Cosmology & Neutrinos

P5 Town Hall at Fermilab & Argonne

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The Cosmological Neutrino

The second most abundant particle in the Universe*
From thermal physics:

$$n_\gamma = \frac{\zeta(3)}{\pi^2}\, g\, T^3 \approx 411\,\mathrm{cm}^{-3}$$

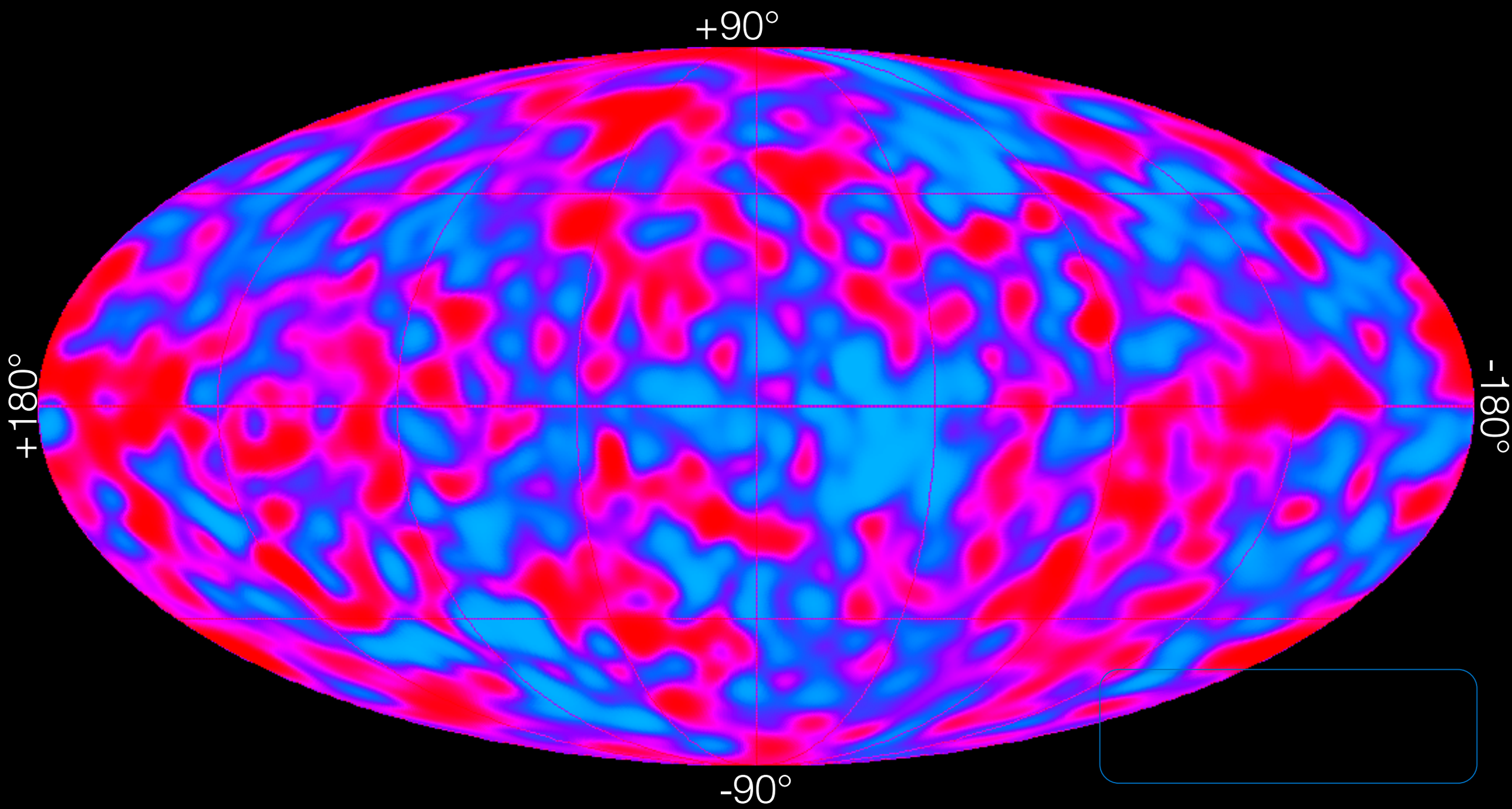
$$n_\nu = N_\nu \times \left(\frac{3}{11}\right) n_\gamma \approx 340\,\mathrm{cm}^{-3}$$

*depends on dark matter particle mass...

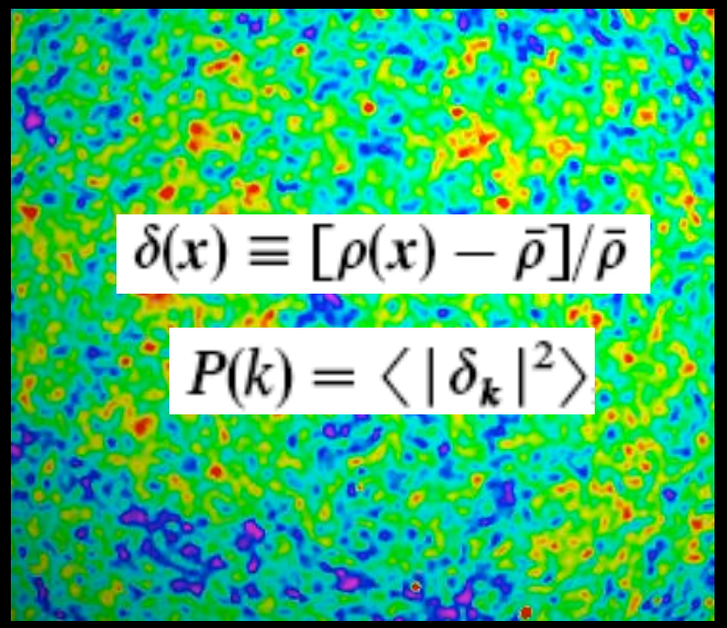
$$\sum_{i=1}^{m} t_v$$

Neutrino Cosmology has a Goal of Measuring Matter Clustering from Large to Small Scales

Cosmic Microwave Background
from the **COBE** Satellite, 1992



Large Scale Structure: the cosmological density perturbation spectrum

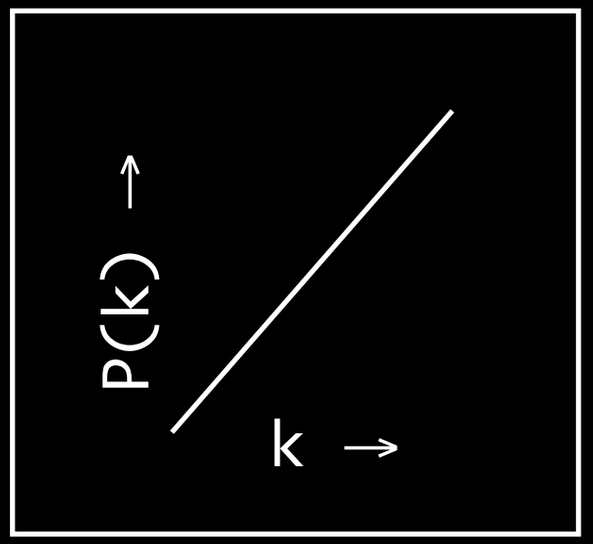


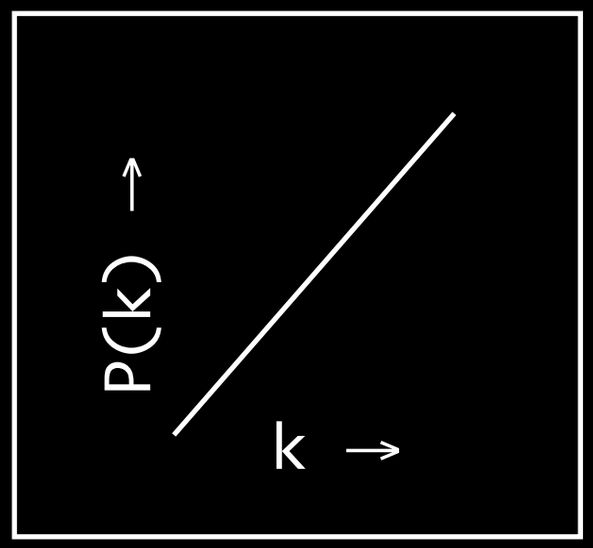
- Power spectrum of cosmological density fluctuations

  $$P(k) = \langle |\delta_k|^2 \rangle$$

- Predicted by inflation

  $$P(k) \propto k^n \qquad n \lesssim 1$$





Primordial Clustering: Cosmic Microwave Background gives a Precision Determination at Large Scales

