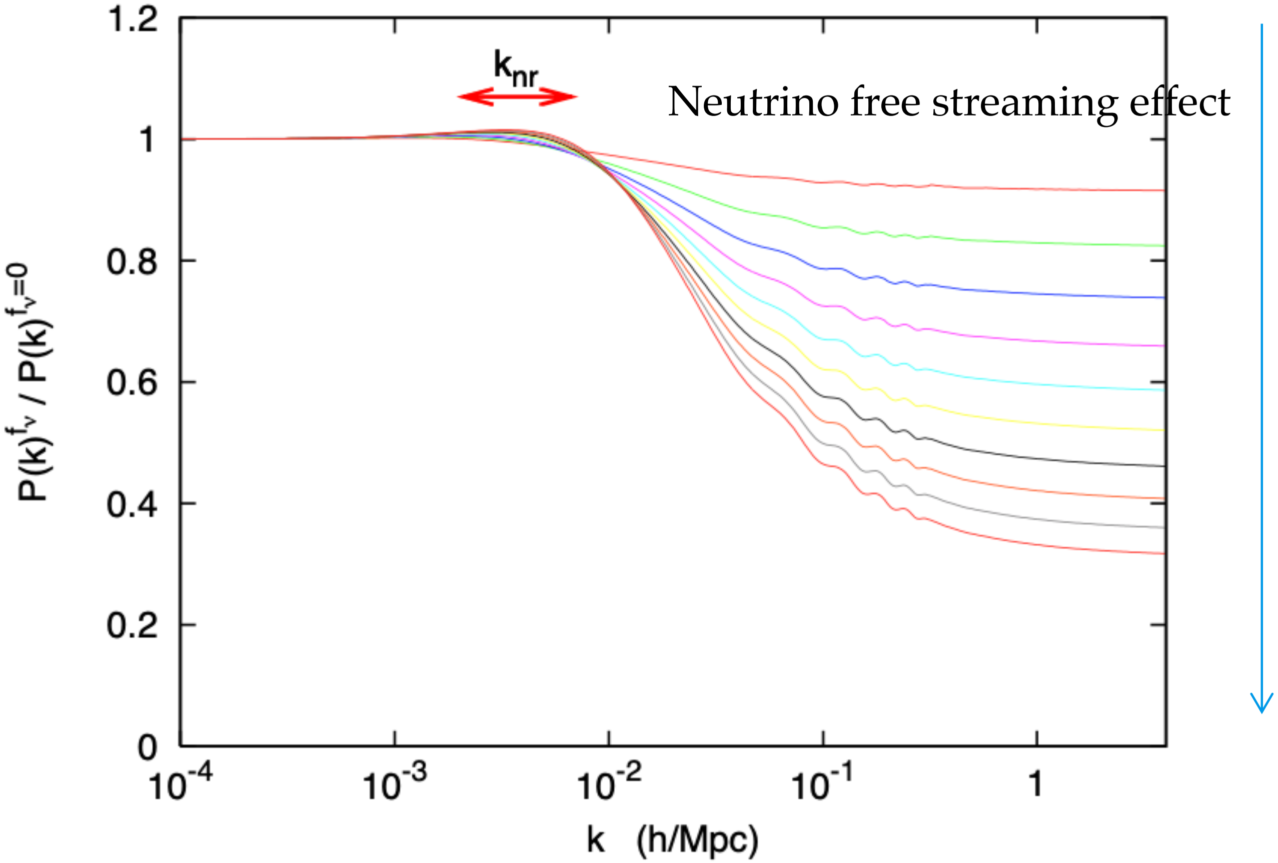
Plan

Matteo Viel

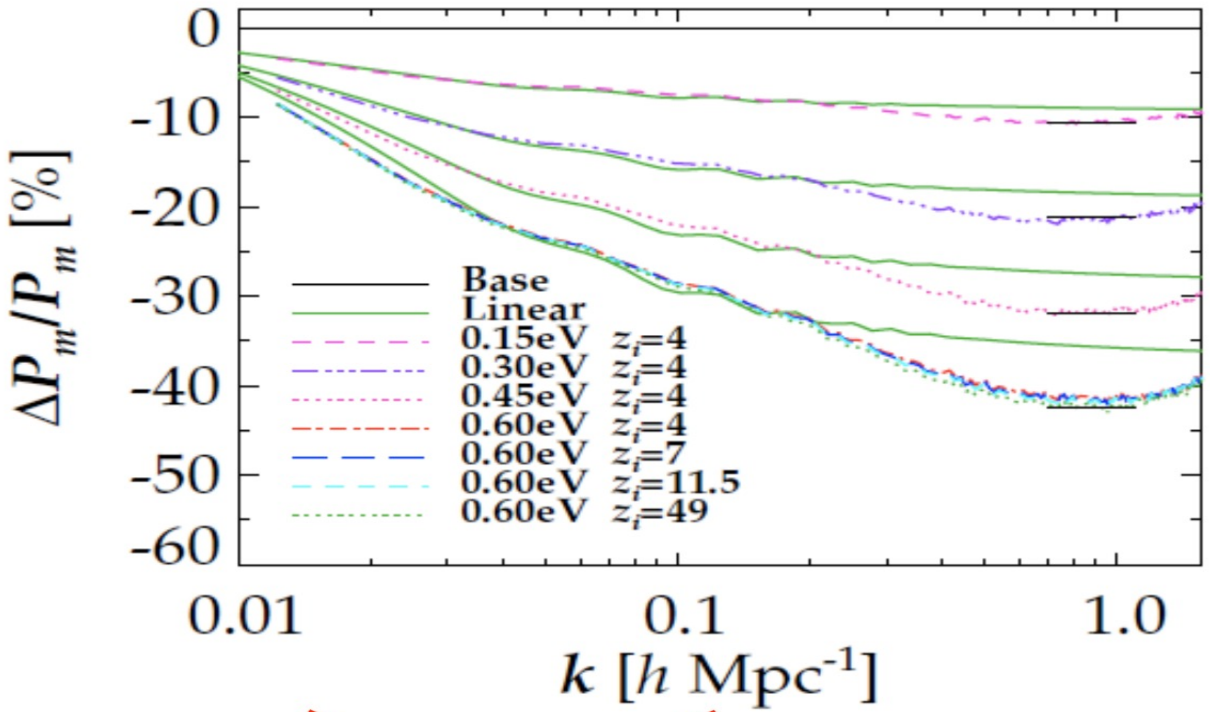
- Lecture 1: Cosmological effects of neutrinos in linear perturbation theory
- Lecture 2: Non-linear regime
- Lecture 3: Neutrinos in Intergalactic space
- Lecture 4: New ways of probing neutrino masses

Matter power spectrum from massive vs massless vs



From 0.15 eV to 1.5eV total neutrino mass

Non-linear matter power



Brandbyge et al 08

$$\left.\frac{\Delta P}{P}\right|_{\max} - 8\frac{\Omega_\nu}{\Omega_m}$$

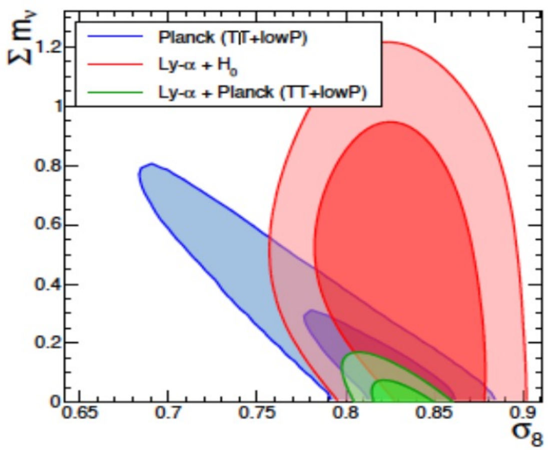
$$\rightarrow \left.\frac{\Delta P}{P}\right|_{\max} \sim -9.8\frac{\Omega_\nu}{\Omega_m}$$

Neutrino impact - IV

UPDATE using Planck 15

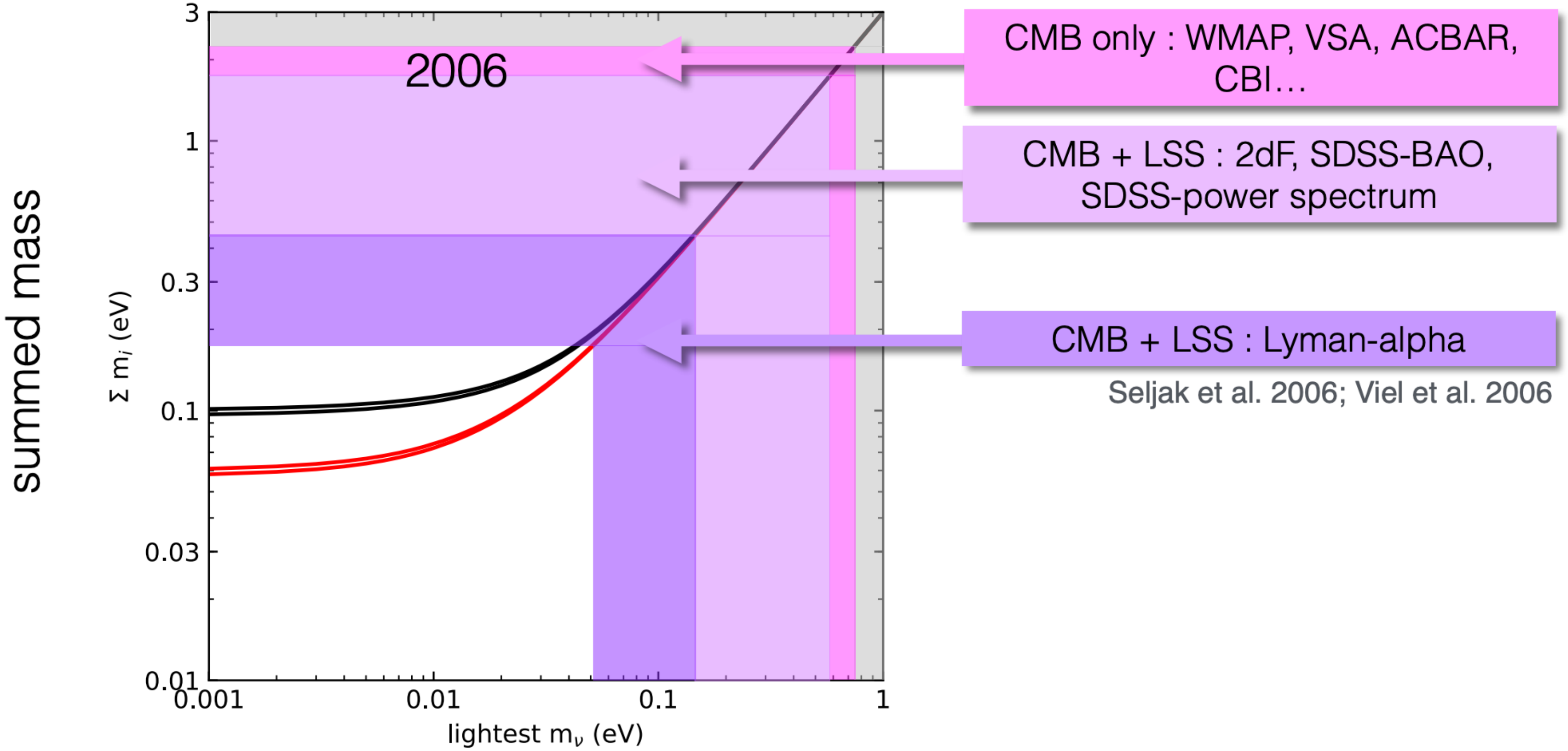
Palanque-Delabrouille+ 2015

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



Some historical background (a successful story!)

