# Cosmological Signals of Neutrino Mass and Lifetime

Peizhi Du

C.N Yang Institute for Theoretical Physics
Stony Brook University

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based on the work with Zackaria Chacko, Abhish Dev, Vivian Poulin, Yuhsin Tsai
(arXiv:1909.05275+19xx.xxxx)

# *Motivation*

**SM neutrinos:**

**We have detected neutrinos 50 years ago**

**Least known particles in the SM**

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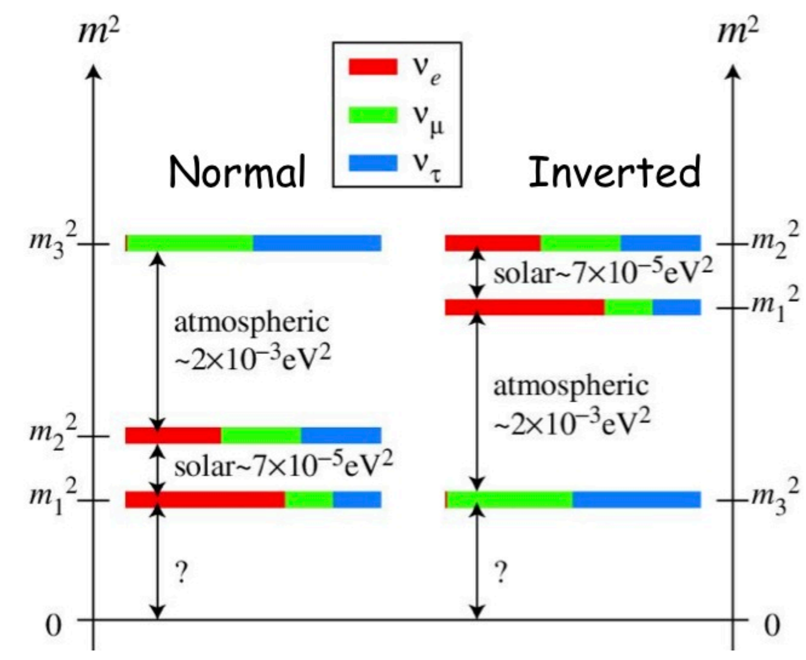


## What we don't know:

- Origin of mass
- Majorana or Dirac
- Mass ordering
- Total mass

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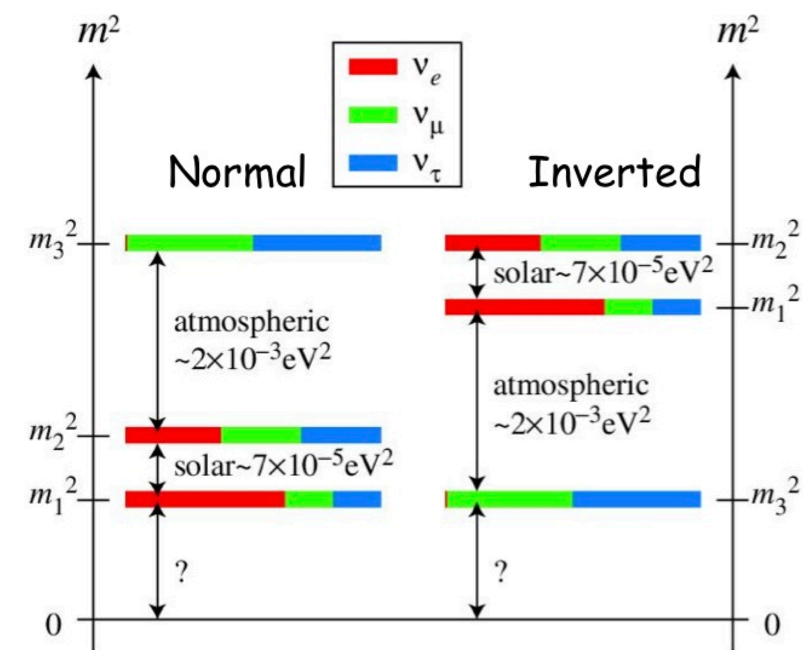


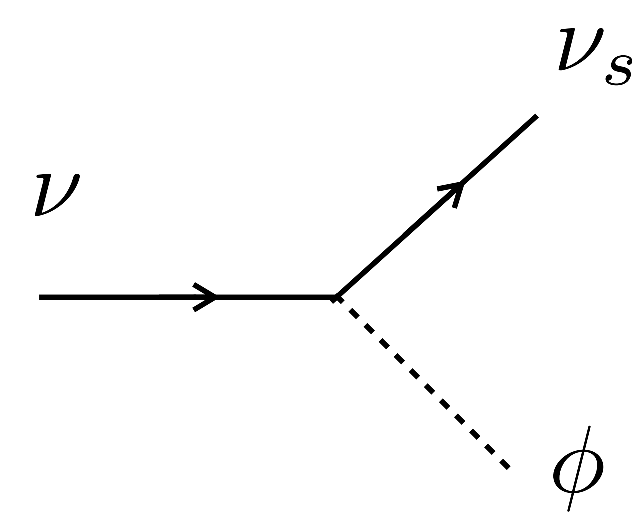


**e.g. Majoron models**

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We have detected neutrinos 50 years ago

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## What we don't know:

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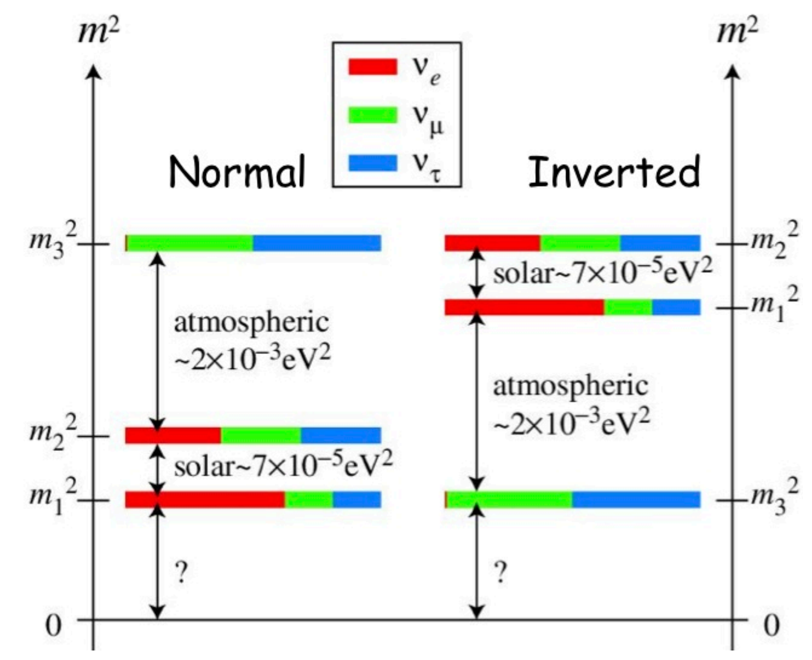
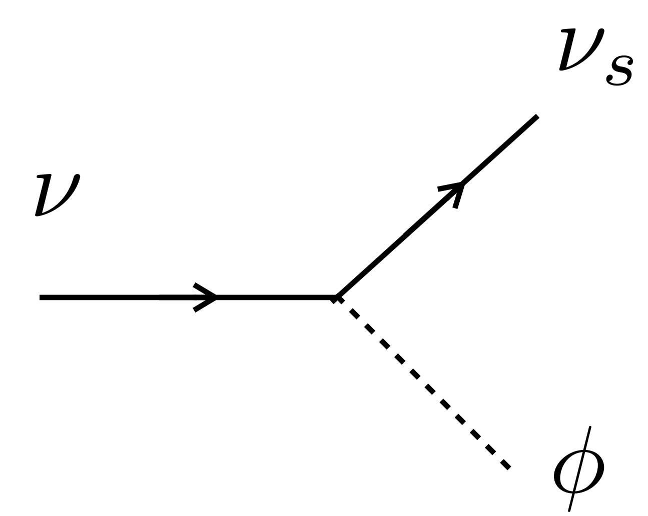
......

probe them in cosmology



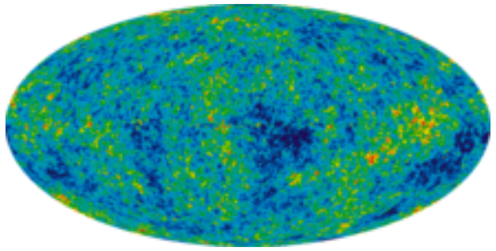




e.g. Majoron models

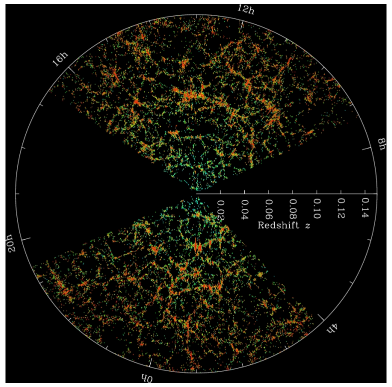
# Why cosmology?

**Best constraints on** $(m_\nu, \tau_\nu)$

**CMB** **LSS**



**Planck**




**SDSS**

**Huge number of neutrinos**

**Cosmological time/length**

**Neutrinos are non-relativistic**

# *Why cosmology?*

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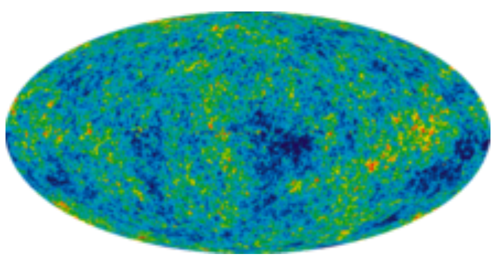

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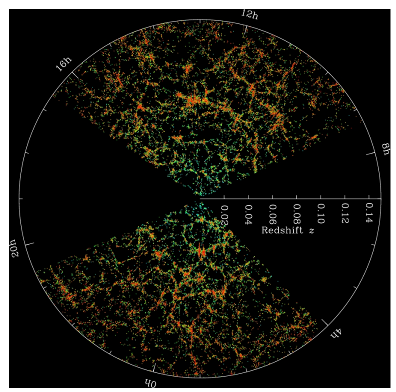


