

Quantum sensing for beta decay

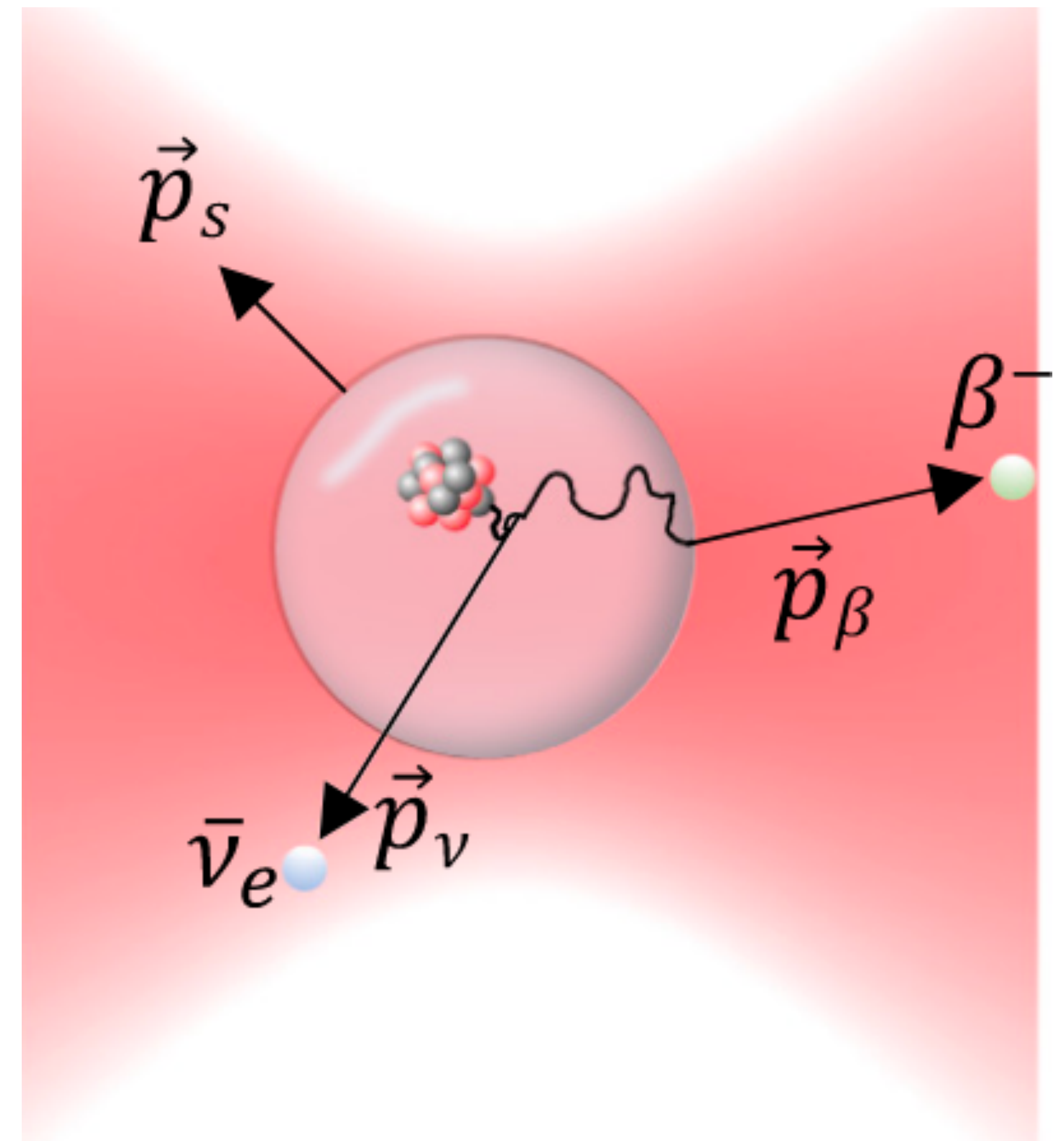
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0. Radioactive optomechanics

- Nanospheres are versatile platforms for new physics searches
- Can implant variety of radioisotopes, opening up decays for which nuclear recoil is measurable



Quantum invisible particle sensor (QuIPS)



Team at Berkeley Lab
— along with D. Moore's
group at Yale!

Use cases

- Sterile neutrinos — is neutrino emitted in beta decay $\sim$ massless?
- Precision electroweak physics — measure differential distribution
- Quantum testbed — push beyond standard quantum limits
- Measure branching ratios of superallowed or mirror decays?
- Axion searches in excited state decays?
- ...

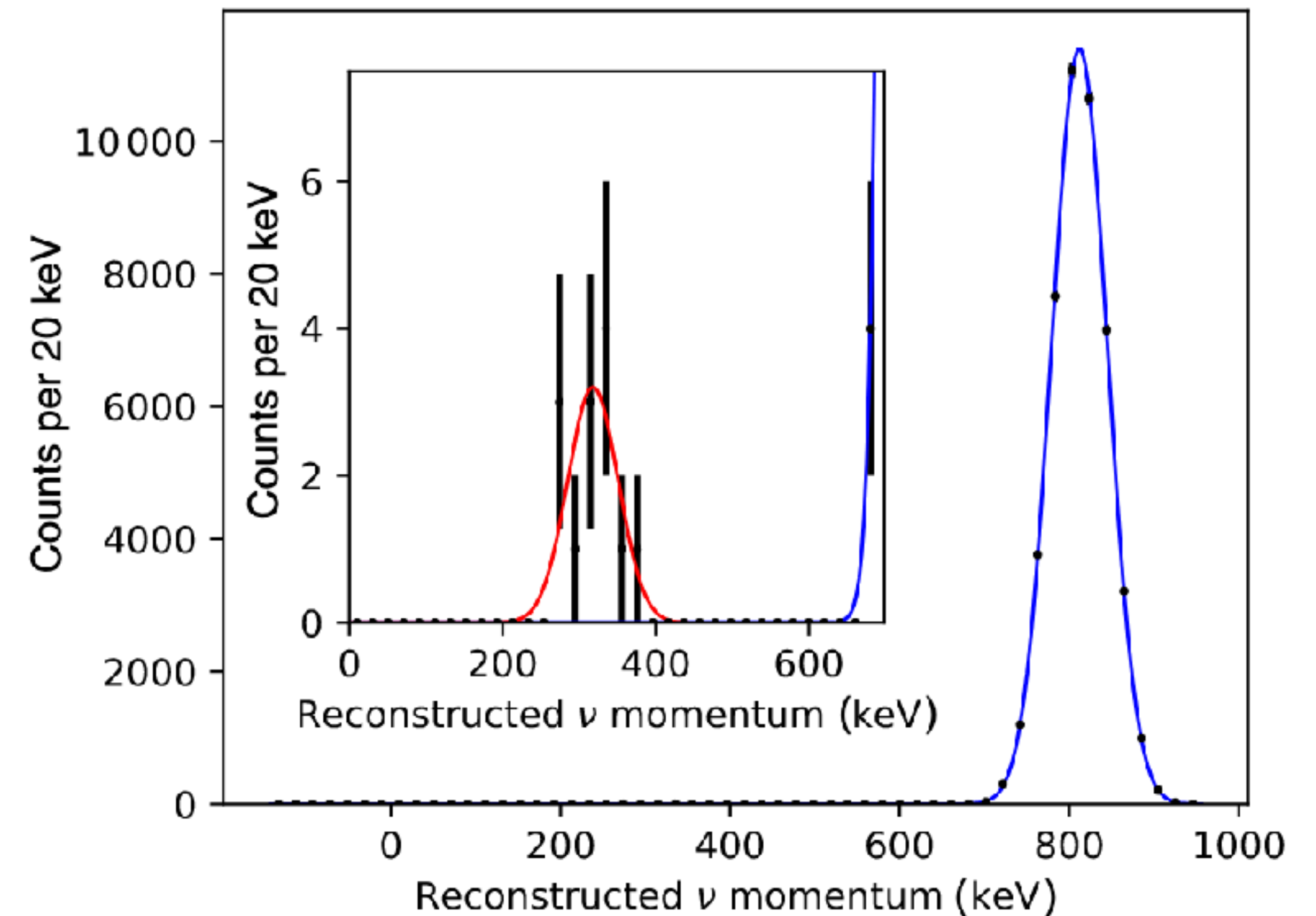
1. Sterile neutrino searches

- Is there a fourth component of the electron neutrino with a small mixing angle?

$$\nu_e = \sum_{i=1}^4 U_{ei} \nu_i, \quad |U_{e4}|^2 \ll 1$$

- In EC decays, can search for “missing momentum”
- Sphere momentum measurable at “standard quantum limit”

$$\Delta p_{\text{SQL}} = \sqrt{m\omega_m} \approx 10 \text{ keV}$$



[Carney, Leach, Moore PRX 4, 010315 (2023)]

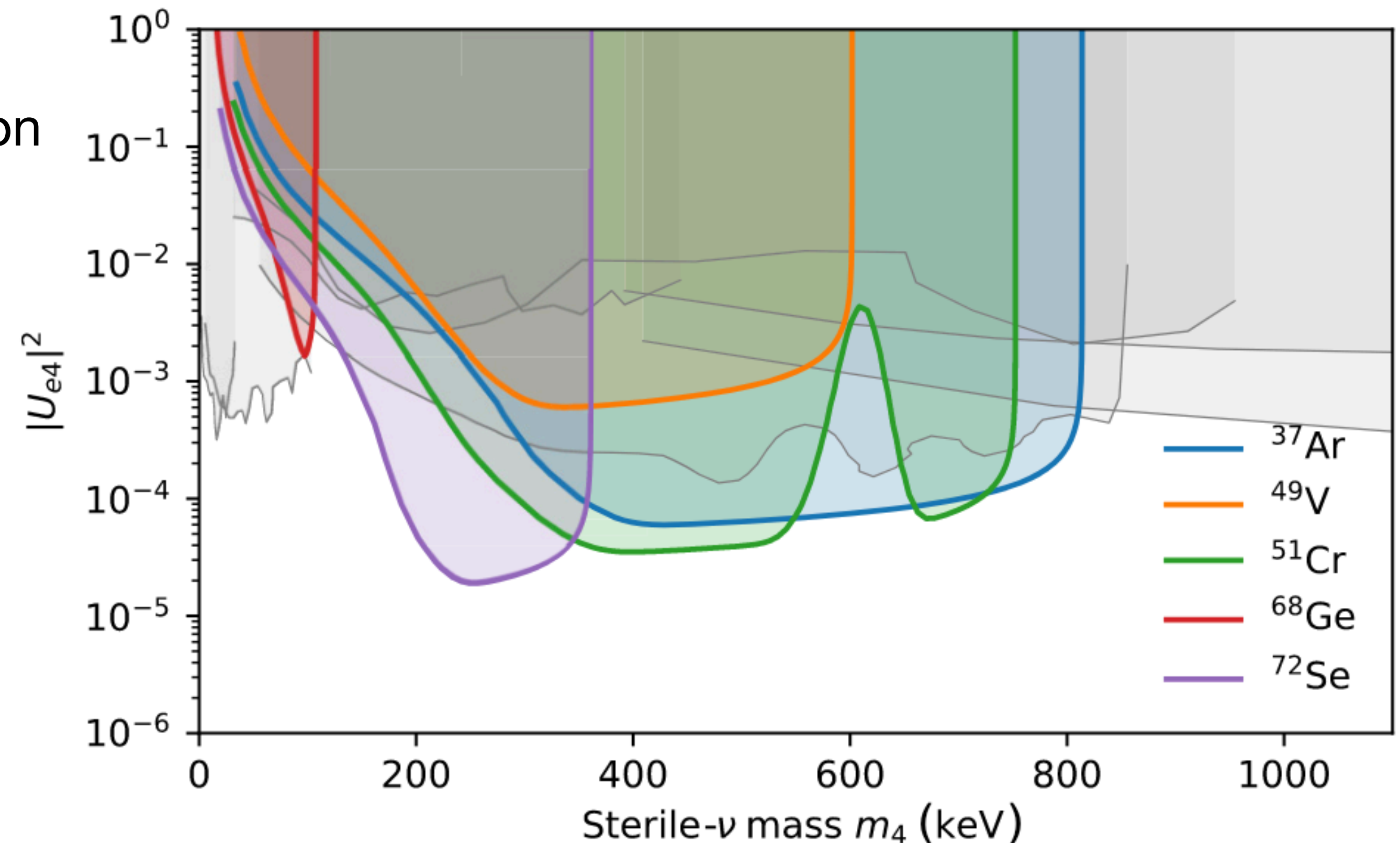
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Measuring betas!

