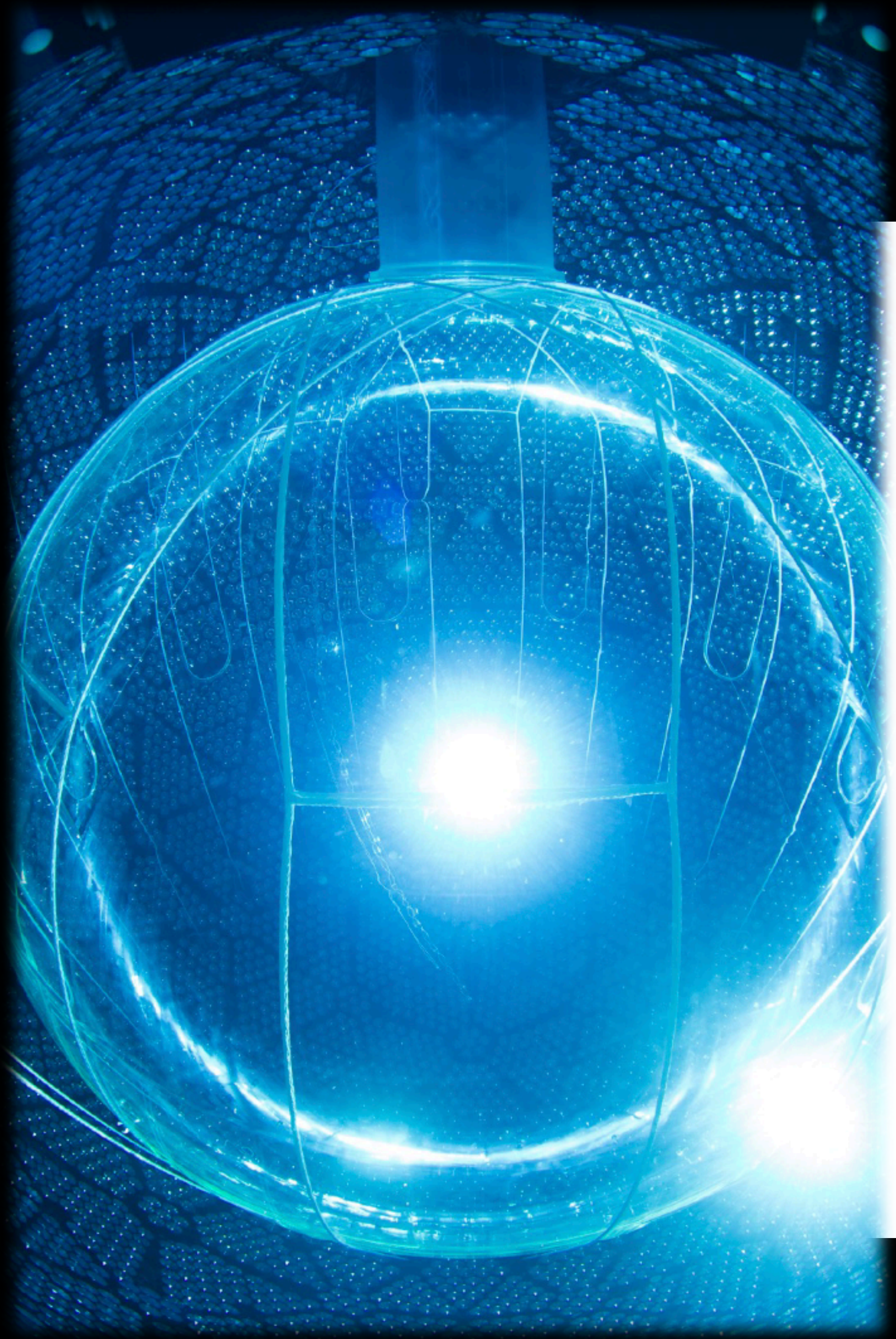

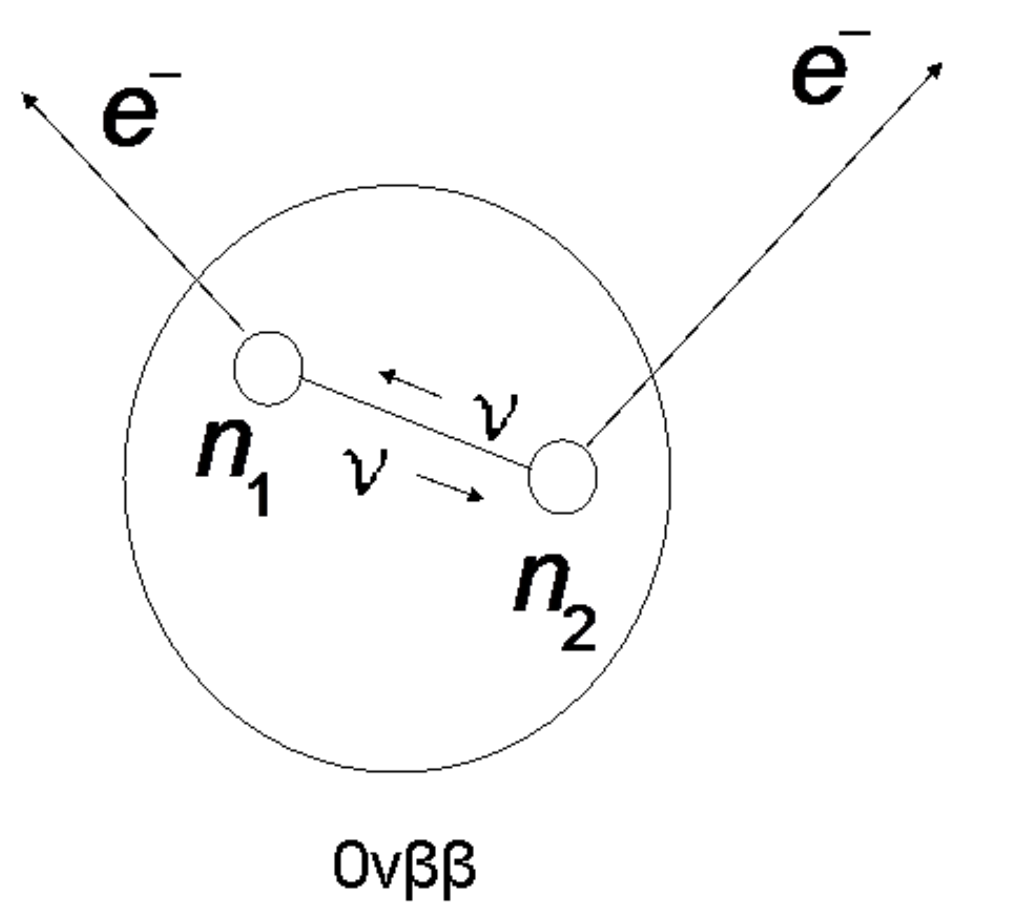


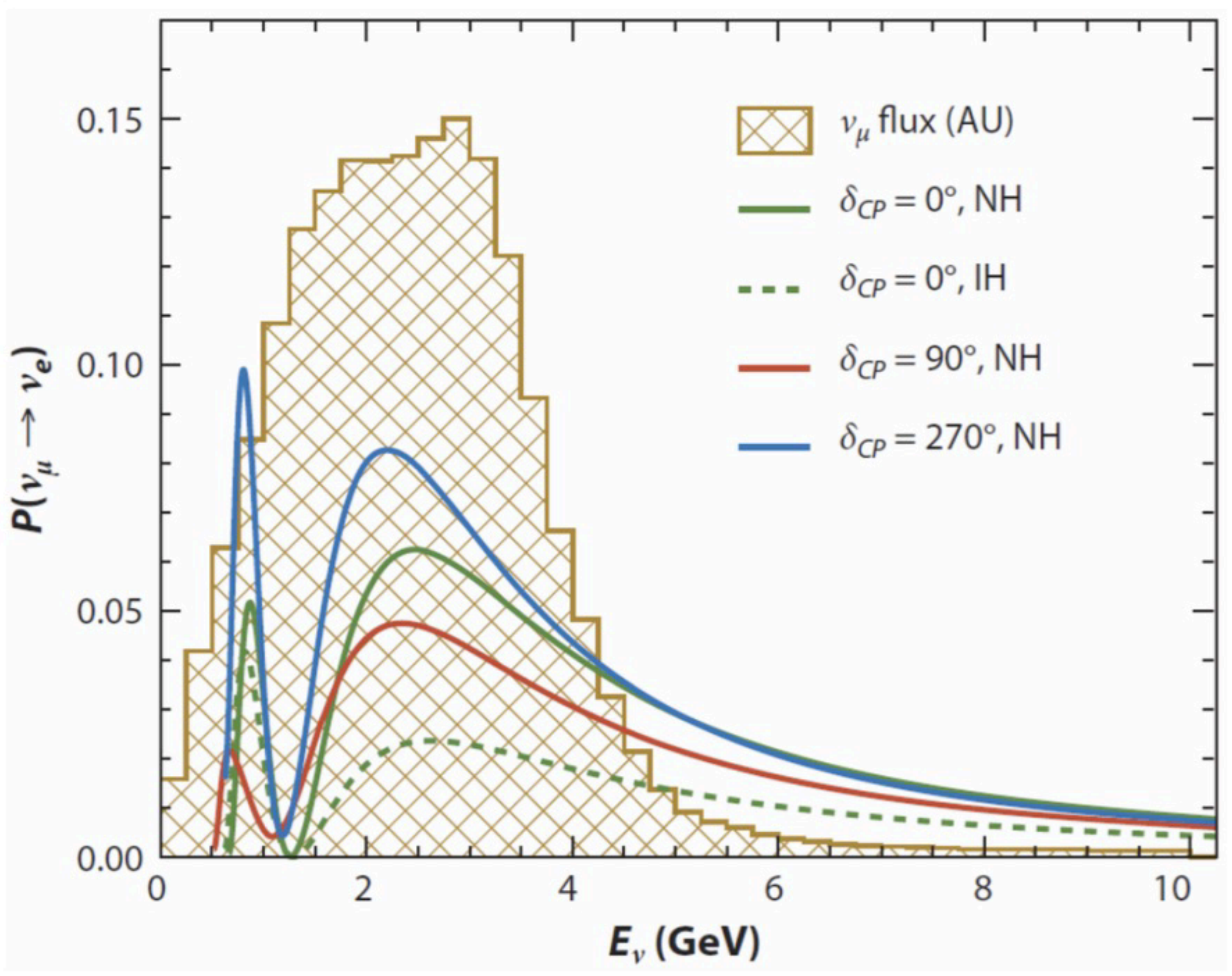


# NEUTRINO PHYSICS PRIORITIES


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FOR THE LIP
NEUTRINO PHYSICS GROUP


EUROPEAN STRATEGY DISCUSSION
LIP, JANUARY 20, 2025

# OPEN QUESTIONS: MIXING

- We know this: neutrino flavors mix, neutrinos are massive!