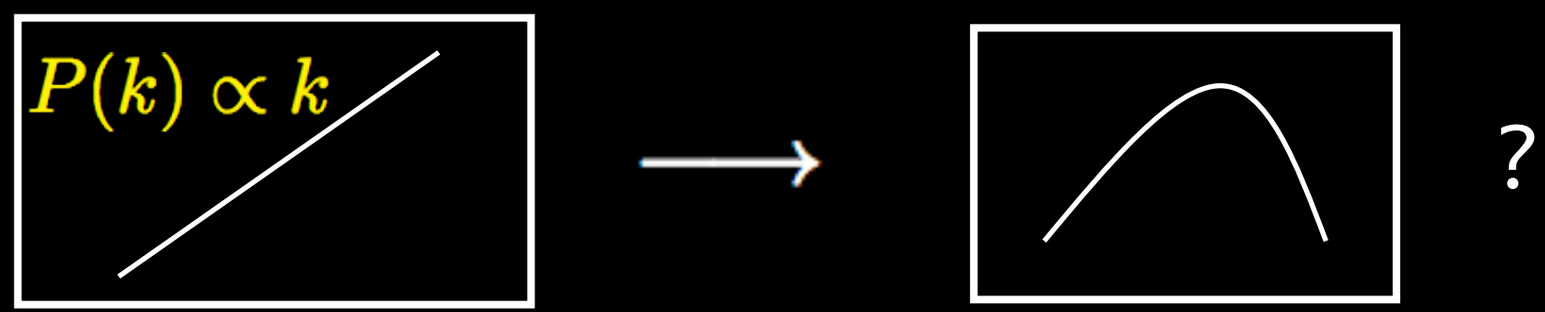
$$P(k) = Ak^n$$

Planck Collaboration 2018:

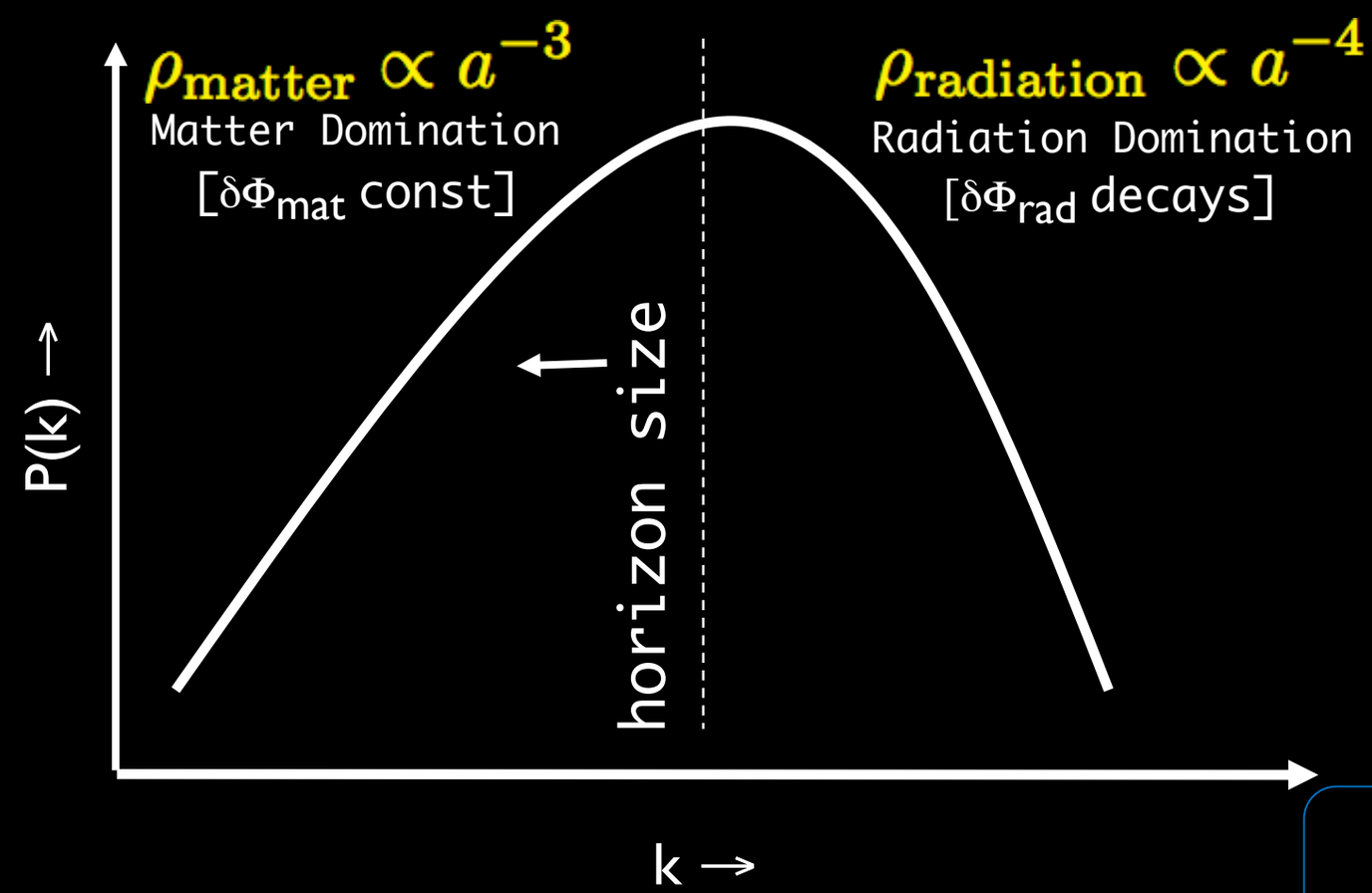
$$\ln(10^{10} A_s) = 3.047 \pm 0.014 \qquad (0.46\%)$$

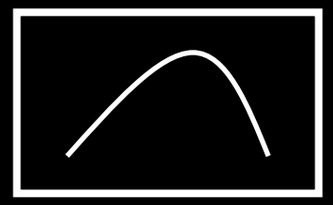
$$n = 0.9665 \pm 0.0038 \qquad (0.39\%)$$

The Cosmological Matter Power Spectrum



Perturbations enter horizon:



How does  probe neutrinos?

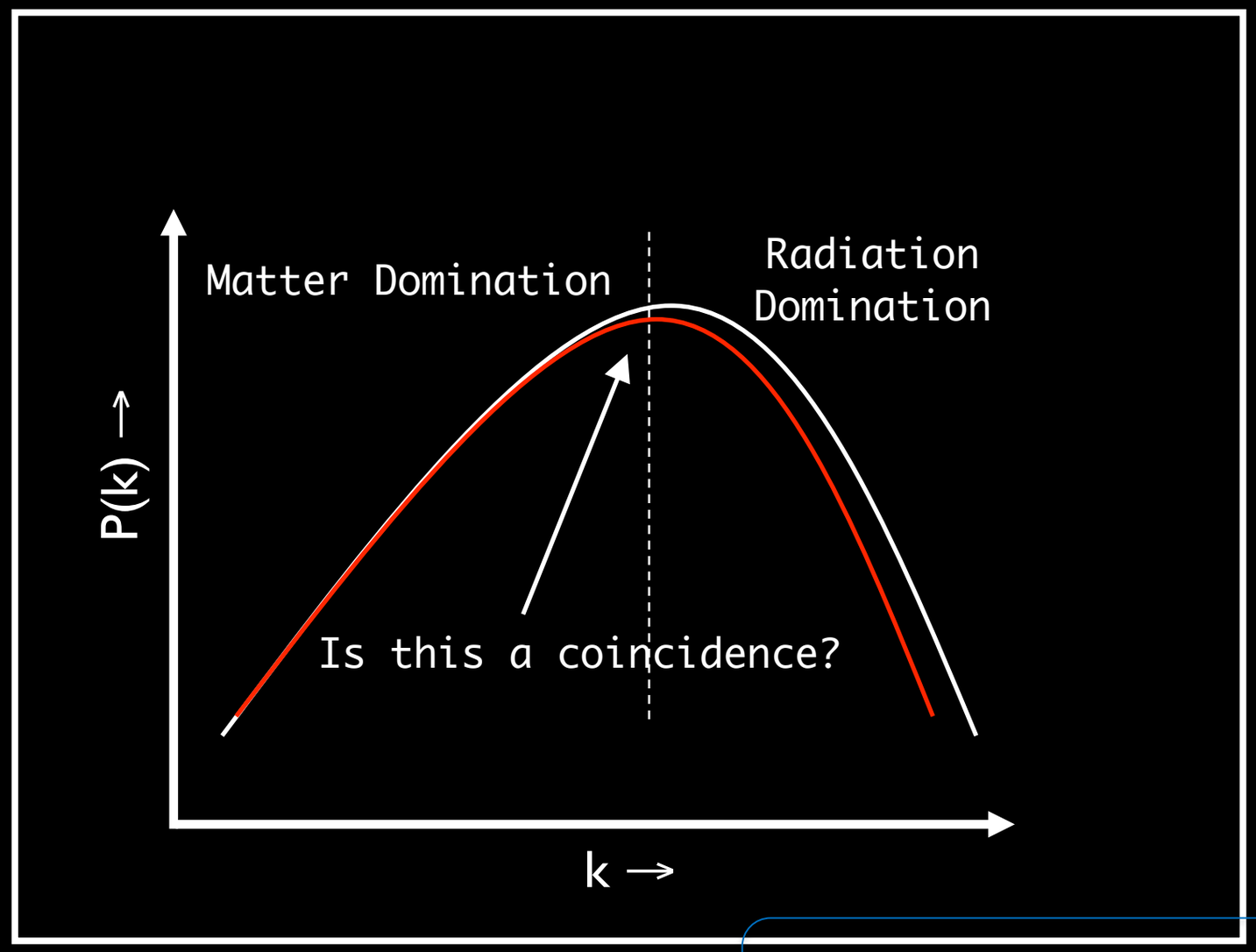
$$n_\nu = N_\nu \times \left(\frac{3}{11}\right) n_\gamma \approx 340 \text{ cm}^{-3}$$