Bird's Eye View (*not to scale*)

Vacuum breakout
i.e CF flange

CMOS and board

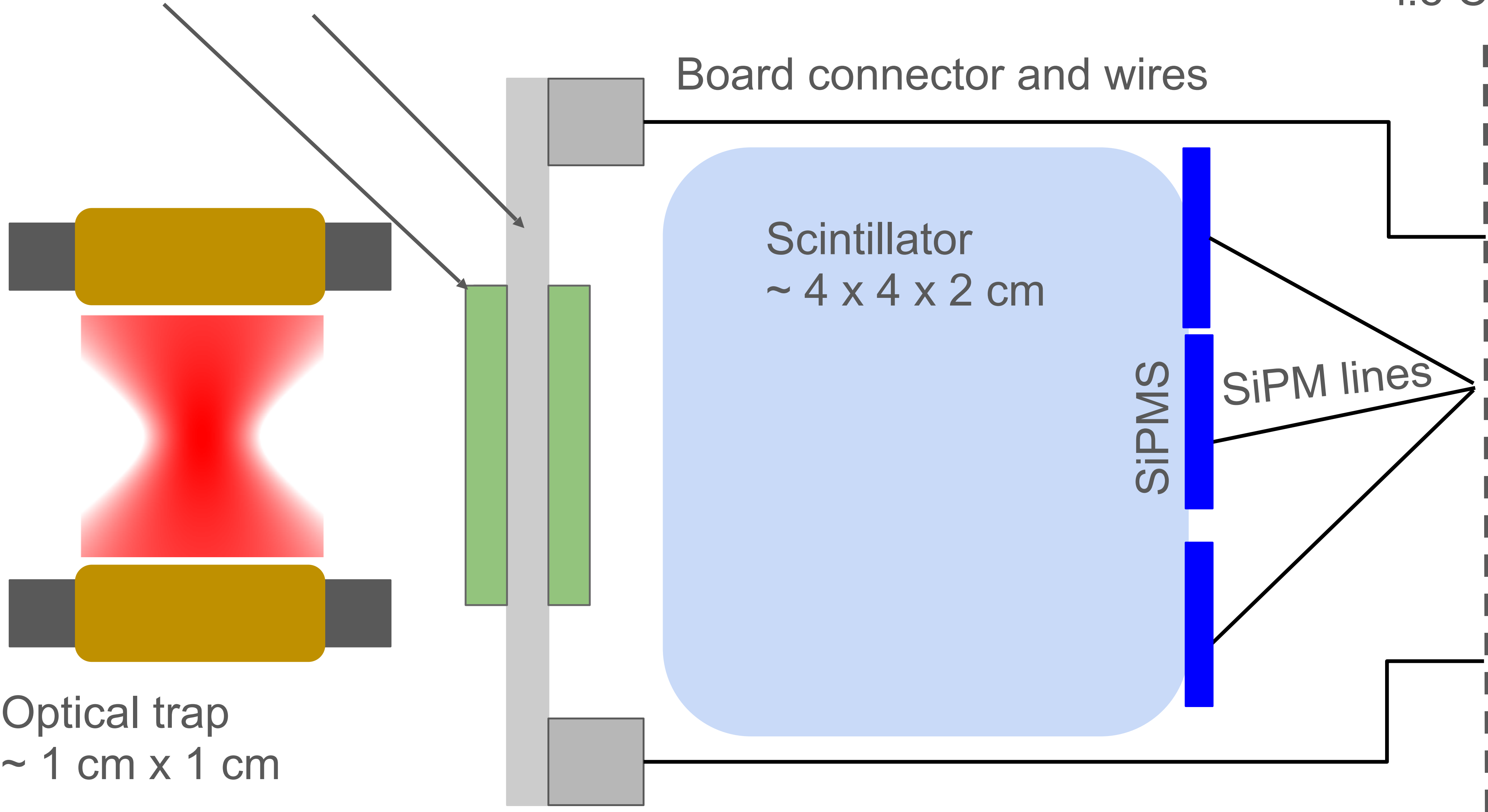
Board connector and wires

Scintillator
~ 4 x 4 x 2 cm

SiPMs

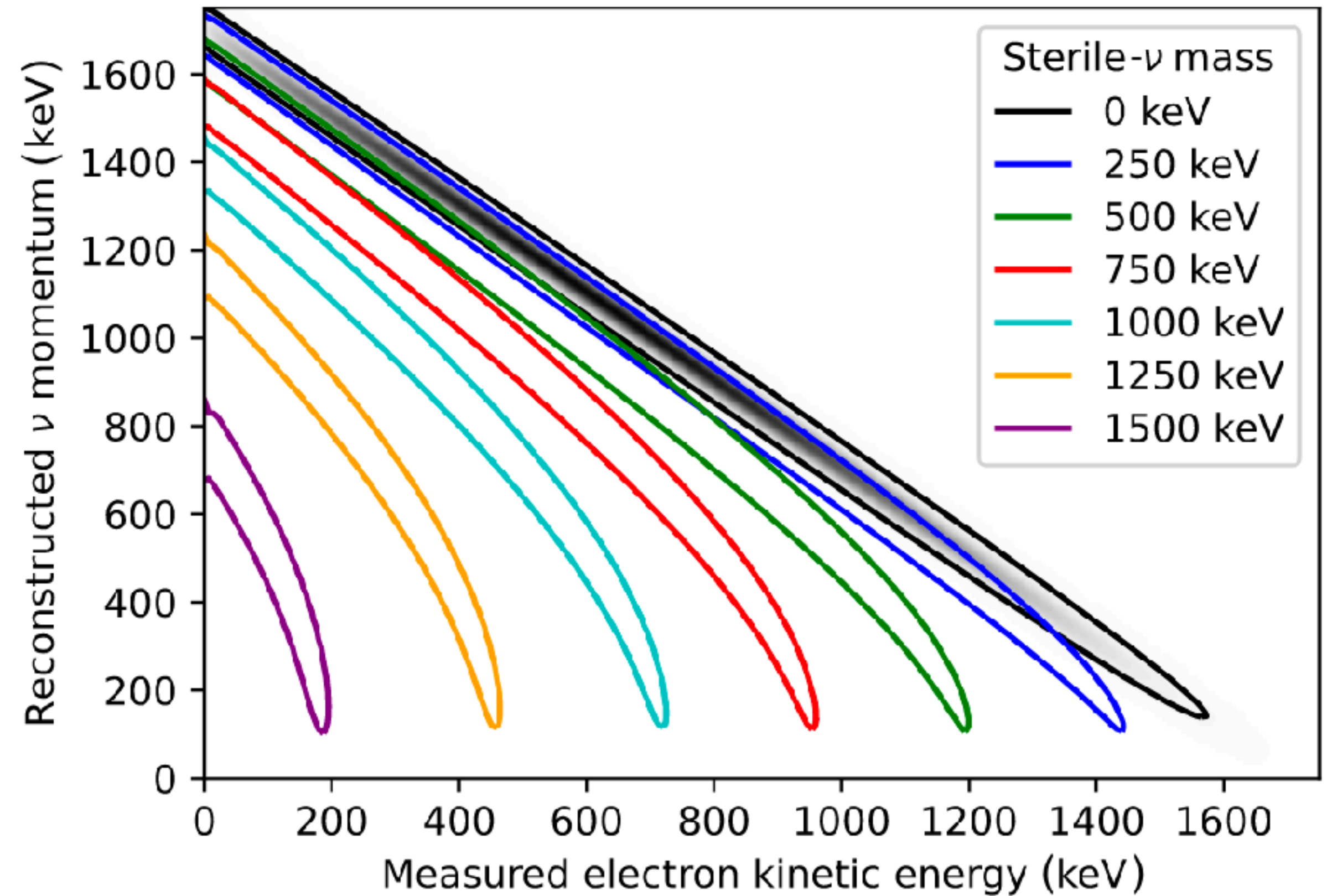
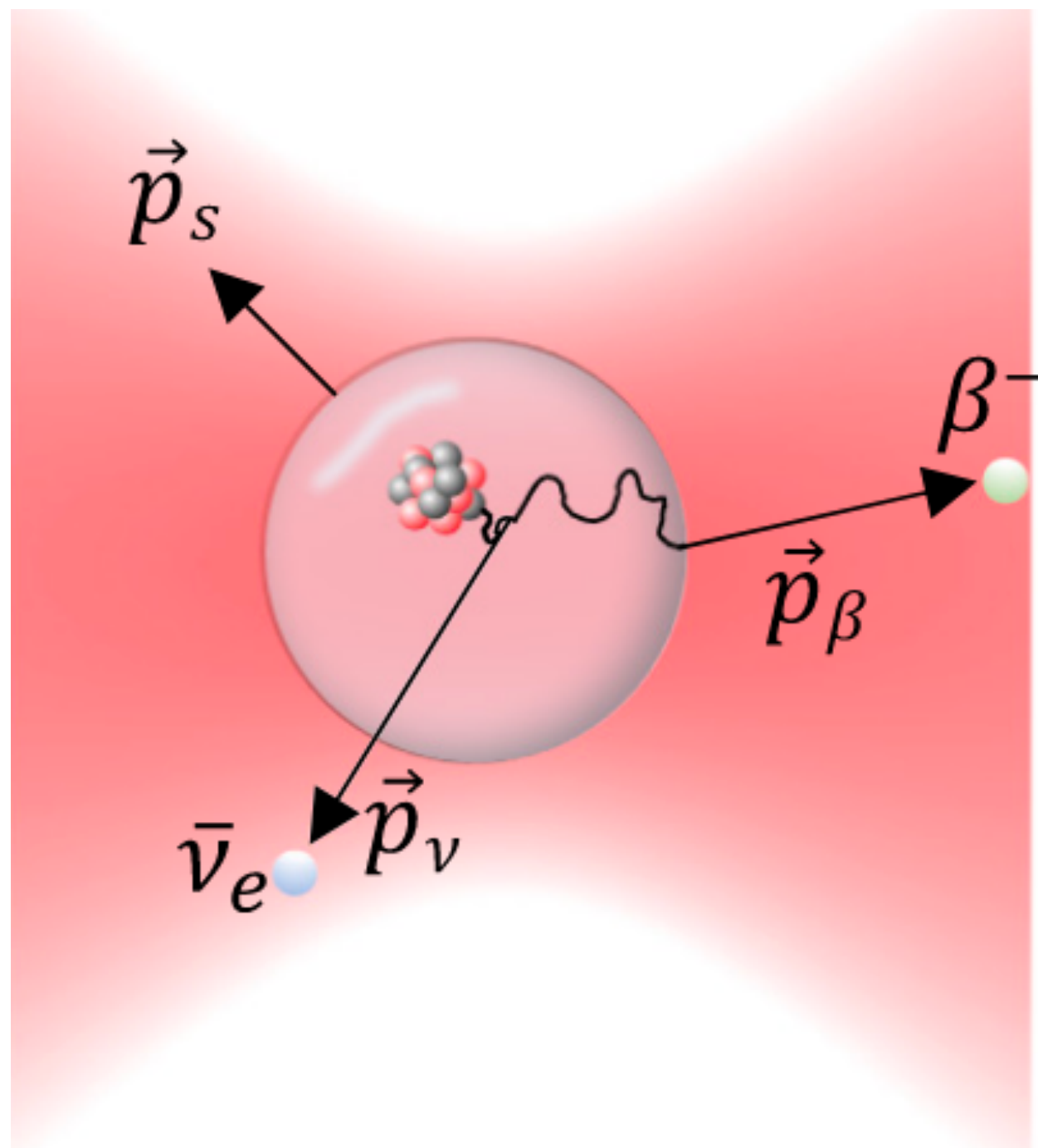
SiPM lines

