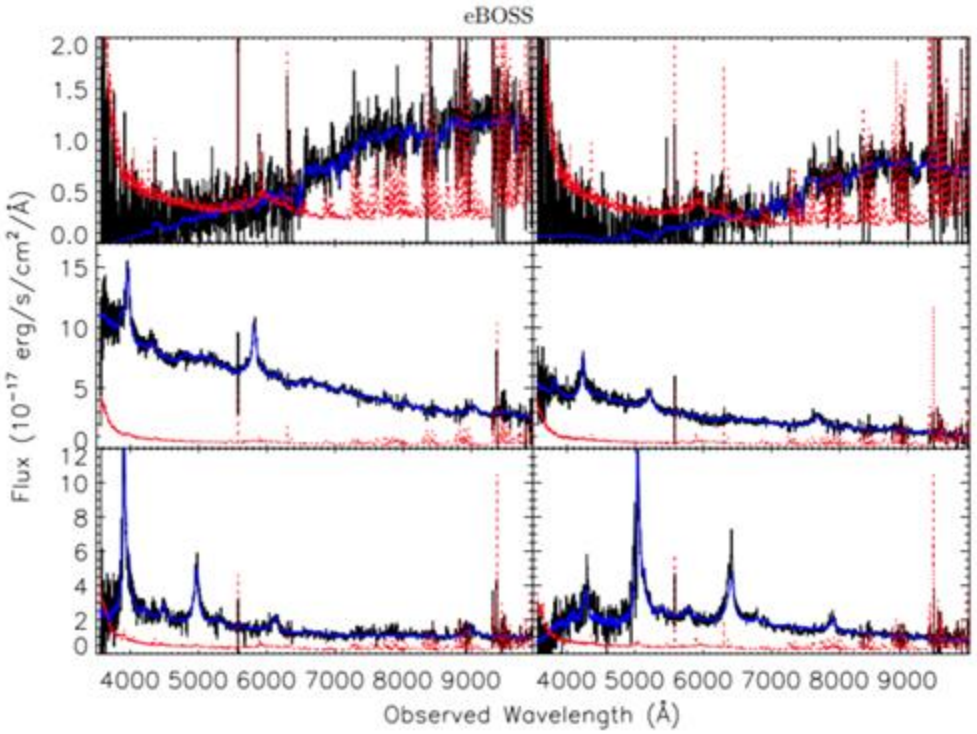
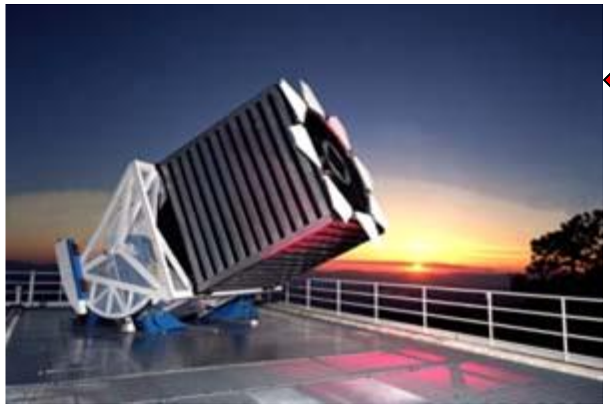
Tensions in Spectroscopic Surveys

