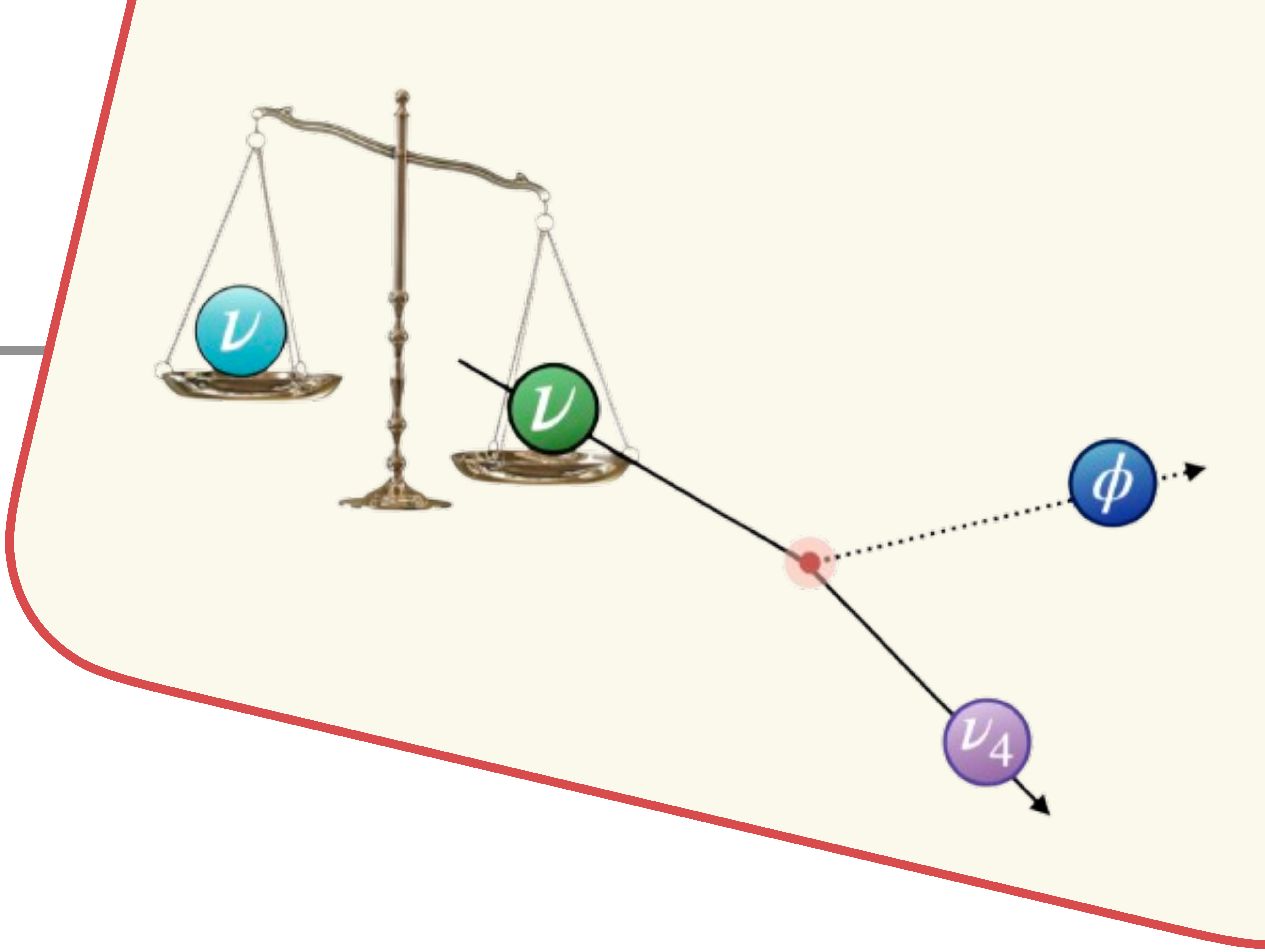
Neutrino decays in light of the neutrino mass tension



Guillermo Franco Abellán (IFIC, Valencia)

Based on:

[arXiv:2601.04312]
PRD 113 (2026), *Editors' Suggestion*

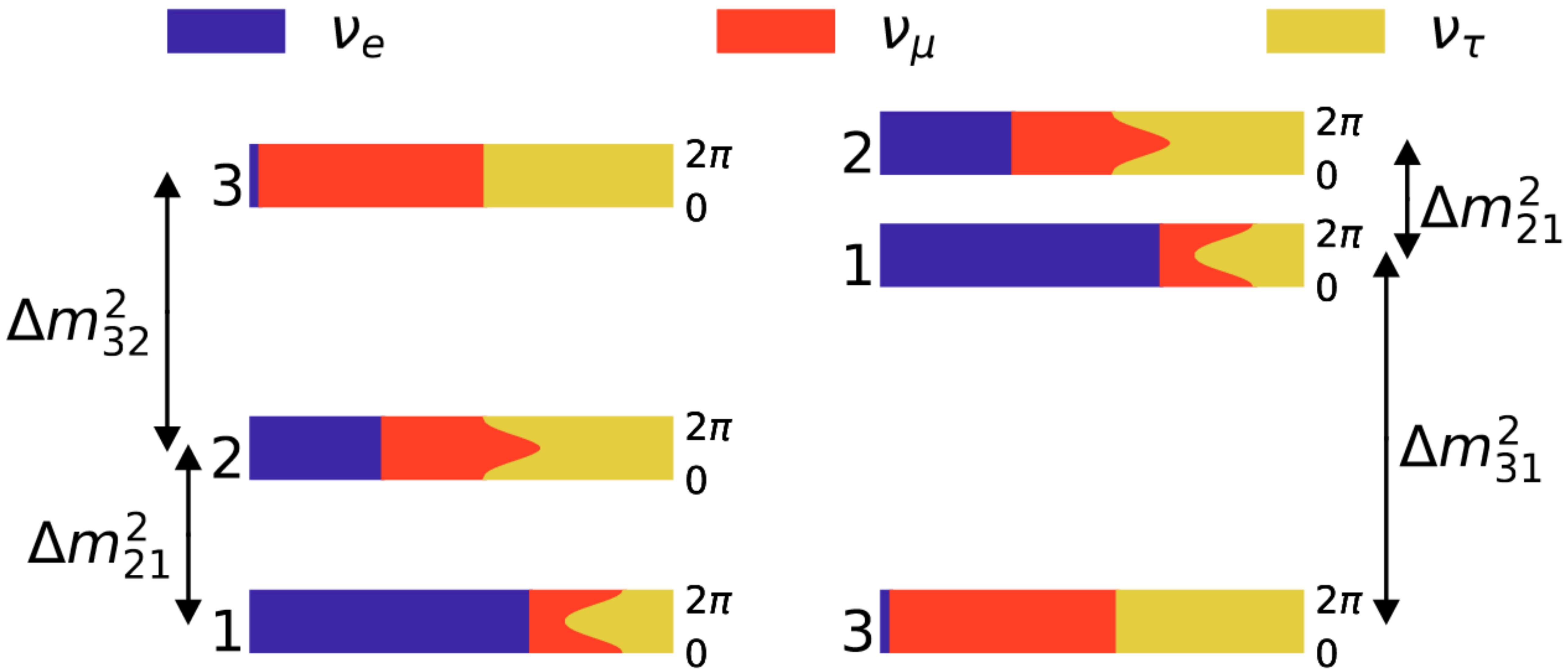
IFIC INSTITUT DE FÍSICA CORPUSCULAR

VNIVERSITAT DE VALÈNCIA

PASCOS 2026, Sheffield

Lower bounds on $\sum m_\nu$

Oscillation experiments



[Salas++ 18]

Normal

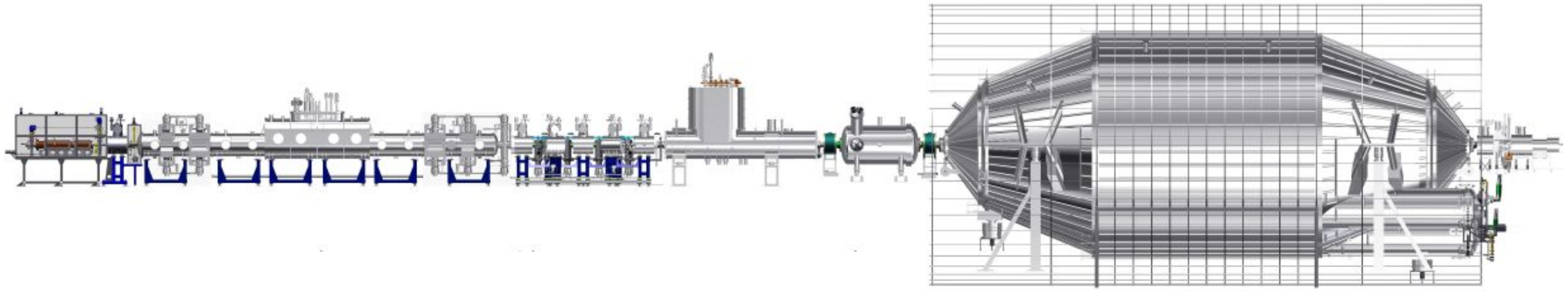
$$\sum m_\nu \gtrsim 0.06\ \text{eV}$$

Inverted

$$\sum m_\nu \gtrsim 0.10\ \text{eV}$$

Upper bounds on $\sum m_\nu$

KATRIN experiment $\quad {}^3\mathrm{H} \longrightarrow {}^3\mathrm{He}^+ + e^- + \bar{\nu}_e$



Current bounds

[KATRIN 24]

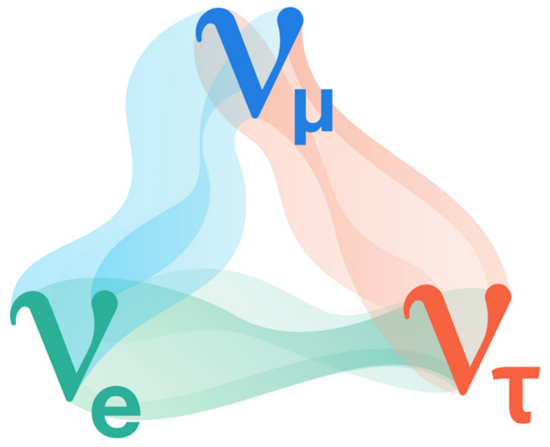
$$m_{\nu_e} < 0.45\ \mathrm{eV}$$
$$\sum m_\nu < 1.35\ \mathrm{eV}$$

Expected KATRIN reach

$$m_{\nu_e} < 0.2\ \mathrm{eV}$$
$$\sum m_\nu < 0.6\ \mathrm{eV}$$

Minimum value

0.06 eV



$\sum m_\nu$

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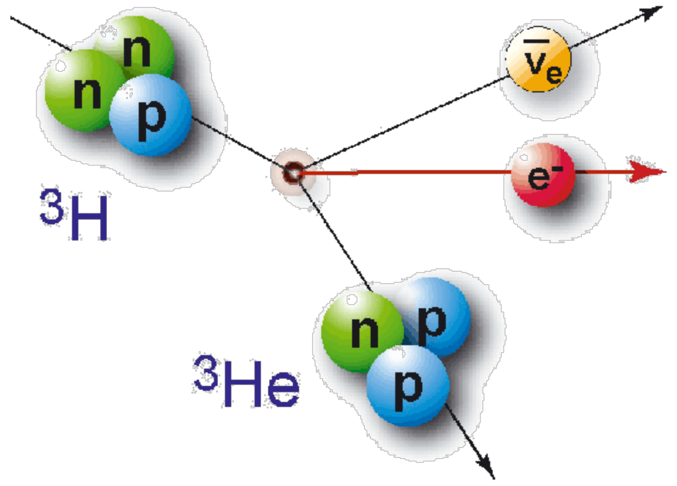

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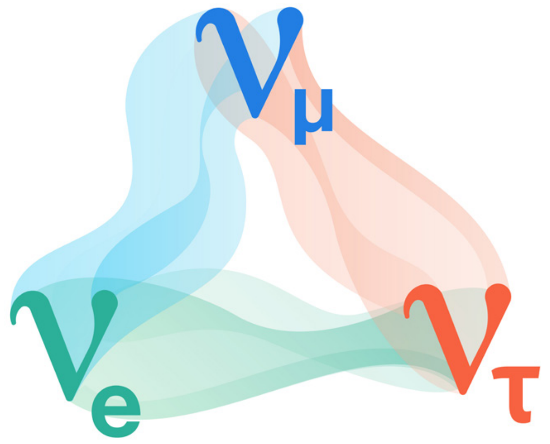

$$\sum m_\nu$$

Cosmology can close this gap

Maximum value

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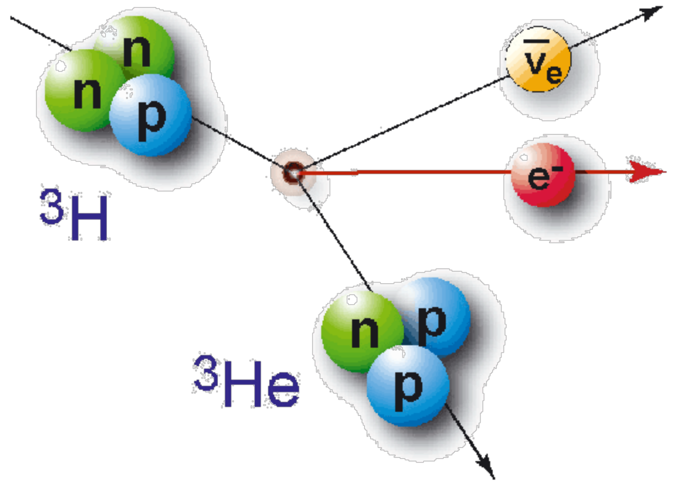
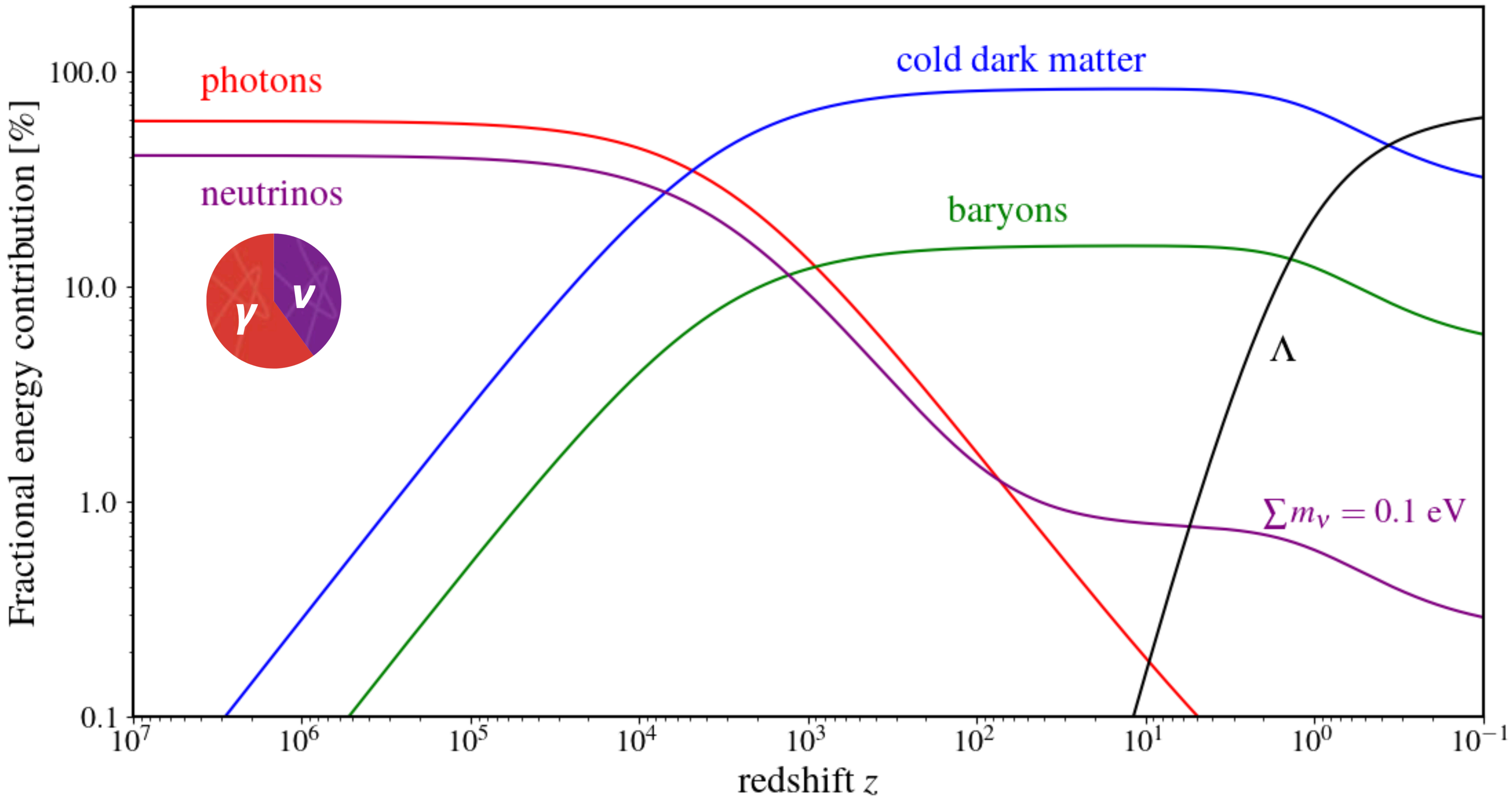


Neutrinos are always relevant for Universe's energy budget



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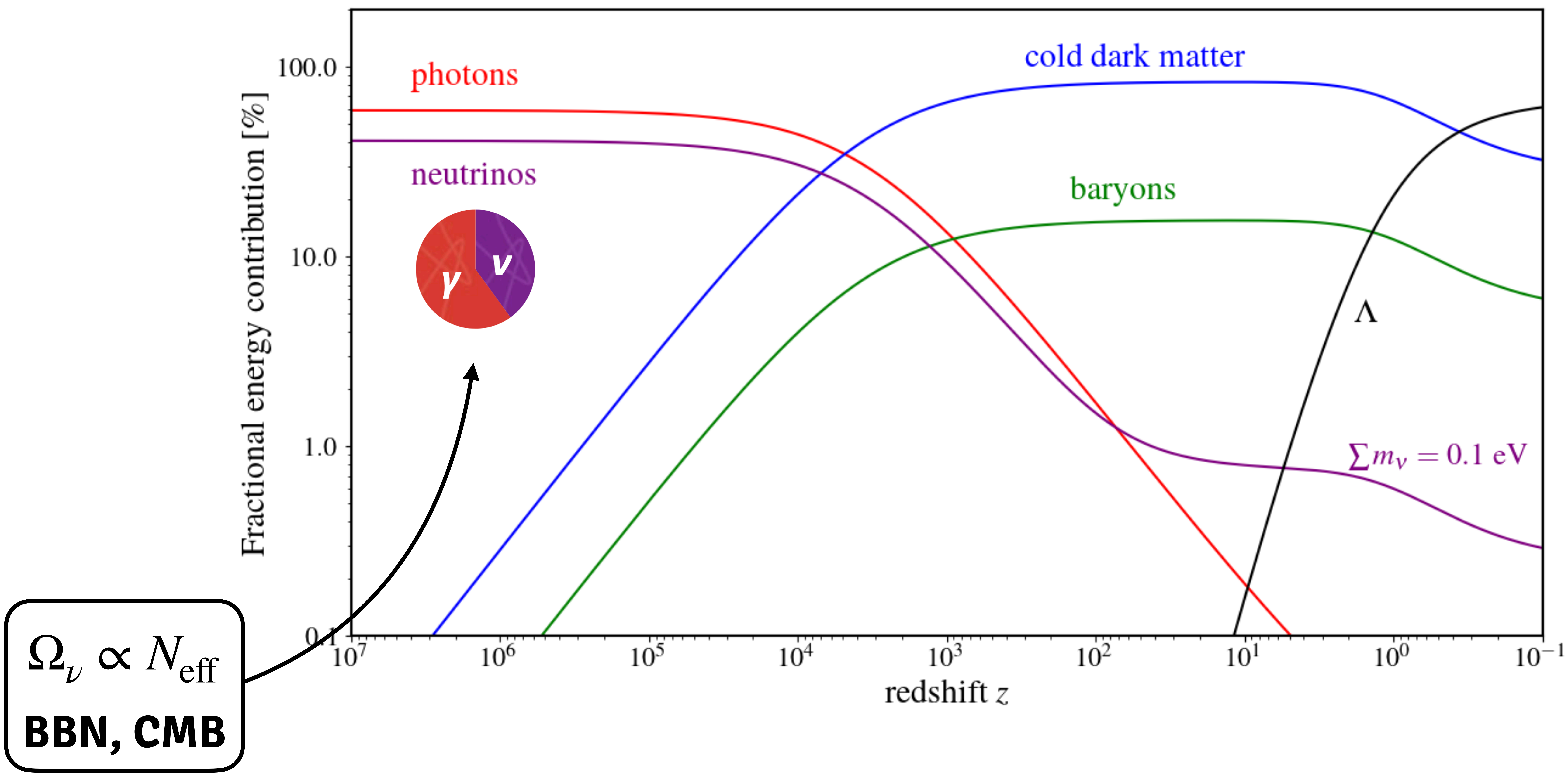

$\Omega_\nu \propto N_{\rm eff}$

BBN, CMB

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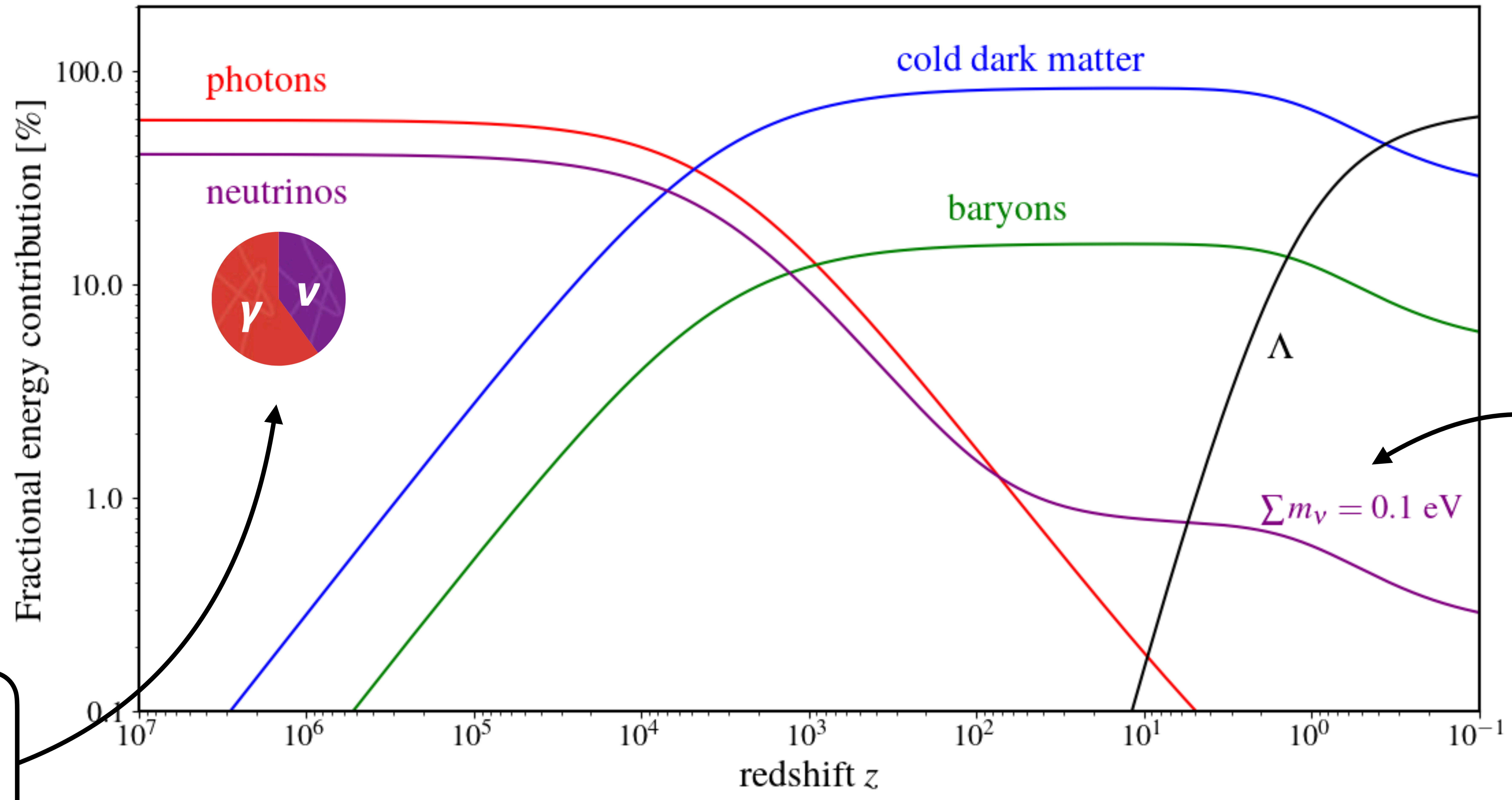


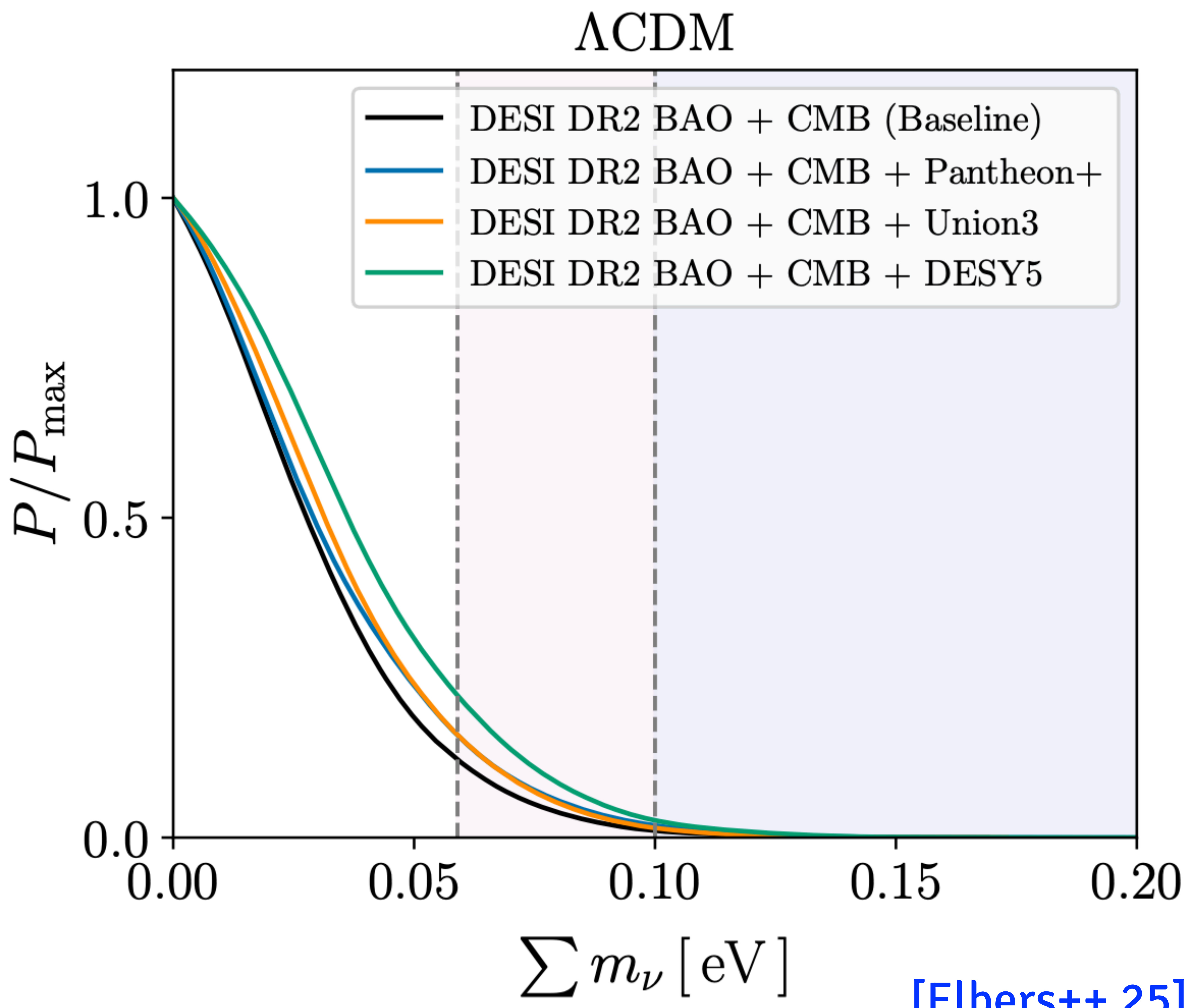
$\Omega_\nu \propto N_{\text{eff}}$

BBN, CMB

$\Omega_\nu \propto \sum m_\nu$

CMB, LSS

Cosmological bounds



[Elbers++ 25]

