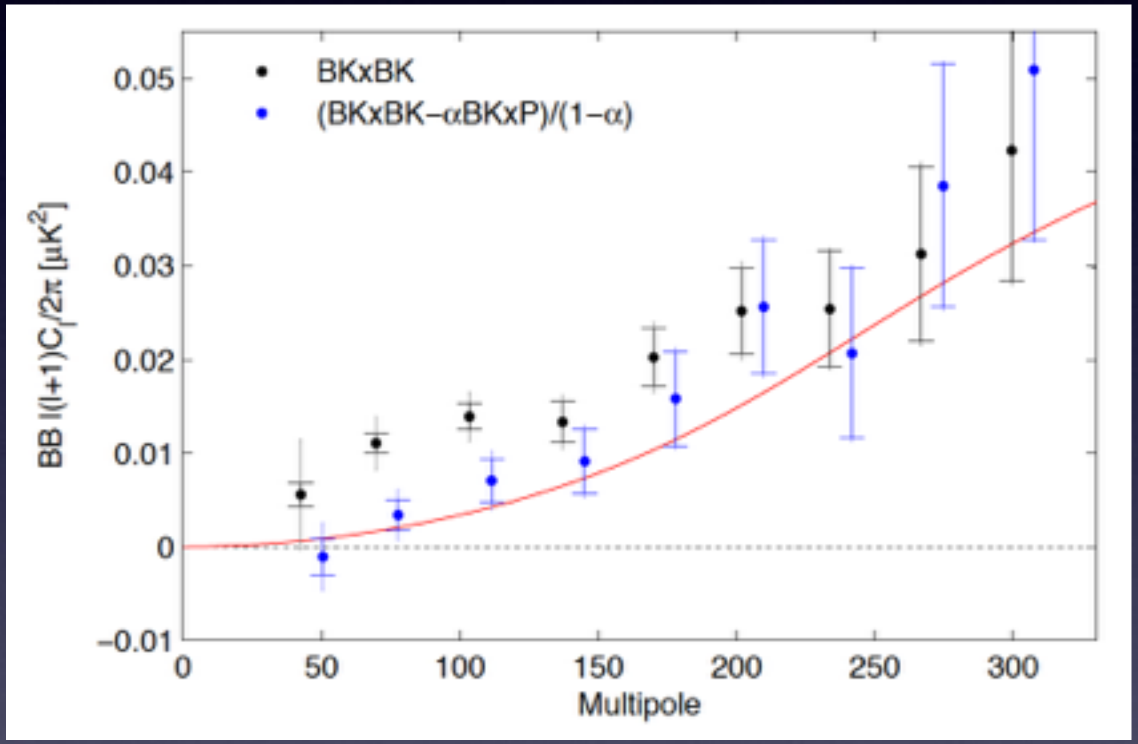
TT, TE, EE+ lensing+BAO+SNIa (JLA) : 1% Level

H_0 . . .	67.74 ± 0.46
Ω_Λ . . .	0.6911 ± 0.0062
Ω_m . . .	0.3089 ± 0.0062
$\Omega_m h^2$.	0.14170 ± 0.00097
$\Omega_m h^3$.	0.09598 ± 0.00029
σ_8 . . .	0.8159 ± 0.0086

Q1 : Gravitational Wave Detection?!
Planck 2015 reports dust contribution



BICEP2
March 2014

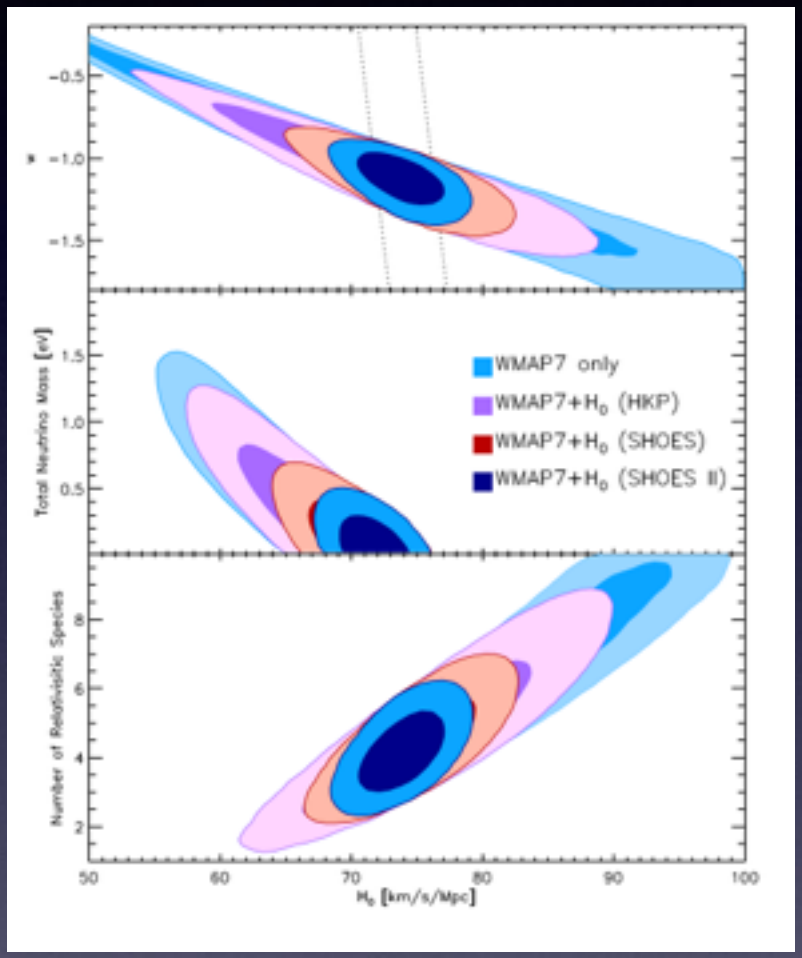


Blue : Dust Subtracted
Red : r=0 model

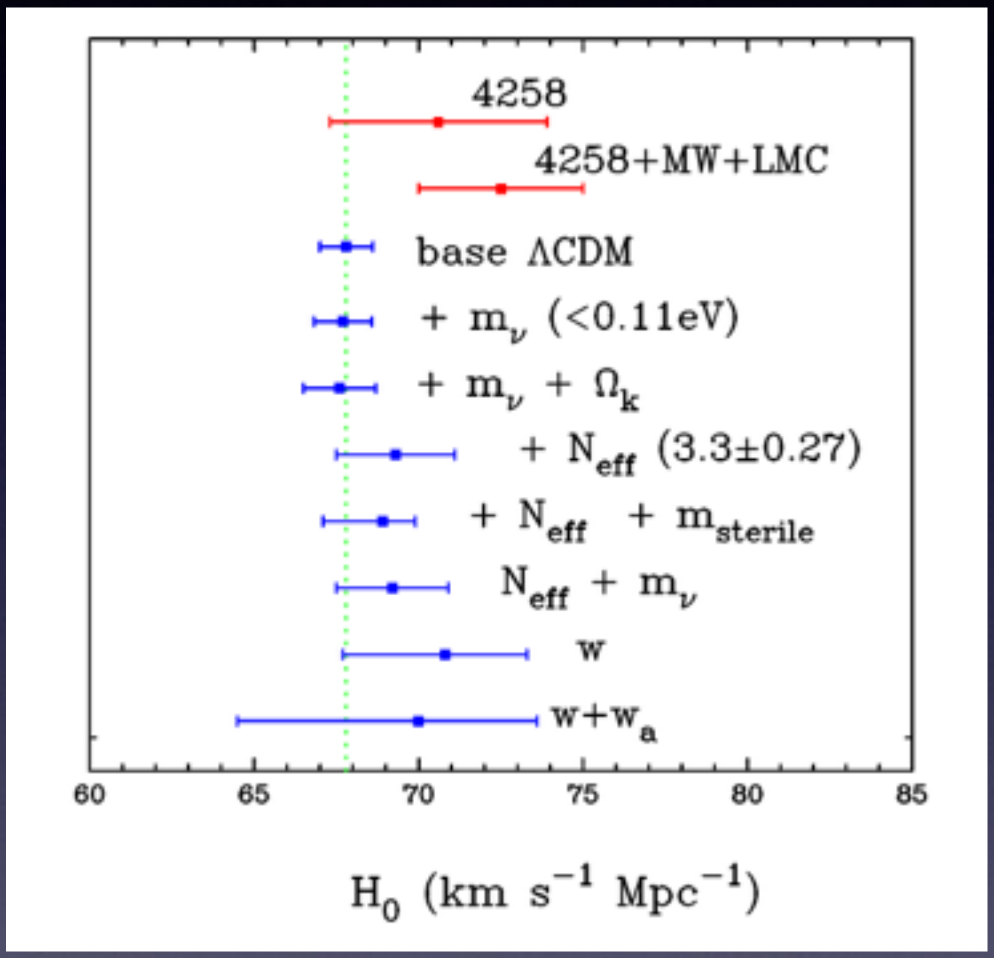
Planck+BICEP2/Keck
arXiv:1502.00612

Q2: Hubble Constant

Cepheids(73.8+/-2.4) vs CMB (67.74+/-0.46)



Riess et al 2011
H=73.8 +/- 2.4



Efstathiau 2013
H=72.5 +/- 2.5 km/s/Mpc

Q3 Dark Energy: Is *w* -1?
w=P/ρ : equation of state

*w*CDM:

w = −1.008 ± 0.052(stat)

−1.013 ± 0.070(sys)

SNe + BAO + CMB

... and allowing for curvature: owCDM

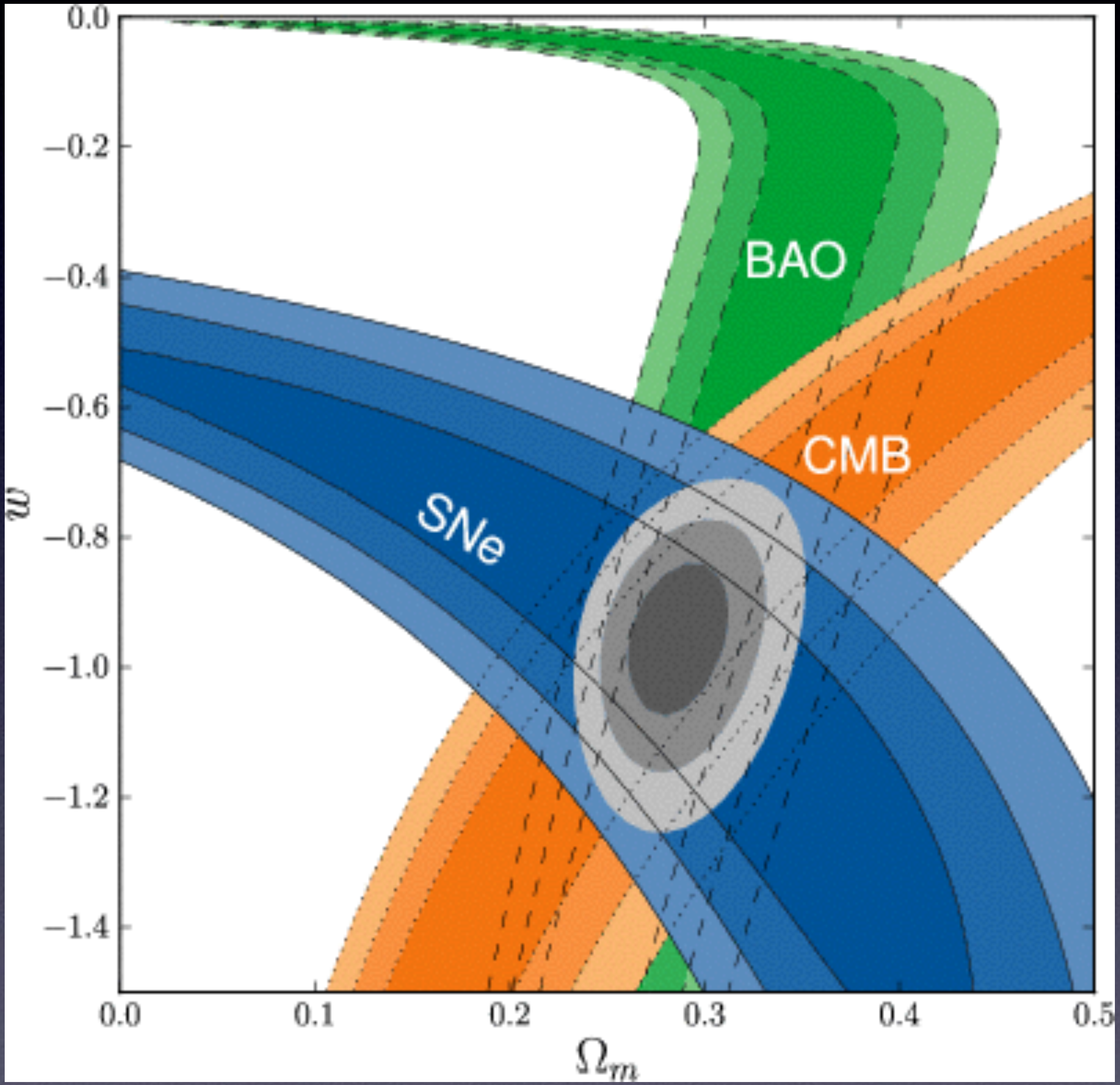
w = −1.006 ± 0.058(stat)

−1.003 ± 0.093(sys)