- flavor states $|\nu_\alpha\rangle = \sum_k U_{\alpha k} |\nu_k\rangle$ • mass states

$\nu_\alpha = \nu_e, \nu_\mu, \nu_\tau$ $\qquad \nu_k = \nu_1, \nu_2, \nu_3$

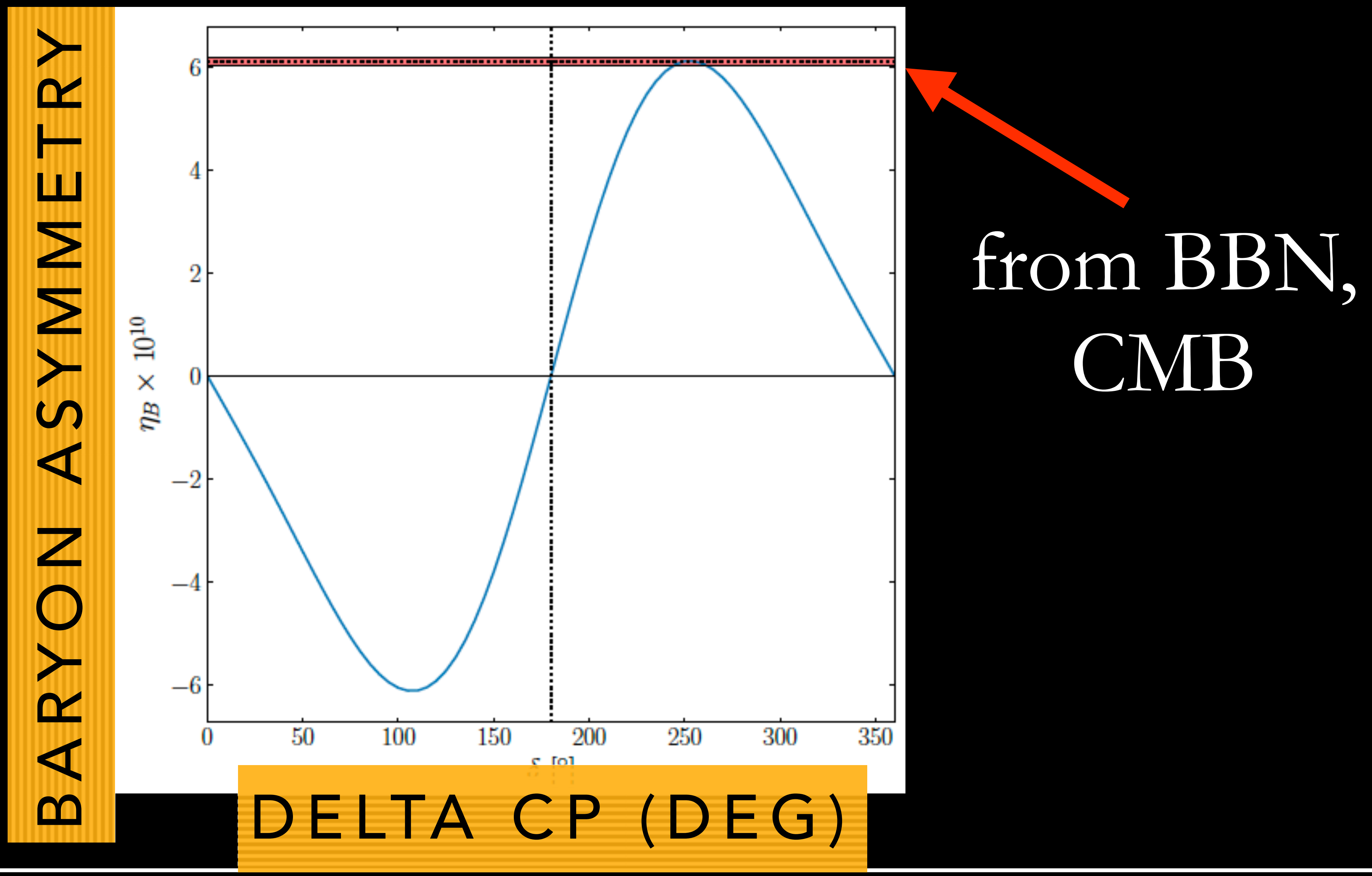
$s_{ij} = \sin\theta_{ij}$
$c_{ij} = \cos\theta_{ij}$

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}\begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{bmatrix}\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}1 & 0 & 0\\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0\\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}}\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

- We know the angles $\theta_{12}, \theta_{13}, \theta_{23}$ **but not the phases $\delta_{CP}, \alpha_{21}, \alpha_{31}$**

IS THE MIXING MATRIX REAL OR COMPLEX?
IS THERE CP VIOLATION IN THE LEPTON SECTOR ?

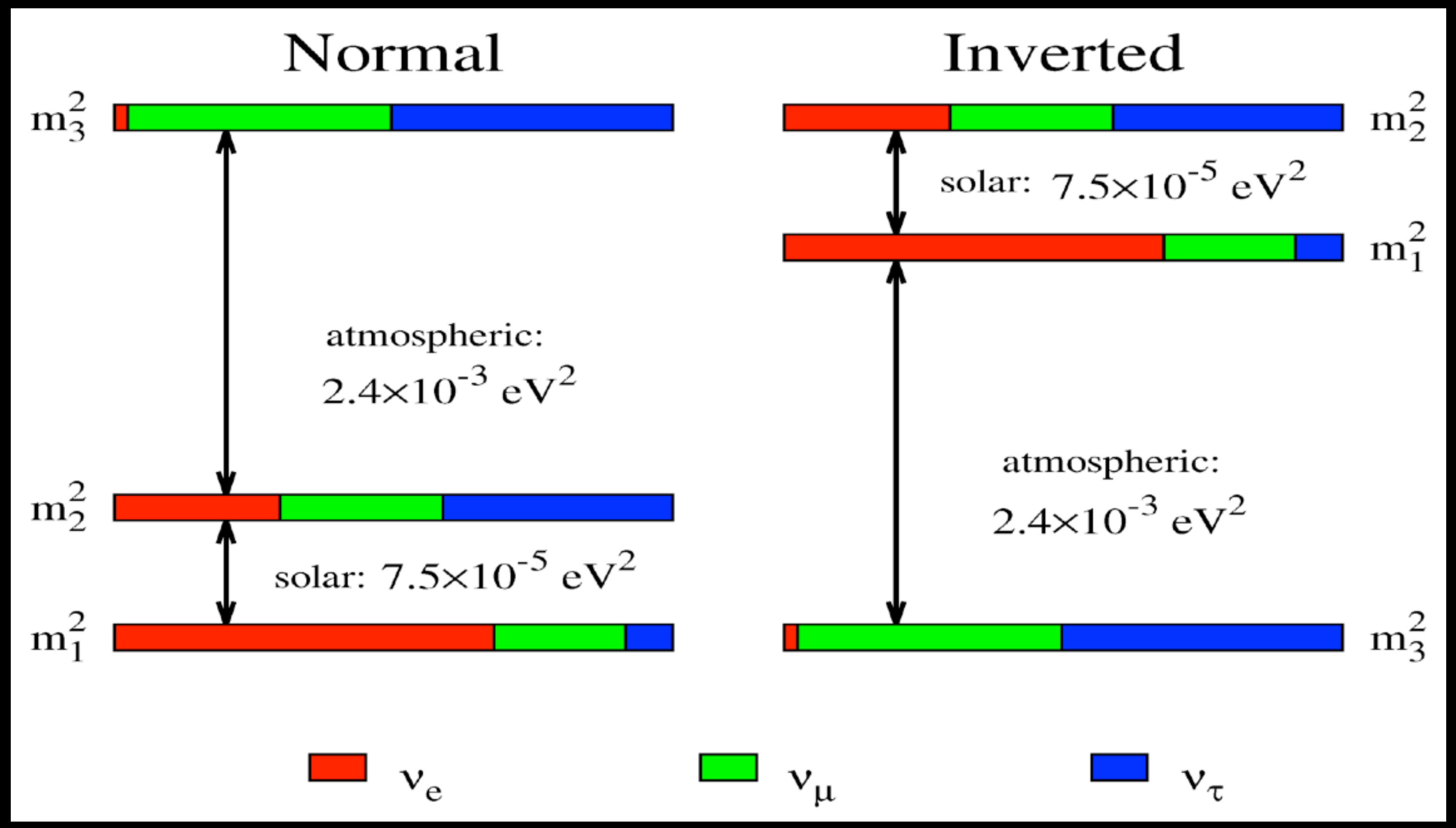
- Strong implications in cosmology. Can explain the matter - antimatter asymmetry in the early Universe.



# OPEN QUESTIONS: MASS, DIRAC/MAJ.

- We know $\Delta m_{ij}^2$ **but not the absolute values $m_1$, $m_2$, $m_3$**

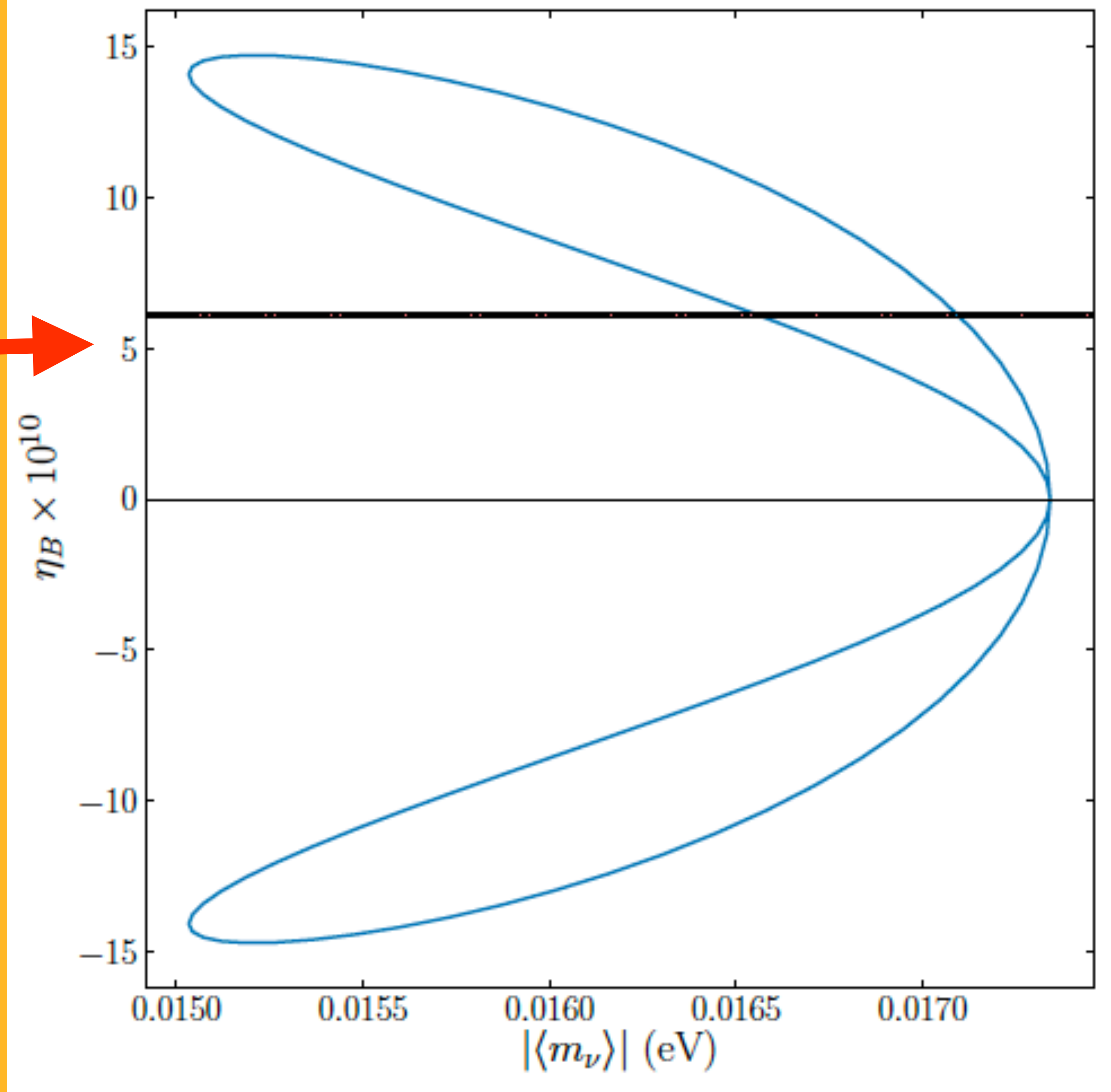
$$\mathcal{L}^{mass} = \begin{bmatrix} \overline{\nu_L^C} & \overline{N_R} \end{bmatrix} \begin{bmatrix} m_L & m_D \\ m_D & m_R \end{bmatrix} \begin{bmatrix} \nu_L \\ N_R^C \end{bmatrix} + h.c.$$




