Neutrinos in Cosmological Environments

Evan Grohs (he/him/his)
North Carolina State University

Interconnections of Particle Physics and Cosmology XV
Washington University St. Louis -- 08 Jun 2022

HEISING-SIMONS FOUNDATION

NC STATE UNIVERSITY

N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

NSF

Outline

I. Observational motivation

II. What we know about the energy density of the universe
   A. Radiation (early universe)
   B. Matter (later universe)

III. Other areas of cosmology to look for neutrino physics

IV. Outlook for neutrino mass
   A. Concordance scenarios
   B. Beyond concordance

V. Summary

Snowmass 2021 White Paper

Synergy between cosmological and laboratory searches in neutrino physics: a white paper

Editors: Martina Gerbino[1], Evan Grohs[2], Massimiliano Lattanzi[3]

Kevork N. Abazajian,[1] Nikita Blinov,[2] Thejs Brinckmann,[3,4] Mu-Chun Chen,[5] Zelimir Djurcic,[6] Peizhi Du,[7] Miguel Escudero,[8] Martina Gerbino,[4] Evan Grohs,[9] Steffen Hagstotz,[10] Kevin J. Kelly,[11,12] Massimiliano Lattanzi,[4] Christiane S. Lorenz,[13] Marilena Loverde,[14] Pablo Martínez-Miravé,[15,16] Olga Mena,[15] Joel Meyers,[17] Walter Pettus,[18] Ninetta Saviano,[19,20] Anna M. Suliga,[21,22] Volodymyr Takhistov,[23] Mariam Tórtola,[15,16] José W. F. Valle,[15] Benjamin Wallisch[24,25]

arXiv: 2203.07377

The coming era of precision cosmology

I. CMB Stage-IV and others
   A. Simons Observatory - Atacama Desert, Chile
   B. South Pole Observatory - South Pole
   C. Other CMB experiments - CLASS and QUIET
   D. Satellites: LiteBIRD and PIXIE

II. Thirty-meter class telescopes
   A. EELT and GMT - Atacama
   B. TMT – Mauna Kea, Hawaii

III. Surveys
   A. DES - Cerro Tololo, Chile
   B. DESI - Kitt Peak, AZ
   C. Vera Rubin Observatory – Cerro Pachón, Chile
   D. Satellites: Euclid, Roman, SPHEREx

Physics of Big Bang Nucleosynthesis

Setting the stage:

a. Homogeneous & Isotropic
b. Nearly CP symmetric (10^{-10})
c. No free quarks

Synthesis of light-elements:

- Hydrogen ~ 0.75
- Helium ~ 0.25
- Deuterium $\sim 10^{-5}$
- Lithium $\sim 10^{-10}$

Sub-epochs of BBN

Weak Decoupling: $\nu(\nu,\nu)\nu$ & $e(\nu,\nu)e$

Weak Freeze Out: $n(\nu,e)p$

EM equilibrium: $e(e,\gamma)\gamma$

Nuclear Freeze Out: $n(p,\gamma)d$

Baryogenesis $\sim ?$

↓

QCD Epoch $\sim 10^{-5}$ s

↓

Time $\lesssim 1$ sec.

↓

Time $\gtrsim 100$ sec.

