Constraining Elusive Neutrino Properties Near and Far

Christina Kreisch
Princeton University
ckreisch@astro.princeton.edu

Francis-Yan Cyr-Racine, Olivier Doré
arXiv: 1902.00534

Alice Pisani, Carmelita Carbone, Jia Liu, Adam Hawken, Elena Massara, David Spergel, Ben Wandelt
arXiv: 1808.07464

UC Berkeley— October 6, 2020

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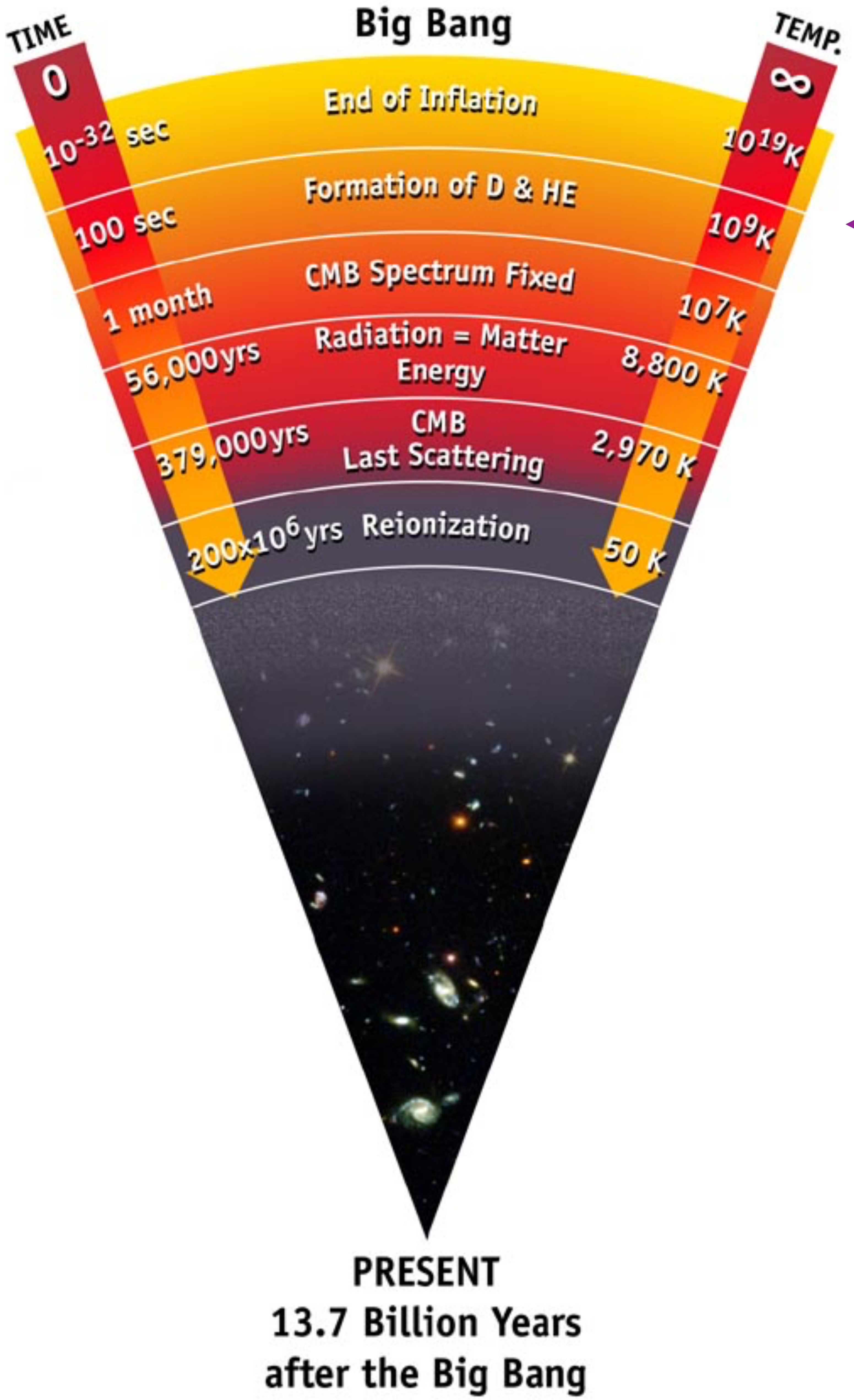
Assumes neutrinos are massless

… but we know they have mass due to observations of neutrino oscillations

A Brief History of Cosmic Ghosts

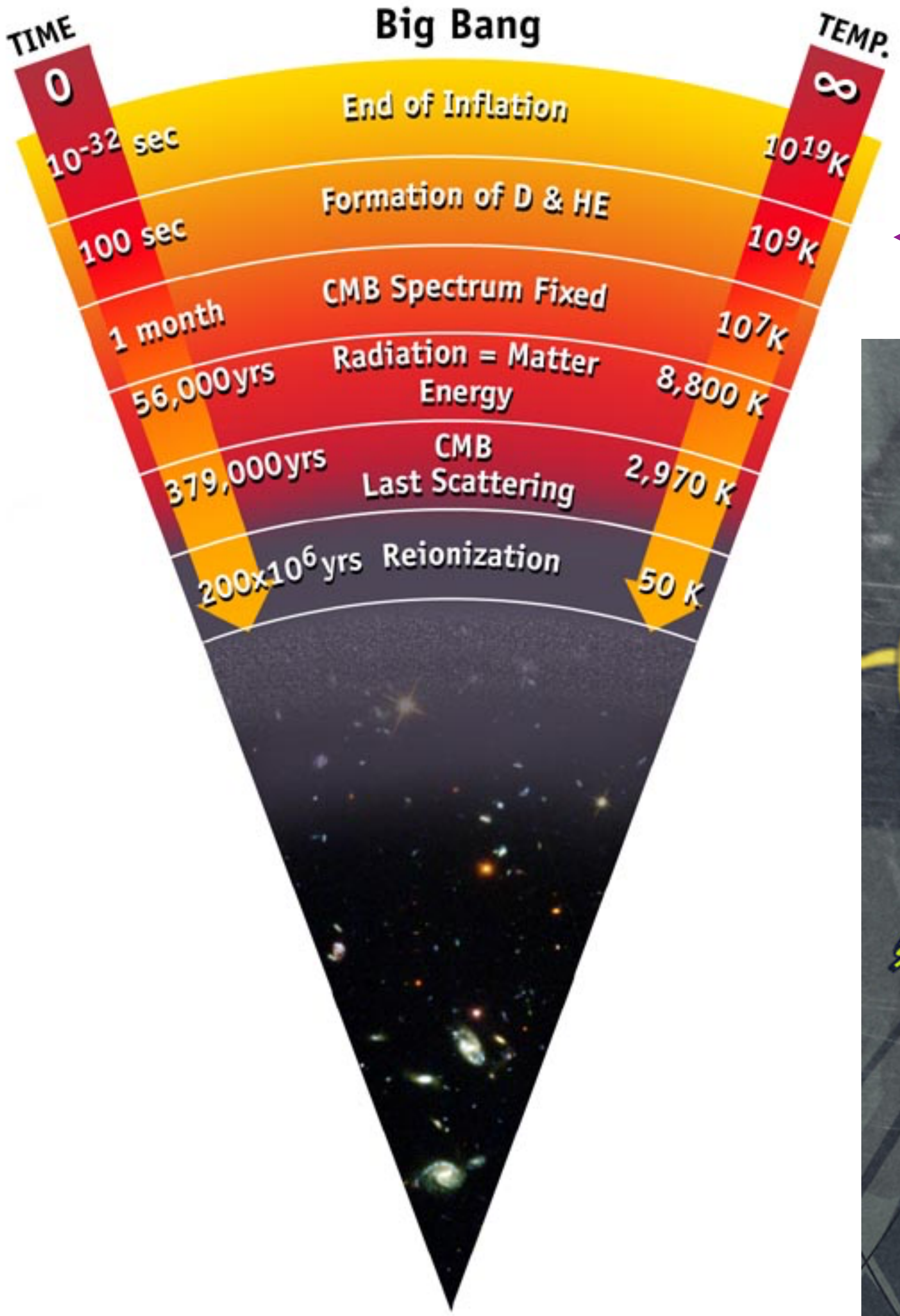


Neutrino decoupling

~MeV

gsfc.nasa.gov

A Brief History of Cosmic Ghosts



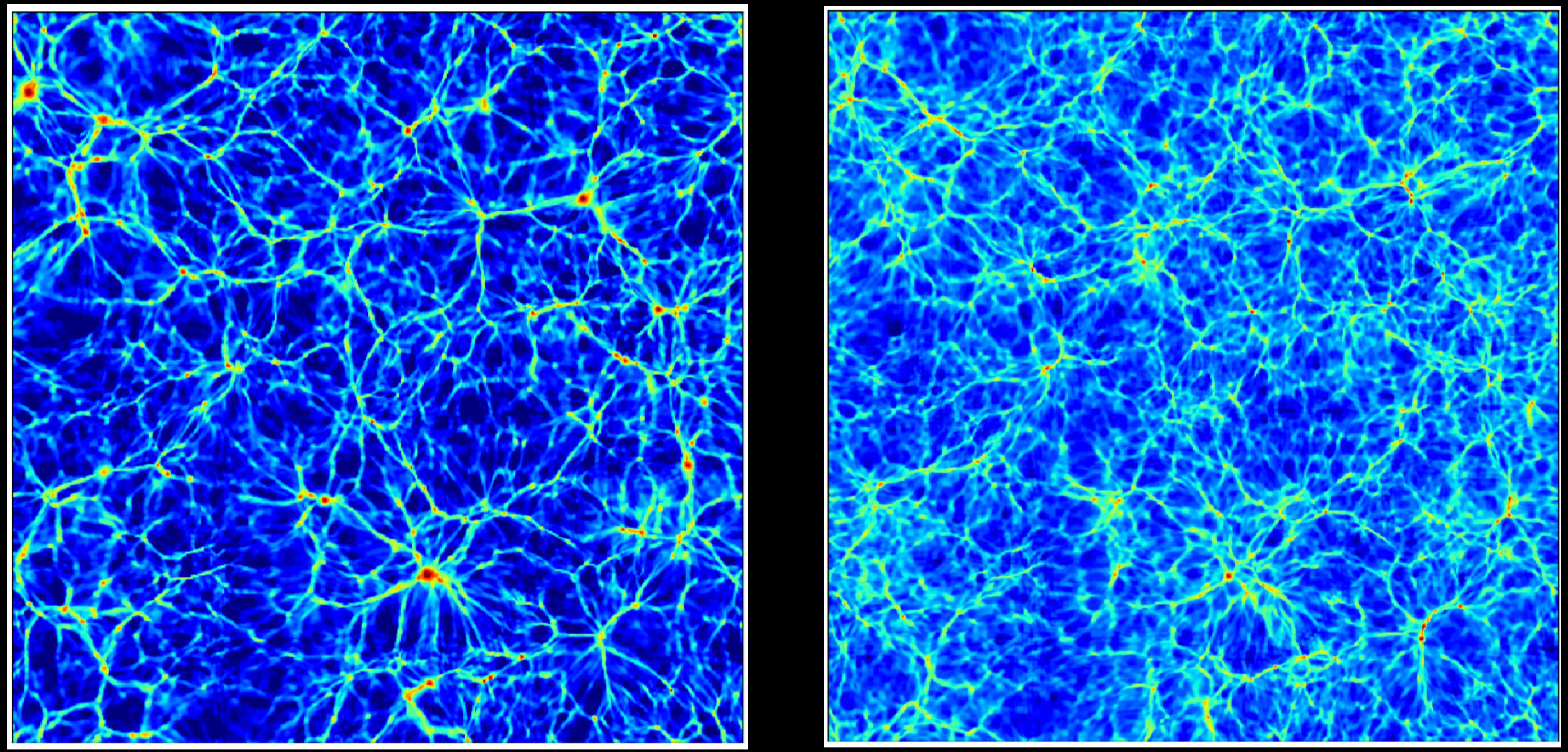
Neutrino decoupling

~MeV

Free-streaming neutrinos impact cosmological observables

gsfc.nasa.gov
symmetrymagazine.com

Impacts structure formation!

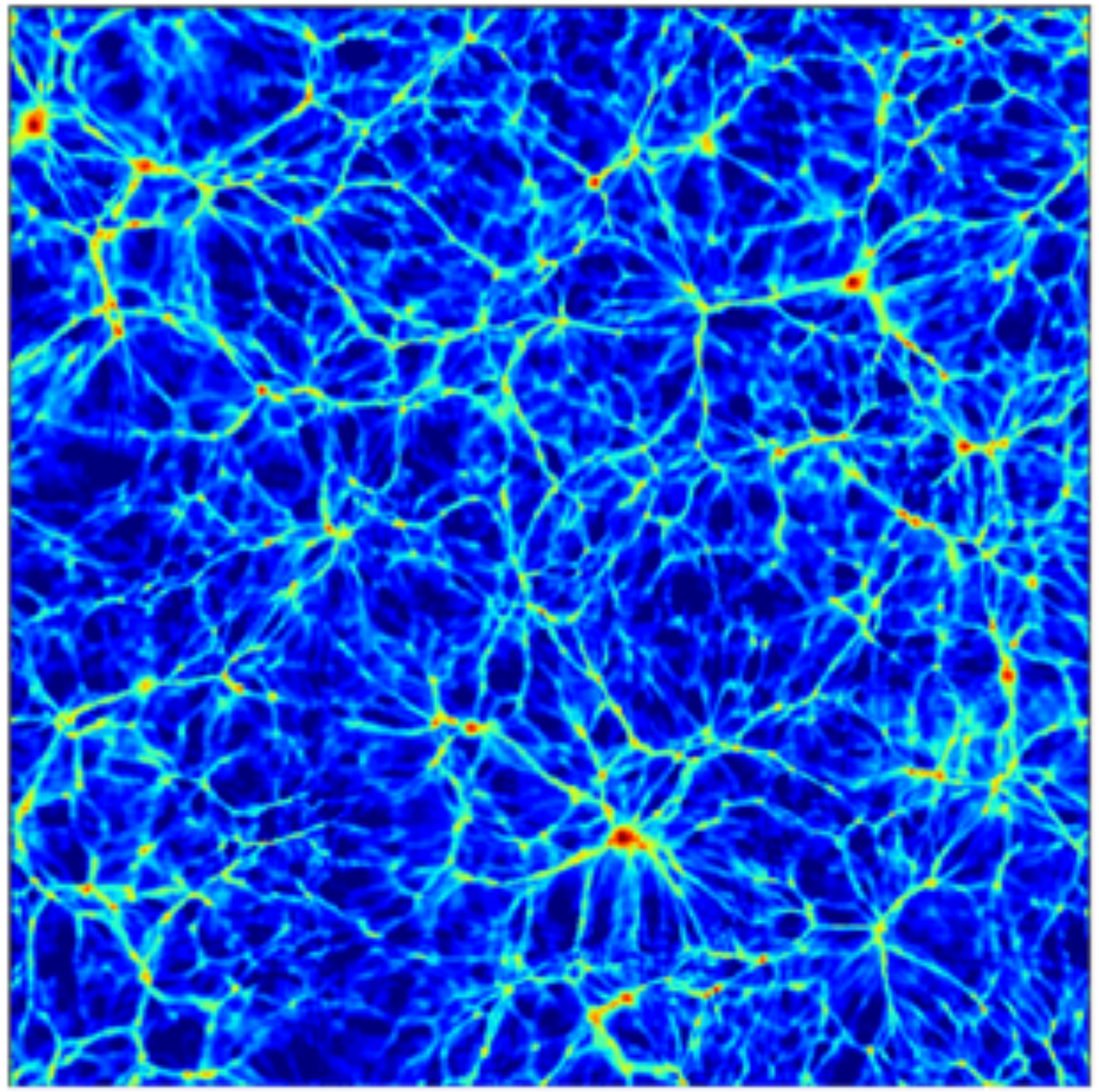


0.0 eV

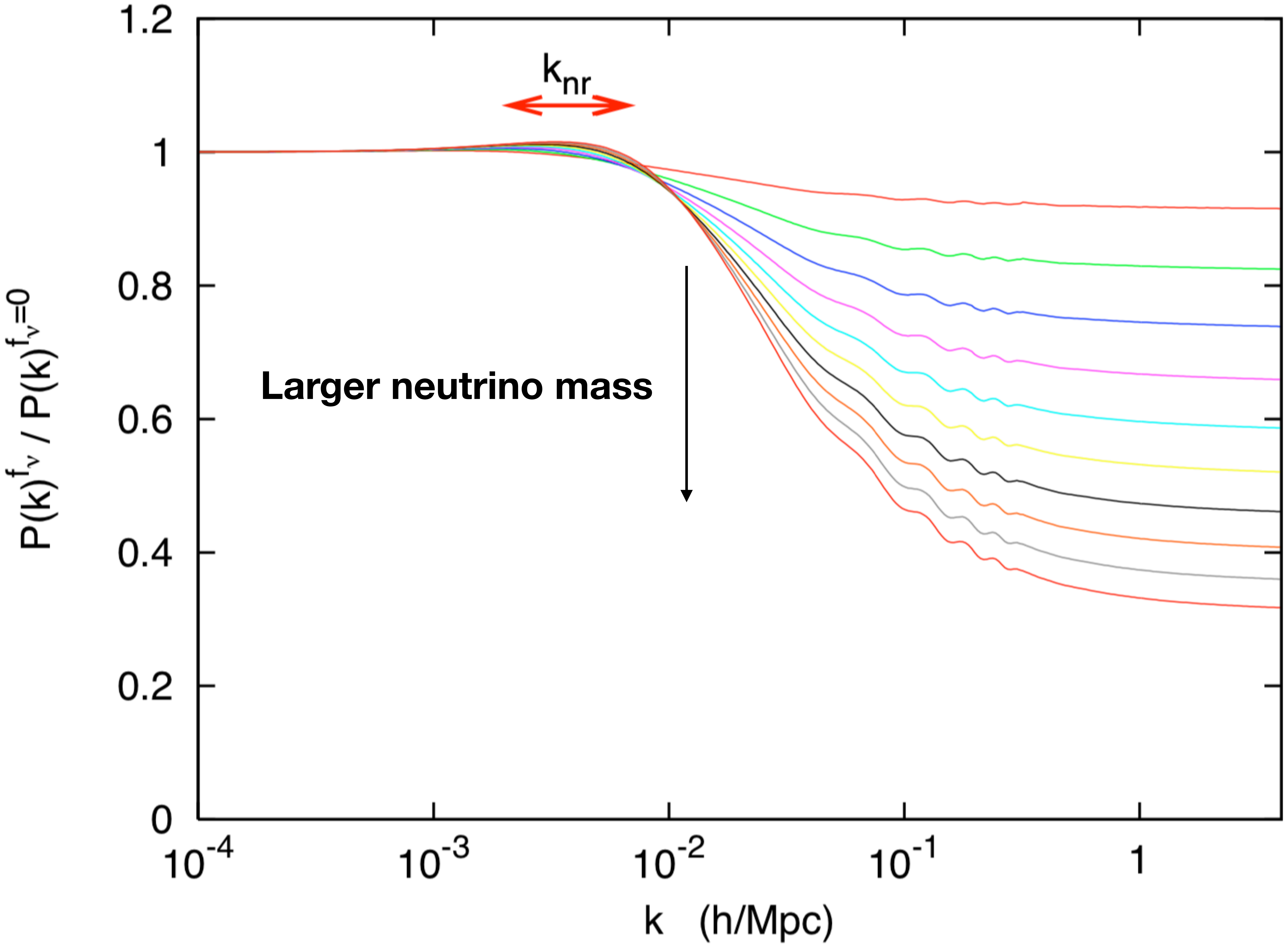
2.0 eV

Massive neutrino cosmology is less evolved → structure is more diffuse

Agarwal & Feldman 2010



400 Mpc/h



Neutrino free-streaming scales:

$$k_{FS} \propto m_\nu \, [h\mathrm{Mpc}^{-1}]$$

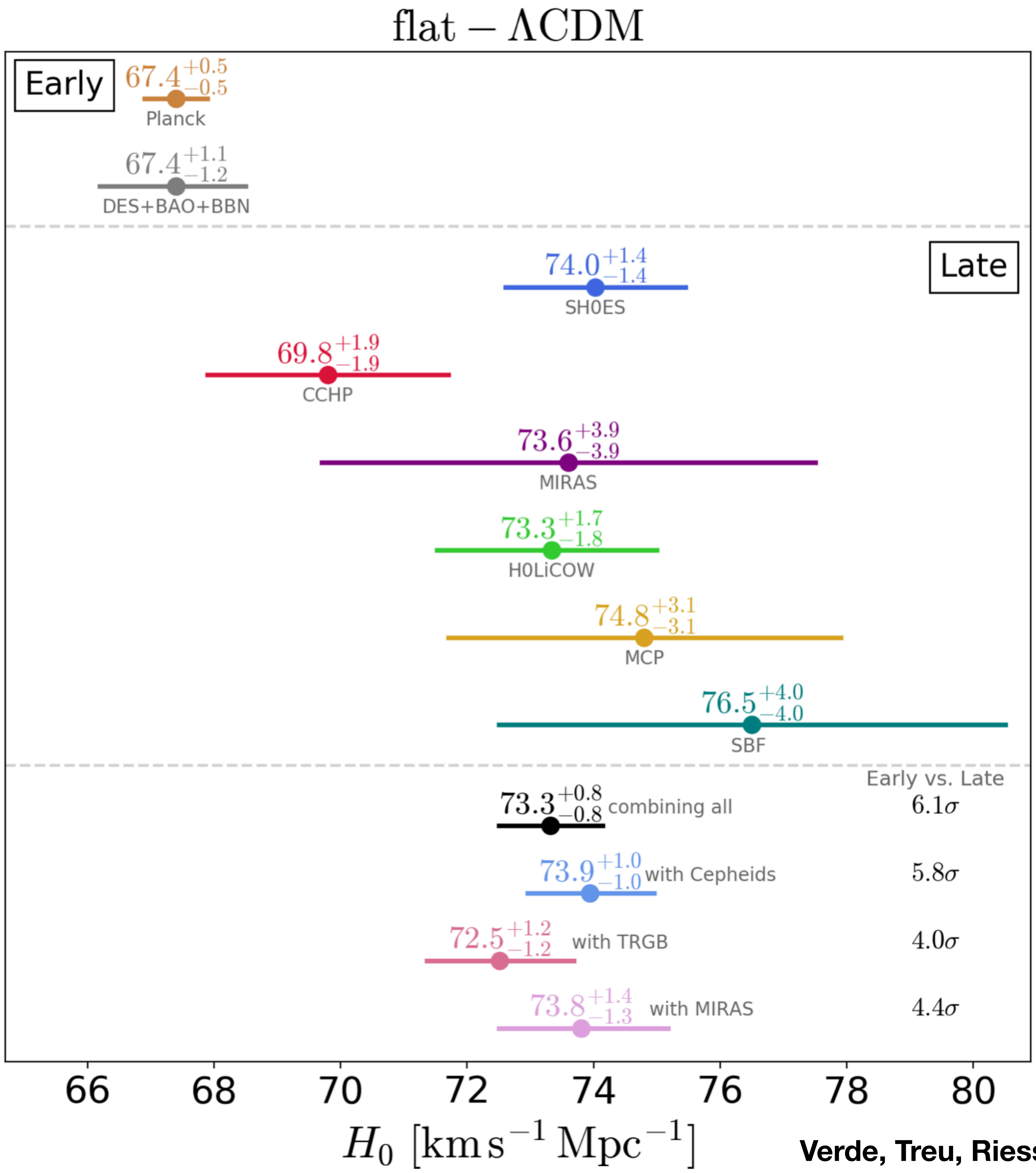
$$r_{\mathrm{FS}} = 130 h^{-1}\mathrm{Mpc} \;\text{ for }\; \Sigma m_\nu = 0.06\,\mathrm{eV}$$

$$r_{\mathrm{FS}} = 39 h^{-1}\mathrm{Mpc} \;\text{ for }\; \Sigma m_\nu = 0.6\,\mathrm{eV}$$

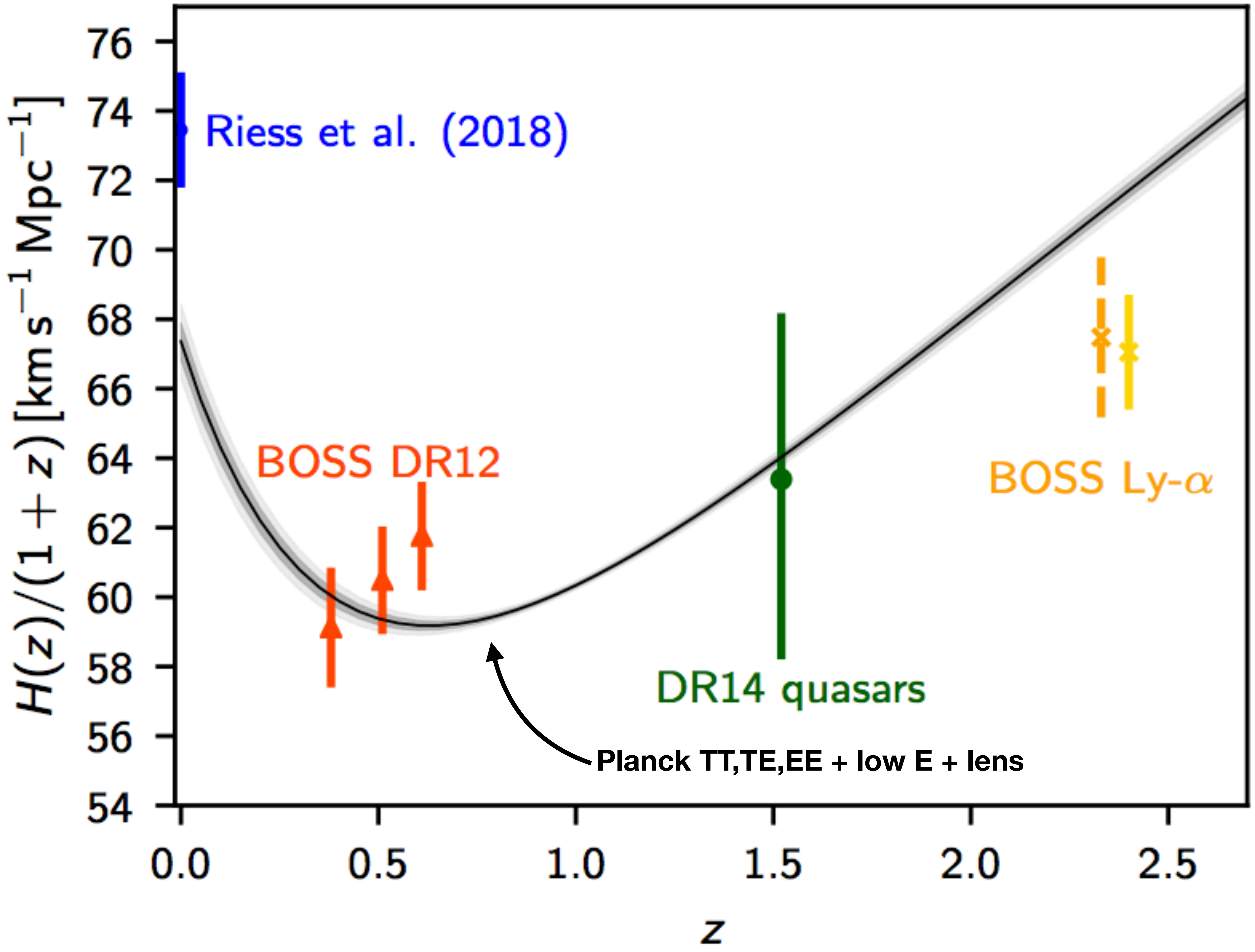
Growth of matter at small scales is delayed
Cosmology is sensitive to the total sum

