13th Rencontres du Vietnam - Cosmology

Neutrino Statistics and Cosmological Tensions

Nhut Truong

Institute For Interdisciplinary Research in Science and Education (IFIRSE)
University of Rome "Tor Vergata"

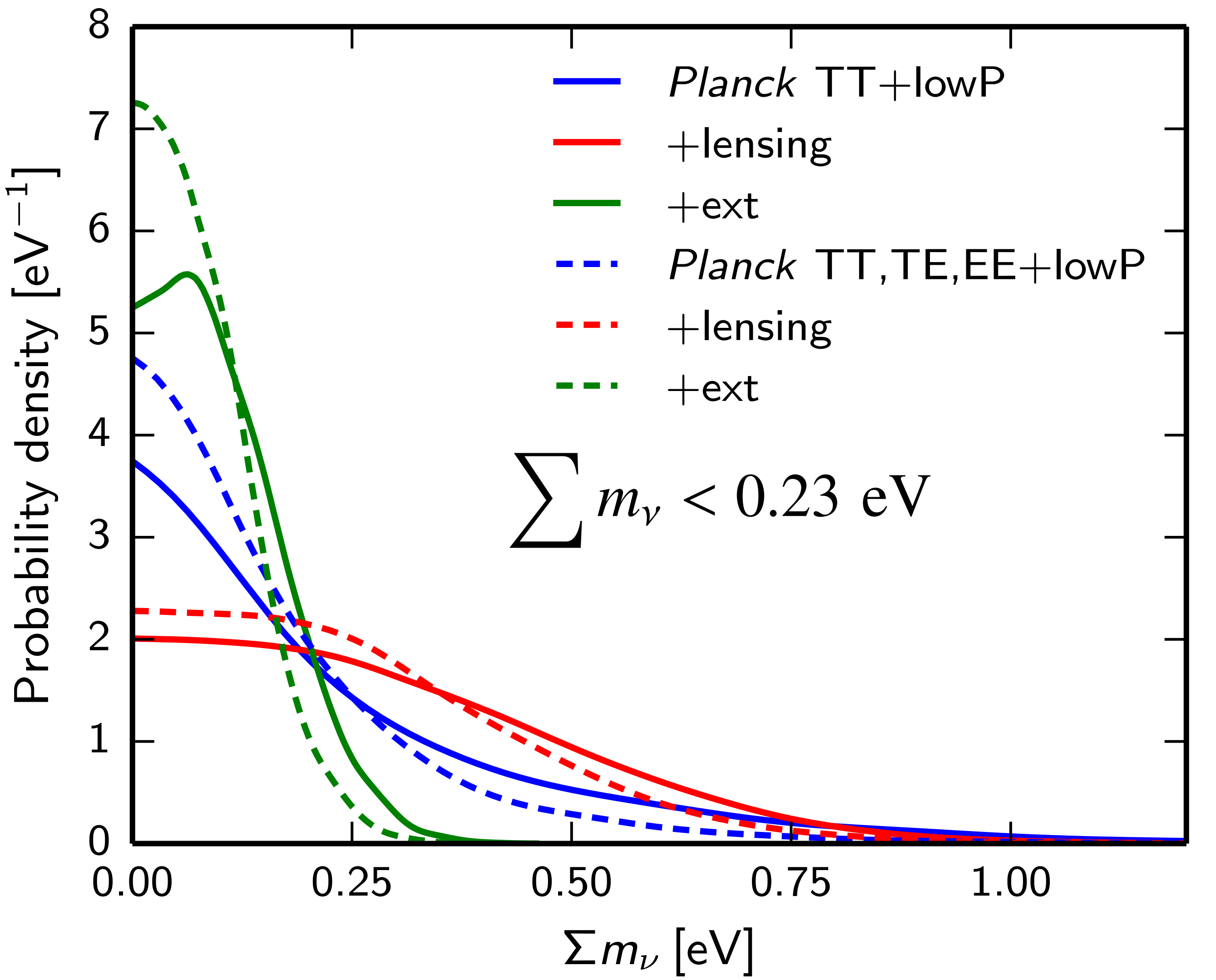
In collaboration with: **Stefano Gariazzo** (University of Valencia)
Marco Laveder (University of Padova)

Neutrino in Precision Cosmology Era

- Many of neutrino properties have been studied in cosmology: mass, neutrino species, *sterile neutrinos, self-interaction* (*e.g., Lesgourgues & Pastor 2014 for a review*)

- How's about neutrino statistics?

Dolgov & Smirnov (2005)
Dolgov, Hansen, Smirnov (2005)
Barabash et al. (2007)
Iizuka & Kitabayashi (2015, 2016, 2017)



Planck Collaboration 2015

Outline

- Neutrino statistics and parametrization.
- Cosmological effects of varying neutrino statistics.
    - *Potential in alleviating H_0 and sigma_8 tensions.*
- Preliminary results: constraint from CMB data alone.

Spin-Statistics Theorem

- *W. Pauli, Phys. Rev. 58, 716 (1940)*: Lorentz invariance, positive energies, positive norms, and causality.

- Integer-Spins: Bosons —> ***Bose-Einstein*** distribution

$$F(E) = \frac{1}{e^{E/k_B T} - 1}$$

- Half-integer-Spins: fermions —> ***Fermi-Dirac*** distribution

$$F(E) = \frac{1}{e^{E/k_B T} + 1}$$

—>as having spin of 1/2, neutrinos should obey FD distribution

Experimental Tests

- Electrons, photons, nuclei: strict limits on the violation (*Tino 1999 for a reviews*).

- Neutrino: absence of direct tests, e.g. violation of Pauli exclusion principle.

