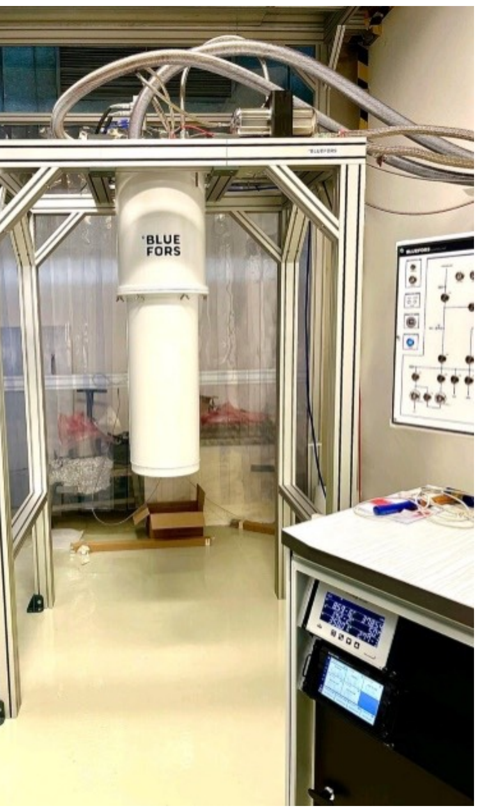
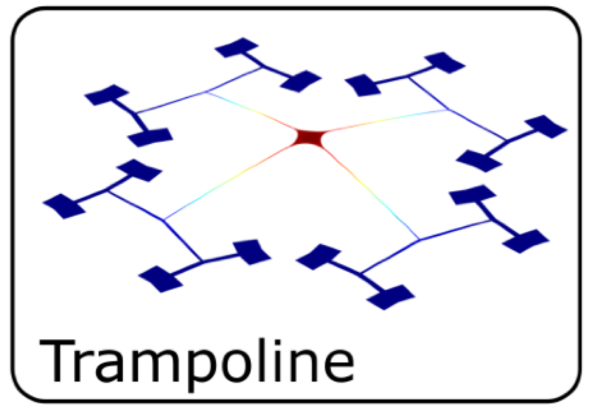
Quantum Sensing for MU Particle Physics

