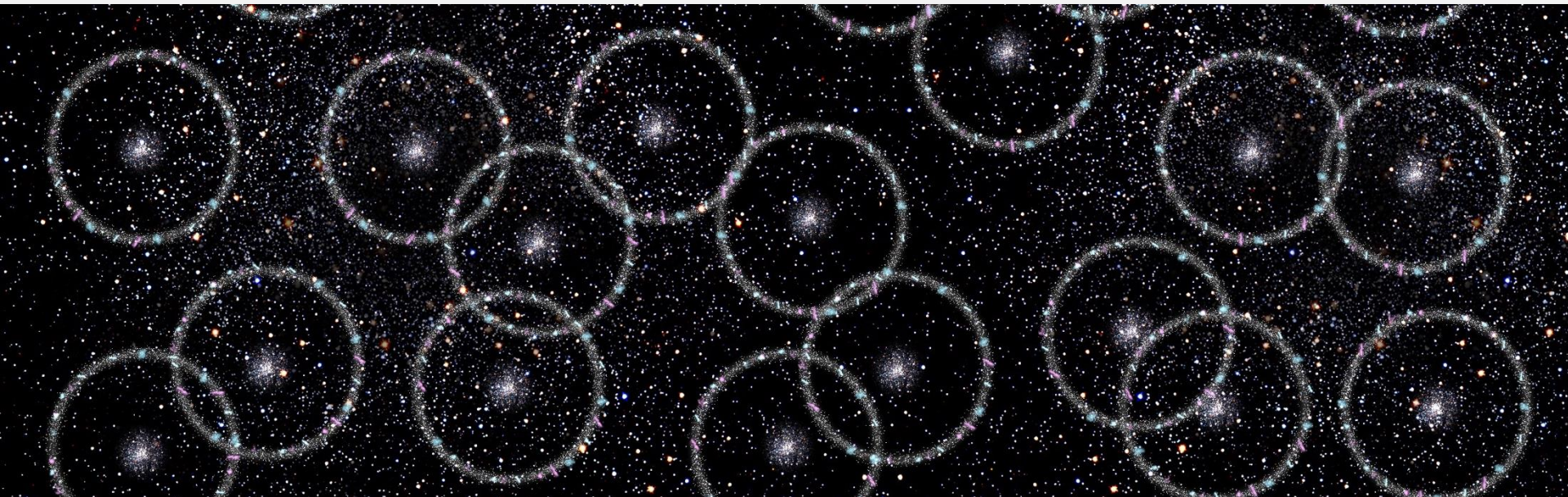


Cosmology with large-scale spectroscopic surveys

Cullan Howlett

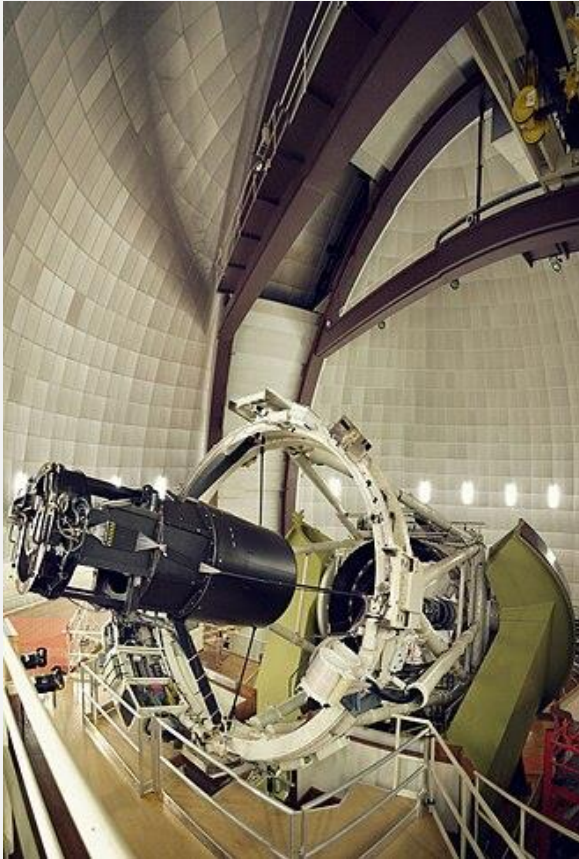
Senior Lecturer, University of Queensland



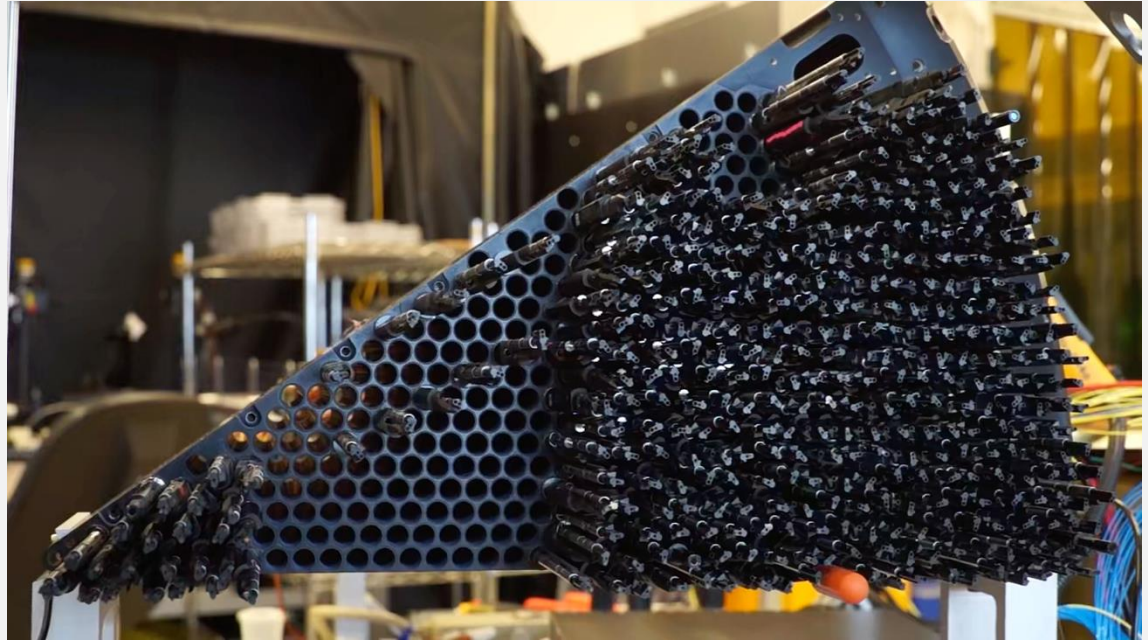
Galaxy surveys are perhaps the most promising modern way of pinning down the precise nature of the cosmos. There's a real possibility that we'll ~finish mapping the Universe in our lifetimes.

- How spectroscopic galaxy surveys constrain cosmology and particle physics
- Current constraints
- Future outlook

Spectroscopic galaxy surveys



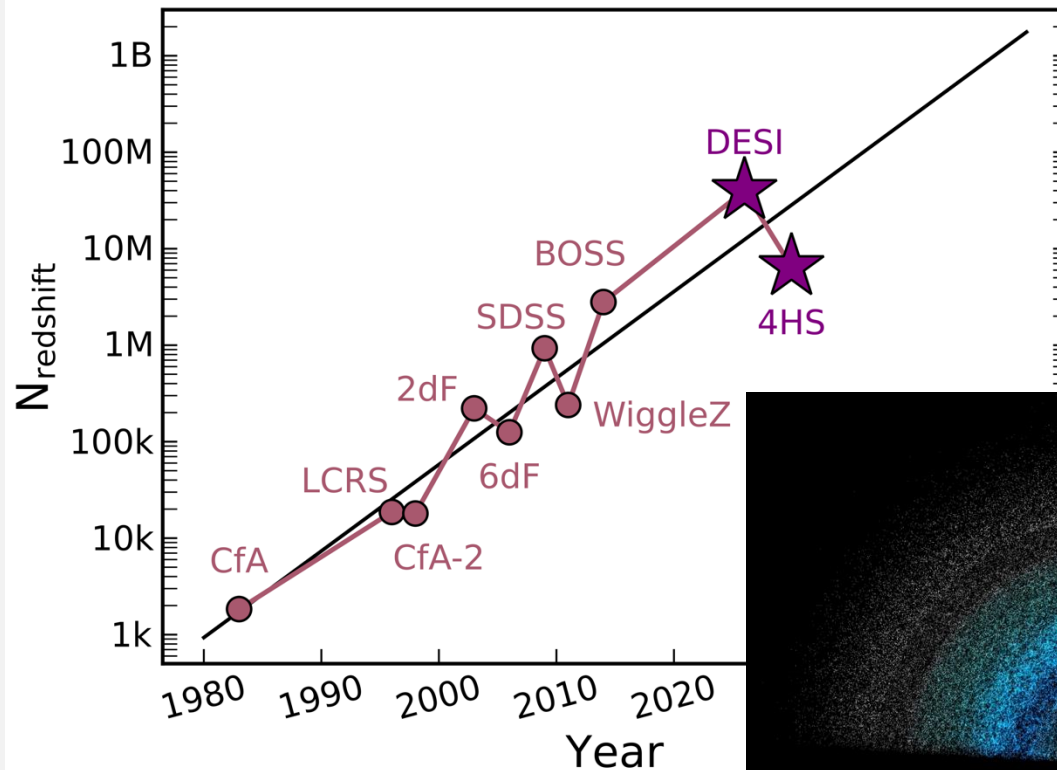
Credit: Ahilan Parameswaran



Credit: Michael Schubnell

Statistical analysis of the large-scale structure of the Universe – mapped via galaxy redshifts – provides a huge amount of cosmological information

