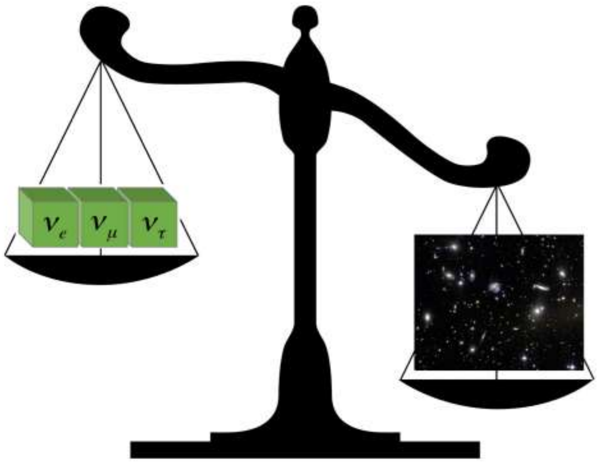
Towards a 5σ detection of the sum of the neutrino masses

Francisco Villaescusa-Navarro

CCA | Flatiron Institute



Matteo Viel (Trieste), Emanuele Castorina (Berkeley), Elena Massara (CCA), Arka Banerjee (Stanford), Andrej Obuljen (Waterloo), David Spergel (CCA/Princeton), Shirley Ho (CCA), Licia Verde (Barcelona), Neal Dalal (Perimeter), Ben Wandelt (IAP), Emiliano Sefusatti (Trieste), Ravi Sheth (Upenn), Avi Loeb (Harvard), Mark Vogelsberger (MIT), Marco Baldi (Bologna), Chi-Ting Chiang (BNL), Marilena LoVerde (Stony Brook), ChangHoon Hahn (Berkeley), Roman Scoccimarro (NYU), Tom Abel (Stanford)…

IPMU

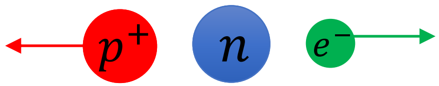
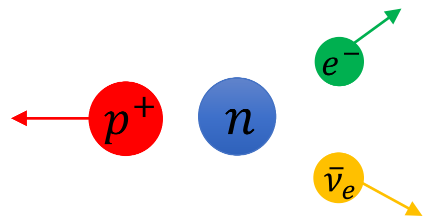
Outline

- Introduction
- Cosmic neutrino background
- Linear effects
- Non-linear effects
- Forecasts
- Future plans

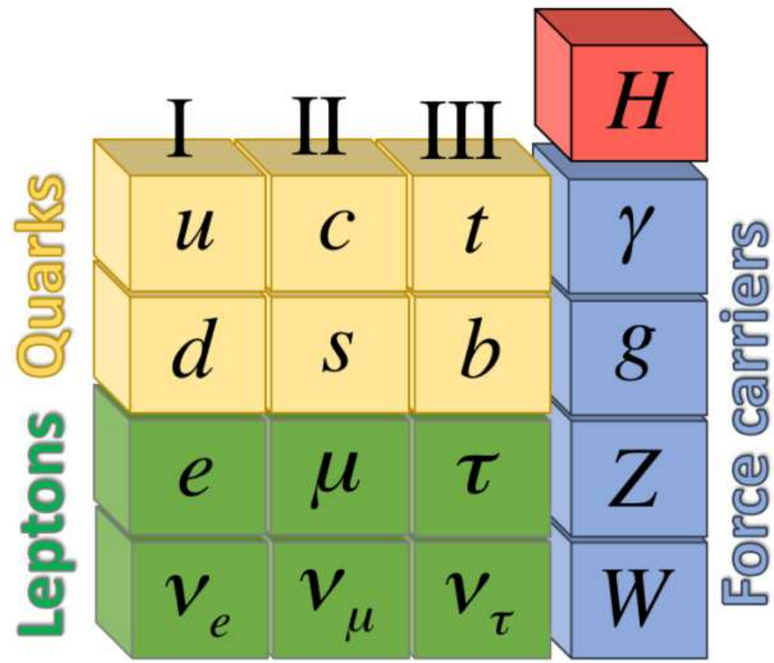
Take away message:

It should be possible to achieve a 5σ detection on the minimum mass of the neutrino masses with PFS/Euclid/DESI/LSST

History and properties

 Violation of Energy Violation of Momentum Violation of Spin	 Pauli (1930)	First detection Cowan & Reines (1956)

- Fundamental particles
- Neutral leptons
- N_ν=3 from Z boson decay
- Very weak cross section
- **<u>Massless</u>** in the SM

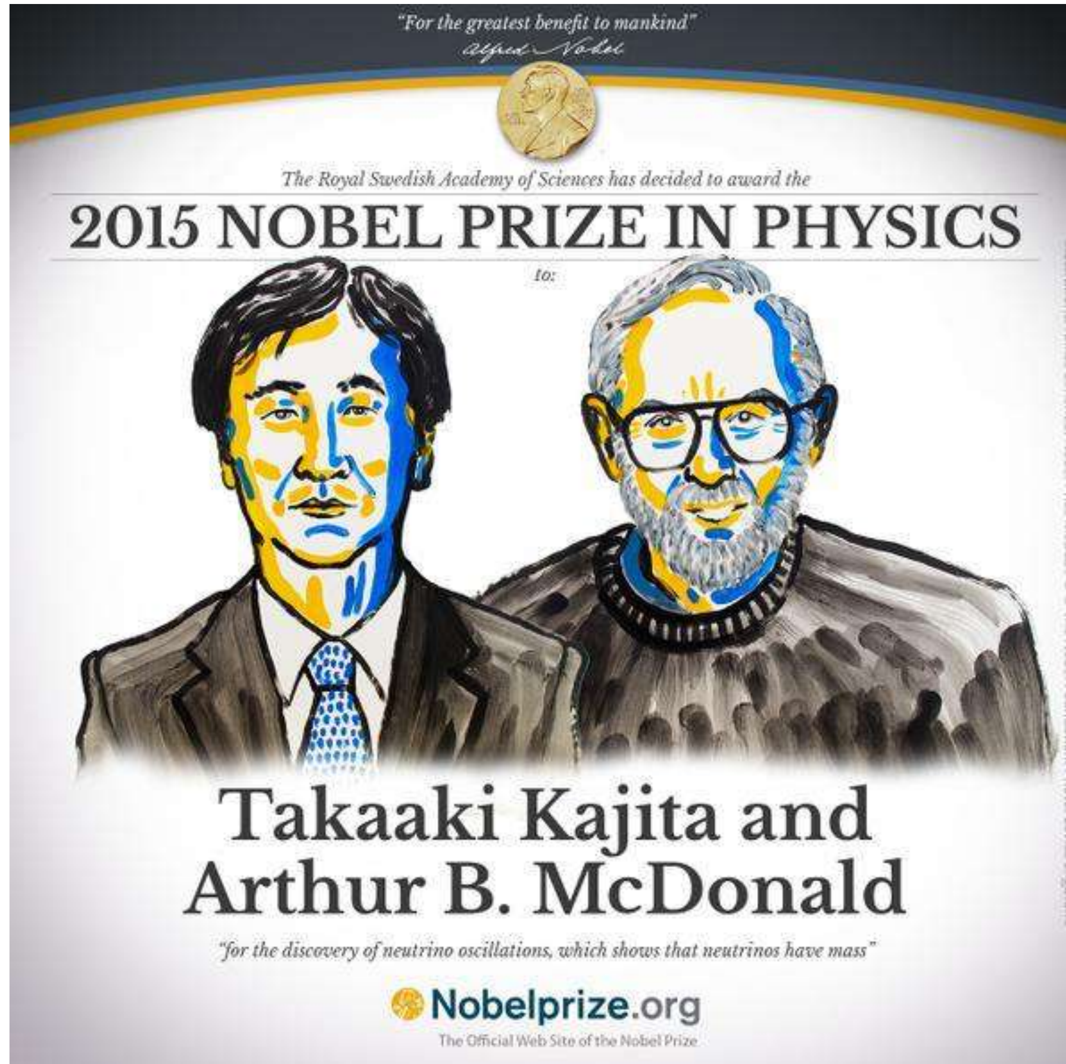


Neutrinos have mass!

Neutrino oscillations

(Neutrinos change flavor as they propagate)

- ~~**Massless** in the SM~~



Neutrino masses: implications

- Physics beyond the standard model

- Cosmology

  (neutrinos are the second most abundant particles in the Universe)

Neutrino masses: current status

What we know

$$0.06 \text{ eV} < \sum m_\nu < 6.9 \text{ eV}$$

Neutrino oscillations

Tritium beta decay

Fundamental questions to be addressed

- What is absolute scale of neutrinos masses?
- What is the neutrino mass hierarchy?
- Are neutrino masses Dirac or Majorana?
- Is there CP violation in the leptonic sector?

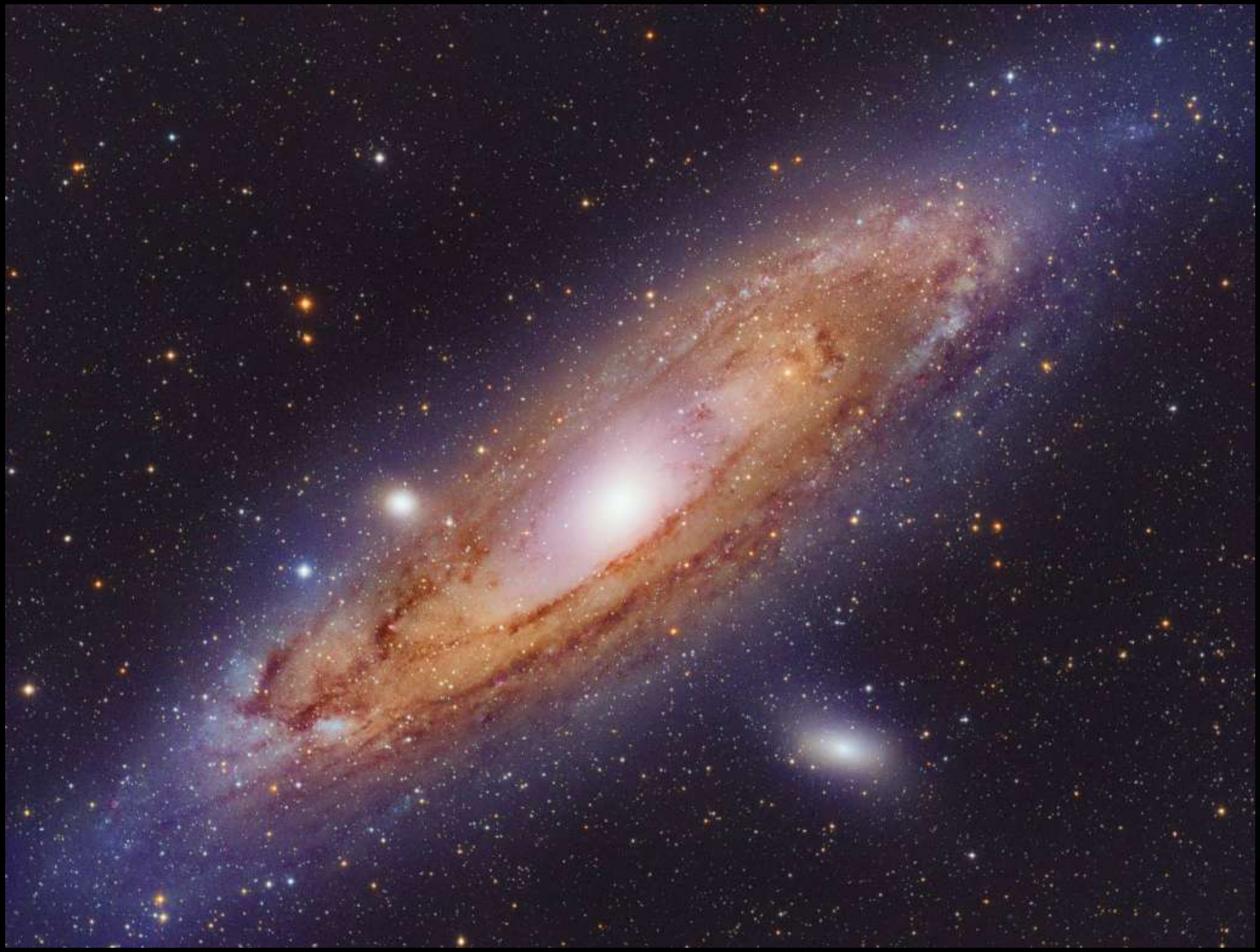
The never ending travelers

~ 1 second

~ 5 hours

~ 4 years

~ 3M years



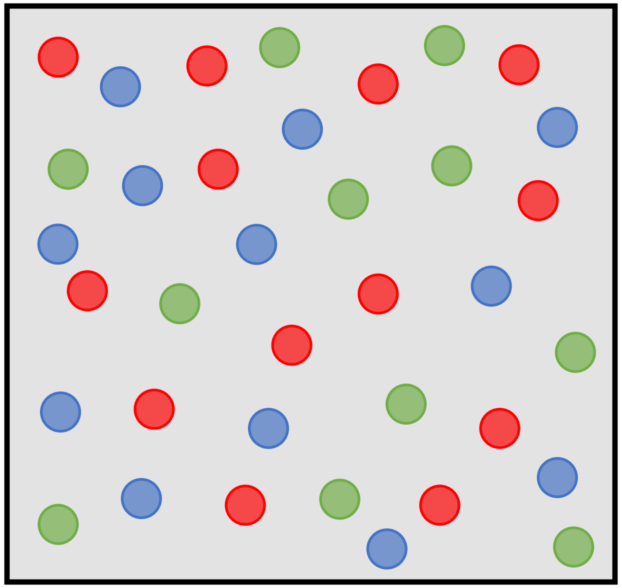
A part of us with travel FOREVER

Recap

• Introduction	Neutrinos have mass! We want to know the neutrino masses, hierarchy, nature and properties to learn about fundamental physics
• Cosmic neutrino background	
• Linear effects	
• Non-linear effects	
• Forecasts	

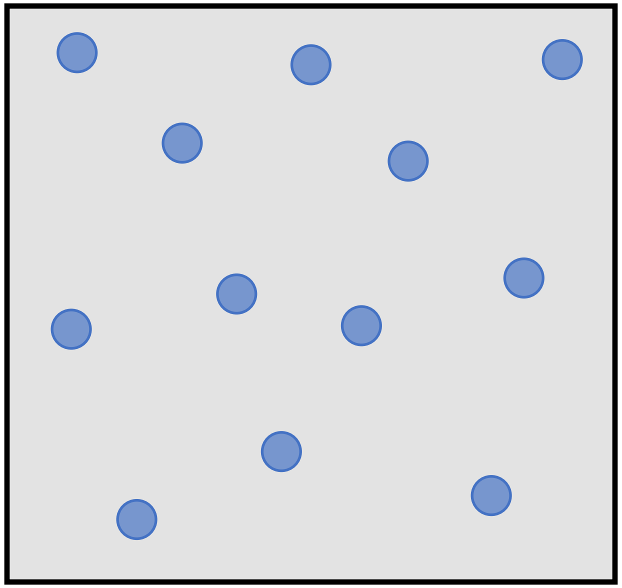
Cosmic neutrino background

$T > 10^{10}\mathrm{K} \sim 1$ MeV



- Neutrinos
- Antineutrinos
- Photons
- Electrons
- Positrons

$T < 10^{10}\mathrm{K} \sim 1$ MeV



$\nu + e^- \Leftrightarrow \nu + e^- \qquad e^- + e^+ \Leftrightarrow \nu + \overline{\nu}$

$$n_\nu(p,T)dp = \frac{4\pi g_\nu}{(2\pi\hbar c)^3}\left(\frac{p^2 dp}{e^{\left(\sqrt{p^2+m_\nu^2}/k_B T\right)}+1}\right)$$

$$n_\nu(p,z)dp \cong \frac{4\pi g_\nu}{(2\pi\hbar c)^3}\left(\frac{p^2 dp}{e^{(p/k_B T_\nu(z))}+1}\right)$$

$$T_{\nu,0} = \left(\frac{4}{11}\right)^{1/3} T_{\gamma,0} \approx 1.95 \text{ K} \qquad T_\nu(z) = T_{\nu,0}(1+z)$$

