DESY. QUANTUM
Center for Quantum Technology and Applications

# Quantum Sensing for Particle Physics

## 14th Joint workshop of the France-Japan and France-Korea Particle Physics Laboratories


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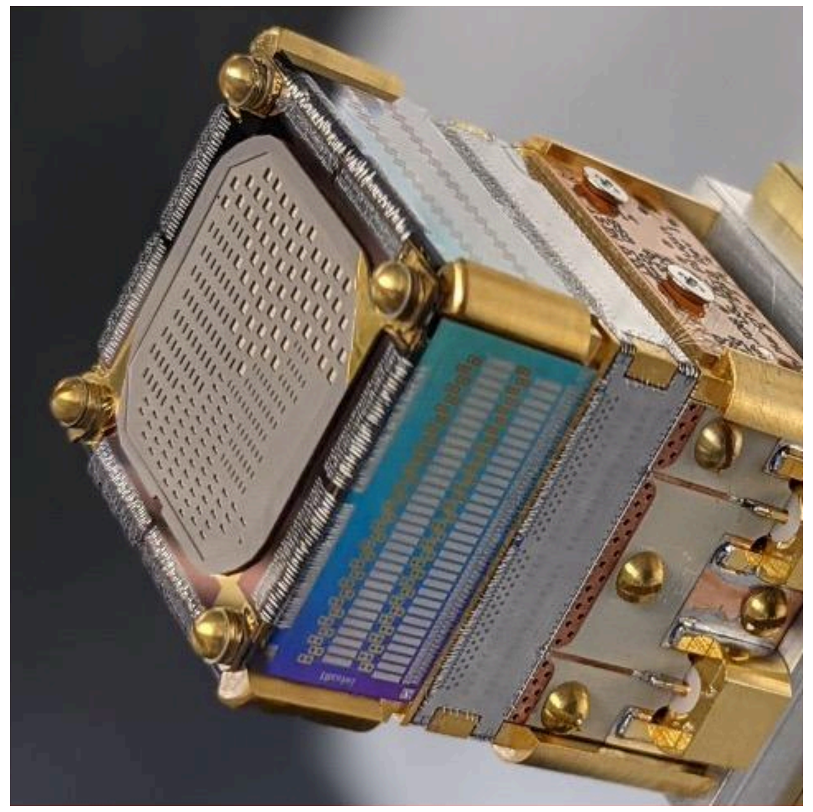
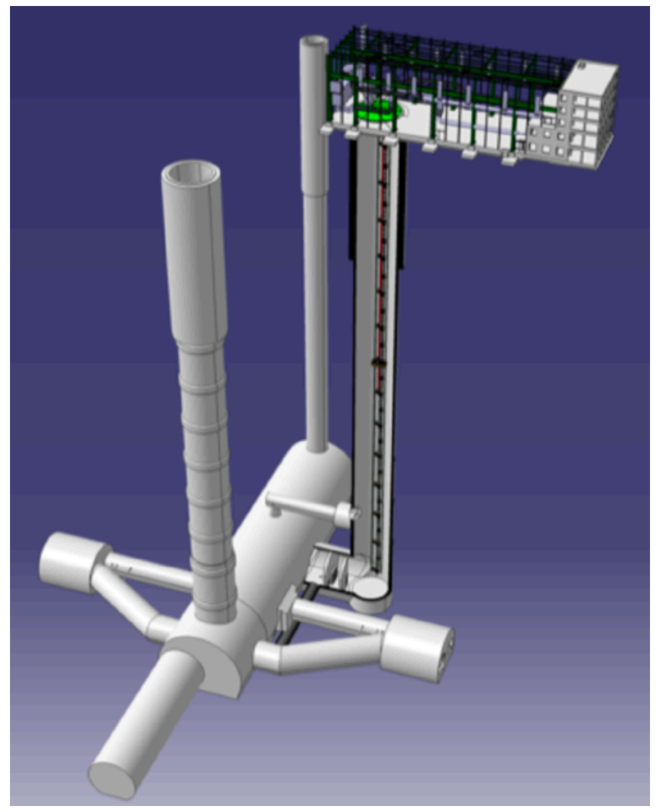
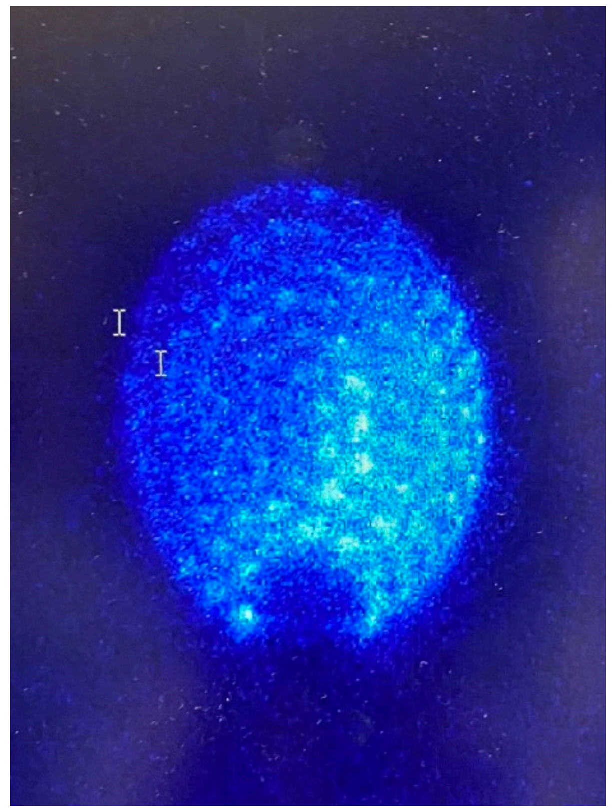
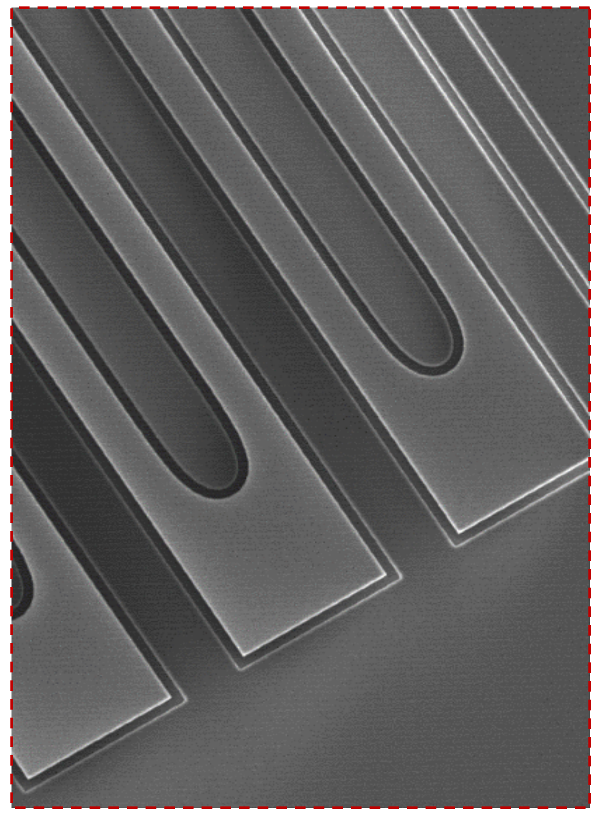
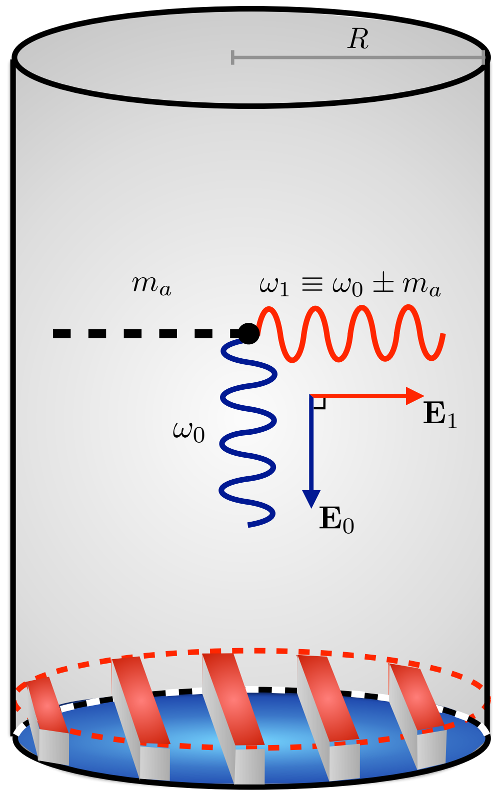
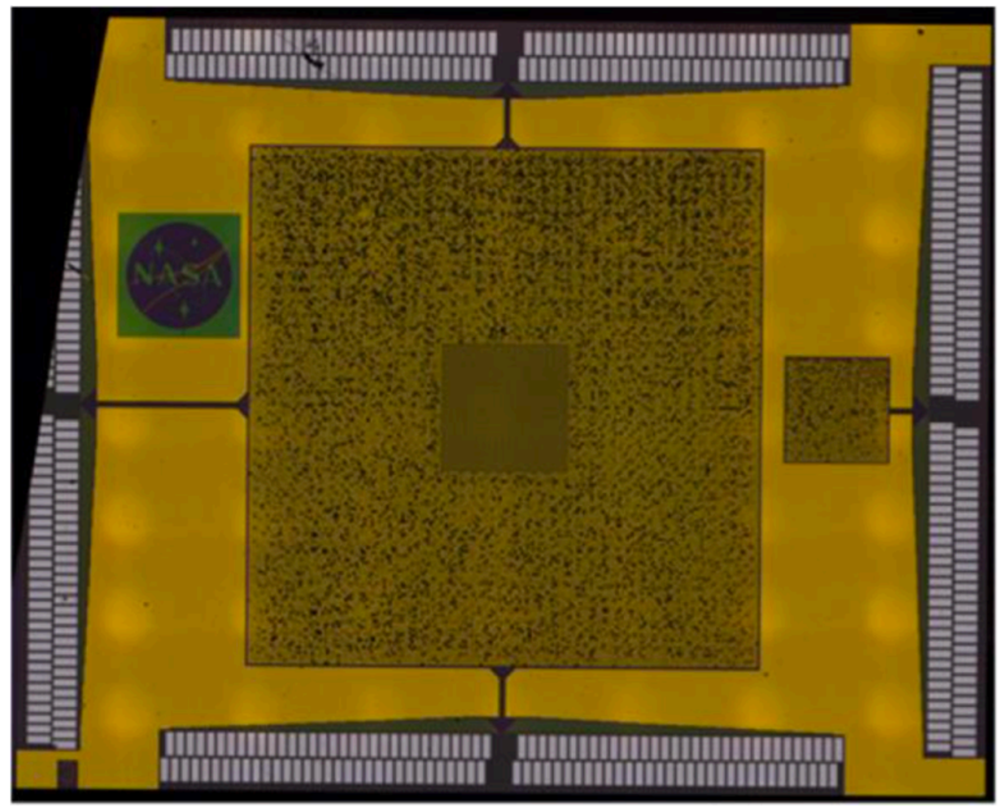
May 15, 2025



# Outline

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

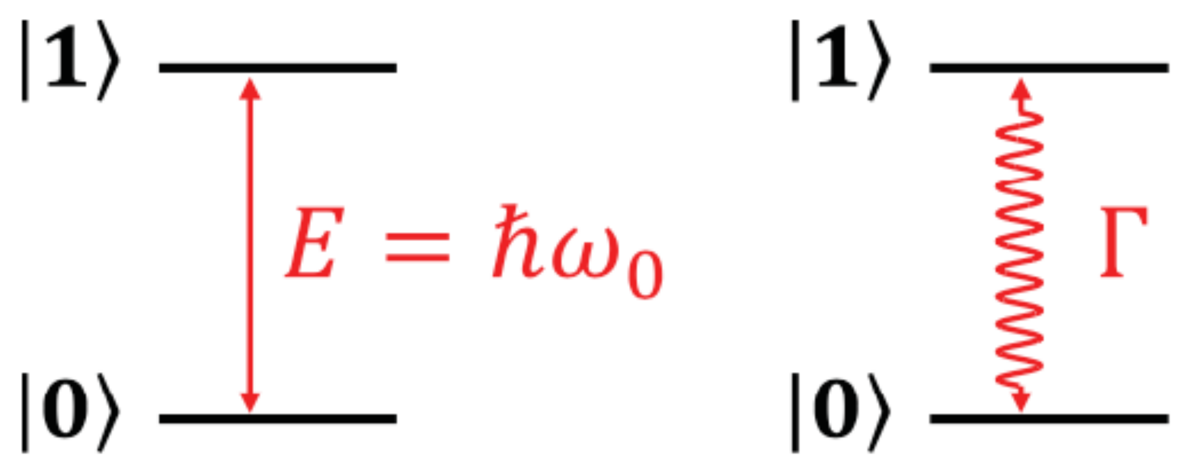
- Selected quantum sensing techniques
  - Cryogenic detectors
  - Superconducting devices
  - Spin-based, NV-diamonds
  - Metamaterials, 0/1/2-D materials
  - Ionic / Atomic / Molecular systems
  - Optical atomic clocks
  - Atom Interferometers
  - Magnetometers

- 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 $\omega_0$ or transition rate $\Gamma$)




- 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

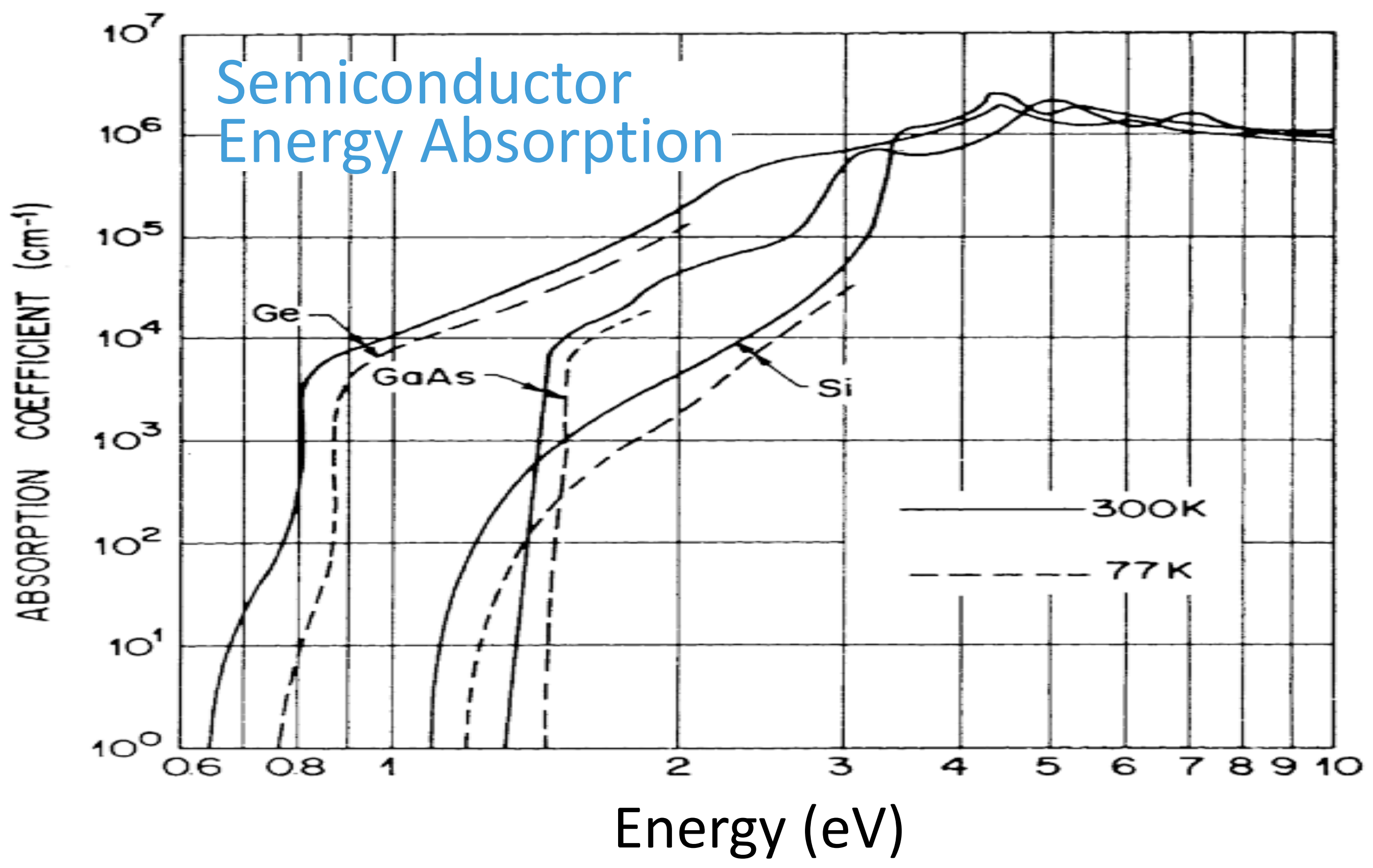
***Why*** **quantum sensing?**

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

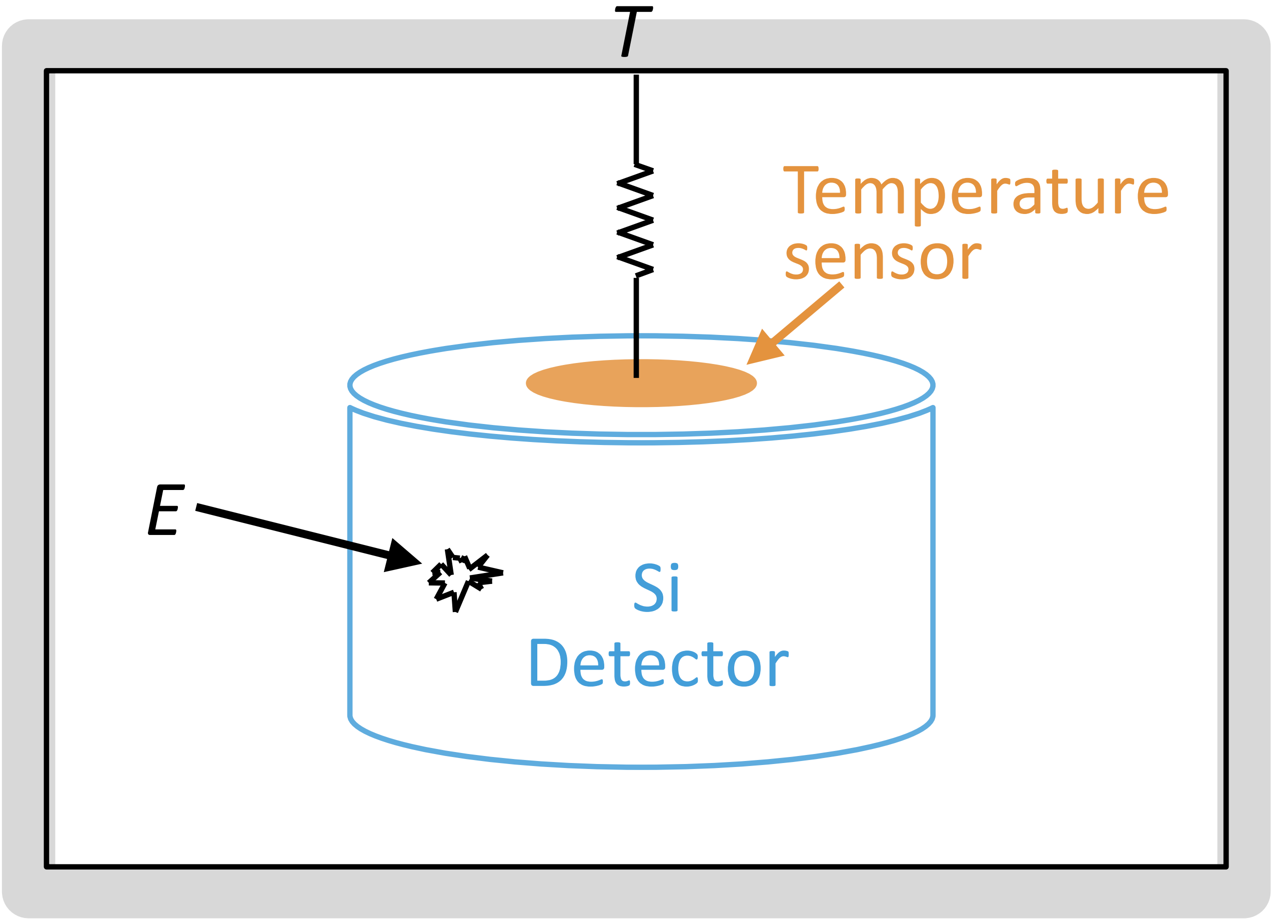
- Quantum Detectors: use quantum sensing to making extreme measurements possible
  - Enables (better) measurements, e.g. wavelengths
  - Extreme sensitivities (single-photon) or low noise