- Type of mass terms, charge conjugation properties?
  - **Dirac?** only one phase $\delta_{CP}$ and one mass $m_D$
  - **Majorana?** more d.o.f.: $\alpha_{21}, \alpha_{31}, m_L, m_R$
    - smallness of mass explained by large $m_R$ scale
    - additional CP violation via $\alpha_{21}, \alpha_{31}$
    - neutrinoless double-beta decay is possible
      - rate directly related to absolute masses

$$m_1 = -\frac{m_D^2}{m_R}$$

BARYON ASYMMETRY

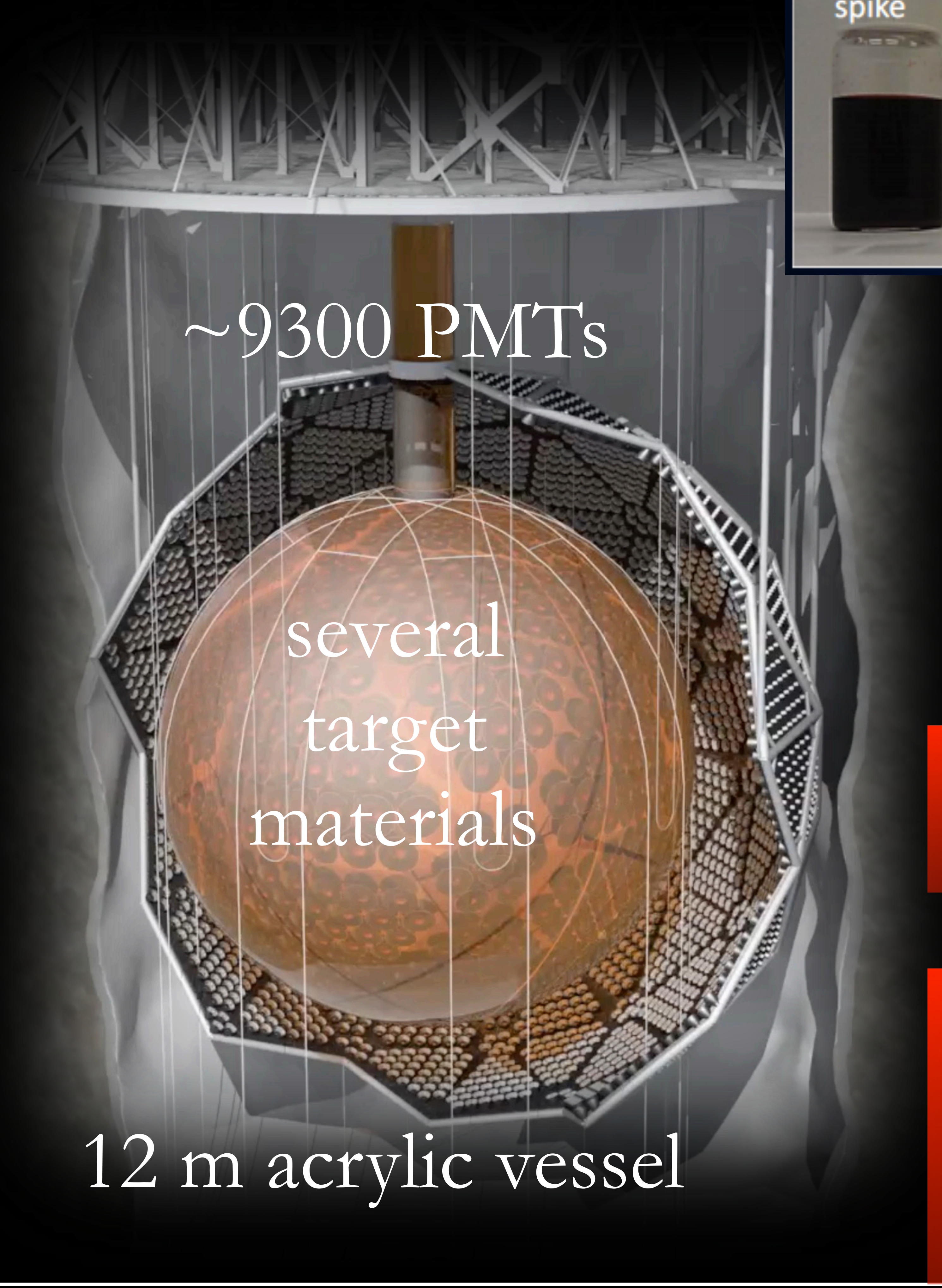



MAJORANA MASS

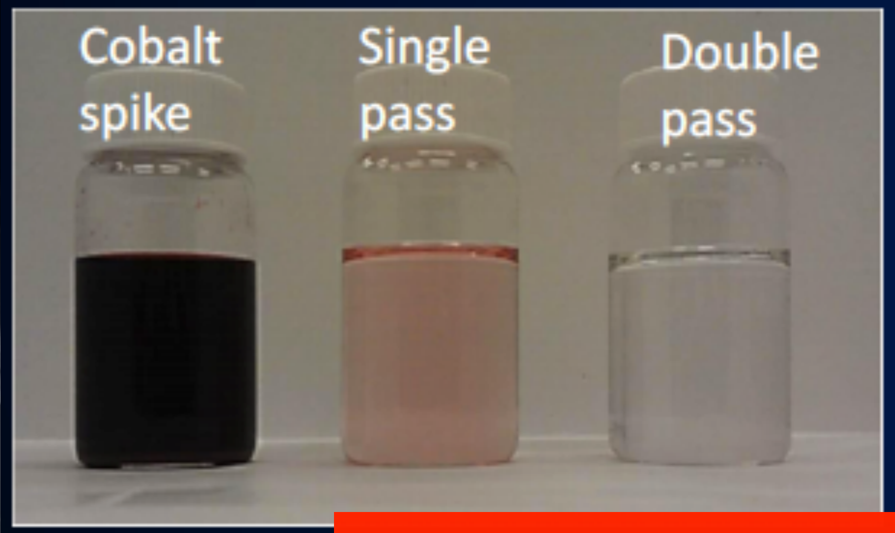
$$m_{\beta\beta} = \left| \sum_{k=1}^{3} m_k U_{ek}^2 \right| = \left| m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i(\alpha_2 - \alpha_1)} + m_3 s_{13}^2 e^{i(\alpha_1 - 2\delta_{CP})} \right|$$

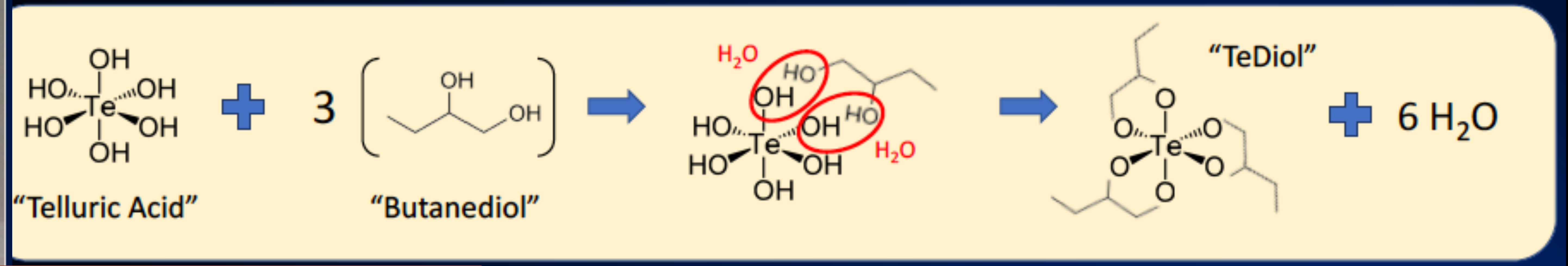
# DOUBLE BETA DECAY: SNO+

Re-using SNO detector (Canada)




