# Large Scale Structure Signals of Neutrino Decay

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University of Maryland

Phenomenology 2019
University of Pittsburgh

based on the work with Zackaria Chacko, Abhish Dev, Vivian Poulin, Yuhsin Tsai (to appear)

# *Motivation*

## SM neutrinos:

**We have detected neutrinos 50 years ago**

**Least known particles in the SM**

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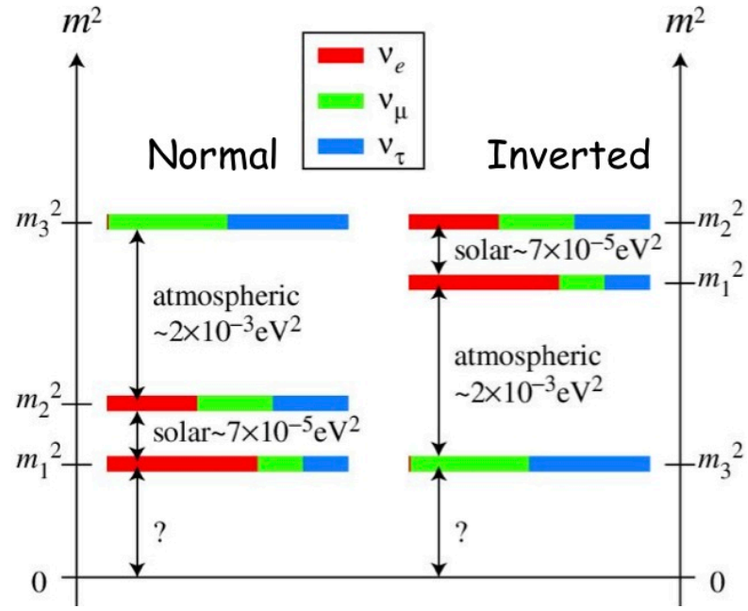


## What we don't know:

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

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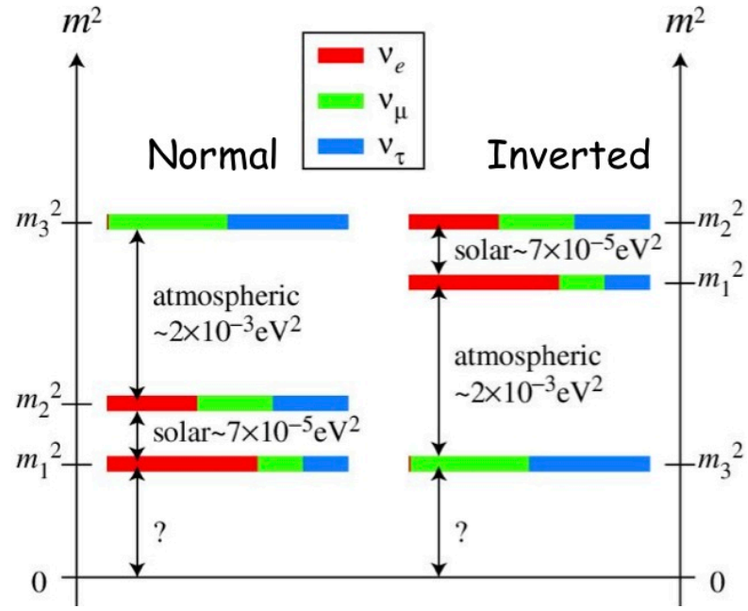


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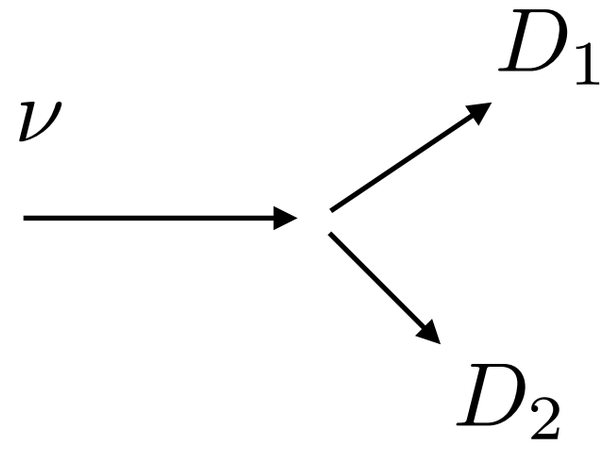

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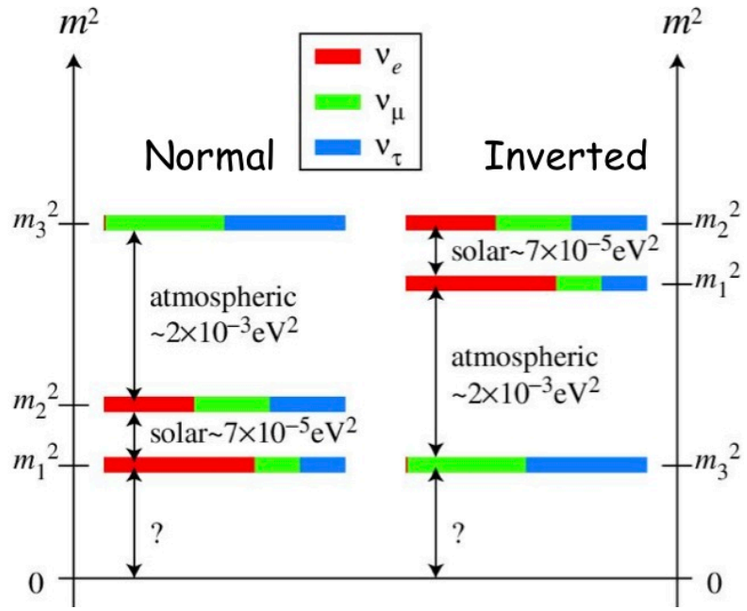


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**probe them in cosmology**

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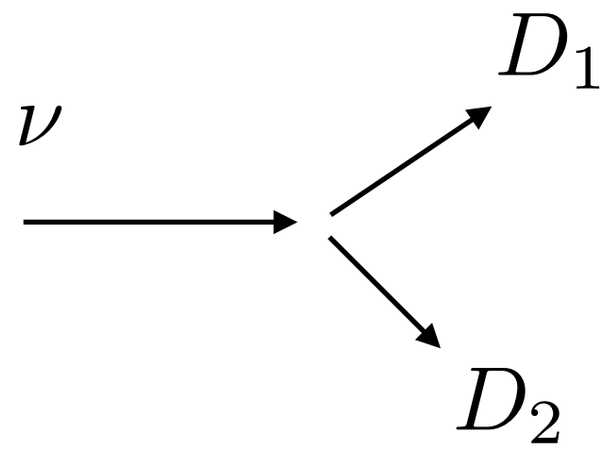
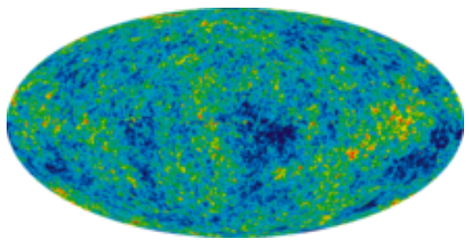
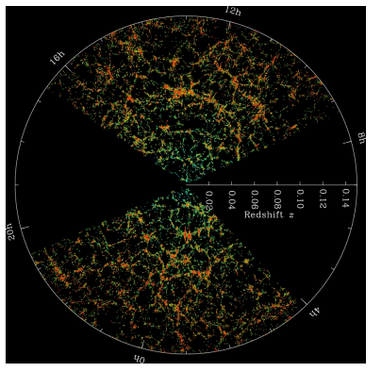


