Quantum Sensing for Particle Physics

QT4HEP-2025: International Conference on Quantum Technology for High-Energy Physics

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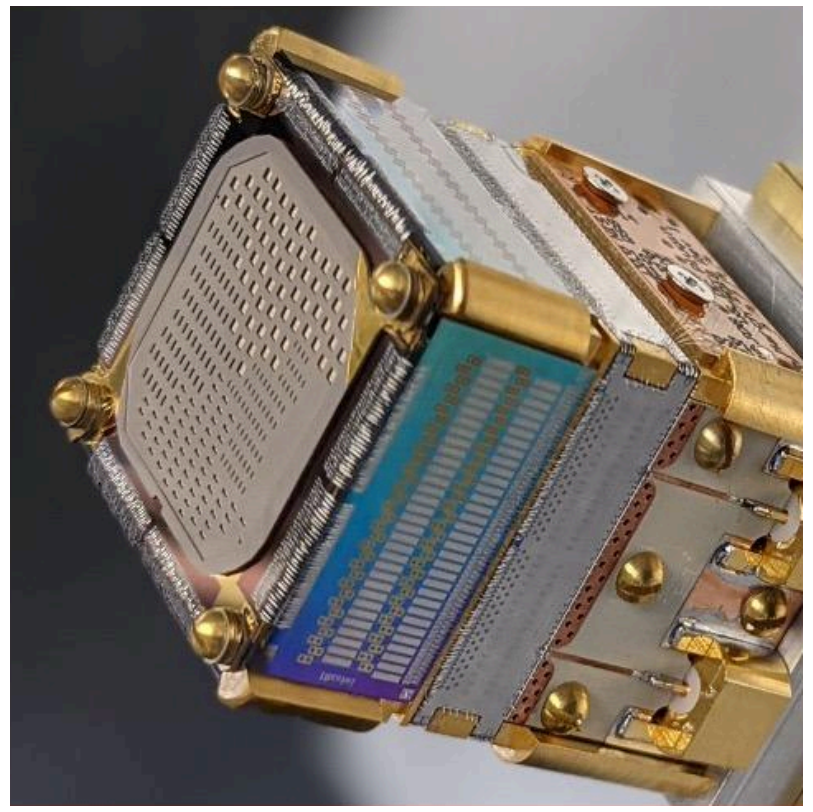
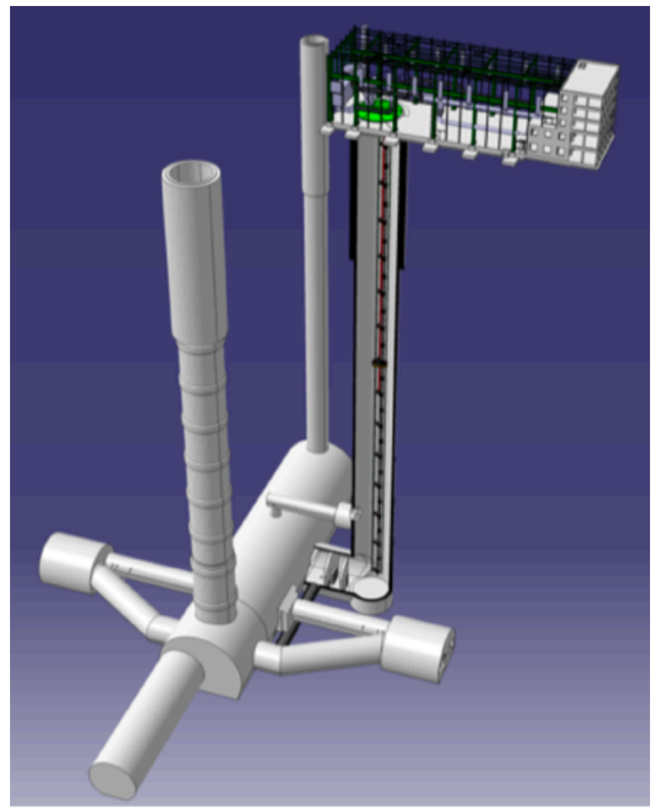
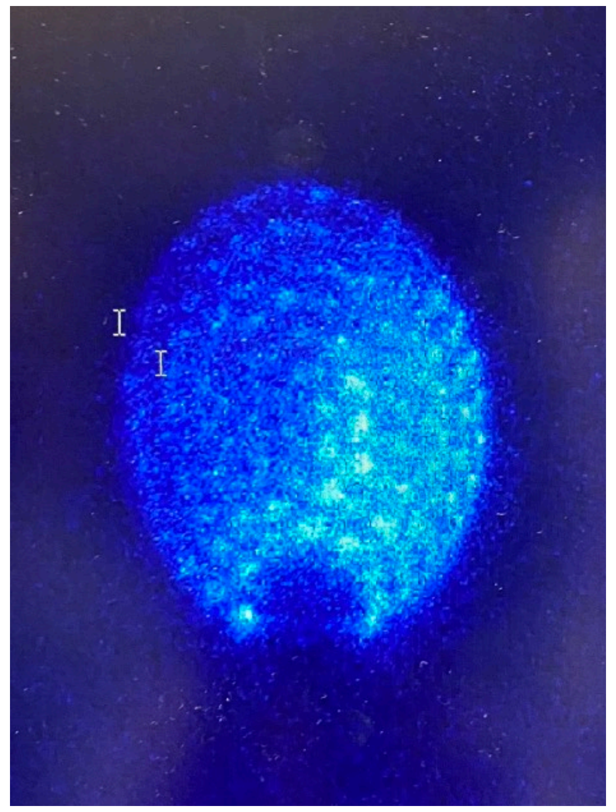
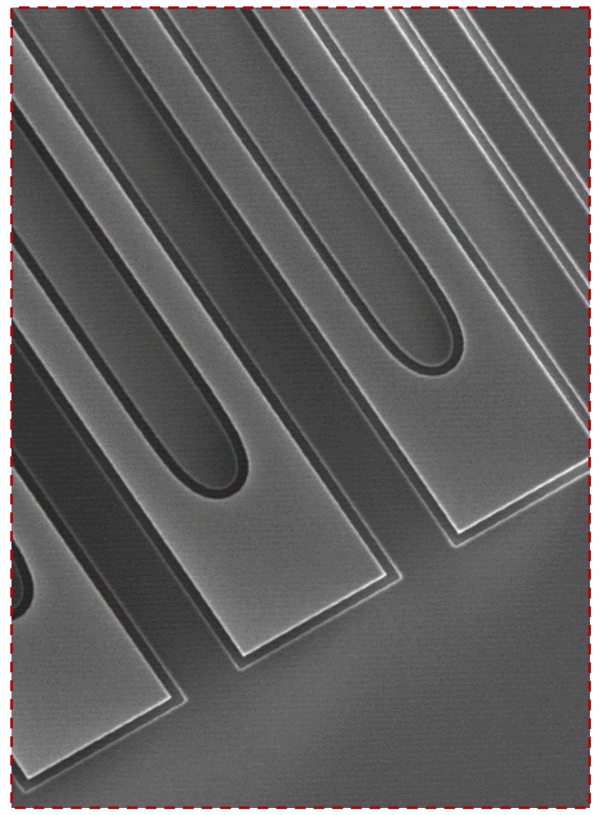
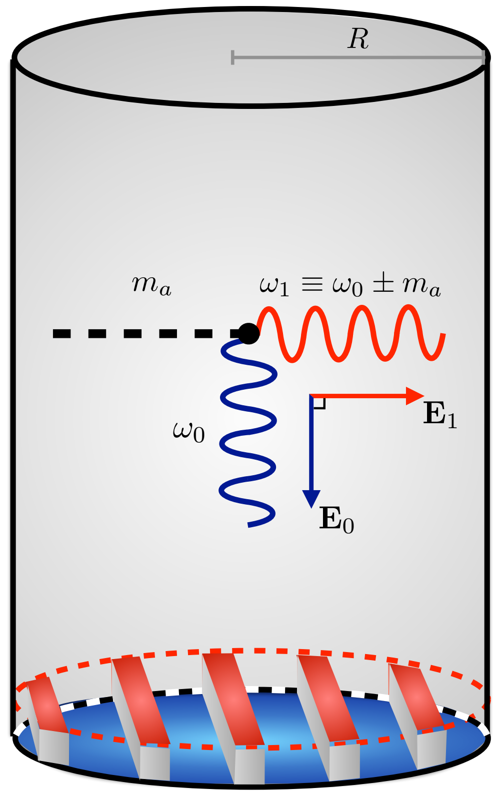
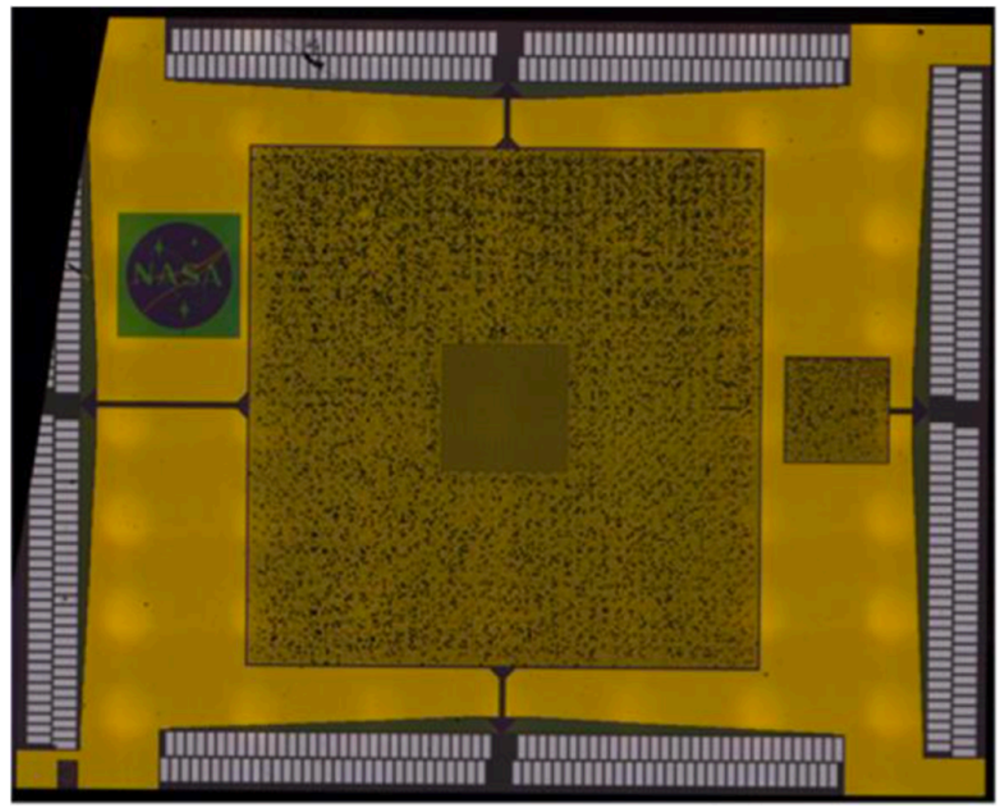








Outline

- Introduction: the “What” and “Why” of quantum sensing for Particle Physics

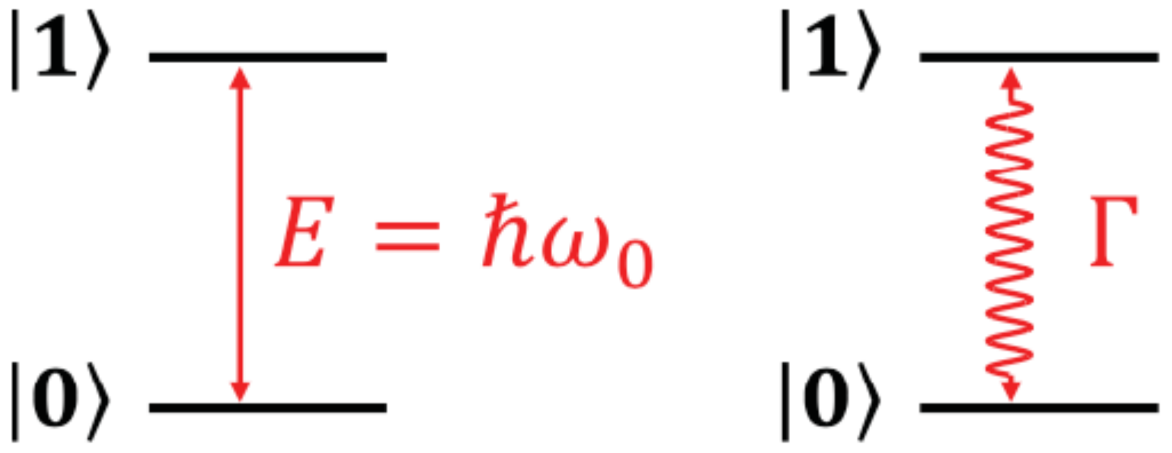
- Selected quantum sensing techniques
  - Cryogenic detectors
  - Superconducting devices
  - Spin-based, NV-diamonds
  - Metamaterials, 0/1/2-D materials
  - Ionic / Atomic / Molecular systems
  - Optical atomic clocks
  - Atom Interferometers
  - Magnetometers

- 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 $|\mathbf{0}\rangle$, $|\mathbf{1}\rangle$)
  - 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 DiVencenzo 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

[Degen, Reinhard, Cappellaro, Rev. Mod. Phys. 89, 035002; DiVencenzo, https://arxiv.org/abs/cond-mat/9612126]

Quantum Detectors, Quantum Experiments

Why **quantum sensing?**

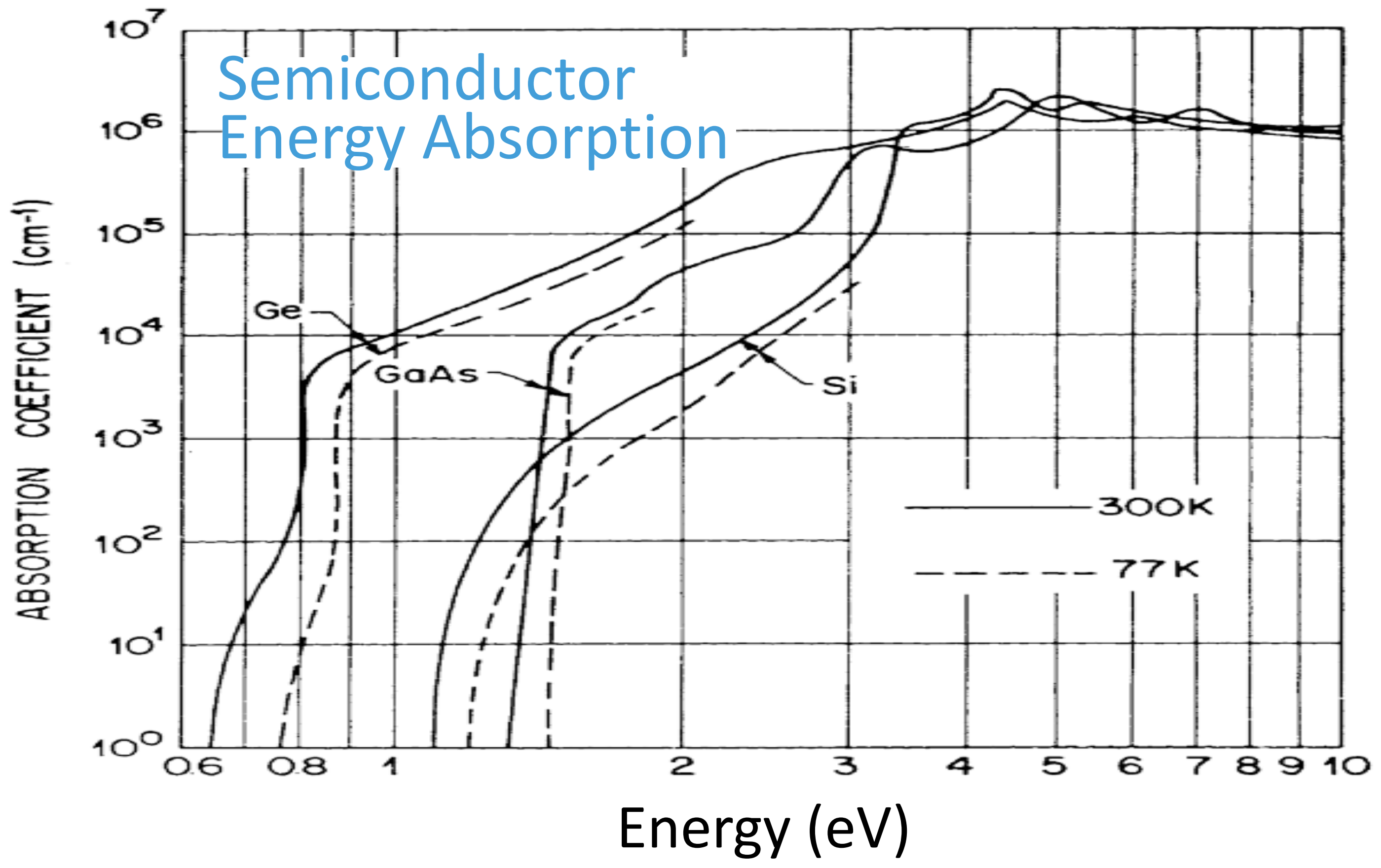
- A1: Potentially better sensitivity or noise performance
- A2: Because we have to (e.g. for ultra-light dark matter)!

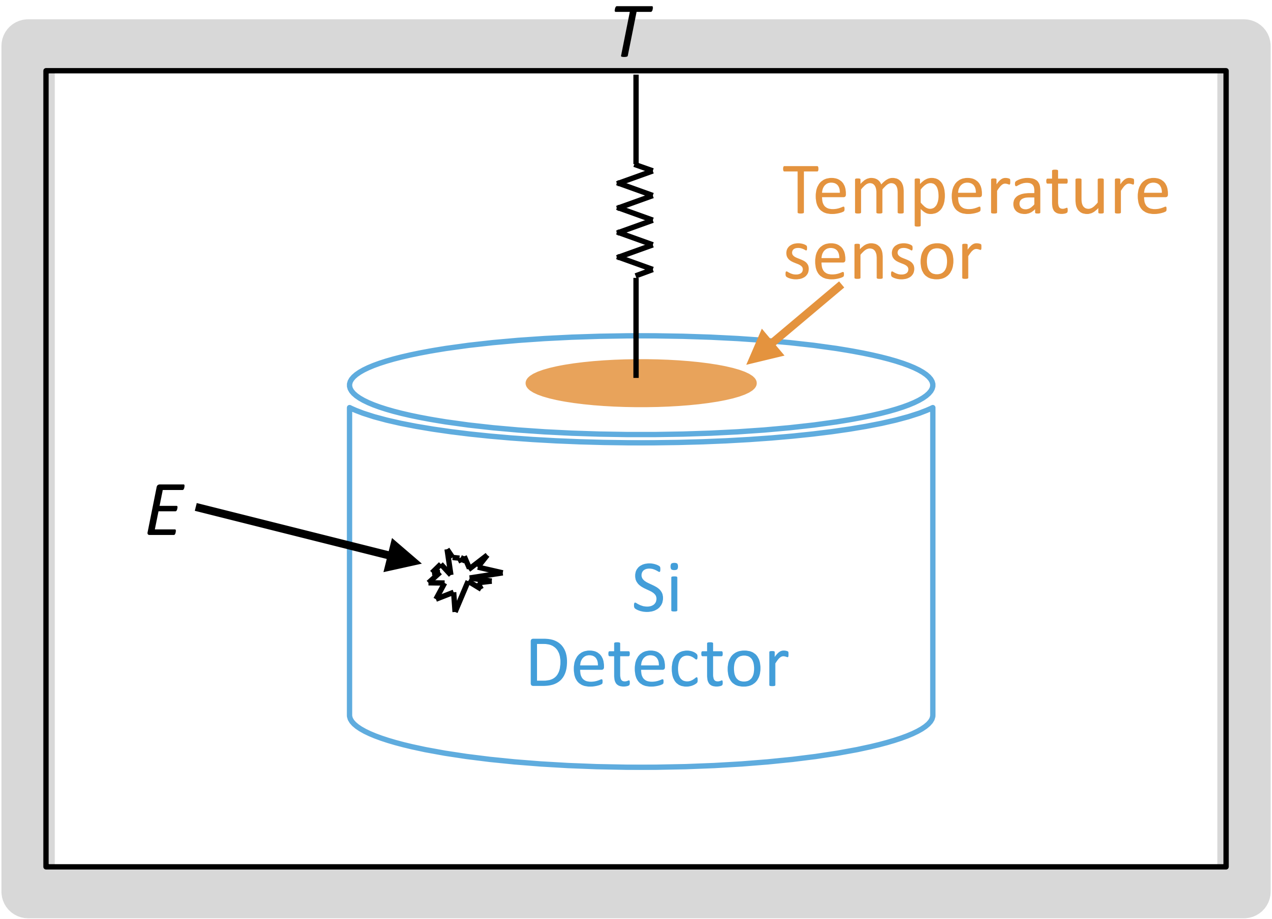
- Quantum Detectors: use quantum sensing to making extreme measurements possible
  - Enables (better) measurements, e.g. wavelengths
  - Extreme sensitivities (single-photon) or low noise

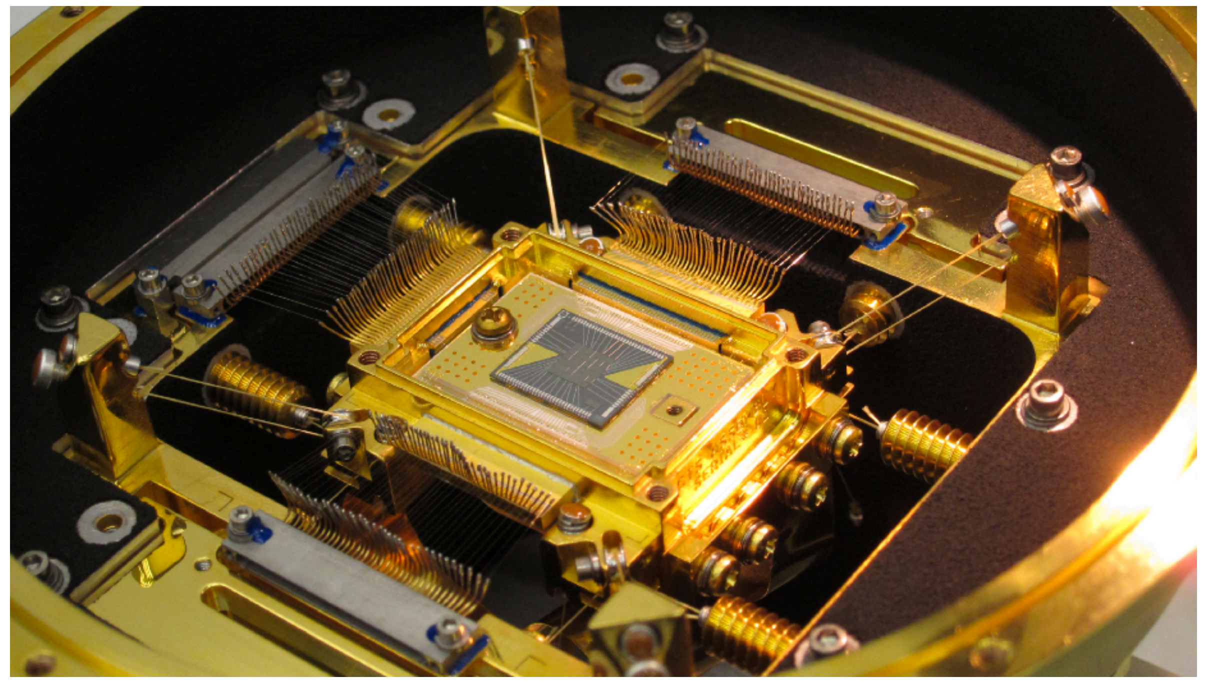
- Quantum Experiments: sensing is used for fundamental physics measurements
  - Gravity, Lorentz Invariance, physical constants (α, μ, dipole moments), etc
  - Techniques such as interferometry, magnetometry, clock-based systems, optomechanical devices

