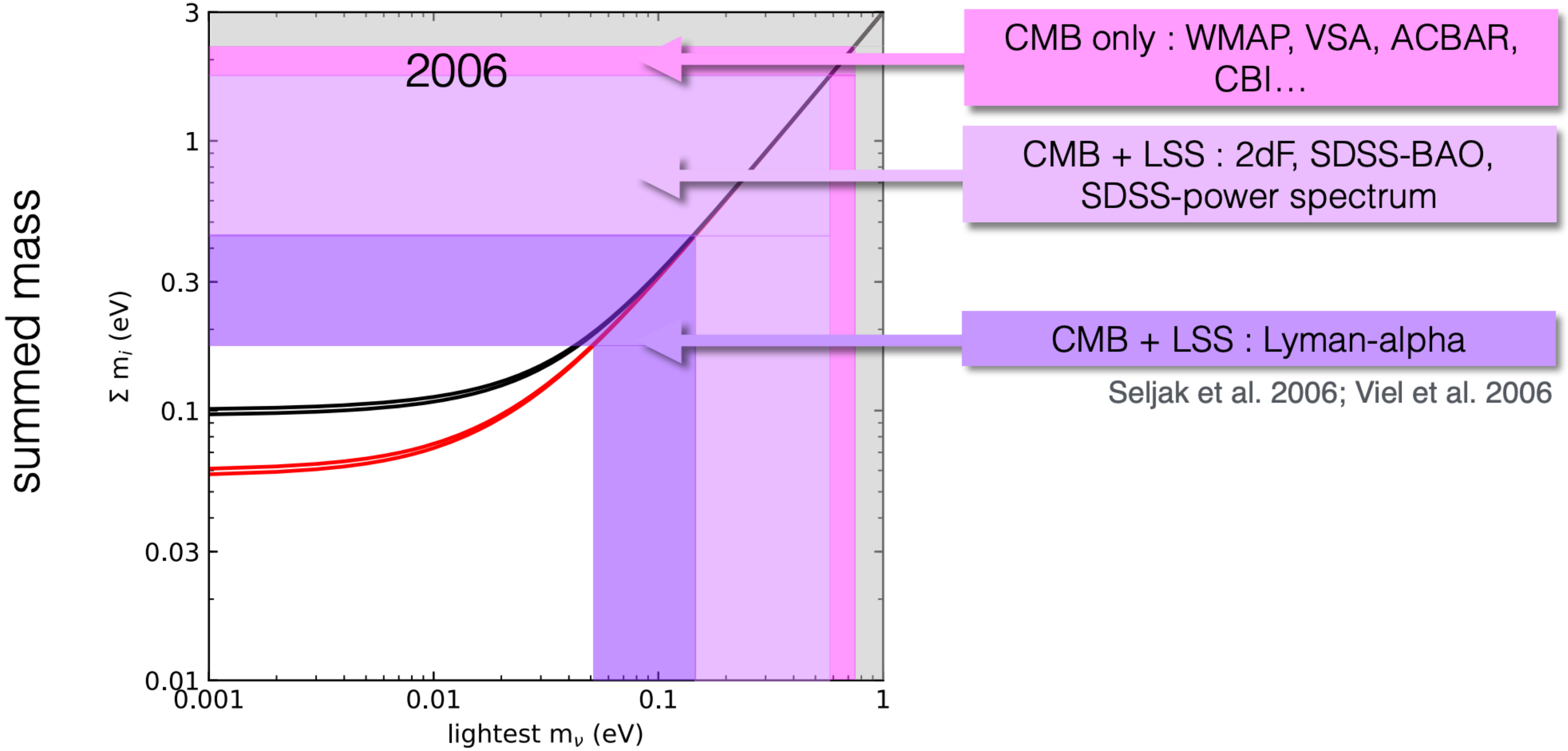
Plan

Matteo Viel

- Lecture 1: Cosmological effects of neutrinos in linear perturbation theory
- Lecture 2: Non-linear regime
- Lecture 3: Neutrinos in Intergalactic space
- Lecture 4: New ways of probing neutrino masses

Some historical background (a successful story!)

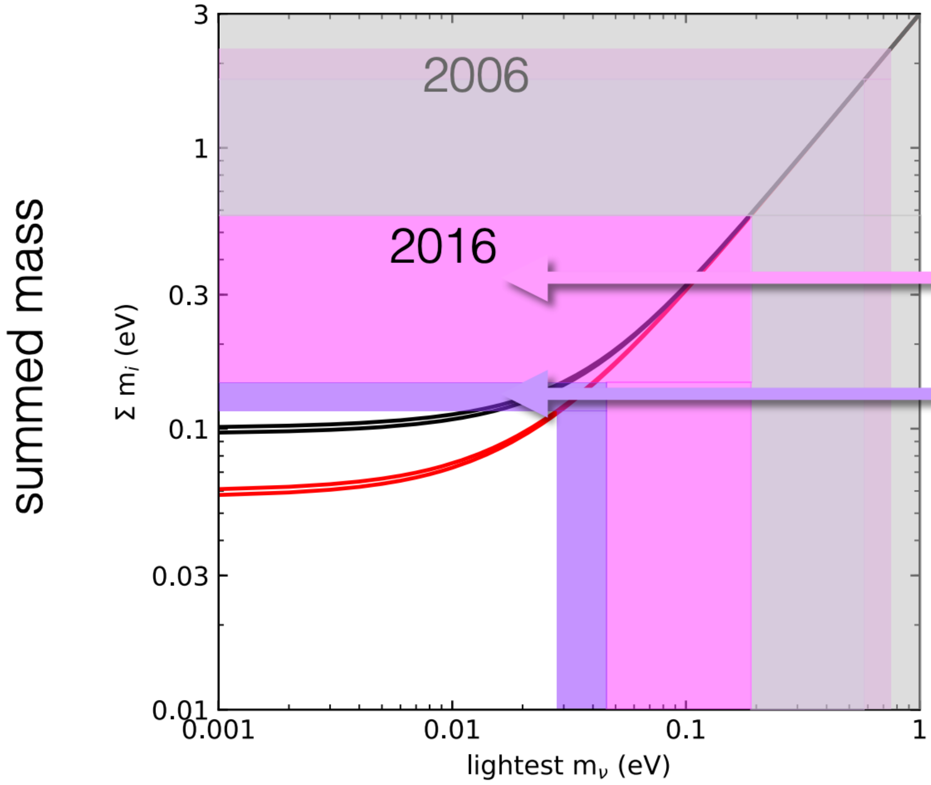
95%CL upper bounds on $\Sigma_i m_i$



Seljak et al. 2006; Viel et al. 2006

Some historical background

95%CL upper bounds on $\Sigma_i m_i$



CMB only: Planck,
w/o polarisation and lensing…
$\Sigma_i m_i$ < 590 to 140 meV (95%CL)

[Planck col.] 1605.02985

CMB + LSS :

- with galaxies: $\Sigma_i m_i$ < 130 meV (95%CL)
- with Lyman-α: $\Sigma_i m_i$ < 120 meV (95%CL)
- with BAOs: $\Sigma_i m_i$ < 118 meV (95%CL)

Cuesta et al. 1511.05983; Palanque-Delabrouille et al. 1506.05976; Vagnozzy et al. 1701.08172

NH already favoured by cosmo. + labo. bounds (Simpson et al. 1703.03425; Capozzi et al. 1703.04471)

Some historical background

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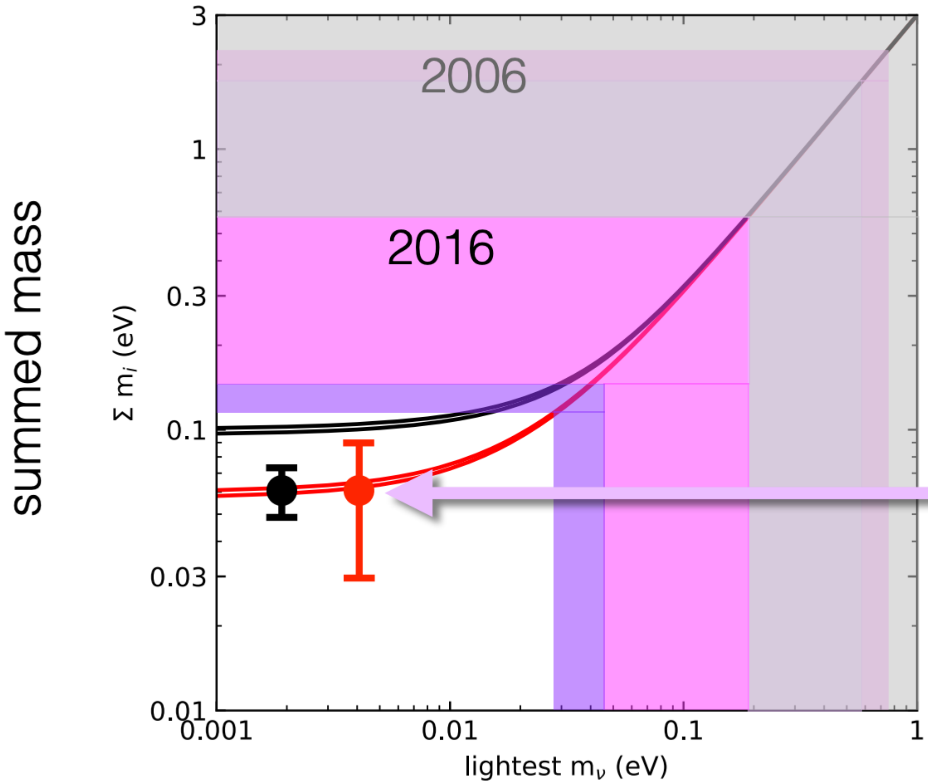
95%CL upper bounds / 1σ forecast errors on $\Sigma_i m_i$



bayer22.pdf

Planck + next generation LSS :
DES, DESI, Euclid, LSST, wFIRST, SKA

σ ~ {
40 -> 12 meV (7 params + …)
60 -> 30 meV (complicated DE)
60 -> 40 meV (complicated MG)

e.g. Font-Ribera et al. 1308.4164

… with conservative use of SKA; 21cm?

New probes/new issues

- Baryons?
- Cosmic Voids
- 21cm cosmology
- Environmental effects
- Higher order?