**SDSS**

**Huge number of neutrinos**

**Cosmological time/length**

**Neutrinos are non-relativistic**

**Near future is exciting!**

**CMB** | **LSS**


**CMB-S4**

**Euclid**

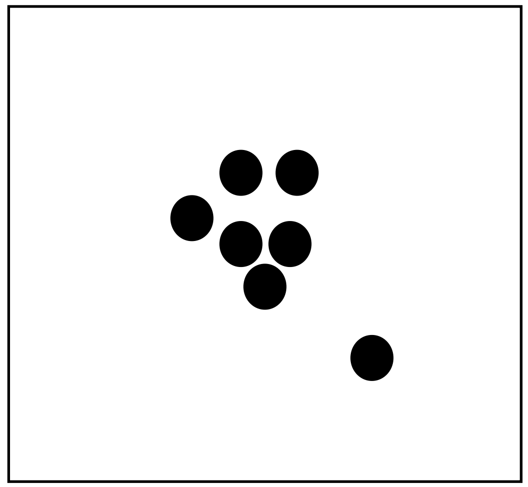
**Passing the threshold:**

$$\sigma(\sum m_\nu) \lesssim 0.02\,\mathrm{eV} < 0.06\,\mathrm{eV}$$

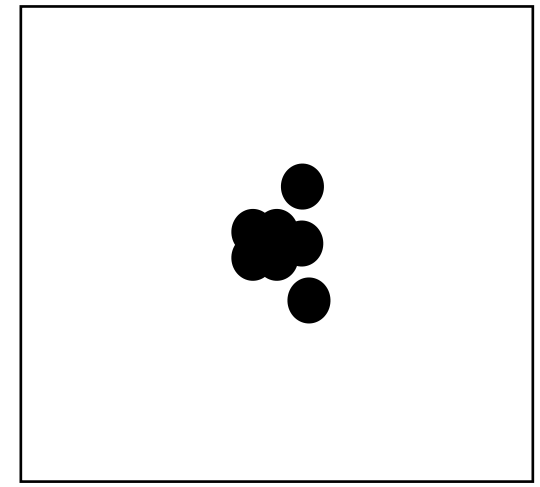
**"Guaranteed" evidence for $(m_\nu, \tau_\nu)$ or new physics**

# Massive neutrinos in structure formation

$$\delta \equiv \delta\rho/\rho$$



$$\Delta t \sim H^{-1}$$



● **Dark matter/baryon**

$$H \propto \sqrt{\Omega_{\mathrm{cdm+b}}}\, a^{-\frac{3}{2}}$$

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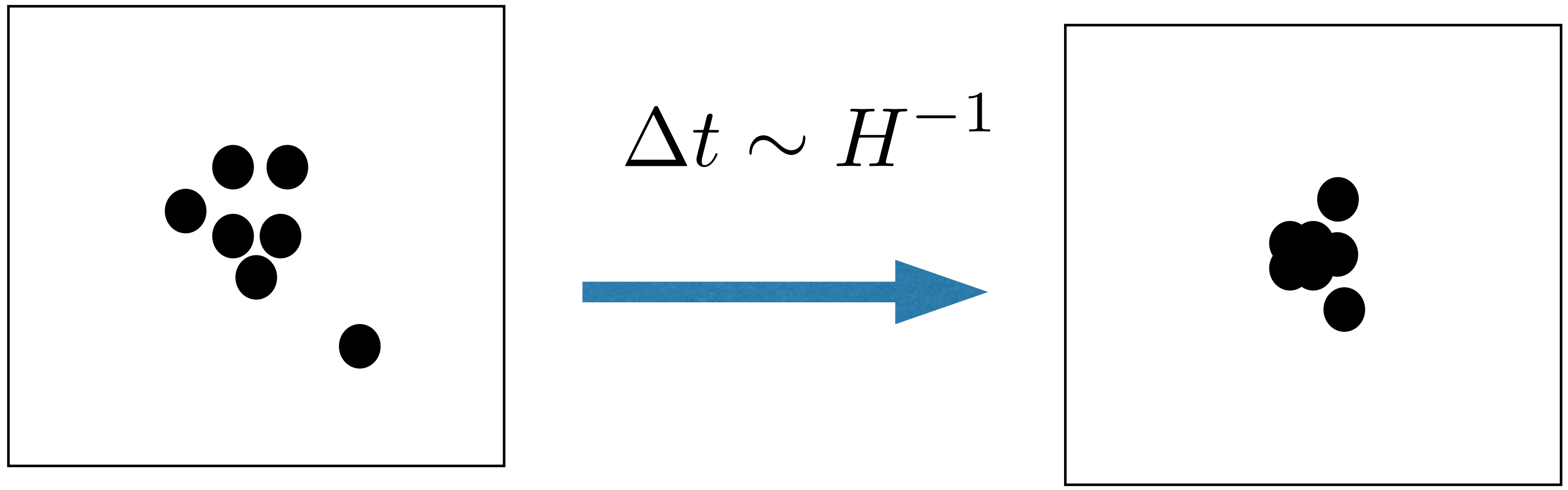


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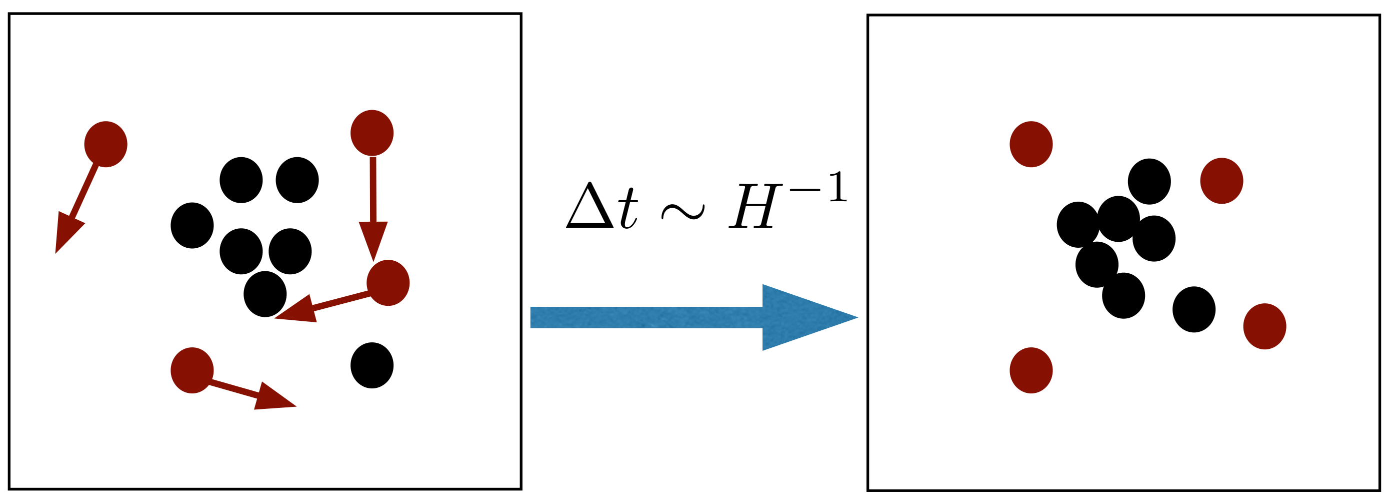



$\Delta t \downarrow$

$\delta_{\rm cdm} \downarrow$

● **Neutrinos**

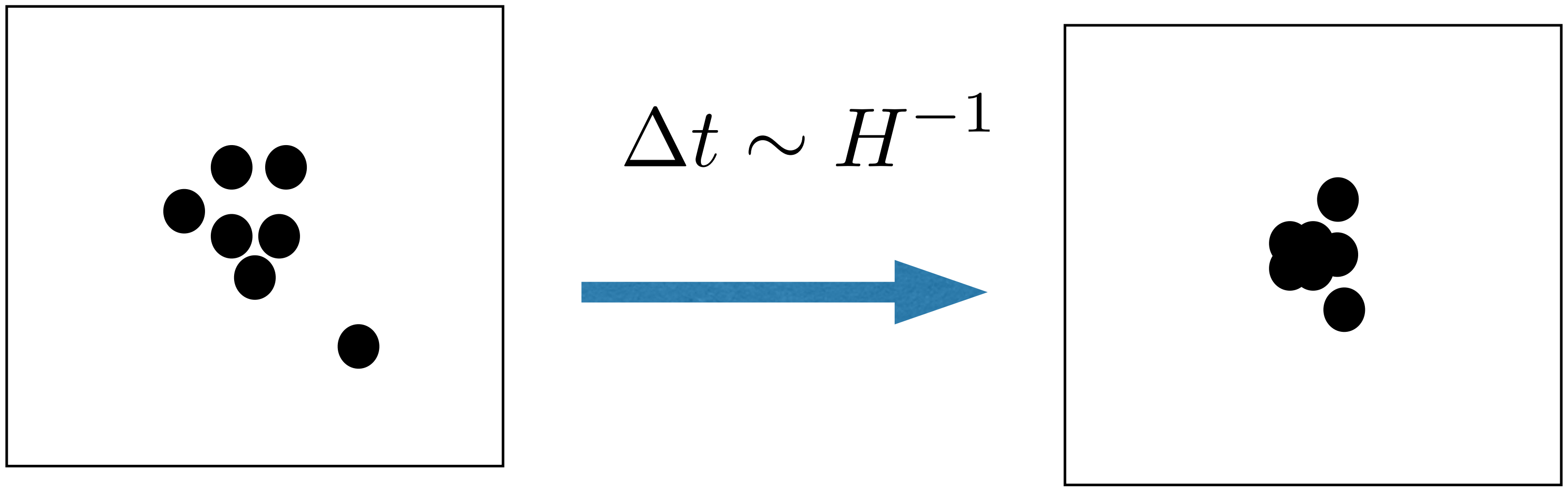
$$H \propto \sqrt{\Omega_{\rm cdm+b} + \Omega_\nu}\, a^{-\frac{3}{2}}$$

**Neutrinos don't clump efficiently** $\delta_\nu \ll \delta_{\rm cdm}$

**Increase H, shorten the time for CDM growth, suppress** $\delta_{\rm cdm}$

**Lesgourgues, Pastor 2006**

# Decaying neutrinos in structure formation



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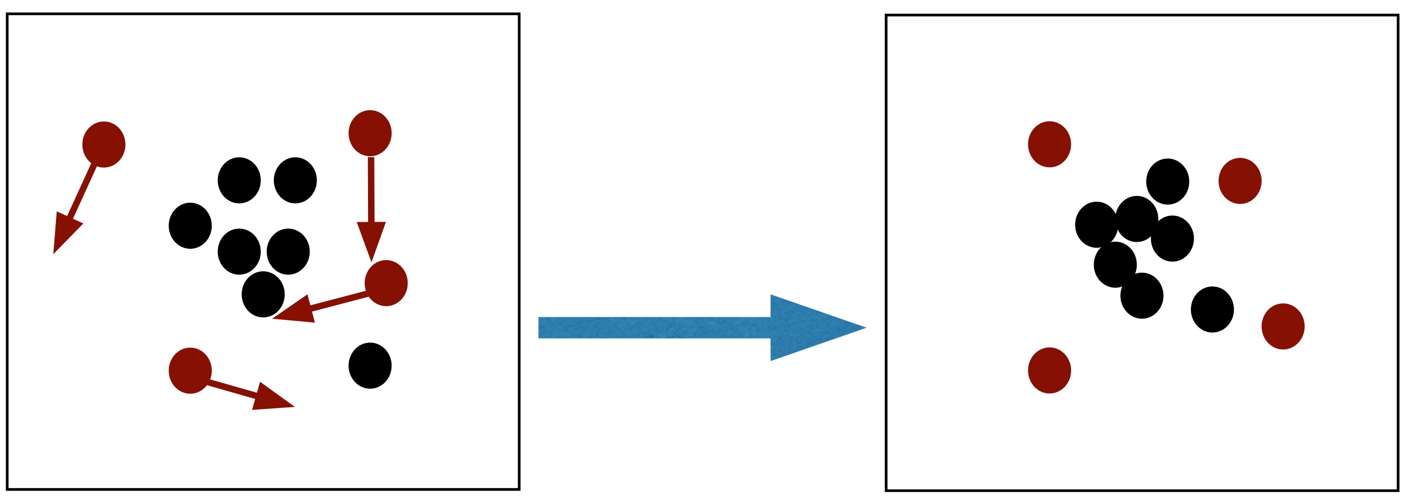