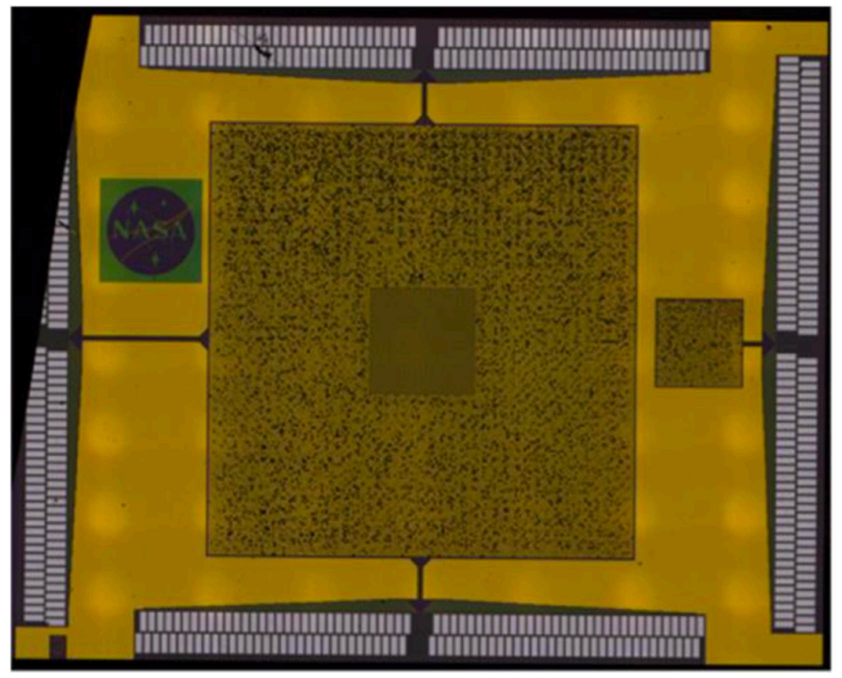
Cryogenic Detectors

- Low energy and limits for ionisation
  - Limit for e/hole pairs in semiconductors is band gap energy (1.12 eV for Si)
  - Ionisation works above the band gap, below we detect the heat (phonons)
- Measuring small temperature differences
  - ΔT depends on energy and heat capacity ($C = c_p m$)
  - Heat capacity given by Debye equation, $C \propto (T/T_D)^3$, where T_D = Debye Temp
  - Silicon example: $\Delta T \approx 1\%$ requires mass of 1 µg and T_0 = 0.1 K
- Example1: Hitomi satellite, SXS (JAXA, CSA)
  - 36 pixels (814 µm) HgTe absorber at 50 mK
  - Energy between 0.3 and 12 keV, resolution ~7 eV
- Example2: Lynx X-ray Microcalorimeter (NASA)
  - ~50k pixels (25-50 µm) Au absorber at 50 mK
  - Energy between 0.2 and 15 keV, resolution <3 eV





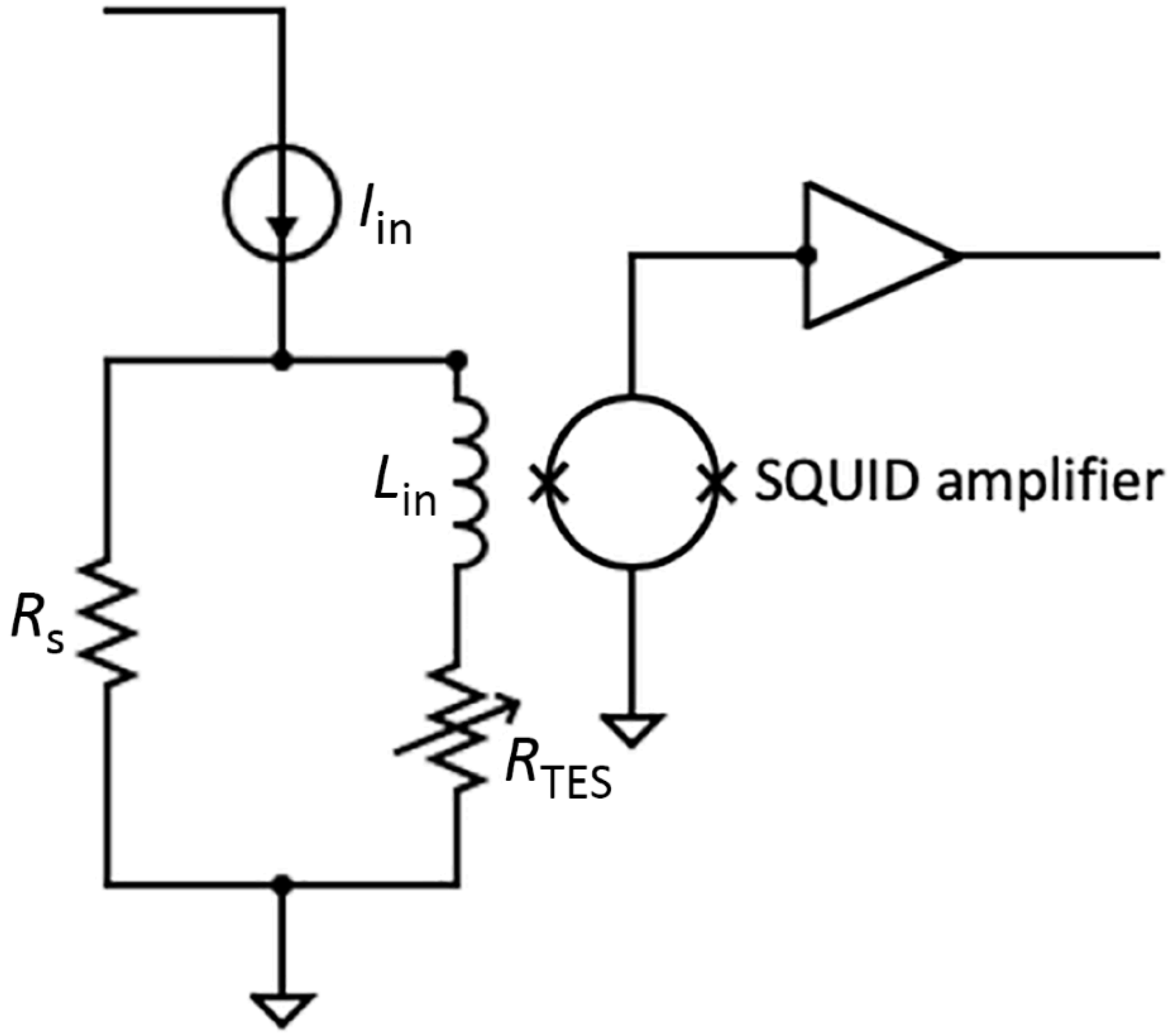


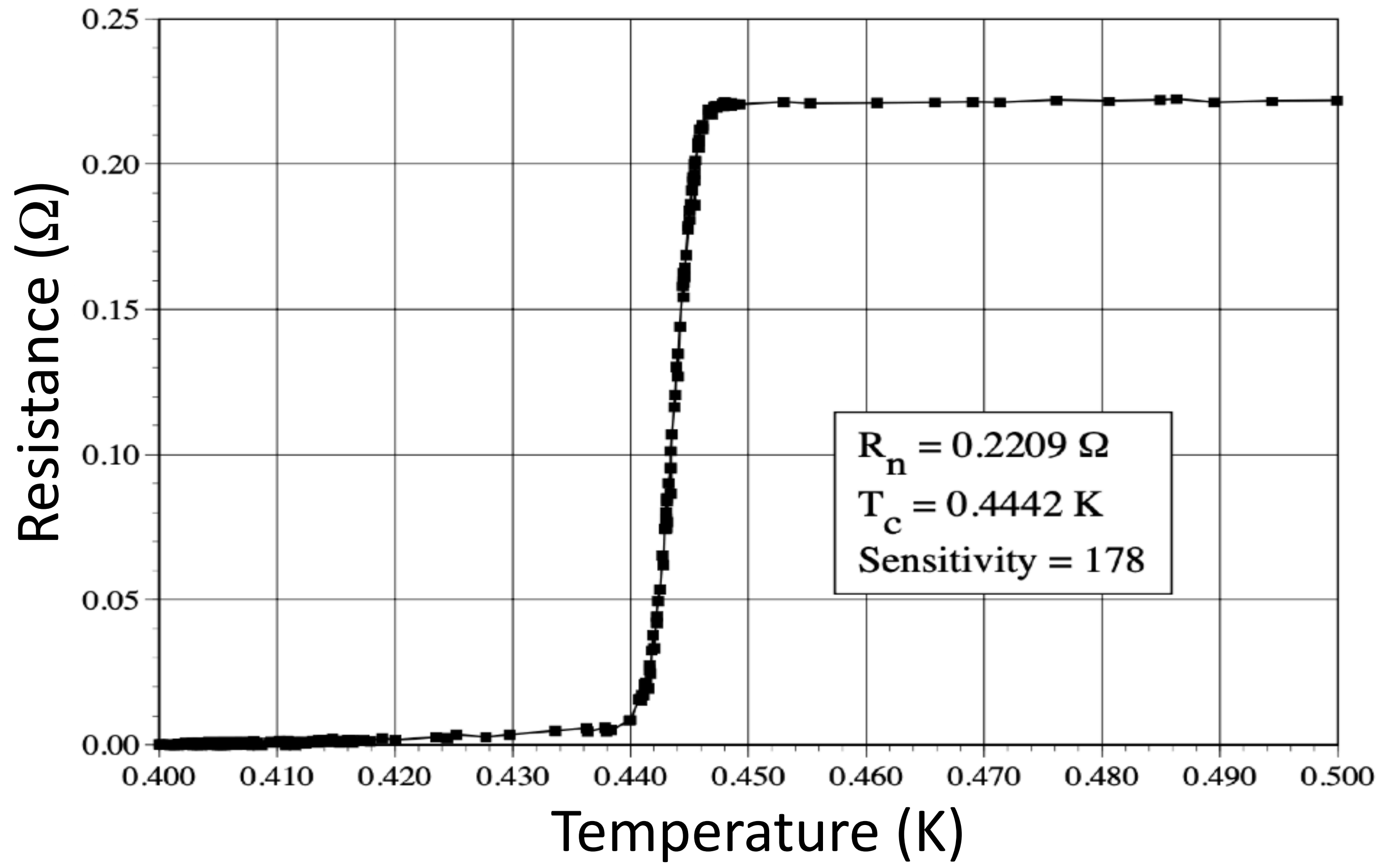


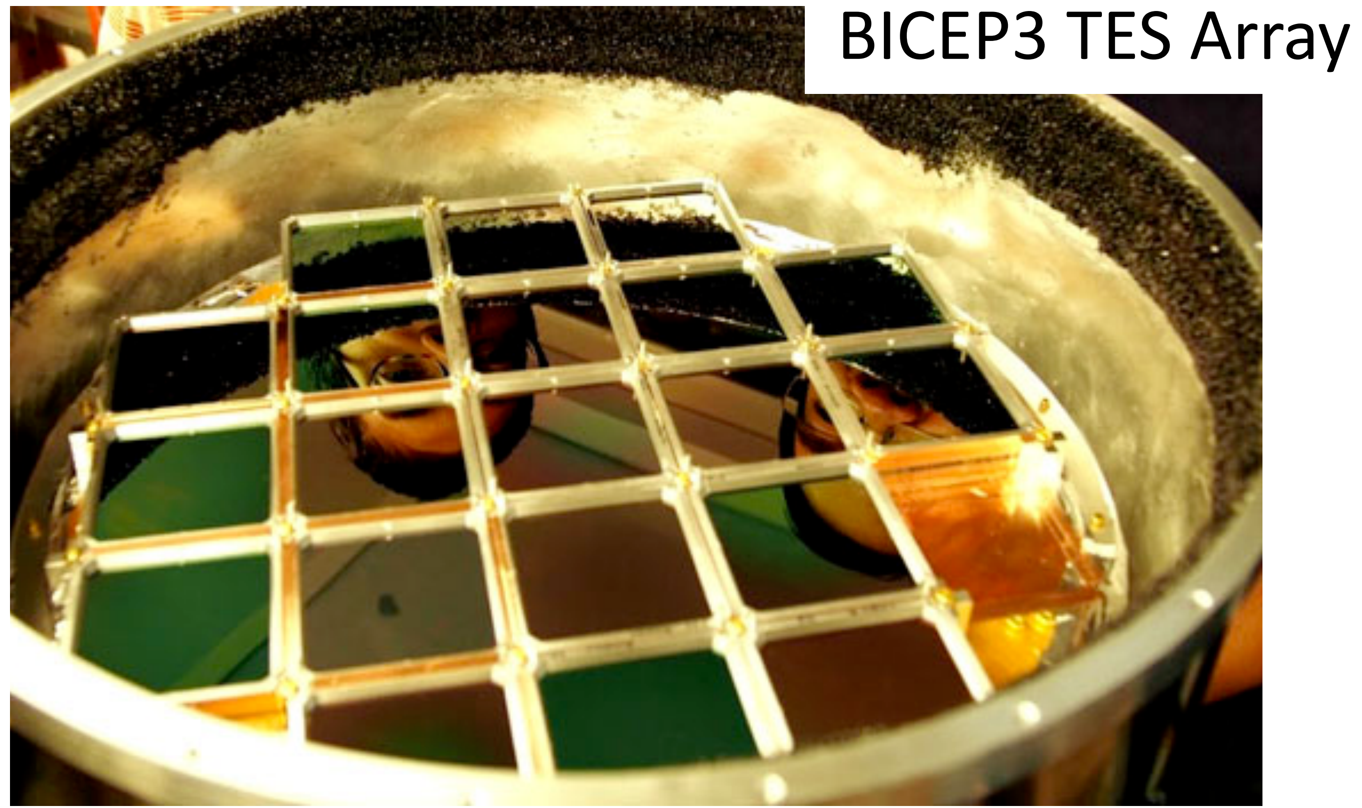
[Hitomi; JATIS, Vol. 5, 021017 (2019)]

Transition Edge Sensors (TES)

- TES Operations: Measure ΔT with superconducting circuit
  - sharp transition between superconducting → conducting
  - small temperature change, large resistance change
  - Detection limited by thermal noise; readout resistance << sensor resistance
- Readout: Superconducting Quantum Interference Devices (SQUIDs)
  - Two Josephson junctions in parallel: low temperature (~0-5 K)
  - Plus: Low temp, very low noise, moderate amplification
  - Minus: limited input, feedback (flux) loop required to lock at operating point
- Example: BICEP3
  - Used to study Cosmic Microwave Background (B-modes)
  - Monolithic arrays of 2400 antenna-array coupled TES detectors
- Arrays used from radio to X-ray with high spectral resolution (SPT, ATHENA, BICEP) → now also particle physics (CDMS, ALPS…)





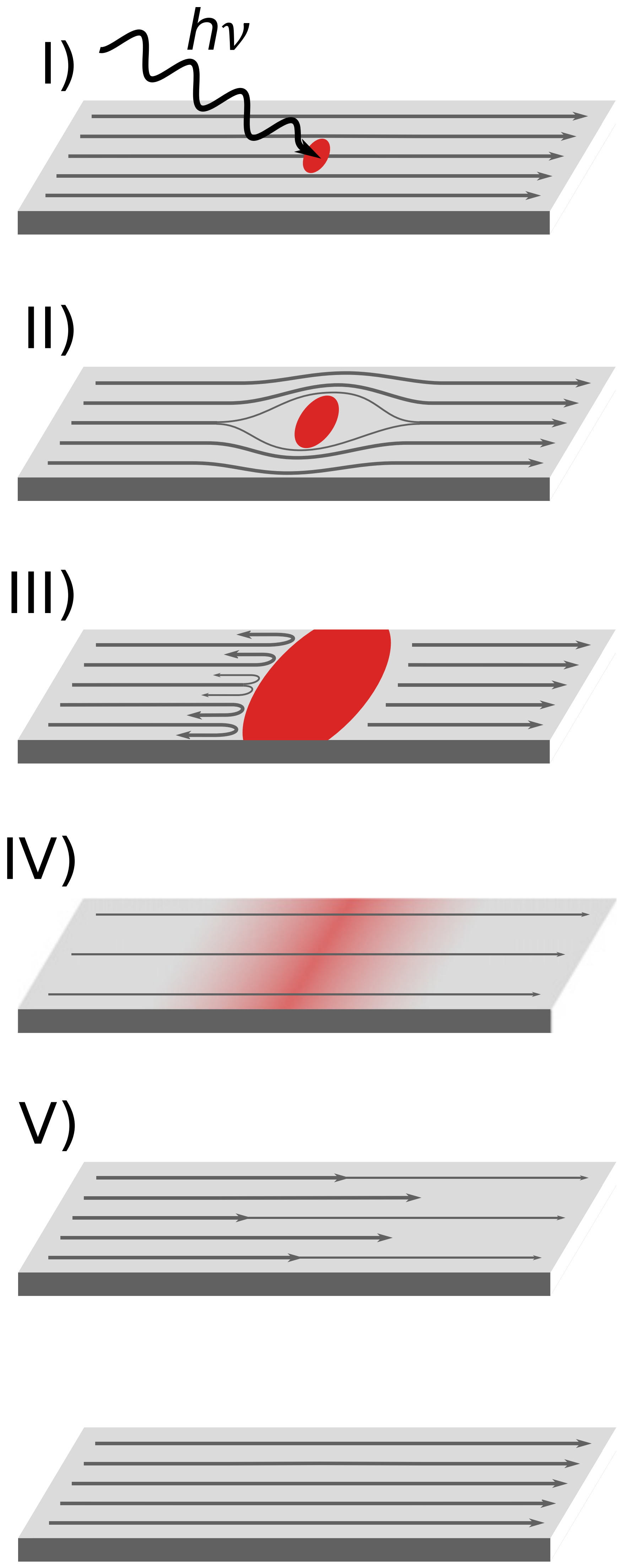

BICEP3 TES Array

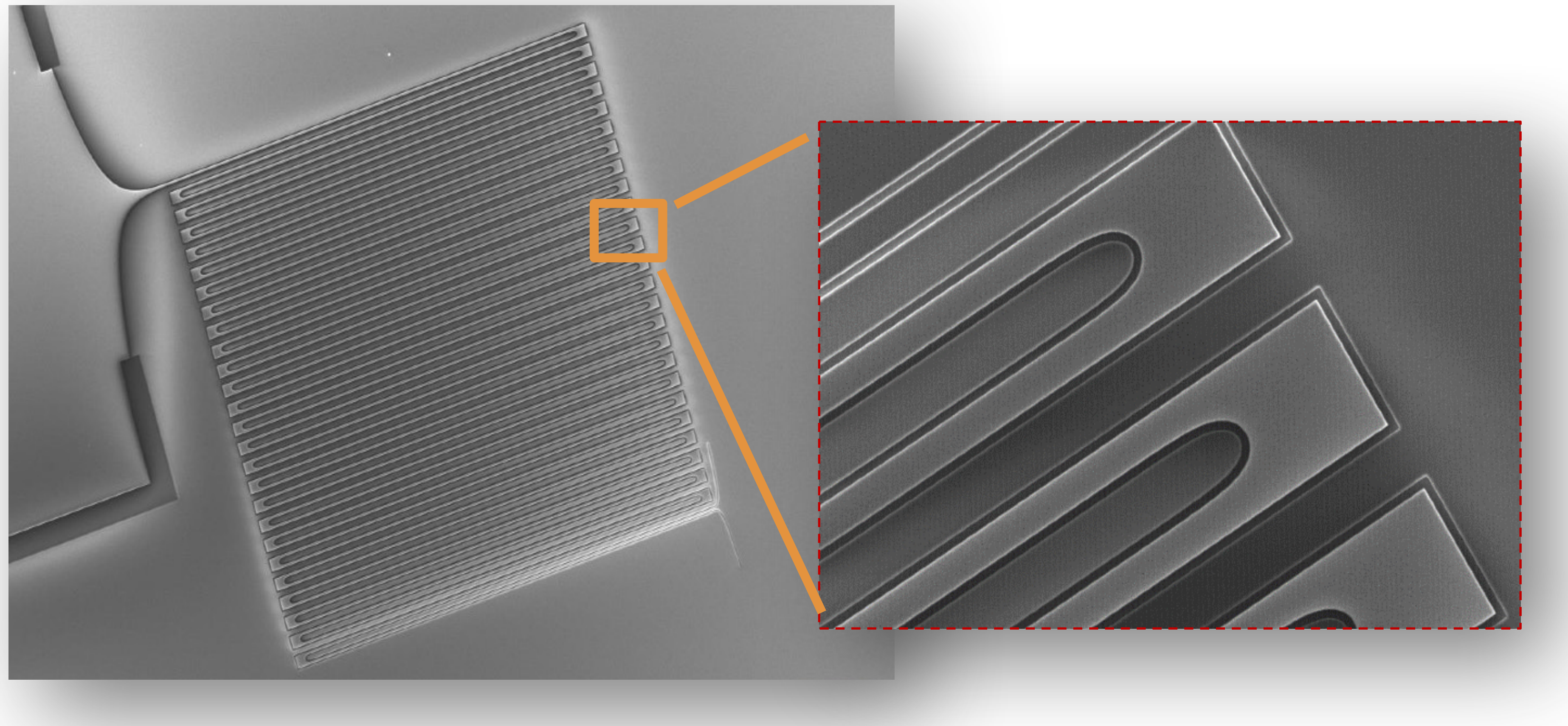
[Nagler et al, JATIS, 7(1), 011005 (2021); BICEP3]

