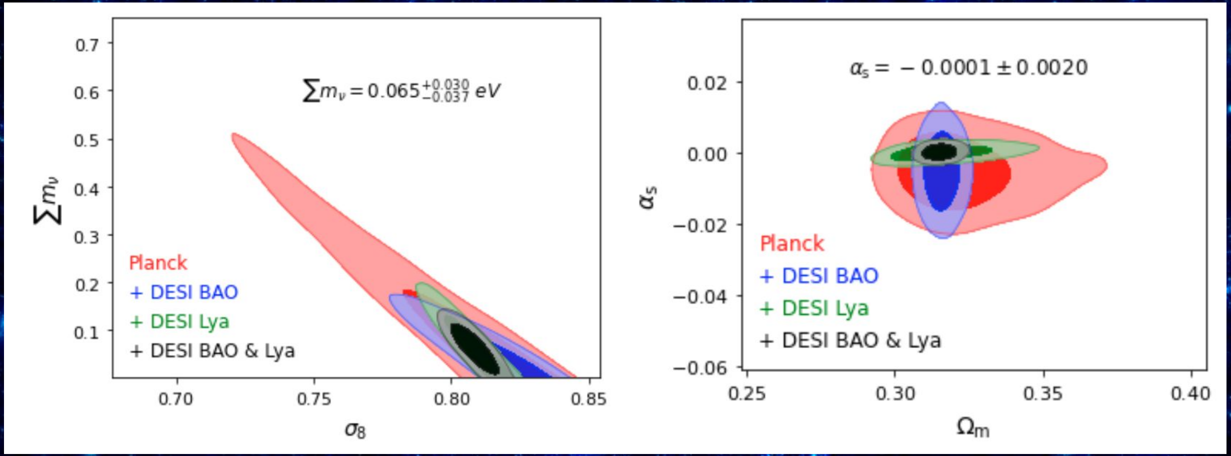
Cosmological interpretation of the Lyman-α forest

Chris Pedersen
New York University/Flatiron Institute
c.pedersen@nyu.edu

BCCP Cosmology seminar, 2nd Nov 2021

***Pedersen** et al. (2020), JCAP04(2020)025*
***Pedersen** et al. (2021), JCAP05(2021)033*

Cosmological interpretation of the Lyman-α forest



***Pedersen** et al. (2020), JCAP04(2020)025*
***Pedersen** et al. (2021), JCAP05(2021)033*

Talk outline

1. Overview of cosmology from Lyaf
2. Study into neutrino mass effects on Lyaf
3. Emulating the Lyaf using Gaussian processes
4. Ongoing work & outlook

Lyα forest

- Absorption features in the spectra of z>2 quasars, caused by the presence of neutral hydrogen

- Tracer of the matter distribution at 5>z>2, before the onset of dark energy

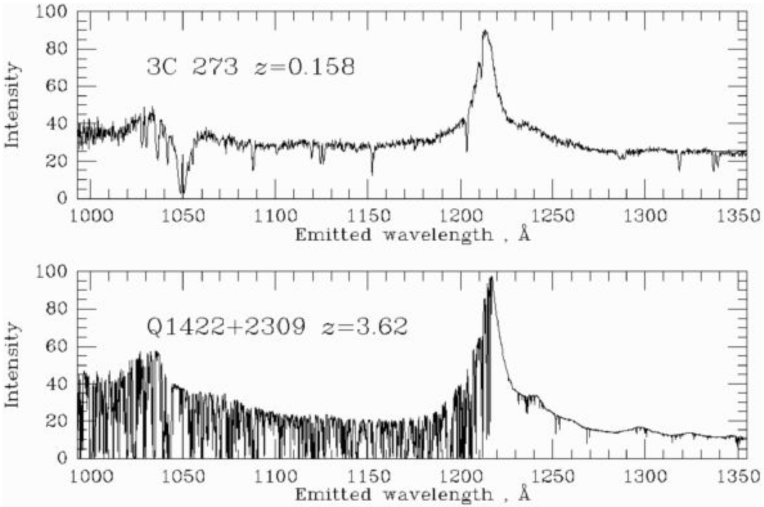
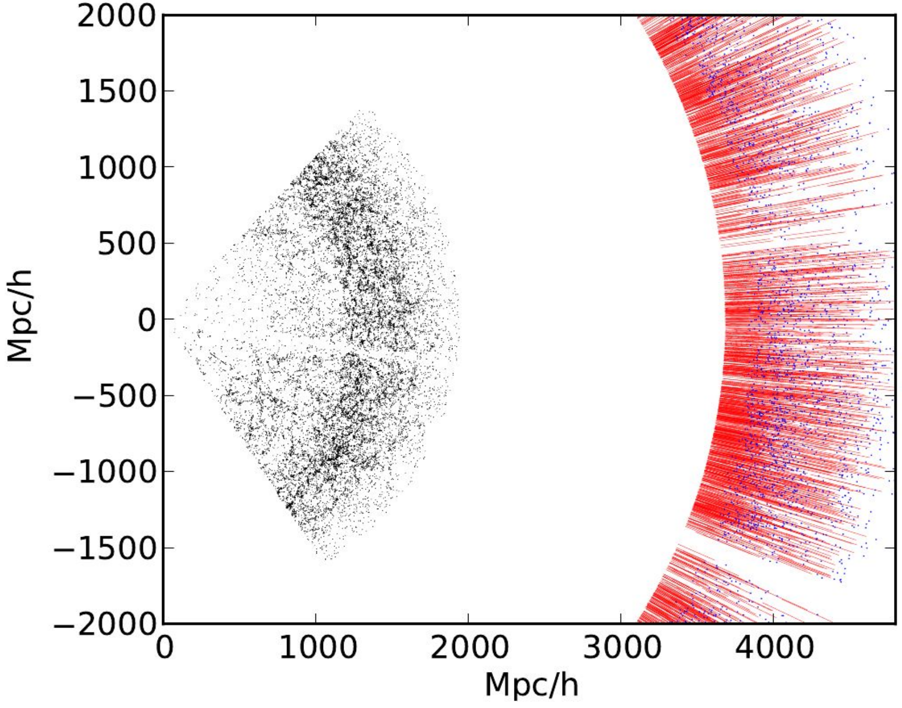


Figure credit William C Keel

Lyα forest observations

- SDSS/BOSS/eBOSS observed **~200,000** quasar spectra
- Complemented by smaller numbers of higher resolution spectra (KECK/UV-HIRES/XShooter)
- DESI will provide **~700,000** new Lya quasar observations over coming years
- Theoretical development necessary to interpret these coming observations

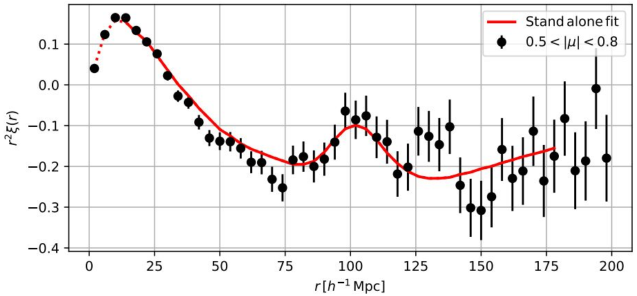


Slosar et al. 2011, 1104.5244.

