Weighing Neutrinos using Cosmology

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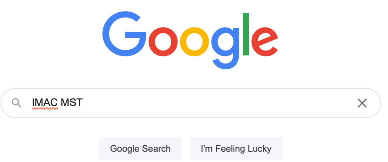
Particle Physics and Cosmology 2022

@Washington University in St. Louis

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



➤ Since 2020: *Institute for Multi-messenger Astrophysics and Cosmology (IMAC)* at Rolla (100 miles west)

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

➤ You should **NOT** miss the contributed talks from two IMAC members **tomorrow**.

Jordan Stevens

Undergraduate

"Early Dark Energy & Hubble tension"

3:45pm Tuesday

Hasti Khoraminezhad

Postdoc

"Baryon-CDM perturbation"

4:30pm Tuesday

Goals

➤1. **(biased) Review**

- Clarify where we are & physics/assumptions

➤2. **New directions**

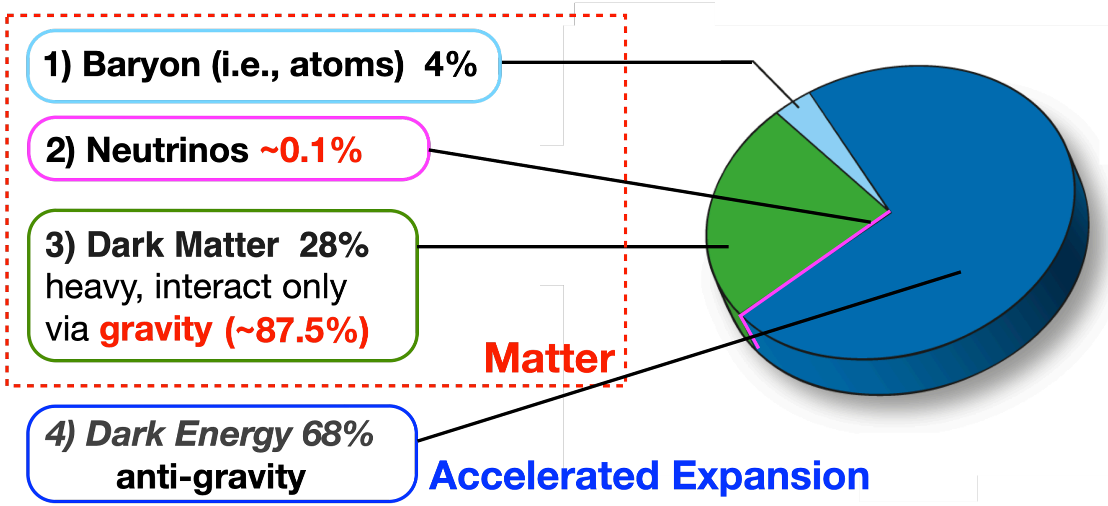
- constraining neutrino masses from the Large-Scale Structure

➤ Disclaimer:

- I only discuss a standard scenario: fiducial flat ΛCDM + Neutrino Mass
- 3 neutrino species, no self interaction etc.

Why Neutrino Masses?

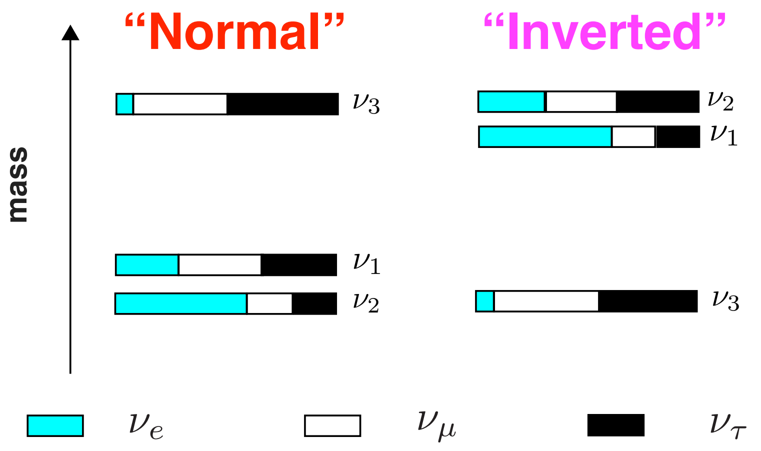
- **Lightest** elementary particles
  - **massless** in Standard Model
  - neutrino oscillations
  - → evidence of **physics beyond SM**



- Neutrino Masses
  - neutrino oscillations: Δm_{ij}^2
  - 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?

