Current Status of the neutrino mass constraint from cosmological observations

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September 25th 2022

NuDM-200

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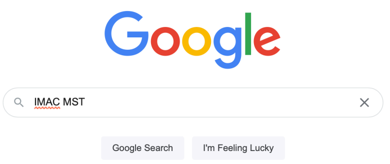
Keep your eyes on *IMAC at Missouri S&T*



- Since 2020: *Institute for Multi-messenger Astrophysics and Cosmology (IMAC)*

  at Rolla, MO, USA (100 miles west from St. Louis)

  - Dr. Marco Cavaglia: Gravitational Wave Physics with LIGO
  - Me: Cosmology with **Galaxy Surveys** (SDSS, **HETDEX**, **Subaru PFS** & Roman Space Telescope)

- Feel free to talk to me if you are interested in joining us!
  - Grad school application expected in Dec-Jan.
  - Future astrophysics faculty hiring.

Goals

- ➤1. **(biased) Review**
  - Clarify where we are & physics/assumptions
- ➤2. **New directions**
  - constraining neutrino masses from the Large-Scale Structure

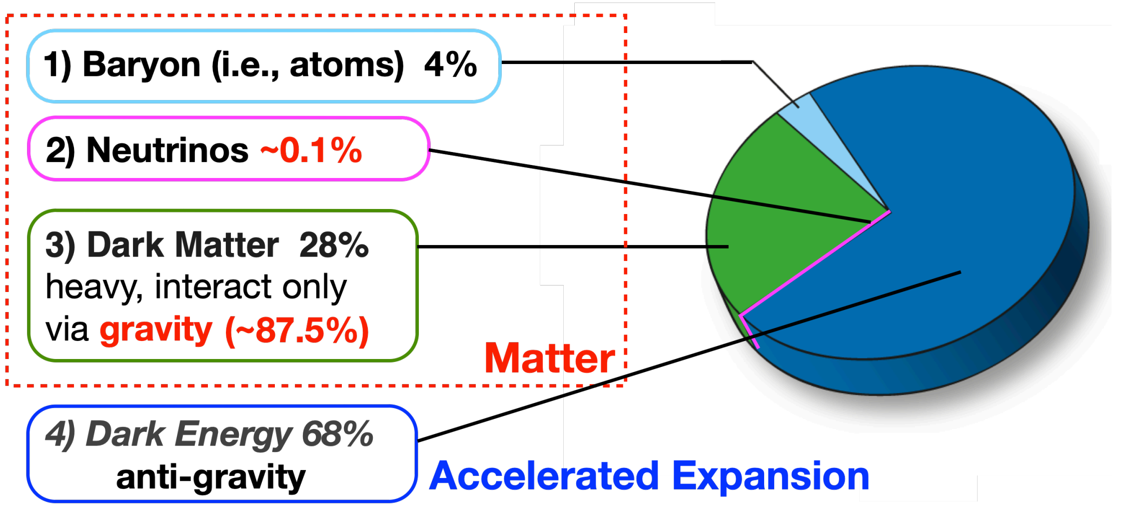
- ➤ Disclaimer:
  - I only discuss a standard scenario: fiducial flat ΛCDM + Neutrino Mass
  - 3 neutrino species, no self interaction etc. *see Olga's talk*

Why Neutrino Masses?

➤ **Lightest** elementary particles

- **massless** in Standard Model
- neutrino oscillations

→ evidence of **physics beyond SM**

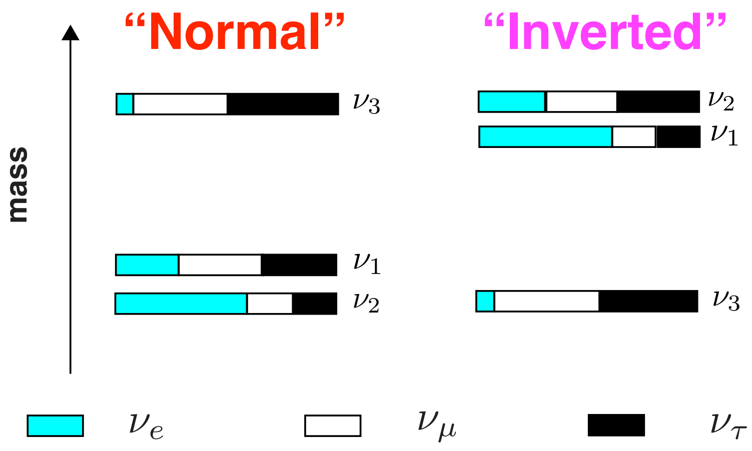


➤ Neutrino Masses

- neutrino oscillations: Δm^2_{ij}
- β decay e.g., KATRIN < 0.9 eV/c² arXiv:2103.04755
- first goal: **determine hierarchy**

minimum mass: *1eV/c² ~ 10^{-33}g!!

Normal 0.058eV vs **Inverted 0.10eV**



Why is Cosmology important?

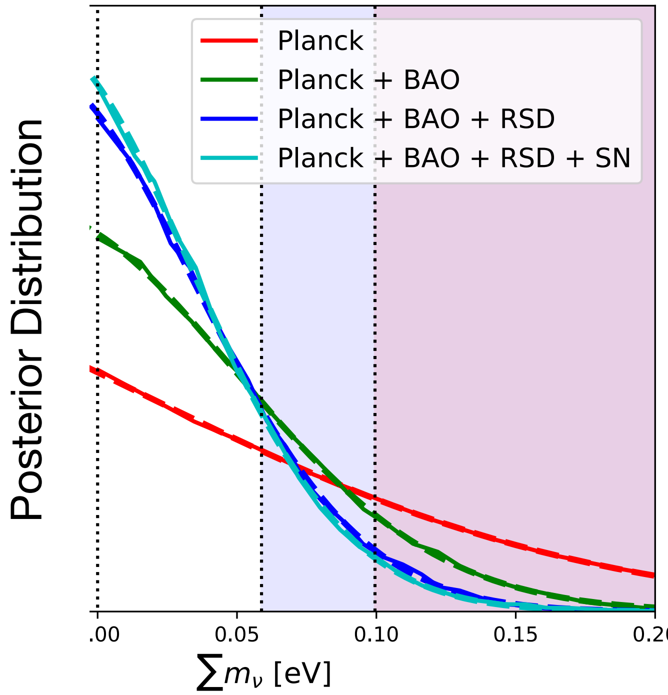
➤ 1) **Direct access to the mass eigenstates**

- though indirect measurements and only sensitive to the total sum.