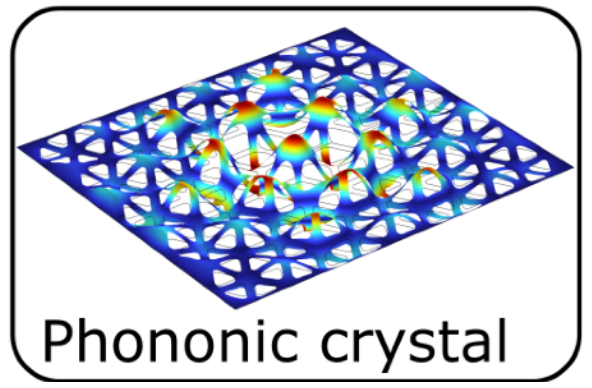
PoF V MU-FPF Retreat

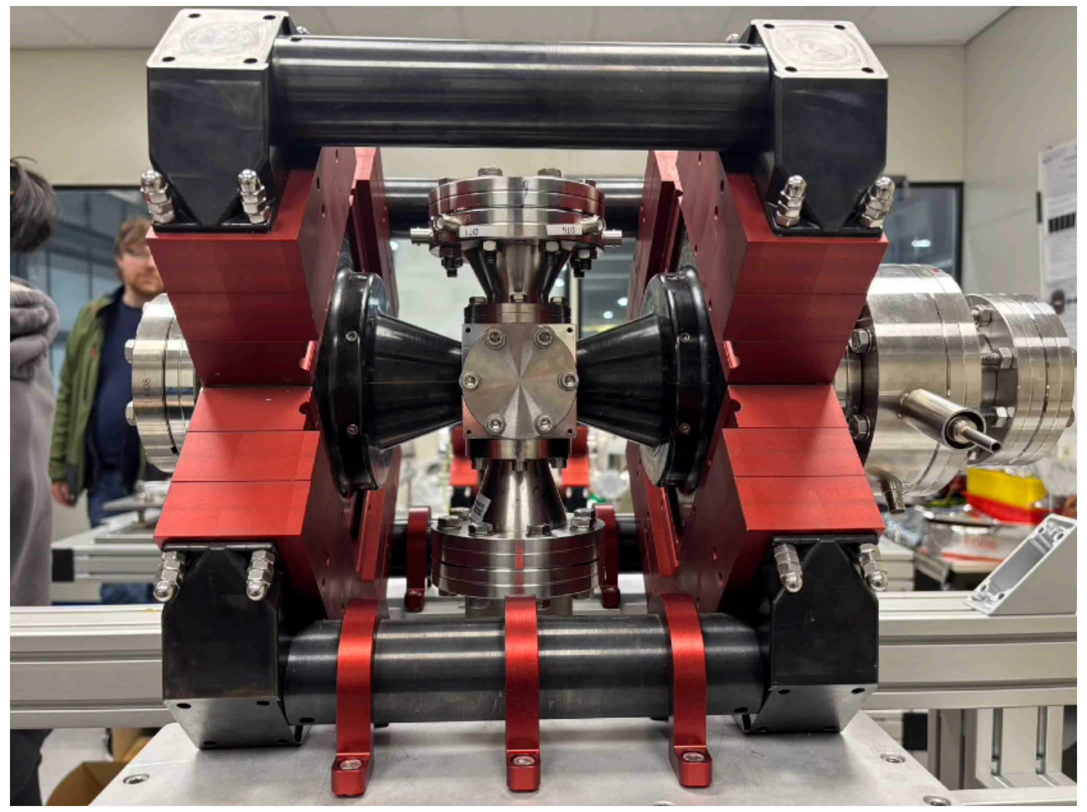
Steven Worm

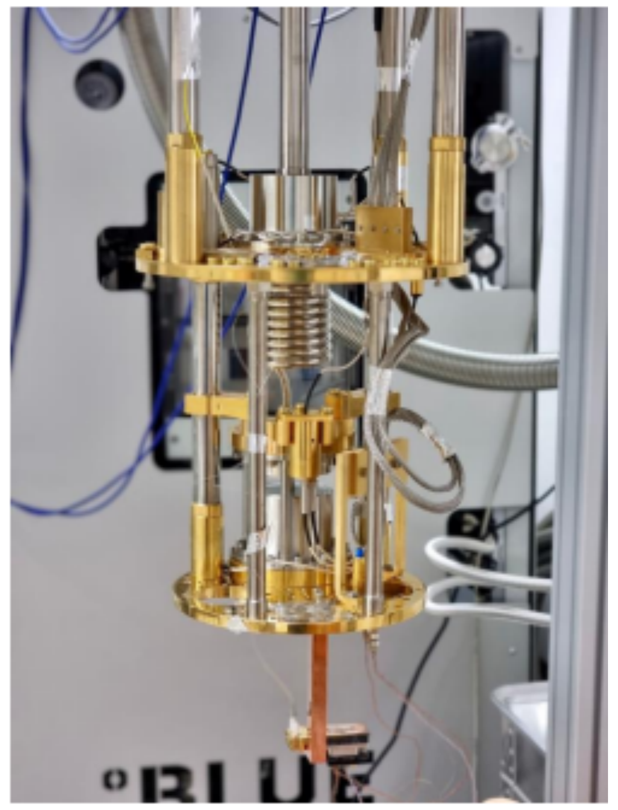
June 19, 2025

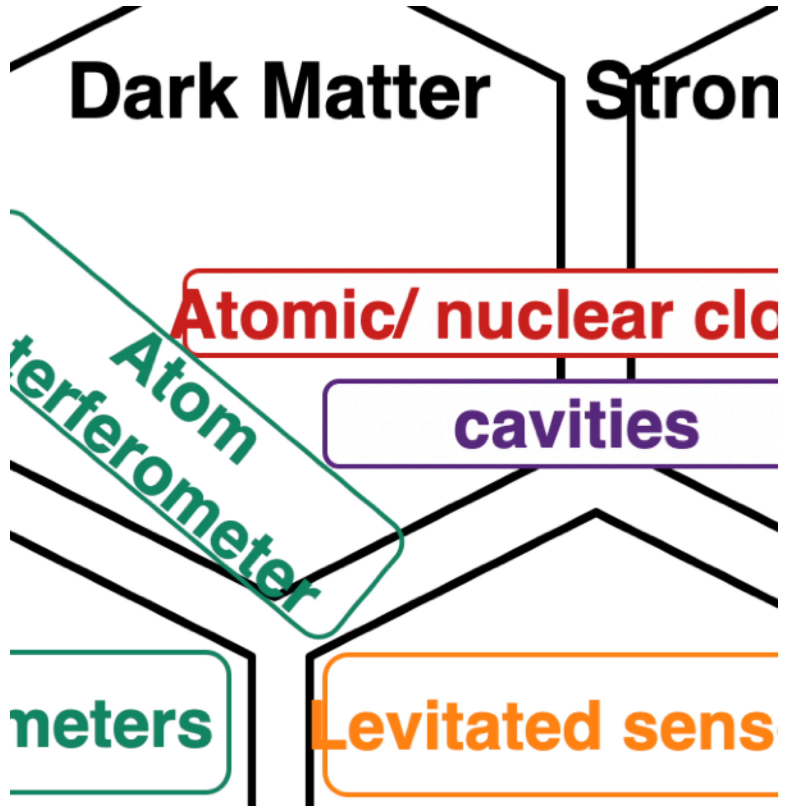


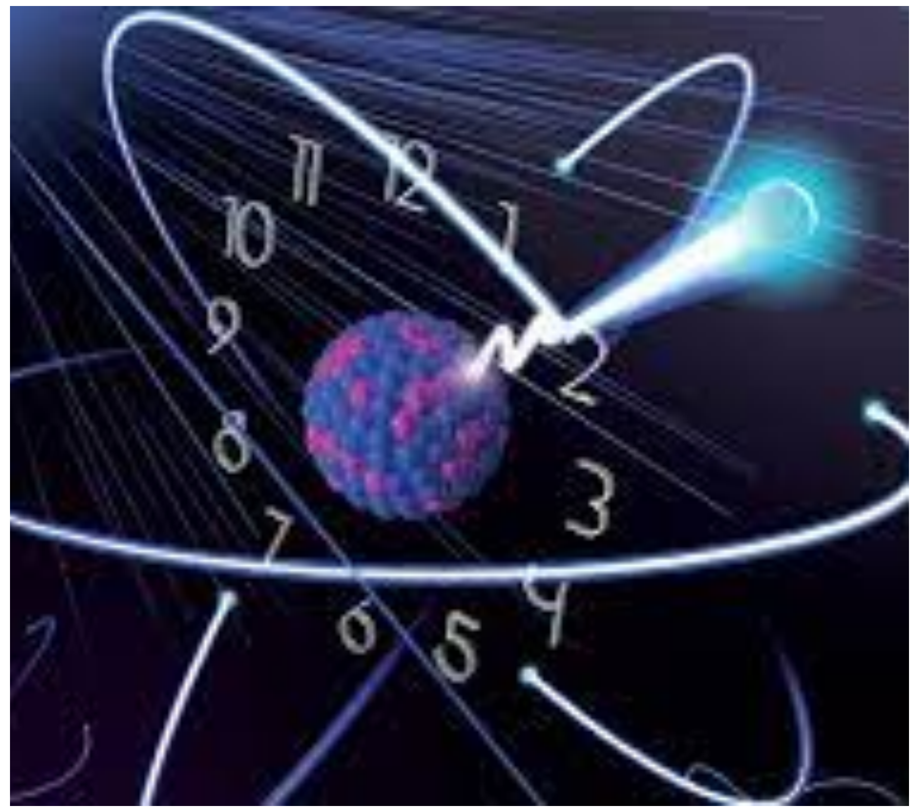


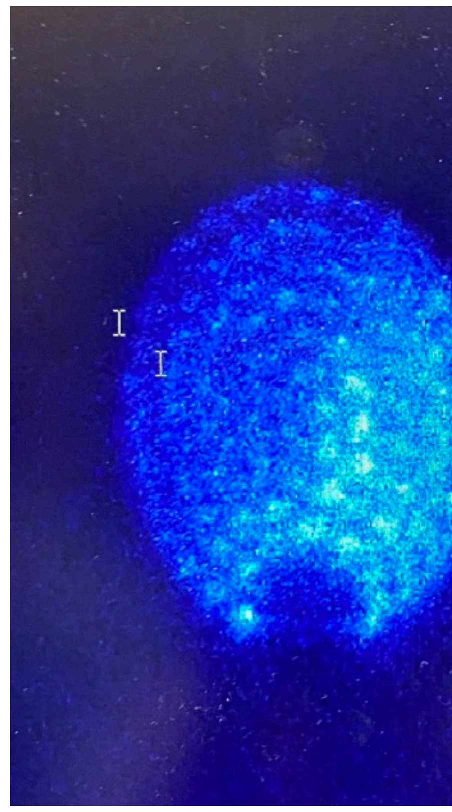