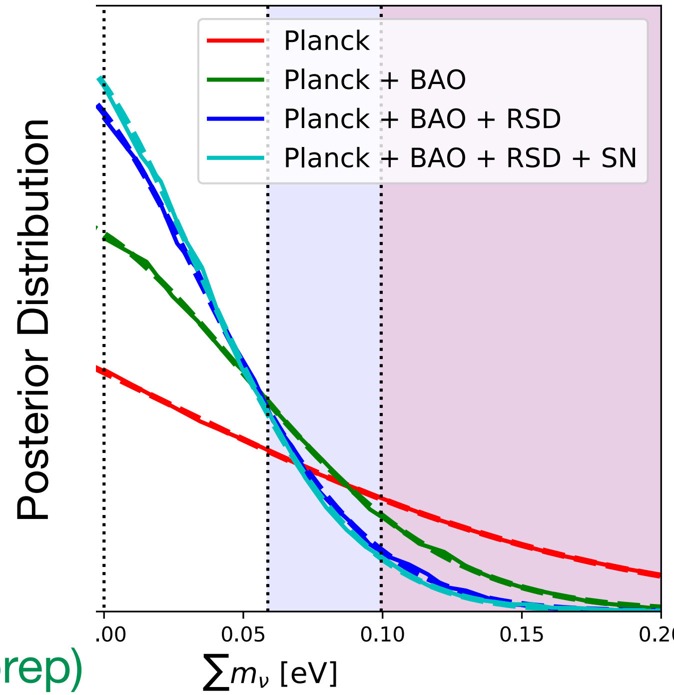
➤ 1) **Direct access to the mass eigenstates**

- 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 (c.f. Stagg's talk)
- Galaxy Surveys for BAOs

e.g., PFS will achieve σ(m_ν) = 0.02eV (Makiya, ***SS***+, in prep)

Cosmology measures the mass via '*Gravity*'

- Friedmann equation

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

  - 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 $m_{\nu,i} = \langle E_{\nu,i}\rangle$

$$1 + z_{\mathrm{nr,i}} = 1890 \left(\frac{m_{\nu,i}}{1\,\mathrm{eV}}\right)$$

  - effective number of neutrinos
    (c.f., standard = 3.046)

$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_\mathrm{eff}\right]\rho_\gamma$$

