Heavy Neutrino Search with Tritiated Levitated Nanoparticles

Optomechanical Sensing for Subatomic and Astroparticle Physics Workshop

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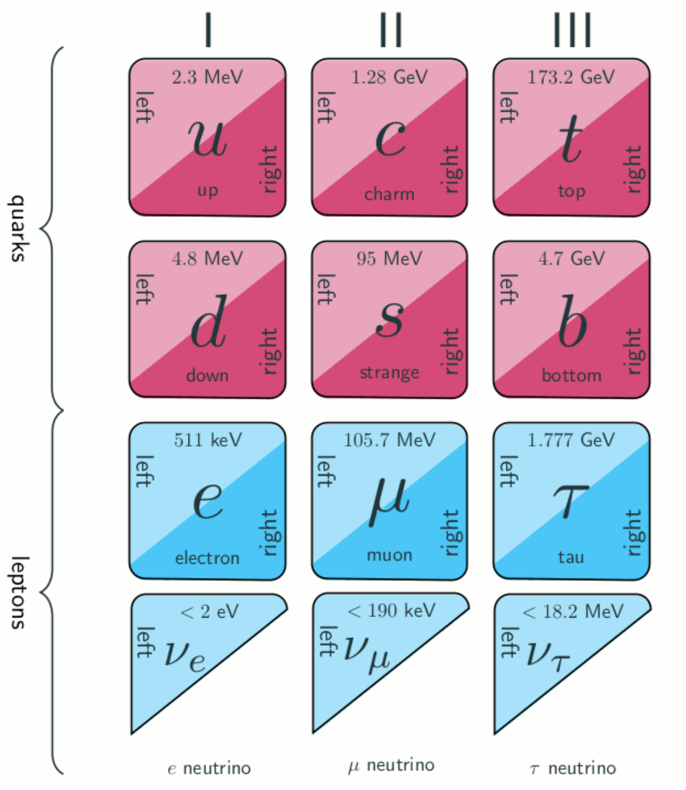
Beyond the Standard Model of Particle Physics

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

New Physics Beyond Standard Model

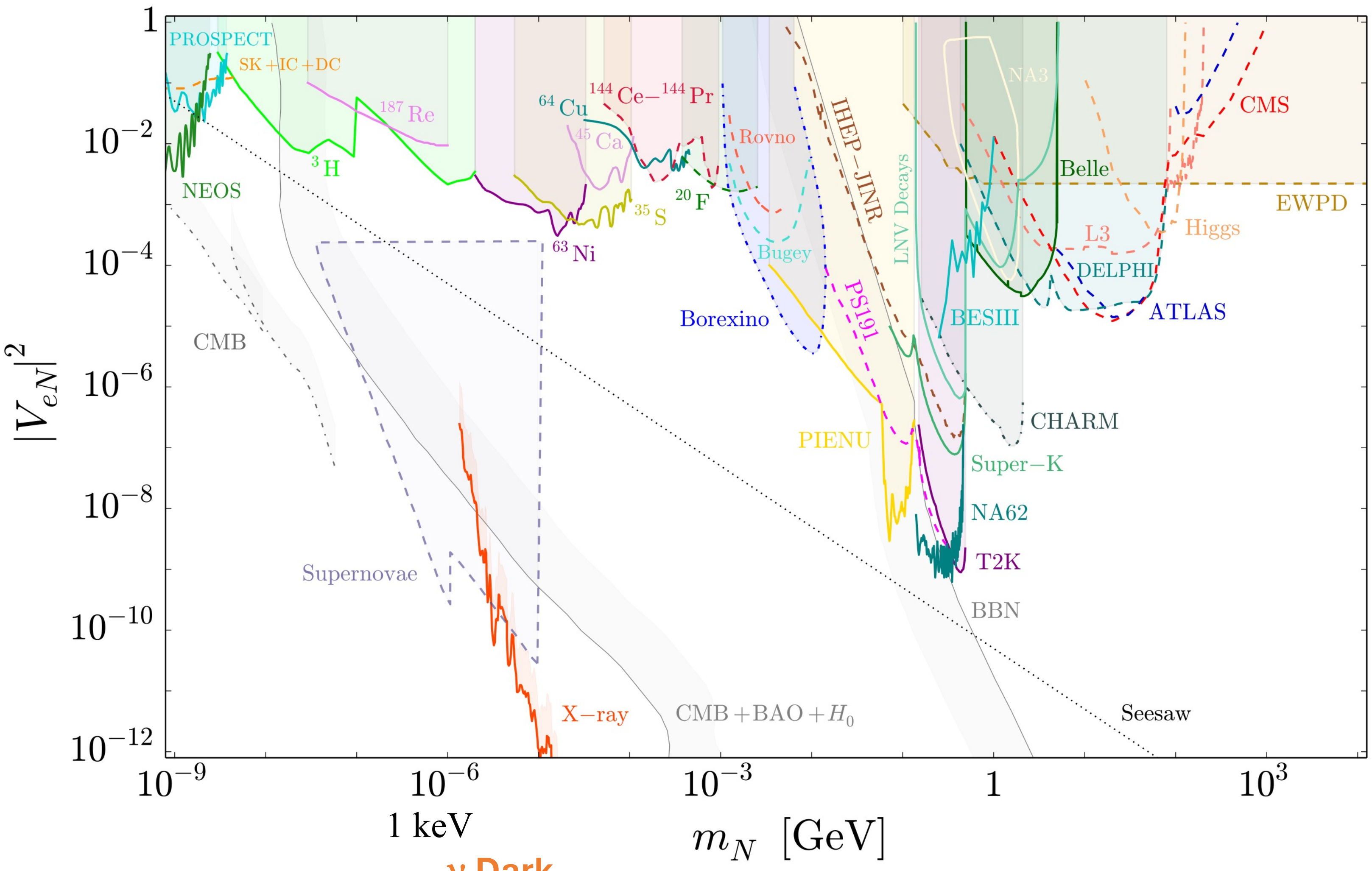
- Explanation of smallness of neutrino masses
- First glimpse into the Hidden Sector
- Compelling Dark Matter candidate (at keV scale)



