Euclid France Galaxy Clustering

Contraindre la masse des neutrinos avec le spectre de puissance sur les simulations DEMNUni

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Thèse sous la direction de William Gillard et Stéphanie Escoffier

CPPM, RENOIR

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Plan of the talk

I. Massive neutrinos in cosmology

II. The power spectra of the DEMNUni simulations

III. Parameter estimation on the DEMNUni spectra

The standard model of cosmology, ΛCDM.

- Homogeneous and isotropic universe
- Λ = Responsible for the accelerated expansion
- CDM = Cold Dark Matter (non-standard and non-relativistic)
- Flat universe

The standard model of particle physics assumes : $m_\nu = 0$

Particle Physics experiment :

➡ $m_\nu \neq 0$

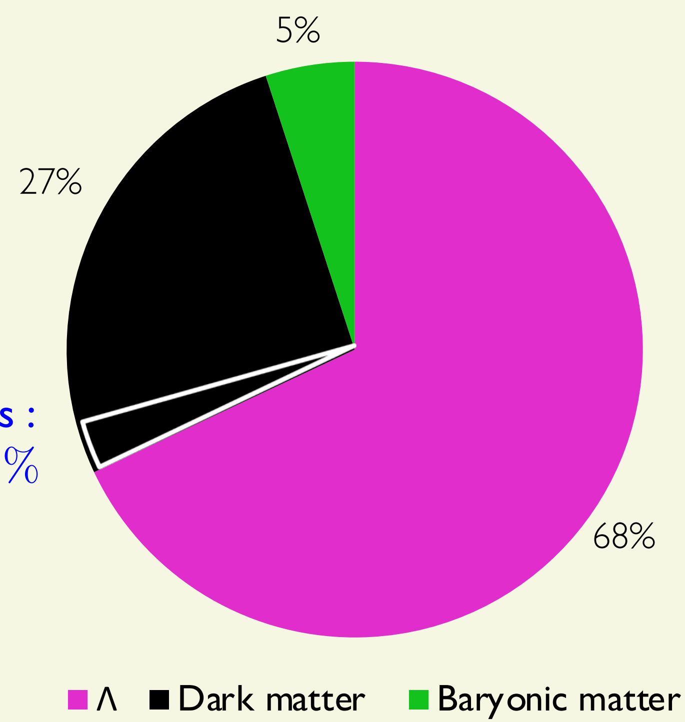
NH $0.056 \text{ eV} \lesssim M_\nu \lesssim 1 \text{ eV}$ → Neutrinos : $0.1\% - 2\%$

IH $0.095 \; eV$

Oscillation experiments
(Kamiokande, SNO, T2K)

Tritium β decay
(KATRIN)

Content of our universe today :



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Cosmology : $M_\nu < 0.13 \text{ eV}$

[A. J. Cuesta et al. 2016]

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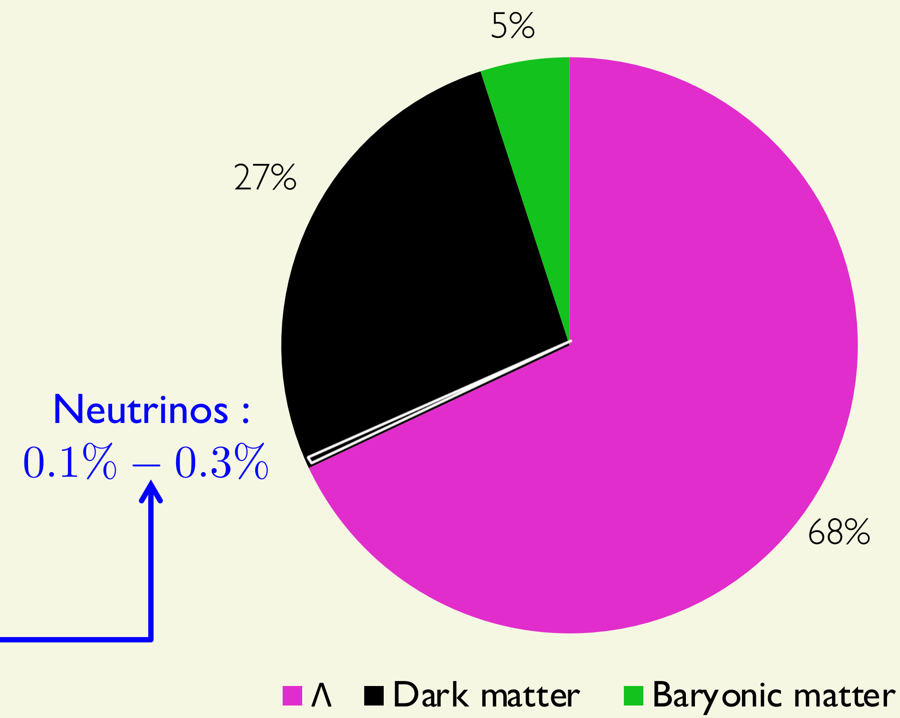


As the universe expands its temperature decreases

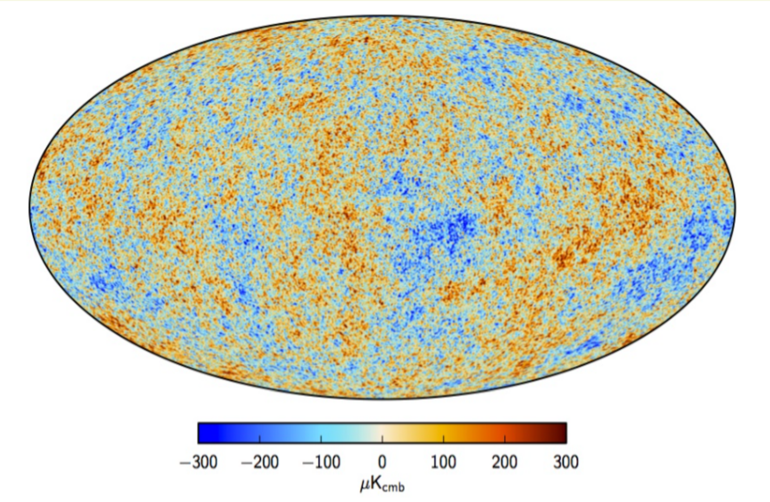
Expanding universe ➡ Relativistic at the beginning, they become non-relativistic.

$T_\nu \gg m_\nu$ → Radiation : No gravitational clustering.

$T_\nu \ll m_\nu$ → Dark matter : Gravitational clustering.

This transition has an impact on the matter distribution.

If we can spot at which redshift $z_{\rm nr}$ this transition happened, we could know the value of m_ν .



$$1 + z_{\rm nr} = 1890 \left(\frac{m_\nu}{1 \text{ eV}} \right)$$

CMB ➡ No trace of non-relativistic neutrinos (in the TT power spectrum) at z = 1100. ➡ $m_\nu \lesssim 0.58 \text{ eV}$

Because of their high velocity dispersion neutrinos are free streaming.

Thermal velocity : $v_{\rm th} = \frac{3T_\nu}{m_\nu} \approx 150(1+z)\left(\frac{1\ \rm eV}{m_\nu}\right)\ \rm km/s$

Free streaming length $\lambda_{\rm FS}(t) \propto v_{\rm th}(t)$: causal horizon for neutrinos.

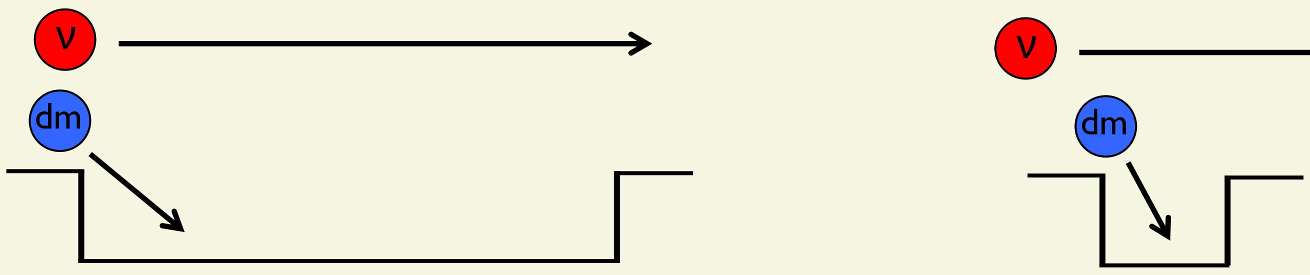
The effect of free streaming is to damp δ_ν on small scales.

- Before the transition : $\lambda_{\rm FS}$ grows like the Hubble radius (causal horizon for photons)
- After the transition : $\lambda_{\rm FS}$ decreases relatively to the Hubble radius

At the non-relativistic transition, $\lambda_{\rm FS}$ reaches a maximum value $\lambda_{\rm nr}$.

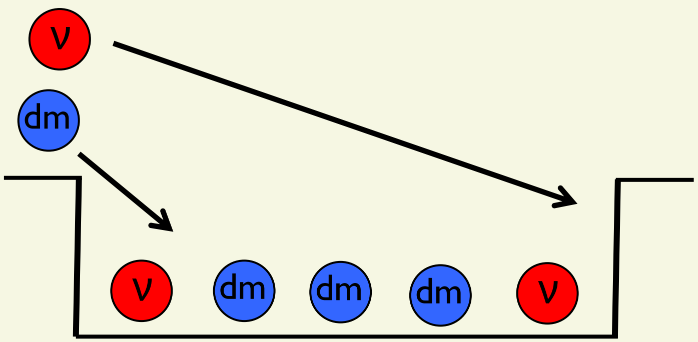
$$k_{\rm nr} = 0.018\ \Omega_{\rm m}^{1/2}\left(\frac{m_\nu}{1\ \rm eV}\right)^{1/2}\ h/\rm Mpc$$

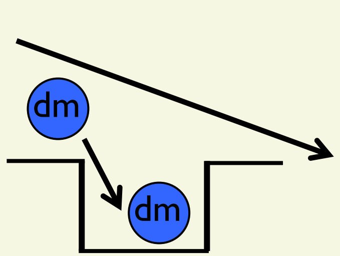
Before the transition (relativistic neutrinos) : Only CDM falls in the gravitational potential wells.



➡ Matter fluctuations are growing on all scales.

After the transition (non-relativistic neutrinos) : Free streaming ➡ neutrinos escape from the potential wells on small scales





For $k < k_{\rm nr}$: $\delta_{\rm tot}$ is not affected by free streaming, because after the transition δ_ν behaves like $\delta_{\rm cdm}$.

For $k > k_{\rm nr}$: δ_ν do not contributes to $\delta_{\rm tot}$ because of the free streaming.

$$f_\nu = \frac{\Omega_\nu}{\Omega_{\rm m}}$$

$$\Delta\Phi = 4\pi G a^2 \bar{\rho}\delta_{tot} = 4\pi G a^2 \bar{\rho}\left[(1-f_\nu)\delta_{cdm} + f_\nu \delta_\nu\right]$$

➡ **The matter power spectrum is damped for $k > k_{\rm nr}$**

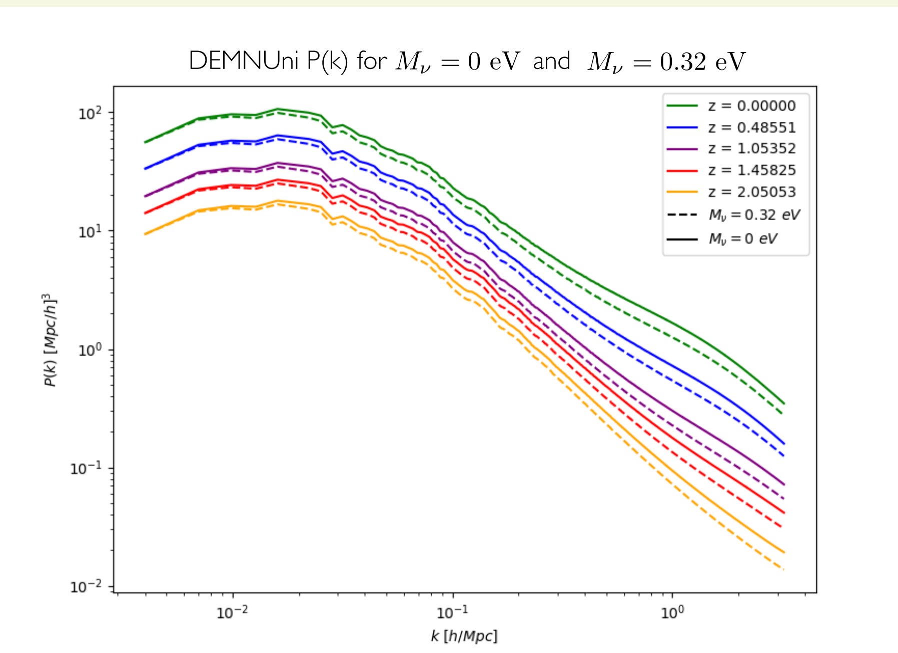
II. The power spectra of the DEMNUni simulations

DEMNUni (Dark Energy and Massive Neutrino Universe) : Set of 11 simulations.