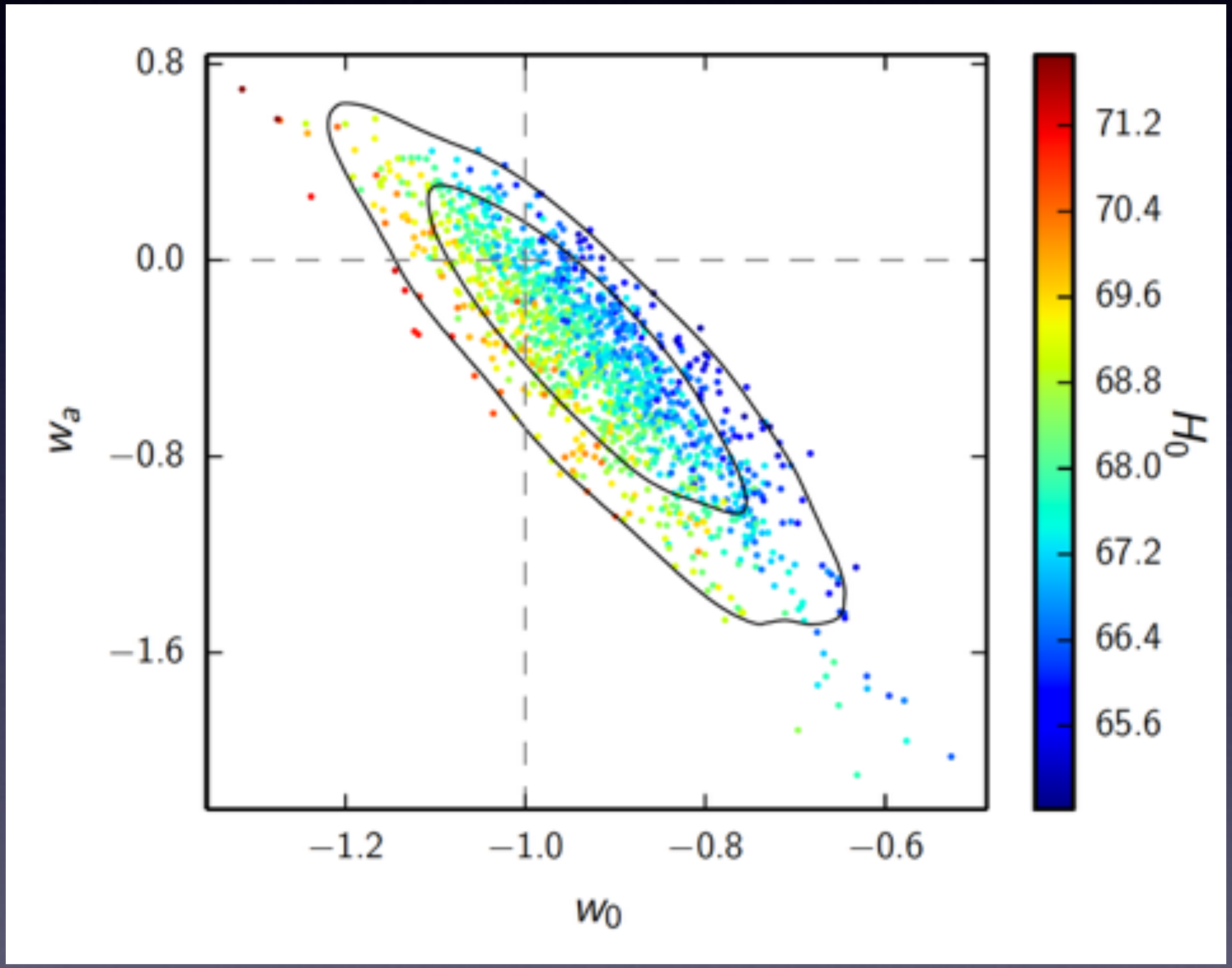
with systematics

- w=-1 : cosmological constant
- w=0 : matter
- w=1/3: radiation

$$E \propto a^{-3(1+w)}$$



Dark Energy
Q3: w=-1 (LCDM) or not?



For wCDM $\rho \propto a^{-3(1+w)}$

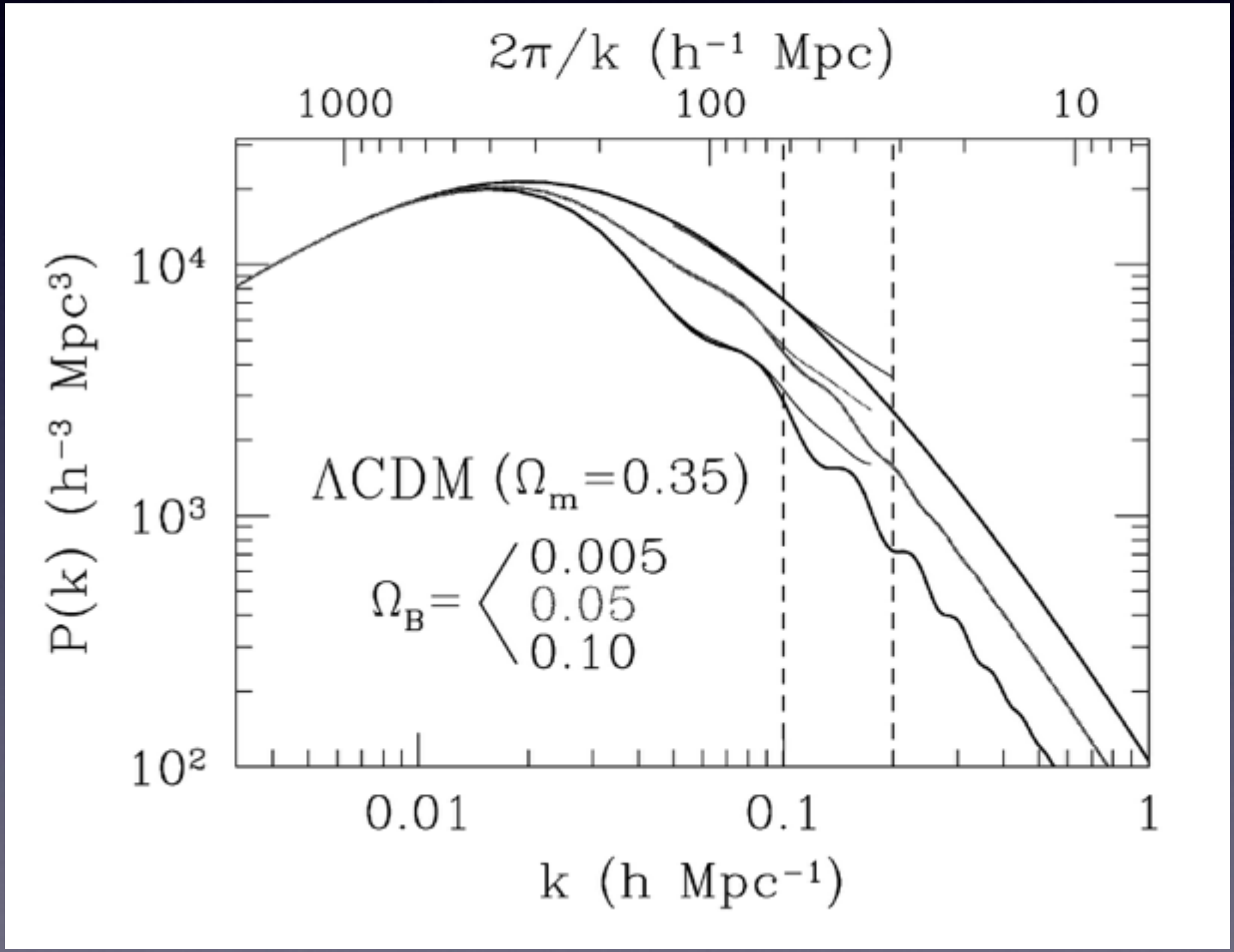
$$w = -1.019^{+0.075}_{-0.080}$$

$$w = w_0 + (1-a)w_a$$

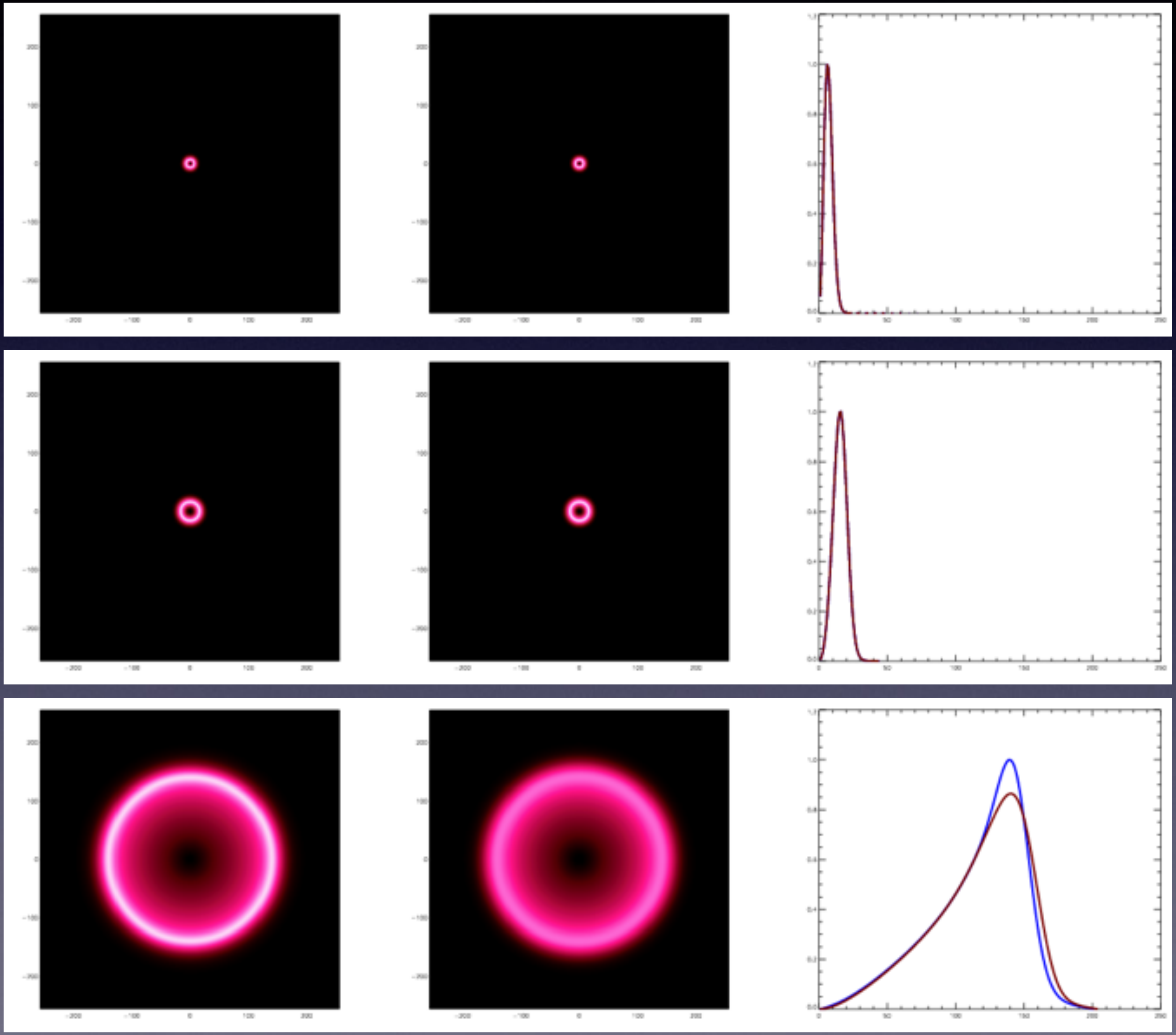
A Brief History of BAO

- Acoustic Oscillation (Bond & Efstahiu 1984, Hu & Sugiyama 1996, Hu & White)
- Baryon Acoustic Oscillation (Kaminonkowski et al 1994, Eisenstein & Hu 1998)
- Application to LRG (Eisenstein et al 2001, 2005)
- WiggleZ, SDSS-III BAO Measurement z=0.3-0.7
- SDSS-III Lyman alpha Forest BAO (2011-2015)
- SDSS-IV ELG BAO

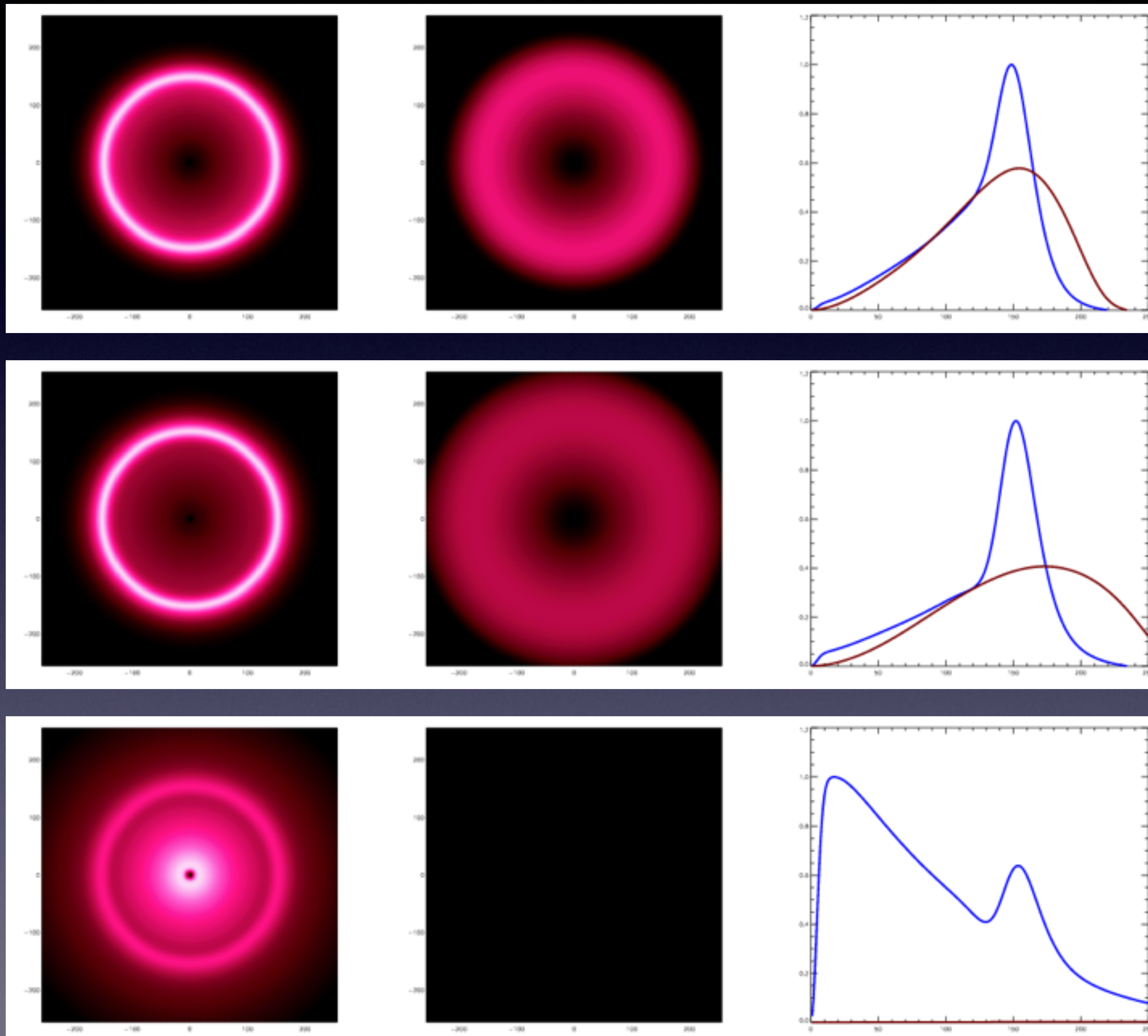
Sign of Baryonic Feature in Power Spectrum
Eisenstein, Hu, Tegmark (1998)