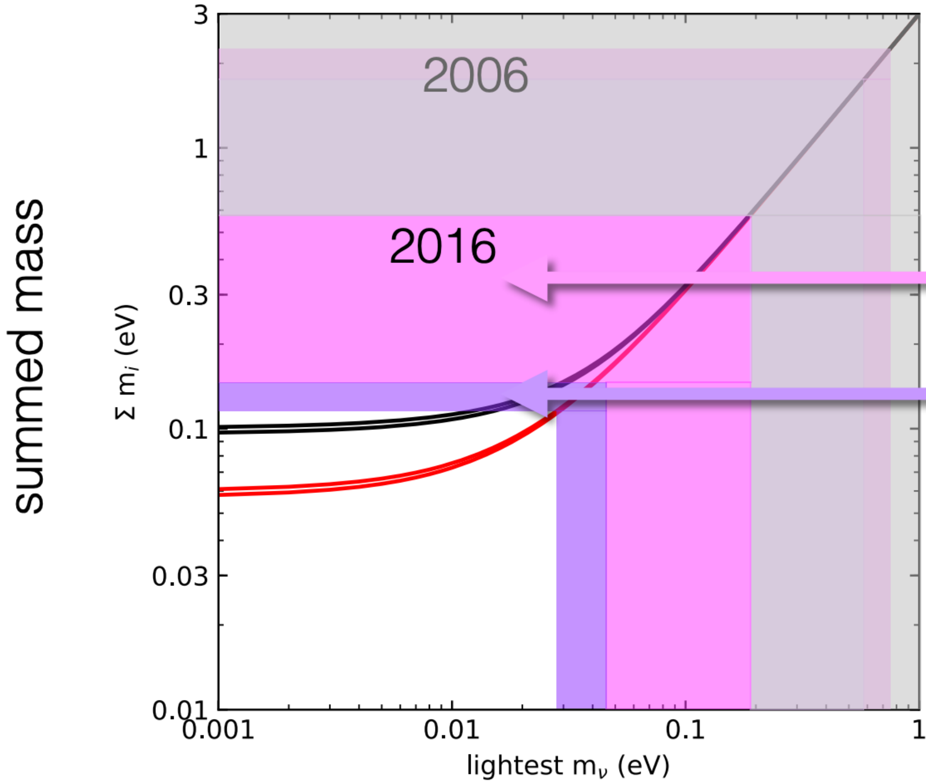
95%CL upper bounds on $\Sigma_i m_i$



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 :

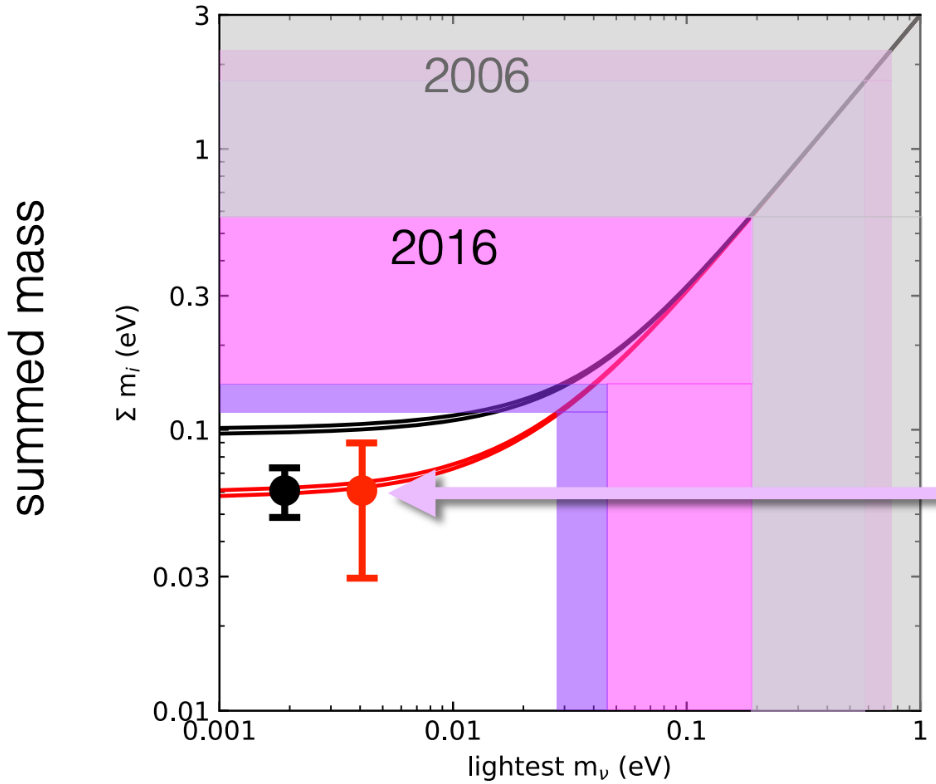
- with galaxies: $\Sigma_i m_i$ < 130 meV (95%CL)
- with Lyman-α: $\Sigma_i m_i$ < 120 meV (95%CL)
- with BAOs: $\Sigma_i m_i$ < 118 meV (95%CL)

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

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

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

Weak lensing

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

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

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

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

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

Baryon feedback - I

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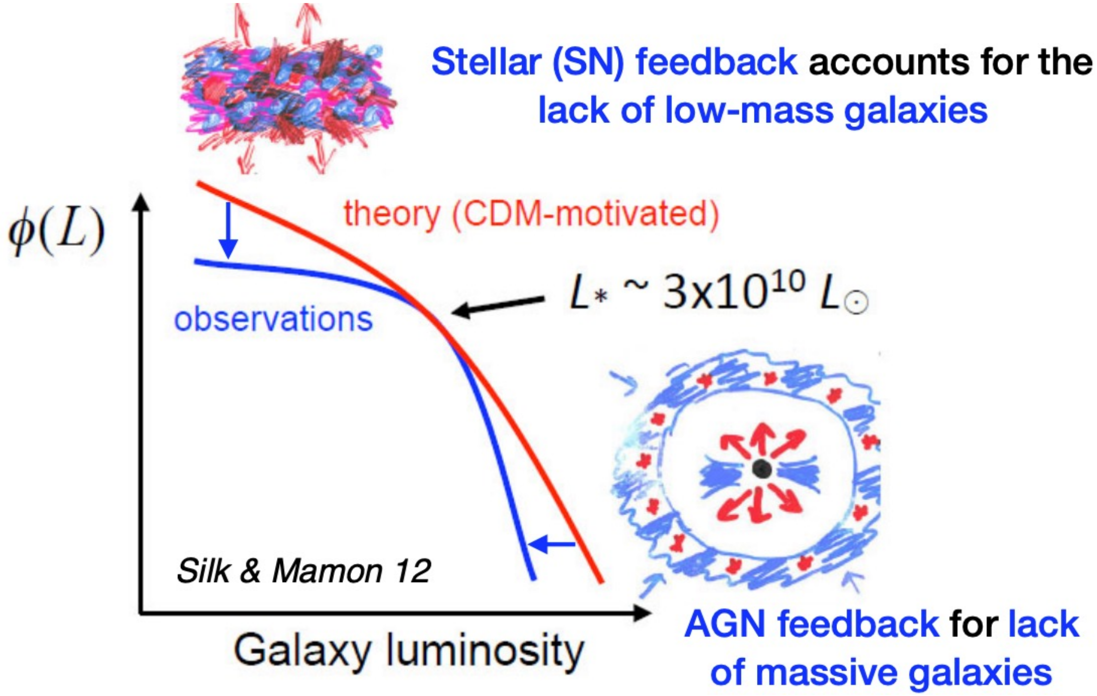
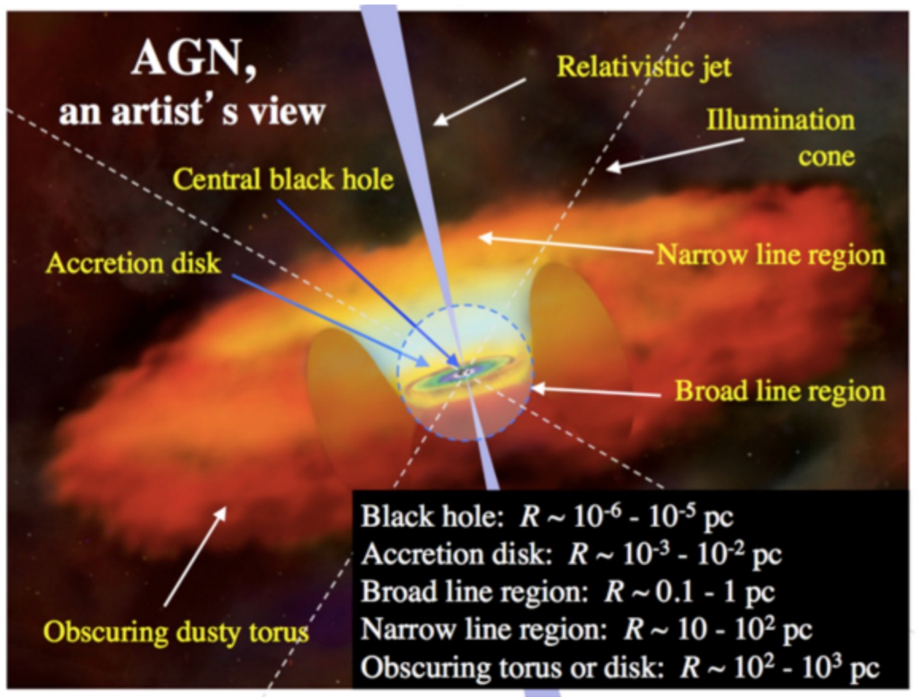




Baryon feedback - II

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

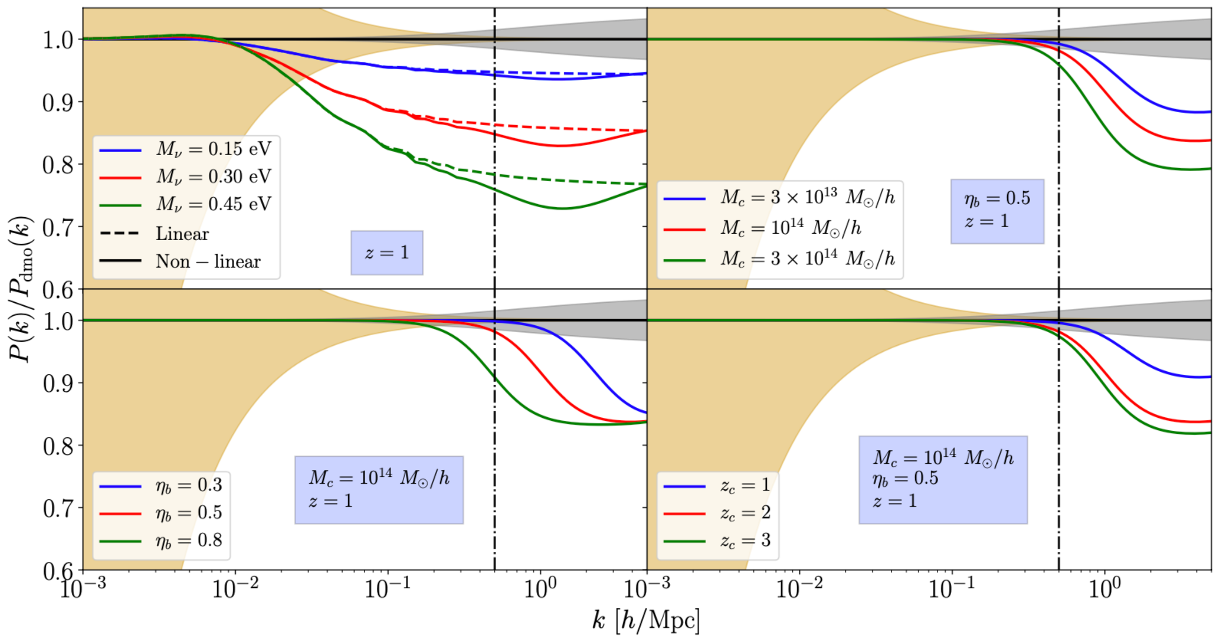
where

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

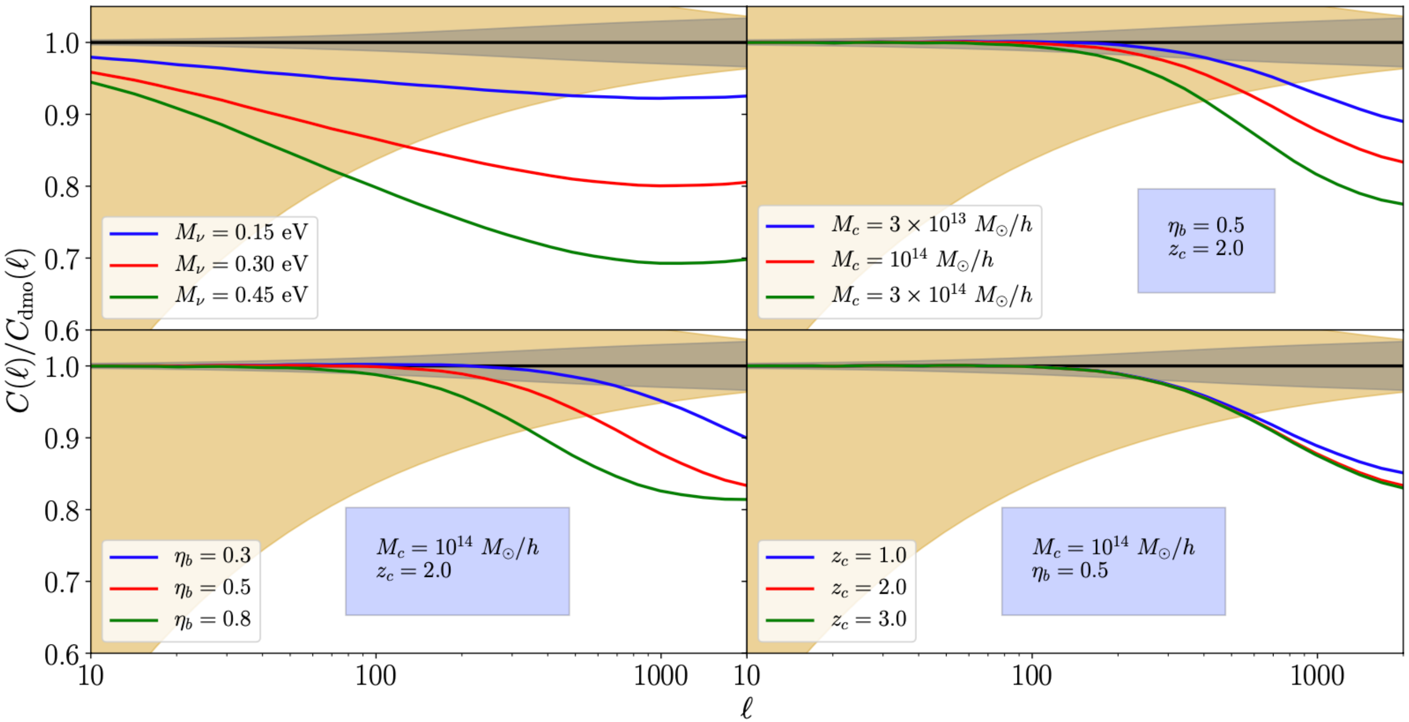
$$S(k) = 1 + \left(\frac{k}{55\,h\,{\rm Mpc}^{-1}}\right)^2$$

