

Quantum Sensing for Particle Physics

57th Herbstschule HEP

Physikzentrum Bad Honnef

Steven Worm

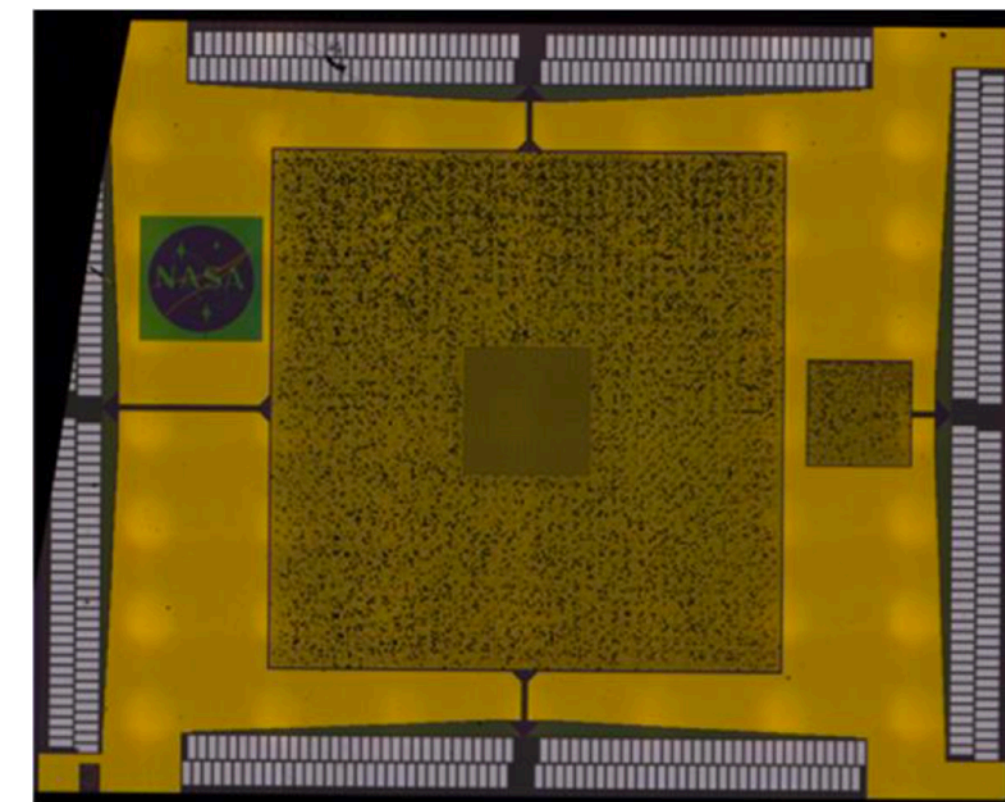
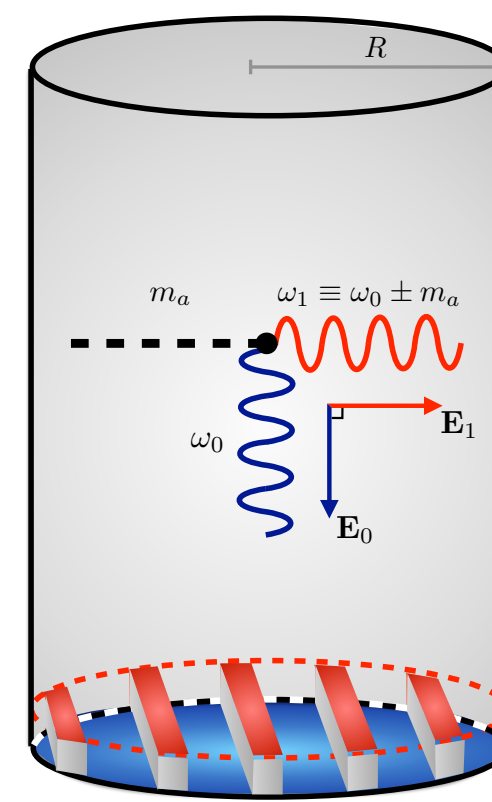
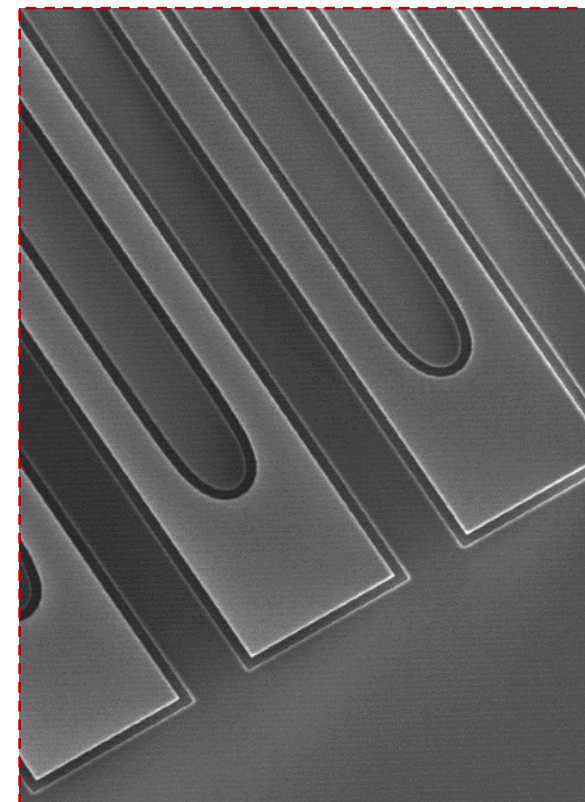
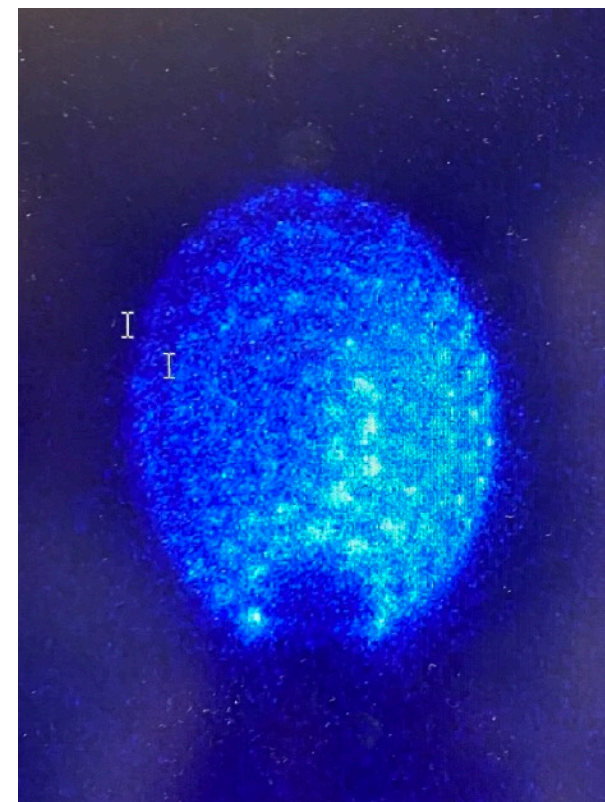
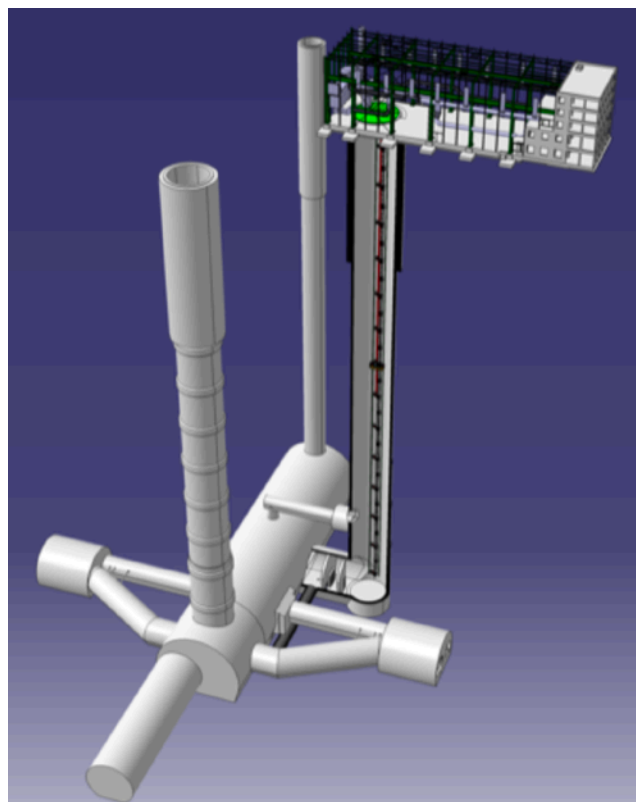
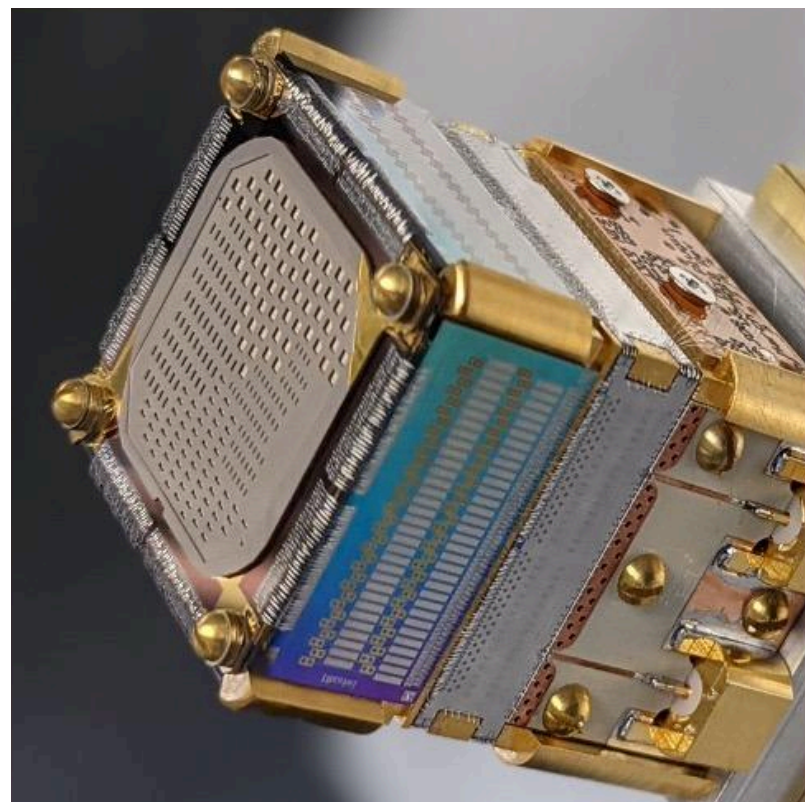
Deutsches Elektronen-Synchrotron (DESY) / Humboldt-Universität zu Berlin

September 8, 2026



DESY.
QUANTUM

Center for
Quantum Technology
and Applications



Quantum Sensing for Particle Physics – Outline

Tuesday Sept. 8, 9:00

- Quantum Sensing:
 - What it is, and why you should be interested
 - Selected cryogenic sensors: TES, MMC, SNSPD
 - Quantum dots and other quantum sensing ideas

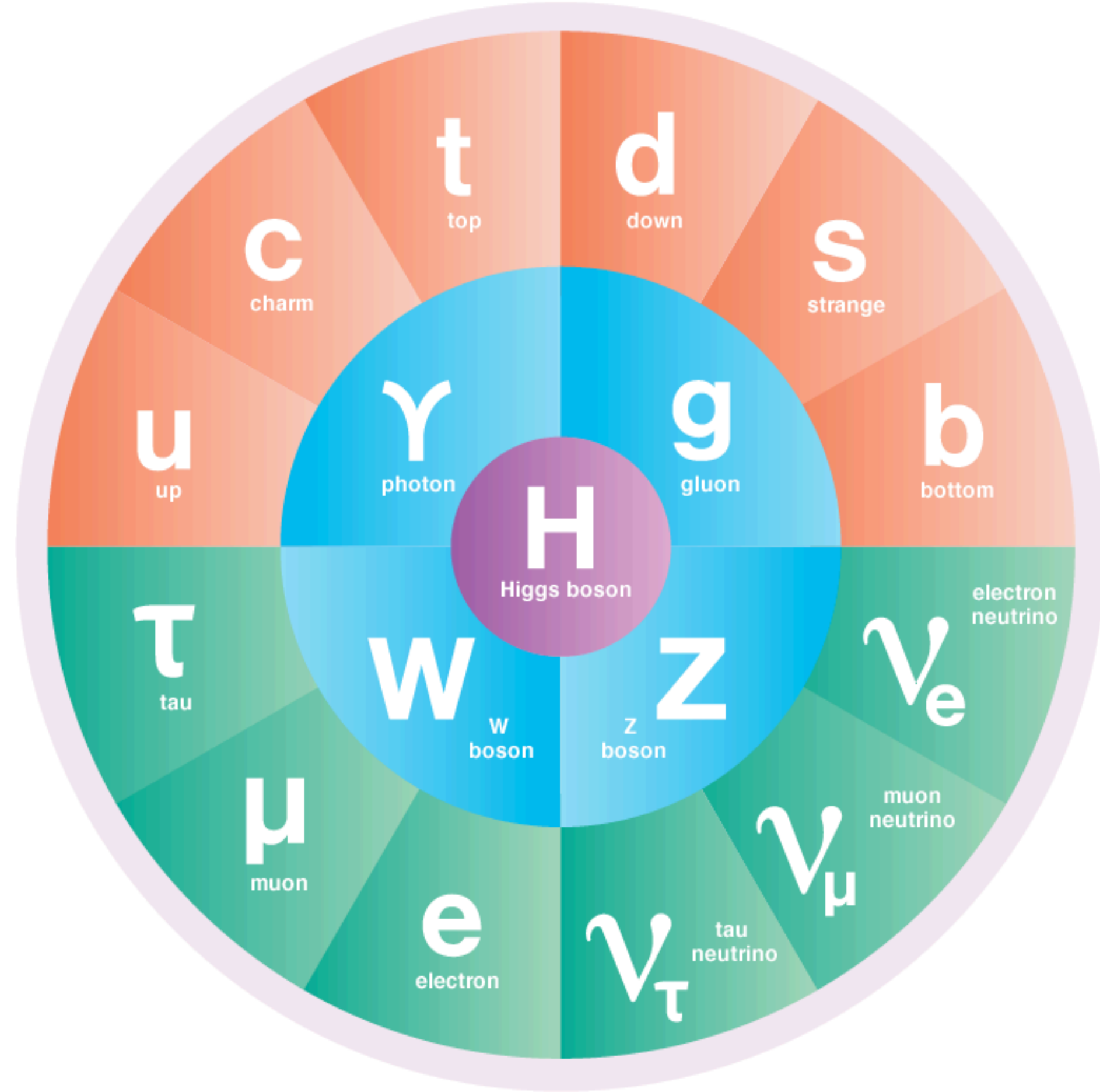
Wednesday Sept 9, 10:10

- Quantum Experiments:
 - A new path to discovery
 - The search for light Dark Matter
 - Fundamental physics and the variation of fundamental constants

Thursday Sept. 10, 11:20

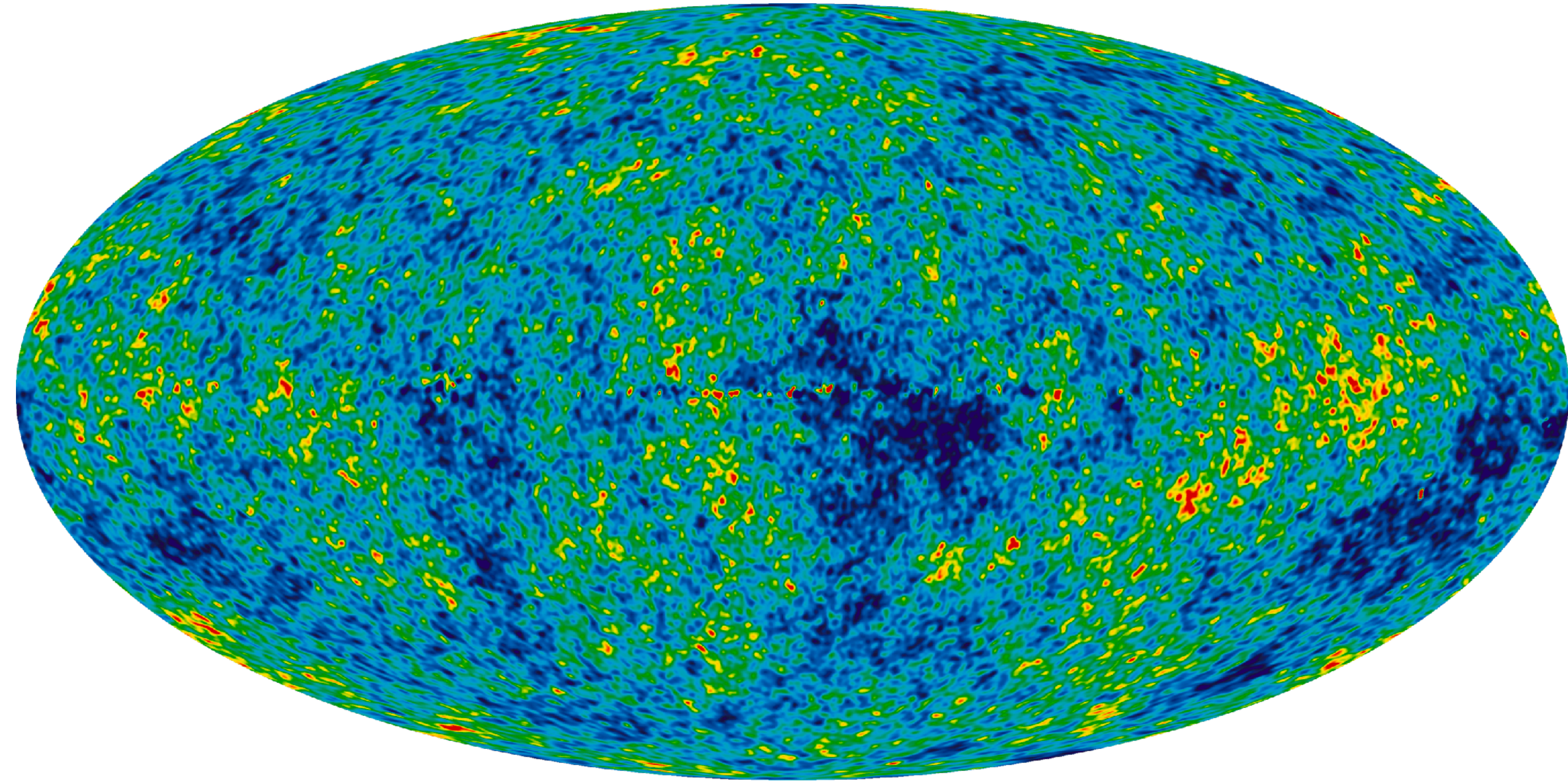
- Quantum in the lab: searching for Dark Matter with an Atomic Clock(!?)
 - Practical considerations and headaches
 - The path from data to discovery
 - Ideas for the future

Standard Models of Particles and Cosmology



Particle Standard Model

- Fundamental particles
- Forces, interactions



Cosmological Standard Model (Λ CDM)

- Cosmic microwave background
- Structure of galaxies, amount of H, He, Li
- Accelerating expansion of the universe

A Question of Scale?

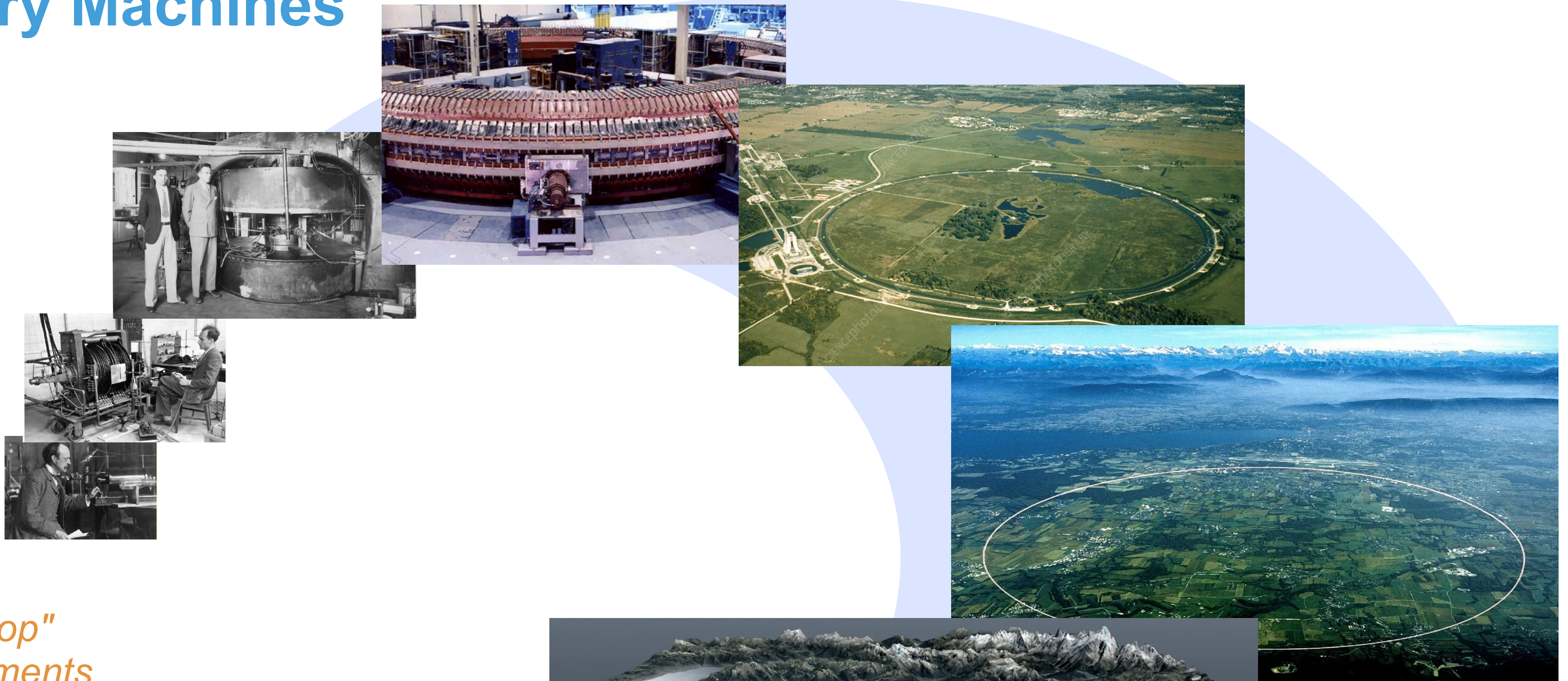
- The Standard Model is incomplete... many questions to answer
 - Baryon Asymmetry
 - Dark Energy
 - Dark Matter
 - Electroweak phase transition
 - Hierarchy problem
 - Neutrino masses
 - Strong CP problem
- Maybe the answers are hiding at a different scale?
 - 1900: Atomic scale $\approx 10^{-8}$ cm $\rightarrow$ Quantum Mechanics, Electrodynamics
 - 1950: Strong interaction scale $\approx 10^{-13}$ cm $\rightarrow$ QCD, Quarks, Gluons
 - 2010: ElectroWeak/TeV scale $\approx 10^{-17}$ cm $\rightarrow$ EWK phase transition, W, Z, Higgs

Search for New Physics at Higher Energies?

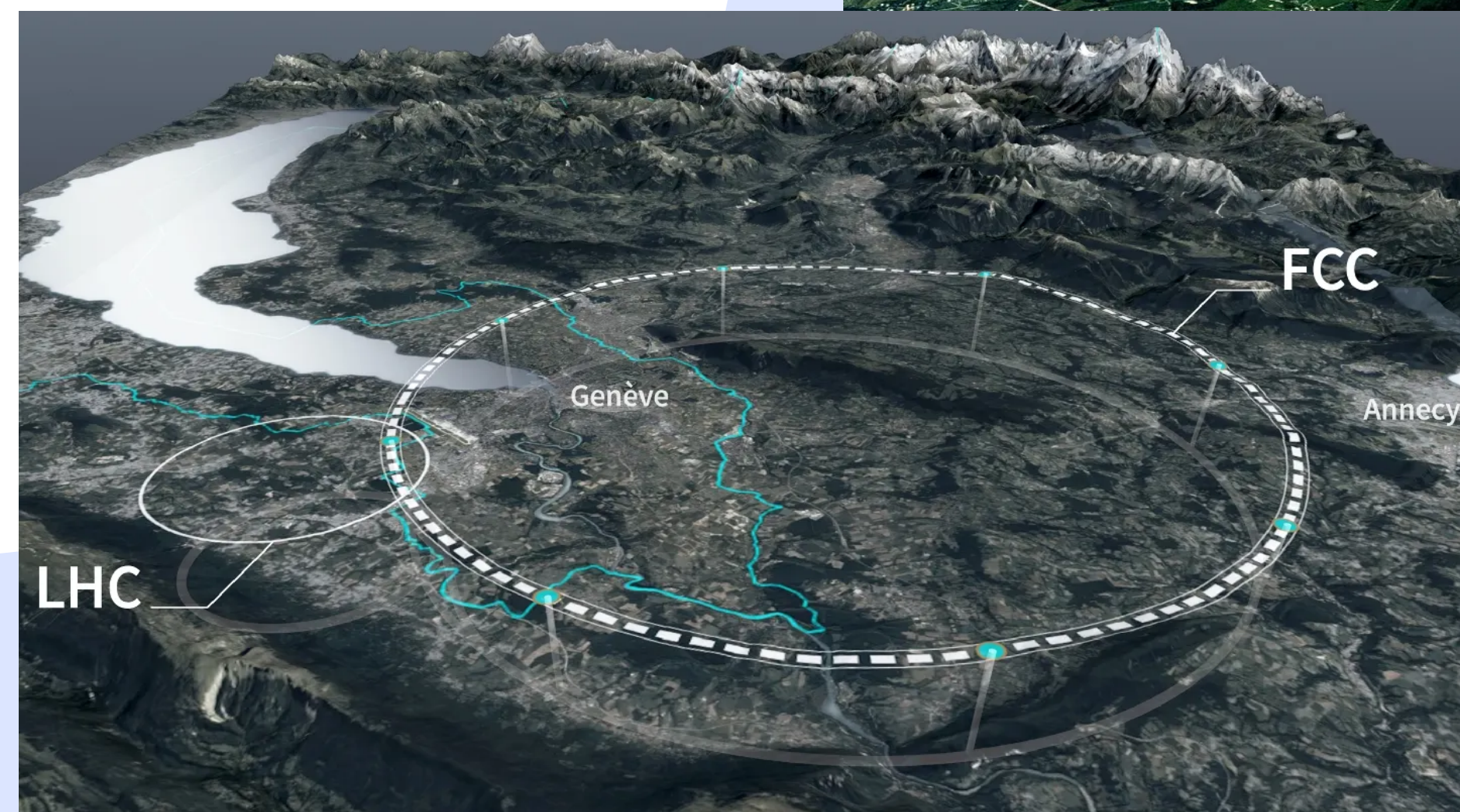
Discovery Machines & Scale



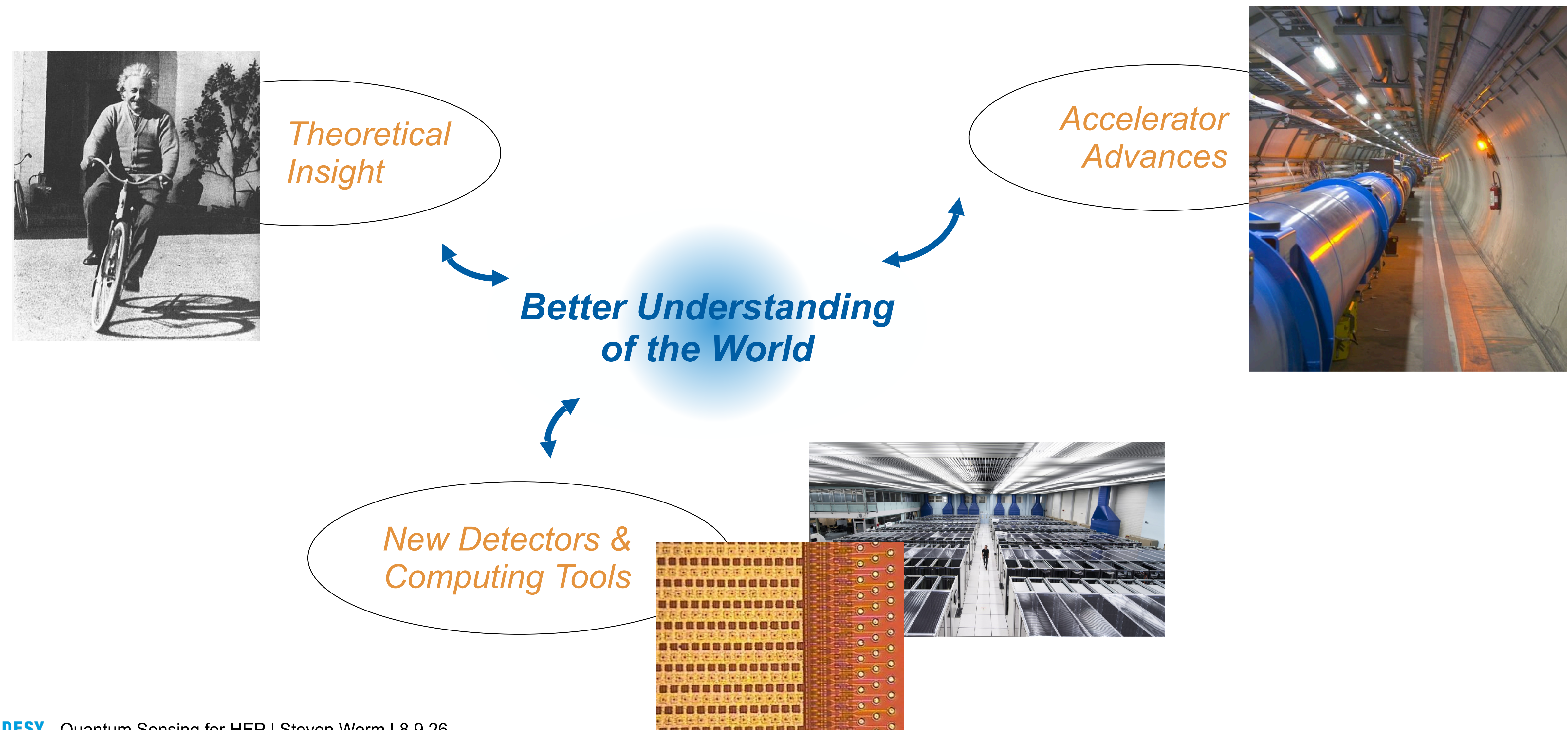
Discovery Machines & Scale



*"Tabletop"
Experiments*

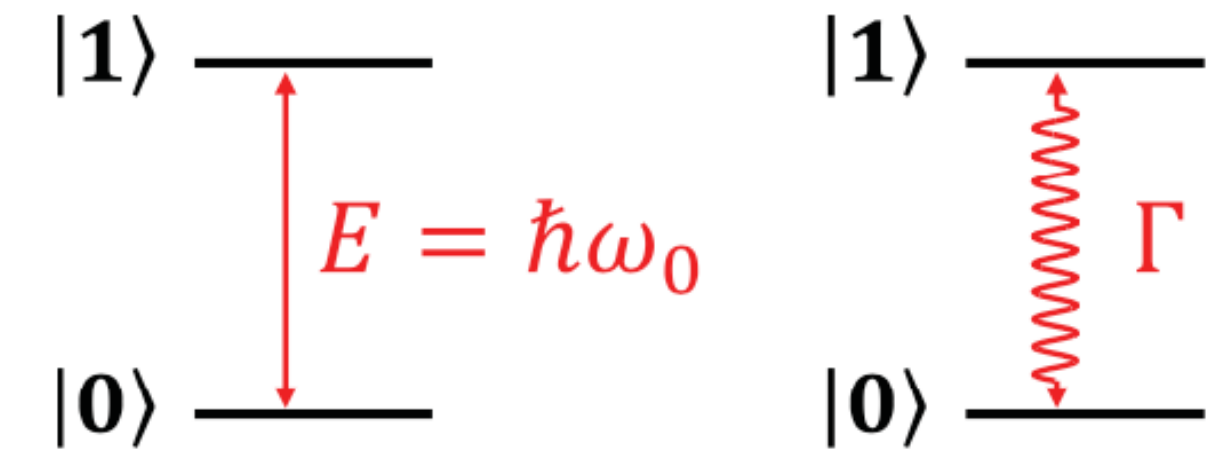


Advancements in Particle & Astroparticle Physics



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)
- 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?

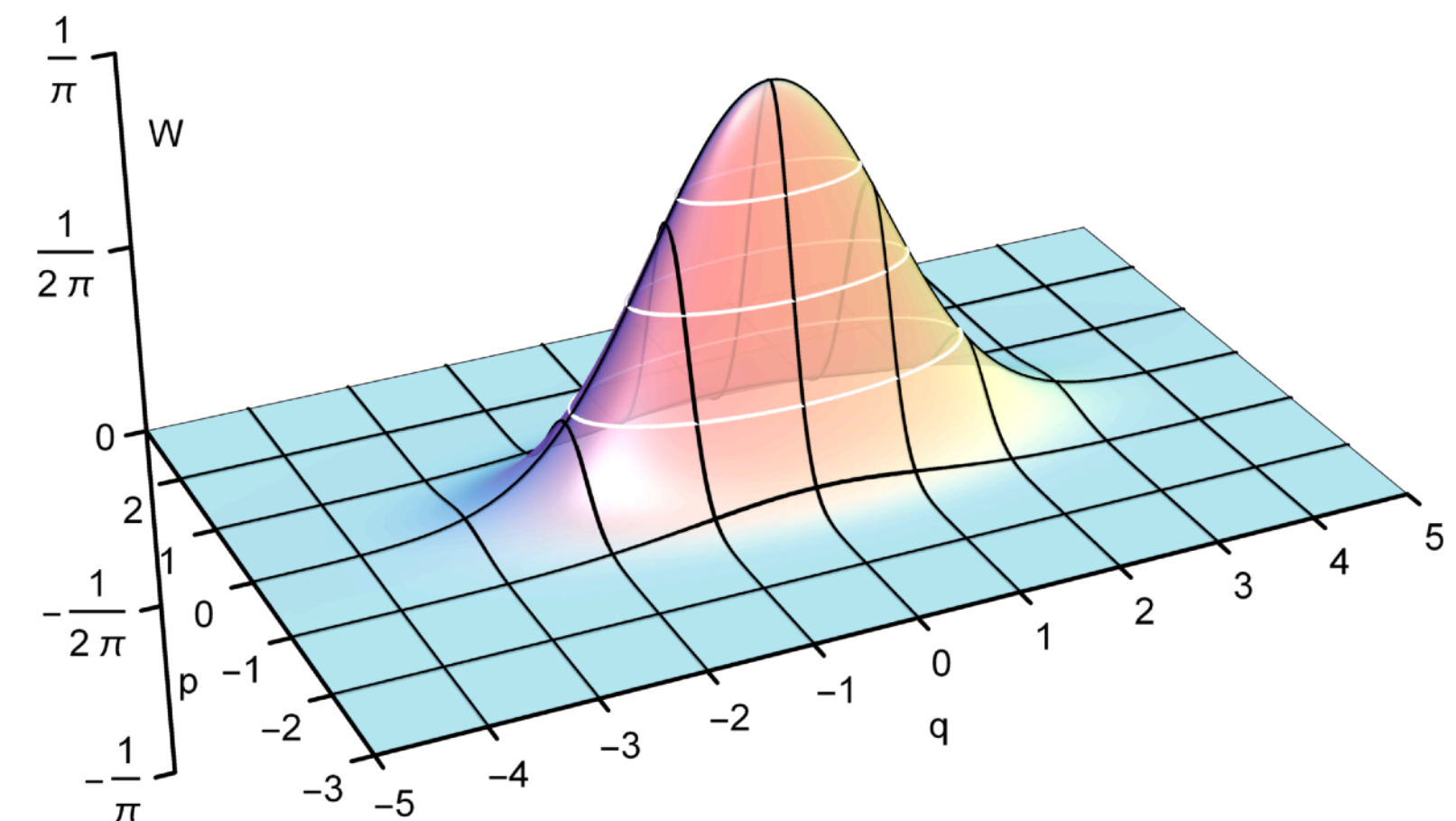
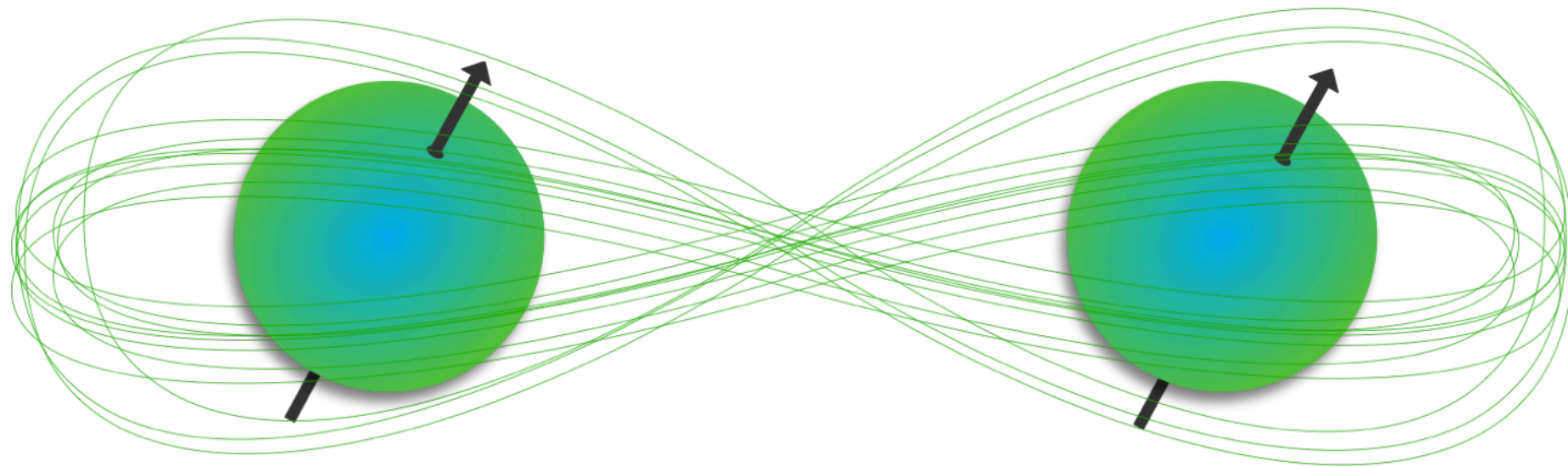
- A1: Potentially better sensitivity or noise performance
- A2: Because we have to (e.g. for ultra-light dark matter)!