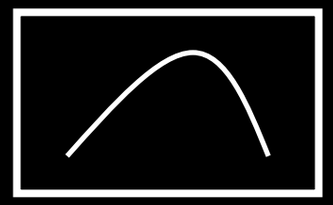
(Assuming thermal equilibrium)

$$\rho_\nu = \sum m_i n_{\nu_i}$$

$$\Omega_\nu \approx \frac{\sum m_{\nu_i}}{93\ h^2 \text{ eV}}$$

$$E^2 = p^2 + m^2$$



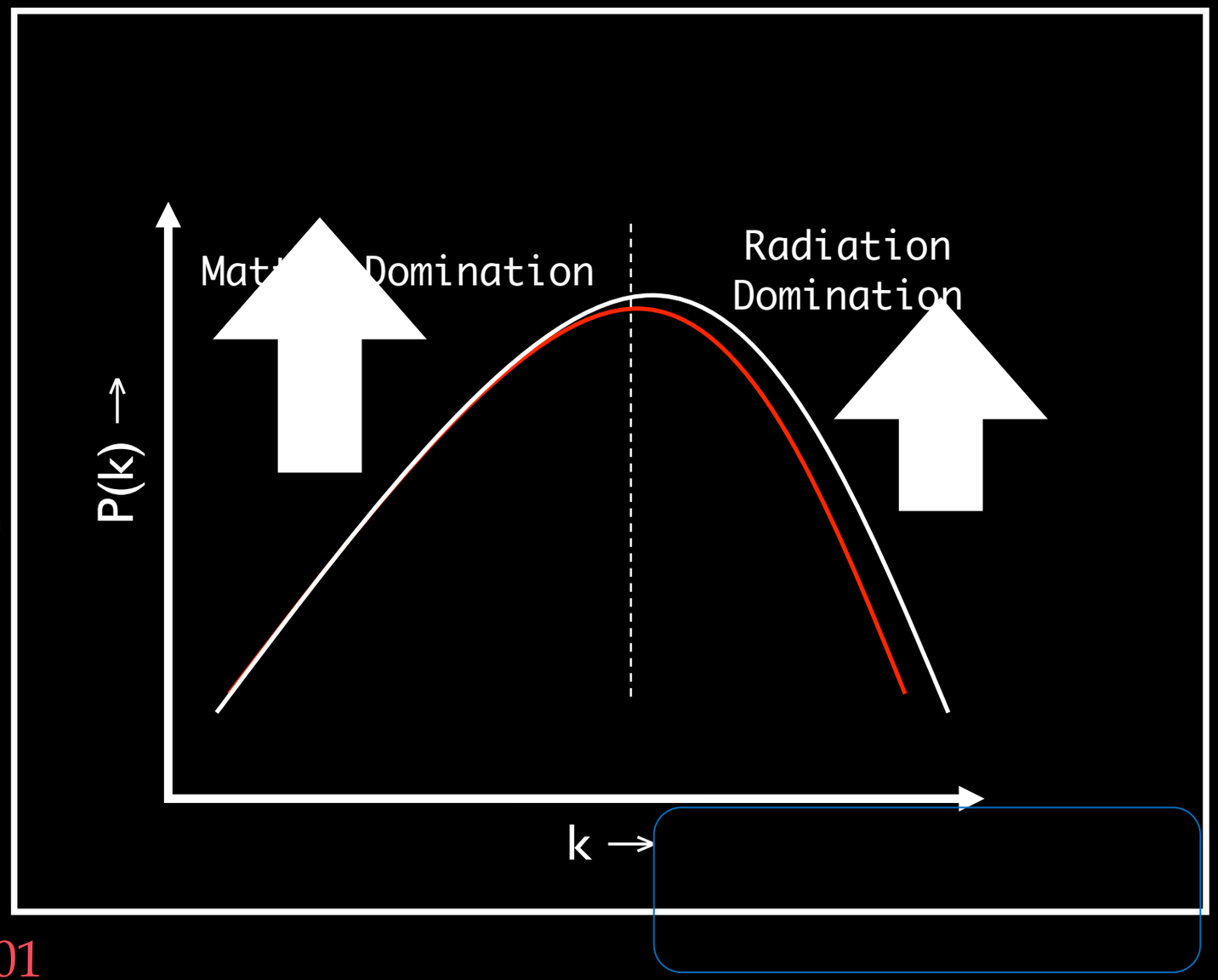
How does  probe neutrinos?

Growth of perturbations since matter domination…

$$\ddot{\delta}_m + 2H\dot{\delta}_m - 4\pi G\bar{\rho}\delta_m = 0$$

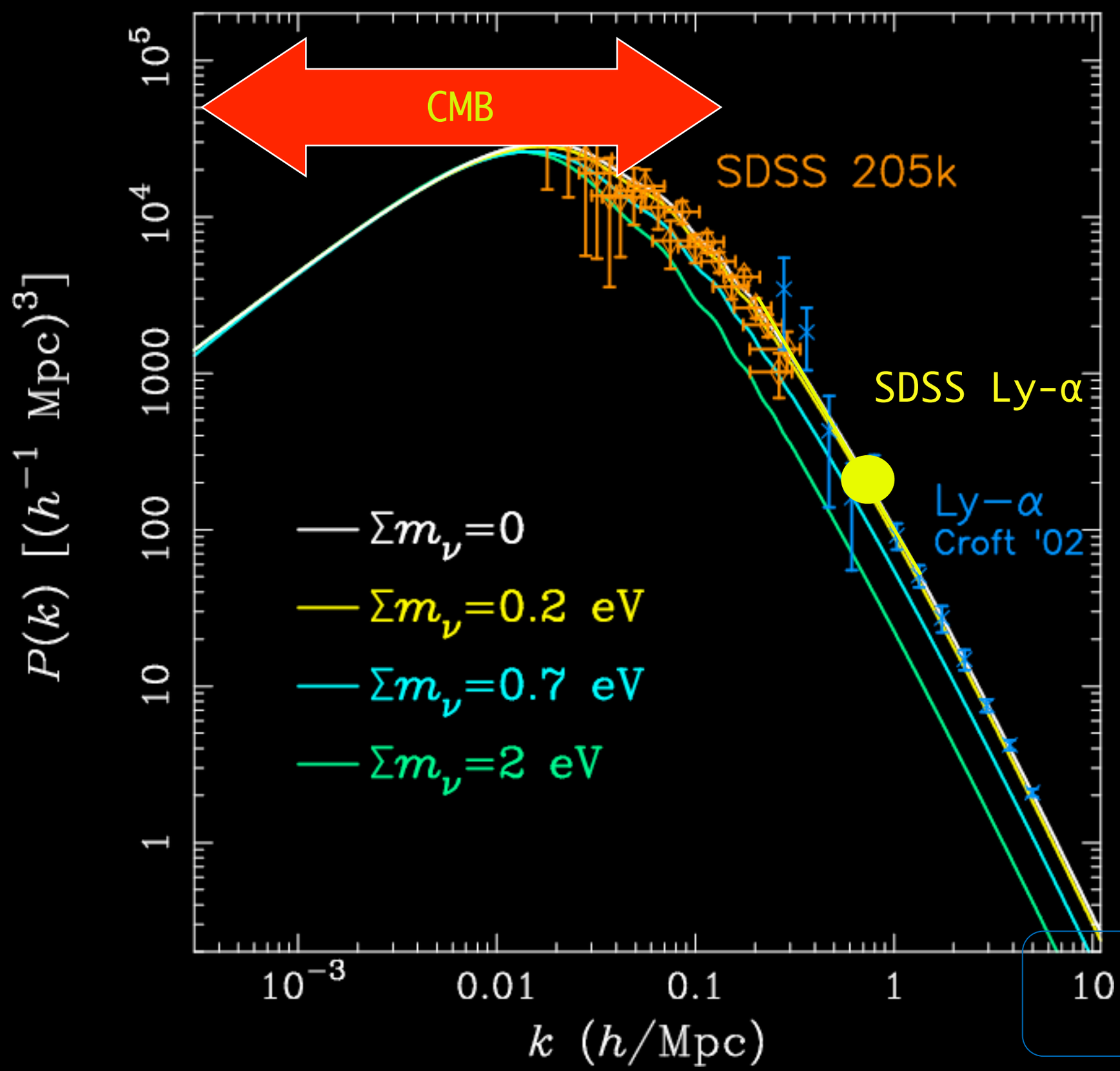
Growth factor of several orders of magnitude since matter/radiation equality, and…

Growth is suppressed for non-relativistic neutrinos below their free-streaming scale