Agarwal & Feldman 2010
Lesgourgues & Pastor 2012

Cosmological Tensions



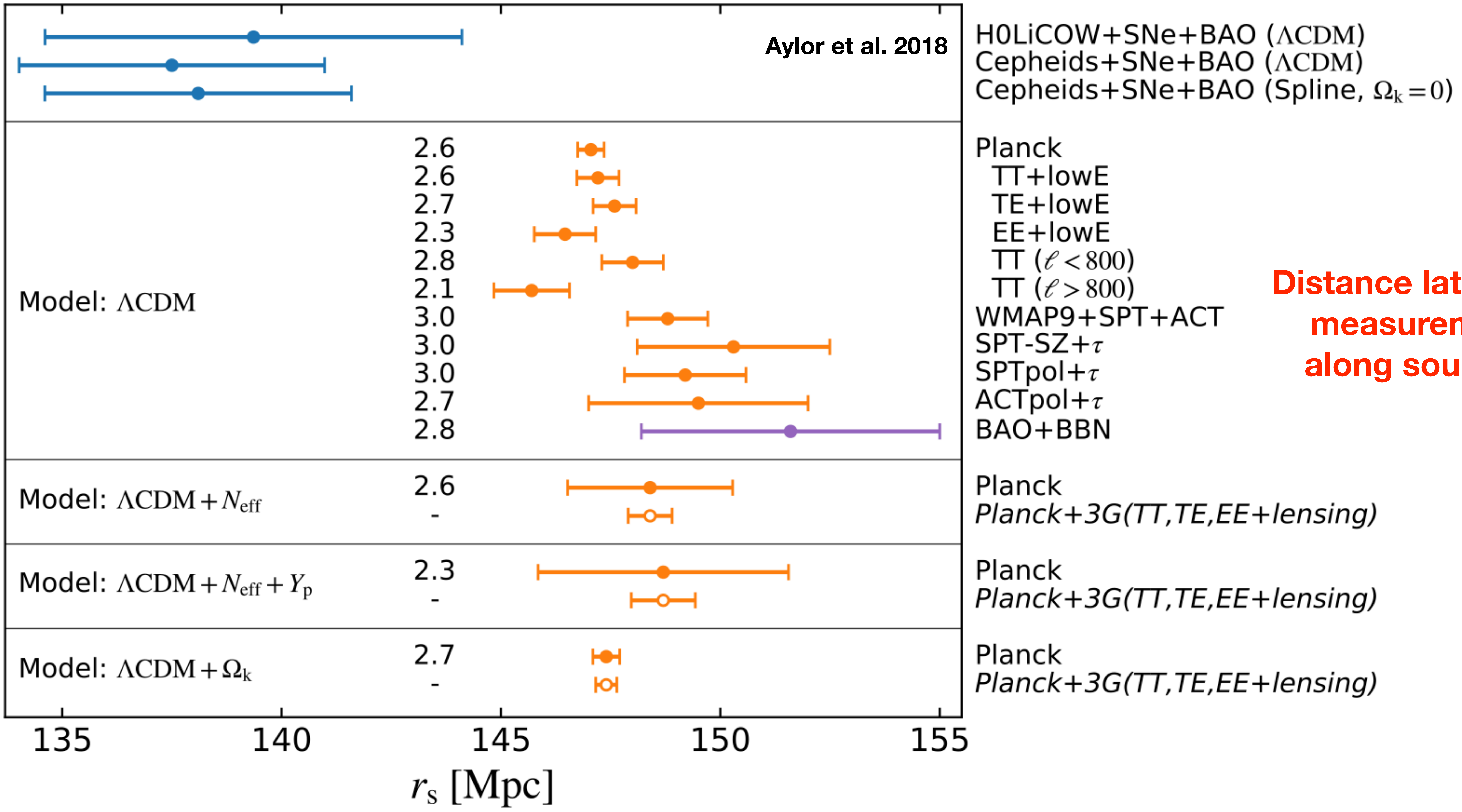
Verde, Treu, Riess 2019



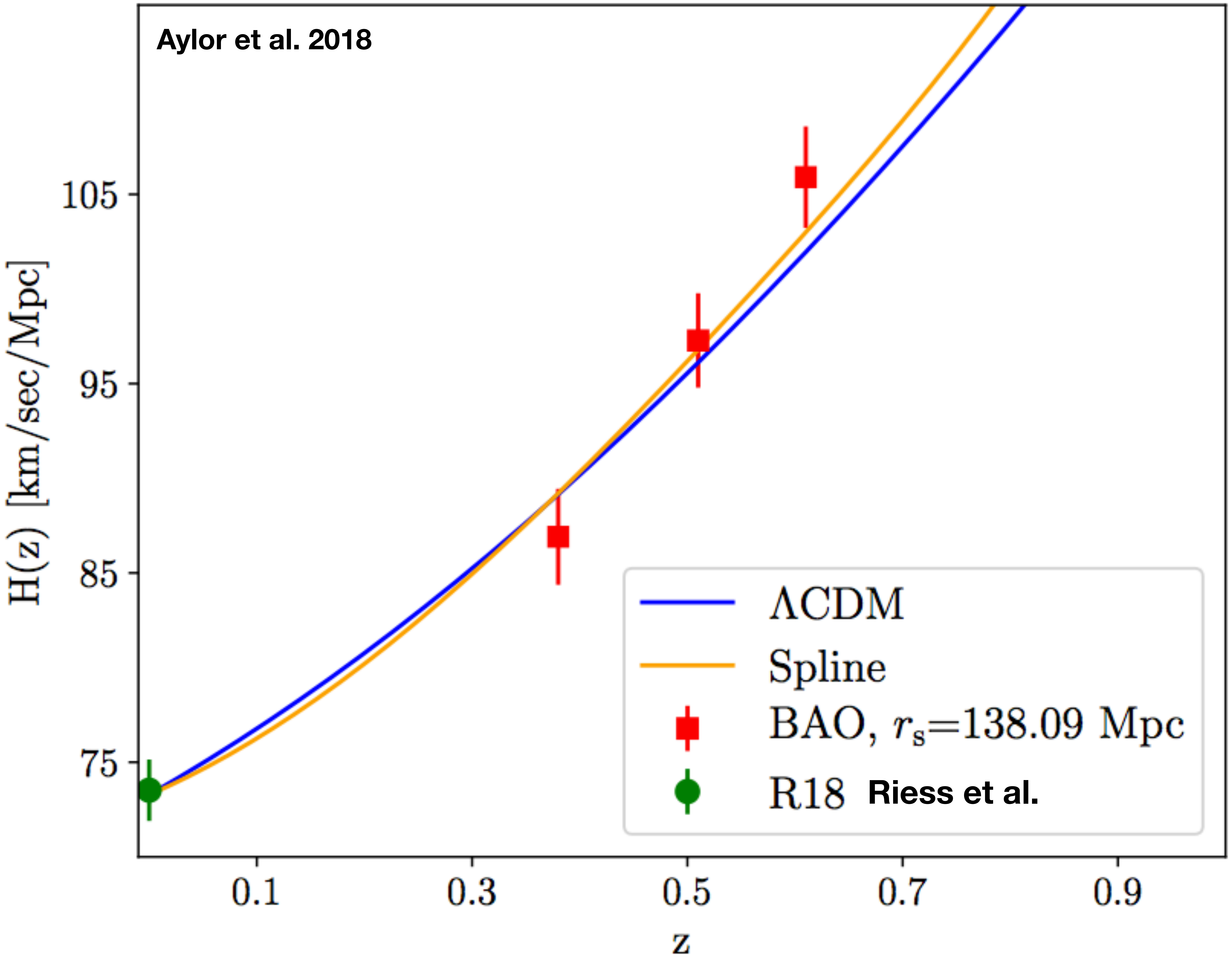
Local measurements seem to be discrepant with other measurements

BOSS measurements are used with Planck model measurements of sound horizon

Planck 2018

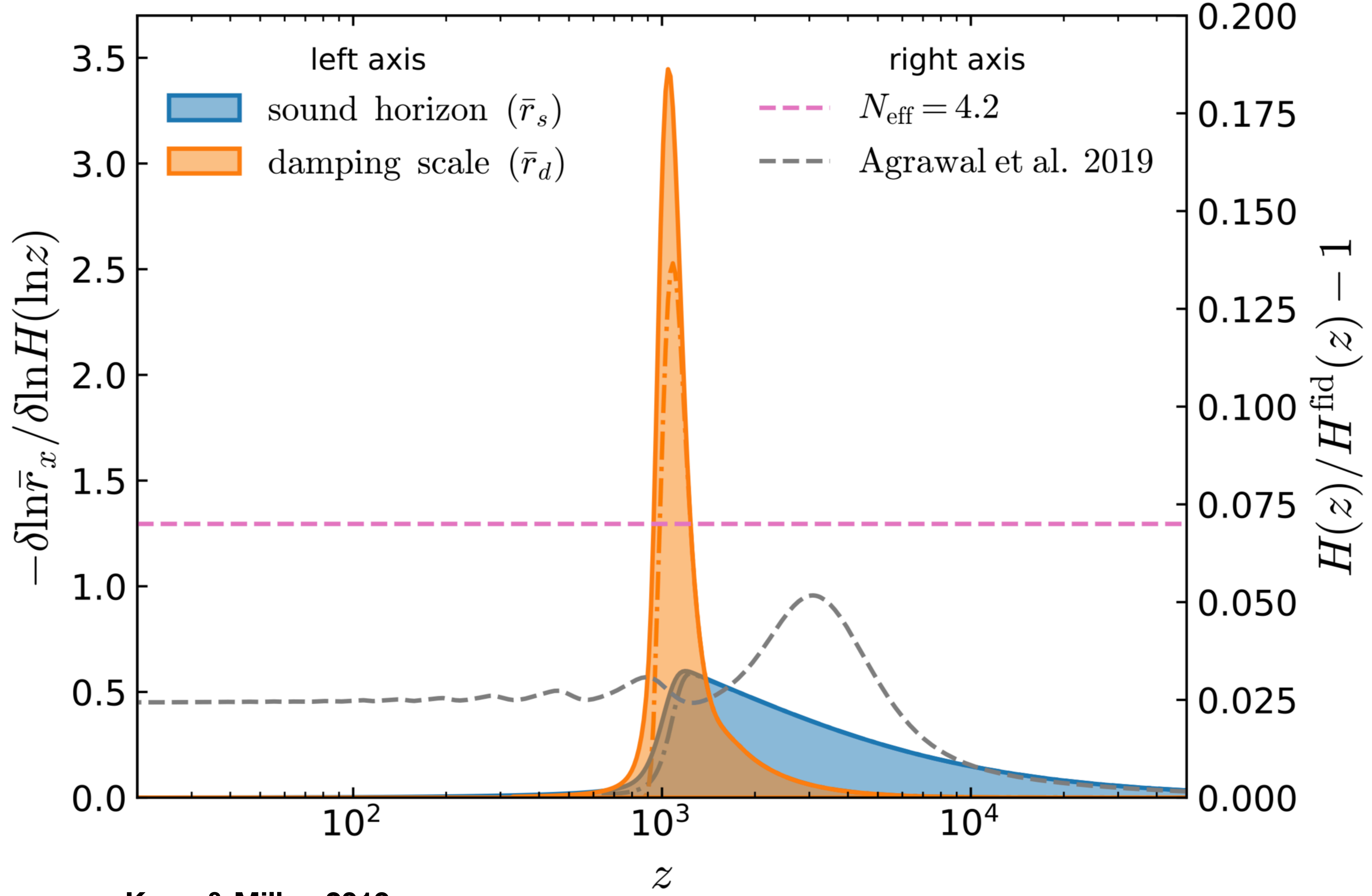


Distance latter and CMB measurements split along sound horizon



Consistency if have smaller sound horizon

→ alter r_s at early times
→ change physics at high redshifts



Knox & Millea 2019

New physics here

Neutrino Model

(arXiv: 1902.00534)

Neutrino Self-Interactions

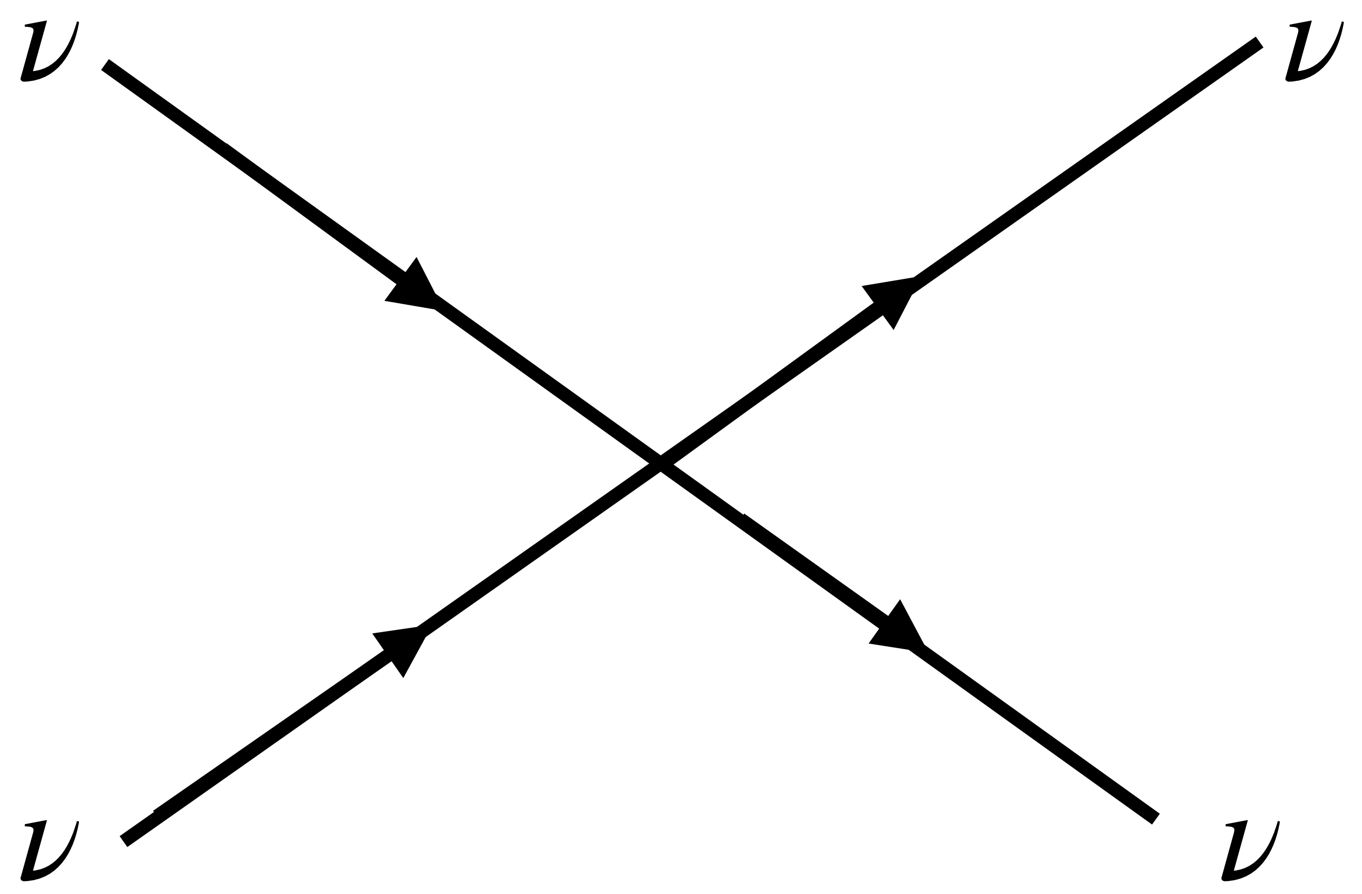
Toy model: Yukawa with massive scalar mediator