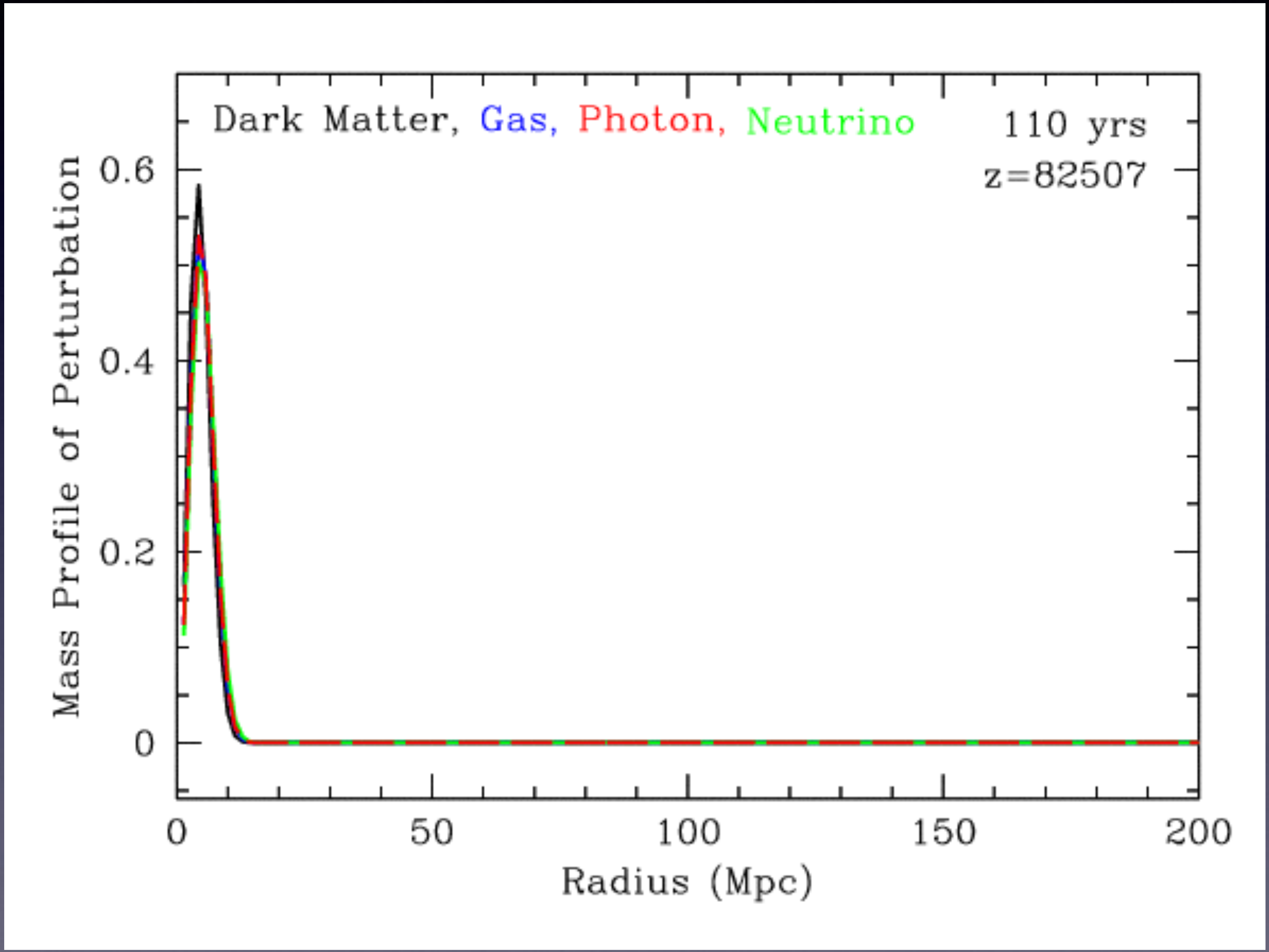
Baryon Photon Credit : Martin White



Baryon Photon Credit : Martin White

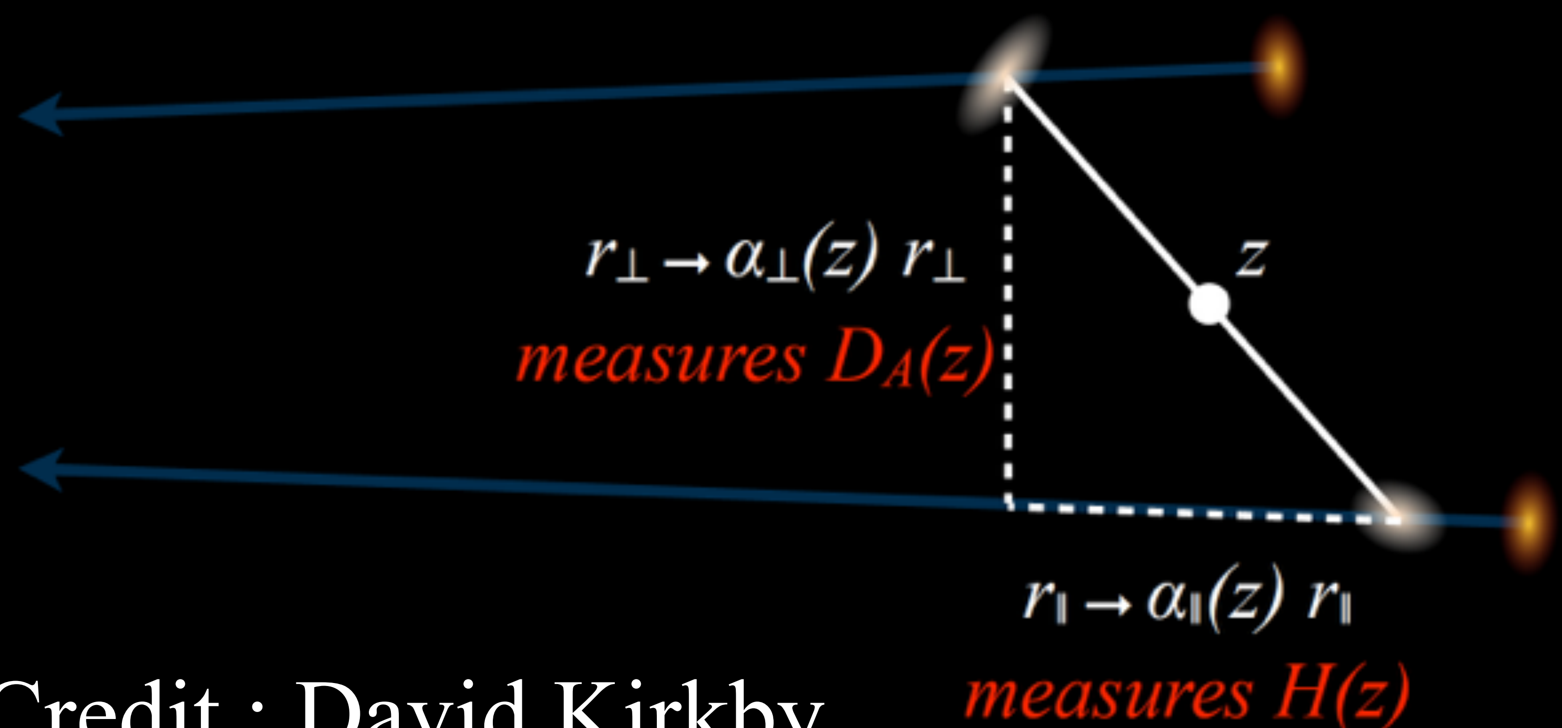


Rise of BAO



Credit : Eisenstein

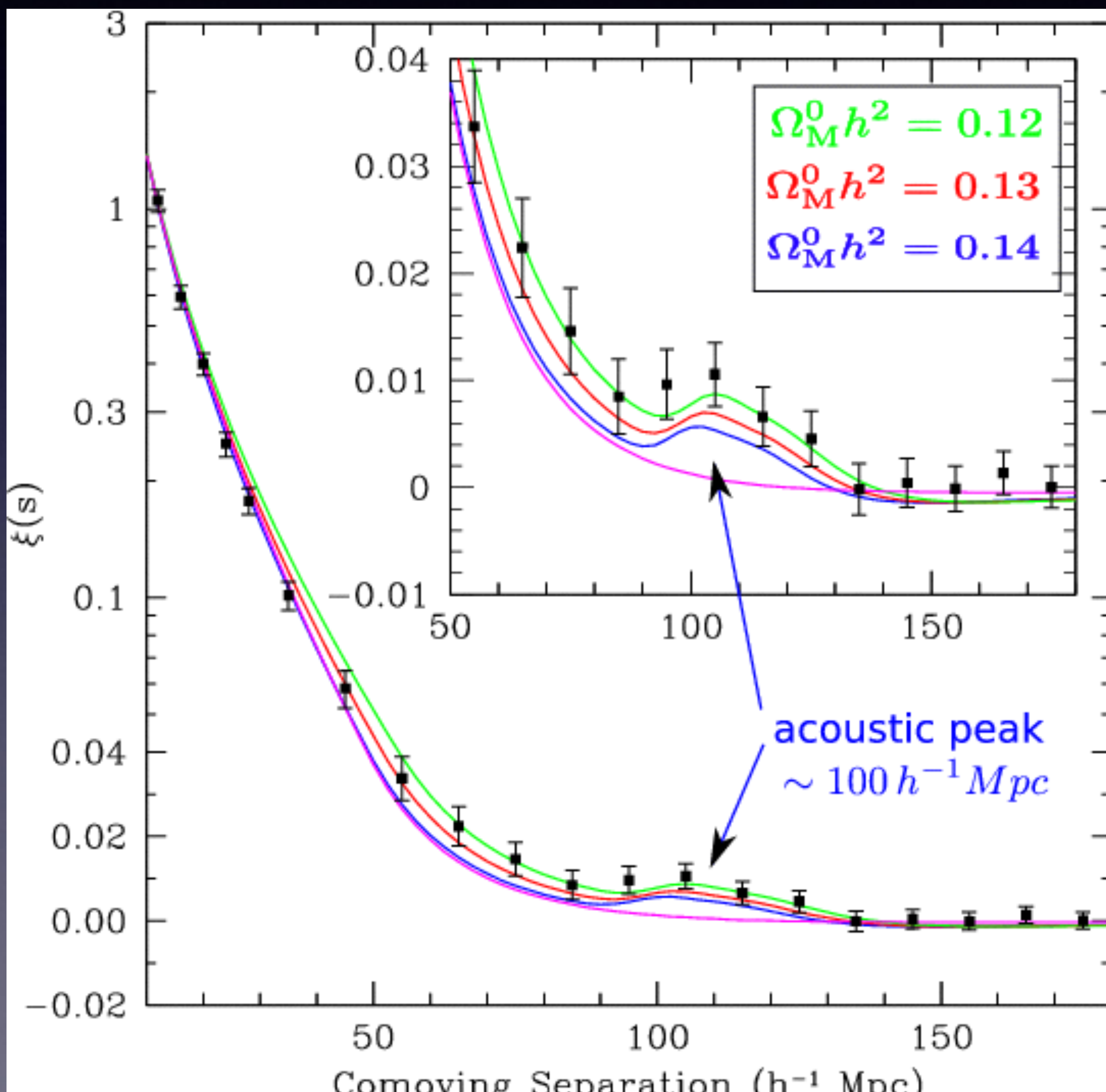
r=147.50+/-0.24 Mpc (Planck)