    - Indirect test on violation of neutrino statistics: 2nu-Double Beta Decay (*Barabash et al. 2007*)

Ideal place to test neutrino statistics: the cosmic neutrino background (CNB)

Cosmic Neutrino Background (CNB)

- Neutrino energy density:

$$\rho_\nu = \frac{g_*}{2\pi^2}\int_0^\infty dE f_\nu(E) \times E^3$$

- **In the early time:** effects on BBN, CMB spectrum

$$\rho_{rad} = \left[1 + N_{eff}\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right]\rho_\gamma \quad (f_\nu(E) \equiv Fermi - Dirac)$$

- **In the late-time:** massive neutrinos suppressing LSS formation.

$$\frac{\Delta P(k)}{P(k)} \propto -\frac{\Omega_\nu}{\Omega_m}$$

—> varying neutrino statistics alternates both early and late-time cosmological observables

Parametrization of neutrino statistics

- ***Dolgov et al. (2005)*** proposed mix statistics distribution:

$$f_\nu(E) = \frac{1}{exp(E/k_B T) + \kappa_\nu}$$

$\kappa_\nu = 1$: purely fermionic

$\kappa_\nu = -1$: purely bosionic

<u>Main Goal:</u> to derive cosmological constraint on kappa_nu.

Kappa Effects

Modify energy density:

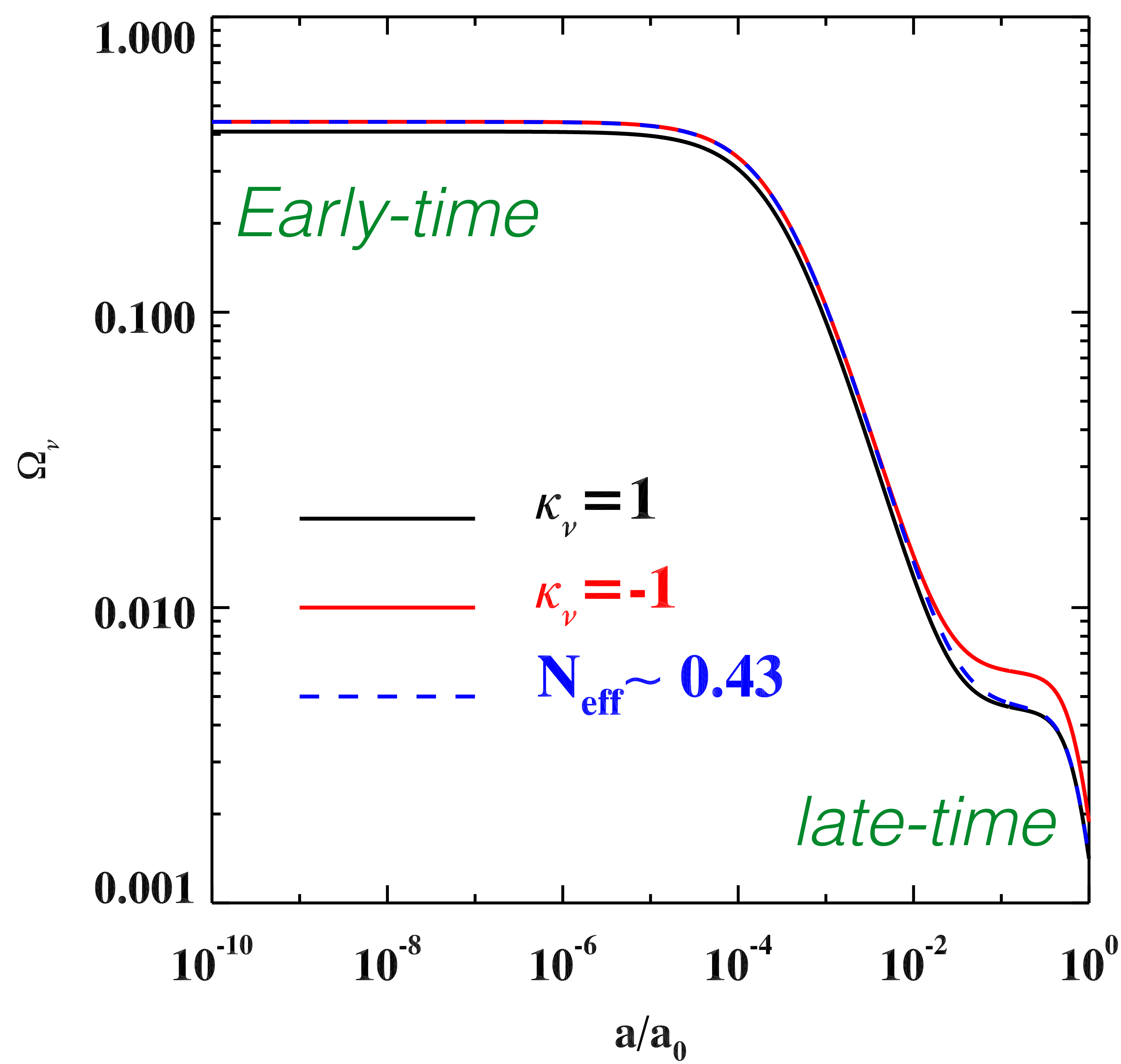
$$\rho_\nu = \frac{g_*}{2\pi^2}\int_0^\infty dE \frac{E^3}{exp(E/k_B T) + \kappa_\nu}$$

