



Sino-Thai International Summer School on High Energy Physics and Astrophysics 2026

12–29 Jul 2026, School of Physics, Sun Yat-sen University, Guangzhou, China



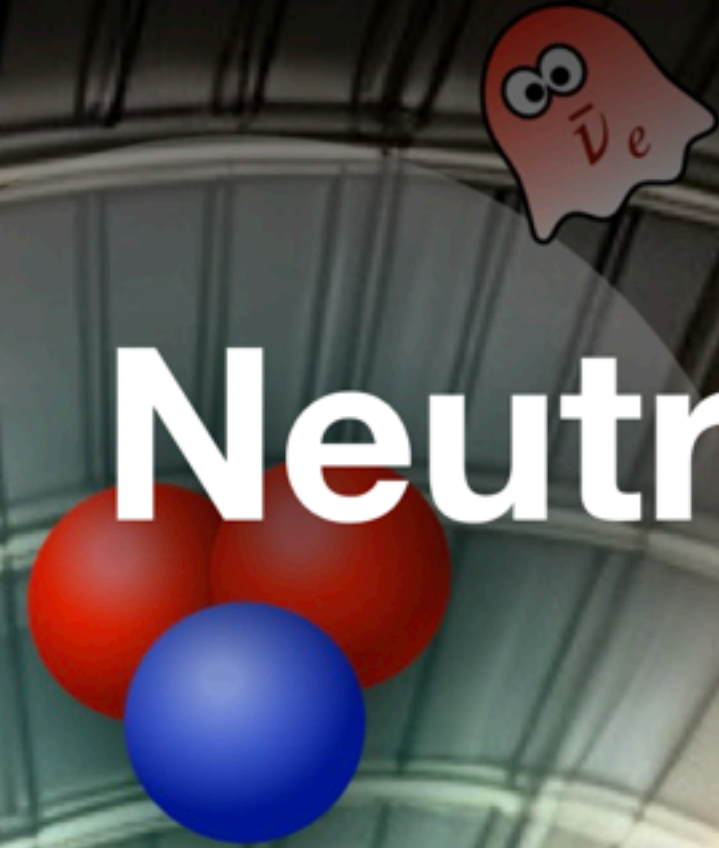
中国高等科学技术中心
China Center of Advanced Science and Technology



苗恩科技
Muon Science and Technology



Beta-Decay Experiments, Neutrino Mass & Beyond SM Physics



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THAILAND

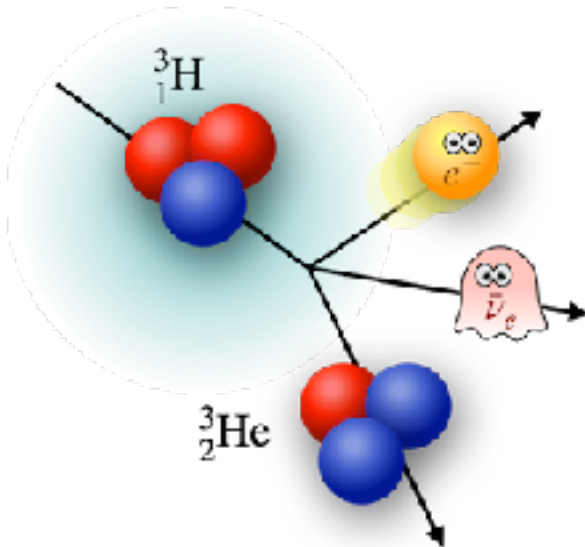
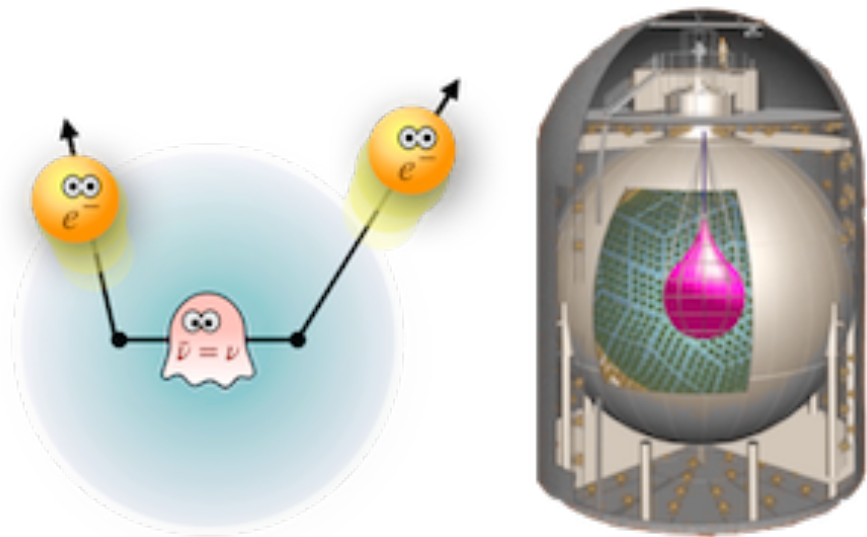
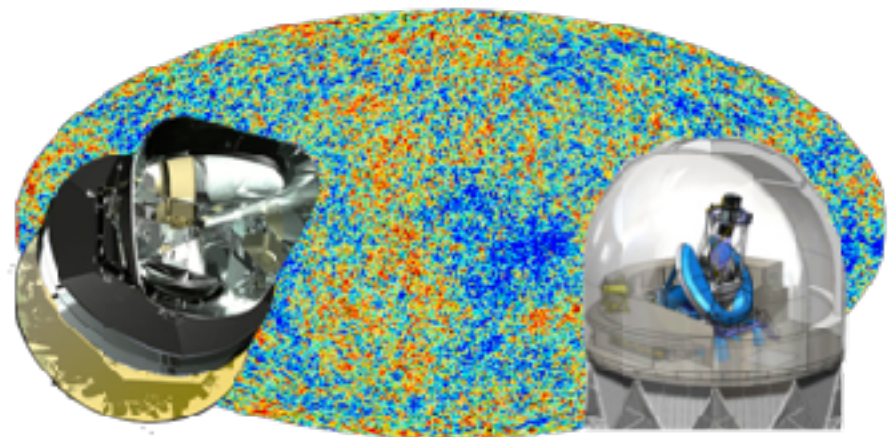


The neutrino mass scale



Three paths to the neutrino mass scale

Complementary
observables and
methods



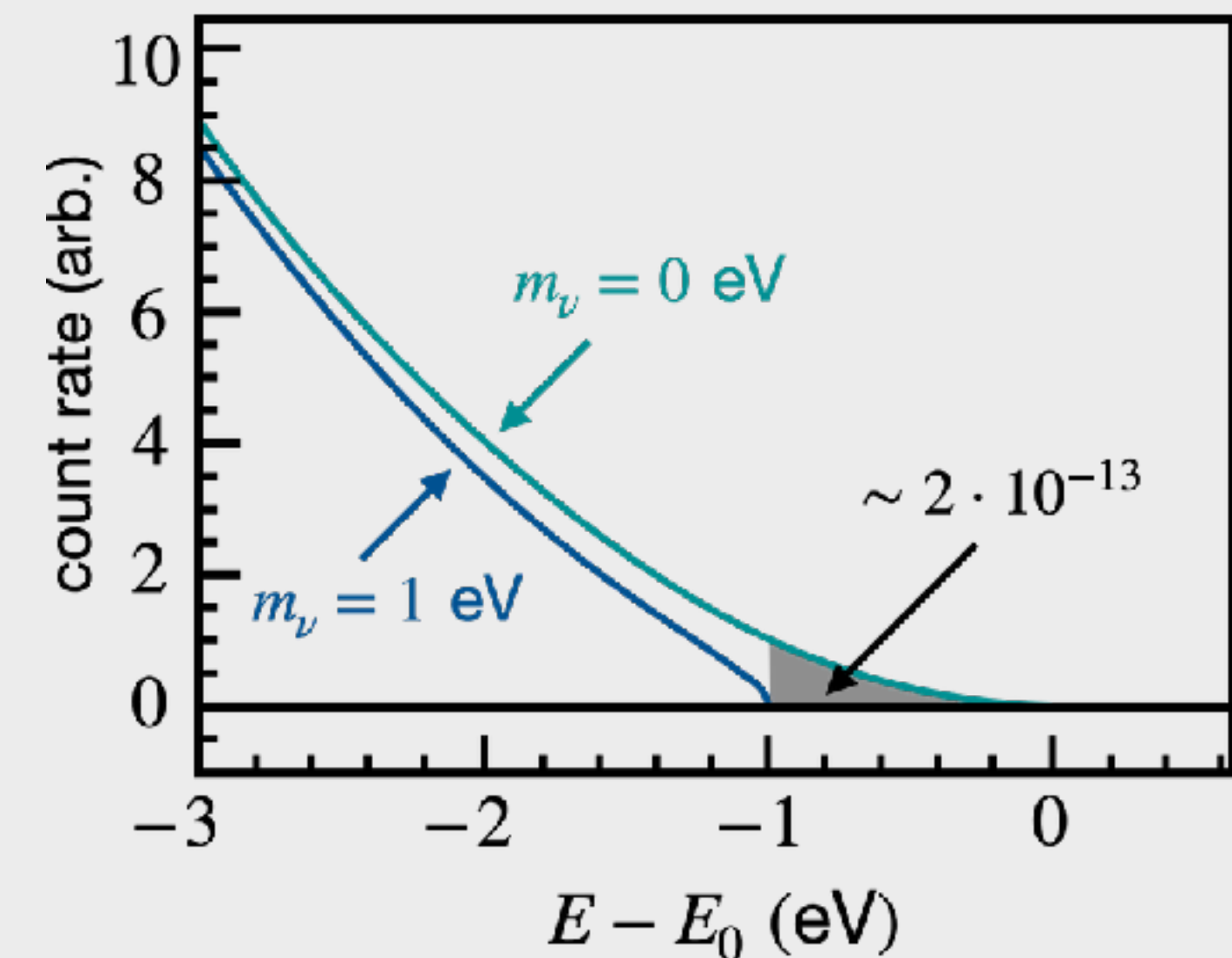
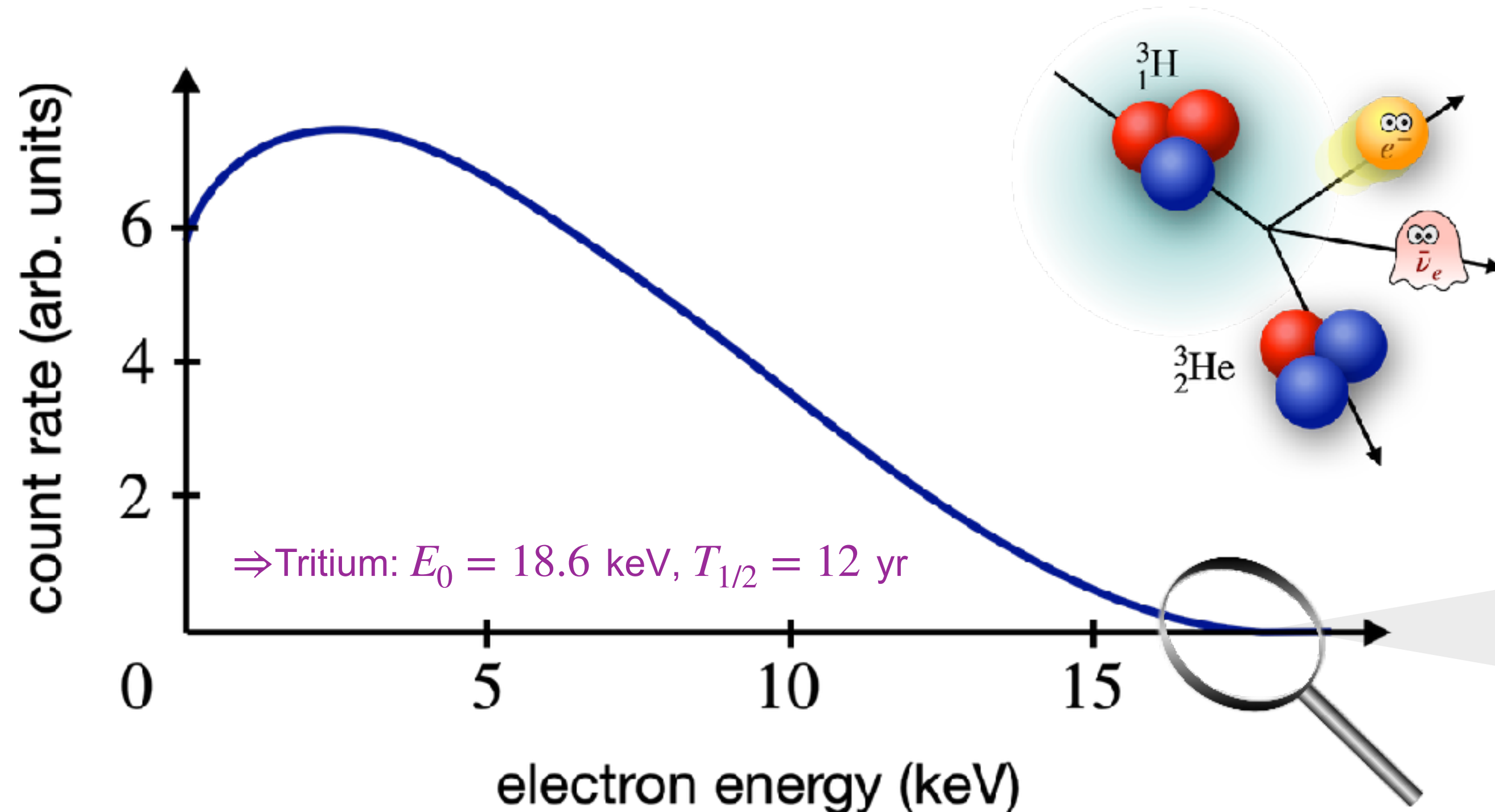
	Cosmology	Search for $0\nu\beta\beta$	Precision kinematics of weak decays
Method	Structure of Universe at early and evolved stages	$\beta\beta$ -decay of ${}^{76}\text{Ge}$, ${}^{130}\text{Te}$, ${}^{136}\text{Xe}$, ...	β -decay of ${}^3\text{H}$, EC of ${}^{163}\text{Ho}$
Observable	$m_\nu = \sum_i m_i$	$m_{\beta\beta}^2 = \left \sum_i U_{ei}^2 m_i \right ^2$	$m_\beta^2 = \sum_i U_{ei} ^2 m_i^2$
Present upper limit	0.12 eV (0.048 eV)	0.036 – 0.156 eV	0.45 eV (from ${}^3\text{H}$)
Method assumption	Multi-parameter cosmological model (Λ CDM)	- Majorana neutrinos - Contrib. other than m_ν? - Nucl. matrix elements, gA	Direct — only kinematics; no cancellations in incoherent sum

Neutrino mass in tritium β -decay

Measurement of effective mass m_ν based on **kinematic parameters & energy conservation**

$$R_\beta \propto (E_0 - E) \sqrt{(E_0 - E)^2 - m_\nu^2}$$

$$\text{with } m_\nu \equiv \sqrt{\sum_{i=1}^3 |U_{ei}|^2 \cdot m_i^2}$$



Neutrino mass in tritium β -decay

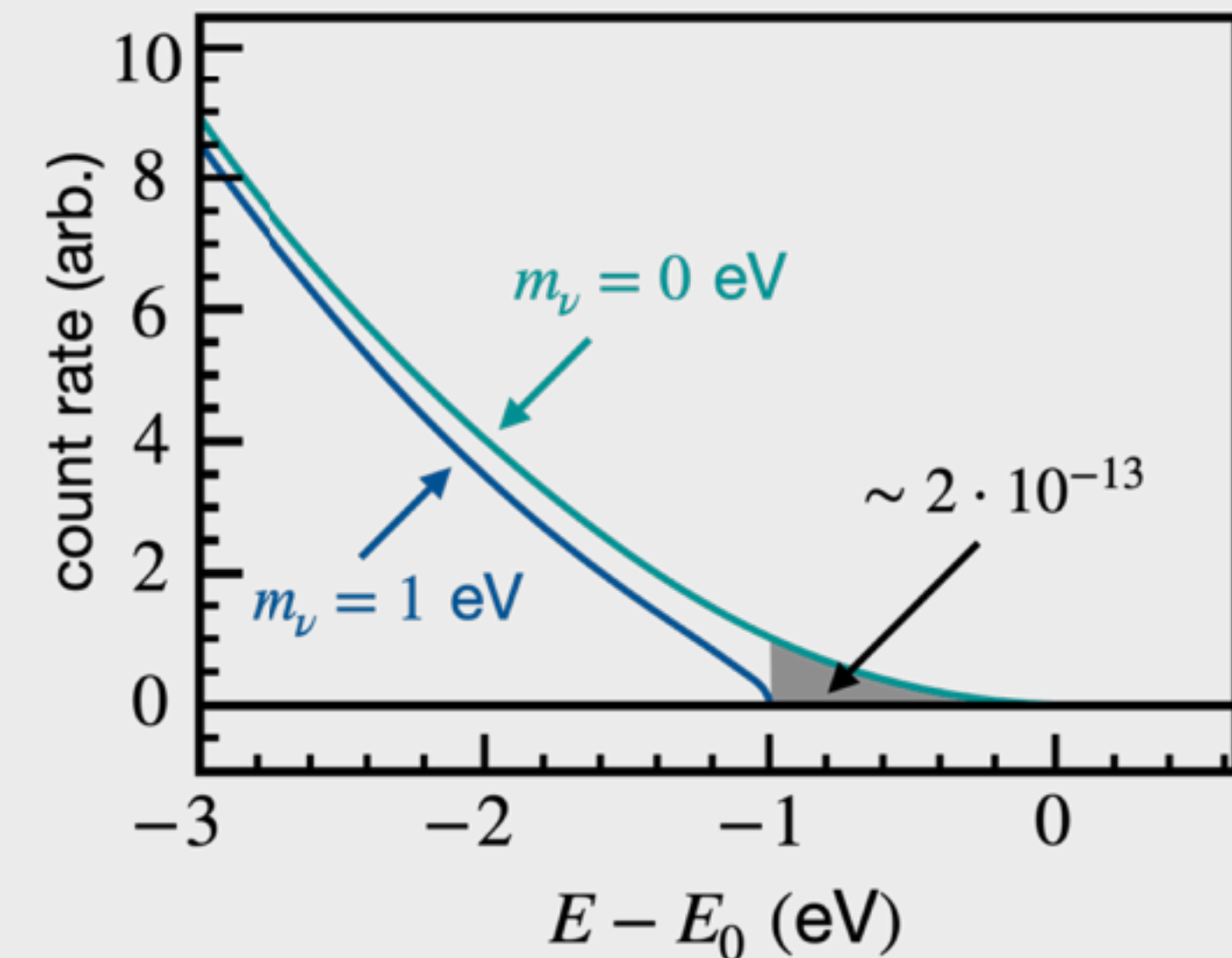
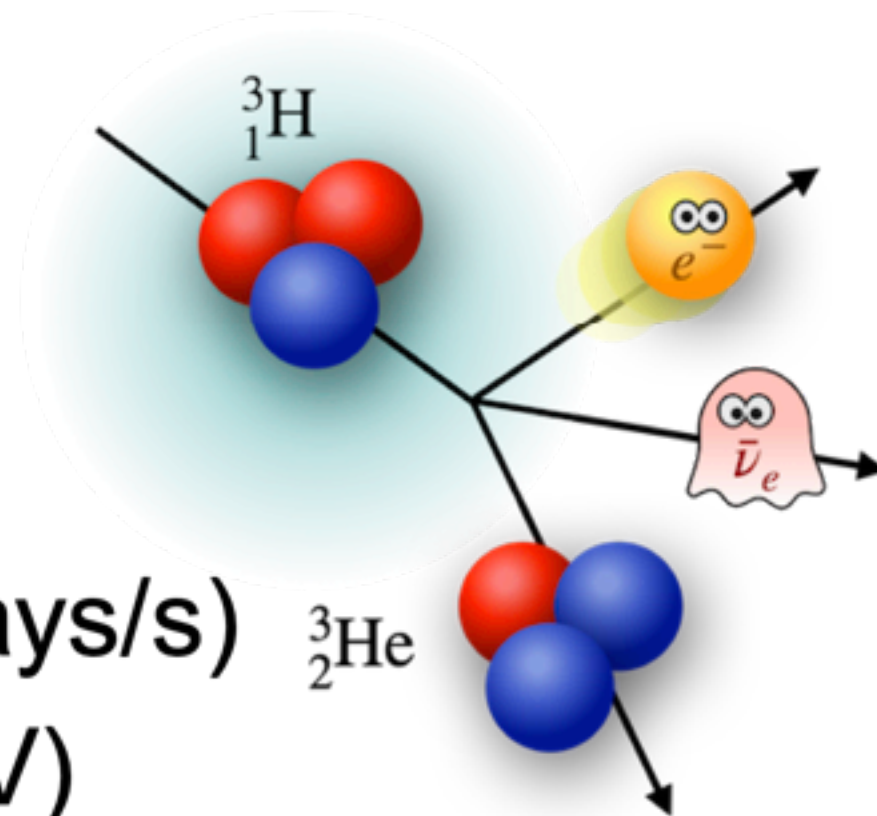
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Experimental challenges:

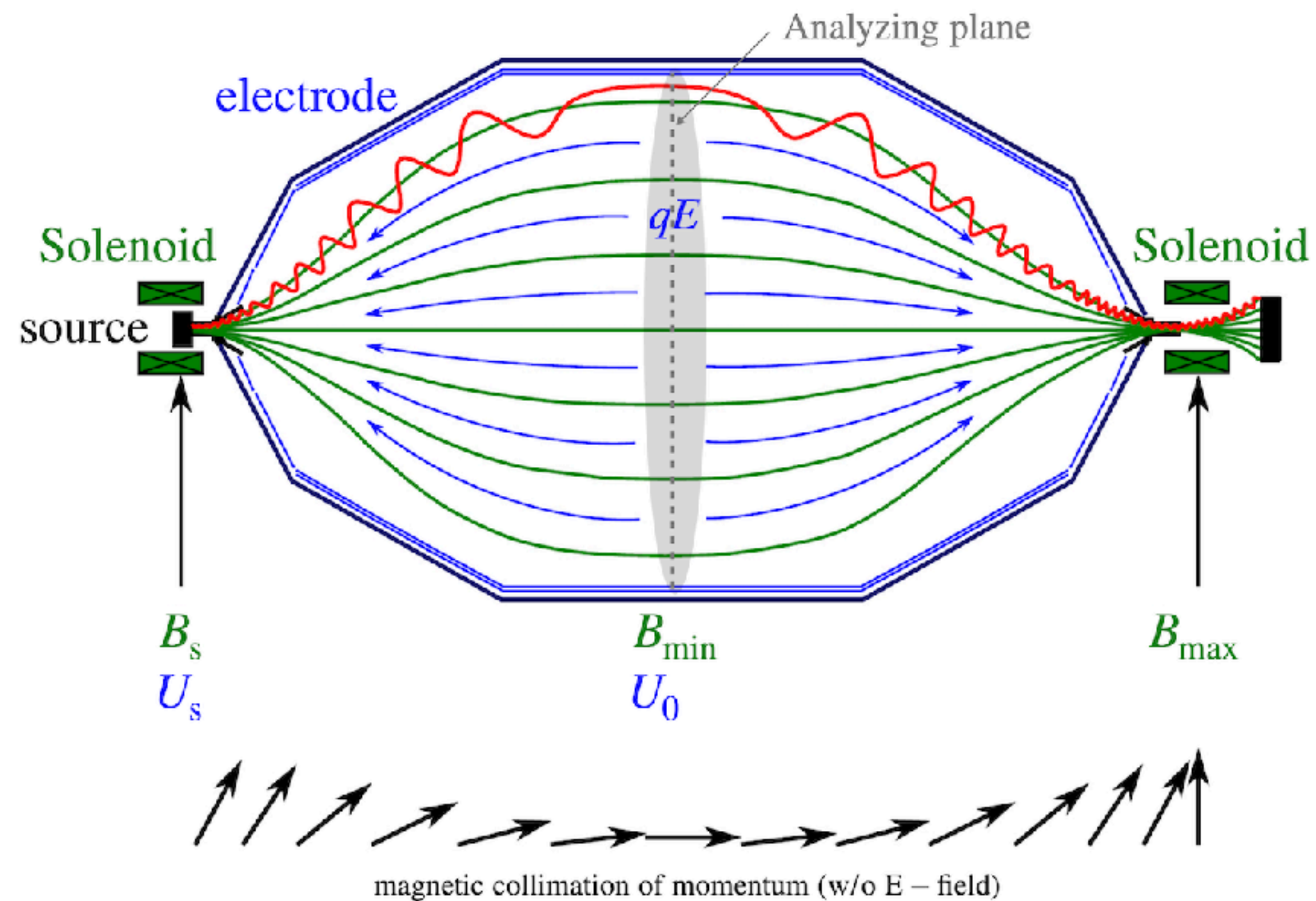
- High source activity ($\sim 10^{11}$ decays/s)
- Excellent energy resolution (~ 1 eV)
- Low background ($\lesssim 0.1$ cps)
- Spectrum and response model
- Hardware stability over years