- **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

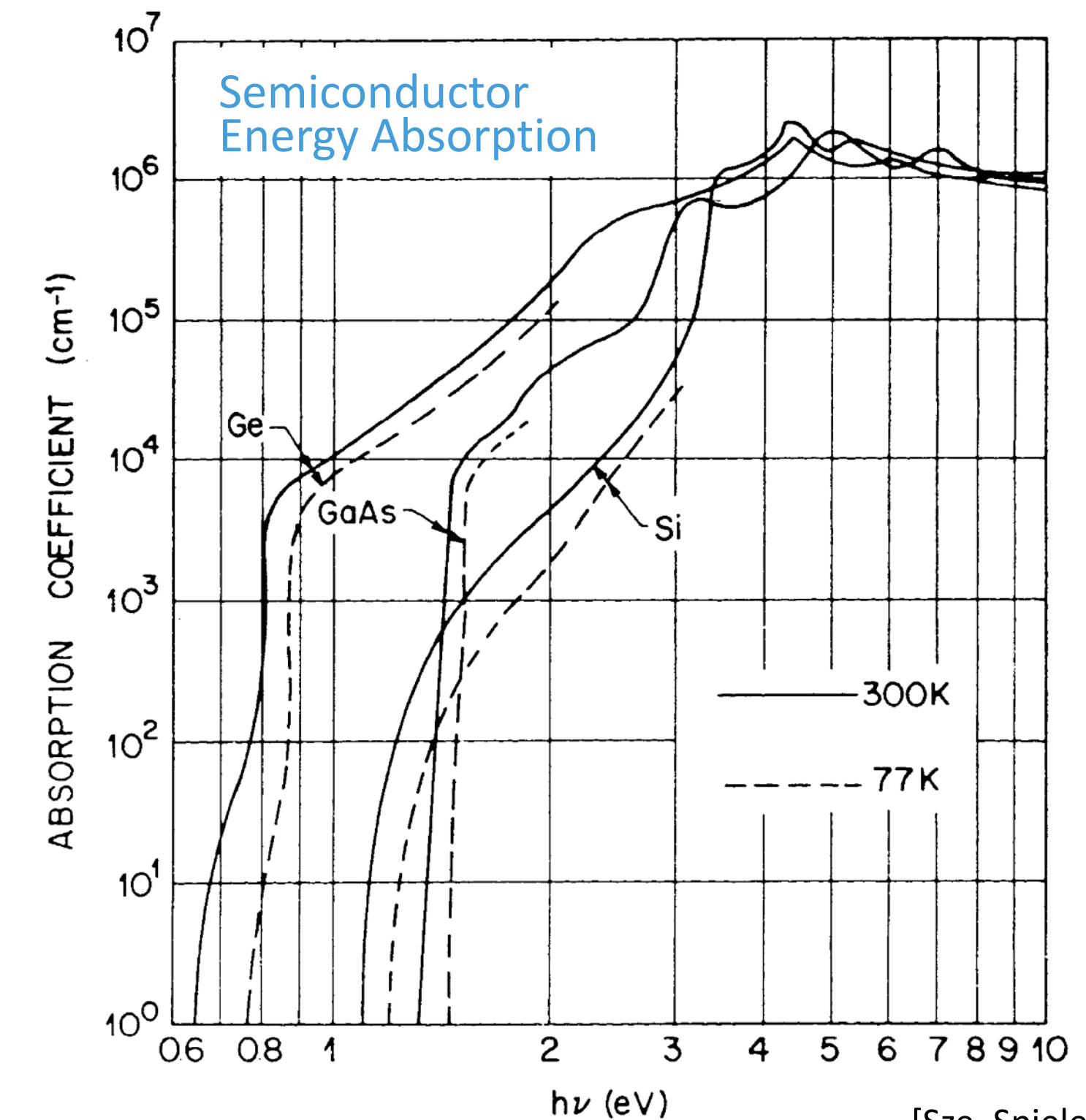
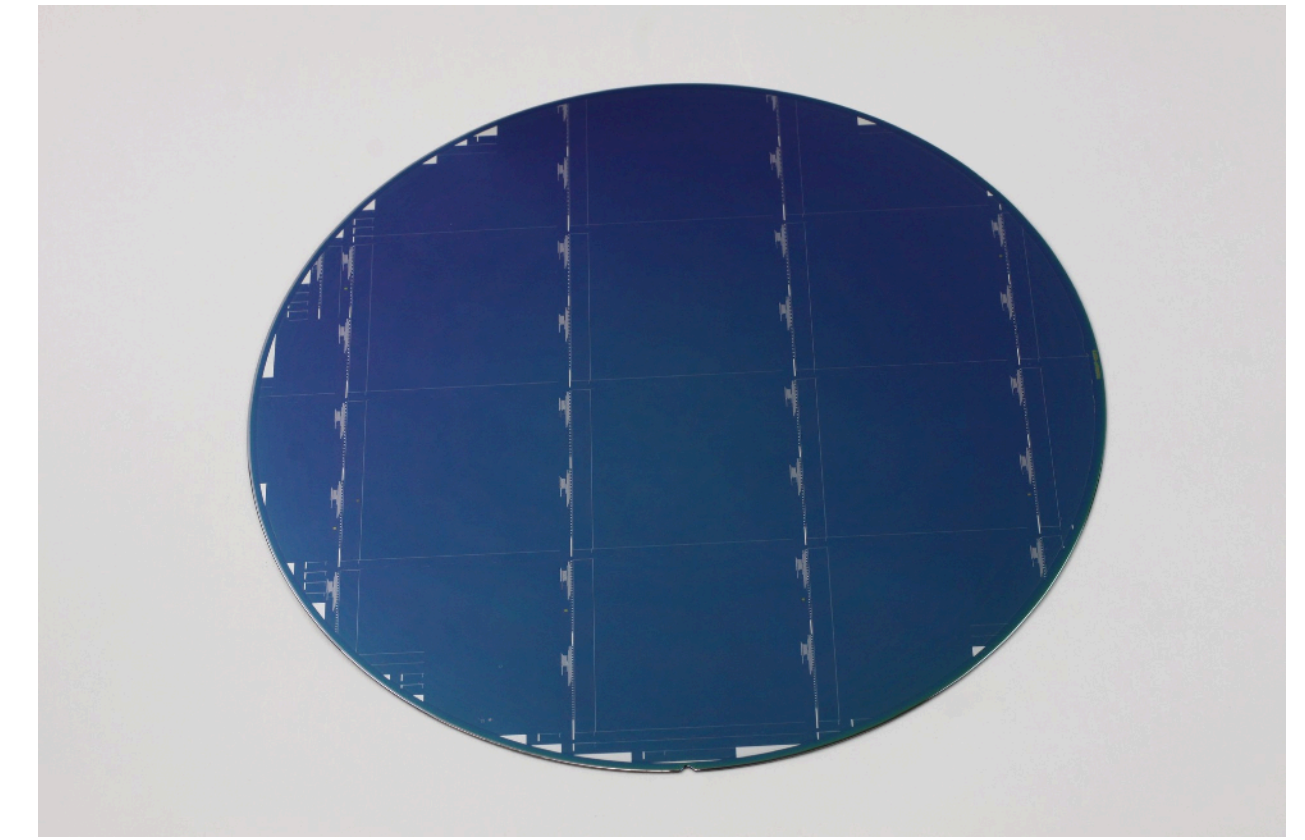
Quantum 2.0 and Detectors

- Research is moving from observing quantum effects to actively using and controlling them
- “Quantum tricks” can overcome limits from shot noise or the standard quantum limit (but not Heisenberg)
 - *Quantum Entanglement*: correlated grouping of states or particle properties, e.g. spin
 - *Squeezed states*: for two variables obeying Heisenberg, one is squeezed if σ below ground state value
- Entanglement/squeezing not required for sensing, but can be used to make even better sensors



Very Small Signals: Limits of Semiconductors

- Semiconductor-based particle detection
 - Example: mobile phone camera (CMOS pixel sensors)
 - Germanium, Cadmium zinc telluride (CZT), Cadmium telluride (CdTe) used for gamma/X-Ray spectroscopy
- Limits for Ionisation
 - the limit for electron/hole pairs in semiconductors is about the band gap energy (1.12 eV for Si)
 - More than half the energy of an ionising particle (in silicon) ends up as phonon excitations (heat)
 - Semiconductors work well above the band gap, but for smaller signals, need to detect the heat



Very Small Signals $\Rightarrow$ Measure Temperature

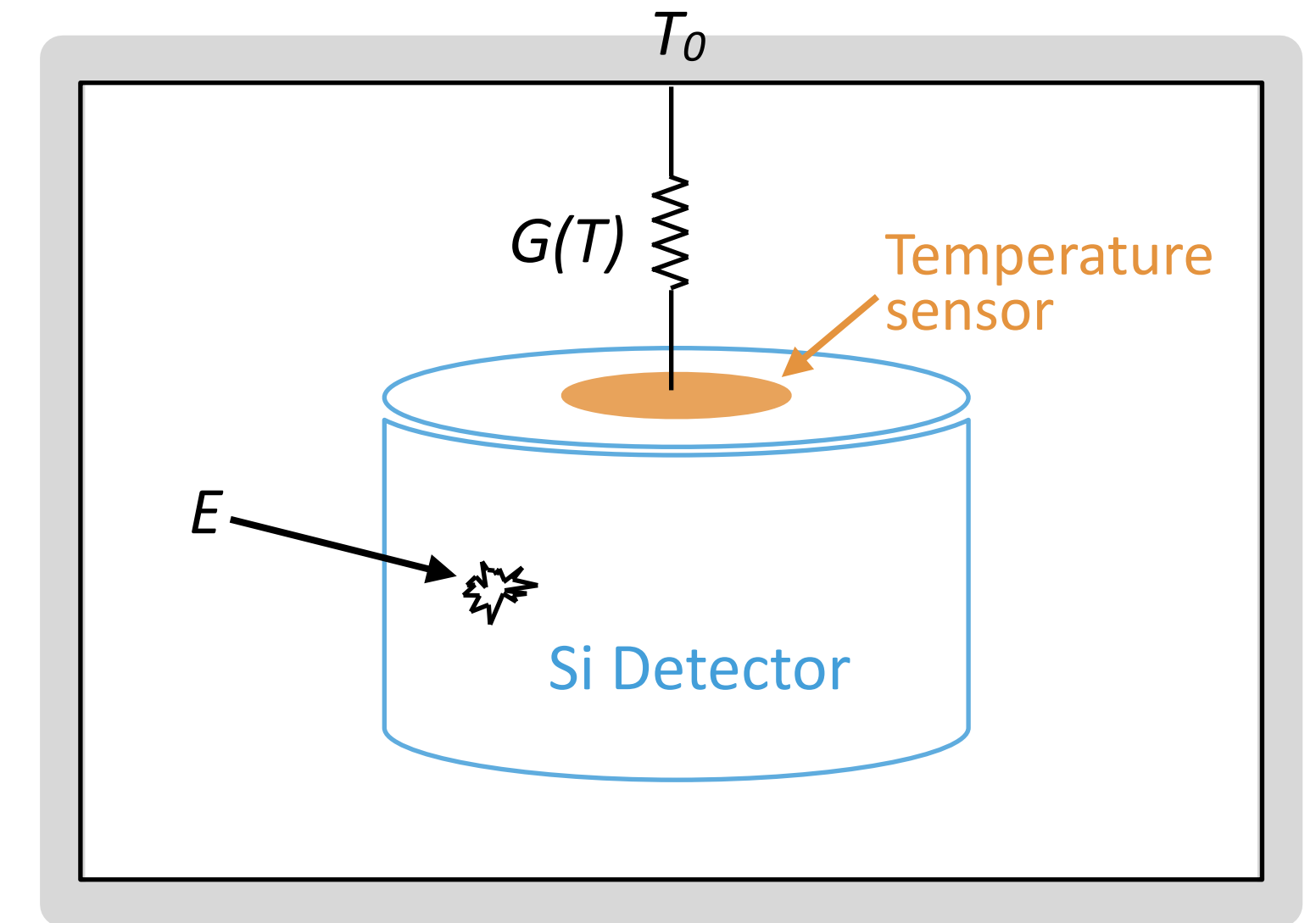
- Measuring temperature
 - change in temperature depends on energy if incoming particle (E), heat capacity ($C = c_p m$, c_p = specific heat and m = mass)

$$\Delta T = \frac{E}{C} = \frac{E}{c_p m}$$

- for a Si mass of 1 g at T_0 room temperature (25C) and $E = 1$ keV, the heat capacity of Si ($0.7 \text{ J/gK} = 4.4 \cdot 10^{15} \text{ keV/gK}$) gives

$$\Delta T = \frac{E}{C} = \frac{1}{(4.4)(10^{15})} \approx 2 \times 10^{-16}$$

- Better with a smaller mass? Different material? Yes, but...



Cryogenic Microcalorimeter

- Lower temperature → lower heat capacity
 - minimise electron contribution, so only lattice (phonon) vibrations
 - heat capacity given by Debye equation, $C \propto (T/T_D)^3$ where T_D ($\equiv \Theta$) is the Debye Temperature (645 K for Si)
 - silicon example with smaller mass of 1 μg and lower temperature $T_0 = 0.1$ K gives

$$\Delta T = \frac{E}{c_p m} = \frac{(1)(645)^3}{(10^{-6})(0.1)^3(0.7)(6.24)(10^{15})} \approx 0.6$$

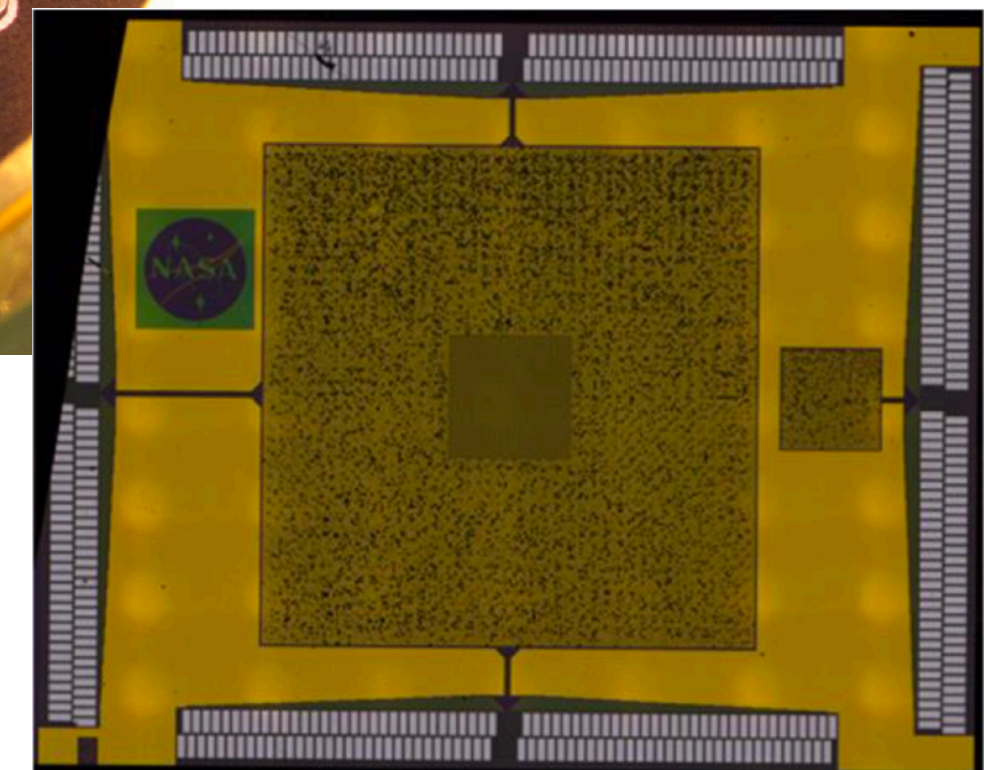
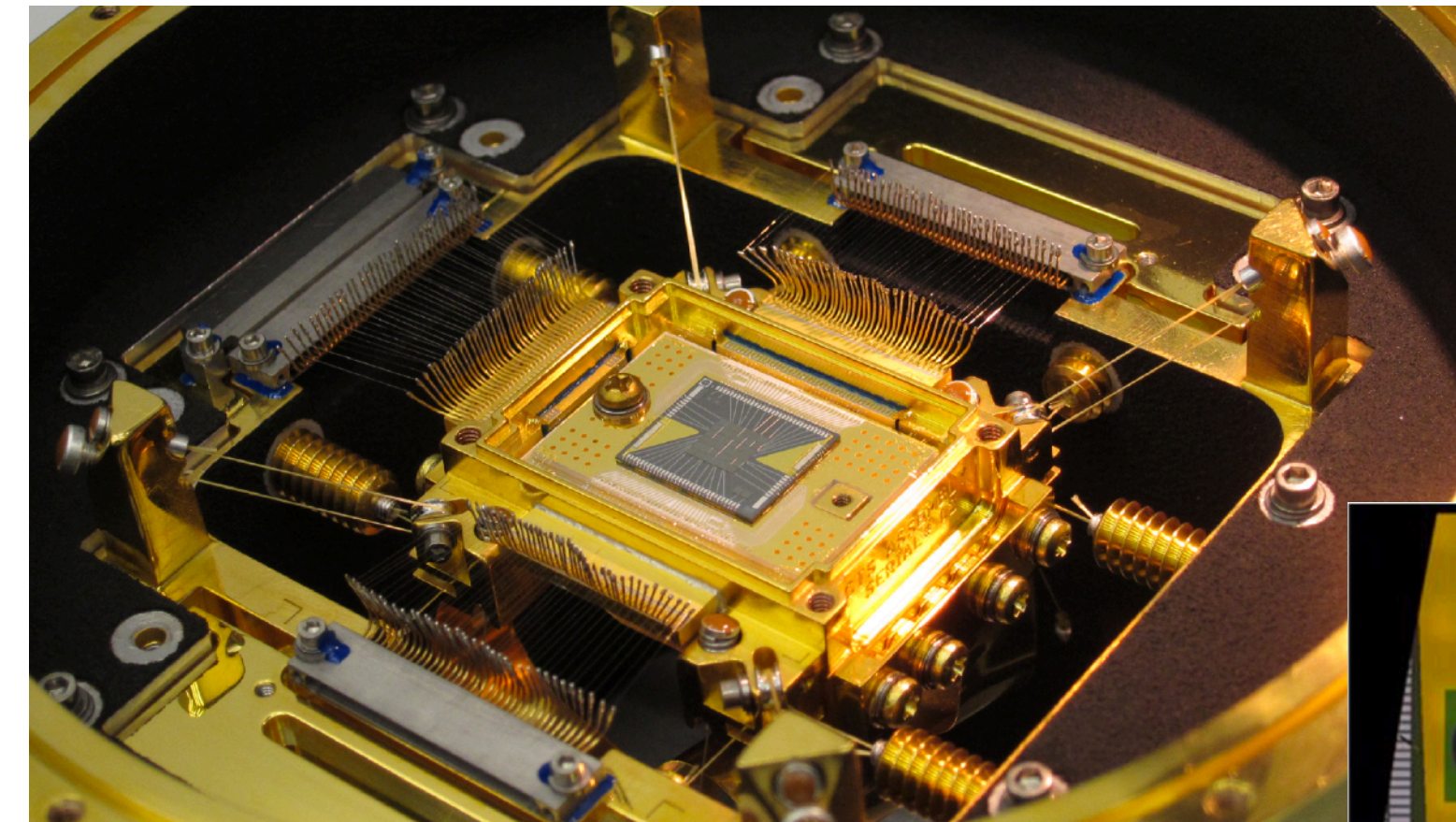
- Some homework to think about
 - What about changing the absorber to a material with higher Debye temperature (sapphire, diamond)?
 - Will it work using an easier temperature (eg liquid nitrogen)?
 - Can it work with a "classic" thermometer, measuring e.g. ± 0.2 C?

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- 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)
 - $\sim 50\text{k}$ pixels (25-50 μm) Au absorber at 50 mK
 - Energy between 0.2 and 15 keV, resolution < 3 eV



Cryogenic Microcalorimeter - Optimisation

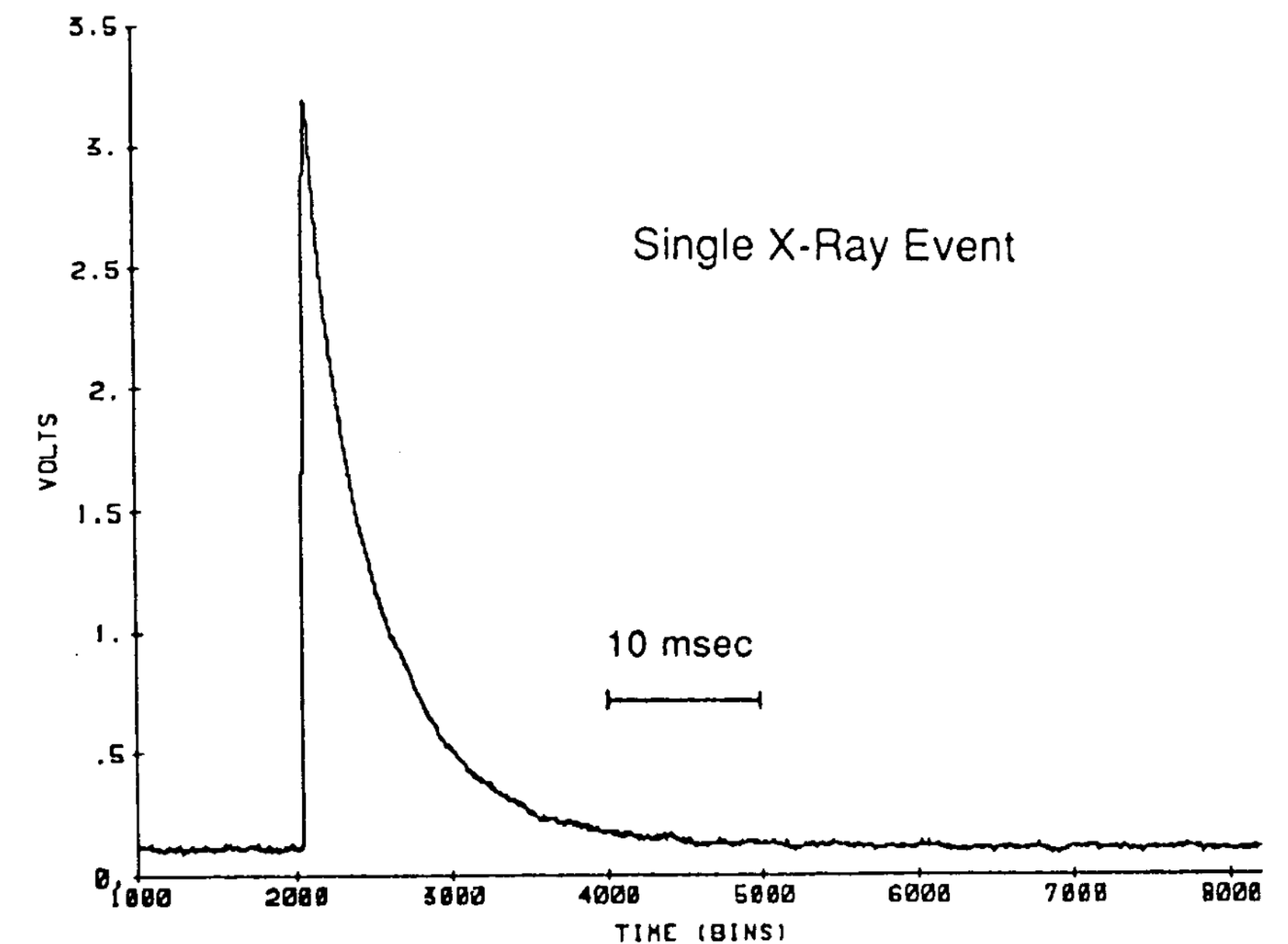
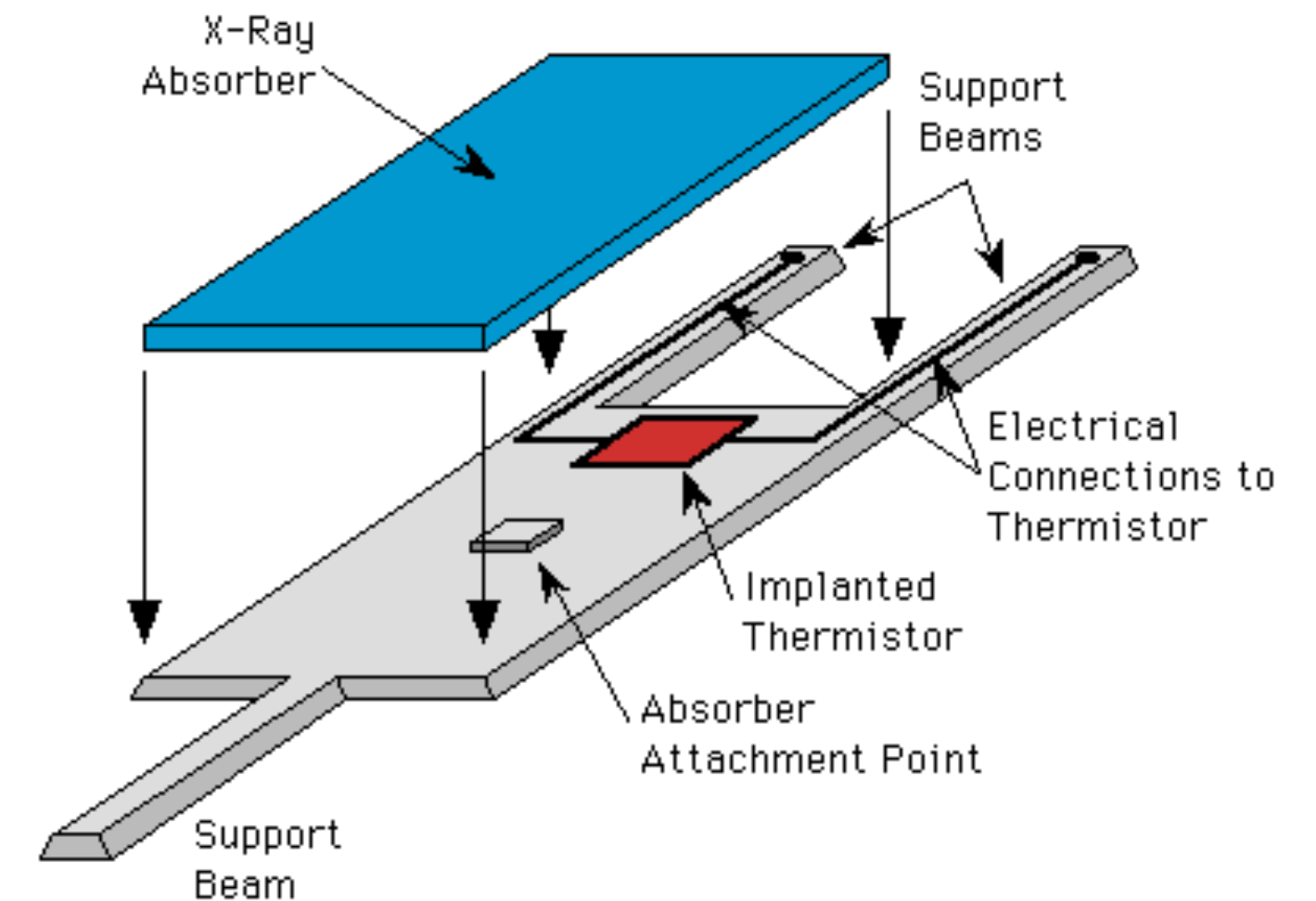
- X-Ray absorber material and coupling
 - absorber chosen for fast rise, efficient conversion
 - coupled to cold head via thin channels; slow exponential decay
 - connection with thermal conductance G

$$T(t) = \Delta T e^{-t/\tau}$$

- with decay time given by

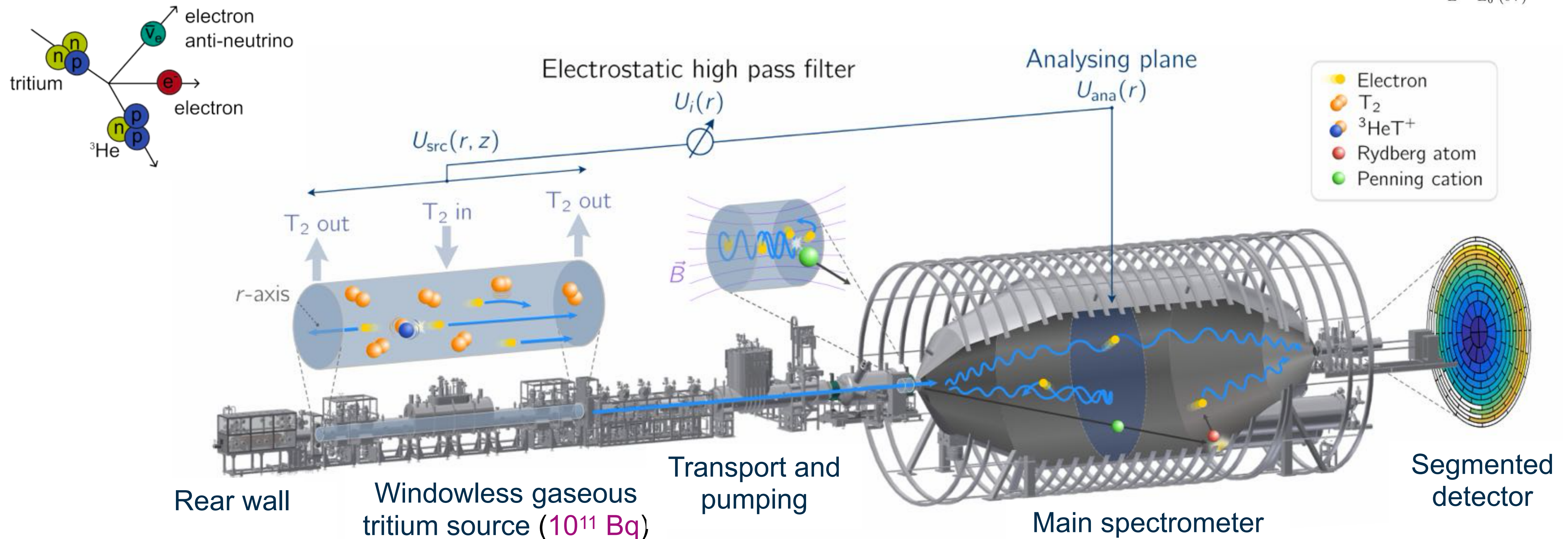
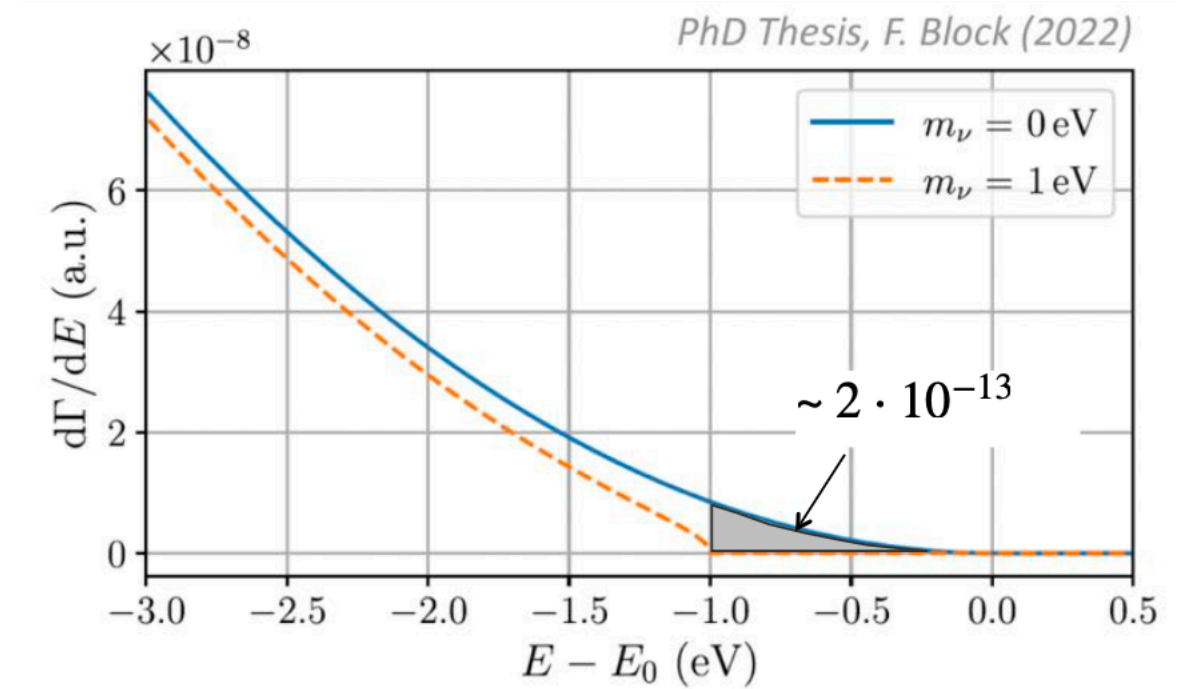
$$\tau = \frac{C}{G}$$

- Noise optimisation
 - Noise will have same shape as signal: same S/N vs frequency
 - Amplification (shaper) should not change sensor S/N, but
 - external sources of noise; resistances, input transistor, vibrations
 - shaper designed to suppress low-frequency noise



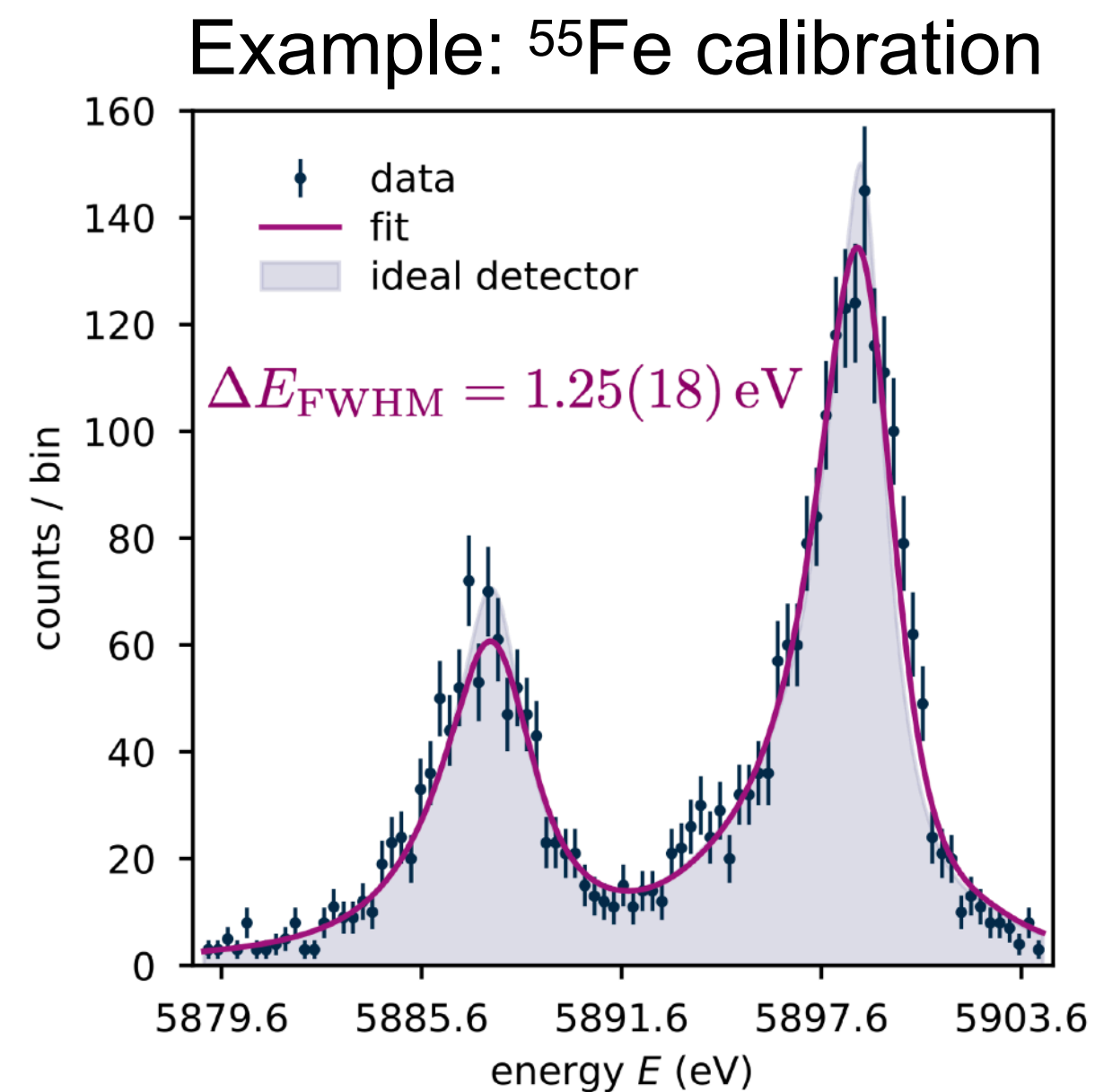
MMC and the Karlsruhe Tritium Neutrino Experiment (Katrinvv)

- Goal: measure tritium β - decay spectrum endpoint $\rightarrow$ electron antineutrino mass
- Measure electron endpoint energy with high resolution (sub-0.7eV FWHM)
- Quantum sensing for electron detection

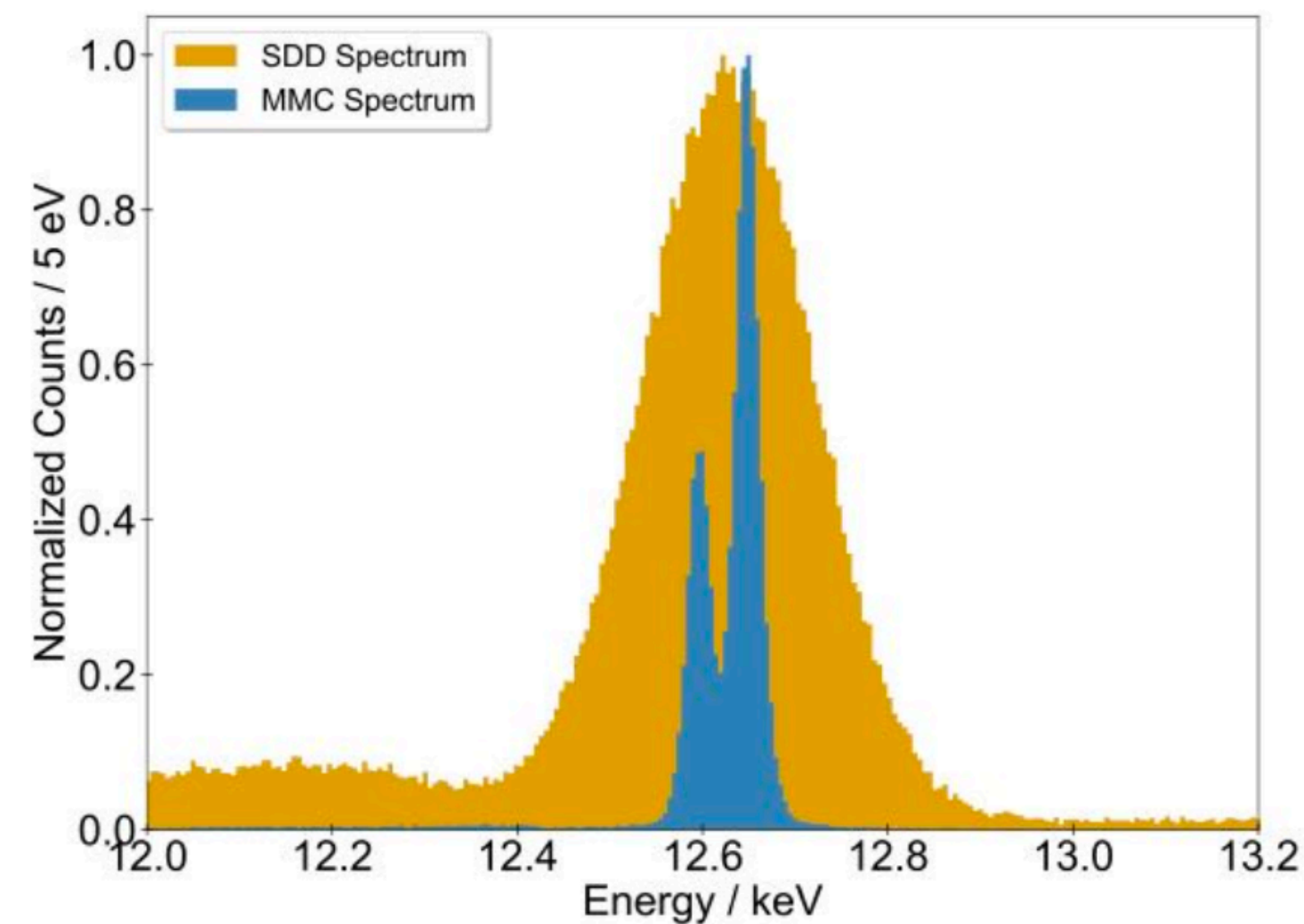


Microcalorimeters and Katrin++

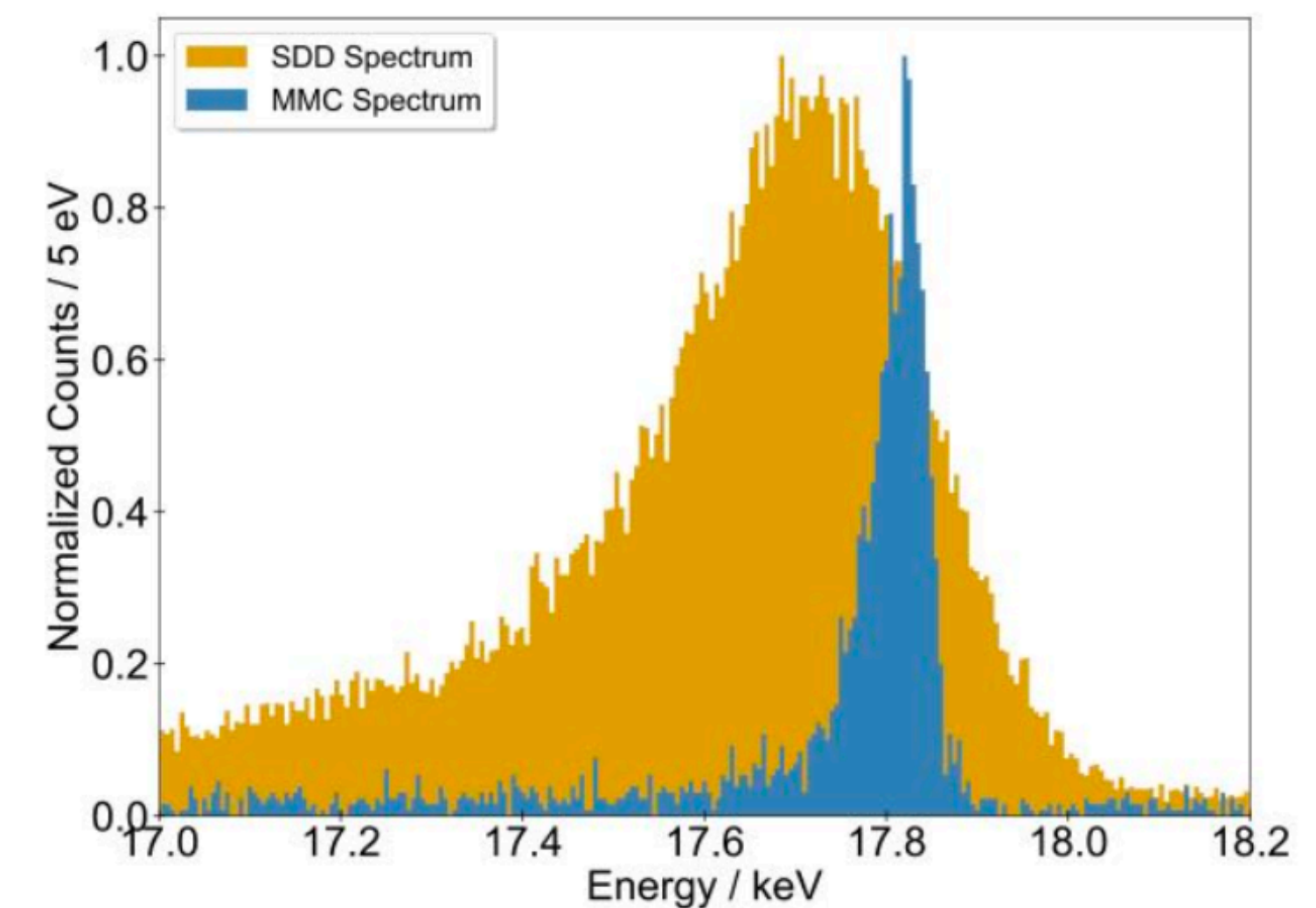
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ELECTRON project $^{83}\text{Rb}/^{83\text{m}}\text{Kr}$ spectrum: SDD vs MMC



X-ray comparison



conversion electrons comparison

Transition Edge Sensors (TES)

- Measure temperature change with superconducting circuit
 - take advantage of very sharp transition between superconducting → conducting
 - small temperature change can give large resistance change
 - coupled to SQUID amplifying circuit for readout
- Voltage-biased powering for stable operating point
 - power is only pW, so μV voltage or μA current
 - constant-current $P = I^2 R$: increased R leads to increased P (unstable)
 - constant-voltage $P = V^2 / R$: increased R leads to decreased P (stable)
- Examples: Cameras with high spectral resolution employed from radio to X-ray (SPT, ATHENA, BICEP2)

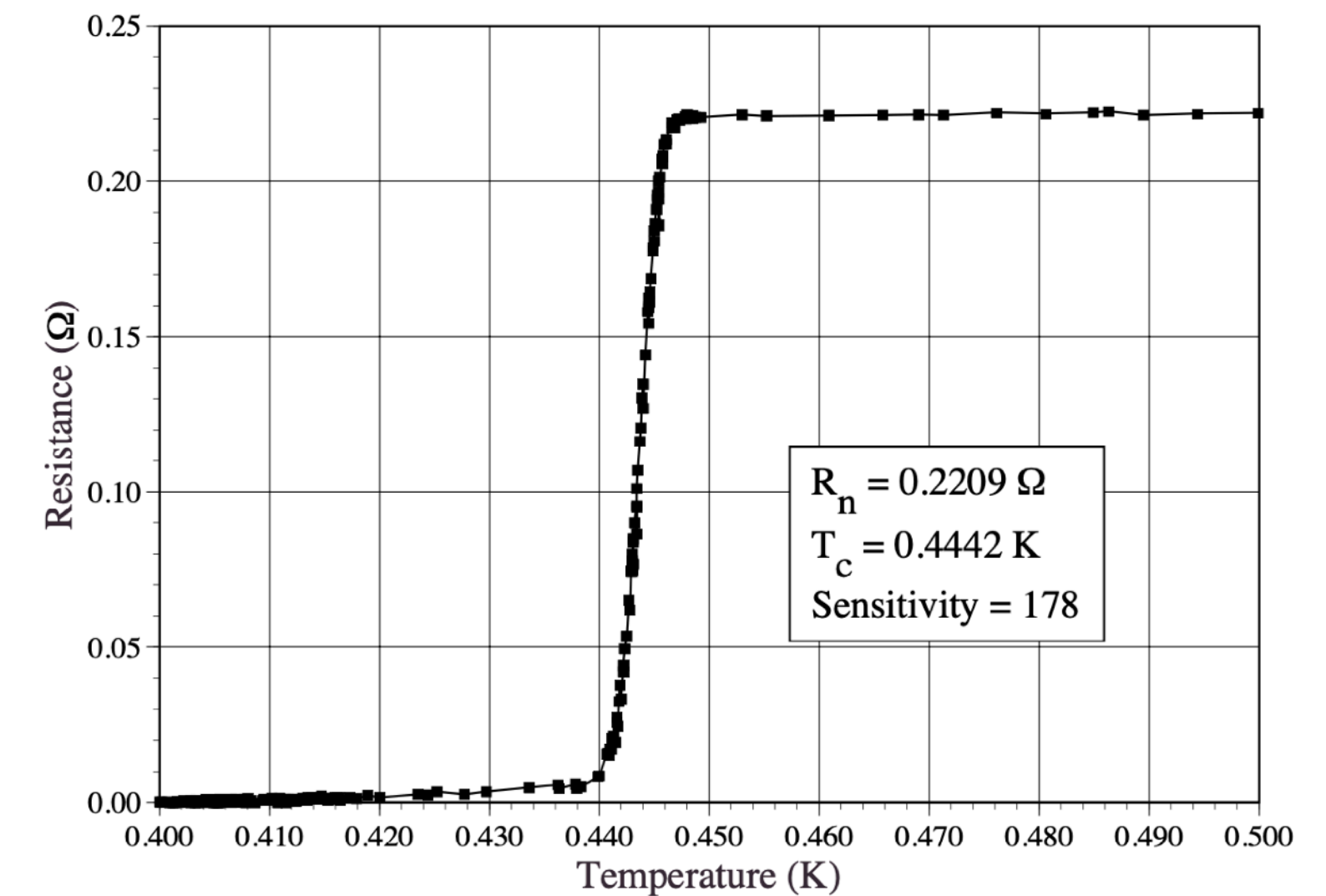
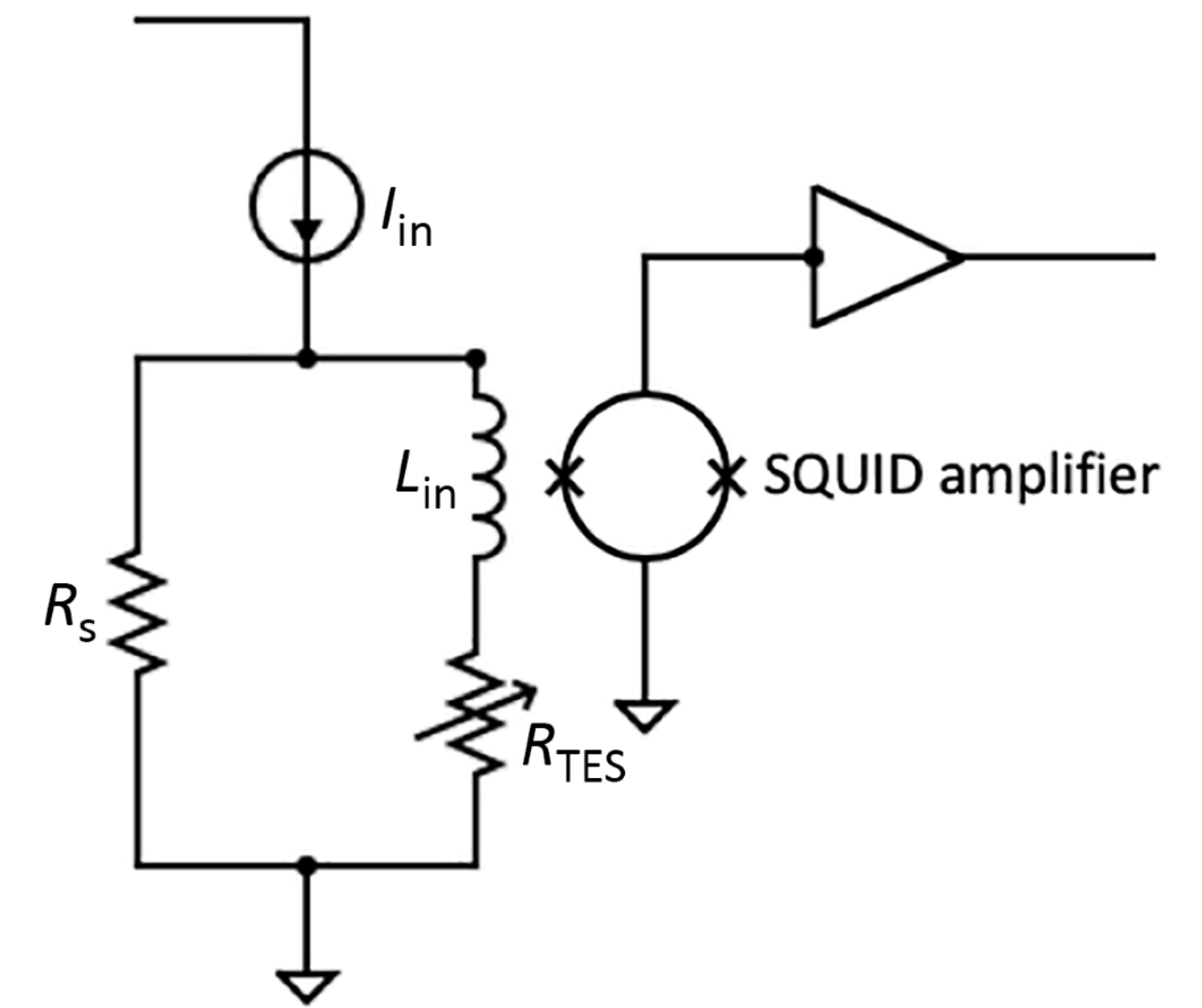


Figure 1. Superconducting transition at 444mK for a Mo/Au bilayer.