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



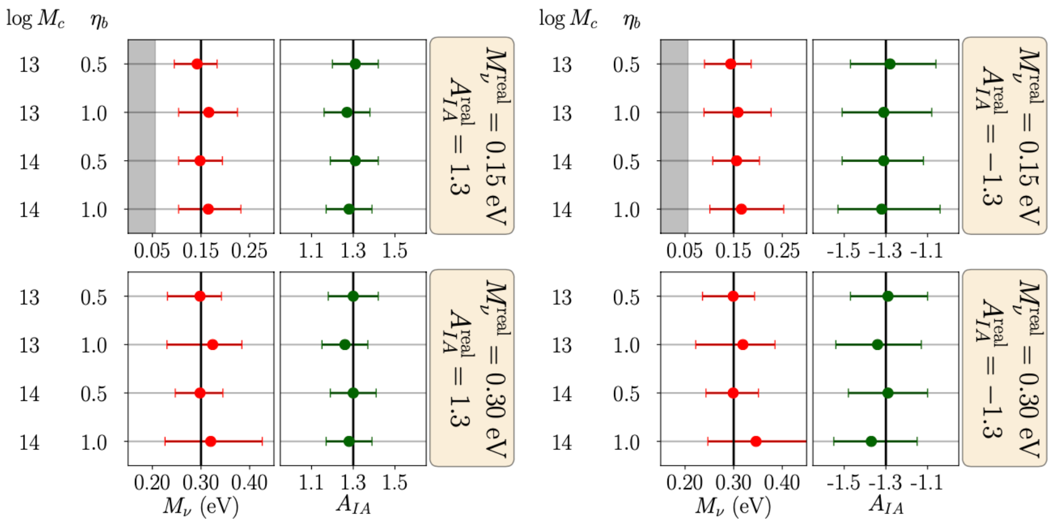
Baryon feedback - IV

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

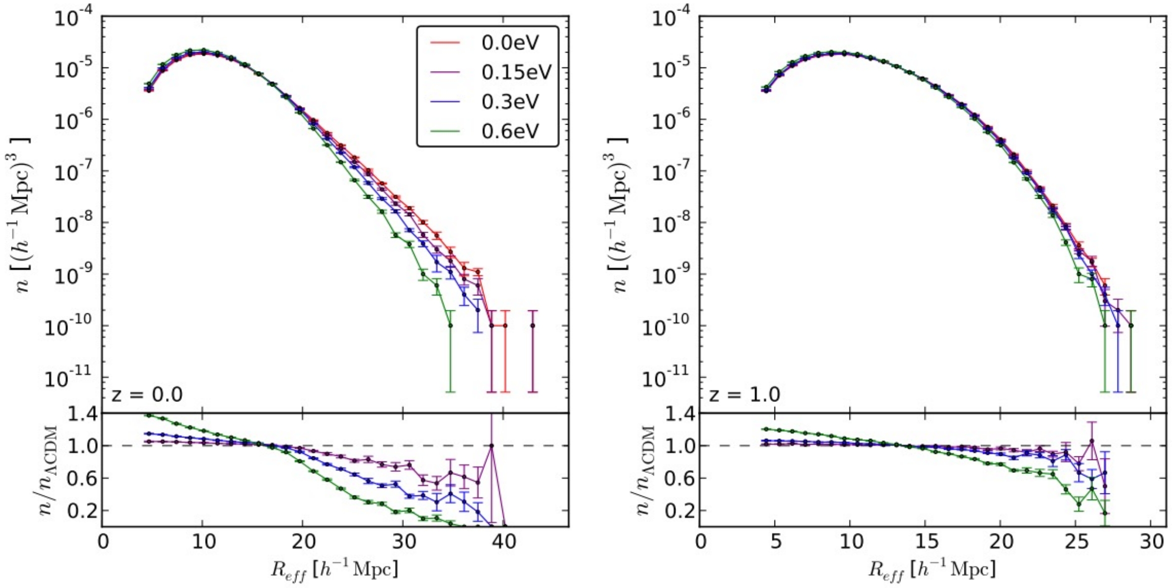


Voids: the void size function

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

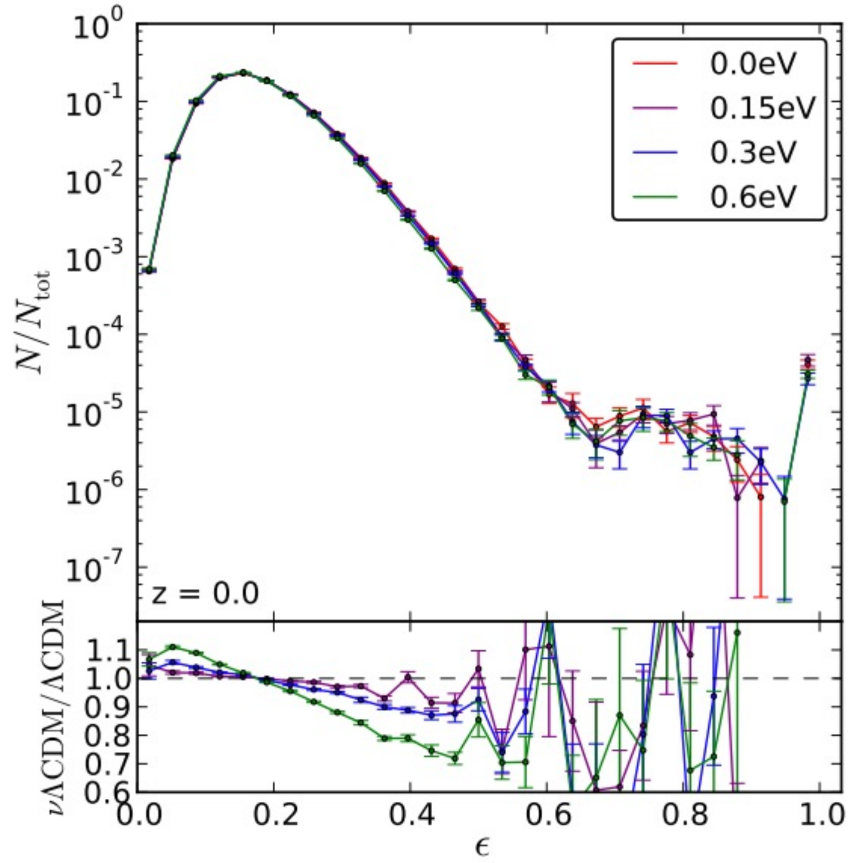


Voids in massive neutrino cosmologies are less evolved (i.e. **younger**) than those in the corresponding massless neutrinos case: there is a larger number of small voids and a smaller number of large ones, their profiles are less evacuated, and they present a lower wall at the edge.

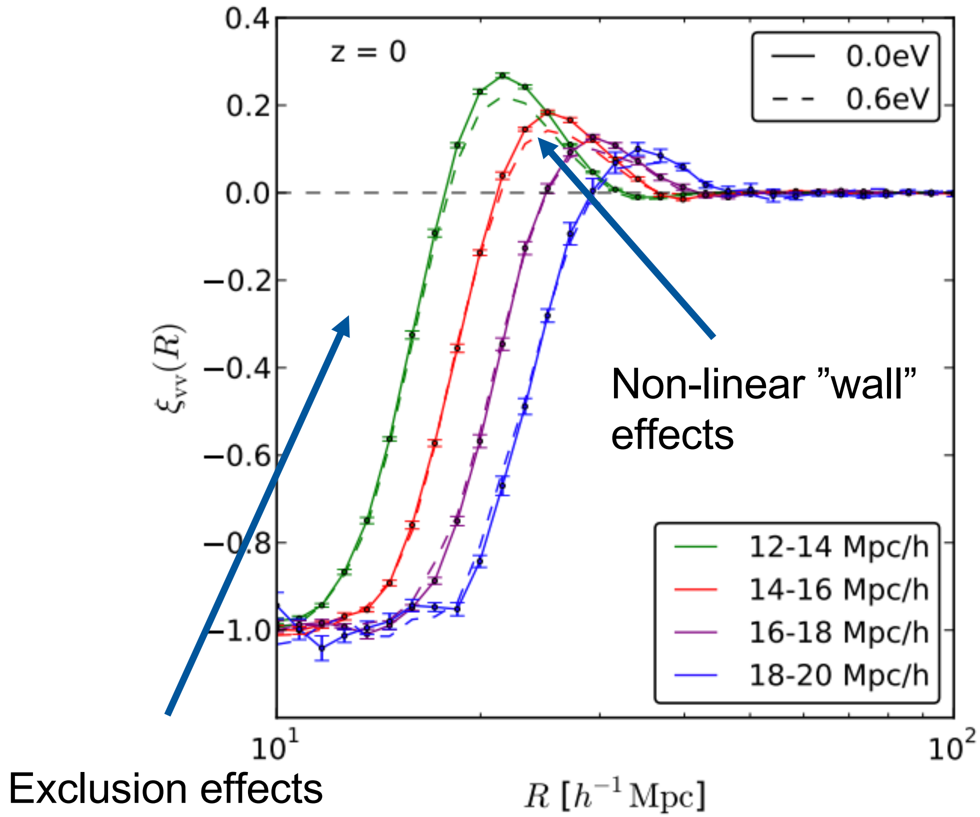
VOIDS evolve by **evacuating particles** (very different from haloes)!

Voids – II: ellipticities and correlation function

Ellipticity



Voids Correlation Functions



Voids – III: density profiles and degeneracies

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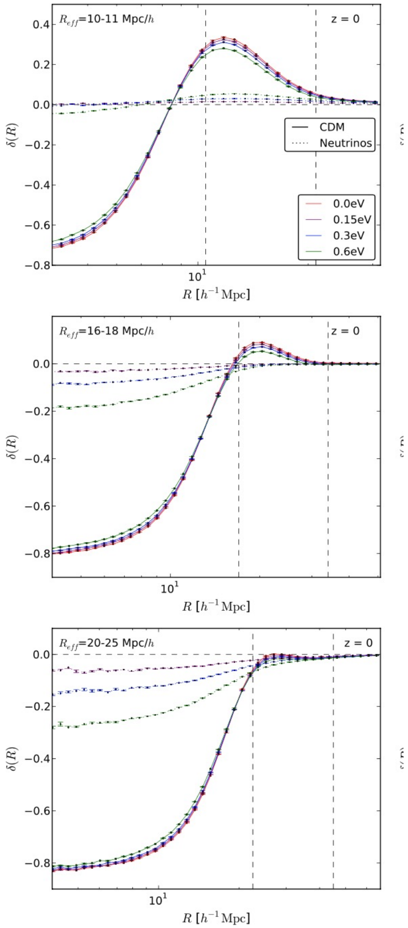
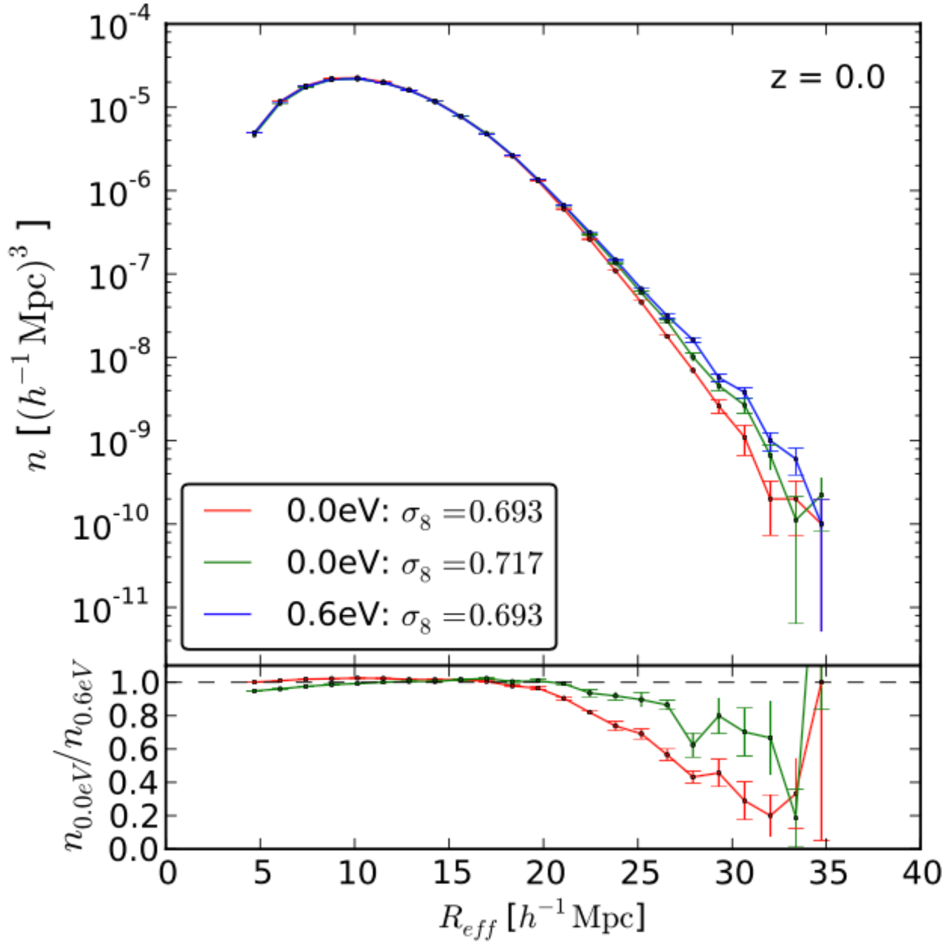
Density profiles