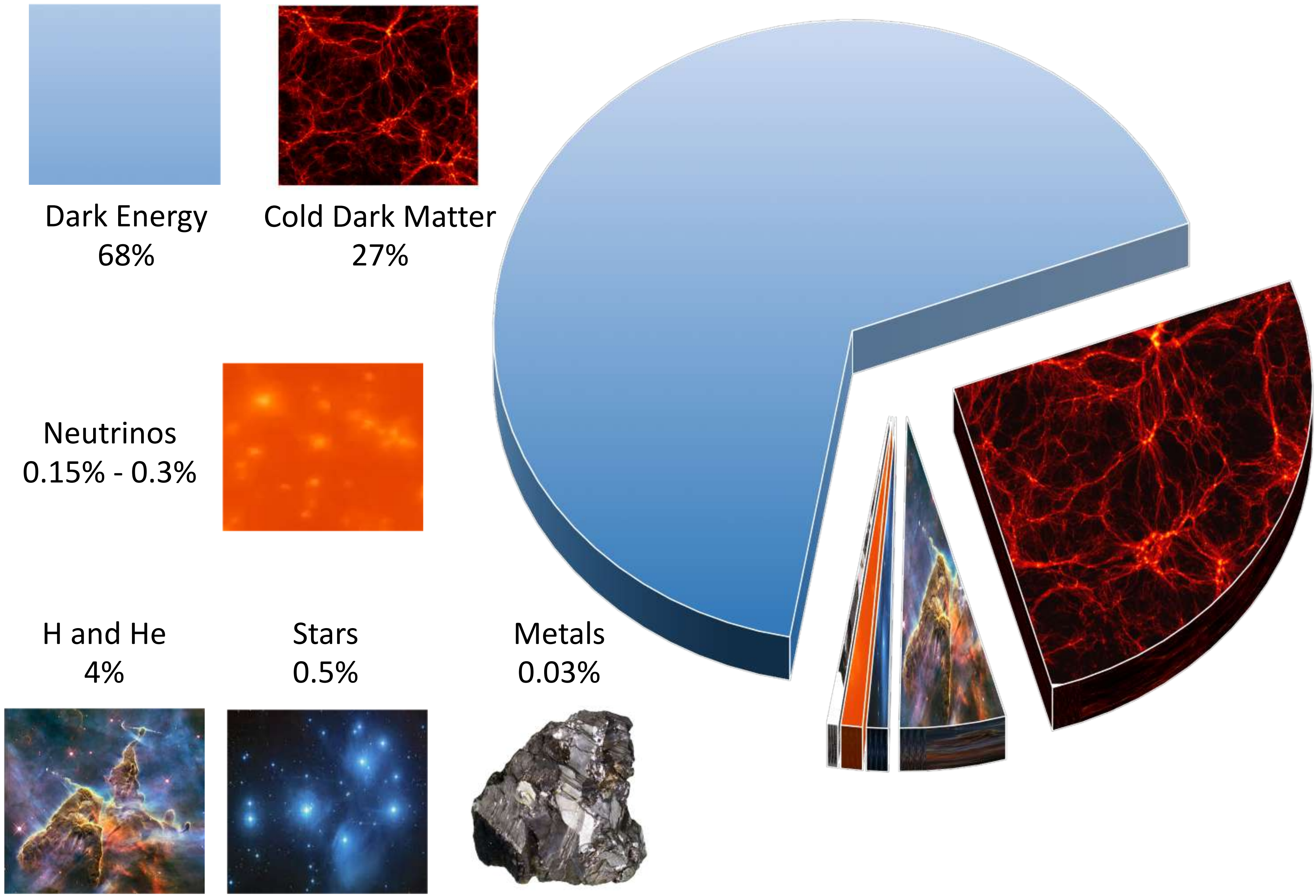
Cosmic neutrino background: properties

$$\bar{n}_\nu(z) = \int_0^\infty n_\nu(p,z)dp \cong 113(1+z)^3 \frac{\nu+\bar{\nu}}{\mathrm{cm}^3}$$

$$\Omega_\nu h^2 = \frac{\bar{\rho}_\nu}{\rho_c^0} = \frac{\sum m_\nu}{94.1\ \mathrm{eV}}$$

$$\bar{V}_\nu(z) = \frac{1}{\bar{n}_\nu(z)}\frac{1}{m_\nu}\int_0^\infty n_\nu(p,z)p\,dp \cong 160(1+z)\left(\frac{\mathrm{eV}}{m_\nu}\right)\mathrm{km/s}$$

Cosmic neutrino background: energy fraction



Recap

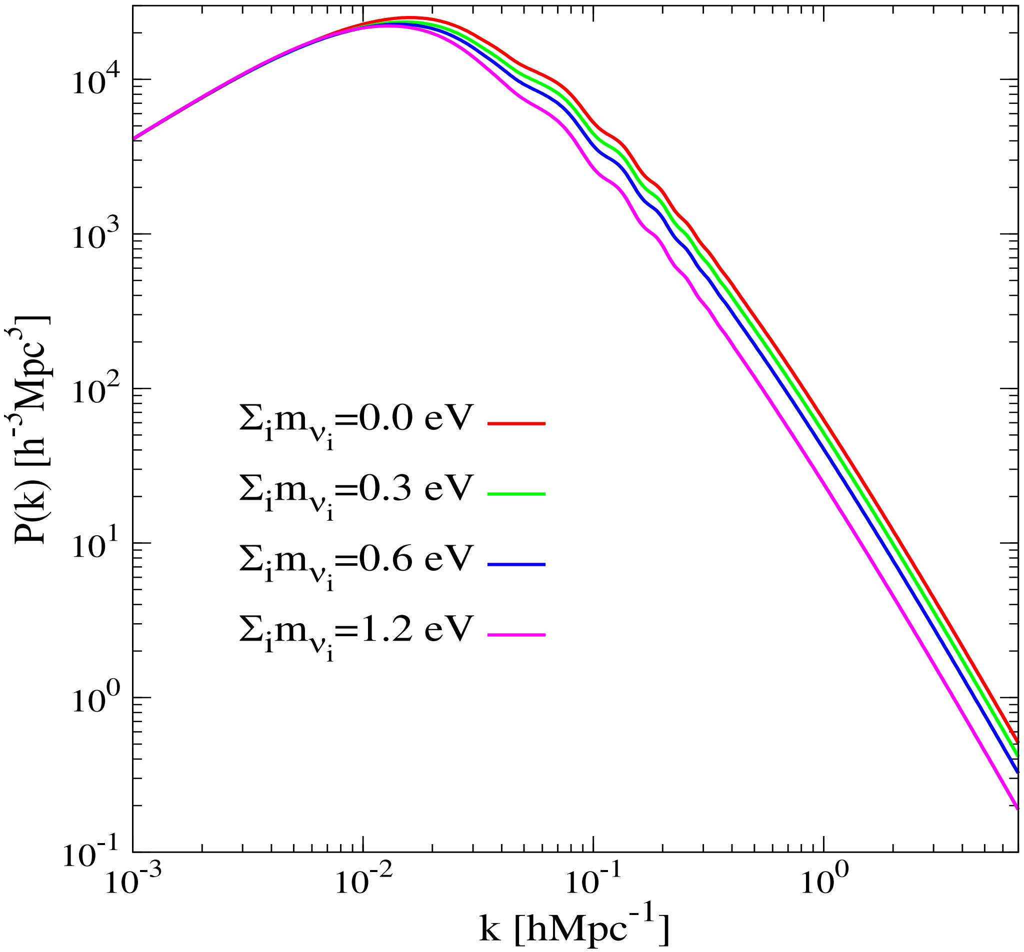
• Introduction	Neutrinos have mass! We want to know the neutrino masses, hierarchy, nature and properties to learn about fundamental physics
• Cosmic neutrino background	$\Omega_\nu \sim 0.3\%$ $\quad$ $\langle V_\nu \rangle \sim 3000\ \mathrm{km/s}$
• Linear effects	
• Non-linear effects	
• Forecasts	

Effects at linear order

Lesgourgues & Pastor, 2006

1. Modification of the Matter-Radiation equality time

2. Slow down the growth of CDM perturbations



The Universe
the largest laboratory ever!

Primary goal of many cosmological missions:

- PFS
- Euclid
- DESI
- LSST
- …

Quest for neutrino masses

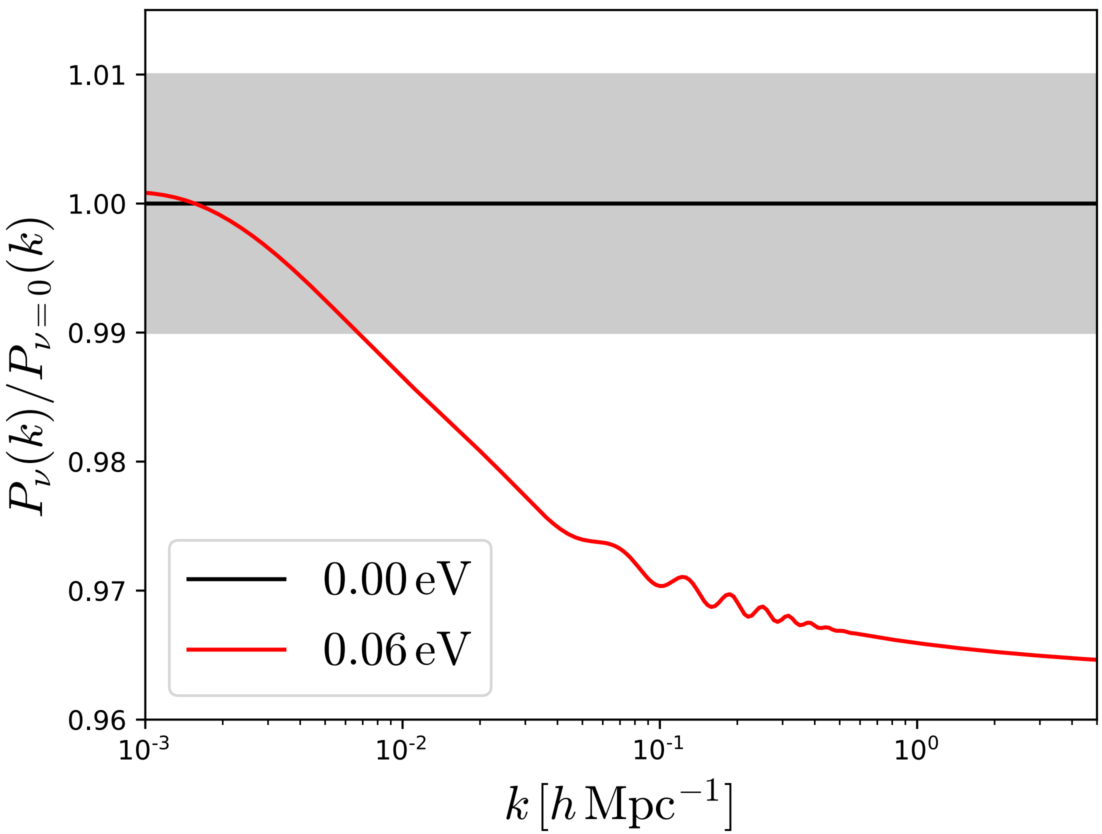
$0.06\ \mathrm{eV} < \Sigma m_\nu < 0.12\ \mathrm{eV}$

Laboratory

Cosmology

Palanque-Delabrouille et al. 2015
Cuesta et al.2016
Vagnozzi et al. 2017
Planck 2018

CMB+BAO *+ Lya/galaxy clustering*



Forecasts:

Benson et al. 2014
Planck+BOSS+SPT-3G
$\sigma(\Sigma m_\nu)$ ~ 0.058 eV

FVN, Bull, Viel 2015
Euclid + Planck + SKA1
$\sigma(\Sigma m_\nu)$ ~ 0.032 eV

Obuljen, Castorina, **FVN**, Viel, 2017
Euclid + CMB S4 + Ext HIRAX
$\sigma(\Sigma m_\nu)$ ~ 0.023 eV

Font-Ribera, McDonald, et al. 2014
DESI / Planck / Euclid / LSST
$\sigma(\Sigma m_\nu)$ ~ [0.011-0.06] eV

3σ - 4σ

Quest for neutrino masses

Many different forecasts have shown that upcoming surveys will measure the minimum sum of the neutrino masses at

3σ - 4σ

1. Very accurate theory predictions: avoid biases
2. New and unique observables: robust 5σ detection

Recap

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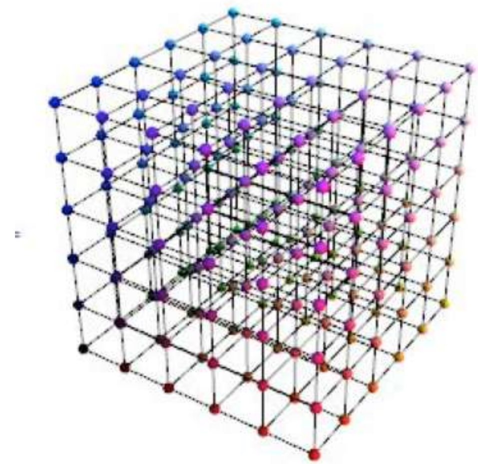
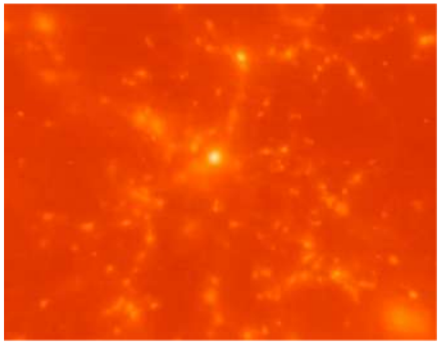
• Cosmic neutrino background	$\Omega_\nu \sim 0.3\%$ $\langle V_\nu \rangle \sim 3000\ \mathrm{km/s}$
• Linear effects	Neutrino masses leave signatures on cosmological observables Standard probes: 3σ - 4σ 1. Very accurate theory predictions: avoid biases 2. New and unique observables: robust 5σ detection
• Non-linear effects	
• Forecasts	