CERN https://ep-news.web.cern.ch/uniting-leptogeneses

Beyond the Standard Model of Particle Physics

Parameter space of Heavy Neutrino searches



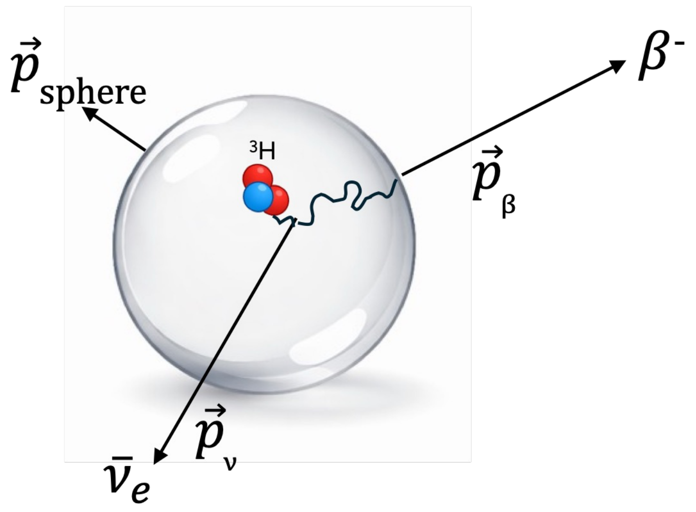
ν Dark Matter

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

Neutrino Mass via β Decay Kinematics

- Micro/Nano-particle with embedded beta emitters.
  - Tritium → probe m_ν < 20 keV
- Reconstruct neutrino momentum from:
  - beta electron energy
  - beta electron direction
  - nanoparticle impulse