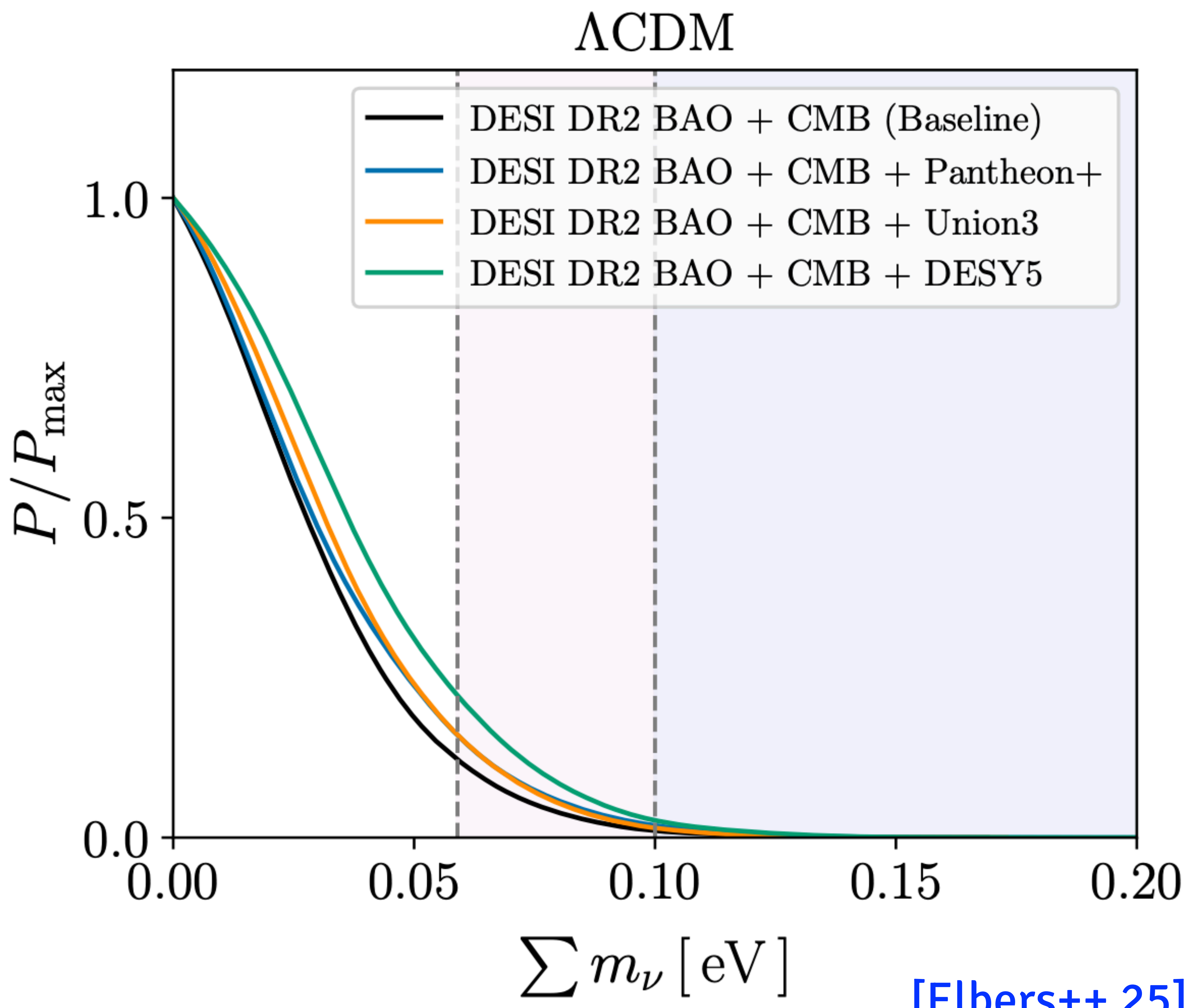
Tightest limits to date!

(DESI DR2 BAO + Planck + ACT DR6 lensing)

$$\boxed{\sum m_\nu < 0.064\ \mathrm{eV}}$$

[DESI DR2 Results II 25]

Cosmological bounds



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[DESI DR2 Results II 25]

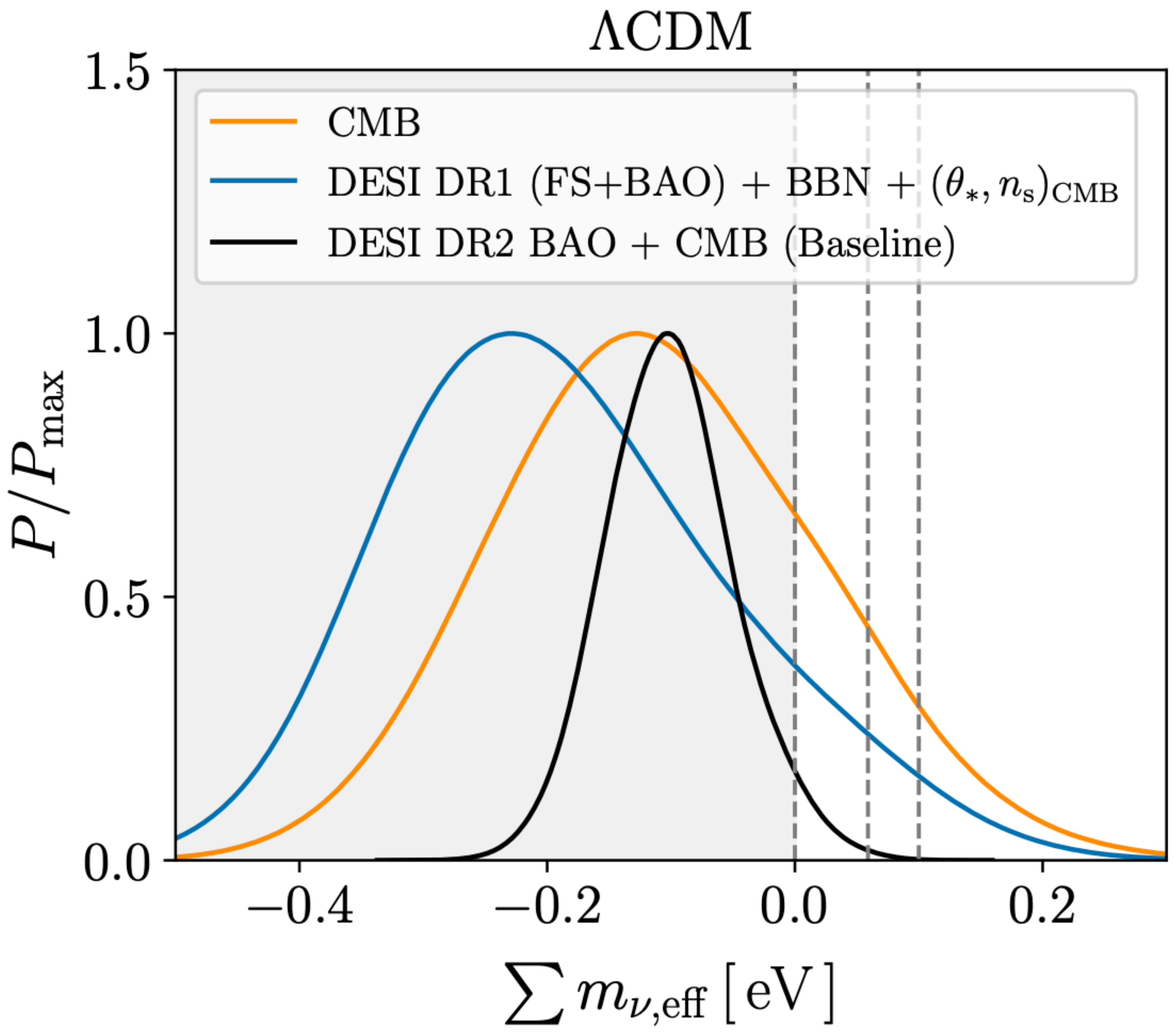
(DESI DR2 BAO + Planck + ACT DR6 + SPT-3G D1)

$$\boxed{\sum m_\nu < 0.055\ \mathrm{eV}}$$

[SPT-3G D1 Results 25]

CMB+BAO data even seem to favor negative neutrino masses

[Craig++ 24]
[Naredo-Tuero++ 24]



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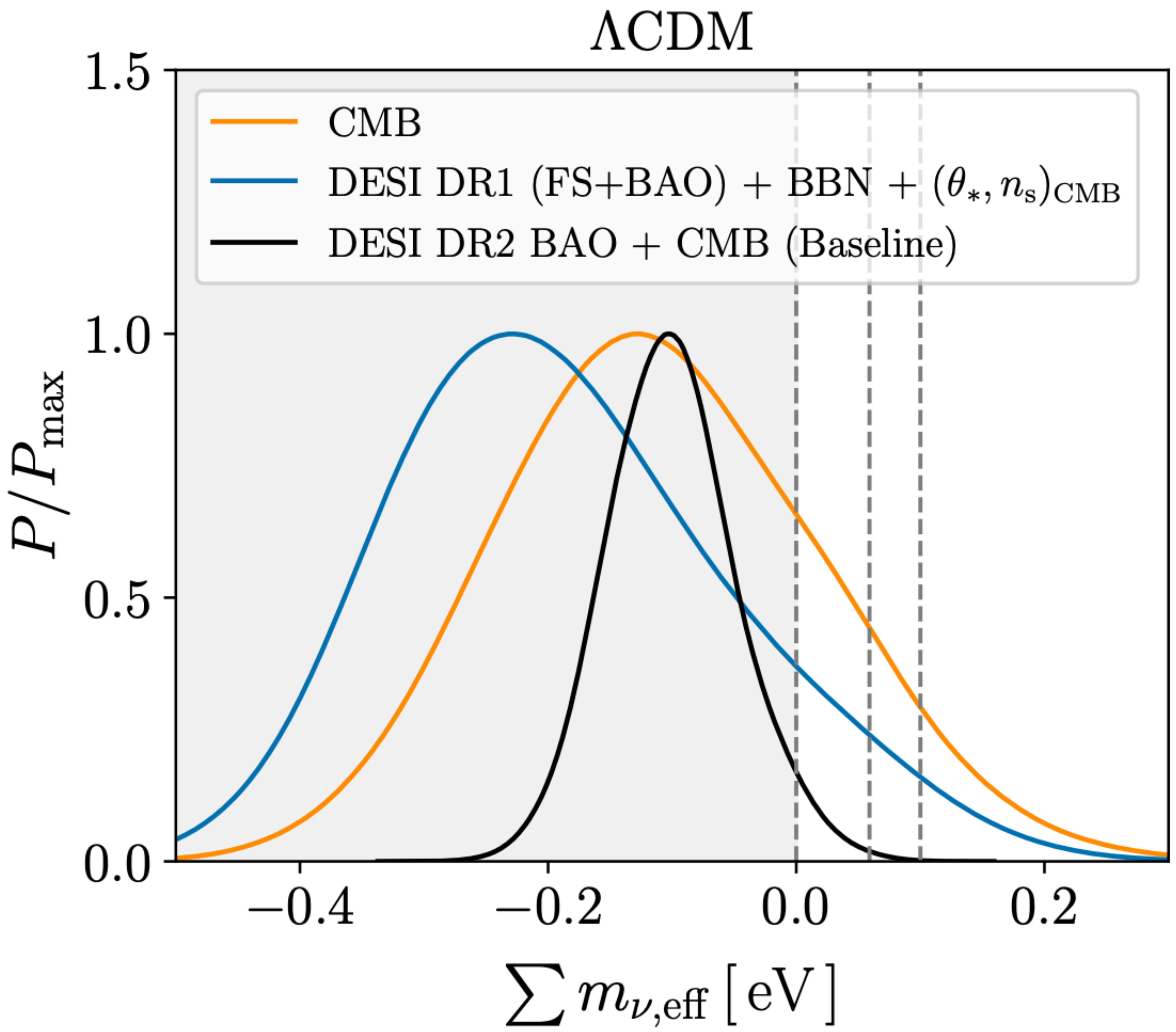

[Elbers++ 25]

These unphysically small limits originate from BAO preference for low Ω_m

[Lynch & Knox 25]
[Loverde & Weiner 25]

BUT the cosmological bounds are **model-dependent**

Some proposed explanations:

- **Evolving dark energy** (e.g. w_0w_a) [Elbers++ 24]
- **Matter conversion to dark energy** [Ahlen++ 25]
- **A large reion. optical depth** τ_{reio} [Jhaveri++ 25]
[Tan & Komatsu 25]
- **A suppressed growth rate** [Giarè++ 25]
- **An excess of CMB lensing** [Cozzumbo++ 25]

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New physics in the neutrino sector?

Decaying neutrinos

- Mass bounds can be relaxed if neutrinos decay with $\tau_\nu \sim (0.01 - 0.1)t_{\mathrm{U}}$ [Serpico 07]

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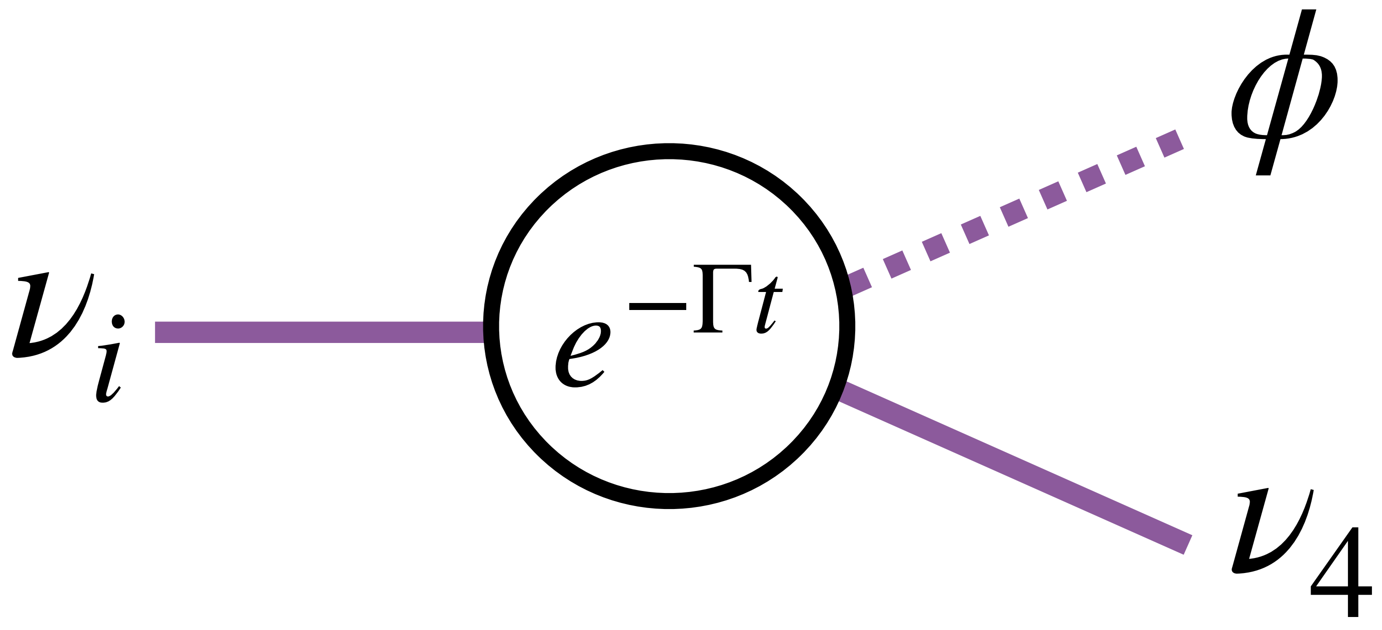
- Radiative decays are strongly constrained $\tau_\nu > 10^2 - 10^{10}\ t_U$

[Aalberts++ 18]

- Decays to dark radiation, much less constrained



Appears naturally in many simple extensions of the seesaw mechanism

$$\mathscr{L}_{\text{int}} = \mathfrak{g}\, \bar{\nu}_i \nu_4 \phi$$

[Escudero & Fairbairn 19]
[Escudero++ 20]

Lifetime bounds on invisible neutrino decays

ν

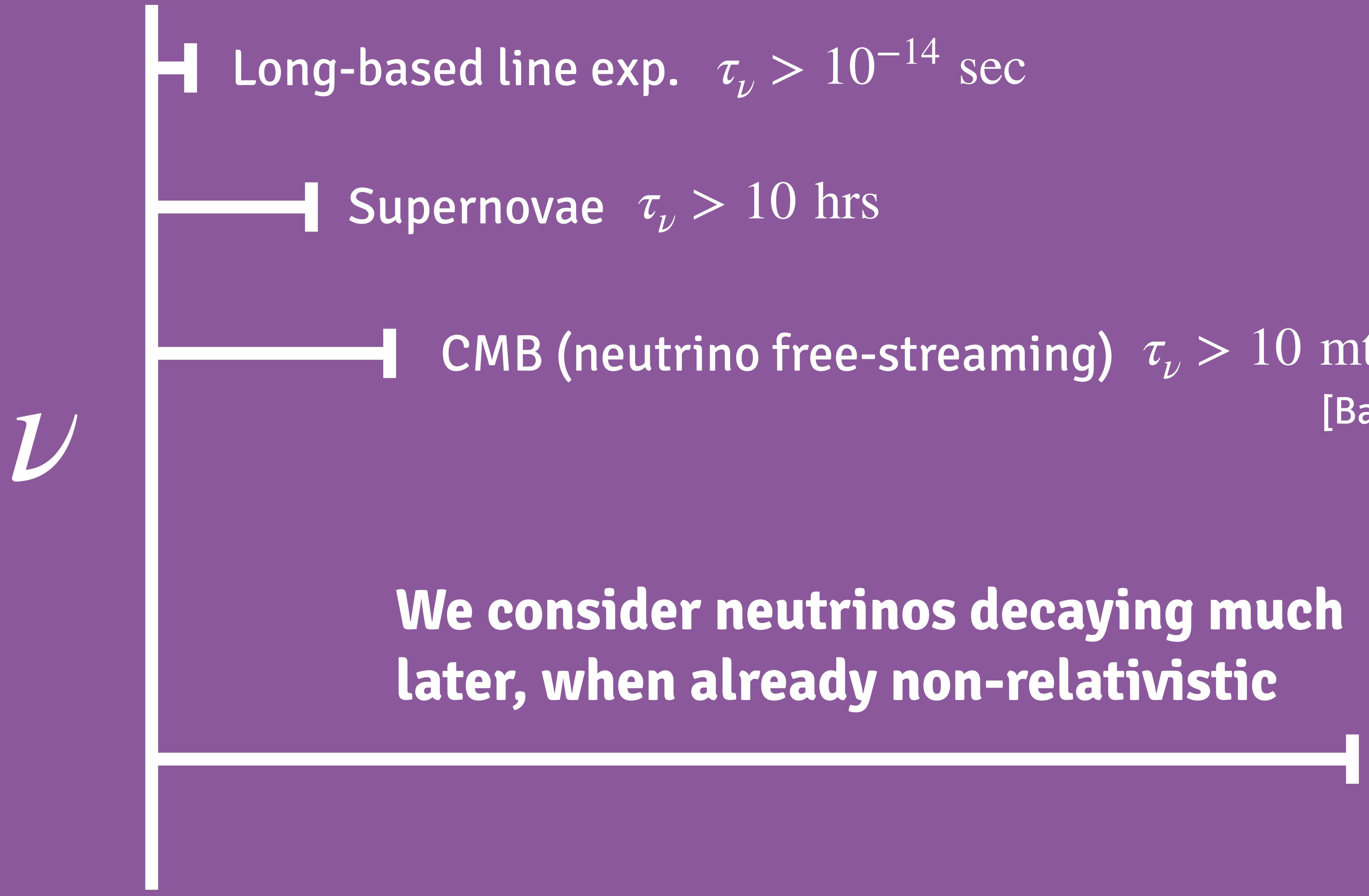
Long-based line exp. $\tau_\nu > 10^{-14}$ sec

Supernovae $\tau_\nu > 10$ hrs

CMB (neutrino free-streaming) $\tau_\nu > 10$ mths

[Barenboim+ 20]

Lifetime bounds on invisible neutrino decays



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Supernovae $\tau_\nu > 10$ hrs

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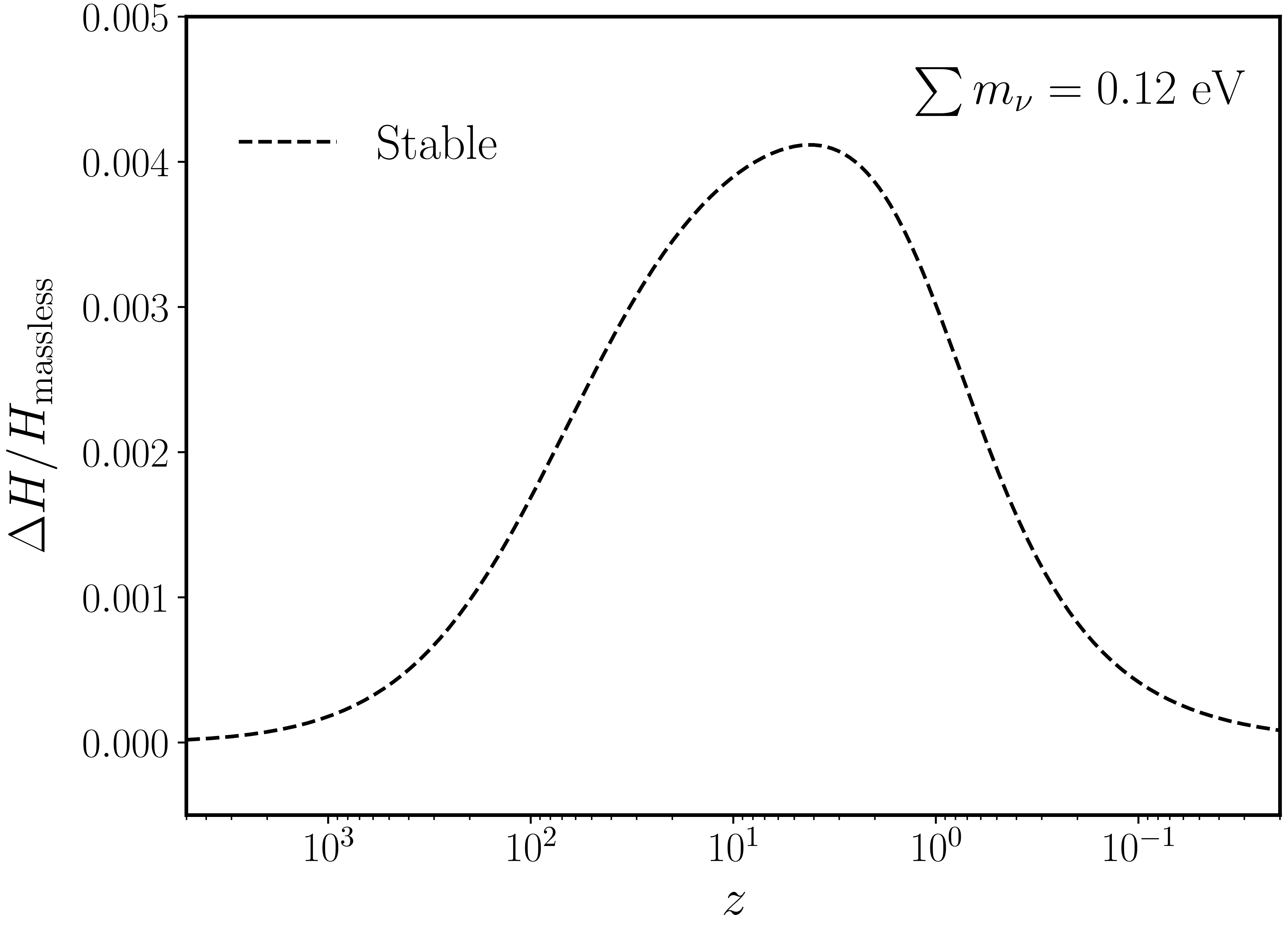
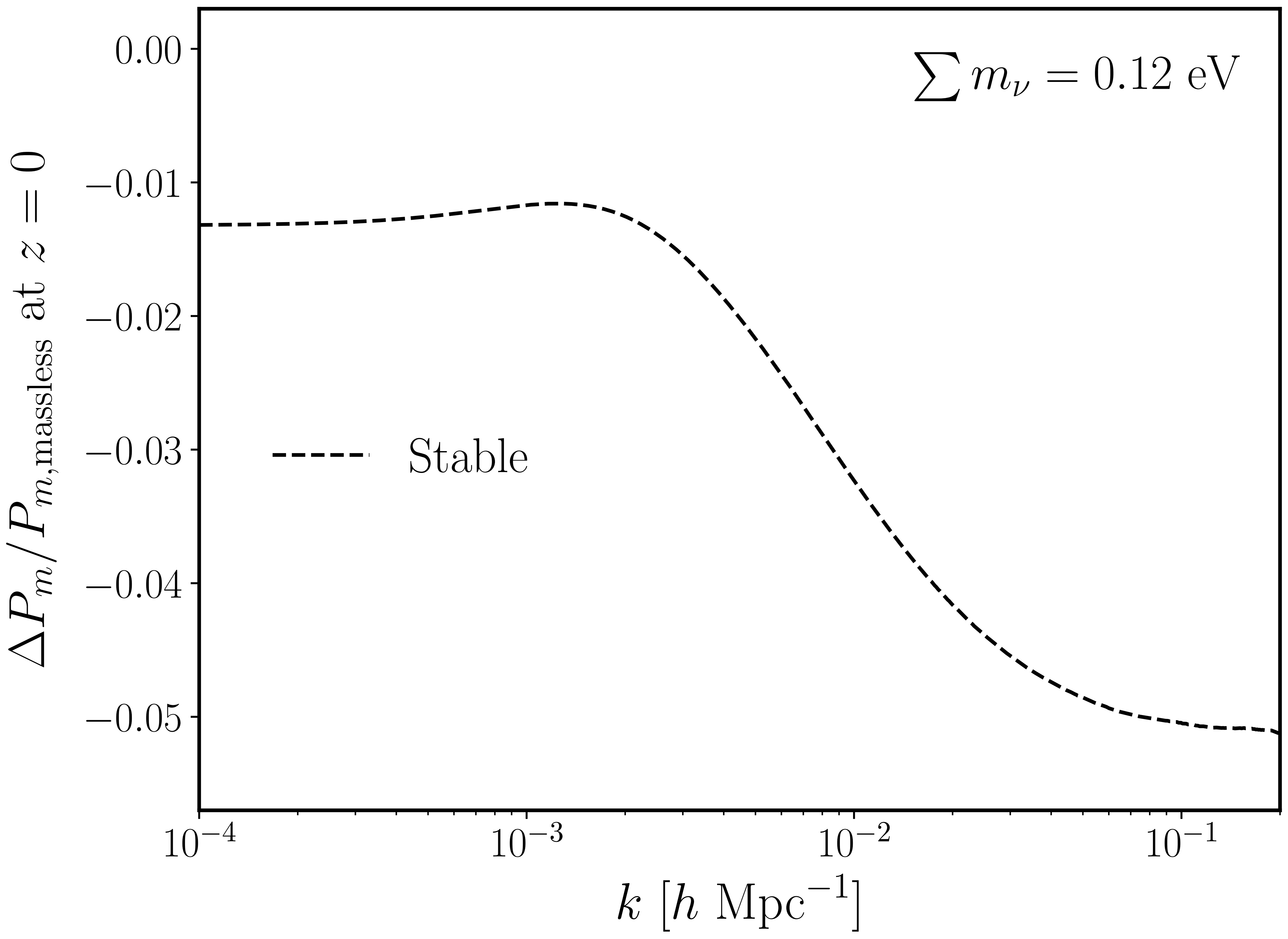
[Barenboim+ 20]

We consider neutrinos decaying much later, when already non-relativistic

How can unstable neutrinos relax mass bounds?