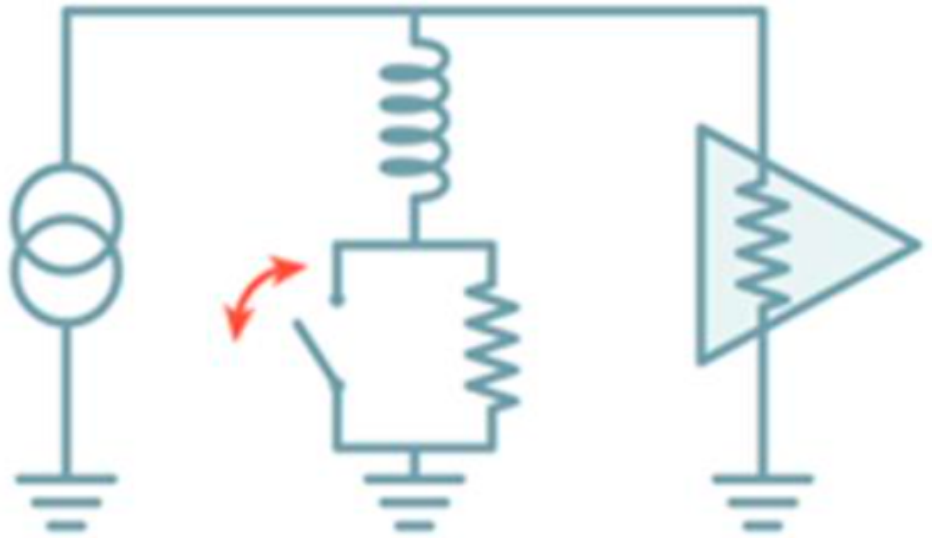
Superconducting Nanowire Single-Photon Detectors (SNSPD)

- Superconducting circuit (wire) or pads (chicane)
  - Absorbed photos create non-superconducting region
  - Extremely low energy threshold, extremely fast
  - Applications for quantum pixels, ultra-sensitive tracking, milli-charged particles

- Recent advances
  - Higher temperature operation (1-4 K)
  - Demonstrated to work for micron size (optical lithography possible)
  - Commercial devices available - quantum communication







SNSPD: Advances & Expected Performance

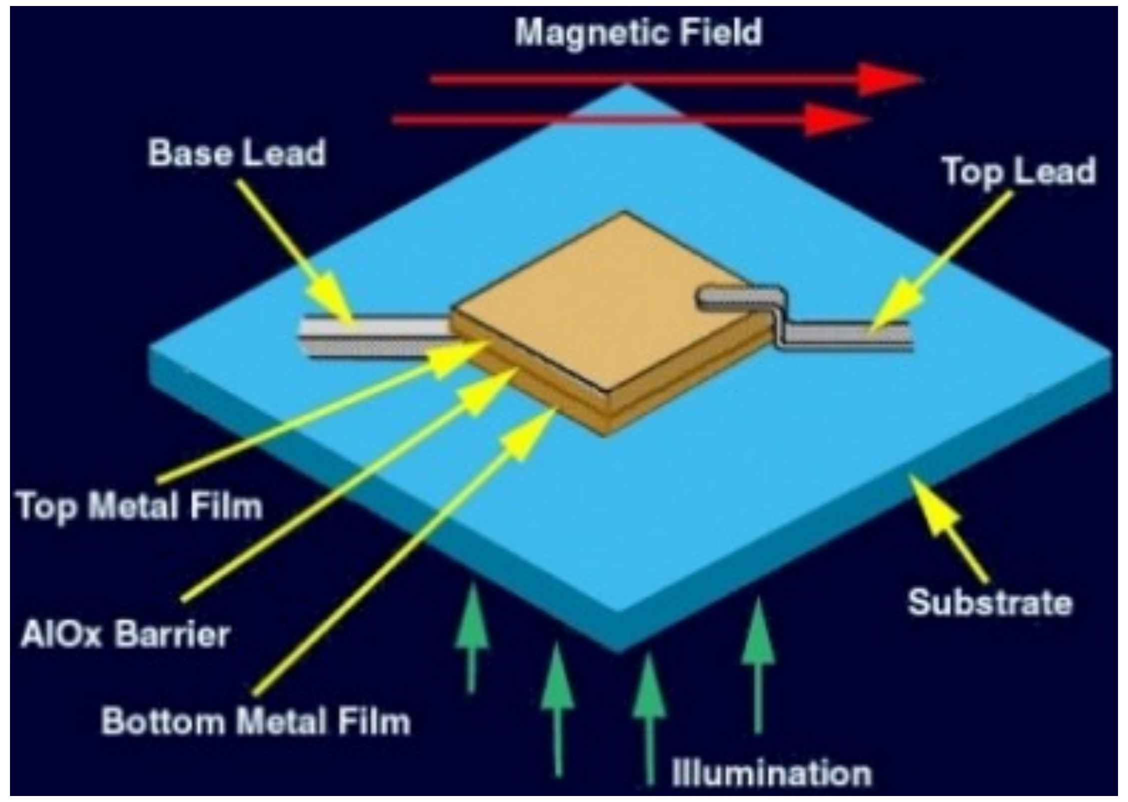
Timing jitter	Intrinsic photon number resolution	Efficiency	Array size	Maximum count rate	Dark count rate	Active area	Cut-off wavelength	
18 ps	None	93%	64	1 Gcps	4 /s/mm^2	0.001 cm^2	5 µm	Records in 2016
2.6 ps [1]	**3-5 photons**	**98%** [2]	**4x10^5** [3]	**1.5 Gcps** [4,5]	**4x10^{-5} /s/mm^2** [6]	**0.1 cm^2** [3]	**29 µm** [7]	**Current records for isolated devices**
1 ps	**10**	**99 %**	**10^7**	**10 Gcps**	**1x10^{-6} /s/mm^2**	**1 cm^2**	**100 µm**	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)

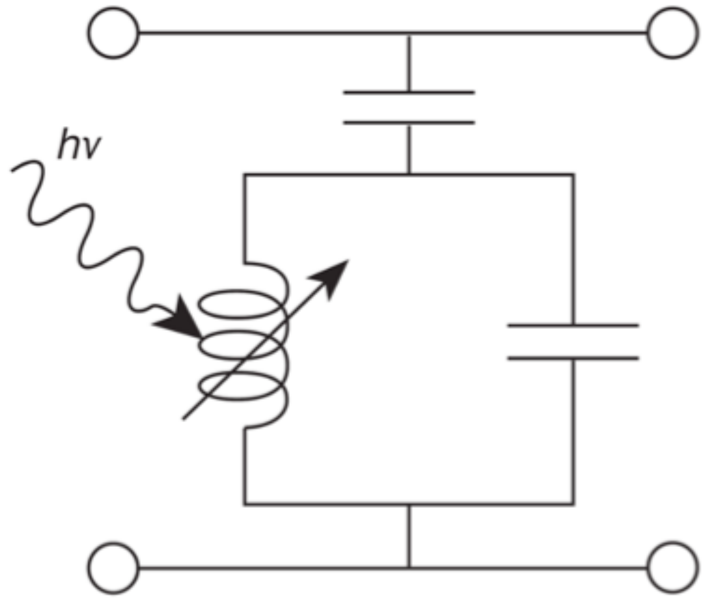
[B. Korzh]

Cryogenic Quantum Sensors

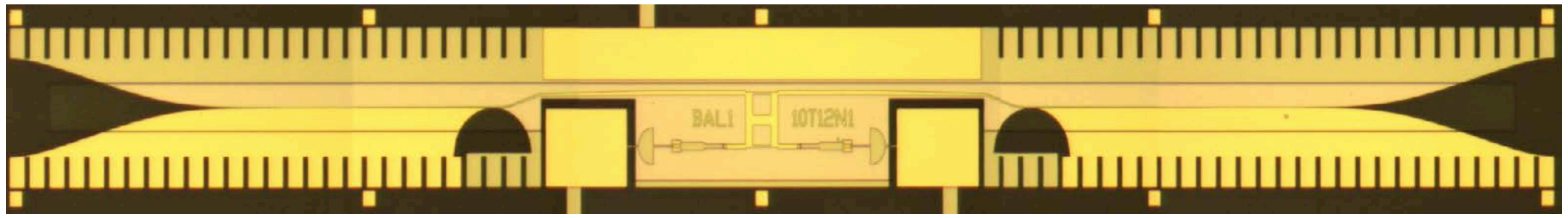
- Superconducting Tunnel Junctions (STJ)
  - Exploit quantum tunnelling in a junction of two superconductors
  - Direct tunnel current measurement (non-Heterodyne): simultaneous fast photon counting and spectroscopy in IR, Vis, UV bands
- Microwave Kinetic Inductance Detectors (MKIDs)
  - Exploits change 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 → GHz



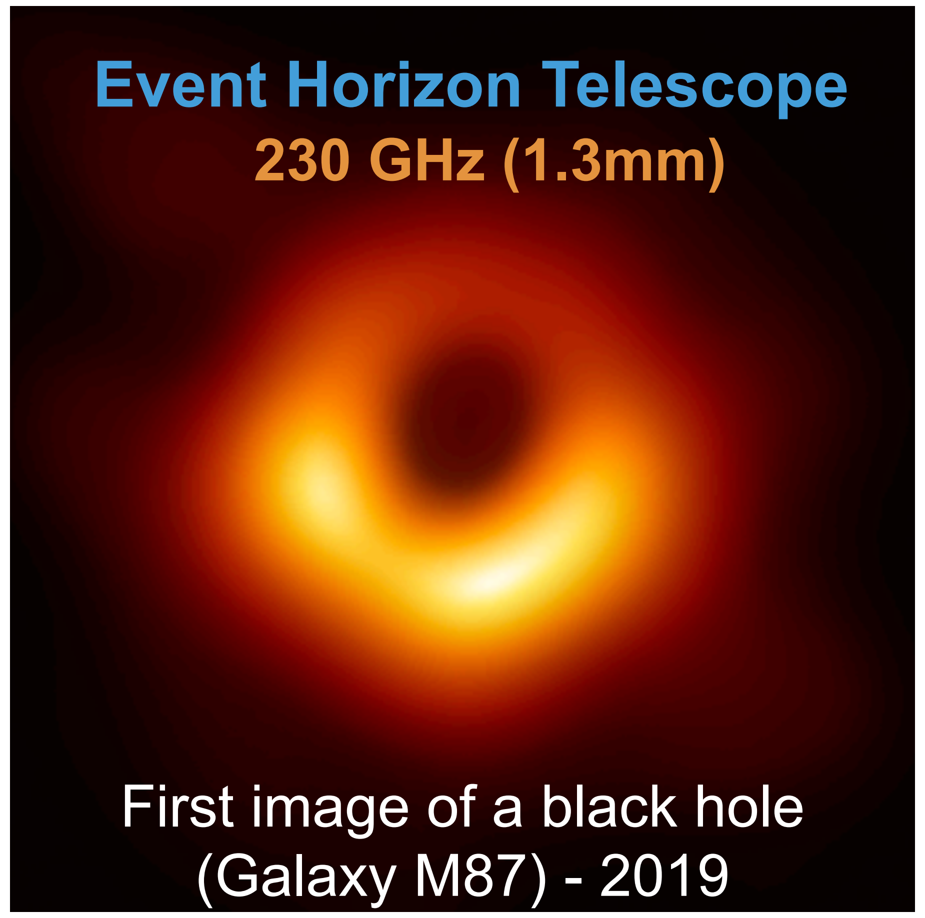
Superconducting Tunnel Junction



MKID operating principle



Superconductor-Insulator-Superconductor (SIS) Mixer Block


Event Horizon Telescope
230 GHz (1.3mm)

First image of a black hole (Galaxy M87) - 2019

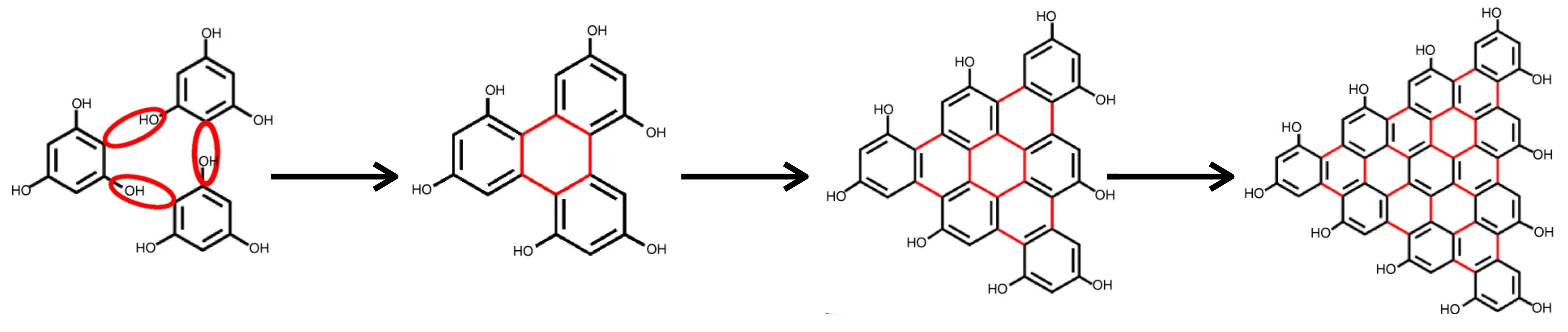
Cryogenic Quantum Sensors vs. Wavelength

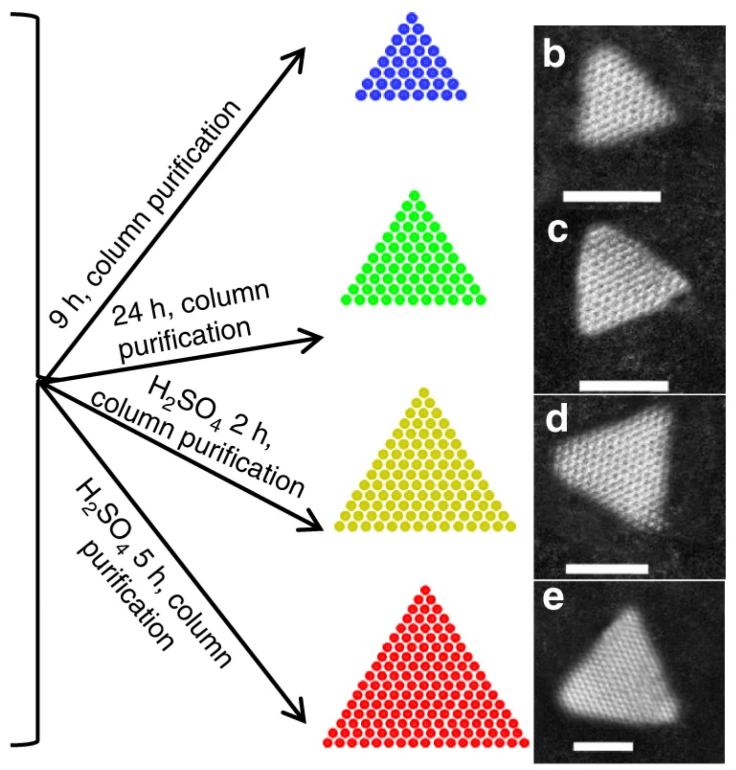
Detector	Microwave 3cm - 3mm 10-100 GHz 0.04-0.4 meV	Submillimeter 3mm - 300µm 100 GHz - 1 THz 0.4-4 meV	Far infrared 300 – 30 µm 1 – 10 THz 4-40 meV	Optical 2 µm - 300 nm 2-37 eV	High Energy UV, X-Ray
Transition Edge Sensors (TES)	🟡	🟢	🟢	🟢	🟢
Kinetic Inductance Detectors (KID)	🟡	🟢	🟢	🟢	
Superconducting 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)	🟢				

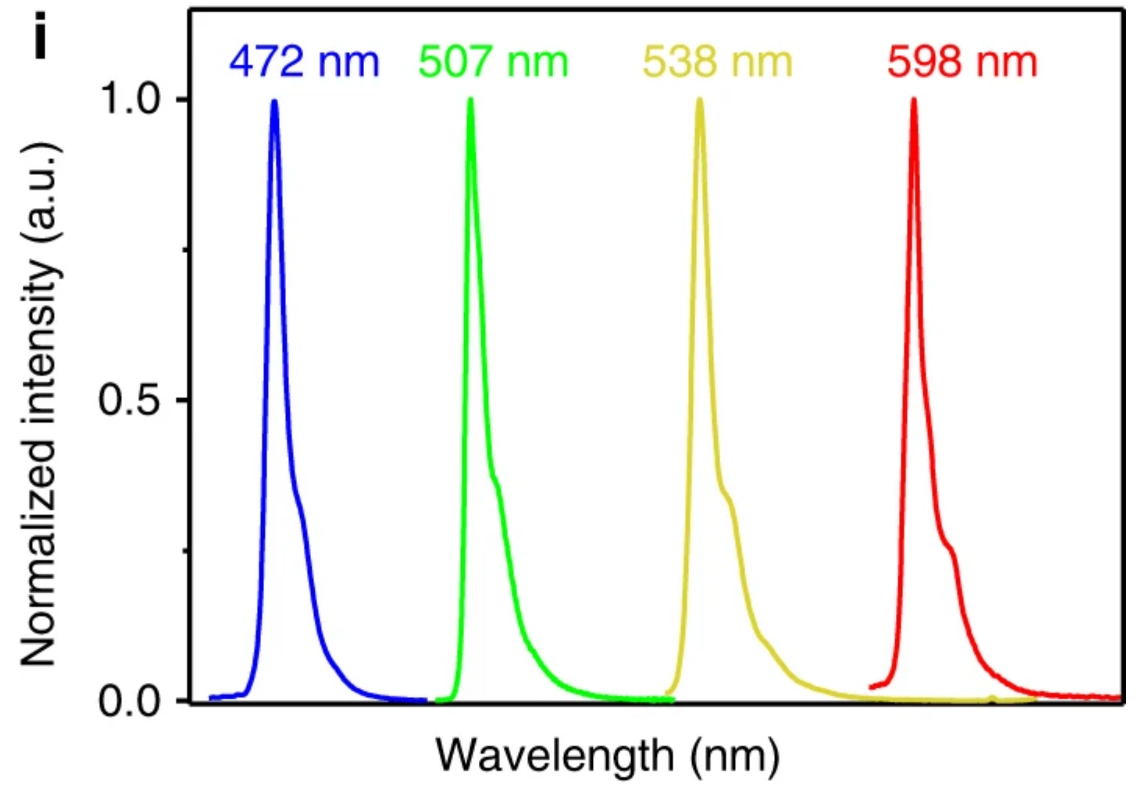
[S. Withington]

Quantum Dots and Chromatic Calorimetry

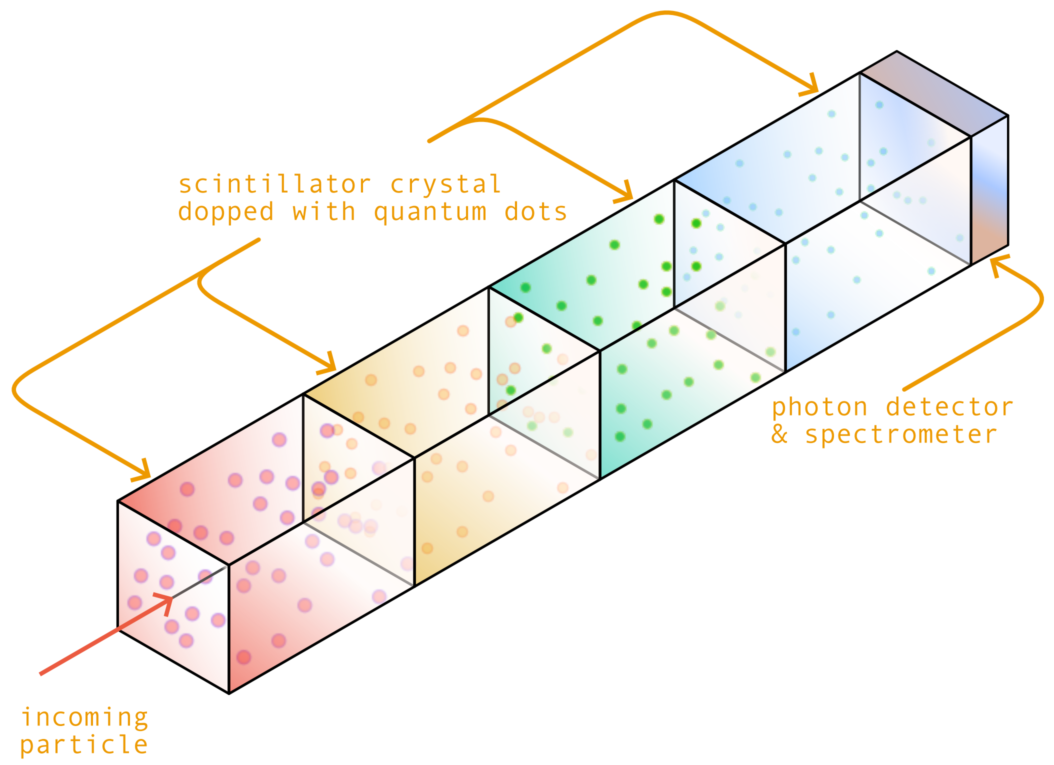
- Quantum dots: nanometer-sized semiconductor structures, e.g. in carbon, perovskites, etc.
- Tuneable, with properties between single atoms and bulk material