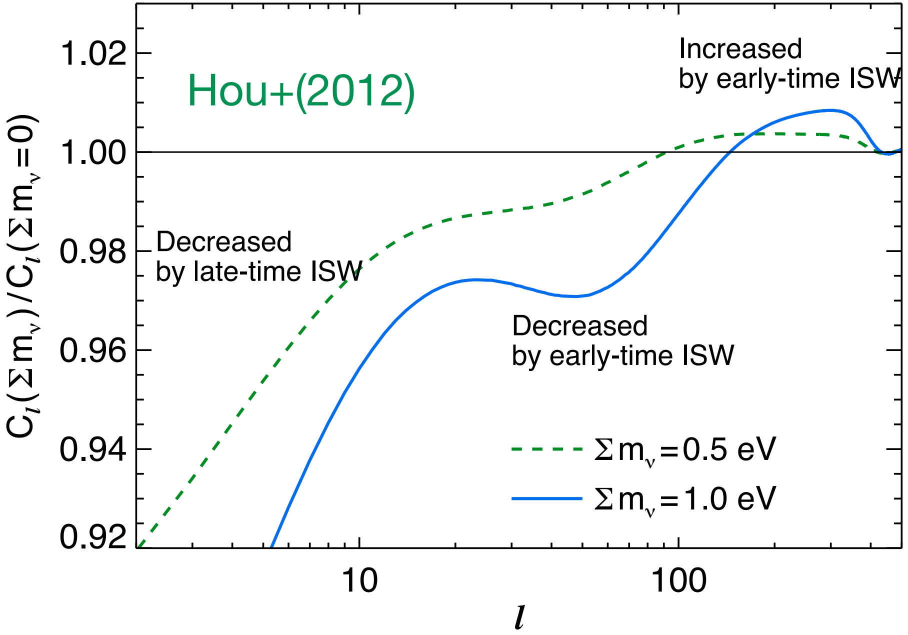
Role of Cosmic Microwave Background

➤ increasing mass means increasing matter at decoupling

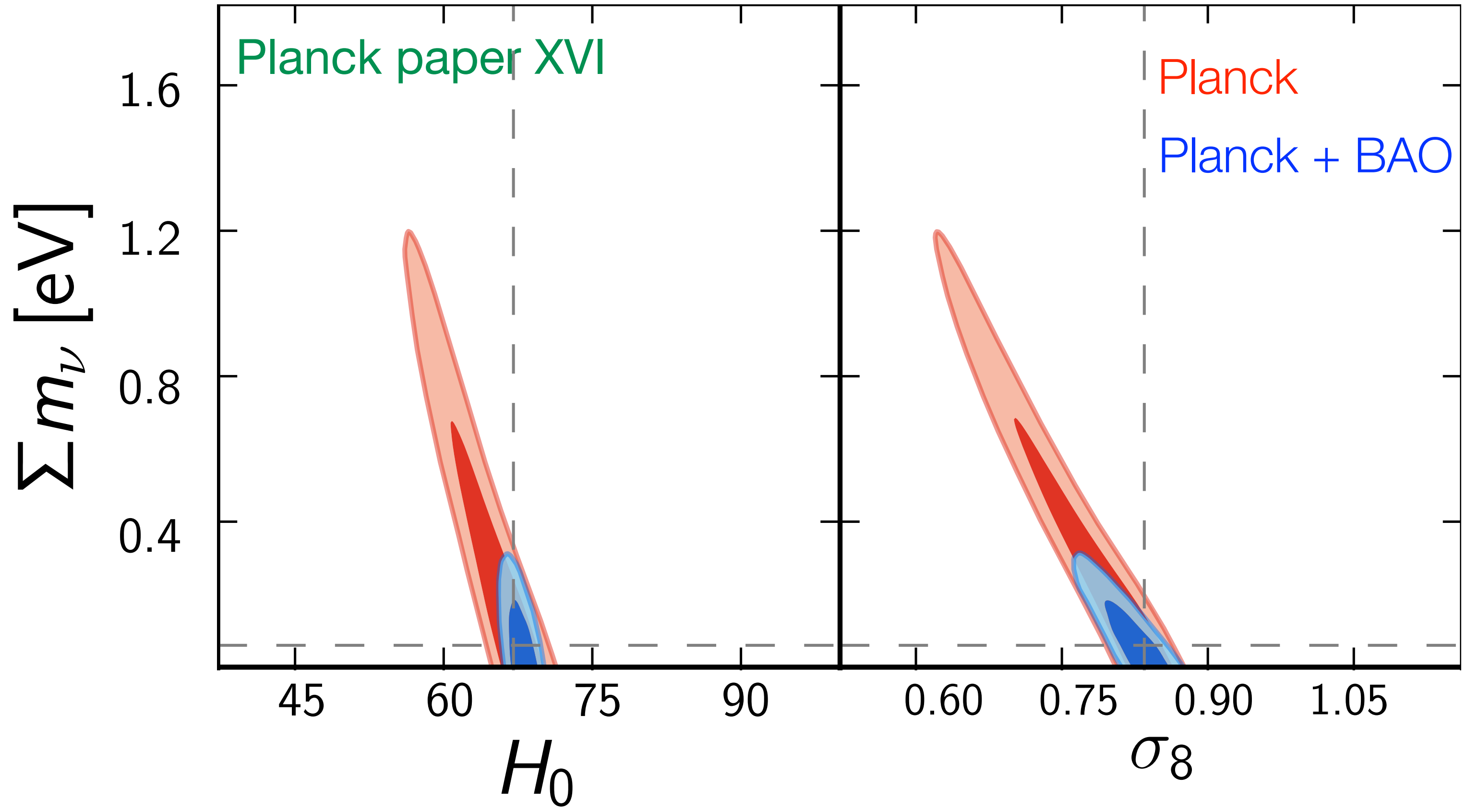
- relativistic neutrino's energy at decoupling $E_i \sim 0.58\,\mathrm{eV}$
- in order to be non-relativistic at that time $\sum m_\nu > 0.58 \times 3 = 1.74\,\mathrm{eV}$
- early ISW leads to up to ~1.5eV Ichikawa, Fukugida, Kawasaki (2005)

➤ 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?

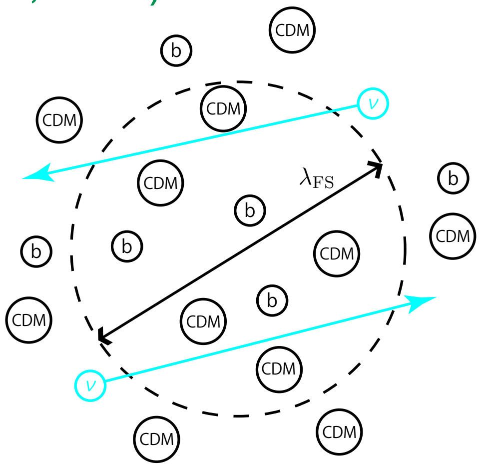


- ➤ Low redshift distance and/or the amplitude of LSS
- ➤ Neutrino mass **cannot** help alleviate the Hubble tension (cf. Riess's talk)
- ➤ CMB constraint is limited by the optical depth Boyle & Komatsu (2018)

Neutrinos suppress the growth of LSS

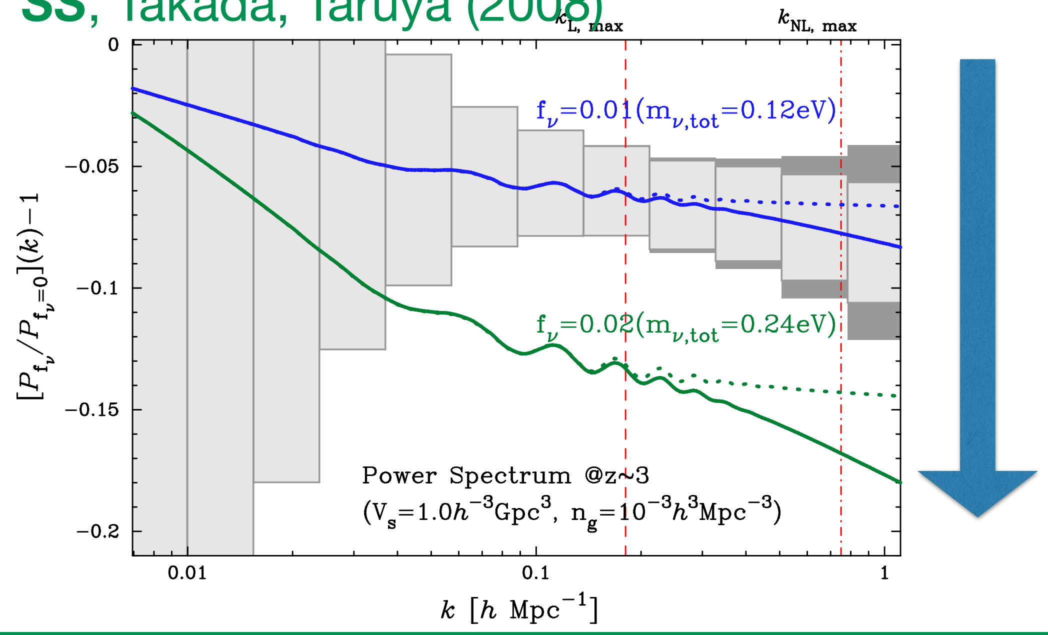
➤ Neutrino free-steaming (Jeans) scale e.g., Lesgourgues & Pastor (2006, 2013)

