Implementing the Neutrino-Induced Scale-Dependent Bias in Photometric Galaxy Surveys

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Outline of this Talk

I. Massive Neutrinos and their Effect on Large-Scale Structure
II. Inferring Underlying Matter Density Fluctuations
III. An Approximate Form of the Neutrino-Induced Scale-Dependent Bias (NISDB)
IV. Applications of the NISDB in DESY3 and LSSTY1 Simulated Analyses
V. Results and Systematic Shifts Using Other Common Linear Galaxy Bias Modeling Choices

The effect of Massive Neutrinos on Large-Scale Structure (LSS)

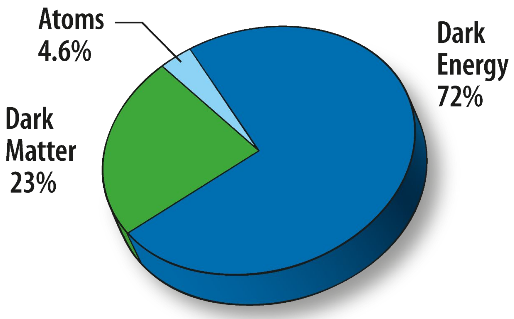
Neutrinos and Cosmology

Neutrinos are massive, weakly-interacting particles and play a role at different cosmological epochs

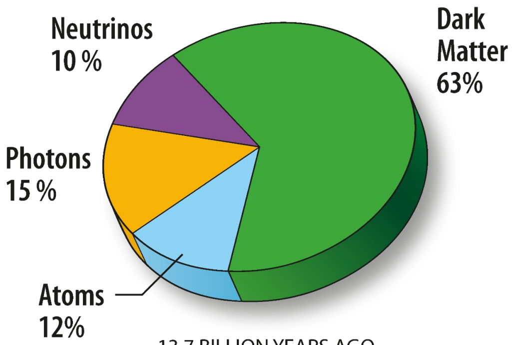
- Being relativistic at early times, neutrinos behaved more like radiation than matter and added to the radiative energy budget
- Closer to today, massive neutrinos affect halo formation, galaxy clustering, and void statistics

Analysis	Constraint
DESY3 + Planck + low-z	<0.13eV at 95%
Planck 2018	<0.54eV at 95%
Katrin (all data)	<0.8eV at 90%

arxiv: 1807.06209
arxiv: 2105.13549
https://doi.org/10.1038/s41567-021-01463-1



TODAY



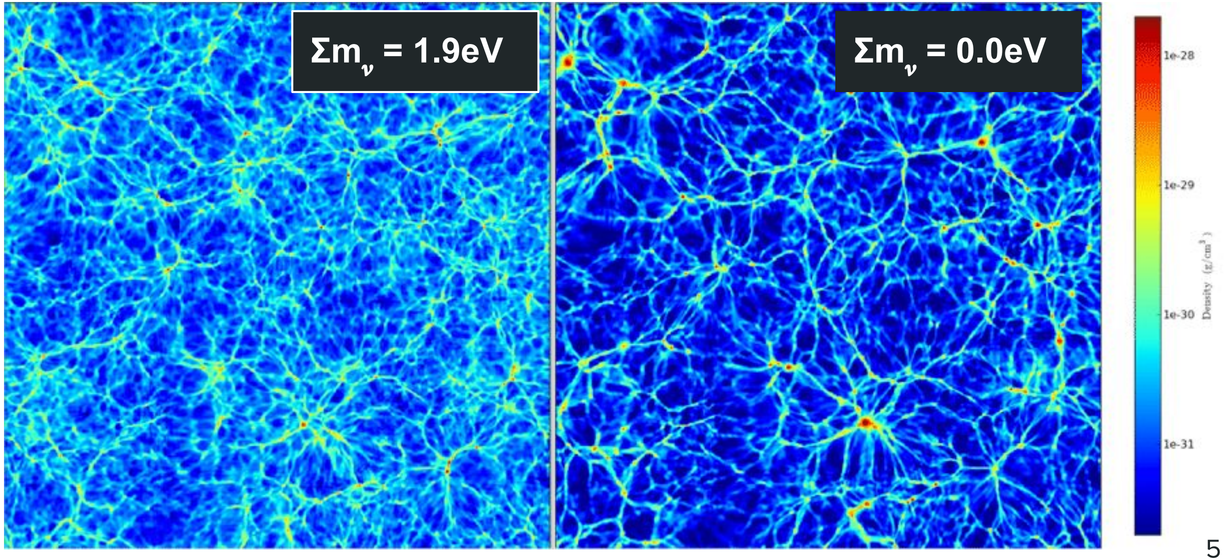
13.7 BILLION YEARS AGO
(Universe 380,000 years old)