In the early time: *similar effects to varying N_eff's*

Ex: $\kappa_\nu = -1 \Leftrightarrow \Delta N_{eff} \simeq 0.43$

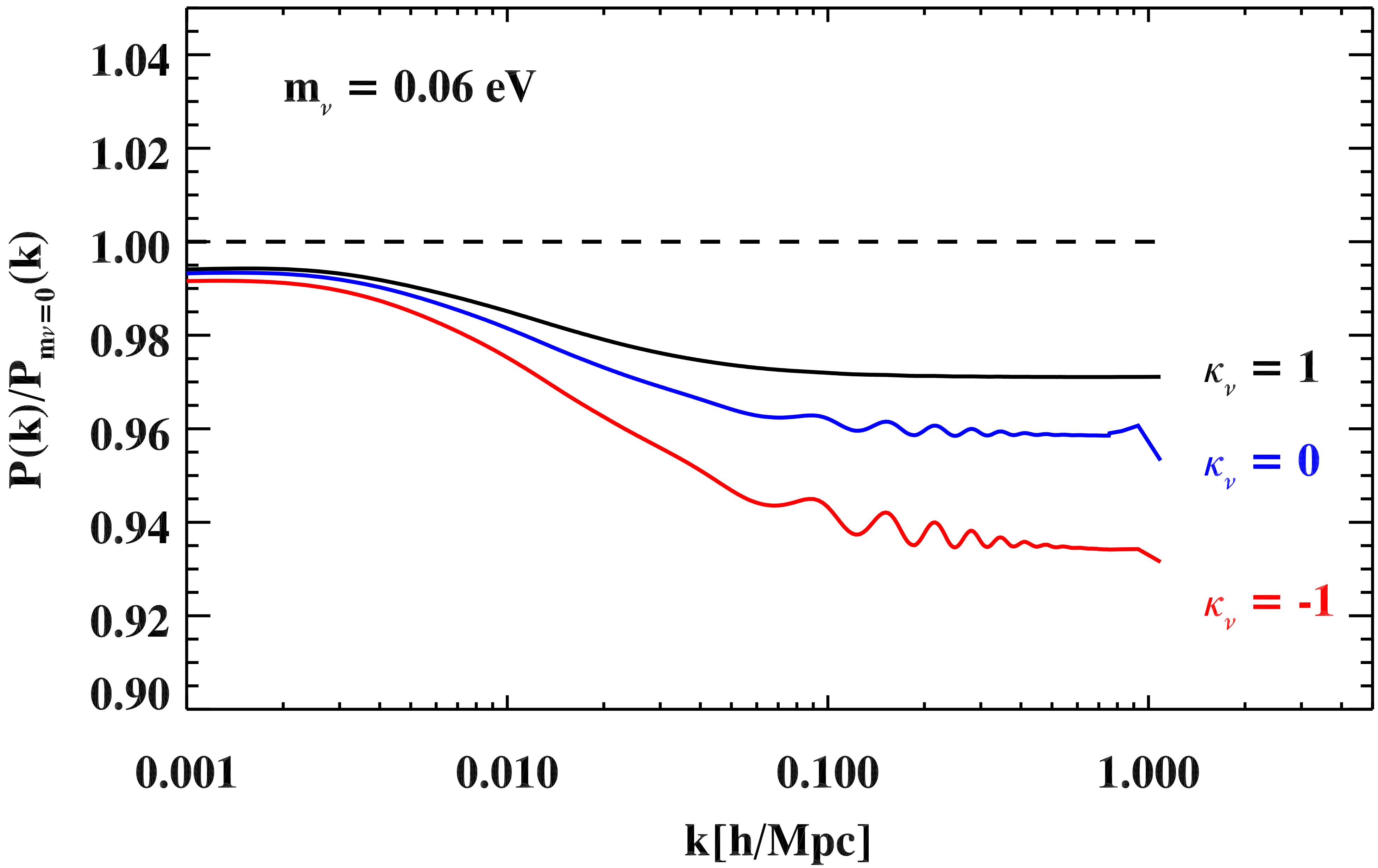
In the late time: *similar effects to varying neutrino mass'*

