Neutrinos as standard & nonstandard dark radiation & dark matter

TRIUMF Neutrinos in Cosmology and Astrophysics

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nonstandard
dark matter &
dark radiation
ν_s
$N_{\rm eff}$
standard
dark matter &
dark radiation
Σm_ν N_ν

The Cosmological Neutrino

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

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

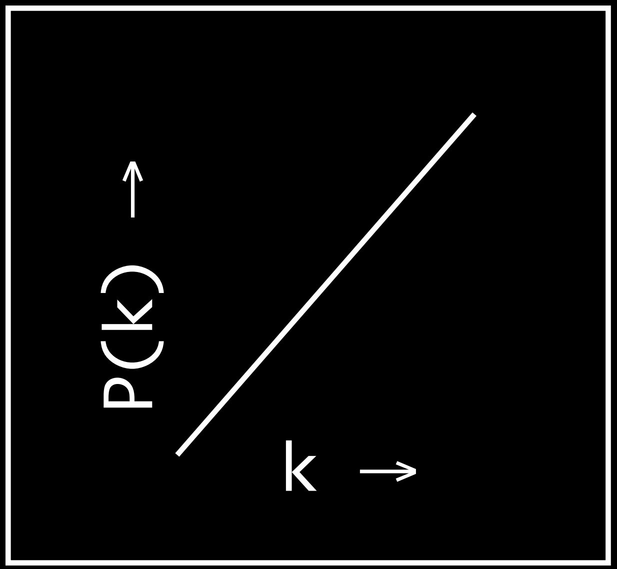
$$n_\nu = N_\nu \times \left(\frac{3}{11}\right) n_\gamma \;\approx 340\,\mathrm{cm}^{-3}$$

*depends on dark matter particle mass...

standard dark matter

$$\Sigma m_\nu$$

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



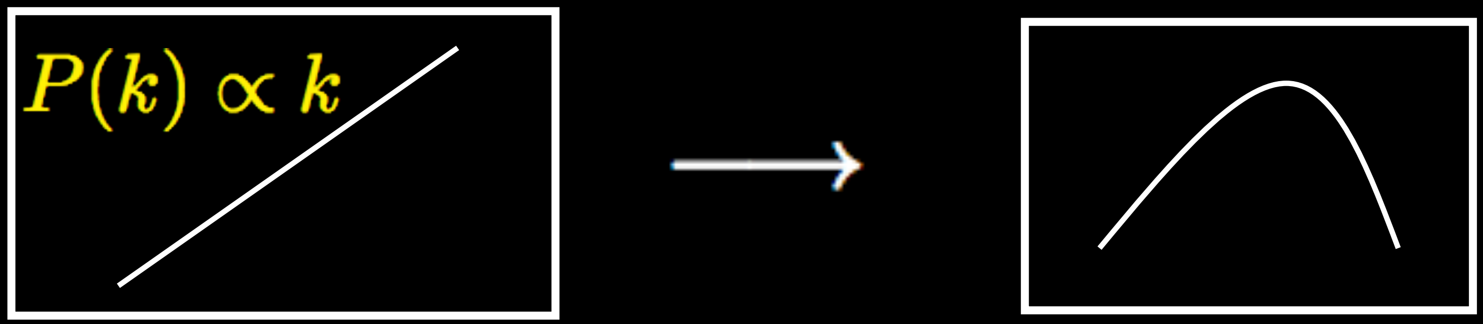
$$P(k) = Ak^n$$

Planck Collaboration 2018:

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

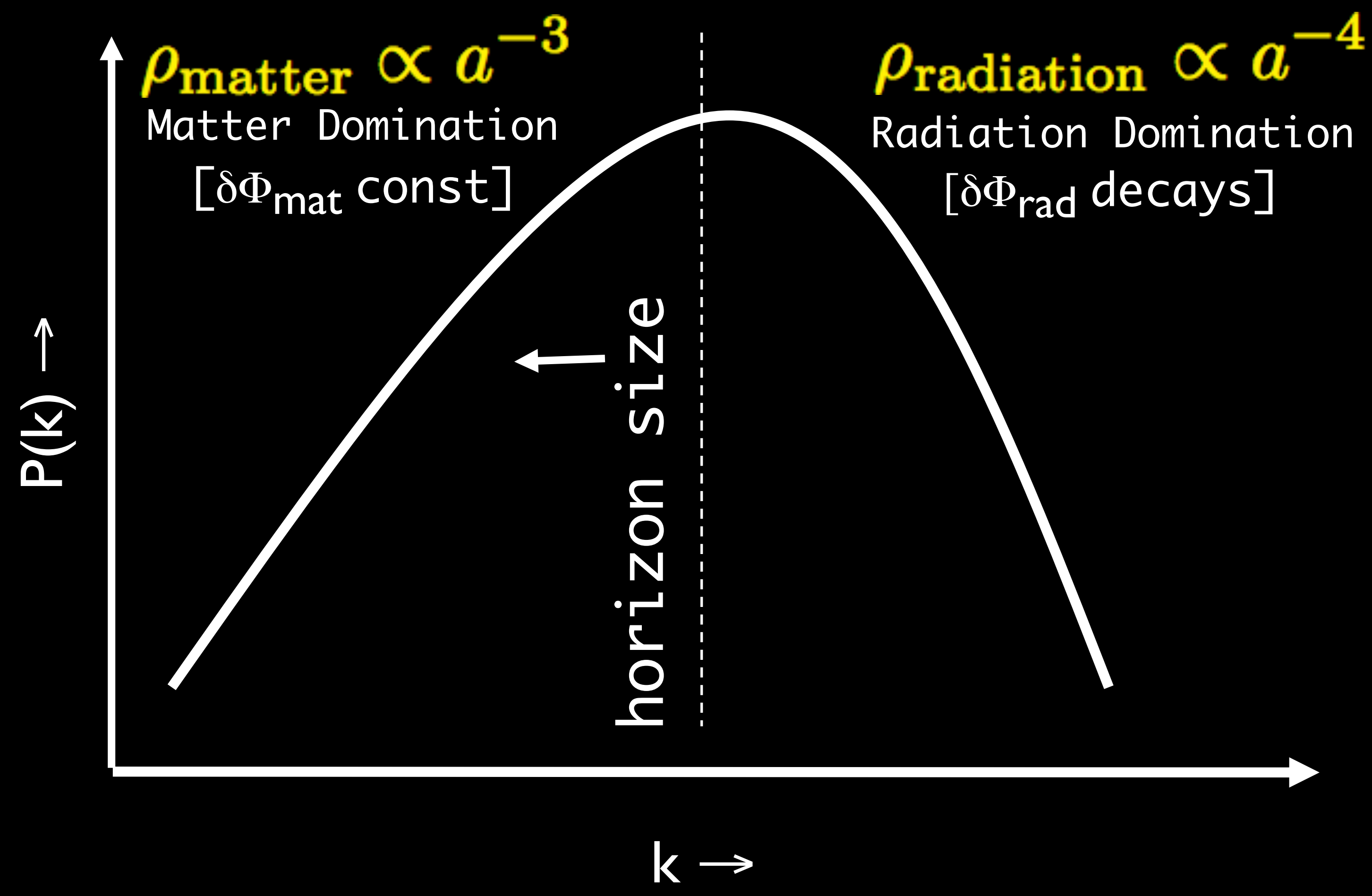
$$n = 0.9665 \pm 0.0038 \qquad (0.39\%)$$

The Cosmological Matter Power Spectrum

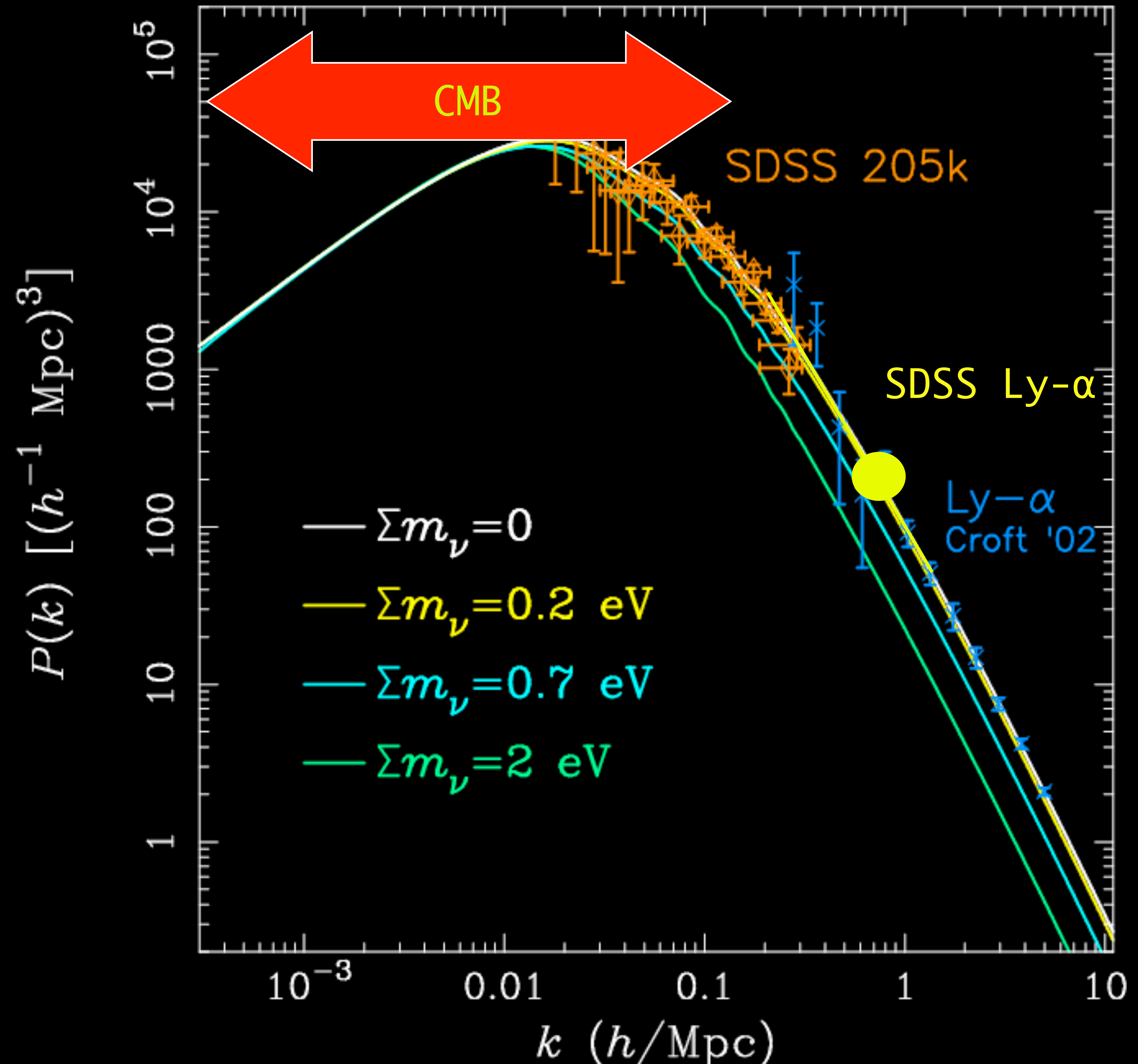


?