Out-of-Equilibrium Neutrino Energy Transport

Neutrino scattering on charged leptons

$$\nu_i + \overline{\nu}_i \leftrightarrow e^- + e^+$$

$$\nu_i + e^\pm \leftrightarrow \nu_i + e^\pm$$

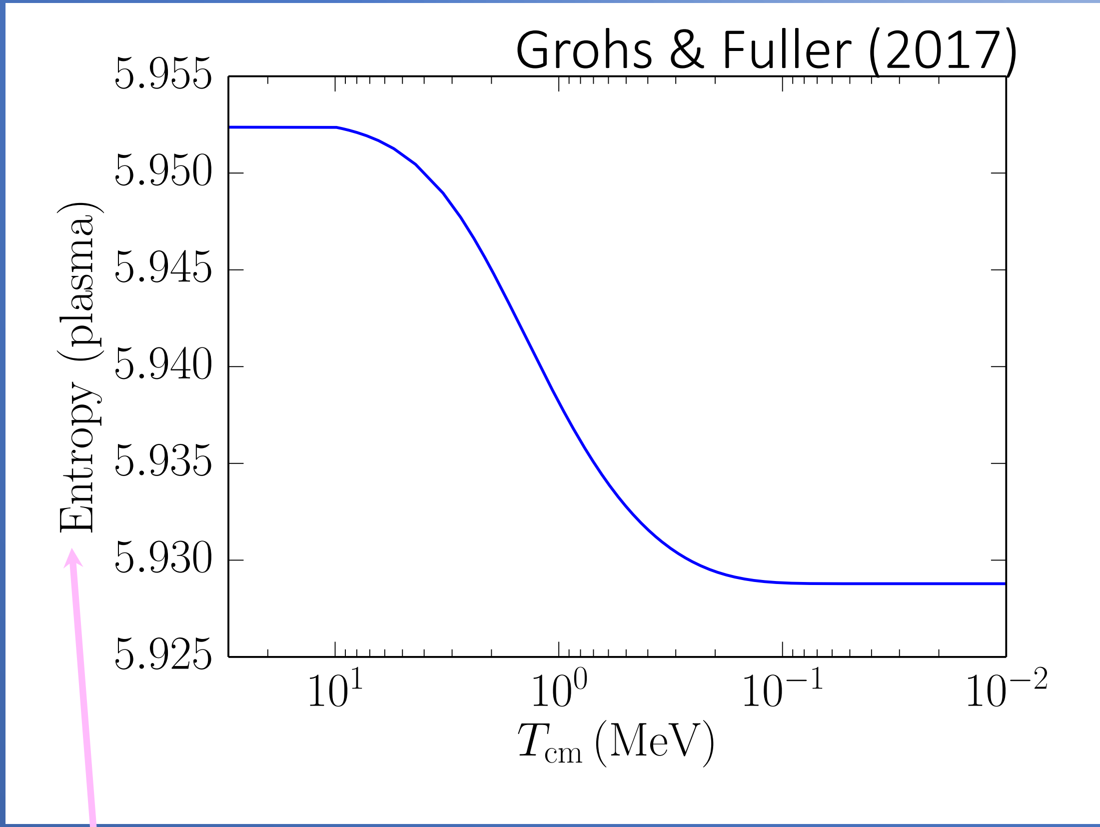
Important for CMB parameter for radiation energy density

$$\delta\rho_\nu \sim 1\%$$

Neutrino Transport coupled to Nuclear Reaction Network (Grohs et al 2016)

$$\delta(^4\mathrm{He}) \sim 4 \times 10^{-4}$$

$$\delta(\mathrm{D/H}) \sim 3 \times 10^{-3}$$



$\sim\omega_b$

Deuterium sensitive to entropy!