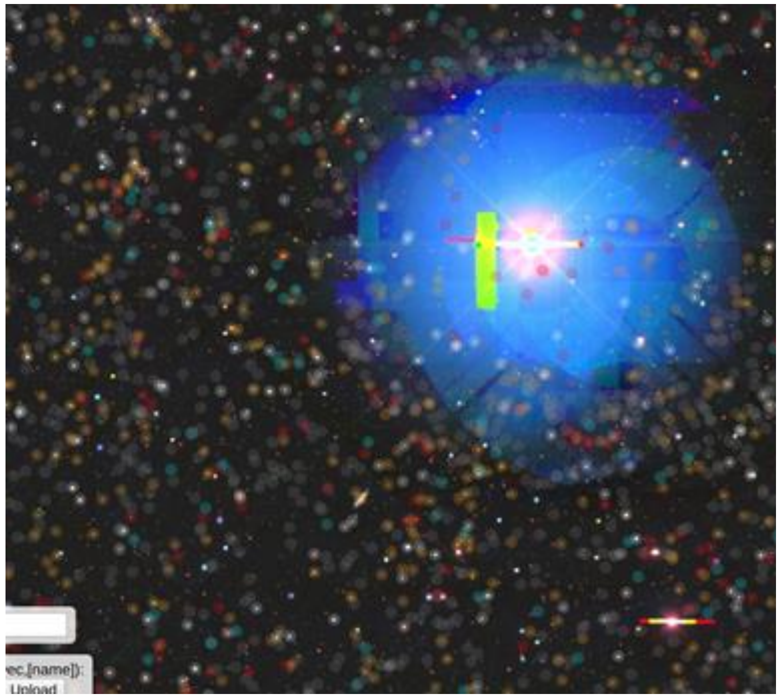
Kyle Dawson
University of Utah

on Behalf of the BOSS/eBOSS Collaborations

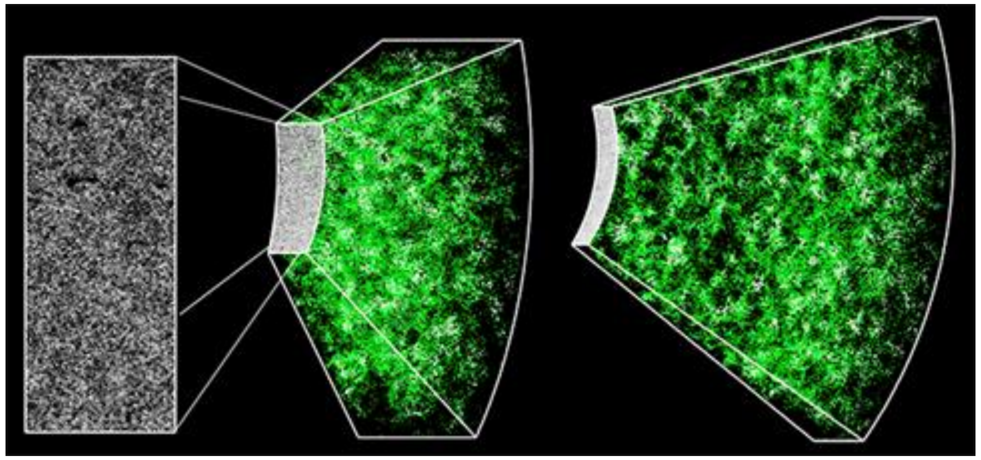
Cosmology with Spectroscopy

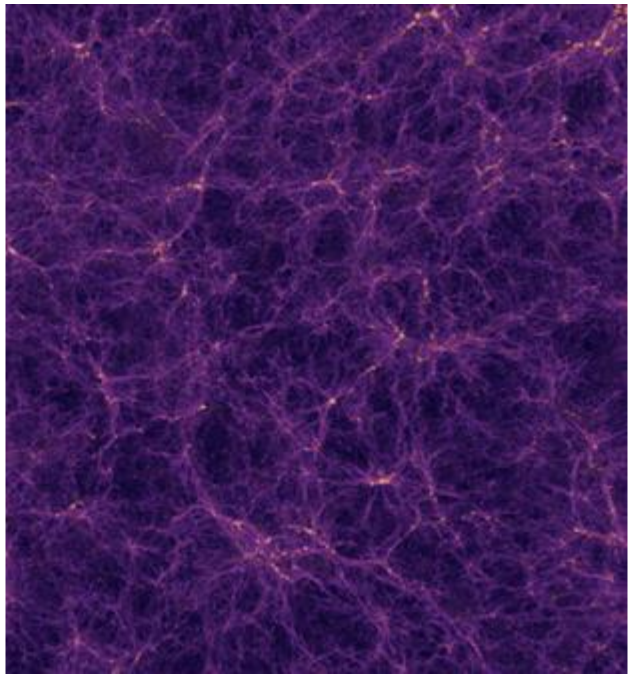


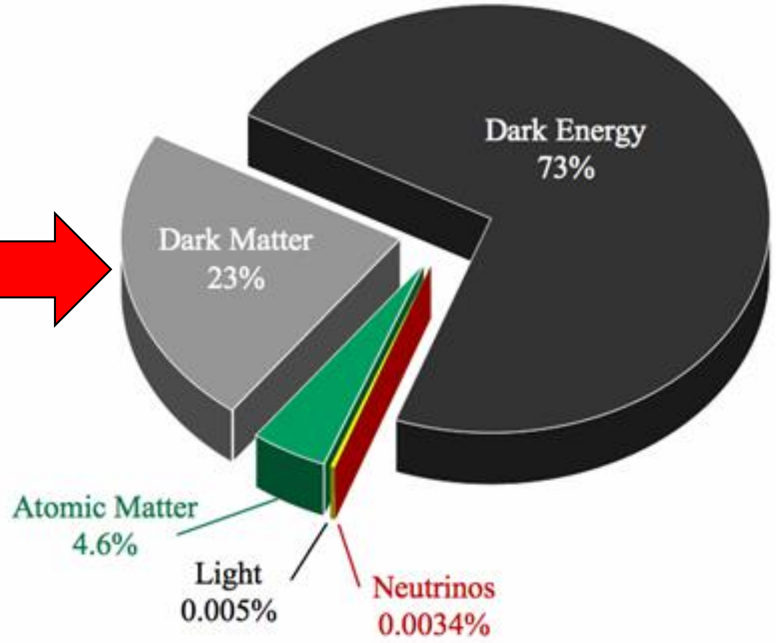




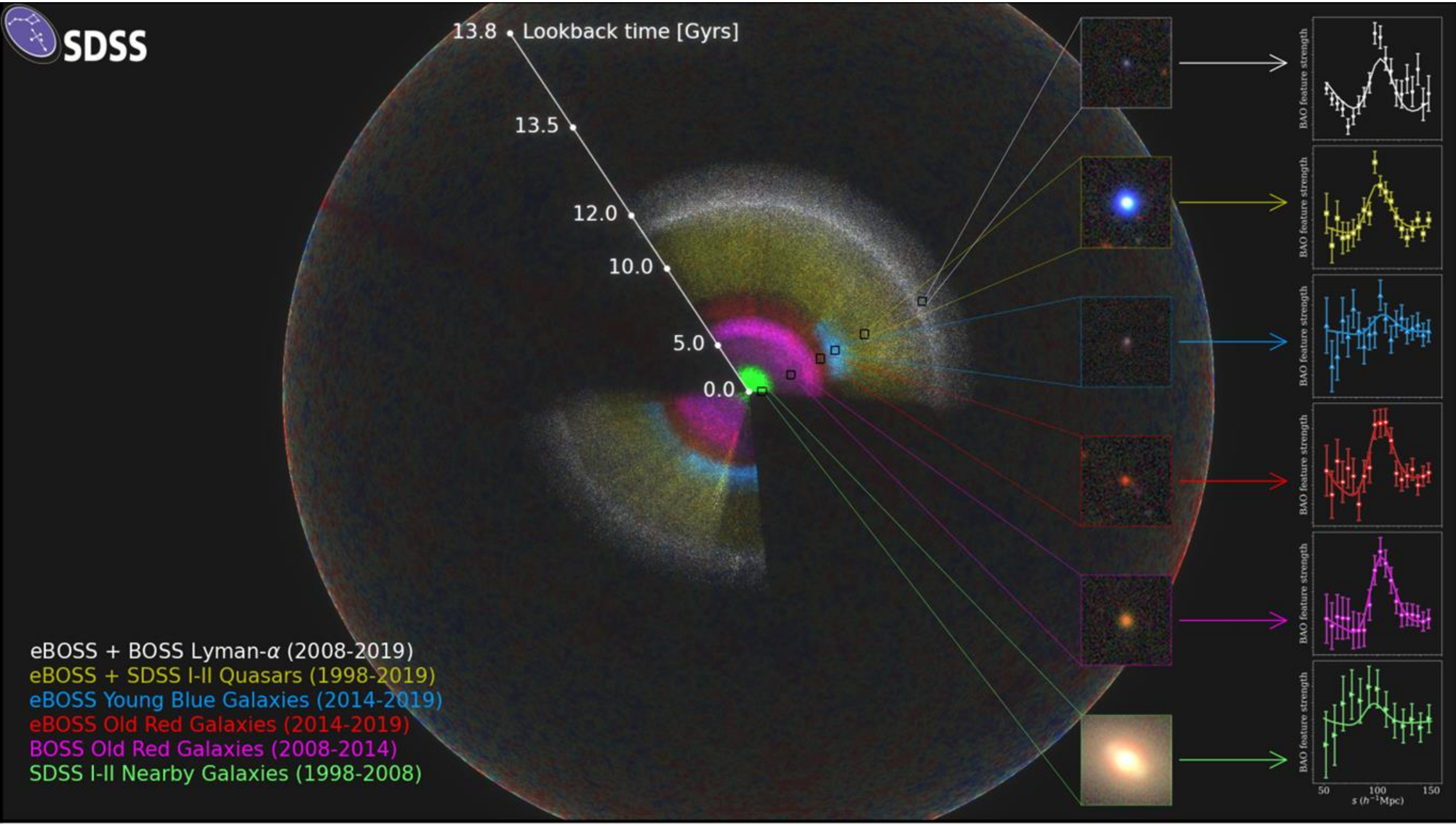
BOSS/eBOSS: 2009-2019
Apache Point Observatory
(SDSS)





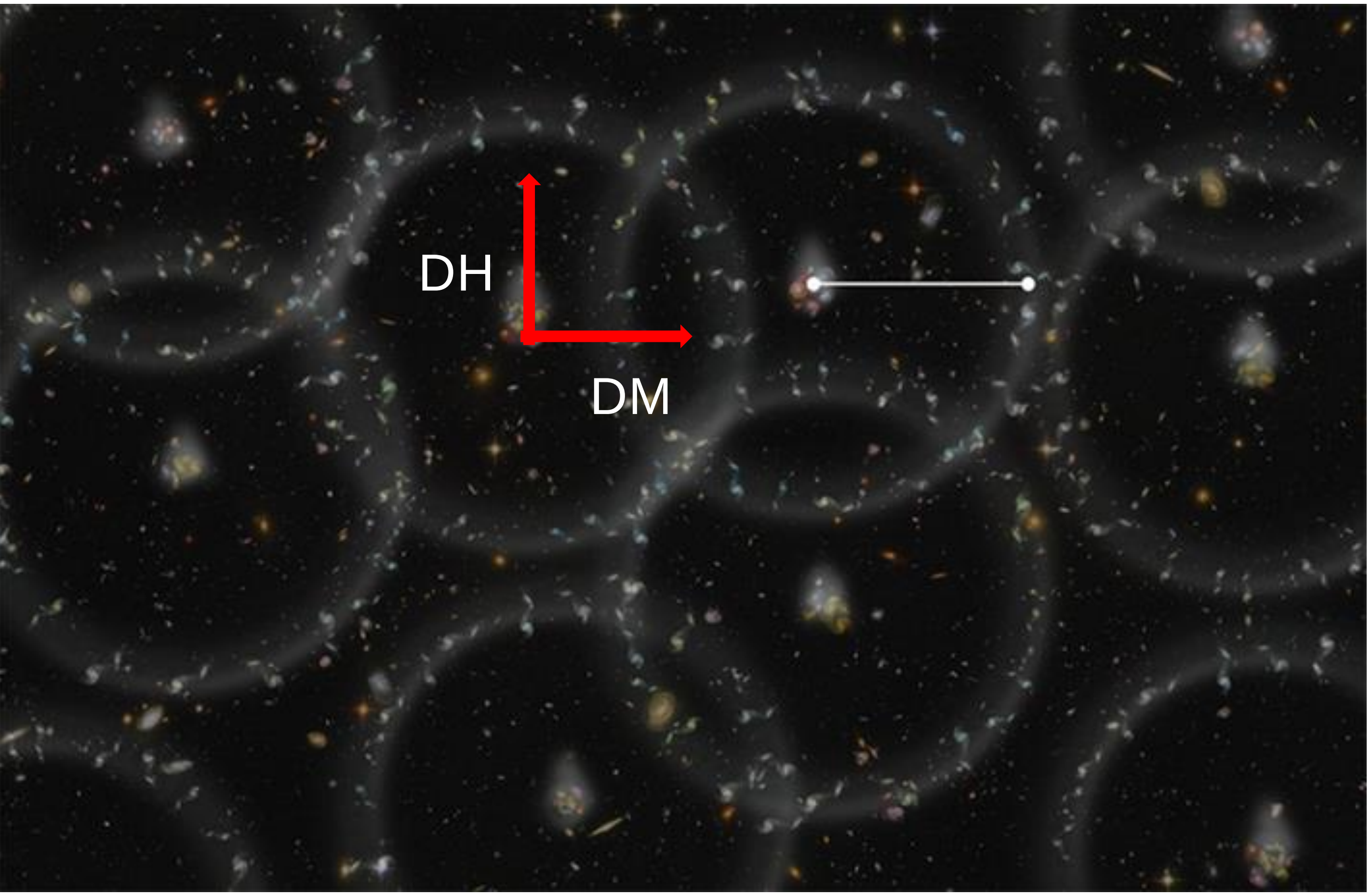


11 Billion Years of Galaxy Clustering

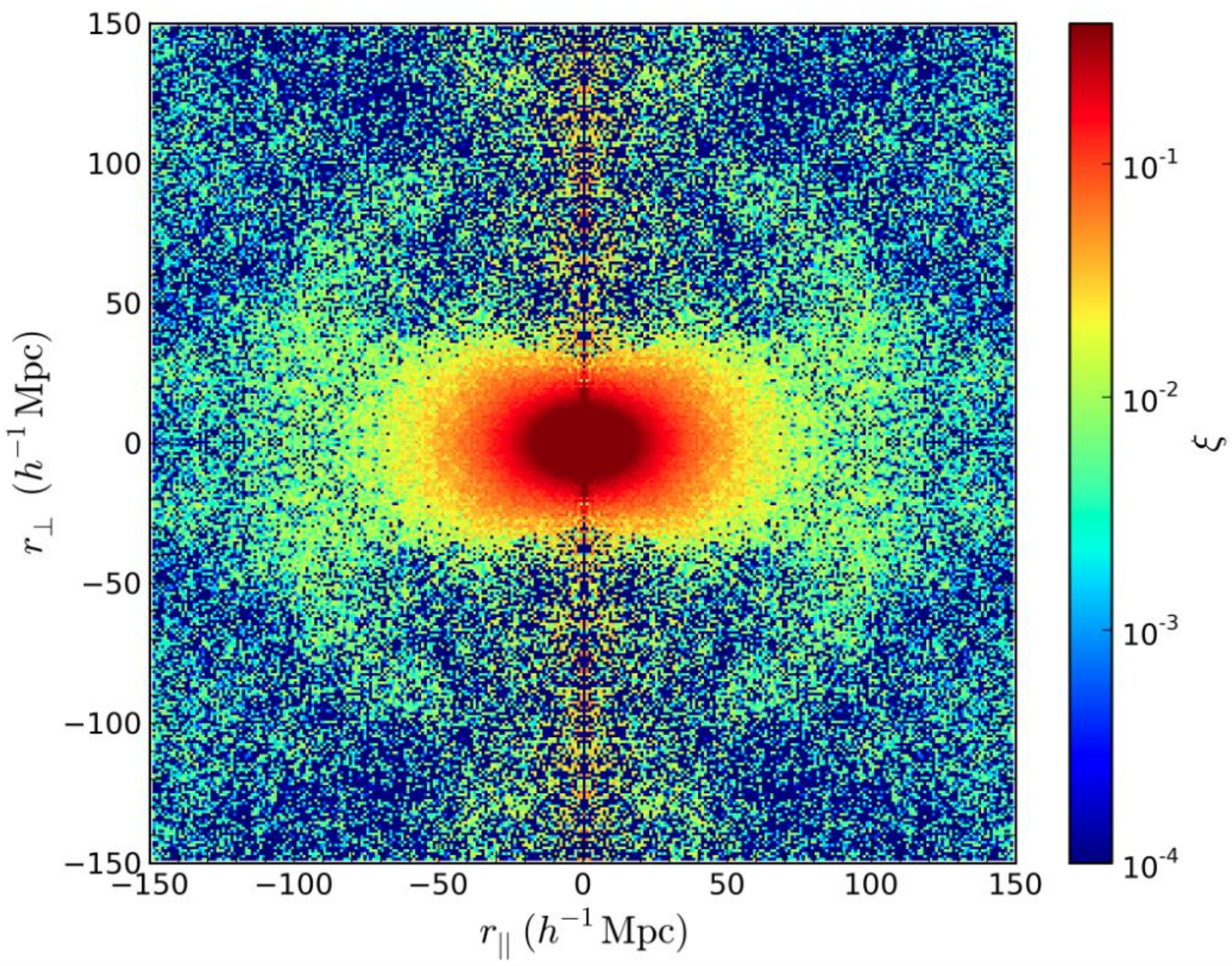


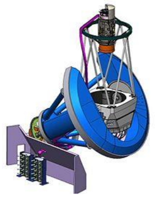
Two Primary Features in Clustering

Baryon Acoustic Oscillations (BAO) measure angular diameter distance and H(z)