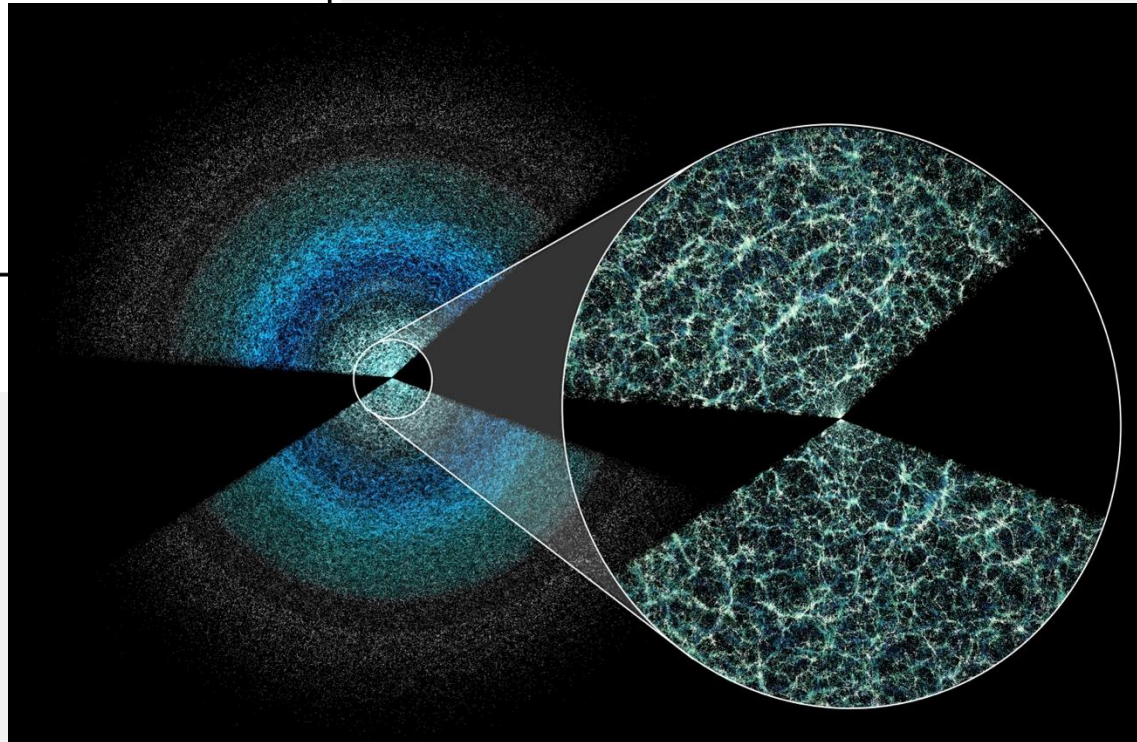
Spectroscopic galaxy surveys



Current state of the art surveys measure 10s of millions of redshifts

Credit: Claire Lamman/DESI Collaboration

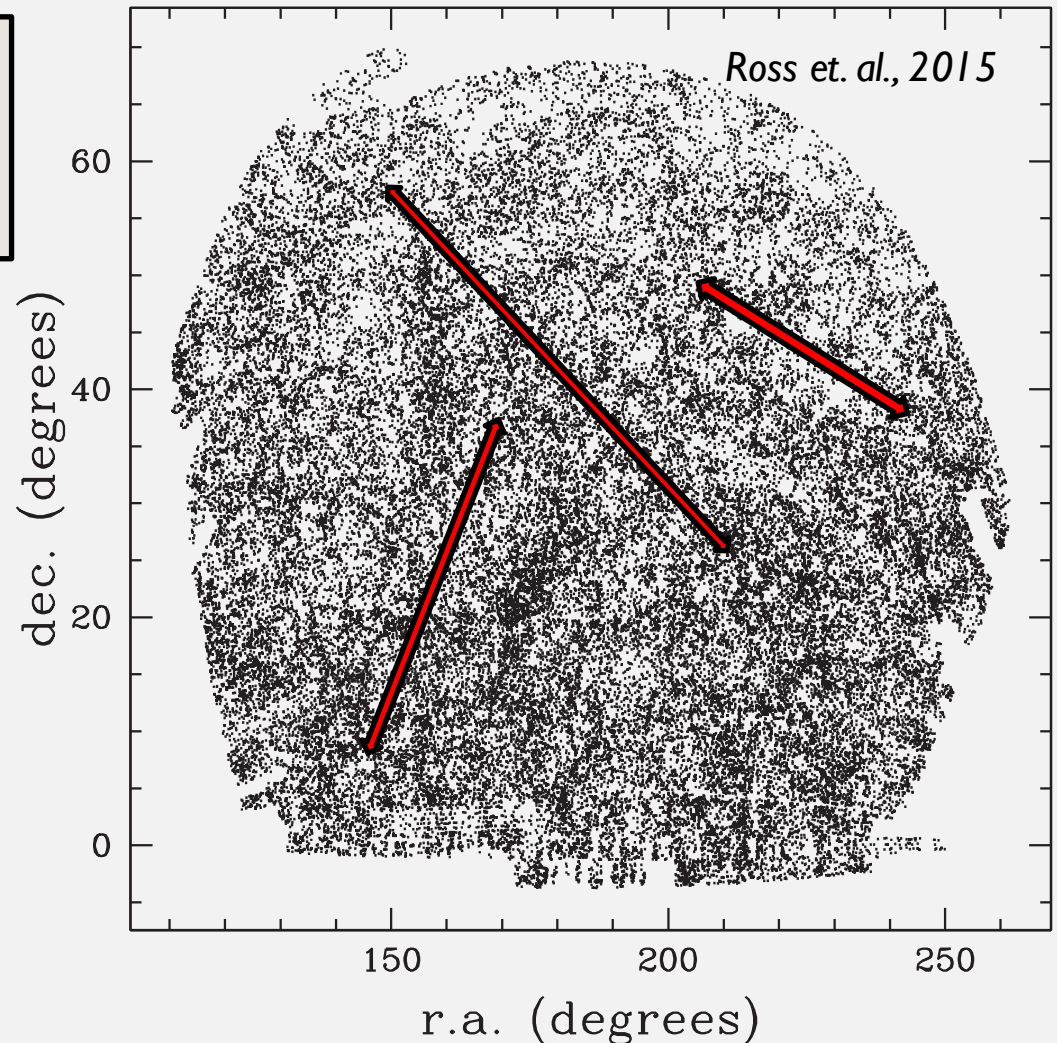
The most advanced (timeline) is the Dark Energy Spectroscopic Instrument (DESI)



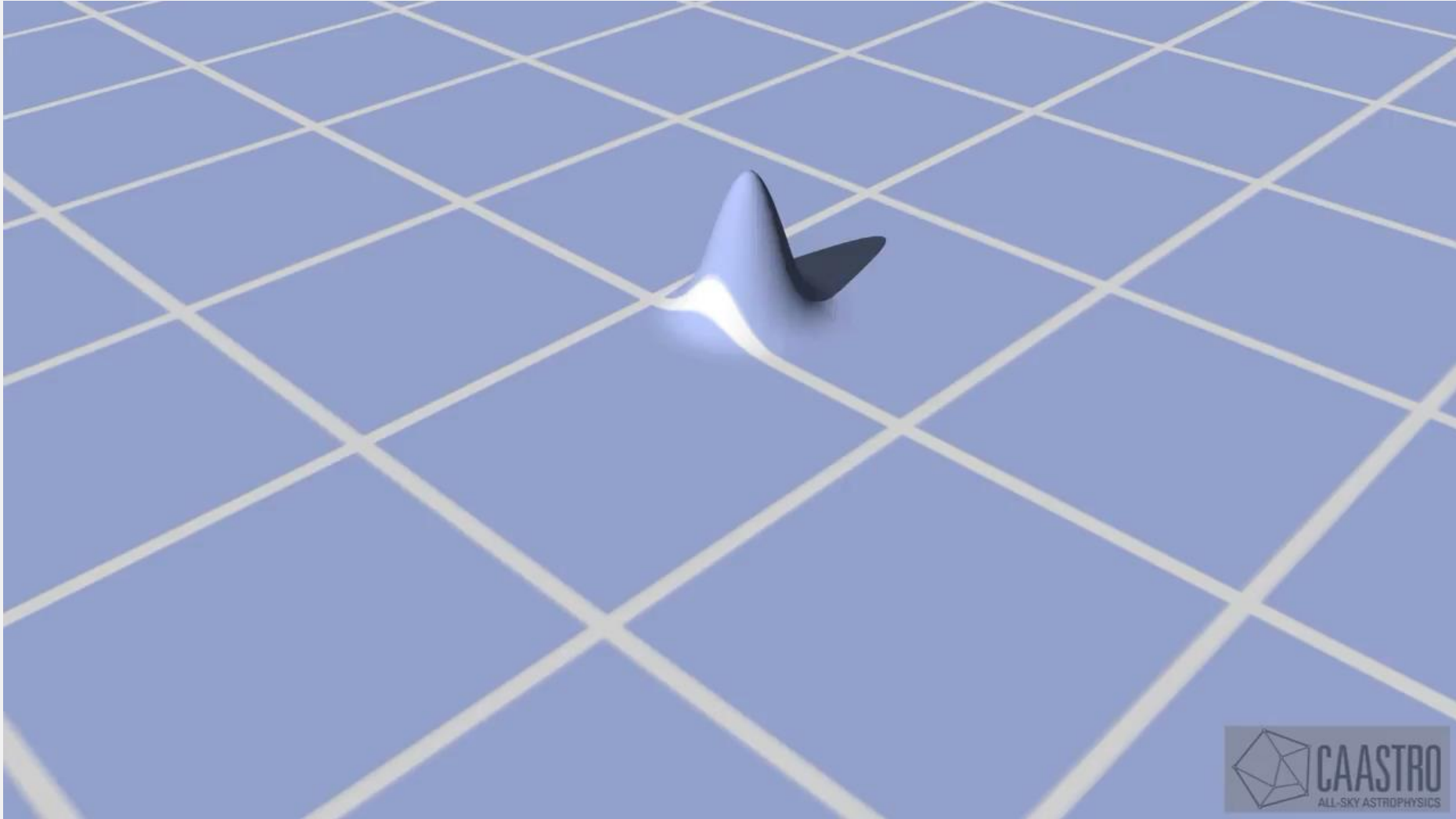
Galaxy clustering

One of our simplest but most useful tools is the two-point correlation function.

This describes the probability, above random, of finding two galaxies separated by some distance and can be theoretically modelled for different cosmologies