# *Why cosmology?*

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

| **CMB** | **LSS** |
| --- | --- |
|  |  |
| **Planck** | **SDSS** |

**Huge number of neutrinos**

**Neutrinos are non-relativistic**

**Cosmological time/length**

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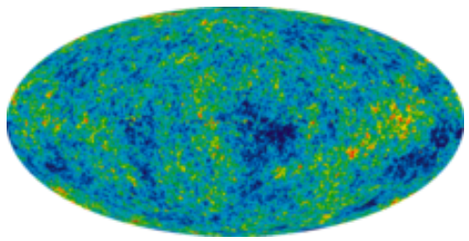

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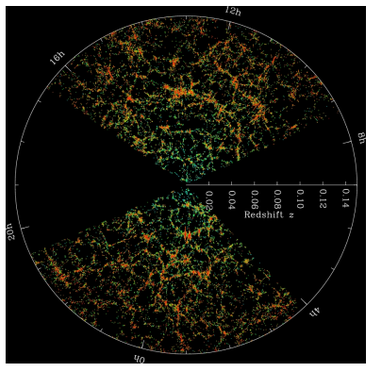
**LSS**




**SDSS**

**Huge number of neutrinos**

**Neutrinos are non-relativistic**

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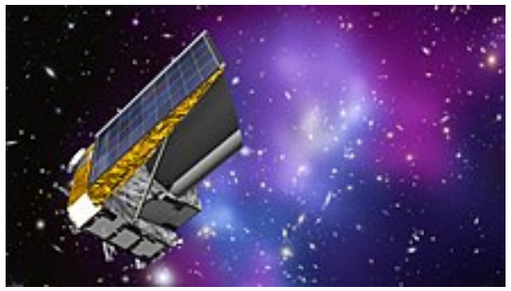
## Near future is exciting!

**CMB**


**CMB-S4**

**LSS**



**Euclid**

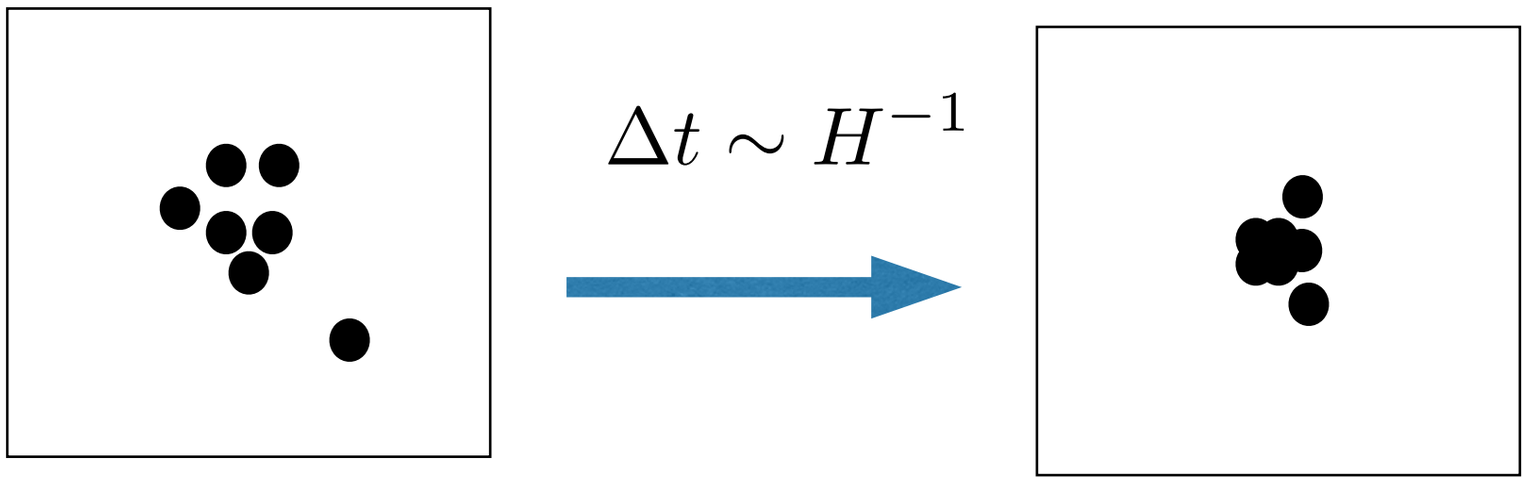
**Passing the threshold:**

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

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

# Massive neutrinos in structure formation

$$\delta_{\rm cdm} \equiv \delta\rho_{\rm cdm}/\rho_{\rm cdm}$$




**Dark matter/baryon**

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

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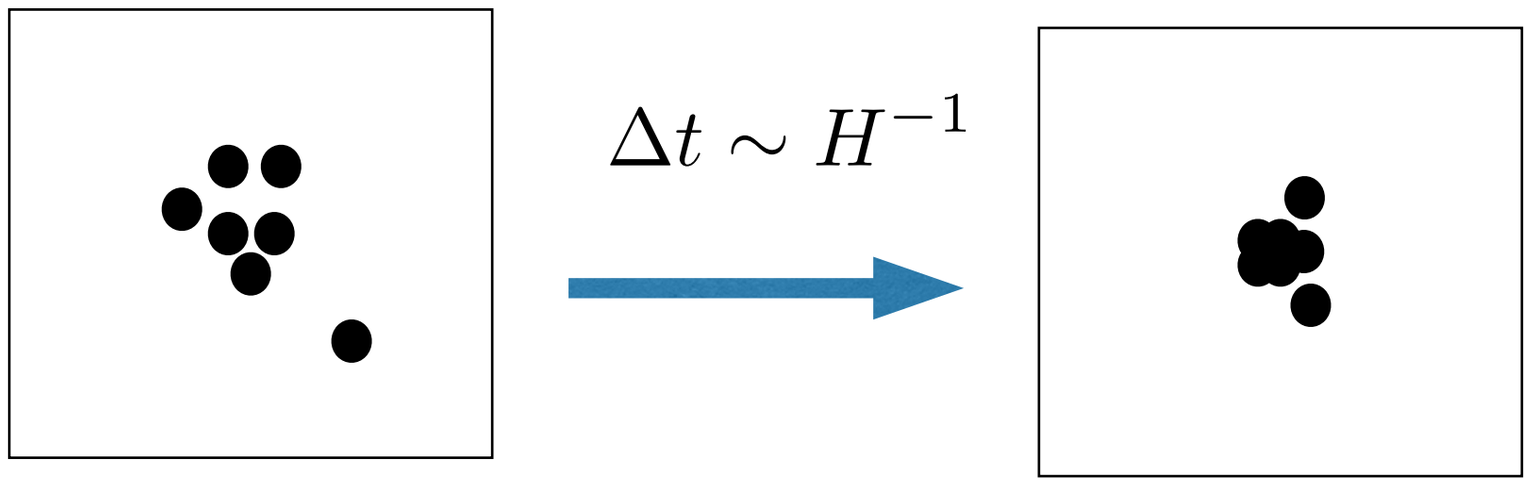