Transition Edge Sensors (TES)

- TES Operations

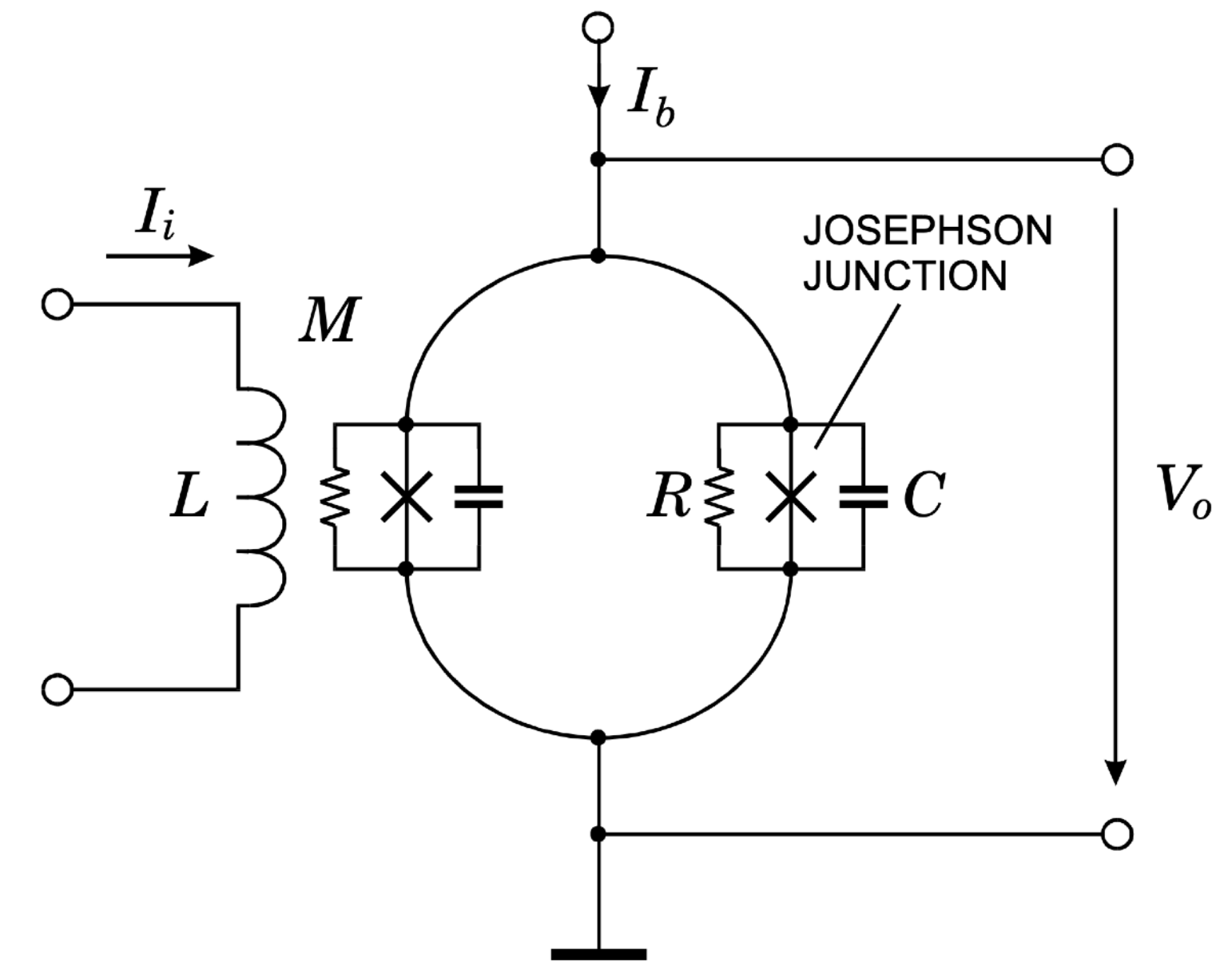
- signal current proportional to signal power: $\Delta P = V\Delta I$
- Detection limit based on thermodynamic noise in the sensor, and thermal noise from the circuit resistance, for b = bandwidth:

$$i_n^2 = \frac{4kT_s}{R} + \frac{\sqrt{4kT_s^2 G}}{V} \Rightarrow P_N = 4kT_s b + \sqrt{4kT_s^2 G b}$$

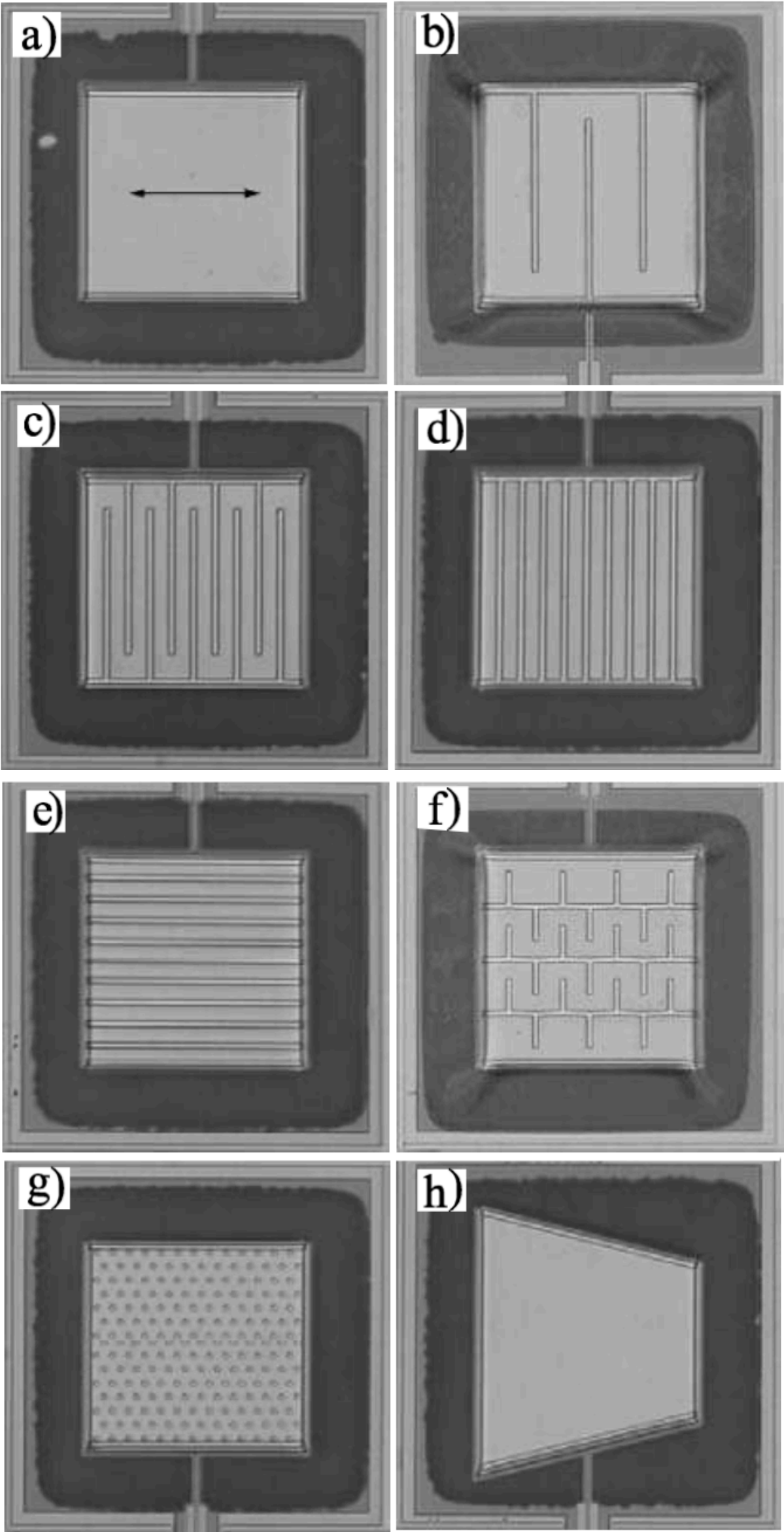
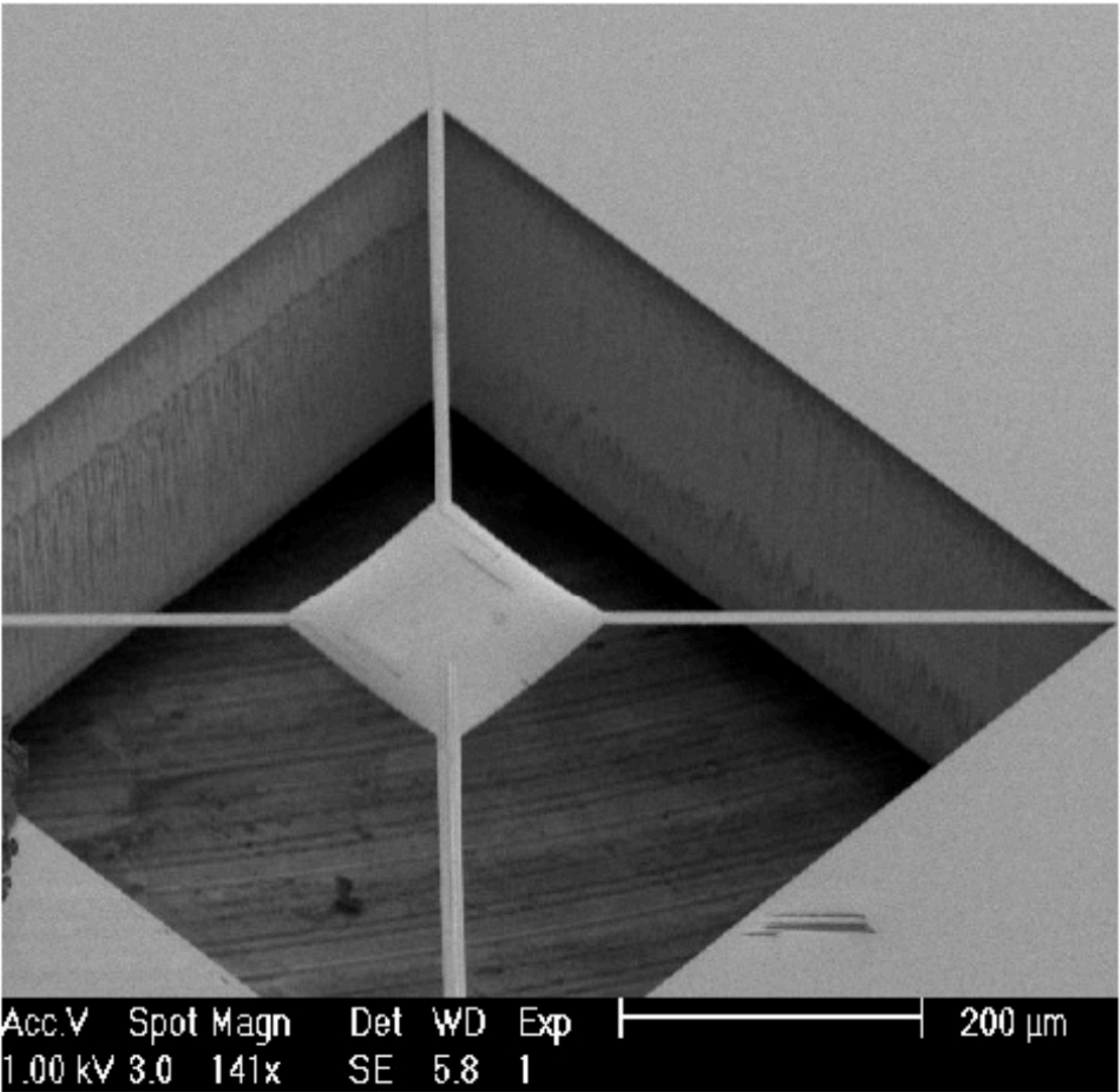
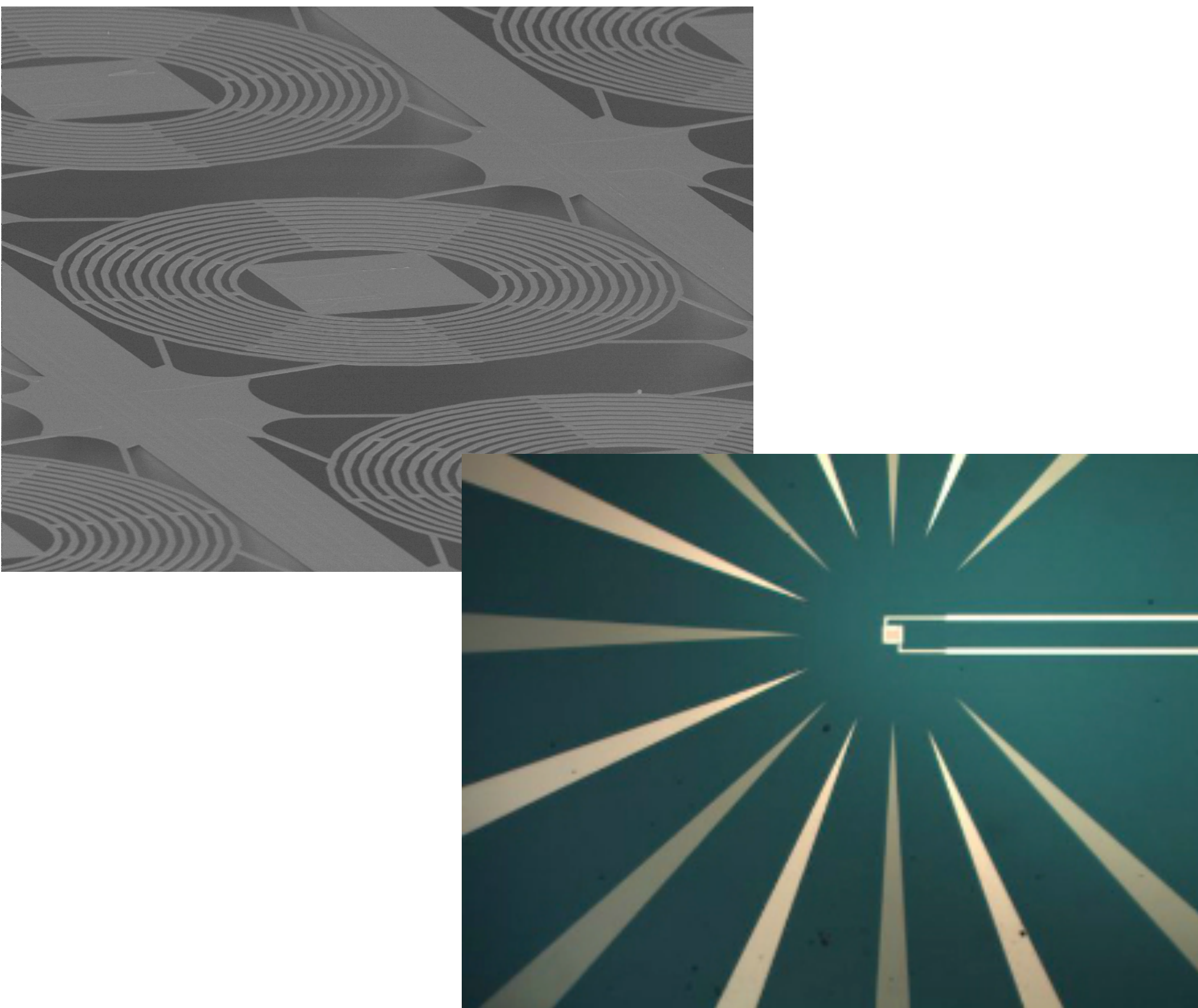
- sensor resistance ~ 0.1 - 1.0 , so voltage source and measurement input resistance must be much smaller $\Rightarrow$ challenge for readout

- Readout: SQUID (Superconducting Quantum Interference Devices)

- Two Josephson junctions in parallel: low temperature (~ 0 - 5 K)
- biased by current I_b
- input is inductively coupled through L (10 nH to 1 μ H)
- output is a voltage V_0 ; sensitivity = $V_0/I_b \approx 500$
- Plus: Low temp, very low noise, adequate gain
- Minus: limited input signal, feedback (flux) loop required to lock at operating point



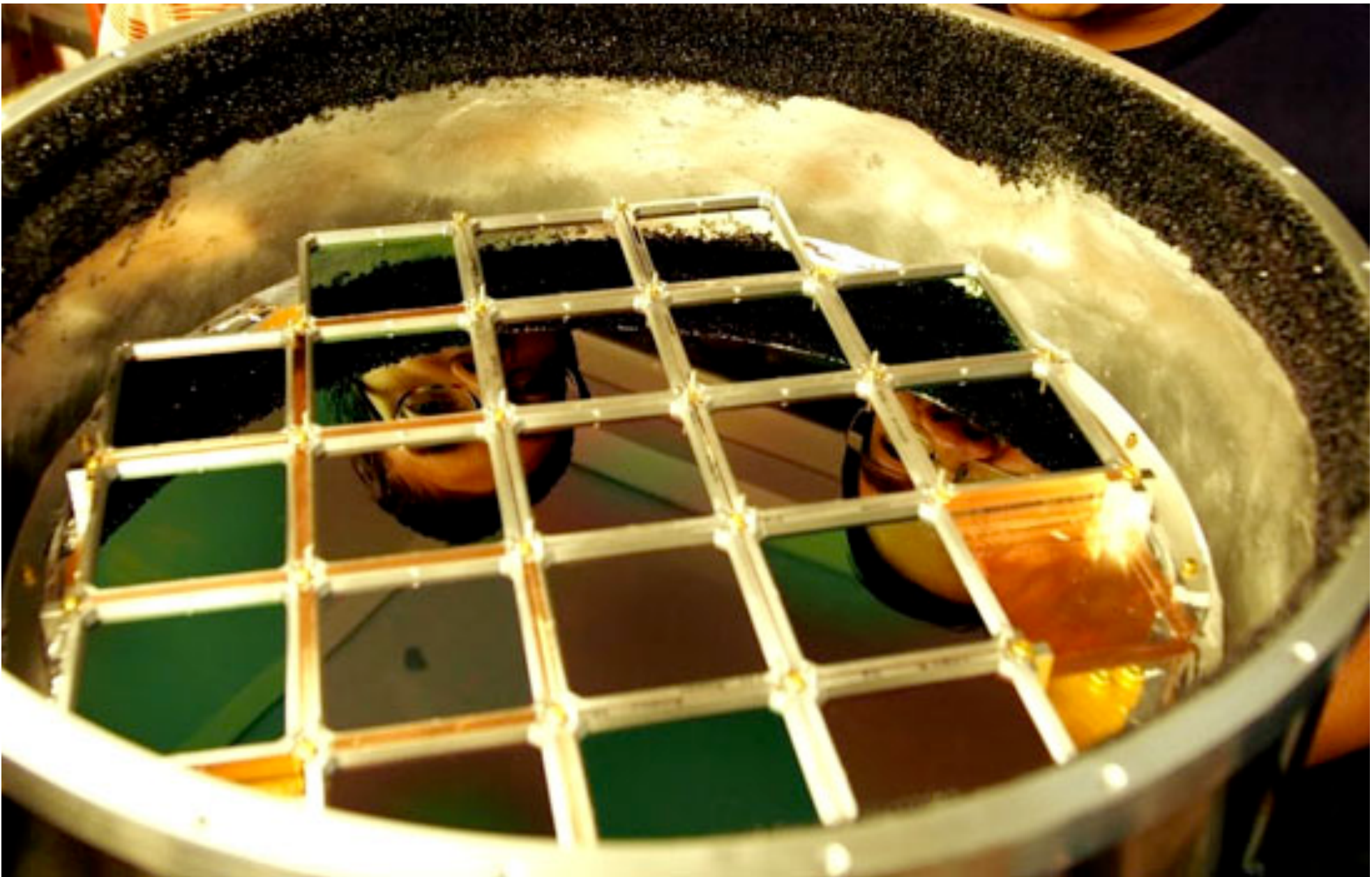
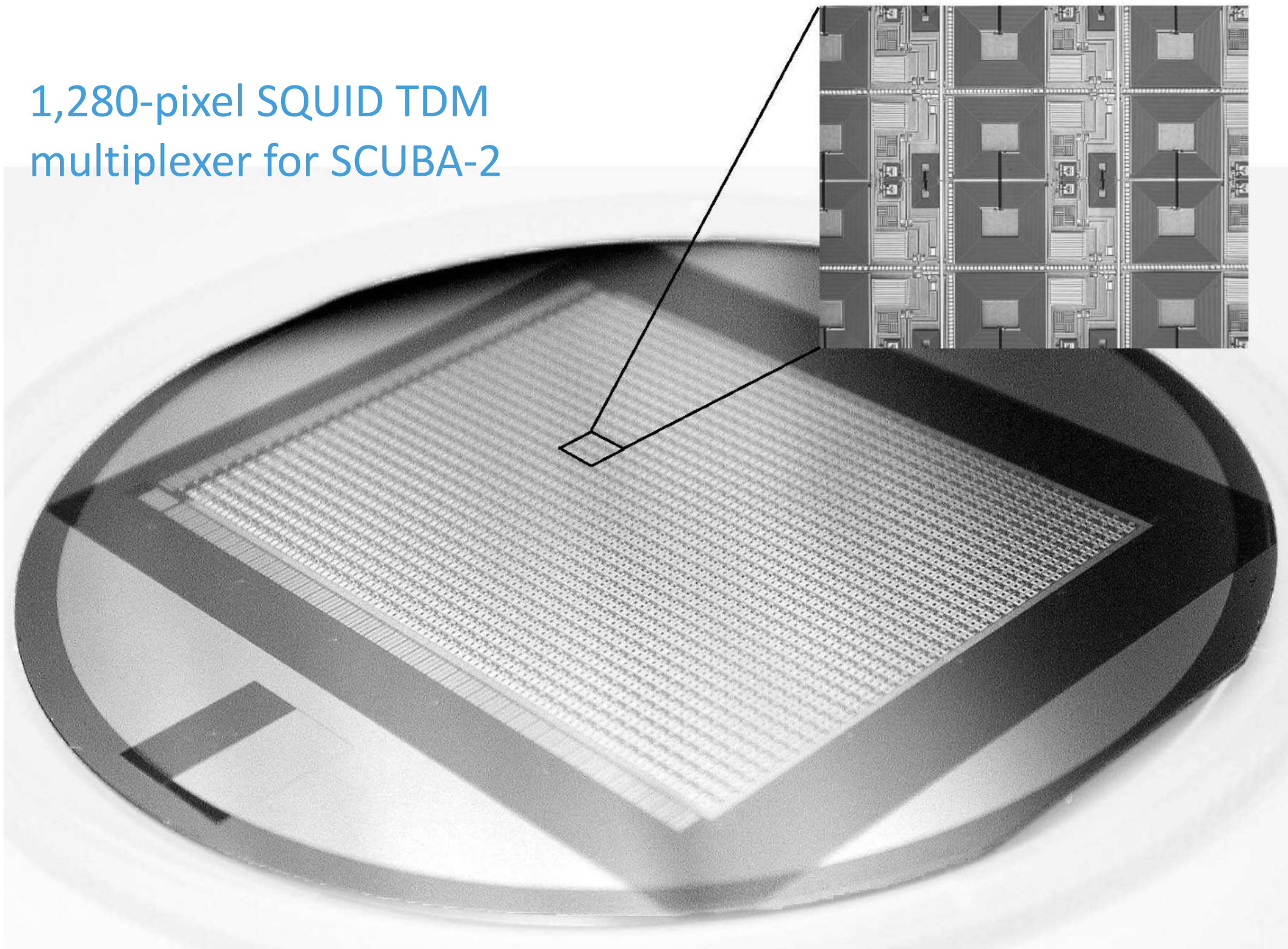
TES Examples



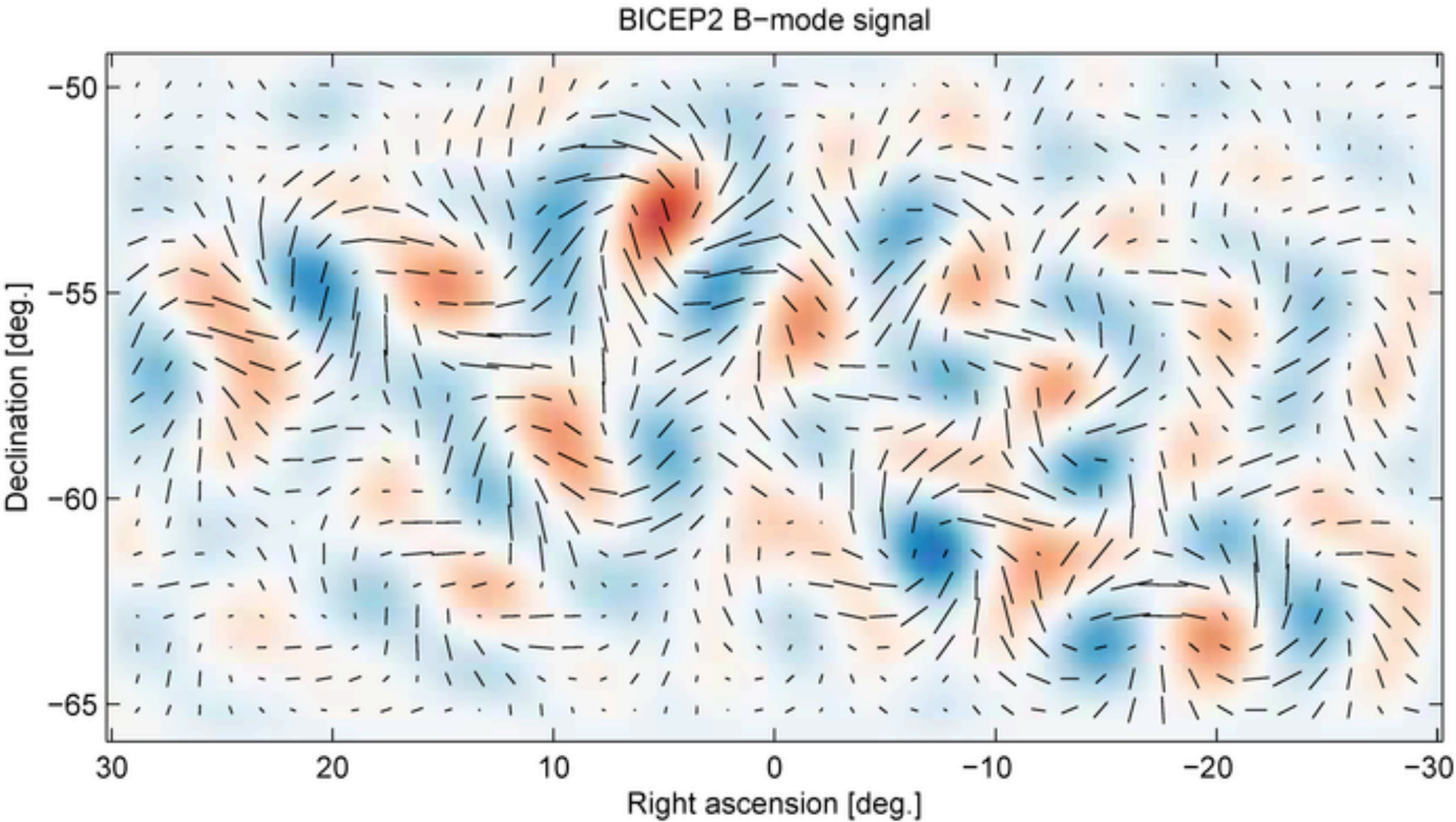
TES sensors on Si₃N₄

TES Arrays & Physics

1,280-pixel SQUID TDM
multiplexer for SCUBA-2

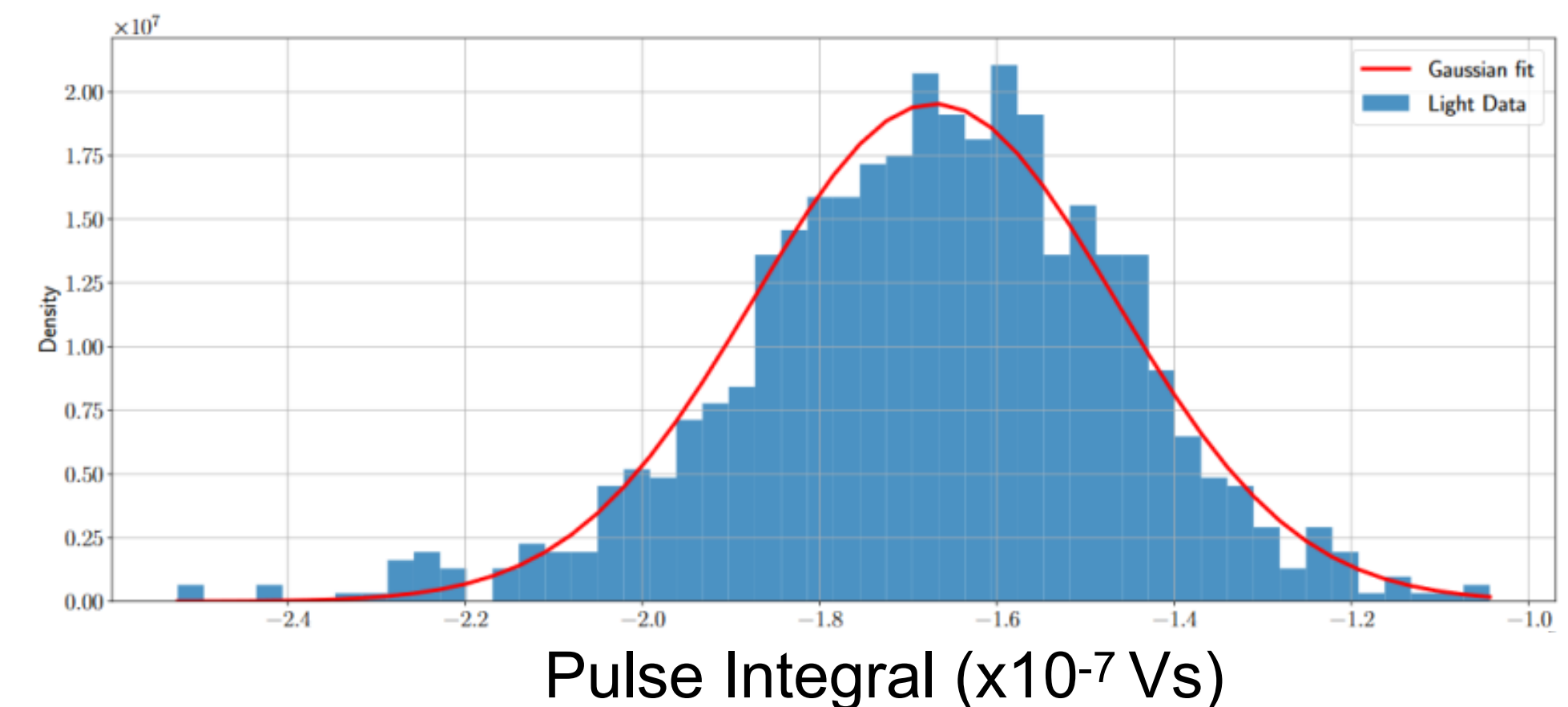
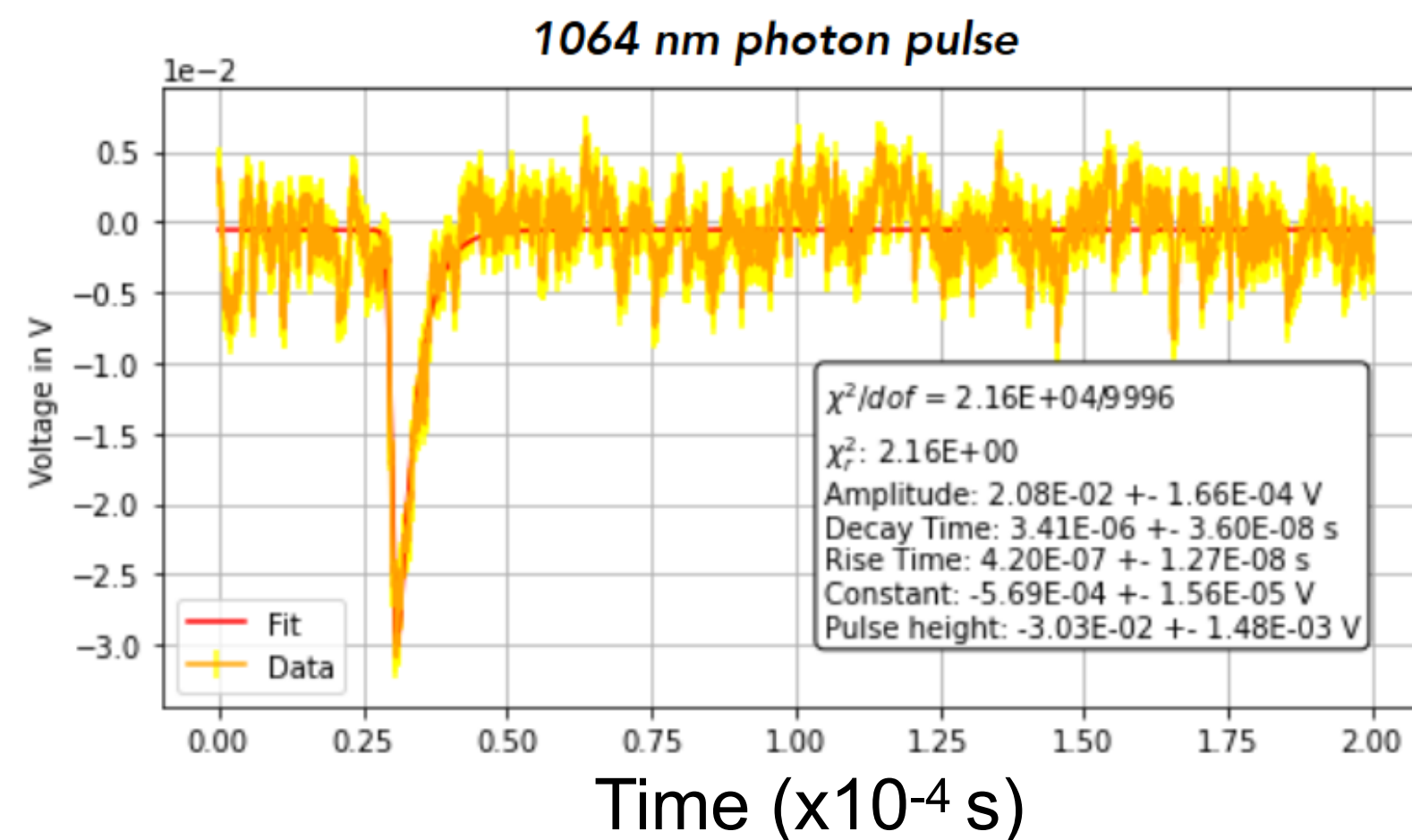
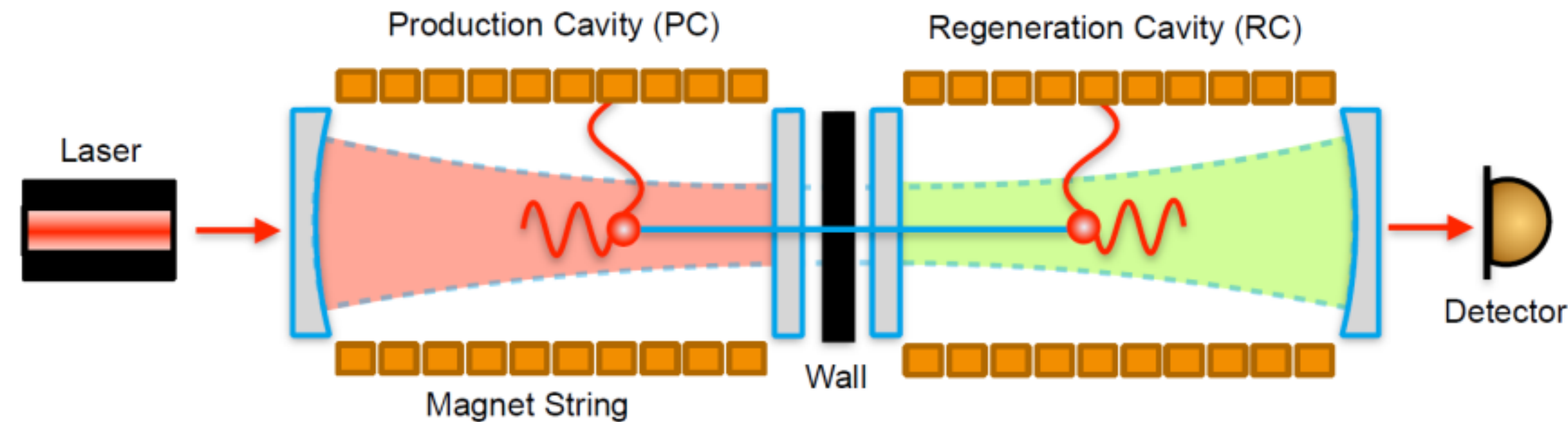


BICEP3 TES Array, BICEP2: CMB Polarization



TES Detector for ALPS II

- ALPS: Producing and detecting axion-like dark matter particles in a Light-shining-through-walls setup
- Detection Challenge:
 - Single 1064 nm photon detection
 - Extremely low rates (about 10^{-5} s^{-1} , i.e. 10^{-24} W)
 - Extremely low dark counts required
- Setup at DESY: Transition Edge Sensor (TES), operating in the superconducting transition region



ALPS TES setup at DESY



Dilution refrigerator
($T \approx 20$ mK)

BLUEFORS

SQUID electronics

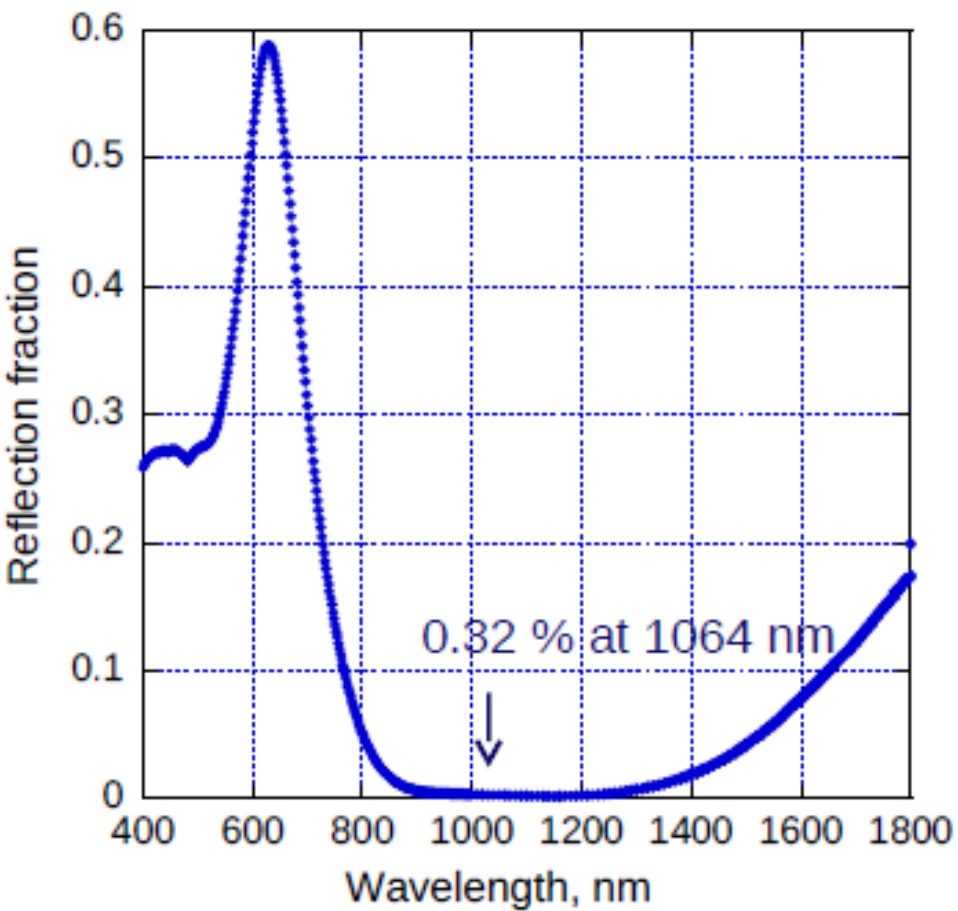
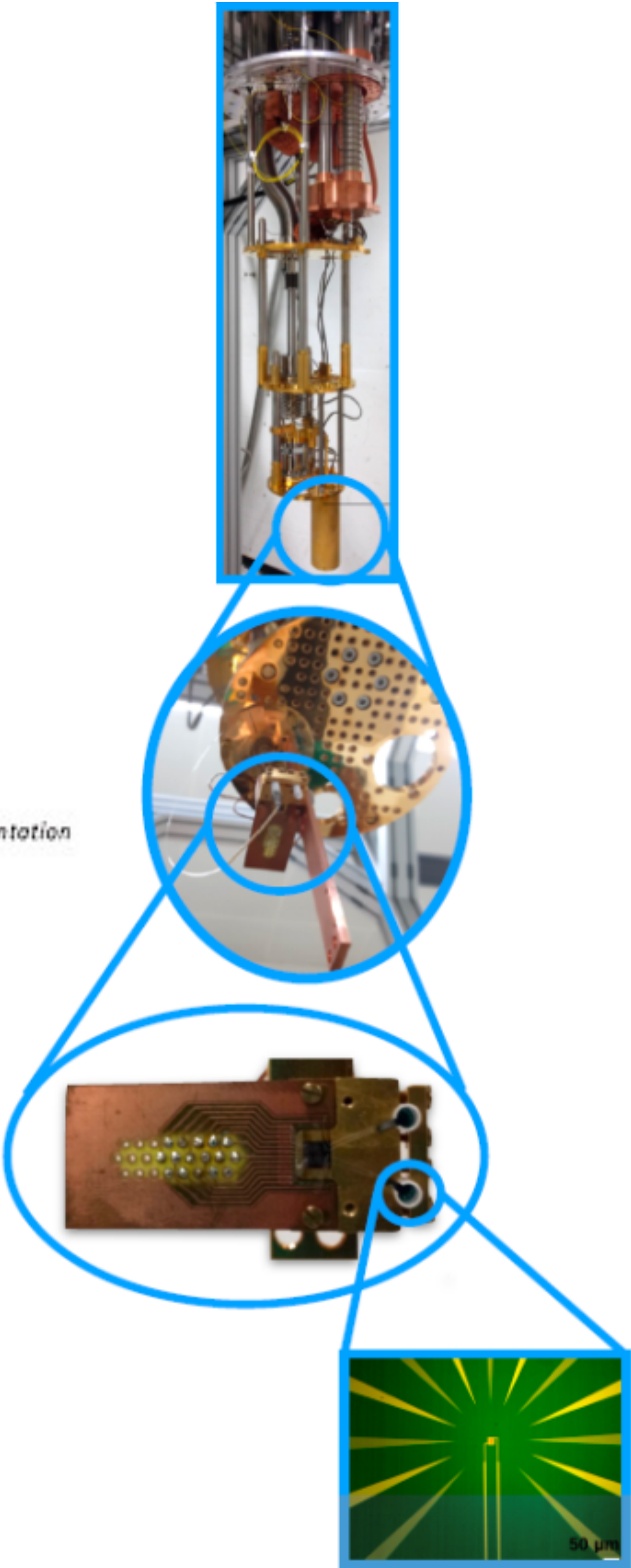
MAGNICON
physical research and instrumentation