Credit : David Kirkby

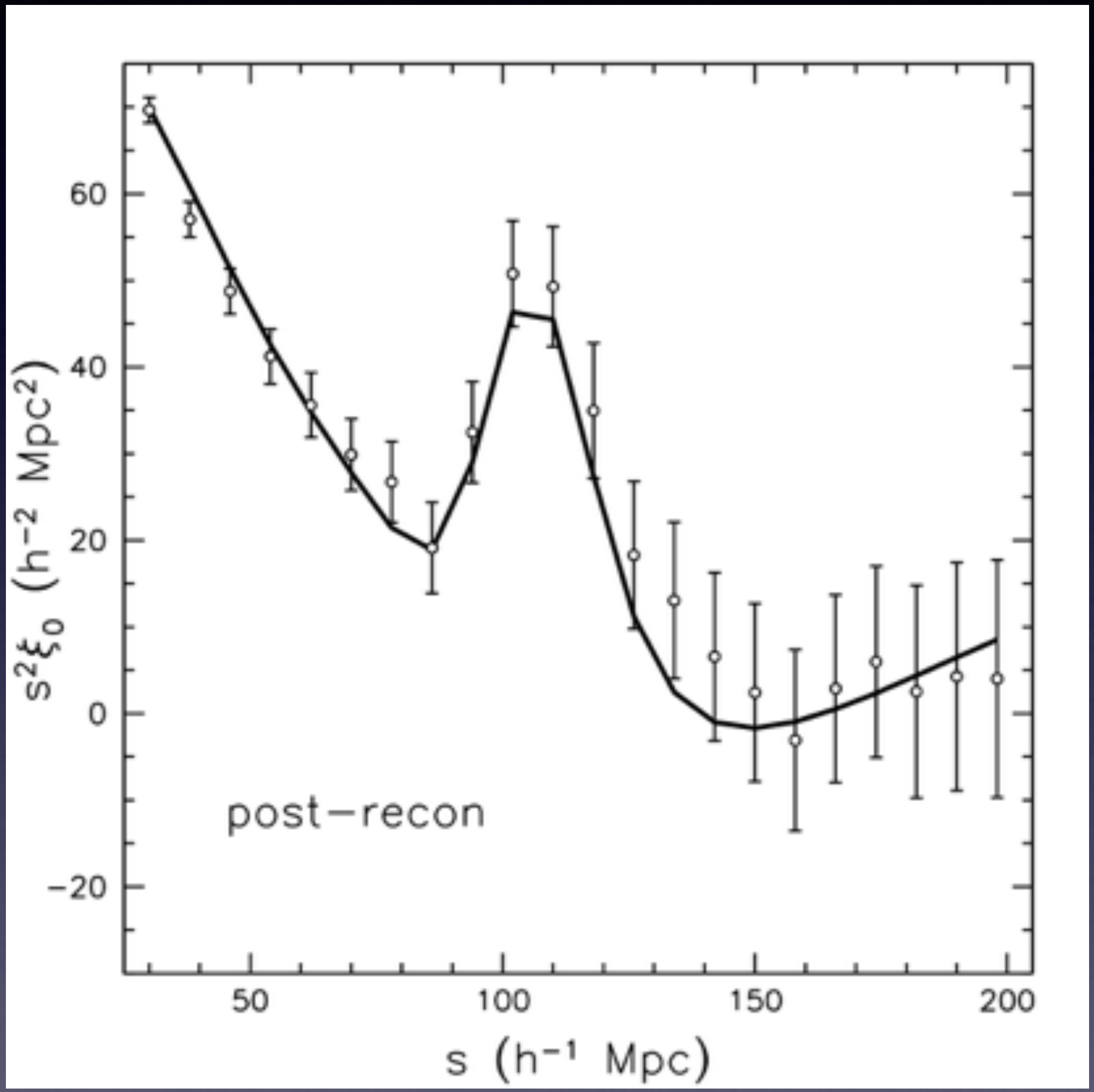
$$\alpha_\parallel(z) = \frac{r_{\mathrm{BAO,fid}}}{r_{\mathrm{BAO}}} \cdot \frac{H_{\mathrm{fid}}(z)}{H(z)} \quad , \quad \alpha_\perp(z) = \frac{r_{\mathrm{BAO,fid}}}{r_{\mathrm{BAO}}} \cdot \frac{D_A(z)}{D_{A,\mathrm{fid}}(z)} \, .$$

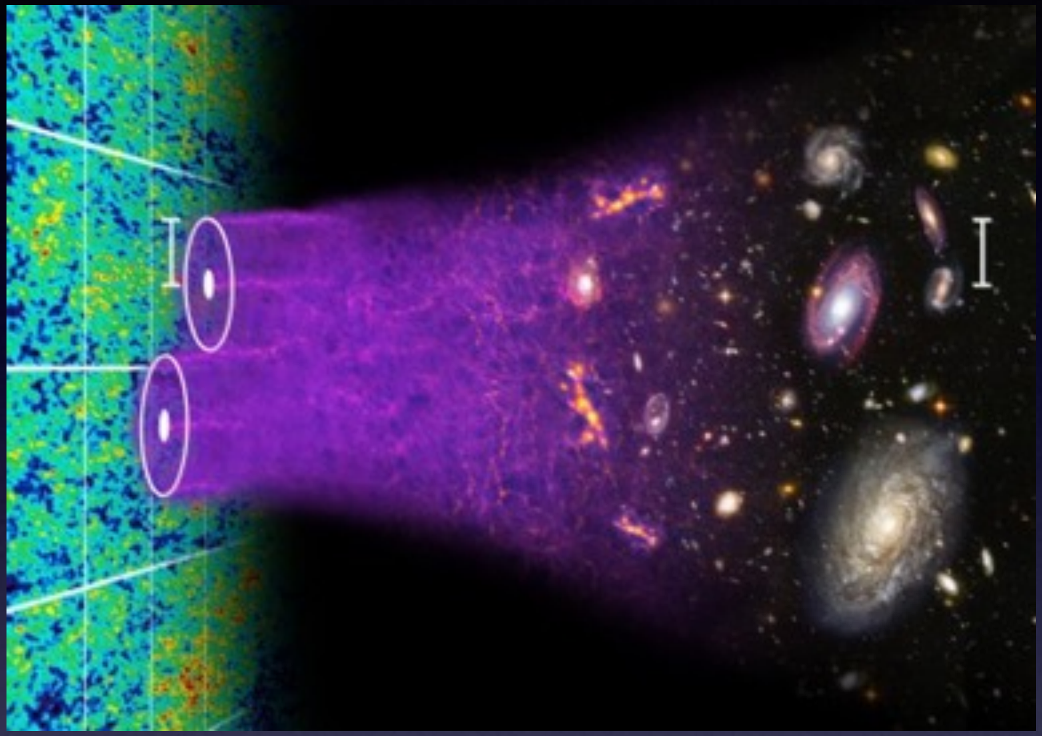
First Detection in 2005
Luminous Red Galaxies (LRG)

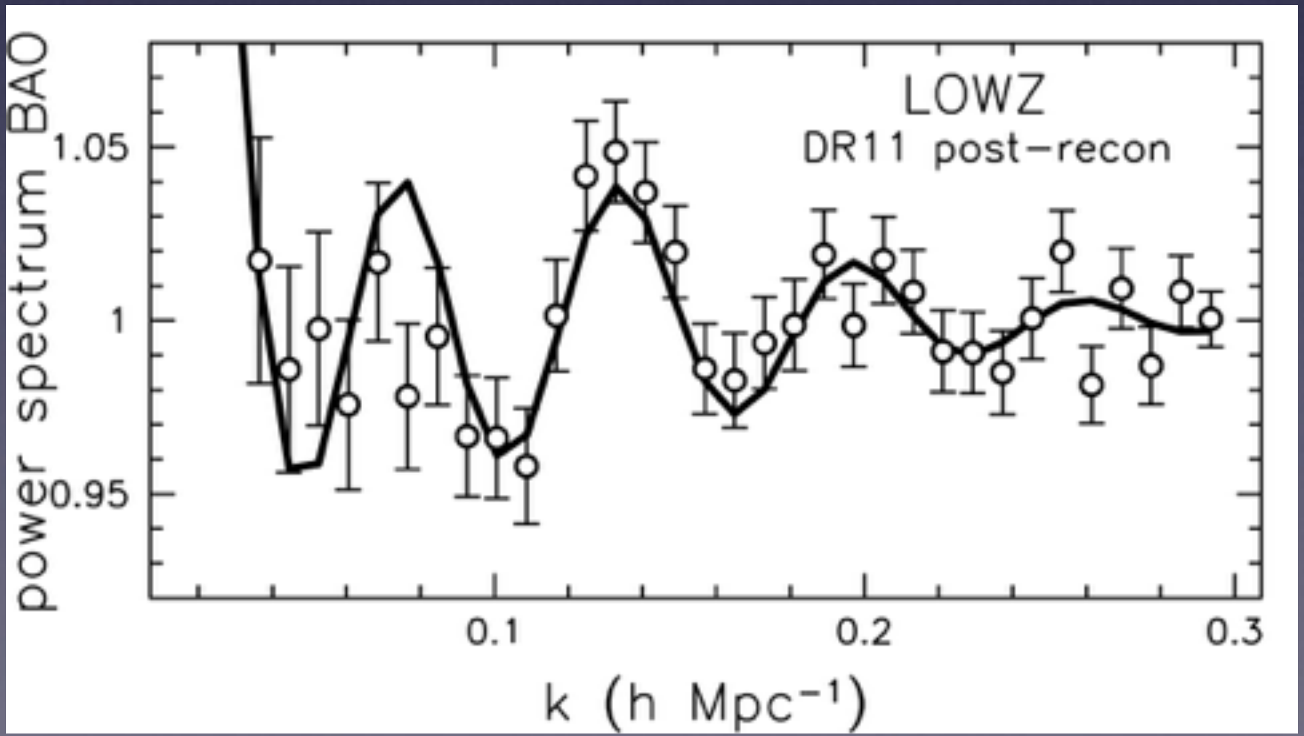


Eisenstein et al 2005

SDSS-III BOSS, Wiggle Z (2005-2014)

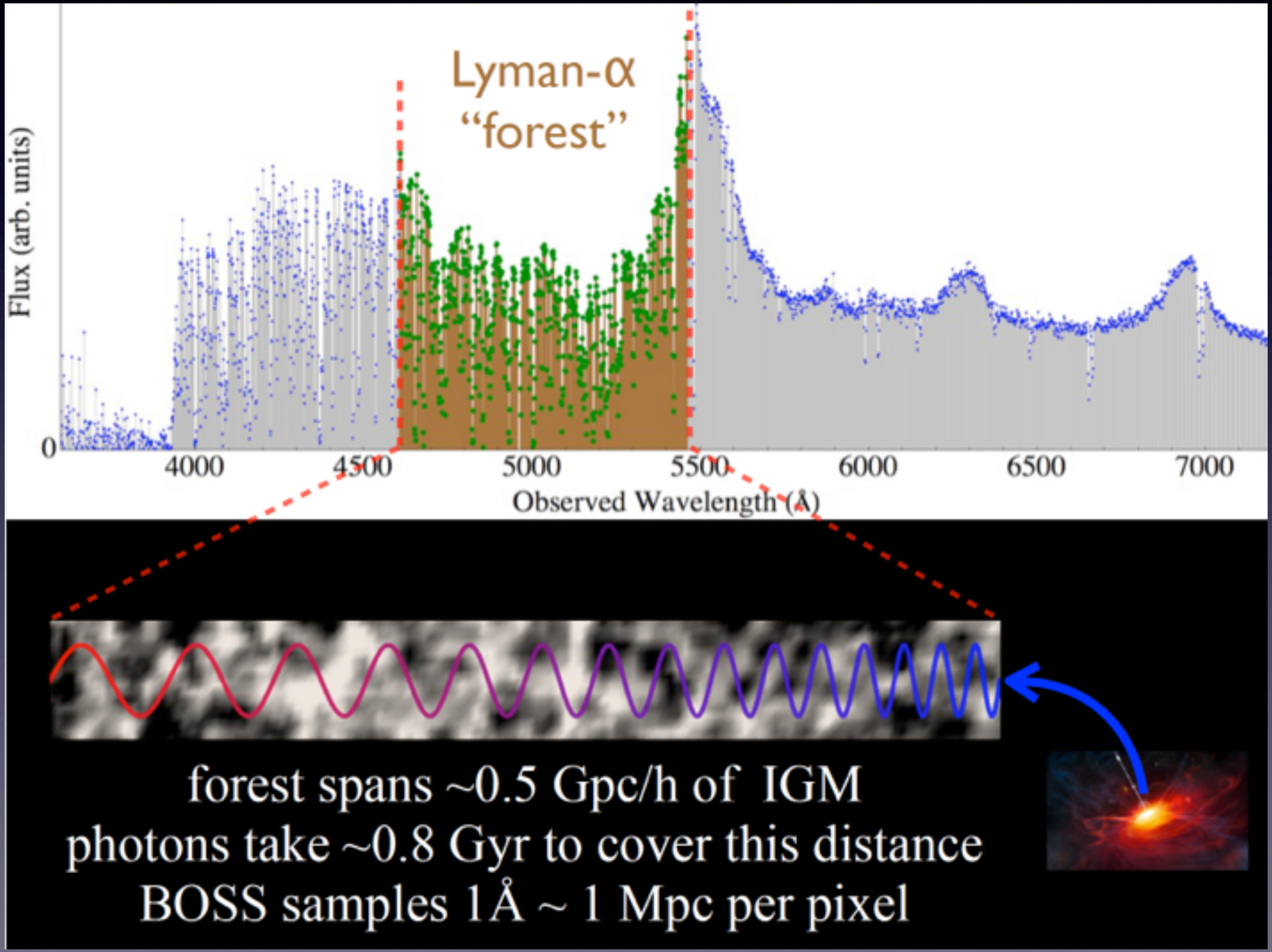




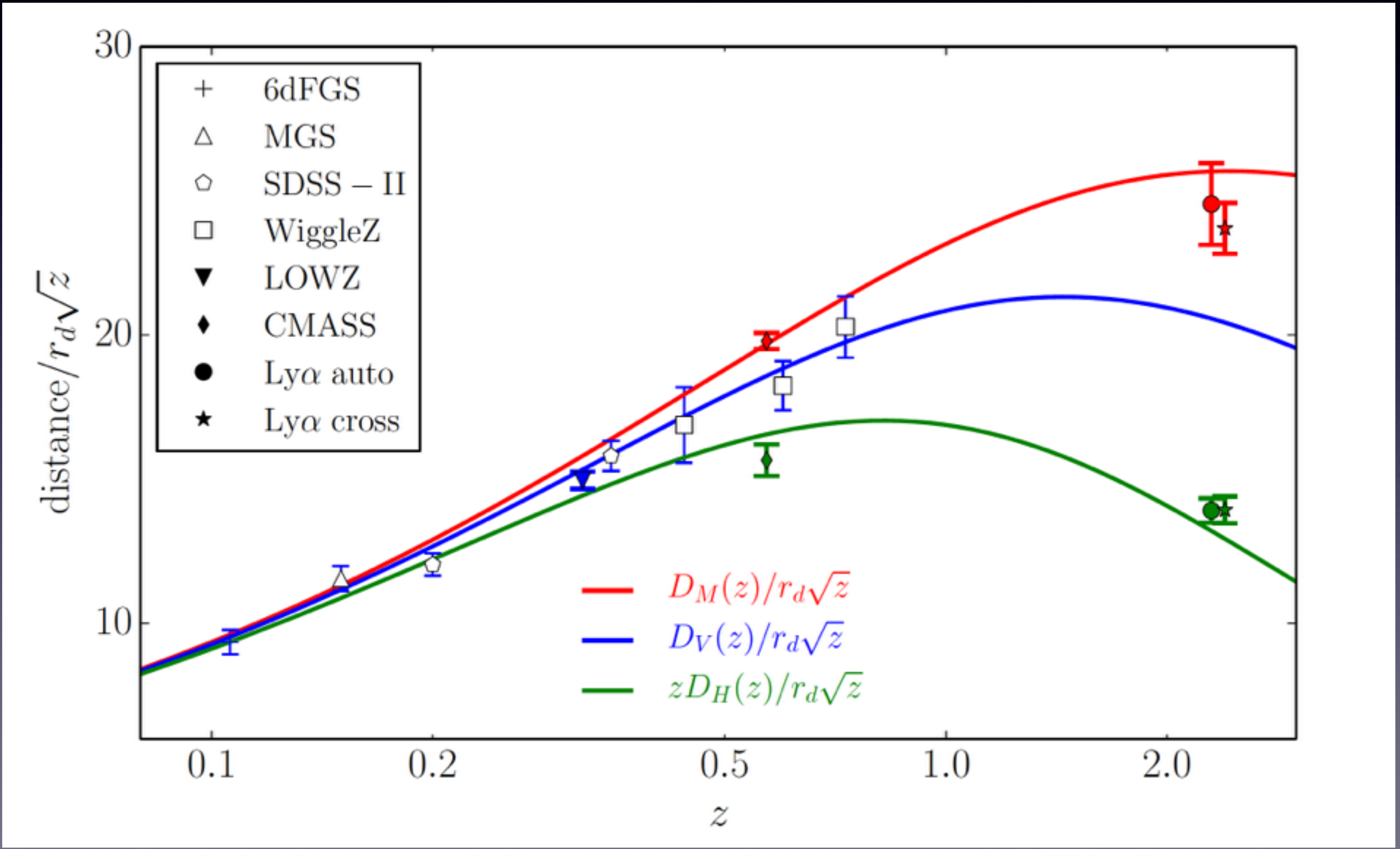


Anderson et al 2011

Ly alpha Forest BAO at z=2.4!



