Thai High Energy Physics Consortium Meeting 2023
18-19 November 2023

Dark Dimension and Neutrino Oscillations

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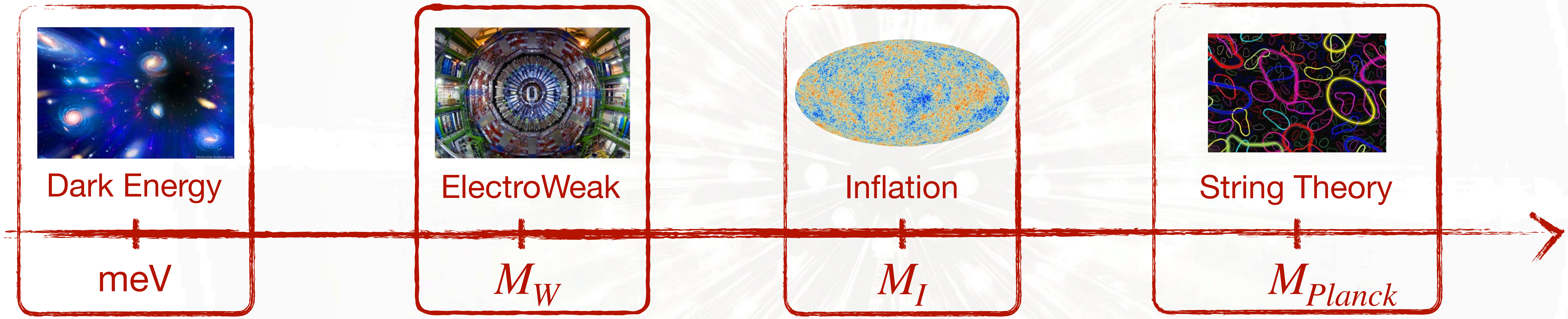
with Ignatios Antoniadis, Hiroshi Isono, and Mitesh Behera
+ the works of Apimook Watcharangkool

Challenge for a fundamental theory

- To describe both particle physics and cosmology



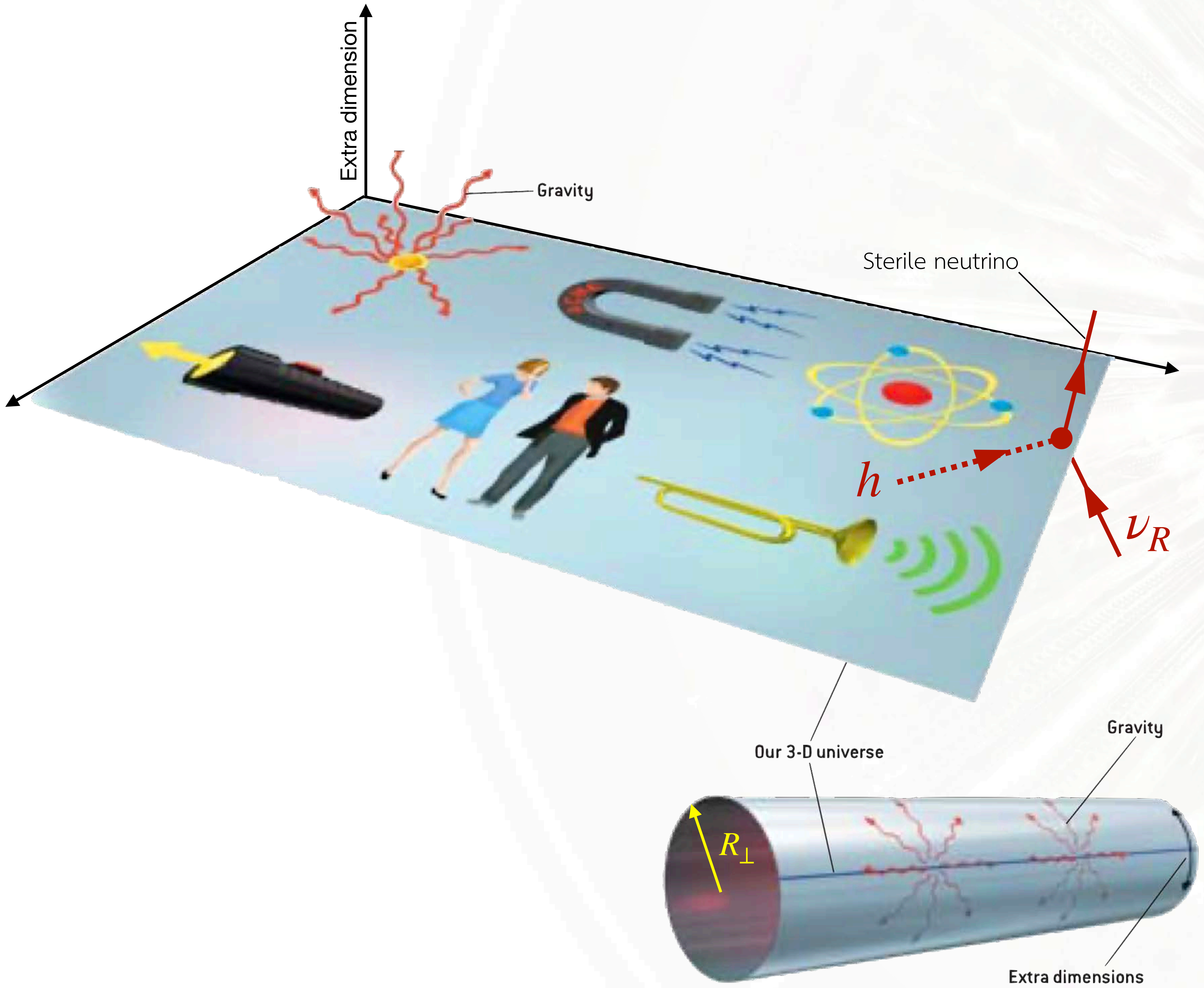
- Inflation from supersymmetry breaking?