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

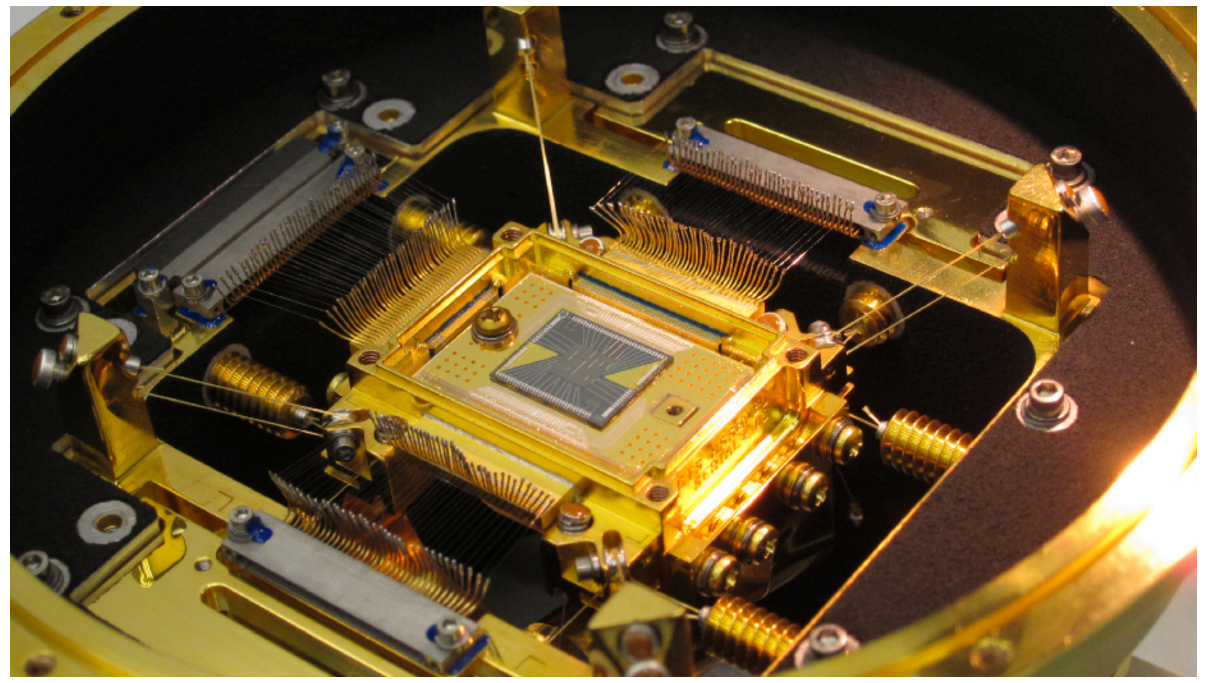
# Cryogenic Detectors

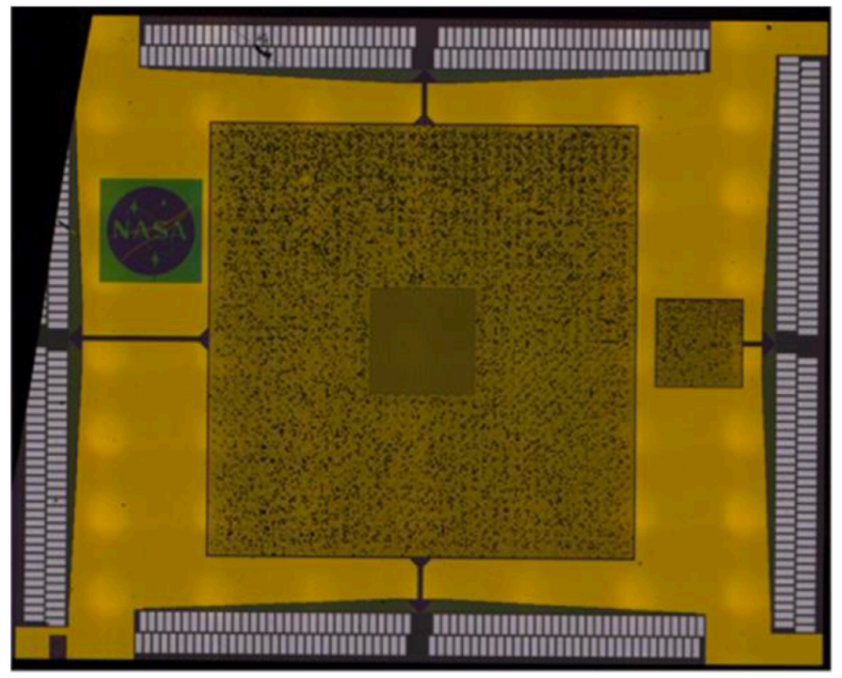



- Low energy and limits for ionisation
  - Limit for e/hole pairs in semiconductors is band gap energy (1.12 eV for Si)
  - Ionisation works above the band gap, below we detect the heat (phonons)
- Measuring small temperature differences
  - $\Delta T$ depends on energy and heat capacity ($C = c_p m$)
  - 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)]

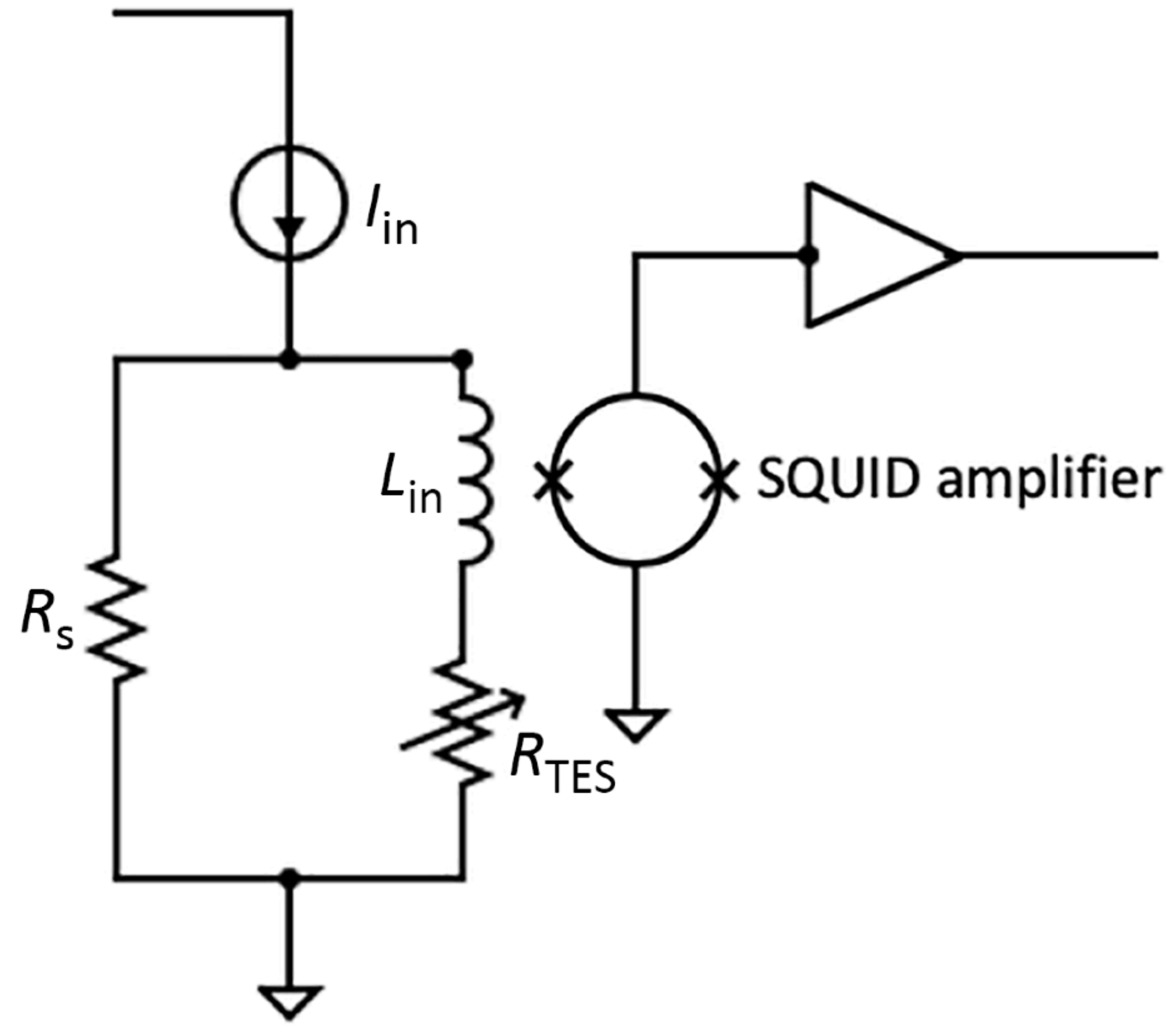
# Transition Edge Sensors (TES)

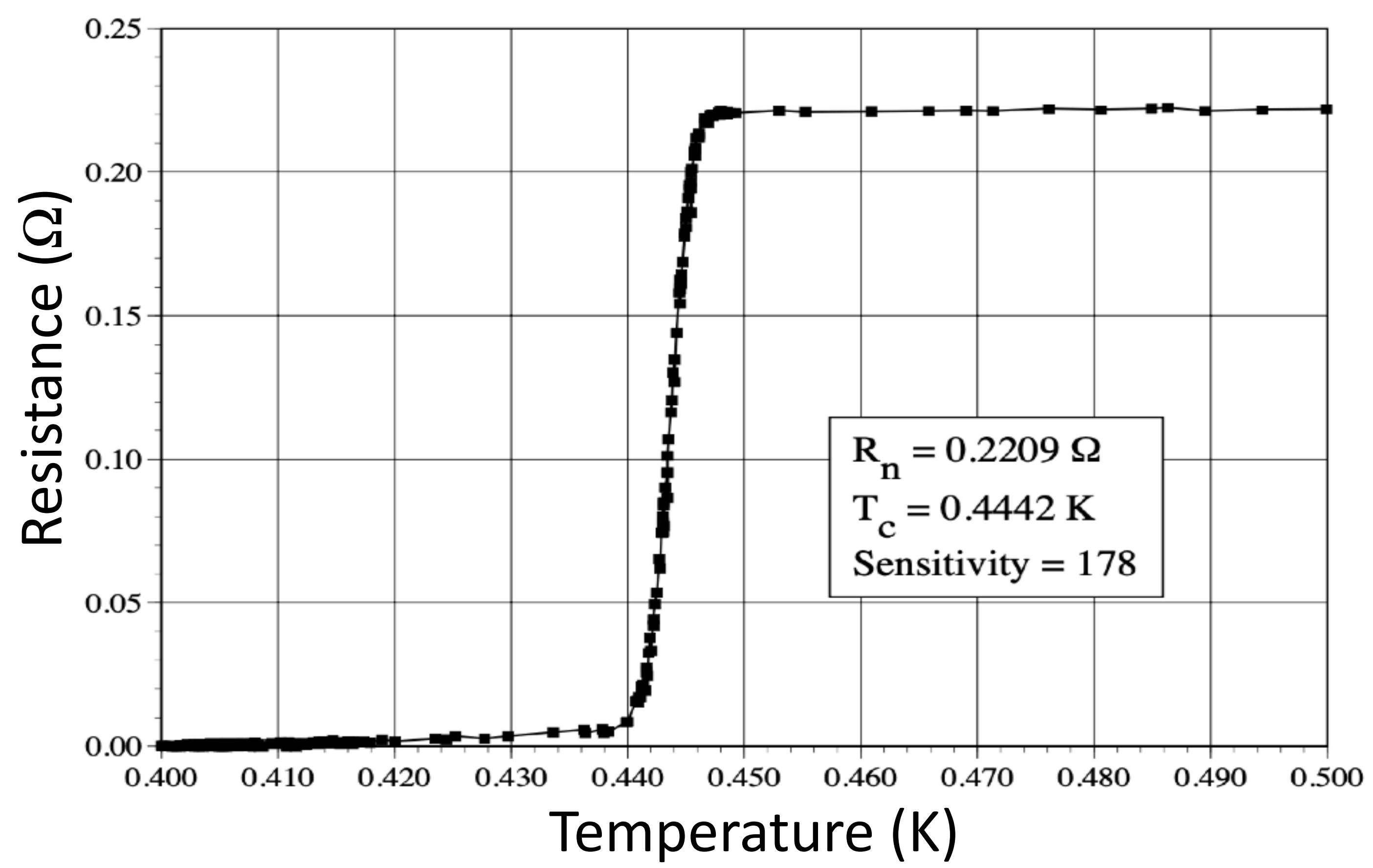
- TES Operations: Measure $\Delta T$ with superconducting circuit
  - sharp transition between superconducting → conducting
  - small temperature change, large resistance change
  - Detection limited by thermal noise; readout resistance << sensor resistance

- 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

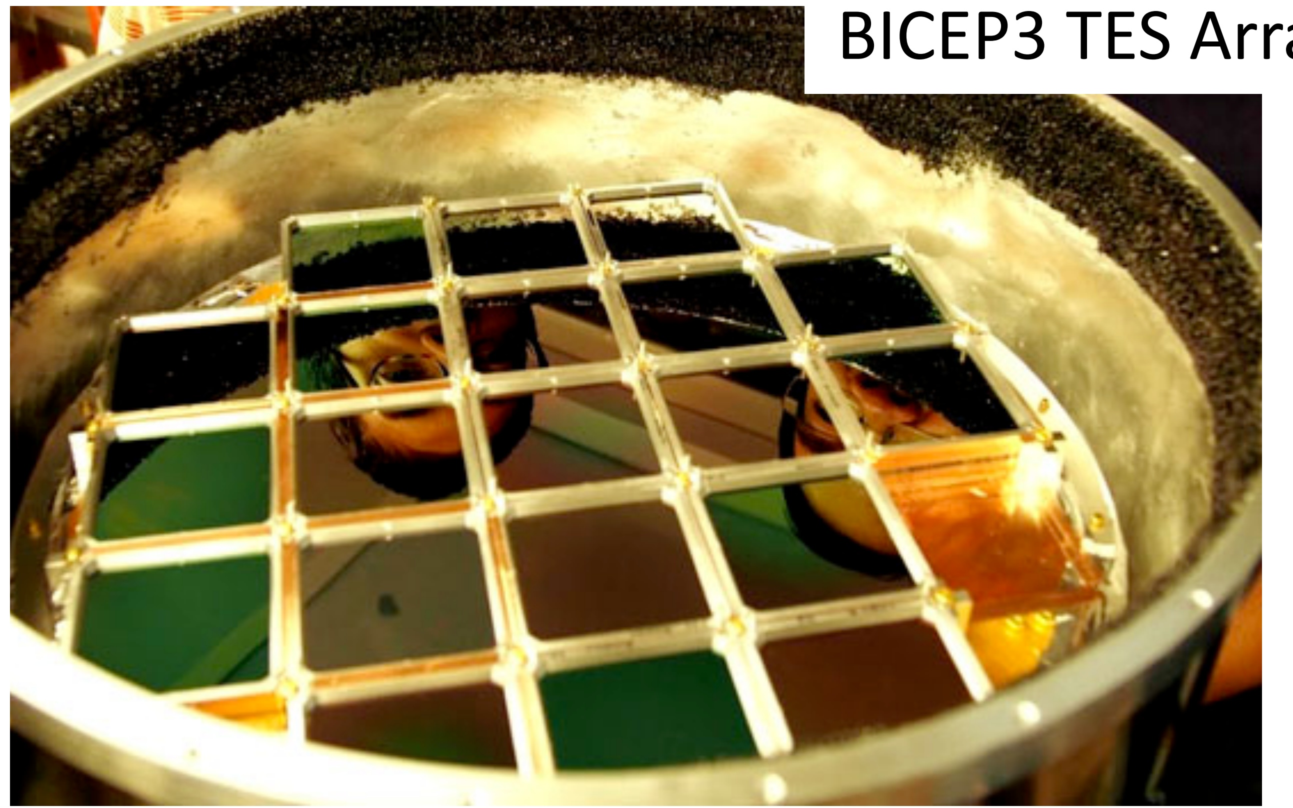
- Example: BICEP3
  - Used to study Cosmic Microwave Background (B-modes)
  - Monolithic arrays of 2400 antenna-array coupled TES detectors

- Arrays used from radio to X-ray with high spectral resolution (SPT, ATHENA, BICEP) → now also particle physics (CDMS, ALPS…)



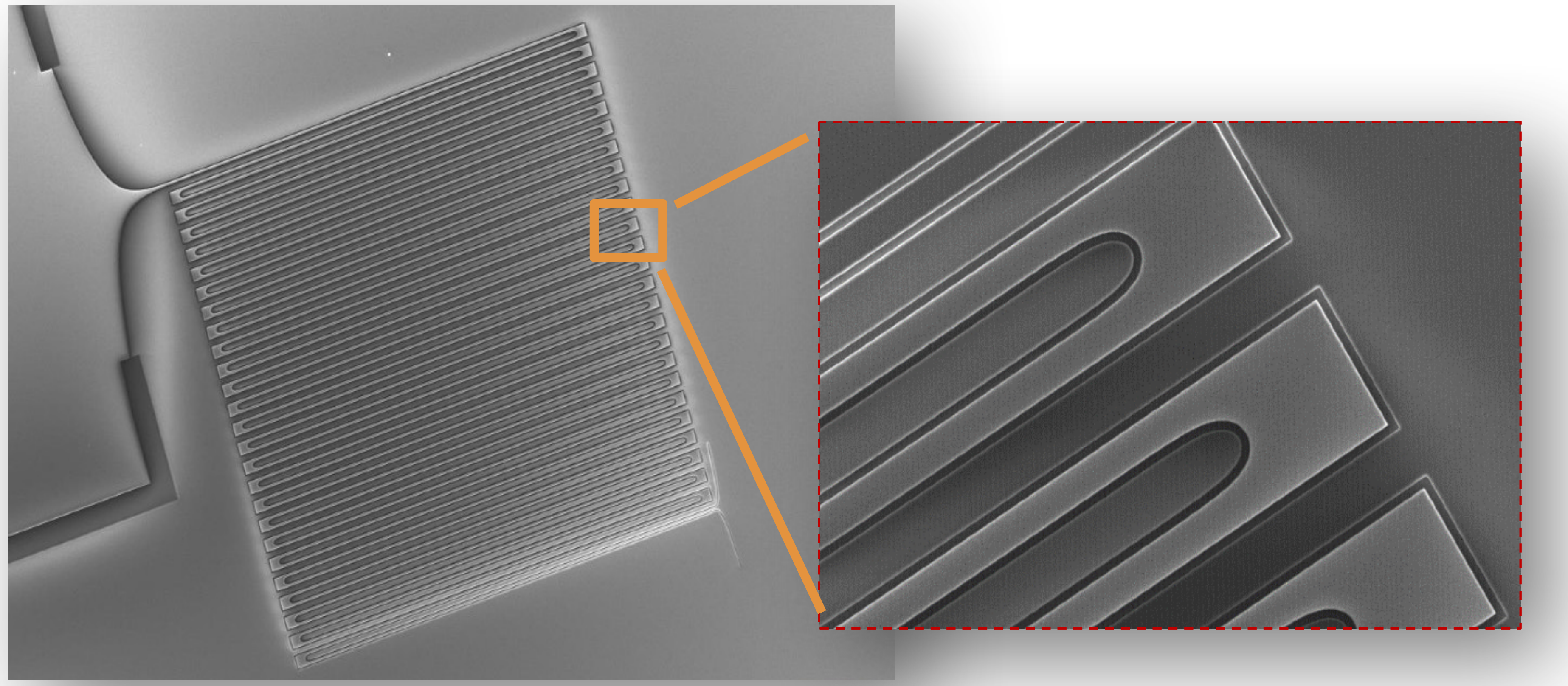

BICEP3 TES Array

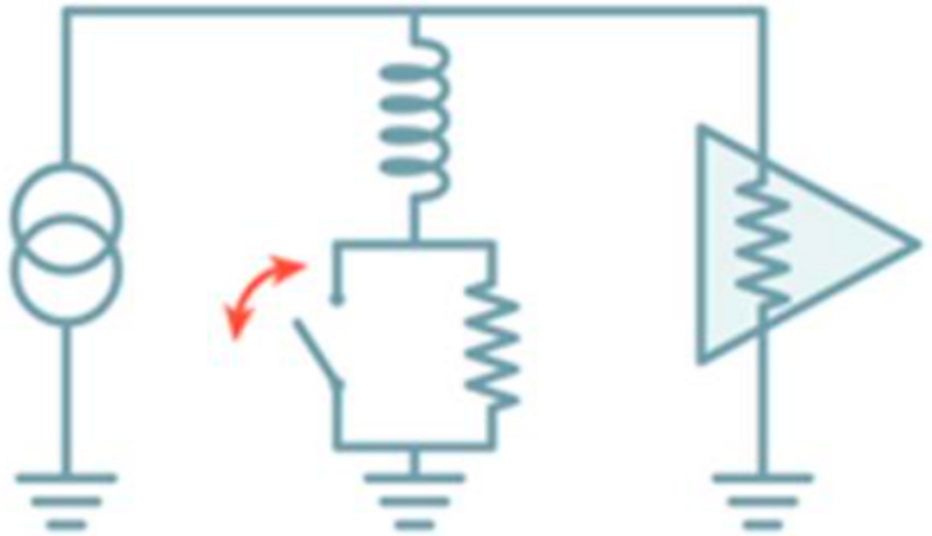


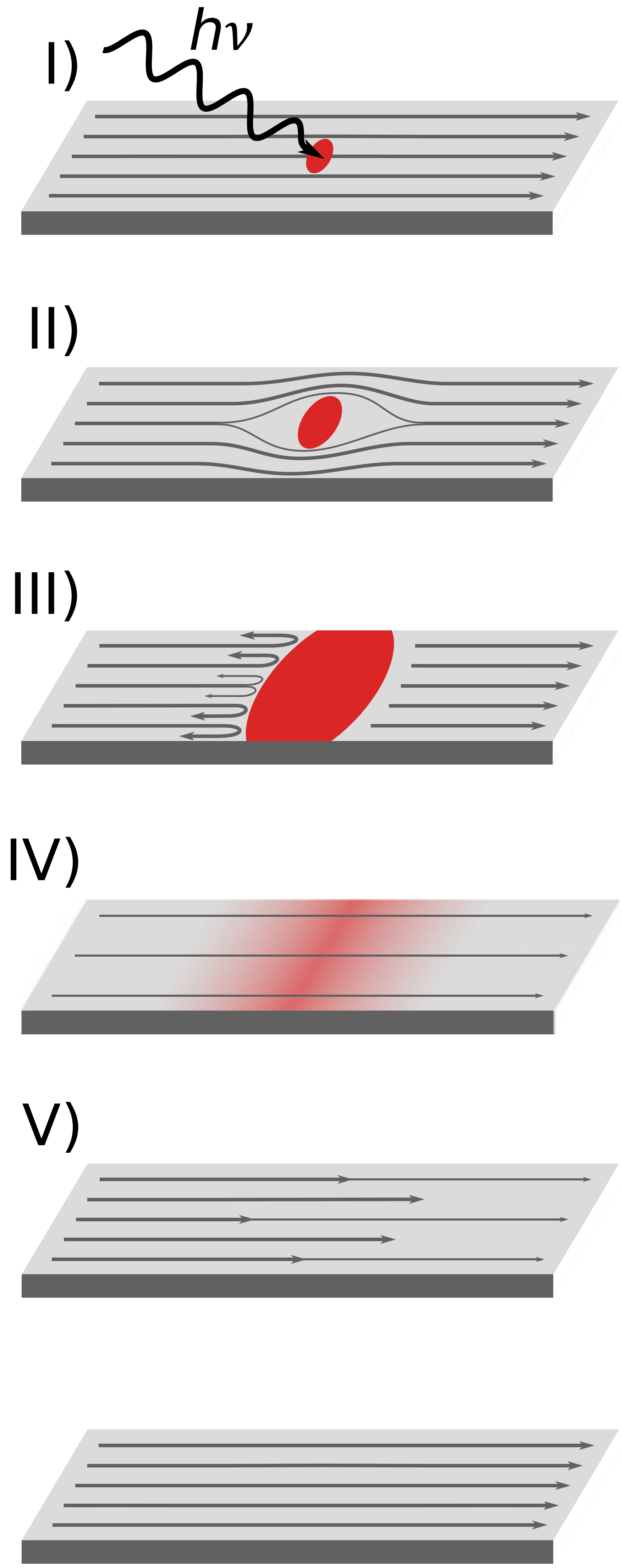
[Nagler et al, JATIS, 7(1), 011005 (2021); BICEP3]

# 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, calorimetry
- Recent advances
  - Higher temperature operation (>few K)
  - Demonstrated to work for micron size (optical lithography possible)
  - Commercial devices available - quantum communication








→ incl. CEA-IRFU, Paris-Saclay

[APL Quantum 2, 026118 (2025)]