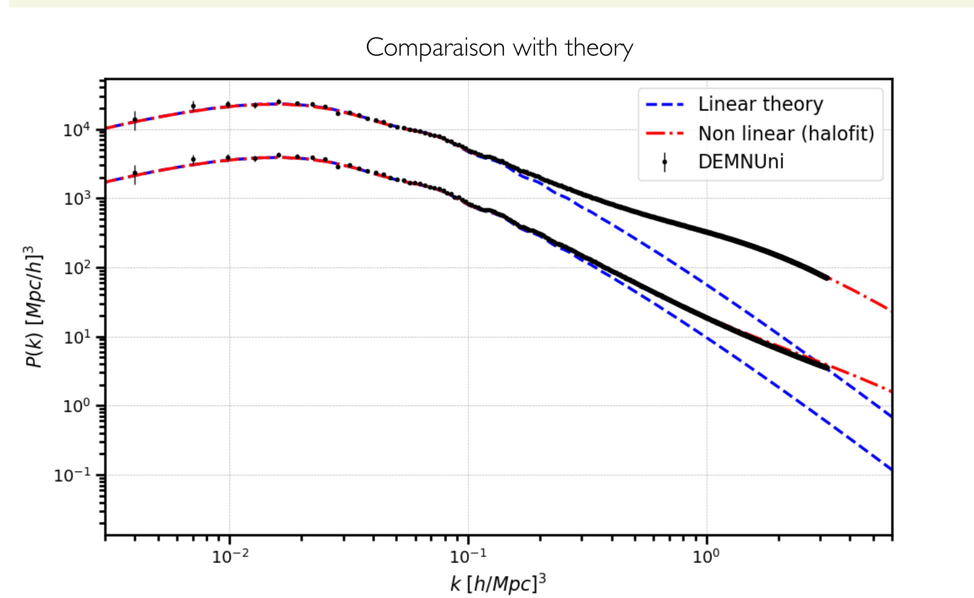
(Box with L = 2000 Mpc/h)

- **Massive neutrinos** : $M_\nu = 0.00,\ 0.16,\ 0.32\ \mathrm{eV}$
- Different equations of state for the **dark energy** (w_0, w_a)
- Number of particles : $N_p^{cdm} = 2048^3 \sim 8.6\ 10^9$ (+ $N_p^{\nu} = 2048^3 \sim 8.6\ 10^9$)
- **Time evolution** with 5 redshifts : $z = [0,\ 0.5,\ 1,\ 1.5,\ 2]$

Managed by Carmelita Carbone in Milan.



Damping of the power spectrum on small scales.



Non linear evolution on small scales.

Estimating the power spectrum ➡ estimating the amplitude of density fluctuations in Fourier Space.

[E.Sefusatti et al. 2015] The estimator is : $$\hat{P}(\mathbf{k}) = k_f^3 \, |\delta(\mathbf{k})|^2 \qquad k_f = \frac{2\pi}{L}$$

There are two methods to estimate $\delta(\mathbf{k})$

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Direct summation :

$$\delta(\mathbf{k}) = \frac{1}{(2\pi)^3}\left[\frac{1}{\bar{n}}\sum_i^{Np} e^{-i\mathbf{k}.\mathbf{x}_i} - \delta_{\mathbf{k}}^K\right]$$

For each mode : take the contribution of all the particles

- **Pros :** No aliasing du to FFT
- **Cons :** (Extremely) time consuming

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Sampling of the field + FFT :

Interpolate the particles on a grid ➡ $\tilde{\delta}(\mathbf{x})$

Perform an FFT on it ➡ $\tilde{\delta}(\mathbf{k})$

- **Pros :** Much faster
- **Cons :** The FFT induces aliasing for large k (near the Nyquist frequency)

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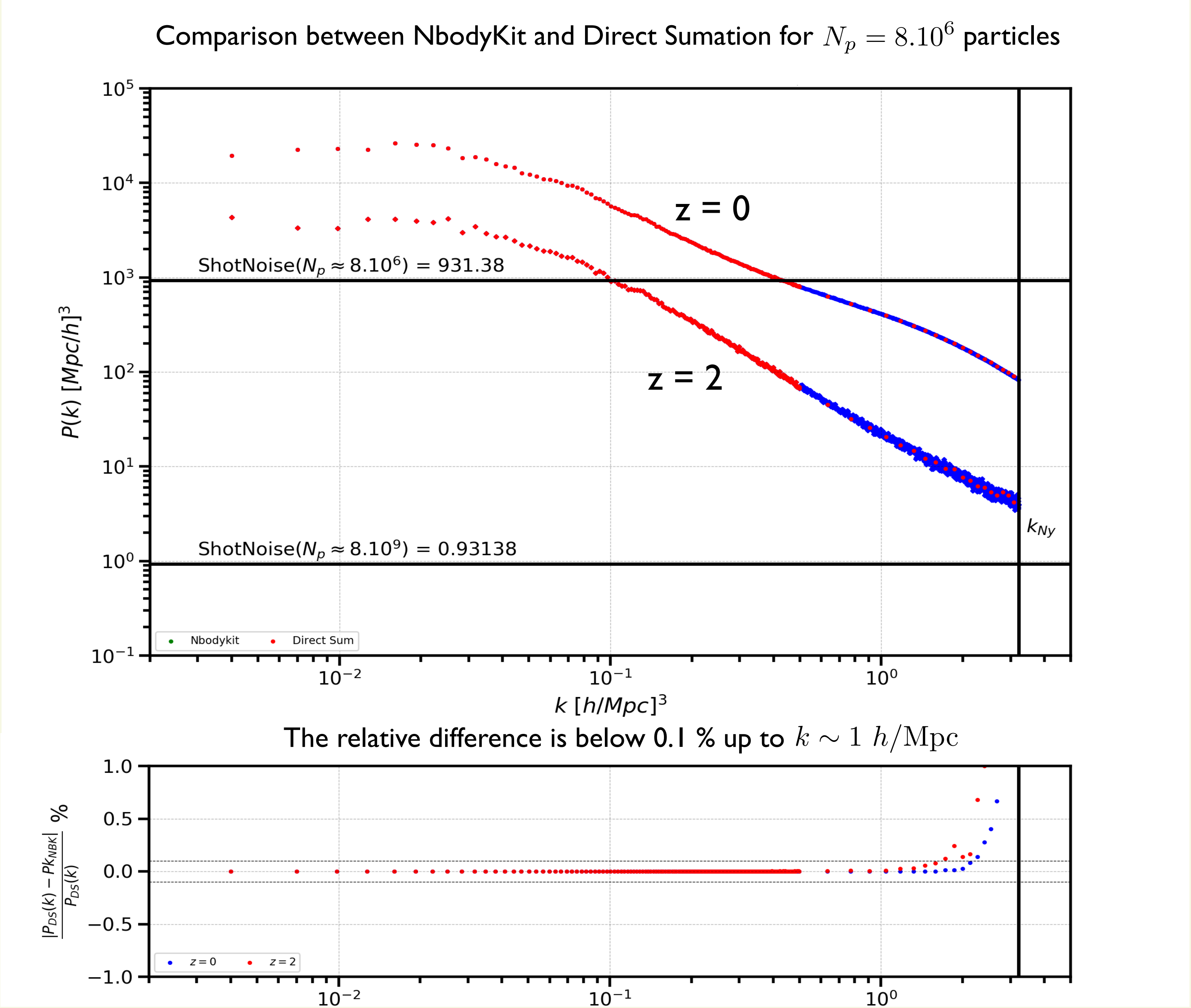
My code

Public code NbodyKit [N. Hand et al. 2017]

Validation of Nbodykit with my code using direct summation on the DEMNUni.

II. The power spectra of the DEMNUni simulations



Set-up for the parameter estimation using MCMC on the DEMNUni spectra :

- Choosing the simulation with $M_\nu = 0.32\ \mathrm{eV}$ $(m_\nu = 0.107\ \mathrm{eV})$
- Theoretical predictions ➡ class with halofit
- Errors on the power spectrum ➡ Gaussian theoretical errors (no covariance)

$$\sigma(k) = \frac{k_f P(k)}{k\sqrt{2\pi}}$$

- Using the 5 redshifts $z = [0,\ 0.5,\ 1,\ 1.5,\ 2]$
- Considering P(k) up to a certain k_{max} .
- Set of parameters to estimate :

$$\{\Omega_\mathrm{b},\ \Omega_\mathrm{cdm},\ h,\ n_s,\ A_s,\ z_\mathrm{reio},\ m_\nu\}$$

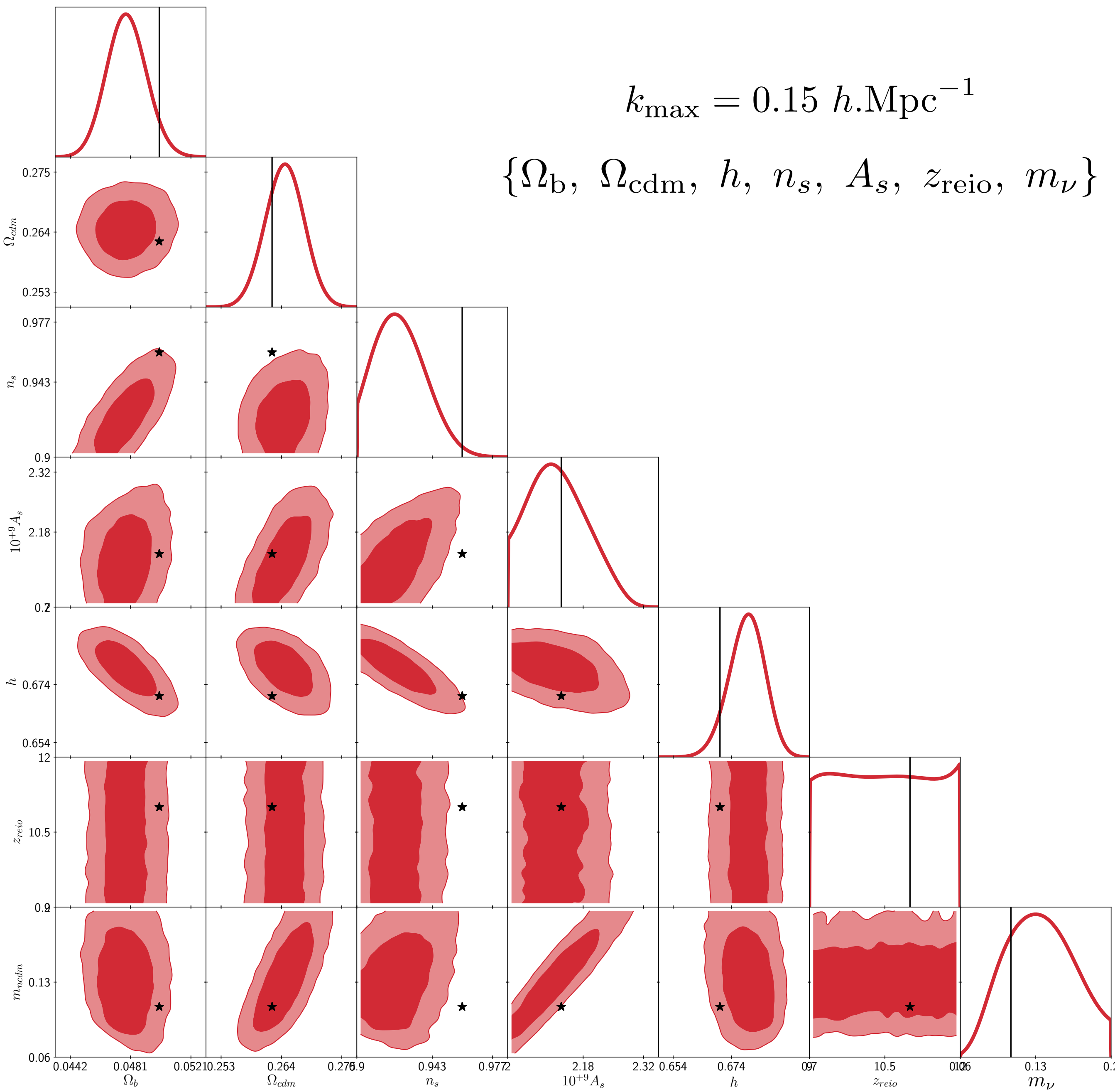
Or

$$\{\Omega_\mathrm{b},\ \Omega_\mathrm{cdm},\ h,\ m_\nu\}$$

III. Parameter estimation on the DEMNUni spectra

$$k_{\max} = 0.15 \ h.\mathrm{Mpc}^{-1}$$

$$\{\Omega_\mathrm{b},\ \Omega_\mathrm{cdm},\ h,\ n_s,\ A_s,\ z_\mathrm{reio},\ m_\nu\}$$