Two categories of analysis

3D correlation function:

- Correlations of flux absorption between different spectra
- Sensitive to matter clustering in the linear regime, on ~100 Mpc/h scales
- Has been used to measure the BAO scale at z~2.3

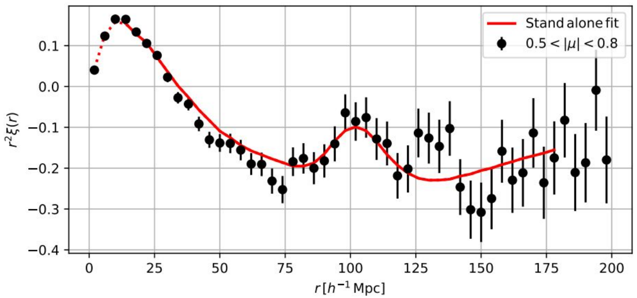


du Mas des Bourboux et al. 2020, 2007.08995

Two categories of analysis

3D correlation function:

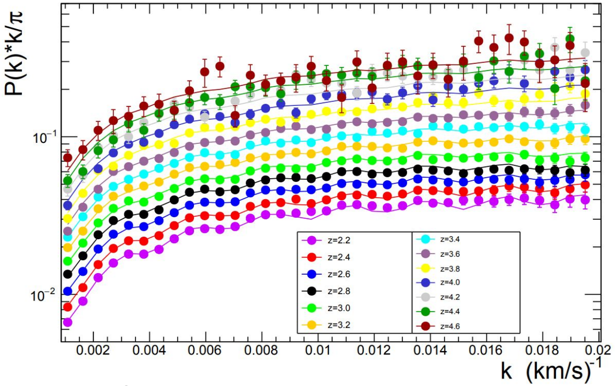
- Correlations of flux absorption between different spectra
- Sensitive to matter clustering in the linear regime, on ~100 Mpc/h scales
- Has been used to measure the BAO scale at z~2.3



du Mas des Bourboux et al. 2020, 2007.08995

1D flux power spectrum (P1D):

- Correlations in flux absorption along the line of sight of each spectrum
- Sensitive to the clustering of matter on small (mildly non-linear) scales around ~1-10Mpc
- How to extract cosmological information from P1D measurements?

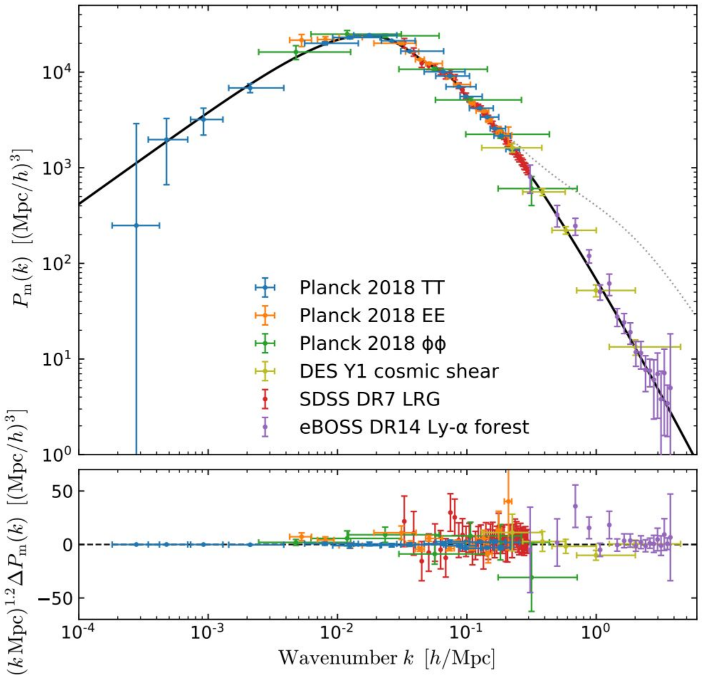


Chabanier et al. 2019, 1812.03554

Why do P1D analysis? Small scale information!

- P1D provides unique small-scale clustering information

- Valuable in constraining parameters that affect overall shape of the matter power spectrum (e.g. neutrino mass, slope + running of the primordial power spectrum)



Chabanier et al. 2019, 1905.08103

Massive neutrinos and the Lyman-α forest

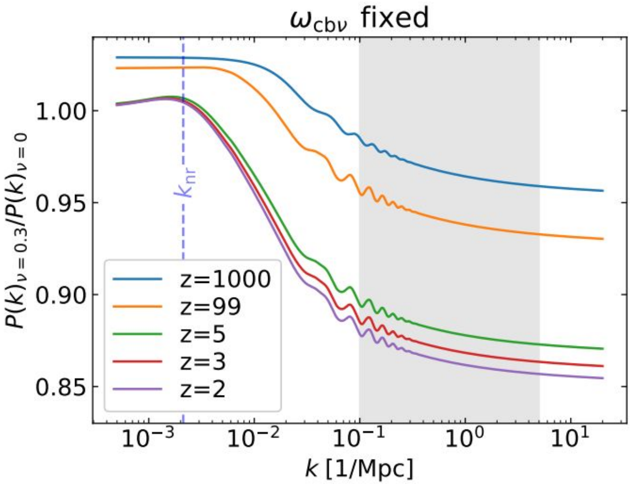
Pedersen et al. (2020), JCAP04(2020)025:

Study the effect of massive neutrinos in

- Linear theory
- Non-linear matter power spectrum
- 1D Lyaf flux power spectrum

Neutrino mass in linear theory

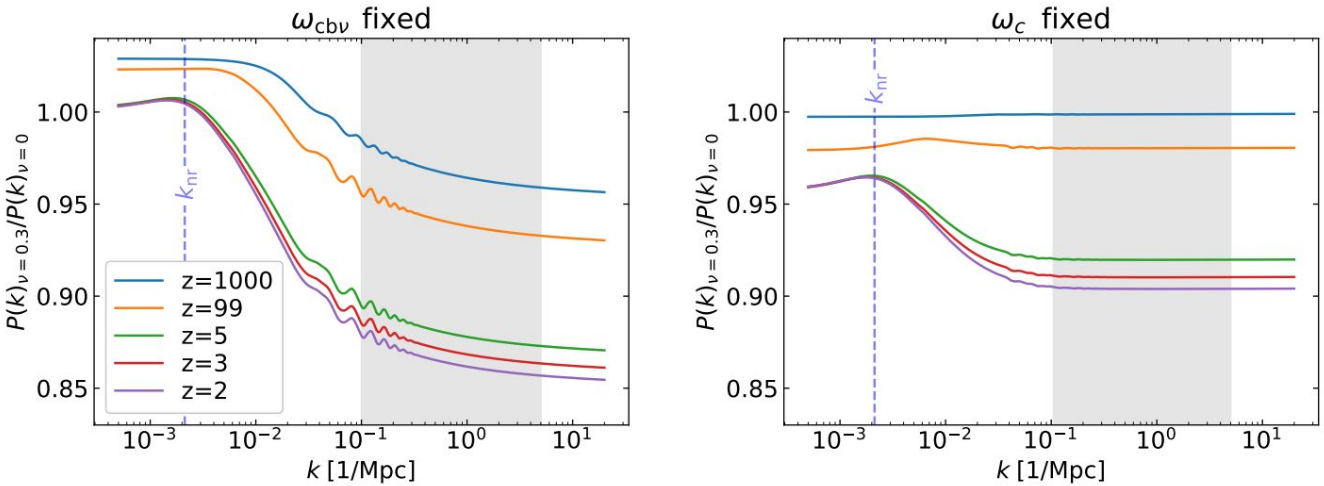
Effect of 0.3eV massive neutrinos on the linear matter power spectrum



