Ateliers Dark Energy

Constraining the total neutrino mass with the power spectrum

Sylvain Gouyou Beauchamps

Philippe Baratta, Julien Bel, Stéphanie Escoffier, William Gillard,

3rd year PhD under the supervision of Stéphanie Escoffier and William Gillard

CPPM, RENOIR

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Neutrino mass in particle physics

- Neutrino oscillations experiments : Super Kamiokande, T2K, KamLand…

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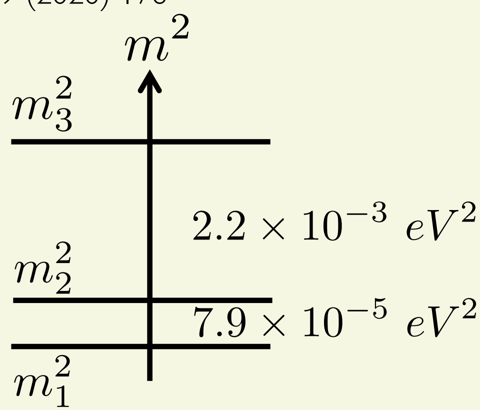
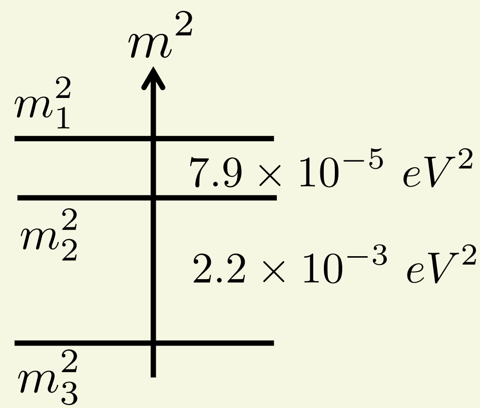


Normal

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



Inverted

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

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- Neutrino oscillations experiments : Super Kamiokande, T2K, KamLand…

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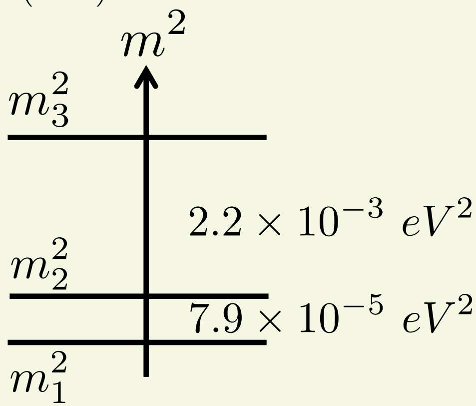

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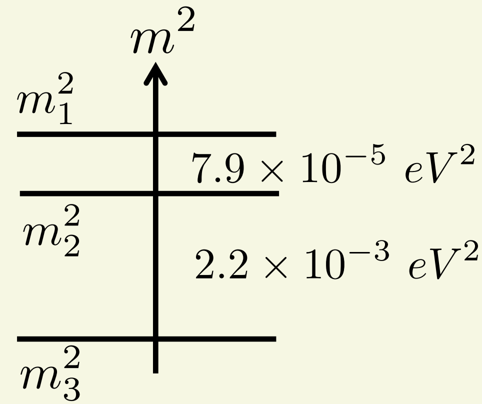


Inverted

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

- Direct kinematic measurments in tritium β decay : KATRIN $\sum m_\nu < 1$ eV

Phys. Rev. Lett. 123, 221802

Overall particle physics experiments constraints

NH	$0.056 \text{ eV} \lesssim M_\nu \lesssim 1 \text{ eV}$
IH	$0.095\ eV$

The standard model of cosmology, ΛCDM.

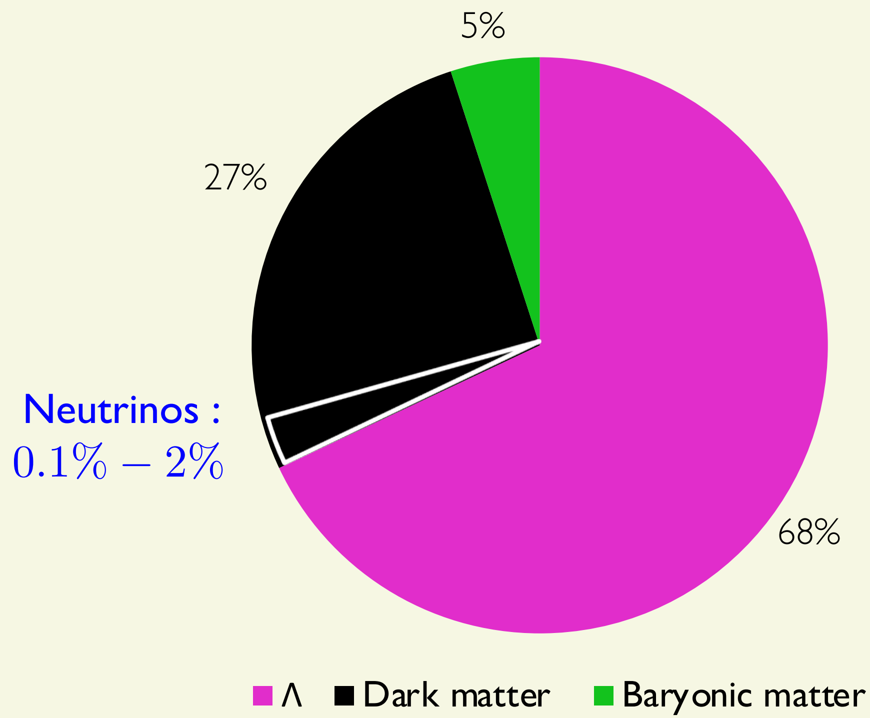
- Homogeneous and isotropic universe
- Λ = Responsible for the accelerated expansion
- CDM = Cold Dark Matter (non-standard and non-relativistic)
- Flat universe

Particle Physics experiment

NH $0.056 \text{ eV} \lesssim M_\nu \lesssim 1 \text{ eV}$

IH $0.095\ eV$

Content of our universe today :



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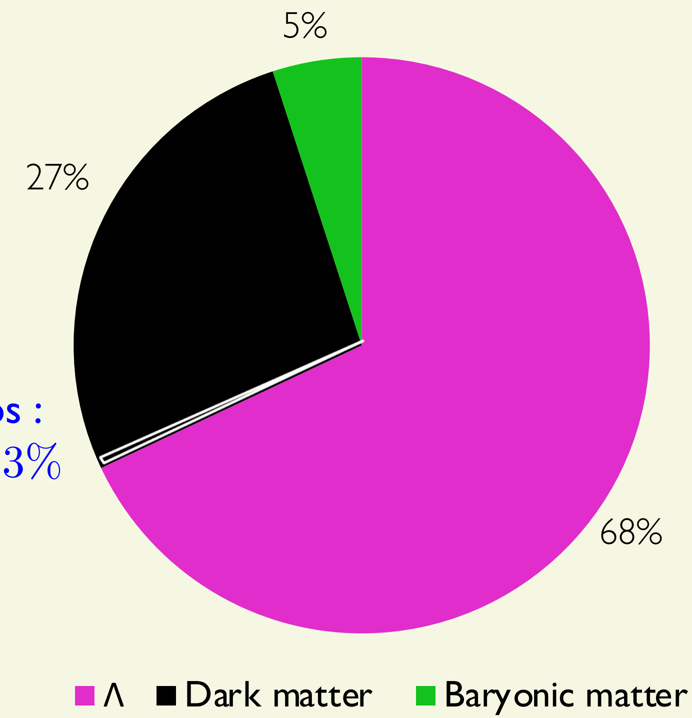
Cosmology

CMB + BAO + RSD + SN $$M_\nu < 0.1 \text{ eV}$$

[eBOSS collaboration 2020]

Content of our universe today :



Neutrinos : $0.1\% - 0.3\%$

I. Introduction

II. Simulations and Covariance

- The DEMNUni simulations
- Likelihood setting
- Covariance choice

III. Fit of the real space matter power spectrum

- Model comparison in ΛCDM + M_ν
- Varying A_s in ΛCDM + M_ν
- Constraints in $w_0 w_a$CDM + M_ν

IV. Conclusions

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

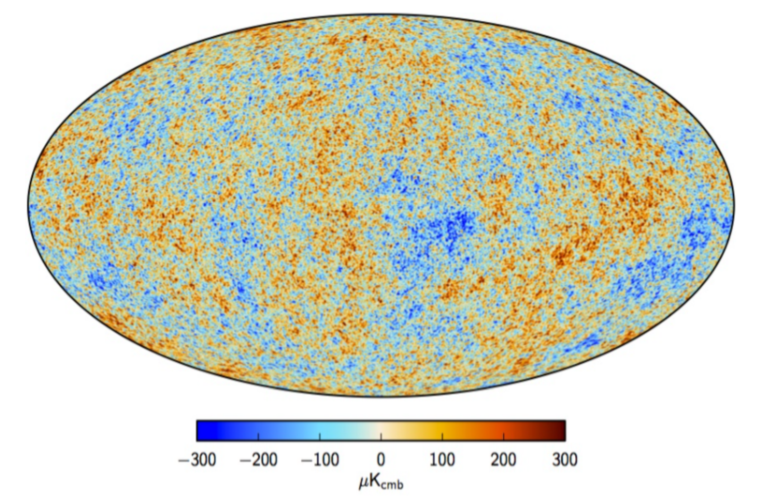
$T_\nu \gg m_\nu$ $T_\nu \ll m_\nu$

Radiation : No gravitational clustering.

Dark matter : Gravitational clustering.

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

Consequences on the CMB



- **No trace of non-relativistic neutrinos**

  $z_{\rm CMB} = 1100$ ➡ $M_\nu < 1.74$ eV

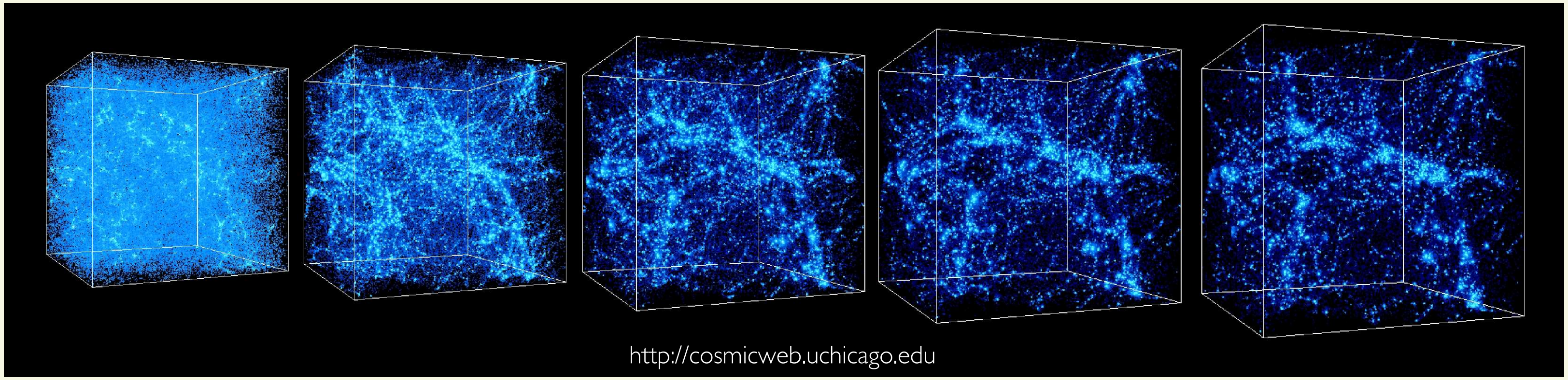
- **Background effects**

  Planck CMB alone (T + P) ➡ $M_\nu < 0.26$ eV

  [Planck Collaboration 2018]