Non-linear neutrino effects

Simulations



Neutrino clustering

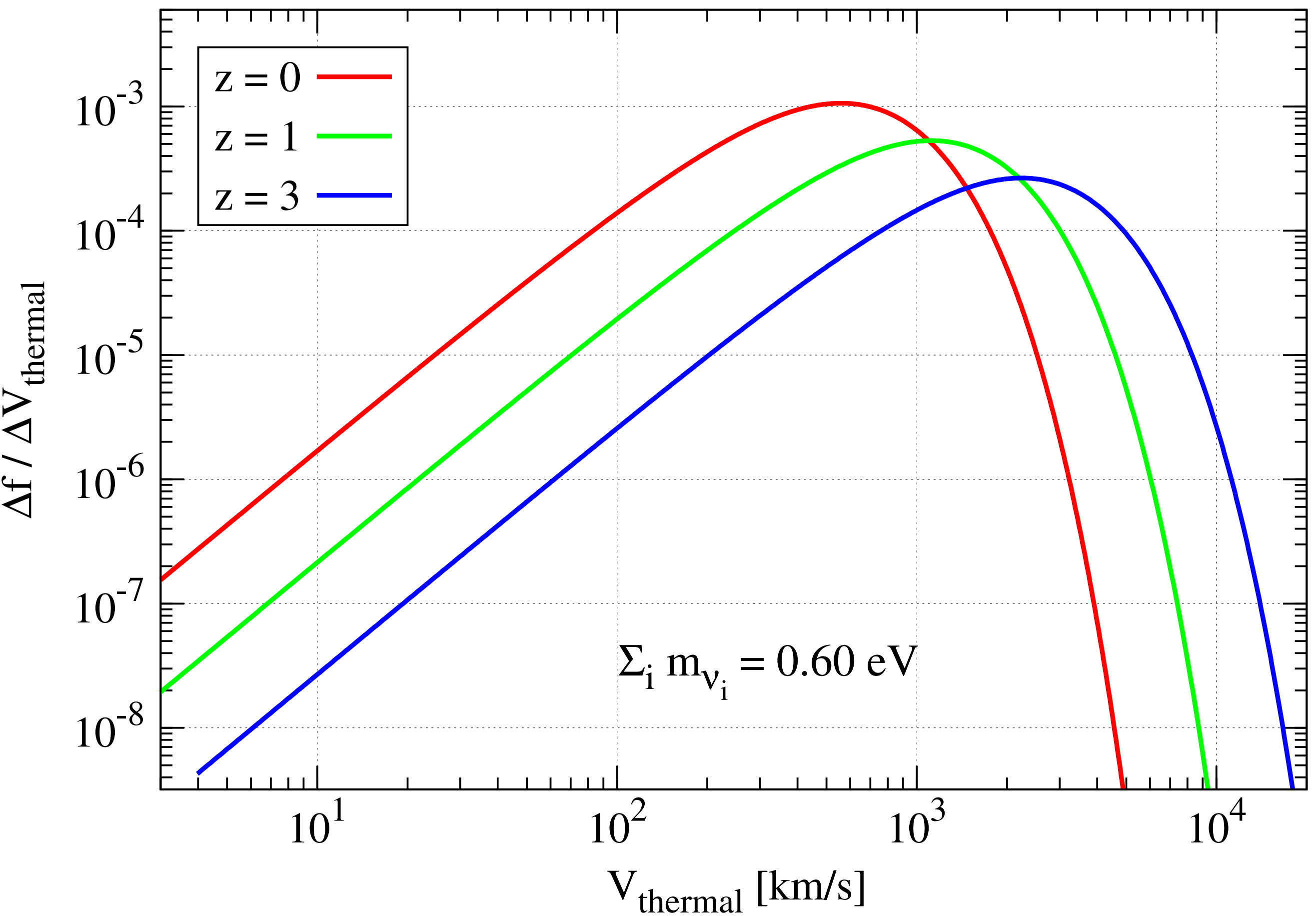


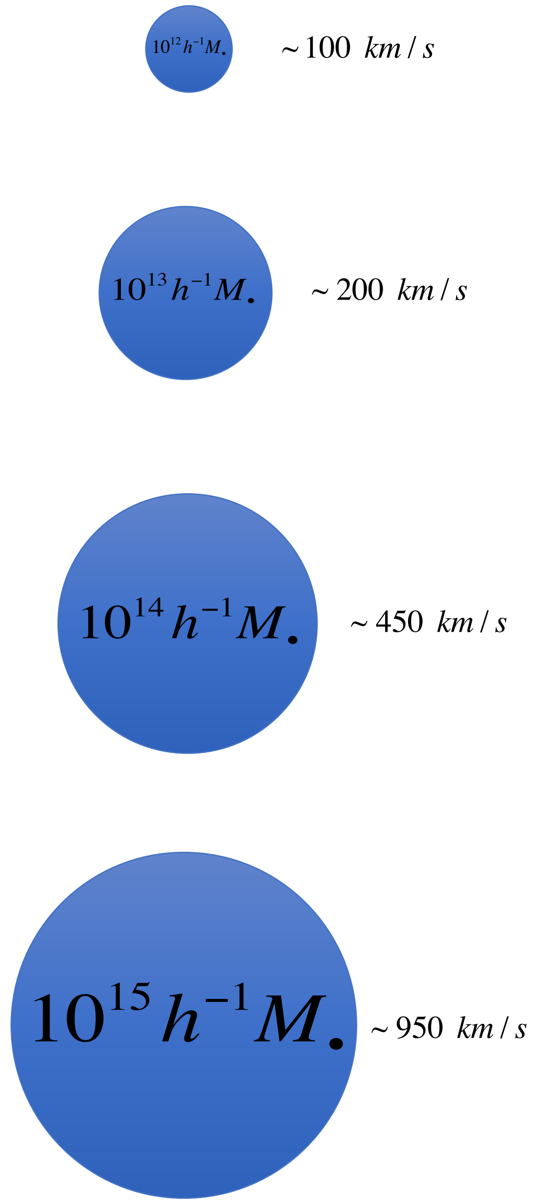
Neutrino effects

- Halo mass function
- Halo/galaxy clustering
- Voids

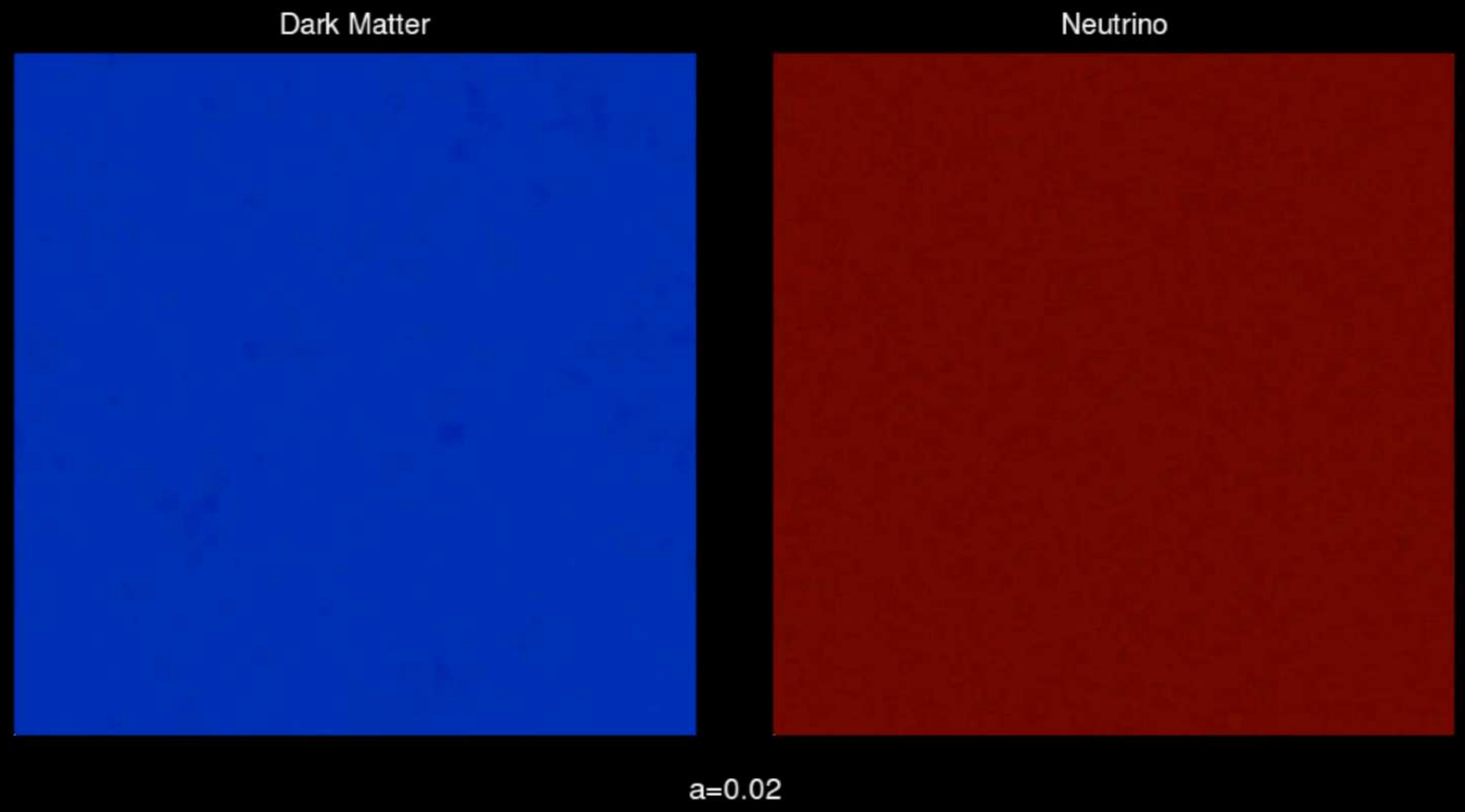
Neutrino clustering

$$n_\nu(p,z)dp \cong \frac{4\pi g_\nu}{(2\pi\hbar c)^3}\left(\frac{p^2 dp}{e^{(p/k_B T_\nu(z))}+1}\right)$$

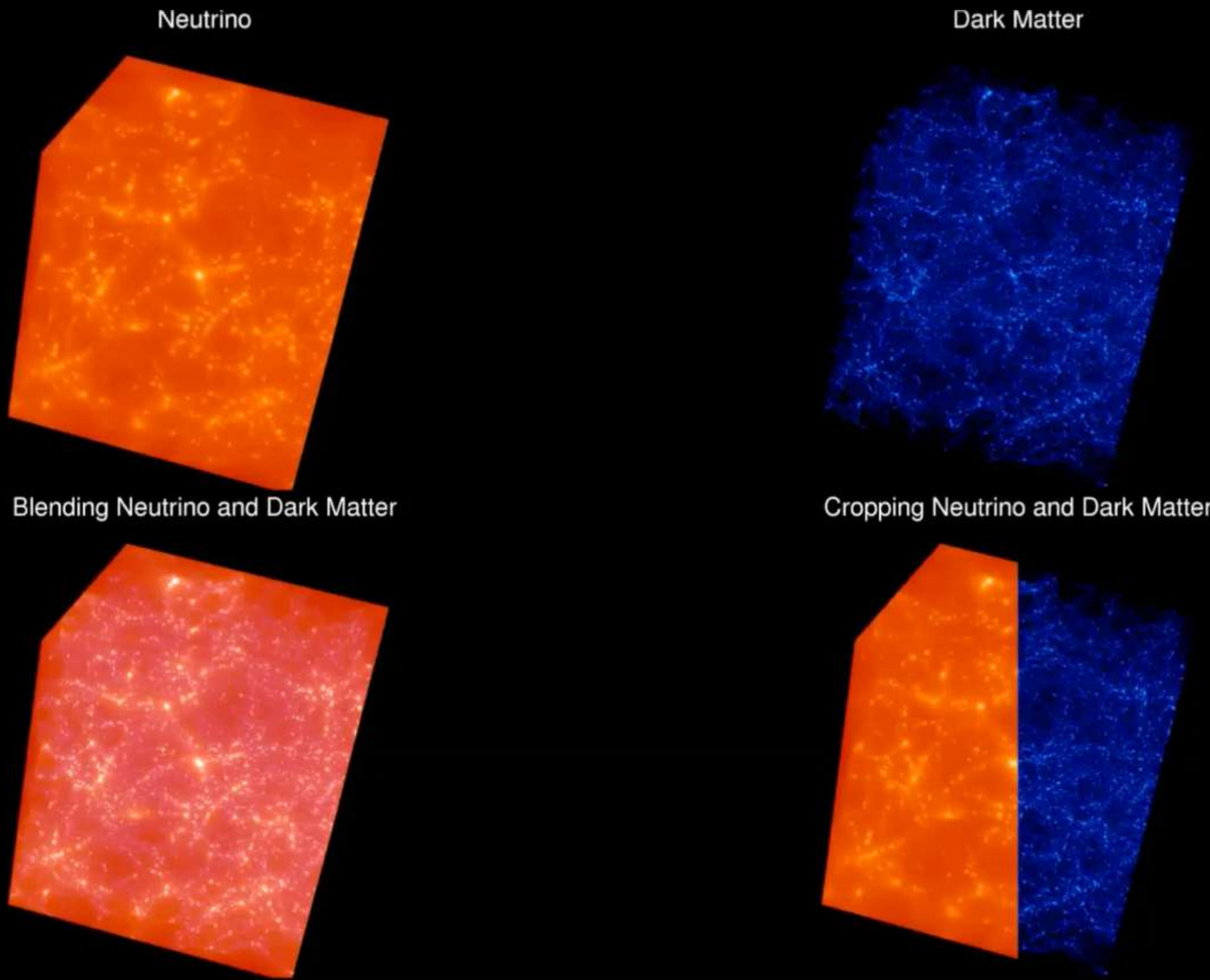




Neutrino clustering

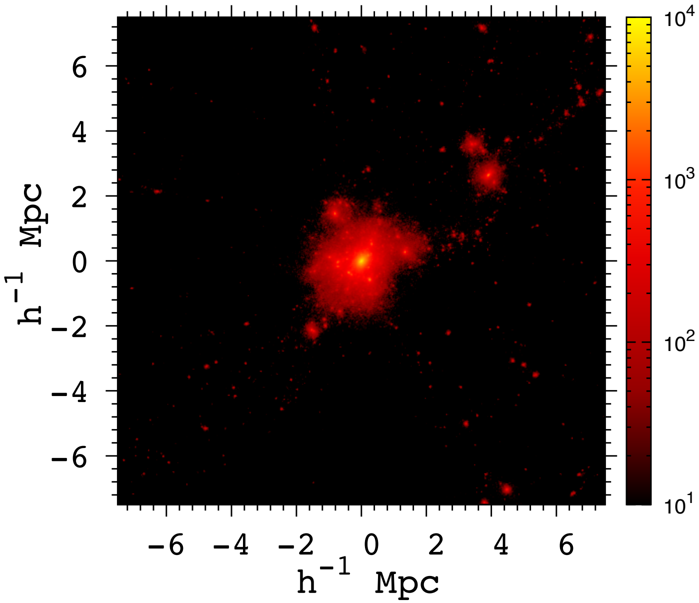


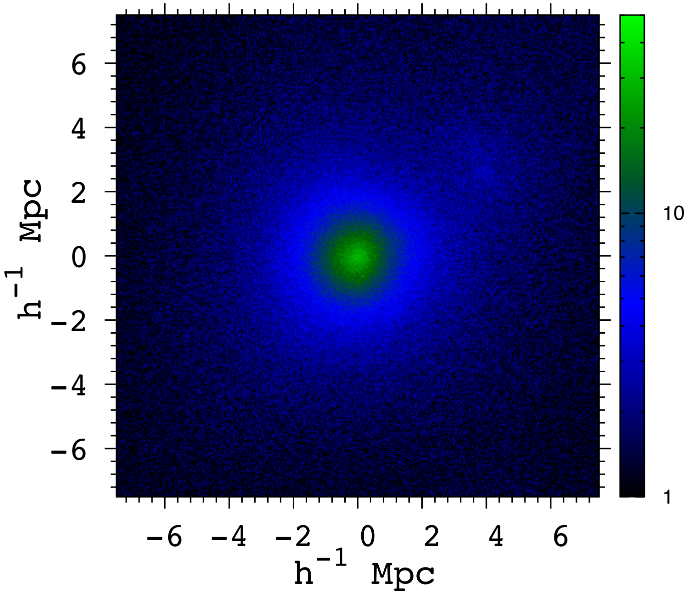
Neutrino clustering



Neutrino clustering

Ichiki & Takada 2011
FVN, Miralda-Escude, Peña-Garay, Quilis, 2011
FVN, Bird, Peña-Garay, Viel, 2013