➤ 2) **Powerful** (c.f. terrestrial experiments, < 3 eV)

- state of the art $\sum m_\nu \lesssim 0.1\,\mathrm{eV}\;(95\%\,\mathrm{C.L.})$
- model-dependent

eBOSS collaboration (2020)
see also Philcox+(2020)



➤ 3) **Guaranteed*** science in Cosmological Surveys

- CMB lensing
- Galaxy Surveys for BAOs

e.g., PFS will achieve σ(m_ν) = 0.02eV

Cosmology measures the mass via '*Gravity*'

- Friedmann equation $$H^2 = H_0^2 \left\{\Omega_\Lambda + \Omega_{\rm m}(1+z)^3 + \Omega_r(1+z)^4\right\}$$

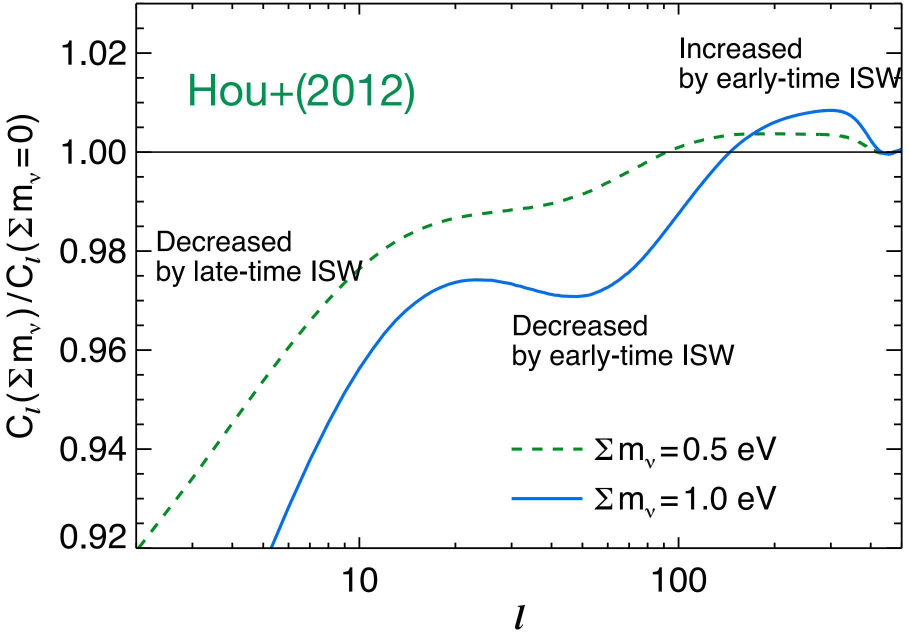
  - At the level of background, expansion history through redshift vs distance.

- Massless → Massive neutrinos
  - become non-relativistic at late times $$\Omega_\nu = 0.0217 \left(\frac{\sum m_\nu}{1\,\mathrm{eV}}\right)\left(\frac{0.7}{h}\right)^2$$
  - becomes non-relativistic at $m_{\nu,i} = \langle E_{\nu,i}\rangle$ $$1 + z_{\rm nr,i} = 1890\left(\frac{m_{\nu,i}}{1\,\mathrm{eV}}\right)$$
  - effective number of neutrinos (c.f., standard = 3.046) $$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

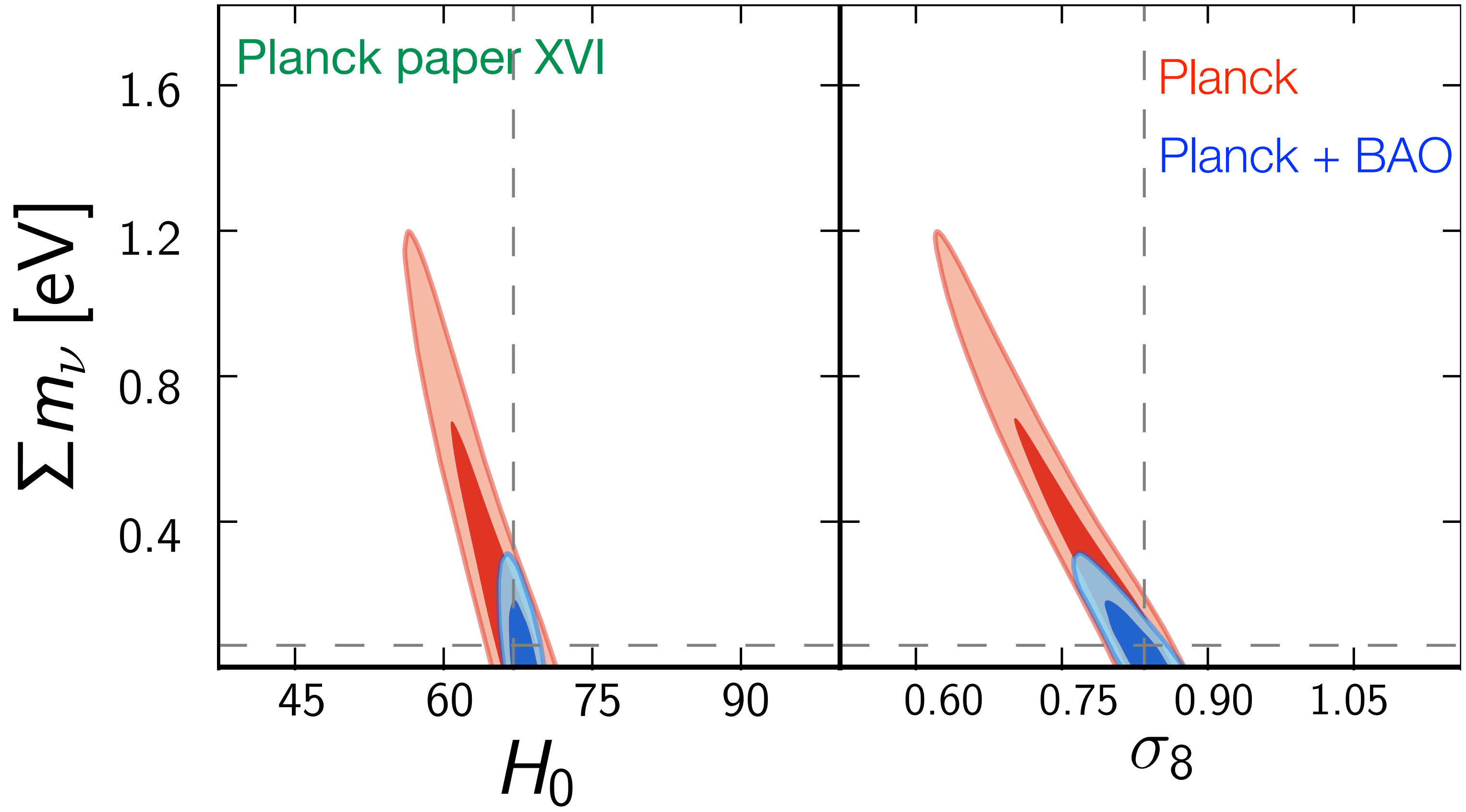
Role of Cosmic Microwave Background

- ➤ increasing mass means increasing matter at decoupling
  - relativistic neutrino's energy at decoupling $E_i \sim 0.58\,\mathrm{eV}$
  - in order to be non-relativistic at that time $\sum m_\nu > 0.58 \times 3 = 1.74\,\mathrm{eV}$
  - early ISW leads to up to ~1.5eV Ichikawa, Fukugida, Kawasaki (2005)

- ➤ A few remarks
  - CMB plays an important role to determine other cosmological parameters
  - Other information
    - phase shift in high ell
    - CMB lensing is a key to go below 1eV.