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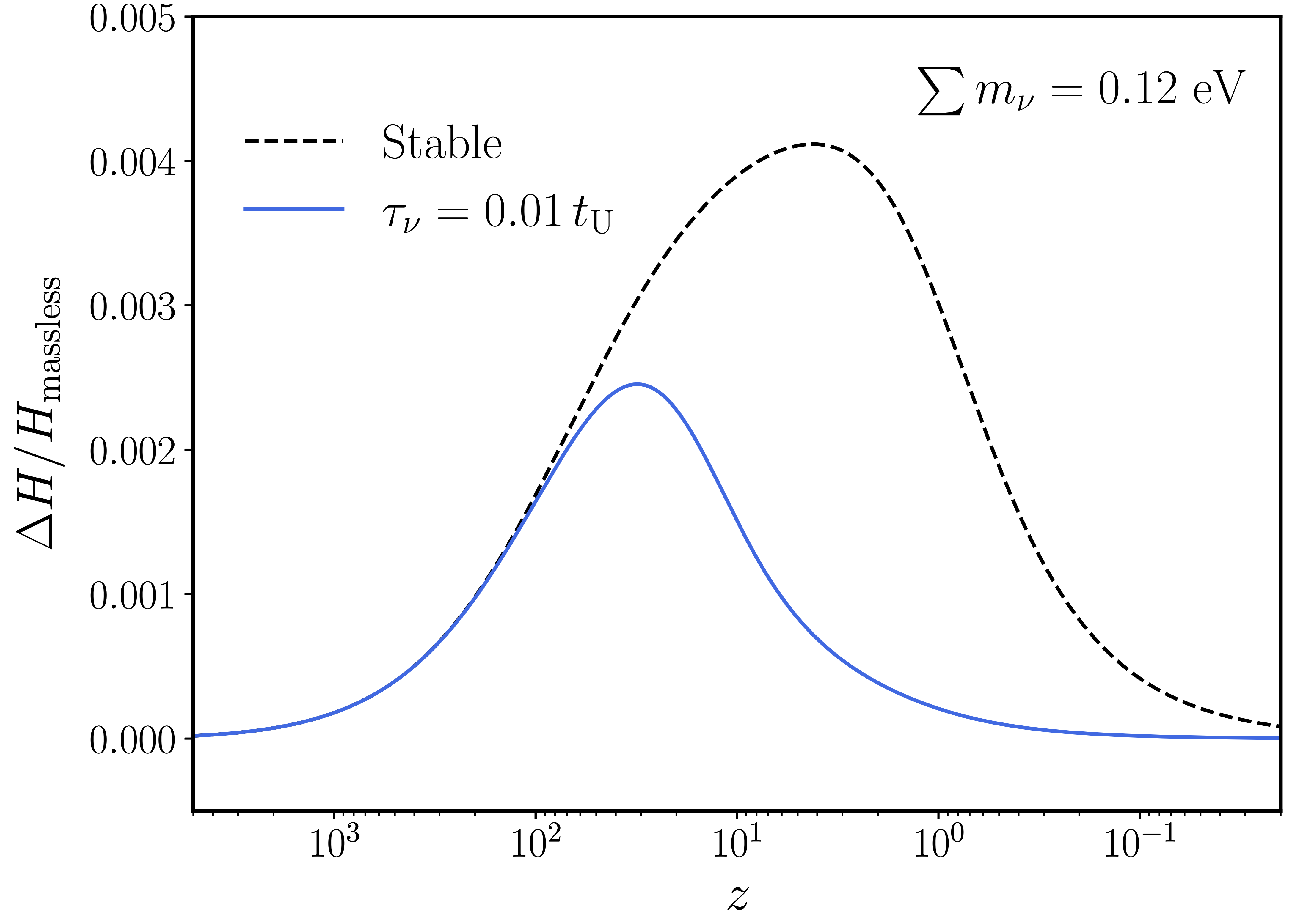
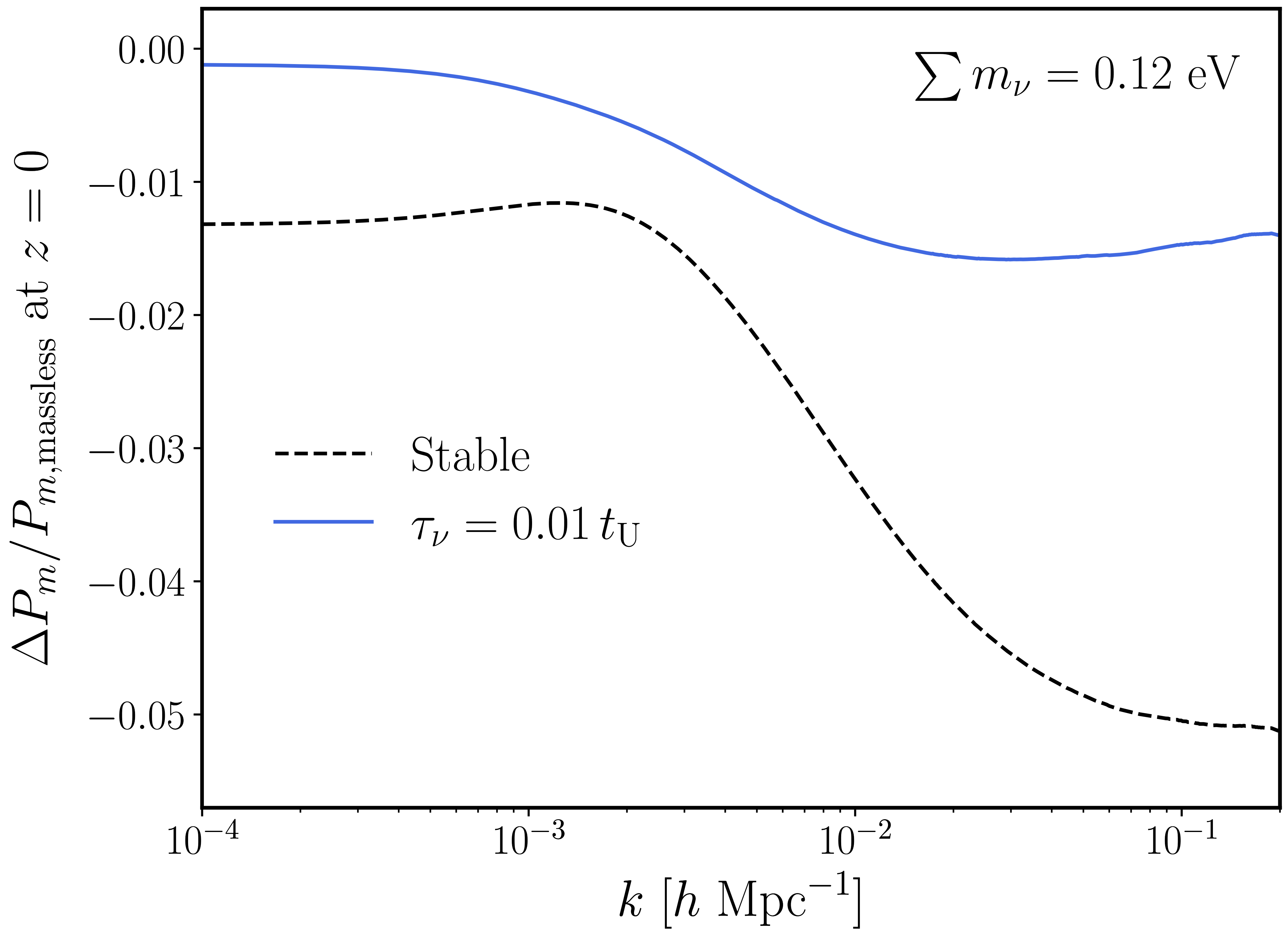
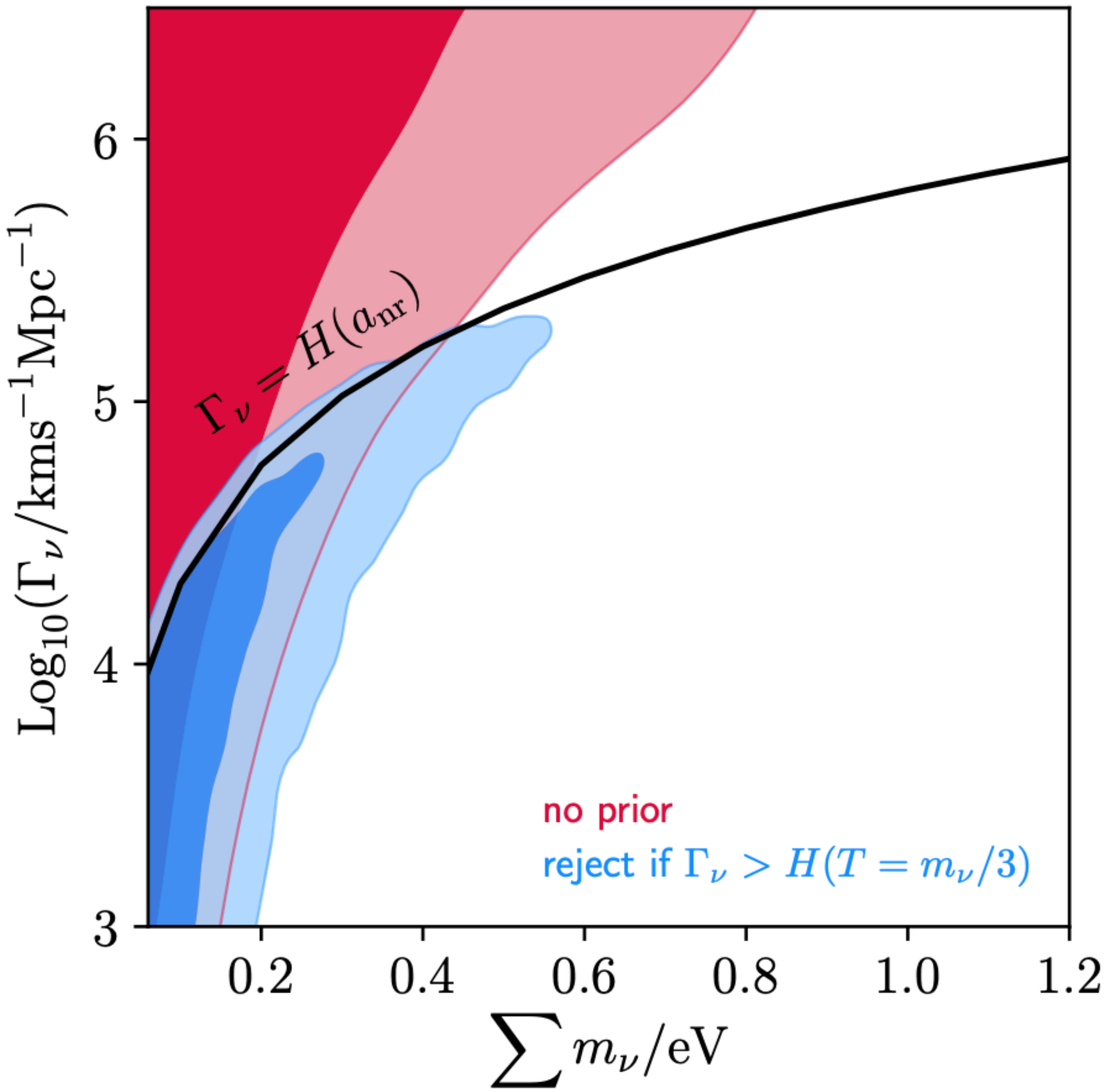




Decays $\nu_i \rightarrow \nu_4 + \phi$ reduce the impact of massive neutrinos on $H(z)$ and $P_m(k)$



Back in 2021, we showed that non-relativistic neutrino decays to DR can relax mass bounds up to:

$\sum m_\nu < 0.42$ eV (BOSS BAO + SNIa + CMB)

[GFA, Poulin++ 21]

Revisiting invisible neutrino decays

1. Update mass and lifetime bounds in light of latest DESI DR2 BAO data

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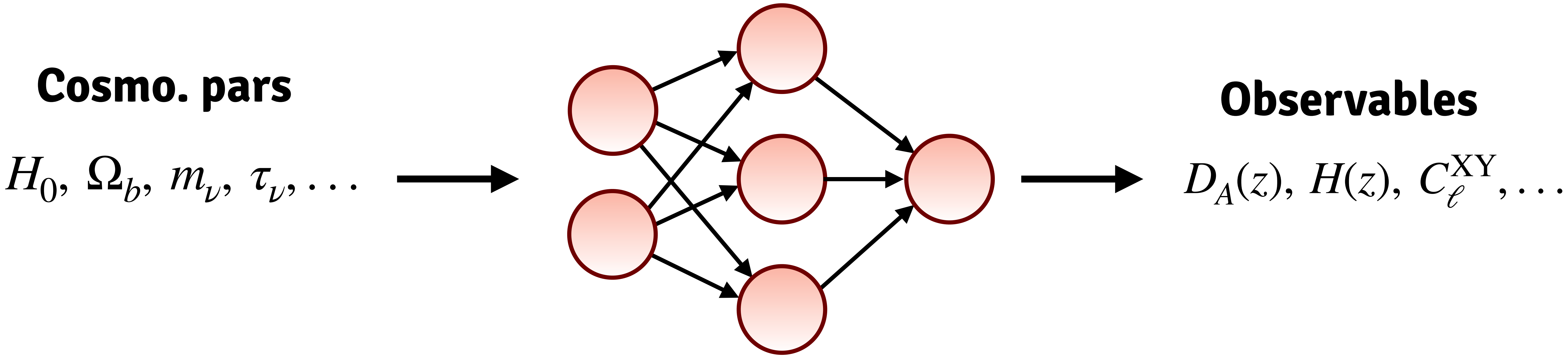
(Boltzmann eqs. implemented in a new CLASS version)

3. Accelerate CLASS predictions with a neural network emulator (CONNECT)

[Nygaard++ 22]

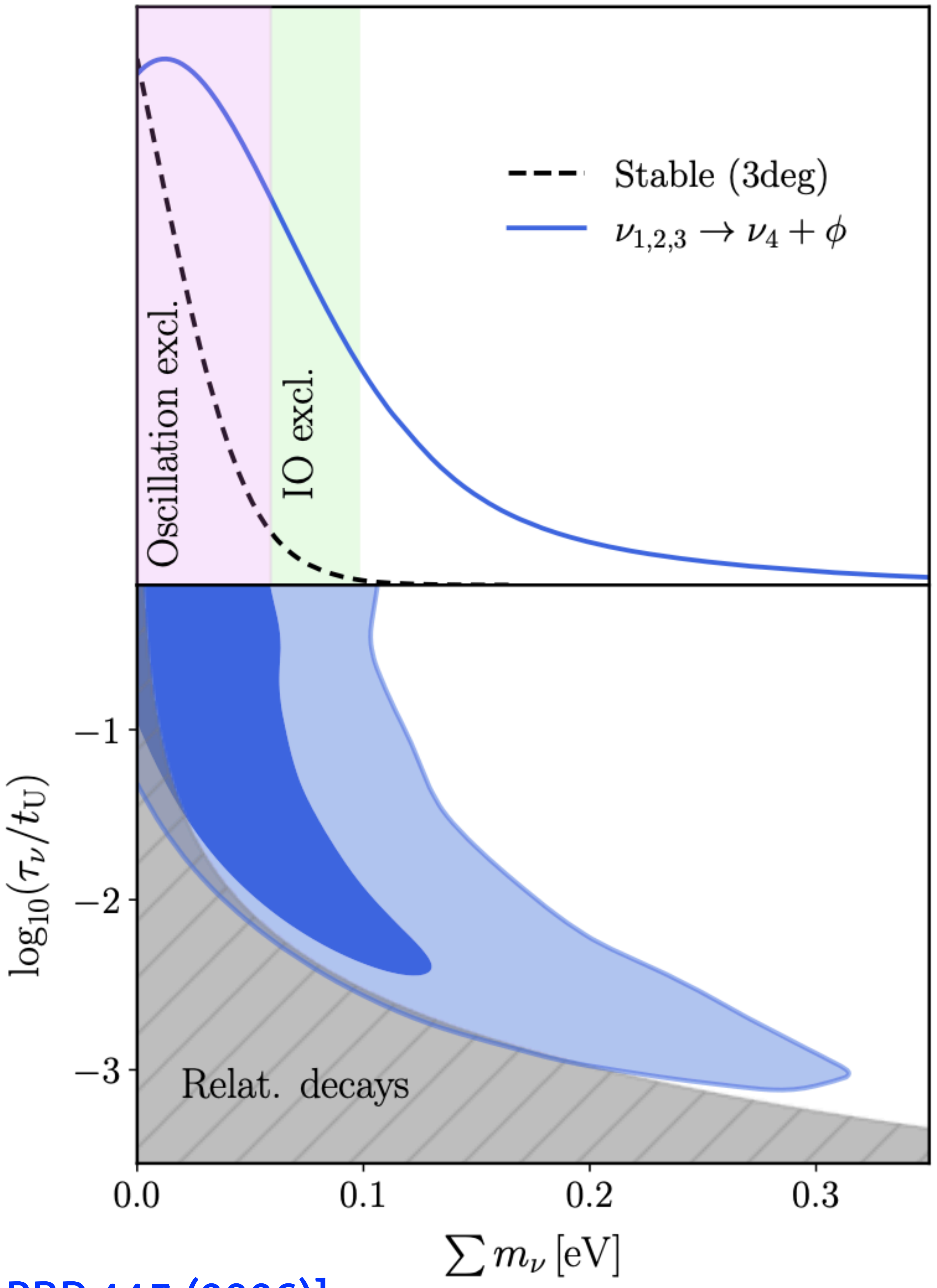

Cosmo. pars

$H_0,\ \Omega_b,\ m_\nu,\ \tau_\nu, \ldots$

Observables

$D_A(z),\ H(z),\ C_\ell^{\rm XY}, \ldots$

Updated mass bound for decays into dark radiation



$$\boxed{\sum m_\nu < 0.24 \text{ eV}}$$

(DESI DR2 BAO + CMB)

[**GFA**, PRD 113 (2026)]

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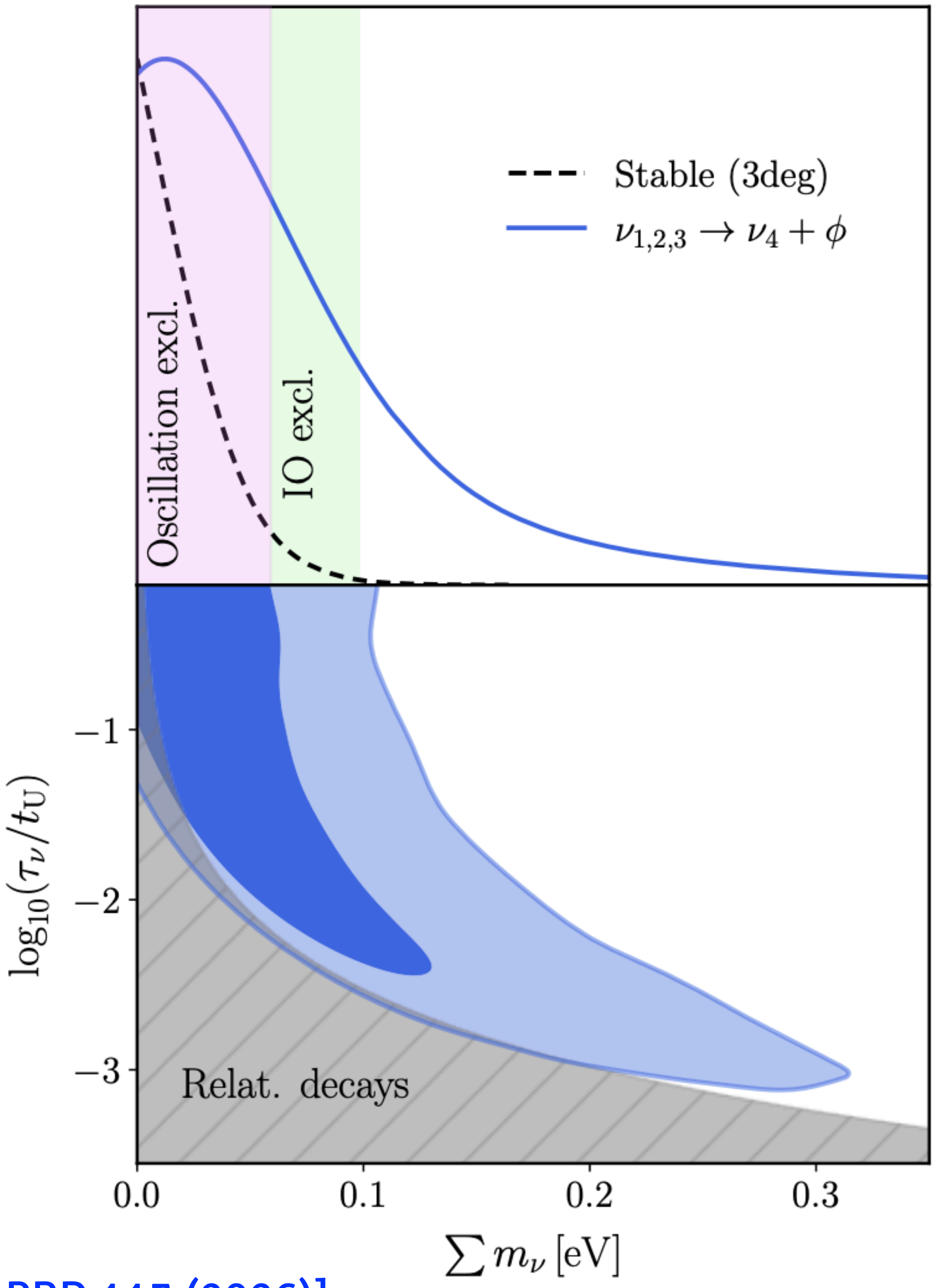

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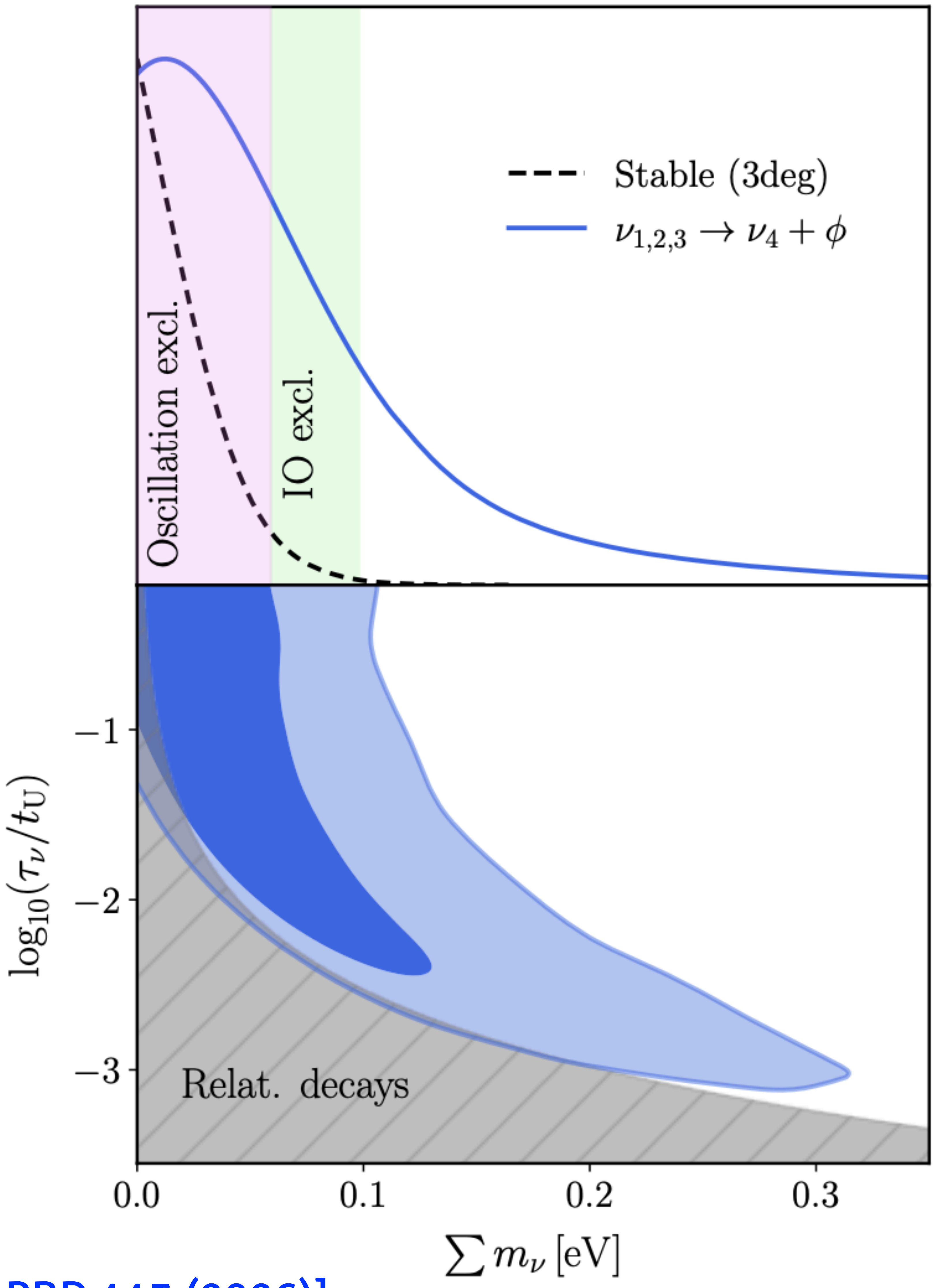
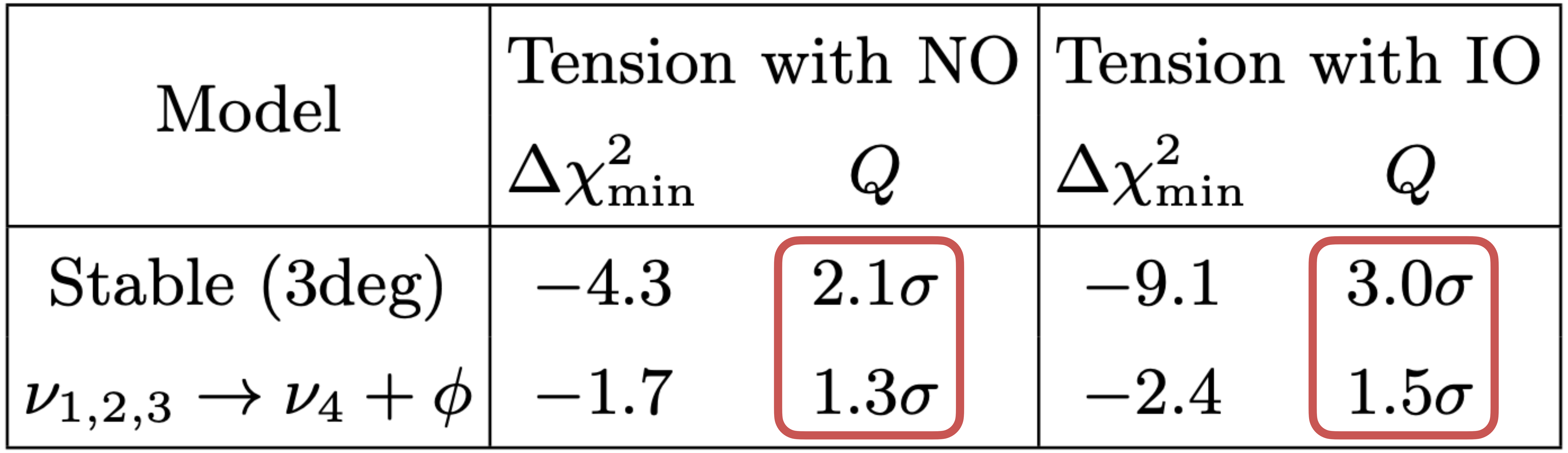


$$\boxed{\sum m_\nu < 0.24\ \mathrm{eV}}$$ (DESI DR2 BAO + CMB)