Weak lensing

$$C^{(ij)}(\ell) = \int_0^\infty \mathrm{d}z \, \frac{c}{H(z)} \frac{W^{(i)}(z)\, W^{(j)}(z)}{\chi^2(z)} P_\mathrm{mm}\left(k = \frac{\ell}{\chi(z)}, z\right)$$

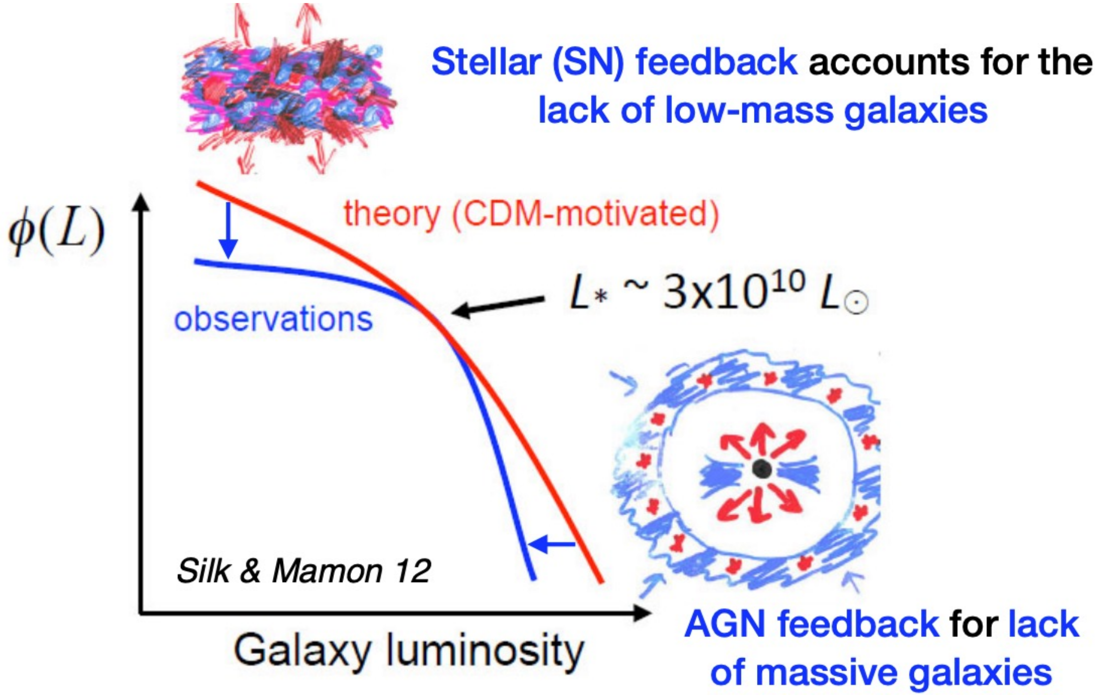
$$W^{(i)}(z) = \frac{3}{2}\, \Omega_\mathrm{m} \left(\frac{H_0}{c}\right)^2 (1+z)\, \chi(z) \int_{\min(z, z_i)}^{z_{i+1}} \mathrm{d}x \; n_\mathrm{s}(x) \, \frac{\chi(x) - \chi(z)}{\chi(x)}$$

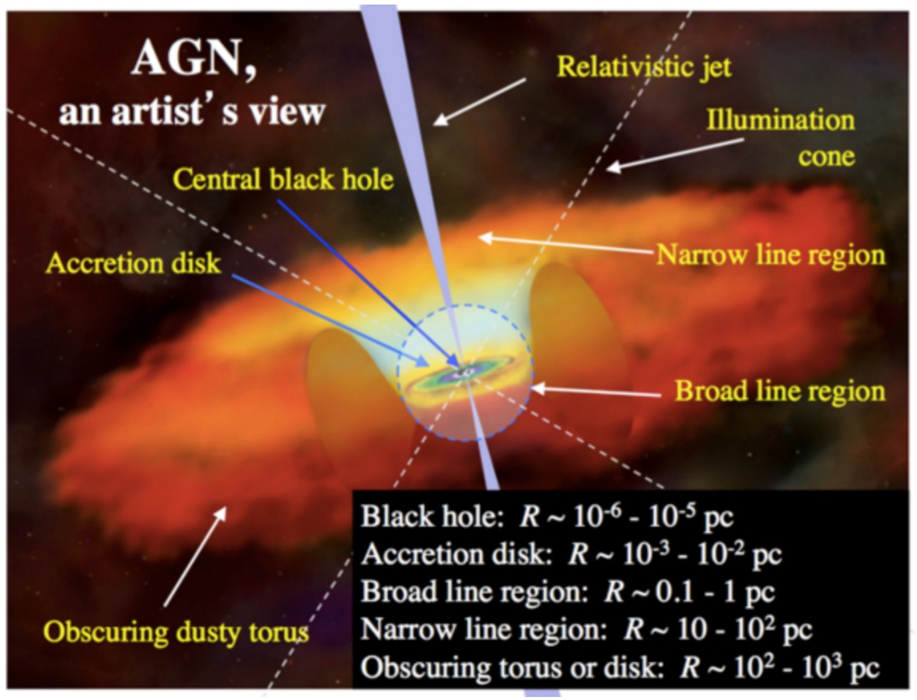
$$k_\mathrm{fs} = 0.82 \, \frac{E(z)}{(1+z)^2} \, \frac{M_\nu}{1\ \mathrm{eV}} \, h\,\mathrm{Mpc}^{-1}$$

$$P_\mathrm{mm}(k) = (1 - f_\nu)^2 \, P_\mathrm{cc}(k) + 2\, f_\nu\, (1 - f_\nu)\, P_{\mathrm{c}\nu}(k) + f_\nu^2\, P_{\nu\nu}(k)$$

$$\frac{\Delta P^\mathrm{L}_\mathrm{cc}(k)}{P^\mathrm{L}_\mathrm{cc}(k)} \approx -6\ f_\nu, \qquad \frac{\Delta P^\mathrm{L}_\mathrm{mm}(k)}{P^\mathrm{L}_\mathrm{mm}(k)} \approx -8\ f_\nu$$

Baryon feedback - I





Baryon feedback - II

$$F_{\rm bf}(k, z|M_c, \eta_{\rm b}, z_c) \equiv \frac{P_{\rm feed}(k)}{P_{\rm dmo}(k)} = \left\{ \frac{B(z)}{1 + (k/k_g)^3} + [1 - B(z)] \right\} S(k),$$

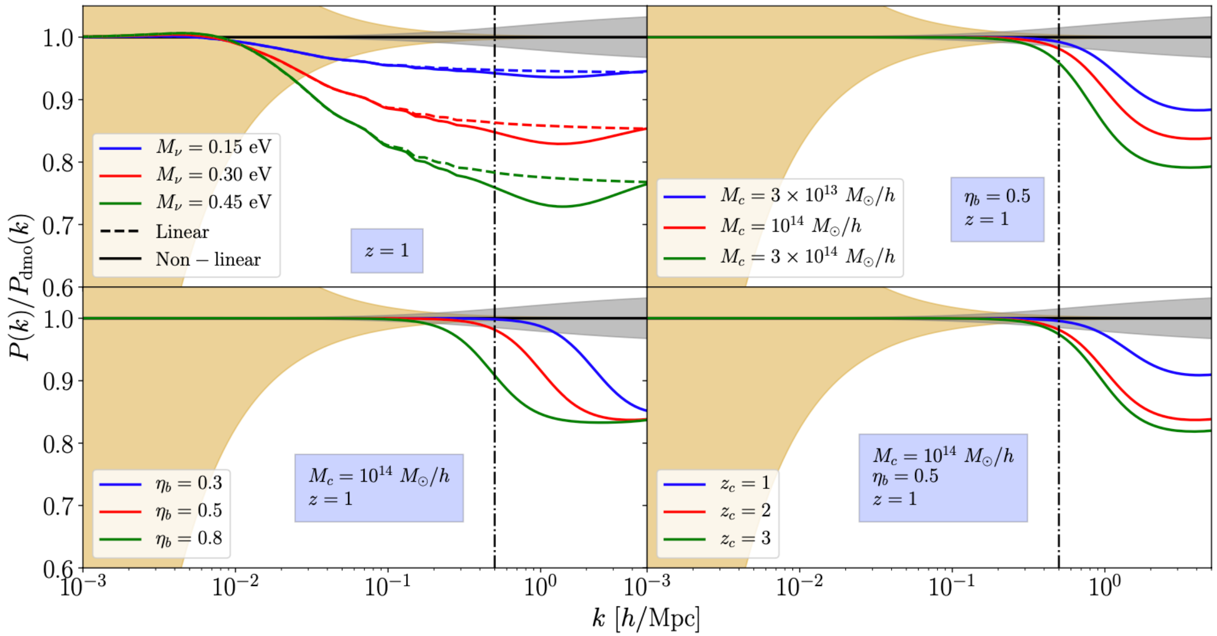
where

$$B(z) = \frac{0.105 \log\left(\frac{M_c}{{\rm M}_\odot/h}\right) - 1.27}{1 + (z/z_c)^{2.5}},$$

$$S(k) = 1 + \left(\frac{k}{55\,h\,{\rm Mpc}^{-1}}\right)^2$$

for $M_c \geq 10^{12}\ {\rm M}_\odot/h$ and zero otherwise,

$$k_g(z) = 0.7\ [1 - B(z)]^4\ \eta_{\rm b}^{-1.6}\,h\,{\rm Mpc}^{-1}\,,$$



Baryon feedback - III

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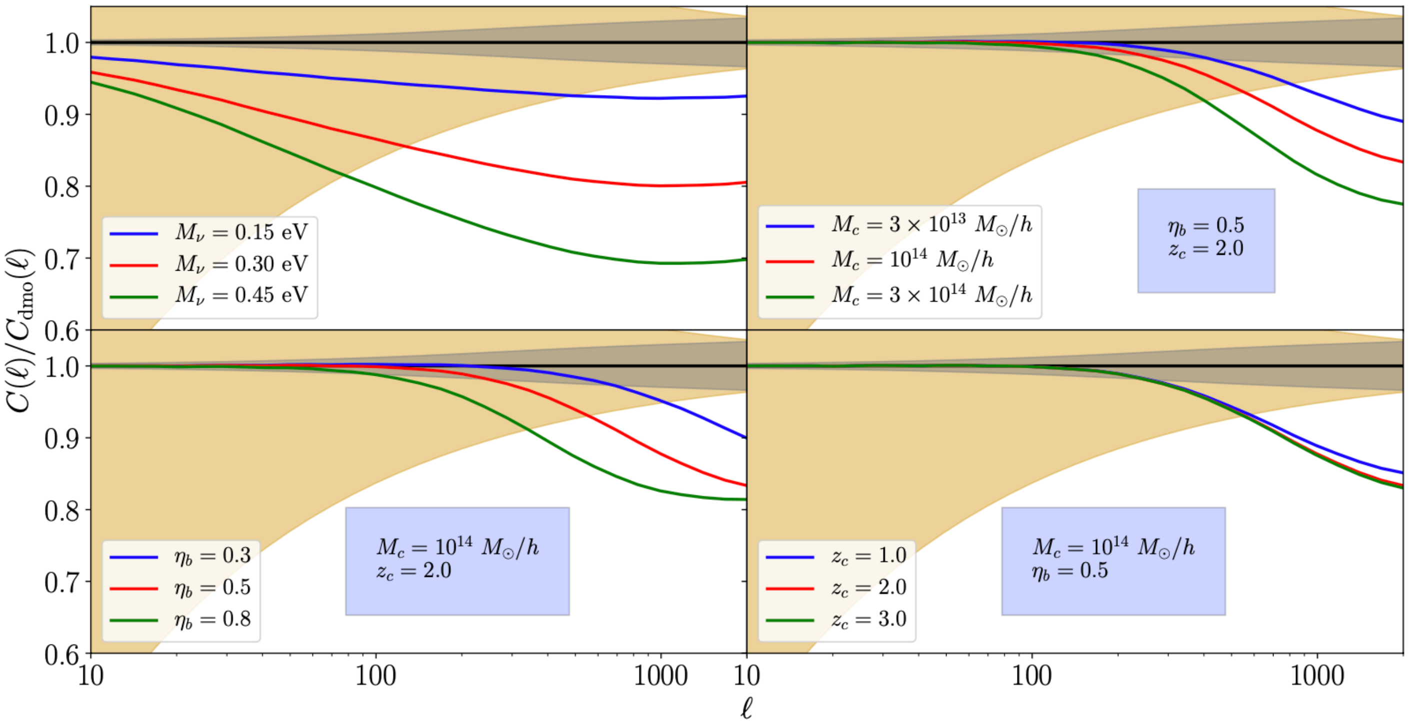