Optical trap
~ 1 cm x 1 cm



Sterile neutrinos

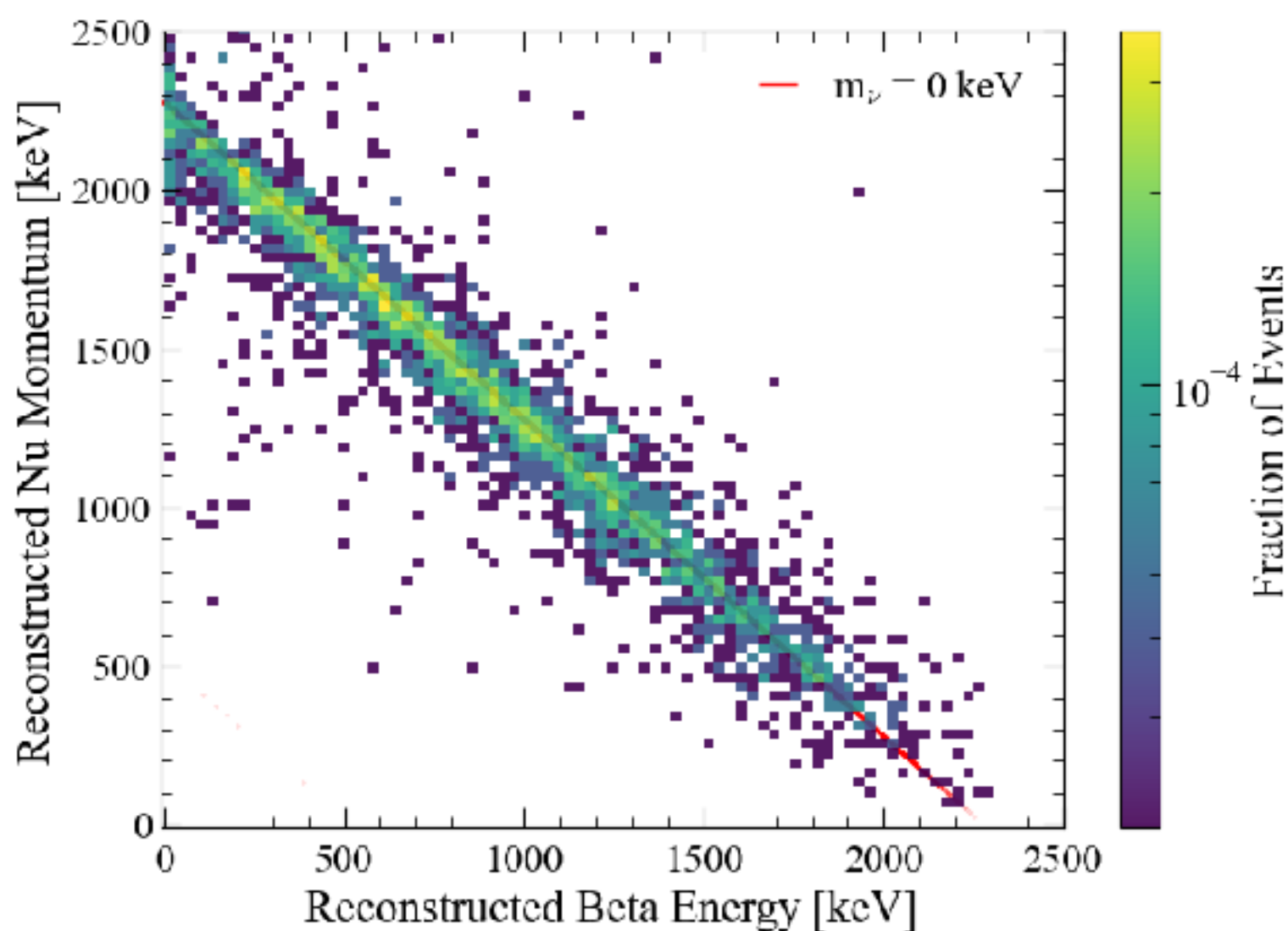
- Dimension of phase space is larger in beta emitters — more experimental handles!



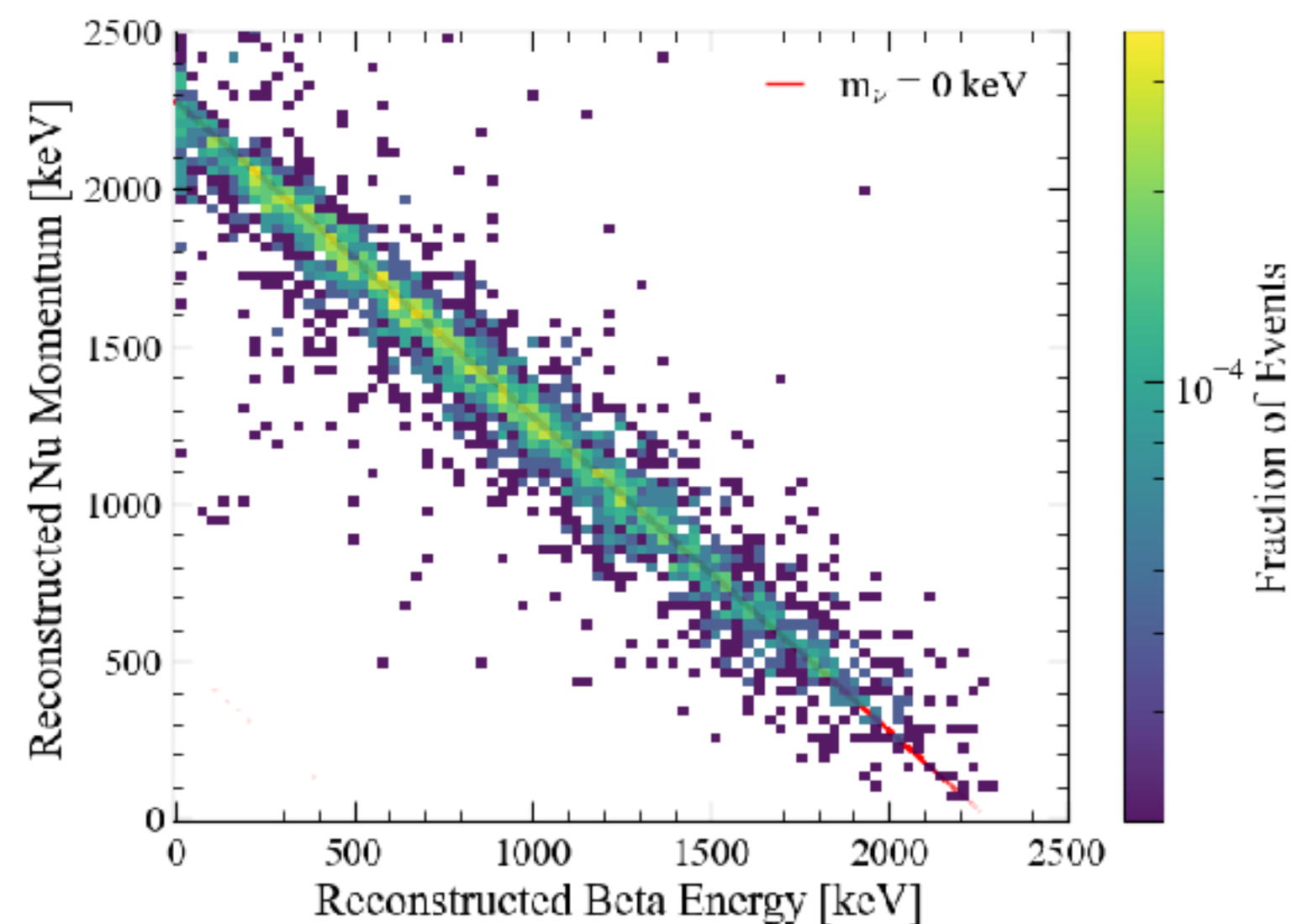
$$E_\nu \approx Q - E_\beta$$

Reconstruction Variables (I)