Neutron-to-Proton Rates

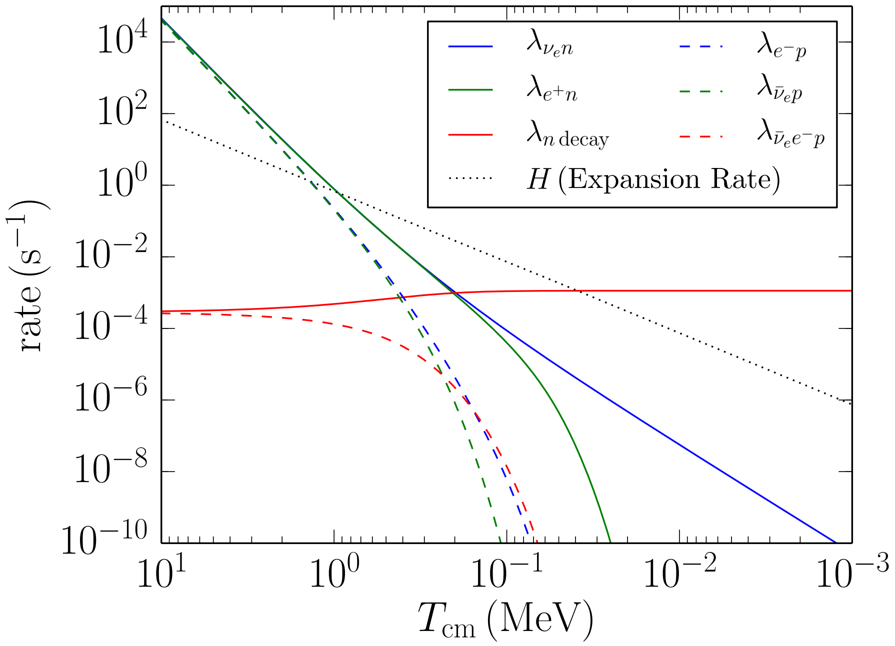
$$\nu_e + n \leftrightarrow p + e^-$$

$$e^+ + n \leftrightarrow p + \overline{\nu}_e$$

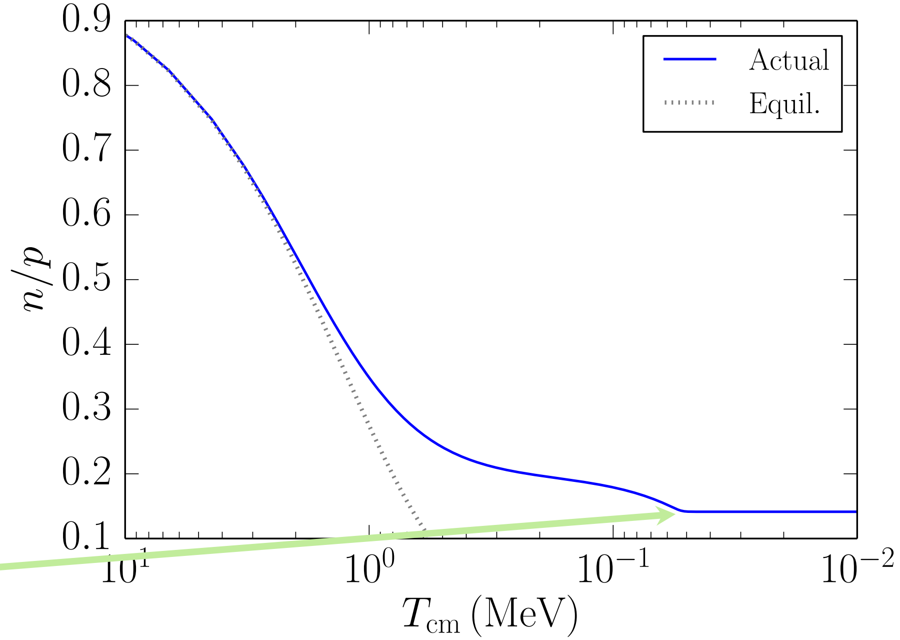
$$n \leftrightarrow p + e^- + \overline{\nu}_e$$

6 rates normalized to neutron lifetime

$m_n - m_p \simeq 1.3$ MeV



Grohs & Fuller (2016)



Rule of thumb: $^4\mathrm{He}$ 25% by mass

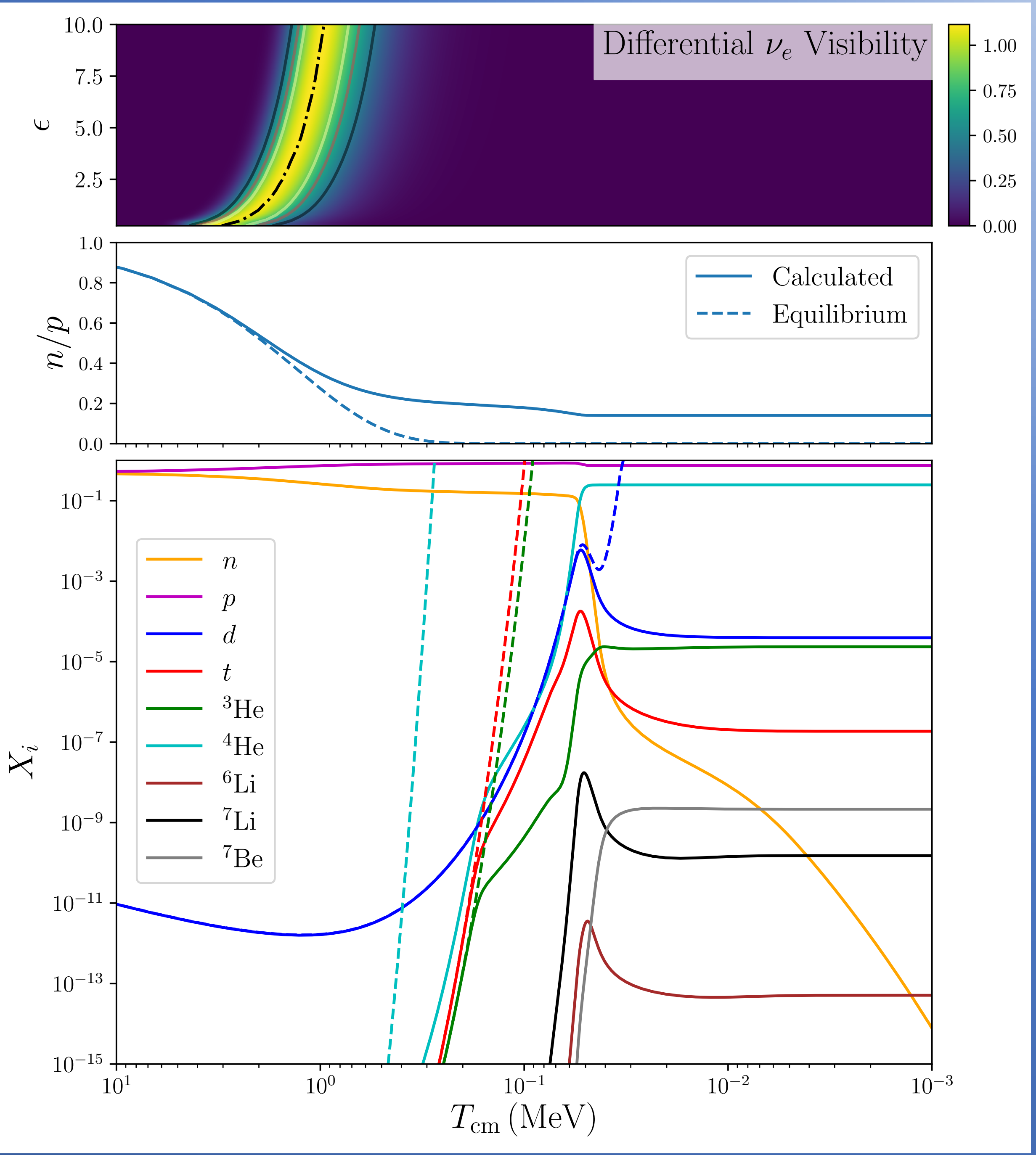
$$p\ p\ p\ p\ p\ p\ \boxed{p\ n}$$
$$p\ p\ p\ p\ p\ p\ \boxed{p\ n}$$

