

Quantum Sensing for Particle Physics

National Tsing Hua University

16th Particle Physics Phenomenology Workshop

Prof. Steven Worm

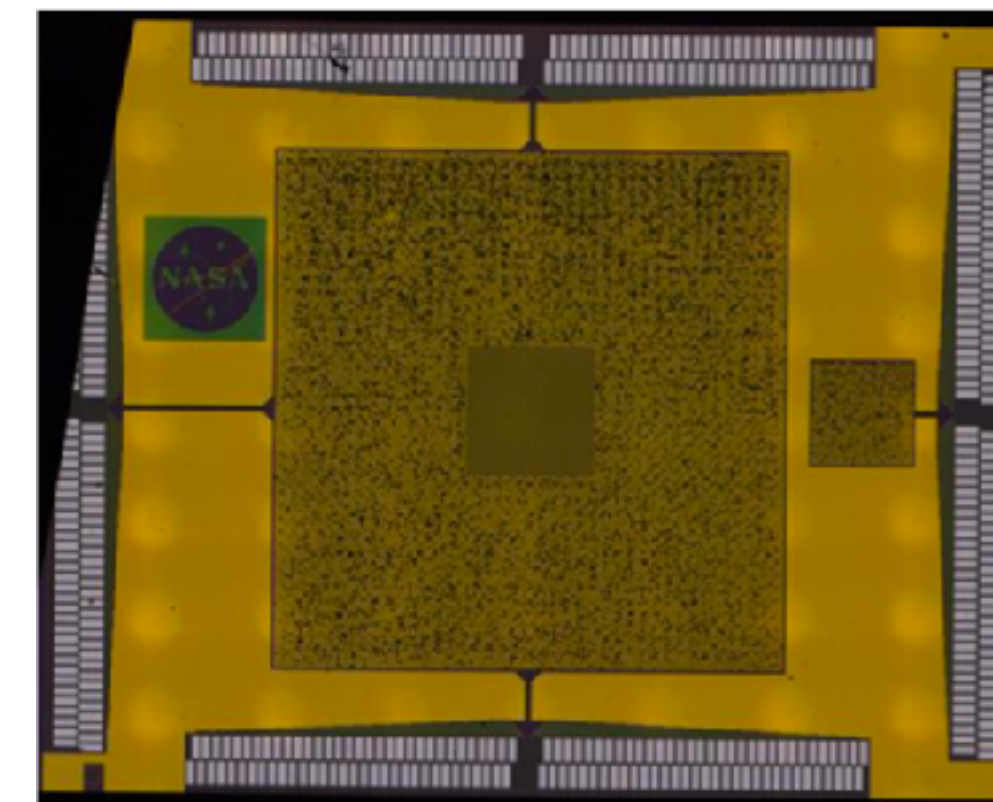
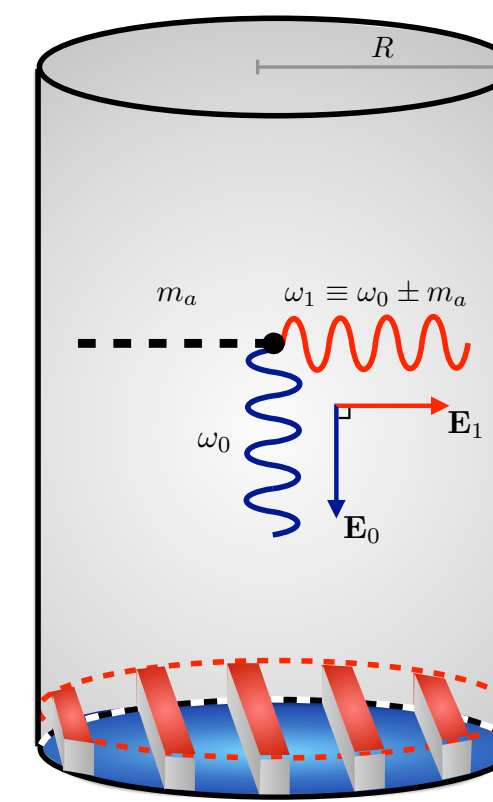
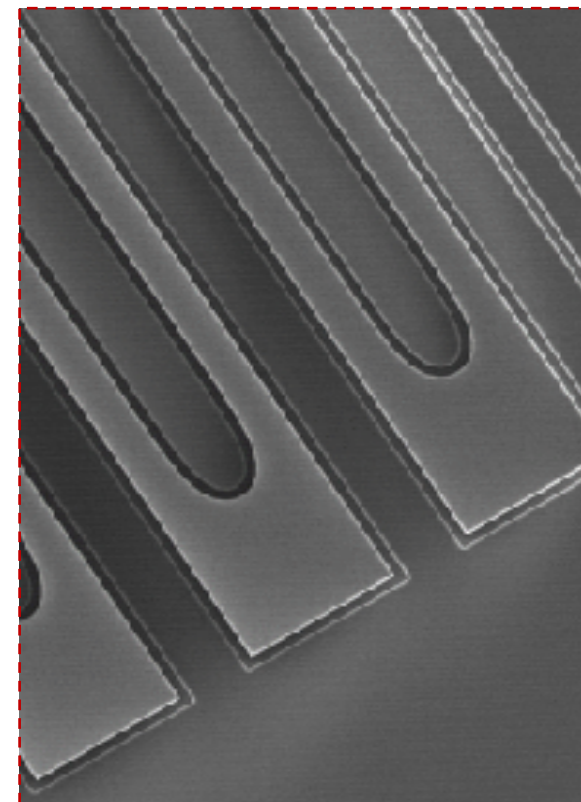
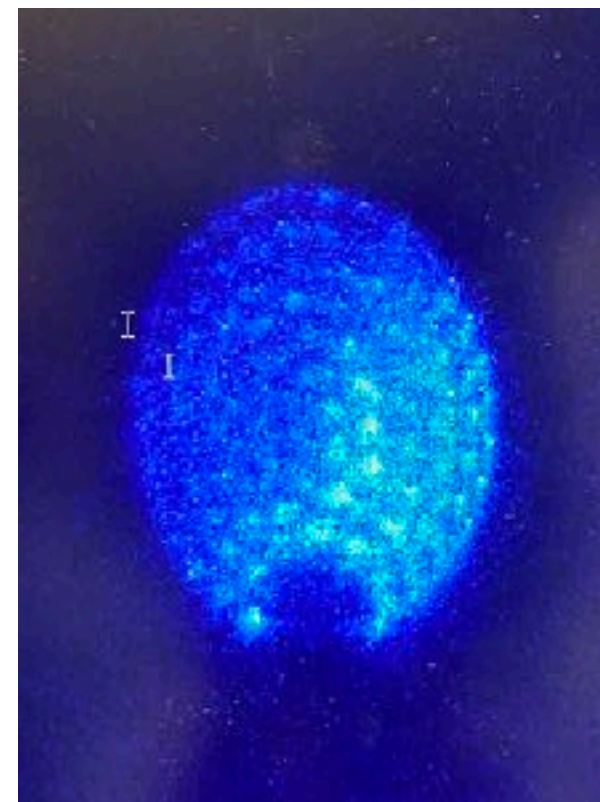
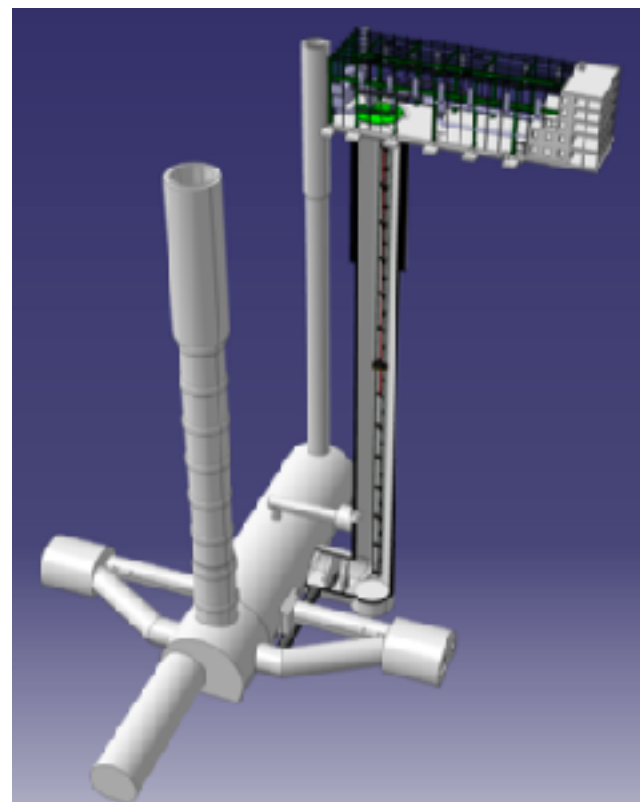
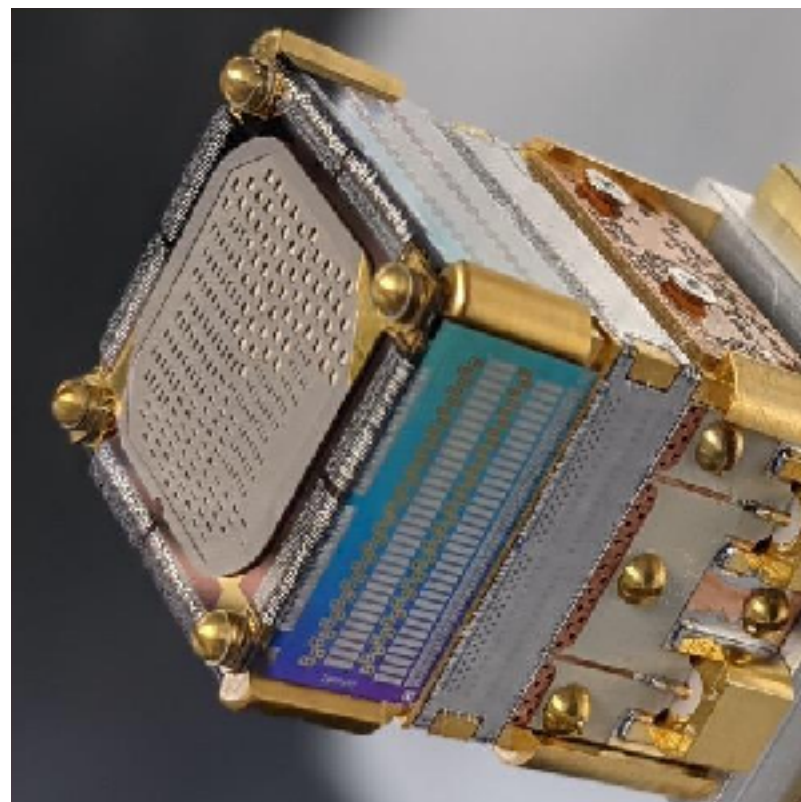
Deutsches Elektronen-Synchrotron (DESY) / Humboldt-Universität zu Berlin

June 17, 2026



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QUANTUM

Center for
Quantum Technology
and Applications

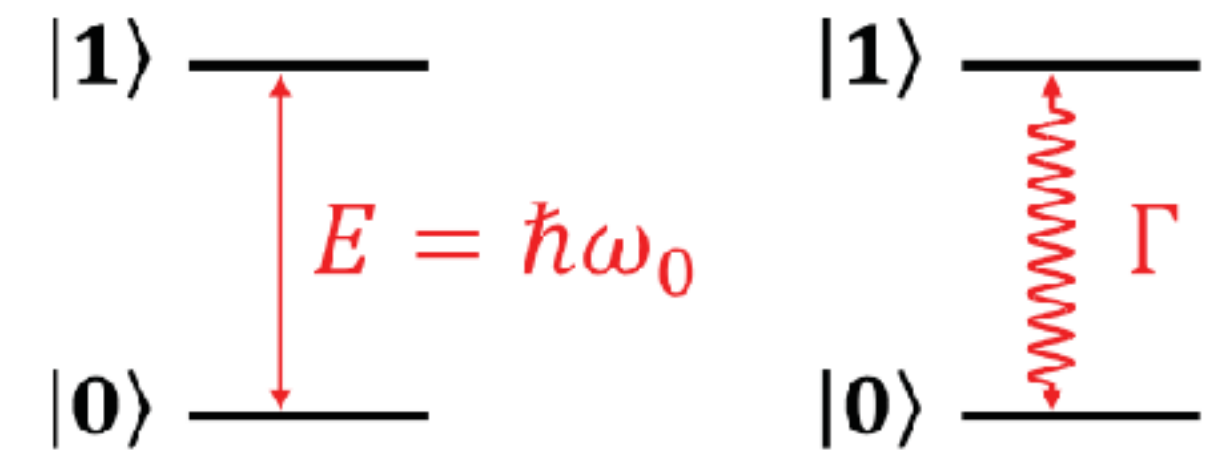


Outline

- **Introduction:** the “What” and “Why” of quantum sensing for Particle Physics
- **Selected quantum sensing techniques**
 - Cryogenic detectors
 - Superconducting devices
 - Spin-based, NV-diamonds
 - Metamaterials, 0/1/2-D materials
 - Ionic / Atomic / Molecular systems
 - Optical atomic clocks
 - Atom Interferometers
 - Magnetometers
- **How to get started in Quantum Sensing:** DRD5 / RDquantum

What is Quantum Sensing?

- **Quantum Sensing:** any sensing device enabled by the ability to manipulate and read out quantum states
- Requirements for a quantum sensor
 - Discrete quantum states (e.g. energy levels $|0\rangle$, $|1\rangle$)
 - Possibility to reset and readout
 - Coherent state manipulation possible (usually)
 - Sensitivity—something measurably changing (e.g. frequency ω_0 or transition rate Γ)
- Note that entanglement/squeezing not required, but can make even better sensors
- Close parallel to DiVincenzo Criteria for Quantum Computing, minus gate requirements
- *Many possible systems:* atoms (neutral, ions, Rydberg states), cavities, atomic clocks, interferometers (photons, matter), superconducting circuits, optomechanical systems, quantum materials



Quantum Detectors, Quantum Experiments

Why quantum sensing?

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

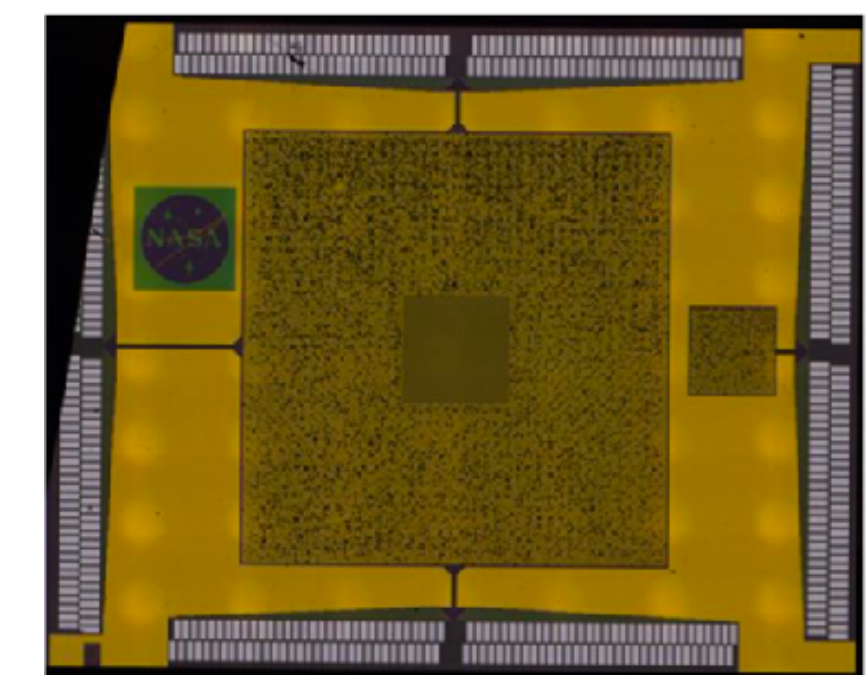
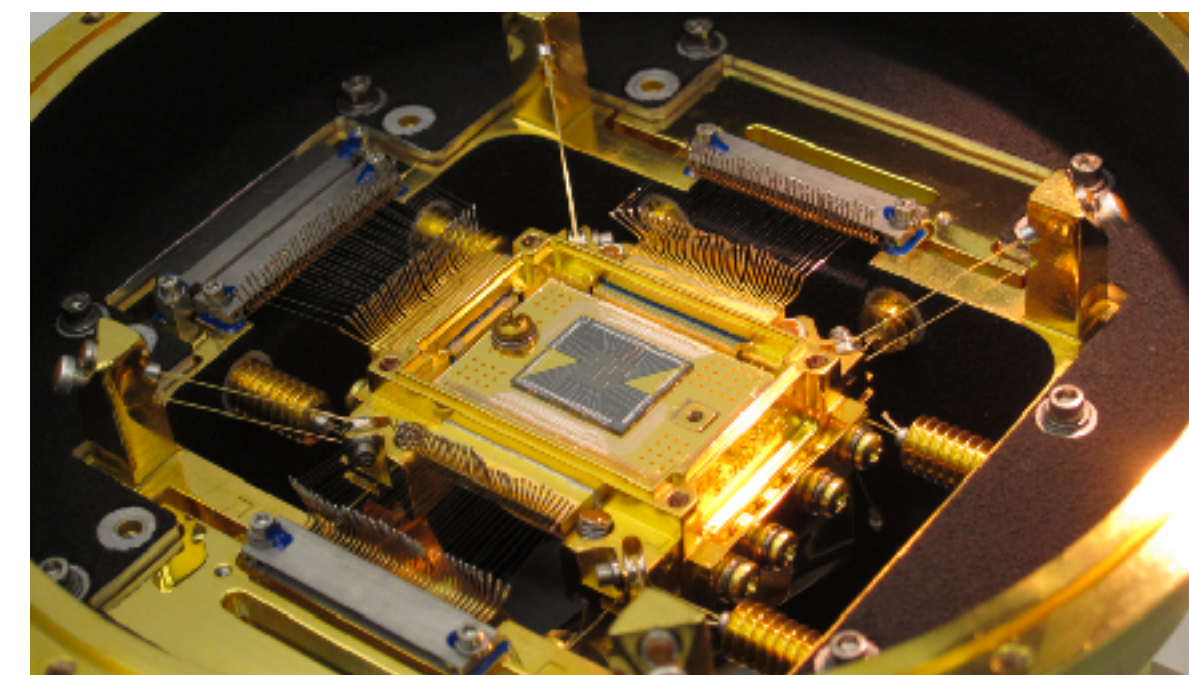
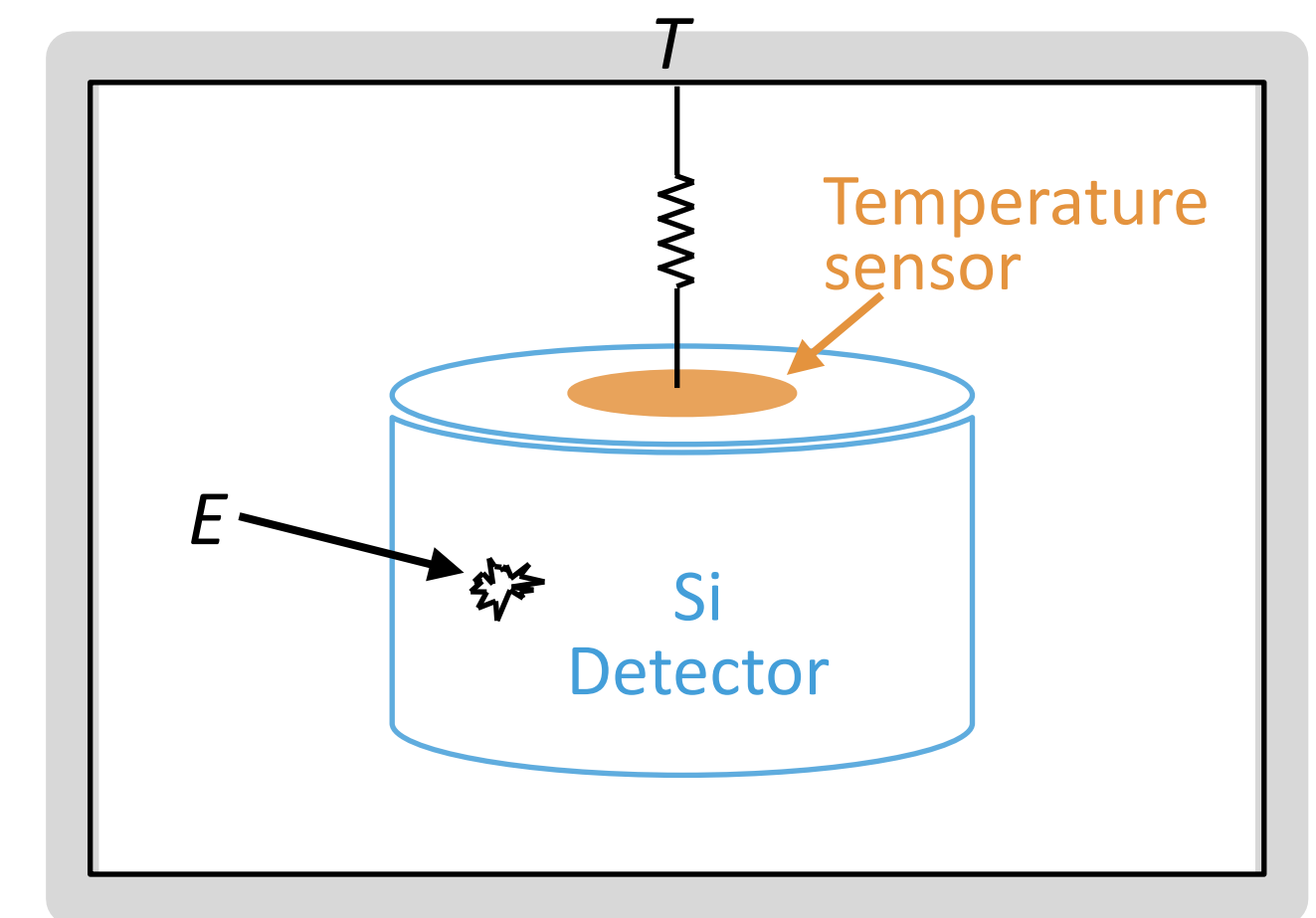
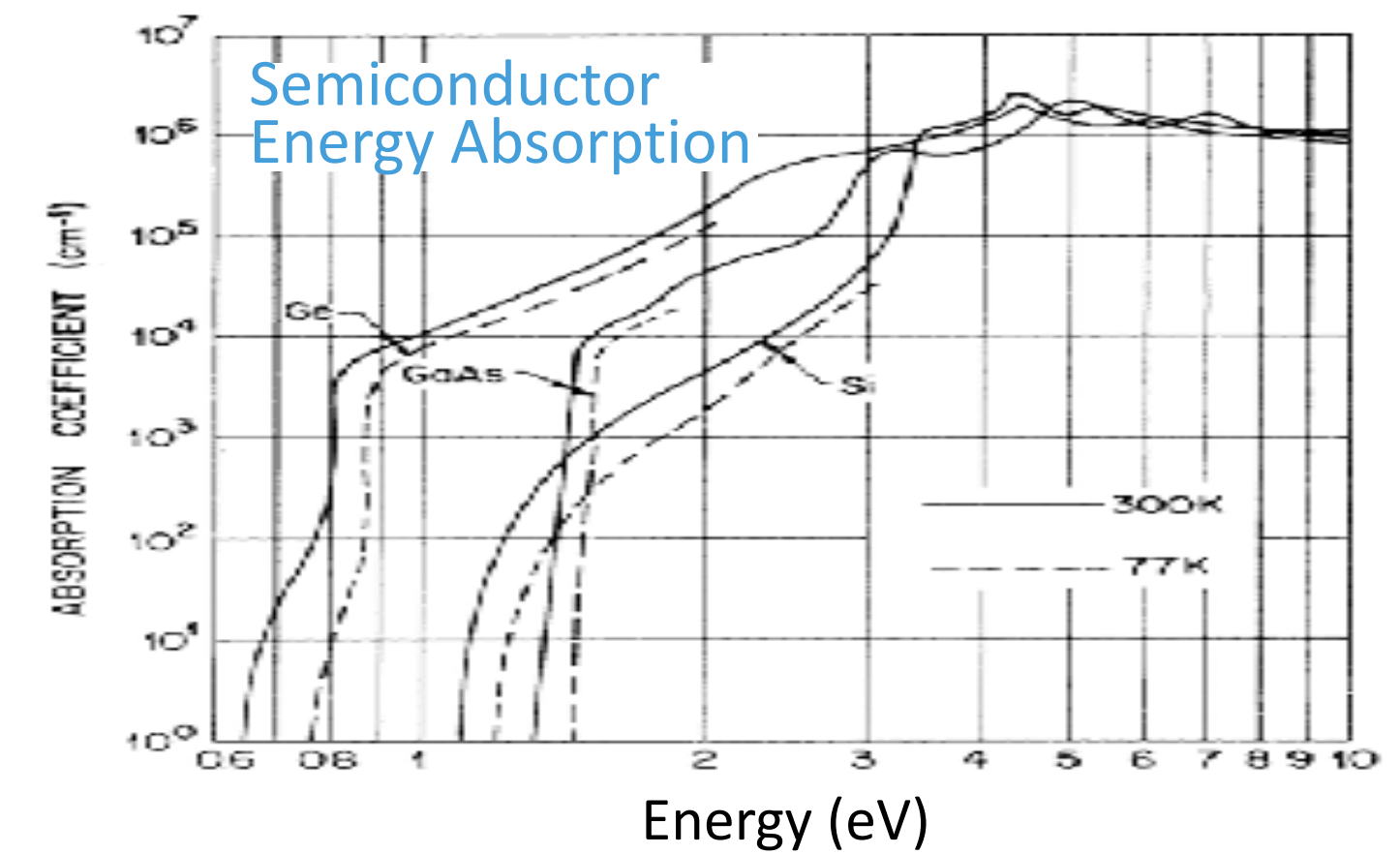