- Bound is ×2 stronger than old analysis (cosmology now leaves little room for large m_ν)
- Still a significant relaxation, fully restores agreement with oscillation data

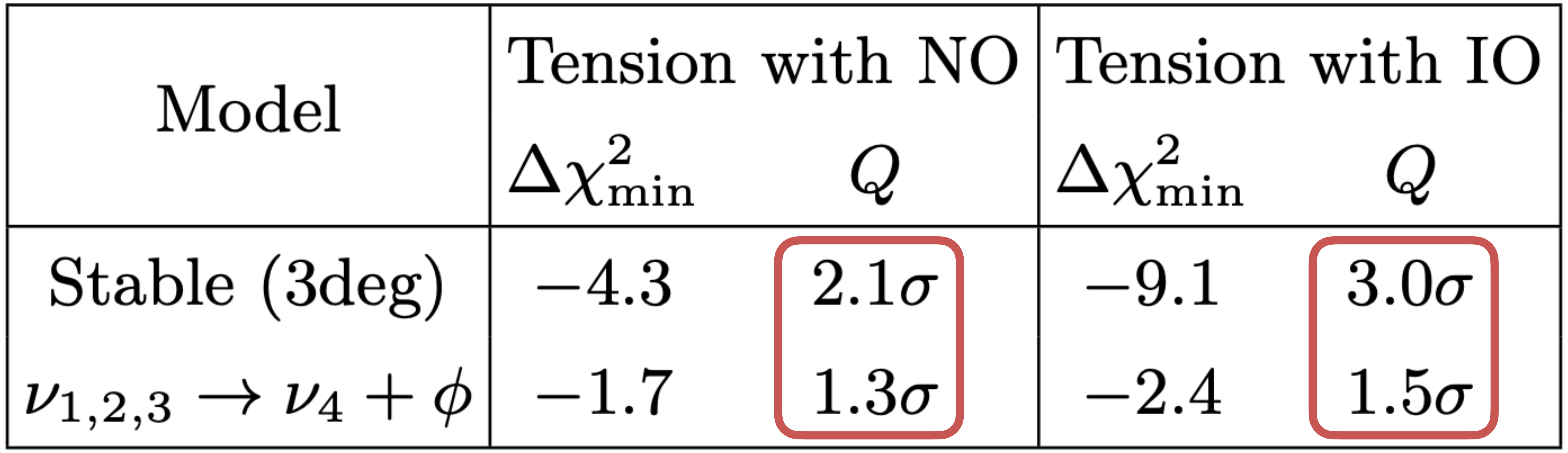
[**GFA**, PRD 113 (2026)]



Model	Tension with NO		Tension with IO	
	$\Delta\chi^2_{\min}$	Q	$\Delta\chi^2_{\min}$	Q
Stable (3deg)	-4.3	2.1σ	-9.1	3.0σ
$\nu_{1,2,3} \to \nu_4 + \phi$	-1.7	1.3σ	-2.4	1.5σ

[**GFA**, PRD 113 (2026)]

$$\Delta\chi^2_{\min} = \chi^2_{\min}\left(\sum m_\nu \text{ free}\right) - \chi^2_{\min}\left(\sum m_\nu = 0.06/0.1 \text{ eV}\right)$$



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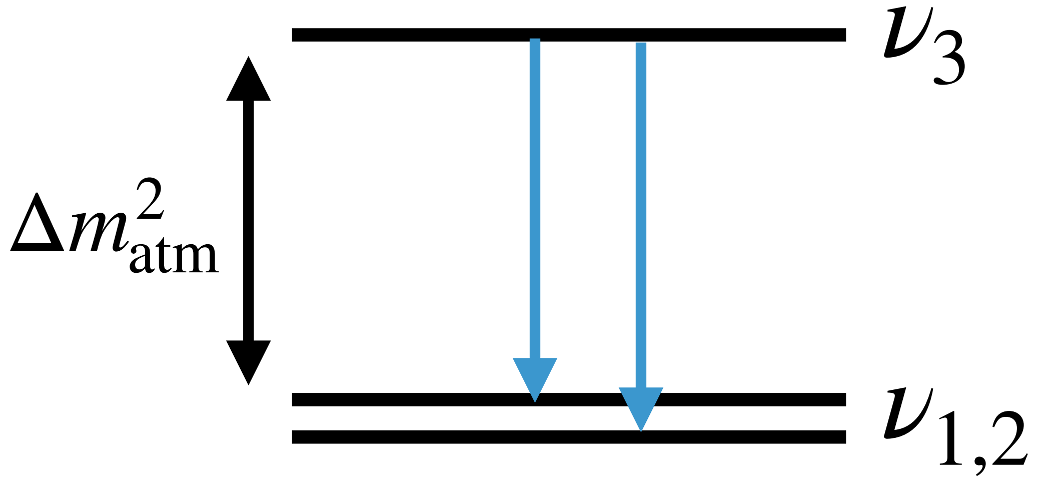
[**GFA**, PRD 113 (2026)]

NOTE: Despite solving the tension, $\sum m_\nu$ is **not** detected (decays cannot mimic $\sum m_{\nu,\rm eff} < 0$, but they provide a better-motivated alternative)

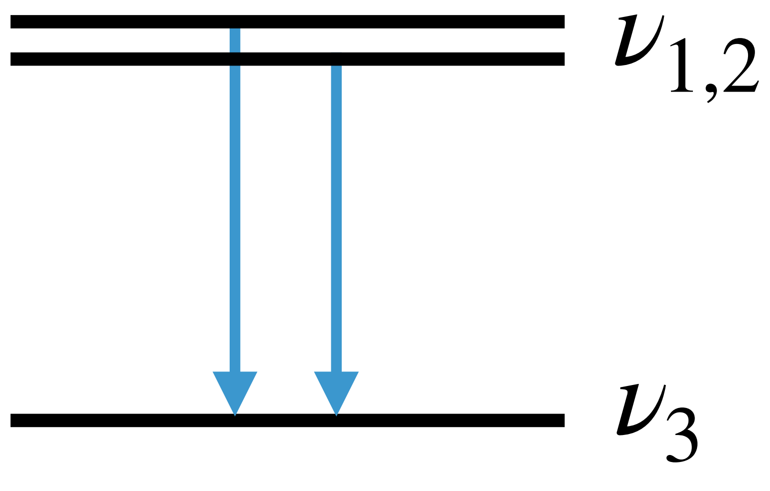
$$\Delta\chi^2_{\rm min} = \chi^2_{\rm min}(\sum m_\nu \text{ free}) - \chi^2_{\rm min}\left(\sum m_\nu = 0.06/0.1 \text{ eV}\right)$$

First late-time analysis of decays into lighter neutrinos

- Two-decay channels with **atmospheric gap**:



Normal ($\sum m_\nu \geq 0.05\,\mathrm{eV}$)



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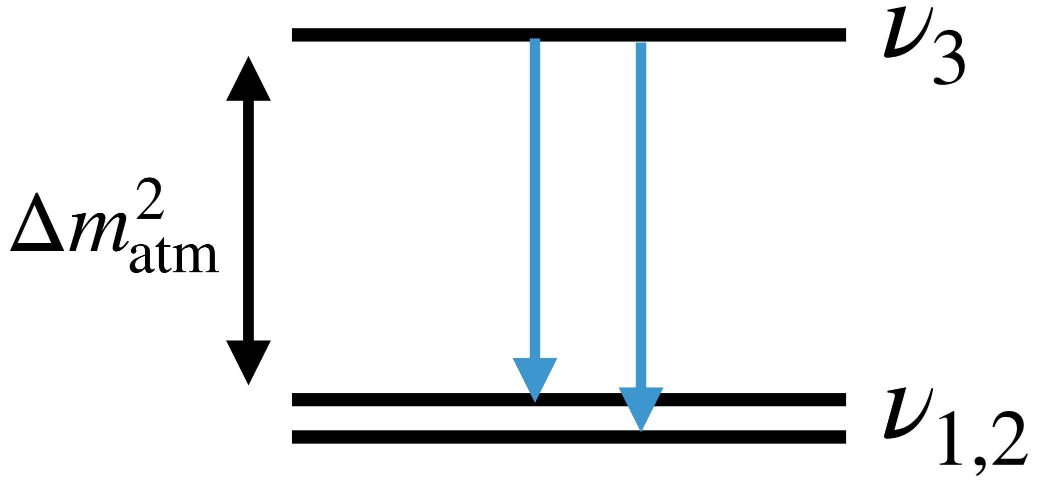

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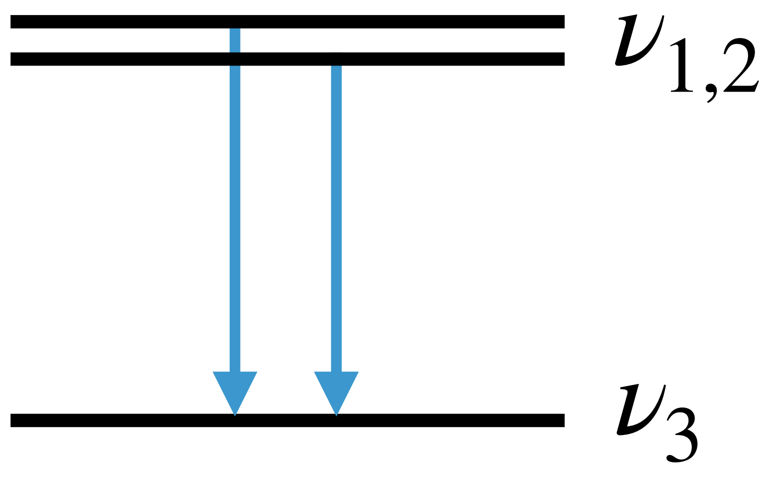

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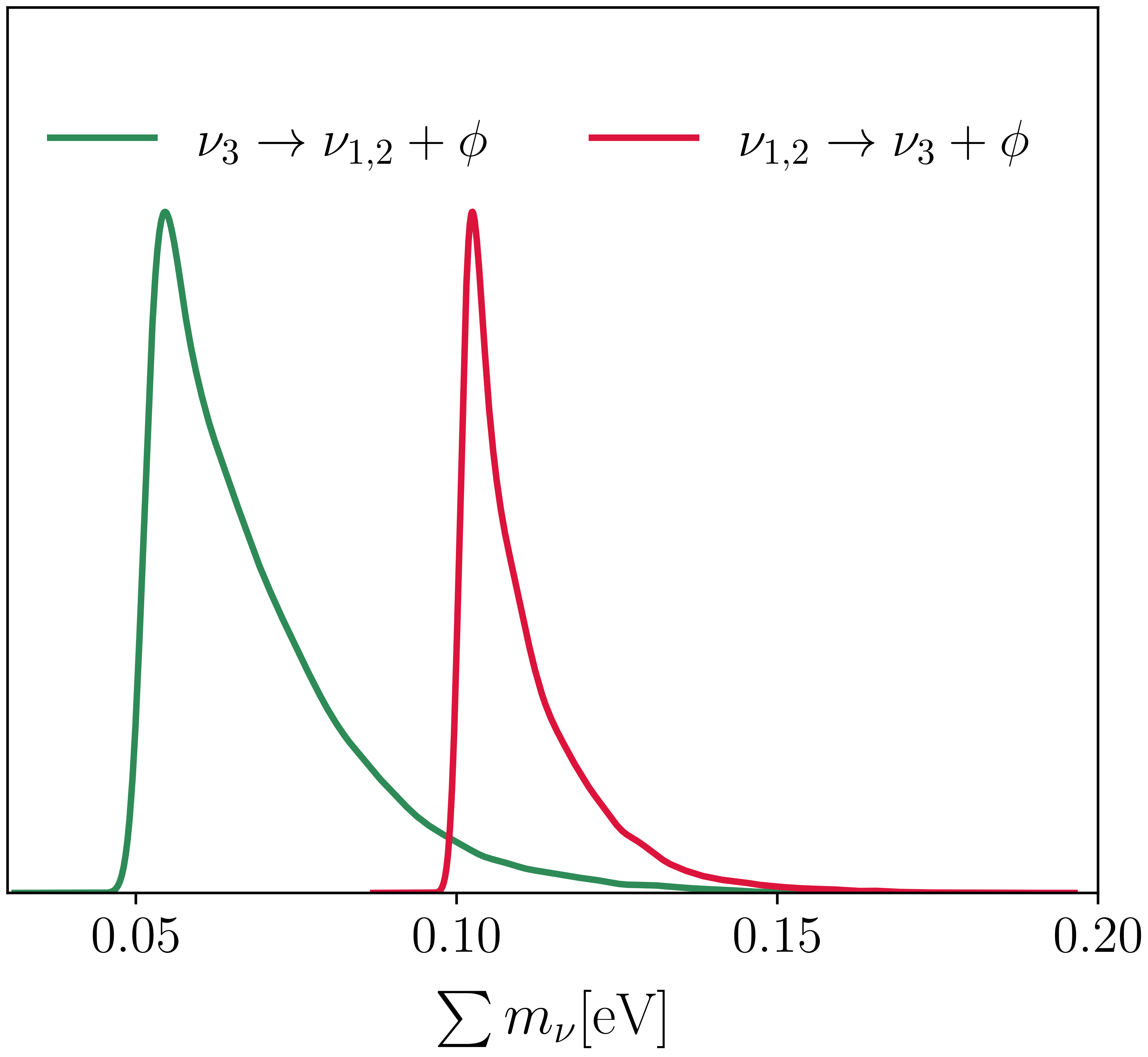
(DESI DR2 BAO + CMB)



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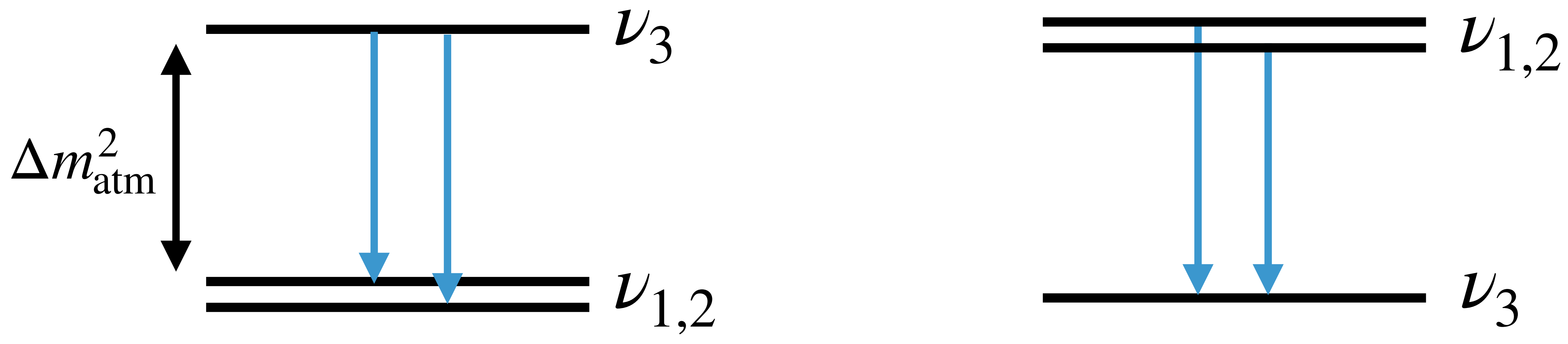
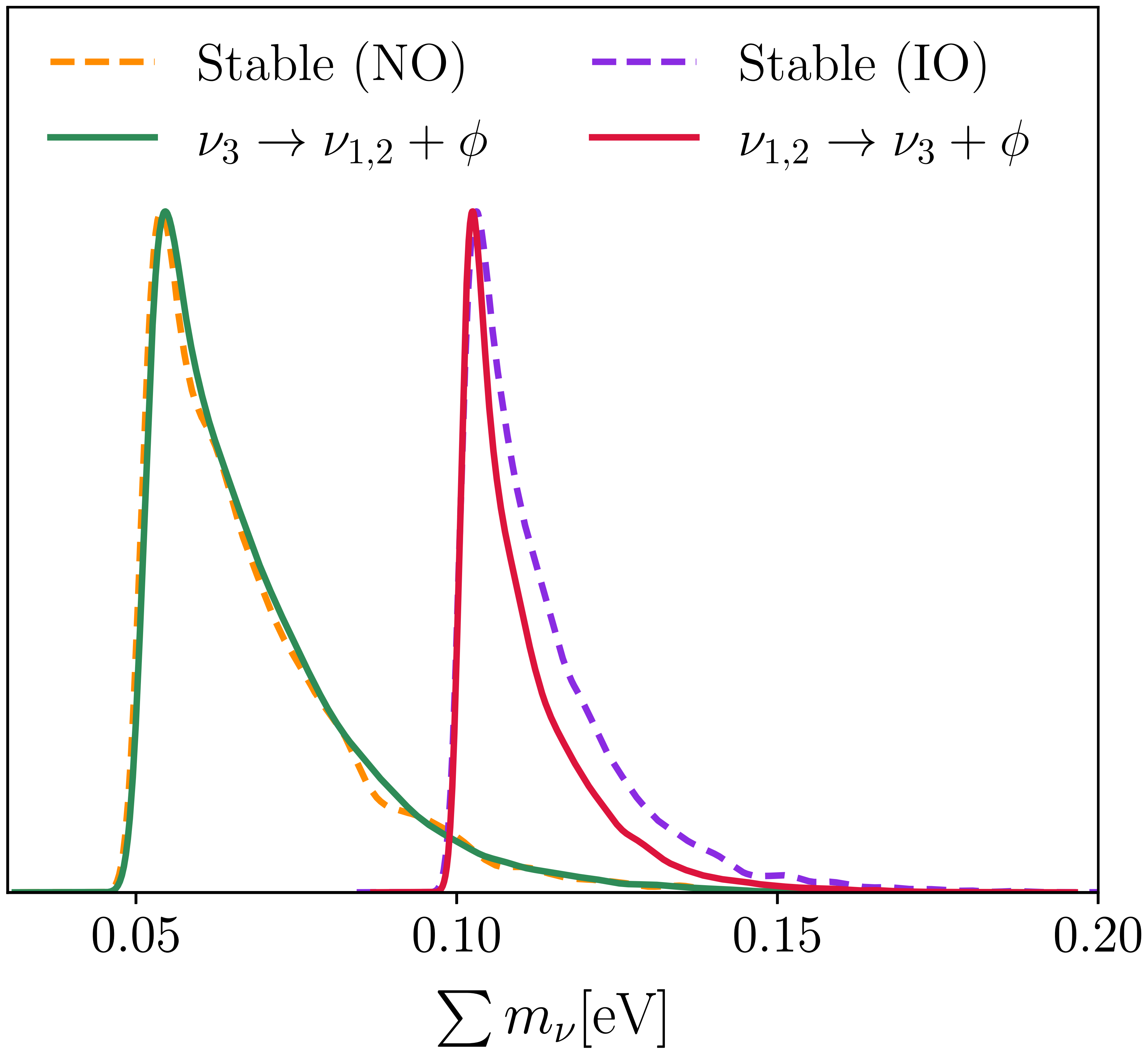


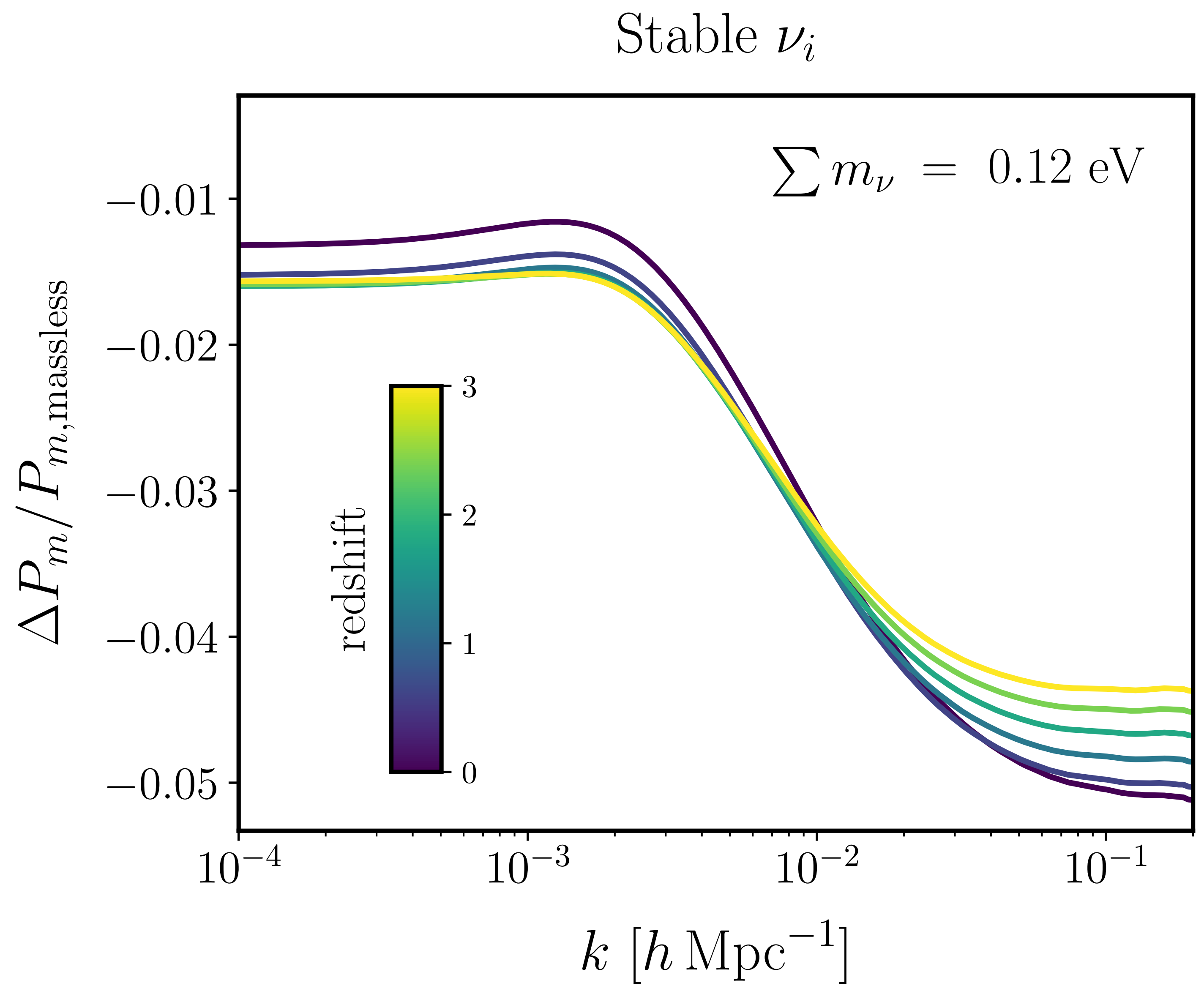
Normal ($\sum m_\nu \geq 0.05\,\mathrm{eV}$) **Inverted** ($\sum m_\nu \geq 0.1\,\mathrm{eV}$)

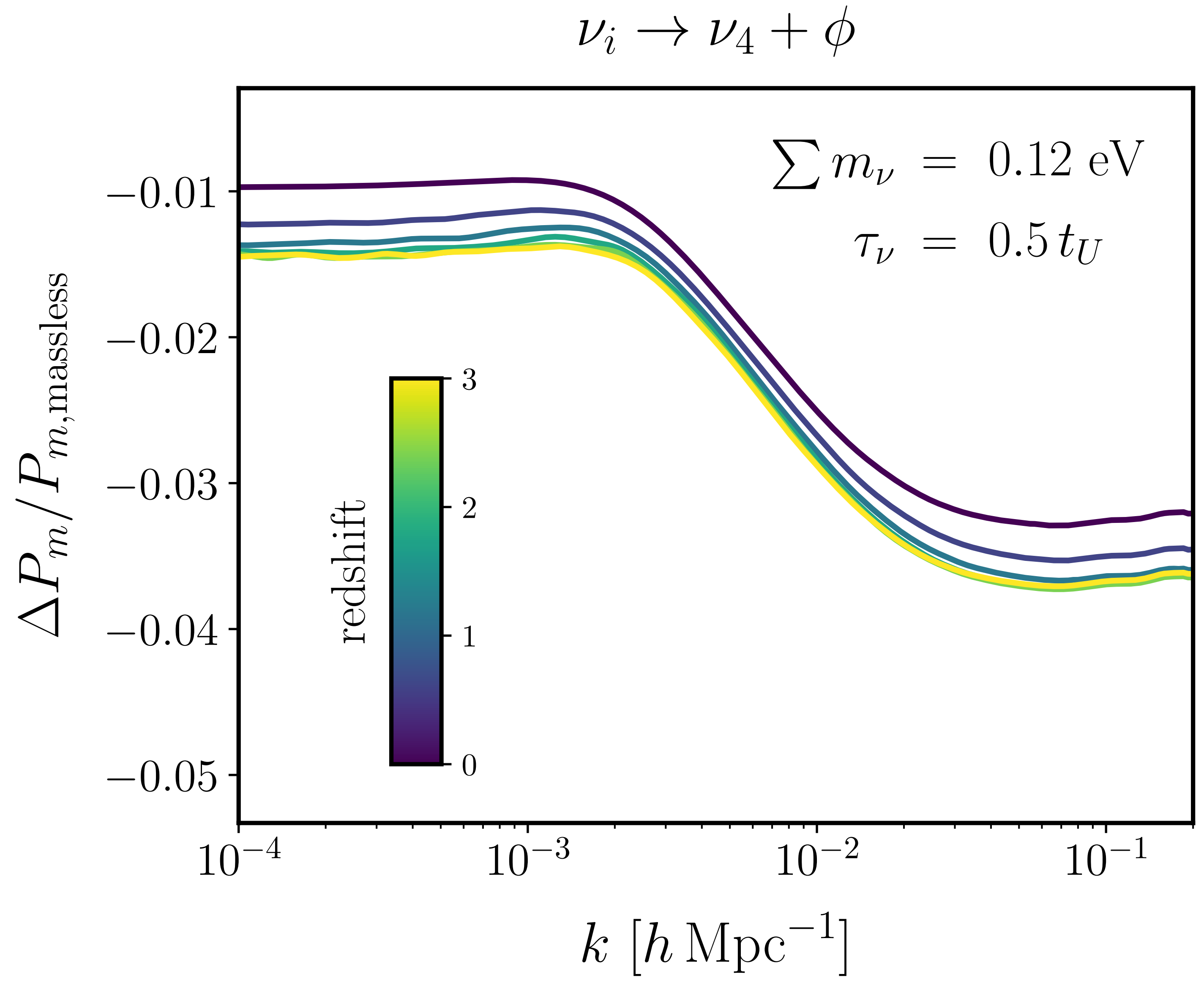
- These decays barely relax the neutrino mass bound, and can even tighten it

(DESI DR2 BAO + CMB)