WMAP

Neutrinos induce a long-wavelength mode

- Neutrinos, due to their finite mass and free-streaming, contribute a long-wavelength mode to modulate CDM Halo collapse
  - On large physical scales, Neutrinos trace the CDM distribution
  - On small physical scales, Neutrinos free-stream and lead to an overall damping of the total matter fluctuations

Since neutrinos affect the clustering of CDM, they affect how halos trace underlying matter



Agarwal and Feldman 2010

Neutrino Free-Streaming Scale

$$k_{FS}(t) = \left(\frac{4\pi G \bar{\rho}(t) a^2(t)}{v_{\text{th}}^2(t)} \right)^{1/2}$$

v_{th} set when neutrinos become non-relativistic

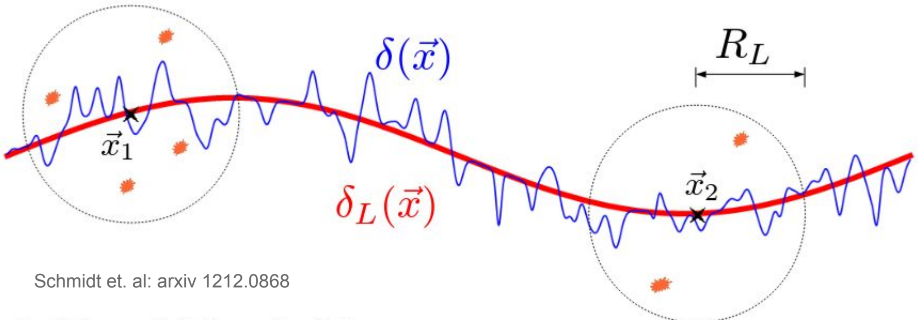
$$k_{FS}(t) = 0.8 \frac{\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}}{(1+z)^2} \left(\frac{m}{1\ \text{eV}} \right) h\ \text{Mp c}^{-1}$$

(Definition comes from similar formulation as the Jean's Mass)

Lesgourgues and Pastor arxiv: 1404.1740

The Halo Bias: Relating Galaxies to their CDM Halos

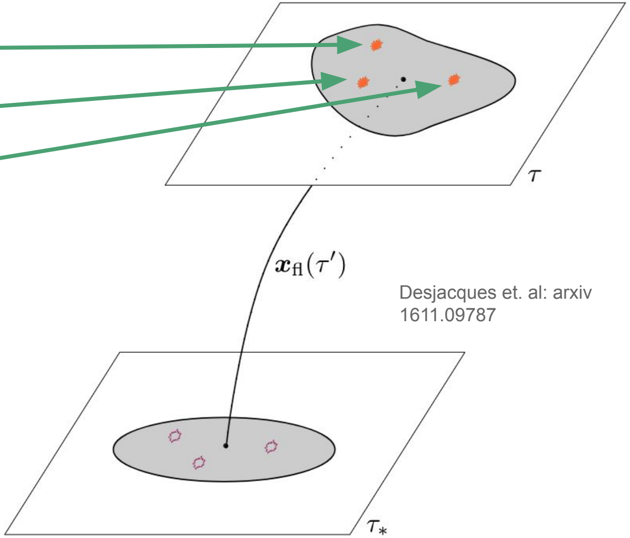
CDM Halos form in regions under the influence of long-wavelength perturbations



Schmidt et. al: arxiv 1212.0868

b^L: Lagrangian Bias relates formation of CDM halos to position of galaxies at the time of formation

Evolution of density perturbations over cosmic time dictate the positions of halos at later times



Desjacques et. al: arxiv 1611.09787

b^E: Eulerian Bias relates distribution of galaxies at earlier time to later time

How do we define the functional form of Halo Bias?