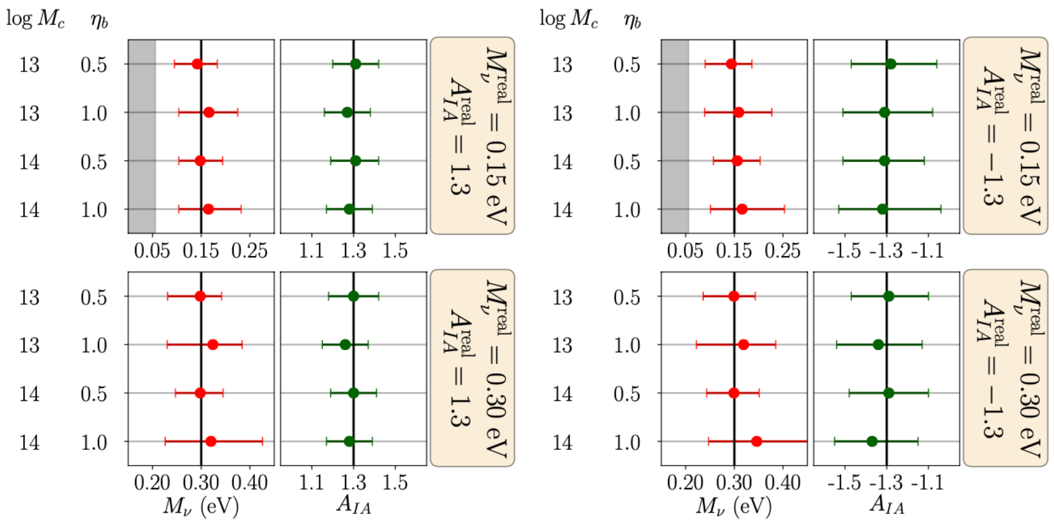
Baryon feedback - IV

Maximum shift in the total neutrino mass is 0.5s

No obvious degeneracies

Apart from one: between neutrino mass and intrinsic alignment (important term in weak lensing modelling)

In general: neutrino free streaming is more gentle, and with different z-dependence compared to baryon feedback

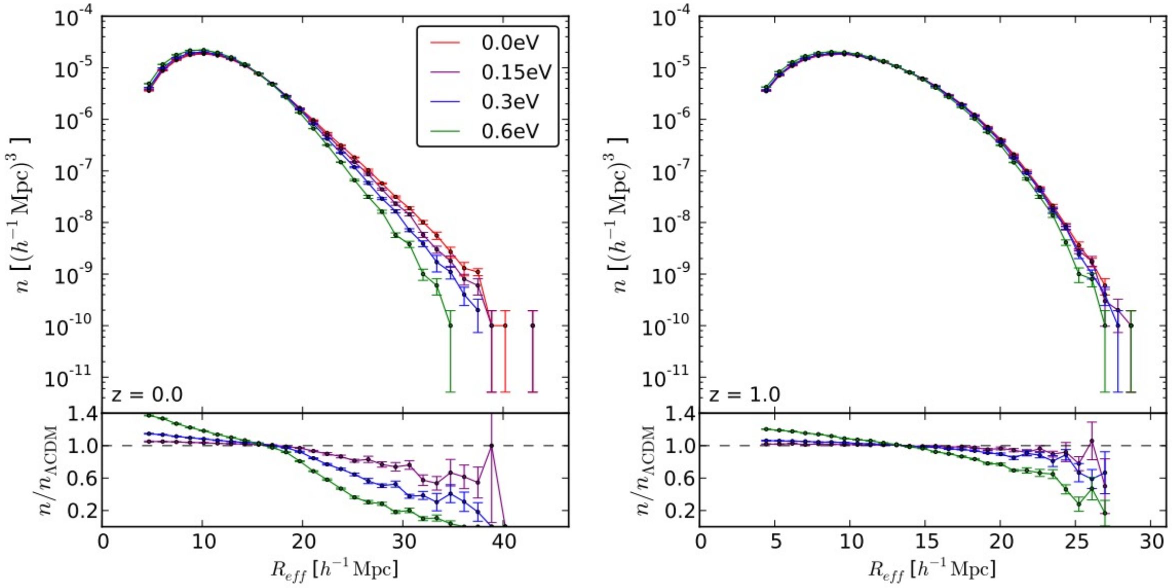


Voids: the void size function

Voids in massive neutrino cosmologies

Elena Massara,[a,b] Francisco Villaescusa-Navarro,[c,b] Matteo Viel,[c,b] P. M. Sutter [c,b,d]

Comprehensive numerical effort



Voids in massive neutrino cosmologies are less evolved (i.e. **younger**) than those in the corresponding massless neutrinos case: there is a larger number of small voids and a smaller number of large ones, their profiles are less evacuated, and they present a lower wall at the edge.

VOIDS evolve by **evacuating particles** (very different from haloes)!

Voids – II: ellipticities and correlation function

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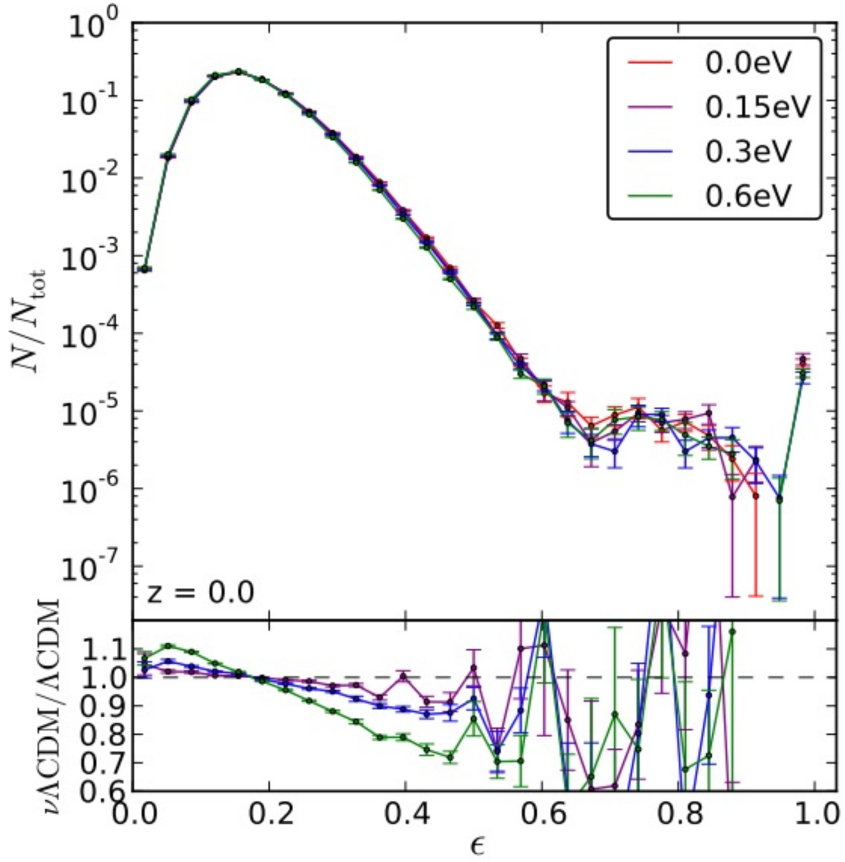
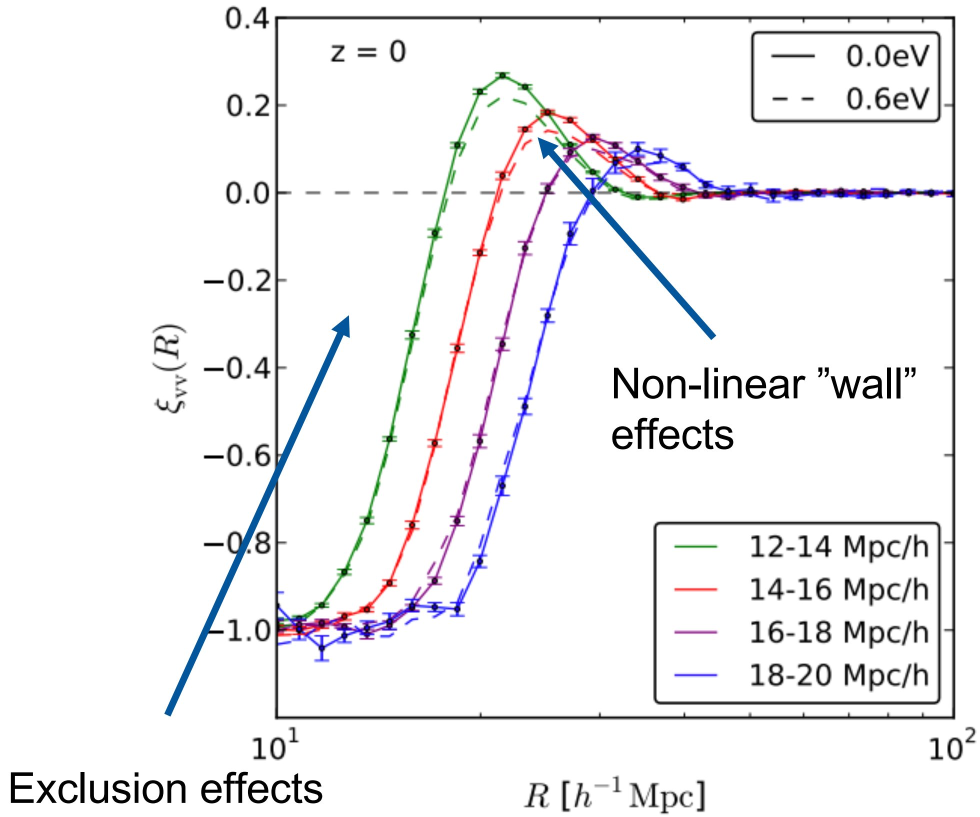
Ellipticity