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



➤ Suppress the growth of LSS smaller than the FS scale

SS, Takada, Taruya (2008)



- Power spectrum (FT of the correlation function)

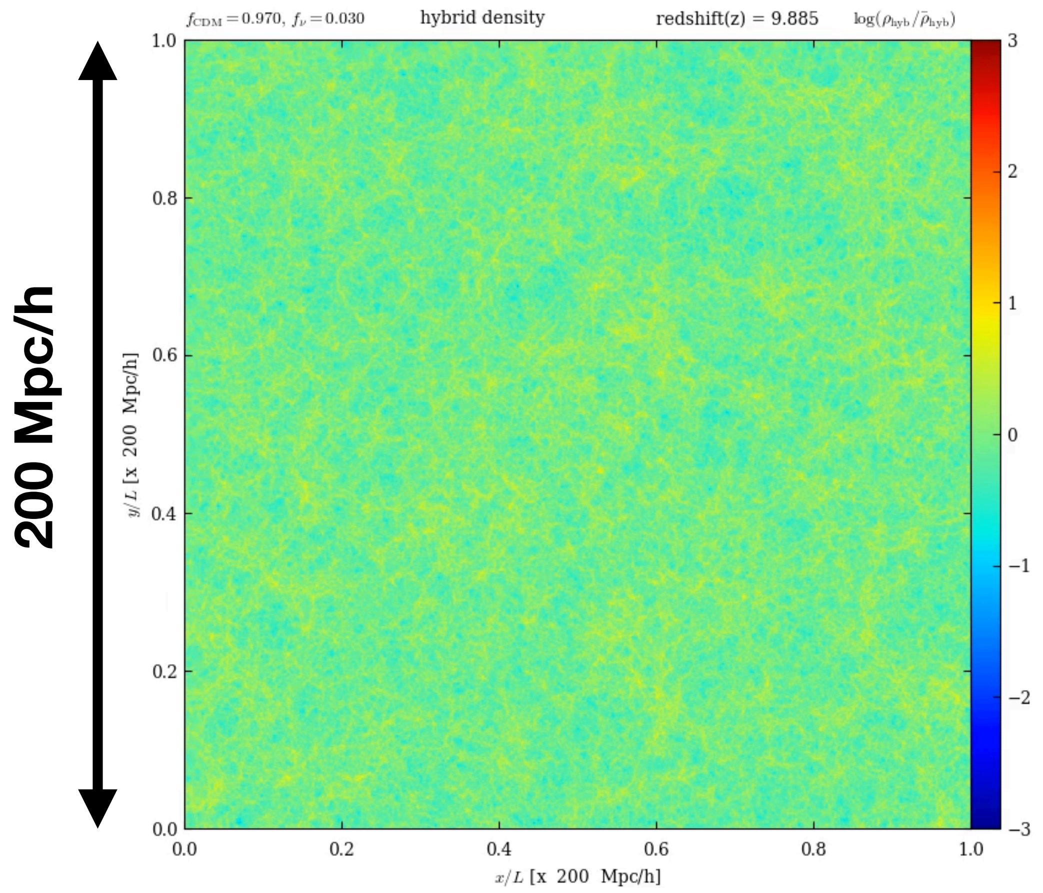
$$P_{\mathrm{m}}(k,z) = \langle|\delta_{\mathrm{m}}(k,z)|^2\rangle$$

- a few % level suppression around BAO scales.