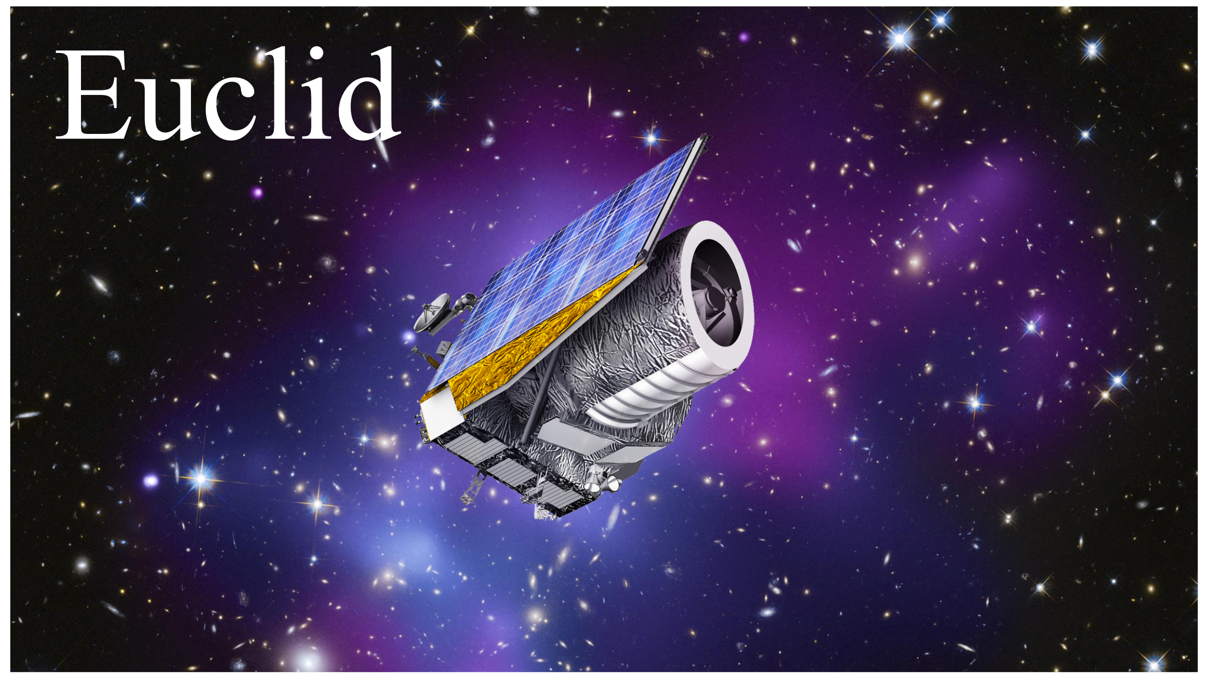
[**GFA**, PRD 113 (2026)]


Stable ν_i


$\nu_i \to \nu_4 + \phi$

Upcoming tomographic weak-lensing surveys may enable an independent determination of neutrino mass and lifetime

[Chacko, Poulin++ 20]



A future laboratory detection of the Cosmic Neutrino Background (CνB) would have profound implications for neutrino decays

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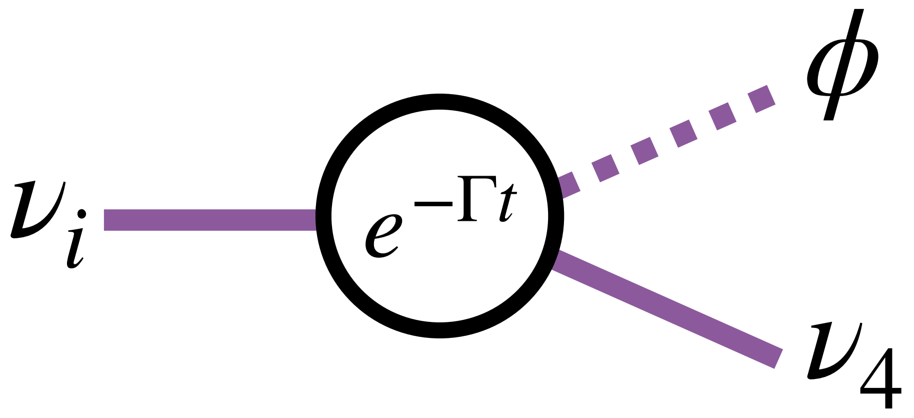
- Rule out decays to dark radiation with $\tau_\nu < t_U$



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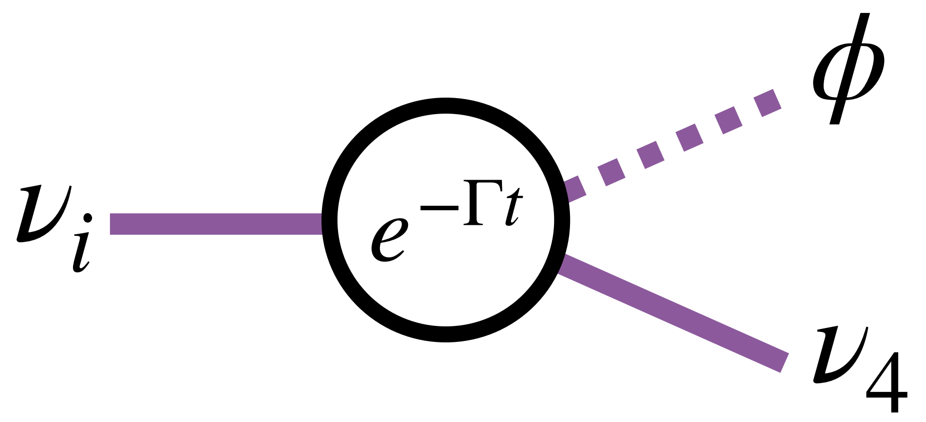
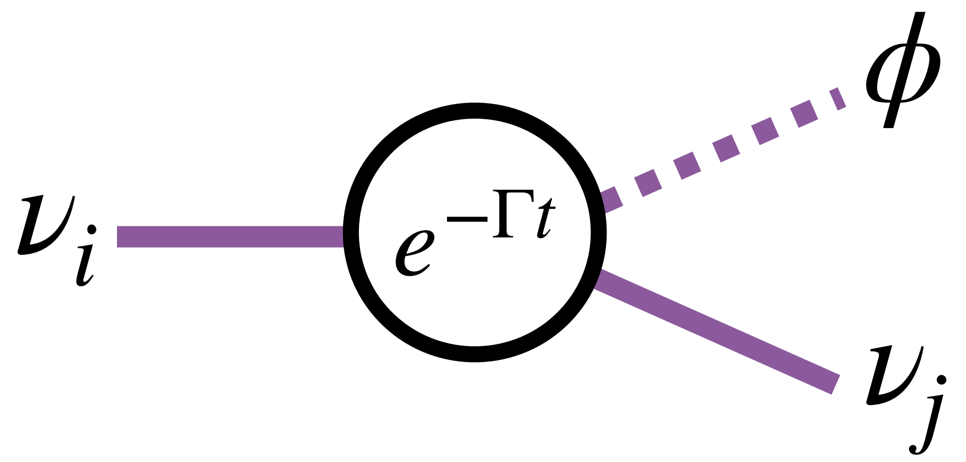
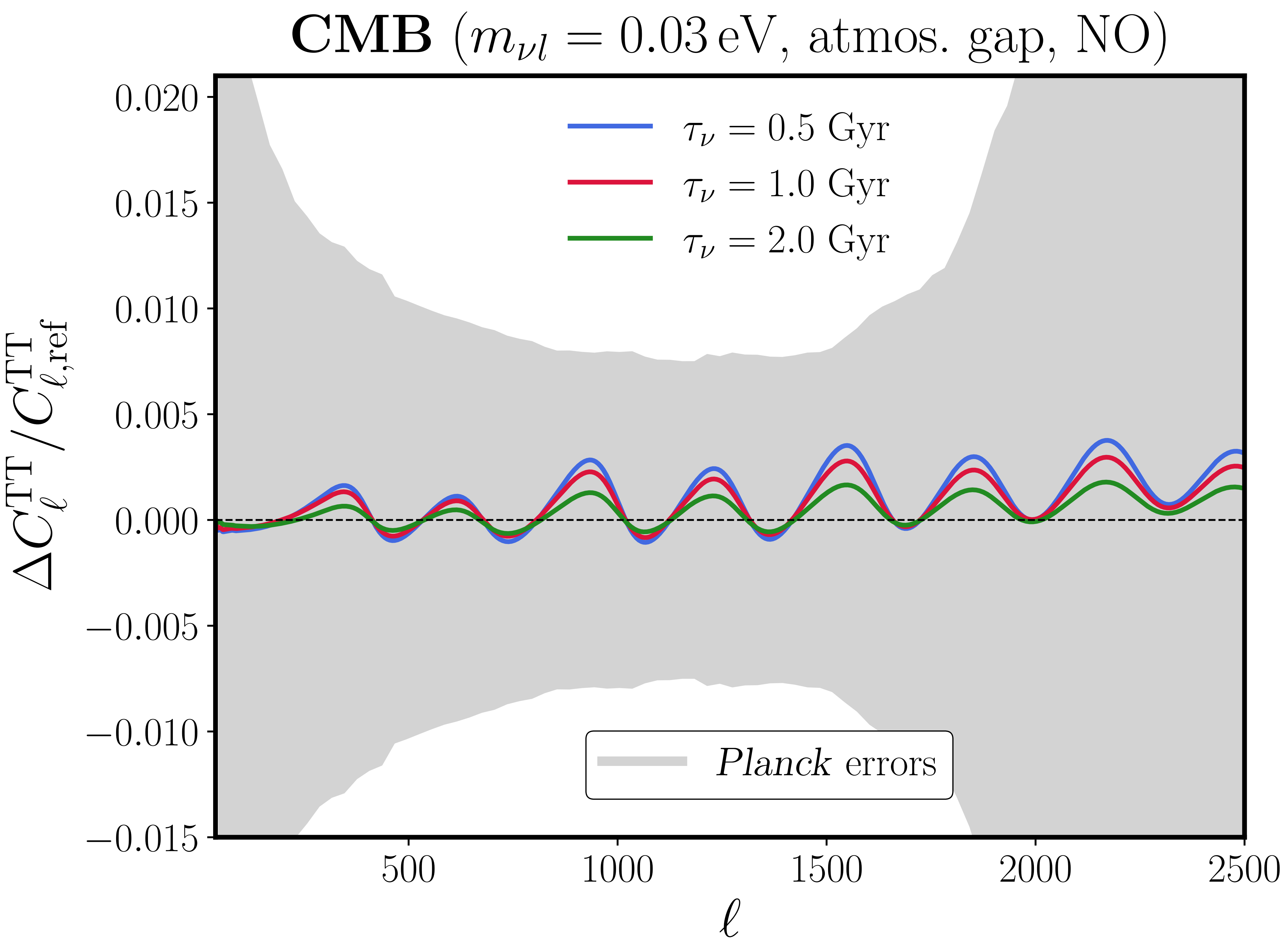
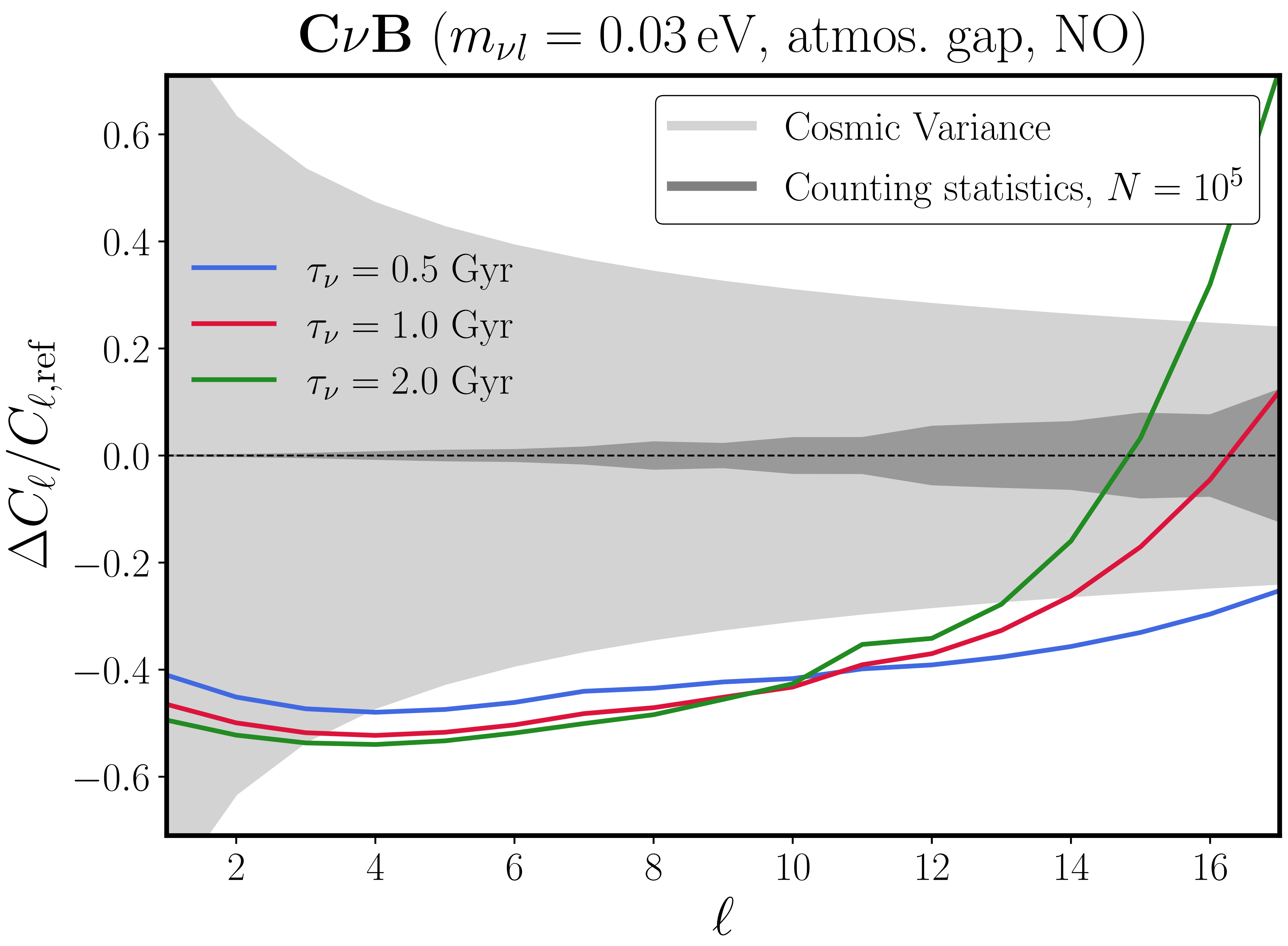


- Constrain decays to lighter neutrinos with $\tau_\nu \sim t_U$



Impact of neutrino decays on CMB and CνB anisotropies





[Terzaghi, **GFA**++ 25]

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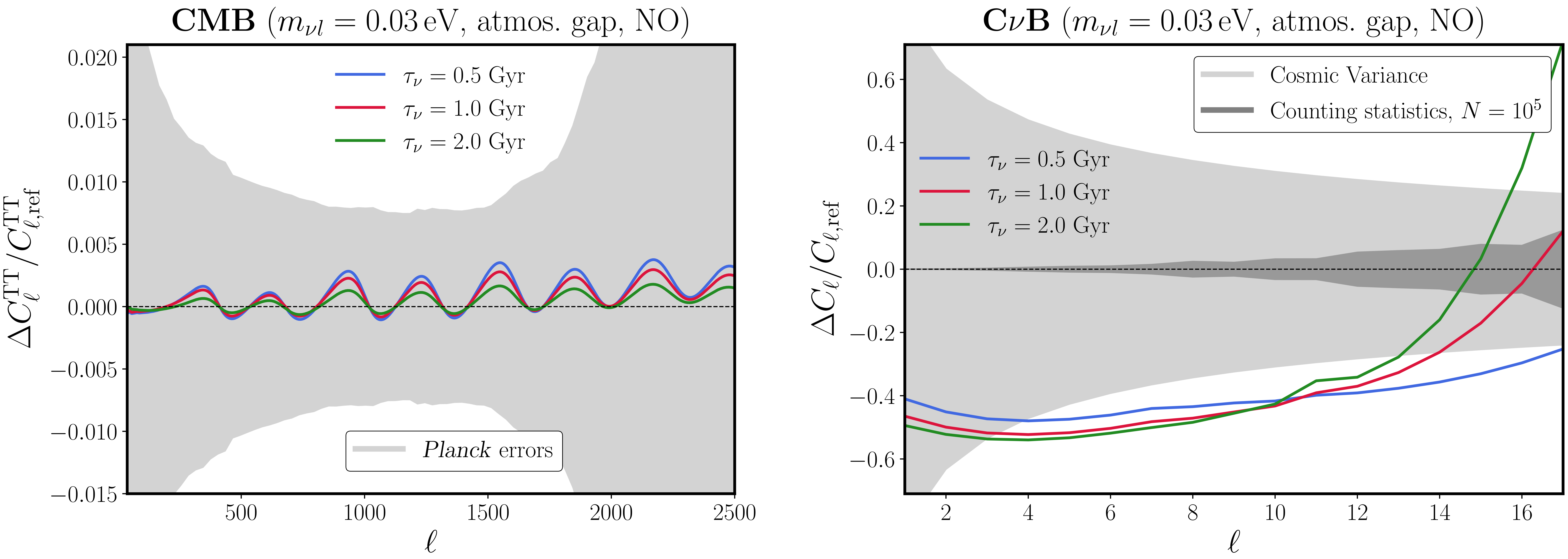


[Terzaghi, **GFA**++ 25]

Decay models that are currently undetectable by the CMB can leave **HUGE** imprints on the CνB

Main takeaways

- Neutrino decays to DR provide a theoretically well-motivated framework to resolve the tension between oscillation and CMB+BAO data ($\sum m_\nu < 0.24$ eV)
- Neutrino decays to lighter neutrinos yield a negligible relaxation (or even a tightening) of the mass bounds
- Upcoming LSS surveys (Euclid, LSST) and futuristic CvB measurements will allow to further test these models

THANK YOU!

g.francoabellan@ific.uv.es

BACK-UP

Boltzmann eqs. for ν_H, ν_L and ϕ

Heavier neutrino

$$\frac{\partial \bar{f}_{\nu_H}(q_1)}{\partial \tau} = -\frac{a^2 m_{\nu \mathrm{H}} \Gamma}{\epsilon_1} \bar{f}_{\nu_H}(q_1)$$

\+ Boltzmann hierarchy for linear perts.

Lighter neutrino

$$\frac{\partial \bar{f}_{\nu_L}(q_2)}{\partial \tau} = \frac{a^2 \Gamma}{\epsilon_2 q_2} \frac{m_{\nu \mathrm{H}}^3}{\left(m_{\nu \mathrm{H}}^2 - m_{\nu \mathrm{L}}^2\right)} \int_{q_{1-}}^{q_{1+}} dq_1 \frac{q_1}{\epsilon_1} \bar{f}_{\nu_H}(q_1)$$

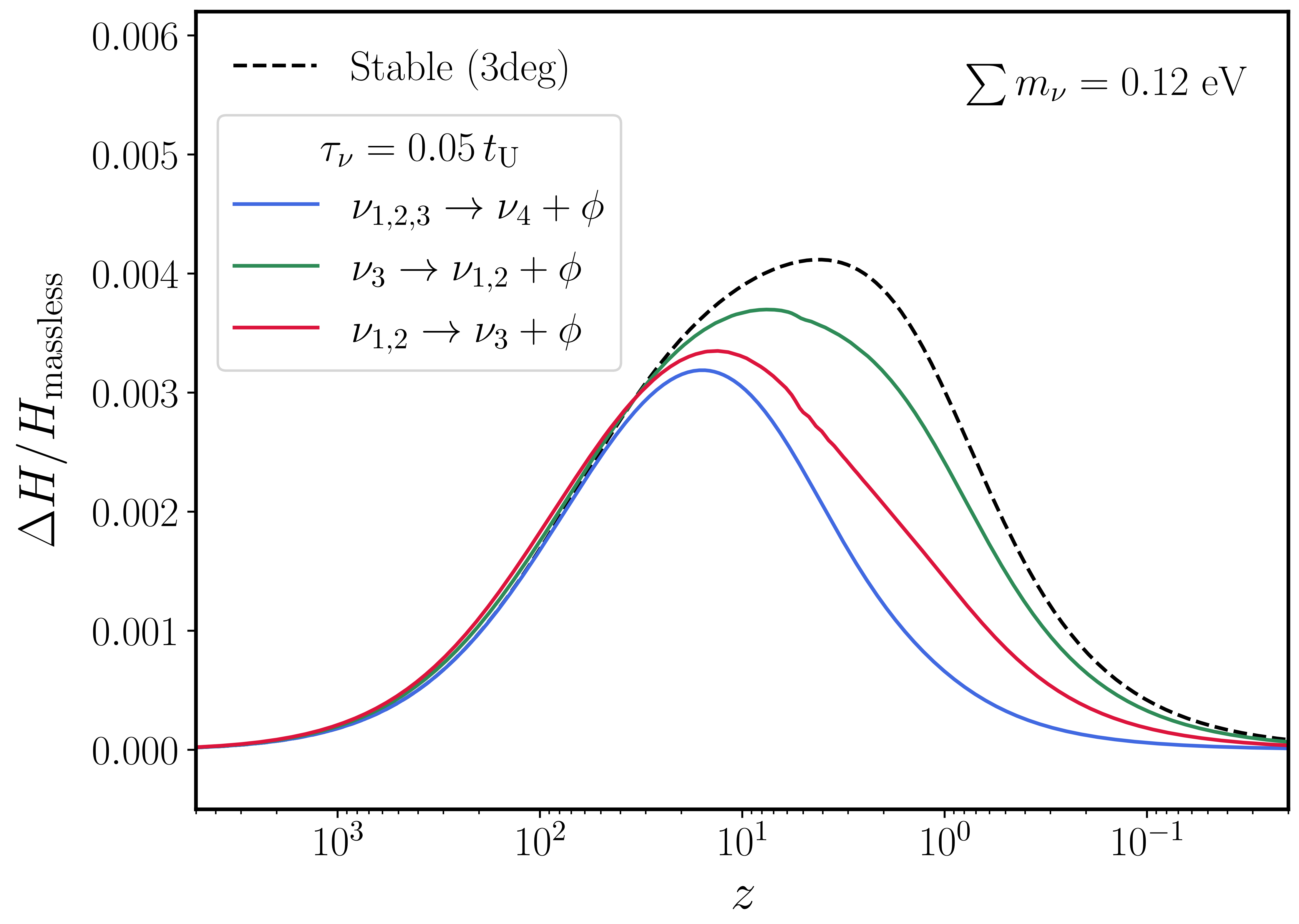
\+ Boltzmann hierarchy for linear perts.

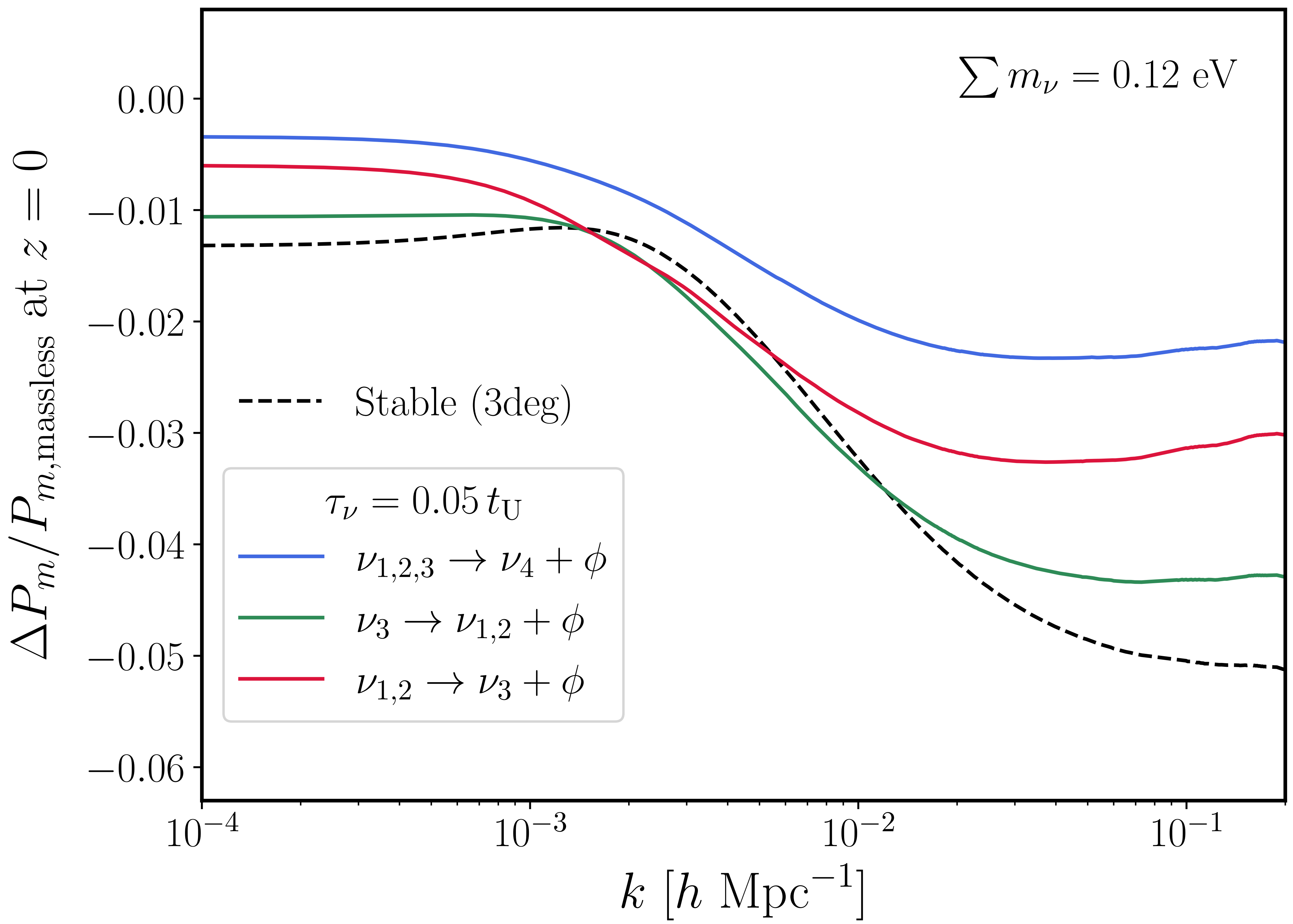
Massless scalar (behaves as **DR fluid**)

$$\frac{d\rho_{\mathrm{dr}}}{d\tau} + 4aH\rho_{\mathrm{dr}} = \varepsilon a \Gamma m_{\nu_H} n_{\nu_H}$$

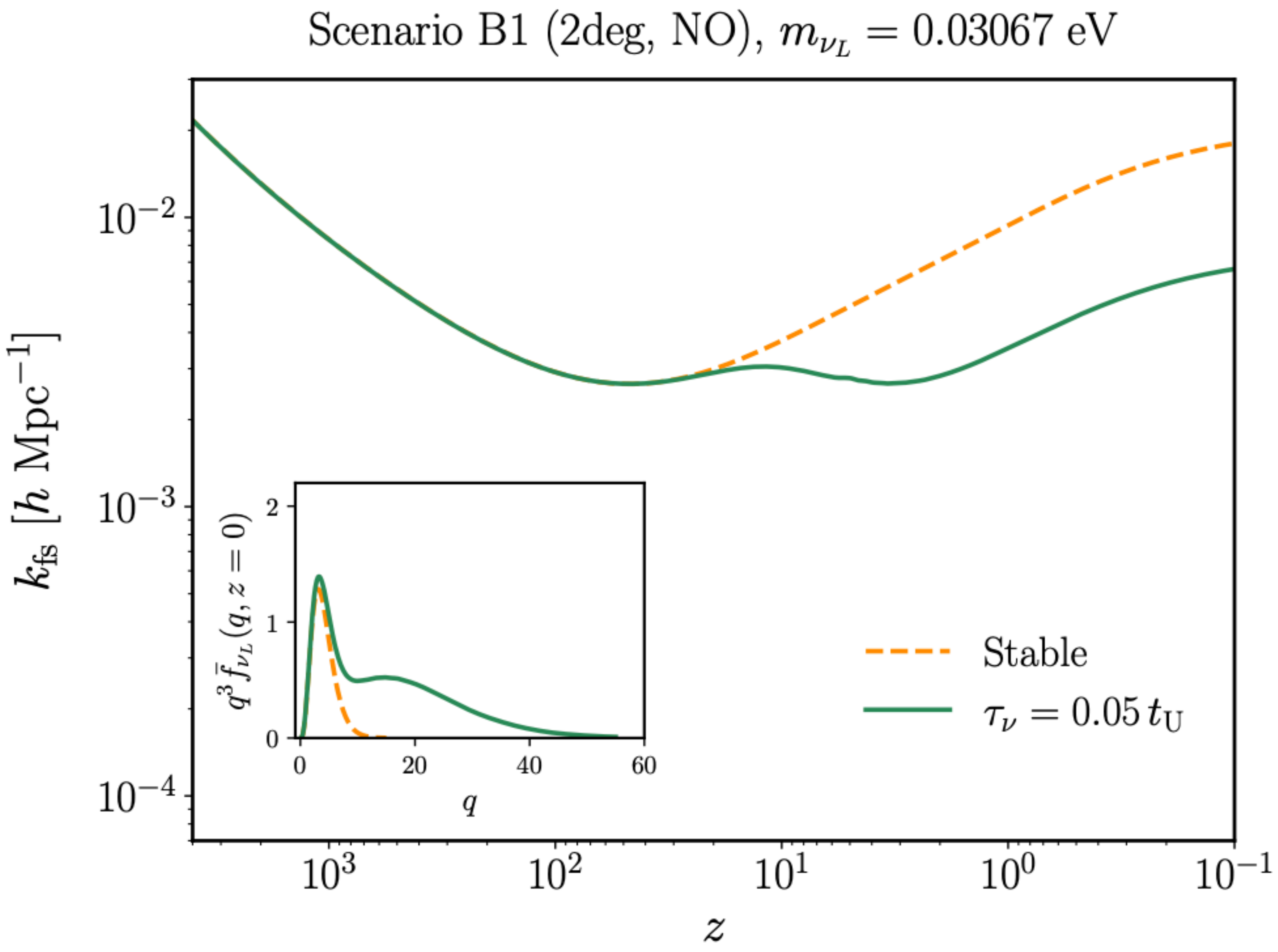
\+ Boltzmann hierarchy for linear perts.