Neutrino mass in linear theory

Effect of 0.3eV massive neutrinos on the linear matter power spectrum

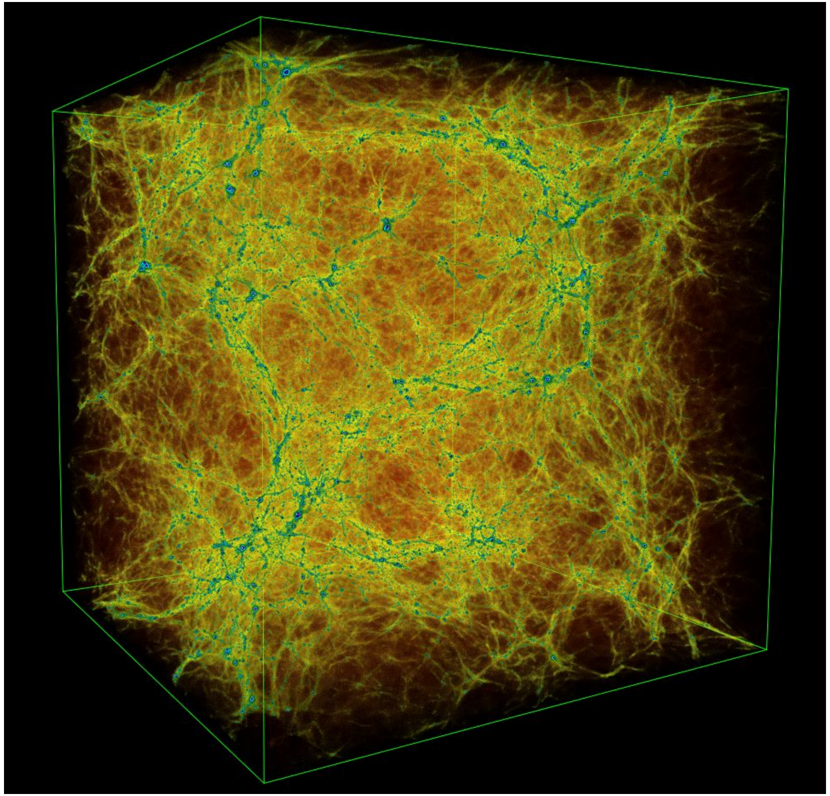
~8% suppression in the z=3 small scale linear power spectrum, when CDM density is kept fixed



Modelling difficulties

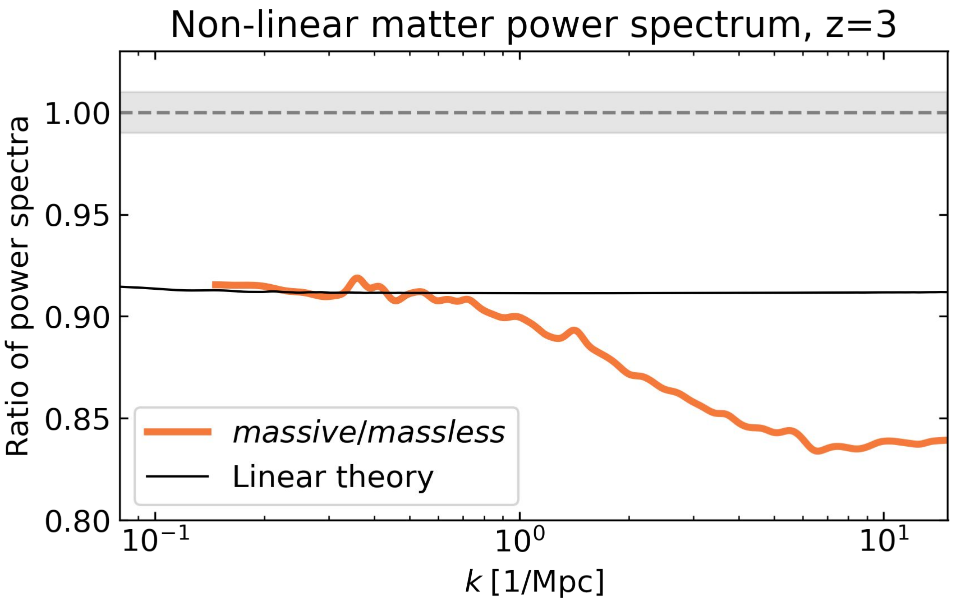
- The Lyman-α forest is sensitive to mildly non-linear clustering, and the state of the intergalactic medium (IGM)

- Modelling these effects simultaneously requires computationally expensive hydrodynamical simulations (i.e. Gadget, MP-Gadget, Nyx)



Studying parameter degeneracies

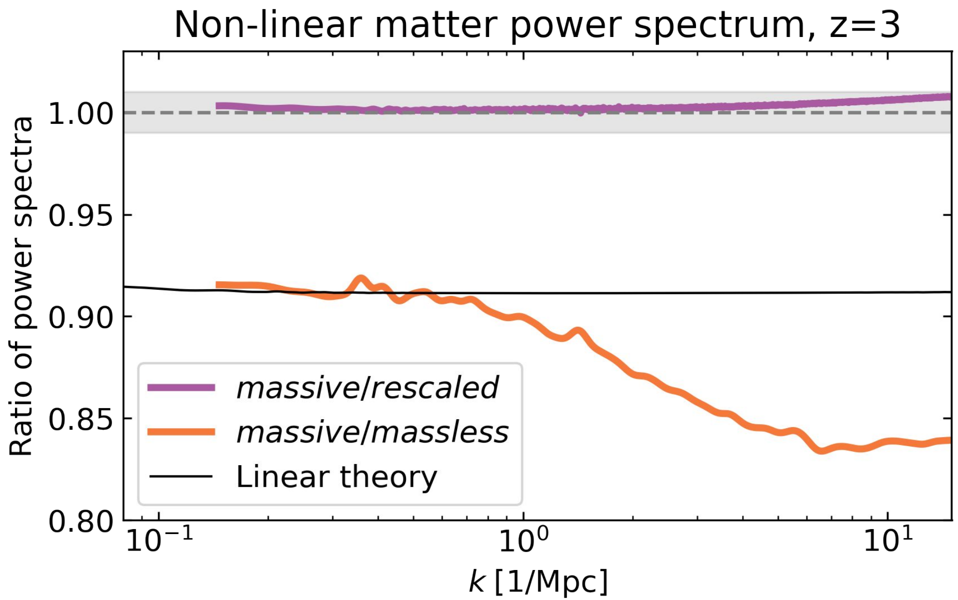
	massive	*massless*	*rescaled*
Σm_ν (eV)	0.3	0.0	0.0
$\Omega_{\mathrm{cb}\nu}$	0.3192	0.3121	0.3121
A_s	2.142e-9	2.142e-9	1.952e-9
Ω_c	0.2628		
Ω_b	0.0493		
n_s	0.9667		
h	0.6724		



Studying parameter degeneracies

	massive	*massless*	*rescaled*
Σm_ν (eV)	0.3	0.0	0.0
$\Omega_{cb\nu}$	0.3192	0.3121	0.3121
A_s	2.142e-9	2.142e-9	1.952e-9
Ω_c	0.2628		
Ω_b	0.0493		
n_s	0.9667		
h	0.6724		

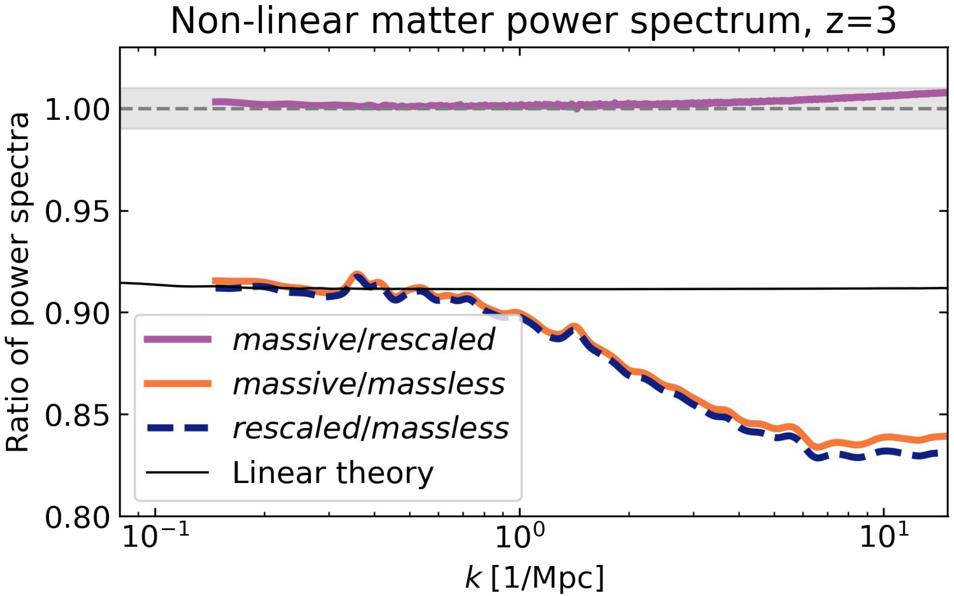
- Changed As by 8% in *rescaled* simulation to mimic massive neutrinos
- Degeneracy predicted by linear theory carries over into the non-linear regime
- If the linear power is the same, the non-linearities are the same