  Connecting inflation with beyond SM physics. (with Antoniadis, Isono, Knoops and Aldabergenov)

- Swampland Program

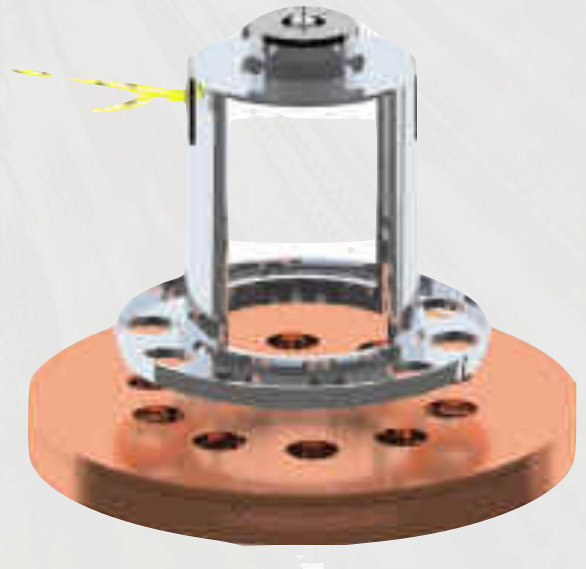
  Combining String Theory (Swampland conjecture) with a positive cosmological constant leading to the “dark dimension” scenario with **an extra dimension of micron size** (or $\sim \mathcal{O}(\text{meV})$)

Extra dimension



Arkani-Hamed, Dimopoulos and Dvali, Scientific American, August 2000

- Standard Model particles are localized on a 3 dimensional brane.
- Gravity can propagate inside the bulk (3+1 dimensional space)
- The extra dimension is compactified (circle with radius $R_\perp$)



Validity of $1/r^2$ experiment

$$\Rightarrow R_\perp < 30\ \mu\text{m}$$

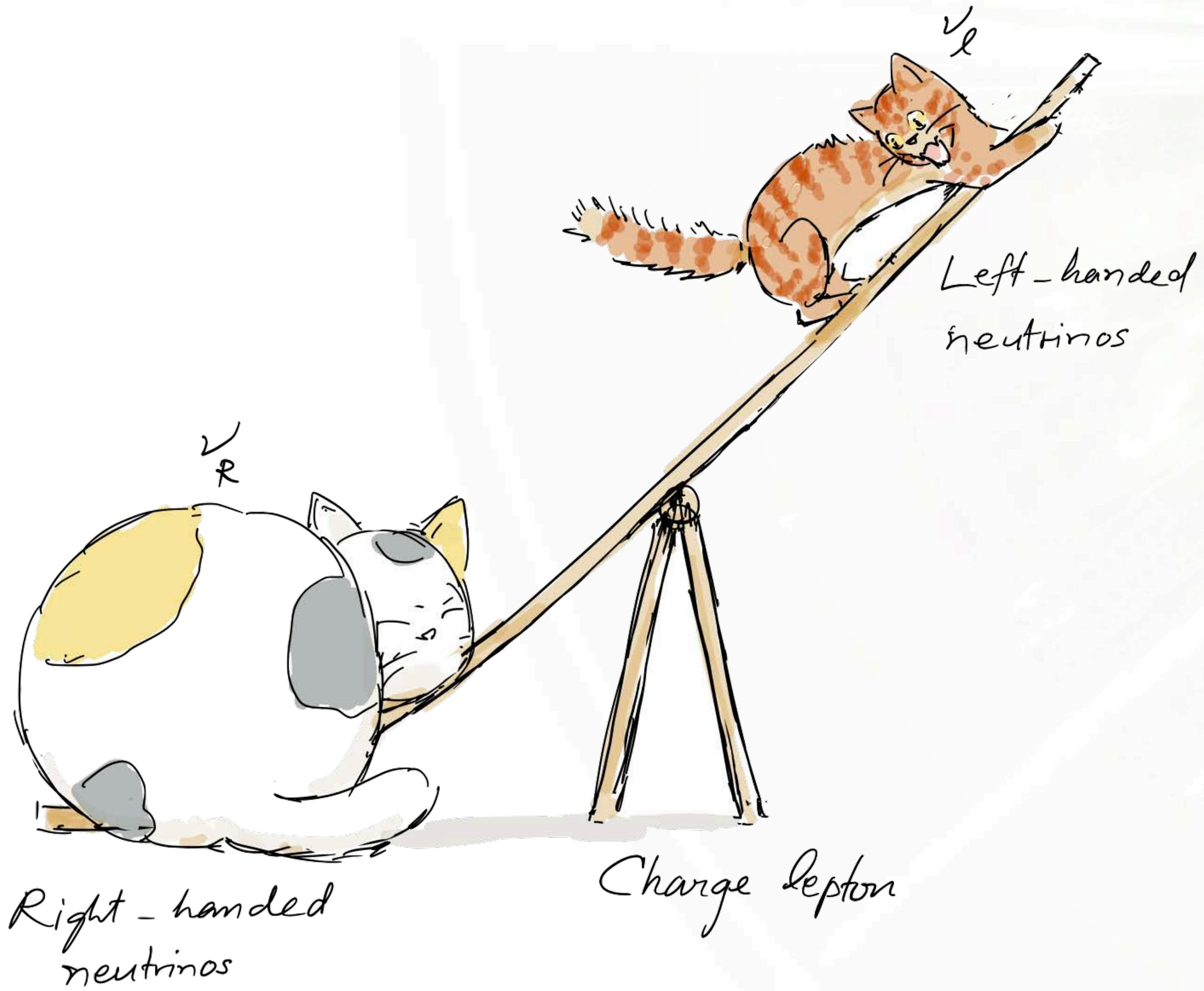
- Sterile neutrino ν_R can also propagate inside the bulk

