The Cake and the Icing in Neutrino Cosmology: Neutrinos in ΛCDM and the Possibilities of Discovery

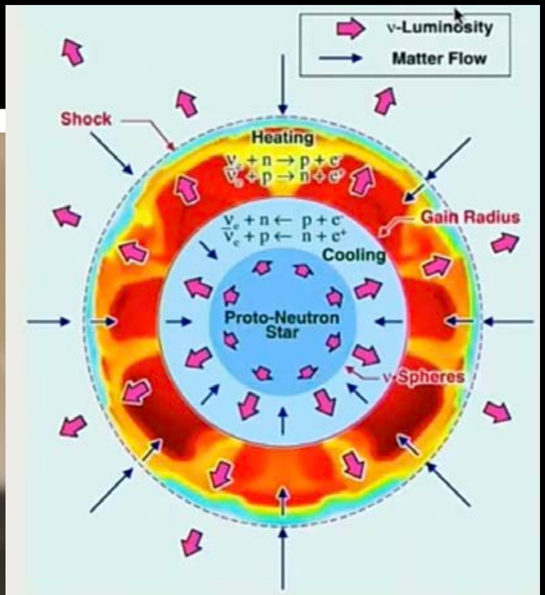
$m_{\nu_s} \sim$ [redacted]

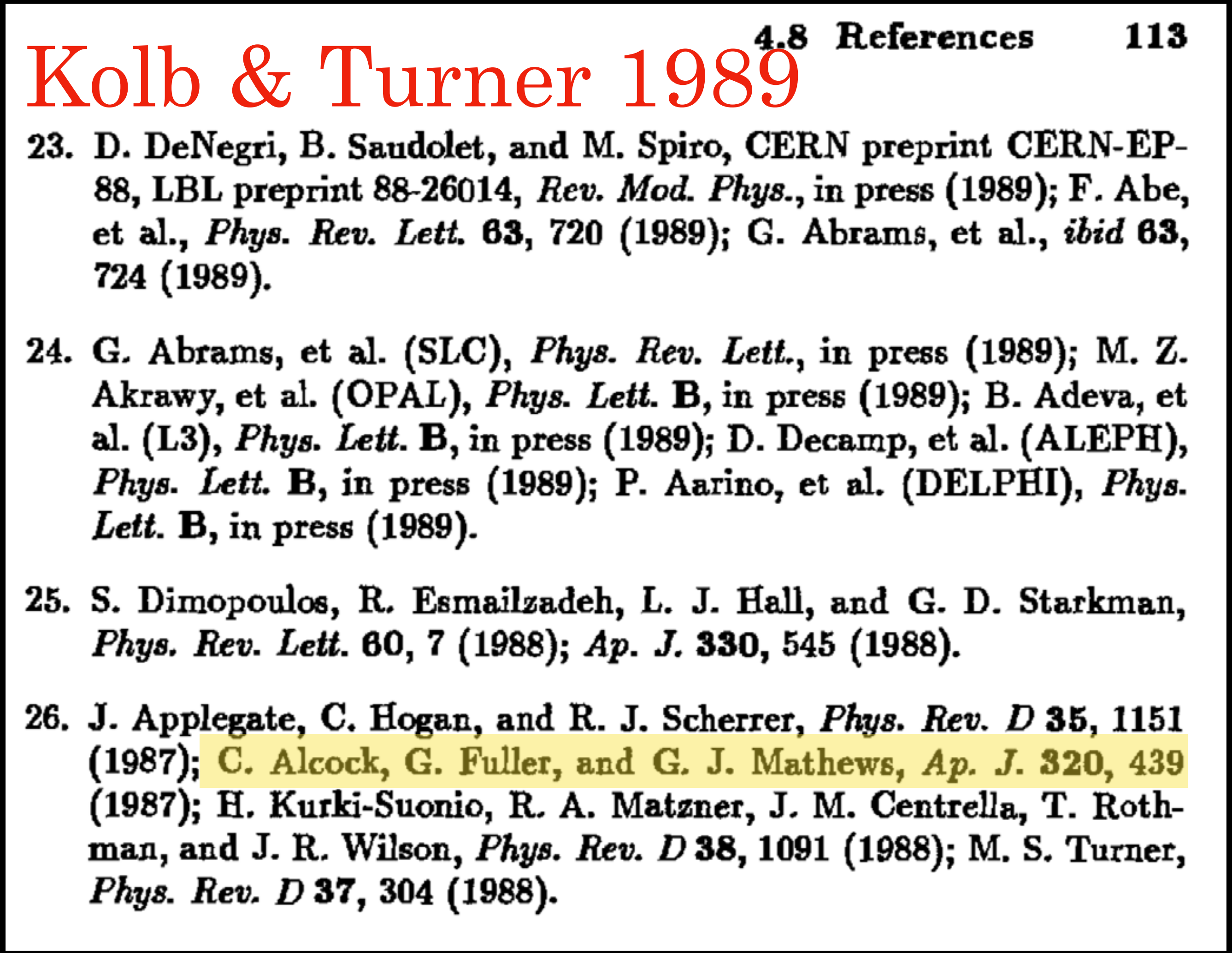
Neutrinos in Physics and Astrophysics:
Celebrating the contributions of Baha Balantekin and George Fuller

Kev Abazajian
University of California, Irvine

January 18, 2025 - N3AS at UC Berkeley

Thank you to these outstanding mentors in the field




Kolb & Turner 1989

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25. S. Dimopoulos, R. Esmailzadeh, L. J. Hall, and G. D. Starkman, *Phys. Rev. Lett.* **60**, 7 (1988); *Ap. J.* **330**, 545 (1988).

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nonstandard
dark matter &
dark radiation
ν_s
$N_{\rm eff}$
standard
dark matter &
dark radiation
$\Sigma m_\nu \; N_\nu$

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

$$\Sigma m_{\nu}$$

Σm_ν: Suppression of Growth

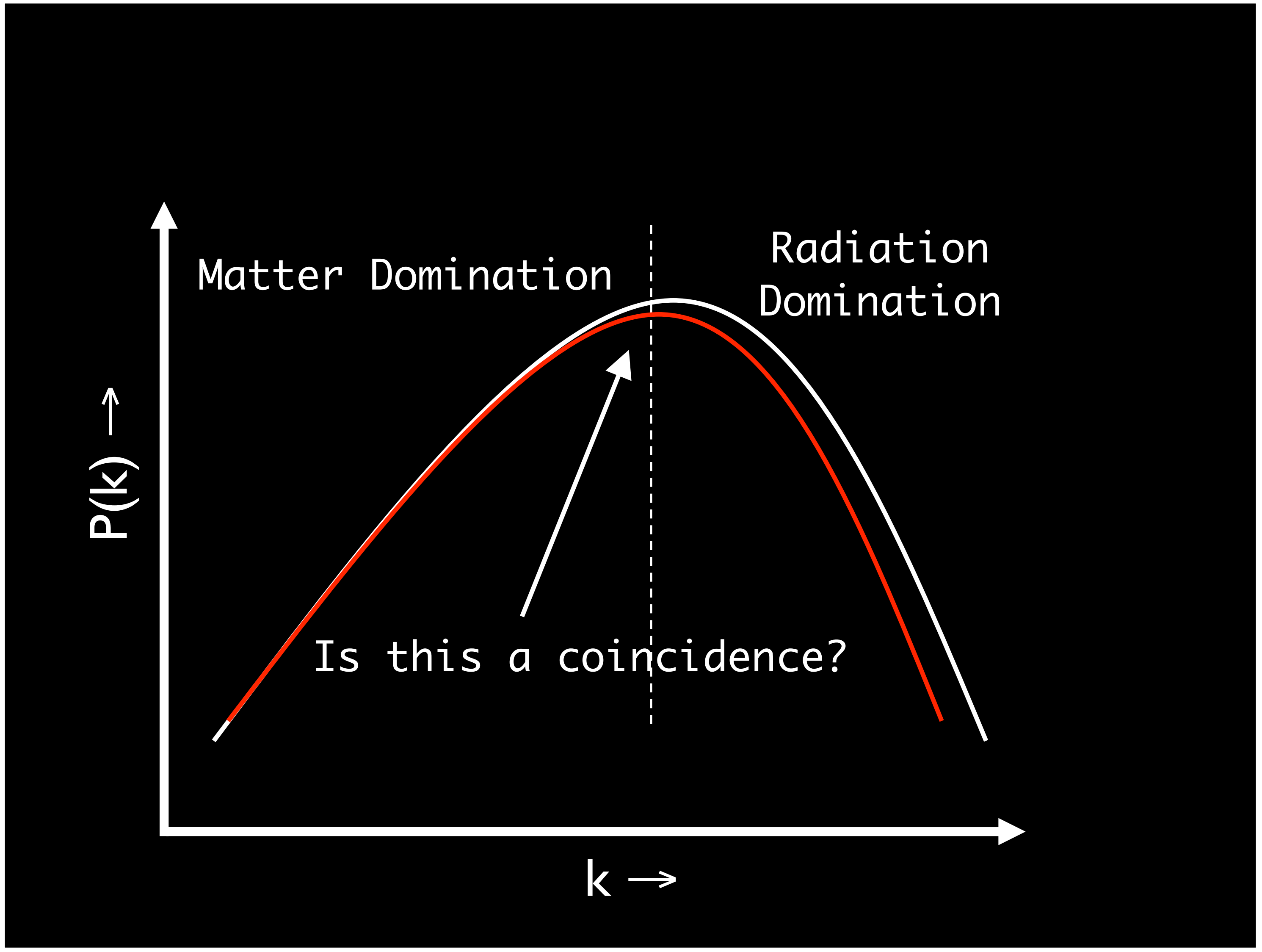
$$n_\nu = N_\nu \times \left(\frac{3}{11}\right) n_\gamma \approx 340 \text{ cm}^{-3}$$

