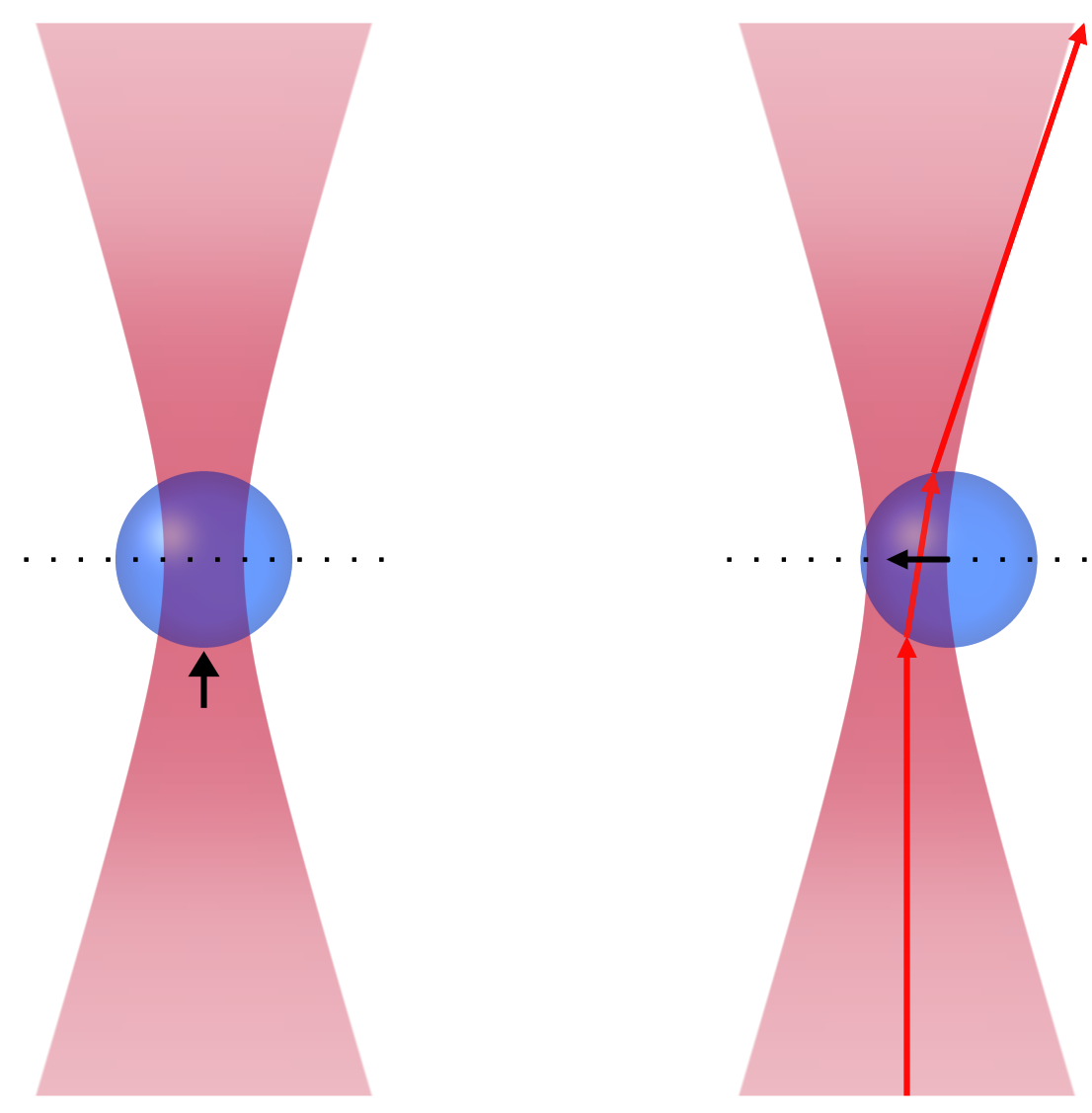


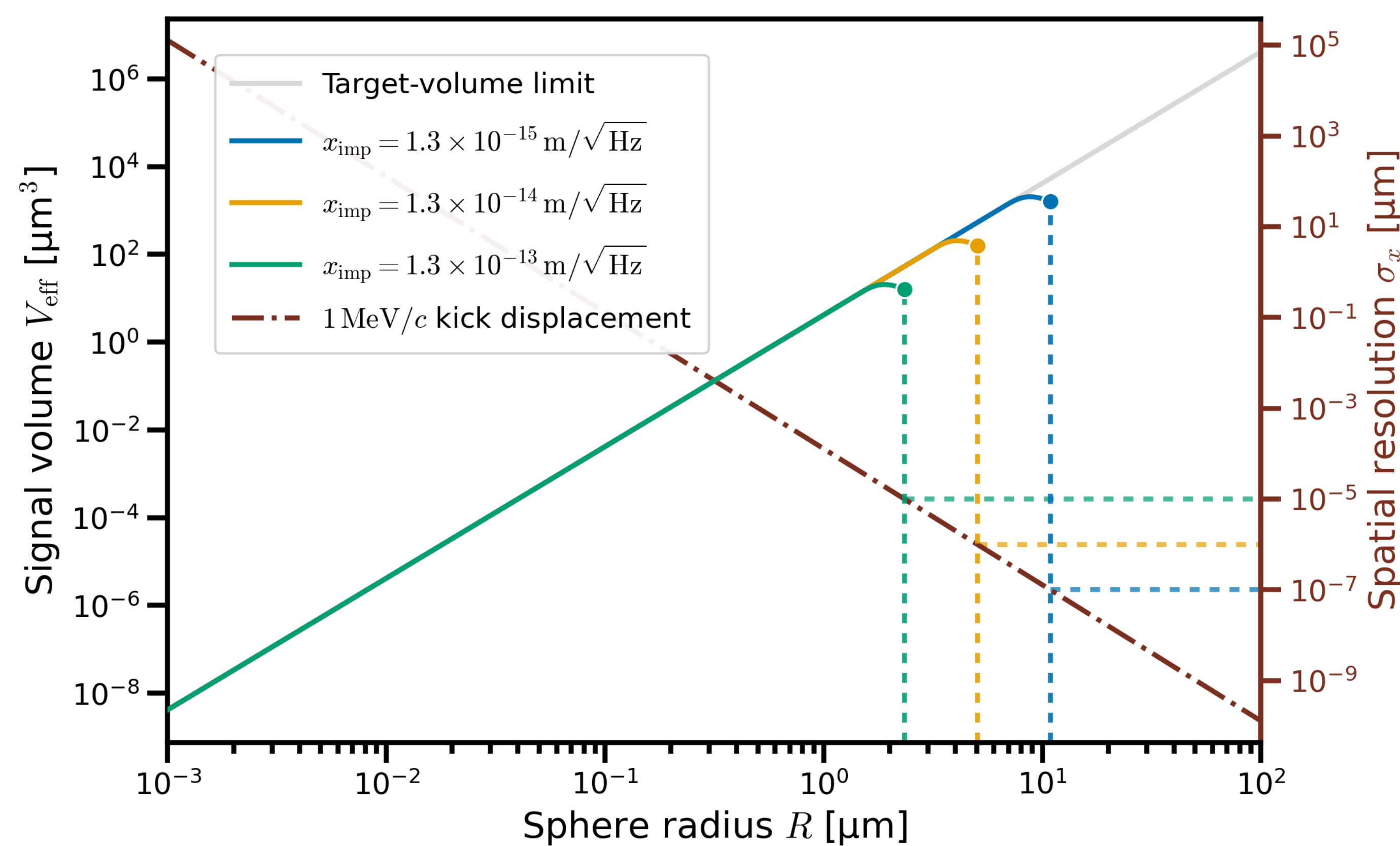
# Directional Momentum Sensing with Optically Levitated Microspheres for Neutrino Physics

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## Sensing with levitated spheres