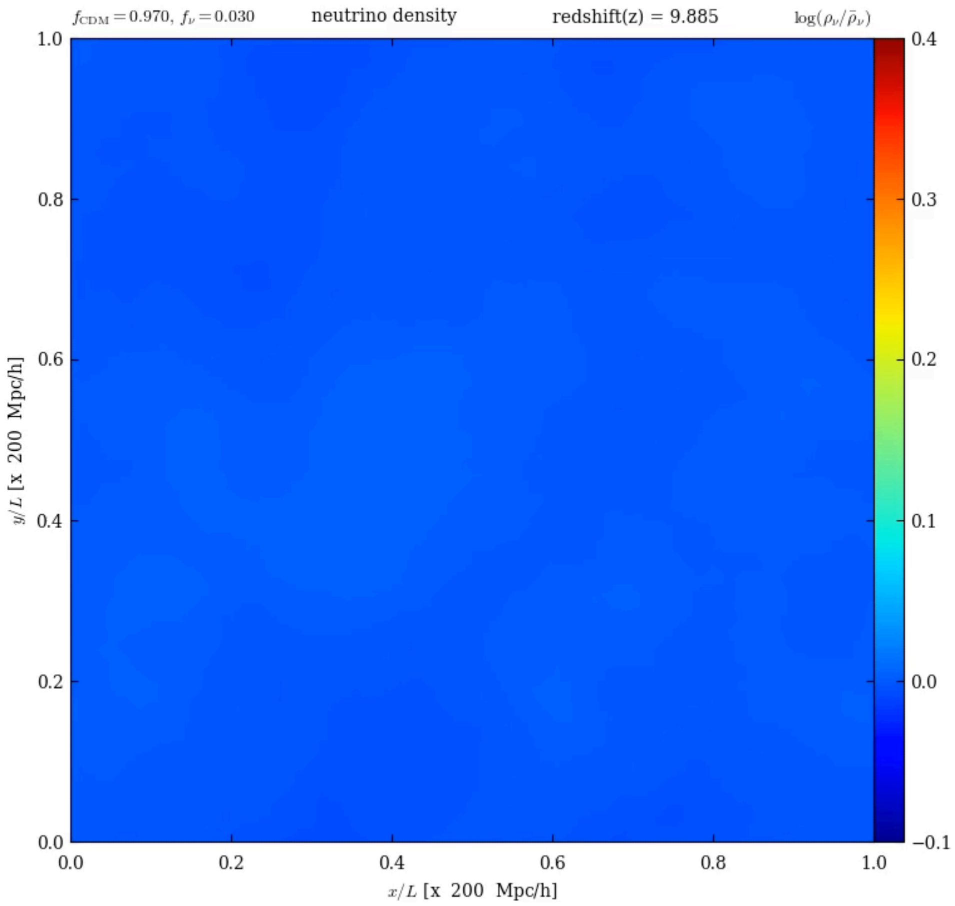
- smaller scale (high k): linear theory is invalid.

The First-ever Vlasov simulation with Neutrinos

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

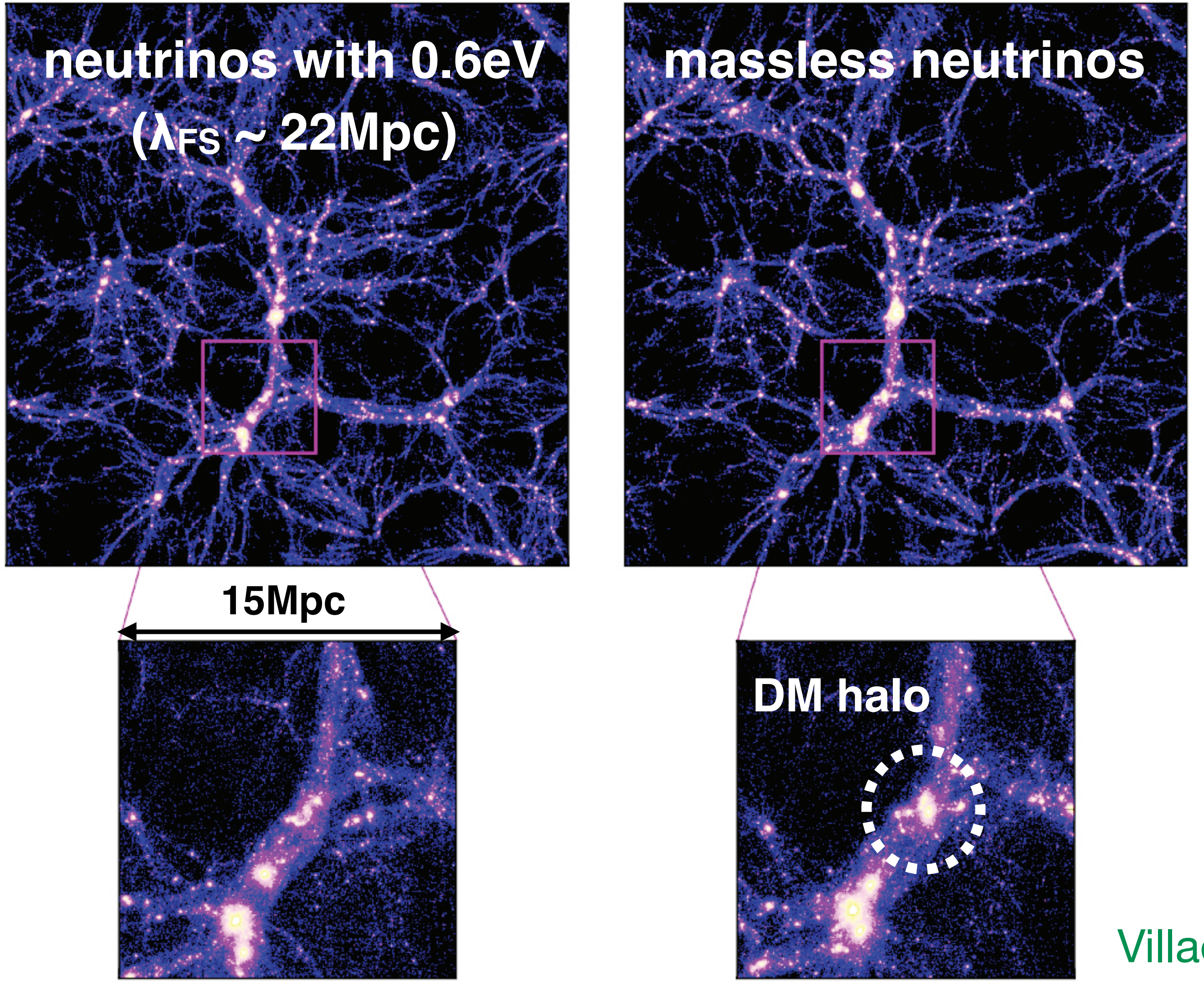


All Matter (CDM)