(Assuming thermal equilibrium)

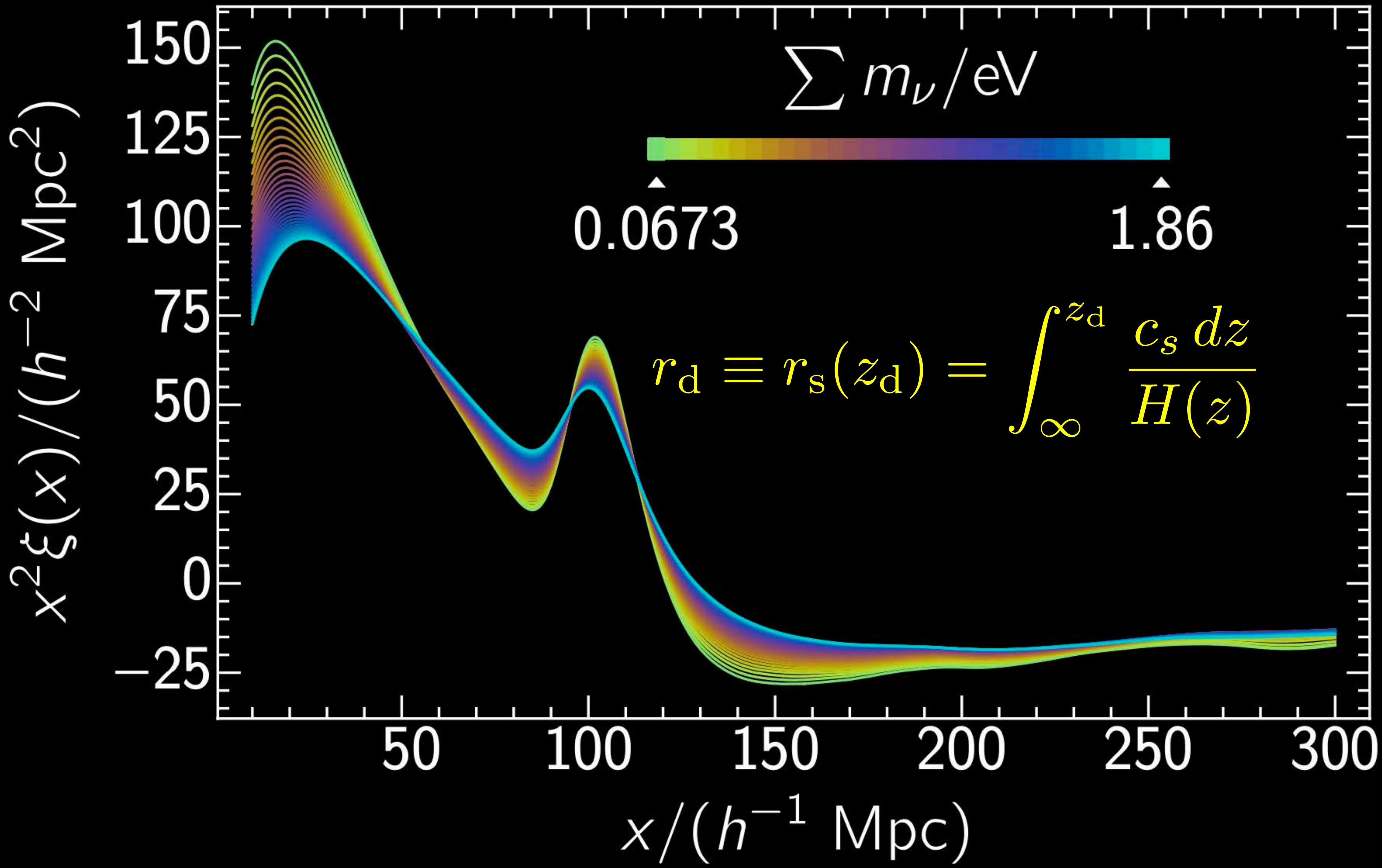
$$\rho_\nu = \sum m_i n_{\nu_i}$$

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

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



Neutrino Mass & BAO



Thepsuriya & Lewis arXiv:1409.5066

Current Σm_ν Limits: **in ΛCDM**

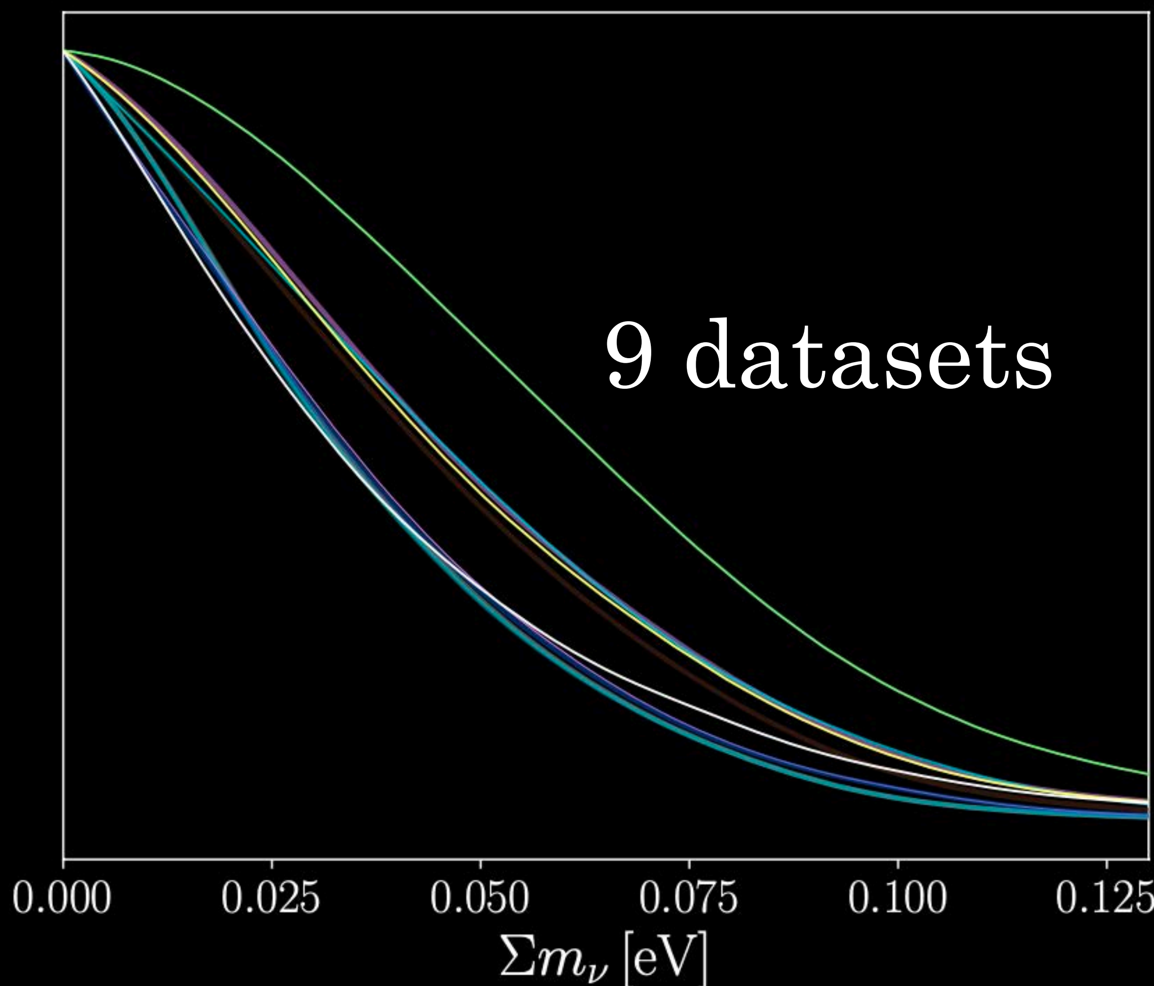
Neutrino mass is degenerate with other cosmological parameters (Ω_m especially), so all cosmological data useful in improving constraints:

CMB
(Planck '18, CamSpec, Planck '20)
+ CMB Lensing (Planck PR4)
+ ACTLens
+ BAO
+ Type Ia SNe
+ (PantheonPlus, Union3, DES Y5)

$$\Sigma m_\nu(\text{P18, DESI, \& PP}) < 82.1\,\text{meV}\,,$$
$$\Sigma m_\nu(\text{P18, DESI, \& U3}) < 82.1\,\text{meV}\,,$$
$$\Sigma m_\nu(\text{P18, DESI, \& DES Y5}) < 98.0\,\text{meV}\,,$$
$$\Sigma m_\nu(\text{CamSpec, DESI, \& PP}) < 76.9\,\text{meV}\,,$$
$$\Sigma m_\nu(\text{CamSpec, DESI, \& U3}) < 77.0\,\text{meV}\,,$$
$$\Sigma m_\nu(\text{CamSpec, DESI, \& DES Y5}) < 86.6\,\text{meV}\,,$$
$$\Sigma m_\nu(\text{P20, DESI, \& PP}) < 94.1\,\text{meV}\,,$$
$$\Sigma m_\nu(\text{P20, DESI, \& U3}) < 93.8\,\text{meV}\,,$$
$$\Sigma m_\nu(\text{P20, DESI, \& DES Y5}) < 108\,\text{meV}\,,$$

García Escudero & Abazajian, arXiv:2412.05451

Current Σm_ν Limits: **in ΛCDM**



$\Sigma m_\nu < 76.9$ meV (95% CL)

…

$\Sigma m_\nu < 108$ meV (95% CL)

[97 meV 11-param]

