The Neutrino Lifetime from Cosmology

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Introduction

Given enough precision, the sum of neutrino masses can be determined from cosmology.

Bond, Efstathiou & Silk (1980)
Hu, Eisenstein & Tegmark (1998)

The bounds have been improving steadily.

WMAP (2010): $\sum \boldsymbol{m}_{\nu} < 0.58$ eV

Planck (2015): $\sum \boldsymbol{m}_{\nu} < 0.23$ eV

Planck (2018): $\sum \boldsymbol{m}_{\nu} < 0.12$ eV

Euclid (to be launched 2023): $\Delta \boldsymbol{m}_{\nu} \approx 0.02$ eV

From oscillation experiments, $\sum \boldsymbol{m}_{\nu} \gtrsim 0.06$ eV

For the first time, experiments will be sensitive to neutrino masses of order the observed neutrino mass splittings! This should happen within the next decade.

Cosmological observables are sensitive to neutrino masses largely through the contribution of the relic neutrinos from the Big Bang to the energy density.

Then any new physics that alters the number density of neutrinos, or their momentum distribution, will affect these measurements.

These measurements can be used to set limits on the neutrino lifetime.

Serpico (2007)

Neutrino decay is a characteristic feature of models in which neutrinos have masses.

Even in the simplest extensions of the SM in which the neutrino acquires a Dirac mass with a SM singlet, or acquires a Majorana mass through the Weinberg operator, the heavier neutrinos are unstable, and decay at one loop into a lighter neutrino and a photon.

Petcov (1977)
Goldman & Stephenson Jr. (1977)
Pal & Wolfenstein (1982)

For a neutrino of mass 0.05 eV decaying into a massless neutrino, the lifetime is about 10^{43} years, much longer than age of universe.

But in more general extensions of the SM that incorporate neutrino masses, the neutrino lifetime can be much shorter.

What are the current bounds on the neutrino lifetime?

Decays of a heavier neutrino to lighter neutrino and a photon are constrained by spectral distortions of the CMB. In this specific case, $\tau_\nu \gtrsim 10^{13}$ years.

Aalberts et al. (2018)

However, in the case of invisible decays, the bounds are much weaker.

Decays and inverse decays of neutrinos during the CMB epoch would prevent neutrinos from free streaming. Then CMB observations constrain $\tau_\nu \gtrsim 10$ years for $m_\nu = 0.05$ eV.

The limit from Supernova 1987A is just $\tau_\nu \gtrsim 5$ hours for $m_\nu = 0.05$ eV.

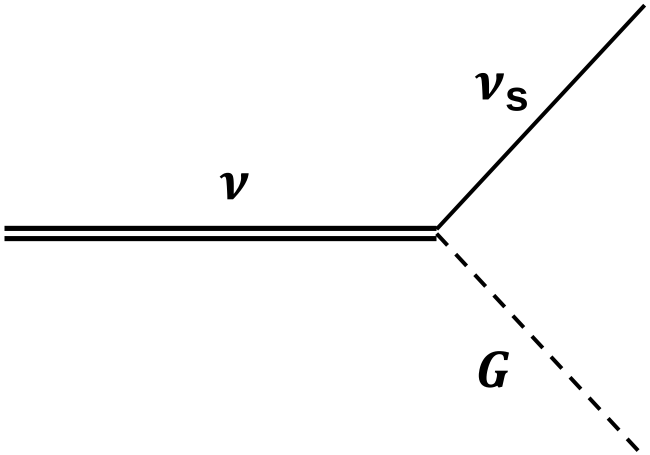
The bounds from the observation of neutrinos from the sun, and from long baseline experiments, are even weaker.

The breaking of global symmetries in the neutrino sector gives rise to Nambu-Goldstone bosons, such as the Majoron.