High-resolution spectrometer

Magnetic Adiabatic Collimation with Electrostatic Filter (“MAC-E”)

(see Picard et al., NIM B 1992; Lobashev & Spivak, NIM A 1985)



Key feature:

Combines large acceptance with eV-scale energy resolution

$$\frac{\Delta E}{E} = \frac{B_{\min}}{B_{\max}} \approx \frac{1}{20,000}$$

Challenge:

Size of a multi-story building

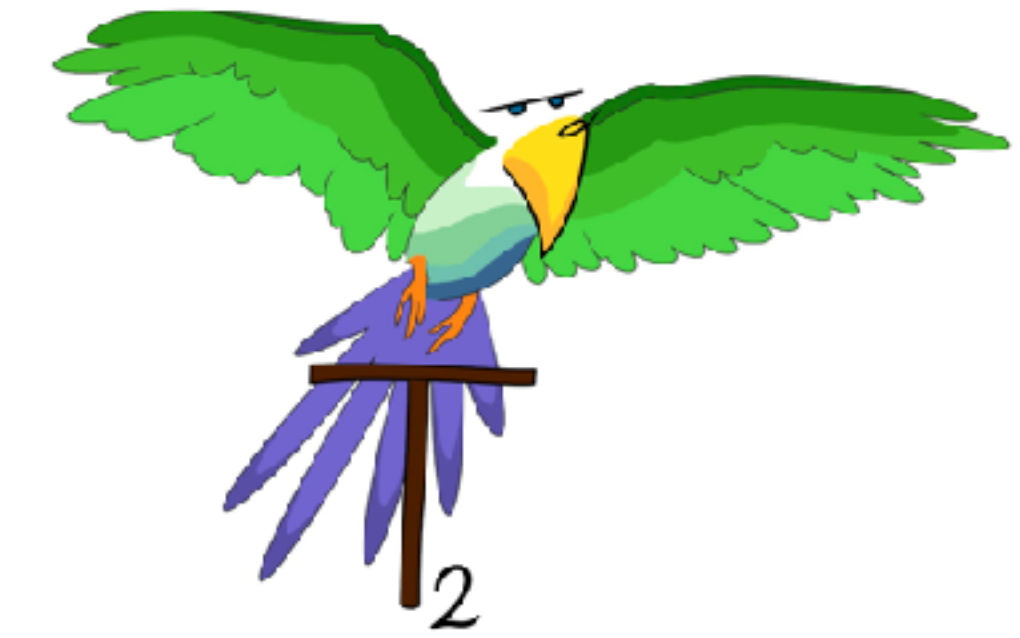


KATRIN: Karlsruhe Tritium Neutrino Experiment

- Experimental site: Karlsruhe Institute of Technology (KIT)
- International collaboration founded in 2001:
 - ~150 members from ~20 institutions in 7 countries
- Reach: m_{ν_e} sensitivity of < 0.3 eV (90% CL)



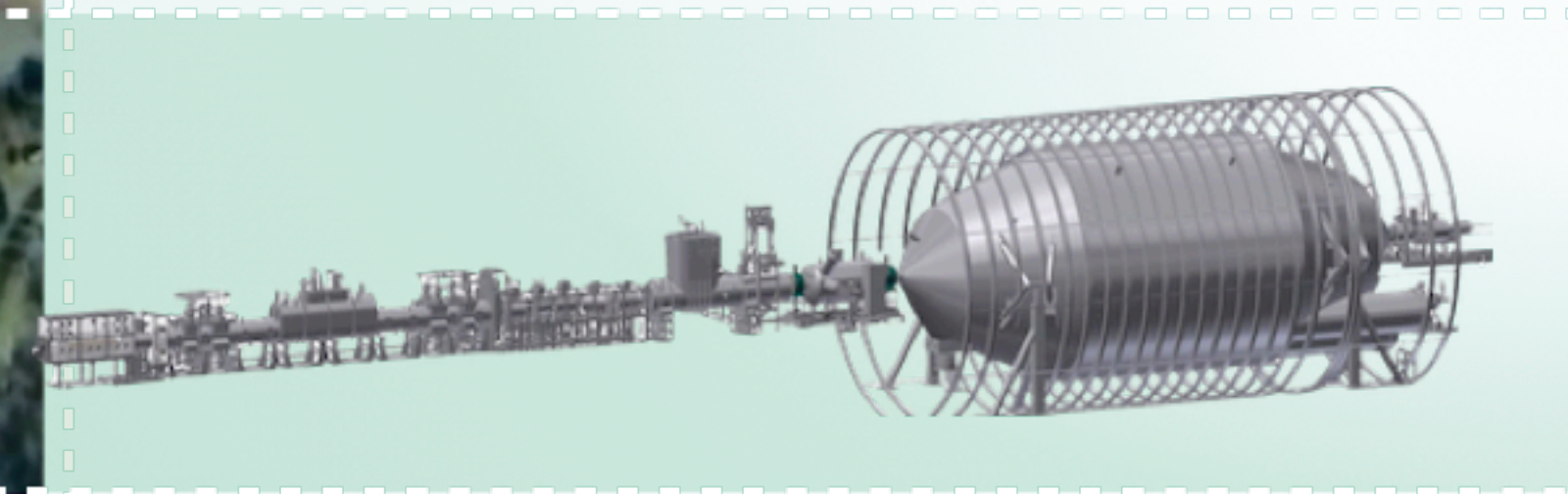
KATRIN collaboration



Collaboration meeting, October 2024, KIT



KATRIN @ Tritium Laboratory Karlsruhe



Tritium Laboratory Karlsruhe (TLK)

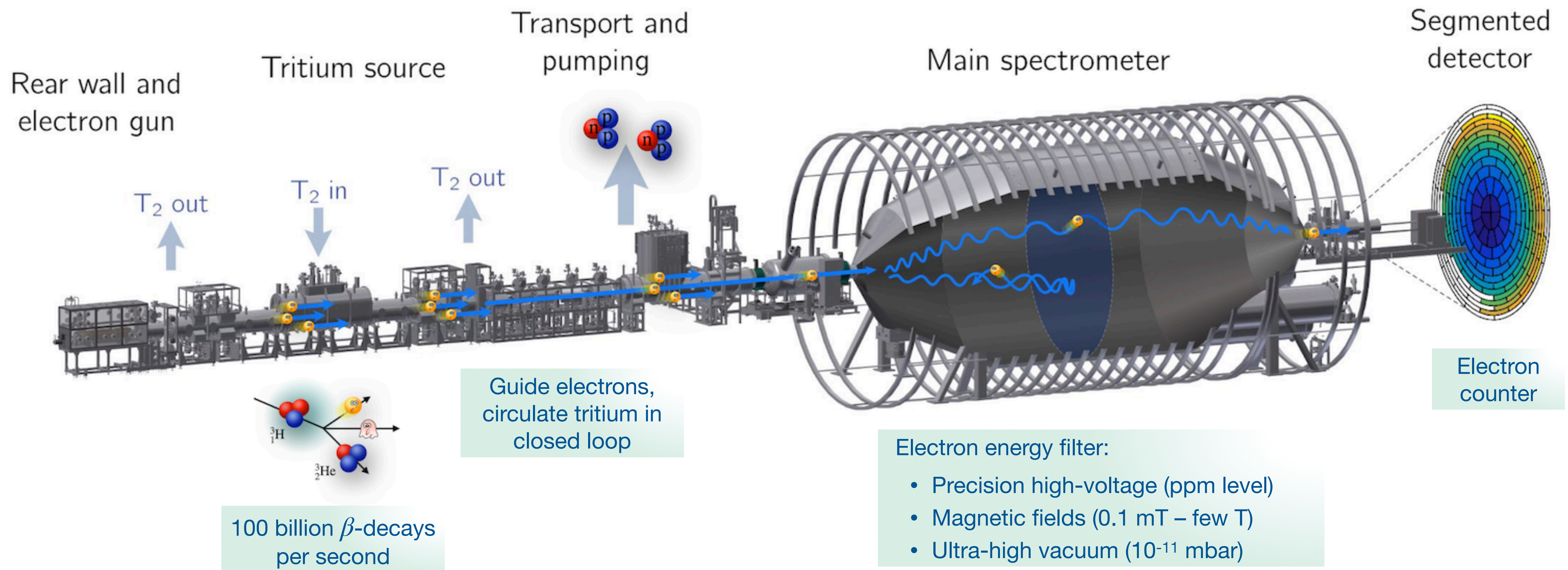
A unique research facility in Europe with 30 years of experience:

- Development of tritium fuel cycle for nuclear fusion
- Closed-loop source operation (~10 kg/year) for KATRIN

(e.g., Hillesheimer et al., *Fusion Sci. Tech.* 80 (2023) 465)

Overview of the KATRIN experiment

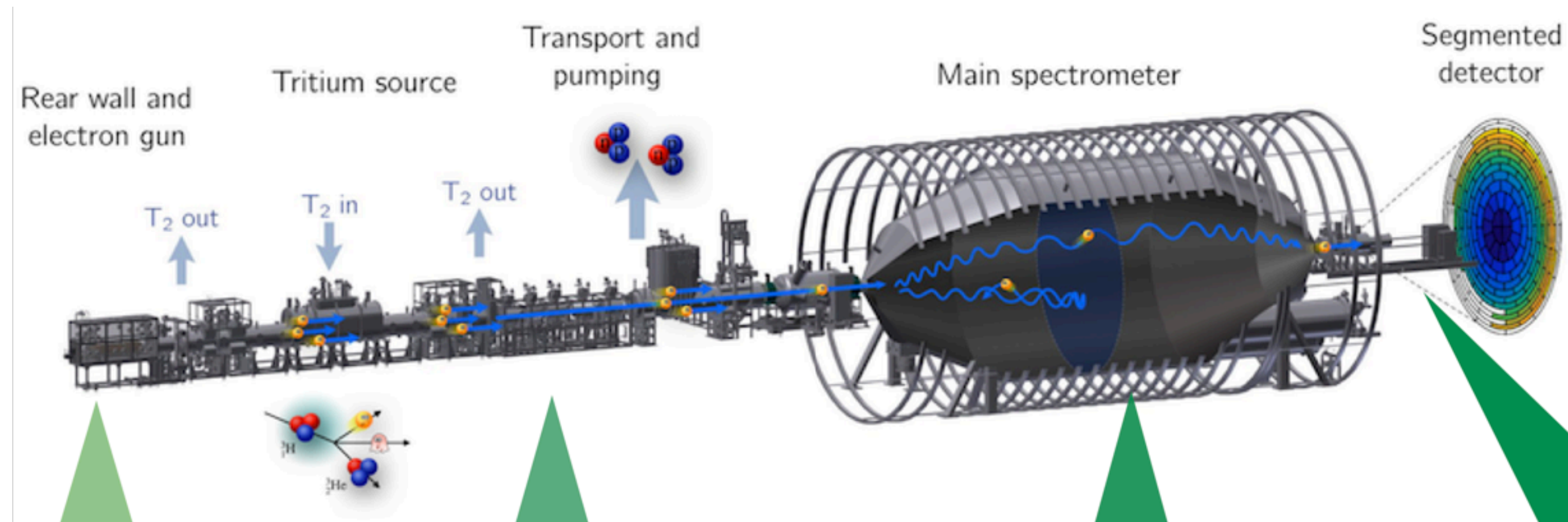
70 m long beam-line: ultra-pure gaseous T_2 source combined with high-resolution electron spectrometer



Full system description & commissioning: KATRIN, JINST 16 (2021) T08015

Overview of the KATRIN experiment

70 m long beam-line: ultra-pure gaseous T_2 source combined with high-resolution electron spectrometer



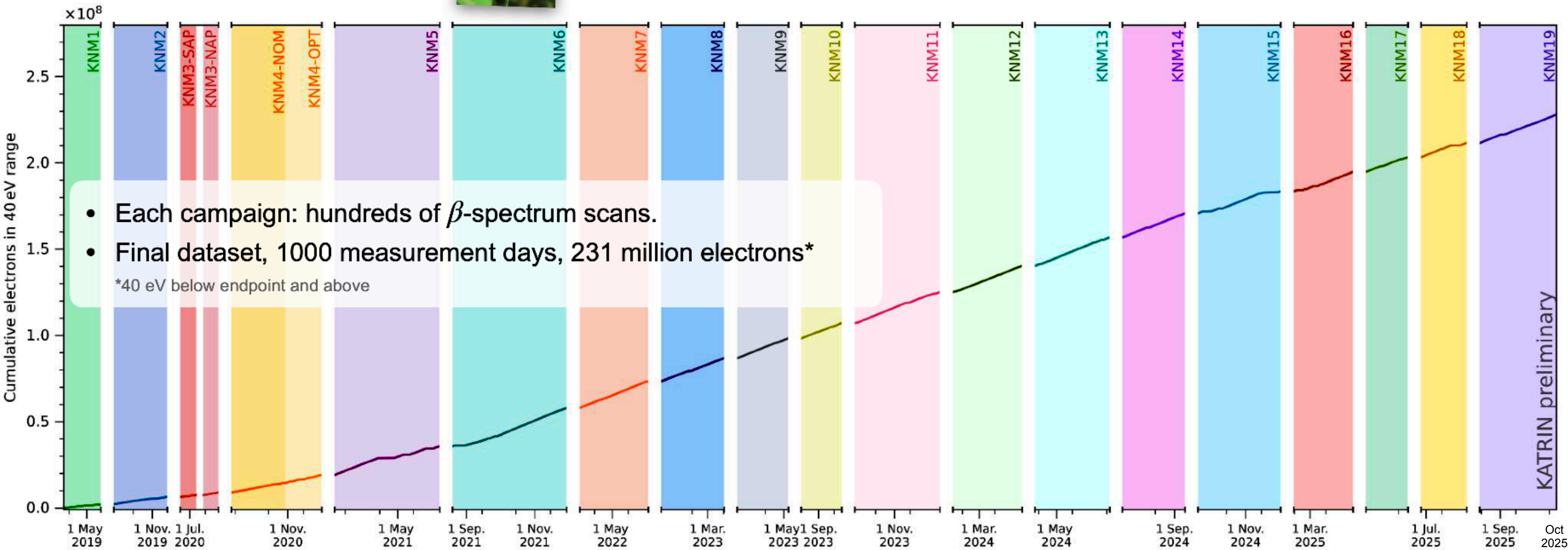
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Data taking overview

SCIENCE 388 (2025) 180



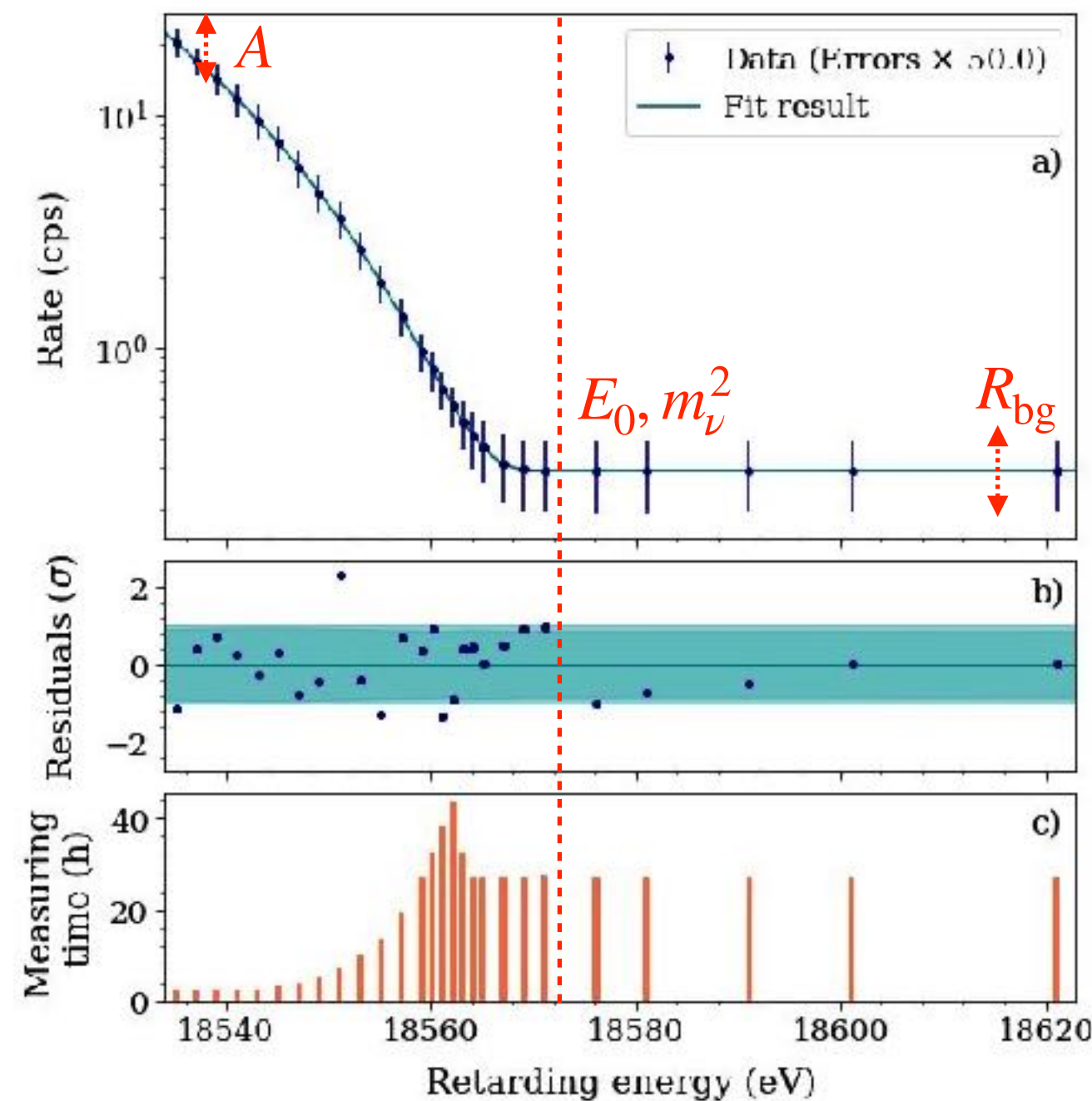
Third result, 5 campaigns,
259 measurement days, 36 million electrons*



spring 2019

Analysis strategy

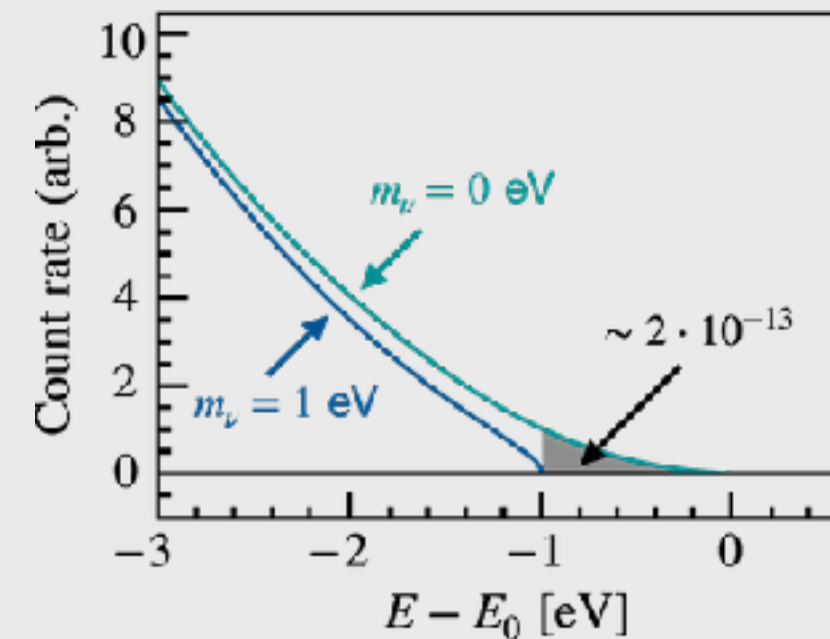
- Convolution of theoretical spectrum with experimental response



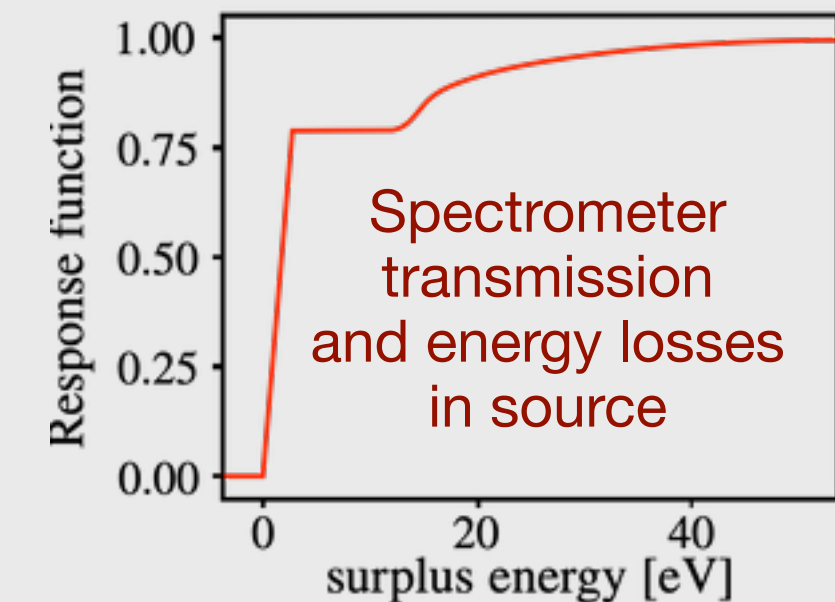
- 2-3 hour scans, $O(100)$ scans per campaign
- Analysis window: $[E_0 - 40 \text{ eV}, E_0 + 135 \text{ eV}]$

$$R(qU) = A \cdot \int_{qU}^{E_0} R_\beta(E; m_\nu^2, E_0) \cdot f(qU, E) dE + R_{bg}$$

Beta decay spectrum



Experimental response



- fitting parameters for neutrino mass: m_ν^2, E_0, A, R_{bg}
- fit model informed by **theoretical** and **experimental** inputs (e-gun, krypton, monitoring, ...)