$$n/p \sim 1/7$$

Neutrino physics occurring during BBN

Coincident epochs during BBN

Dashed lines: weak equilibrium or NSE



Bond+ (In Prep.)

Radiation energy density during Recombination

Computing CMB observables requires energy density

$$\rho_{\rm rad} = \rho_\gamma + \rho_{\rm other} = \left[2 + 2\frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff} \right] \frac{\pi^2}{30} T^4$$

Photon Contribution

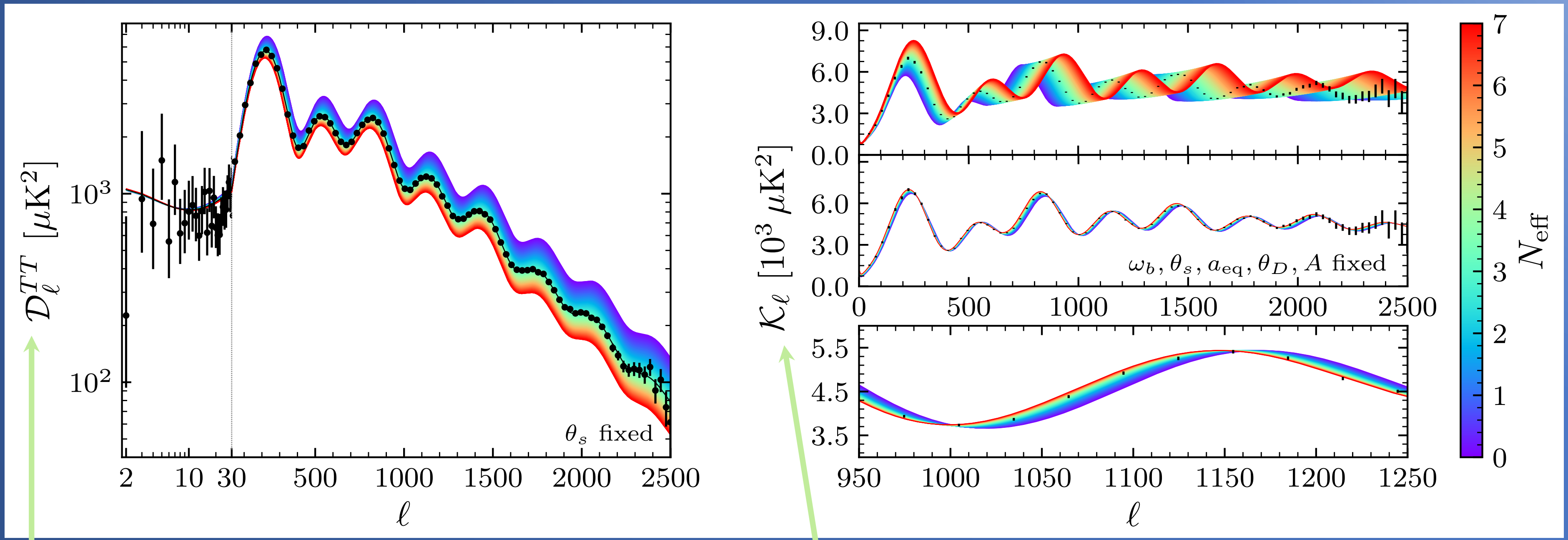
Non-Photon Contribution

Effective number of neutrinos: parameter for non-photon energy density

Need not be an integer!