Gelmini & Roncadelli (1981)
Chikashige, Mohapatra & Peccei (1981)

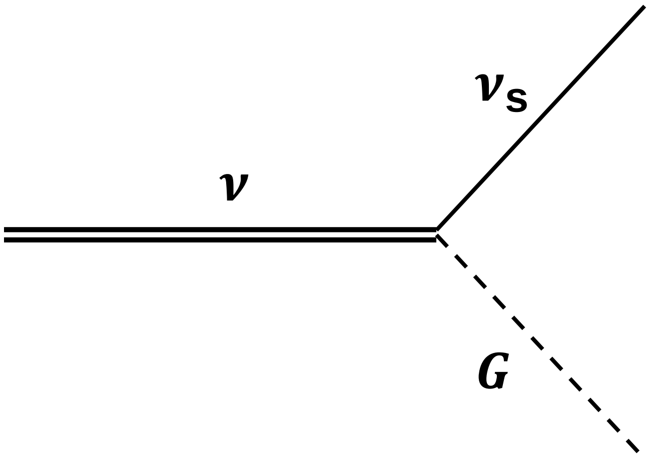
In these theories neutrinos can decay into a lighter neutrino and a Goldstone boson.

Valle (1983), Gelmini & Valle (1984)



For symmetry breaking scales up to $f \sim 100$ TeV, the neutrino lifetime is less than the age of the universe, with implications for cosmology.

In this talk, I will focus on a model in which the massive SM neutrinos decay into a massless sterile neutrino and a Goldstone boson.



In this construction, the widths of the three massive neutrinos scale as $\Gamma_i \sim m_i^3$.

Restrict to the case in which neutrinos decay after becoming non-relativistic.

- Determine the current limits on the neutrino mass and lifetime.
- Explore the potential for near-future experiments to independently determine the neutrino mass and lifetime.

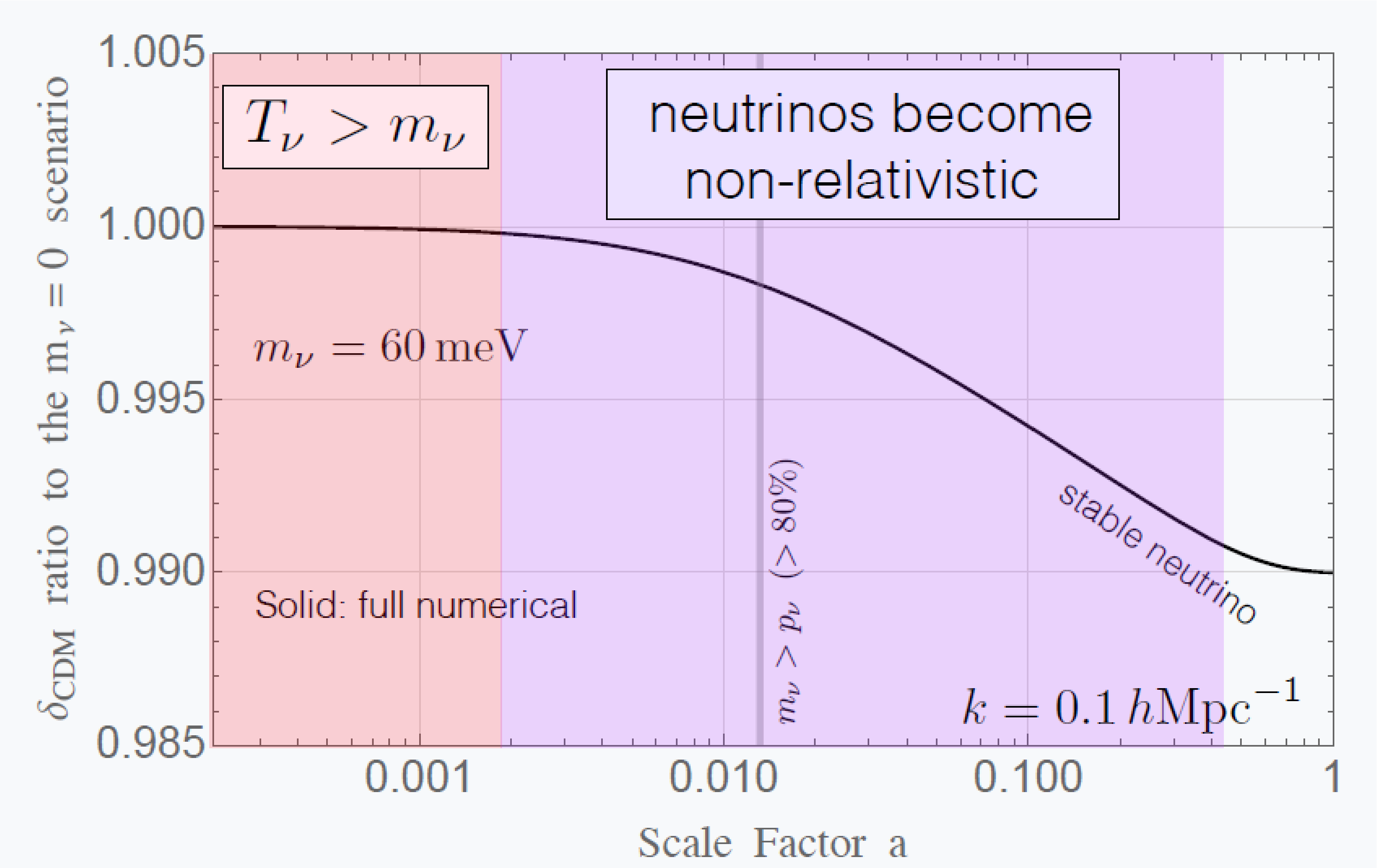
How do neutrino masses affect cosmological observables?