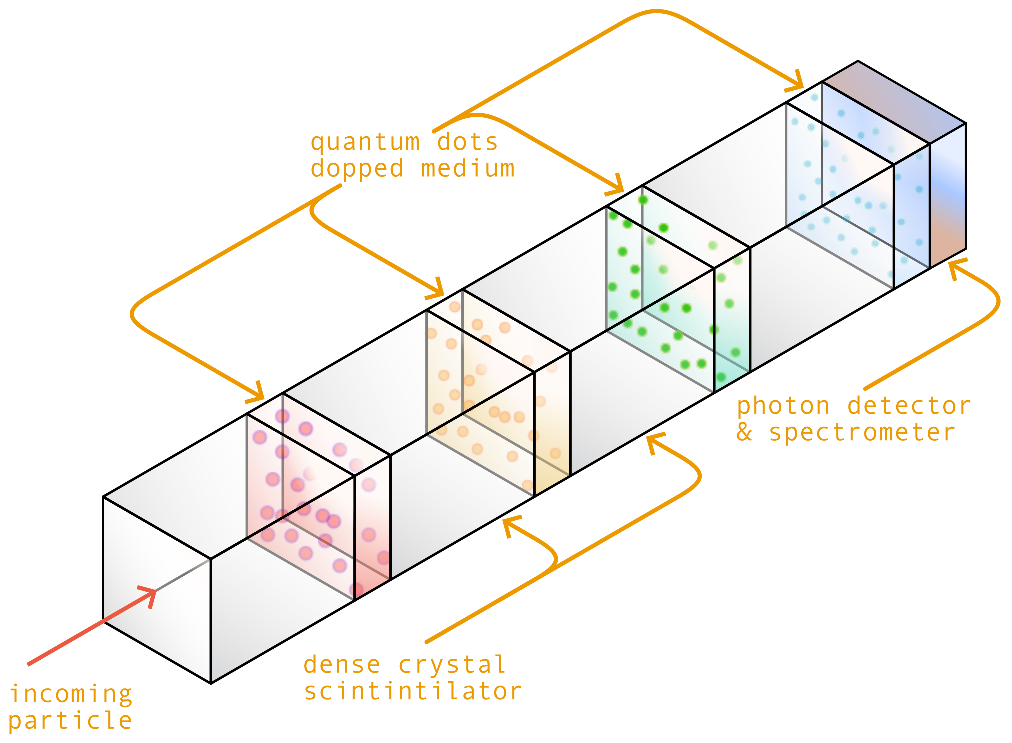


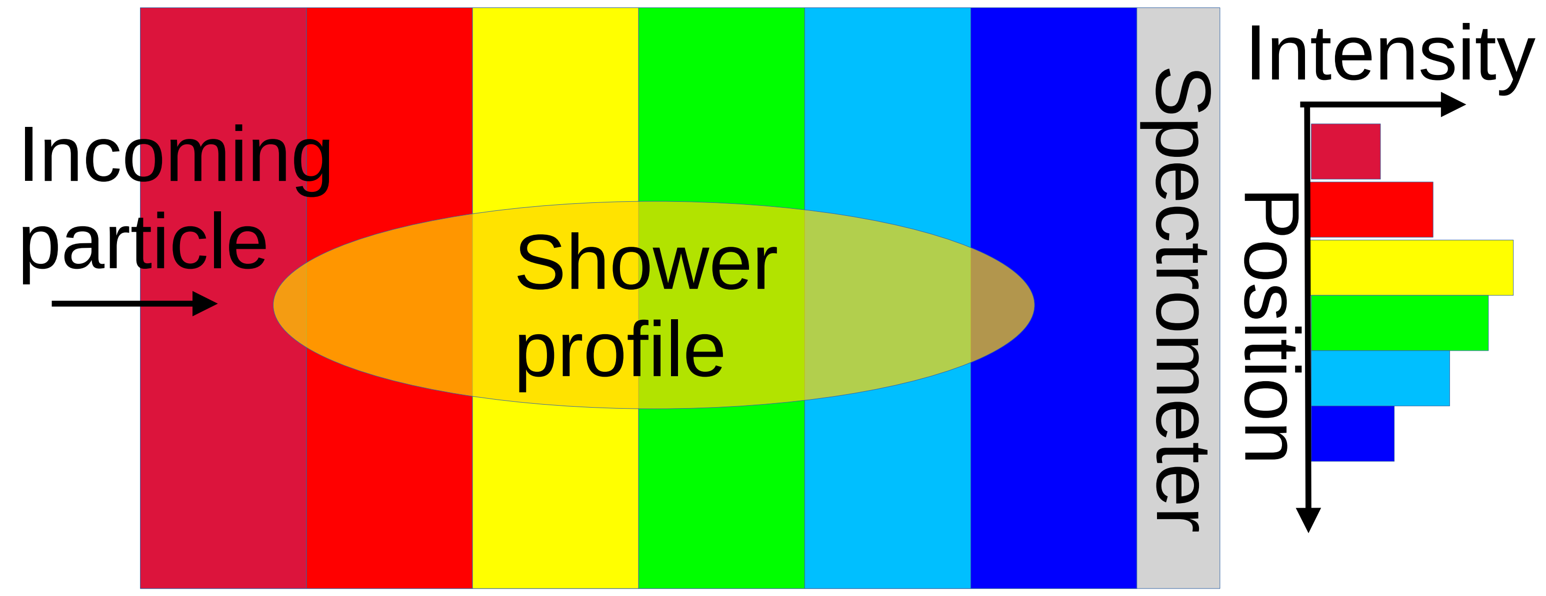




- Seed different parts of a detector with nanodots emitting at different wavelengths
- Wavelength of fluorescence photon indicates specific nanodot position: shower profile from spectrometry







[Y. Haddad and also F. Yuan et al., Nature Comm. 9 (2018) 2249]

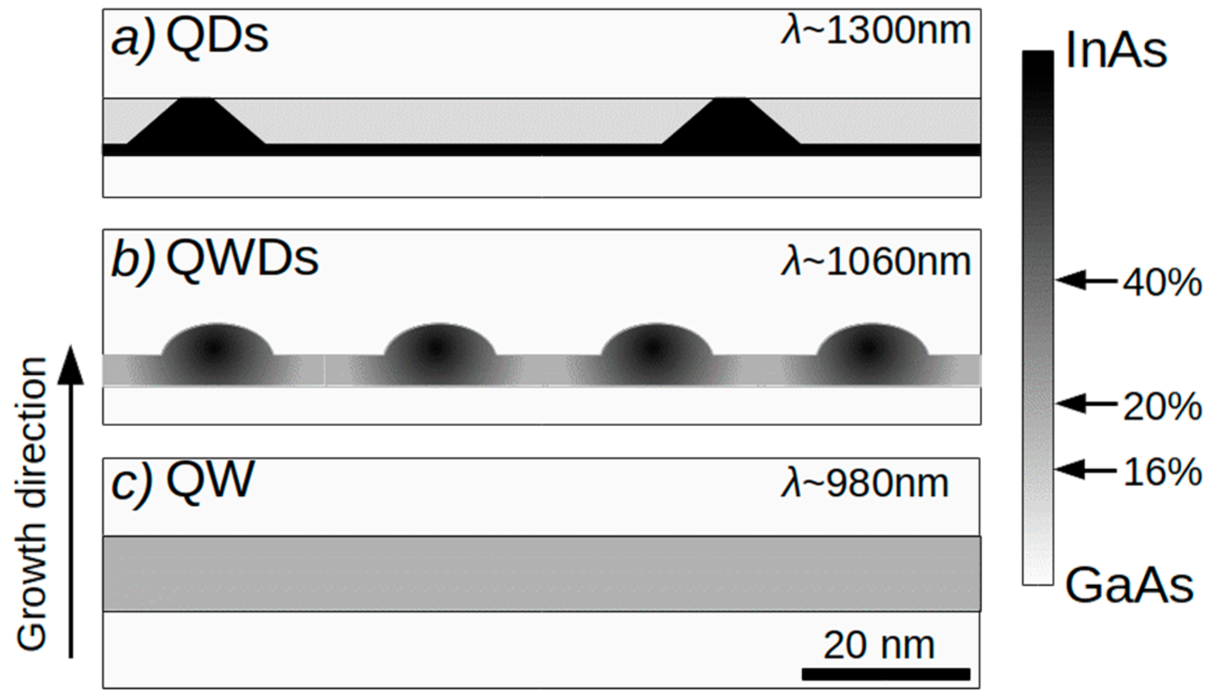
Quantum Dots: Active Scintillators & Tracking

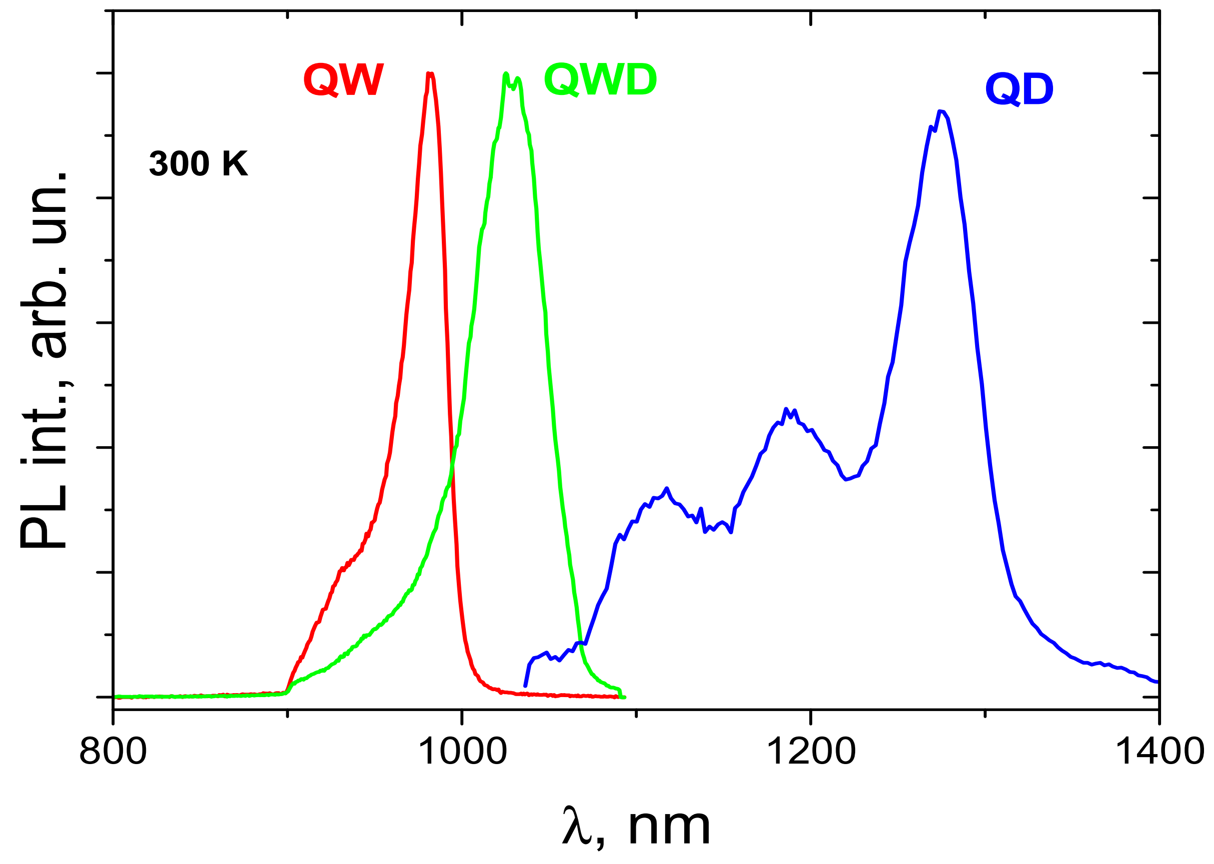
- Quantum Dots, Quantum Wires, Quantum Wells… many structures possible

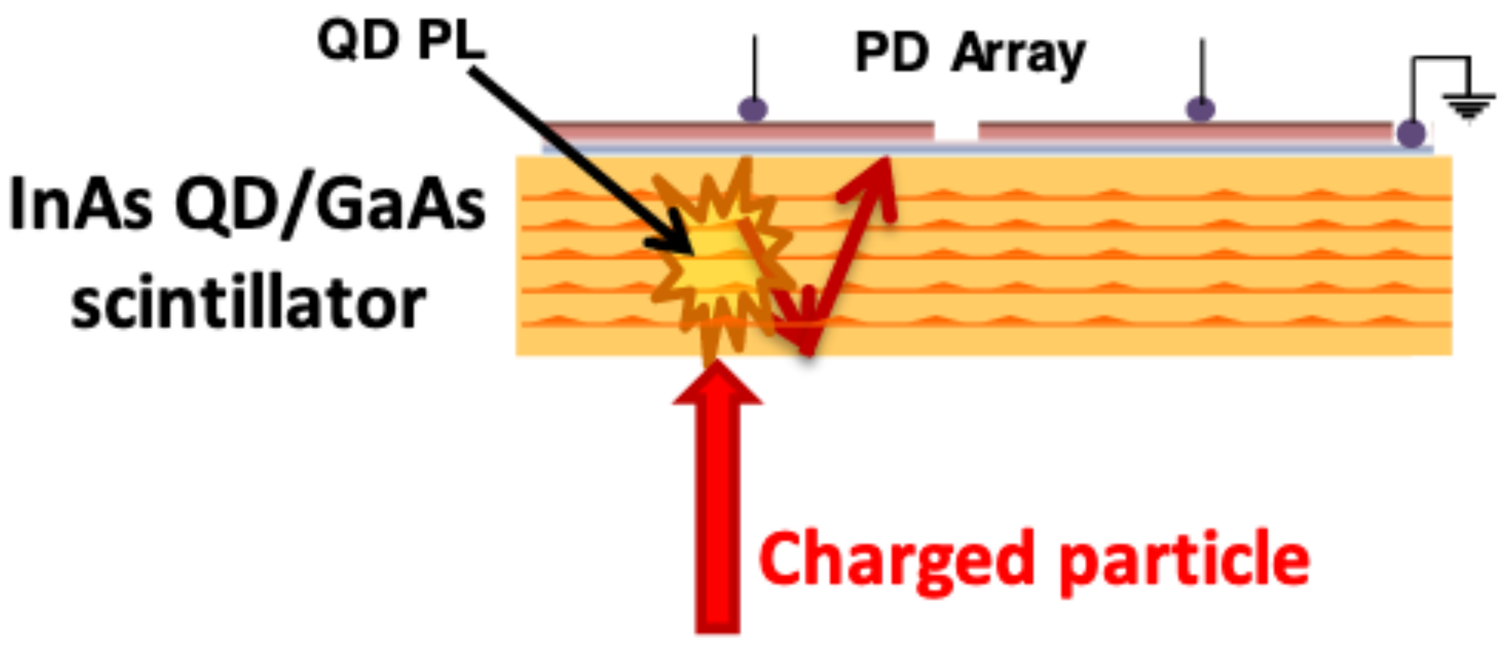
- Quantum Well-dots: aiming for active scintillators
  - electronic amplification / modulation
  - pulsed / primed operation
  - gain adapted in-situ

- 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

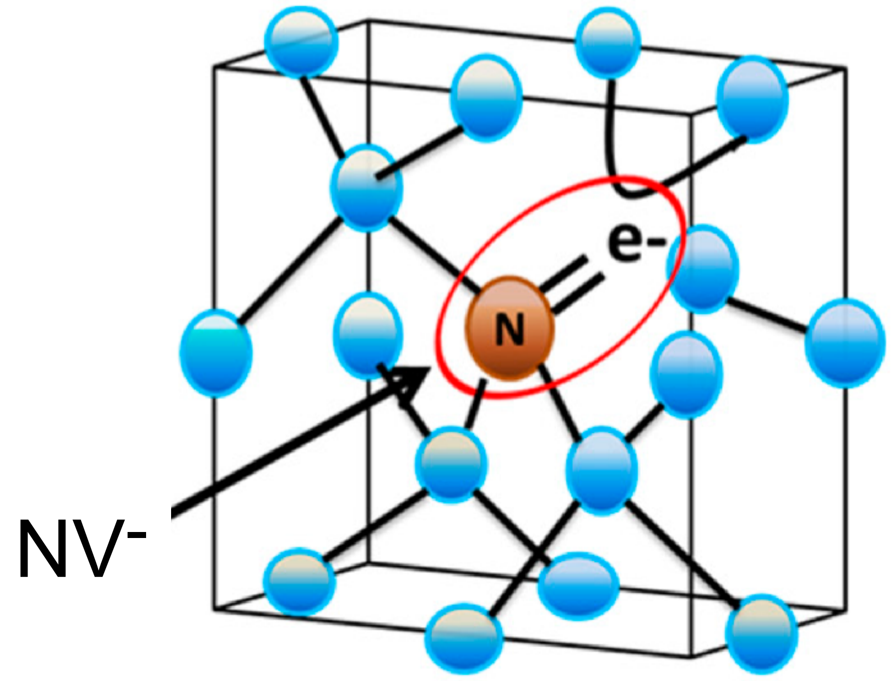




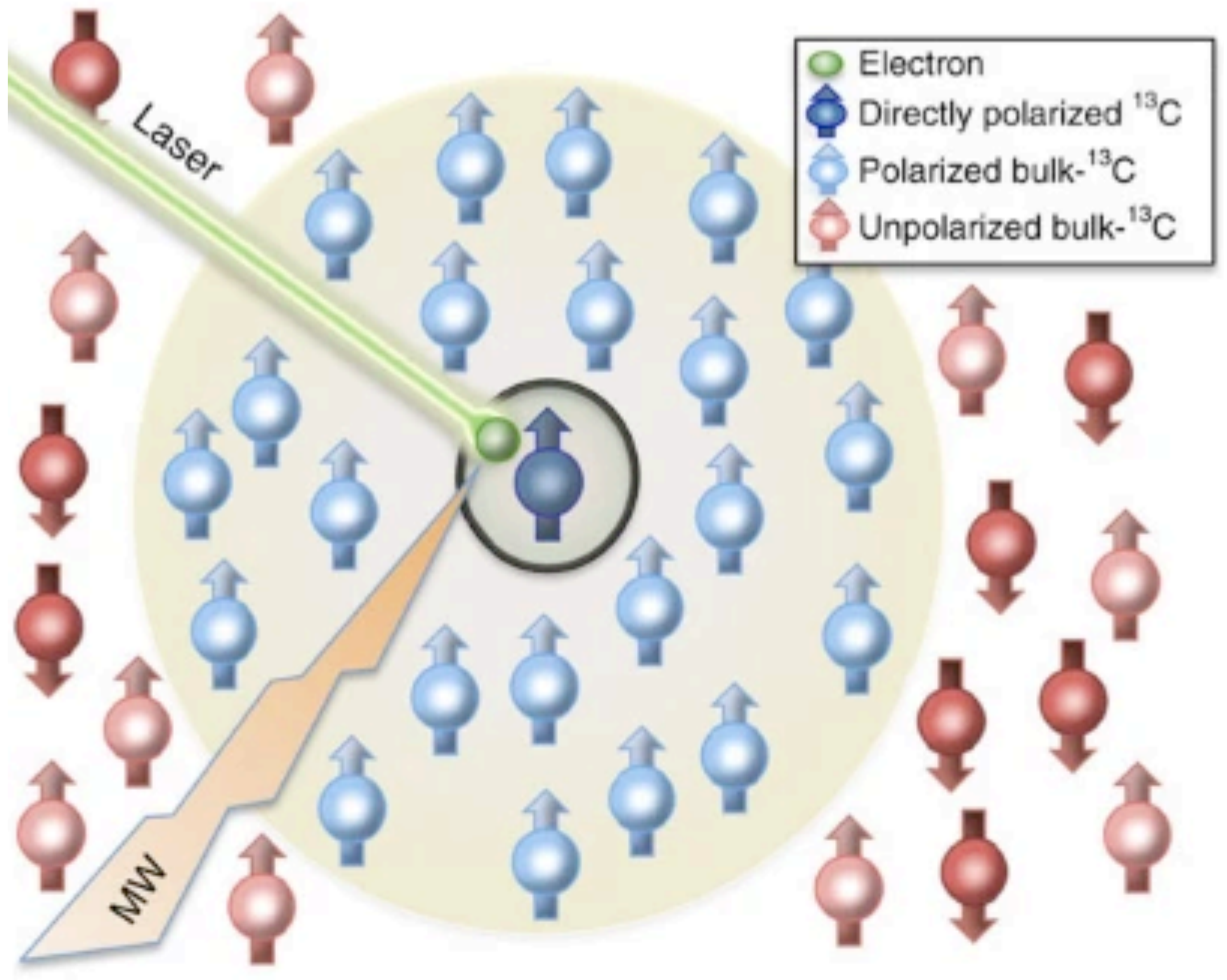


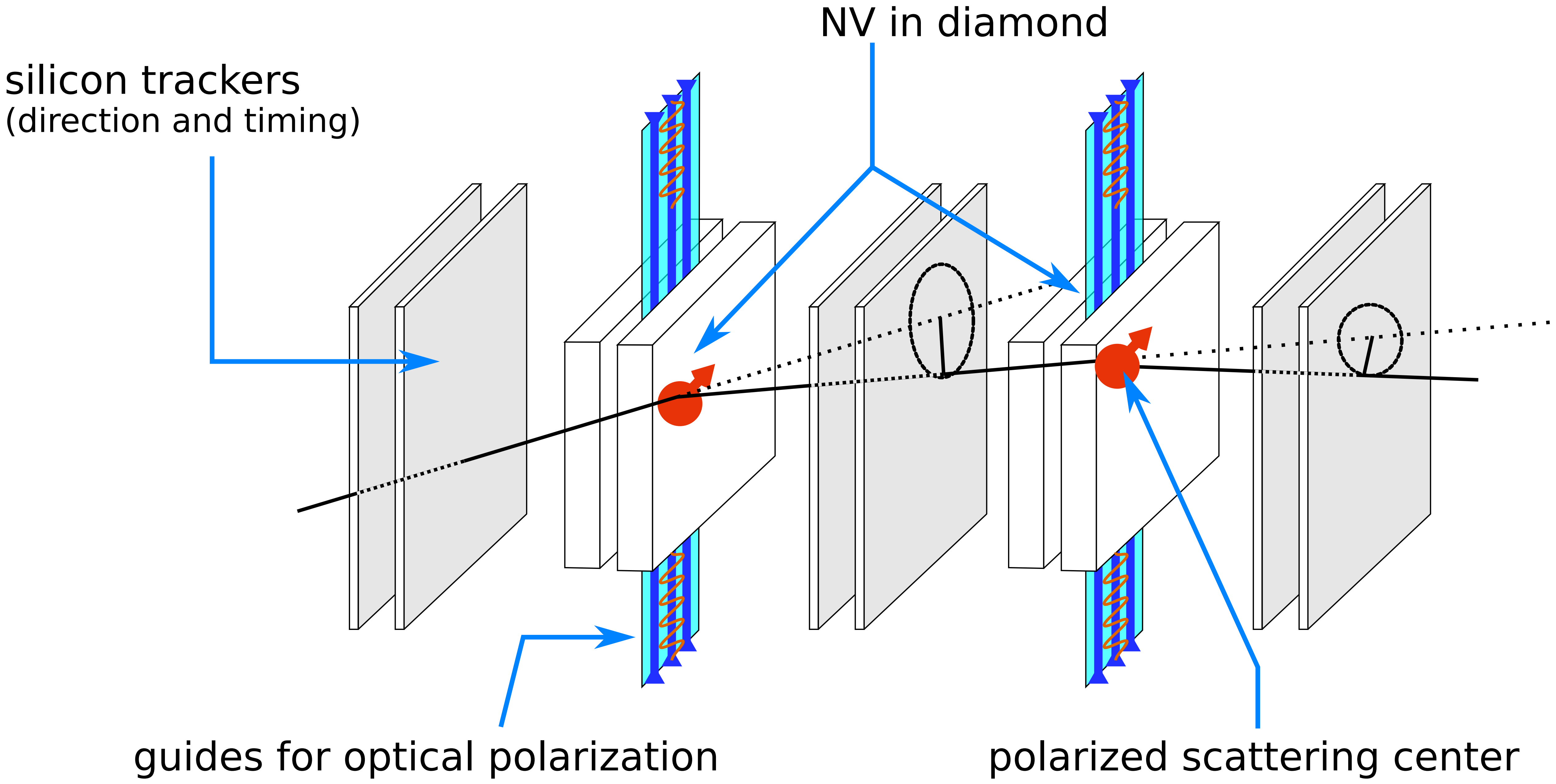
[Maximov et al., Appl. Sci. 2020, 10, 1038; M.Hoeferkamp et al., arXiv:2202.11828; A. Minns et al., MRS Advances 6, 297–302 (2021)]