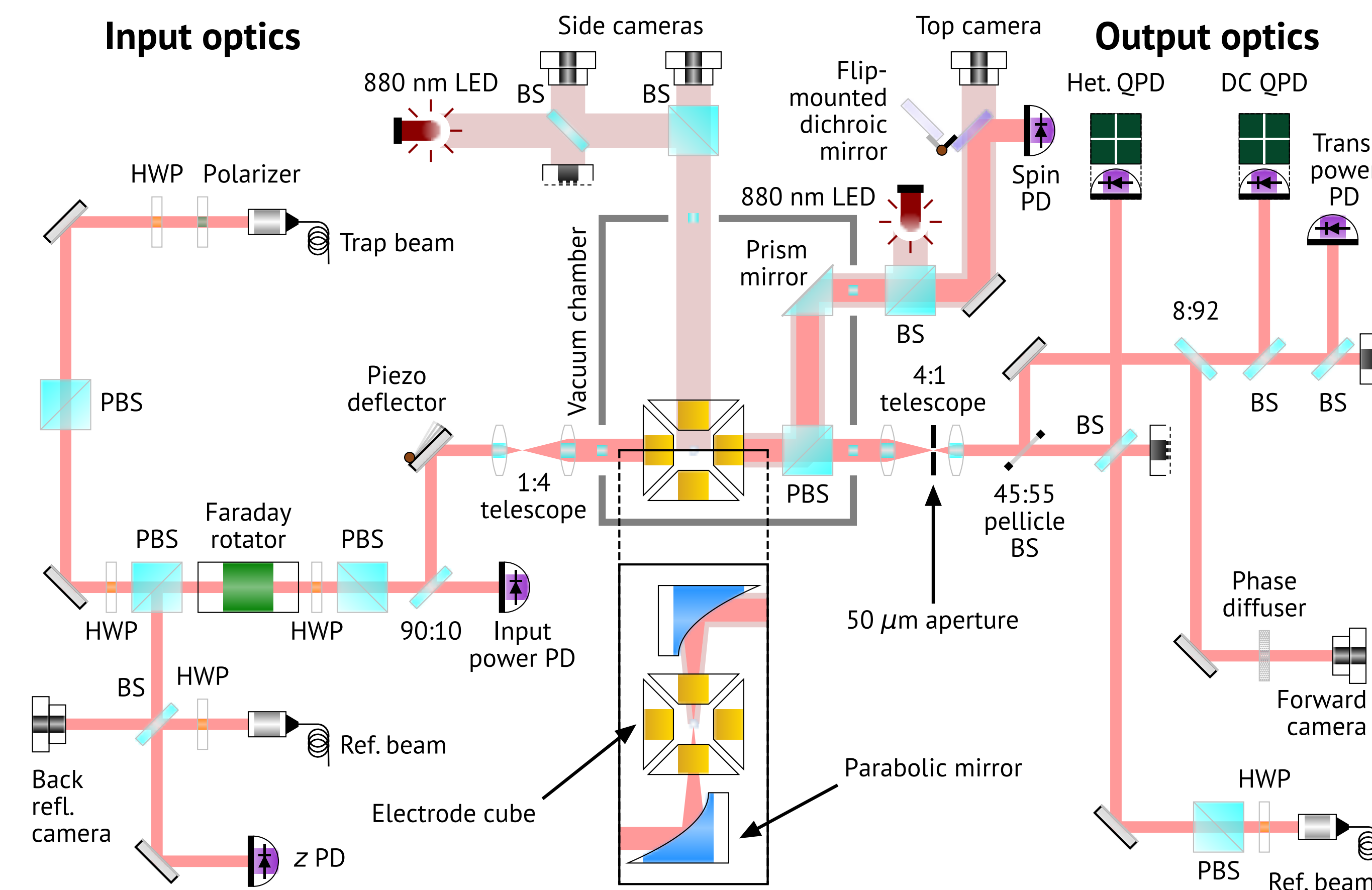


- Optical levitation principle:
  - Radiation pressure along optical axis
  - Restoring force from beam deflection
- High-resolution optical readout for sensing
  - Displacement from scattered light
  - Momentum and force sensing from position



