Cosmology with the Dark Energy Spectroscopic Instrument (DESI)

Florian Beutler, University of Edinburgh
On behalf of the DESI Collaboration

Münster Kolloquium:

European Research Council
Established by the European Commission

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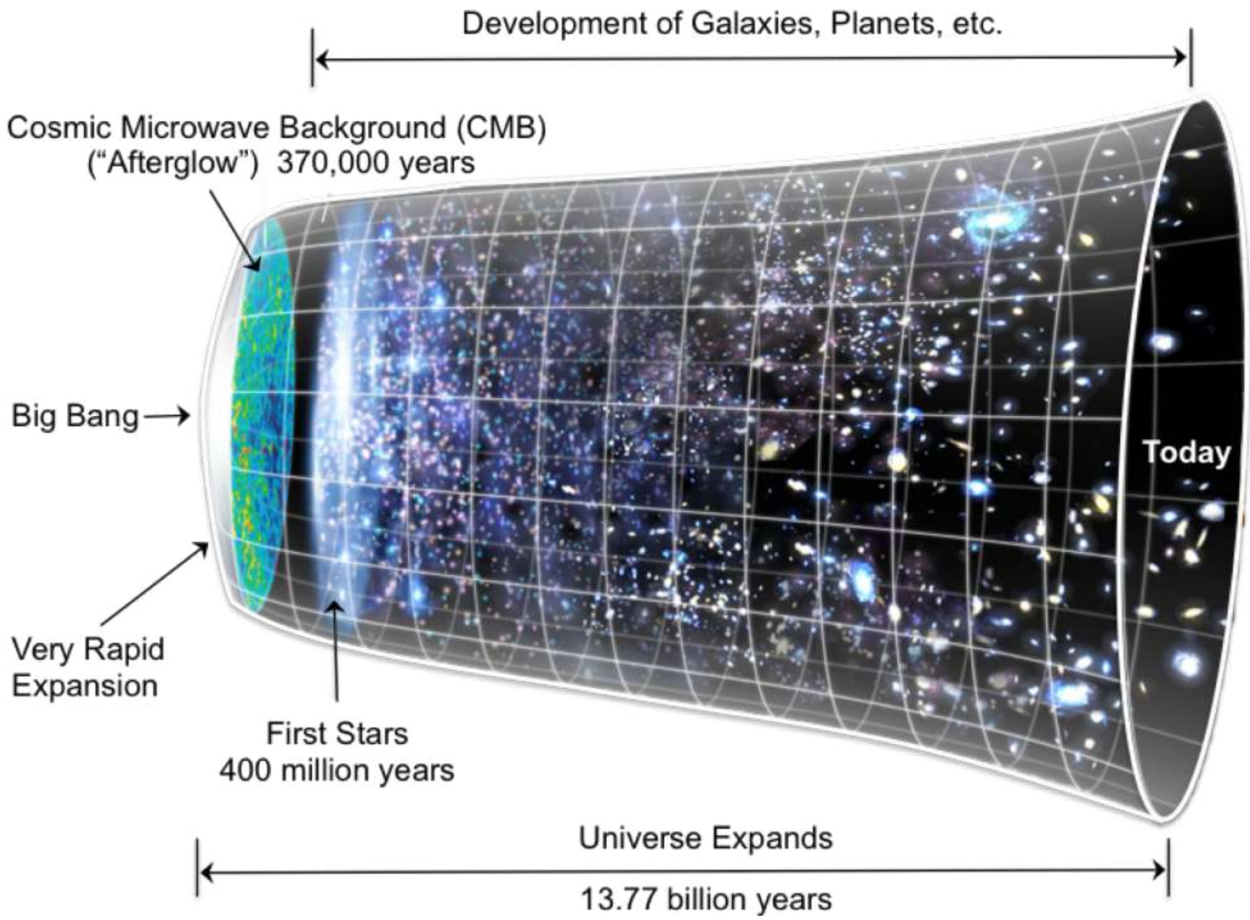
The standard model of cosmology

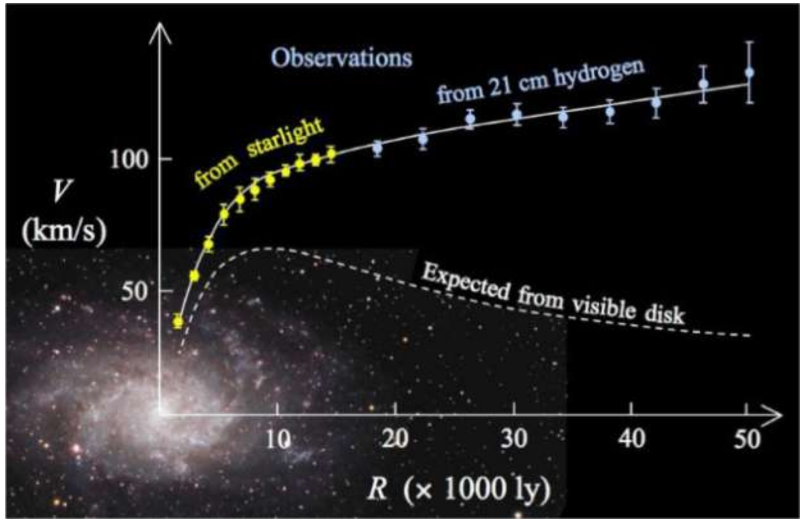


$$\left(\frac{H(z)}{H_0}\right)^2 = \Omega_r(1+z)^4+\Omega_m(1+z)^3+\Omega_k(1+z)^2+\Omega_\Lambda$$

Adding some “Dark Matter”

In the 1930s Fritz Zwicky found evidence for “Dunkle Materie” in the Coma cluster, Helvetica Physica Acta, Vol. 6, p. 110-127

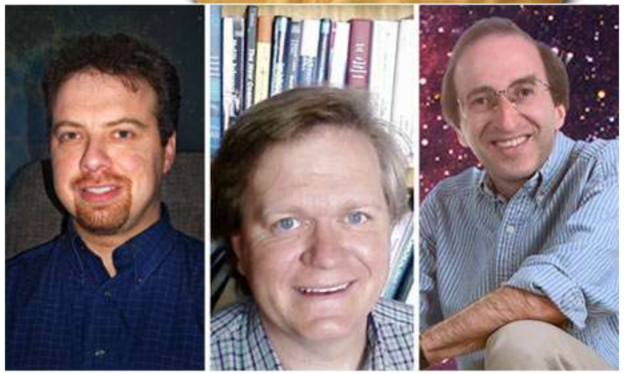
In the 1970 Vera Rubin measured rotation curves and found clear evidence in multiple Systems, Astrophysical Journal, vol. 159, p.379

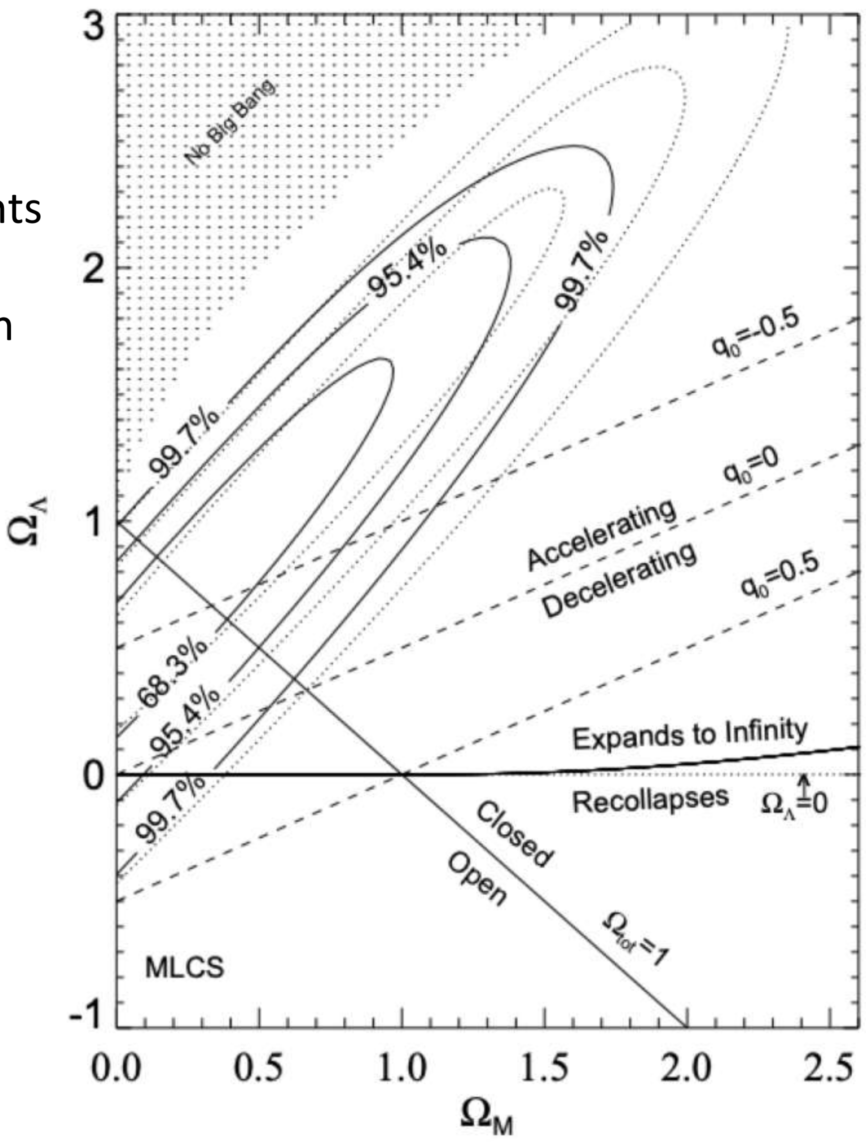


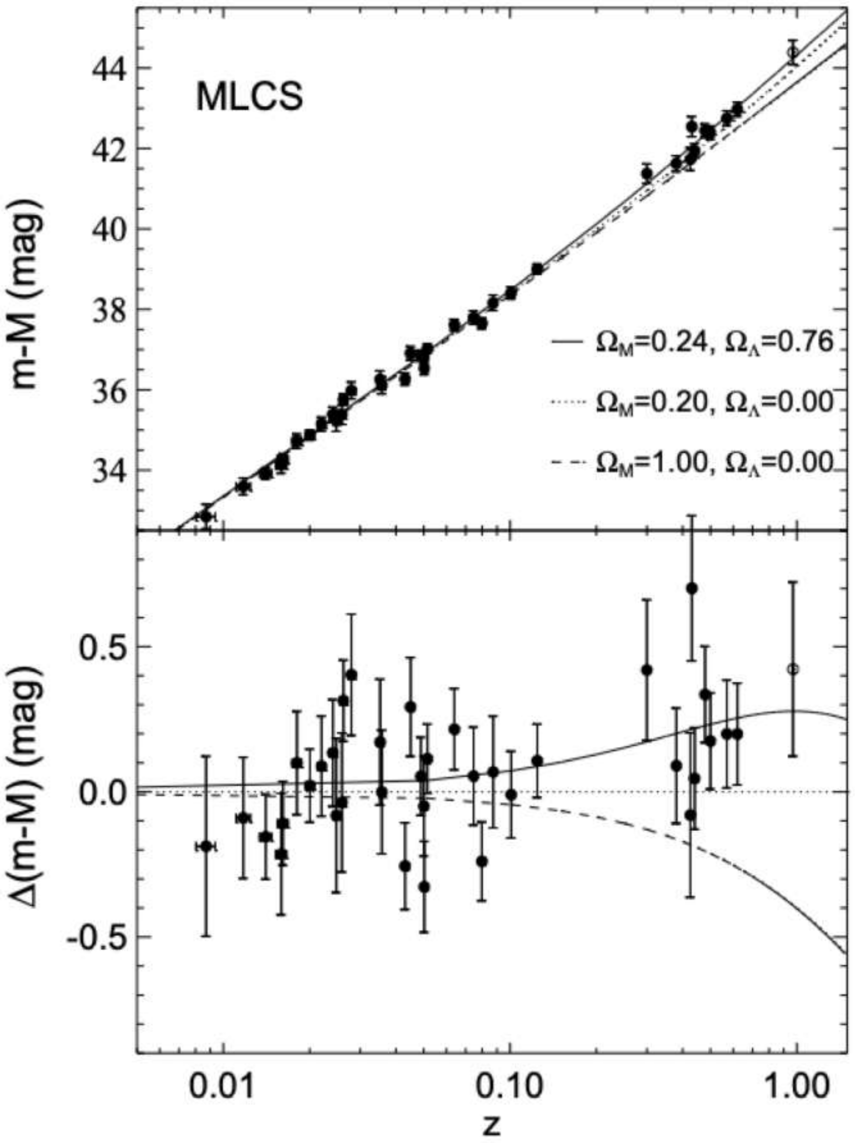
Adding some "Dark Energy"

Riess et al. (1998)

- Type 1a supernovae can be used for distance measurements
- The current Universe seems to be accelerating in its expansion
- 2011 Nobel Prize







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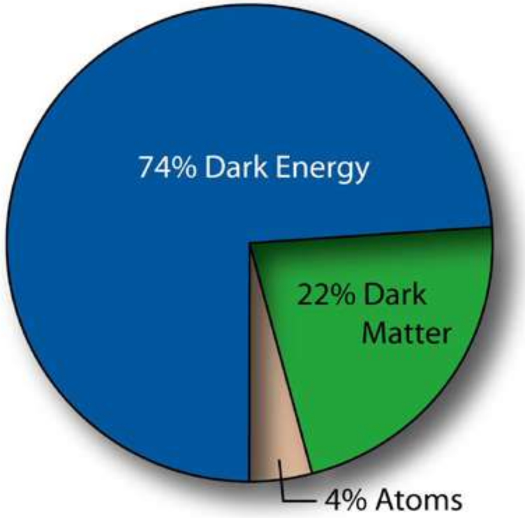
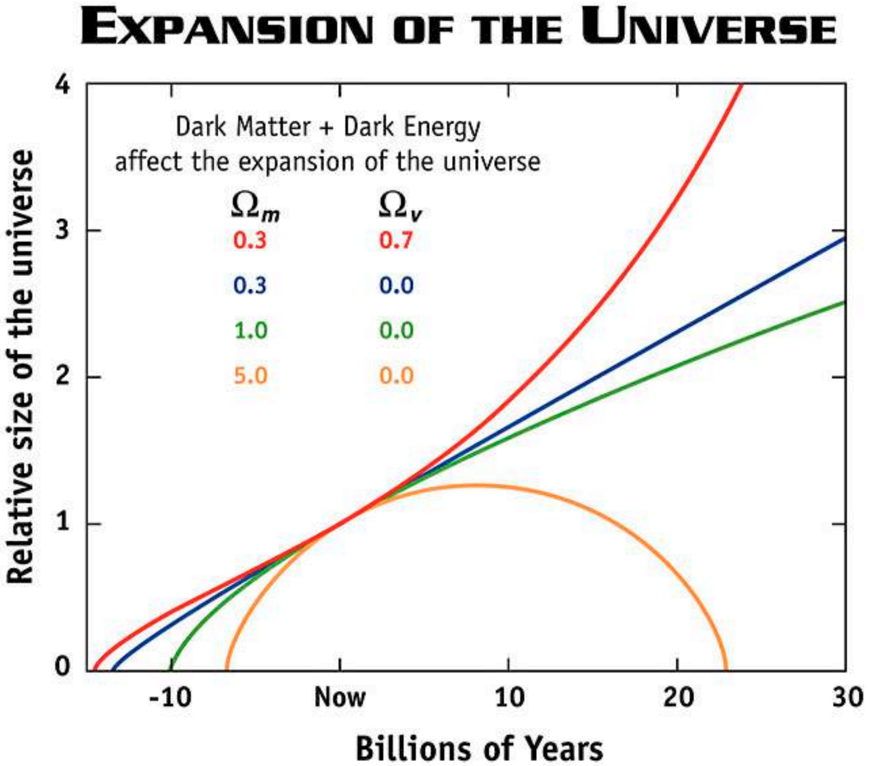
The standard model of cosmology



$$\rho_c = \frac{3H_0^2}{8\pi G};$$

$$\Omega_m \equiv \frac{\rho_{m_0}}{\rho_c} = \frac{8\pi G}{3H_0^2}\rho_{m_0}$$

$$\left(\frac{H(z)}{H_0}\right)^2 = \Omega_r(1+z)^4+\Omega_m(1+z)^3+\Omega_k(1+z)^2+\Omega_\Lambda$$