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





NV in diamond

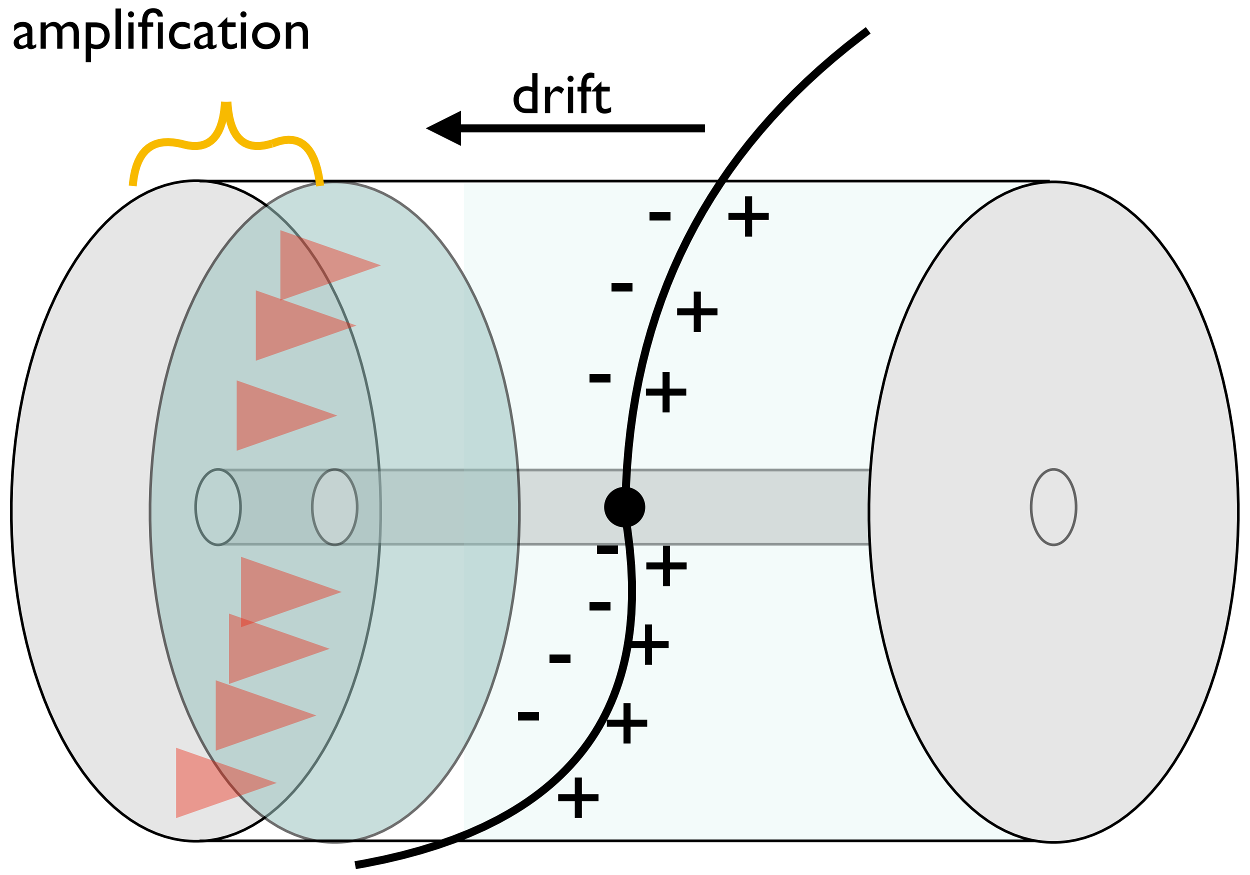
silicon trackers
(direction and timing)

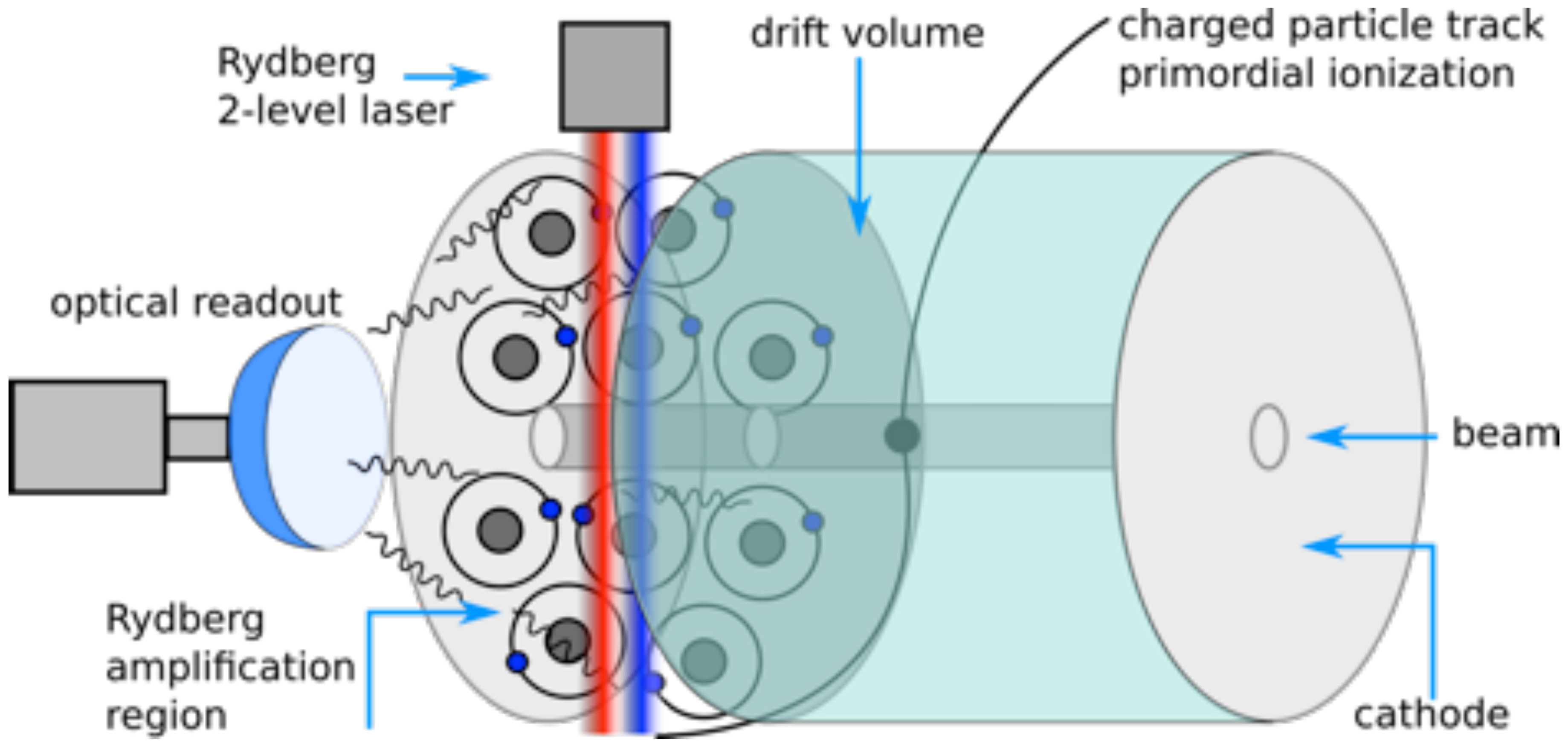
guides for optical polarization

polarized scattering center

[G. Alvarez et al., Nature Communications 6, 8456 (2015)]

Quantum Sensing and Rydberg Atoms

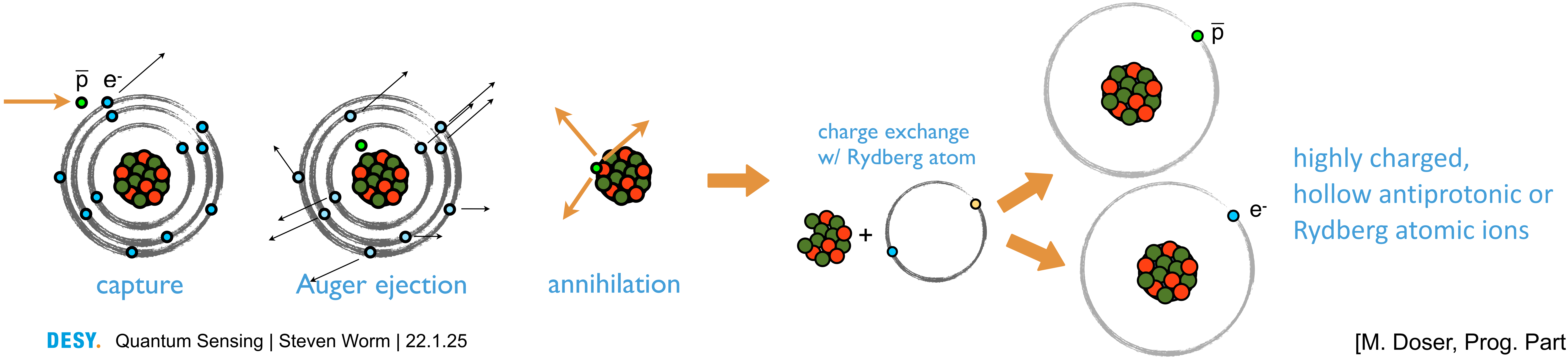




- Rydberg atoms: highly excited valence electrons

- 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

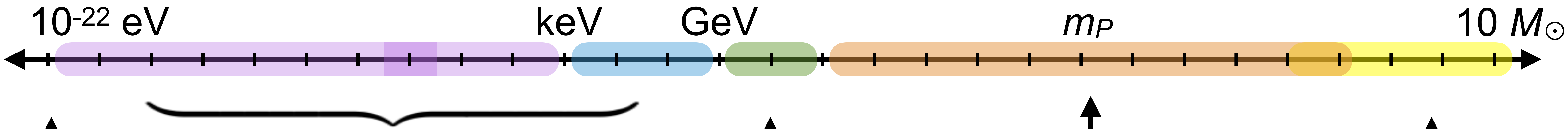
- Antiprotonic atoms and novel HCI systems
  - Anti-proton tests in Penning trap for Highly Charged Ions or molecules
  - Tests of QED, CPT, fundamental constants, fifth force, precision isotope shift (King plot), EDM measurements



[M. Doser, Prog. Part. Nucl. Phys, (2022); G. Kornakov]

Quantum-enabled Experiments & Ultra-light Dark Matter

Quantum Sensing needed for Light/Ultralight Dark Matter



Light and Ultra-light Dark Matter
Axions, ALPs
Quantum Sensing

Composite Dark Matter
WIMPzillas, Q-balls, bound states
CMB, Cosmic Rays

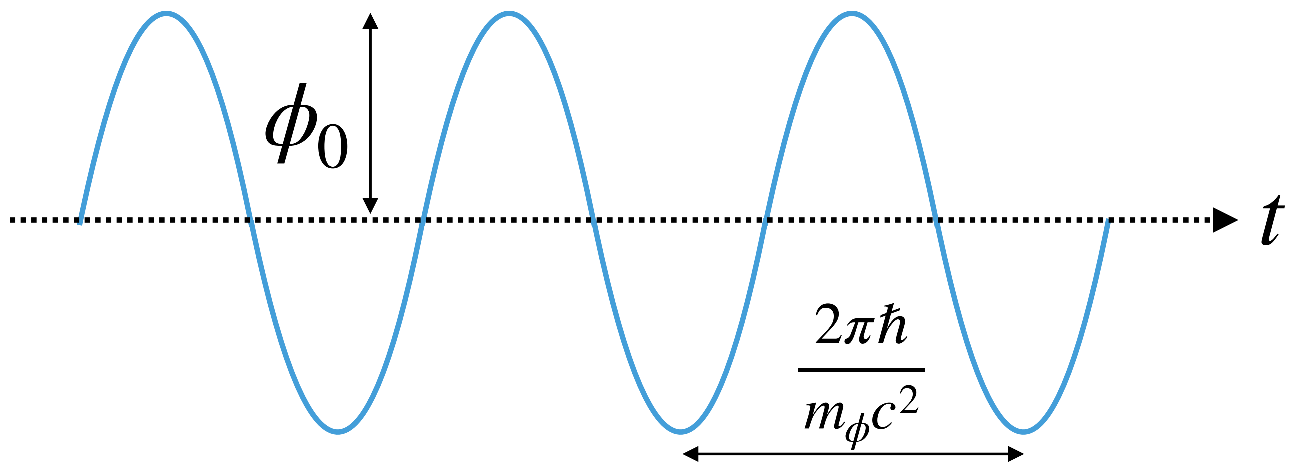
probably not below:
de Broglie wavelength too long

Standard Model Particle Scale
Weakly Interacting Massive Particles
Collider Searches

Superheavy Dark Matter
Primordial Black Holes
Gravitational Lensing

[T. Lin, arXiv:1904.07915]

Ultra-Light Dark Matter: Phenomenology



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

- Adding new DM interaction (field) to Standard Model Lagrangian
  - 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 → wave-like

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

- Coupling to Lagrangian is linear (in ϕ) for lowest order interaction w/ scalar field

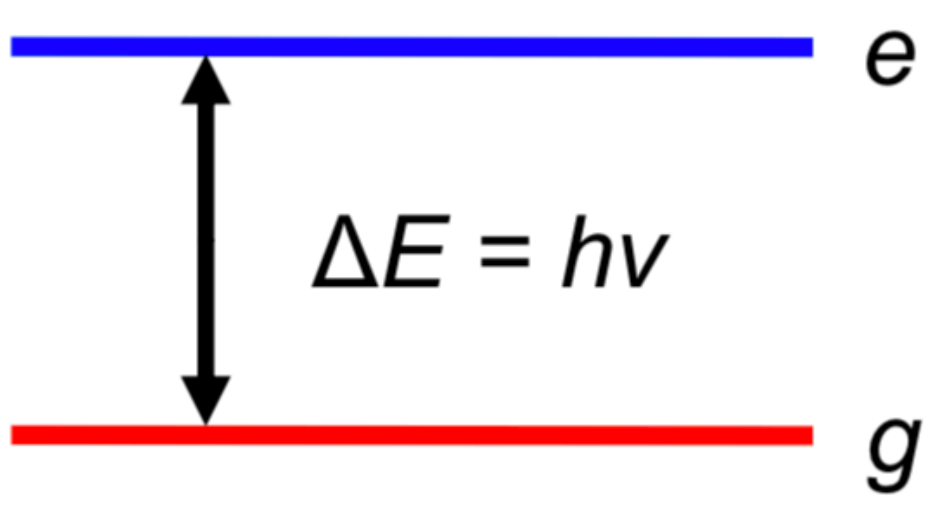
$$\mathscr{L}_{DM} = \frac{\phi}{\Lambda_\gamma}\frac{F_{\mu\nu}F^{\mu\nu}}{4} - \frac{\phi}{\Lambda_e}m_e\bar{\psi}\psi$$

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

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

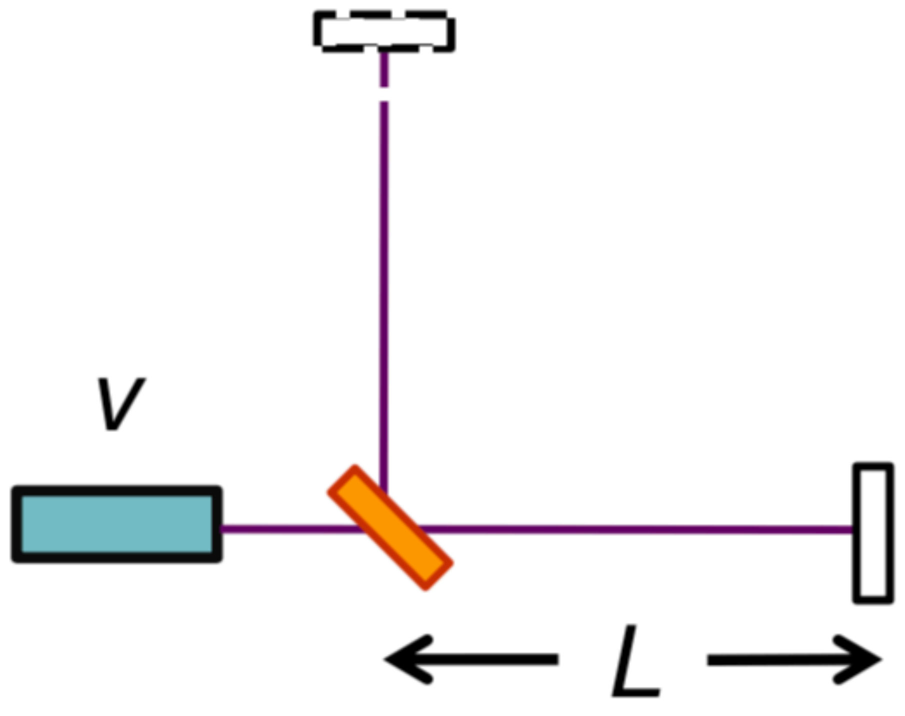
[Damour & Donoghue, PRD 82, 084033 (2010); Arvanitaki et al., Phys. Rev. D 91, 015015 (2015); Safranova et al., RMP 90, 025008 (2018)]

Quantum Sensing Methods for Testing Δα/α



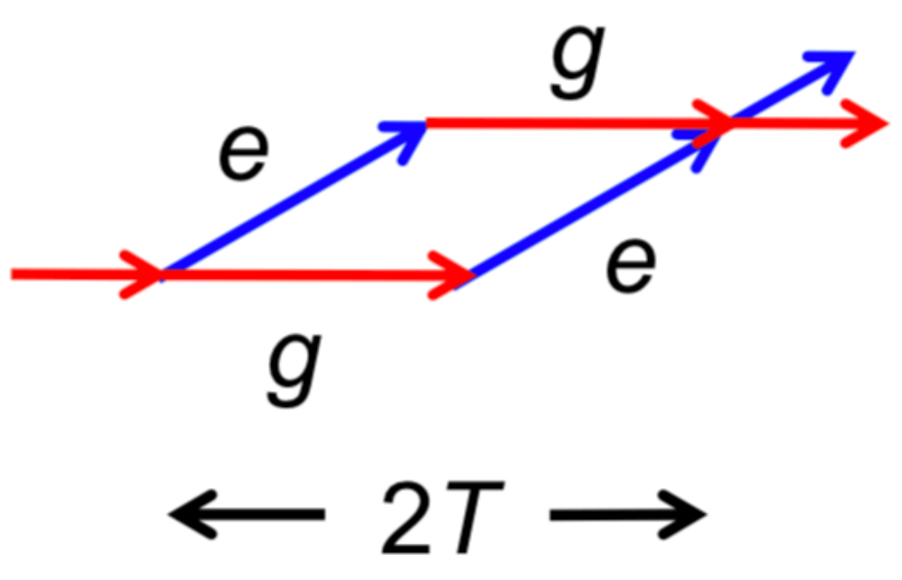
Atomic spectroscopy (clocks)

$$\delta(\nu_1/\nu_2) \propto \cos(m_\varphi t) \qquad 10^{-23}\ \text{eV} < m_\varphi < 10^{-16}\ \text{eV}$$



Laser interferometry (cavities)

$$\delta\Phi \propto \delta(\nu L) \propto \cos(m_\varphi t) \qquad 10^{-20}\ \text{eV} < m_\varphi < 10^{-15}\ \text{eV}$$

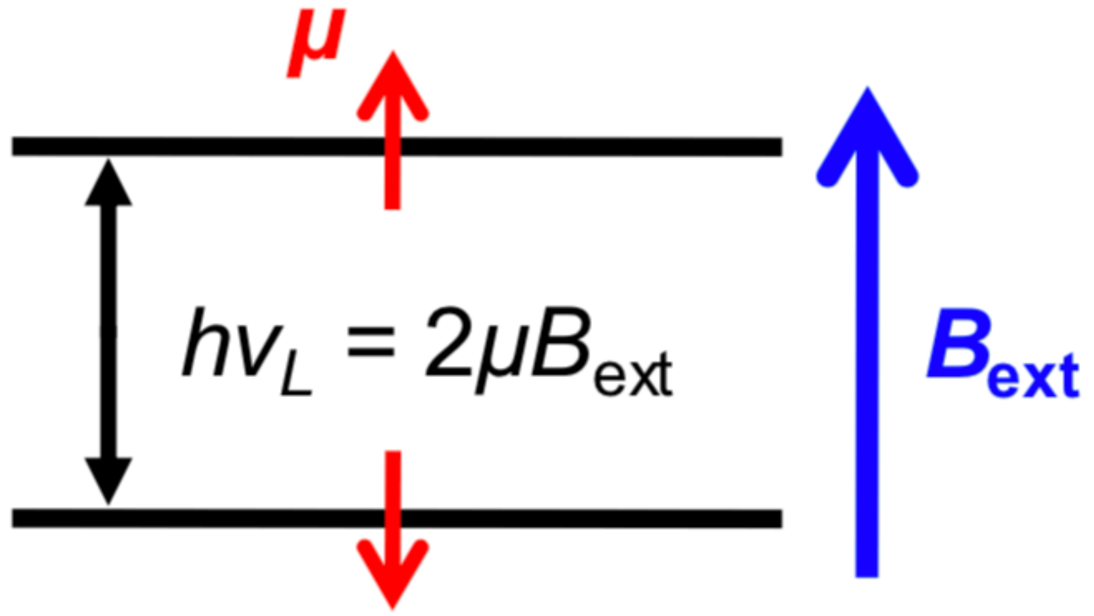


Atom interferometry

$$\boldsymbol{F}(t) \propto \boldsymbol{p}_\varphi \sin(m_\varphi t) \qquad 10^{-23}\ \text{eV} < m_\varphi < 10^{-16}\ \text{eV}$$

[Y. Stadnik]