- **Quantum Detectors:** use quantum sensing to making extreme measurements possible
 - Enables (better) measurements, e.g. wavelengths
 - Extreme sensitivities (single-photon) or low noise

- **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

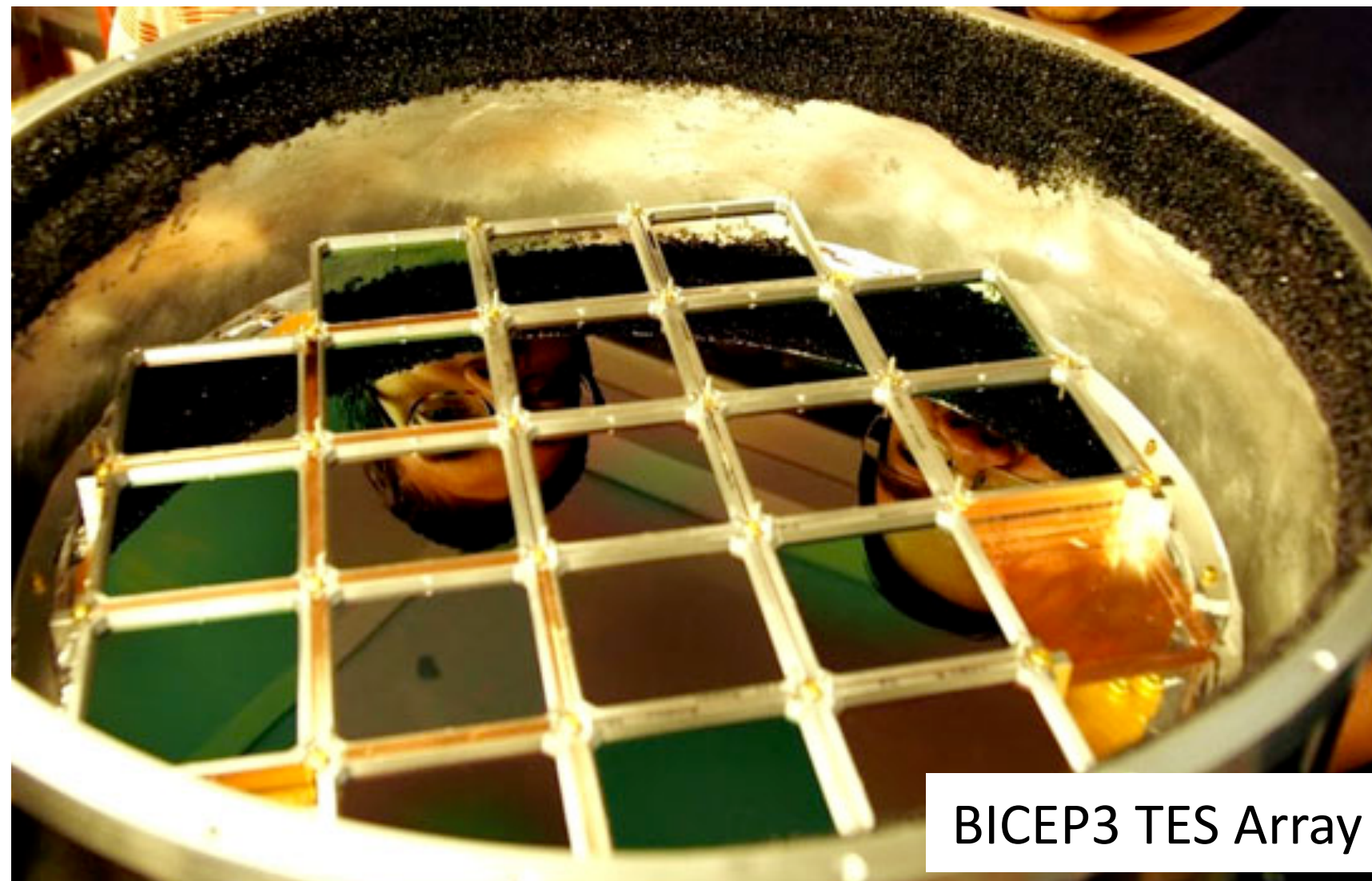
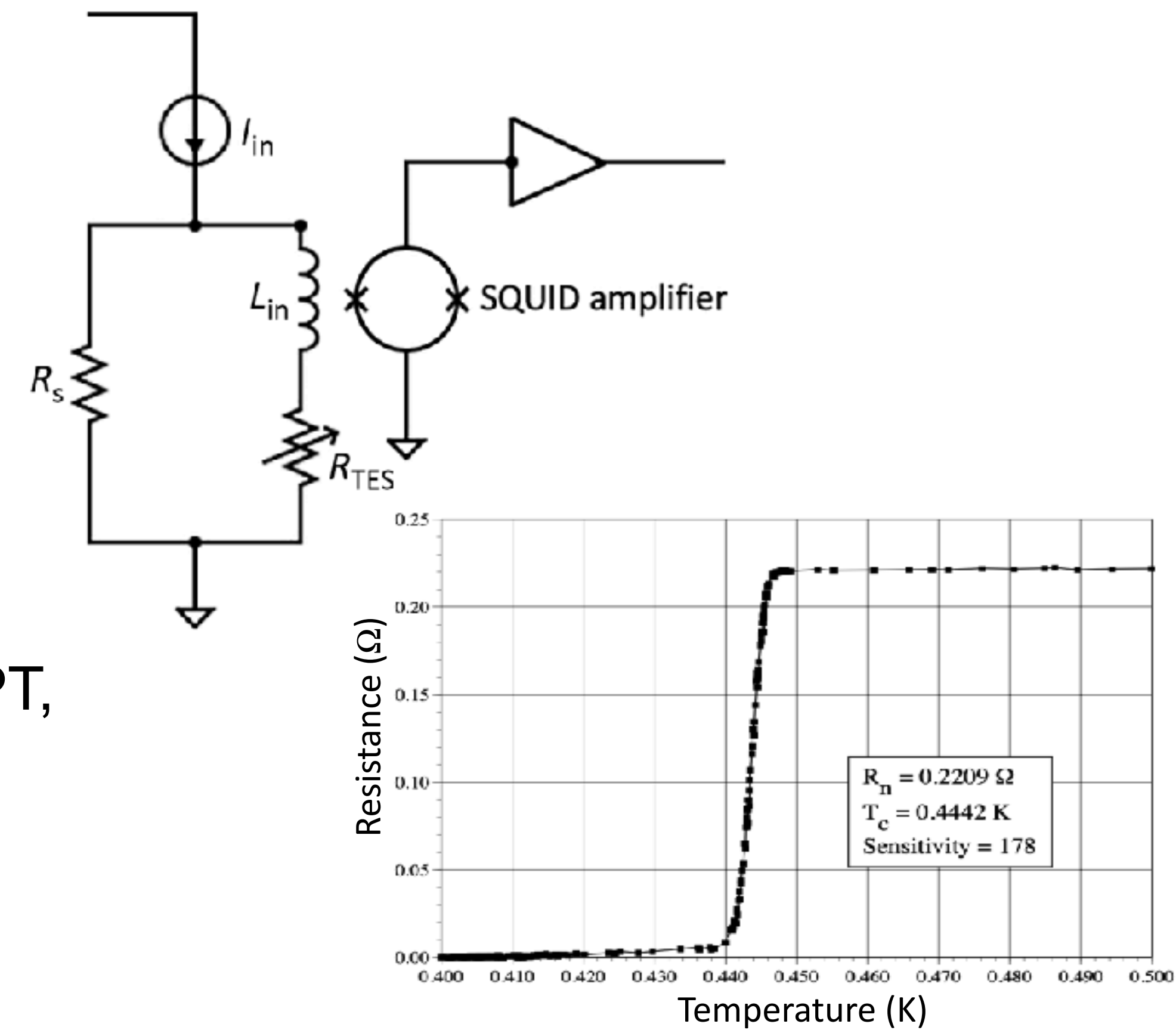
Cryogenic Detectors

- Measuring small temperature differences
 - ΔT depends on energy and heat capacity ($C = c_p m$)
 - Heat capacity given by Debye equation, $C \propto (T/T_D)^3$, $T_D =$ Debye Temp
 - Silicon example: $\Delta T \approx 1\%$ requires mass of $1 \mu\text{g}$ and $T_0 = 0.1 \text{ K}$
- Example 1: Hitomi satellite, SXS (JAXA, CSA)
 - 36 pixels ($814 \mu\text{m}$) HgTe absorber at 50 mK
 - Energy between 0.3 and 12 keV, resolution $\sim 7 \text{ eV}$
- Example 2: Lynx X-ray Microcalorimeter (NASA)
 - $\sim 50\text{k}$ pixels ($25\text{-}50 \mu\text{m}$) Au absorber at 50 mK
 - Energy between 0.2 and 15 keV, resolution $< 3 \text{ eV}$



Transition Edge Sensors (TES)

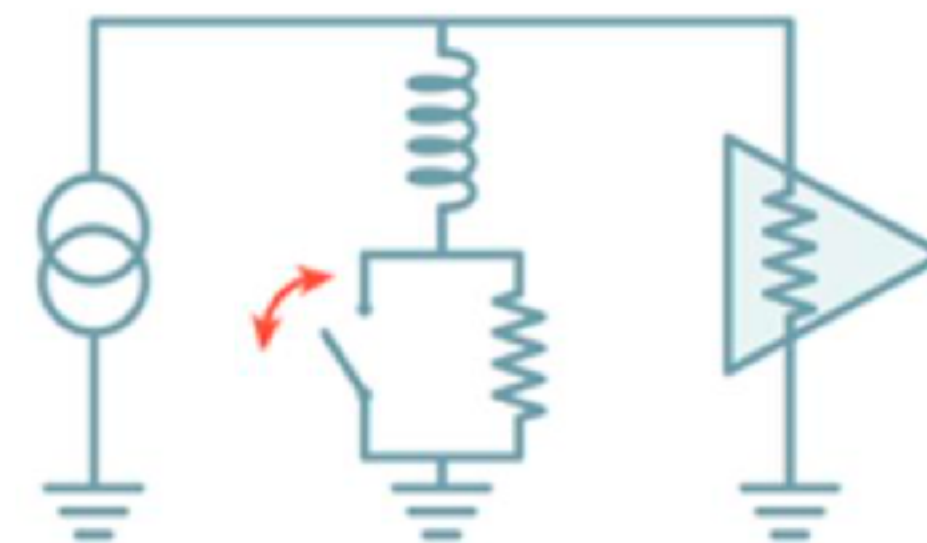
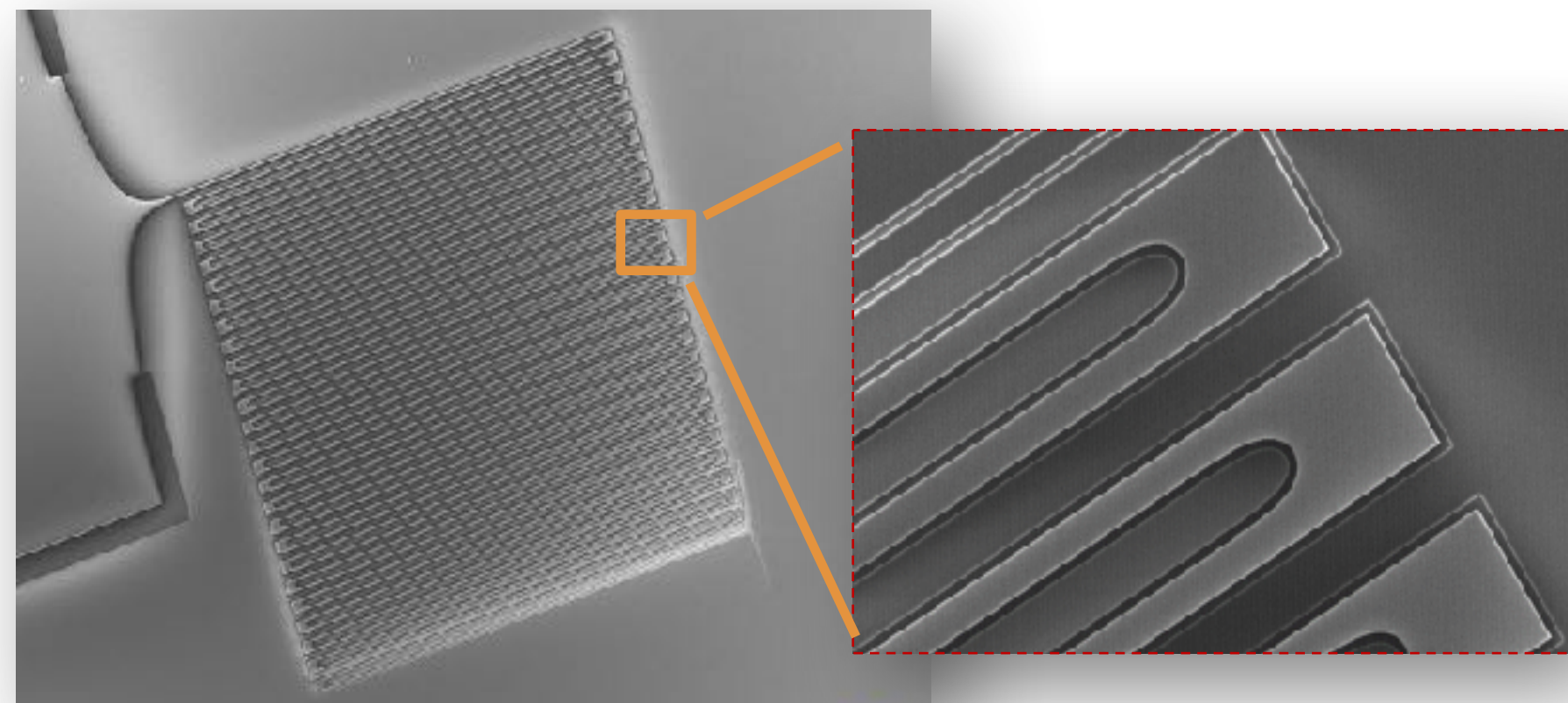
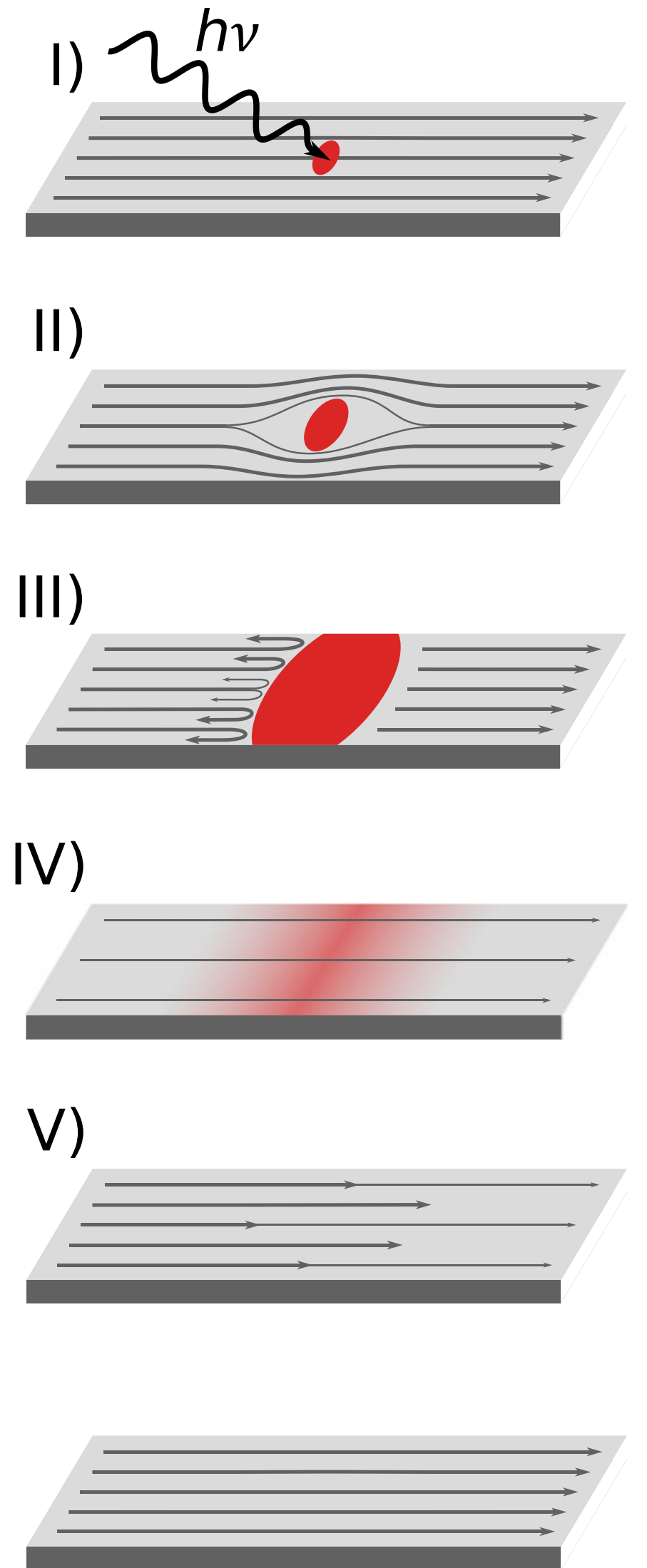
- TES Operations: Measure ΔT with superconducting circuit
 - sharp transition between superconducting \rightarrow conducting
 - small temperature change, large resistance change
 - Detection limited by thermal noise; readout resistance \ll sensor resistance
- Arrays used from radio to X-ray with high spectral resolution (SPT, ATHENA, BICEP) \rightarrow now also particle physics (CDMS, ALPS...)