- Sub-eV neutrinos do not contribute significantly to the growth of structure until the neutrinos have become non-relativistic. Perturbations on scales below the neutrino free streaming length are suppressed.

- After neutrinos have become non-relativistic, their overall contribution to the background energy density is greater than that of a relativistic species. This speeds up the Hubble expansion, reducing the time available for structure formation, leading to suppression of the matter power spectrum.

Neutrino masses affect LSS observables through a suppression of the matter power spectrum on scales below the neutrino free streaming length.

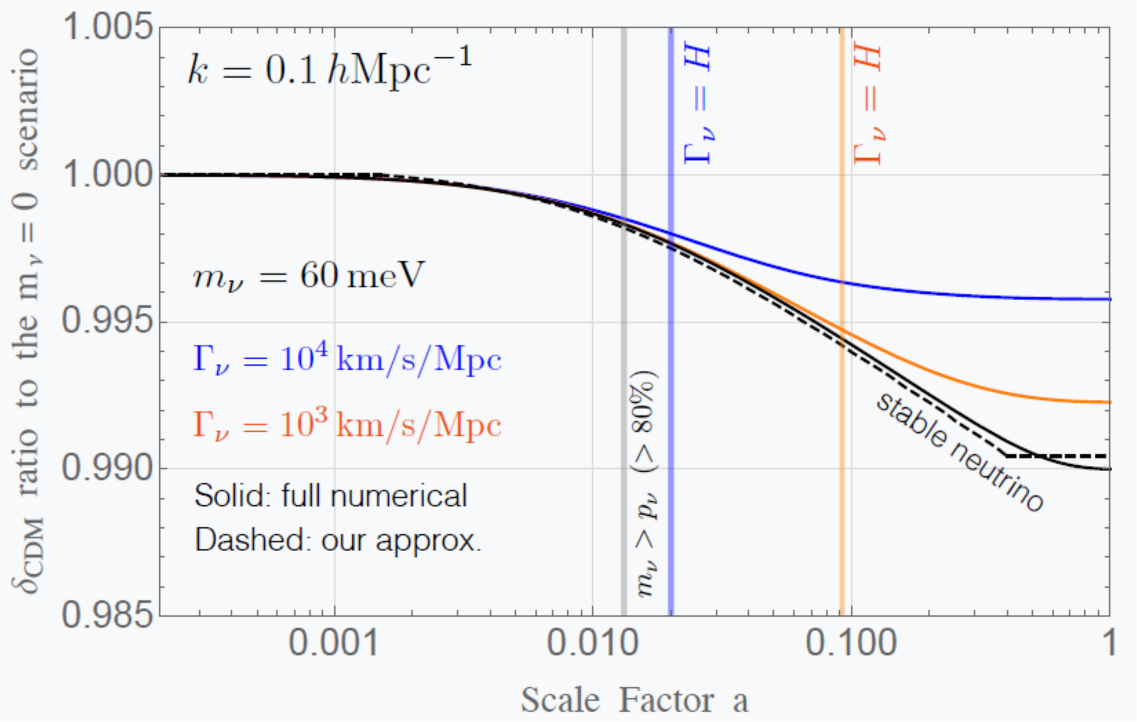
- Neutrino masses also affect the CMB. At the precision of Planck, the CMB is most sensitive to sub-eV neutrino masses through the “secondary” effect of lensing. Since neutrino masses affect the growth of structure, they impact the lensing of the CMB.