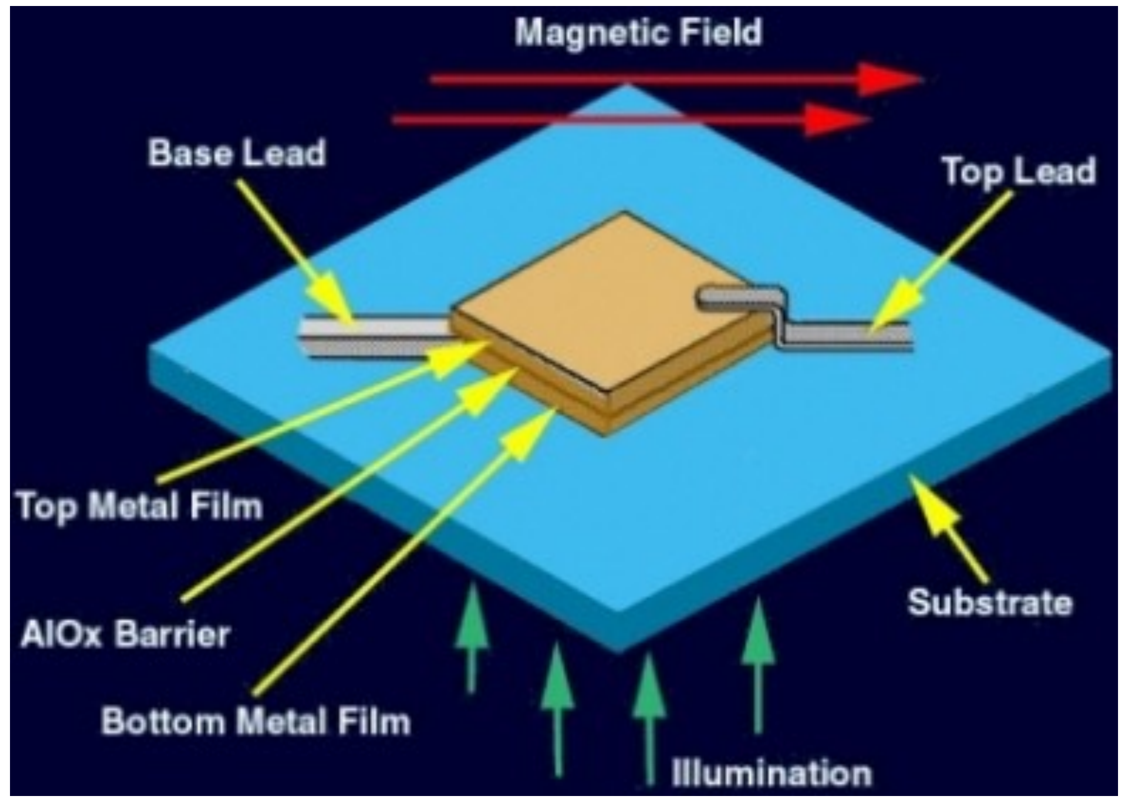
# SNSPD: Advances & Expected Performance

| | Timing jitter | Intrinsic photon number resolution | Efficiency | Array size | Maximum count rate | Dark count rate | Active area | Cut-off wavelength |
|---|---|---|---|---|---|---|---|---|
| Records in 2016 | 18 ps | None | 93% | 64 | 1 Gcps | 4 /s/mm$^2$ | 0.001 cm$^2$ | 5 µm |
| **Current records for isolated devices** | **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] |
| Expected performance by 2030 | **1 ps** | **10** | **99 %** | **10$^7$** | **10 Gcps** | **1x10$^{-6}$ /s/mm$^2$** | **1 cm$^2$** | **100 µm** |

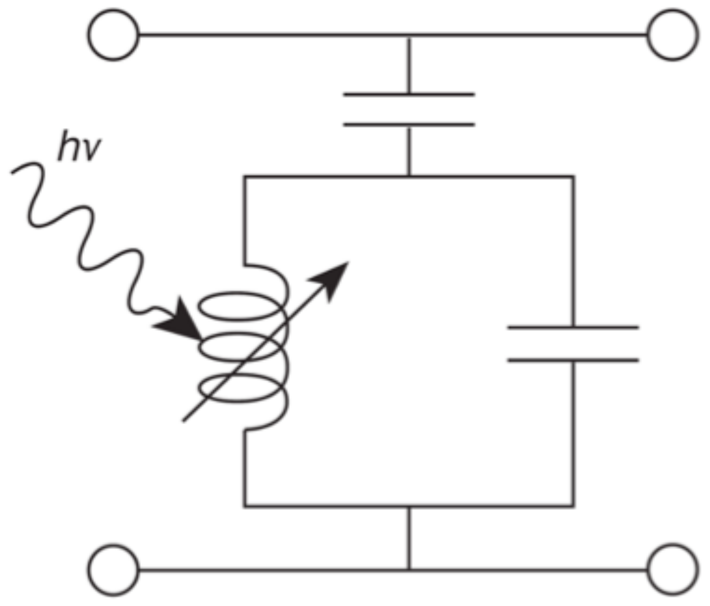

[1] Korzh, Zhao et al, ***Nature Photonics*** *14*, 250 (2020)
[2] Reddy et al, ***Optica*** 7, 1649 (2020)
[3] Oripov, Rampini, Allmaras, Shaw, Nam, Korzh, and McCaughan, ***Nature*** 622, 730 (2023)
[4] Craiciu, Korzh et al, ***Optica*** 10, 183 (2023)
[5] Resta et al, ***Nano Letters*** (2023)
[6] Chiles, ***PRL*** 128, 231802 (2022)
[7] Taylor, Walter, Korzh et al, ***Optica***, (2023)

# Cryogenic Quantum Sensors

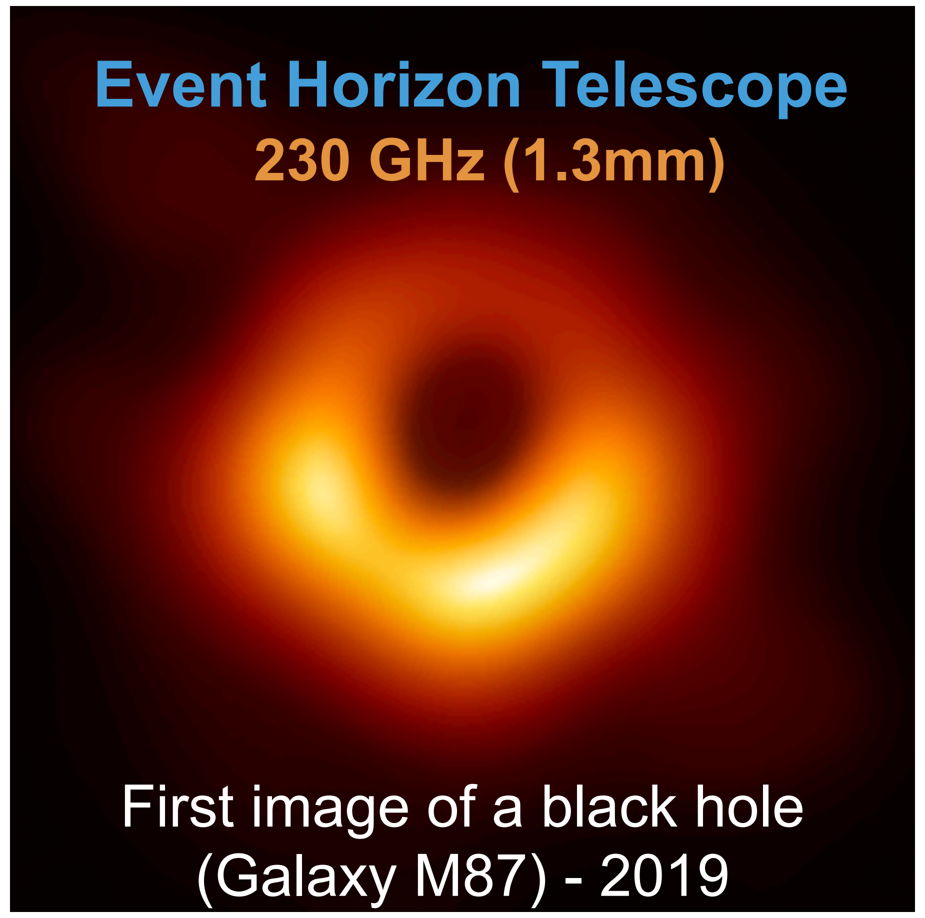
- Superconducting Tunnel Junctions (STJ)
  - Exploit quantum tunnelling in a junction of two superconductors
  - Direct tunnel current measurement (non-Heterodyne): simultaneous fast photon counting and spectroscopy in IR, Vis, UV bands
- Microwave Kinetic Inductance Detectors (MKIDs)
  - Exploits change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

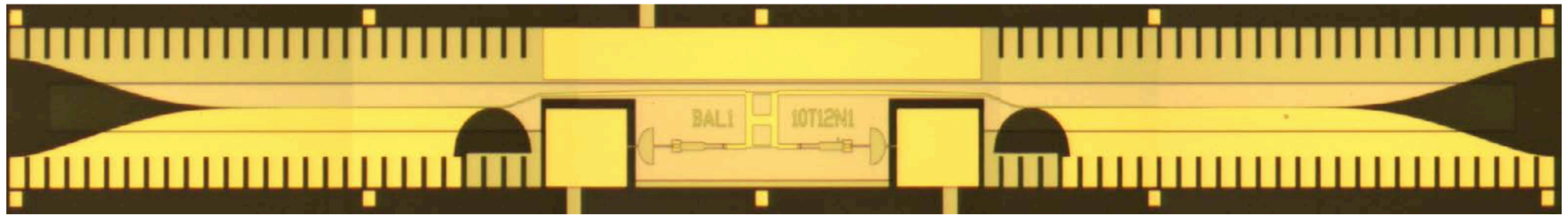



Superconducting Tunnel Junction




MKID operating principle




Superconductor-Insulator-Superconductor (SIS) Mixer Block

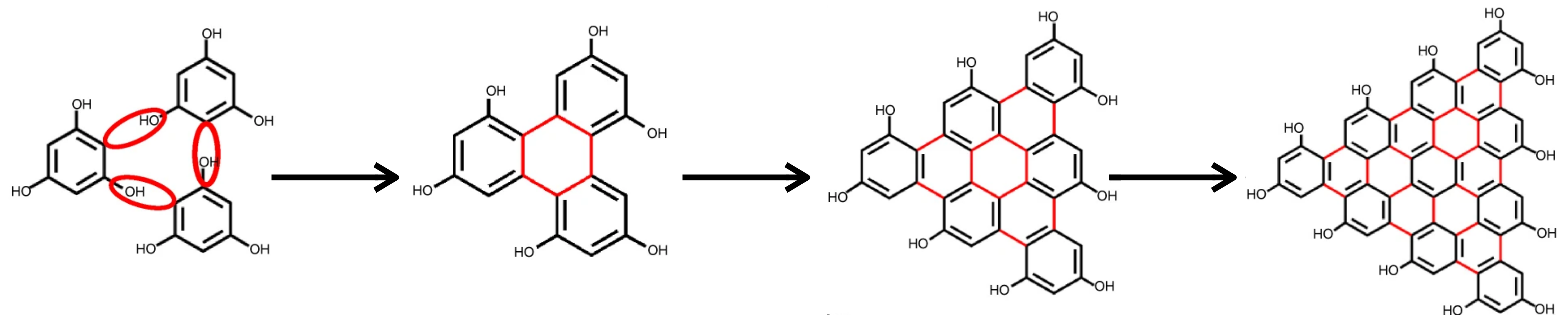
# Cryogenic Quantum Sensors vs. Wavelength

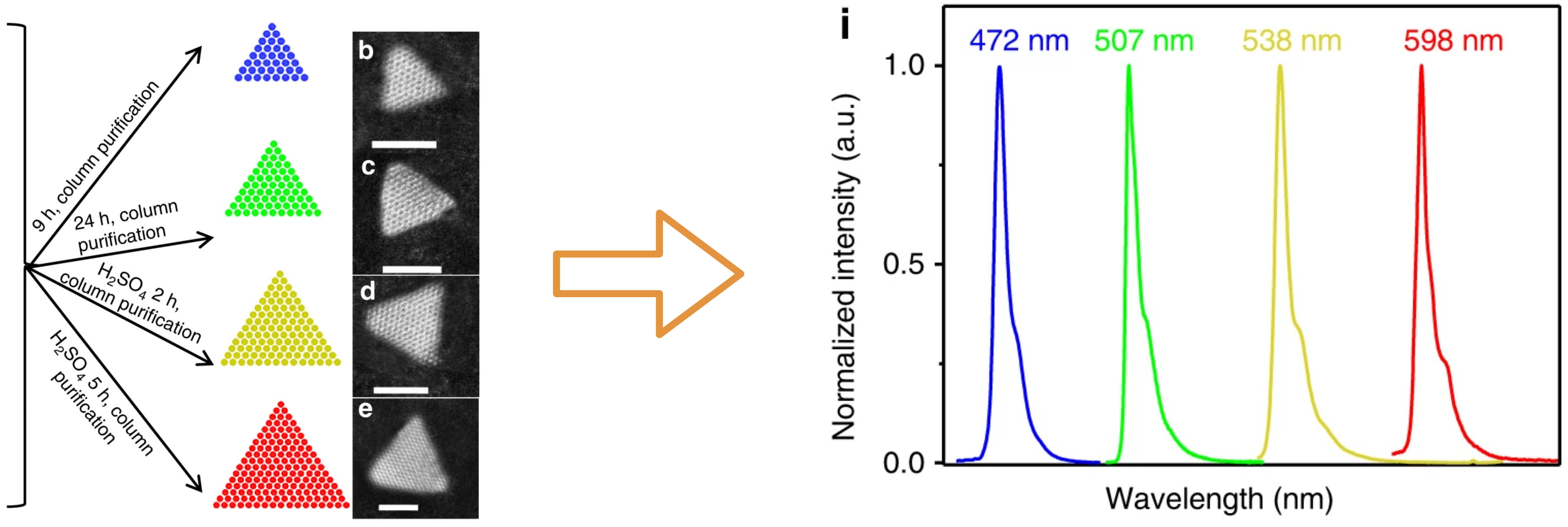
| Detector | Microwave<br>3cm - 3mm<br>10-100 GHz<br>0.04-0.4 meV | Submillimeter<br>3mm - 300µm<br>100 GHz - 1 THz<br>0.4-4 meV | Far infrared<br>300 – 30 µm<br>1 – 10 THz<br>4-40 meV | Optical<br>2 µm - 300 nm<br>2-37 eV | High Energy<br>UV, X-Ray |
|---|---|---|---|---|---|
| Transition Edge Sensors (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]

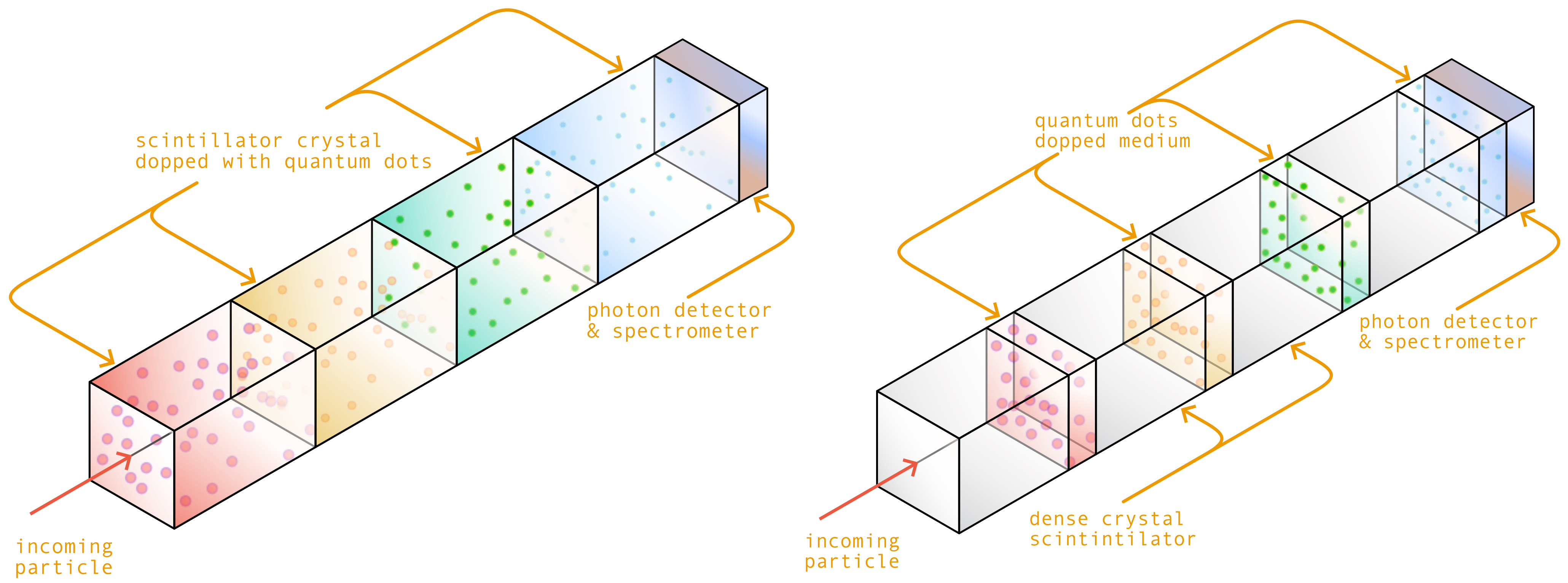
# Quantum Dots and Chromatic Calorimetry

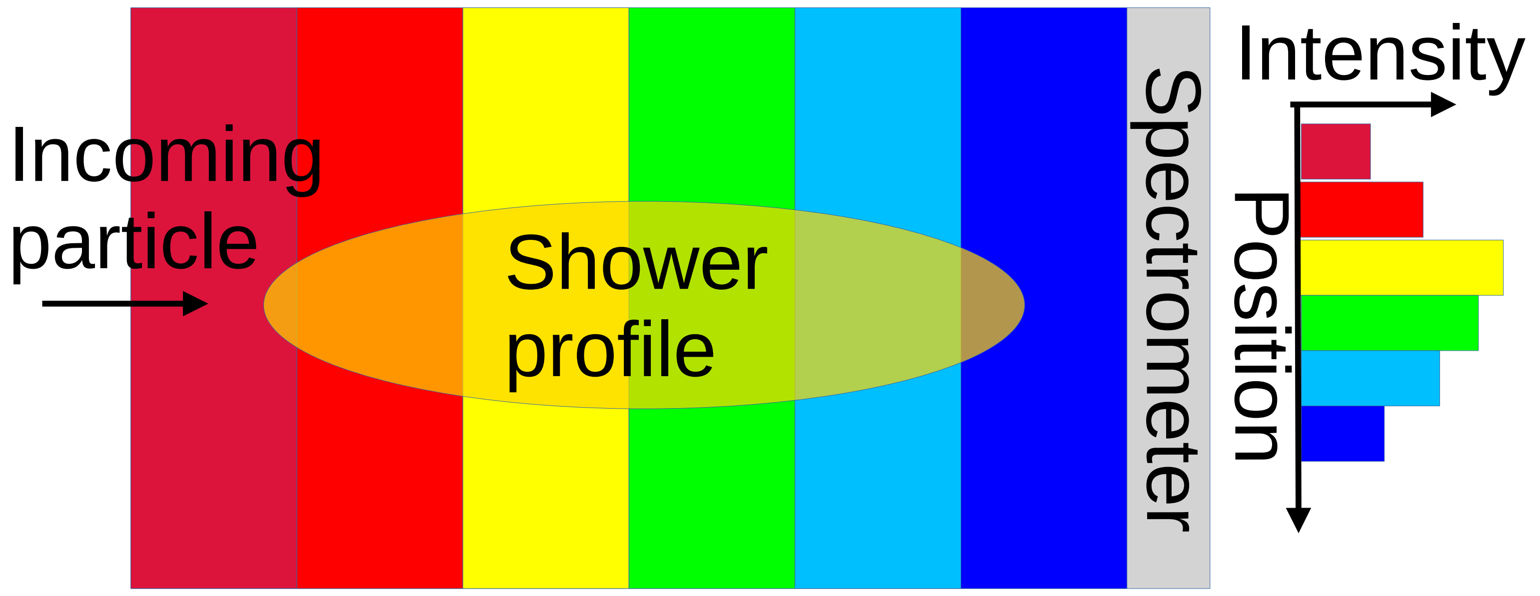
- Quantum dots: nanometer-sized semiconductor structures, e.g. in carbon, perovskites, etc.
- Tuneable, with properties between single atoms and bulk material






- 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

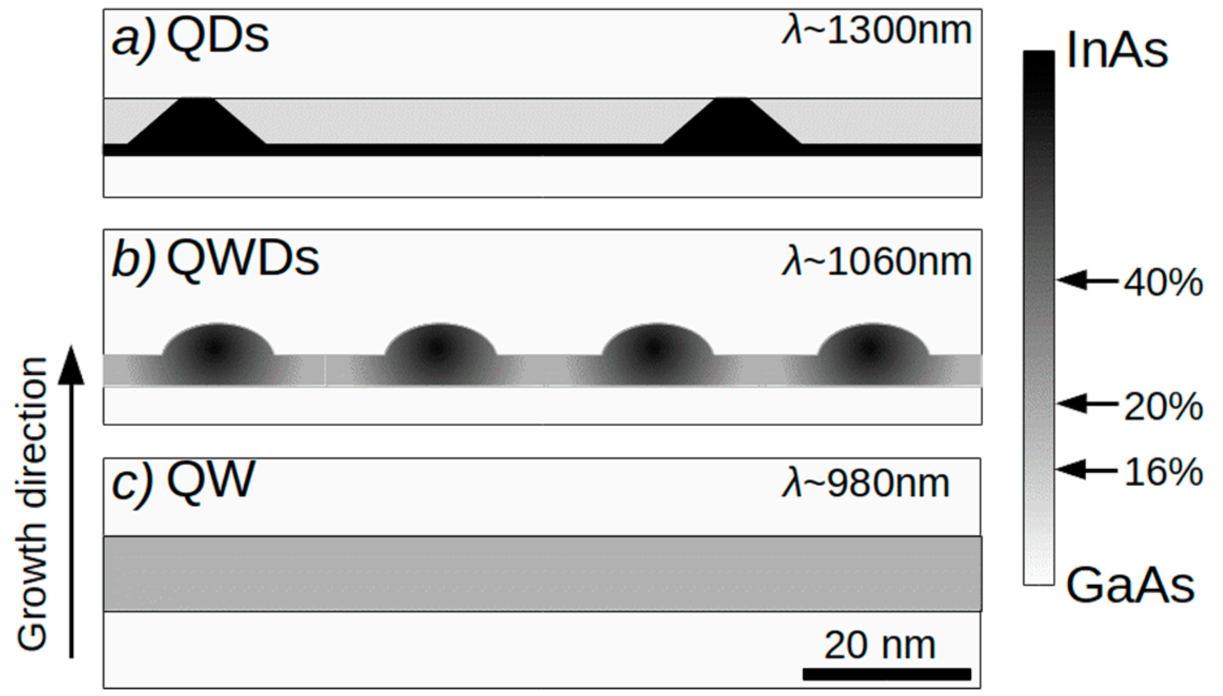
- Quantum Dots, Quantum Wires, Quantum Wells… many structures possible