Sensitivity outlook

- Current world-best direct neutrino mass constraint:

[Aker et al., Science 388 (2025) 6743]

$$m_\nu < 0.45 \text{ eV (90 \% CL)}$$

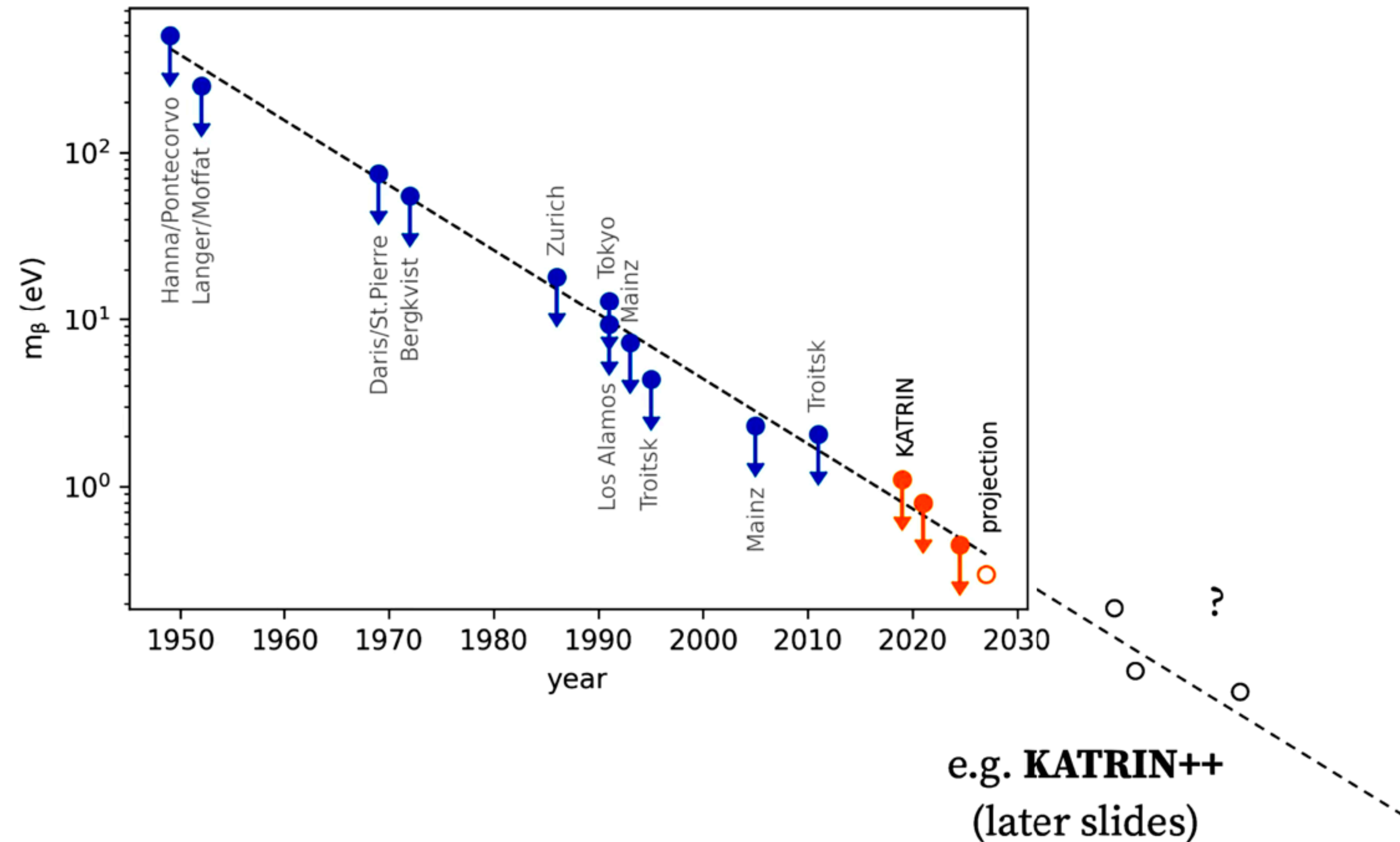
based on 259 measurement days and 36 million electrons

- Final dataset with 1000 measurement days and 231 million electrons

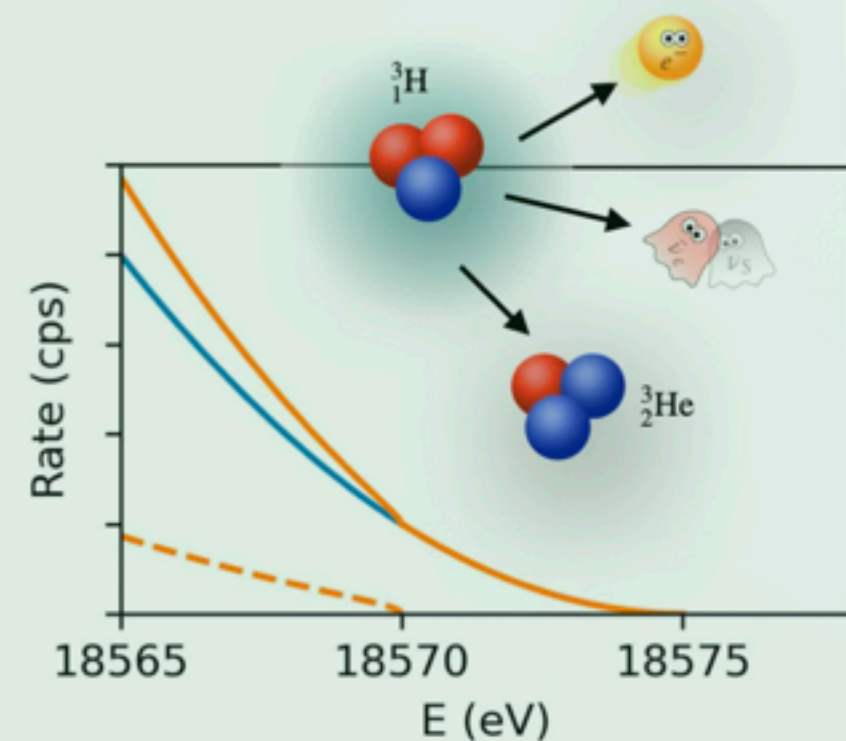
$$m_\nu < 0.28 \text{ eV}^* \text{ (90 \% CL)}$$

* statistical sensitivity, no systematics

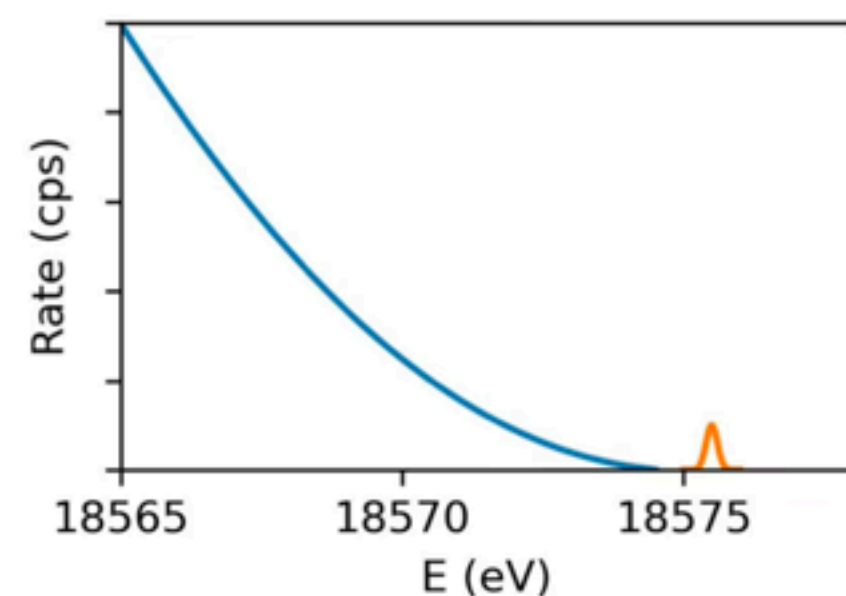
Credit: Christoph Wiesinger's presentation @ Neutrino2026



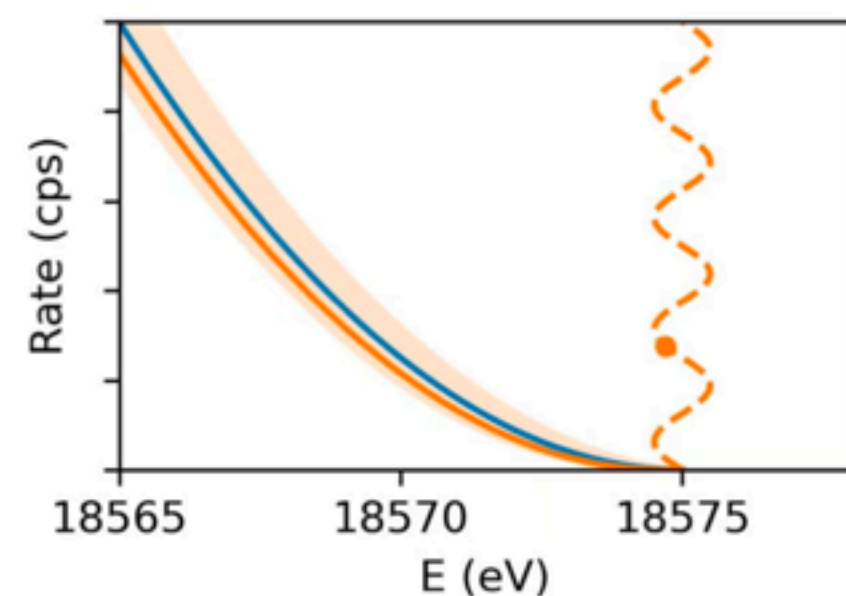
Beyond neutrino mass studies



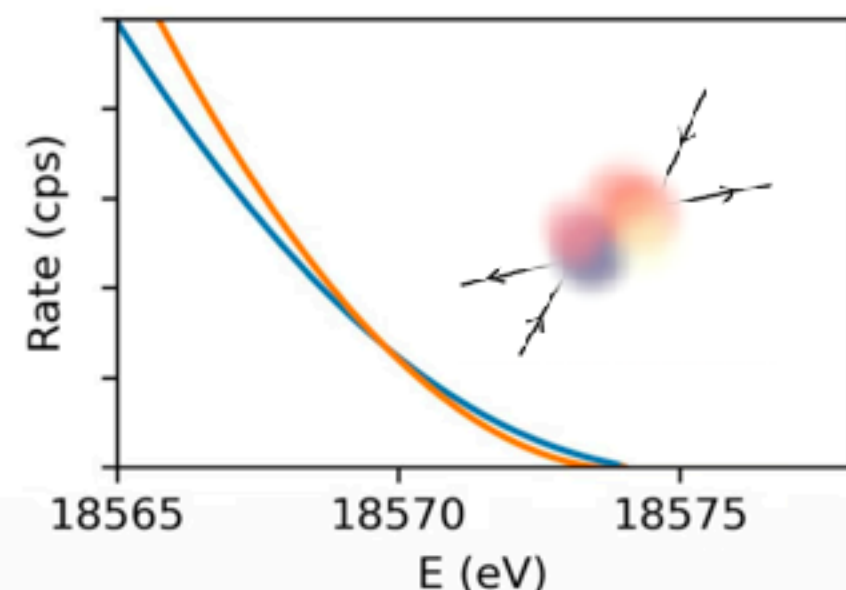
- **Sterile neutrinos**, eV-scale (next slide) to keV-scale (later slides), additional spectral component, kink, [Acharya et al., Nature 648 (2025) 8092, 70-75]
- **Extra dimensions**, multiple kinks [Antoniadis, AC, Isono, JHEP 02 (2026) 015]



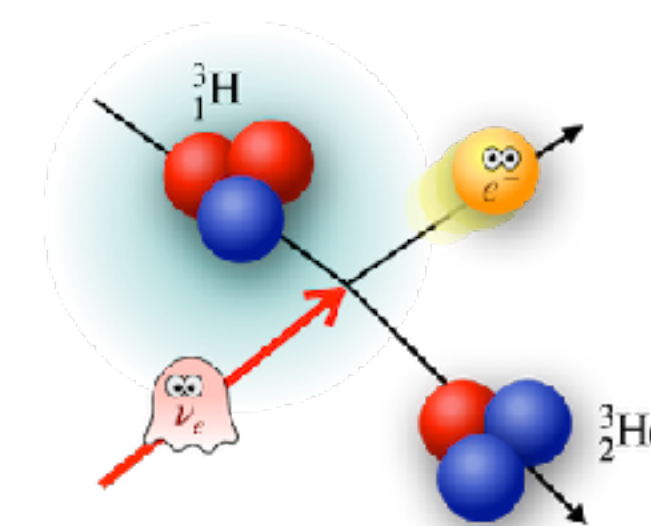
- **Relic neutrino overdensity**, population above endpoint [Aker et.al, PRL 129 (2022) 1, 011806]



- **Lorentz invariance violation**, sidereal modulation [Aker et. al, PRD 107 (2023) 8, 082005]
- **Ultra-light axions**, modulation [Lee et al., PRR 2 (2020) 3, 033392]



- **General neutrino interactions**, shape distortion [Aker et. al, PRL 134 (2025) 25, 251801]
- **Light Bosons**, additional spectral component, shape distortion [Lauer, PoS ICHEP2024 (2025) 326]



Credit: Christoph Wiesinger's presentation @ Neutrino2026

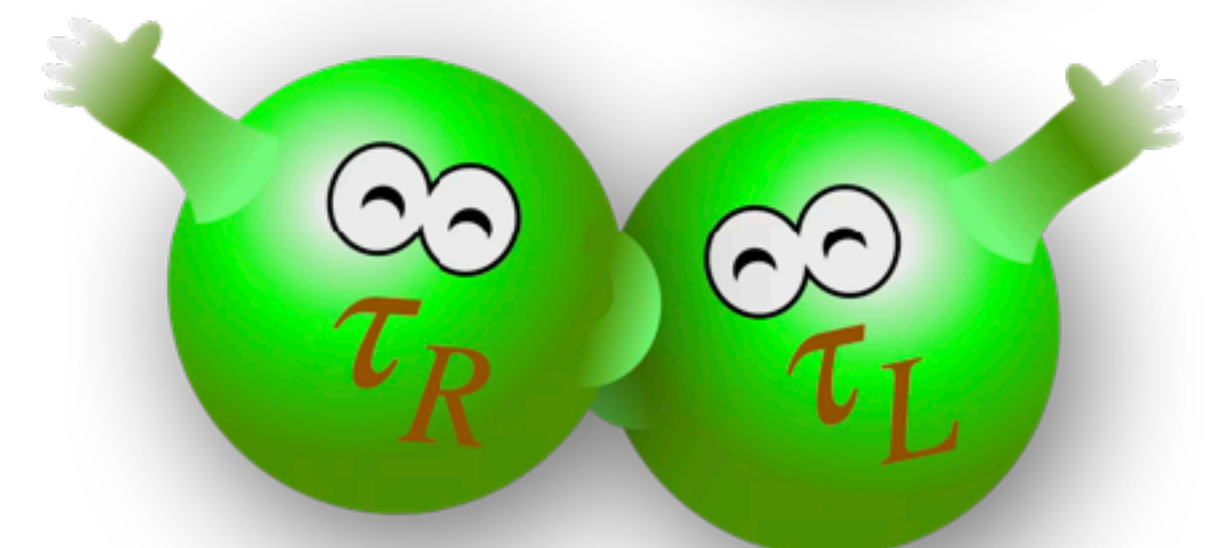
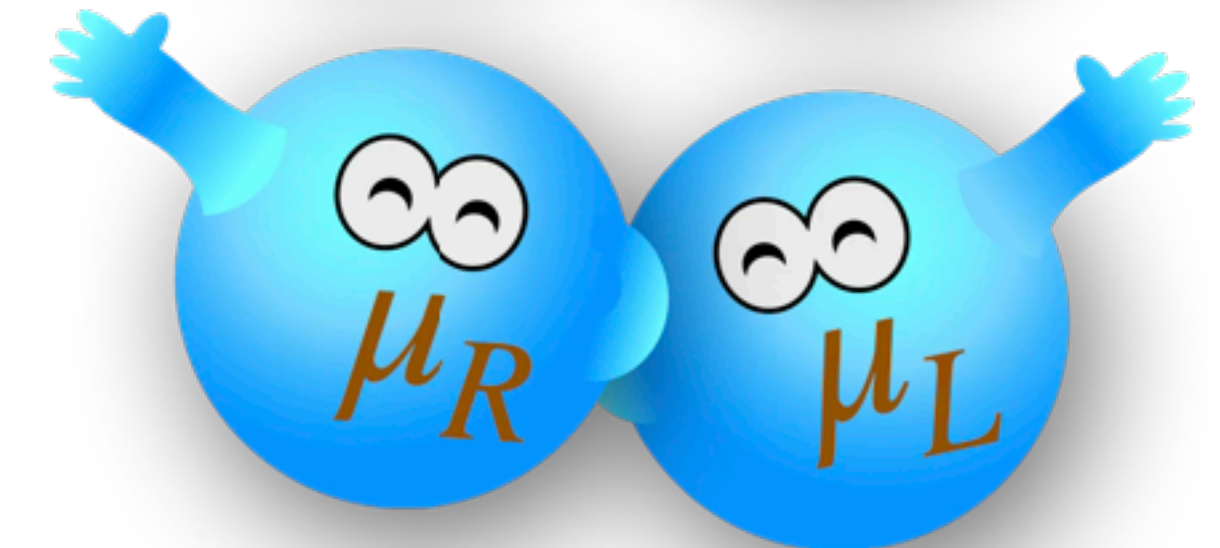
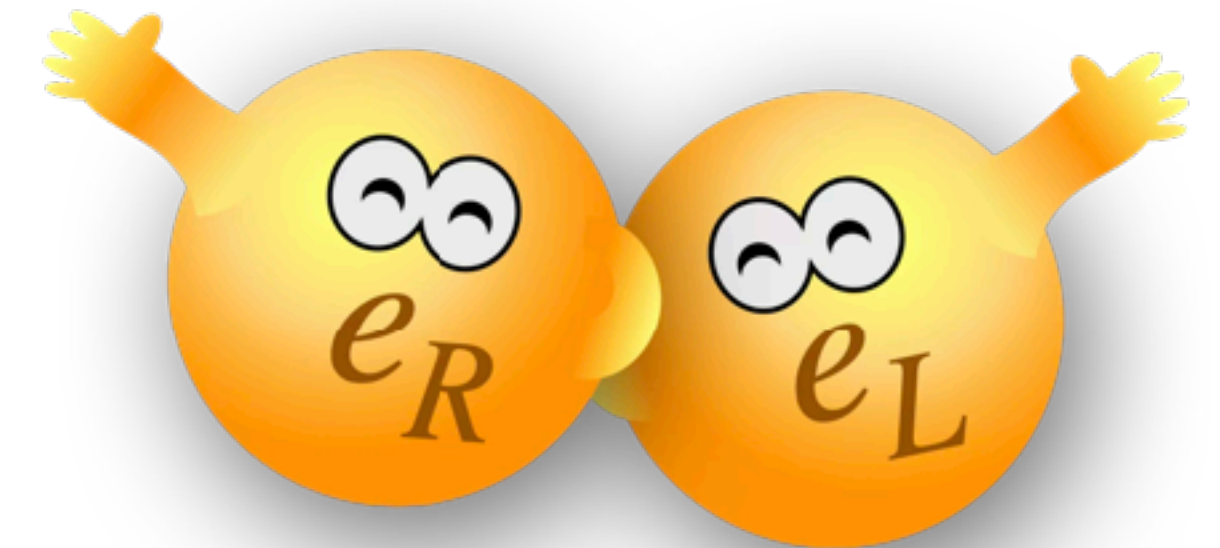
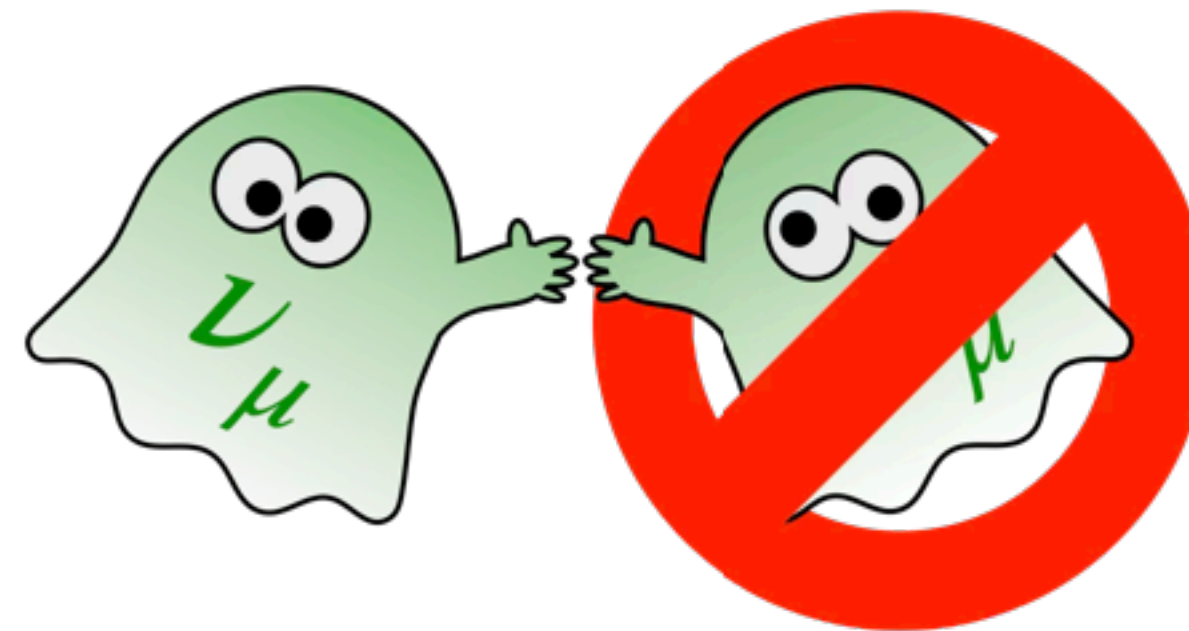
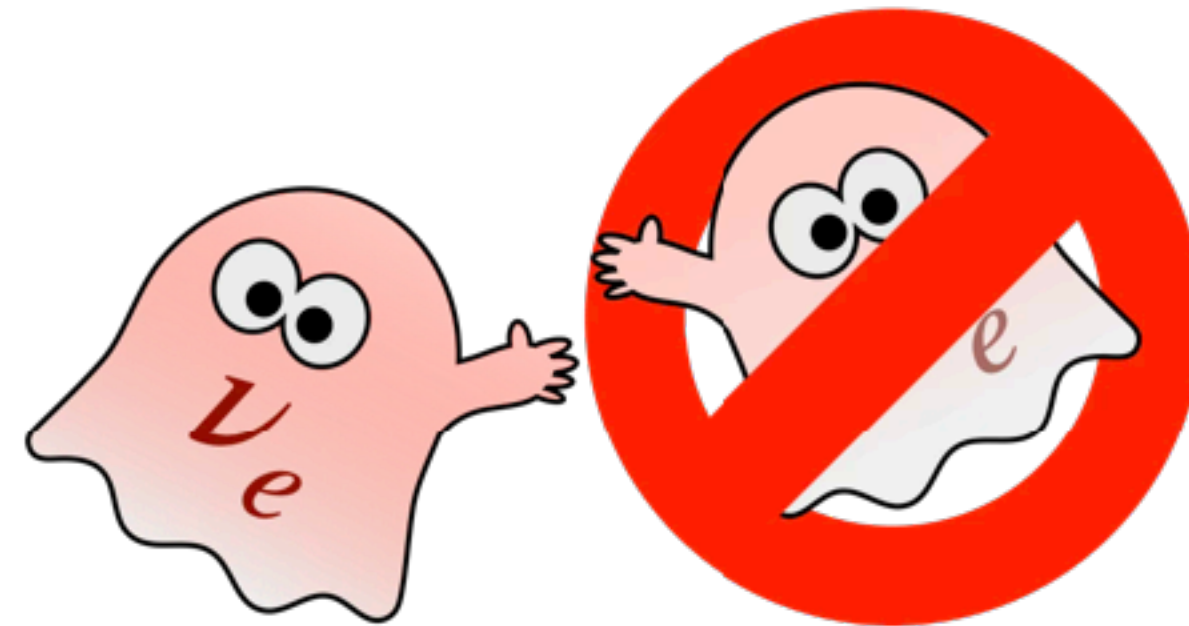


How neutrino has their mass?