DESY. QUANTUM

Center for Quantum Technology and Applications

Quantum Sensing → Quantum Experiments for MU-FPF

Why **quantum sensing?**

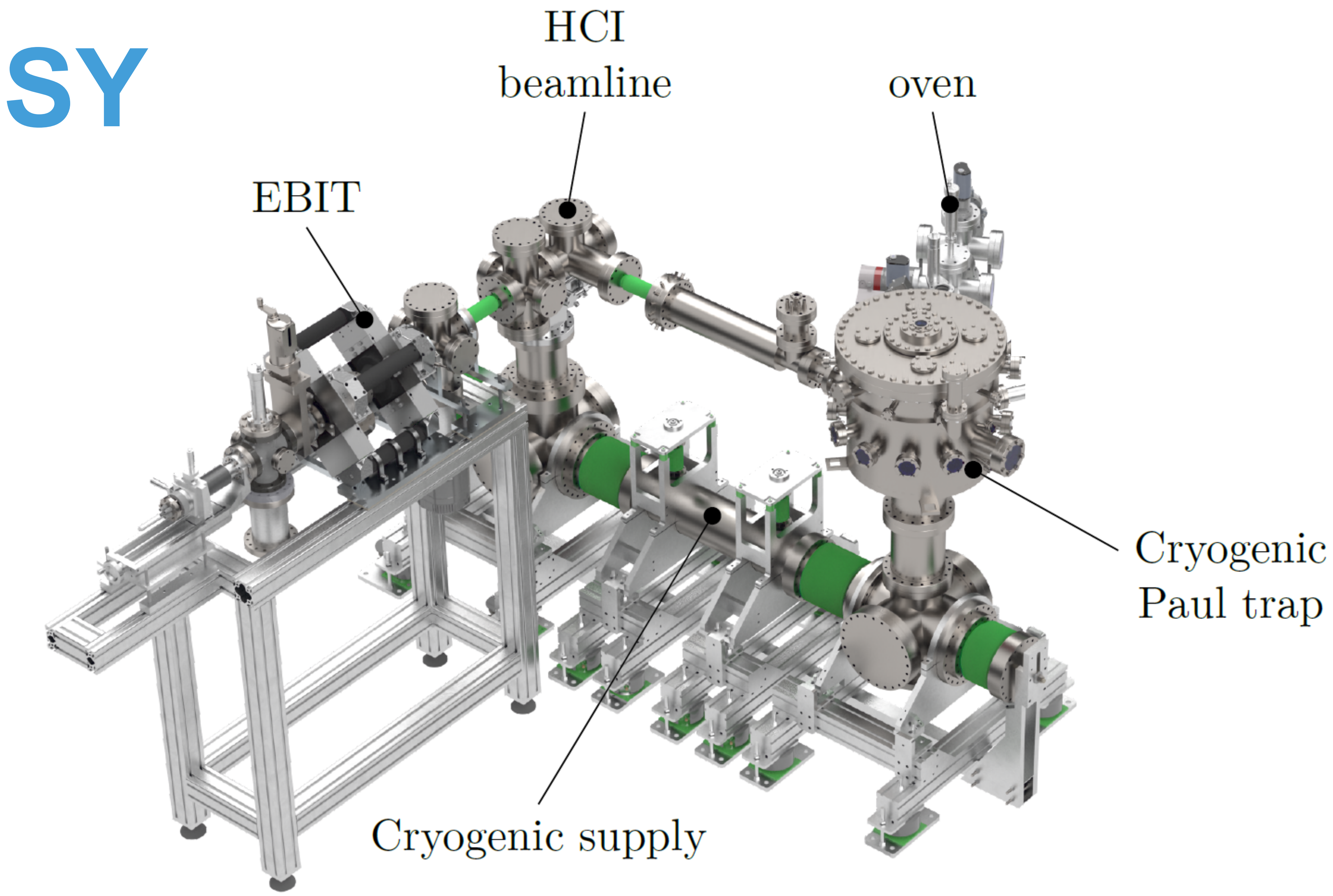
- A1: Potentially better sensitivity or noise performance
- A2: Because we have to (e.g. for ultra-light dark matter)!