SDSS-III : Distance Measurement



Near Future Satellite Programs

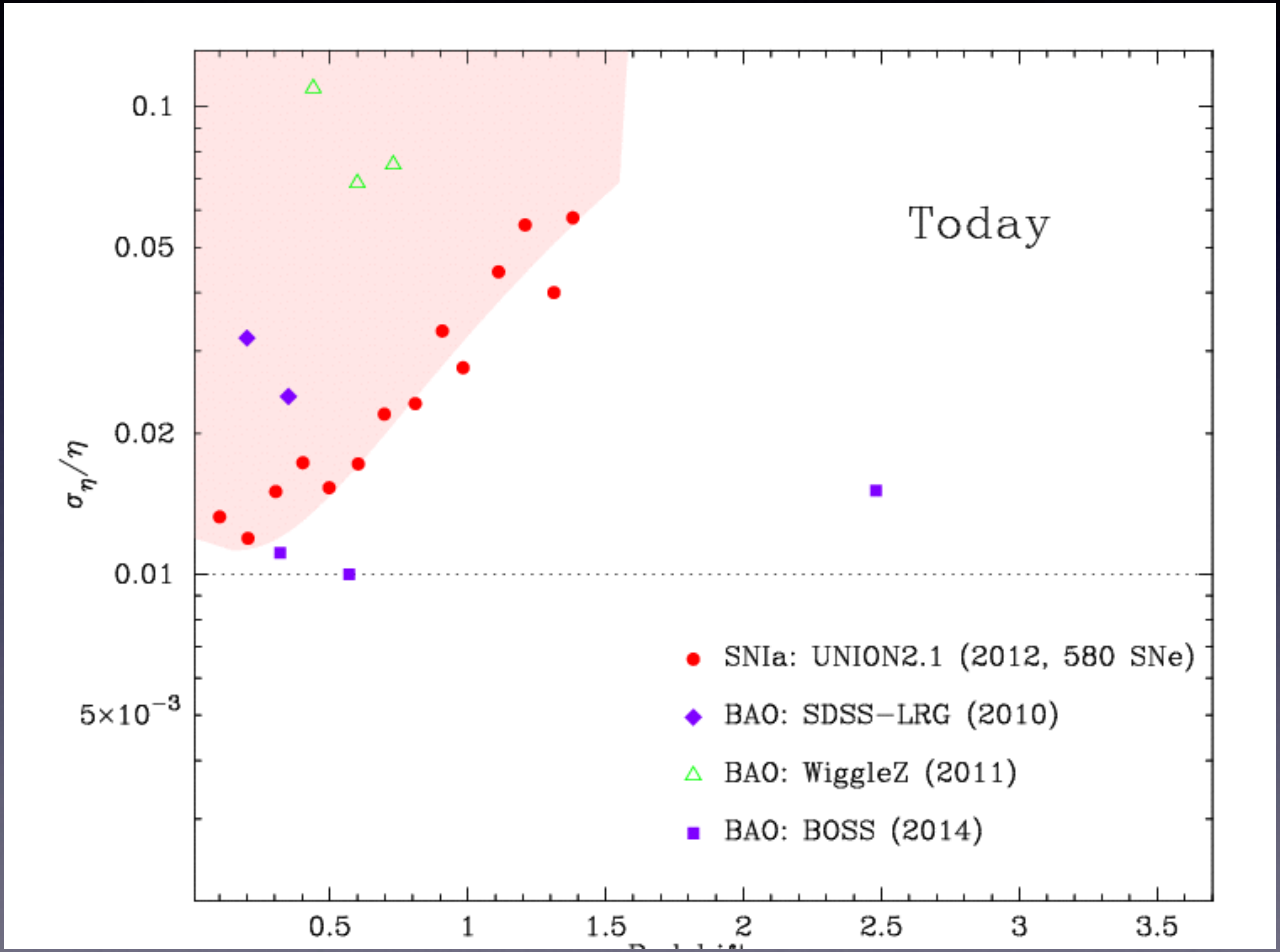
Euclid (2022- Europe)

WFIRST (US: 2025-)

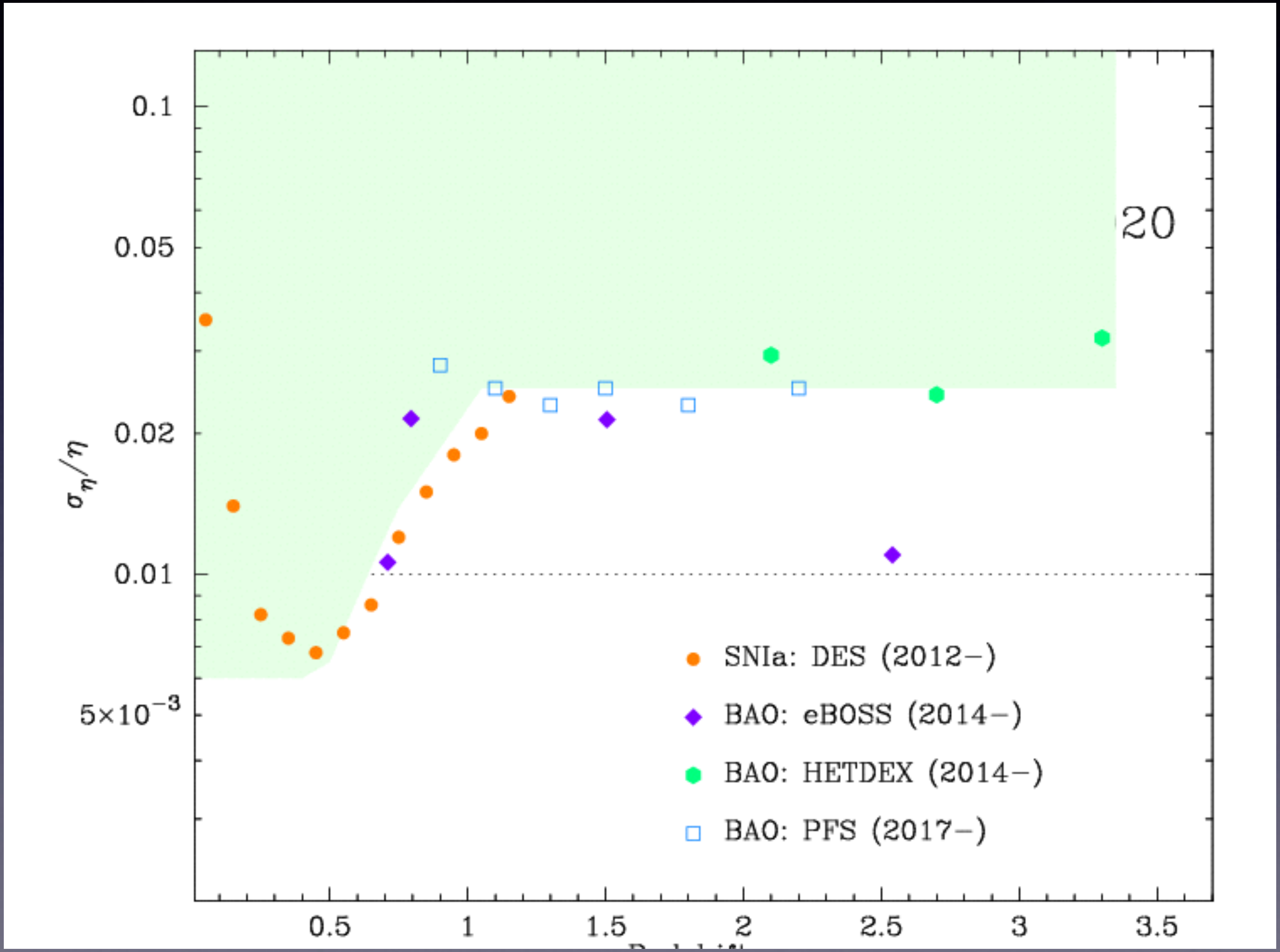
TMT (30m Telescope)

JWST (US: 2018)