$$\mathbf{p}_{\bar{\nu}} = -\left(\Delta \mathbf{p}_s + \mathbf{p}_e\right)$$

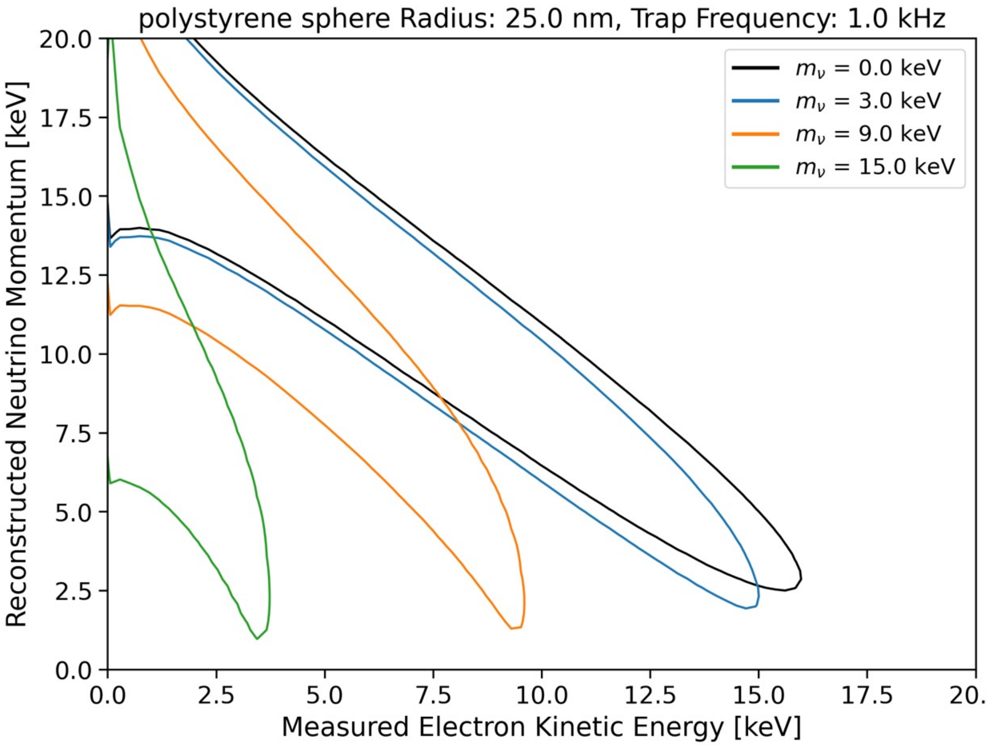


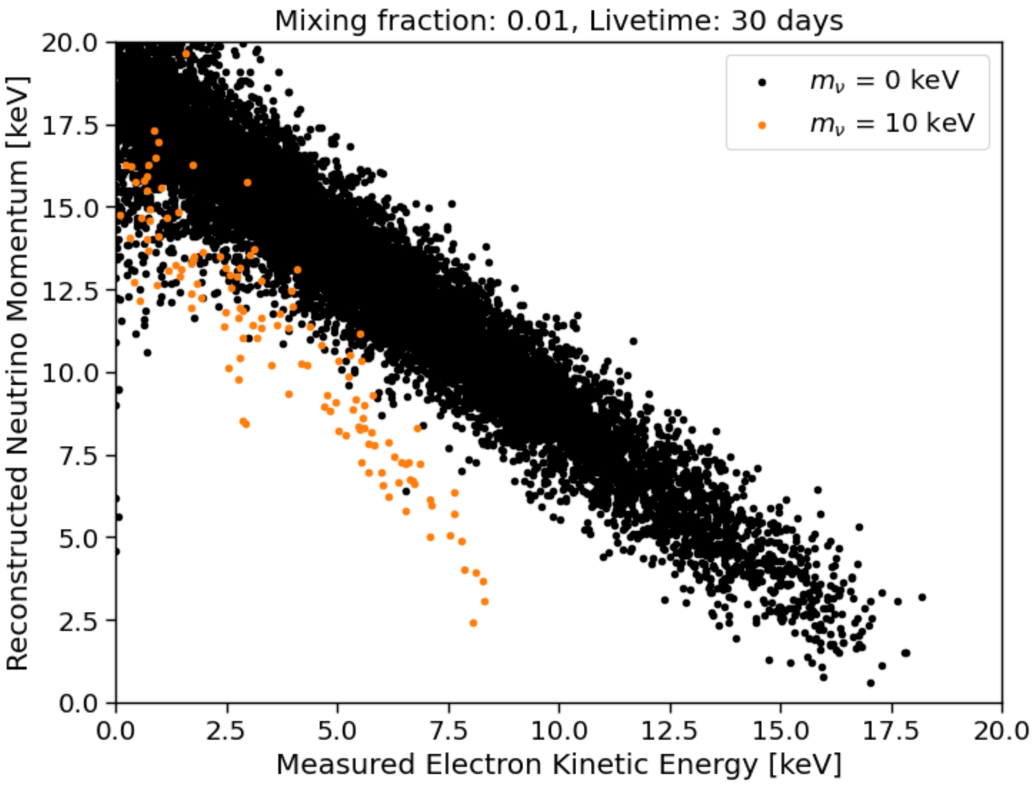
Optomechanical measurement:
- Levitated nanoparticle
- Sphere recoil momentum