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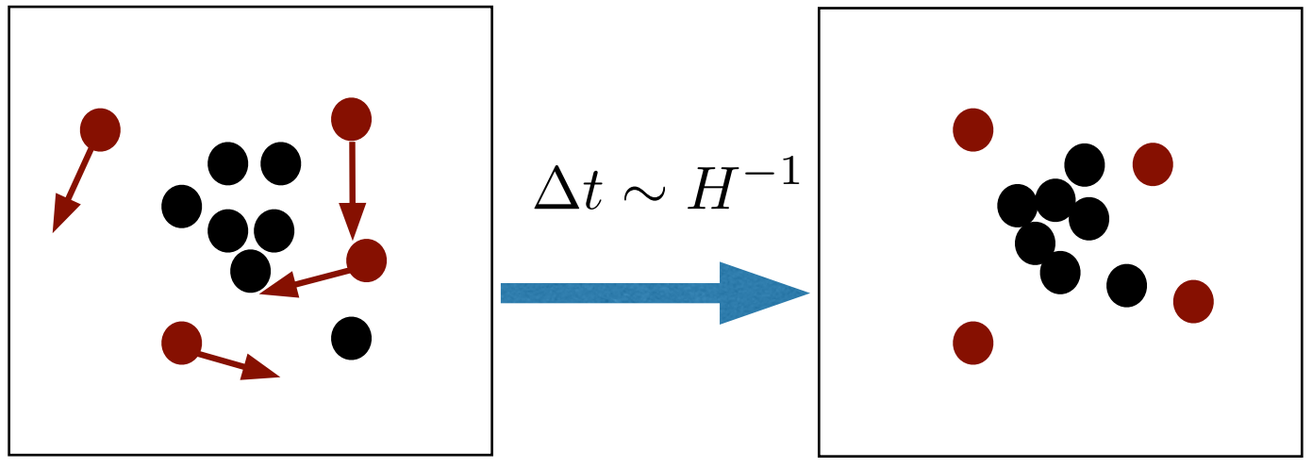



$\Delta t$ ↓

$\delta_{\rm cdm}$ ↓

- **Neutrinos**

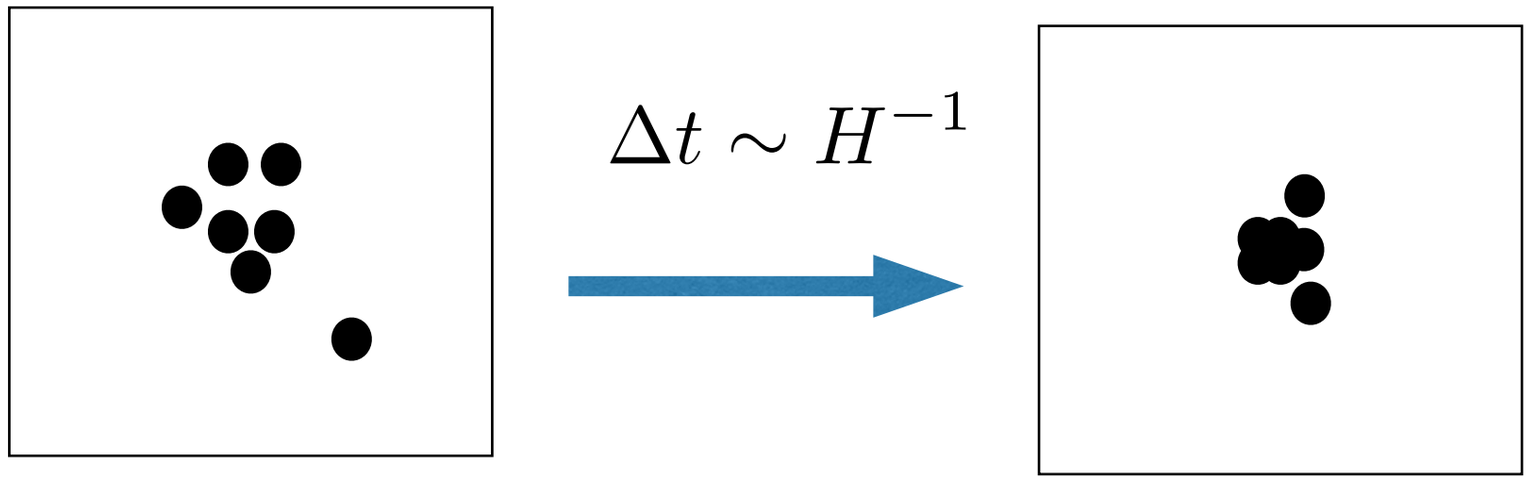
$$H \propto \sqrt{\Omega_{\rm cdm+b} + \Omega_\nu}\, a^{-\frac{3}{2}}$$

**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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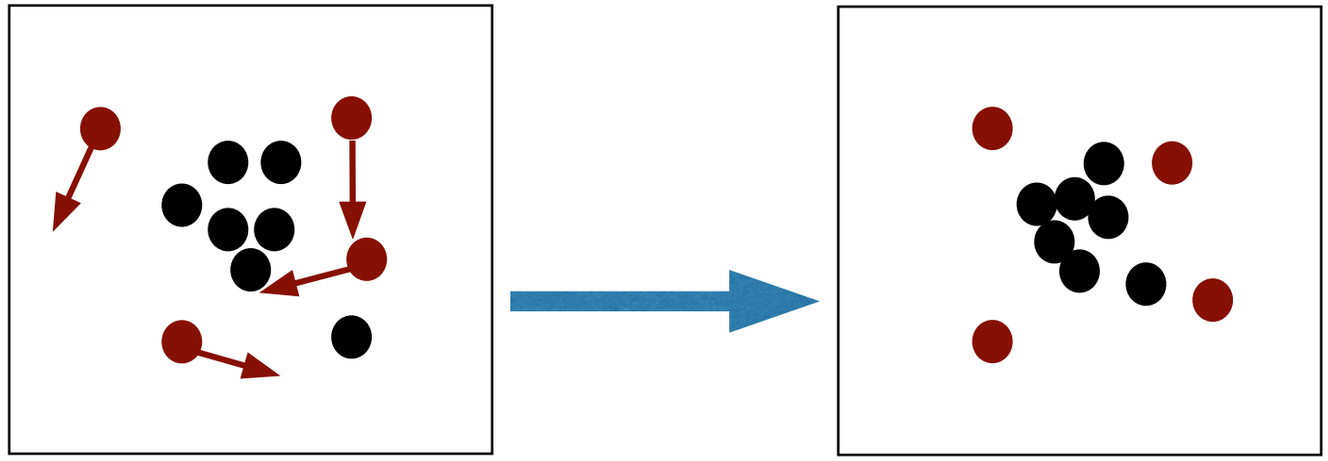