- Example: BICEP3
 - Used to study Cosmic Microwave Background (B-modes)
 - Monolithic array of 2400 antenna-coupled TES detectors

Superconducting Nanowire Single-Photon Detectors (SNSPD)

- Superconducting circuit (wire) or pads (chicane)
 - Absorbed photons create non-superconducting region
 - Extremely low energy threshold, extremely fast
 - Applications for quantum pixels, ultra-sensitive tracking, milli-charged particles, calorimetry
- Recent advances
 - Higher temperature operation (>few K)
 - Demonstrated to work for micron size (optical lithography possible)
 - Commercial devices available - quantum communication



SNSPD: Advances & Expected Performance

Timing jitter	Intrinsic photon number resolution	Efficiency	Array size	Maximum count rate	Dark count rate	Active area	Cut-off wavelength
18 ps	None	93%	64	1 Gcps	4 /s/mm ²	0.001 cm ²	5 μm
↓ [1] 2.6 ps	↓ 3-5 photons	↓ [2] 98%	↓ [3] 4x10 ⁵	↓ [4,5] 1.5 Gcps	↓ [6] 4x10 ⁻⁵ /s/mm ²	↓ [3] 0.1 cm ²	↓ [7] 29 μm
1 ps	10	99 %	10 ⁷	10 Gcps	1x10 ⁻⁶ /s/mm ²	1 cm ²	100 μm

Records in 2016

Current records for isolated devices

Expected performance by 2030

[1] Korzh, Zhao et al, *Nature Photonics* 14, 250 (2020)

[2] Reddy et al, *Optica* 7, 1649 (2020)

[3] Oripov, Rampini, Allmaras, Shaw, Nam, Korzh, and McCaughan, *Nature* 622, 730 (2023)

[4] Craiciu, Korzh et al, *Optica* 10, 183 (2023)

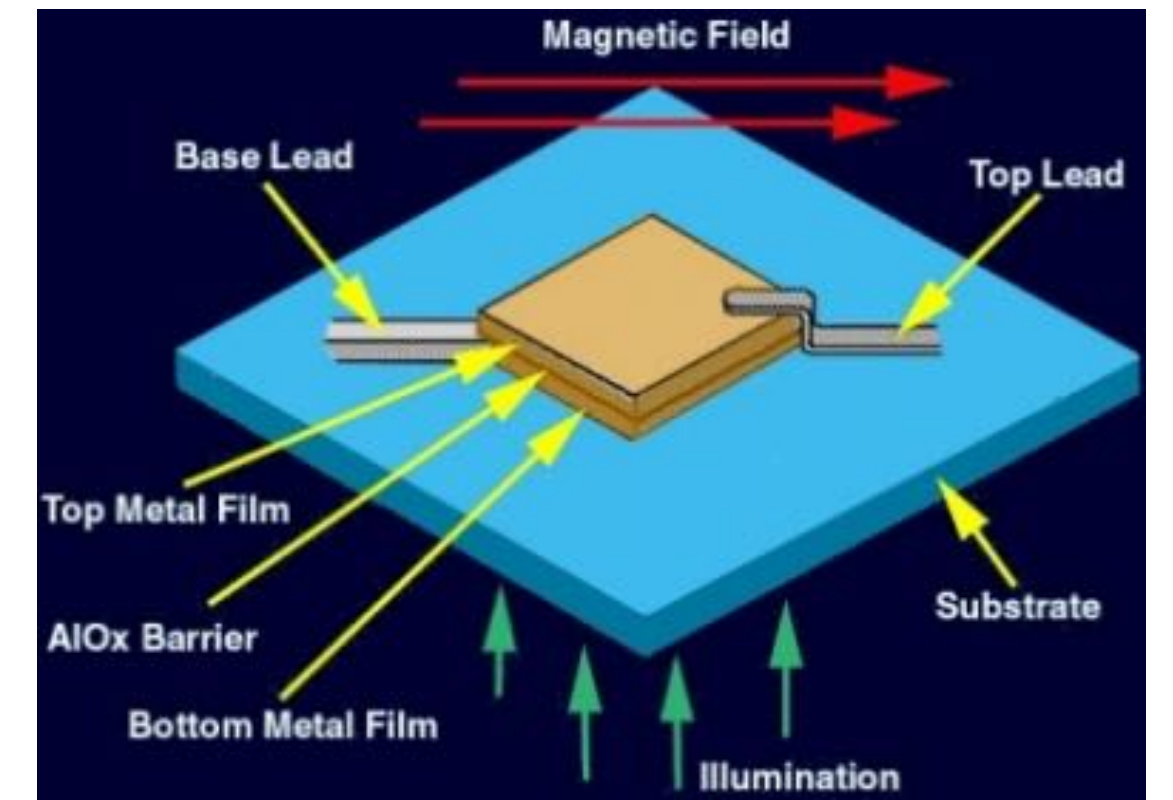
[5] Resta et al, *Nano Letters* (2023)

[6] Chiles, *PRL* 128, 231802 (2022)

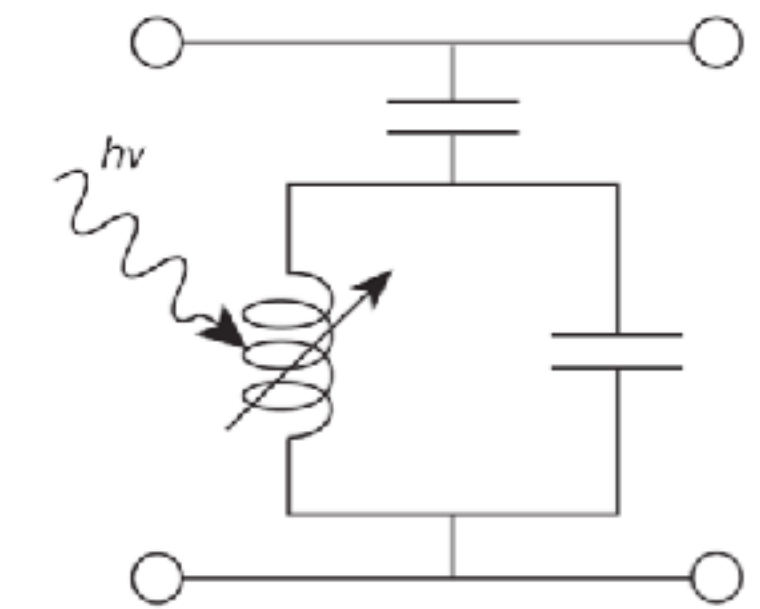
[7] Taylor, Walter, Korzh et al, *Optica*, (2023)

Cryogenic Quantum Sensors

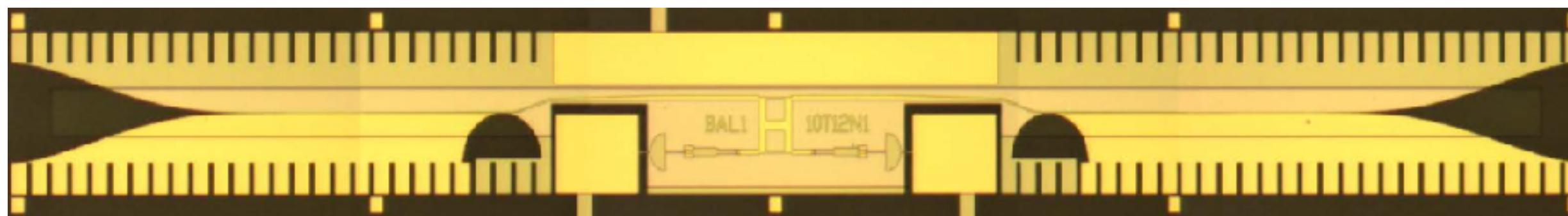
- Superconducting Tunnel Junctions (STJ)
 - Exploit quantum tunnelling in a junction of two superconductors
 - Direct tunnel current measurement (non-Heterodyne): simultaneous fast photon counting and spectroscopy in IR, Vis, UV bands
- Microwave Kinetic Inductance Detectors (MKIDs)
 - Exploits change in phase of an inductor capacitor (LC) oscillator in thin superconductor
 - Read-noise free, easier multiplexing: arrays of ~10k under test
- Superconductor-Insulator-Superconductor (SIS) receivers
 - Enabling technology for sub-mm Astronomy
 - Superconducting circuits allow phase coherent downconversion THz \rightarrow GHz



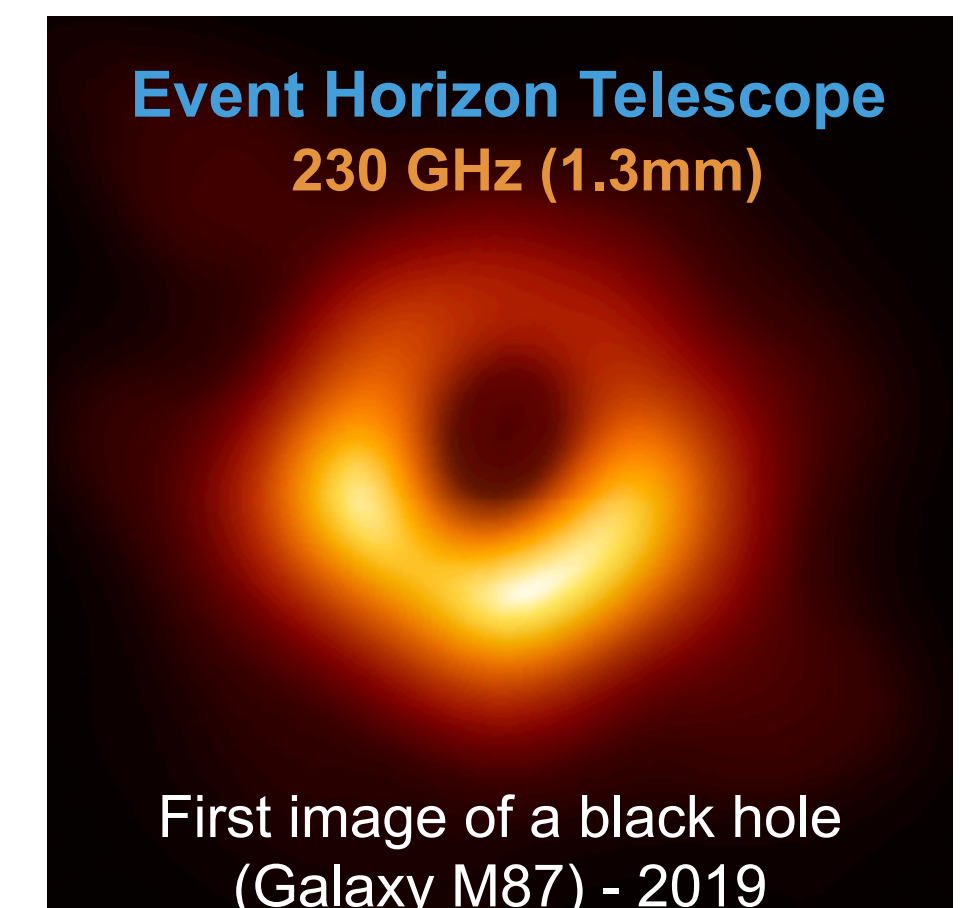
Superconducting Tunnel Junction



MKID operating principle



Superconductor-Insulator-Superconductor (SIS) Mixer Block

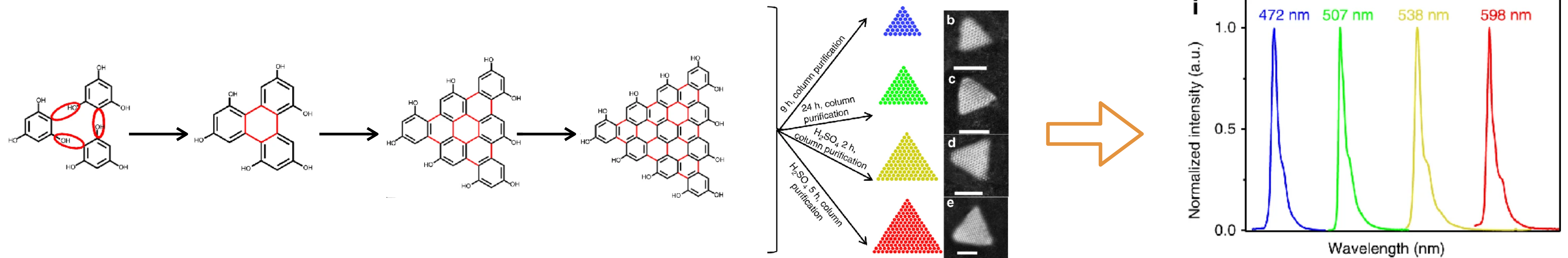


Cryogenic Quantum Sensors vs. Wavelength

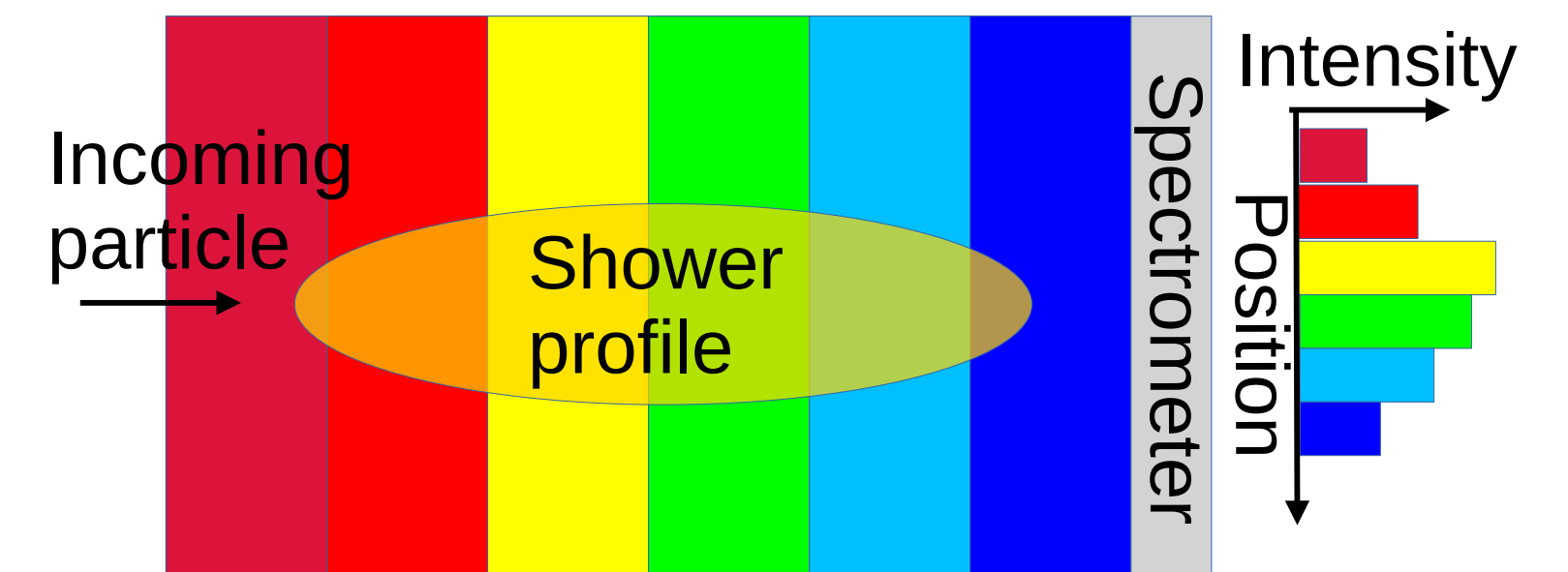
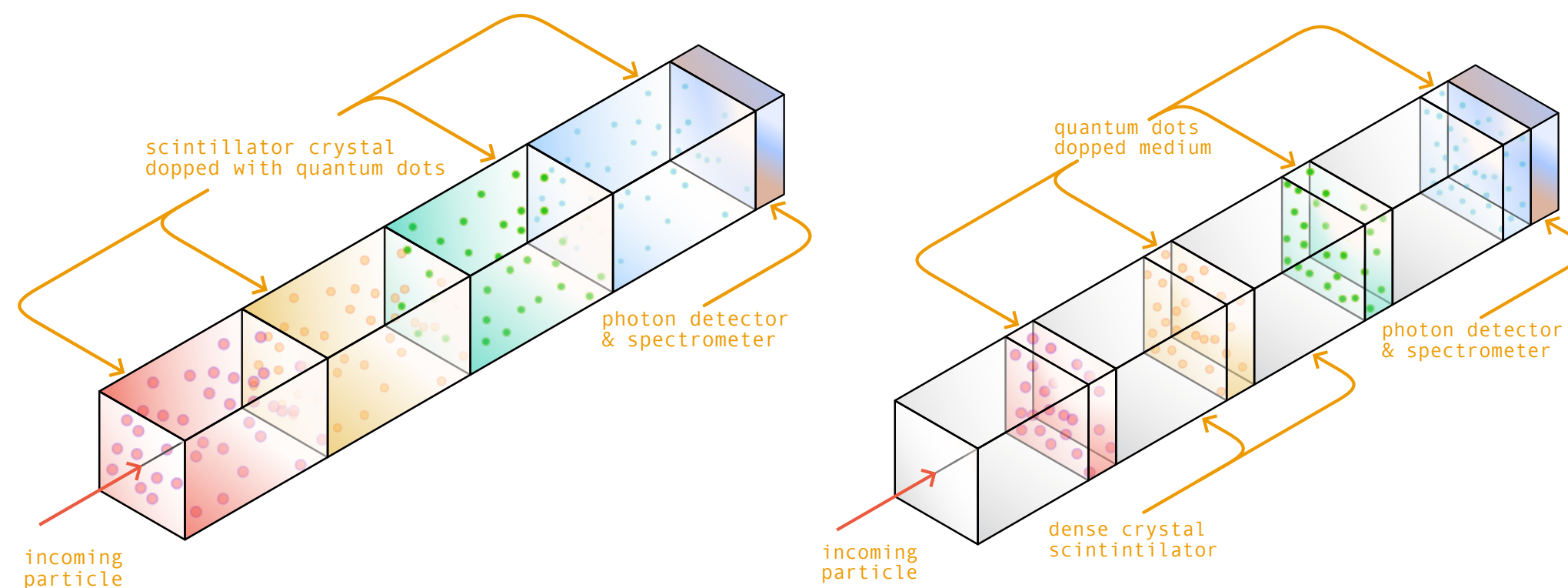
Detector	Microwave	Submillimeter	Far infrared	Optical	High Energy
	3cm - 3mm 10-100 GHz 0.04-0.4 meV	3mm - 300 μ m 100 GHz - 1 THz 0.4-4 meV	300 – 30 μ m 1 – 10 THz 4-40 meV	2 μ m - 300 nm 2-37 eV	UV, X-Ray
Transition Edge Sensors (TES)	●	●	●	●	●
Kinetic Inductance Detectors (KID)	●	●	●	●	
Superconducting Nanowire Single-Photon Detector (SNSPD)			●	●	
Hot-Electron Bolometer (HEB)			●		
Cold-Electron Bolometer (CEB)		●			
Superconductor-Insulator-Superconductor (SIS)		●			
Travelling Wave Parametric Amplifier (TWPA)	●	●			
Josephson Junction Parametric Amplifiers (JJPA)	●				

Quantum Dots and Chromatic Calorimetry

- **Quantum dots:** nanometer-sized semiconductor structures, e.g. in carbon, perovskites, etc.
- Tuneable, with properties between single atoms and bulk material

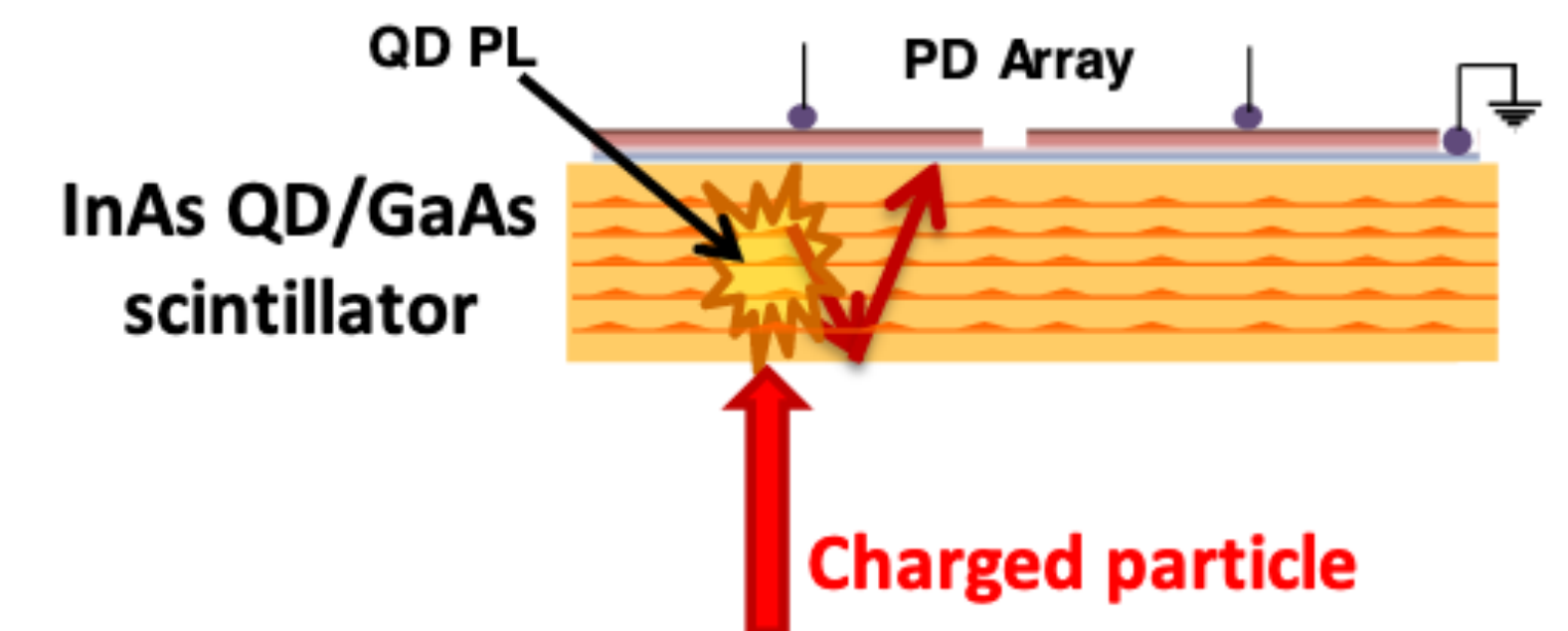
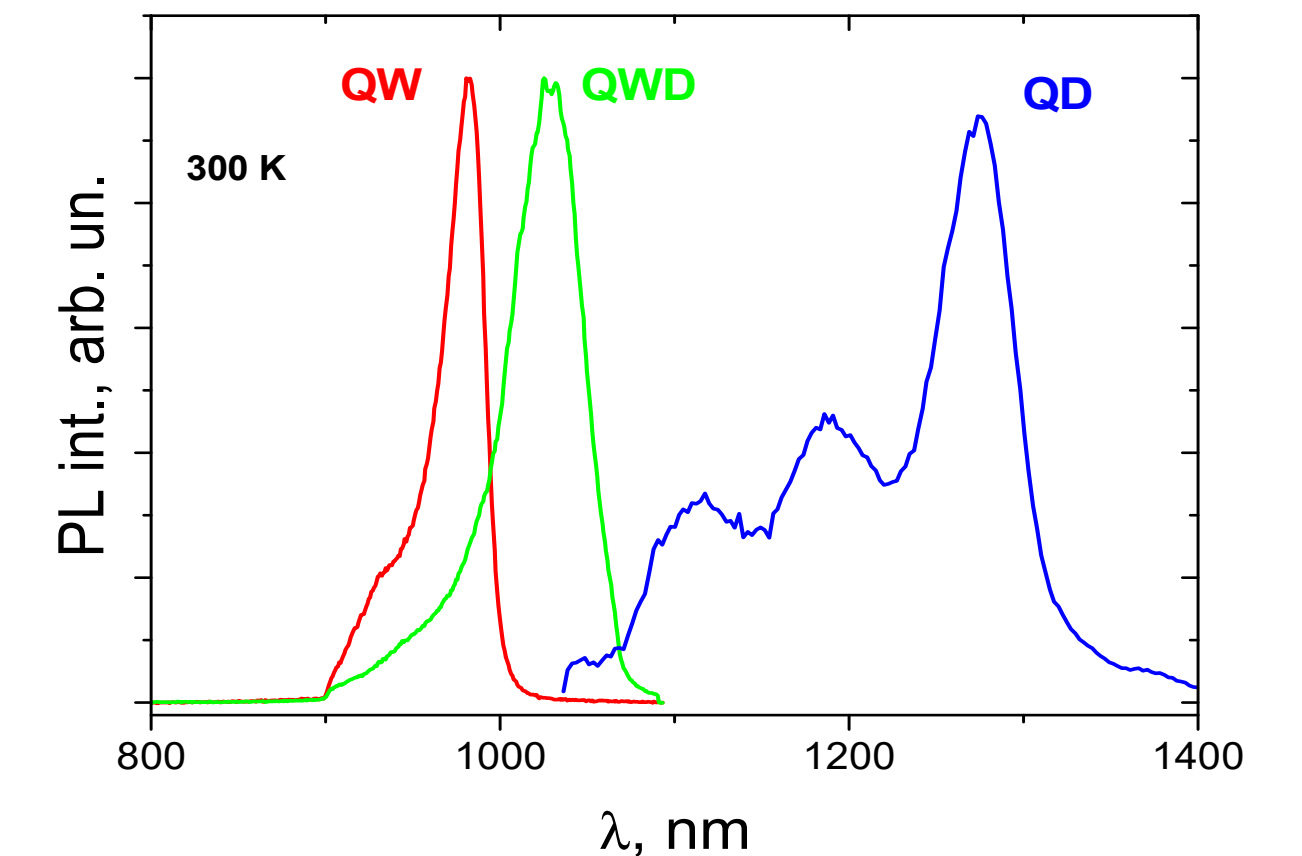
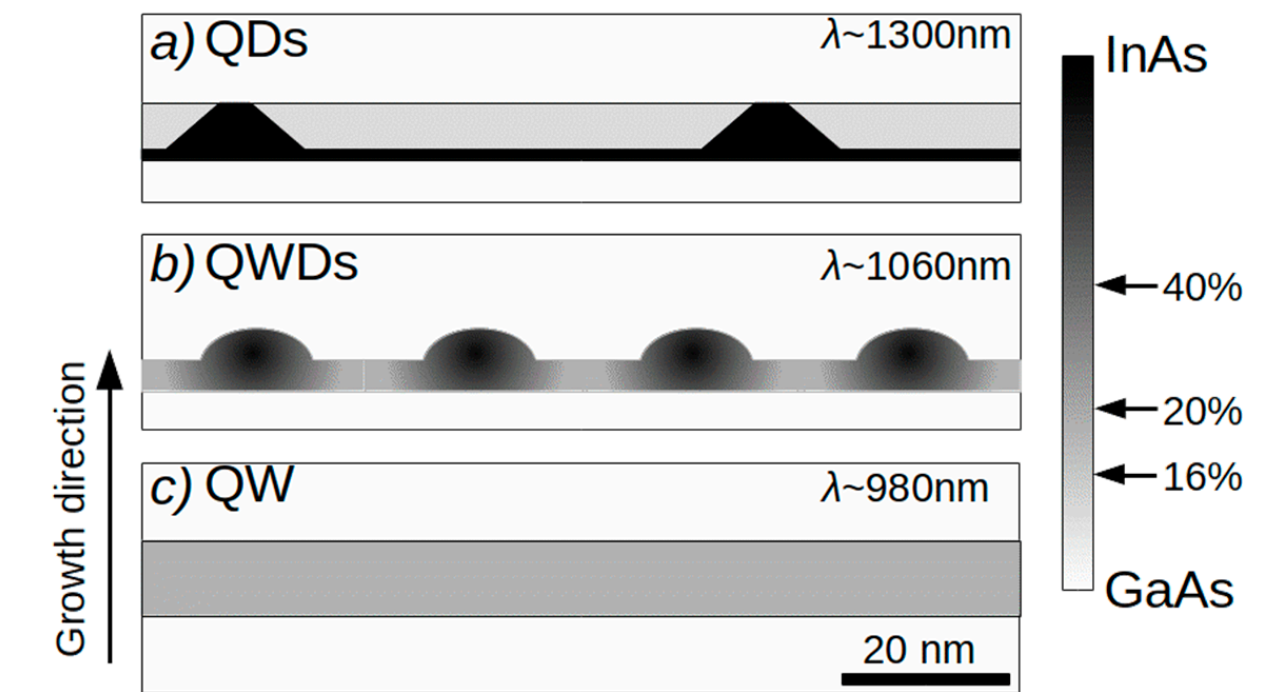