$$\mathcal{L}_{\rm int} = g_{ij}\bar{\nu}_i \nu_j \varphi$$

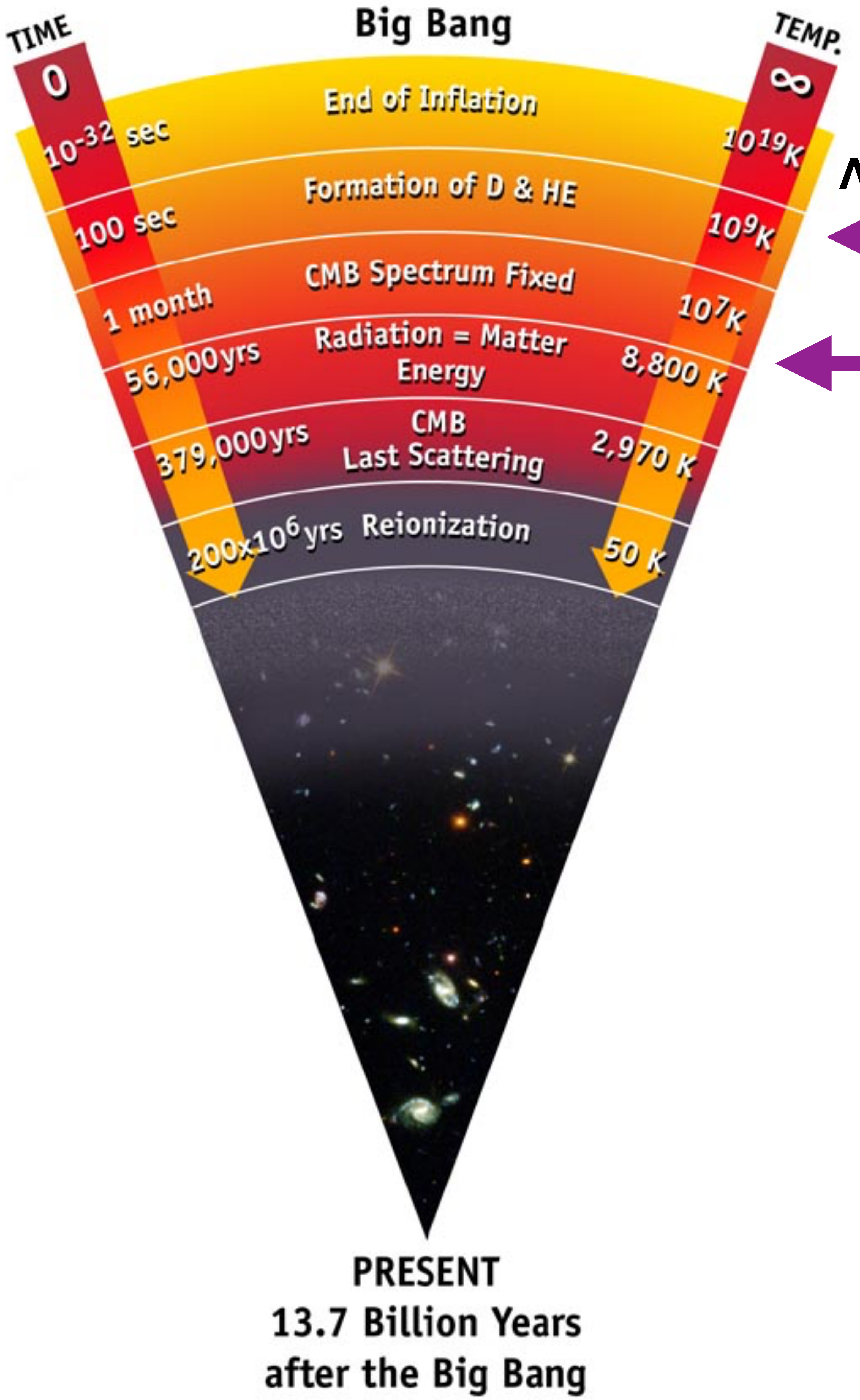
$$g_{ij} \equiv g_\nu \delta_{ij}$$

$$G_{\rm eff} \equiv |g_\nu|^2/m_\varphi^2$$

self-interaction strength



Delays neutrino free-streaming

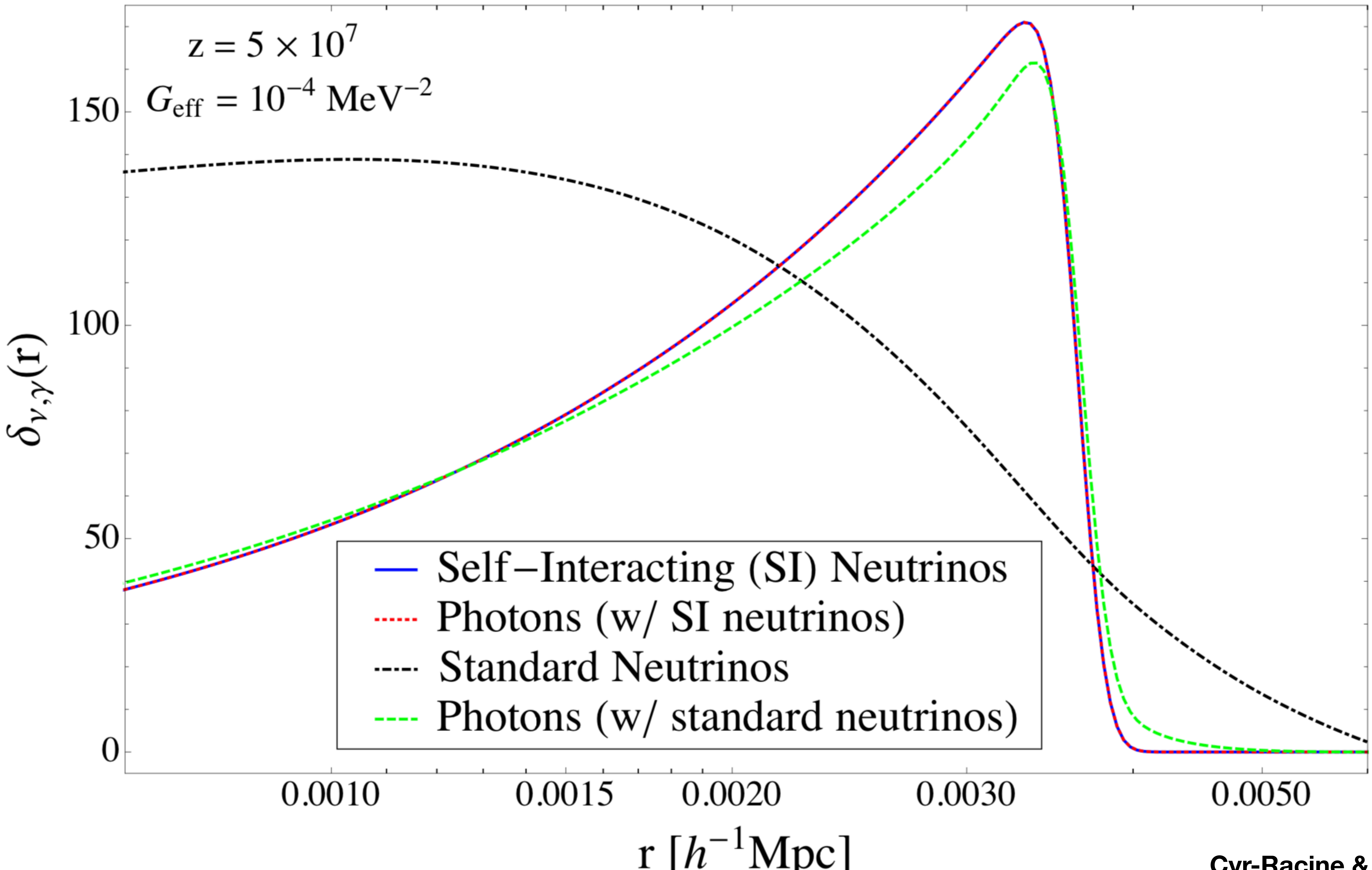


ΛCDM ~MeV

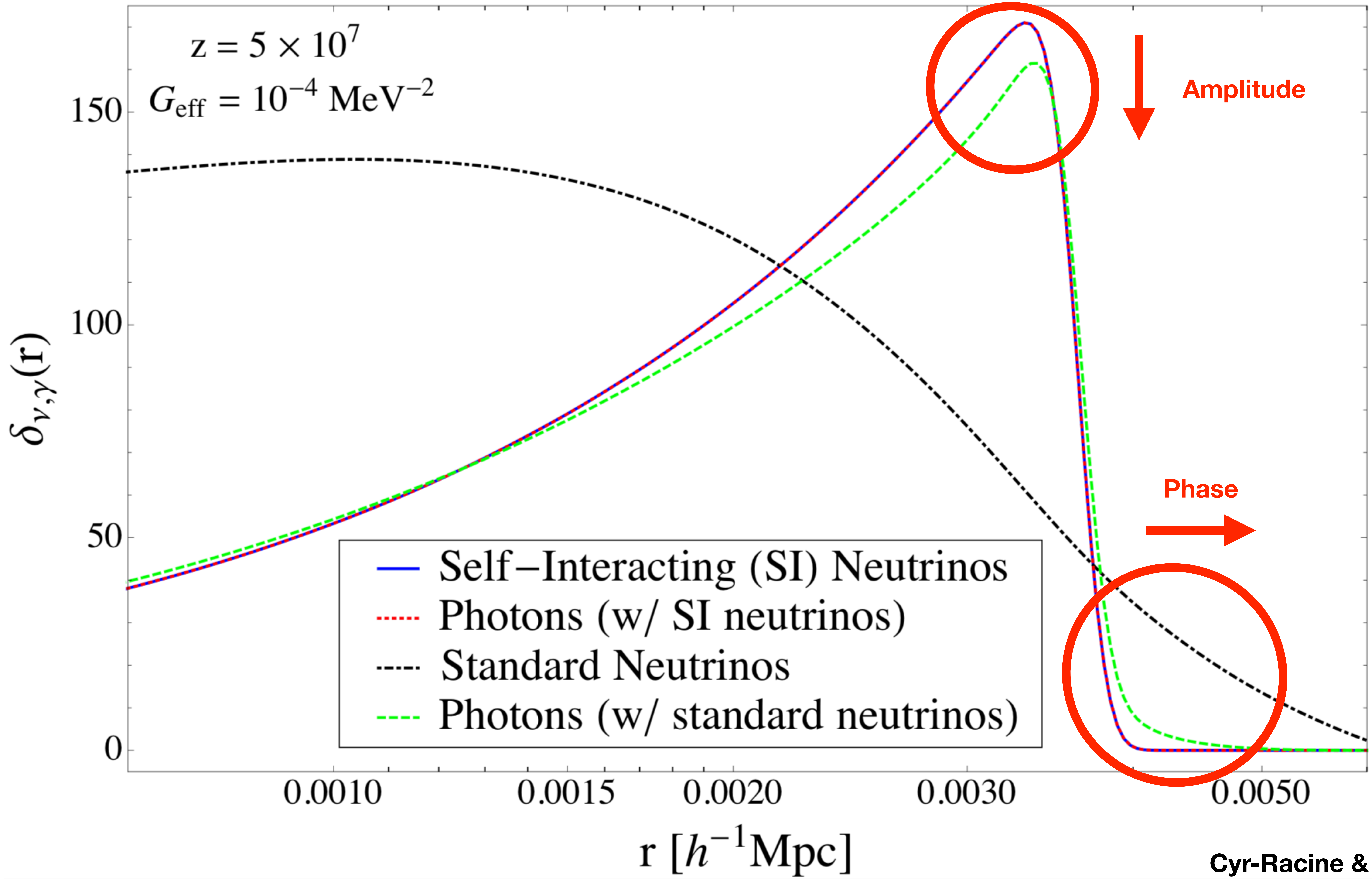
ν-ν ~25 eV

gsfc.nasa.gov

Cosmic Microwave Background



Cyr-Racine & Sigurdson 2014



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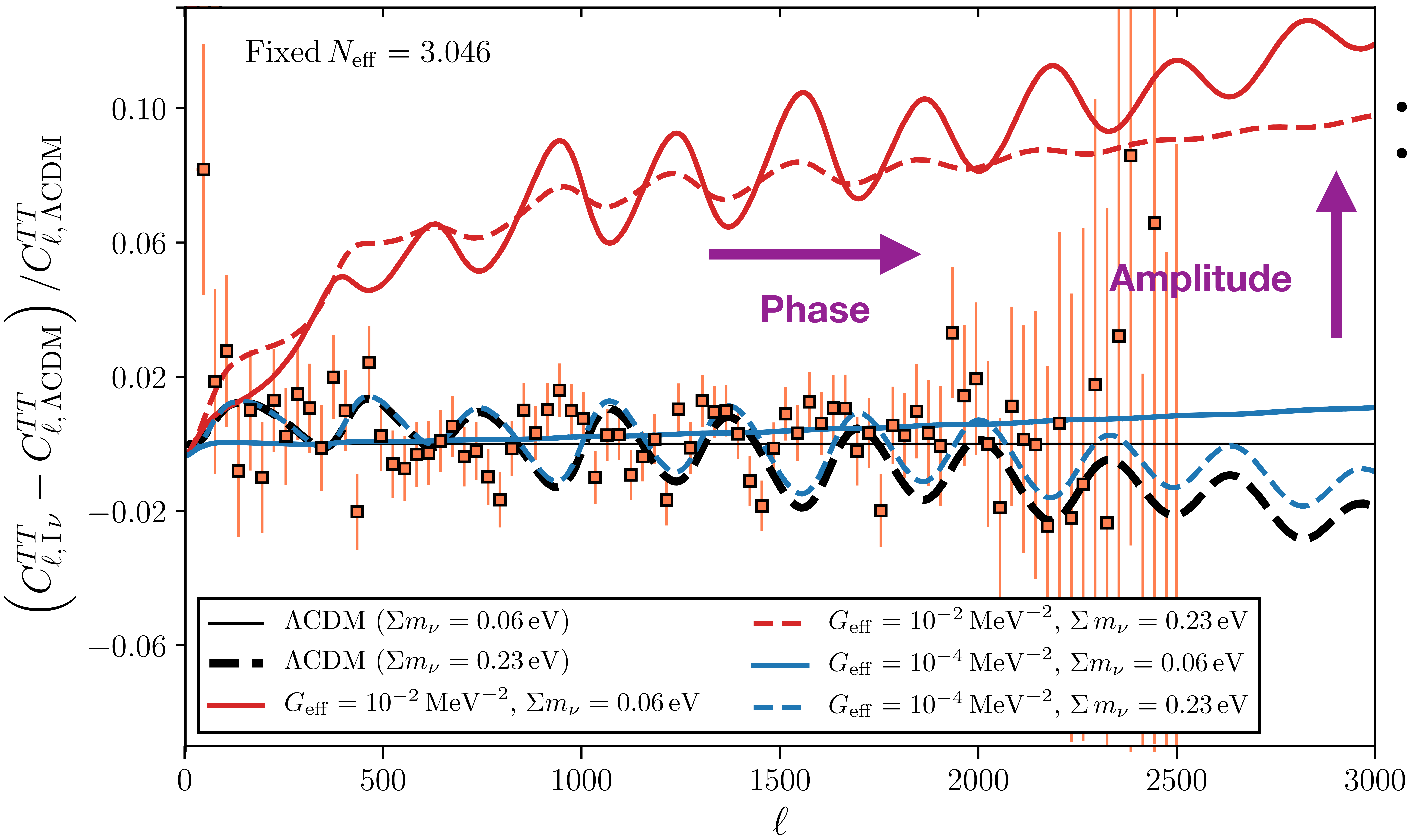
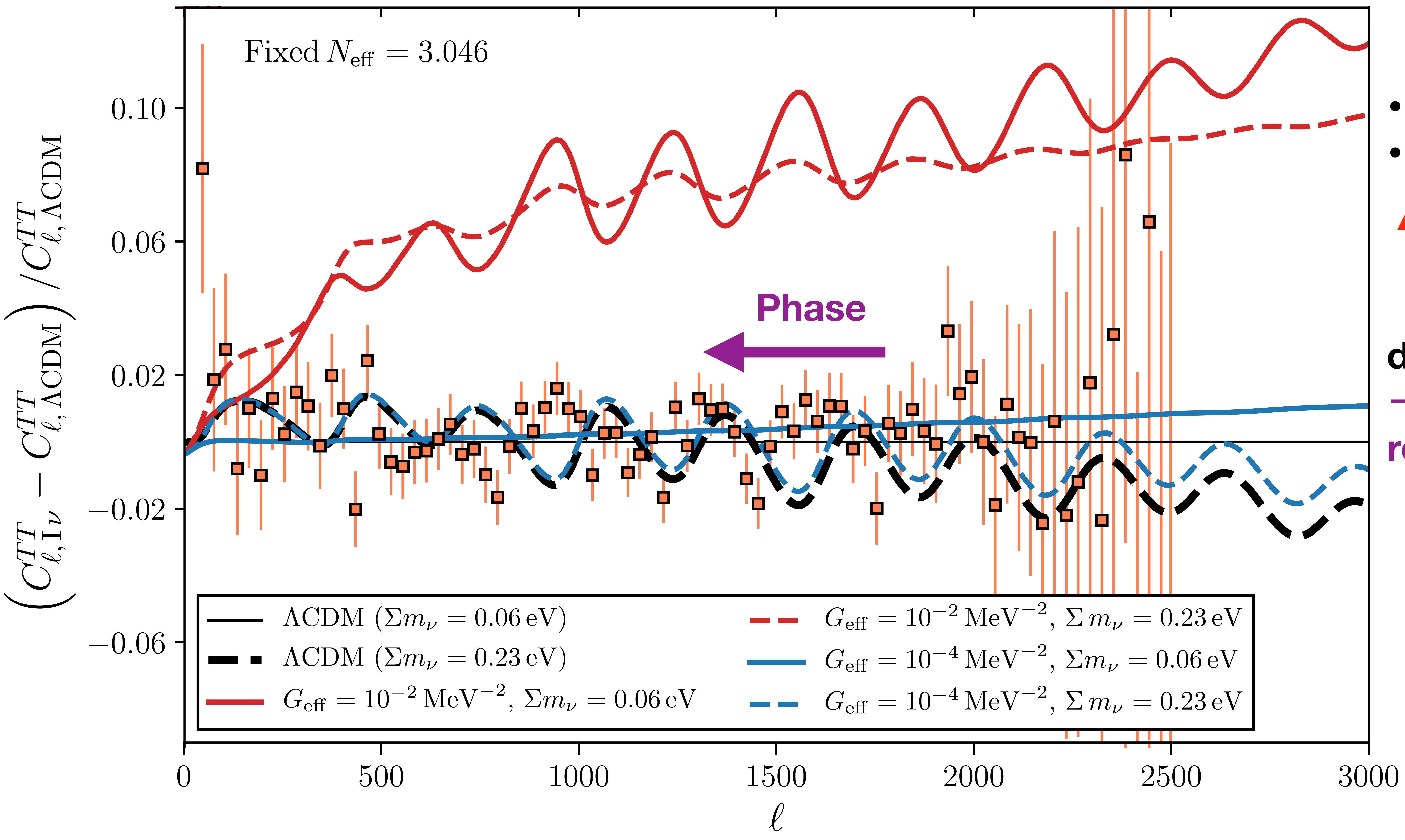


↑ $G_{\rm eff}$

- **phase shift to small scales**
- **boost in amplitude**

Kreisch et al. 2019



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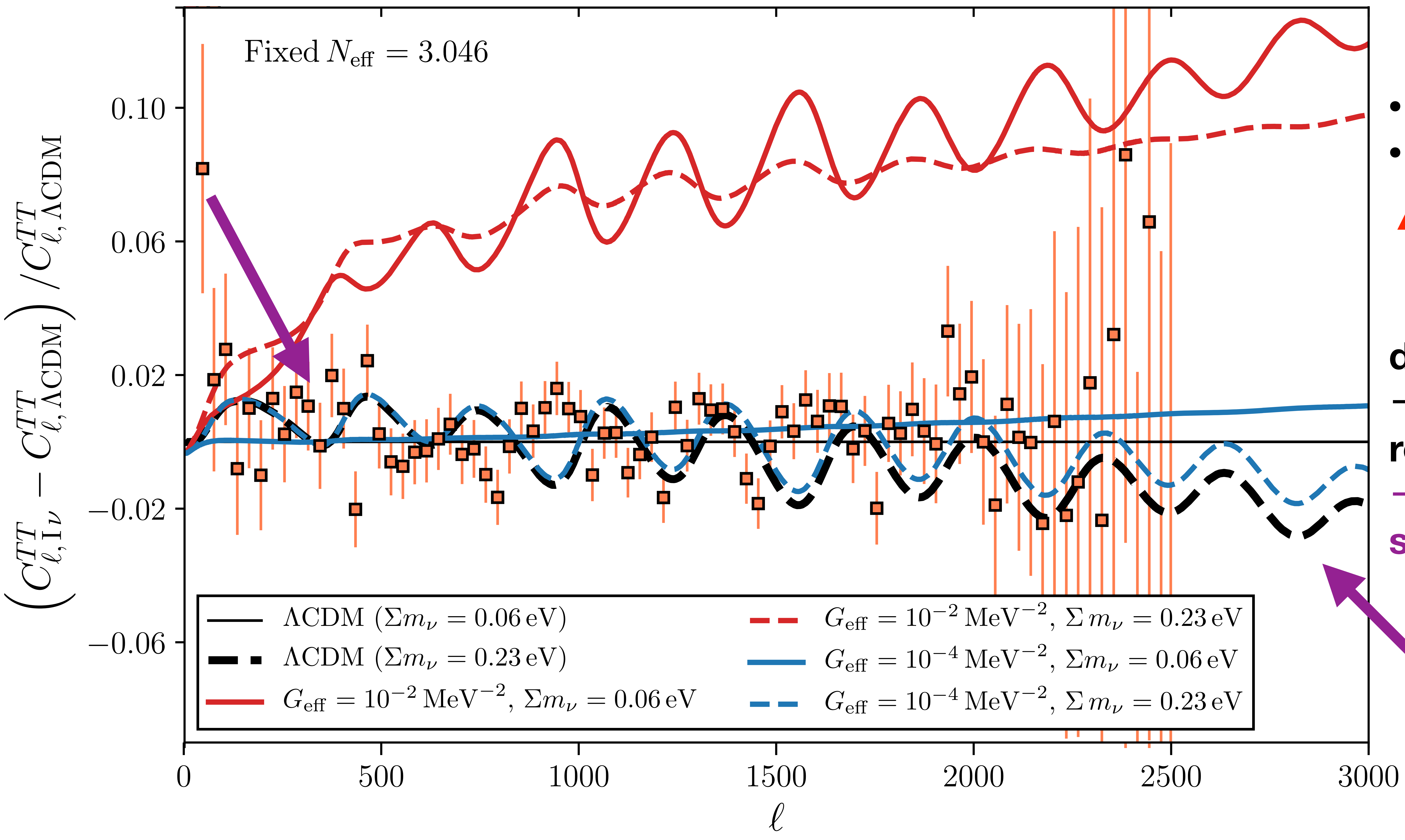
↑ $\sum m_\nu$

delays matter-radiation equality
→ increases sound horizon at recombination

Kreisch et al. 2019



$\uparrow G_{\rm eff}$

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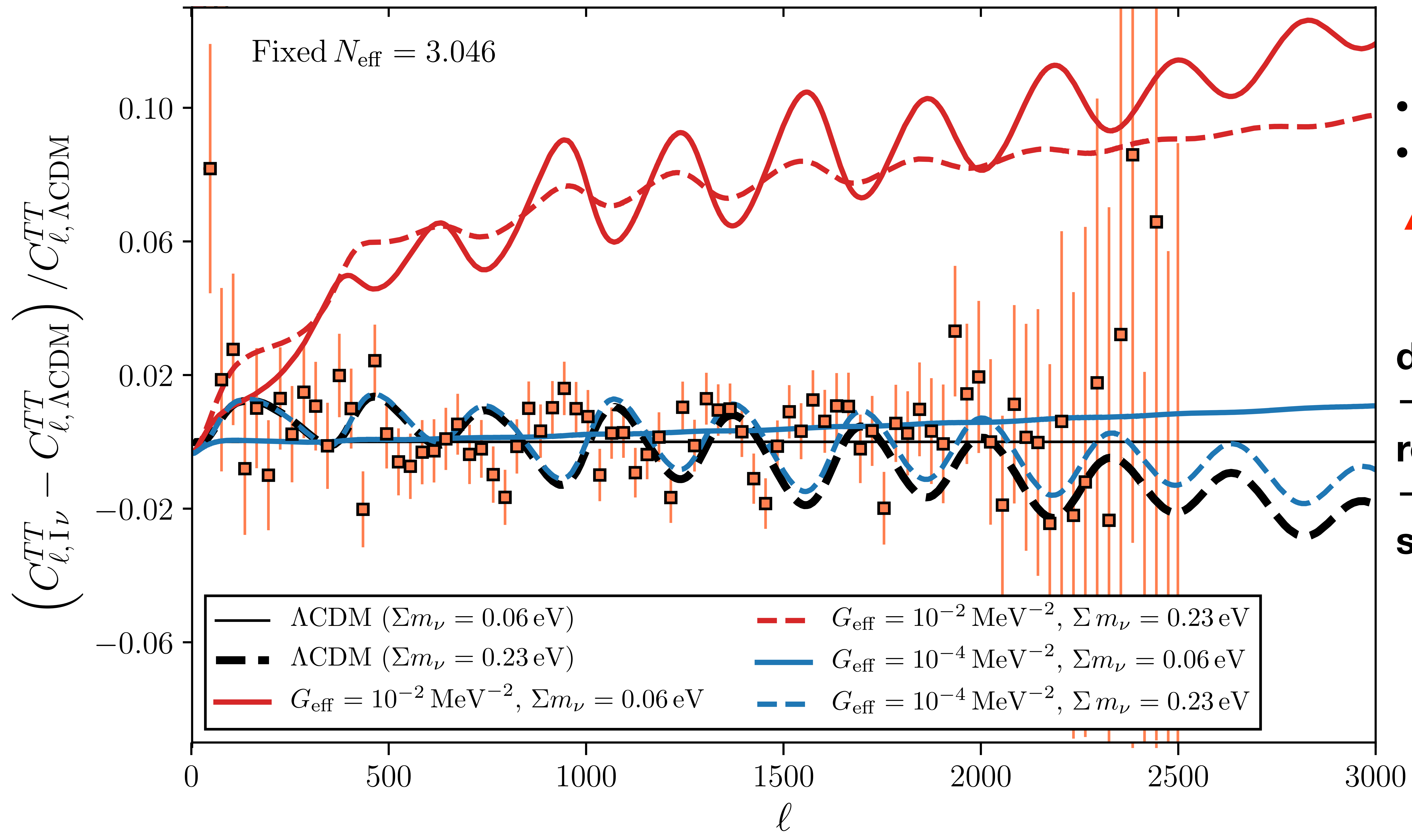
→ boost large scale and damps small scale power

Kreisch et al. 2019



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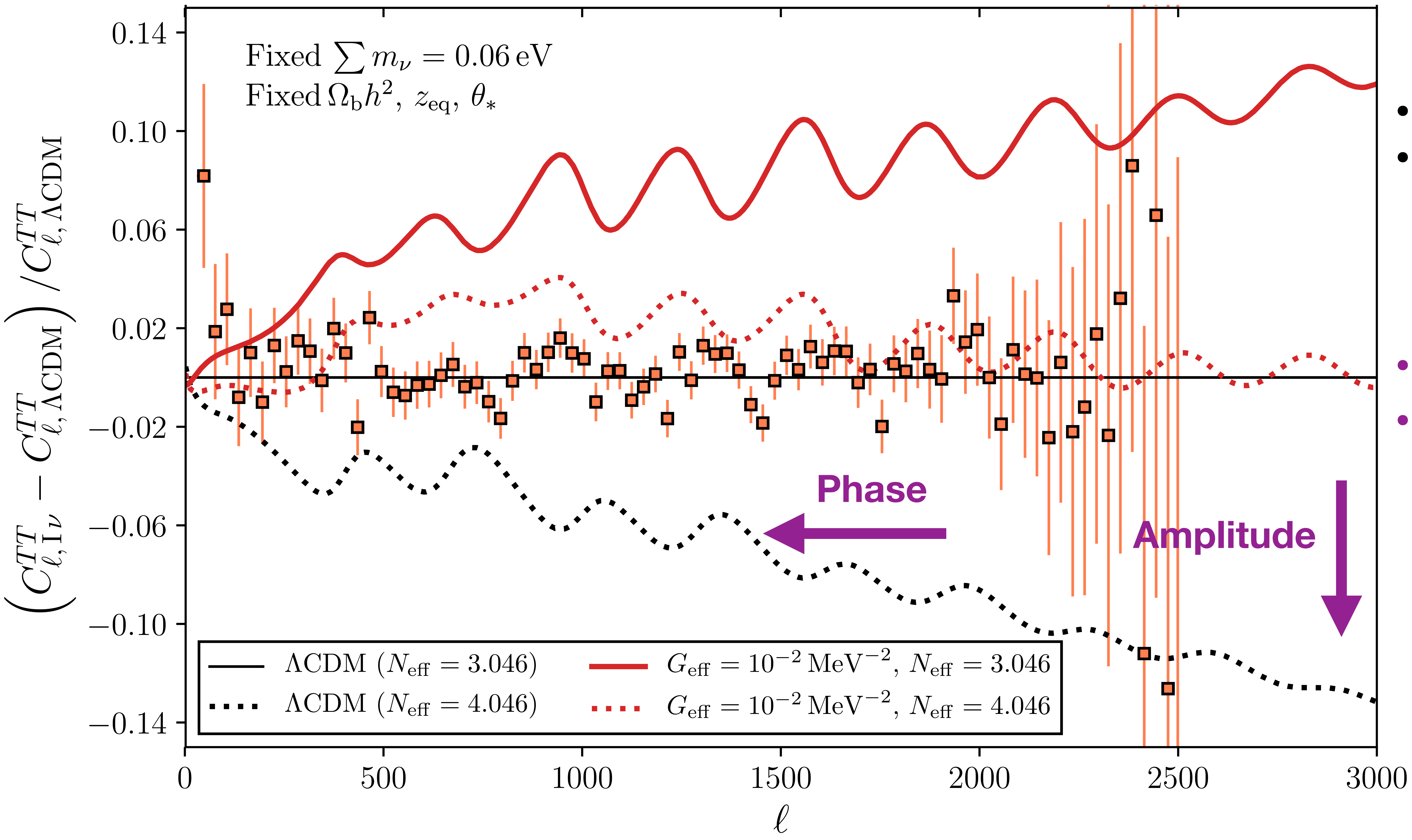
↑ $G_{\rm eff}$ + ↑ $\sum m_\nu$

cancellations in phase and amplitude
→effects of neutrino mass and interaction strength are additive

Kreisch et al. 2019



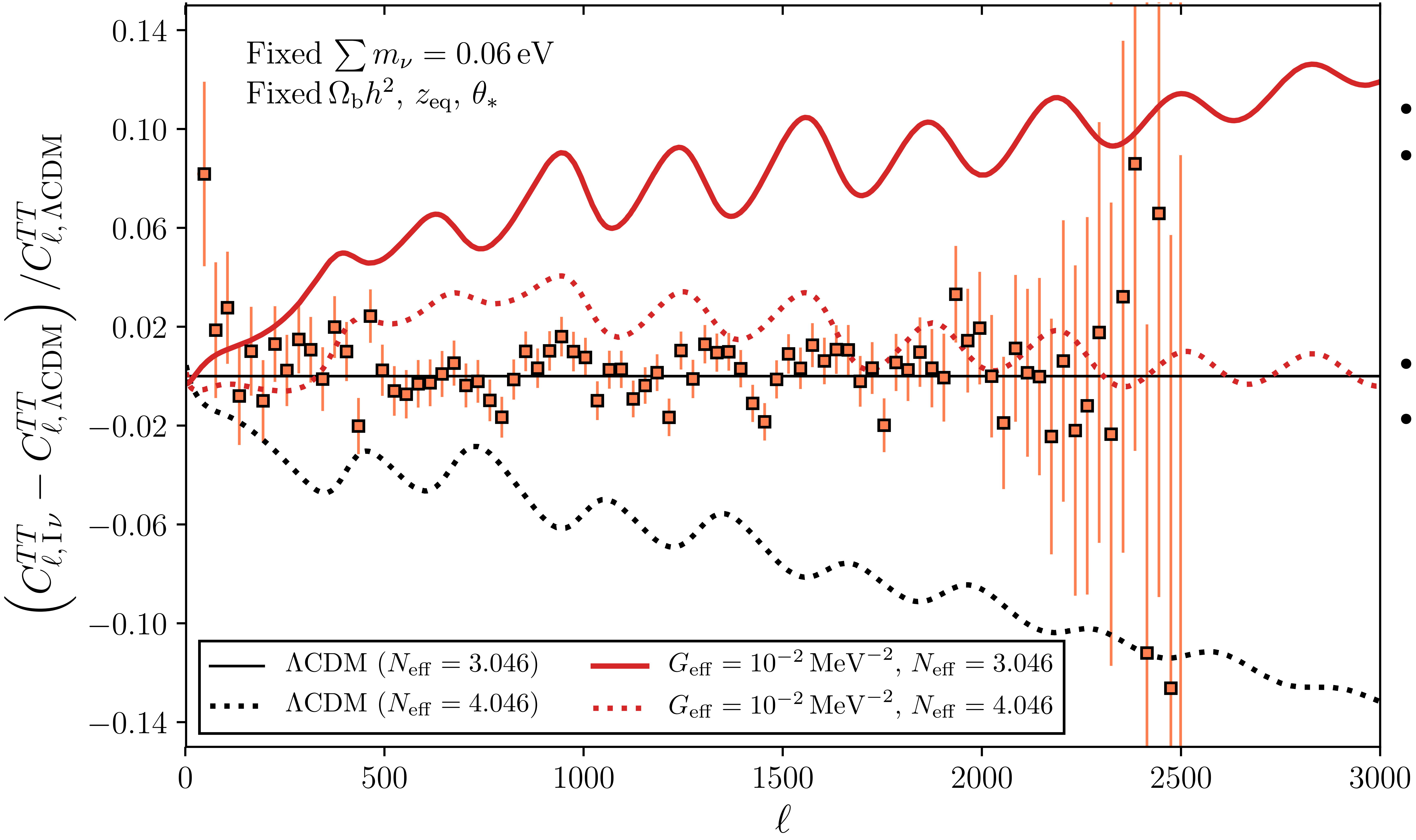
↑ G_{eff}

- **phase shift to small scales**
- **boost in amplitude**

↑ N_{eff}

- **phase shift to large scales**
- **damp high-ℓ tail**

Kreisch et al. 2019



↑ G_{eff}

- **phase shift to small scales**
- **boost in amplitude**

↑ N_{eff}

- **phase shift to large scales**
- **damp high-ℓ tail**

↑ G_{eff} **+** ↑ N_{eff}

some <u>cancellations</u> in phase and amplitude →alleviates damping from N_{eff}

Kreisch et al. 2019

So Far…

	Phase	Amplitude
$\uparrow G_{\mathrm{eff}}$	To small scales $\rightarrow$	$\uparrow$
$\uparrow \sum m_\nu$	To large scales $\leftarrow$	Scale-dependent (red tilt)
$\uparrow N_{\mathrm{eff}}$	To large scales $\leftarrow$	$\downarrow$

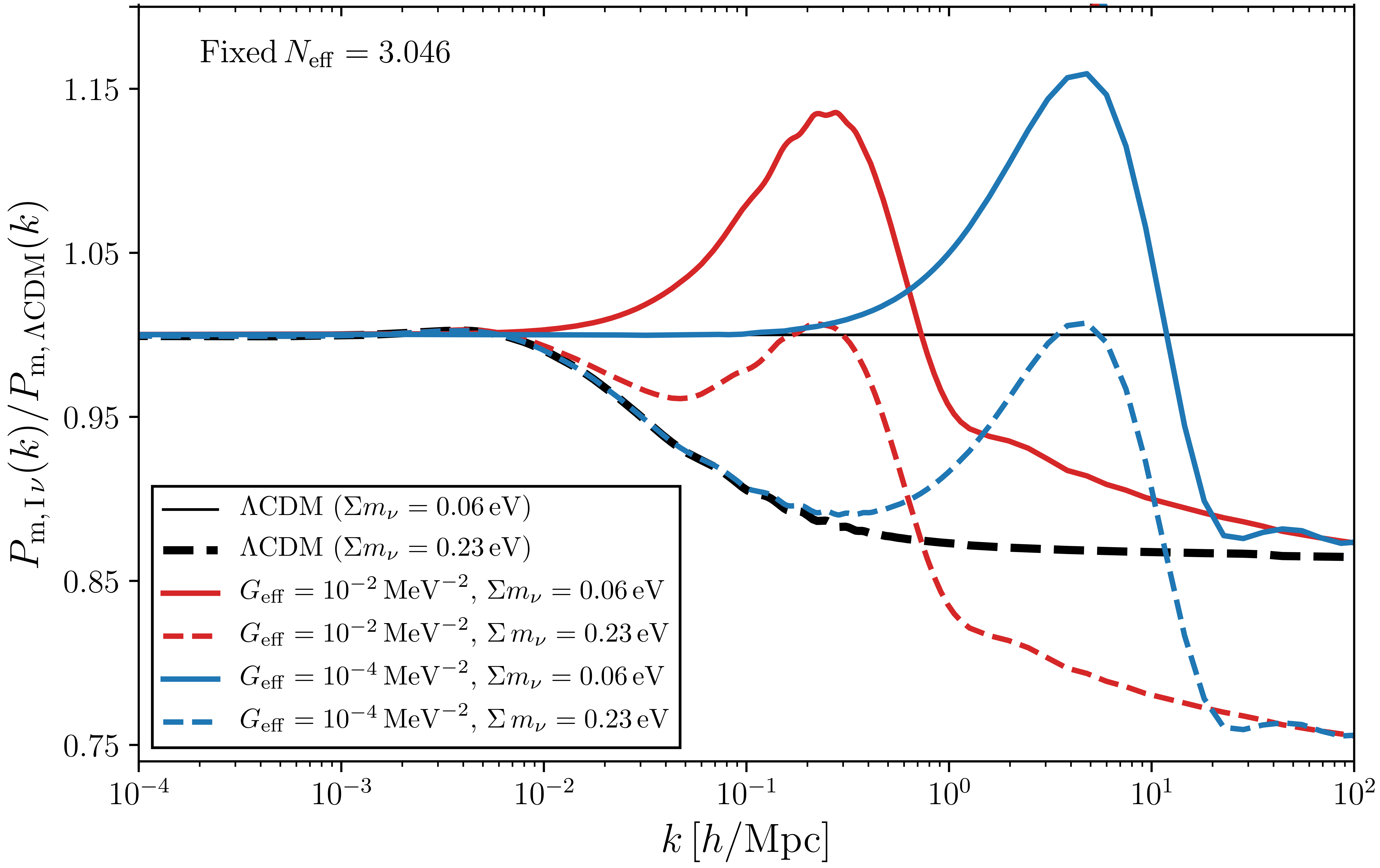
Phase important for *H_0* $\longrightarrow$ $r_* = \int_0^{a_*} \frac{c_{\mathrm{s}}(a)}{a^2 H(a)} da$