$T_\nu > m_\nu$
neutrinos become non-relativistic
$m_\nu = 60\,\mathrm{meV}$
Solid: full numerical
$m_\nu > p_\nu$ (> 80%)
stable neutrino
$k = 0.1\,h\mathrm{Mpc}^{-1}$
δ_{CDM} ratio to the $\mathrm{m}_\nu = 0$ scenario
Scale Factor a
1.005
1.000
0.995
0.990
0.985
0.001
0.010
0.100
1

How is the signal affected by neutrino decay (to dark radiation)?

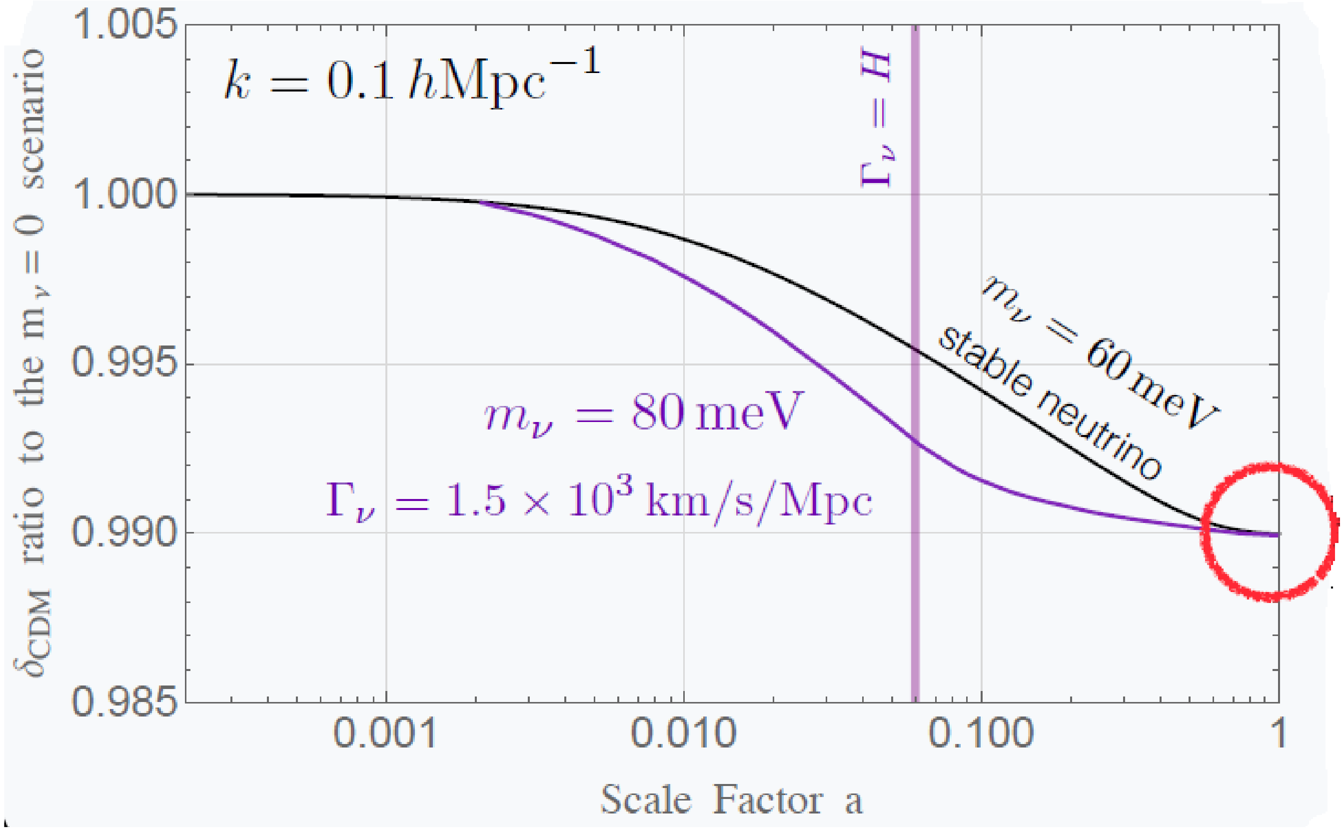
Suppression of structure now only occurs in period of time between neutrinos becoming non-relativistic and their decay.