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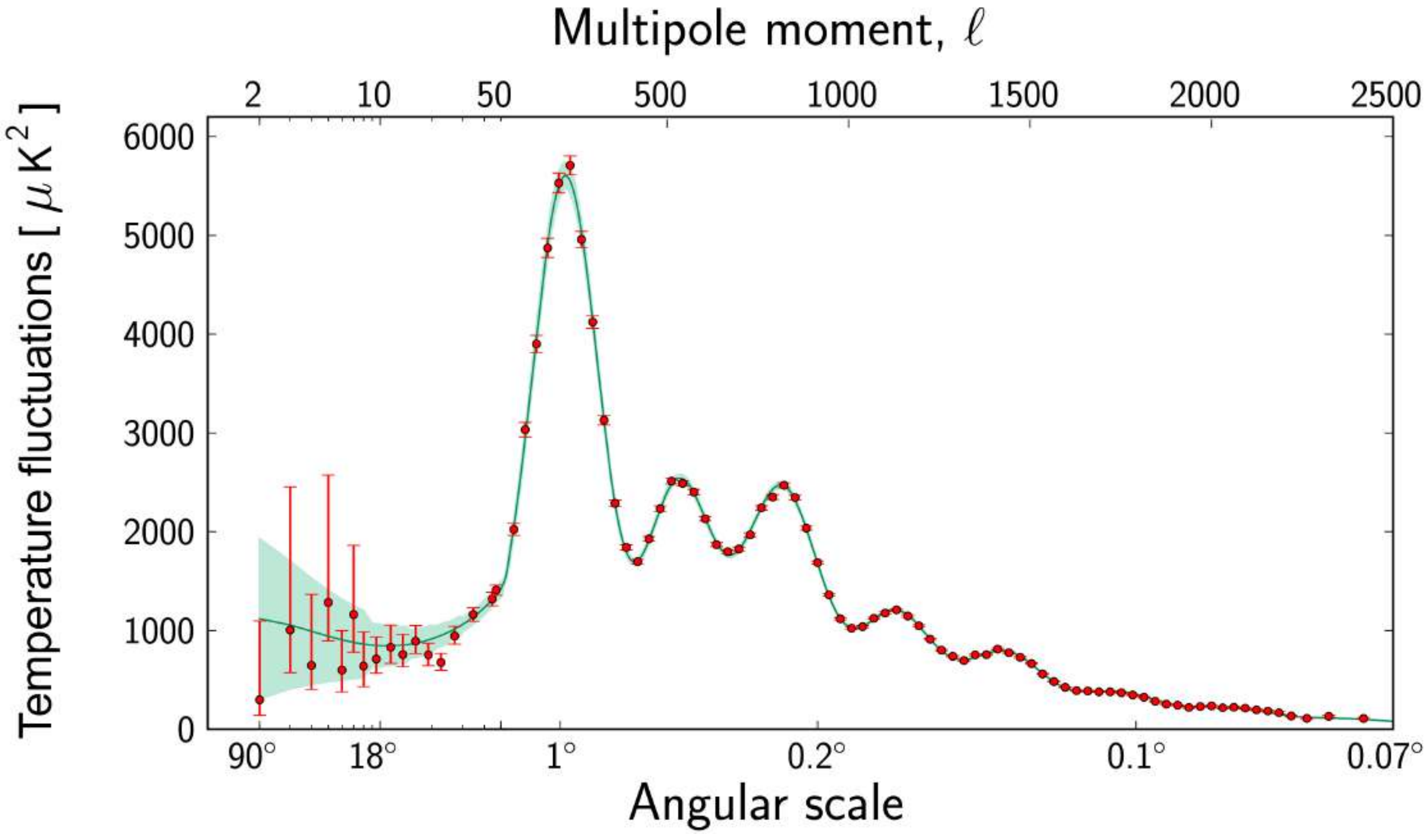
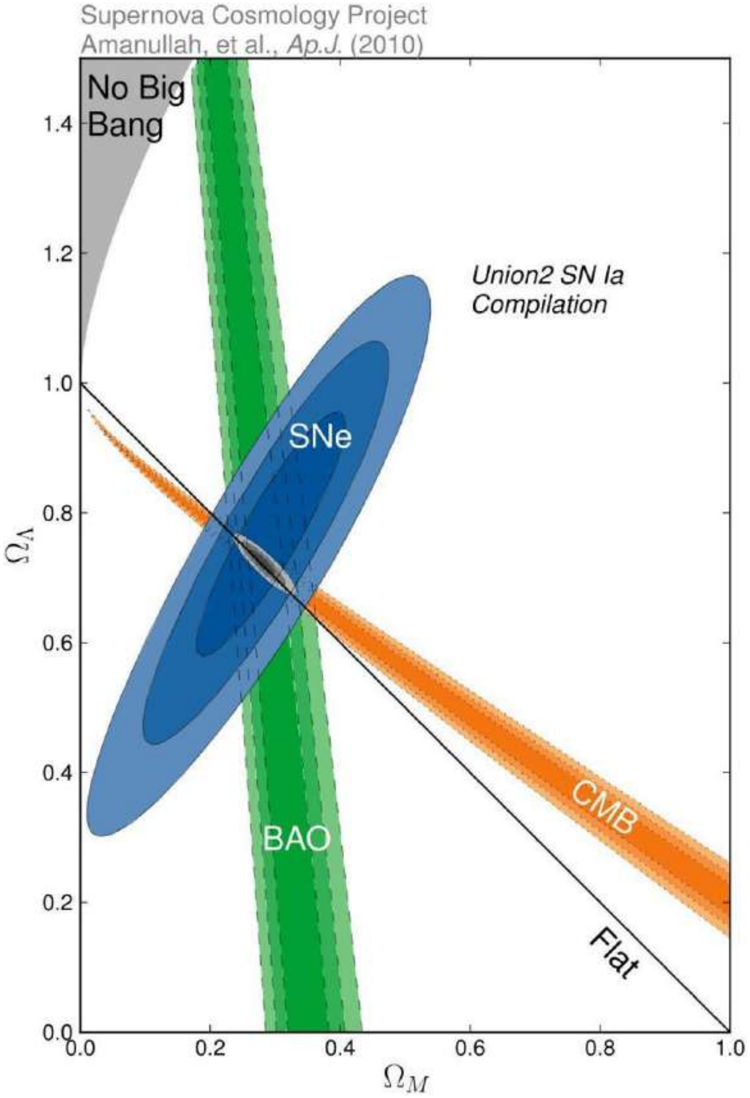
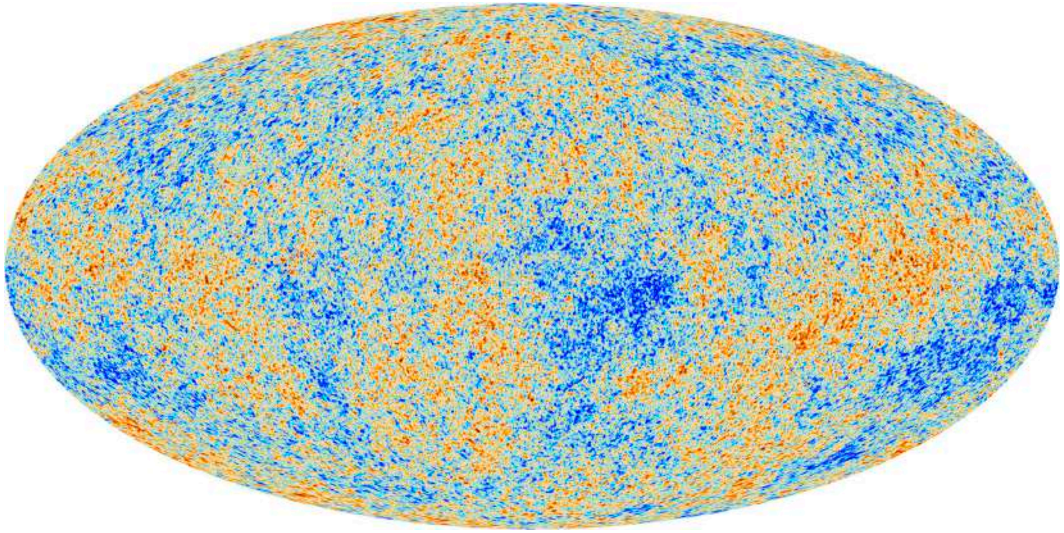
What does the data say?

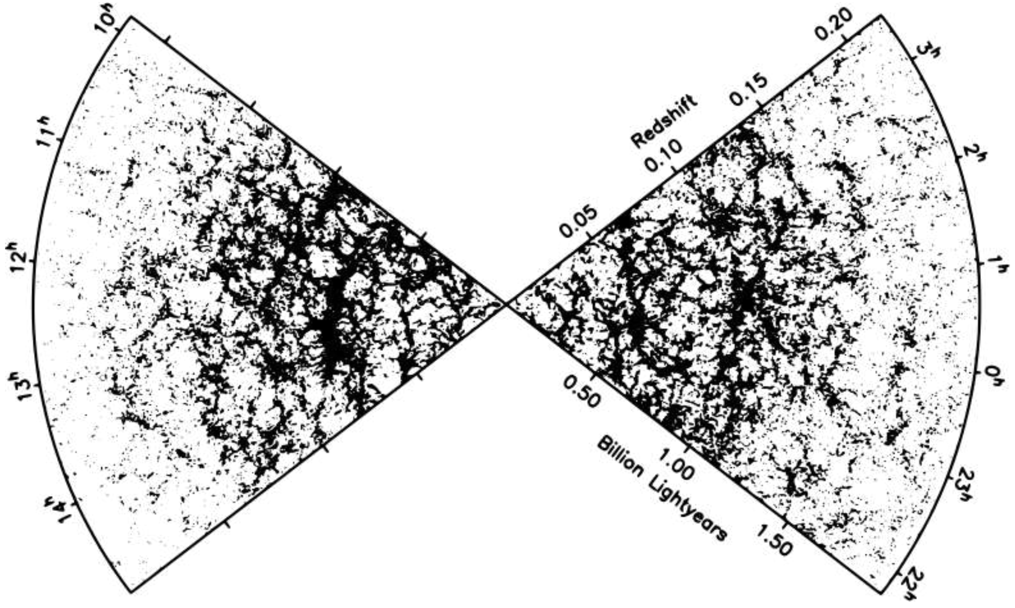


Planck collaboration



What is a galaxy redshift survey?





1. Measure the position of galaxies (RA, DEC + redshift).
2. The CMB tells us the initial conditions for today's distribution of matter.
3. The evolution of the initial density perturbations depends on the theory of gravity and the background expansion given by $\Omega_m, \Omega_\Lambda, H_0$

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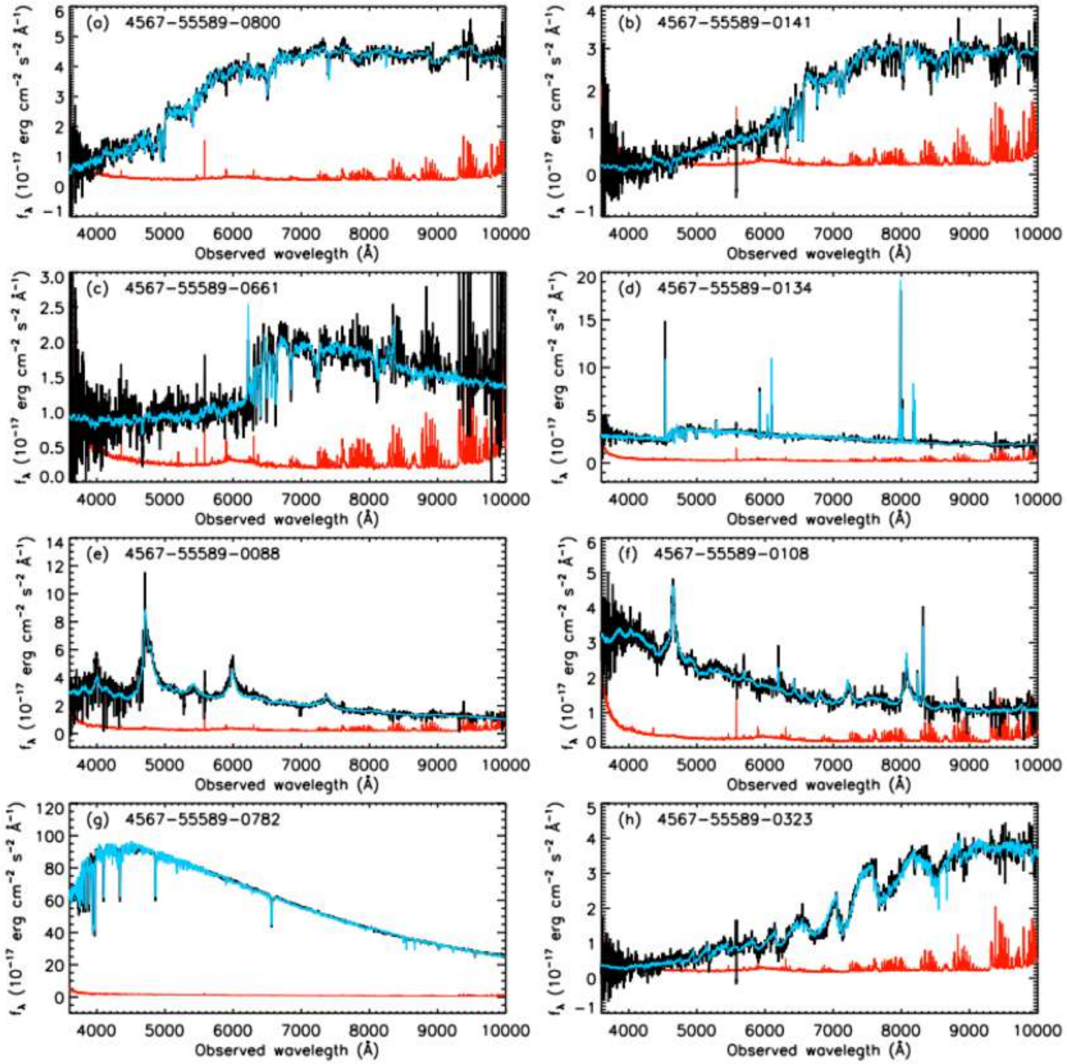
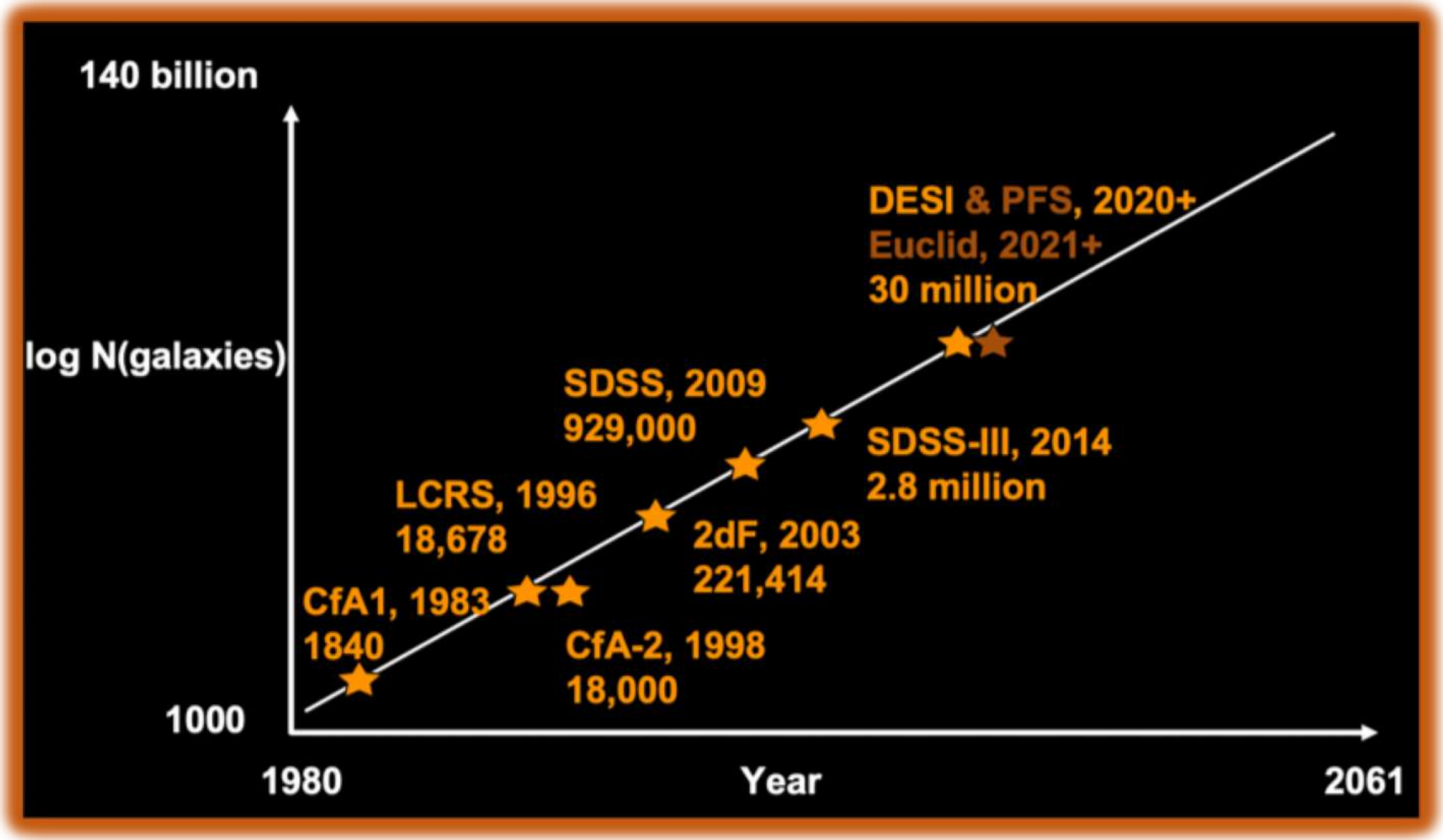
How to get the distance