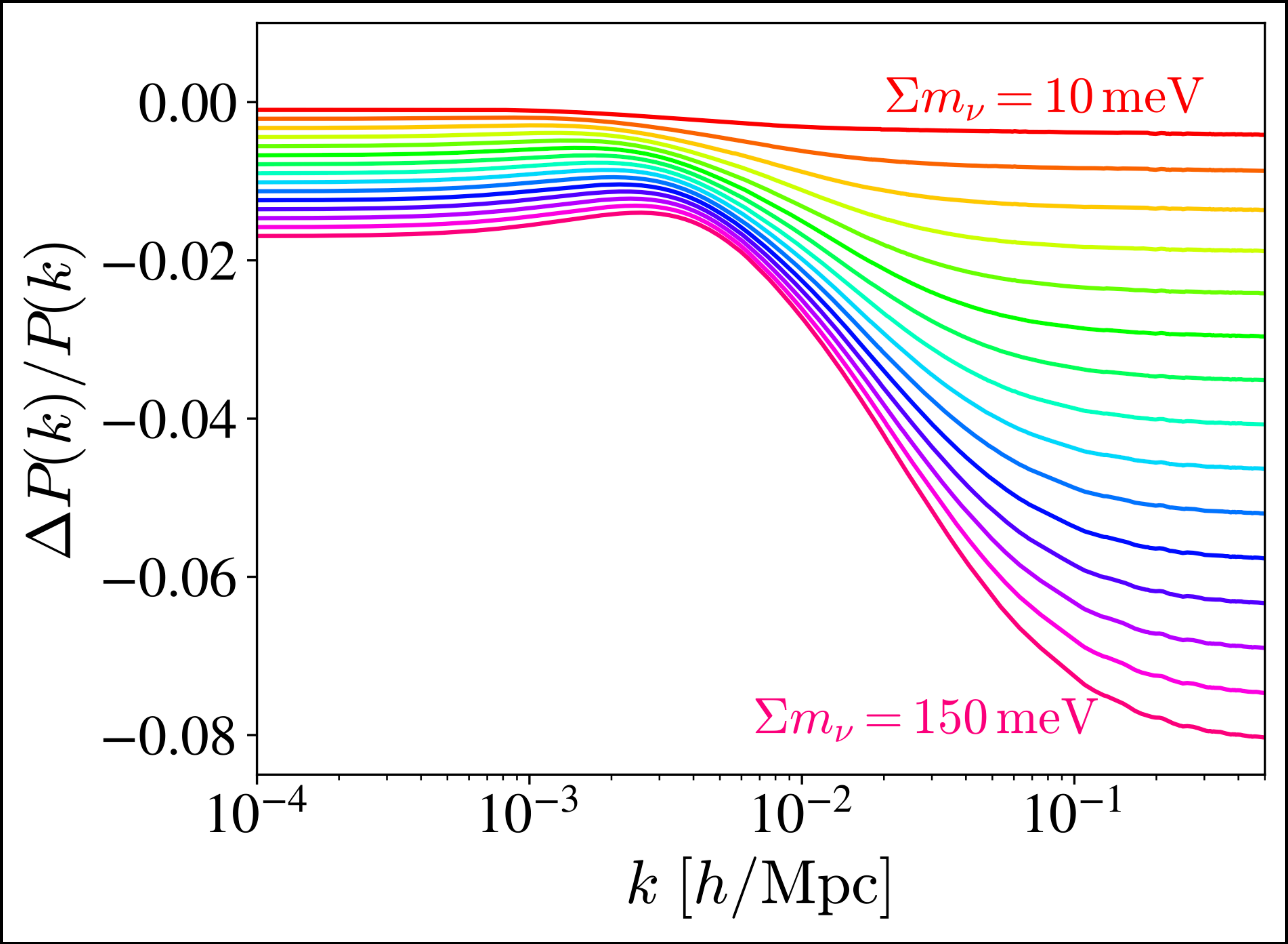
Perturbations enter horizon:



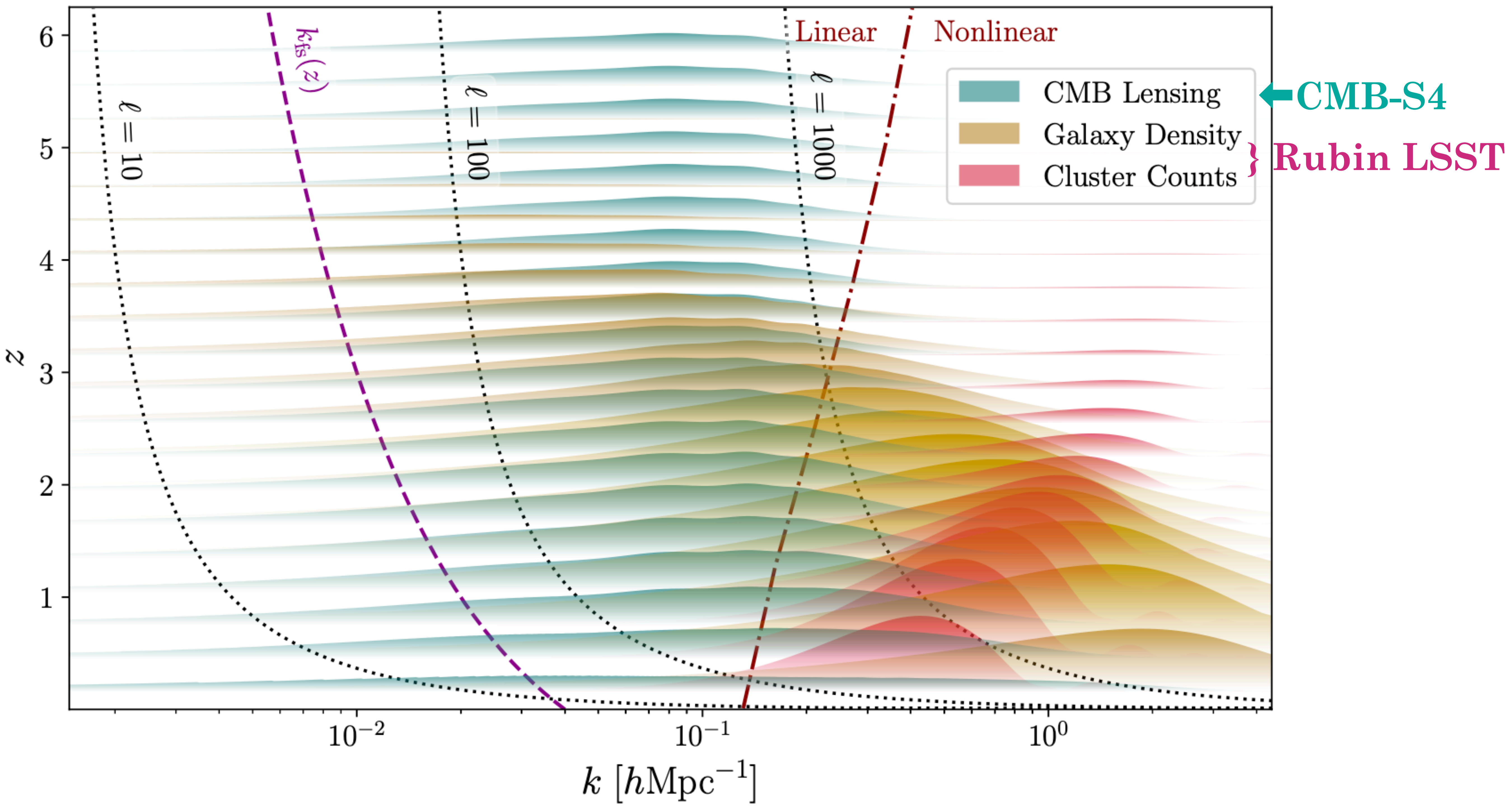
Measuring Large Scale Structure $P(k)$ & $\sum m_\nu$



Measuring Large Scale Structure $P(k)$ & Σm_ν



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



Abazajian et al. arXiv:2203.07377

Current Σm_ν Limits

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

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

$\Sigma m_\nu < 90$ meV (95% CL)

Di Valentino, Gariazzo & Mena, arXiv:2106.15267

Employing the most robust data sets, statistical validations, theory accuracy

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

García-Escudero & Abazajian, in prep.

NO preferred over IO at 1.80σ

$m_\nu = 0$ preferred over NO at 1.83σ

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

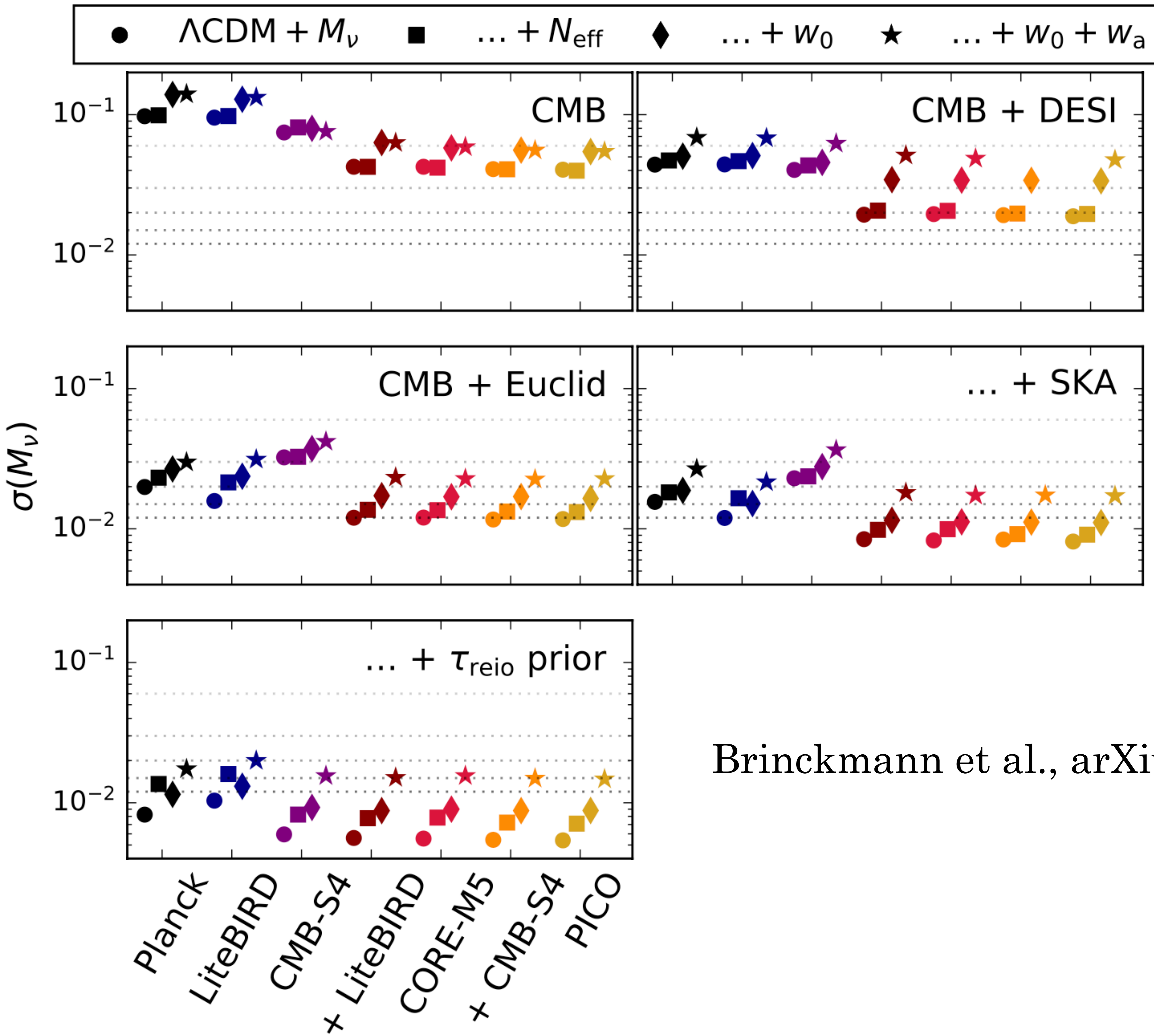
$$\Omega_\nu \approx \frac{\sum m_{\nu_i}}{93\ h^2\ \mathrm{eV}}$$