SQUIDS

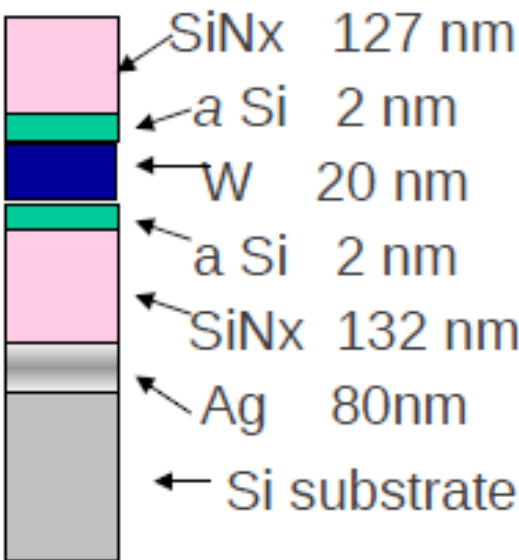
PTB
Messen ■ Forschen ■ Wissen

TES (1064 nm)

NIST



Optical stack



Any Light Particle Search II Technical Design Report

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Reza Hodajerd^b, Dieter Horns^c, Friederike Januschek^b, Ernst-Axel Knabbe^b, Axel
Lindner^b, Dieter Notz^b, Andreas Ringwald^b, Jan Eike von Seggern^b, Richard
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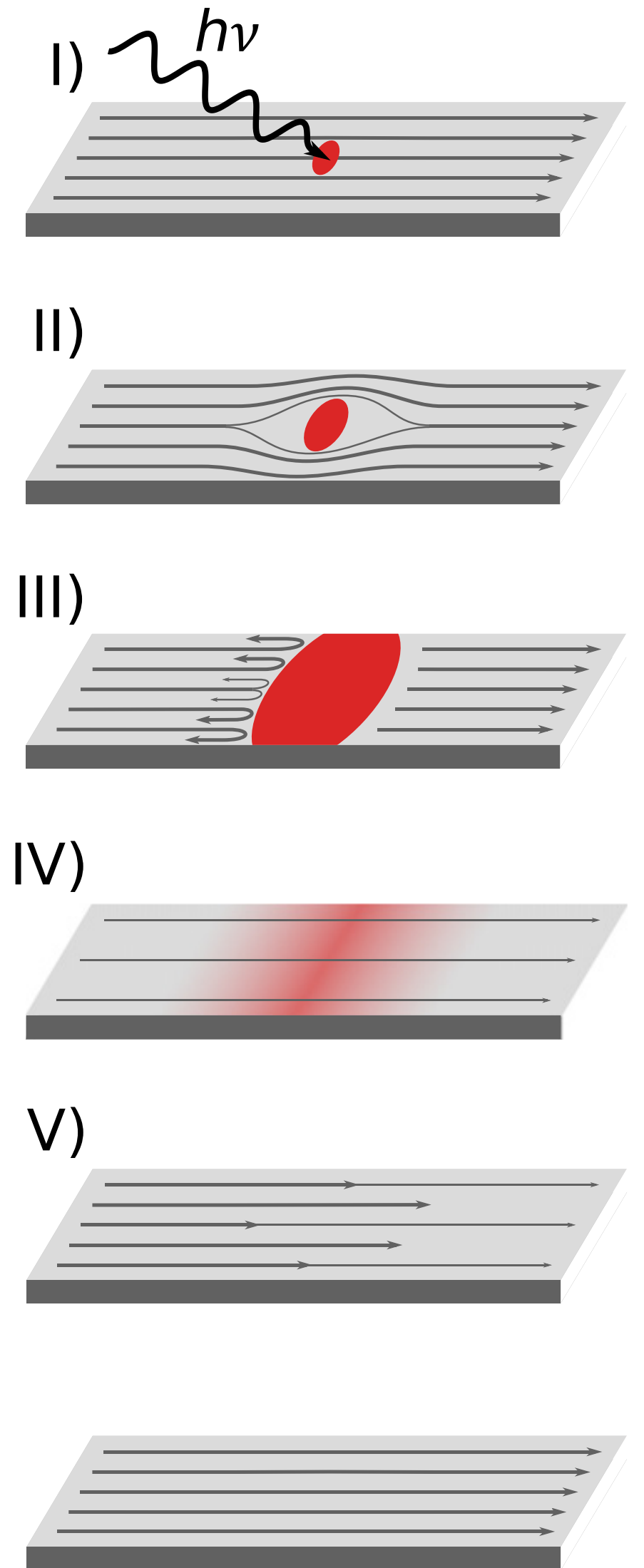
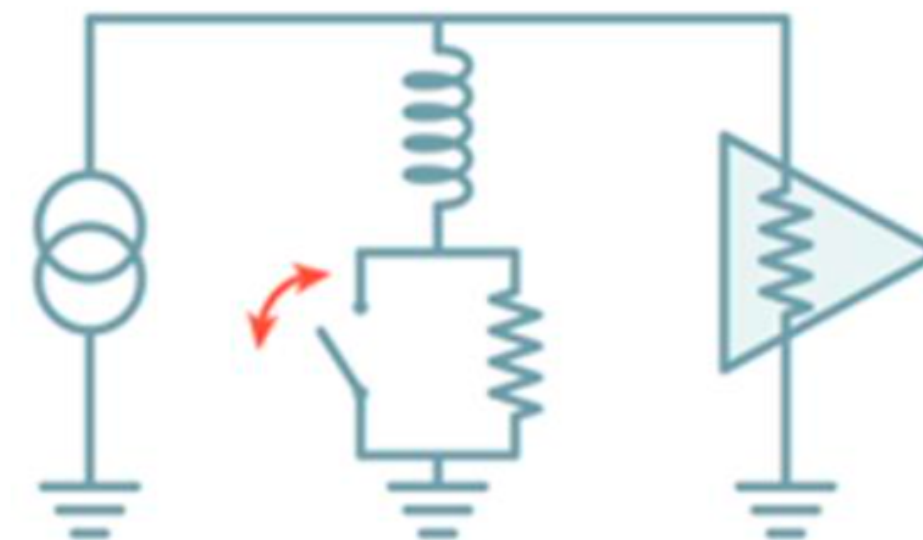
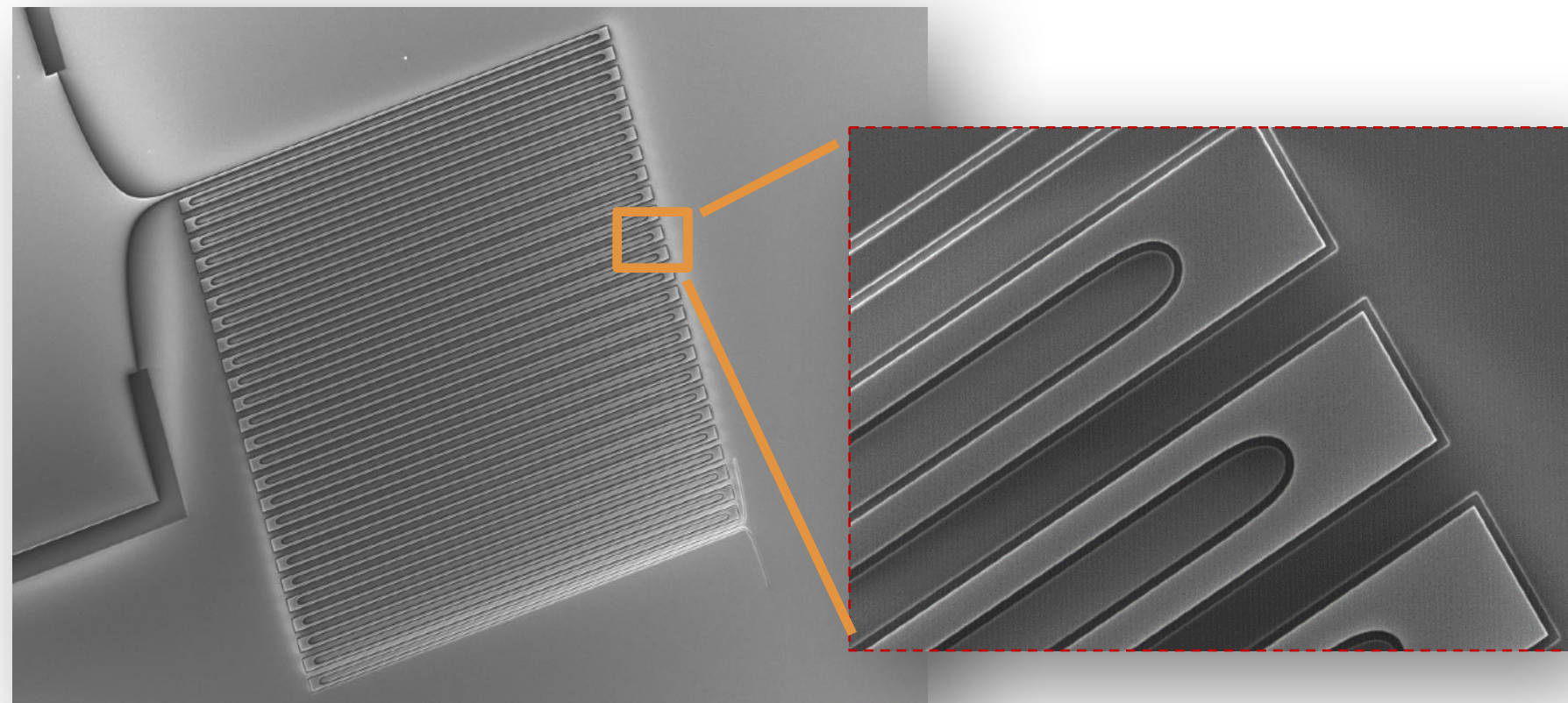
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E-mail: axel.lindner@desy.de

ABSTRACT: This document constitutes an excerpt of the Technical Design Report for the second stage of the “Any Light Particle Search” (ALPS-II) at DESY as submitted to the DESY PRC in August 2012 and reviewed in November 2012. ALPS-II is a “Light Shining through a Wall” experiment which searches for photon oscillations into weakly interacting sub-eV particles. These are often predicted by extensions of the Standard Model and motivated by astrophysical phenomena. The first phases of the ALPS-II project were approved by the DESY management on February 21st, 2013.

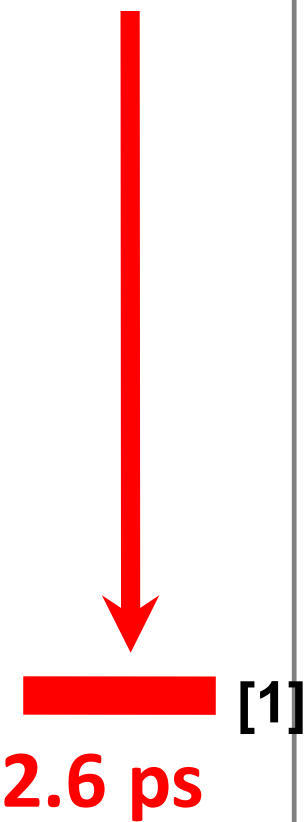
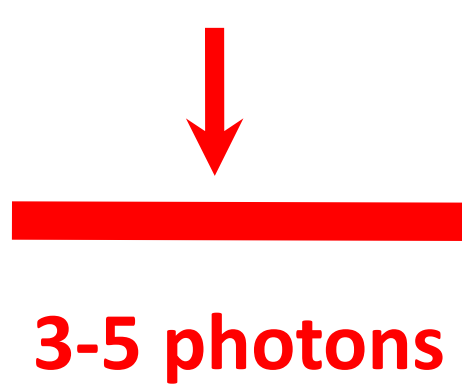
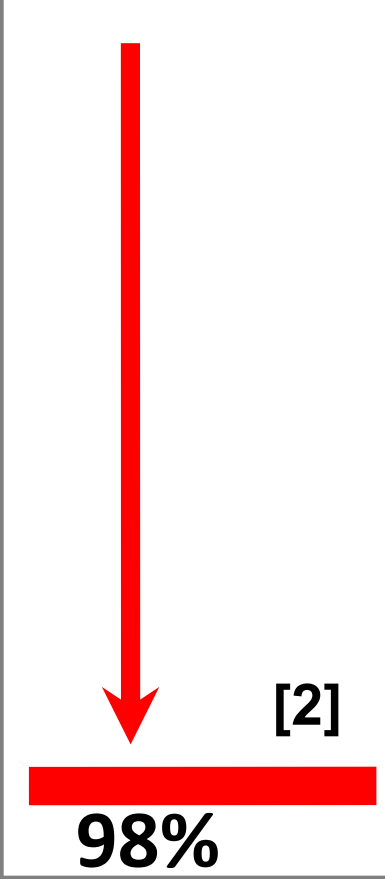
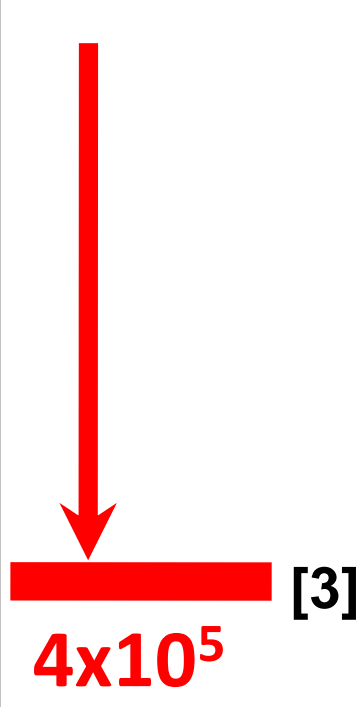
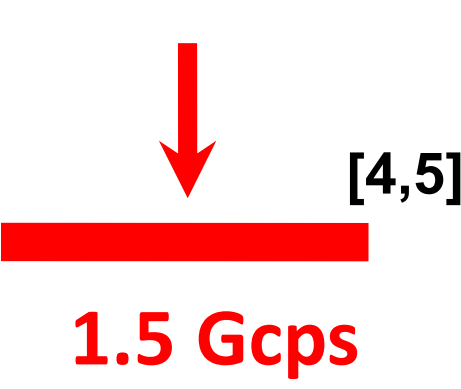
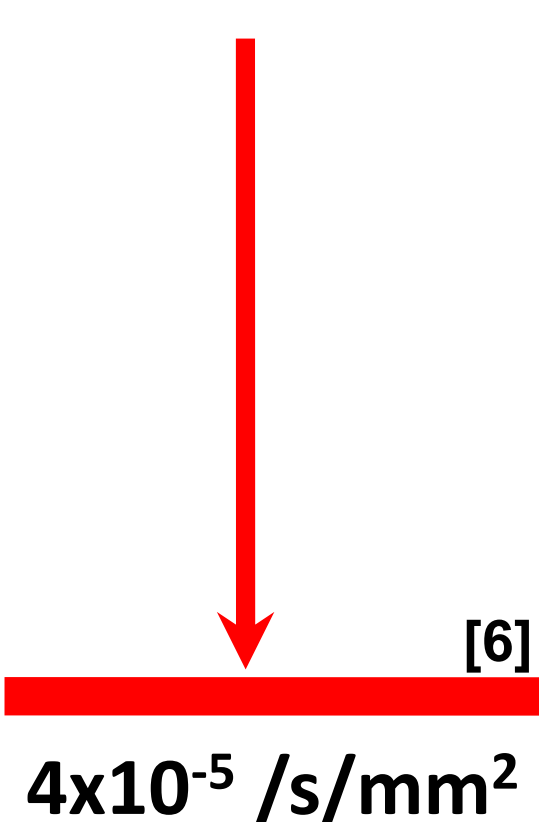
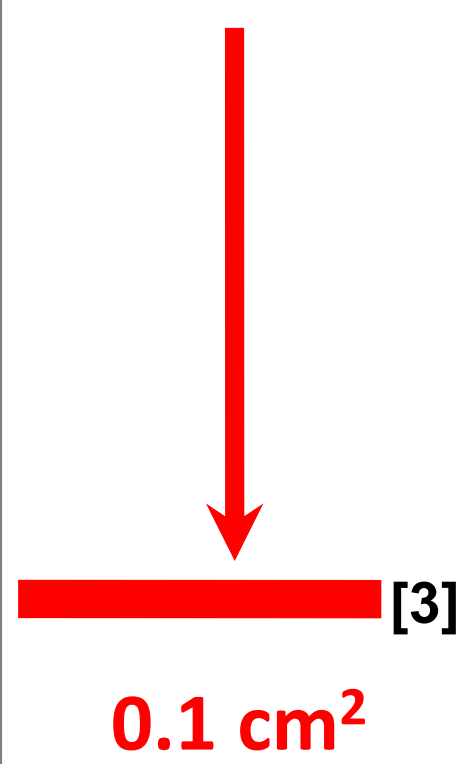
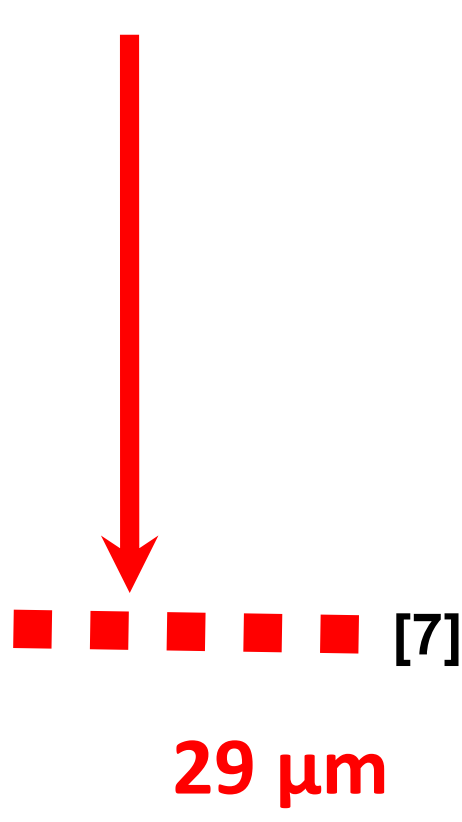
KEYWORDS: Dark Matter detectors (WIMPs, axions, etc.), Large detector systems for particle and astroparticle physics; Resonant Detectors.

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 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

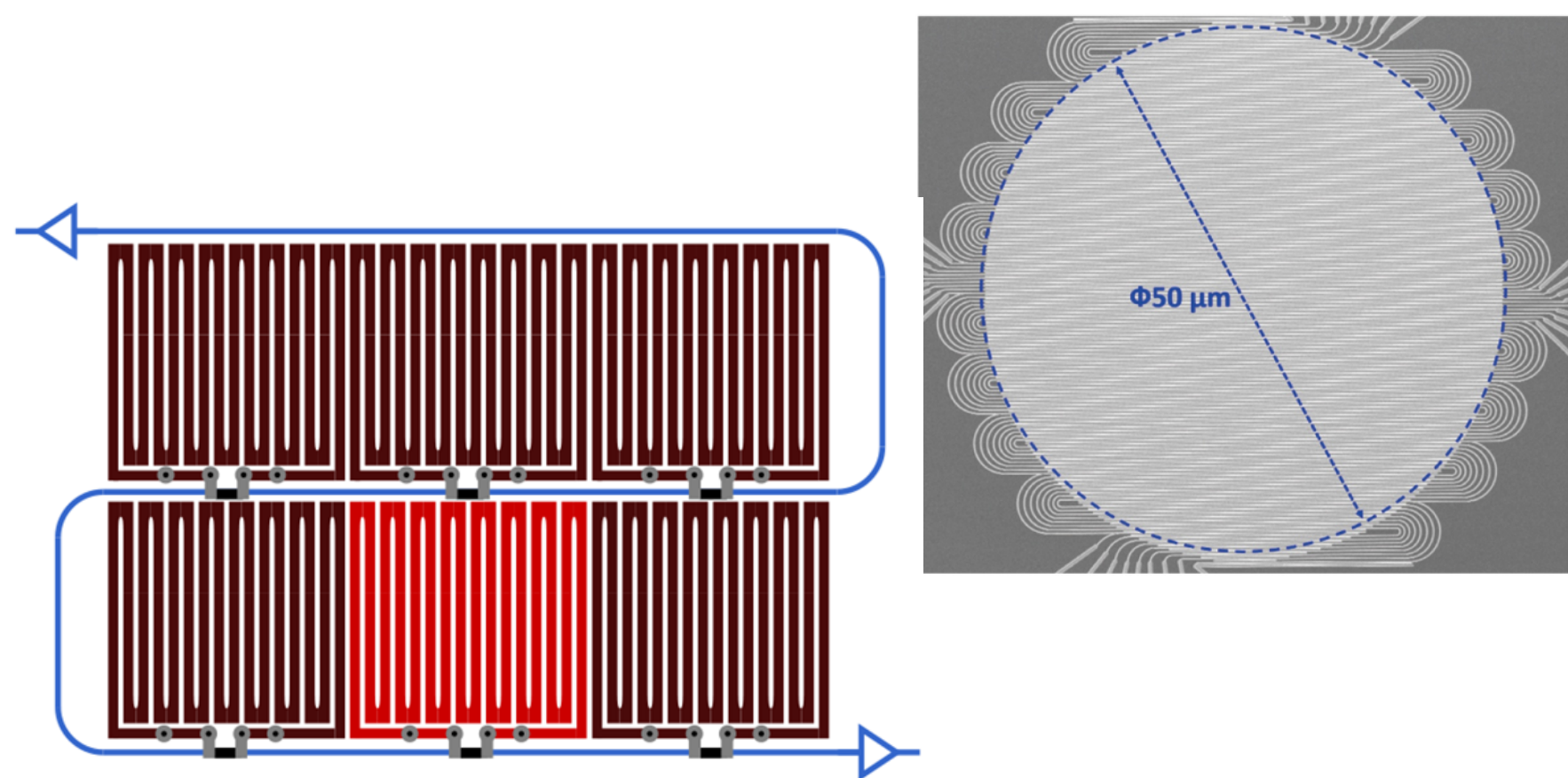
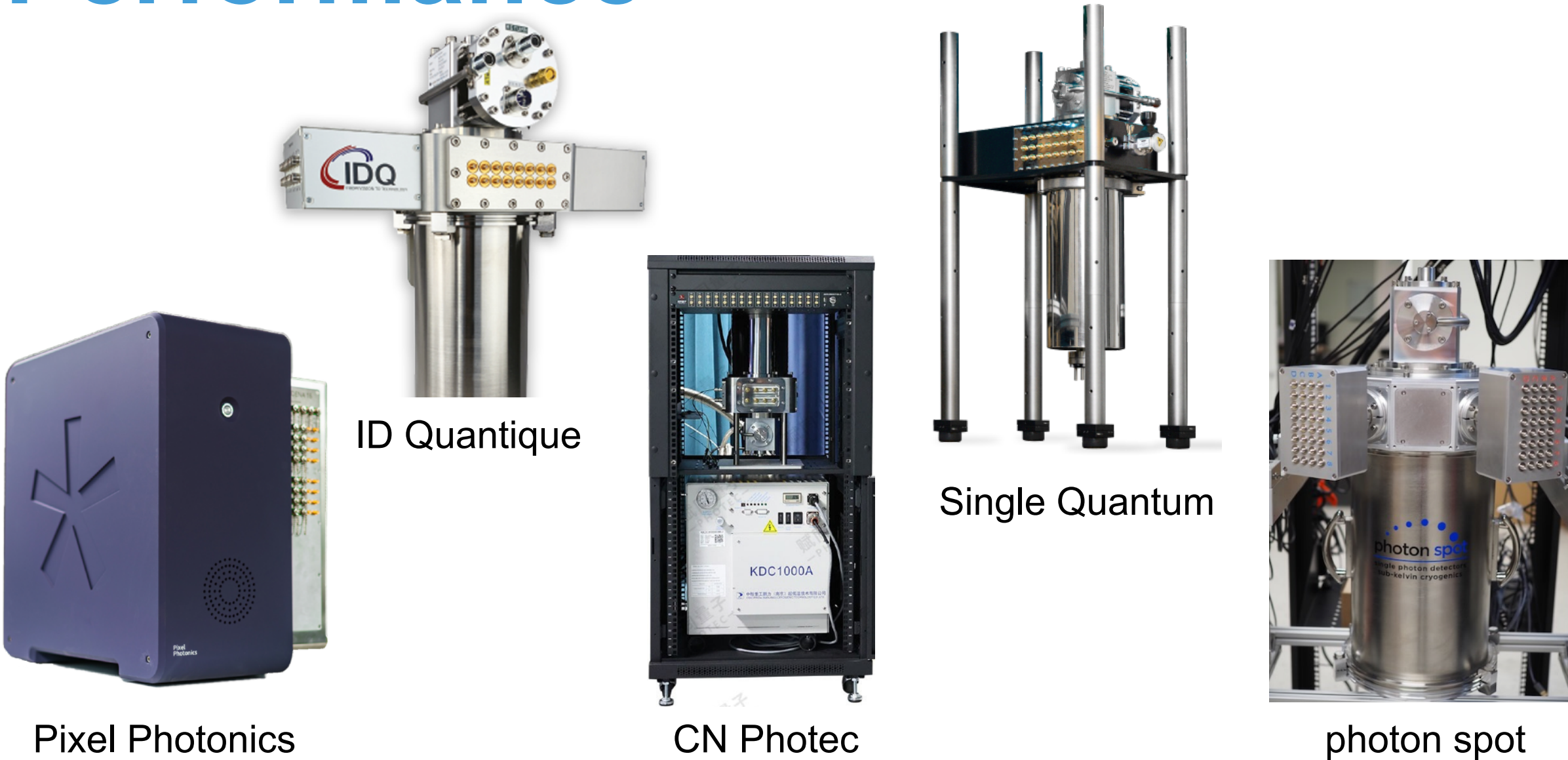
Expected performance by 2030

[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)

SNSPD: Commercial Products & Performance

- Many commercial devices available
 - 1550 nm (single fibre)
 - Arrays available (cameras), e.g. 64 pixel
 - Quantum optics, quantum communications, QKD
- Excellent performance for single-photon detection
 - Extremely high rates possible
 - Very low dark counts
- Work for HEP?



Detector	η [%] @1550 nm	Dark count rate	Timing jitter	Max. count rate
PMT	~2	100s Hz-100s kHz	~100s ps	~10s MHz
SPAD	~10	10s Hz-10s kHz	10s-100s ps	10s kHz-100 MHz
SiPM	0	10s kHz-10s MHz	~100s ps	~10s MHz
SNSPD	~60	~Hz	~10s ps	100s MHz-1 GHz
TES	~50-~95	~Hz	~100s ns	~100 kHz

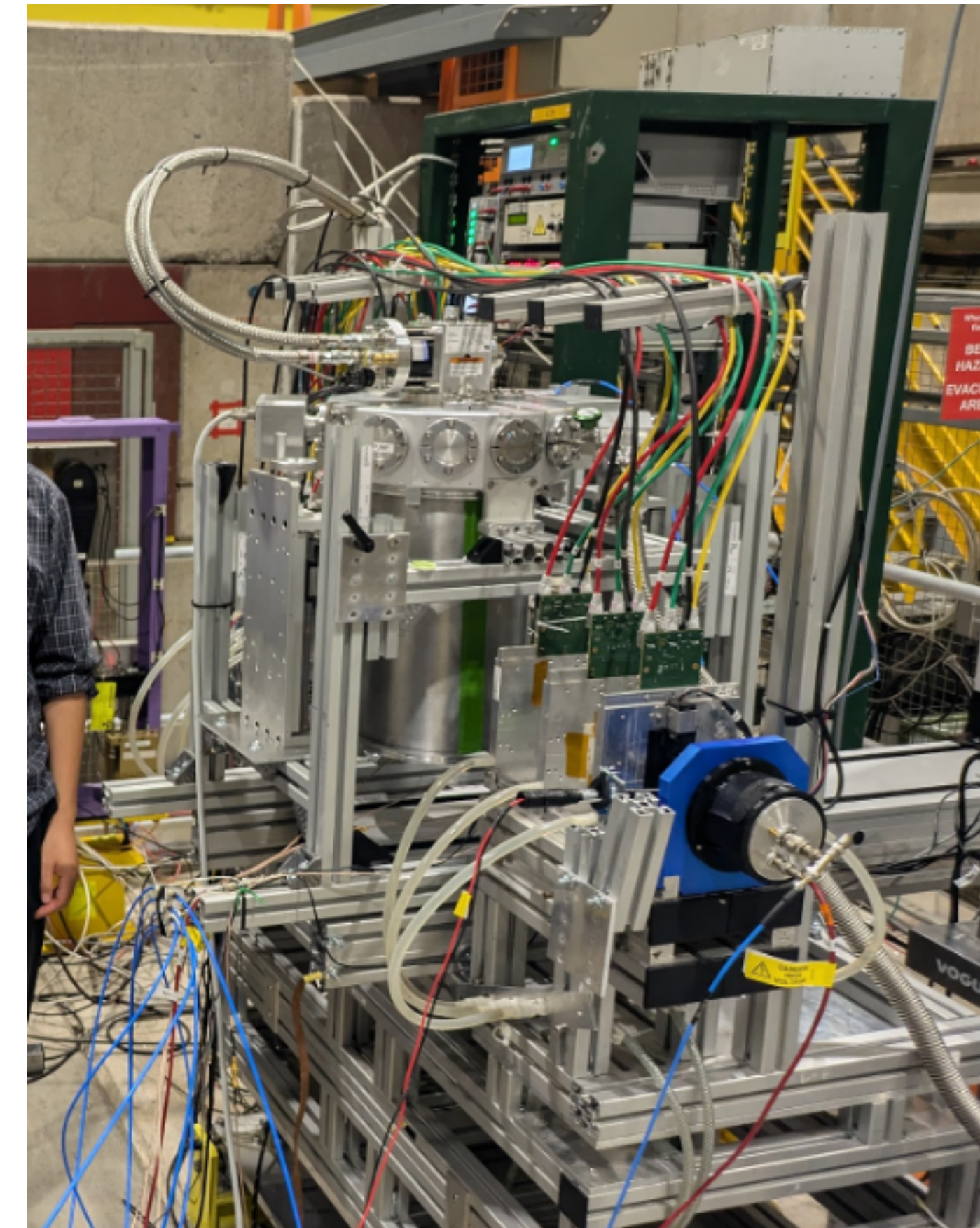
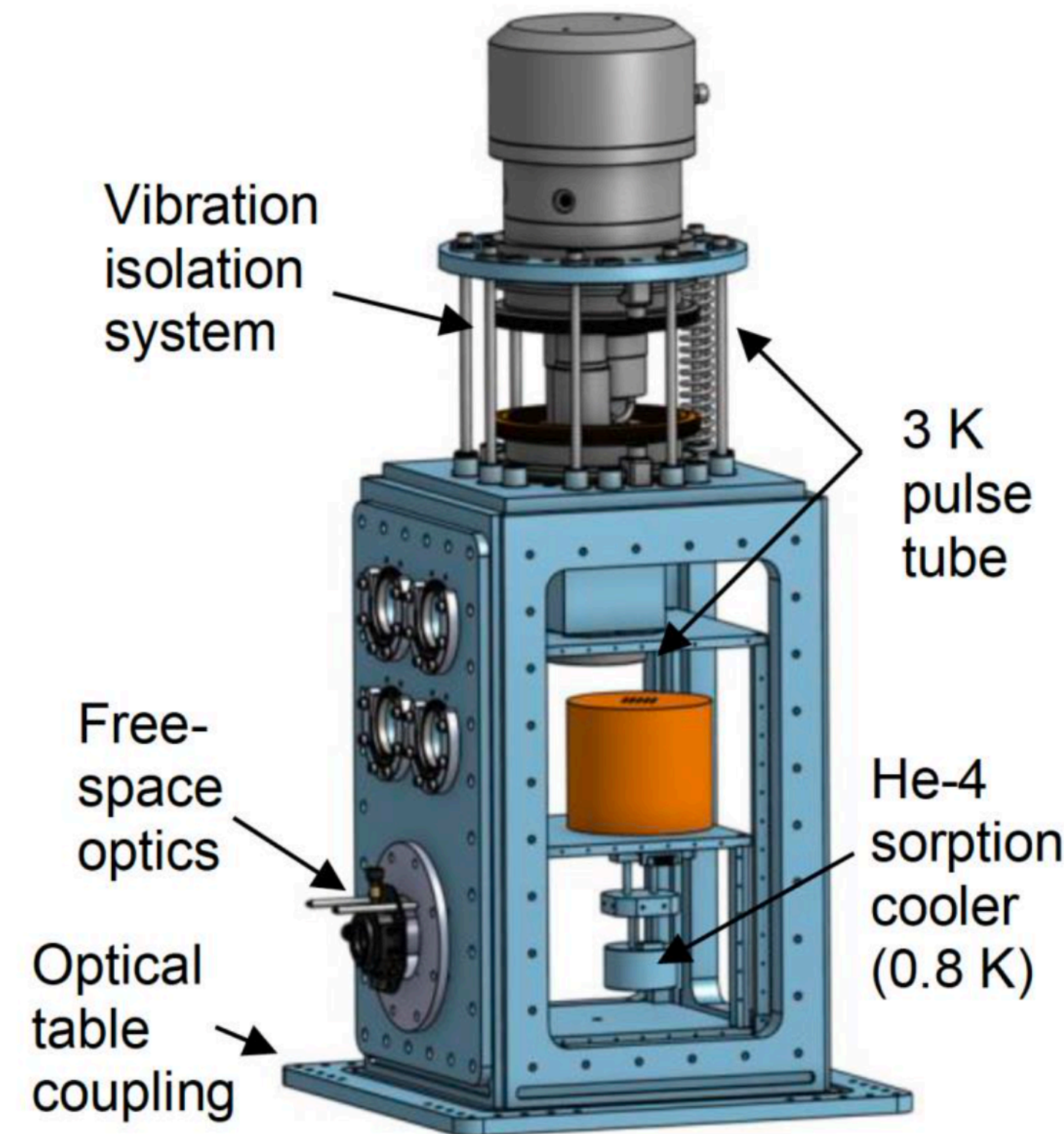
CERN Test Beam Platform for Quantum Technologies

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

📍 31/3-004 - IT Amphitheatre (CERN)

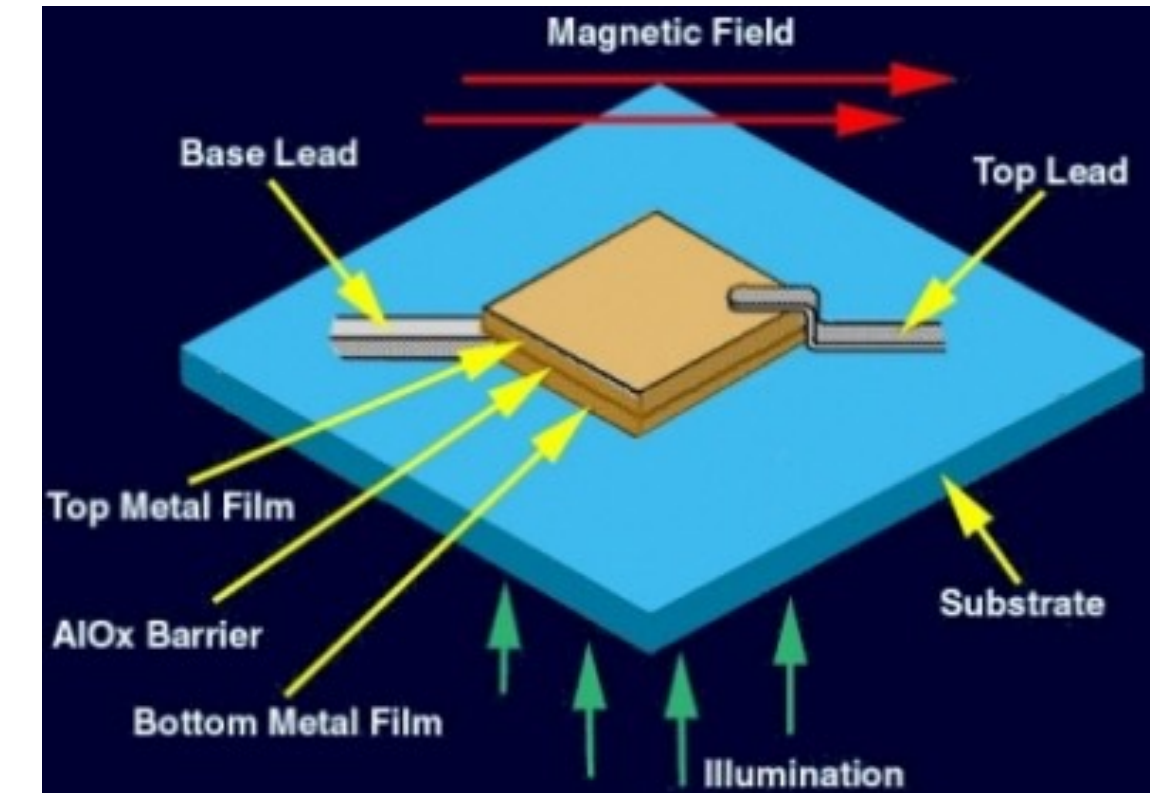
<https://indico.cern.ch/event/1580512/>

- Sessions covered:
 - Testbeam Setup & Experience
 - Quantum Scintillators
 - DRACuLA: a sub-Kelvin facility
 - SNSPD Use Case
- Example talk: B. Korzh (U. Geneva)
 - Testbeam experience from 2025, and plans to improve setup for the future
- Developed in collaboration with the DRD5 Collaboration

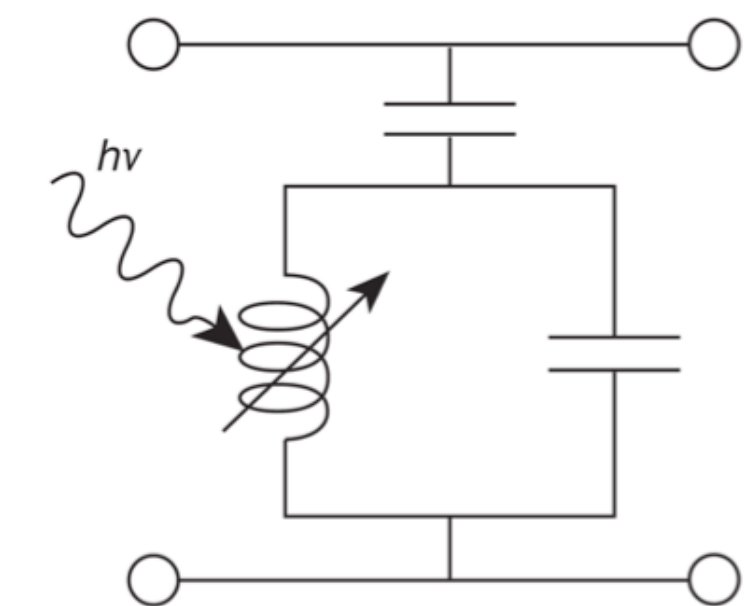


Cryogenic Quantum Sensors

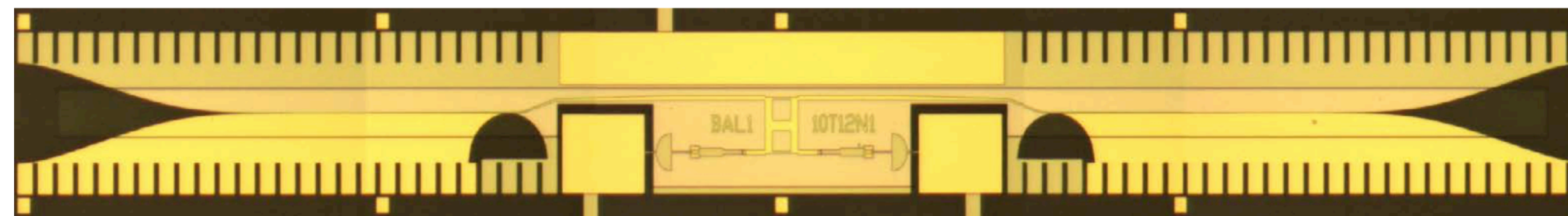
- Superconducting Tunnel Junctions (STJ)
 - Exploit quantum tunnelling in a junction of two superconductors
 - Direct tunnel current measurement (non-Heterodyne): simultaneous fast photon counting and spectroscopy in IR, Vis, UV bands
- Microwave Kinetic Inductance Detectors (MKIDs)
 - Exploits change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