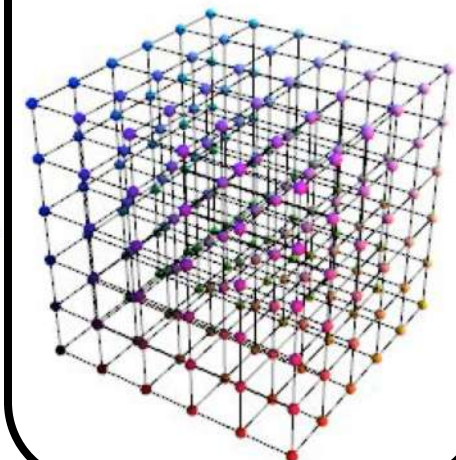


$$F_h \sim 10^{-3} \longrightarrow 0.3\ \text{eV}$$

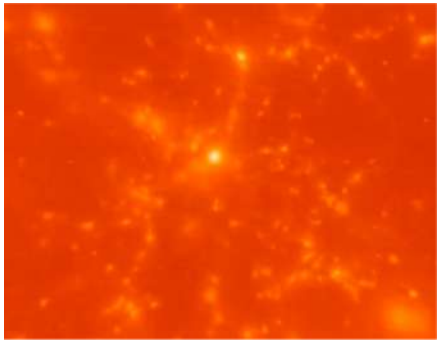
$$M_h = M_{\text{CDM}} + M_{\text{b}} + \cancel{M_\nu}$$

Non-linear effects

Simulations



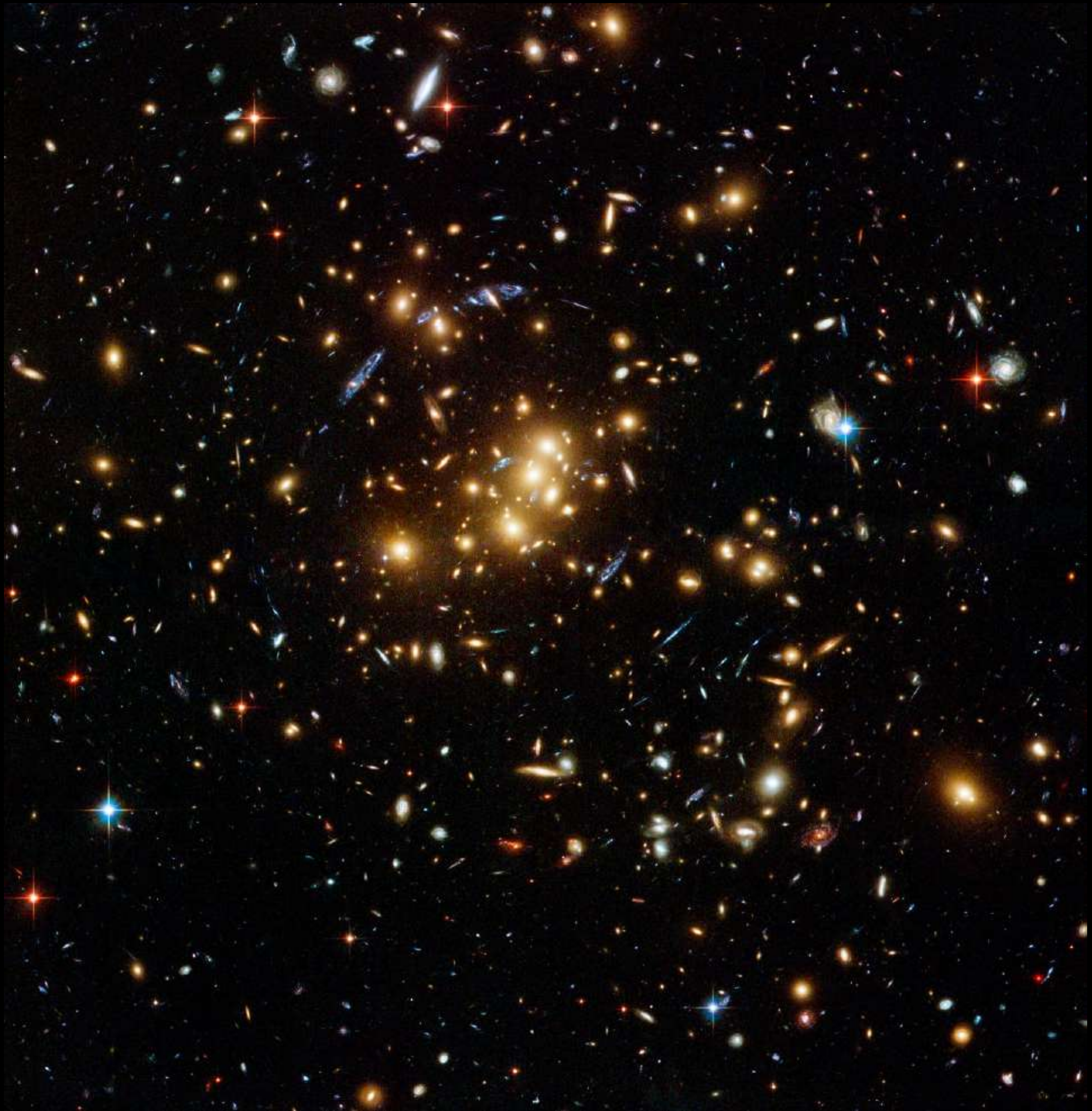
Neutrino clustering



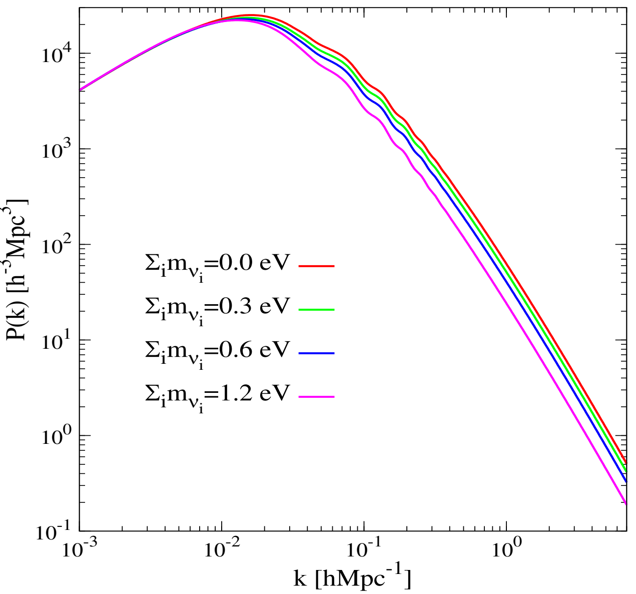
Neutrino effects

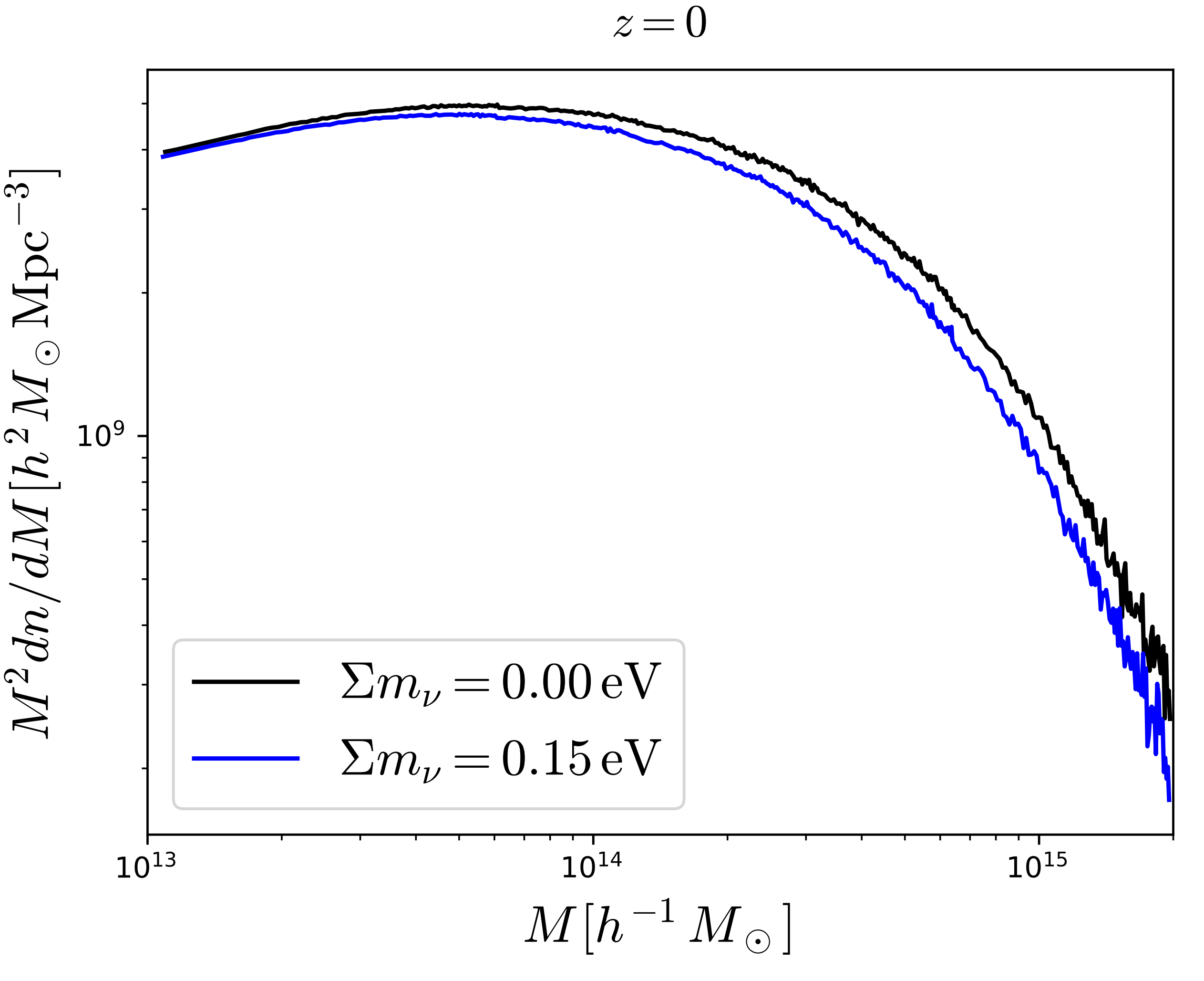
- Halo mass function
- Halo/galaxy clustering
- Voids

Neutrino effects I: halo mass function



Neutrino effects I: halo mass function





Neutrino effects I: halo mass function

Ichiki & Takada 2011
Castorina, Sefussati, Sheth, **FVN**, Viel 2013
Costanzi, **FVN**, Viel, Xia, Borgani, Castorina, Sefusatti, 2013

$$\frac{dn(M,z)}{dM} = f(\Omega_m, \Omega_b, h, n_s, \sigma_8, M_\nu)$$

$$\frac{dn(M,z)}{dM} = g(M, \rho_m(z), P_m(k,z))$$

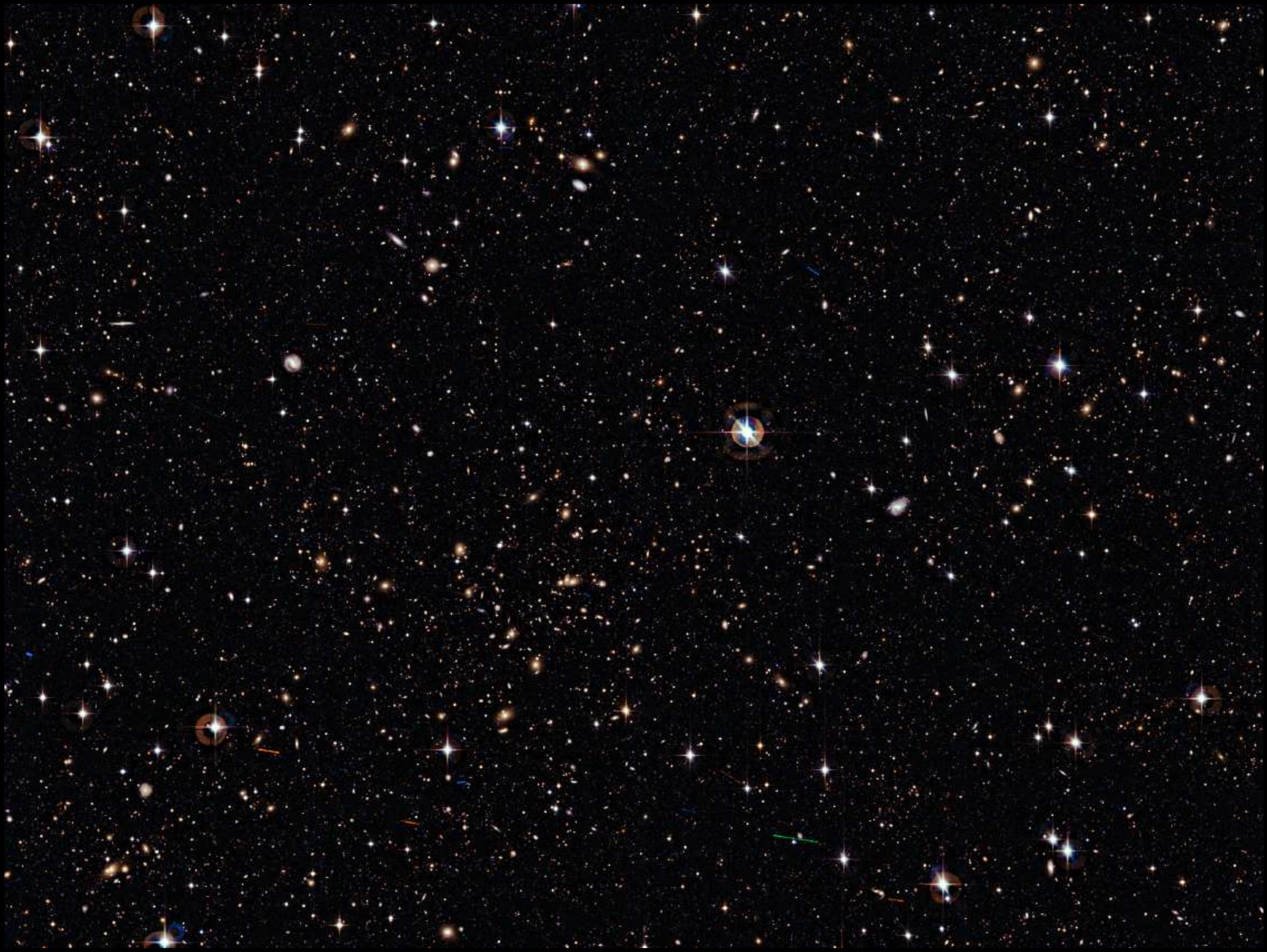
g is an Universal function

What about massive neutrino cosmologies?

