Heavy Neutrino Search with Tritiated Levitated Nanoparticles

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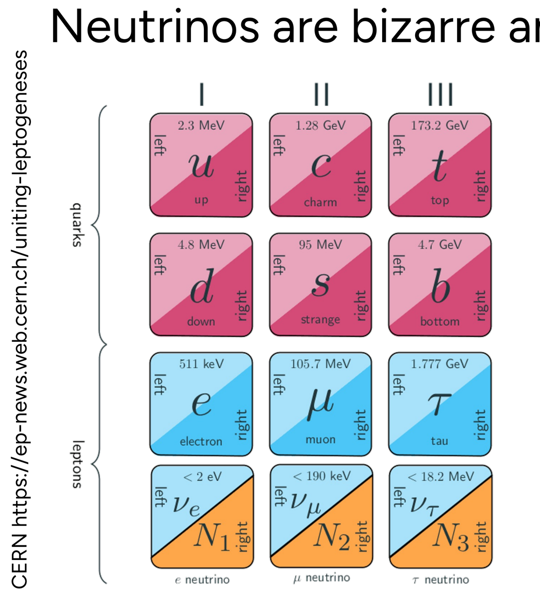
Beyond the Standard Model

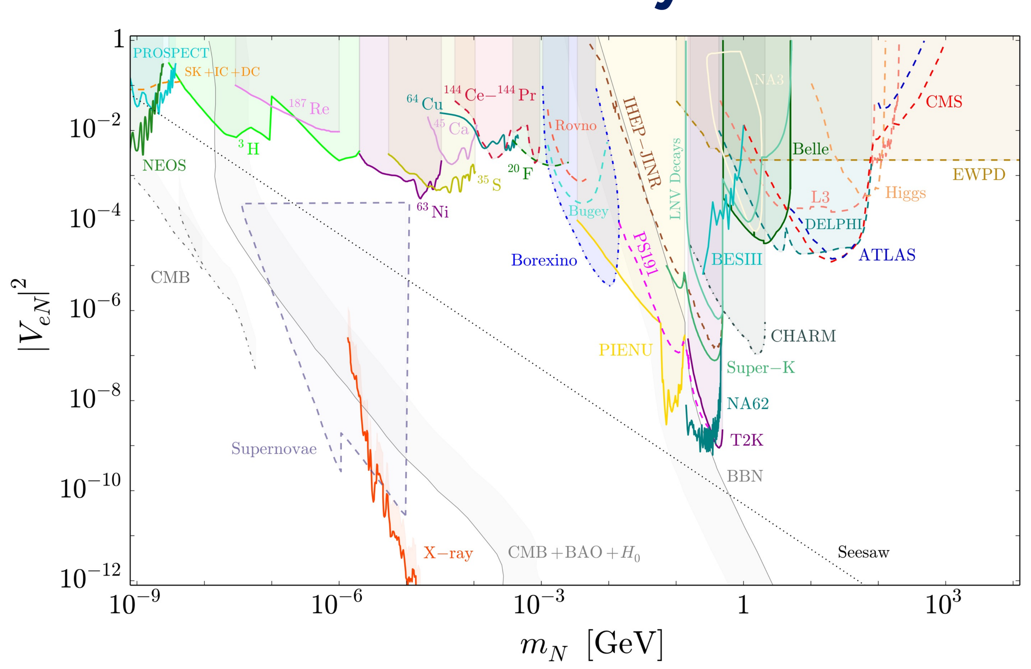
Neutrinos are bizarre and not fully understood



- Why are neutrinos only left-handed?
- Do right-handed neutrinos exist?
- Are they **heavy**?
- Are they Dark Matter?

Many extensions of the Standard Model contain heavy neutrinos. Can we detect them?

State of the Art of Heavy ν Search



P. Bolton, F. Deppisch, P. Bhupal Dev, J. High Energ. Phys. 2020, 170 (2020)

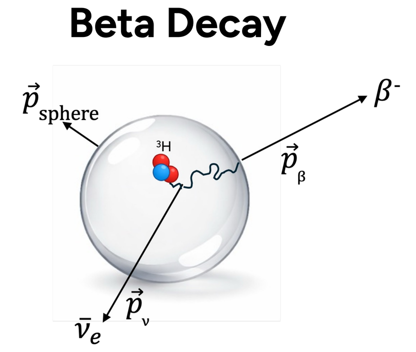
Neutrino Mass via β Decay Kinematics

Consider a nanoparticle with embedded beta emitters.