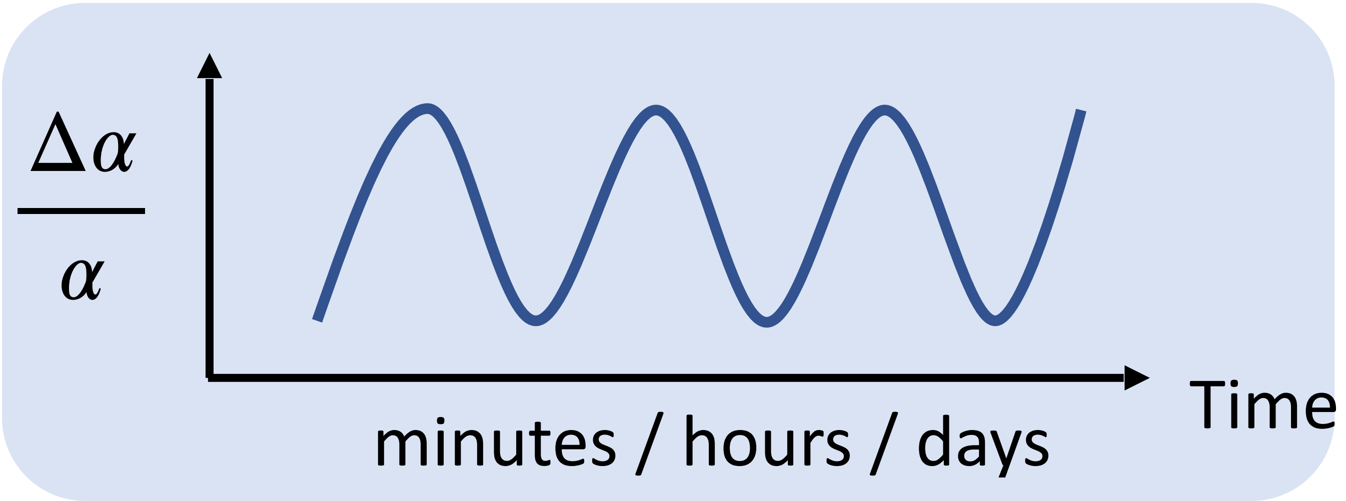
- Quantum Detectors: use quantum sensing to making extreme measurements possible
  - Enables (better) measurements, e.g. wavelengths
  - Extreme sensitivities (single-photon) or low noise

- Quantum Experiments: sensing is used for fundamental physics measurements
  - Gravity, Lorentz Invariance, physical constants (α, μ, dipole moments), etc
  - Techniques such as interferometry, magnetometry, clock-based systems, optomechanical devices

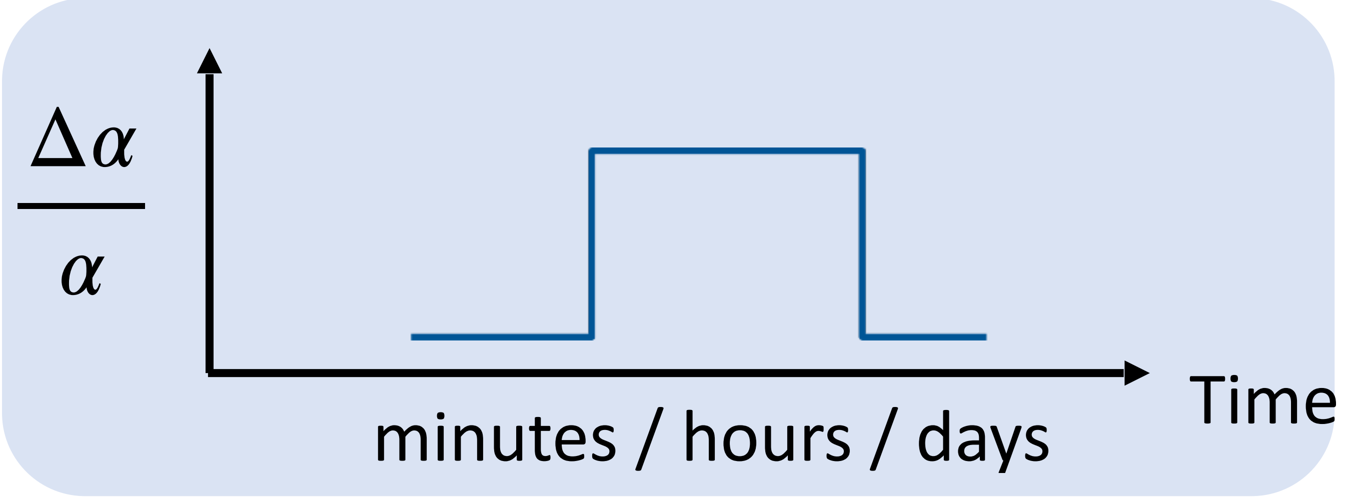
Optical Atomic Clock Experiment @ DESY

- Search for variations in alpha — optical atomic clock based on trapped, highly charged ion
- Ultra-stable laser excites atomic transitions → a clock
- Laser/sympathetic cooling with a second ion (eg Be^+)
- Frequency comb: optical → countable microwave
- Highly charged ions (HCI) for best sensitivity to ultra-light DM