- In a universe with neutrinos, we can separate the matter density fluctuation in terms of its CDM and neutrino components as $\delta_m(k, z_{obs}) = f_\nu \delta_\nu(k, z_{obs}) + f_{cb}\delta_{cb}(k, z_{obs})$
- Therefore, using $\delta_g(k, z_{obs}) = \left(1 + \frac{\partial \ln n(z)}{\partial \delta_{crit}(z)} \frac{d\delta_{crit}(z)}{d\delta_{cb,L}(z)}\right)\delta_{cb,L}(k, z_{obs})$

Implicitly a function of halo mass!

b^L: Linear Lagrangian Bias

yields: $$P_{g,m}(k, z_{obs}) = \left(1 + \frac{\partial \ln n(z)}{\partial \delta_{crit}(z)} \frac{d\delta_{crit}(z)}{d\delta_{cb,L}(z)}\right) \times \left[f_\nu P_{cb,\nu}(k, z_{obs}) + f_{cb} P_{cb,cb}(k, z_{obs})\right]$$

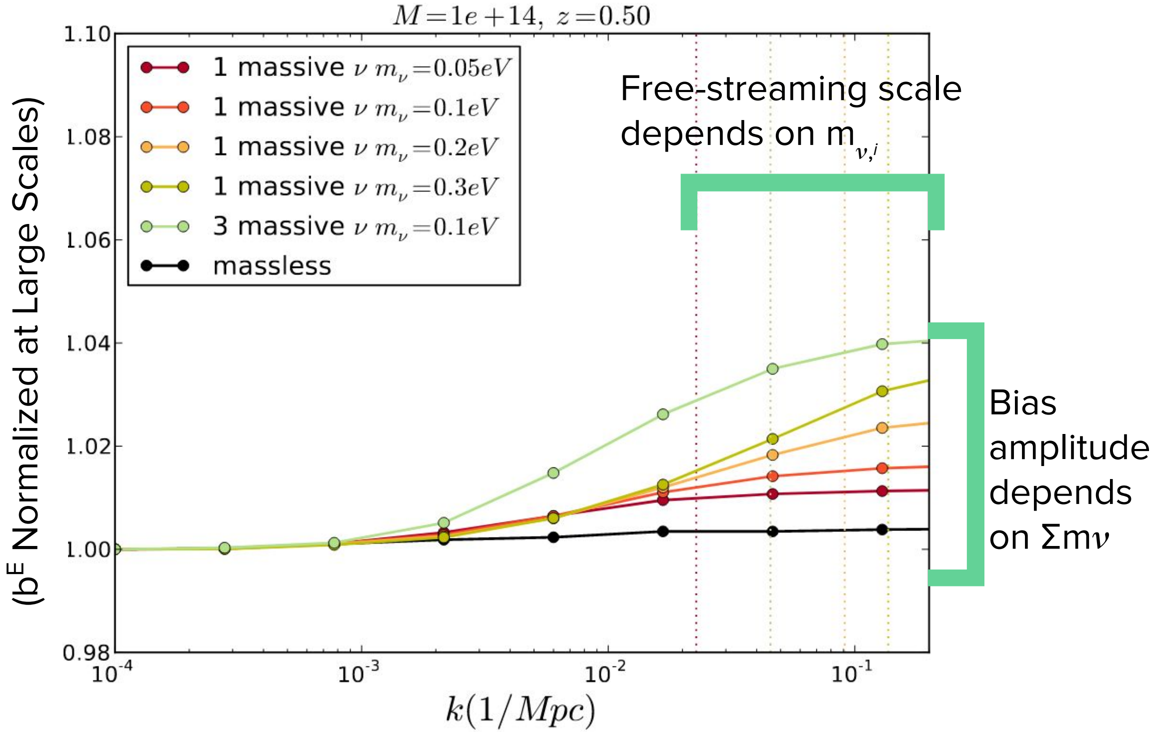
b^E: Eulerian Bias

$$b(k, z) = \frac{P_{gm}}{P_{mm}} = \left(1 + \frac{\partial \ln n(z)}{\partial \delta_{crit}(z)} \frac{d\delta_{crit}(z)}{d\delta_{cb,L}(z)}\right) \frac{f_\nu P_{cb,\nu}(k, z_{obs}) + f_{cb} P_{cb}(k, z_{obs})}{P_m(k, z_{obs})}$$