- ~~No prescription~~ $\cancel{\rho_m \rightarrow \rho_m \quad P_m(k) \rightarrow P_m(k)}$
- CDM prescription $\rho_m \rightarrow \rho_{cdm} \quad P_m(k) \rightarrow P_{cdm}(k)$

Universality extended to massive neutrino cosmologies

Neutrino effects II: halo clustering



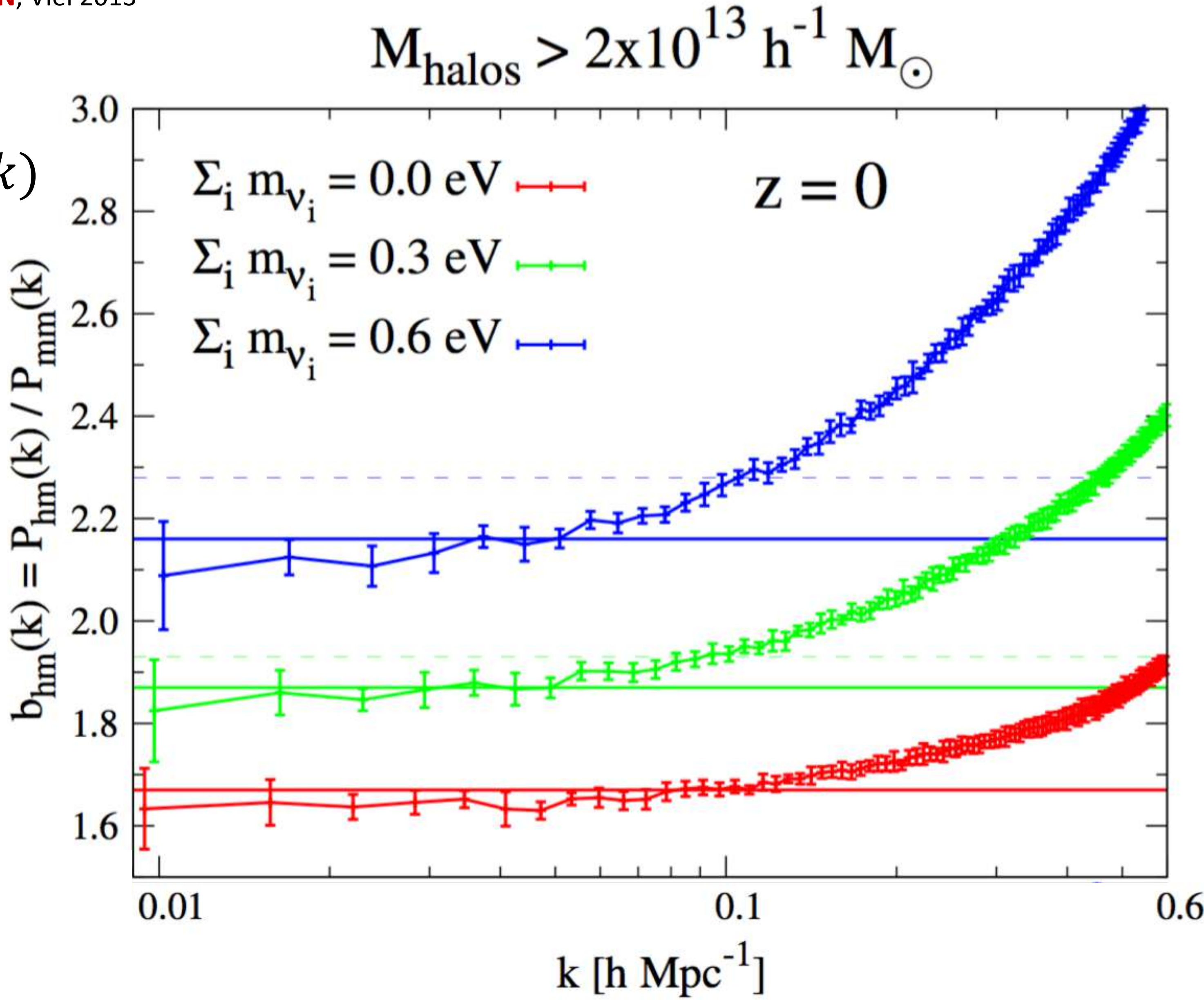
$$P_g(k) = b^2(k)P_m(k)$$

$$\lim_{k \ll 1} b(k) = B$$

Neutrino effects II: halo clustering

FVN, Marulli, Viel, Branchini, Castorina, Sefusatti, Saito 2013
Castorina, Sefusatti, Sheth, **FVN**, Viel 2013
Chiang, Hu, Li, LoVerde 2018
Chiang, LoVerde, **FVN**, 2018

$$P_h(k) = b^2 P_m(k)$$



Neutrino effects II: halo clustering

FVN, Marulli, Viel, Branchini, Castorina, Sefusatti, Saito 2013
Castorina, Sefusatti, Sheth, **FVN**, Viel 2013
Chiang, Hu, Li, LoVerde 2018
Chiang, LoVerde, **FVN**, 2018

$$\rho_m = \rho_c + \rho_b \cancel{+ \rho_\nu}$$

$$\cancel{P_g(k) = b^2 P_m(k)}$$

$$P_g(k) = b^2 P_{cb}(k)$$

Bias defined in this way becomes universal across halo mass, neutrino masses and redshift.

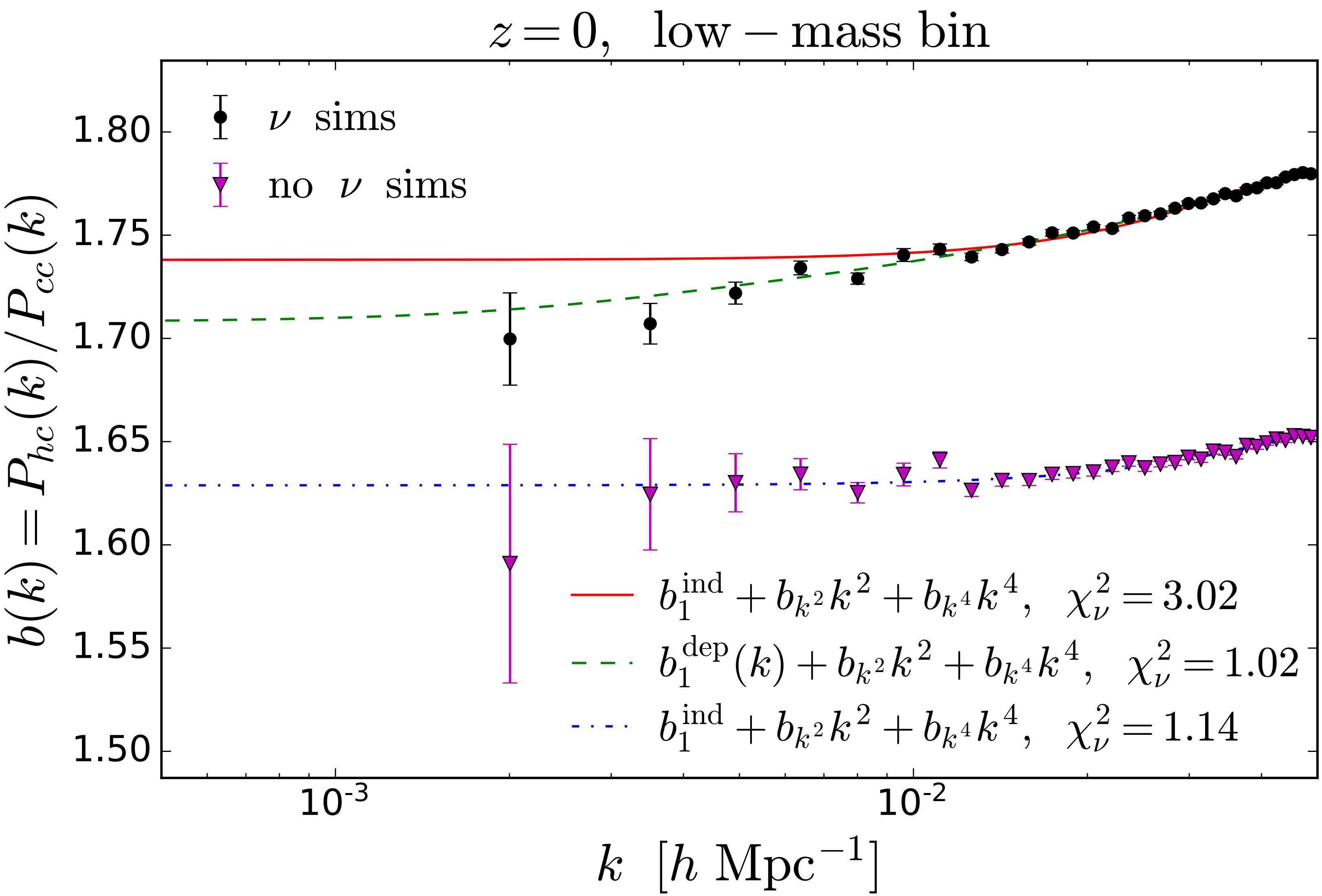
Raccanelli, Verde, **FVN**, 2017
Vagnozzi et al. 2018

→ If this systematic effect is not taken into account, it will biased the derived value of the cosmological parameters between 0.5σ and 1σ.

Neutrino effects II: halo clustering

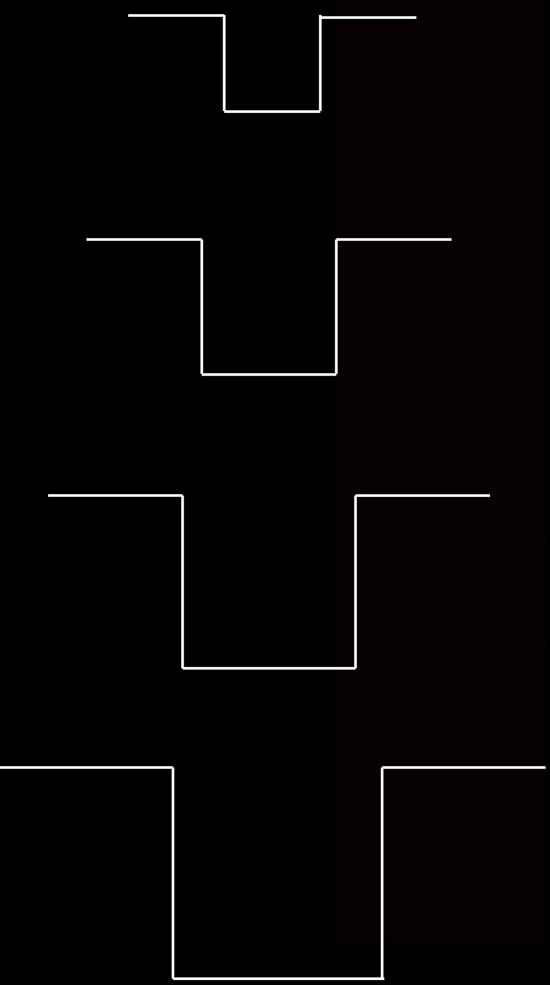
LoVerde 2014
Chiang, Hu, Li, LoVerde 2018
Chiang, LoVerde, **FVN**, 2018

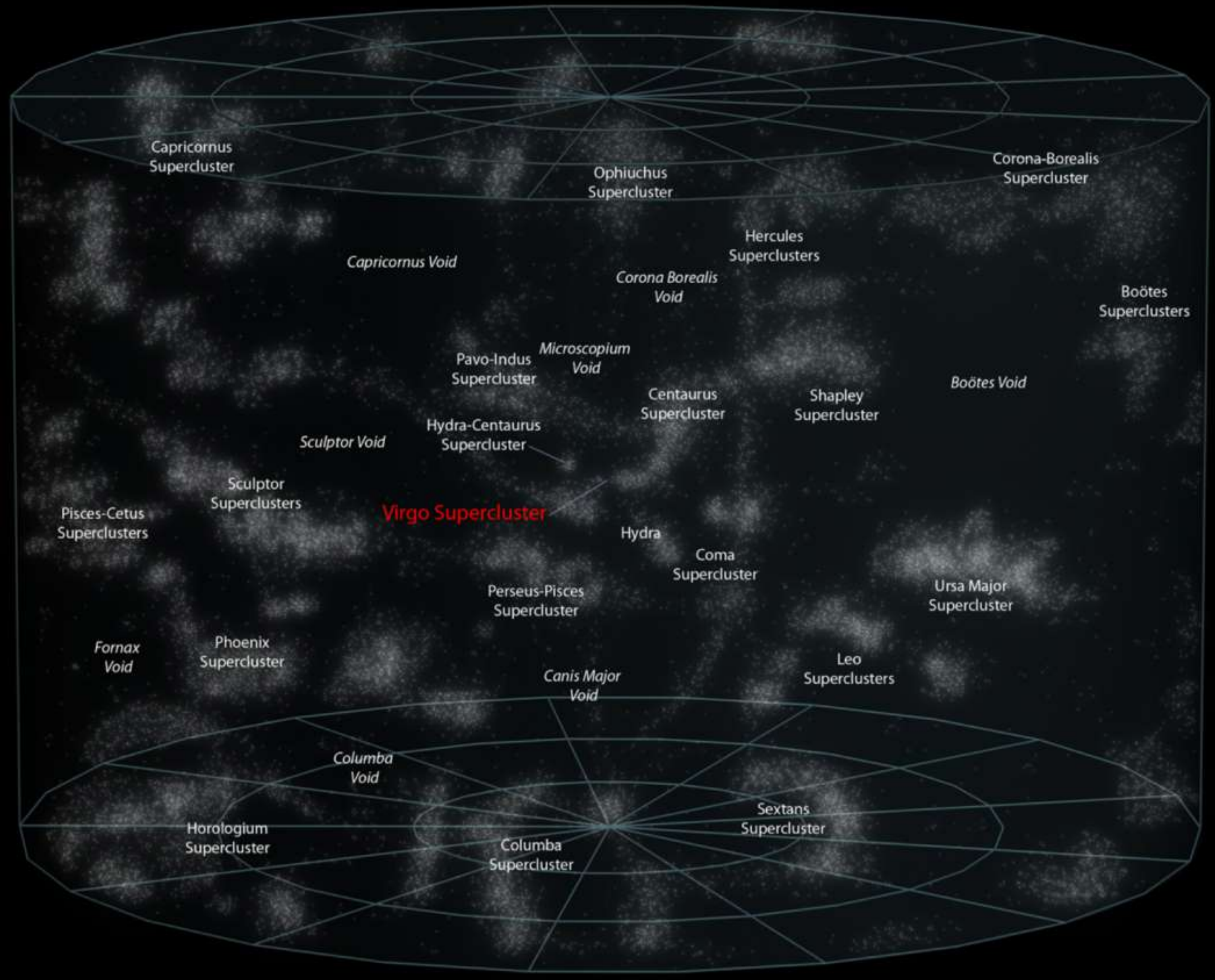
Unique neutrino effect!