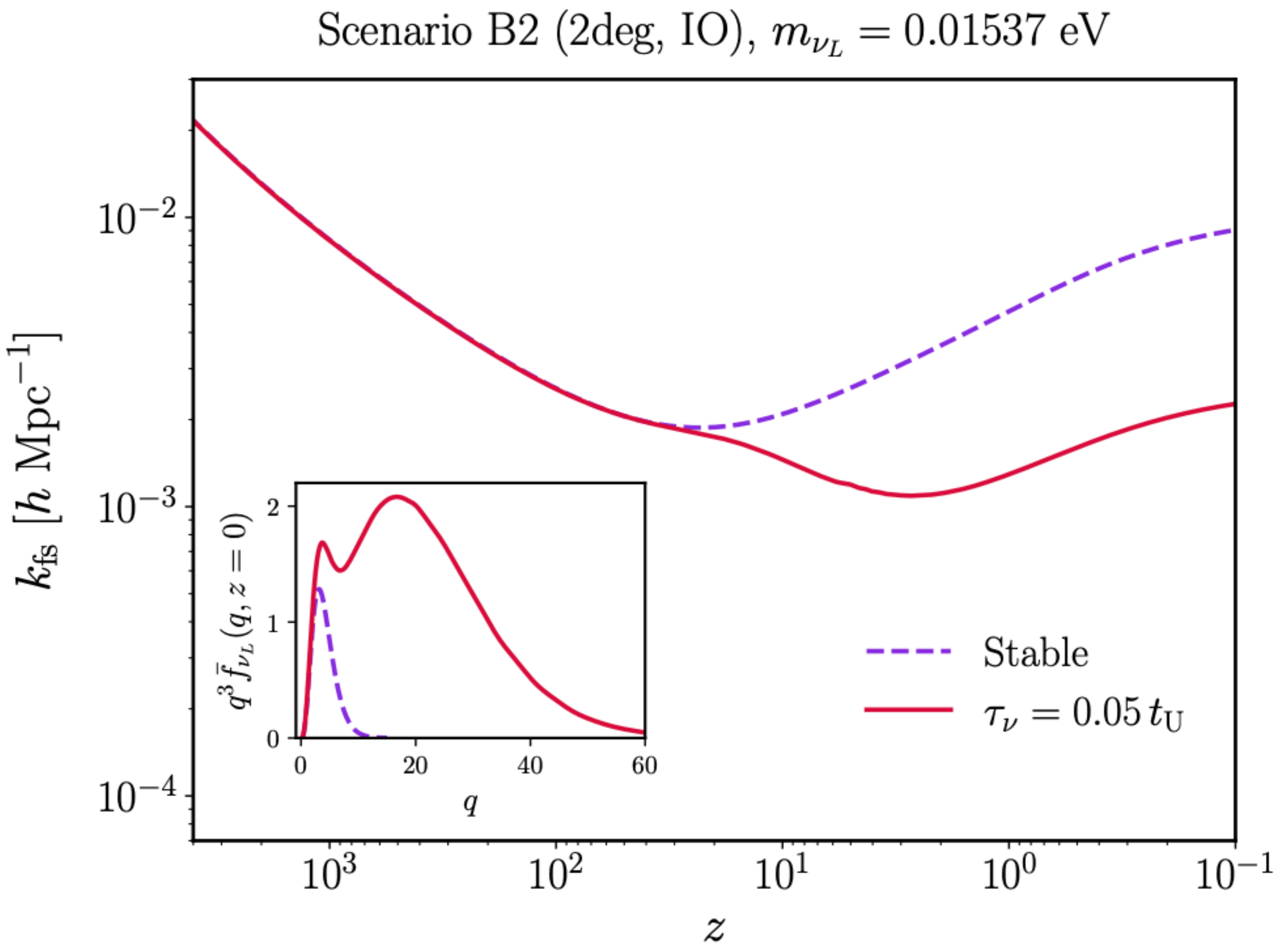
Detailed impact on H(z) and $P_m(k)$





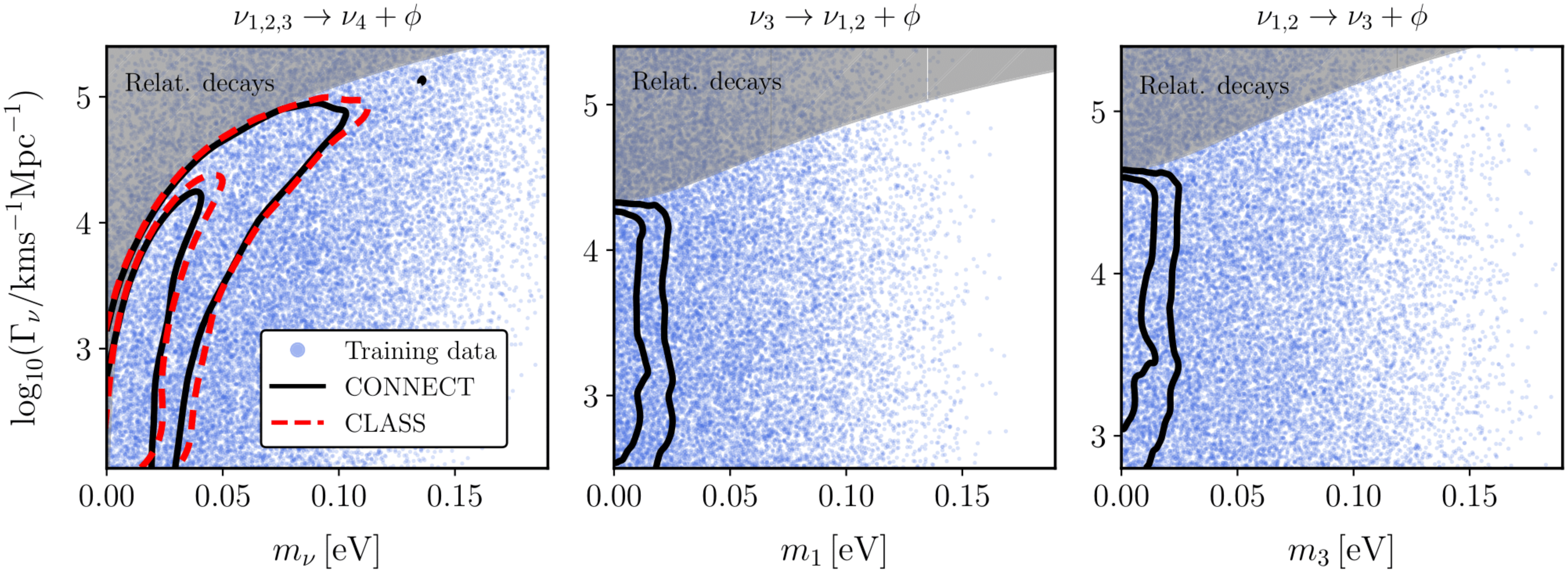
Impact on free-streaming scale of daughter neutrino


Scenario B1 (2deg, NO), $m_{\nu_L} = 0.03067$ eV


Scenario B2 (2deg, IO), $m_{\nu_L} = 0.01537$ eV

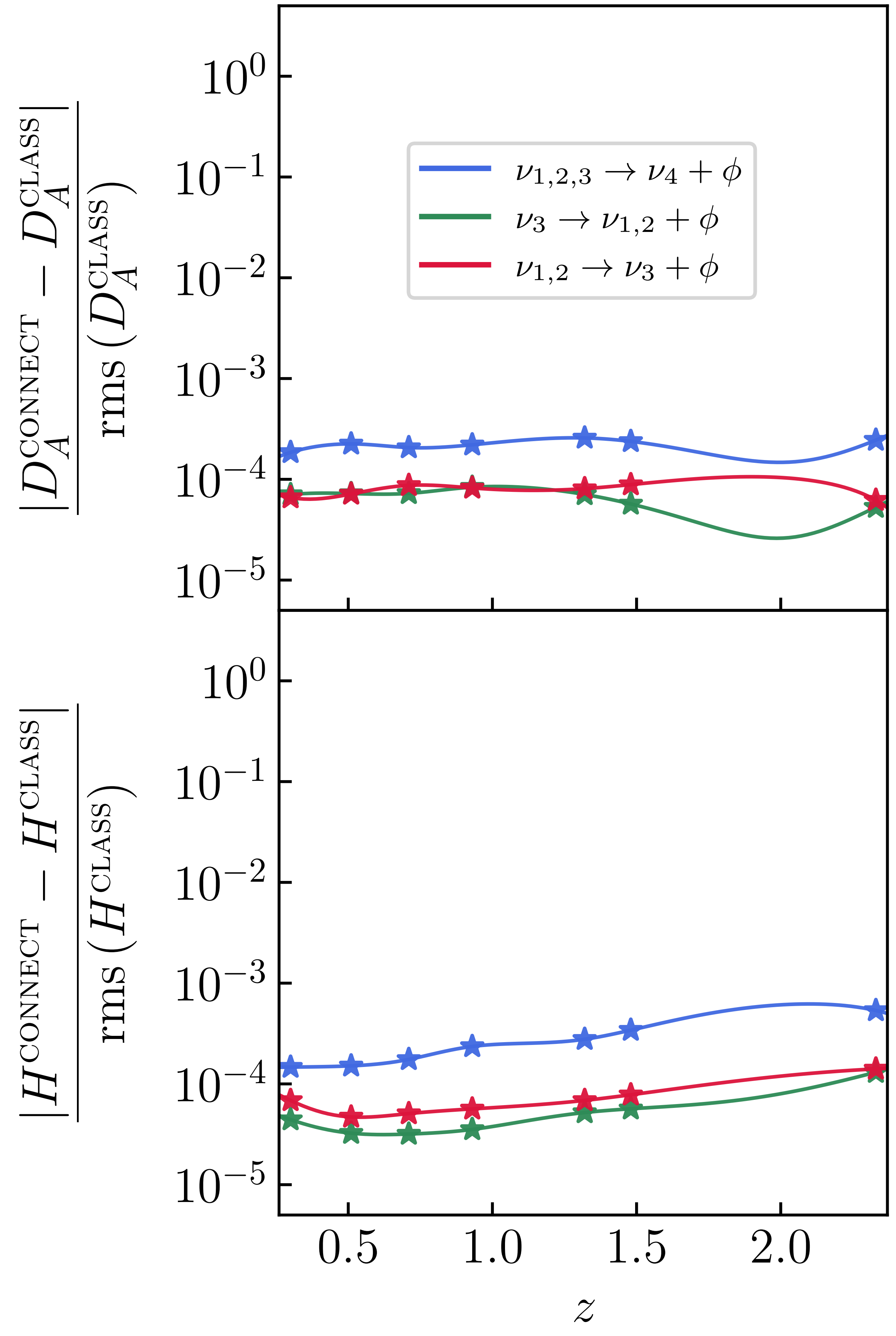
Neural Network Emulator

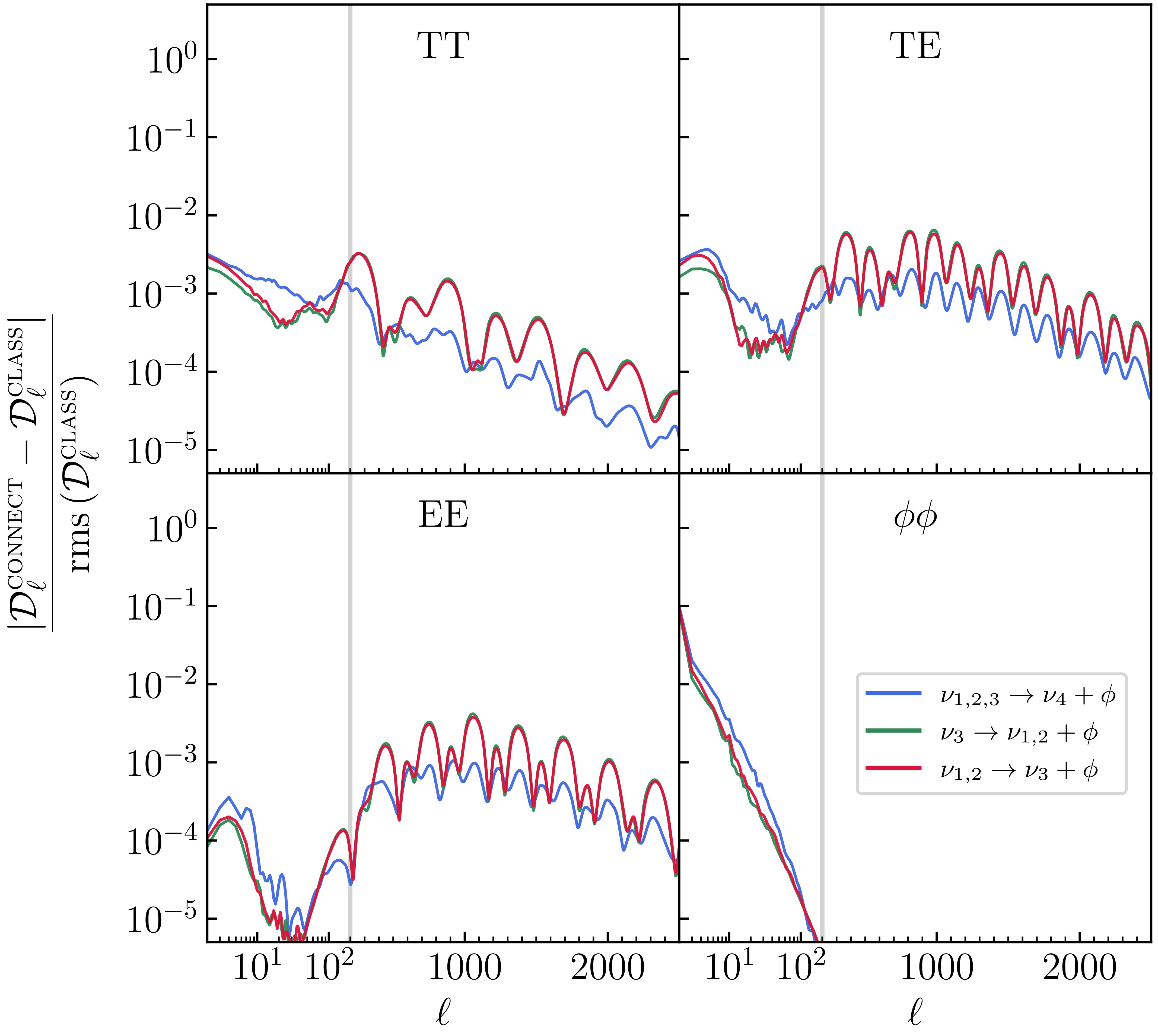
We rely on CONNECT [Nygaard++ 22], which uses hypersphere sampling for efficient generation of training data.



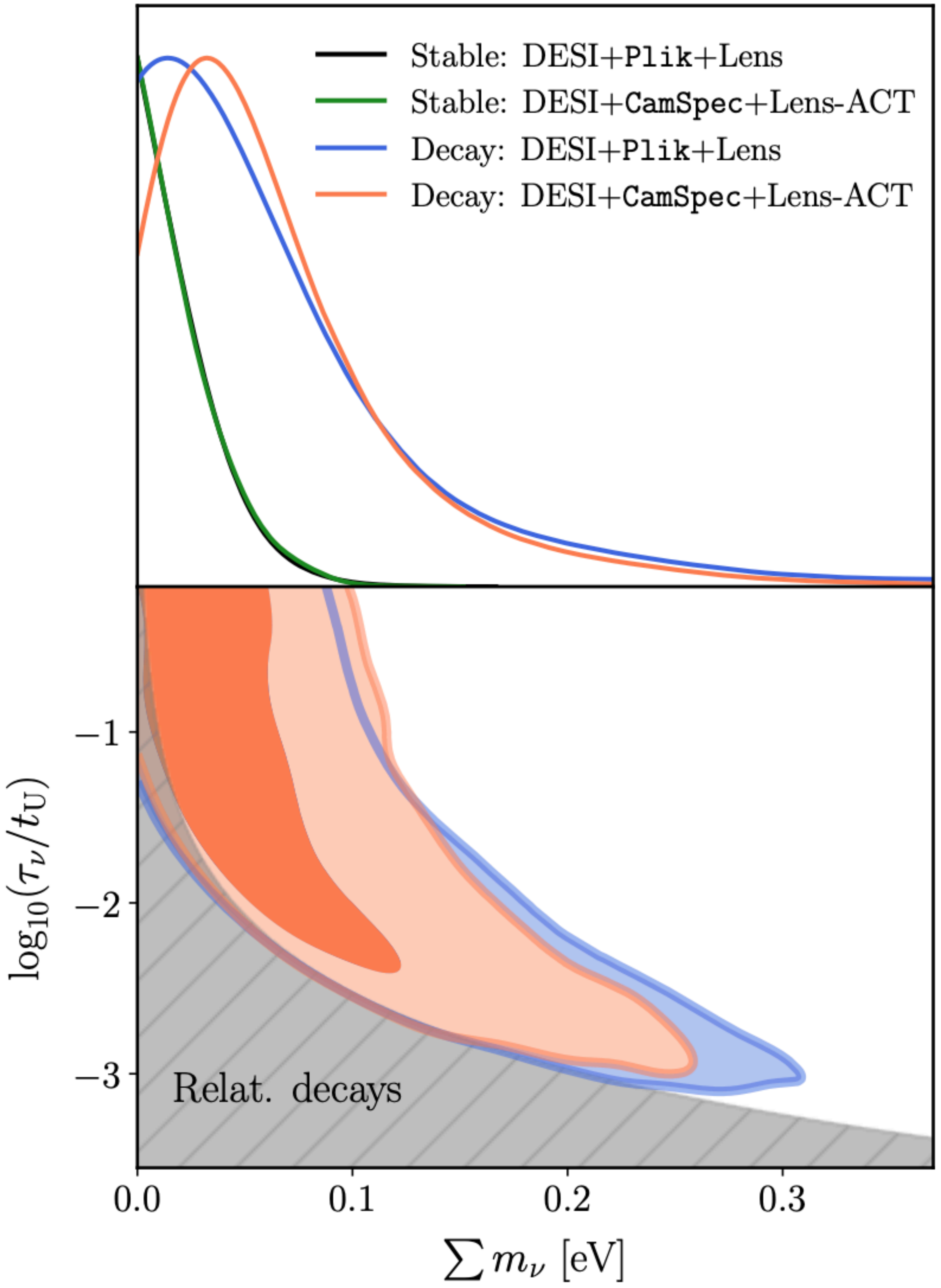
Neural Network Emulator

The 2σ percentile errors in the emulated quantities are below 1% for all decay models



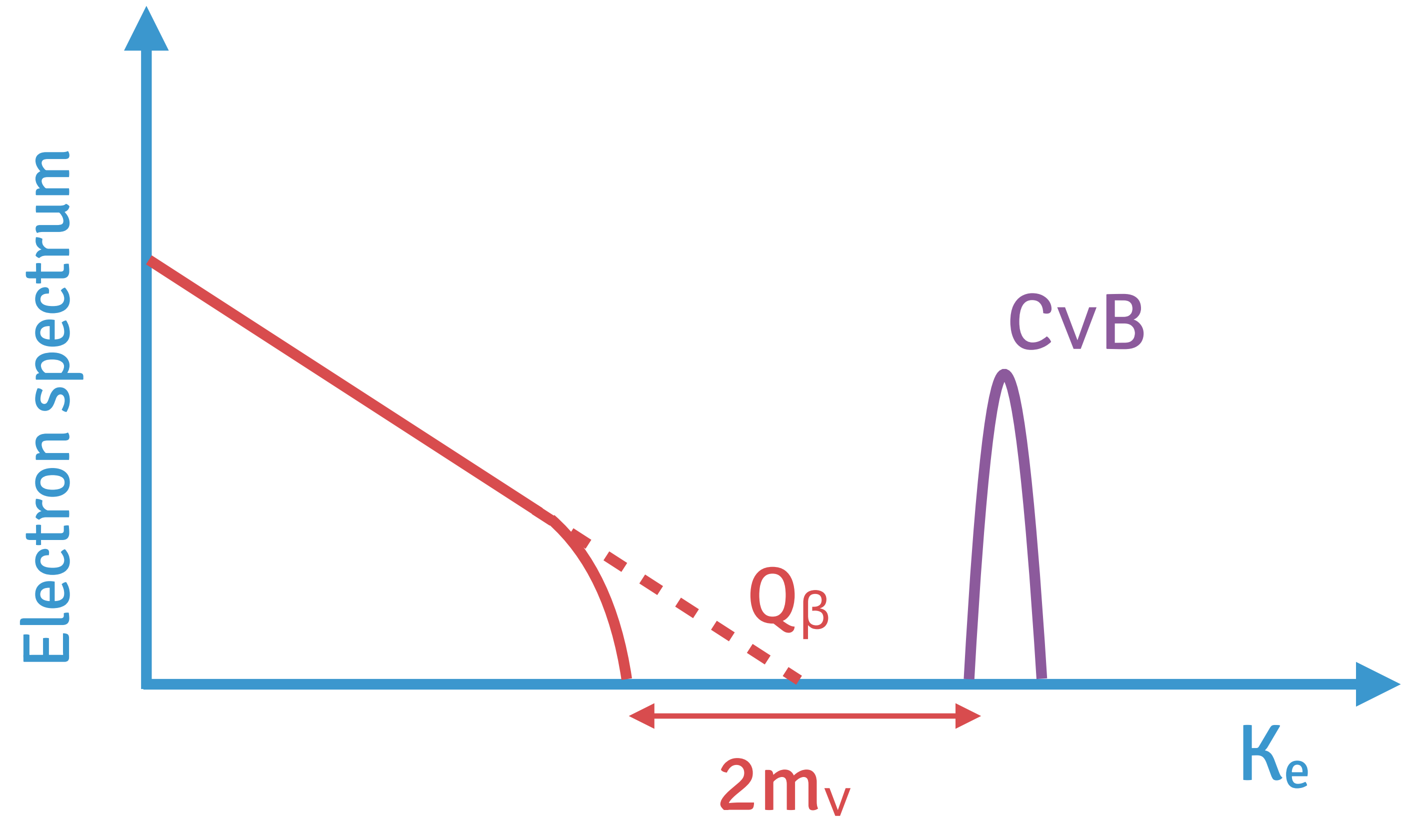


Impact of CMB likelihoods



- Future experiments like **PTOLEMY** aim to detect the CνB via neutrino capture on tritium $\nu_e + {}^3\mathrm{H} \longrightarrow {}^3\mathrm{He}^+ + \mathrm{e}^-$

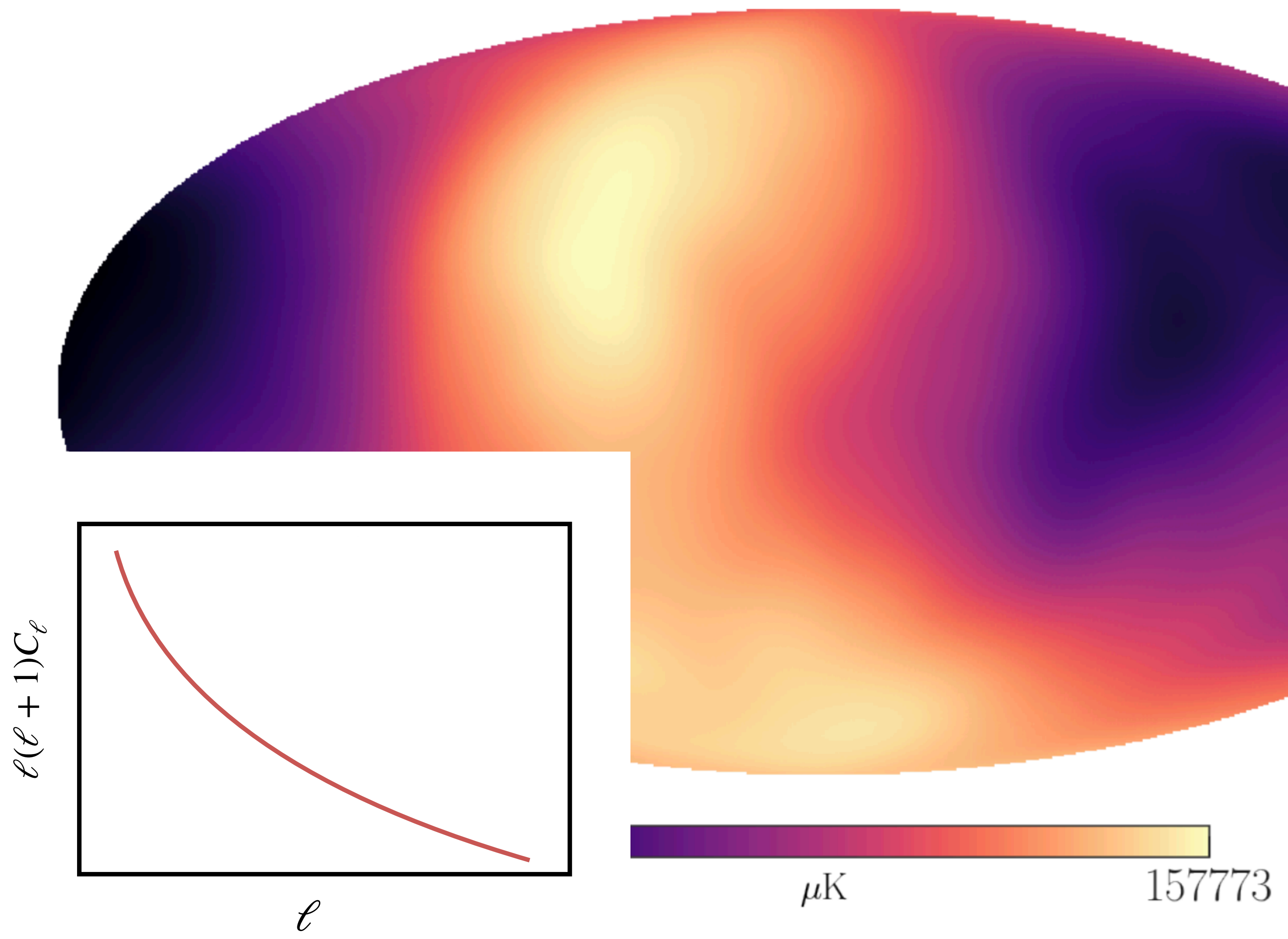
[PTOLEMY 18]