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

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

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



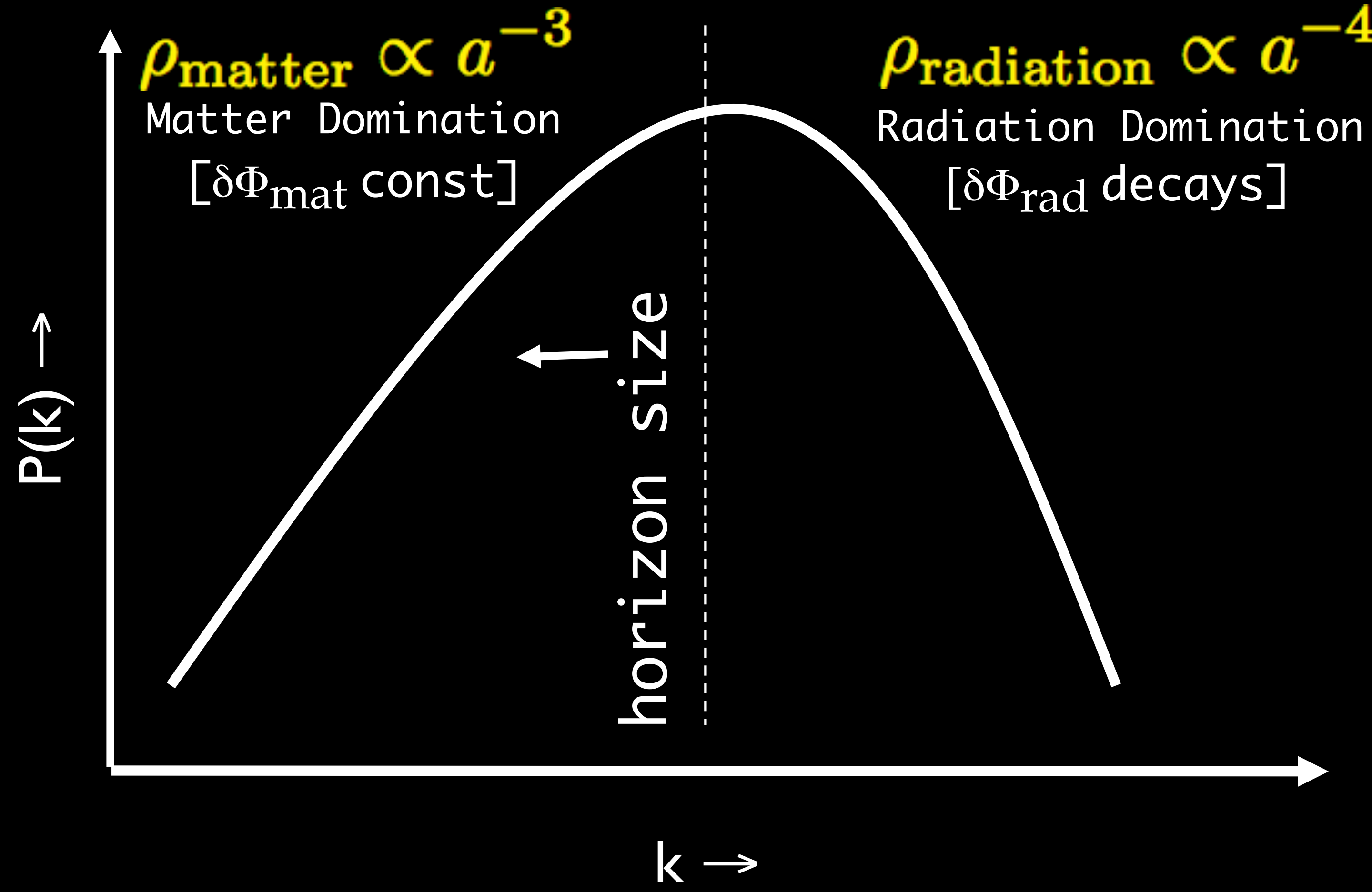
Brinckmann et al., arXiv:1808.05955

$$N_{\mathrm{eff}}$$

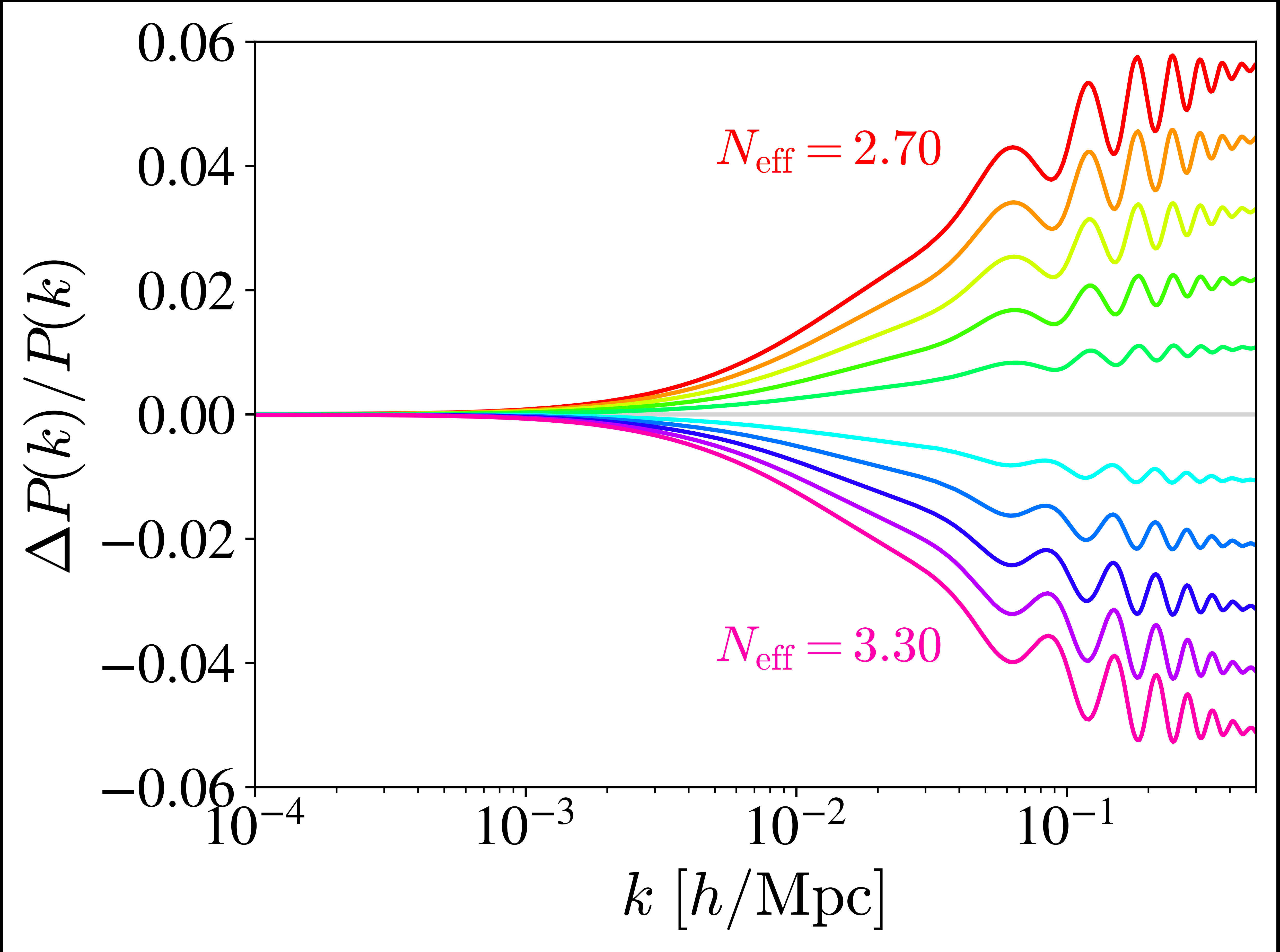
Cosmological Matter Power Spectrum & CMB Measures of N_{eff}

For Large Scale Structure:

Perturbations enter horizon at M/R equality



$N_{\rm eff}$ Effects on Matter Clustering



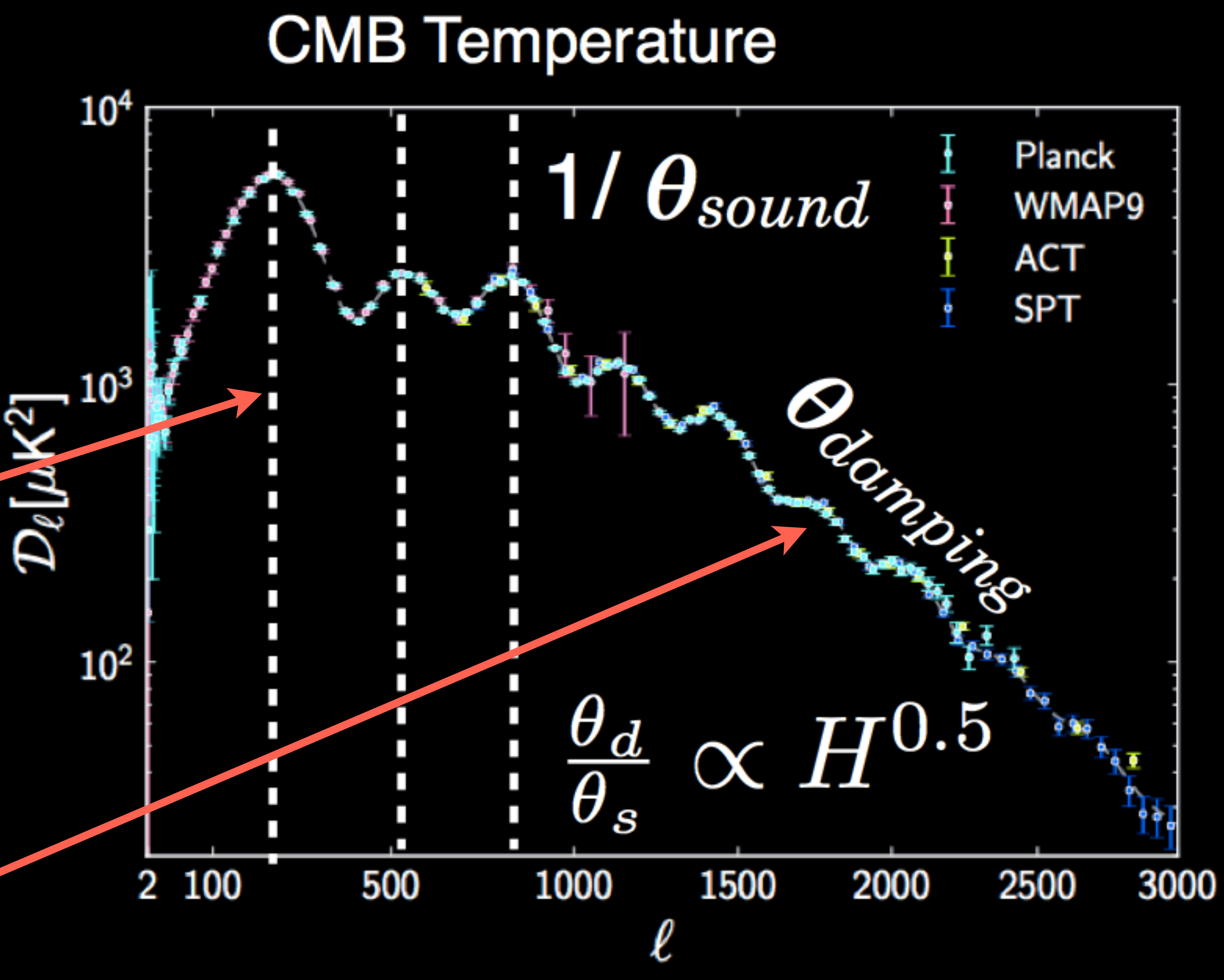
N_{eff} Effects on CMB

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

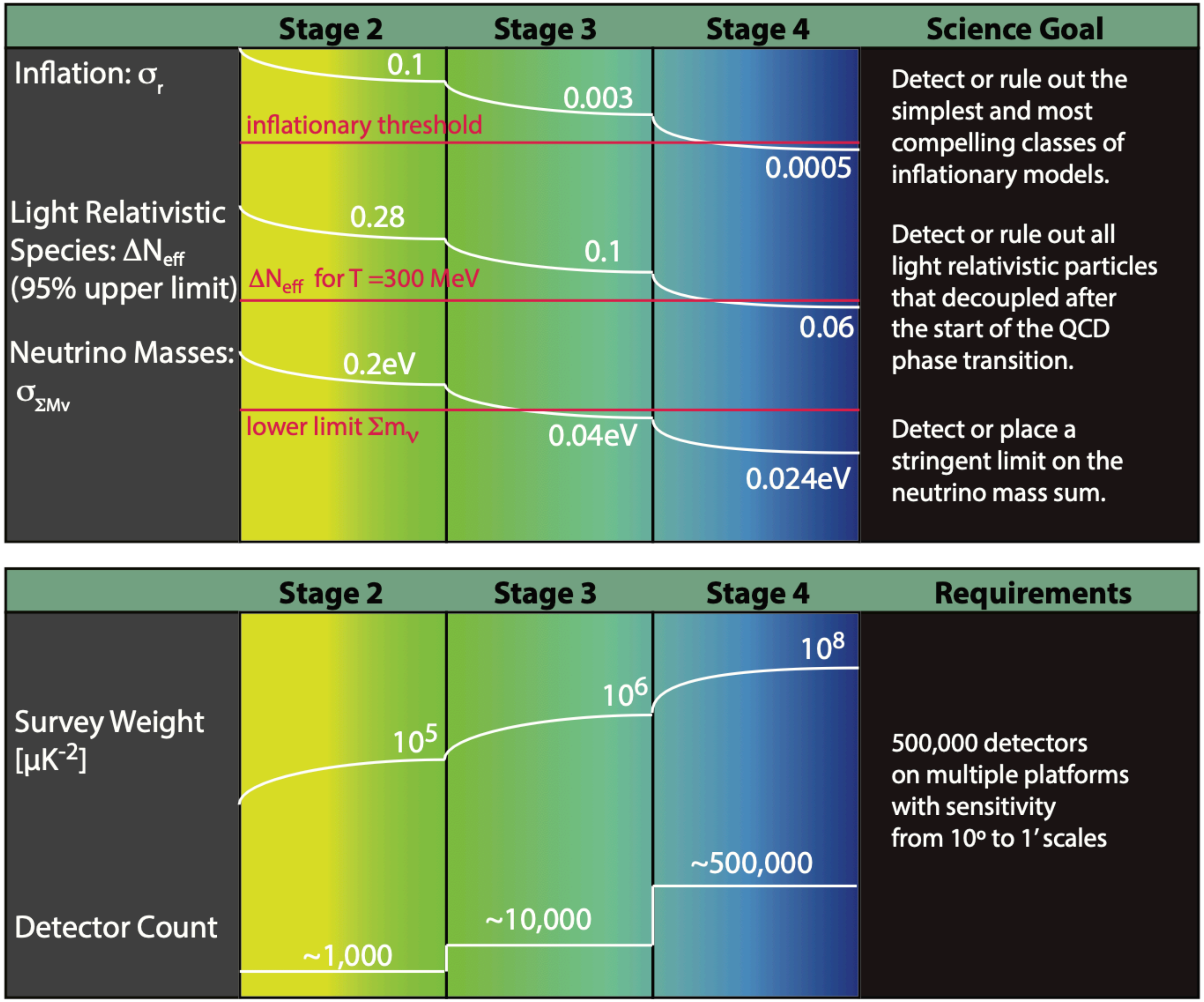
Larger N_{eff} Leads to More Damping

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_ν ($N_{\rm eff}$) *Forecast*



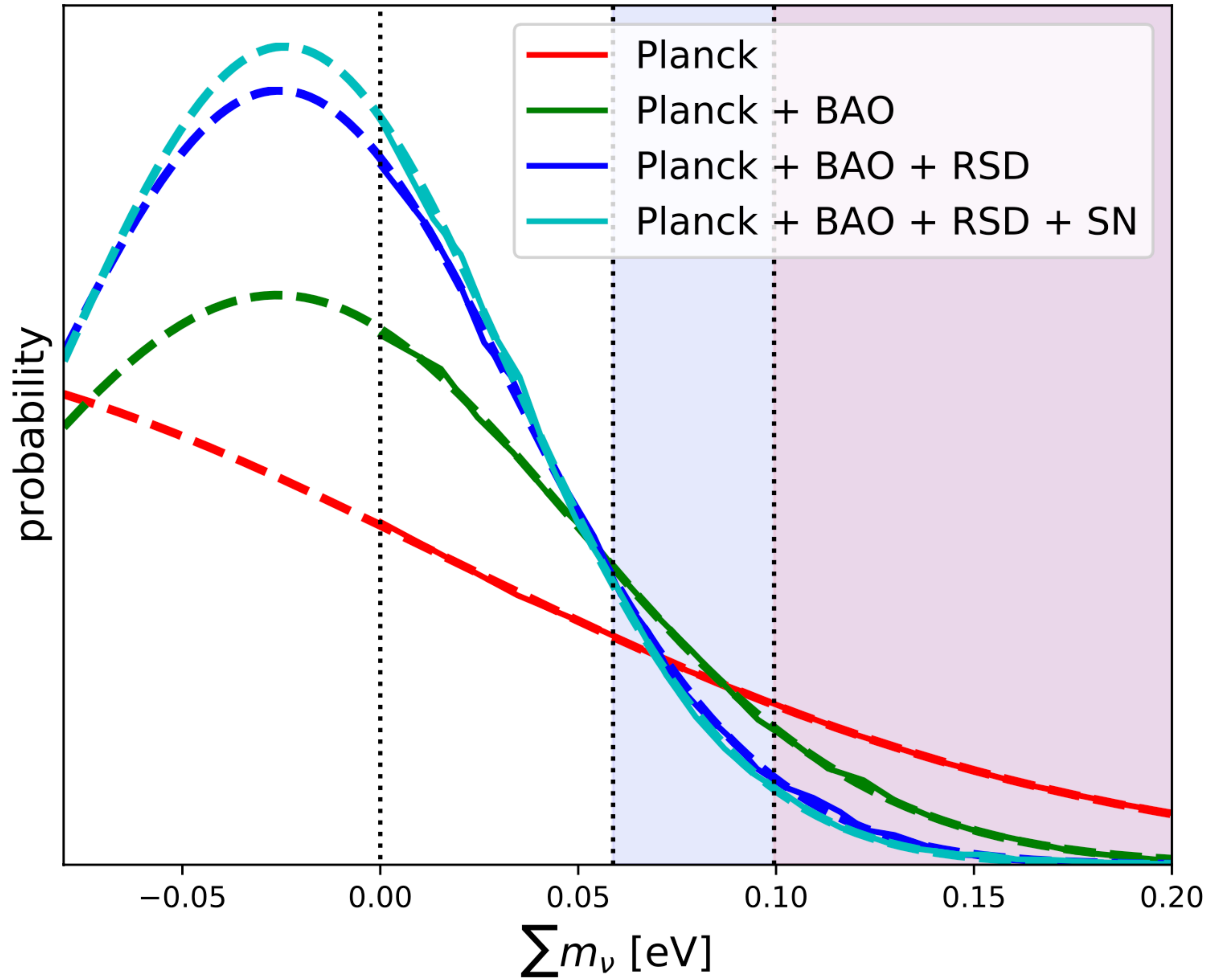
C. Chang et al., arXiv:2203.07638 [Snowmass]

Tensions!
&
New Physics?

“standard” dark matter

$$\Sigma m_\nu$$

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}

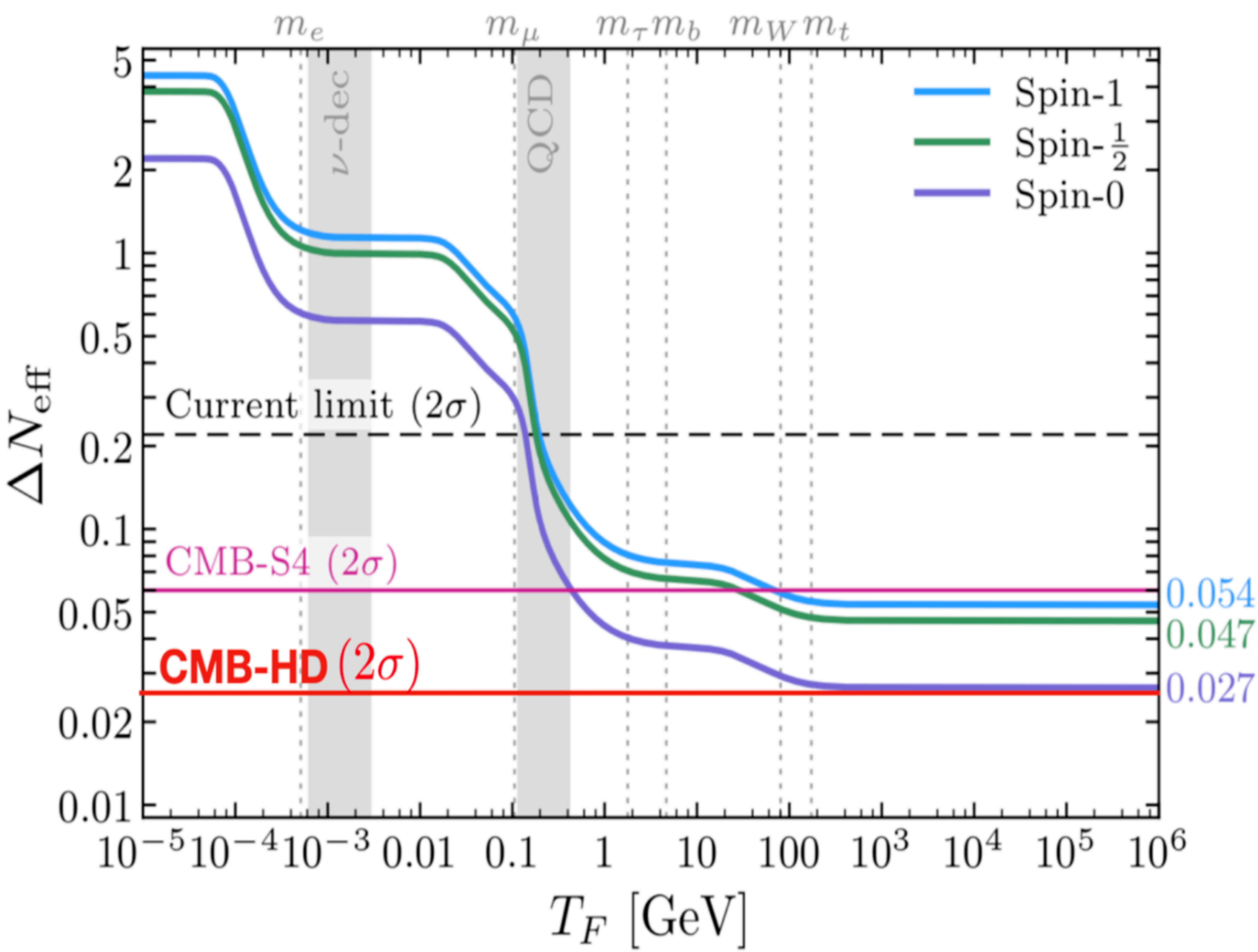
- **σ_8 Tension:**
  Planck 2018 + BOSS DR12 + KIDS-1000 self-calibration (Sgier et al. arXiv:2110.03815):

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

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

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

N_{eff}: Not just Neutrinos, Light Relics



C. Chang et al., arXiv:2203.07638 [Snowmass] *nonstandard* **dark matter**

$$\nu_s$$

Sterile Neutrino Dark Matter Production

$\Gamma_\alpha(p) \sim G_F^2 p T^4 \sim T^5$

$\Delta^2 \sim p^{-2} \sim T^{-2}$

$$\Gamma(\nu_\alpha \to \nu_s) \sim \frac{\Gamma_\alpha(p)\Delta^2(p)\sin^2 2\theta}{\Delta^2(p)\sin^2 2\theta + D^2(p) + [\Delta(p)\cos 2\theta - V^L(p) - V^T(p)]^2}$$