Effects of Radiation on CMB

Black points are Planck 2018 data values



Temperature Power Spectrum

Non-damped Temperature Power Spectrum

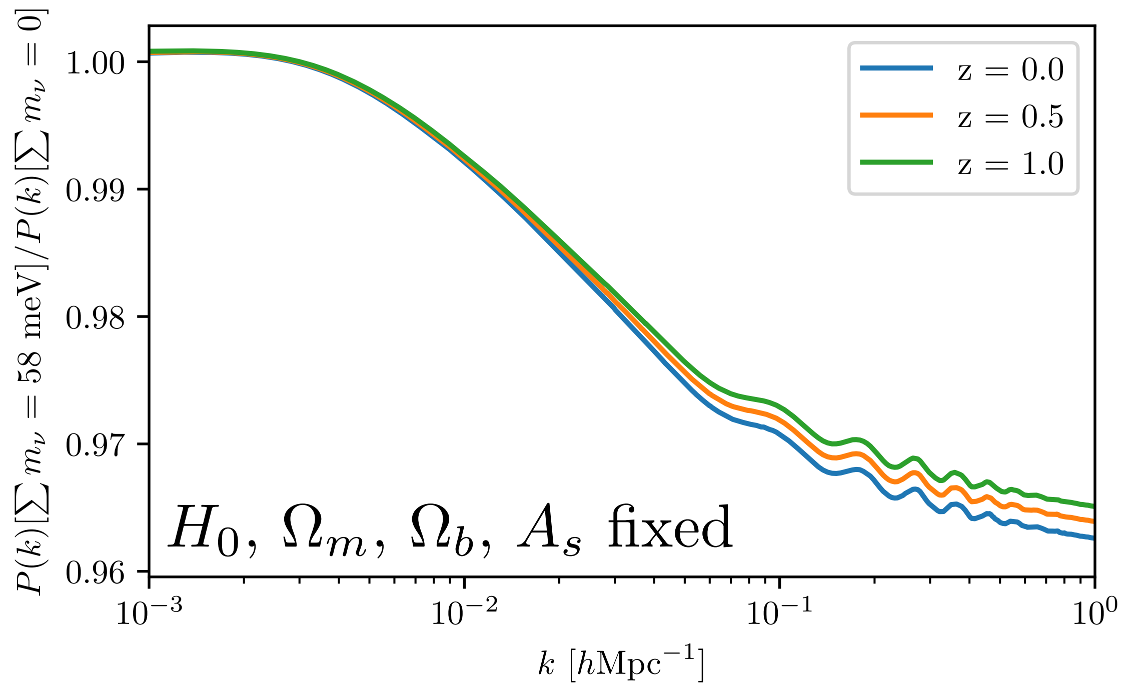
Non-photon radiation

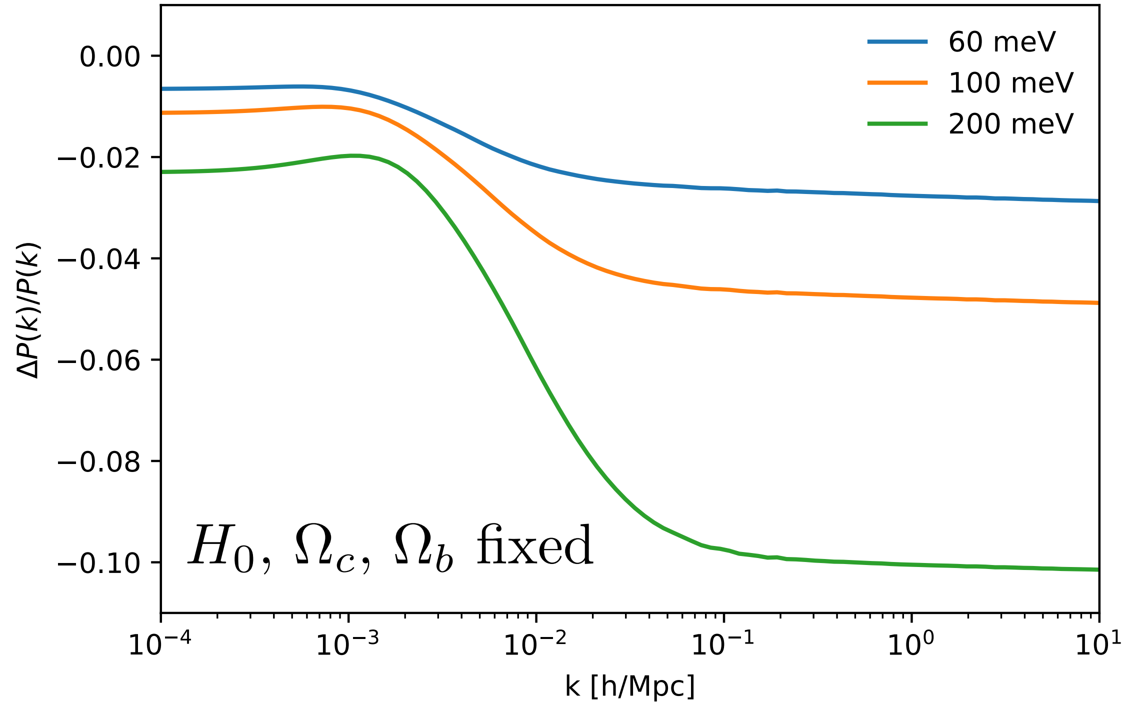
Free-streaming radiation

Planck 2018: $N_{\rm eff} = 2.92^{+0.18}_{-0.19}\,(1\sigma)$