Studying parameter degeneracies

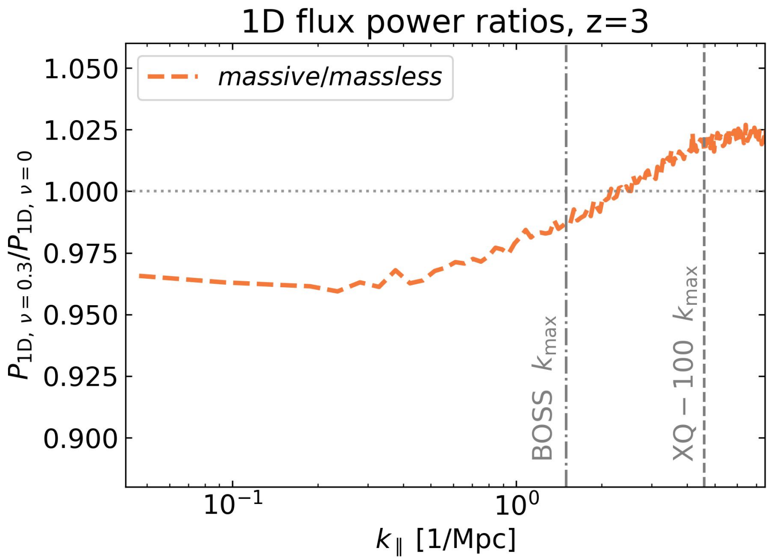
	massive	*massless*	*rescaled*
Σm_ν (eV)	0.3	0.0	0.0
$\Omega_{\mathrm{cb}\nu}$	0.3192	0.3121	0.3121
A_s	2.142e-9	2.142e-9	1.952e-9
Ω_c	0.2628		
Ω_b	0.0493		
n_s	0.9667		
h	0.6724		

- Changed As by 8% in *rescaled* simulation to mimic massive neutrinos
- Degeneracy predicted by linear theory carries over into the non-linear regime
- If the linear power is the same, the non-linearities are the same



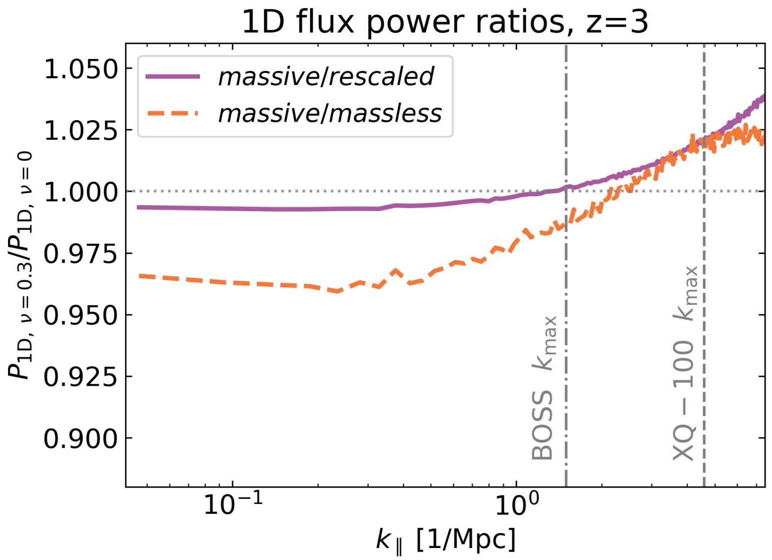
1D flux power spectra

- Effect of 0.3eV massive neutrinos on the 1D flux power spectrum



1D flux power spectra

- Effect of 0.3eV massive neutrinos on the 1D flux power spectrum
- When rescaling As to match the linear power spectrum, the P1D agrees to sub-percent in the BOSS regime



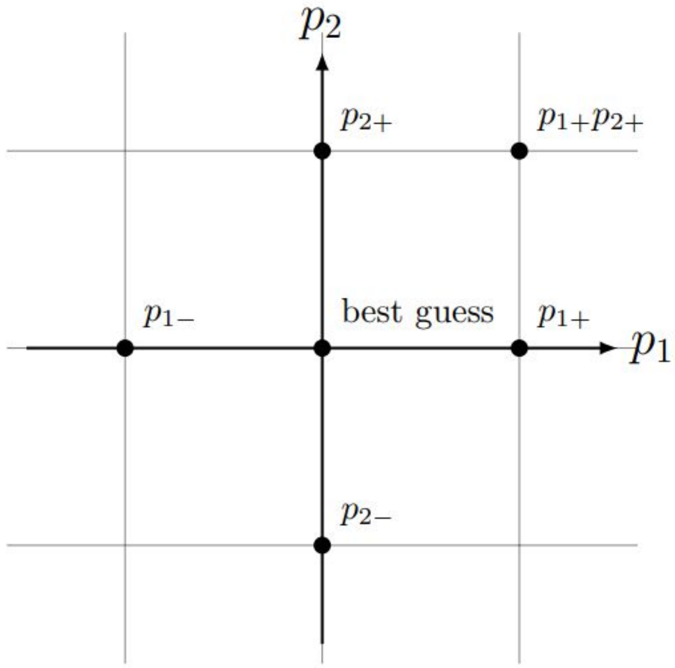
Emulating the Lyman-α forest

Pedersen et al. (2021), JCAP05(2021)033:

Constructing a Gaussian process emulator for the 1D flux power spectrum

The need for emulators

- Due to computational cost, only a small number (<100) of simulations can be run
- Far fewer than the ~10^5 likelihood evaluations required to obtain robust statistical constraints
- Recent work has demonstrated the benefits of using Gaussian processes to solve this problem (Bird et al. 2019, Rogers et al. 2019, Takhtaganov et al. 2019)



Borde et al. 2014, 1401.6472

Parameterising the P1D - two approaches

Linear matter power spectrum

- Universe is close to Einstein de-Sitter at 5>z>2
- 10% change in H0 -> 1% change in H(z=3)
- Cosmological information is concentrated in the linear power spectrum

Cosmological parameters

- BOSS/eBOSS analysis models the P1D directly as a function of ΛCDM + extended parameters
- Degeneracies within ΛCDM+neutrinos
- Requires constructing an emulator for each ΛCDM extension

Parameterising the P1D - two approaches

Linear matter power spectrum

- Universe is close to Einstein de-Sitter at 5>z>2
- 10% change in H0 -> 1% change in H(z=3)
- **Cosmological information is concentrated in the linear power spectrum (can we ignore changes to the growth & expansion rate?)**

Cosmological parameters

- BOSS/eBOSS analysis models the P1D directly as a function of ΛCDM + extended parameters
- Degeneracies within ΛCDM+neutrinos
- Requires constructing an emulator for each ΛCDM extension

Parameterising the P1D

2 parameters to describe cosmology:

The slope and amplitude of the linear matter power spectrum at a small-scale pivot, k_p=0.7 [1/Mpc]

$$\Delta_p^2(z) = k^3 P_{\rm lin}(k,z)|_{k=k_p}$$
$$n_p(z) = {\rm dln}P_{\rm lin}(k,z)/{\rm dln}k|_{k=k_p}$$