Quantum Sensing Methods for Testing Δμ/μ



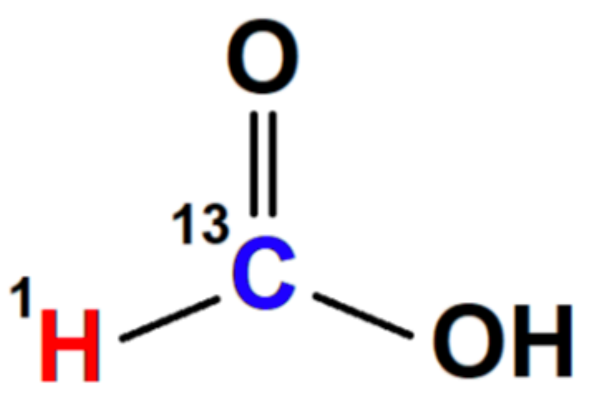
Co-magnetometry

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

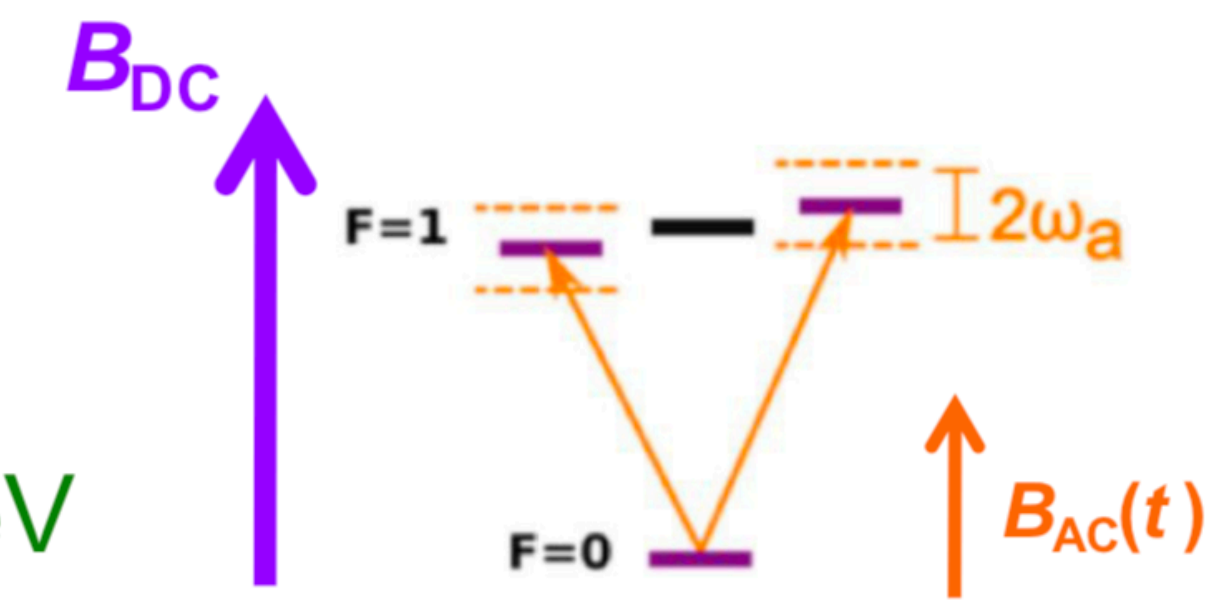
$$\text{or } \hat{\boldsymbol{\sigma}} \cdot \boldsymbol{p}_a \sin(m_a t)$$

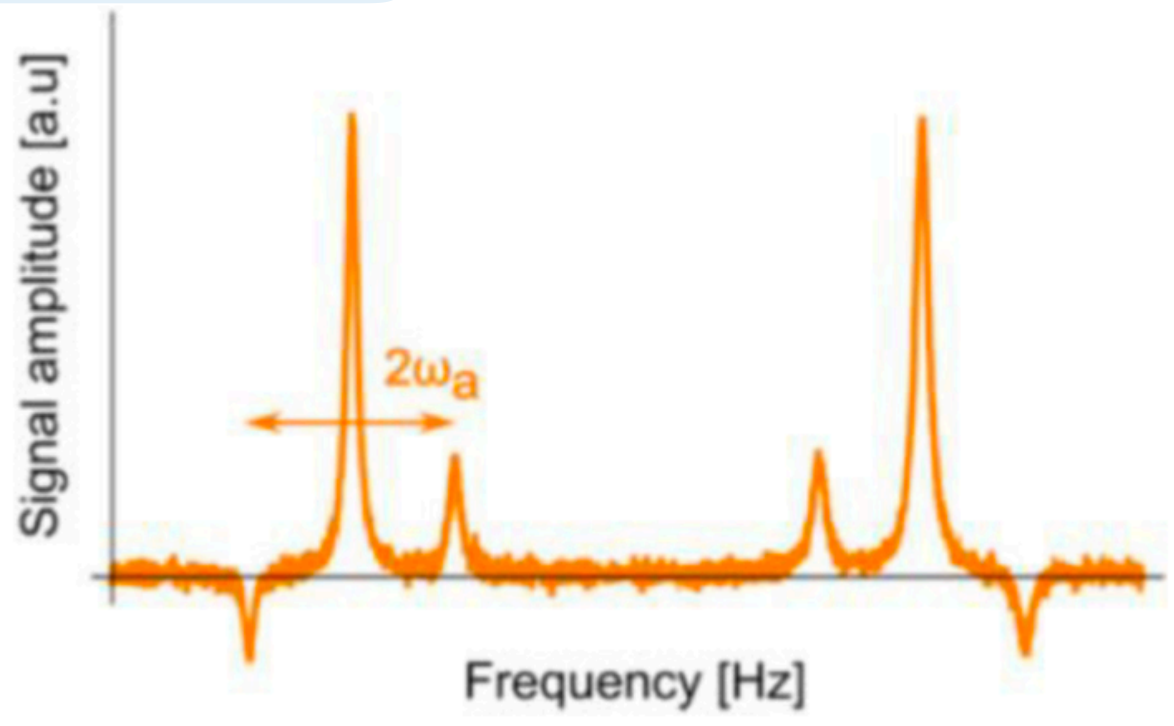
$10^{-23}\ \text{eV} < m_a < 10^{-17}\ \text{eV}$

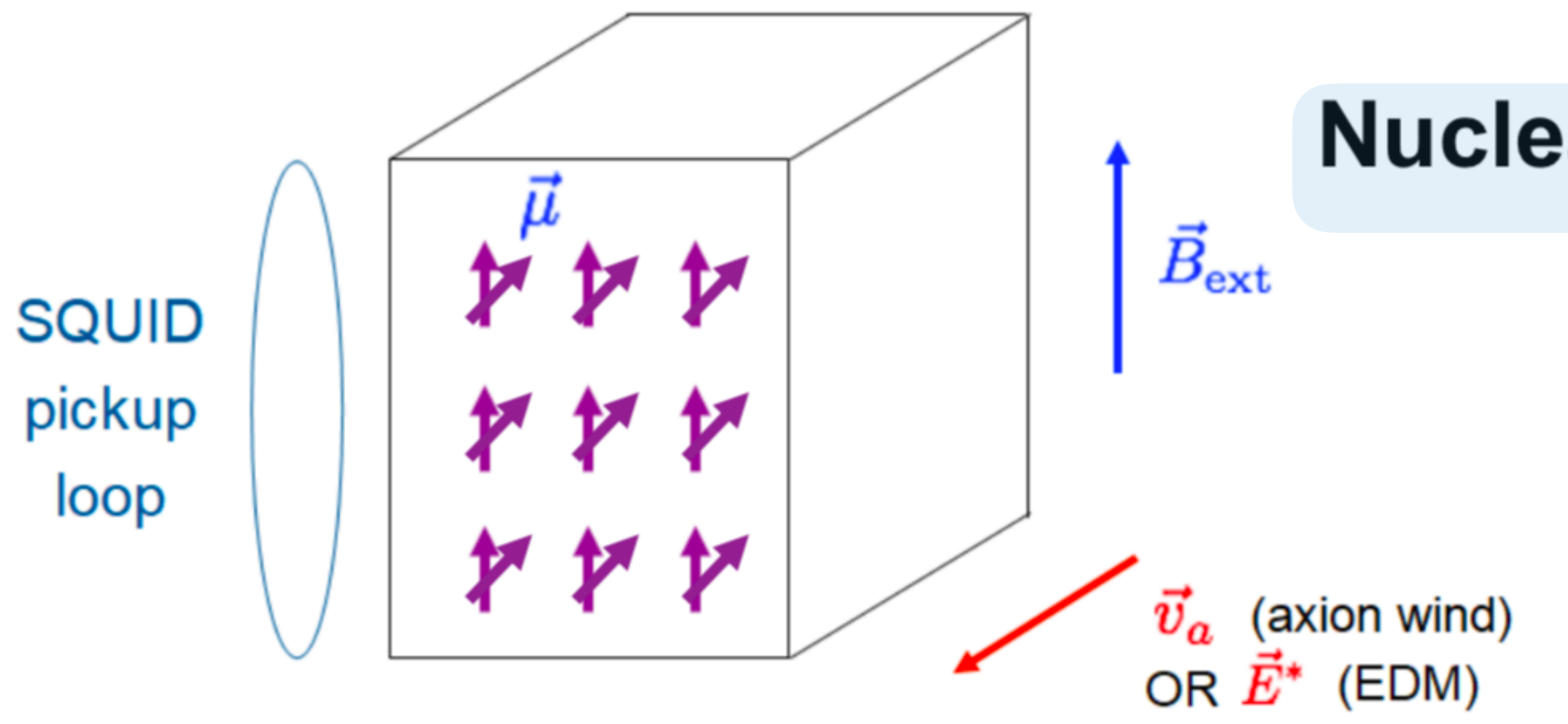
Nuclear magnetic resonance (“sidebands”)



$10^{-16}\ \text{eV} < m_a < 10^{-13}\ \text{eV}$







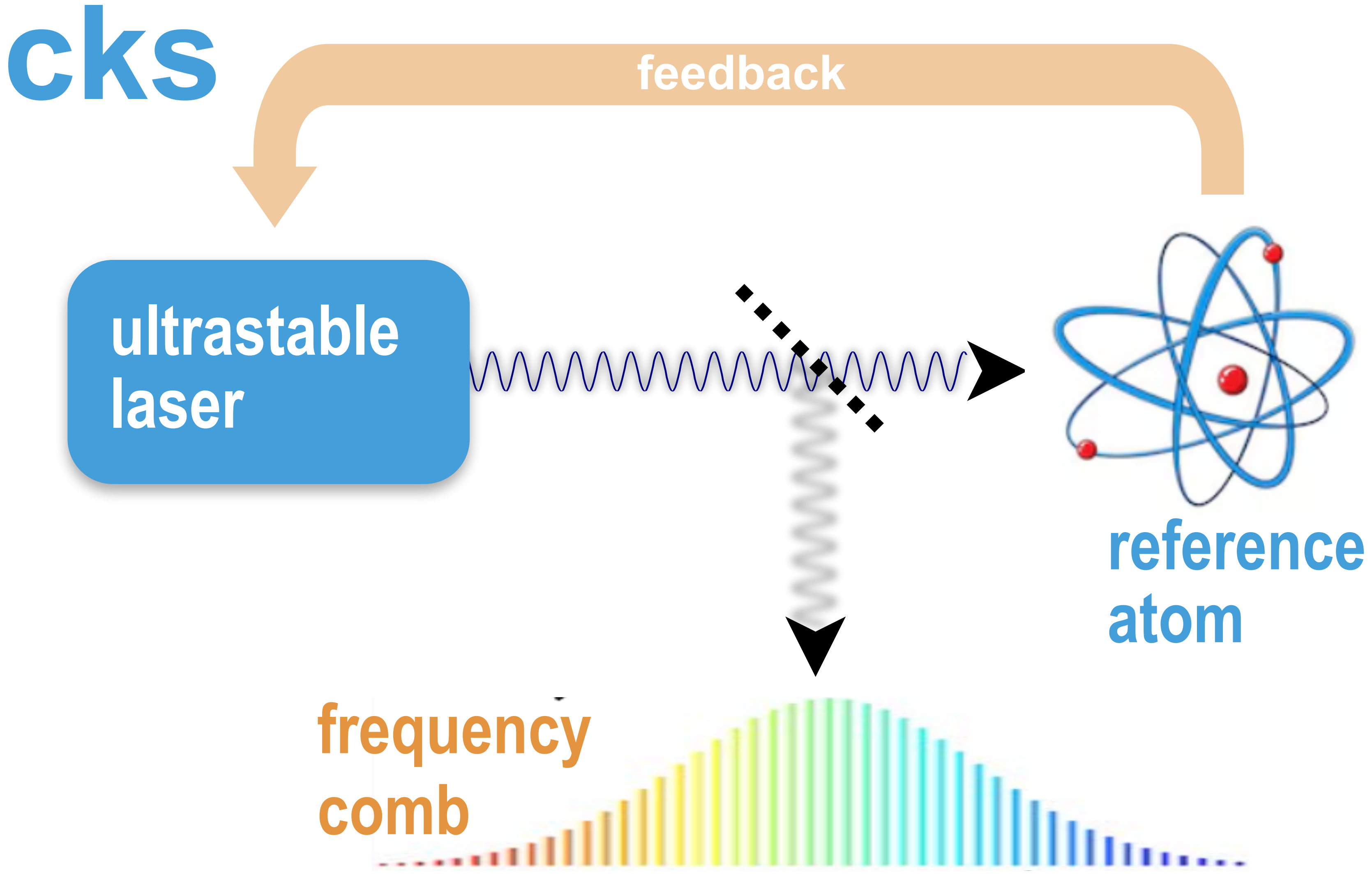
Nuclear magnetic resonance

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

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

[Y. Stadnik]

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

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

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

  - 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

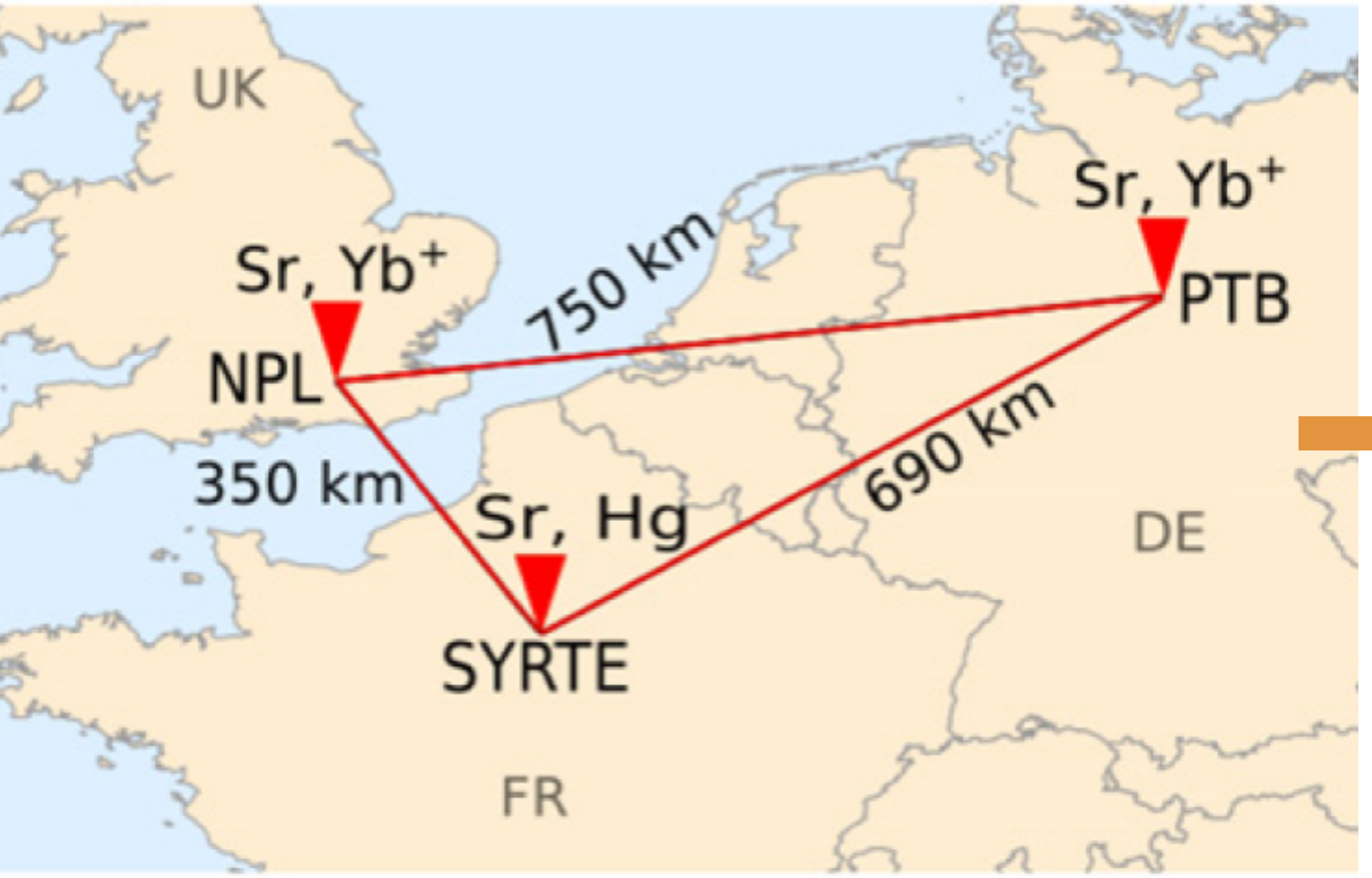
Clocks proposed for QSNET

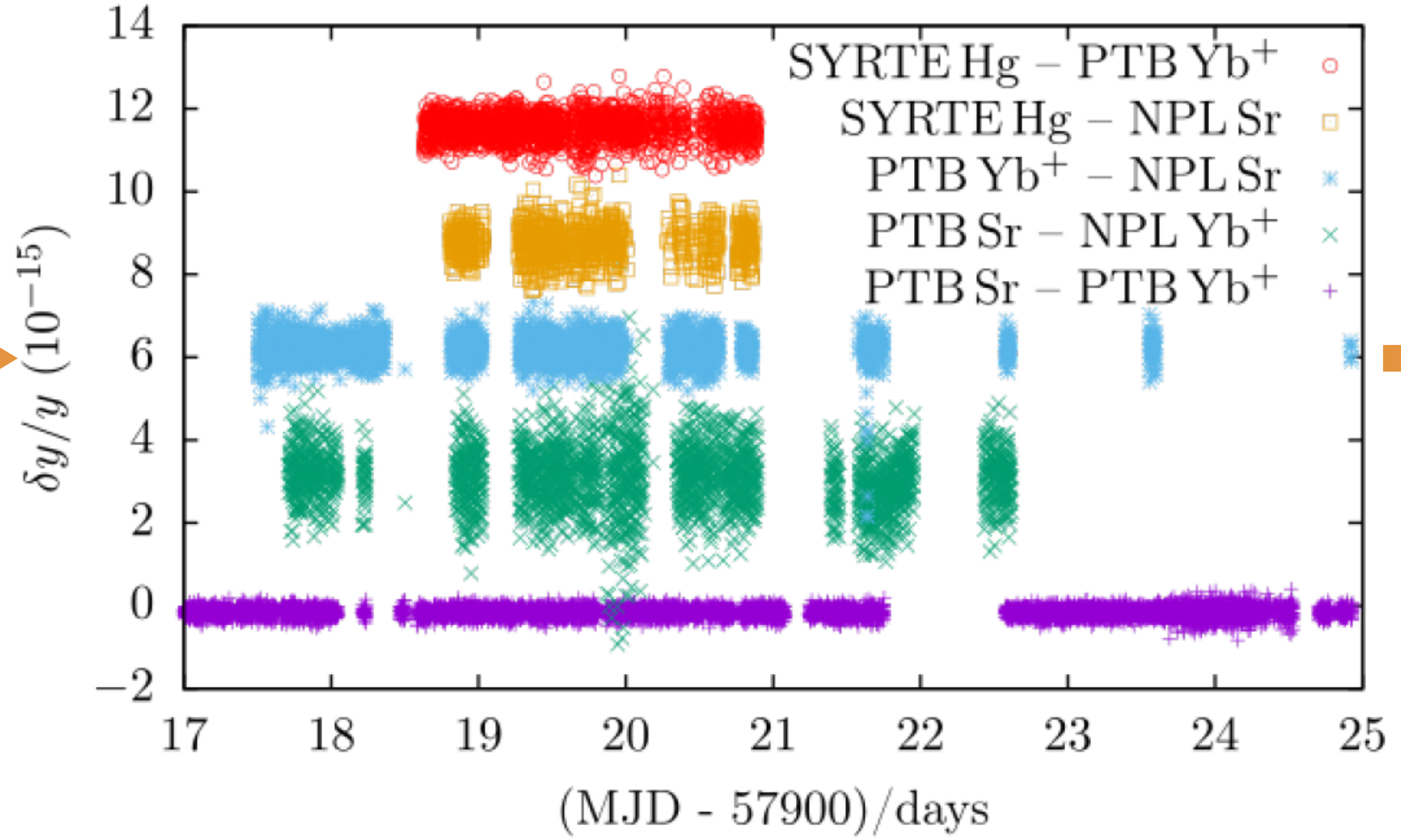
Clock	Kα	Kμ
Yb^+ (467 nm)	-5.95	0
Sr (698 nm)	0.06	0
Cs (32.6 mm)	2.83	1
CaF (17 μm)	0	0.5
N_2^+ (2.31 μm)	0	0.5
Cf^{15+} (618 nm)	47	0
Cf^{17+} (485 nm)	-43.5	0

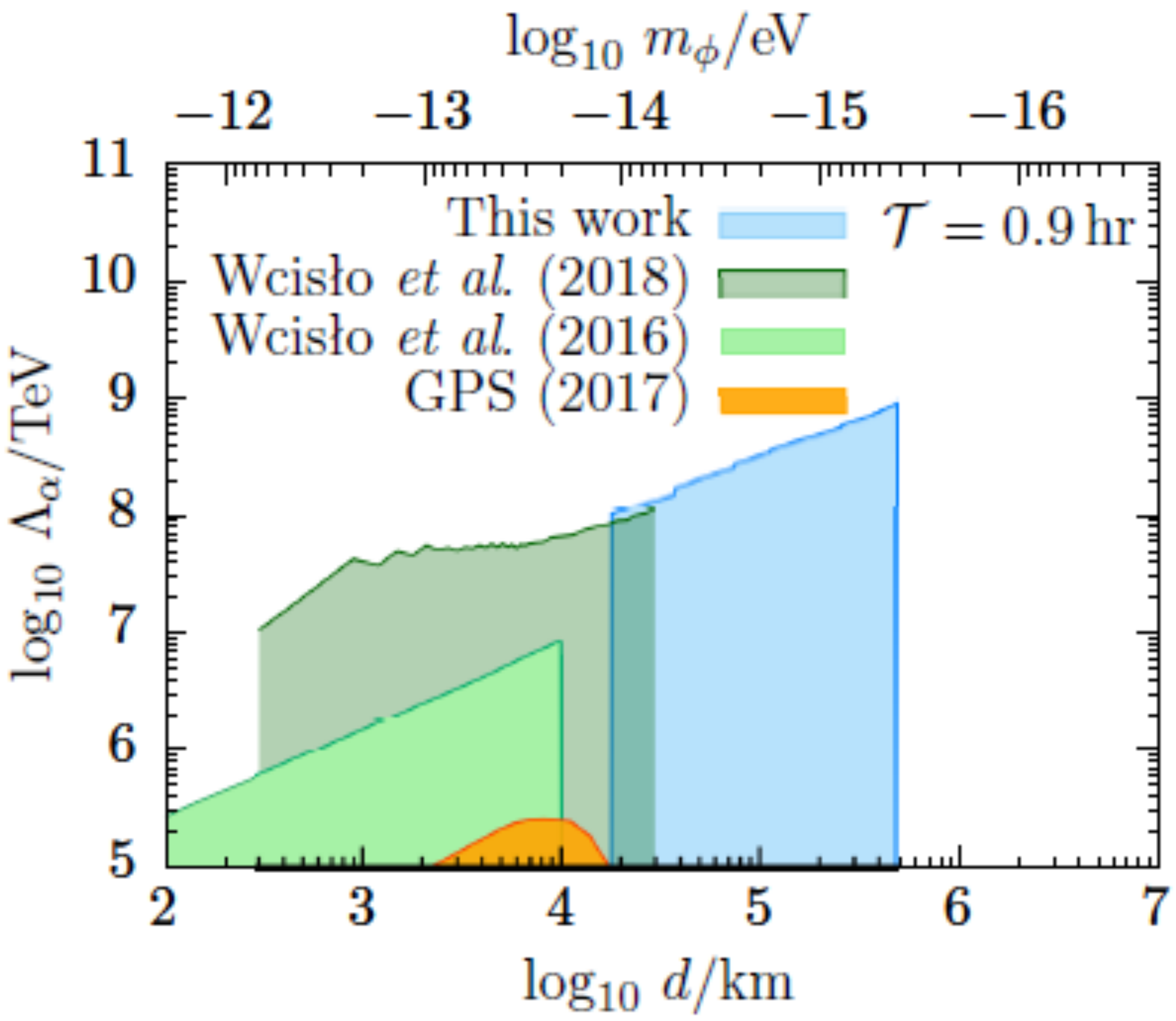
[G. Barontini et al., EPJ Quant.Technol. 9 (2022) 1; E. Peik et al 2021 Quantum Sci. Technol. 6 034002]