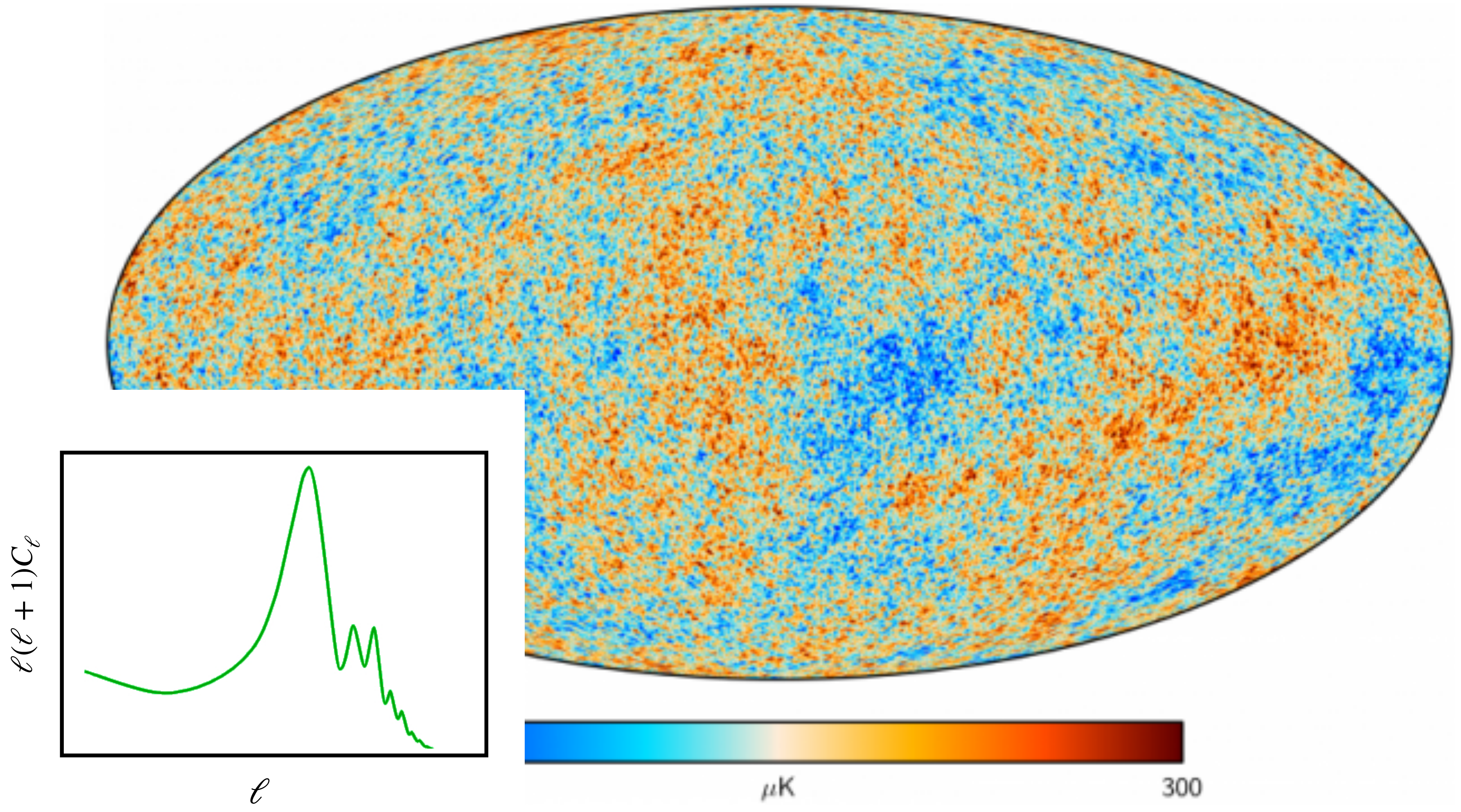


- If tritium targets are polarised, this could allow to measure CνB anisotropies

[Lisanti++ 14]

CνB anisotropies: linear theory prediction



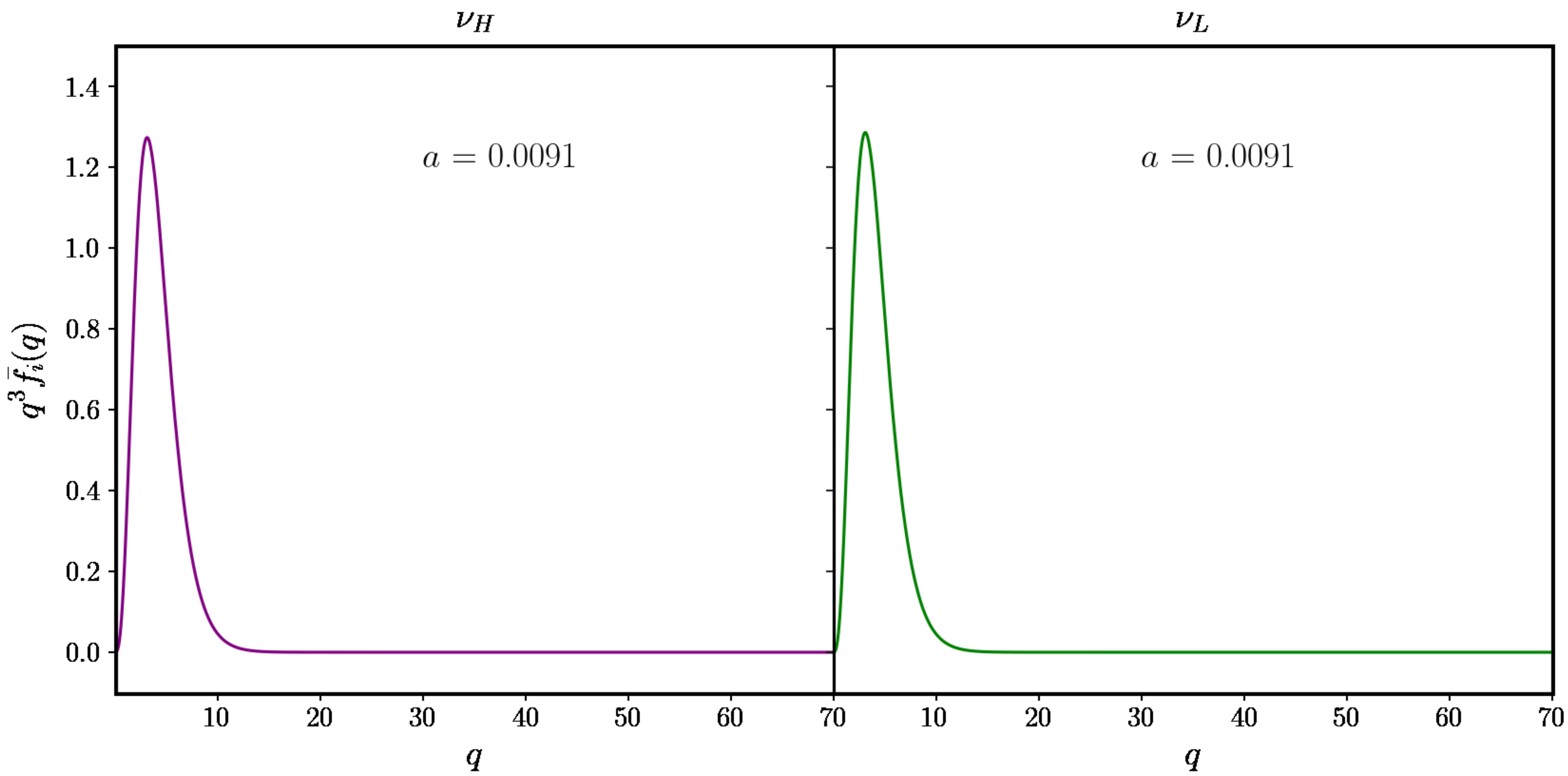


Angular power spectrum of CνB obtained via solutions of Einstein-Boltzmann hierarchy:

$$\boxed{C_\ell(q) = 4\pi A_s \overline{T}_\nu^2 \int d\ln k\, \Delta_\ell^2(q)}$$

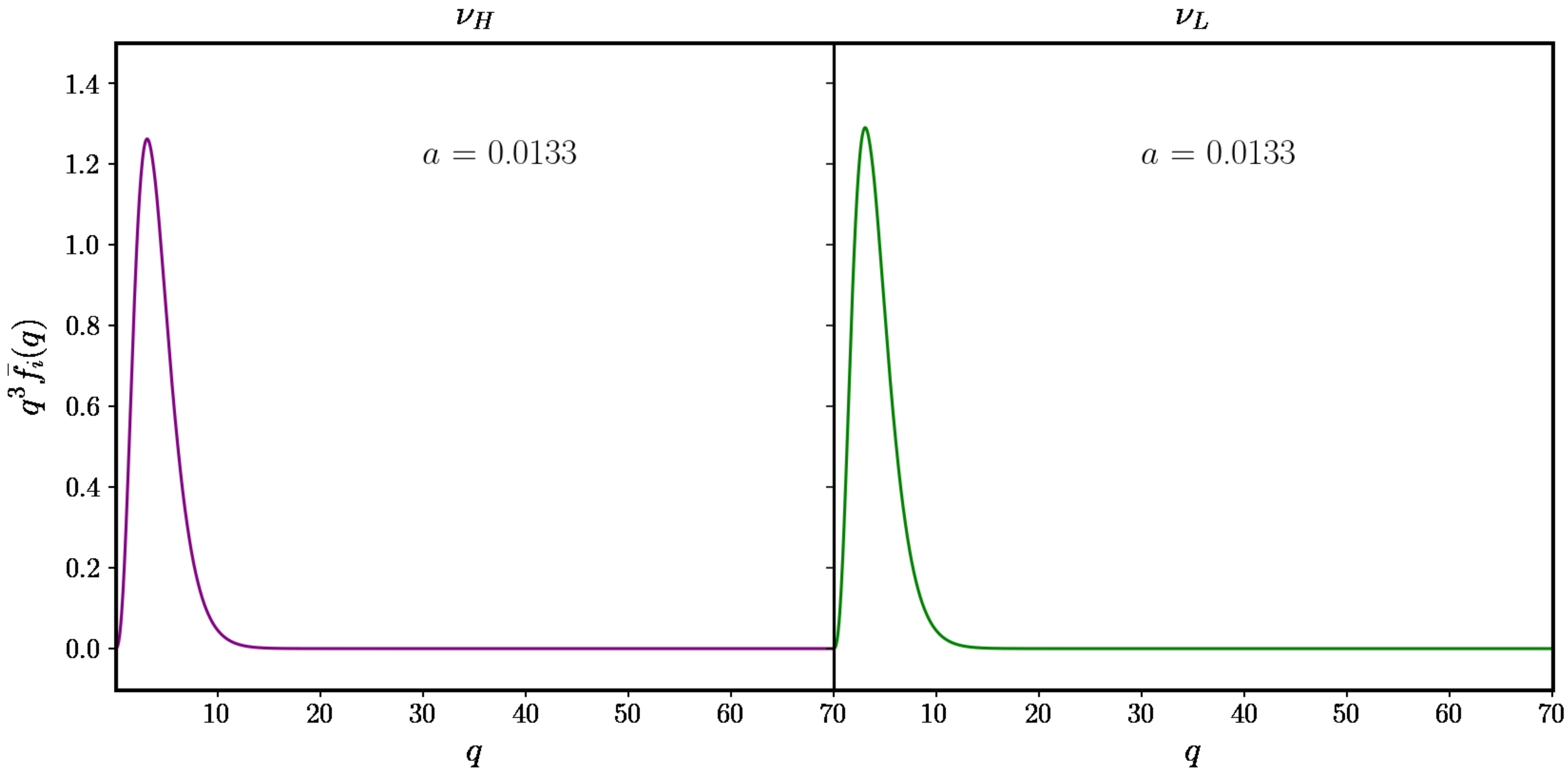
[Tully & Zhang 21]

Evolution of the phase-space distribution



$\tau_\nu = 1\,\mathrm{Gyrs}$, $m_L = 0.03$ eV, Atmospheric gap, Normal Ordering

Evolution of the phase-space distribution



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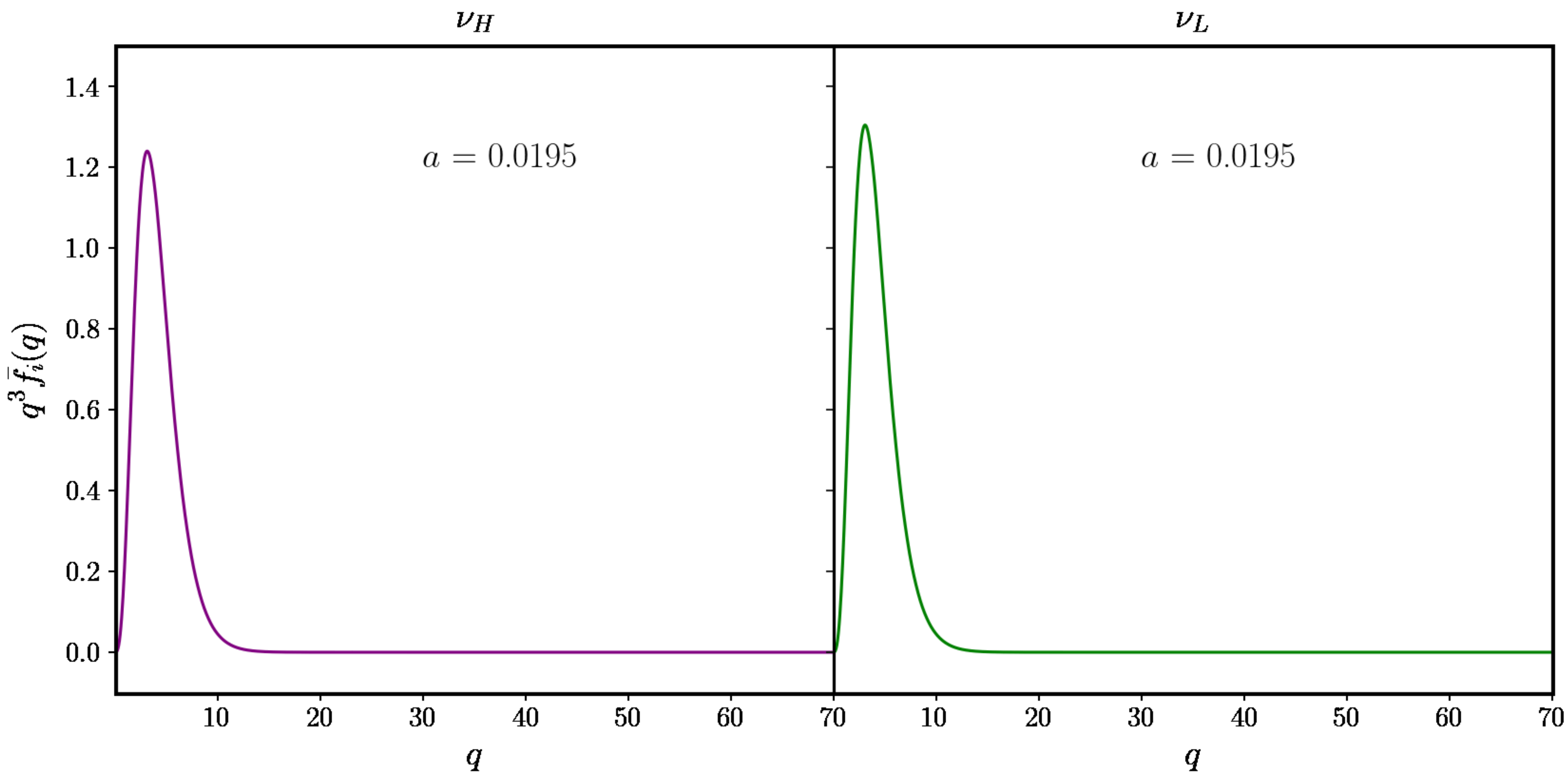

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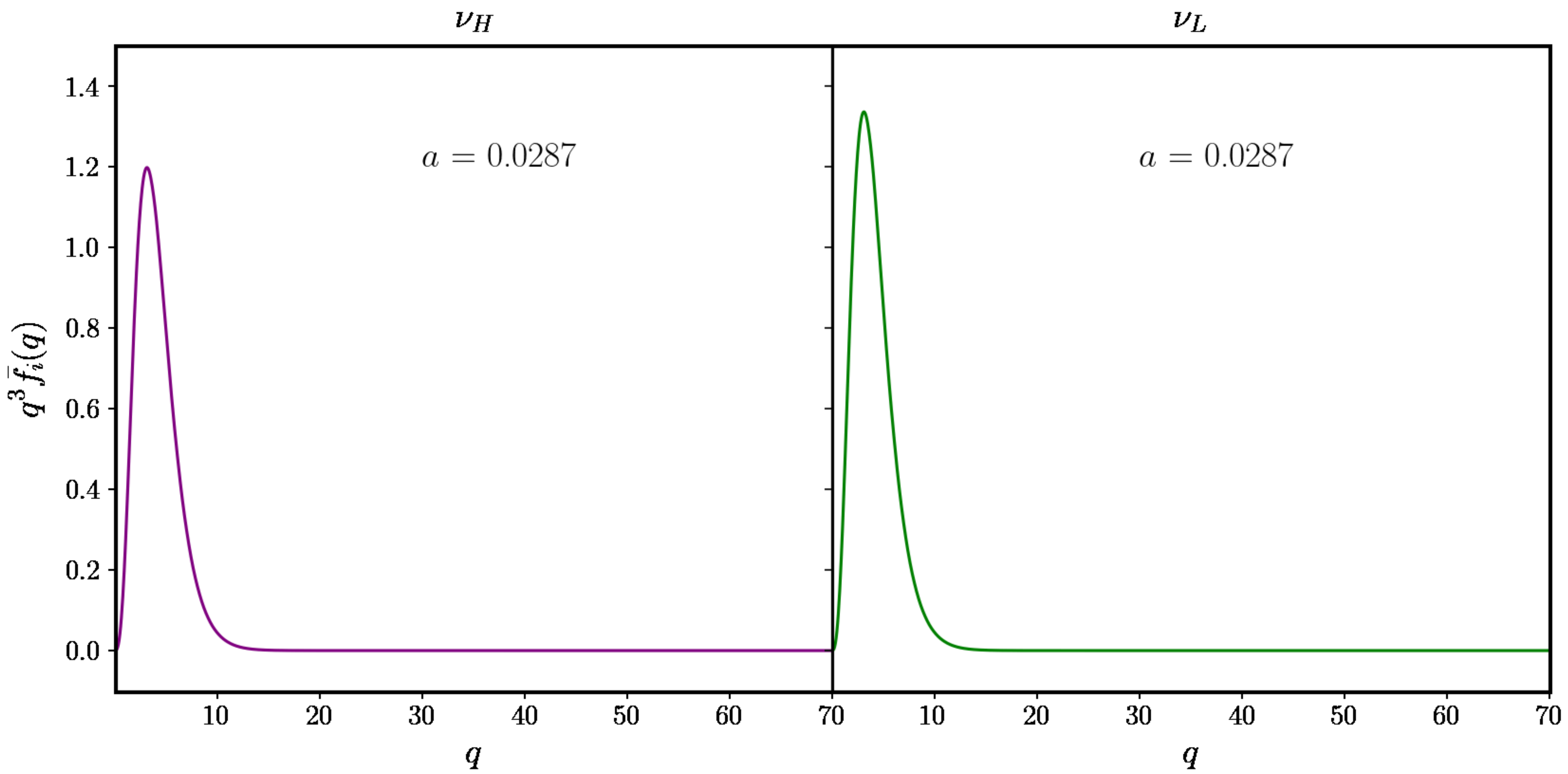

$\tau_\nu = 1$ Gyrs, $m_L = 0.03$ eV, Atmospheric gap, Normal Ordering

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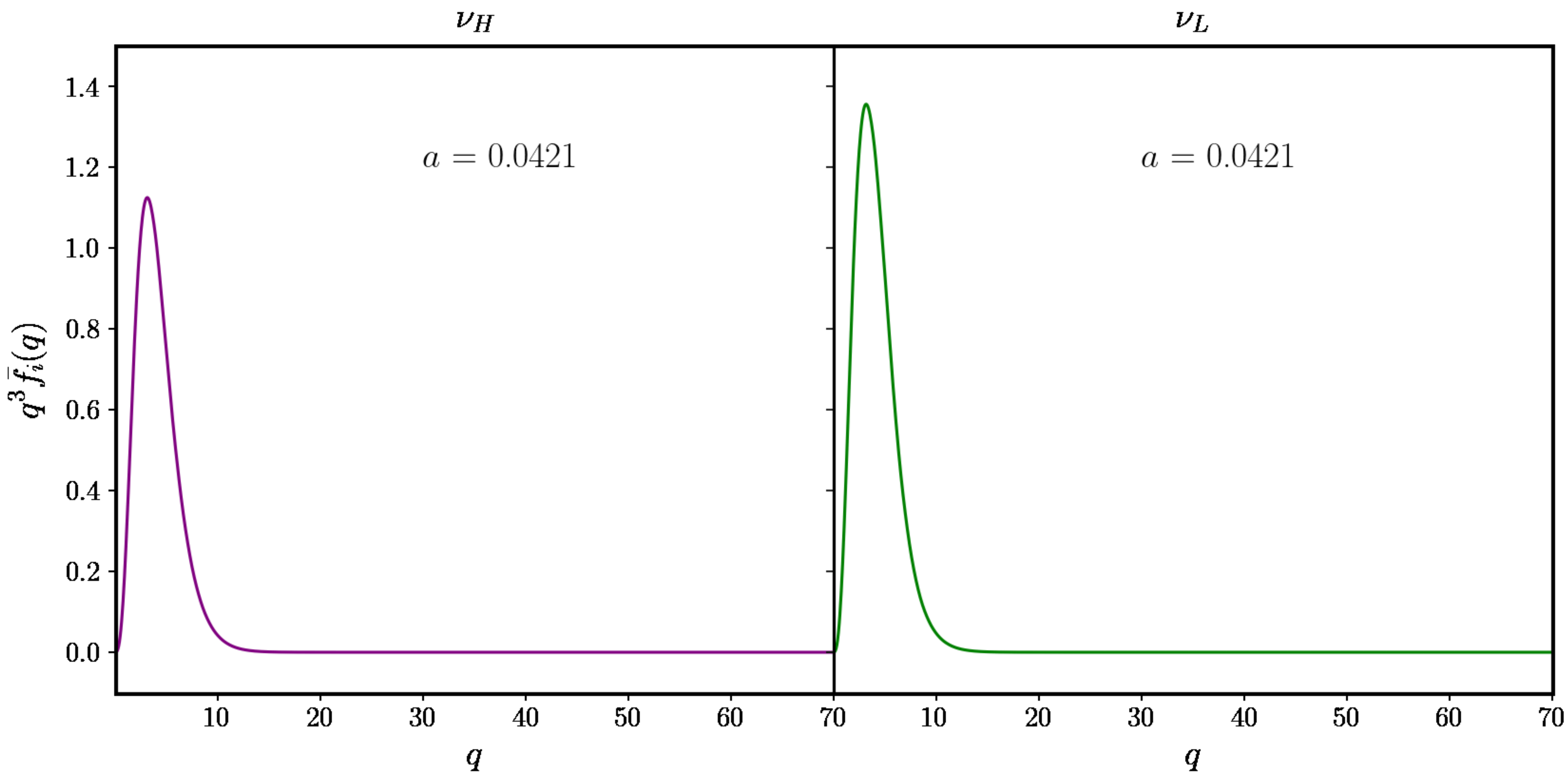

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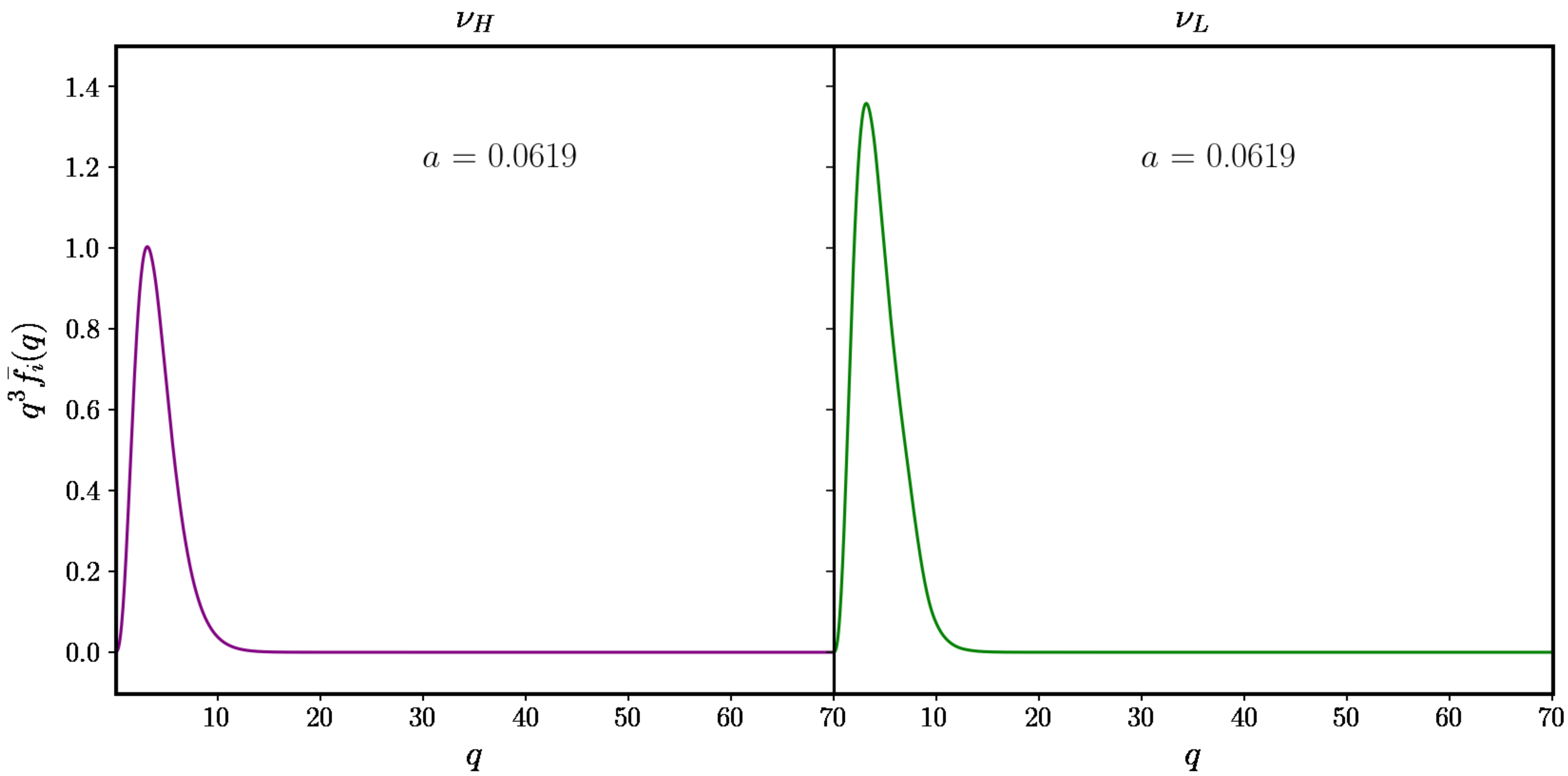