Something is missing in Lepton sector

- In the Standard Model of particle physics, there are “**no right-handed neutrinos**”
- while electrons, muons, and taus, as well as all quarks, are found to be both right-handed and left-handed.

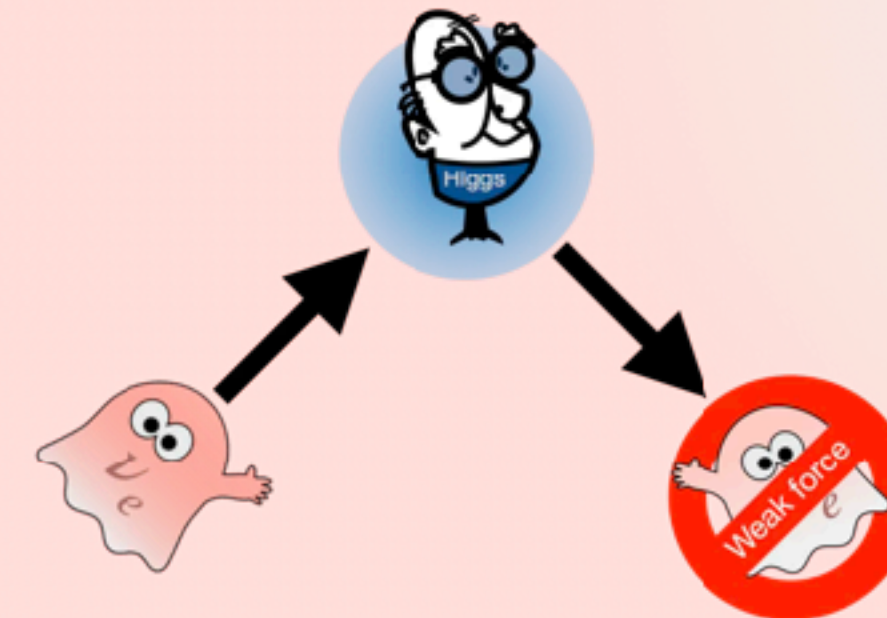
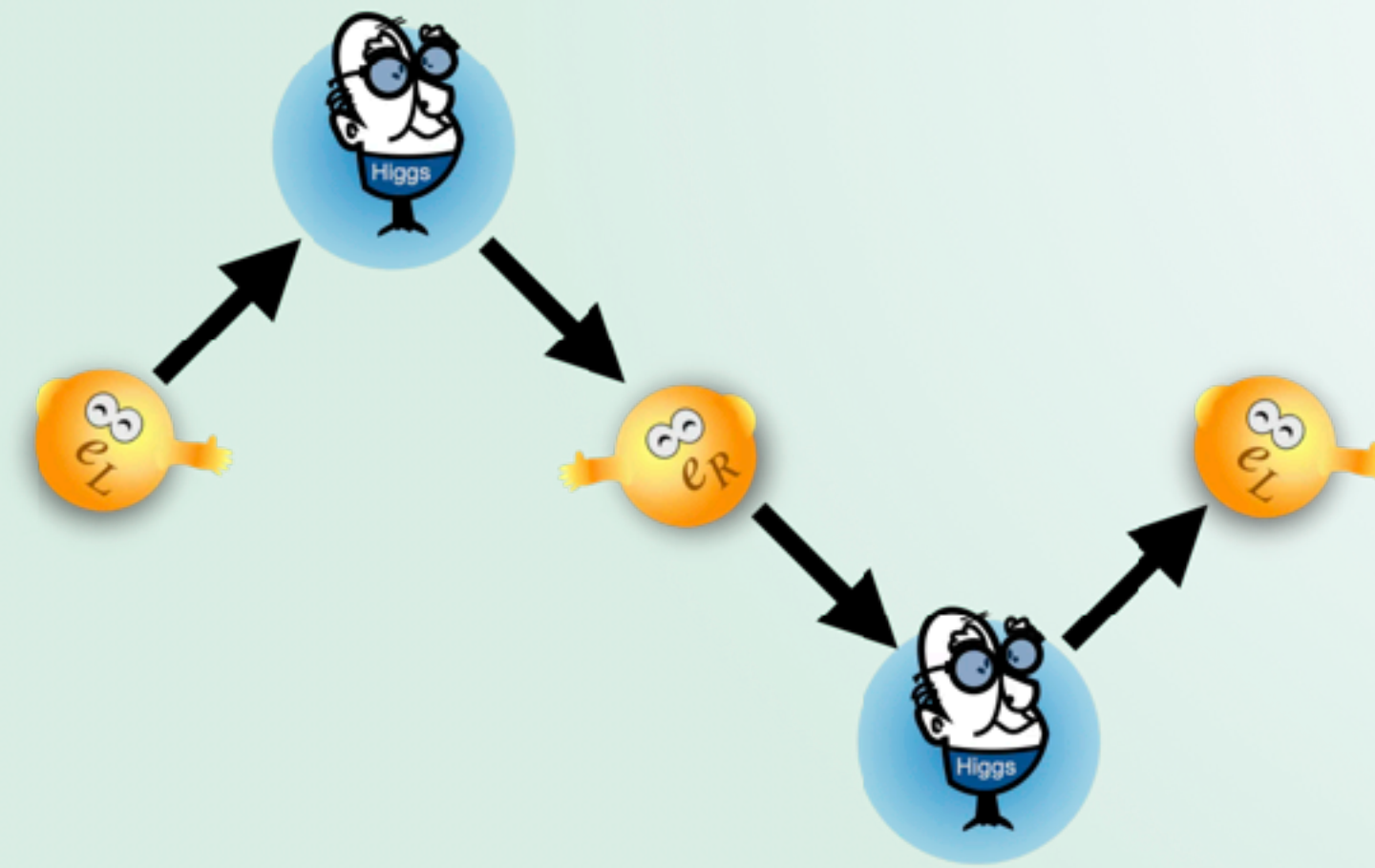


Role of the Higgs

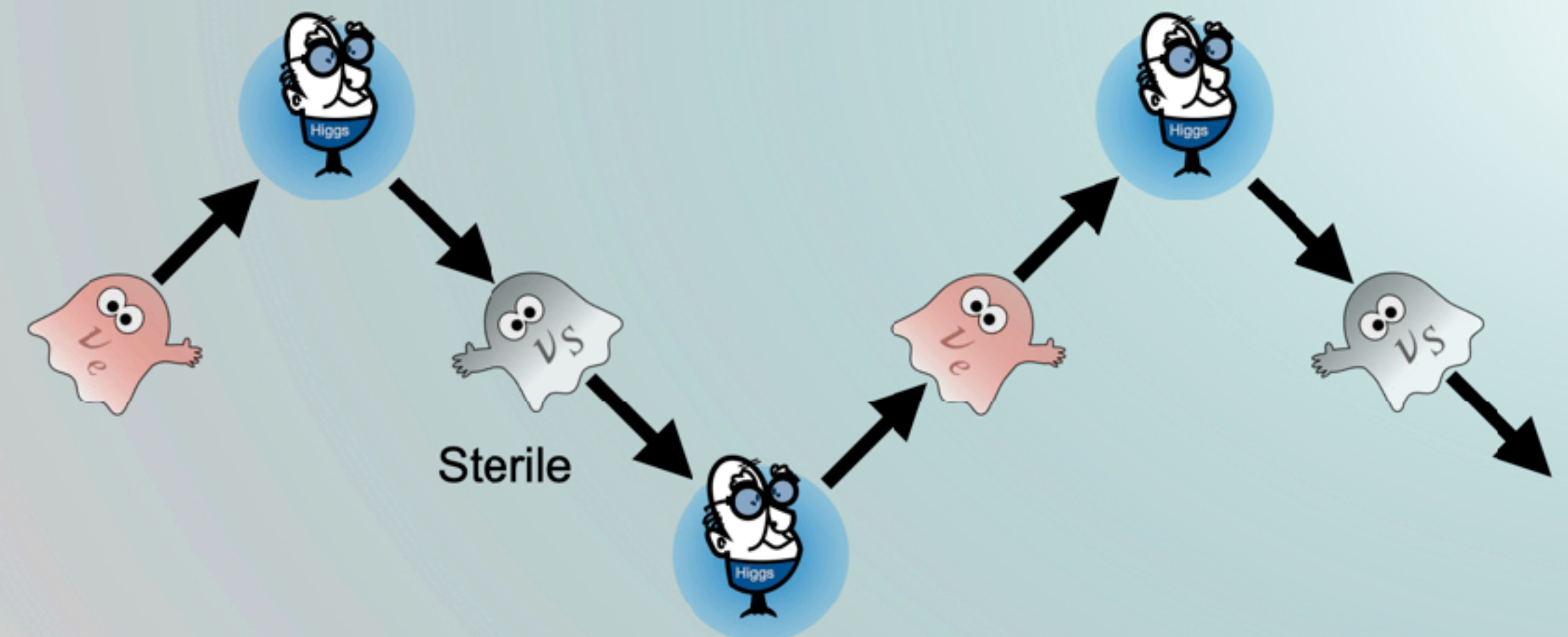
- **Particle mass:** interaction with Higgs field via Yukawa coupling
- Higgs transforms left- to right-handed chirality
- Right-handed neutrino as **natural extension of SM**
- Right-handed neutrino would be **sterile**



Not in SM



How does neutrino have mass?

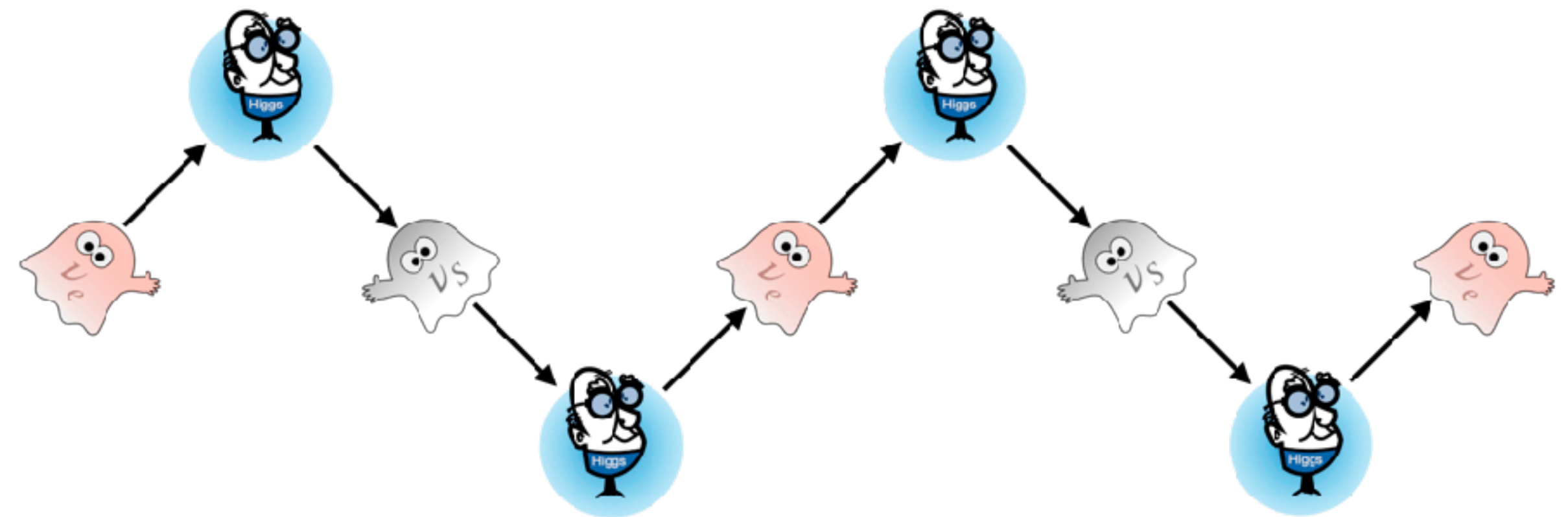
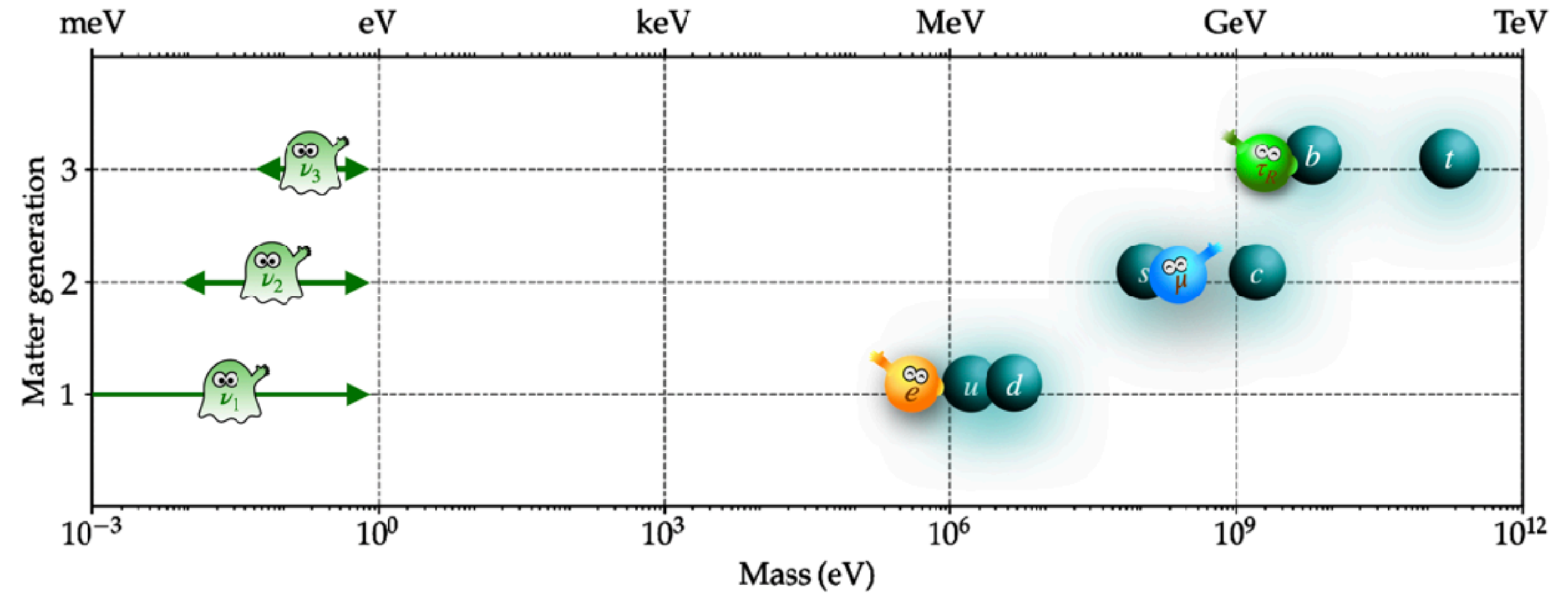


Dirac neutrino mass

- The Dirac mass term

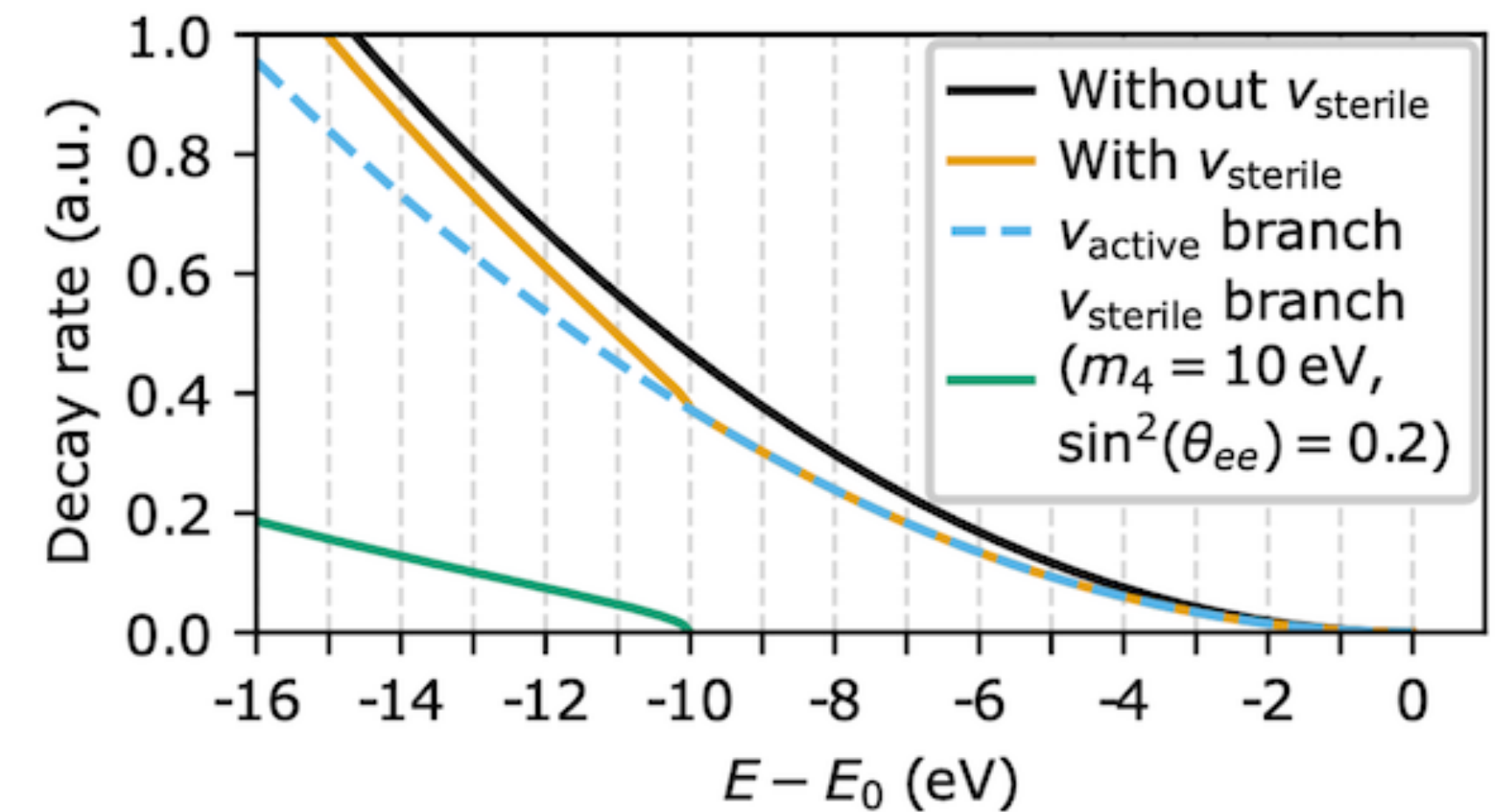
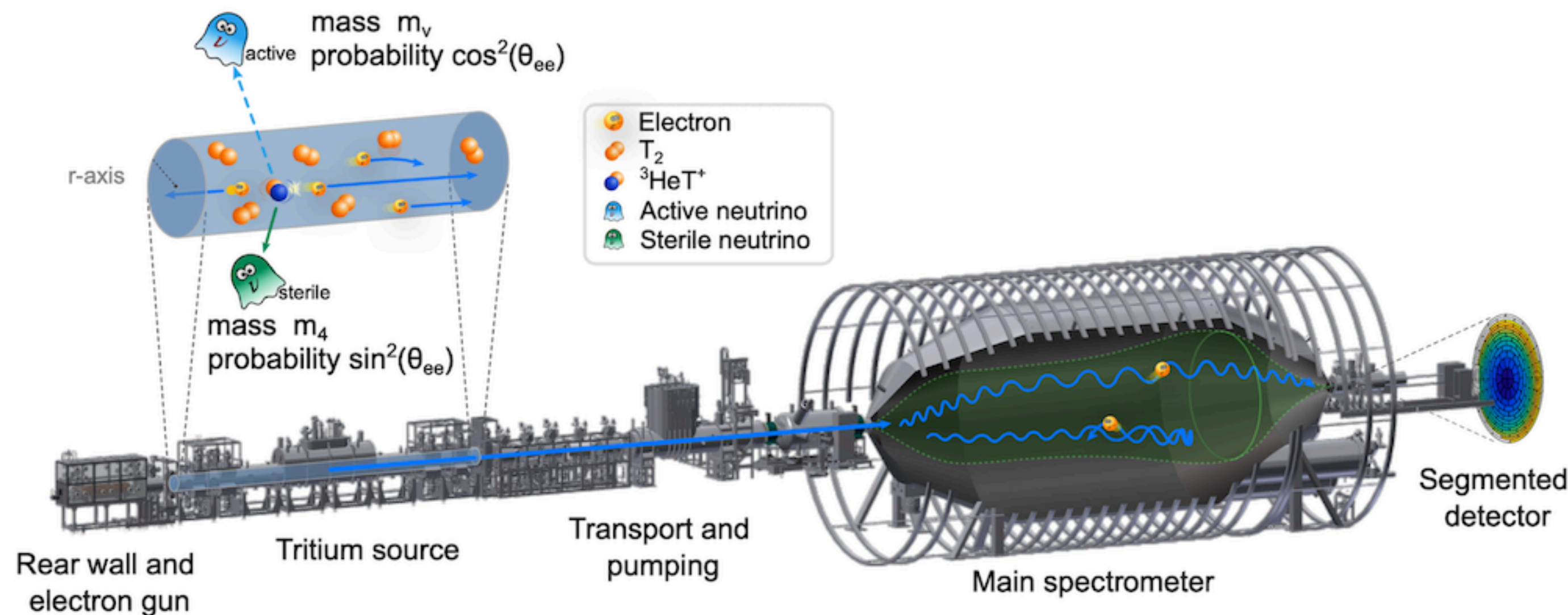
$$\mathcal{L}_D \propto \mu \langle H \rangle \bar{\nu}_L \nu_R \sim m_D \bar{\nu}_L \nu_R$$

- Yukawa coupling** to Higgs (μ) would have to be tiny to **explain smallness of neutrino mass**
- What mechanism** causes the Yukawa coupling value to be so small?



