

News from ECFA Roadmap Implementation: **Quantum and Emerging Technologies**

Quantum Sensors for Fundamental Physics, and Opportunities for the Future

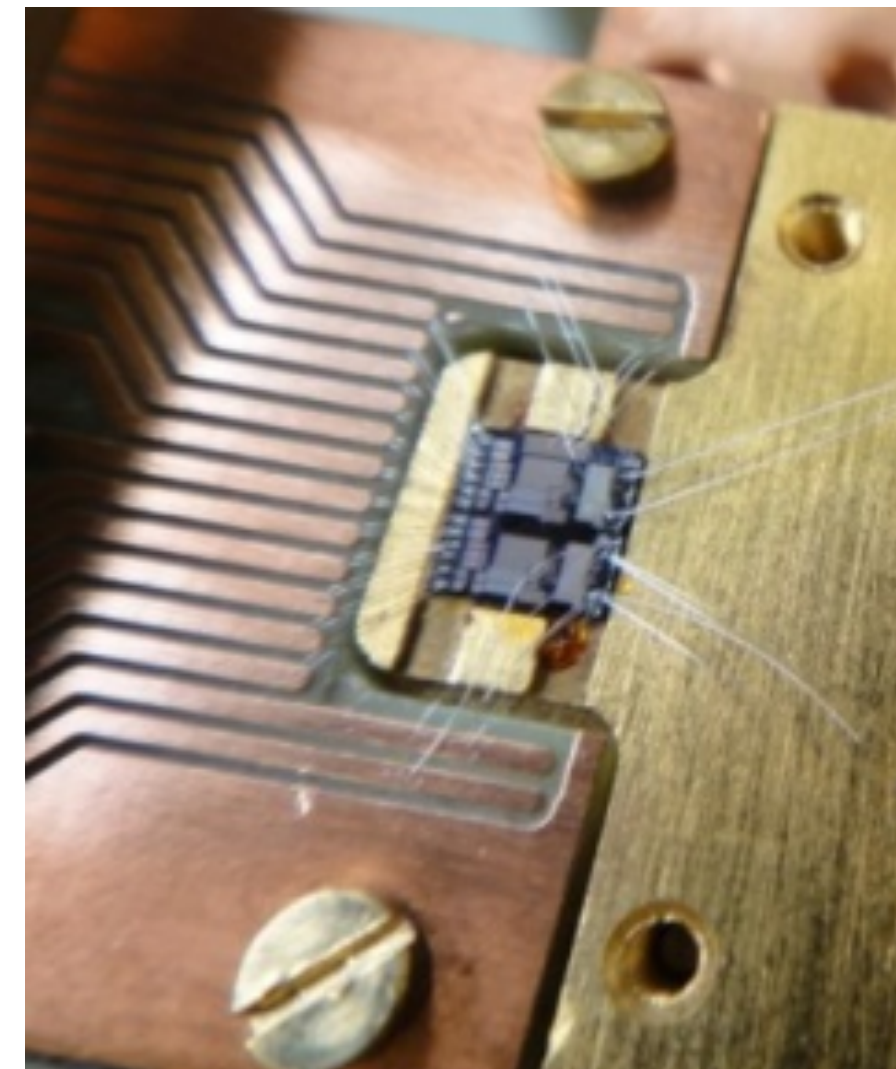
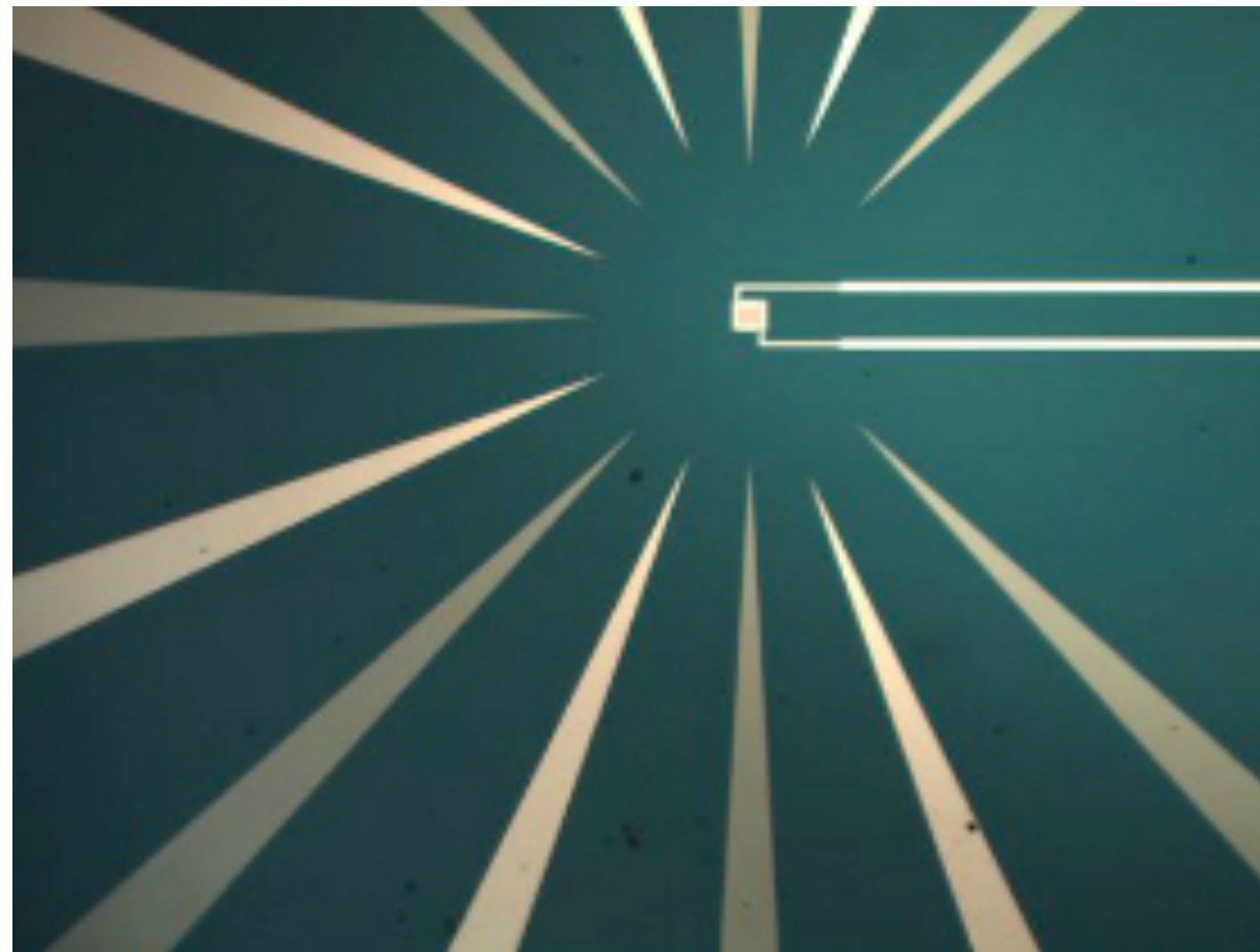
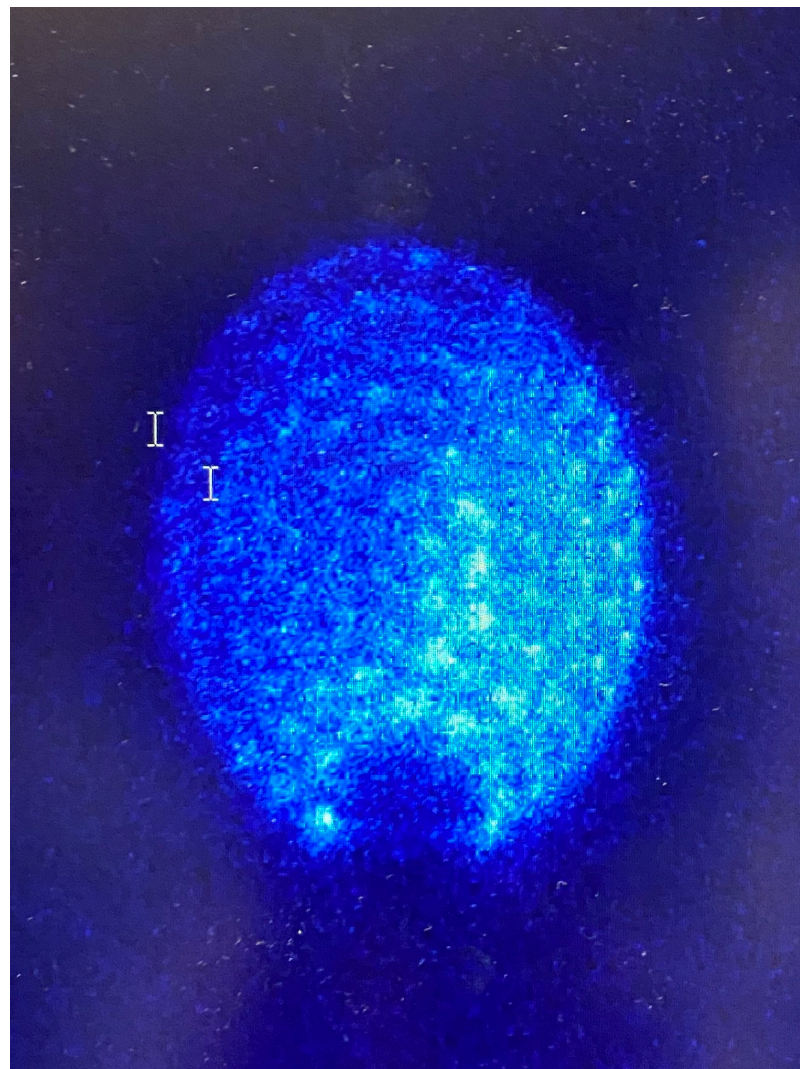
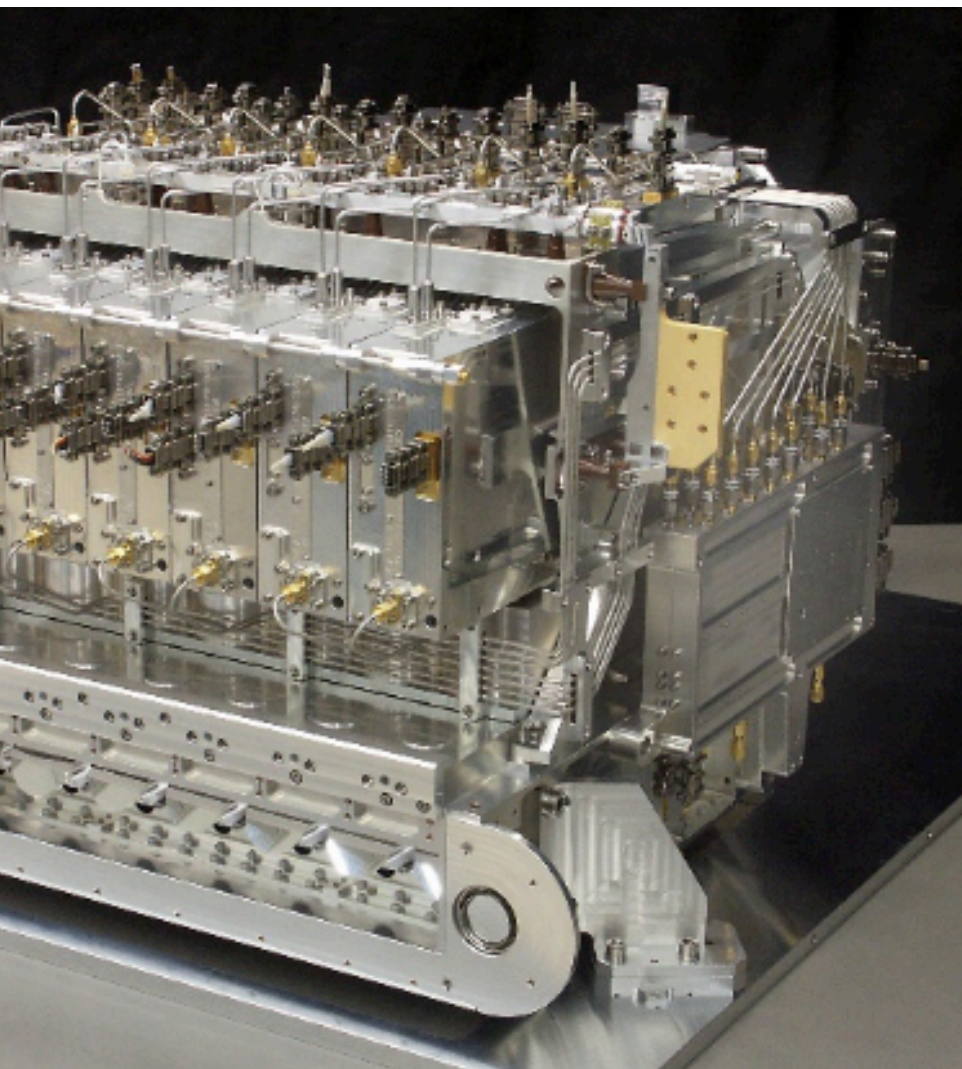
Steven Worm
DESY Zeuthen and Humboldt-Universität zu Berlin

