Euclid forecasts for neutrino masses: How to use the data?

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Outline

Neutrinos in cosmology

Parameter inference

Ignoring neutrino mass biases parameter estimation.

- Cosmic Microwave Background: taking a total neutrino mass of 0 or 0.06 eV shifts the central value of H_0 by 0.6 km/s/Mpc
- Large Scale Structure: even more sensitive: a minima, $\frac{\Delta P_k}{P_k} \simeq 5\%$ at small scales, today.

Complementary probe to laboratory experiments

- Cosmology probes the total mass, giving upper bounds.
  Planck: $\sum m_\nu < 0.23$ eV
- Laboratory probes Δm^2, giving lower bounds.
  Current: $\sum m_\nu \geq 0.06$ eV ($\Delta m^2 = 0.25\ 10^{-3}$ev^2, $\delta m^2 = 7.5\ 10^{-5}$ev^2)

Neutrinos mass from Planck (CMB)

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Planck constraint

Actually, Planck + Baryon Acoustic Oscillations (BAO) + low-ℓ WMAP polarization data + high-ℓ ACT/SPT data:

$$\sum m_\nu < 0.23 \text{ eV} \ @ \ 2\sigma$$

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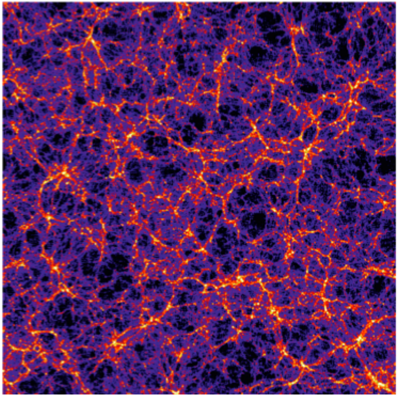
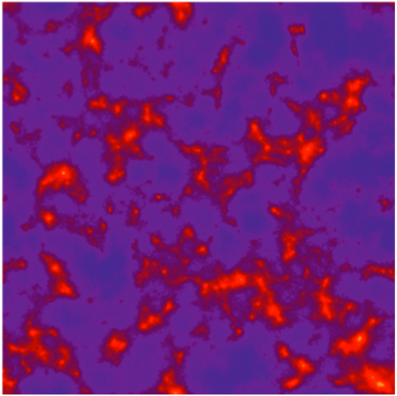
However...

- Planck temperature (TT) probes $\sum m_\nu$ through Early Integrated Sachs Wolfe Effect (EISW) and lensing smoothing : prefers zero mass
- Planck reconstructed lensing potential slightly prefers non-zero mass
- Planck SZ cluster count prefers non-zero mass but is based on many (relatively) uncontroled assumptions.

Neutrinos in structure formation

Effect of washing out of structures: small mass induces large velocities, removing power from too small over-densities.





N-body simulation w and w/o massive neutrinos (Credits to Matteo Viel)

Neutrinos in structure formation

Effect of washing out of structures: small mass induces large velocities, removing power from too small over-densities.

Details

- @ large scales: peculiar velocity negligible: behaves like CDM
- @ small scales: velocity is important: do not fall in the potentials wells: washing out of structures
- Collapse rate of CDM: competition expansion - gravitational collapse @ small scales, matter power spectrum is suppressed

Neutrinos in structure formation

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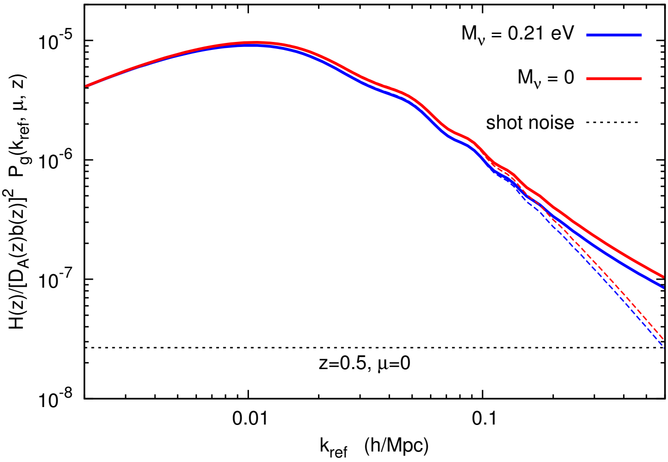