Today : 5% Level

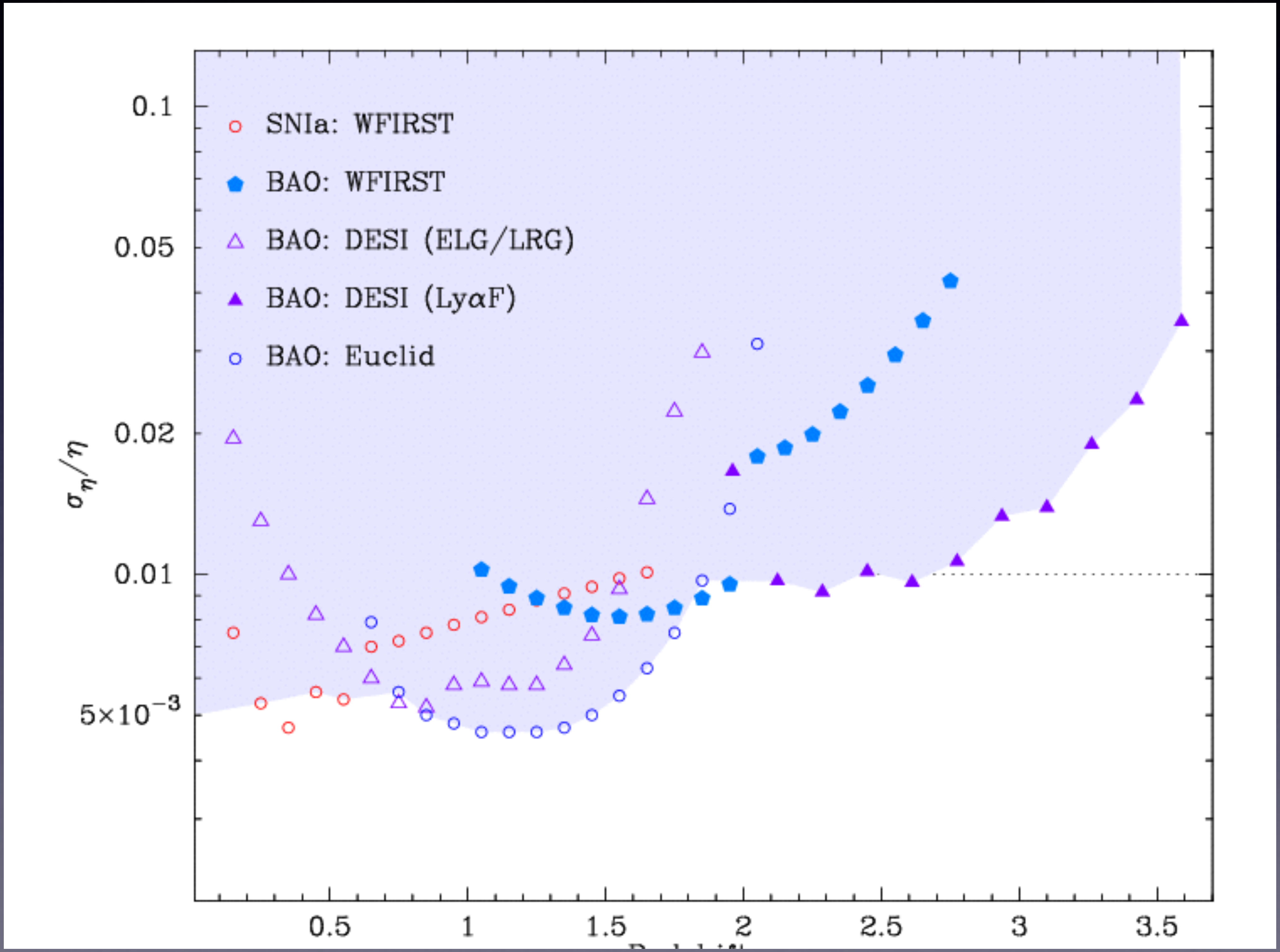


2020 : 2% Level



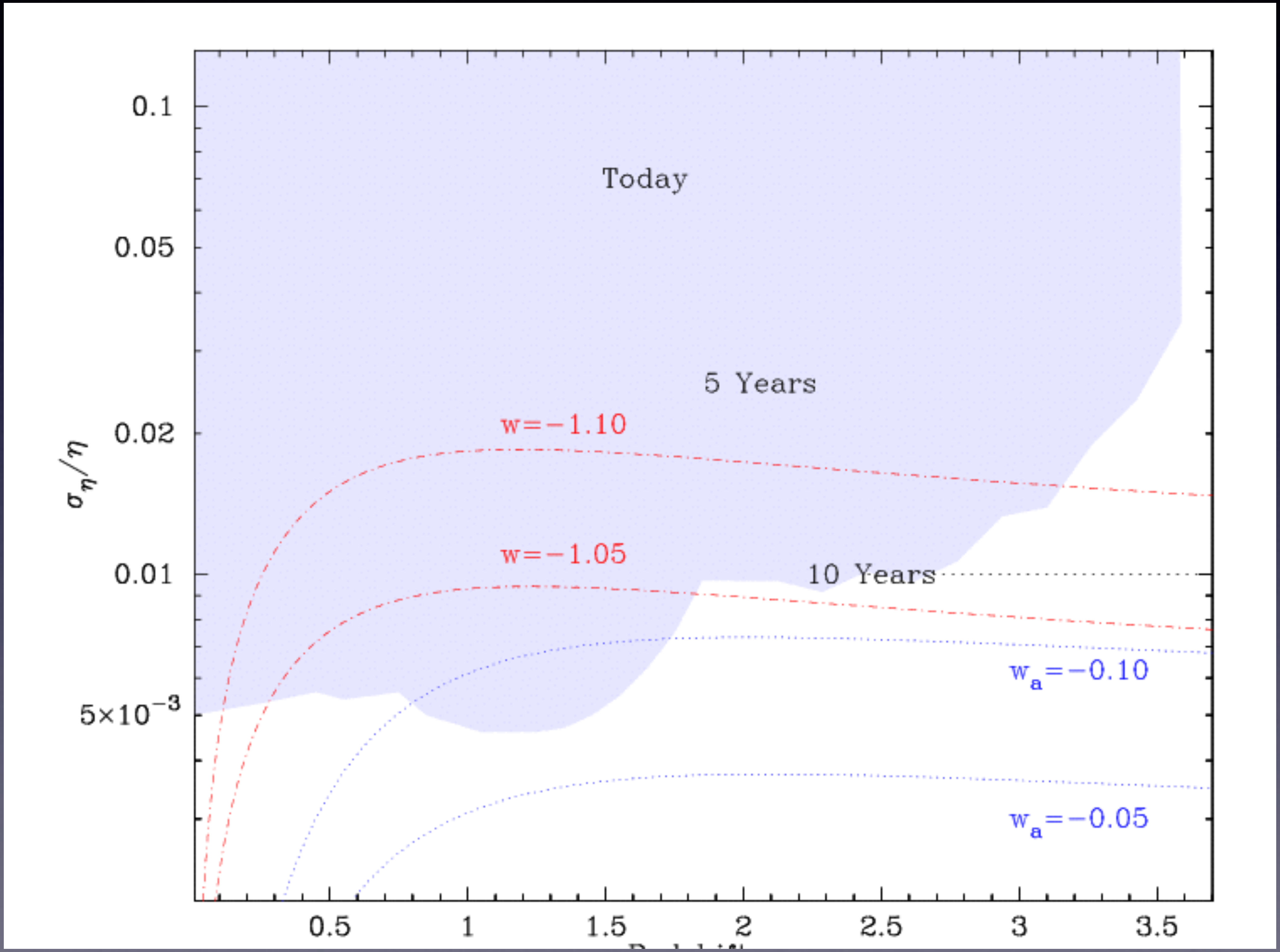
0.1
0.05
0.02
0.01
5×10^−3
σ_η/η
20
0.5
1
1.5
2
2.5
3
3.5
SNIa: DES (2012−)
BAO: eBOSS (2014−)
BAO: HETDEX (2014−)
BAO: PFS (2017−)

2025 1% Level

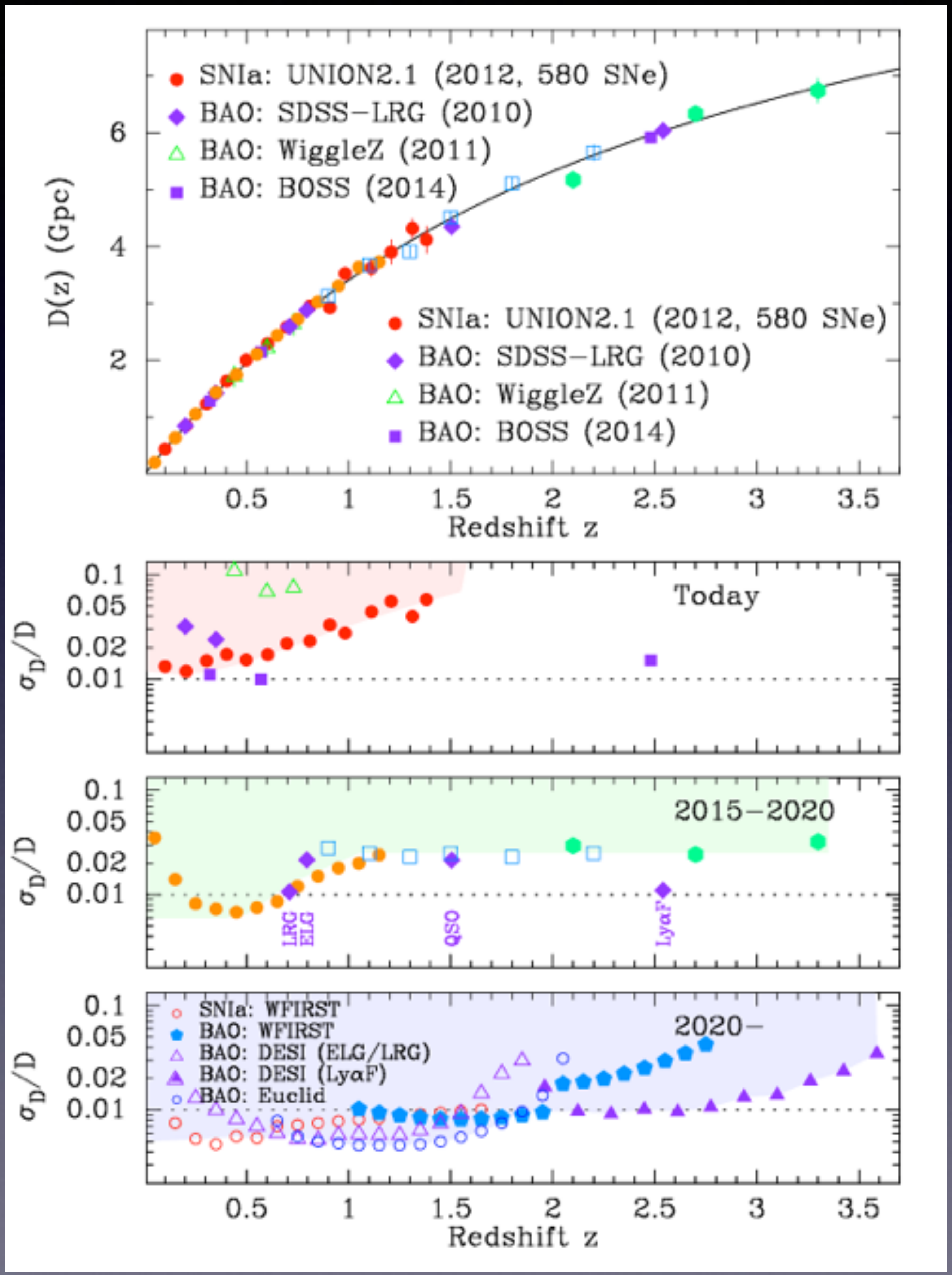


SNIa: WFIRST
BAO: WFIRST
BAO: DESI (ELG/LRG)
BAO: DESI (LyαF)
BAO: Euclid
σ_η/η
0.1
0.05
0.02
0.01
5×10^-3
0.5
1
1.5
2
2.5
3
3.5