Matter Power Spectrum

Neutrinos become non-relativistic: $z_{\rm nr} \sim 100$

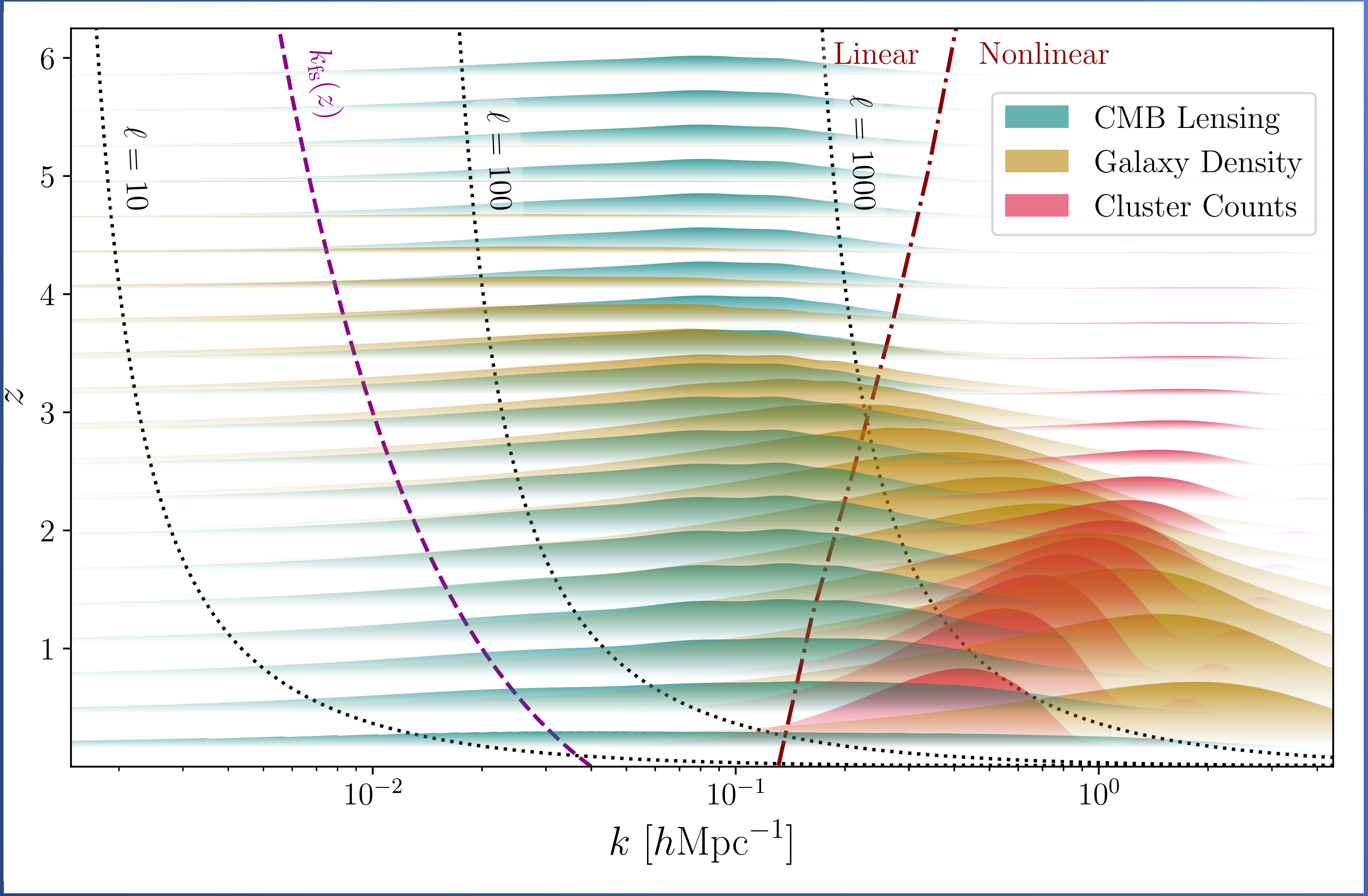




Power suppressed from neutrino free-streaming at small scales

Planck 2018: $\Sigma m_\nu < 0.120\,\text{eV}\ (2\sigma)$

Contributions to Matter Power Spectrum (forecasts)