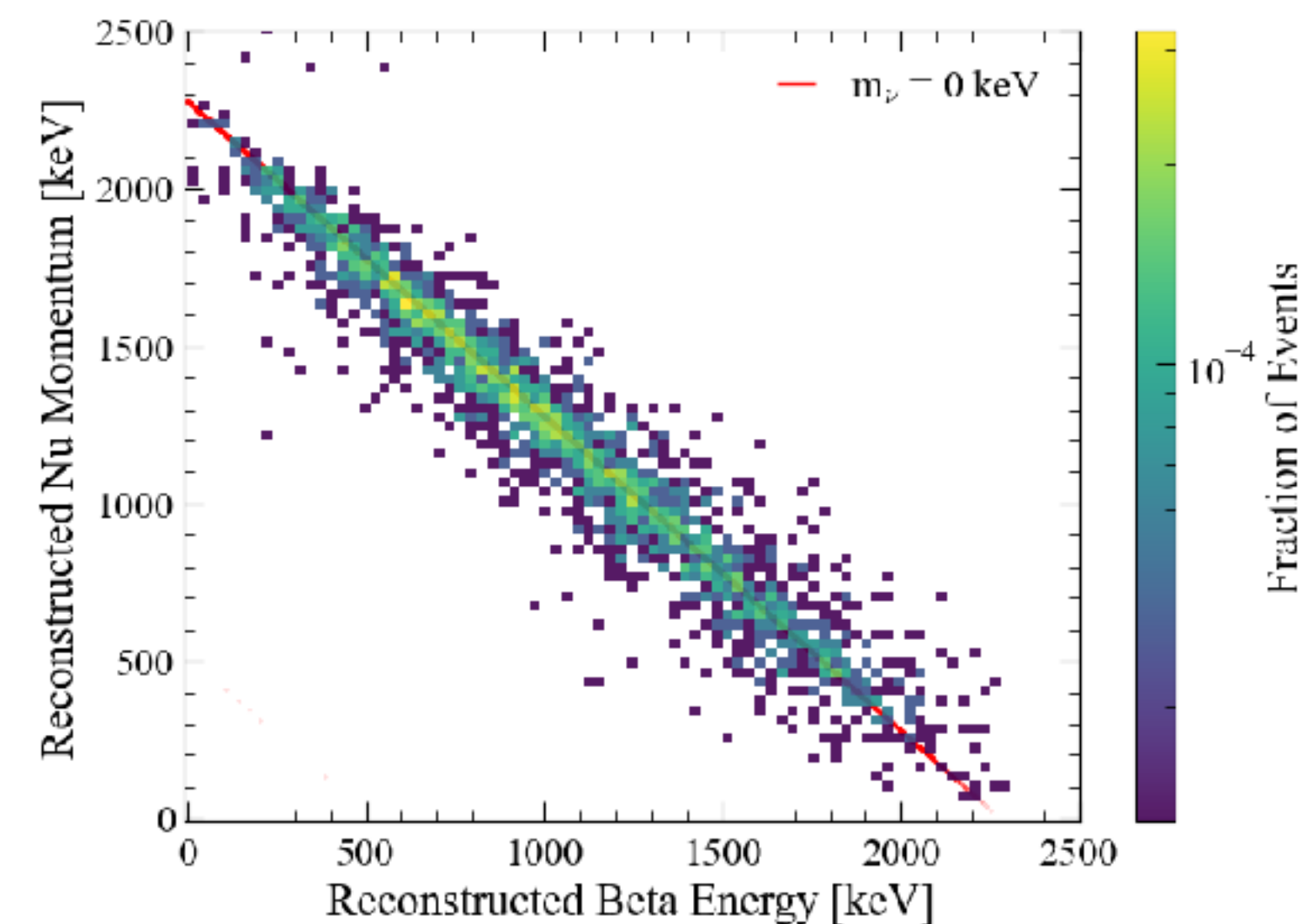
No cuts
Acceptance: 6.7%
Leakage: 3.3%



Backscatter cut
Acceptance: 6.5%
Leakage: 3.0%

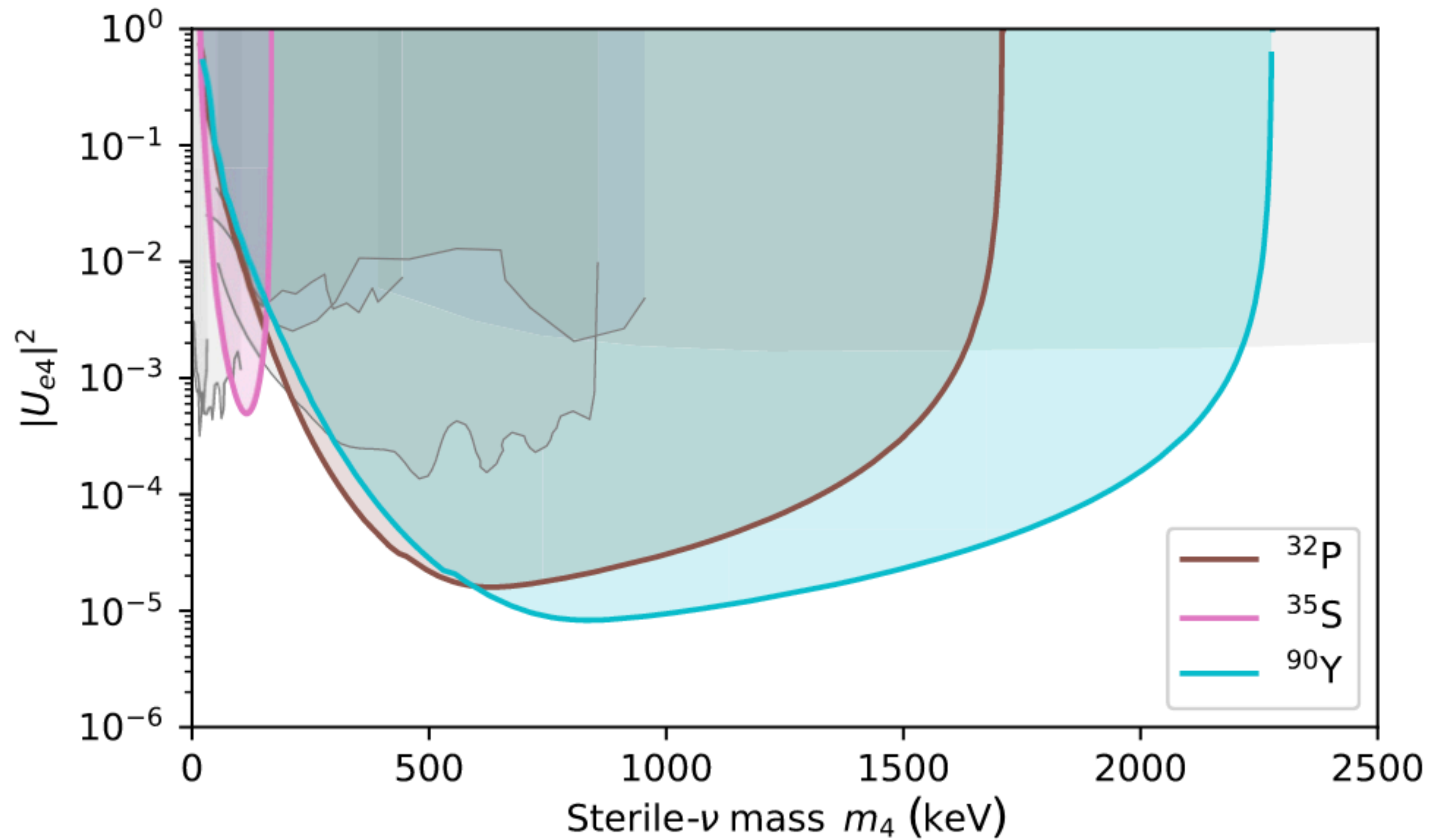


Backscatter + 1 mm Vertex cut
Acceptance: 4.9%
Leakage: 1.7%



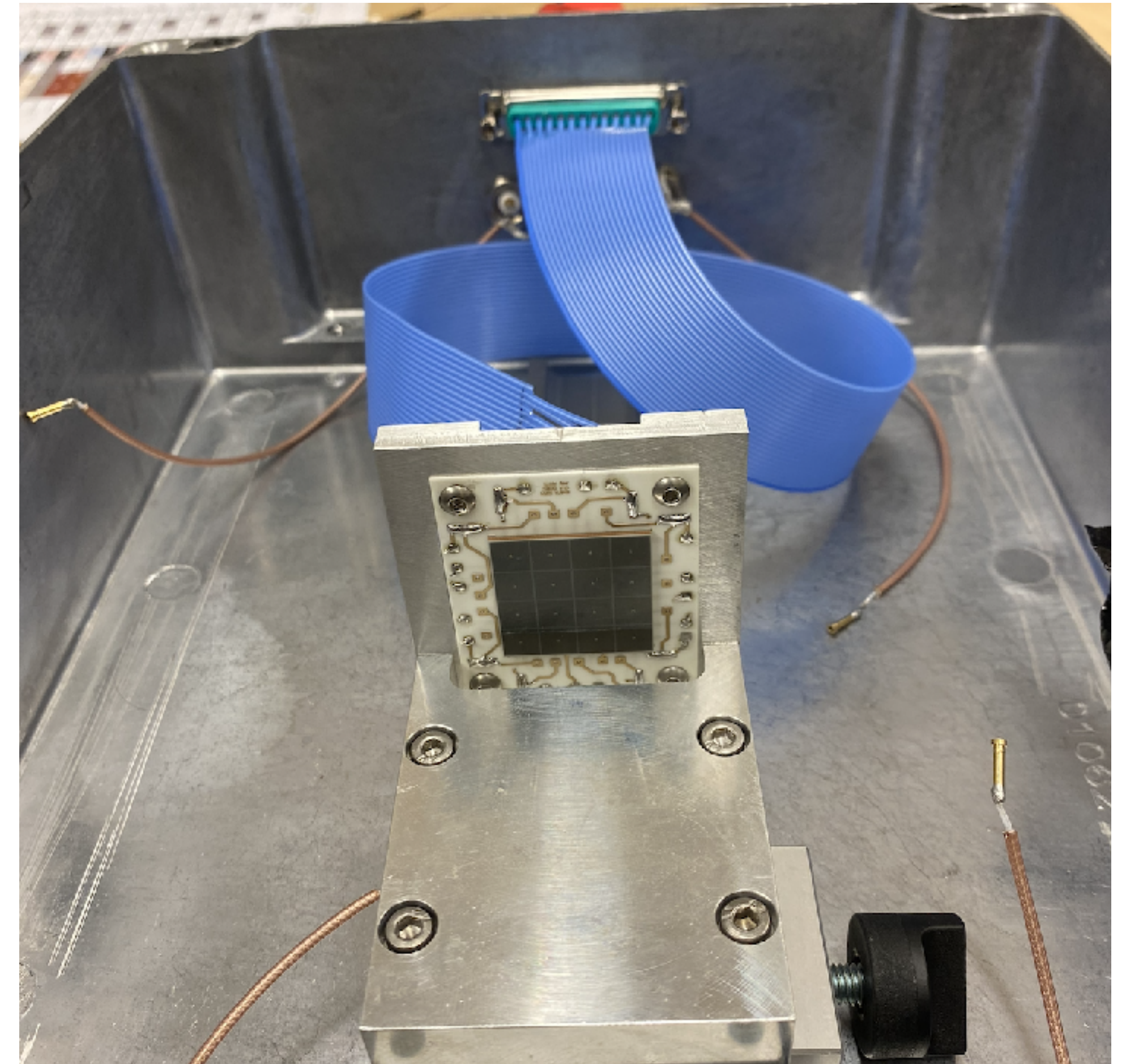
Leakage defined as events in which events differ by > 300 keV from the true nu - beta line

Projections for beta decay



Near-term

- Experiment is being built!
- Ongoing calibration and simulations, to be shipped to Yale soon, with results expected next year.