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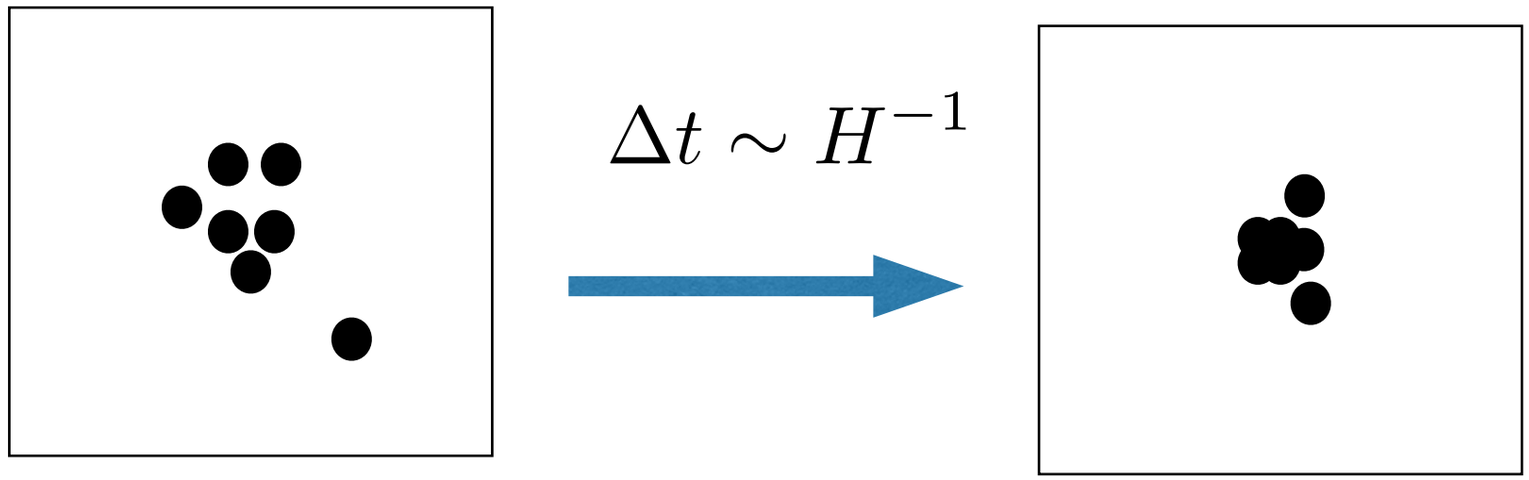


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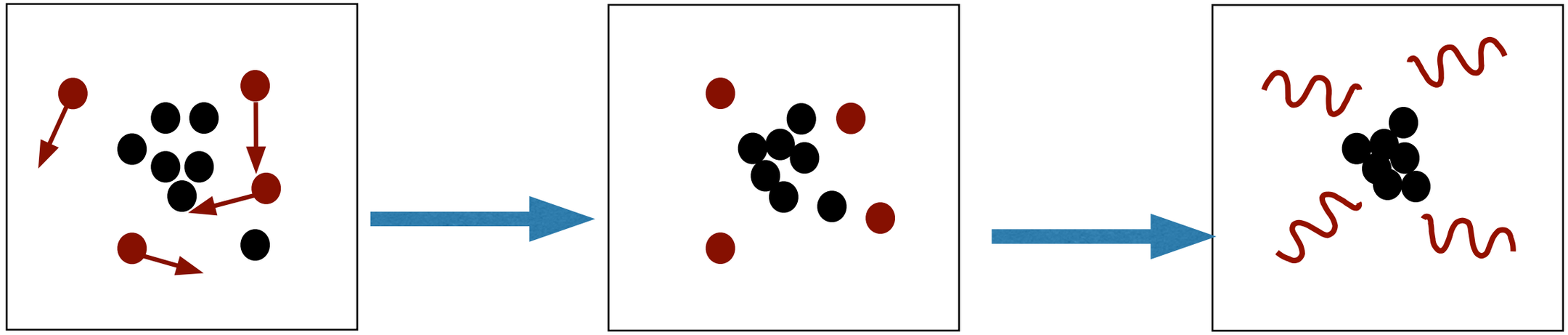
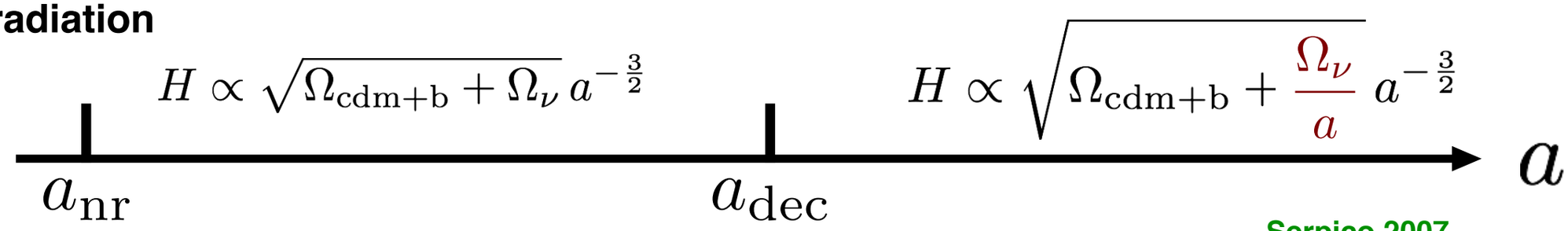
***Assuming daughter are massless***