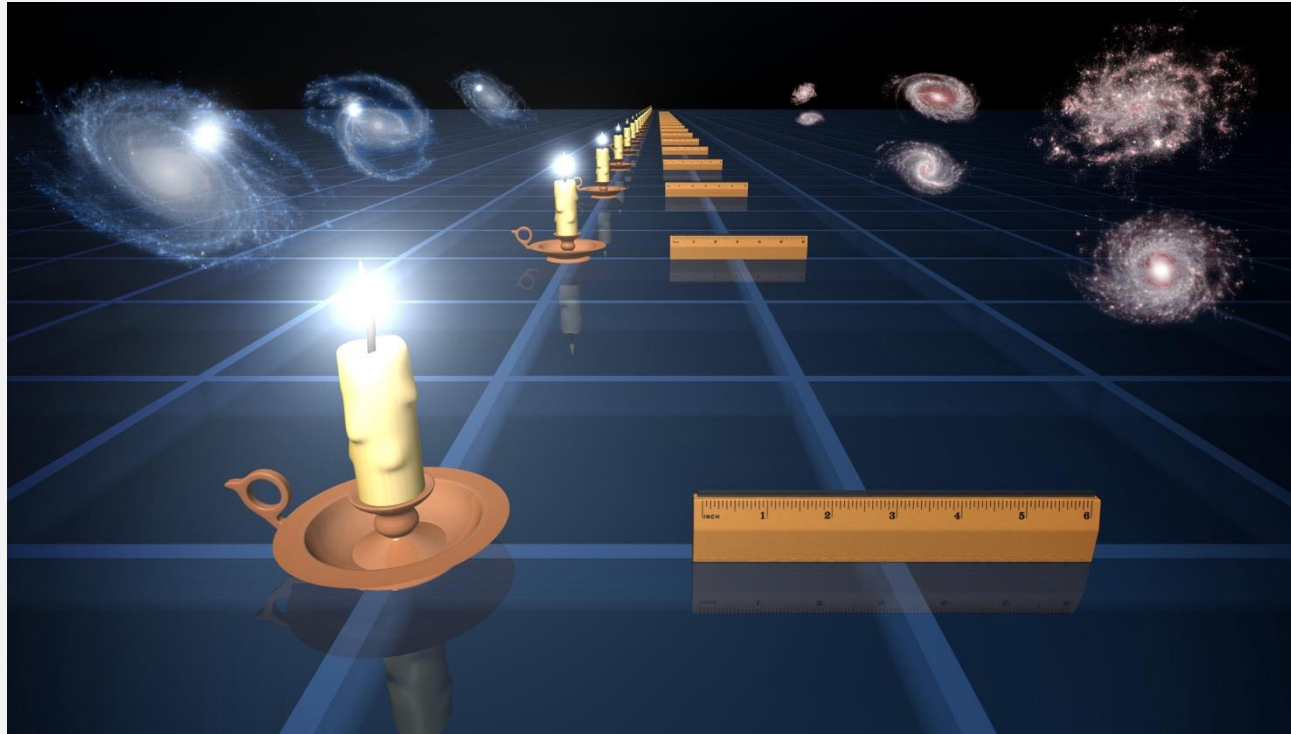


Galaxy clustering



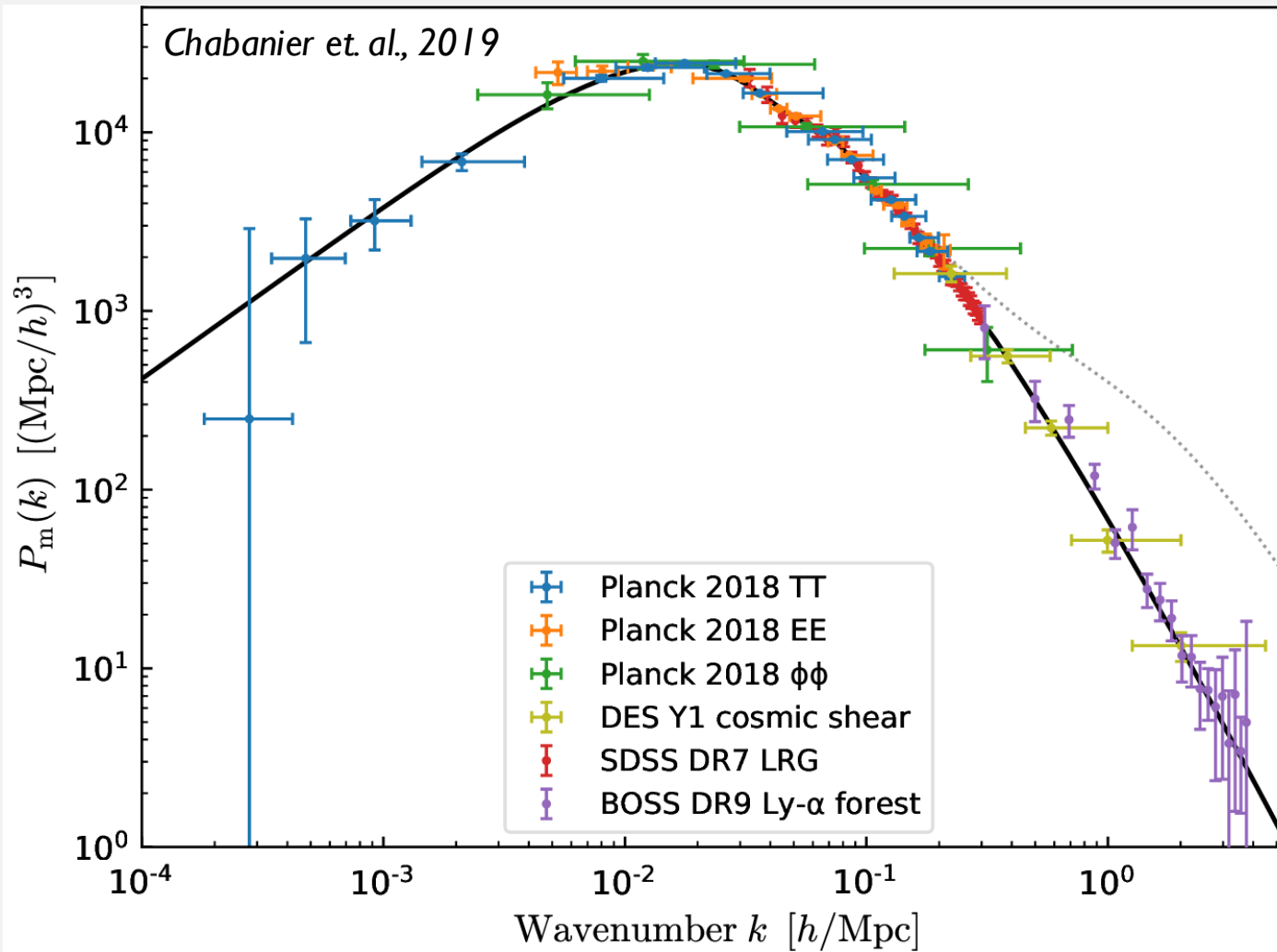
Baryon Acoustic Oscillations

Because we expect the BAO to be fixed since the early Universe, they act as ‘standard rulers’



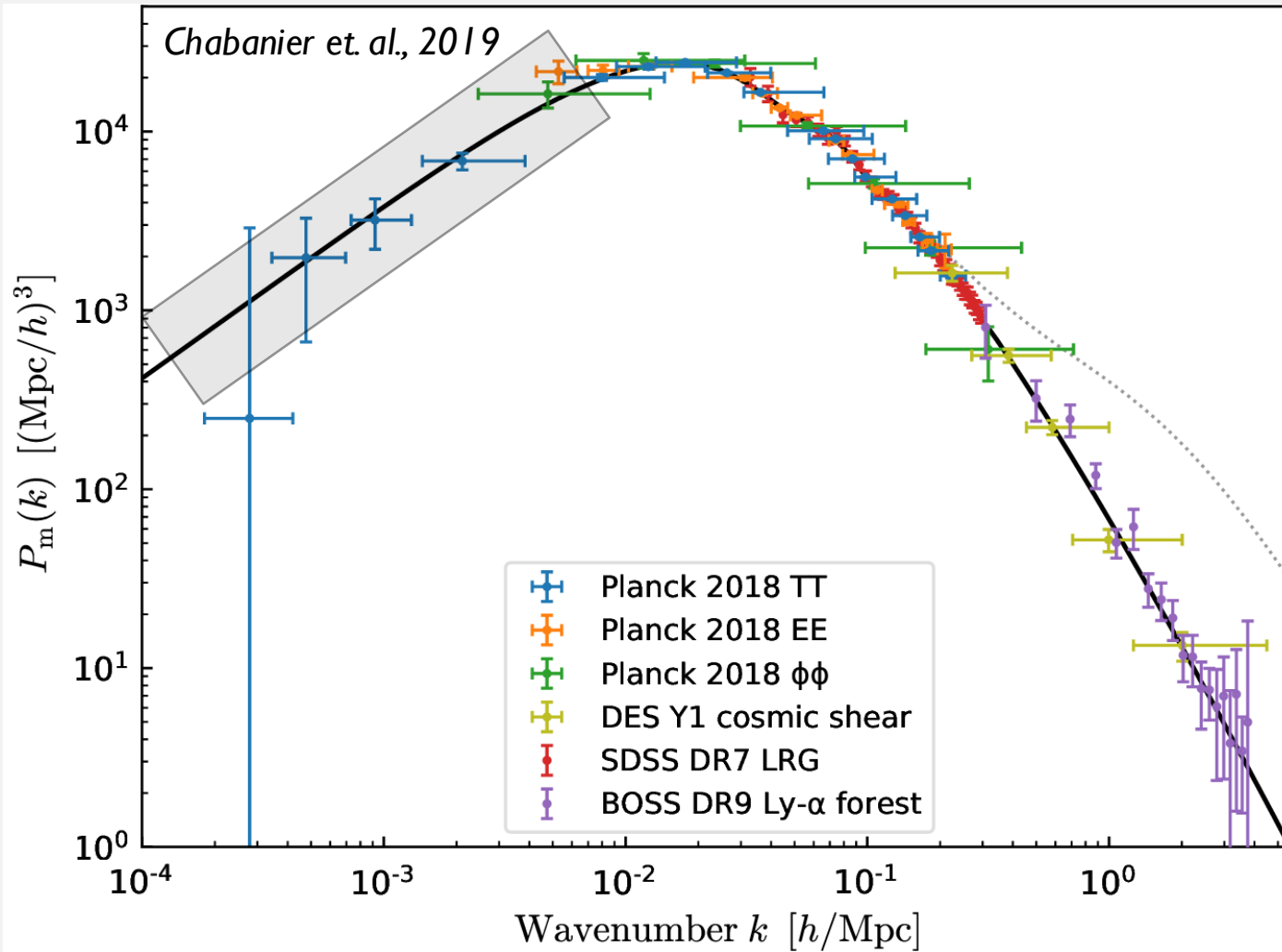
They are great for measuring distance ratios. For absolute distances we need their intrinsic size (r_d)