Consequences on the Large Scale Structure (LSS)

Formation of structures in an N-Body simulation



Initial conditions → **Today**

Matter + Gravity + Expansion

Consider 2 components to gravitational clustering

ν : After the transition they behave as Warm Dark Matter

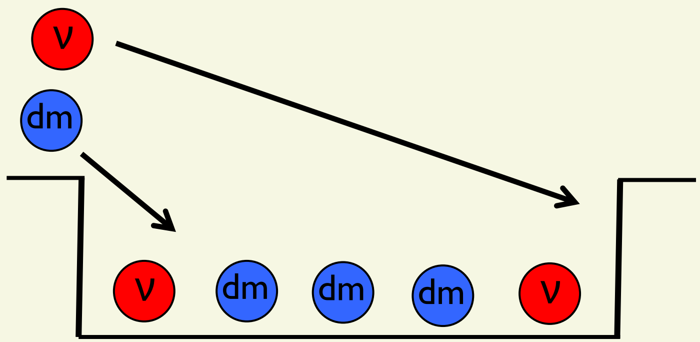
Neutrinos High thermal velocity but still non-relativistic

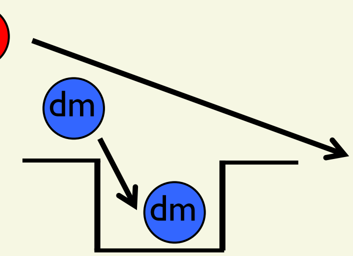
dm : Low velocity at all time

Cold Dark Matter

Consequences on the Large Scale Structure (LSS)

Free streaming : Neutrinos escape from the potential wells on small scales





On large scales : Neutrinos behave like CDM

On small scales : Neutrinos do not cluster

Smoothing of density perturbations on small scales

$M_\nu = 1.9 \text{ eV}$

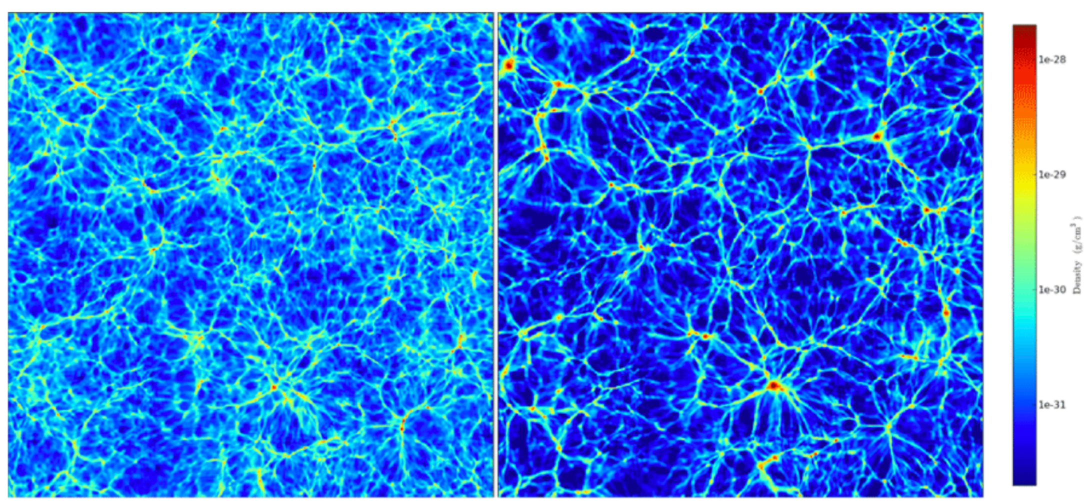
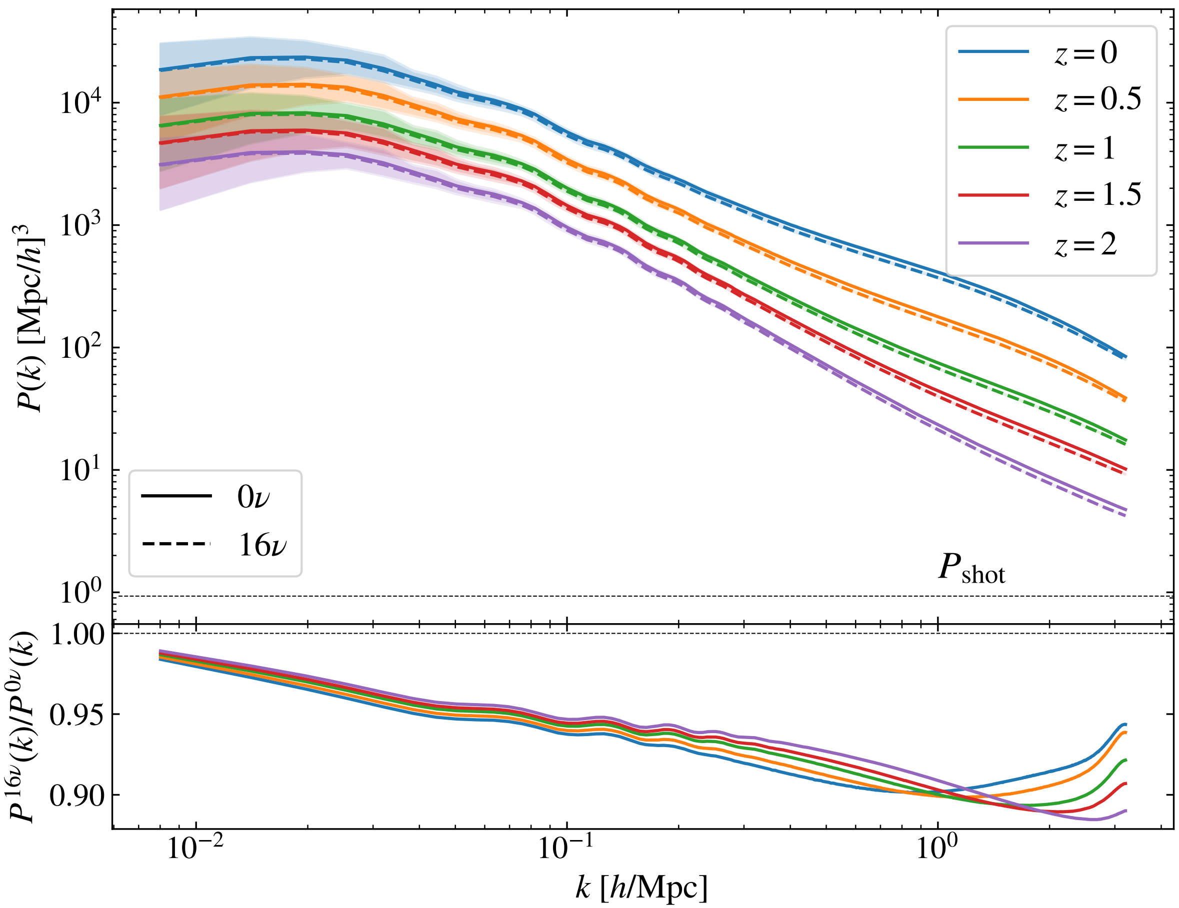


Illustration: Courtesy of Shankar Agarwal and Hume Feldman, University of Kansas; submitted to Mon. Not. R. Astron. Soc.

$M_\nu = 0 \text{ eV}$

The DEMNUni-Cov simulations, *50 realisations for each cosmology*

CDM power spectrum : $P_{cb}(k)$



- Cosmologies : 0ν and 16ν

$$\begin{cases} \Omega_m = 0.32 \\ \Omega_b = 0.05 \\ h = 0.67 \\ n_s = 0.96 \\ A_s = 2.1265 \times 10^9 \\ \mathbf{3m_\nu} = \mathbf{0} \text{ or } \mathbf{0.16} \text{ eV} \\ \mathbf{\Omega_{cdm}} = \mathbf{0.27} \text{ or } \mathbf{0.2663} \end{cases}$$

- V = 1 Gpc/h^3
- $N_p = 1024^3$ (+ 1024^3)

Managed by Carmelita Carbone in Milan

Aim : Fit of the P(k) full shape to study its constraining power for M_ν

Set-up for the MCMC : Fit of the CDM P(k) in real space

$$\chi^2(\hat{\boldsymbol{P}}(k)|\boldsymbol{\theta}) = \left[[\hat{\boldsymbol{P}}(k) - \boldsymbol{P}(k;\boldsymbol{\theta})]^T \mathbf{C}^{-1} [\hat{\boldsymbol{P}}(k) - \boldsymbol{P}(k;\boldsymbol{\theta})] \right]$$

DEMNUni

Set-up for the MCMC : Fit of the CDM P(k) in real space

$$\chi^2(\hat{\boldsymbol{P}}(k)|\boldsymbol{\theta}) = \left[[\hat{\boldsymbol{P}}(k) - \boldsymbol{P}(k;\boldsymbol{\theta})]^T \mathbf{C}^{-1} [\hat{\boldsymbol{P}}(k) - \boldsymbol{P}(k;\boldsymbol{\theta})]\right]$$

DEMNUni ← $\hat{\boldsymbol{P}}(k)$

Choice of model for $P_{nl}(k)$ ← $\boldsymbol{P}(k;\boldsymbol{\theta})$

- **Halofit, « TakaBird »**
  [Takahashi et al. 2012 + Bird et al. 2011]
- **HMcode**
  [Mead et al. 2015]

Halo model + calibration with N-Body simulations — **Account for neutrinos**

- **RegPT (2 loops)**
  [Taruya et al. 2012]

Regularized Perturbation Theory — **Account for neutrinos at the linear level only**

Set-up for the MCMC : Fit of the CDM P(k) in real space

$$\chi^2(\hat{\boldsymbol{P}}(k)|\boldsymbol{\theta}) = \left[[\hat{\boldsymbol{P}}(k) - \boldsymbol{P}(k;\boldsymbol{\theta})]^T \mathbf{C}^{-1}[\hat{\boldsymbol{P}}(k) - \boldsymbol{P}(k;\boldsymbol{\theta})]\right]$$

DEMNUni

Choice of model for $P_{nl}(k)$

Choice for the covariance

- Gaussian covariance
- Estimate non-Gaussian covariance with mocks

Set-up for the MCMC : Fit of the CDM P(k) in real space

$$\chi^2(\hat{\boldsymbol{P}}(k)|\boldsymbol{\theta}) = \left[[\hat{\boldsymbol{P}}(k) - \boldsymbol{P}(k;\boldsymbol{\theta})]^T \mathbf{C}^{-1}[\hat{\boldsymbol{P}}(k) - \boldsymbol{P}(k;\boldsymbol{\theta})]\right]$$

- DEMNUni ← $\hat{\boldsymbol{P}}(k)$
- Choice of model for $P_{nl}(k)$ ← $\boldsymbol{P}(k;\boldsymbol{\theta})$
- Choice for the covariance ← $\mathbf{C}^{-1}$

$k = [0.01, k_{\rm max}],\ \Delta k = 0.01\ h/{\rm Mpc}$ with $k_{\rm max} = [0.1,\ 0.3]$

Fitting 5 uncorrelated redshifts $\chi^2 = \sum_{i=0}^{n_z=5} \chi^2(z_i)$ with $z_i = [0,\ 0.5,\ 1,\ 1.5,\ 2]$

4 parameters

$\boldsymbol{\theta}$	Priors
$\omega_{\rm b}$	$[0.01,\ 0.06]$
$\omega_{\rm cdm}$	$[0.01,\ 0.8]$
h	$[0.3,\ 1.5]$
m_ν [eV]	$[0,\ 1]$