LoVerde arxiv: 1405.4855

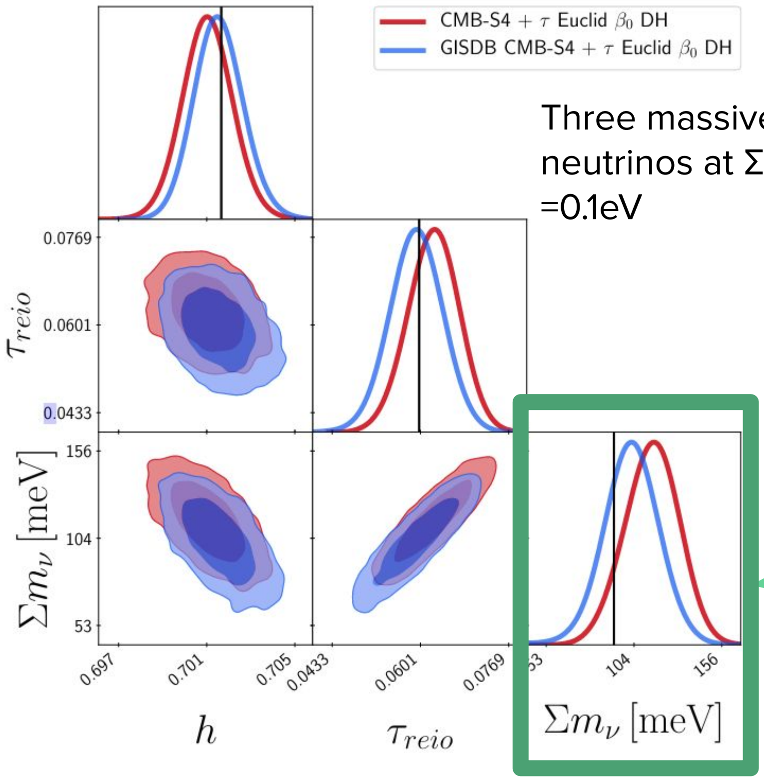
How sensitive is LSS to detailed neutrino modeling?

Analytical Computation of the Full Halo Bias



LoVerde arxiv: 1405.4855

Forecasted Impact of Neutrino-Induced Scale-Dependent Bias



Three massive neutrinos at Σm_ν =0.1eV

Blue: With scale-dependent bias

Red: With constant bias

Shift in inferred neutrino mass!

Xu et. al. arxiv: 2006.09395

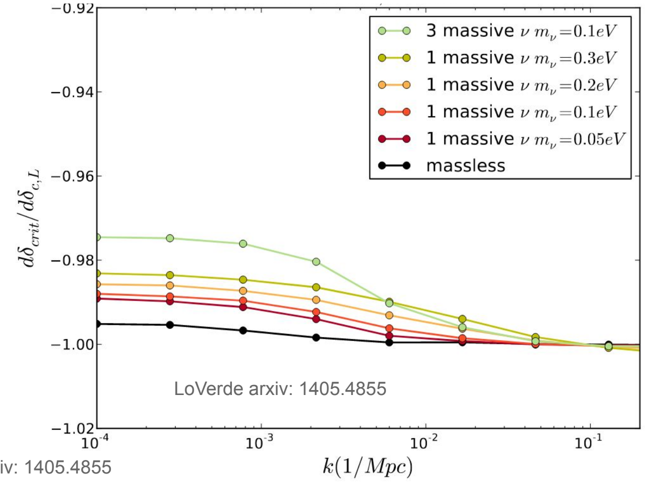
Complications when calculating full NISDB

- Modelling uncertainties
  - Halo mass distribution of the galaxy sample
  - Solvers assume only spherical collapse
  - Redshift of collapse unknown
  - Collapse depends on the exact cosmological parameters you're looking at
- Need to recompute for every likelihood evaluation, expensive!
- Non-trivial Non-Limber integration and fourier transform of 3D power spectra to 2D correlation functions

What approximations can be made to simplify detailed neutrino modeling?

Neutrino Impact on the *Galaxy Bias*

$$b(k,z) = \frac{P_{gm}}{P_{mm}} = \left(1 + \frac{\partial \ln n(z)}{\partial \delta_{\rm crit}(z)} \frac{d\delta_{\rm crit}(z)}{d\delta_{\rm cb,L}(z)}\right) \frac{f_\nu P_{{\rm cb},\nu}(k, z_{\rm obs}) + f_{\rm cb} P_{\rm cb}(k, z_{\rm obs})}{P_{\rm m}(k, z_{\rm obs})}$$