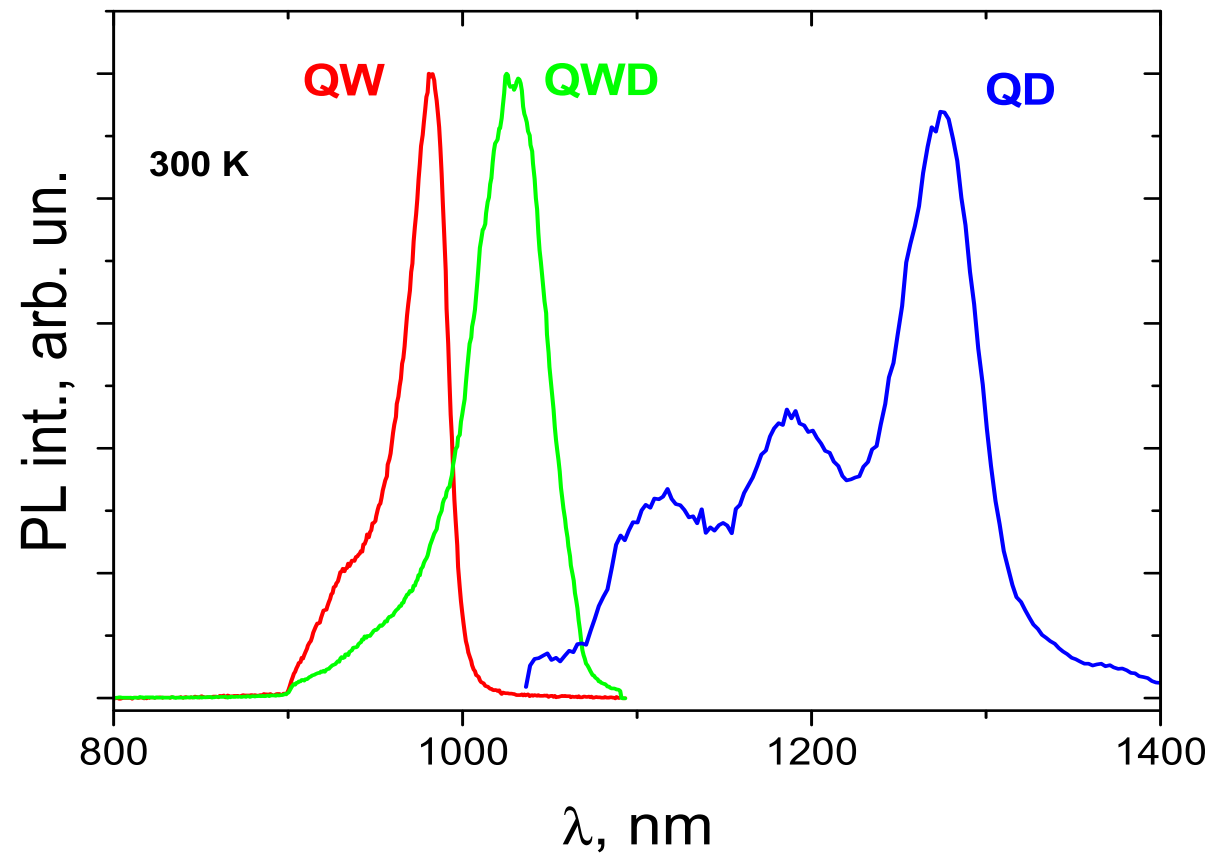
- Quantum Well-dots: aiming for active scintillators
  - electronic amplification / modulation
  - pulsed / primed operation
  - gain adapted in-situ

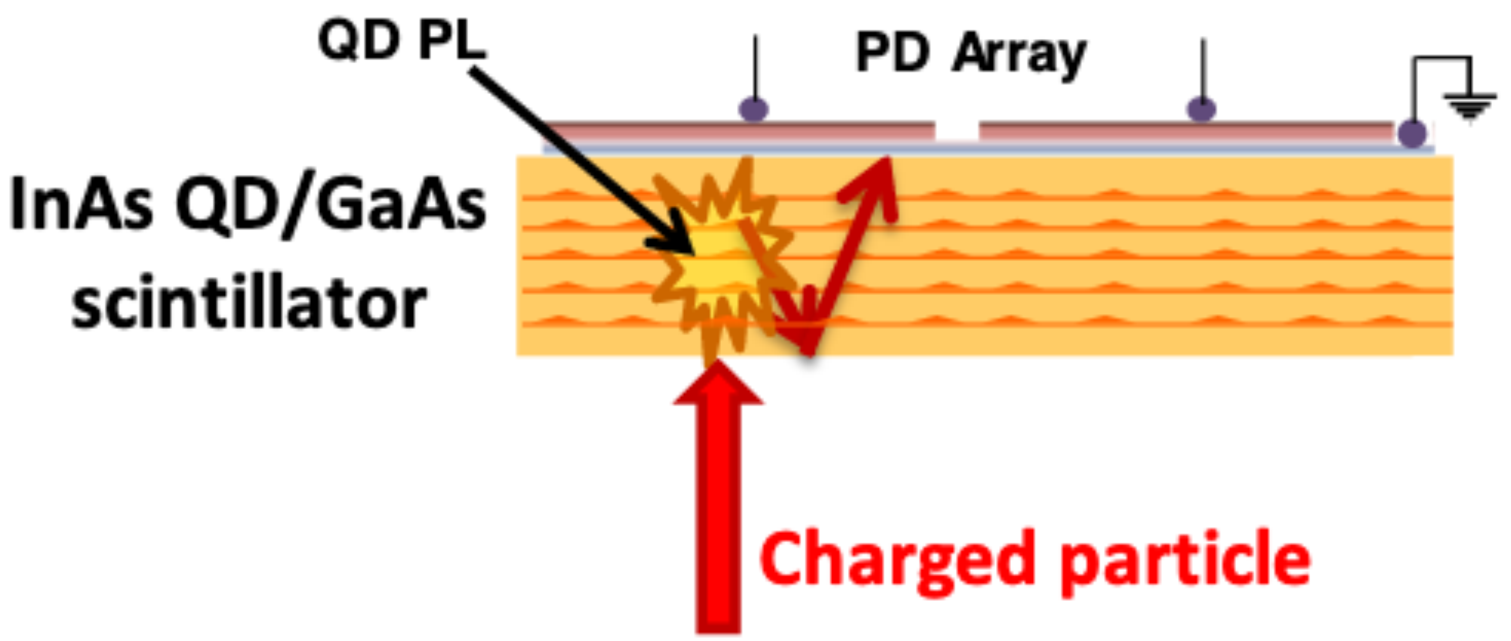
- Quantum Dots in CMOS pixels:  DoTPiX
  - n-channel MOS transistor + buried quantum well gate
  - gate collects holes, modulates current

→ CEA, CNRS/C2N Paris-Saclay

- 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



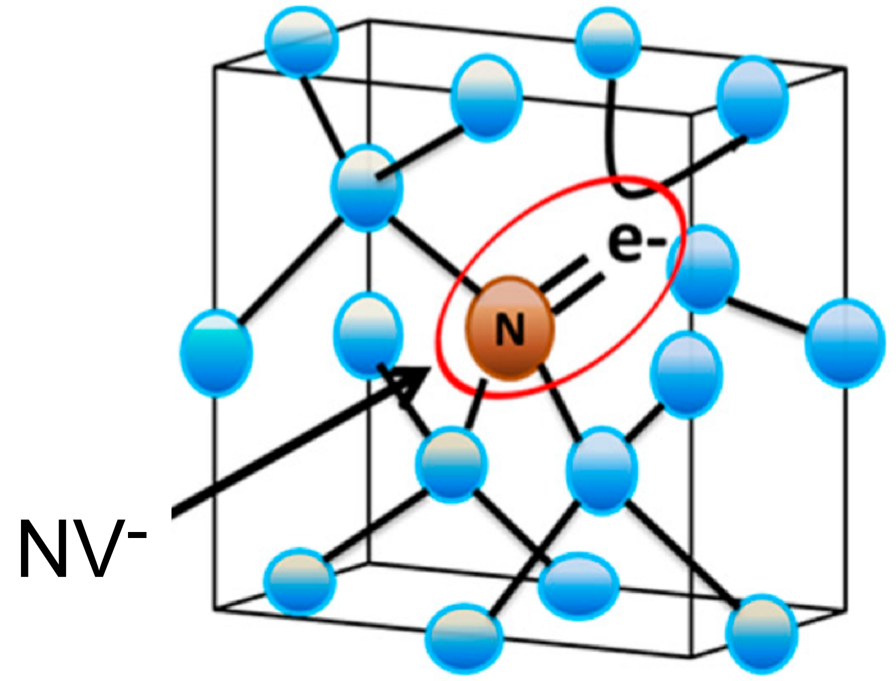





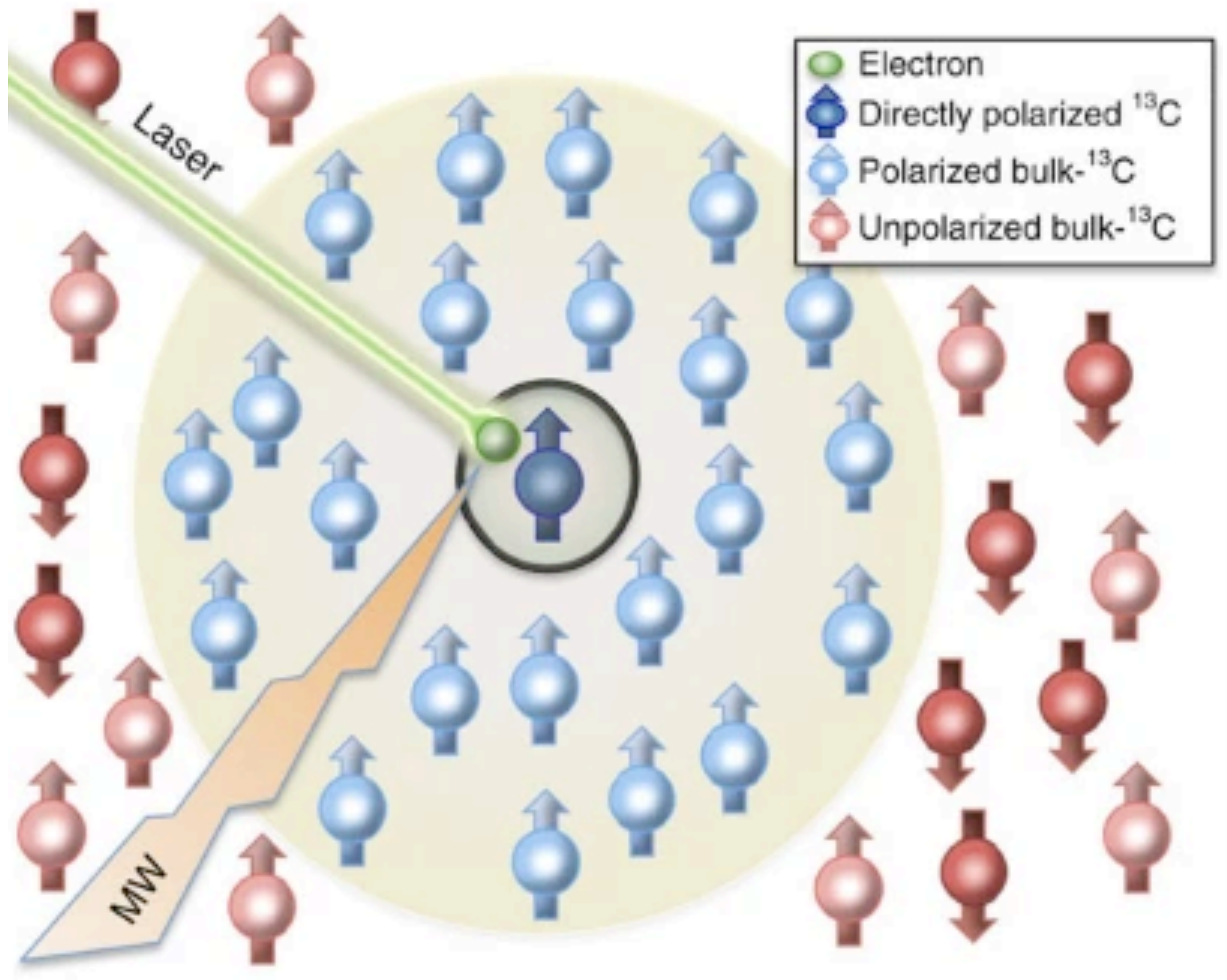

[Maximov et al., Appl. Sci. 2020, 10, 1038; M.Hoeferkamp et al., arXiv:2202.11828; A. Minns et al., MRS Advances 6, 297–302 (2021)]

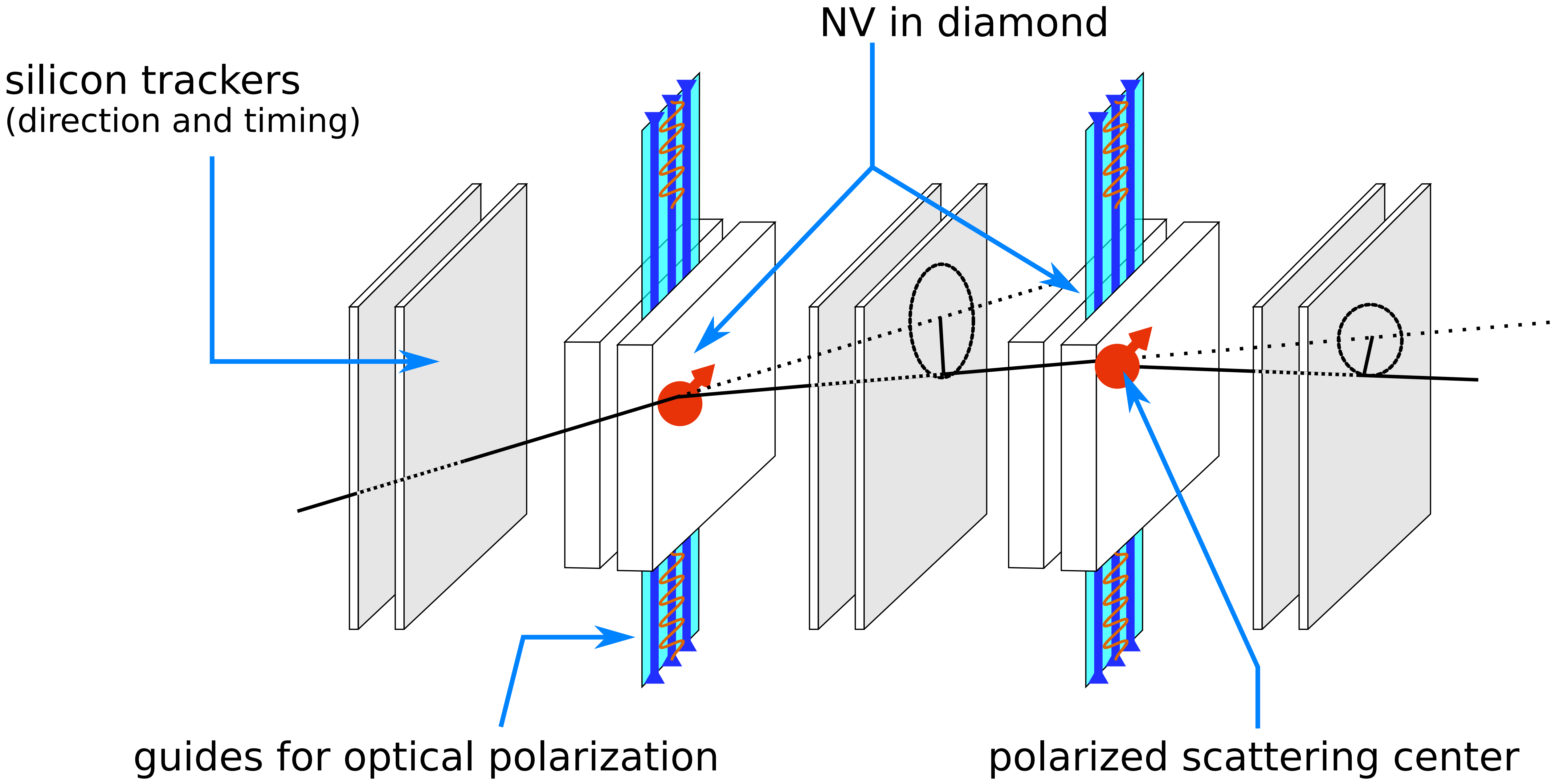
# Quantum-Polarized Helicity Detection in NV Centres

- 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

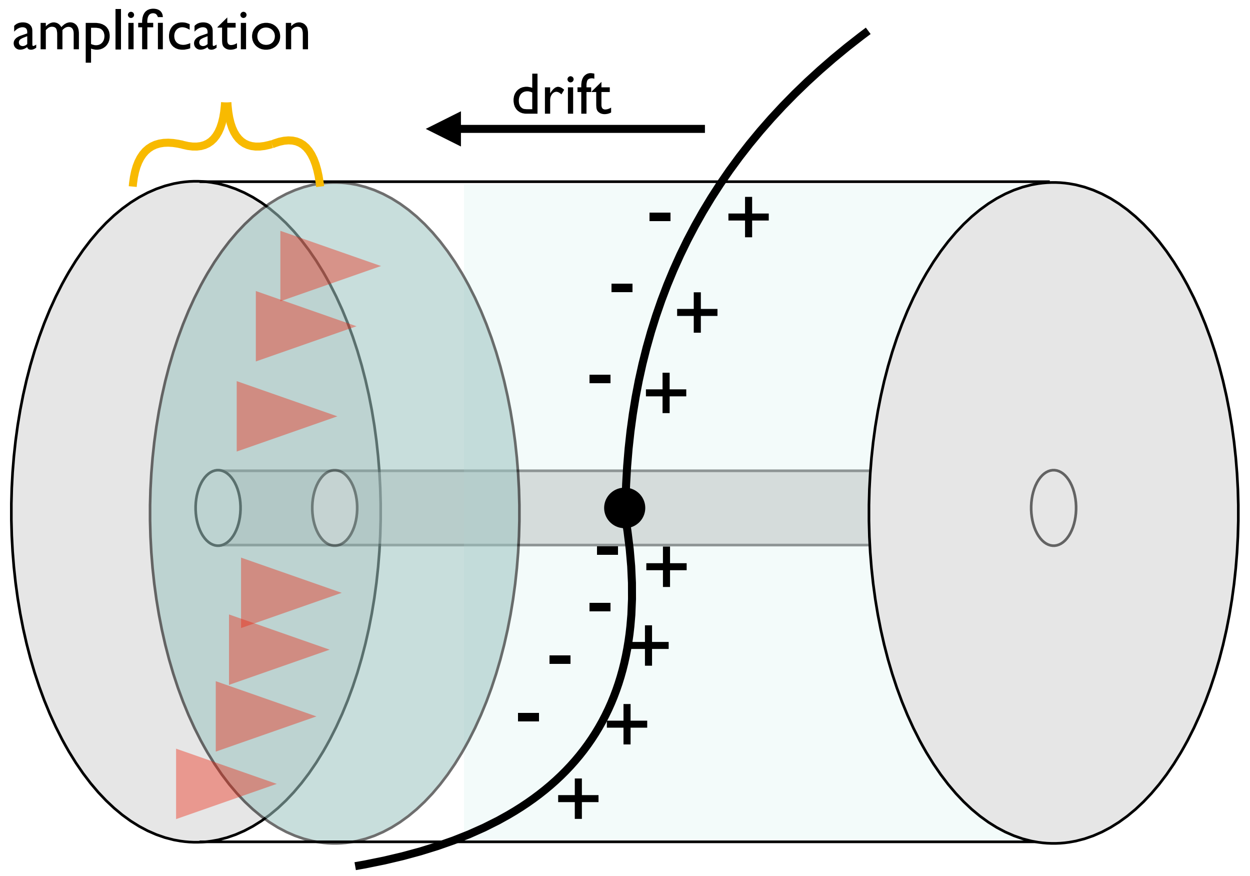




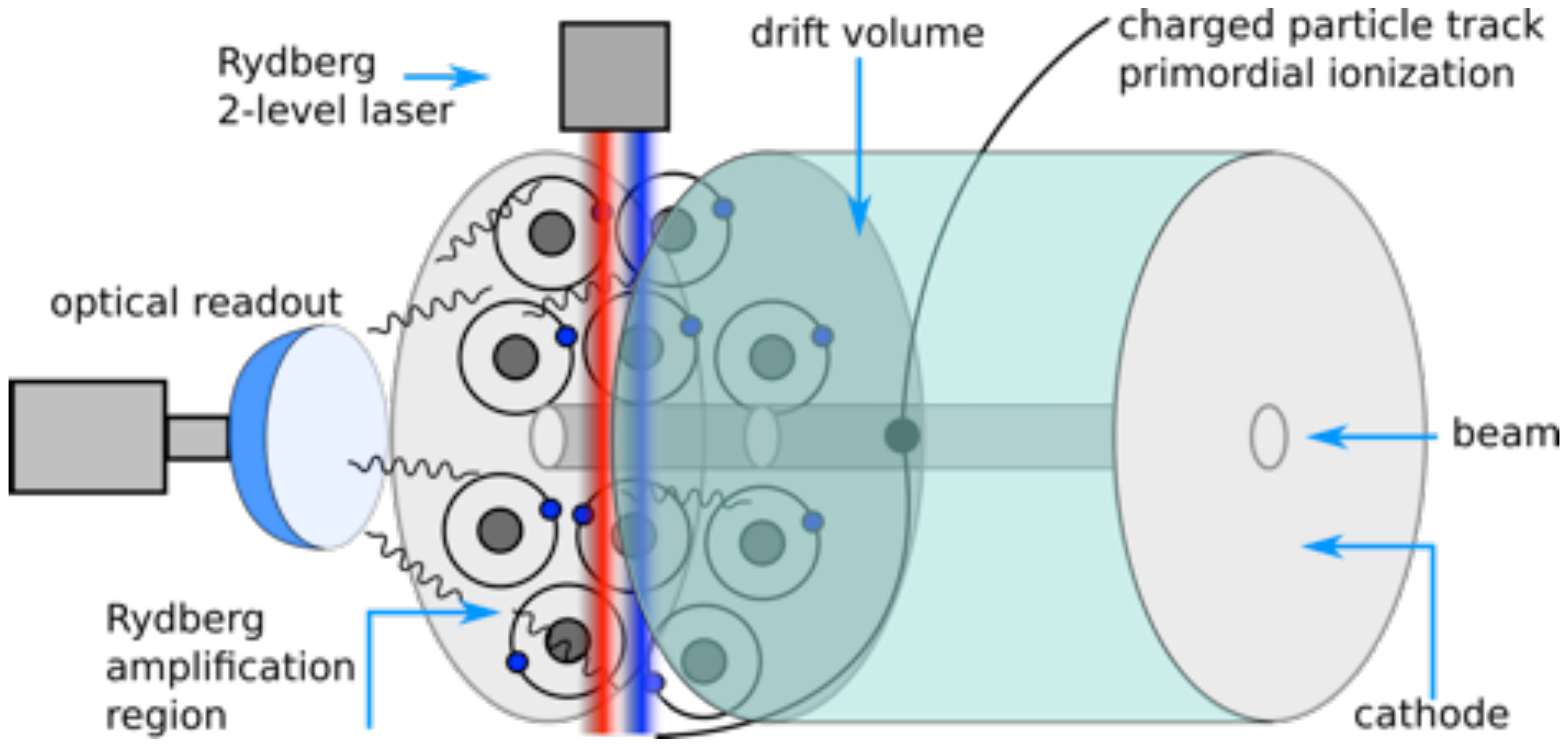

[G. Alvarez et al., Nature Communications 6, 8456 (2015)]