March 2, 2023



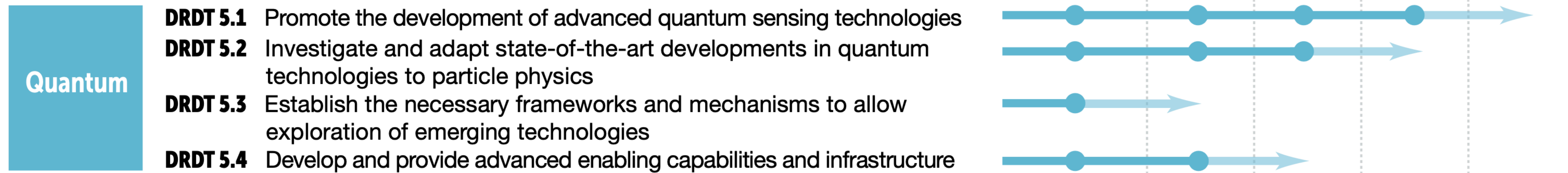
Outline

- ECFA Roadmap outline and physics motivation
- **Quantum Sensors:** Superconducting sensor examples
- **Quantum Experiments:** Table-top and larger
- Next steps: Germany, DRD5, RDq, ErUM-Pro



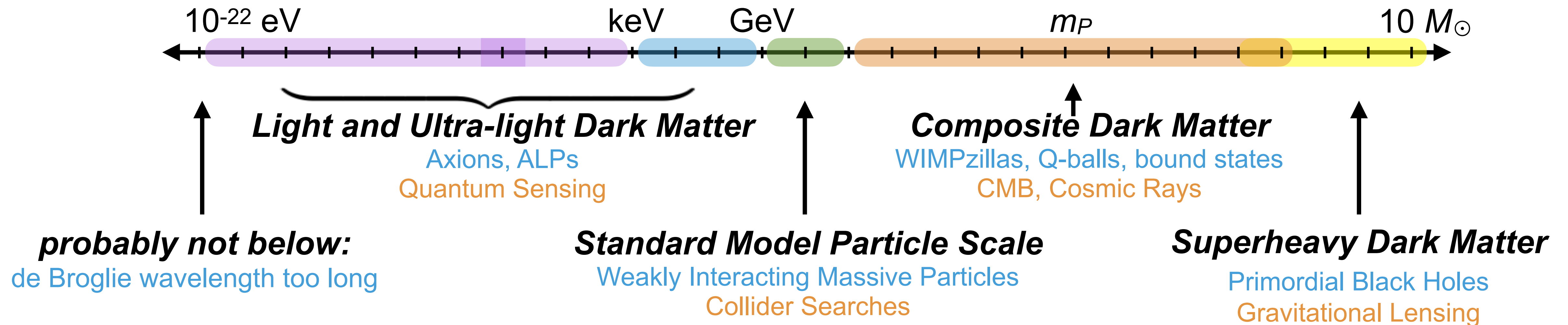
ECFA Detector Strategy: Quantum

- ECFA Detector Roadmap summary:



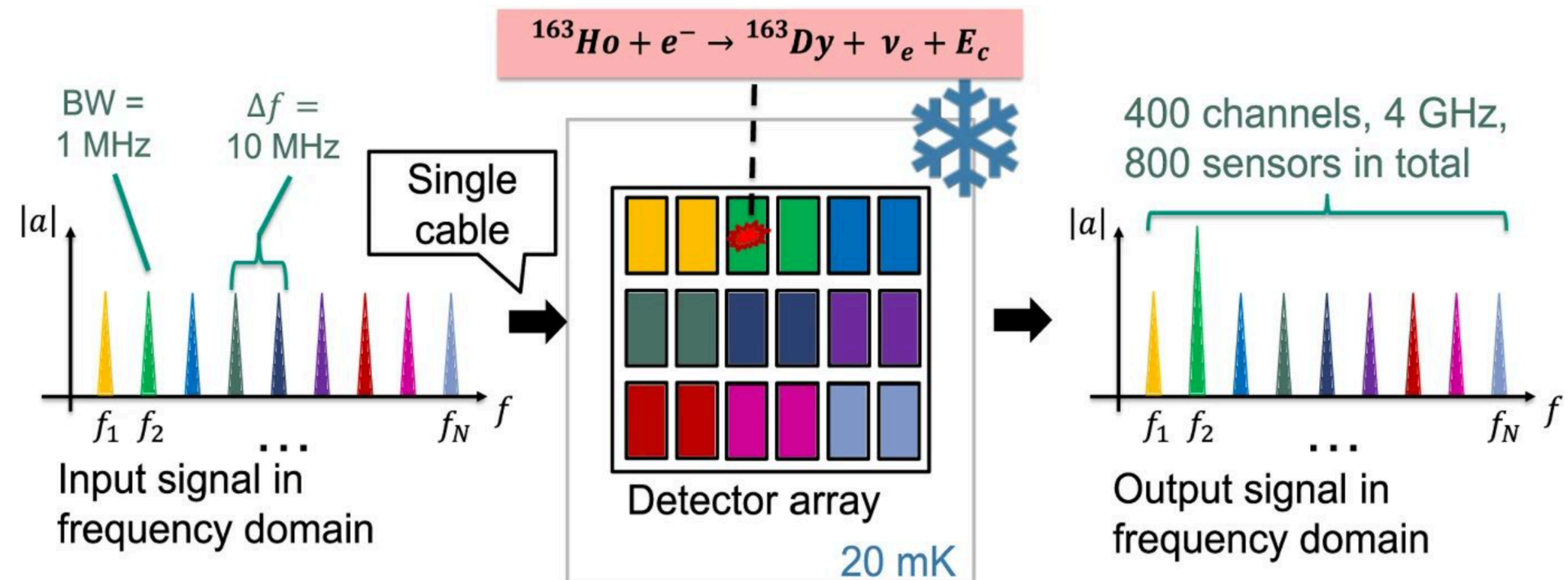
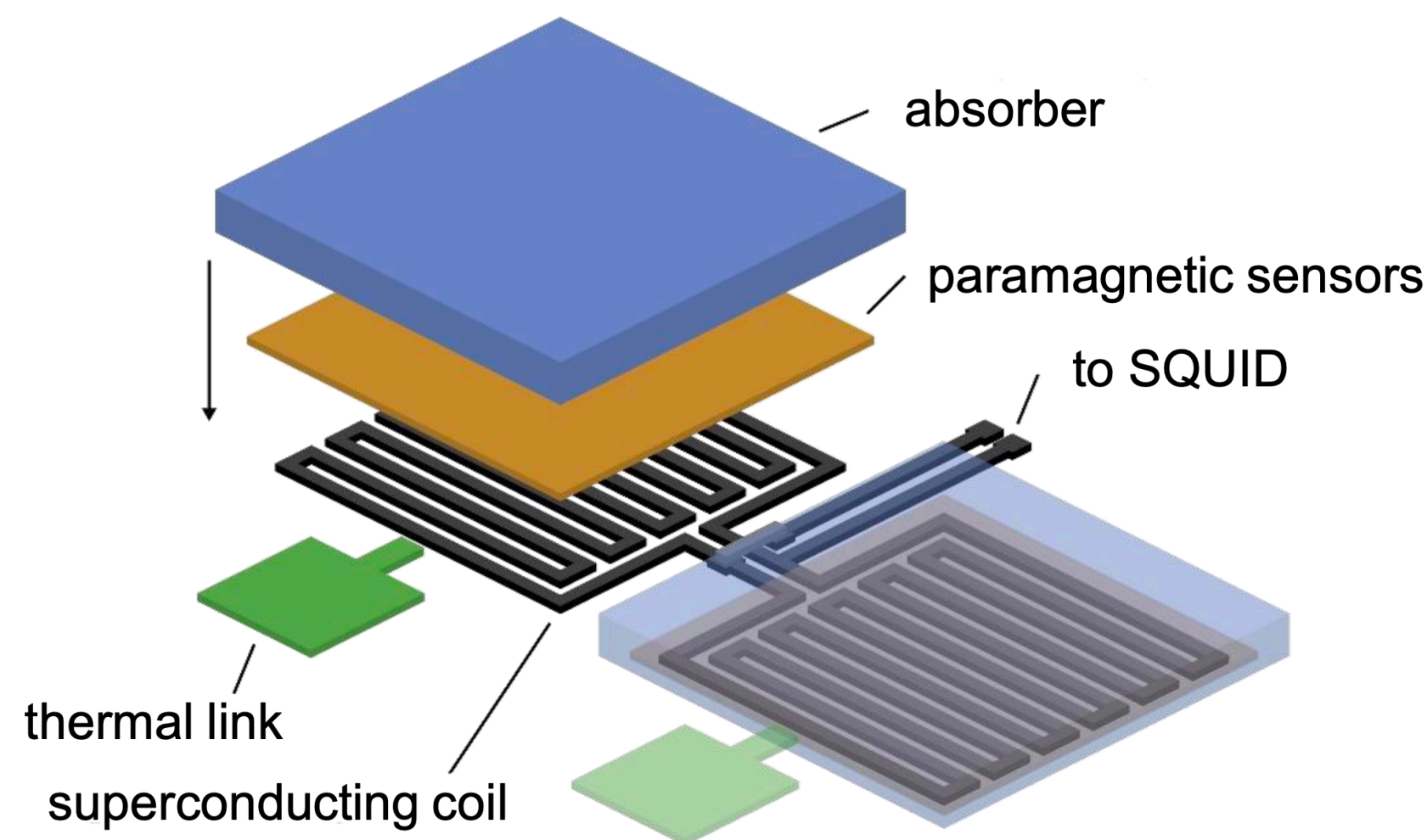
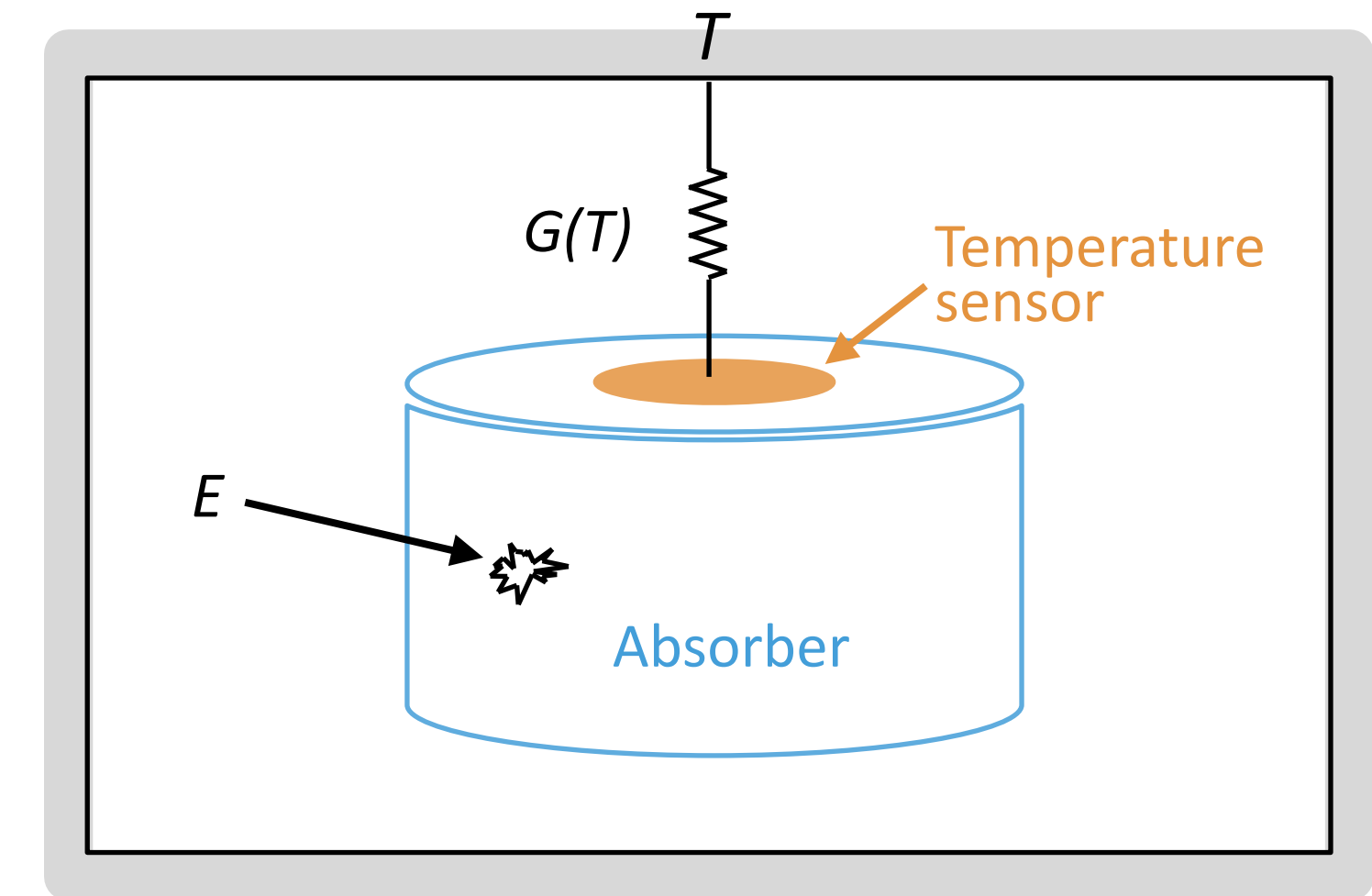
Why Quantum?: Mass Scales for Dark Matter