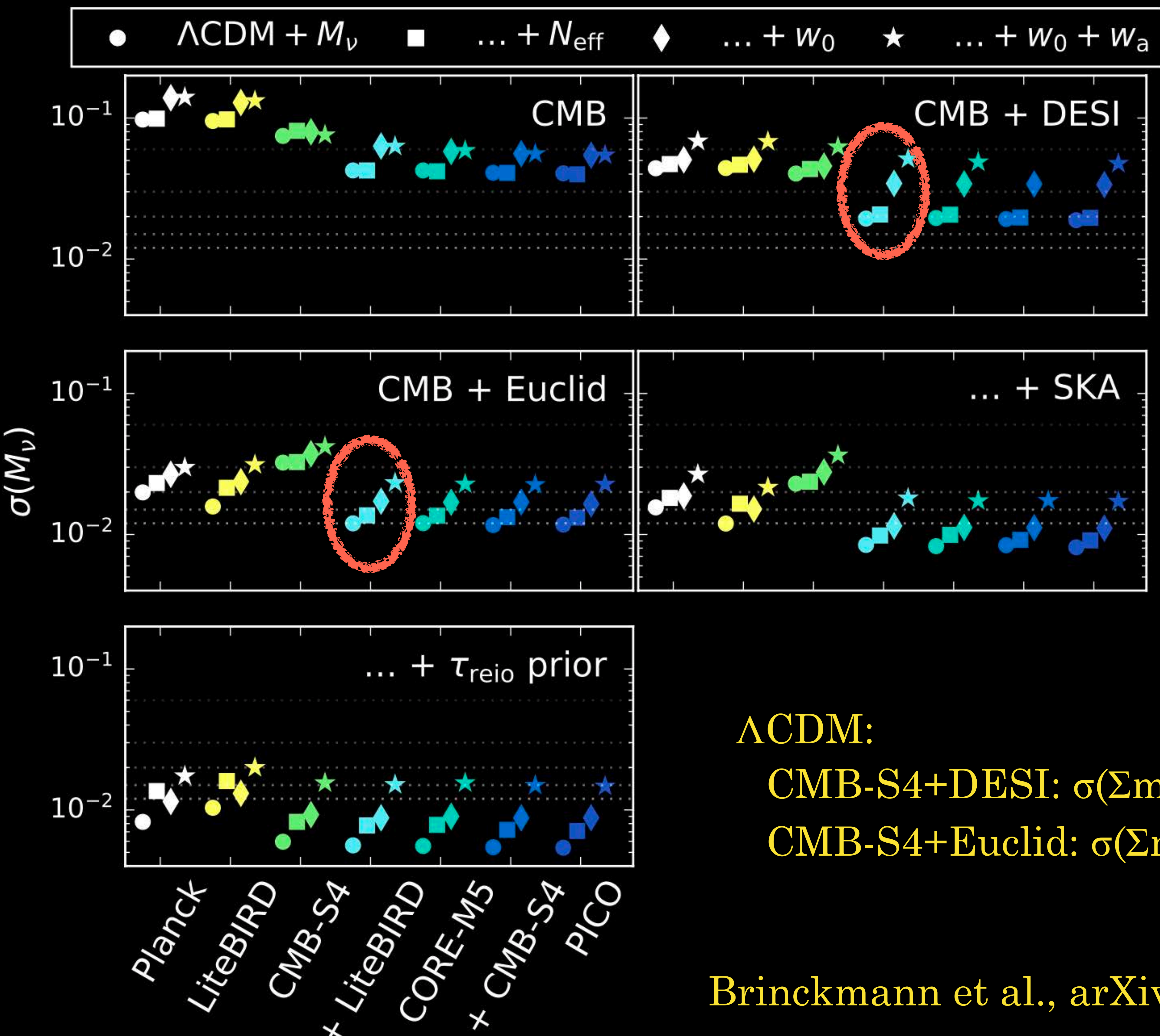
Employing a $\Delta\chi^2$ test (benchmark dataset):

NO preferred over IO at **1.47σ**

(***nonstandard***) $m_\nu = 0$ preferred over NO at **1.36σ**

García Escudero & Abazajian, arXiv:2412.05451

Sensitivity Forecasts for Neutrino Mass with Standard Model Extension Dependence



ΛCDM:

CMB-S4+DESI: $\sigma(\Sigma m_\nu)$ = 20 meV

CMB-S4+Euclid: $\sigma(\Sigma m_\nu)$ = 12 meV

Brinckmann et al., arXiv:1808.05955

$$N_{\text{eff}}$$

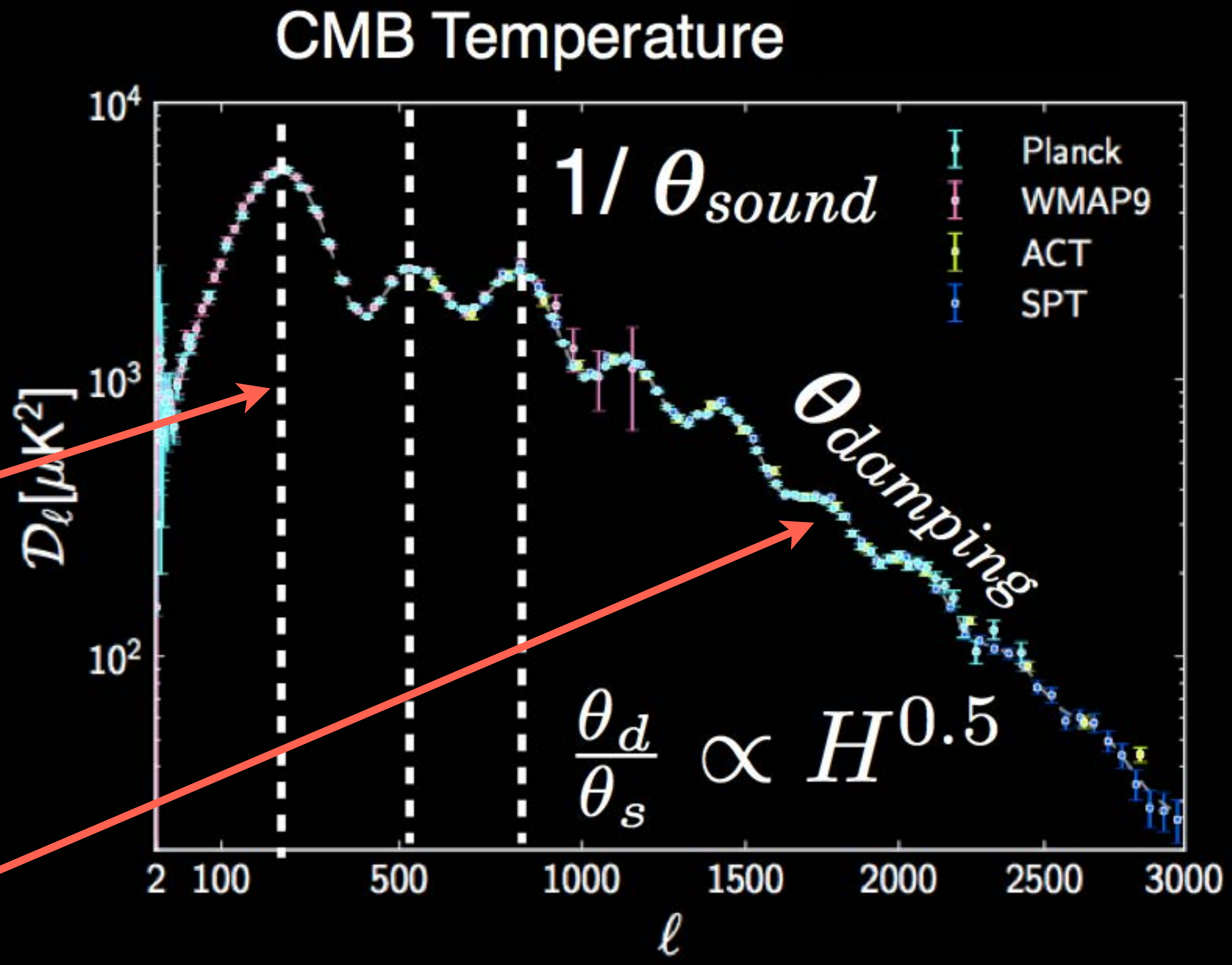
$N_{\rm eff}$ Effects on CMB

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

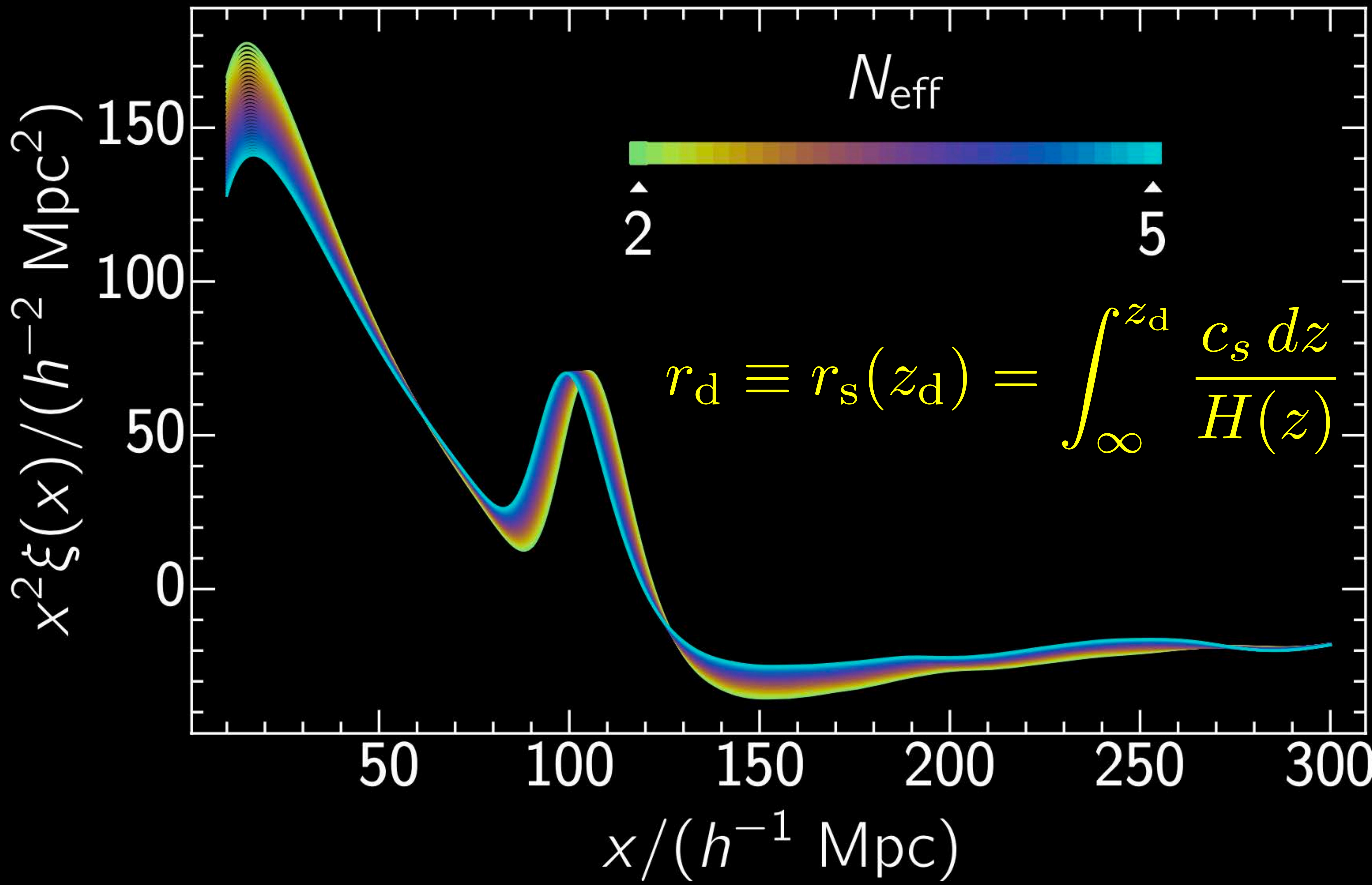
Larger $N_{\rm eff}$ Leads to More Damping

Angular scale of acoustic peaks $\theta_{\rm s} \sim r_{\rm s}/D$ is known precisely

Angular scale of damping $\theta_{\rm d} \sim r_{\rm d}/D$ measured more recently



Neutrino Number & BAO

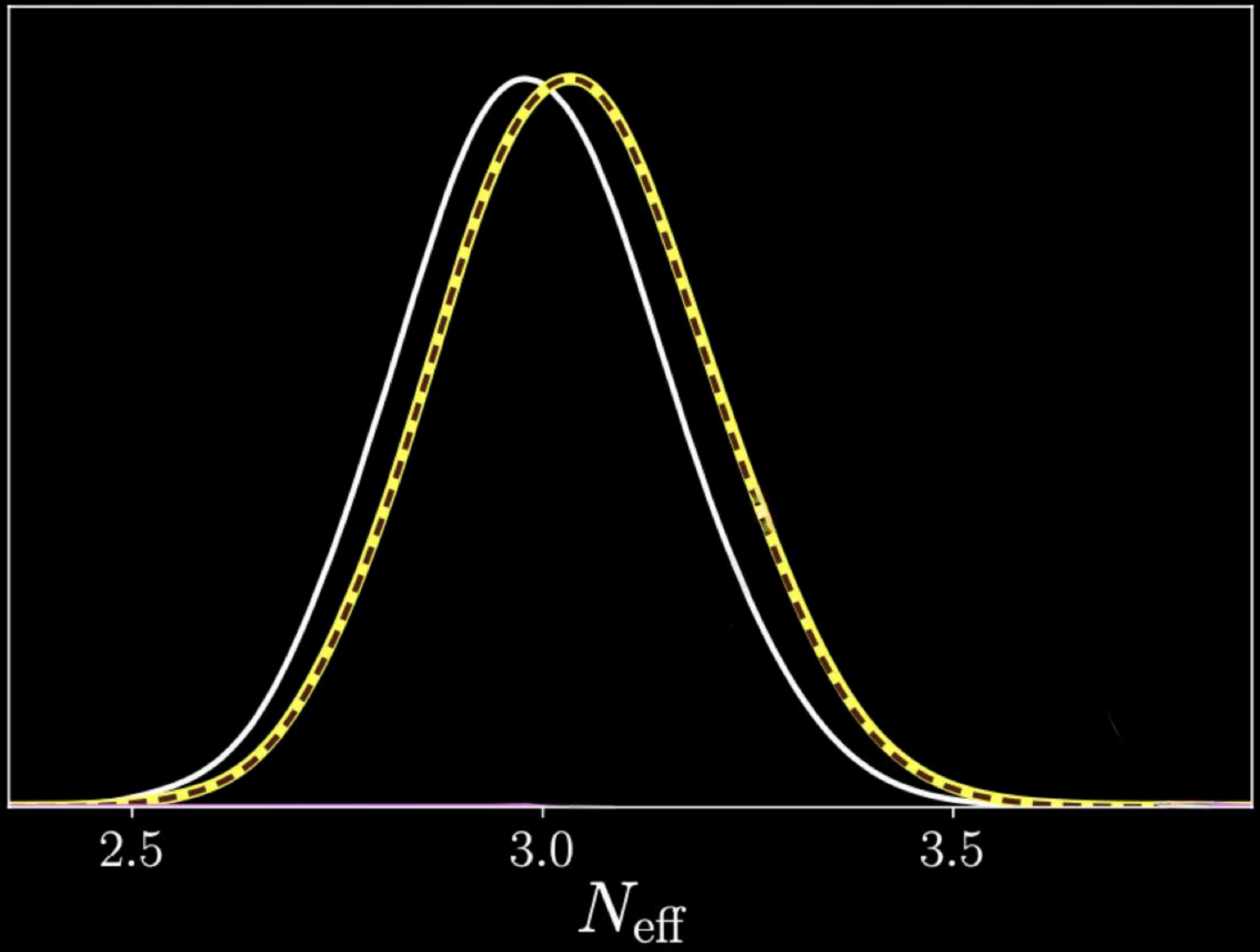


$$r_{\rm d} \equiv r_{\rm s}(z_{\rm d}) = \int_{\infty}^{z_{\rm d}} \frac{c_s\, dz}{H(z)}$$

Thepsuriya & Lewis arXiv:1409.5066

Neutrino Number & H_0

$$r_d \equiv r_s(z_d) = \int_{\infty}^{z_d} \frac{c_s\, dz}{H(z)}$$



$$N_{\rm eff} = 3.05 \pm 0.17$$

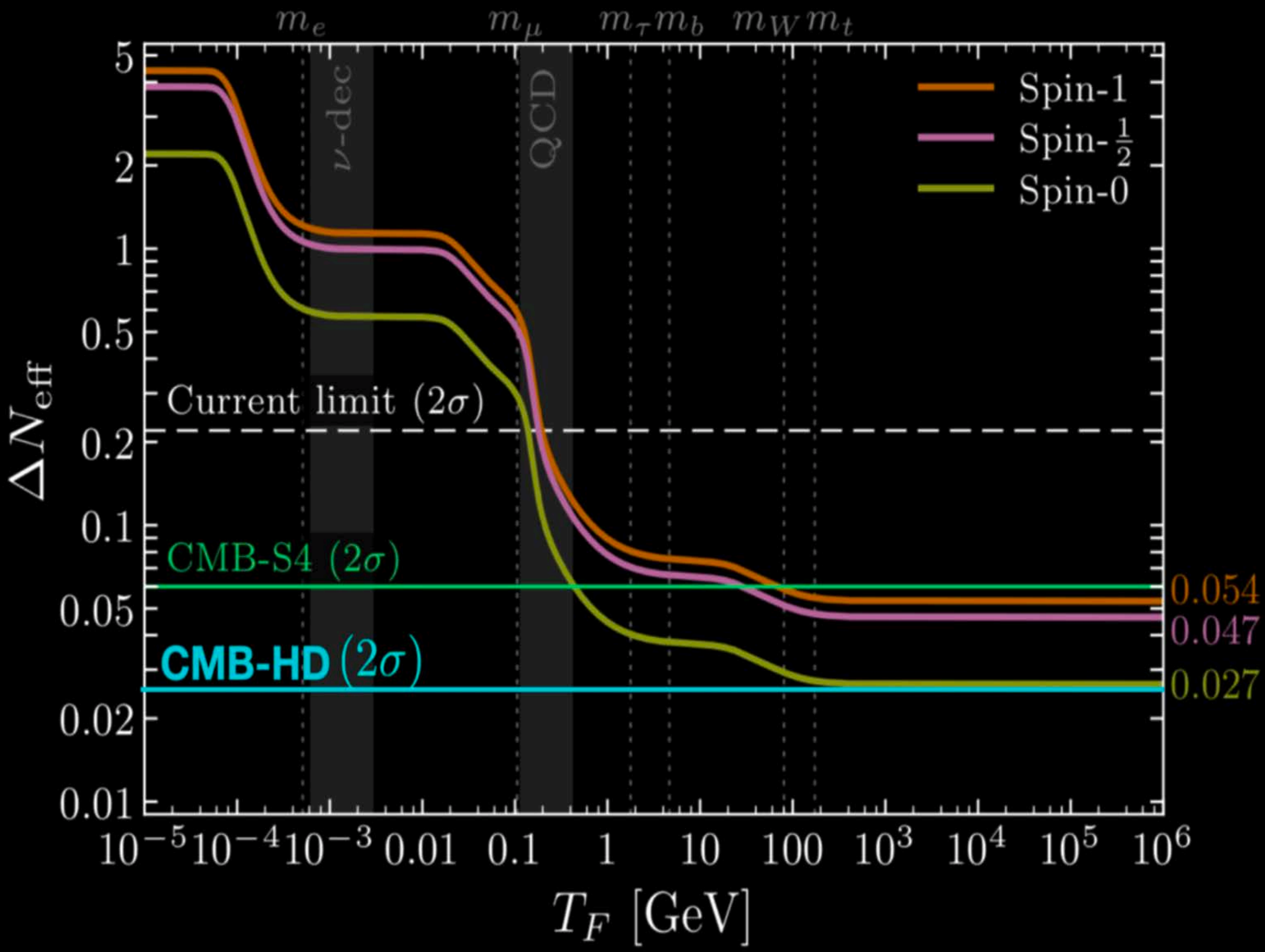
PantheonPlus, Union3 SNe

$$N_{\rm eff} = 2.99 \pm 0.17$$

DES Y5 SNe

García Escudero & Abazajian, arXiv:2412.05451

N_{eff} : Not just Neutrinos, Light Relics



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

CMB-S4: $\sigma(N_{eff}) = 0.03$

Measuring the Smallest with the Largest

Standard Model Scenario:

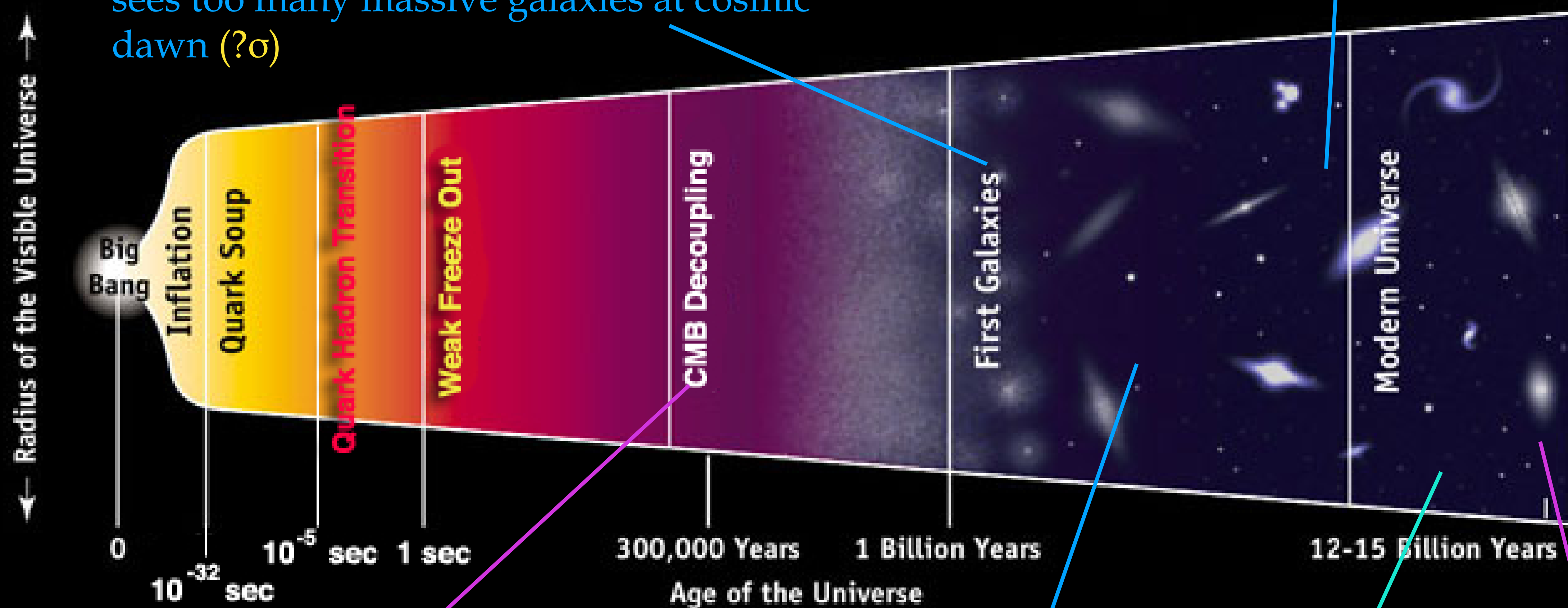
- *3-5*σ measurements of Σm_ν = 58 meV
- 2σ N_{eff} = 3.044 in ~15 years


Tensions!
&
New Physics?

Tensions!

***BAO +SNe Anomaly*:** DESI sees smaller BAO scale at z = 0.5 - 0.7, with SNe adding to signal of evolving dark energy (4σ)

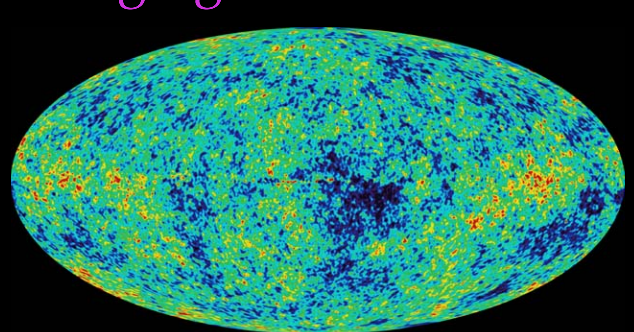
***Massive first galaxies*:** JWST possibly sees too many massive galaxies at cosmic dawn (?σ)



***Large Growth*:** CMB lensing observations by Planck, ACT, SPT see too much of a lensing signal by intervening large scale structure at $z \sim 2$. "Negative" neutrino mass (2σ to 3σ)

H_0 problem: evolving "phantom" dark energy (5σ)

H_0 problem: Extra early dark radiation or dark energy near matter-radiation equality, changing r_s

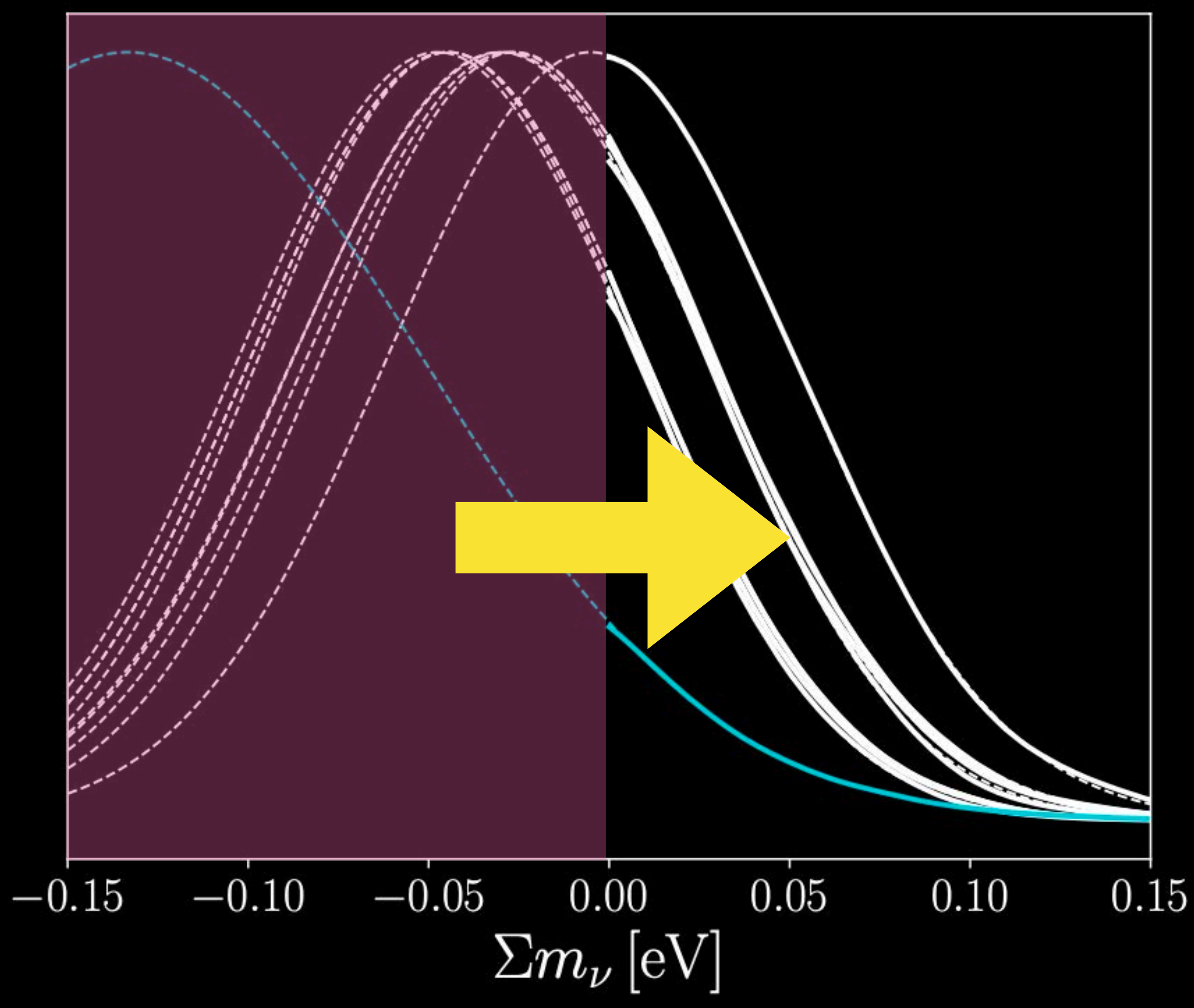


***Small Growth (S_8 problem)*:** Measures of structure growth by weak lensing and cluster counts show smaller than expected clustering amplitudes (2σ to 3σ)

Tensions!