D. Carney, K. Leach, D. Moore, PRX Quantum 4, 010315 (2023)

Neutrino Mass via β Decay Kinematics

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





Based on PRX Quantum 4, 010315 (2023)

Experiment Requirements

1. Impulse sensitivity
2. Resolution of beta energy and direction detector
3. Control of incomplete/incorrect reconstructed beta
4. Coincident beta + nanosphere recoil measurement
5. Statistics

“Standard” quantum limit:
- Photon readout shot noise
- Photon-recoil back-action

$$(\Delta p)^{SQL} = \sqrt{\hbar m \omega_0}$$

See, e.g., A. Clerk, PRB 70, 245306 (2004)

Target Δp ~ 400 eV/c on all axis:
- 25 nm radius nanoparticle
- 1 kHz trapping frequency

Active experimental R&D

Experiment Requirements

1. Impulse sensitivity
2. Resolution of beta energy and direction detector
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5. Statistics

Targets:

- Electron energy resolution < 300 eV
- Electron direction resolution < 0.02 rad

Experiment Requirements

1. Impulse sensitivity
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4. Coincident beta + nanosphere recoil measurement
5. Statistics

- Energy loss in the nanosphere
- Downscattering of electrons
  - Experiment structures
  - Gas
- Emission of undetected secondary particles
- Partial energy deposits (e.g. due to backscattering)

Experiment Requirements

1. Impulse sensitivity
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5. Statistics

- Monitor the charge state of the nanoparticle and detect change upon
  - Single electron sensitivity demonstrated

See e.g. J. Wang, et al, Phys. Rev. Lett. 133, 023602 (2024).