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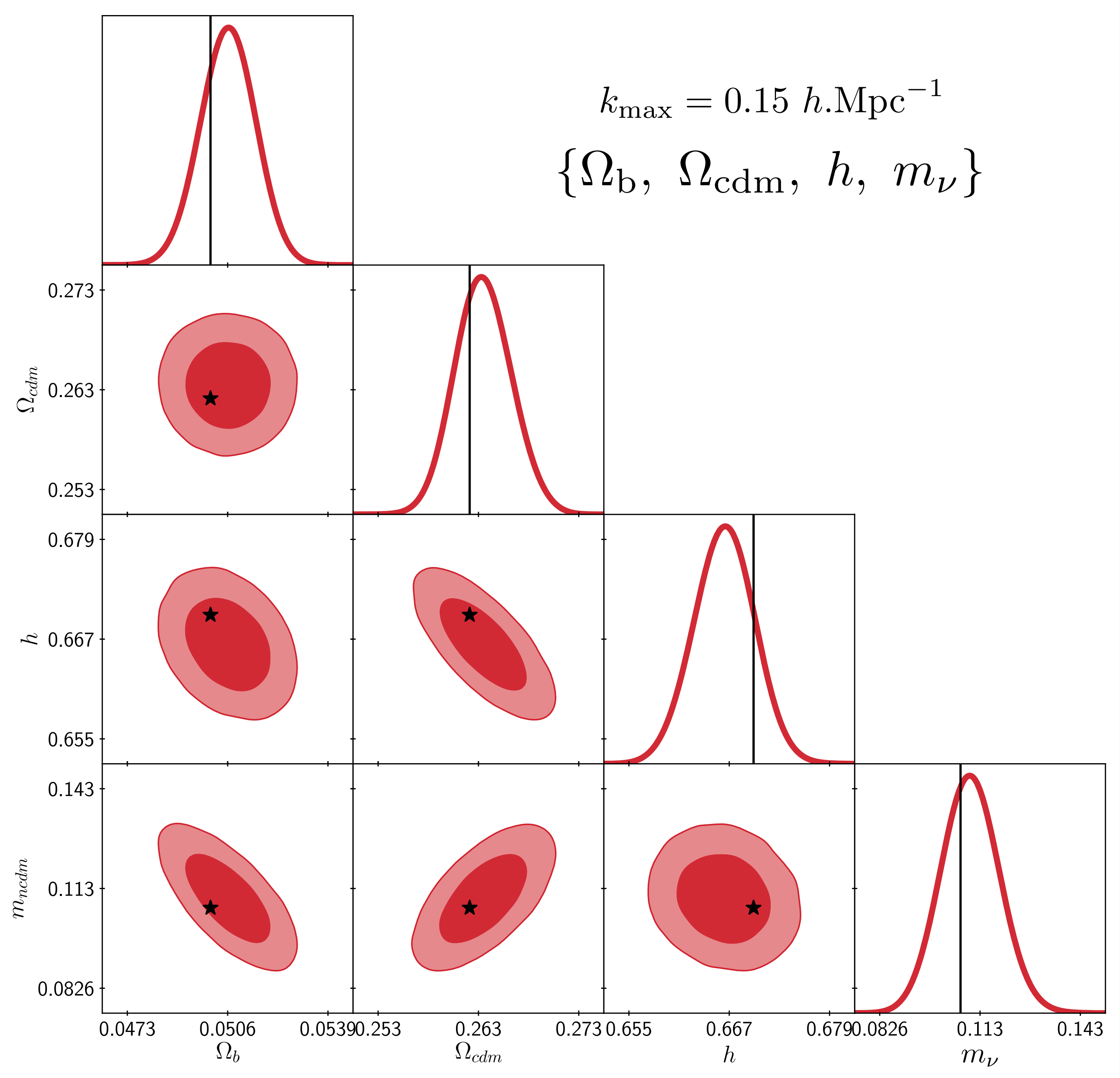

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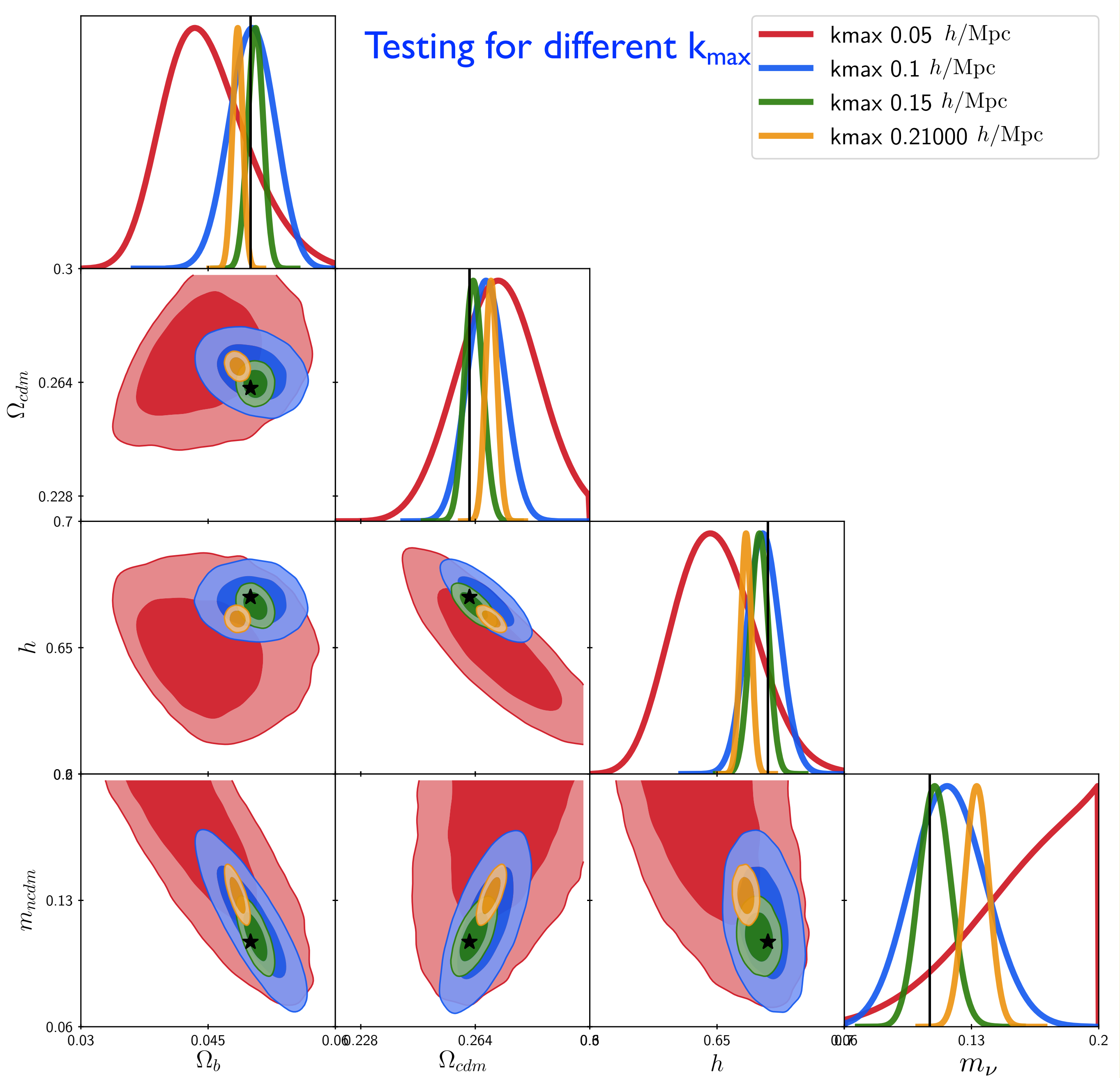
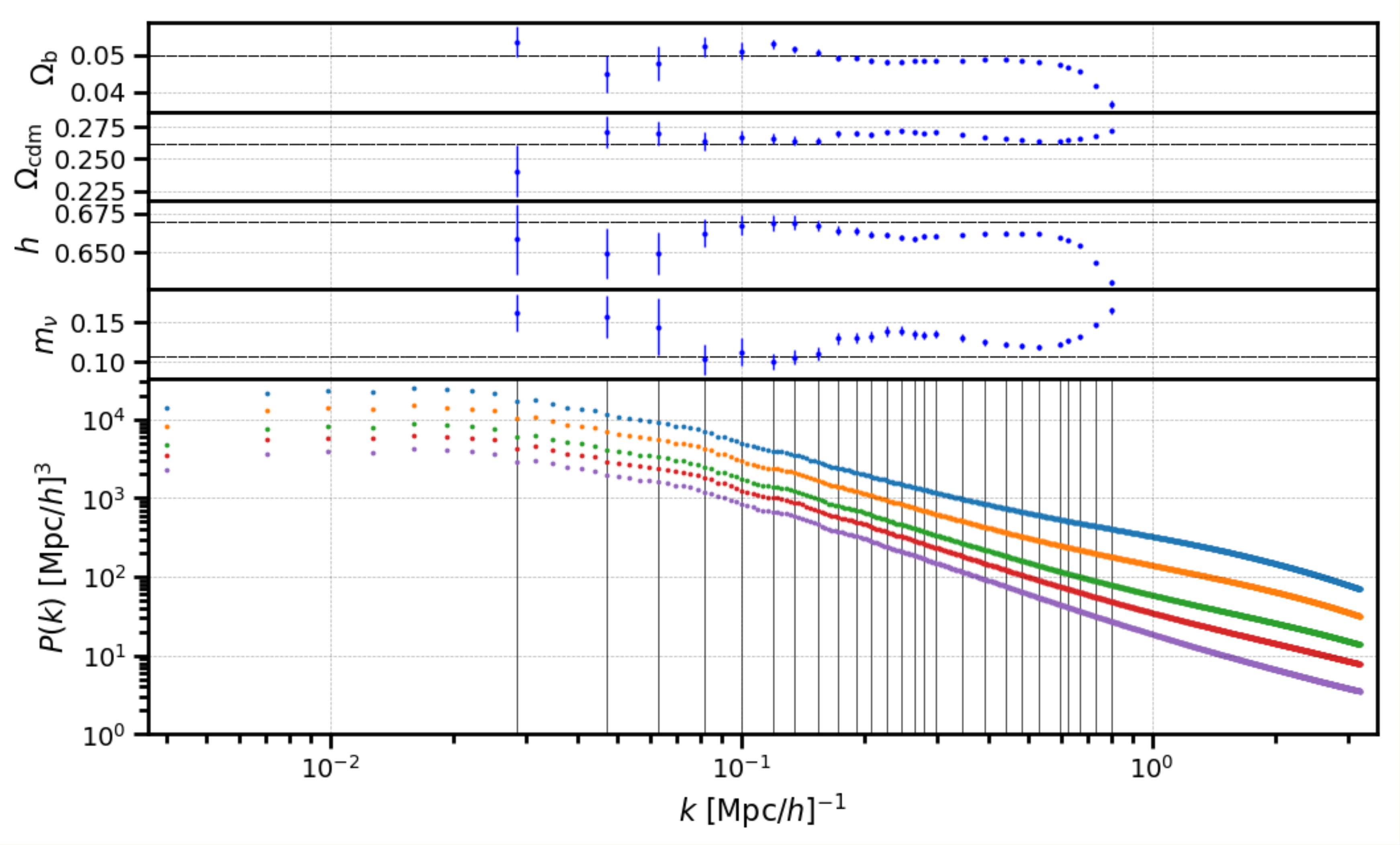


Testing for different k_{max}

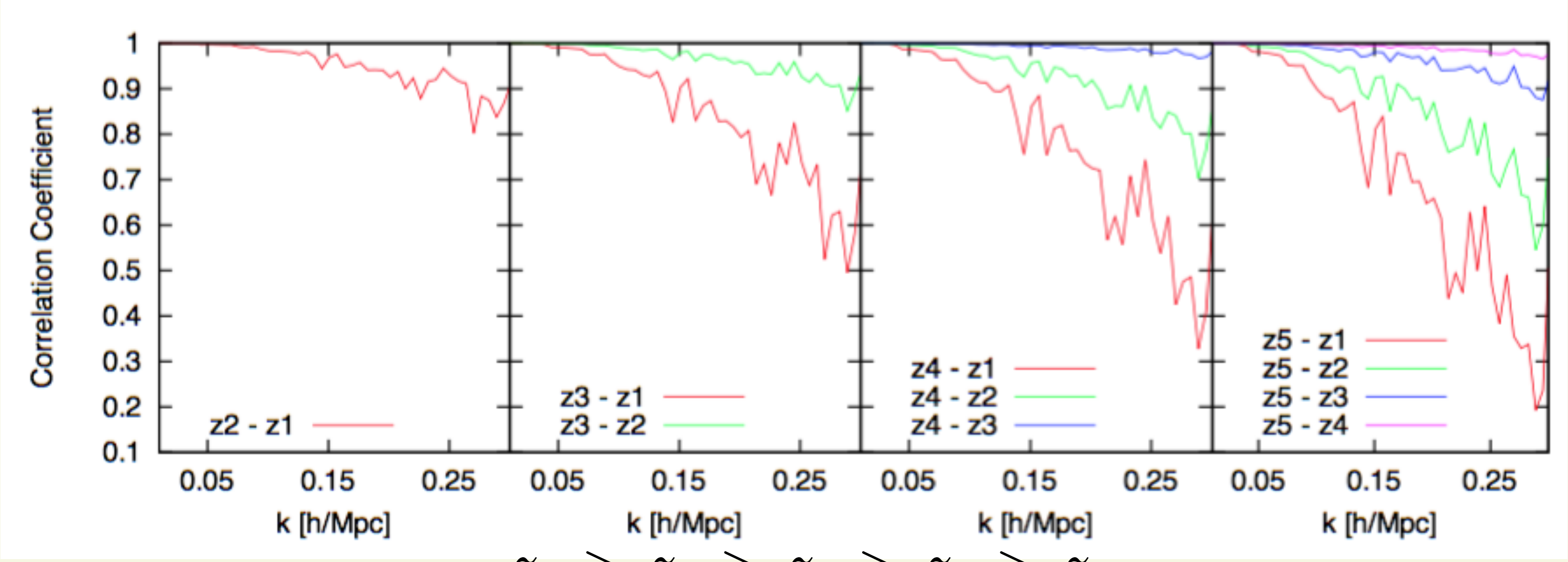


The error bars should be larger if we include the covariance.