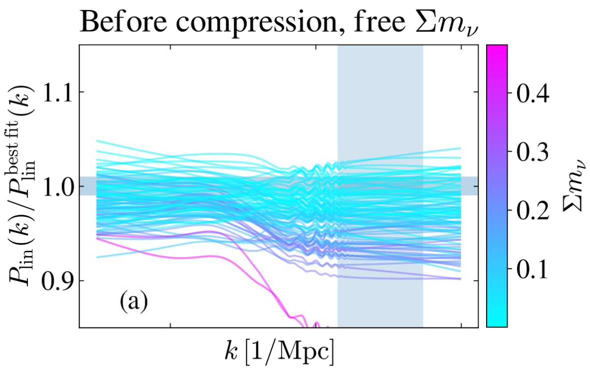
4 parameters to describe the IGM

These are considered nuisance parameters in cosmological analysis

$$\{\langle F\rangle, \sigma_T, \gamma, k_F\}$$

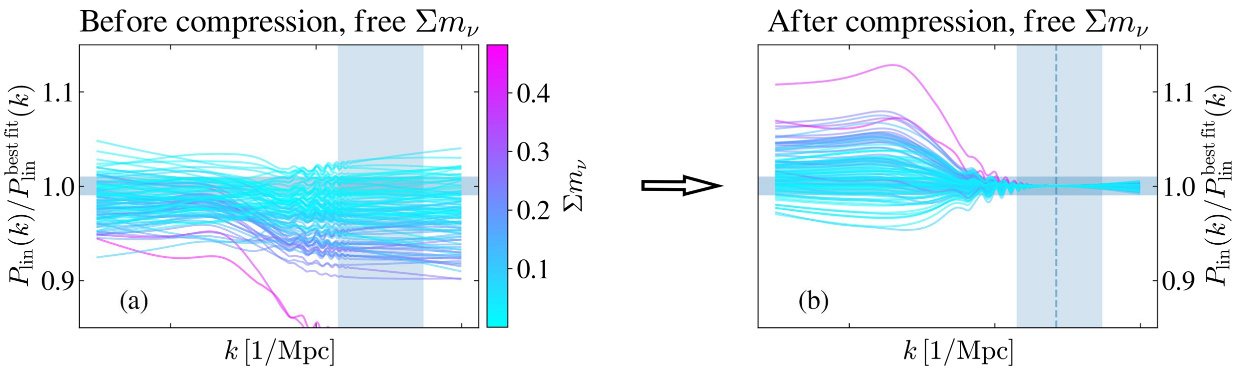
Parameterising the P1D

- Randomly sample 100 points in the Planck chain.
- Plot the ratio of the z=3 linear matter power spectrum, with respect to the best fit cosmology



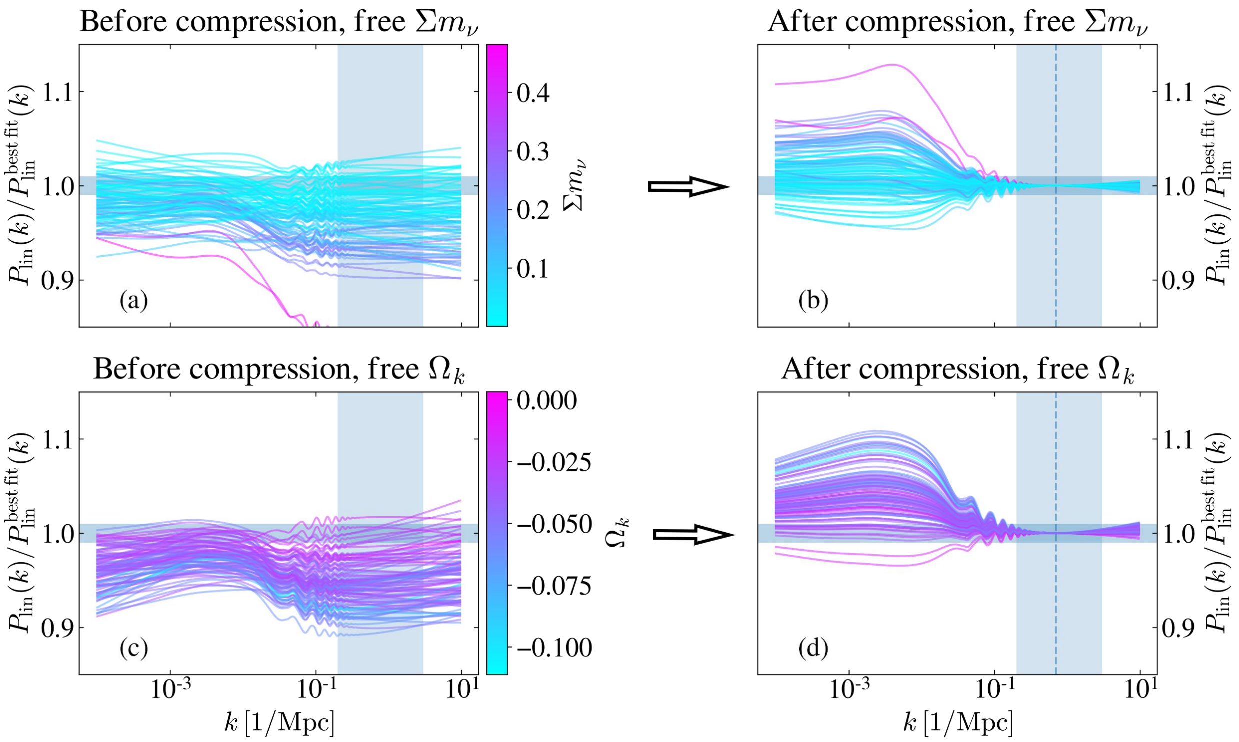
Parameterising the P1D

- Randomly sample 100 points in the Planck chain.
- Plot the ratio of the z=3 linear matter power spectrum, with respect to the best fit cosmology
- Take the same 100 chains, and rescale the slope and amplitude to match $\Delta_p^2(z=3)$ and $n_p(z=3)$

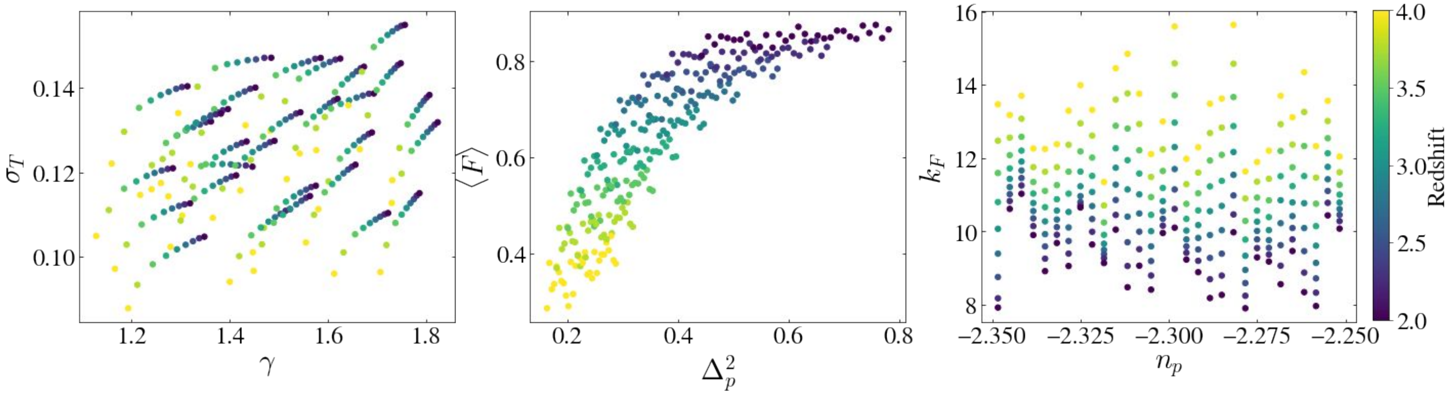


Parameterising the P1D

- Randomly sample 100 points in the Planck chain.
- Plot the ratio of the z=3 linear matter power spectrum, with respect to the best fit cosmology
- Take the same 100 chains, and rescale the slope and amplitude to match $\Delta_p^2(z=3)$ and $n_p(z=3)$
- Repeat the process with free curvature parameter
- All variation within Lyαf regime captured by 2 parameters