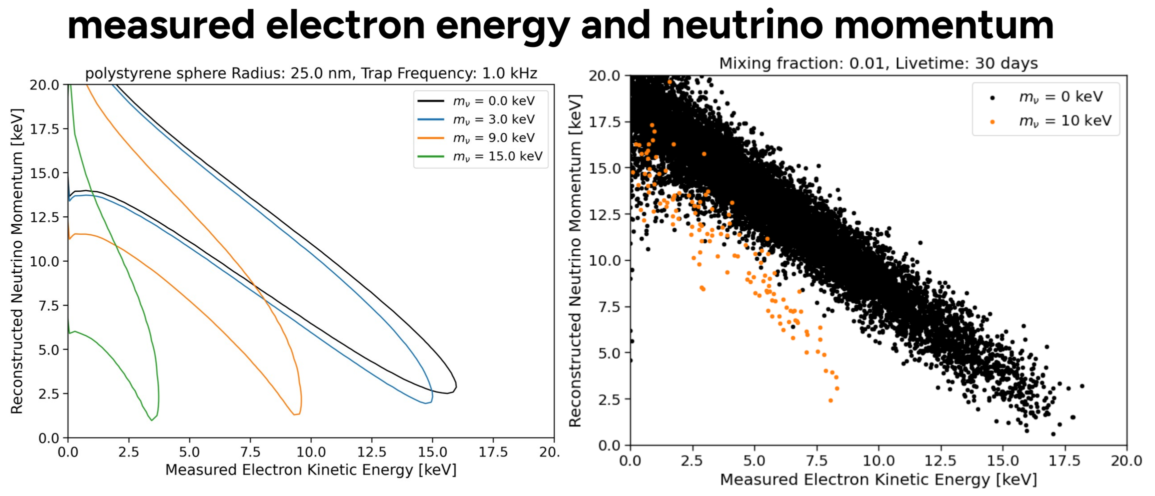
The neutrino momentum can be reconstructed from the measurement of:

- beta electron energy
- beta electron direction
- nanoparticle momentum

Beta Decay



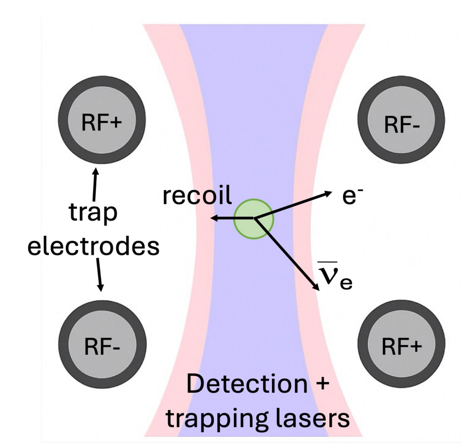
Effect of heavy neutrino mass on distribution of measured electron energy and neutrino momentum



Based on PRX Quantum 4, 010315 (2023)

Nanoparticle Levitation Technology

- Optomechanical systems allow extremely precise measurement of position and impulse of small particles
- Recent results:
  - Alpha particle decay
  - Gas recoils (200 keV/c)
- Correlation with charge change
- At the Standard Quantum Limit (SQL), Δp ~ 0.4 keV with
  - 25 nm polymer sphere radius
  - 1 kHz trapping frequency



$$\Delta p_{SQL} = \sqrt{\hbar m_s \omega_s}$$

- **Requirements for heavy neutrino experiment**:
  - Electron energy resolution < 300 eV
  - Electron direction resolution: < 0.02 rad
  - High activity beta (or EC) emitter
  - Nanoparticle cooling
  - Low gas damping
  - Particle stability under laser light

EXPERIMENT DESIGN: Hybrid RF-optical Trap

Benefits:

- Greater trap depth for low-mass particles
- Laser used only for position measurement, with lower power requirement → lowers particle heating from laser absorption

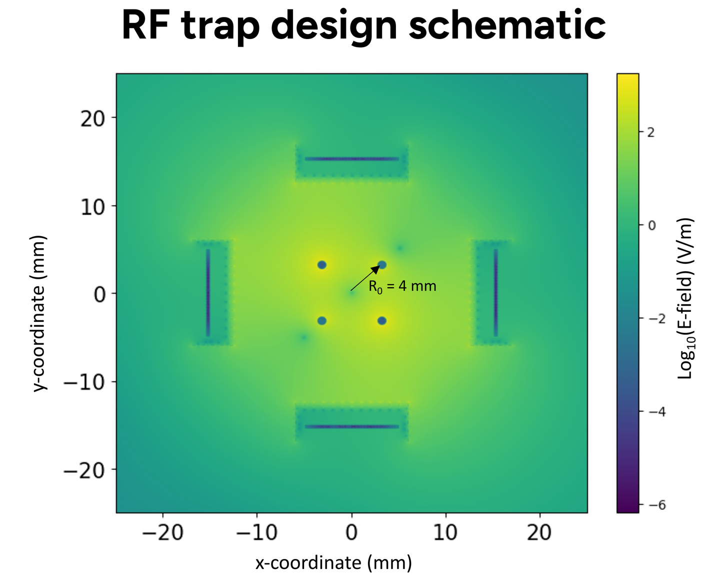
Challenges:

- Adds scattering from RF trap structures

RF Trap Parameters:

- Design: simple quadrupole trap, other designs with more open architecture are possible
- Include compensation electrodes
- Trap frequency: 1 kHz
- Particle charge: +10 e-

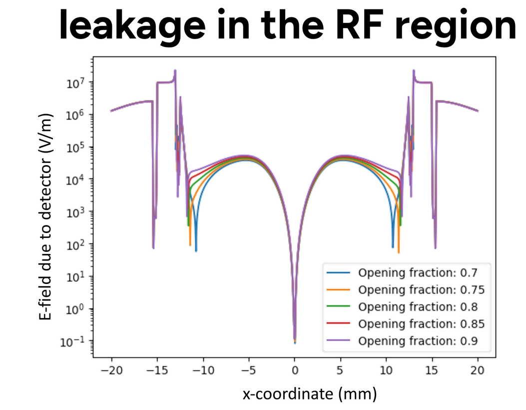
RF trap design schematic



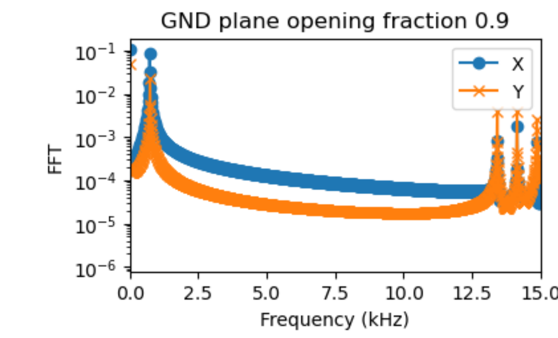
Quadrupole C_2 coeff of trap radial potential

Electrode radius	C_2
0.5 mm	0.36
1 mm	0.42
1.5 mm	0.44
2 mm	0.46
Ideal value	0.5

Acceleration field E leakage in the RF region



Nanoparticle motion dependence on acceleration E field leakage



EXPERIMENT DESIGN: Tritium Beta Electrons Measurements

Beta detectors:

- Pixelated Silicon Drift Detectors (SDD) have demonstrated acceptable resolution
  See e.g. Gugiatti, M. et al, NIM A 979, 2020

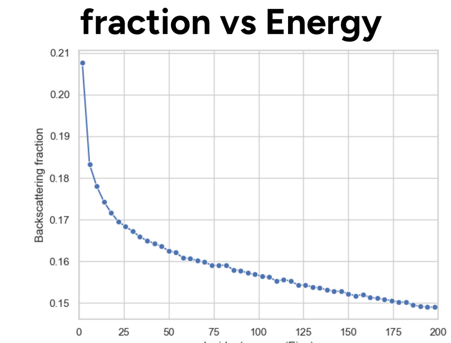
The Electron Scattering Challenges:

- Backscattering on detector
- Downscattering on intervening materials

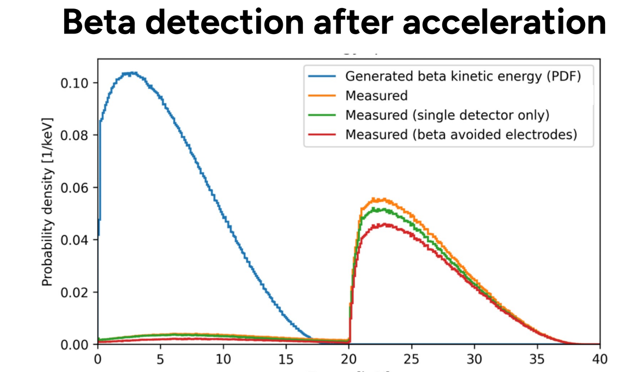
Mitigations:

- Accelerate electrons with a 20 kV radial field See TRISTAN Collaboration, arXiv:2603.23256
- Coincidence tagging

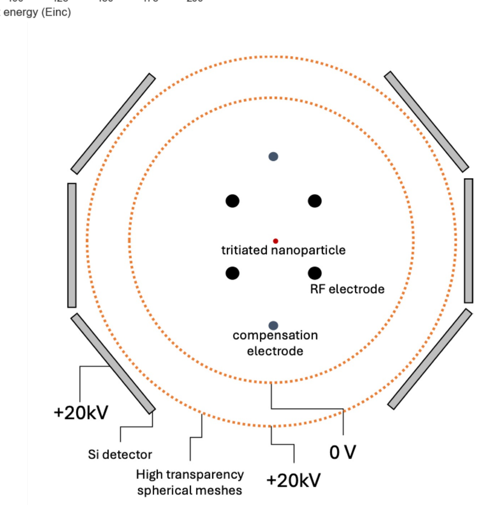
Electron Backscattering fraction vs Energy