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$a$

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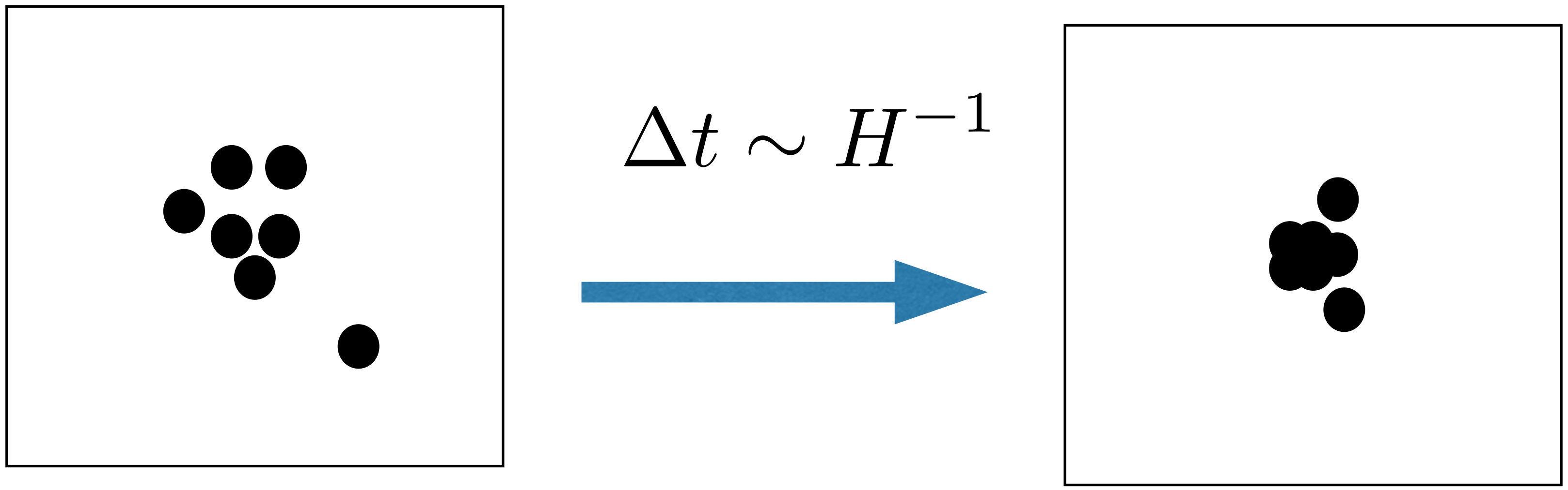

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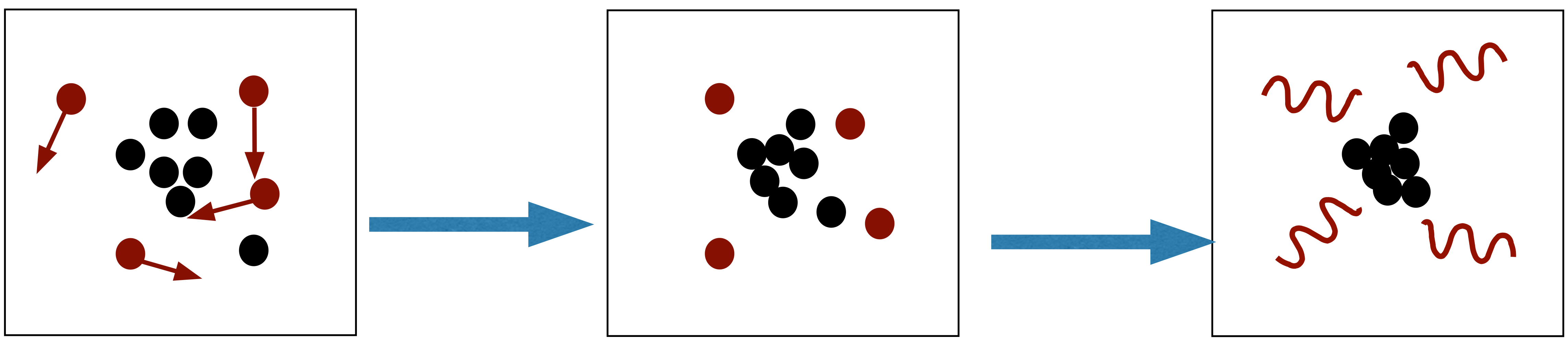
***Assuming daughter are massless***



● **Neutrinos**

**Daughter radiation**

$$H \propto \sqrt{\Omega_{\rm cdm+b} + \Omega_\nu}\, a^{-\frac{3}{2}}$$

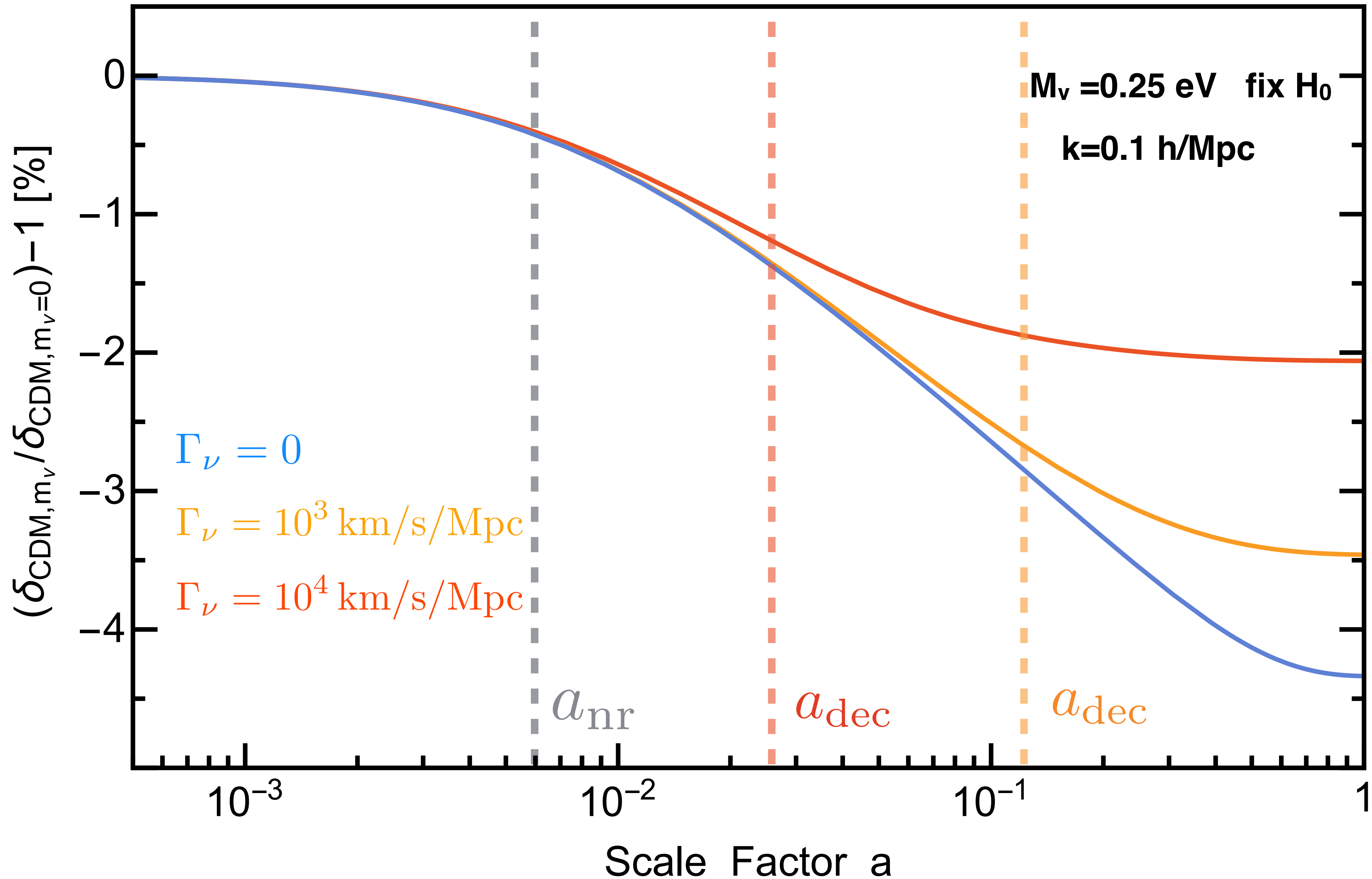
$$H \propto \sqrt{\Omega_{\rm cdm+b} + \frac{\Omega_\nu}{a}}\, a^{-\frac{3}{2}}$$