Choice for the covariance

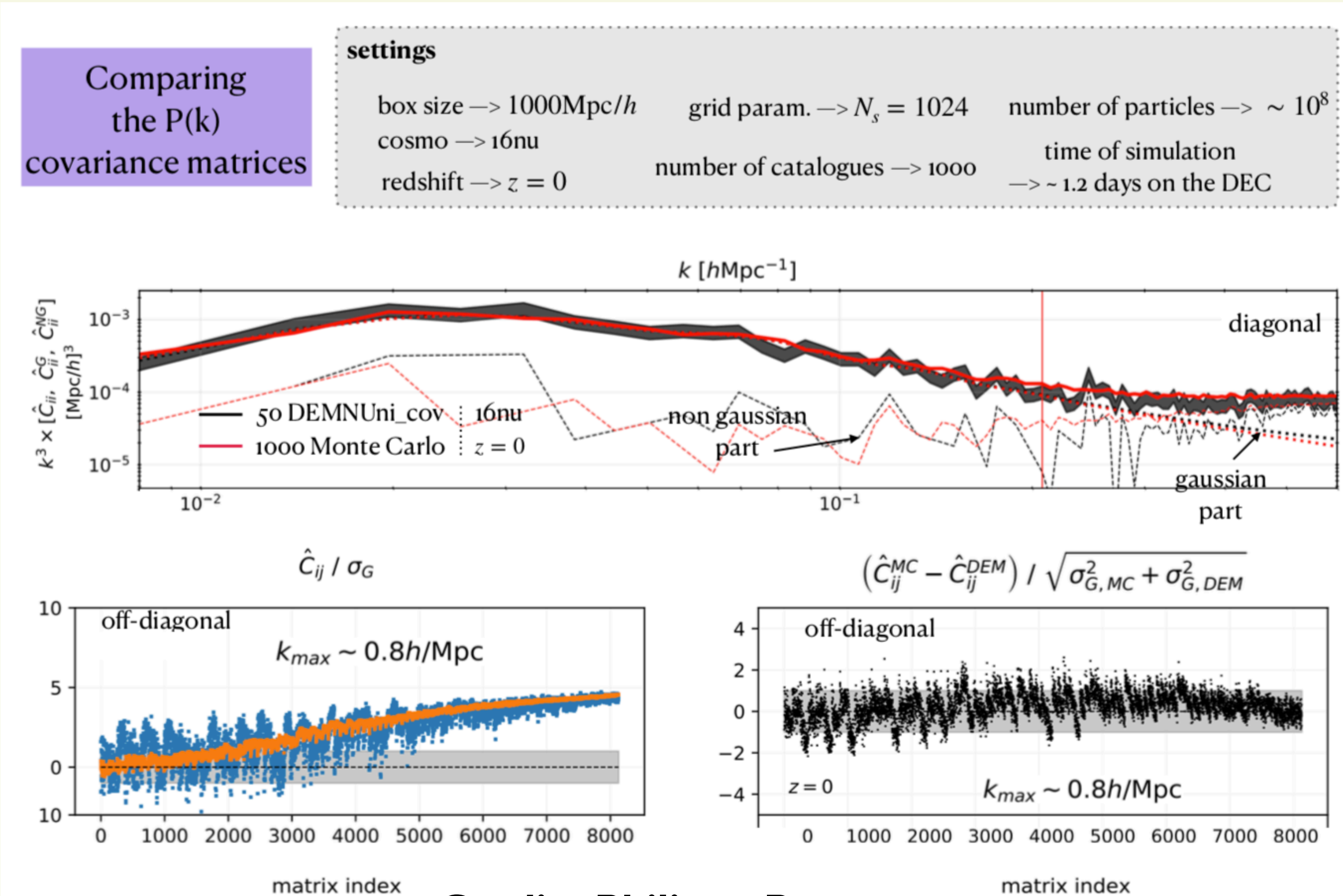
- **Approximated gaussian covariance :** $\mathcal{C}^G_{ij} \propto P(k)^2 \delta_{ij}$
  - ➡ Not reliable on small scale

- **Estimated covariance from simulations**
  - ➡ With the DEMNUni-Cov : Only 50 realisations
  - ➡ Semi analytic Monte-Carlo realisations : Fast and precise enough

COVMOS by Philippe Baratta, [Baratta et al. 2019]

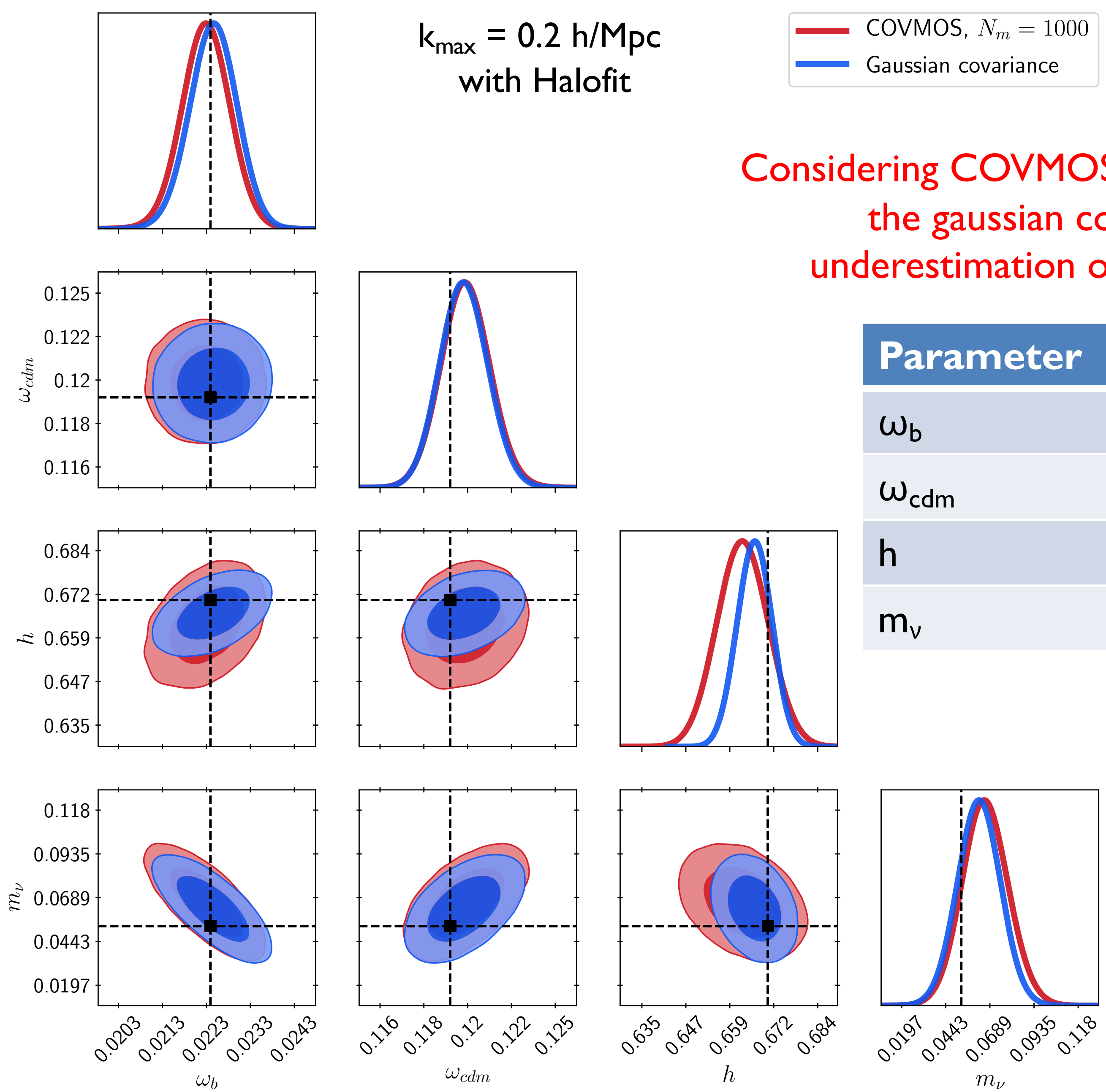
Fast non-Gaussian mock generation with *covmos*

Cloning the DEMNUni-Cov covariance matrix by targeting the P(k) and PDF(δ)



Credit : Philippe Baratta

II. Simulations and Covariance



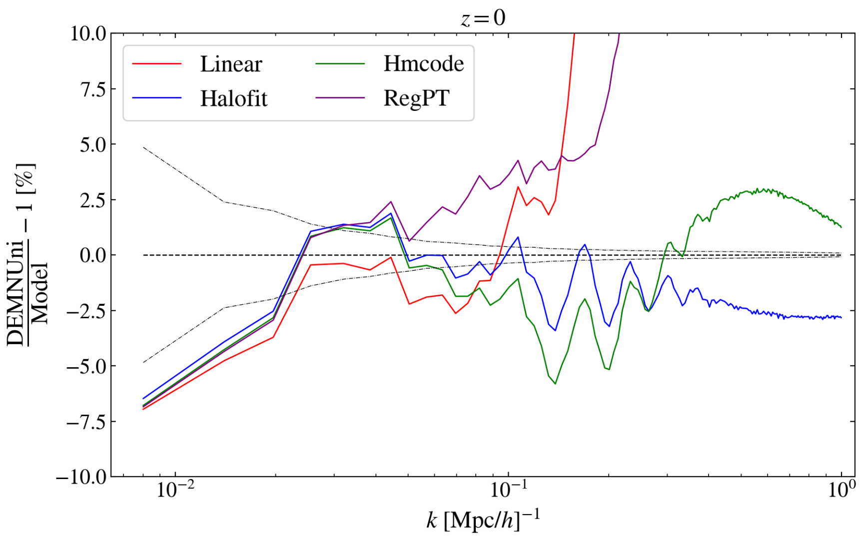
Considering COVMOS as the « True » covariance, the gaussian covariance leads to an underestimation of the parameters errors

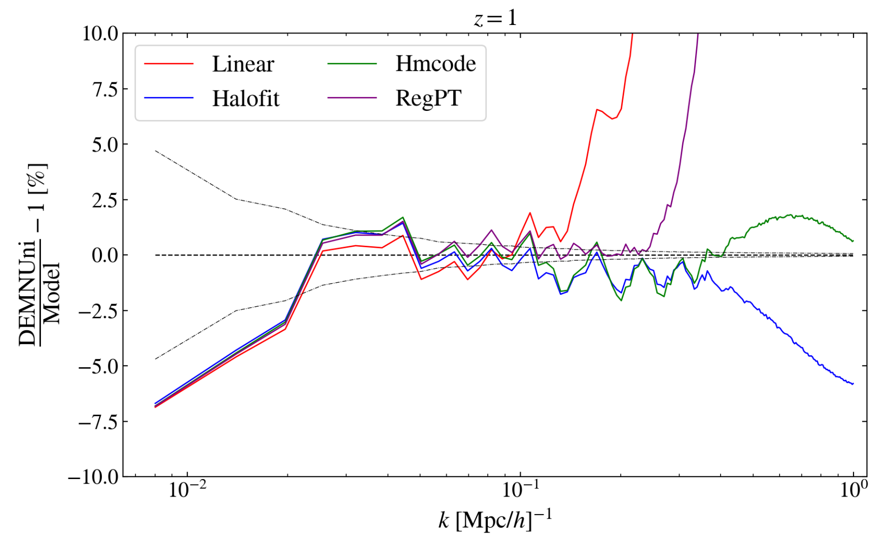
Parameter	σ/σ_{Gauss} - 1
ω_b	0.68 %
ω_{cdm}	2.40 %
h	21.38 %
m_ν	3.68 %

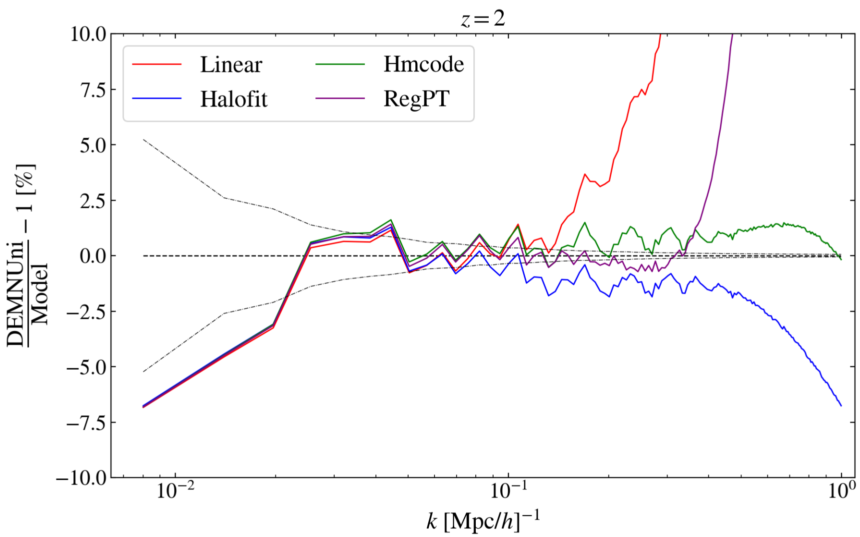
We will keep COVMOS in the following !