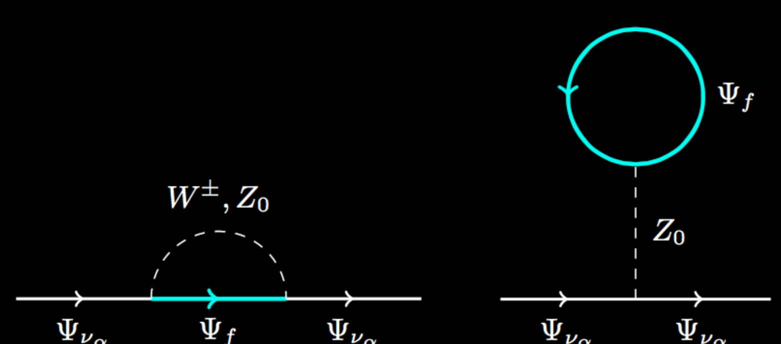
$D(p)^2 \sim T^{10}$

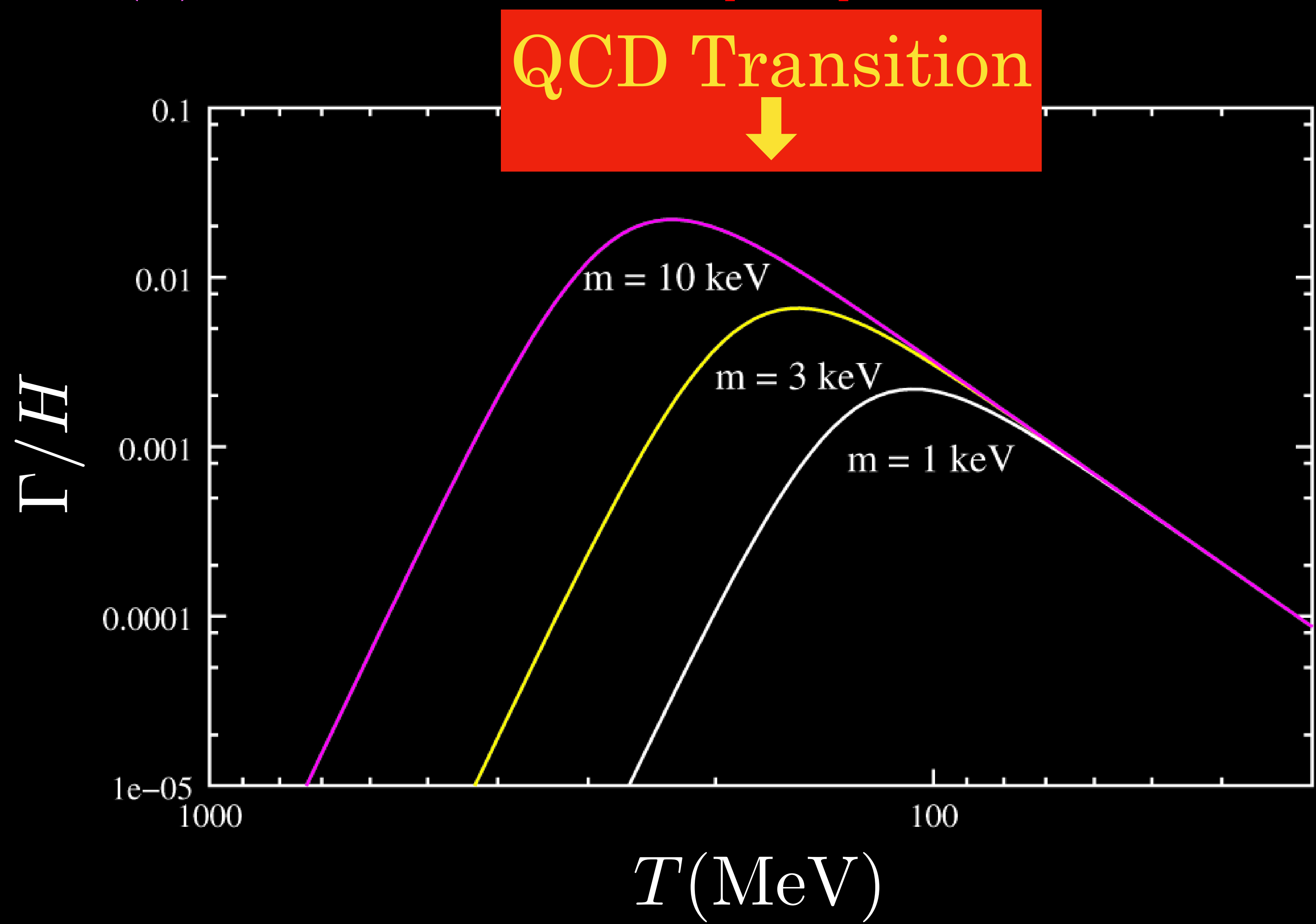
$[V^T]^2 \sim T^{10}$

$$H^2 = \frac{8\pi}{3} G\rho \sim T^4$$

$$\frac{\Gamma}{H} \sim \begin{cases} T^{-9} & \text{High } T \\ T^3 & \text{Low } T \end{cases}$$

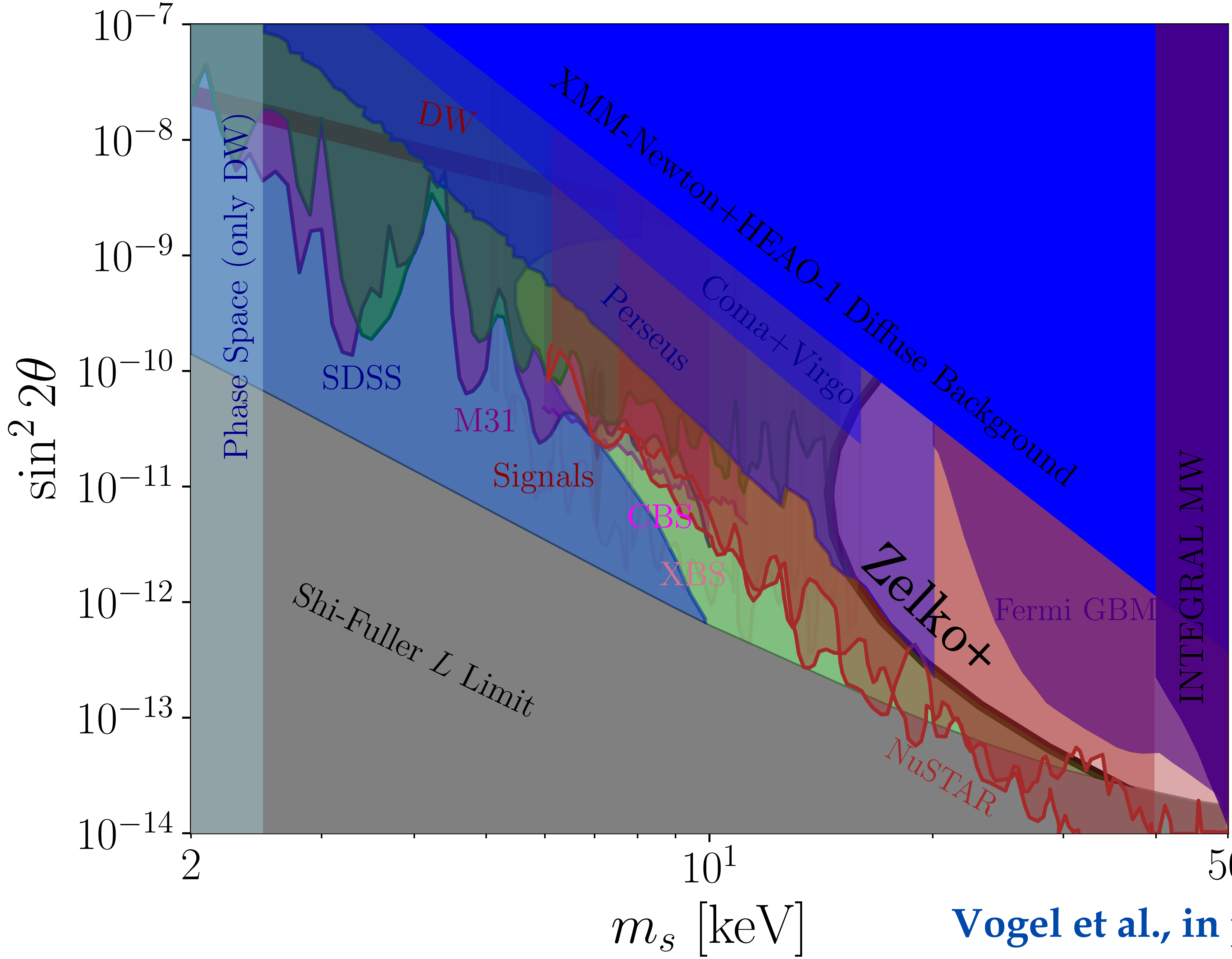
Never in Equilibrium!!