How to go beyond CMB?

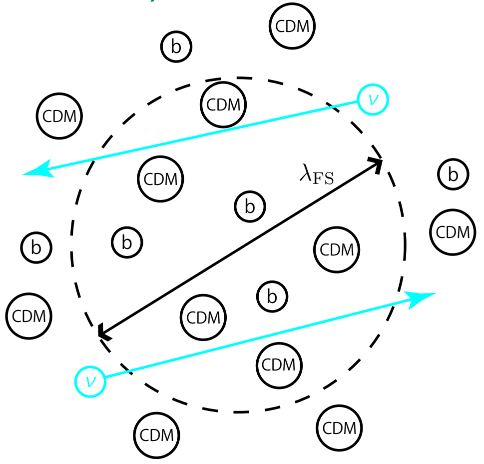


- ➤ Low redshift distance and/or the amplitude of LSS
- ➤ Neutrino mass **cannot** help alleviate the Hubble tension
- ➤ CMB constraint is limited by the optical depth Boyle & Komatsu (2018)

Neutrinos suppress the growth of LSS

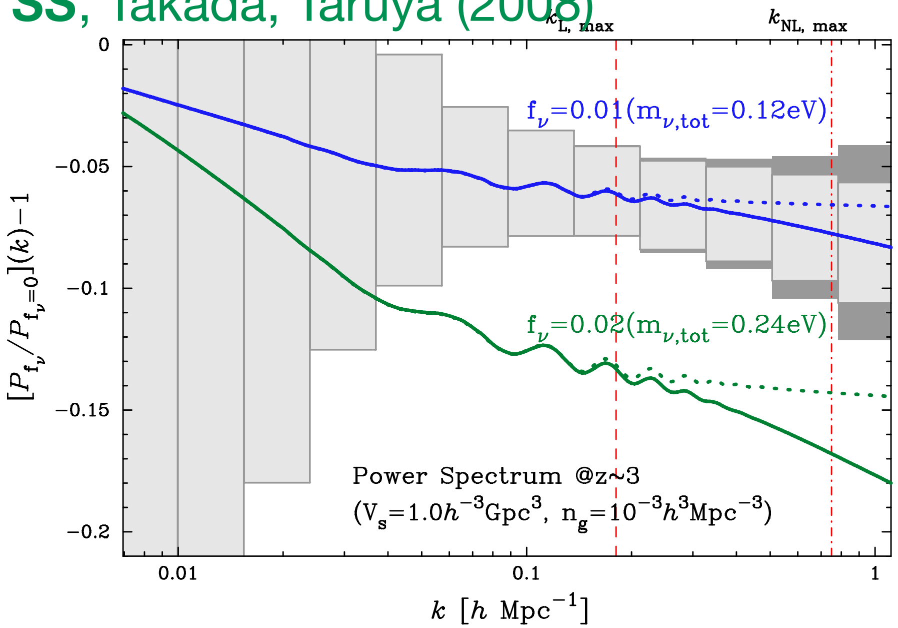
➤ Neutrino free-steaming (Jeans) scale e.g., Lesgourgues & Pastor (2006, 2013)

$$k_{\mathrm{FS},i} \equiv \sqrt{\frac{3}{2}} \frac{H(z)}{(1+z)\sigma_{v,\nu i}}$$
$$\simeq 0.0676 \left(\frac{m_{\nu,i}}{0.1\ \mathrm{eV}}\right) \frac{\sqrt{\Omega_{w0}(1+z)^{-3(1+w_0)} + \Omega_{\mathrm{m0}}(1+z)^3}}{(1+z)^2}\ h\mathrm{Mpc}^{-1}$$



➤ Suppress the growth of LSS smaller than the FS scale

SS, Takada, Taruya (2008)



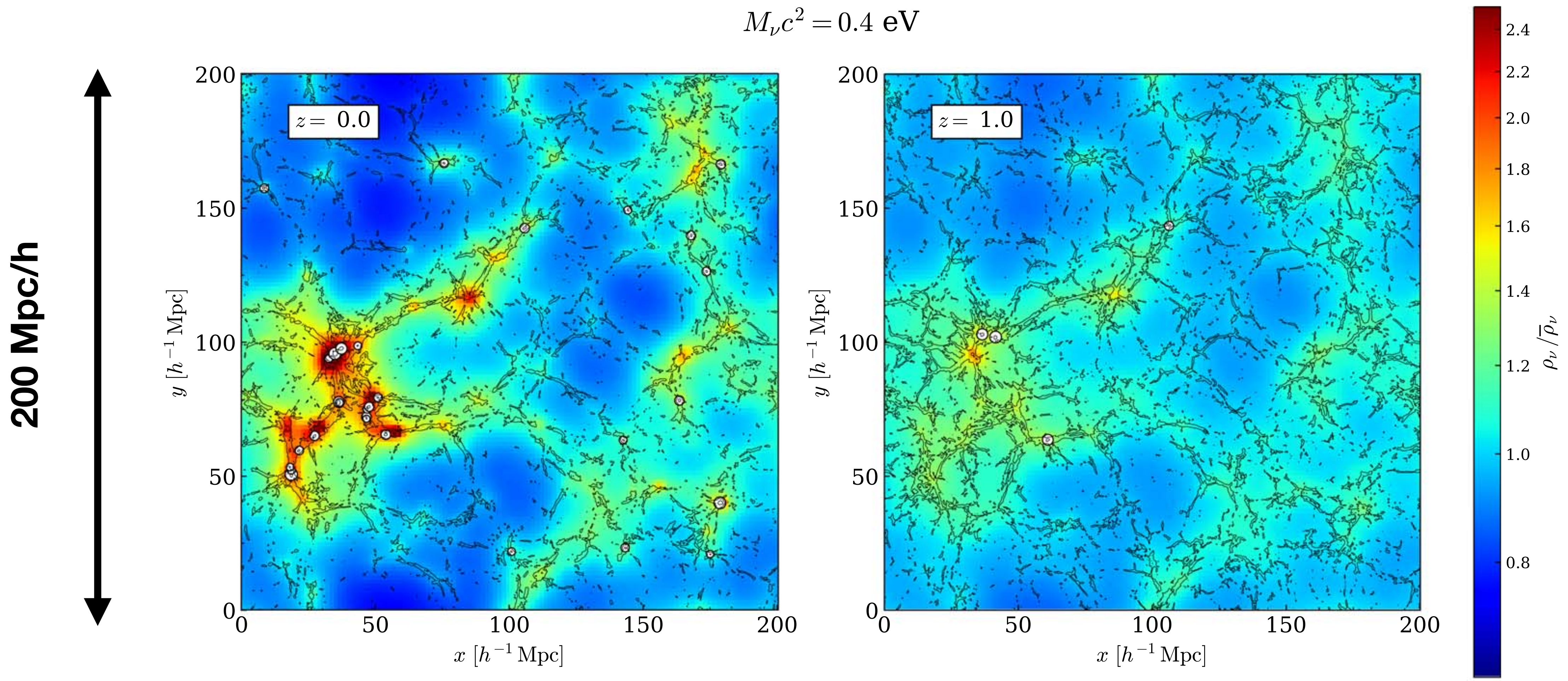
- Power spectrum (FT of the correlation function)