Right-handed Neutrinos

Neutrinos' mass expected to be very small

Seesaw mechanism ⇒ Right-handed neutrinos

- How to distinguish effects from different seesaw models?
- Consider higher dimensional operator



There are 3 types of Seesaw models

- Heat Kernel expansion ⇒ calculate one-loop correction
- Obtained effective field theory
- Check with JUNO & other experiments

[This part is explored by Apimook Watcharangkool's group]

Neutrino and Extra dimension

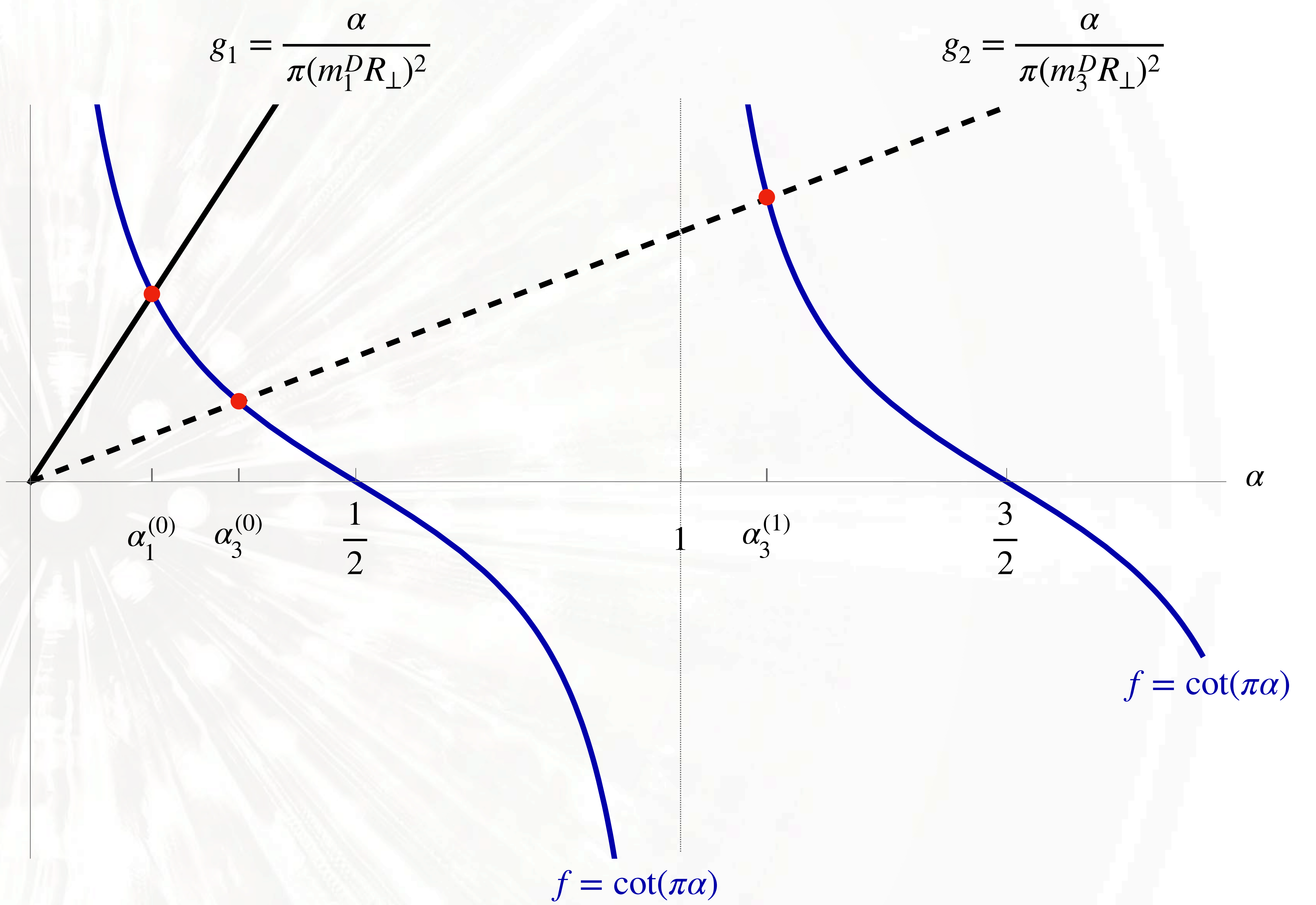
- natural explanation of neutrino masses, introducing ν_R in the bulk
- recent analysis of ν-oscillation data with 3 bulk neutrinos

$$\Rightarrow \quad R_\perp \lesssim 0.4\ \mu\text{m} \quad (\text{or } m_{KK} \gtrsim 2.5\ \text{eV})$$

[Forero-Giunti-Ternes-Tyagi '22 , Roy 23]

- from a 4-dimensional perspective, each of the bulk neutrinos can be decomposed as an <u>infinite</u> tower of KK states with mass $m_i^{(n)} = \dfrac{\alpha_i^{(n)}}{R_\perp}$, $n = 0,1,\ldots\infty$
- $(\alpha_i/R_\perp)^2$ are the eigen value of the matrix $\mathbb{M}_i^\dagger \mathbb{M}_i$ satisfying the transcendental equation

$$\frac{\alpha_i}{\pi(m_i^D R_\perp)^2} - \cot(\pi\alpha_i) = 0$$



- Let us consider the zero-mode, we have

$$\alpha_i^{(0)} \leq 1/2$$

From ν-oscillation: $R_\perp < \dfrac{1}{2\sqrt{\Delta m_{31}^2}}$.