- Seed different parts of a detector with nanodots emitting at different wavelengths
- Wavelength of fluorescence photon indicates specific nanodot position: shower profile from spectrometry



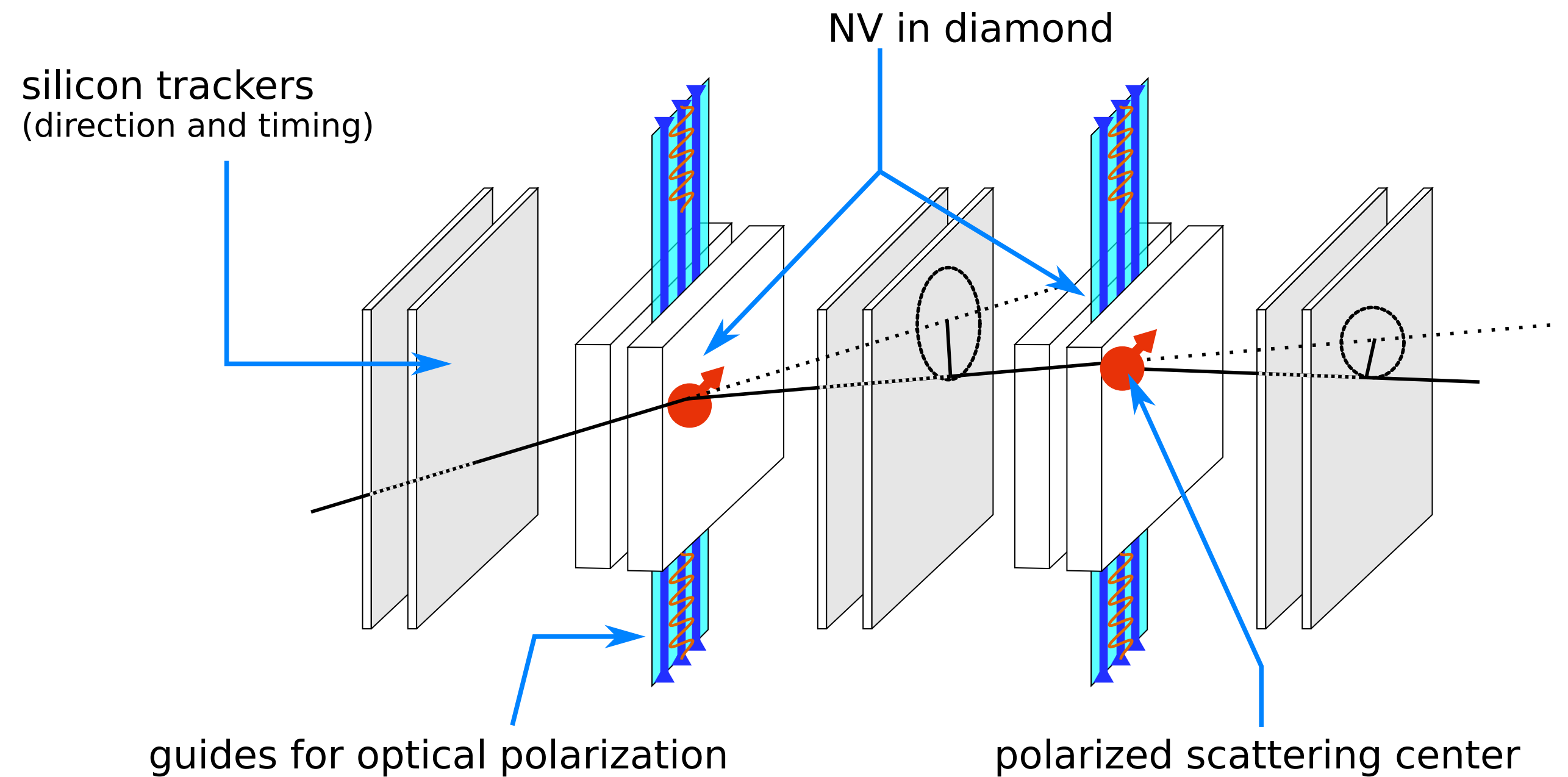
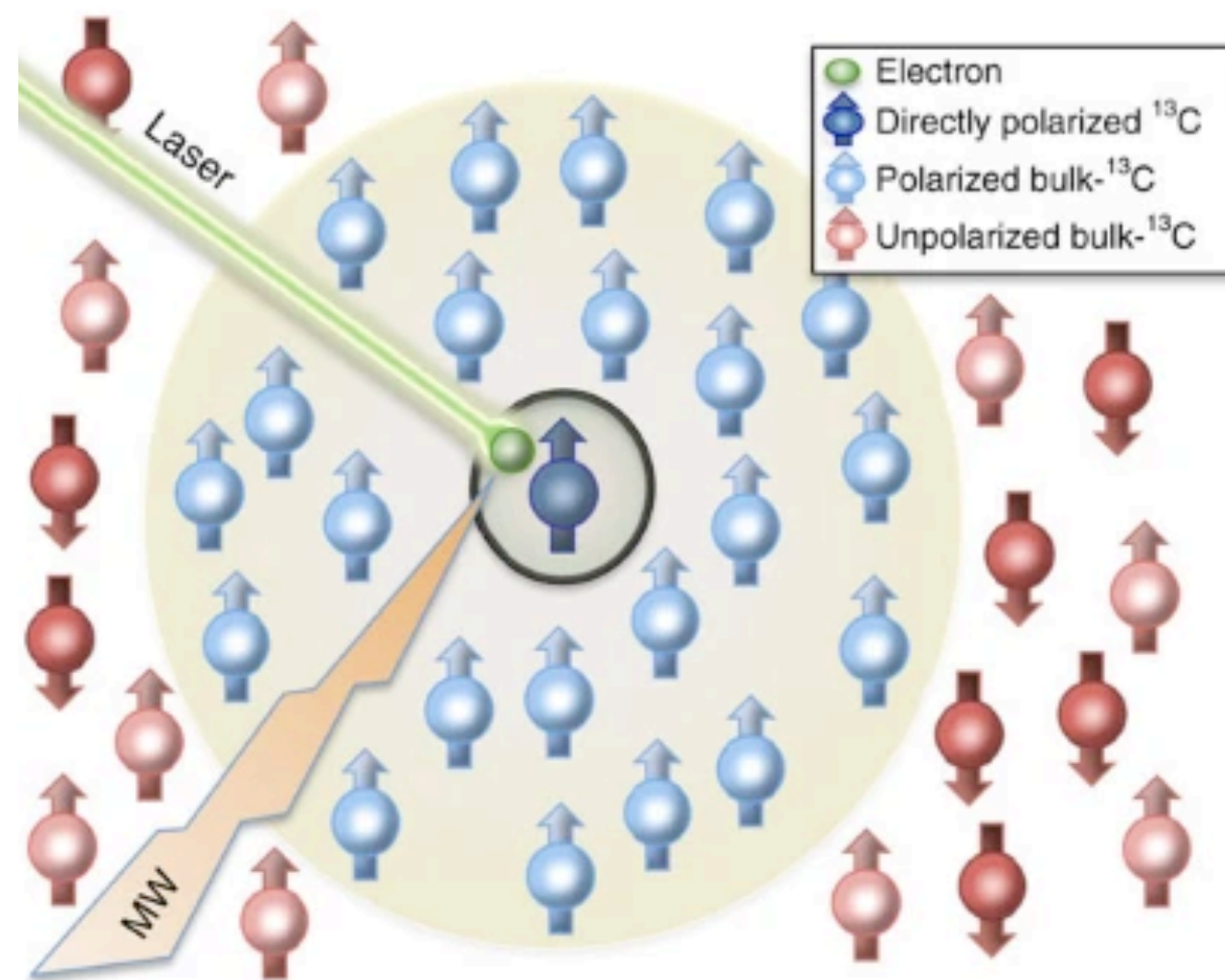
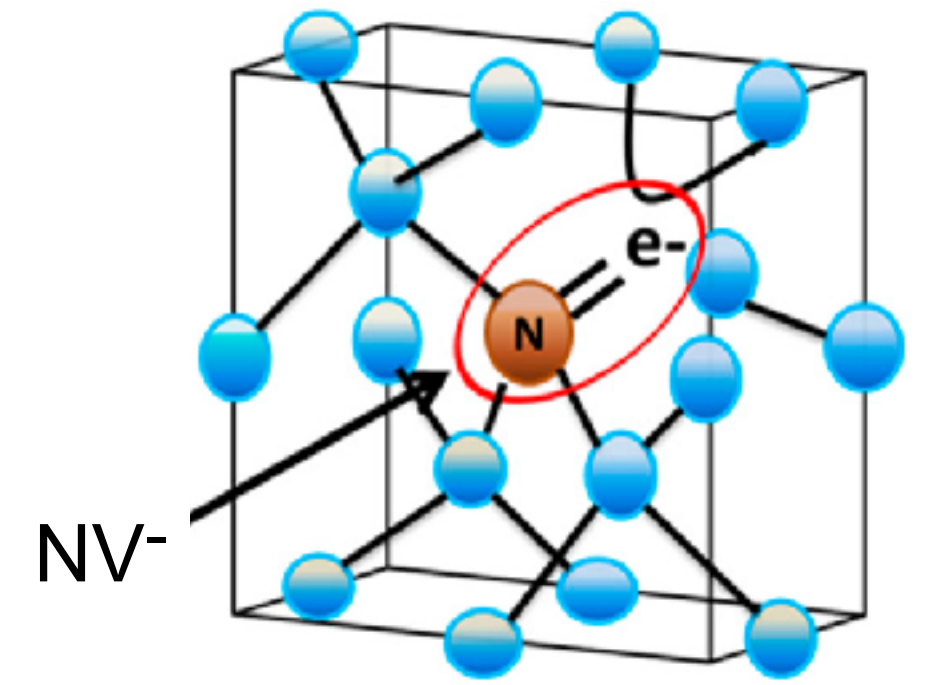
Quantum Dots: Active Scintillators & Tracking

- Quantum Dots, Quantum Wires, Quantum Wells... many structures possible
- Quantum Well-dots: aiming for active scintillators
 - electronic amplification / modulation
 - pulsed / primed operation
 - gain adapted in-situ
- Quantum Dots in CMOS pixels: DoTPIX
 - n-channel MOS transistor + buried quantum well gate
 - gate collects holes, modulates current
- Tracking with Quantum Dots: Scintillating (Chromatic) Tracking
 - GaAs bulk to generate e/h pairs, InAs quantum dots to trap charge
 - Dots emit photons from photoluminescence, collected by photodiode



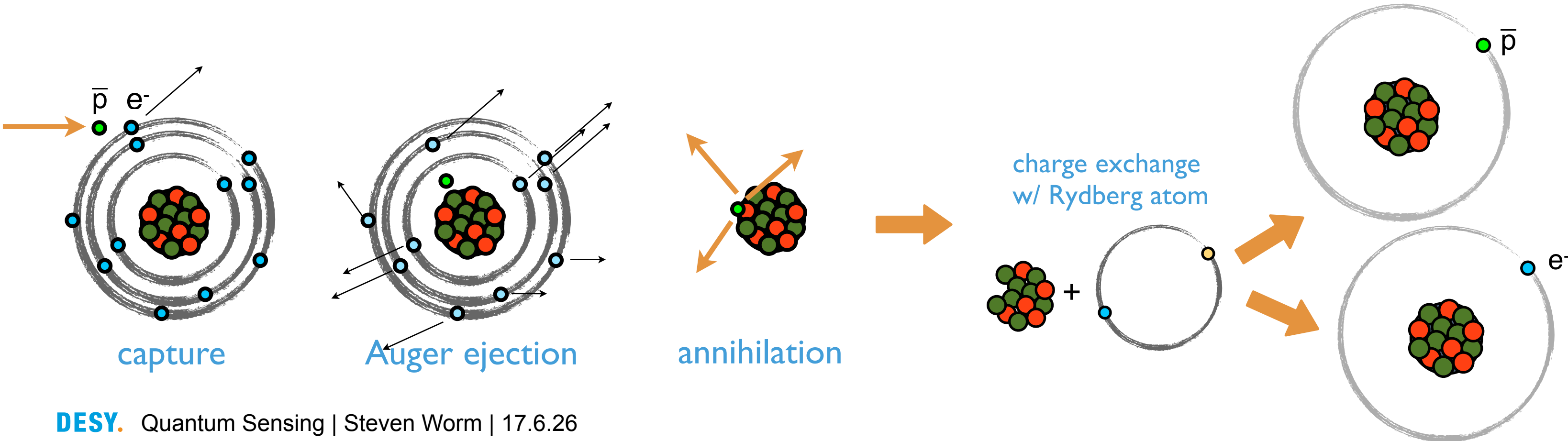
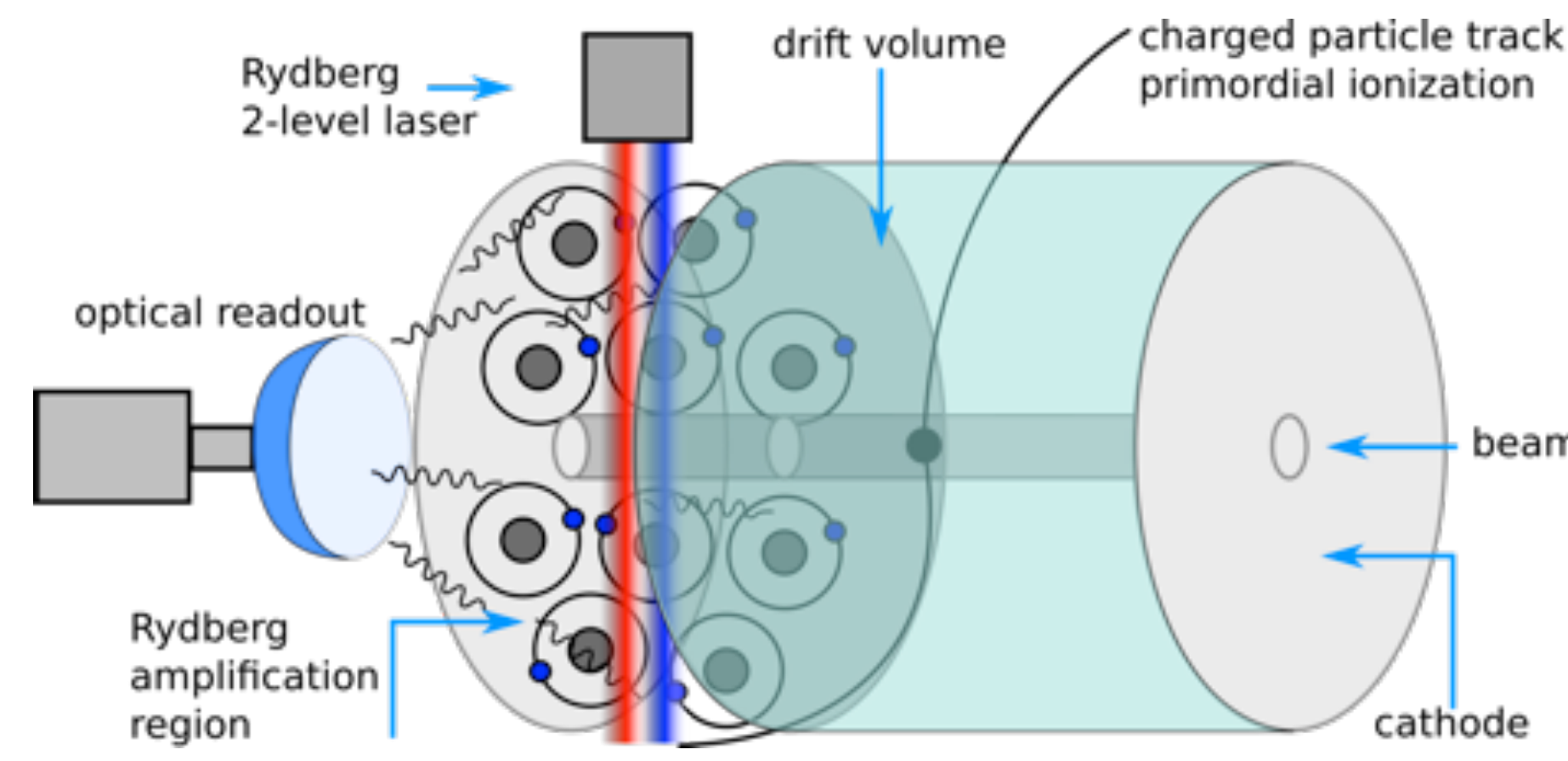
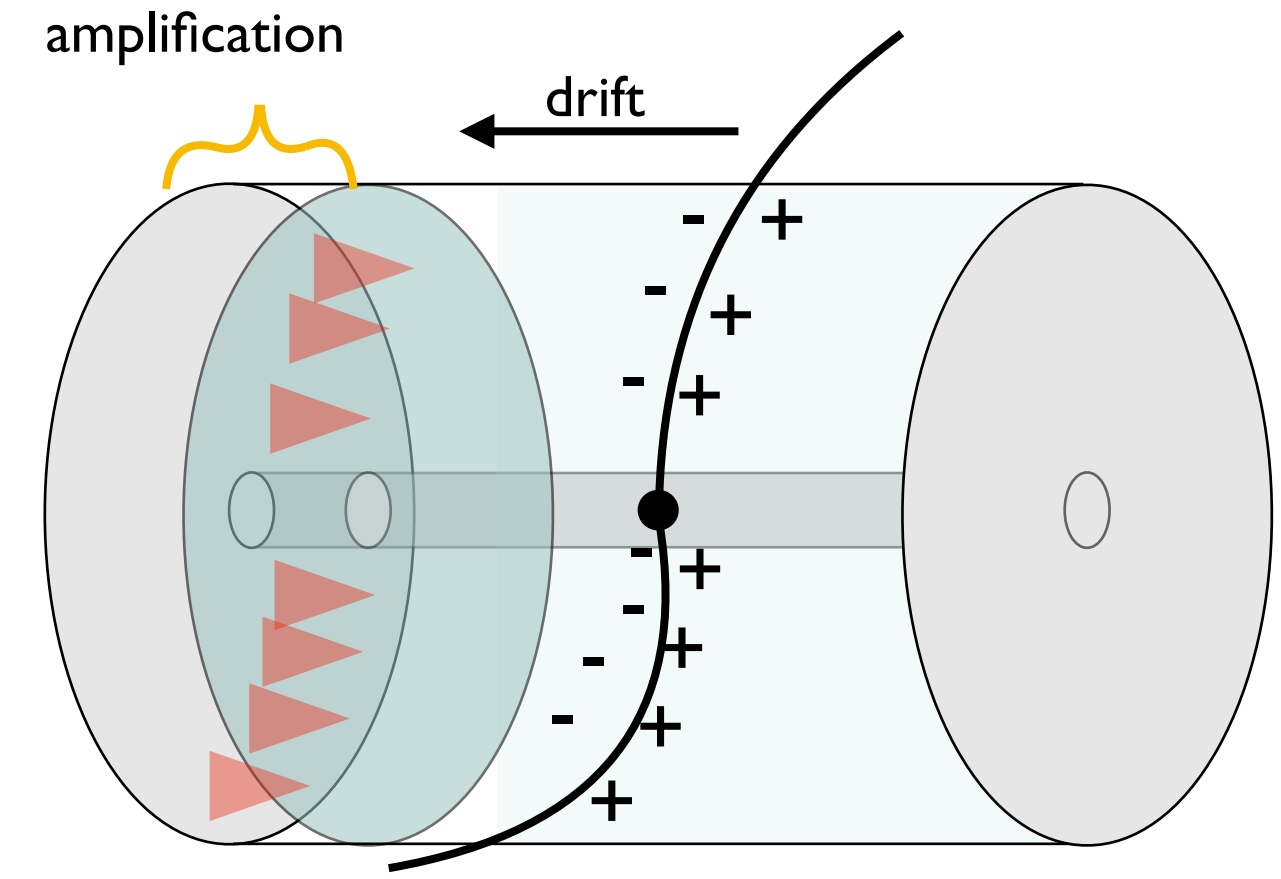
Quantum-Polarized Helicity Detection in NV Centres