Neutrinos in structure formation

Affect both linear and non-linear scales

There is *a priori* a lot of information in the non-linear scales, but the effect is also there at the linear level (effect in % $\simeq$ total mass in eV)

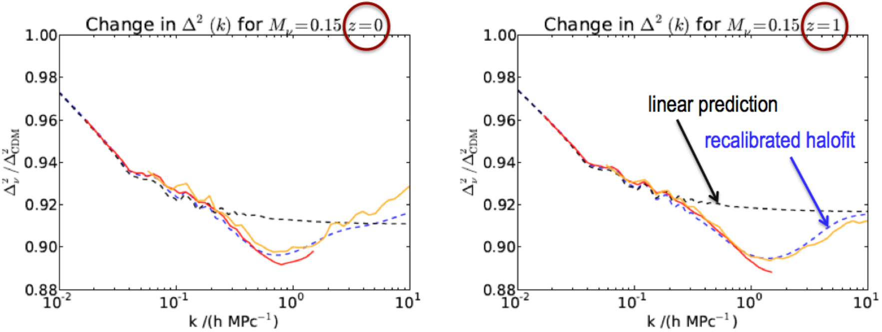

Figure: Redshift dependence of the non-linear effect of the neutrinos

Euclid survey(s)

Probing the very non-linear scales

- Euclid surveys coming in 2019 (galaxy redshift, Weak Lensing, cluster number count, cluster clustering)

- Probing matter distribution down to very small scales ($k \simeq 1$h/Mpc) with high precision
- Huge lever arm on effect of neutrinos on structure formation

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Question

Can we use this new wealth of data ? If yes, how ?

What do we need ?

Using non-linear data

- Theoretical prediction must be accurate enough compared to the predicted effect
- Computation fast enough to be used in a Markov Chain Monte Carlo process.

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Corrected halofit method

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Let's go then !

Different options

Methodology

Markov Chains Monte Carlo (Monte Python) analysis with redbook specification for Euclid and Planck.

Taking the data down to which scale ?

- Take only linear scales ($k < 0.1$ h/Mpc)
- Take non-linear scales, with N-body simulations
- Take up to mildly non-linear scales ($k < 0.6$ h/Mpc) with semi-analytical or fitting formulas

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Taking the data down to which scale ?

- Take only linear scales ($k < 0.1$ h/Mpc) ⟶☹: loosing the data!
- Take non-linear scales, with N-body simulations⟶☹: too slow !
- **Take up to mildly non-linear scales ($k < 0.6$ h/Mpc) with semi-analytical or fitting formulas**⟶☺: looking good !

Treading Carefully

Mildly Non-Linear Scales Are Close to Linear, Right ?

Assumptions

- Perfect knowledge of the non-linear power spectrum (halofit)
- Knowledge of the uncertainty (dependent on m_ν): correlated error in Fourier space
- Mock data simulating expected Euclid sensitivity

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We get . . .

- Amazingly good constraints ($\pm$ 6 meV at 1σ for the galaxy survey)
- but wait. . .

Treading Carefully

Right ?. . .

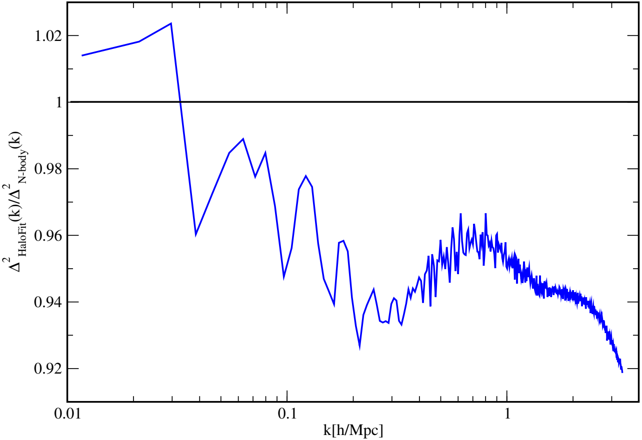

Figure: From 0812.1052 (Heithmann et al.) and **that is just for matter !**

Add bias, redshift-space distortions. . .