Set of 50 smaller independant realizations to compute the covariance matrix.

Snapshot problem : One realization evolving with time ➡ High correlation between the redshifts.

Considering only the correlation for the same modes at different redshifts : $\rho(k;\ z_i,\ z_j)$



$$z_5 > z_4 > z_3 > z_2 > z_1$$

- High correlation for linear scales.
- Consecutive redshifts → high correlations.
- Small correlation at late times $\rho(z_1, z_2) < \rho(z_4, z_5)$: information is lost in non-linearities.

$\rho \sim 1$ ➡ The covariance matrix is almost singular.

Possible Solutions :

- Take 5 independent realizations for the 5 redshifts ➡ Remove the correlation.
- Create more simulations to divide the set of realizations in 5 subsets coresponding to the 5 redshifts ➡ Independent set for each z.
- Use Monte Carlo semi-analytique methods to predict the covariance matrix (see Philippe's talk). [Baratta et al. 2019]
- Jackknife.

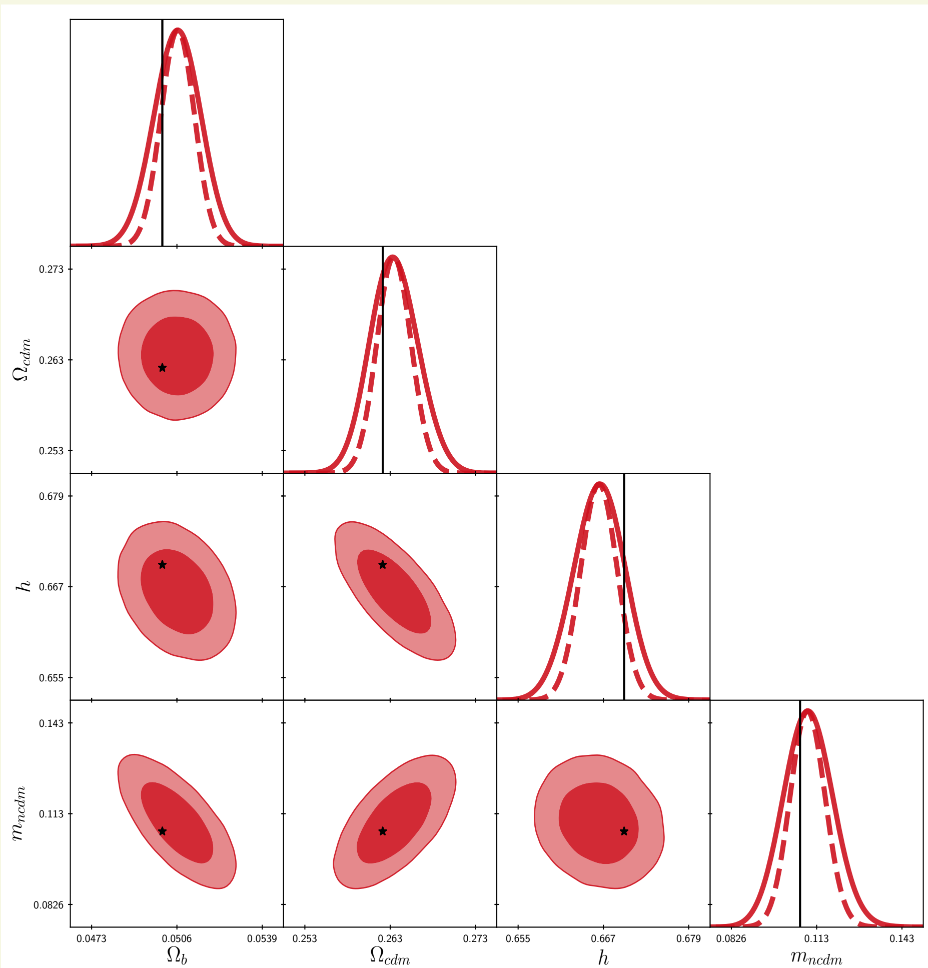
BACK UP

Étude sur {n_s , A_s , z_{reio}}

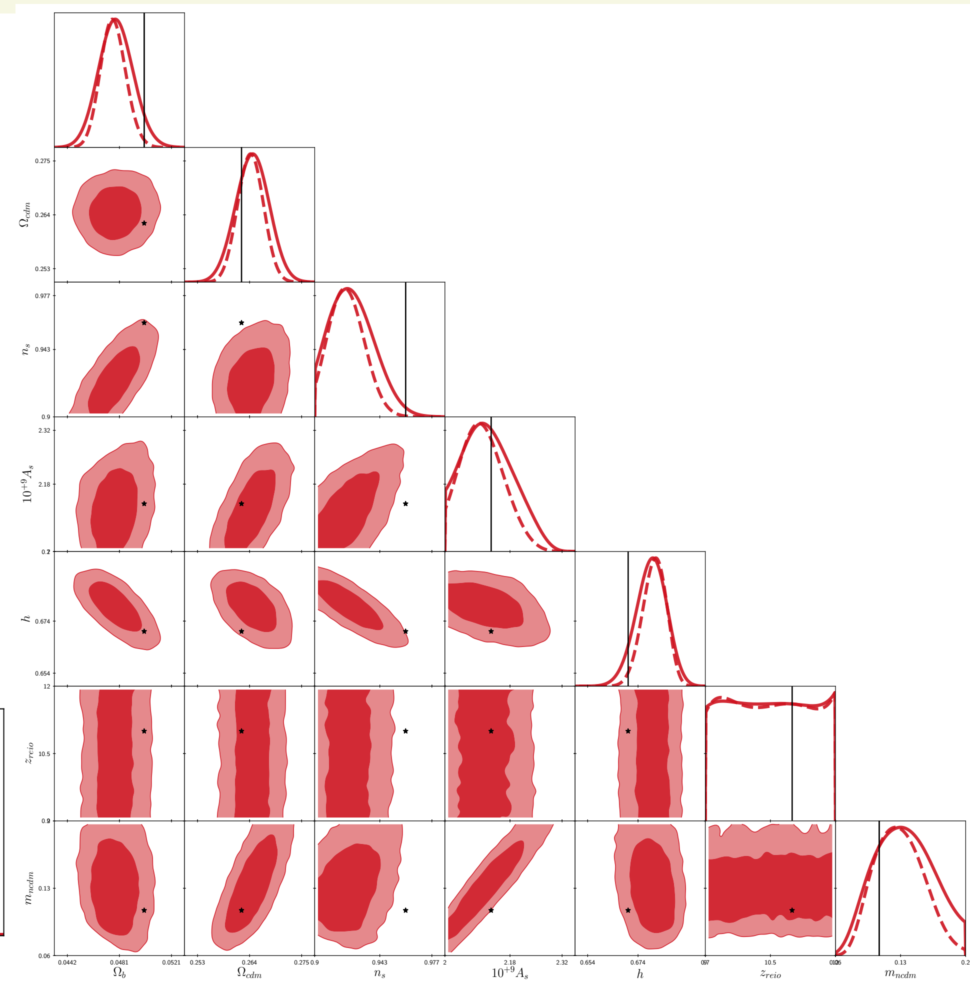
With MontePython

$k_{\max} = 0.15\ h.\mathrm{Mpc}^{-1}$

Fixed = $\{\Omega_\mathrm{b},\ \Omega_\mathrm{cdm},\ h,\ m_\nu\}$



All free = $\{\Omega_\mathrm{b},\ \Omega_\mathrm{cdm},\ h,\ n_s,\ A_s,\ z_\mathrm{reio},\ m_\nu\}$



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As

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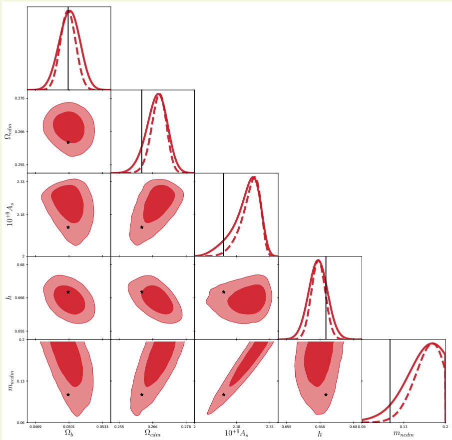
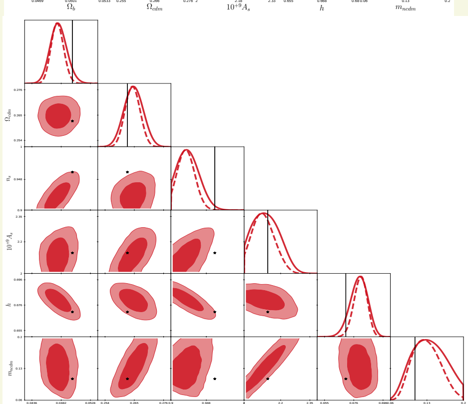
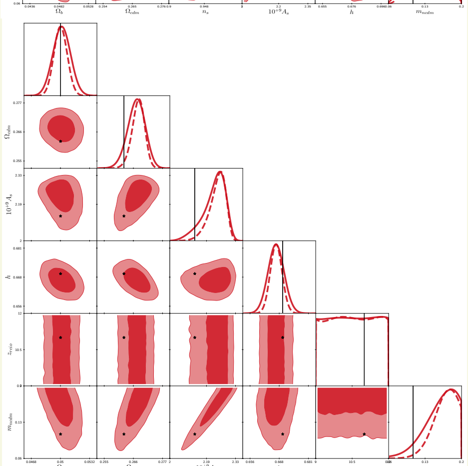


ns



z



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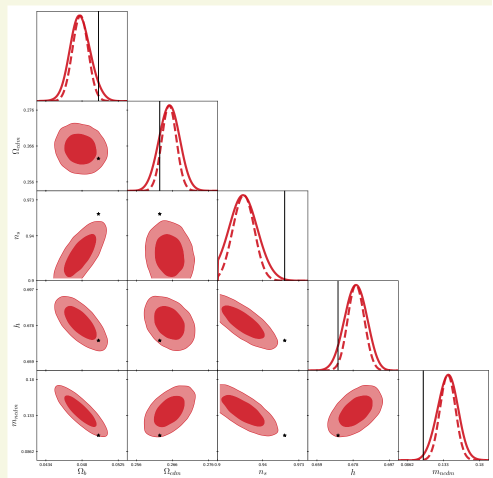
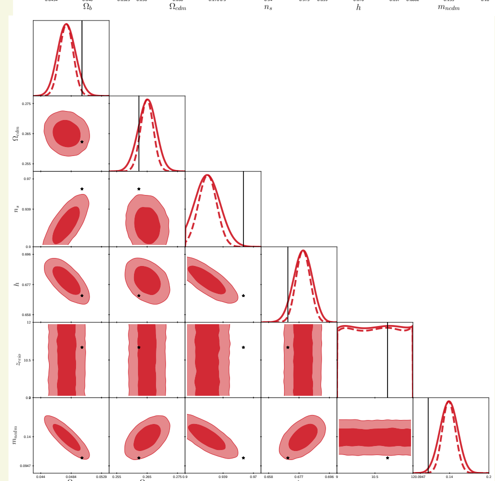
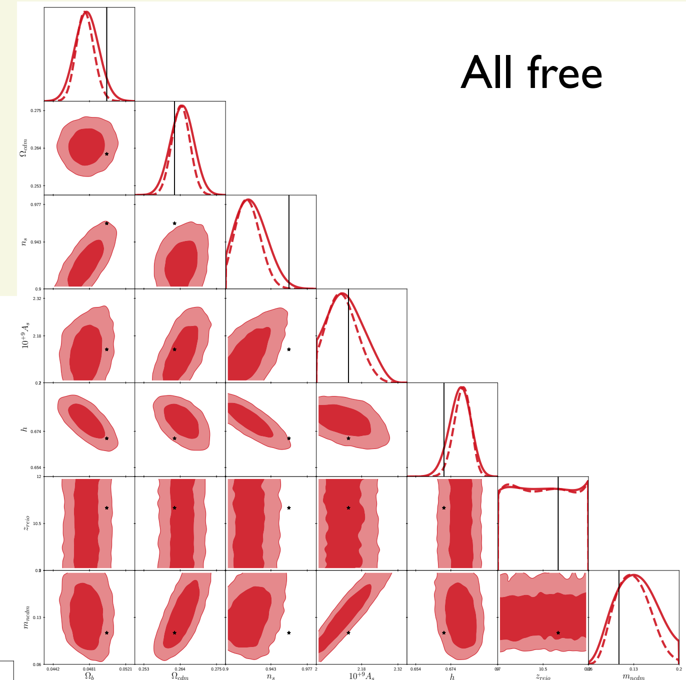
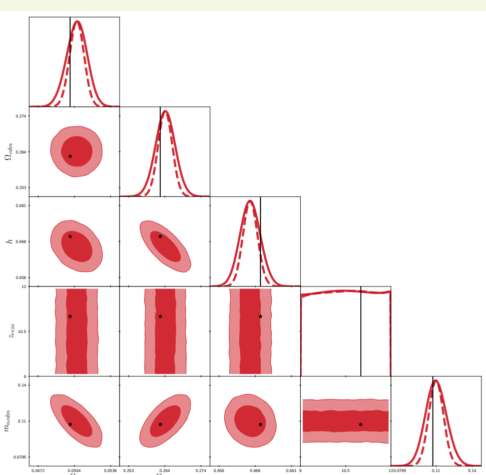