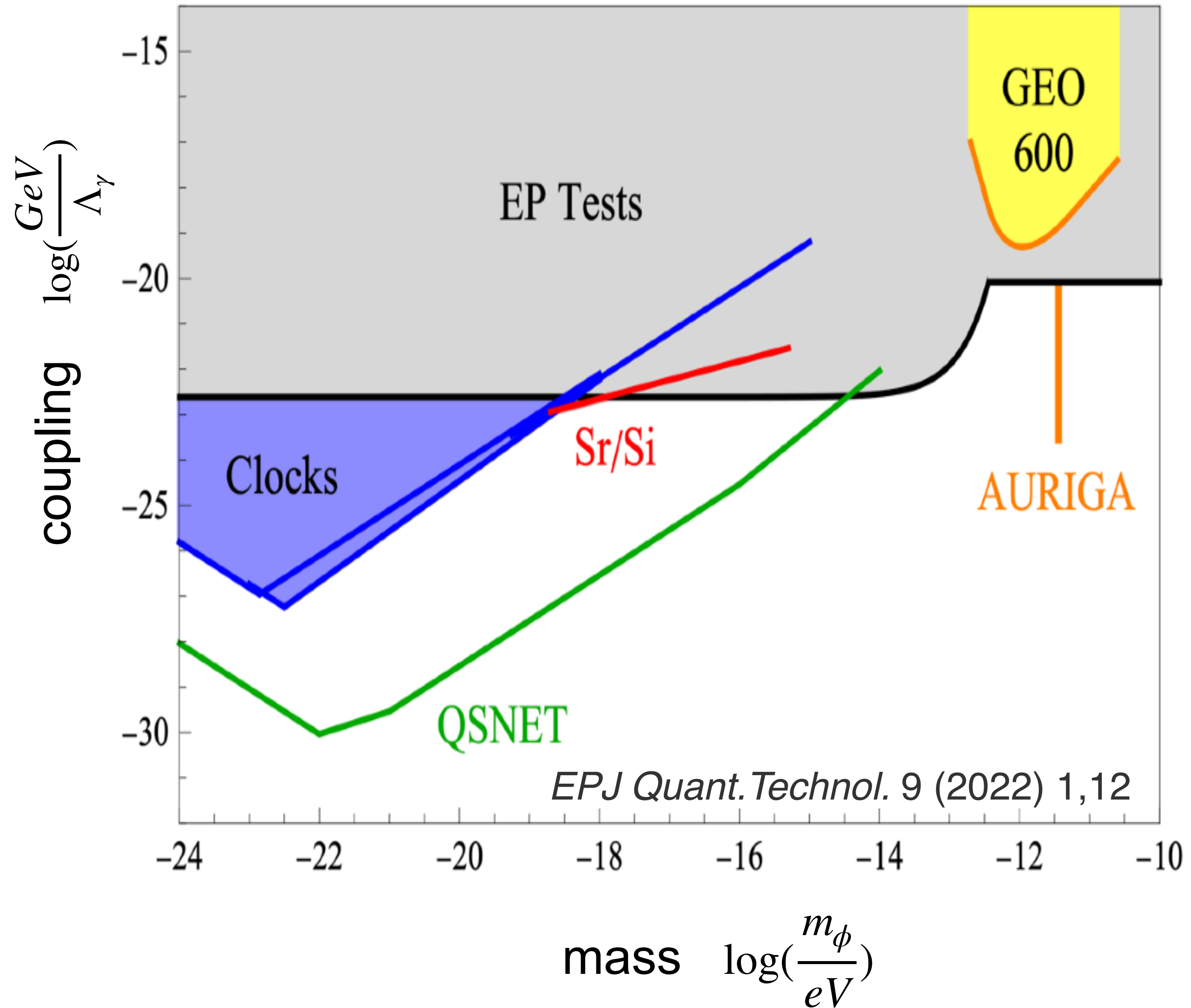


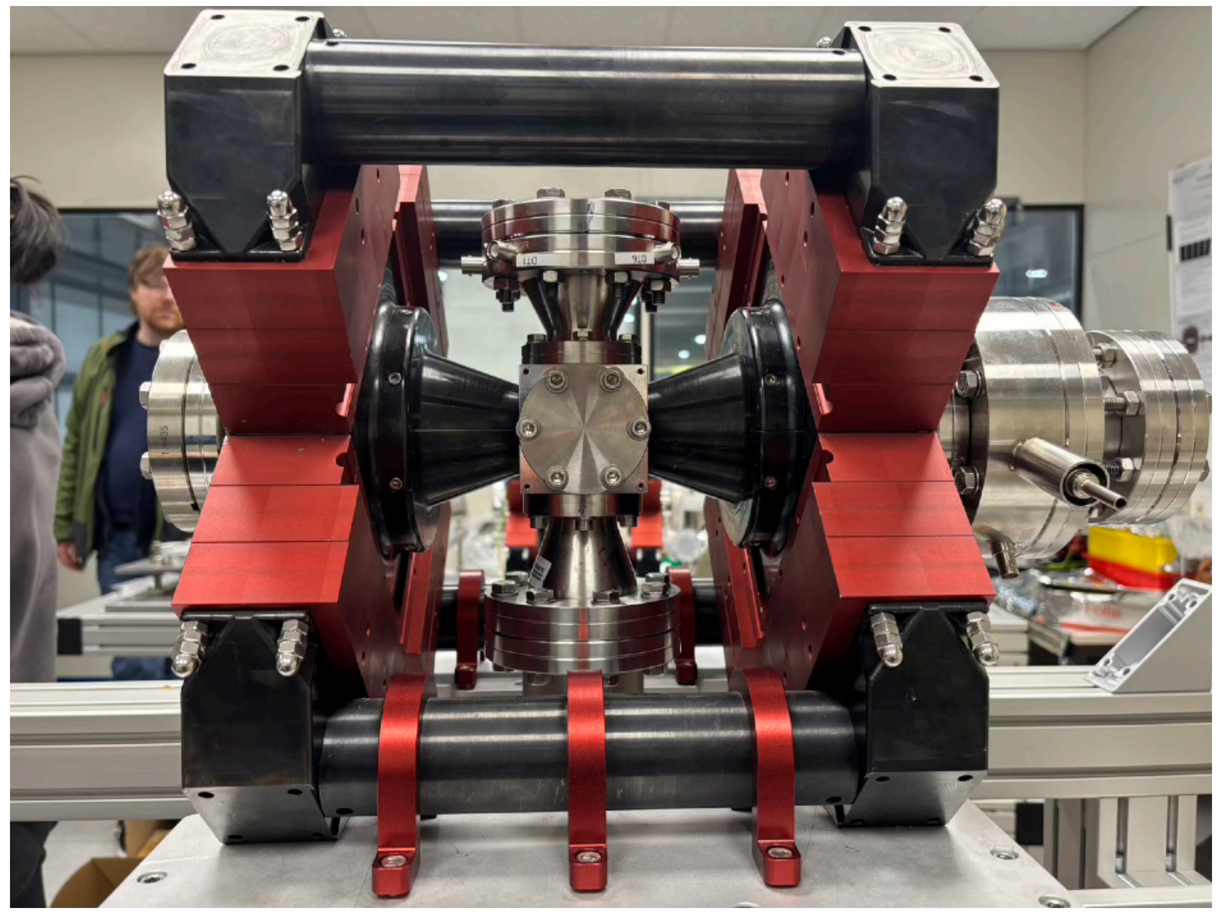
→ Ultra-light dark matter



→ Dark matter, topological defects

oscillating scalar DM field + EM

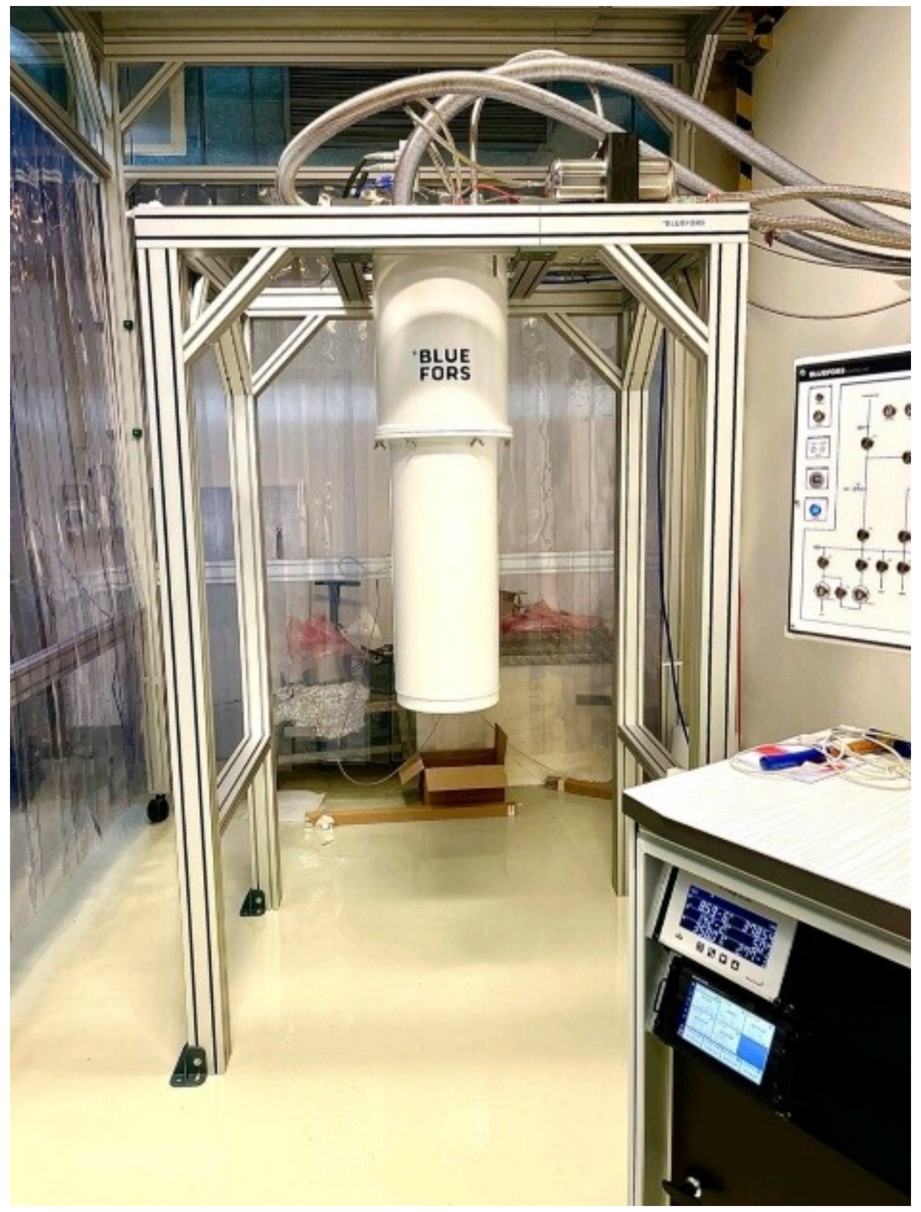


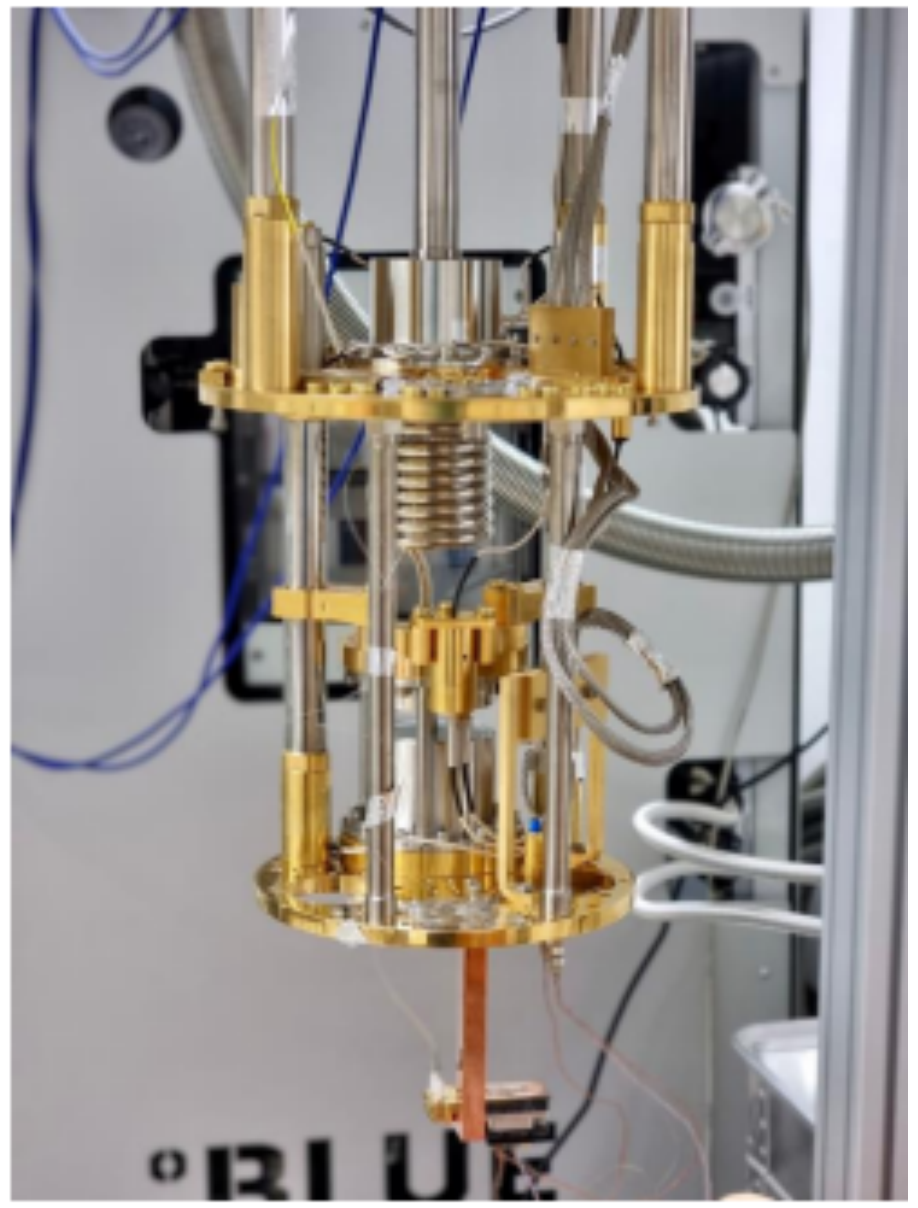


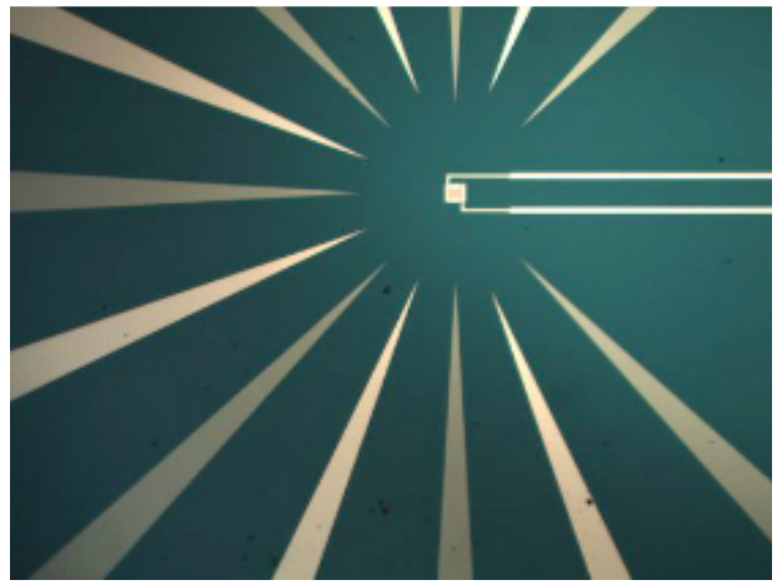
DESY electron beam ion trap (EBIT)

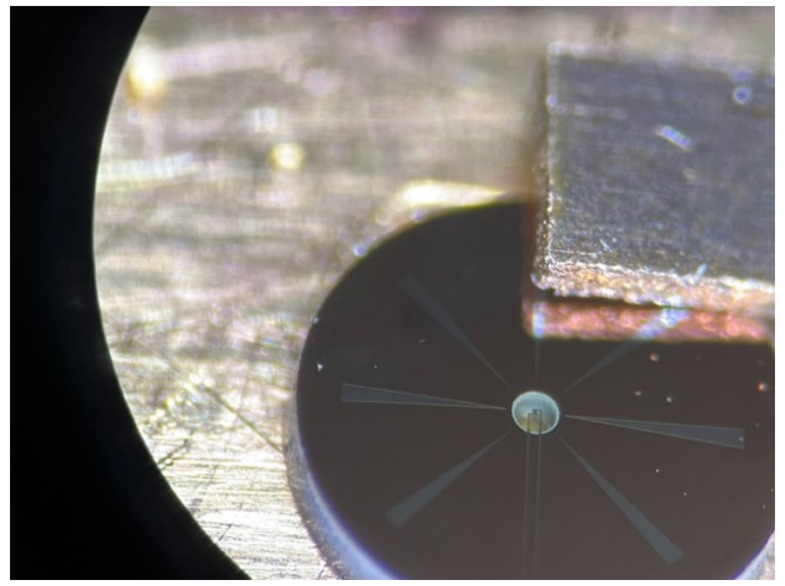
Transition Edge Sensors @ DESY