After neutrinos have decayed, their contribution to the energy density redshifts like that of massless neutrinos, resulting in a milder suppression of structure as compared to stable neutrinos of the same mass.



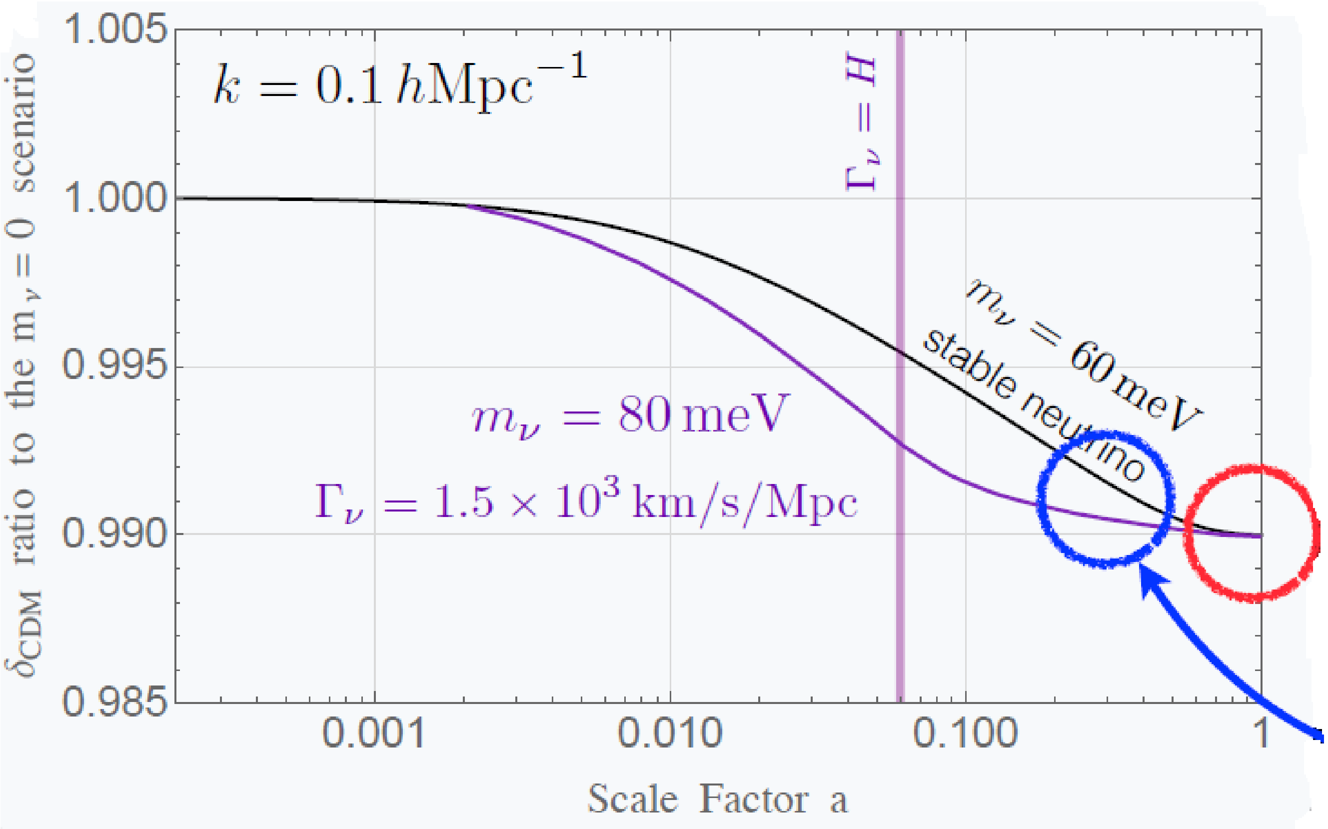
The suppression of structure now depends on the neutrino lifetime!

There is a strong degeneracy in the matter power spectrum between neutrino mass and lifetime. A heavy neutrino that decays can give rise to the same suppression of the matter power spectrum as a lighter stable neutrino.



The cosmological limits on the neutrino mass are lifetime dependent! In the case of unstable neutrinos, they must be reconsidered.