Strong interactions allow larger *N_{eff}*, and so smaller *r_{drag}*

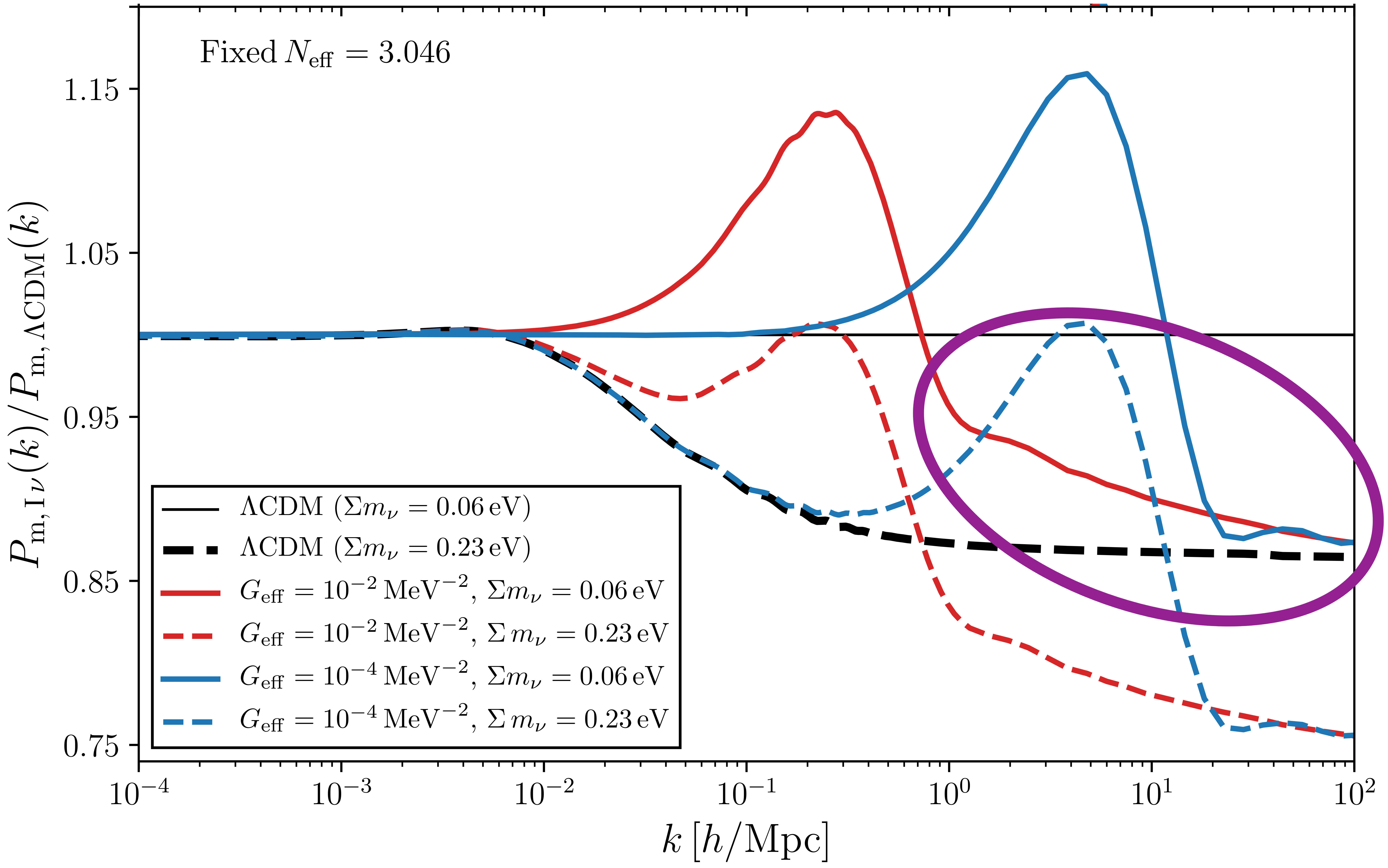
Matter Clustering

$\uparrow G_{\text{eff}}$

<u>Scale-dependent</u> impact



Kreisch et al. 2019



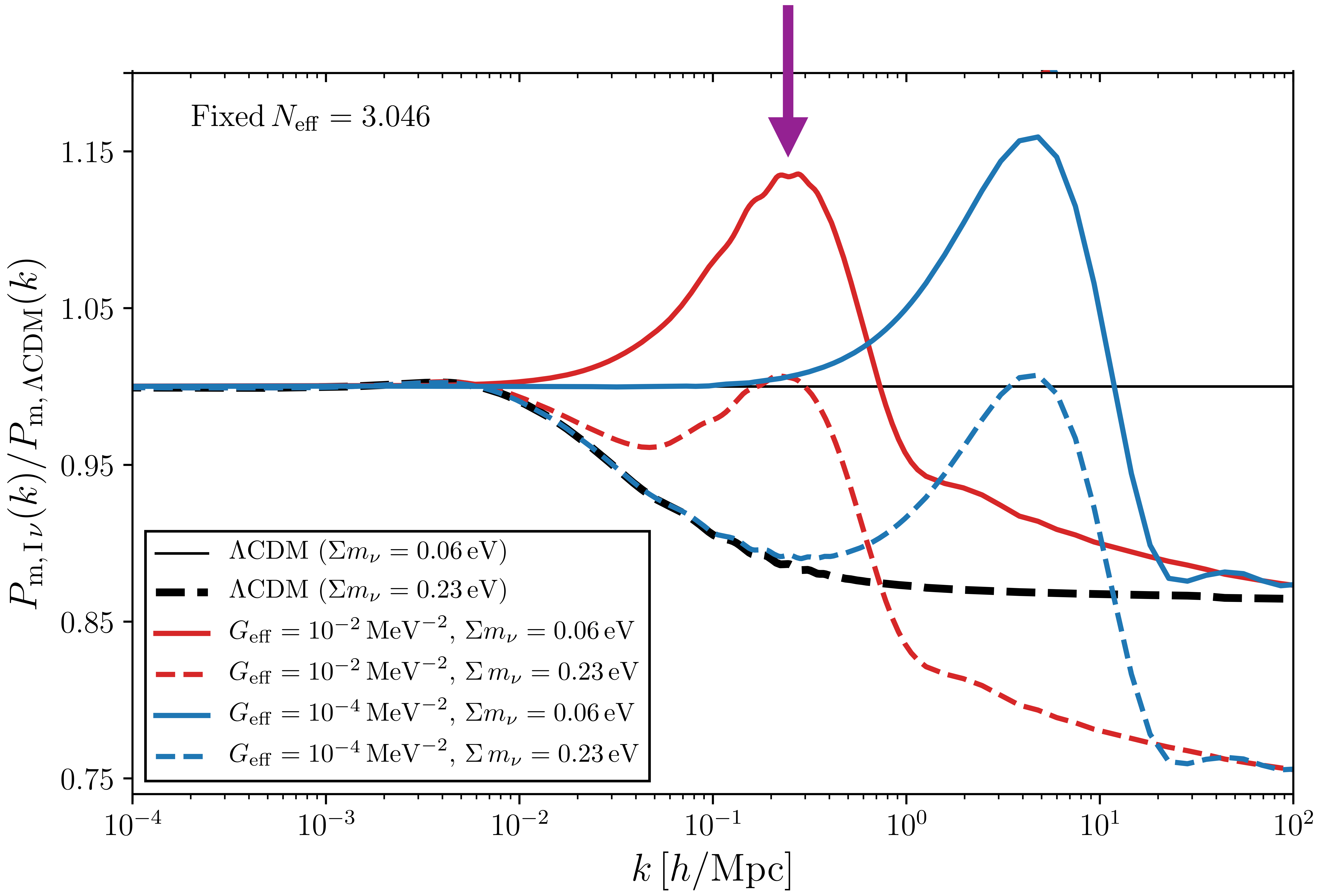
↑ G_{eff}

Scale-dependent impact

1. **Small scales: modes enter horizon while neutrinos still self-scatter**
   - **absence of anisotropic stress leads to longer decay of potential → damps DM fluctuations**

Kreisch et al. 2019

Neutrino-Neutrino Decoupling



↑ $G_{\rm eff}$

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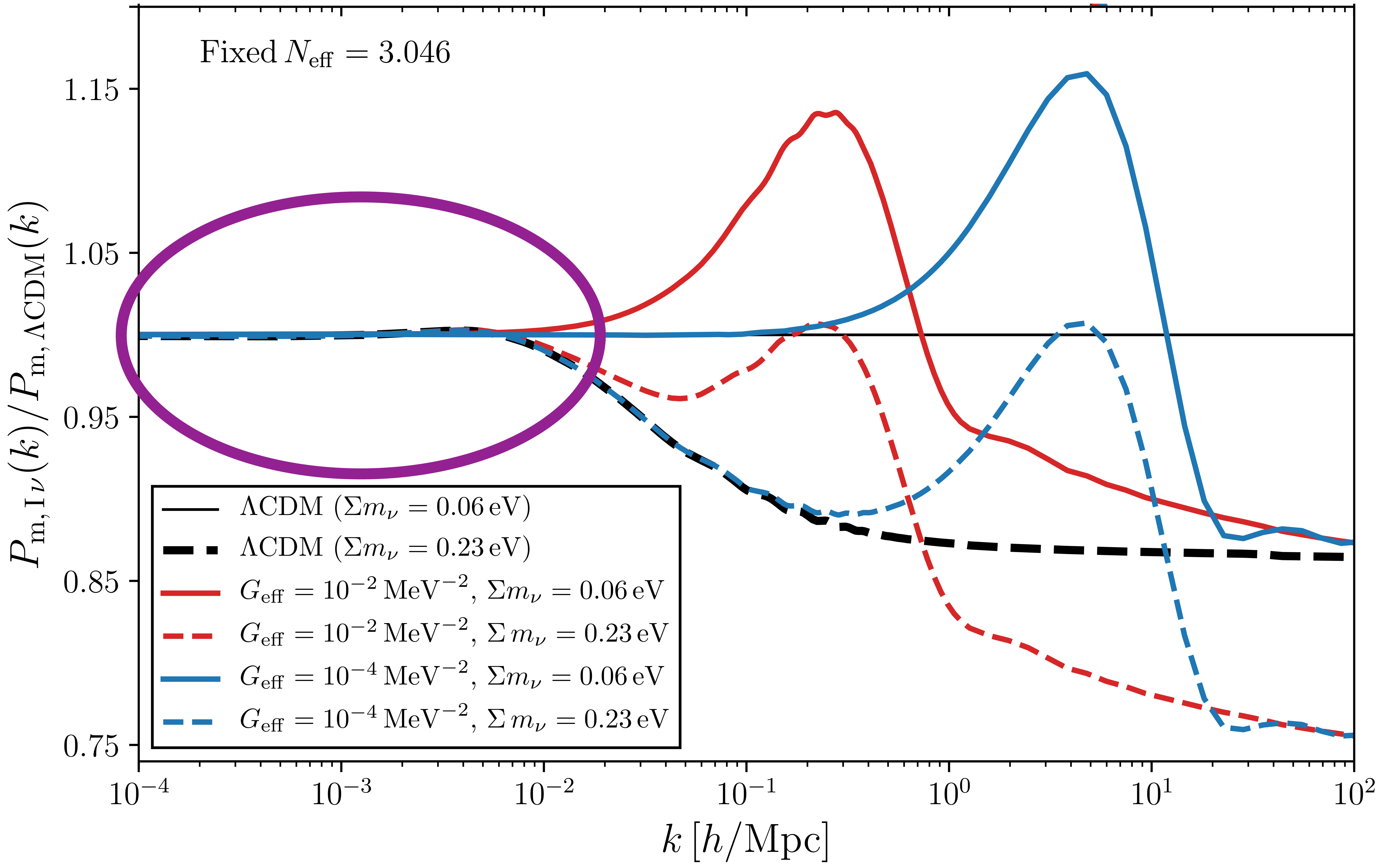
2. Epoch of neutrino-neutrino decoupling
   - potential decays from boosted value, as before, BUT locks into ΛCDM evolution and quickly decays
     → boosts DM fluctuations

Kreisch et al. 2019

↑ G_{eff}



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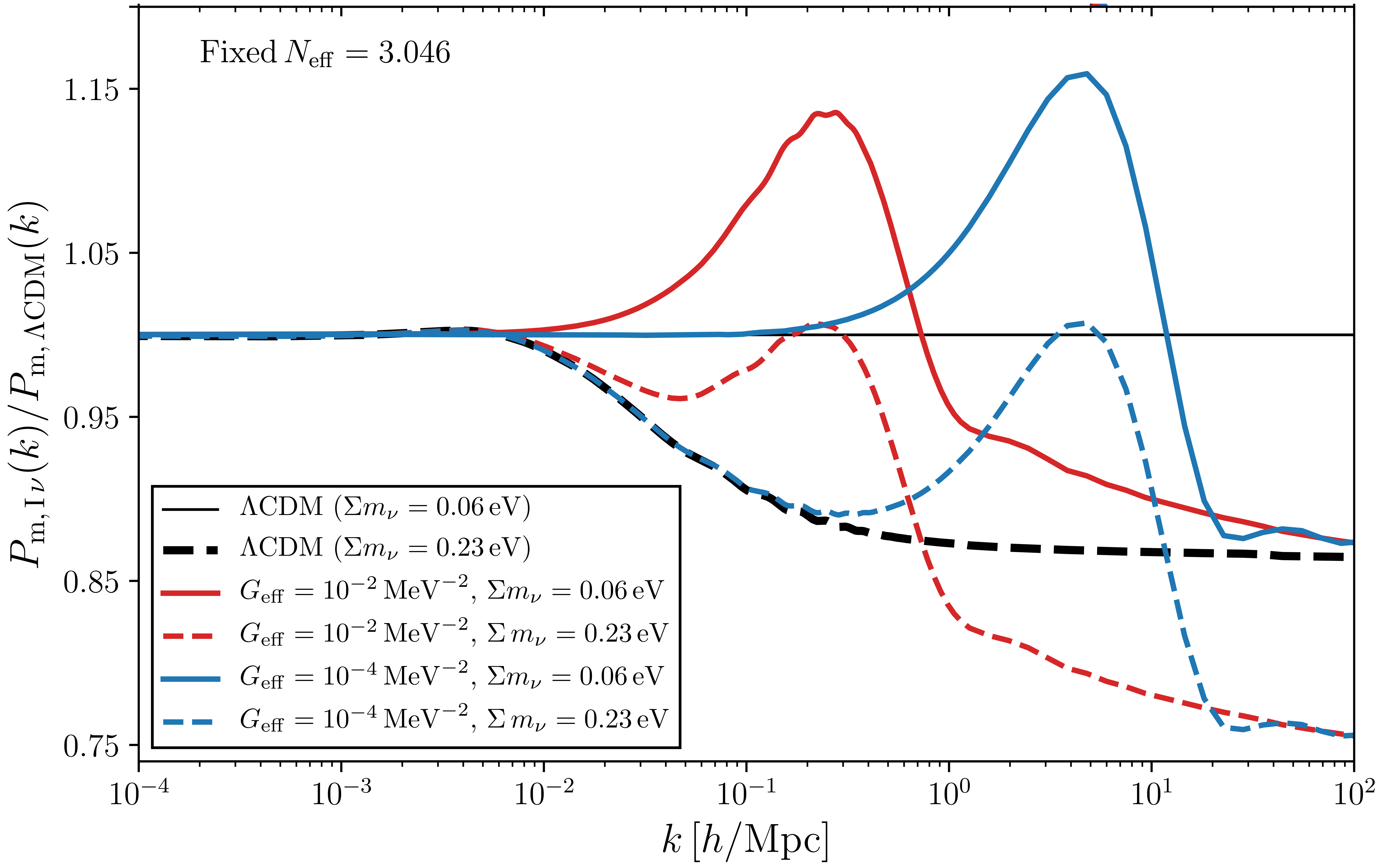
3. **Large scales: standard ΛCDM**

Kreisch et al. 2019



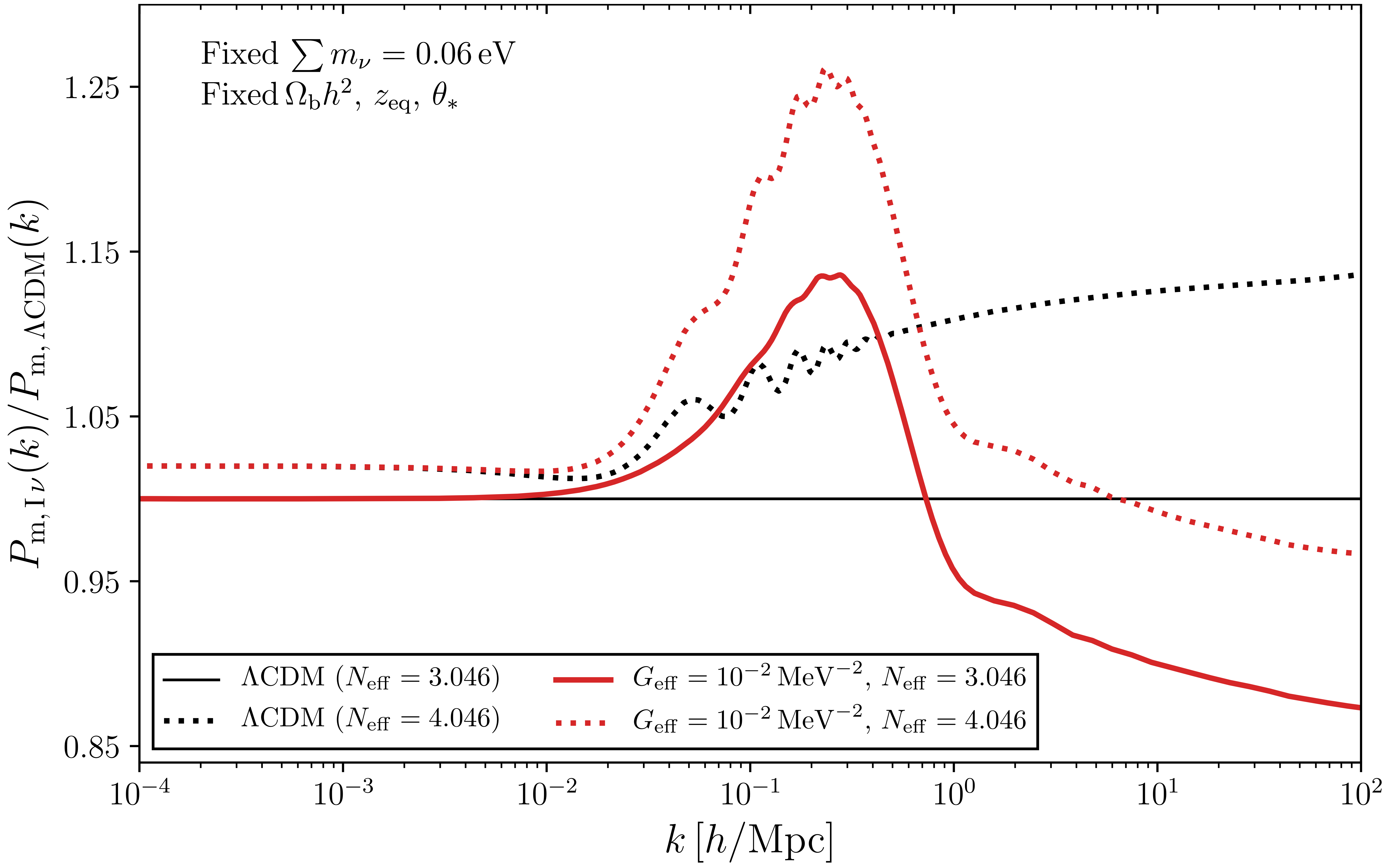
↑ $\sum m_\nu$

Damps small-scale power (e.g. Lesgourgues 2006)

↑ $G_{\rm eff}$ + ↑ $\sum m_\nu$

Small-scale power suppressed from both →effects of neutrino mass and interaction strength are additive

Kreisch et al. 2019



↑ N_{eff}

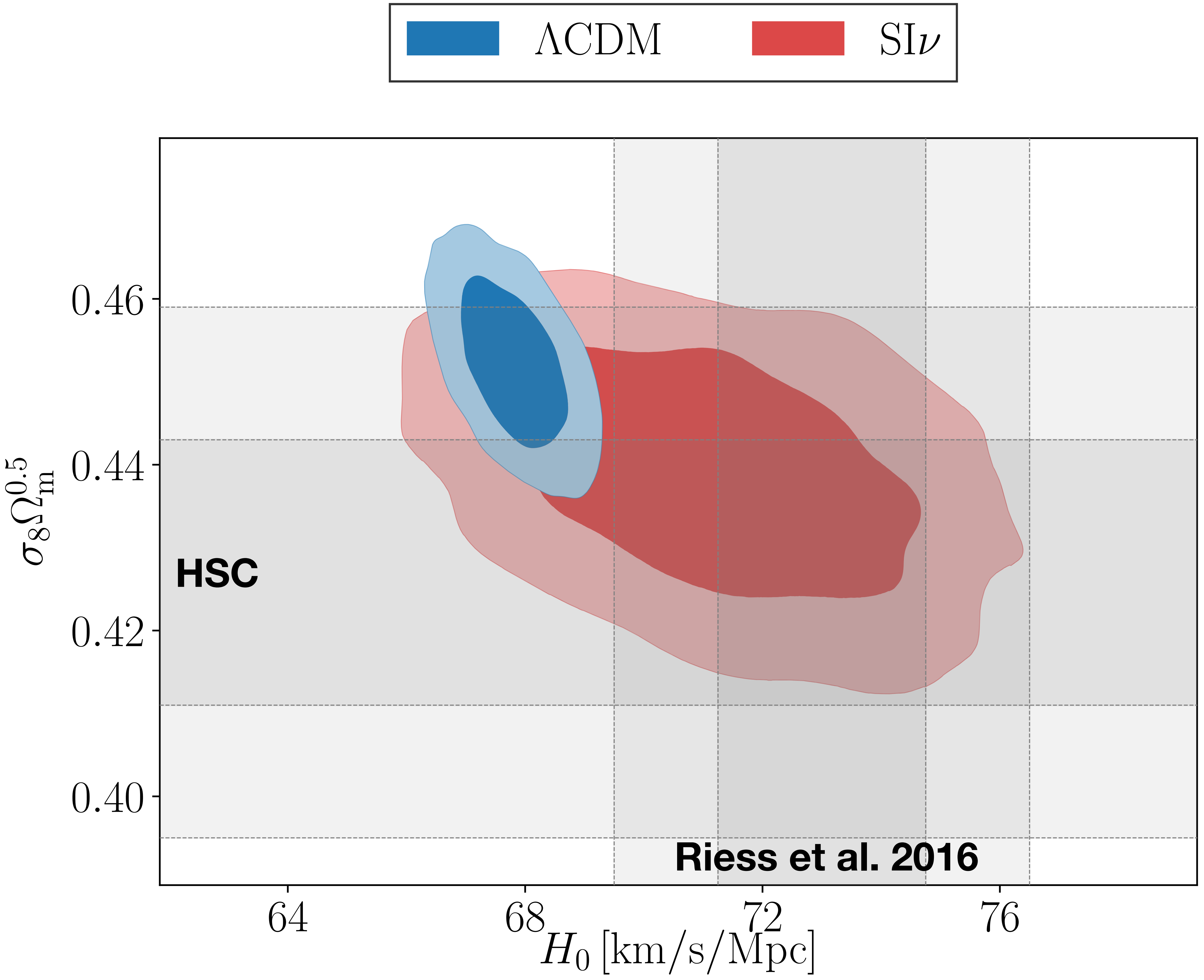
Boosts small-scale power (Bashinsky & Seljak 2004)

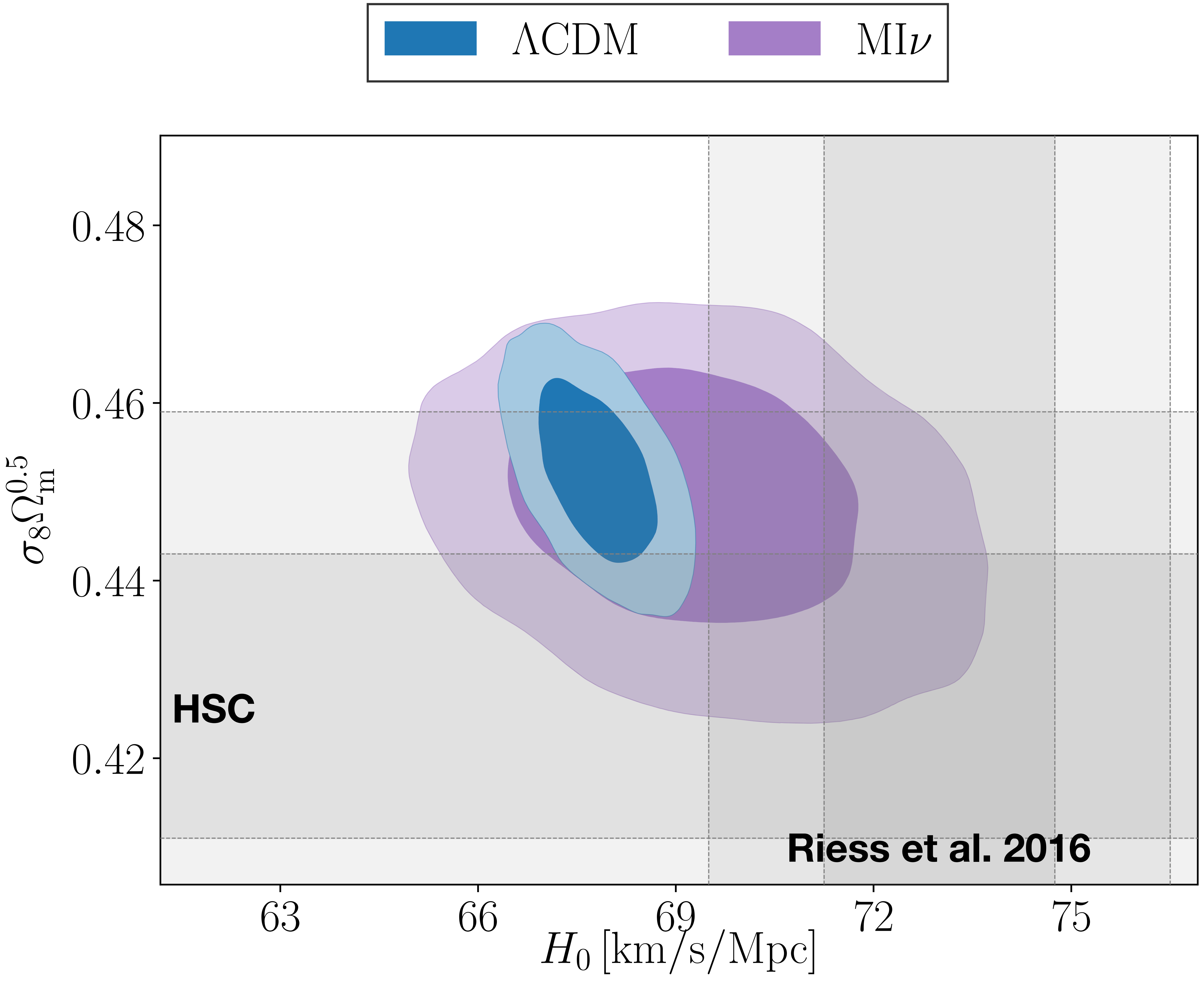
↑ G_{eff} + ↑ N_{eff}

<u>cancellations</u> in small-scale power

Kreisch et al. 2019


74.0 km/s/Mpc
67.4 km/s/Mpc
A Remedy for Cosmological Tensions?