—> Increase rho_nu at both early- and late-time



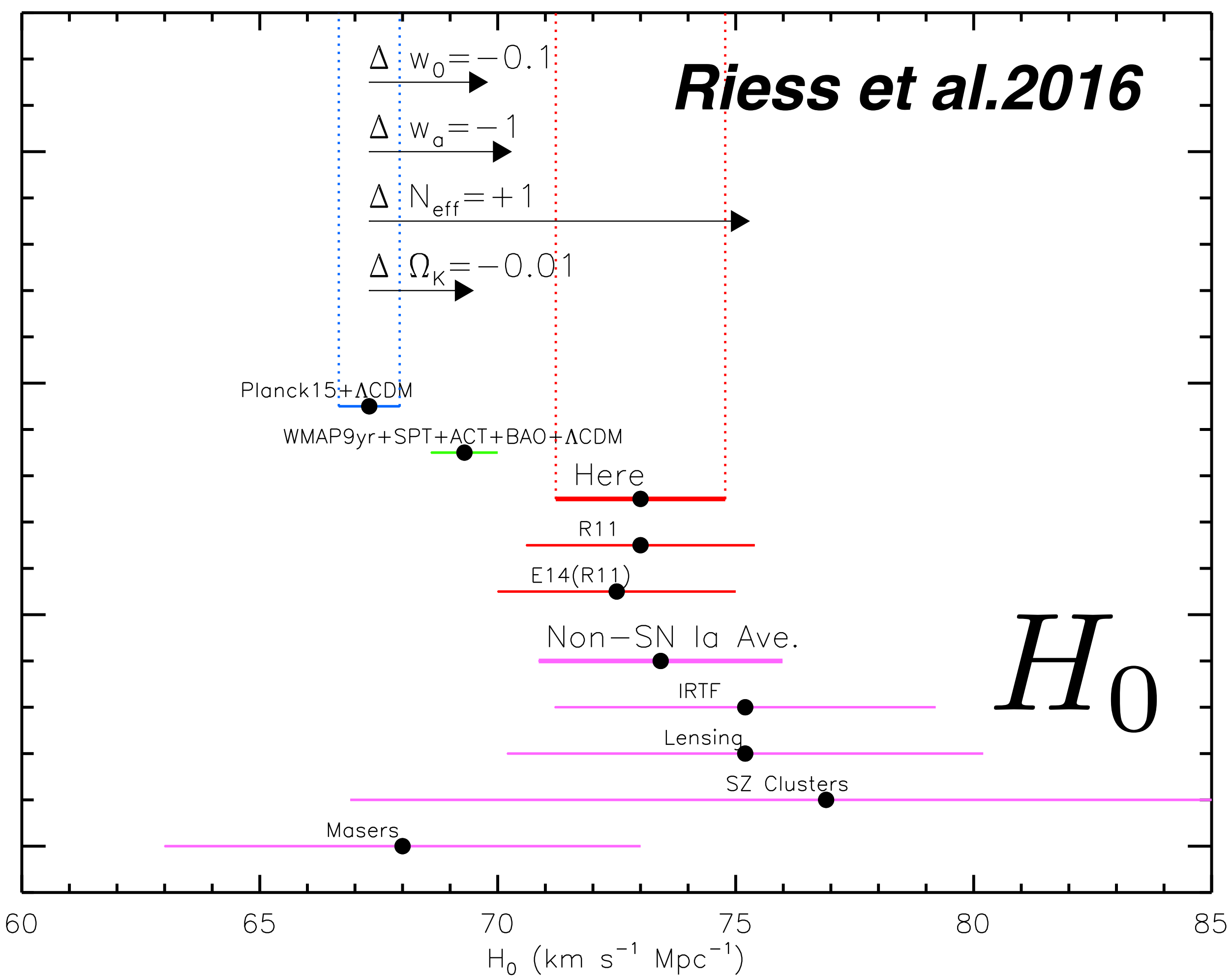
Kappa Effects

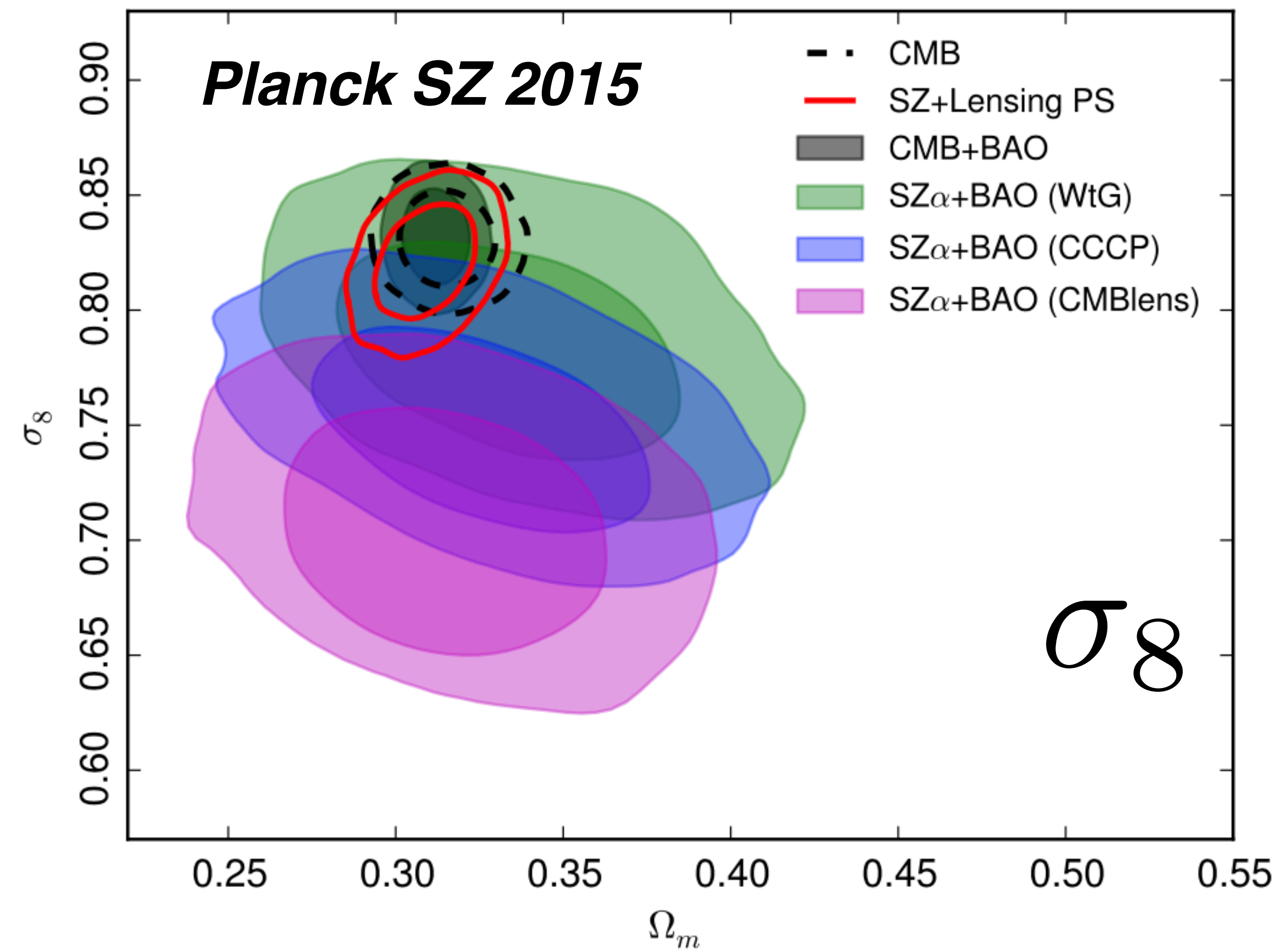
enhance the suppression of late-time power spectrum:



—> similar effect to neutrino mass

H0 and Sigma_8 tensions





Possible solution from neutrino sector: increase both N_eff and neutrino mass (e.g., Planck Collaboration 2015)

$\kappa_\nu < 1$ **may have potential to alleviate the current tensions**

Method of Analysis

- Cosmological datasets:
    - Public Planck CMB release 2015 (*preliminary results*).
    - External datasets: BAO, BBN, LSS.
- Method: MCMC analysis using Monte-Python+CLASS code (*Audren et al. 2012*).