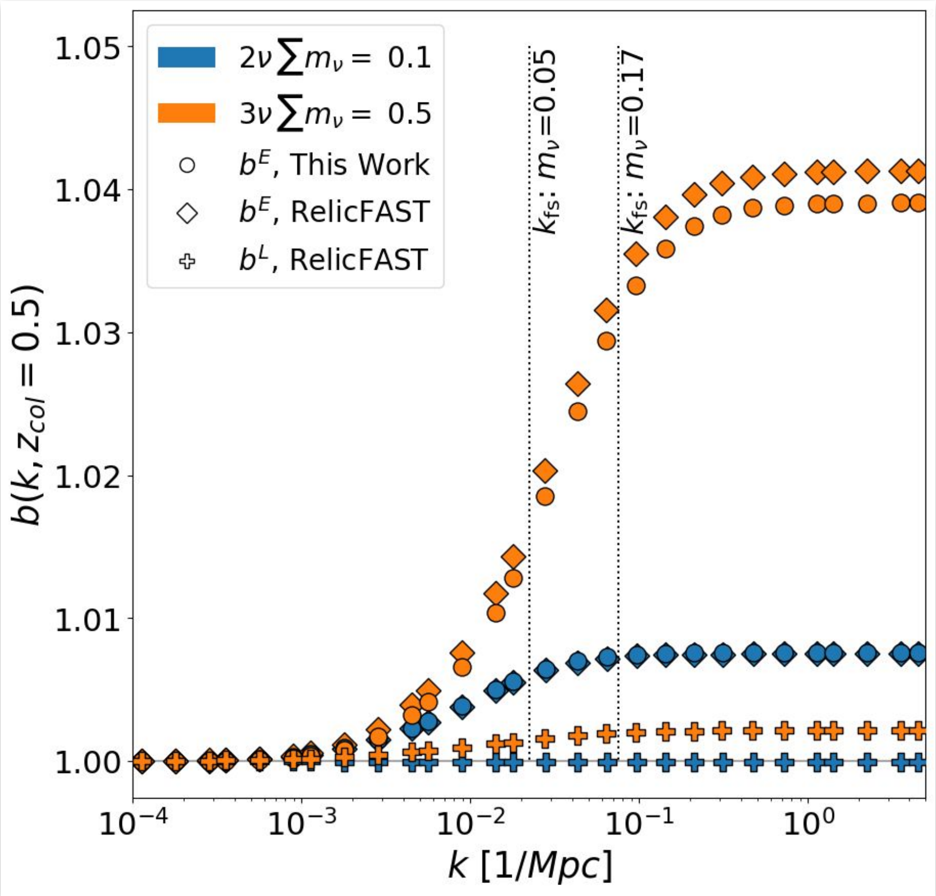
LoVerde arxiv: 1405.4855

Halo Mass Distribution across fourier modes insensitive to neutrino mass $\approx b(z)$

$$\approx \frac{1 + f_{\rm cb} \frac{P_{\rm cb}(k, z_{\rm obs})}{P_{\rm m}(k, z_{\rm obs}))}}{1 + f_{\rm cb}}$$

Small Impact of Lagrangian Bias

- Evaluated at median halo mass of MAGLIM sample with RelicFAST (arxiv: 1805.11623)
- Scales of disagreement usually contaminated (e.g. by Baryonic effects) and often discarded