- **Neutrinos**
- **Daughter radiation**

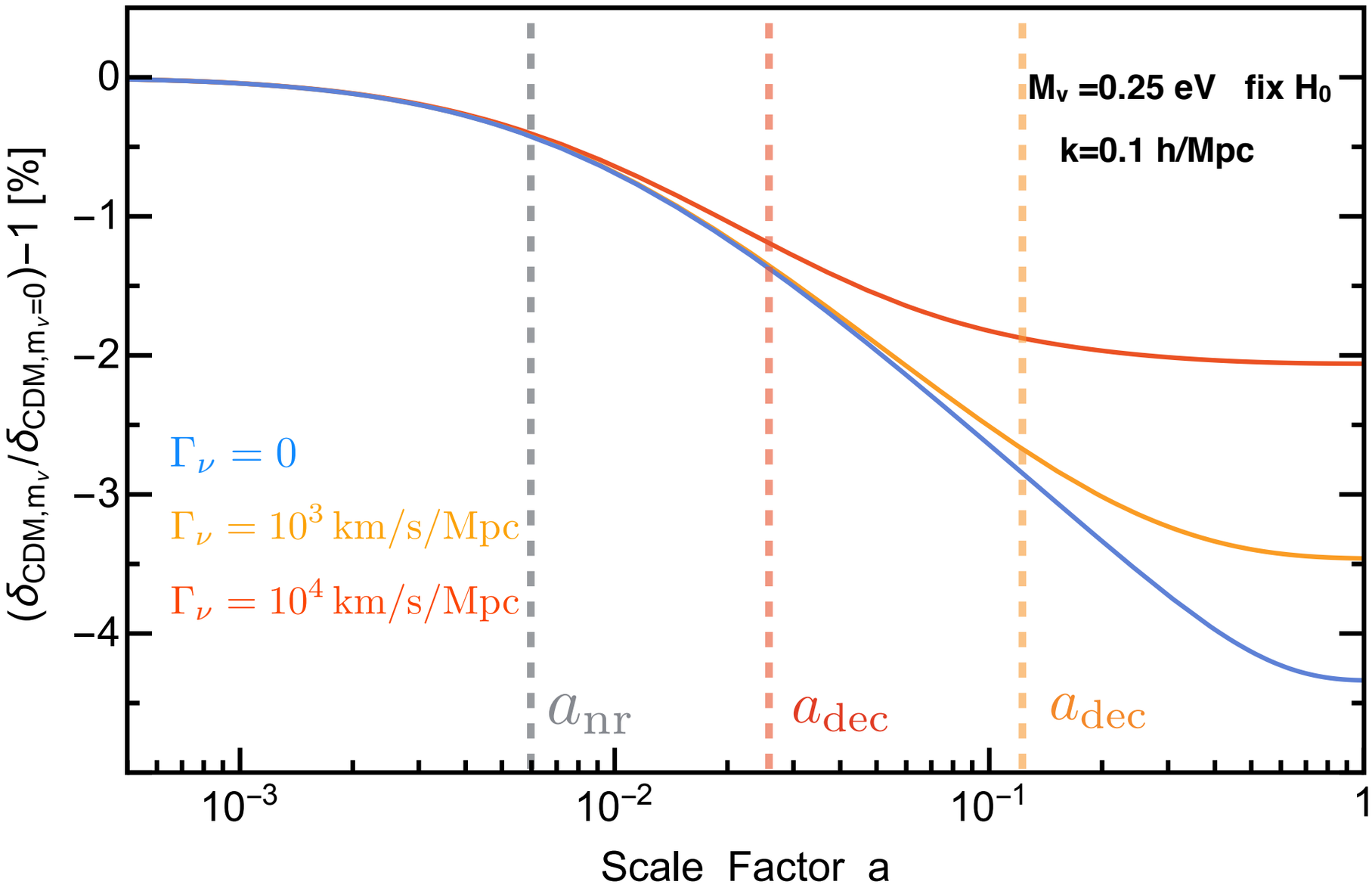



Serpico 2007

Serpico 2009

# *Decaying neutrinos in structure formation*

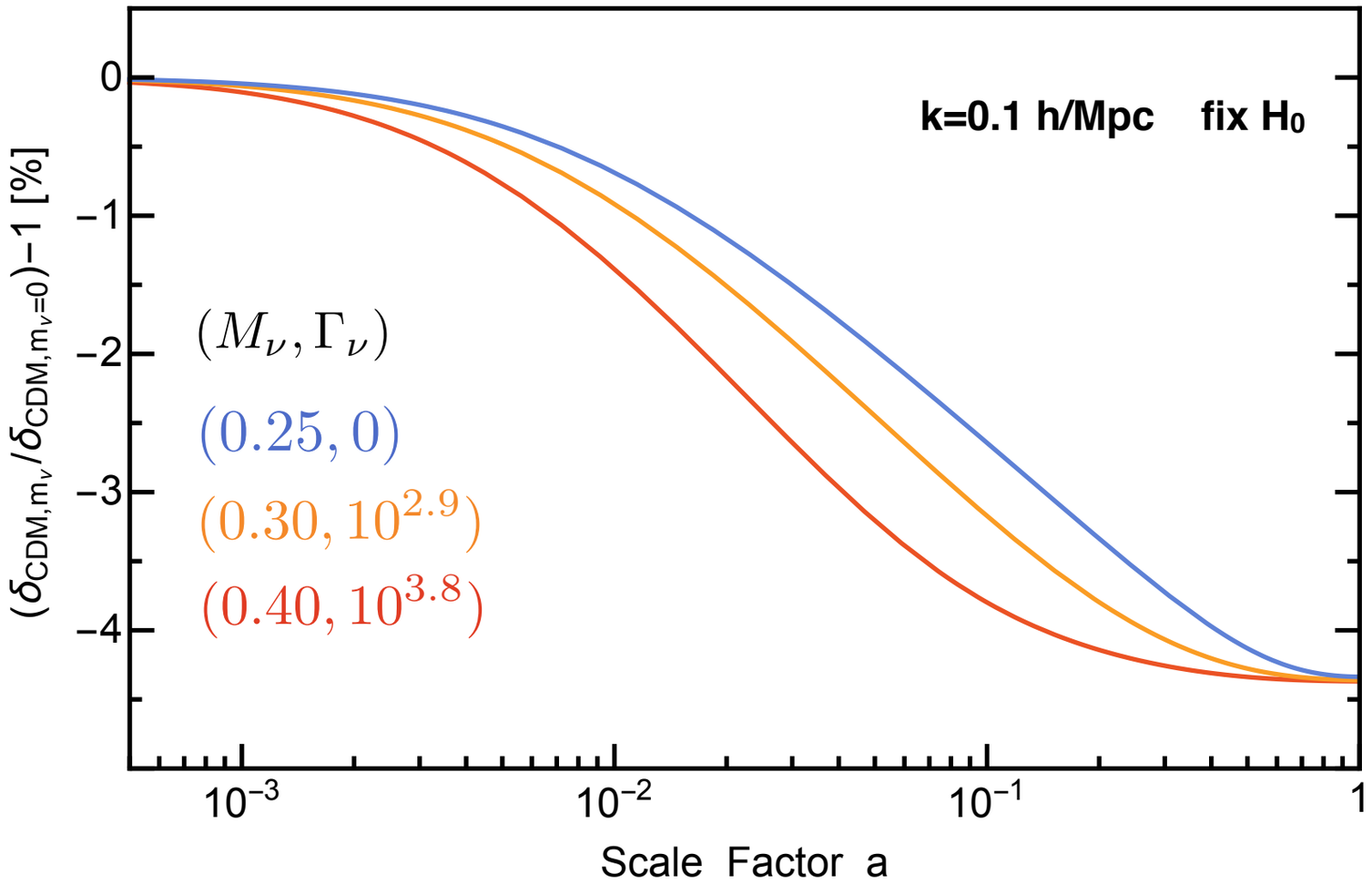
## **Numerical simulation**: modified CLASS code