Hubble's law: $v = H_0\, D$

Bolton et al. (2012)

A long time coming



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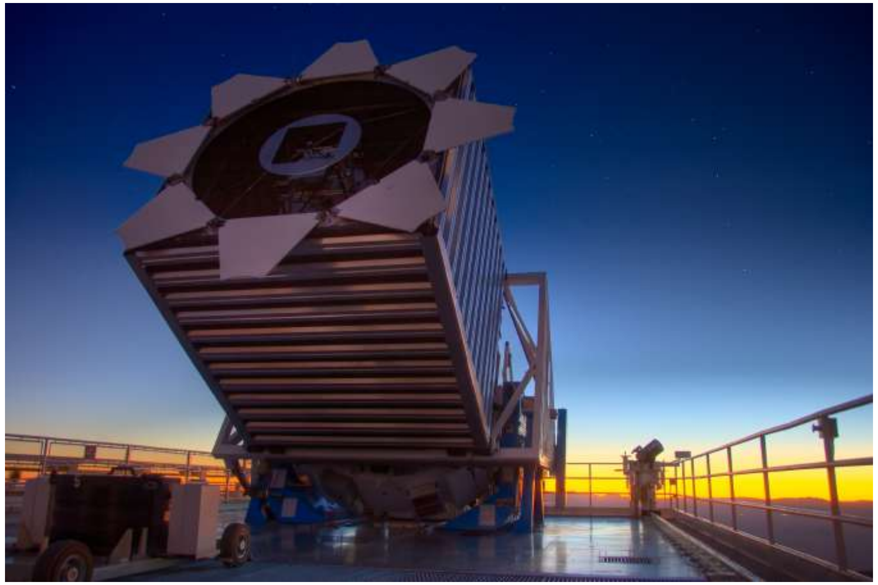
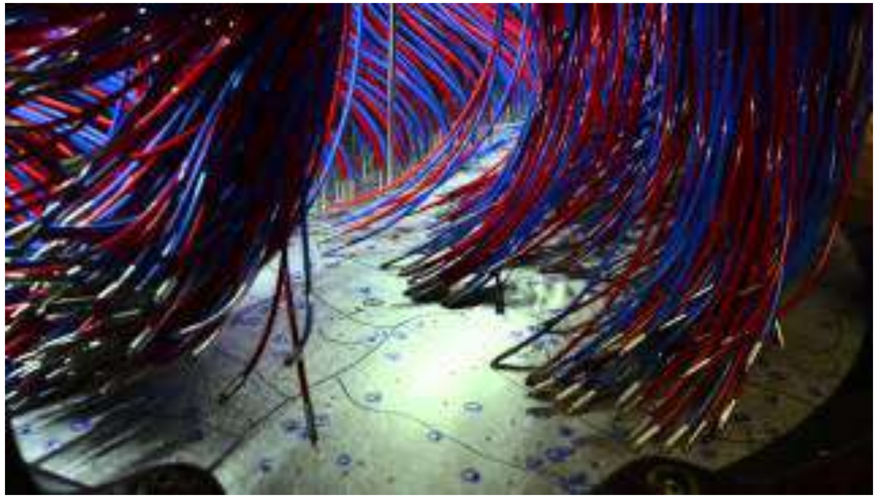
The Baryon Oscillation Spectroscopic Survey (BOSS)

- Fall 2009 - Summer 2014
- 1000 fibres/redshifts per pointing
- Located in New Mexico, USA
- 2.5m Sloan telescope -> Each pointing takes about to 1h
- The fibres are manually "positioned"





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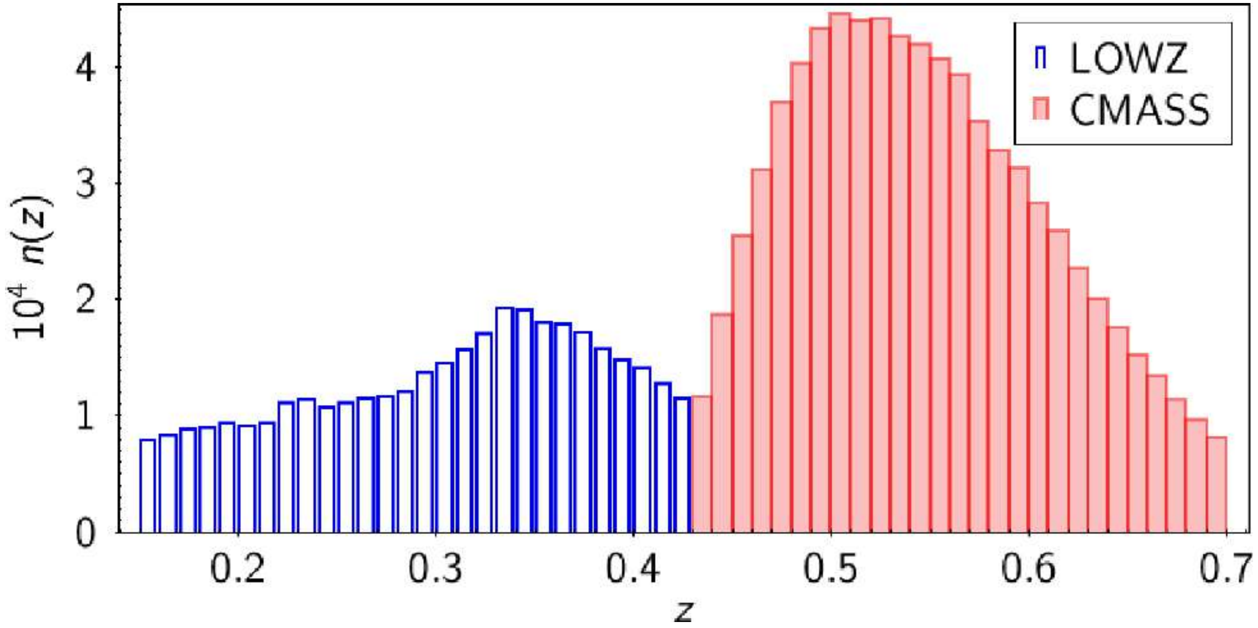
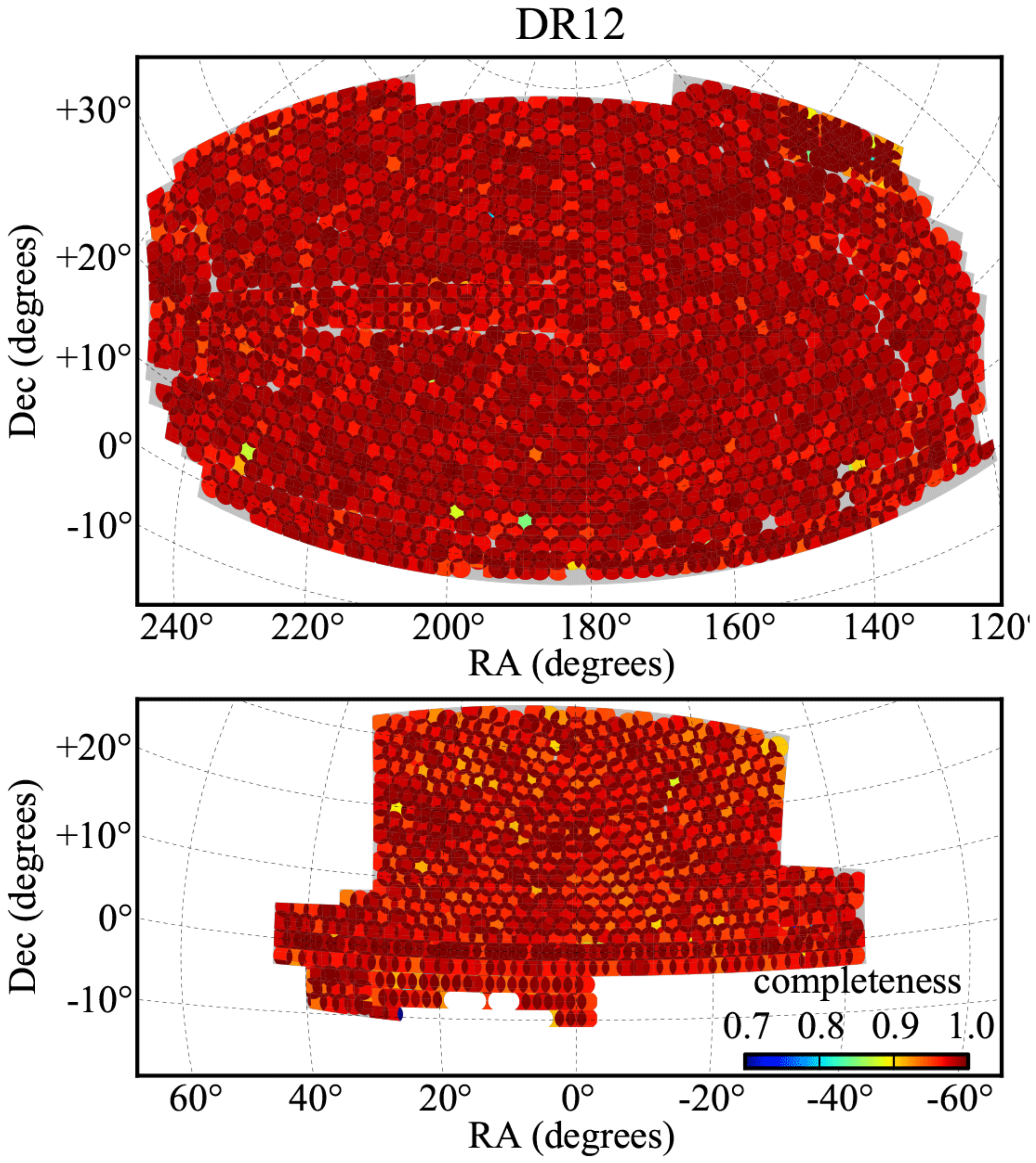
The Baryon Oscillation Spectroscopic Survey (BOSS)

- 10 000 square degrees
- 1.5 million Luminous red galaxies (LRGs), z < 0.7, i < 19.9
- 150 000 quasars, z > 2.2, g < 22.0





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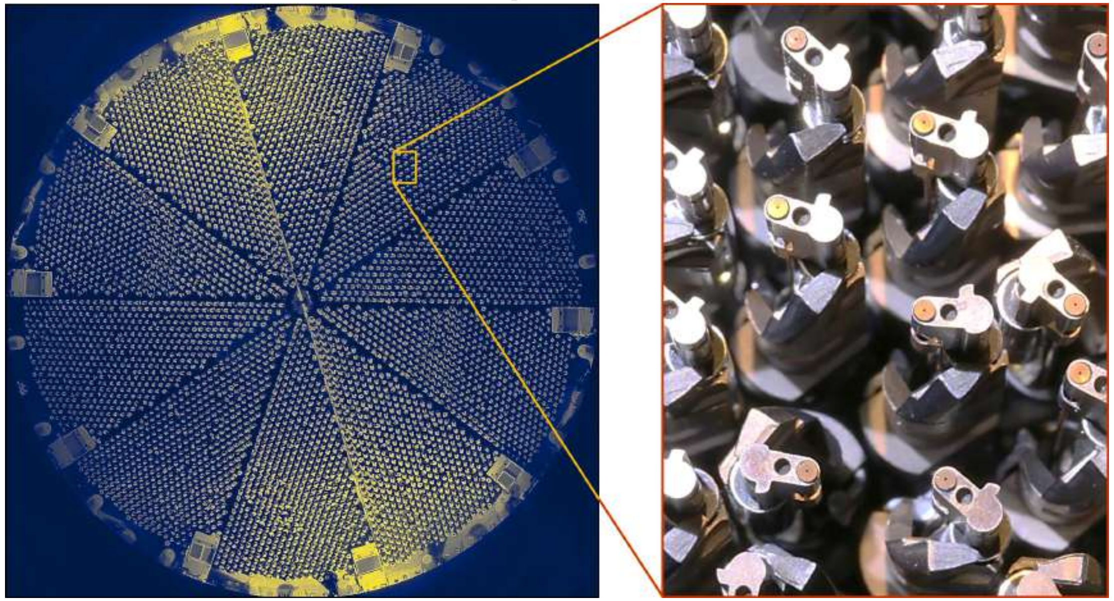
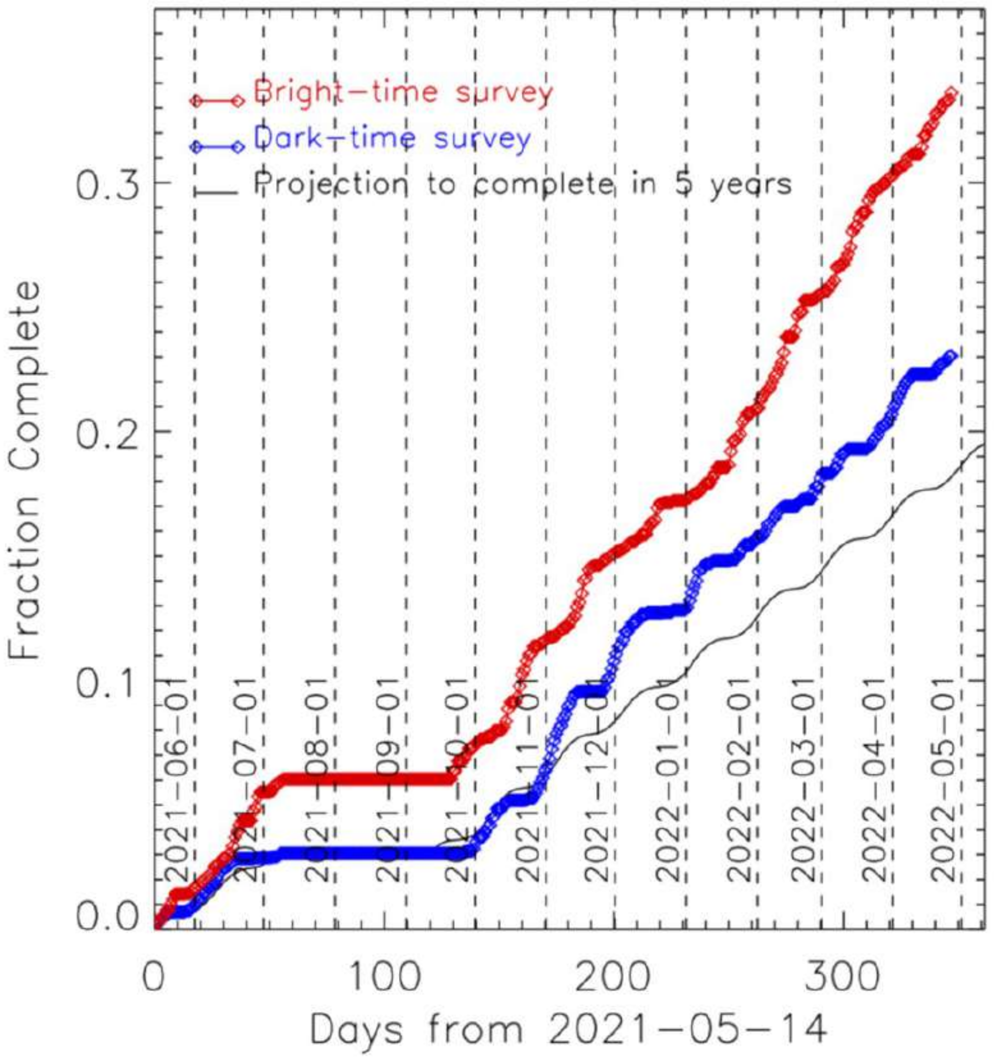
The Dark Energy Spectroscopic Instrument

- 4-meter Mayall telescope at Kitt Peak, AZ
- DESI ~~will produce~~ is producing the most detailed 3D map of the universe, ever
- 2.8 million Quasars at $z > 0.8$
- 23.7 million color-selected galaxies at $0.4 < z < 1.5$
- 13.6 million flux-limited sample of galaxies at $z < 0.4$
- 5000 fibres/redshifts per pointing
- **Shorter integration time and more fibres**

4m Mayall at Kitt Peak, Arizona. Twin to the Blanco, CTIO



DESI: Ahead of schedule



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DESI: Ahead of schedule?