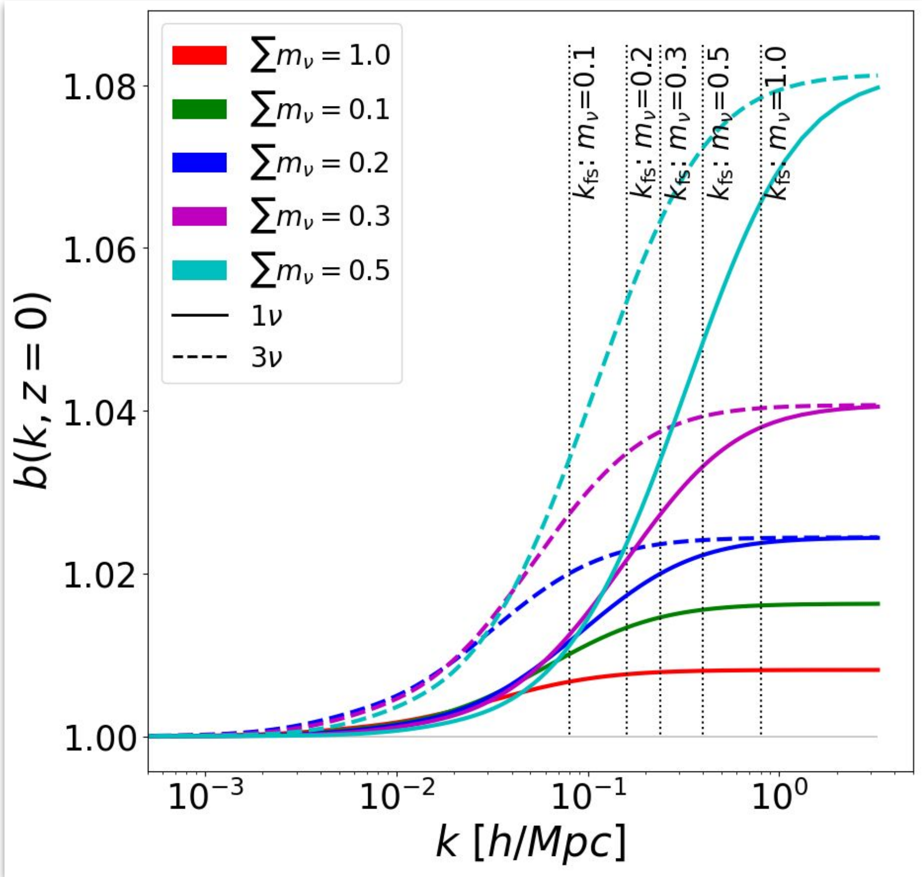


NISDB: Recap

$$b(k, z_{\mathrm{obs}}) \approx \bar{b}(z_{\mathrm{obs}}) \frac{1 + f_{\mathrm{cb}} \frac{P_{\mathrm{cb}}(k, z_{\mathrm{obs}})}{P_{\mathrm{m}}(k, z_{\mathrm{obs}}))}}{1 + f_{\mathrm{cb}}}$$
$$\equiv \bar{b}(z_{\mathrm{obs}}) \mathcal{T}(k, z_{\mathrm{obs}}).$$

To Summarize:

- Generalize halo bias to galaxy bias suitable for a range of masses in a given galaxy sample
- Galaxy bias increases towards smaller physical scales to better correlate galaxy number density fluctuations to total matter density fluctuations



What is the impact of detailed neutrino modeling on DESY3 synthetic data?

How does this change for LSSTY1?

Synthetic Analysis Methodology

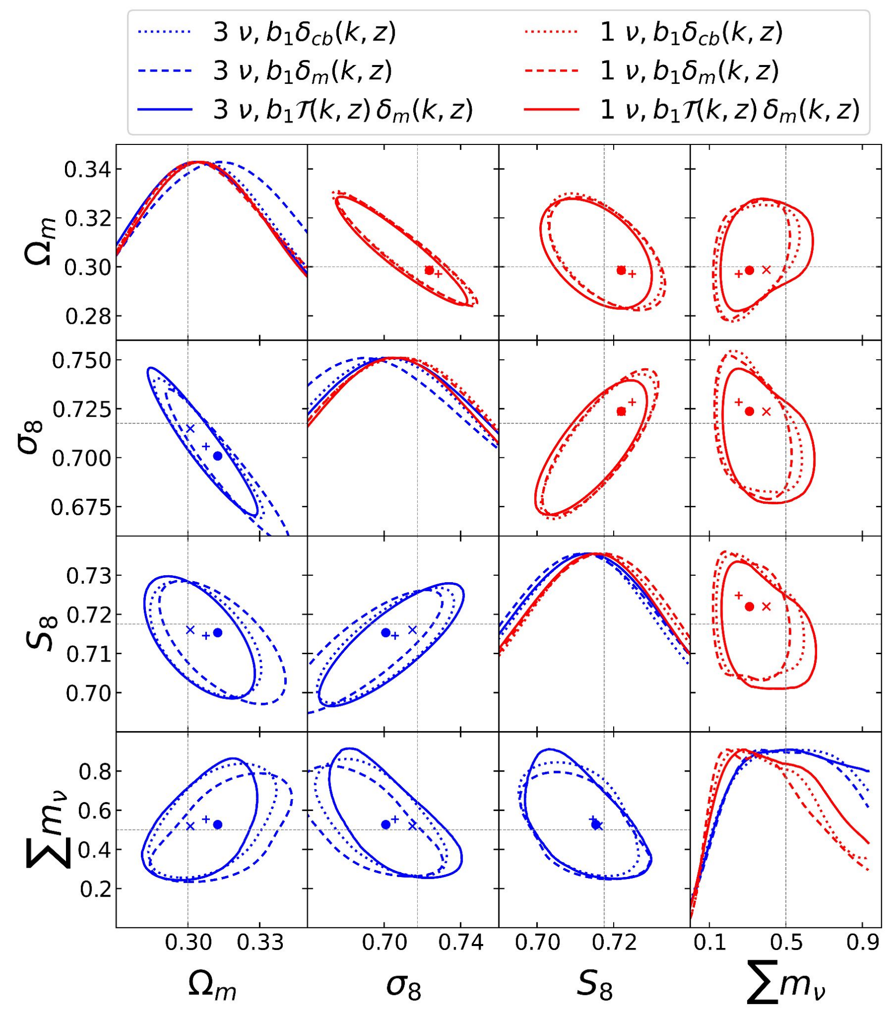
Create synthetic DESY3 (real space) & LSSTY1 (fourier space) data for systematics analysis