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

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

# Degeneracy in mass and lifetime




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

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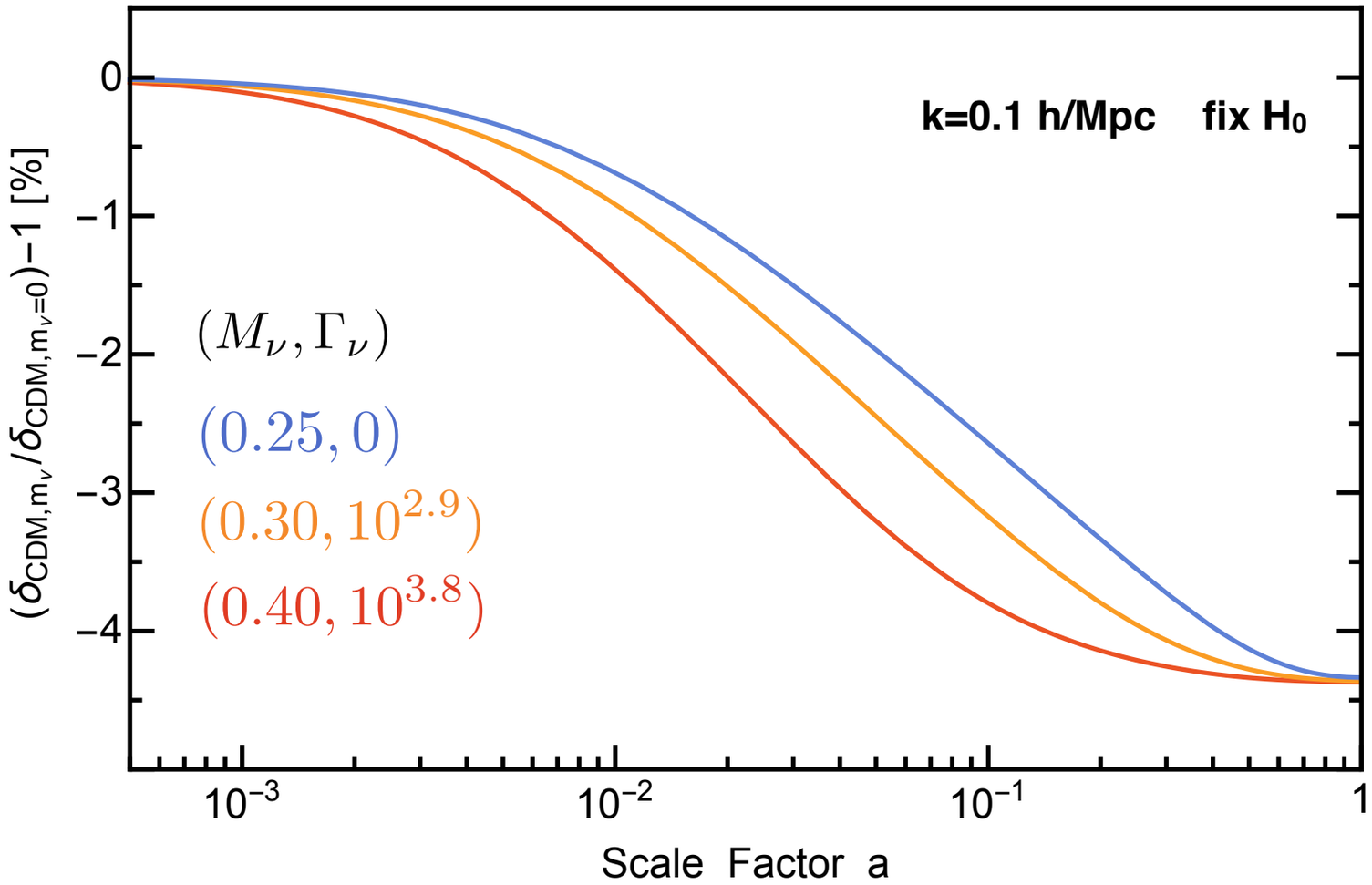
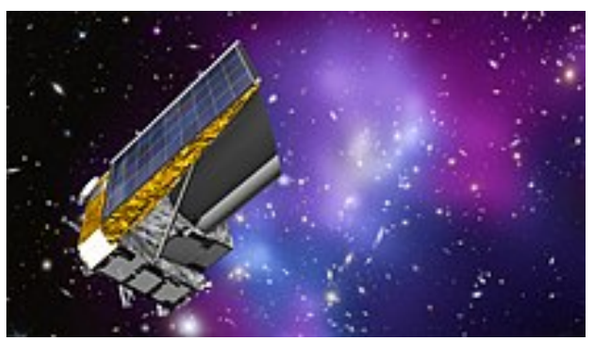



**Can we measure $M_\nu$ , $\Gamma_\nu$ independently ?**

**Resolution:**

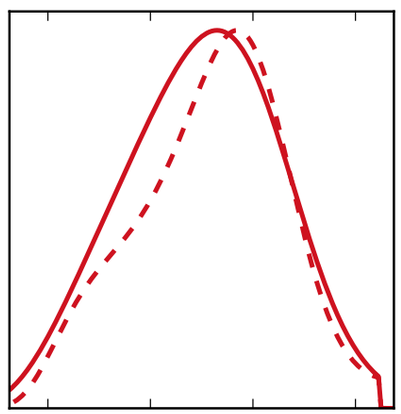
- **Need measurements at earlier time/ higher redshift z**
- **Need precision $\lesssim 1\%$**