It may be possible to break the degeneracy between neutrino mass and lifetime by measuring the power spectrum at different redshifts.



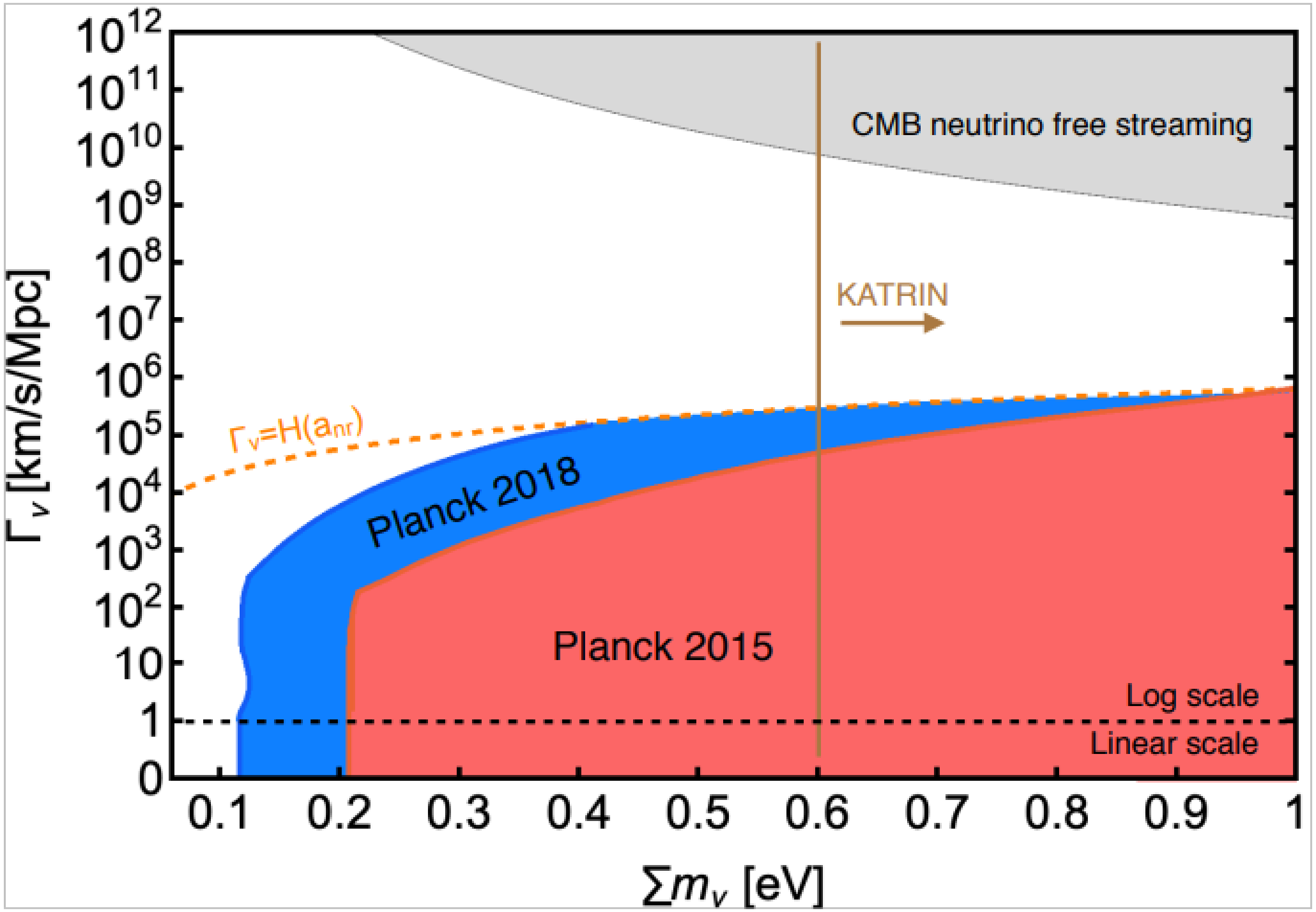
measurement at higher redshift

It may be possible to determine the neutrino lifetime from cosmology!

Parameter Space of the Unstable Neutrino

The blue region is excluded based on the data from CMB and BAO (Planck 2018 + BOSS).

We limit our analysis to the case when the neutrinos decay only after becoming non-relativistic (below orange dashed line).