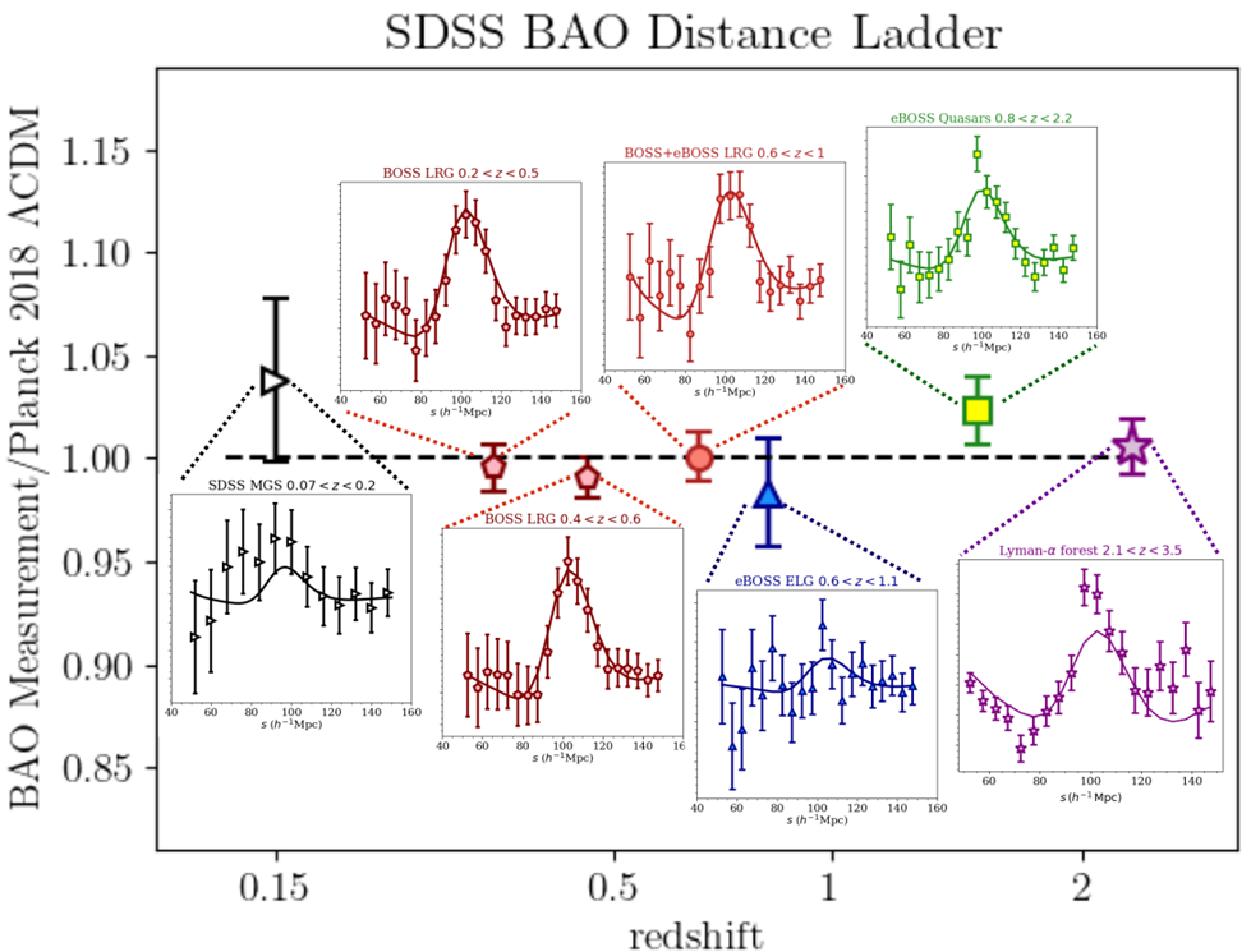


Redshift Space Distortions (RSD) measure balance between cosmic expansion and gravity

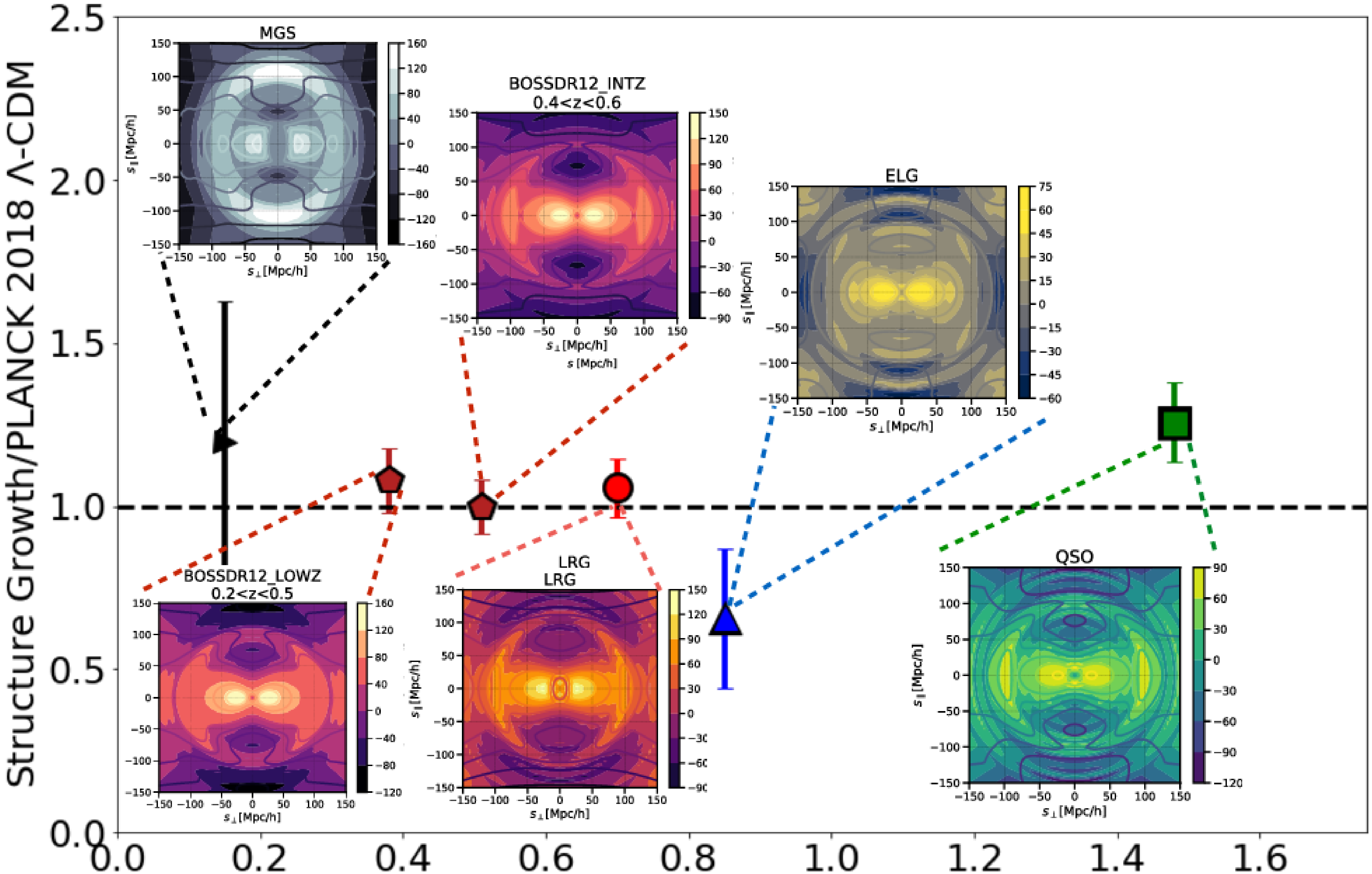




BOSS/eBOSS BAO Results



BOSS/eBOSS RSD Results



Credit: M.Vargas-Magaña and SDSS.

Cosmology Interpretation

eBOSS Collaboration, "The Completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: Cosmological Implications from two Decades of Spectroscopic Surveys at the Apache Point observatory"

interpretation of 23-paper arXiv submission from July 20, 2020

Special thanks to Eva-Maria Mueller, Andreu Font-Ribera, Anze Slosar, and Zheng Zheng




Global Preferred Model

- SDSS: 40X decrease in curvature/H0/sigma8/w0/neutrino mass posterior volume relative to Stage-II (WMAP + SNe)
- SDSS+Planck+SNe (Pantheon)+weak lensing (DES): additional 25X improvement → average 4X per parameter
- $w_p(z=0.36)$ = -1.013 +/- 0.029 in w0waCDM, little degradation with w_a

Standard model parameters **Extended model parameters**

	Ω_Λ	H_0	σ_8	Ω_K	w_0	w_a	Σm_ν [eV]
ΛCDM	0.6959 ± 0.0047	68.19 ± 0.36	0.8073 ± 0.0056	–	–	–	–
oΛCDM	0.6958 ± 0.0048	68.21 ± 0.55	0.8076 ± 0.0065	0.0001 ± 0.0017	–	–	–
wCDM	0.6992 ± 0.0066	68.64 ± 0.73	0.8128 ± 0.0092	–	-1.020 ± 0.027	–	–
owCDM	0.6997 ± 0.0069	68.59 ± 0.73	0.8127 ± 0.0091	-0.0004 ± 0.0019	-1.023 ± 0.030	–	–
$w_0 w_a$CDM	0.6971 ± 0.0069	68.47 ± 0.74	0.8139 ± 0.0093	–	-0.939 ± 0.073	$-0.31^{+0.28}_{-0.24}$	–
o$w_0 w_a$CDM	0.6988 ± 0.0072	68.20 ± 0.81	0.8140 ± 0.0093	-0.0023 ± 0.0022	-0.912 ± 0.081	$-0.48^{+0.36}_{-0.30}$	–
$m_\nu\Lambda$CDM	0.6975 ± 0.0053	68.34 ± 0.43	$0.8115^{+0.0092}_{-0.0068}$	–	–	–	$< 0.111 (95\%)$
m_νwCDM	0.6993 ± 0.0067	68.65 ± 0.73	$0.813^{+0.011}_{-0.0098}$	–	$-1.019^{+0.034}_{-0.029}$	–	$< 0.161 (95\%)$