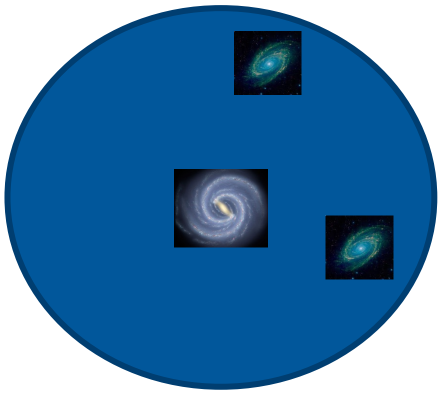
Notice
The wall
For small voids



Voids – IV: populating with galaxies

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

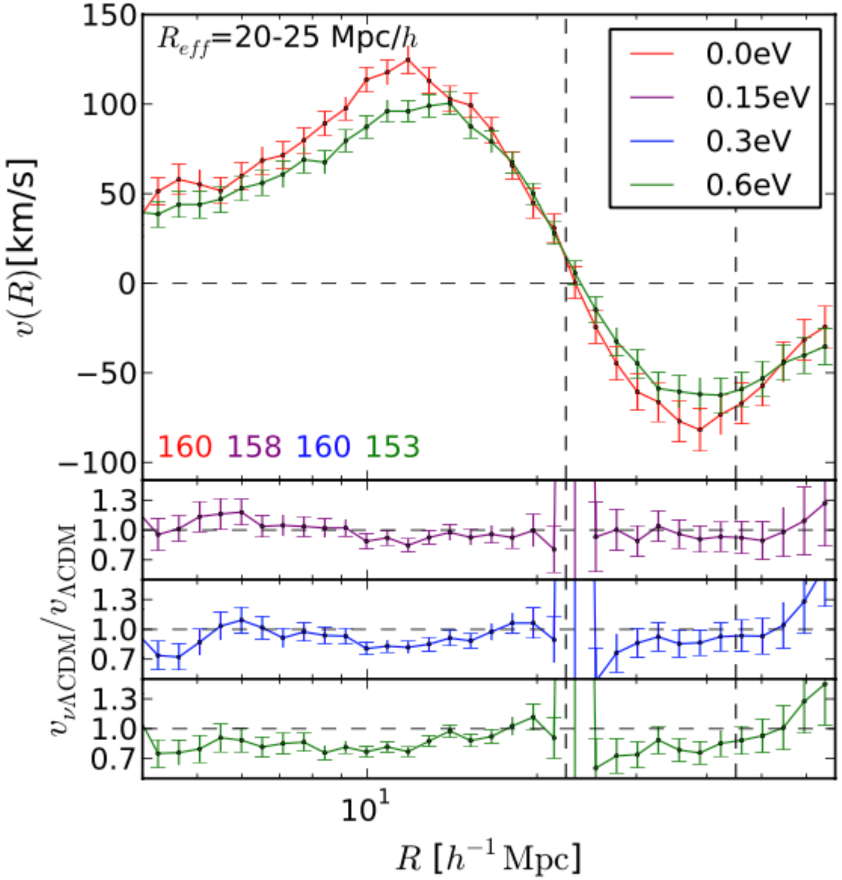
$$\langle N_c|M\rangle = \begin{cases} 1 & \text{if } M \geq M_{\rm min} \\ 0 & \text{if } M < M_{\rm min} \end{cases} \qquad \langle N_s|M\rangle = \begin{cases} (M/M_1)^{\alpha} & \text{if } M \geq M_{\rm min} \\ 0 & \text{if } M < M_{\rm min}\,. \end{cases}$$

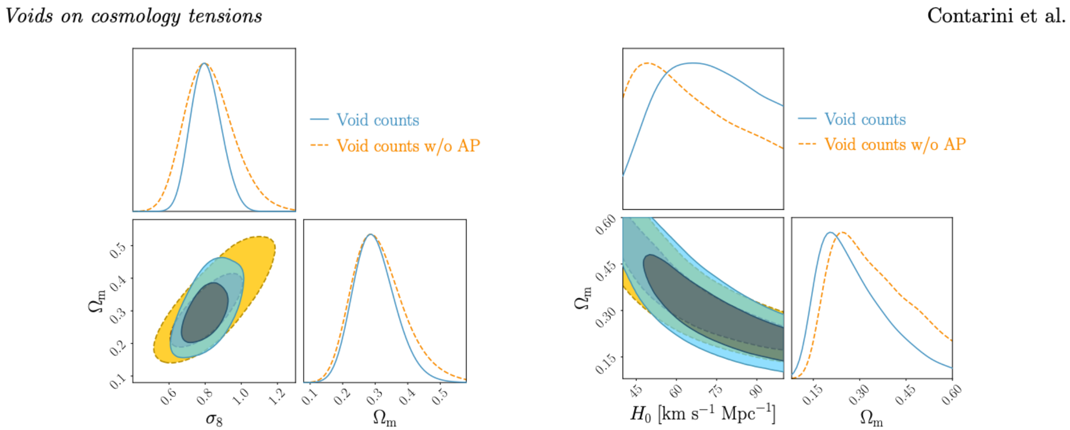


You can build simple HOD models
By asking to reproduce observed
Correlation functions or luminosity
properties of galaxies

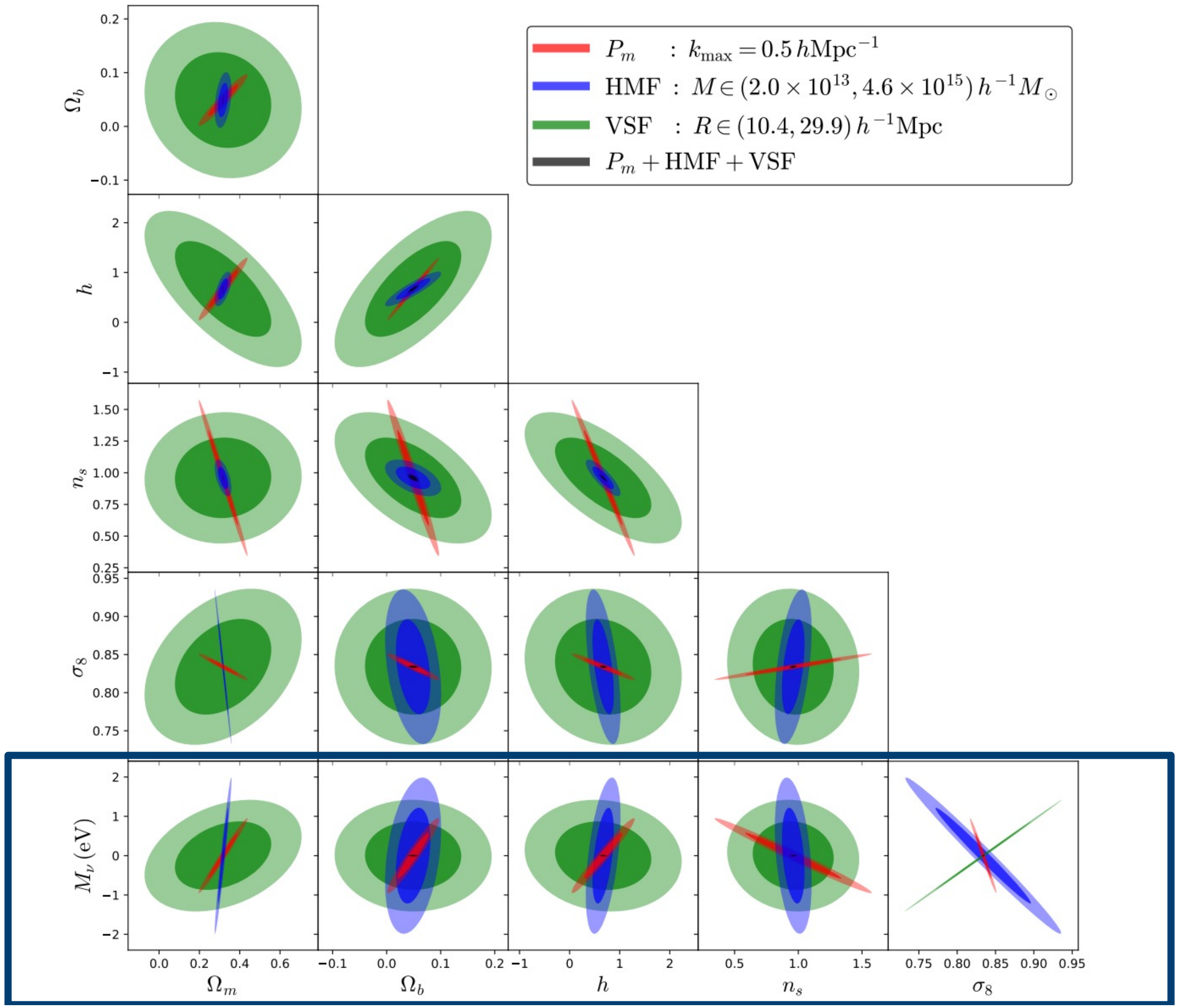
Once you build such a model you can then run your voidfinder on top of the galaxy distribution