- Compare NISDB to two constant linear bias models and neutrino-mass models
- Validate fiducial scale-cuts, run chains on synthetic data with CosmoLike with like/unlike models of input datavector
- Determine any systematic shifts in inferred cosmological parameter due to neutrino modeling
  - Δ□^{2}<1 between best-fit datavectors
  - σ_{2D}<0.3 in best-fit cosmological parameters (S_8- □$_m$ a popular choice)

Analysis Model / Datavector Model	3ν $b_1\mathcal{T}(k,z)\delta_m(k,z)$	3ν $b_1\delta_m(k,z)$	1ν $b_1\delta_m(k,z)$	1ν $b_1\mathcal{T}(k,z)\delta_m(k,z)$	3ν $b_1\delta_{cb}(k,z)$	1ν $b_1\delta_{cb}(k,z)$
$3\nu, \sum m_\nu = 0.5$ $b_1\mathcal{T}(k,z)\delta_m(k,z)$	baseline	**(1)** bias model	**(2)** bias model & m_ν mass model	**(3)** m_ν mass model	**(4)** underlying field galaxies trace	**(5)** underlying field galaxies trace & m_ν mass model

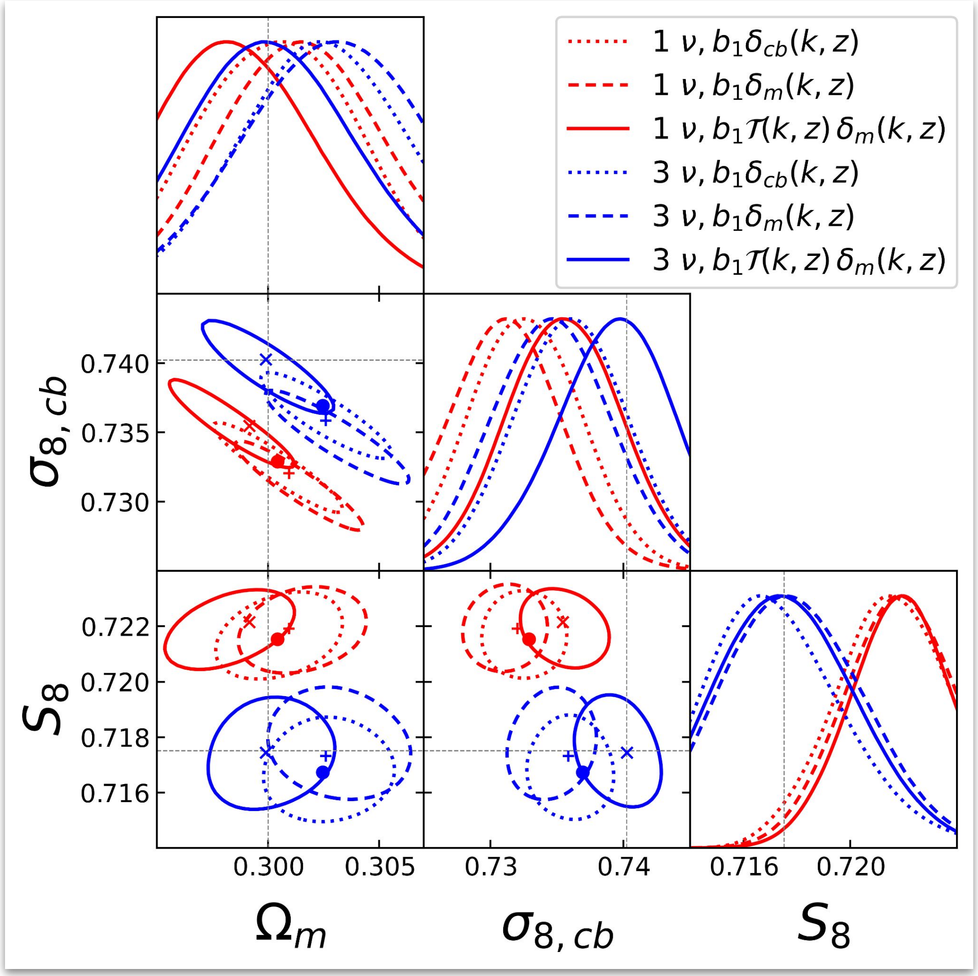
DESY3 0.3σ Cosmological Contours

- DESY3 mostly insensitive to detailed neutrino modeling
- Constant galaxy bias decreases parameter inference precision up to 10%