Quantum Sensing needed for Light/Ultralight Dark Matter, Dark Energy, cosmology, ...



Quantum Sensors: Cryogenic Micro Calorimeters

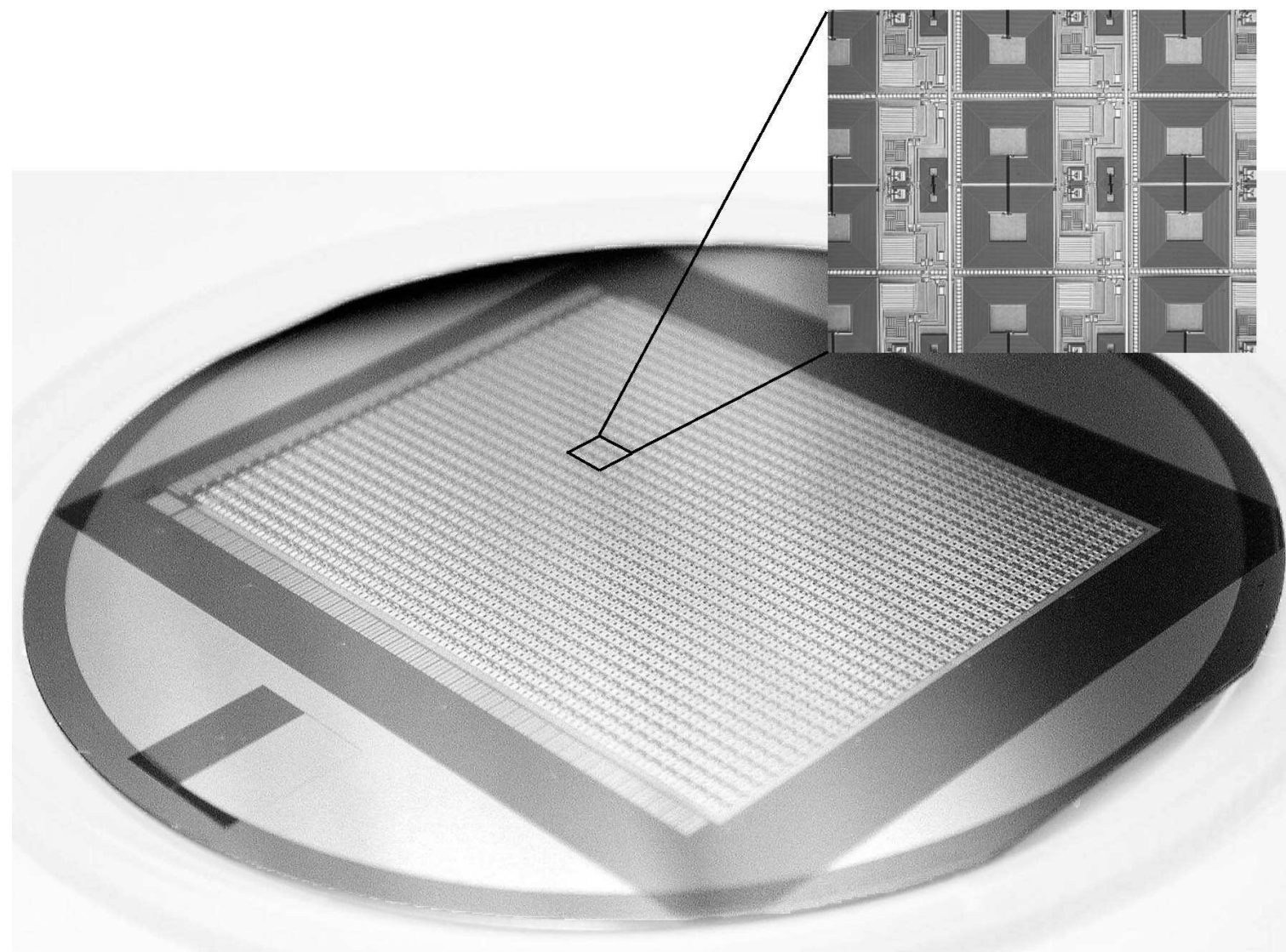
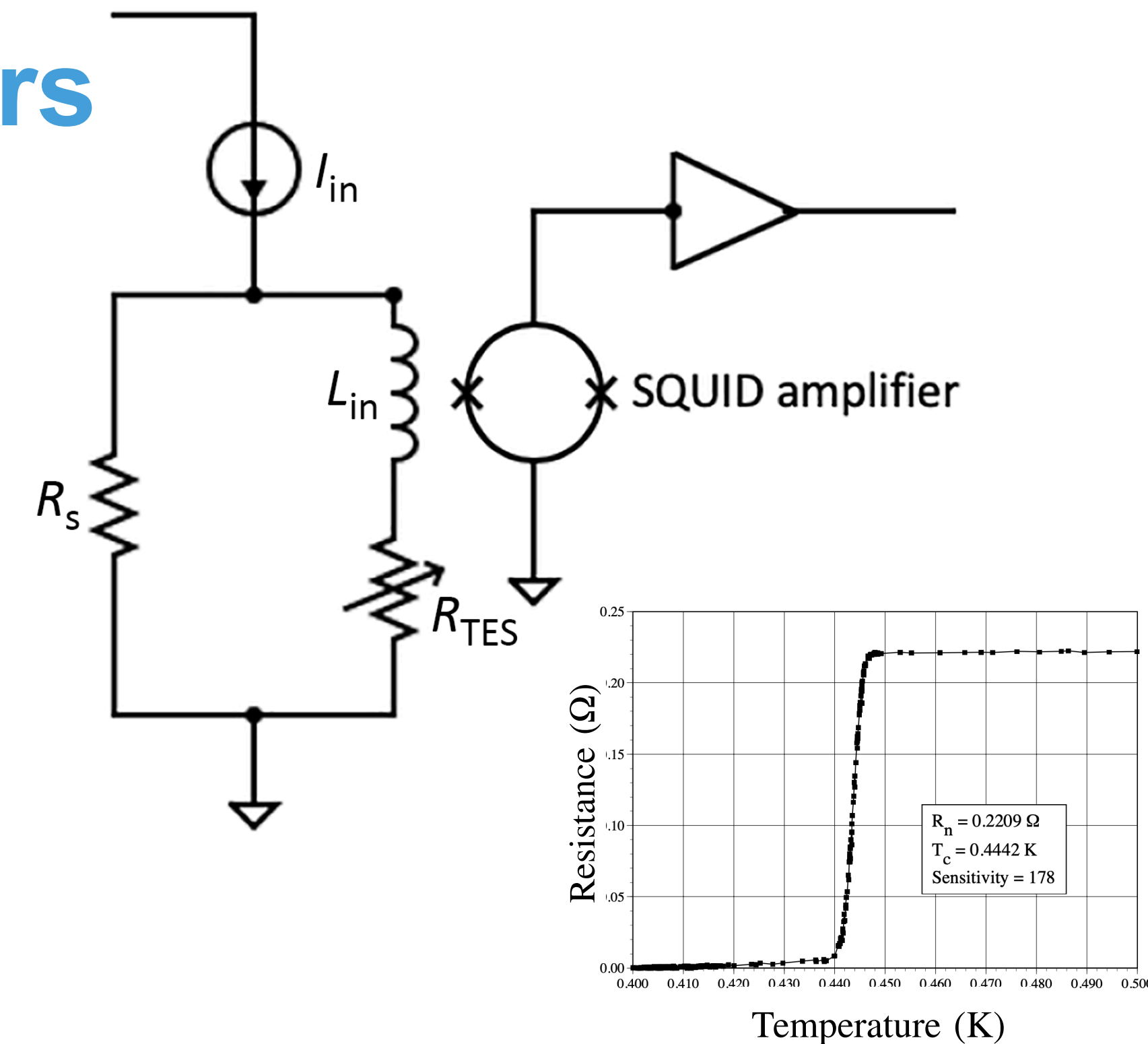
- Very Small Energy → Measure Temperature
 - Below a certain point, particle energy ends up as phonon excitations (heat)
 - Lower temperature to lower heat capacity and thus larger ΔT
 - Hitomi (X-ray): energy between 0.3 and 12 keV, resolution ~ 7 eV
- Magnetic Micro Calorimeters (MMC)
 - X-ray and γ -ray spectroscopy (astroparticle/astronomy, LYNX...)
 - nuclear and atomic physics (APPA)
 - neutrino physics (AMoRE, ECHo)
 - light dark matter, axions (DELight, IAXO)