Voids Correlation Functions



Voids – III: density profiles and degeneracies

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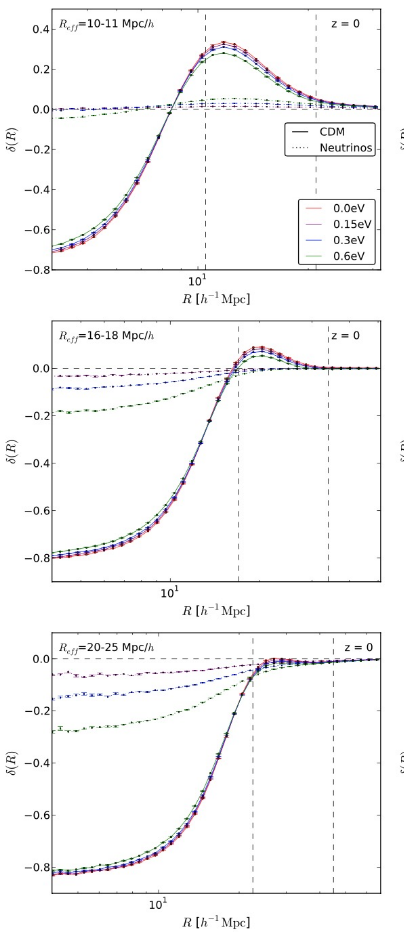
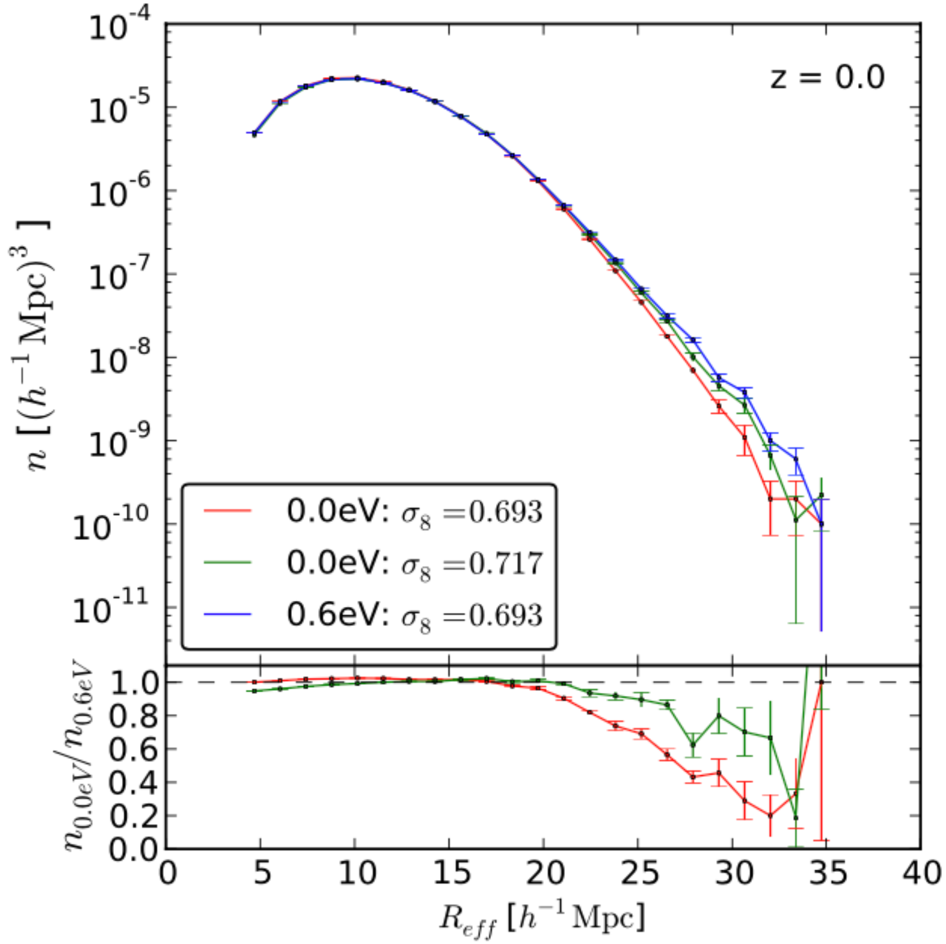
Density profiles



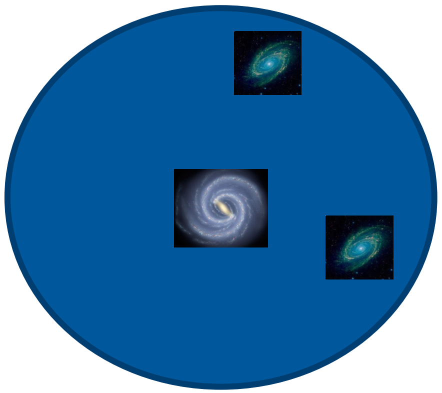
Notice
The wall
For small voids



Voids – IV: populating with galaxies

So far: used the matter or halo distributions … but….real universe is different
We need galaxies --> HOD simple model

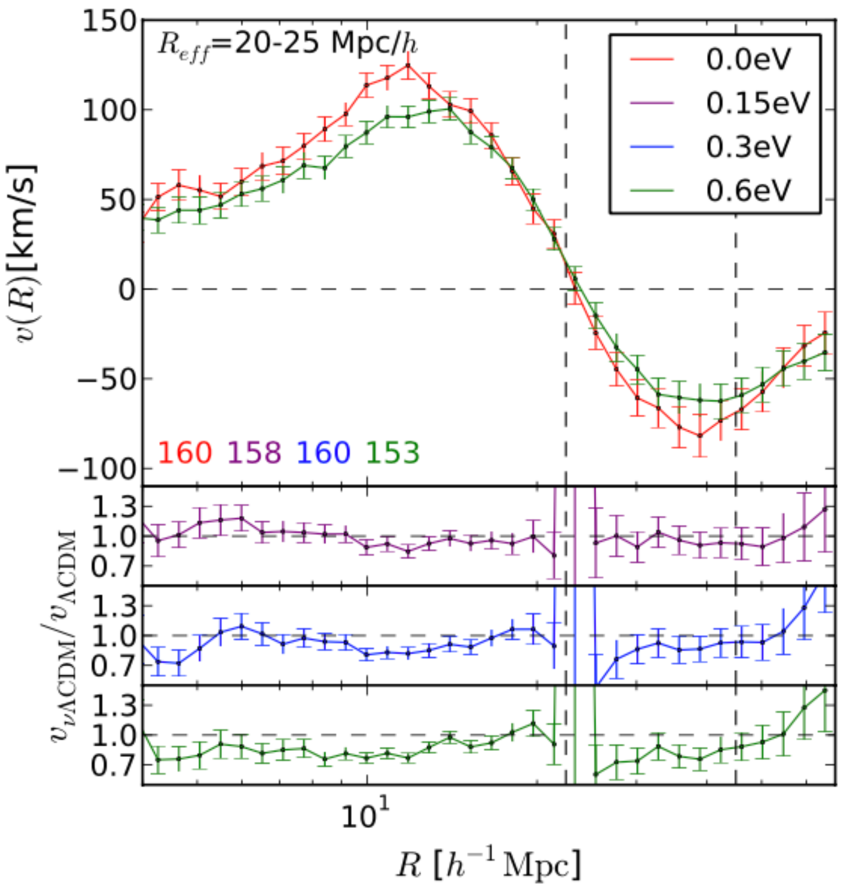
$$\langle N_c|M\rangle = \begin{cases} 1 & \text{if } M \geq M_{\rm min} \\ 0 & \text{if } M < M_{\rm min} \end{cases} \qquad \langle N_s|M\rangle = \begin{cases} (M/M_1)^{\alpha} & \text{if } M \geq M_{\rm min} \\ 0 & \text{if } M < M_{\rm min}\,. \end{cases}$$

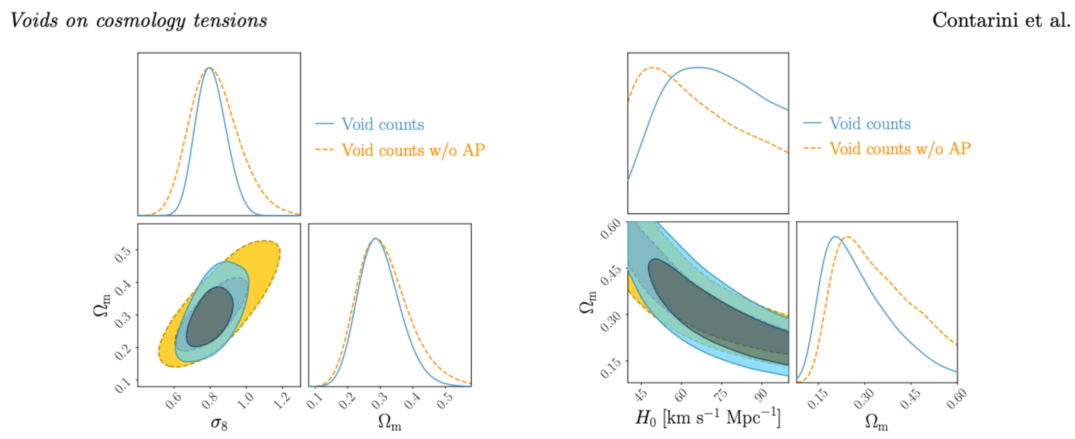


You can build simple HOD models
By asking to reproduce observed
Correlation functions or luminosity
properties of galaxies

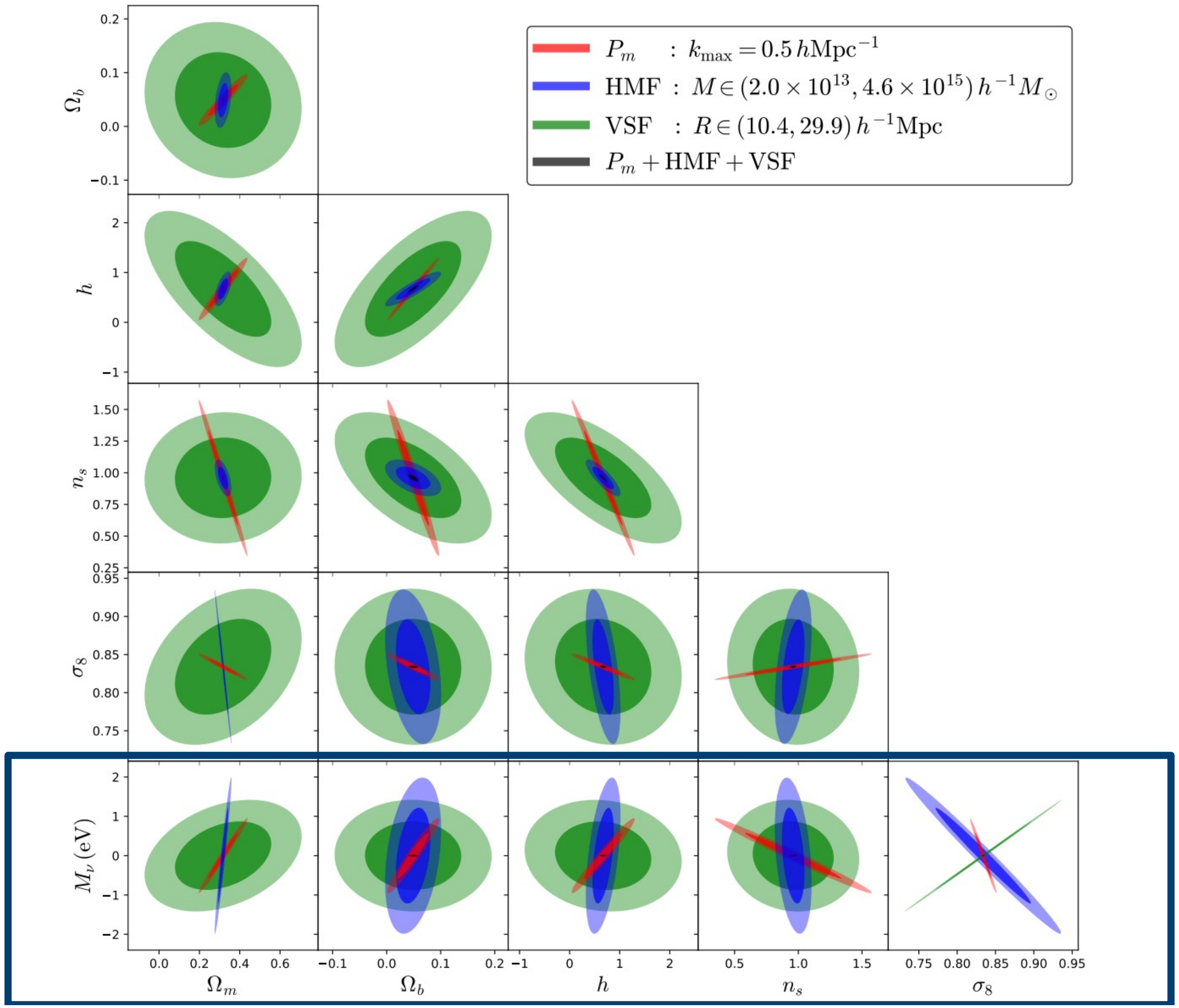
Once you build such a model you can then run your voidfinder on top of the galaxy distribution