All free

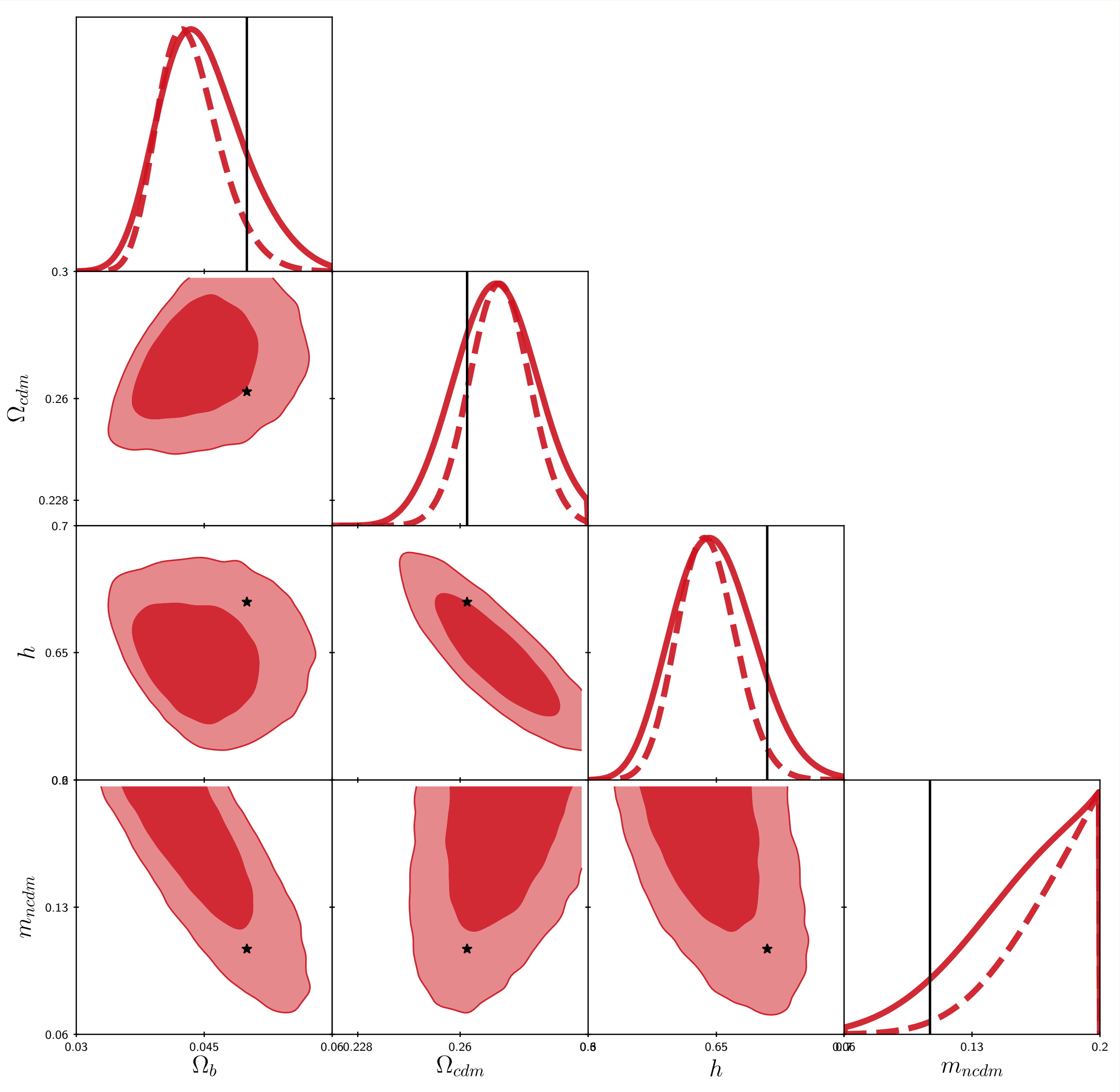


z



Dégénérescence entre Ω_b et m_ν

$k_{\max} = 0.05\ h.\mathrm{Mpc}^{-1}$



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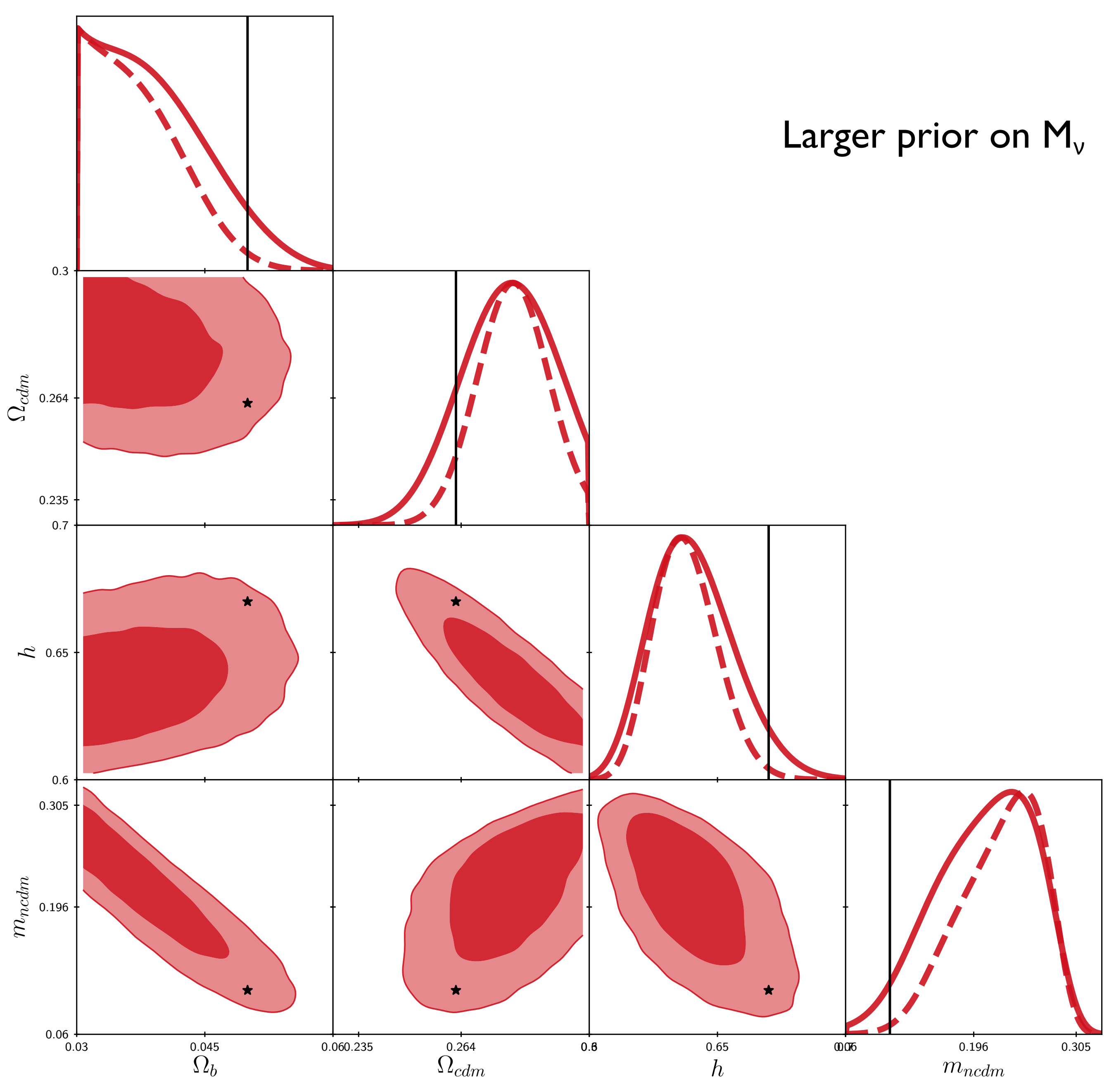
Larger prior on M_ν



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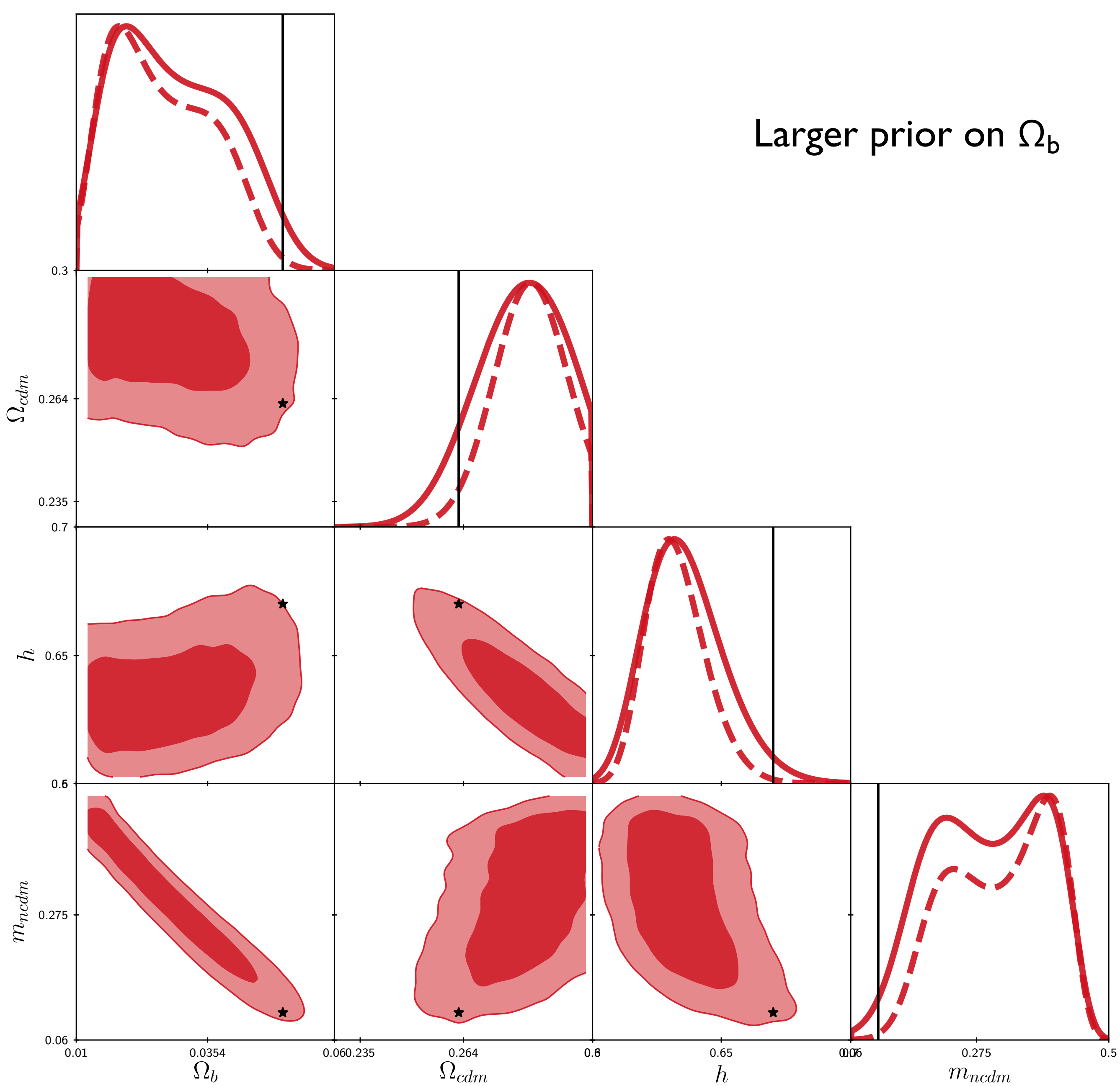