Serpico 2007

Serpico 2009

# Decaying neutrinos in structure formation

**Numerical simulation: modified CLASS code**




***degenerate neutrino masses and massless daughters***

Chacko, Dev, PD, Poulin, Tsai, 2019

# Massive neutrinos in structure formation

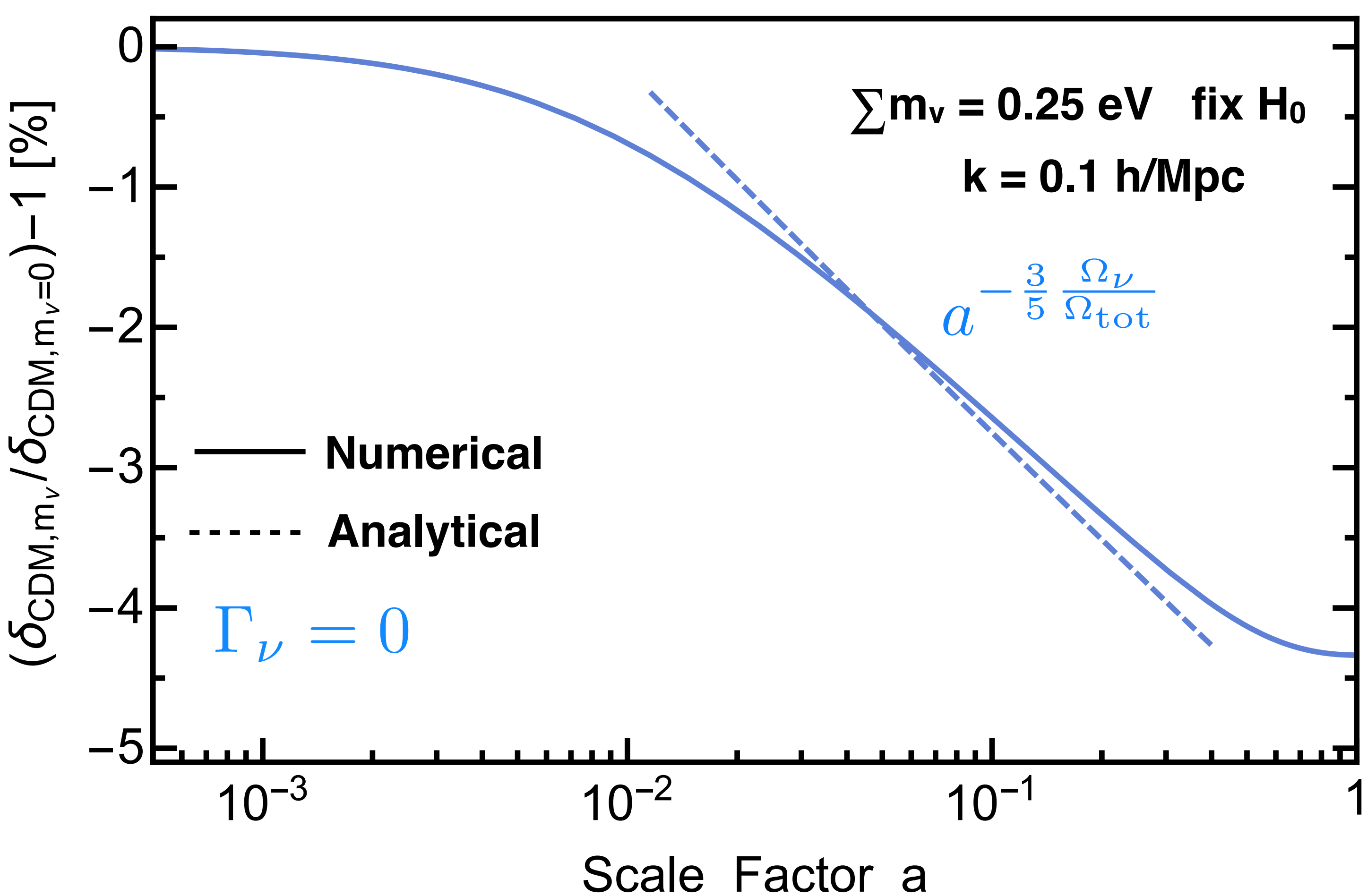
## Simple analytical estimation:

$\eta$ **conformal time**

$\Omega_{\rm tot} = \Omega_{\rm cdm+b} + \Omega_\nu$

$$\ddot{\delta}_{\rm cdm} + \frac{2}{\eta}\dot{\delta}_{\rm cdm} \approx \frac{6}{\eta^2}\left(1 - \frac{\Omega_\nu}{\Omega_{\rm tot}}\right)\delta_{\rm cdm}$$

$$\delta_{\rm cdm}(a) \sim a^{1-\frac{3}{5}\frac{\Omega_\nu}{\Omega_{\rm tot}}} \Rightarrow \quad \frac{\delta_{\rm cdm}^{m_\nu}(a)}{\delta_{\rm cdm}^{m_\nu=0}(a)} = \left(\frac{a}{a_i}\right)^{-\frac{3}{5}\frac{\Omega_\nu}{\Omega_{\rm tot}}}$$



# Decaying neutrinos in structure formation

Chacko, Dev, PD, Poulin, Tsai, 2019

## Improved analytical estimation:

$$\ddot{\delta}_{\rm cdm} + \frac{2}{\eta}\dot{\delta}_{\rm cdm} \approx \frac{6}{\eta^2}\left(1 - \frac{\Omega_\nu(\eta)}{\Omega_{\rm tot}}\right)\delta_{\rm cdm} \quad \Rightarrow \quad \frac{\delta^{m_\nu}_{\rm cdm}(a)}{\delta^{m_\nu=0}_{\rm cdm}(a)} \propto \exp\left[-\frac{3}{5}\int_{a_i}^{a}\frac{da}{a}\frac{\Delta\Omega_\nu(a)}{\Omega_{\rm tot}}\right]$$

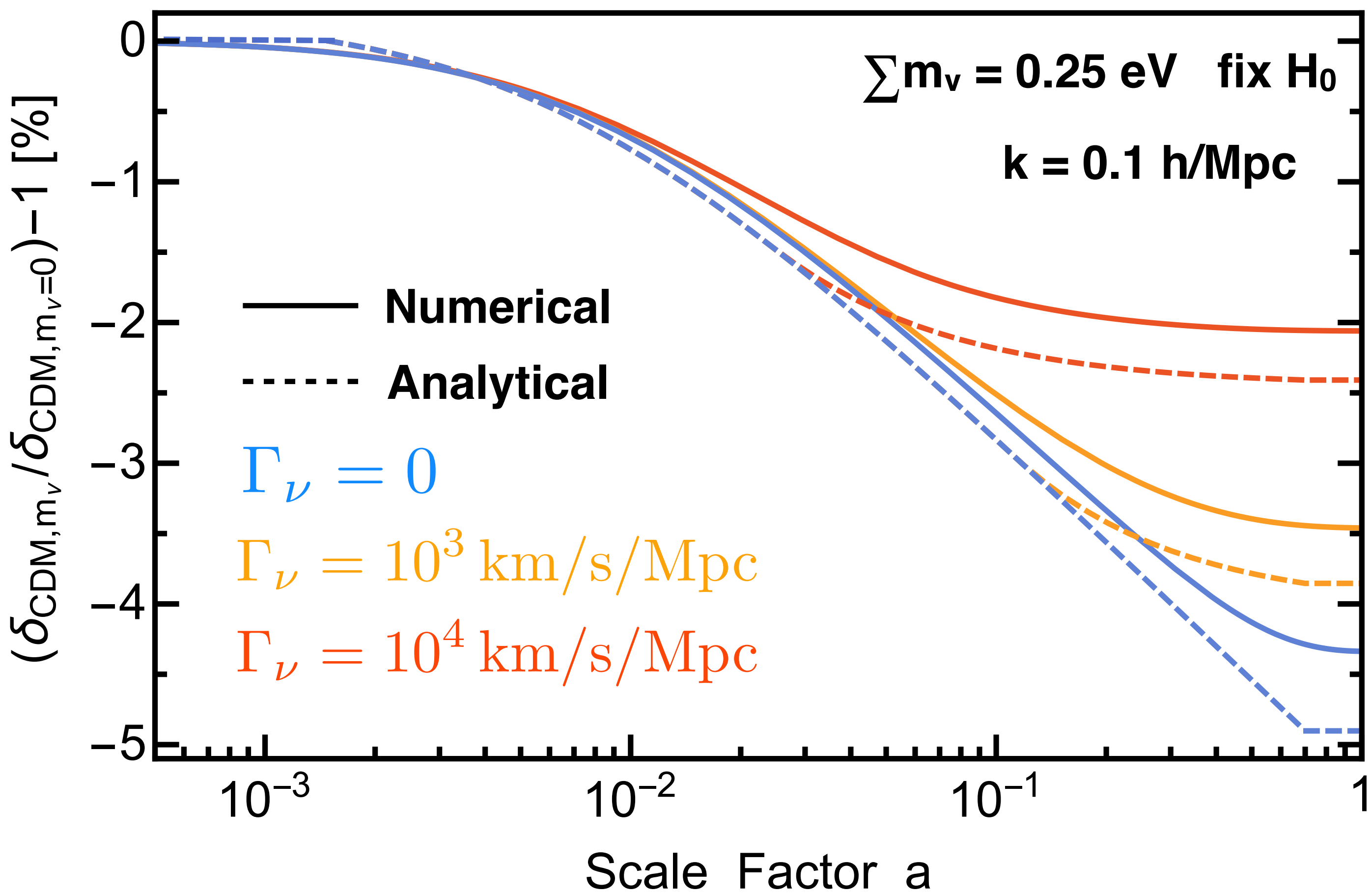
$$\Delta\Omega_\nu(a) \propto \frac{1}{a}\int_0^\infty dy y^2\left(\epsilon_{m_\nu}(y) - \epsilon_{m_\nu=0}(y)\right) f_\nu(y) \begin{cases} 1 & (a < a_{\rm dec}) \\ \left(\frac{a_{\rm dec}}{a}\right) & (a \geq a_{\rm dec}) \end{cases}$$

$$y \equiv \frac{q}{T_\nu} \quad f_\nu(y) = \frac{1}{e^y + 1}$$

$$\epsilon_{m_\nu}(y) = \sqrt{y^2 + \left(\frac{m_\nu}{T_\nu}\right)^2 a^2}$$

Difference in energy

Effect of decay



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Chacko, Dev, PD, Poulin, Tsai, 2019