Constraint on Kappa_nu (*preliminary*)

$\Lambda CDM + \kappa_\nu \;\; (N_{eff} = 3.046, \; \sum m_\nu = 0.06 \text{ eV})$

- From CMB alone:

$$\kappa_\nu > -0.18 \quad (68\%)$$

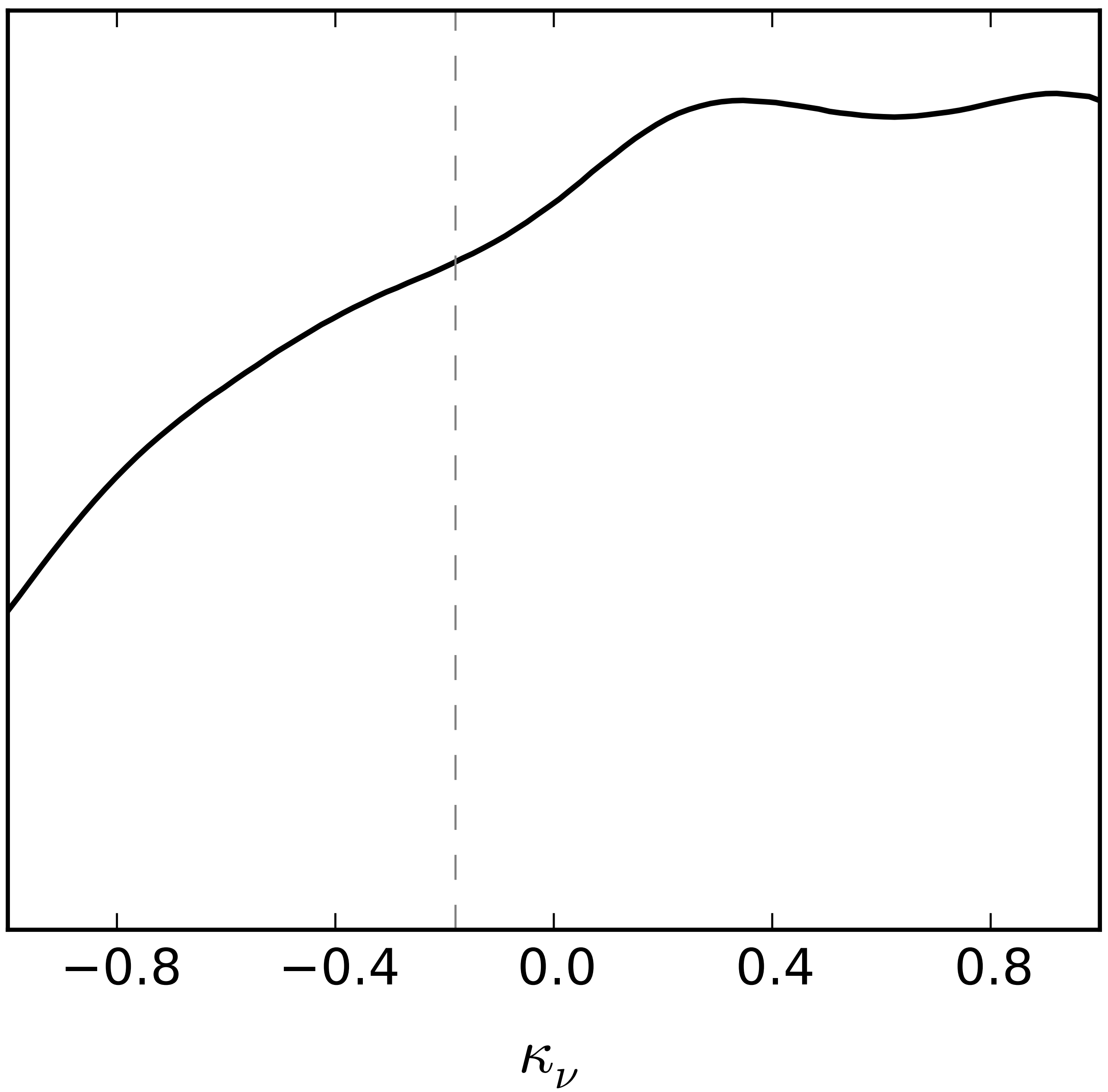
- In agreement with 2-neutrino double beta decay constraint:

$$\kappa_\nu > -0.2$$

(Barabash et al. 2007)

Mix-statistics is still allowed!