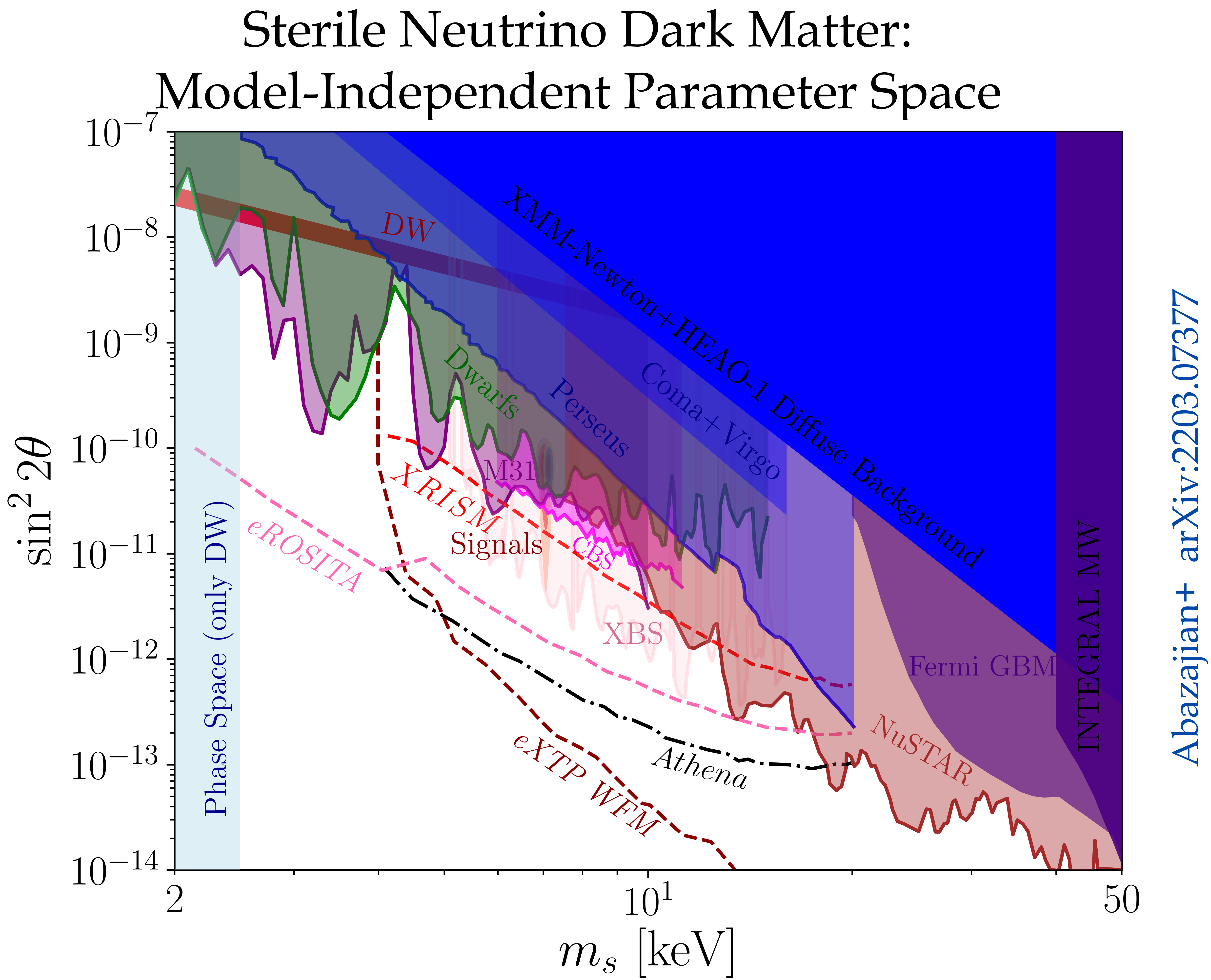


Venumadhav+ 1507.06655

Sterile Neutrino Dark Matter: Shi-Fuller Mechanism Excluded

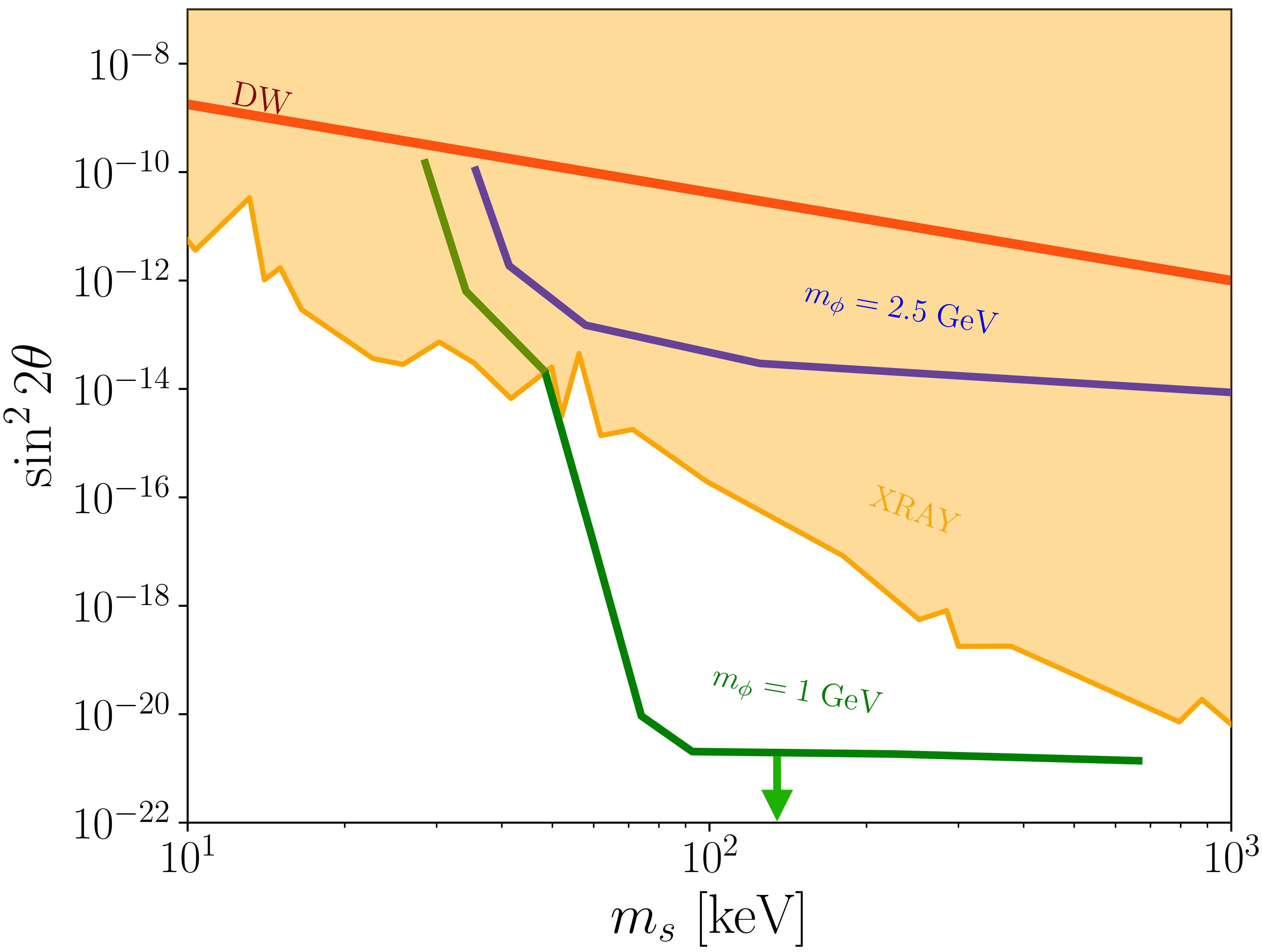


Vogel et al., in prep.



Sterile Neutrino Dark Matter:
Model-Independent Parameter Space
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
$\sin^2 2\theta$
2
10^1
50
m_s [keV]
DW
XMM-Newton+HEAO-1 Diffuse Background
Dwarfs
Perseus
Coma+Virgo
M31
XRISM
Signals
CBS
eROSITA
XBS
Fermi GBM
INTEGRAL MW
NuSTAR
Athena
eXTP WFM
Phase Space (only DW)
Abazajian+ arXiv:2203.07377

Sterile Neutrino Dark Matter: NSI Assisted Production



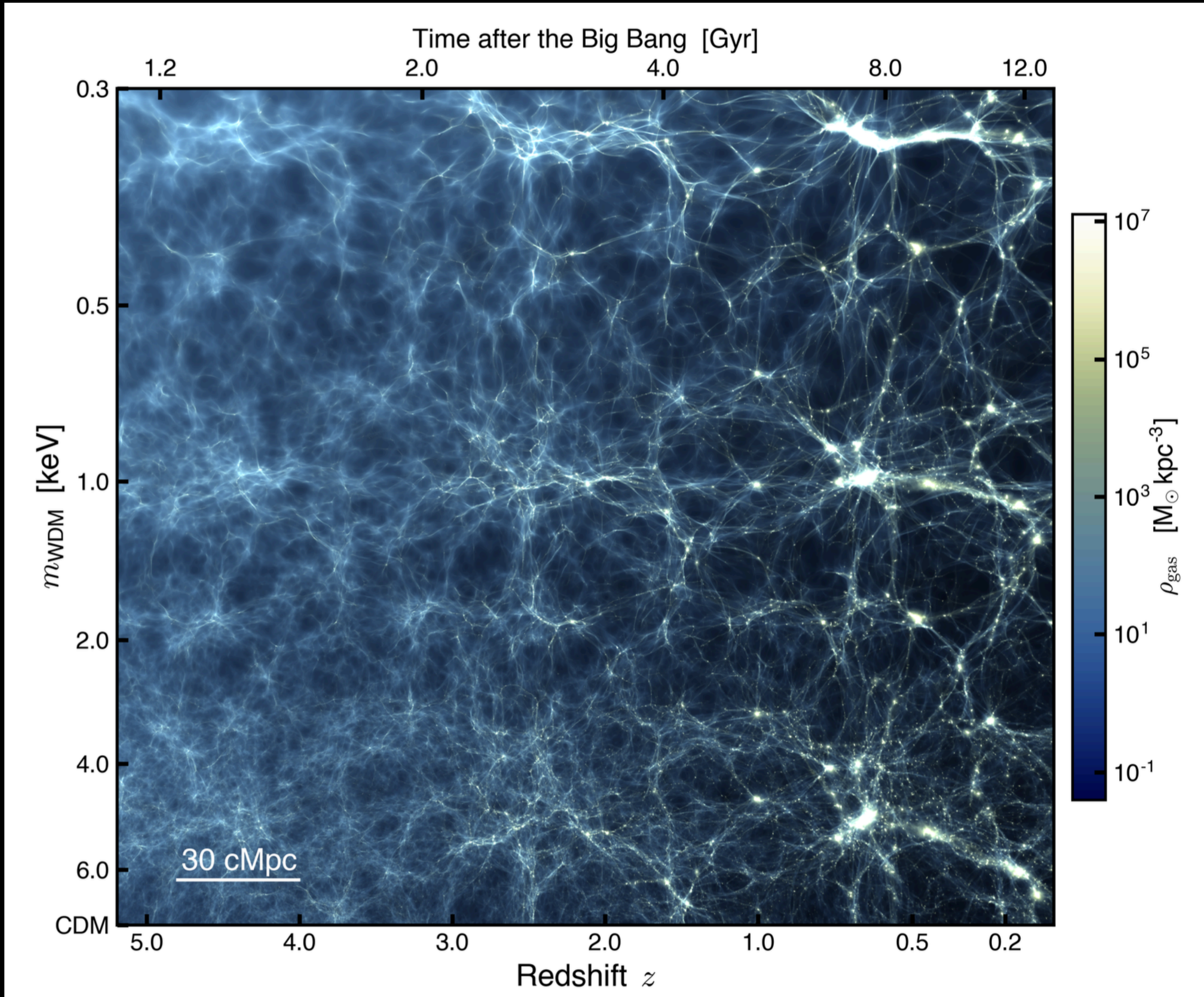
Vogel+ in prep., Kelly+ arXiv:2005.03681, de Gouvêa+ arXiv:1910.04901

nonstandard dark matter

WDM

Simulation Resolution to Match Ly-α Observations

Villasenor+ 2209.14220



Simulation Resolution to Match Ly-α Observations

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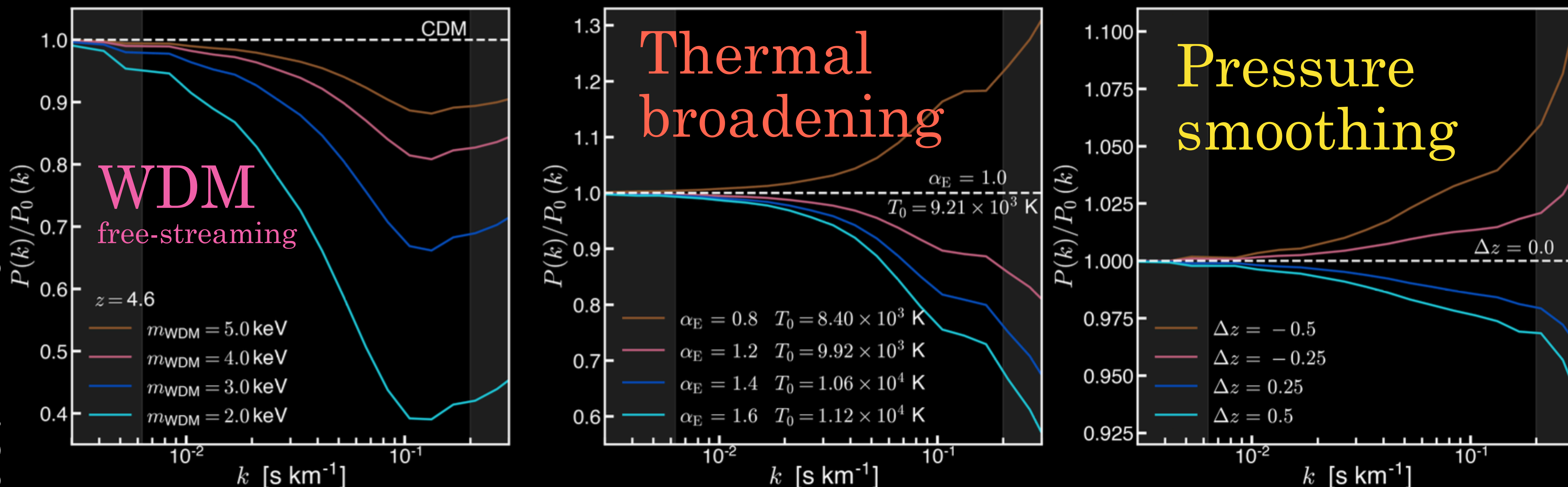