This gives the theoretical bound: $R_\perp \lesssim 2\ \mu$m.

Adding bulk neutrino masses

- the bound can be relaxed in the presence of **bulk ν_R -neutrino masses c_i**, with (modified) transcendental equation

$$\frac{(c_iR_\perp)^2 + (m_i^D R_\perp)^2 \pi c_i R_\perp + (\tilde{\lambda}_i)^2}{\pi \tilde{\lambda}_i (m_i^D R_\perp)^2} - \cot(\pi \tilde{\lambda}_i) = 0$$

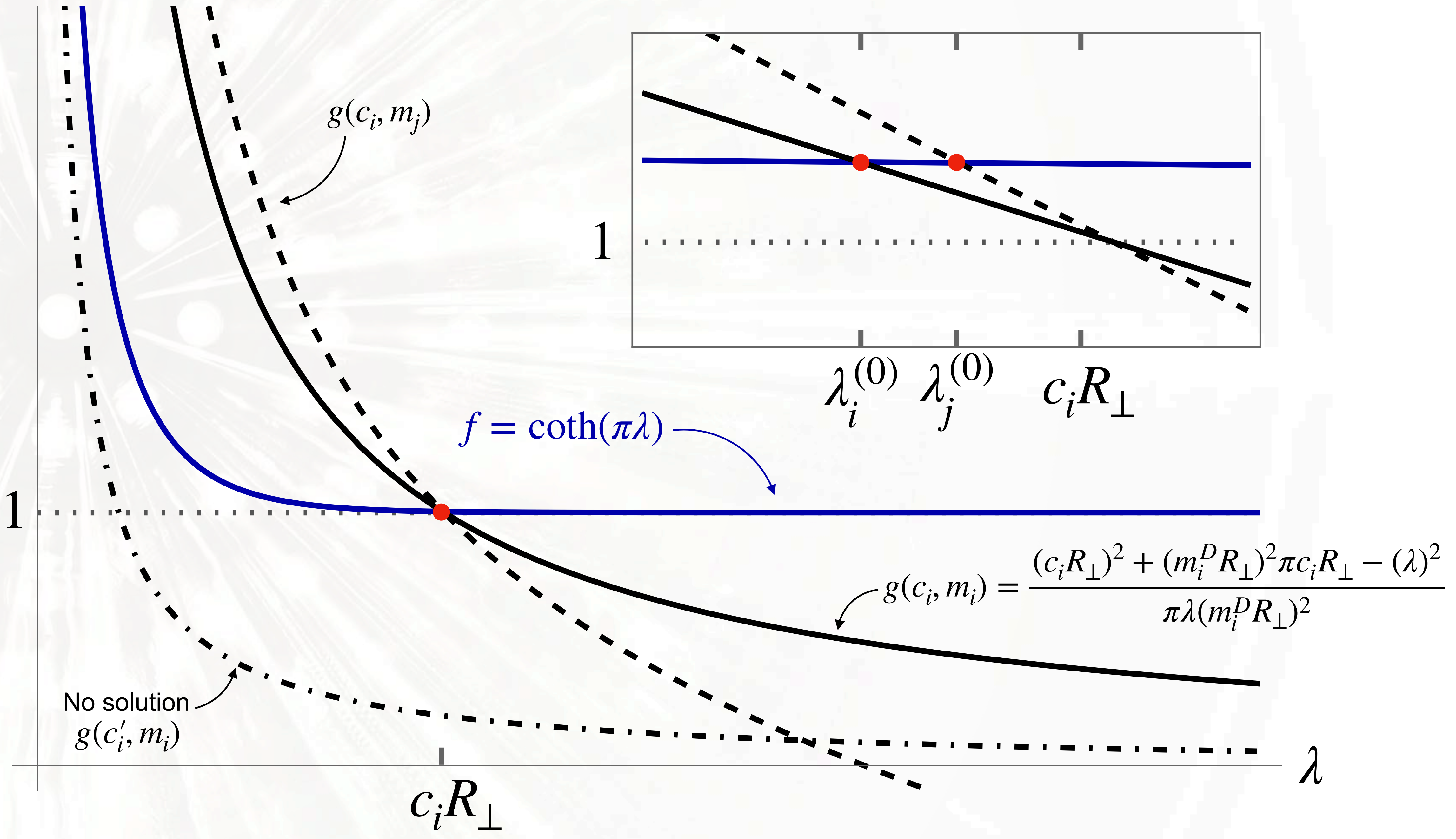
with $\tilde{\lambda}_i = \sqrt{(\alpha_i)^2 - c_i^2 R_\perp^2}$.