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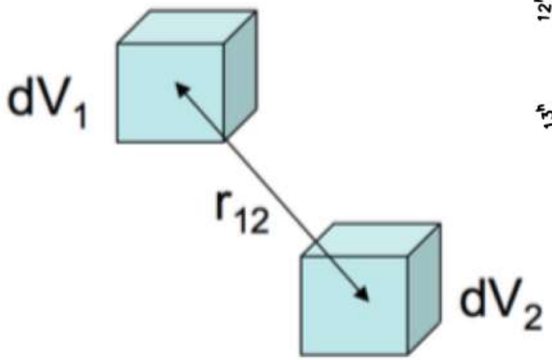
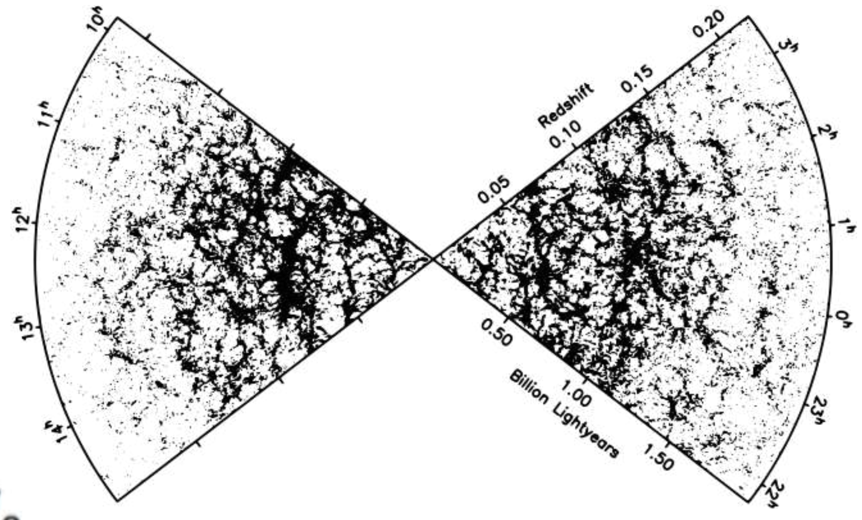
From a point distribution to the power spectrum

- Overdensity-field:

$$\delta(\mathbf{x}) = \frac{\rho(\mathbf{x}) - \overline{\rho}}{\overline{\rho}}$$





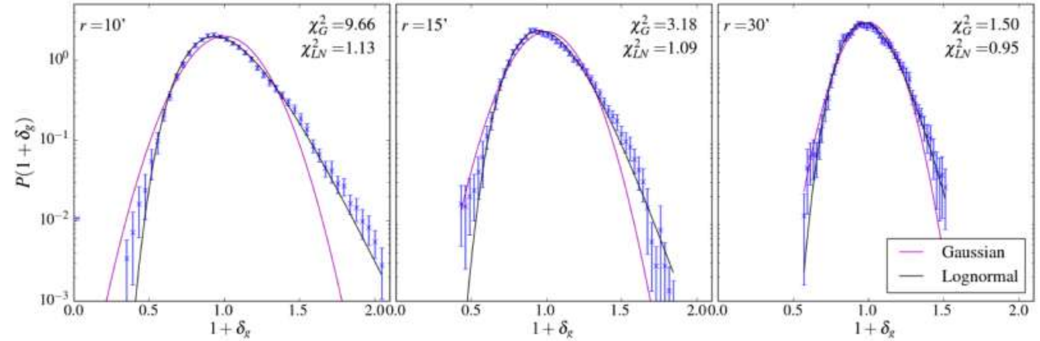
- Two-point function:

$$\xi(\mathbf{r}) \overset{\text{homogeneity}}{=} \langle \delta(\mathbf{x}+\mathbf{r})\delta(\mathbf{x}) \rangle \begin{cases} \overset{\text{isotropy}}{=} & \xi(r) \\ \overset{\text{anisotropy}}{=} & \xi_\ell(r) = \int_{-1}^{1} d\mu\, \xi(r,\mu)\mathcal{L}_\ell(\mu) \end{cases}$$

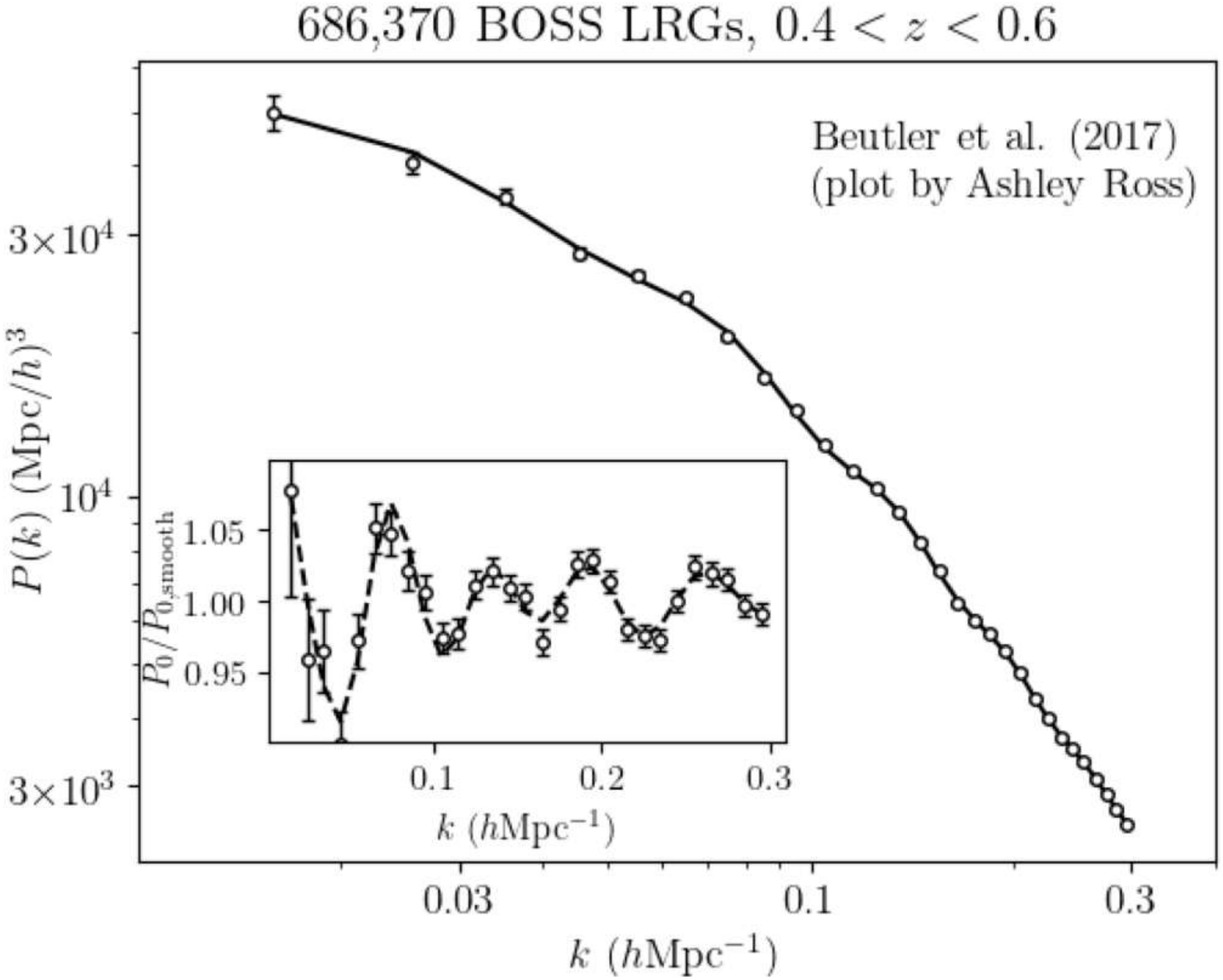
- ...and in Fourier-space:

$$P_\ell(k) = 4\pi(-i)^\ell \int r^2 dr\, \xi_\ell(r) j_\ell(kr)$$

Clerkin et al. (2016)



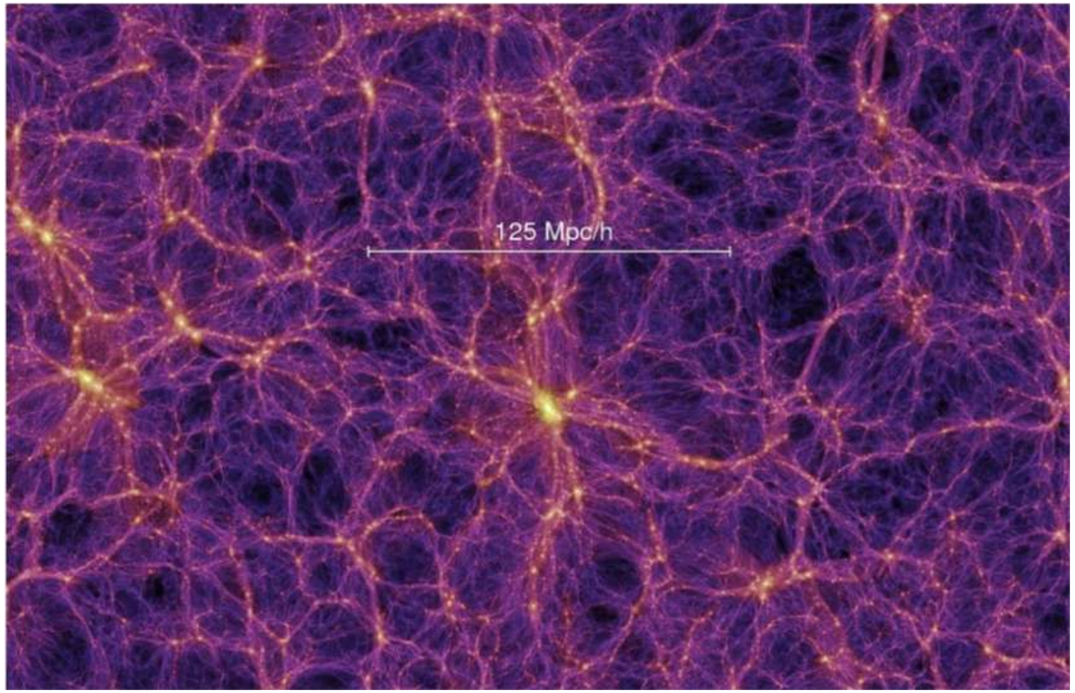
The galaxy power spectrum



Galaxy vs. matter clustering

- We can only observe galaxies (not dark matter)
- We can only (reliably) predict the matter clustering
- Density peaks in the matter distribution are also density peaks in the baryon/galaxy distribution
- But the exact connection between galaxies and matter is one of the main issues with the exploitation of galaxy survey datasets

$$P_m(k) = b^2 P_g(k)$$



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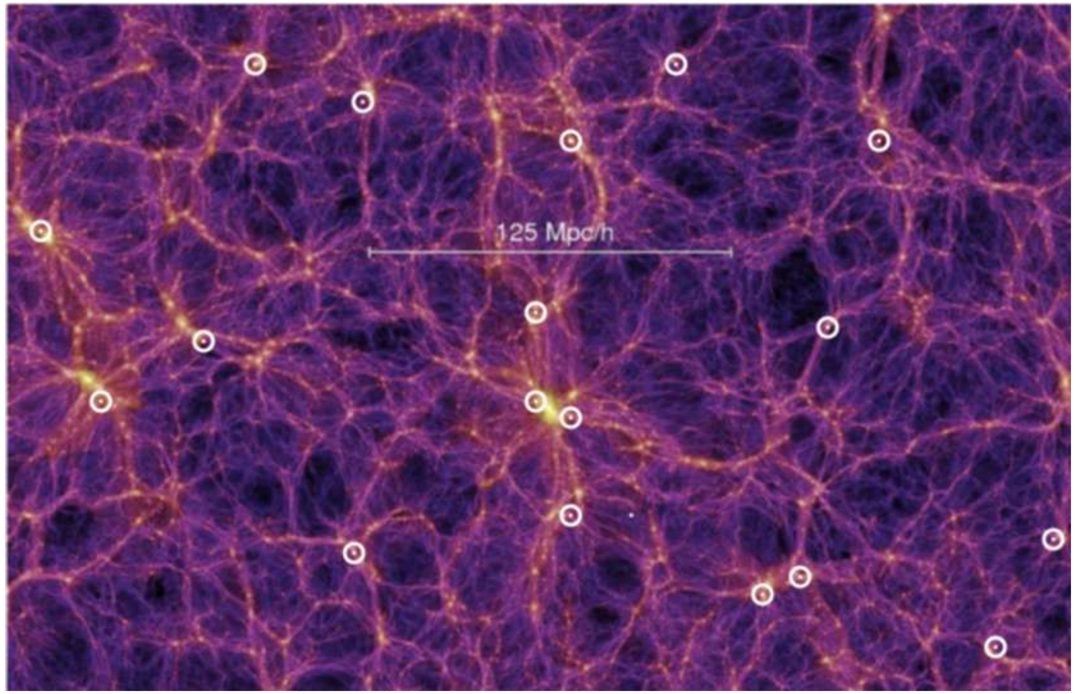