Quantum Sensing: Networks of Optical Clocks

- NPL-SYRTE-PTB demonstrated an optical clock network with dark fibres
- Comparing optical clocks with different sensitivities to variations of α
- Results for T = 0.9, 12, 45 hours
- Results for previously unconstrained parameter space (topological defect DM)



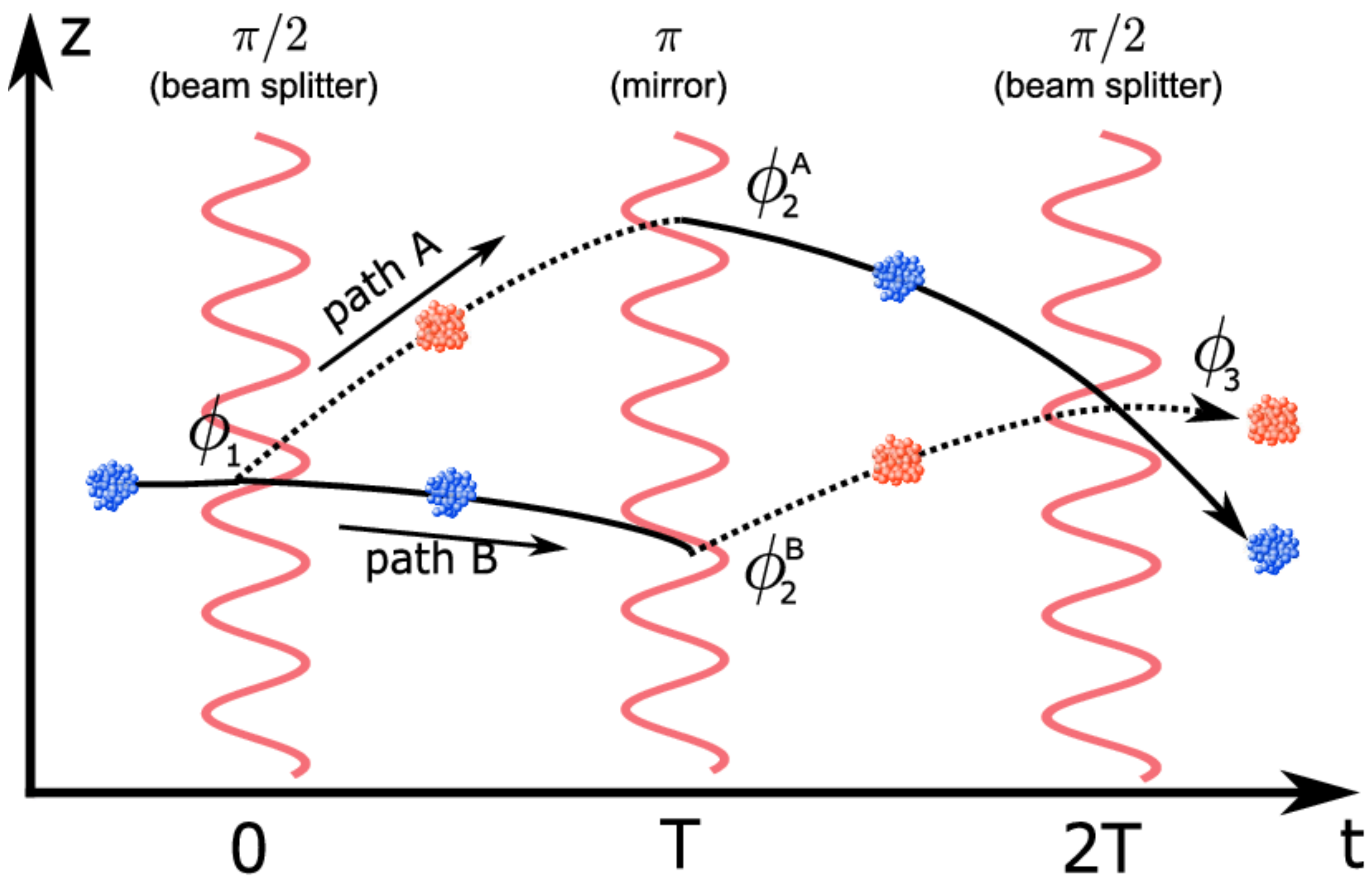


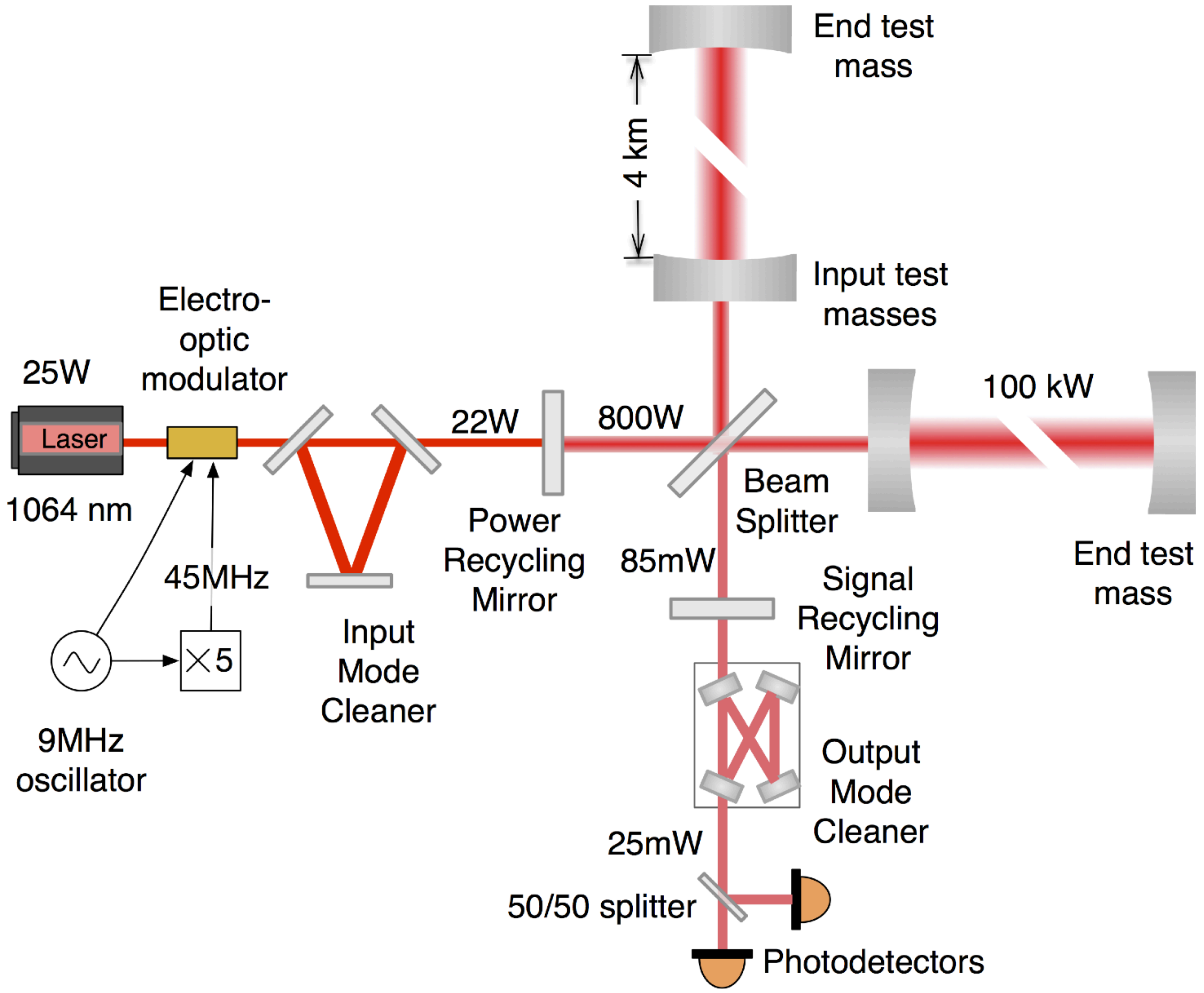


[Roberts et al, New J. Phys. 22, 093010 (2020); P. Delva et al., Phys. Rev. Lett., 118 221102 (2017)]

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.

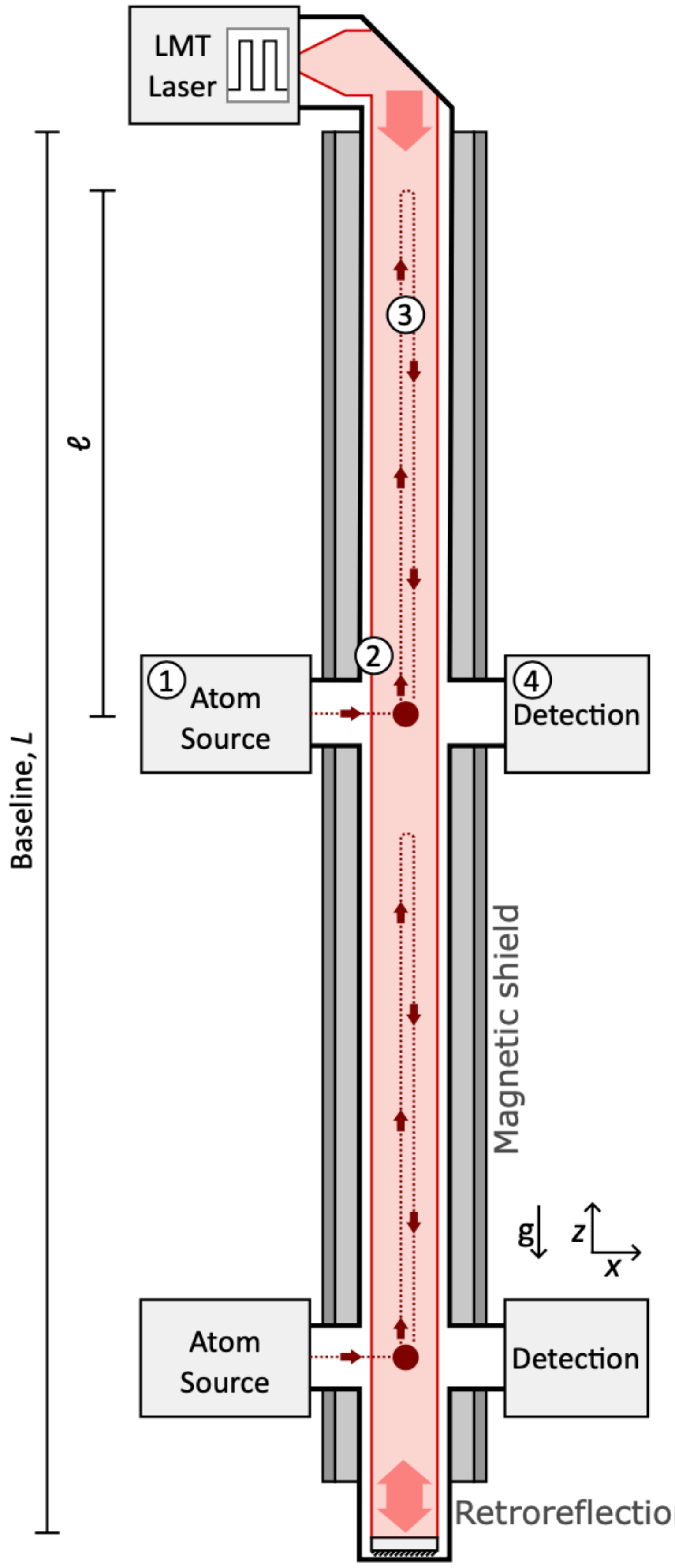




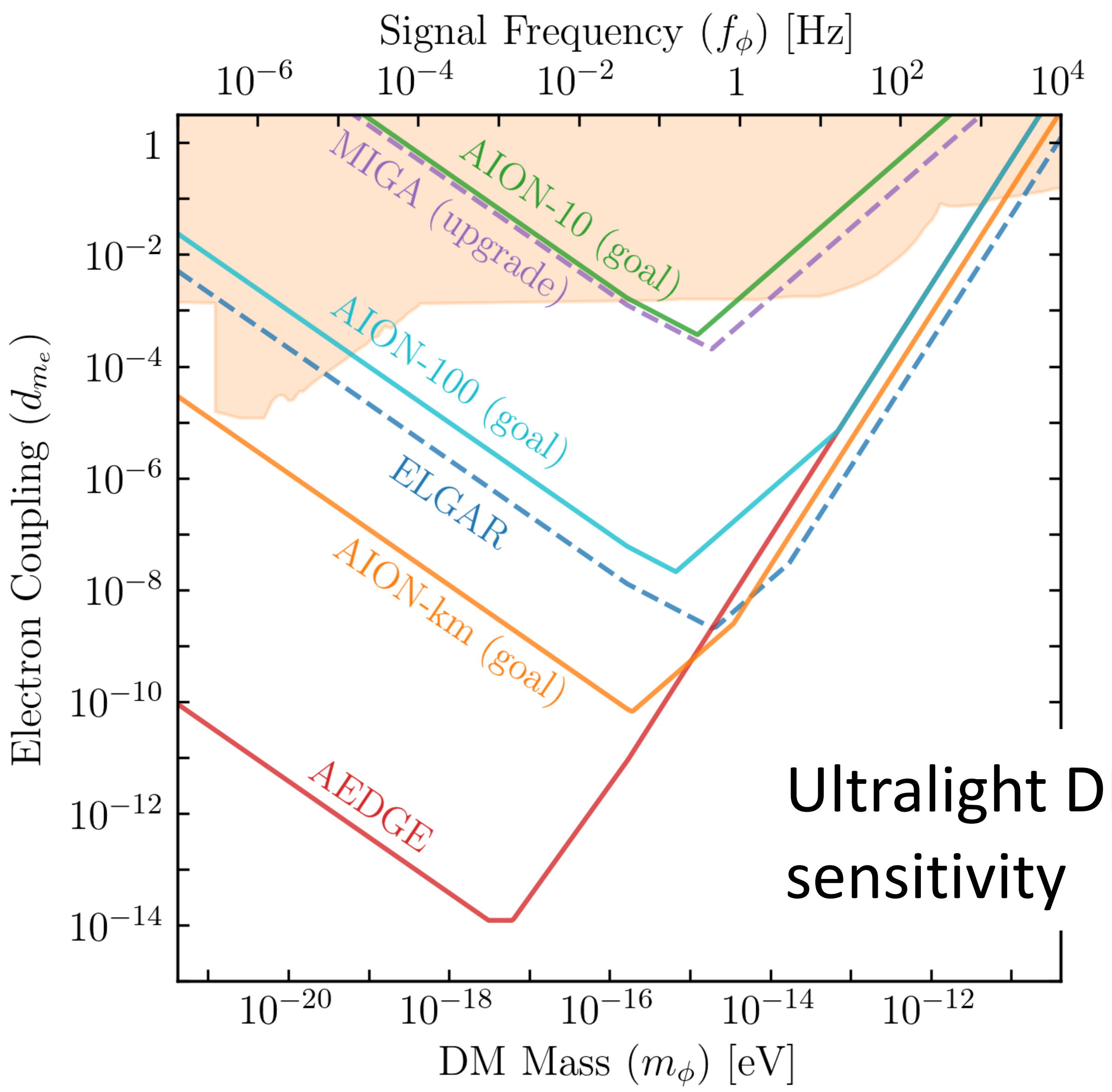
[Richmond, LIGO; Hauth et al, DOI:10.3254/978-1-61499-448-0-557]

Long-Baseline Atom Interferometry

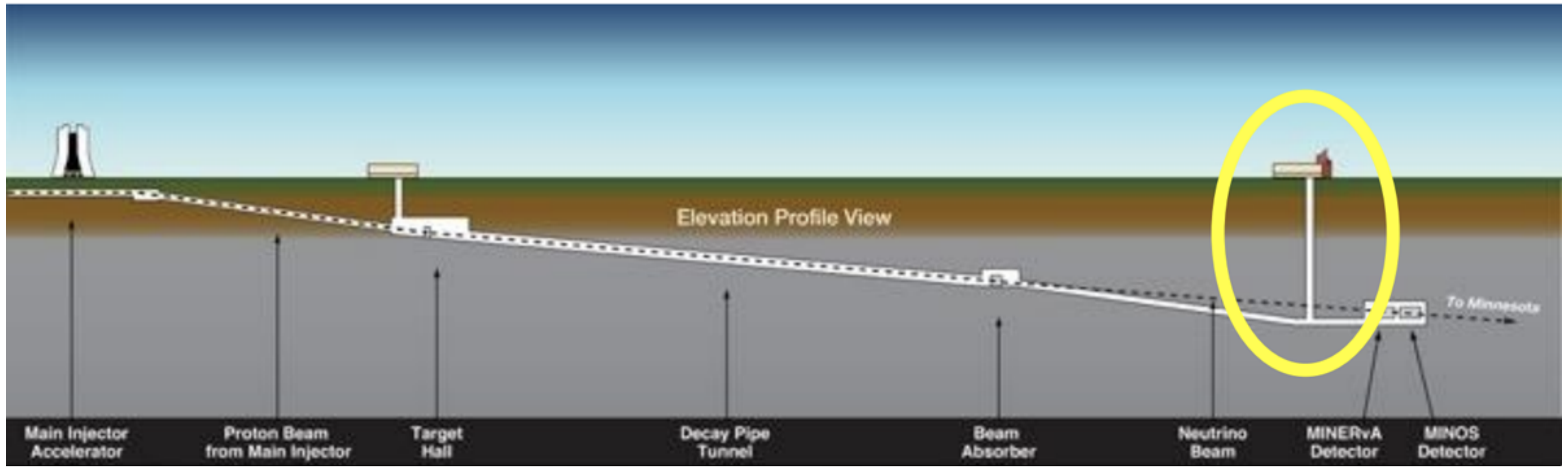
- Demonstrated at ~meter scale, proposing 100m and ultimately km (space)
  - AION: Atom Interferometer Observatory and Network
  - ELGAR: European Laboratory for Gravitation and Atom-interferometric Research
  - MIGA: Matter wave-laser based Interferometer Gravitation Antenna
  - MAGIS: Matter-wave Atomic 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



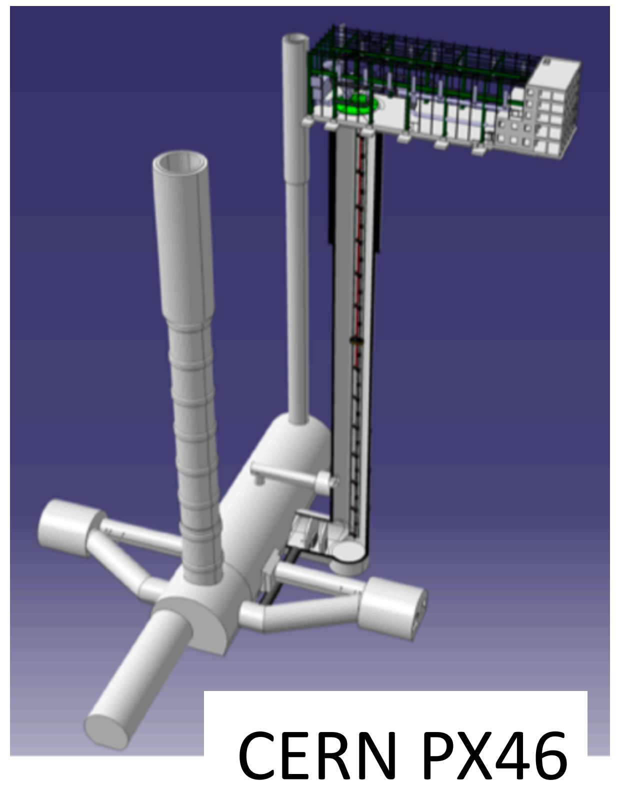
AION experiment concept



Ultralight DM sensitivity

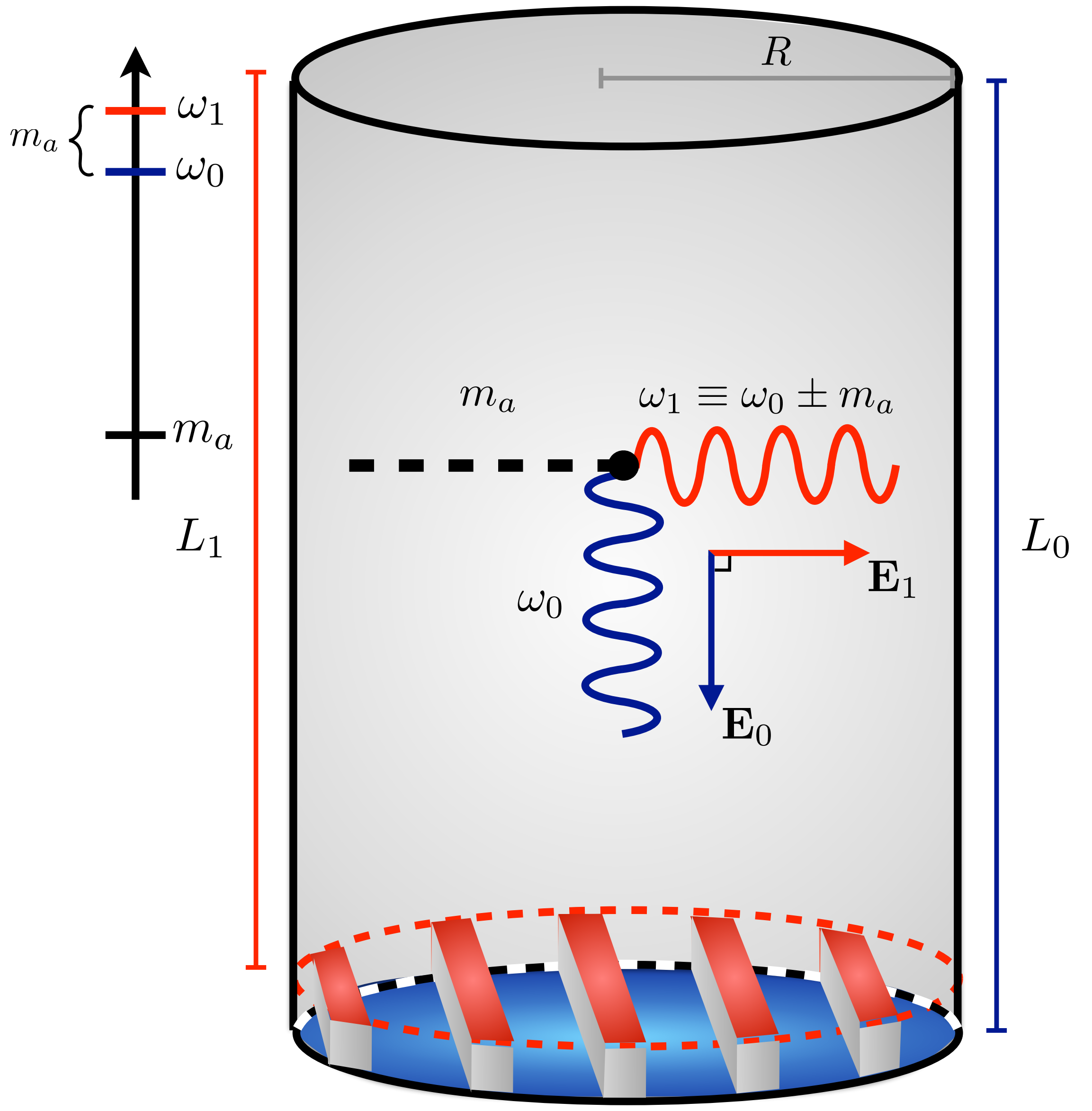


MAGIS-100 experiment



CERN PX46

Cavities: Axion Heterodyne Detection



(a) Cartoon of cavity setup.