Planck TT_lowl_lensing



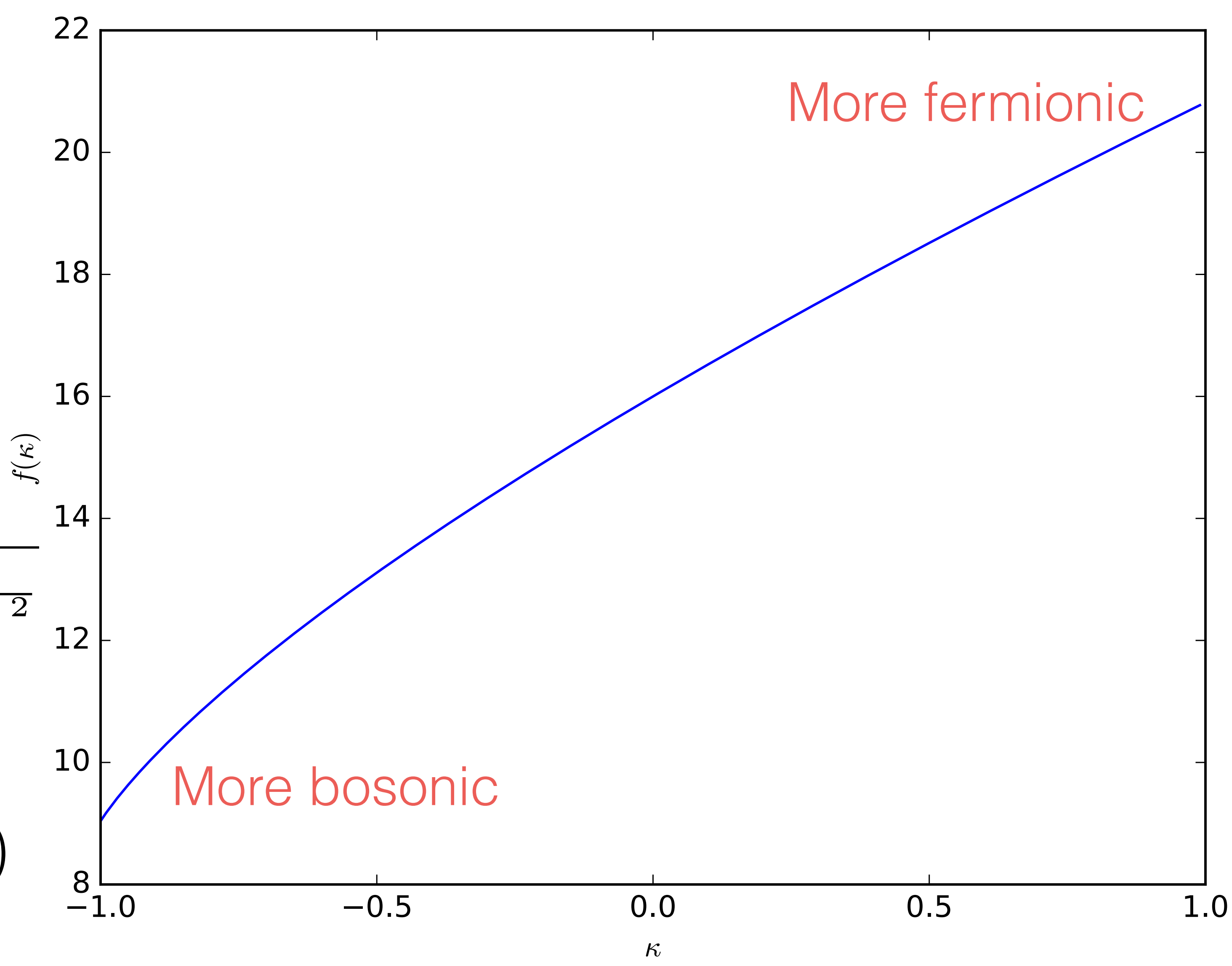
Cosmological Sensitivity to kappa

kappa effects are manifested via neutrino energy density:

$$\rho_\nu = \frac{g_*}{2\pi^2}\int_0^\infty dE \frac{E^3}{exp(E/k_B T)+\kappa}$$

$$\Rightarrow \Delta\kappa \propto \frac{\Delta\rho_\nu}{\rho_\nu} \times \frac{\int_0^\infty dE \frac{E^3}{exp(E/k_B T)+\kappa}}{\int_0^\infty dE \frac{E^3}{\left[exp(E/k_B T)+\kappa\right]^2}}$$