Strong neutrino interactions independently produce preferred S_8 and H_0 values without using these measurements

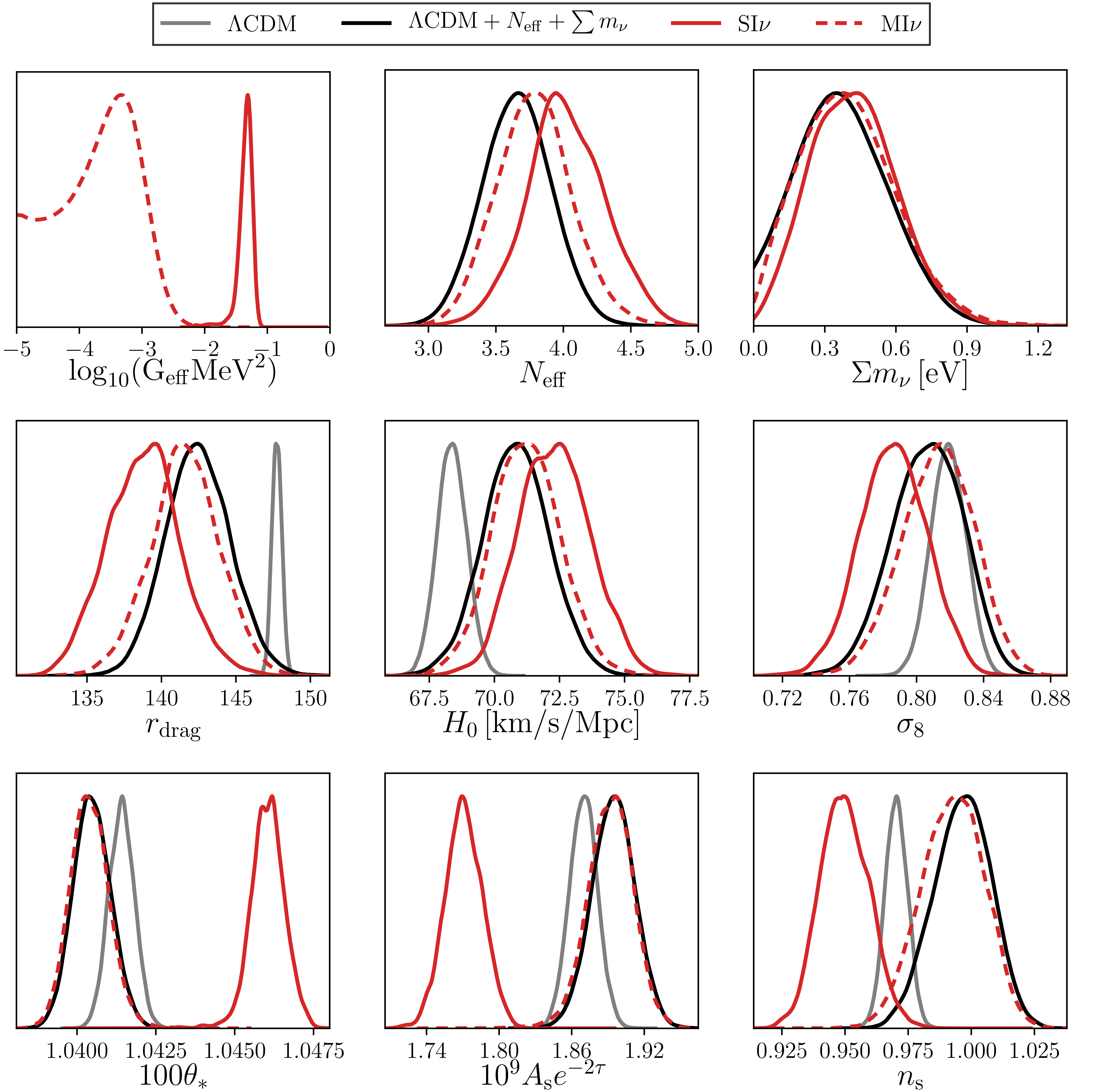
Kreisch et al. 2019

TT+lens+BAO+H₀

Bimodal: phase shift for all multipoles or none

- **Recall**

  $G_F \sim \mathcal{O}(10^{-11}\,\mathrm{MeV}^{-2})$



Kreisch et al. 2019

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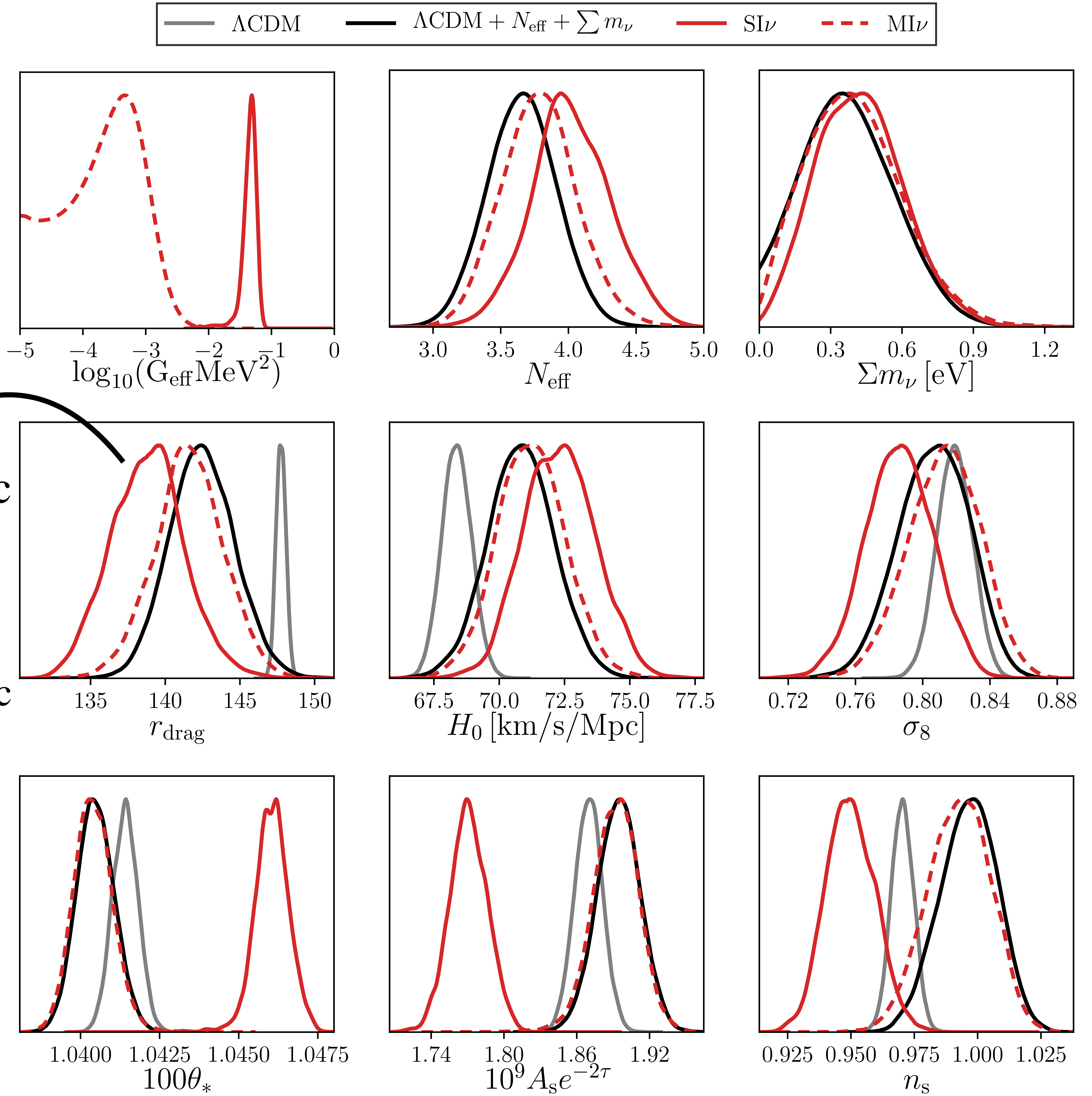

$r_{\rm drag} = 138.8 \pm 2.5\,\mathrm{Mpc}$

helps reconcile BAO with local H_0

$H_0 = 72.3 \pm 1.4\,\mathrm{km/s/Mpc}$

Kreisch et al. 2019

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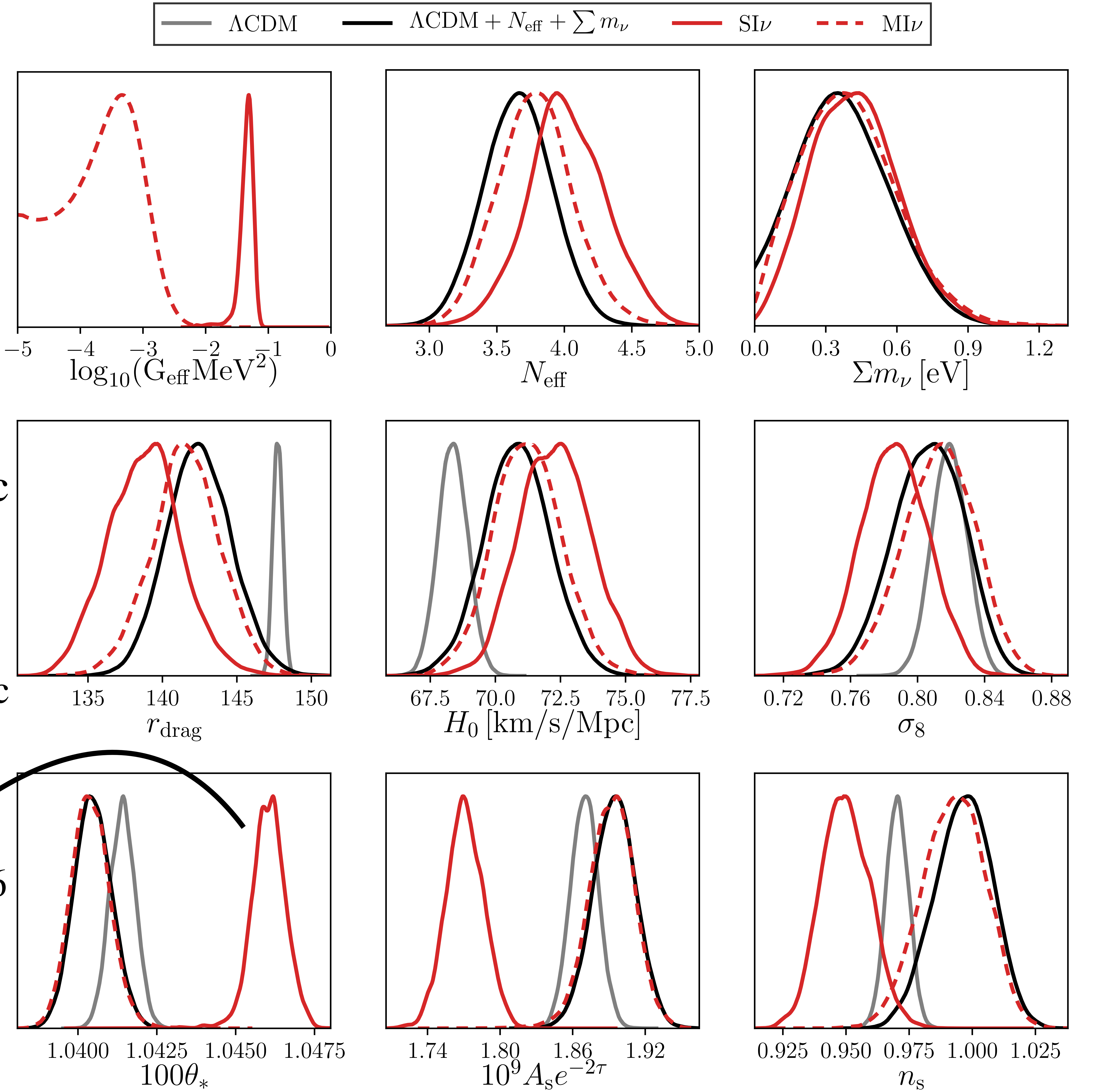
$$100\theta_* = 1.04604 \pm 0.00056$$

absence of free-streaming phase shift

offset phase shift to small scales



Kreisch et al. 2019

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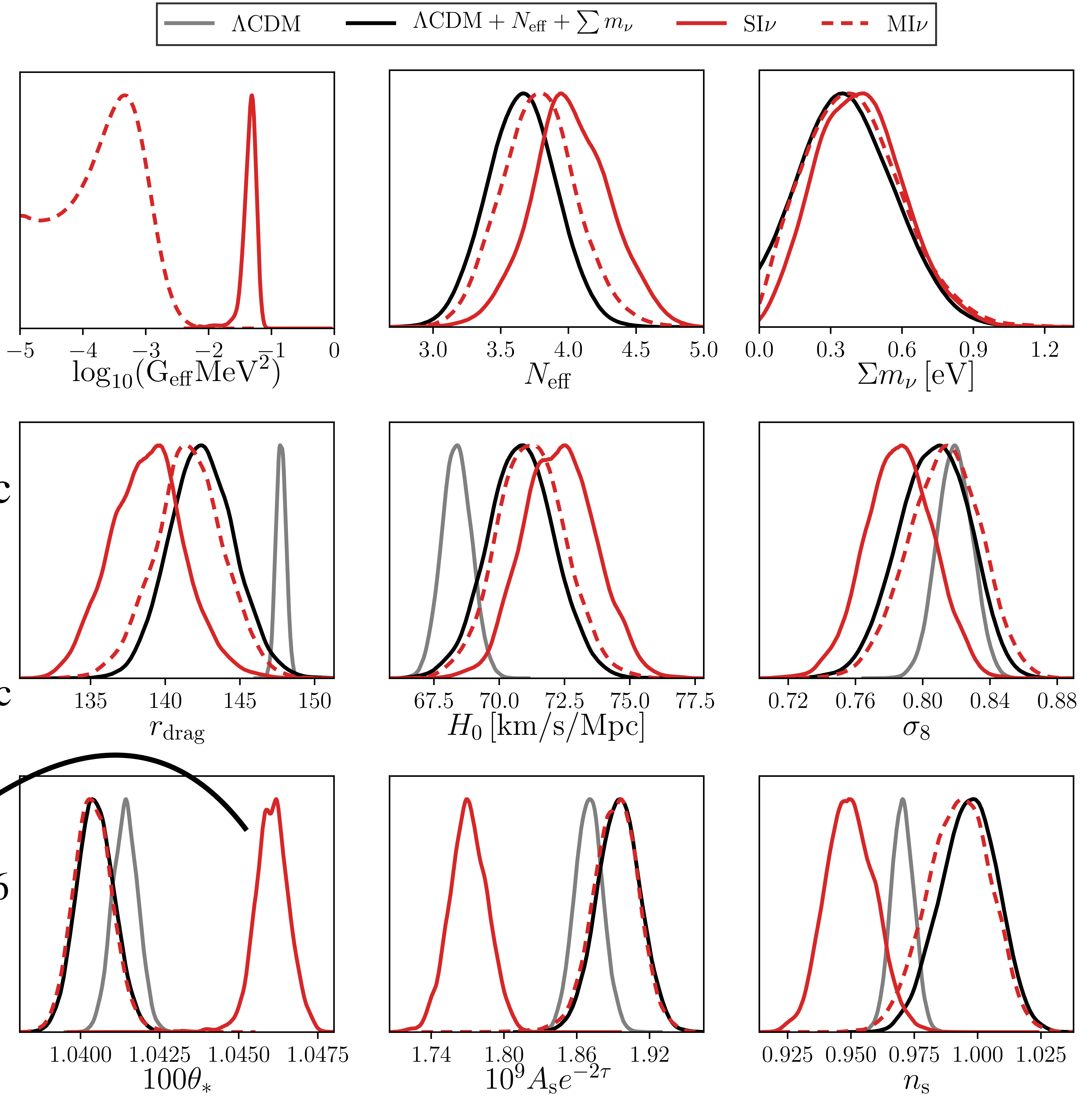

A_s: offset amplitude boost

n_s: offset slight blue tilt

Kreisch et al. 2019

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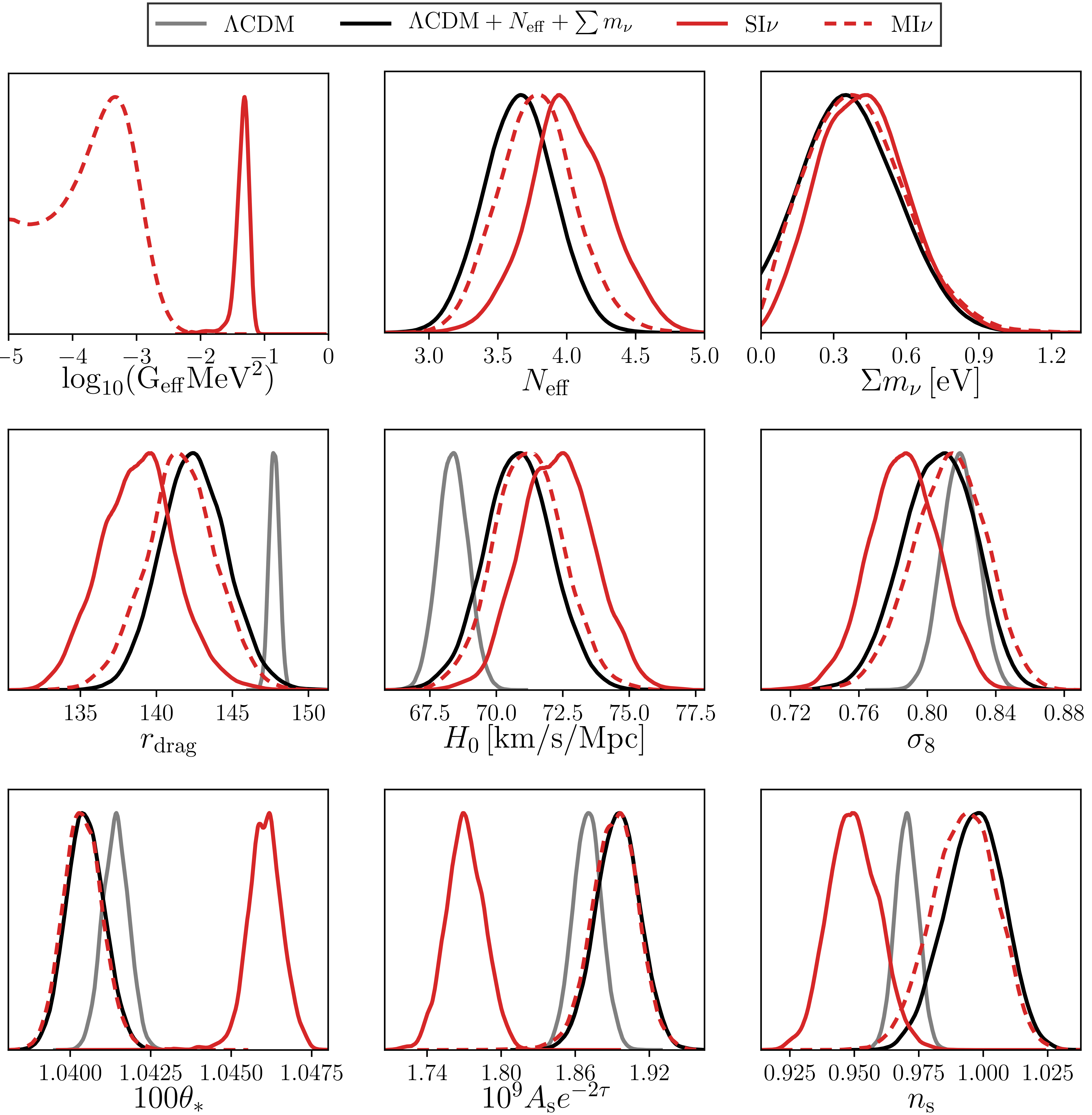

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$$\sigma_8 = 0.786 \pm 0.020$$

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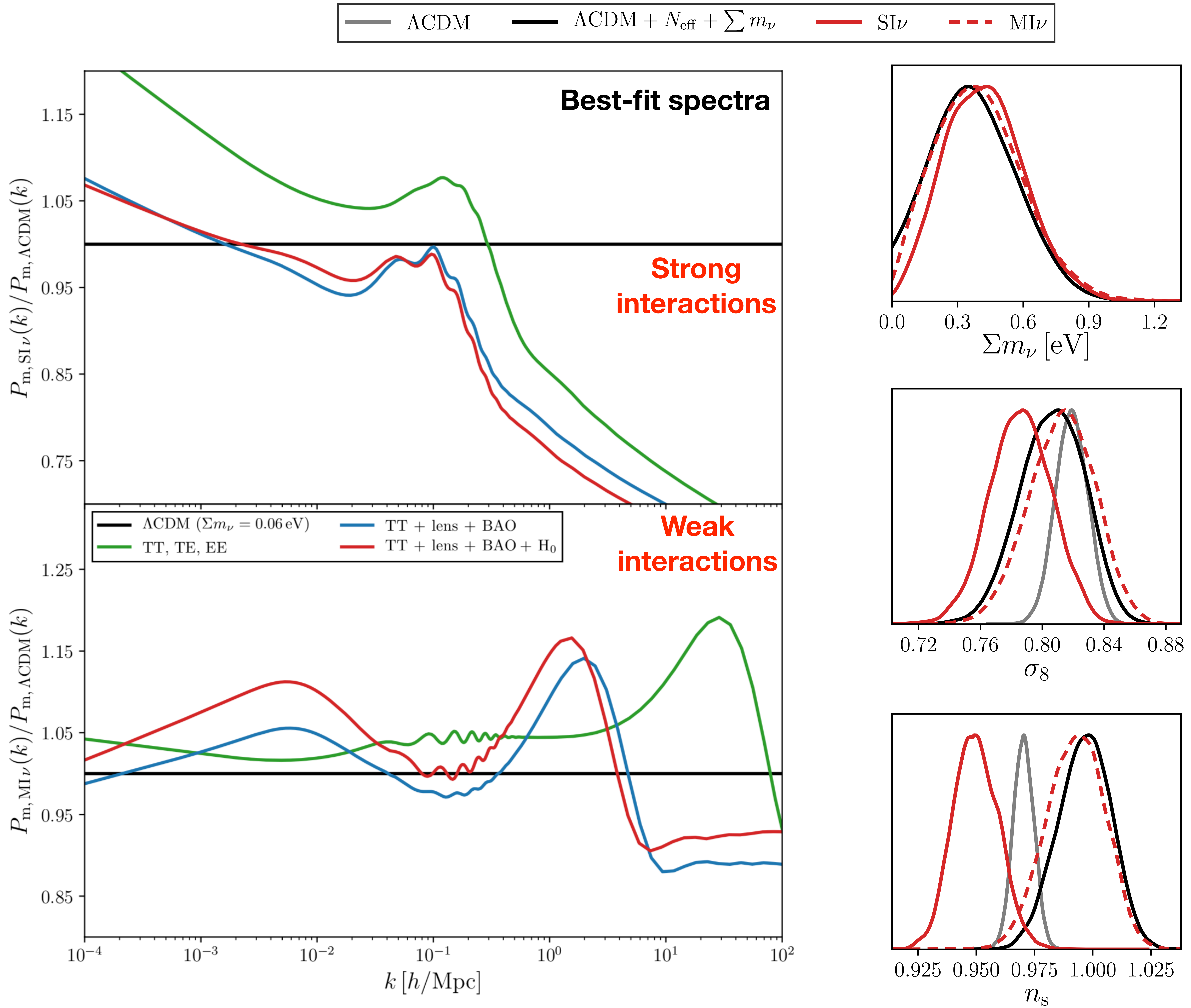
Kreisch et al. 2019

TT+lens+BAO+H$_0$



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Kreisch et al. 2019

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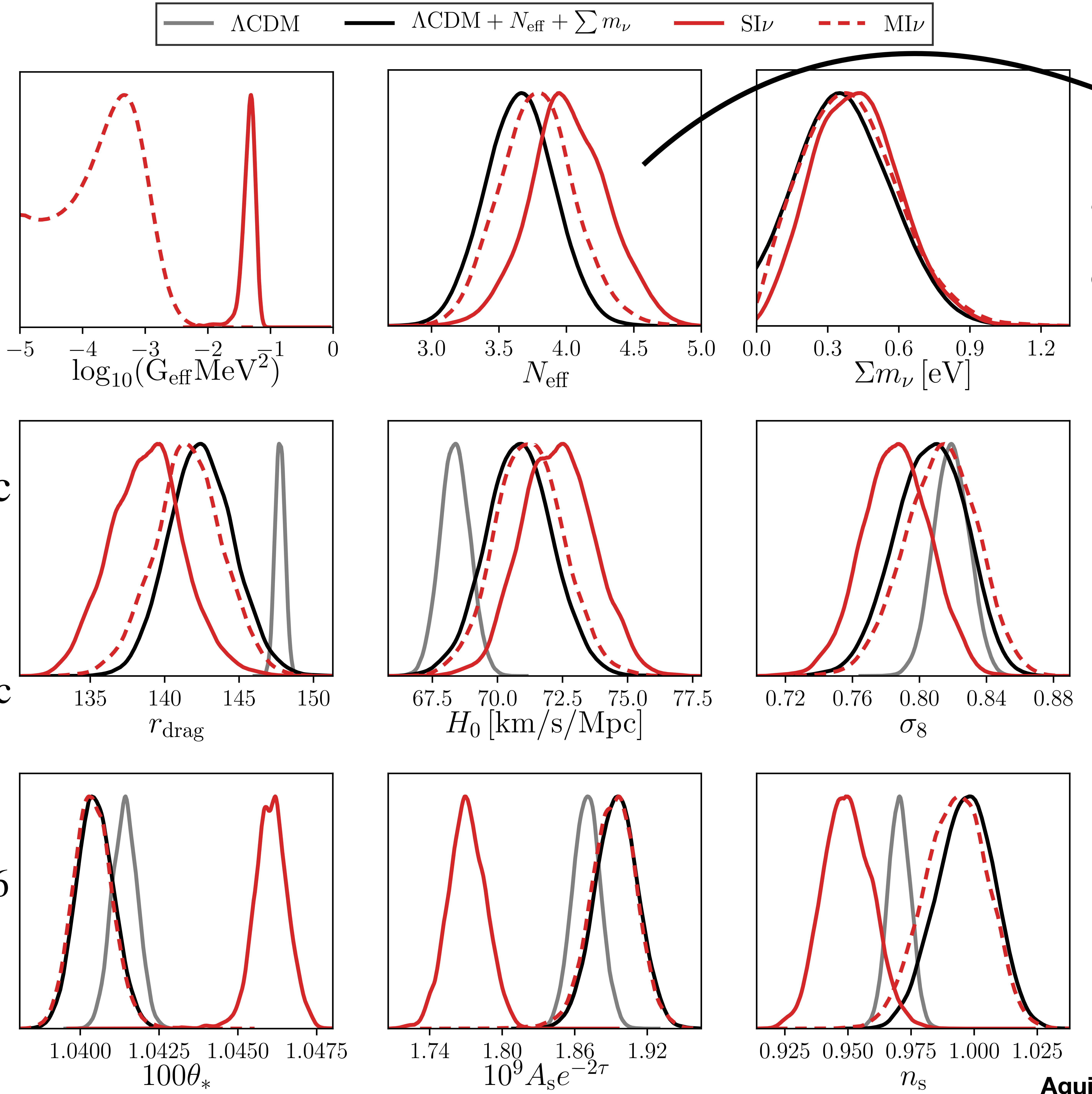

$N_{\mathrm{eff}} = 4.02 \pm 0.29$

additional neutrino species??