## LIQUID SCINTILLATOR LOADING TECHNIQUE: HIGH ISOTOPE MASS, LOW BACKGROUNDS

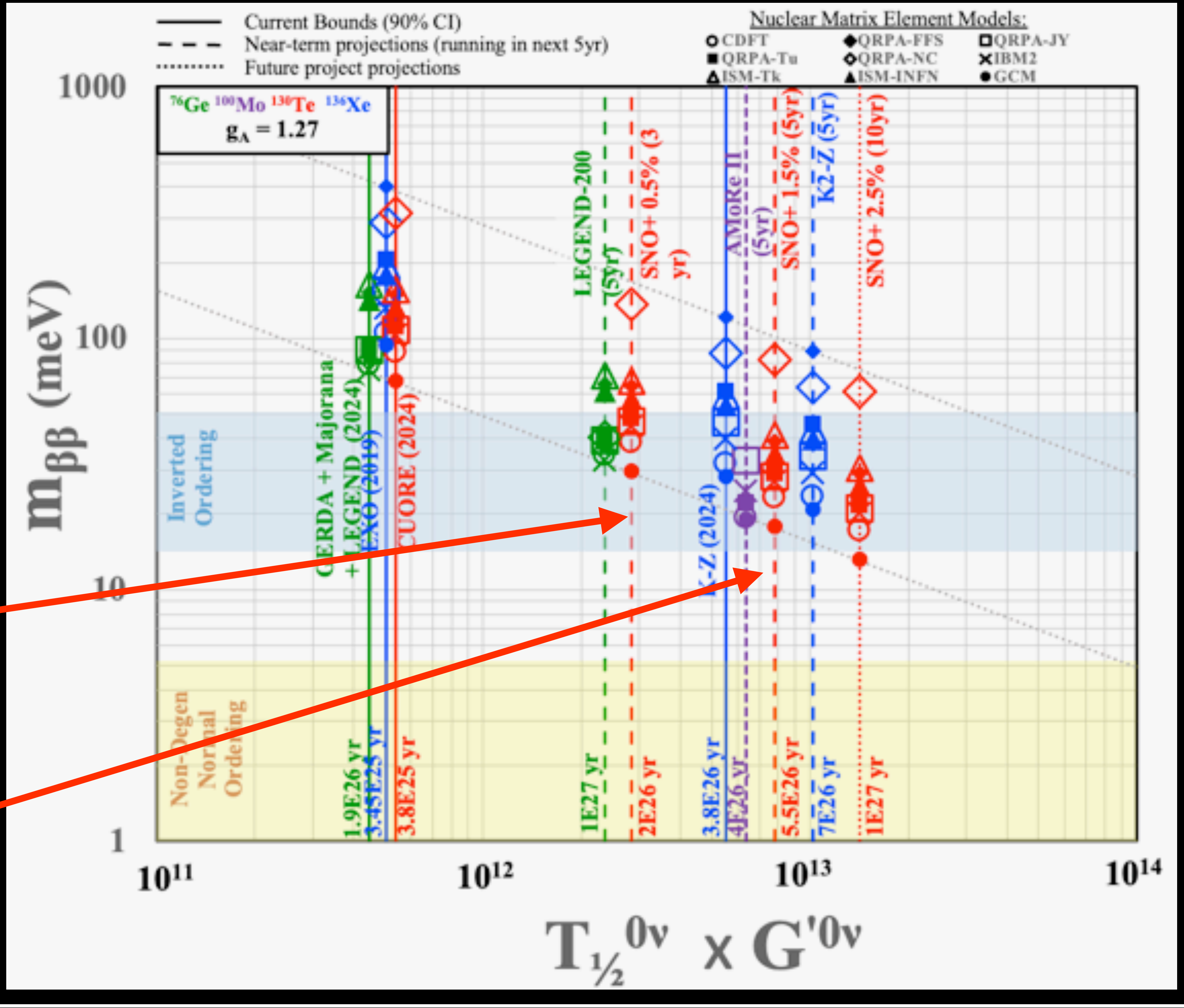



SNO+ DEVELOPED TECHNIQUES FOR TELLURIUM PURIFICATION AND LOADING

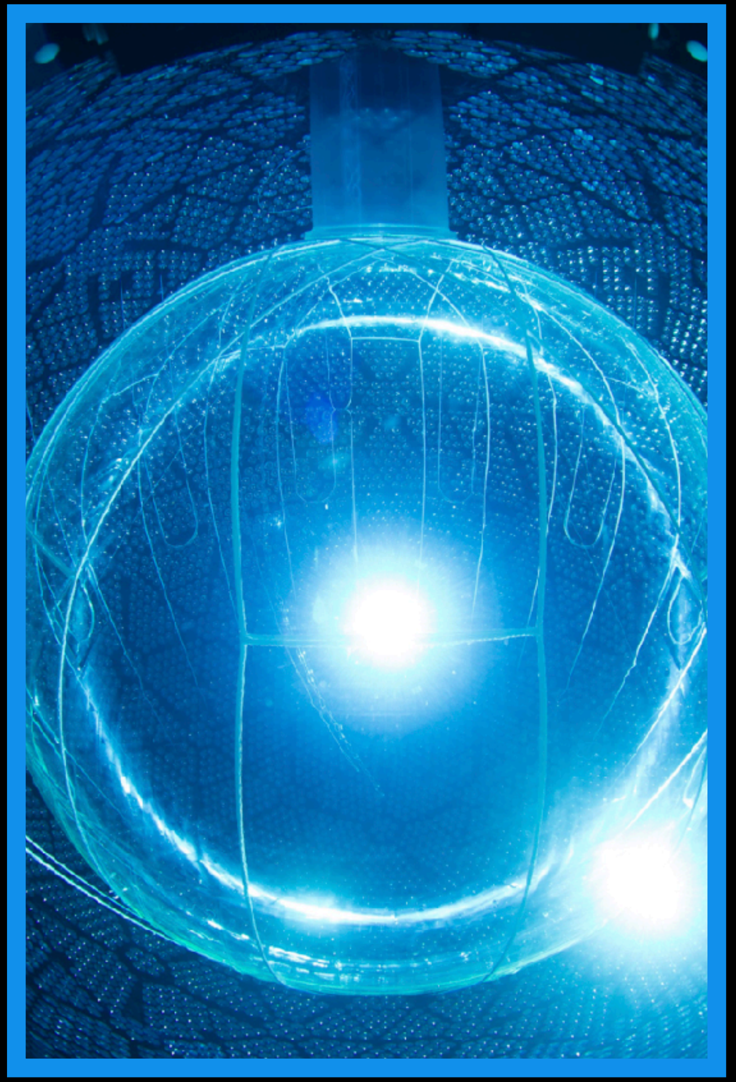
0.5% LOADING: BEST TE130 SENSITIVITY

1.5% LOADING: WINDOW OF OPPORTUNITY FOR BEST SENSITIVITY, ANY ISOTOPE (BEFORE "TON-SCALE")



# DOUBLE BETA DECAY: SNO+

2017 2018 2019 2020 2021 2022 2023 2024 2025



## Water phase

best invisible nucleon decay limits; first reactor ν in pure water

## Partial fill phase

solar ν directionality

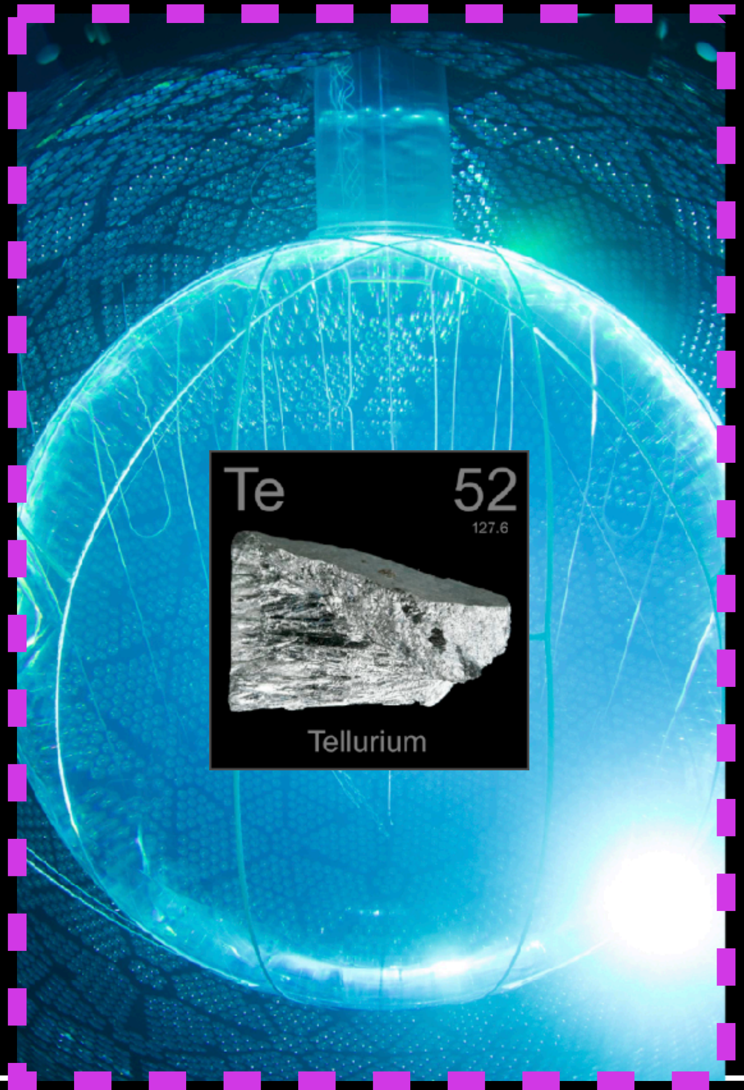
reactor ν in LS

## Scintillator phase

reactor ν: 2nd world measurement of $\Delta m^2_{12}$;

first solar CC on $^{13}C$

low energy $^{8}B$ solar ν




2026 2027 2028 2029 2030 2031 2032

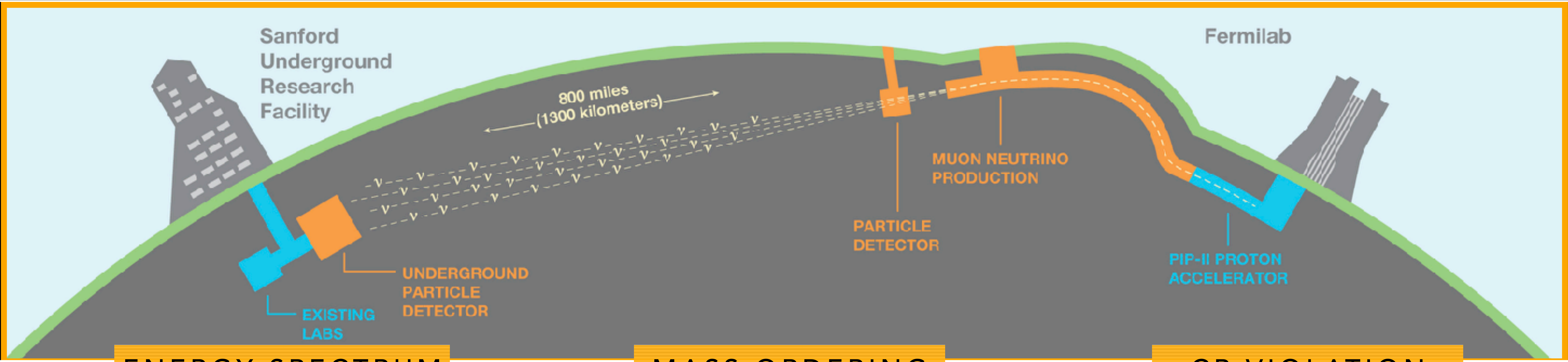
Fill 0.5% Te | 0.5% data | Fill 1.5% Te | 1.5% data

## Tellurium-loaded phases:

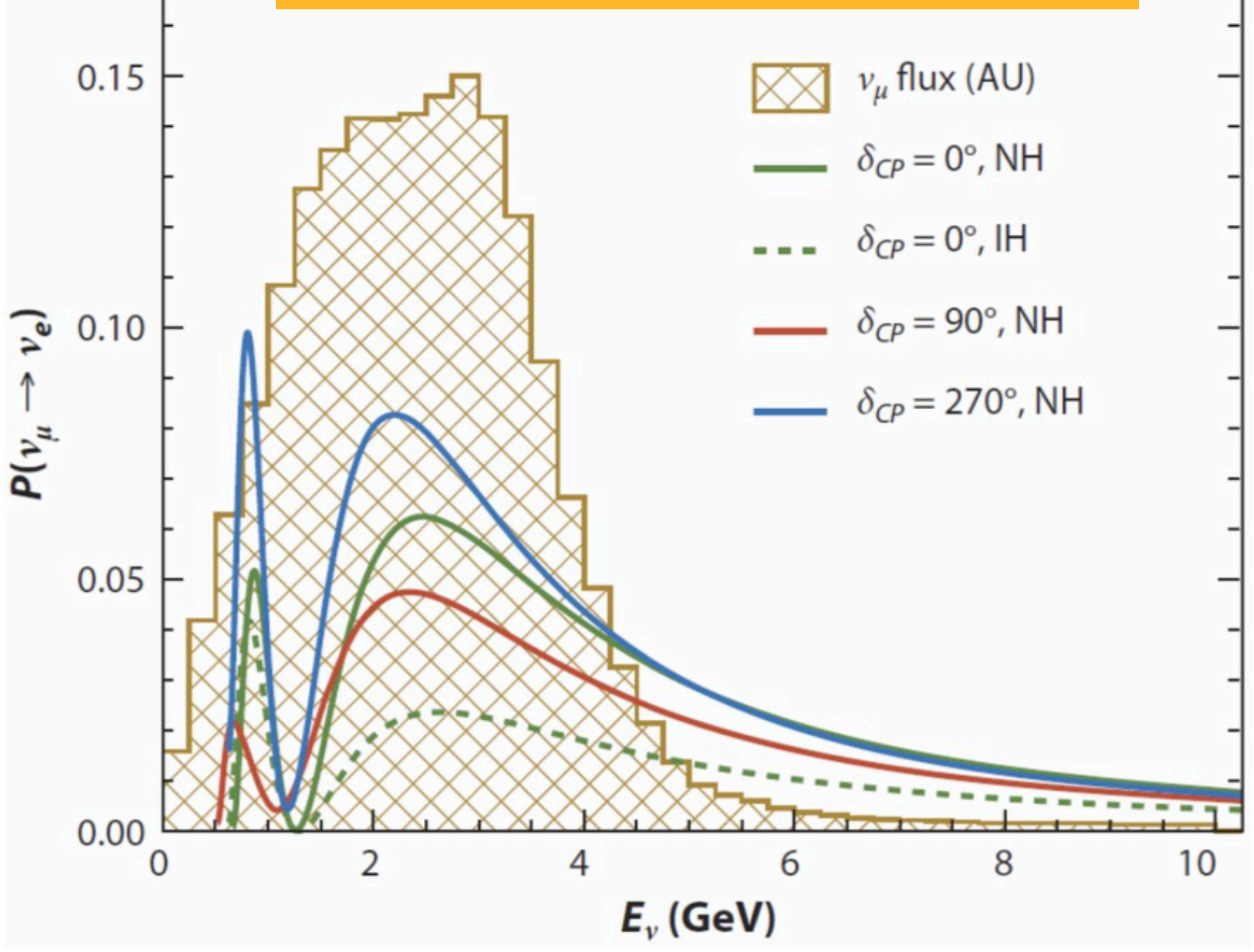
0.5%: best sensitivity to $^{130}Te$ $0\nu\beta\beta$ (2x$10^6$ yr in 3 yrs)