Future plans

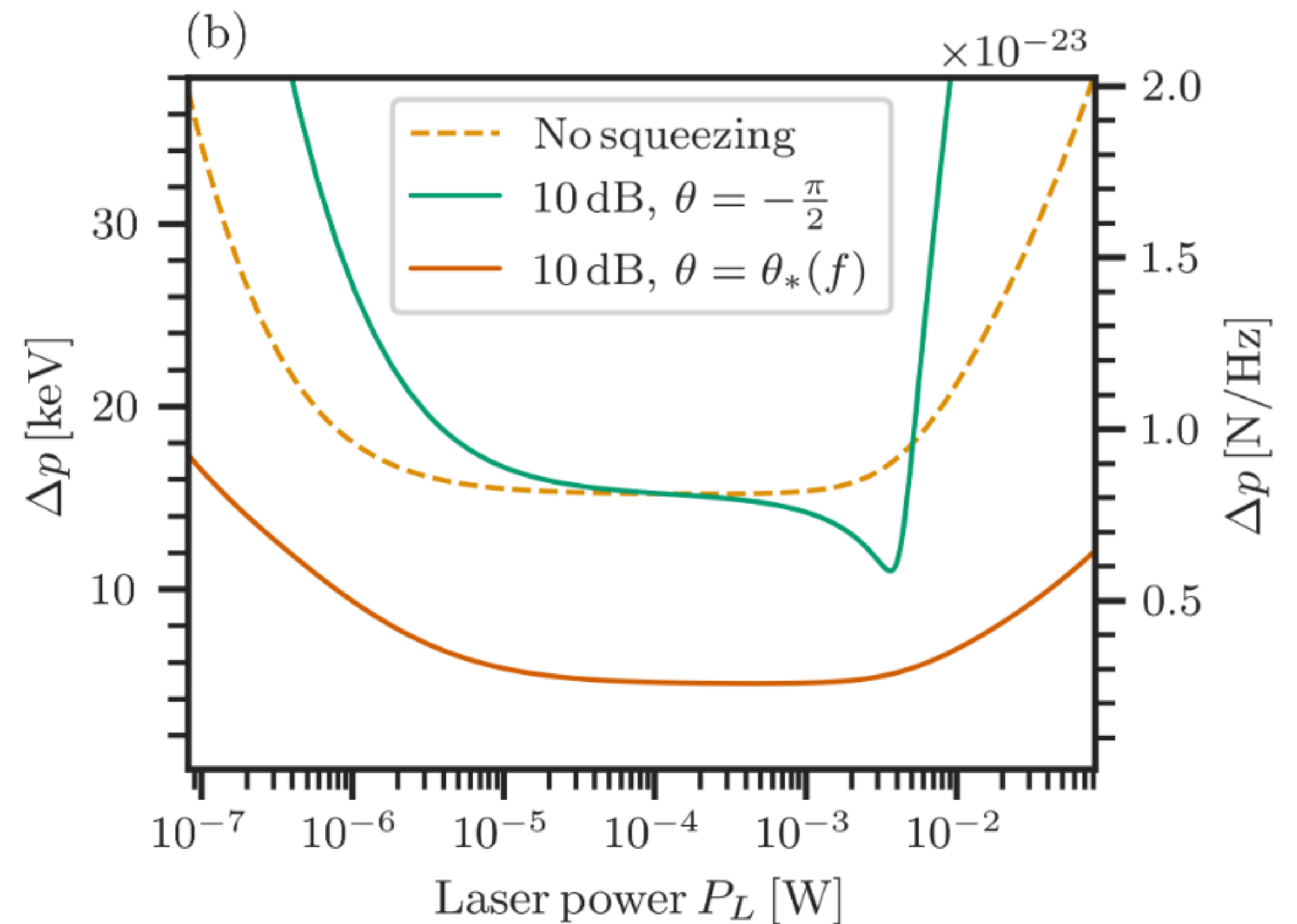
- Going forward, the experiment is systematically improvable
 - Improve statistics $\Leftrightarrow$ arrays
 - Improve mass reconstruction $\Leftrightarrow$ better calorimetry + squeezing

2. Squeezing of light

- The use of squeezed light can improve the recoil sensitivity below the standard quantum limit
- Requires “frequency-dependent squeezing” HARD!
- Very sensitive to losses:

$$\Delta p(r, \eta) \approx \left[1 + (1 - \eta)e^{2r}\right]^{1/4} e^{-r} \Delta p_{\text{SQL}}$$

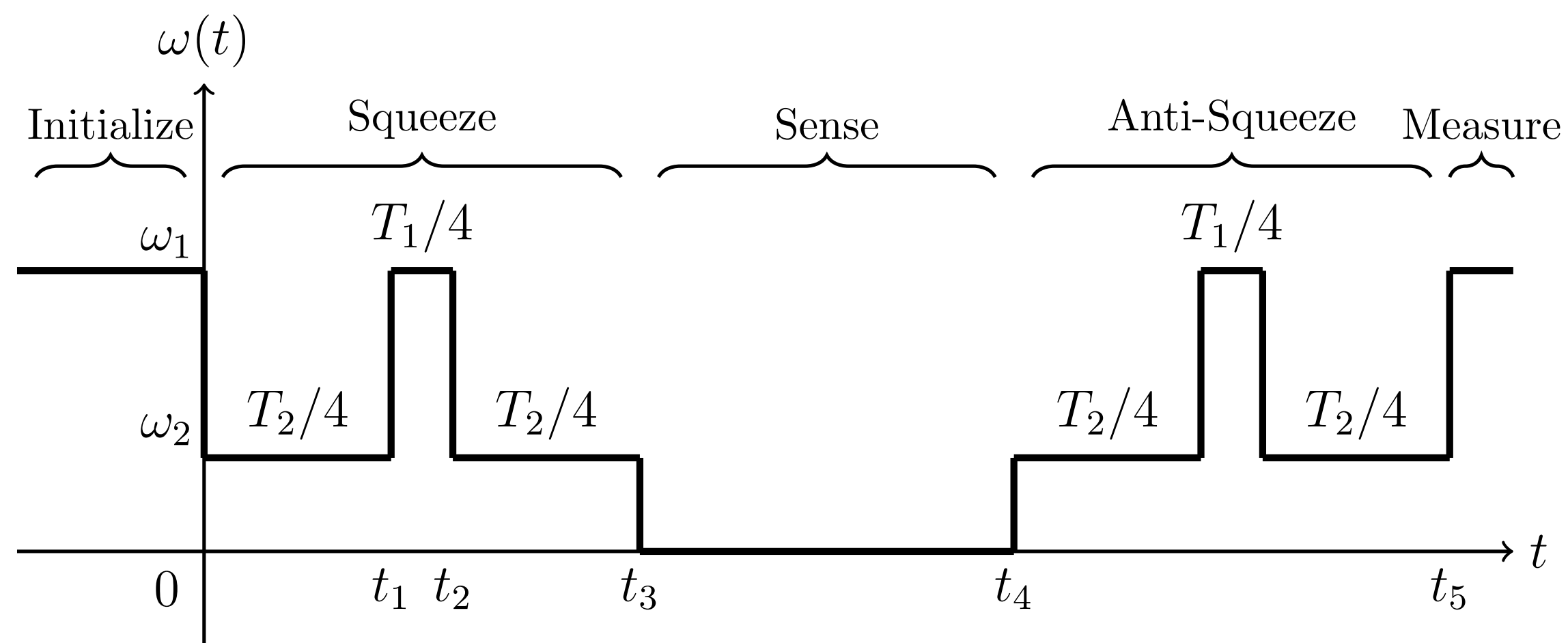
$$\rightarrow \eta^{-1/4} e^{-r/2} \Delta p_{\text{SQL}}$$
- Only along one axis :(



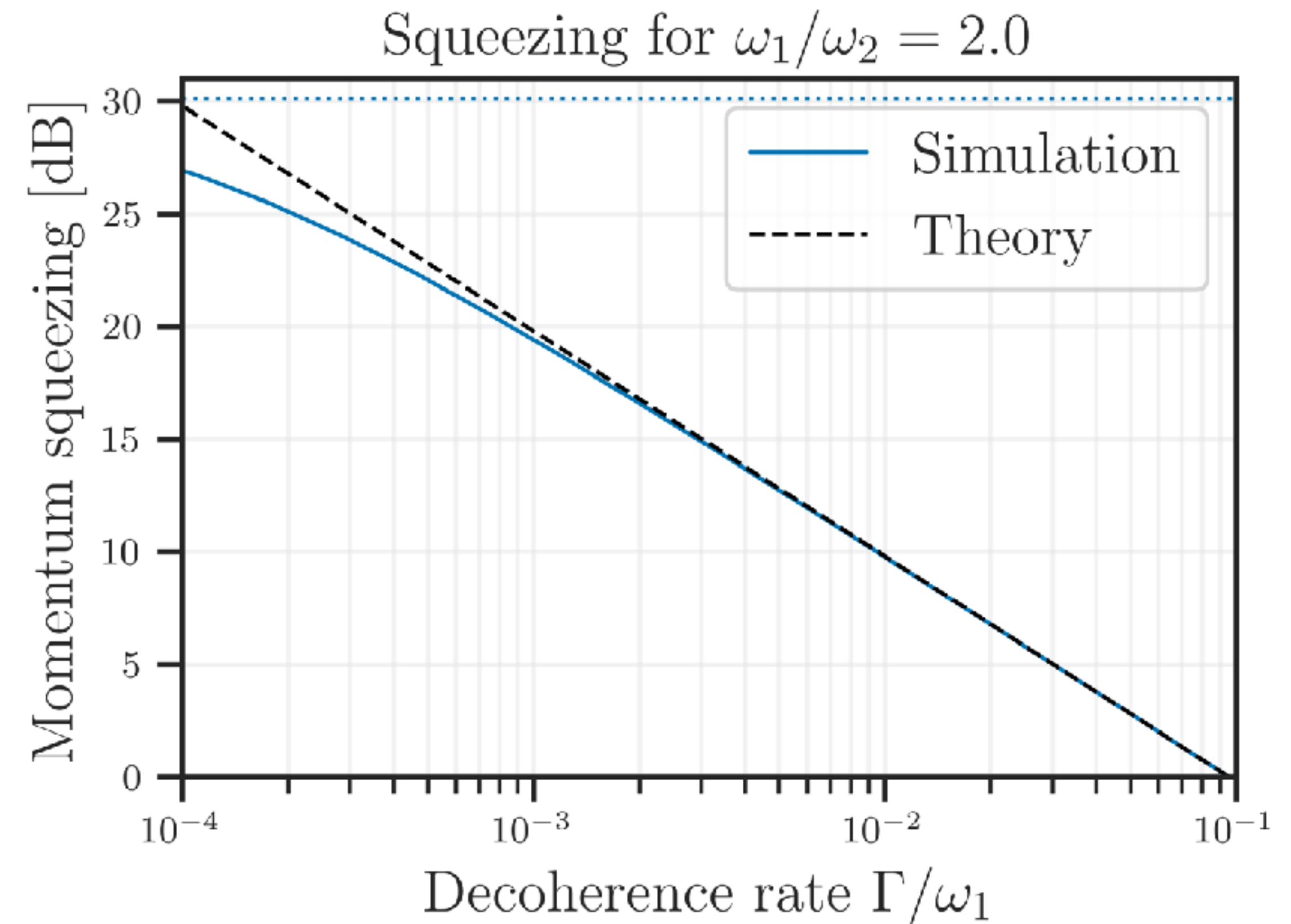
[T.C. Lee, J. Beckey, GM, D. Carney
Phys. Rev. Res. 7 (2025)]