LSSTY1 0.3σ Cosmological Contours

- LSST Y1 sensitive to detailed neutrino modeling
- NISDB increases inference precision up to 20%
- 1 -neutrino models significantly biased



Systematic Bias Criteria

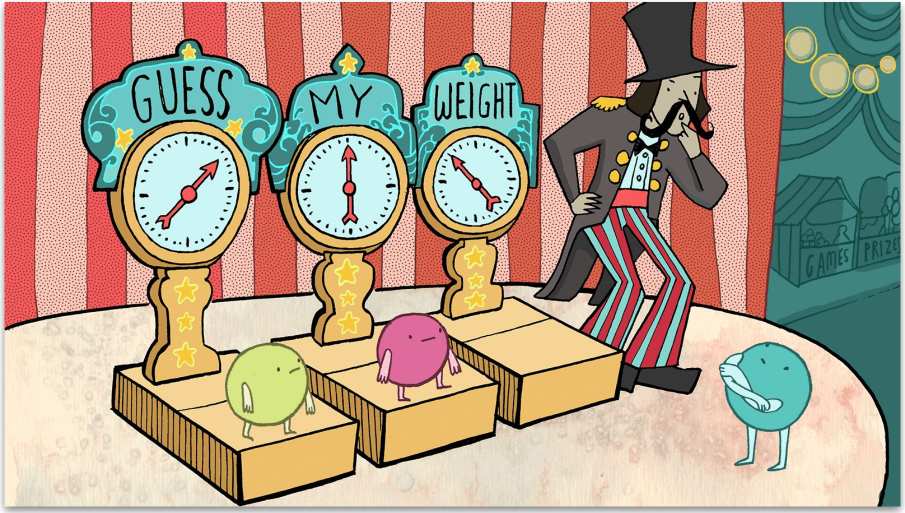
Depending on the parameters used to define internal consistency, biases due to galaxy clustering modeling choices **can be hidden** in the final 3x2pt inferences

Model		$S_8 - \Omega_m$ DESY3	$S_8 - \Omega_m$ LSSTY1	$\sigma_8 - \sigma_{8,\mathrm{cb}}$ DESY3	$\sigma_8 - \sigma_{8,\mathrm{cb}}$ LSSTY1
3ν	$b_1 \mathcal{T}(k,z)\,\delta_\mathrm{m}(k,z)$	0.02	0.01	0.07	0.01
	$b_1 \delta_\mathrm{m}(k,z)$	0.1	0.31	0.23	**0.89**
	$b_1 \delta_\mathrm{cb}(k,z)$	0.03	0.31	0.13	0.49
1ν	$b_1 \mathcal{T}(k,z)\,\delta_\mathrm{m}(k,z)$	0.02	**2.34**	**2.51**	**10.08**
	$b_1 \delta_\mathrm{m}(k,z)$	0.03	**1.54**	**2.85**	**10.08**
	$b_1 \delta_\mathrm{cb}(k,z)$	0.03	**1.48**	**2.73**	**8.28**

Model		$\Delta\chi^2$ DESY3 3x2pt	$\Delta\chi^2$ DESY3 $\gamma_t + w$	$\Delta\chi^2$ DESY3 w	$\Delta\chi^2$ LSSTY1 3x2pt	$\Delta\chi^2$ LSSTY1 $\gamma_t + w$	$\Delta\chi^2$ LSSTY1 w
3ν	$b_1 \mathcal{T}(k,z)\,\delta_\mathrm{m}(k,z)$	0.03	0.03	0.01	0.00	0.00	0.00
	$b_1 \delta_\mathrm{m}(k,z)$	0.15	0.11	0.05	0.19	**2.40**	**1.43**
	$b_1 \delta_\mathrm{cb}(k,z)$	0.25	0.24	0.18	0.05	**2.33**	**1.65**
1ν	$b_1 \mathcal{T}(k,z)\,\delta_\mathrm{m}(k,z)$	0.29	0.29	0.24	**1.84**	0.62	0.48
	$b_1 \delta_\mathrm{m}(k,z)$	0.34	0.31	0.24	**2.70**	**4.60**	**3.57**
	$b_1 \delta_\mathrm{cb}(k,z)$	0.32	0.30	0.25	**2.74**	**3.83**	**3.19**

Conclusions

- Detailed neutrino modeling results in increased precision of cosmological parameter inference
- Constant galaxy bias schemes degrade precision and induce biases in inferences
- S_8-Ω_m plane can hide systematic biases in galaxy clustering models



https://www.symmetrymagazine.org/article/how-heavy-is-a-neutrino