Large Growth at z ~2
(“Negative” Neutrino Mass)

“Negative” Neutrino Mass



CMB (Planck ’18, CamSpec, Planck ’20)
+ CMB Lensing (Planck PR4)
+ ACTLens
+ BAO
+ Type Ia SNe
+ (PantheonPlus, Union3, DES Y5)

in ΛCDM

All central values < 2σ from NO (58 meV)

with extended parameters

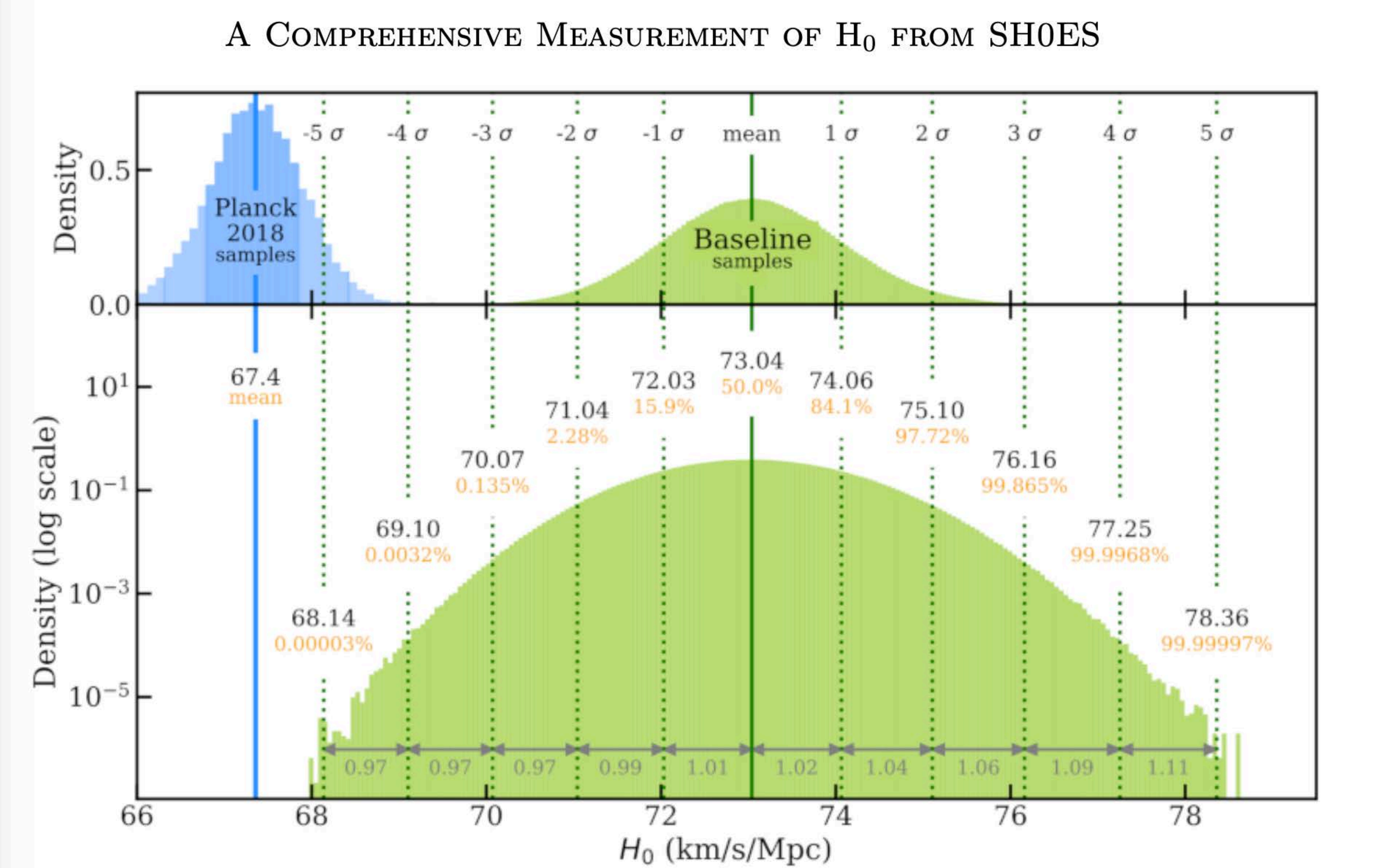
Central value 2.3σ from NO (58 meV)

García Escudero & Abazajian, arXiv:2412.05451

The H_0 Problem

New Physics at Early or Late Times?

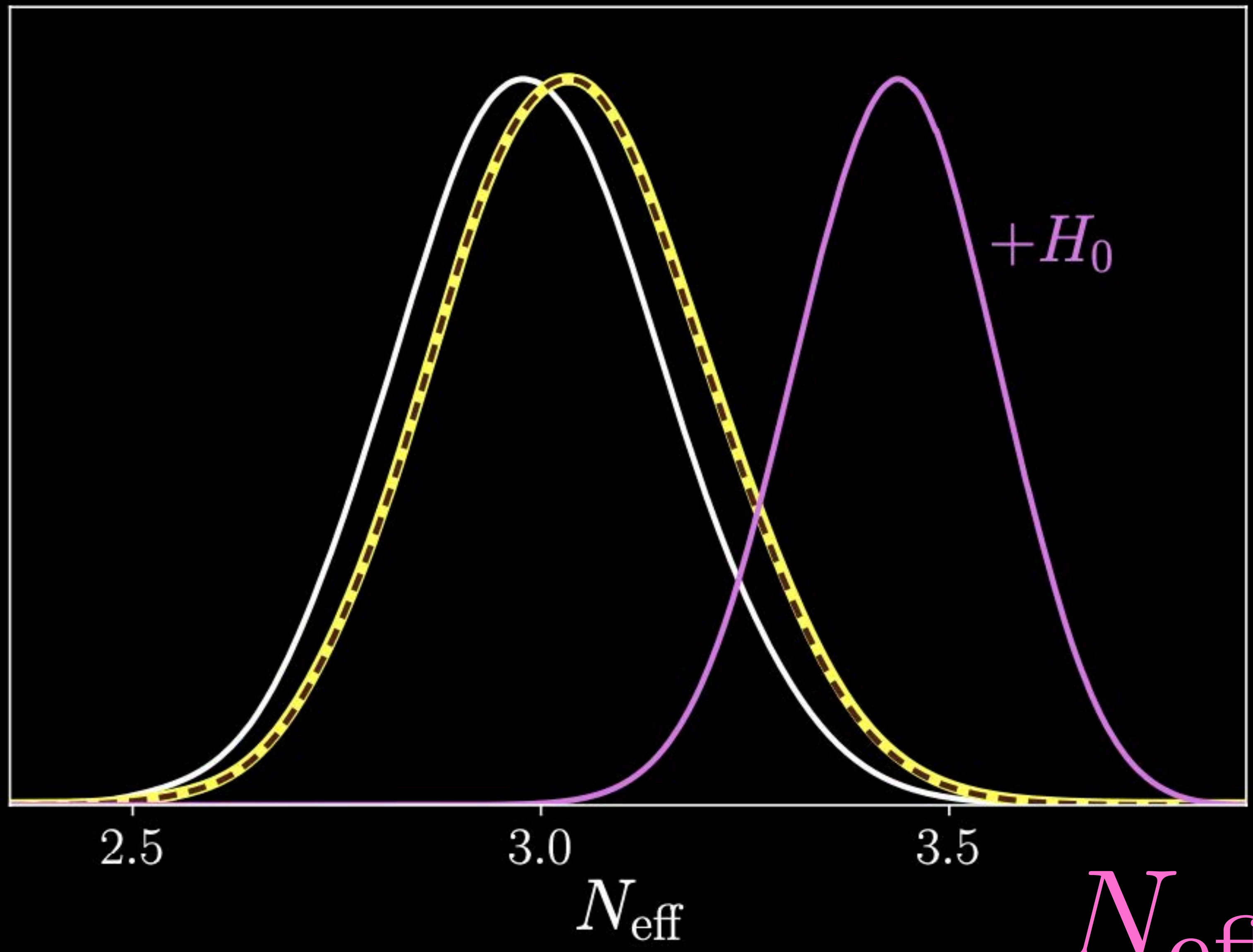
The H_0 Problem



Riess+ arXiv:2112.04510

Neutrino Number & H_0

$$r_{\rm d} \equiv r_{\rm s}(z_{\rm d}) = \int_{\infty}^{z_{\rm d}} \frac{c_s\, dz}{H(z)}$$