Squeezing of mechanics

- Instead of squeezing the readout light, we can manipulate the center-of-mass state!



- Largely insensitive to measurement efficiency, dominated by decoherence!
- Along all three axes :)



[Preliminary — work in progress!]

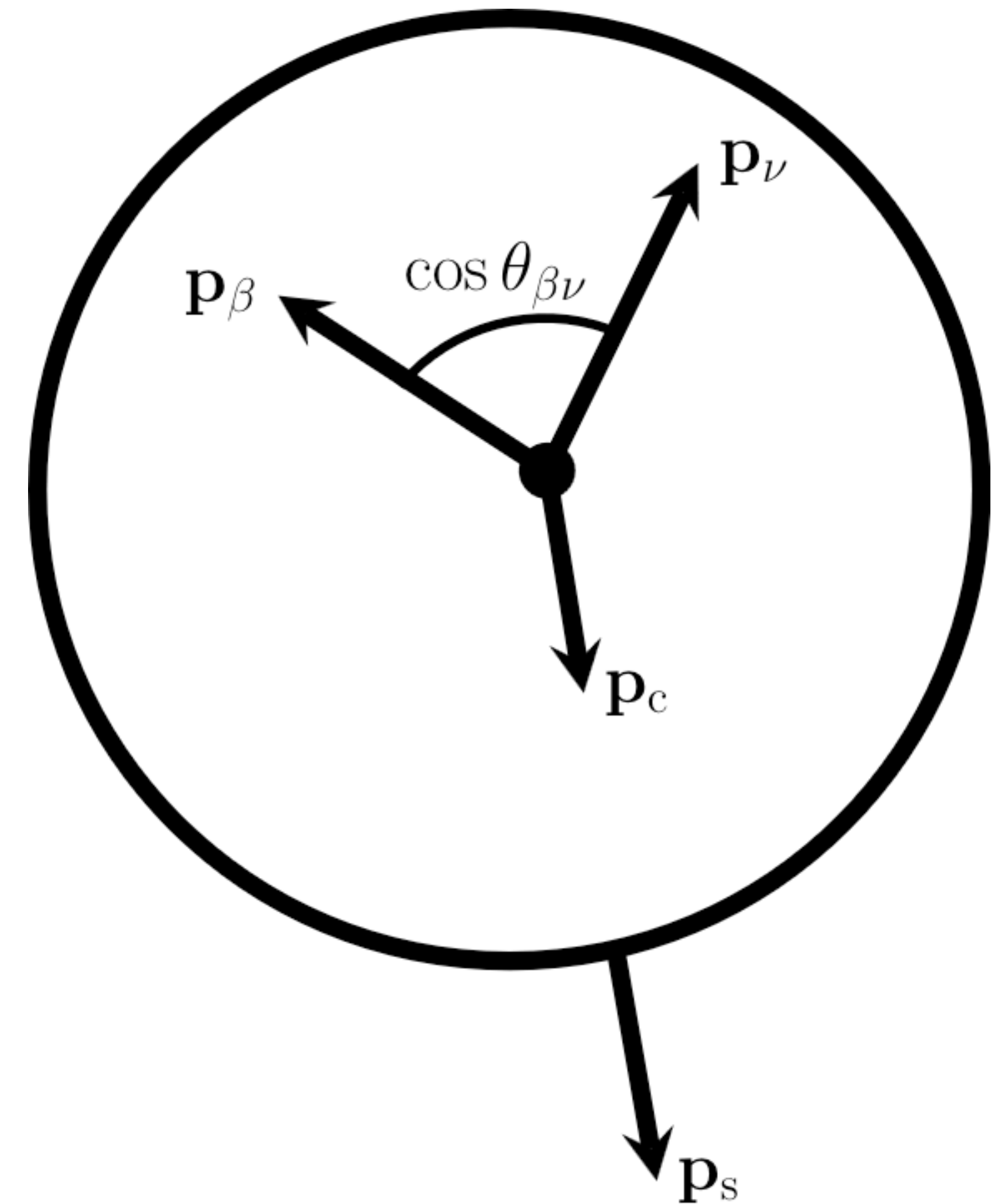
3. Beta decay spectrum

For unpolarised nuclei,

$$\frac{d^2\Gamma}{dE_\beta d\cos\theta_{\beta\nu}} \approx F_0(Z, E_\beta, Q)\xi \left[1 + a_{\beta\nu} \frac{\mathbf{p}_\beta \cdot \mathbf{p}_\nu}{E_\beta E_\nu} + b \frac{m_e}{E_e} \right]$$

In SM, for a Gamow-Teller decay

$$a_{\beta\nu} \approx -\frac{1}{3}, \quad b \approx 0.$$



New physics

Beta decay is mediated by W-bosons, giving V-A structure:

Can there be “tensor currents”?

$$\Delta\mathcal{L}_\beta = C_T \bar{p} \sigma^{\mu\nu} n \bar{e} \sigma_{\mu\nu} (1 - \gamma^5) \nu + \text{h.c.}$$

Induces **linear** “Fierz interference term”:

$$b = \text{Re} \frac{C_T + C'_T}{C_A}$$

$$a_{\beta\nu} = -\frac{1}{3} \left(1 - \left| \frac{C_T}{C_A} \right|^2 \right)$$

Signature

Simple observable: correlation of $\beta - \nu$ angle

$$\frac{d^2\Gamma}{dE_\beta d\cos\theta_{\beta\nu}} = A(E_\beta) \cos\theta_{\beta\nu} + B(E_\beta)$$
$$\mathcal{R}(E_\beta) := \frac{A(E_\beta)}{B(E_\beta)}$$
$$= - \frac{p_\beta}{3E_\beta(1 + bm_\beta/E_\beta)}$$

Many nuclear uncertainties cancel in ratio!

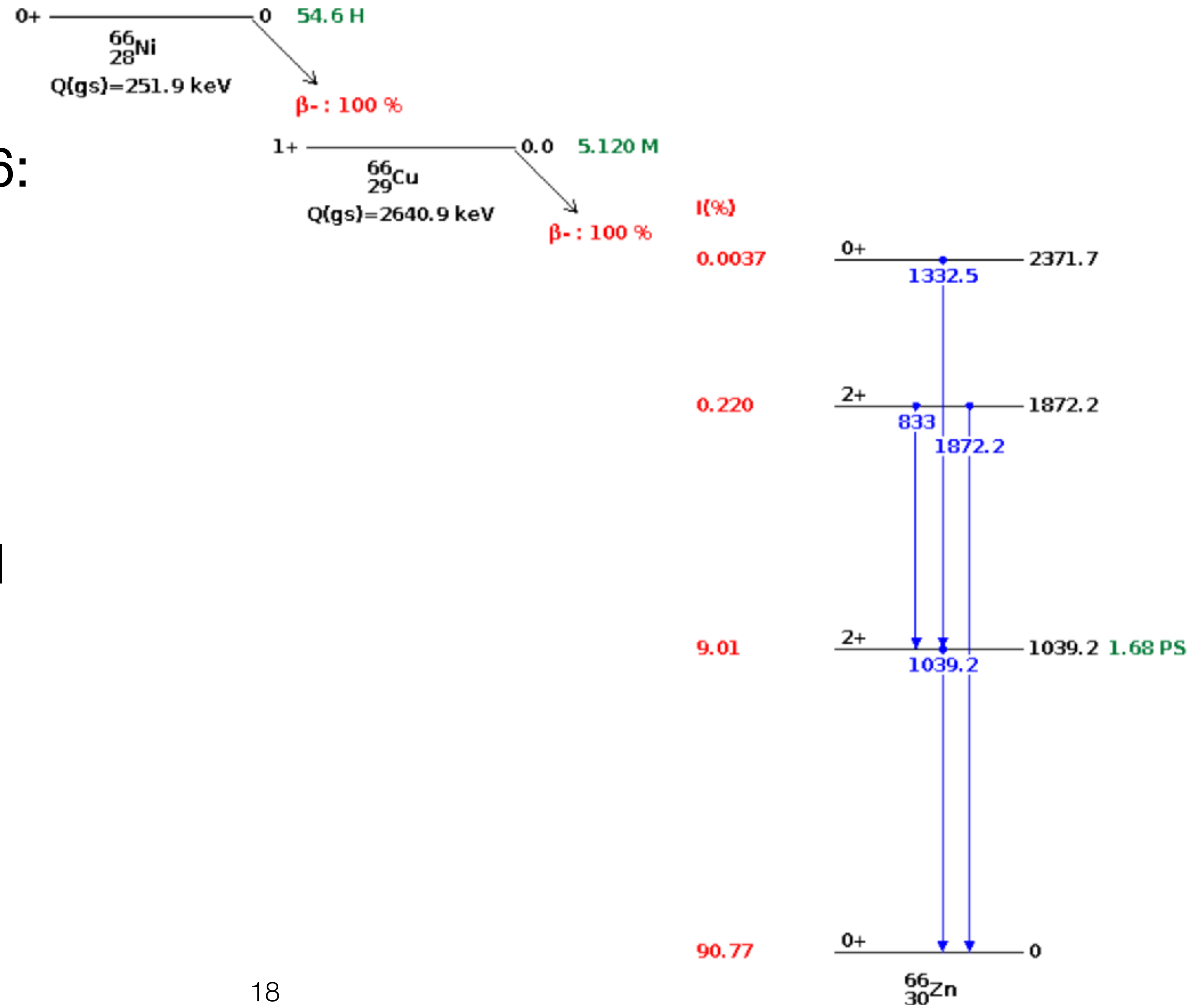
Bin in energy, fit to linear slope, and take ratio.