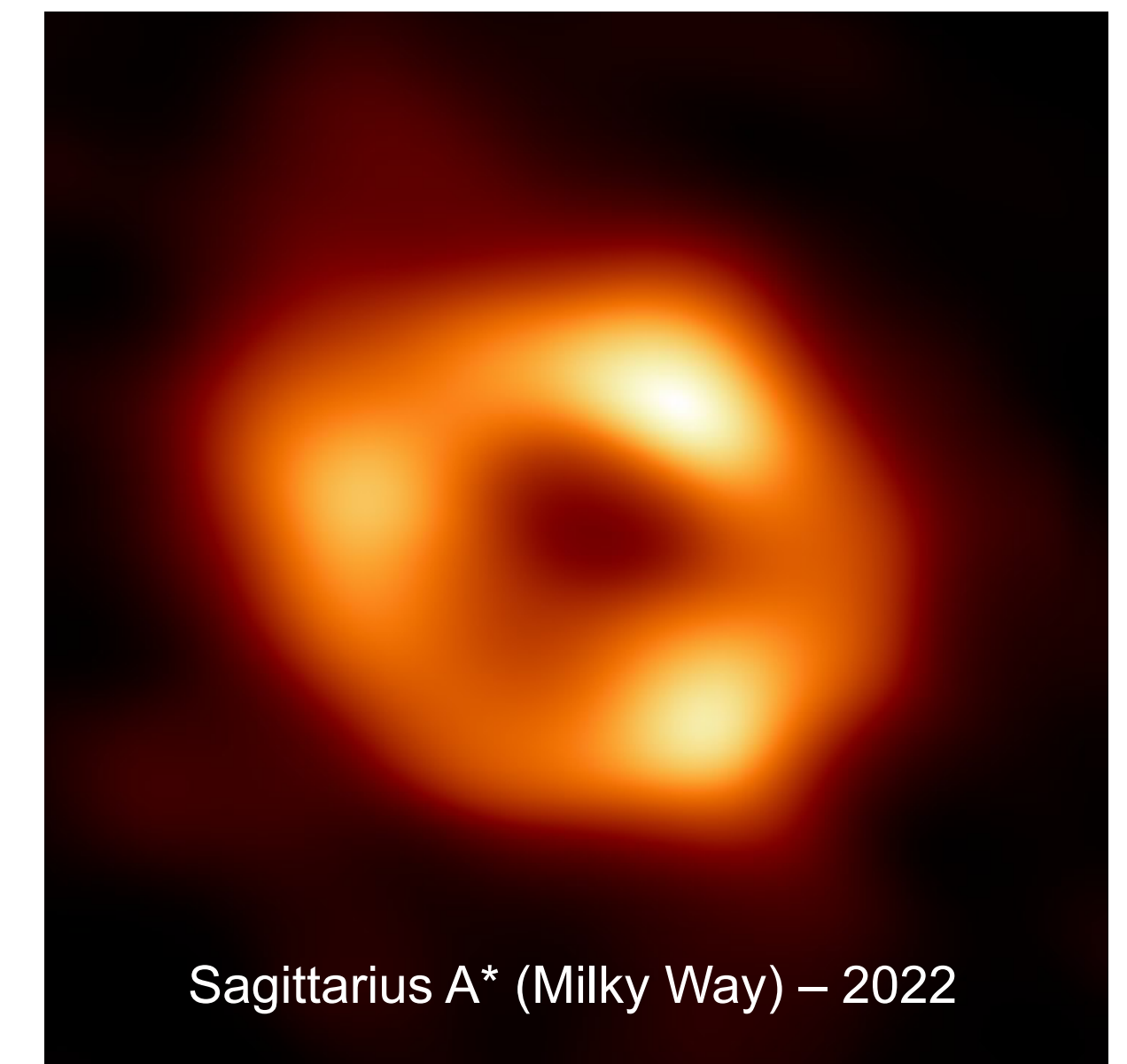
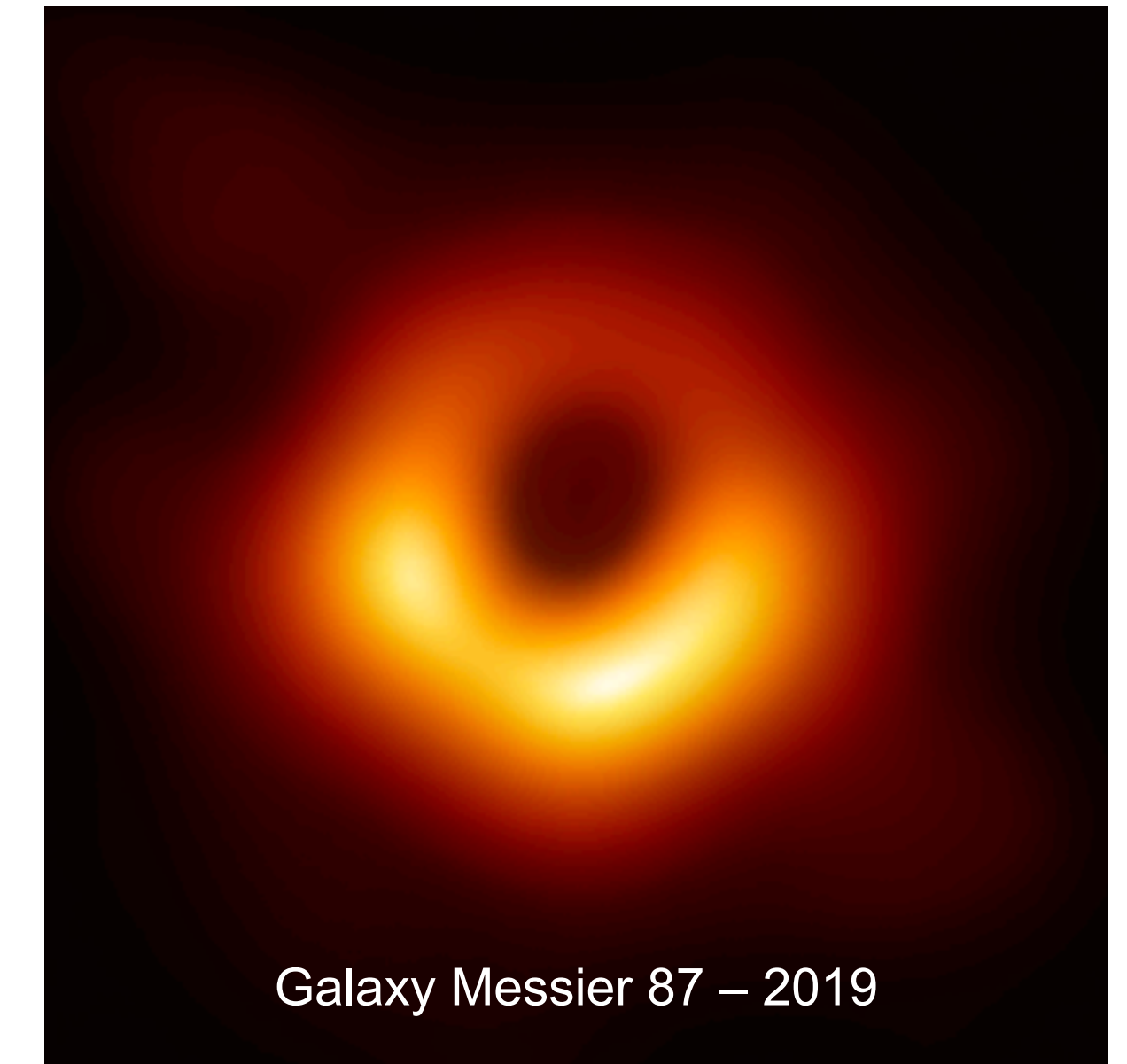
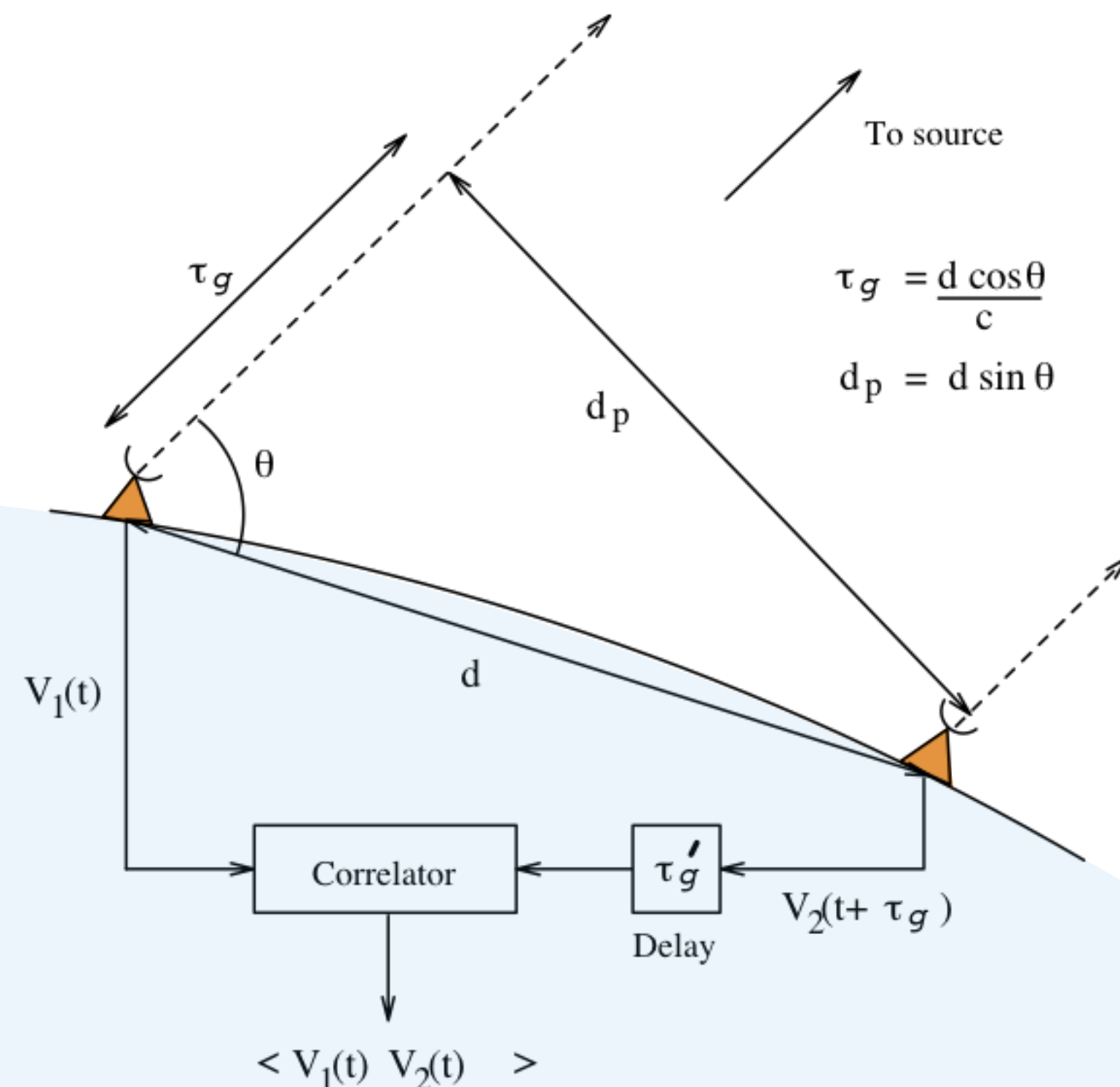
MKID operating principle



Superconductor-Insulator-Superconductor (SIS) Mixer Block

Event Horizon Telescope, VLBI and Quantum

- Cryogenic receivers/amplifiers/mixers used for mm wave astronomy
- Very Long Baseline Interferometry also requires precision timing
- Local stability: hydrogen maser (10^{-15}) at each telescope
- Synchronisation to single-ns precision via GNSS (GPS)
- First image of a black hole: M87



Cryogenic Quantum Sensors vs. Wavelength

Detector	Microwave	Submillimeter	Far infrared	Optical	High Energy
	3cm - 3mm	3mm - 300μm	300 – 30 μm	2 μm - 300 nm	UV, X-Ray
	10-100 GHz	100 GHz - 1 THz	1 – 10 THz		
	0.04-0.4 meV	0.4-4 meV	4-40 meV	2-37 eV	
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

- **Quantum dots:** nanometer-sized semiconductor structures
- Can be carbon structures, crystals (e.g. perovskites – ABX_3), etc.
- Tuneable, with properties between single atoms and bulk material
- Many creative uses being explored for particle physics
- Seed different parts of a detector with nanodots emitting at different wavelengths

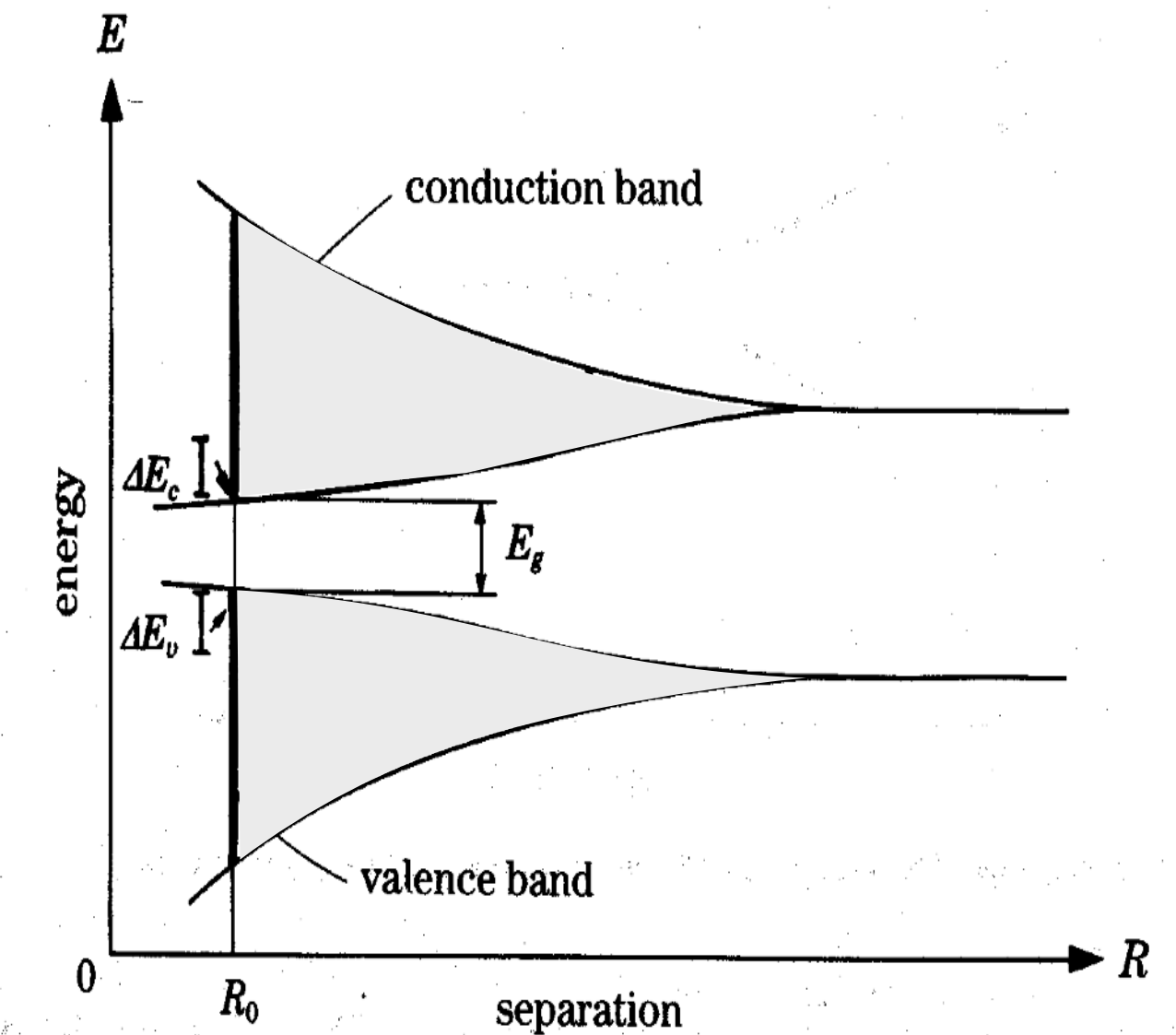
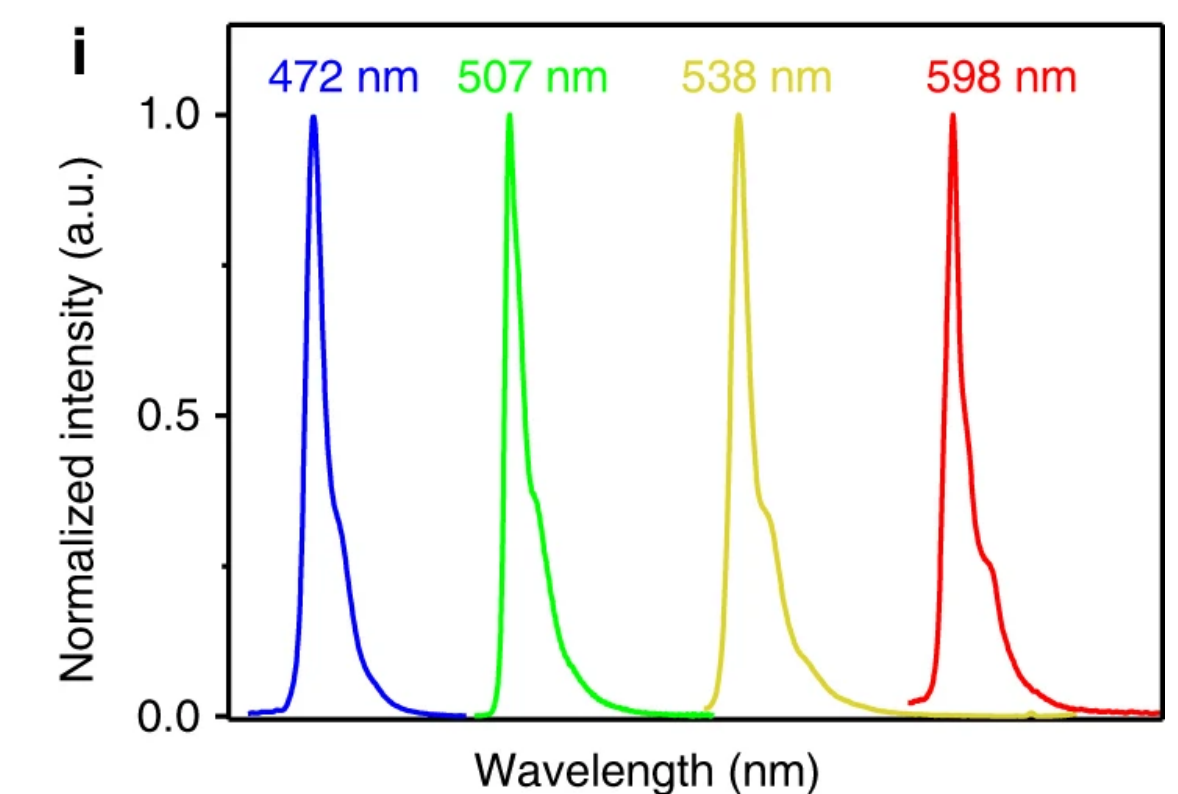
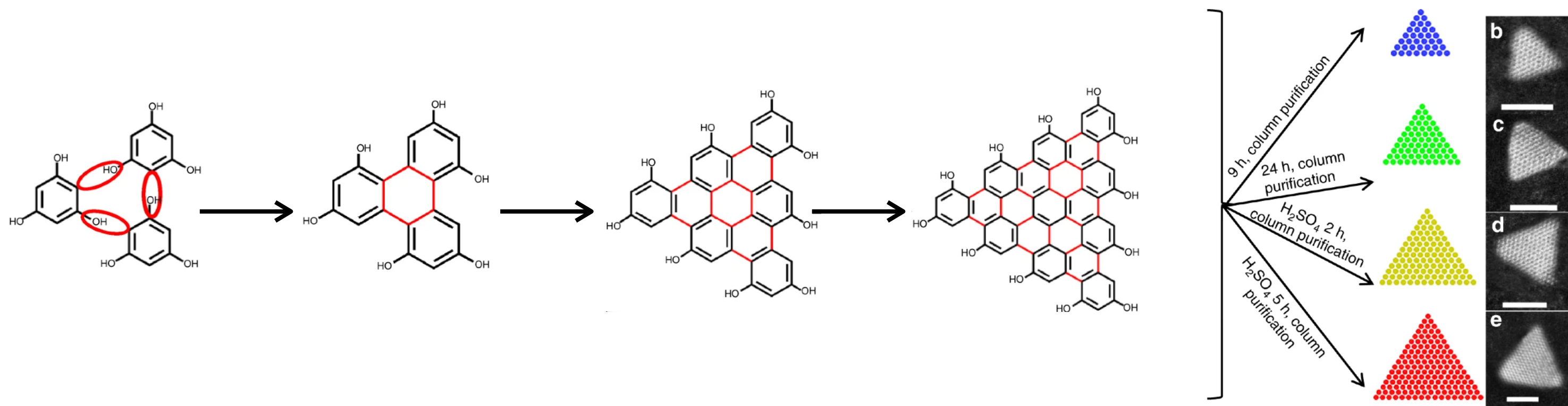
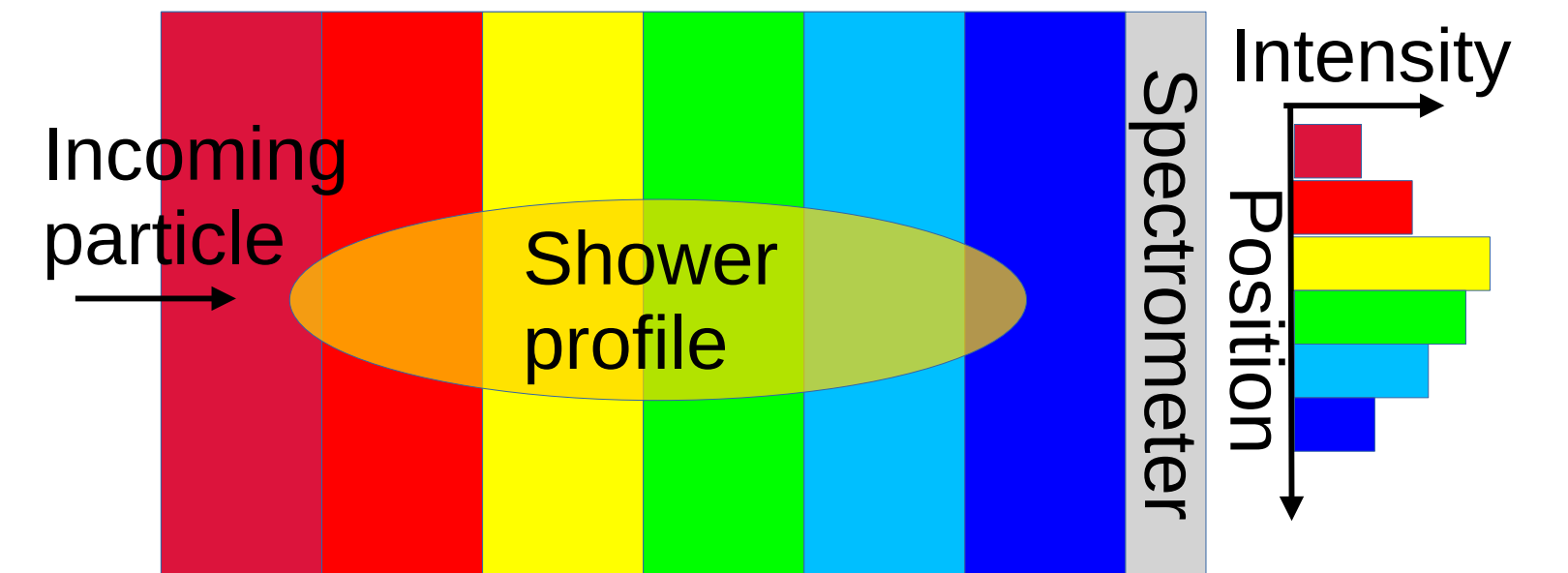
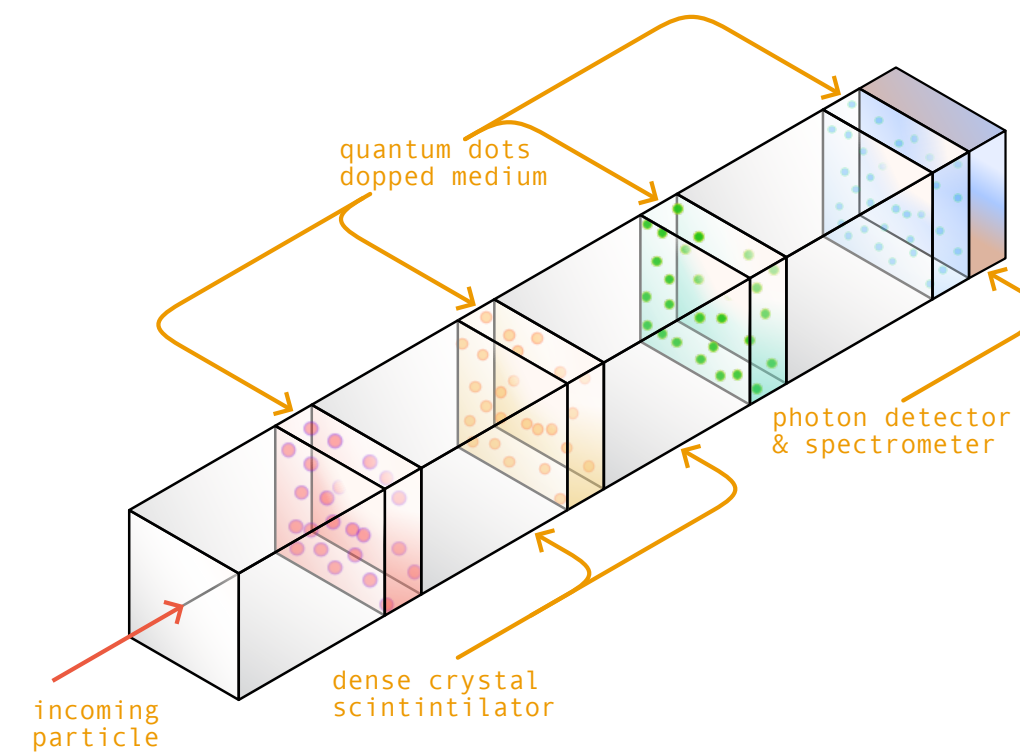
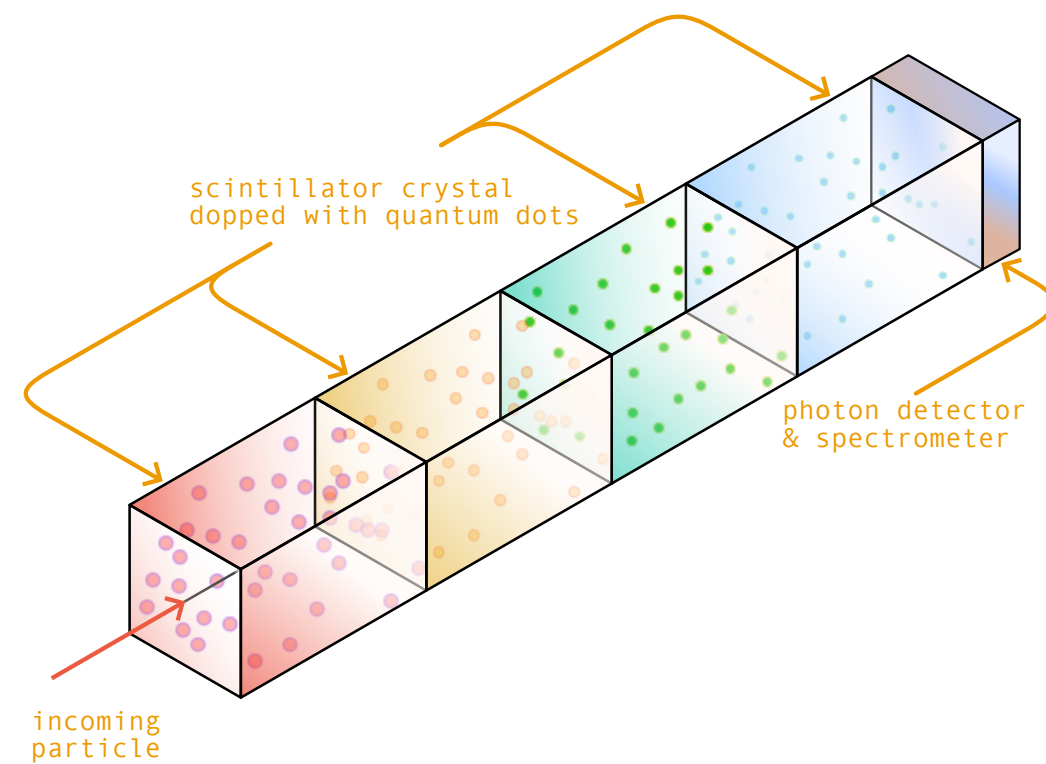


Fig. 1.2. Energy levels in a system of N atoms as a function of the separation R between the atoms. The equilibrium atomic separation is R_0 .

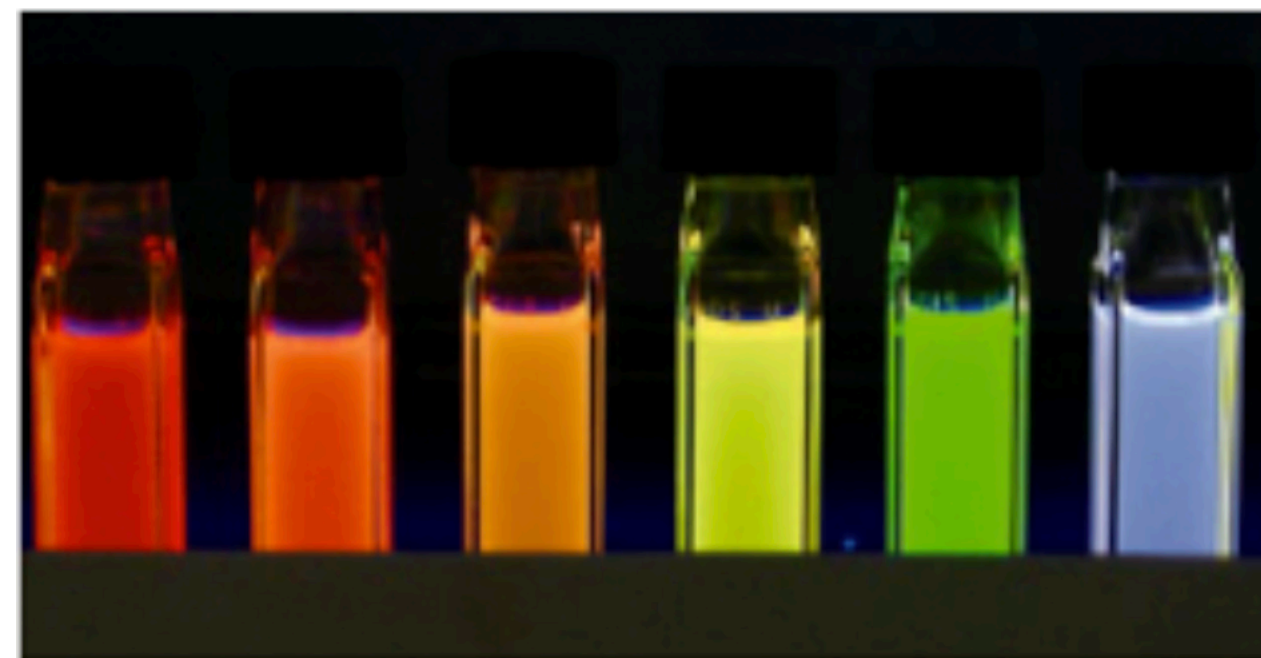


Quantum Dots and Chromatic Calorimetry

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

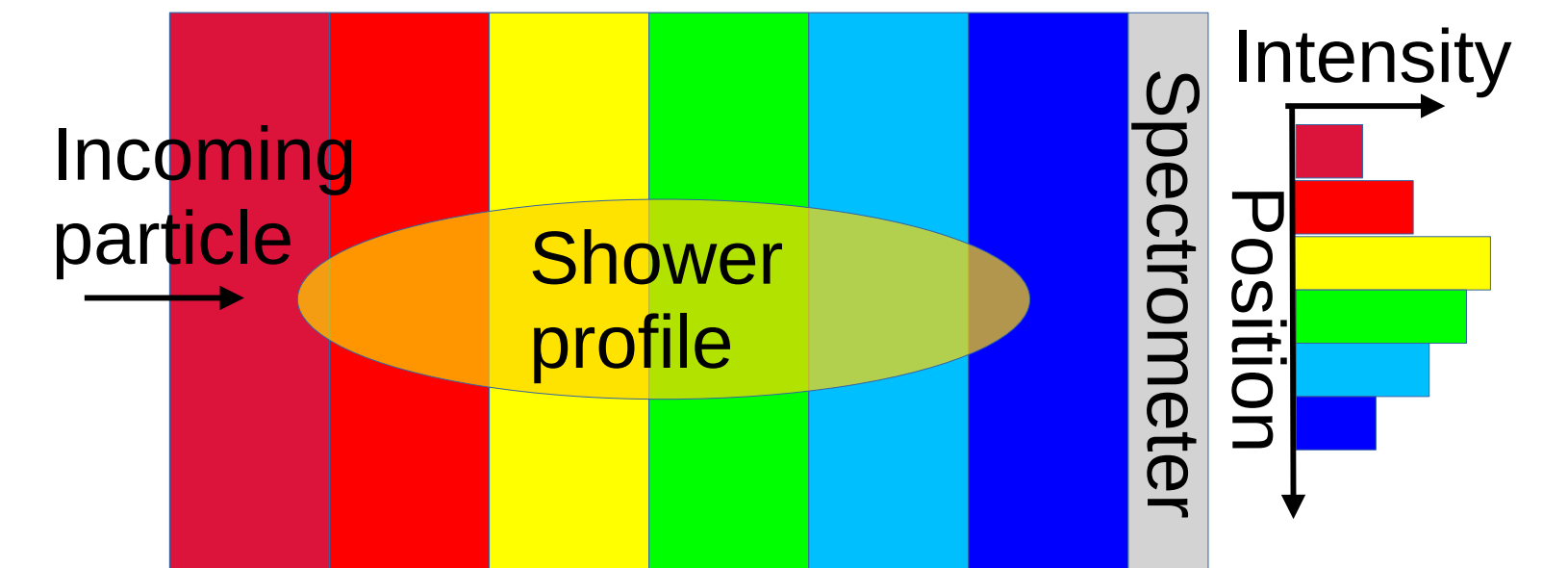
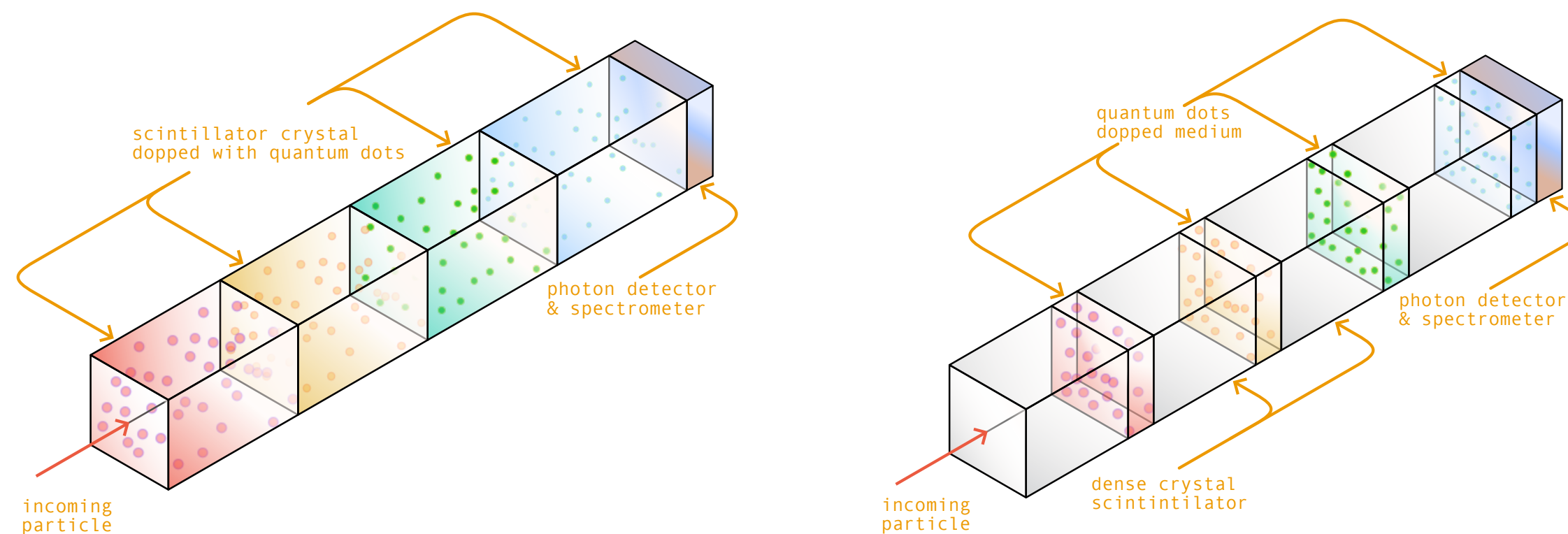


- Requires: narrowband emission (~ 20 nm) with short rise / decay times
- Absorption only at longer wavelengths

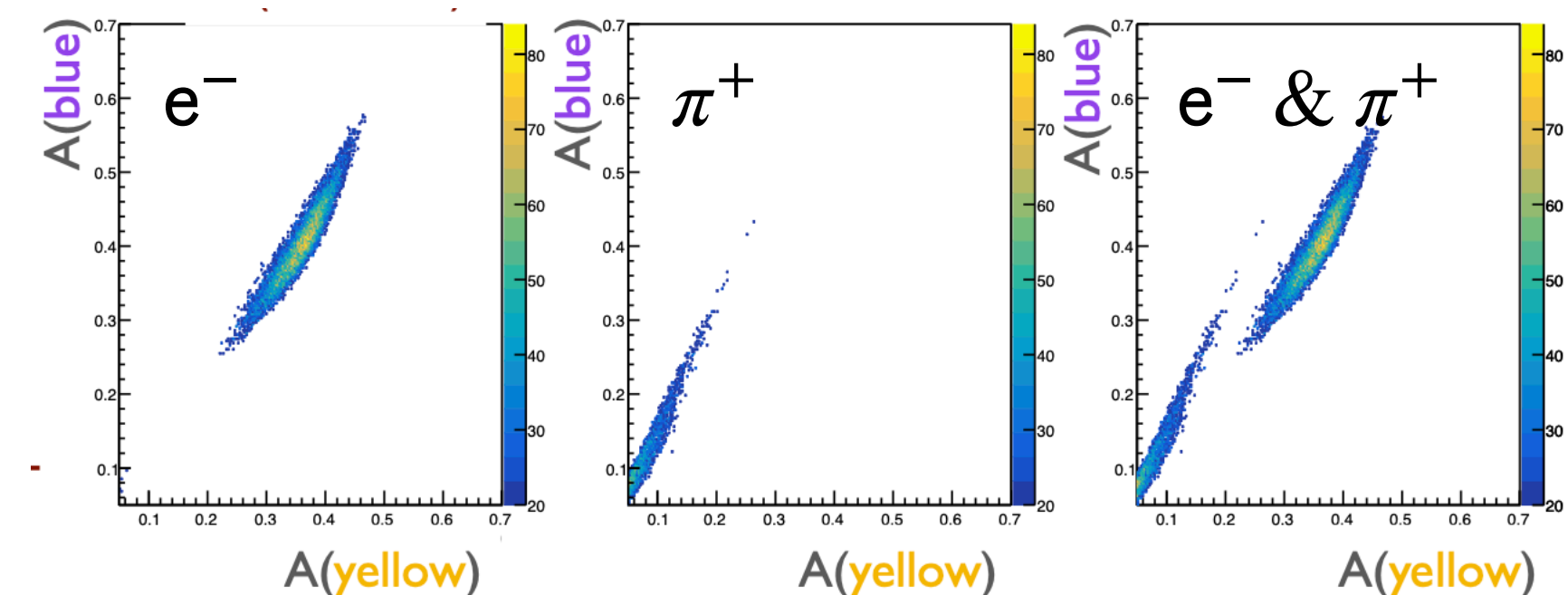
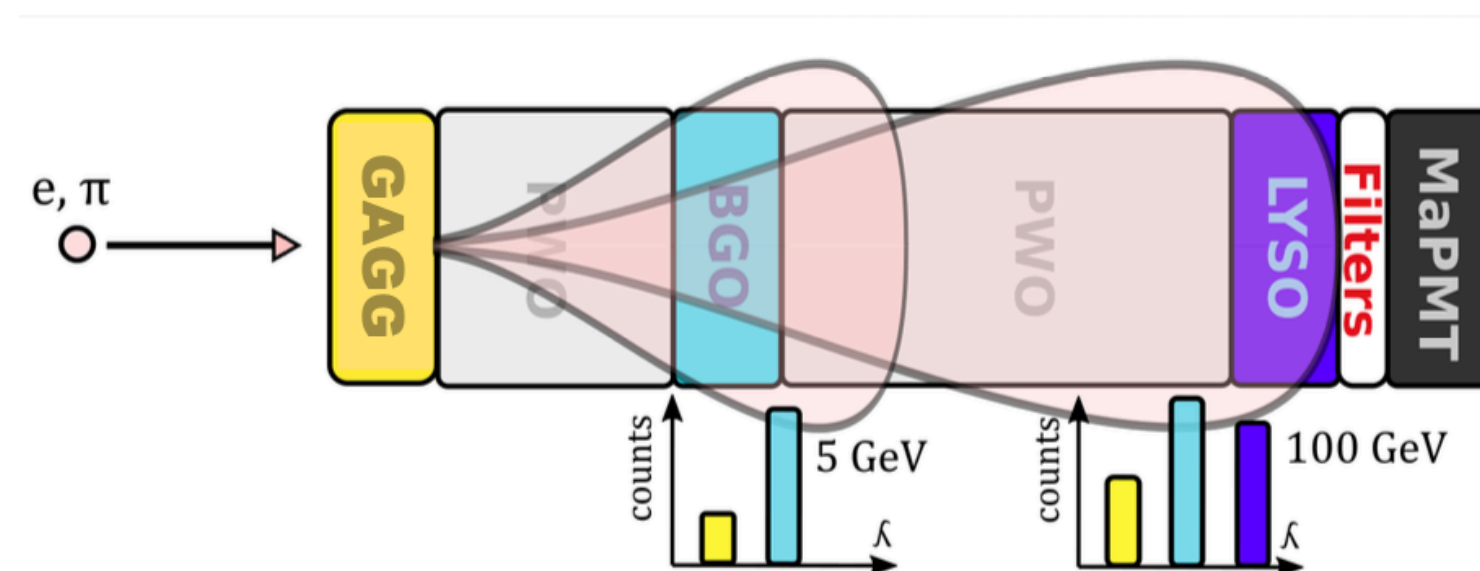