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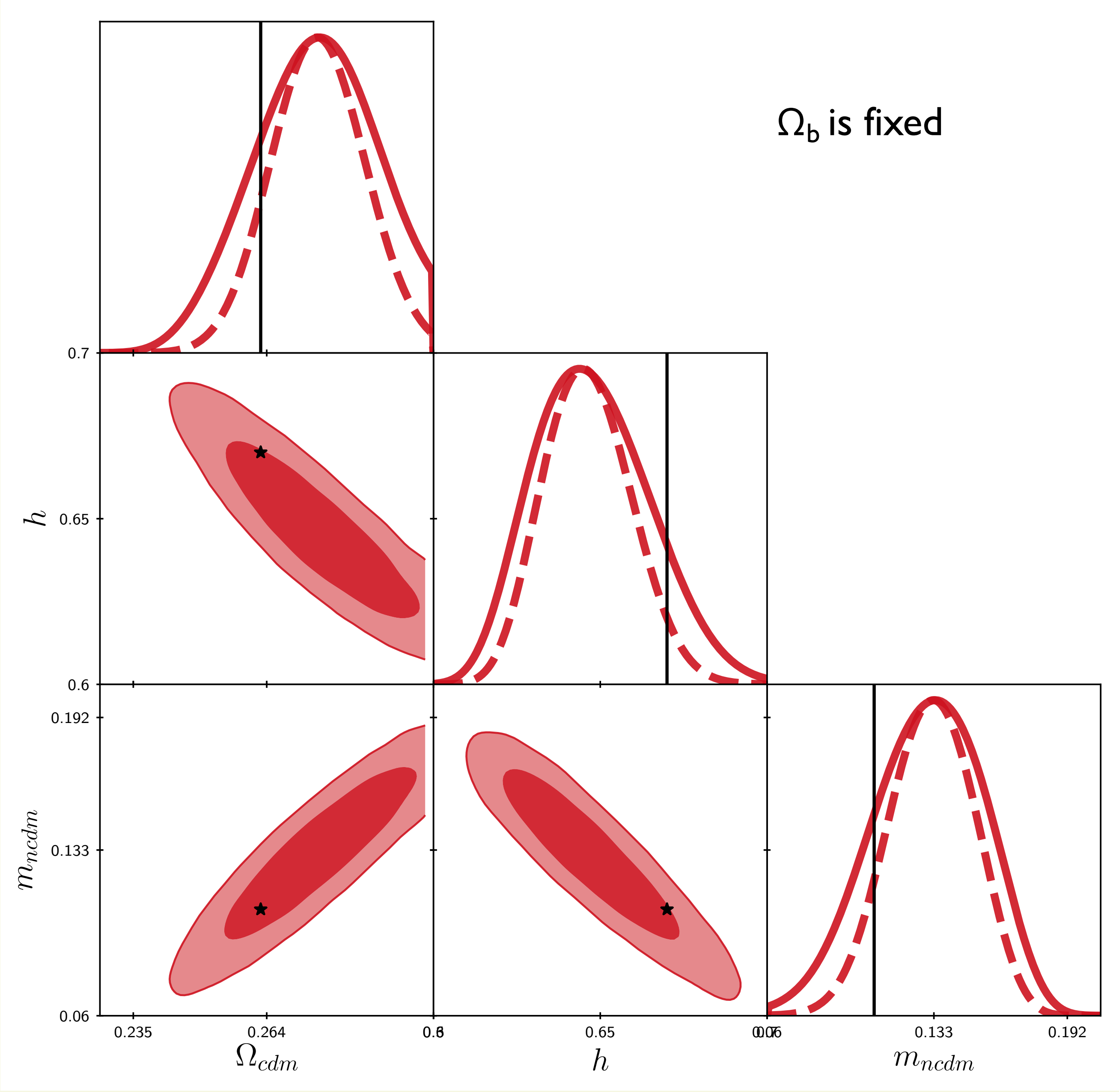


Bibliographic study :

« State of the art » on the cosmological total neutrino mass constraints.

Focus on 3 papers :

- G-B. Zhao et al. 2013
- A.J. Cuesta et al. 2016
- N. Palanque-Delabrouille et al. 2015

CMB constraints

- If neutrinos become non-relativistic before the CMB emission ➡ direct effect on the CMB temperature power spectrum.

We don't see the effect ➡

$$1 + z_{\rm nr} = 1890 \left(\frac{m_\nu}{1 \text{ eV}} \right)$$

$$z_{CMB} = 1100$$

$$m_\nu \lesssim 0.58 \text{ eV}$$

$$M_\nu \lesssim 1.7 \text{ eV}$$

- For any neutrino mass there are effects due to secondary anisotropies (CMB lensing and Integrated Sachs Wolff) and background effects.

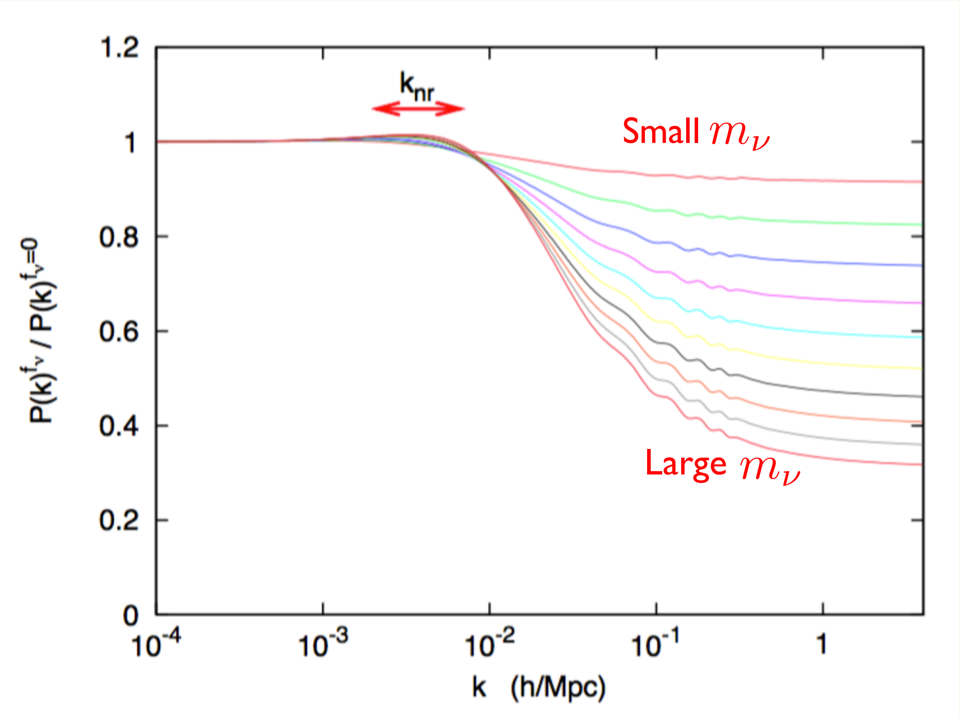
Planck 2015 (TT,TE,EE + lowP + lensing) ➡ $M_\nu < 0.59 \text{ eV}$

Power spectrum constraints

The power spectrum should be the most sensitive probe.

⬇

Add P(k) constraining power to CMB.



Focus on 3 papers :

- (1) Zhao et al. 2013 : Galaxy power spectrum using BOSS DR9 ⟹ $M_\nu < 0.34$ eV
- (2) Cuesta et al. 2016 : Halo power spetrum using BOSS DR7 ⟹ $M_\nu < 0.13$ eV
- (3) P-Delabrouille et al. 2015 : Ly-α power spectrum using BOSS DR9 ⟹ $M_\nu < 0.12$ eV

In all cases they choose to have three degenerate massive neutrinos.

Paper (1) : Galaxy power spectrum (BOSS DR9)

Main systematics : Bias determination, RSD and non-linearities modeling.

2 ways to handle the problem.

Pertubation theory (SPT)

$$P_m^{\mathrm{L}}(k) \longrightarrow P_m^{\mathrm{NL}}(k) \longrightarrow P_g(k) \longrightarrow P_g^{\mathrm{S}}(k)$$

Can go up to different orders for each step.

Fitting formula

Based on N-body simulation.

Halofit.

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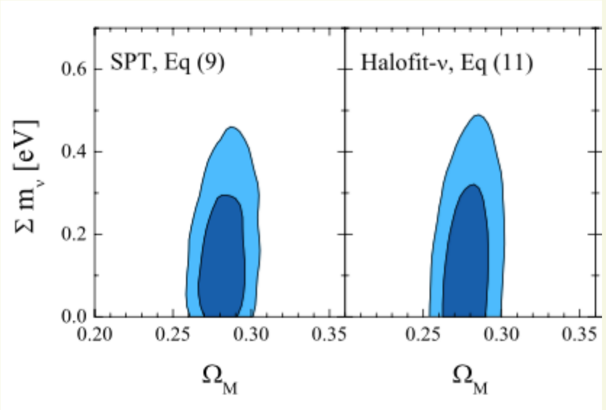
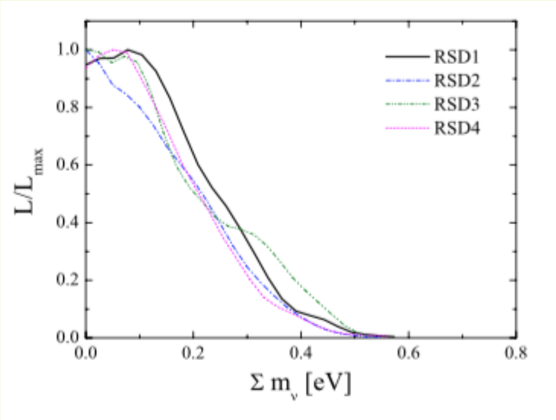


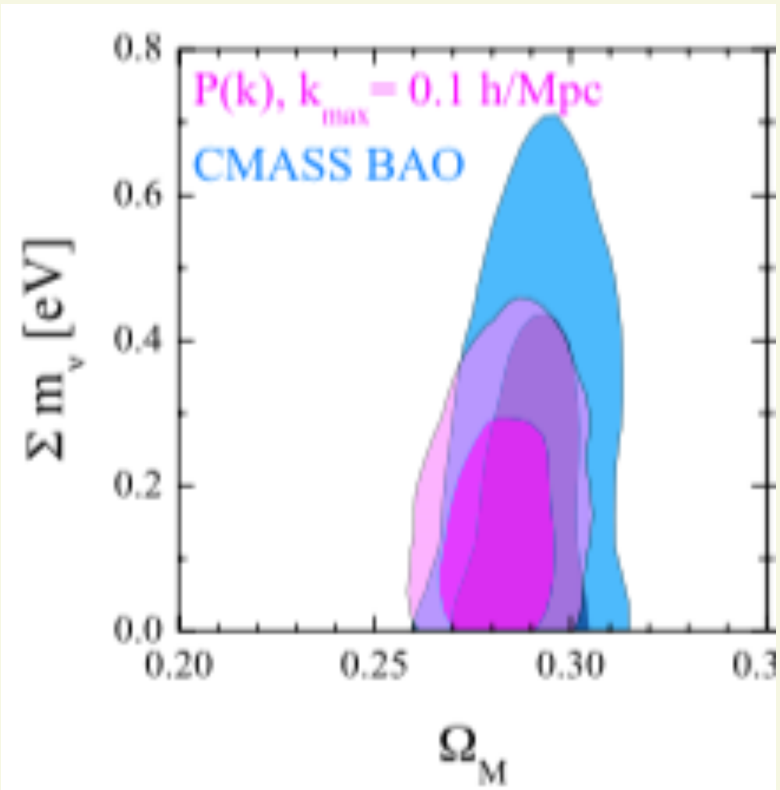


$$0.01 < k < 0.1 \ \mathrm{Mpc}^{-1}\ h$$

In the end they choose to use the simplest perturbation theory model.

Paper (1) : Galaxy power spectrum (BOSS DR9)

BAO peak constraining power :



$M_\nu < 0.579$ eV For WMAP7 + SNLS3 + BAO

$M_\nu < 0.340$ eV For WMAP7 + SNLS3 + P(k)

(+ all BAO measurement expect BOSS)

Paper (2) : Halo power spectrum (BOSS DR7)

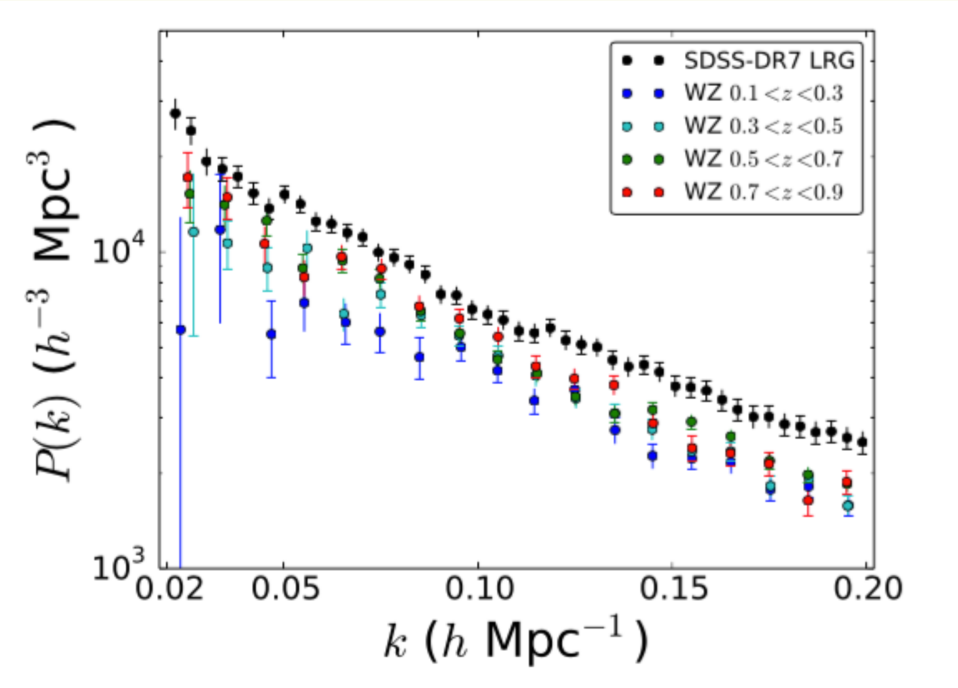
Combination and comparison for :

halo P(k) from DR7 LRG and galaxy P(k) from WiggleZ ELG.

↓

Using the halo power spectrum reduces systematics from non-linearities and RSD.

(investigate more on this ?)