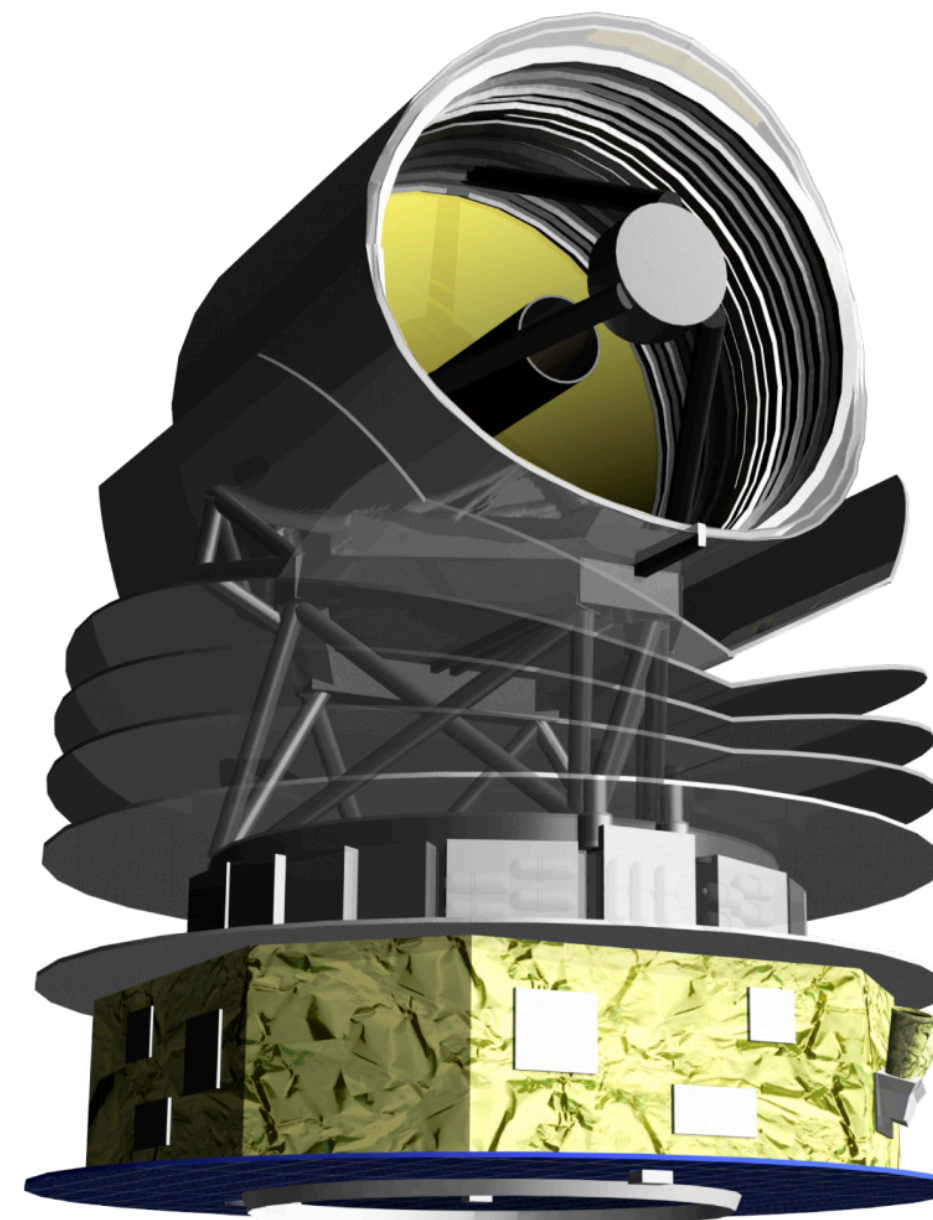
Electron Capture $^{163}\text{Holmium}$ Experiment (ECHo)

Quantum Sensors: Transition Edge Sensors

- Measure temperature change with superconducting circuit
 - take advantage of sharp transition superconducting→conducting
 - small temperature change can give large resistance change
 - coupled to SQUID amplifying circuit for readout
- Examples: Cameras in astronomy with high spectral resolution employed from radio to X-ray (SPT, ATHENA, BICEP2)