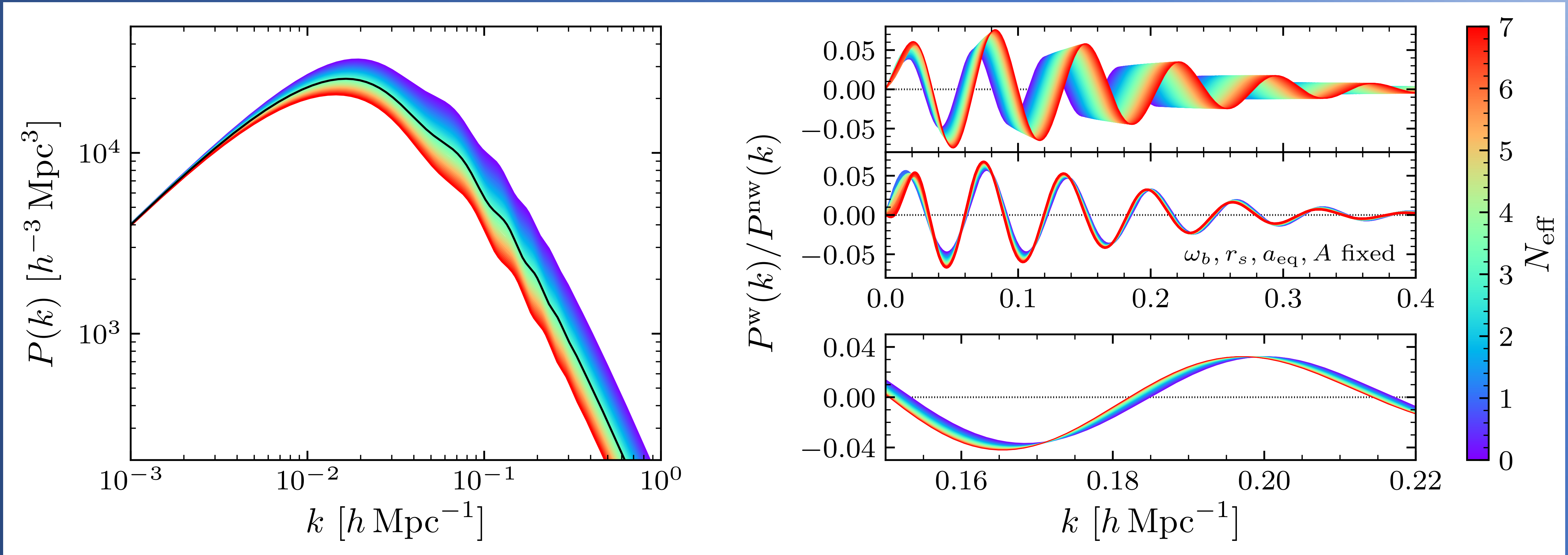
CMB Lensing
CMB-S4

Galaxy Density
VRO Gold sample

Cluster Counts
tSZ counts from CMB-S4

Contributions weighted by S/N (x3 for CMB Lensing)

Baryon-Acoustic Oscillation Phase Shift



Similar physics of free-streaming radiation influencing CMB phase shifts

Detectable [see Baumann et al (2019)]

Constraints on non-standard Neutrino Cosmologies

I. Sterile Neutrinos
   a. N_{eff} sensitivity from O(eV)
   b. Dark matter contribution for O(keV)
   c. Early Universe dynamics O(MeV)