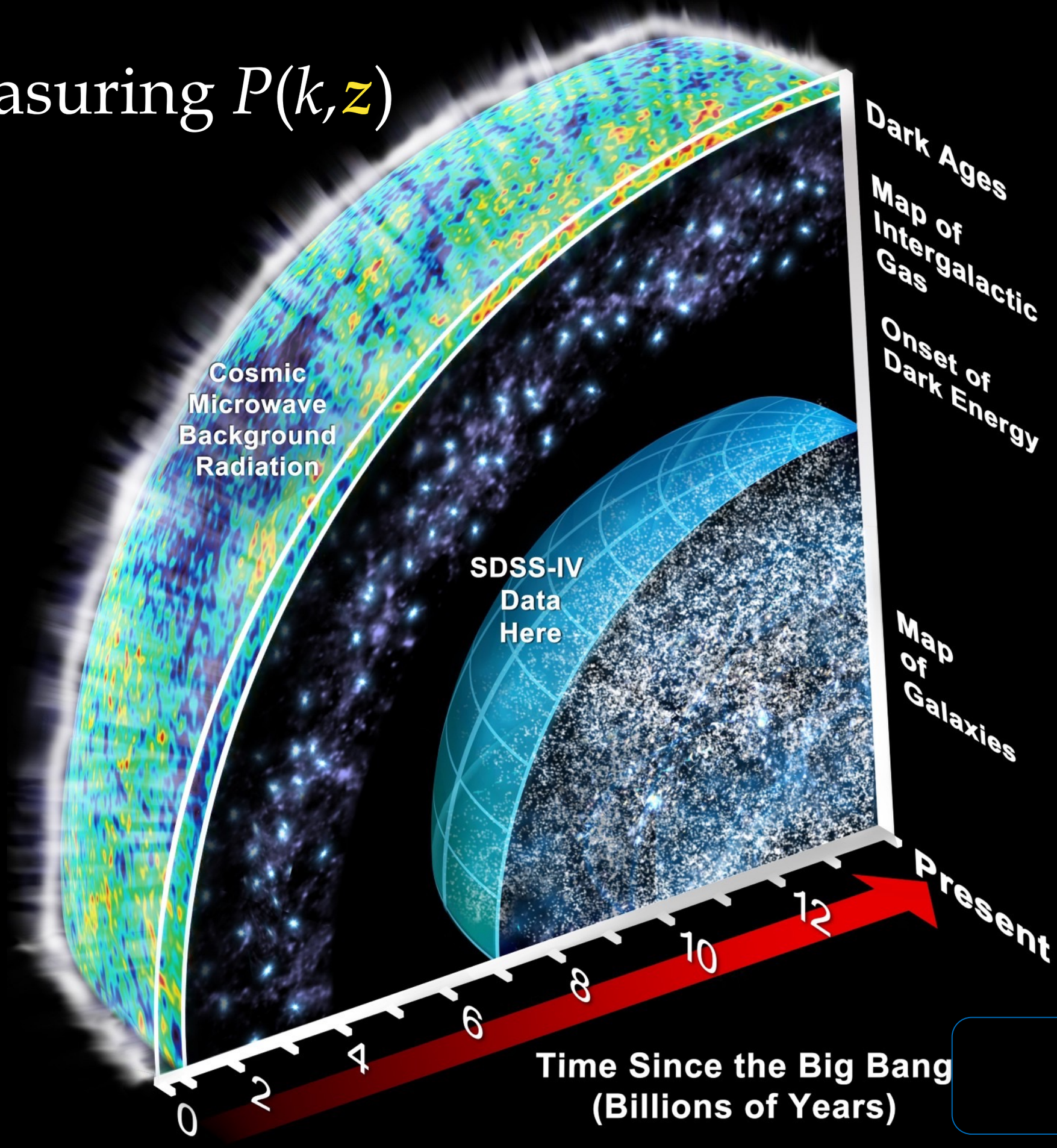


Abazajian & Kaplinghat, *Ann. Rev. Nucl. Part. Sci.* 66 (2016) 1, 401

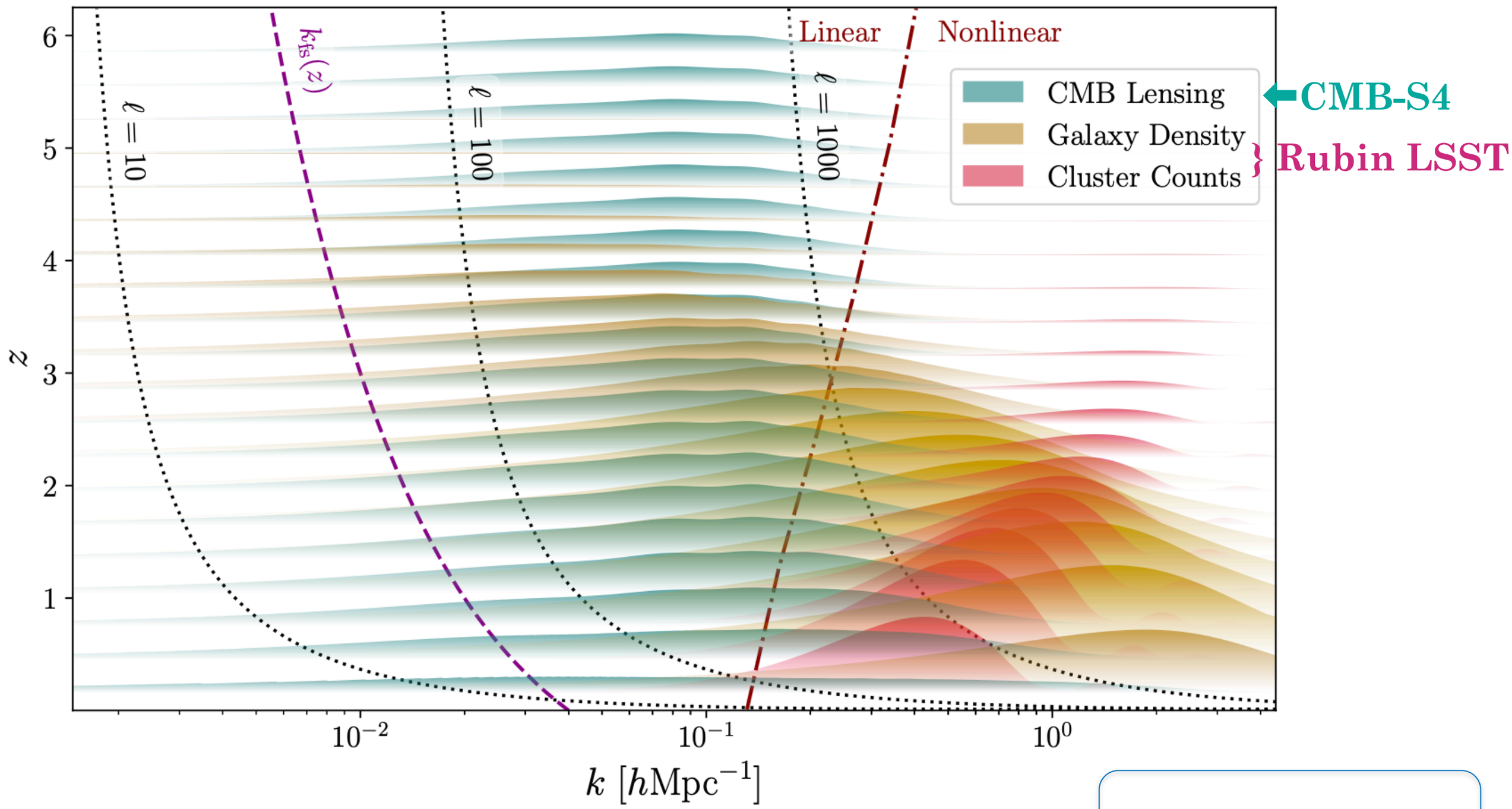
Measuring Large Scale Structure $P(k)$ & $\sum m_\nu$