Beyond the Standard Model

Article | Published: 04 November 2019

Planck evidence for a closed Universe and a possible crisis for cosmology

Eleonora Di Valentino, Alessandro Melchiorri & Joseph Silk

Nature Astronomy **4**, 196–203(2020) | Cite this article

SPACE

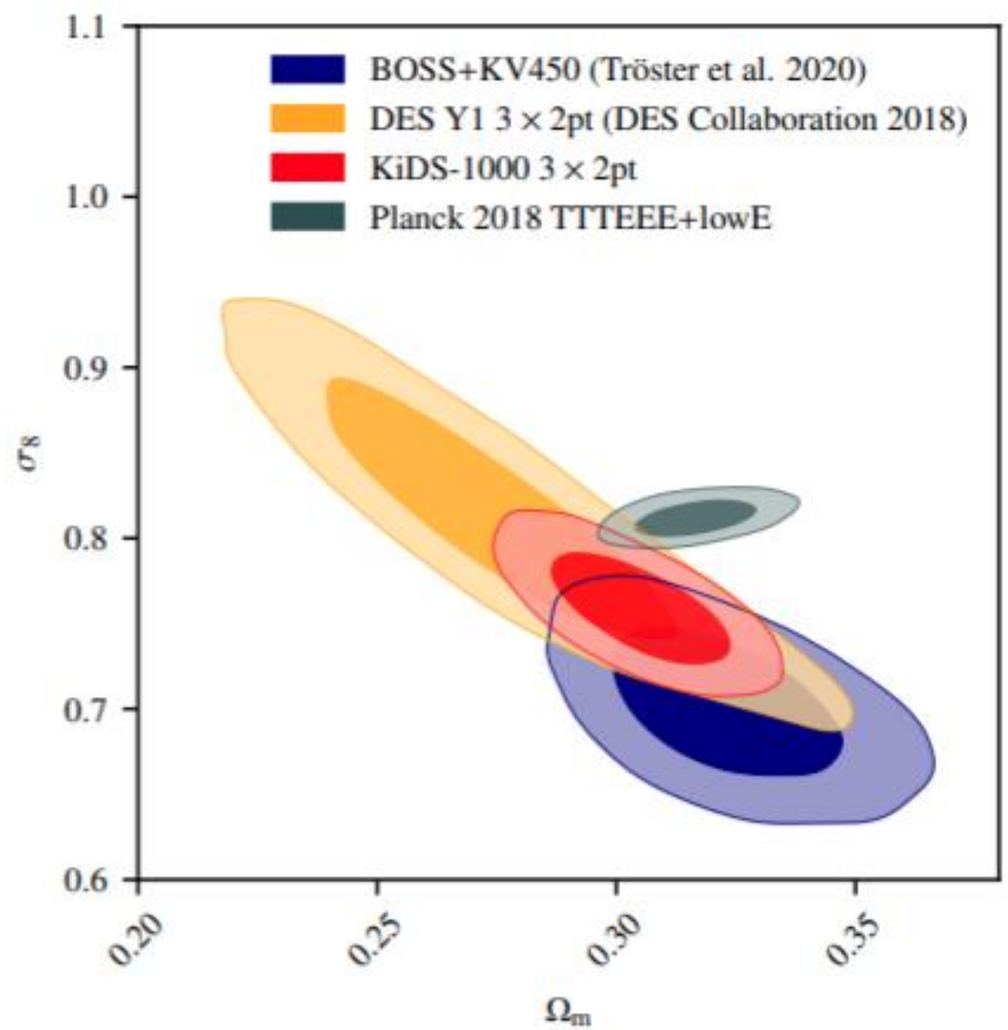
Hubble Tension Headache: Clashing Measurements Make the Universe's Expansion a Lingering Mystery

Researchers hoped new data would resolve the most contentious question in cosmology. They were wrong

By Leila Sloman on July 29, 2019

Growth of Structure:

Planck versus local Universe



Heymans et al., 2020
(KiDS - 1000 sqdeg WL survey)

New physics of Inflation?

- BAO Combined with Planck temperature and polarization data → order of magnitude improvement on curvature constraints
- Strong evidence for a nearly flat geometry → roughly one order of magnitude within the fundamental limit set by cosmic variance.

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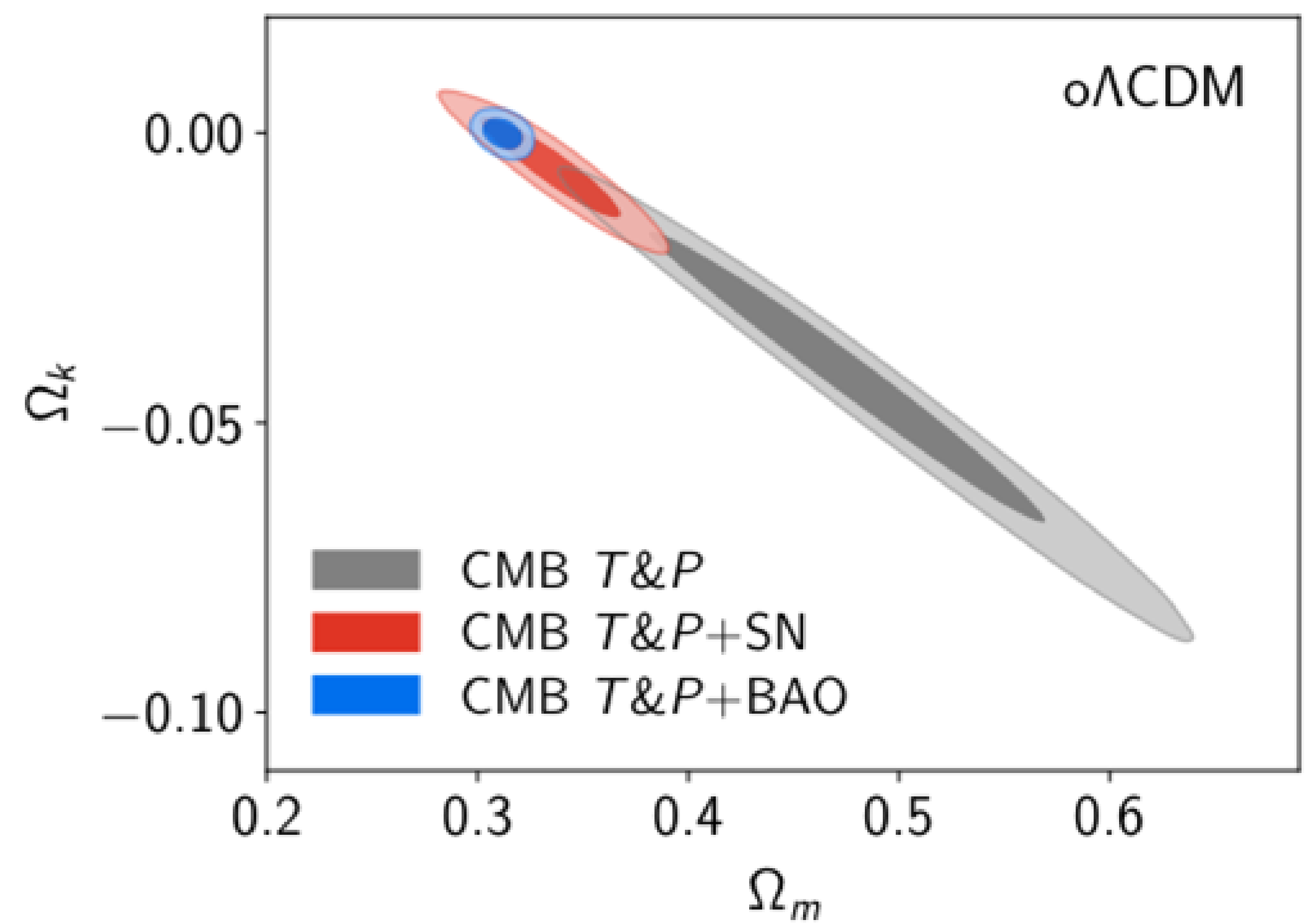