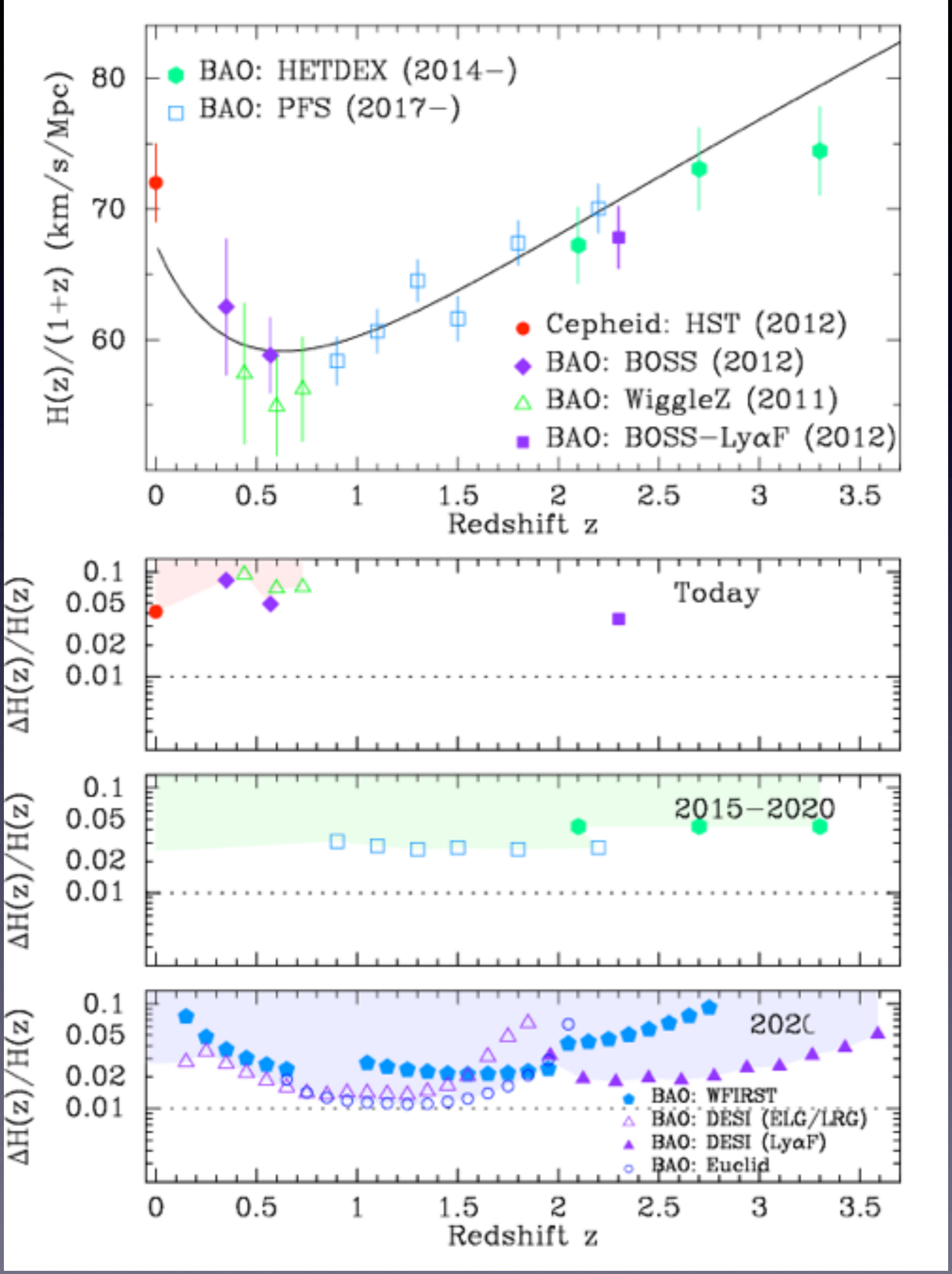
Wa Constraints in 2025



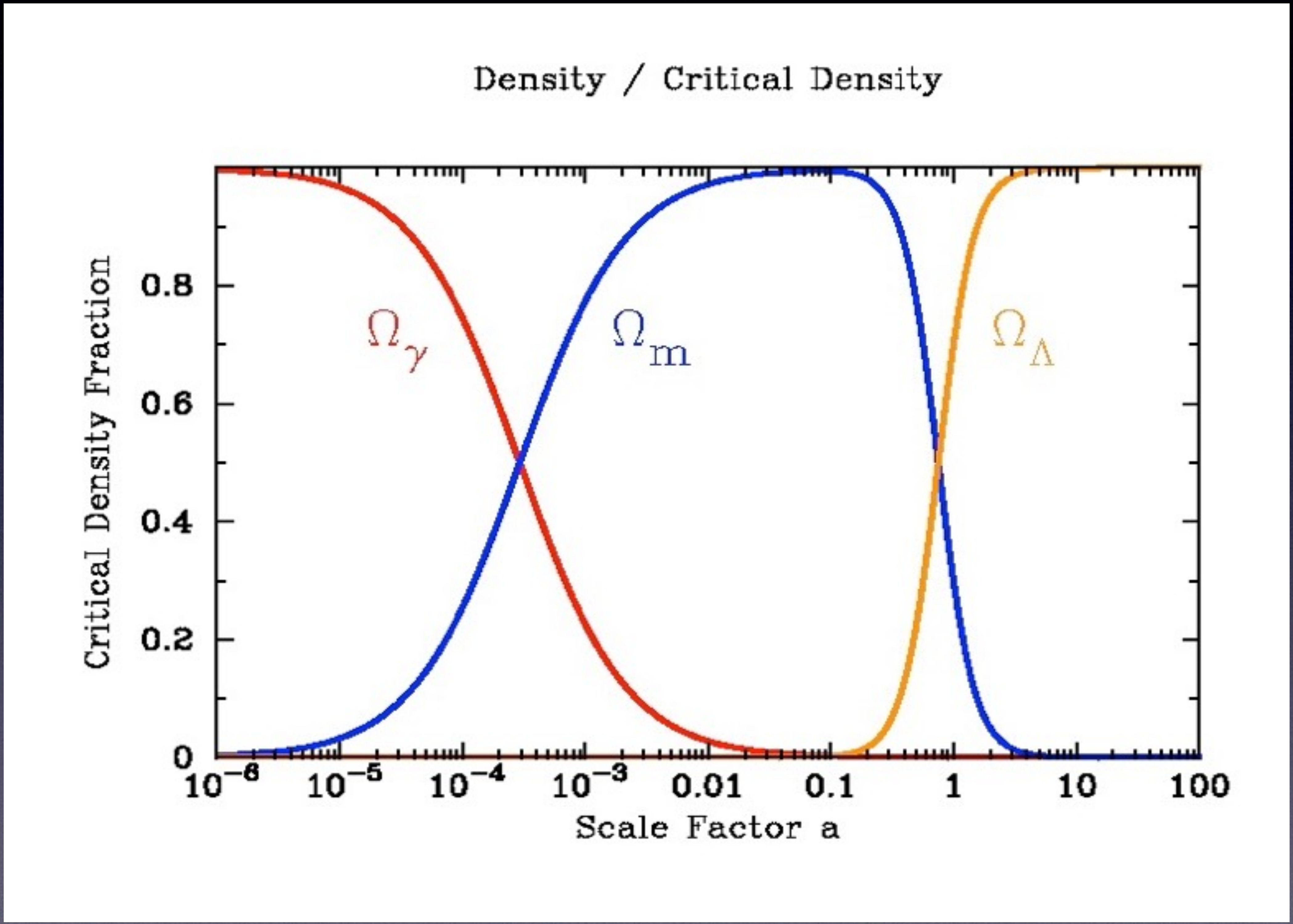
Distance vs Brightness



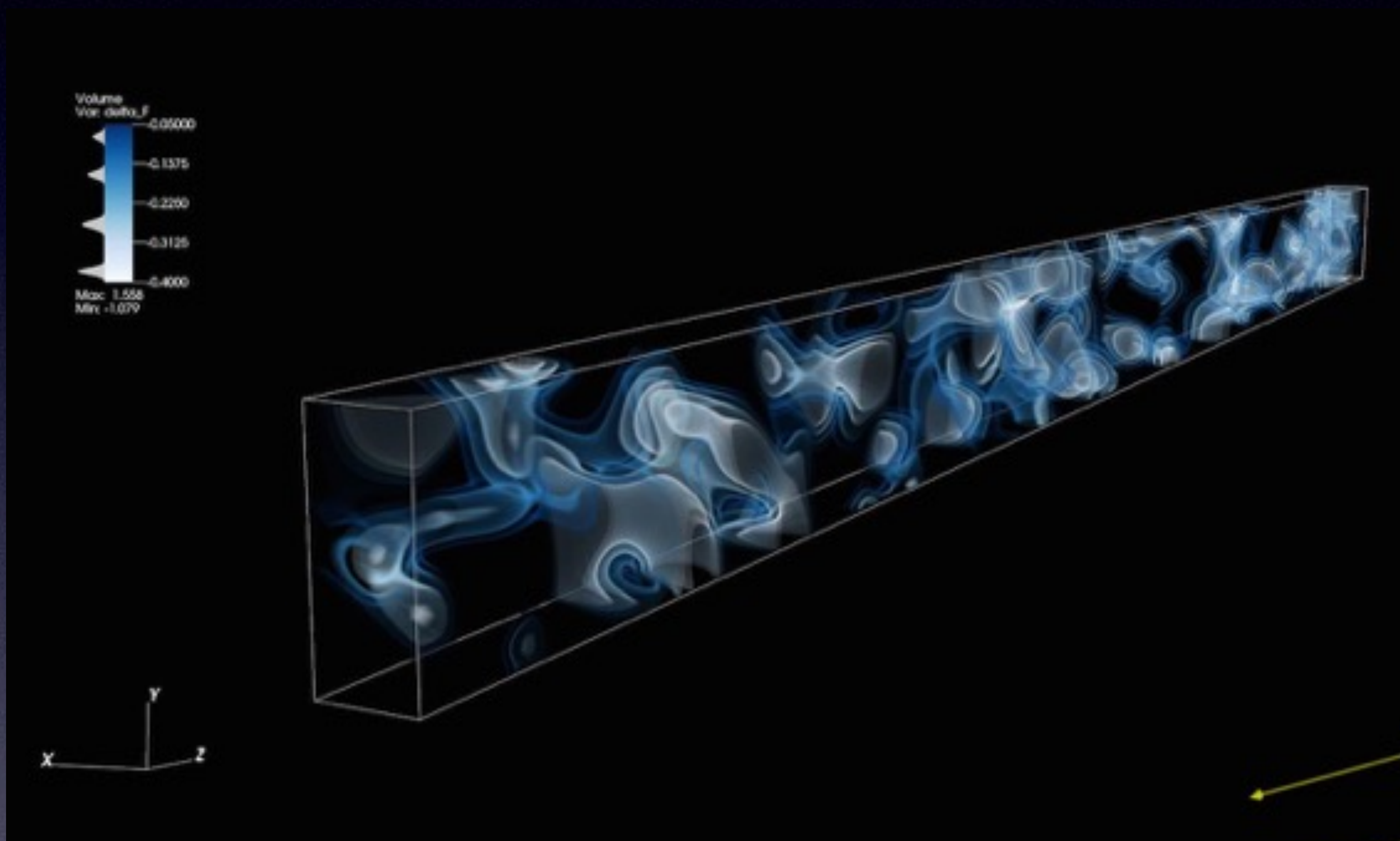
Distance & Acceleration

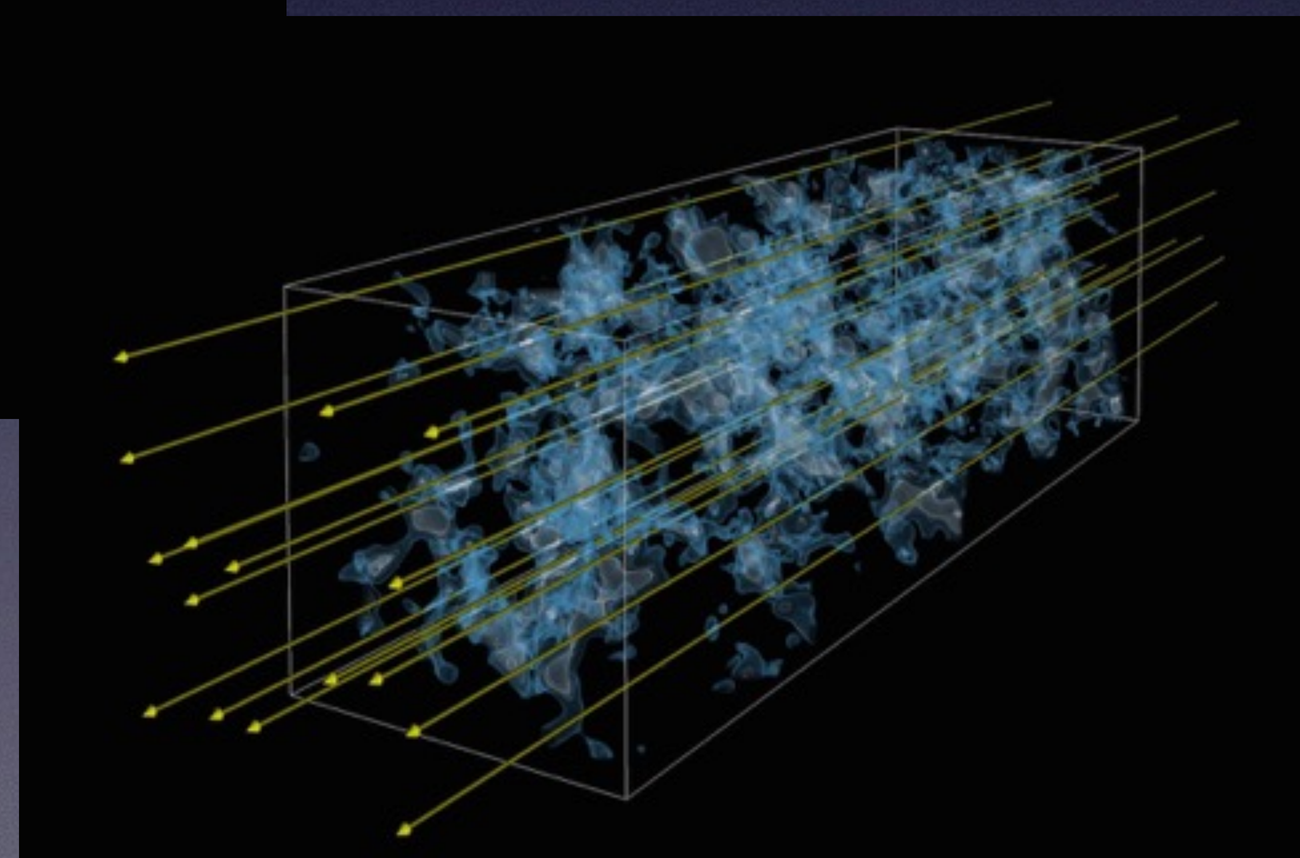


From Deceleration to Acceleration

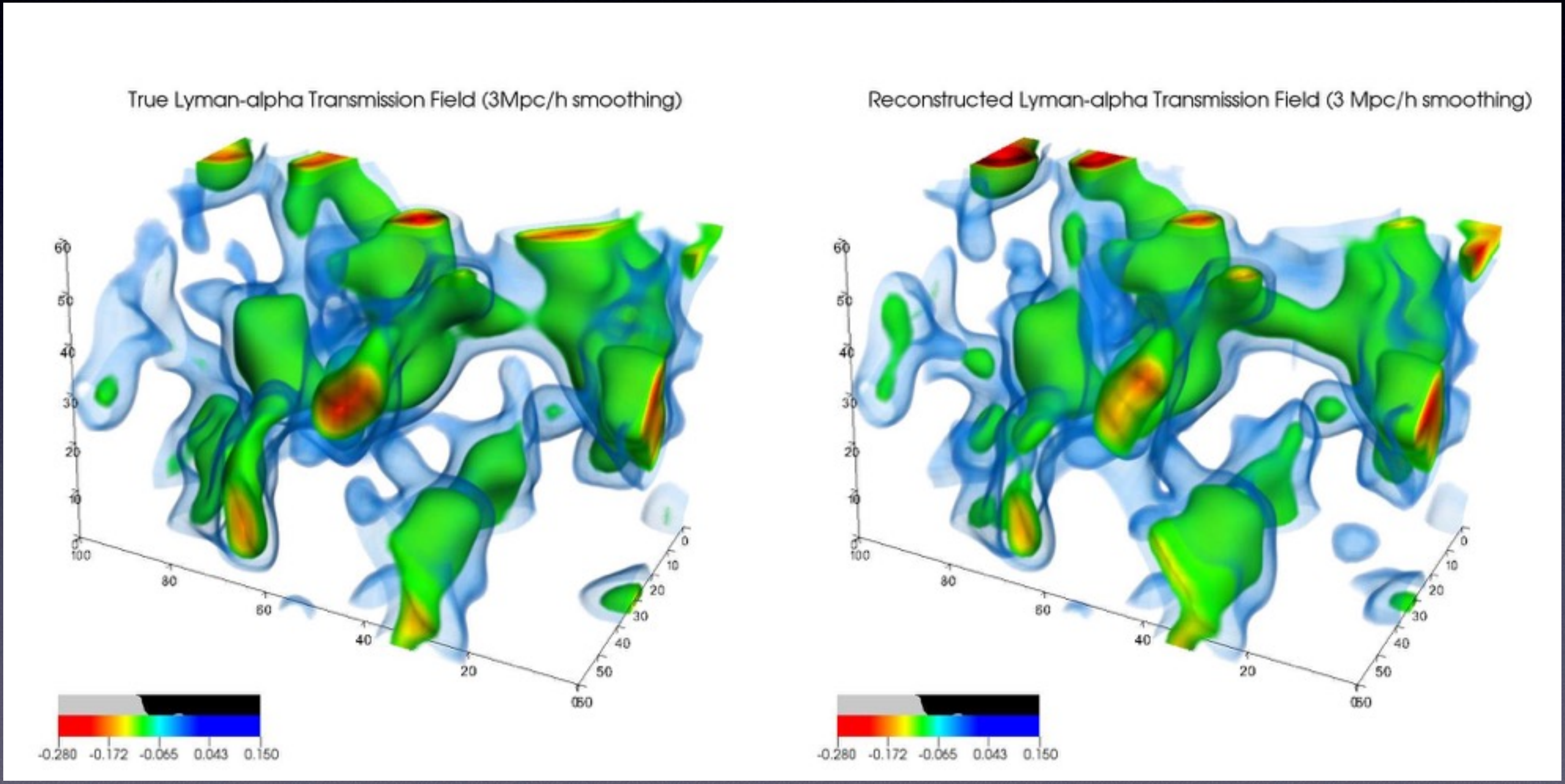


What's Unique about PFS?
Tomography





3D Tomography by LBG



Hubble Diagram by Quasars

Risaliti & Lusso (arxiv 1505.0711)