III. Model comparison : relative difference

Relative difference with the mean on 50 realisations from the 16ν cosmology



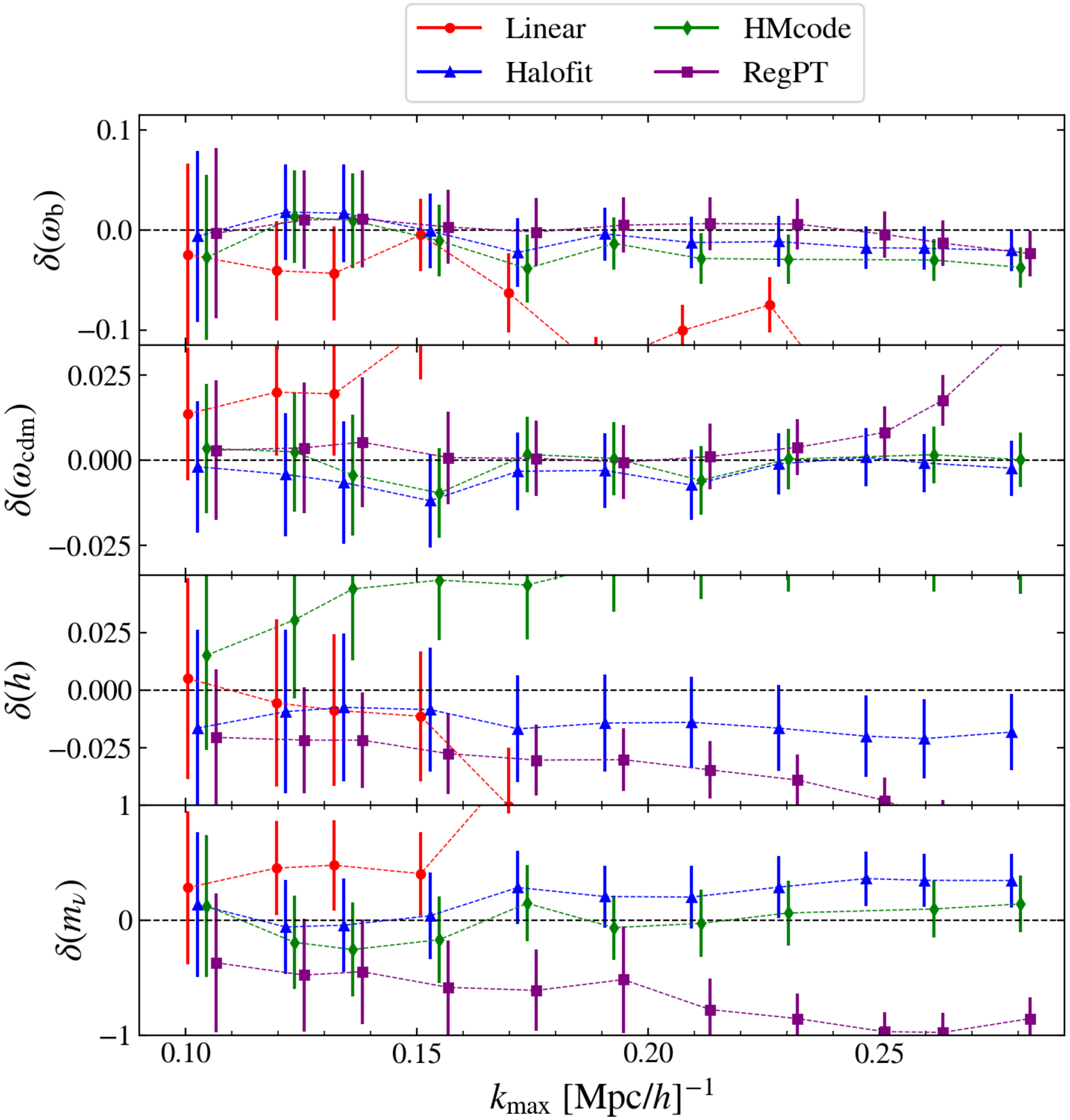




- Linear : Does not hold for k_{max} > 0.1 h/Mpc
- Halofit and HMCode : Bad BAO reproduction.
- RegPT : Good for BAO

z=0 is highly non-linear

Estimation of the bias induced by the modeling of the non-linearities.



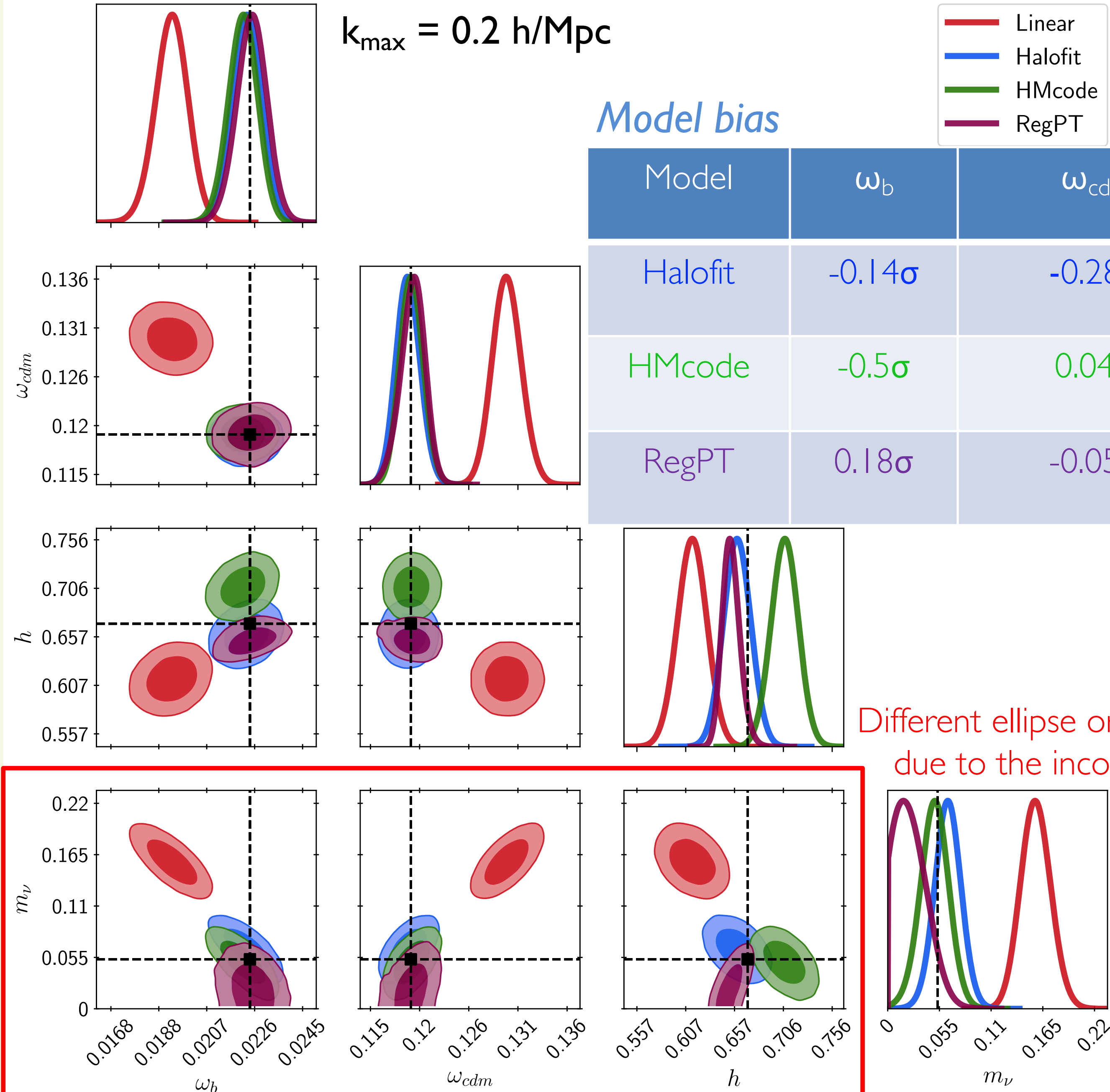
To have a precise estimation of the bias :
Fit the mean on 12 realisations for each redshift z = [0.5, 1, 1.5, 2]

- RegPT : ω_b and ω_{cdm} unbiased up to k_{max} = 0.23 h/Mpc.
  But high bias for h and m_ν.
- HMcode : unbiased m_ν but highly biased h
- Halofit : the bias is < 1σ for all parameters up to k_{max}=0.21 h/Mpc

We choose a cut at k_{max} = 0.2 h/Mpc

III. Model comparison : bias on parameter estimation

k_{max} = 0.2 h/Mpc



Model bias

Model	ω_b	ω_{cdm}	h	m_ν
Halofit	-0.14σ	-0.28σ	0.67σ	-0.72σ
HMcode	-0.5σ	0.04σ	**2.62σ**	0.22σ
RegPT	0.18σ	-0.05σ	**-2.21σ**	1.11σ

Different ellipse orientation for RegPT ➔ Might be due to the incomplete treatment of neutrinos

We keep Halofit for the following

Set-up for the MCMC : Fit of the CDM P(k) in real space

$$\chi^2(\hat{\boldsymbol{P}}(k)|\boldsymbol{\theta}) = \left[[\hat{\boldsymbol{P}}(k) - \boldsymbol{P}(k;\boldsymbol{\theta})]^T \mathbf{C}^{-1} [\hat{\boldsymbol{P}}(k) - \boldsymbol{P}(k;\boldsymbol{\theta})]\right]$$

- $\hat{\boldsymbol{P}}(k)$ ← DEMNUni
- $\boldsymbol{P}(k;\boldsymbol{\theta})$ ← Halofit
- $\mathbf{C}^{-1}$ ← Estimated non-Gaussian covariance with covmos

$k = [0.01, k_{\rm max}],\ \Delta k = 0.01\ h/{\rm Mpc}$ with $k_{\rm max} = 0.2\ h/{\rm Mpc}$