Back To Square One

If One Can Not Trust His Prediction...

How To Express What One Does Not Know ?

- Intrinsic uncertainty in theoretical prediction
- Translated into the likelihood analysis

Framework

Different possibilities:

- Functional expansion: form filling function (Kitching et al. 2008)
- Uncorrelated error: errors can be arbitrarily shaped (BA et al. 2012)
- Something else ?

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Details on the method

Ideal World

- Theoretical prediction has a systematic error: known, $f(k, z)$
- One nuisance parameter added to the analysis, marginalized over.
- The underlying theory is thought to be spot-on.
- correlated theoretical error

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Real World

- We are not sure of the underlying theory. No(t yet!) model describing its error.
- Add a shape, $\alpha(k, z)$ describing the envelope of the possibilities
- Marginalize independently one nuisance parameter per data point
- uncorrelated theoretical error

Visual solution to the problem

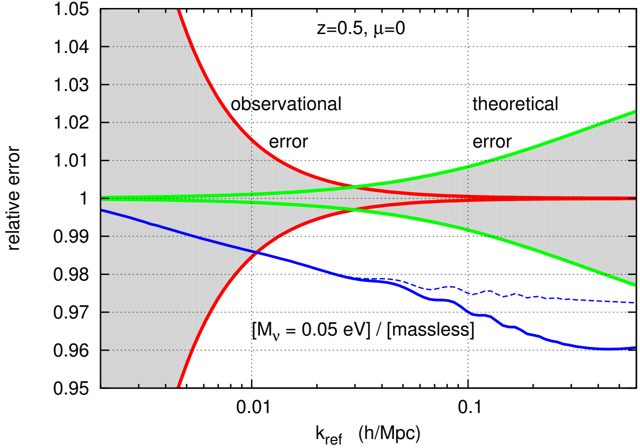


Figure: Uncorrelated error with a plausible envelope

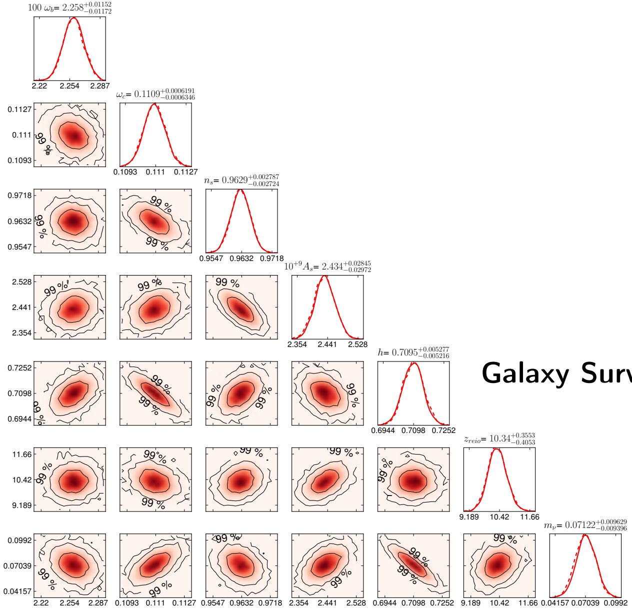
Visual solution to the problem

Design Policy: $\Delta\chi^2 = 1$

- Modification of standard likelihood: shift of the prediction within the green band produces $\Delta\chi^2 = 1$.
- Shape of the error:

$$\alpha(k, z) = \frac{\log(1 + k/k_{\rm NL}(z))}{1 + \log(1 + k/k_{\rm NL}(z))} 0.05 \qquad (1)$$

- Independent on the number of data points
- Uncorrelated error increases with k and decreases with z
- Envelope's shape is arbitrary (but plausible !)
- Also tried an error saturating at $\frac{1}{2}$, or $\frac{1}{10}$ of the amplitude.