# Quantum Sensing and Rydberg Atoms

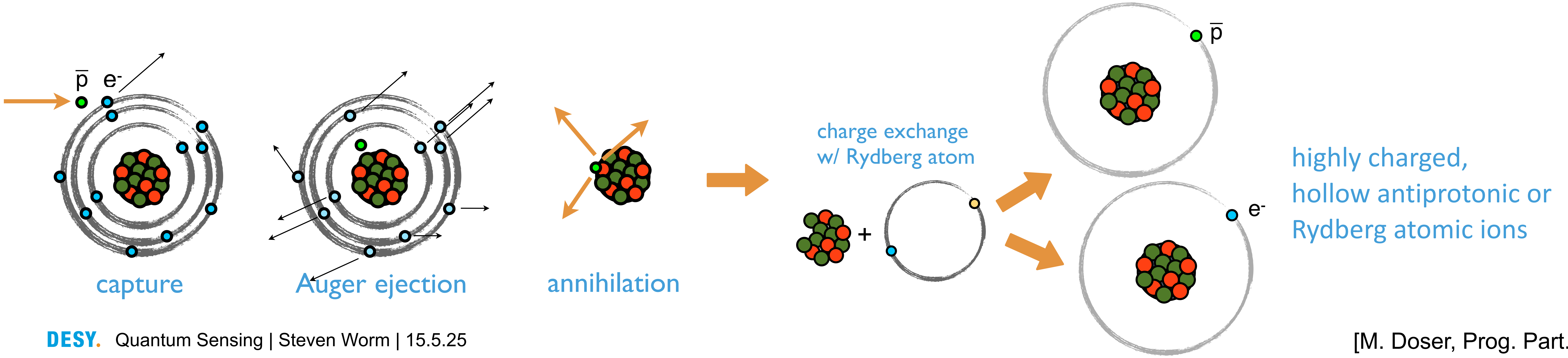



- Rydberg atoms: highly excited valence electrons

- 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



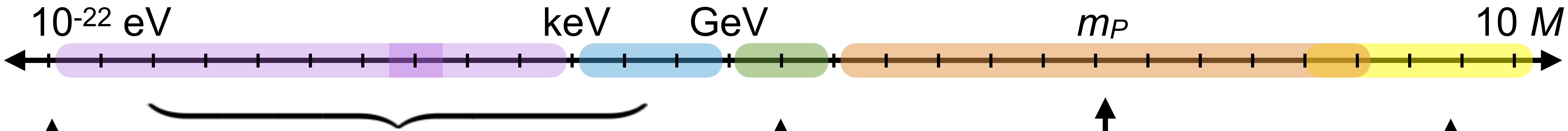

- Antiprotonic atoms and novel HCI systems
  - Anti-proton tests in Penning trap for Highly Charged Ions or molecules
  - Tests of QED, CPT, fundamental constants, fifth force, precision isotope shift (King plot), EDM measurements




[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***

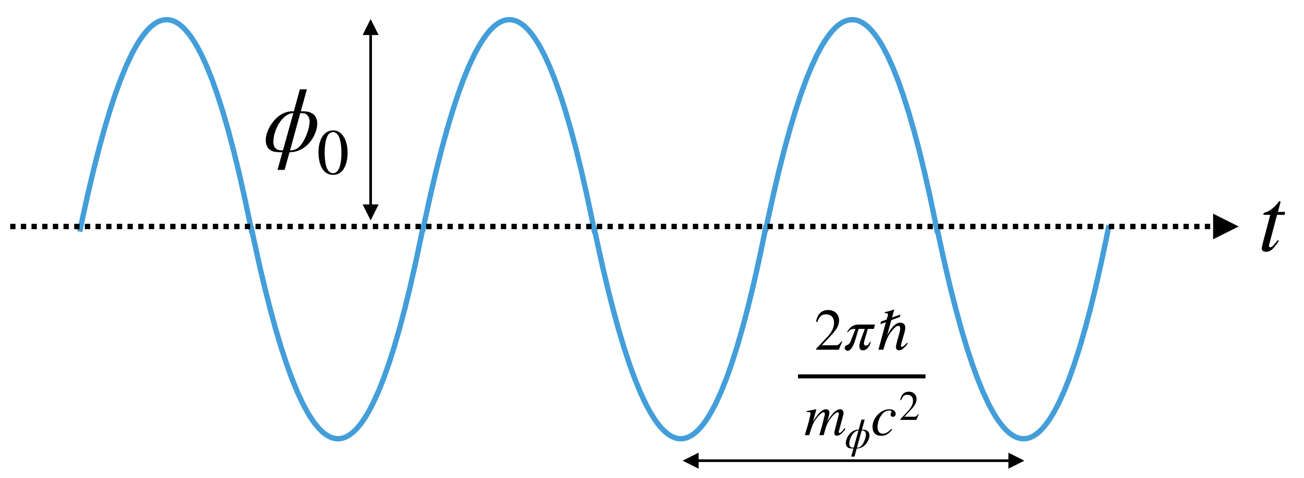
Primordial Black Holes

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 $\phi$) for lowest order interaction w/ scalar field

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

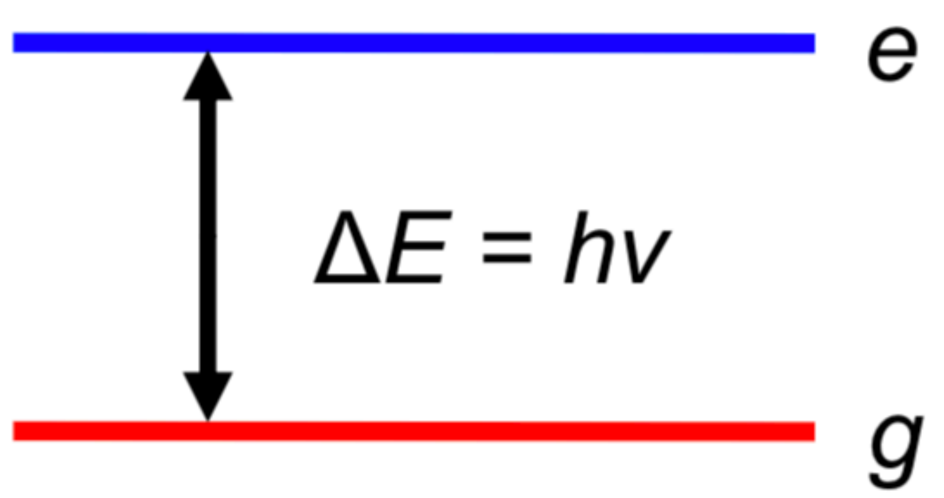
- At the effective new physics energy scales $\Lambda_\alpha$ and $\Lambda_e$, $\alpha$ and $m_e$ appear to oscillate

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



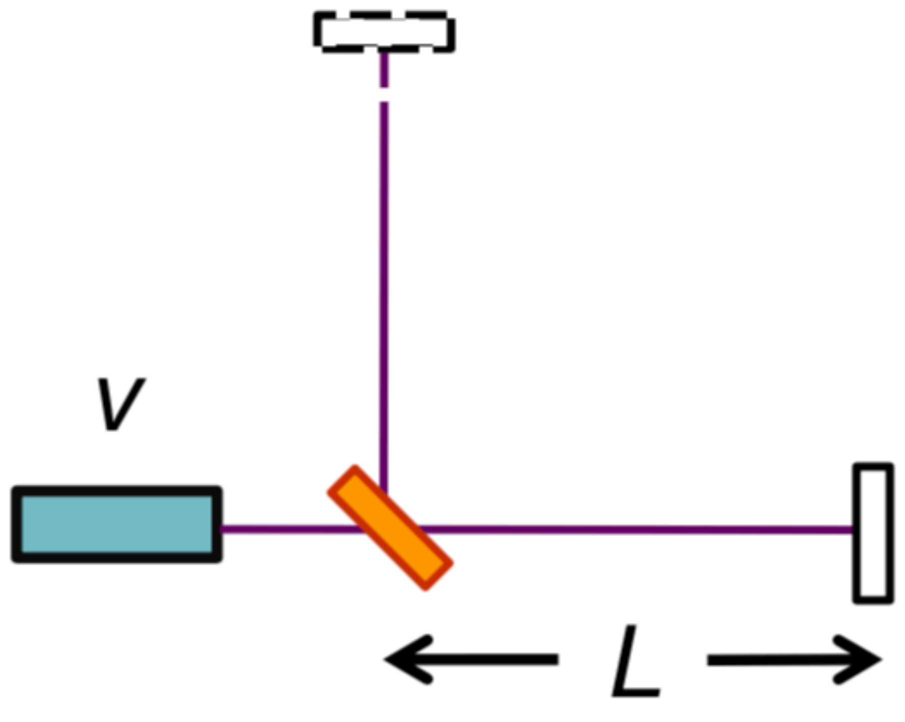
[Damour & Donoghue, PRD 82, 084033 (2010); Arvanitaki et al., Phys. Rev. D 91, 015015 (2015); Safranova et al., RMP 90, 025008 (2018)]

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



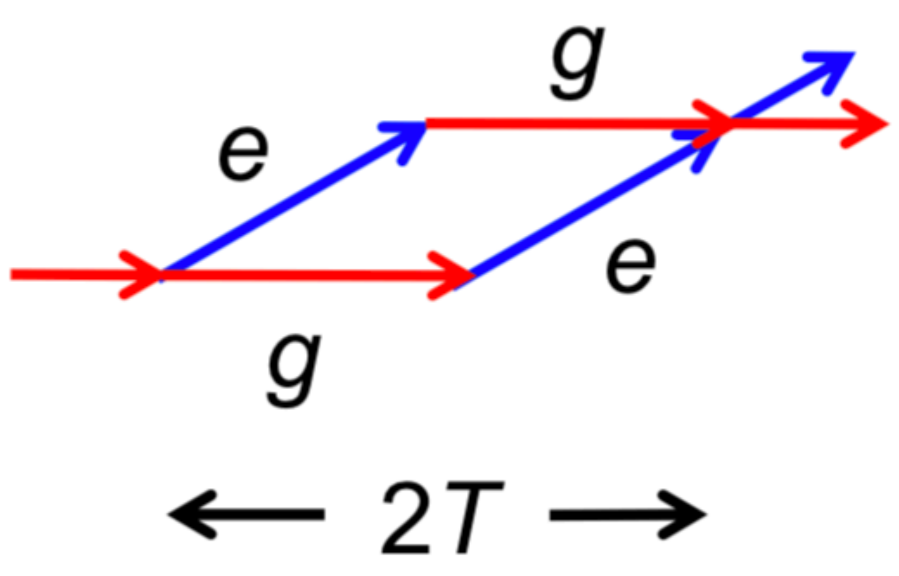

**Atomic spectroscopy (clocks)**

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




**Laser interferometry (cavities)**

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



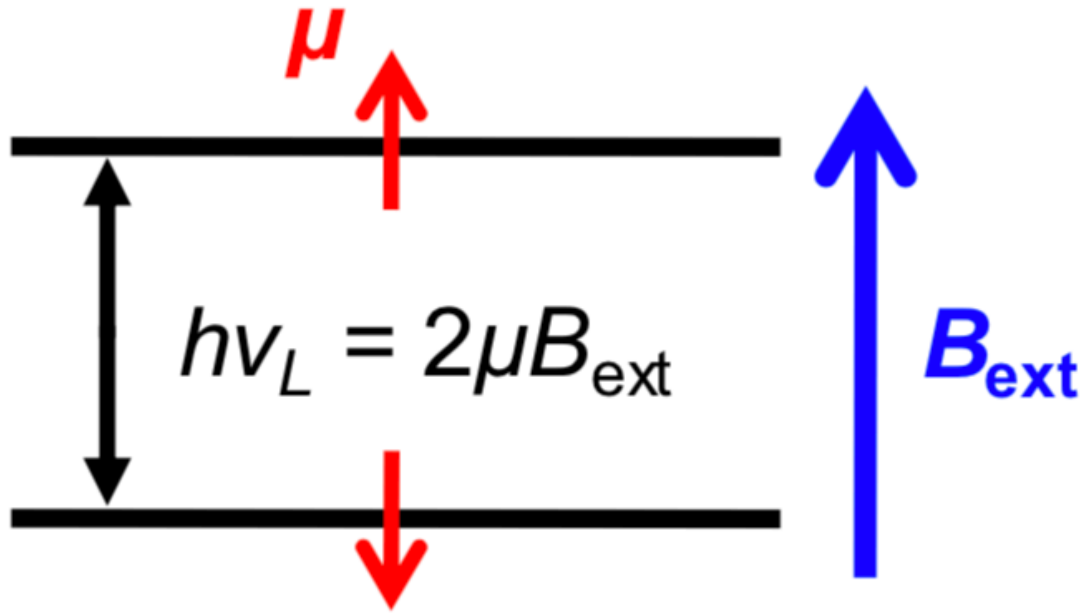

**Atom interferometry**

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



[Y. Stadnik]

# Quantum Sensing Methods for Testing Δμ/μ



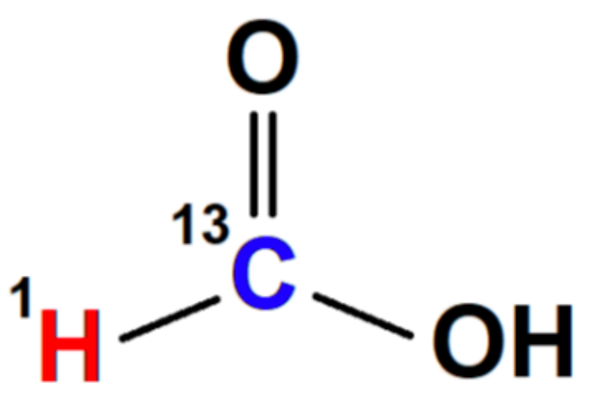

**Co-magnetometry**

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

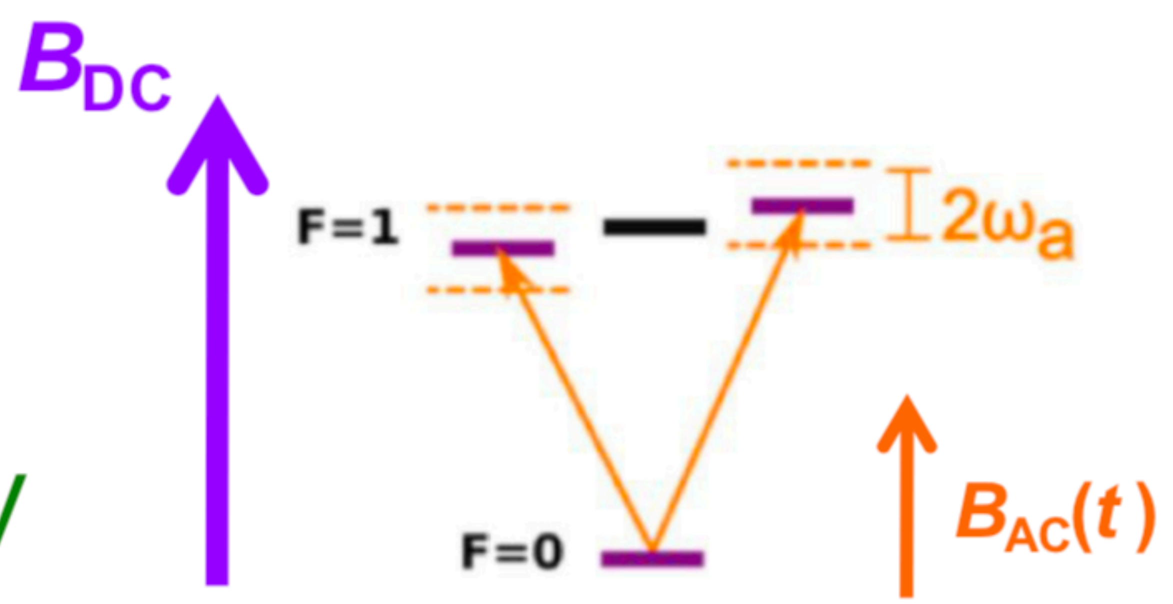
$$\text{or } \hat{\boldsymbol{\sigma}} \cdot \boldsymbol{p}_a \sin(m_a t)$$

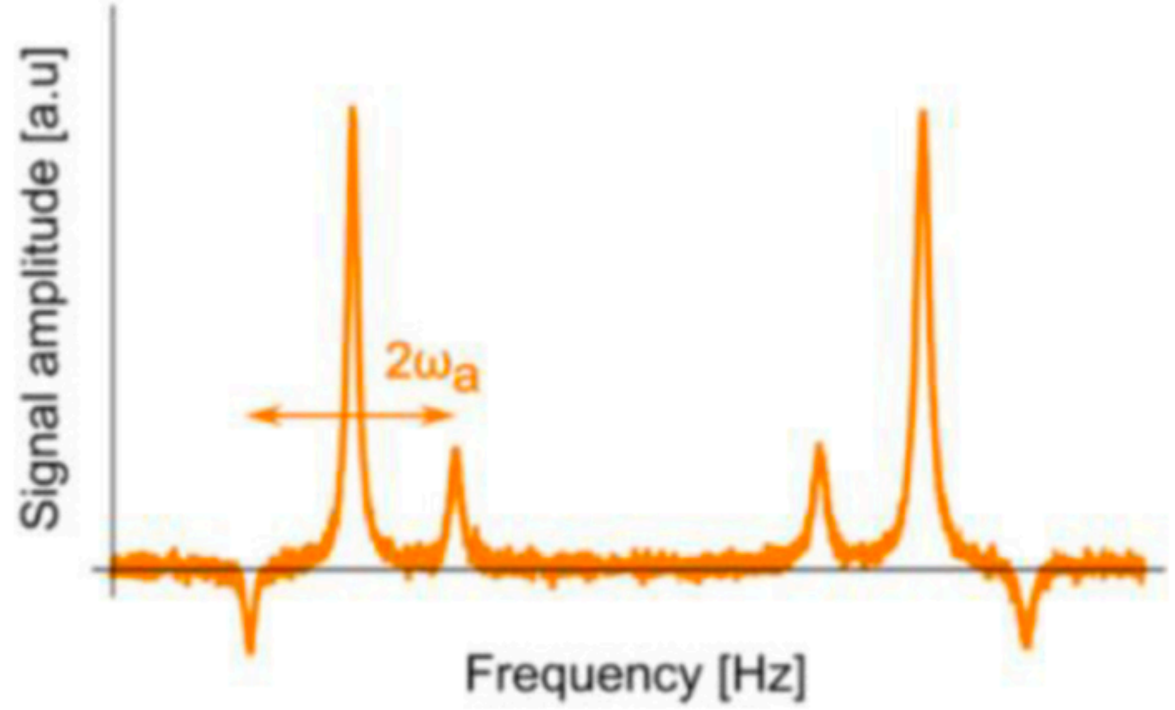
$10^{-23}$ eV $< m_a <$ $10^{-17}$ eV

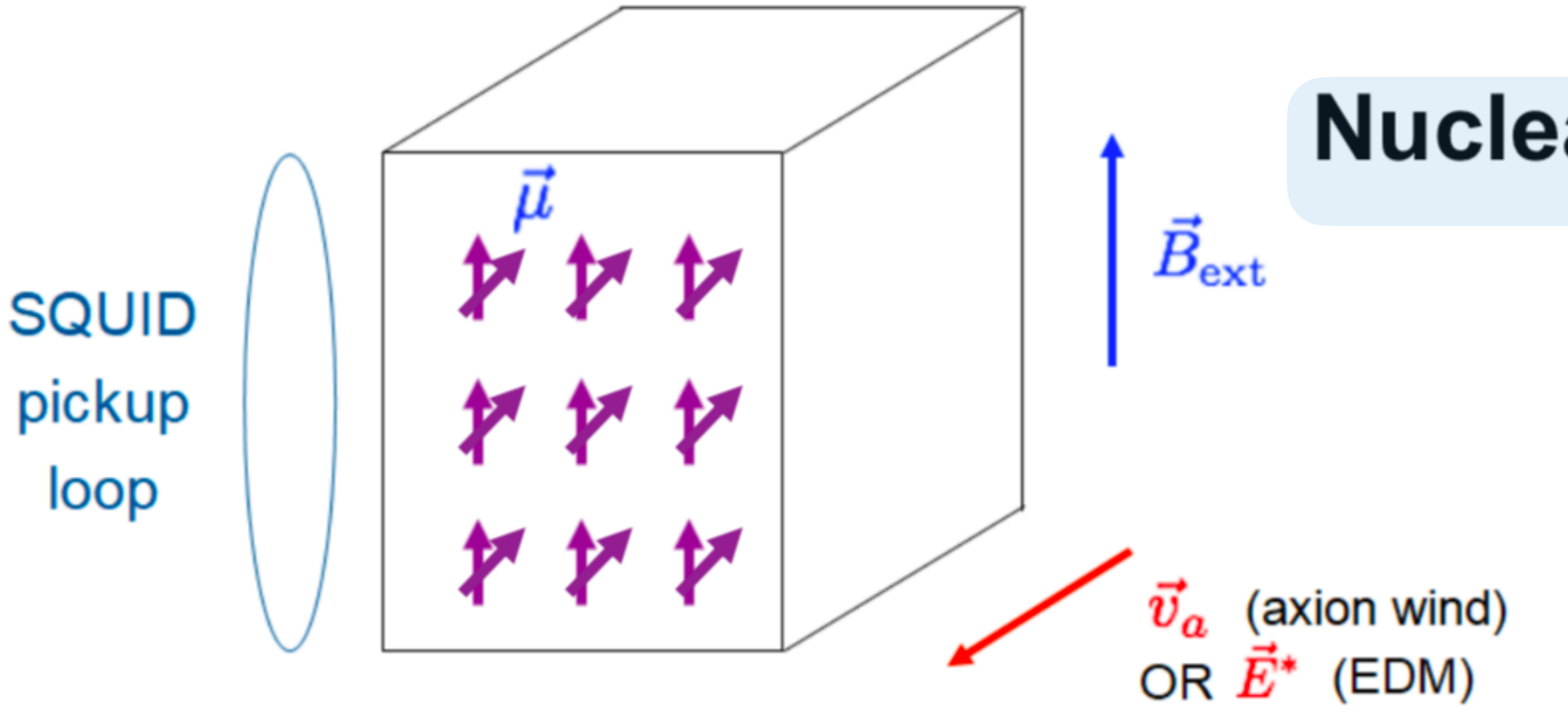
**Nuclear magnetic resonance (“sidebands”)**