Data sets	M_ν at 95% CL
CMB15 + LRG	0.38 eV
CMB15 + WZ	0.37 eV
CMB15 + LRG + WZ	0.30 eV
CMB15 + LRG + BAO	0.13 eV
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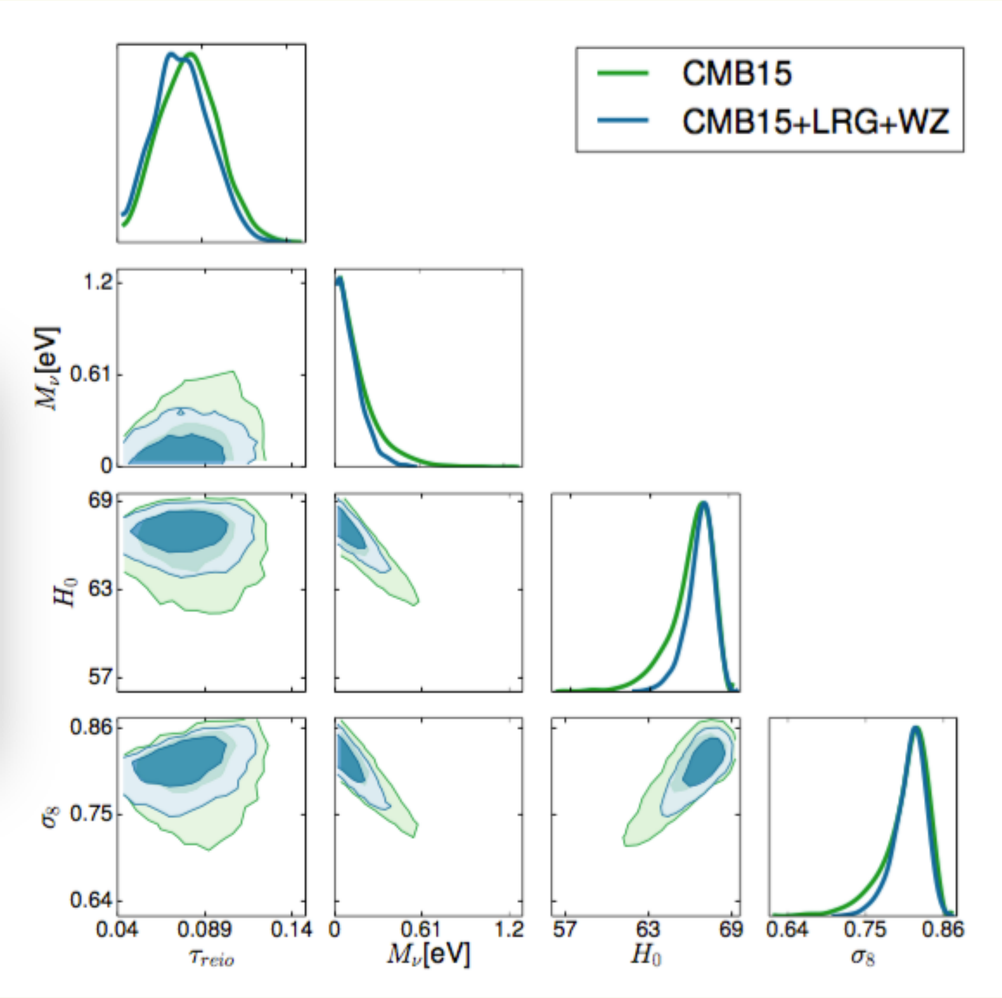
- Always combined with CMB (Planck).
- BAO greatly improves the constraint.

Paper (2) : Halo power spectrum (BOSS DR7)

CMB / Power spectrum



CMB alone : $M_\nu < 0.59$ eV

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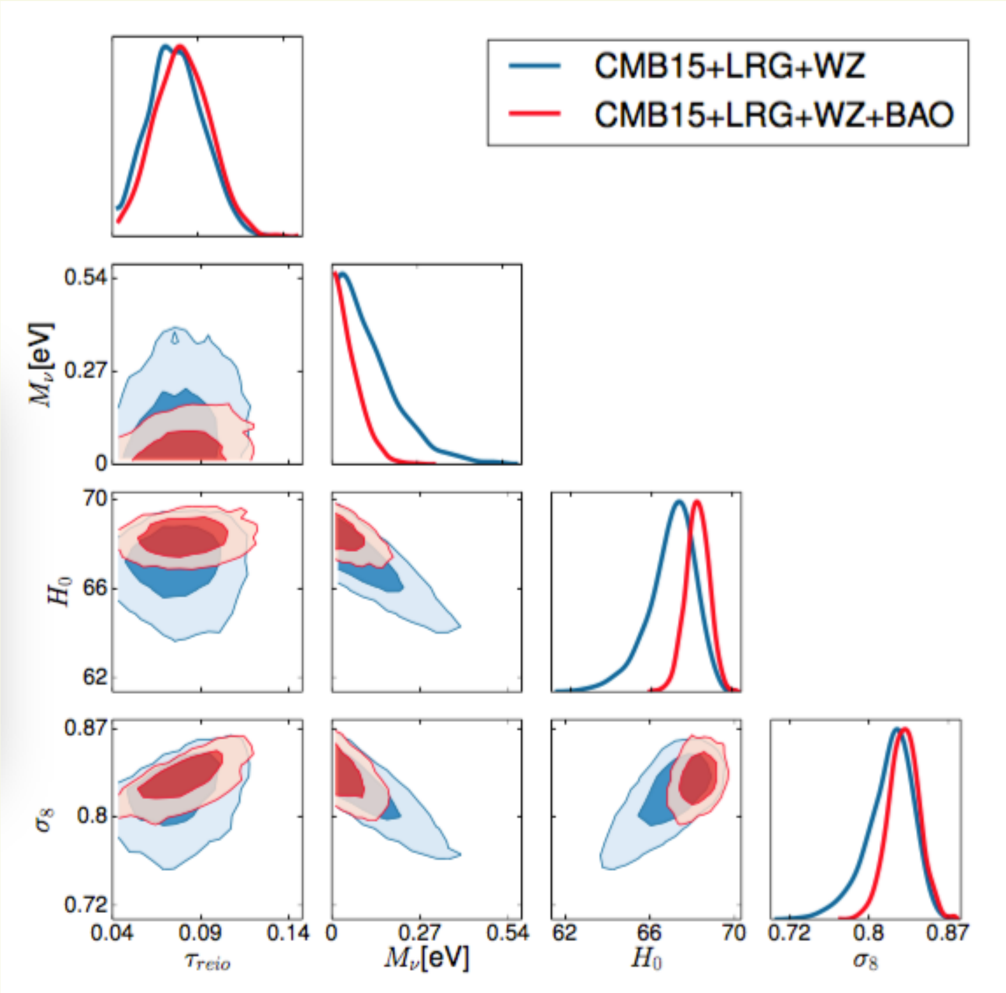
Paper (2) : Halo power spectrum (BOSS DR7)

Power spectrum / BAO peak



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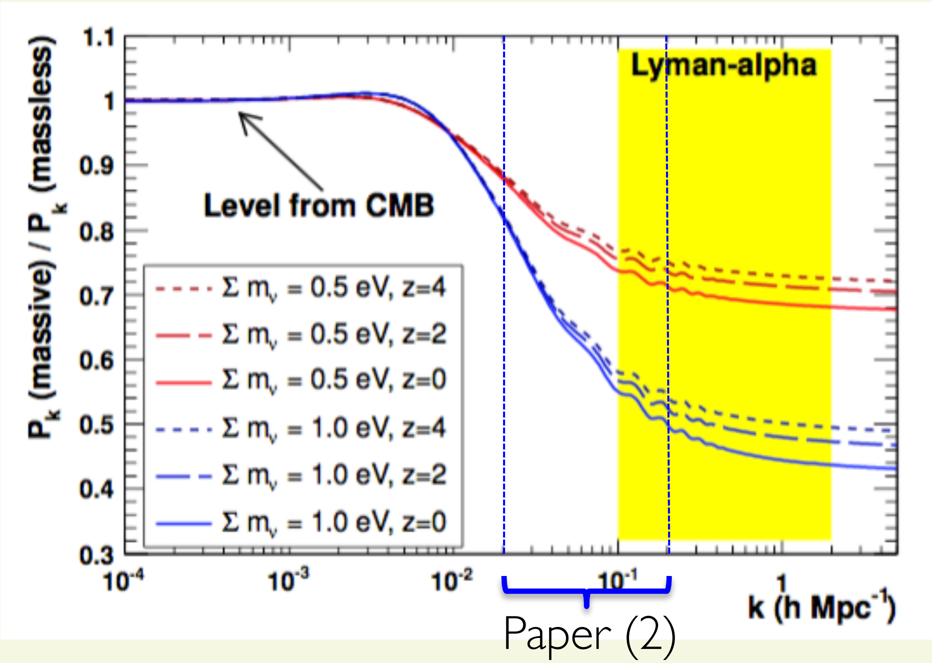
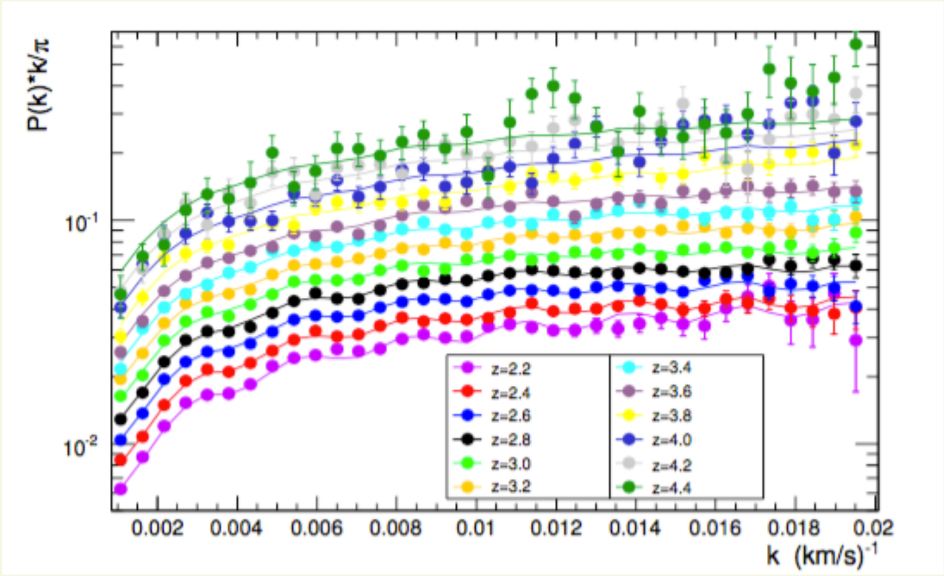
Break the degeneracy with H_0 and σ_8.

Paper (3) : Ly-α power spectrum (BOSS DR9)





Different probe/tracer ➡ Different anaylisis and different systematics.

- Astrophysical systematics : optical depth, absorbers (Si II or Si III), heating rate of IGM.
- Noise and resolution on the spectra.
- Hydrodynamical simulation technique (instead of using Boltzmann solvers like CLASS or CAMB).

Paper (3) : Ly-α power spectrum (BOSS DR9)

Results

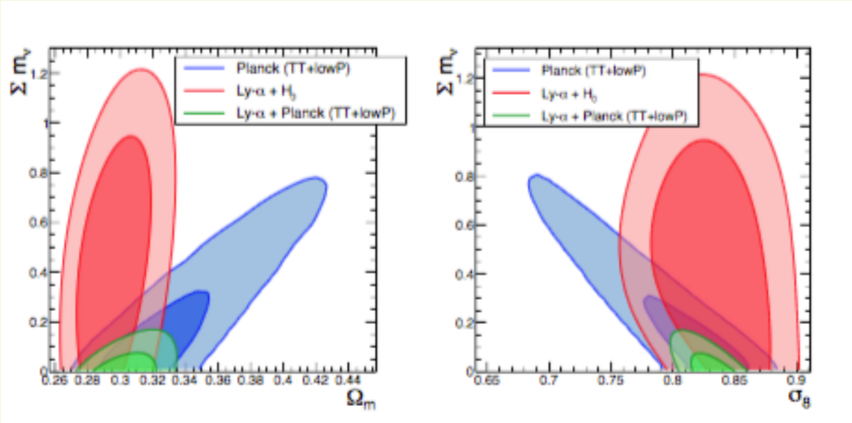
Parameter	(1) Lyα + H_0^{Gaussian} ($H_0 = 67.3 \pm 1.0$)	(2) Lyα + Planck TT+lowP	(3) Lyα + Planck TT+lowP + BAO	(4) Lyα + Planck TT+TE+EE+lowP + BAO
σ_8	0.831 ± 0.031	0.833 ± 0.011	0.845 ± 0.010	0.842 ± 0.014
n_s	0.938 ± 0.010	0.960 ± 0.005	0.959 ± 0.004	0.960 ± 0.004
Ω_m	0.293 ± 0.014	0.302 ± 0.014	0.311 ± 0.014	0.311 ± 0.007
H_0 (km s^{-1} Mpc^{-1})	67.3 ± 1.0	68.1 ± 0.9	67.7 ± 1.1	67.7 ± 0.6
$\sum m_\nu$ (eV)	< 1.1 (95% CL)	< 0.12 (95% CL)	< 0.13 (95% CL)	< 0.12 (95% CL)
Reduced χ^2	0.99	1.04	1.05	1.05

With Ly-α alone : need a prior for H_0 ➡ $M_\nu < 1.1$ eV.

Still need the CMB.

No need for BAO to have the best actual constraint :

$$M_\nu < 0.12 \text{ eV}$$



Conclusion

- We need the information from the CMB and the BAO peak to have tight constraints on M_ν with the galaxy power spectrum because of the systematics and the degeneracies.