- For the zero-modes with small eigen values $\alpha_i^{(0)} < c_i R_\perp$,

$\tilde{\lambda}_i \Rightarrow \lambda_i = \sqrt{c_i^2 R_\perp^2 - (\alpha_i)^2}$ with

$$\frac{(c_iR_\perp)^2 + (m_i^D R_\perp)^2 \pi c_i R_\perp - (\lambda_i)^2}{\pi \lambda_i (m_i^D R_\perp)^2} - \coth(\pi \lambda_i) = 0$$

[L. A. Anchordoqui, I. Antoniadis and J. Cunat, ArXiv:2306.16491]



- No theoretical bound on $R_\perp$
- Dark dimension with $R_\perp \sim 5 - 10\ \mu$m is possible?

Mass of the 0^{th} modes and KK modes

- With this setup, the model depends on five parameters: $R_\perp$, m_1^D, c_1, c_2 and c_3.
- Let use focus on the case $\alpha_1^{(0)} \ll c_1 R_\perp$, mass formula for the zero modes

$$m_1^{(0)} = \frac{1}{R_\perp}\sqrt{\frac{2\pi c_1^2 (m_1^D)^2 R_\perp^4 (1-\coth(\pi c_1 R_\perp))}{\pi^2 c_1 (m_i^D)^2 R^3 \mathrm{csch}^2(\pi c_1 R_\perp) - 2c_1 R_\perp - \pi (m_1^D)^2 R_\perp^2}}\,,$$

$$m_2^{(0)} = \sqrt{\left(m_1^{(0)}\right)^2 + \Delta m_{21}^2}\,,$$

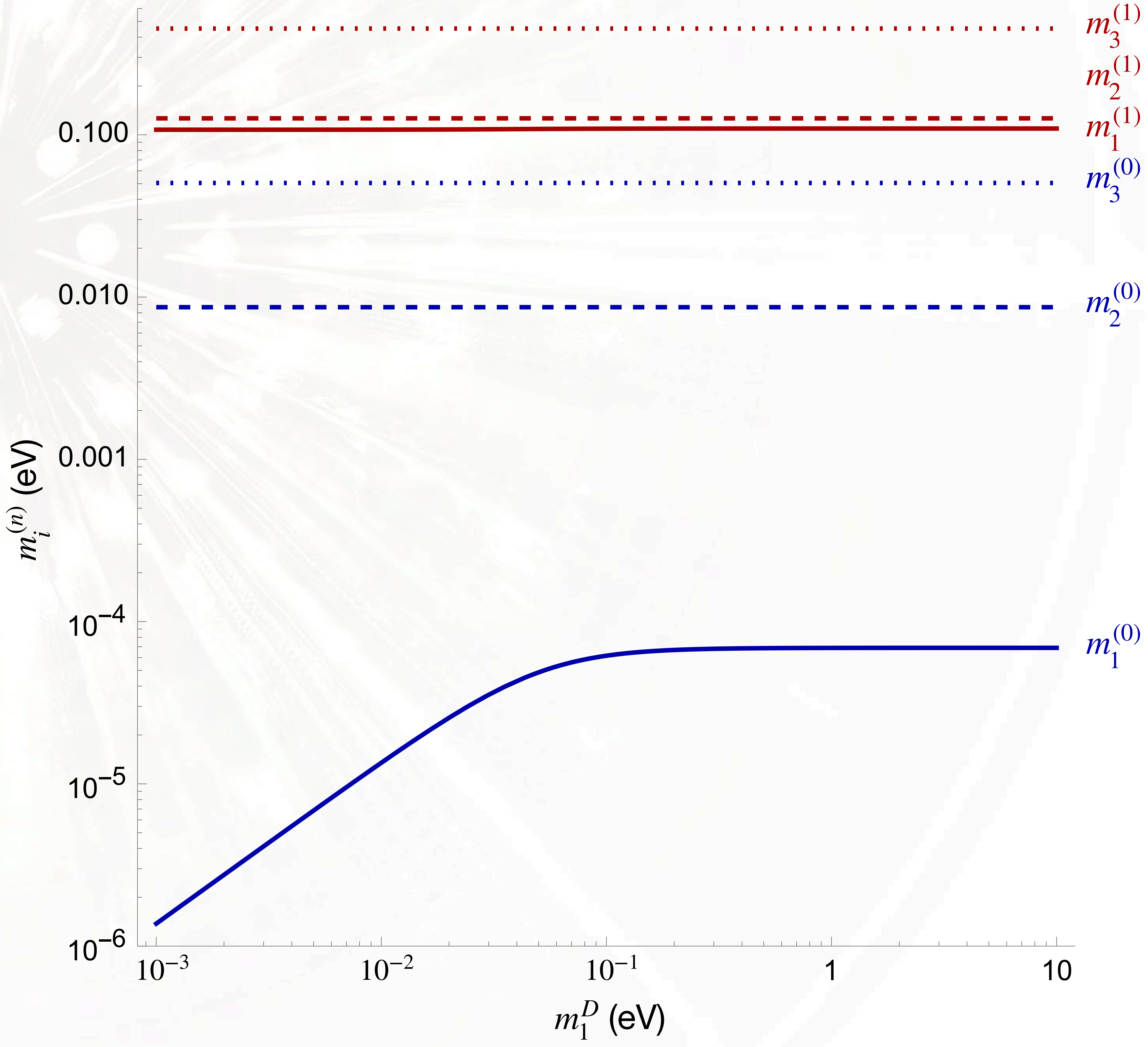
$$m_3^{(0)} = \sqrt{\left(m_1^{(0)}\right)^2 + \Delta m_{31}^2}$$