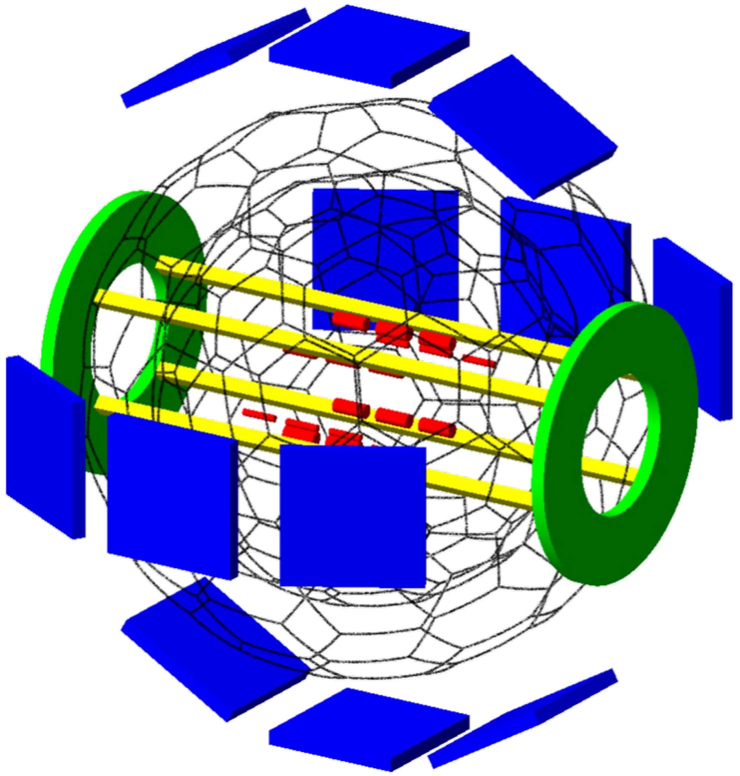
Experiment Requirements

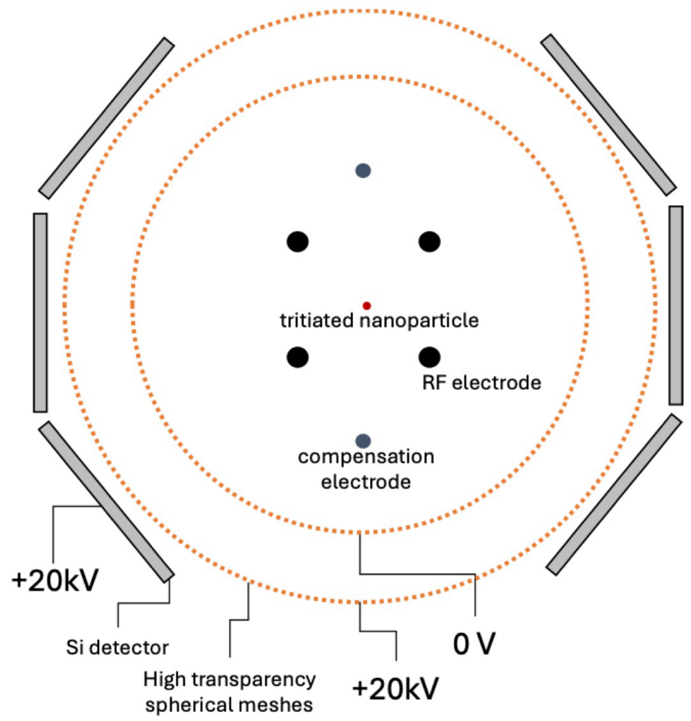
1. Impulse sensitivity
2. Resolution of beta energy and direction detector
3. Control of incomplete/incorrect reconstructed beta
4. Coincident beta + nanosphere recoil measurement
5. Statistics

- Expect ~500 β decays/day assuming 20% tritium loading on r=25 nm particle
- Need high beta detector coverage
- Need low dead time
- Scale number of deployed experiments

Experiment Concept

- RF trap with optical readout
- Pixelated Si Drift Detectors for beta measurement
- Electrostatic beta acceleration
- Tritiated polymeric nanoparticle





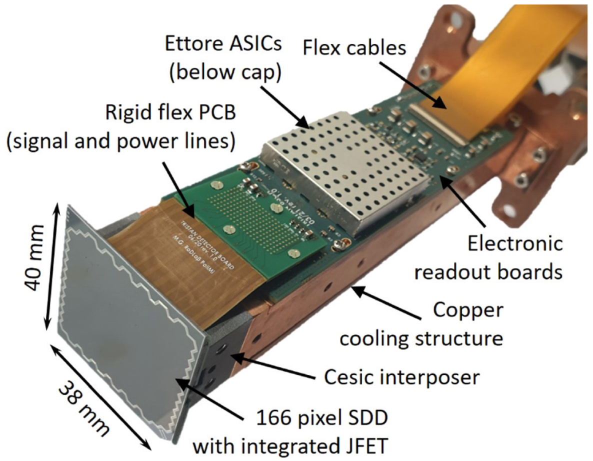
Experiment Design
Beta Detection

- **Design**:
  - Multiple technologies evaluated
  - Pixelated Silicon Drift Detectors (SDD) viable and demonstrated

See e.g. Gugiatti, M. et al, NIM A 979, 2020

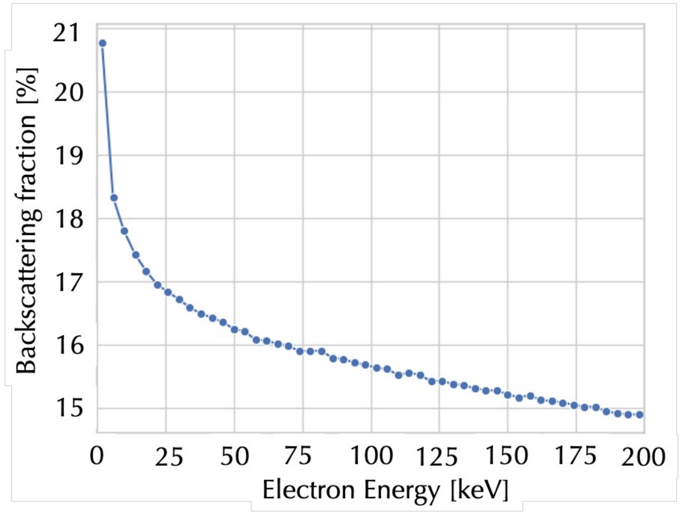
- **Challenges**:
  - Electron backscattering on detector
  - Electron downscattering on intervening materials
- **Mitigations:**
  - Electron acceleration in a 20 kV field
  - Multisite tagging