More direct measurement of linear interference than “tilde prescription”

Which nuclei???

- We are considering Ni-66:

- 54.6 h half-life
- GS to GS transition
- $Q = 251.9$ keV (small nuclear corrections)
- Pure Gamow-Teller transition



- Work in progress — ignoring scattering of beta, for now!

Beta energy resolution:

$$\sigma_E = \epsilon \sqrt{\sigma_{e^-}^2 + F \frac{E}{\epsilon}}$$

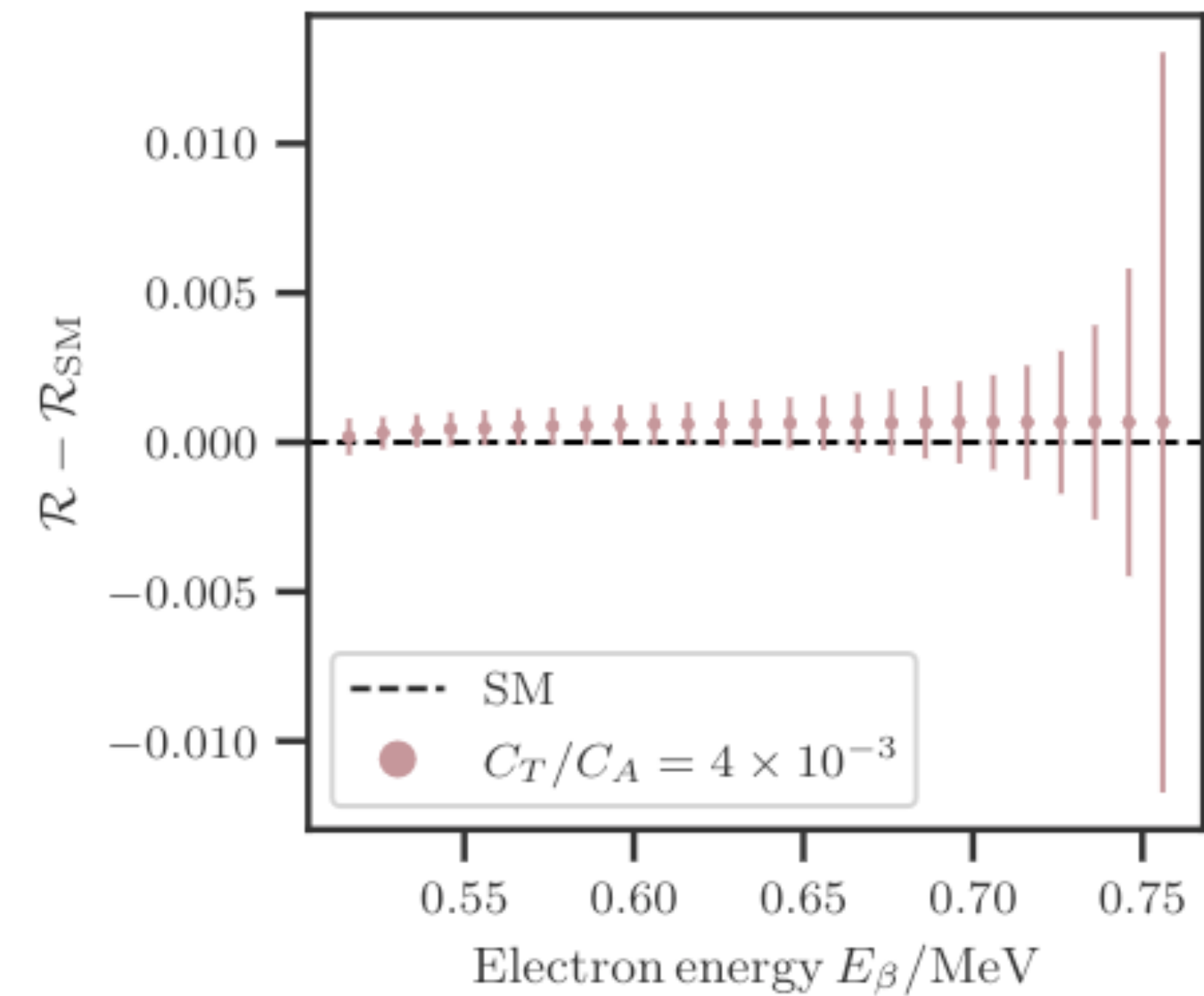
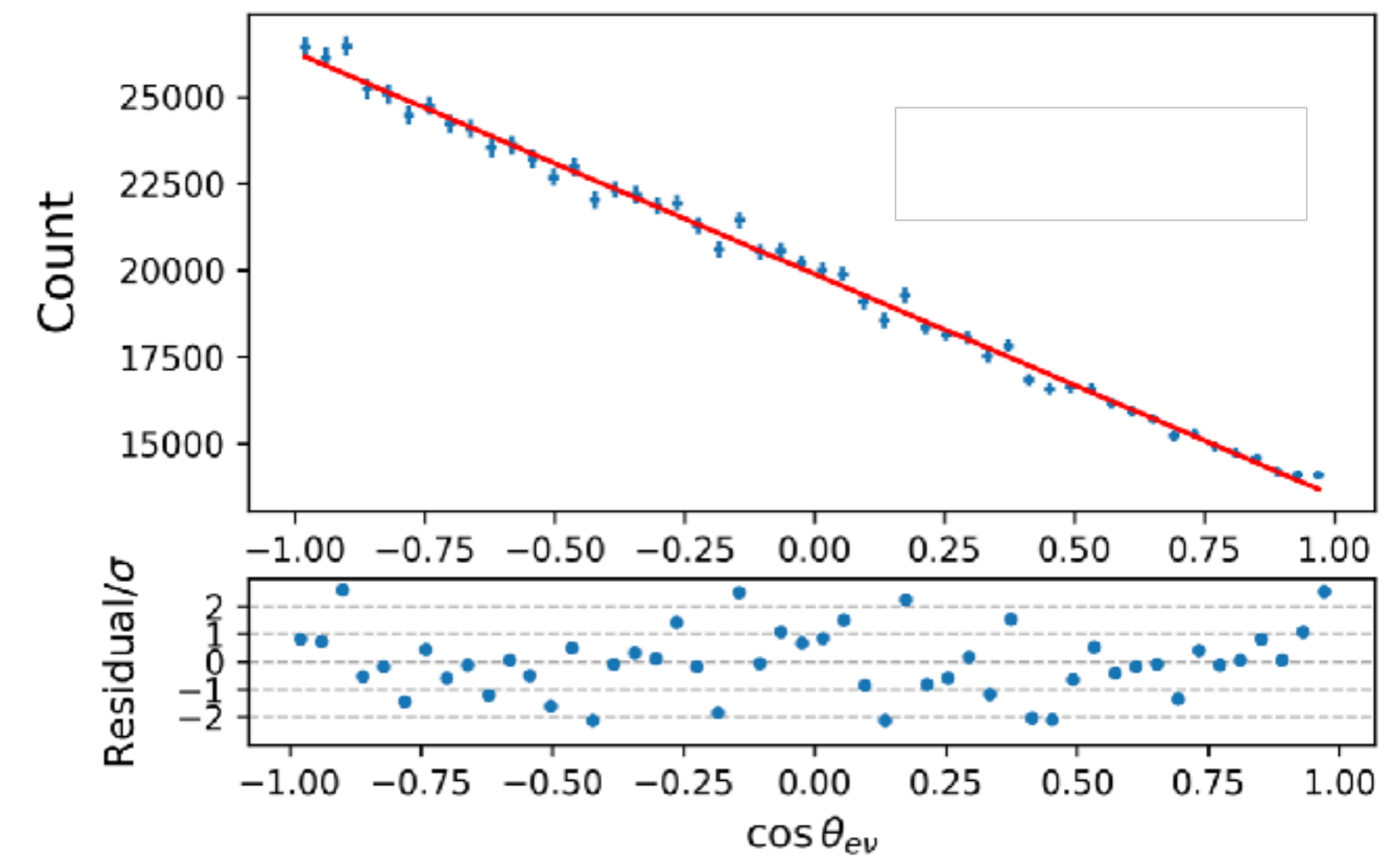
$$\epsilon = 3.65 \text{ eV/e}^-$$