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



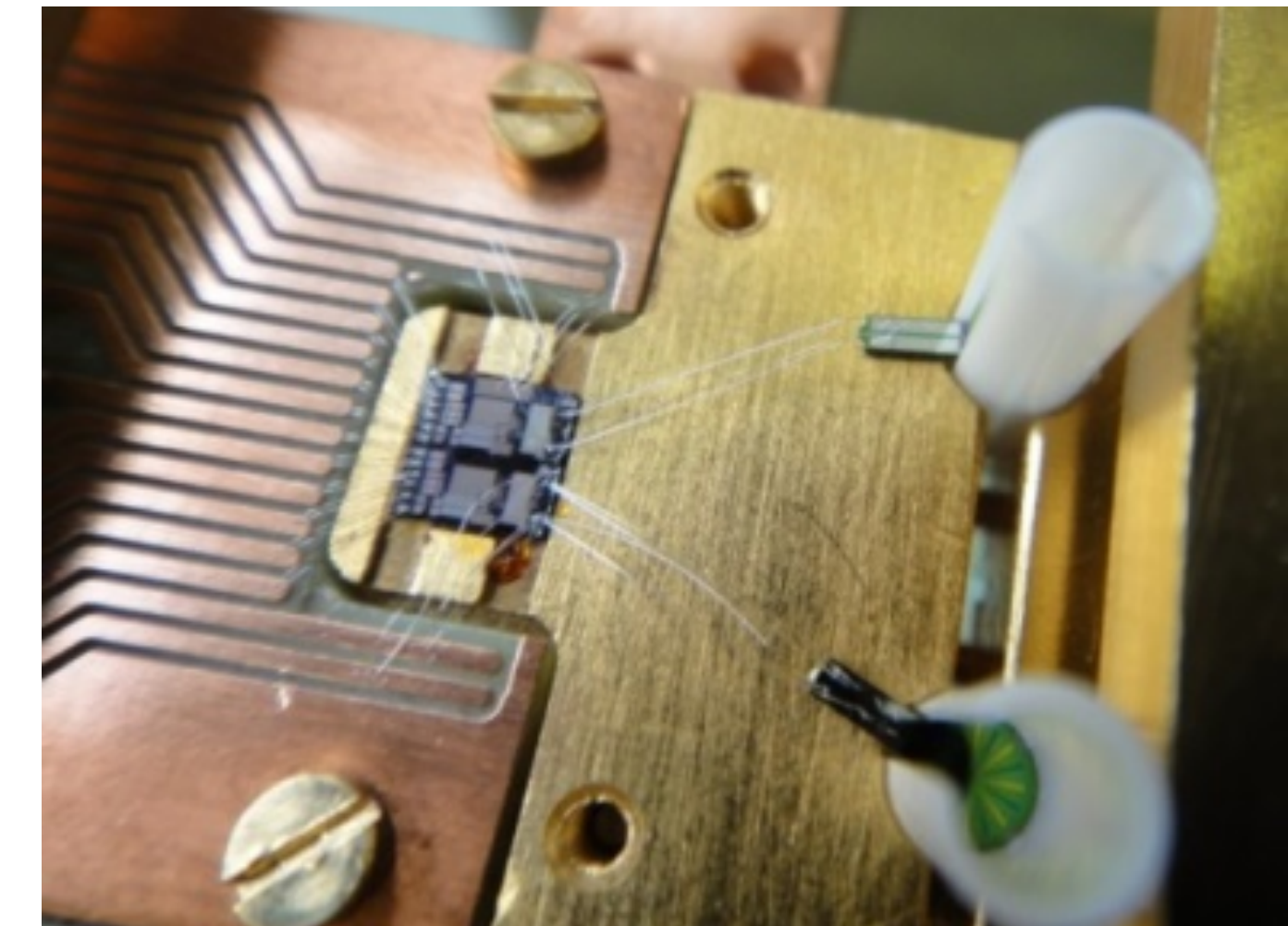
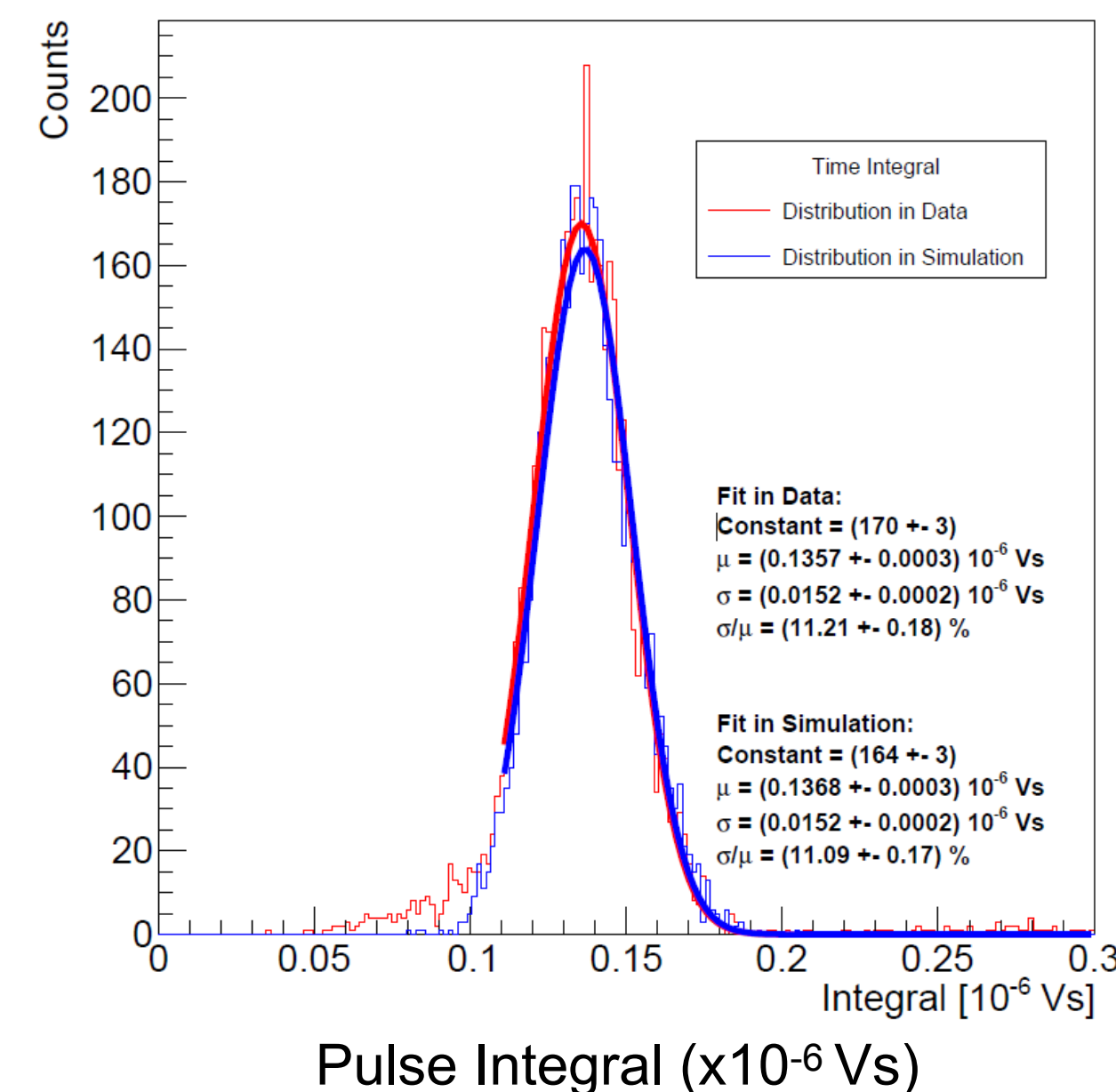
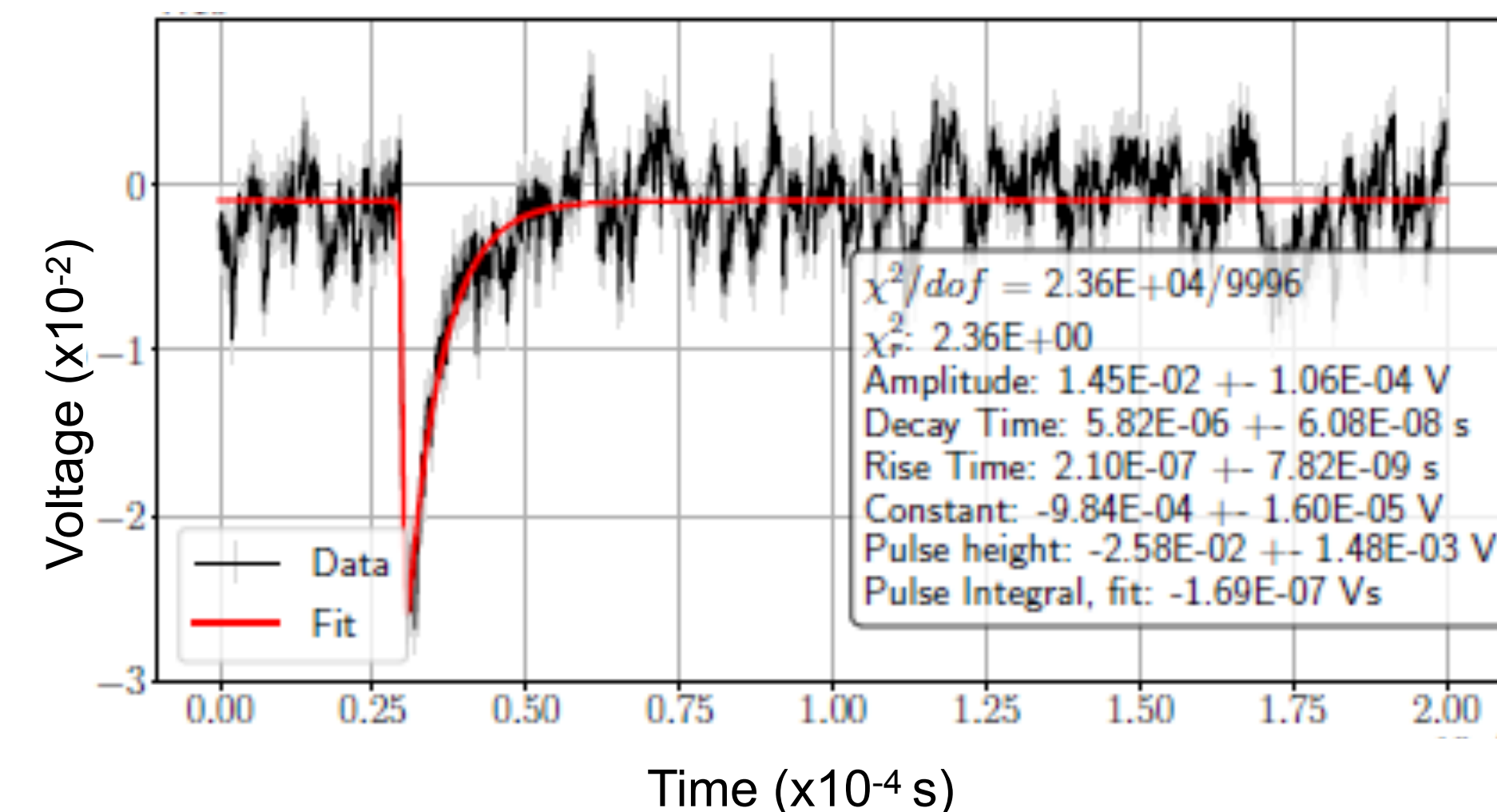
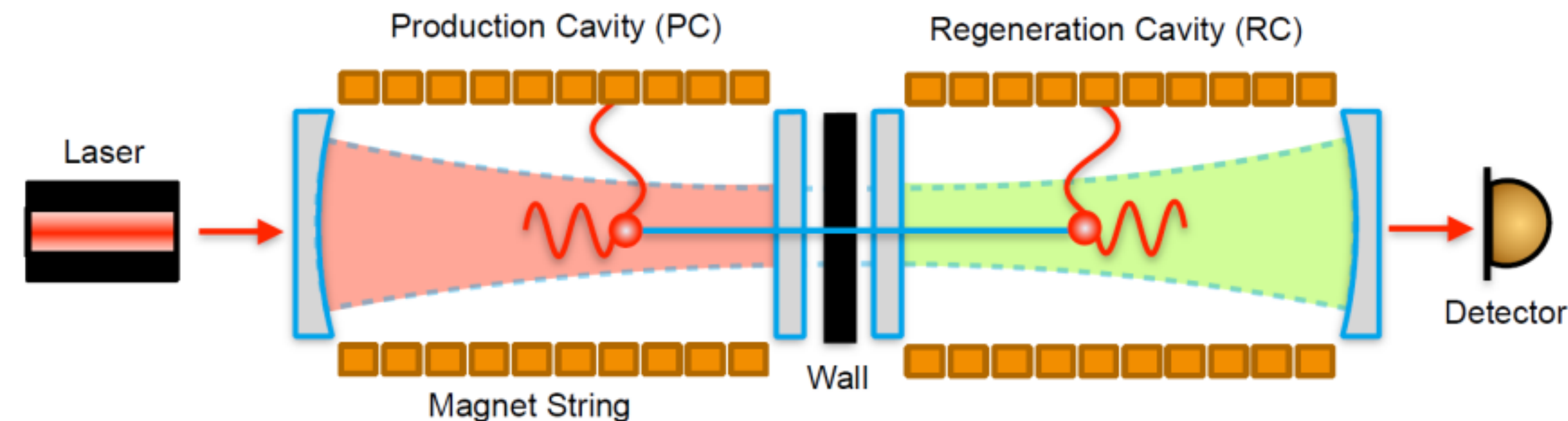
SPICA (SAFARI)