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



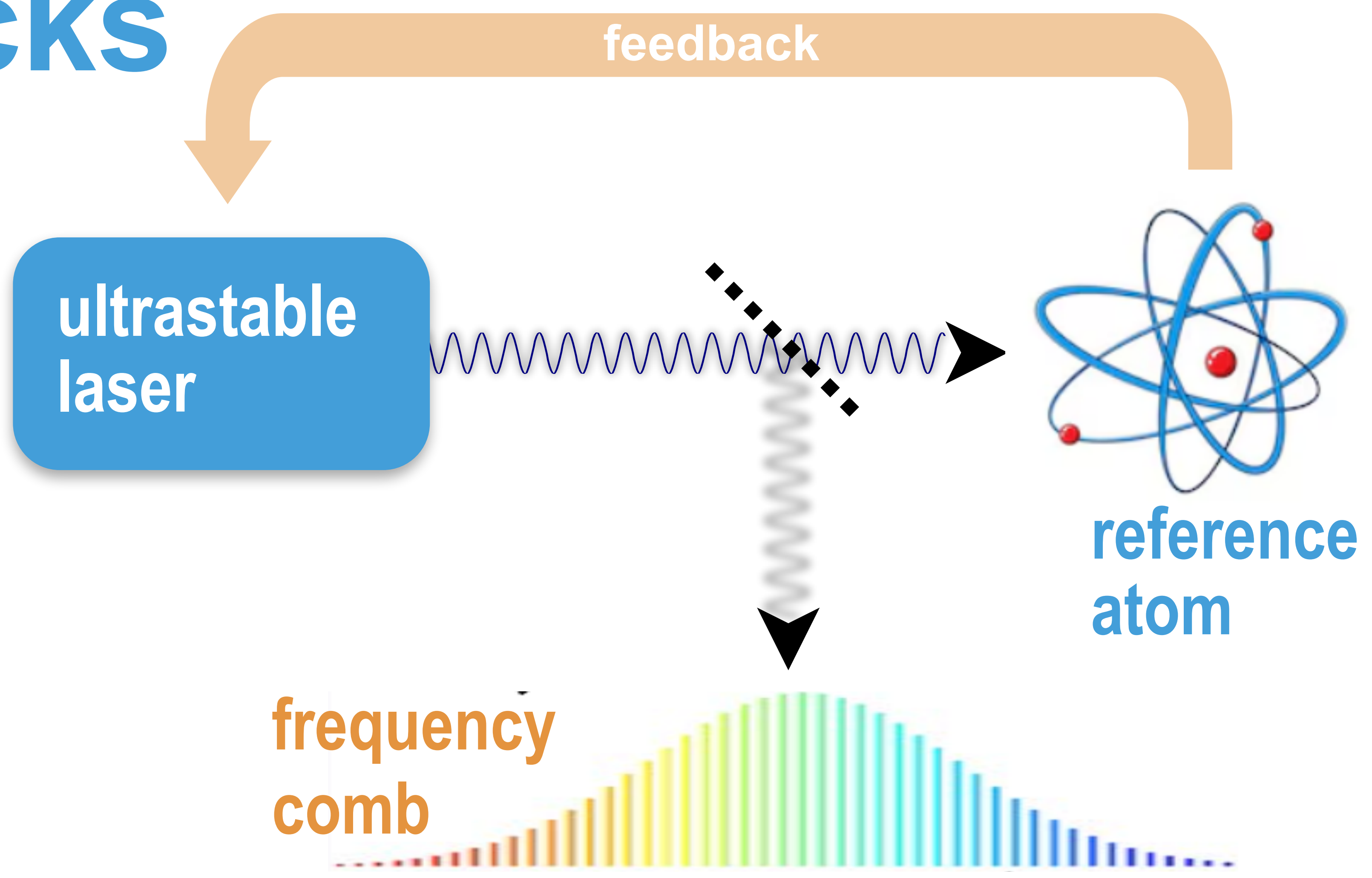




**Nuclear magnetic resonance**

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

$10^{-14}$ eV $< m_a <$ $10^{-7}$ 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. $\alpha$, 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 $\alpha$ or $\mu$ given by $K_\alpha$ and $K_\mu$
- Search for variation in $\alpha$: 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

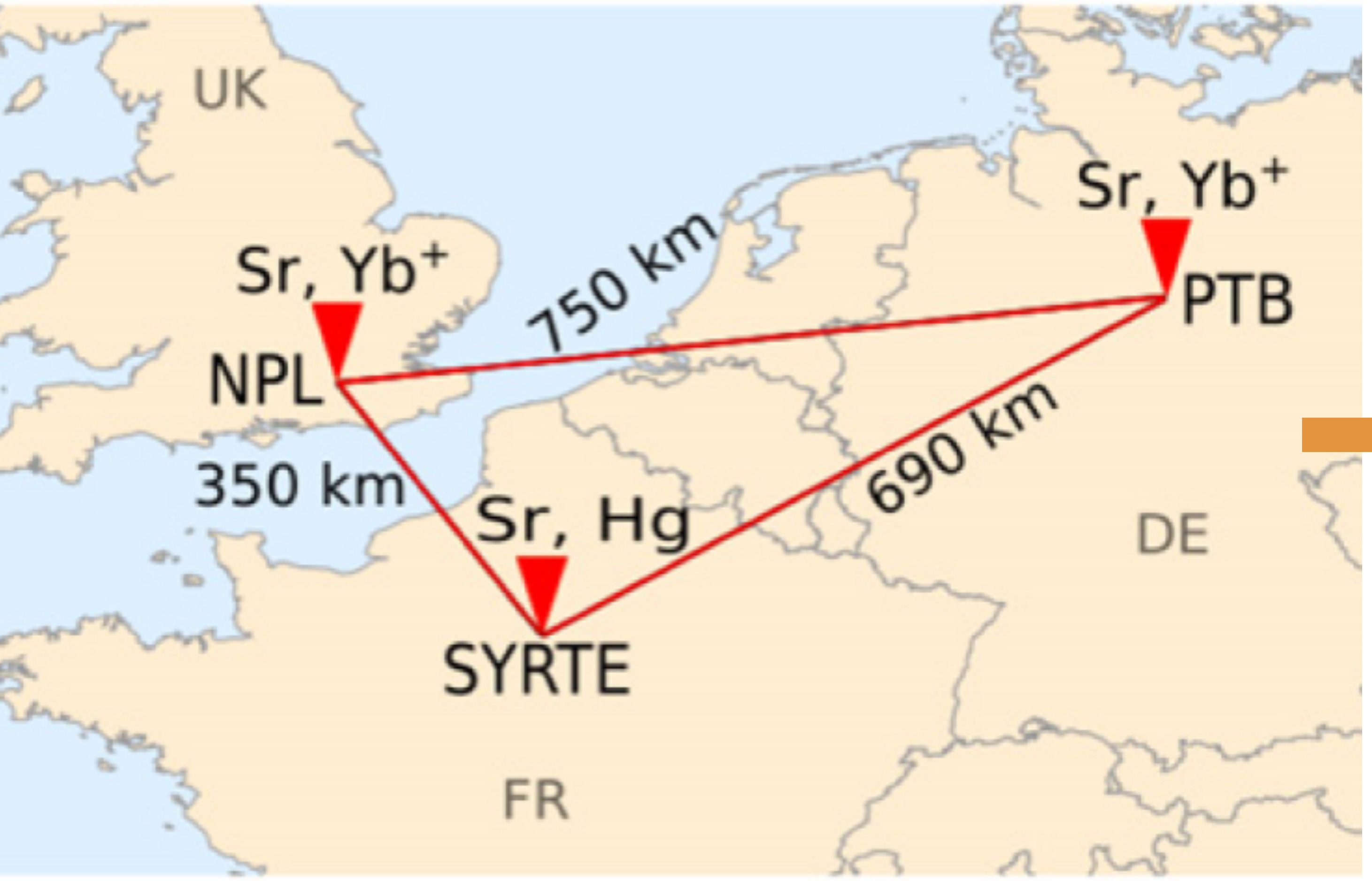
Clocks proposed for QSNET

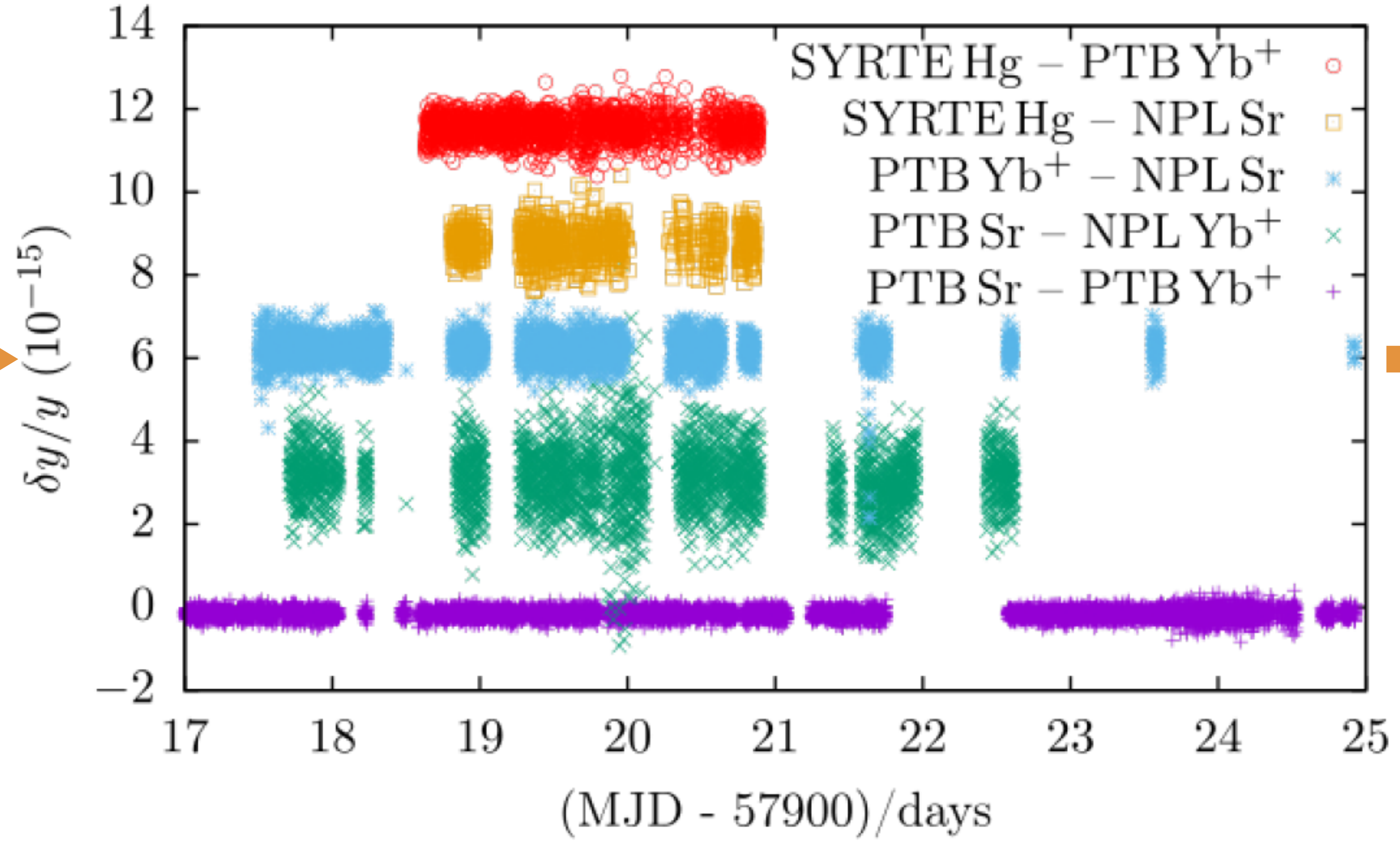
| Clock | Kα | Kμ |
|---|---|---|
| $Yb^+$ (467 nm) | -5.95 | 0 |
| Sr (698 nm) | 0.06 | 0 |
| Cs (32.6 mm) | 2.83 | 1 |
| CaF (17 μm) | 0 | 0.5 |
| $N_2^+$ (2.31 μm) | 0 | 0.5 |
| $Cf^{15+}$ (618 nm) | 47 | 0 |
| $Cf^{17+}$ (485 nm) | -43.5 | 0 |

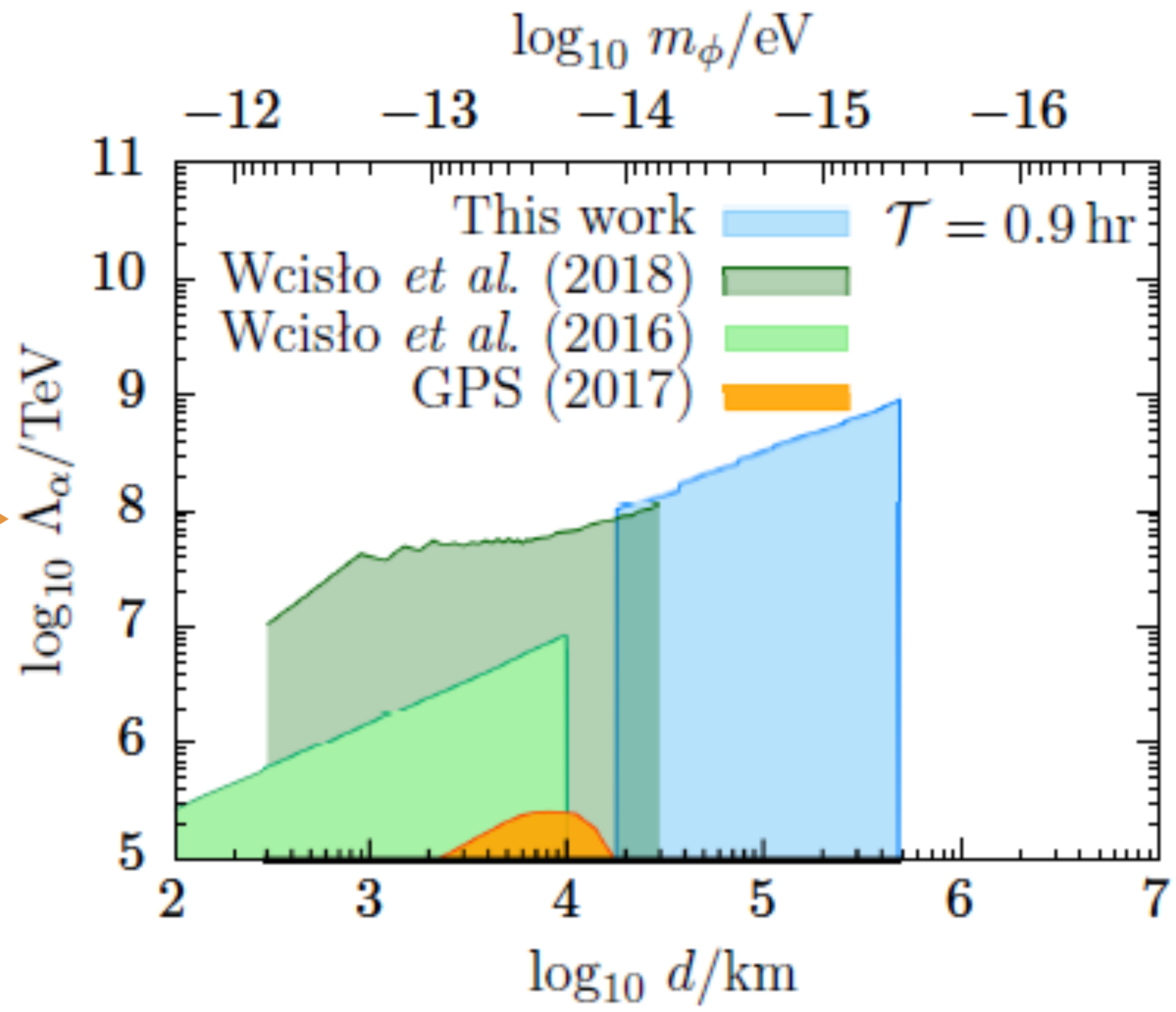
[G. Barontini et al., EPJ Quant.Technol. 9 (2022) 1; E. Peik et al 2021 Quantum Sci. Technol. 6 034002]

# 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 $\alpha$
- 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)]

# The REFIMEVE+ Network

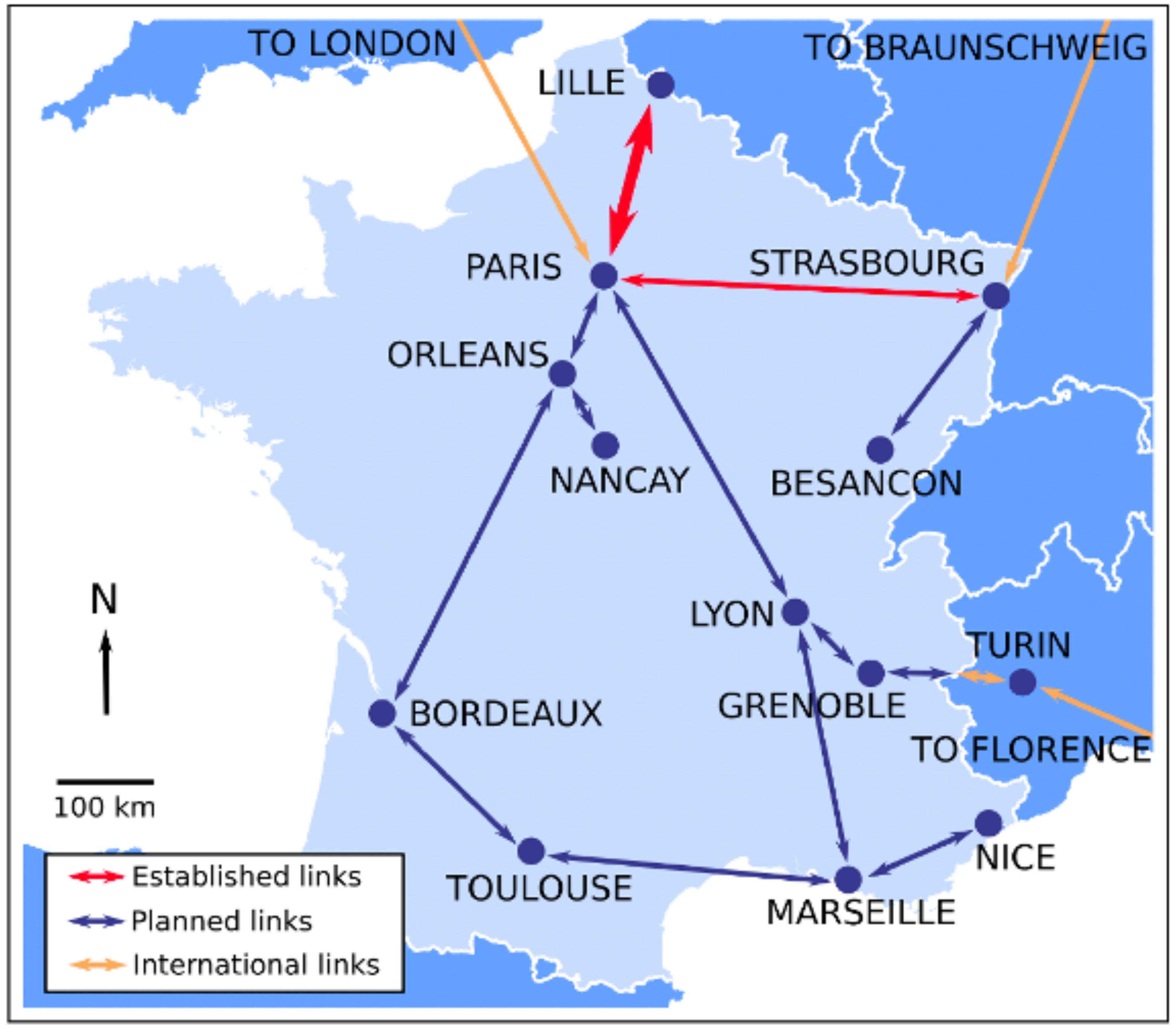



**Fig. 1.** Map of France with the REFIMEVE+ network. Red arrows: operational links. Blue arrows: planned links. Orange arrows: international cross-border links towards Braunschweig (Germany), London (UK) and Torino (Italy). In this paper, we focus on the link between Paris and Lille (thick red line).

Performance for frequency transfer (Δf/f)

- $5.4 \times 10^{-16}$ at 1s
- $1.7 \times 10^{-20}$ at 65000s (=18h)
- Accuracy: $3 \times 10^{-20}$

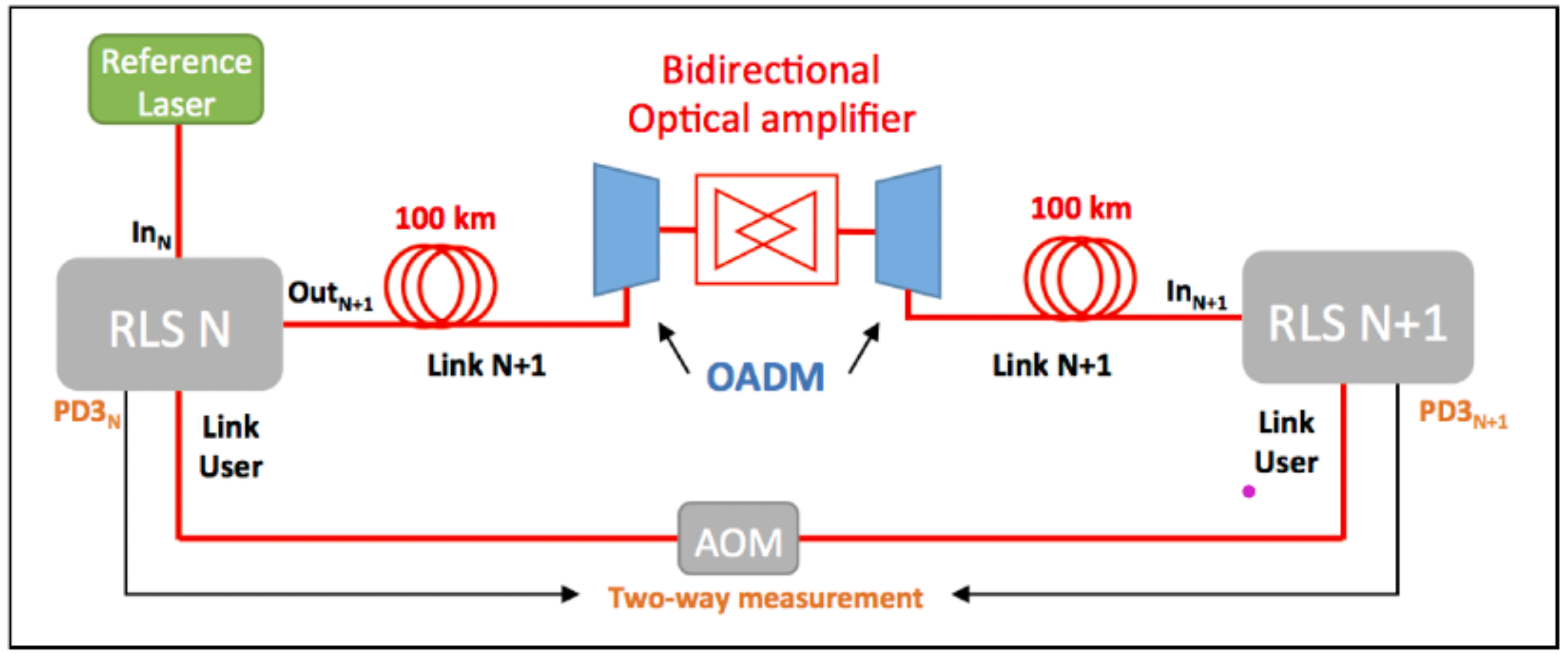



**Fig. 3.** Scheme of the testbench with a simulated link of 200 km, including two bi-directional OADMs and one bi-directional EDFA. For the noise floor measurement, the 200 km link is replaced by a short single mode fiber.