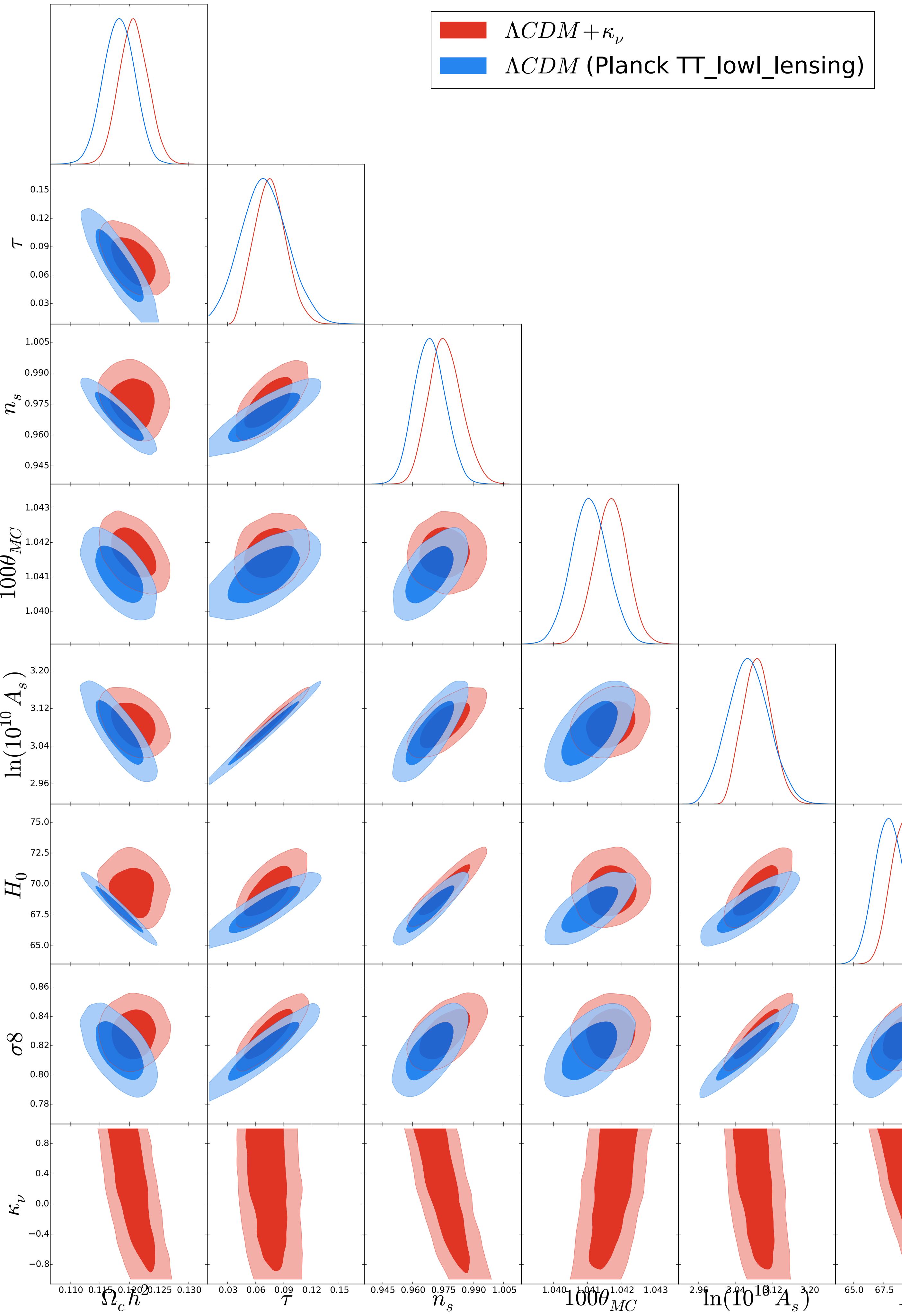
$$\frac{\Delta N_{eff}}{N_{eff}} \sim 5\% \rightarrow \Delta\kappa \sim 1.1(\kappa=1)$$

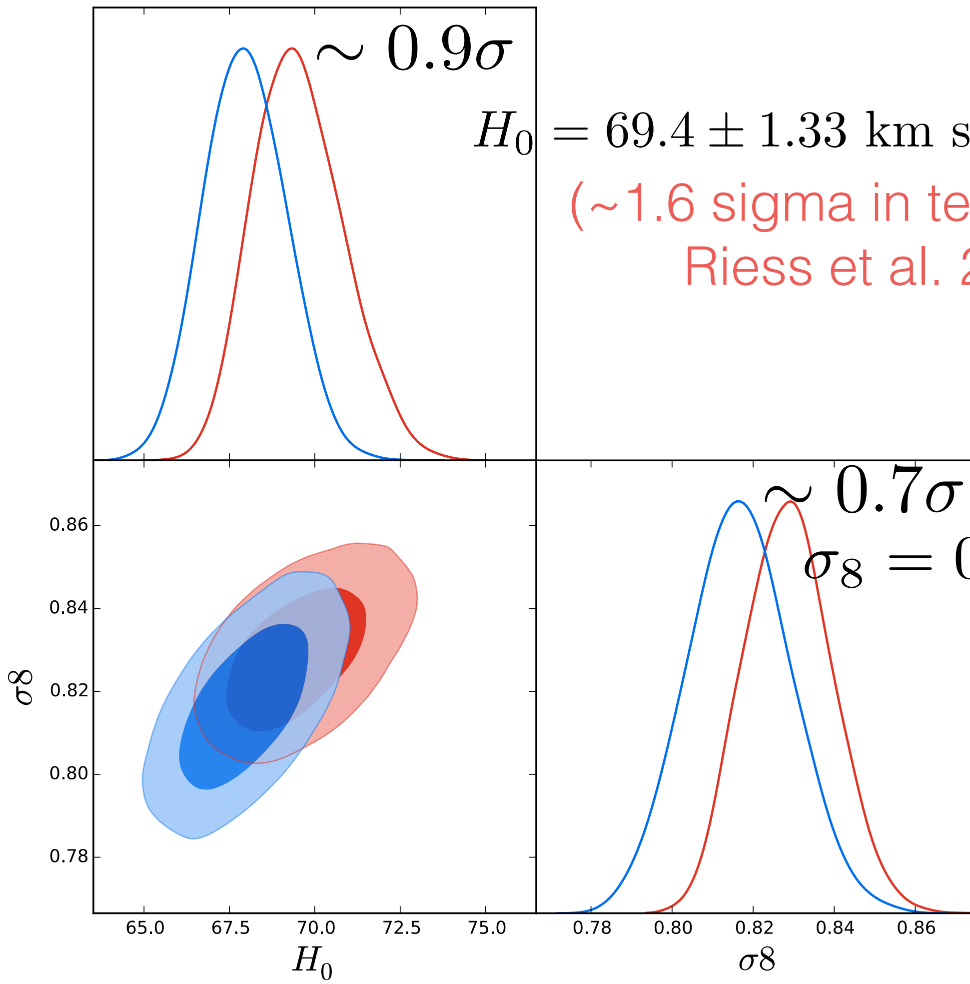


Future sub-percent accuracy of N_eff —> kappa at 0.1

Harder to constrain fermionic neutrinos

Degeneracies
(preliminary)





$H_0 = 69.4 \pm 1.33 \text{ km s}^{-1}\text{Mpc}^{-1}$

(~1.6 sigma in tension with Riess et al. 2016)