- For the KK excitations, in the limit $m_i^D R_\perp \ll 1$, mass formula for the n^{th} KK mode is

$$m_i^{(n)} = \sqrt{c_i^2 + \frac{n^2}{R_\perp^2}} + \frac{1}{R_\perp}\frac{n^2 (m_i^D R_\perp)^2}{\left(n^2 + (c_i R_\perp)^2\right)^{3/2}} \qquad , i = 1,2,3$$

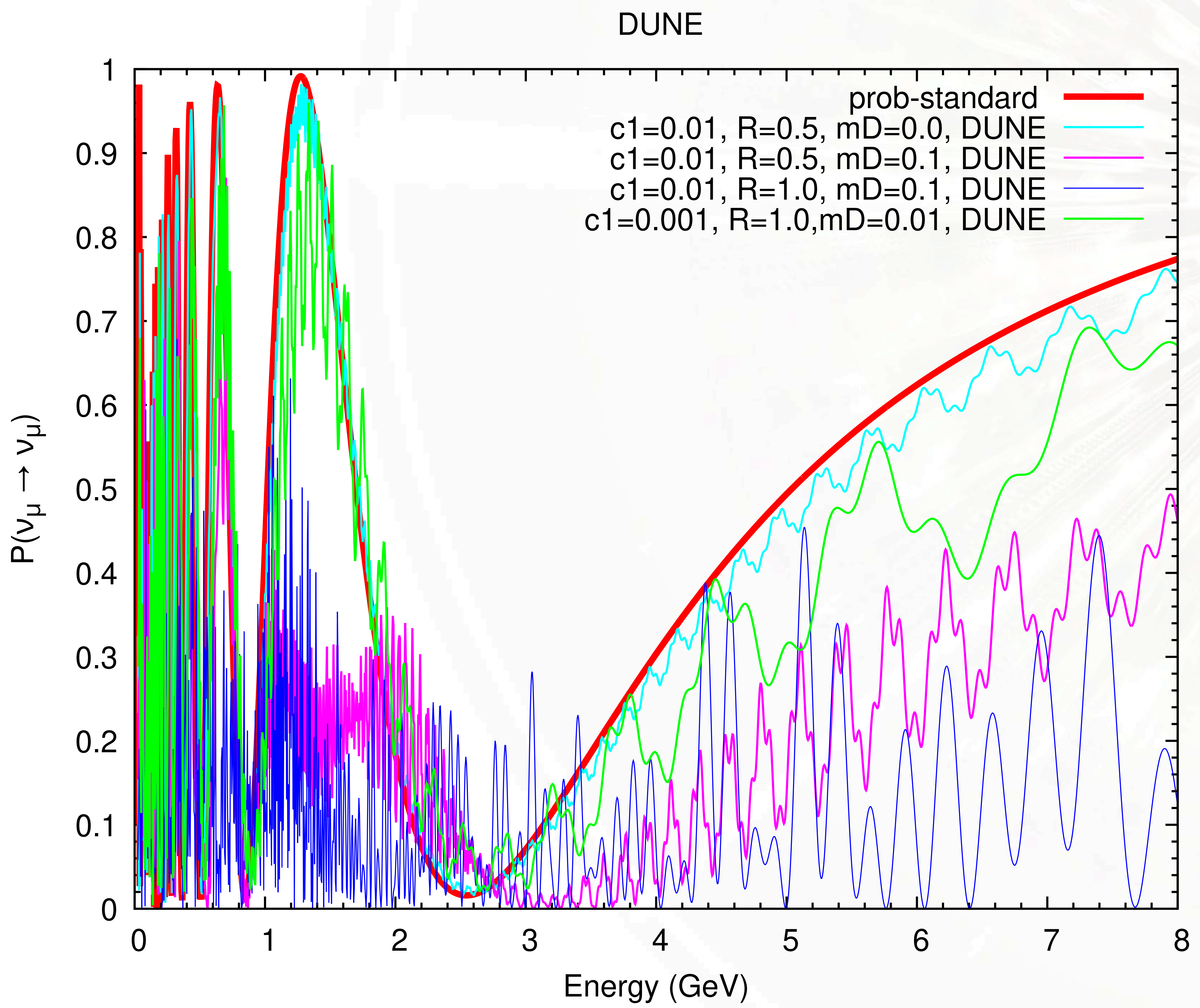
- we choose

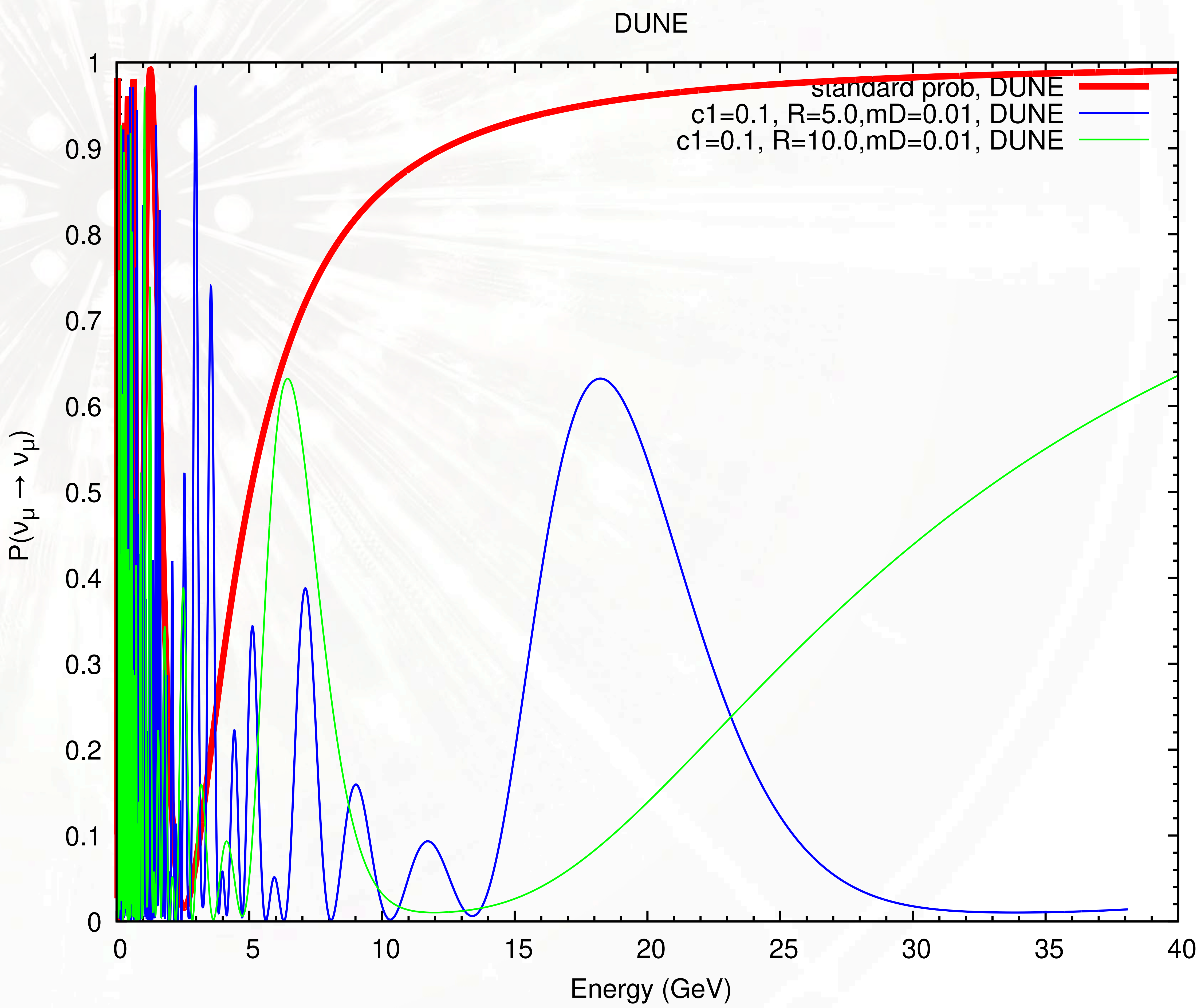
$R_\perp = 5\ \mu$m, $c_1 = 0.1$ eV,
$c_2 = -0.12$ eV and $c_3 = -0.45$ eV



- Next, use oscillation data to put constraints on parameter space experiment (DUNE, JUNO, …)