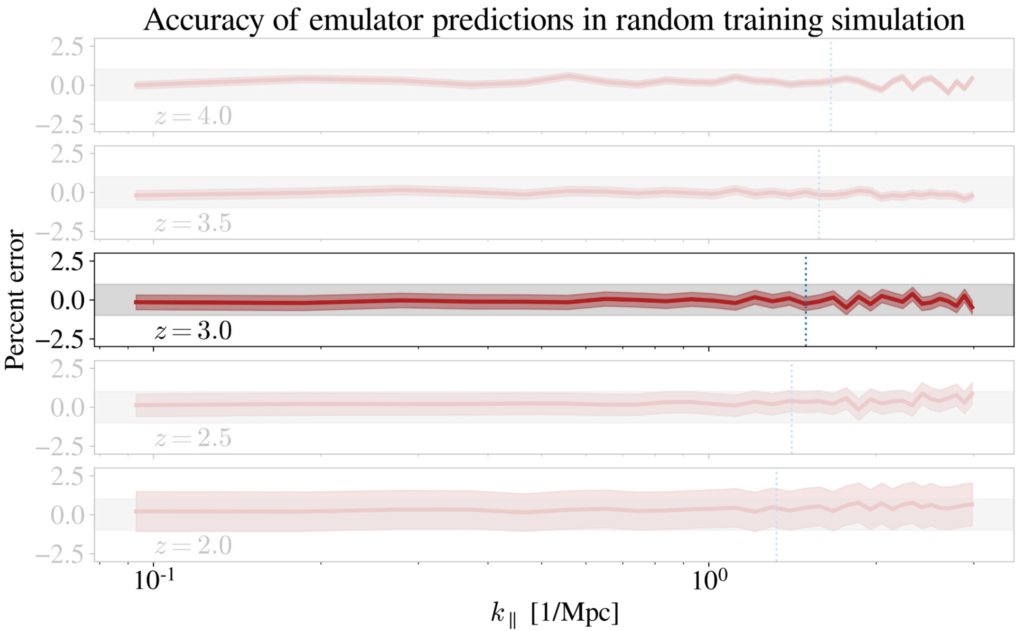
Constructing an emulator



- Ran 30 hydrodynamical simulations in MP-Gadget, 9 snapshots each - 270 training points
- Trained a Gaussian process in the 6 dimensional parameter space - all training points in a single emulator
- **Only varied the primordial power spectrum** in the training set (fixed h=0.67)

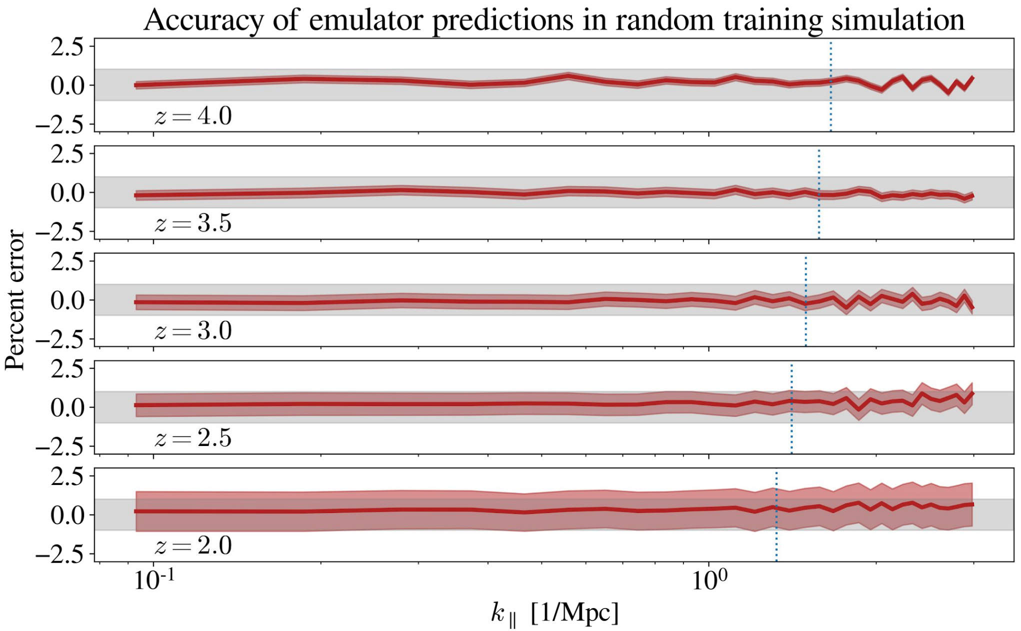
Verifying emulator predictions

- Drop a single simulation (i.e. 9 training points) from the training set
- Compare emulator predictions with the truth in that simulation



Verifying emulator predictions

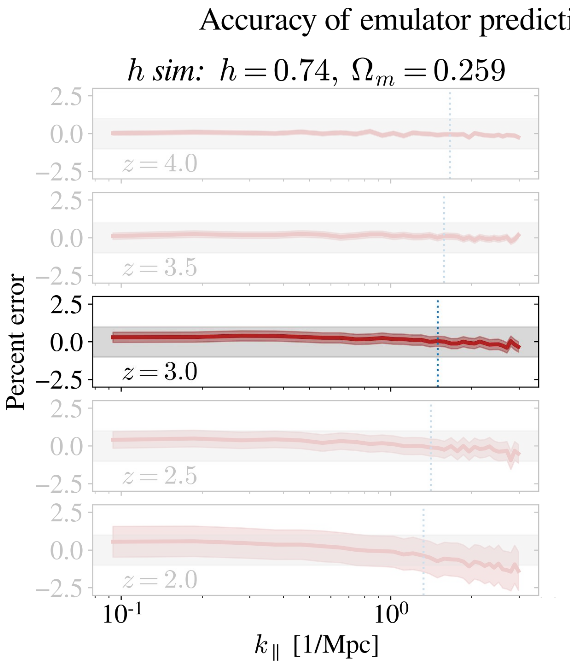
- Drop a single simulation (i.e. 9 training points) from the training set
- Compare emulator predictions with the truth in that simulation
- Sub-percent accuracy at all redshifts
- eBOSS measurement uncertainties between 3-15%



Emulating external models

Sub-percent accuracy in emulated P1D:

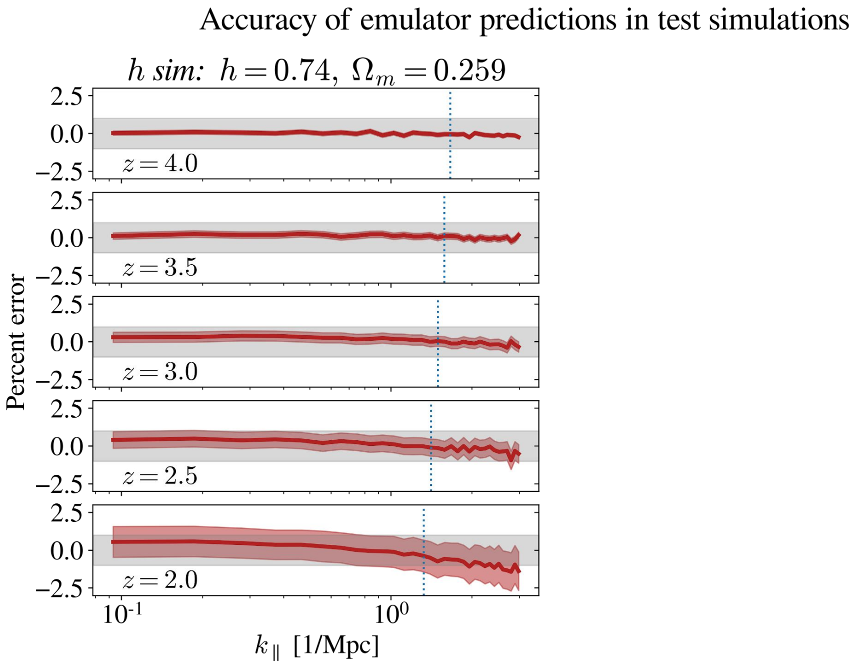
- in cosmologies with a different background evolution,