1.5%: best sensitivity, any isotope (6x$10^6$ yr in 5 yrs)

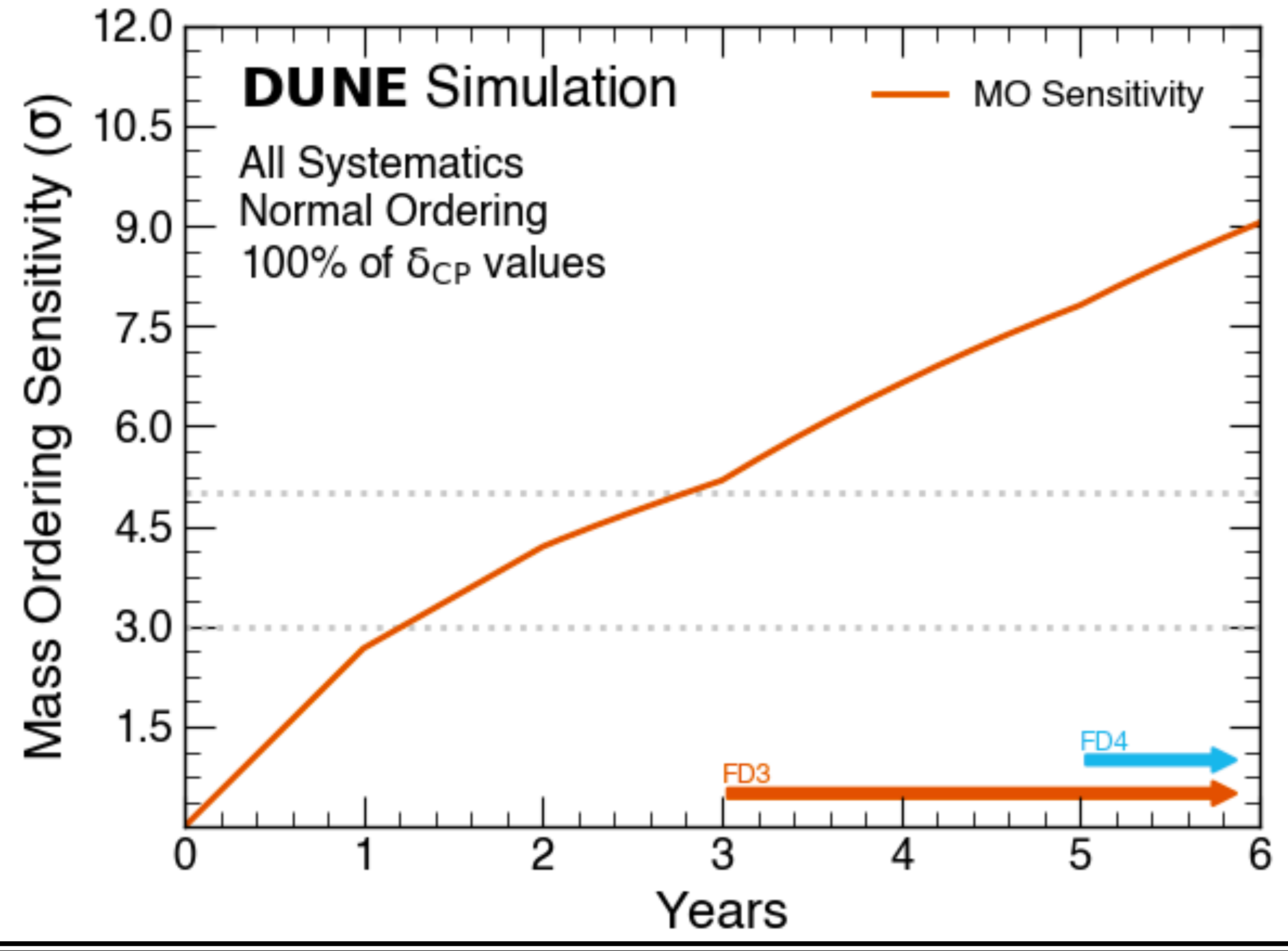
# LONG BASELINE OSCILLATIONS: DUNE



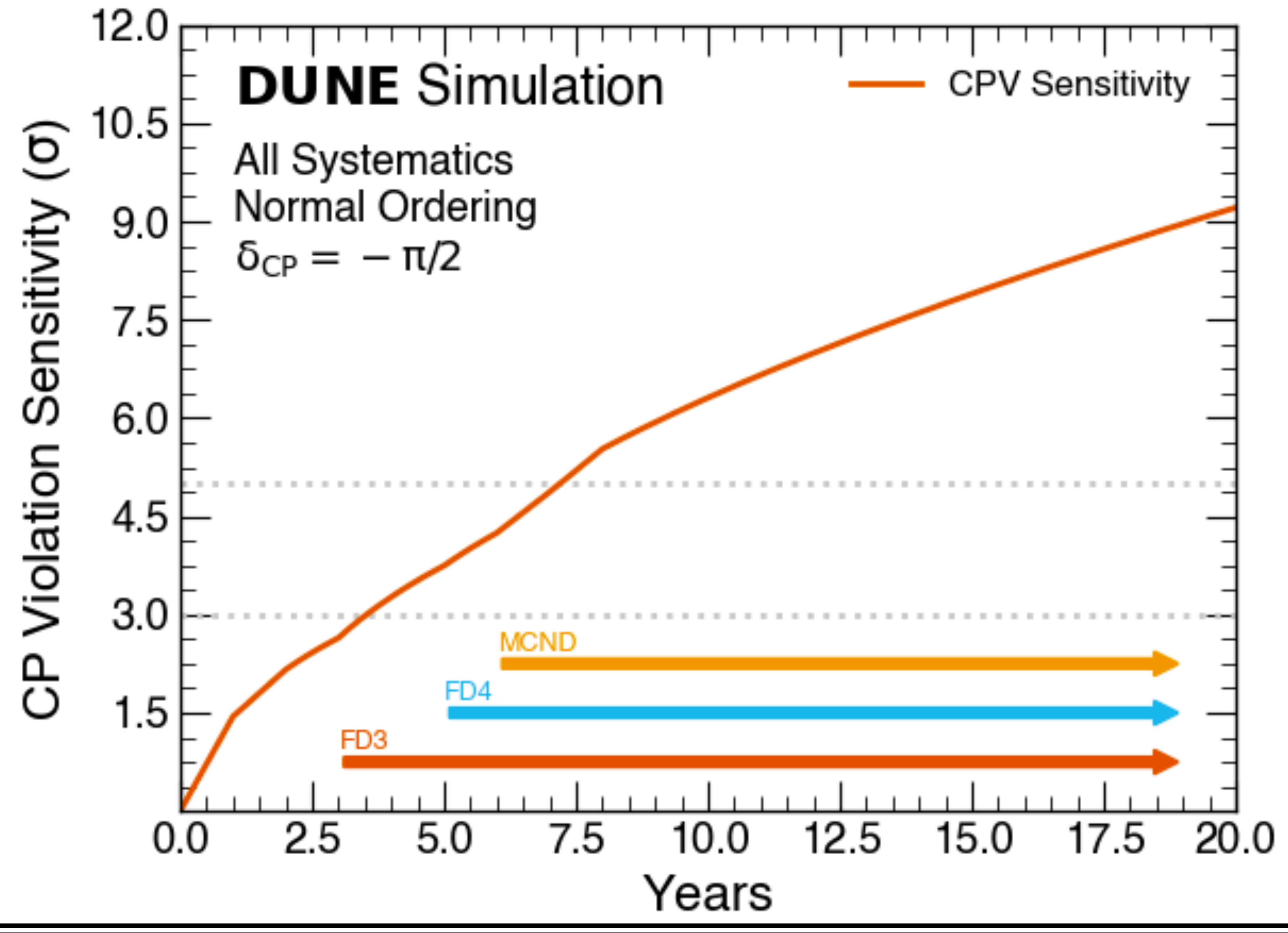

## ENERGY SPECTRUM




## MASS ORDERING

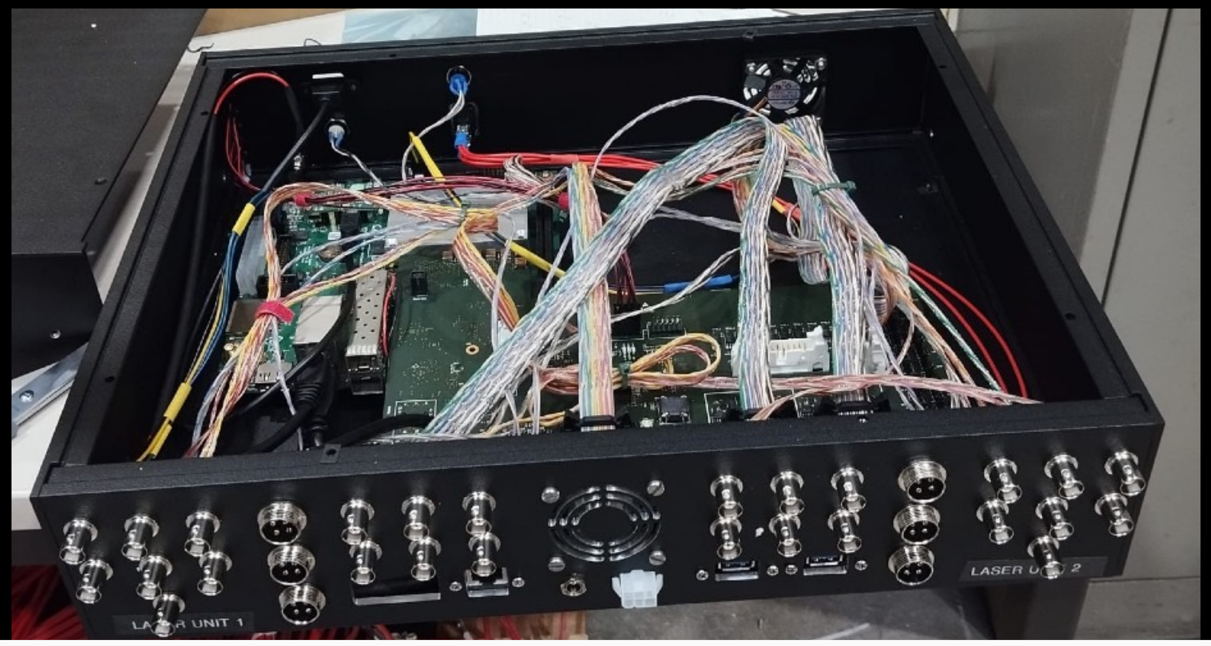


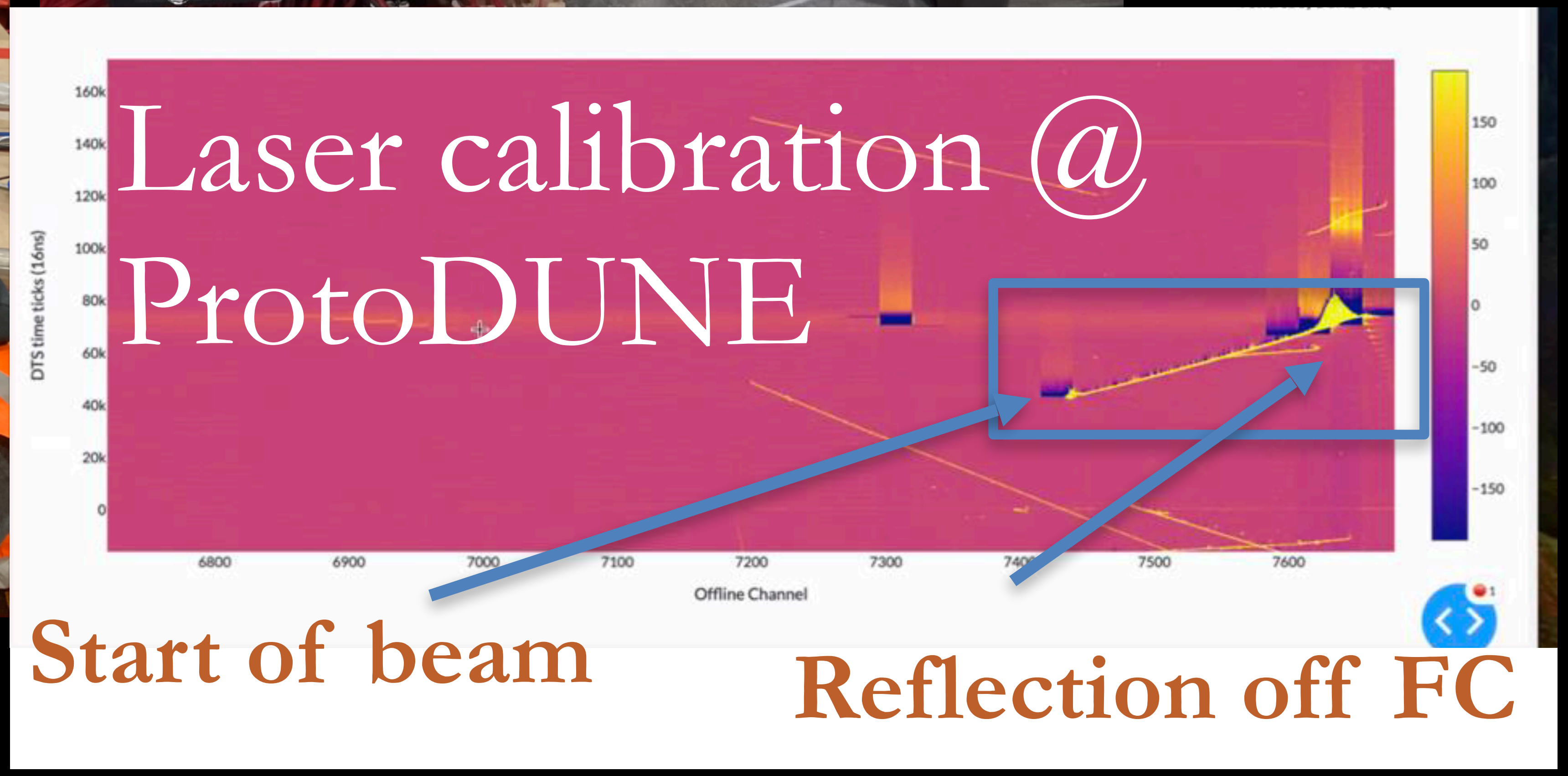

## CP VIOLATION

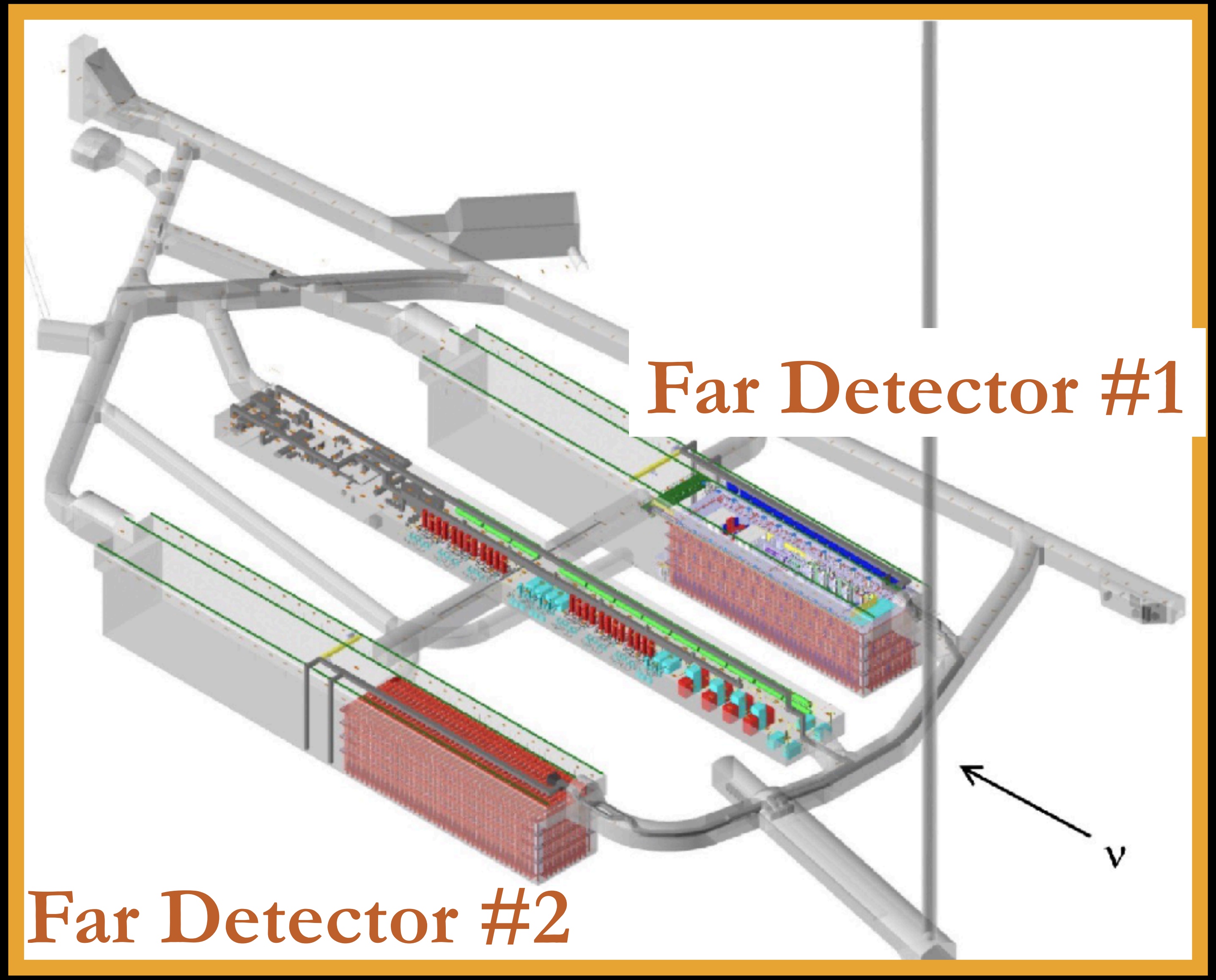


# LONG BASELINE OSCILLATIONS: DUNE

- DUNE Phase I: FD1 and FD2, beam start 2031
  - Horizontal and vertical drift LAr TPCs (17 kt each)
  - Testing this technology at ProtDUNEs (CERN)
  - LIP leading Calibration and Cryogenic Instrumentation






- DUNE Phase II: FD3 and FD4
  - FD4 not necessarily LAr, open to expand physics
  - Theia: Liquid scintillator option proposed for FD4. Possible convergence with SNO+ expertise

# PRIORITIES

| | DUNE | SNO+ |
|---|---|---|
| PHYSICS POTENTIAL | MASS ORDERING AND LEPTONIC CP VIOLATION (+ BSM)<br>SUPERNOVAE, PROTON DECAY | BEST SENSIVITY TO 0VBB WITH TE130 @0.5% |
| LONG-TERM POTENTIAL | WIDEBAND GIVES GOOD SENSITIVITY TO BSM<br>R&D FOR DUNE PHASE II | BEST SENSIVITY WITH ANY ISOTOPE @1.5%<br>TECHNIQUE FOR FUTURE EXPERIMENTS |
| FINANCIAL, HUMAN RESOURCES | LEVERAGE LEADERSHIP ROLES AND LIP INFRASTRUCTURES. | LEADERSHIP ROLES<br>MODEST NEEDS FOR FUTURE R&D |