→may help with neutrino experiment tensions

MiniBooNe + LSND:

$\nu_\mu \to \nu_e$ **appearance**

$\sigma_8 = 0.786 \pm 0.020$

- **low A_s and n_s damp scales**
- **boost at decoupling coincident with BAO**

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Kreisch et al. 2019

Aguilar-Arevalo et al. (LSND), (2001)

Aguilar-Arevalo et al. (MiniBooNE), (2018)

Interacting neutrinos a success due to multi-parameter degeneracy

G_{eff}

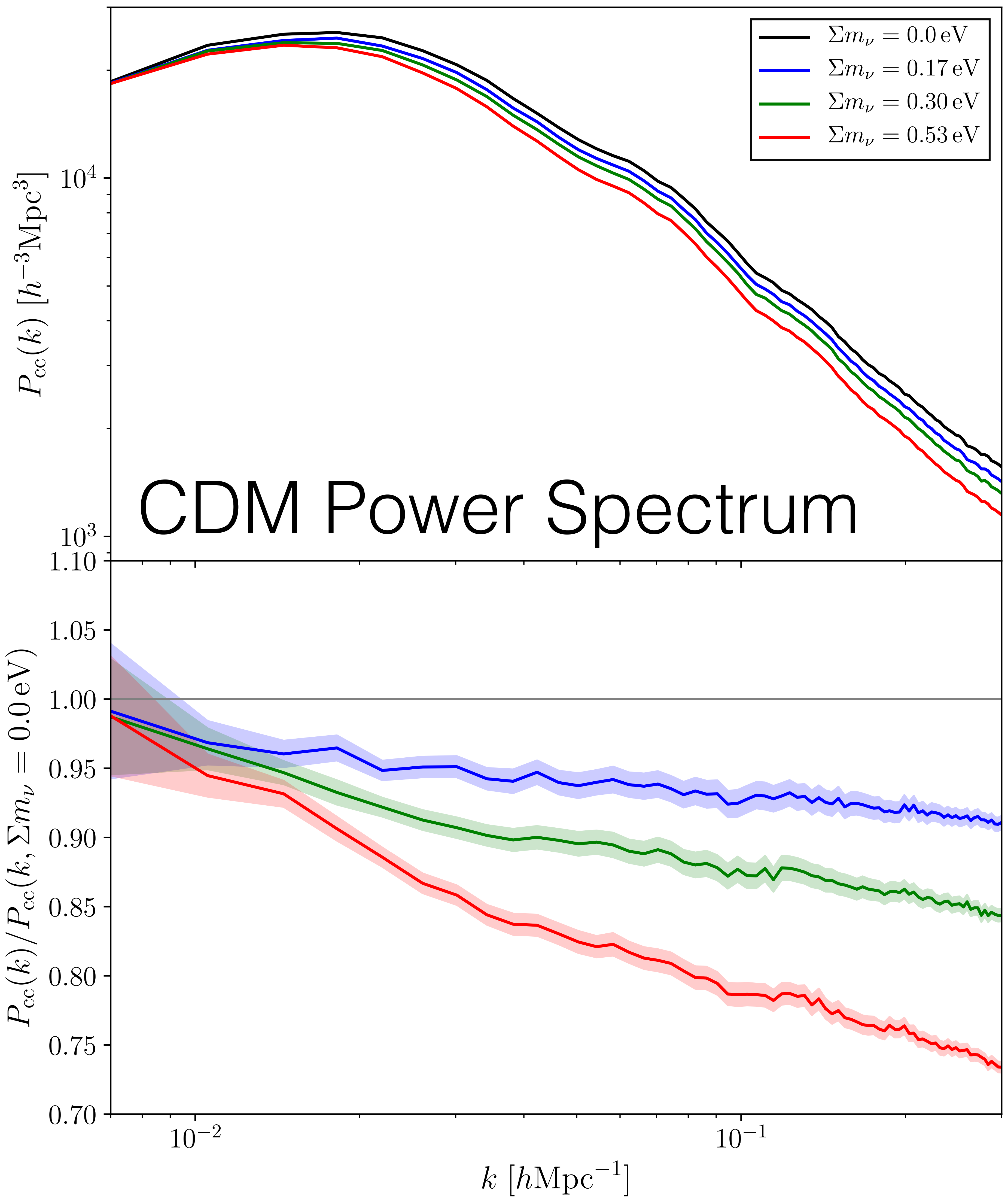
delays neutrino
free-streaming

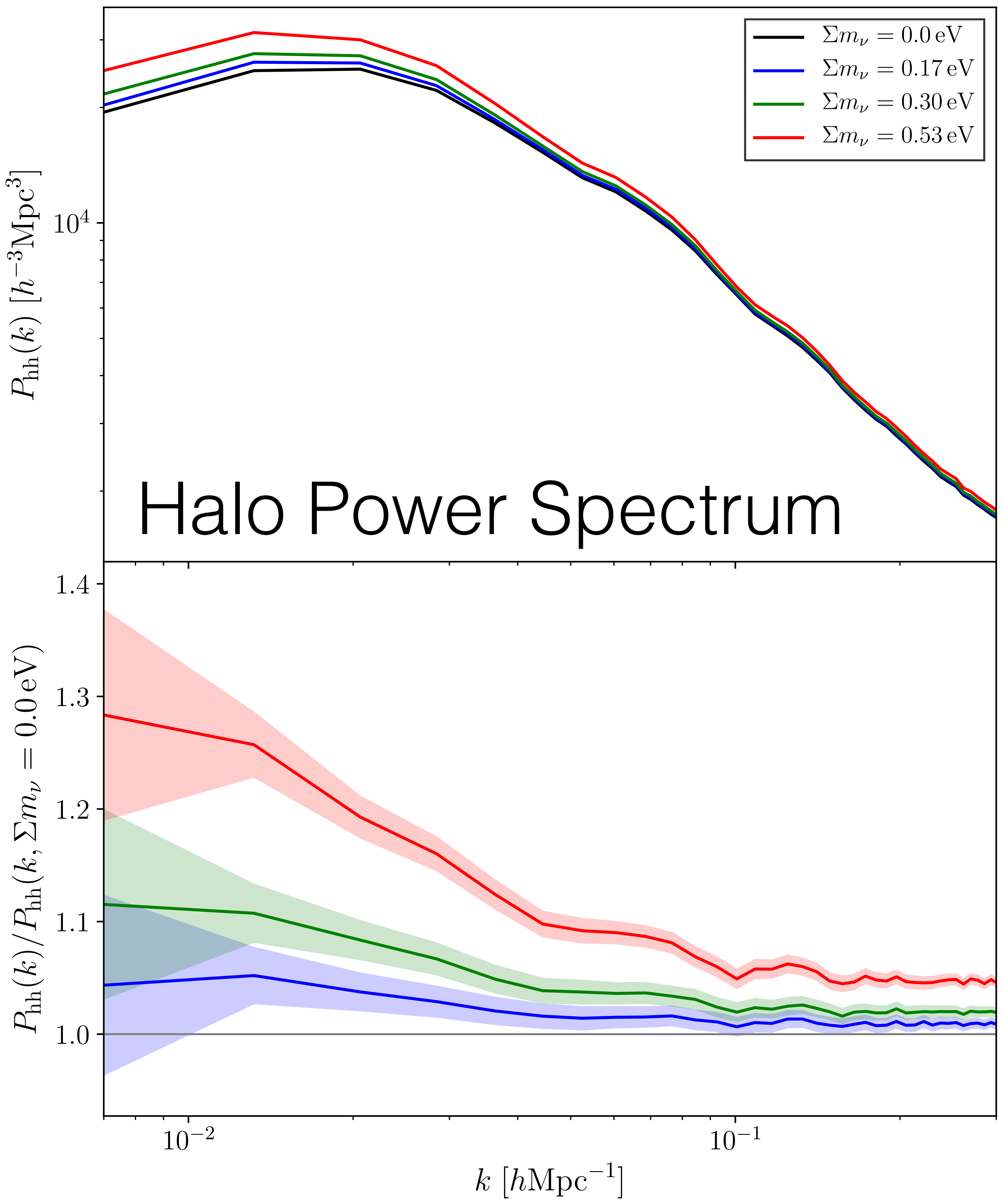
impact on
phase & amplitude

$N_{\mathrm{eff}}, \sum m_\nu, \theta, A_{\mathrm{s}}, n_{\mathrm{s}}, r,$
and, thus, H_0 respond

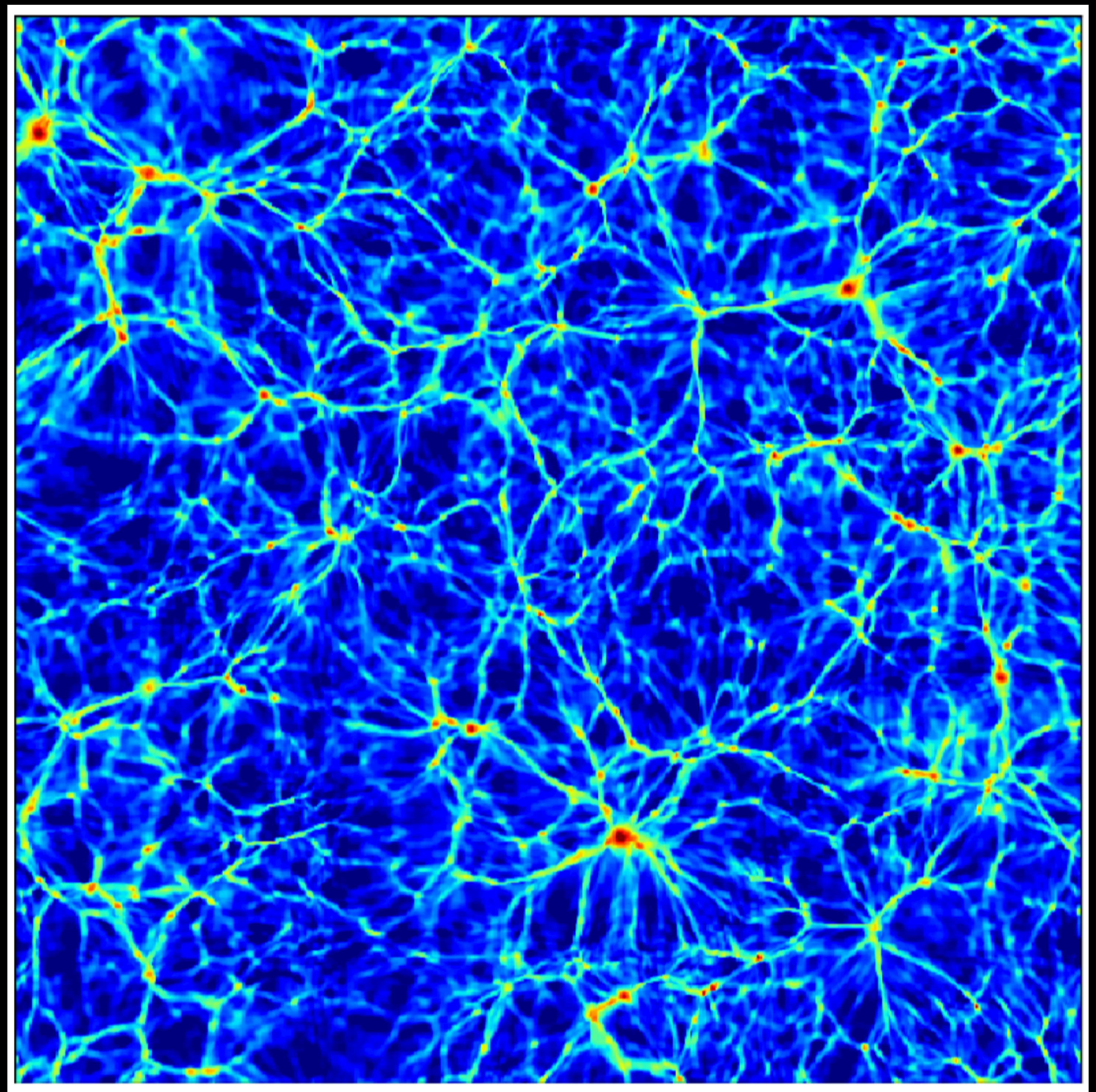
Neutrino Degeneracies

Can we break this degeneracy?

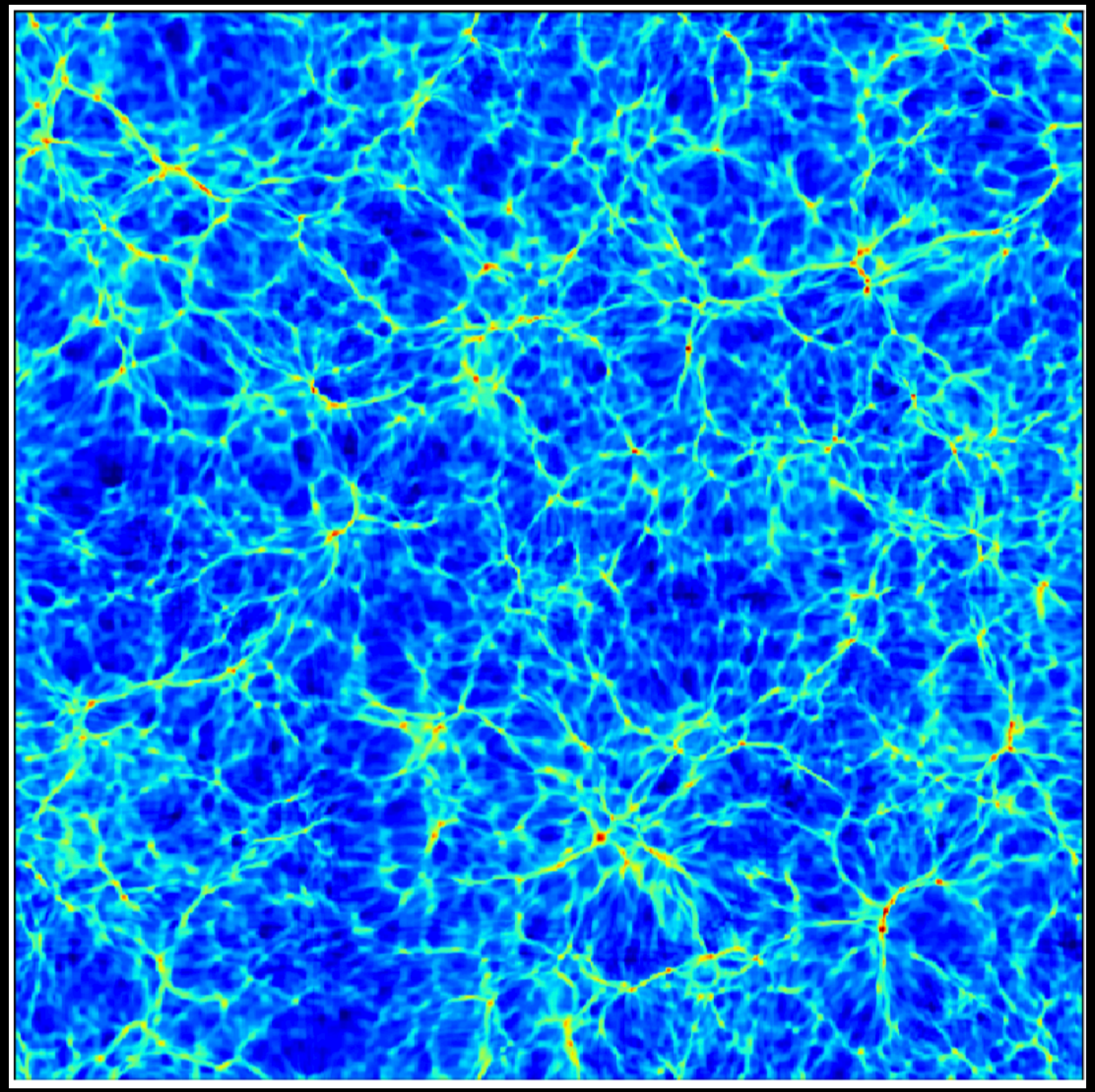




Impacts structure formation!



0.0 eV



2.0 eV

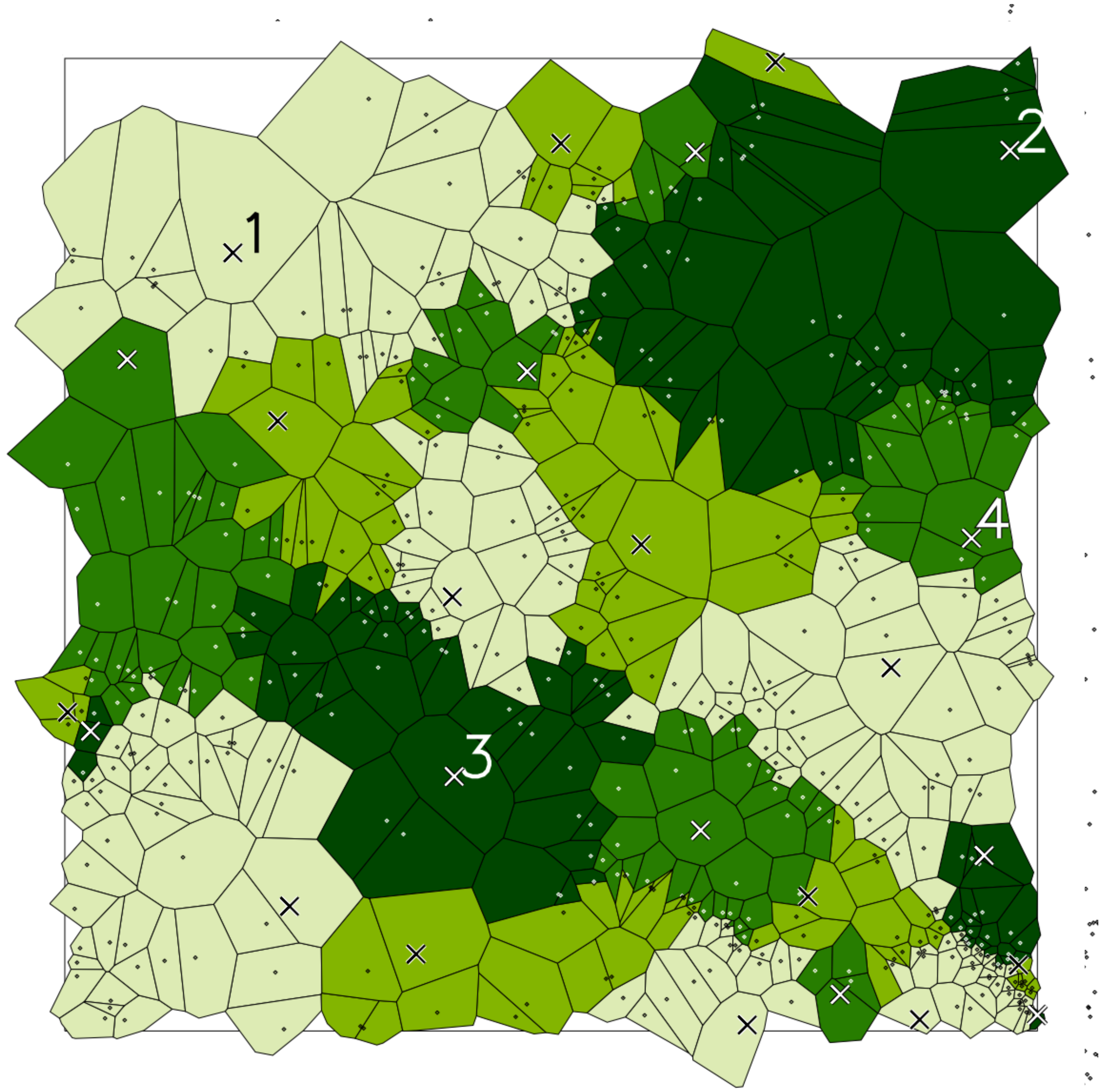
Agarwal & Feldman 2010

What are Cosmic Voids

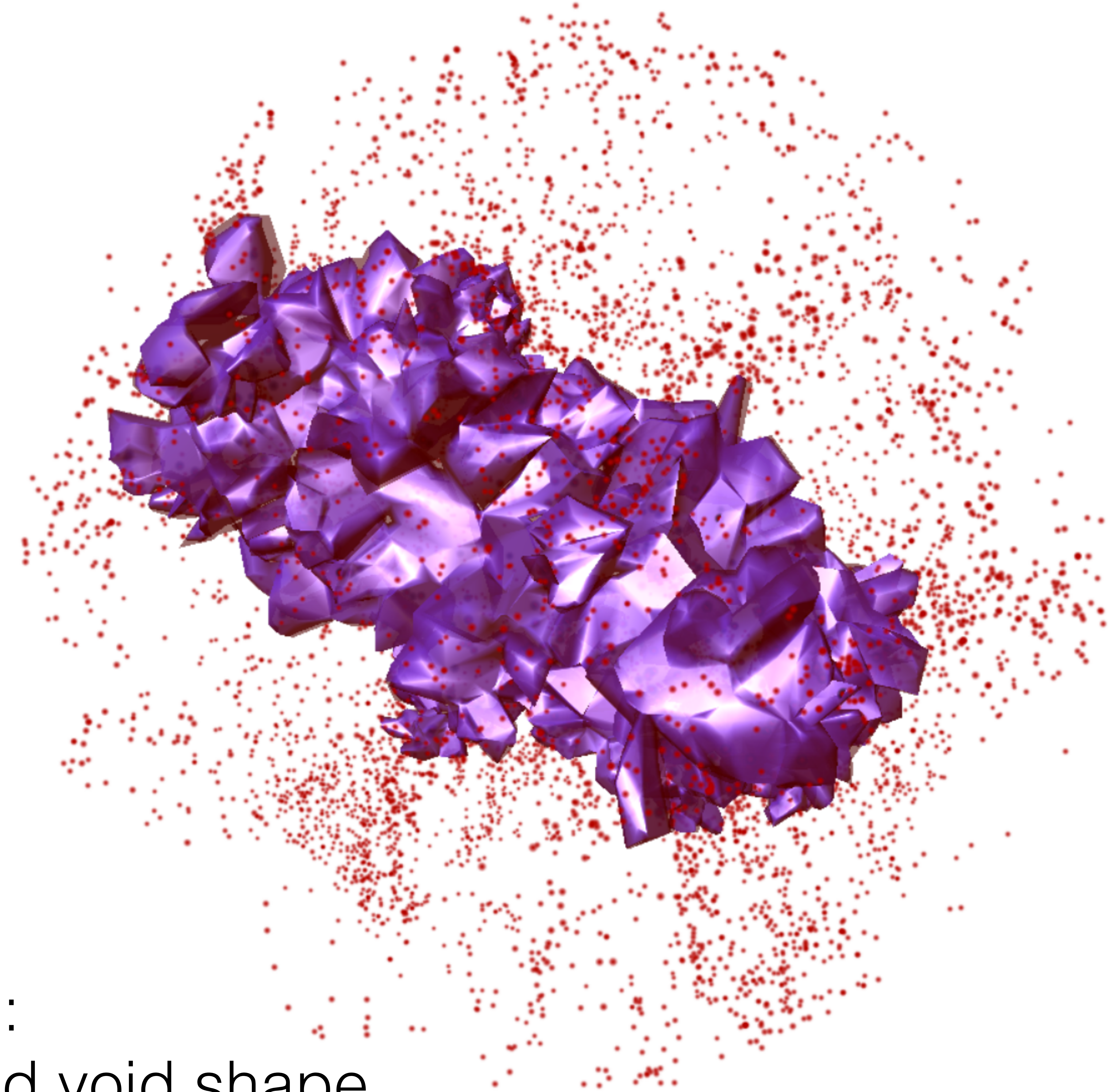
How do we Find Them?