$$\sigma_{e^-} = 30$$

$$F = 0.115$$

50 μm pitch at 5 cm

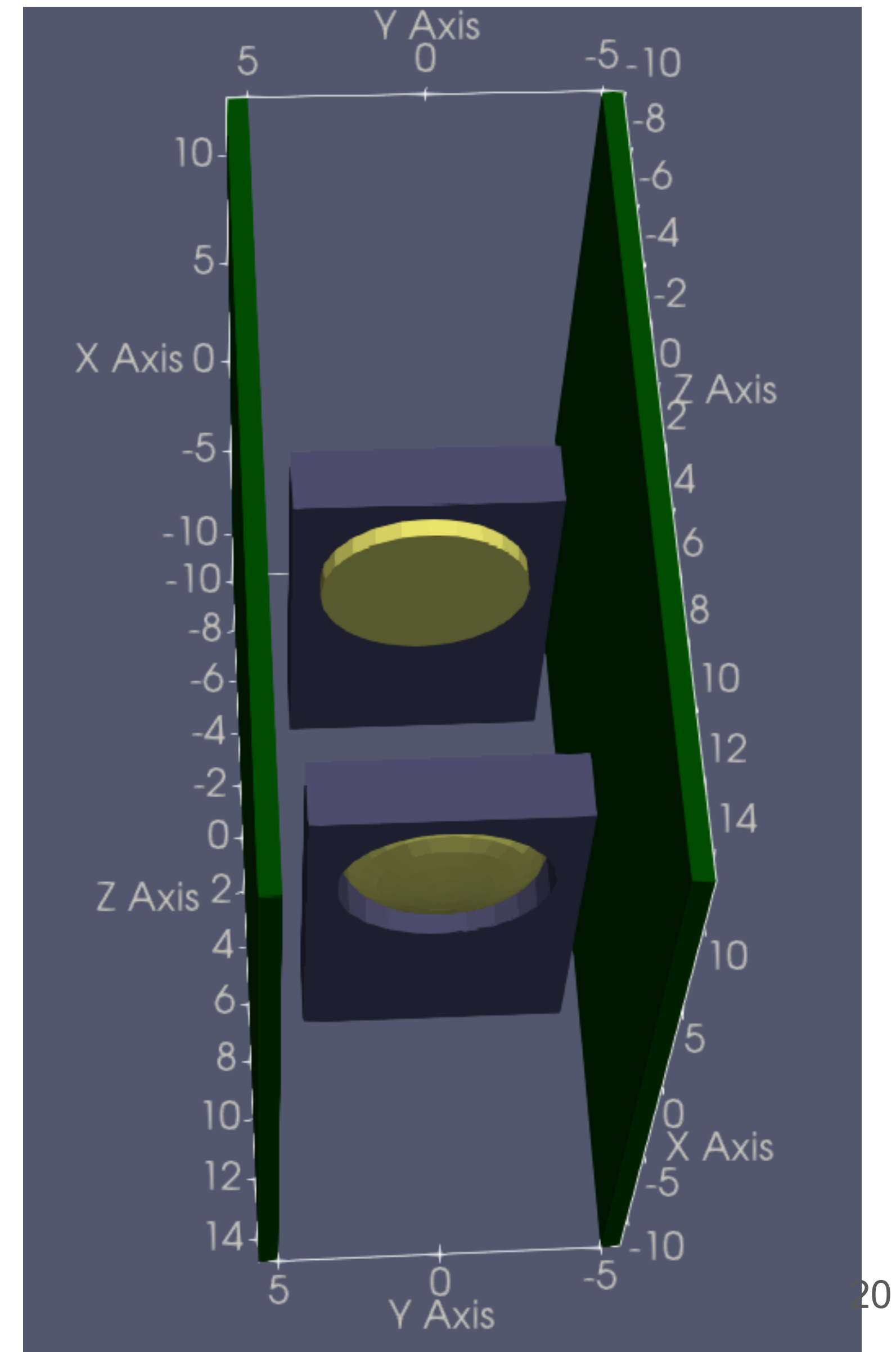
15 keV sphere momentum resolution



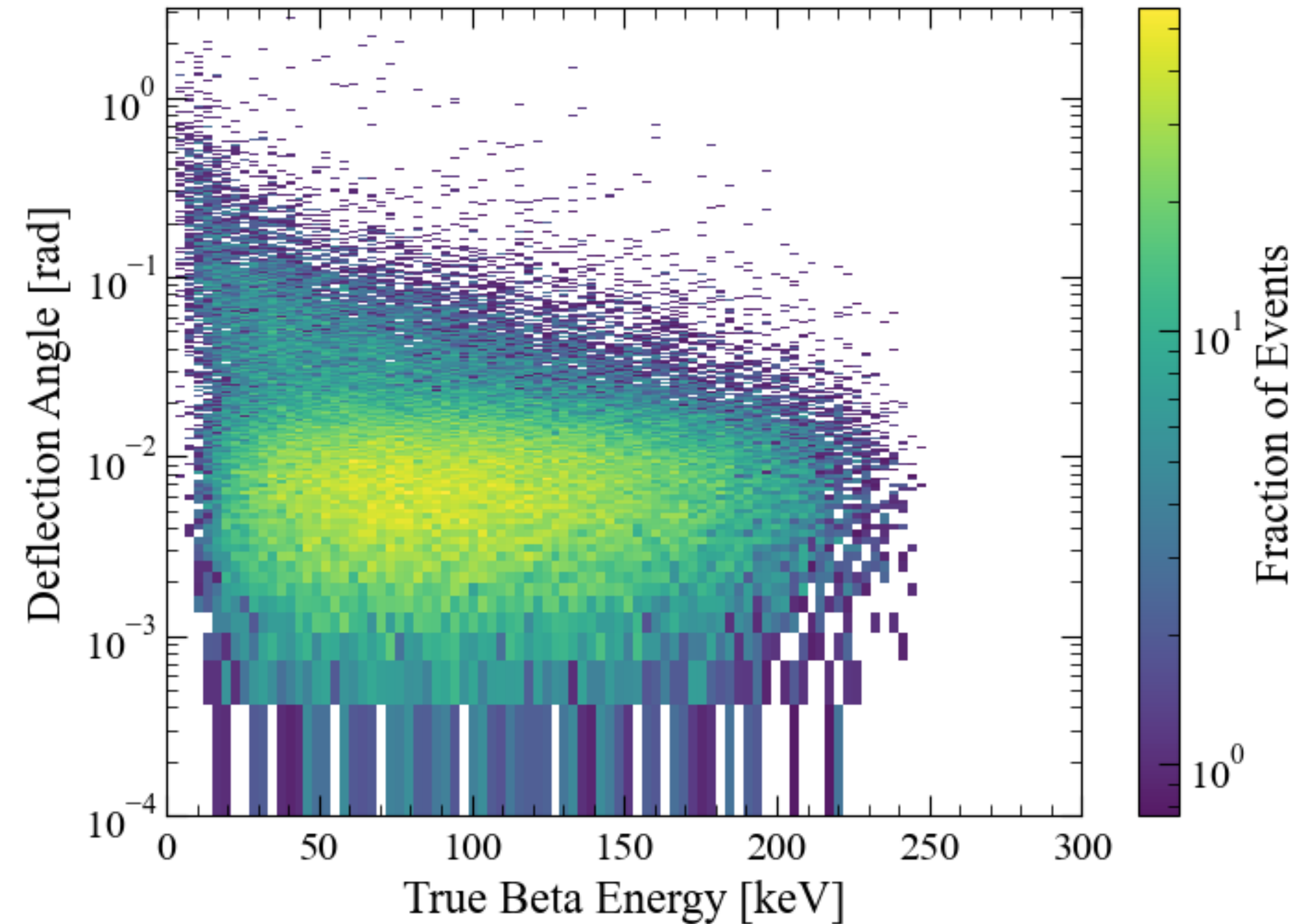
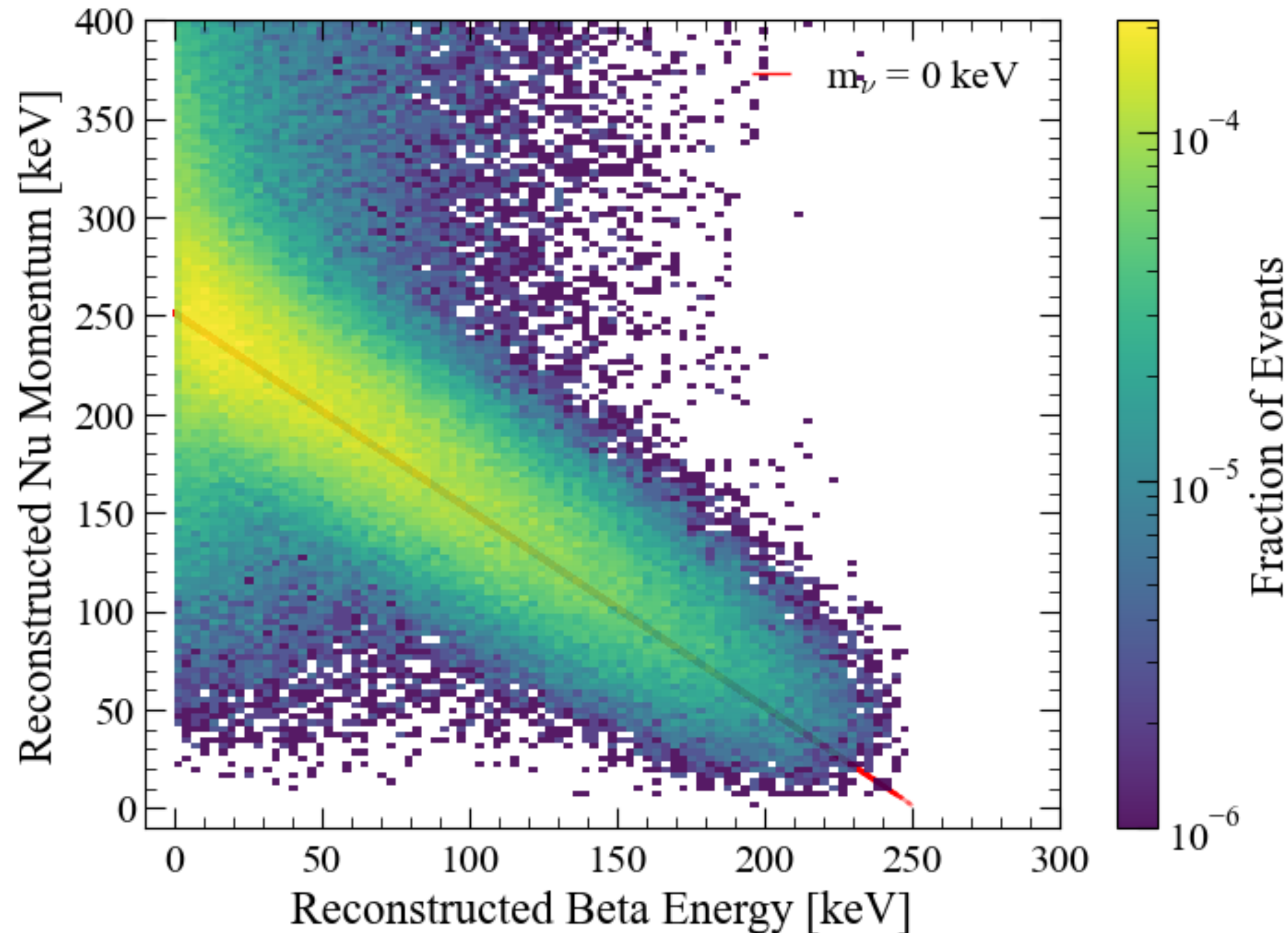
1 year of decays

Overview of Sims

- 100 nm sphere, 1.6 mm from trapping lens (yellow)
- Trapping geometry same as Yale setup and base QuIPS simulations
- CCD (green) faces 5 mm away from trapping lens
 - 2 CCD faces on either side
 - 50 micron pitch
 - 600 micron thick (CSDA projected range of 250 keV beta in 2.33 g/cc silicon is ~400 microns)
 - 25 x 25 mm face size
 - 100 nm deadlayer in front of CCDs



Simulations



Cut on only 1 CCD hit (22% efficiency)

[D. Kodroff]

Nuclear uncertainties?

Super naive estimates of recoil corrections:

Recoil corrections goes as either

$$\frac{Q}{m_N} \approx 5 \times 10^{-4} \frac{Q}{0.5 \text{ MeV}},$$

$$\text{or as } (QR_{\text{nuc}})^2 \approx 10^{-4} \left(\frac{A}{100} \right)^{2/3} \left(\frac{Q}{0.5 \text{ MeV}} \right)^2 :$$

We may ignore higher-order derivative operators.

What about others?

Future directions

- Finalize choice of radioisotope (help!)
- Move to shorter-lived isotopes/other nuclei with calculable nuclear structure?
- Optimize beta calorimeters around this
- Are arrays necessary to move to this facility? Would this allow superallowed branching ratios?

Conclusions

- Levitated optomechanical sensors are sensitive to “invisible momentum”, allowing measurement of neutrino momentum. Ideas to push this!
- Beta decays of long-lived ($>\sim$ days) isotopes enable probes of new physics, with much work in progress

Back up slides

Matching of frequency ratio to required harmonic