Voids – V: populating with galaxies



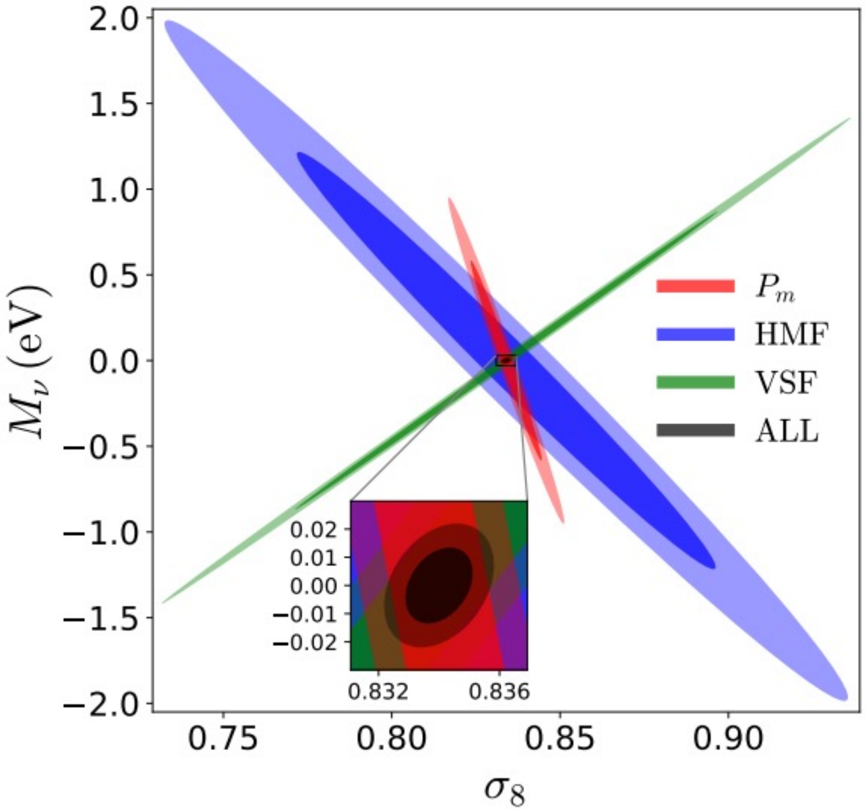


Voids – VI: combining with other probes



Voids – VI: combining with other probes

Bayer+22 arXiv: 2102.05049



Marginalized Fisher Constraints

Probe(s)	Ω_m	Ω_b	h	n_s	σ_8	M_ν(eV)
P_m	0.098	0.039	0.51	0.50	0.014	0.77
HMF	0.034	0.042	0.28	0.12	0.082	1.6
VSF	0.31	0.12	1.3	0.42	0.083	1.1
P_m + HMF	0.00077	0.0089	0.076	0.034	0.0016	0.061
P_m + VSF	0.016	0.011	0.12	0.074	0.0018	0.025
HMF + VSF	0.0063	0.037	0.23	0.10	0.0069	0.096
P_m + HMF + VSF (diag)	0.0015	0.0088	0.066	0.028	0.00061	0.031
P_m + HMF + VSF (auto)	0.0015	0.0086	0.071	0.033	0.0016	0.025
P_m + HMF + VSF (full)	0.00071	0.0084	0.064	0.025	0.0015	**0.018**
Multiplicative improvement	137	5	8	20	10	43

Without CMB priors to “fix” the large
Scales

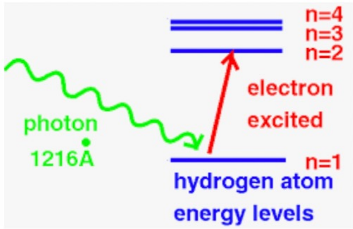
Volume 1 (Gpc/h)3, kmax=0.5 h/Mpc
From sims

But real surveys will have 100 more volume

21cm – atomic processes & hydro sims

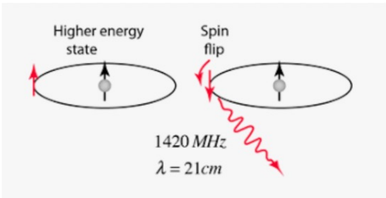
Matteo Viel

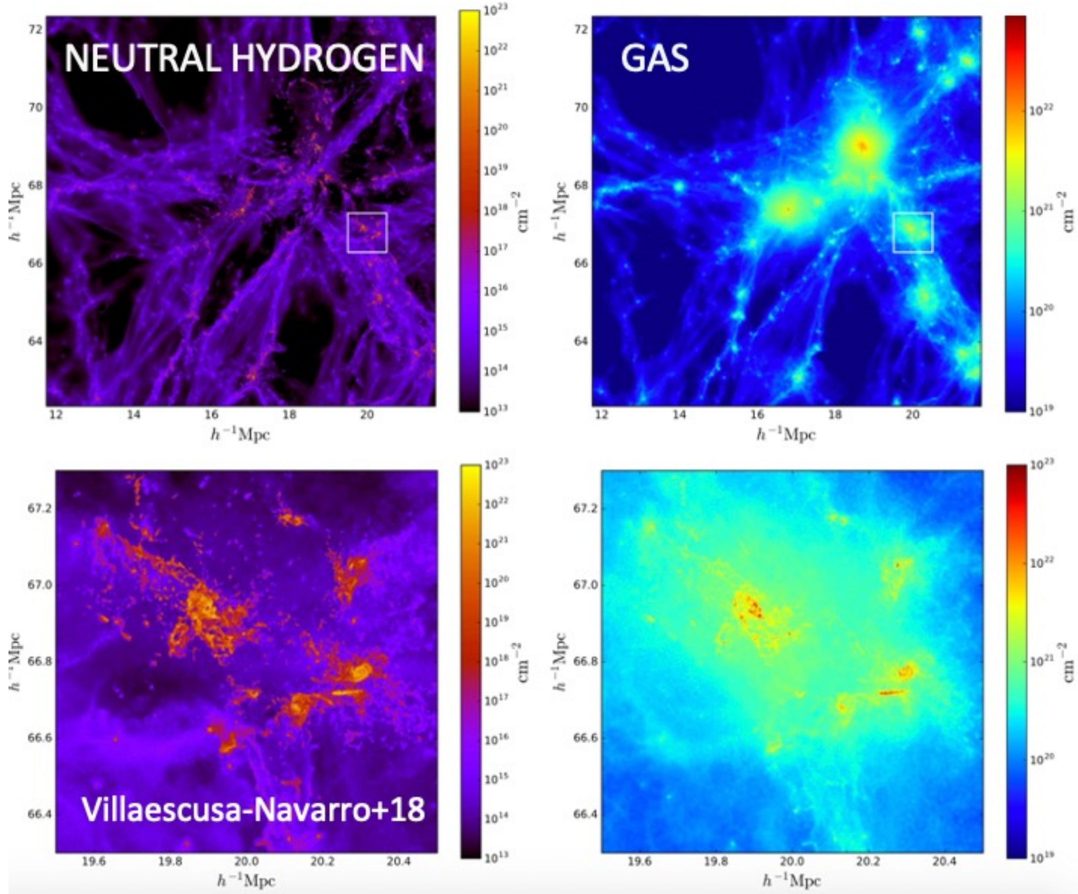
Atomic processes



Absorption - Lyman-alpha forest

Emission - 21cm intensity mapping





21cm – A simple model

NEUTRAL HYDROGEN GAS

Linear theory model:

$$P_{21\,\mathrm{cm}}(k,\mu,z) = \bar{T}_b(z)^2[(b_{\mathrm{H\,I}}(z) + f(z)\mu^2)^2 P_{\mathrm{m}}(k,z) + P_{\mathrm{SN}}(z)],$$

$$\bar{T}_b(z) = 189h\left(\frac{H_0(1+z)^2}{H(z)}\right)\Omega_{\mathrm{H\,I}}(z)\ \mathrm{mK},$$

$$\Omega_{\mathrm{H\,I}}(z) = \frac{1}{\rho_c^0}\int_0^\infty n(M,z)M_{\mathrm{H\,I}}(M,z)dM,$$

$$b_{\mathrm{H\,I}}(z) = \frac{1}{\rho_c^0\Omega_{\mathrm{H\,I}}(z)}\int_0^\infty n(M,z)b(M,z)M_{\mathrm{H\,I}}(M,z)dM,$$