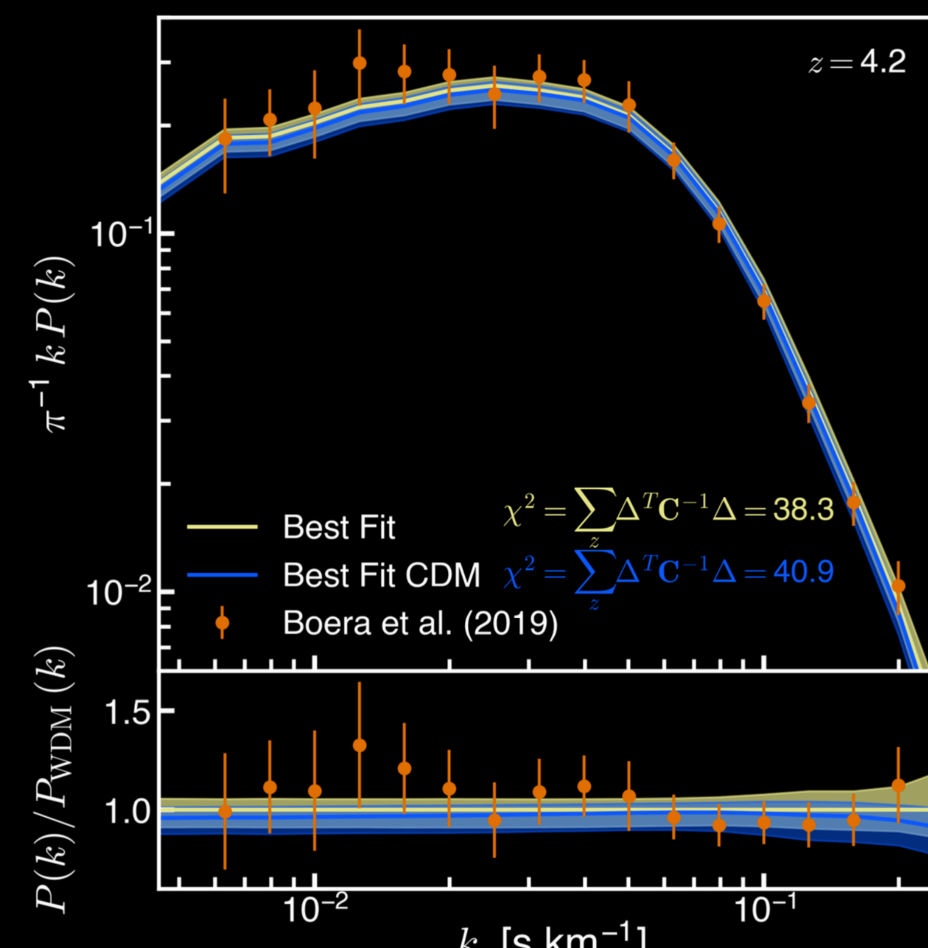
1080 2×1024³ particle sims

"We find a weak (3σ) preference for WDM over ΛCDM"

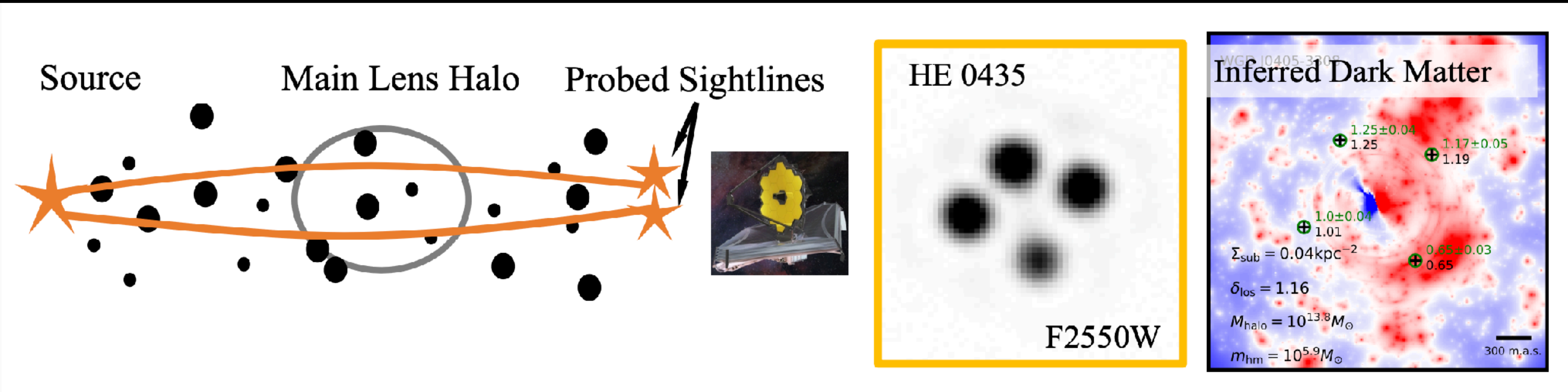
$$m_{\rm th,WDM} = 4.5^{+45}_{-1.4}\ \text{keV}$$

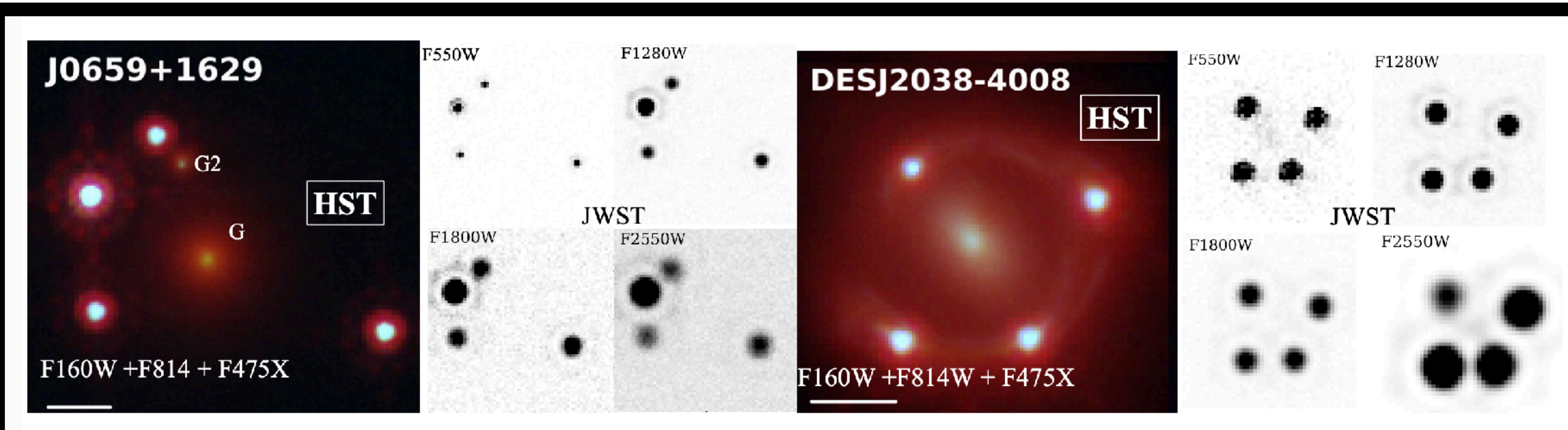
DESI, EUCLID, LSST, WEAVE forecast (1/4 covariance)

$$m_{\rm th,WDM} = 4.5^{+1.9}_{-1.0}\ \text{keV}$$



Strong Lensing Tests of WDM: Quadruply-Lensed Systems





Lensing substructure constraint: m_{th} **> 5.3 keV** (Gilman+ 2019)

Studied in a wide range of sterile neutrino DM models (Zelko+ ’22)

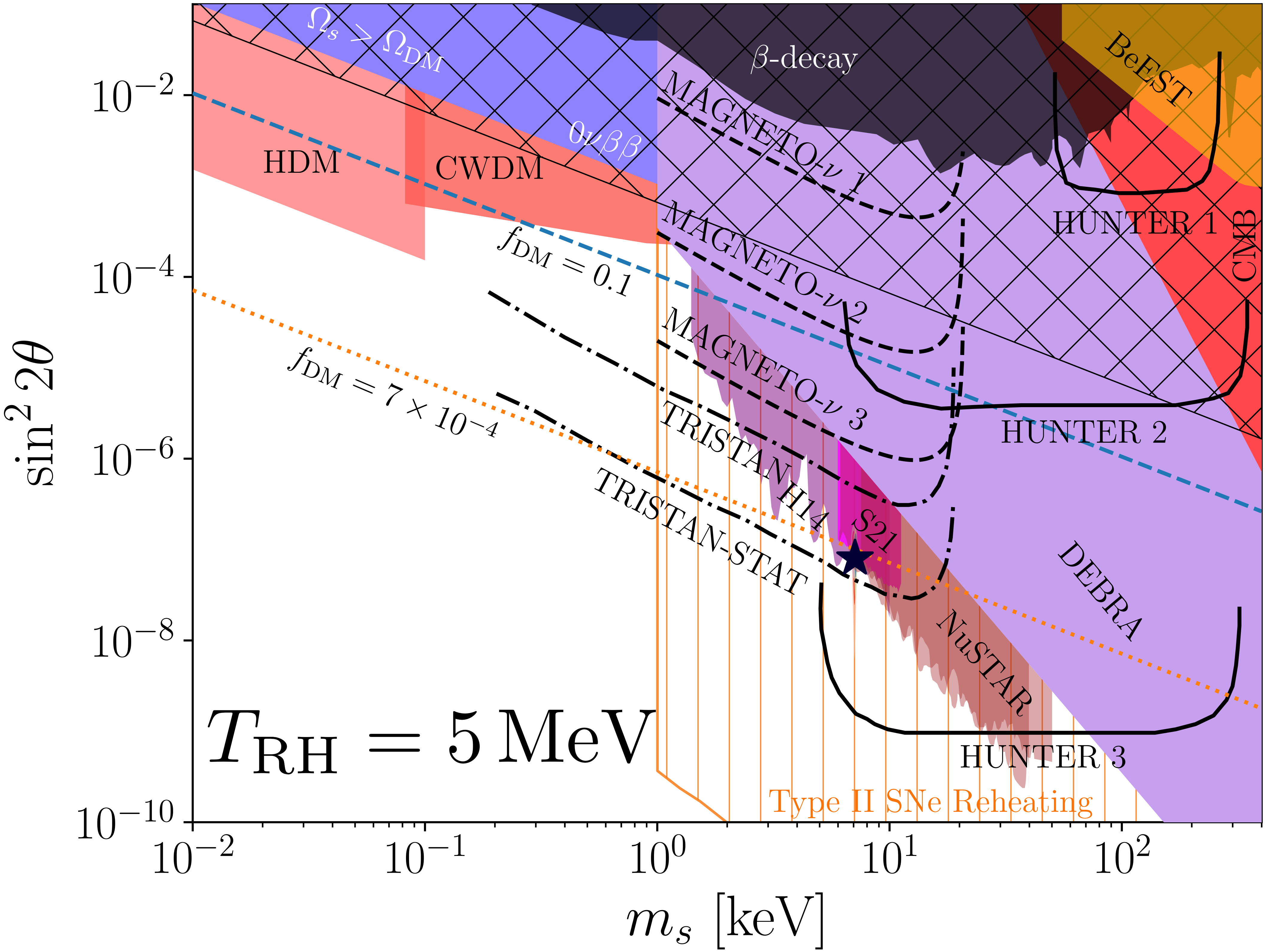
JWST Cycle 1 Proposal (Ryan Keeley+ in prep.): m_{th} **> 10 keV**