Quantum Dots and Chromatic Calorimetry

- Seed different parts of a detector with nanodots emitting at different wavelengths
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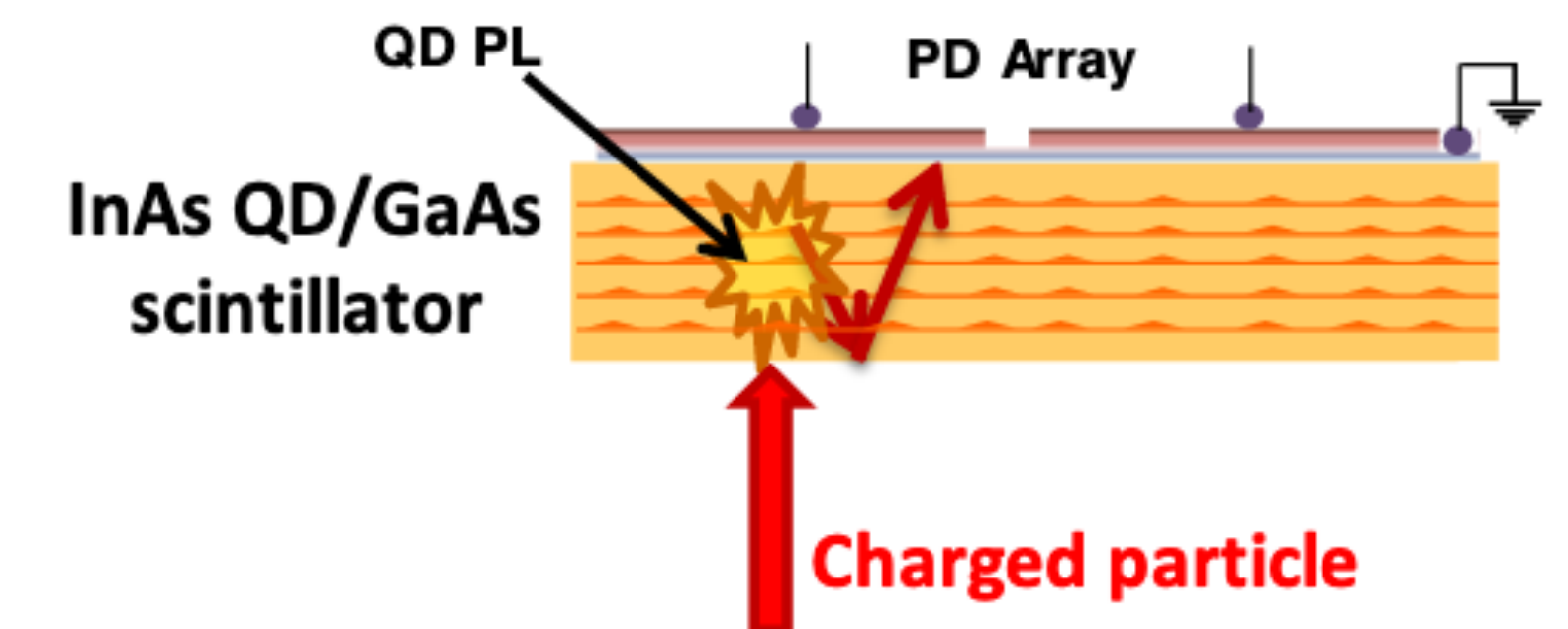
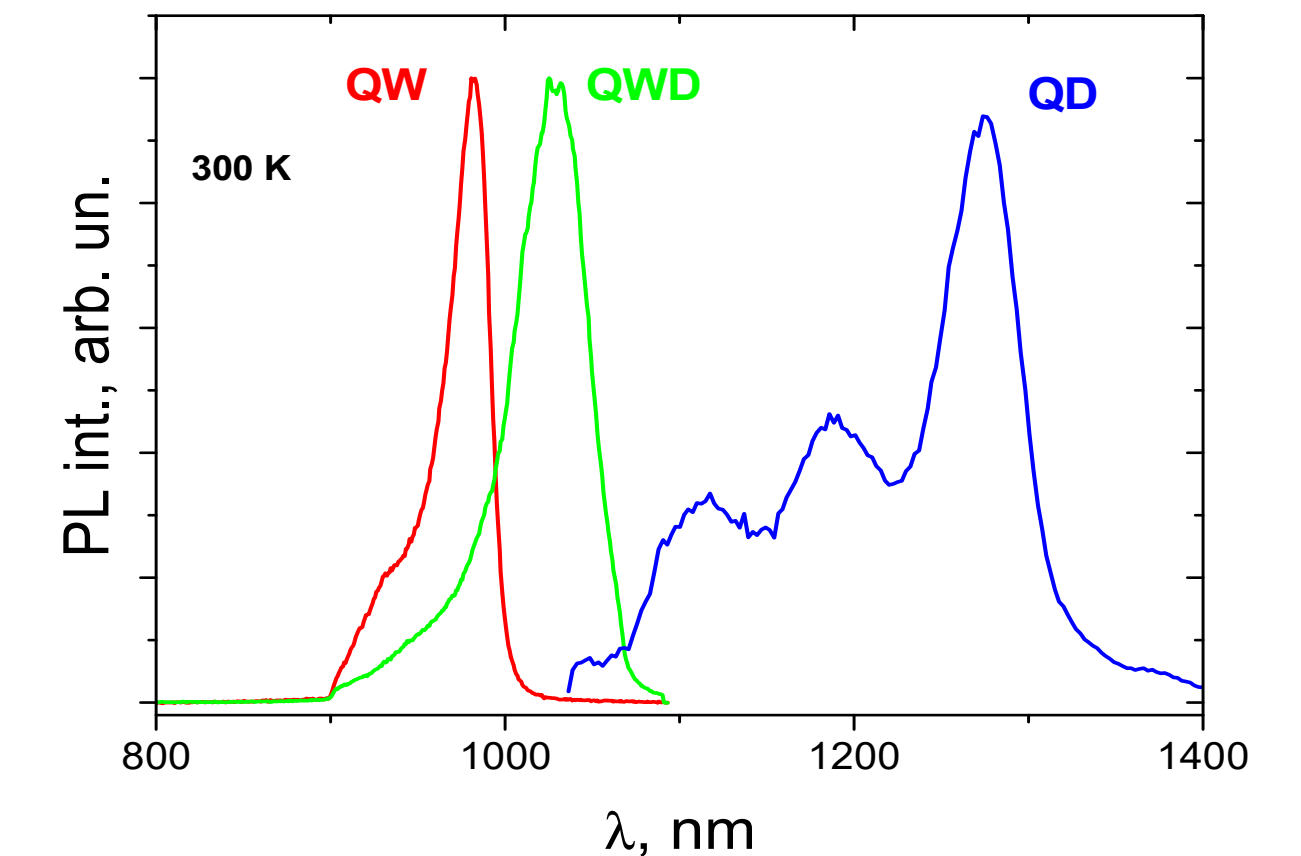
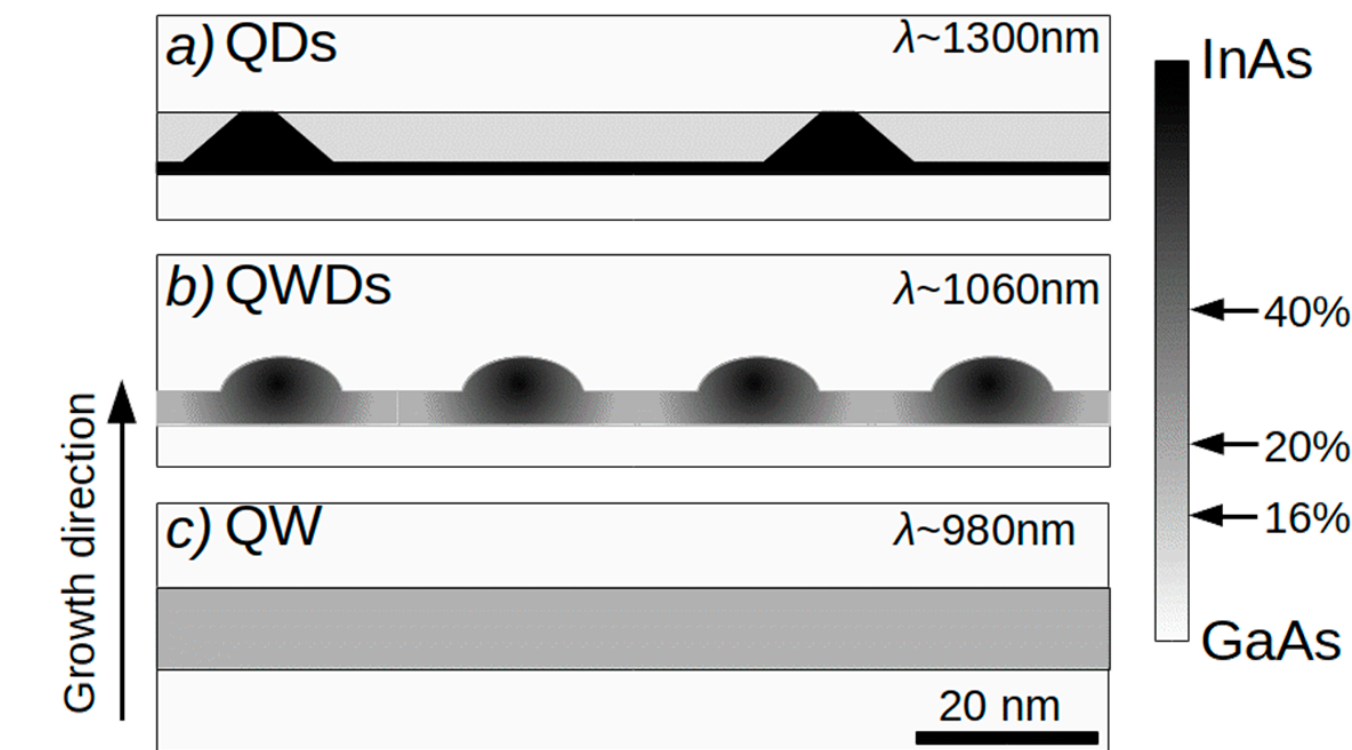


- Requires: narrowband emission (~ 20 nm) with short rise / decay times
- Absorption only at longer wavelengths
- Proof-of-principle CERN testbeam 2023



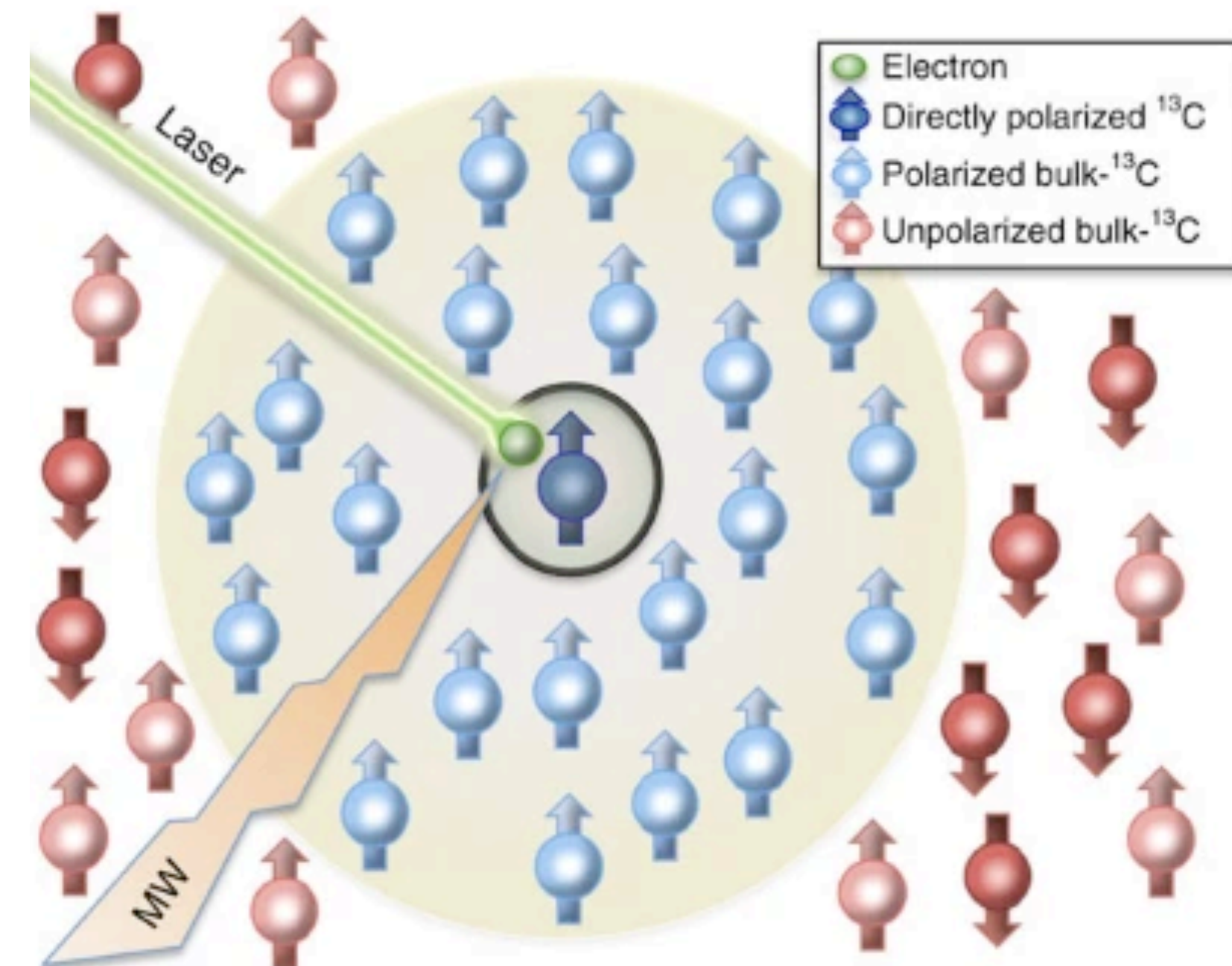
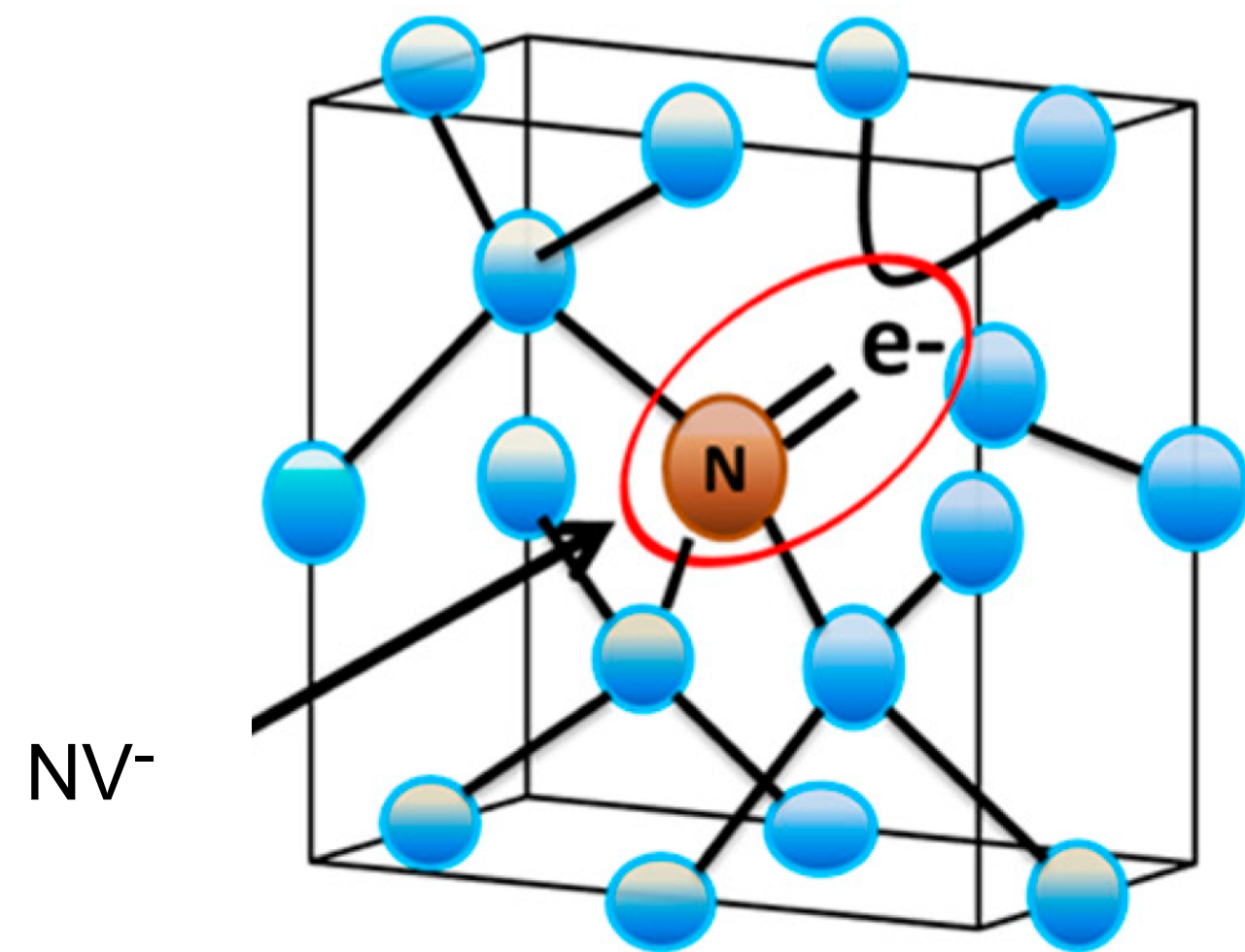
Quantum Dots: Active Scintillators & Tracking

- 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
- Also timing (10's of ps response) and as wavelength shifters (of course)



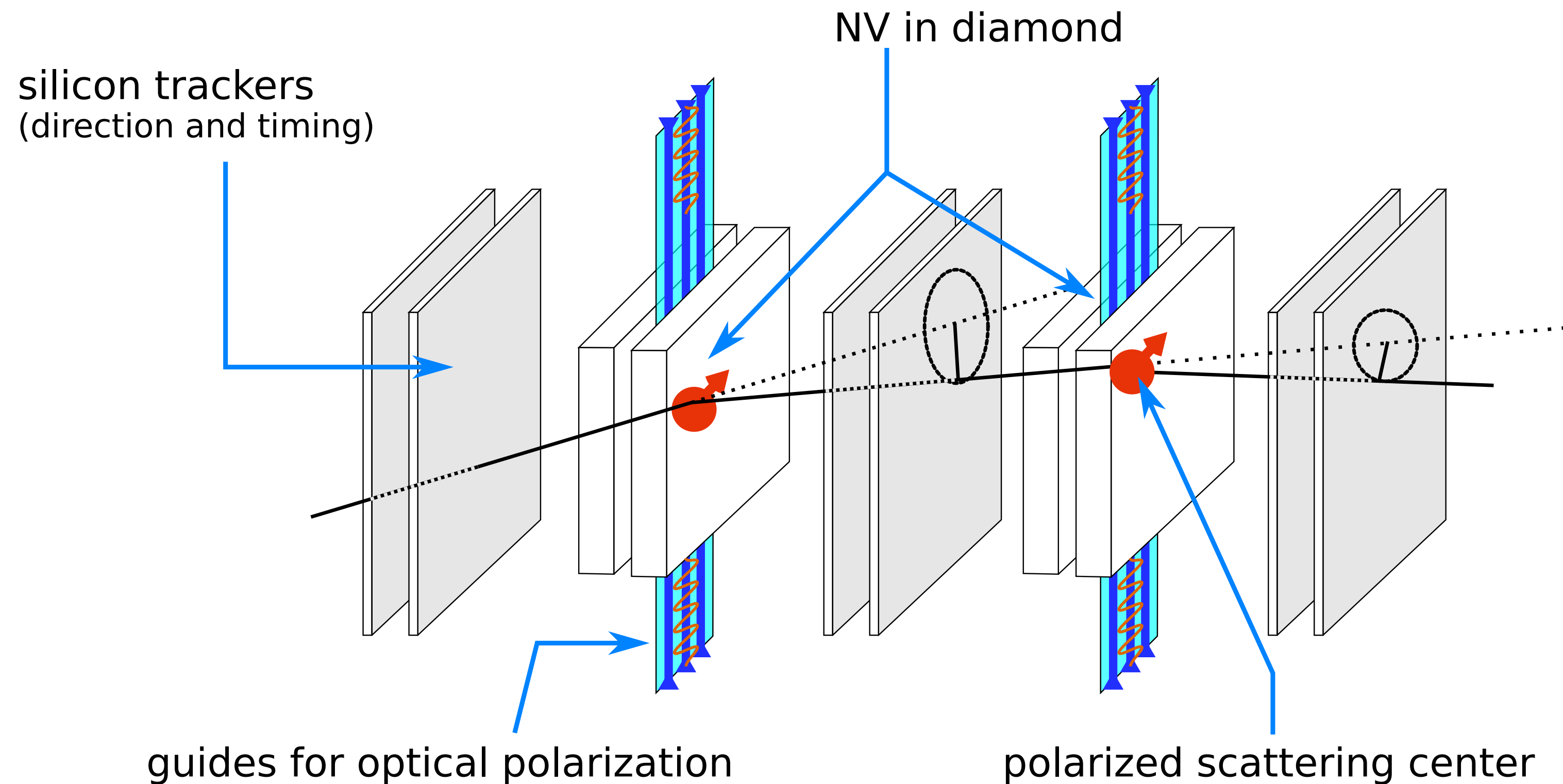
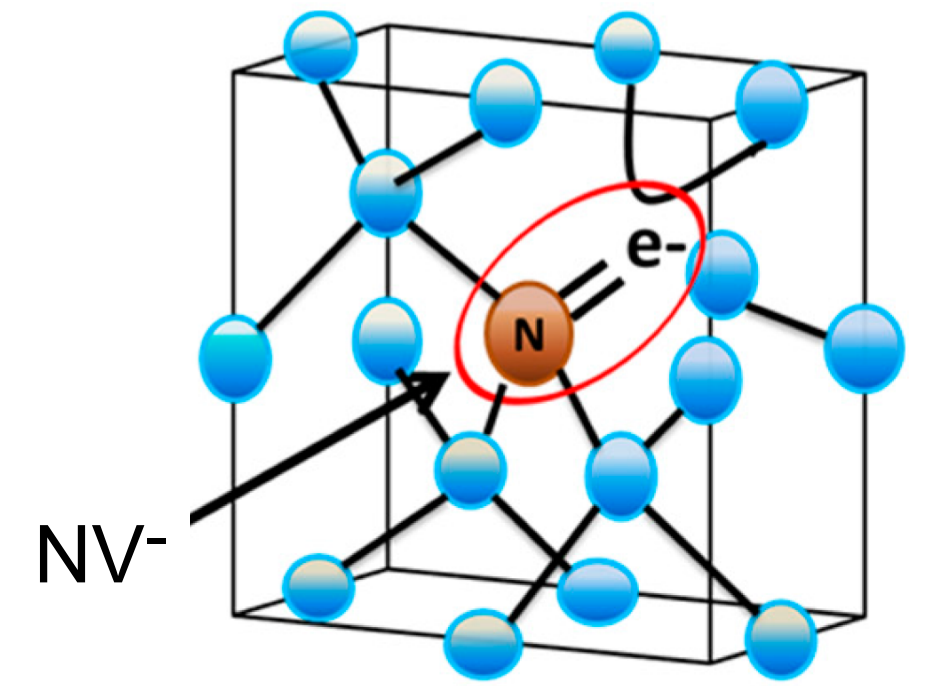
Quantum-Polarized Helicity Detection in NV Centres

- 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
- Useful for helicity determination in particle physics?



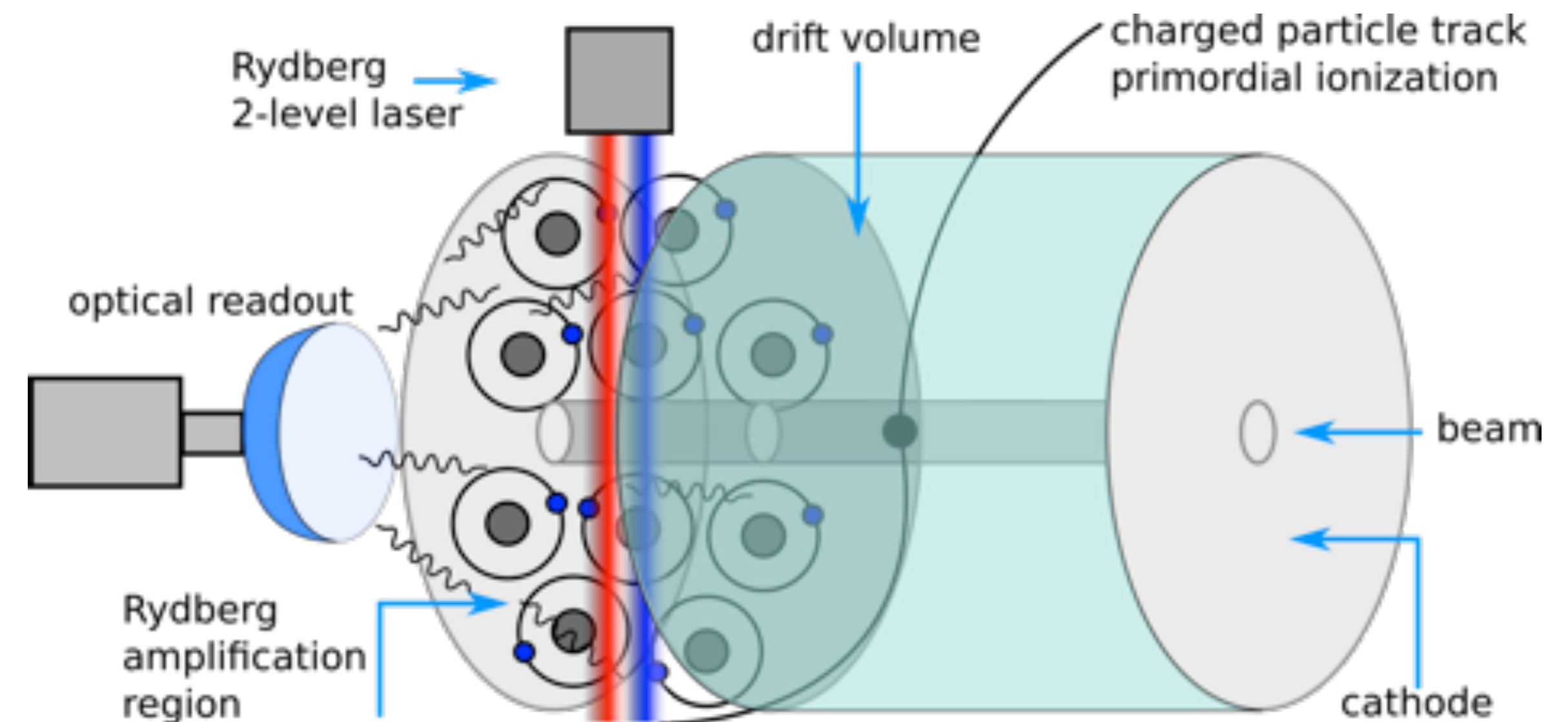
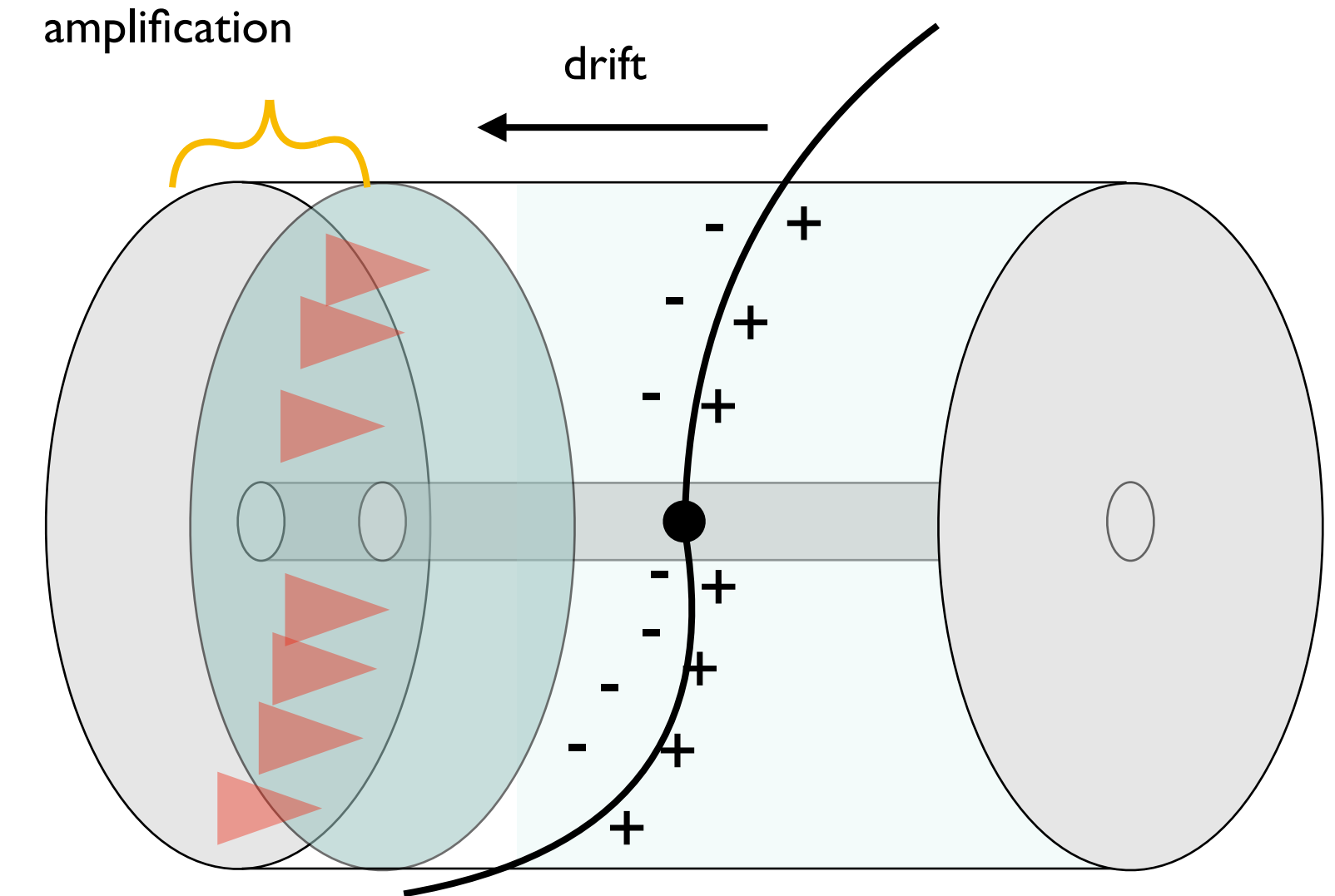
Quantum-Polarized Helicity Detection in NV Centres

- NV centre acts as optically polarisable element
- 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



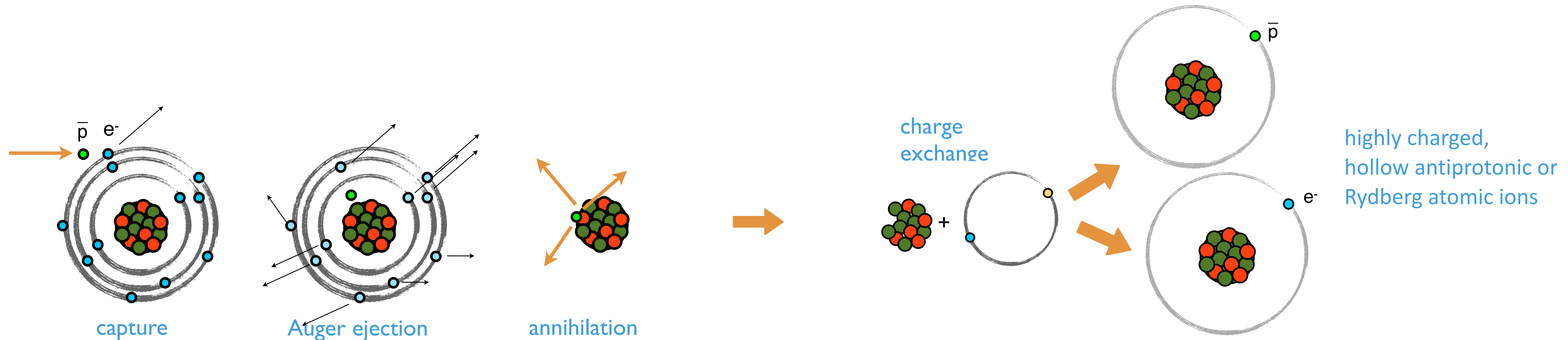
Quantum Sensing and Rydberg Atoms

- Rydberg atoms: highly excited valence electrons
 - Electron in high n orbital
 - High sensitivity to magnetic and electric fields
 - Can have long lifetime
 - Polarisation from anisotropic potential
- Q: What can you do with these in Particle Physics?
- Rydberg readout of a Time Projection Chamber
 - Up-convert THz / GHz radiation $\rightarrow$ optical readout
 - Larger signal via Rydberg “priming” in amplification
 - Lower ionization threshold $\rightarrow$ higher electron yield



Quantum Sensing and Rydberg Atoms

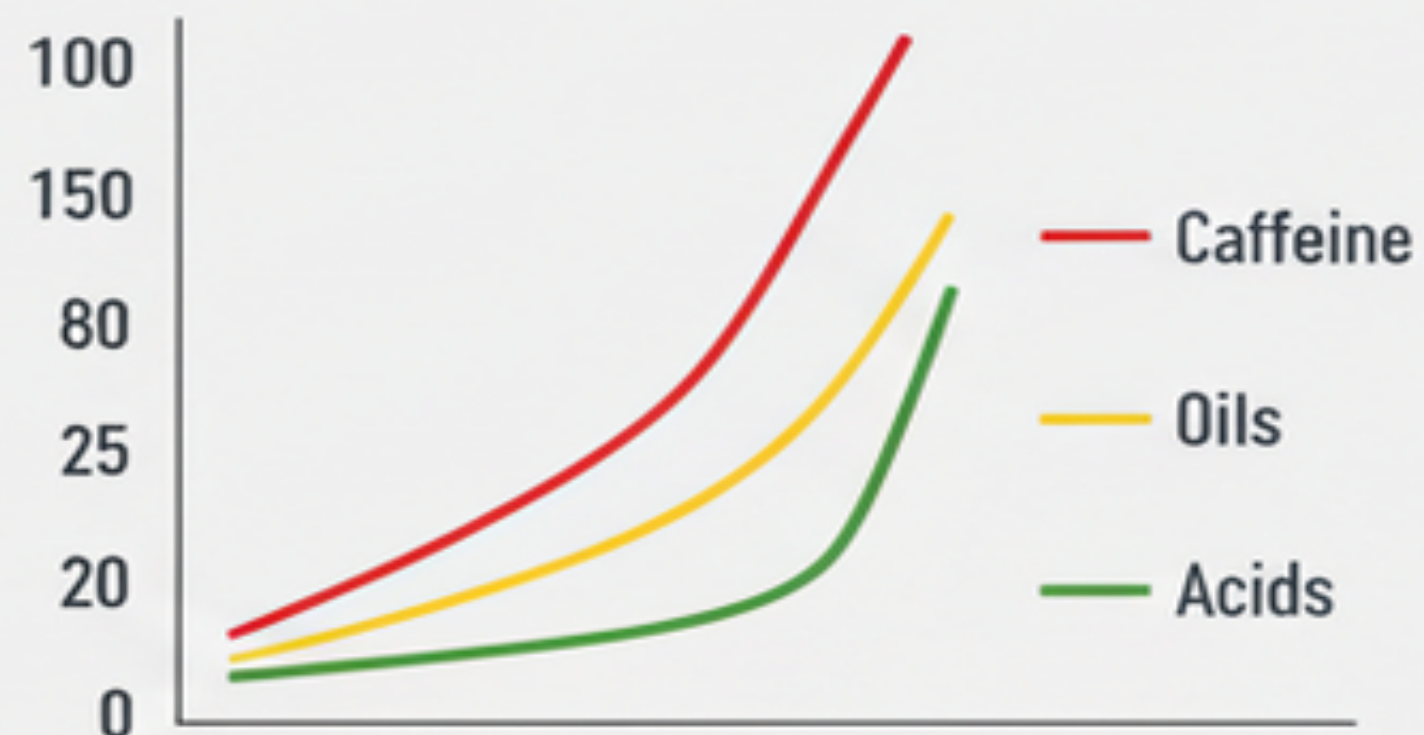
- Antiprotonic atoms and novel Highly Charged Ion systems
 - Anti-proton tests in Penning trap for HCLs or molecules
 - Tests of QED, CPT, fundamental constants, fifth force, precision isotope shift (King plot), EDM measurements
- New atomic systems and extreme environments → new physics!



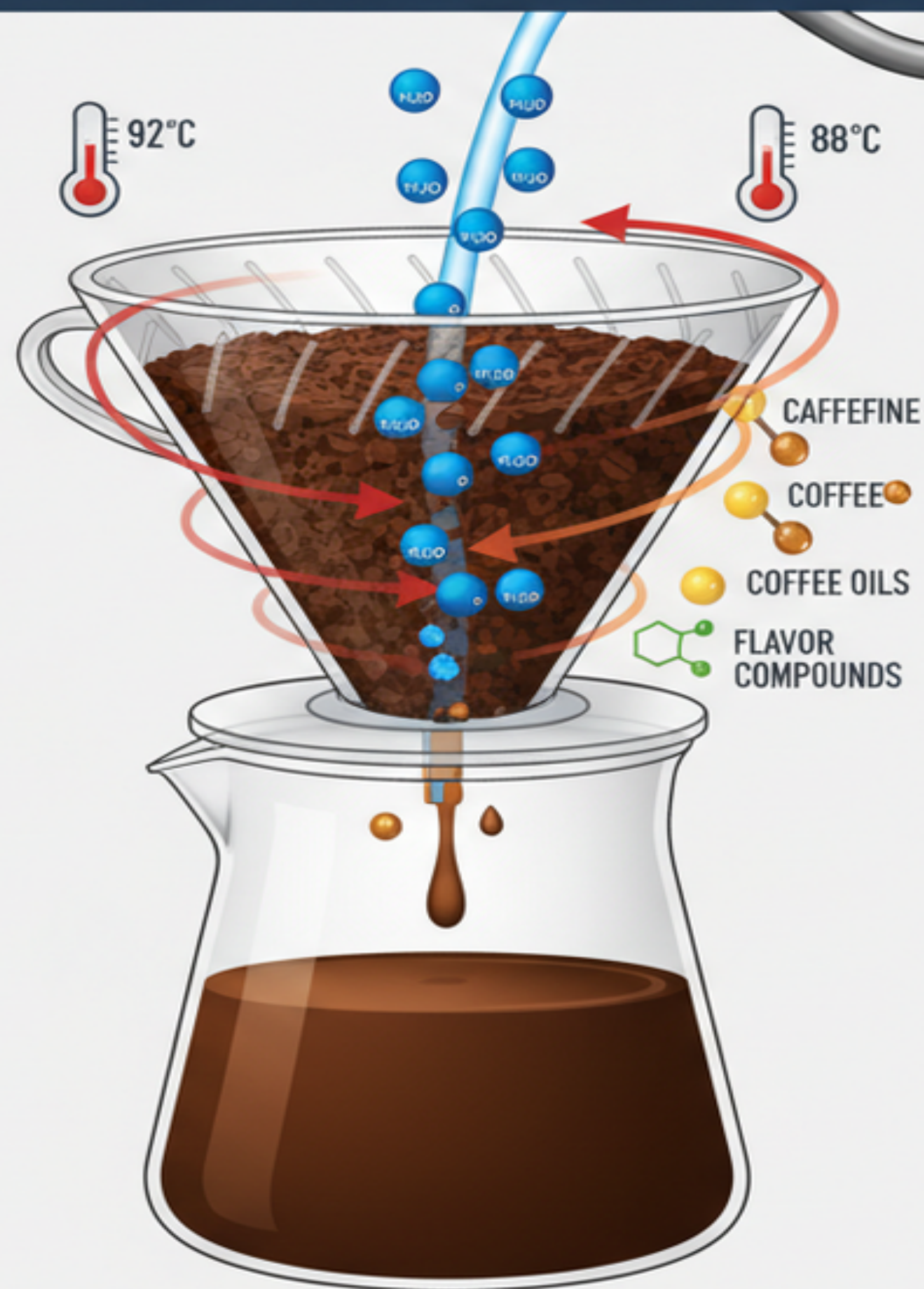
COFFEE EXTRACTION KINETICS



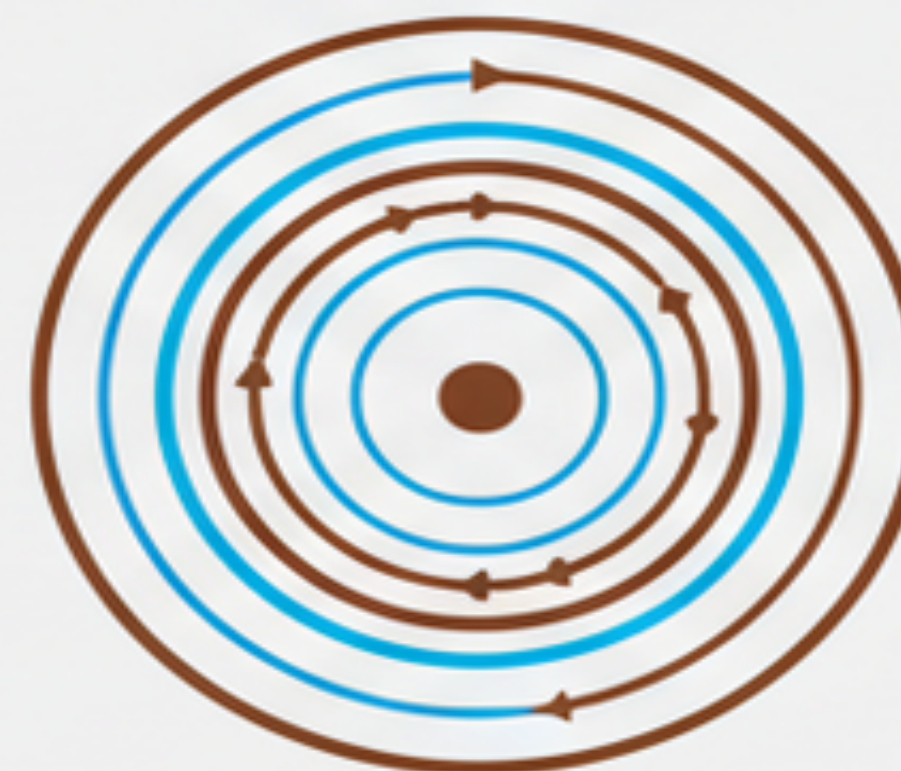
EXTRACTION YIELD (%)
vs. TIME (min)



SOLUSIIBITY vs TEMPERATURE (°C)



PARTICLE DIFFUSION



Quantum Sensing for Particle Physics – Outline

Tuesday Sept. 8, 9:00

- Quantum Sensing:
 - What it is, and why you should be interested
 - Selected cryogenic sensors: TES, MMC, SNSPD
 - Quantum dots and other quantum sensing ideas

Wednesday Sept 9, 10:10

- Quantum Experiments:
 - A new path to discovery
 - The search for light Dark Matter
 - Fundamental physics and the variation of fundamental constants

Thursday Sept. 10, 11:20

- Quantum in the lab: searching for Dark Matter with an Atomic Clock(!?)
 - Practical considerations and headaches
 - The path from data to discovery
 - Ideas for the future

Quantum Detectors, Quantum Experiments

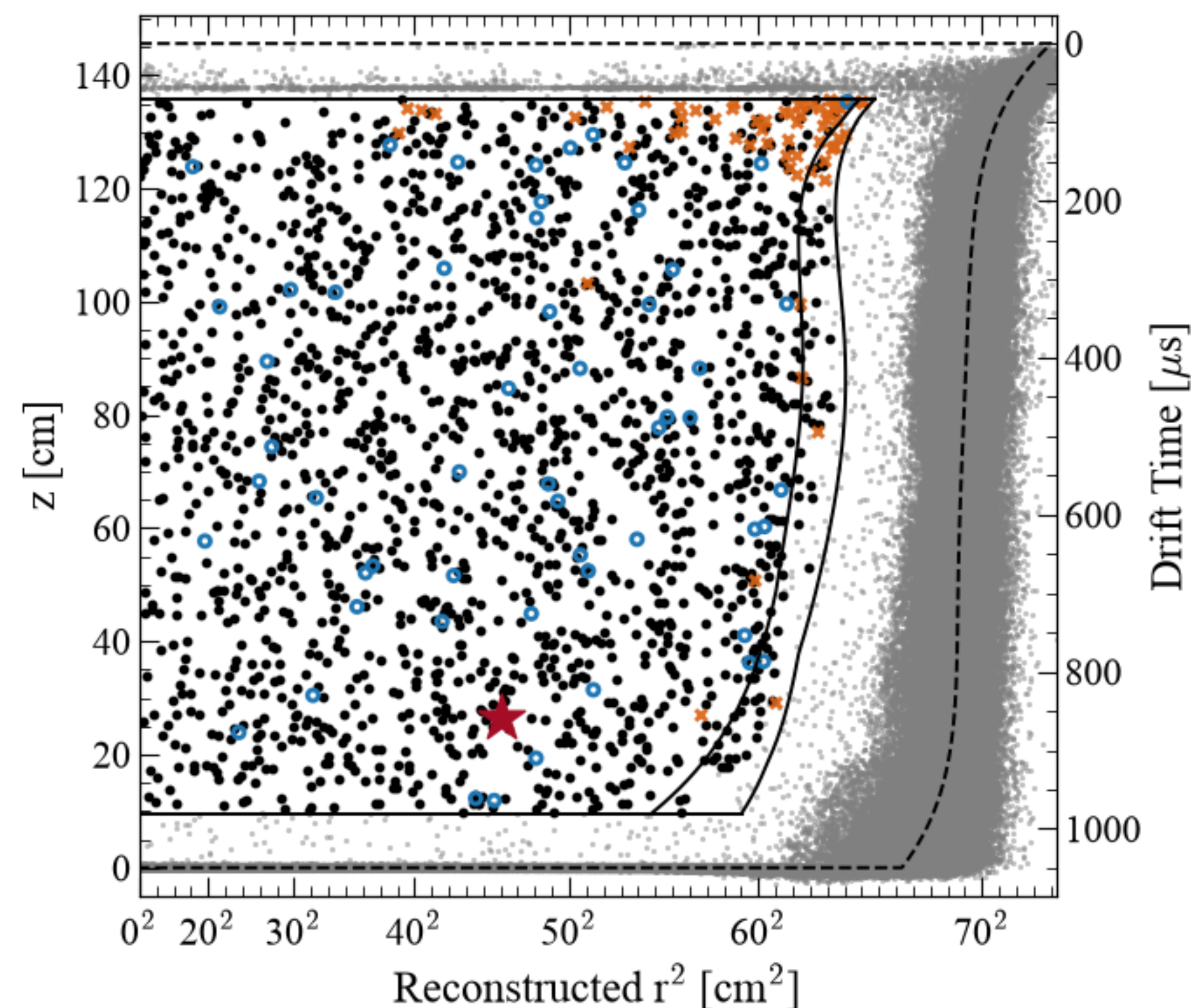
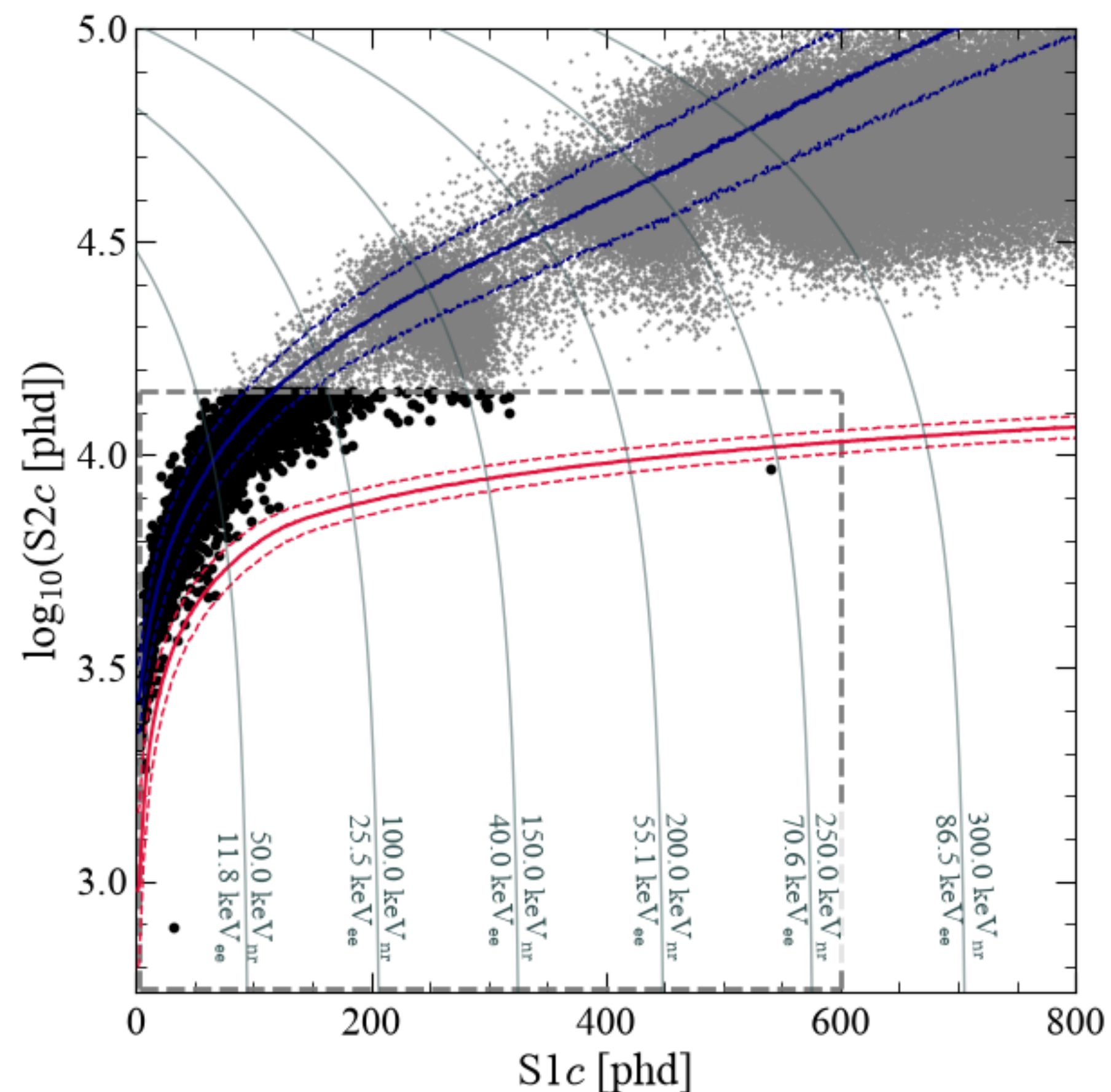
Why quantum sensing?