Neutrino effects III: voids

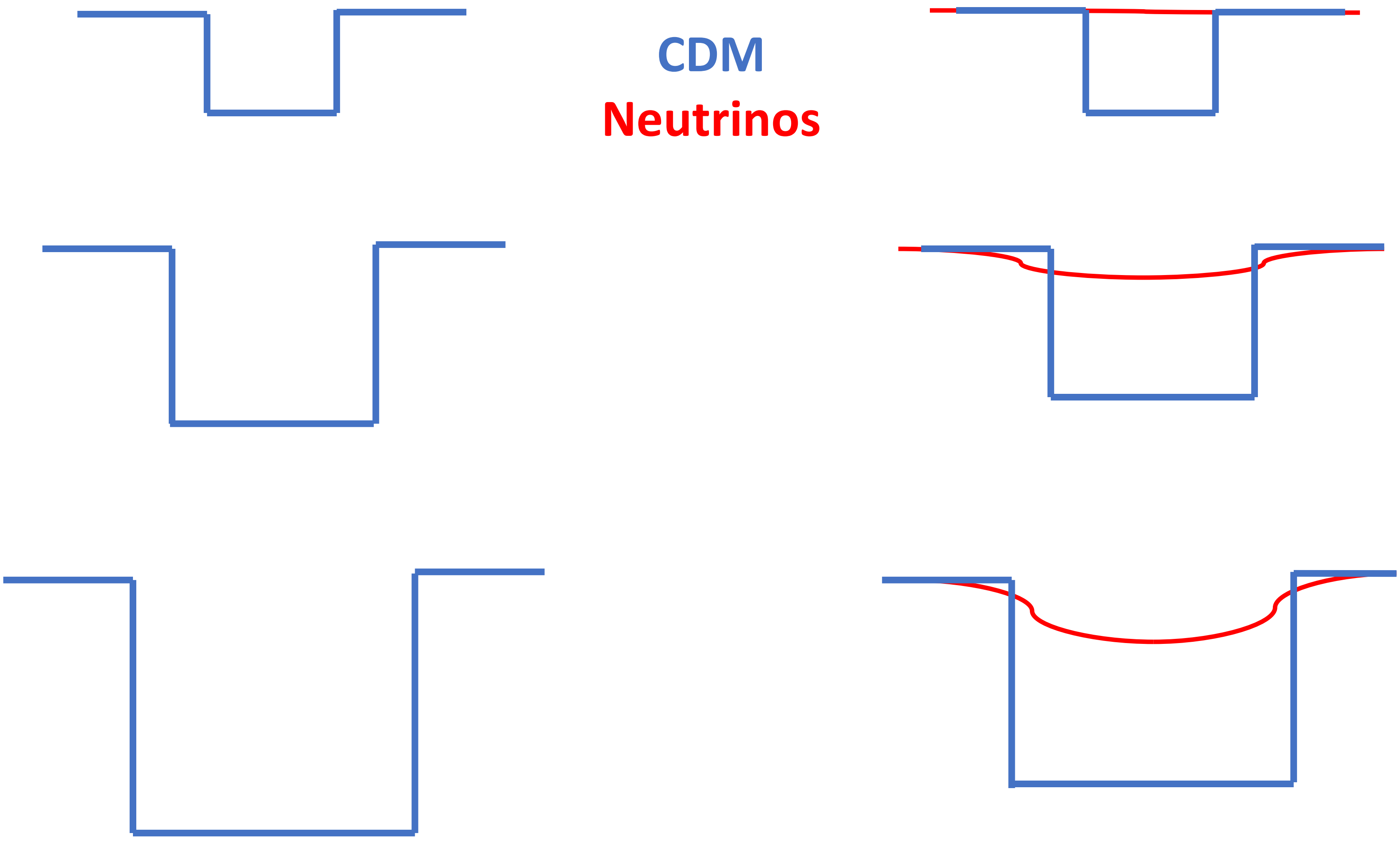
Massless neutrinos





Neutrino effects III: voids

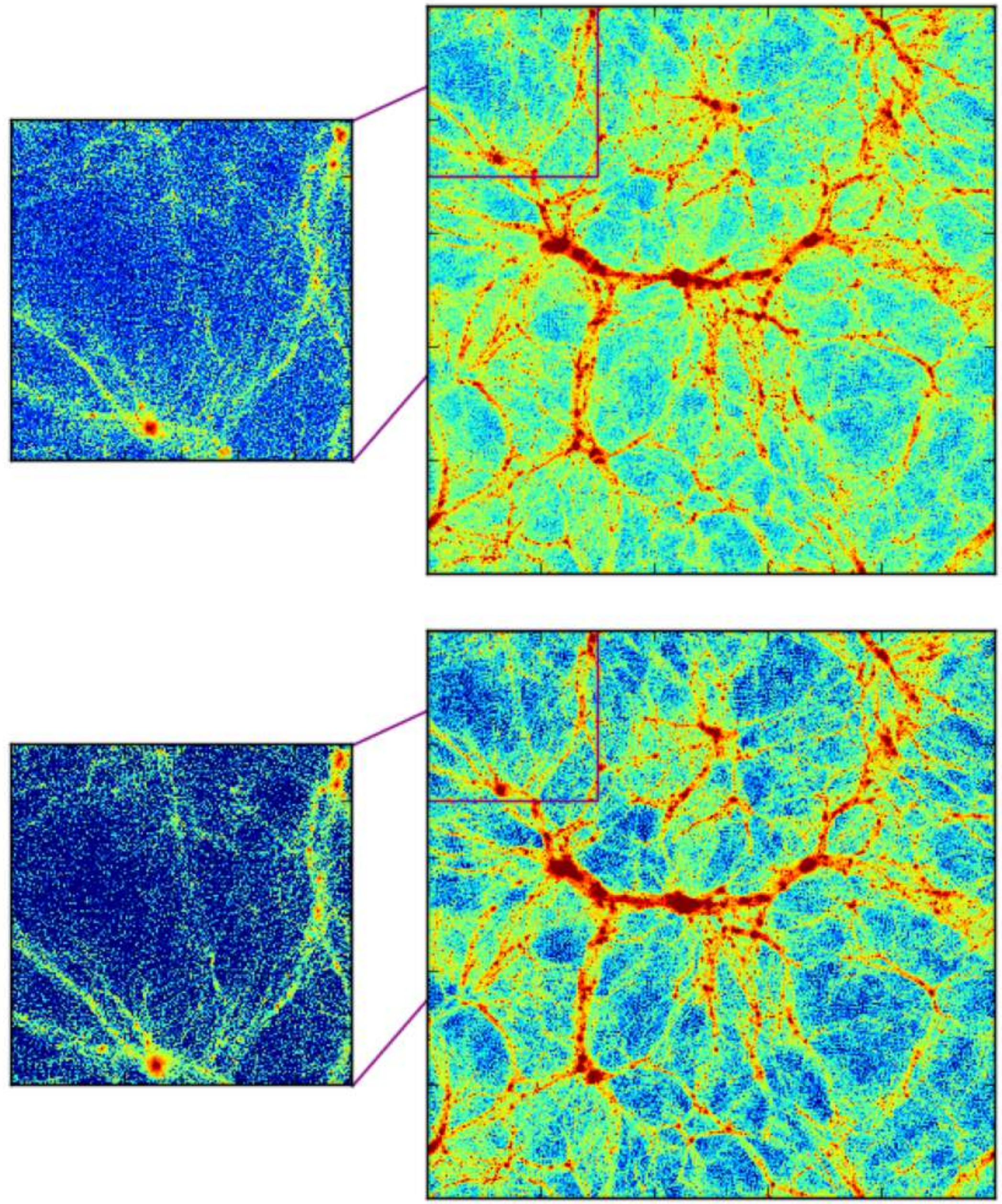
Massless neutrinos ***Massive neutrinos***



Neutrino effects III: voids

Massive neutrinos

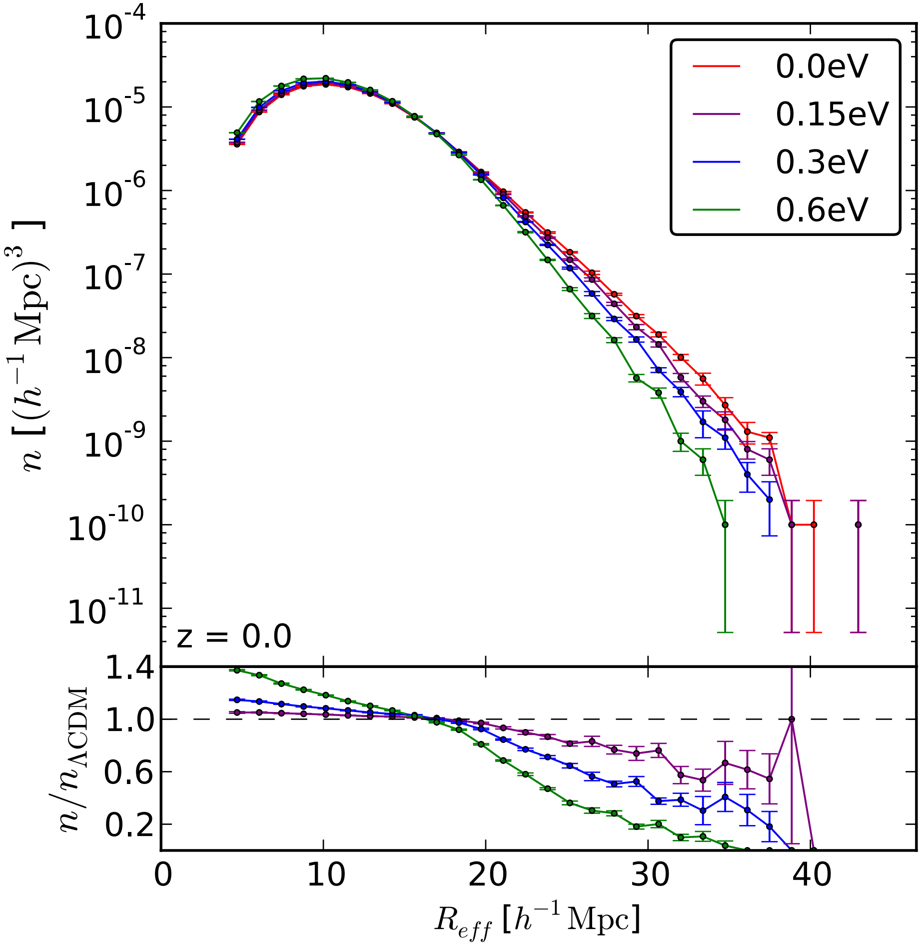
Massless neutrinos



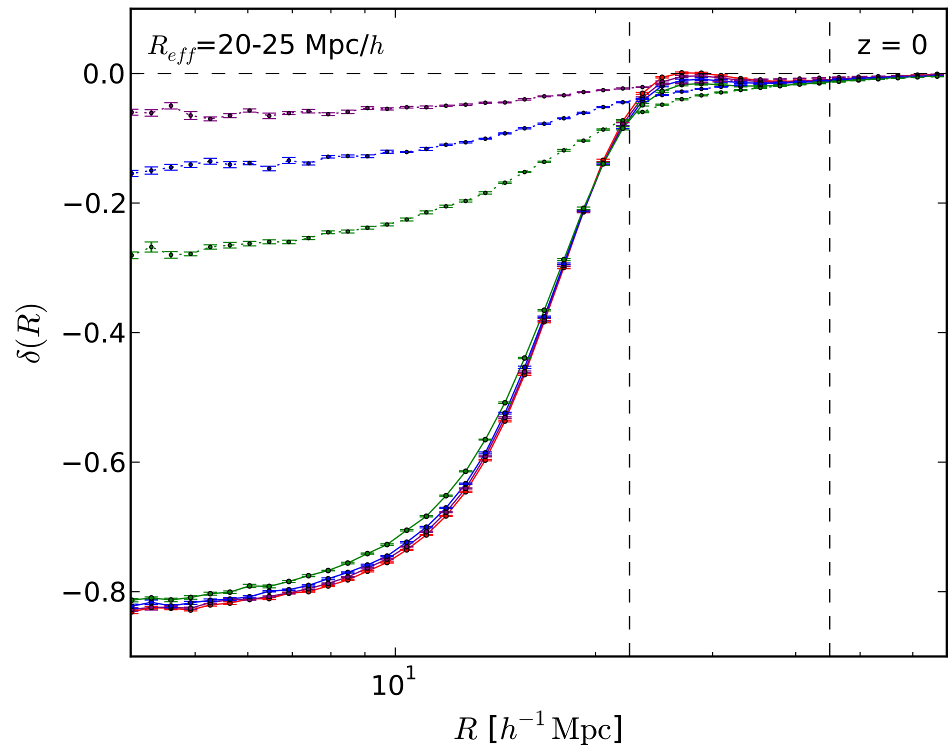
Neutrino effects III: voids

FVN, Vogelsberger, Loeb, Viel, 2012
Massara, **FVN**, Viel, Sutter 2015

Abundance



Density profiles



Neutrino effects are amplified in voids
Use Lyα or galaxy voids to measure neutrino masses

Recap

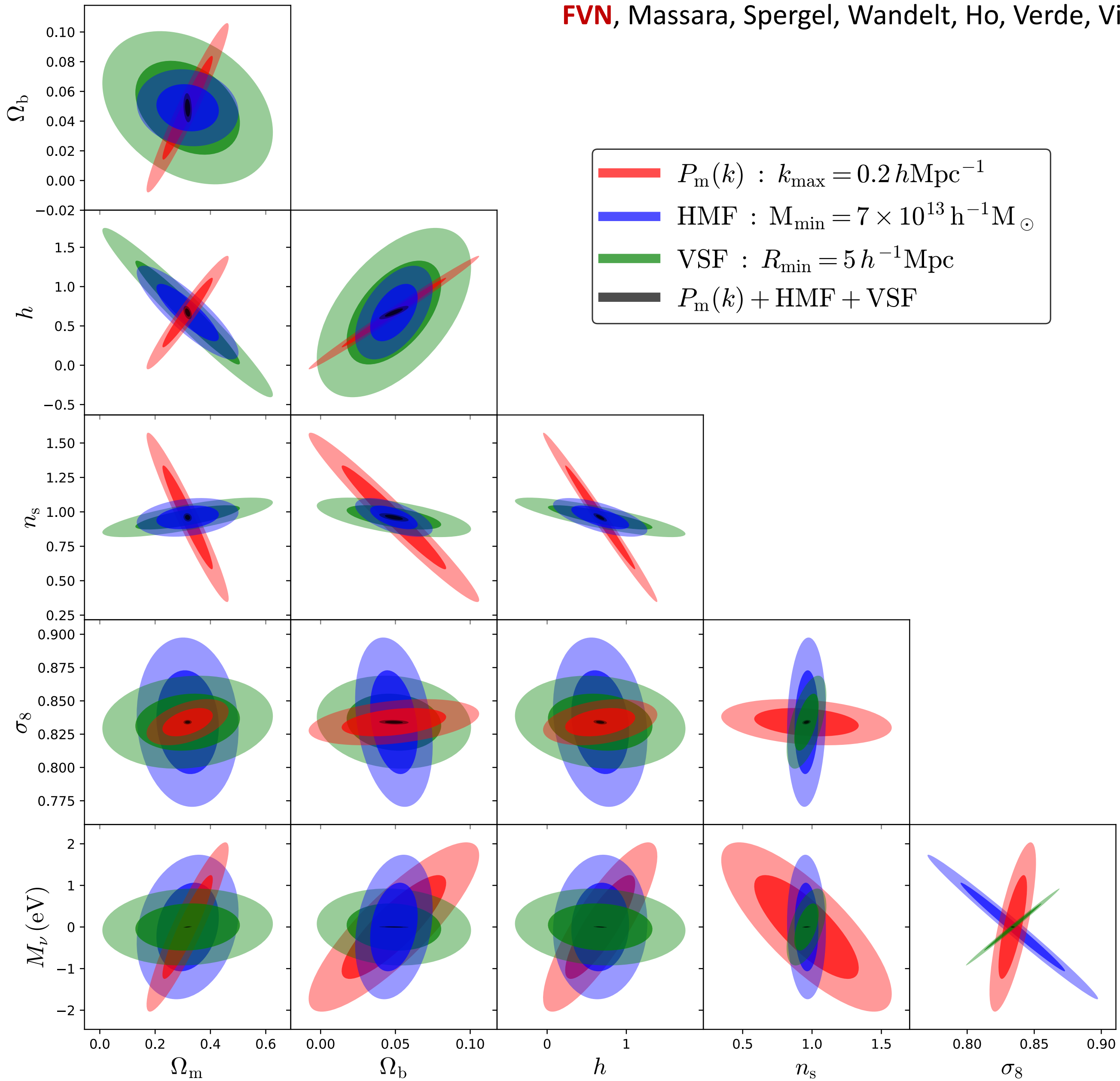
• Introduction	Neutrinos have mass! We want to know the neutrino masses, hierarchy, nature and properties to learn about fundamental physics
• Cosmic neutrino background	$\Omega_\nu \sim 0.3\%$ $\langle V_\nu \rangle \sim 3000\ \mathrm{km/s}$
• Linear effects	Neutrino masses leave signatures on cosmological observables Standard probes: 3σ - 4σ 1. Very accurate theory predictions: avoid biases 2. New and unique observables: robust 5σ detection
• Non-linear effects	• Halos/galaxies $\rho_m = \rho_c + \rho_b \cancel{+ \rho_\nu}$ • Voids $\rho_m = \rho_c + \rho_b + \rho_\nu$
• Forecasts	

Forecasts

How well can we constraint the sum of the neutrino masses by combining information from the power spectrum, the halo mass function and the void size function?