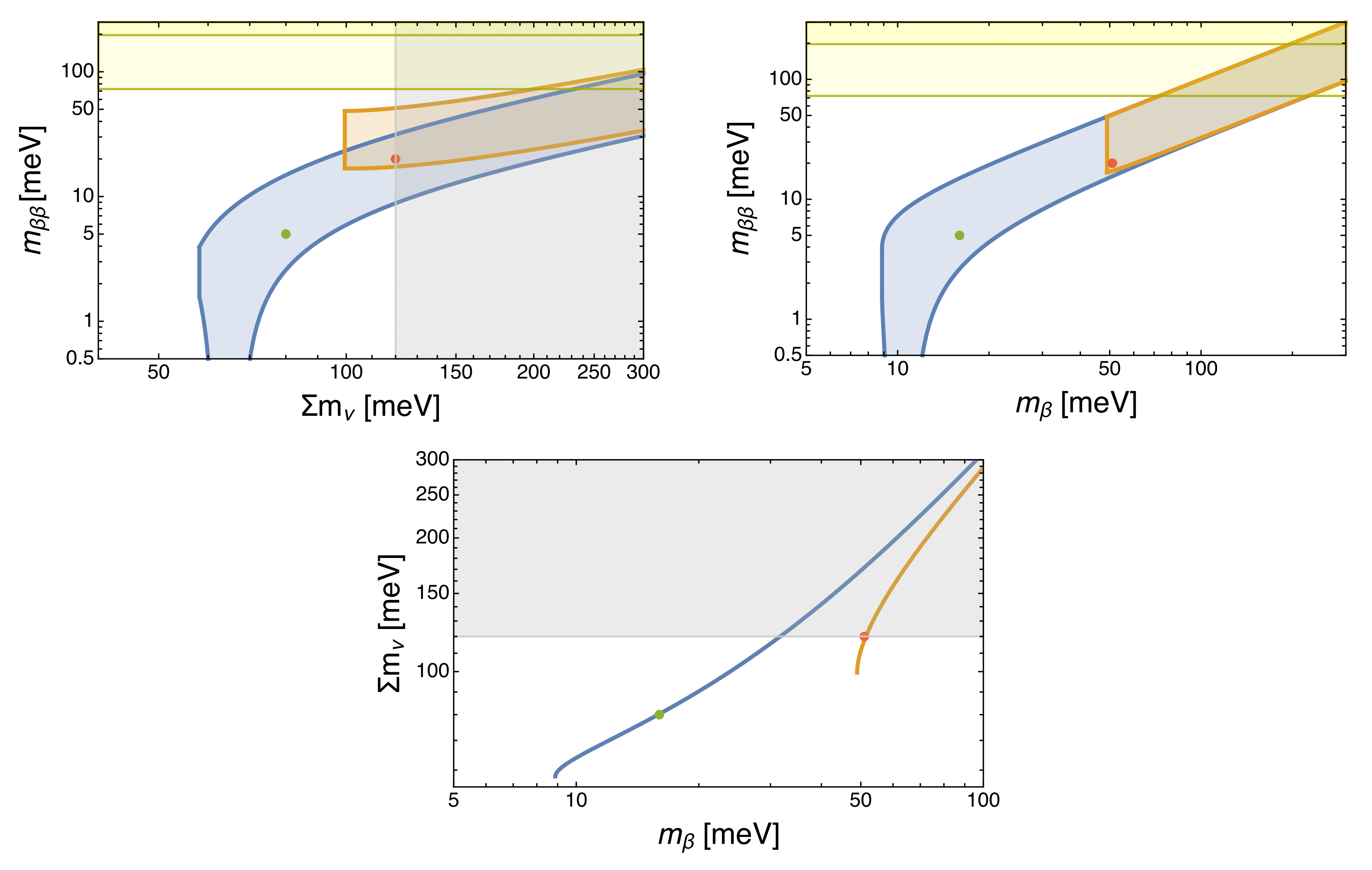
II. Neutrino non-standard interactions
   a. Influence on free-streaming assumptions (possible Hubble tension amelioration)

III. Neutrino lepton numbers
   a. Leptogenesis models
   b. BBN abundances

IV. Neutrino lifetime (from free-streaming): $\tau_\nu \geq 4 \times 10^6 (m_\nu / 0.05\,\mathrm{eV})^5$

V. Low-temperature Reheating (decrease in N_{eff})

Concordance Scenarios for neutrino mass



Beyond Concordance for neutrino mass

1. First Scenario
   a. Signal in $0\nu 2\beta$
   b. No detection of $\Sigma m_\nu \neq 0$
   c. Severe challenge to ΛCDM and thermal history of neutrino spectra
   d. Any detection from endpoint experiments would further challenge ΛCDM

2. Second Scenario
   a. Signal in $0\nu 2\beta$
   b. Detection of $\Sigma m_\nu \neq 0$
   c. Signals discordant, i.e., do not lie in bounded areas of previous plot
   d. Possible Causes:
      i. Another challenge to ΛCDM
      ii. Sterile states contributing to $m_{\beta\beta}$
      iii. Exotic physics beyond neutrino mass

Summary

1. Solid evidence for the existence of neutrinos in hot big bang cosmology
    1. CMB and BAO show N_{eff} not equal to zero
    2. BBN shows neutrinos have $\sim$thermal spectra

2. Future probes will show even more sensitivity to neutrino energy spectra

3. Convolution of terrestrial experiments and cosmological probes may reveal basic neutrino properties

4. Discordance between terrestrial and cosmology will undoubtedly reveal new physics