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



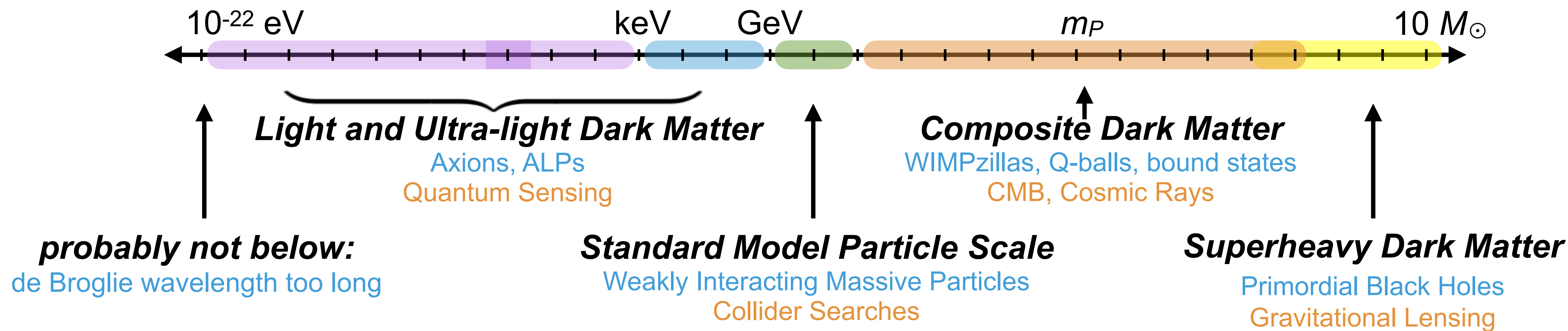
- **Quantum Detectors:** use quantum sensing to making extreme measurements possible
 - Enables (better) measurements, e.g. wavelengths
 - Extreme sensitivities (single-photon) or low noise
- **Quantum Experiments:** sensing is used for fundamental physics measurements
 - Gravity, Lorentz Invariance, physical constants (α , μ , dipole moments), etc
 - Techniques such as interferometry, magnetometry, clock-based systems, optomechanical devices

- Occurred on 16 June 2023 (LZ230616)
- $248 \pm 23_{\text{stat}} \pm 23_{\text{sys}}$ keV compatible with elastic nuclear recoil
- 26.4 cm from cathode
- 26.9 cm from TPC wall



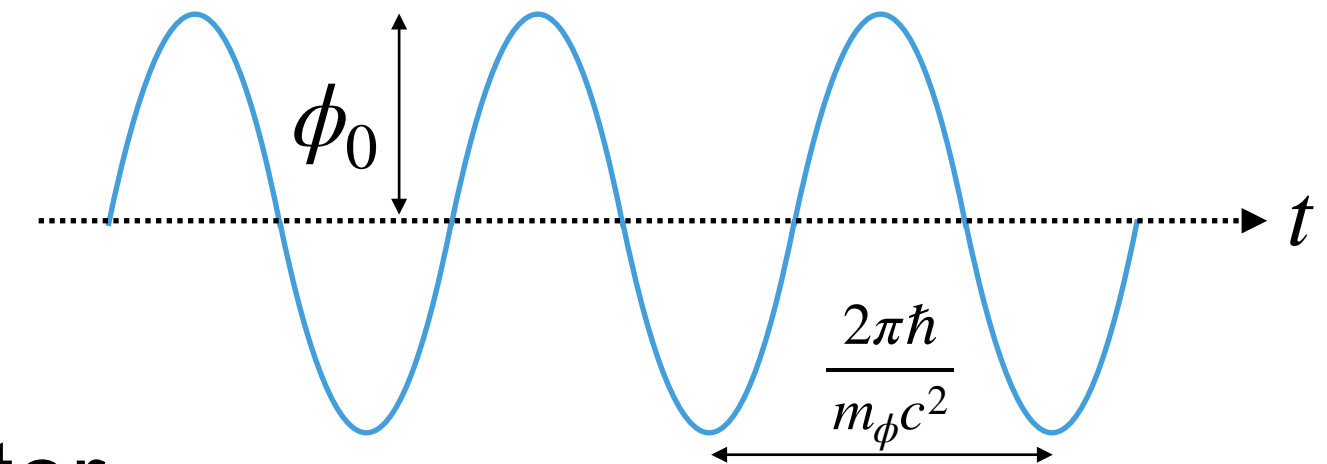
Quantum-enabled Experiments & Ultra-light Dark Matter

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

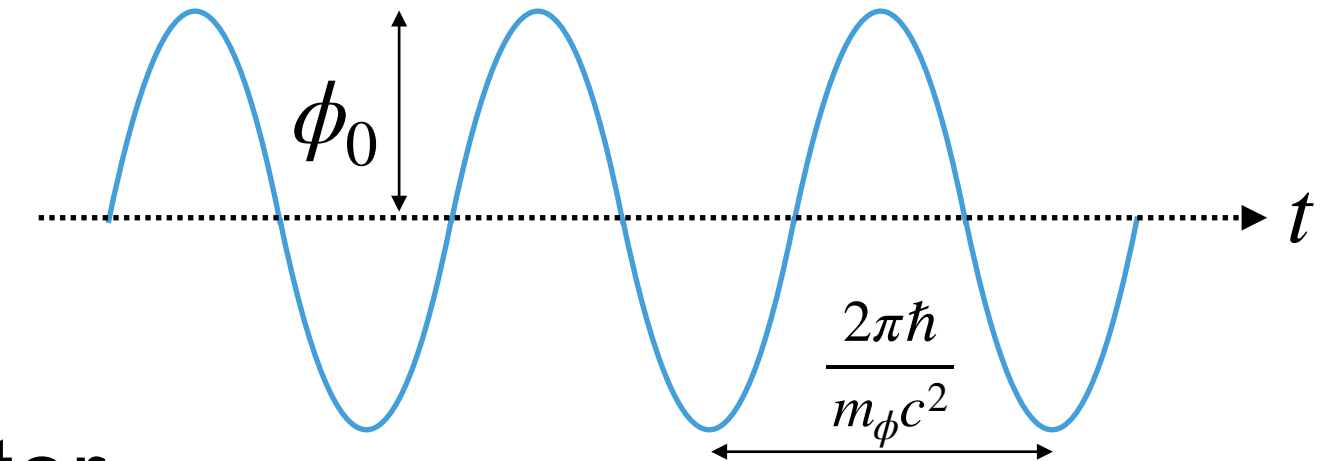
$$\mathcal{L}_{DM} = \frac{\phi}{\Lambda_\gamma} \frac{F_{\mu\nu} F^{\mu\nu}}{4} - \frac{\phi}{\Lambda_e} m_e \bar{\psi} \psi$$

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

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

Ultra-Light Dark Matter: Phenomenology

- Starting with Standard Model Lagrangian, adding **new DM interaction** (field)
- Bosonic**: Ultra-light DM must be bosonic in nature
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- 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)

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

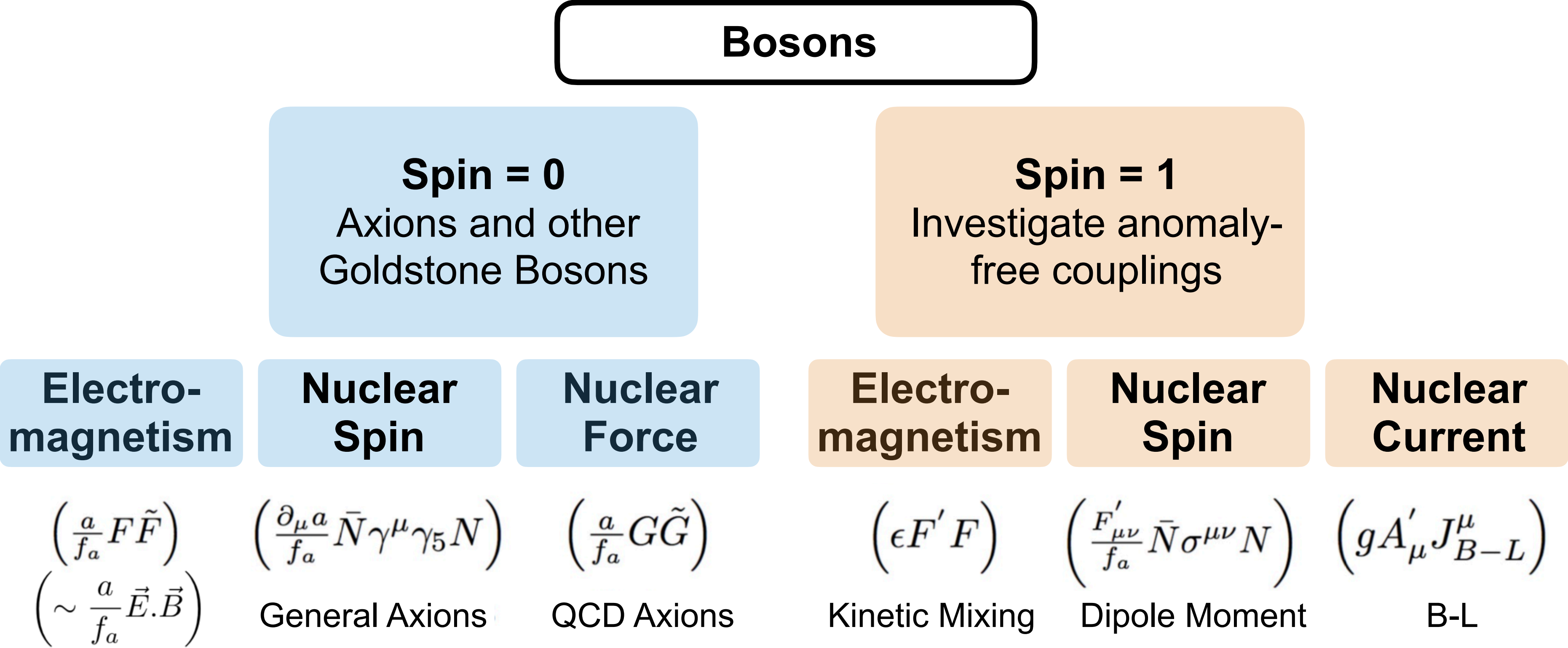
$$\mathcal{L}_{DM} = \frac{\phi^2}{(\Lambda'_\gamma)^2} \frac{F_{\mu\nu} F^{\mu\nu}}{4} - \frac{\phi^2}{(\Lambda'_e)^2} m_e \bar{\psi} \psi$$

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

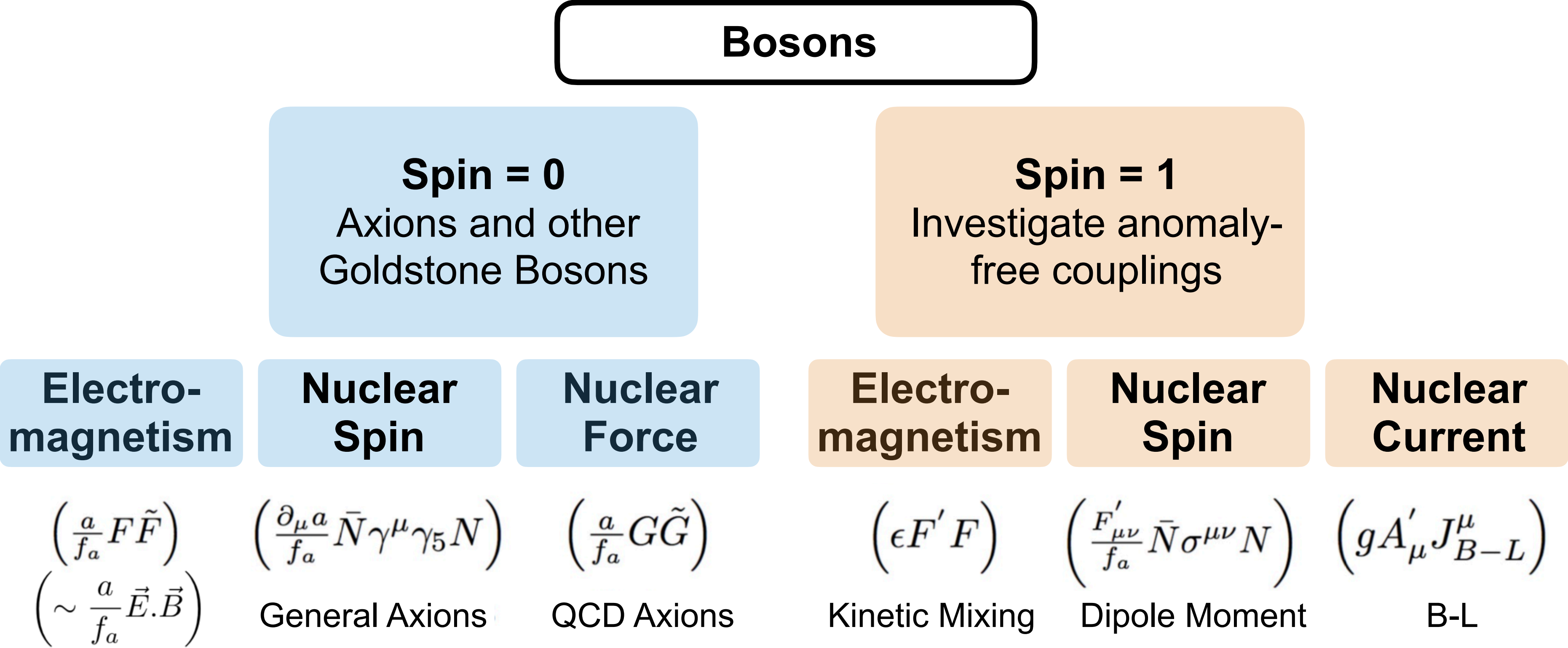
$$\frac{d\alpha}{\alpha} \approx \frac{\phi_0 \cos(m_\phi t)}{\Lambda_\gamma}, \quad \frac{dm_e}{m_e} \approx \frac{\phi_0 \cos(m_\phi t)}{\Lambda_e}$$

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

Light Bosonic Dark Matter Couplings



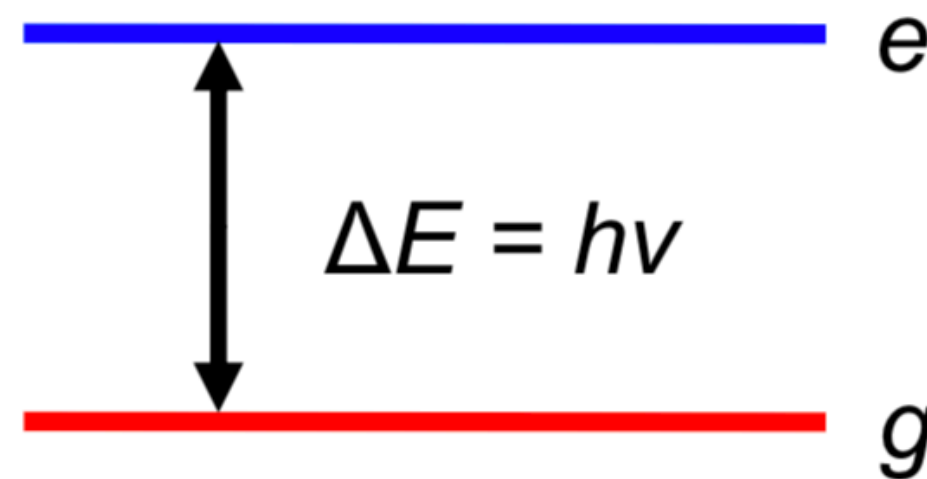
Light Bosonic Dark Matter Couplings



- 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

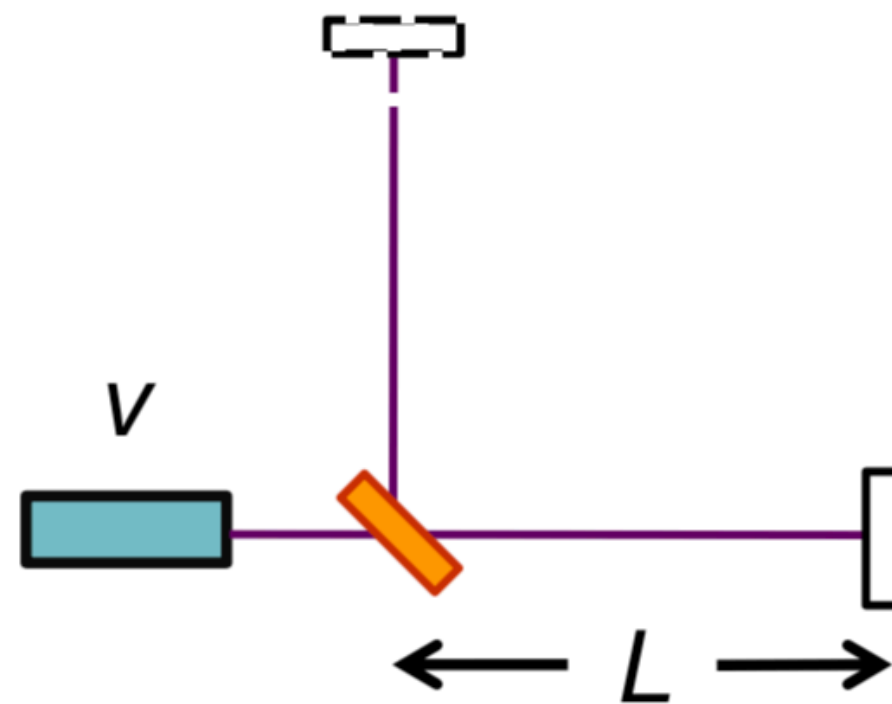
Quantum Sensing Methods for Testing $\Delta\alpha/\alpha$



Atomic spectroscopy (clocks)

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

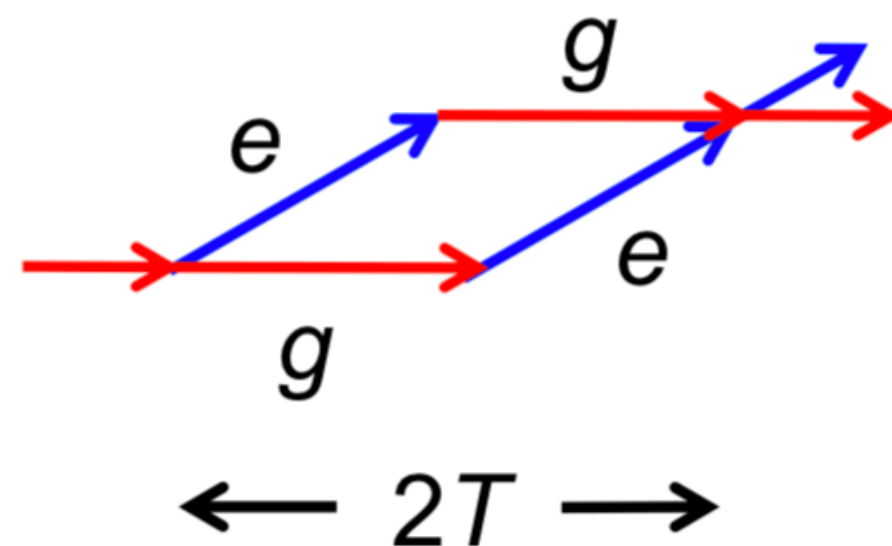
$$10^{-23} \text{ eV} < m_\phi < 10^{-16} \text{ eV}$$



Laser interferometry (cavities)

$$\delta\phi \propto \delta(\nu L) \propto \cos(m_\phi t)$$

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

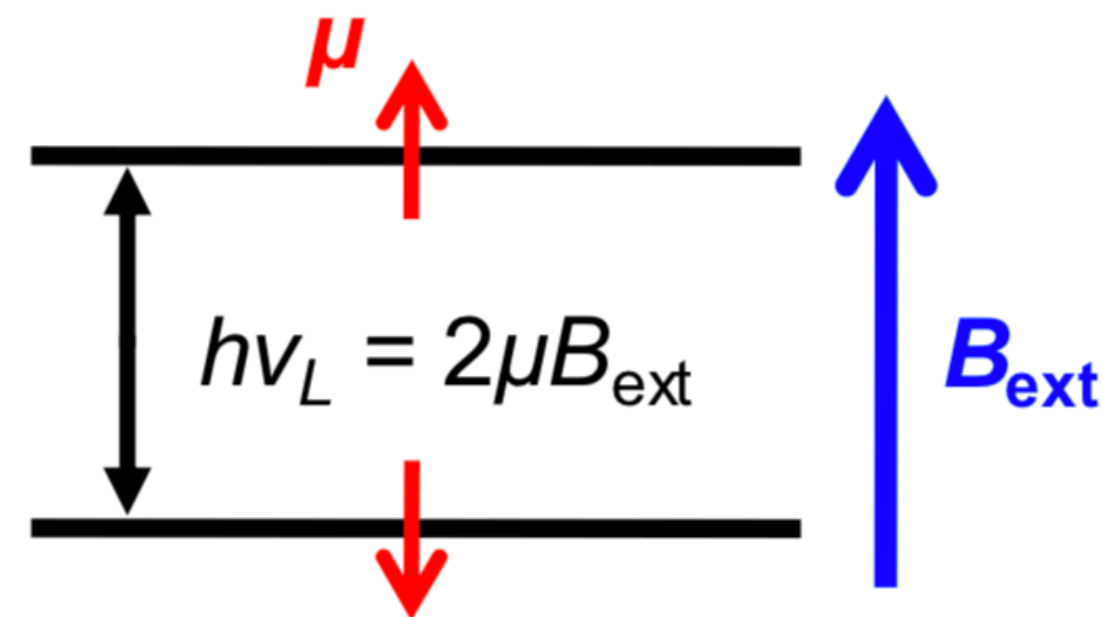


Atom interferometry

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

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

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



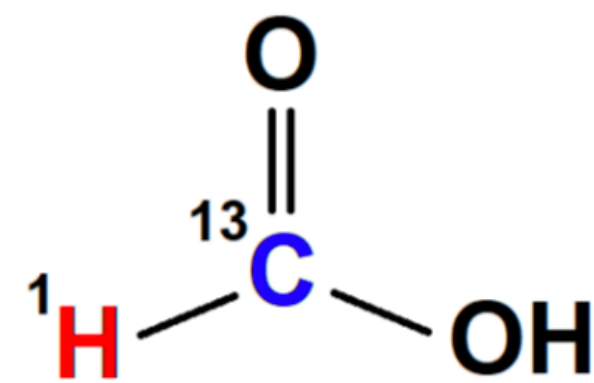
Co-magnetometry

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

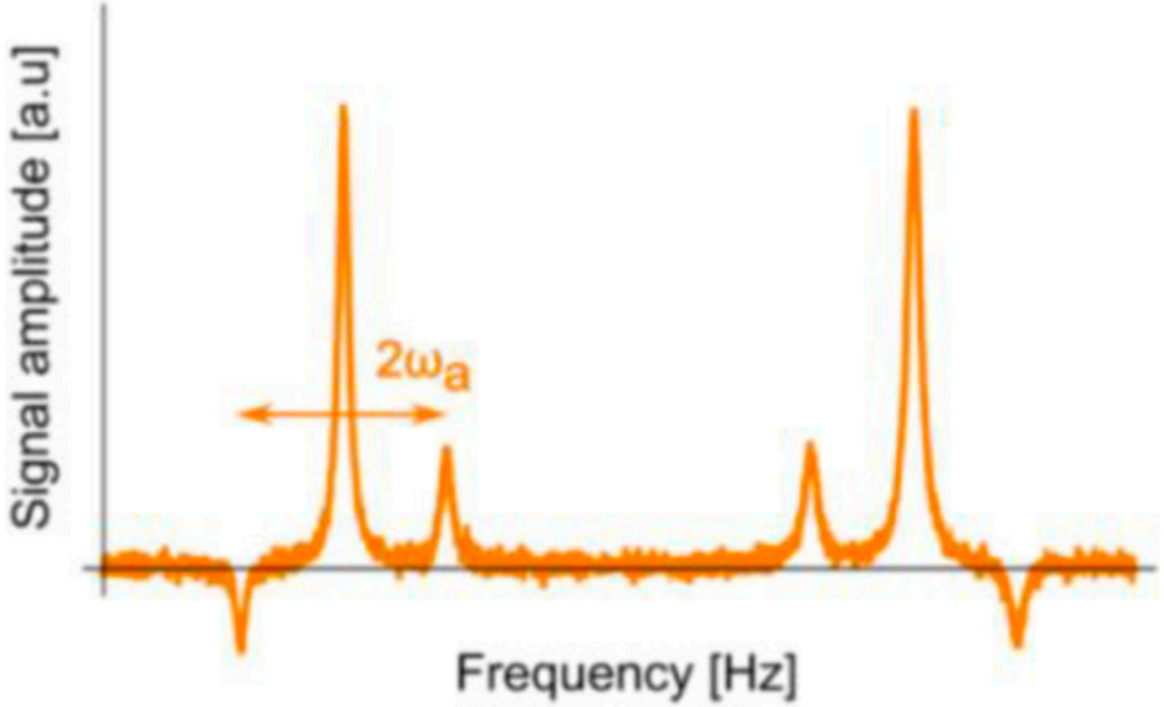
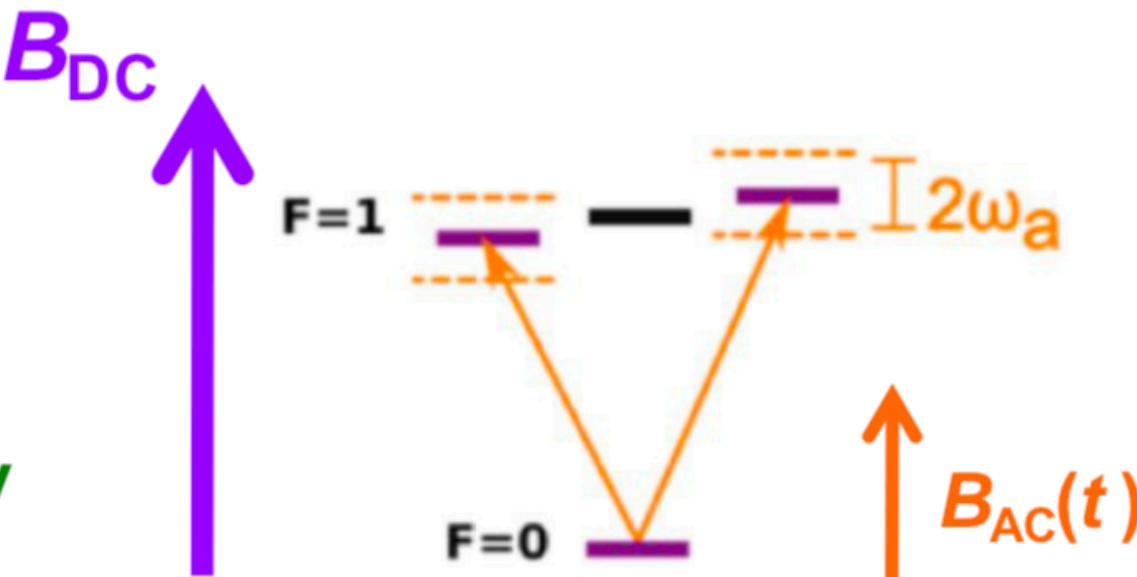
$$\text{or } \hat{\sigma} \cdot \mathbf{p}_a \sin(m_a t)$$

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

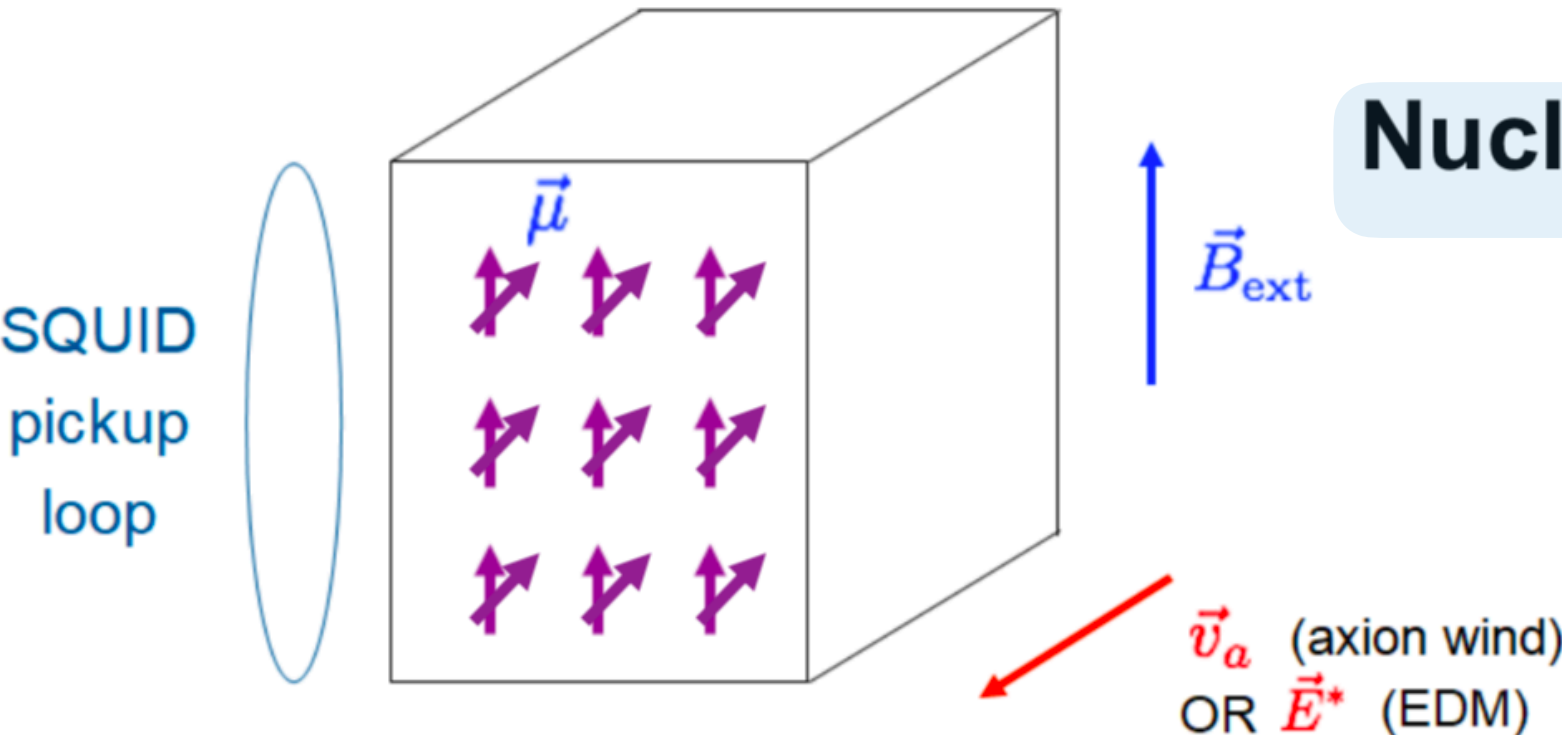
Nuclear magnetic resonance (“sidebands”)



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



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

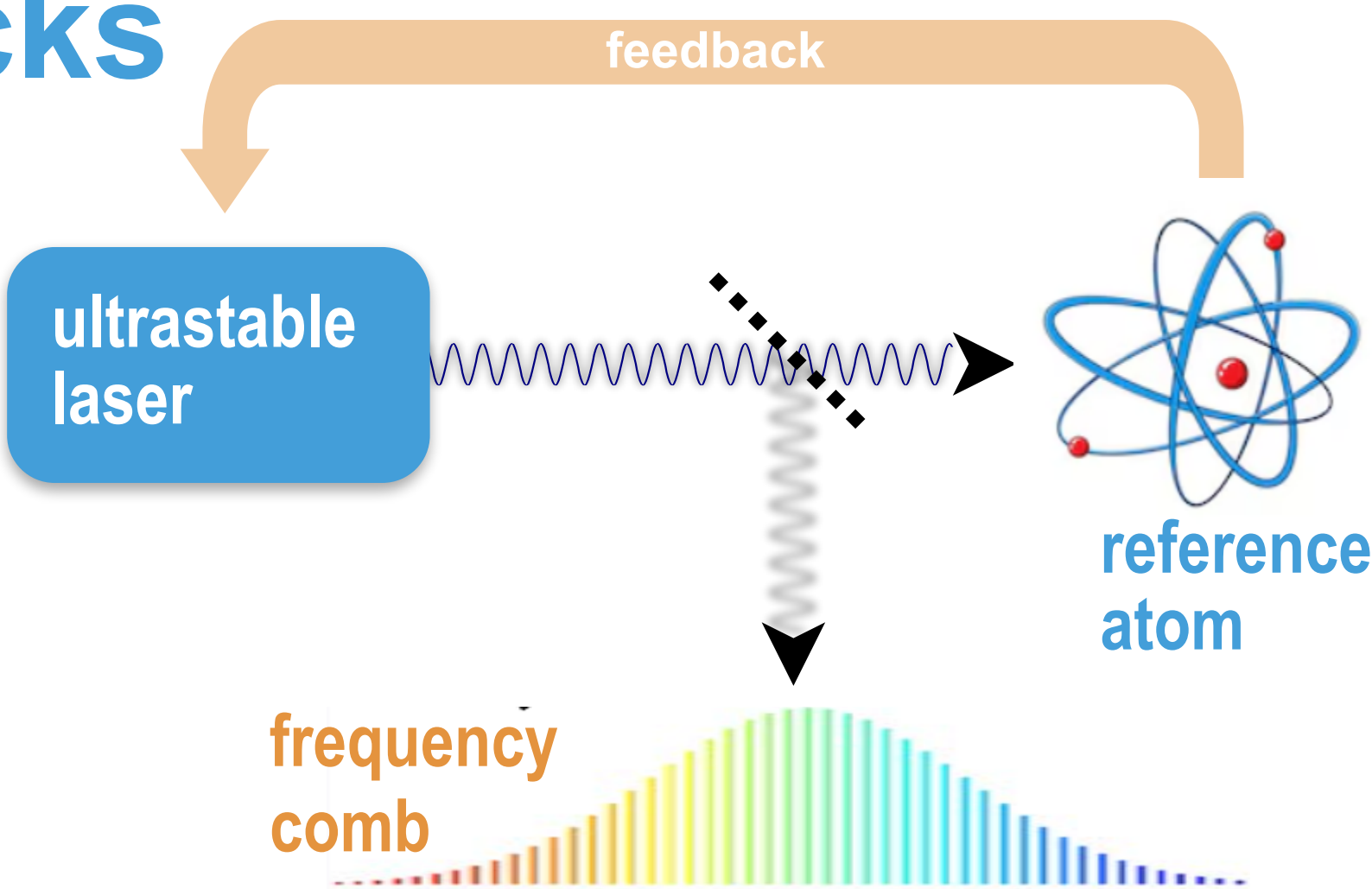
- Optical Atomic Clock
 - Laser for oscillator, usually a narrow frequency around atomic transition
 - Ultra-stable laser locked to atomic transition, “counted” with frequency comb
- Atomic clock transition scale and sensitivity is “selectable”
 - For $R_\infty = \alpha^2 m_e c / 4\pi \hbar$, fine structure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

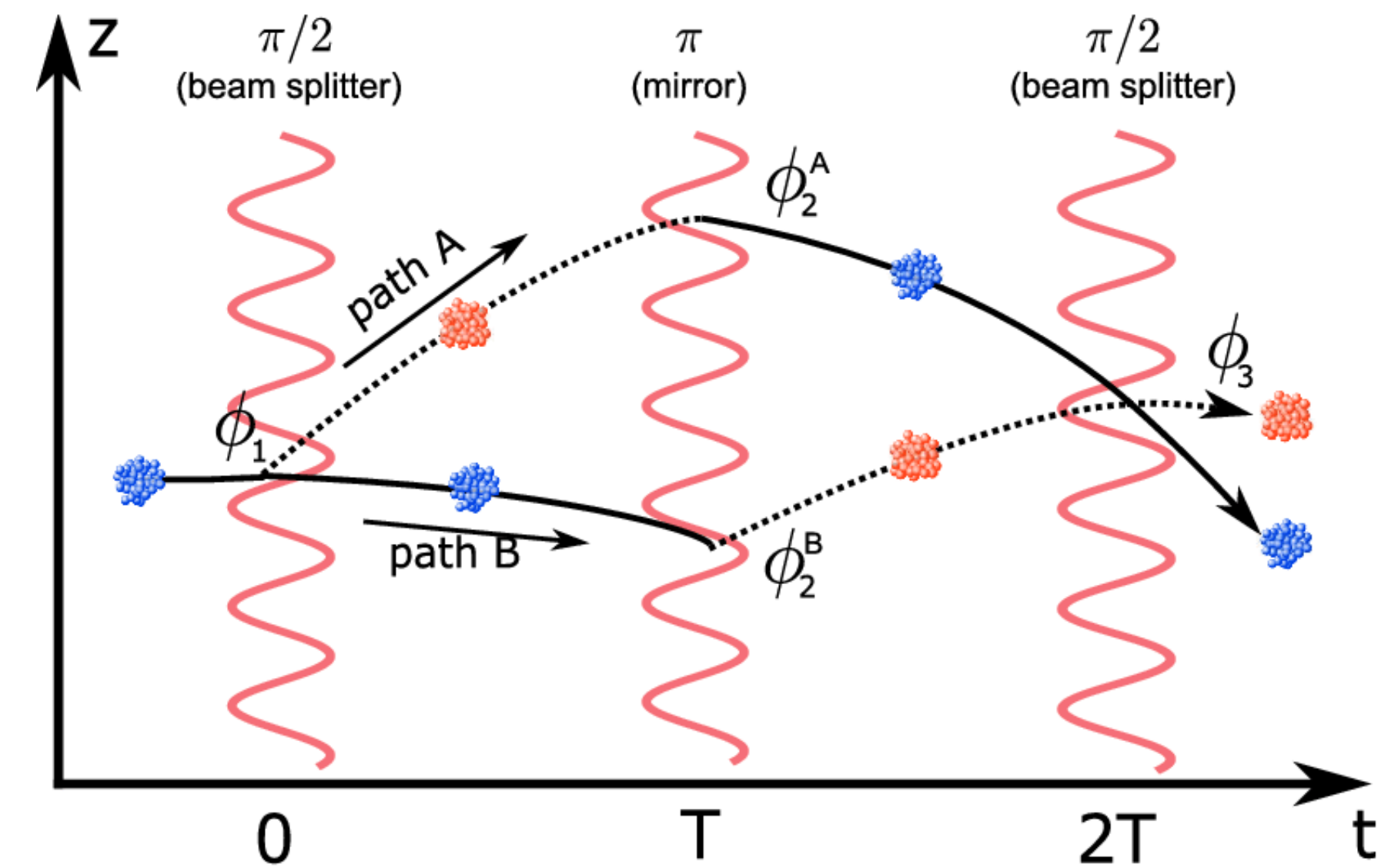
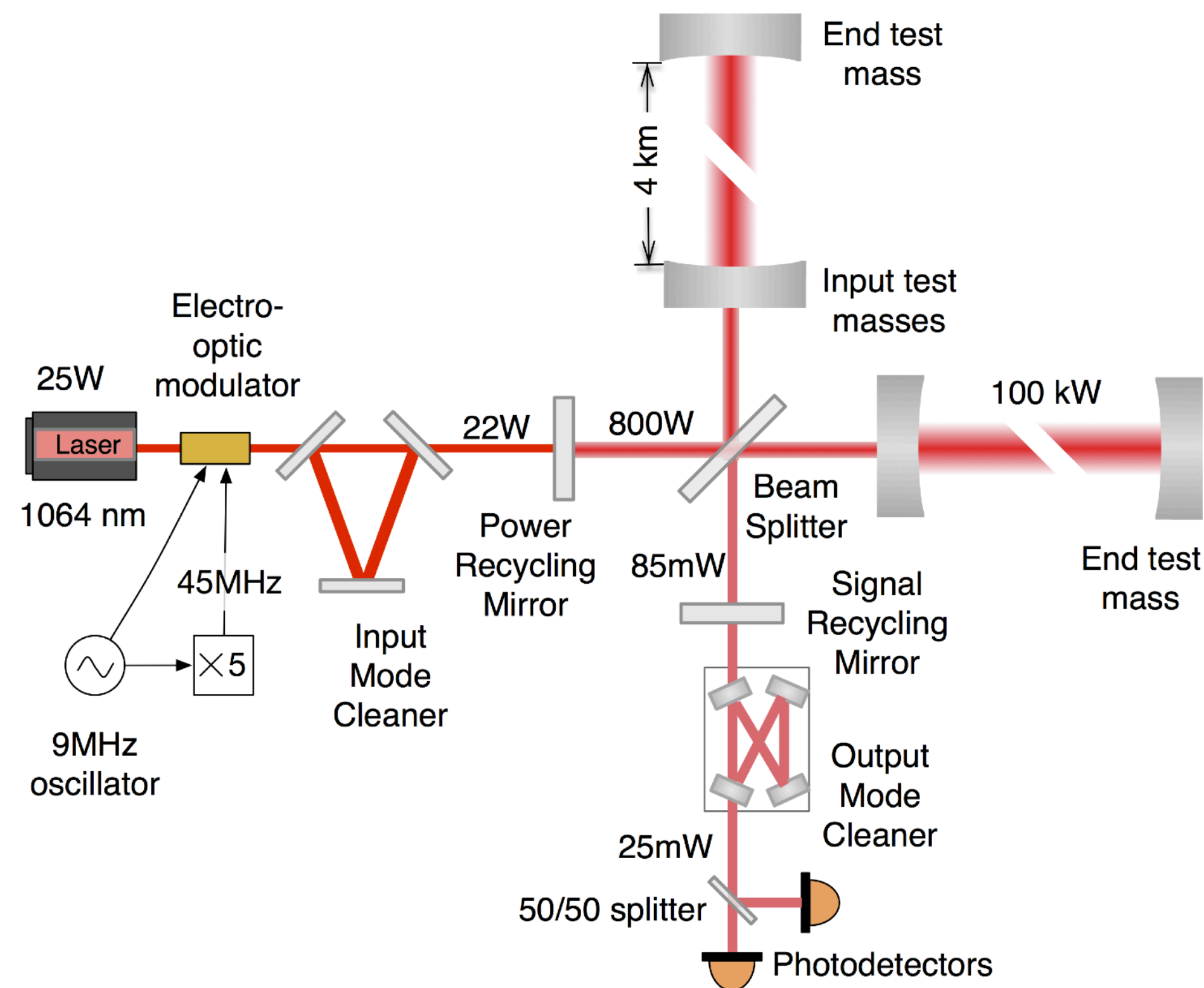