Emulating external models

Sub-percent accuracy in emulated P1D:

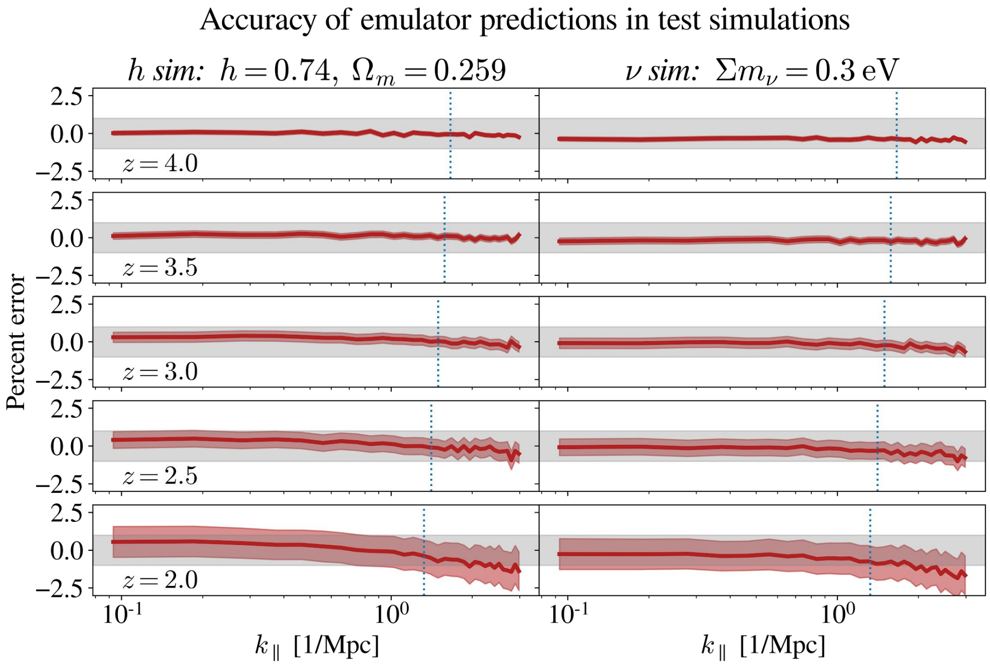
- in cosmologies with a different background evolution,



Emulating external models

Sub-percent accuracy in emulated P1D:

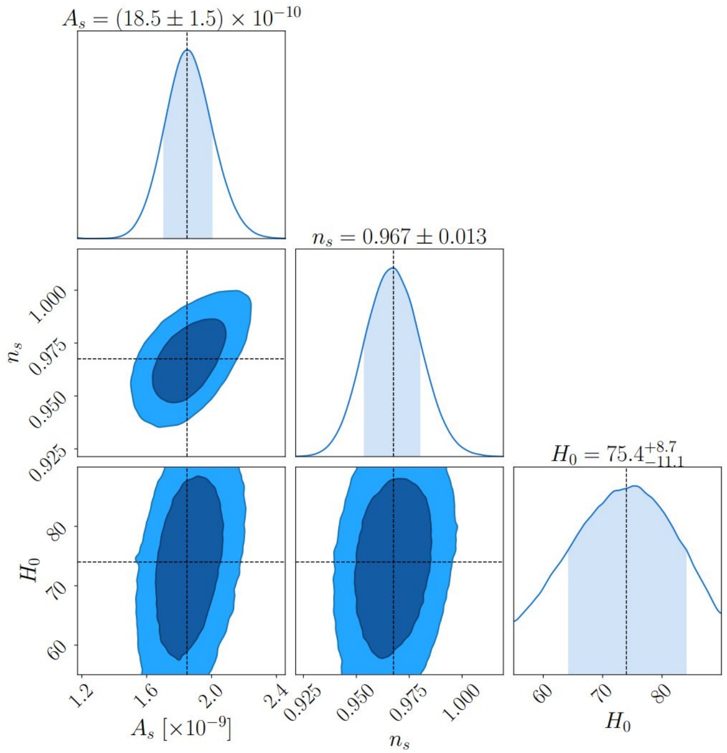
- in cosmologies with a different background evolution,
- and in massive neutrino cosmologies, without massive neutrinos in the training simulations.
- Expect the same argument to be applied to other extensions (curvature, running of spectral index)



Mock data constraints

***h sim* as mock data:**

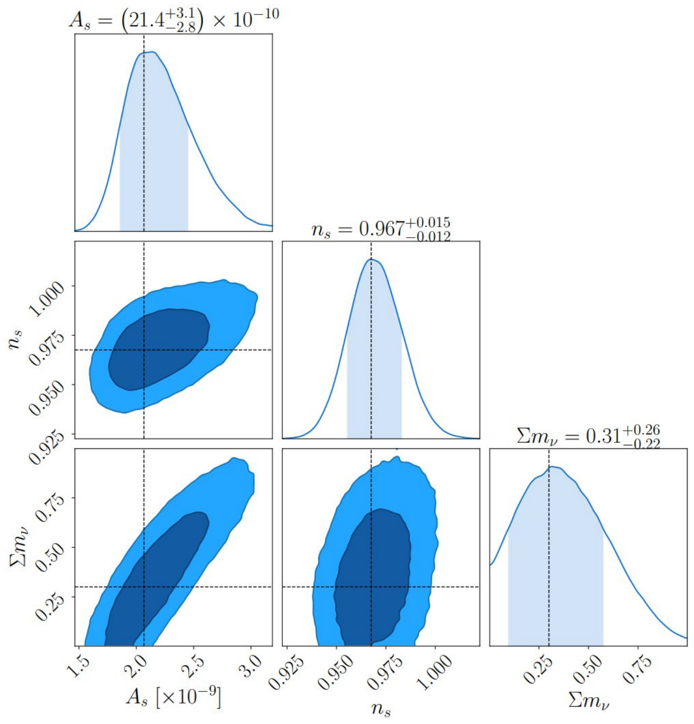
- Using the h=0.74 sim as mock data, run a sampler to constrain primordial power spectrum
- Using eBOSS as mock data covariance
- Marginalised over 8 IGM parameters
- Recover unbiased primordial power
- Largely insensitive to H0



Mock data constraints

0.3eV neutrino sim as mock data:

- Still recover the correct values for the primordial power
- Strong degeneracy band between As and neutrino mass - consistent with previous work

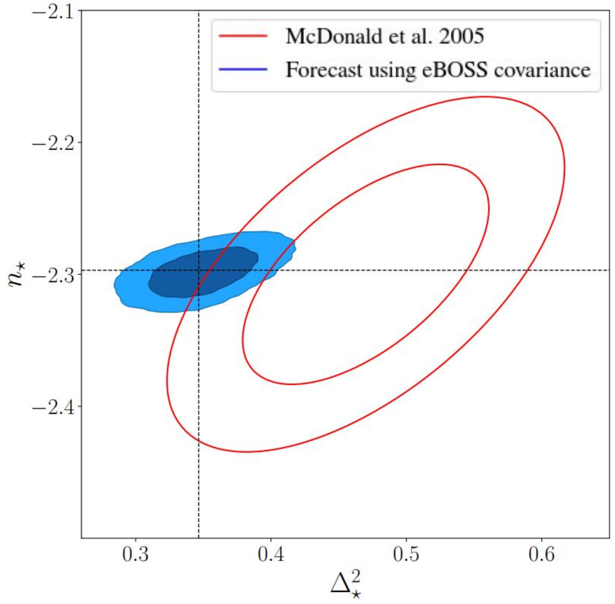


Ongoing work - compressing the P1D

$$\Delta_\star^2 = k^3 P_{\rm lin}(k,z)|_{k=0.009\,{\rm s/km},z=3}$$

$$n_\star = {\rm dln}P_{\rm lin}(k,z)/{\rm dln}k|_{k=0.009\,{\rm s/km},z=3}$$

- Early analysis (SDSS + WMAP) constrained the linear power from P1D, then combined these constraints with CMB
- Benefits - P1D information can be used by non-Lyaf experts
- How much information is lost in this compression at the level of current data?