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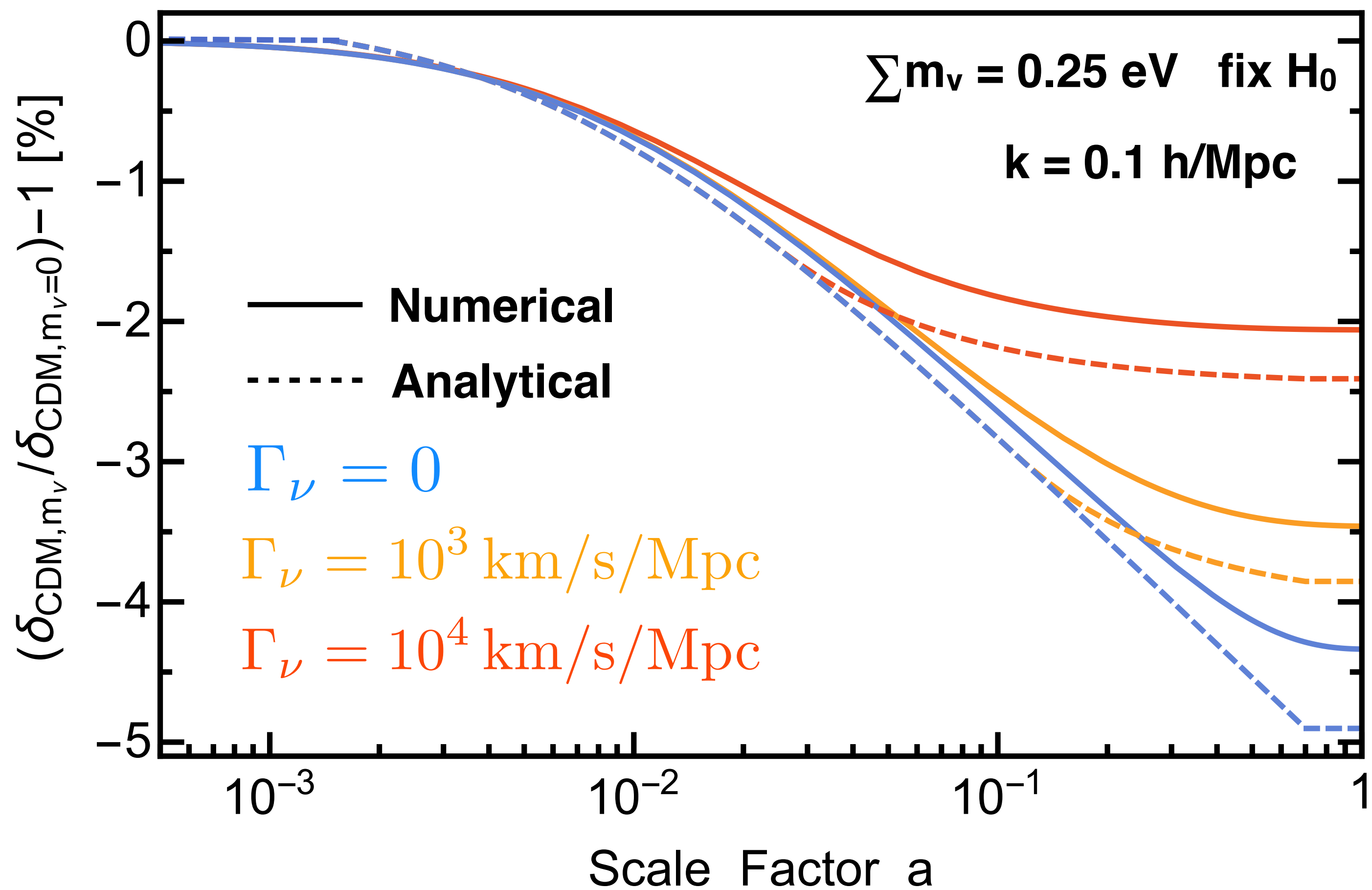
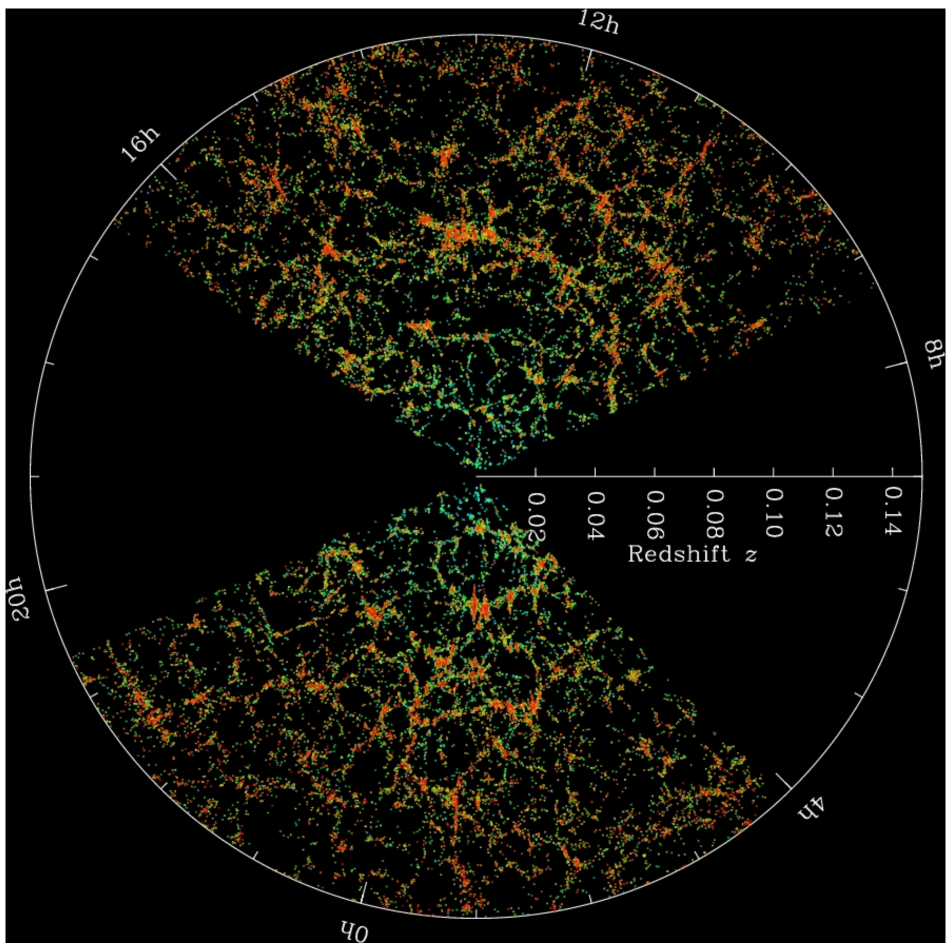



**Decaying neutrinos affects $\delta_{\rm cdm}$ mostly through their background energy (modifying H)**

# *Cosmological signals of decaying neutrino*

**Matter Power Spectrum**

$$P_{cb} \sim \langle \delta_{\rm cdm} \delta_{\rm cdm} \rangle$$



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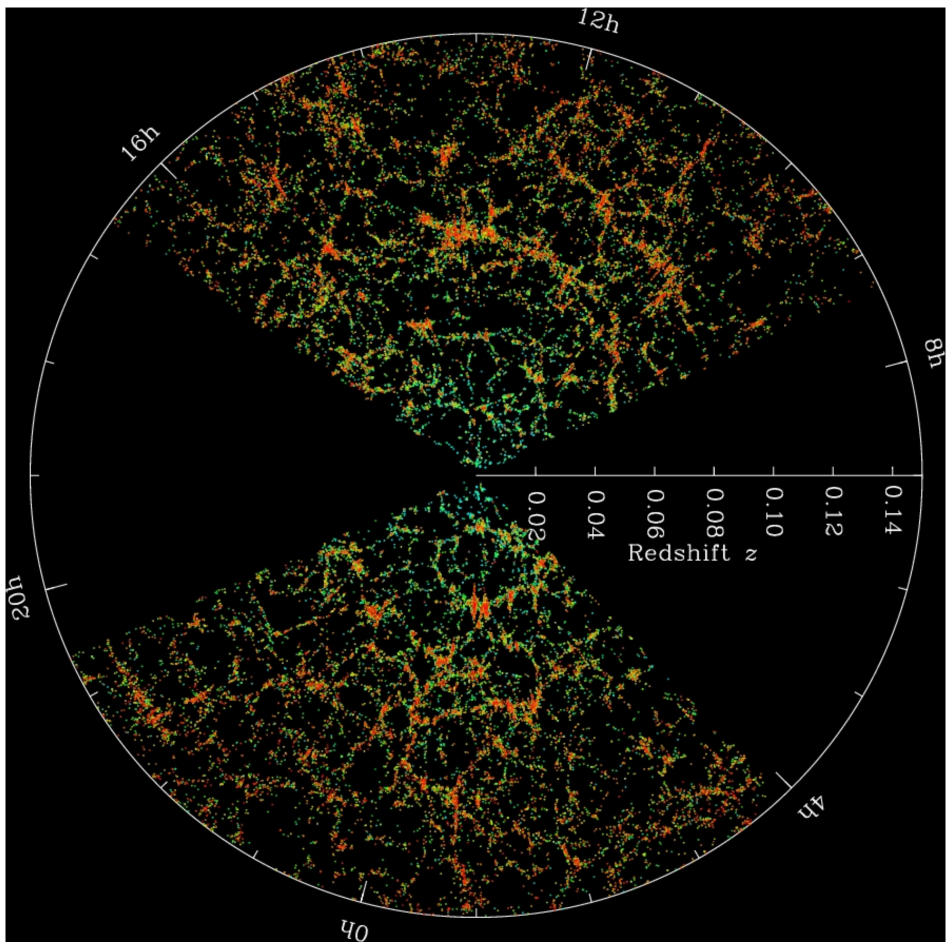
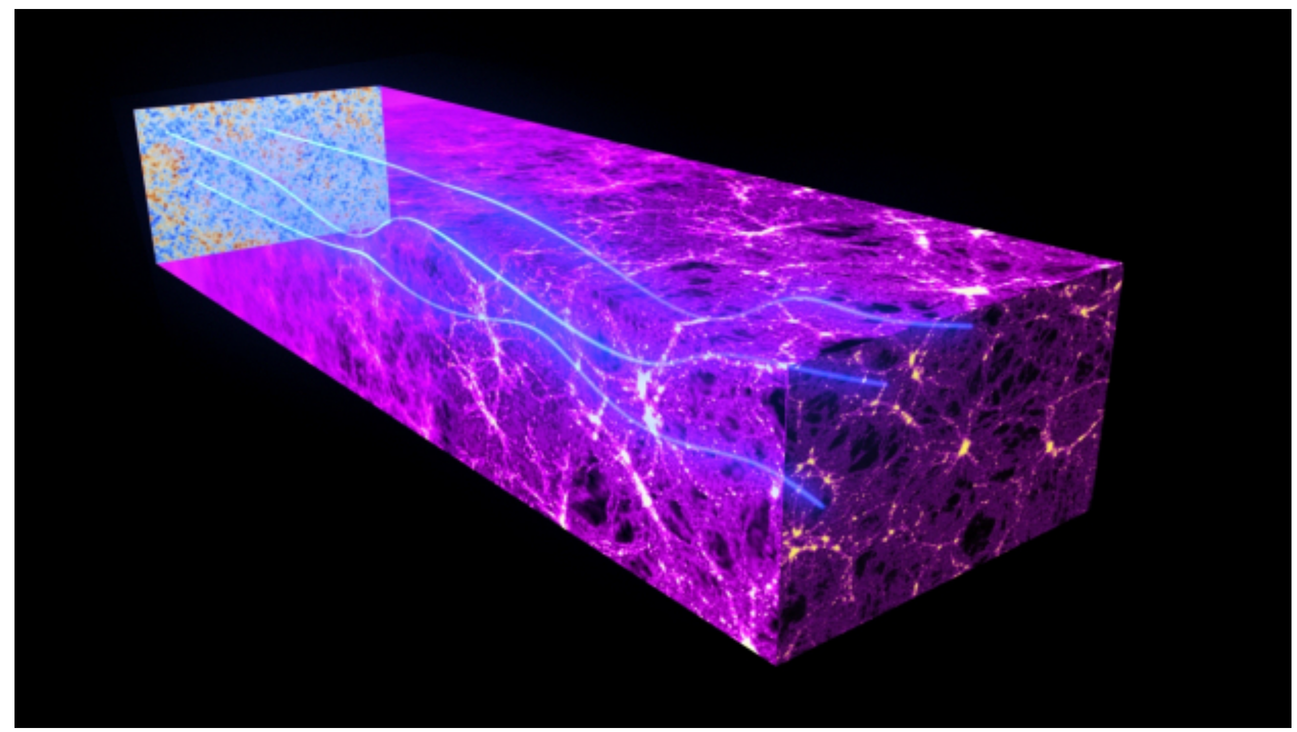