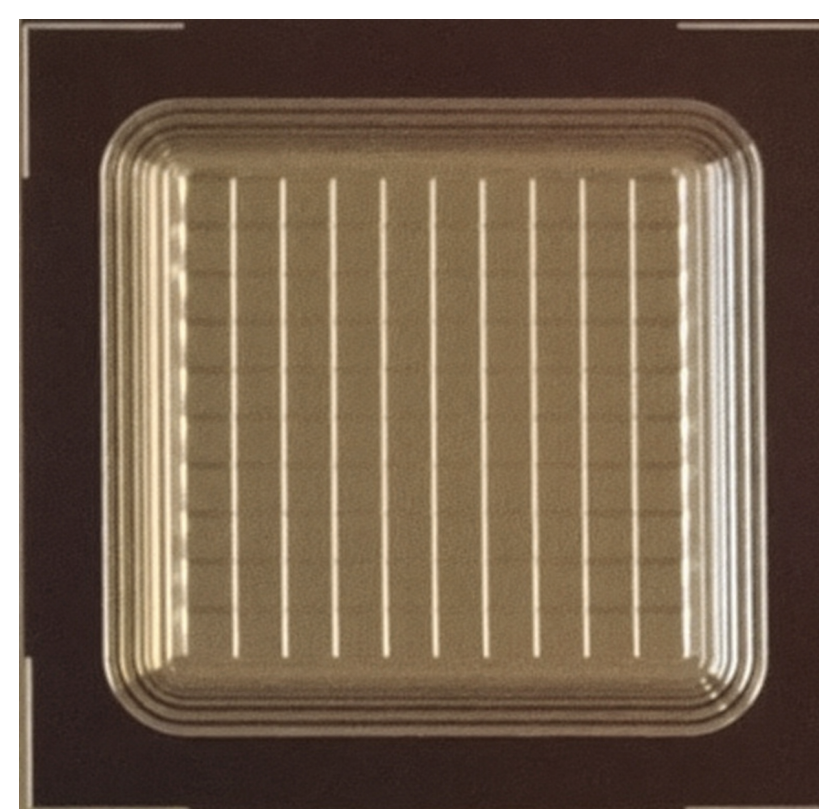
- Isolated environment and active feedback cooling minimize center-of-mass motion for levitated spheres.
- Larger spheres provide more target volume for interactions, while the kick-induced displacement scales as  $R^{-3}$ .
- Resolving kicks in larger spheres requires lower imprecision noise  $x_{\text{imp}}$  in position readout.

## Experimental Platform



- Silica spheres with diameters  $d \sim 10 \mu\text{m}$  are levitated at  $\mathcal{O}(10^{-7})$  mbar in a vertical trap with 1064 nm laser.
- 125 kHz heterodyne readout of forward-scattered light measures transverse position ( $x, y$ ); interferometric readout of back-scattered light measures height  $z$ .