- Photoluminescent point defect in diamond nitrogen-vacancy centres (NV⁻)
 - Spin-dependent photoluminescence to measure electronic spin state
 - Relatively long (millisecond) spin coherence at room temperature
- Spin-spin scattering for helicity determination
 - Usually requires polarized beams and/or polarized targets
 - Polarized scattering planes possible to measure track-by-track particle helicity



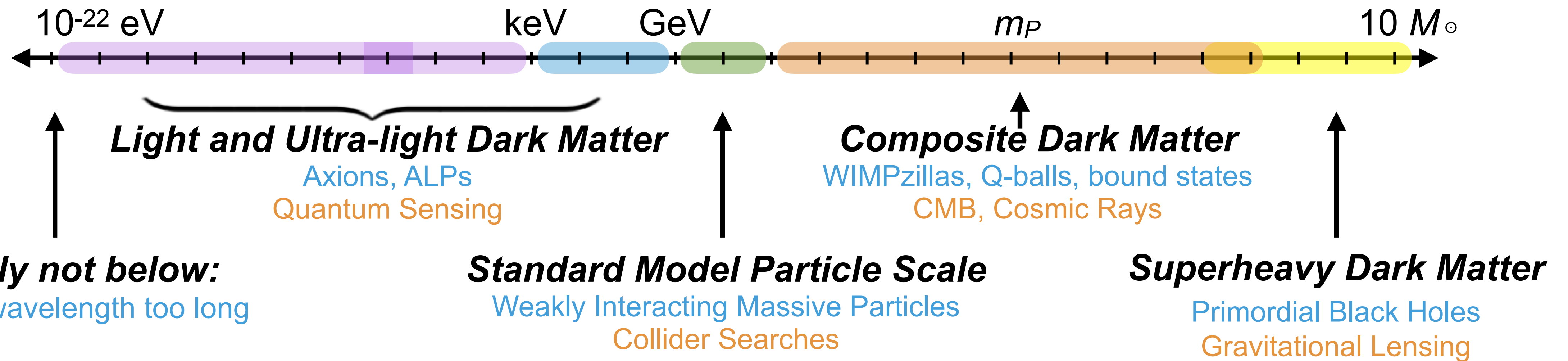
Quantum Sensing and Rydberg Atoms

- Rydberg atoms: highly excited valence electrons
- Rydberg readout of a Time Projection Chamber
 - Up-convert THz / GHz radiation → optical readout
 - Larger signal via Rydberg “priming” in amplification
 - Lower ionization threshold → higher electron yield
- Antiprotonic atoms and novel Highly Charged Ion systems
 - Anti-proton tests in Penning trap for HCl or molecules
 - Tests of QED, CPT, fundamental constants, fifth force, precision isotope shift (King plot), EDM measurements



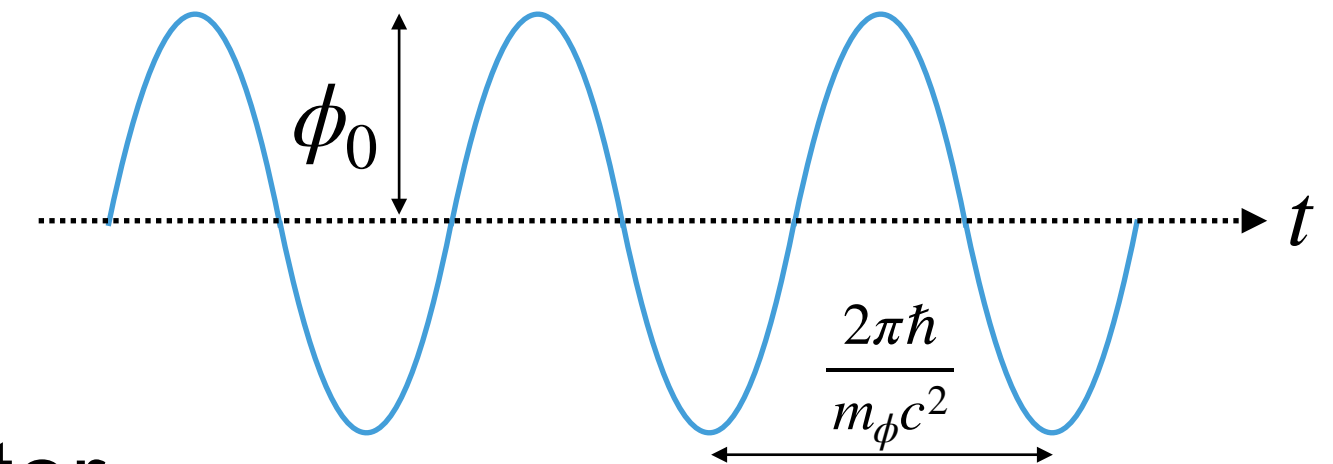
Quantum-enabled Experiments & Ultra-light Dark Matter

Quantum Sensing needed for Light/Ultralight Dark Matter



Ultra-Light Dark Matter: Phenomenology

- Starting with Standard Model Lagrangian, adding **new DM interaction** (field)
- **Bosonic**: Ultra-light DM must be bosonic in nature
- **Non-relativistic** ($\sim 10^{-3}c$): so it neither leaves the galaxy or clumps near the center
- **Oscillating classical field**: coherent, practically monochromatic \rightarrow wave-like



$$\phi(t) \approx \phi_0 \cos(m_\phi c^2 t / \hbar)$$

$$\mathcal{L}_{int} = \frac{4\pi\phi}{M_{pl}} \left(\frac{d_e}{4e^2} F_{\mu\nu} F^{\mu\nu} - d_{m_e} m_e \bar{e} e - \frac{d_g \beta_3}{2g_3} G_{\mu\nu}^A G^{A\mu\nu} - \sum_{i=u,d} (d_{m_i} + \gamma_{m_i} d_g) m_i \bar{\psi}_i \psi_i \right)$$

- Coupling to Lagrangian is linear (in ϕ) for lowest order interaction w/ scalar field (or quadratic with $\phi \leftrightarrow -\phi$ symmetry)

$$\mathcal{L}_{DM} = \frac{\phi}{\Lambda_\gamma} \frac{F_{\mu\nu} F^{\mu\nu}}{4} - \frac{\phi}{\Lambda_e} m_e \bar{\psi} \psi$$

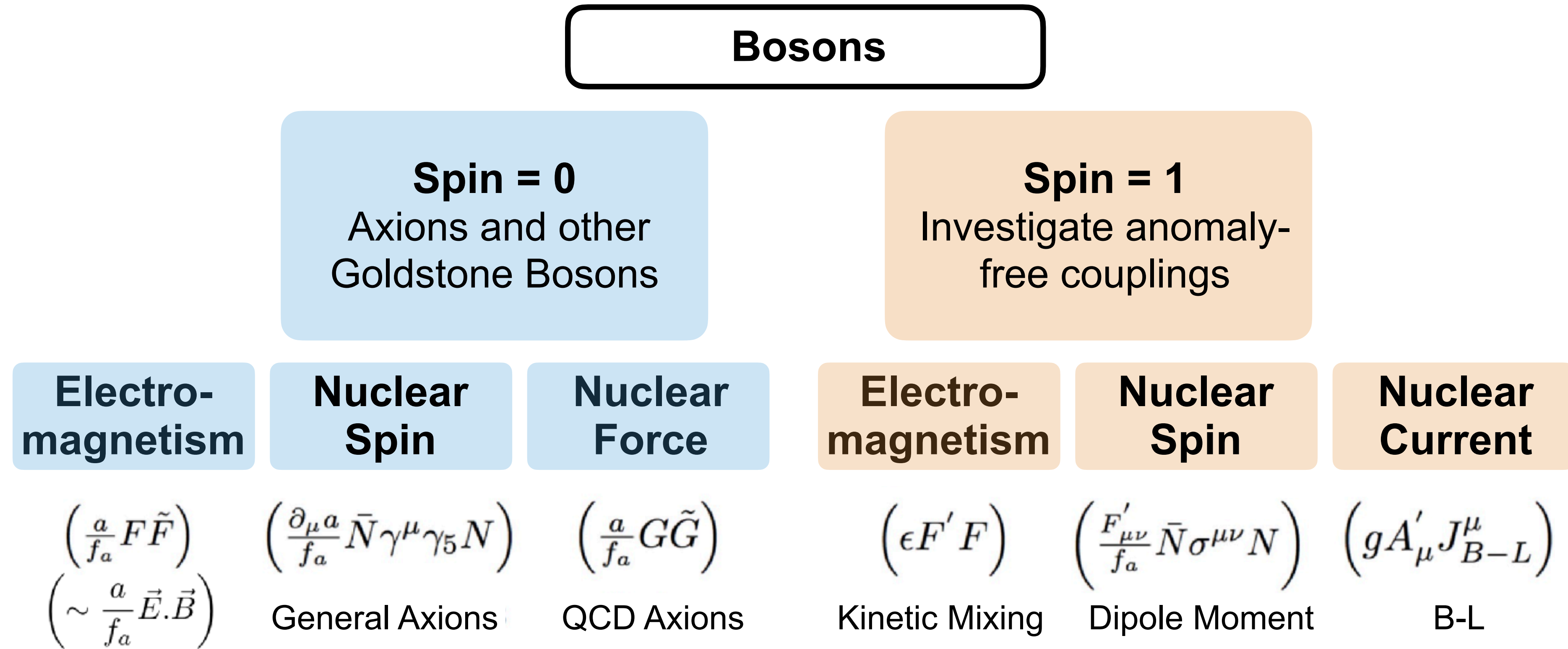
$$\mathcal{L}_{DM} = \frac{\phi^2}{(\Lambda'_\gamma)^2} \frac{F_{\mu\nu} F^{\mu\nu}}{4} - \frac{\phi^2}{(\Lambda'_e)^2} m_e \bar{\psi} \psi$$

- At the effective new physics energy scales Λ_α and Λ_e , α and m_e appear to **oscillate**

$$\frac{d\alpha}{\alpha} \approx \frac{\phi_0 \cos(m_\phi t)}{\Lambda_\gamma}, \quad \frac{dm_e}{m_e} \approx \frac{\phi_0 \cos(m_\phi t)}{\Lambda_e}$$

$$\frac{d\alpha}{\alpha} \approx \frac{\phi_0^2 \cos^2(m_\phi t)}{(\Lambda'_\gamma)^2}, \quad \frac{dm_e}{m_e} \approx \frac{\phi_0^2 \cos^2(m_\phi t)}{(\Lambda'_e)^2}$$

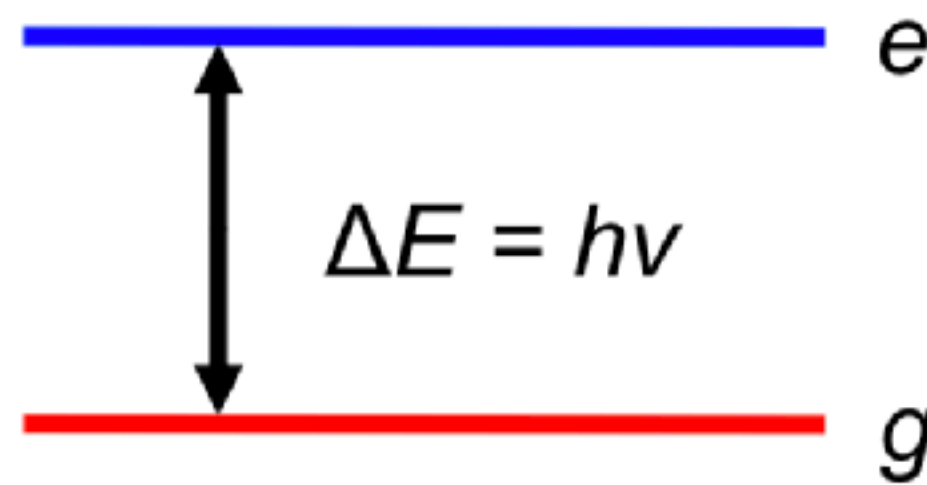
Light Bosonic Dark Matter Couplings



- New boson fields for Dark Matter can change fixed, fundamental constants into dynamic variables
- For example: α = fine structure constant, and μ = proton to electron mass ratio, no longer constants

Search for Dark Matter by looking for spatial and temporal violations of α , μ

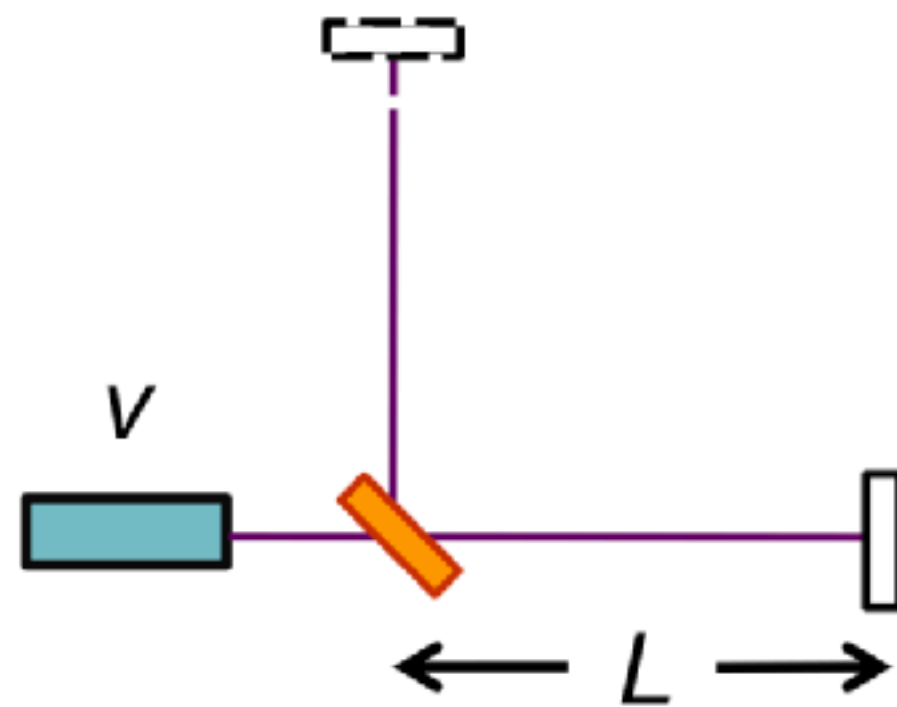
Quantum Sensing Methods for Testing $\Delta\alpha/\alpha$



Atomic spectroscopy (clocks)

$$\delta(\nu_1/\nu_2) \propto \cos(m_\varphi t)$$

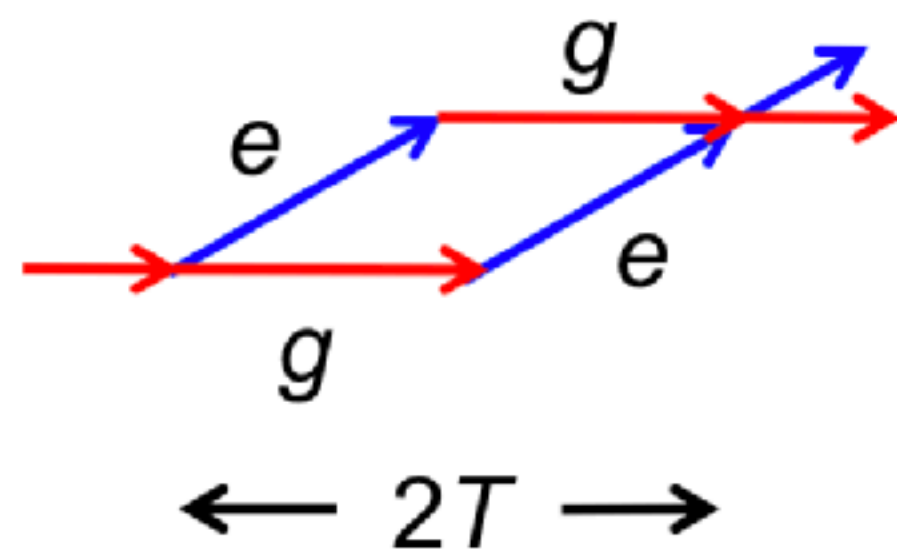
$$10^{-23} \text{ eV} < m_\varphi < 10^{-16} \text{ eV}$$



Laser interferometry (cavities)