Voids – V: populating with galaxies



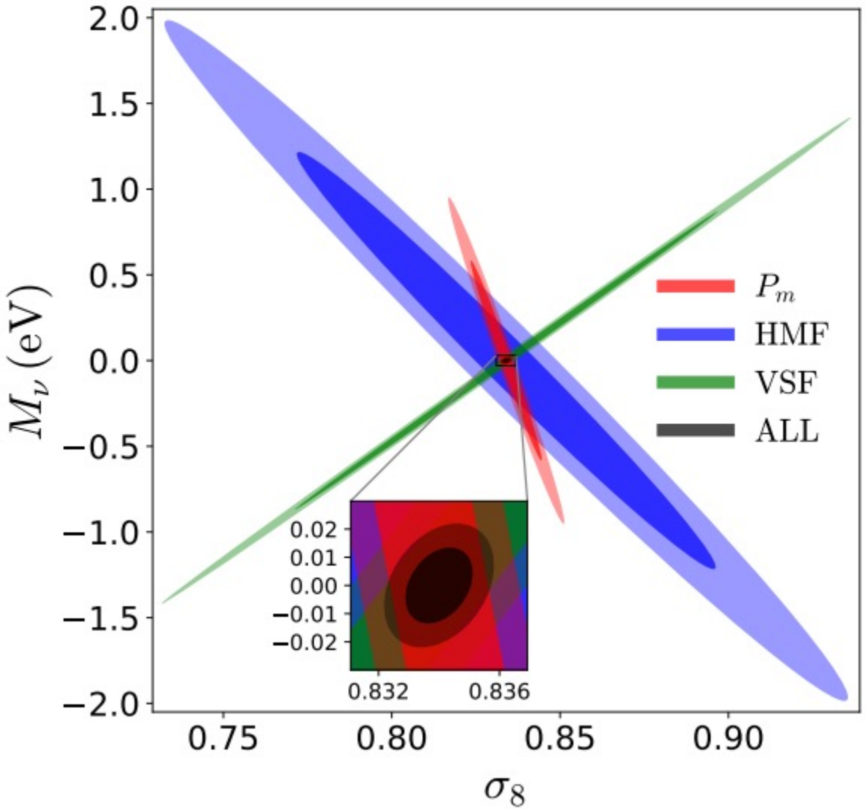


Voids – VI: combining with other probes



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

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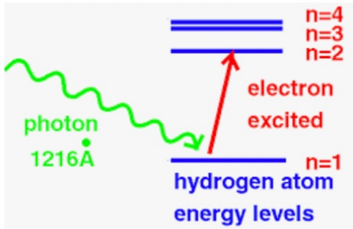
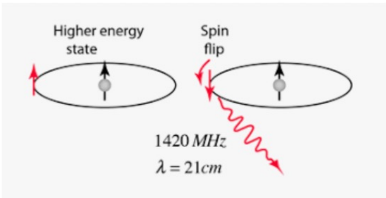
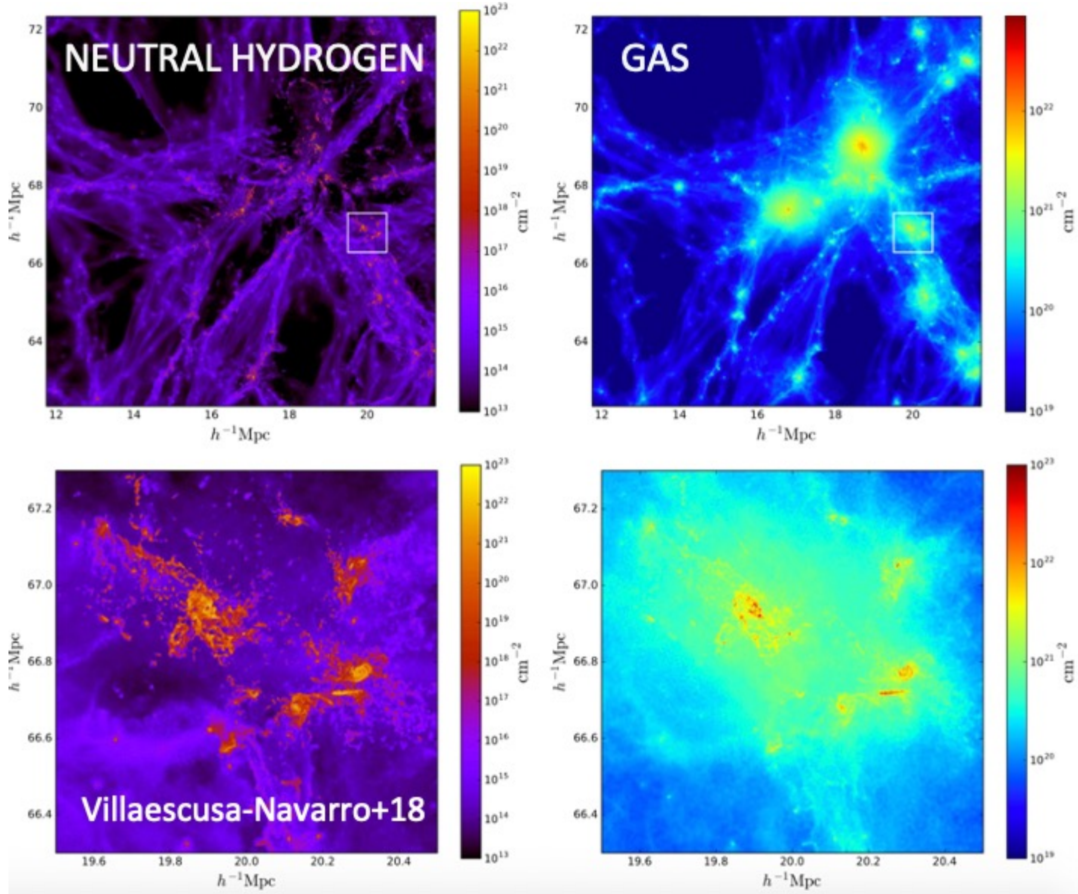
Atomic processes



Absorption - Lyman-alpha forest

Emission - 21cm intensity mapping





21cm – A simple model

NEUTRAL HYDROGEN GAS

Linear theory model:

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

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

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

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

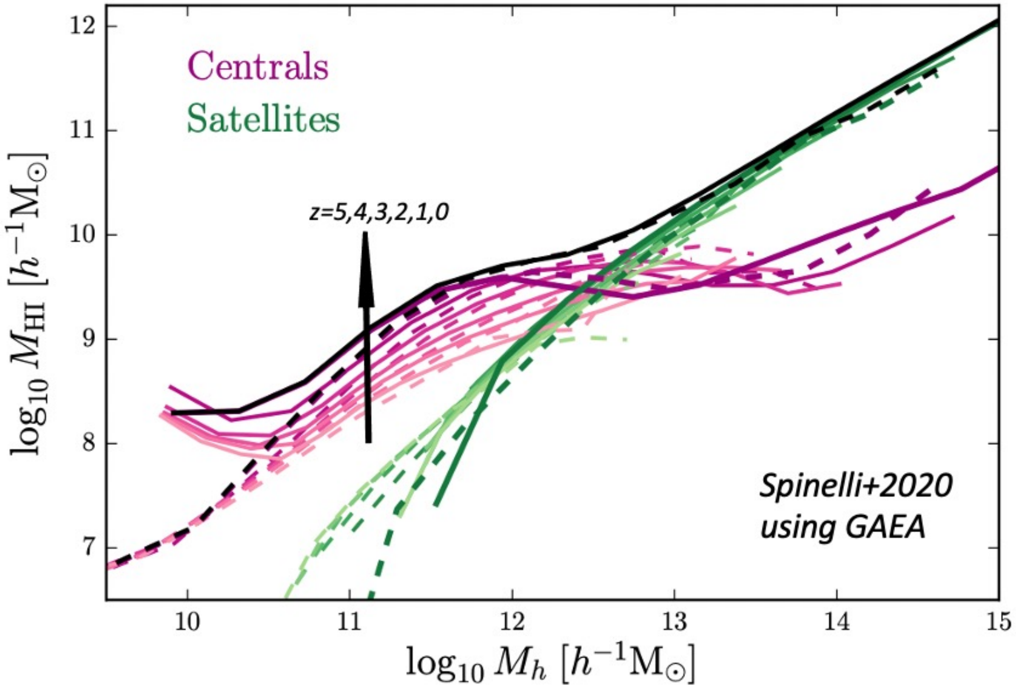
$$P_{\mathrm{SN}}(z) = \frac{1}{(\rho_c^0\Omega_{\mathrm{H\,I}}(z))^2}\int_0^\infty n(M,z)M_{\mathrm{H\,I}}^2(M,z)dM,$$

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

M_{min} decreases with redshift
alpha increases with redshift

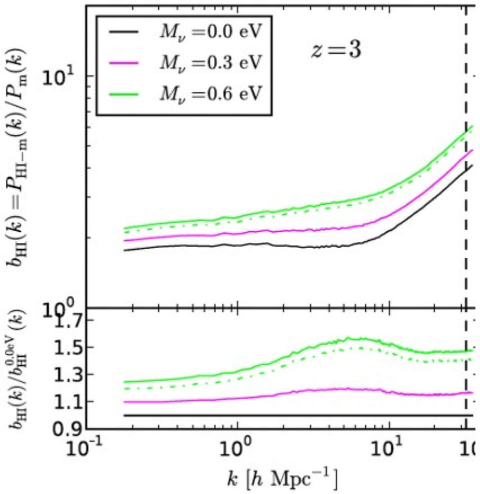
- degeneracy between b_{HI} and $Omega_{HI}$, which can be broken by using other probes (cross-corr.)
- Progress made mainly in the modelling and in determining the low-z HI bias (~0.8) from observations (Obuljen+18) - Pen+09, Switzer+13 (auto and cross to constrain Omega_HI x bias_HI), Anderson+18 (cross.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

21cm – Cross correlations?

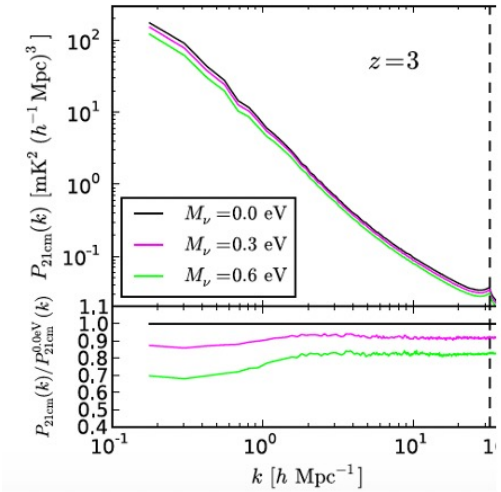


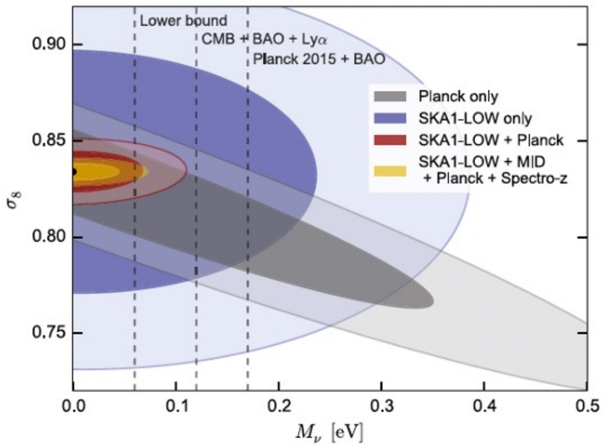
…further progress: interfacing this "small-scale" accurate and physical information with large scale methods for extensive mock productions e.g. PINOCCHIO LPT light-cone halos (Spinelli, Carucci+2021)

21cm and neutrinos



- Scale dependence bias also present in massive neutrino cosmologies.
- M_{HI}(M) not affected by the presence of neutrinos.
- HI is more clustered in massive neutrino sims. (but Ω_{HI} lower) - because small mass haloes are suppressed i.e. impact on n_{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