Fitting 5 uncorrelated redshifts $\chi^2 = \sum_{i=0}^{n_z=5} \chi^2(z_i)$ with $z_i = [0,\ 0.5,\ 1,\ 1.5,\ 2]$

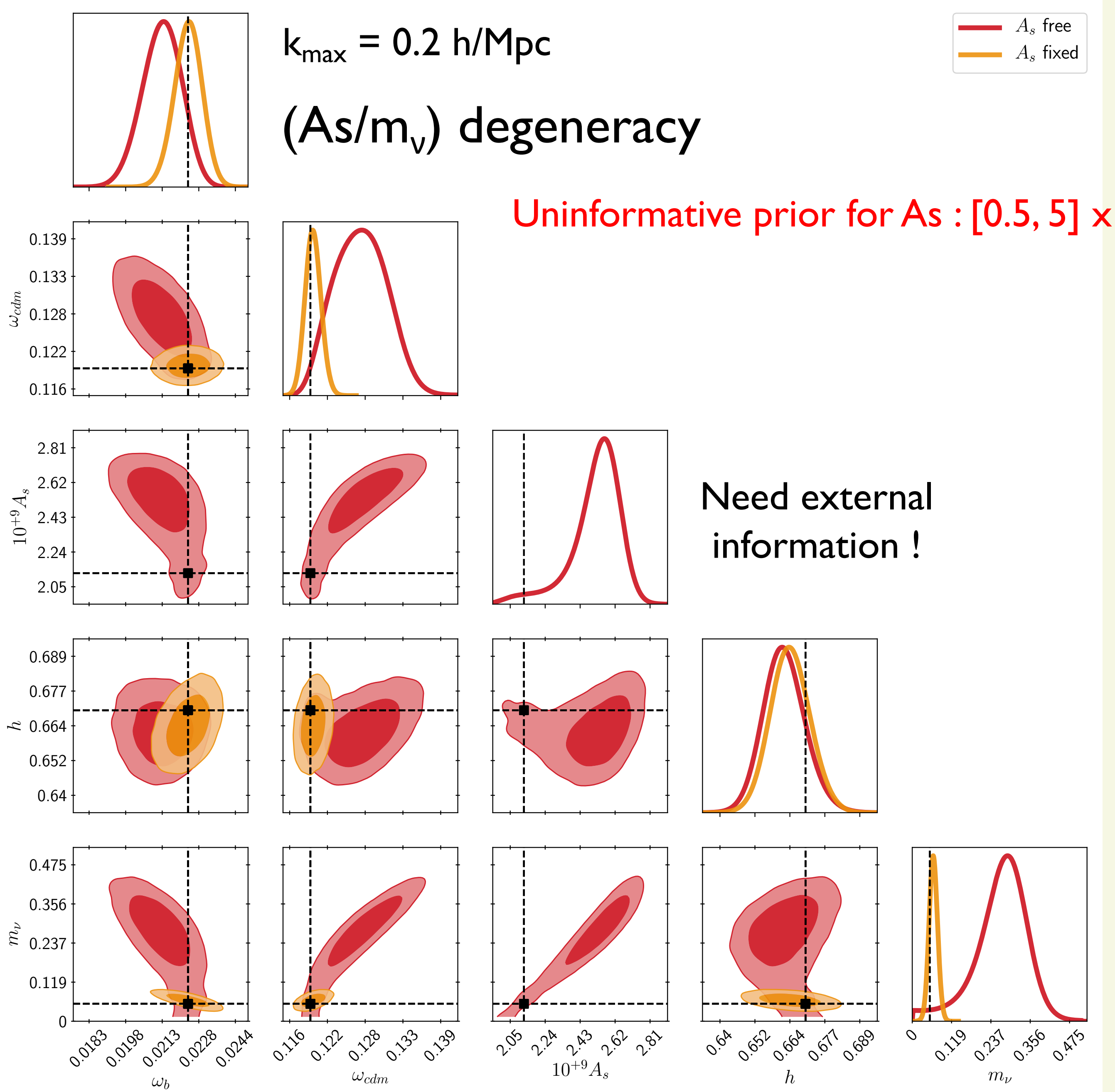
5 parameters

$\boldsymbol{\theta}$	Priors
$\omega_{\rm b}$	$[0.01,\ 0.06]$
$\omega_{\rm cdm}$	$[0.01,\ 0.8]$
h	$[0.3,\ 1.5]$
m_ν [eV]	$[0,\ 1]$

$+A_s$

As (or equivalently σ_8) is highly degenerated with m_ν

III. Varying As



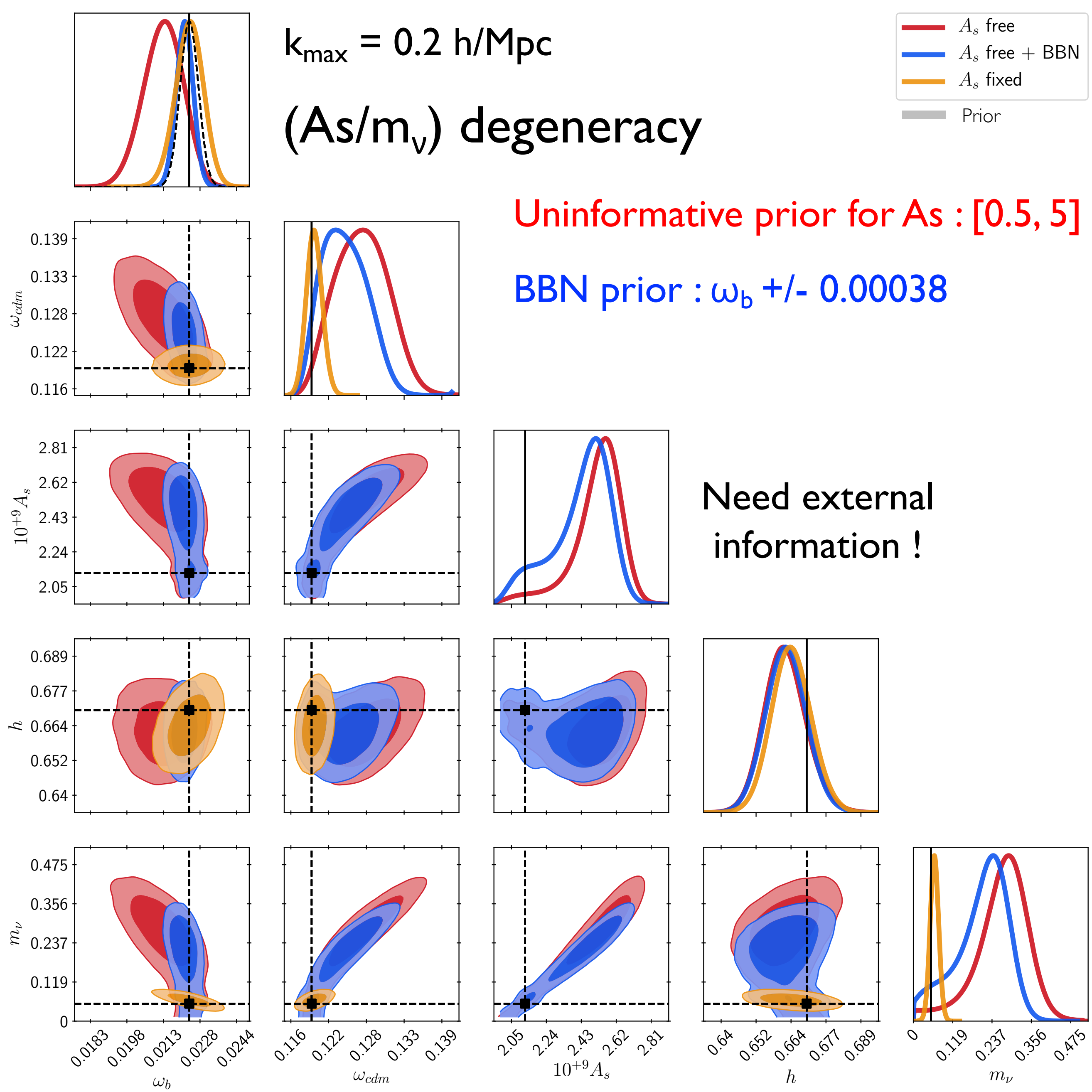
k_{max} = 0.2 h/Mpc

(As/m_ν) degeneracy

Uninformative prior for As : [0.5, 5] x 10^{-9}

Need external information !

III.Varying As



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BBN prior : ω_b +/- 0.00038

Need external information !