Beyond BAO



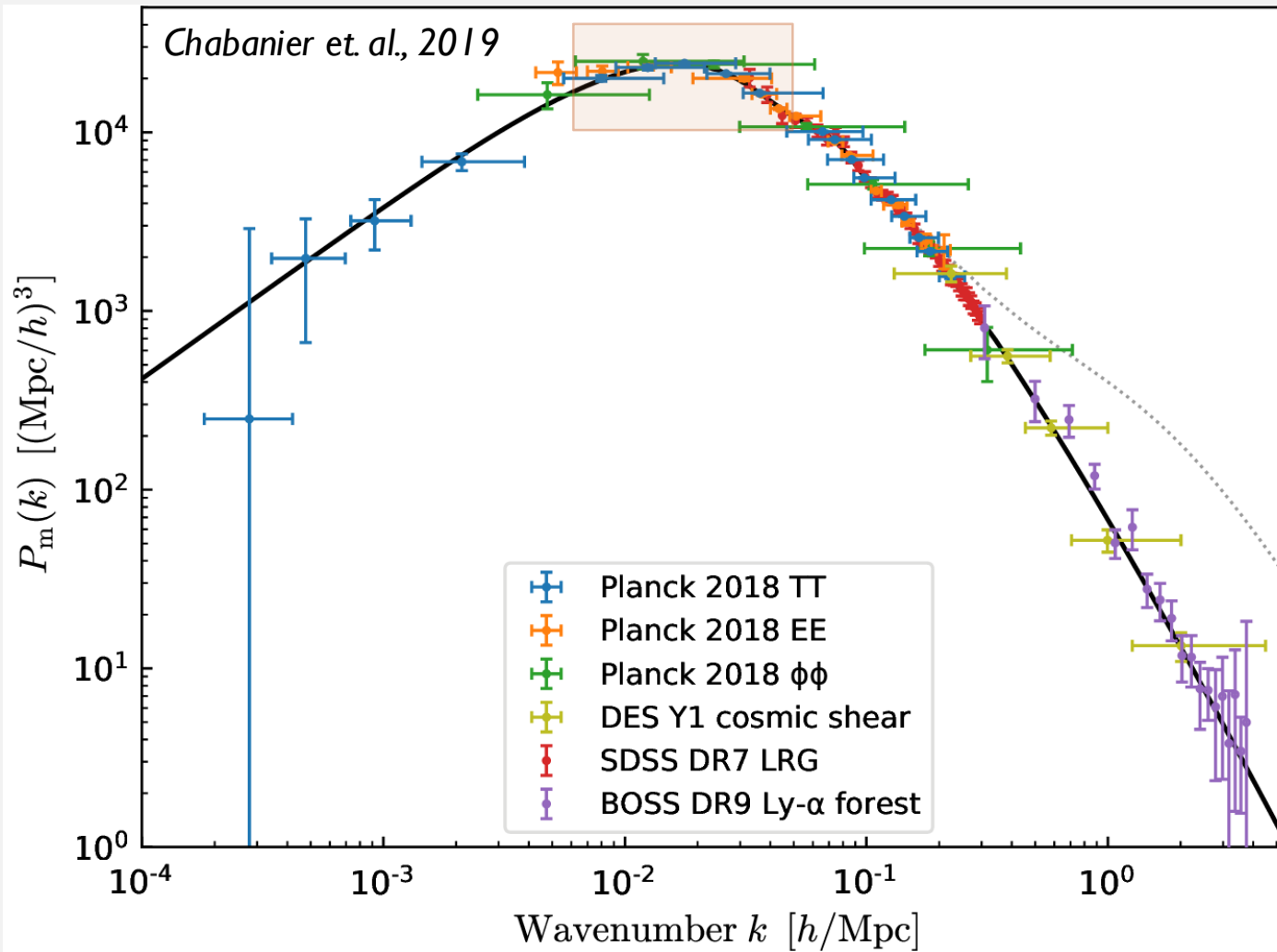
“Full-modelling”
of the power
spectrum
contains a huge
amount more
information.

Beyond BAO



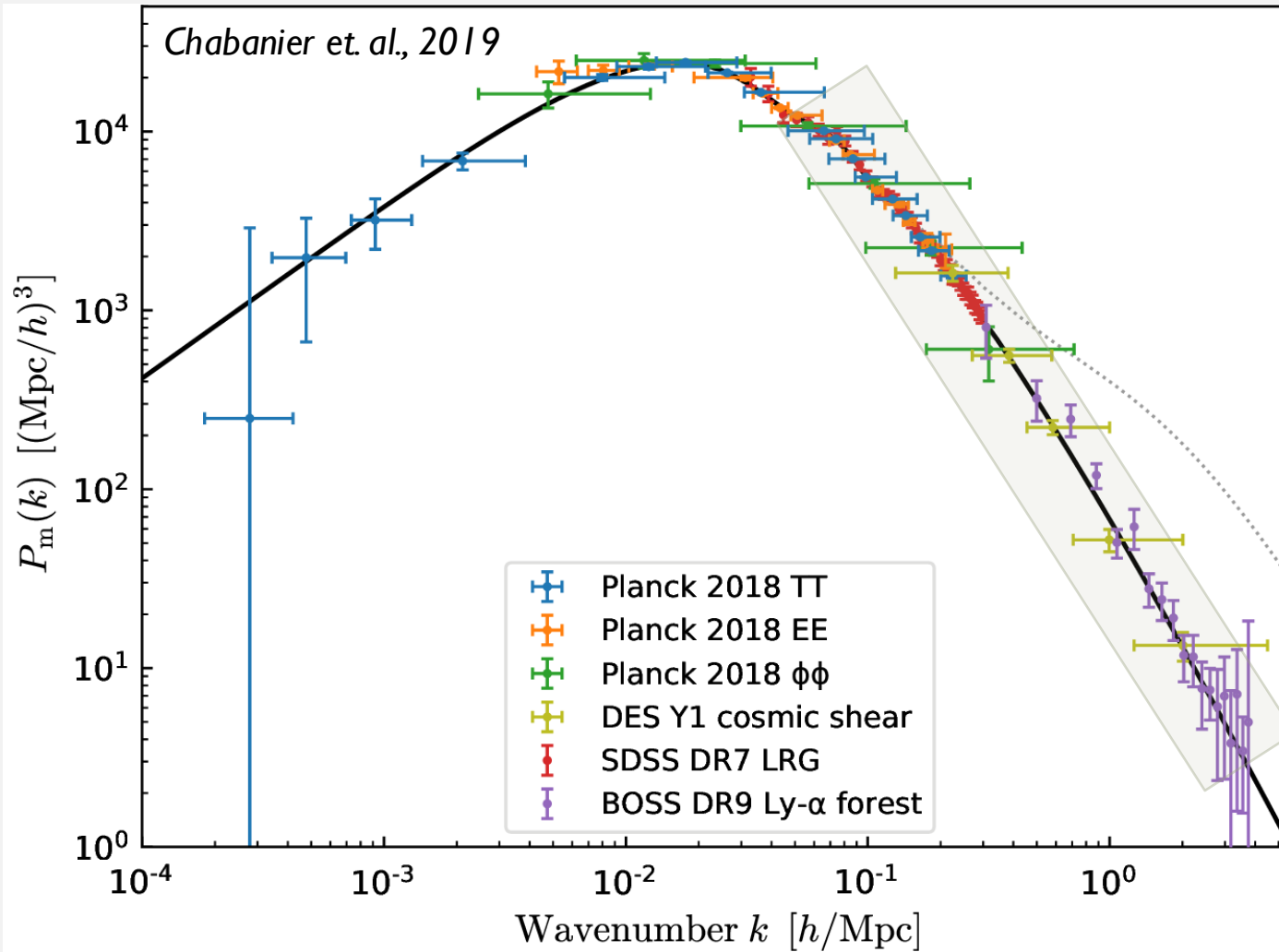
The large-scale modes tell us about inflation.

Beyond BAO



The turnover scale is another standard ruler, given by the size of the Universe at matter-radiation equality.

Beyond BAO



The amplitude of the BAO and the slope tell us the relative abundance of baryons to dark matter

Also baryonic physics, neutrinos and thermal dark matter properties

Redshift Space Distortions



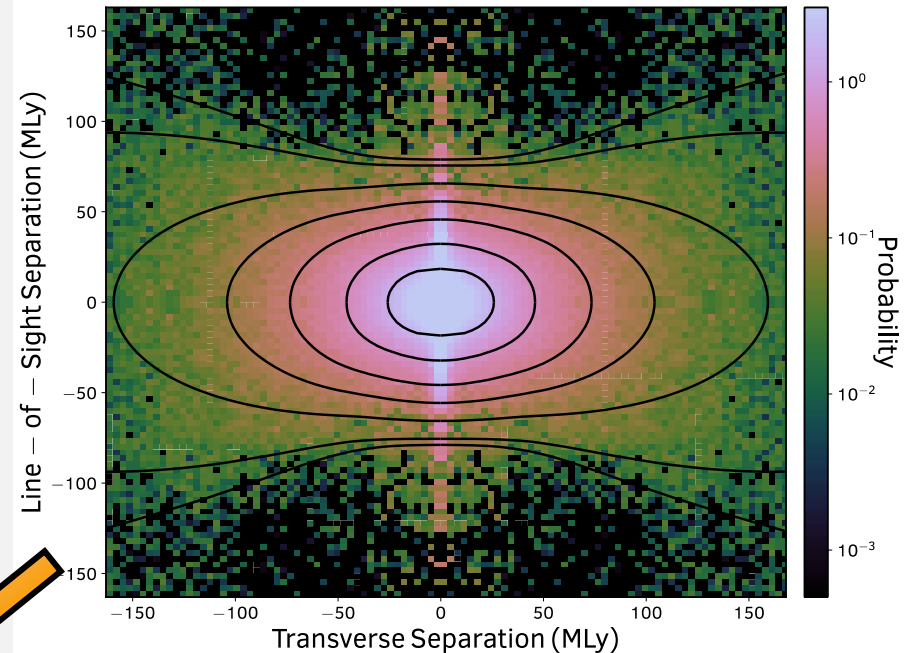
Contaminant

$$(1 + \boxed{z}) = (1 + \boxed{v/c})(1 + \boxed{\bar{z}})$$

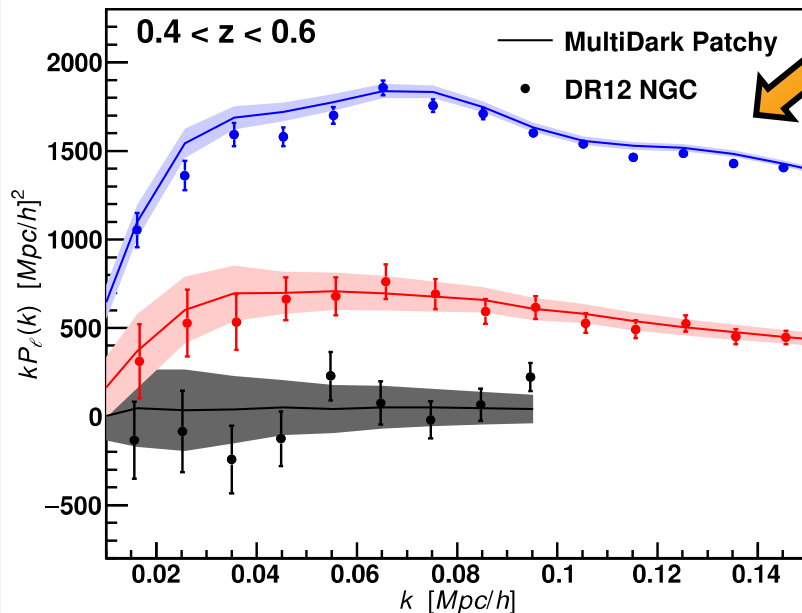
Galaxy positions
inferred from this

This should
be isotropic

Furthermore, the clustering of
inferred galaxy positions depends
on the angle to the line of sight



Howlett et. al., 2015



Fourier transform and
compress based on
angle to line of sight.