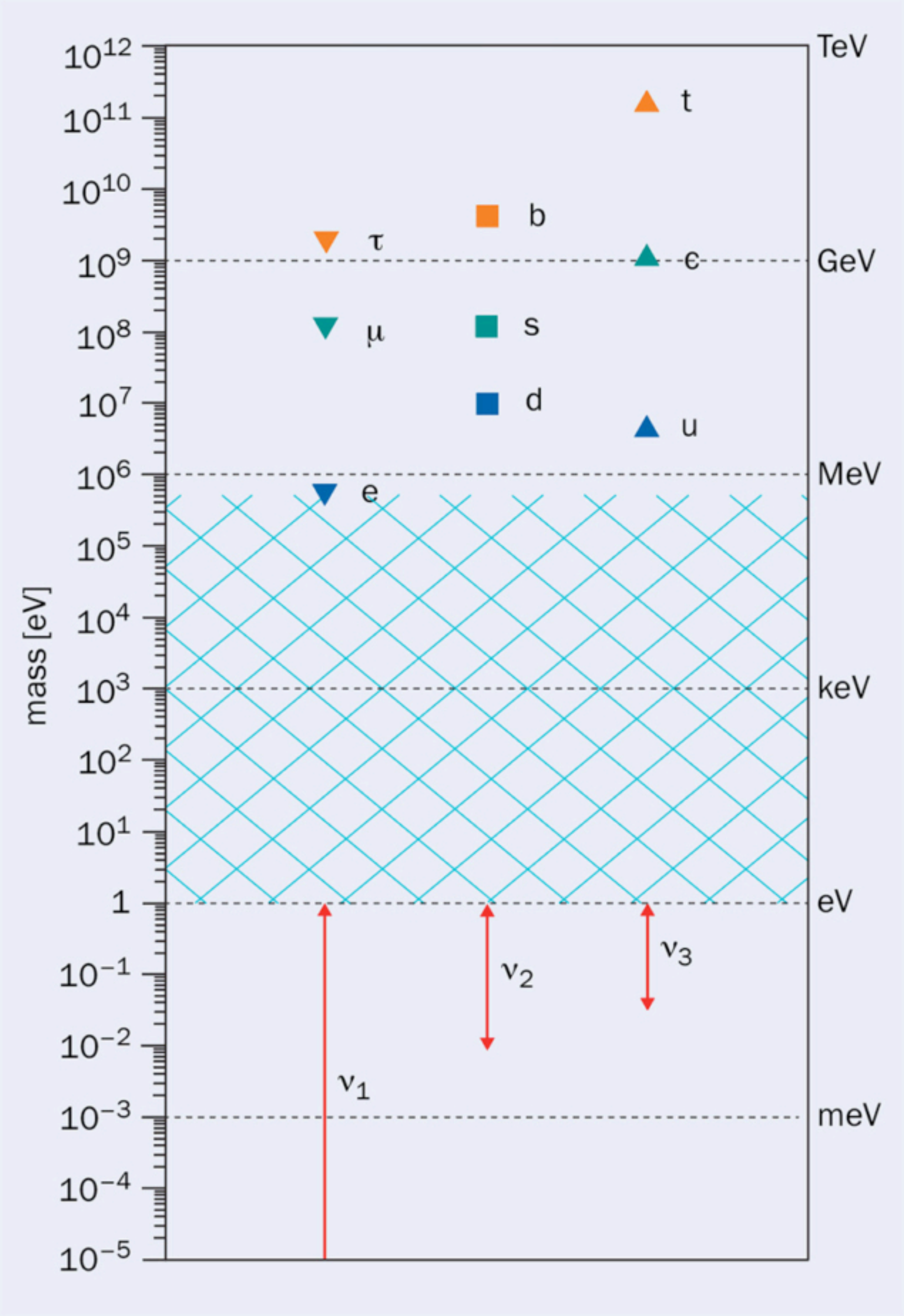
# PRIORITIES

| | DUNE | SNO+ |
|---|---|---|
| TIMING | PROTODUNE ANALYSIS IN PARALLEL WITH FD CONSTRUCTION. LATER, R&D FOR PHASEII | DATA ANALYSIS NOW. FUTURE LS TECHNIQUE POTENTIALLY CONVERGE AS DUNE FD4 |
| CAREERS, TRAINING | LARGE INTERNATIONAL COLLABORATIONS, GOOD COMBINATION OF HW, ANALYSIS | |

# EXTRA SLIDES

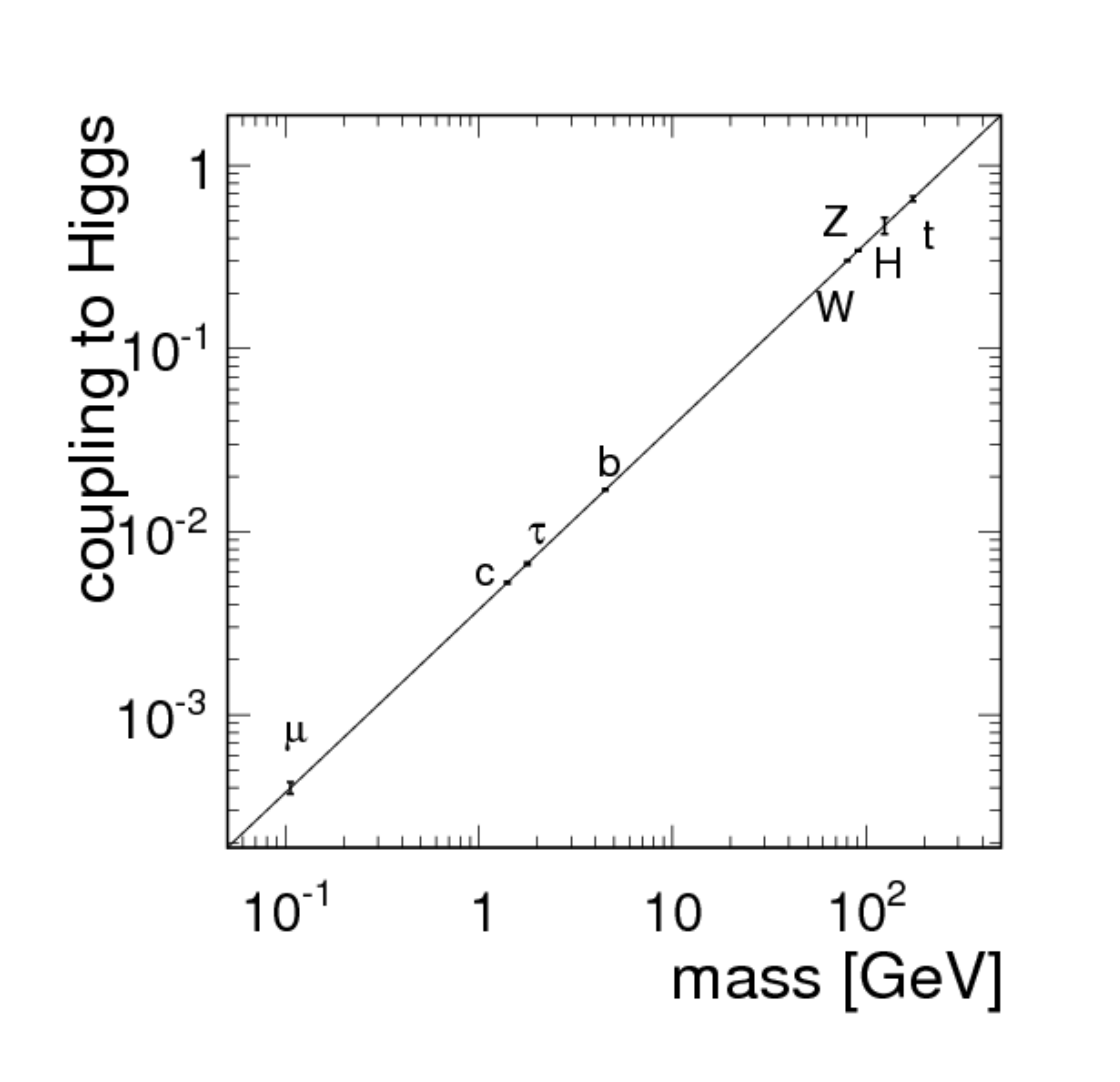
# NEUTRINO MASS, WHY SO TINY?

Fermion masses

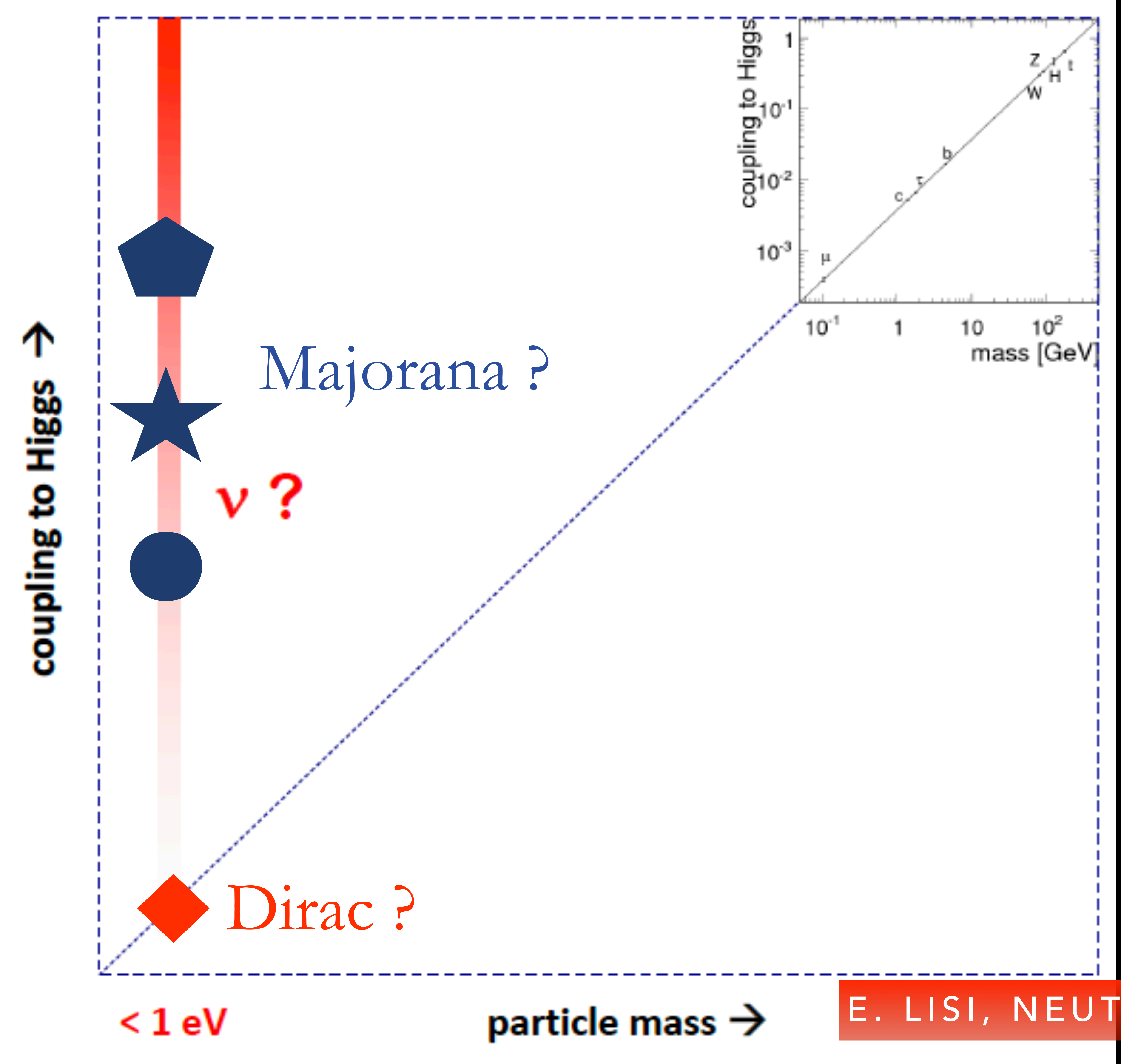



Why this huge gap?