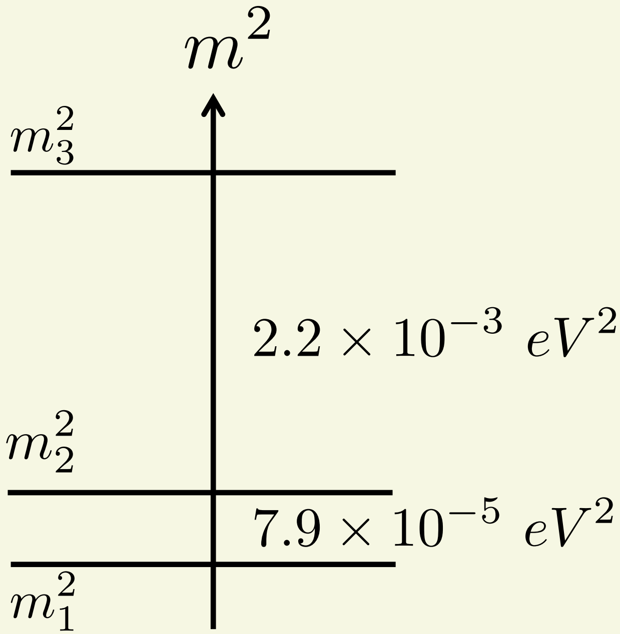
- The actual limits are getting closer to the Inverted Hierarchy limit ($M_\nu < 0.1~\mathrm{eV}$).

- Future : Effect of the neutrino mass ordering (only with high precision measuments) ? Sterile neutrinos with cosmology ? Neutrinos with different Dark Energy scenarios (Possible degenracies) ?

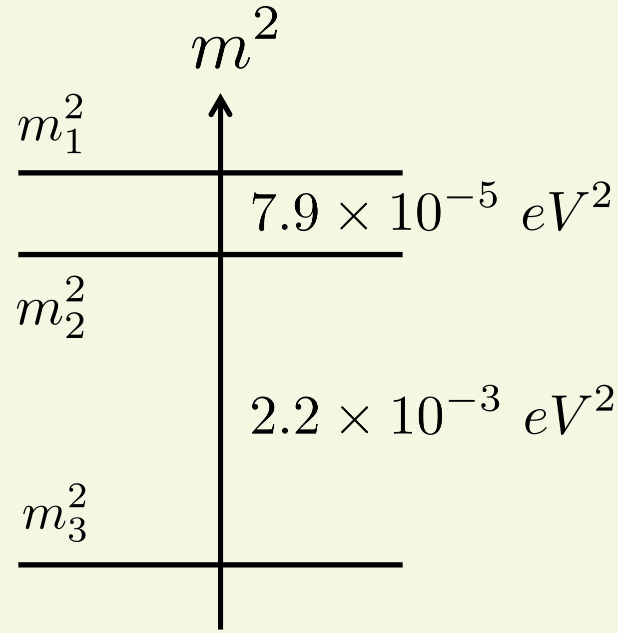
Hiérarchie de masse des neutrinos

Les expériences d'oscillations mesurent $\Delta m^2_{ij} = m^2_i - m^2_j$

➡ 2 hiérarchies possibles.



Normale



Inversée

$$\sum m_\nu > 0.056\ eV$$

$$\sum m_\nu > 0.095\ eV$$

Sommation Direct

2.2 Direct summation

Theoretical predictions for the correlation functions of the matter density, or of the galaxy number density, often assume such quantities to be continuous random fields. However, in practical applications such as the analysis of N-body simulations or galaxy surveys they are given in terms of a finite number N_P of objects with positions $\{\mathbf{x}_i\}$ for $i = 1, \ldots, N_P$. In this case we can write the density as

$$\rho(\mathbf{x}) = \sum_{i=1}^{N_P} m\, \delta_D(\mathbf{x} - \mathbf{x}_i)\,, \qquad (6)$$

m being the particle mass which we assume here to be the same for all particles, for simplicity. It follows that

$$\delta(\mathbf{x}) = \frac{1}{\bar{n}} \sum_{i=1}^{N_P} \delta_D(\mathbf{x} - \mathbf{x}_i) - 1\,, \qquad (7)$$

$\bar{n} \equiv N_P/V$ being the particle density. The overdensity in Fourier space can be obtained by direct summation as the Fourier transform of the equation above, that is

$$\delta(\mathbf{k}) = \frac{1}{(2\pi)^3} \left[\frac{1}{\bar{n}} \sum_{i=1}^{N_P} e^{-i\,\mathbf{k}\cdot\mathbf{x}_i} - \delta^K_{\mathbf{k}} \right]. \qquad (8)$$

The Fourier-space 2-point function defining the power spectrum is now given by

$$\langle \delta(\mathbf{k}_1)\, \delta(\mathbf{k}_2) \rangle = \frac{\delta^K_{\mathbf{k}_{12}}}{k_f^3} \left[P(k_1) + \frac{1}{(2\pi)^3\, \bar{n}} \right], \qquad (9)$$

where the second term on the r.h.s. represents the shot-noise contribution due to the self-correlation of individual particles (see, for instance, Peebles 1980; Jing 2005). The direct summation estimator for the power spectrum of a particle distribution is then

$$\hat{P}(k) \equiv k_f^3\, |\delta(\mathbf{k})|^2 = k_f^3 \left[|\delta(\mathbf{k})|^2 - \frac{1}{N_P} \right], \qquad (10)$$

and the true power spectrum is recovered as $P(k) = \langle \hat{P}(k) \rangle$.

- Définir une grille de mode k (arbitrairement) :

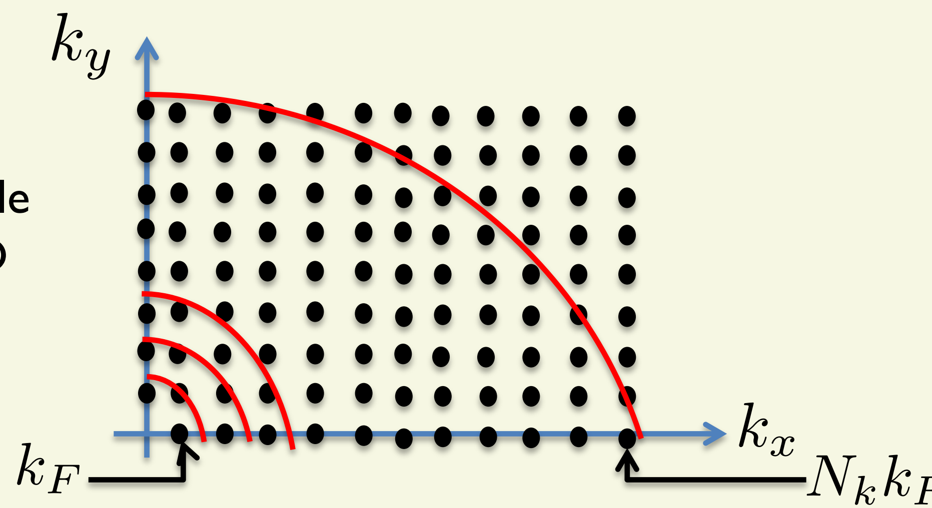
$$N_k = N_p/2$$

$$\boldsymbol{k_n} = k_F \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} \qquad n_i = 0, \ldots, N_k \qquad k_F = 2\pi/L$$

- Pour chaque mode calculer $P(\boldsymbol{k})$ avec l'equation (10)

- Calculer le monopole : Par isotropie on peut définir des shells de $|\boldsymbol{k}|$ constant : On obtient $P(k)$.

Exemple en 2D



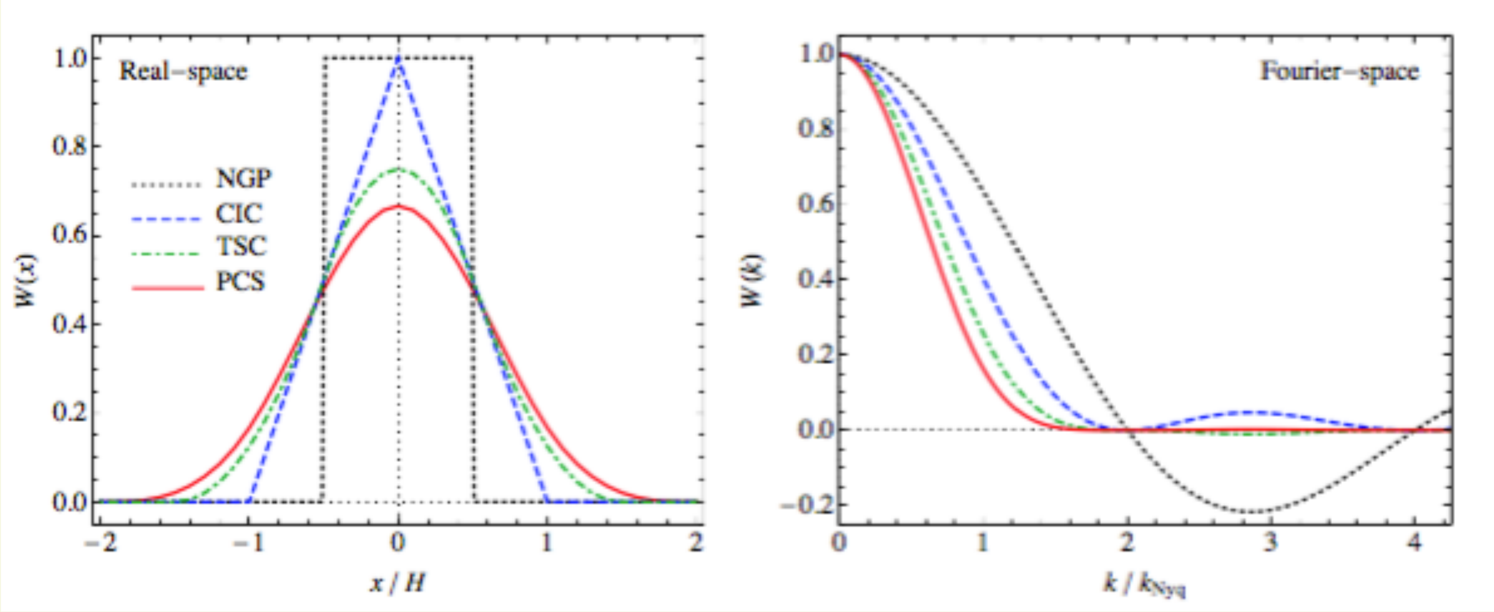
Mass assignement

Principe : Faire une FFT du champ de densité $\delta(x)$

Faire un sampling de $\delta(x)$ dans l'espace réel :

Induit des effet de grille ➔ Aliasing dans l'espace de Fourier

- Définir une grille d'interpolation dans l'espace réel
- Choisir un schéma d'interpolation (convolution de W(x) avec $\delta(x)$)

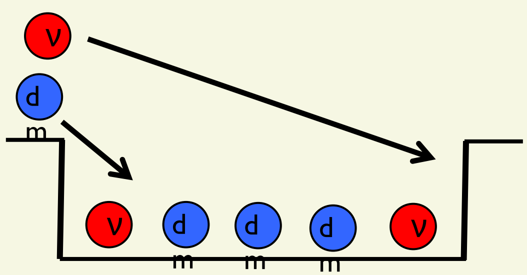


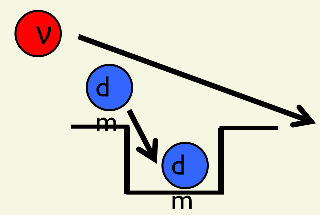
- Déconvolution de W(x) dans l'espace réel ➔ division dans l'espace de Fourier $\frac{\delta(\boldsymbol{k})}{W(\boldsymbol{k})}$

Sylvain Gouyou Beauchamps

Constraining neutrino properties with the Euclid cosmological survey

When neutrinos became non-relativistic : Free streaming ➡ neutrinos escape from the potential wells on small scales.

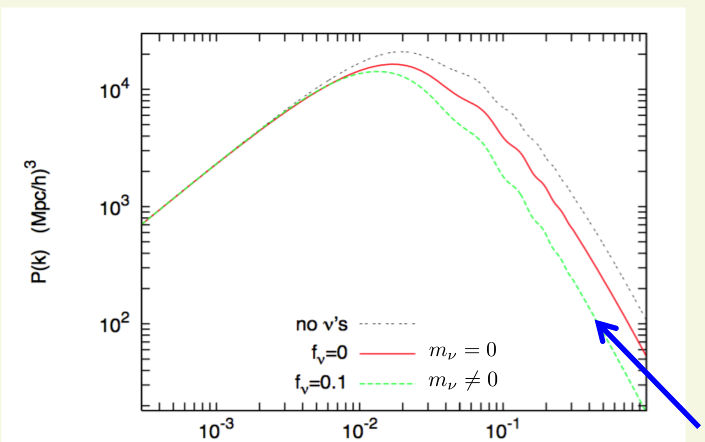




Particle Physics constraints

$$(NH)\ \ 0.056\ eV \lesssim \sum m_\nu \lesssim 6\ eV$$
$$(IH)\ \ 0.095\ eV$$

Cosmological constraints



J. Lesgourgues and S. Pastore

The presence of massive neutrinos causes a damping of the power spectrum on small scales.

Galaxy clustering : $\sum m_\nu < 0.13\ eV$ (P(k) + BAO + Planck15)
A.J. Cuesta et al. 2016

CMB : $\sum m_\nu < 0.12\ eV$ (Planck18 + CMB-lensing + BAO)
Planck Collaboration 2018

My work :

- Tests on the DEMNUni(i) simulations.
- Apply on eBOSS/DESI data.
- Incorporate instrumental systematics from Euclid.