$$P_{\mathrm{m}}(k,z) = \langle|\delta_{\mathrm{m}}(k,z)|^2\rangle$$

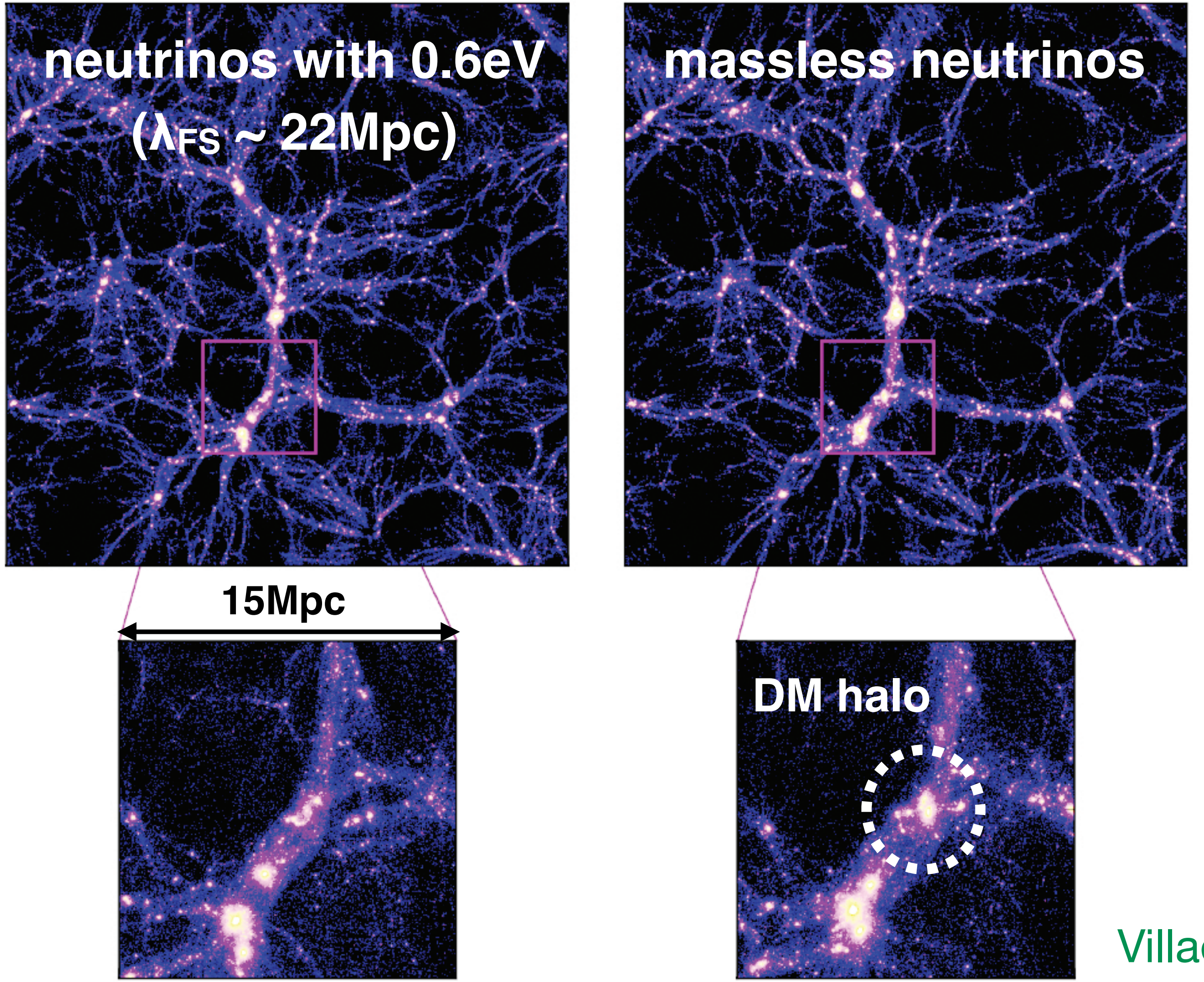
- a few % level suppression around BAO scales.
- smaller scale (high k): linear theory is invalid.

The First-ever Vlasov simulation with Neutrinos

Yoshikawa, Tanaka, Yoshida, ***SS*** (2020)



Neutrinos suppress the growth of LSS

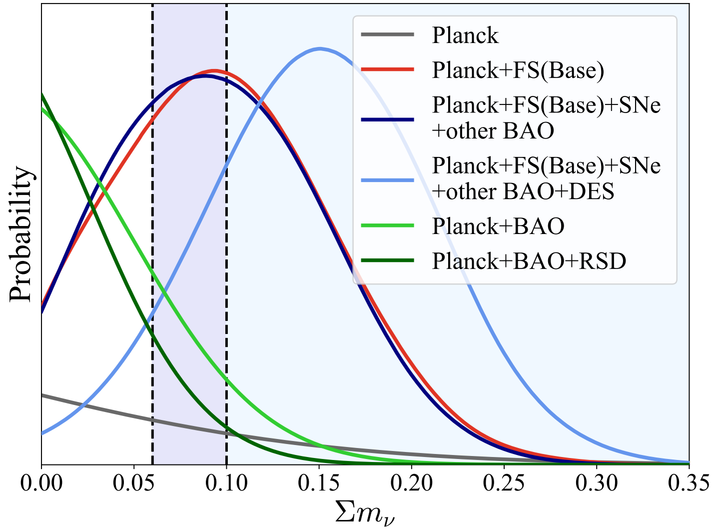


Villaescusa-Navarro (2015)

State of the art: from Galaxy P(k) [Actual Data]

Zhang, ***SS***+ (in prep)

Posterior Distribution



➤ Fit the Perturbation Theory to nonlinear P(k) in the BOSS DR12 galaxies.