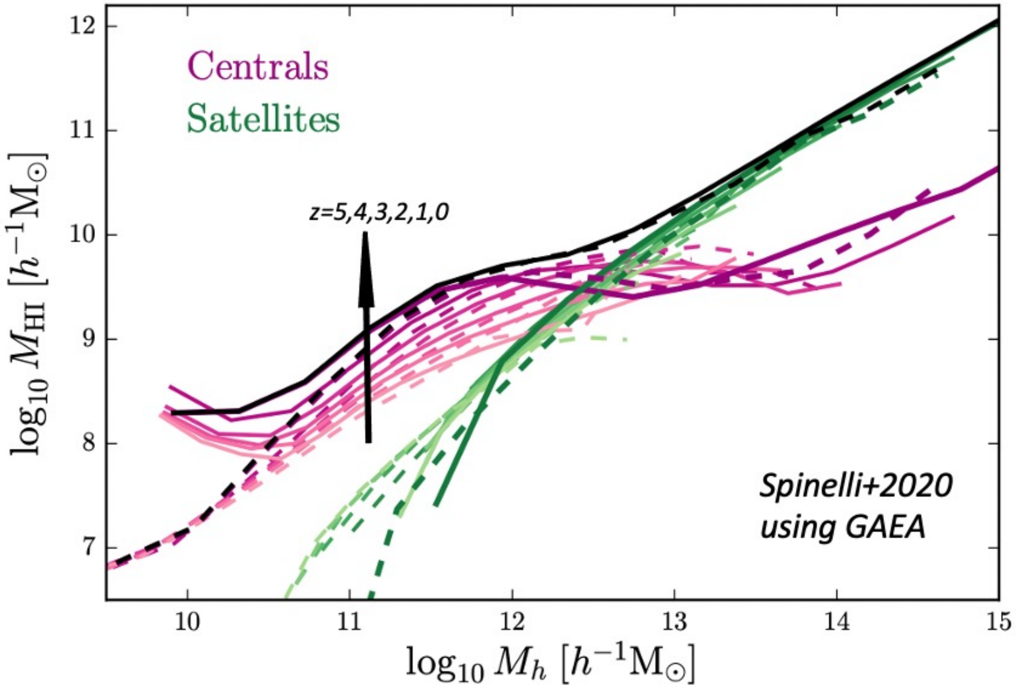
$$P_{\mathrm{SN}}(z) = \frac{1}{(\rho_c^0\Omega_{\mathrm{H\,I}}(z))^2}\int_0^\infty n(M,z)M_{\mathrm{H\,I}}^2(M,z)dM,$$

$$M_{\mathrm{H\,I}}(M,z) = M_0\left(\frac{M}{M_{\mathrm{min}}}\right)^\alpha \exp(-(M_{\mathrm{min}}/M)^{0.35}).$$

M_{min} decreases with redshift
alpha increases with redshift

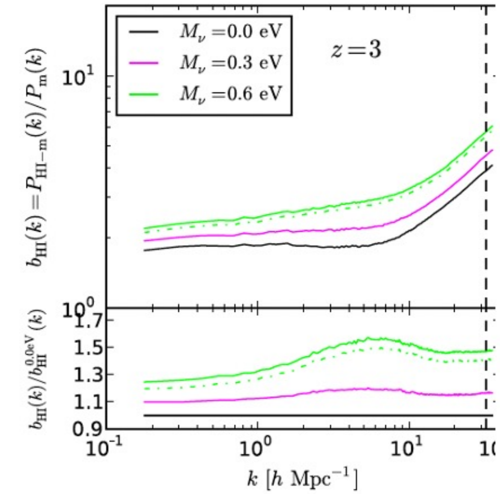
- degeneracy between b_{HI} and $Omega_{HI}$, which can be broken by using other probes (cross-corr.)
- Progress made mainly in the modelling and in determining the low-z HI bias (~0.8) from observations (Obuljen+18) - Pen+09, Switzer+13 (auto and cross to constrain Omega_HI x bias_HI), Anderson+18 (cross. with galaxies).
- **IM signal:** main ingredient is the function $M_{HI}(M_{halo})$ with its scatter.

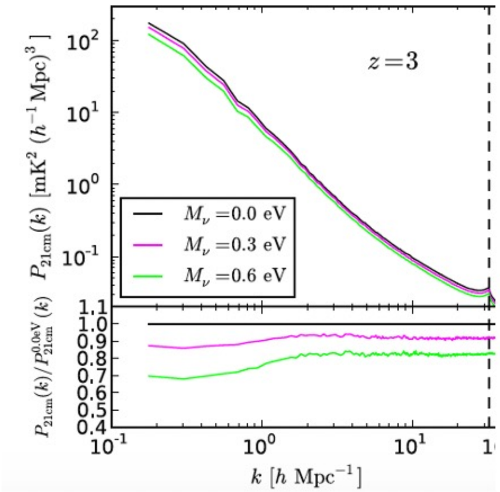
21cm – Cross correlations?



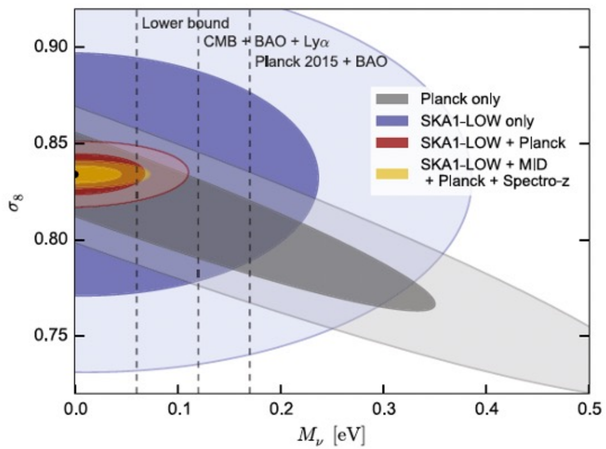
…further progress: interfacing this "small-scale" accurate and physical information with large scale methods for extensive mock productions e.g. PINOCCHIO LPT light-cone halos (Spinelli, Carucci+2021)

21cm and neutrinos





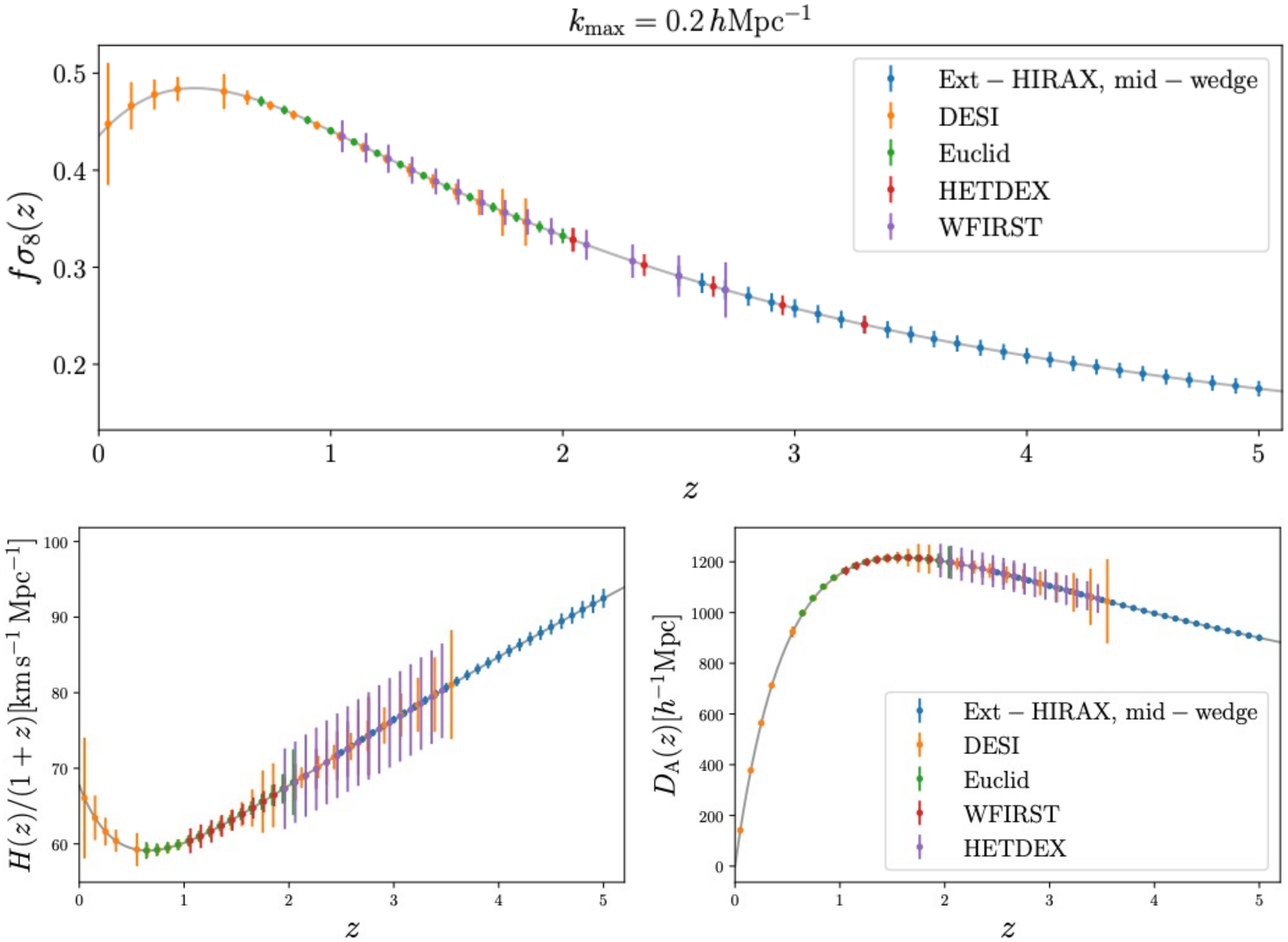
- Scale dependence bias also present in massive neutrino cosmologies.
- M$_{\rm HI}$(M) not affected by the presence of neutrinos.
- HI is more clustered in massive neutrino sims. (but Omega$_{\rm HI}$ lower) - because small mass haloes are suppressed i.e. impact on n$_{\rm HALO}$(M).
- IM alone would provide constraint of about sigma(M_nu) = 30 meV (not very constraining compared to other probes).
- Radiative transfer postprocessing important but does not impact much the limit above