BICEP3 TES Array

Transition Edge Sensors 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),



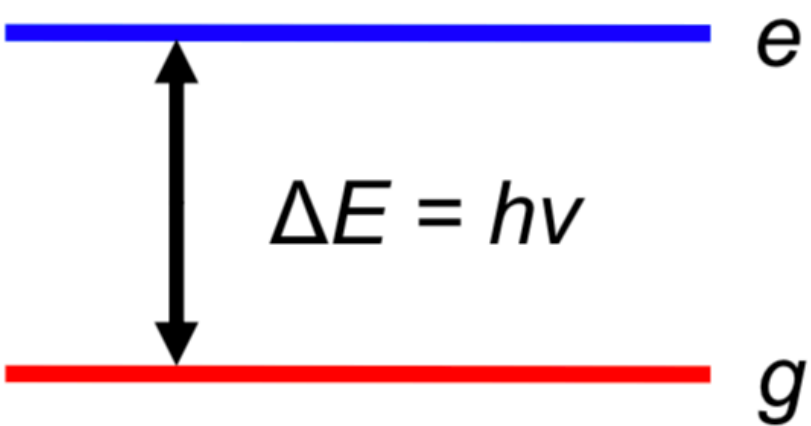
Quantum Sensors vs. Wavelength

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)	●				

- Many “particle” applications for quantum: Single-photon sensitivity, extremely low noise, low-energy...
 - See Stefan Ulmer’s talk yesterday for many more examples
- What about quantum *experiments*?

Quantum Methods for Testing Variations in α and μ

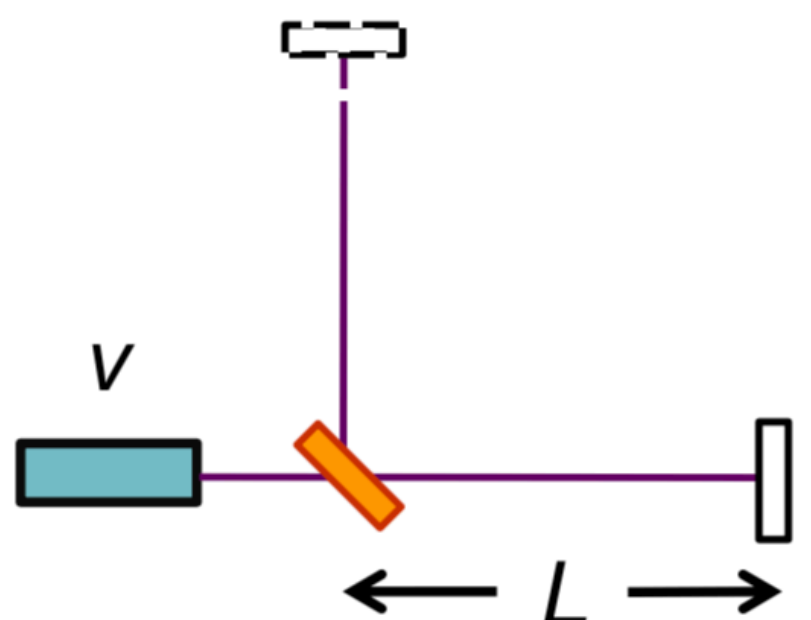
Methods for Testing $\Delta\alpha/\alpha$



Atomic spectroscopy (clocks)

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

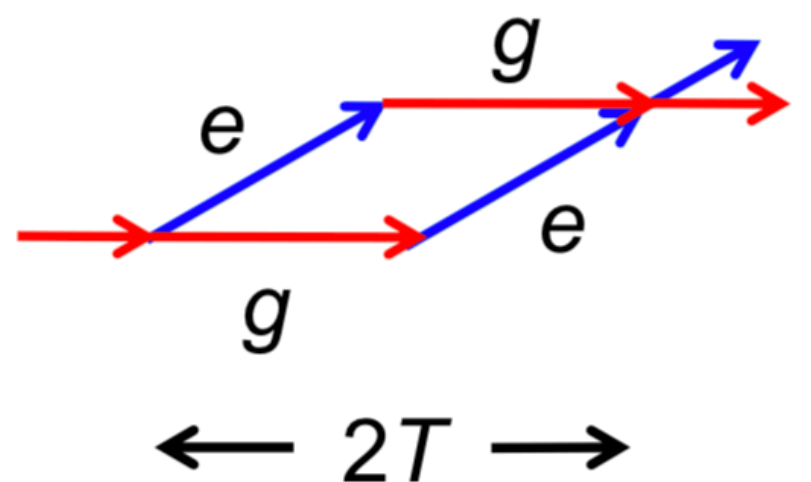
$$10^{-23} \text{ eV} > m_\phi > 10^{-16} \text{ eV}$$