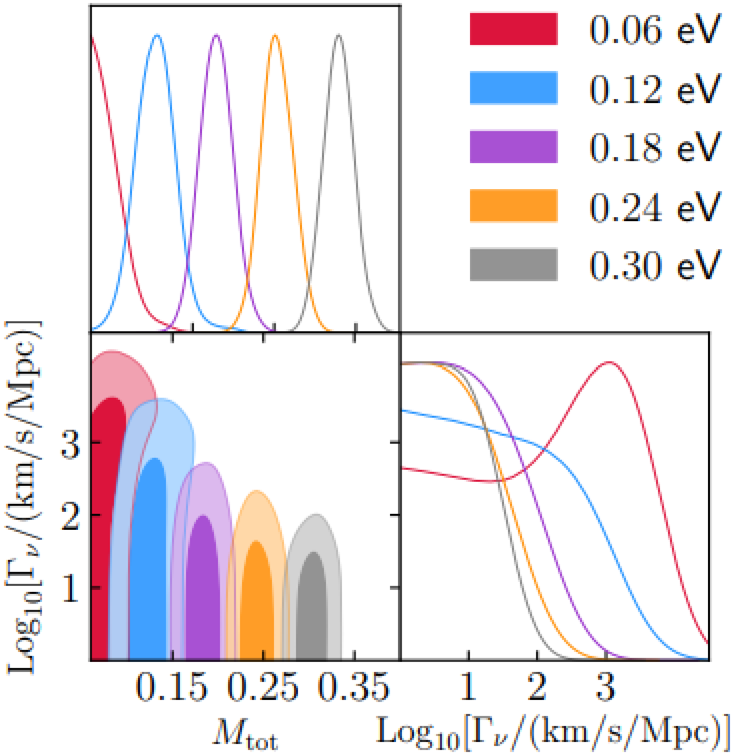
Once we admit the possibility that neutrinos are unstable, values of $\sum m_{\nu}$ as large as 0.4 eV are allowed by the data! Compare to limit of $\sum m_{\nu} \lesssim 0.12$ eV for stable case.

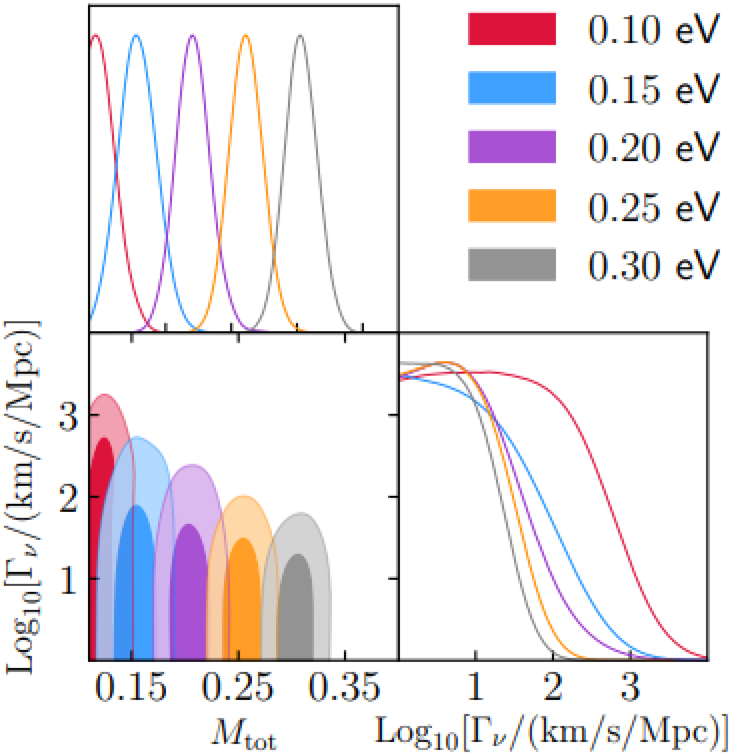
This result has important implications for experiments looking to detect neutrino masses in the lab, such as KATRIN (sensitive to $\sum m_{\nu} \gtrsim 0.6$ eV) and KLZ-800 (sensitive to $\sum m_{\nu} \gtrsim 0.17$ eV for normal hierarchy).