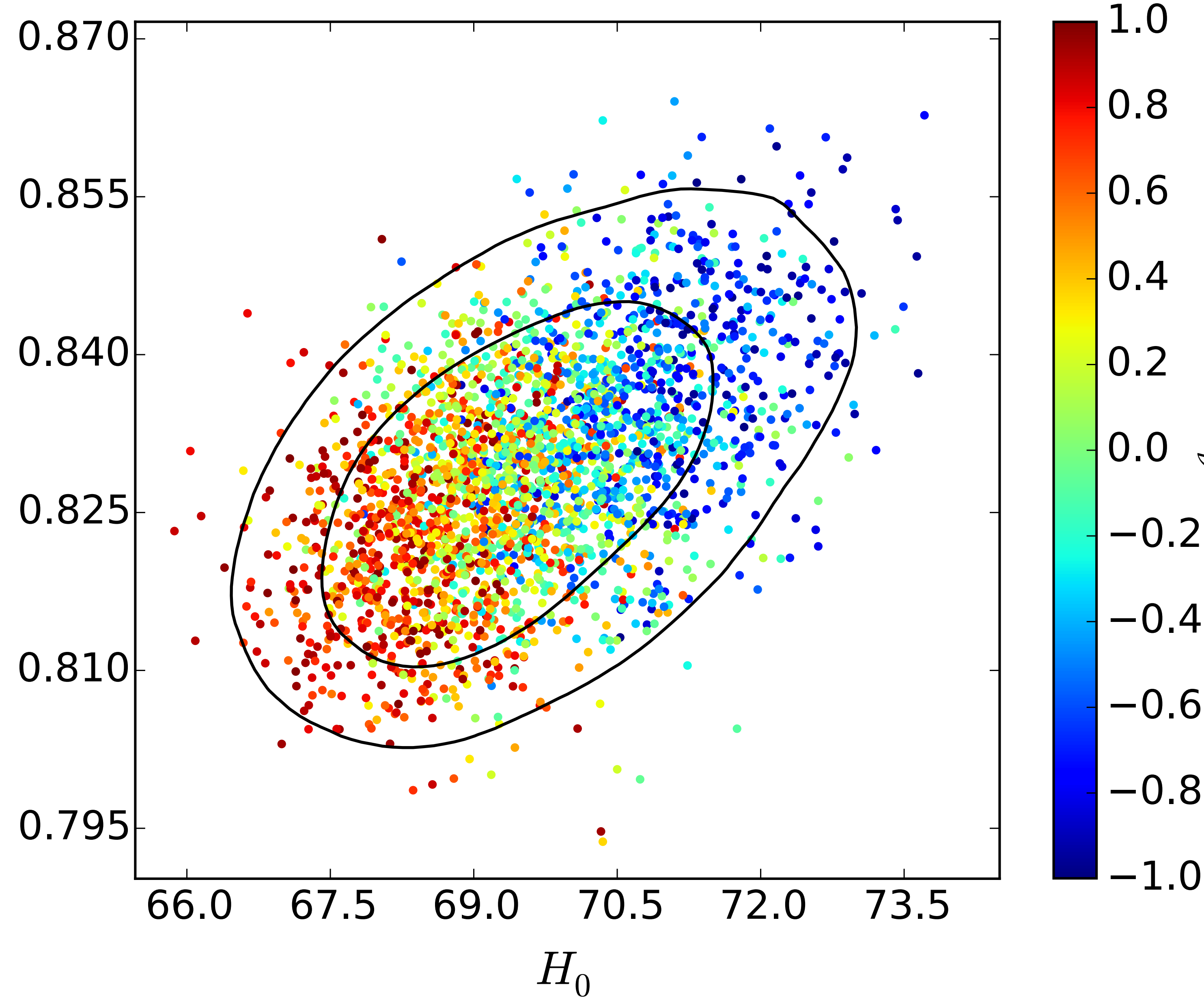
$\sigma_8 = 0.828 \pm 0.011$

Mix-statistics causes both H0 and sigma8 increased

H0-Sigma8 Degeneracy (*preliminary*)

- Lower kappa_nu increases H0 to preserve the acoustic scale.
- Lower kappa_nu also causes sigma_8 increase due to degeneracy to the matter density.

—> Similar degeneracy pattern to N_eff



kappa_nu alone is not sufficient to resolve both tensions

kappa_nu + neutrino mass?

Summary

- Observations are sensitive to neutrino statistics.

- Cosmological effects: similar to N_eff's in the early time and to m_nu in the time.

- First constraint from CMB alone:

    - kappa_nu>-0.18 (68%), in agreement with 2nu Double beta decay.

    - *Lambda CDM+Kappa_nu: alleviating H0 tension, however, worsen the sigma_8.*

- **Next step:** joint CMB+BBN+LSS analysis.

Summary

- Observations are sensitive to neutrino statistics.
- Cosmological effects: similar to N_eff's in the early time and to m_nu in the time.
- First constraint from CMB alone:
    - kappa_nu>-0.18 (68%), in agreement with 2nu Double beta decay.
    - *Lambda CDM+Kappa_nu: alleviating H0 tension, however, worsen the sigma_8.*
- <u>**Next step:**</u> joint CMB+BBN+LSS analysis.

Thank for Your Attention!

Back-up Slides

Cosmic Neutrino Background (CNB)

- Similar to CMB, ideal laboratory to test neutrino statistics!
- Before decoupling: in thermal equilibrium with photons, electrons, and positrons.

$$T_\nu = T_\gamma \propto a^{-1}$$

- After decoupling (free-out): thermal distribution maintains with

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \propto a^{-1}$$

$$T_{\nu,0} \simeq 1.9K$$
$$T_{\gamma,0} \simeq 2.7K$$

CNB has not detected yet! Statistics constraints are only obtained in indirect ways!