Beutler et. al., 2017

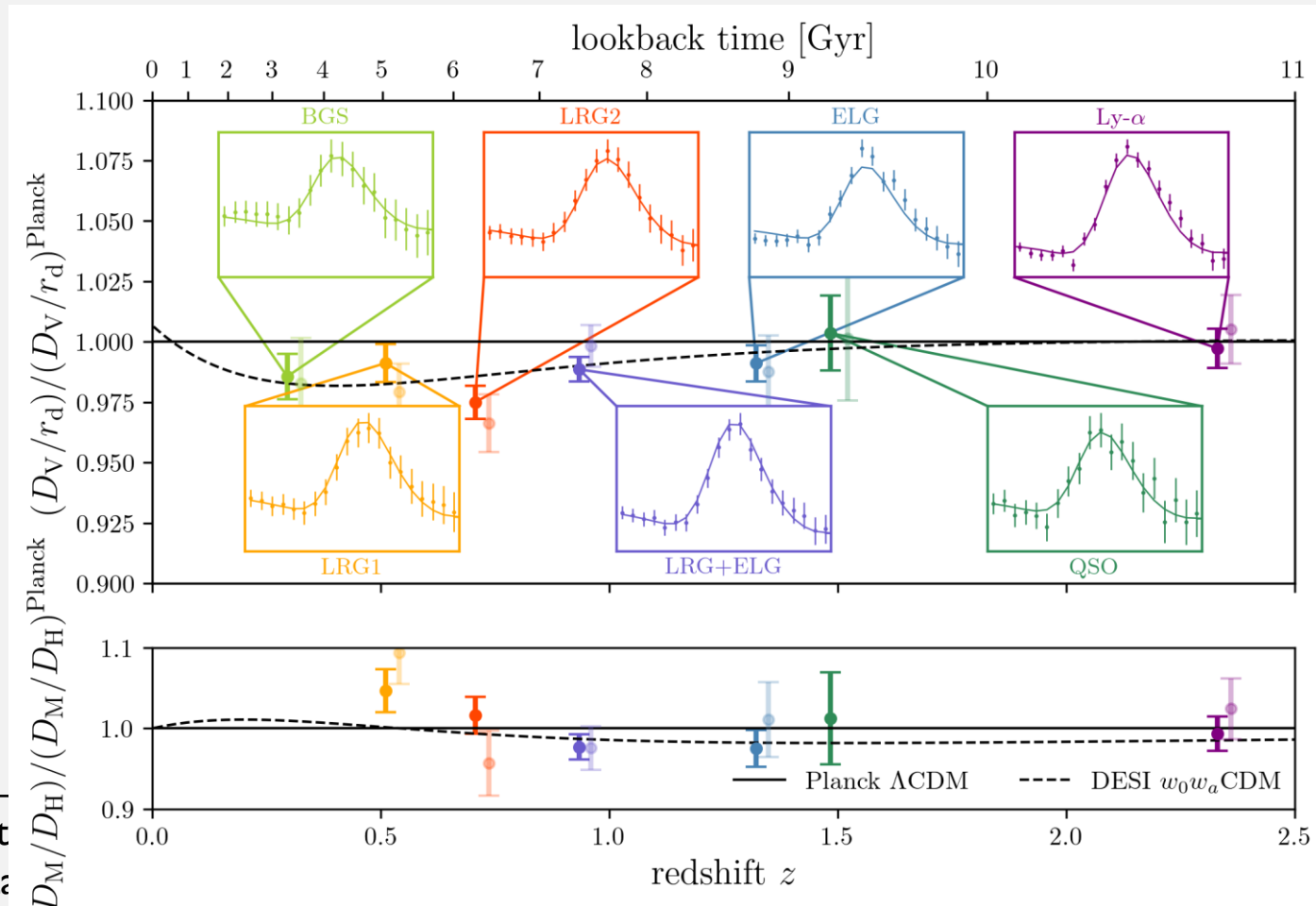
Dark Energy Constraints



A key unknown in cosmology is the equation of state of Dark Energy.

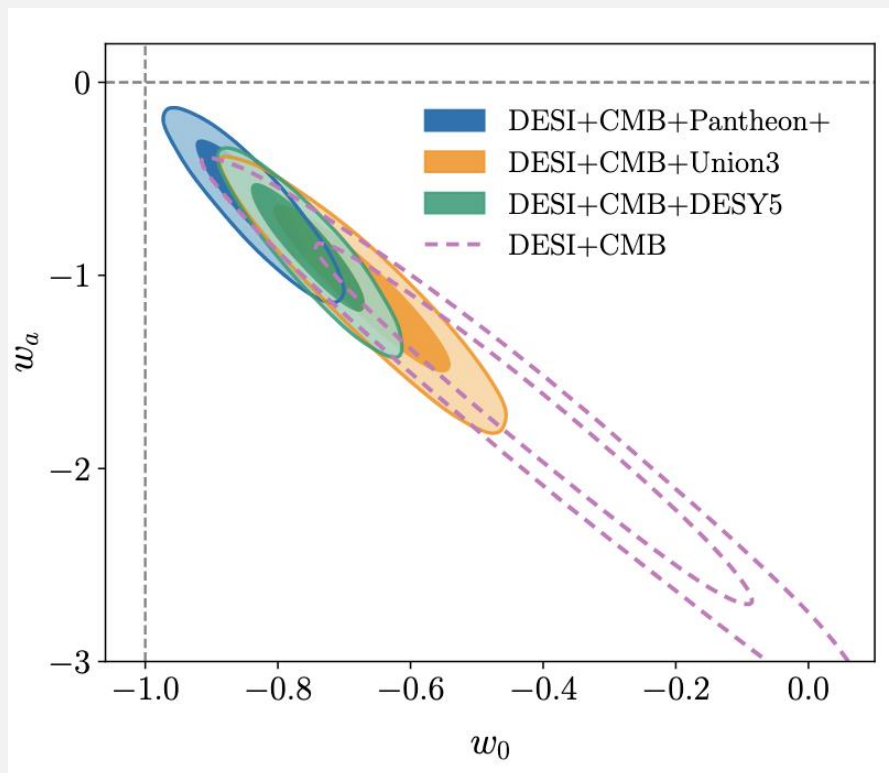
The simplest models have this as a Cosmological Constant (Λ).

DESI+CMB
+Type Ia
supernovae
hint at time
varying dark
energy

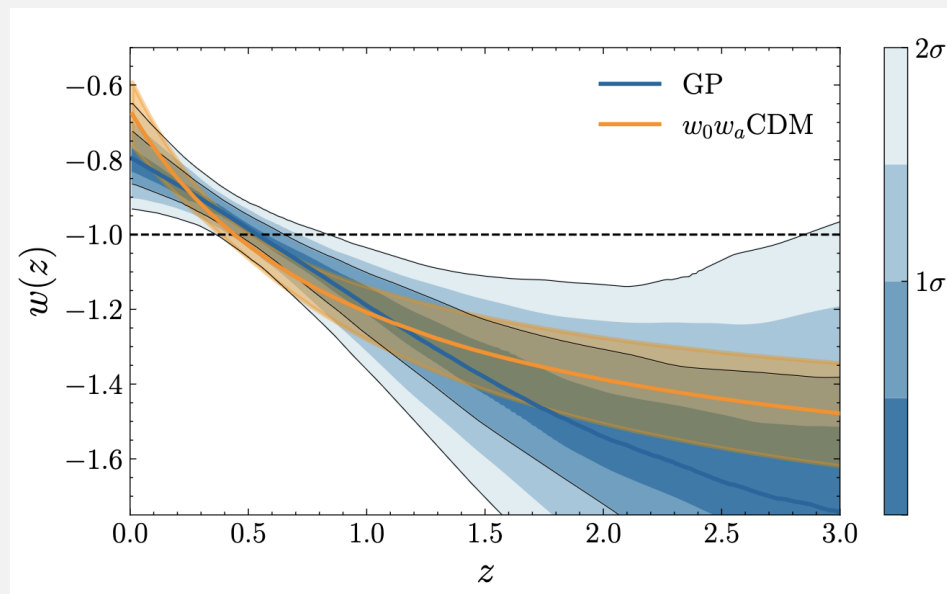


Dark Energy Constraints

DESI Collaboration 2025



Lodha et al., 2025

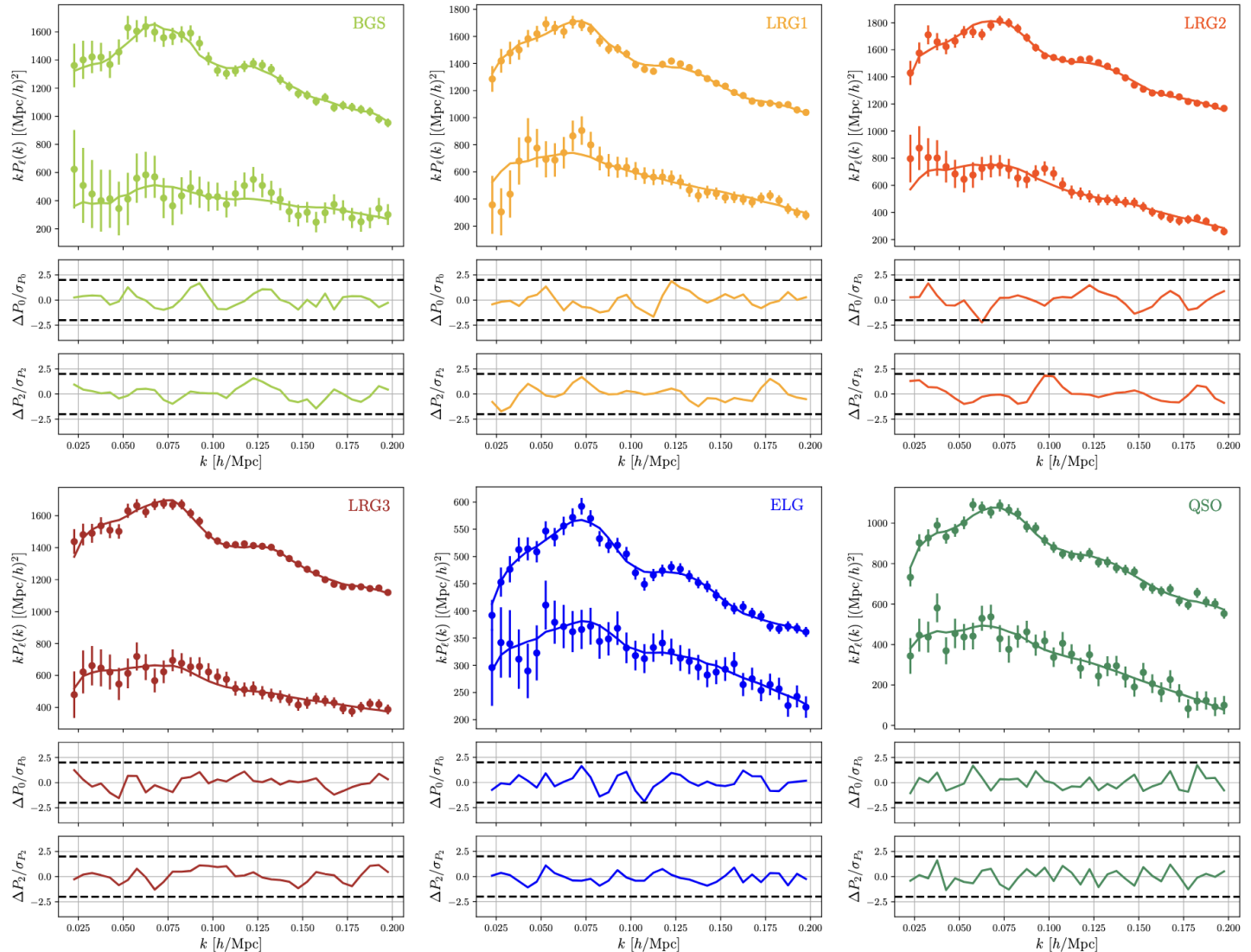


The preference for linearly time-varying Dark Energy over a cosmological constant is $2.8 - 4.2\sigma$