Neutrino Lifetime from Cosmology

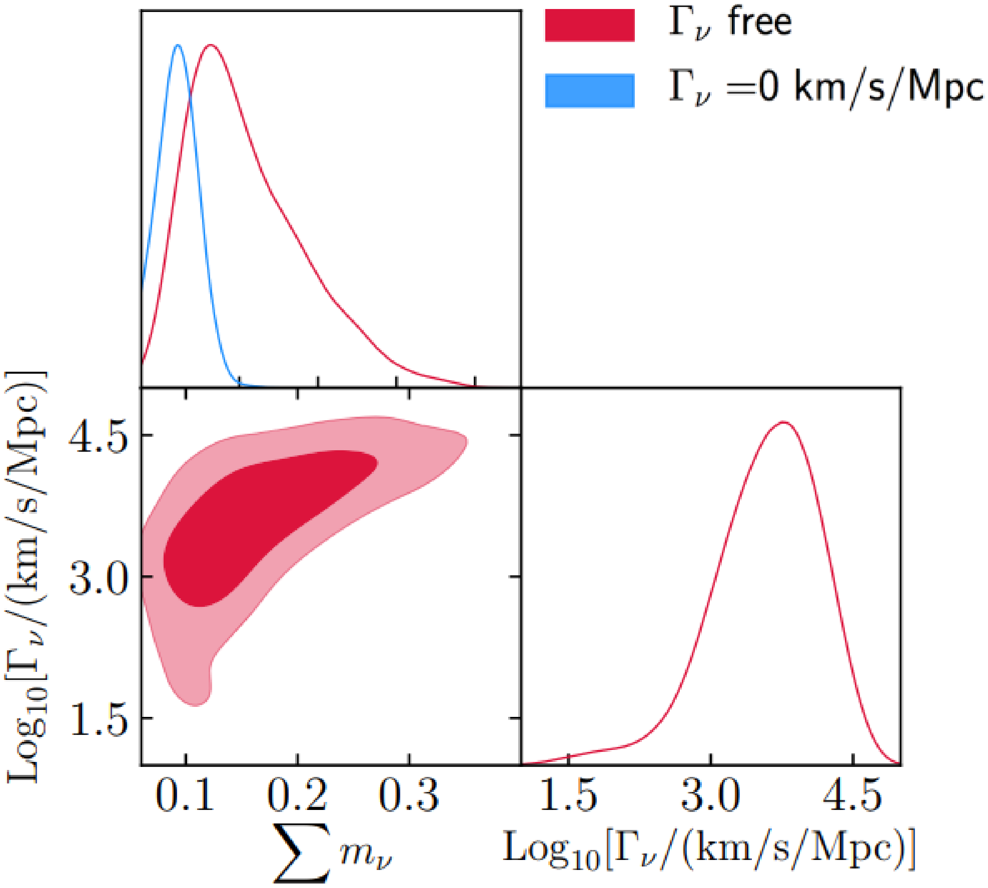
By combining measurements of the power spectrum at different redshifts, we can break the degeneracy between neutrino mass and lifetime.

Euclid measurements will extend from redshifts z =0.15 to z = 2. In combination with Planck, it should be possible to improve the limits on the neutrino lifetime from 10 years to $\sim 10^8$ years. No significant degradation in measurement of neutrino mass.





In some regions of parameter space, the combination of Euclid + Planck will be able to independently determine the sum of neutrino masses and lifetime.



Future experiments are designed to probe even higher redshifts, which will increase the region in which we can determine these two fundamental parameters.

Conclusions

Upcoming cosmological observations will be sensitive to neutrino masses of order the observed mass splittings.

Any new physics that alters the number density or momentum distribution of the neutrinos will affect these measurements.

In particular, these measurements will be affected if neutrinos decay on timescales shorter than the age of the universe.

This can occur in theories in which the generation of neutrino masses is associated with the spontaneous breaking of global symmetries, for $f \lesssim 100$ TeV.

We have determined the bounds on the neutrino mass and lifetime from cosmology. For unstable neutrinos, values of $\sum m_\nu$ as large as 0.4 eV allowed.

This has important implications for laboratory experiments seeking to determine the neutrino masses, such as KATRIN and KLZ-800.

Near-future cosmological observations can greatly improve the bound on the neutrino lifetime. Will be able to determine the neutrino mass and lifetime independently in some regions of parameter space.