Galaxy Survey

k_{max} (h/Mpc)	un. err.	co. err.	$10^4\omega_b$	$10^4\omega_c$	$10^3 n_s$	$10^{11} A_s$	$10^3 h$	z_{reio}	$3m_\nu = M_\nu$ (meV)
0.1	–	–	1.2	6.2	2.8	3.0	4.1	0.38	18
0.1	1/10	–	1.2	6.9	2.8	3.1	4.5	0.39	18
0.1	1/2	–	1.3	9.5	3.2	3.5	6.1	0.39	23
0.1	•	–	1.3	11	3.4	3.6	6.7	0.40	25
0.1	•	•	1.3	11	3.4	3.6	6.7	0.40	25
0.6	–	–	0.86	2.1	0.37	1.2	0.40	0.23	5.9
0.6	1/10	–	1.1	4.8	2.5	2.7	3.0	0.37	14
0.6	1/2	–	1.2	8.6	3.2	3.4	5.7	0.39	22
0.6	•	–	1.3	10	3.4	3.6	6.7	0.39	25
0.6	•	•	1.3	10	3.4	3.6	6.7	0.39	25

Marginalized 1-σ error for each model parameter for the galaxy survey

$k_{\max}$ (h/Mpc)	un. err.	co. err.	$10^4\omega_b$	$10^4\omega_c$	$10^3 n_s$	$10^{11}A_s$	$10^3 h$	z_{reio}	$3m_\nu = M_\nu$ (meV)
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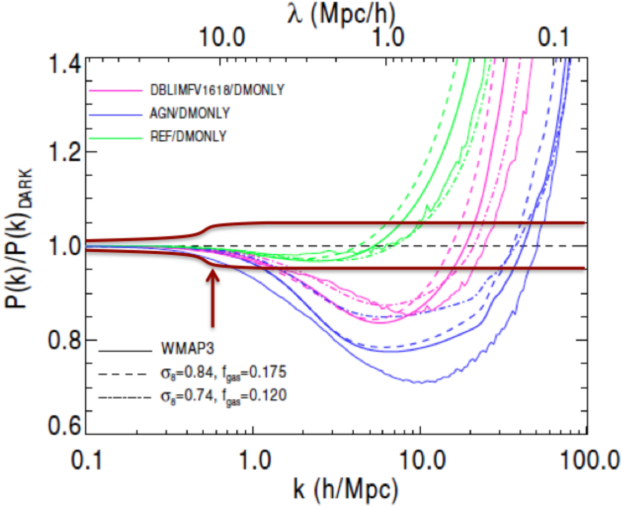
–	–	1.1	3.9	2.4	2.8	4.0	3.7	26
•	–	1.2	6.3	2.7	2.9	5.2	3.8	28
•	•	1.2	6.6	2.7	3.0	5.3	3.9	32

Marginalized 1-σ error for each model parameter for the lensing survey

Baryonic effects

Semboloni et al. 2011, 2012; Zentner et al. 2012



Ways to improve the study

Breaking degeneracies by using other surveys

- Costanzi et. al. 2013, Basse et. al 2013
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Understand better what we are measuring !

- Determine, at least roughly, the scale/time dependence of the error
- This might not be trivial. . .

Tools of the trade

Boltzmann code

Cosmic Linear Anisotropy Solving System (Lesgourgues Blas Tram 2010)

- Written in C, with structures (much like C++ classes)
- Available at http://class-code.net

Markov Chain Monte Carlo

Monte Python, a Monte Carlo code in Python (no pun intended)

- Modular, Pythonesque, Automatic documentation with code browsing
- Available at http://montepython.net and on GitHub
- Tracking of code version, likelihood options, stored with data

Current usage

Planck data analysis (alongside CosmoMC), WiggleZ analysis, etc.

Tools of the trade

Monte Python

- Comes with Planck likelihoods, Euclid forecasts, WiggleZ likelihoods
- Convenient way to implement new likelihoods (class inheritance)
- Python is A Good Thing™:
  → plays nicely with C, fortran, flexible, fast (to develop), readable
- Saving data with the chains !!
- No need to edit the code - if the boltzmann code knows the parameter, it will work
- Version Control with git - clone, download, patch, submit !

What Did We Learn ?

Ignorance comes with a price

- Errors are tricky to deal with in likelihoods
- With the current knowledge about non-linear Power Spectrum:
  $\rightarrow$ better sticking to linear scales
- 0.2% precision for the galaxy (!) power spectrum up to $k = 0.6$h/Mpc would help:
  $\rightarrow$ Can we do that ?
- Current estimates might be overly optimistic even though they stop at supposedly linear scales. . .