Wealth of observables

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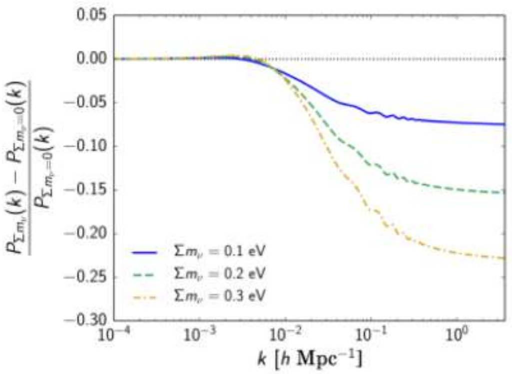
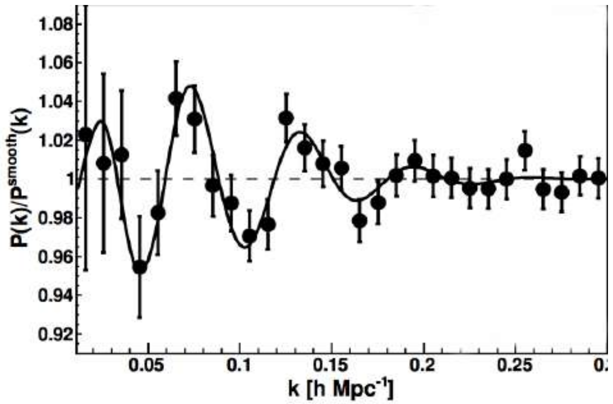
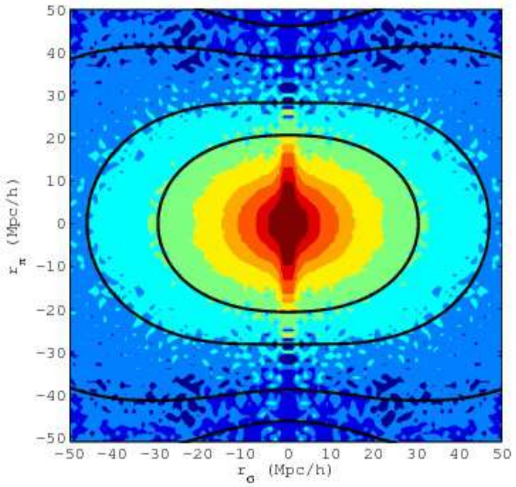
1. Constraining the neutrino mass



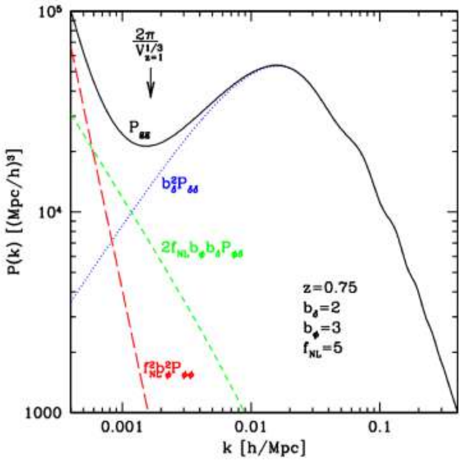
2. Baryon Acoustic Oscillations

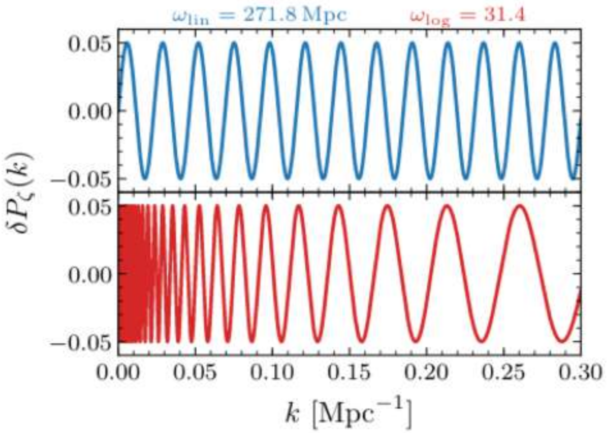


3. Redshift-space distortions

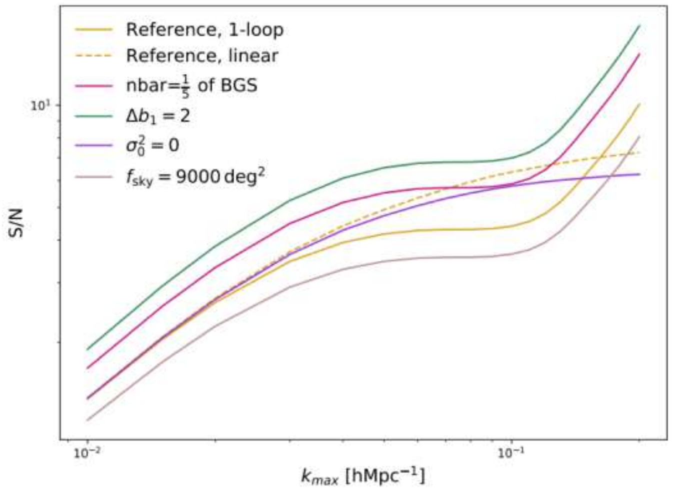


4. Primordial non-Gaussianity/primordial features





5. Relativistic effects



and many more…

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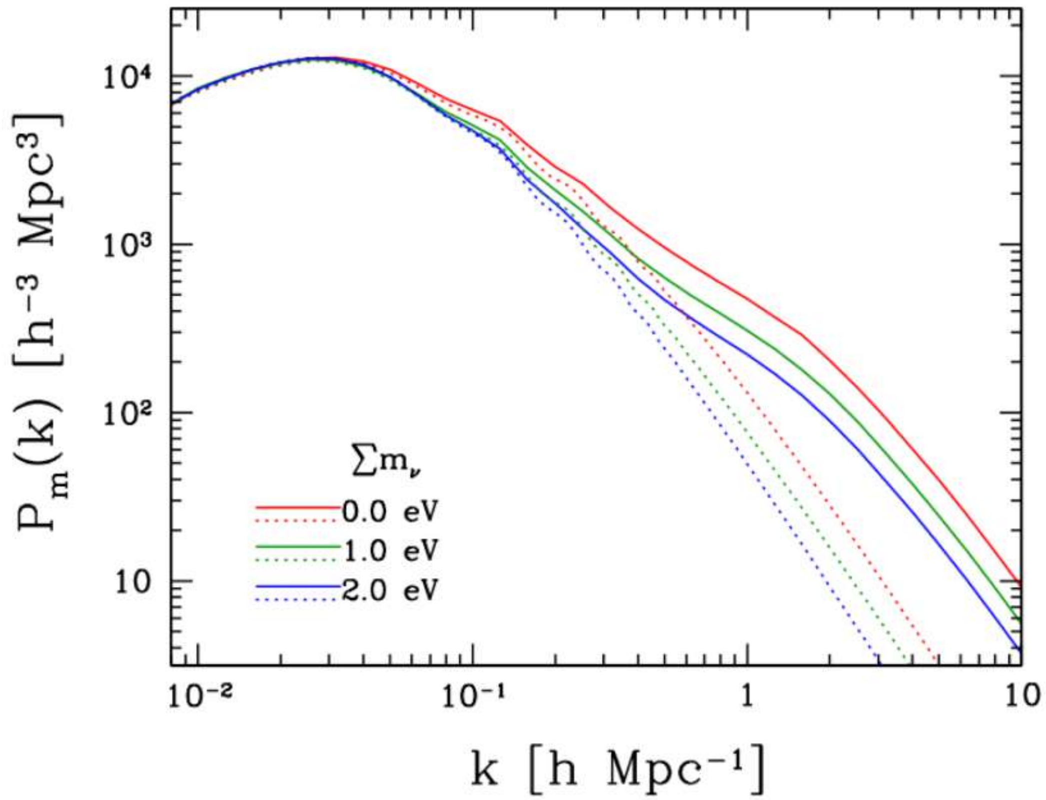
1. Constraining the neutrino mass

Hannestad et al. (2006)

- Neutrino Oscillation experiments have determined the difference between the masses of the neutrino mass eigenstates (Nobel Prize in 2015)
- The minimum of the sum of the neutrino masses is around 0.06 eV (>1 million times smaller than the mass of the electron)
- The sum of the neutrino masses does reduce the matter power spectrum

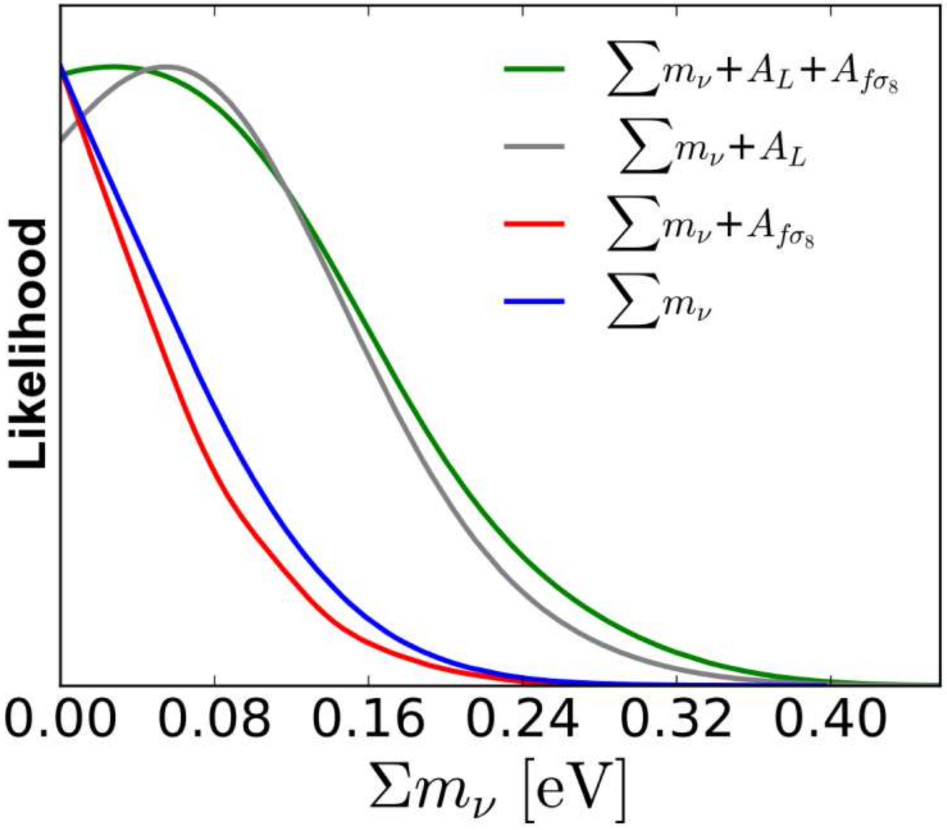


Neutrino mass hierarchy
$$\begin{cases} m_{\nu_1} < m_{\nu_2} \ll m_{\nu_3} \rightarrow \textbf{min}\left(\sum m_\nu\right) \simeq 0.06\, eV \\ m_{\nu_3} \ll m_{\nu_1} < m_{\nu_2} \rightarrow \textbf{min}\left(\sum m_\nu\right) \simeq 0.1\, eV \end{cases}$$

1. Constraining the neutrino mass

Alam et al. (2016)

- **Planck + DESI will yield:** $\sigma_{\sum m_\nu} = 0.017\,eV$
- Tritium beta decay (Troitzk): $m_{\bar{\nu}_e} < 2.05\,eV$
- KATRIN forecast: $m_{\bar{\nu}_e} \sim 0.2\,eV\ (\sum m_\nu \simeq 0.6\,eV)$



$|\Delta m^2_{31}| \simeq 2.56\times10^{-3}\,eV^2$

$\Delta m^2_{21} \simeq 7.37\times10^{-5}\,eV^2$

$$0.06\,eV \lesssim \text{Planck}\left(\Lambda\text{CDM} + \sum m_\nu\right) + \text{BOSS} < 0.16\,eV$$

2. What are Baryon Acoustic Oscillations

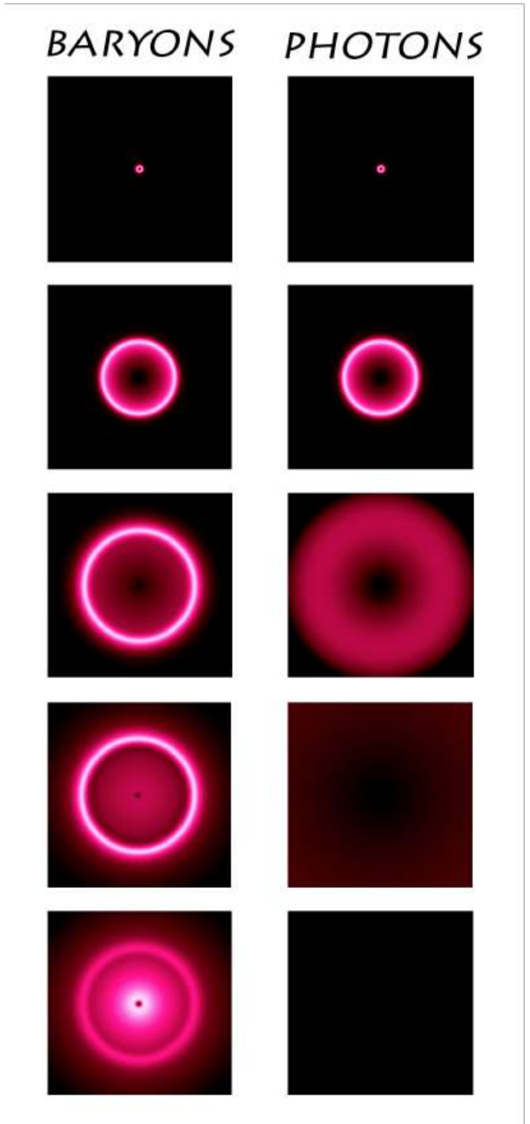
- For the first 370 000 years the evolution eq. of baryon and photon perturbations can be written as

$$\ddot{\delta}_{b\gamma} - c_s^2 \nabla^2 \delta_{b\gamma} = \nabla^2 \Phi$$

with the plane wave solution

$$\delta_{b\gamma} = A\cos(kr_s + \phi)$$

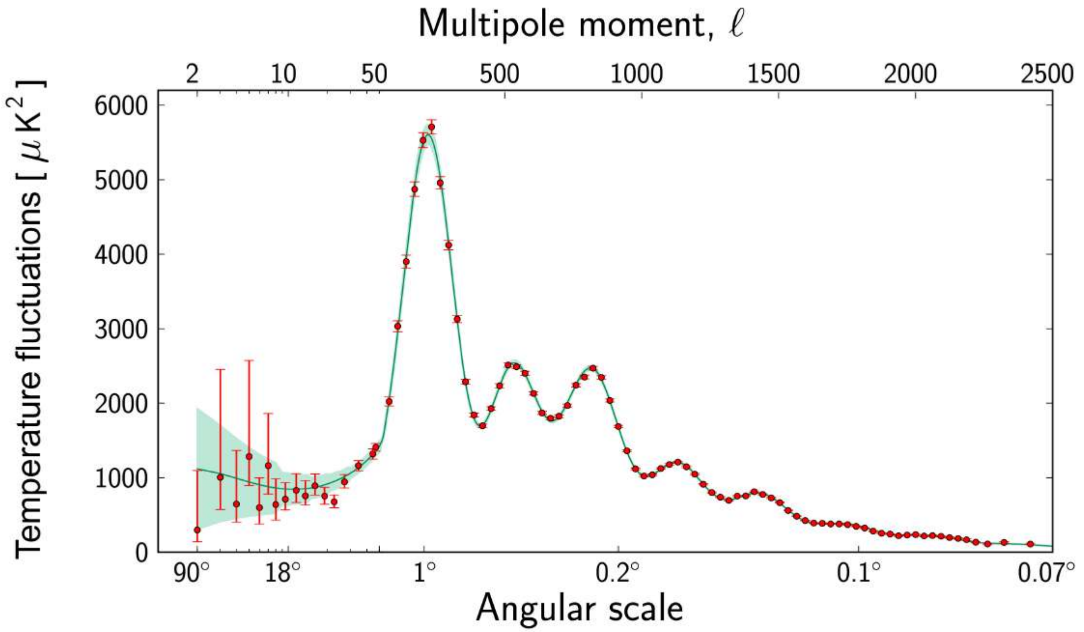
- Preferred distance scale between galaxies as a relic of sound waves in the early Universe.
- This signal is present at low redshift and detectable in the correlation function or power spectrum **on very large scales**.