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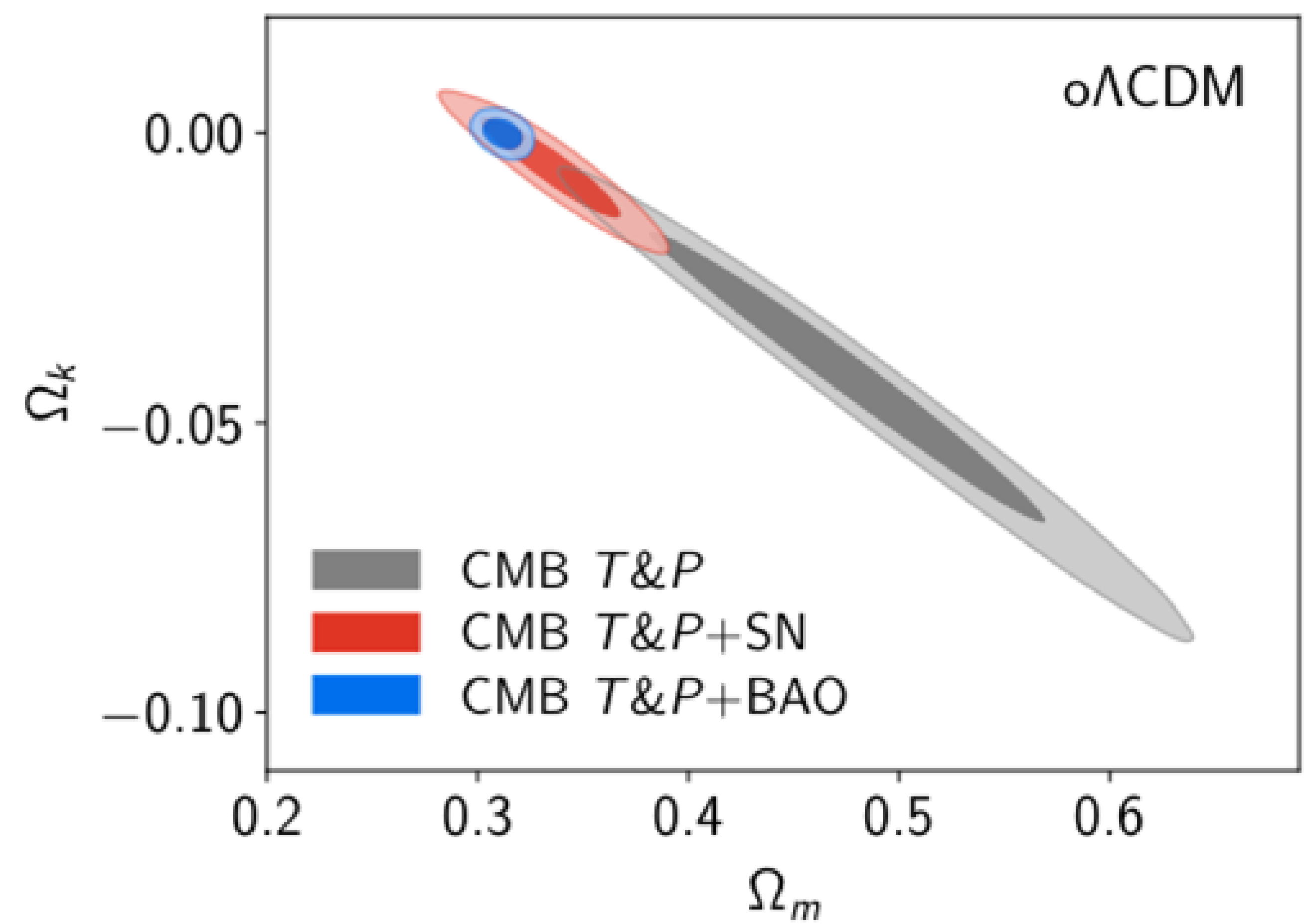
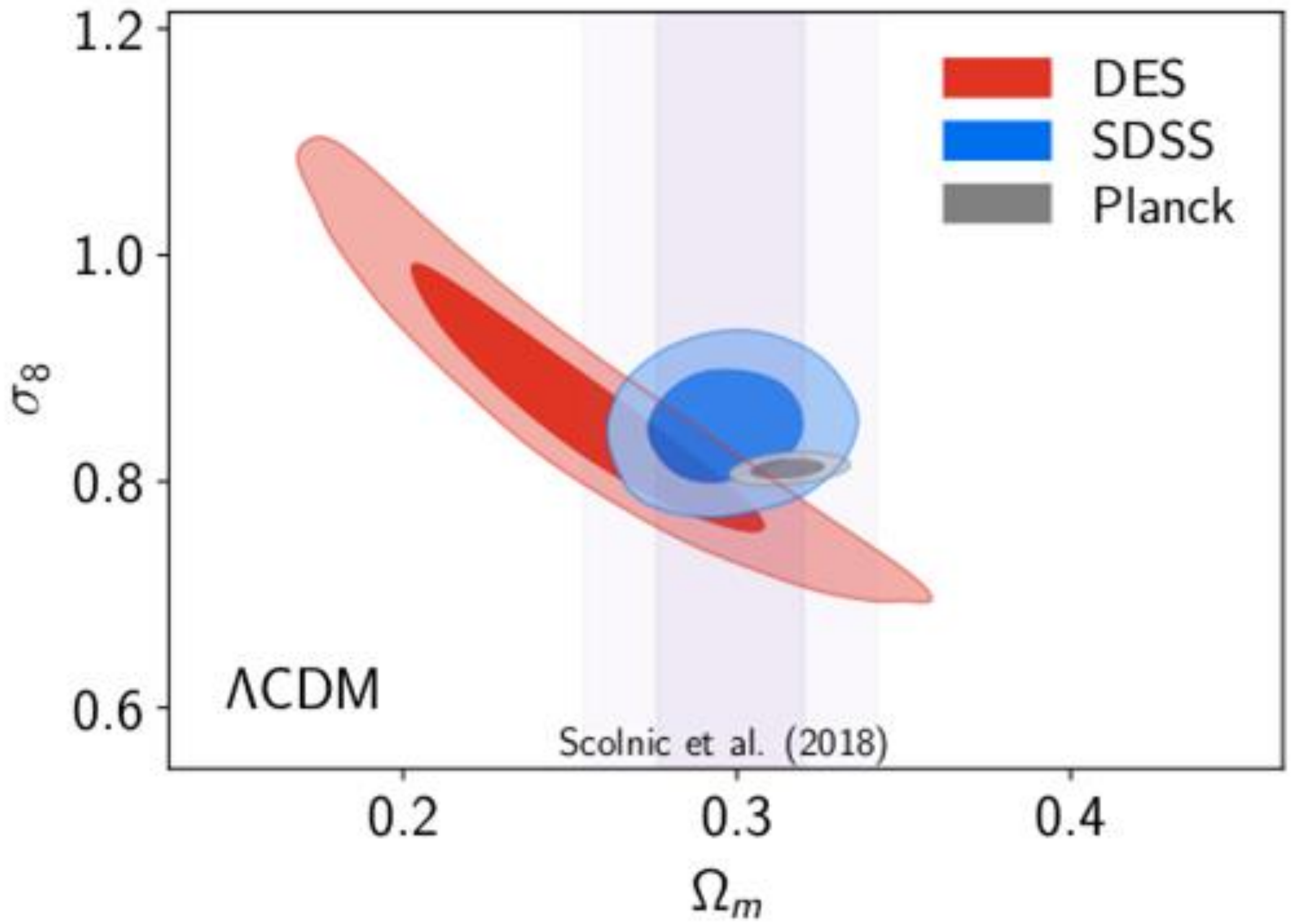
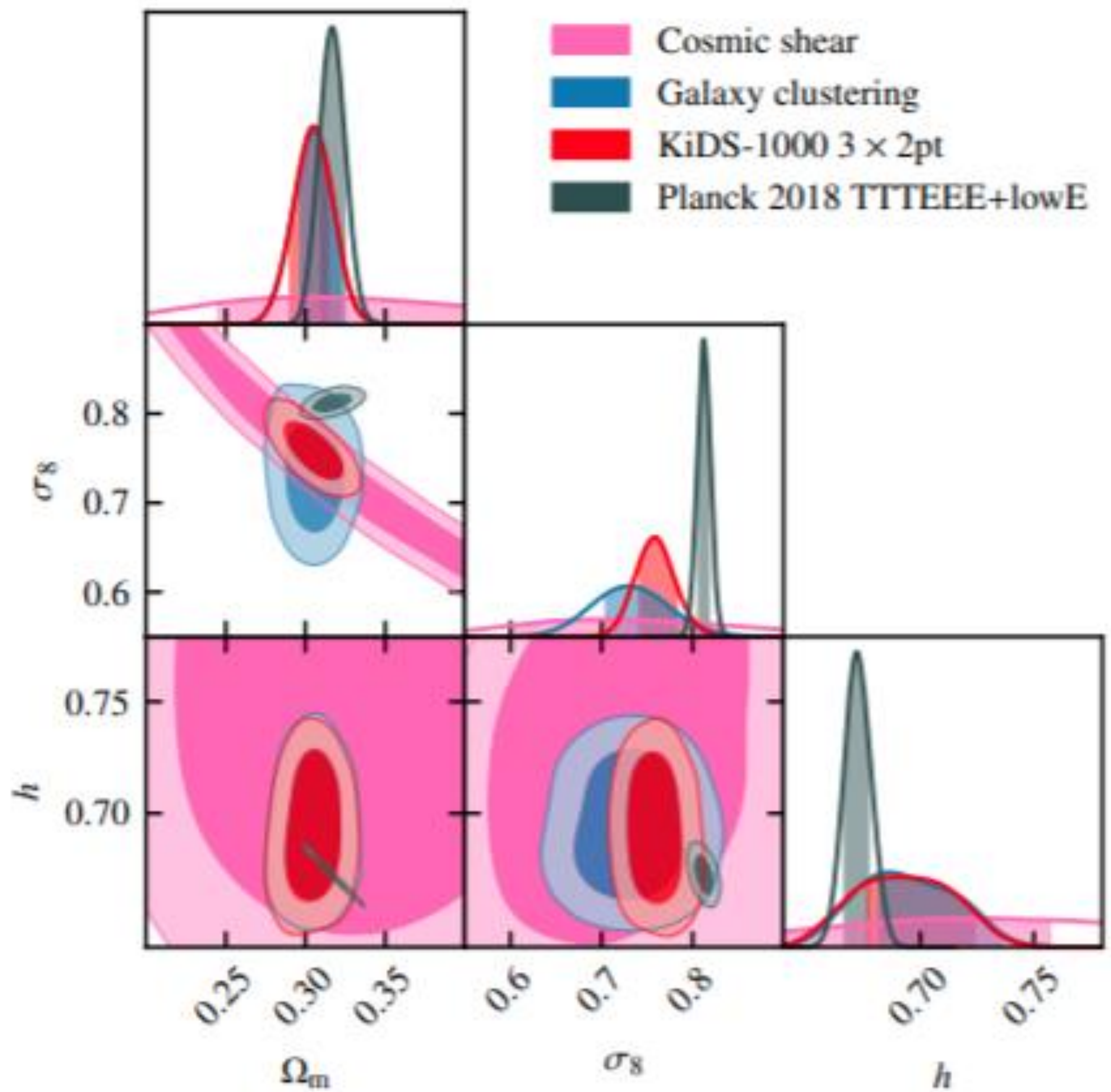


New physics of Structure Growth?

- BAO+RSD consistent with Planck at 3.5% precision under LCDM
- Weak lensing: sigma8 tension, suppression of small-scale clustering, or no tension?





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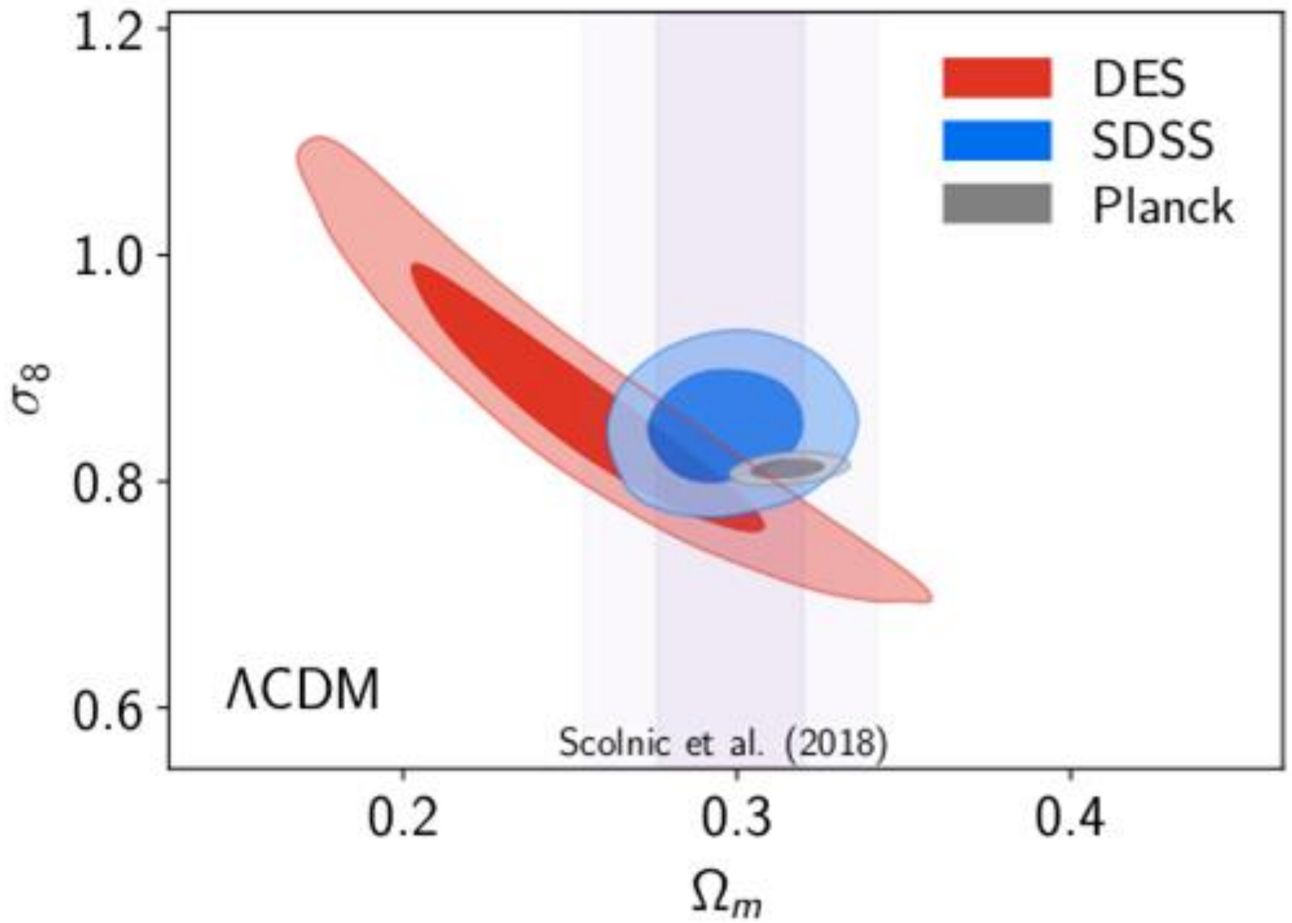