Tests of General Relativity

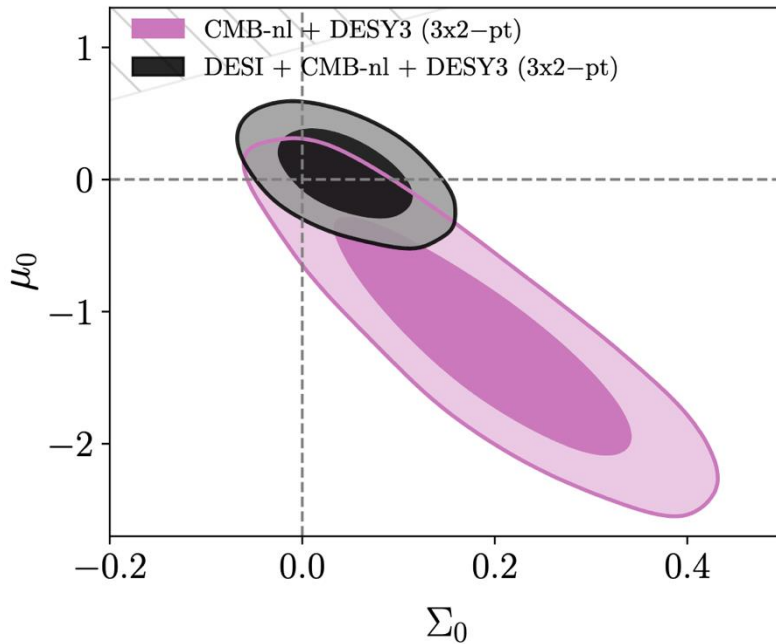


DESI Collaboration 2024V



For more information, we can fit the full-shape of the clustering over cosmic history

Tests of General Relativity

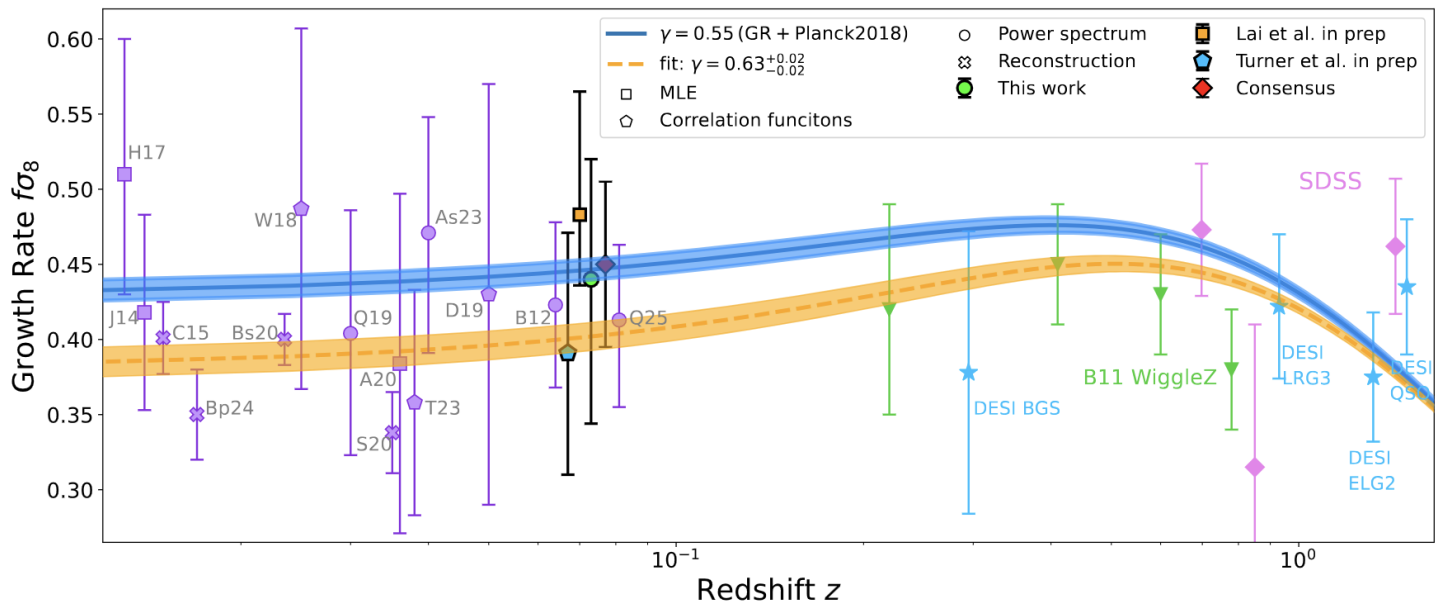


Full-modelling DE results
consistent with BAO-only

No serious indication of
anything beyond GR...yet

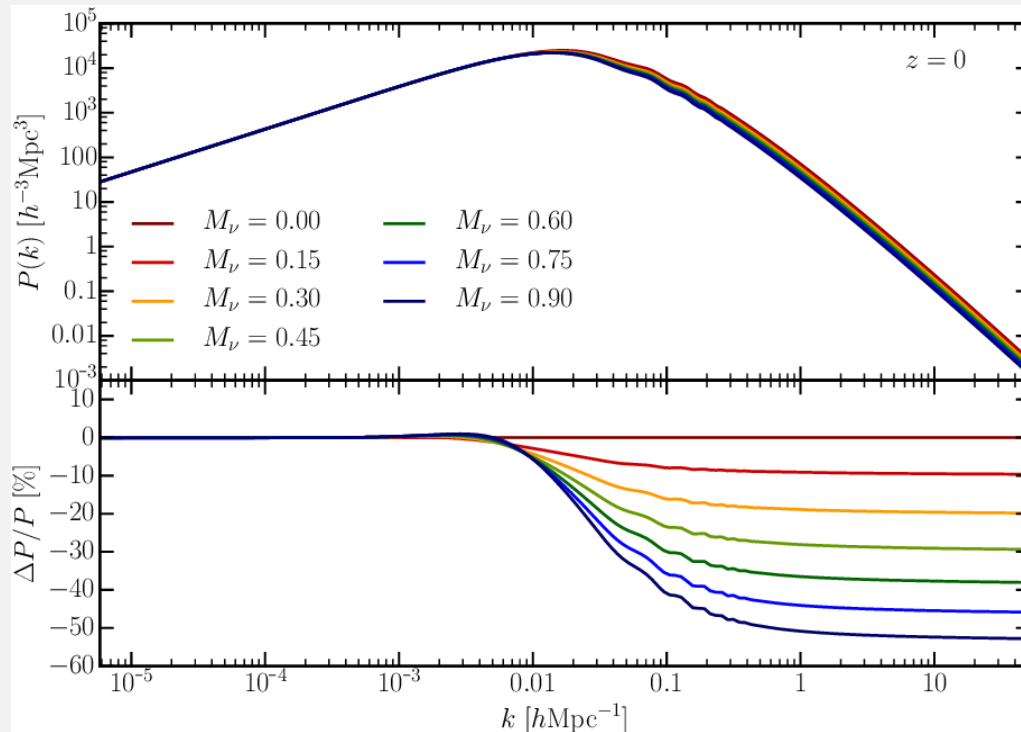
DESI 2024 VII

Qin et al., 2026



Neutrinos - Masses

Neutrinos act as a form of warm dark matter and suppress the growth of small scale structures.

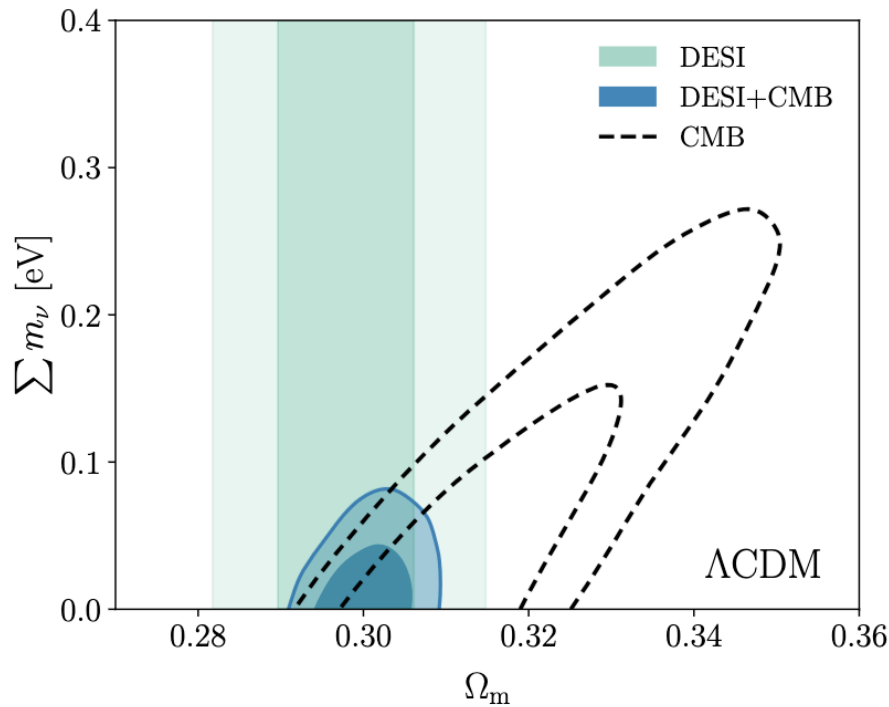


However, most current information doesn't come from this scale dependence but instead comes from their impact on the expansion history

$$\Omega_r(z_{\text{cmb}}) \rightarrow \Omega_m(z_0)$$

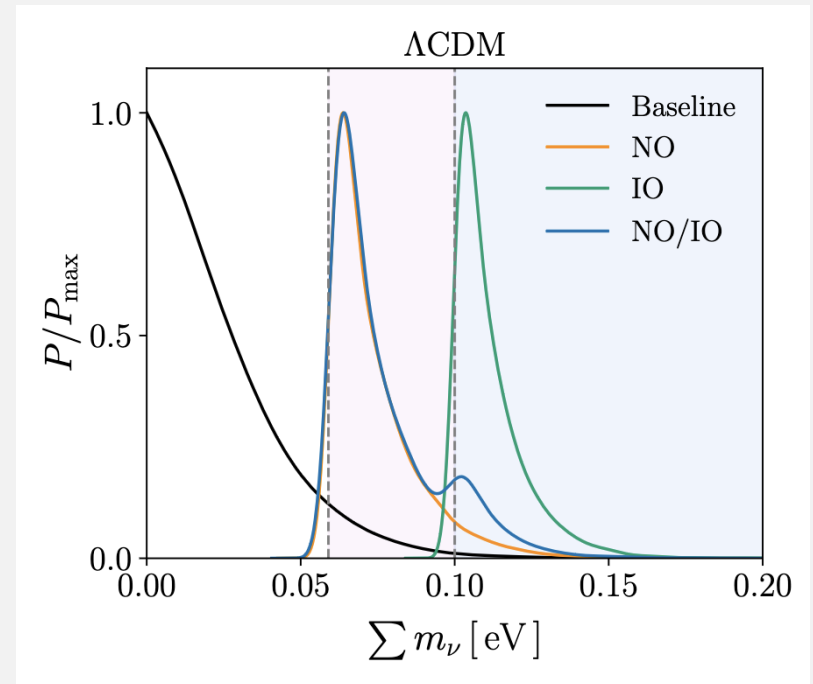
Neutrinos - Masses

At first glance, the latest DESI constraints prefer the normal hierarchy (or even no neutrinos!)