Neutrino

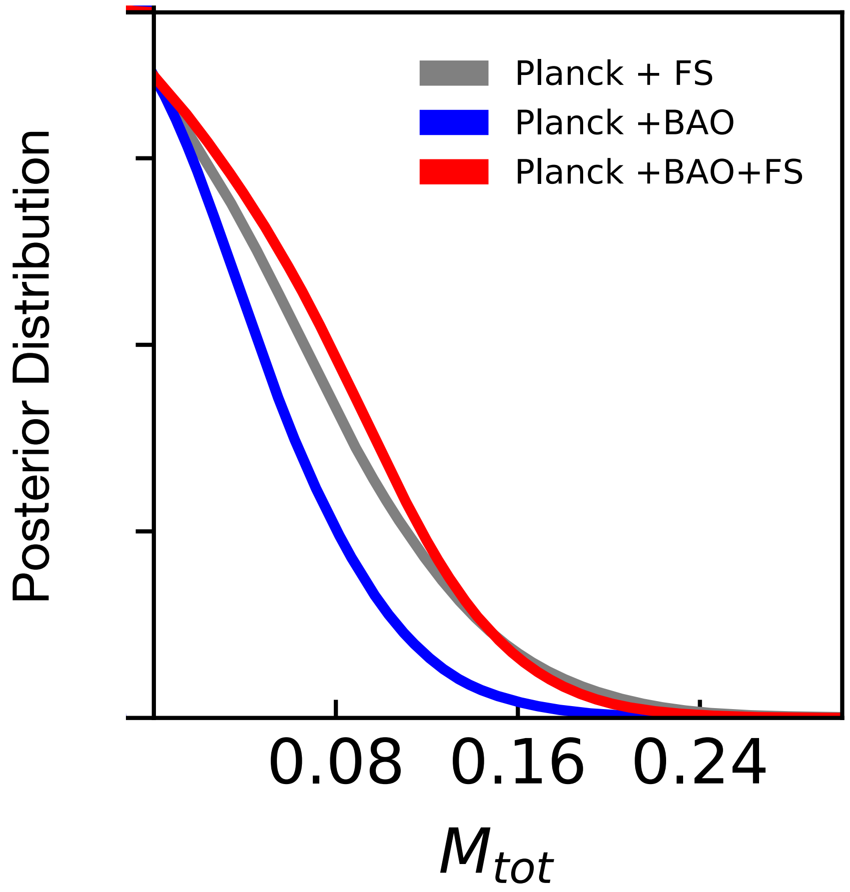
Neutrinos suppress the growth of LSS



Villaescusa-Navarro (2015)

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

Philcox+(2020)



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

See also ***SS***+(2011), Zhao, ***SS***+(2013), Zhang, ***SS***+ (in prep)

➤ Hint of the discrepancy between

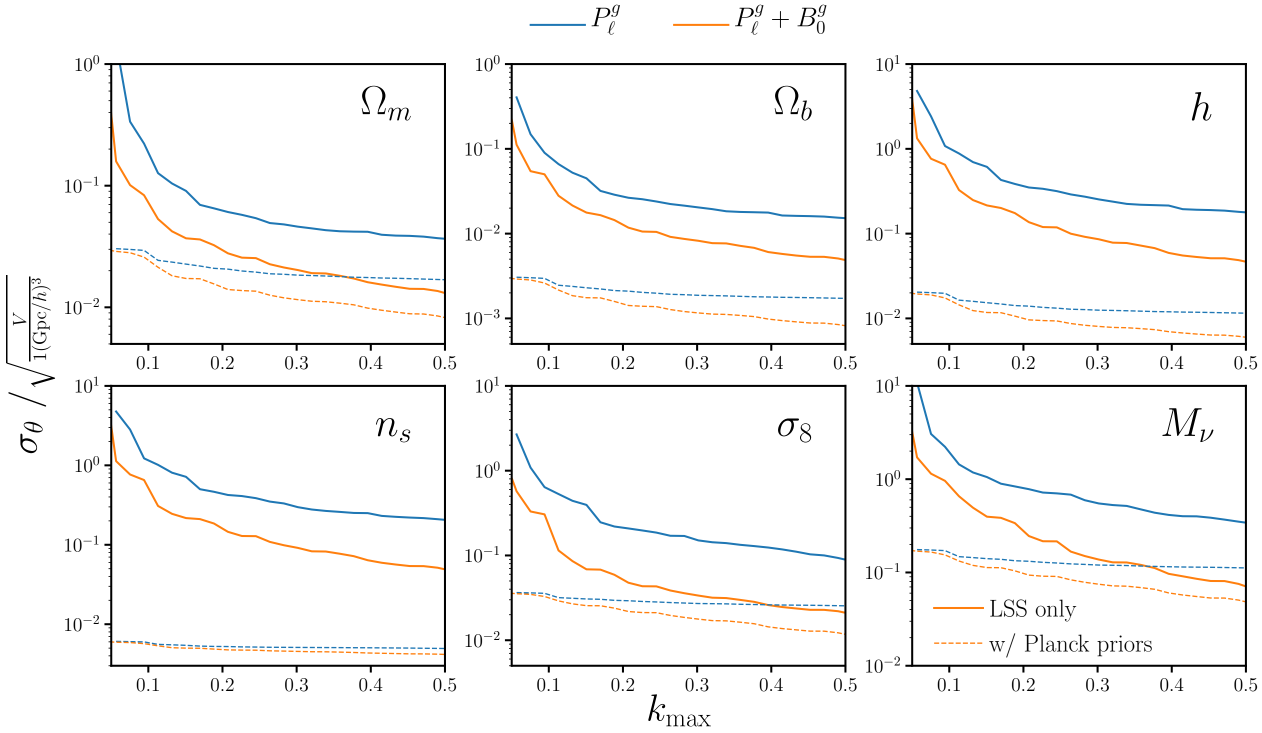
- the BAO scale (distance) &
- the broadband shape?