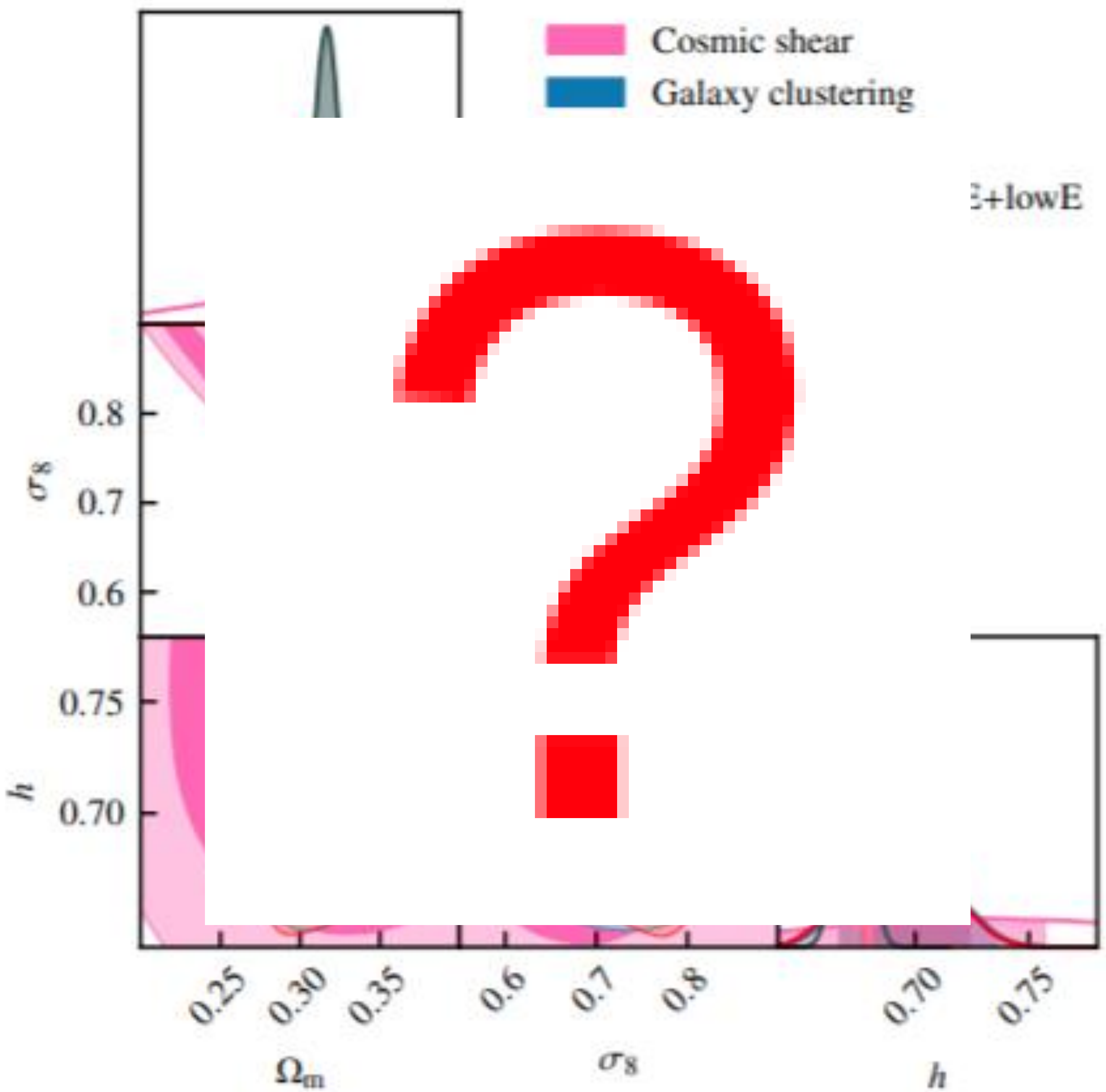

Heymans et al., 2020
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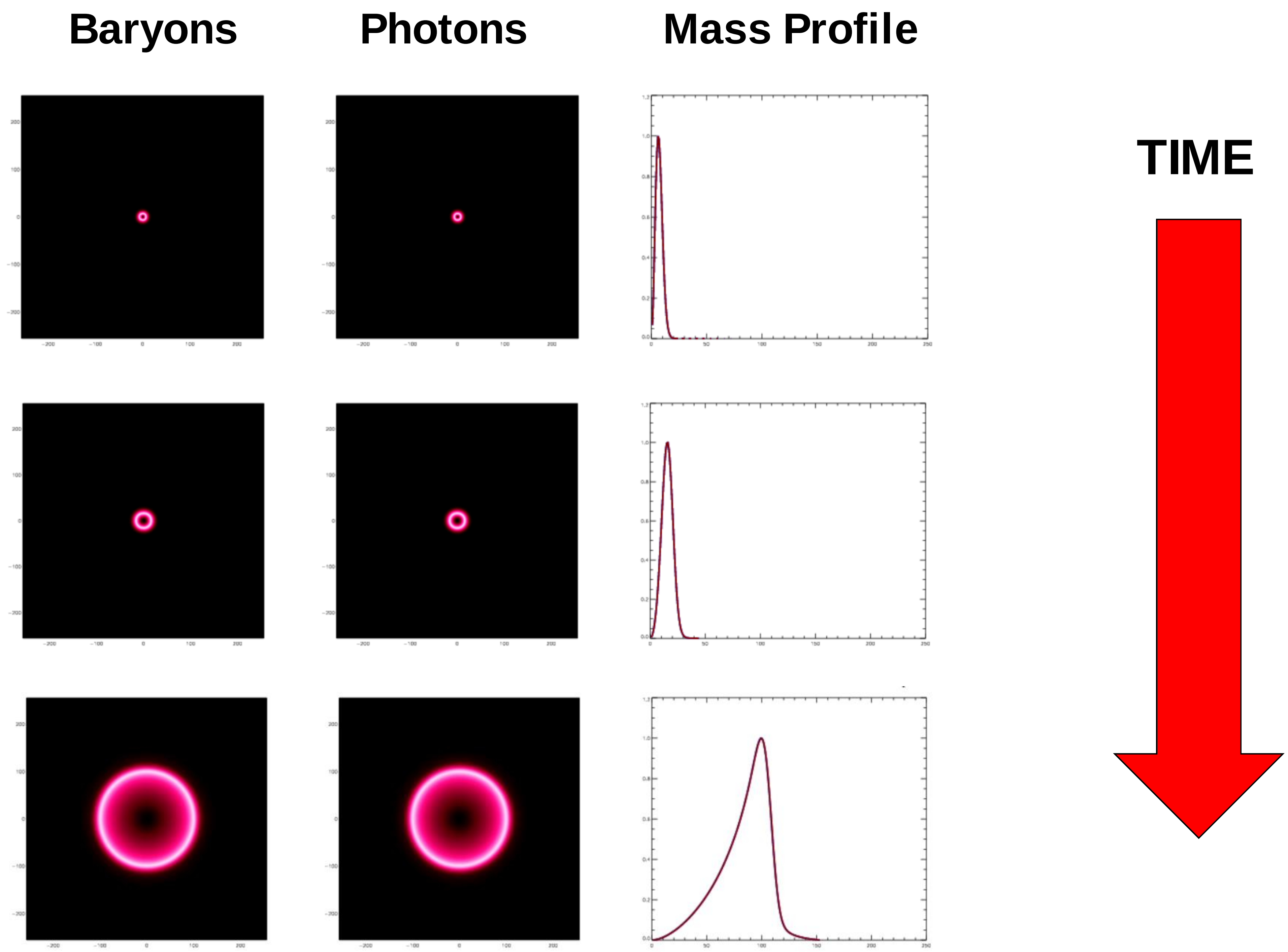
New Physics from Hubble Constant?