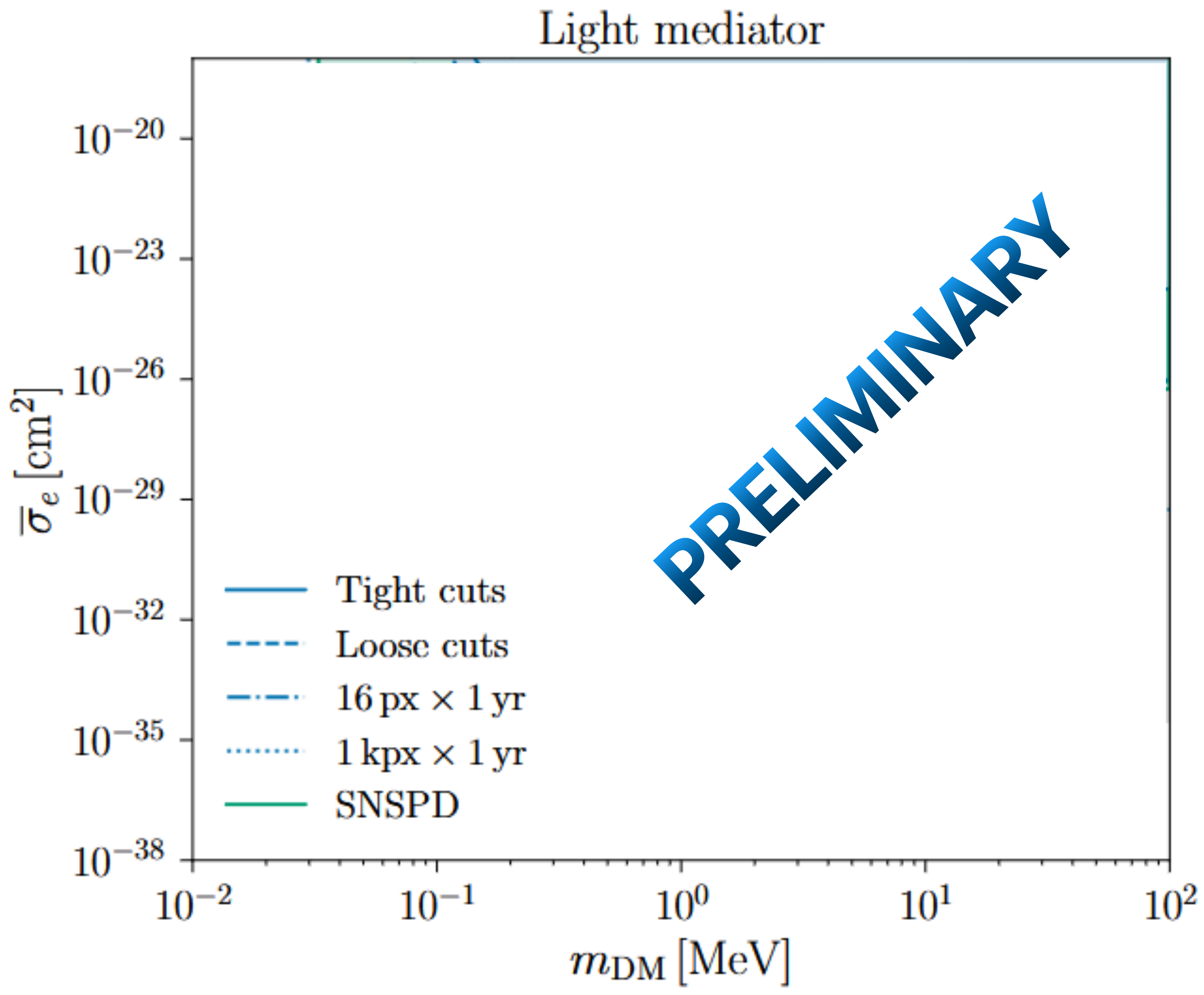
- Cryogenic sensors (TES, SNSPD, etc): extremely low noise, unprecedented energy resolution
- TES developed for ALPS II: extremely low photon-like dark counts
- Exploring sub-MeV regions in direct dark matter search (MIT & Hebrew University Jerusalem)
- Key Helmholtz detector activity in the next PoF funding period: catalyst for innovative DM/axion searches