Time since the Big Bang: 2.7 billion years
ILLUSTRIS

Finding Voids



Zobov, Neyrinck 2008



Captures:
- Detailed void shape
- Hierarchical pattern of cosmic web

VIDE, Sutter et al. 2014

Neutrinos

+

Voids

(arXiv: 1808.07464)

Voids are Sensitive Probes

Pristine environments:

- Undergo minimal virialization
- Maintain initial conditions

A complementary probe to CMB and galaxy cluster measurements:

- RSD and relative growth rate of cosmic structure
- Alcock- Paczyński distortions
- Weak gravitational lensing
- BAO
- ISW
- Dark energy

Beyond the Standard Model Physics:

- Modified gravity

Neutrino free-streaming ~ void sizes

- Void sizes:

$$R_{\rm V} \approx 10 - 100\, h^{-1}{\rm Mpc}$$

- Neutrino free-streaming scales:

$$r_{\rm FS} = 130 h^{-1}{\rm Mpc} \quad \text{for} \quad \Sigma m_\nu = 0.06\,{\rm eV}$$

$$r_{\rm FS} = 39 h^{-1}{\rm Mpc} \quad \text{for} \quad \Sigma m_\nu = 0.6\,{\rm eV}$$

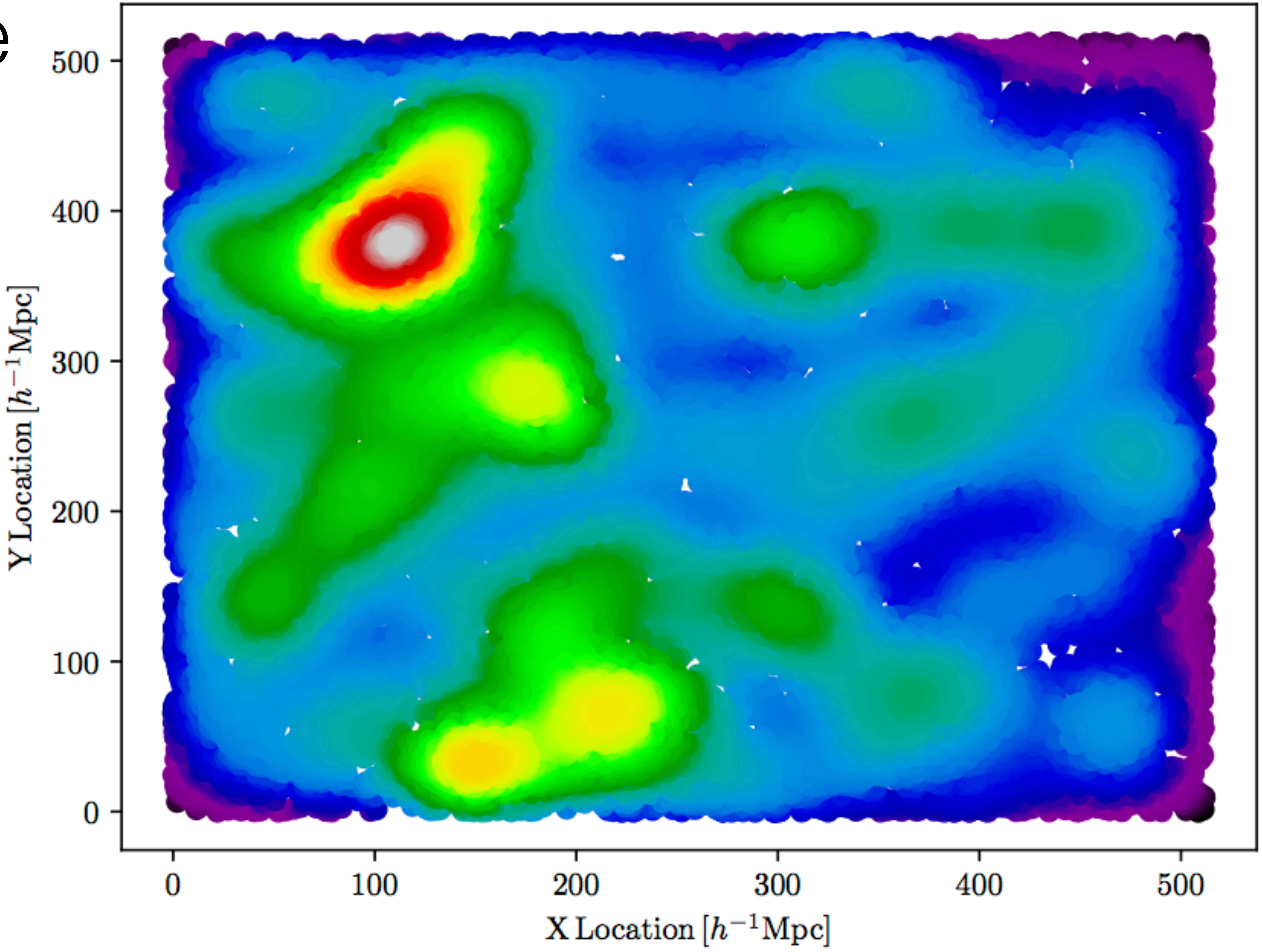
Voids are an interesting tool to study neutrinos!

Void Abundance:
Void Size Distribution

Voids in the CDM Particle Field

CDM Particle Field

10 Mpc corner slice of DEMNUni Simulations, $\Sigma m_\nu = 0.0\,\mathrm{eV}$

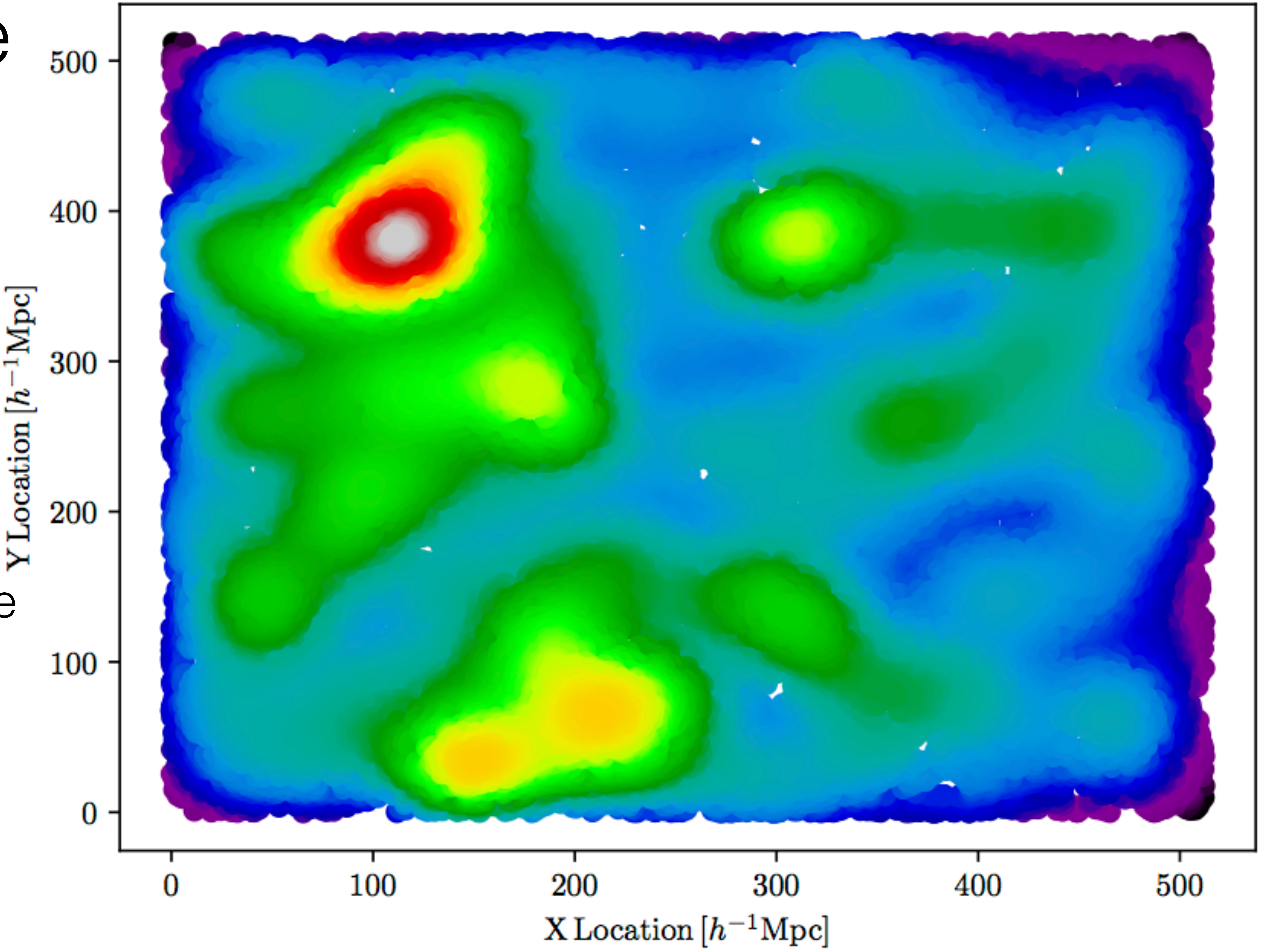


CDM Particle Field

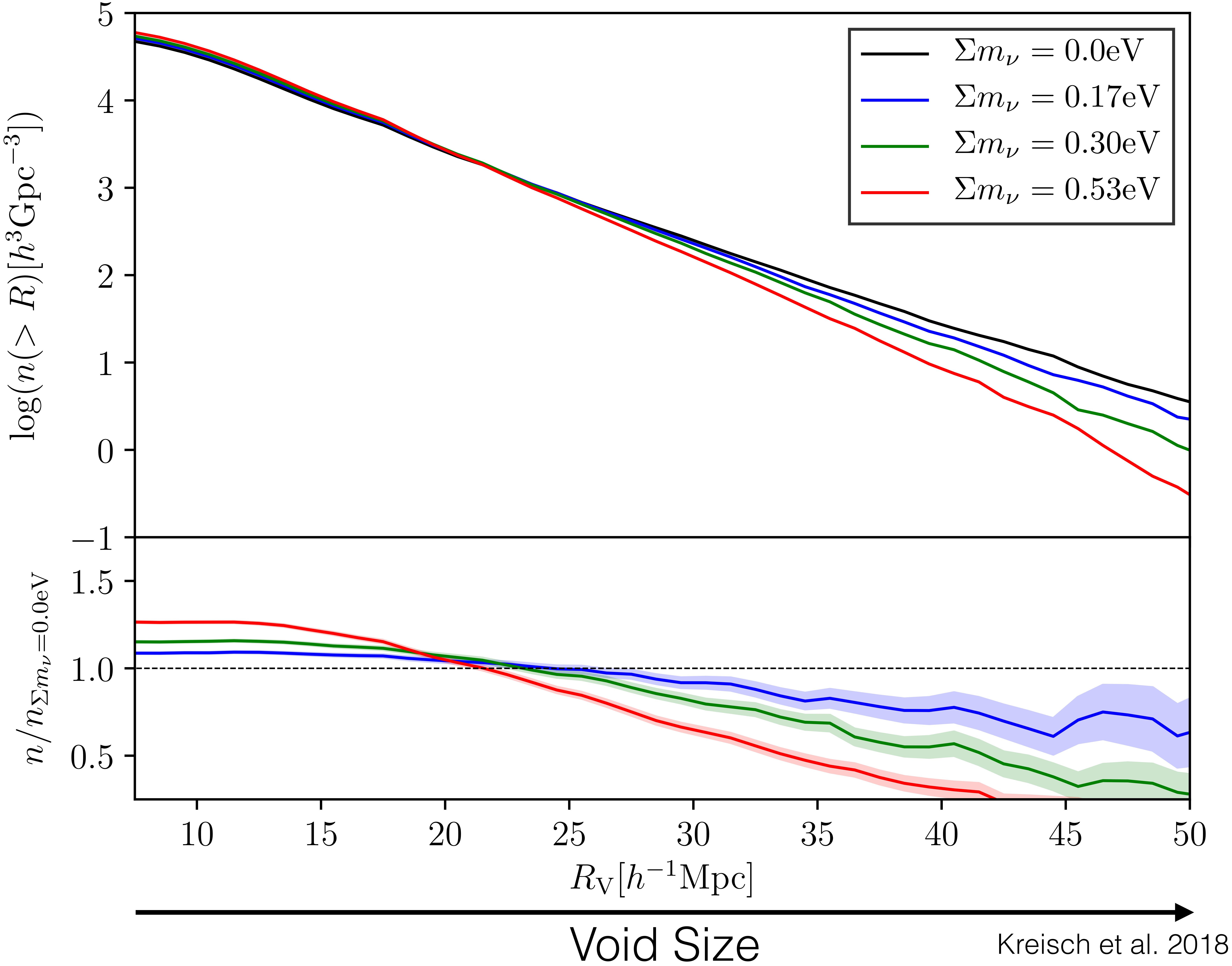
10 Mpc corner slice of DEMNUni Simulations, $\Sigma m_\nu = 0.53\,\mathrm{eV}$

<u>Increasing Σm_ν</u>:

- Structure more diffuse
- Small islands appear
- Voids fill low density areas
  → more small voids
  → less large voids



Void Abundance: CDM Particle Field



Kreisch et al. 2018

<u>Increasing Σm_ν</u>:

- Structure more diffuse
- Small islands appear
- Voids fill low density areas
  → more small voids
  → less large voids

Voids in the Halo Field

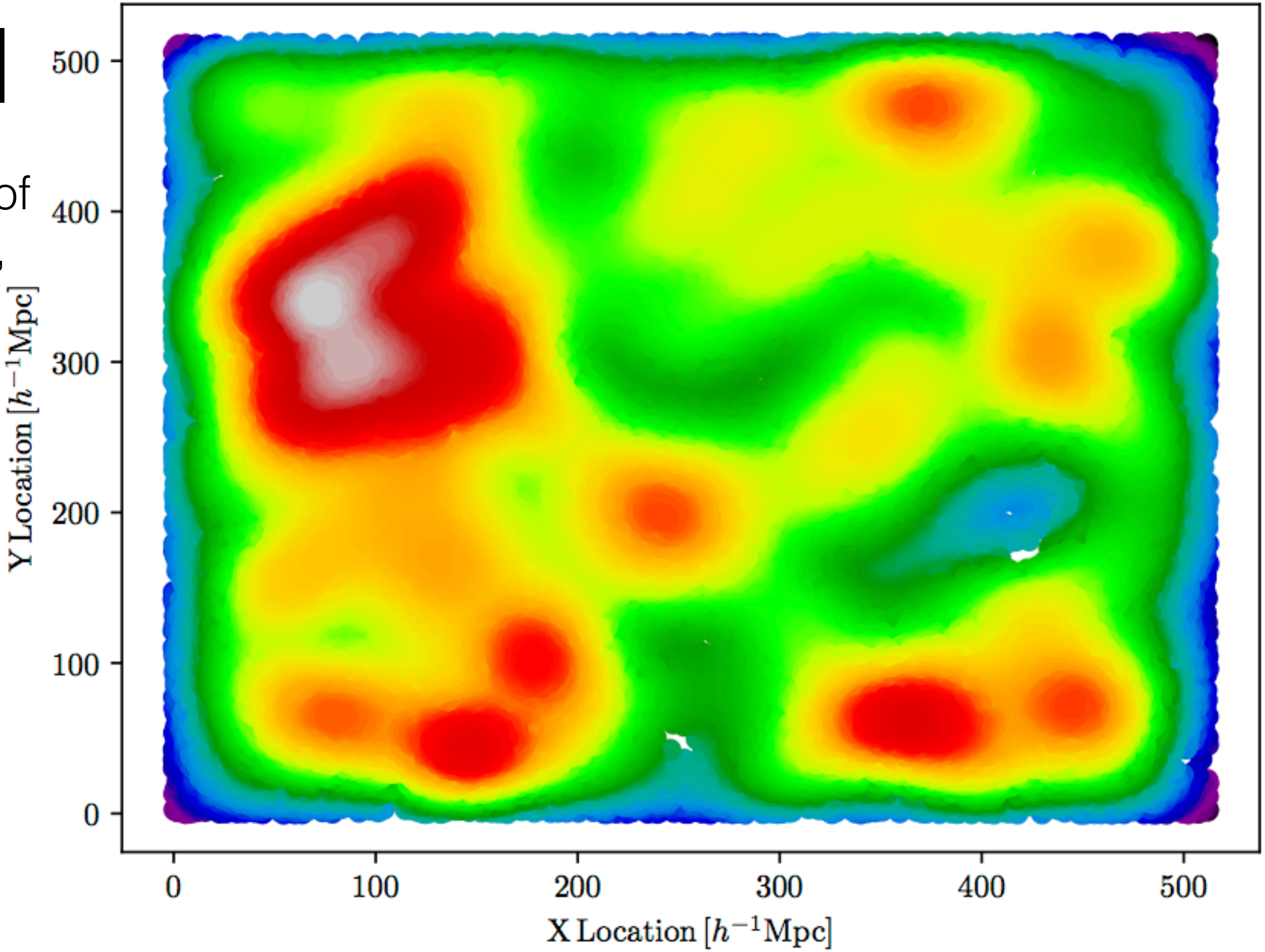
Halo Field

100 Mpc corner slice of DEMNUni Simulations,

$\Sigma m_\nu = 0.0\,\mathrm{eV}$

Halos:

$M \geq 2.5 \times 10^{12}\, h^{-1} M_\odot$



Halo Field

100 Mpc corner slice of DEMNUni Simulations,

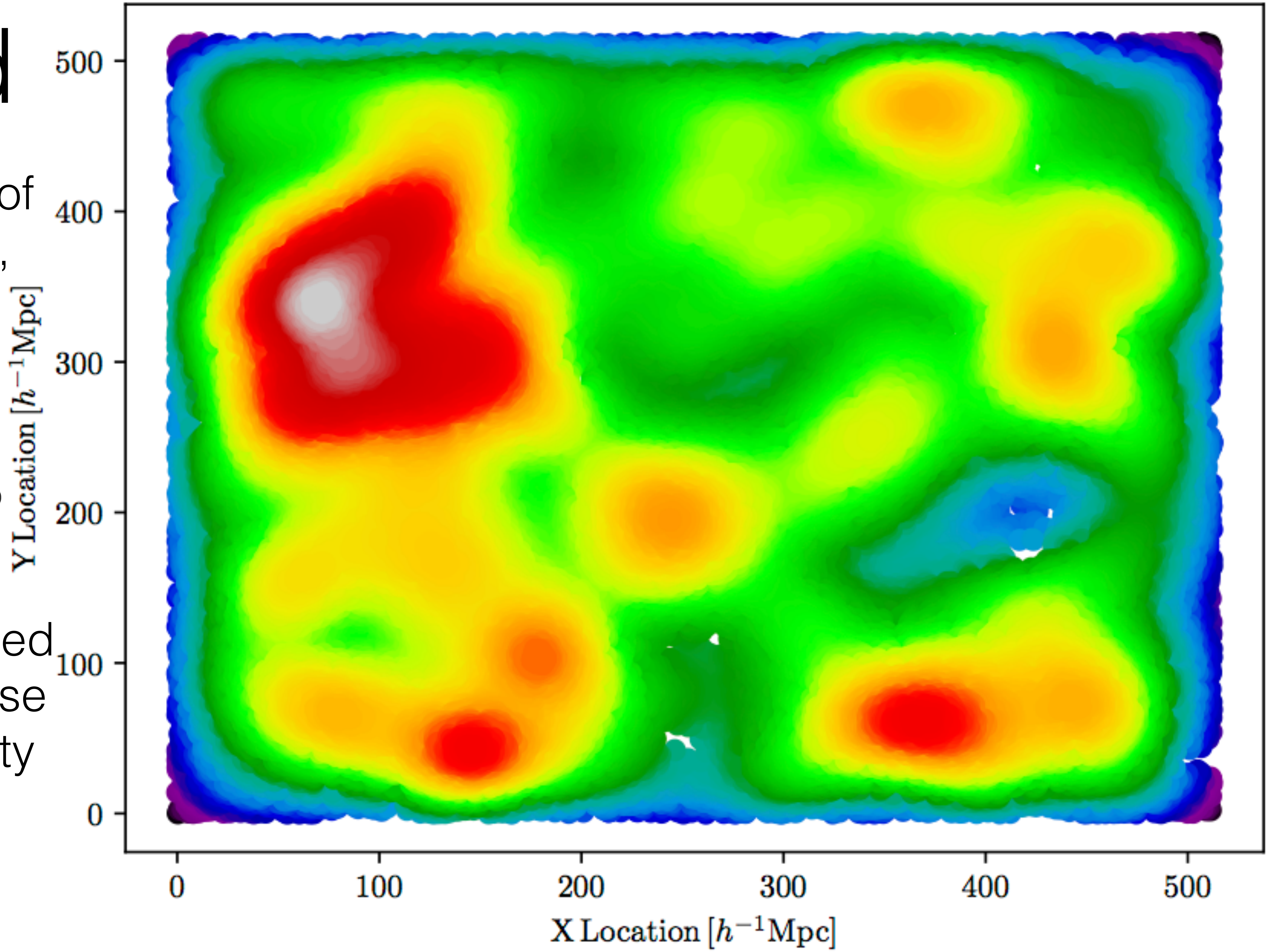
$\Sigma m_\nu = 0.53\,\mathrm{eV}$

Halos:

$M \geq 2.5 \times 10^{12}\,h^{-1}M_\odot$

<u>Increasing Σm_ν</u>:

- Structure concentrated at peaks + less diffuse
- Voids fill lower density areas (watershed)
  → more large voids
  → less small voids

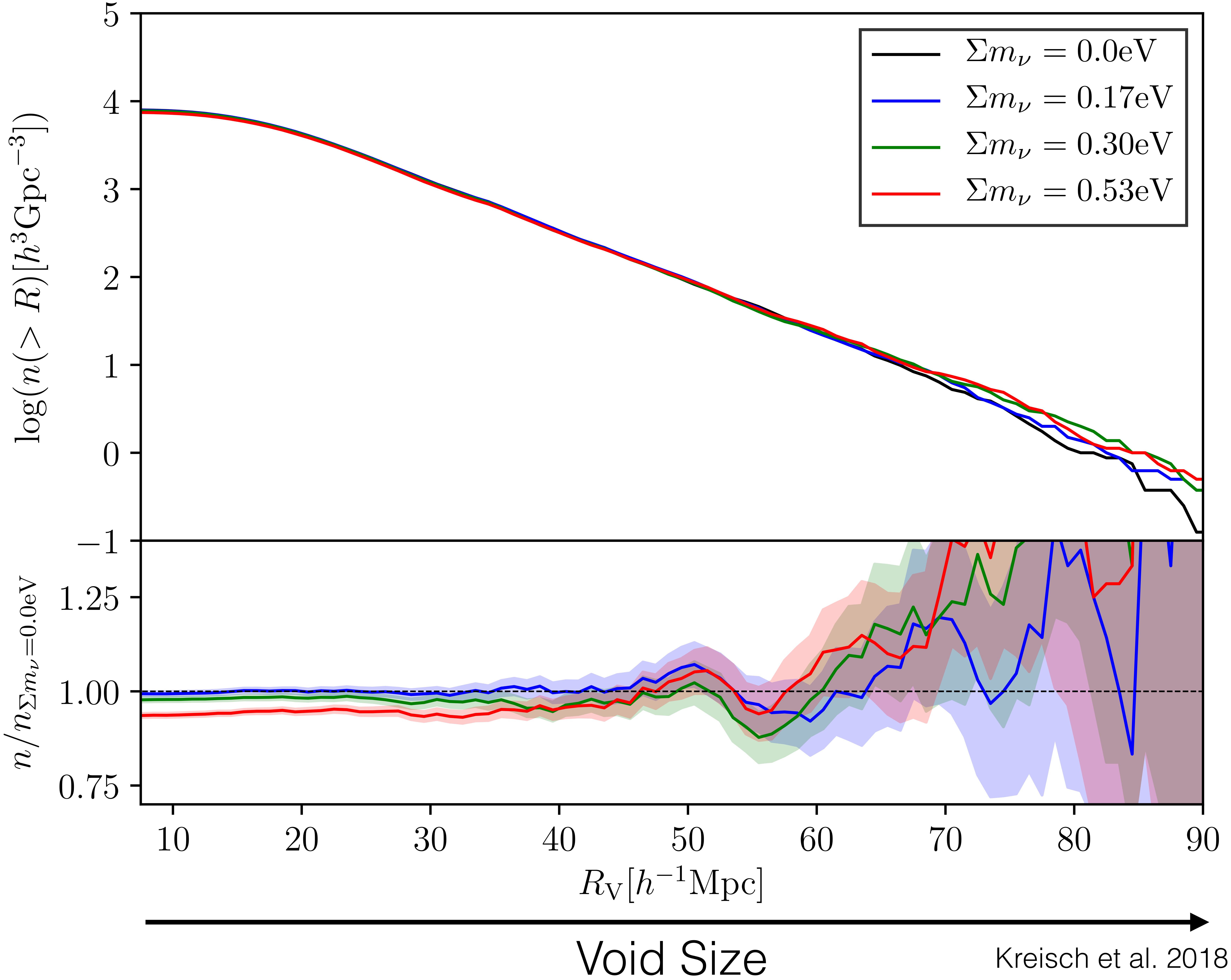


Void Abundance: Halo Field

Opposite to CDM particle case!