Forecasts: P(k) + HMF + VSF

FVN, Massara, Spergel, Wandelt, Ho, Verde, Viel, (To be submitted)

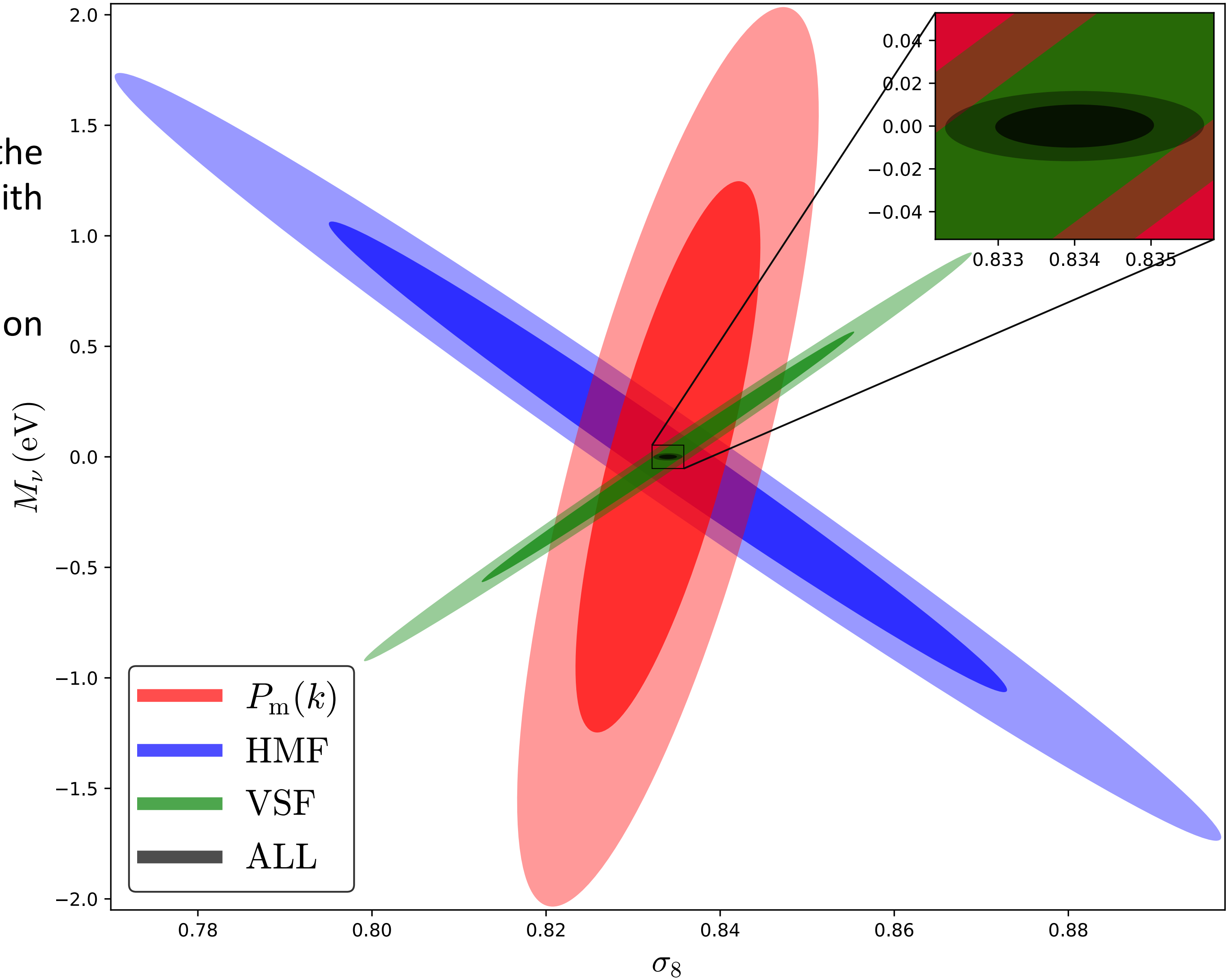


Forecasts: P(k) + HMF + VSF

FVN, Massara, Spergel, Wandelt, Ho, Verde, Viel, (To be submitted)

5σ constraint on the minimum mass with just 1 (Gpc/h)^3

No CMB information at all!



The Quijote simulations

FVN, Massara, Spergel, Wandelt, Ho, Verde, Viel (To be submitted)

$$F_{\alpha\beta} = \frac{1}{2}\left[\frac{\partial \vec{d}}{\partial \theta_\alpha} C^{-1} \frac{\partial \vec{d}}{\partial \theta_\beta} + \frac{\partial \vec{d}}{\partial \theta_\beta} C^{-1} \frac{\partial \vec{d}}{\partial \theta_\alpha}\right] + \frac{1}{2}\mathrm{Tr}\left[C^{-1} \frac{\partial \vec{d}}{\partial \theta_\alpha} C^{-1} \frac{\partial \vec{d}}{\partial \theta_\beta}\right]$$

			500				
		500	500				
+	500	500	500	500	500	500	
	$\{\Omega_m$	Ω_b	M_ν	h	n_s	$\sigma_8\}$	**15000**
-	500	500	500	500	500	500	
		500					

- A set of 23000 N-body simulations
- 1000 Mpc/h 512^3 DM particles (+ 512^3 ν particles)   z = {0, 0.5, 1, 2, 3}
- **Publicly available:** Snapshots, power spectra, bispectra, halo/voids catalogs…
- More than 3.3 trillion particles at a single redshift
- 450 Tb, 12M cpu hours

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• Non-linear effects	• Halos/galaxies $\rho_m = \rho_c + \rho_b \cancel{+ \rho_\nu}$ • Voids $\rho_m = \rho_c + \rho_b + \rho_\nu$
• Forecasts	Power spectrum + Halo mass function + Void size function $\longrightarrow$ 5σ with 1 (Gpc/h)^3

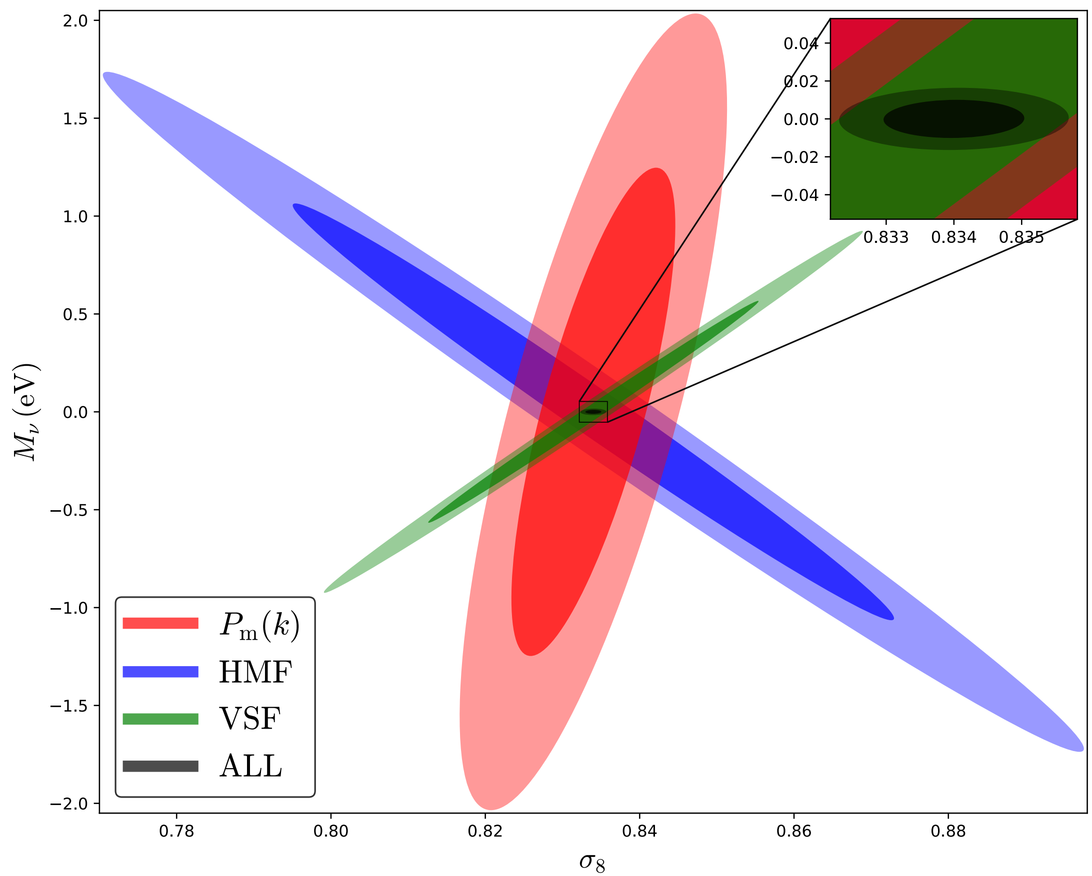
Future plans

TO DO

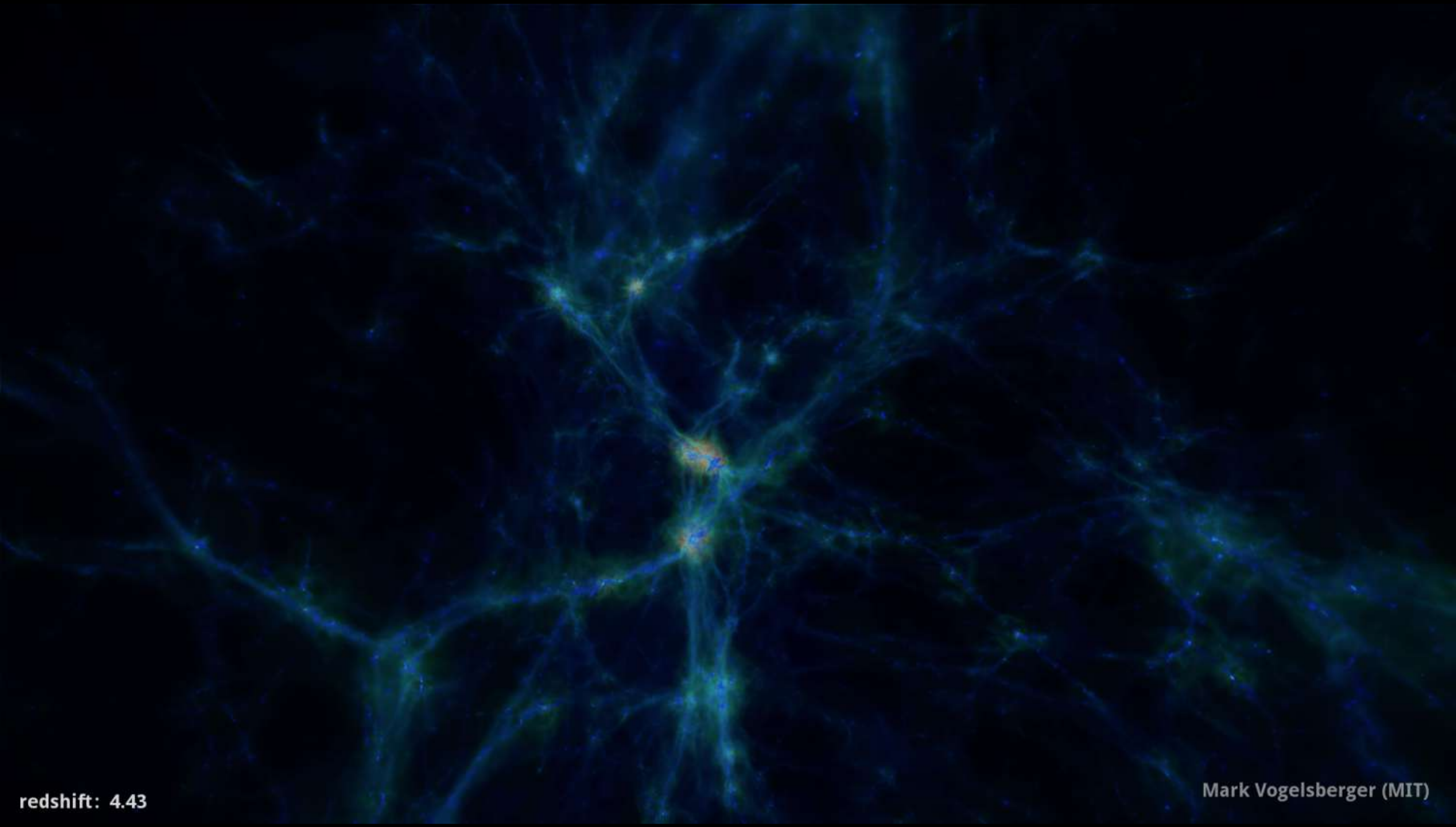
- Repeat with realistic galaxies in redshift-space
- Marginalize over bias (HOD), baryonic effects…
- Detectability for PFS, Euclid & DESI
- Full bispectrum, pdf…

Challenges

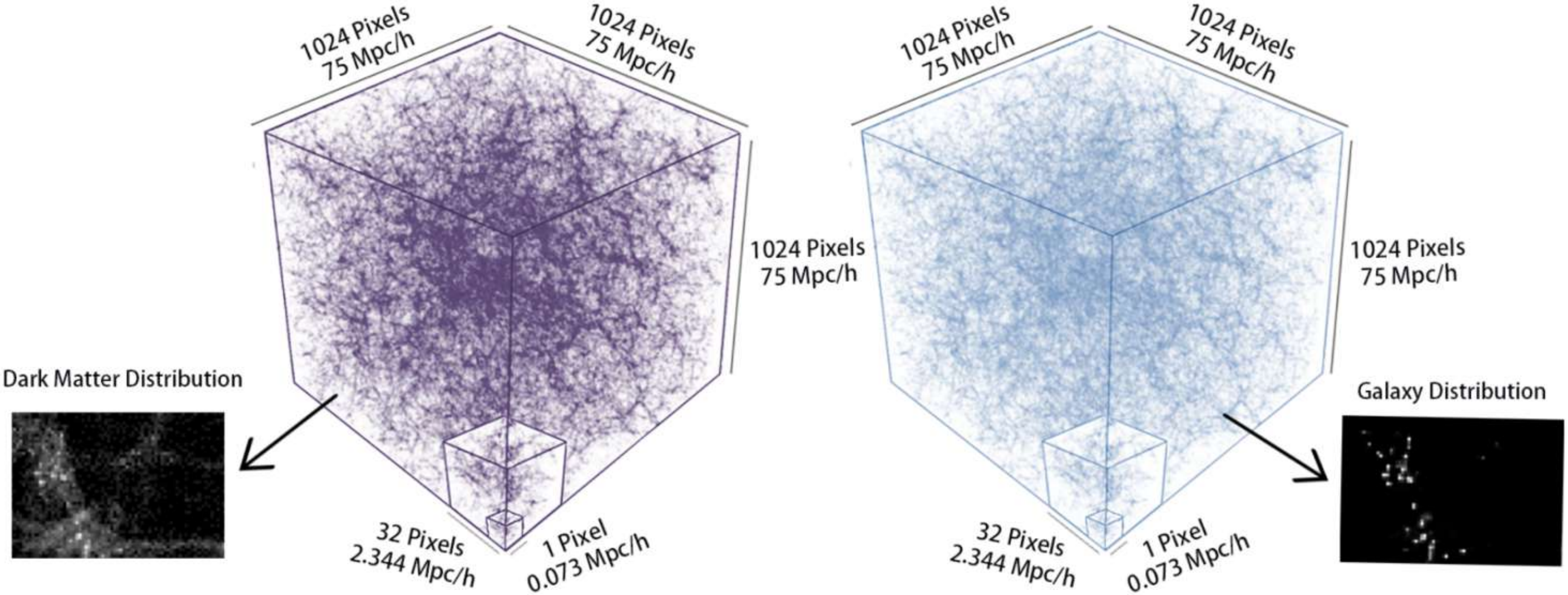
- Cluster counts
- Mass calibration with HSC / LSST
- Voids in redshift-space
- Baryonic effects