➤ Planck + BAO + FS: **< 0.14eV** (95% C.L.)

What's next? The Galaxy Bispectrum?

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

Hahn & Villaescusa-Navarro (2021)

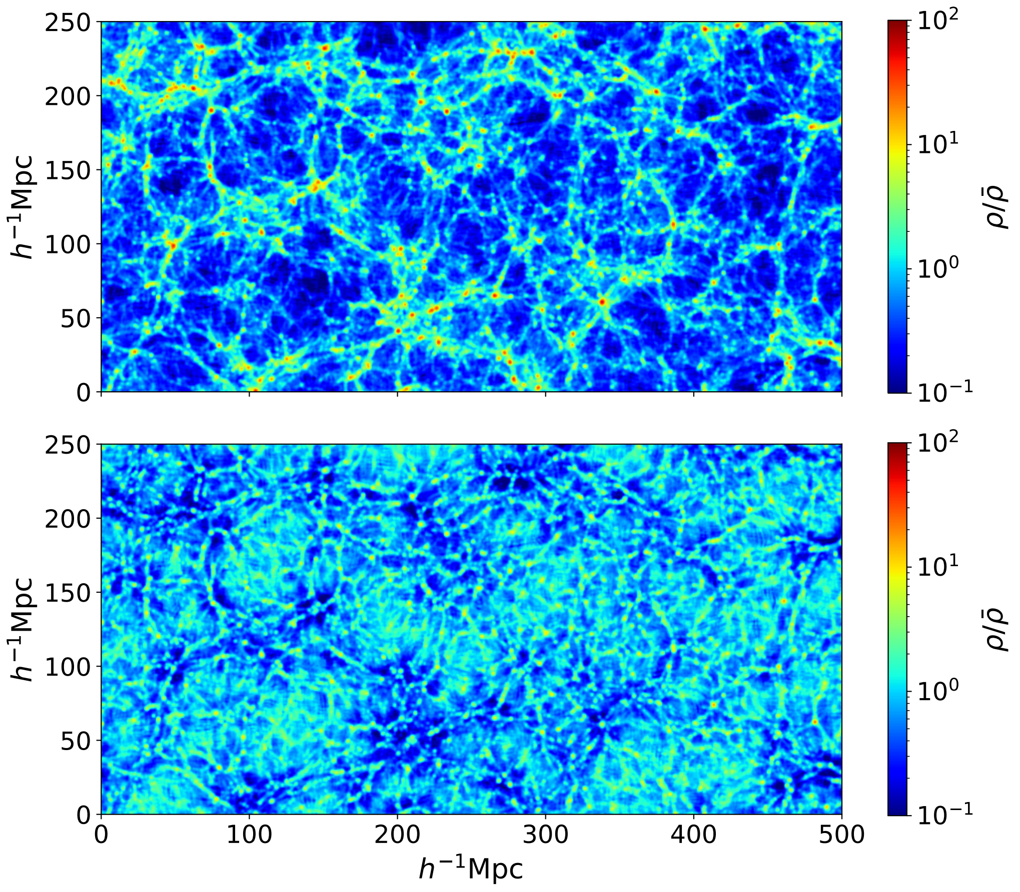


- ➤ Open Questions
  - Same is true for higher redshift?
  - Same is true for other types of galaxies?
  - More information from the anisotropic bispectrum?

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

What's next? The Marked Statistics?