SDD for low-energy electron measurement

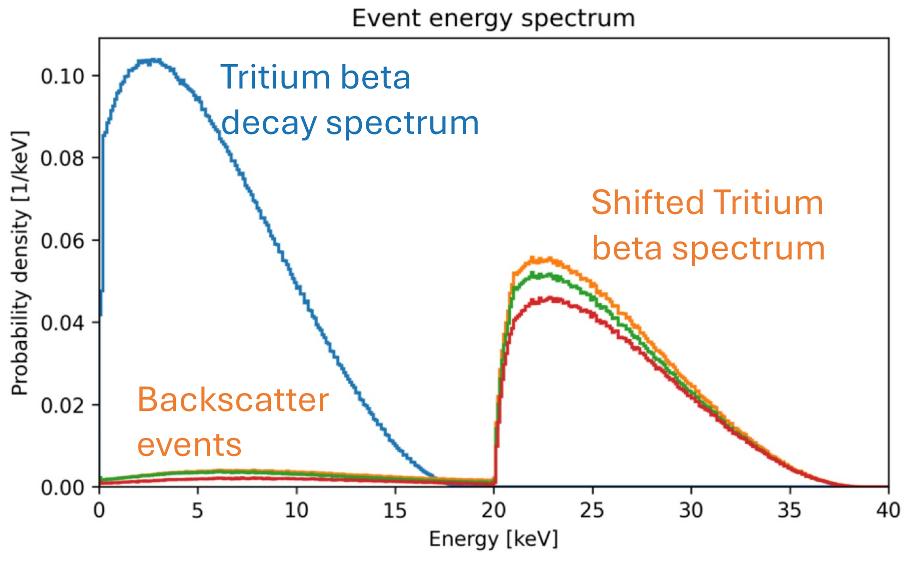


J. Phys. G: Nucl. Part. Phys. **51** 085202 (2024)

Electron Backscattering Fraction vs Energy



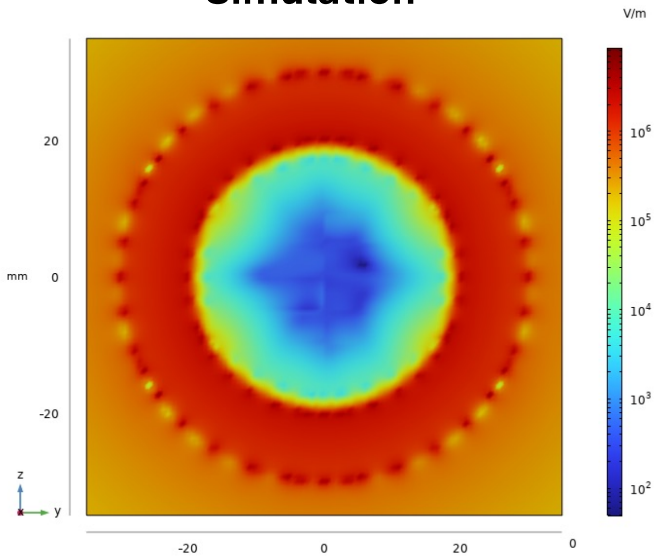
Post-acceleration shifts background outside of the ROI



Experiment Design:
RF Trap

- **Need for RF Trap**:
  - Provide sufficient trap depth for 25 nm particles
  - Reduce laser energy delivered to nanoparticle
- **Challenge**:
  - Minimize RF component footprint
  - Handle RF with external 20 kV field
- **Current Design Parameters:**
  - Quadrupole geometry for first iteration
  - Compensation electrodes
  - Trap frequency: 1 kHz
  - RF voltage / frequency: +/- 250 V at 15 kHz
  - Nanoparticle charge: ~ +10 e-