**CMB Lensing**

$$C_\ell^{\phi\phi} \sim \langle \phi\phi \rangle$$



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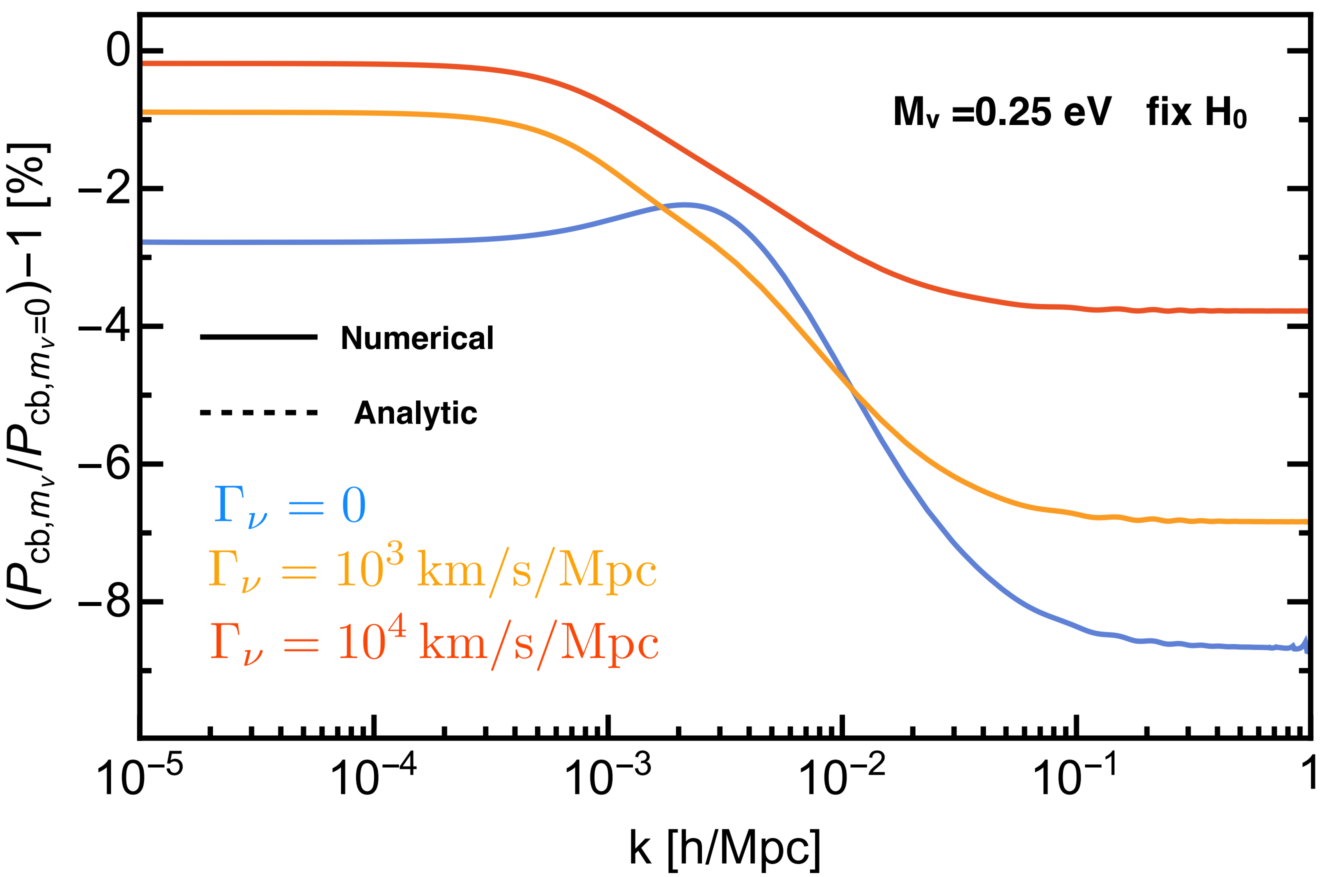


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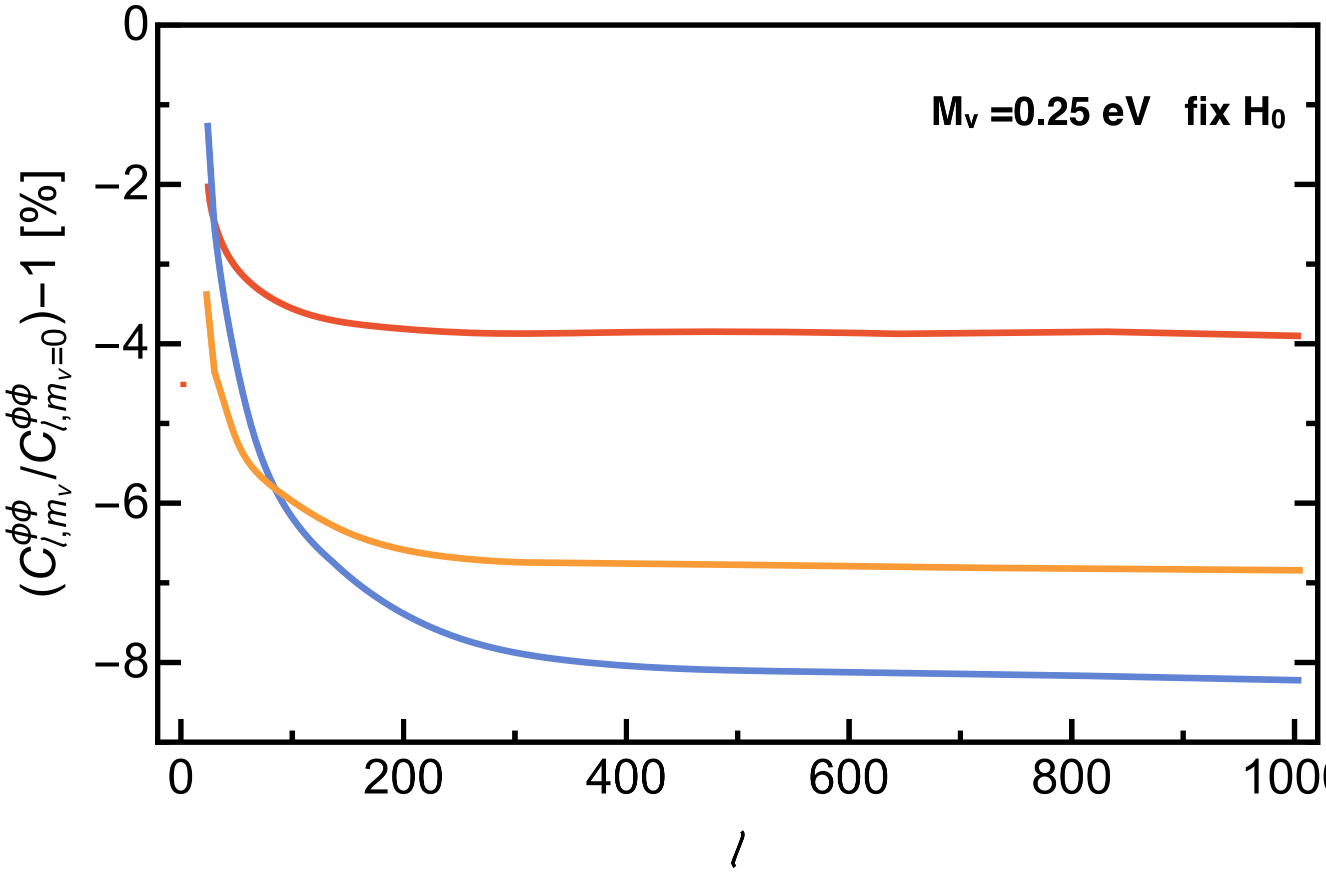


# 2D parameter space

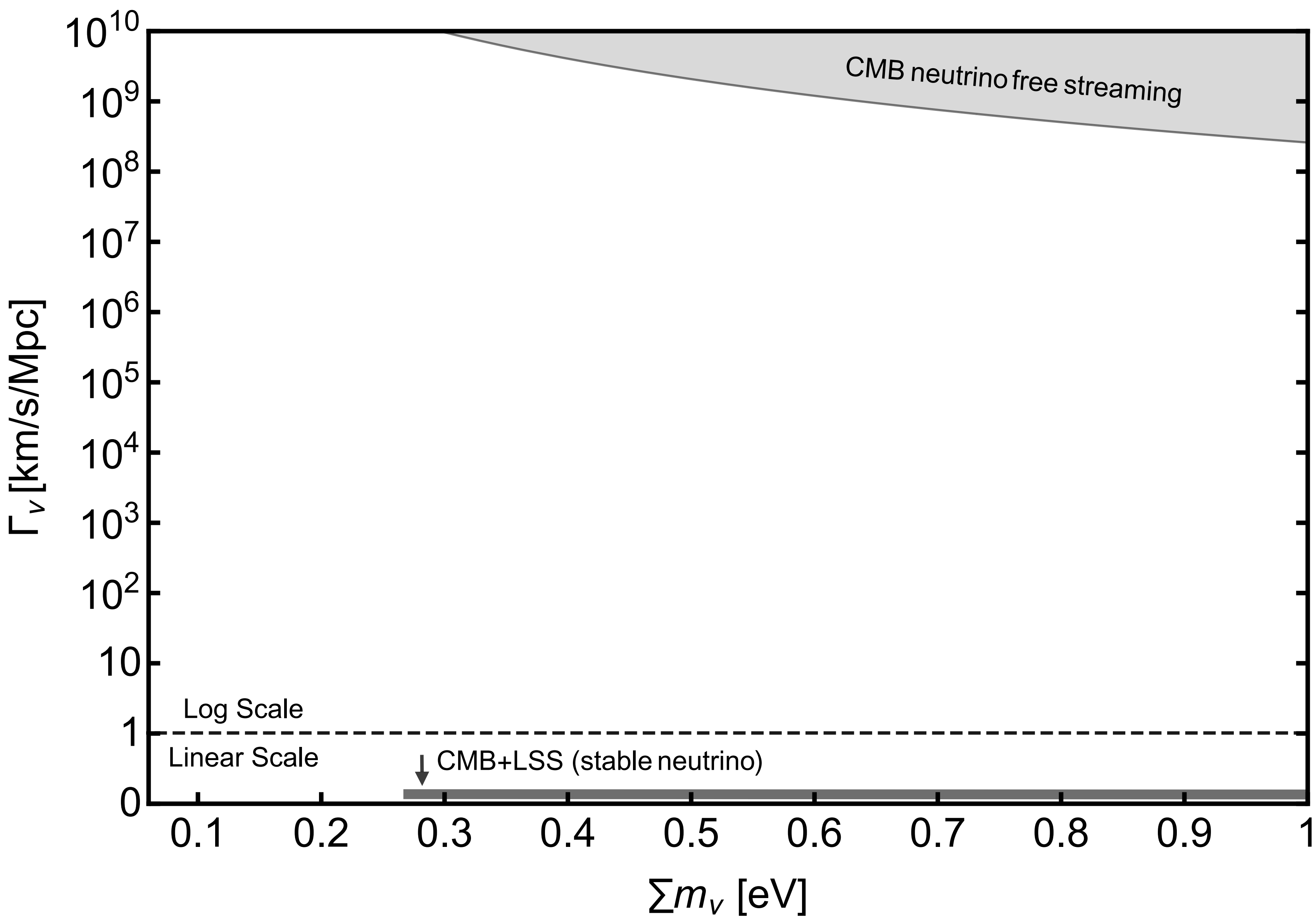
## Existing constraints:

**Non-radiative decay lifetime: CMB neutrino free streaming**

Archidiacono, Hannestad 2014
Escudero, Fairbairn 2019

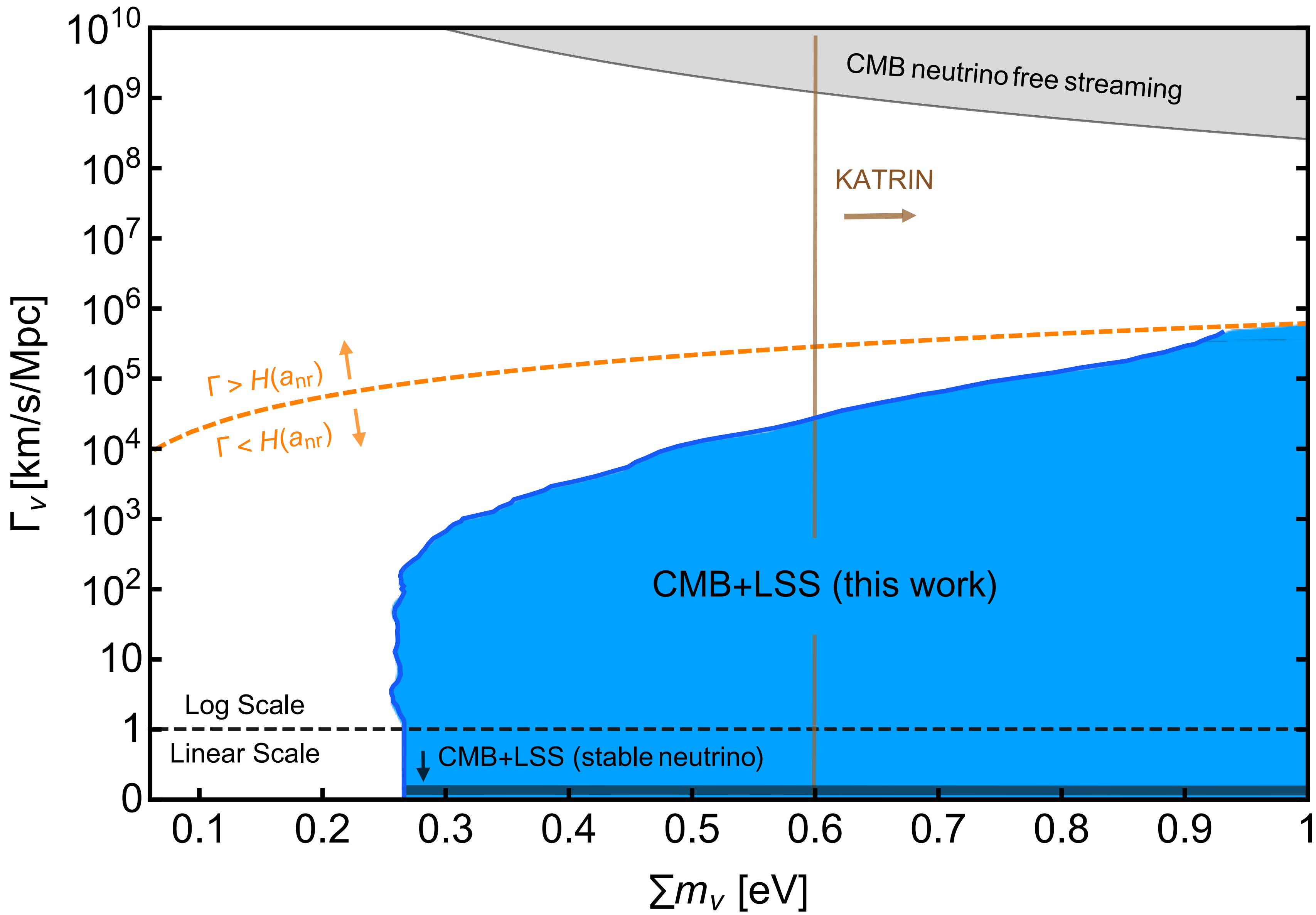
**Total mass:** $\sum m_\nu < 0.25\,\mathrm{eV}$ **Planck 2015+BAO+LSS**

Assuming neutrinos are stable

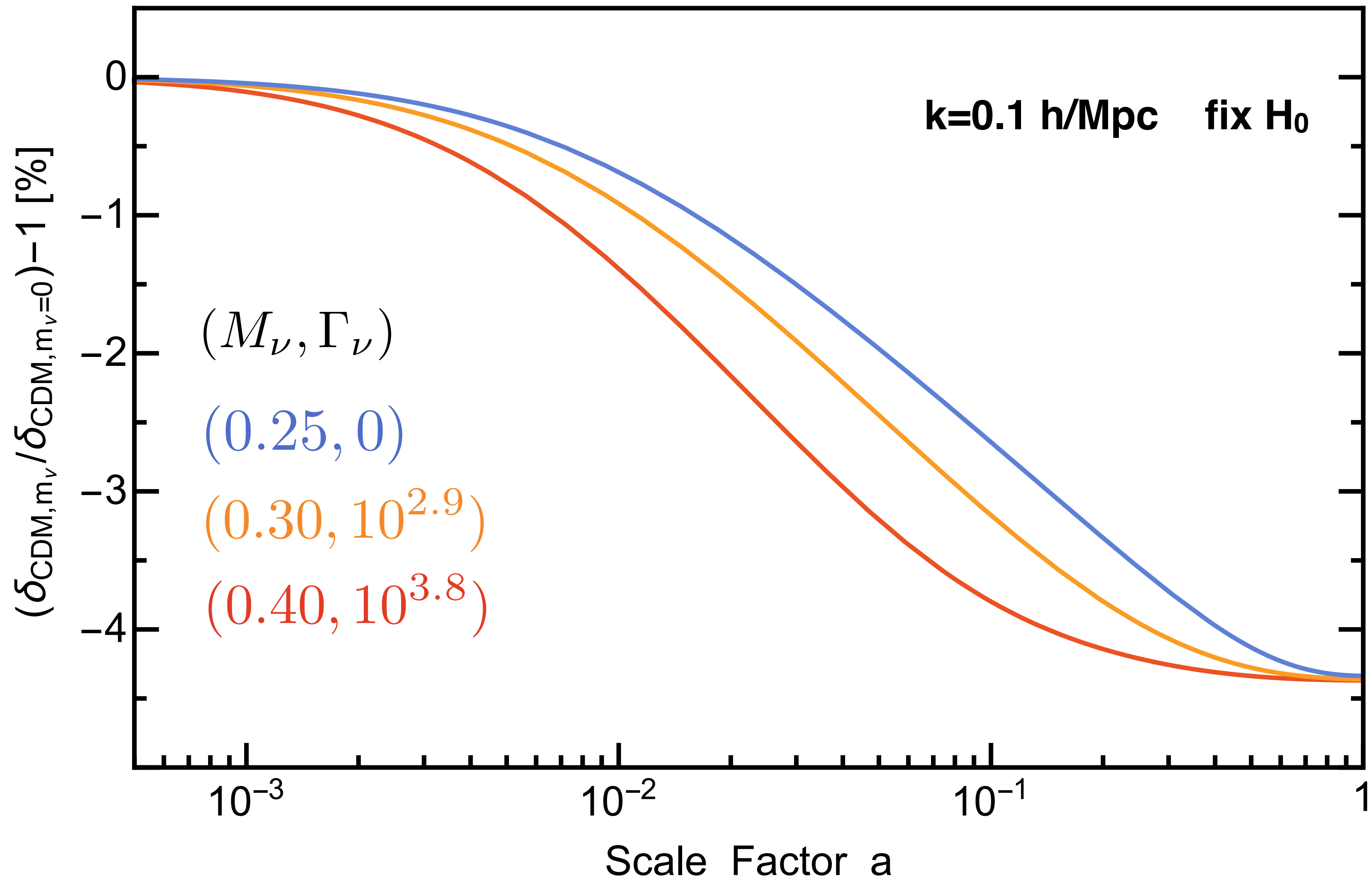


# 2D parameter space

- **The best exclusion for non-radiative decay neutrino lifetime!**
- **Interplay with terrestrial neutrino mass measurements: e.g KATRIN**