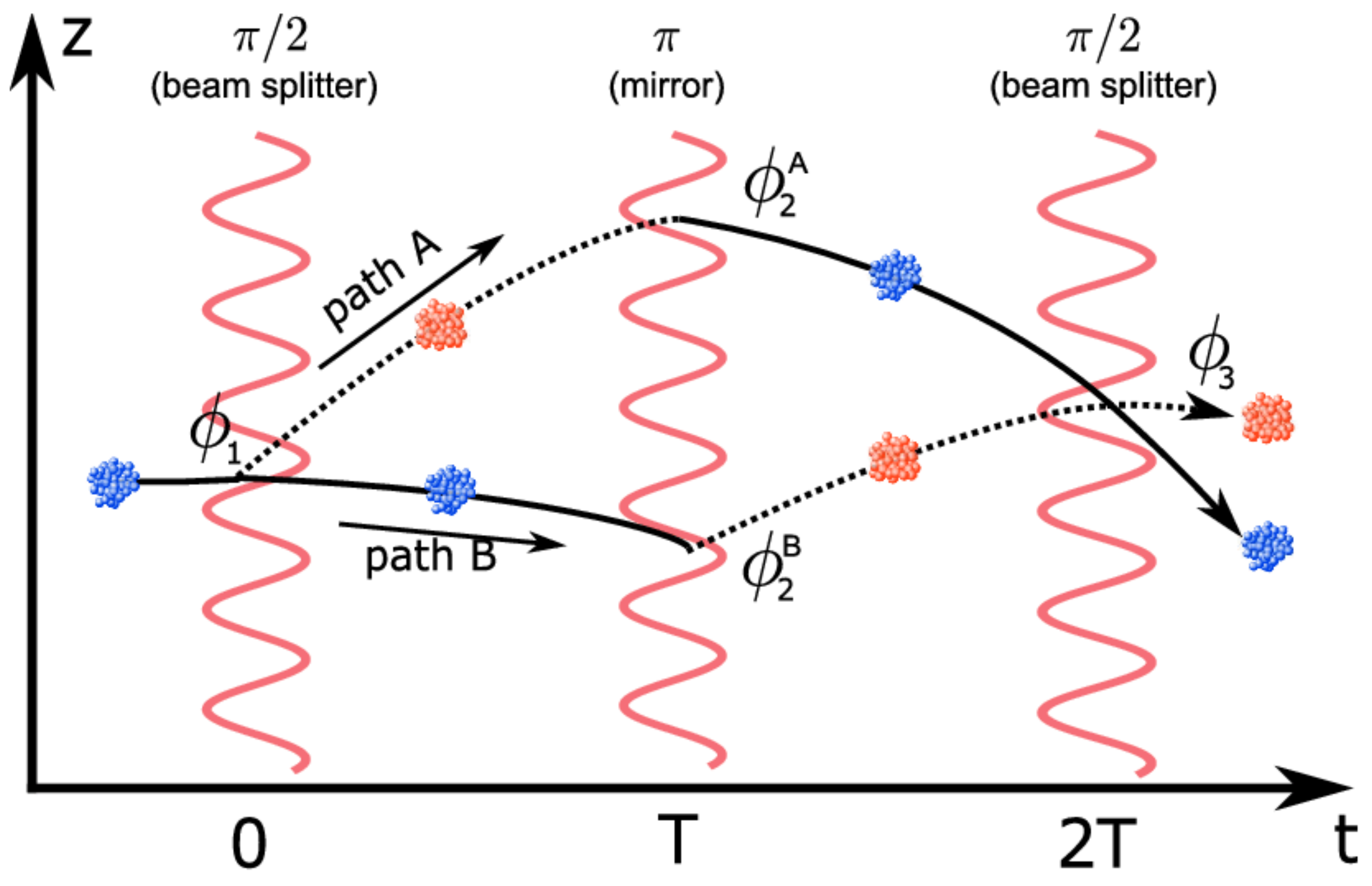
→ Muquans, CNRS/Laboratoire de Physique des Lasers, SYRTE, RENATER, Syrlinks, LP2N...

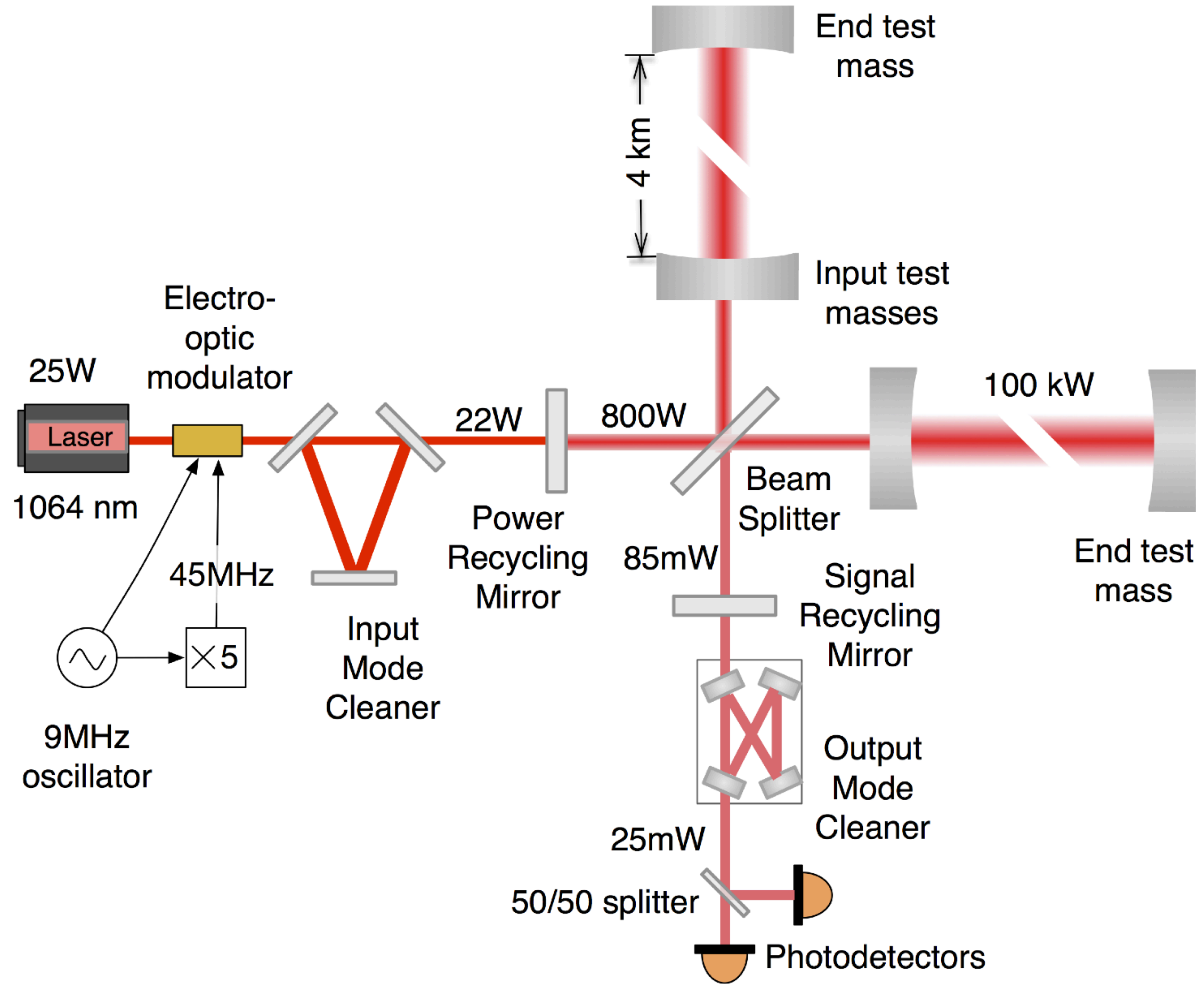


[Applied Optics Vol. 57, Issue 25, pp. 7203-7210 (2018)]

# 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.



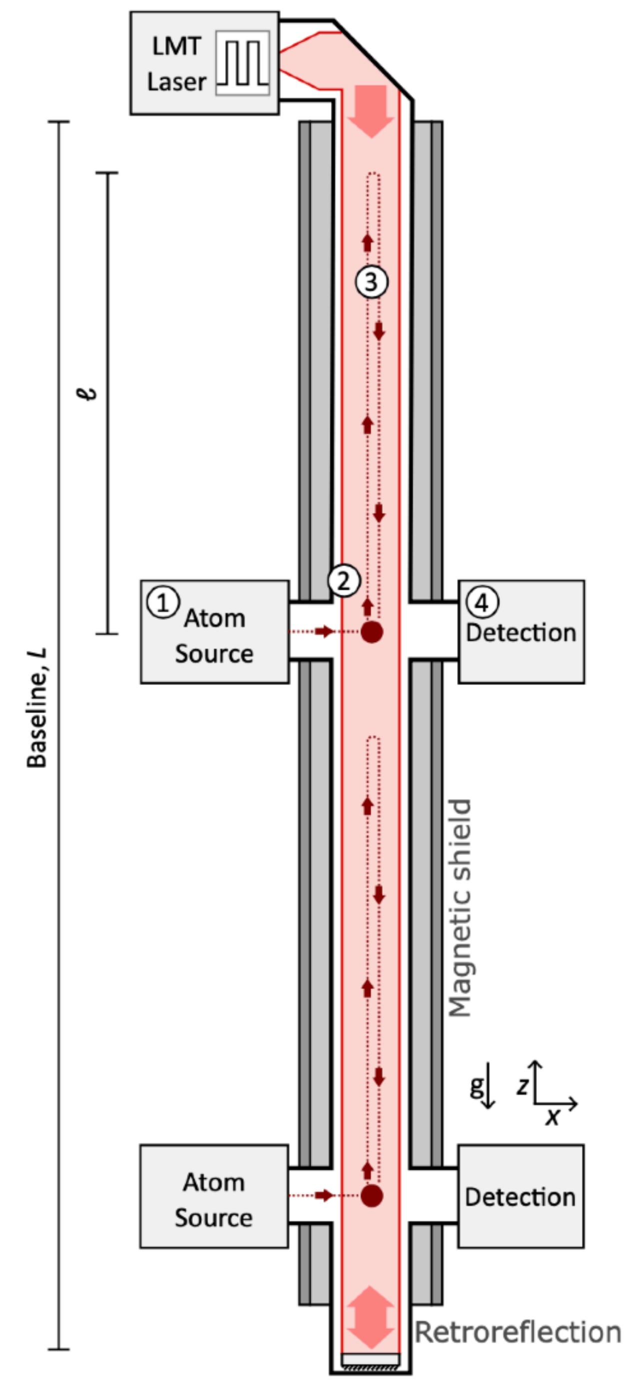





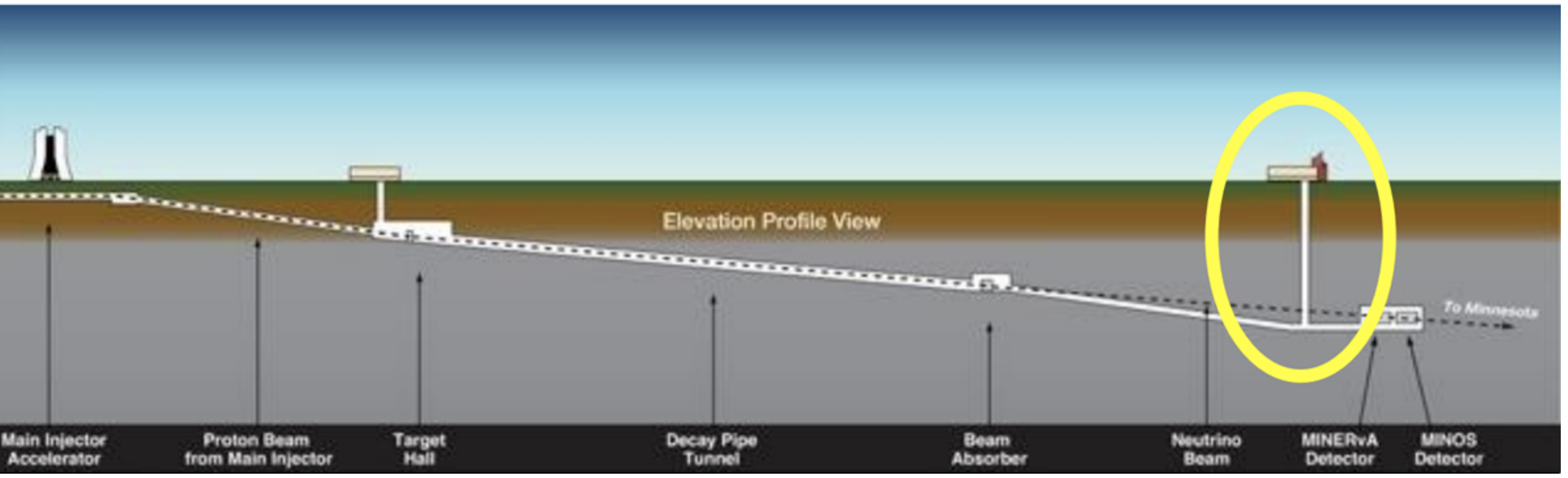

[Richmond, LIGO; Hauth et al, DOI:10.3254/978-1-61499-448-0-557]

# Long-Baseline Atom Interferometry

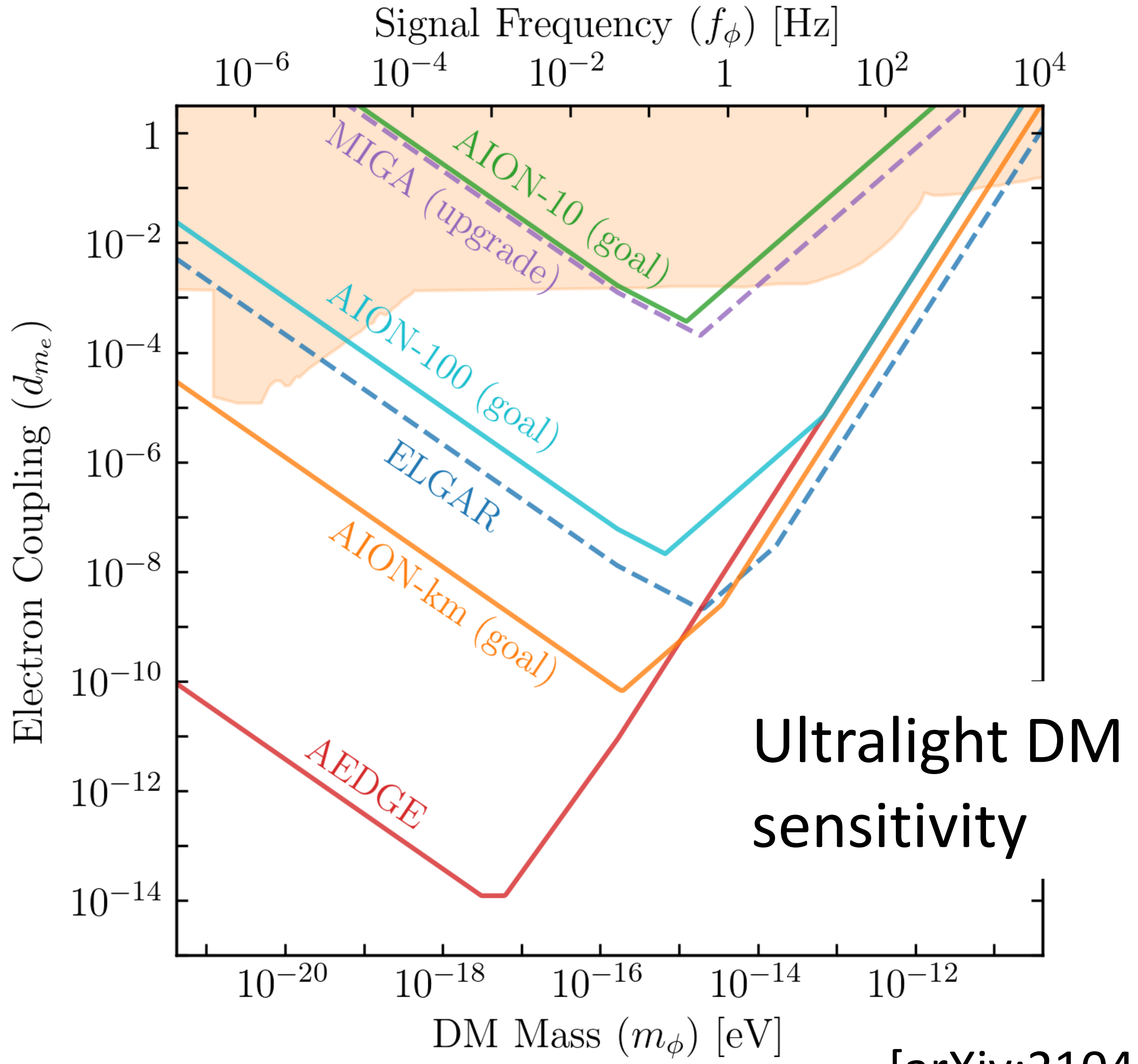
- Demonstrated at ~meter scale, proposing 100m and ultimately km (space)
  - AION: Atom Interferometer Observatory and Network
  - ELGAR: European Laboratory for Gravitation and Atom-interferometric Research
  - MIGA: Matter wave-laser based Interferometer Gravitation Antenna
  - MAGIS: Matter-wave Atomic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



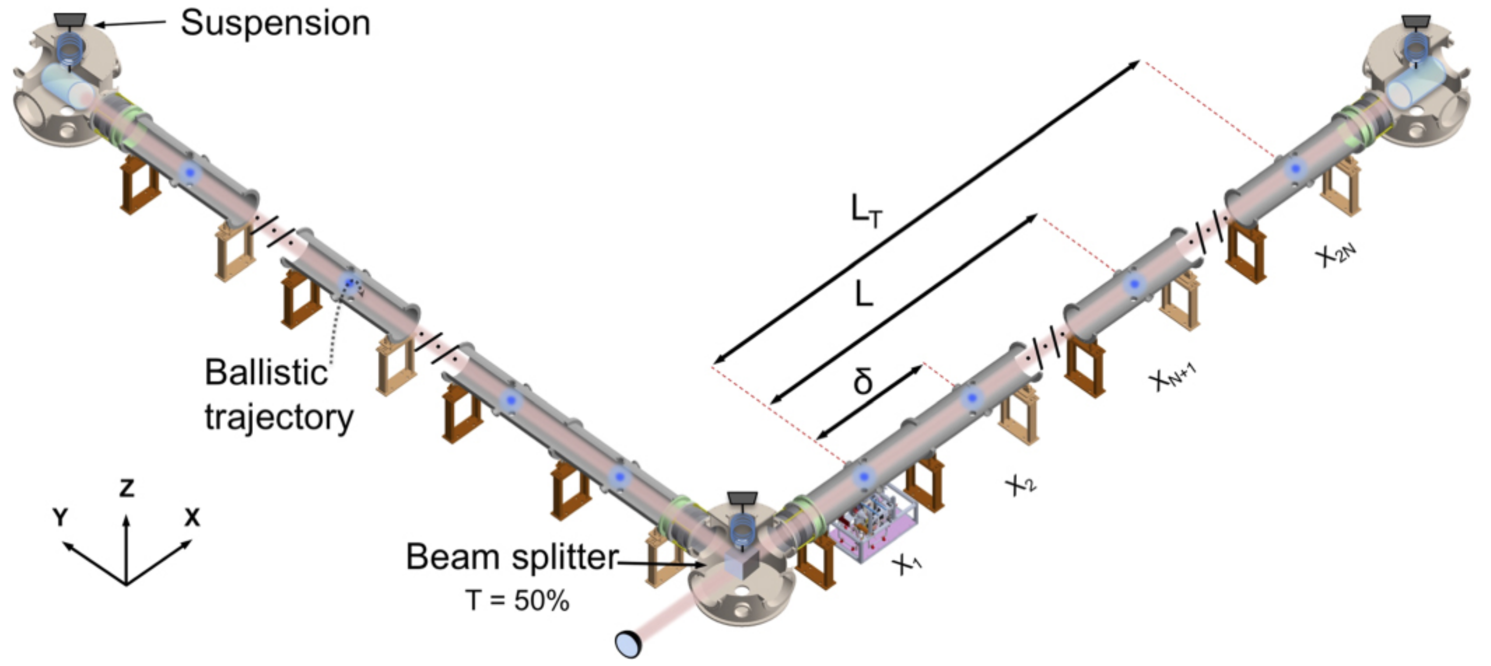

AION experiment concept




MAGIS-100 experiment concept
→ incl. Korea University




Ultralight DM sensitivity




ELGAR experiment concept
→ Univ. Bordeaux, CNRS, IOGS, LP2N



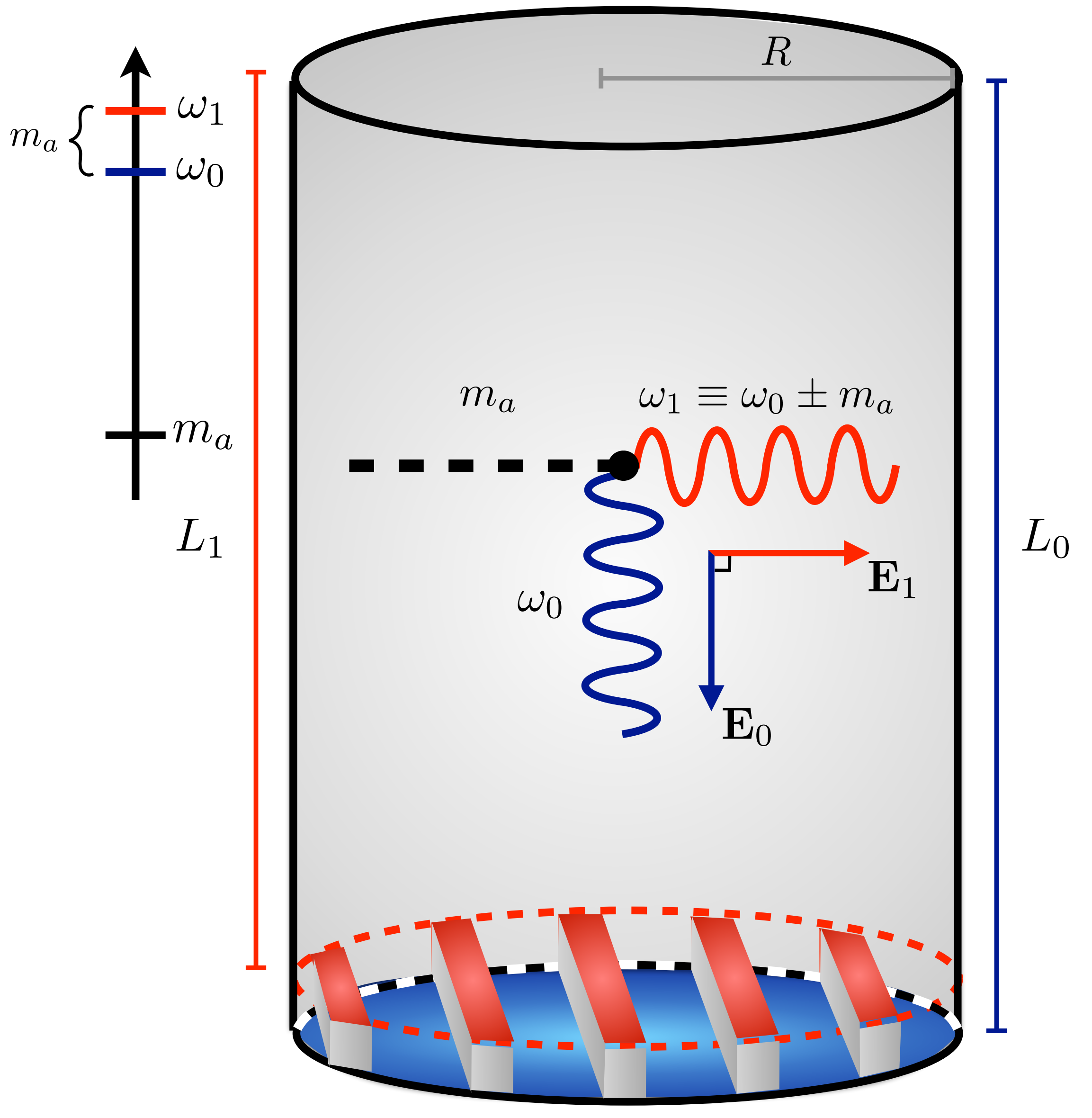
[arXiv:2104.02835, B Canuel et al 2020 Class. Quantum Grav. 37 225017]