Credit: Martin White

2. BAO in photons and galaxies

Cosmic Microwave Background (Planck, z = 1000)



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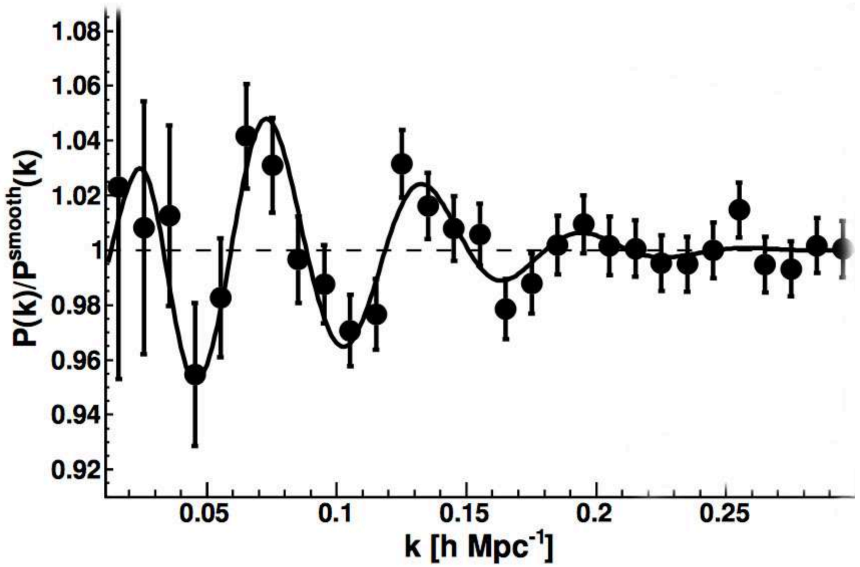
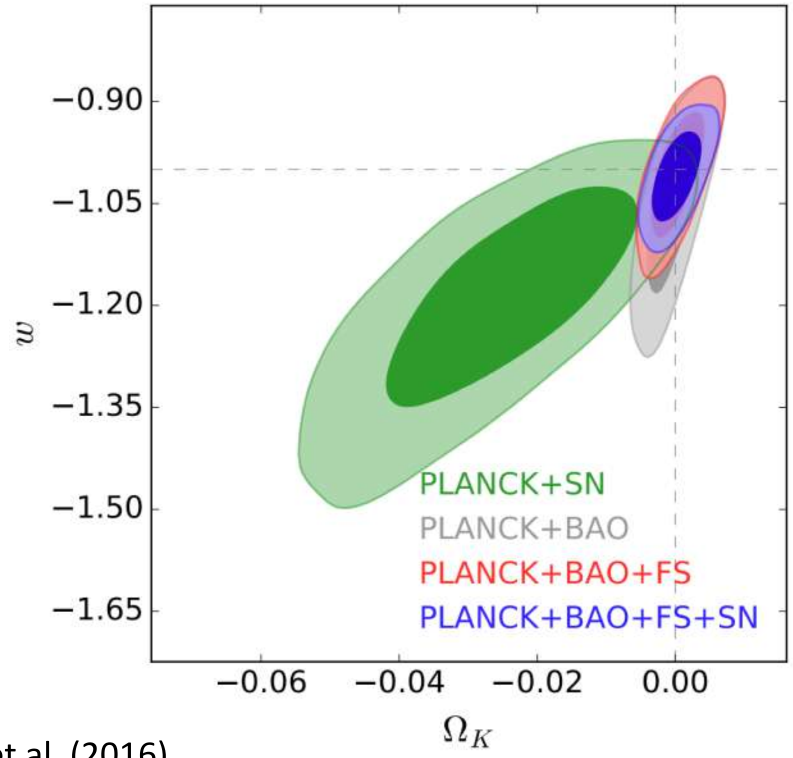
Galaxy redshift survey (BOSS, z = 0.5)



2. Constraining cosmological parameters



Alam et al. (2016)

Planck+SN:

$$\Omega_k = 0.025 \pm 0.012$$
$$w = -1.01 \pm 0.11$$

Planck+SN+BAO:

$$\Omega_k = 0.0003 \pm 0.0027$$
$$w = -1.05 \pm 0.08$$

$$\left(\frac{H(z)}{H_0}\right)^2 = \Omega_r(1+z)^4+\Omega_m(1+z)^3+\Omega_k(1+z)^2+\Omega_\Lambda(1+z)^{3(1+w)}$$

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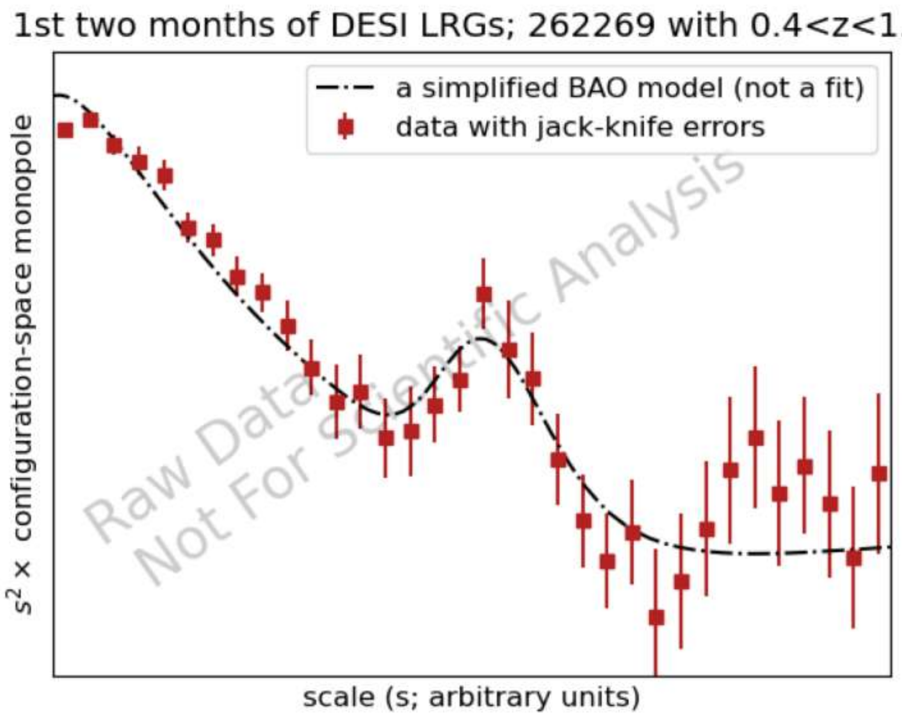
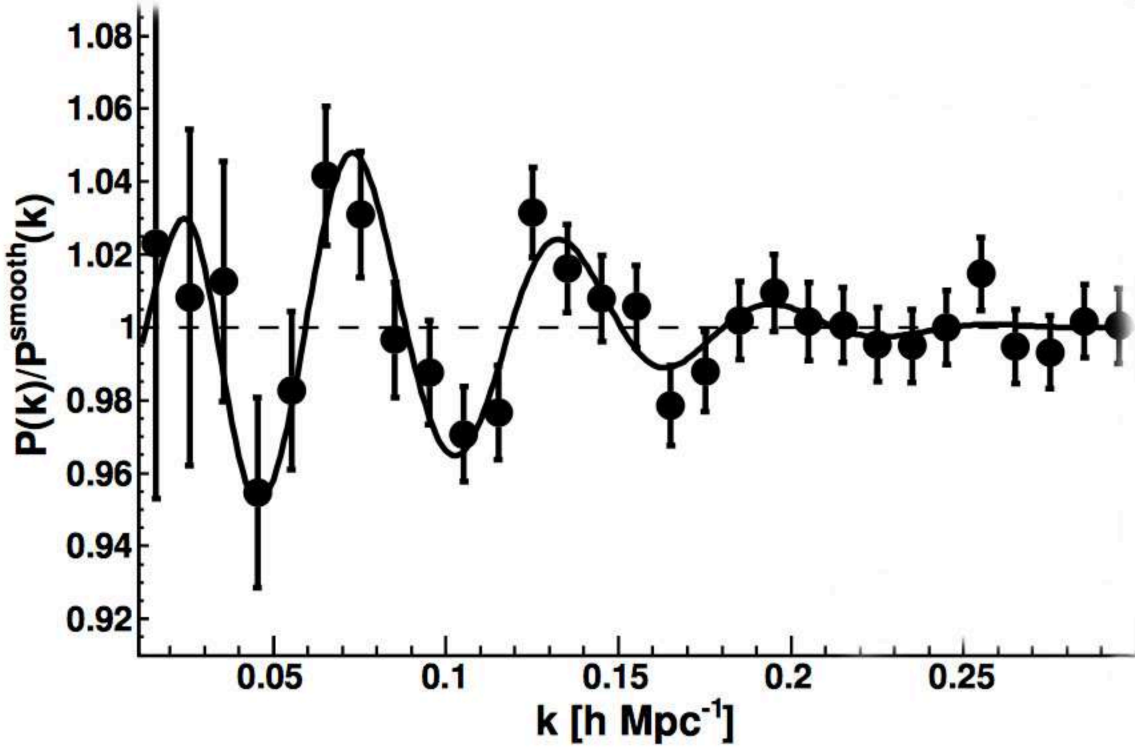
2. BAO detection in BOSS and DESI

- In BOSS the BAO signal has been detected with > 8σ in two independent redshift bins after 5 years
- In DESI we already have a 5σ detection after 2 months





$D_V(z = 0.38)\, r_s^{\mathrm{fid}}/r_s = 1476 \pm 15$ Mpc (1.0%)

$D_V(z = 0.61)\, r_s^{\mathrm{fid}}/r_s = 2146 \pm 19$ Mpc (0.9%)

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

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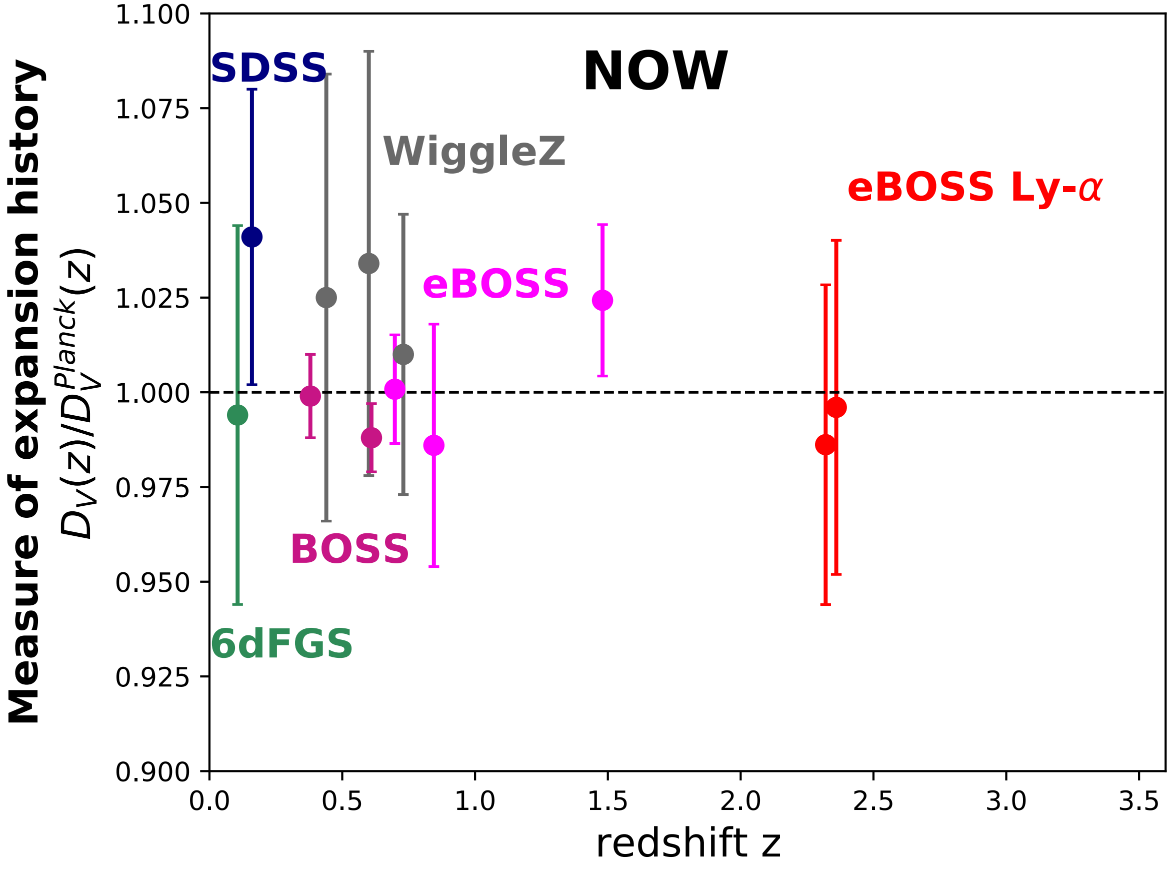
2. DESI forecasts



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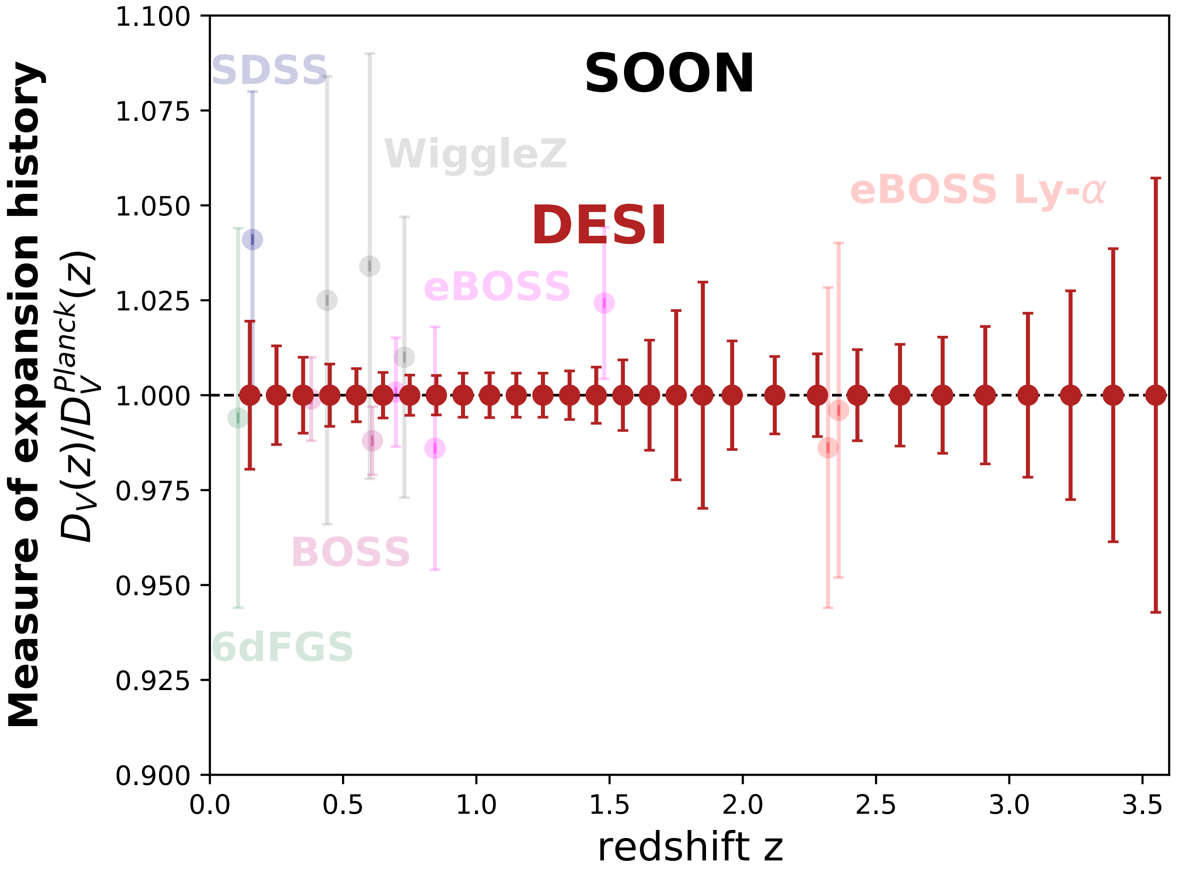
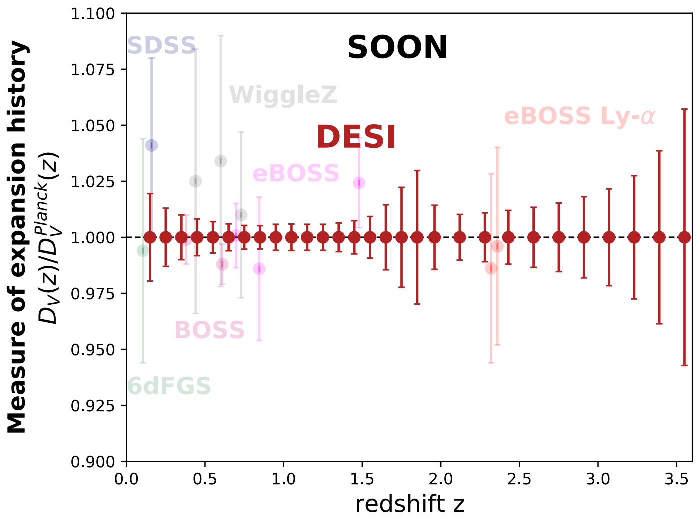
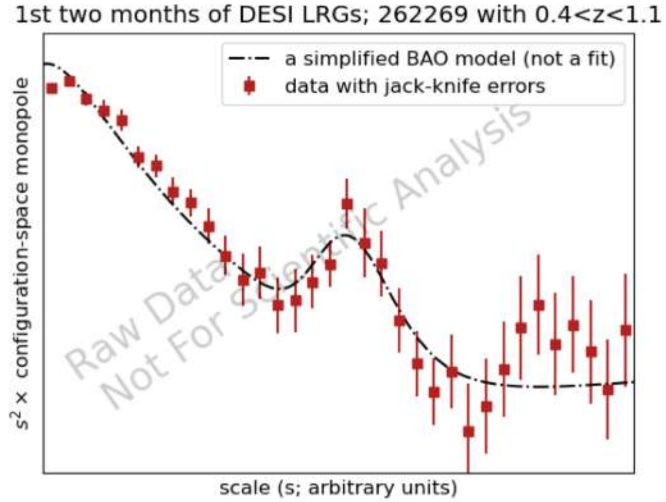