Measuring $P(k,z)$

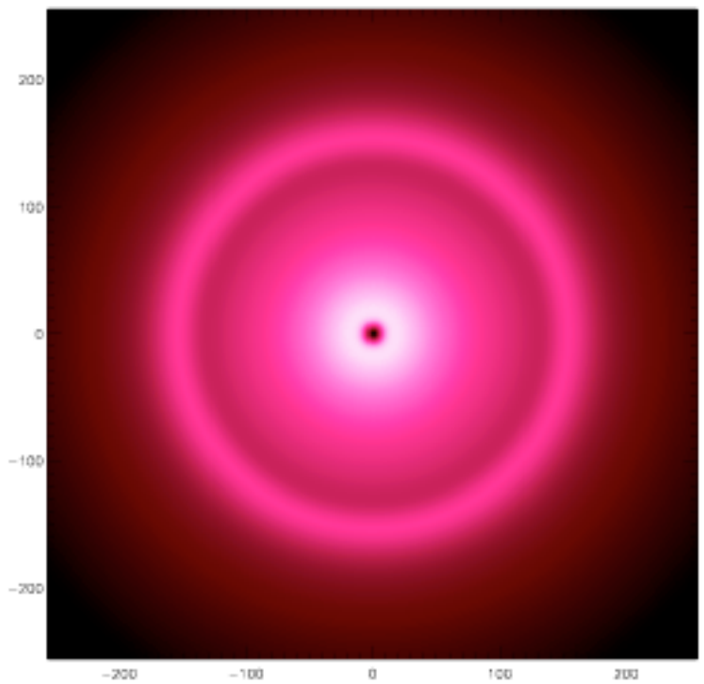


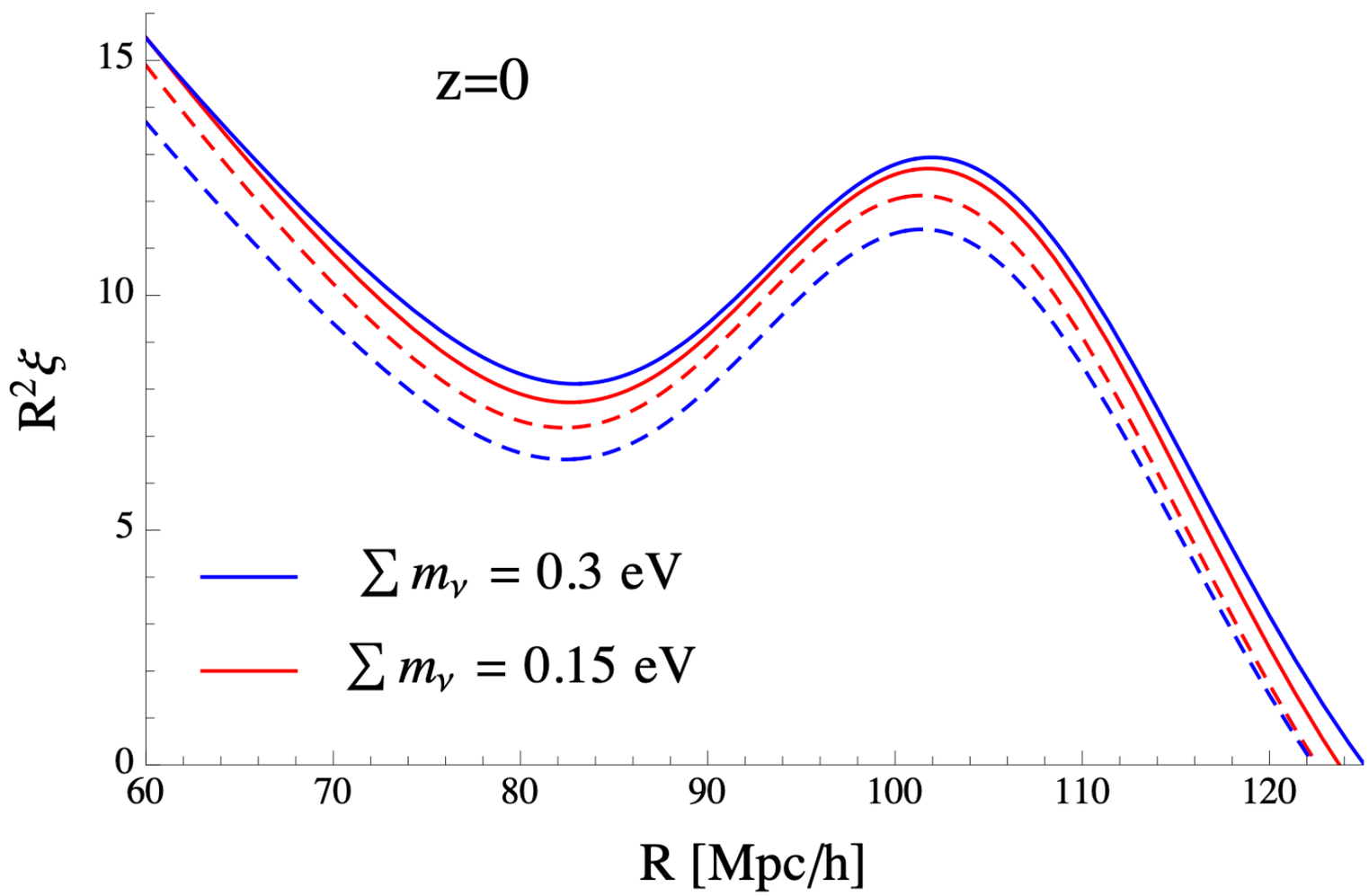
Observations' Sensitivity to LSS $P(k,z)$



Abazajian et al. arXiv:2203.07377

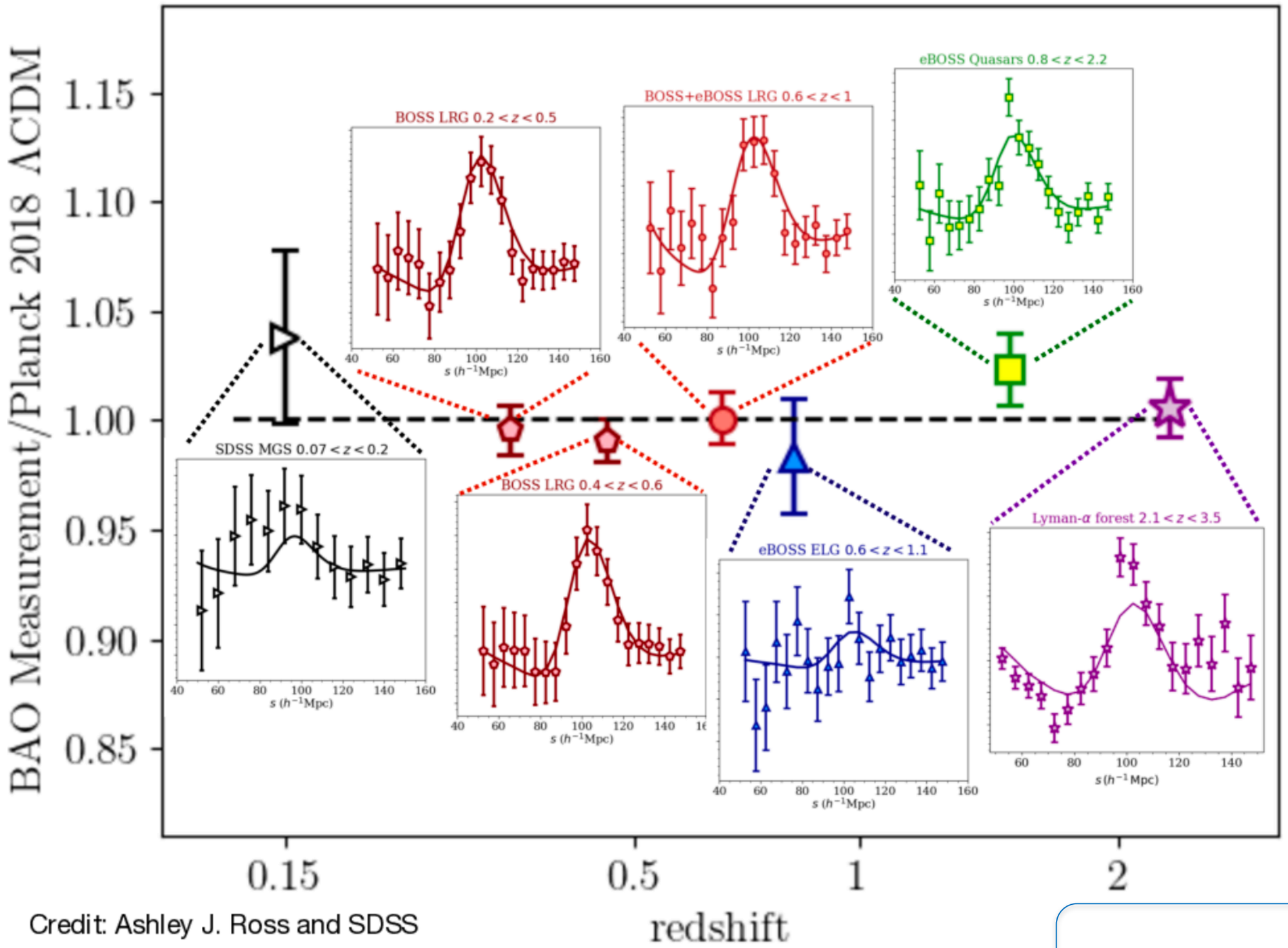
Baryon Acoustic Oscillations





Peloso et al., arXiv:1505.07477

Baryon Acoustic Oscillations: SDSS Distance Ladder



Credit: Ashley J. Ross and SDSS

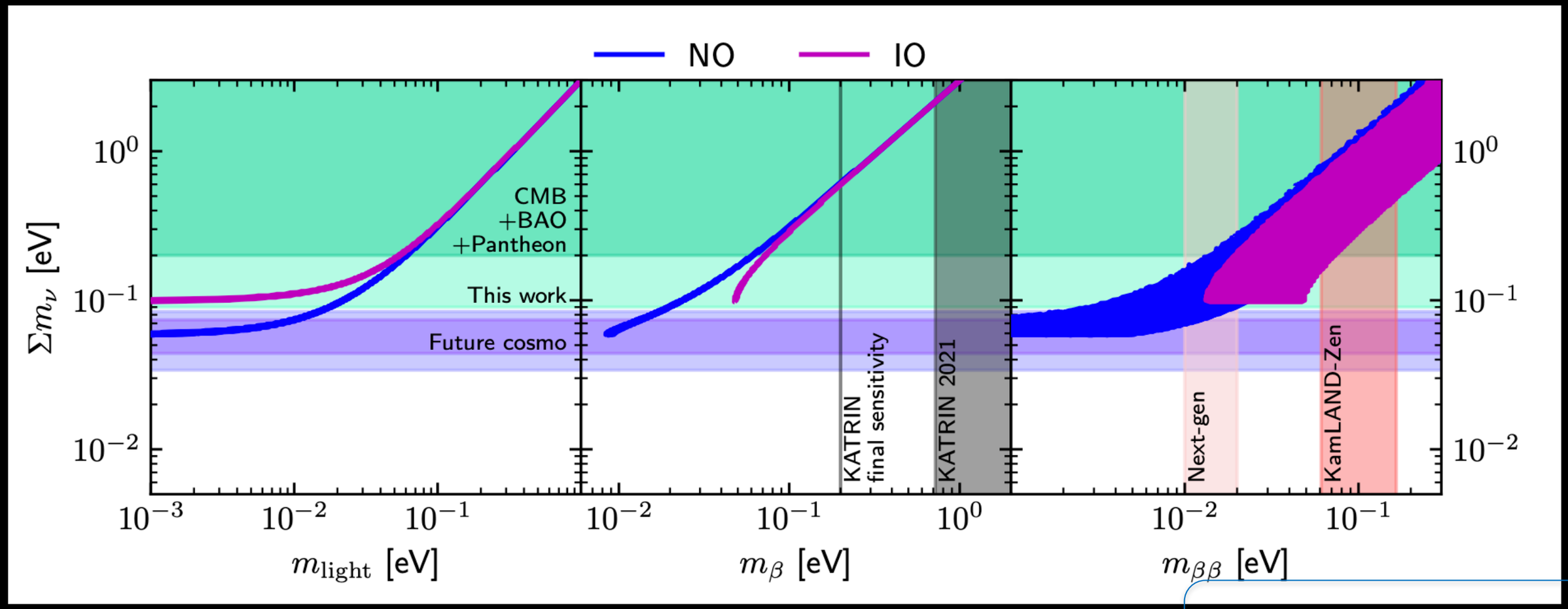
via Di Valentino

Current Σm_ν Limits

Neutrino mass is degenerate with other cosmological parameters (Ω_m especially), so all cosmological data useful in improving constraints:

$\Sigma m_\nu < 0.09$ eV (95% CL)

CMB + CMB Lensing (Planck 2018)
+ Type Ia SNe (Pantheon)
+ BAO + RSD (SDSS DR12+DR16)



Di Valentino, Gariazzo & Mena, arXiv:2106.15267

Estimating Upcoming Cosmological Neutrino Mass Sensitivities

$$\frac{\Delta P(k)}{P(k)} \approx 1\% \approx -8\frac{\Omega_\nu}{\Omega_m}$$

Hu, Eisenstein & Tegmark 1998

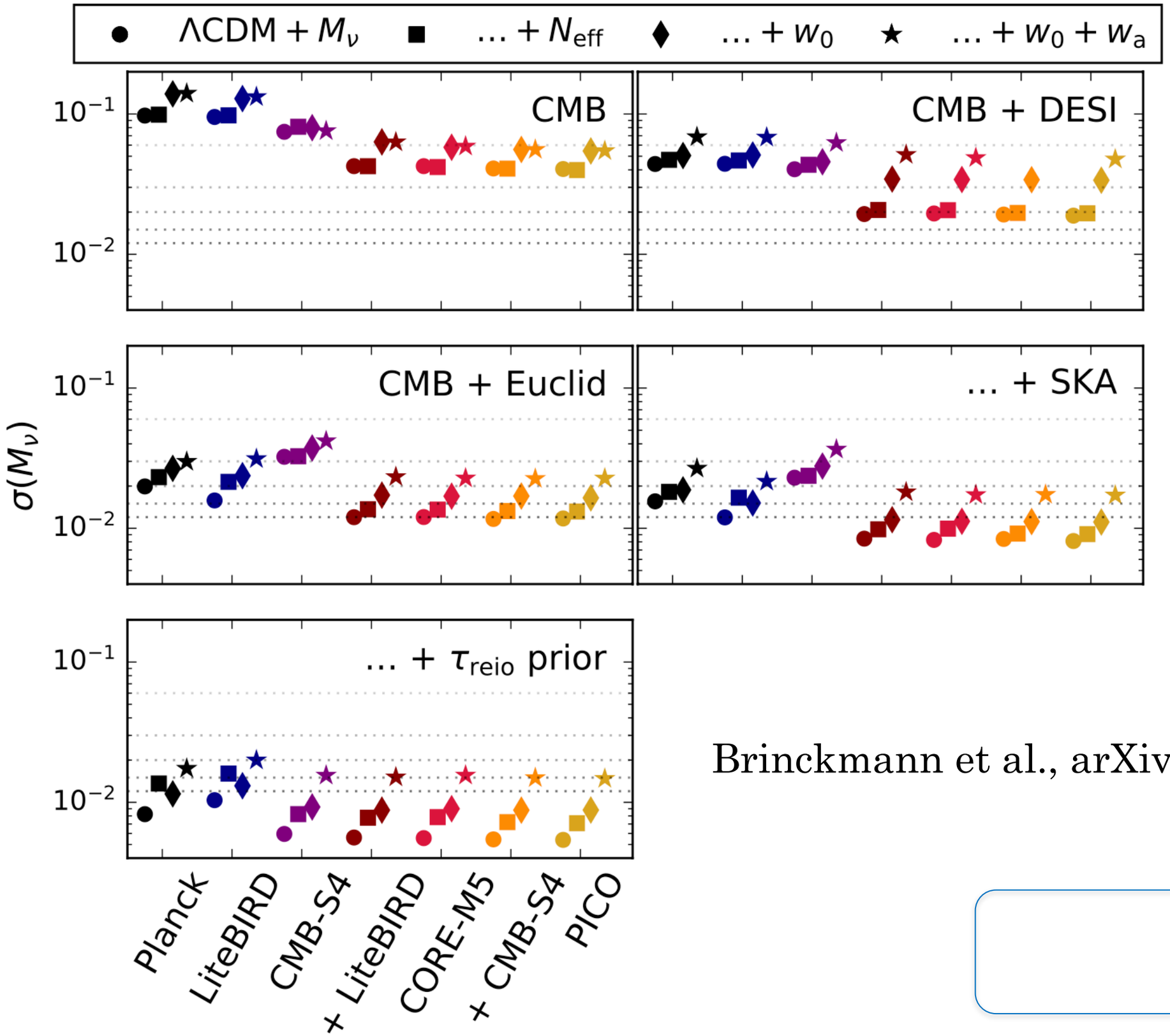
$$\Omega_\nu \approx \frac{\sum m_{\nu_i}}{93\ h^2\ \mathrm{eV}}$$

$$\Longrightarrow \sigma\left(\Sigma m_\nu\right) \lesssim (1\%/8) \times \Omega_m \left(93 h^2\ \mathrm{eV}\right)$$

$$\Longrightarrow \sigma\left(\Sigma m_\nu\right) \lesssim 20\ \mathrm{meV}$$

Kaplinghat et al PRL 2003 (CMB WL)
Wang et al PRL 2005 (WL Clusters)
De Bernardis et al. 2009 (Opt. WL)
Joudaki & Kaplinghat 2011 (LSST)
Basse et al. 2013 (Euclid)
Wu et al. 2014 (CMB-S4 + DESI)

Sensitivity Forecasts for Neutrino Mass with Standard Model Extension Dependence



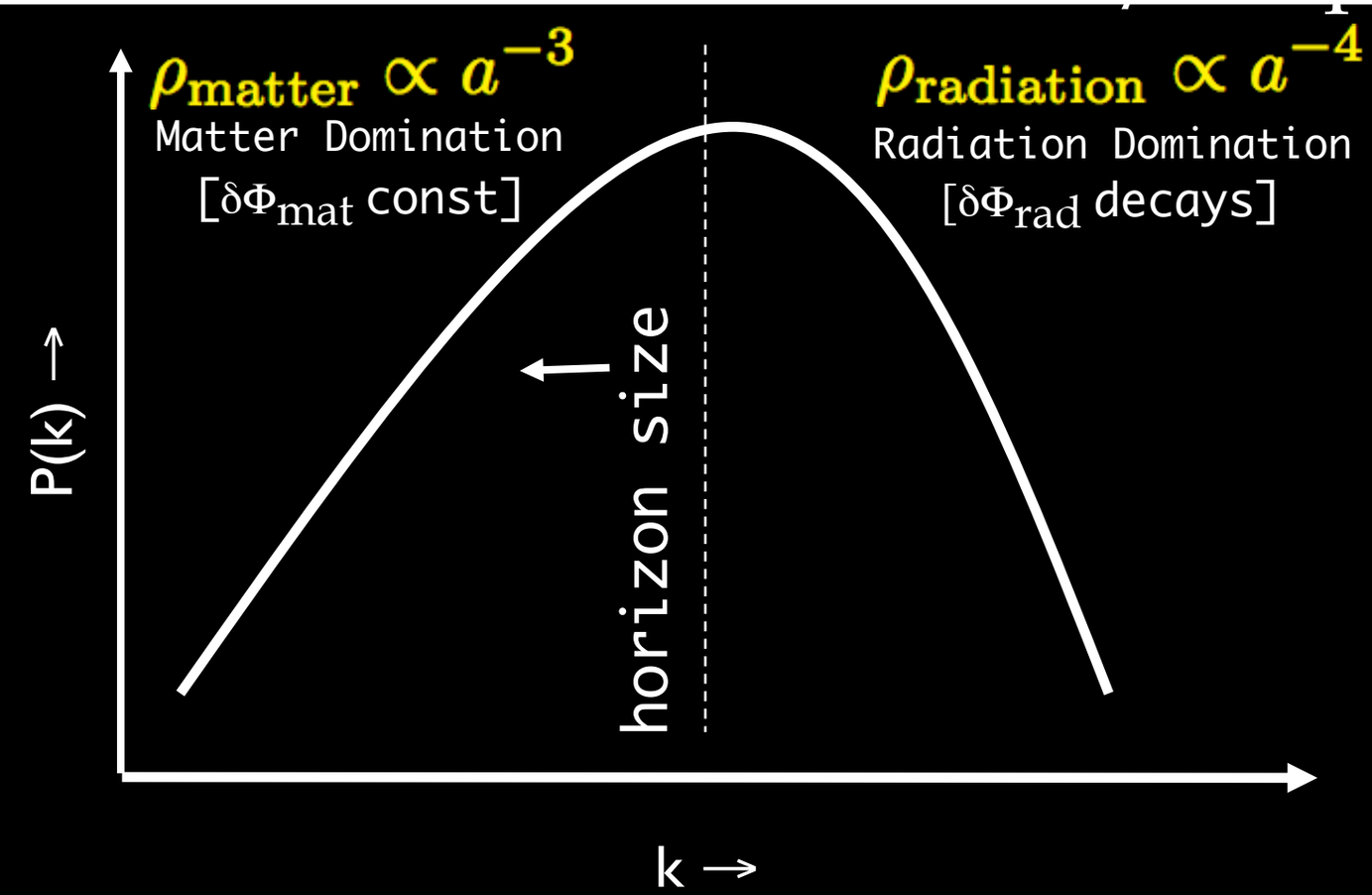
Brinckmann et al., arXiv:1808.05955

N_{eff}

Cosmological Matter Power Spectrum & CMB Measures of N_{eff}

For Large Scale Structure:

Perturbations enter horizon at M/R equality



For BAO:

Extra radiation changes expansion rate from Perturbation evolution through baryon decoupling

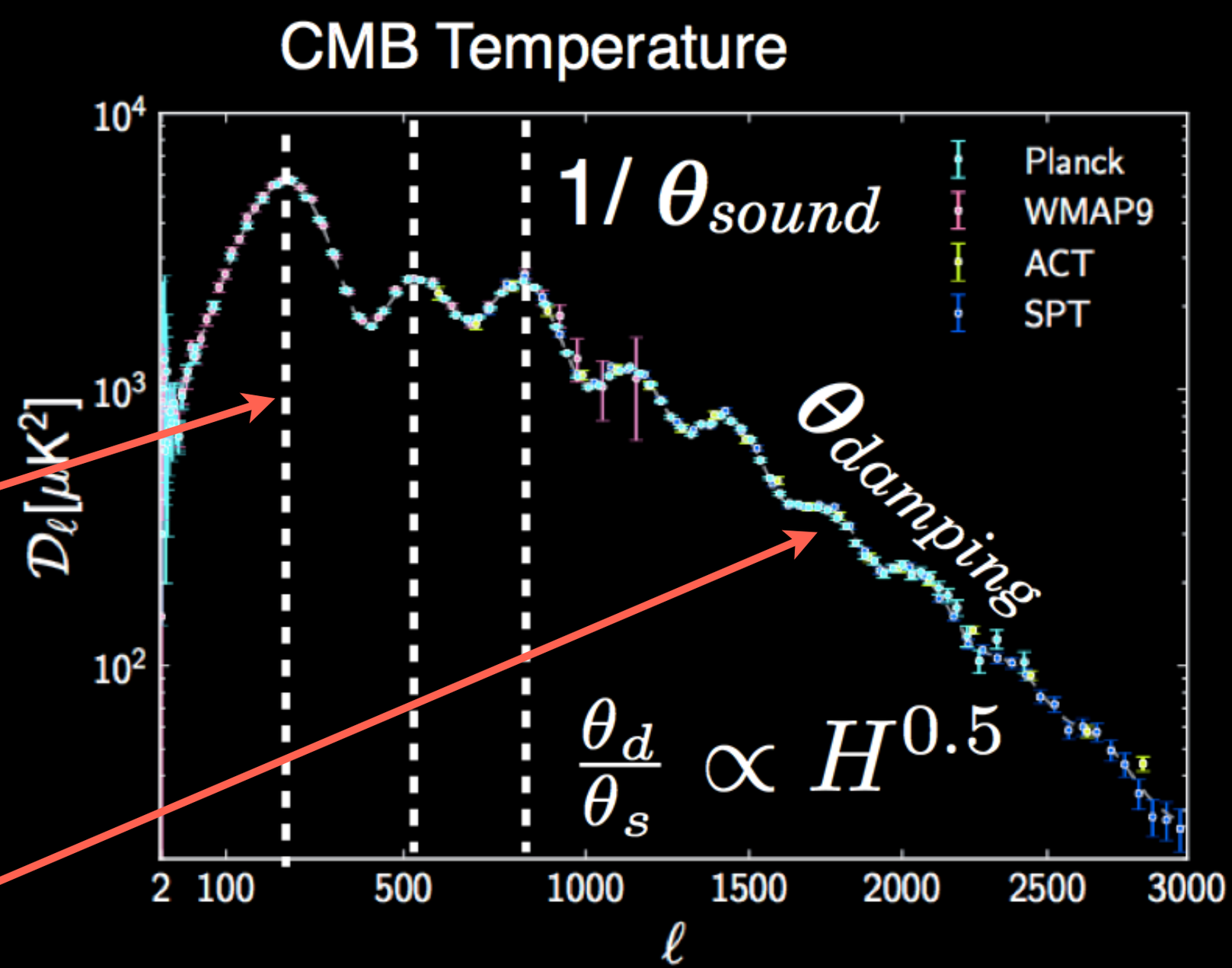
$N_{\rm eff}$ Effects on CMB

$$\frac{\theta_{\rm damping}}{\theta_{\rm sound}} \propto H^{1/2}$$

Larger $N_{\rm eff}$ Leads to More Damping

Angular scale of acoustic peaks $\theta_s \sim r_s/D$ is known precisely

Angular scale of damping $\theta_d \sim r_d/D$ measured more recently



Σm_ν and N_{eff} *Forecast*

	Stage 2	Stage 3	Stage 4	Science Goal
Inflation: σ_r	0.1	0.003	0.0005	Detect or rule out the simplest and most compelling classes of inflationary models.
Light Relativistic Species: ΔN_{eff} (95% upper limit)	0.28	0.1	0.06	Detect or rule out all light relativistic particles that decoupled after the start of the QCD phase transition.
Neutrino Masses: $\sigma_{\Sigma M\nu}$	0.2eV	0.04eV	0.024eV	Detect or place a stringent limit on the neutrino mass sum.

inflationary threshold

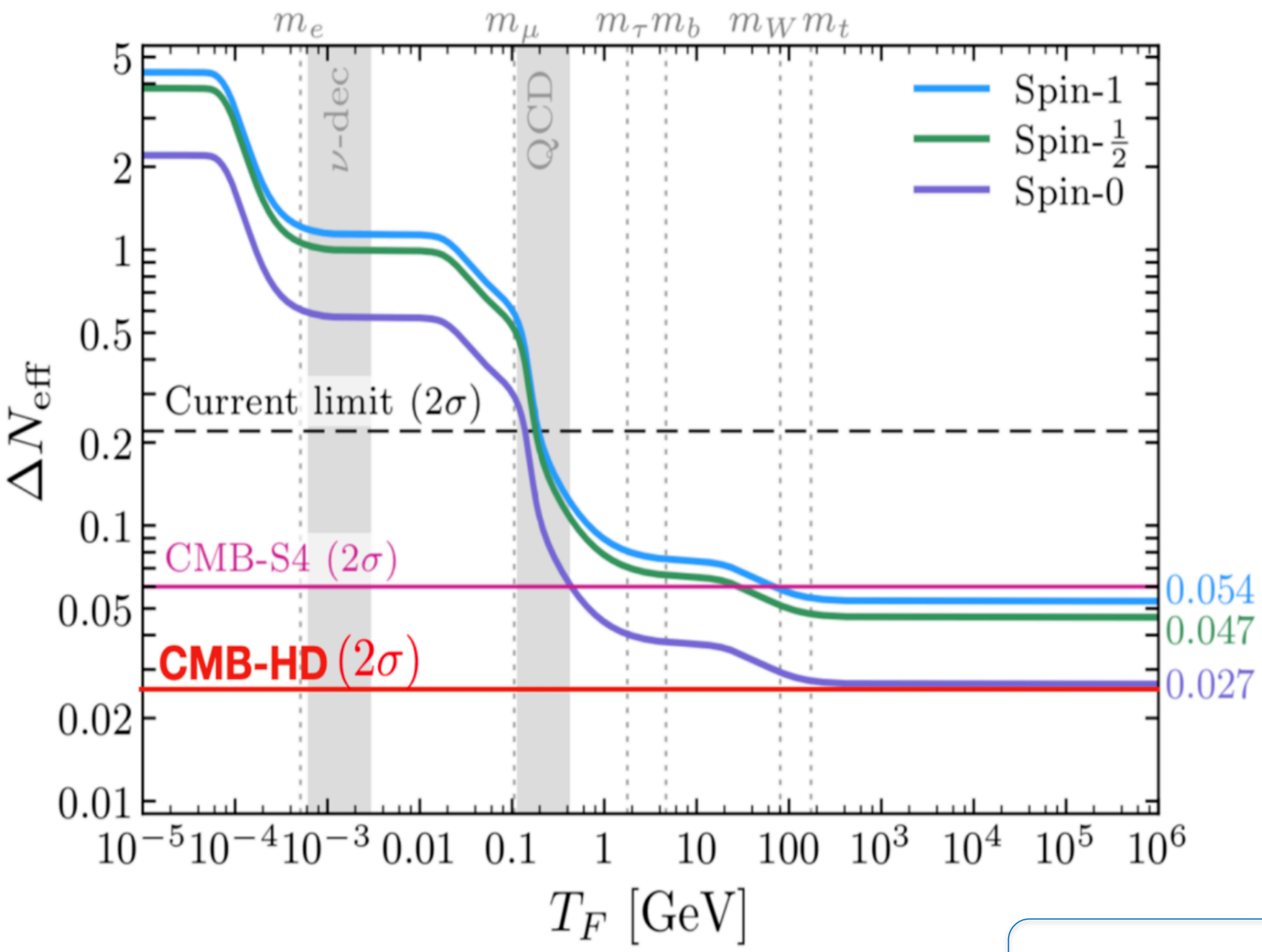
ΔN_{eff} for T =300 MeV

lower limit Σm_ν

	Stage 2	Stage 3	Stage 4	Requirements
Survey Weight [μK^{-2}]	10^5	10^6	10^8	500,000 detectors on multiple platforms with sensitivity from 10° to 1′ scales
Detector Count	~1,000	~10,000	~500,000	