DESI Collaboration 2025

Cullan Howlett, University of Queensland
Cosmology with large-scale spectroscopic surveys



Elbers et al., 2025

But this is mostly driven by small differences in the preferred matter densities between datasets.

Particle Physics and Cosmology 2026 @ UNSW
3rd September 2026

Neutrinos – N_{eff}

Different numbers of relativistic species also change the evolution of the BAO and small-scales

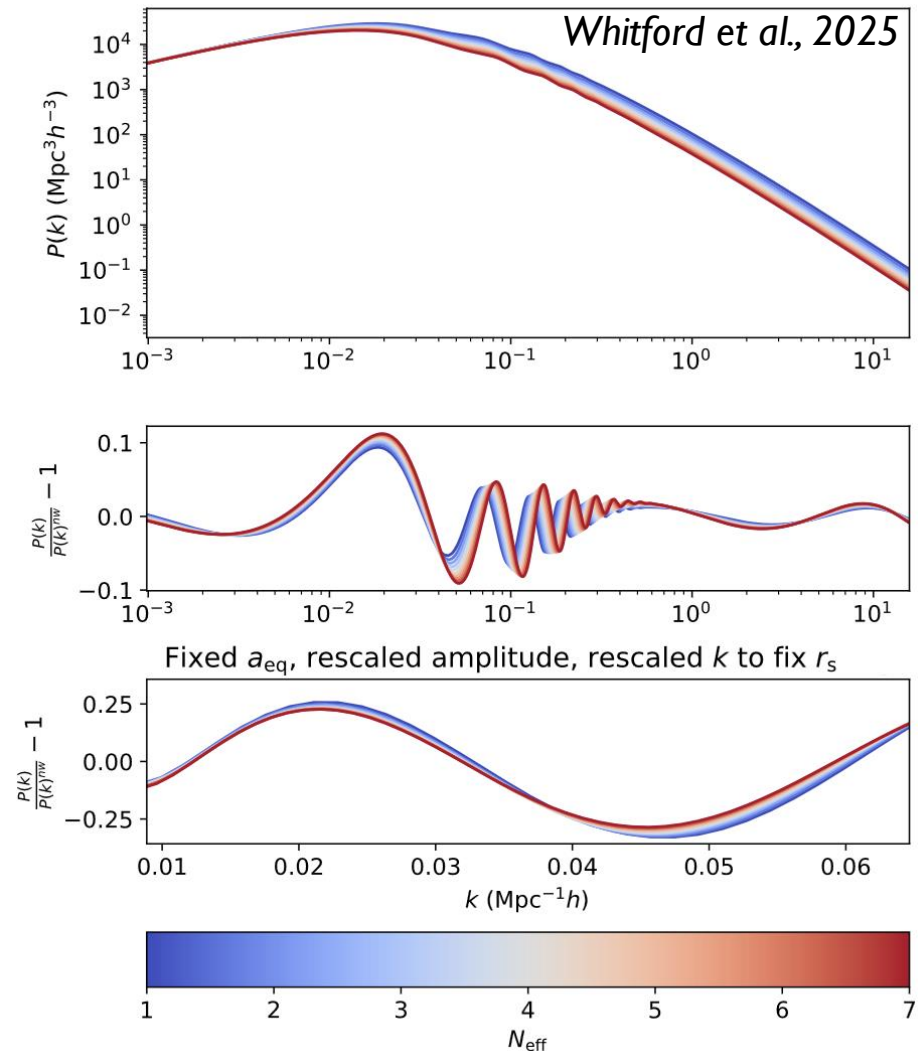
(Elbers et al., 2025)

DESI DR2 BAO + CMB:

$$\begin{cases} \sum m_\nu < 0.0741 \text{ eV} \\ N_{\text{eff}} = 3.16^{+0.34}_{-0.33} \end{cases} \quad (95\%).$$

Neutrinos can also be seen as a phase-shift in the BAO

Detected at $\sim 3\sigma$ in DESI data



Primordial non-Gaussianity

(local) primordial non-Gaussianity changes the tails of the PDF of density fluctuations which then changes the abundance of massive halos

This adds scale-dependence to large-scale galaxy clustering

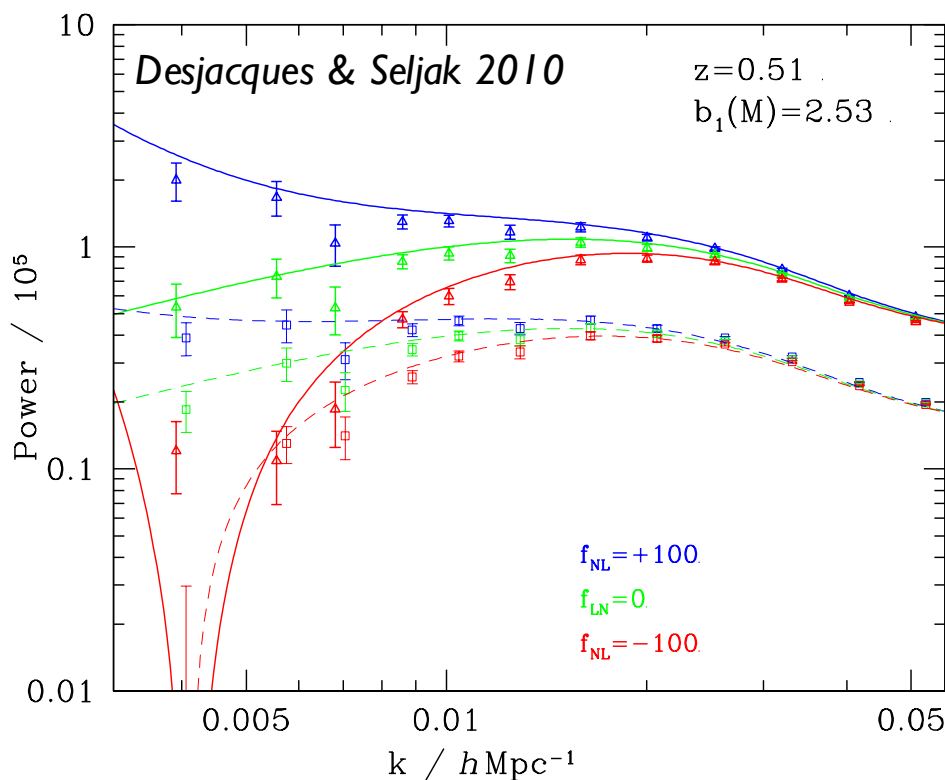
Clustering constraints are comparable to CMB

Planck DR4 (Jung et al., 2025)

$$f_{\text{NL}}^{\text{loc}} = -0.1 \pm 5.0$$

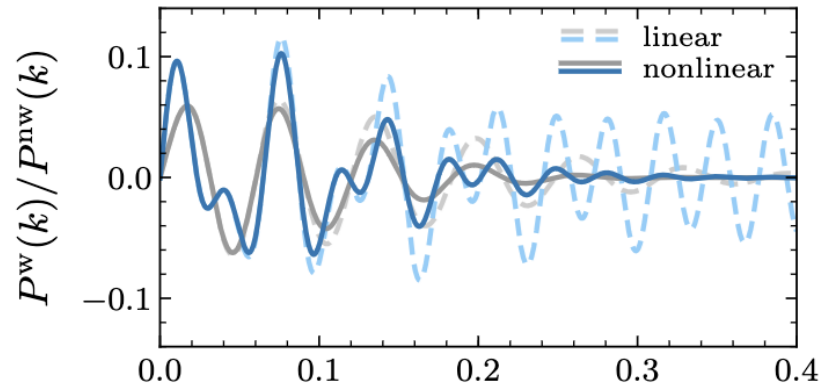
DESI DRI (Chaussidon et al., 2025)

$$f_{\text{NL}}^{\text{loc}} = -3.6_{-9.1}^{+9.0}$$

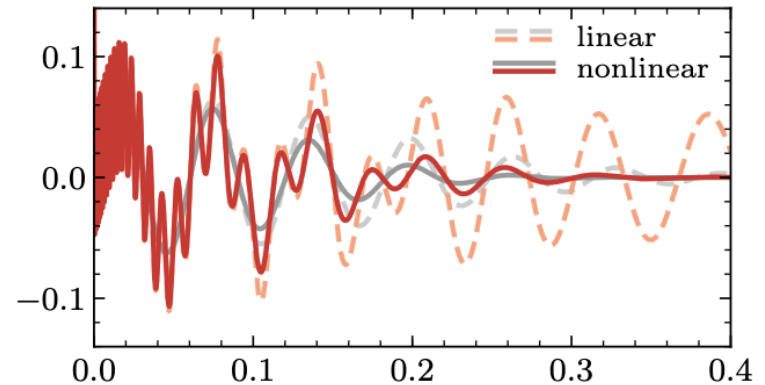


Primordial oscillatory features

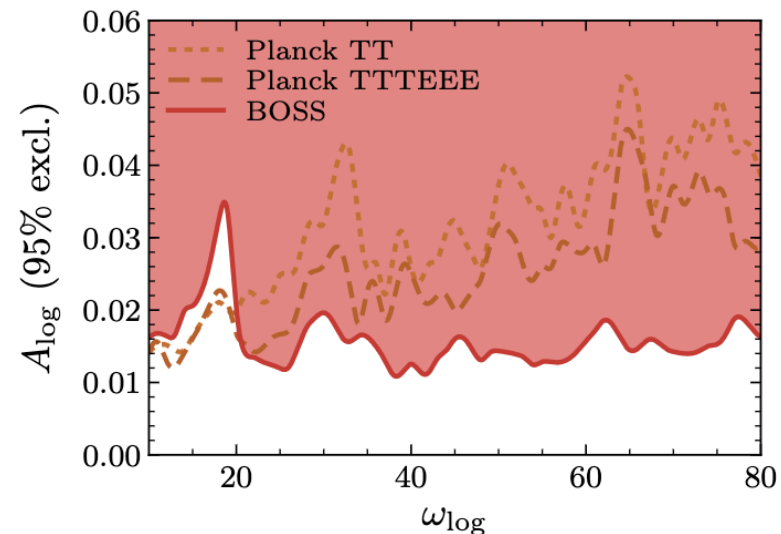
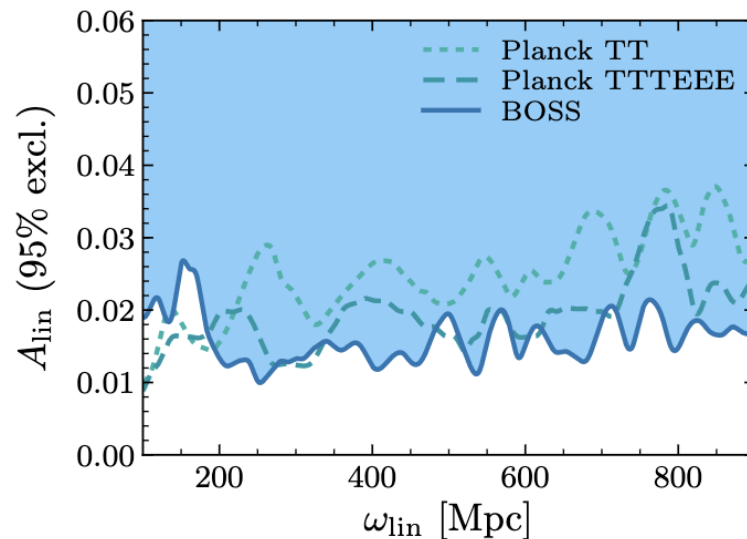
Different inflation models can give rise to oscillatory features in the primordial spectrum that can be constrained in clustering akin to BAO