nonstandard cosmological thermal history

$$T_{\mathrm{RH}} \gtrsim 1.8\,\mathrm{MeV}$$

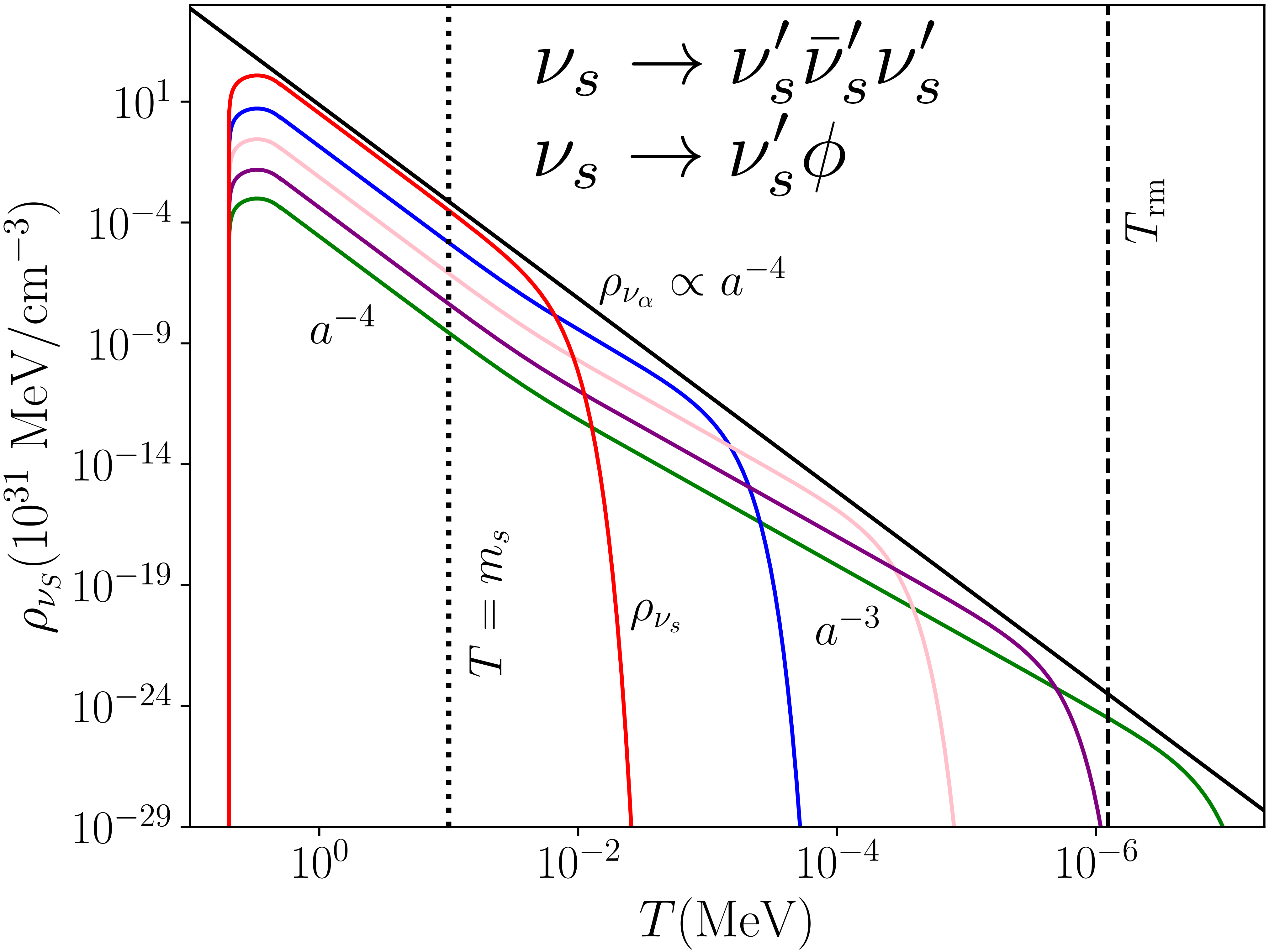
Hasegawa+ 1908.10189, 2003.13302

Low Reheating Temperature Universes



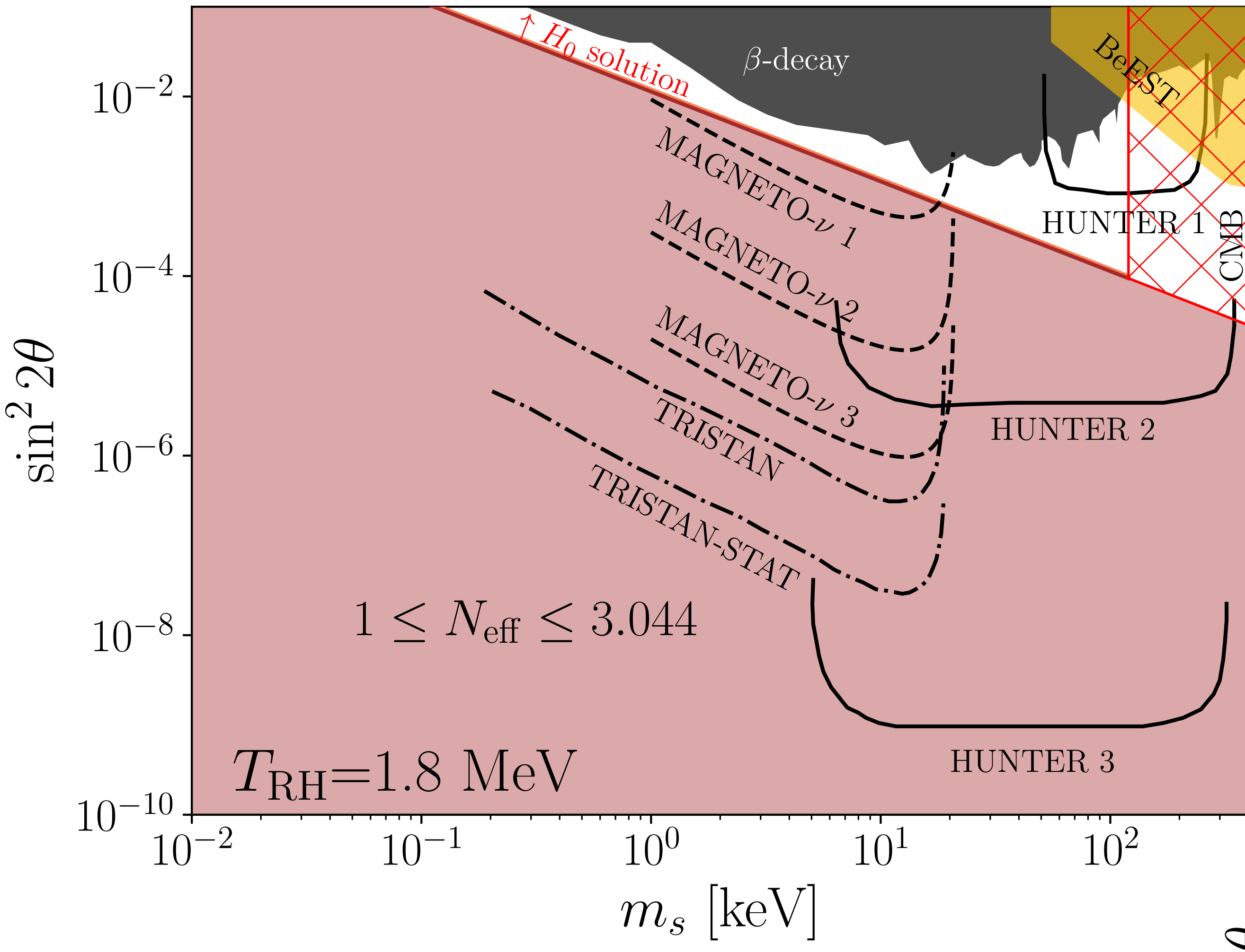
Abazajian & García-Escudero 2309.11492
Gelmini, Palomares-Ruiz & Pascoli astro-ph/0403323

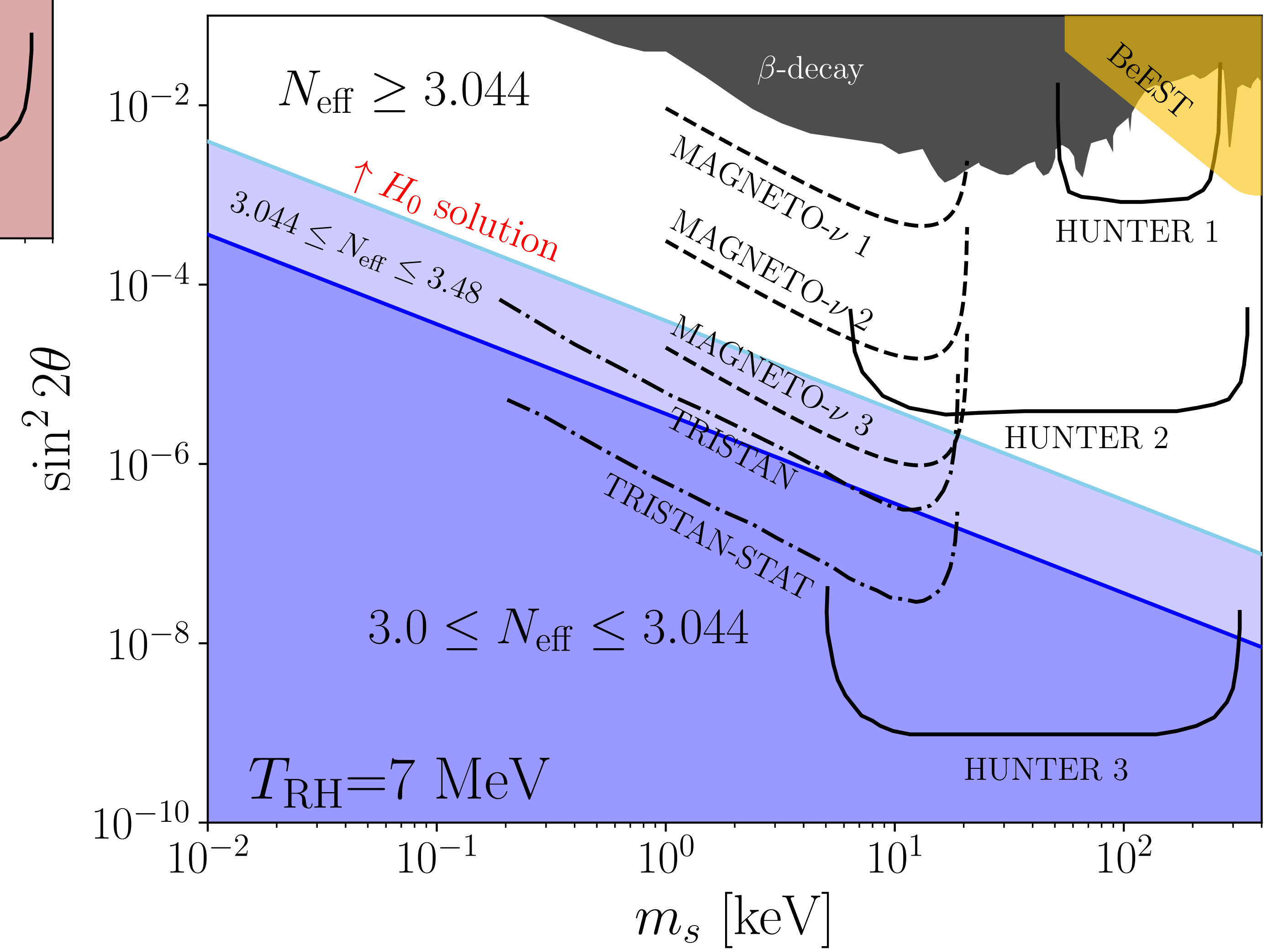
Low Reheating Temperature Universes with *decaying* ν_s



Abazajian & García-Escudero 2309.11492

Low Reheating Temperature Universes with decaying ν_s





Cosmology & Neutrinos:

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

- **Icing:**
  Surprises from tensions, novel early universe scenarios & dark matter models