C. Chang et al., arXiv:2203.07638 [Snowmass]

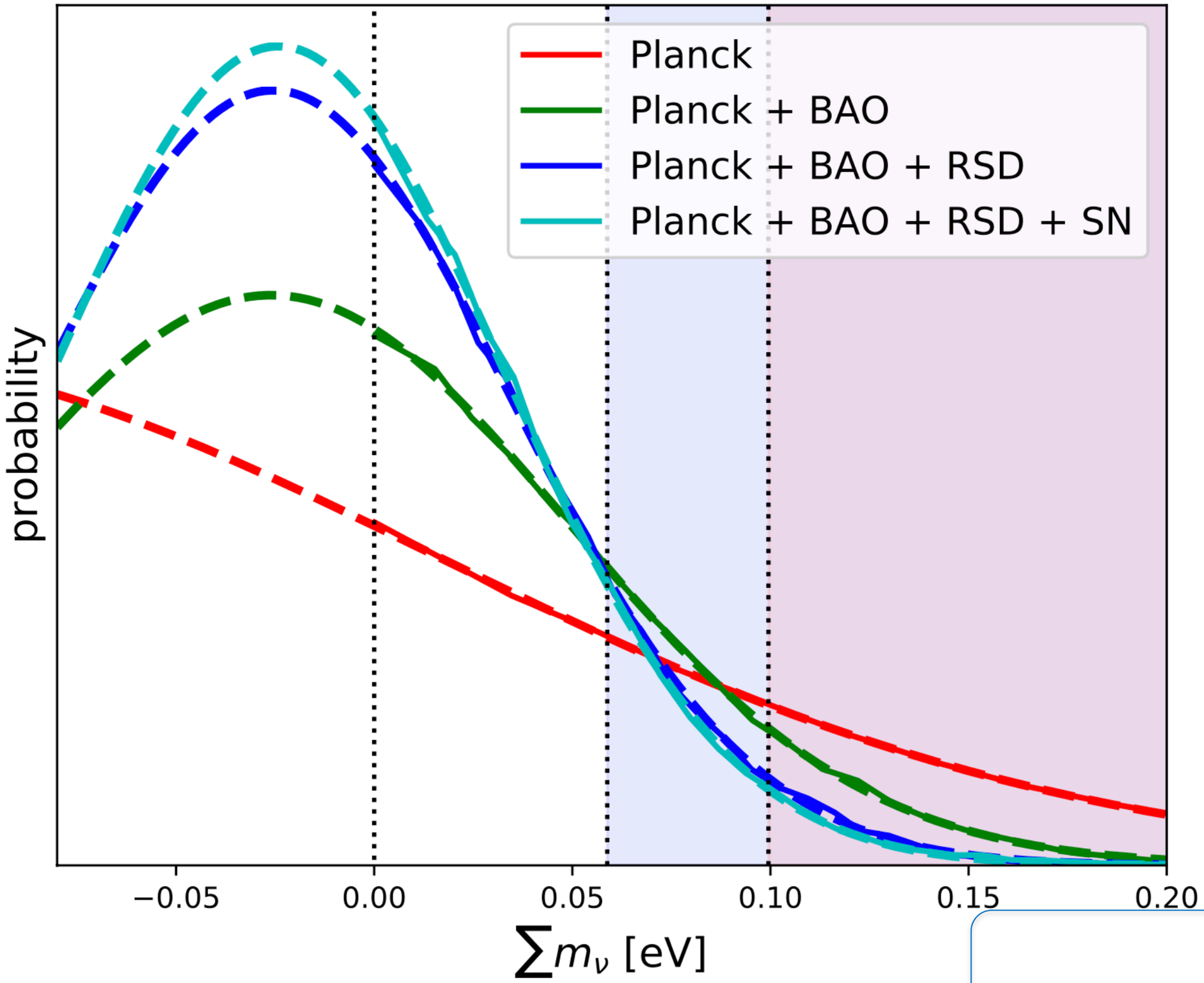
$N_{\rm eff}$: Not just Light Relics



C. Chang et al., arXiv:2203.07638 [Snowmass]

Tensions!

Planck 2018 Strongly Prefers $\Sigma m_\nu = 0$ ($\Sigma m_\nu \overset{?}{<} 0$)



S. Alam et al., arXiv:2007.08991 [eBOSS]

Tension Data Sets May Prefer Large Σm_ν or N_{eff}

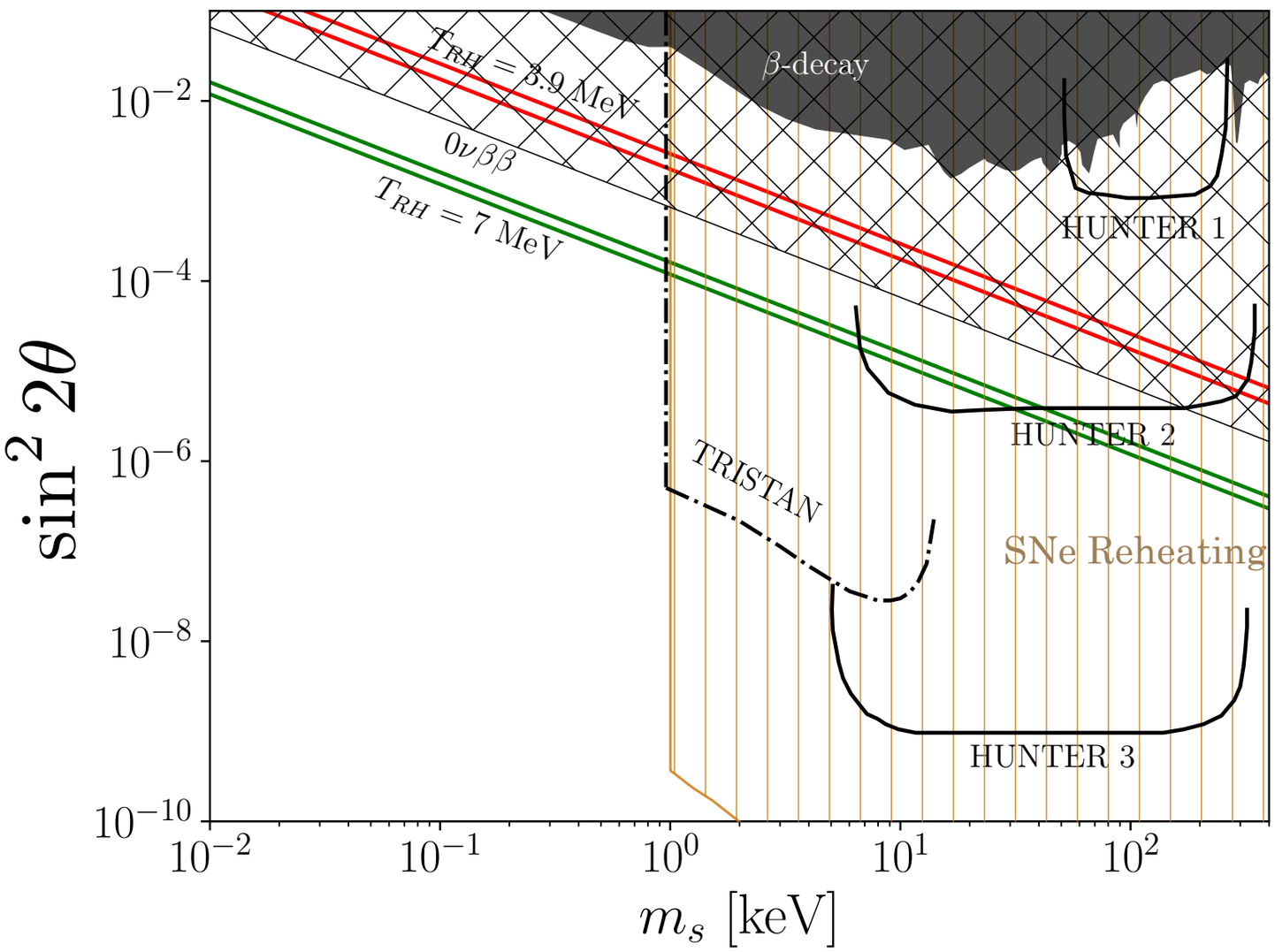
- **σ_8 Tension:**
  Planck 2018 + BOSS DR12 + KIDS-1000 self-calibration (Sgier et al. arXiv:2110.03815):

$$\Sigma m_\nu = 0.51^{+0.21}_{-0.24}\ \mathrm{eV}$$

- **H_0 Tension:**
  Planck 2018 + BOSS DR16 + Pantheon + 2021 SH0eS H_0 (Garcia Escudero+ arXiv: 2208.14435):

$$N_{\mathrm{eff}} = 3.48 \pm 0.12$$

Neutrino-less & Low Reheating Temperature Universes



- Neutrino-less universe: neutrinos convert to lighter particles on cosmological scales, evading LSS constraints (Beacom, Bell, Dodelson 2004)
- Low-Reheating Universe with massless relics from particle decay producing $N_{\rm eff}$ (Garcia Escudero et al. 2023)

Cosmology & Neutrinos:

- **Scenario (A):**
  Σm_ν & $N_{\rm eff}$: 2-3σ+ measurements of Σm_ν = 58 meV and $N_{\rm eff}$ = 3.044 in ~10 years

- **Scenario (B):**
  Surprises from Tensions & Model Dependencies

The End...

Visible Sterile ν in the Low-Reheat Universe