# Breaking the degeneracy

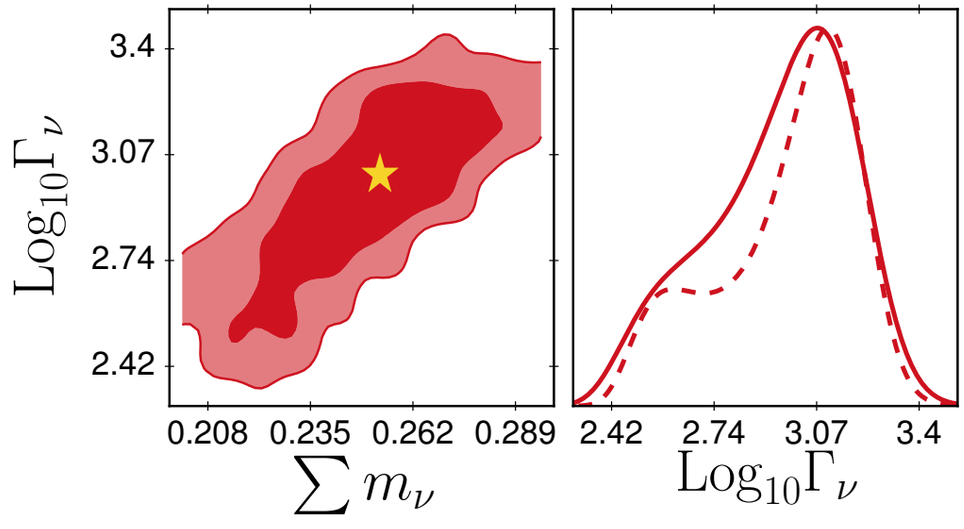


**Euclid 2021**

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



***Preliminary***




**For mock data** $M_\nu = 0.25\,\mathrm{eV}$

$\Gamma_\nu = 10^3\,\mathrm{km/s/Mpc}$

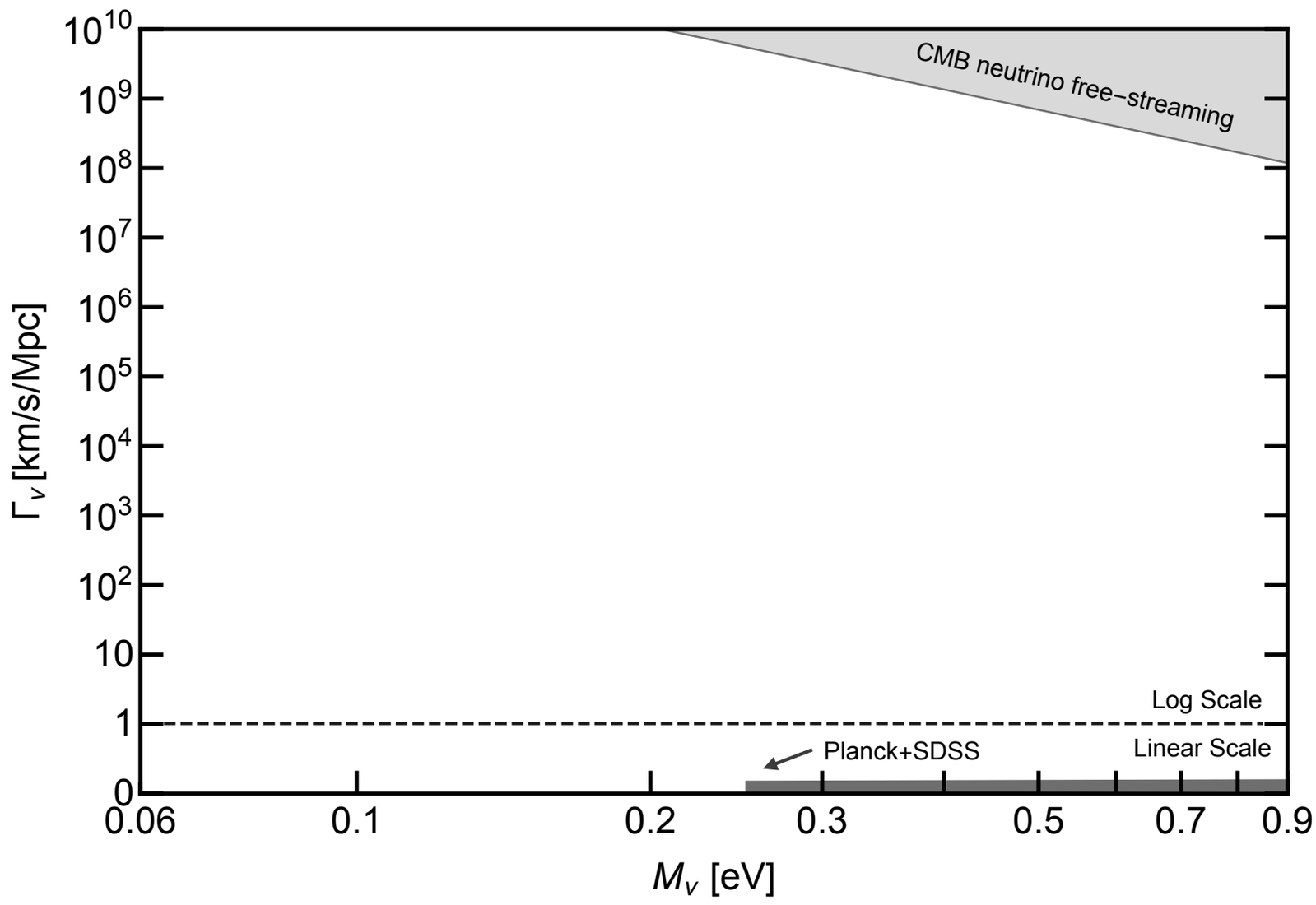
# 2D parameter space

## Existing constraints:

**Non-radiative decay lifetime: CMB neutrino free-streaming** Archidiacono, Hannestad 2014

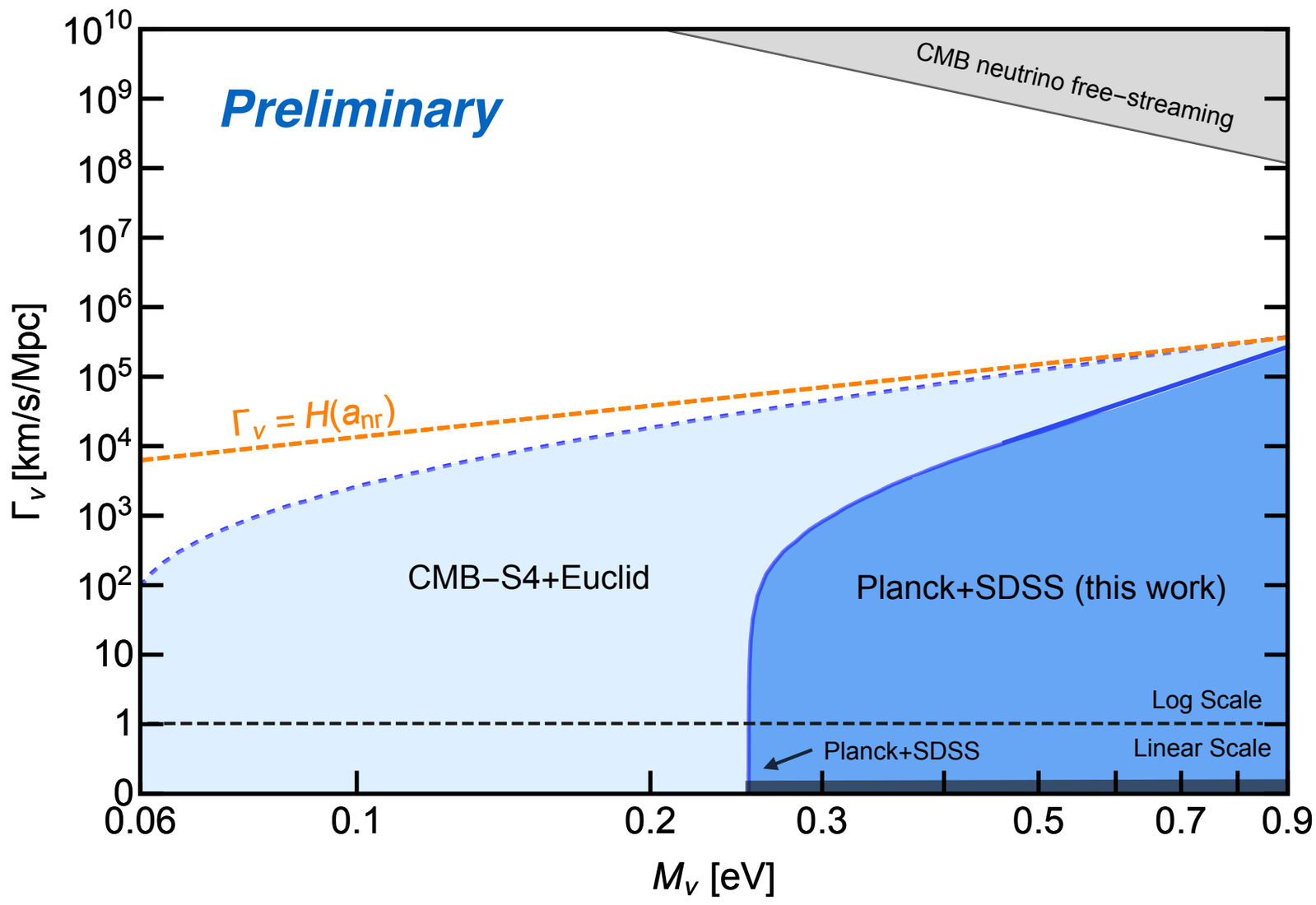
**Total mass:** $M_\nu \equiv \sum m_\nu < 0.23\,\mathrm{eV}$ **Planck+SDSS**