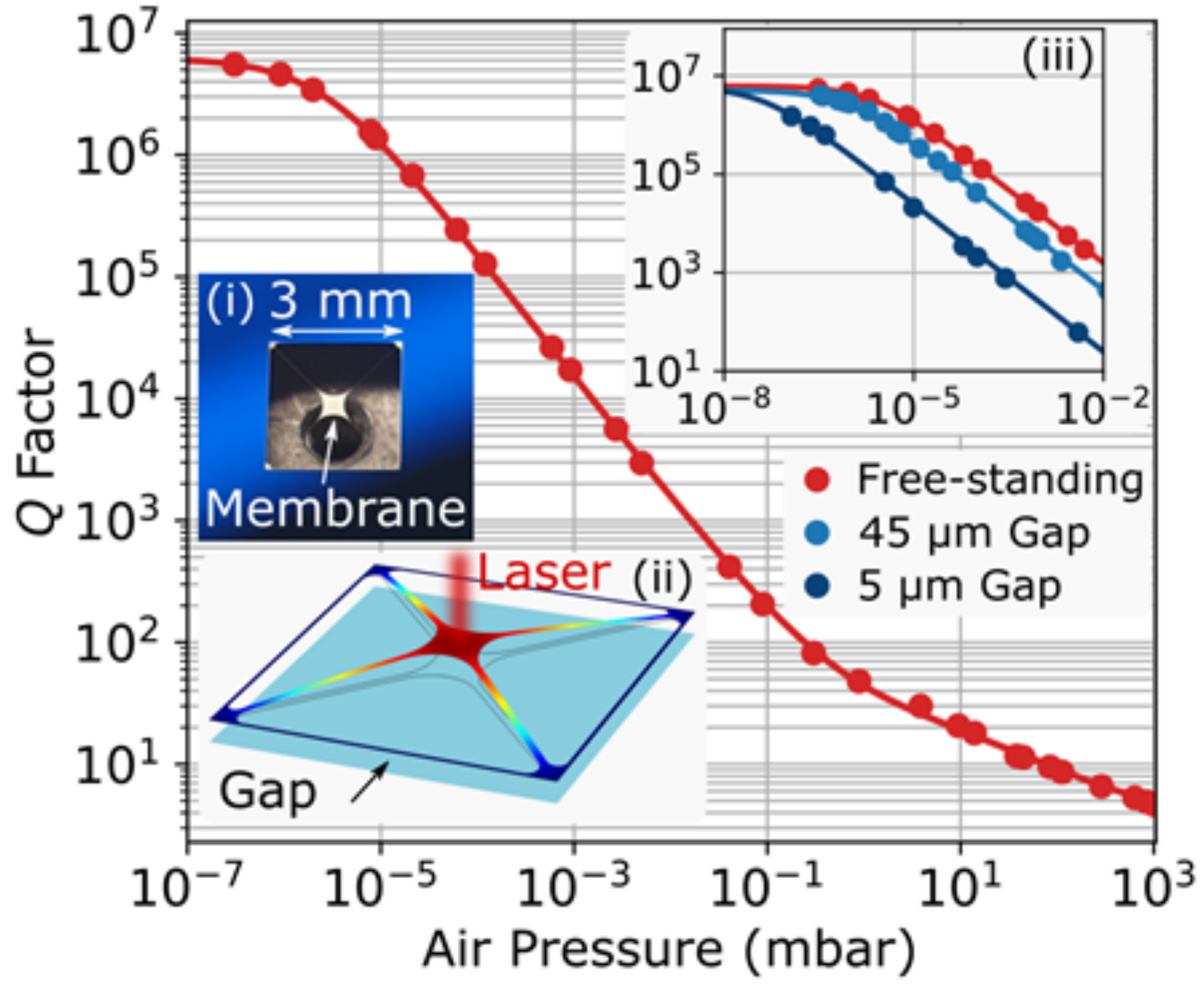


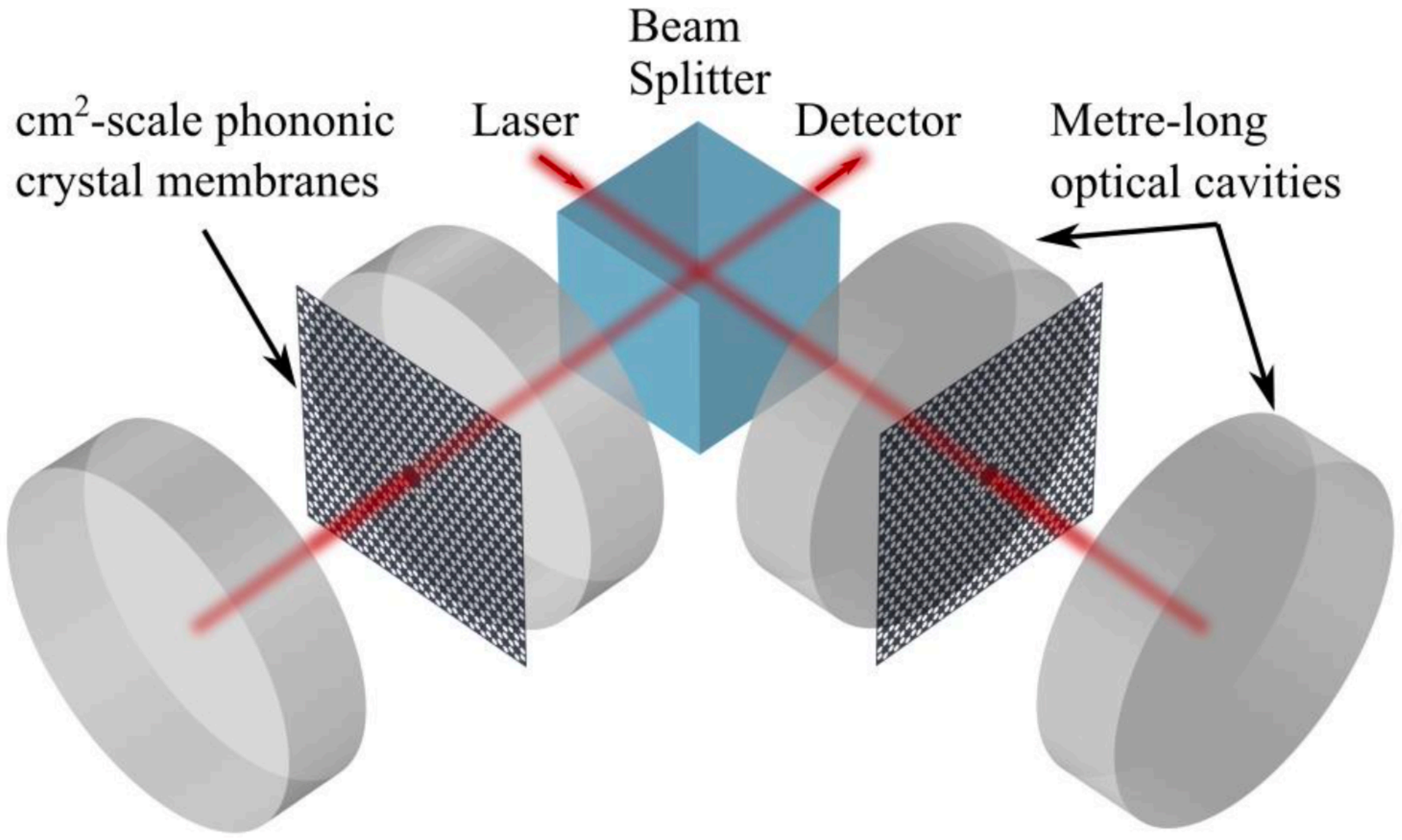


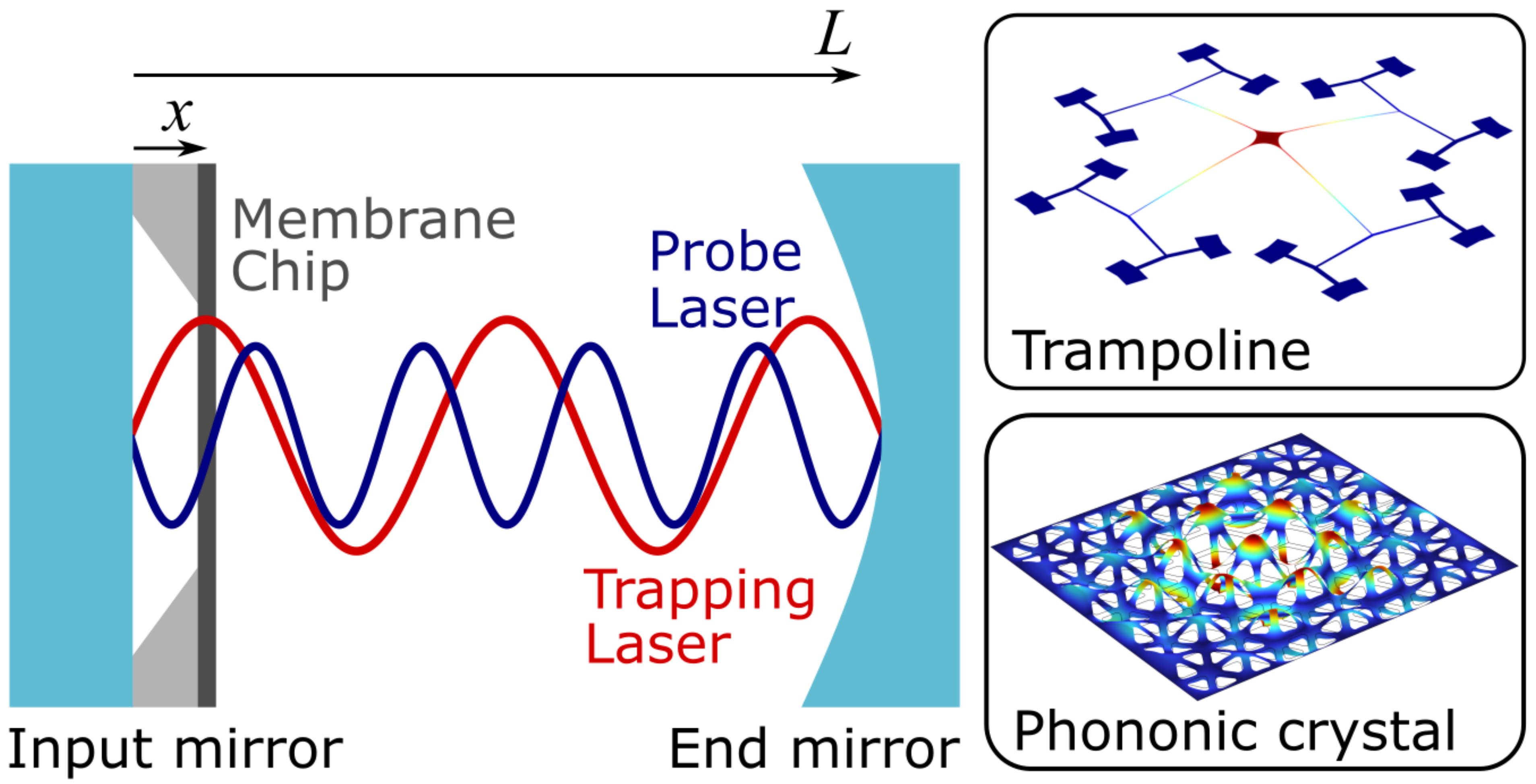
→ Friederike Januschek

Membrane-based High-frequency Gravitational Wave Detection

- Optically-trapped membrane as gravitational wave detector
- Sensitive to high-frequency (kHz - MHz) gravitational waves
- Based on optomechanical sensor for extreme pressure measure
- GW displaces membrane → resonant enhancement in optical trap