See also ***SS***+(2011), Zhao, ***SS***+(2013), Philcox+(2019), Ivanov (2020).

➤ Hint of the discrepancy between

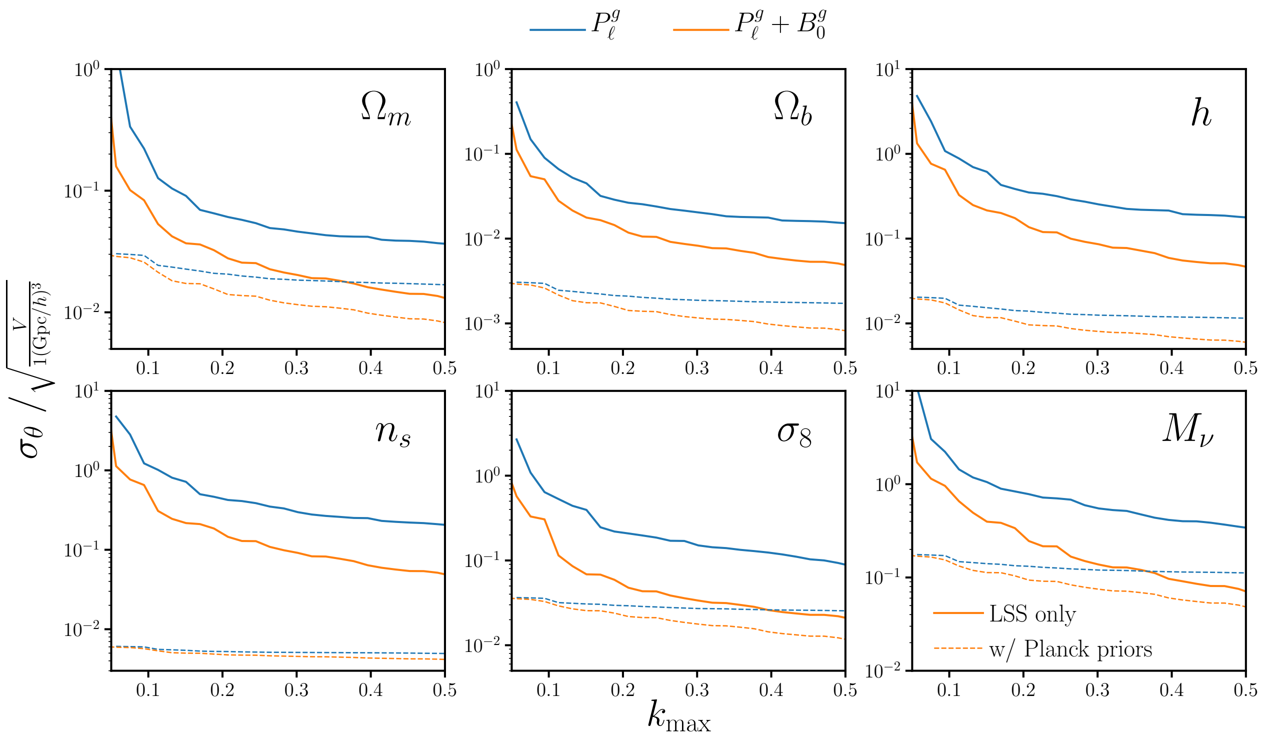
- the BAO scale (distance) &
- the broadband shape?

➤ Planck + FS: **0.10+-0.05** eV

What's next? The Galaxy Bispectrum? [Sim]

- ➤ The galaxy bispectrum, directly measured from 'mock' simulations improves by a factor of two, even after marginalizing over galaxy parameters.

Hahn & Villaescusa-Navarro (2021)

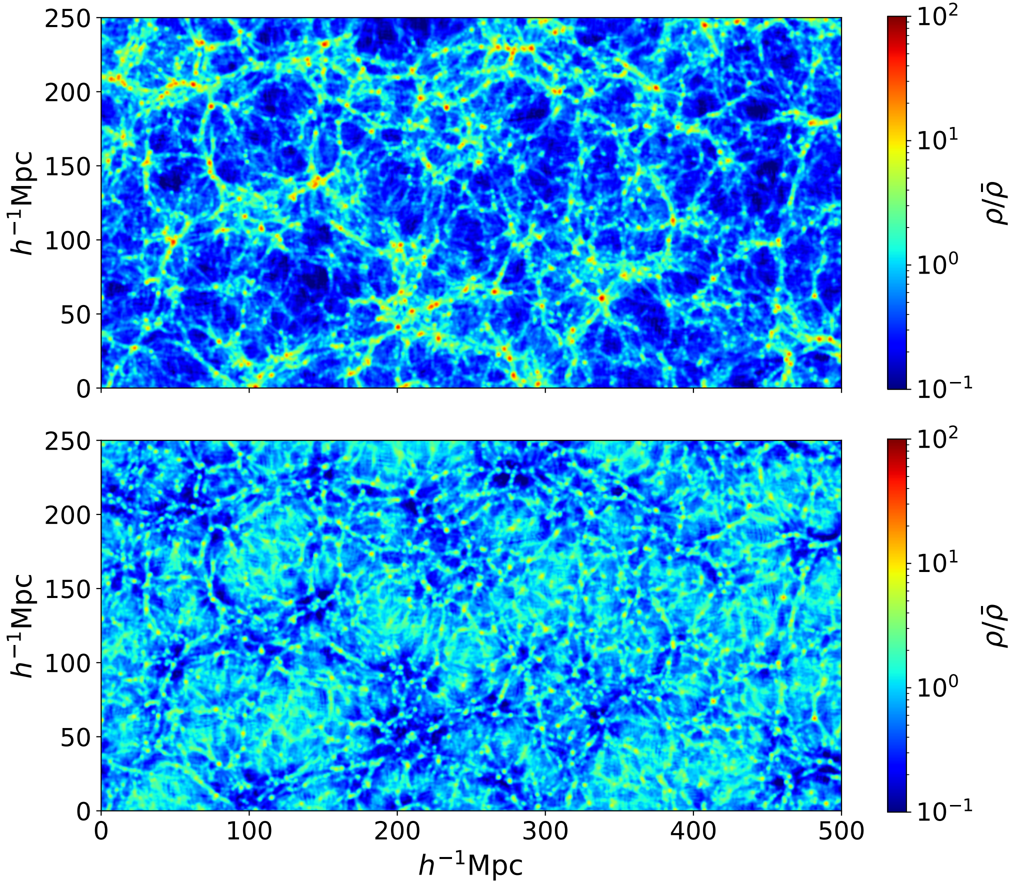


- ➤ Open Questions
  - Same is true for higher redshift?
  - Same is true for other types of galaxies?
  - More information from the anisotropic bispectrum?