$$\delta\Phi \propto \delta(\nu L) \propto \cos(m_\varphi t)$$

$$10^{-20} \text{ eV} < m_\varphi < 10^{-15} \text{ eV}$$

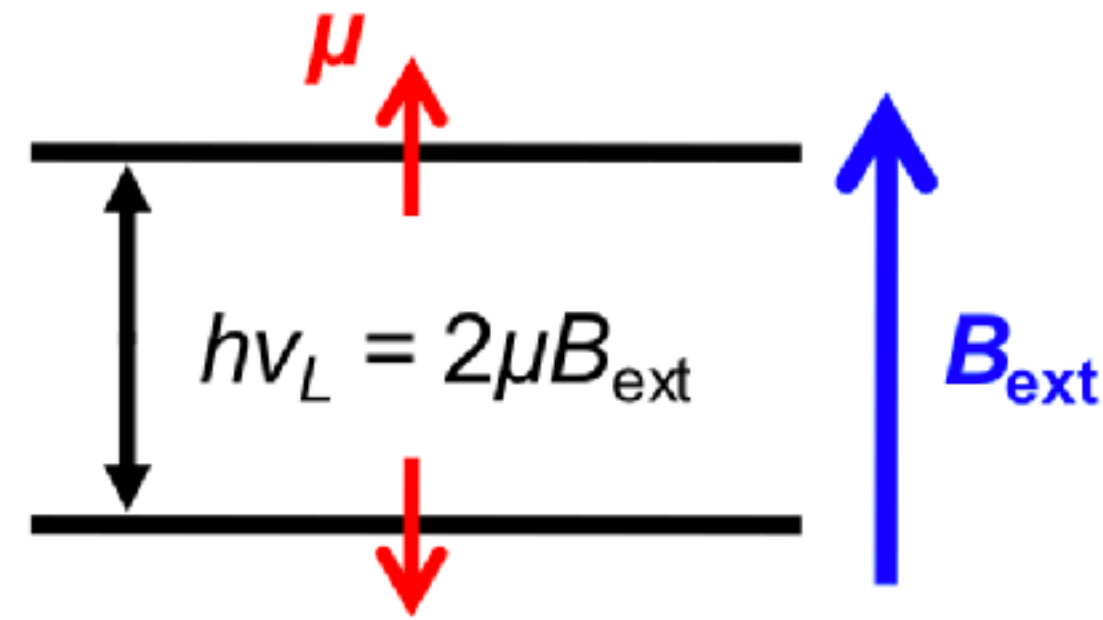


Atom interferometry

$$\mathbf{F}(t) \propto \mathbf{p}_\varphi \sin(m_\varphi t)$$

$$10^{-23} \text{ eV} < m_\varphi < 10^{-16} \text{ eV}$$

Quantum Sensing Methods for Testing $\Delta\mu/\mu$



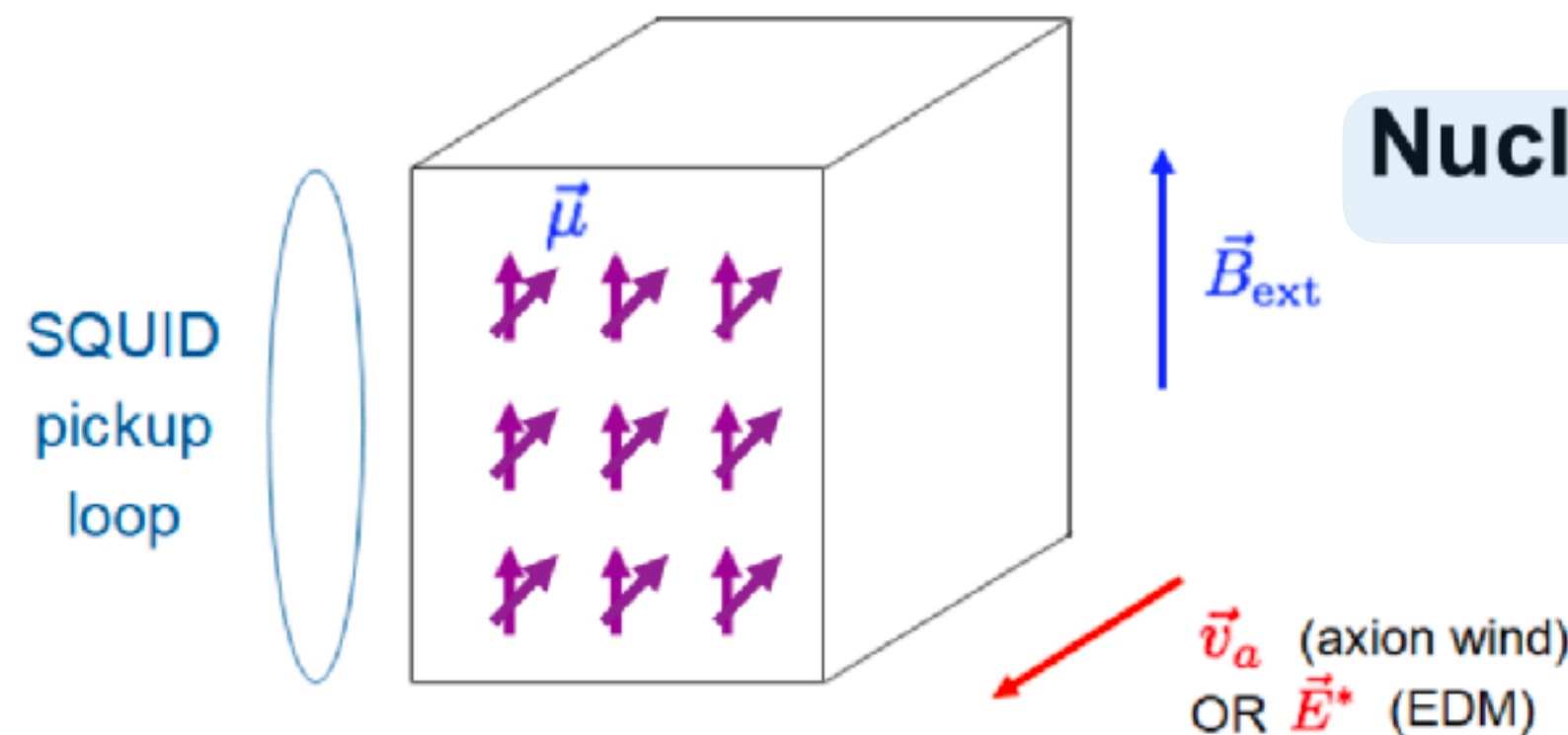
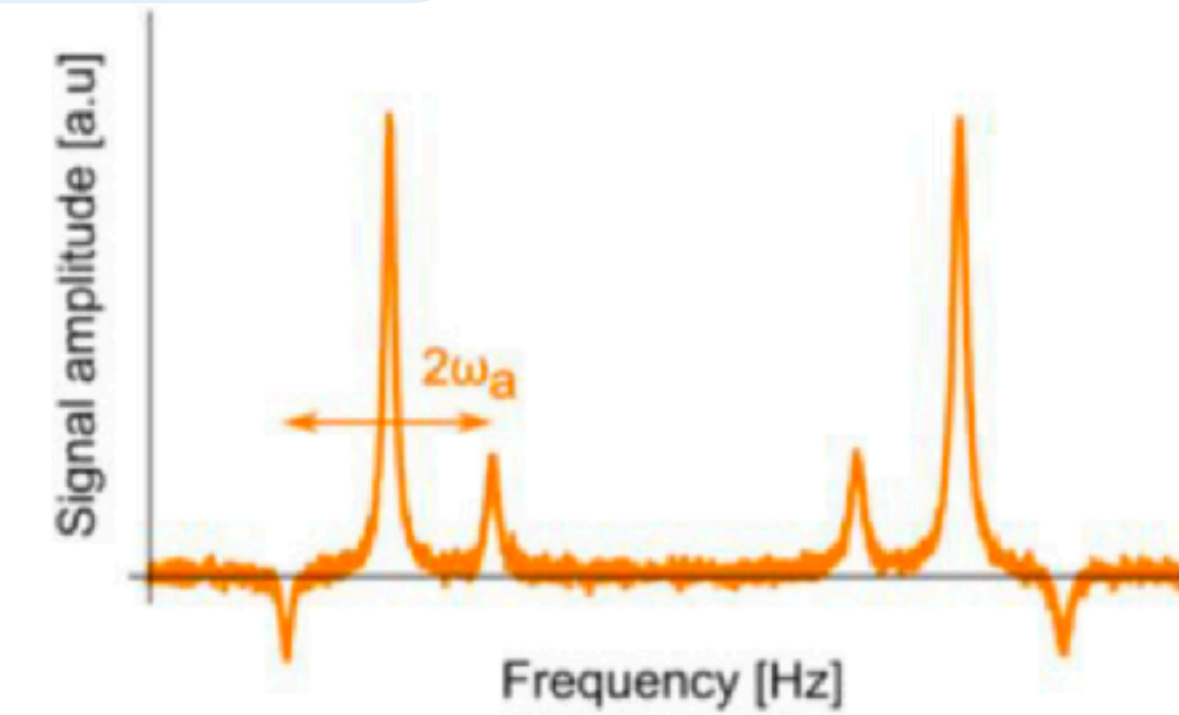
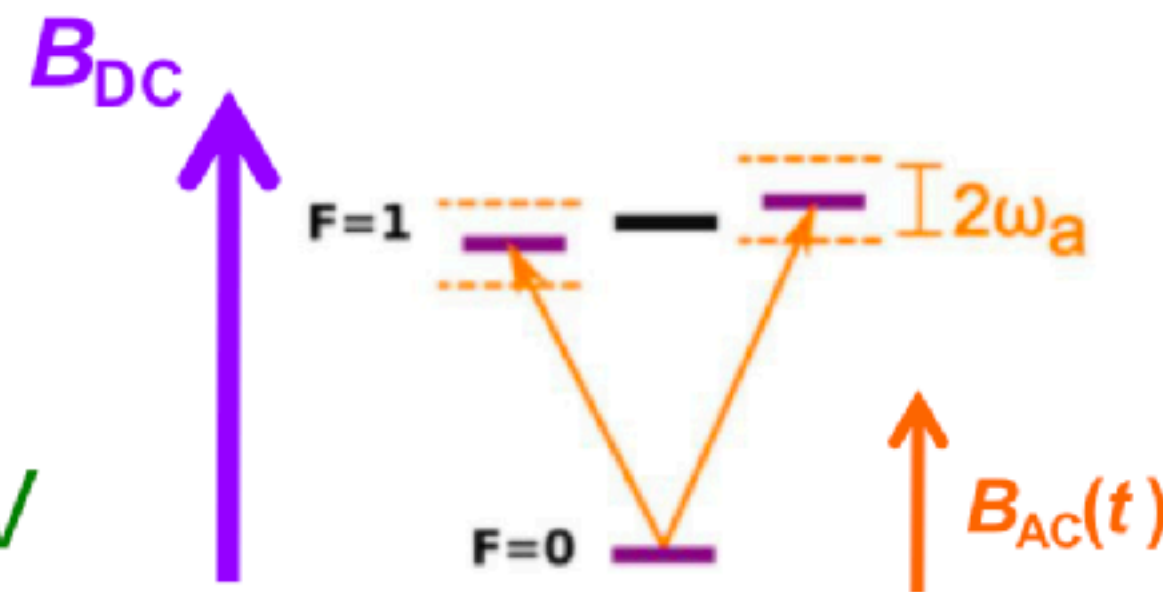
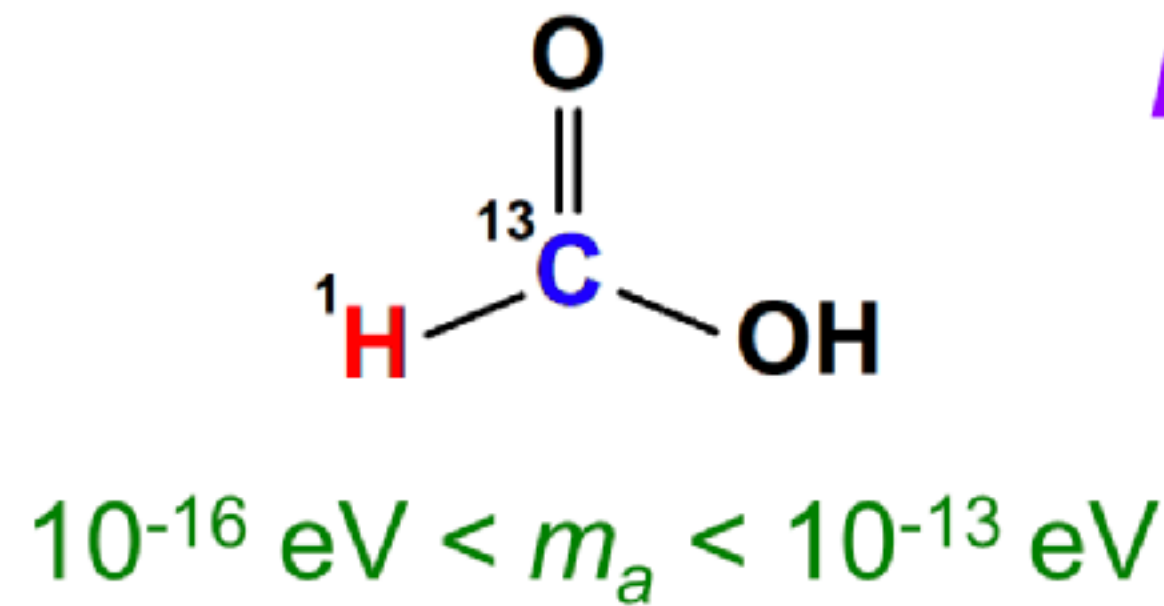
Co-magnetometry

$$\delta(v_{L,1}/v_{L,2}) \propto \cos(m_a t)$$

$$\text{or } \hat{\sigma} \cdot \mathbf{p}_a \sin(m_a t)$$

$$10^{-23} \text{ eV} < m_a < 10^{-17} \text{ eV}$$

Nuclear magnetic resonance (“sidebands”)



Nuclear magnetic resonance

$$\text{Resonance: } 2\mu B_{\text{ext}} \approx m_a$$

$$10^{-14} \text{ eV} < m_a < 10^{-7} \text{ eV}$$

Quantum Sensing with Optical Atomic Clocks

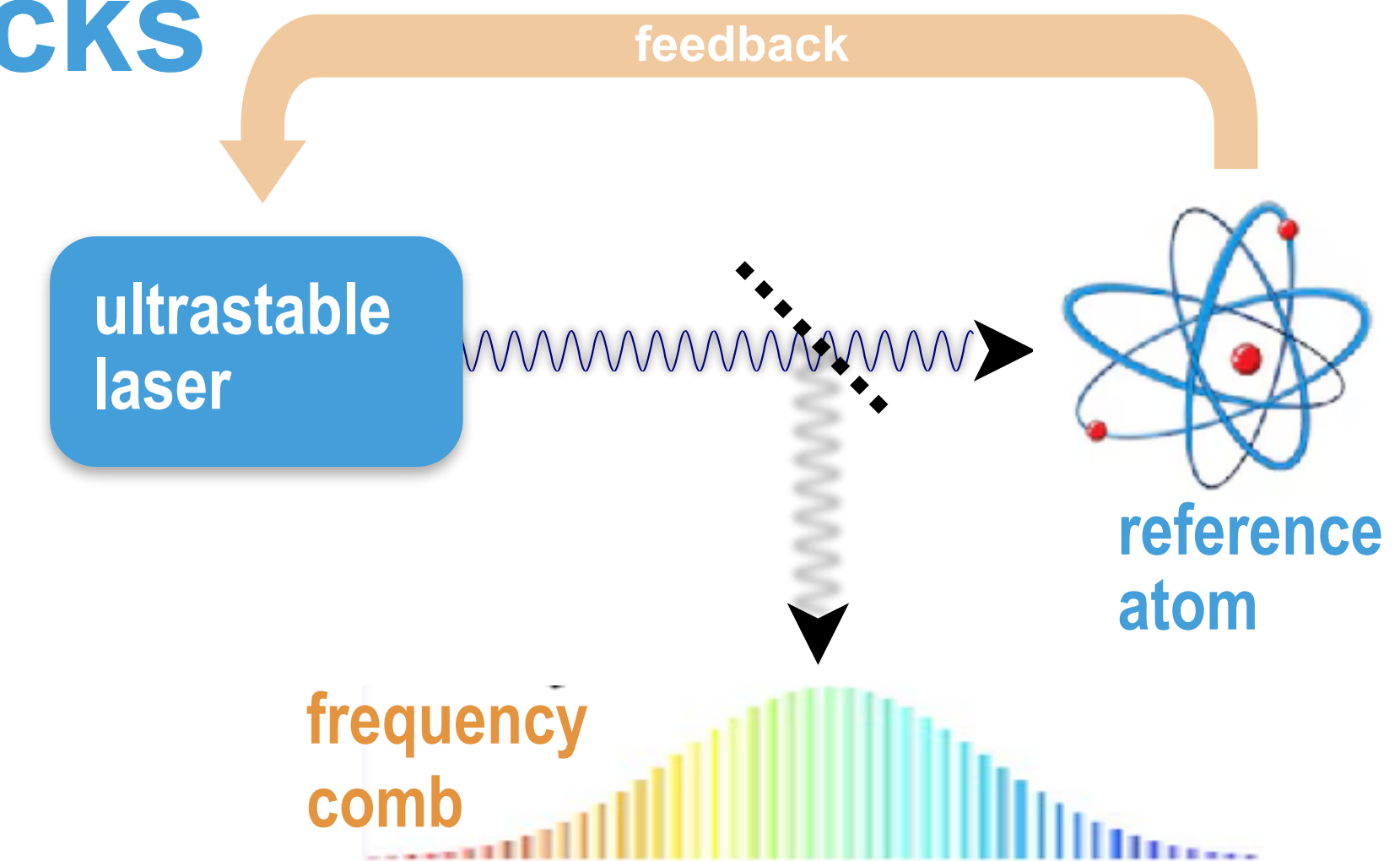
- Optical Atomic Clock
 - Laser for oscillator, usually a narrow frequency around atomic transition
 - Ultra-stable laser locked to atomic transition, “counted” with frequency comb
- Atomic clock transition scale and sensitivity is “selectable”
 - For $R_\infty = \alpha^2 m_e c / 4\pi\hbar$, fine structure const. α , and $\mu \equiv m_p / m_e$

Hyperfine transitions: $\nu_{\text{hf}} = A \cdot \mu \alpha^2 F_{\text{hf}}(\alpha) \cdot R_\infty$

Optical transitions: $\nu_{\text{opt}} = B \cdot F_{\text{opt}}(\alpha) \cdot R_\infty$

Vibrational transitions: $\nu_{\text{vib}} = C \cdot \mu^{1/2} \cdot R_\infty$

- Calculate sensitivities to variations in α or μ given by K_α and K_μ
- Search for variation in α : ultra-light Dark Matter
 - Measure ratios of frequencies ($R = \nu_1 / \nu_2$) for two clocks, look for oscillations
 - Highly charged ions give excellent sensitivity
 - Th-229 nuclear clock → extreme sensitivity

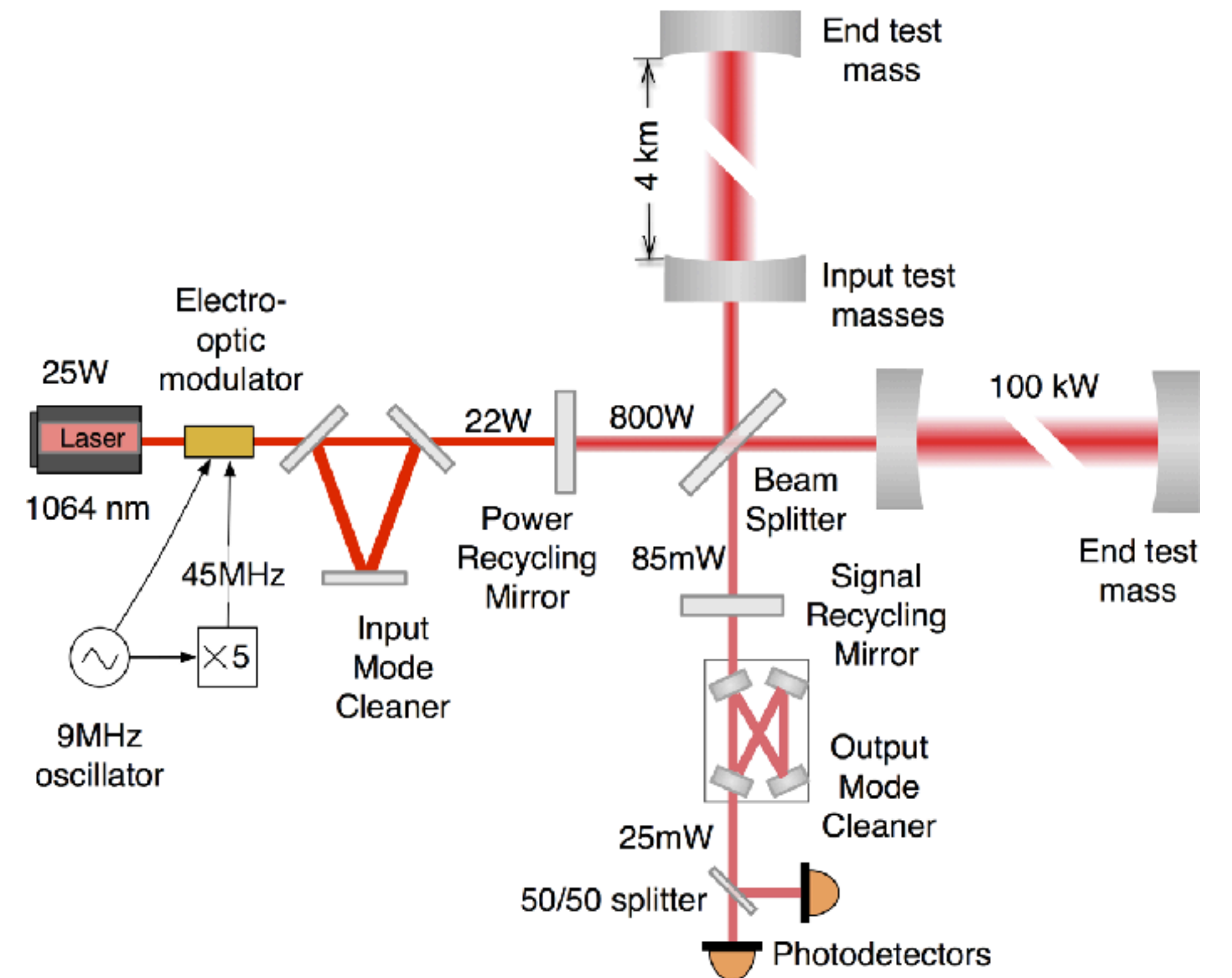
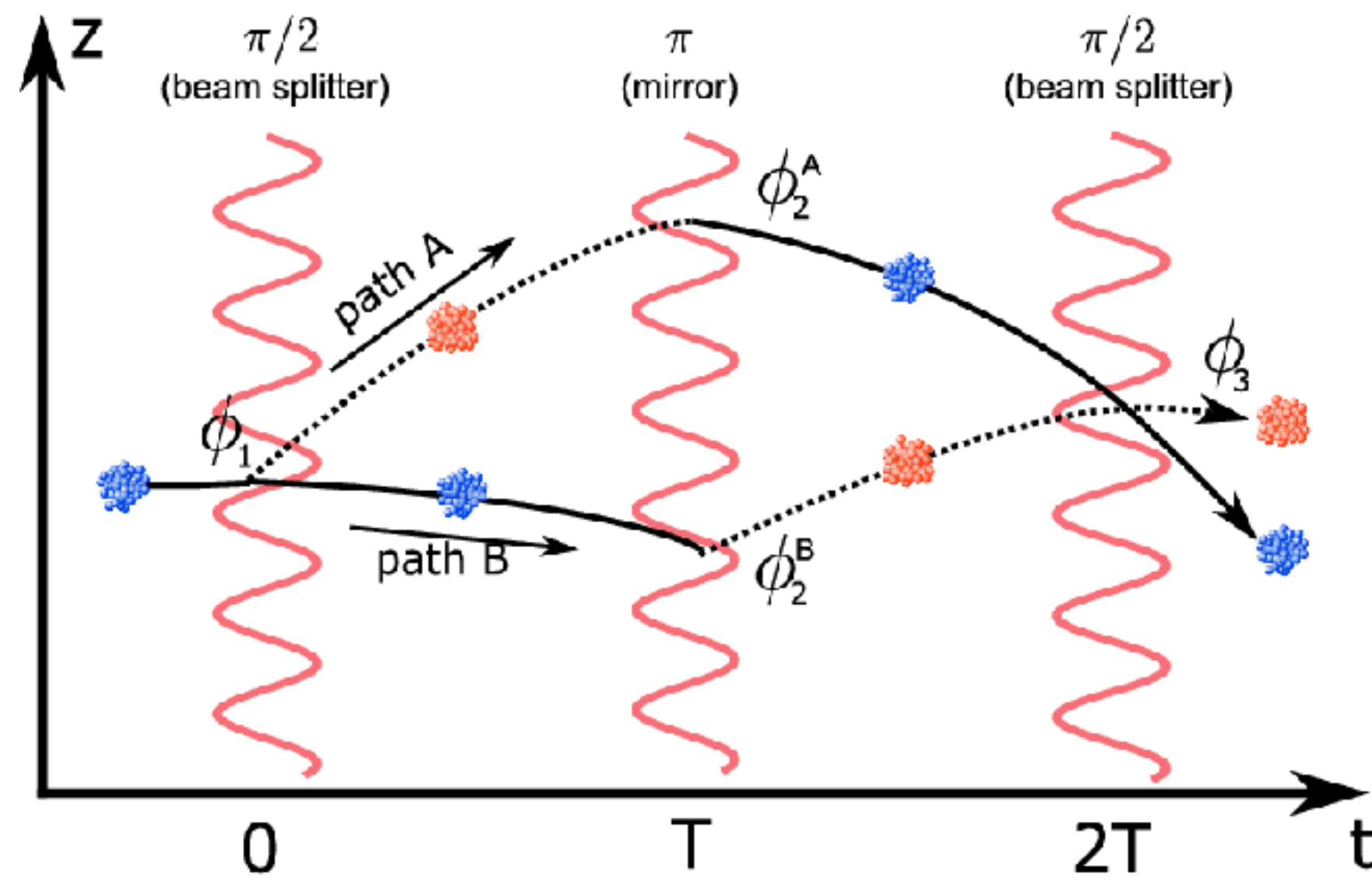


Clocks proposed for QSNET

Clock	K_α	K_μ
Yb ⁺ (467 nm)	-5.95	0
Sr (698 nm)	0.06	0
Cs (32.6 mm)	2.83	1
CaF (17 μm)	0	0.5
N ₂ ⁺ (2.31 μm)	0	0.5
Cf ¹⁵⁺ (618 nm)	47	0
Cf ¹⁷⁺ (485 nm)	-43.5	0

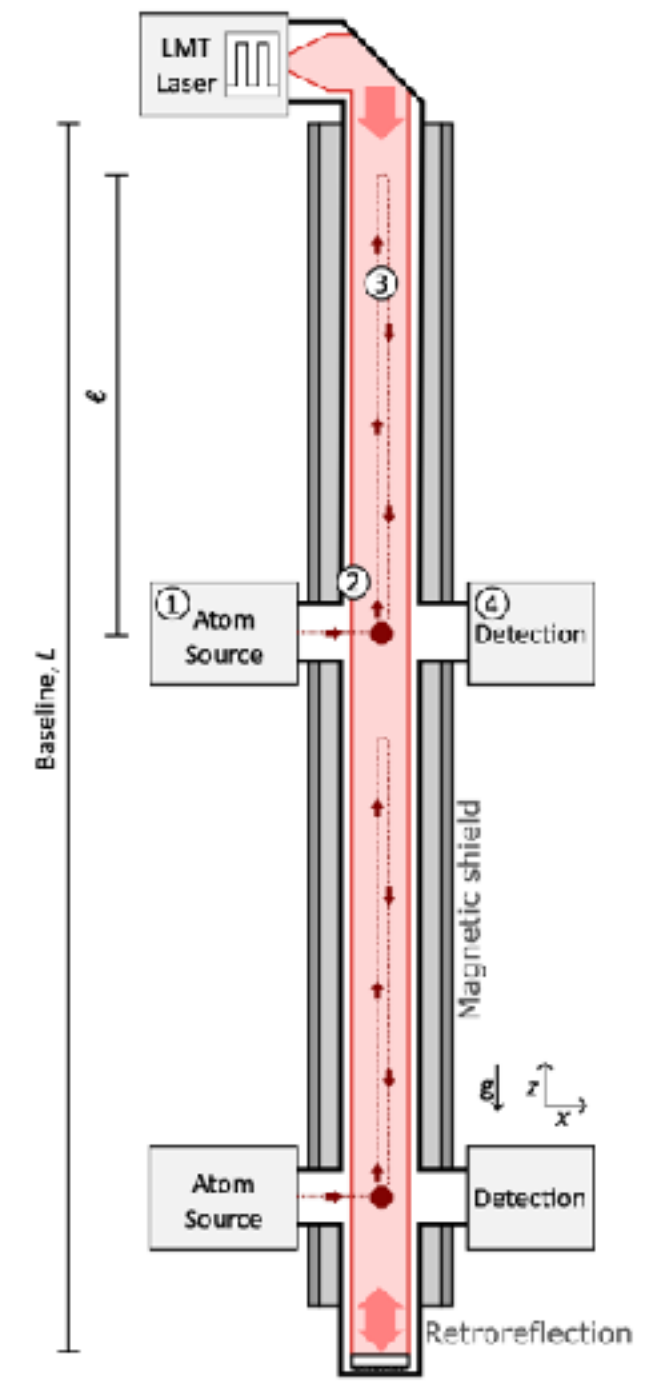
Quantum Sensing with Interferometry

- Superimpose waves to look for interference → precise measure of (e.g.) distance
- Source is split and sent on two (or more) different paths, then recombined
- Interference (eg from changes in arm length) analysed by Fourier analysis, fringes, etc.