Search for Sterile Neutrino @ KATRIN

- **Light sterile neutrinos (eV mass scale):** motivated by short-baseline oscillation anomalies (almost ruled out by the MicroBooNE result)
- **Heavy sterile neutrinos (keV mass scale):** motivated as a dark matter candidate

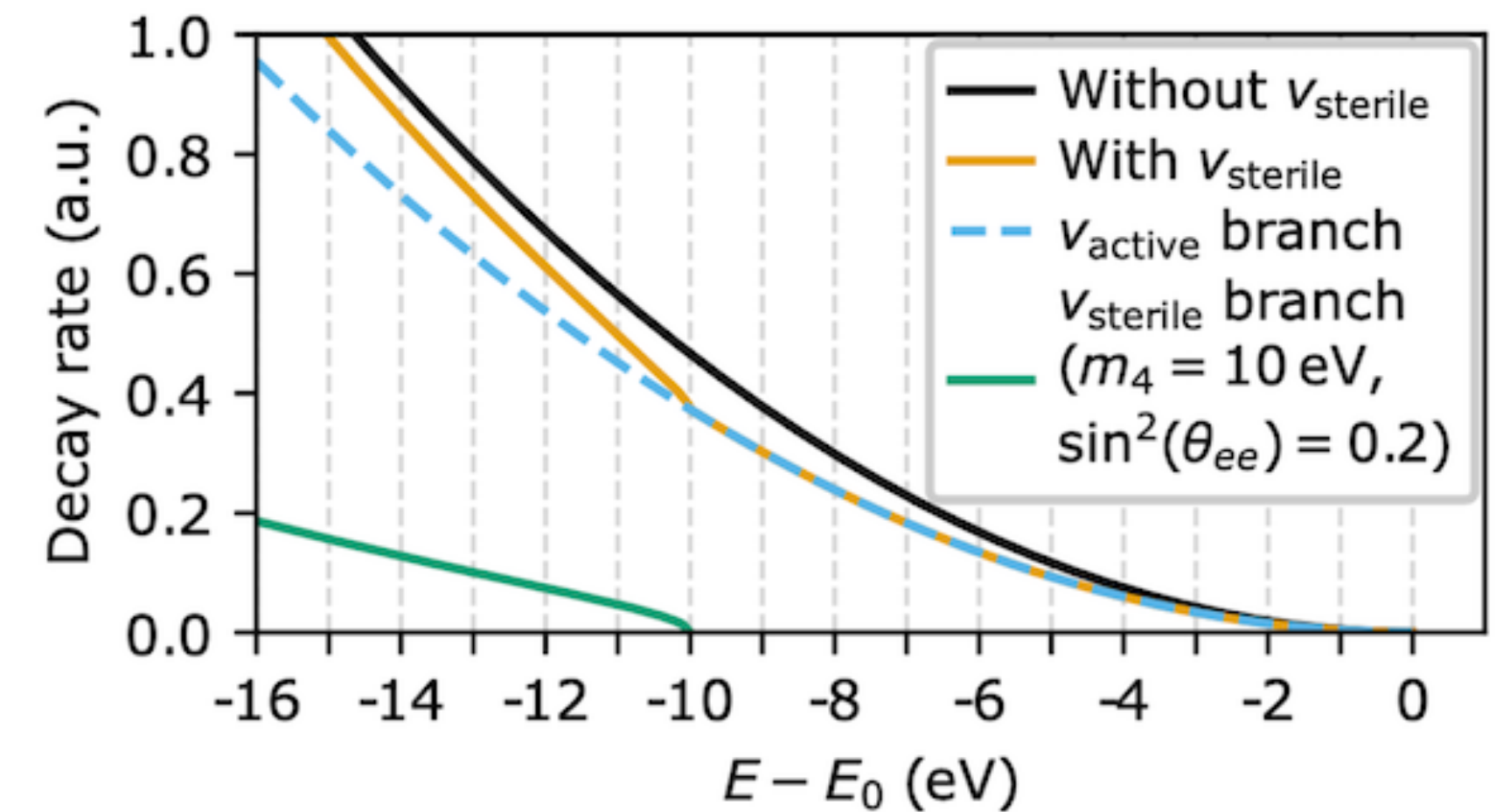
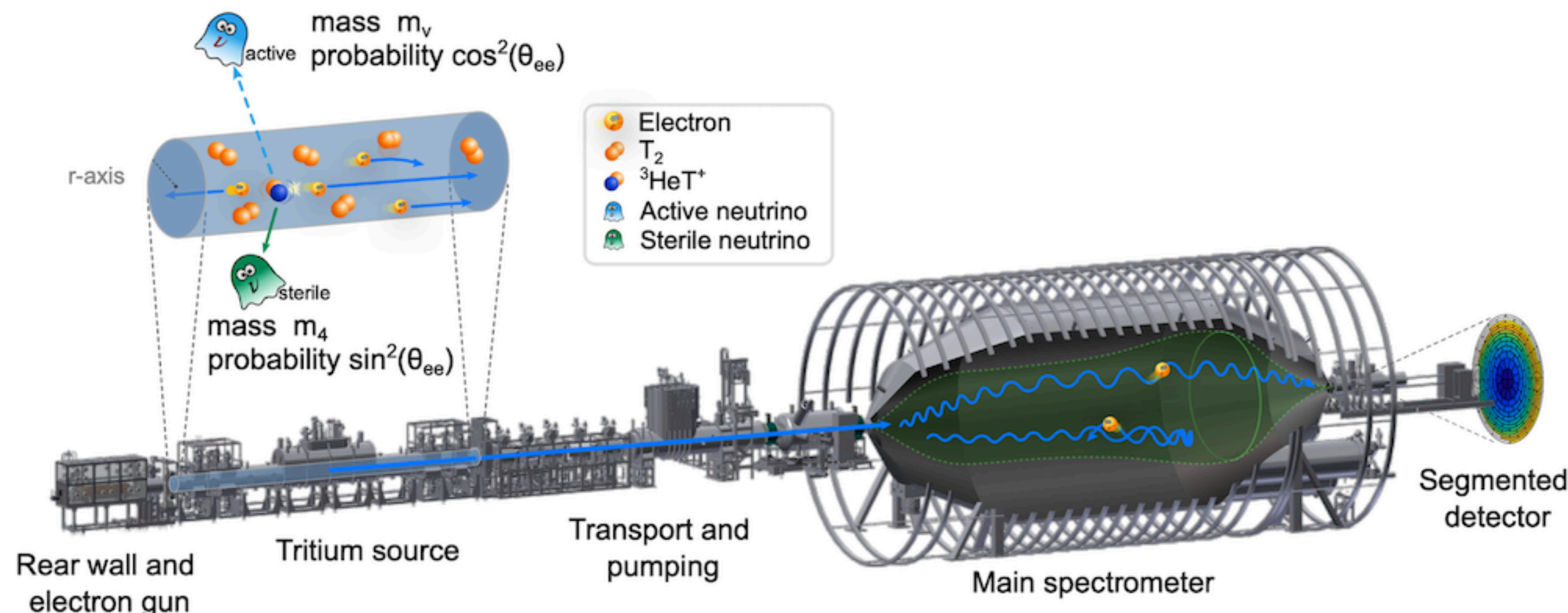


[Acharya et al., Nature 648 (2025) 8092, 70-75]

The 3+1 model for Sterile Neutrino

- Model parameters are the **mass** m_4^2 and the **mixing** (θ_{ee}) and **the active ν mass** m_ν^2
- The beta decay spectrum are

$$R_\beta(E, E_0, m_\nu^2, m_4^2, \theta_{ee}) = \cos^2(\theta_{ee}) R_\beta(E, E_0, m_\nu^2) + \sin^2(\theta_{ee}) R_\beta(E, E_0, m_4^2)$$

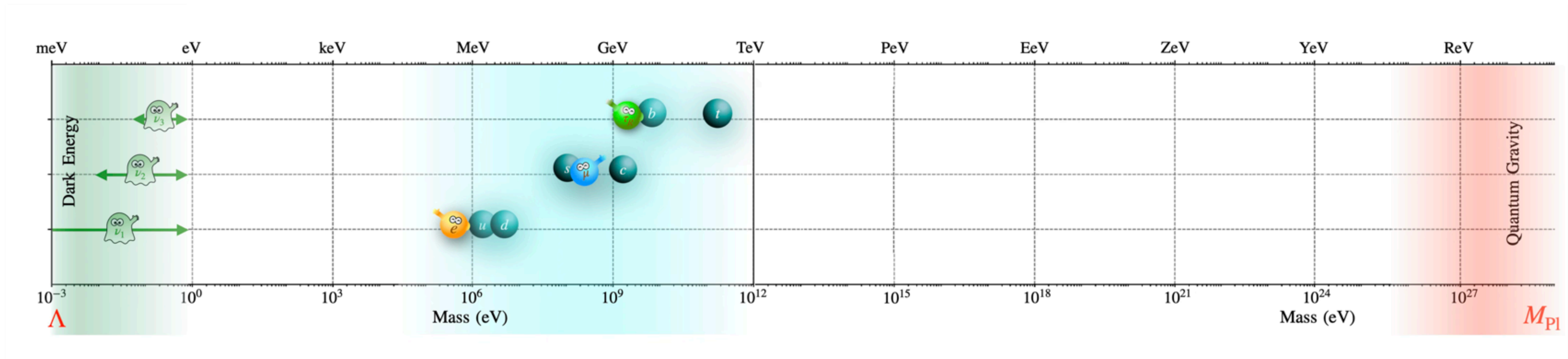


[Acharya et al., Nature 648 (2025) 8092, 70-75]



Why neutrino mass so small?

Large hierarchies in particle physics and cosmology



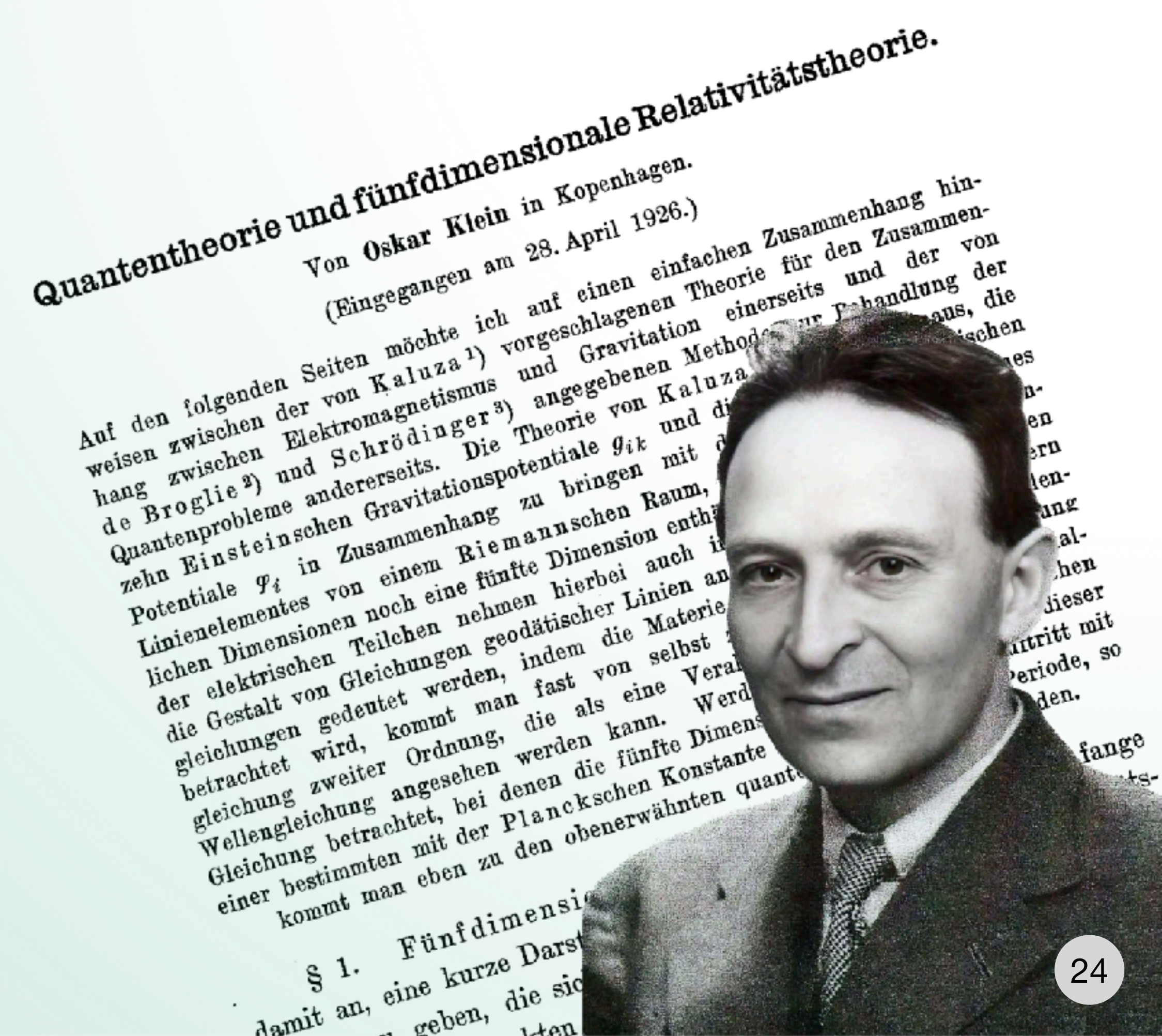
- **Why gravity appears so weak** compared to other forces?

$$G \propto \frac{1}{M_{Pl}^2}, \text{ and } M_{Pl} \sim 10^{29} \text{ eV}$$

- Neutrino Mass Scale (and Dark Energy Scale) is $< \text{eV}$. **Why they are so different?**
- One possible solution $\Rightarrow$ **Extra Dimension**

100th Anniversary of the Kaluza Klein Theory

- In 1919, Kaluza submitted his research to Einstein, proving that Einstein's equations in 5-dim spacetime unified gravity in the original 4-dim and Maxwell's equations of electromagnetism simultaneously.
- In 1926, Oskar Klein further developed Kaluza's ideas, explaining why this 5th dim is invisible. He pointed out that it is a dimension that is compactified at a level too small to be observed.
- The combined ideas of the two are now known as **the Kaluza–Klein theory**.



Gravitational Force & Extra Dimensions

- From Gauss's law, considering 4D space time

$$\text{Field} = \frac{\text{Flux}}{\text{Area}} \propto \frac{M}{4\pi r^2} = G_4 \frac{M_\odot}{r^2}$$

- Gravitational constant can be written as

$$G_4 \propto 1/M_{\text{Pl}}^2, \quad M_{\text{Pl}} \text{ is the 4D Planck mass}$$

- Since $M_{\text{Pl}} \sim 10^{19}$ GeV, gravity is very weak!

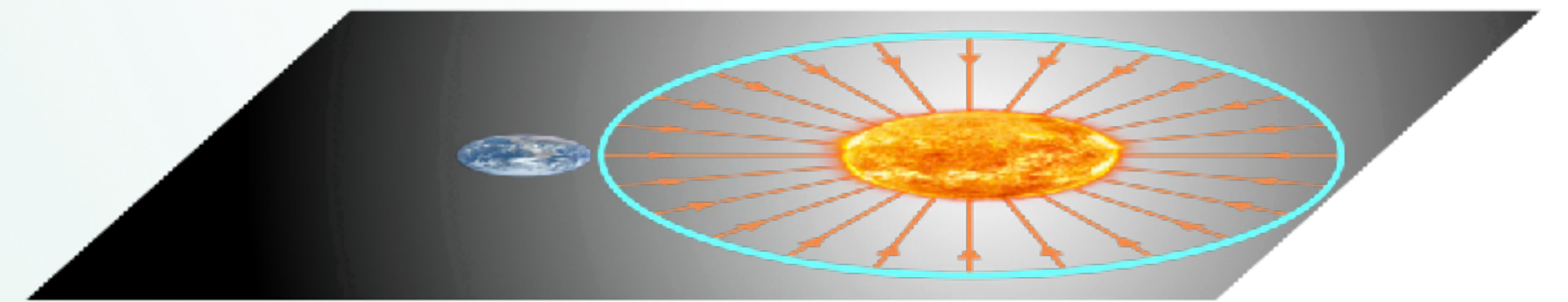
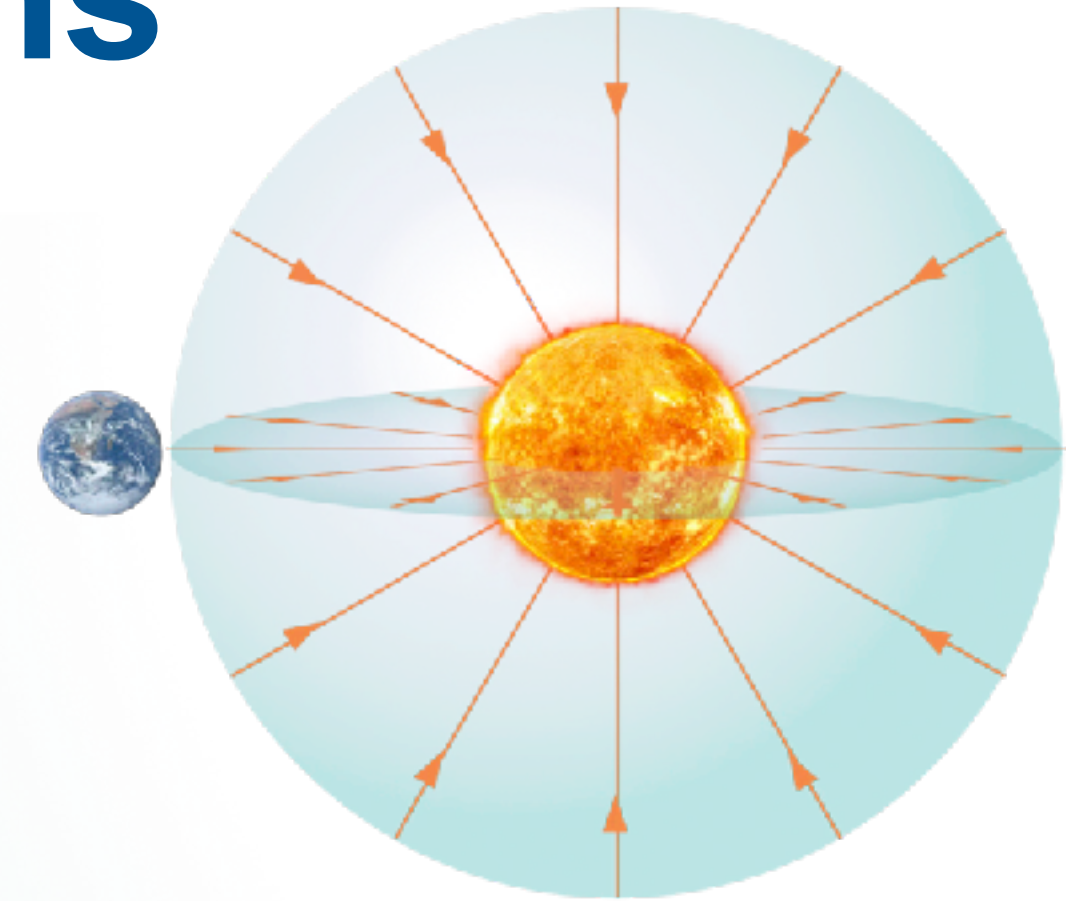
- In 5D, we have

$$\text{Field} = G_5 \frac{M_\odot}{r^3}$$

and

$$G_5 \propto 1/M_*^3$$

where M_* is 5D Planck mass



$$3\text{D (1+2) spacetime} \rightarrow \text{Area} \propto r \Rightarrow |\vec{g}| \propto 1/r$$

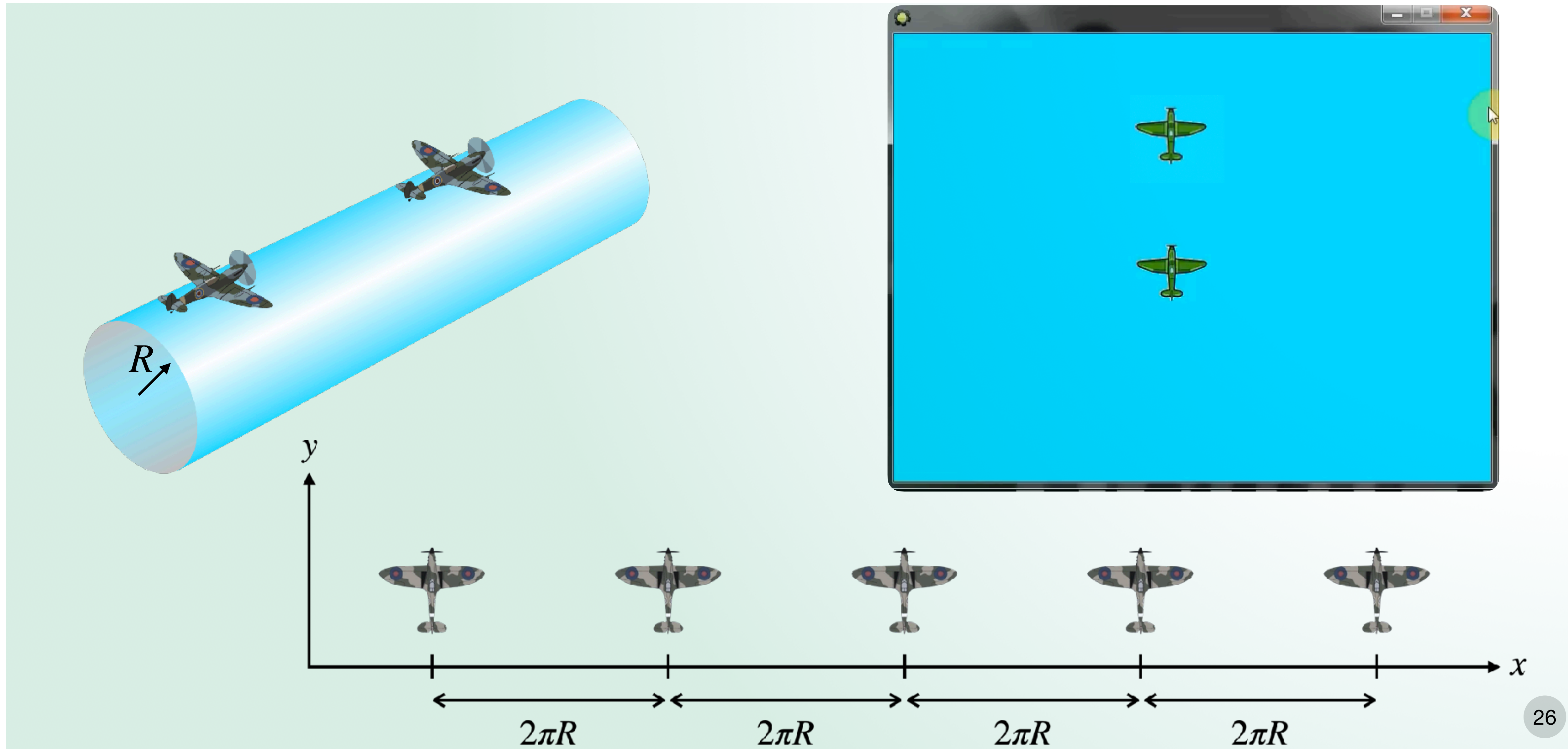
$$4\text{D (1+3) spacetime} \rightarrow \text{Area} \propto r^2 \Rightarrow F \propto 1/r^2$$

$$5\text{D (1+4) spacetime} \rightarrow \text{Area} \propto r^3 \Rightarrow F \propto 1/r^3$$

$\vdots$

$$D\text{-dim spacetime} \rightarrow \text{Area} \propto r^{D-2} \Rightarrow F \propto 1/r^{D-2}$$

Compacted Extra Dimension



5-dimensional Planck Mass

- For $R \ll r$, let define $\lambda = M_{\odot}/2\pi R$. The gravitational field from the mass $M_{\odot}$

$$|\vec{g}| \propto \frac{\lambda \mathcal{L}}{(4\pi r^2) \mathcal{L}} = G_5 \frac{\lambda}{r^2} = G_5 \left(\frac{M_{\odot}}{2\pi R} \right) \frac{1}{r^2}$$