c.f. Sugiyama, ***SS***, Beutler & Seo (2019, 2020, 2021)

What's next? The Marked Statistics? [Sim]

Massara+(2021)



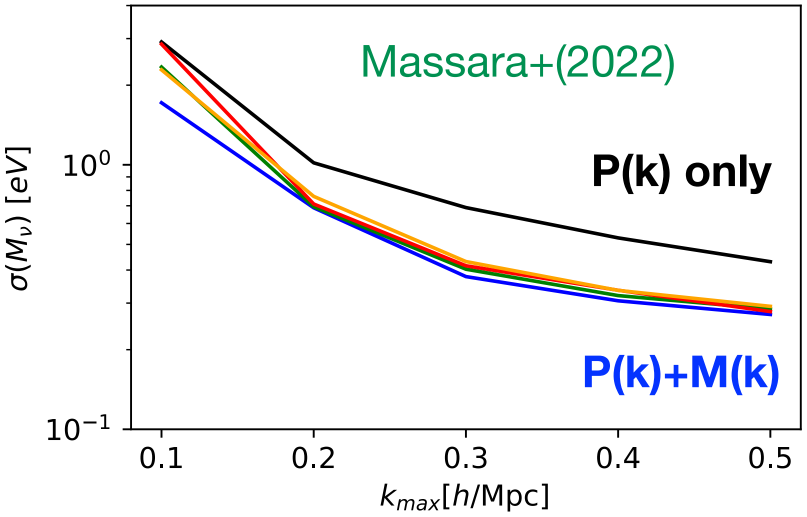
➤ The two-point correlation function weighted by the mark:

$$m(\vec{x}; R, p, \delta_s) = \left[\frac{1+\delta_s}{1+\delta_s+\delta_R(\vec{x})}\right]^p$$

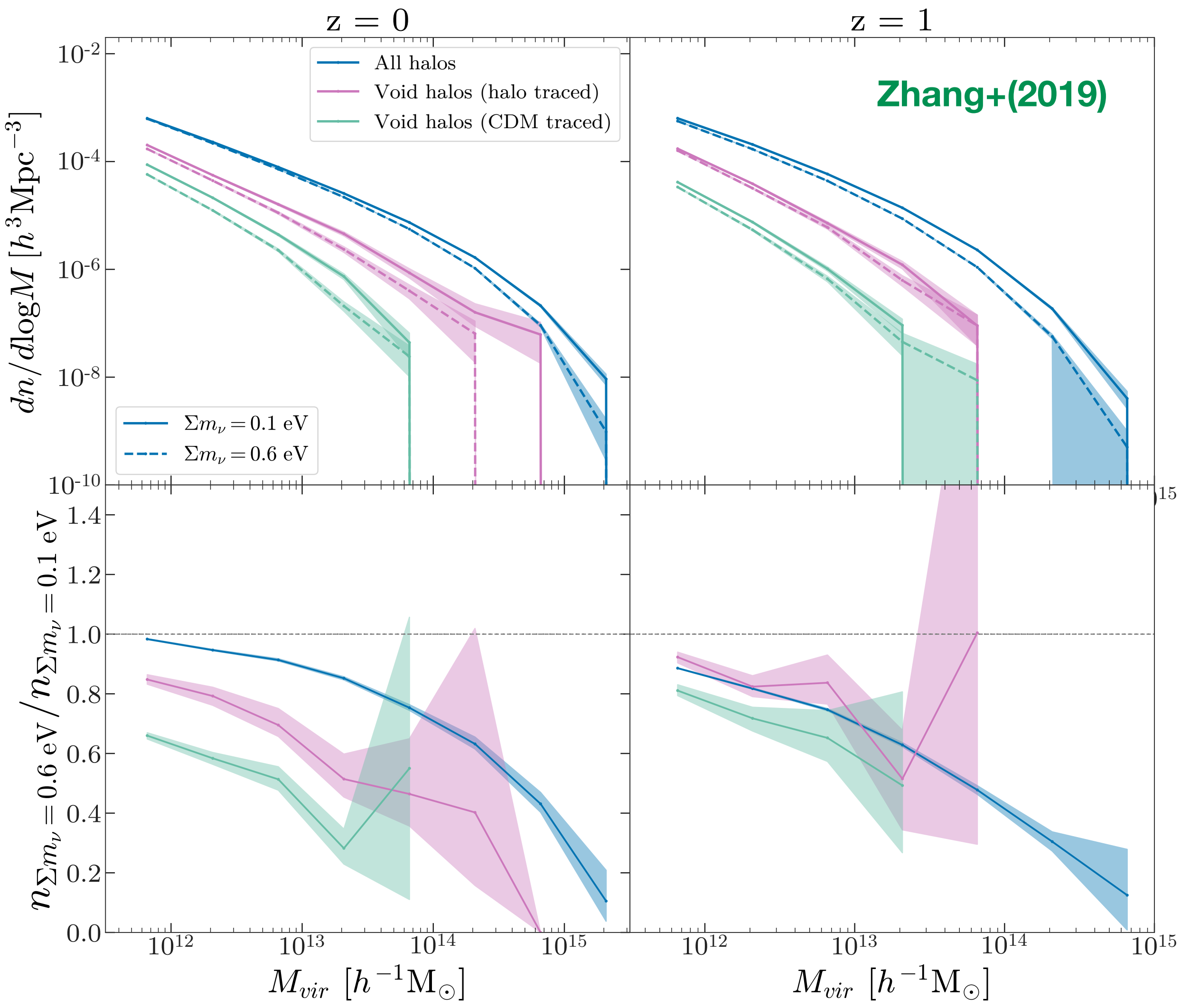
➤ p>0 puts more weight in **low density** region.

➤ Effectively include higher-order information.

Philcox+(2020)



What's next? The Void Statistics? [Sim]



- Neutrinos affect halo formation history inside/outside voids.
- Detailed forecast not provided
  - looks the biggest neutrino effect I have ever seen!

Summary

➤ Now entering a new era: LSS competitive with CMB.

- Planck + BOSS/eBOSS already reaching **0.1eV** in ΛCDM.

➤ More interestingly, we do not fully unlock the potential in LSS.

- have been focusing on the two-point statistics around the BAO scales.
- other LSS observables: Weak lensing < 0.13 eV DES collaboration (2021)

  Lyα forest < 0.12 eV Palanque-Delabrouille et al. (2015)

- recent studies: low-density region, higher-order statistics

  → **Simulations** will be a key & Many Surveys (DESI,PFS,Euclid,Roman)!