Beutler et al., 2019 $k [h \text{ Mpc}^{-1}]$

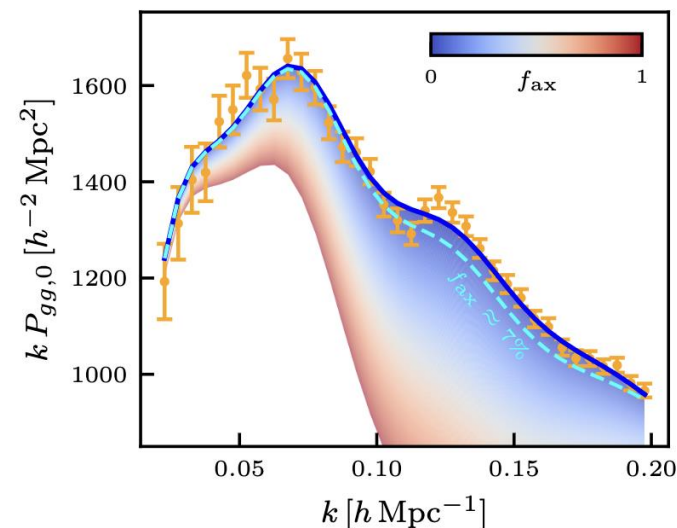
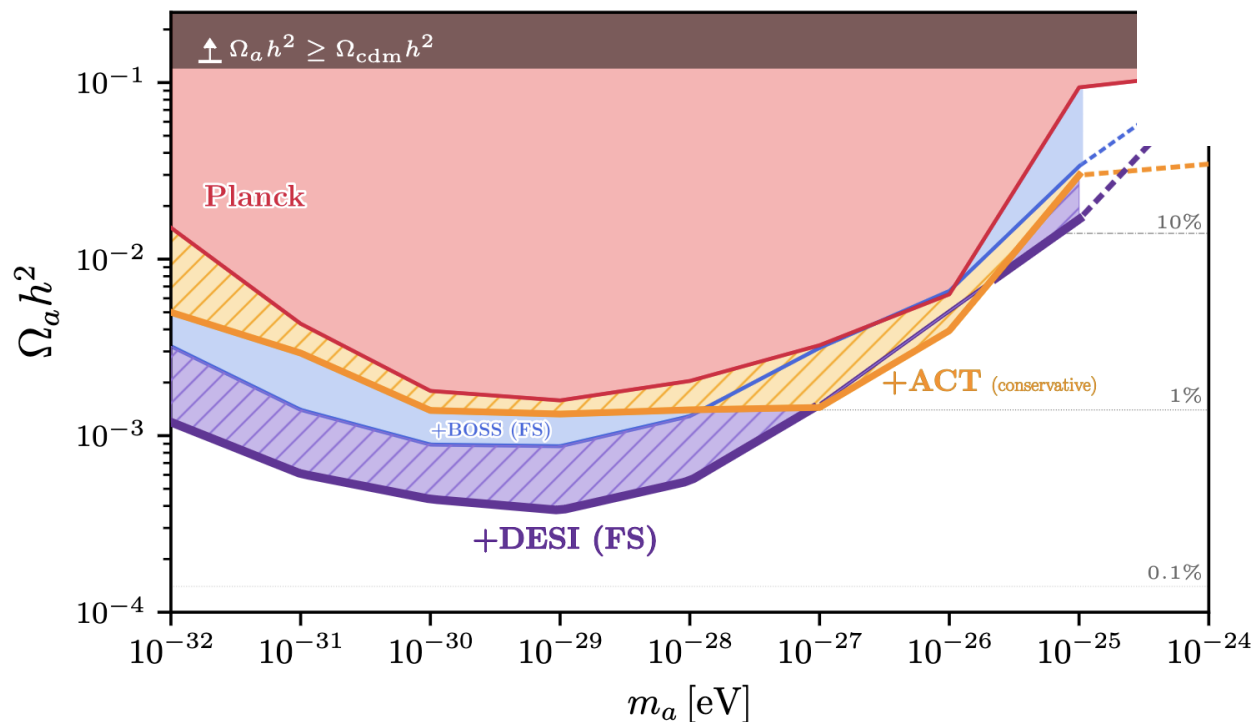


$k [h \text{ Mpc}^{-1}]$



Warm DM and ultra-light axions

ULAs and other DM candidates can modify the non-linear galaxy power spectrum



Verdiani et al., 2026

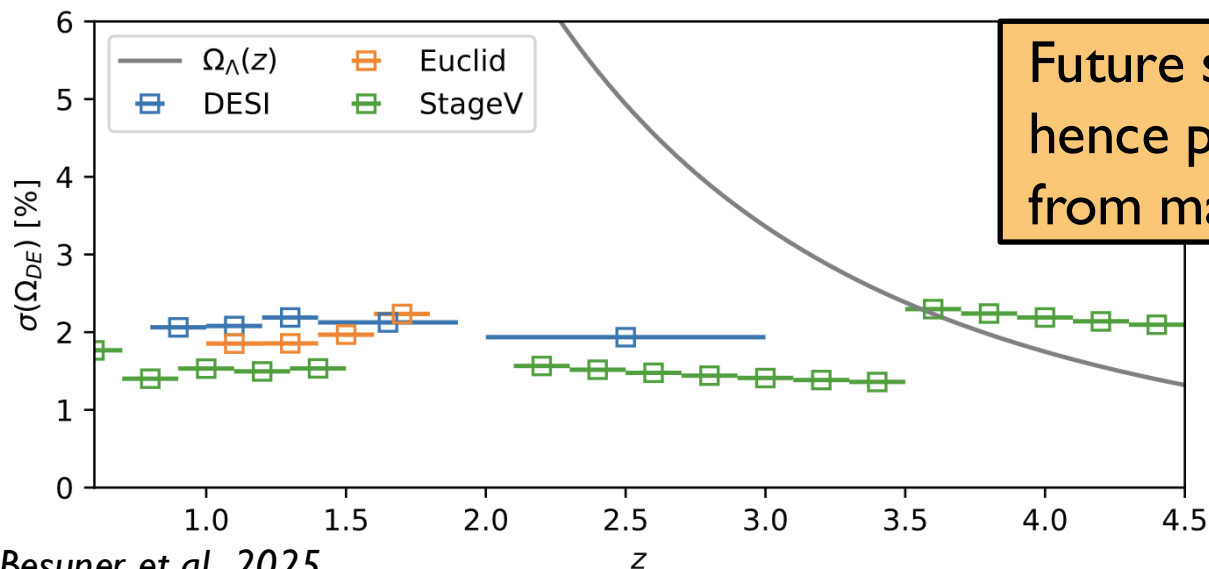
So what's next?

- DESI has completed its original 5-year plan
 - public Data Release 2 ~mid 2027
 - We are currently observing run-1b, with run-2 to start ~2029.
- Euclid expected to release first galaxy clustering results and data over the next 9 months.
- The 4-metre Multi Object Spectrograph (4MOST) starts main survey operations later this year.



The linear $z \leq 1.5$ universe will be almost cosmic variance limited after these surveys

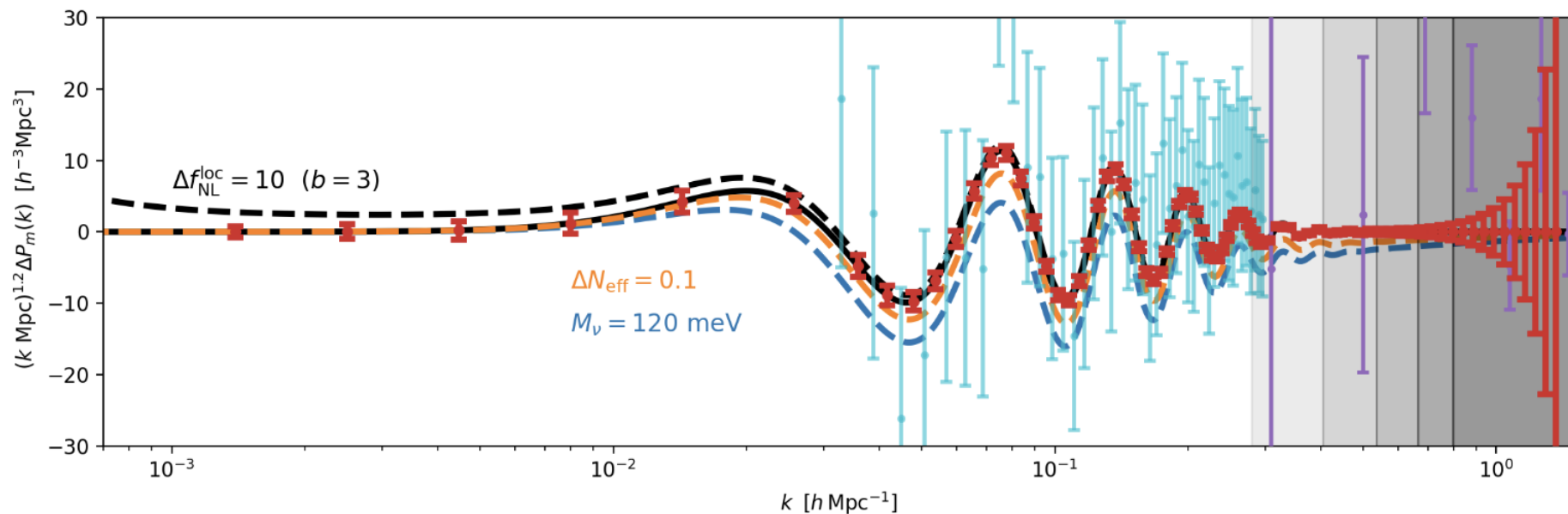
So what's next?



Future surveys (Stage V) will hence probe the high- z transition from matter to DE domination

And focus on non-linear physics, neutrinos and the primordial universe

Besuner et al., 2025



Conclusions

Galaxy surveys are perhaps the most promising modern way of pinning down the precise nature of the cosmos. There's a real possibility that we'll ~finish mapping the Universe in our lifetimes.