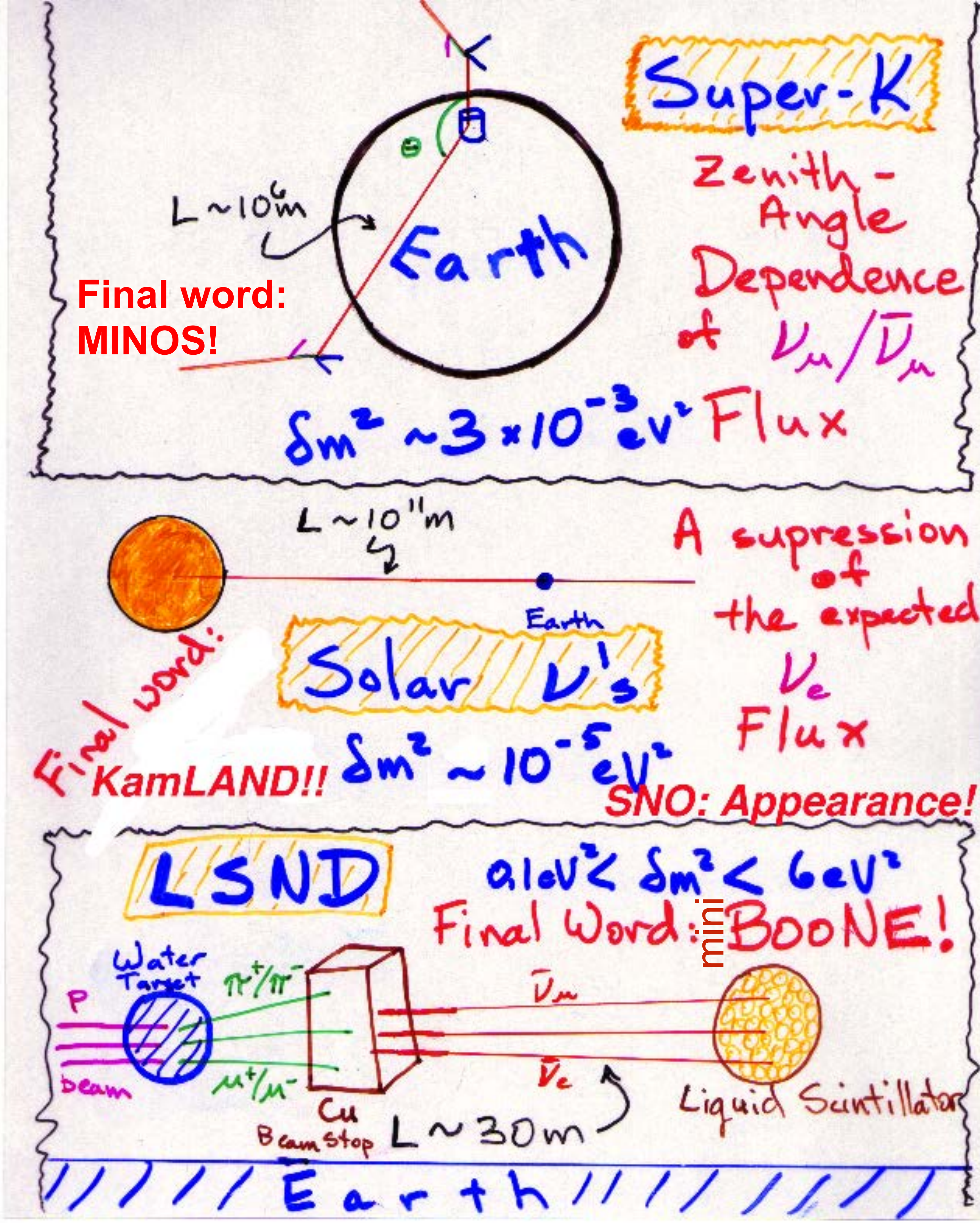
Among the best alleviations to the Hubble tension

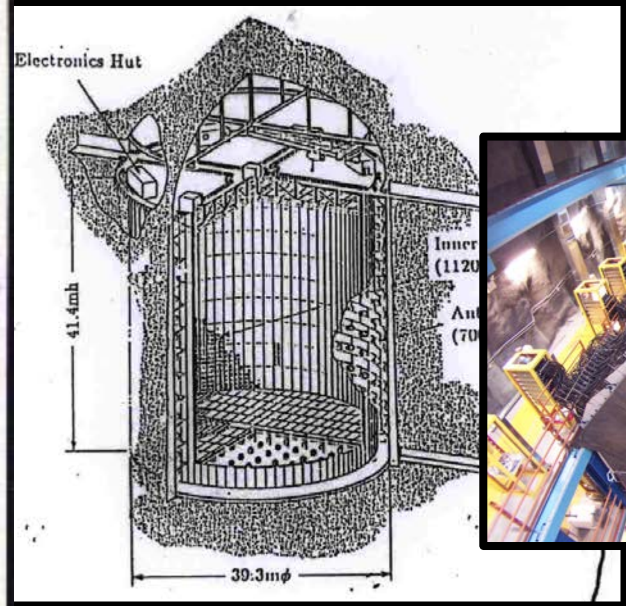
García Escudero+
arXiv:2208.14435

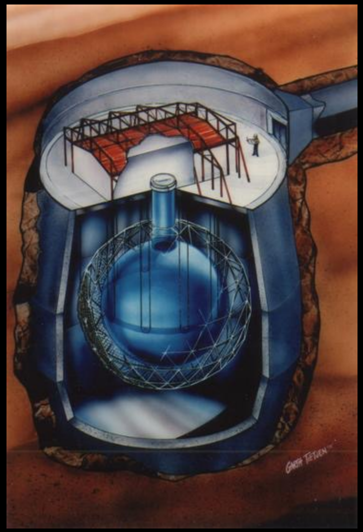
$$N_{\rm eff} = 3.45 \pm 0.12$$

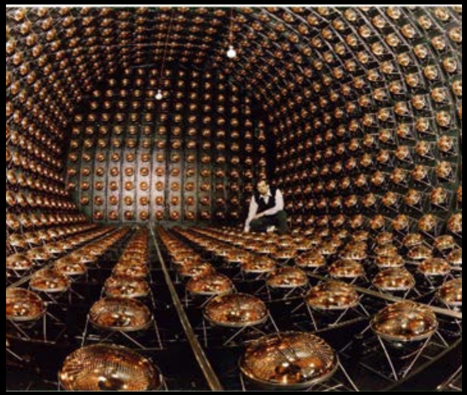
García Escudero+
arXiv:2208.14435, arXiv:2412.05451

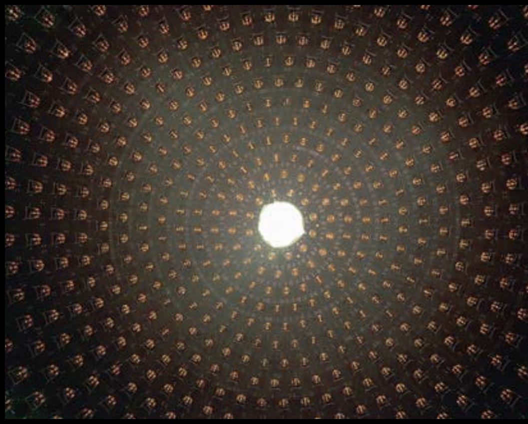
Short Baseline Neutrino Oscillations?


Super-K
Zenith-Angle Dependence of $\nu_\mu/\bar{\nu}_\mu$ Flux
$L \sim 10^6$m
Earth
Final word: MINOS!
$\delta m^2 \sim 3\times10^{-3}$ eV^2
$L \sim 10^{11}$m
Earth
Solar ν's
A supression of the expected ν_e Flux
Final word: KamLAND!!
$\delta m^2 \sim 10^{-5}$ eV^2
SNO: Appearance!
LSND
0.1 eV$^2 < \delta m^2 < 6$ eV^2
Final Word: miniBooNE!
Water Target
π^+/π^-
P beam
μ^+/μ^-
Cu Beam Stop
$\bar{\nu}_\mu$
$\bar{\nu}_e$
$L \sim 30$m
Liquid Scintillator
Earth