Problems in *N*-body with Neutrinos

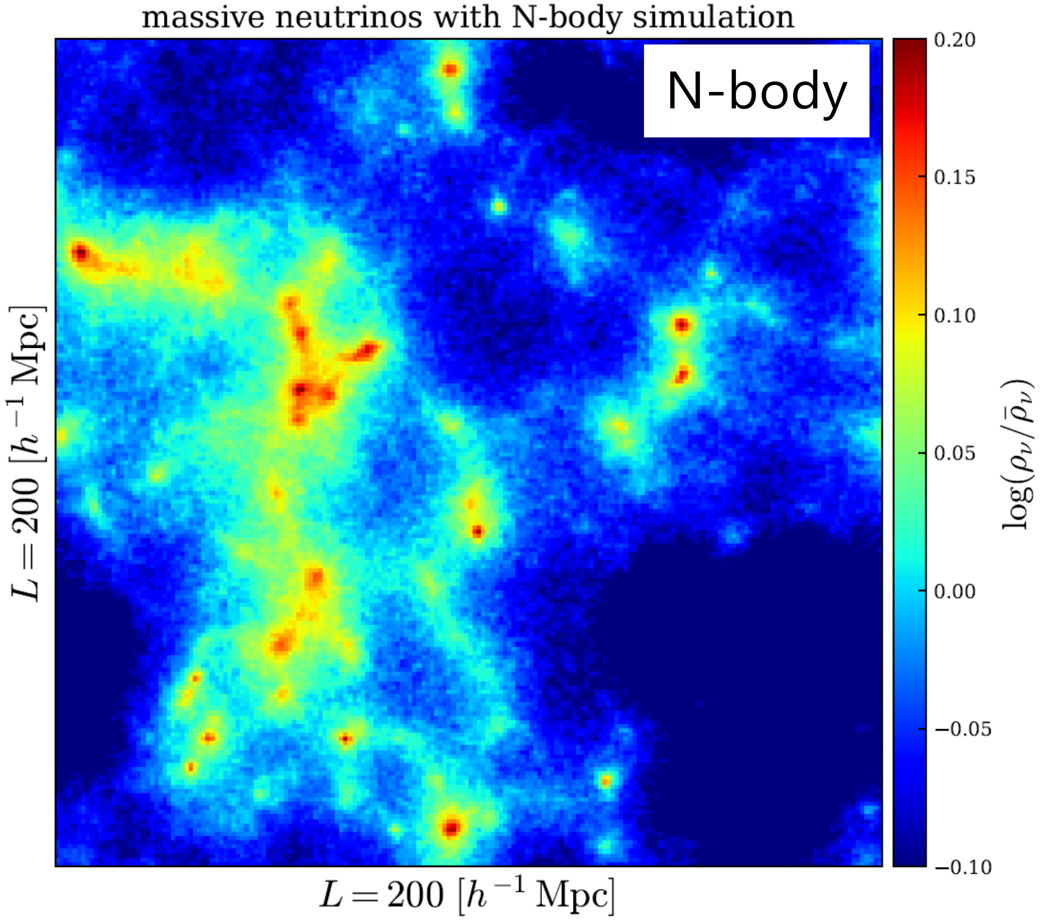
- An accurate simulation is a key!
- Structure formation simulation with massive neutrinos.
  - Hot dark matter scenario back in 80-90s.
  - Realistic ***N*-body** simulations with light neutrinos since 2010.

Brandbyge+(2010), Bird+(2012), Vilaescusa-Navarro+(2014,2020), Inman+(2015, 2017) etc…

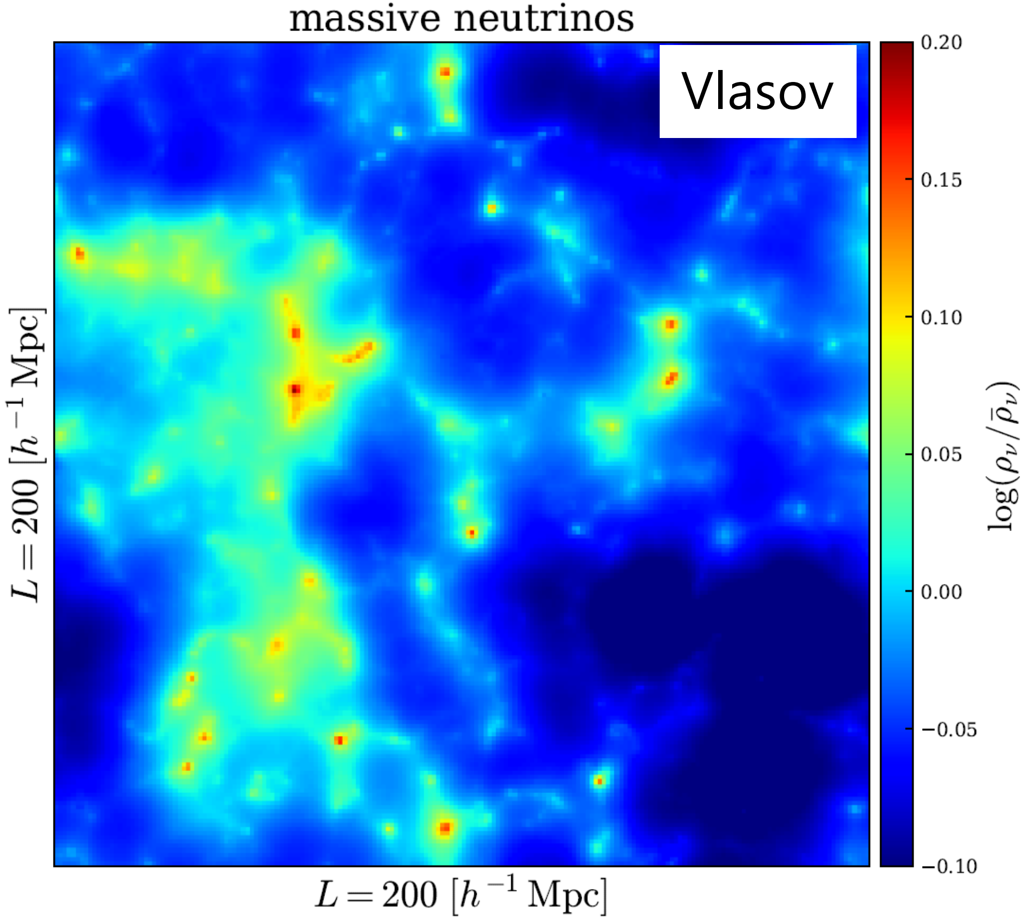
- difference b/w CDM & neutrinos = initial condition in thermal velocity
- typically $N_\nu = 8N_{CDM}$, sampling only 8 points in velocity space.