# 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 ($V$)

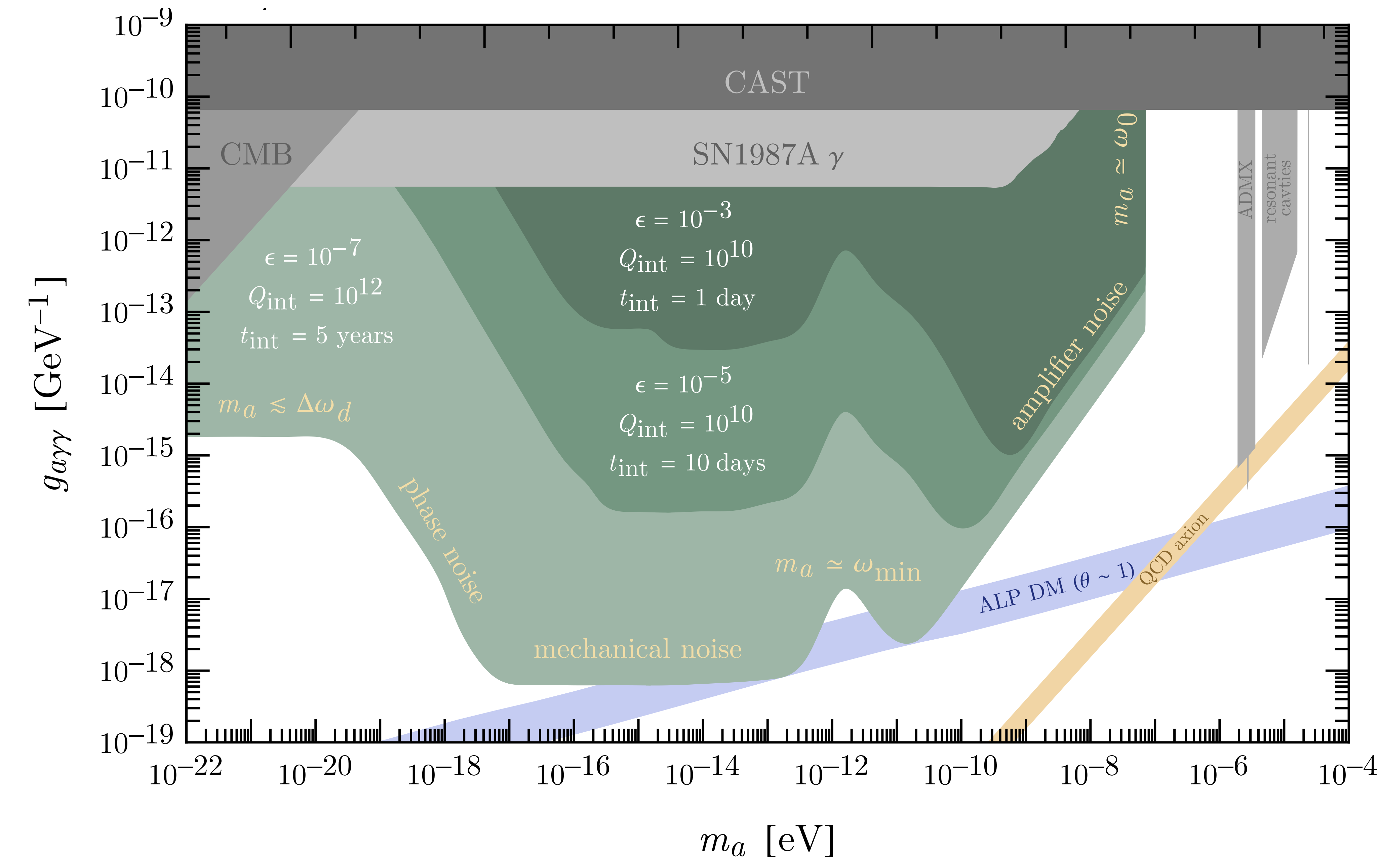
$$F \sim g_{a\gamma}^2 m_a^2 B^4 V^2 T_{sys}^{-2} G^4 Q$$

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



(a) Cartoon of cavity setup.

- 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 $\omega_0$ and $\omega_1$



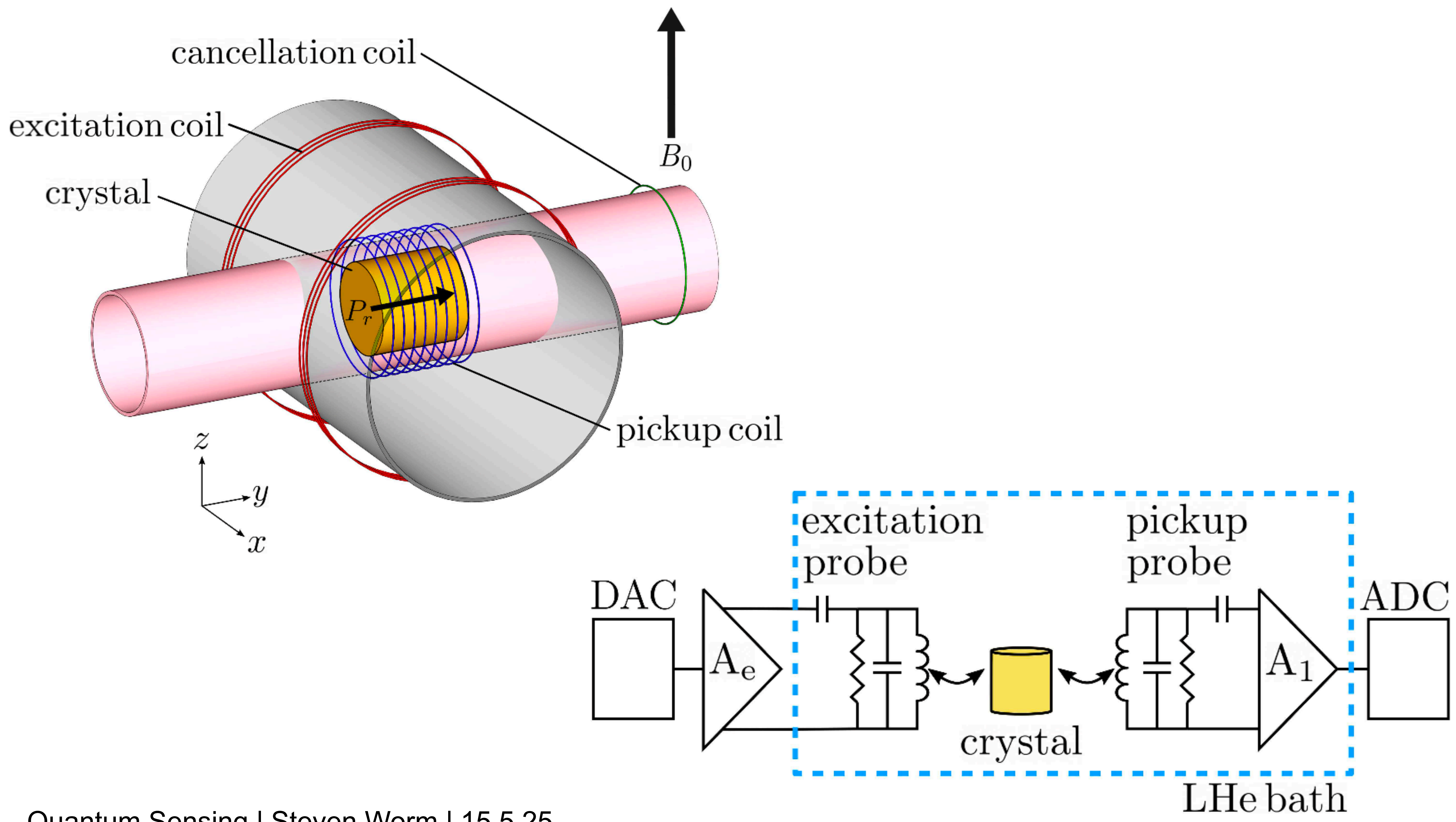

- Scan over axion masses:
  - Change of cavity geometry modulates the frequency splitting $\omega_0 - \omega_1$
  - Huge parameter space to explore, but technical (cryo) challenges

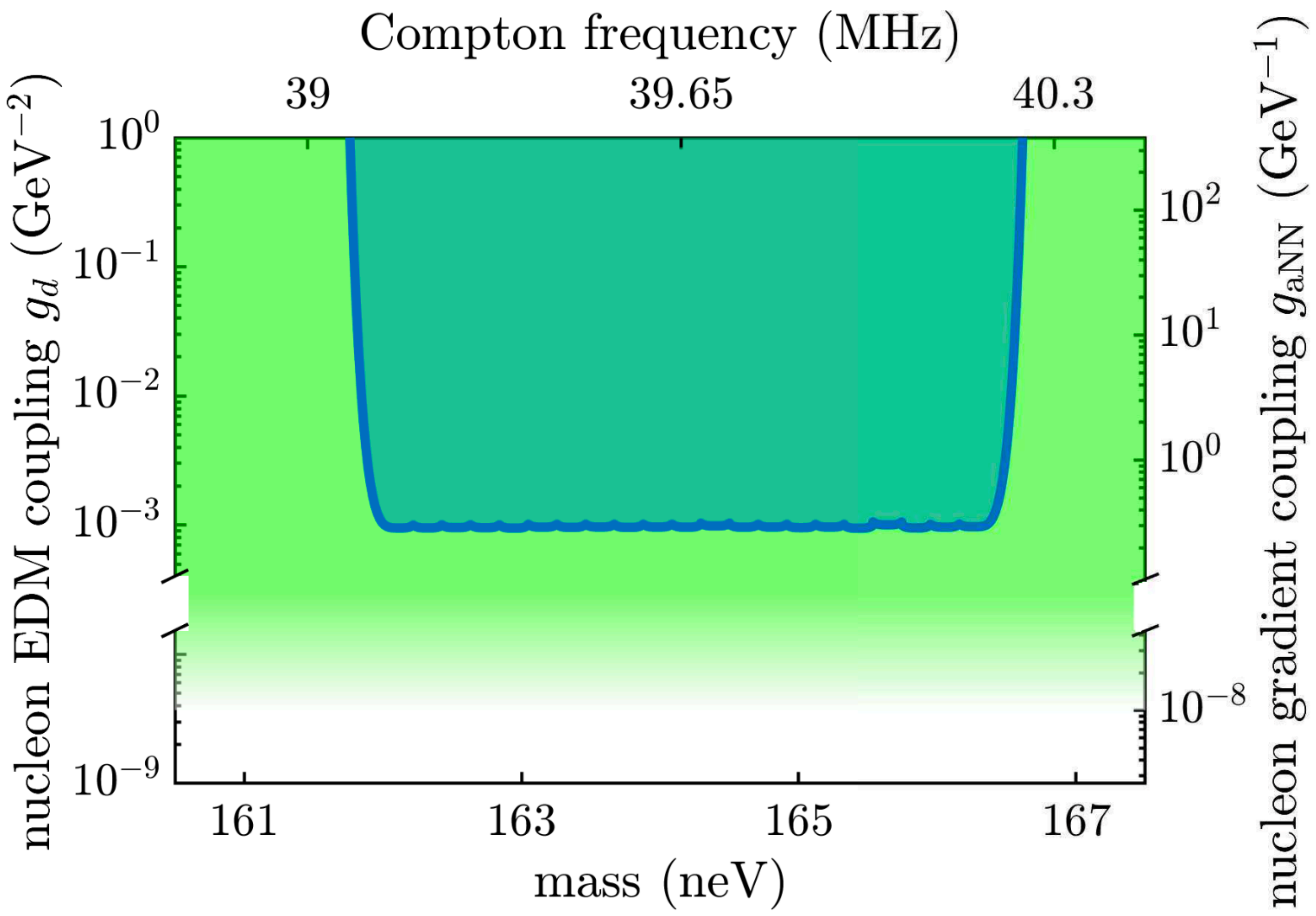
→ see also KAIST (CAPP/DMAG) also KEK...

[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

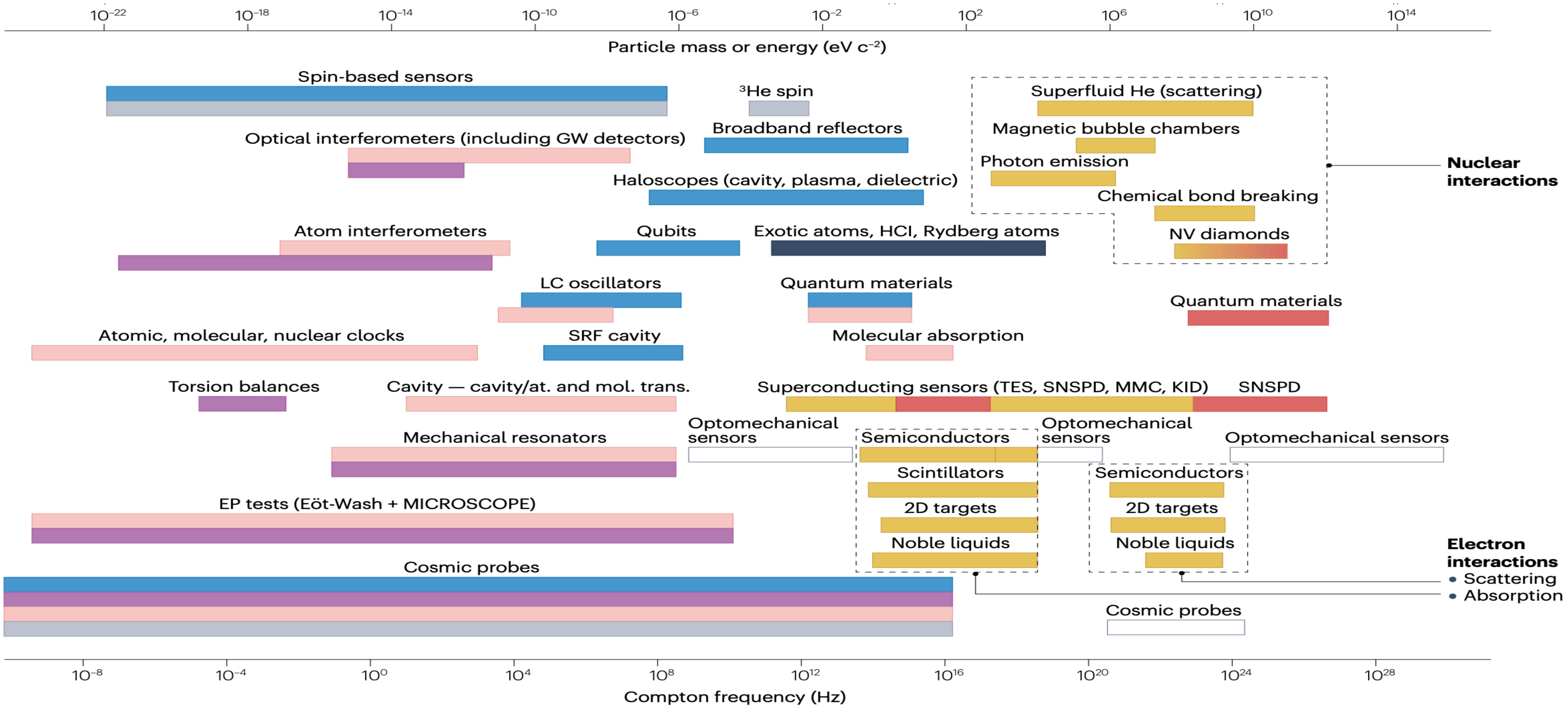





[D. Aybas et al., Phys. Rev. Lett. 126, 141802]

# Quantum Sensing Techniques for Dark Matter




Specific dark matter (DM) candidates:

- Scalar bosons
- Vector bosons (gauge coupling)
- Vector bosons (kinetic mixing); pseudoscalar (axion–photon coupling)
- Pseudoscalar (other)
- Precision tests of QED and spectroscopic BSM searches
- Enhanced sensitivity and functionality for HEP detectors
- Light DM detection by electron or nuclear scattering or absorption
- Other light DM detection (annihilating, decaying, fifth-force coupling, phonon scattering)



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

# RDquantum

# DRD5

## >100 Institutes

Norway: Oslo University

Netherlands: U. of Groningen

UK: Oxford University
Univ. of Warwick
Univ. of Birmingham
NPL
Imperial College
Univ. of Southhampton
Univ. of Sussex

France: IRFU / CEA Saclay
SYRTE / OBSPM
CNRS - U. Sorbonne Paris Nord
LKB
ILM - University Lyon 1

Canada: McGill Univ.
TRIUMF

USA: UCLA
ORNL
Northwestern Univ.
Caltech
MIT
Arizona State Univ.
Yale
Univ. of Arizona
NIST
LBNL
Univ. of Delaware
FNAL
SLAC

Mexico: U. de Aguascalientes

Spain: U. de Zaragoza
U. de Cartagena
U. de Valencia
U. de Lleida

Switzerland: U. of Geneva
U. of Zürich
CERN
ETHZ

Germany: PTB
Univ. Ulm
Leibnitz Univ. Hannover
KIT, Karlsruhe
TU München
DESY
MPP Garching
HU Berlin
FBH Berlin
Univ. Heidelberg
Univ. Tübingen
Univ. Düsseldorf
Univ. Mainz
Univ. Bremen / ZARM
Semiconductor Lab HLL / MPG
TU Darmstadt

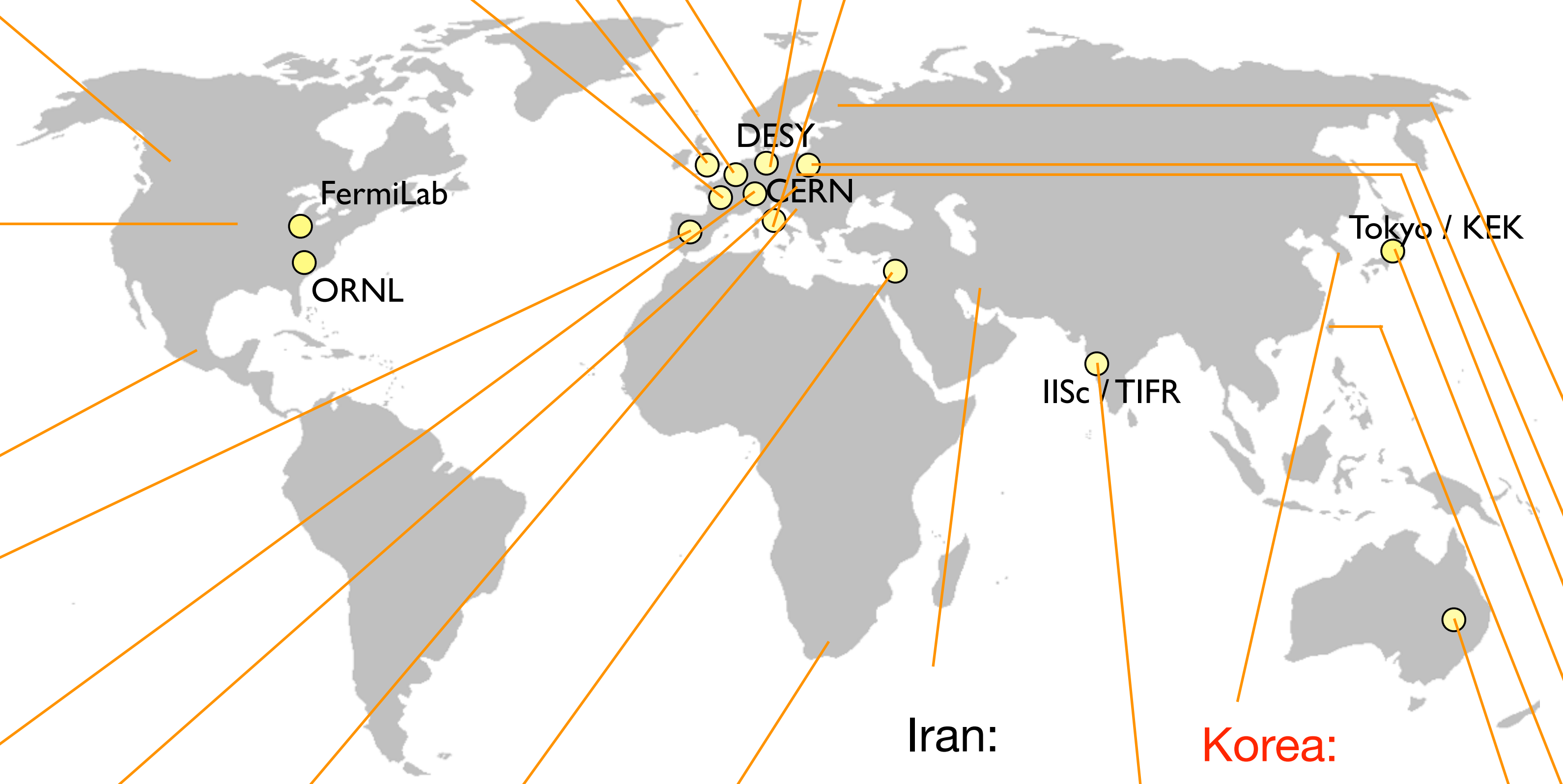
Italy: U. of Pisa & INFN
U. of Pavia
U. of Firenze
U. of Milano-Bicocca
Fondazione Bruno Kessler, Trento
IOM CNR, Elettra Sincrotrone, Trieste
Univ. of Bari / INFN
INFN Padova
Univ. Roma 1 & 3
Univ. Napoli
INFN Roma Tor Vergata
INFN LNF
INFN Trento (TIFPA)
INFN Torino
INFN LNL
INFN Lecce
INFN Roma Tor Vergata
U. of Camerino

Finland: Helsinki Inst. of Physics
VTT

Poland: Warsaw TU
Nat. Centre Nucl. Research / Warsaw
Nat. Lab. FAMO / Torun

Czech Republic:
Czech Tech. University
University West Bohemia

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




Iran:
Isfahan U. of Tech.

Korea:
Korea University

Austria:
IQOQI Vienna

Israel:
Technion, Haifa

India:
IITTP, Tirupati
IISER, Kolkata
TIFR, Mumbai
University SOA Bhuvaneswar

Australia:
University of Western Australia
Swinburne University of Technology

Croatia:
Inst. of Physics, Zagreb

South Africa:
U. of Cape Town

Taiwan:
Academia Sinica & NTU

# 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***

***Many connections to France, Korea, Japan already listed, also Christophe Dujardin WP-2 co-leader, Shion Chen sub-WP leader for WP-3, Su-Yong Choi from Korea University on MAGIS-100 (WP1)…***

## Contact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