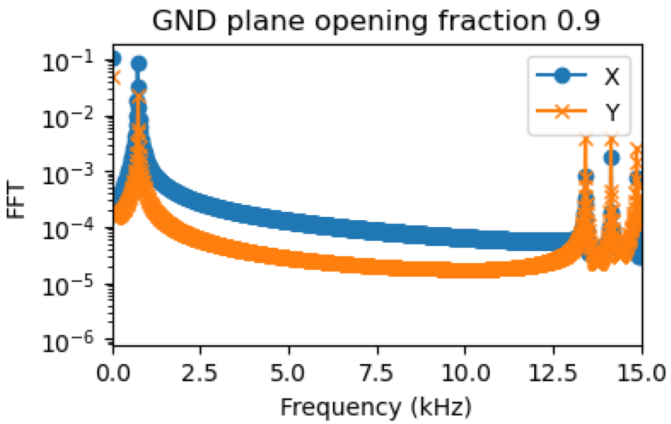
COMSOL Electrostatic Simulation



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

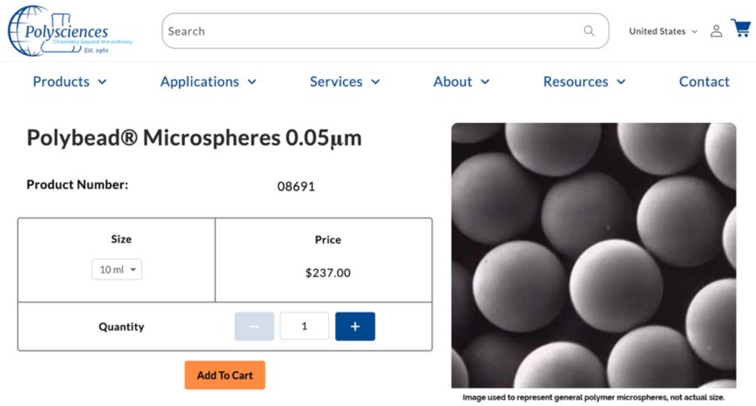
Nanoparticle motion in the trap and dependence on field leakage



Experiment Design: Polymeric NanoParticles

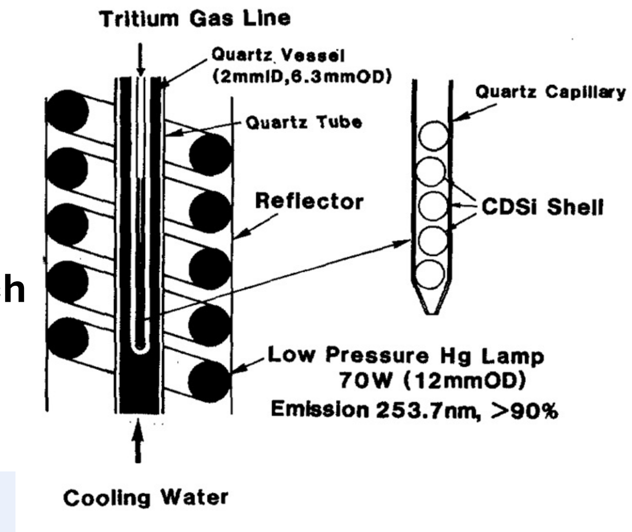
- Polymer nanospheres manufacturability demonstrated (commercially)
  - Polystyrene, polyethylene, PMMA
- **Risk**: polymer melting from photothermal heating under laser light
- **Evaluate photothermal stability experimentally**
  - Material chemical purity
  - Configuration (hollow vs solid)
- **Develop path to tritiation**
  - Tritium gas chemistry of polymer precursors
  - H-T isotope exchange (e.g. Wilzbach process)

Polystyrene, polyethylene, PMMA nanoparticles are commercially available



AI rendering of nanoparticle heating up in laser beam

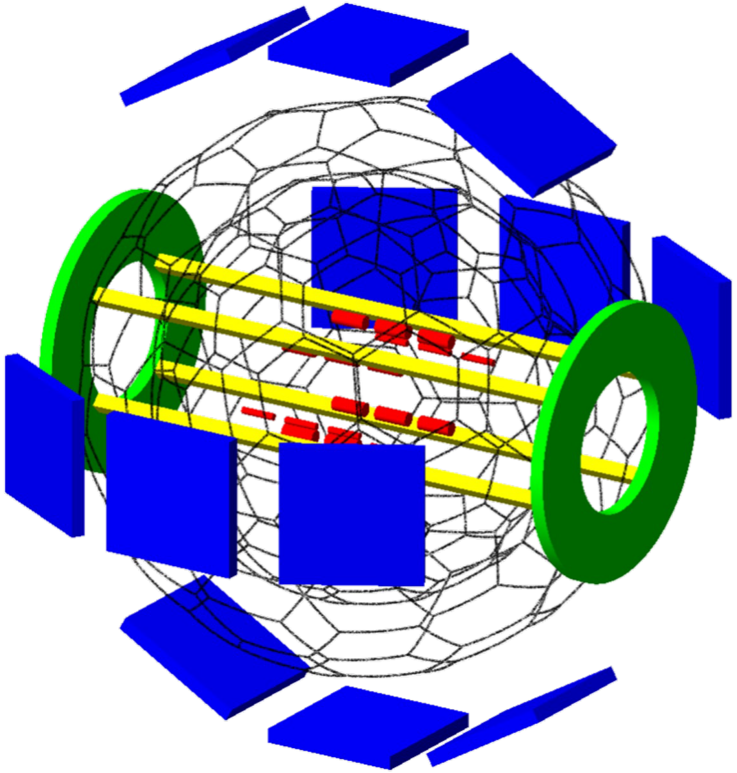
Schematic of apparatus of Wilzbach tritium exchange in polystyrene