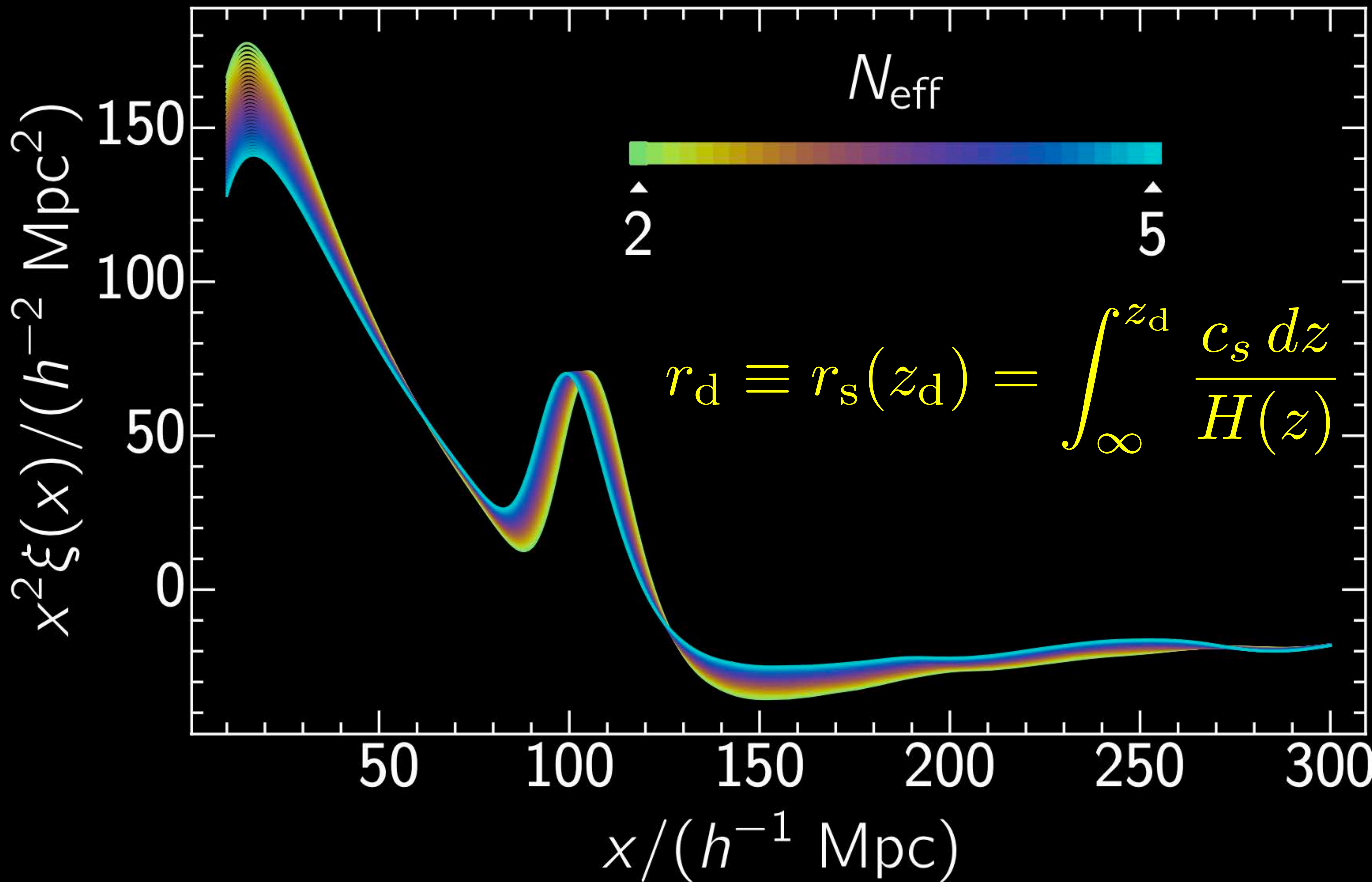

Electronics Hut
41.4mh
39.3mφ







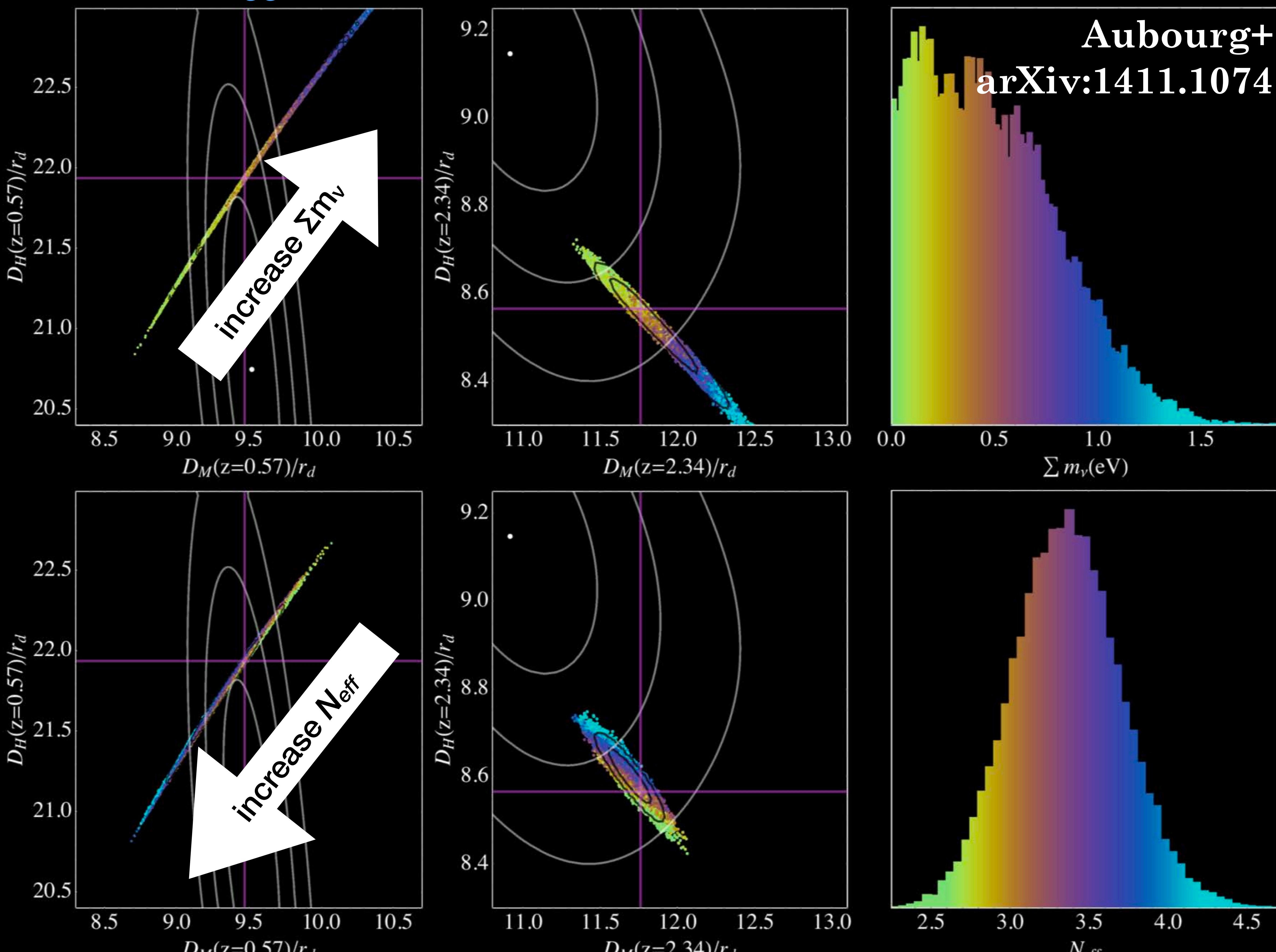
Neutrino Number & BAO



$$r_{\rm d} \equiv r_{\rm s}(z_{\rm d}) = \int_{\infty}^{z_{\rm d}} \frac{c_s\, dz}{H(z)}$$

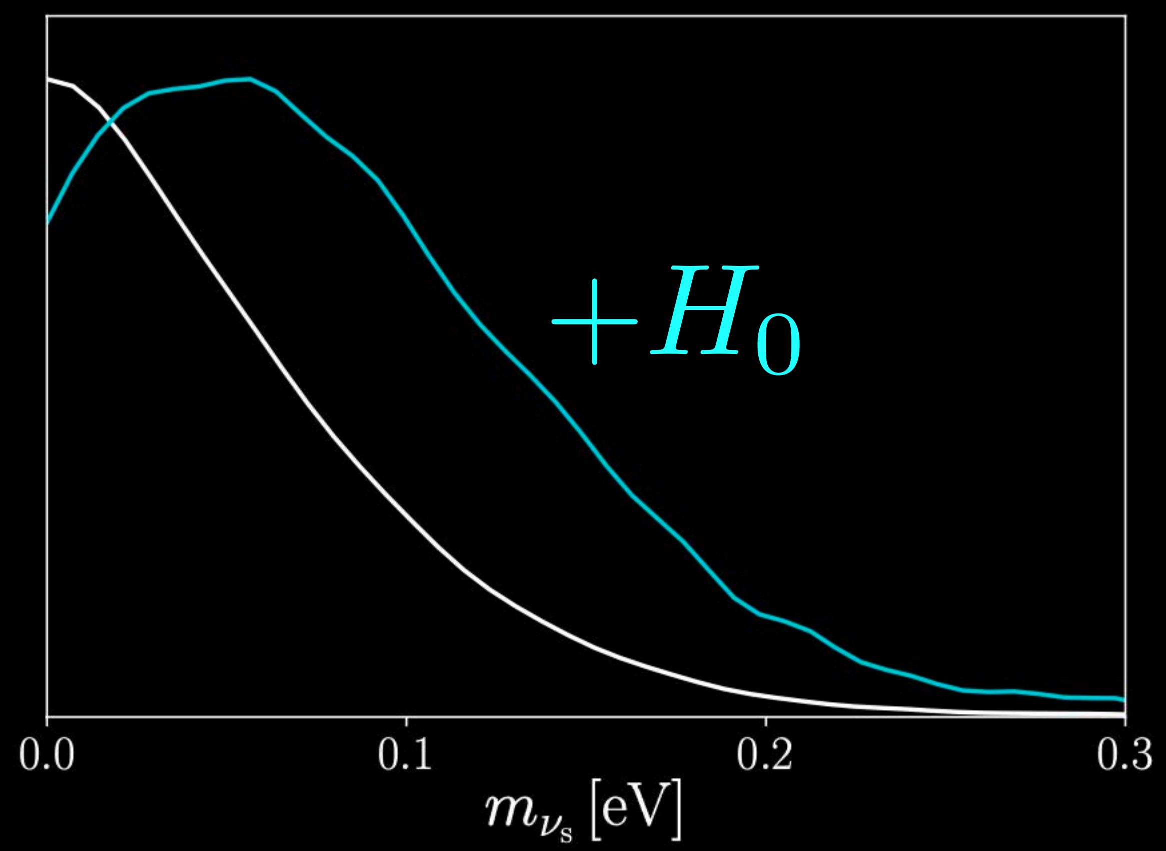
Thepsuriya & Lewis arXiv:1409.5066

Σm_ν, N_{eff} & BAO



Loverde & Weiner arXiv:2410.00090

Short Baseline Neutrino in Cosmology?



We tested fully and partially thermalized sterile neutrino cosmologies **when adopting the SH0ES H_0 measurement** and found:

- A fully thermalized 1 eV sterile neutrino is only disfavored by ~2σ relative to ΛCDM
- A partially thermalized ($\Delta N_{\rm eff}$ = 0.07) 1 eV sterile neutrino fits as well as ΛCDM $\Delta\chi^2$ = 0.8
- A partially thermalized ($\Delta N_{\rm eff}$ = 0.45) 0.1 eV sterile neutrino **is favored over ΛCDM** by $\Delta\chi^2$ = 11 (3.3σ)

García Escudero & Abazajian, arXiv:2412.05451

Cosmology & Neutrinos:

Current Status:

- $\Sigma m_\nu < 77$ to 108 meV (95% CL)
- NO preferred relative to IO at ~1.4σ
- slight tension with CMB lensing preferring $\Sigma m_\nu = 0$
- $N_{\text{eff}} = 3.05 \pm 0.17$

Future:

Cake: Standard Model Scenario (A) <u>All is well</u>

George-ism:

"God is in his heaven and all is right in the world."

- 5σ measurements of $\Sigma m_\nu = 58$ meV
- 2σ $N_{\text{eff}} = 3.044$ in ~15 years

Icing: Beyond SM Scenario (B) <u>Surprises set in</u>

- Cosmological Tensions Are Signals
- Lab Neutrino Anomalies Are Signals