III. Varying As

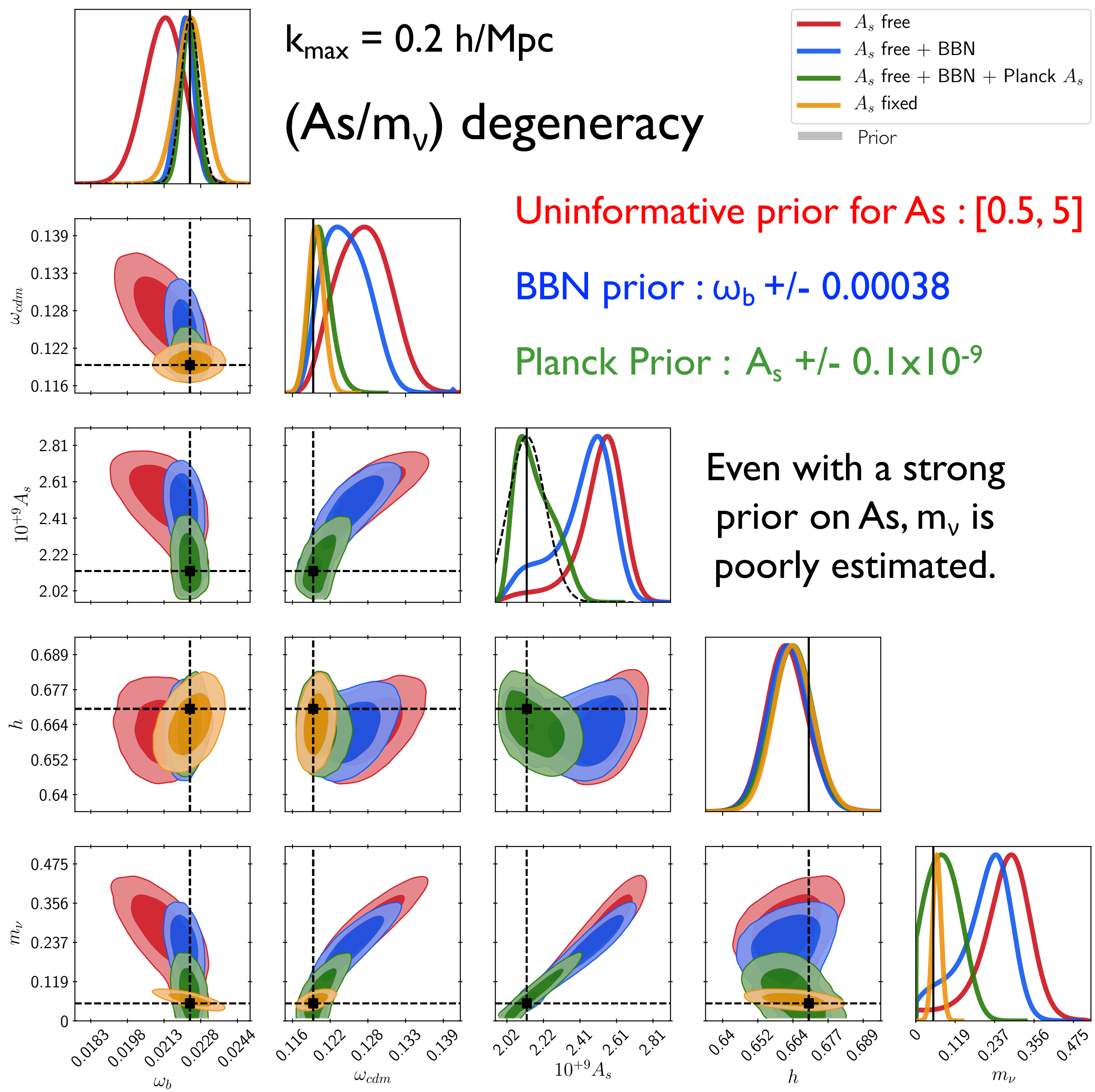
k_{max} = 0.2 h/Mpc

(A_s/m_ν) degeneracy

Uninformative prior for As : [0.5, 5] x 10^{-9}

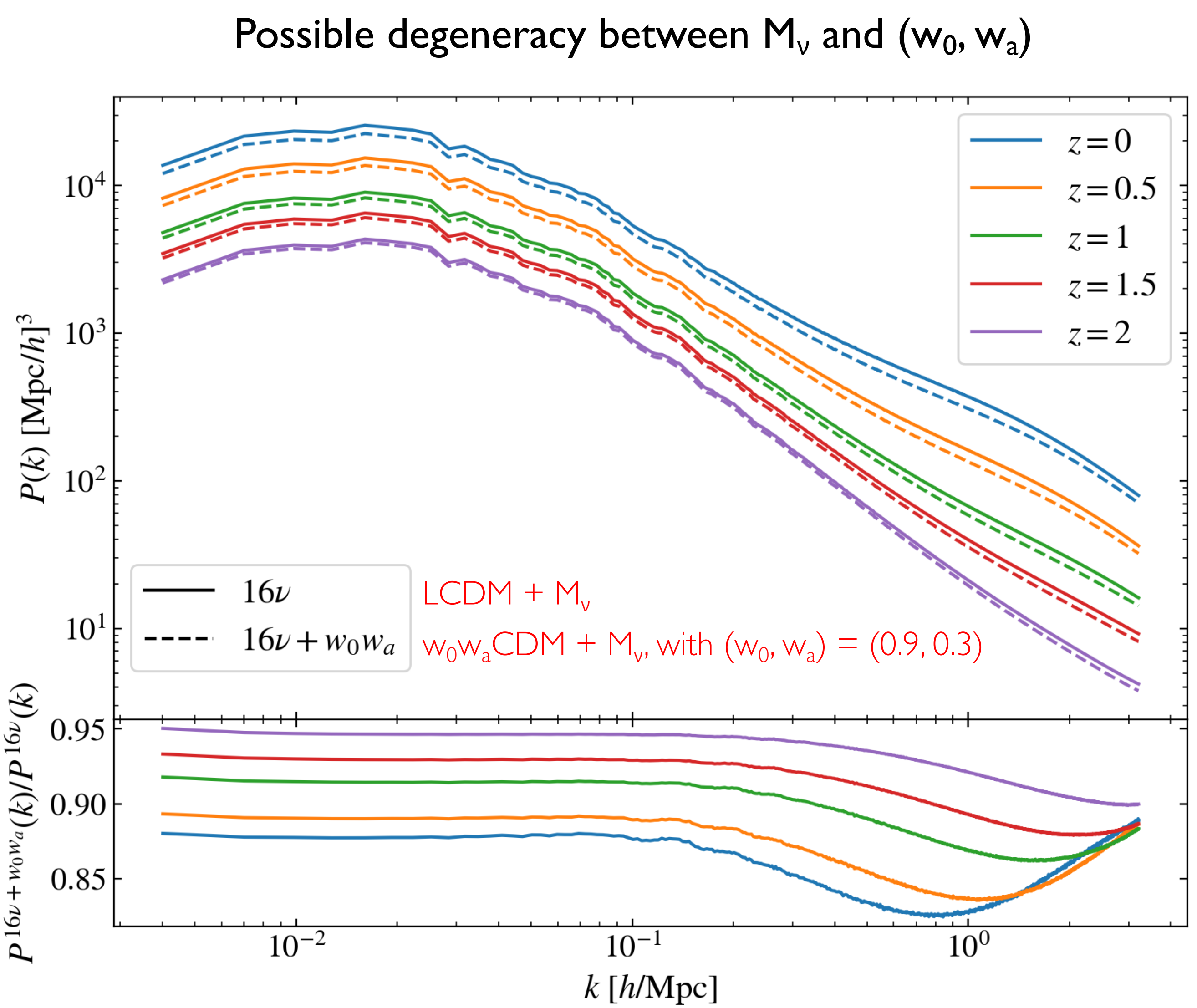
BBN prior : ω_b +/- 0.00038

Planck Prior : A_s +/- 0.1x10^{-9}



Even with a strong prior on As, m_ν is poorly estimated.

DEMNUnii ➔ Additional cosmologies with time dependent dark energy : $w(z) = w_0 + w_a \frac{z}{1+z}$

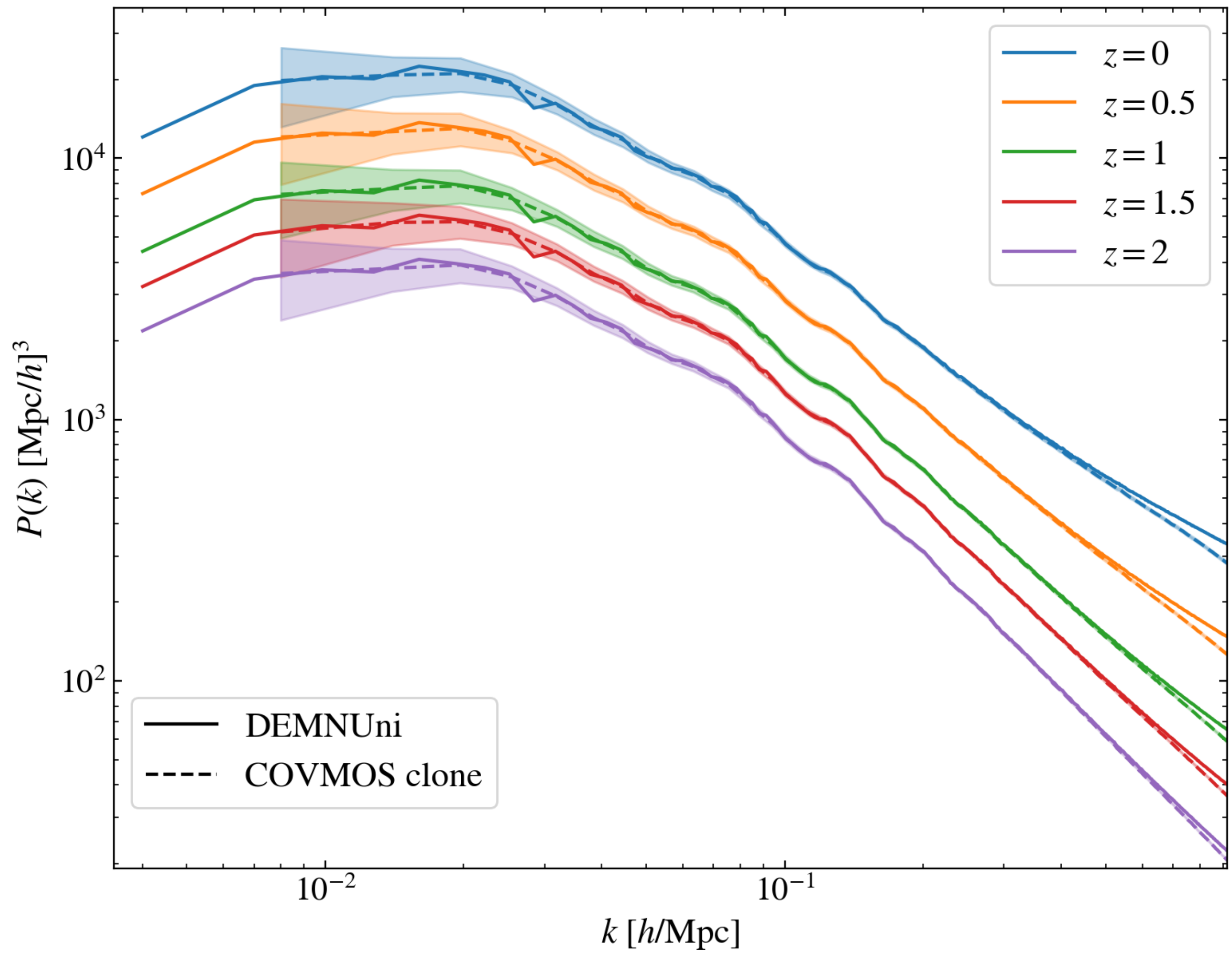


But, only one DEMNUnii realisation
(redshifts are highly correlated)

We can produce many realisations of the P(k) with COVMOS

DEMNUnii ➔ Additional cosmologies with time dependent dark energy : $w(z) = w_0 + w_a \frac{z}{1+z}$

1000 Clones of DEMNUnii with COVMOS ➔ independent redshifts + covariance

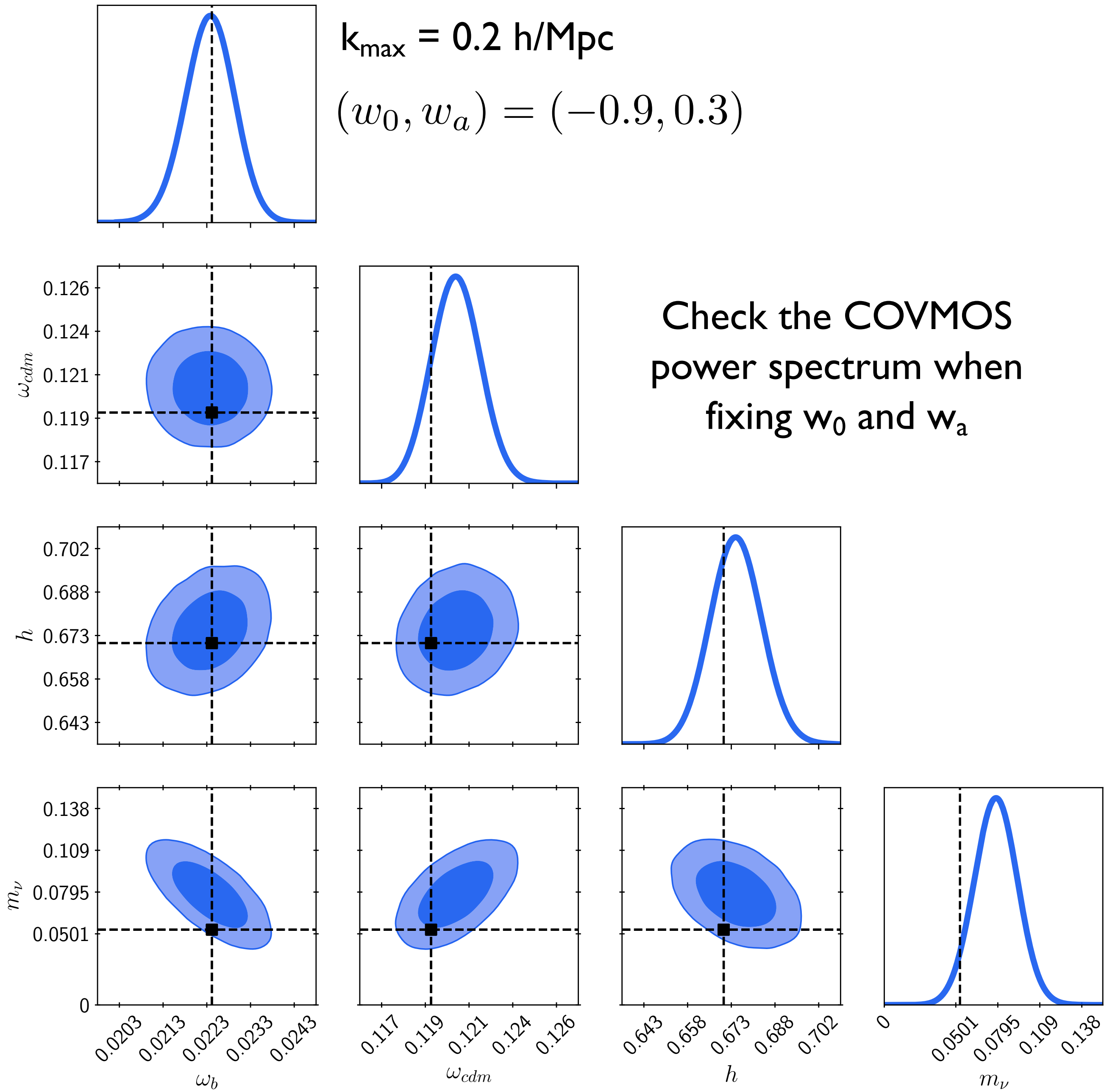


But, only one DEMNUnii realisation (redshifts are highly correlated)