J. Vac. Sci. Technol. A 10, 239 (1992)

Experiment Simulations

Detailed GEANT4 model and experiment simulation



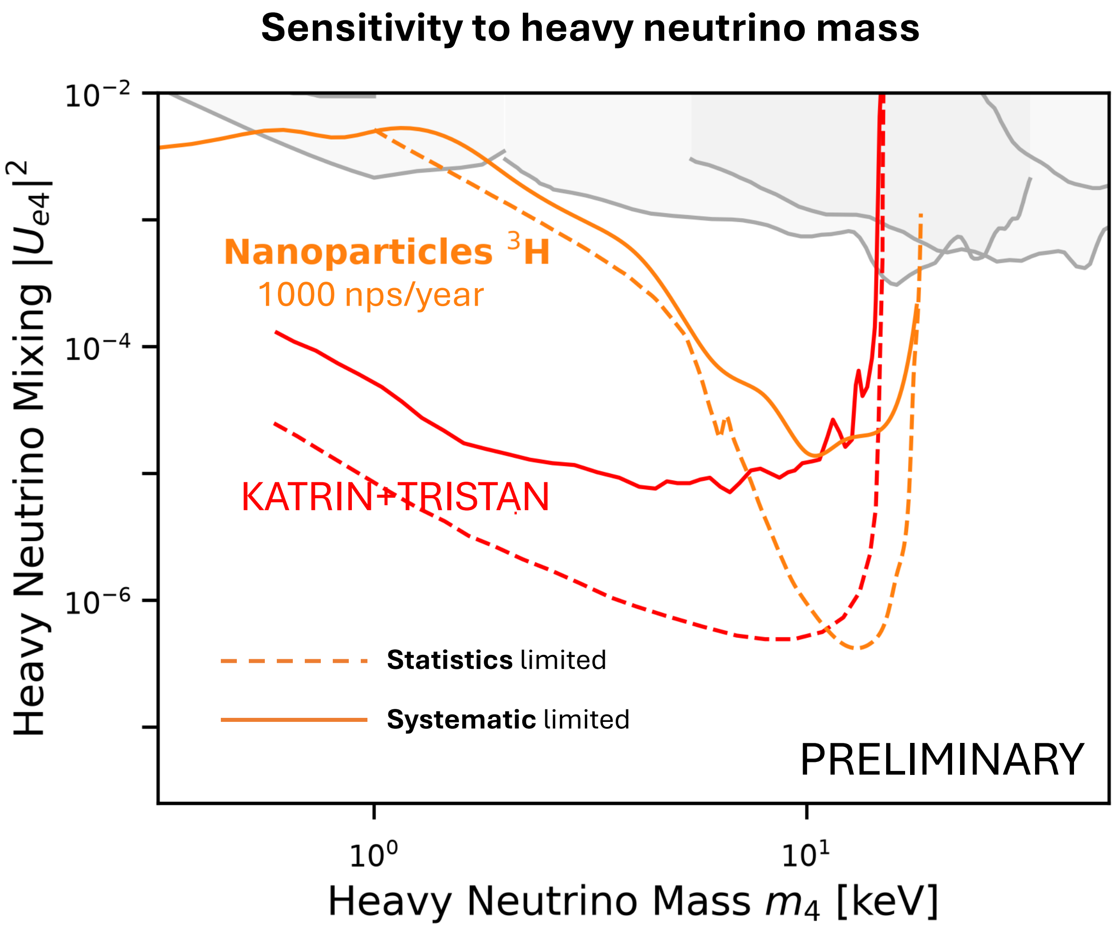
Physics Included
- Electron backscattering
- Electron downscattering
- Beta energy loss in nanosphere

In progress
- Beta momentum transfer to nanosphere
- Detector Pixelization

Assumptions
- 20% nanoparticle tritium loading
- Perfectly uniform electric field

Sensitivity Estimate

WORK IN PROGRESS



Tabletop experiment with sensitivity comparable to leading technology in the field

Conclusions

- A table-top experiment with tritiated levitated nanoparticles could explore relevant BSM physics with keV-scale heavy neutrinos
- Simulations ongoing to assess sensitivity
- Collaboration welcome!

Thanks to QUIPS team at LBL and Yale!