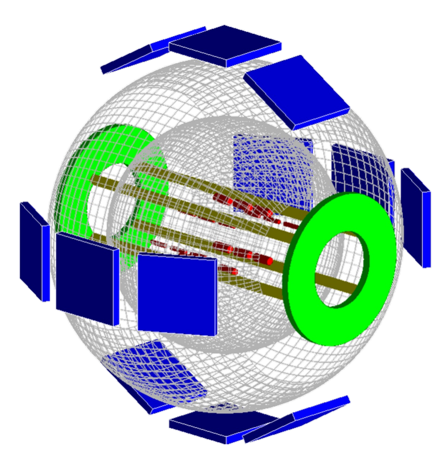


Beta detection after acceleration



Experiment schematic and GEANT4 model

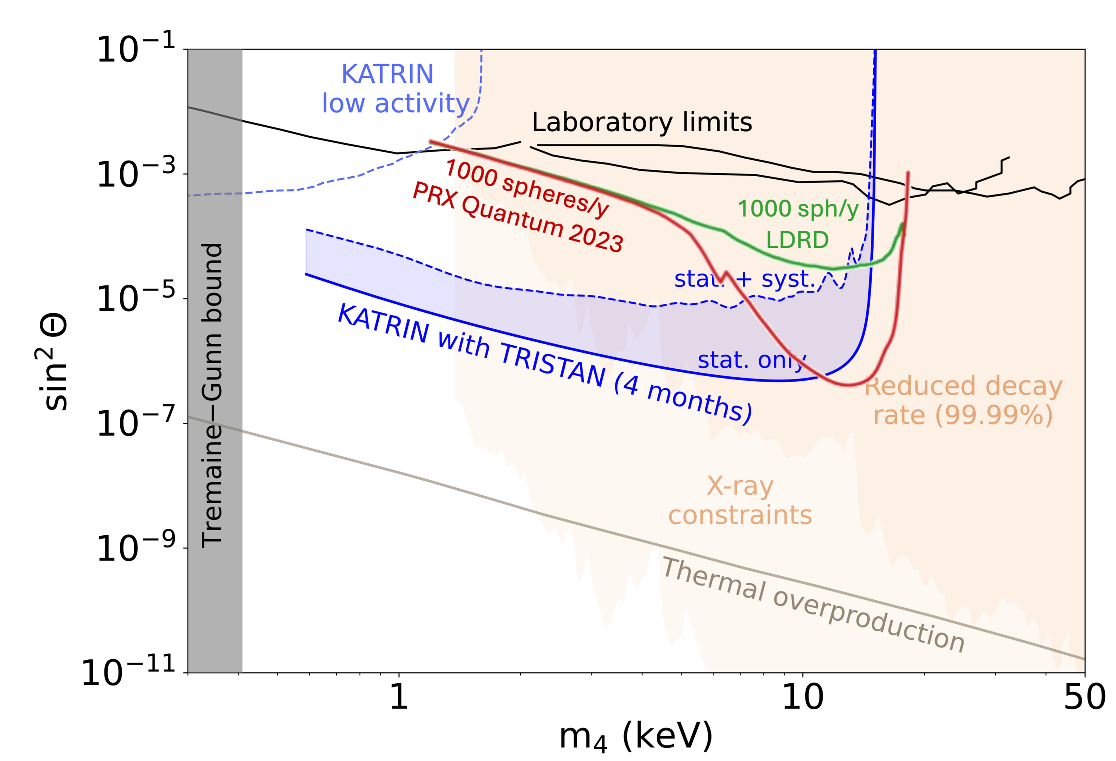




Tritiated Nanoparticles

- Multiple polymers can be manufactured commercially into nanoparticles of suitable size
- **Evaluate polymers suitability**
  - Laser adsorption & scattering
  - Material chemical purity
  - Melting point
  - Configuration (solid vs hollow)
- **Develop path to tritiation**
  - Tritium gas chemistry of polymer precursors
  - H-T isotope exchange (e.g. Wilzbach process)
  - LLNL's tritium handling capabilities

Expected Sensitivity



Adapted from KATRIN Collaboration, arxiv:2603.23256

Ongoing and Future Work

- Complete conceptual design of all detector components (optical, RF, β detectors)
- Perform detailed simulations and sensitivity estimate
- Fabricate tritiated nanoparticles
- Assemble prototype and demonstrate
  - Nanoparticle loading
  - Stable particle trapping and cooling
  - Recoil measurement
  - Beta detection

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Lawrence Livermore National Laboratory
LLNL-POST-2020490
Prepared by LLNL under Contract DE-AC52-07NA27344. This work is supported by LLNL LDRD.
National Nuclear Security Administration