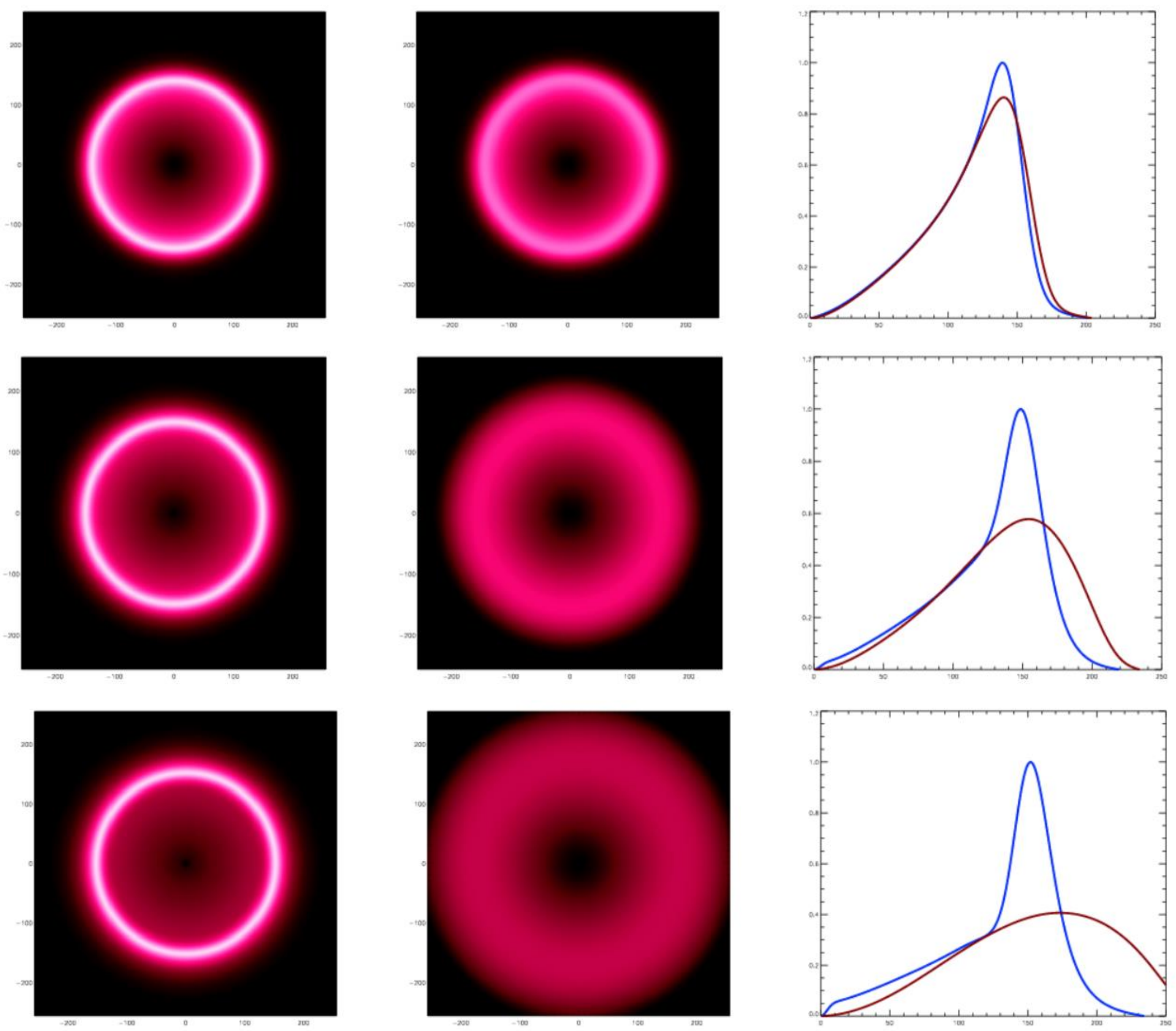
- BAO in combination with early Universe physics → calibrated ruler
- Calibrated ruler → H_0

Origins of BAO: First 300,000 years



Origins of BAO: Decoupling

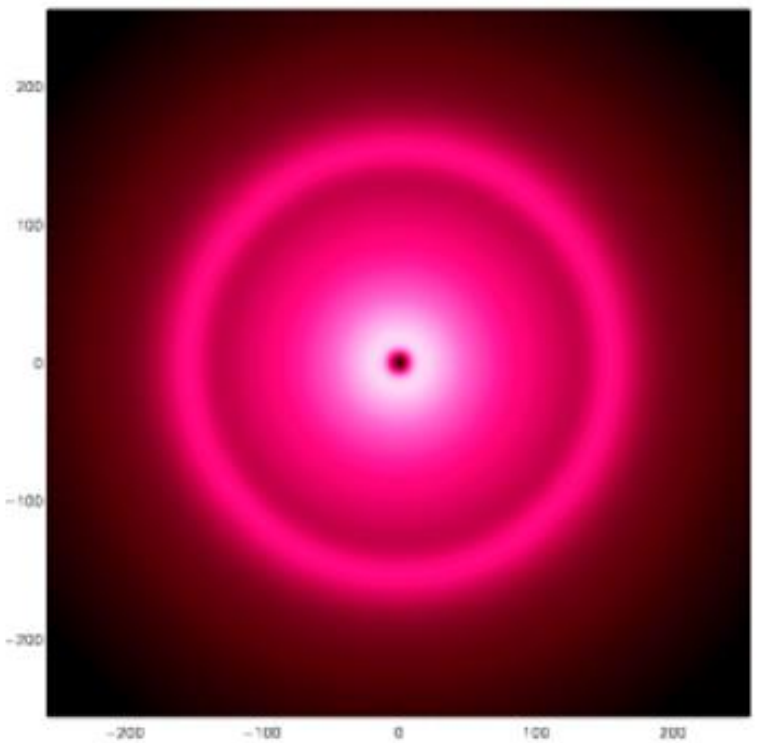
Baryons **Photons** **Mass Profile**



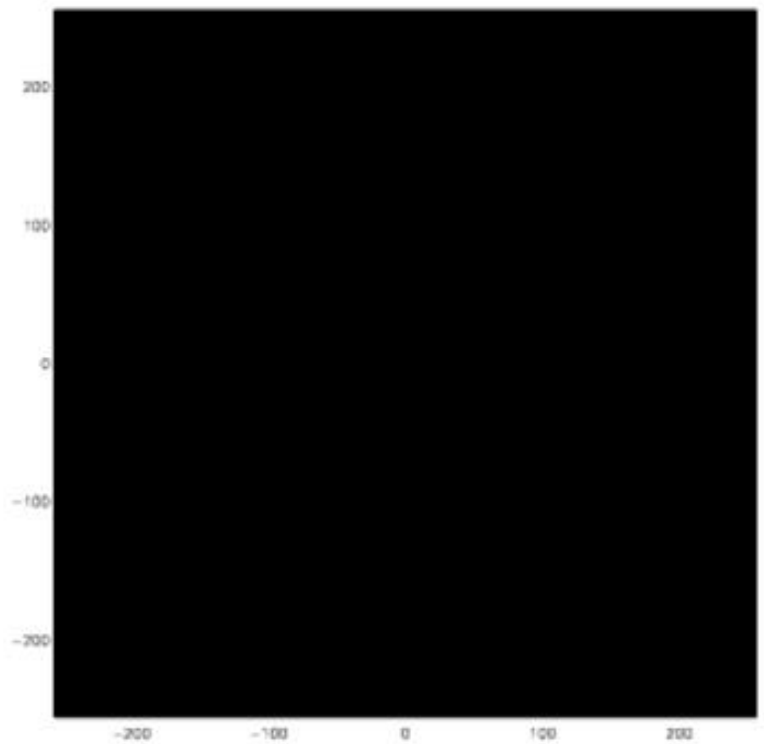
TIME

Origins of BAO: Today

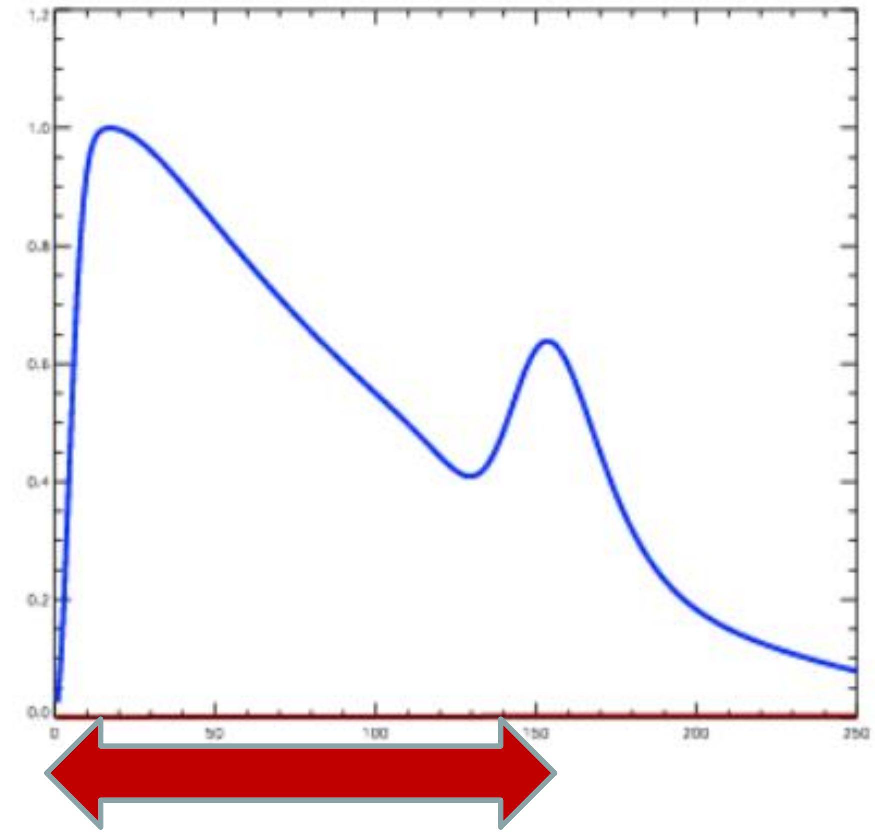
Baryons (aligned with Dark Matter)



Photons (free-streamed and uniform)



Mass Profile (BAO peak)



Sound Horizon
(r_d, drag scale)

Credit: Martin White (UC-Berkeley)
https://w.astro.berkeley.edu/~mwhite/bao/

Drag Scale Physics

- Standard physics (e.g. 3 neutrino species) to compute r_d
  - baryon density, matter density, and CMB temperature leads to:
  - drag epoch (z_d), sound speed (c_s), hubble parameter ($H(z)$)
- CMB temperature: CMB
- Baryon density: CMB or Big Bang Nucleosynthesis
- Matter density: CMB or supernovae Ia or BAO