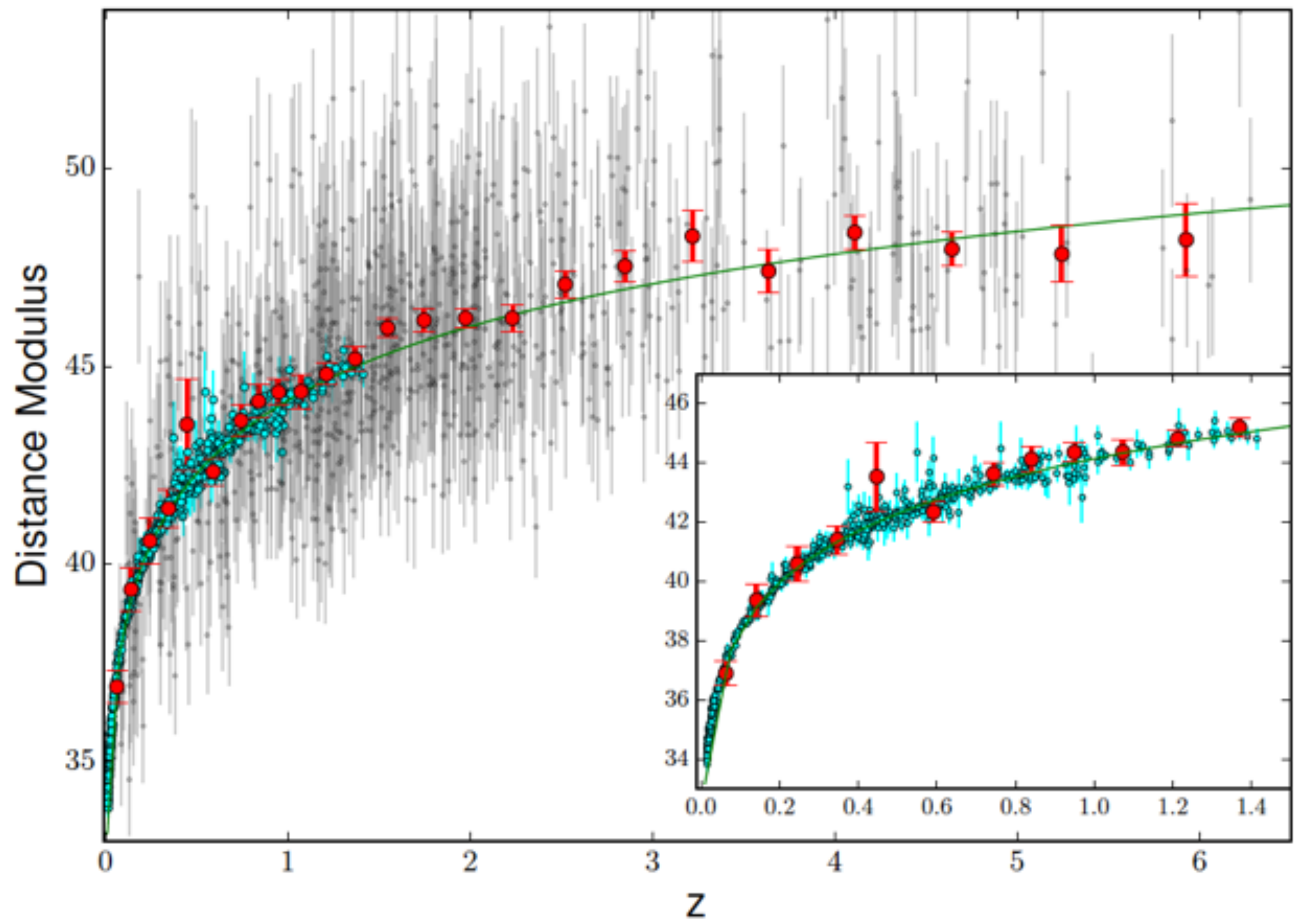


FIG. 5.— Hubble Diagram for the quasar sample (small gray points) and supernovae (cyan points) from the Union 2.1 sample (Suzuki et al. 2012). The large red points are quasar averages in small redshift bins. The inner box shows a zoom of the $z = 0 - 1.5$ range, in order to better visualize the match between the SNe and the quasar samples. The continuous line is obtained from a joint fit of the two samples assuming a standard ΛCDM cosmological model.

Hubble Diagram by Quasars

Risaliti & Lusso (arxiv 1505.0711)

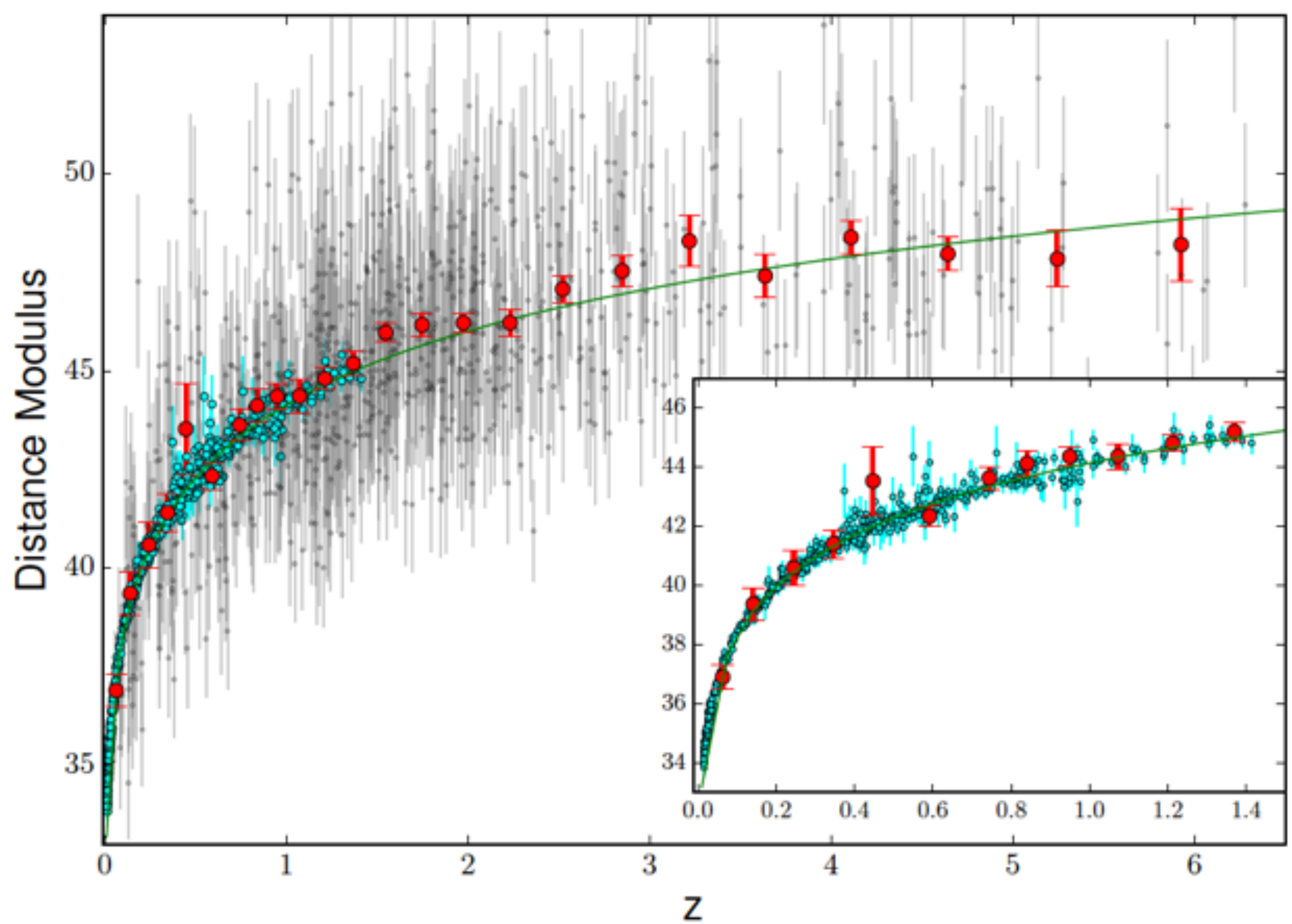
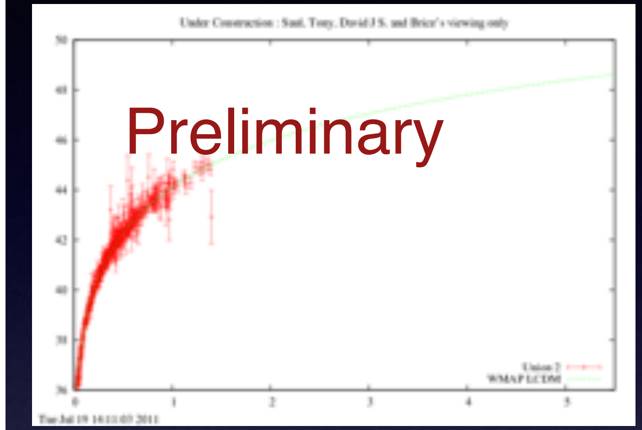
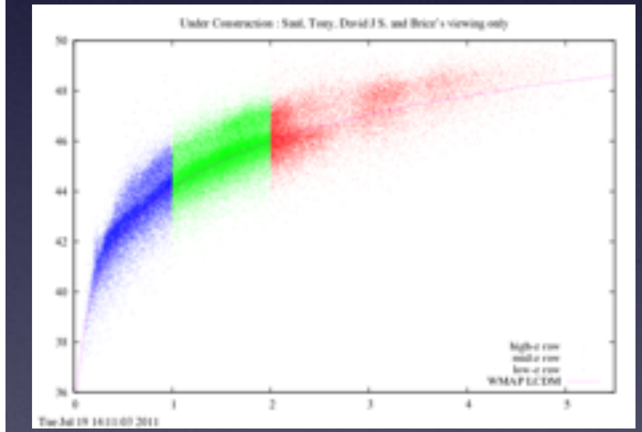
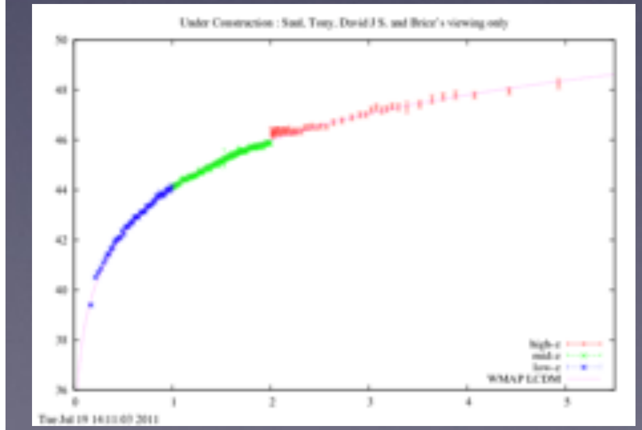


FIG. 5.— Hubble Diagram for the quasar sample (small gray points) and supernovae (cyan points) from the Union 2.1 sample (Suzuki et al. 2012). The large red points are quasar averages in small redshift bins. The inner box shows a zoom of the $z = 0 - 1.5$ range, in order to better visualize the match between the SNe and the quasar samples. The continuous line is obtained from a joint fit of the two samples assuming a standard ΛCDM cosmological model.



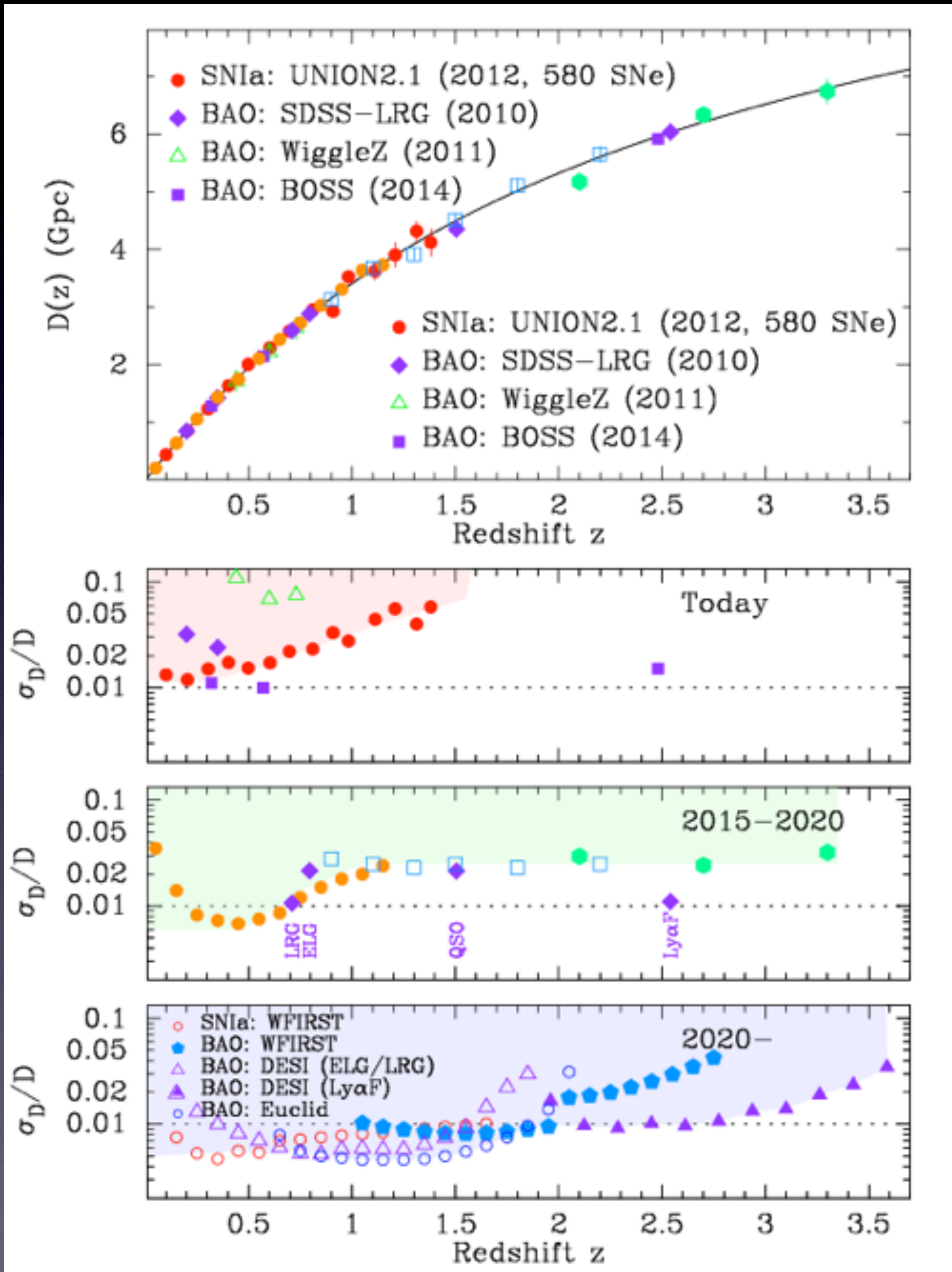




Summary

- BAO should be and will be done
- Mock Catalog can be started NOW!
- Simulated Data will be needed
- Target Selection / Tiling Coordinator is needed
- Flux Calibration always helps good science
- Let’s challenge new science not on white paper!!!

Distance vs Brightness



Distance & Acceleration