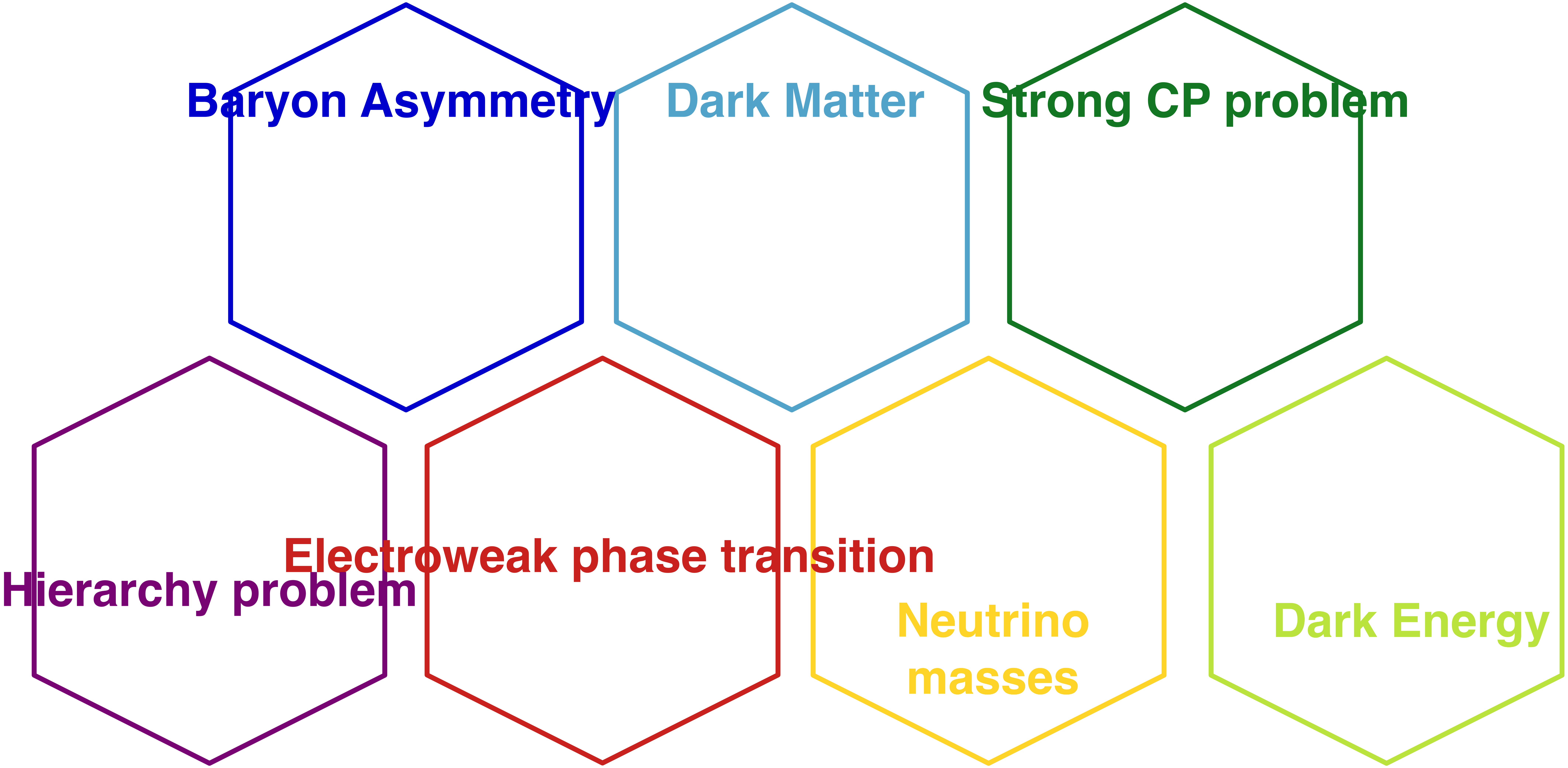






→ Christoph Reinhardt

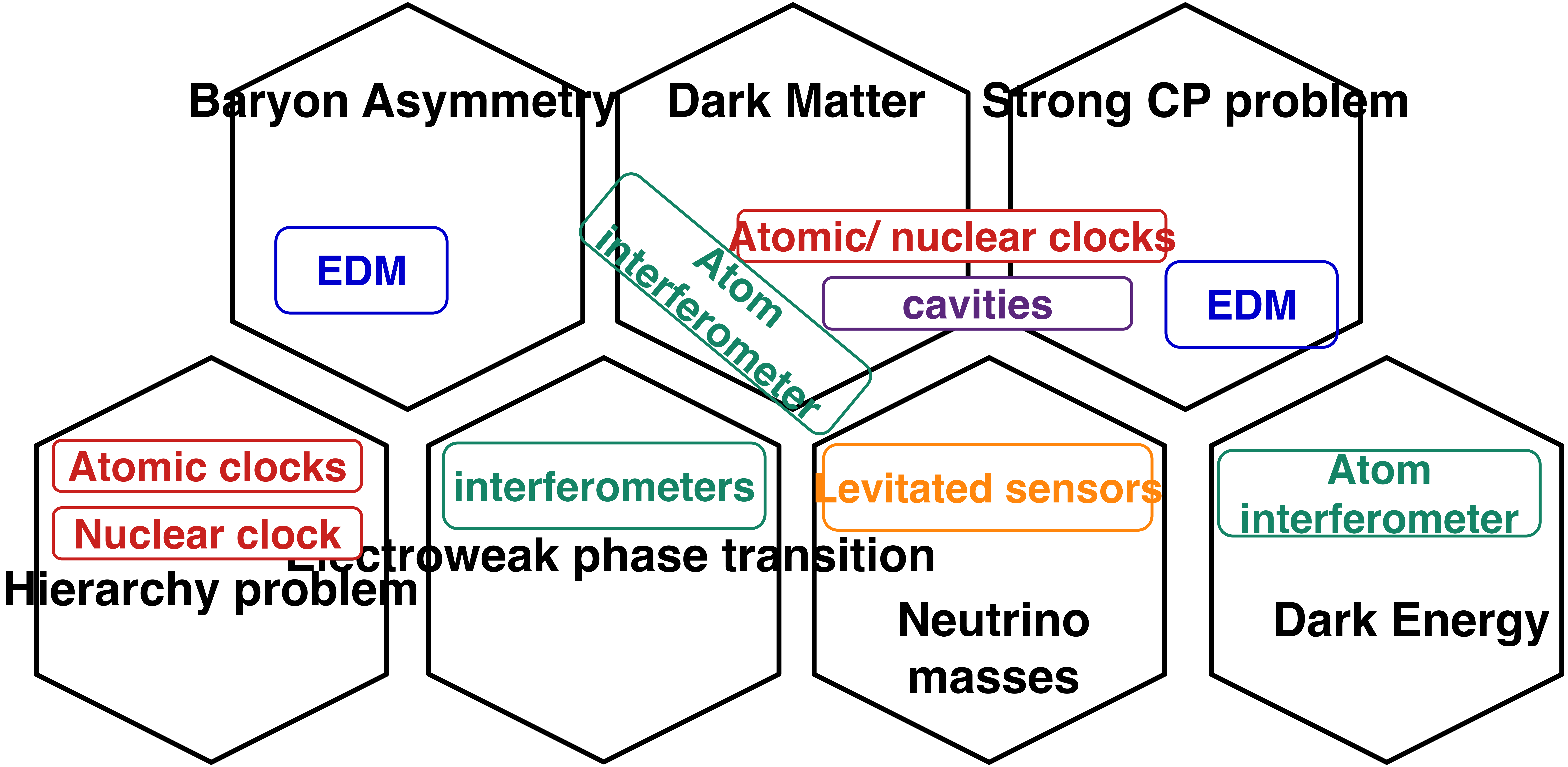
Particle questions ↔ Quantum sensing



Review:
Safronova, Budker, DeMille, Kimball, Derevianko, Clark 2017: “Search for New Physics with Atoms and Molecules”

→ Elina Fuchs

Particle questions ↔ Quantum sensing



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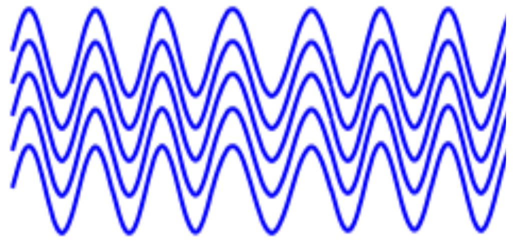
(Ultra)light DM searches

Simple SM extension: ultralight scalar ϕ → DM candidate

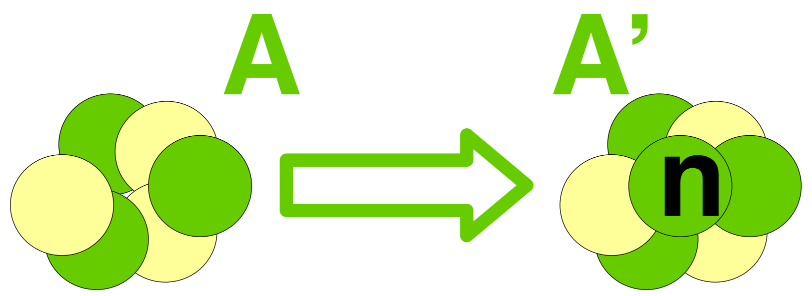
Ultralight ($m_\phi \lesssim 10$ eV) → DM as classical, coherently oscillating field $\phi(t) \approx \phi_0 \cos(m_\phi t)$



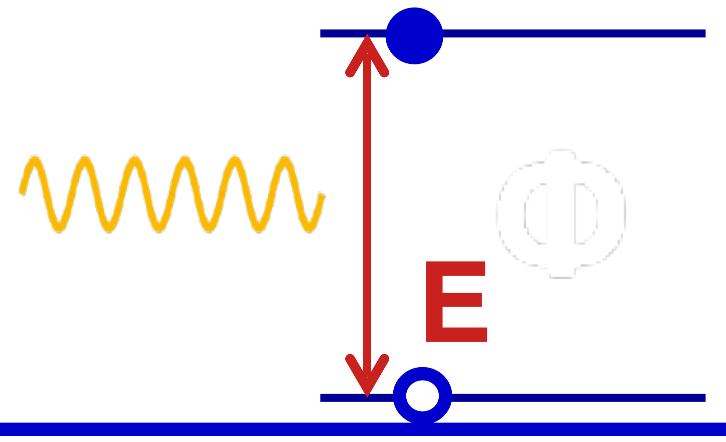
→ induces **oscillations** of α and fermion masses

→ oscillations of electron levels in atoms and ions: testable by frequency ratios of (atomic) clocks

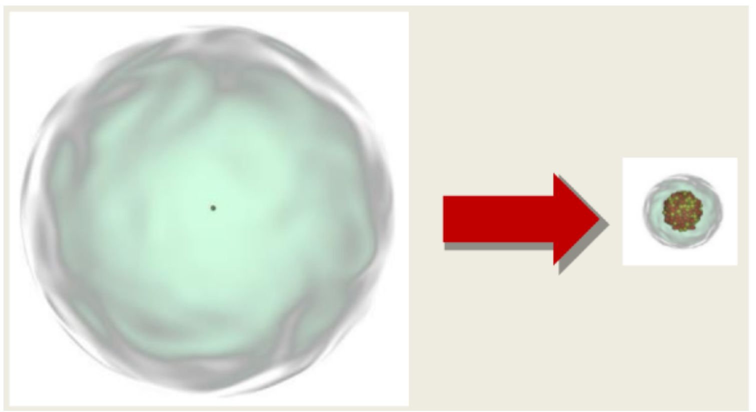
Isotope shifts for Dark Mediator



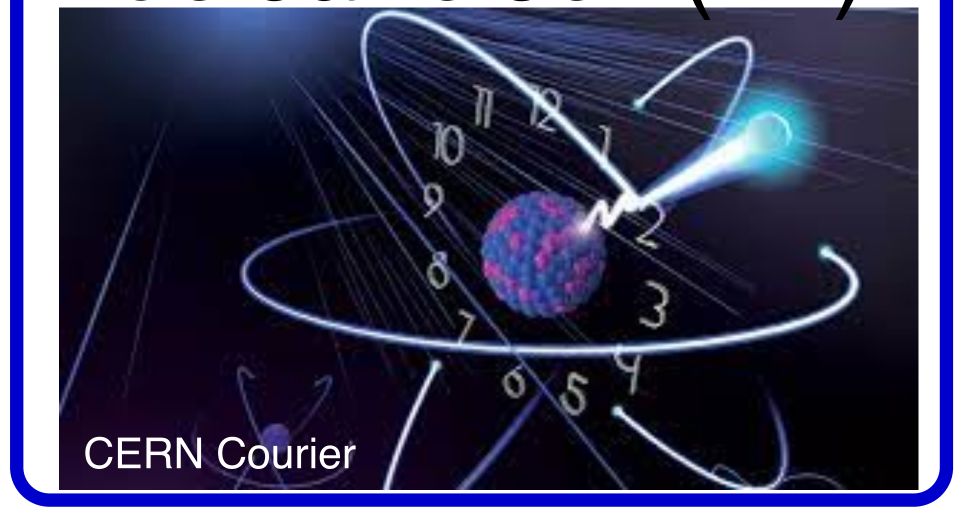
Atom/ion clocks



Highly charged ions



Nuclear clock (Th)



Enhanced sensitivity to ULDM ϕ

Additional directions:

- **Cavities** for axions and High-Frequency Gravitational Waves
- **Atom interferometers** for ULDM and Gravitational Waves
- **Quantum Information Theory** for optimizing detection schemes
- **Non-minimal models**

Theory – experimental collaboration!

→ Elina Fuchs

Conclusions

- Quantum Sensing: fantastic new tools lead to new, innovative table-top experiments in MU-FPF
- New experiments and collaborations being developed now for ULDM (e.g. axion/ALPs), gravitational waves and more
- Cross-divisional: strong links to quantum computing, FH, AP, FS, Accelerator
- Cross-cutting activity within Helmholtz
- Catalyst for collaboration: QS4Physics InnoPool, Sub-MeV DM Search, QTF-Backbone Uhrennetzwerk, DRD5, …