## Ongoing Improvements

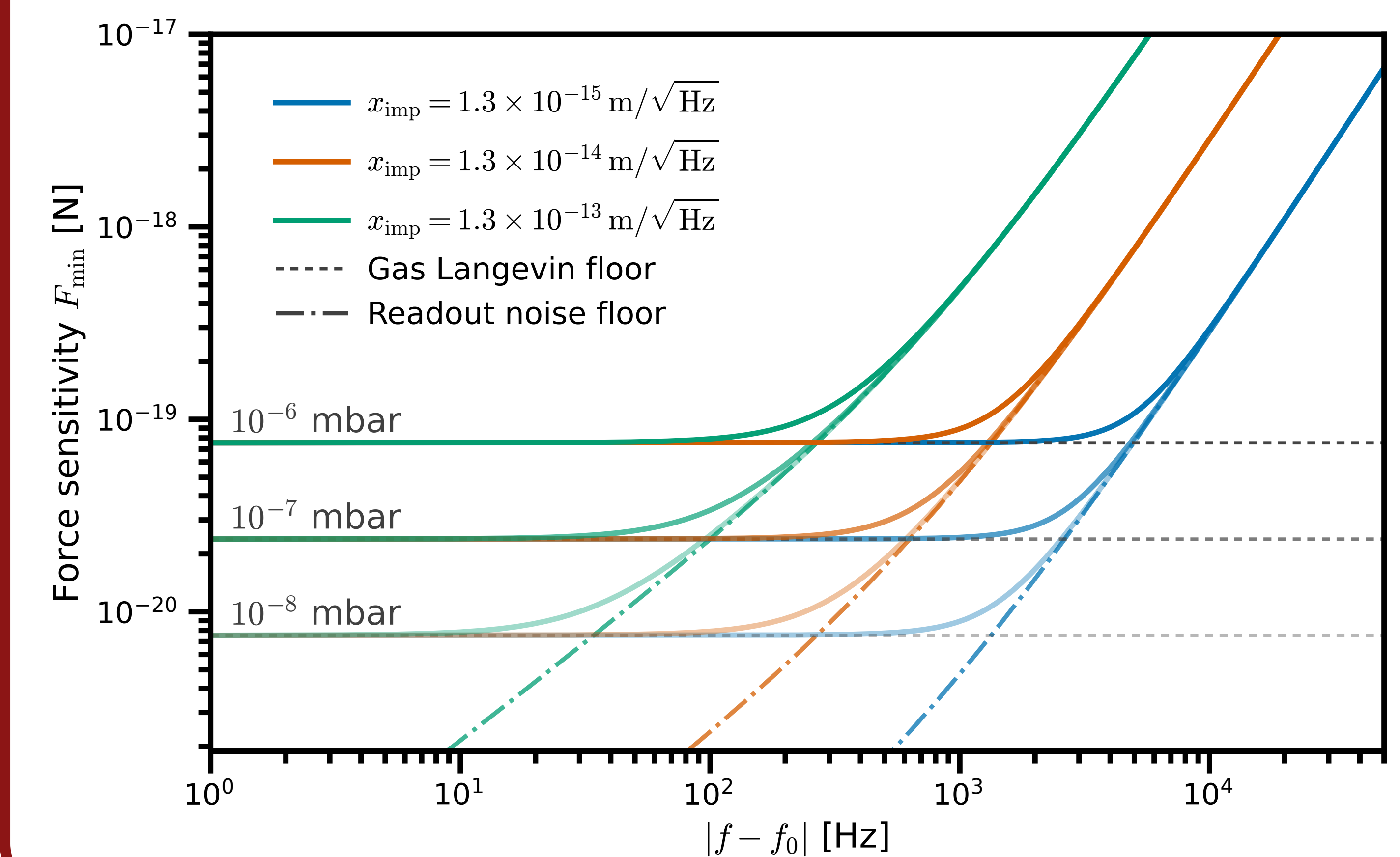


10 × 10 array of 0.5mm × 0.5mm silicon PIN pixels

- Projected noise-equivalent power reduction of 90% with a 100-pixel silicon PIN array.
- Stray light background rejected by forward scattering pattern.
- Full simulation and machine-learning based position reconstruction.
- Commissioning and data taking are planned in the coming months.