Villaescusa-Navarro, MV, Bull, 2015

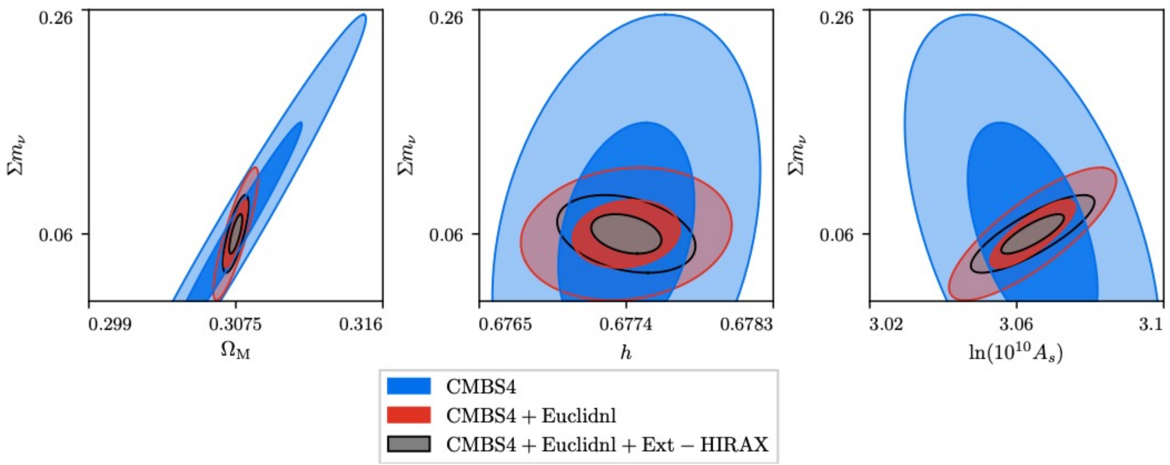
21cm and forecasts

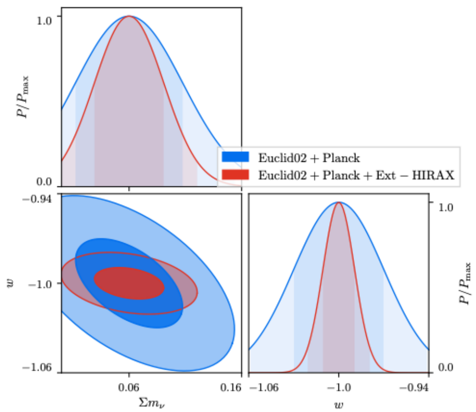
Obuljen+18

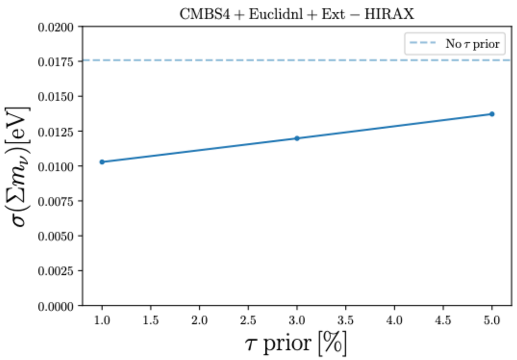


21cm and forecasts

Obuljen+18







21cm and forecasts

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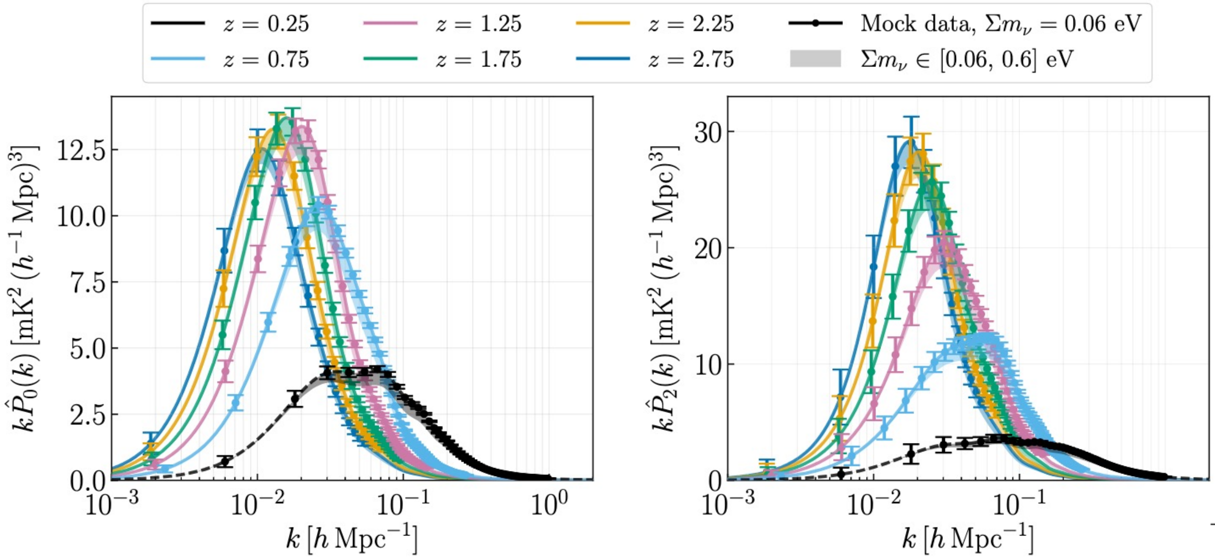
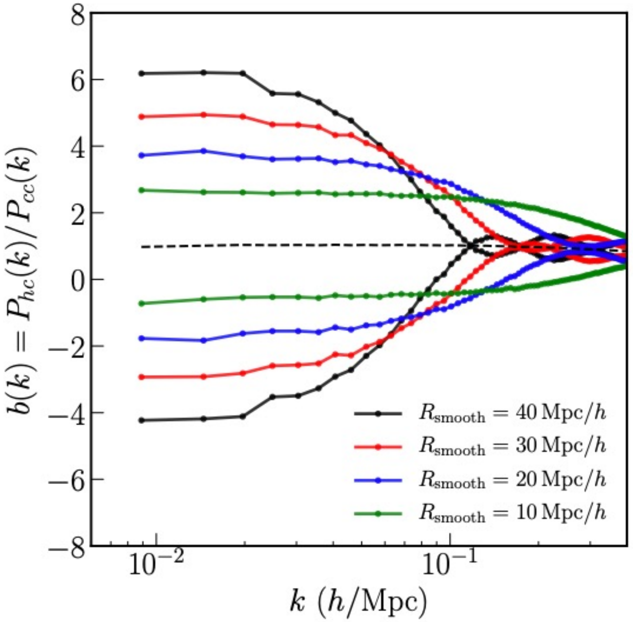


Berti, Viel, Spinelli 23 [to appear]

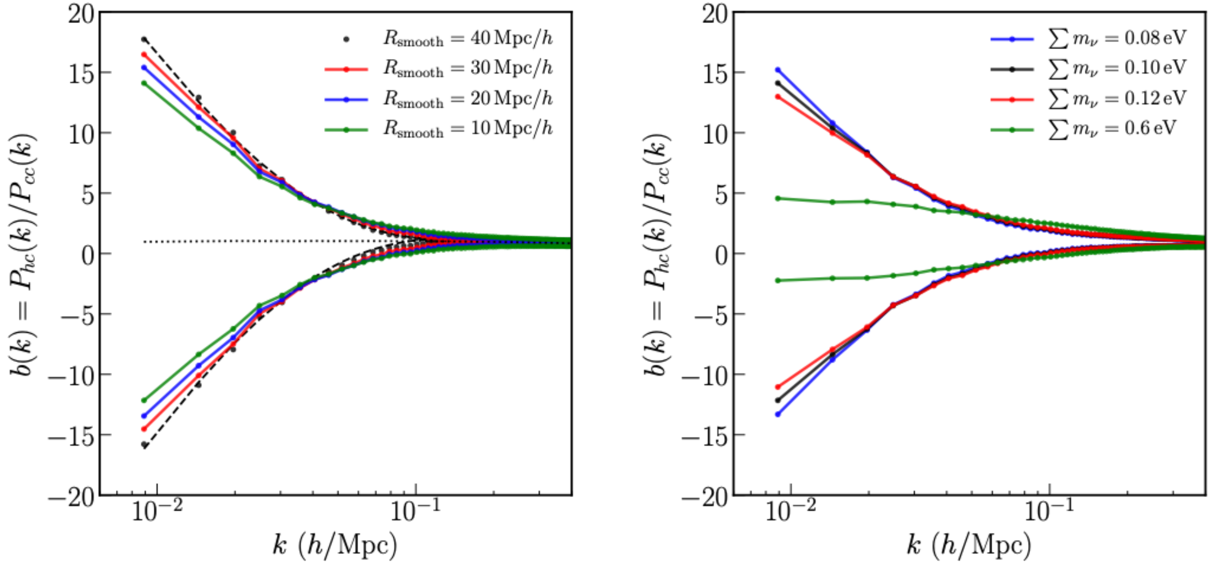
Likelihoods		$\Sigma m_\nu^{\rm fid} = 0.1$
$\hat{P}_0 + \hat{P}_2$	< 0.216	< 0.227
+ nuisances	< 0.478	< 0.535
$\hat{P}_0 + \hat{P}_2$ + BAO	< 0.227	
+ nuisances	< 0.413	
Planck 2018	< 0.259	
+ $\hat{P}_0 + \hat{P}_2$	< 0.101	< 0.117
+ nuisances	< 0.129	< 0.127
Planck 2018 + BAO	< 0.149	
+ $\hat{P}_0 + \hat{P}_2$	< 0.101	
+ nuisances	< 0.130	

Environmental effects

Clustering of haloes in a massive Mn=0.1eV which are below and above the median CDM density



Clustering of haloes in a massive Mn=0.1eV which are below and above the median neutrino density

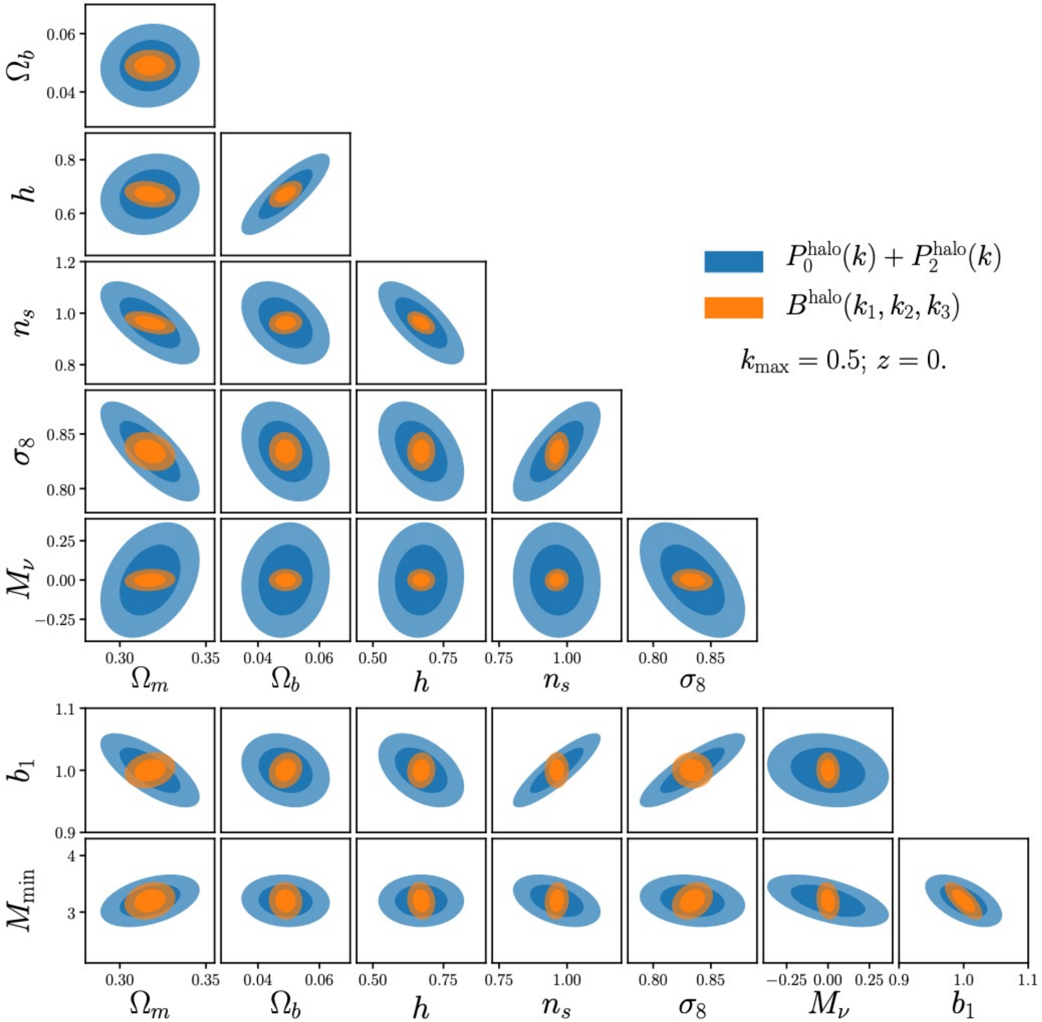


Strong scale dependence found → need a way to probe environment

From galaxies to halo to cdm…..