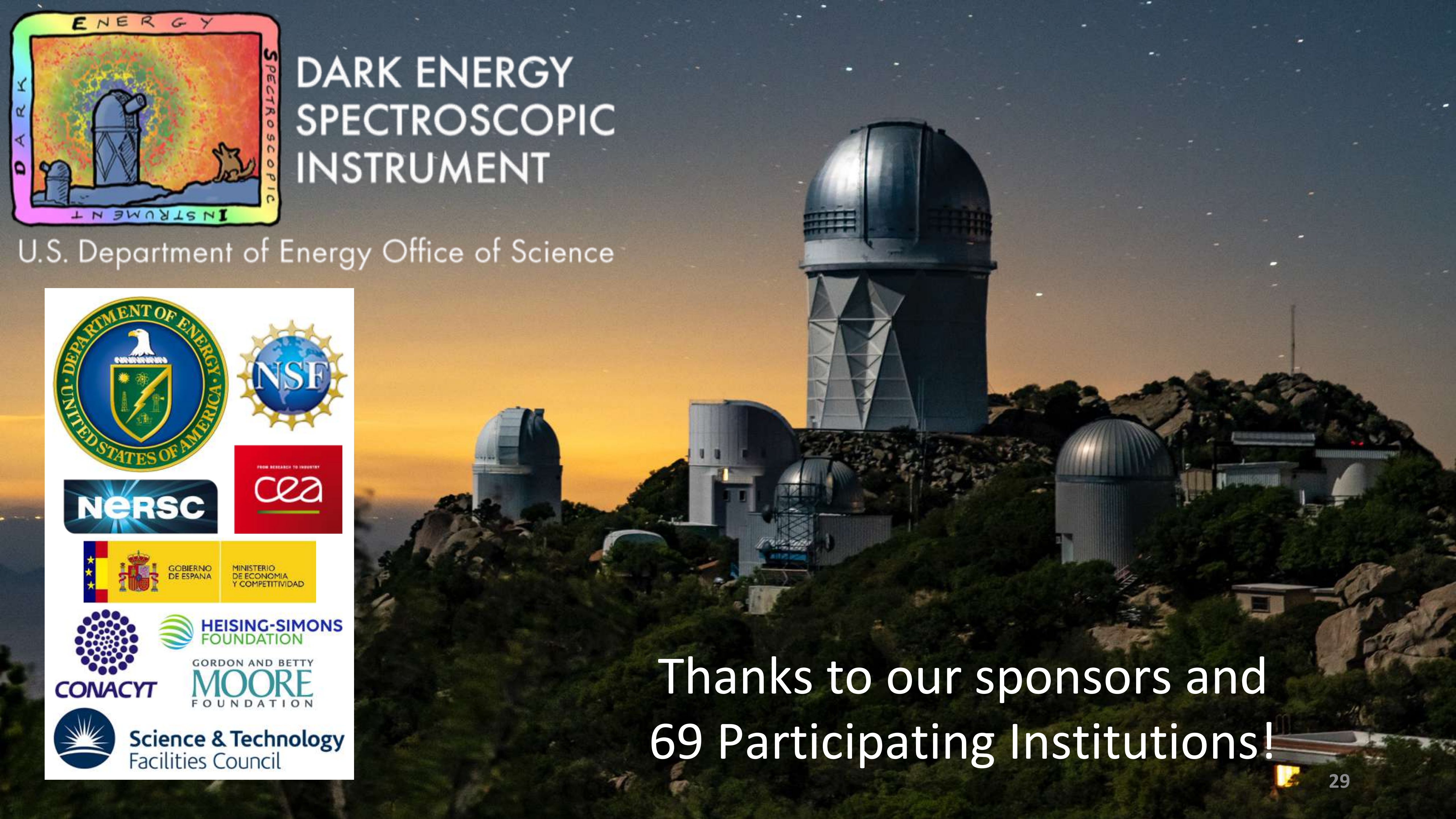
$$D_V(z) = \left[(1+z)^2 D_A^2(z) \frac{cz}{H(z)}\right]^{1/3}$$

Conclusion





- Galaxy surveys have matured into one of the most powerful cosmological tools
- The BAO peak provides a standard ruler for measuring the cosmic expansion rate and constraining the dark energy equation of state
- The growth of structure allows tests of gravity as well as measuring the neutrino mass scale
- DESI is providing the next generation galaxy redshift survey datasets, more than an order magnitude larger than past datasets
- **Look for the Year 1 cosmology results and Data Release 1 in late 2023**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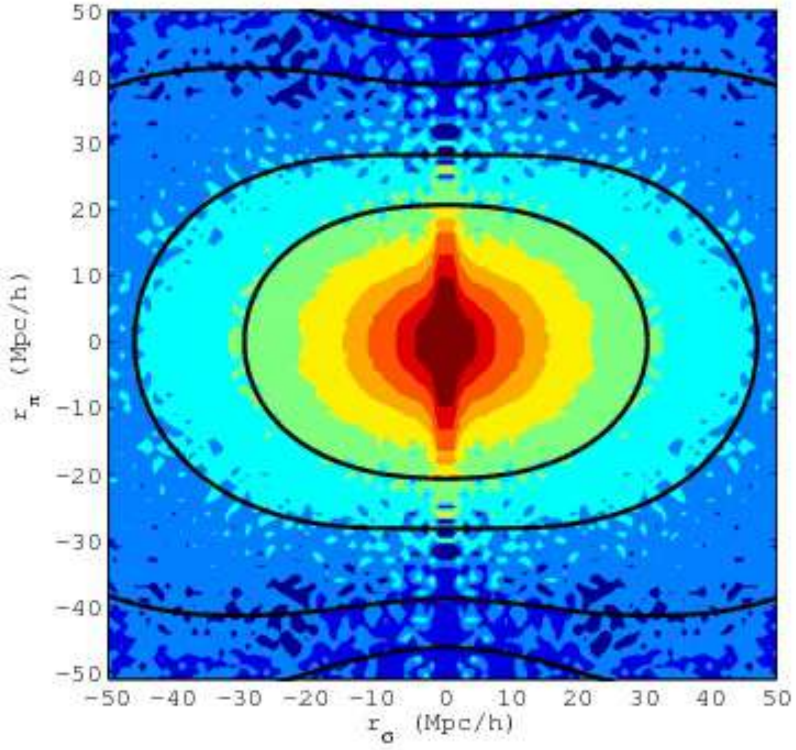
3. Redshift-space distortions

- Galaxy bias prevents us from using the amplitude of the galaxy power spectrum to measure structure growth straight forwardly
- However, redshift-space distortions allow us the measure the velocity field
- Introduces a quadrupole in the galaxy clustering signal
- Redshift-space distortions are proportional to the matter content

$$f = \frac{\partial \ln D}{\partial \ln a} \approx \Omega_m^{0.55}$$

- The growth rate is also sensitive to the laws of gravity as well as the general expansion history



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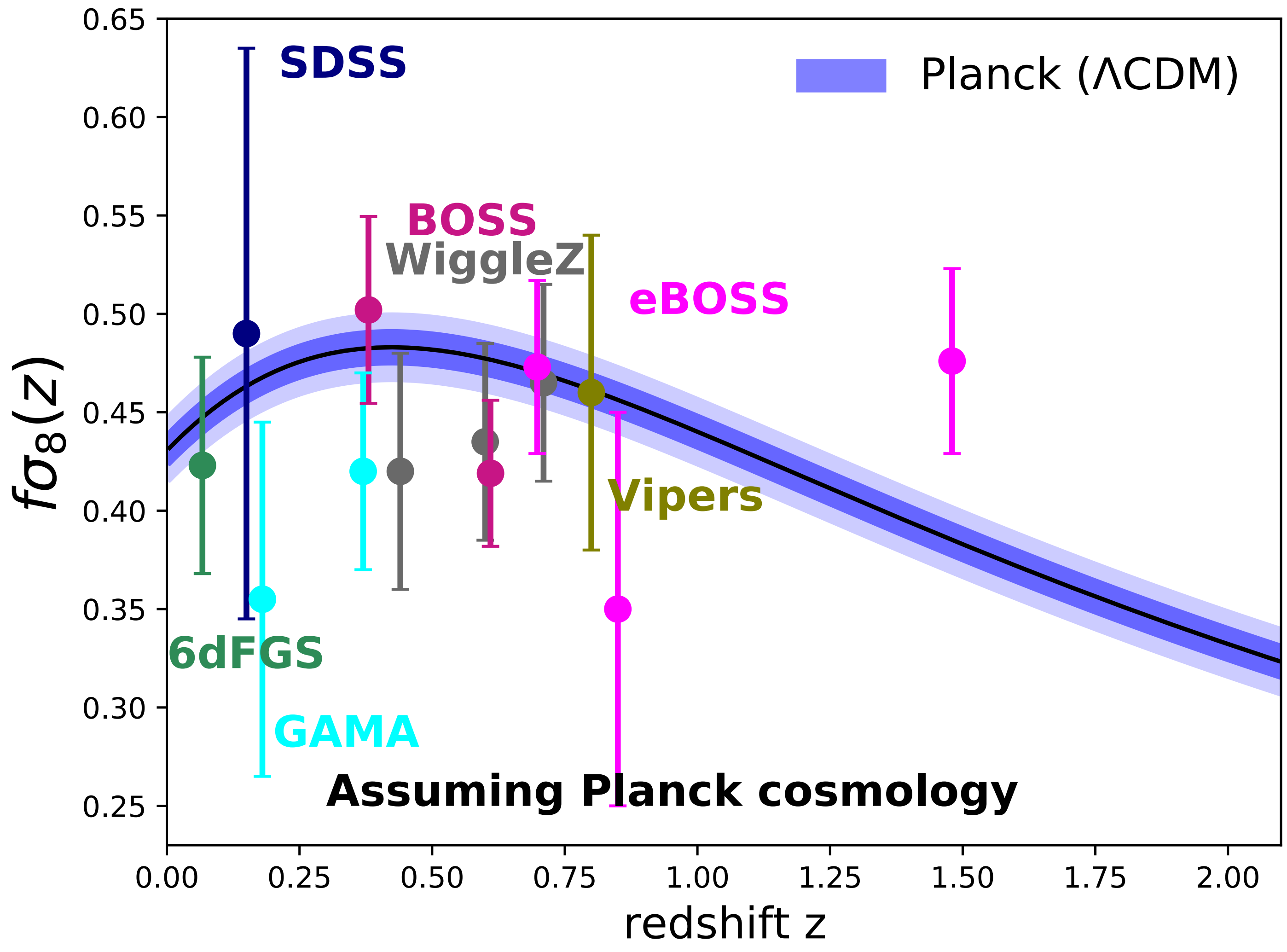

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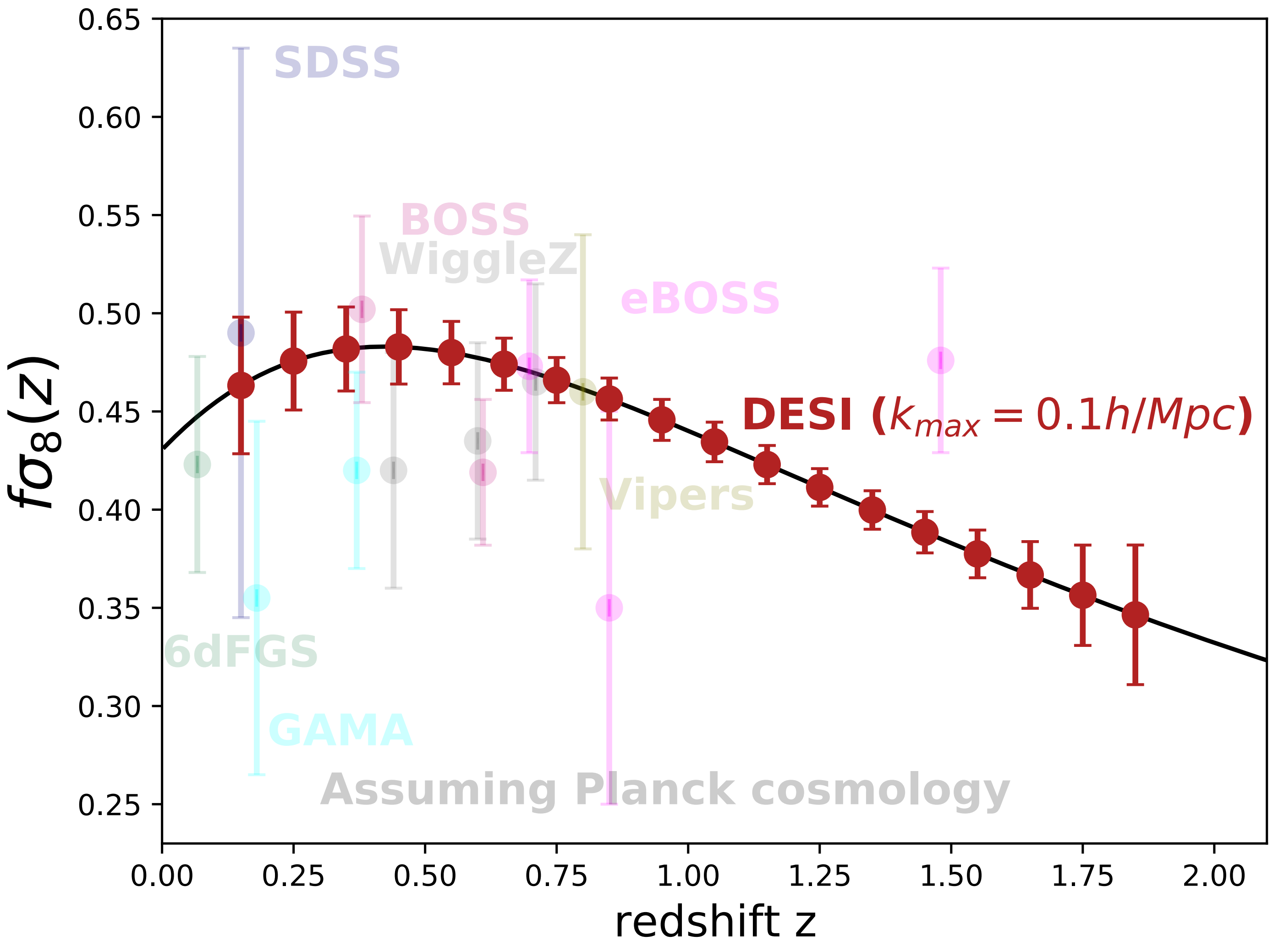