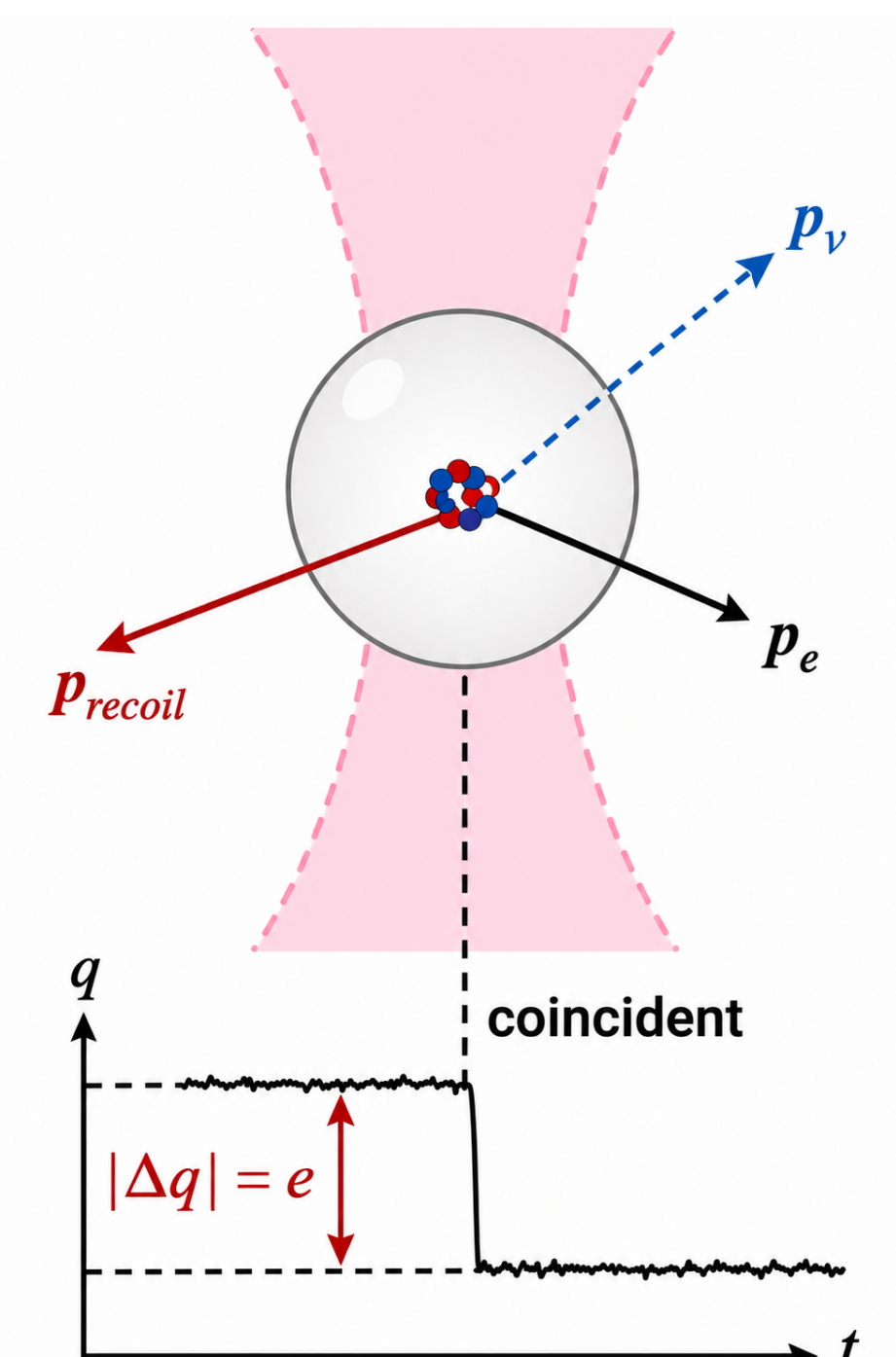
## Phase-coherent force sensing

- Phase-coherent force near the trap resonance produces a  $Q$ -enhanced displacement response.
- Force sensitivity is jointly limited by residual-gas Langevin noise and readout noise.
- Benchmark assumptions:  $10 \mu\text{m}$ -diameter  $\text{SiO}_2$  sphere, trapping frequency  $f_0 = 400 \text{ Hz}$ , 1000s measurement time.



## Applications in Neutrino Physics

- Directional momentum sensing for neutrinos, targeting  $\mathcal{O}(\text{keV}/c) \sim \mathcal{O}(\text{MeV}/c)$  threshold with nano- and micro-spheres.
- Coincident single-electron charge steps offer an independent tag.
- Phase-coherent or periodic forces may signal new interactions.



## REFERENCES

- [1] G. Venugopalan *et al.*, "Optomechanical vector sensing of new forces at 6 micron separation," *Sci. Rep.* **16**, 5180 (2026).
- [2] J. Wang *et al.*, "Mechanical detection of nuclear decays," *Phys. Rev. Lett.* **133**, 023602 (2024).

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