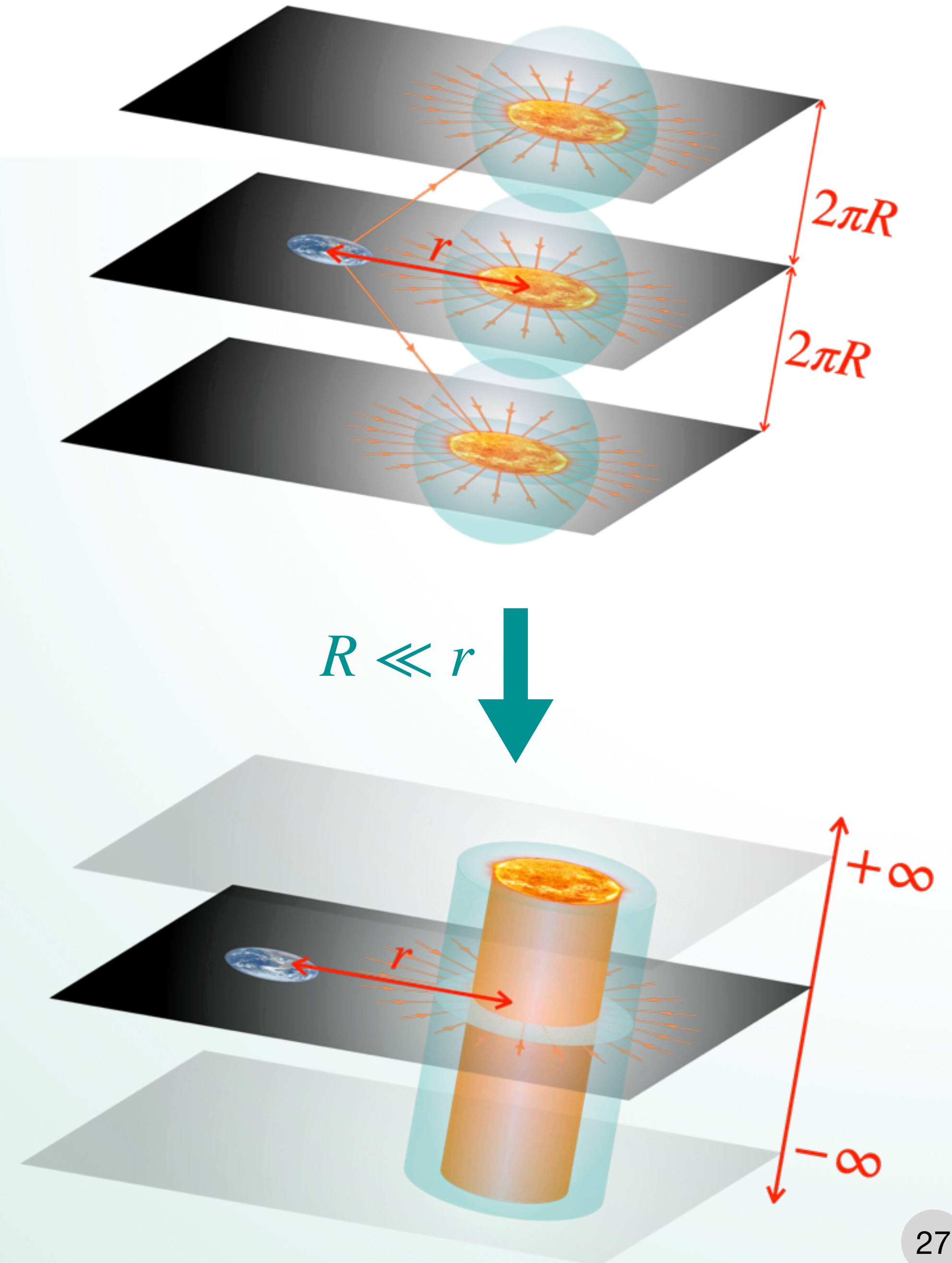
Since $|\vec{g}| \propto 1/r^2$ effectively 4D gravity, we can write:

$$|\vec{g}| = G_4 \frac{M_{\odot}}{r^2}$$

This implies $G_4 = G_5/2\pi R$. In terms of the Planck mass

$$M_{\text{Pl}}^2 = M_*^3 (2\pi R)$$

- For $R \sim 10 \mu\text{m}$, we have $M_* \sim 10^9 \text{ GeV}$



Motivation for Extra Dimension

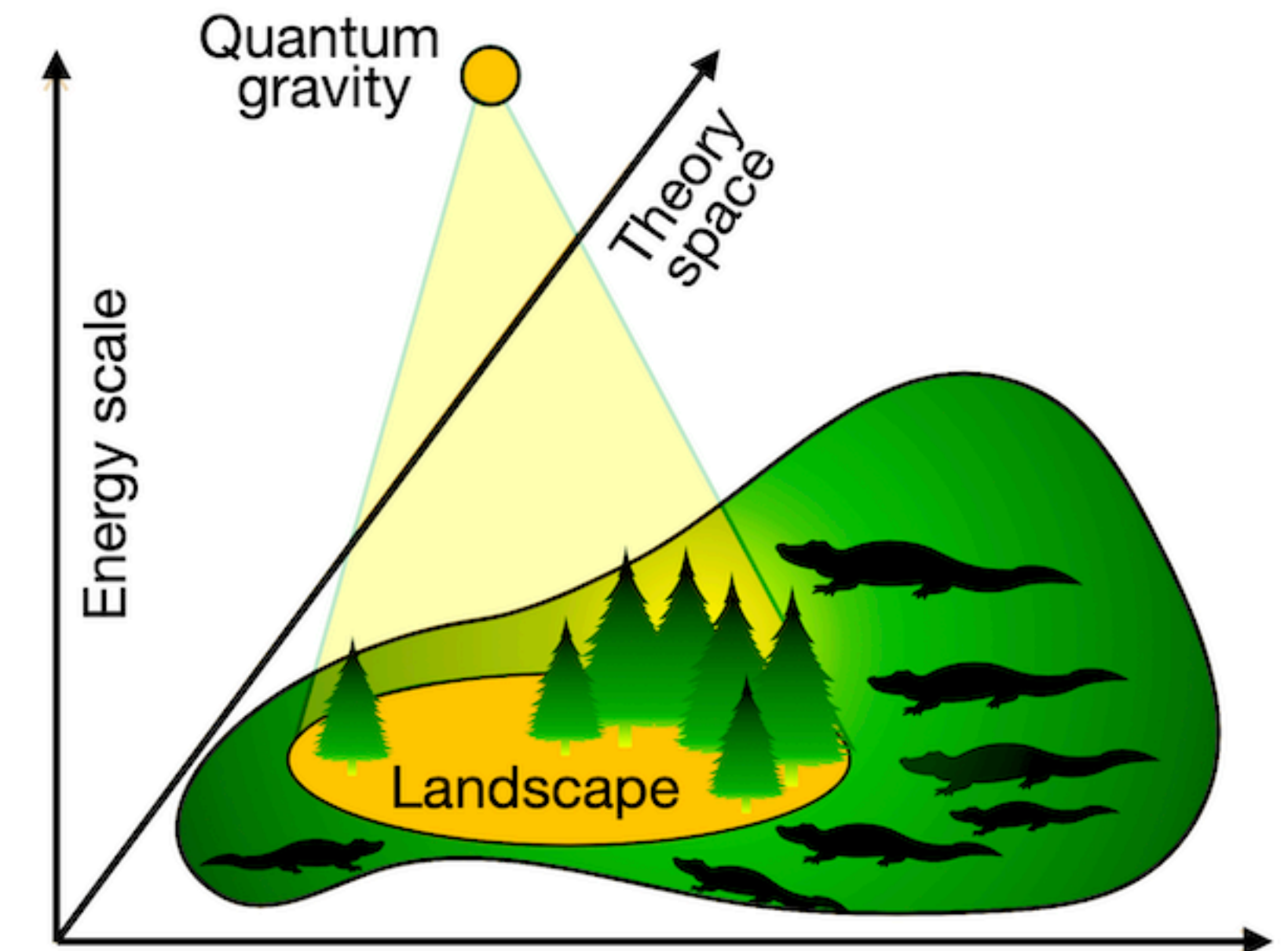
- **Extra dimensions** is an important ingredient of theories of quantum gravity, such as superstring theory. One of the simplest setups is **compact** extra dimensions $\Rightarrow$ **has a finite size**
- If their **size is large** compared to the four-dimensional (4D) Planck scale $\Rightarrow$ **origin of several mass hierarchies in high energy physics**, such as electroweak scale, the smallness of neutrino masses and the scale of dark energy
- **Bound on the size R** of one extra dimension:
 - short distance measurements of $1/R^2$ law $\Rightarrow$ **$R \lesssim 30 \mu\text{m}$** [Phys.Rev.Lett. 124 (2020)]
 - astrophysical bound $\Rightarrow$ **$R \lesssim 8 \text{ m}$ (for 2 extra-dims $R \lesssim 1 \mu\text{m}$)** [Hannestad-Raffelt, Phys.Rev.D67(2003)125008, hep-ph/0304029 - New Corrections March 2025]
- More recently, **Swampland conjectures** suggest the existence of **“one extra (dark) dimension of a size in the micron range”**



String Landscape and Swampland Program

- Not all effective field theories (EFT) can be consistently coupled to gravity
 - Anomaly cancellation is not sufficient
 - Consistent ultraviolet completion can bring non-trivial constraints
- **Swampland Program:** searching for conditions on EFTs that can consistently coupled to gravity
criteria $\Rightarrow$ conjectures supported by arguments based on string theory and black-hole physics
- Motivated by **the smallness of dark energy scale Λ** , swampland conjecture suggests our universe has at least **one (Dark) extra dimension with $R \sim 0.1$ to $10 \mu\text{m}$** .

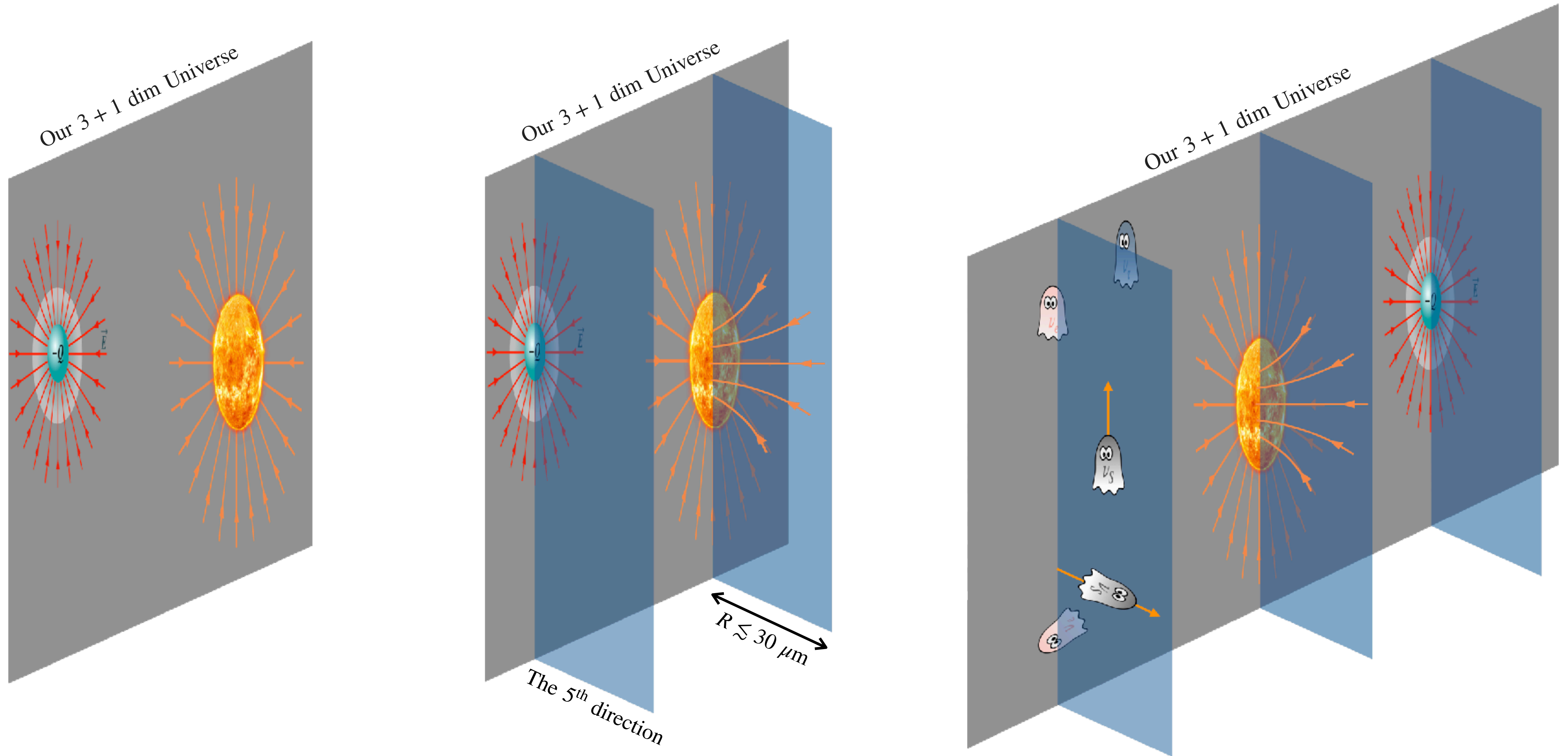
[Montero-Vafa-Valenzuela, JHEP02(2023)022]



**“Good” theory lives in the landscape
and “bad” one lives in swampland**

[Vafa, arXiv: 0509212 [hep-th]]

Dark Dimension Sterile Neutrino



Dark Dimension proposal

[Montero-Vafa-Valenzuela, JHEP02(2023)022]

- Our observable universe should be localized on “3-brane” $\perp$ to the Dark dimension

- Size of DD: $R \sim 0.1 - 30 \mu\text{m}$

- The 5D Planck mass $\Lambda_{\text{QG}} \sim 10^9 \text{ GeV}$

$\Rightarrow$ standard sea-saw require
4D Majorana state with
mass $10^{13} - 10^{14} \text{ GeV}$

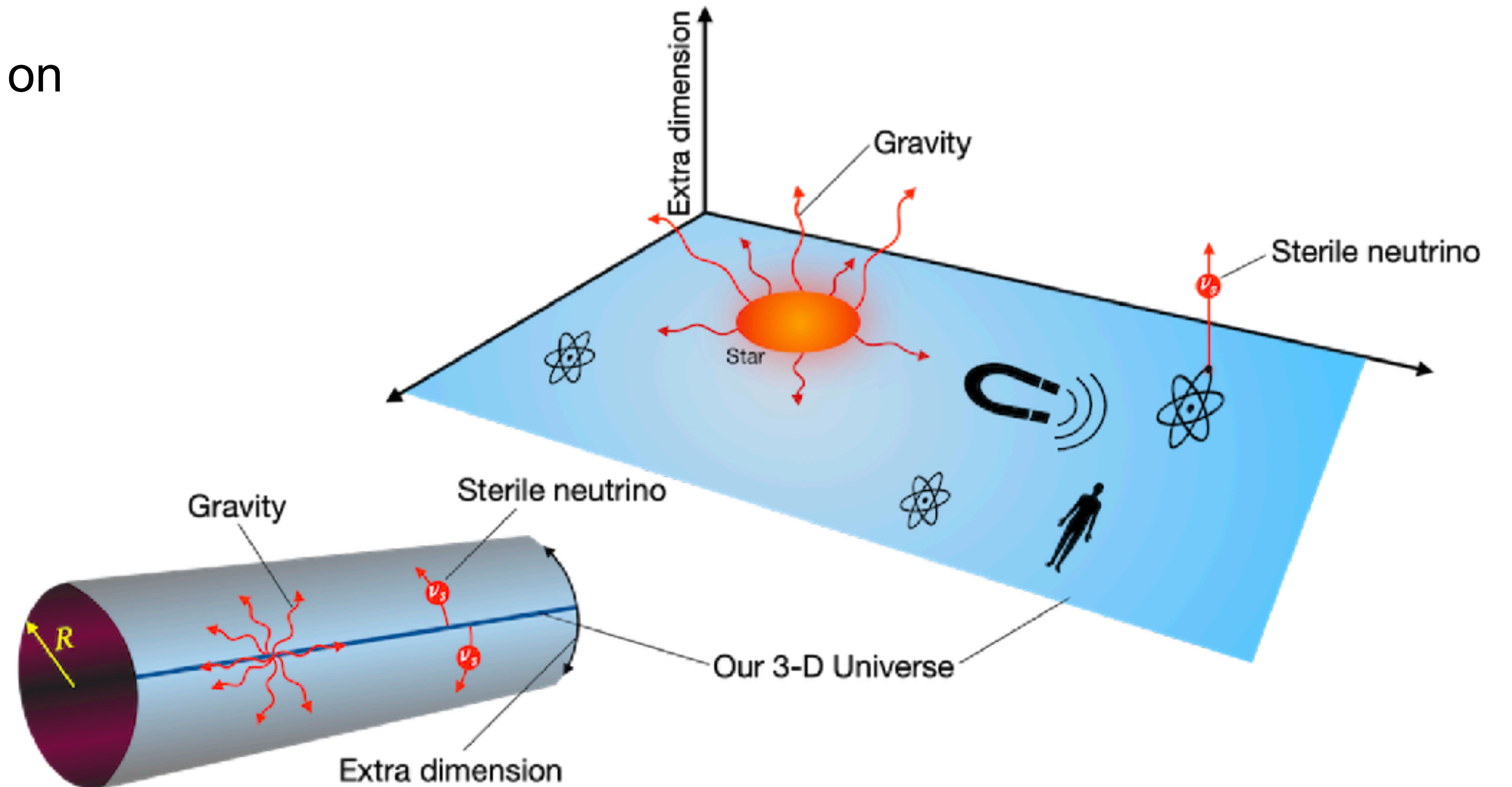
- Our model: allow bulk 5D fermions and couple them to SM leptons and Higgs in 3-brane.

- The total action: $S_{\text{tot}} = S_{5\text{D}} + S_{\text{bulk-brane}} + S_{\text{SM}}$ with the bulk action

$$S_{5\text{D}} = \int d^4x dz \sum_{i=1}^3 (i\bar{\Psi}_i \Gamma^M \partial_M \Psi_i - c_i \bar{\Psi}_i \Psi_i),$$

where c_i are 5D mass parameters

[Anchordoqui-Antoniadis-Cunat, Phys.Rev.D109 (2024) 016028]



Dark Dimension & Neutrino Physics

- Neutrino masses originate in 5D bulk brane interactions

$$S_{\text{bulk-brane}} = -\Lambda_{\text{QG}}^{1/2} \int d^4x \left(\sum_i y_i \bar{\ell}_i^L \tilde{H} \Psi_i^R(z=0) + c.c. \right)$$

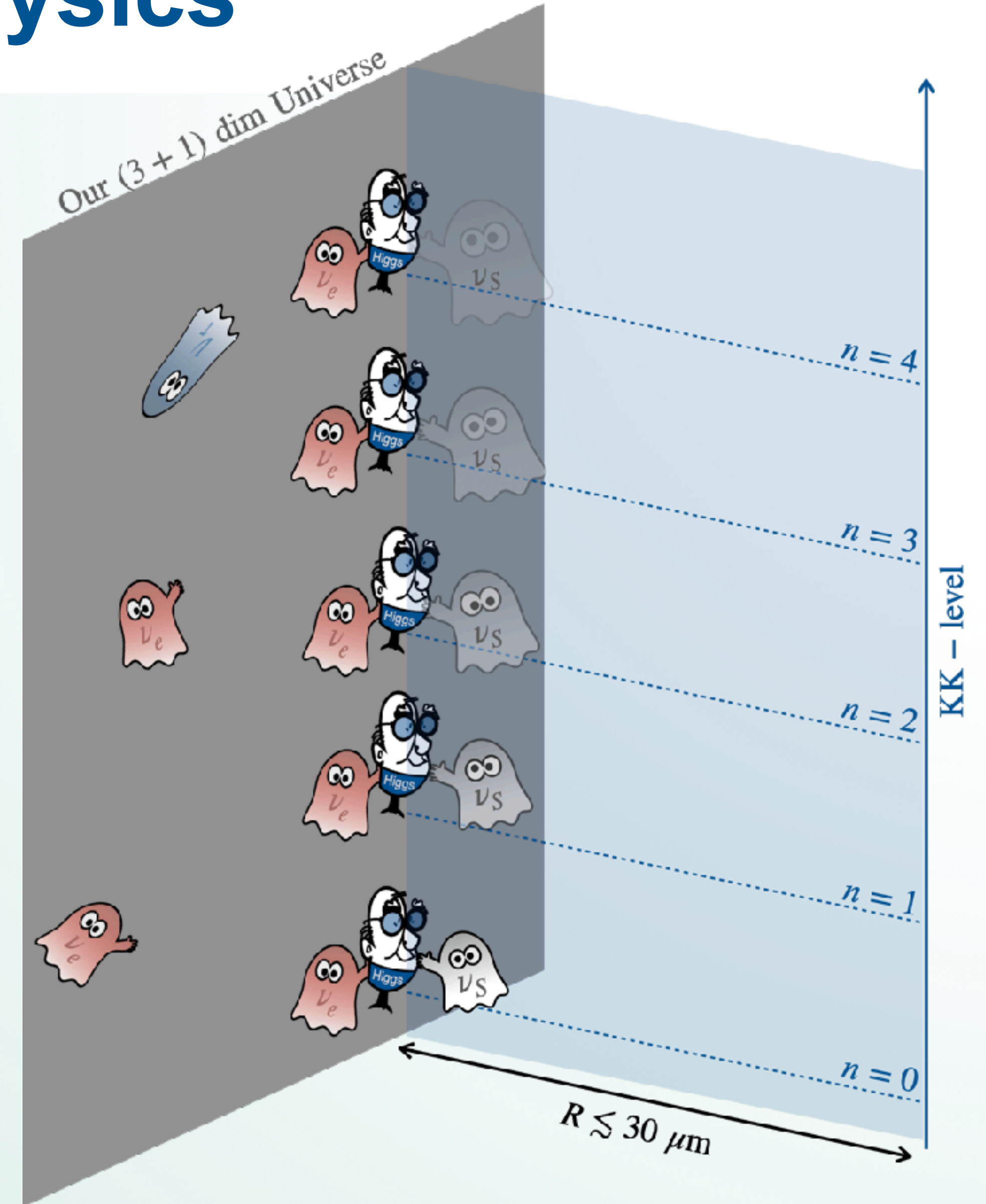
- Expand Ψ_j into canonically normalized modes:

ψ_n^i with $n = 0, 1, \dots, \infty$ (KK modes)
leads to 4D Yukawa coupling
(suppressed by square root of bulk volume)

$$\mu_i \equiv \frac{vy_i}{\sqrt{\pi R \Lambda_{\text{QG}}}}$$

with $v = 174$ GeV and $\Lambda_{\text{QG}} \sim 10^9$ GeV

Not that it is suppressed by square root of bulk volume!