Clocks in QSNET

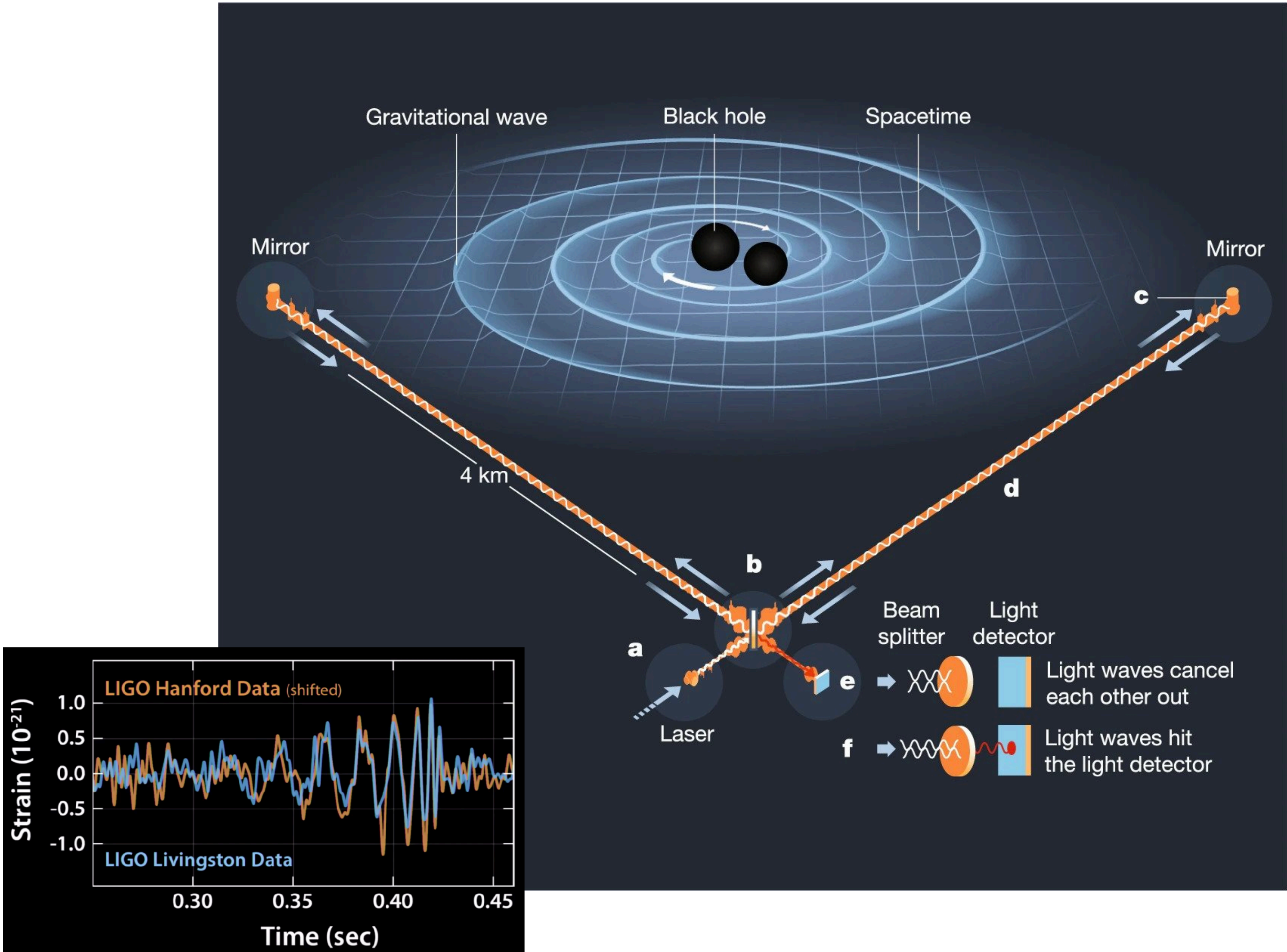
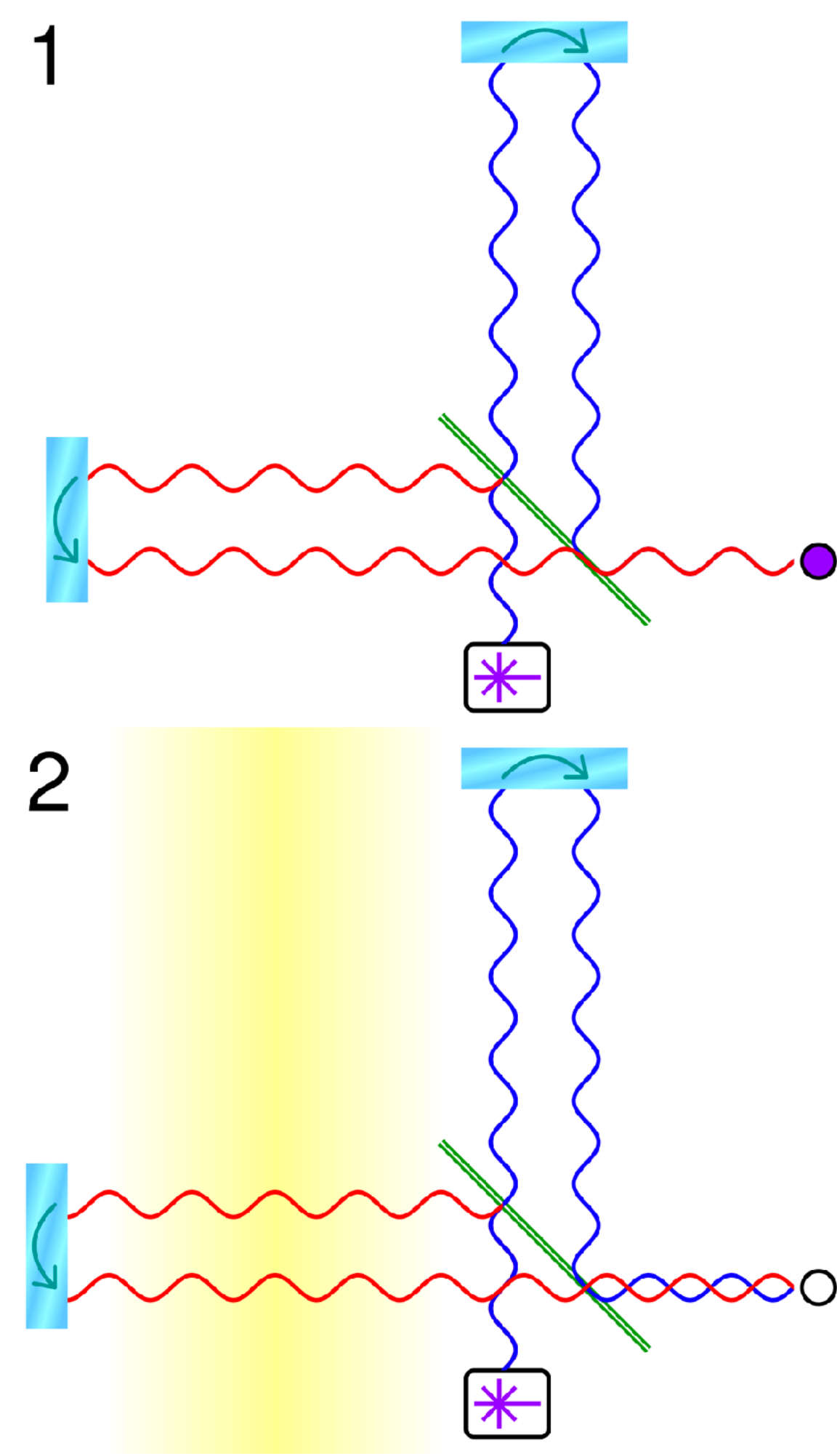
Clock	K_α	K_μ
Yb ⁺ (467 nm)	-5.95	0
Sr (698 nm)	0.06	0
Cs (32.6 mm)	2.83	1
CaF (17 μm)	0	0.5
N ₂ ⁺ (2.31 μm)	0	0.5
Cf ¹⁵⁺ (618 nm)	47	0
Cf ¹⁷⁺ (485 nm)	-43.5	0

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.



Gravitational Wave Detection

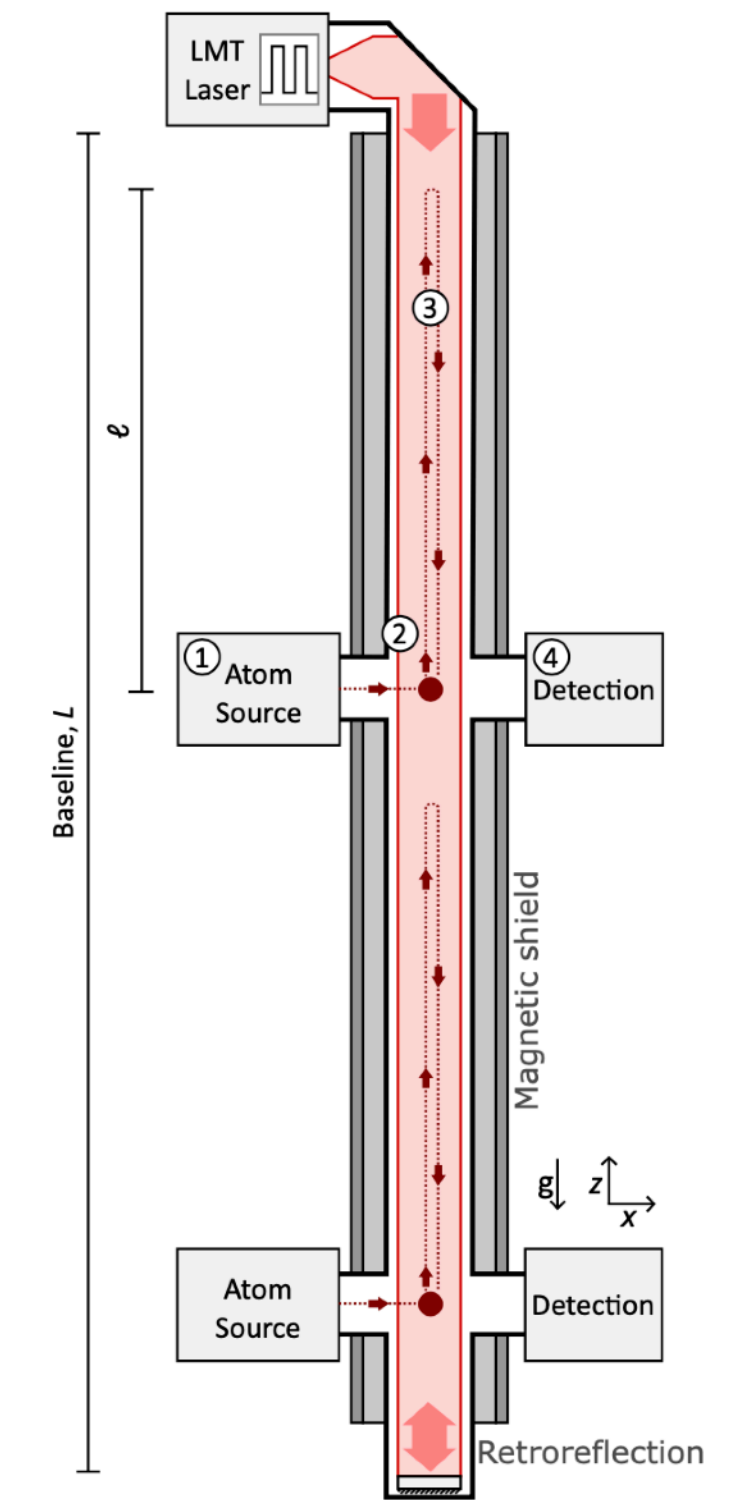


Laser Interferometer Gravitational-Wave Observatory (LIGO)

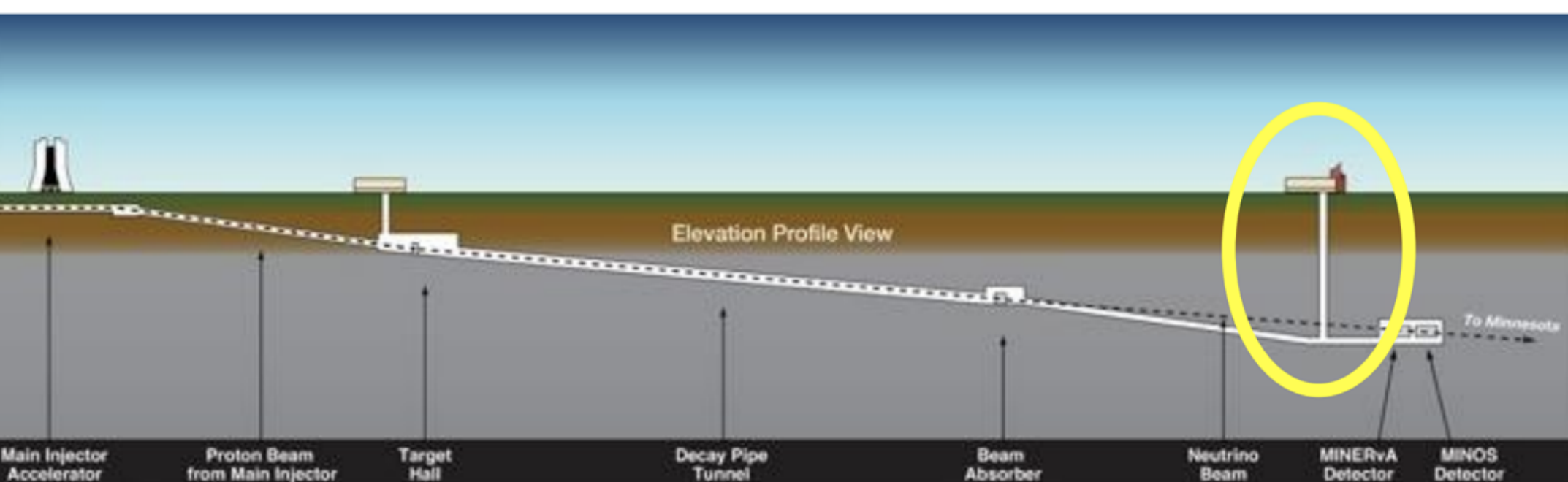


Long-Baseline Atom Interferometry

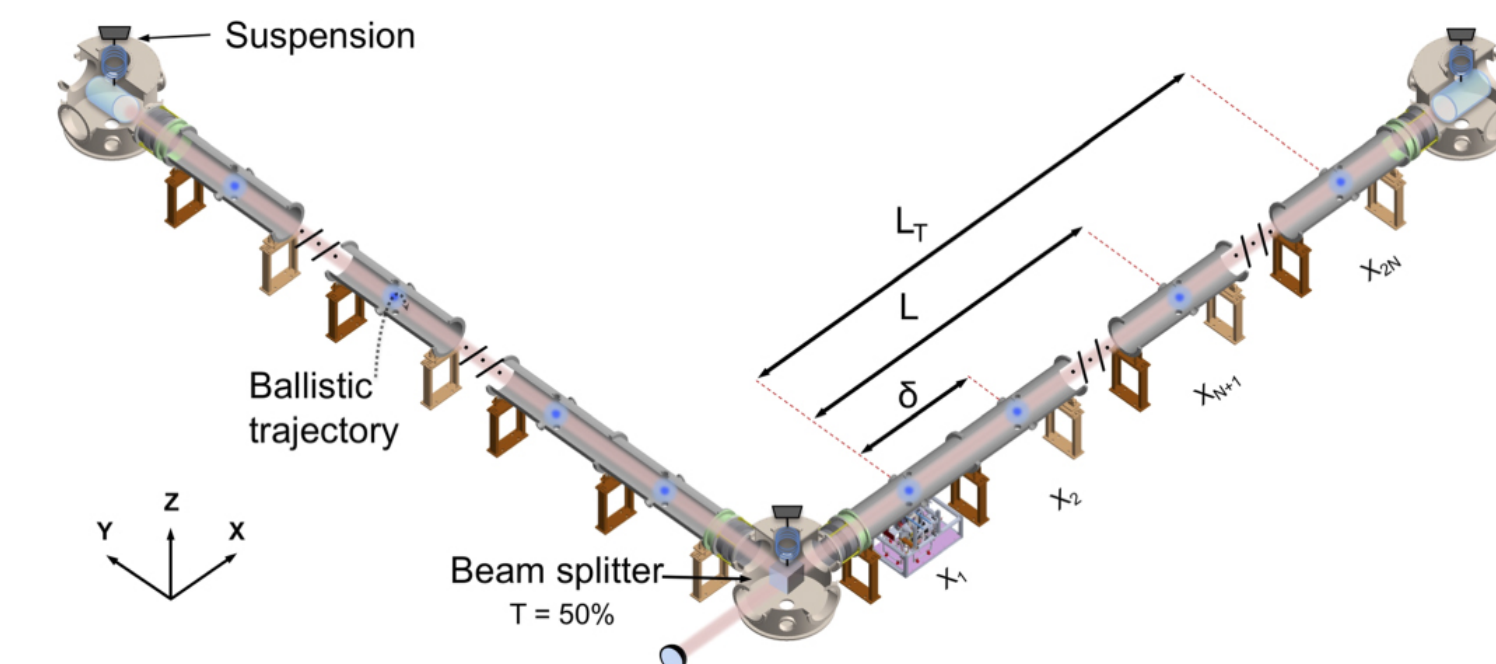
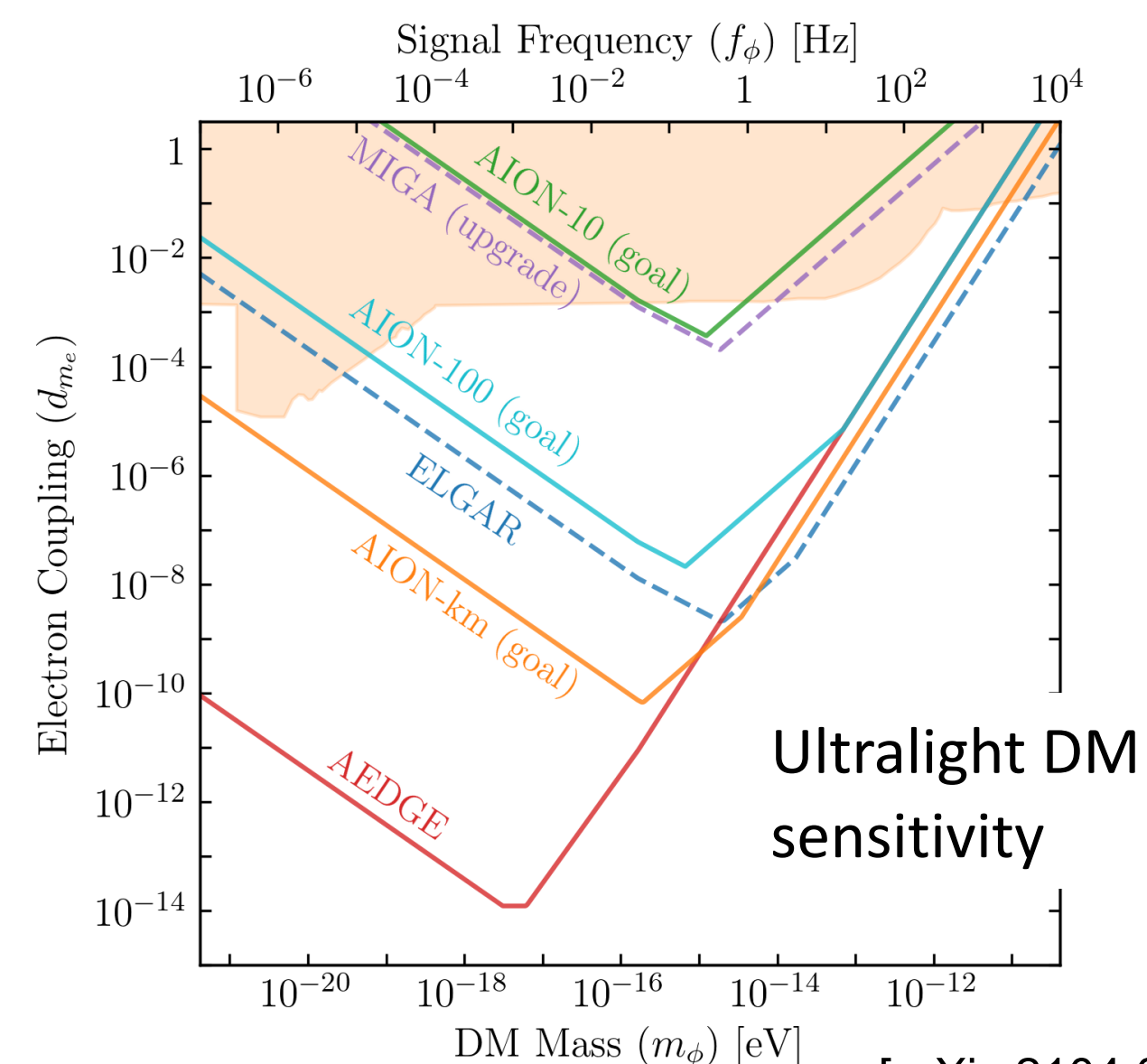
- Demonstrated at ~meter scale, proposals for 100m and ultimately km (space)
 - **AION / AICE**: Atom Interferometer Observatory and Network / Atom Interferometer CERN Experiment
 - **ELGAR**: European Laboratory for Gravitation and Atom-interferometric Research
 - **MIGA**: Matter wave-laser based Interferometer 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



AICE experiment concept



MAGIS-100 experiment concept



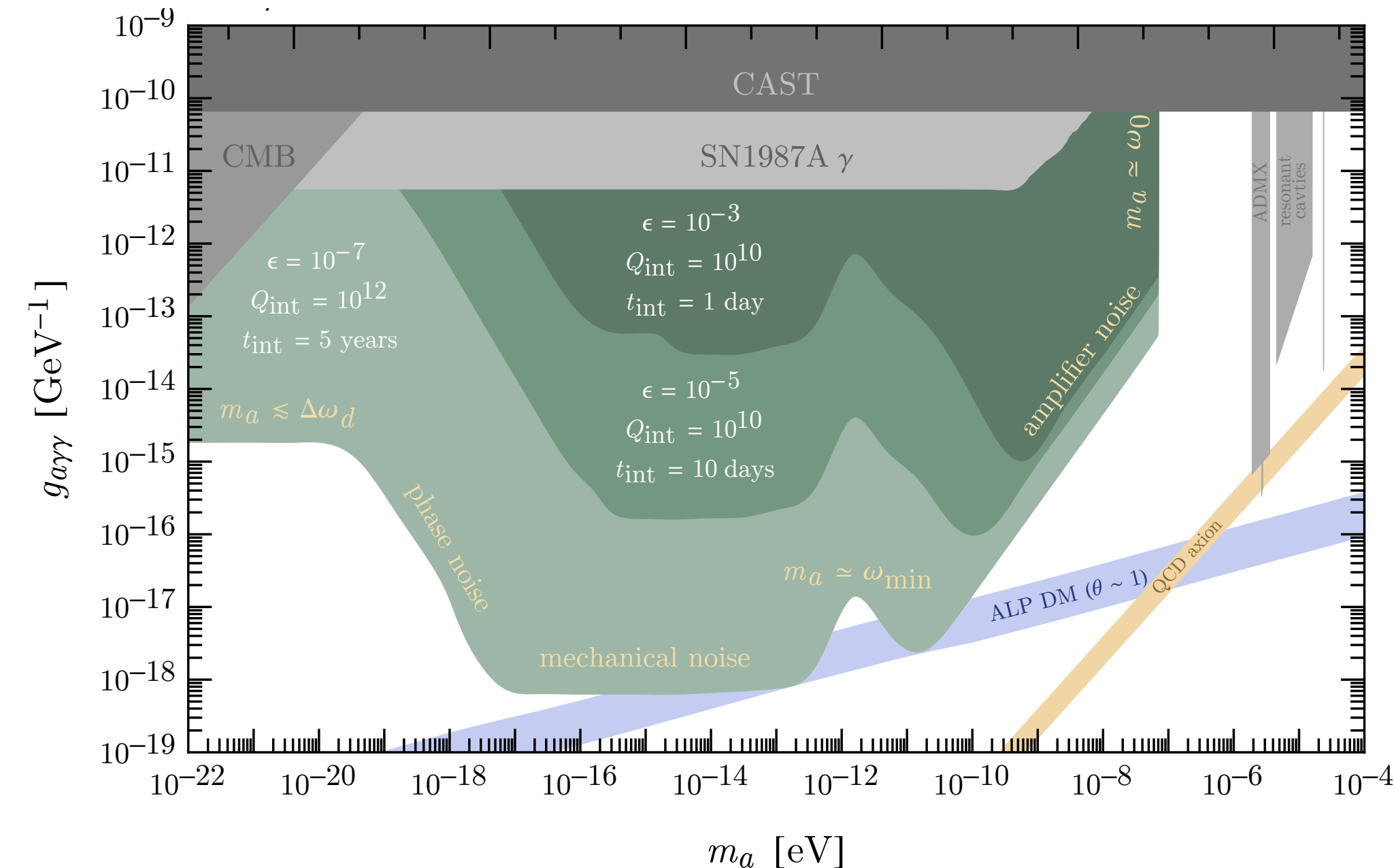
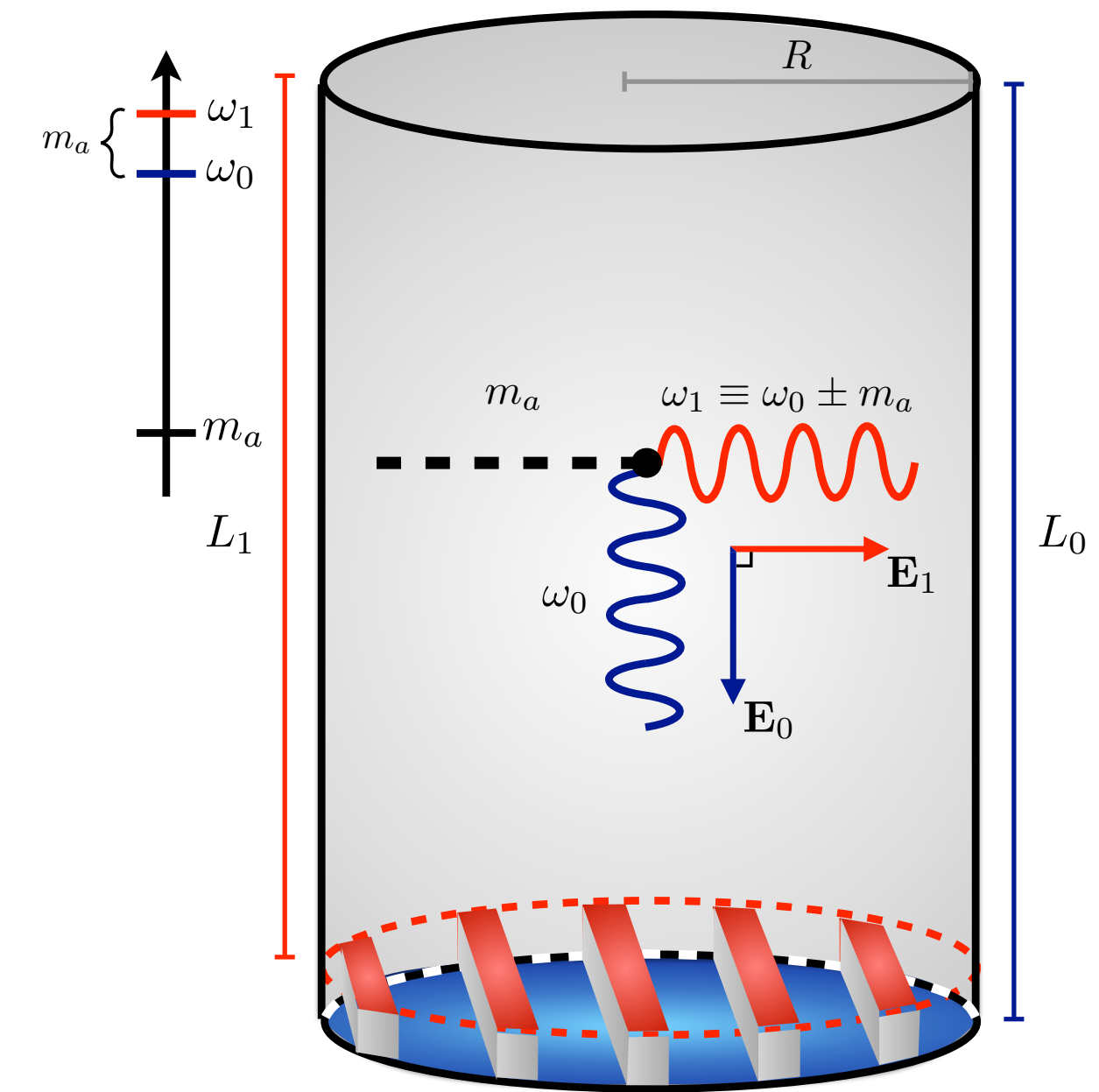
ELGAR experiment concept

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)

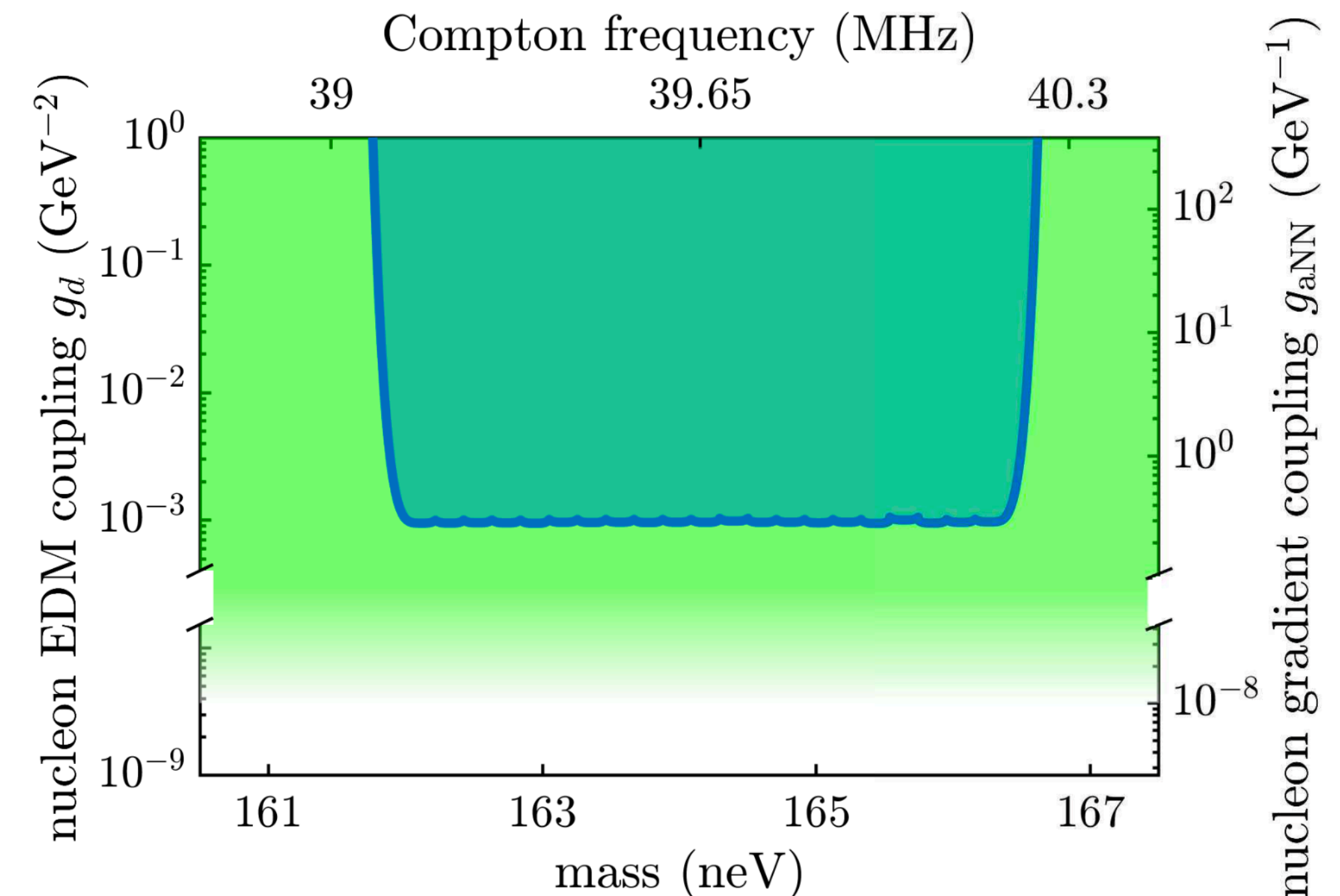
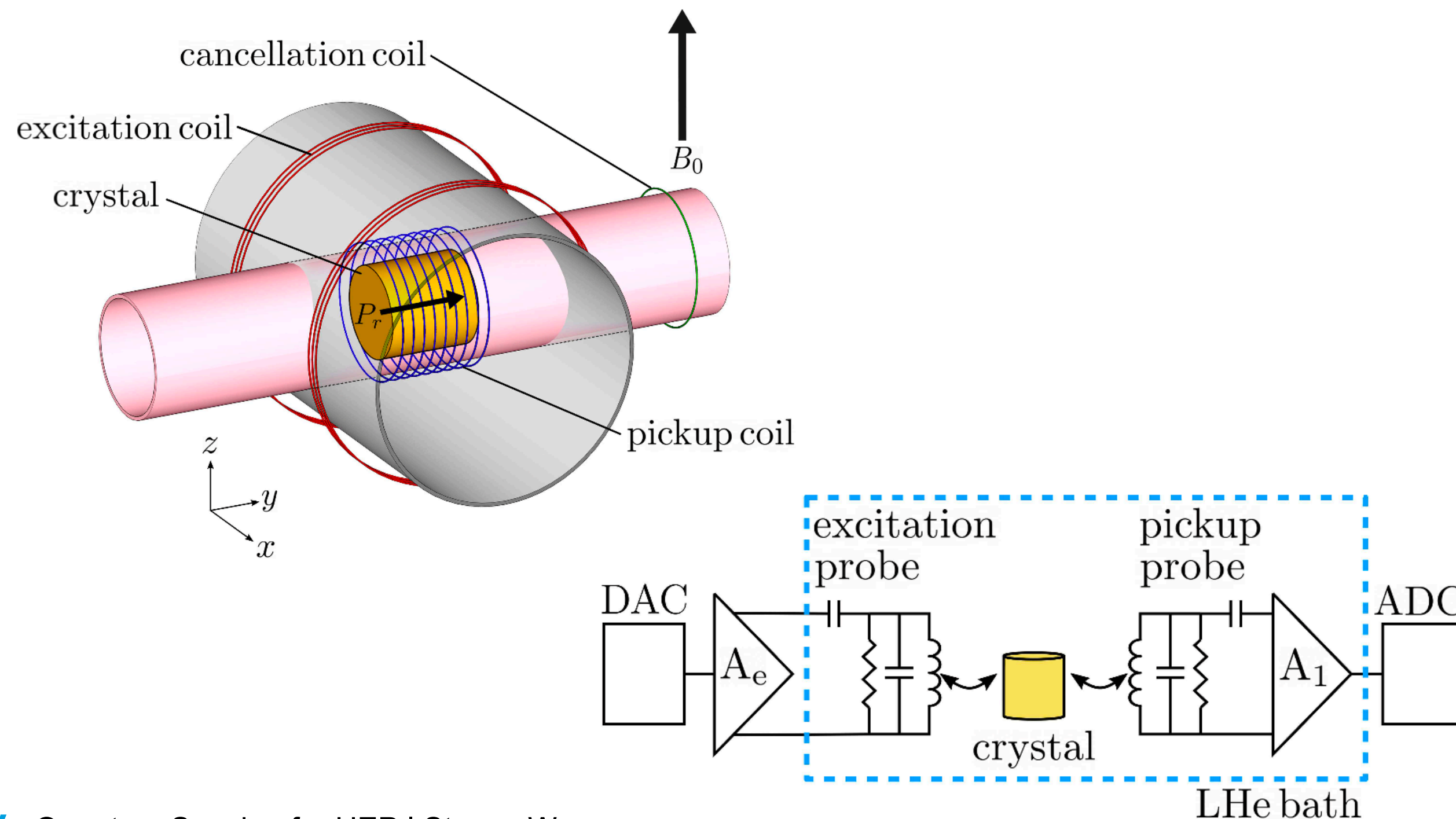
$$F \sim g_{a\gamma}^2 m_a^2 B^4 V^2 T_{sys}^{-2} G^4 Q$$

- 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

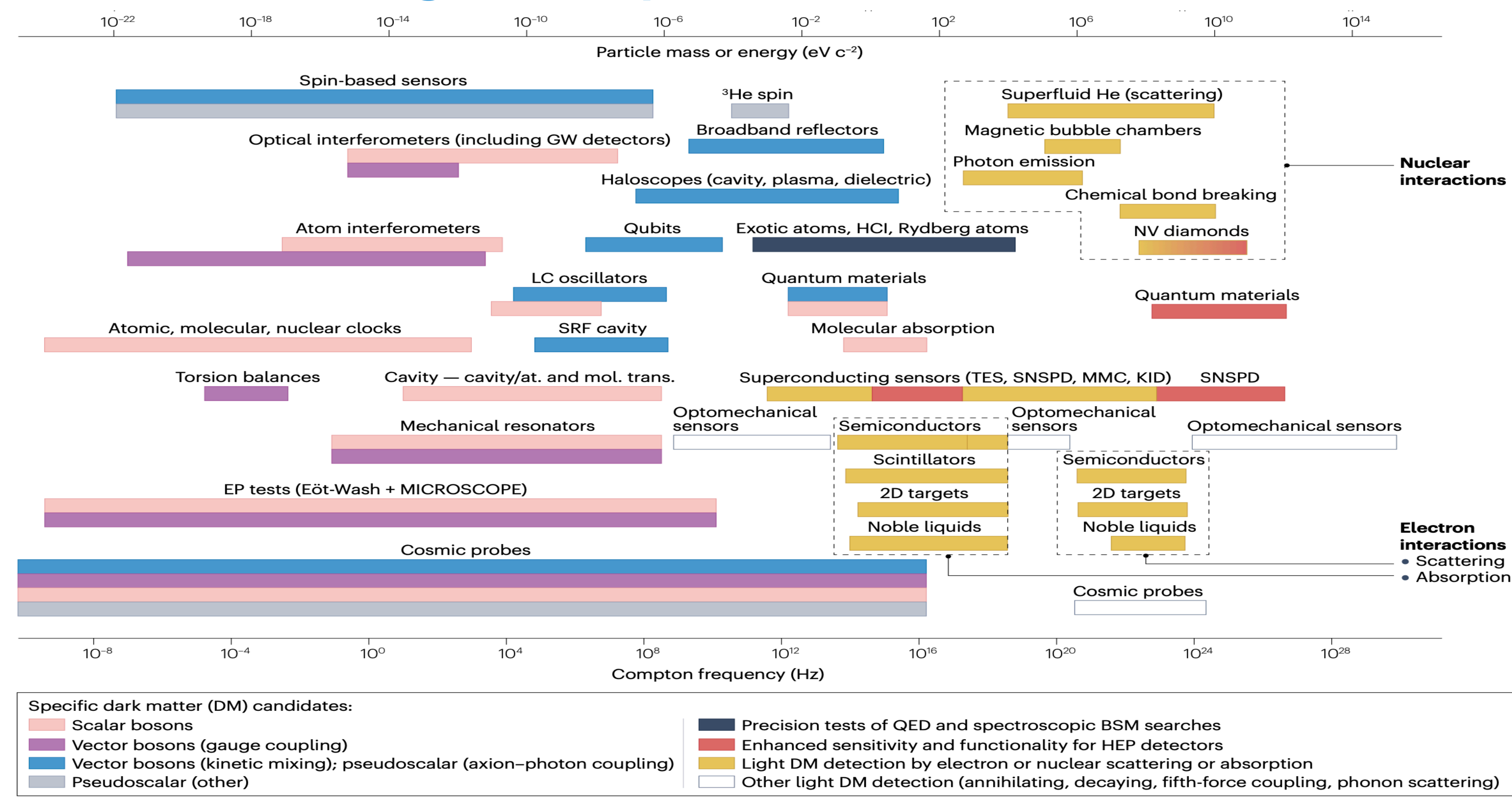


Quantum Sensing with Magnetometry: CASPEr

- 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



Quantum Sensing Techniques for Dark Matter



DRD5 Collaboration

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

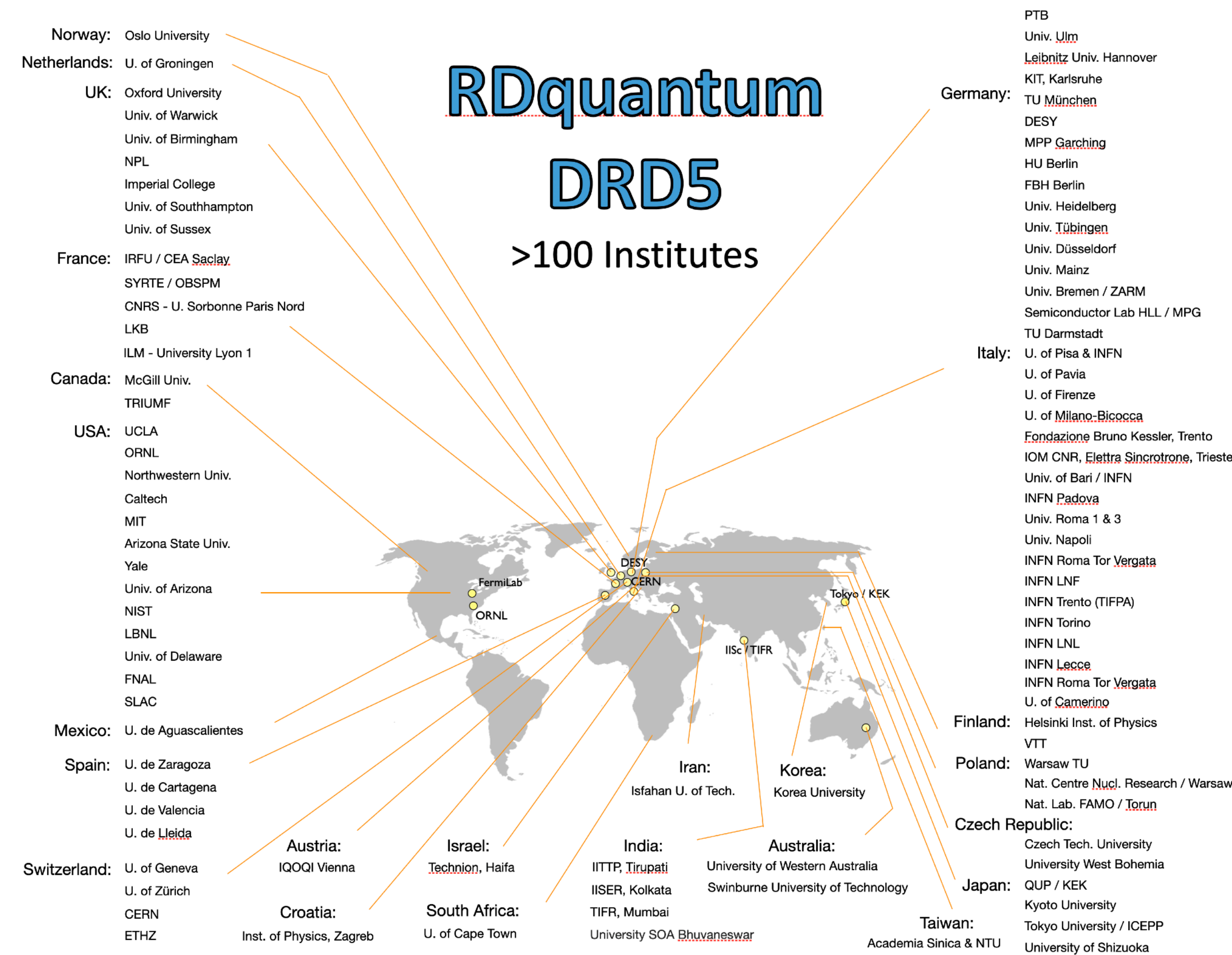
Addressing Challenges for Science

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)



Conclusions

- Many different quantum sensing techniques are being developed for Particle/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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