➜ spurious behavior due to the shot noise at small scales Banerjee & Dalal (2016)

N-body vs Vlasov



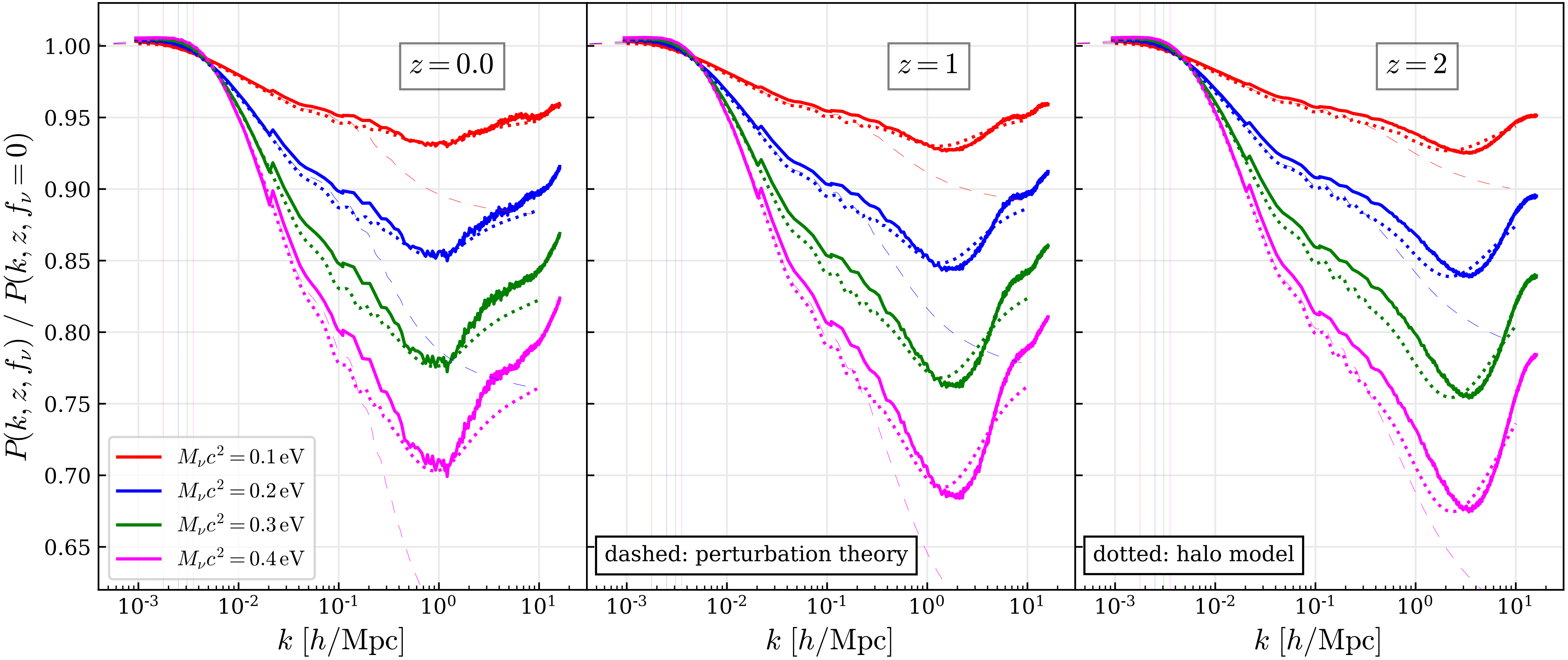
N-body simultion with $\boldsymbol{N}$=**1536**^{3}



Vlasov simulation with N_x=**192**^{3} and N_v=**64**^{3}

Neutrino suppression the matter P(k)

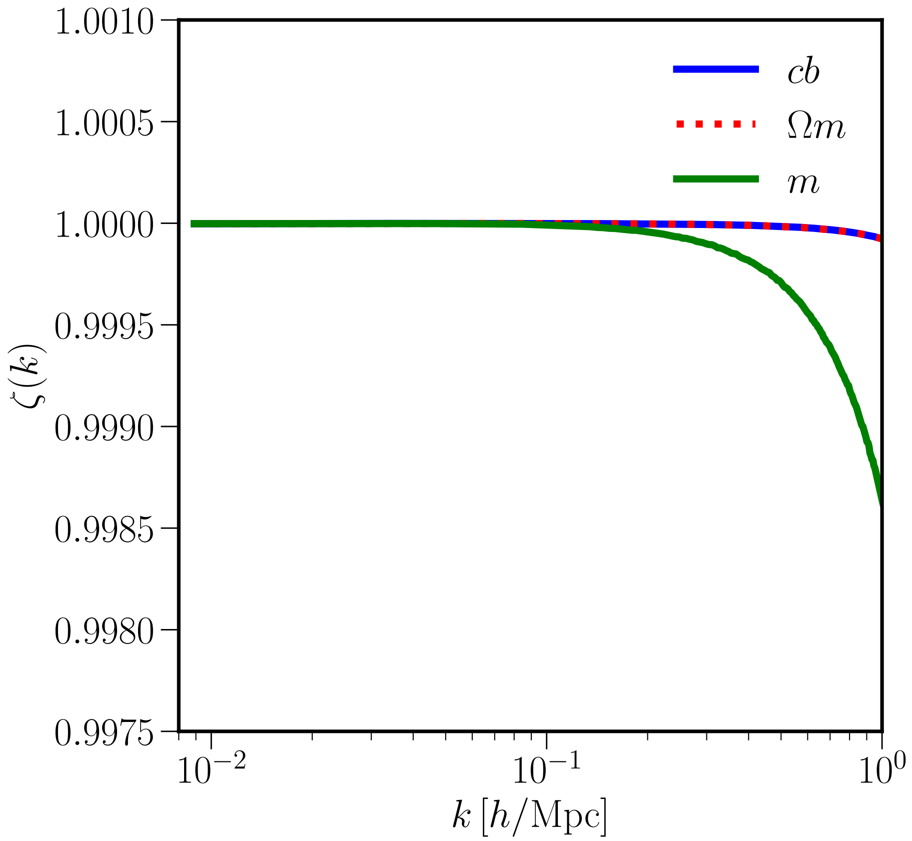
Yoshikawa, Tanaka, Yoshida, ***SS*** (2020)



➤ Consistent with previous work ***SS***, Takada, Taruya (2008, 2009)

Information in nonlinear vs linear?

Bayer, Banerjee, Seljak (2021)



- ➤ Two sets of simulation w/ and w/o neutrinos which gives the exactly same matter linear P(k) at z=0.
- ➤ No difference in the two simulations.
  → implies that max. information on neutrino masses is equivalent to that of linear theory.
- ➤ To go beyond the linear information
  - 3d matter field; not observable.
  - Redshift Space Distortion, i.e., the velocity field.
  - combining different redshift.