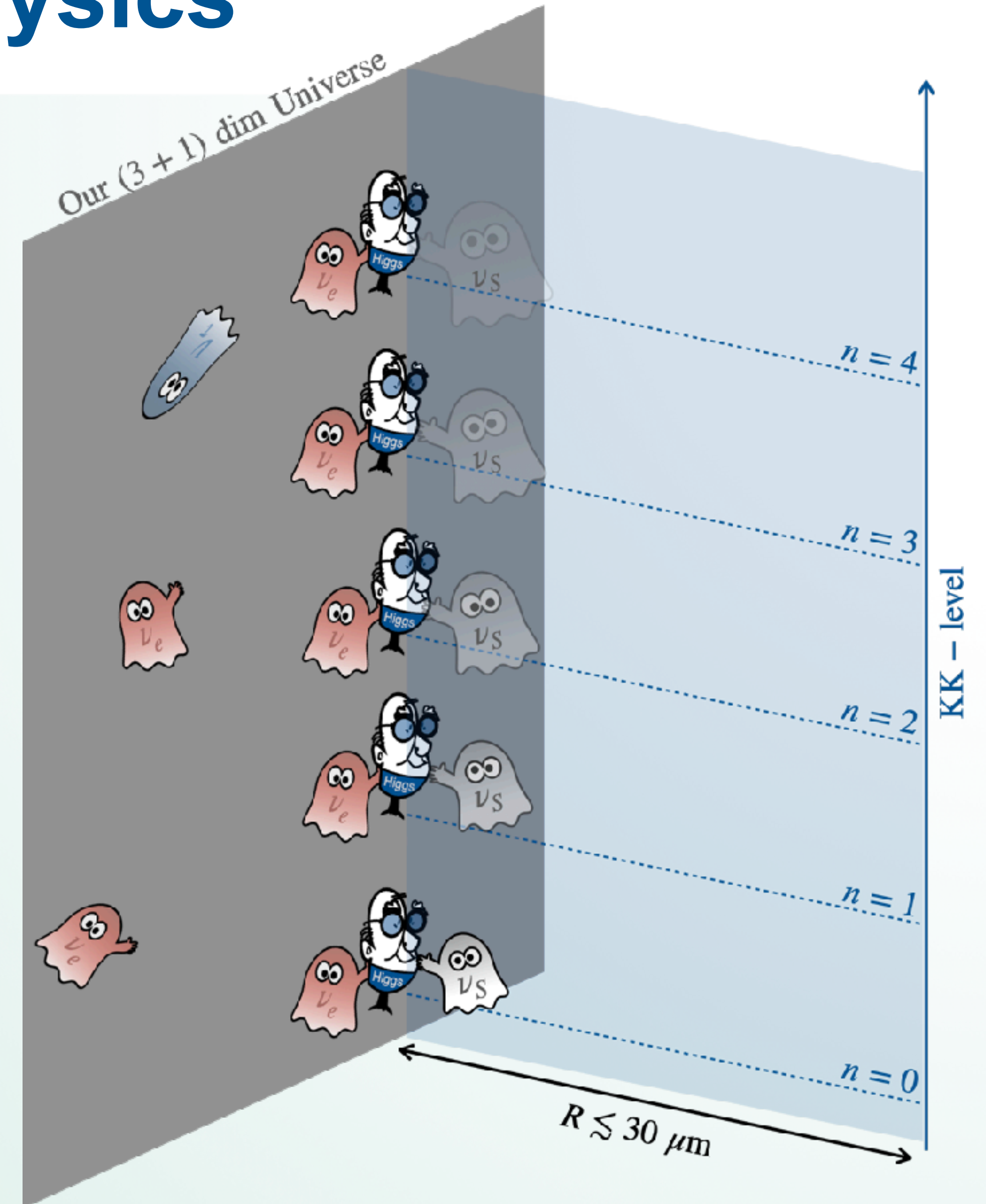
Dark Dimension & Neutrino Physics

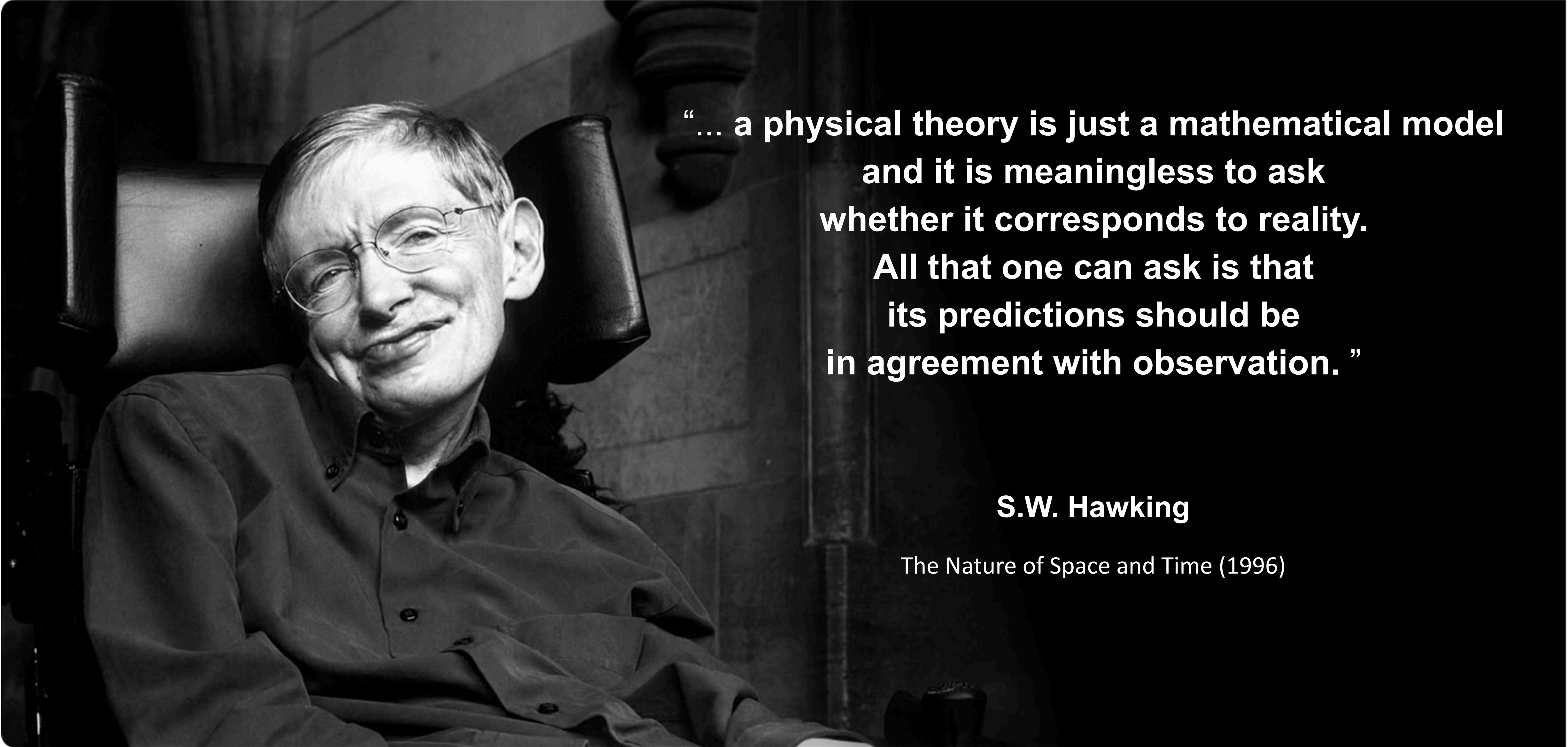
- The **right-handed 0th-mode** ($\psi_{n=0}^{i,R}$) couple with the standard model left-handed $\nu^{i,L}$. This produce the mass of the active neutrino.
- Mesoscopic extra dimensions ($R \lesssim 10 \mu\text{m}$) produces suppression of 4-dimensional Yukawa couplings yielding naturally **light Dirac neutrino masses**.
- Recent analysis of ν -oscillation data with 3 **massless** bulk neutrinos ($c_i = 0$) [Forero-Giunti-Ternes-Tyagi, Phys.Rev.D106 (2022), 035027]

$$R \lesssim 0.2 \mu\text{m}$$

- **Bound can be relaxed** in the presence of bulk 5D neutrino mass ($c_i \neq 0$)

[Anchordoqui-Antoniadis-Cunat, Phys.Rev.D109 (2024), 016028, Eller-Ettengruber-Zander, Phys.Rev.D112(2025), 055009, Antoniadis-AC-Isono, JHEP02 (2026) 15, Bai-AC-Huang-Isono-Tang, JHEP05(2026)196]





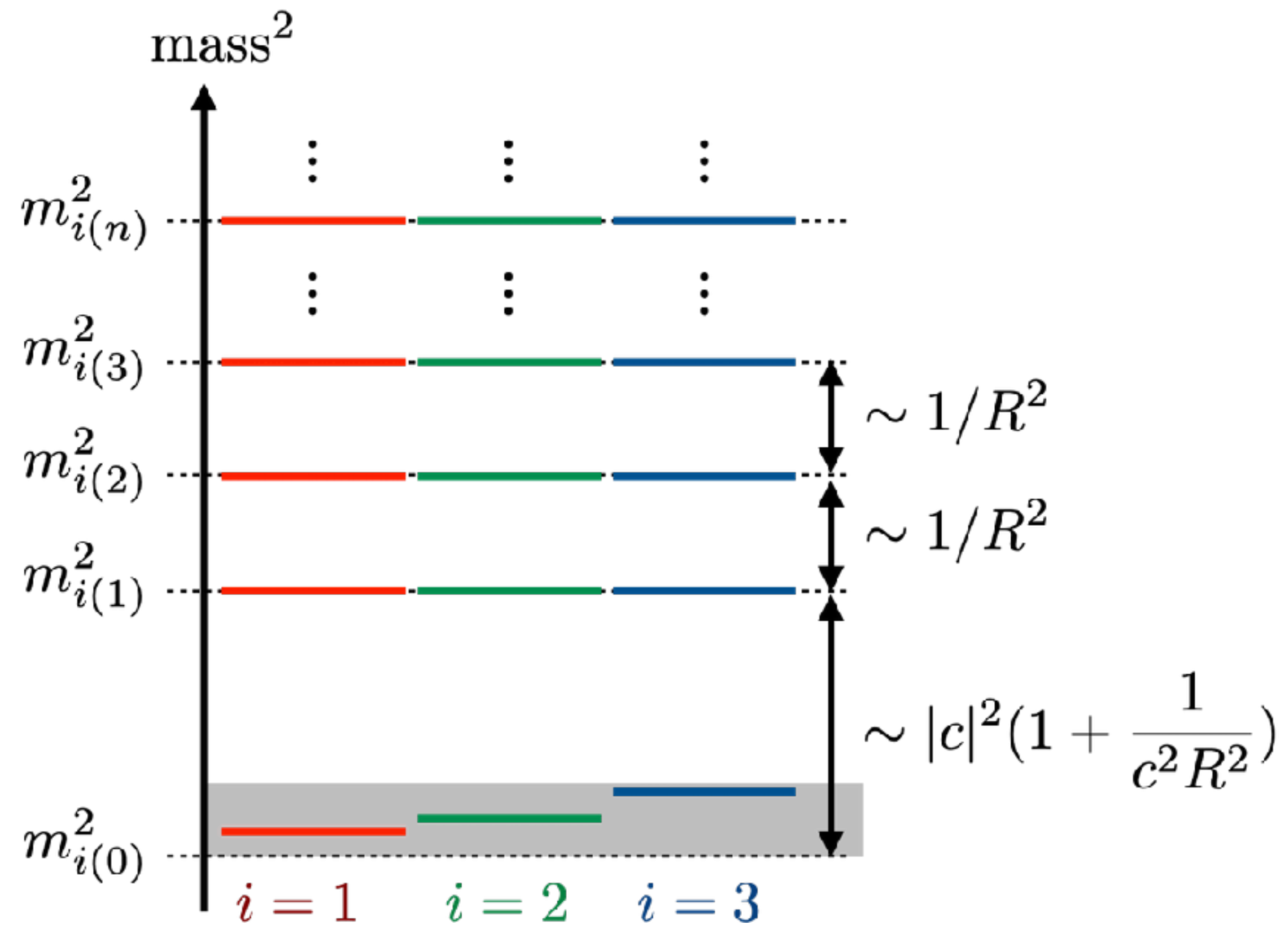
**“... a physical theory is just a mathematical model
and it is meaningless to ask
whether it corresponds to reality.
All that one can ask is that
its predictions should be
in agreement with observation.”**

S.W. Hawking

The Nature of Space and Time (1996)

Kaluza-Klein (KK) “sterile” neutrino

- Our model has infinite number of sterile neutrinos $\Rightarrow 3 \times (1 \text{ active} + \infty \text{ sterile})$



- Model parameters:
 - **Extra dim radius:** R ($\sim 0.1 - 20 \mu\text{m}$)
 - **5-dim fermion mass:** c
 - **Yukawa coupling:** μ_1
- For small coupling, the n^{th} KK sterile is

$$m_{KK}^{(n)} \approx \frac{1}{R} \sqrt{n^2 + c^2 R^2}$$
- The mixing matrix $\sim \frac{n\mu_i R}{n^2 + c^2 R^2}$
- Expect to see **more kinks** in the spectrum

Differential beta decay spectrum

- In our model, the differential beta decay rate is given by

$$R_\beta(\epsilon, \{m_{i(n)}\}) = R_0 + R_{\text{KK}}$$

where ($\epsilon = E_0 - E$)

$$R_0 = \mathcal{C} \sum_{i=1}^3 |U_{ei} \mathcal{L}_{00}^i|^2 \epsilon \sqrt{\epsilon^2 - m_{i(0)}^2} \theta(\epsilon - m_{i(0)}) \propto R_\beta(\epsilon, m_\nu^2),$$

$$R_{\text{KK}} = \mathcal{C} \sum_{i=1}^3 \sum_{n=1}^{n_{\text{max}}} |U_{ei} \mathcal{L}_{0n}^i|^2 \epsilon \sqrt{\epsilon^2 - m_{i(n)}^2} \theta(\epsilon - m_{i(n)}).$$

- Note that the active left-handed neutrino in the flavour basis ν_α^{L} in SM is related to the KK tower $\nu_{i(n)}^{\text{L}}$ in the mass basis by

$$\nu_\alpha^{\text{L}} = \sum_{i=1}^3 U_{\alpha i} \nu_i^{\text{L}} = \sum_{i=1}^3 \sum_{n=0}^{\infty} U_{\alpha i} \mathcal{L}_{0n}^i \nu_{i(n)}^{\text{L}},$$

where $\mathcal{L}_{0n}^i$ are the mixing matrix element.

Small bulk mass limit ($|c| \ll 1/R$)

- Expect to see **more kinks** in the spectrum

Rodejohann & Zhang, Phys.Lett.B 737 (2014), 81

arXiv:1407.2739

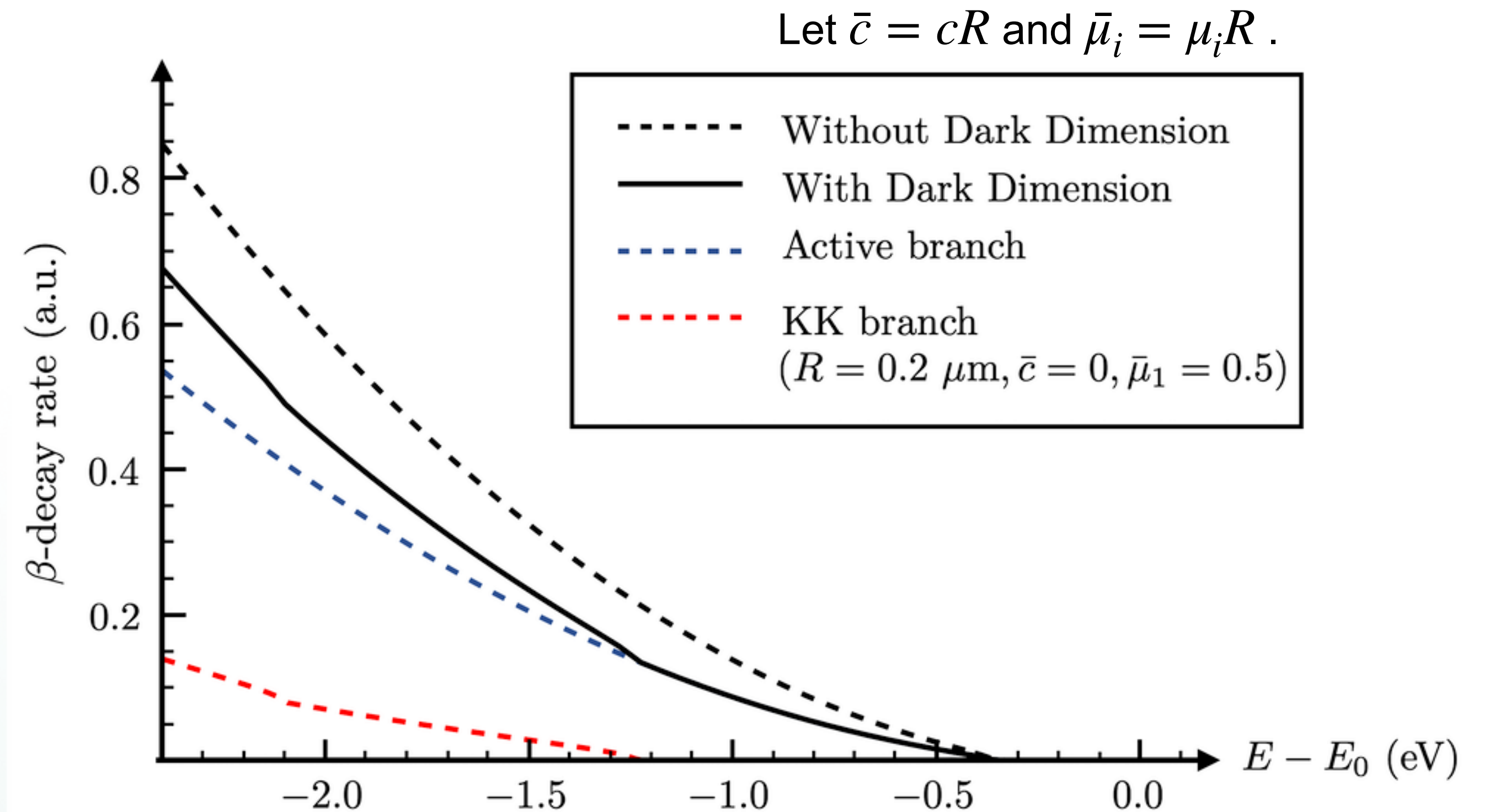
- Dark dimension could be probed **within KATRIN's energy resolution (~ 1 eV)**

$$\frac{1}{R_{(1 \mu\text{m})}} \approx 0.2 \text{ eV}$$

$$\frac{1}{R_{(0.2 \mu\text{m})}} \approx 1 \text{ eV}$$

- Note that for $|c| \ll 1/R$, the 0^{th} -mode mass (or the lightest neutrino mass):

$$m_{1(0)} \approx \mu_1$$



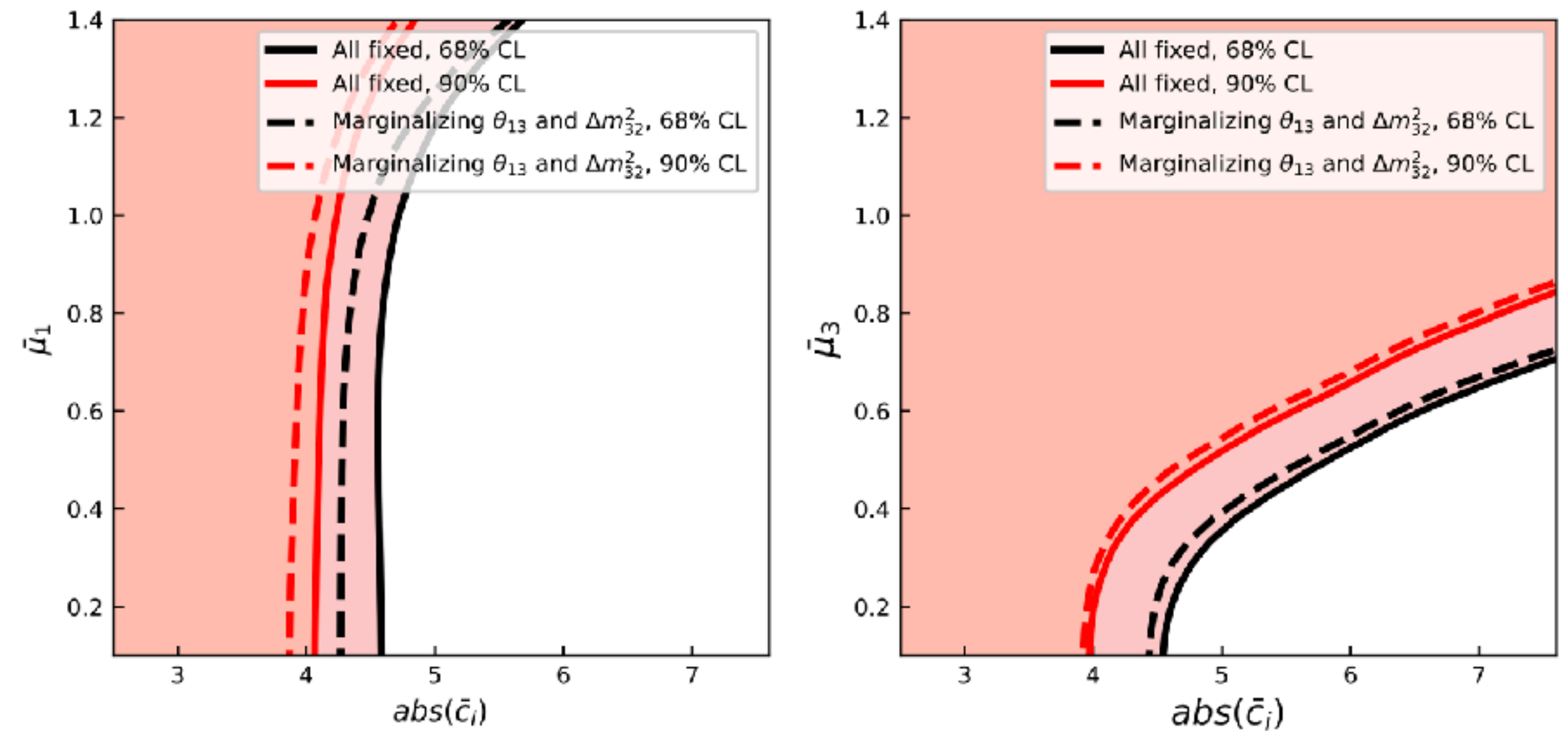
Ongoing analysis with KATRIN collaboration!