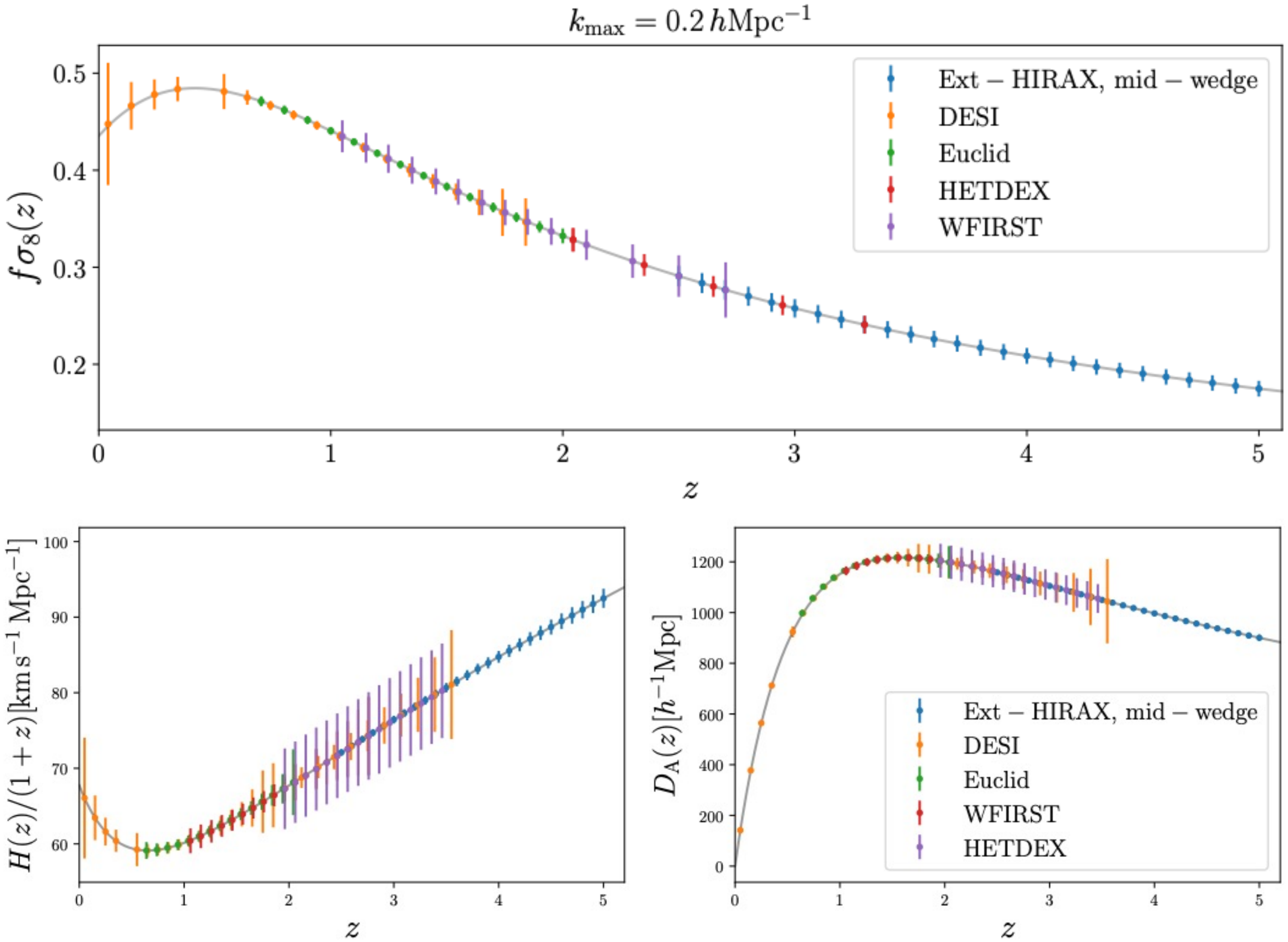




Villaescusa-Navarro, MV, Bull, 2015

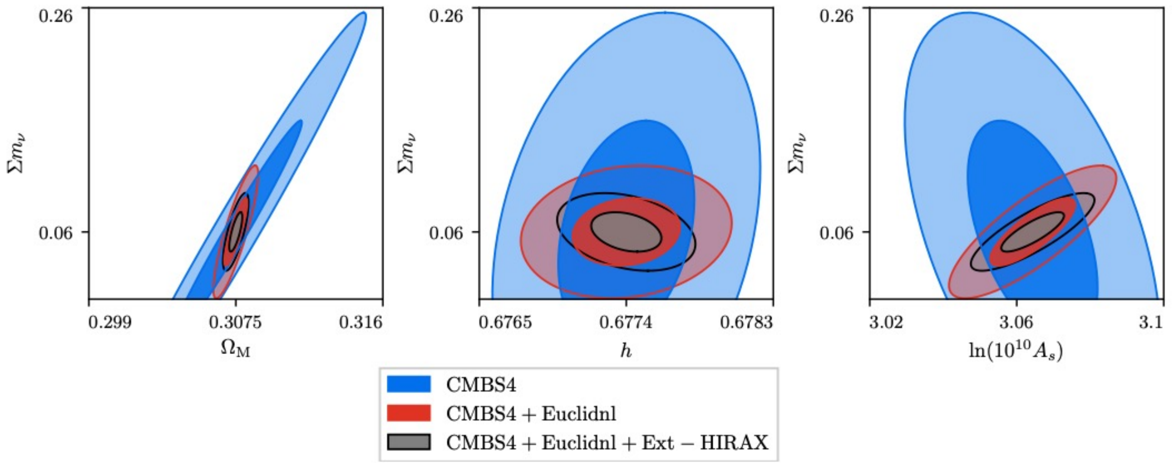
21cm and forecasts

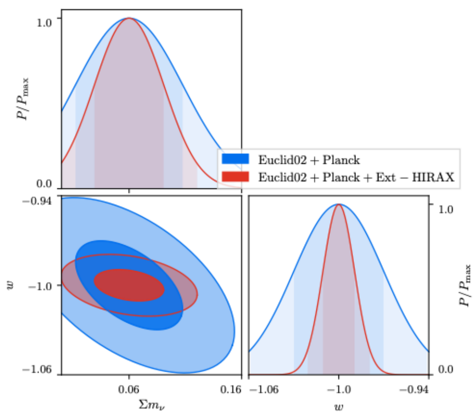
Obuljen+18

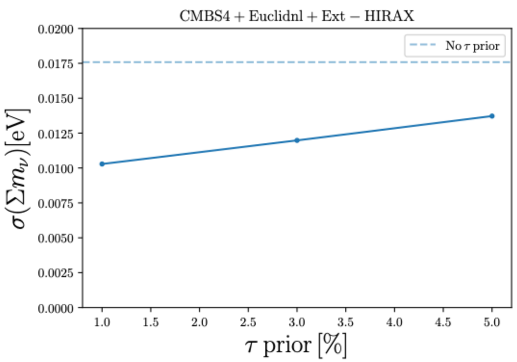


21cm and forecasts

Obuljen+18







21cm and forecasts

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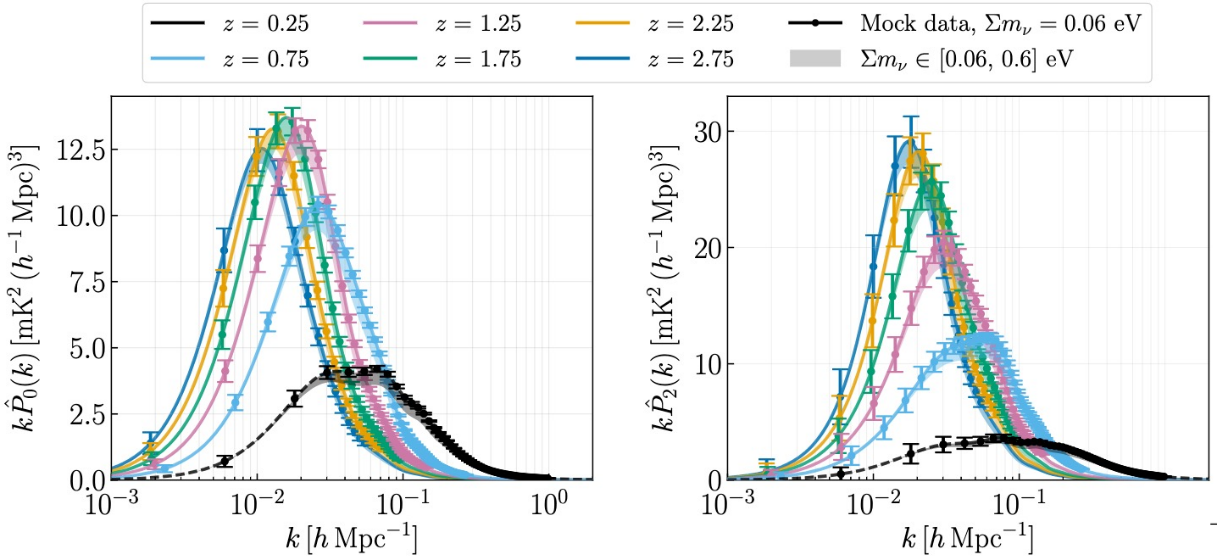
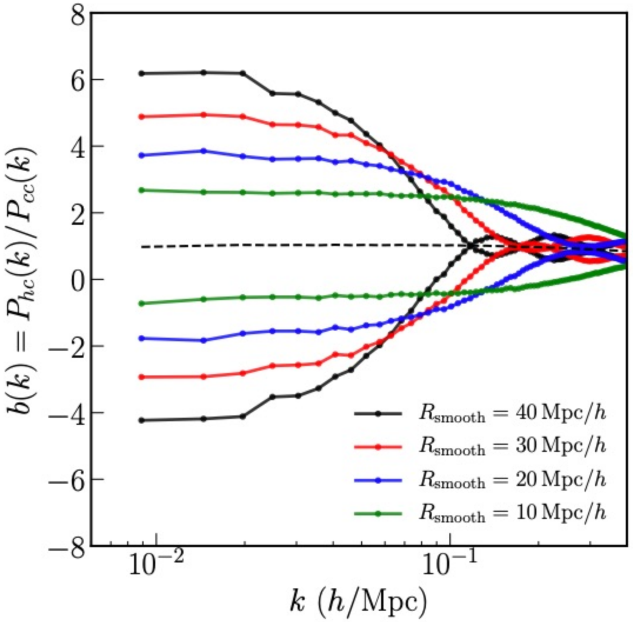


Berti, Viel, Spinelli 23 [to appear]

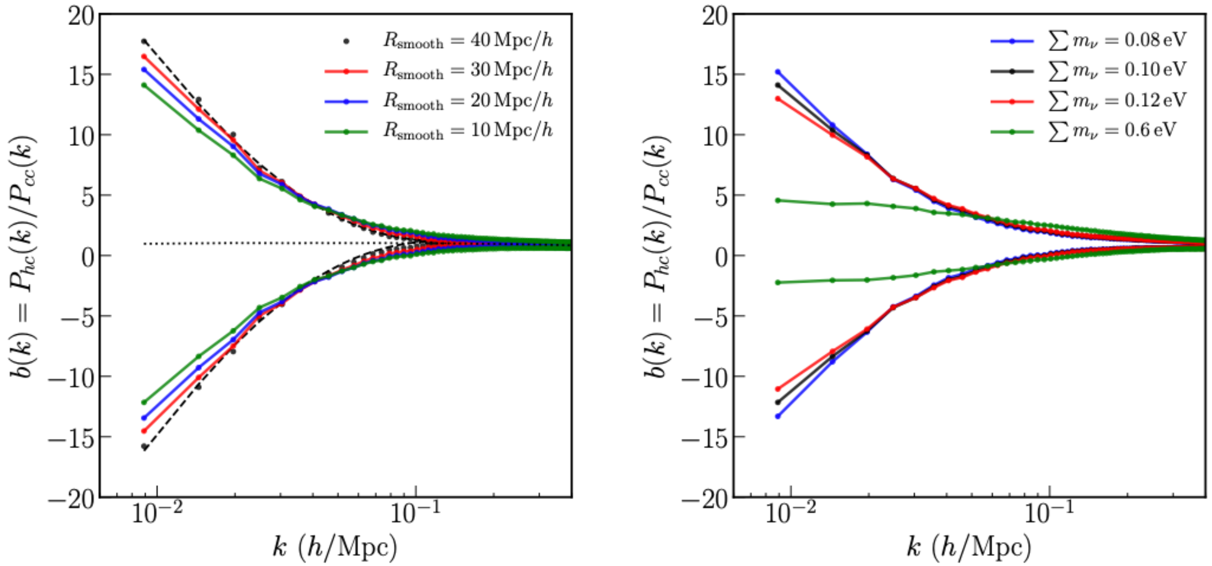
Likelihoods		$\Sigma m_\nu^{\rm fid} = 0.1$
$\hat{P}_0 + \hat{P}_2$	< 0.216	< 0.227
+ nuisances	< 0.478	< 0.535
$\hat{P}_0 + \hat{P}_2$ + BAO	< 0.227	
+ nuisances	< 0.413	
Planck 2018	< 0.259	
+ $\hat{P}_0 + \hat{P}_2$	< 0.101	< 0.117
+ nuisances	< 0.129	< 0.127
Planck 2018 + BAO	< 0.149	
+ $\hat{P}_0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

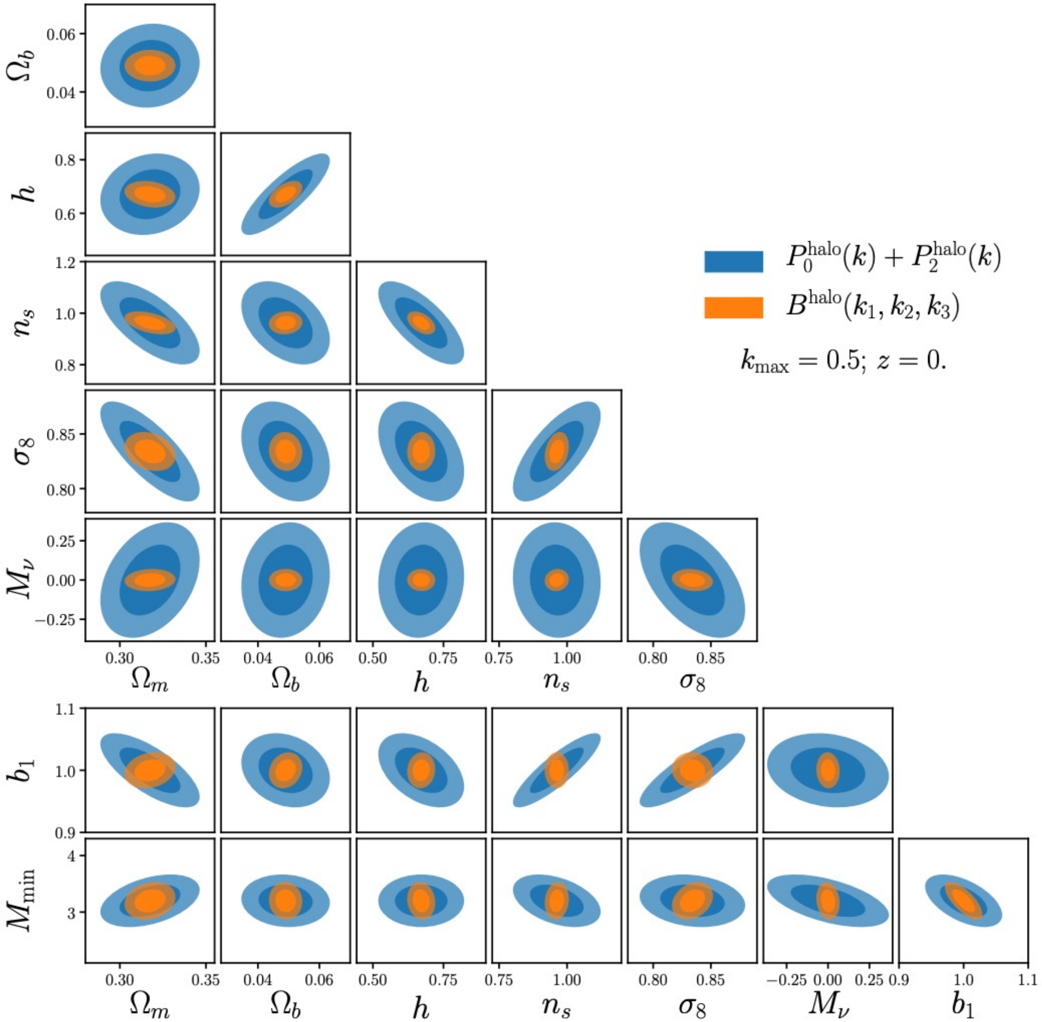


Strong scale dependence found → need a way to probe environment

From galaxies to halo to cdm…..