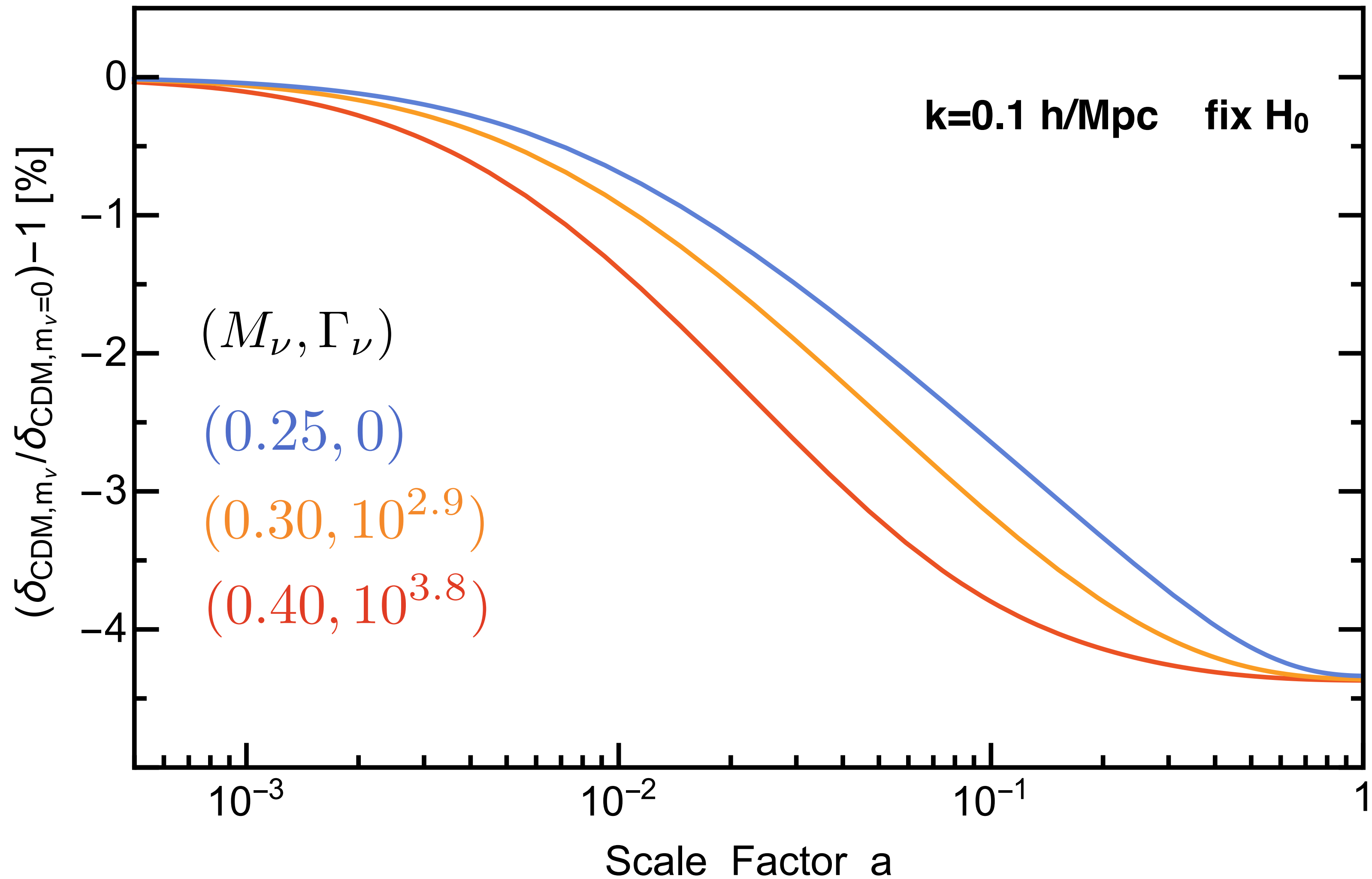


# Degeneracy in mass and lifetime




**Can we measure** $M_\nu$ **,** $\Gamma_\nu$ **independently ?**

# *Degeneracy in mass and lifetime*



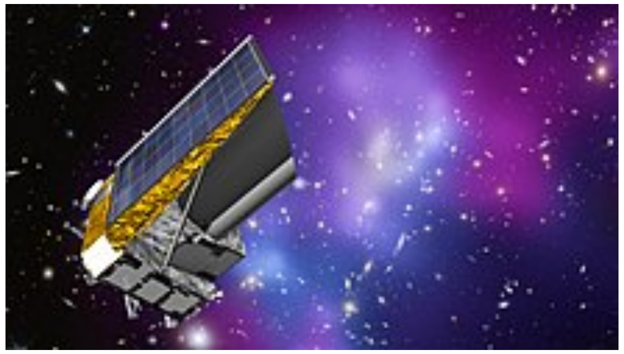

**Can we measure $M_\nu$ , $\Gamma_\nu$ independently ?**

**Resolution:**

- **Need measurements at earlier time/ higher redshift z**
- **Need precision $\lesssim 1\%$**

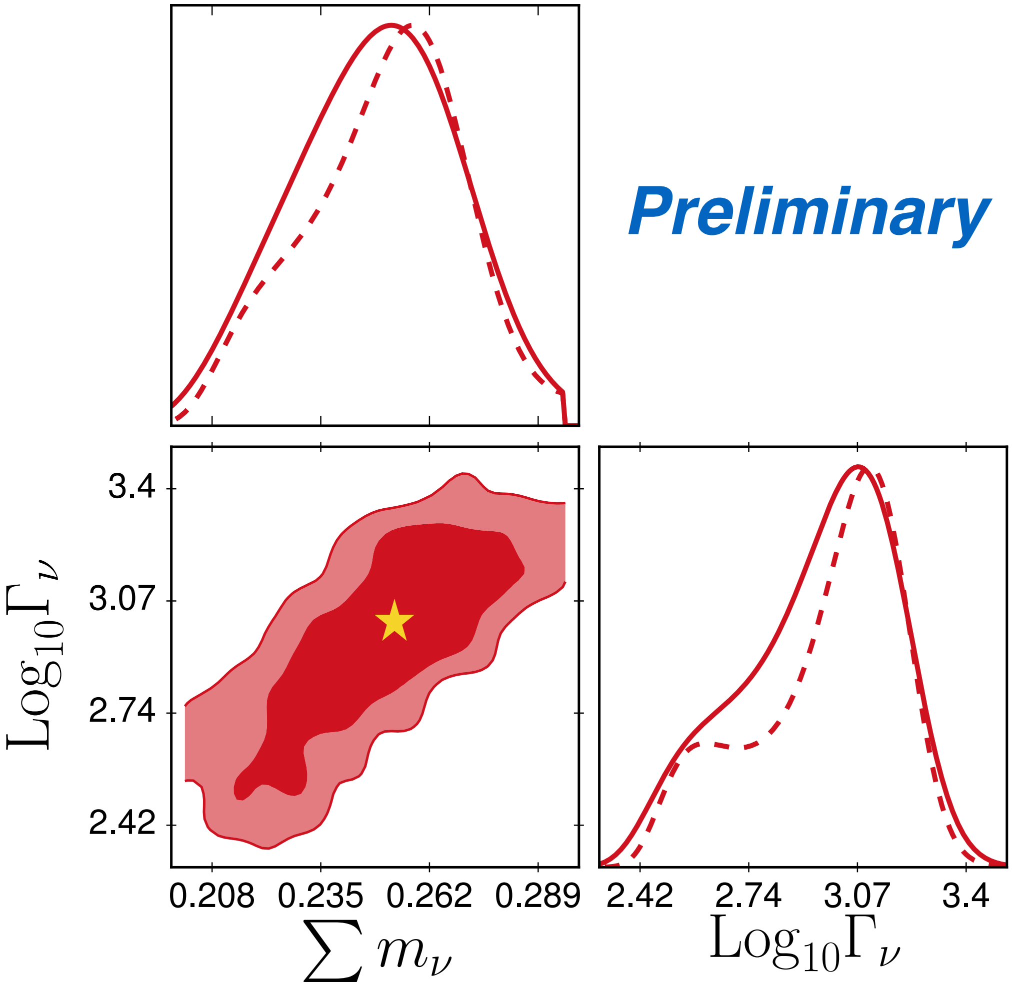
# *Breaking the degeneracy*

Chacko, Dev, PD, Poulin, Tsai (to appear)



**Euclid 2022**

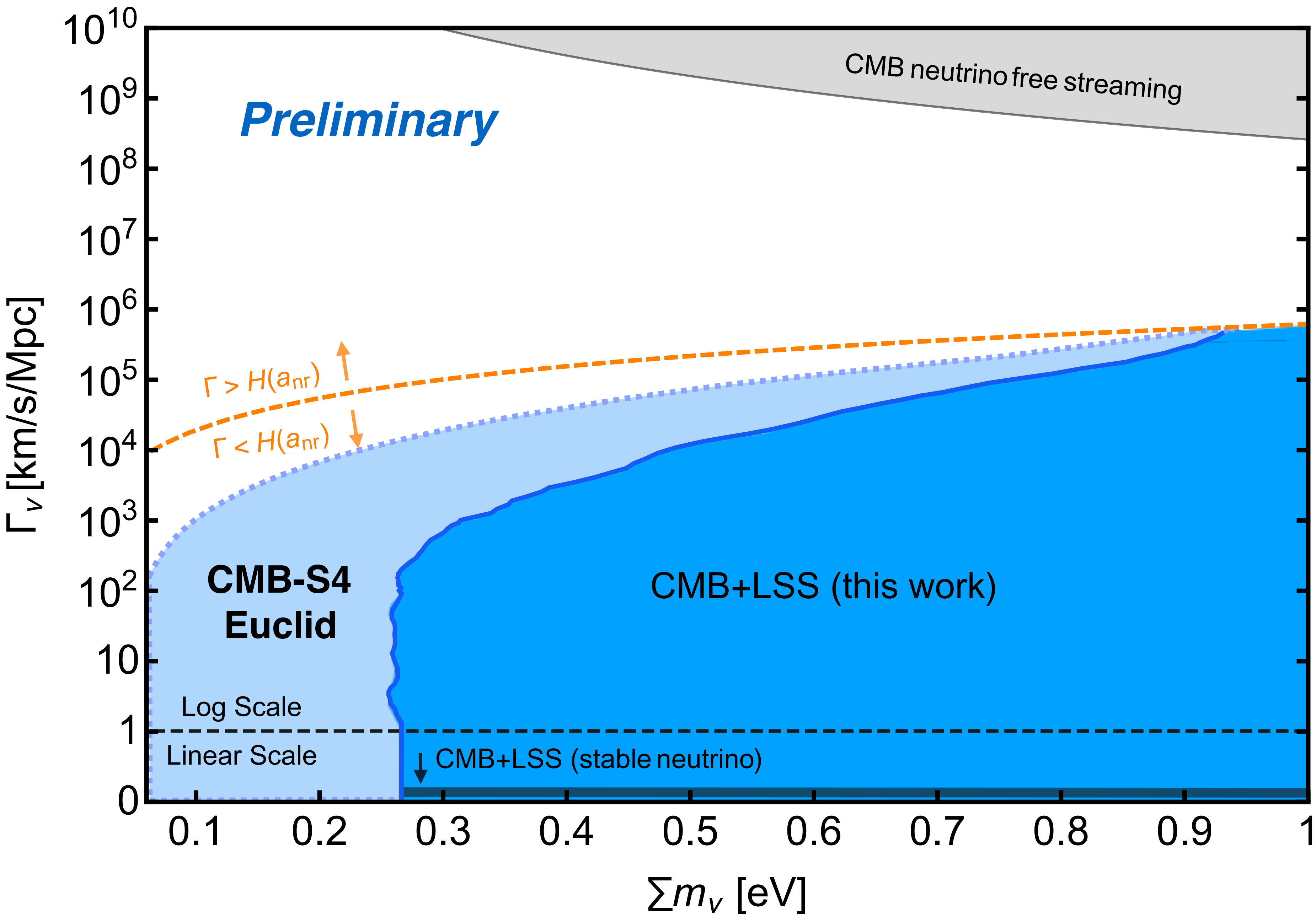
- **can probe** $0.5 \lesssim z \lesssim 2$
- **from 2D map to 3D map**
- **with ~ 0.1 - 1% precision**




**For mock data**
$$\sum m_\nu = 0.25\,\mathrm{eV}$$
$$\Gamma_\nu = 10^3\,\mathrm{km/s/Mpc}$$

# *Future experiments*

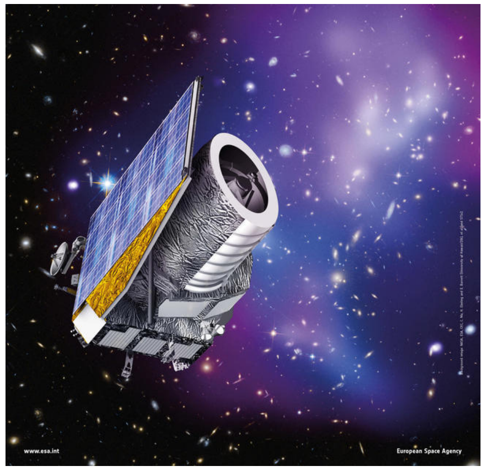
- **Cover all regions of stable neutrino**
- **CMB-S4+Euclid can measure $M_\nu$ ,$\Gamma_\nu$ independently**



# *Conclusions*

- The non-radiative decay lifetime of neutrino is hard to probe.
- Current CMB and LSS data place the best constraint on both neutrino mass and lifetime
- Near future experiments could break the degeneracy and measure the mass and lifetime separately.

DESI (2019)



Euclid (2022)

LSST (2023)


CMB-S4 (2020s)

**Near future precision cosmology can tell us a lot about neutrino physics and much more!**


BROOKHAVEN FORUM 2019
PARTICLE PHYSICS AND
COSMOLOGY IN THE
2020s
September 25–27, 2019
Brookhaven National Laboratory
Upton, NY USA

*Thank you!*