We can produce many realisations of the P(k) with COVMOS

Take COVMOS spectra as the data vector

III. Results : w0waCDM + Mν



k_{max} = 0.2 h/Mpc

$$(w_0, w_a) = (-0.9, 0.3)$$

Check the COVMOS power spectrum when fixing w_0 and w_a

Set-up for the MCMC : Fit of the CDM P(k) in real space

$$\chi^2(\hat{\boldsymbol{P}}(k)|\boldsymbol{\theta}) = \left[[\hat{\boldsymbol{P}}(k) - \boldsymbol{P}(k;\boldsymbol{\theta})]^T \mathbf{C}^{-1} [\hat{\boldsymbol{P}}(k) - \boldsymbol{P}(k;\boldsymbol{\theta})]\right]$$

- DEMNUni ← $\hat{\boldsymbol{P}}(k)$
- Halofit ← $\boldsymbol{P}(k;\boldsymbol{\theta})$
- Estimated non-Gaussian covariance with covmos ← $\mathbf{C}^{-1}$

$k = [0.01, k_{\rm max}],\ \ \Delta k = 0.01\ h/{\rm Mpc}$ with $k_{\rm max} = 0.2\ h/{\rm Mpc}$

Fitting 5 uncorrelated redshifts $\chi^2 = \sum_{i=0}^{n_z=5} \chi^2(z_i)$ with $z_i = [0,\ 0.5,\ 1,\ 1.5,\ 2]$

6 parameters

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$\omega_{\rm b}$	$[0.01,\ 0.06]$
$\omega_{\rm cdm}$	$[0.01,\ 0.8]$
h	$[0.3,\ 1.5]$
m_ν [eV]	$[0,\ 1]$

+

$\boldsymbol{\theta}$	Priors
w_0	$[-2,\ 0]$
w_a	$[-5,\ 5]$

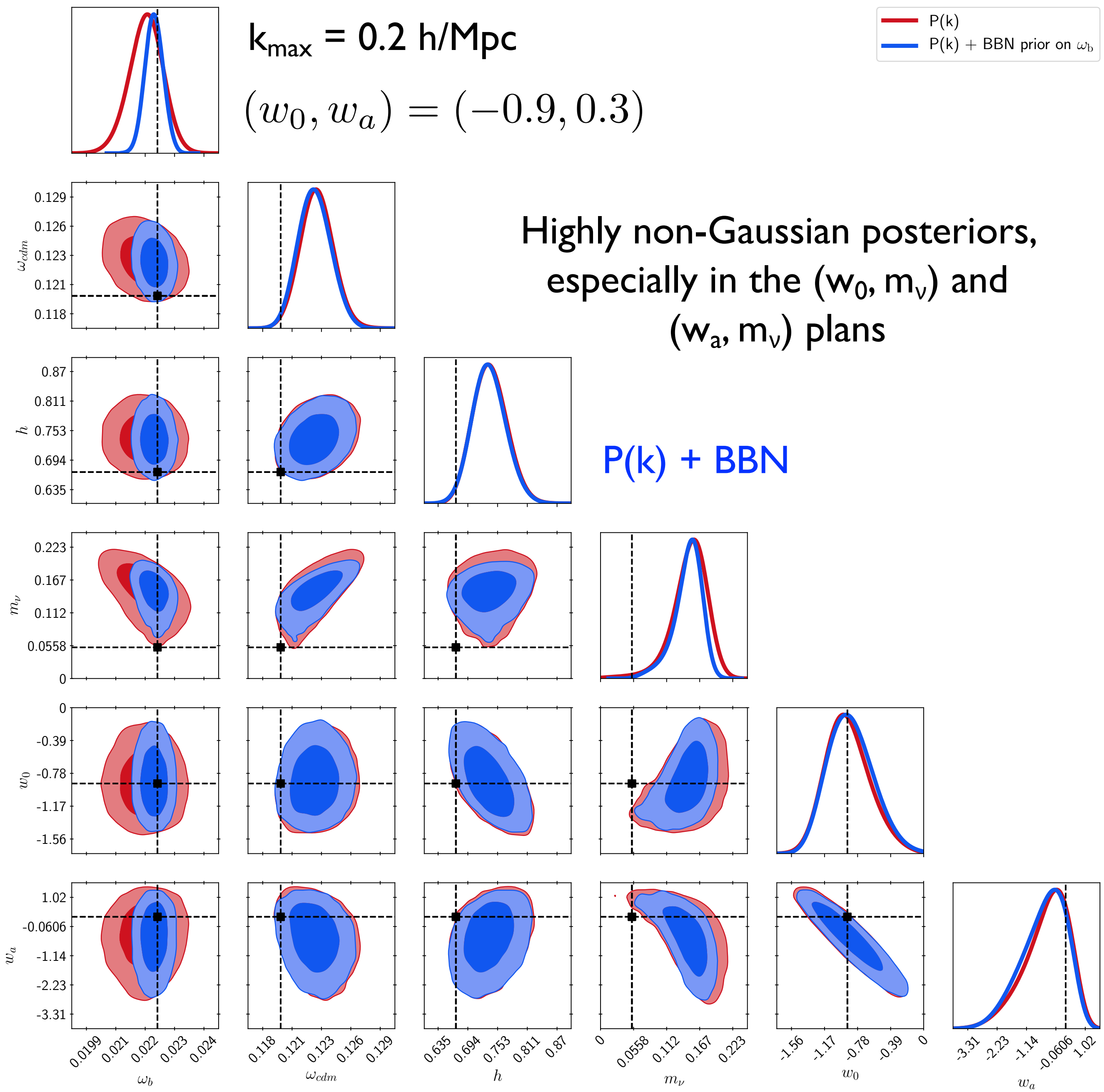
III. Results : w0waCDM + Mν

k_{max} = 0.2 h/Mpc

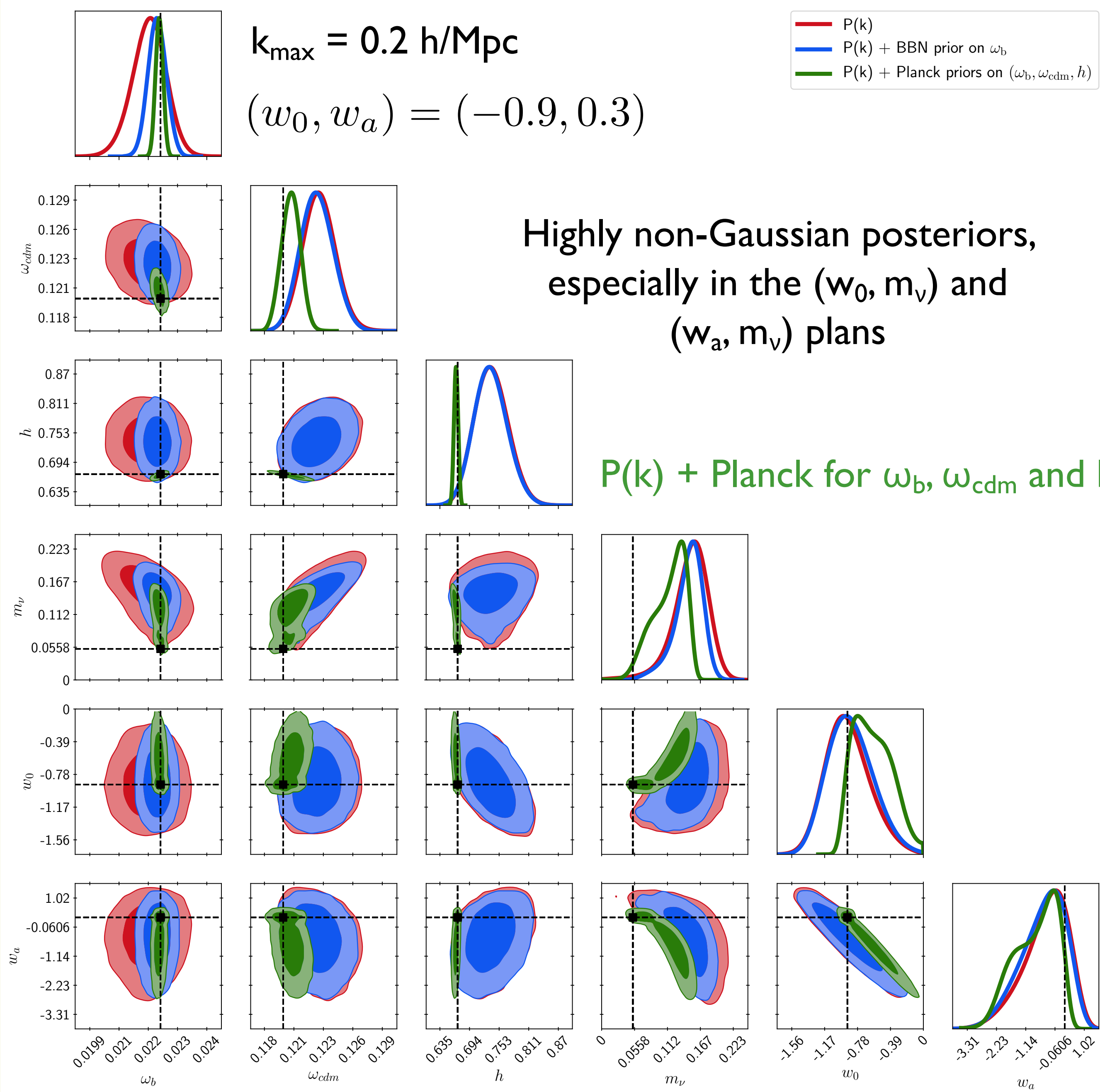
$$(w_0, w_a) = (-0.9, 0.3)$$

Highly non-Gaussian posteriors, especially in the (w_0, m_ν) and (w_a, m_ν) plans