Massara+(2021)

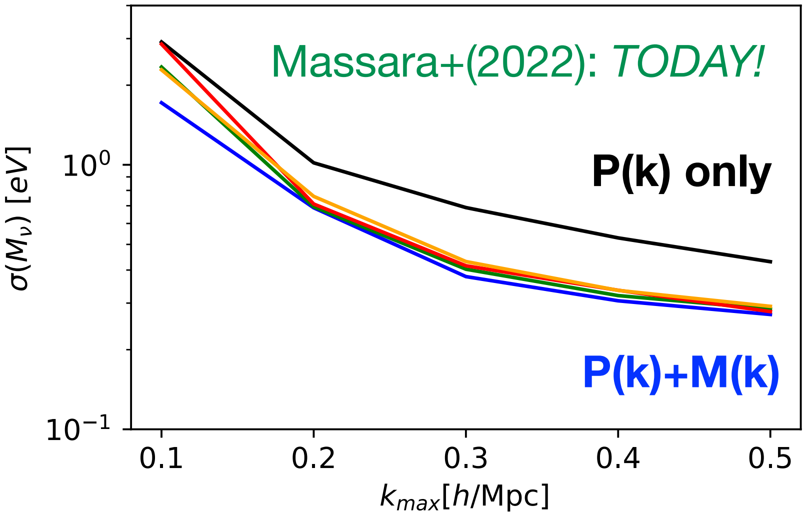


- The two-point correlation function weighted by the mark:

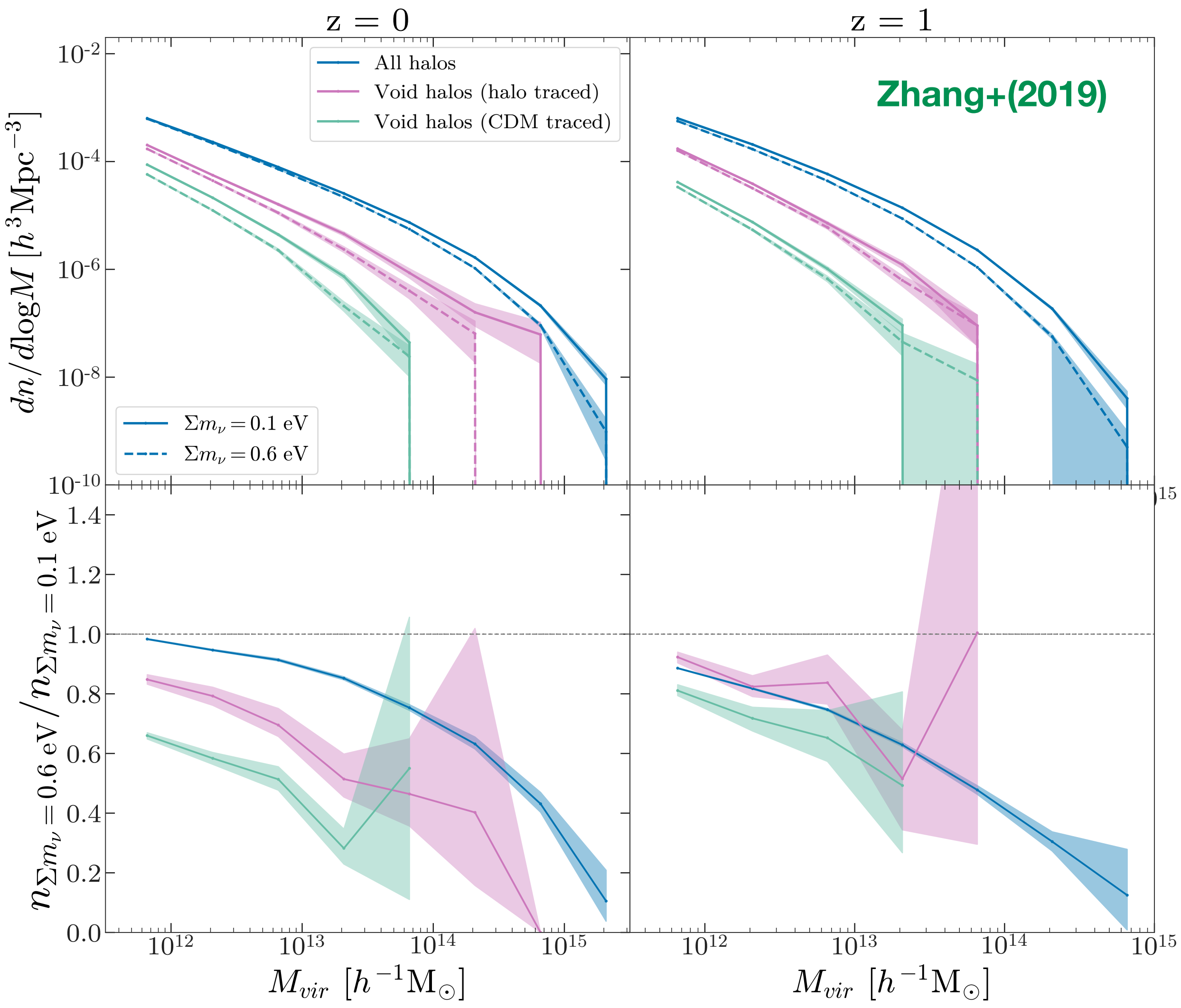
$$m(\vec{x}; R, p, \delta_s) = \left[\frac{1+\delta_s}{1+\delta_s+\delta_R(\vec{x})}\right]^p$$

- p>0 puts more weight in **low density** region.
- Effectively include higher-order information.

Philcox+(2020)



What's next? The Void Statistics?



- ➤ 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)!