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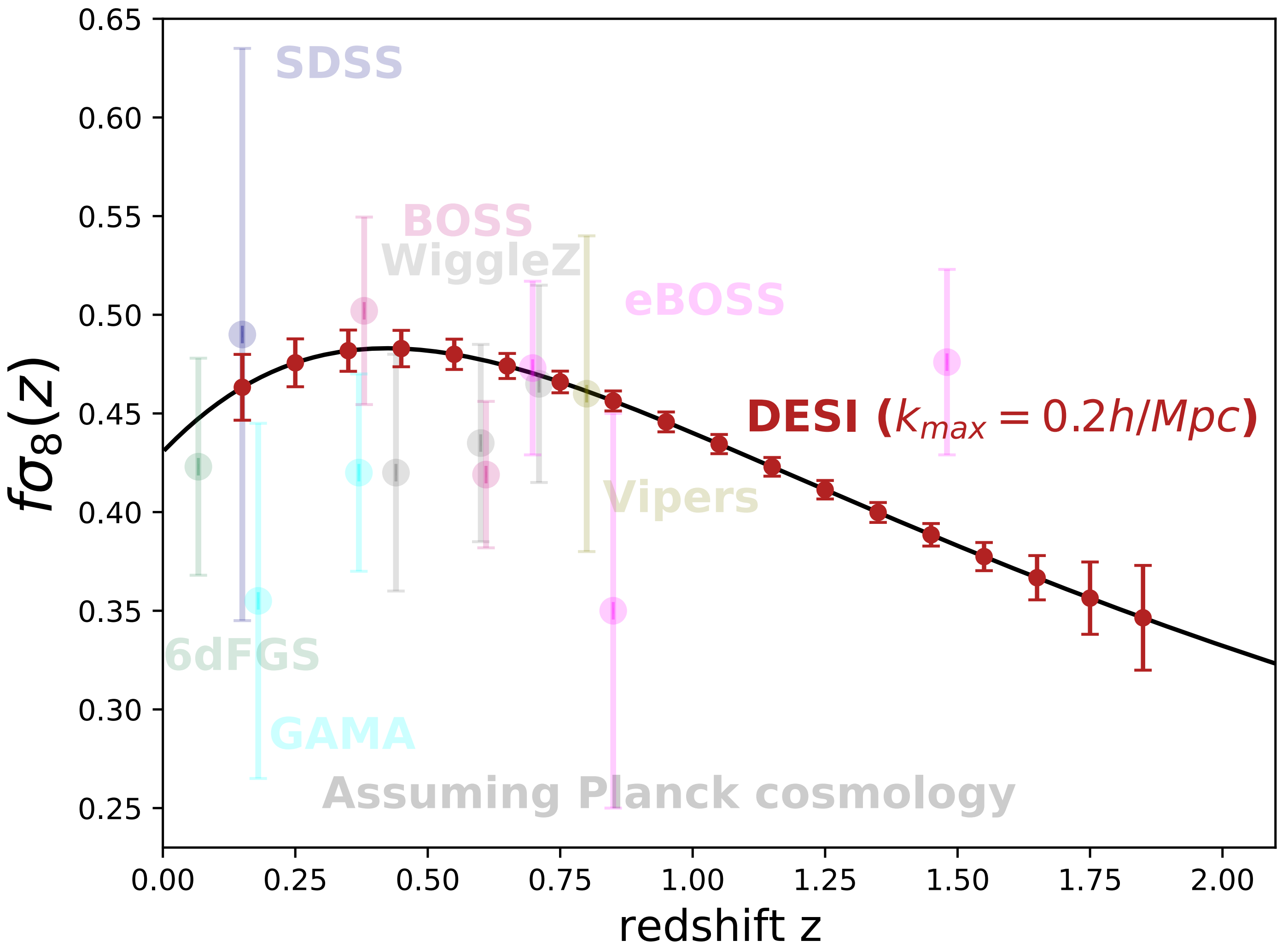
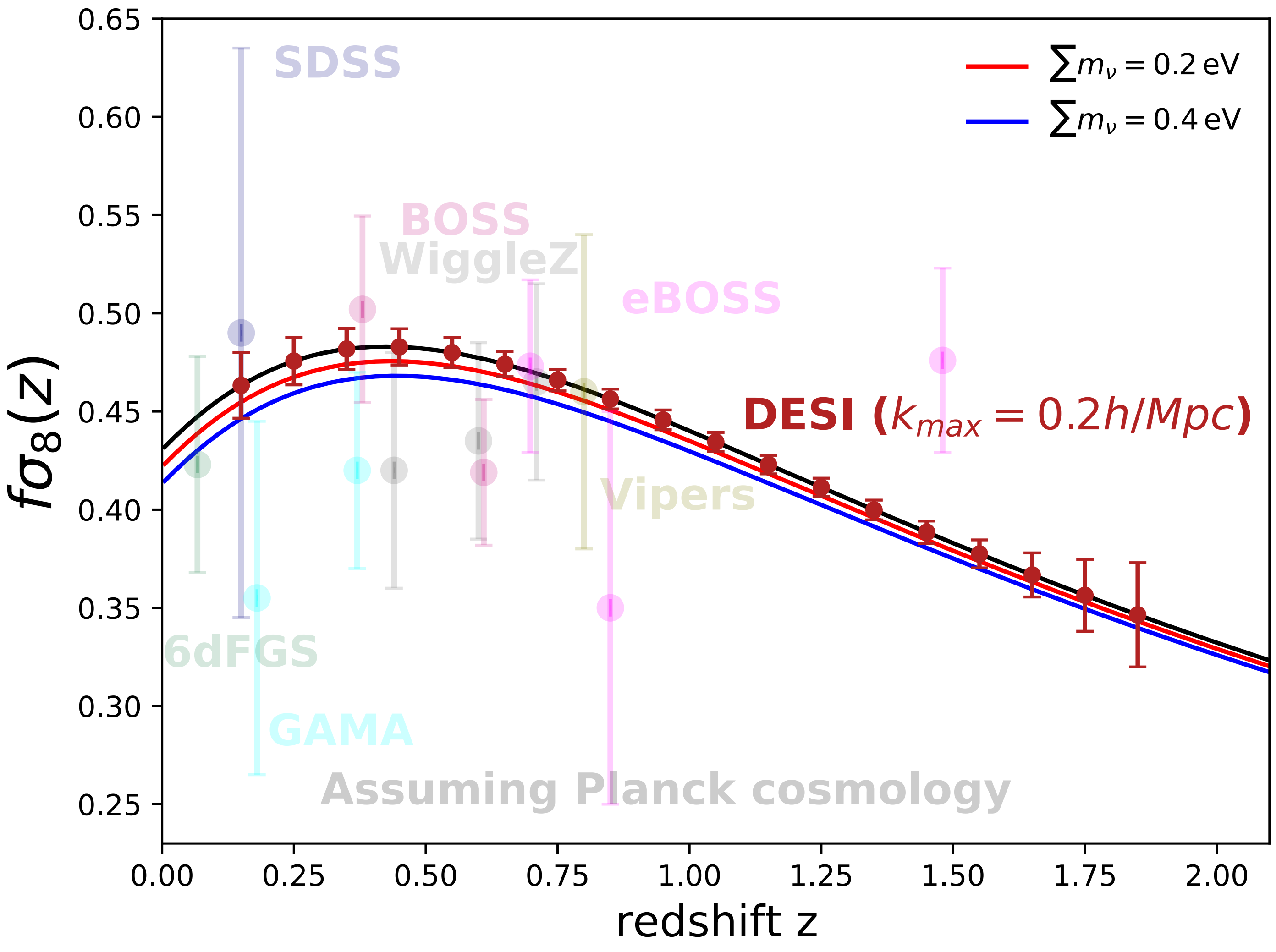
3. Redshift-space distortions



3. Redshift-space distortions

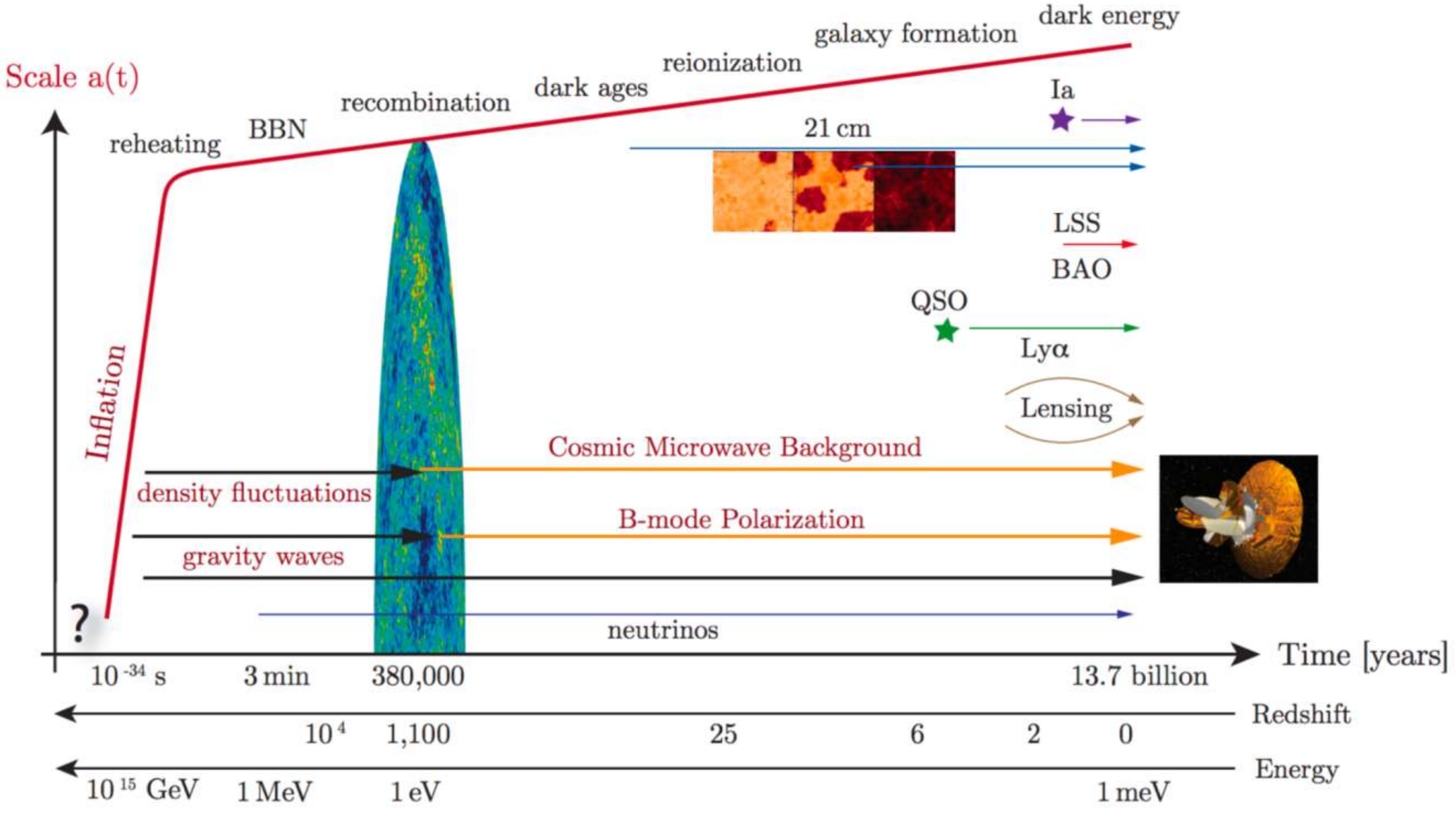
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science



4. Testing the primordial Universe

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science



Baumann (2009)

4. Testing the primordial Universe

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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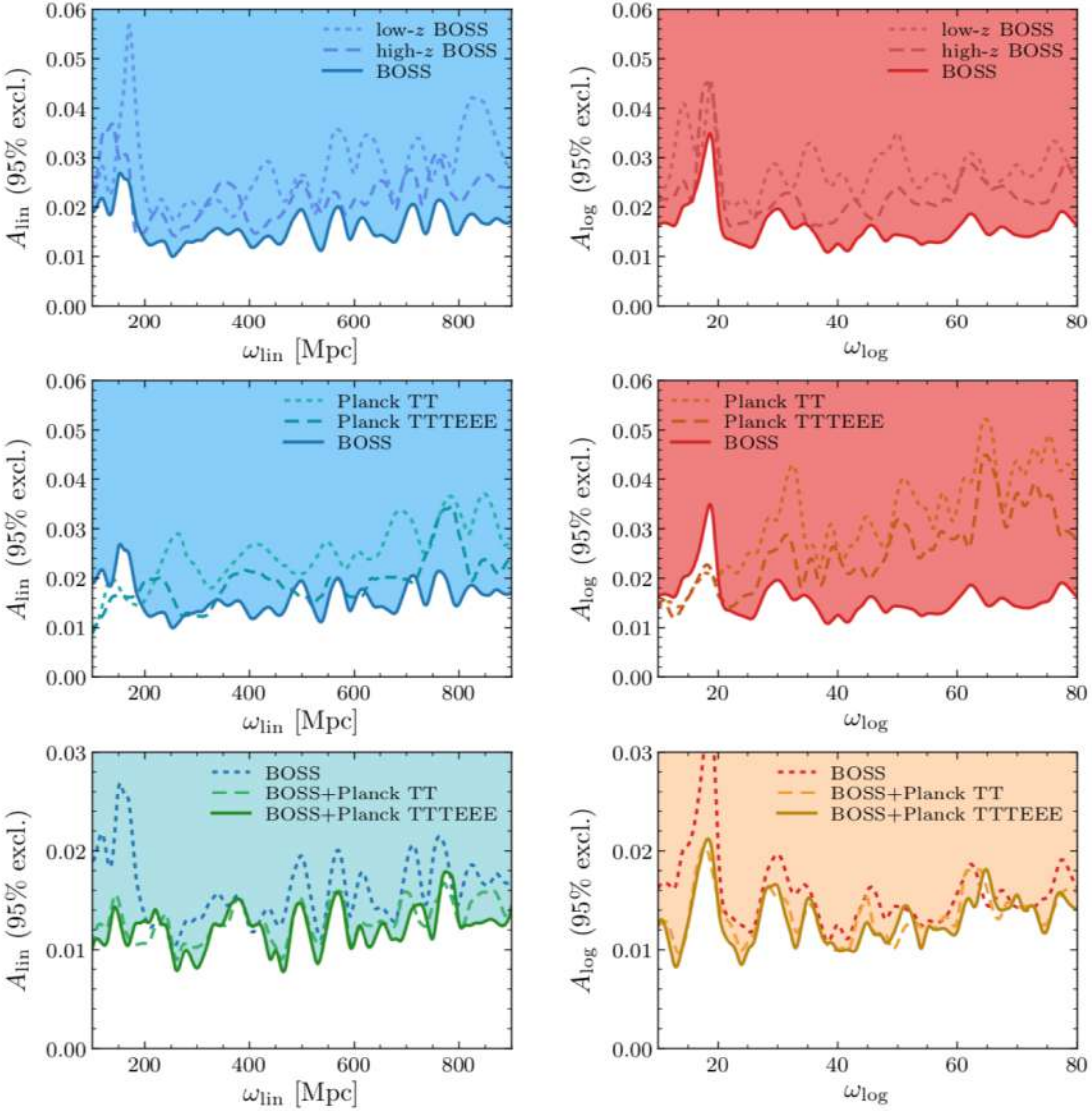

BOSS

BOSS vs. Planck

BOSS + Planck

FB++ (2019)

5. Relativistic effects