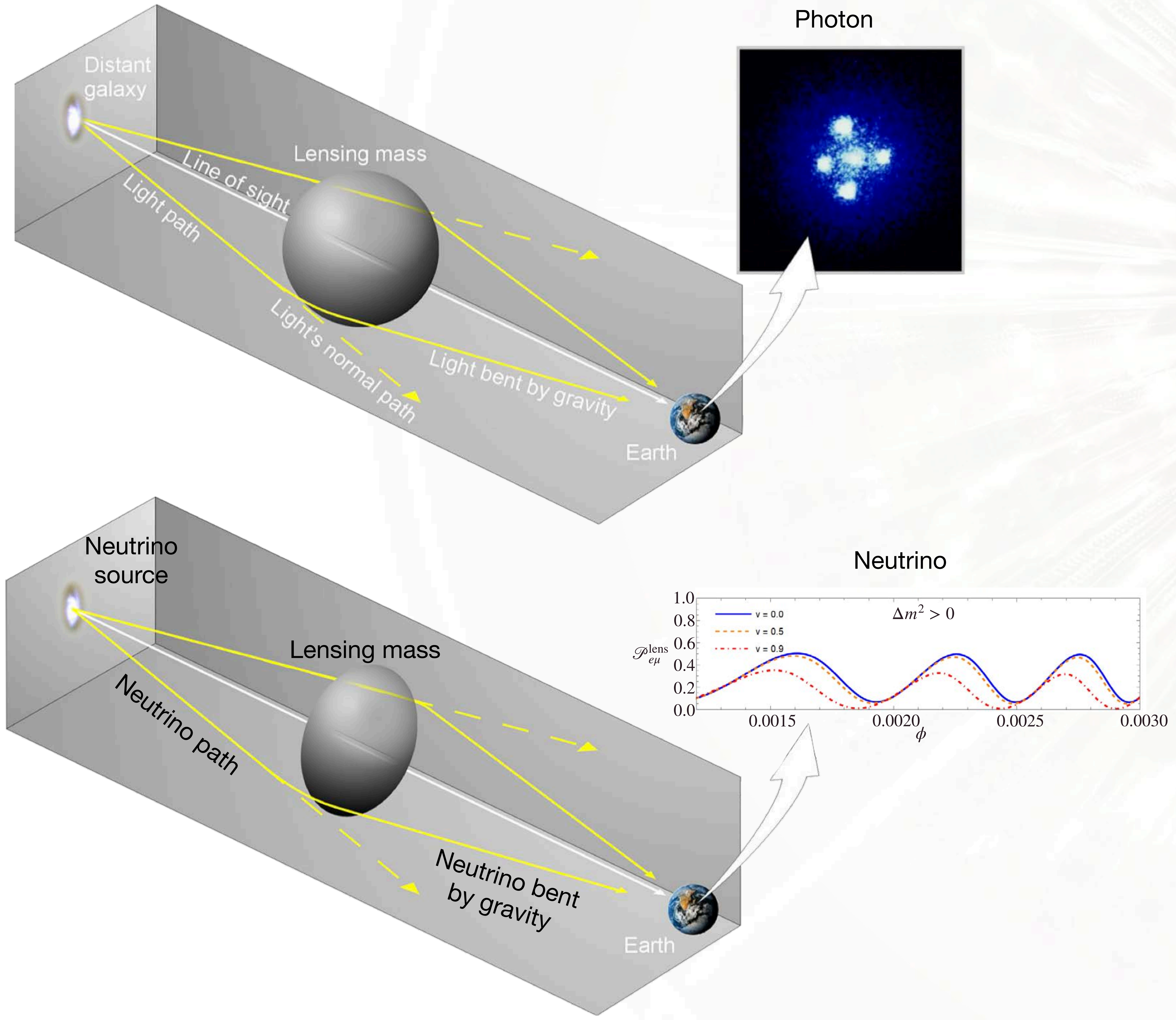
Some Results





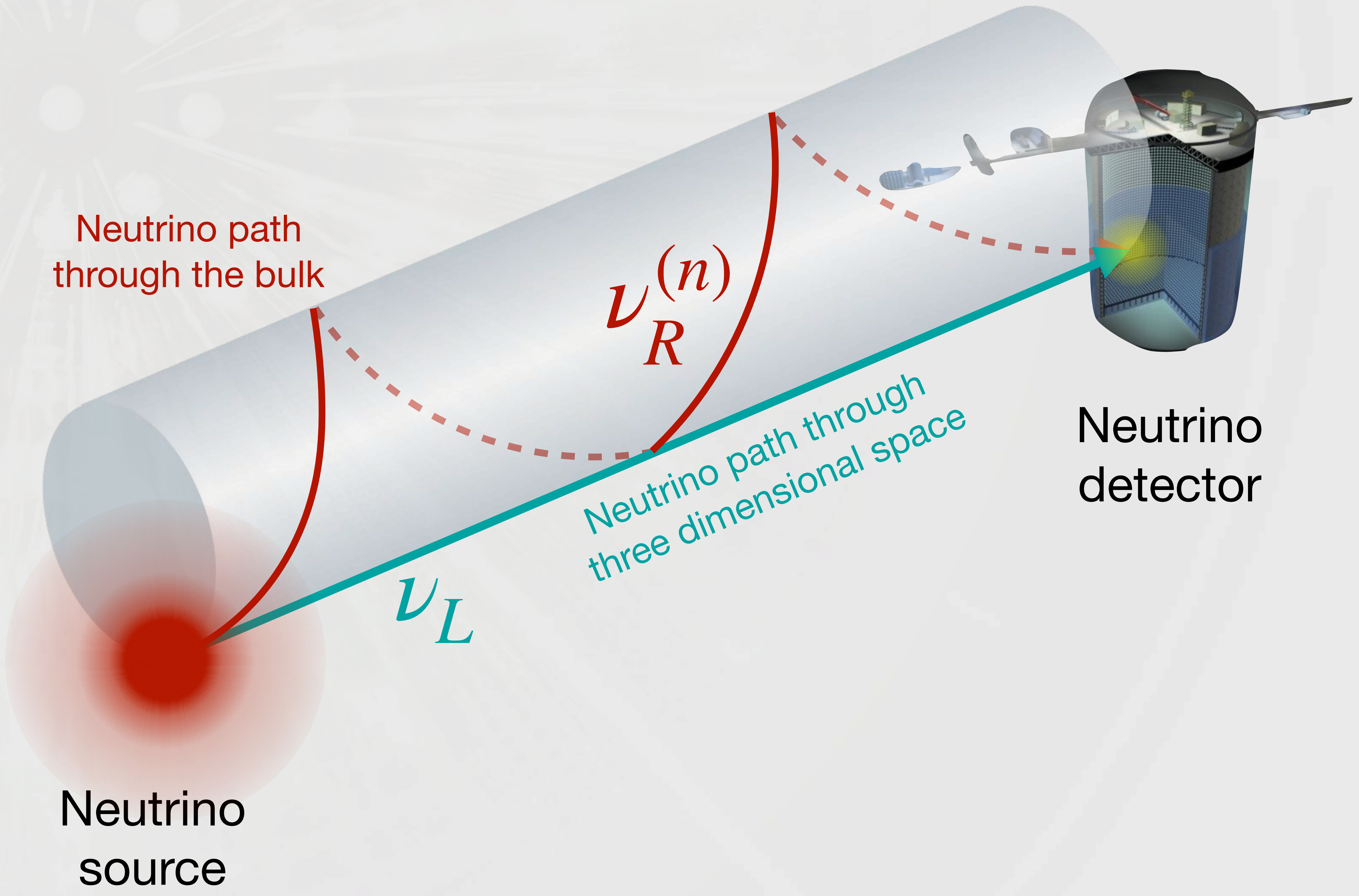
Lensing Effects on ν-oscillation

- Lensing by geometry (curved space)



[H. Chakrabarty, A. Chatrabhuti, D. Malafarina, B. Silasan, T. Tangphati, **JCAP 08** (2023) 018, ArXiv:2302.01564]

- Lensing by Dark Dimension (flat space)



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ขอบคุณครับ - Thank you