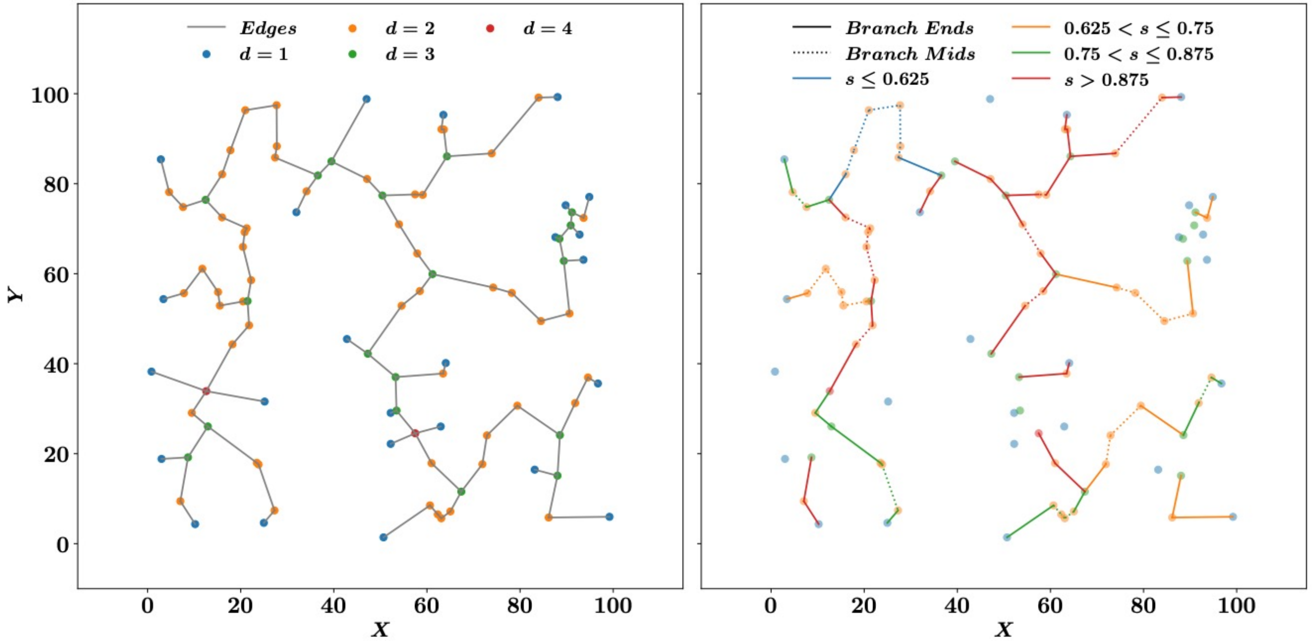
Banerjee, Castorina, Villaesusa-Navarro, Court, MV, 2019

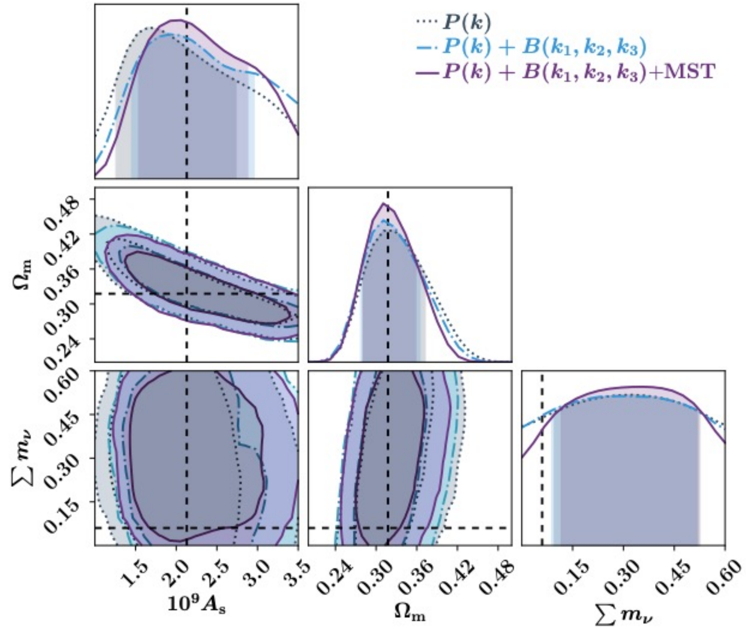
Bispectrum



Hahn+19

Minimum Spanning Tree





Statistics which is extra-sensitive to topology of clustering

Naidoo+19
Naidoo+22

Tensions

At present there are 2 tensions in cosmology

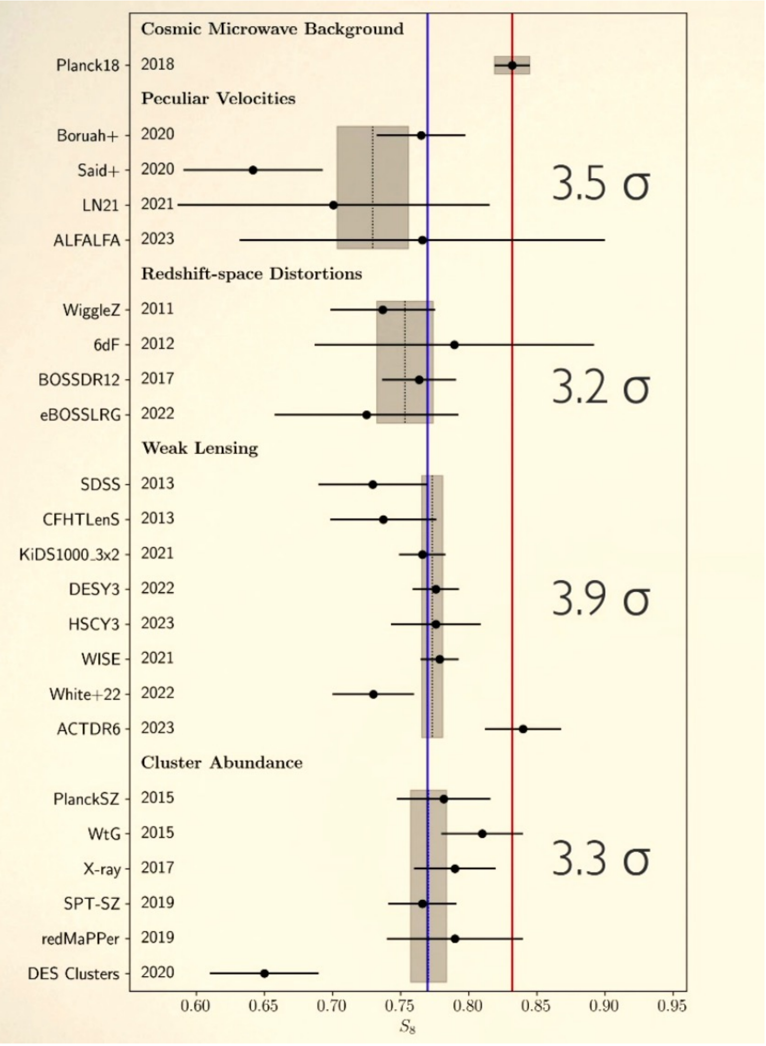
1) H0 tension: 5sigma level reached
2) S8 tension: ~3 sigma

Can a low s8 be explained by neutrino free streaming?

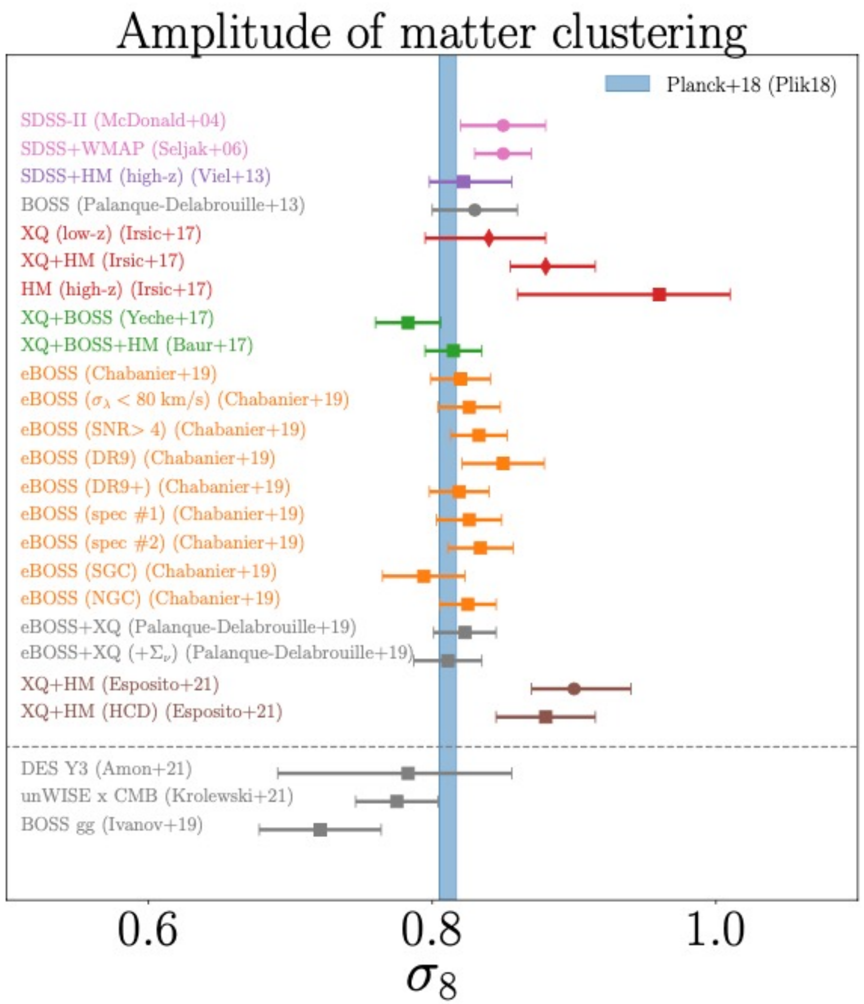
Can the different Hubble parameter inferred from local and early Universe probes be reconciled with neutrinos?

Tensions - II

Matteo Viel



σ_8 tension – I



This is from the forest only

Summary

- Neutrino background detected from CMB through Neff

- In the structure formation epoch, neutrino perturbations not detected yet

- Effect is small but not incredibly small: whitin reach of planned and ongoing experiments (like Euclid)

- Neutrino free streaming is scale and z depdendent → should be tested/seen by different experiments subjected to different systematics/statistical errors

- Neutrino non-linearities are very interesting. Neutrino fluid reacts differently When considering different environments (galaxies, voids, etc.)

- Neutrino constraints from cosmology – so far a success story! [Could have been wrong.. But so far.. All predictions were correct]

- Suprises still possible: modification/new physics beyons standard models