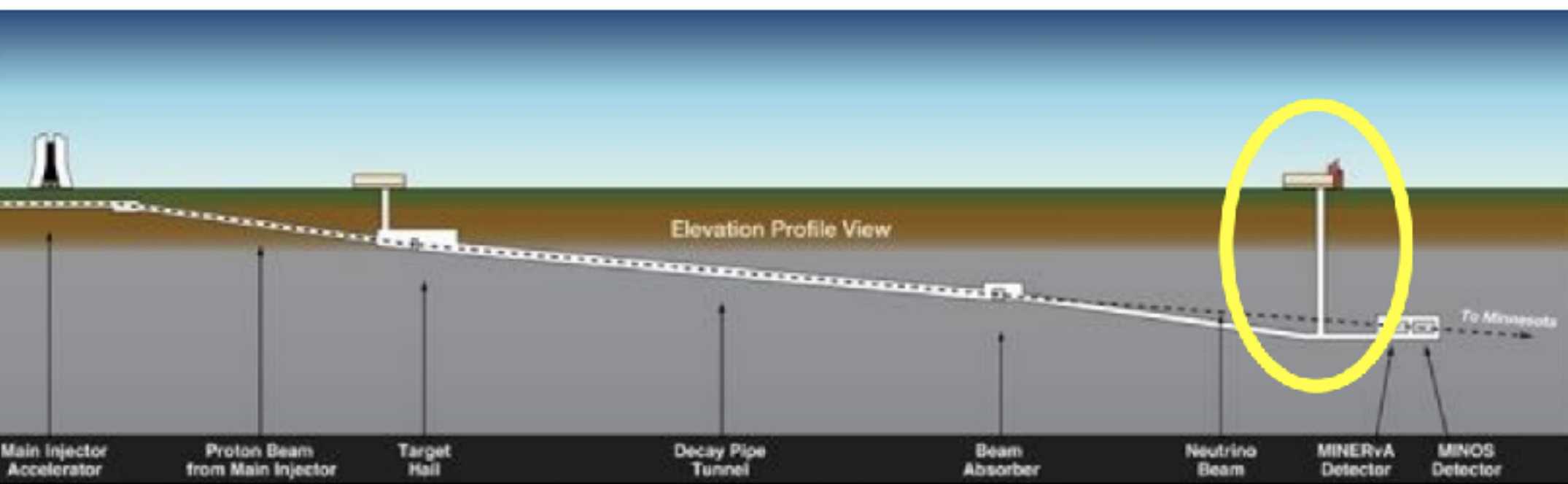


Long-Baseline Atom Interferometry

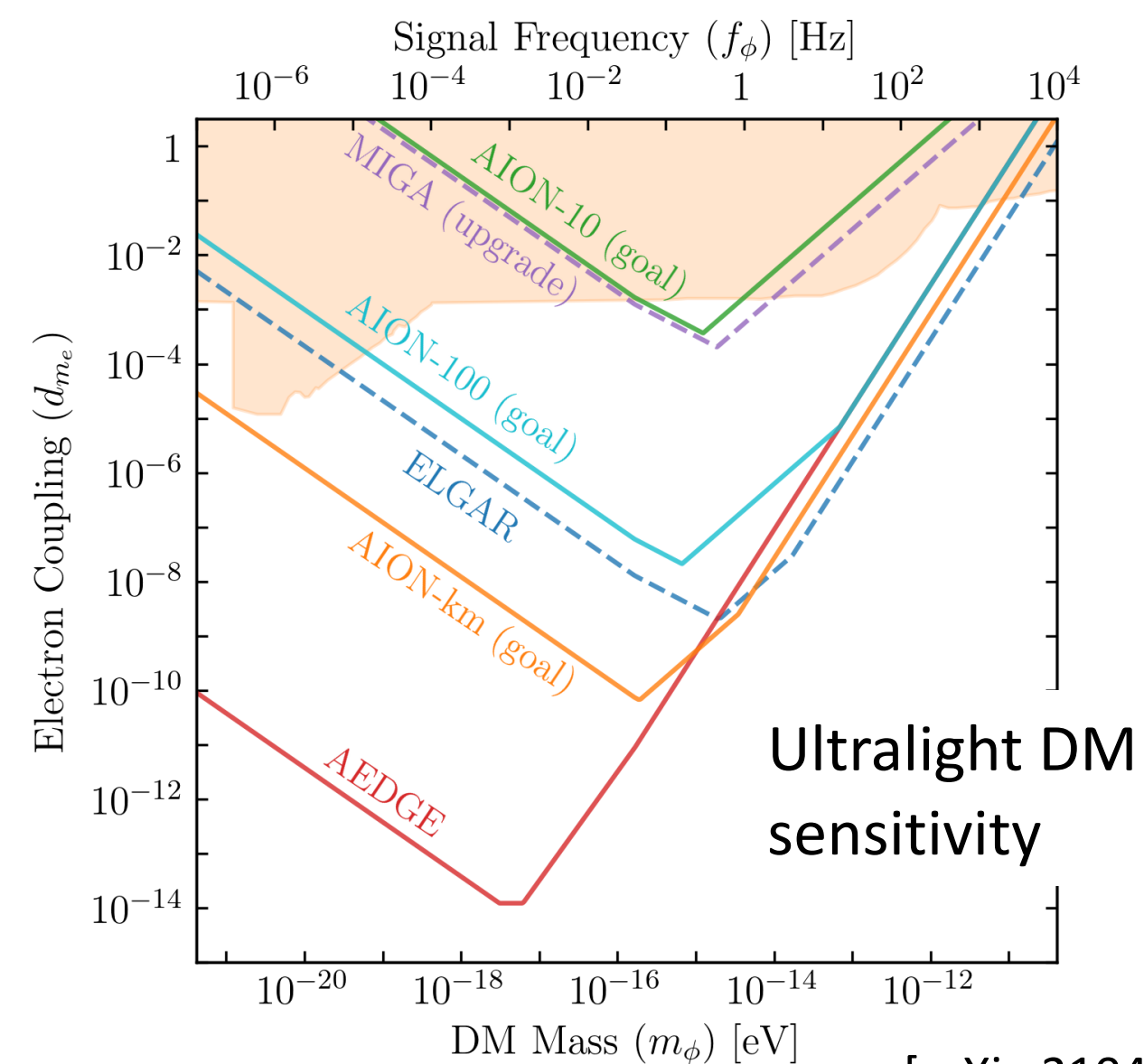
- Demonstrated at ~meter scale, proposing 100m and ultimately km (space)
 - **AION / AICE**: Atom Interferometer Observatory and Network / Atom Interferometer CERN Experiment
 - **ELGAR**: European Laboratory for Gravitation and Atom-interferometric Research
 - **MIGA**: Matter wave-laser based Interferometer Gravitation Antenna
 - **MAGIS**: Matter-wave Atomic Gradiometer Interferometric Sensor
 - **ZAIGA**: Zhaoshan Long-baseline Atom Interferometer Gravitation Antenna
 - **AEDGE**: Atomic Experiment for Dark Matter and Gravity Exploration in Space
- Matches lab infrastructure; underground shafts (CERN, Fermilab, etc)
- Ultralight DM, but also topological DM, gravitational waves, Lorentz invariance



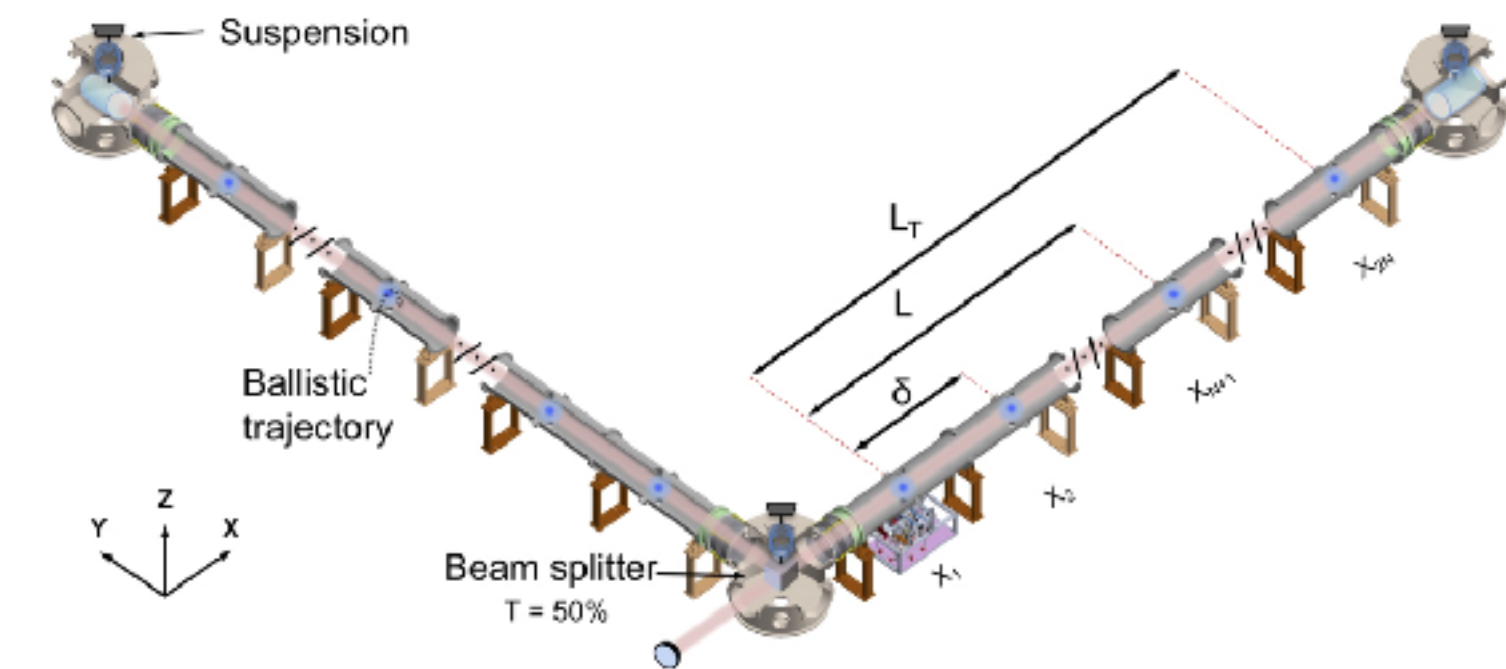
AION experiment concept



MAGIS-100 experiment concept



Ultralight DM sensitivity



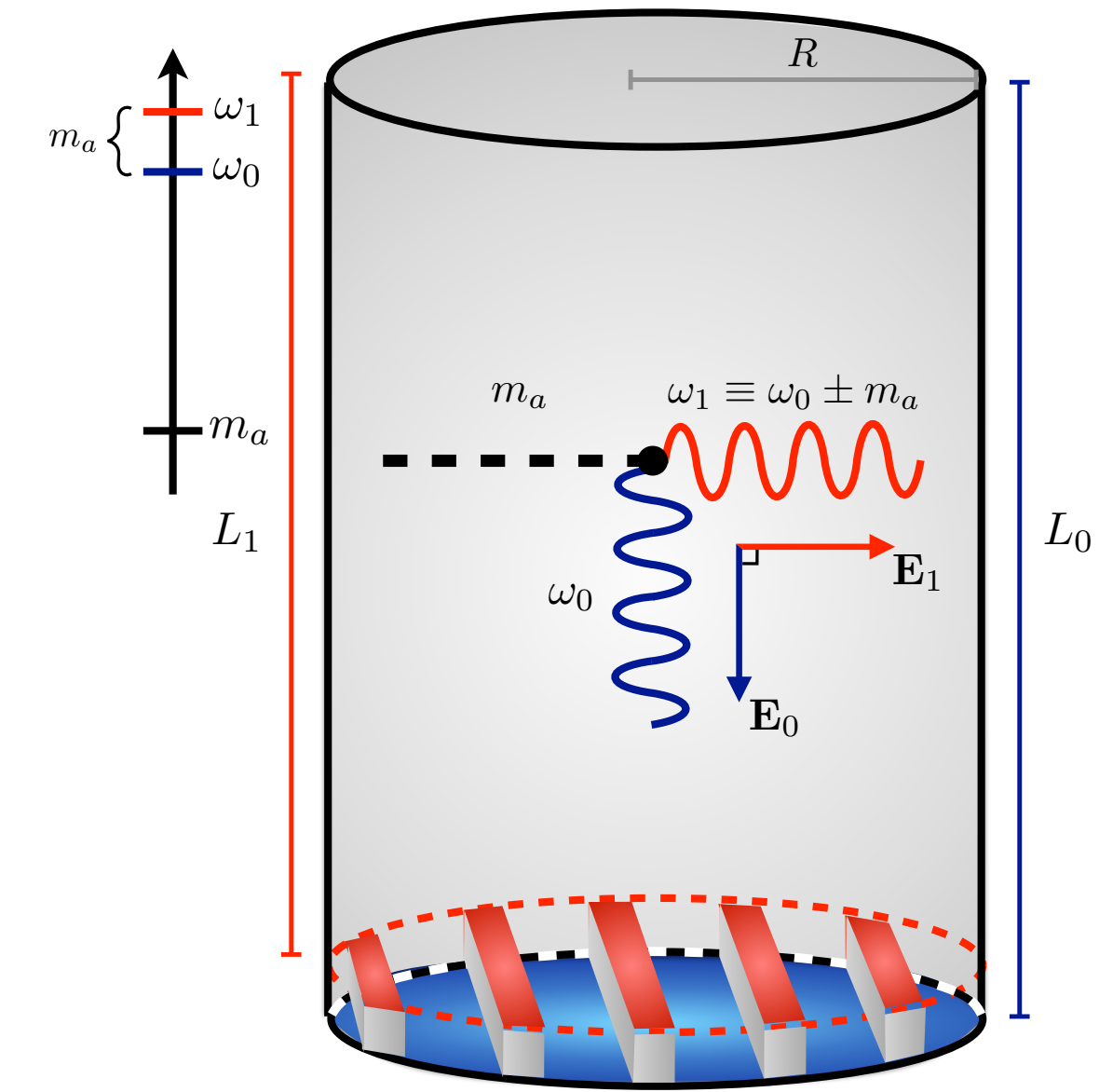
ELGAR experiment concept

Cavities: Axion Heterodyne Detection

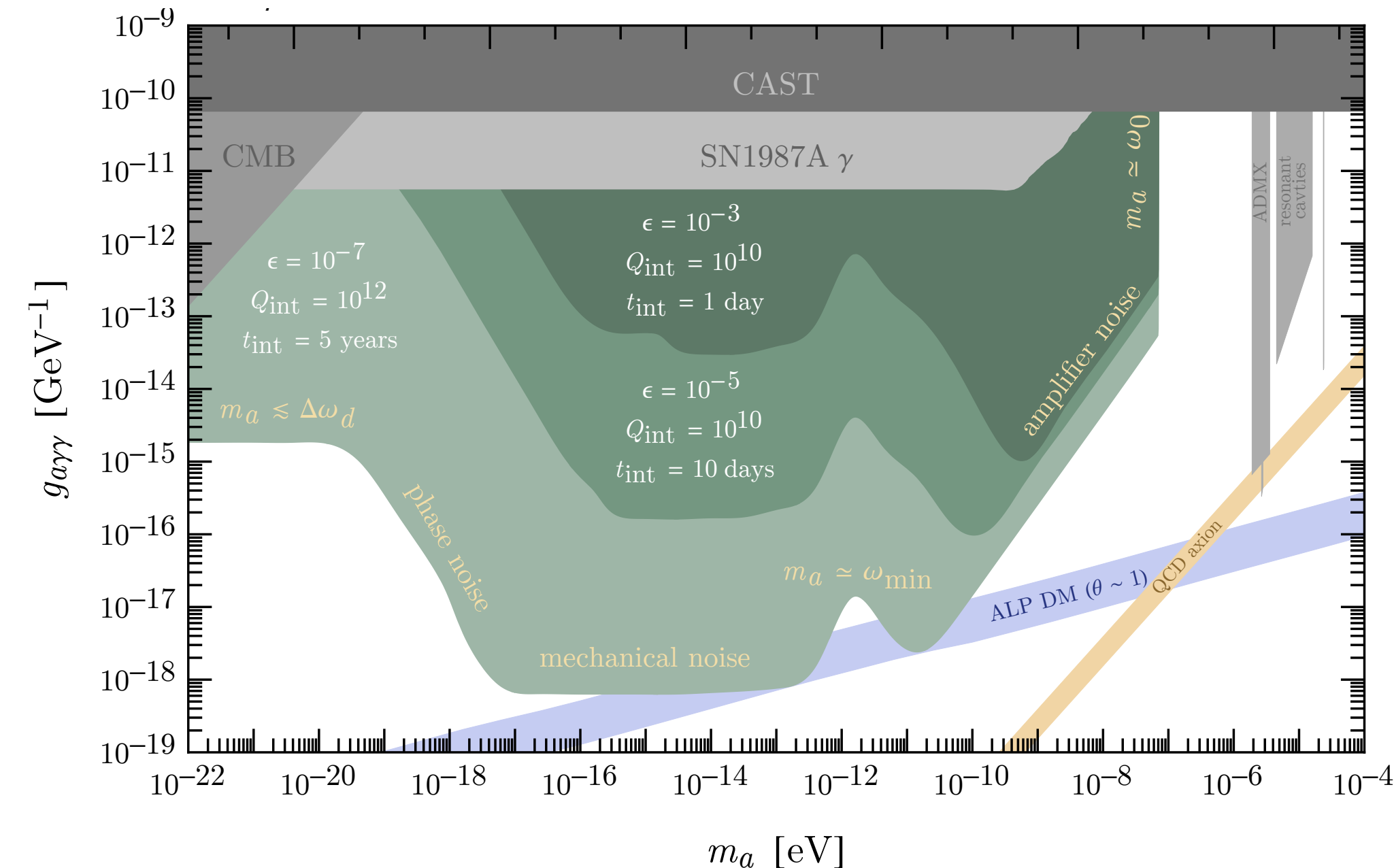
- DarkSRF Collaboration aiming for tunable cavities
 - Figure of merit (F) proportional to *square* of DM mass (m_a) and cavity volume (V)

$$F \sim g_{a\gamma}^2 m_a^2 B^4 V^2 T_{sys}^{-2} G^4 Q$$

- Resonant cavities possible down to μeV ; below that, need huge volume
- Tunable superconducting RF cavity:
 - Frequency conversion: drive $\omega_0 \approx \text{GHz} \rightarrow$ axion gives $\omega_1 \approx \omega_0 \pm m_a$
 - Corrugated cavity with two polarizations (and lengths)
 - Separate scales allows separate tuning of ω_0 and ω_1
- Scan over axion masses:
 - Change of cavity geometry modulates the frequency splitting $\omega_0 - \omega_1$
 - Huge parameter space to explore, but technical (cryo) challenges