$\tau_\nu = 1\,\mathrm{Gyrs}$, $m_L = 0.03$ eV, Atmospheric gap, Normal Ordering

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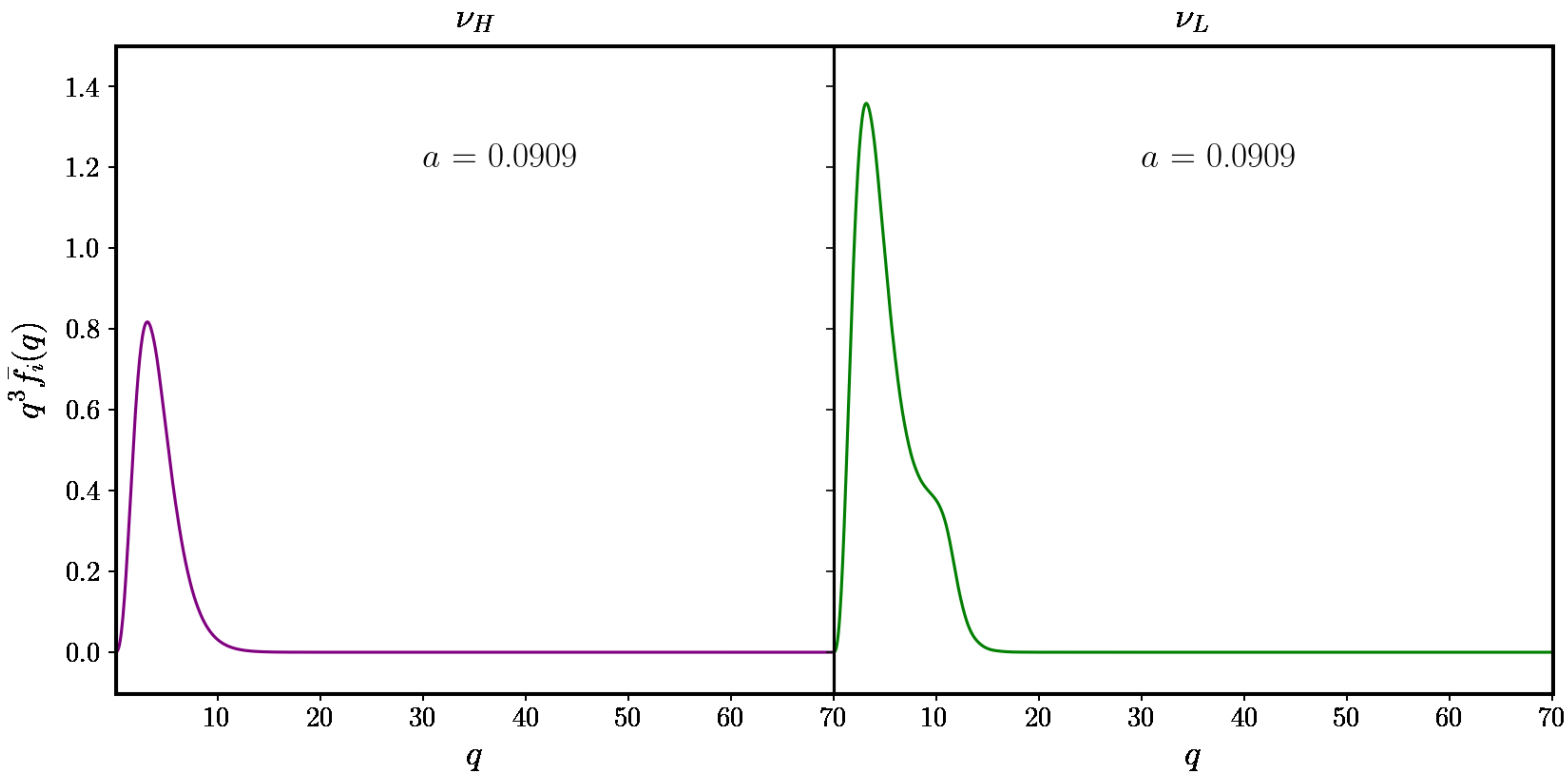
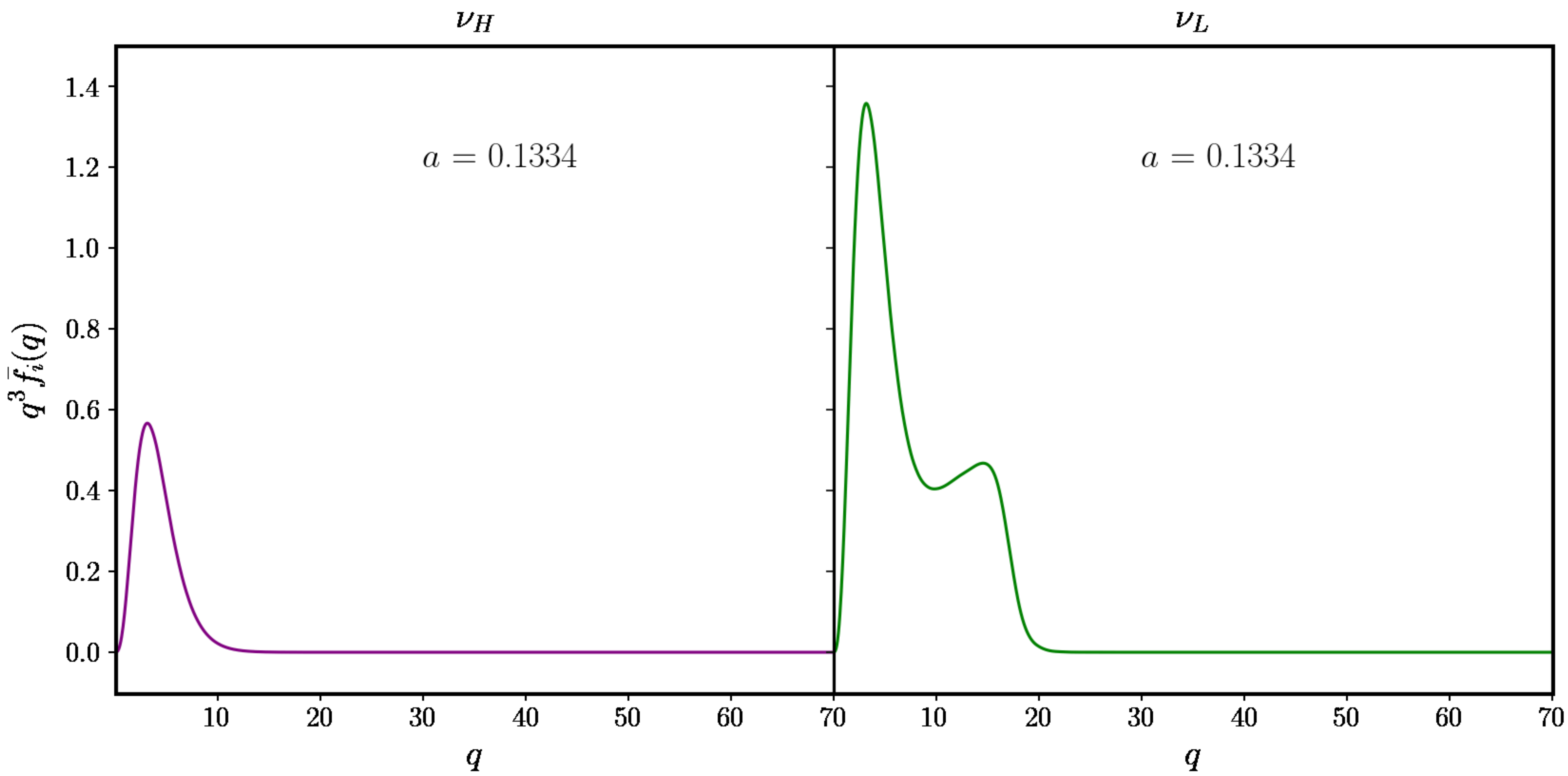


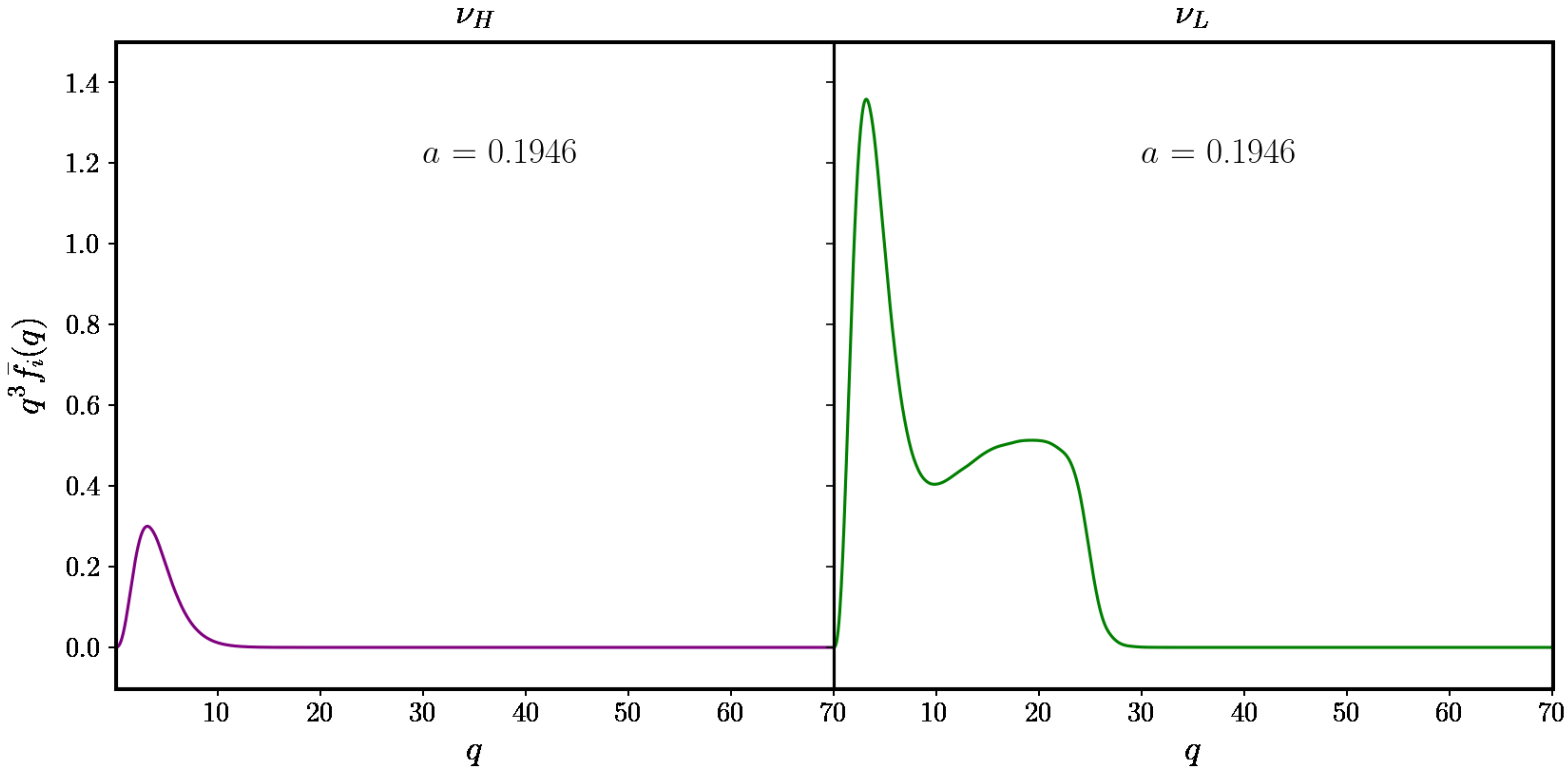
$\tau_\nu = 1\,\mathrm{Gyrs}$, $m_L = 0.03$ eV, Atmospheric gap, Normal Ordering

Evolution of the phase-space distribution



$\tau_\nu = 1\,\text{Gyrs}$, $m_L = 0.03\ \text{eV}$, Atmospheric gap, Normal Ordering

Evolution of the phase-space distribution



$\tau_\nu = 1$ Gyrs, $m_L = 0.03$ eV, Atmospheric gap, Normal Ordering

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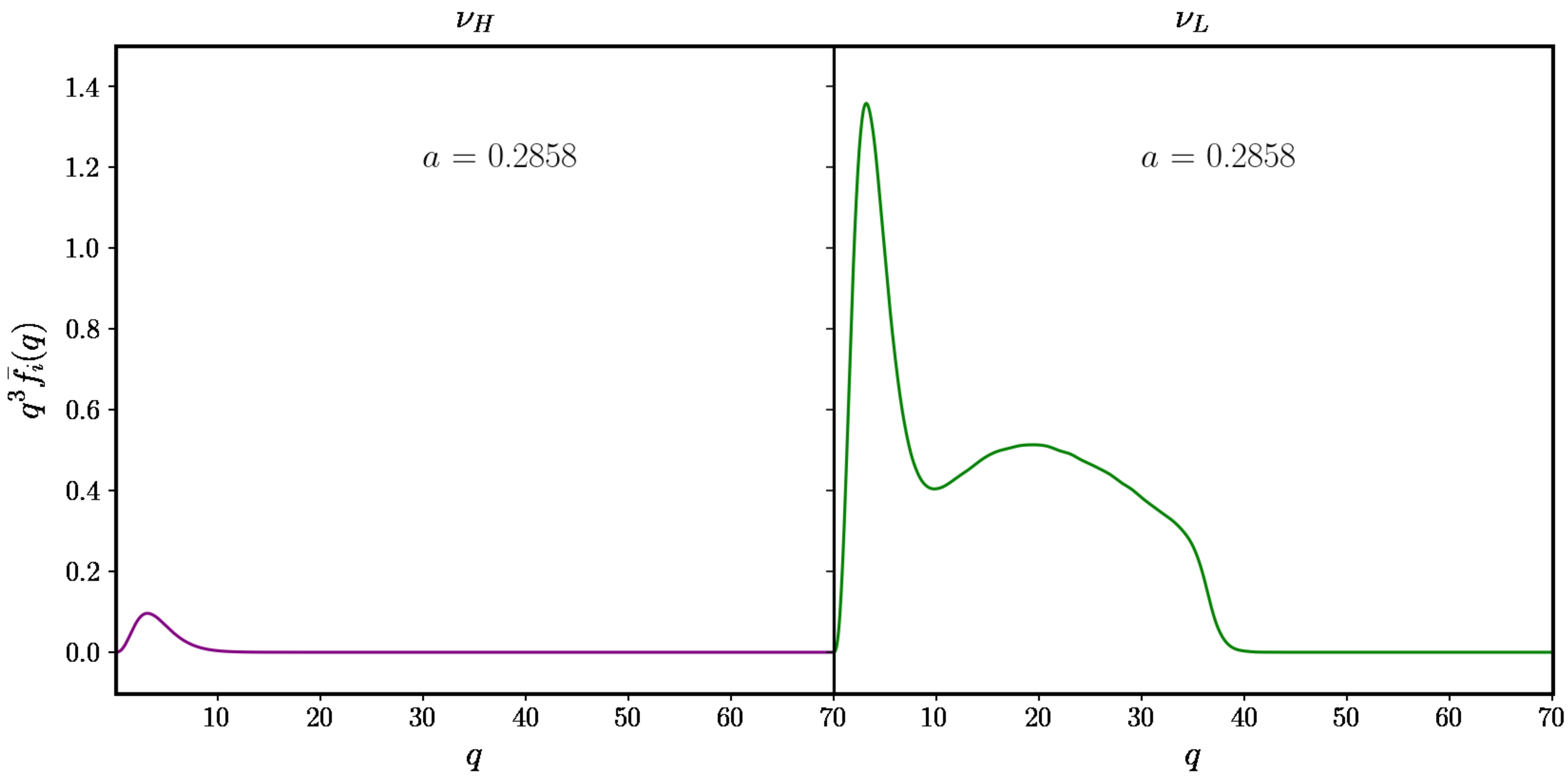

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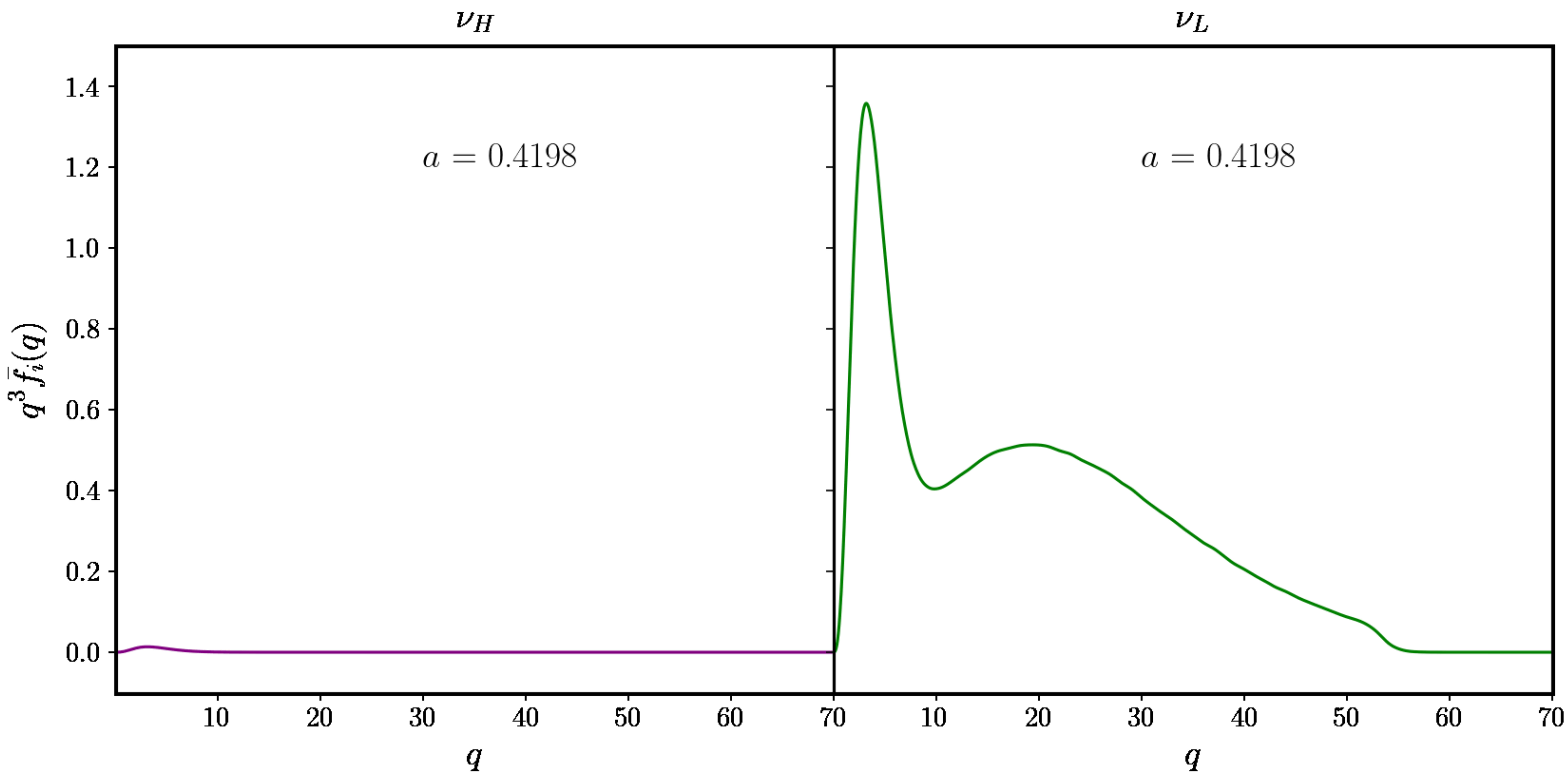

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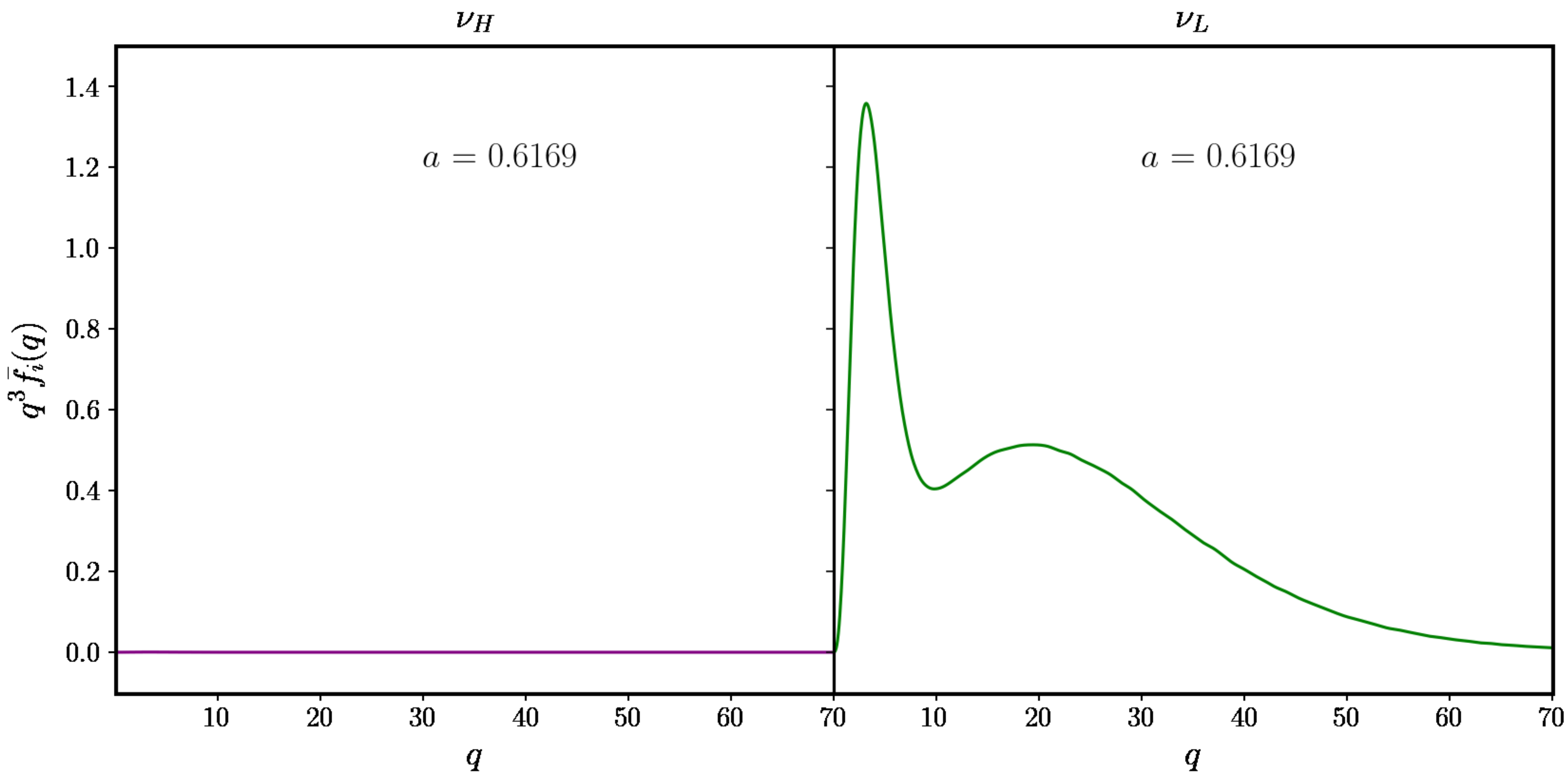

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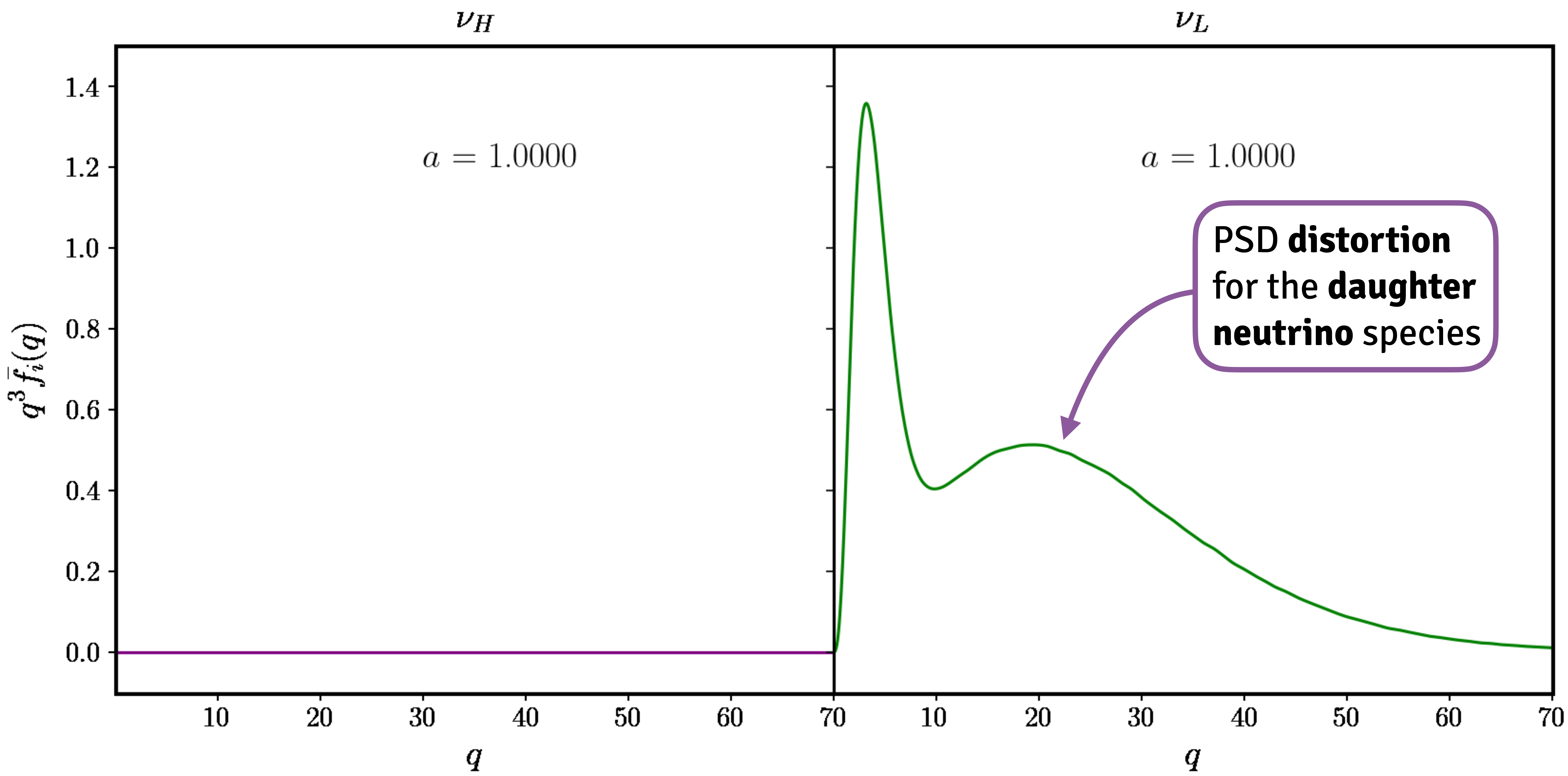

PSD **distortion** for the **daughter neutrino** species

$\tau_\nu = 1\,\mathrm{Gyrs}$, $m_L = 0.03\ \mathrm{eV}$, Atmospheric gap, Normal Ordering