Mass of elementary particles directly related to Higgs interaction



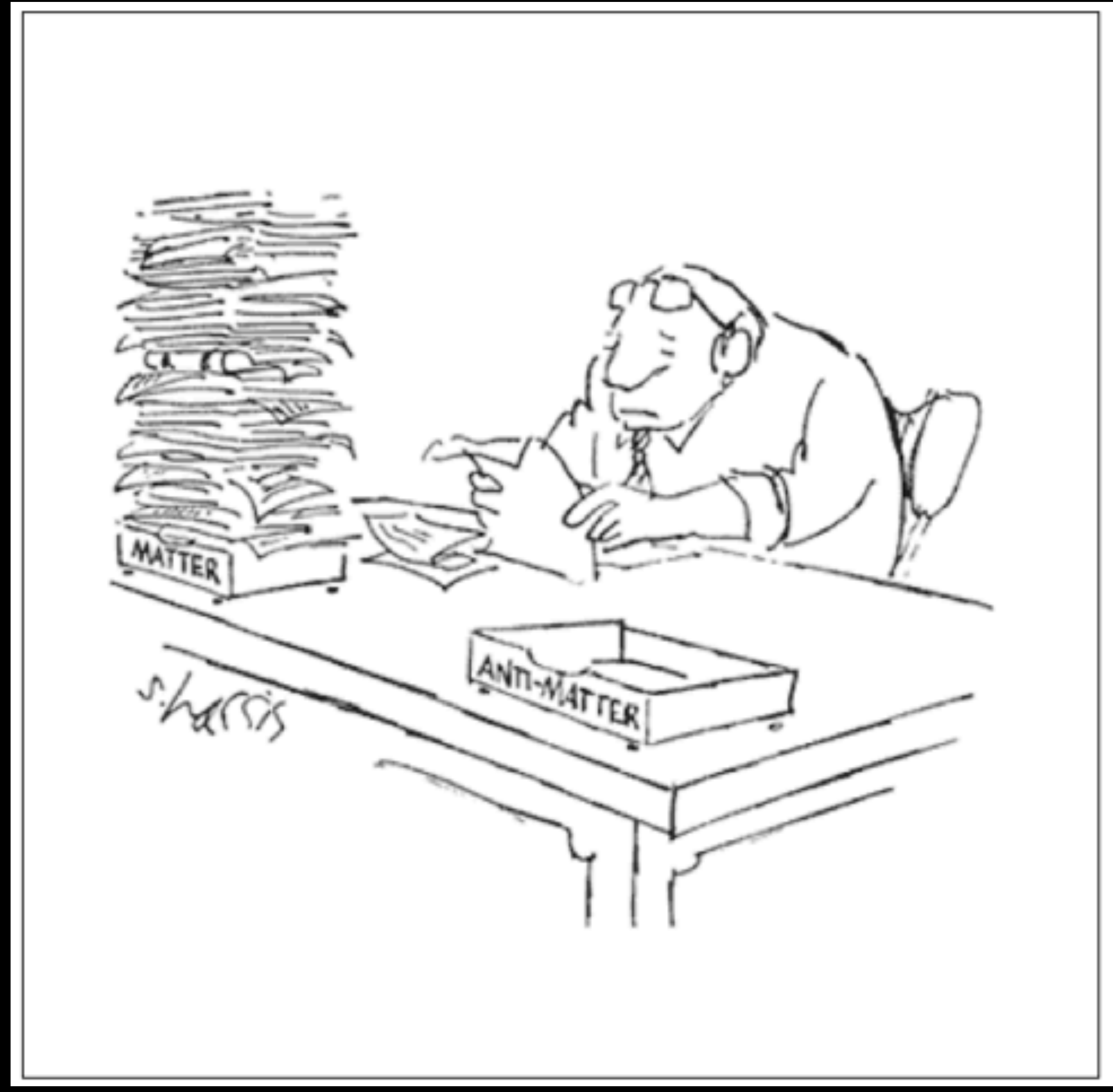
# NEUTRINO MASS, WHY SO TINY?



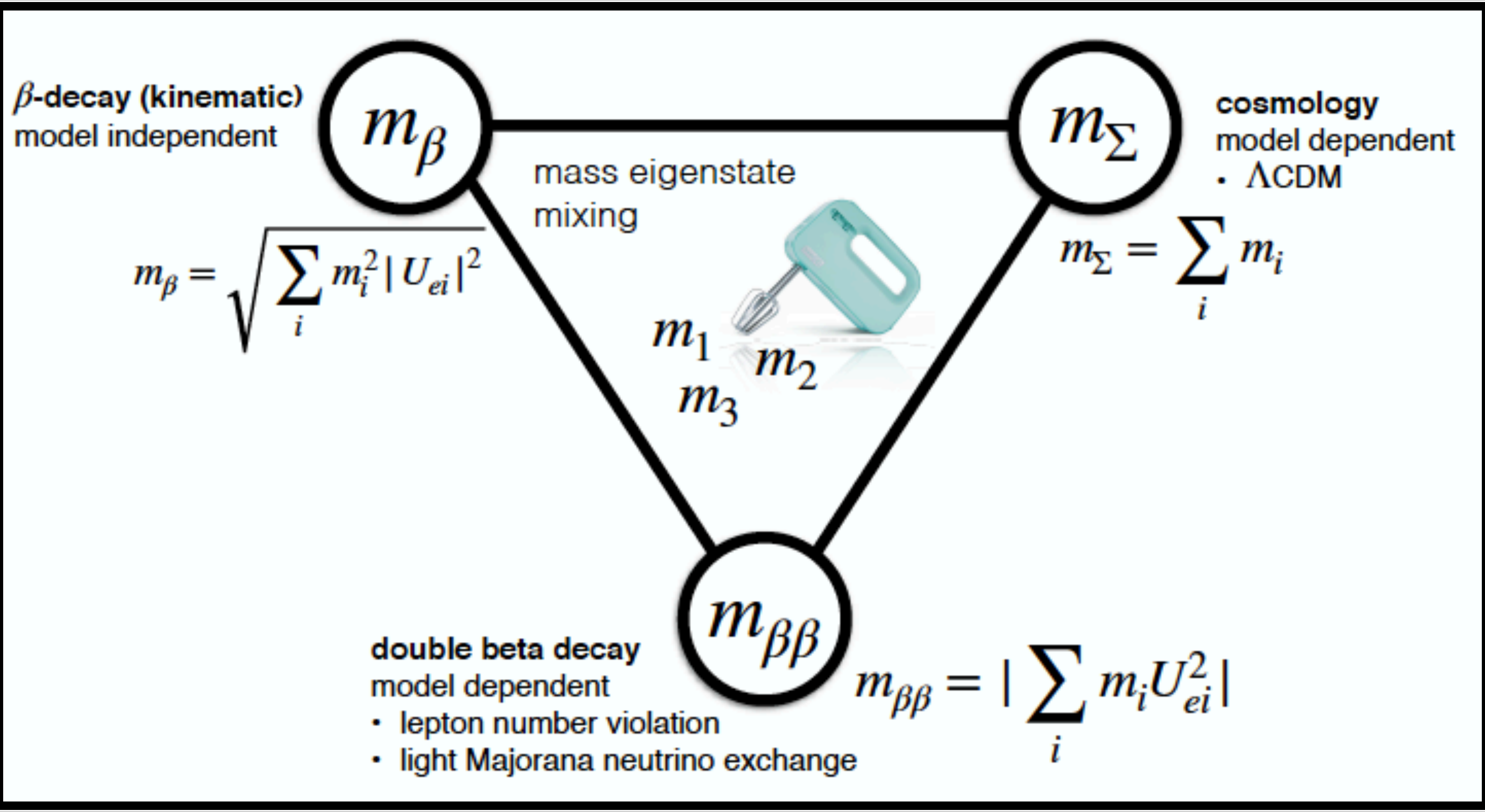

E. LISI, NEUTRINO 2024 (ADAPTED)

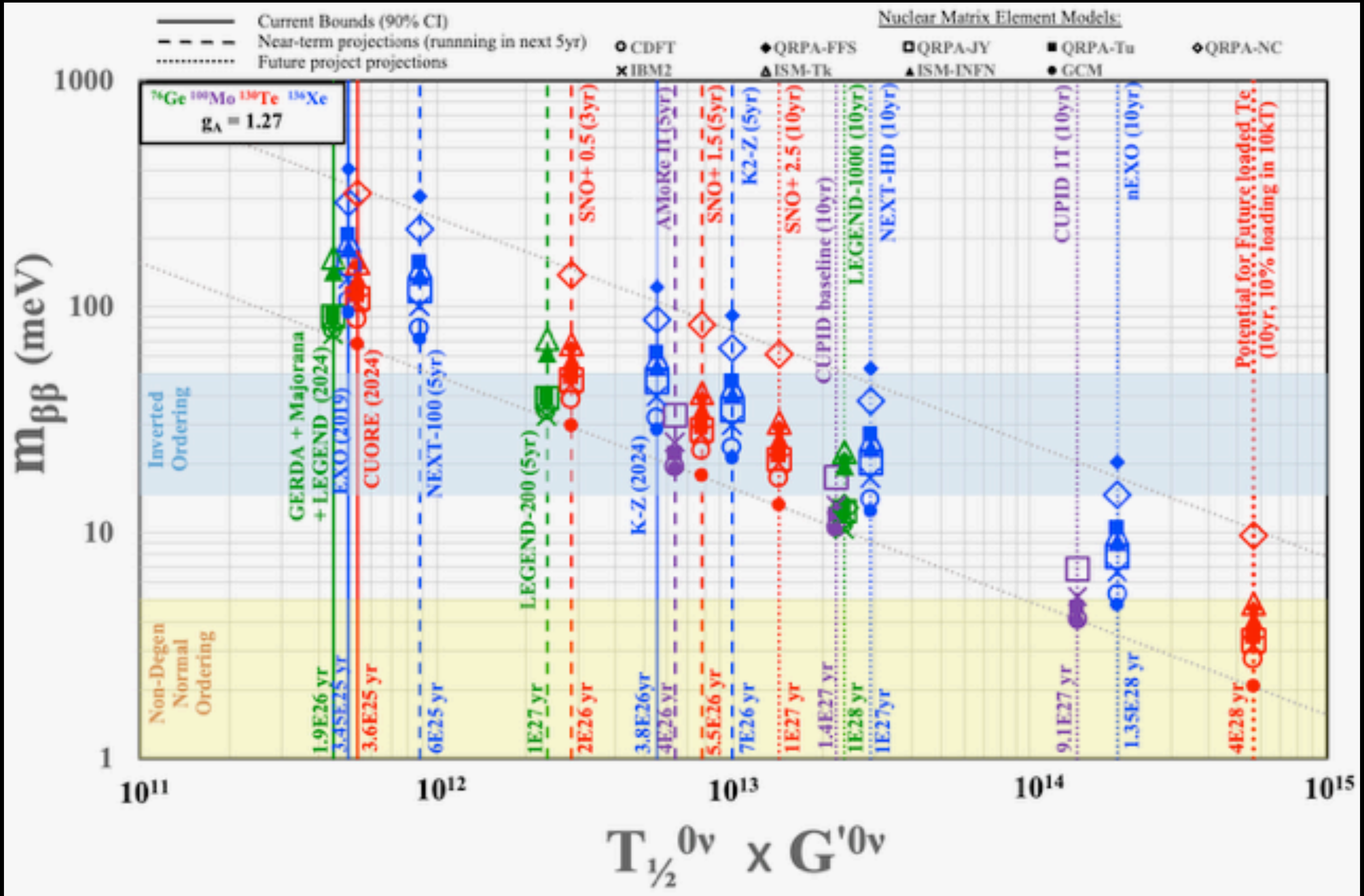
Do neutrinos couple to the Higgs in the same way as charged fermions?

- A test ground for New Physics!
- Possible explanation for matter/antimatter asymmetry.



# NEUTRINO MASS OBSERVABLES





Current Bounds (90% CI)
Near-term projections (runnning in next 5yr)
Future project projections
Nuclear Matrix Element Models:
CDFT
QRPA-FFS
QRPA-JY
QRPA-Tu
QRPA-NC
IBM2
ISM-Tk
ISM-INFN
GCM
76Ge 100Mo 130Te 136Xe
gA = 1.27
Inverted Ordering
Non-Degen Normal Ordering
GERDA + Majorana + LEGEND (2024)
EXO (2019)
CUORE (2024)
NEXT-100 (5yr)
LEGEND-200 (5yr)
SNO+ 0.5 (3yr)
K-Z (2024)
AMoRE II (5yr)
SNO+ 1.5 (5yr)
K2-Z (5yr)
SNO+ 2.5 (10yr)
CUPID baseline (10yr)
LEGEND-1000 (10yr)
NEXT-HD (10yr)
CUPID 1T (10yr)
nEXO (10yr)
Potential for Future loaded Te (10yr, 10% loading in 10kT)
1.9E26 yr
3.4SE25 yr
3.6E25 yr
6E25 yr
1E27 yr
2E26 yr
3.8E26yr
4E26 yr
5.5E26 yr
7E26 yr
1E27 yr
1.4E27 yr
1E28 yr
1E27yr
9.1E27 yr
1.35E28 yr
4E28 yr
mββ (meV)
T½0ν x G'0ν