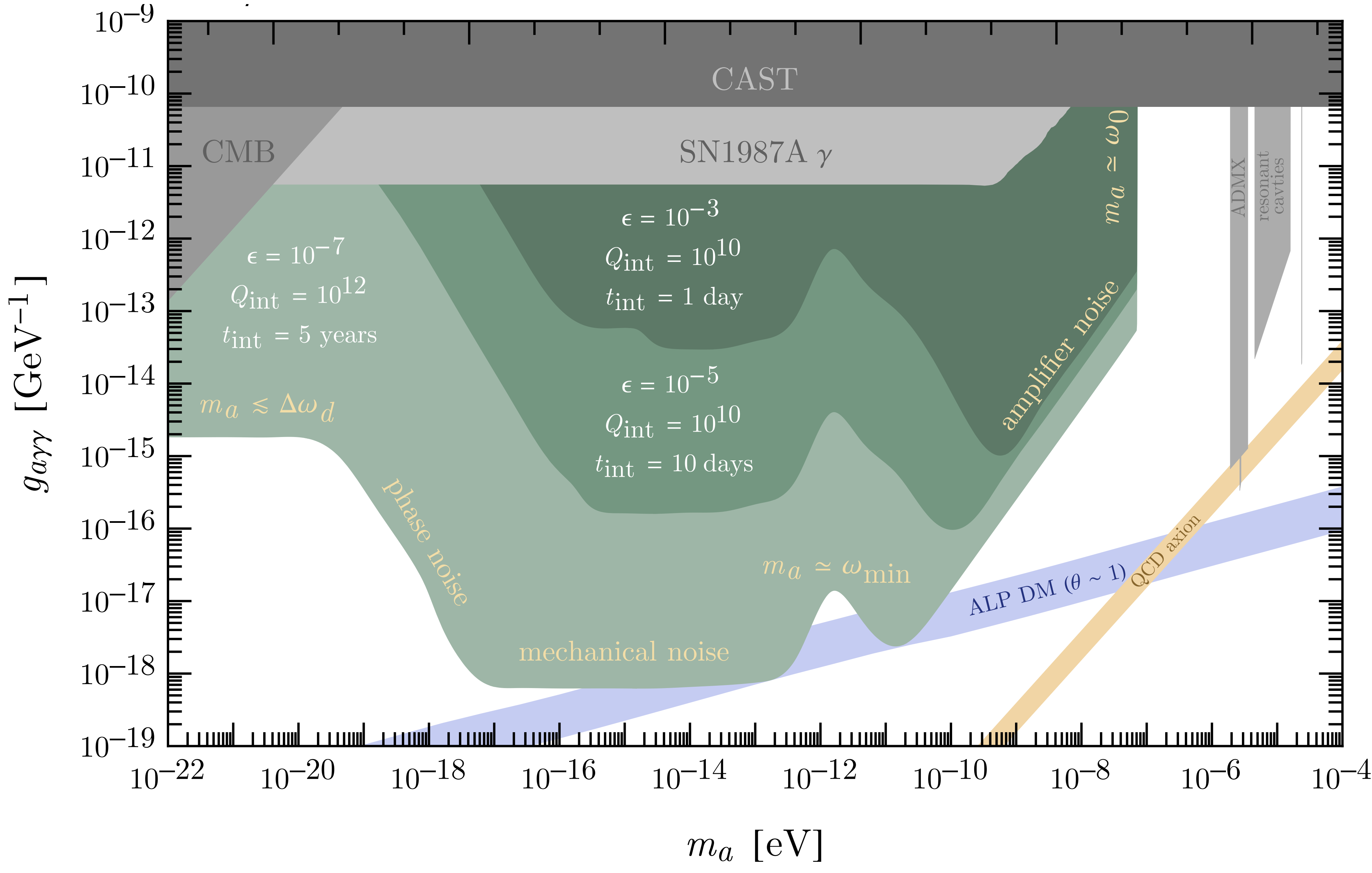
- DarkSRF Collaboration aiming for tunable cavities
  - Figure of merit (F) proportional to *square* of DM mass (m_a) and cavity volume (V)

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

  - Resonant cavities possible down to μeV; below that, need huge volume

- Tunable superconducting RF cavity:
  - Frequency conversion: drive $\omega_0 \approx$ GHz → 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

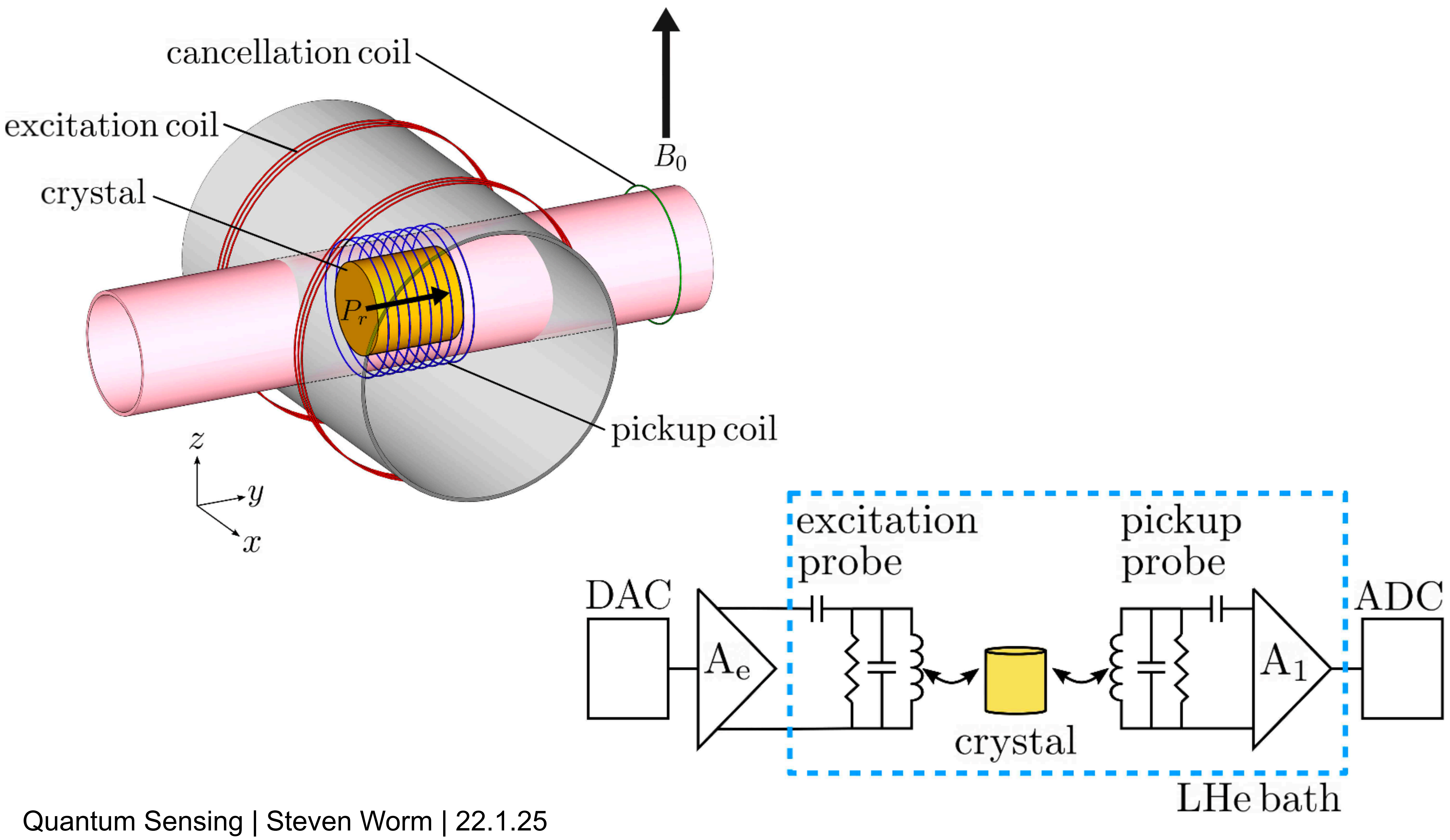


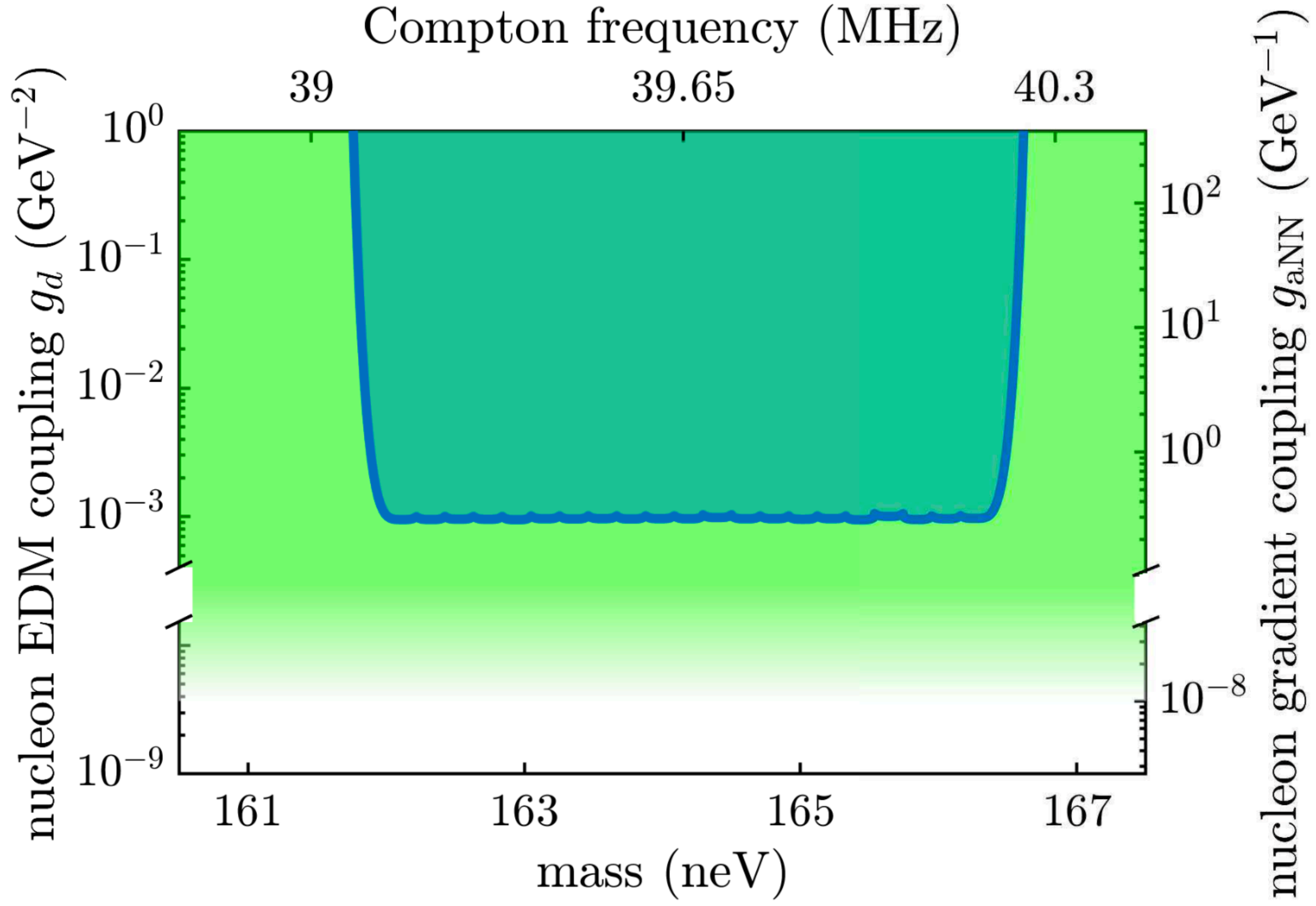
[A. Berlin et al., JHEP 07 (2020) 07, 088; arXiv:2007.15656]

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

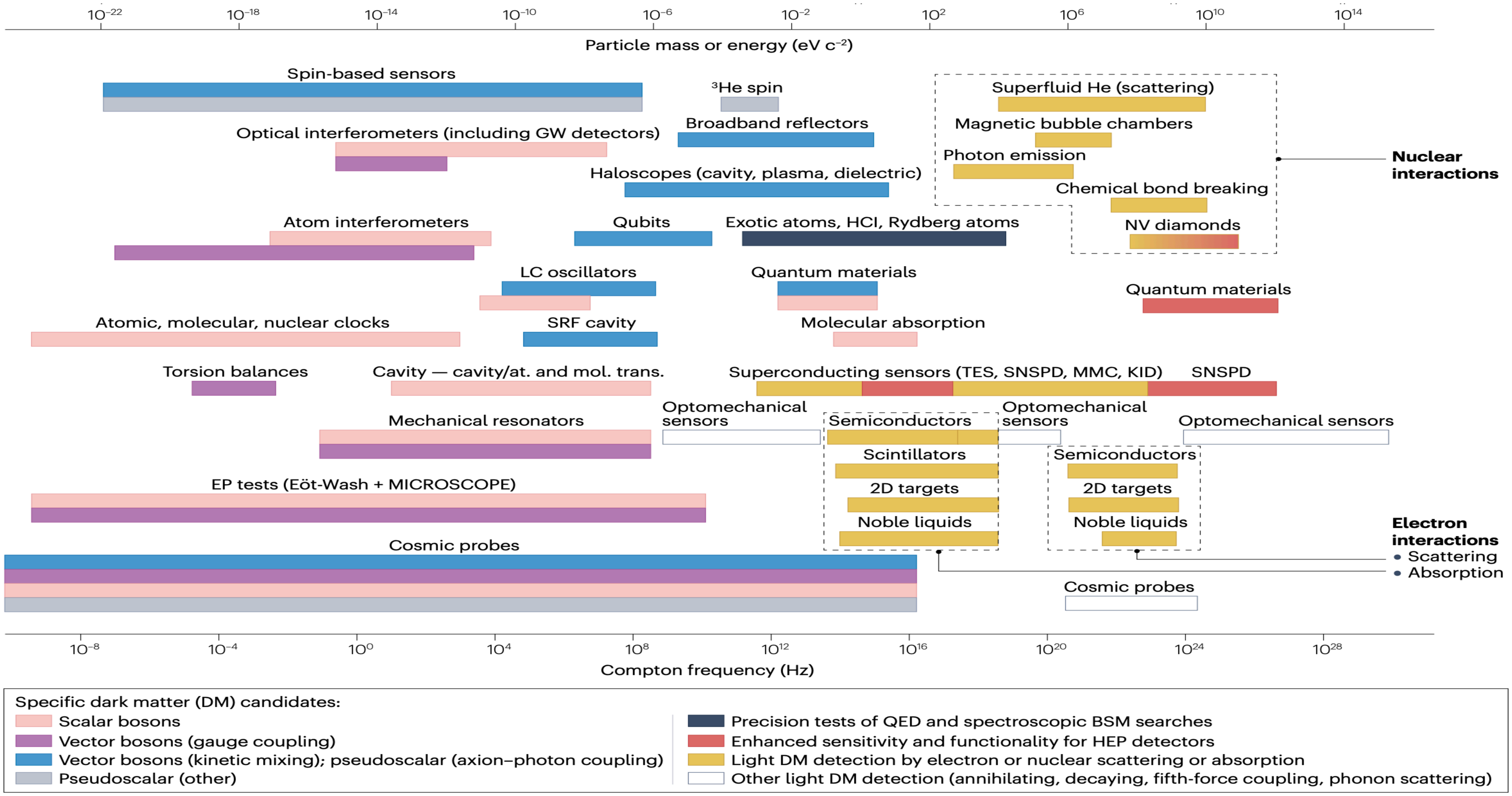
- Limits for neV DM masses vs EDM coupling g_d and gradient coupling g_{aNN}; many ideas for improvements





[D. Aybas et al., Phys. Rev. Lett. 126, 141802]

Quantum Sensing Techniques for Dark Matter

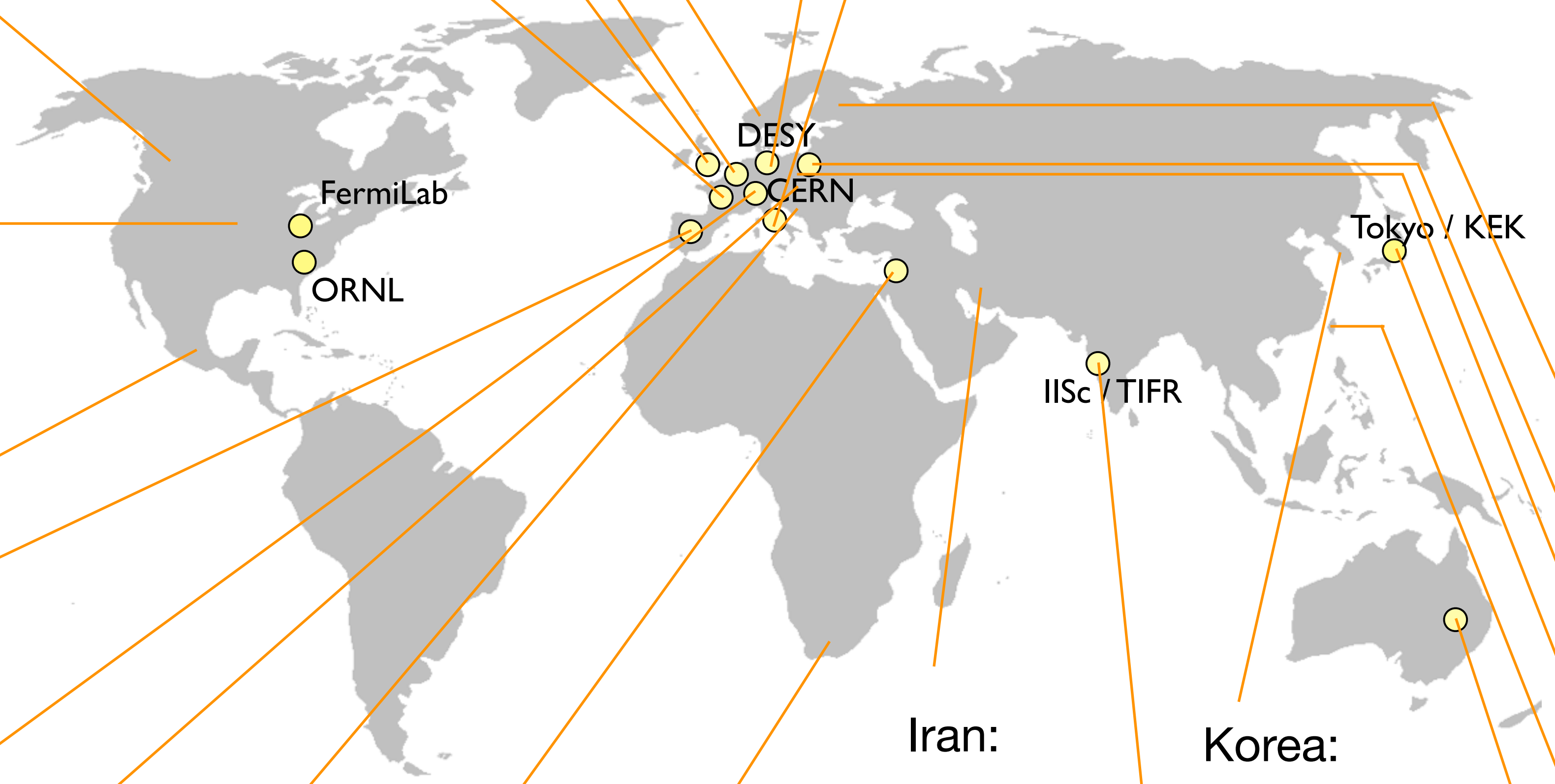


[S. Bass, M. Doser, Nat Rev Phys 6, 329–339 (2024)]

RDquantum

DRD5

>100 Institutes



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France: SYRTE / OBSPM
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ILM - University Lyon 1

Canada: McGill Univ.
TRIUMF

USA: UCLA
ORNL
Northwestern Univ.
Caltech
MIT
Arizona State Univ.
Yale
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University West Bohemia

Japan: QUP / KEK
Kyoto University
Tokyo University / ICEPP
University of Shizuoka

RDquantum / DRD5: Get started with Quantum Sensing

- Collaboration recently launched, preliminary WP structure now set

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

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

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

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

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

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

- Focus on exploring new technologies, connecting to HEP needs, and ***community-building***

1st Collaboration Meeting: 17-19 February @ CERN (https://indico.cern.ch/event/1503433/)

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