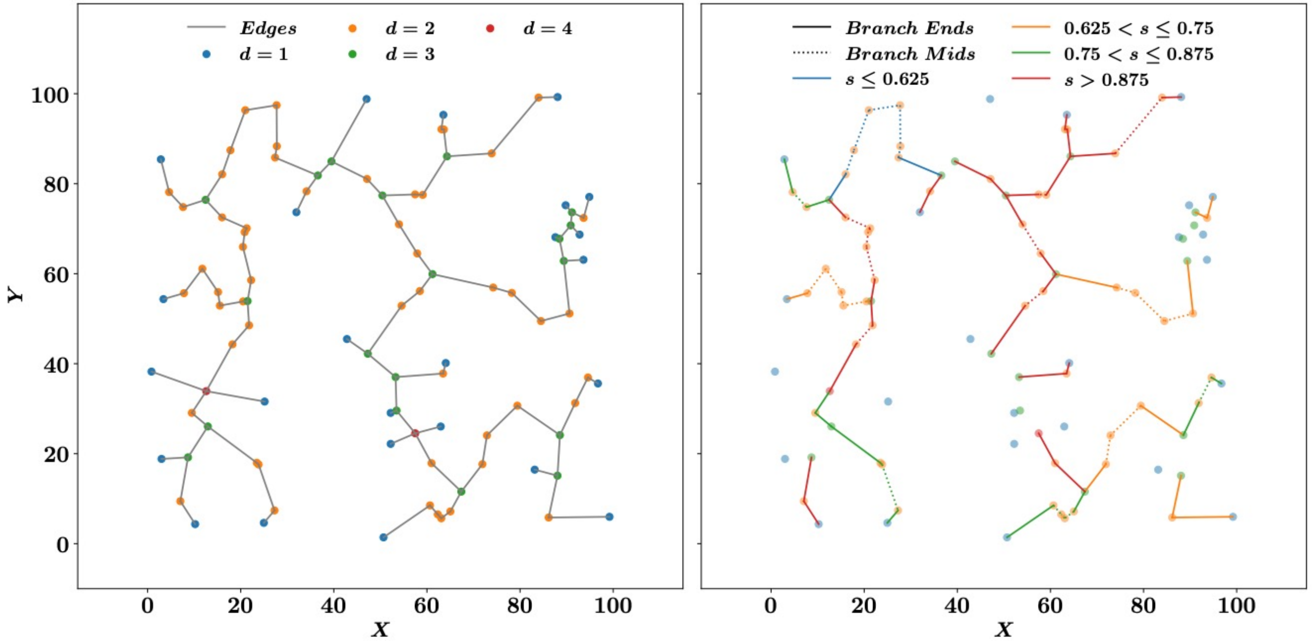
Banerjee, Castorina, Villaesusa-Navarro, Court, MV, 2019

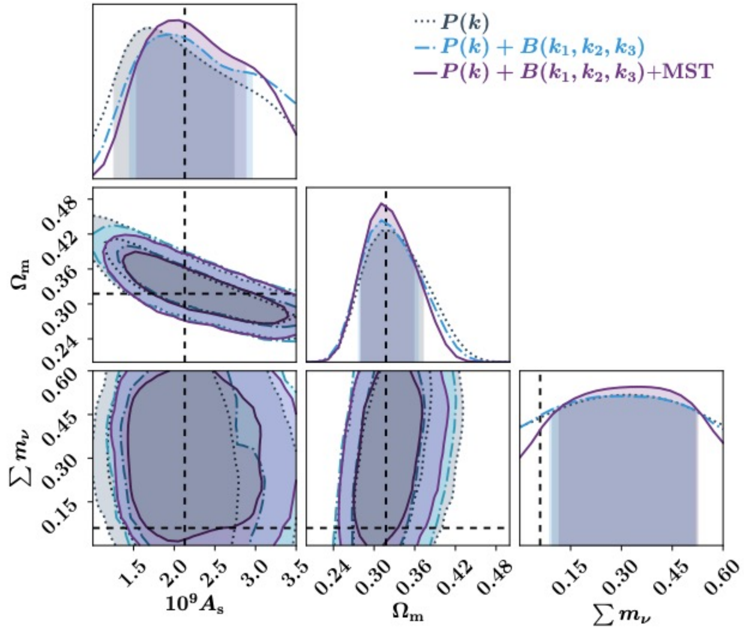
Bispectrum



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? Very difficult

Can the different Hubble parameter inferred from local and early Universe probes be reconciled with neutrinos? Possible, but extra (testable) physics is needed in connection with sterile neutrinos (SBL experiments also)

Tensions – H_0

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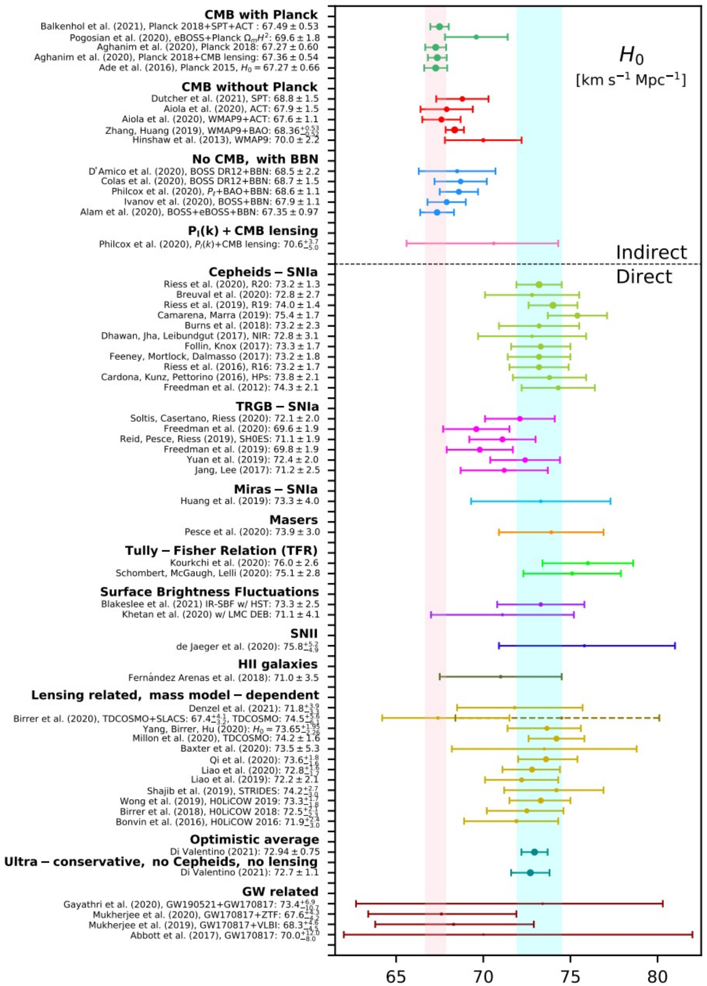
Di Valentino+21



Appendix B. Successful Models in light of the Hubble constant tension

tension $\leq 1\sigma$ *"Excellent models"*	tension $\leq 2\sigma$ *"Good models"*	tension $\leq 3\sigma$ *"Promising models"*
Dark energy in extended parameter spaces [289]	Early Dark Energy [235]	Early Dark Energy [229]
Dynamical Dark Energy [309]	Phantom Dark Energy [11]	Decaying Warm DM [474]
Metastable Dark Energy [314]	Dynamical Dark Energy [11, 281, 309]	Neutrino-DM Interaction [506]
PEDE [392, 394]	GEDE [397]	Interacting dark radiation [517]
Elaborated Vacuum Metamorphosis [400–402]	Vacuum Metamorphosis [402]	Self-Interacting Neutrinos [700, 701]
IDE [314, 636, 637, 639, 652, 657, 661–663]	IDE [314, 653, 656, 661, 663, 670]	IDE [656]
Self-interacting sterile neutrinos [711]	Critically Emergent Dark Energy [997]	Unified Cosmologies [747]
Generalized Chaplygin gas model [744]	$f(\mathcal{T})$ gravity [814]	Scalar-tensor gravity [856]
Galileon gravity [876, 882]	Über-gravity [59]	Modified recombination [986]
Power Law Inflation [966]	Reconstructed PPS [978]	Super ΛCDM [1007]
$f(\mathcal{T})$ [818]		Coupled Dark Energy [650]

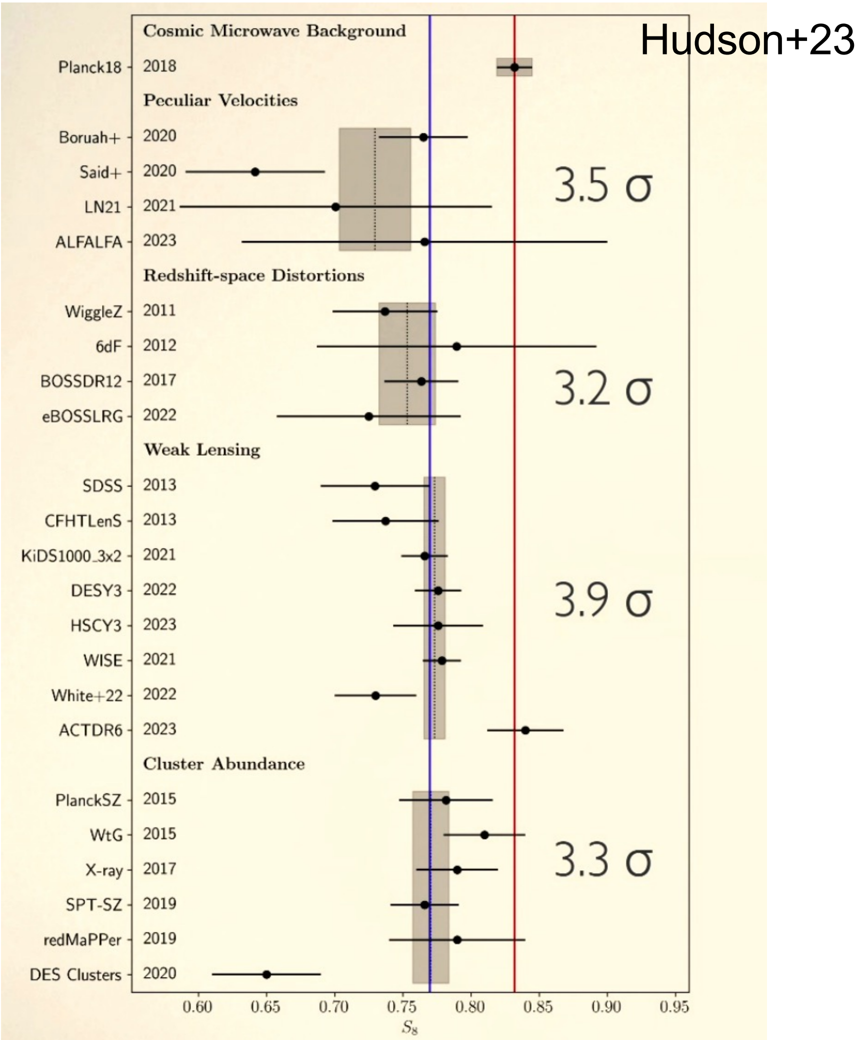
Table B1. Models solving the H_0 tension with R20 within the 1σ, 2σ and 3σ confidence levels considering the *Planck* dataset only.