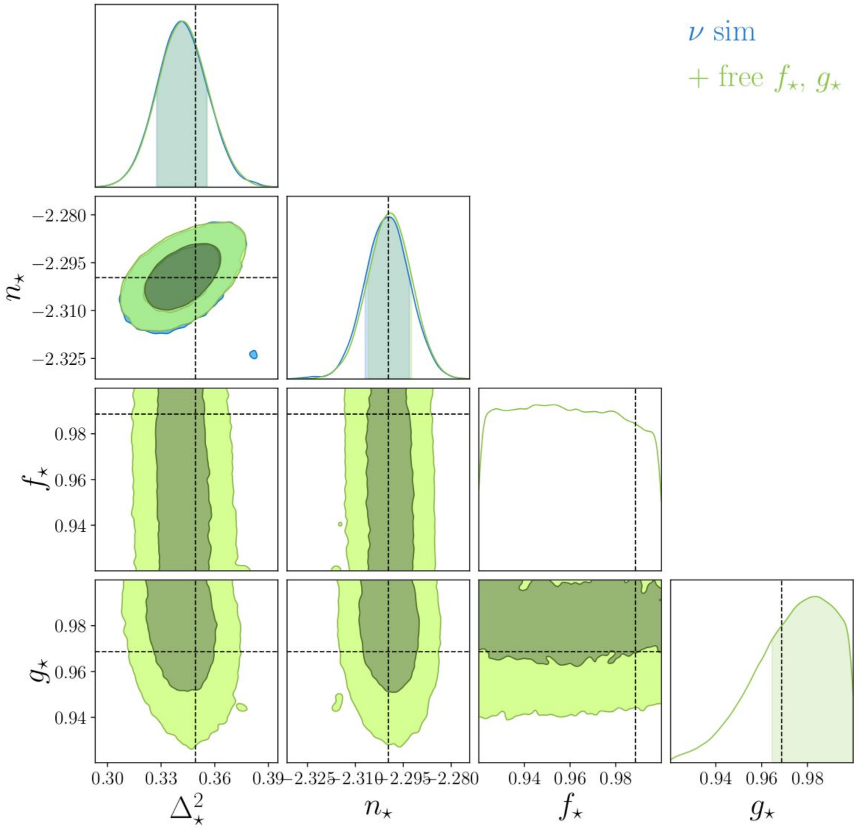
Ongoing work - compressing the P1D

- Are we sensitive to changes to the growth and expansion rate?
- Define parameters to allow for variation, and examine our sensitivity to them
- Defined at z=3

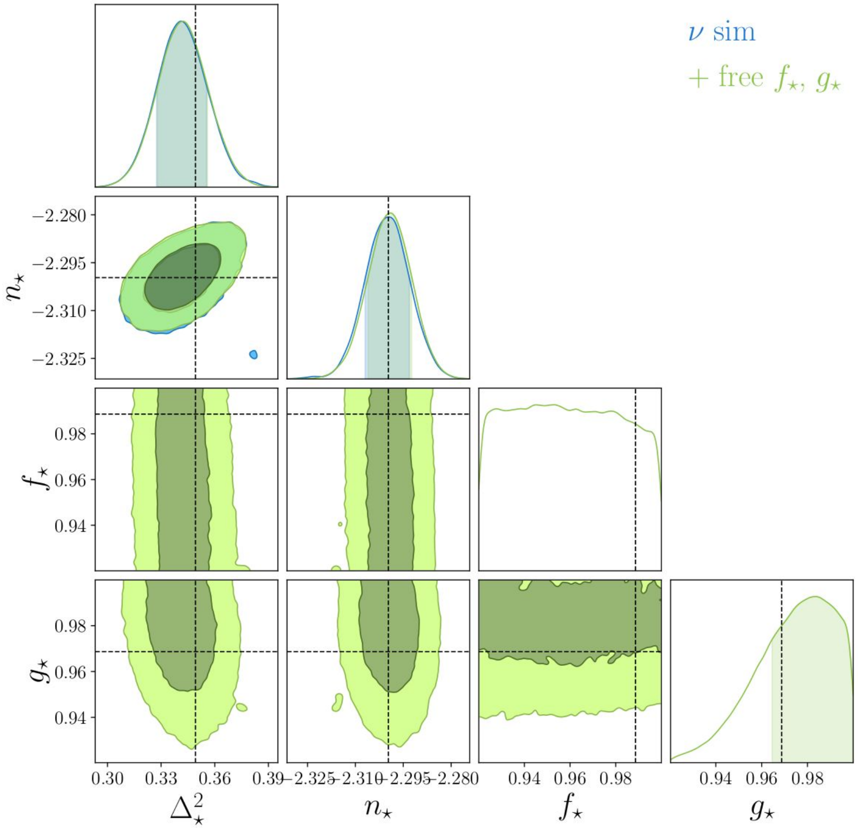
$$f(z) = \frac{\partial \ln D(z)}{\partial \ln a(z)}$$

$$g(z) = \frac{\partial \ln H(z)}{\partial \ln(1+z)^{3/2}}$$

Ongoing work - compressing the P1D



Ongoing work - compressing the P1D



- Next step is to run a mock CMB + P1D analysis
- Compare constraints when using compressed vs uncompressed likelihoods

Outlook

Much more work to do!

- 3D flux power spectrum analysis (both modelling and measurement) - contains more information
- Higher order statistics (bispectrum, or CMB lensing X Lya)
- Likelihood-free or field level inference

Extra slides below

Extra slides - 1D and 3D flux power spectra

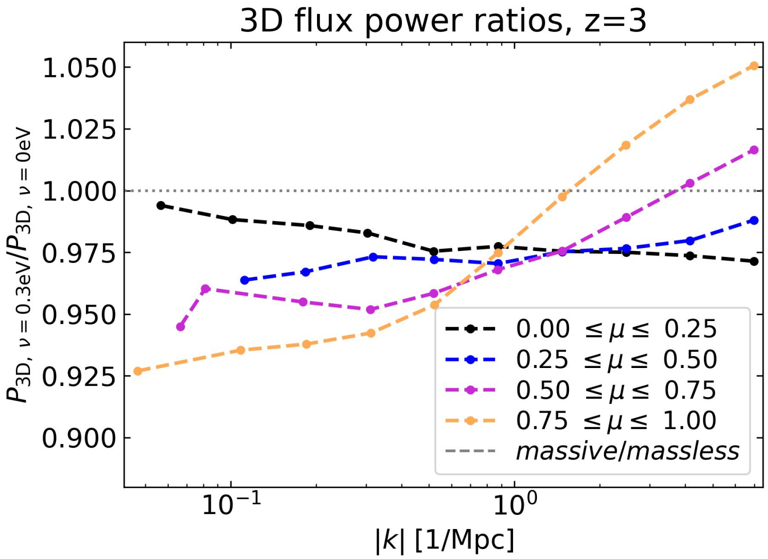
- 3D flux power spectrum gaining increasing attention
- μ represents cosine of the angle between LoS and wavevector
- More information than the P1D (Font-Ribera et al. 2013)
- Not yet been measured from SDSS/eBOSS, but work in progress in preparation for DESI

$$\langle \delta_F(\mathbf{k}) \delta_F(\mathbf{k}') \rangle = (2\pi)^3 \delta^D(\mathbf{k} + \mathbf{k}') P_{3D}(k, \mu)$$

$$P_{\mathrm{1D}}(k_{\parallel}) = \int_0^{\infty} \frac{dk_{\perp} k_{\perp}}{2\pi} P_{\mathrm{3D}}(k_{\perp}, k_{\parallel})$$

Extra slides - 3D flux power spectra

- Effect of 0.3eV massive neutrinos on the 3D flux power spectrum



Extra slides - 3D flux power spectra

- Effect of 0.3eV massive neutrinos on the 3D flux power spectrum

- P3D also degenerate to <2.5% - features at high k caused by differences in IGM