$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz$$

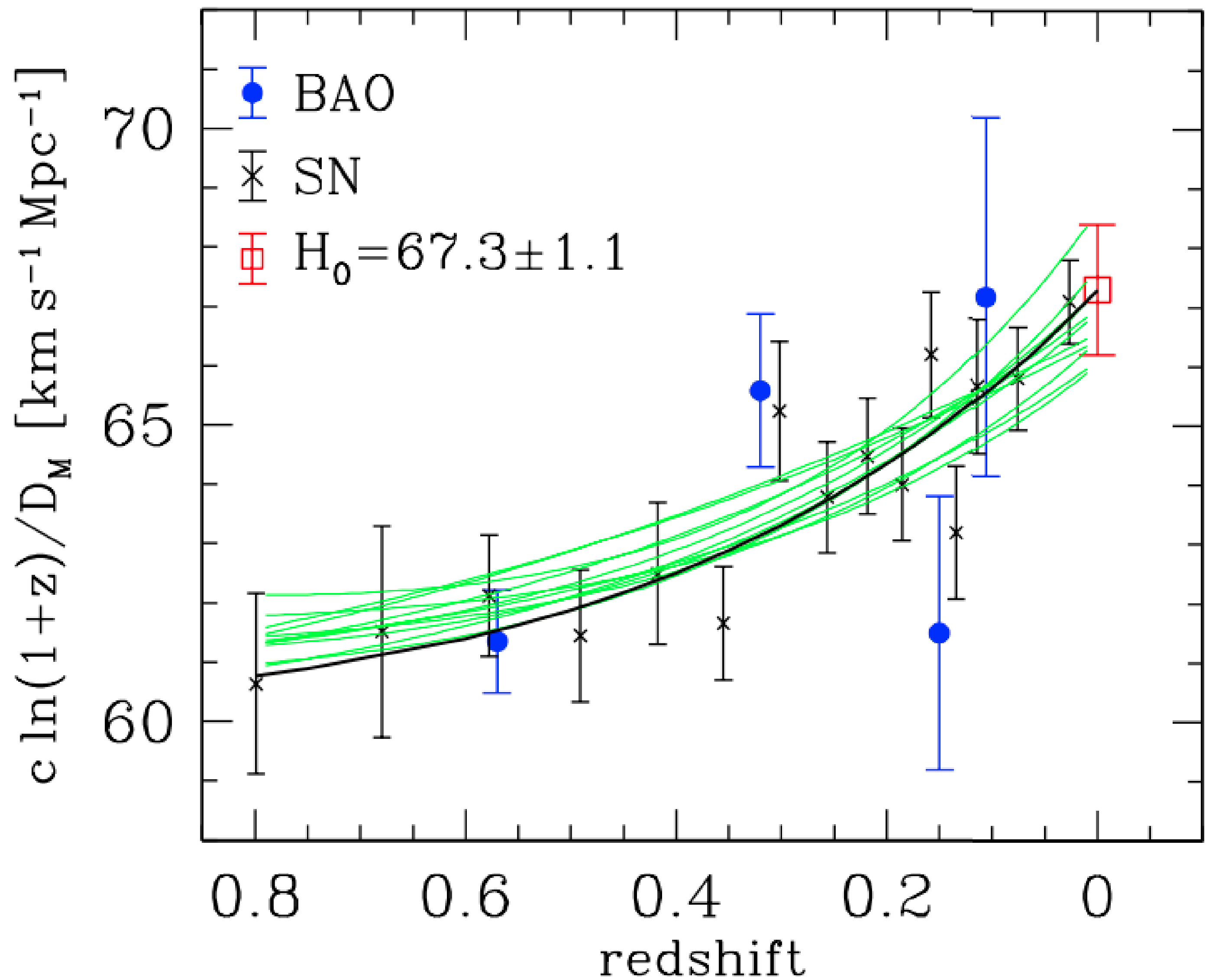
Drag Scale and the Hubble Parameter

- Calibrated drag scale: measure absolute Hubble parameter at any redshift
  - Measure radius of BAO feature in radial direction (dz)

$$H(z) = c\Delta z / r_d$$

Inverse Distance Ladder

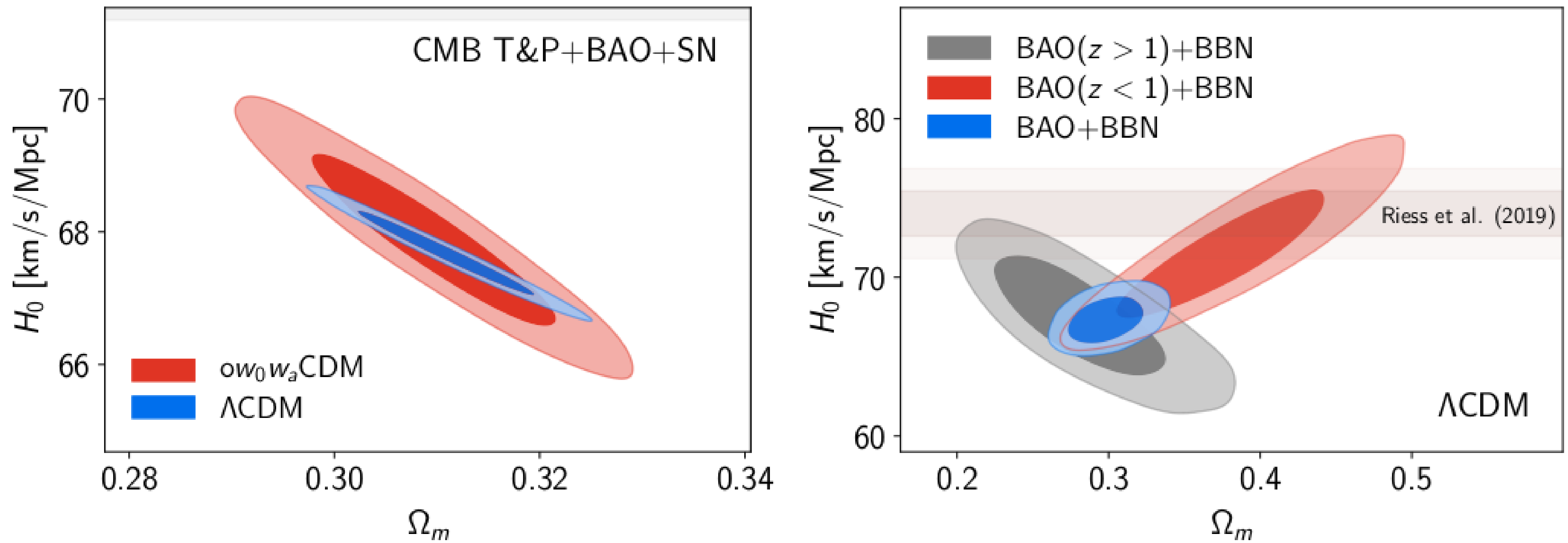
- Use absolute distance scale from BAO to calibrate absolute SN luminosity
- Many supernovae at low-z: interpolate over all measurements to z=0
- Not sensitive to interpolant



BOSS Collaboration 2015

New Physics in Expansion History?

- BAO → insensitive to the strict cosmological priors in CMB-only estimates.
- BAO → insensitive to CMB anisotropies if using LCDM and BBN

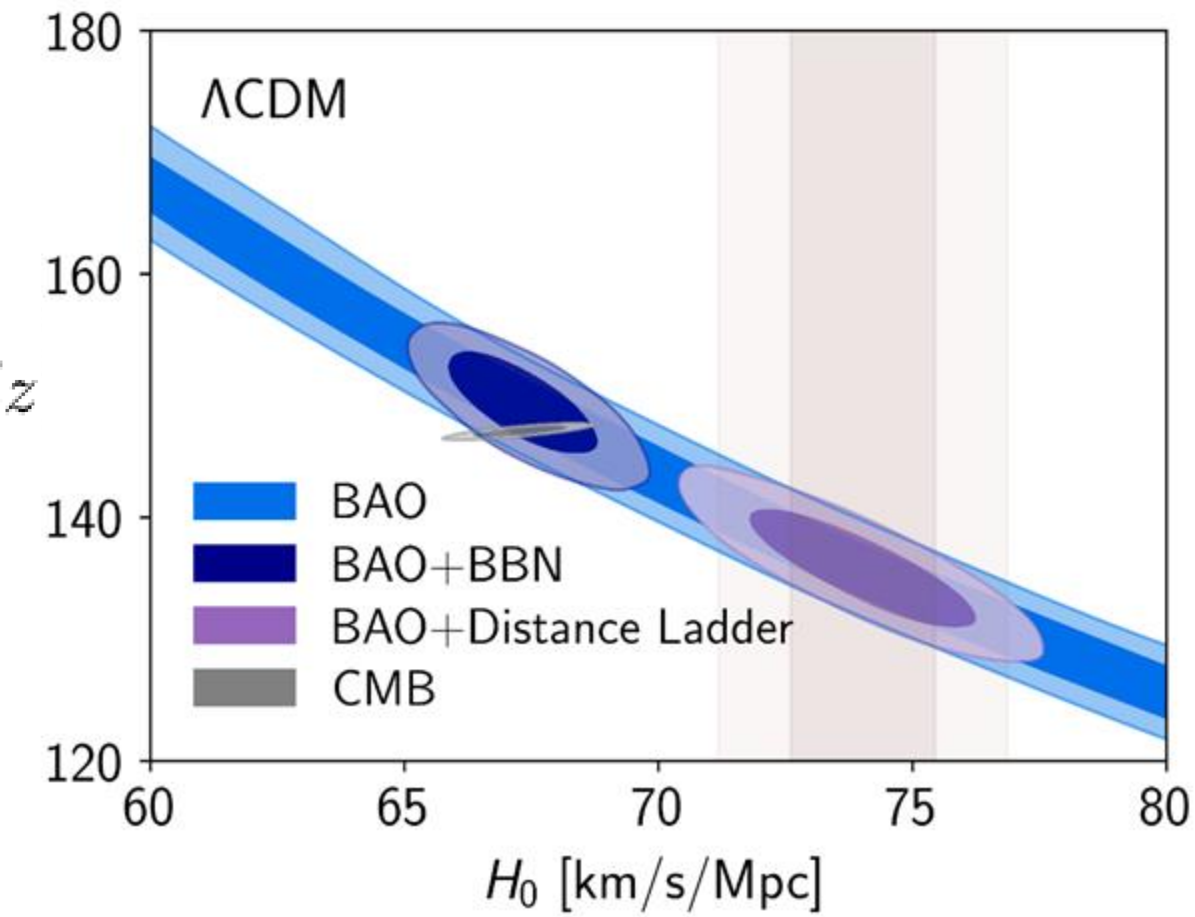


Dataset	Cosmological model	H_0 in $\mathrm{km\,s^{-1}Mpc^{-1}}$	Comments
CMB T&P+BAO+SN	ow_0w_aCDM	67.87 ± 0.86	Inverse distance ladder
BBN+BAO	ΛCDM	67.27 ± 0.97	No CMB anisotropies
CMB T&P	ΛCDM	67.36 ± 0.54	*Planck* 2018 (a)
CMB T&P	oΛCDM	63.6 ± 2.2	*Planck* 2018 (a)
Lensing time delays	ΛCDM	73.3 ± 1.8	H0LiCOW (b)
Distance ladder	-	74.0 ± 1.4	SH0ES (c)
GW sirens	-	70 ± 10	LIGO (d)
TRGB	-	69.6 ± 1.9	LMC anchor (e)
TFR	-	76.2 ± 4.3	Cosmicflows (f)

New Physics in the Drag Scale?

- Value of r_d can be calibrated from theory or distance ladder
- `H_0 tension' not restricted to systematic errors in Planck or to the strict assumptions of the LCDM model → new physics?

$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz$$



Summary

- **BOSS/eBOSS**
  - Conclusion of Stage-III Dark Energy surveys with spectroscopy
  - BAO measurements over 11 Gyr & RSD measurements to $z<1.5$

- **Tensions in cosmology**
  - Curvature consistent with inflationary mode
  - Jury out on sigma8 tensions:
    - Correction to general relativity?
    - New physics affecting small scale clustering?
    - Modeling errors in lensing?
  - BAO allow robust estimates of H_0 not possible otherwise
    - <1% precision unchanged under differing assumptions
    - Hints of new physics in the drag scale

- **Stage-IV Spectroscopic Survey**
  - Dark Energy Spectroscopic Instrument (DESI): 2021-