Future plans



From dark matter to galaxies



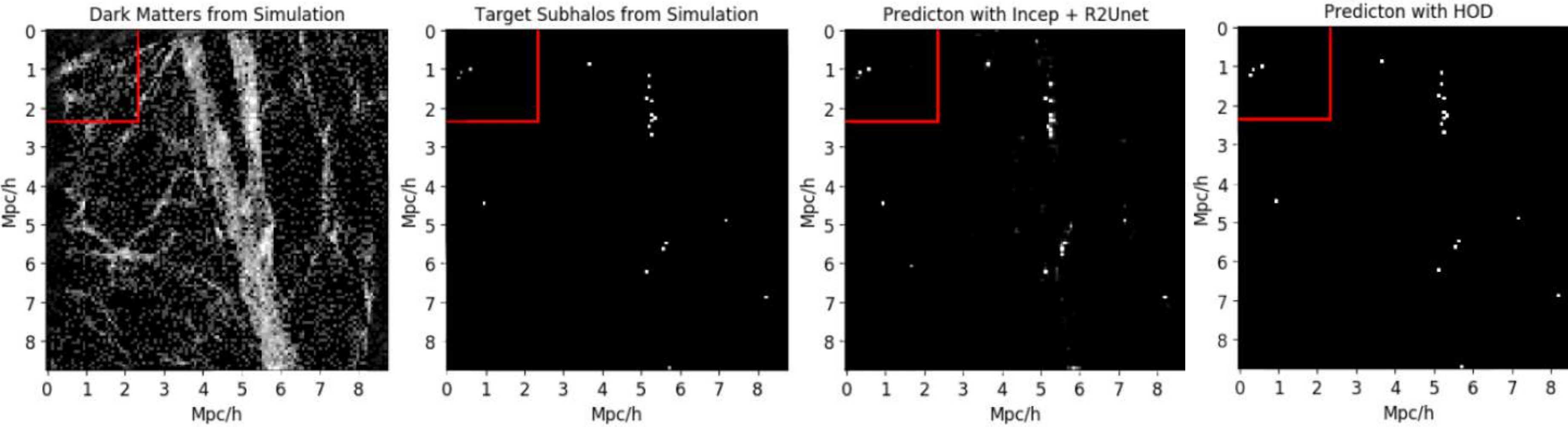
$$\delta_g(\vec{x}) = f(\delta_m(\vec{x}), \nabla_i \nabla_j \phi(\vec{x}), \dots)$$

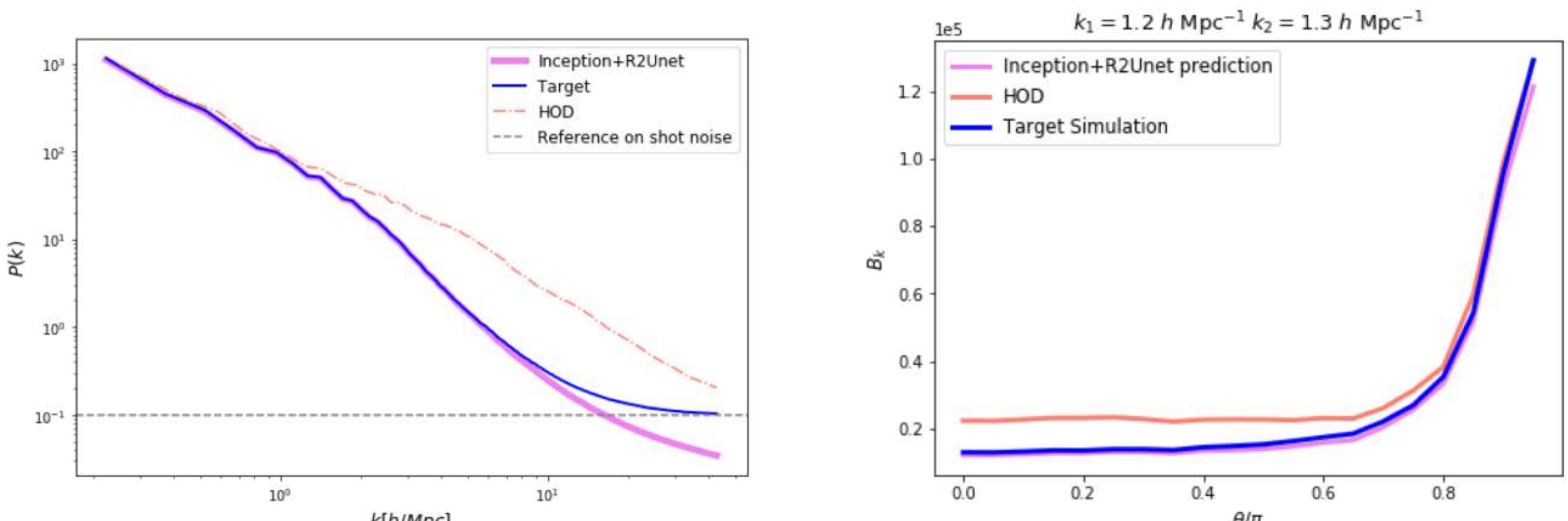
Very complicated function
Deep learning will find it

From dark matter to galaxies with neural networks

Zhang, Wang, Zhang, Sun, He, Contardo, **FVN**, Ho

Combine with Emulators:
Nishimichi, Takada et al. 2019





Simulating Multiscale Astrophysics to Understand Galaxies

- CCA-based multi-institutional collaboration bringing together expertise from accretion disk physics and star formation to galaxy evolution and cosmology

- Understand baryonic processes to the accuracy required to improve astrophysical constraints on cosmology and non-standard physics

- Maximize the science return of next generation cosmological experiments (e.g., Simons Observatory, WFIRST, Euclid, LSST)

SMAUG

Directors: Greg Bryan (CCA/Columbia), Rachel Somerville (CCA)
Planning Committee: Lars Hernquist (CfA, Harvard), Eve Ostriker (Princeton), Eliot Quataert (UC Berkeley), David Spergel (CCA), Volker Springel (MPA), Jim Stone (Princeton), Romain Teyssier (University of Zurich)

Working groups on:

- Black hole feeding and feedback
- Resolved star formation and feedback
- Cosmological tests
- Circumgalactic medium
- Cosmological simulations
- …

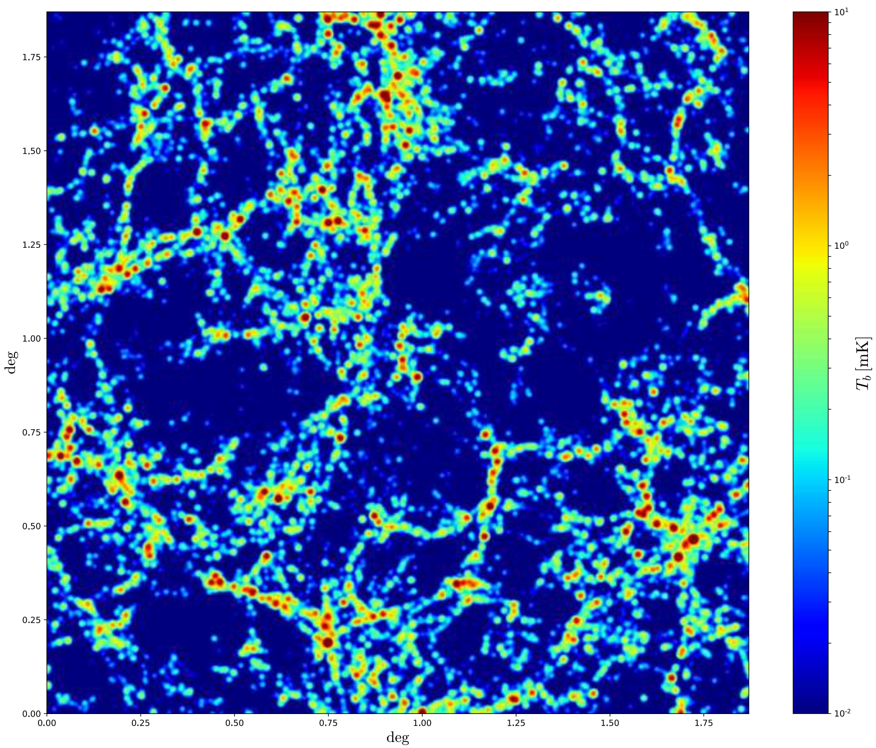
→ **I co-lead the Cosmological probes WG with Nick Battaglia (Cornell)**

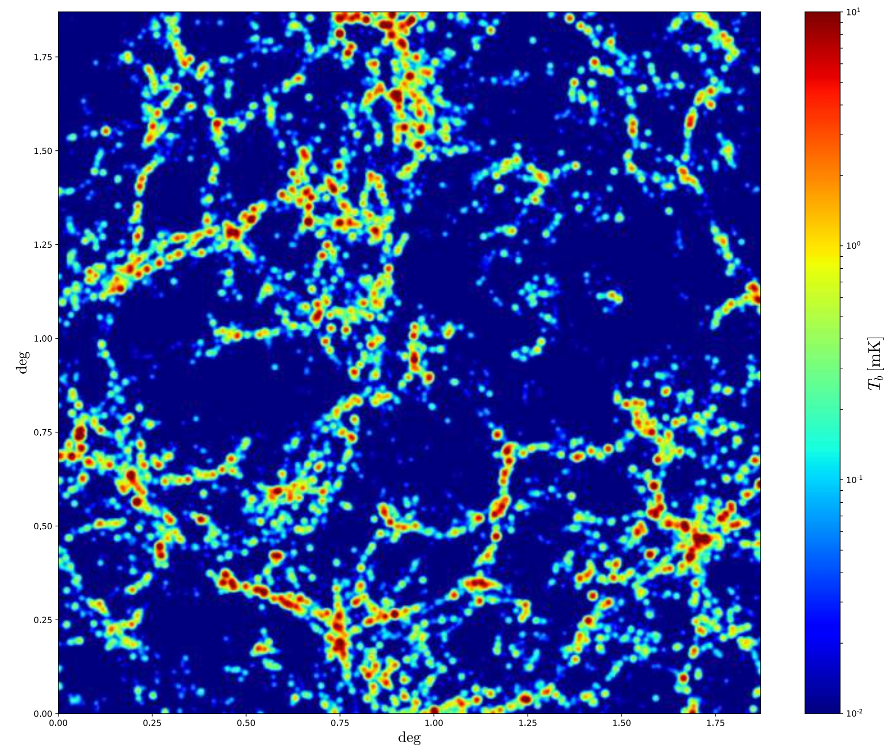
Future plans: 21cm

NAOJ

Cosmology and astrophysics with 21cm intensity mapping

1) Isolated line
2) Spectro-z survey
3) Very large volumes
4) Ground telescopes
5) New wavelength





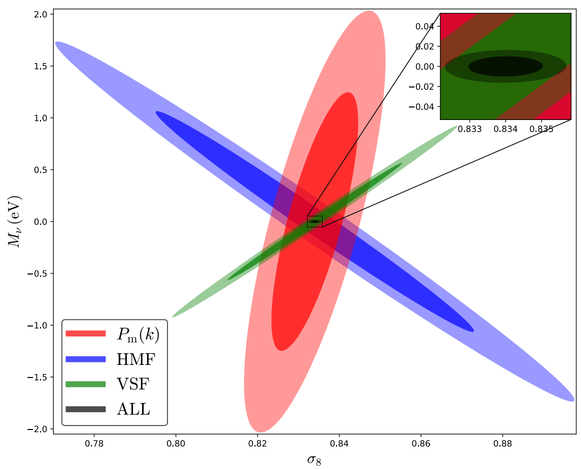
I co-lead the SKA cosmological simulations WG with David Alonso (Oxford)

Conclusions I

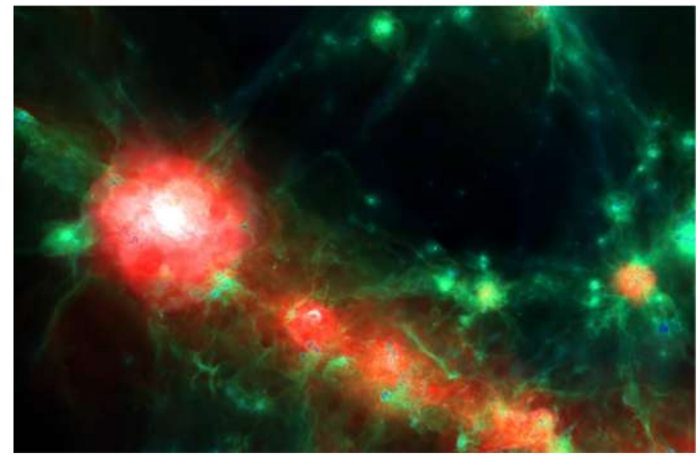
• Introduction	Neutrinos have mass! We want to know the neutrino masses, hierarchy, nature and properties to learn about fundamental physics
• Cosmic neutrino background	$\Omega_\nu \sim 0.3\%$ $\langle V_\nu \rangle \sim 3000\ \mathrm{km/s}$
• Linear effects	Neutrino masses leave signatures on cosmological observables Standard probes: 3σ - 4σ 1. Very accurate theory predictions: avoid biases 2. New and unique observables: robust 5σ detection
• Non-linear effects	• Halos/galaxies $\rho_m = \rho_c + \rho_b \cancel{+ \rho_\nu}$ • Voids $\rho_m = \rho_c + \rho_b + \rho_\nu$
• Forecasts	Power spectrum + Halo mass function + Void size function $\longrightarrow$ 5σ with 1 (Gpc/h)^3

Conclusions II

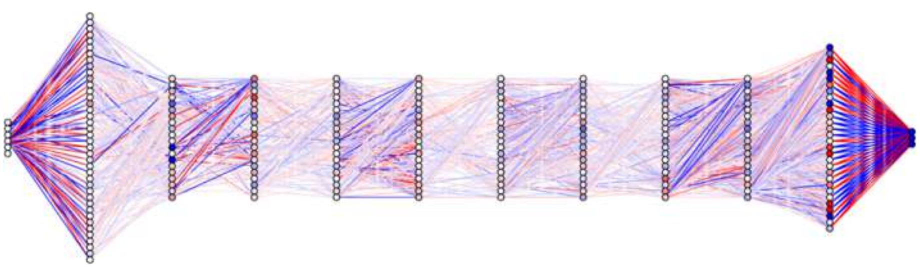
Large-Scale Structure



Numerical Simulations



Machine Learning



21cm Intensity Mapping