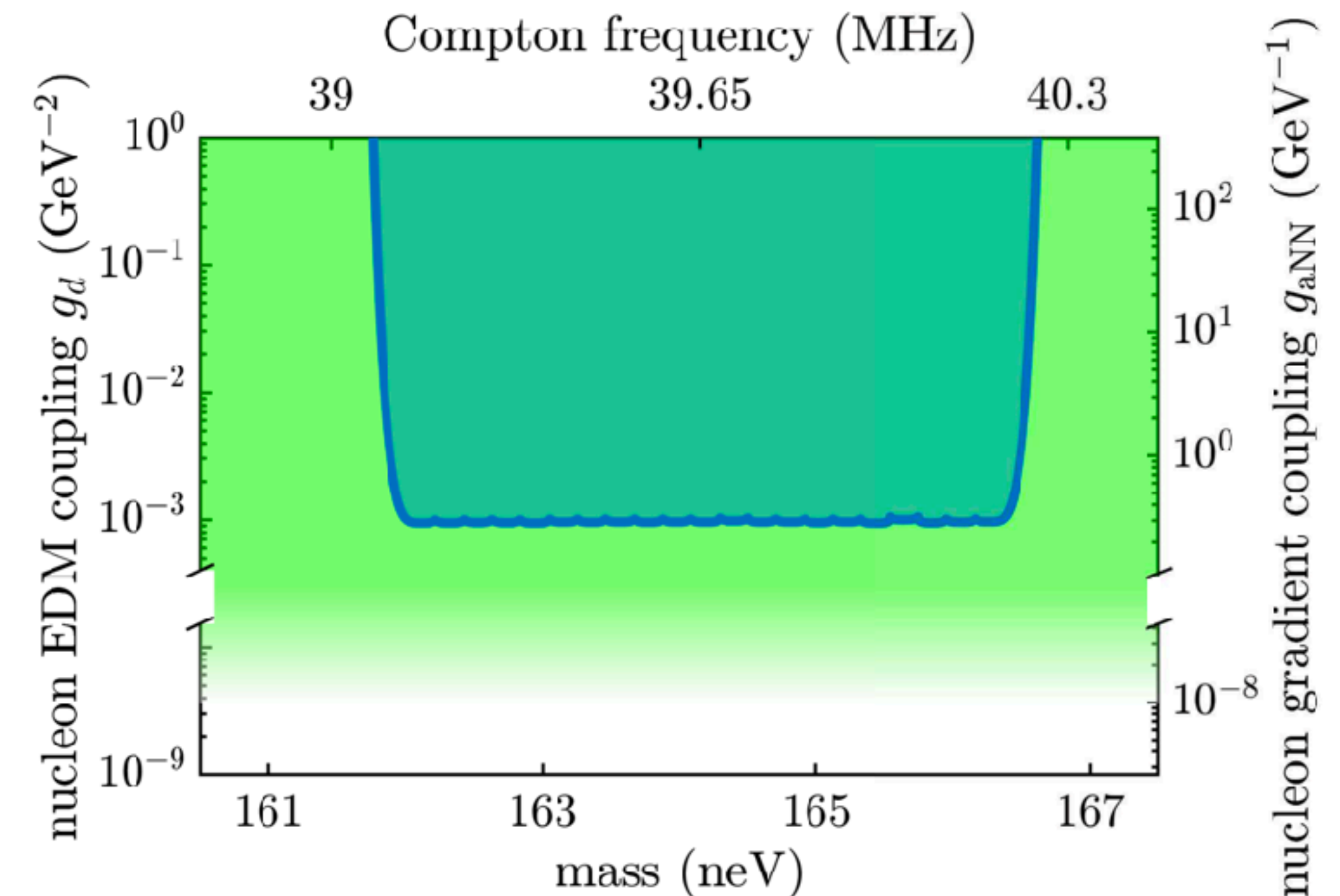
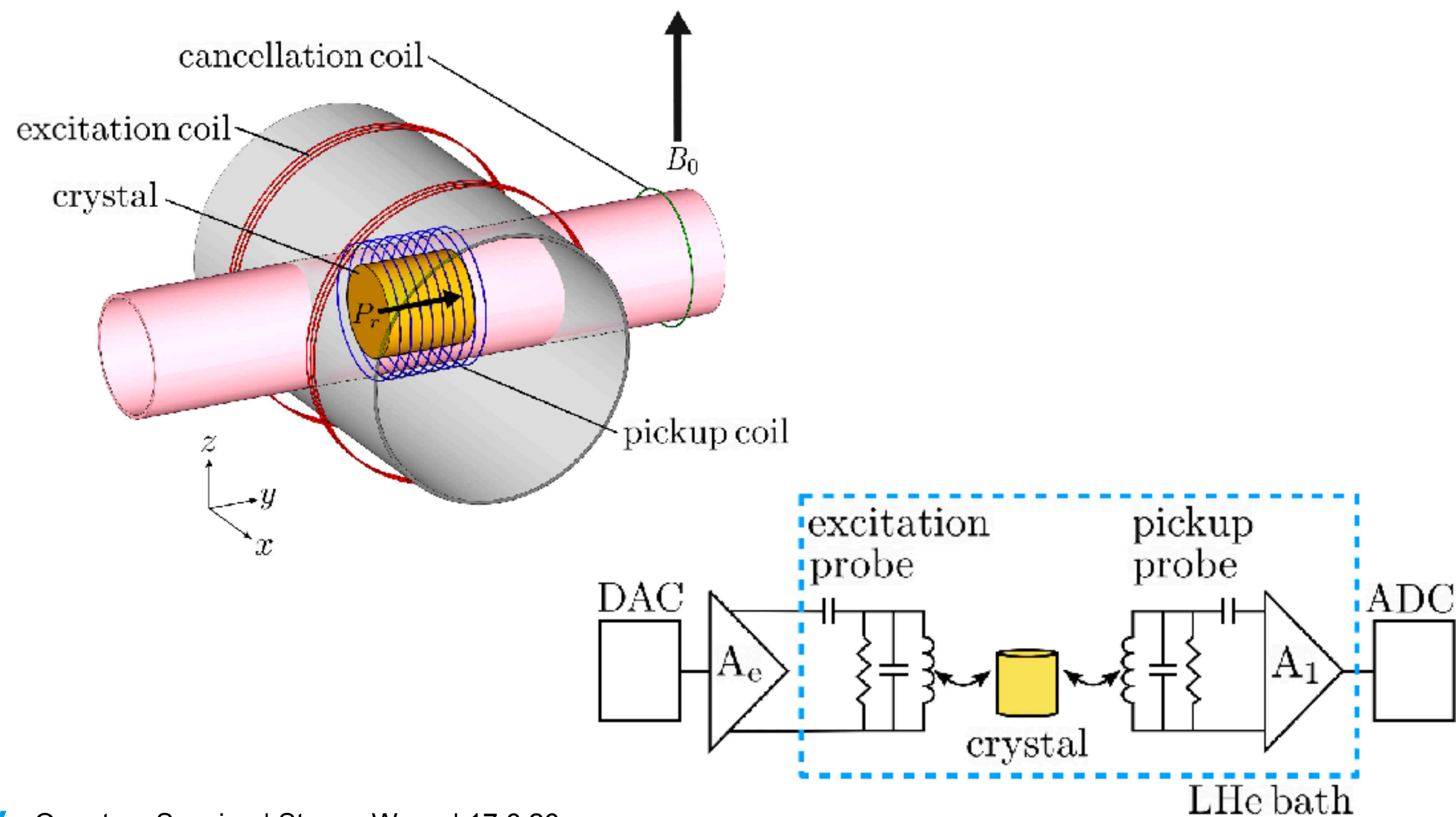


(a) Cartoon of cavity setup.



Quantum Sensing with Magnetometry: CASPEr

- Cosmic Axion Spin Precession Experiment (CASPEr)
 - Measure two interactions: electric dipole moment (EDM) and the gradient interaction with nuclear spin
 - Solid-state NMR of ^{207}Pb in a polarized ferroelectric crystal
 - Axion-like DM exerts an oscillating torque
- Limits for neV DM masses vs EDM coupling g_d and gradient coupling g_{aNN} ; many ideas for improvements



DRD5 Collaboration

- Supporting R&D on quantum sensing technologies for the particle and fundamental physics community

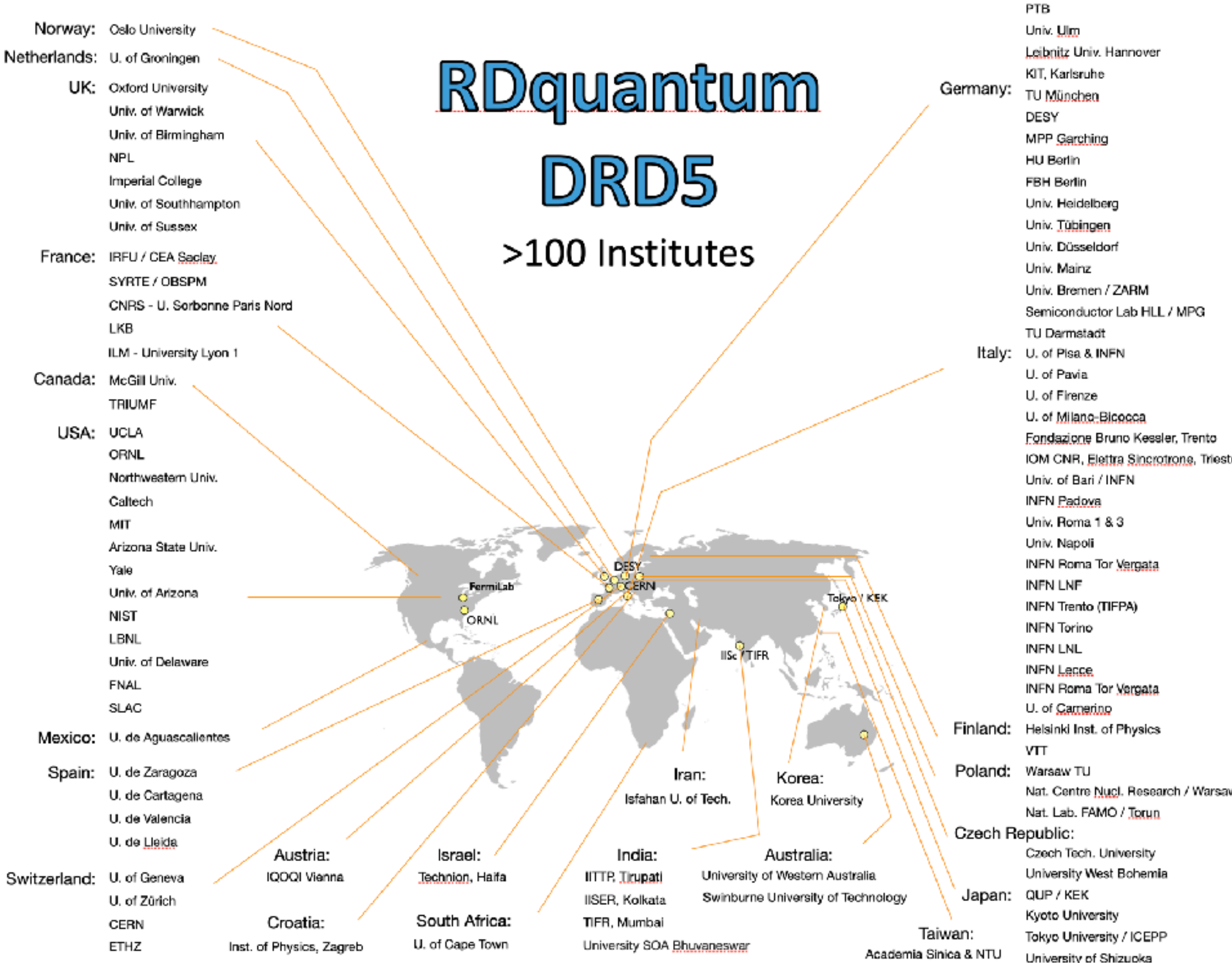
Addressing Challenges for Science

Educational hurdles: what can quantum sensing do for me? How do I get started?

Supporting R&D: Development of sensing techniques for new physics applications (low TRL)

Real-world challenges: scaling to large arrays and dealing with harsh environments (high TRL)

Supported by CERN and European Committee for Future Accelerators (ECFA)



Getting started with Quantum Sensing?

- RDquantum / DRD5 Collaboration recently launched, with preliminary WP structure:

WP1 Exotic systems in traps & beams
(HCI's, molecules, Rydberg systems,
clocks, interferometry, ...)

WP4 Scaling up to macroscopic ensembles
(spins; nano-structured materials; hybrid
devices, opto-mechanical sensors,...)

WP2 Quantum materials (0-, 1-, 2-D)
(Engineering at the atomic scale)

WP5 Quantum techniques for sensing (back
action evasion, squeezing, entanglement,
Heisenberg limit)

WP3 Quantum superconducting systems
(4K electronics; MMC's, TES, SNSPD,
MKID's... integration challenges)

WP6 Capability expansion (cross-disciplinary
exchanges; infrastructures; education)

- Mix of theorist and experimentalists (e.g. WP1, WP5)
- Focus on exploring new technologies, connecting to HEP needs, and **community-building**

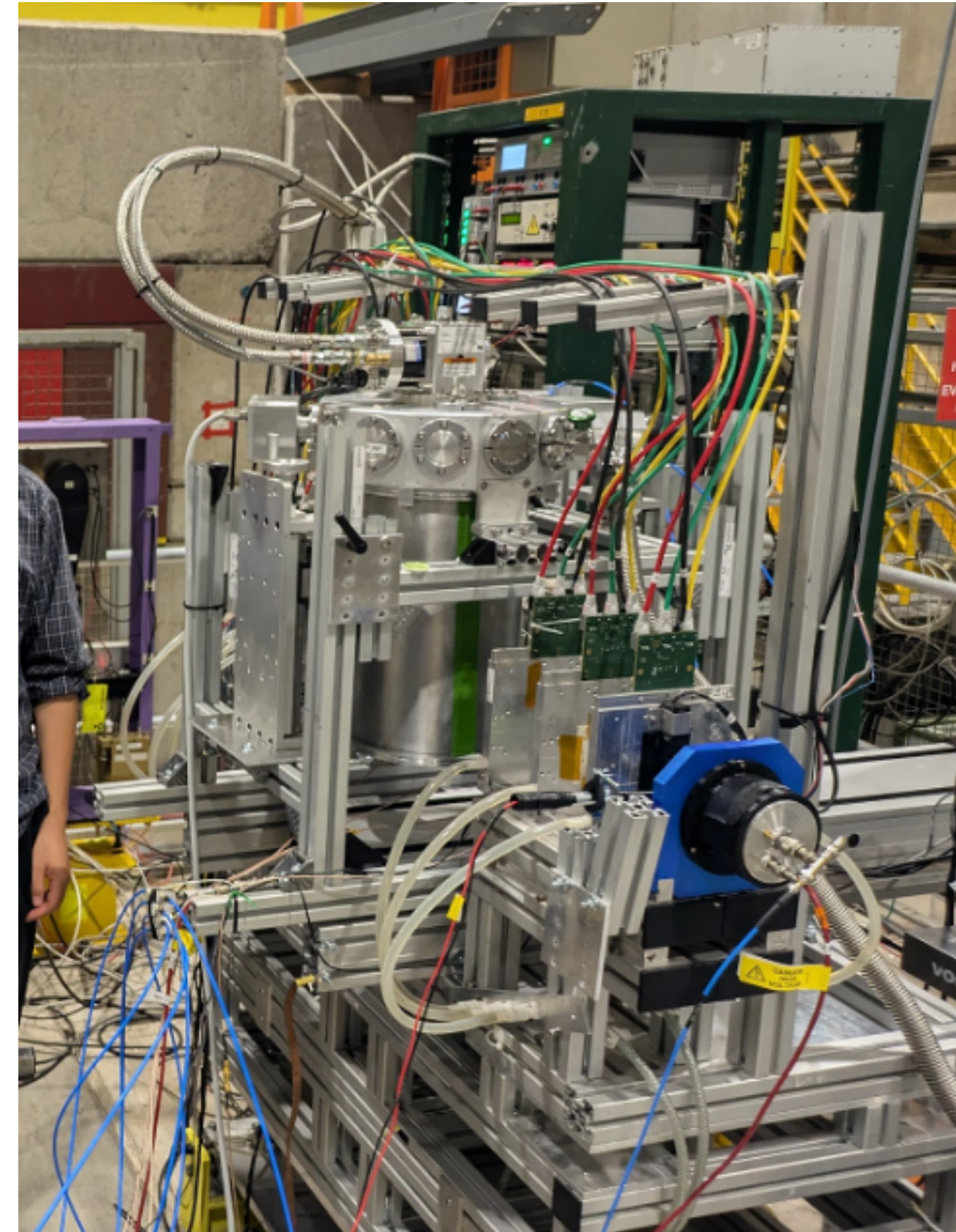
CERN Test Beam Platform for Quantum Technologies

Wednesday 29 Oct 2025, 09:00 → 18:00 Europe/Zurich

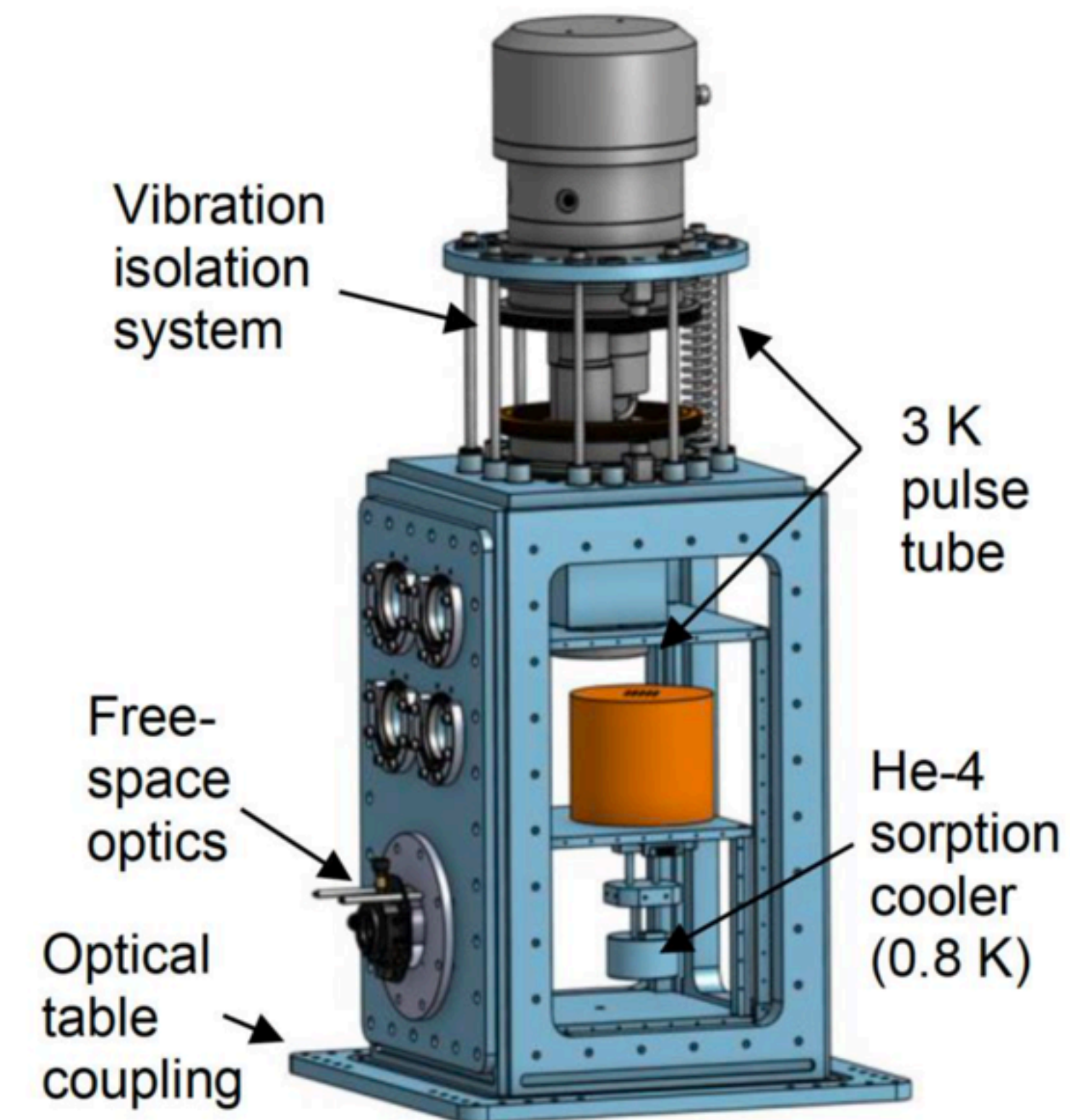
31/3-004 - IT Amphitheatre (CERN)

<https://indico.cern.ch/event/1580512/>

- Sessions covered:
 - Testbeam Setup & Experience
 - Quantum Scintillators
 - DRACuLA: a sub-Kelvin facility
 - SNSPD Use Case
- Example talk: Boris Korzh (Geneva)
 - Testbeam experience from 2025, and plans to improve setup for the future



Boris Korzh
University of Geneva



Joint DRD5-Unicorn workshop on radiation damage to quantum dots

Wednesday 26 Nov 2025, 09:00 → 18:30 Europe/Zurich

222/R-001 (CERN)

Anne-Mazarine Lyon (CERN), Michael Doser (Massachusetts Inst. of Technology (US))

<https://indico.cern.ch/event/1590522>

- Sessions covered:
 - Lecture - Dos and don'ts with nanocrystals
 - Nanocomposite R&D
 - Irradiation and Beam Tests
 - Applications
 - Simulation
- Example talk: Sergio Brovelli (University of Milano-Bicocca)
 - Quantum Dot fundamentals
- Videos available

Towards Novel Nanotechnological scintillators

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

New generation of HYBRID NANOCOMPOSITE SCINTILLATORS

Inorganic Crystal Scintillators

- Energy Resolution
- High Density
- Expensive
- Hardly scalable
- Fragile

Plastic Scintillators

- Mass scalability/Low cost
- Compositional/Shape flexibility
- Low energy resolution
- Radiation soft

Synthesis & Processing

- Colloidal Synthesis
- Multi Grams Scales

Heavy Inorganic Composition

- High Light Yield
- High Z
- Radiation Hard

Quantum Confinement

- Ultrafast emission
- Tunability

The Th nuclear clock: challenges and opportunities

Thursday 15 Jan 2026, 15:30 → 18:30 Europe/Zurich

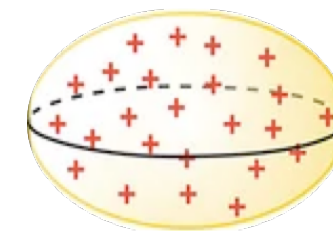
<https://indico.cern.ch/event/1624634/>

- Themes covered:
 - Theory introduction and motivation
 - Experimental status (Ye, Peik)
 - Th Ions: electron bridge, highly charged
 - Lineshape and K-factor calculations
- Example talk: Gilad Perez (Weizmann)
 - New Physics Motivation and the challenge of the K-Factor
- 100 people connected!

How robust is the sensitivity factor, K_{canc} ?

Geometrical classical modeling

$\Delta E_{\text{EM}} \Leftrightarrow$ charge distribution



Berengut, Dzuba, Flambaum & Porsev (09)

Depends on incalculable variables

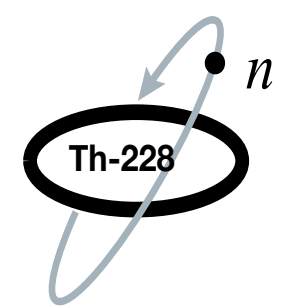
Data - inconclusive, *radius uncertainty - crucial*:

$$K_{\text{canc}} \sim 10^3 \left[6 \pm 5 \times \frac{\Delta(\delta r^2)}{0.0013 \text{ fm}^2} \right] (2\sigma) + \text{hexa?} + \text{thickness?}$$

Caputo, Gazit, Hammer, Kopp, Paz, GP & Springmann (24);
Beeks et al. (24)

Quantum based approach

Halo model:

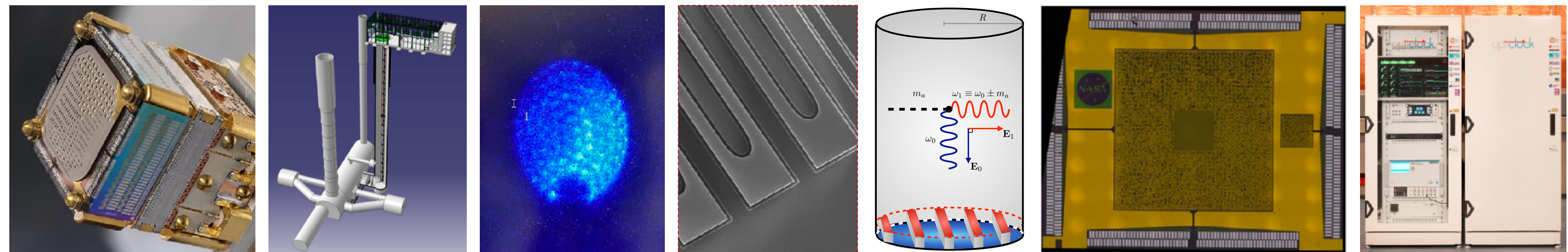


Successful postdictions, predicted the charge radius (quadruple moment) differences to 50% (15%); yet, it's only a model, with several shortcomings

Caputo, Gazit, Hammer, Kopp, Paz, GP & Springmann (24);

Conclusions

- Many different quantum sensing techniques are being developed for Fundamental Physics
- Examples include new quantum detectors, and also new experiments using quantum techniques
- Community effort is starting now to develop new devices and build new experiments



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