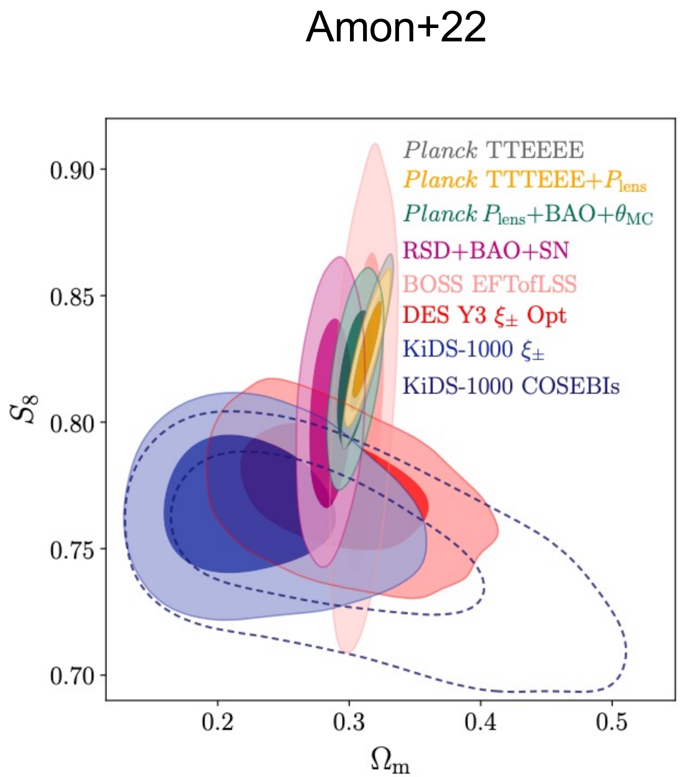
tension $\leq 1\sigma$ *"Excellent models"*	tension $\leq 2\sigma$ *"Good models"*	tension $\leq 3\sigma$ *"Promising models"*
Early Dark Energy [228, 235, 240, 250]	Early Dark Energy [212, 229, 236, 263]	DE in extended parameter spaces [289]
Exponential Acoustic Dark Energy [259]	Rock 'n' Roll [242]	Dynamical Dark Energy [281, 309]
Phantom Crossing [315]	New Early Dark Energy [247]	Holographic Dark Energy [350]
Late Dark Energy Transition [317]	Acoustic Dark Energy [257]	Swampland Conjectures [370]
Metastable Dark Energy [314]	Dynamical Dark Energy [309]	MEDE [399]
PEDE [394]	Running vacuum model [332]	Coupled DM - Dark radiation [534]
Vacuum Metamorphosis [402]	Bulk viscous models [340, 341]	Decaying Ultralight Scalar [538]
Elaborated Vacuum Metamorphosis [401, 402]	Holographic Dark Energy [350]	BD-ΛCDM [852]
Sterile Neutrinos [433]	Phantom Braneworld DE [378]	Metastable Dark Energy [314]
Decaying Dark Matter [481]	PEDE [391, 392]	Self-Interacting Neutrinos [700]
Neutrino-Majoron Interactions [509]	Elaborated Vacuum Metamorphosis [401]	Dark Neutrino Interactions [716]
IDE [637, 639, 657, 661]	IDE [659, 670]	IDE [634–636, 653, 656, 663, 669]
DM - Photon Coupling [685]	Interacting Dark Radiation [517]	Scalar-tensor gravity [855, 856]
$f(\mathcal{T})$ gravity theory [812]	Decaying Dark Matter [471, 474]	Galileon gravity [877, 881]
BD-ΛCDM [851]	DM - Photon Coupling [686]	Nonlocal gravity [886]
Über-Gravity [59]	Self-interacting sterile neutrinos [711]	Modified recombination [986]
Galileon Gravity [875]	$f(\mathcal{T})$ gravity theory [817]	Effective Electron Rest Mass [989]
Unimodular Gravity [890]	Über-Gravity [871]	Super ΛCDM [1007]
Time Varying Electron Mass [990]	VCDM [893]	Axi-Higgs [991]
ΛsCDM [995]	Primordial magnetic fields [992]	Self-Interacting Dark Matter [479]
Ginzburg-Landau theory [996]	Early modified gravity [859]	Primordial Black Holes [545]
Lorentzian Quintessential Inflation [979]	Bianchi type I spacetime [999]	
Holographic Dark Energy [351]	$f(\mathcal{T})$ [818]	

Table B2. Models solving the H_0 tension with R20 within 1σ, 2σ and 3σ considering *Planck* in combination with additional cosmological probes. Details of the combined datasets are discussed in the main text.

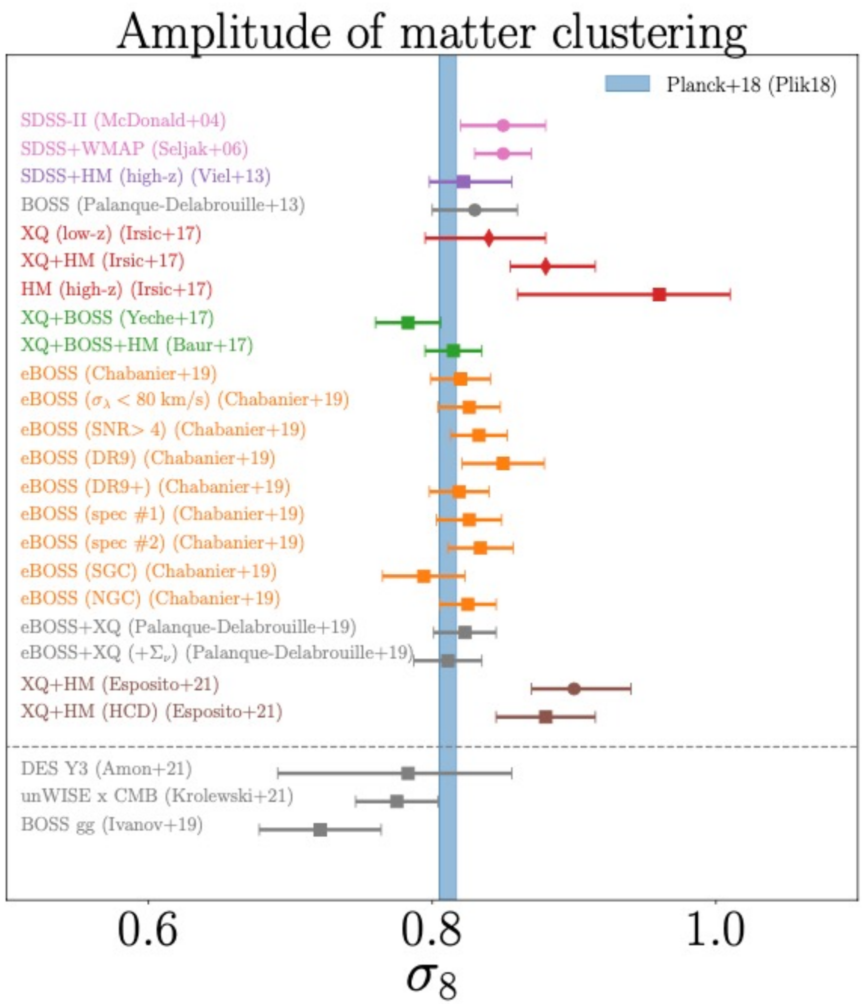
Tensions - II

Matteo Viel





σ_8 tension (the forest view)

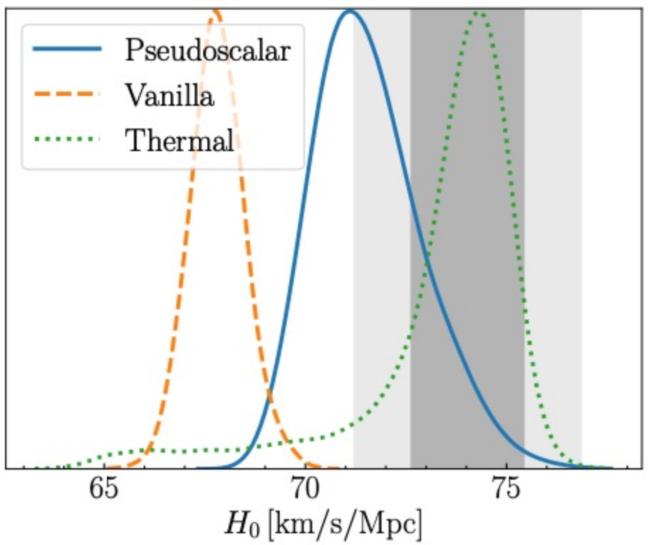


This is from the forest only

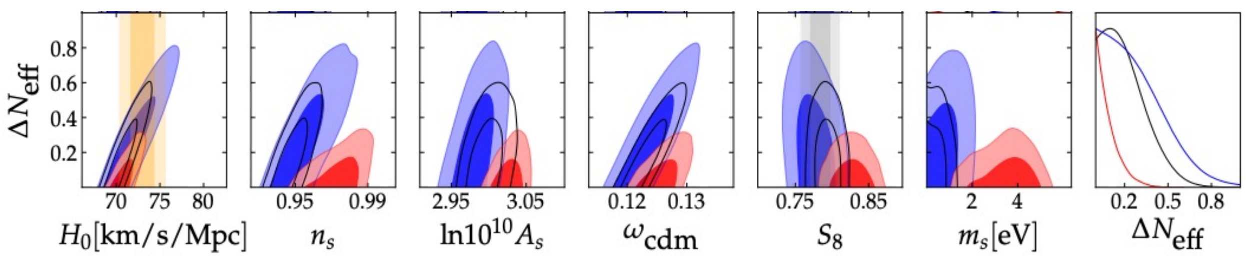
Neutrino self interactions?

Several models put forward following seminal work by Archidiacono and Hannestad in 2014
Model building based on adding new physics: - coupling neutrinos (and possibly dark matter) to a massless or very light pseudoscalar such as the majoron.

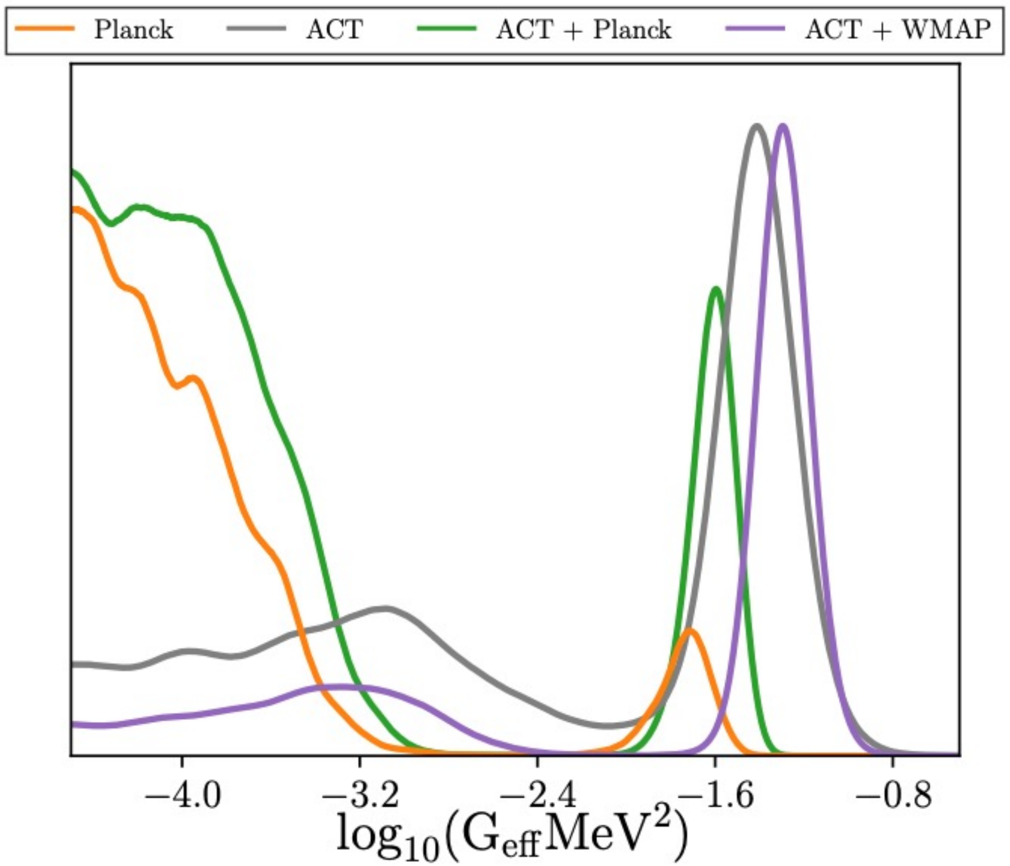
Interactions via a light pseudoscalar have the interesting property that they make the sterile neutrinos very strongly self-interacting at late times and effectively remove sterile neutrino anisotropic stress



Corona+22
Archidiacono+20



Neutrino self interactions?



The Atacama Cosmology Telescope: The Persistence of Neutrino Self-Interaction in Cosmological Measurements

Christina D. Kreisch,[1] Minsu Park,[2] Erminia Calabrese,[3] Francis-Yan Cyr-Racine,[4] Rui An,[5] J. Richard Bond,[6] Olivier Doré,[7,8] Jo Dunkley,[9,1] Patricio Gallardo,[10] Vera Gluscevic,[5] J. Colin Hill,[11,12] Adam D. Hincks,[13,14] Mathew S. Madhavacheril,[15] Jeff McMahon,[16,10,17,18] Kavilan Moodley,[19,20] Thomas W. Morris,[9] Federico Nati,[21] Lyman A. Page,[9] Bruce Partridge,[22] Maria Salatino,[23,24] Cristóbal Sifón,[25] David N. Spergel,[12,1] Cristian Vargas,[26] and Edward J. Wollack[27]

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 with promising avenues in the sterile sector!