**Assuming neutrinos are stable**



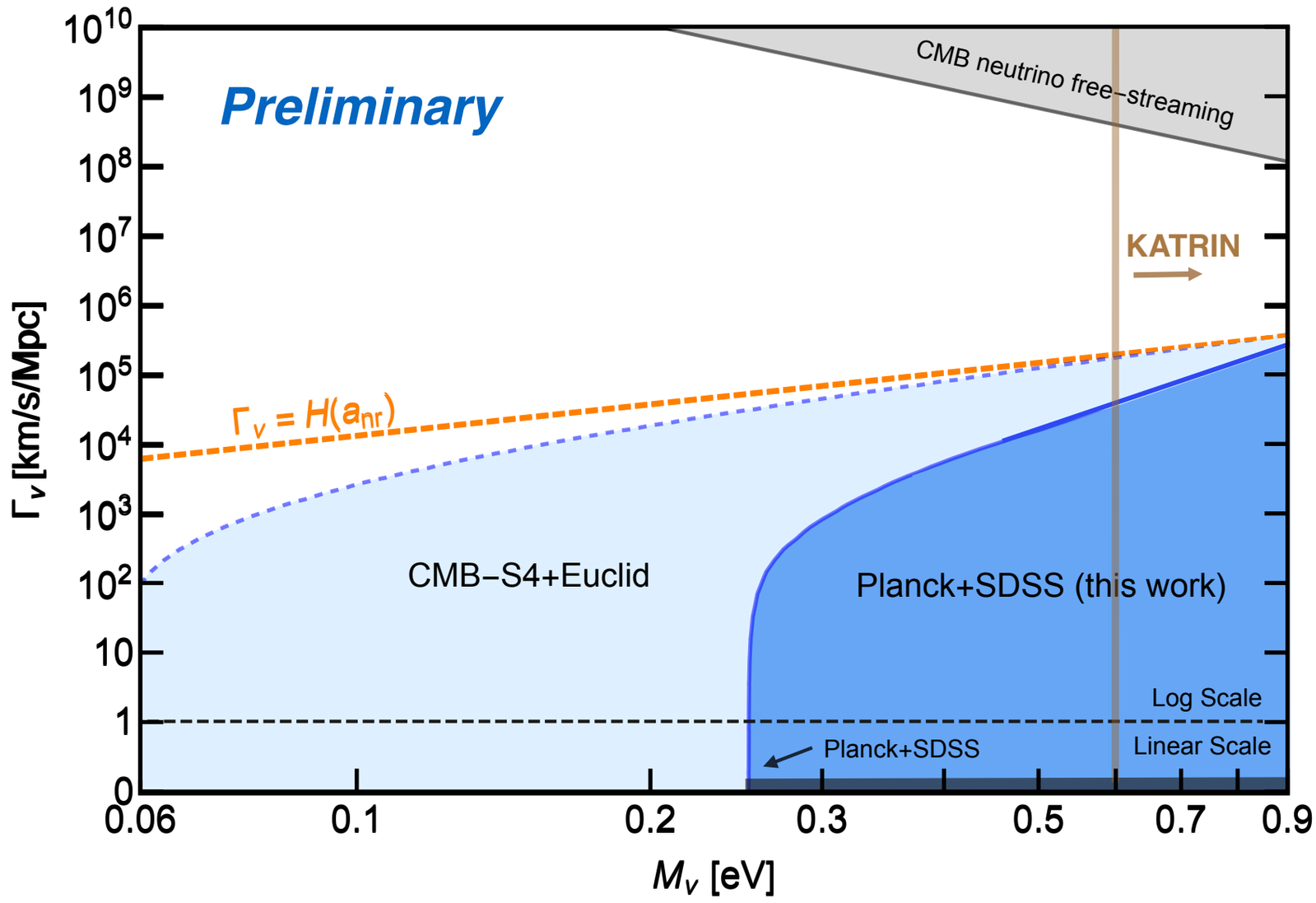
# 2D parameter space

- **The best exclusion for non-radiative decay neutrino lifetime!**
- **CMB-S4+Euclid can measure $M_\nu$ ,$\Gamma_\nu$ independently**



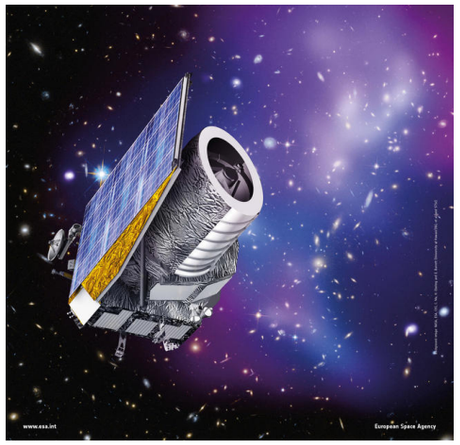
# 2D parameter space

- **The best exclusion for non-radiative decay neutrino lifetime!**
- **CMB-S4+Euclid can measure $M_\nu$ ,$\Gamma_\nu$ independently**
- **Interplay with terrestrial neutrino mass measurements: e.g KATRIN**



# *Conclusions*

- The non-radiative decay lifetime of neutrino is poorly constrained.
- 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 (2021) LSST (2023) CMB-S4 (202?)

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

*Thank you!*

# Decaying neutrinos in structure formation

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

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

**Difference in energy**

**Effect of decay**

$$y \equiv \frac{q}{T_\nu}$$

$$f_\nu(y) = \frac{1}{e^y + 1}$$

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