Oscillation Results

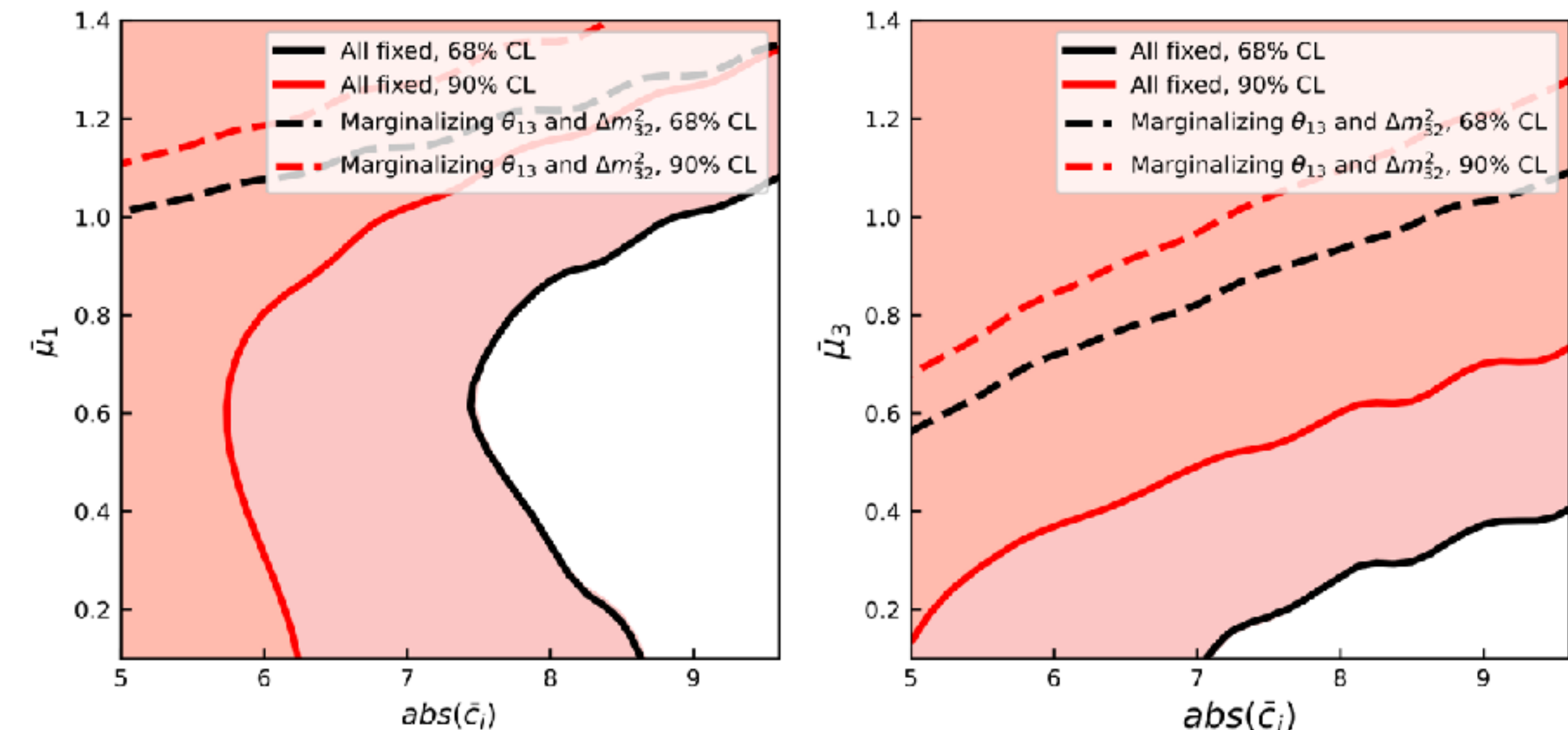
[Bai-AC-Huang-Isono-Tang, JHEP05(2026)196]

- Studies **DD model with $R = 10 \mu\text{m}$**
- Let define the dimensionless parameters $\bar{c} = cR$ and $\bar{\mu}_i = \mu_i R$.
- Using data from **T2K and NOvA** experiments, there is a lower bound on the bulk fermion mass:
 - For NO and $\bar{\mu}_1 \sim 0.1$,
 $|\bar{c}_1| \gtrsim 5.2$
 or, equivalently, $|c_1| \gtrsim 0.1 \text{ eV}$
 - For IH and $\bar{\mu}_3 \sim 0.1$,
 $|\bar{c}_3| \gtrsim 4.0$
 or, equivalently, $|c_3| \gtrsim 0.08 \text{ eV}$.

The exclusion limits in the T2K experiment.

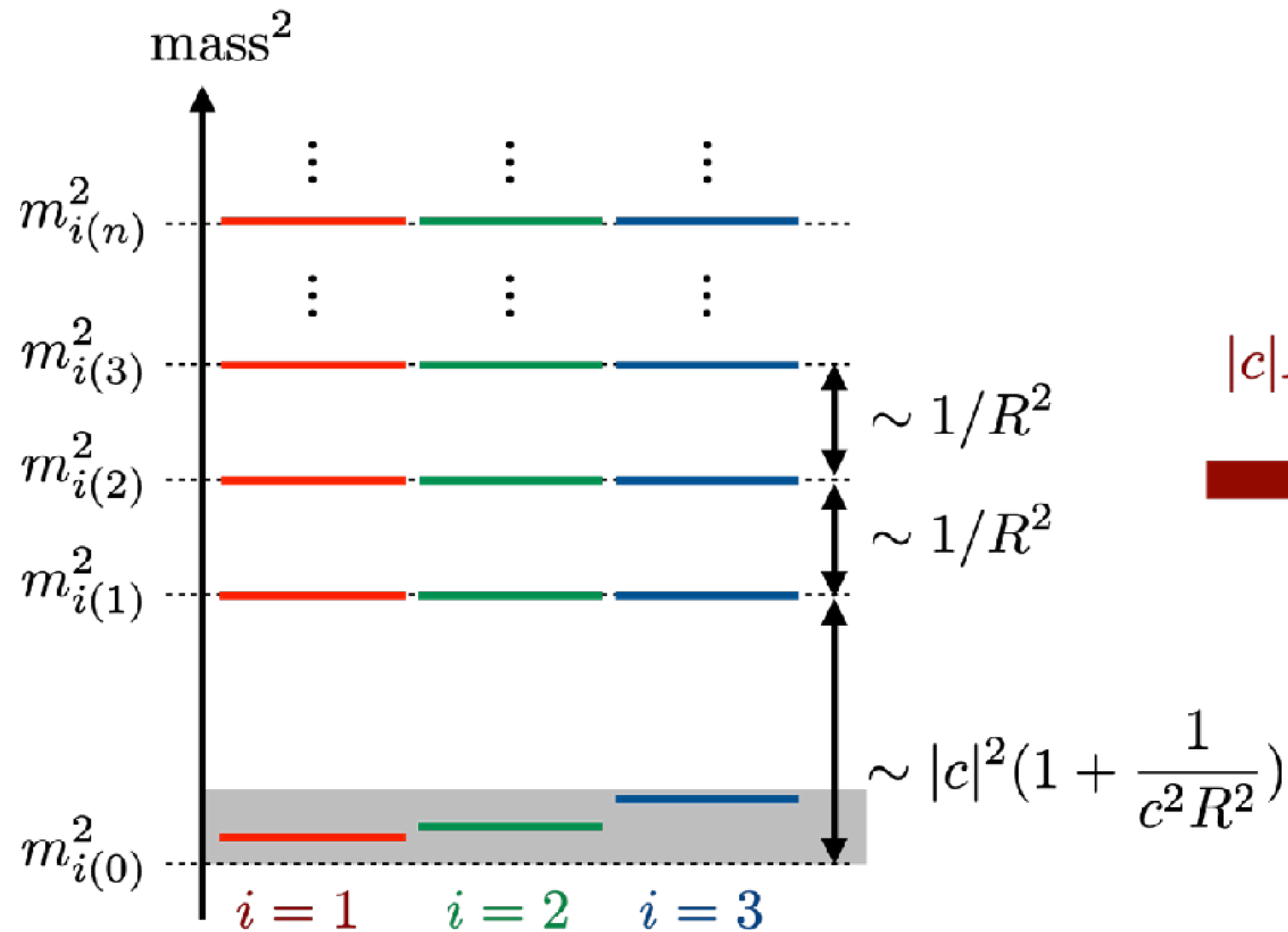


The exclusion limits in the NOvA experiment.



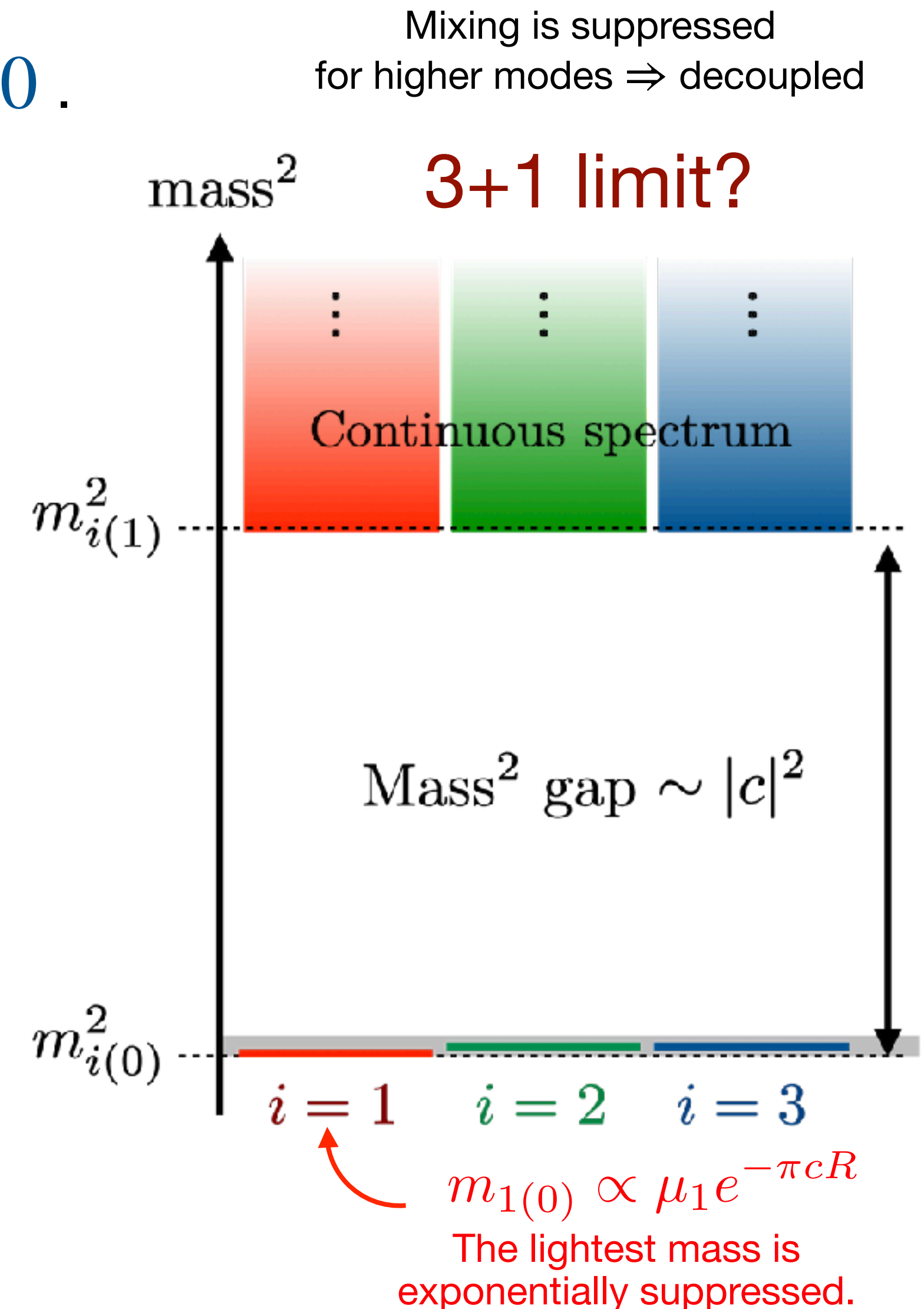
Large bulk mass limit ($|c|R \gg 1$)

- Here we consider the case with $c = c_1 = -c_2 = -c_3 > 0$.



$|c|R \gg 1$

→



Differential beta decay spectrum in 3+1 limit

- In the $|\bar{c}| \gg 1$ and $\frac{\bar{\mu}_1^2}{2|\bar{c}|} \ll 1$ limit, the differential beta decay rate can be written as

$$R_\beta \simeq \mathcal{C} \cos^2 \theta_{\text{eff}} \epsilon \sqrt{\epsilon^2 - m_\nu^2} \theta(\epsilon - m_\nu) + \mathcal{C} \sin^2 \theta_{\text{eff}} (\epsilon - |c|)^2 \theta(\epsilon - |c|)$$

“Active branch”
“Sterile branch”

[Antoniadis-**AC**-Isono, JHEP 02 (2026) 15]

- Comparing with 3+1 model, we have

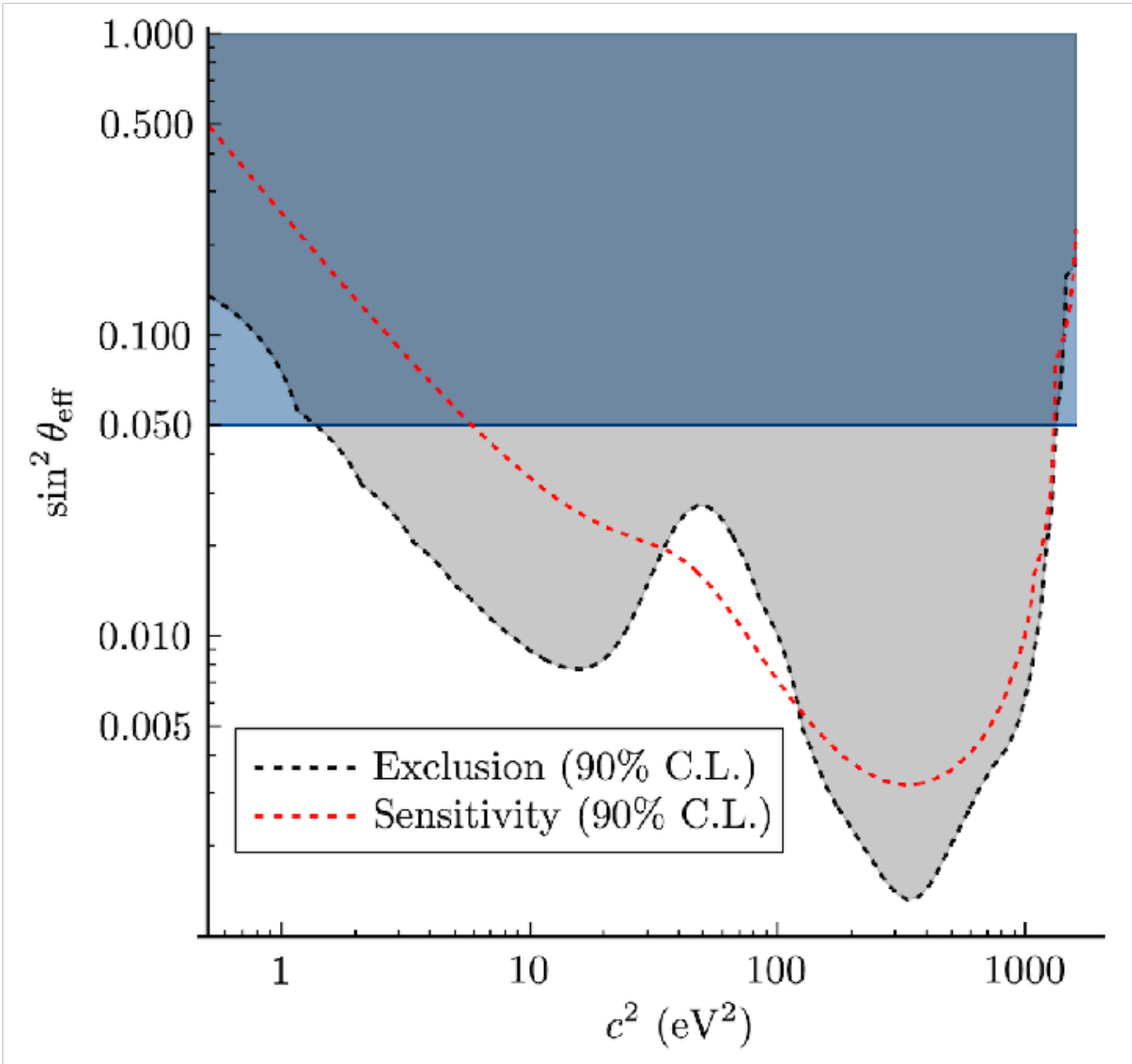
$$m_4 \rightarrow |c| \quad \text{and} \quad \sin^2(\theta_{44}) \rightarrow \sin^2(\theta_{\text{eff}})$$

where

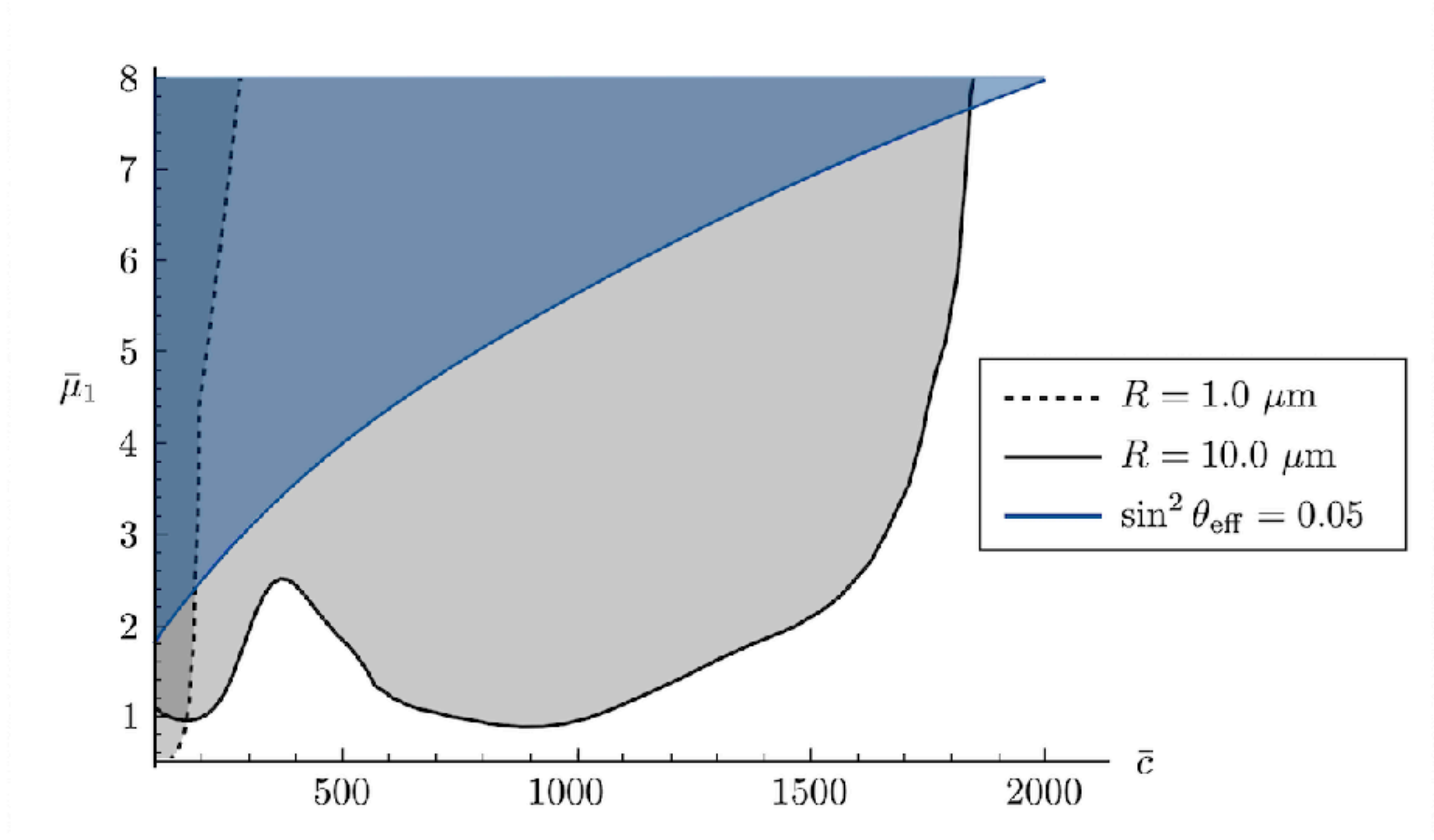
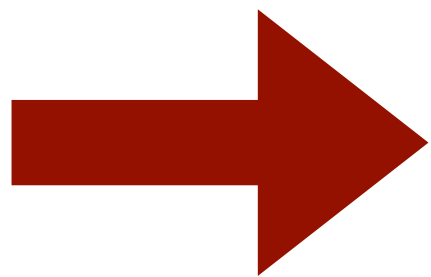
$$\sin^2 \theta_{\text{eff}} \simeq \frac{\pi \bar{\mu}_1^2}{2|\bar{c}|}$$

KATRIN results for 3+1 model

[KATRIN collaboration, Nature 648 (2025) 8092, 70-75]



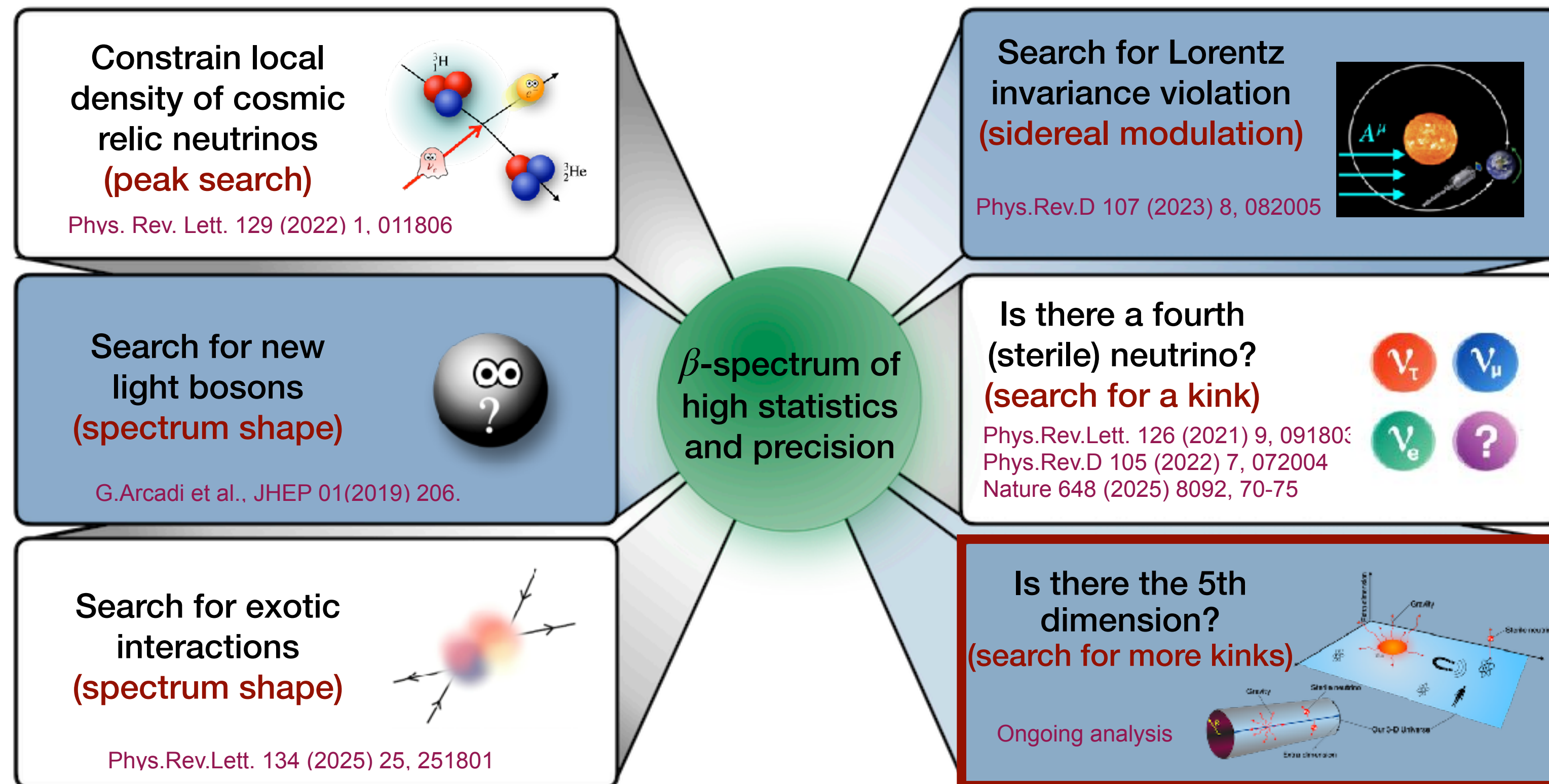
For fixed R



[Antoniadis-AC-Isono, JHEP02 (2026) 15]

Conclusions

- Right-handed neutrinos propagate in the bulk, dark dimension can be probed within the sensitivity of KATRIN experiment and other next generation β -decay experiments such as TRISTAN (+ PTOLEMY and also for reactor experiment such as JUNO-TAO)
- This has be **added to KATRIN's list of BSM searches**



Thank you!!
谢谢大家。
ขอบคุณครับ!!