P(k) + BBN



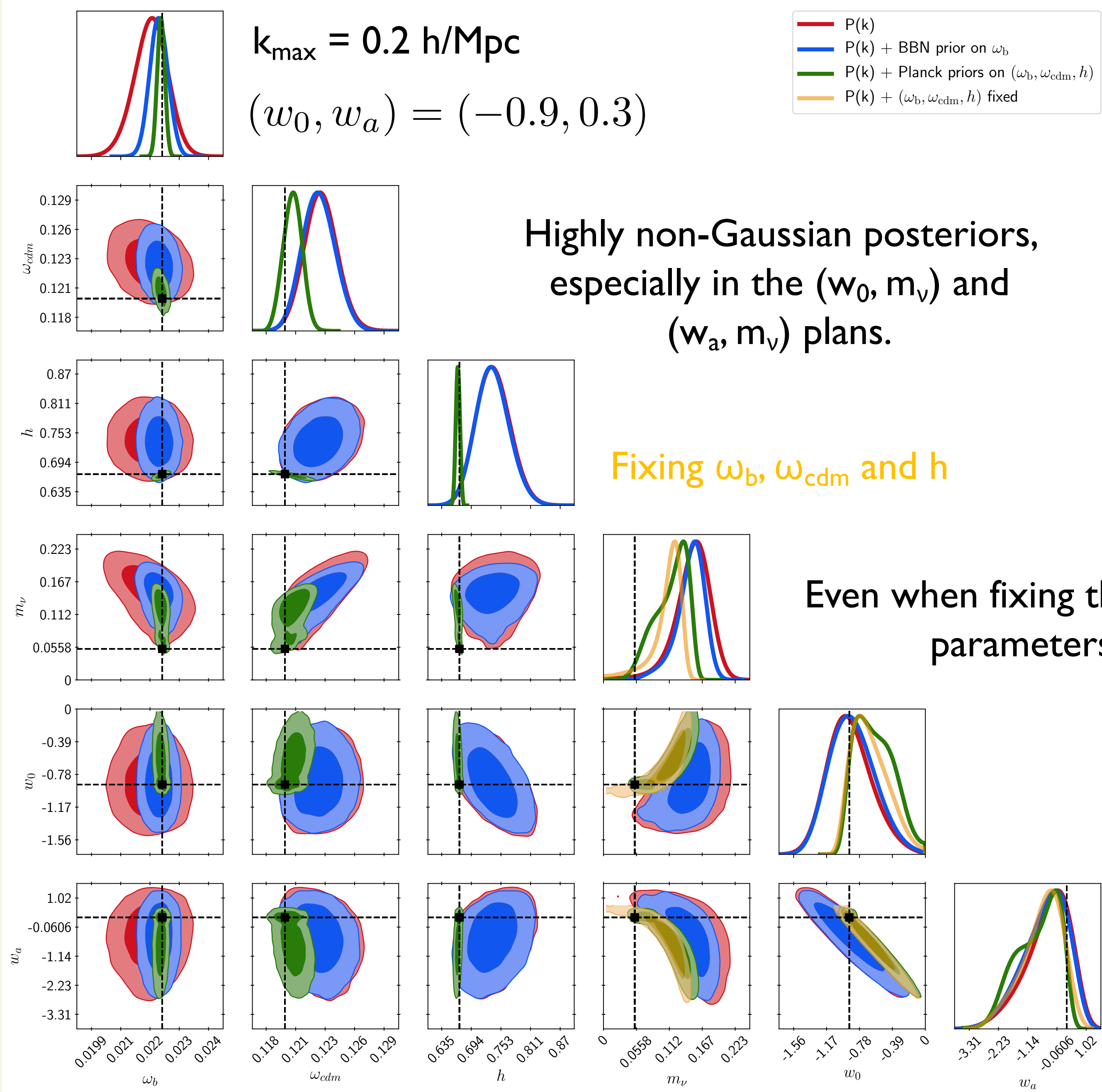
III. Results : w0waCDM + Mν



Highly non-Gaussian posteriors, especially in the (w_0, m_ν) and (w_a, m_ν) plans

P(k) + Planck for ω_b, ω_{cdm} and h

III. Results : w0waCDM + Mν



k_{max} = 0.2 h/Mpc

$$(w_0, w_a) = (-0.9, 0.3)$$

Highly non-Gaussian posteriors, especially in the (w_0, m_ν) and (w_a, m_ν) plans.

Fixing ω_b, ω_{cdm} and h

Even when fixing the other parameters

Conclusions

- Galaxy clustering is highly sensitive to massive neutrinos ➔ We studied the constraining power of the real space matter power spectrum's full shape.
- Test on the covariance : We should not neglect non-Gaussian covariance in that kind of analysis.
- Test on the model for the non-linear P(k) :
  - Halofit ➔ bias < 1σ on ω_b, ω_{cdm}, M_ν and h
  - RegPT ➔ bias < 0.3σ on ω_b and ω_{cdm}. But poor treatment of massive neutrinos
  - Hmcode ➔ bias > 2.5σ on h
- Accurate estimation of M_ν in ΛCDM when fixing As, with the real space matter power spectrum's full shape.
- When varying As, the P(k) alone cannot constrain M_ν.
- M_ν estimation in w_0w_aCDM : High degeneracy for (w_0,w_a, M_ν).
- Interesting to study the pure constraining power of matter P(k) ➔ But need to extend the analysis to galaxies + RSD.

Perspectives

We are close to finally measure M_ν thanks to cosmology.

CMB + BAO + RSD + SN $M_\nu < 0.1$ eV

[eBOSS collaboration 2020]

VS

NH $0.056 \text{ eV} \lesssim M_\nu \lesssim 1 \text{ eV}$

IH $0.095\ eV$

Overall particle physics experiments constraints

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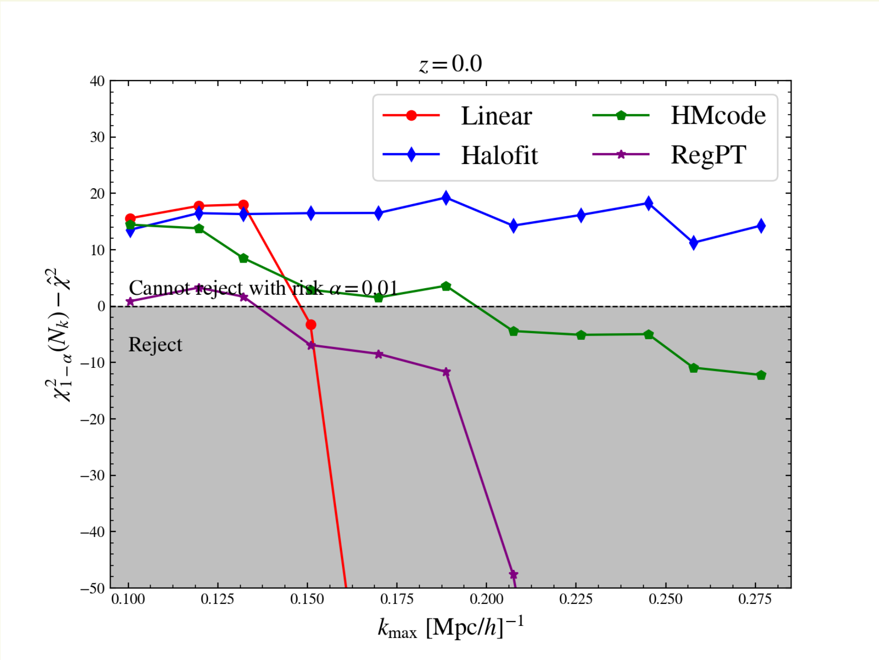
Overall particle physics experiments constraints

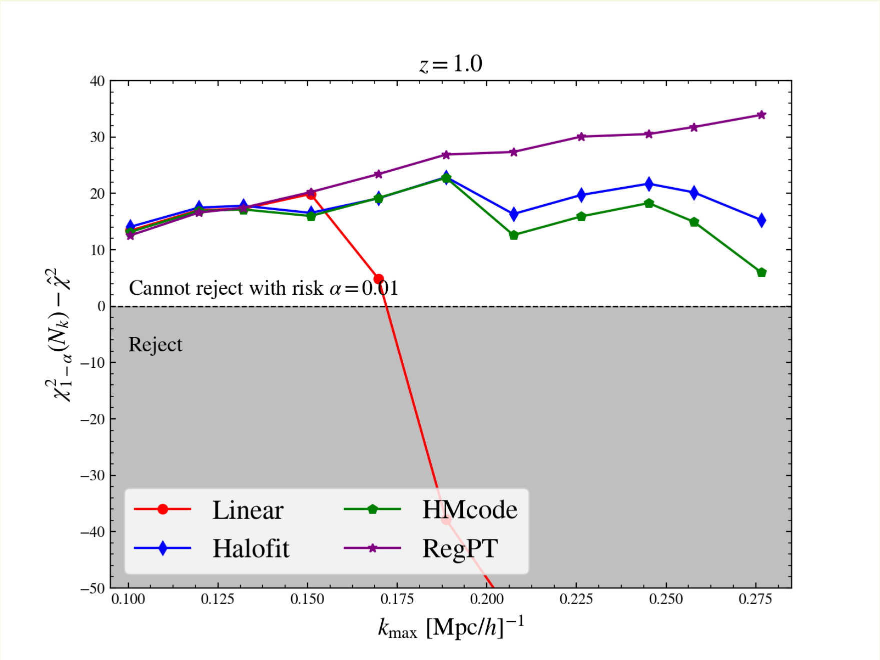
But the full-shape P(k) alone cannot constrain M_ν

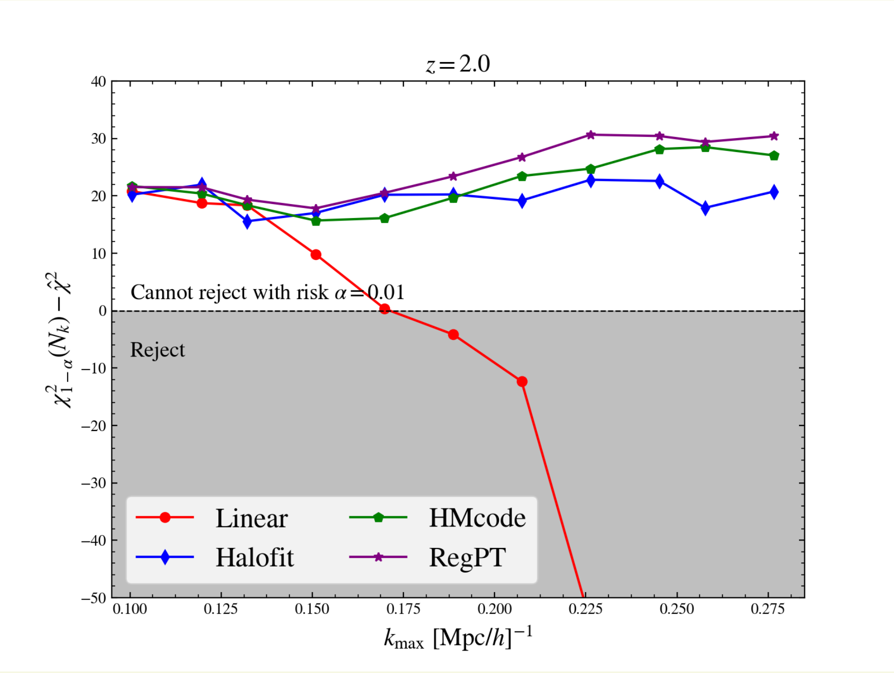
- RSD breaks degeneracies with As and the galaxy bias b_g, by allowing the measurement of different multipoles [Chudaykin and Ivanov 2019].
- The addition of the Bispectrcum also breaks the degeneracy with b_g [Hahn et al. 2020a,b].
- Voids are a promising probe to study neutrinos [Bayer et al. 2021, Kreisch et al. 2018].
- Velocity statistics seem to be very sensitive to neutrinos [Hagstotz at al. 2019, Kuruvilla et al. 2020]
- The Lyman-α power spectrum from eBOSS already gives tight constraints on M_ν when combined with CMB : $M_\nu < 0.1$ eV. [Palanque-Delabrouille et al. 2020]

Thank you !

Back up







Goodness of fit test, with significance α=0.01