<u>Increasing Σm_ν</u>:

- Structure concentrated at peaks + less diffuse
- Voids fill lower density areas (watershed)
  → more large voids
  → less small voids



Kreisch et al. 2018

Void
Clustering

<u>Increasing Σm_ν</u>:

CDM Particle Field-

- Structure more diffuse
- Small islands appear

→ matter field less concentrated

→ voids less correlated

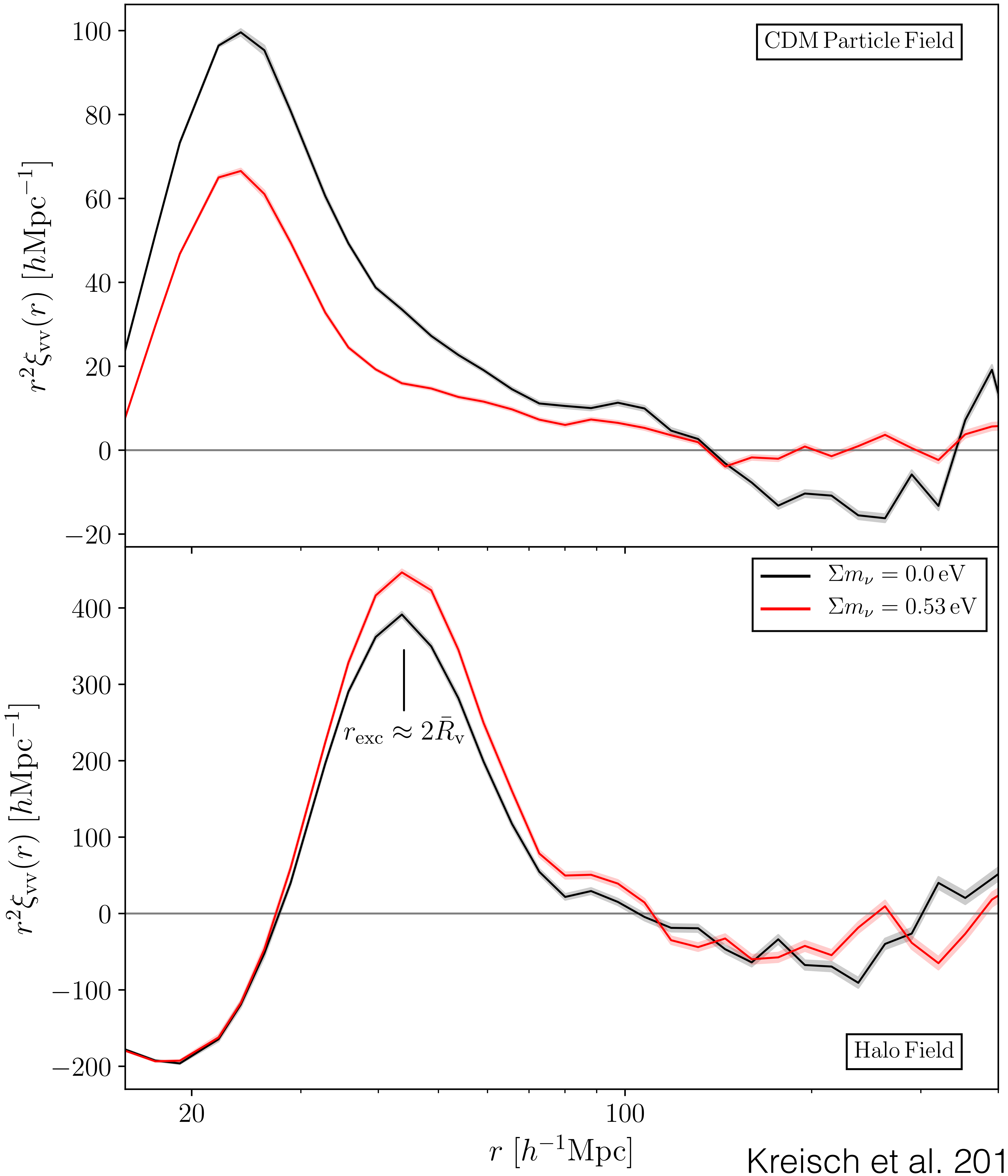
Halo Field-

- Structure concentrated at peaks

+ less diffuse

→ halos more concentrated

→ voids more correlated



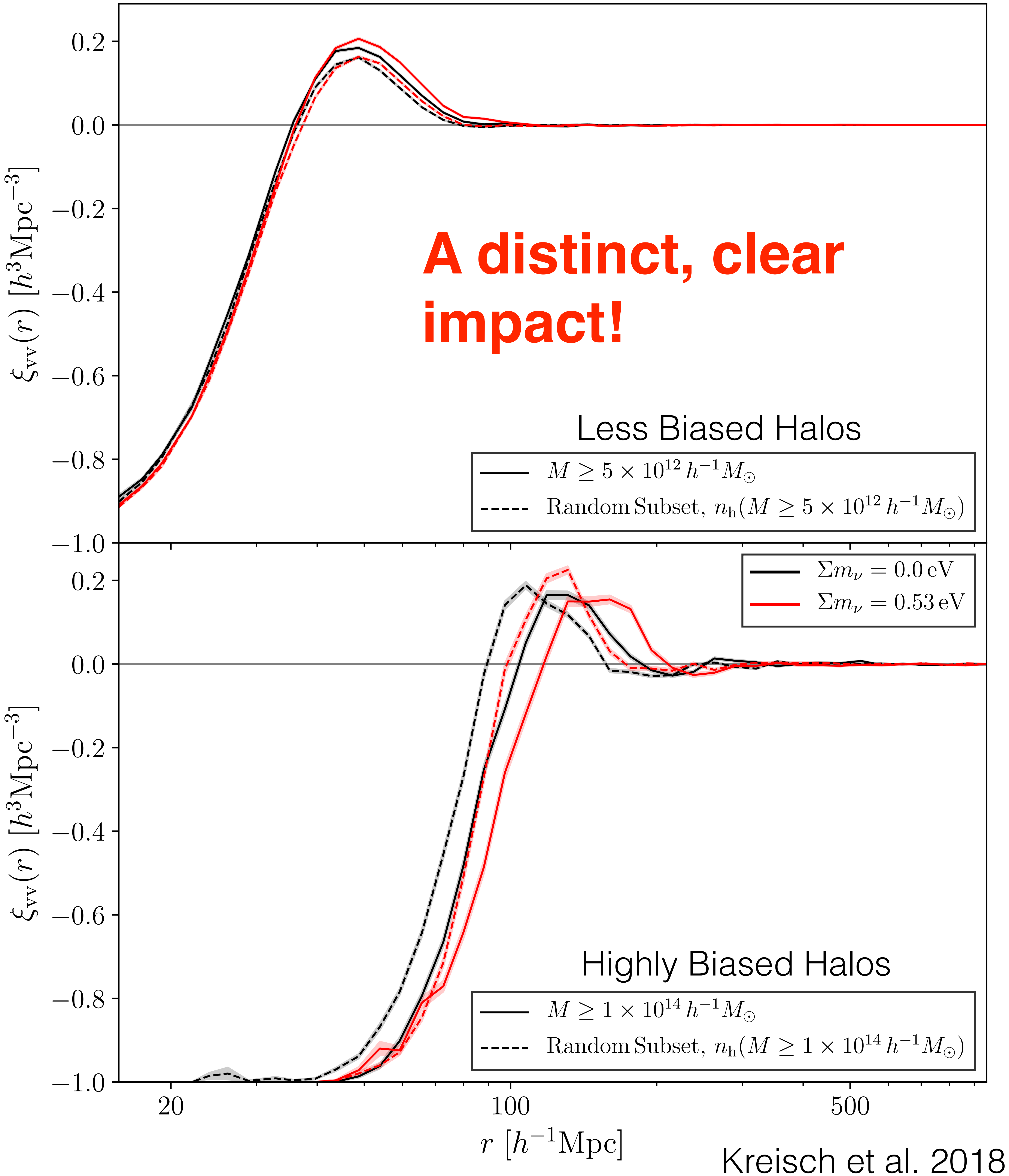
Kreisch et al. 2018

Increasing halo bias:

- Diffuse structure almost vanishes, structure concentrated at peaks
- Voids fill lower density areas (watershed)
  → larger voids
  → voids more correlated

Increasing Σm_ν:

- Structure concentrated at peaks + less diffuse
- Voids fill lower density areas (watershed)
  → larger voids
  → voids more correlated



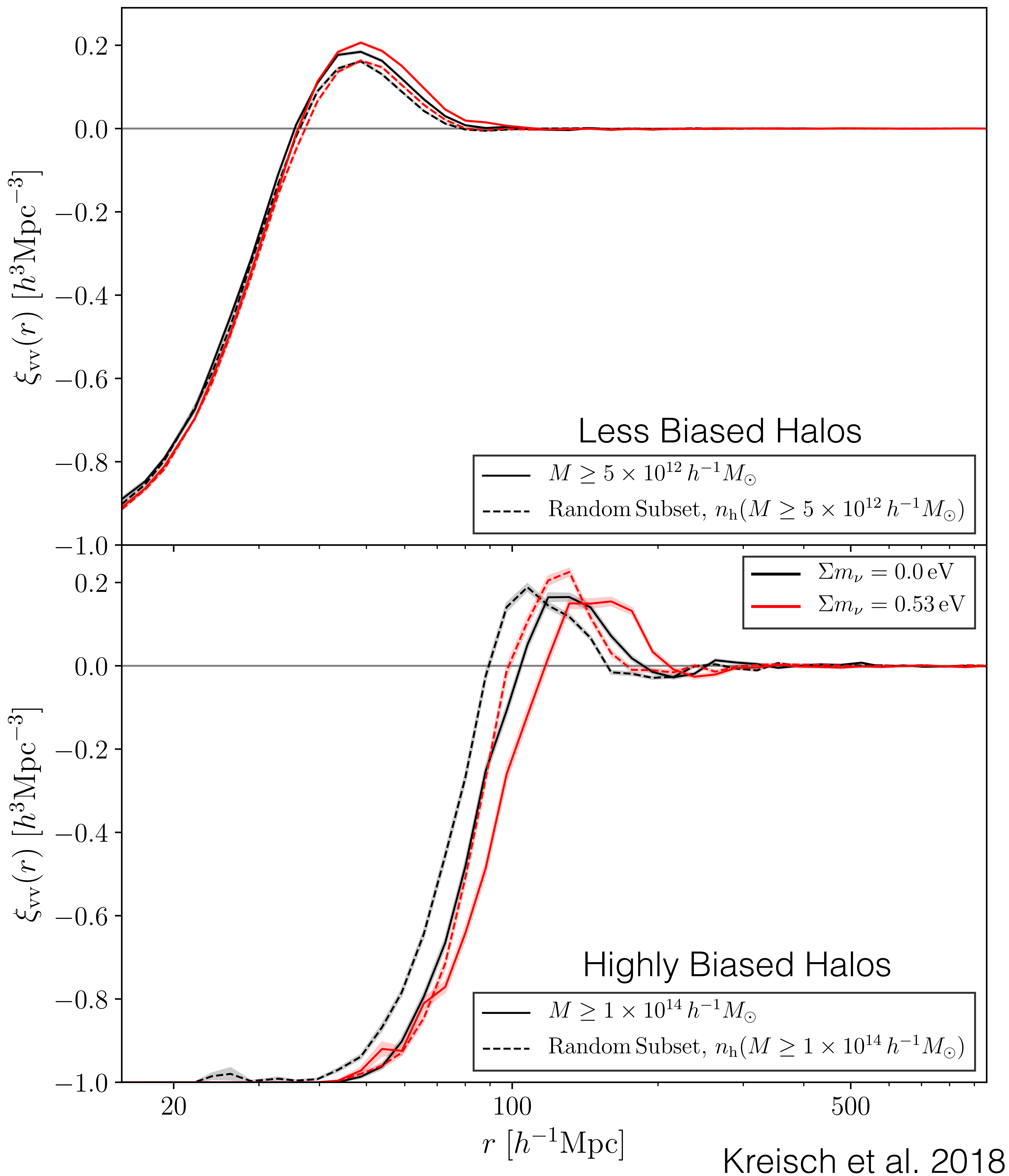
Kreisch et al. 2018

Voids contain information about 3- and 4-point clustering of tracers

- Voids are extended 3D objects, defined by at least 4 (non-planar) points
- Void exclusion scale is a manifestation of this

  $\longrightarrow$ shifts in response to Σm_ν

  $\longrightarrow$ halos do not have an equivalent feature or response



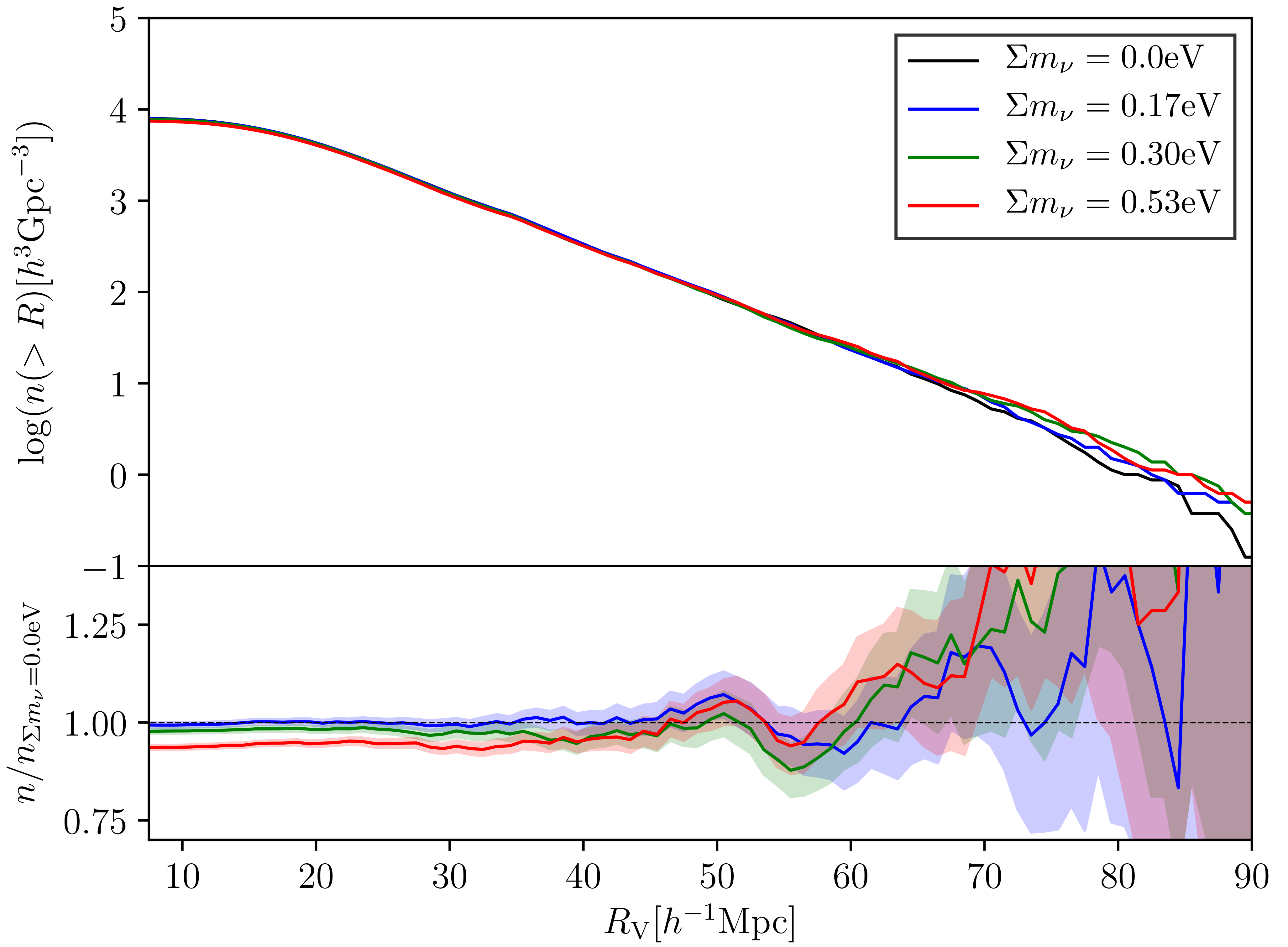
Kreisch et al. 2018

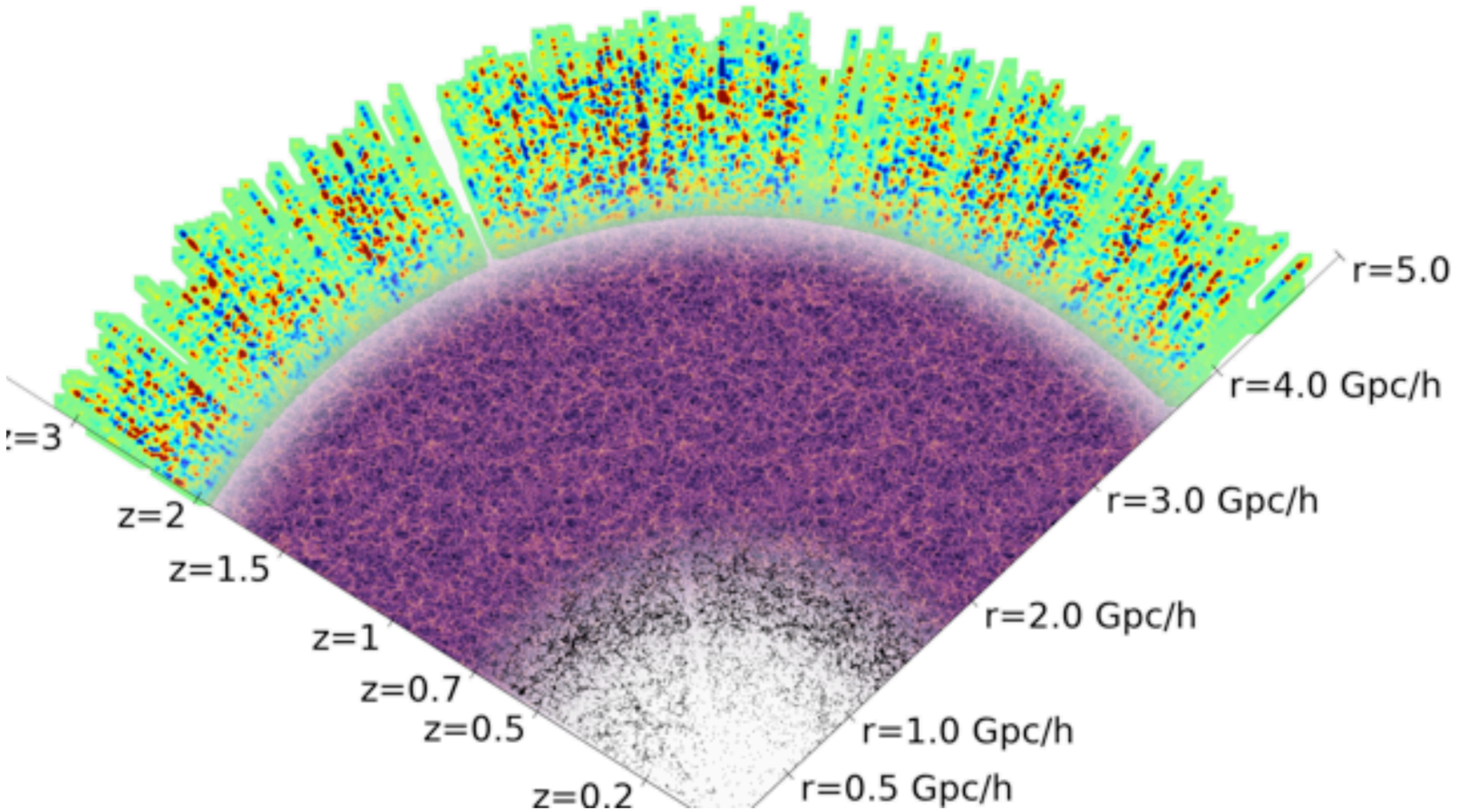
Multiple effects at work- a distinct fingerprint on voids!

What the future has in store

Constraining neutrinos from near…

Large Scale Surveys





Errors shrink by 3.5x ← DESI: 800,000 voids

(# from Alice Pisani)

What the future has in store

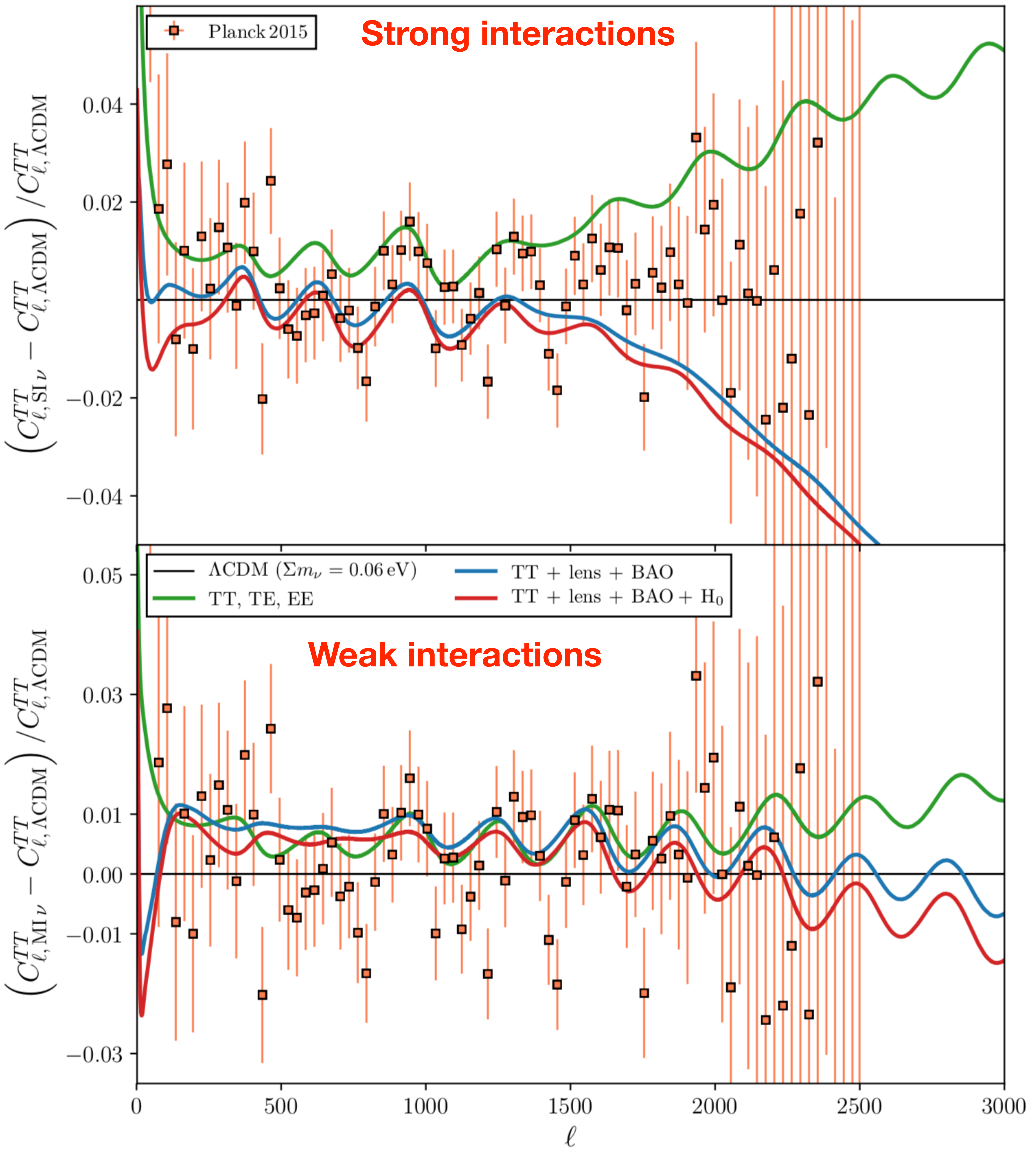
…and far

Exquisite small scale CMB measurements ($\ell > 2000$)

- **Current best-fit spectra for strong and weak interactions diverge at high-ℓ**

- **Need high-ℓ data with low uncertainties to pin down model**

- **Also important for interplay with N_{eff}**
  - **Important role for H_0**



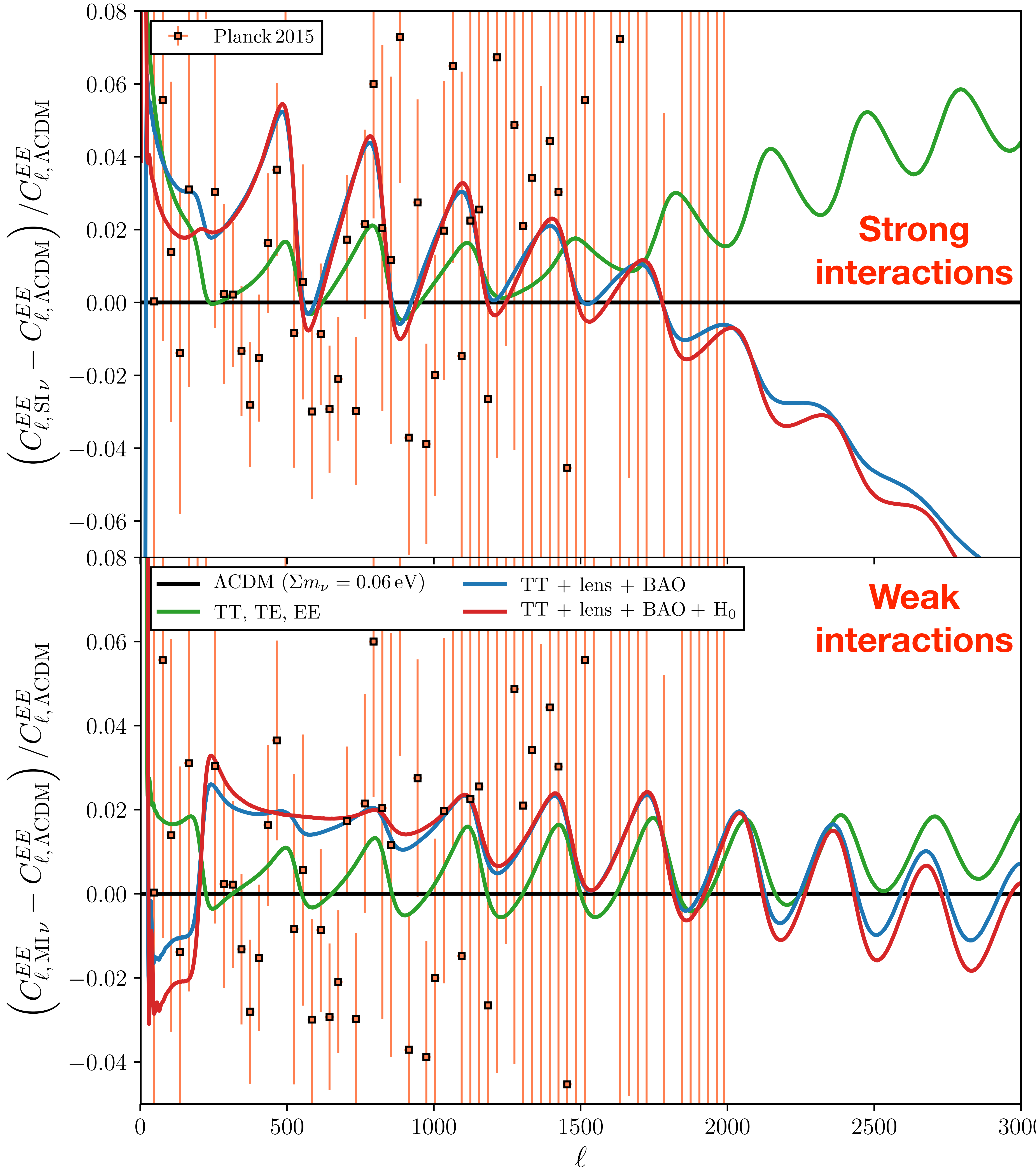
Kreisch et al. 2019


Strong Polarization Constraints
Q
U
ACT
Planck

EE Spectra

- Sensitive to phase shift (see also Baumann et al 2016) → constraints on θ

- Rule out or confirm strong phase shift → Rule out or confirm strong interaction



Kreisch et al. 2019

Conclusions + Looking Forward

This toy self-interaction model provides a taste of model features that may be needed to reconcile tensions:

1. Onset of neutrino free-streaming is delayed until close to matter-radiation equality
2. The sound horizon is reduced, via a multi-parameter degeneracy, providing a good fit to both CMB temperature and local distance ladder measurements of H_0
3. The combination of low A_s, n_s, and the scale dependent effects of G_{eff} lead to lower σ_8
   → Could strong neutrino self-interactions help with small-scale structure problems?

DESI has a large tracer density and volume, making it excellent (and critical!) for studying voids and higher order statistics

The effect neutrinos have on voids depends on the tracer the void catalog is built from

- Response of void clustering to $\sum m_\nu$ changes sign as a function of halo bias, a trend uncommon for cosmological parameters like σ_8

Void power spectra and correlation functions are powerful tools for distinguishing neutrino masses

Voids contain information beyond the tracer 2-point clustering

- Void exclusion scale is a manifestation of this $\longrightarrow$ shifts in response to $\sum m_\nu$

Neutrinos leave a distinct fingerprint on voids, which could help break degeneracies between cosmological parameters