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

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

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

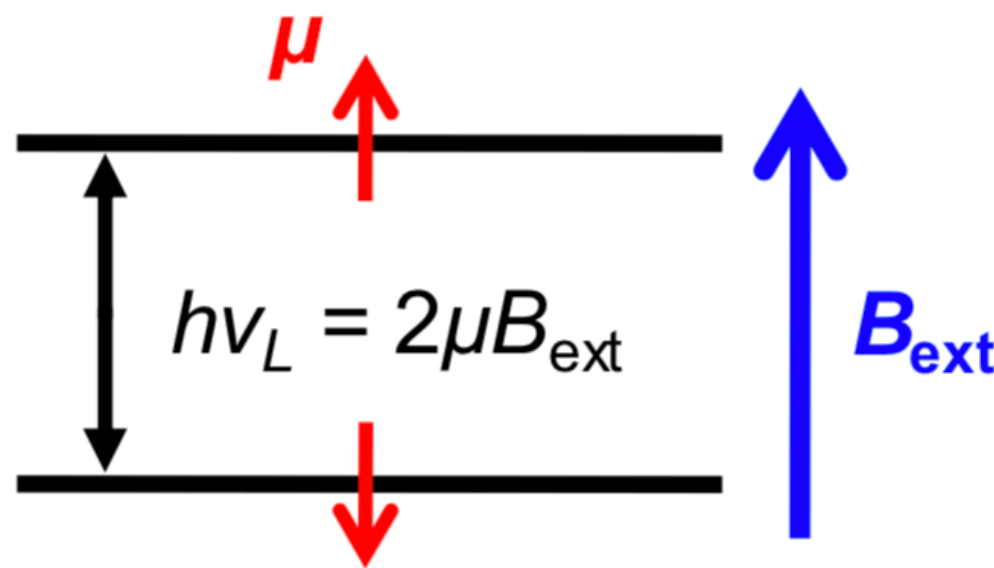
Methods for Testing $\Delta\mu/\mu$

Co-magnetometry

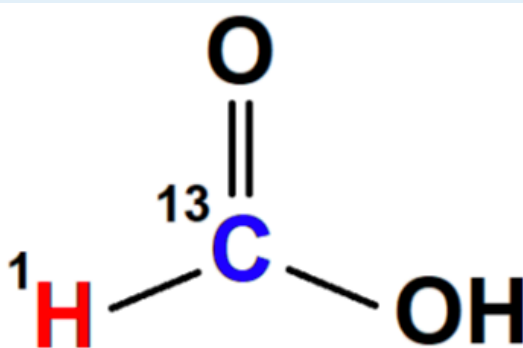
$$\delta(\nu_{L,1}/\nu_{L,2}) \propto \cos(m_a t)$$

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

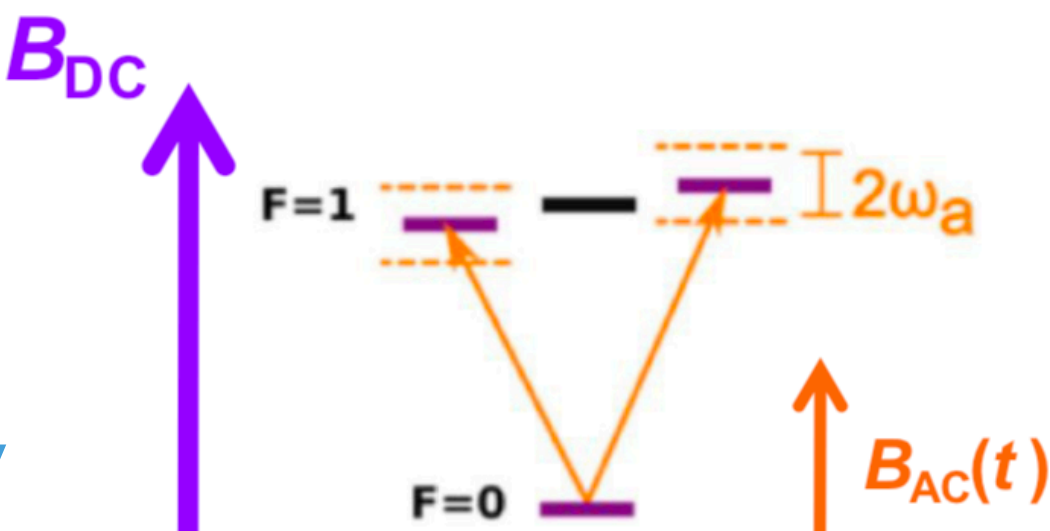
$$10^{-23} \text{ eV} > m_\phi > 10^{-17} \text{ eV}$$



Nuclear magnetic resonance (“sidebands”)



$$10^{-16} \text{ eV} > m_\phi > 10^{-13} \text{ eV}$$

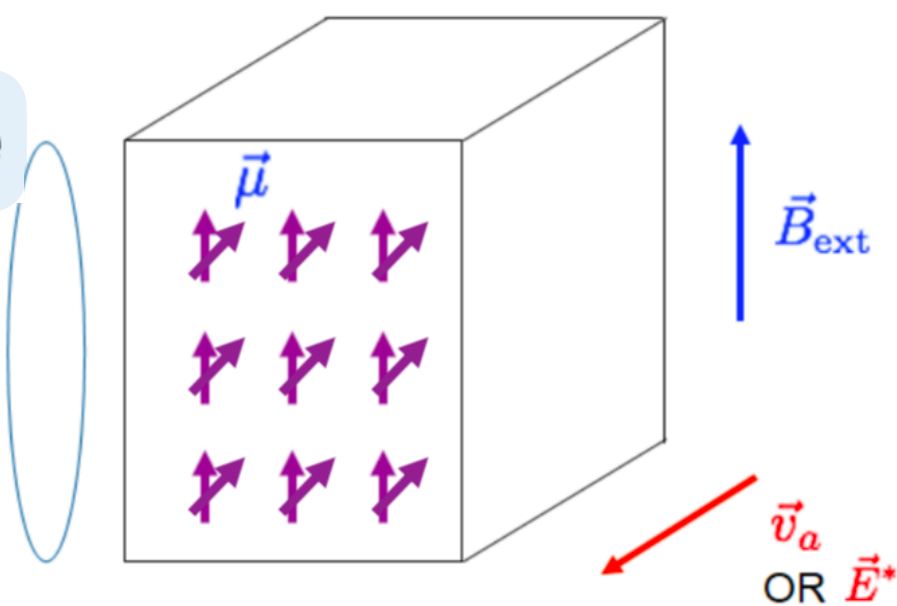


Nuclear magnetic resonance

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

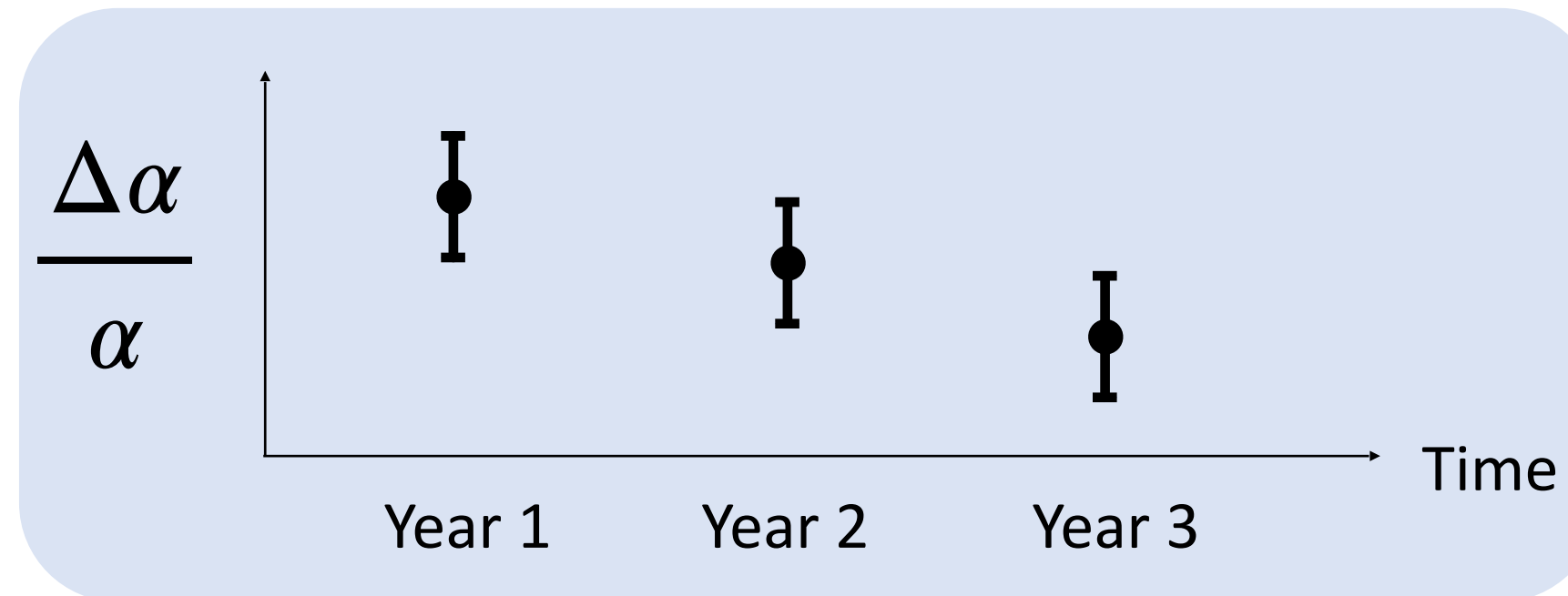
$$10^{-14} \text{ eV} > m_\phi > 10^{-7} \text{ eV}$$

SQUID pickup loop



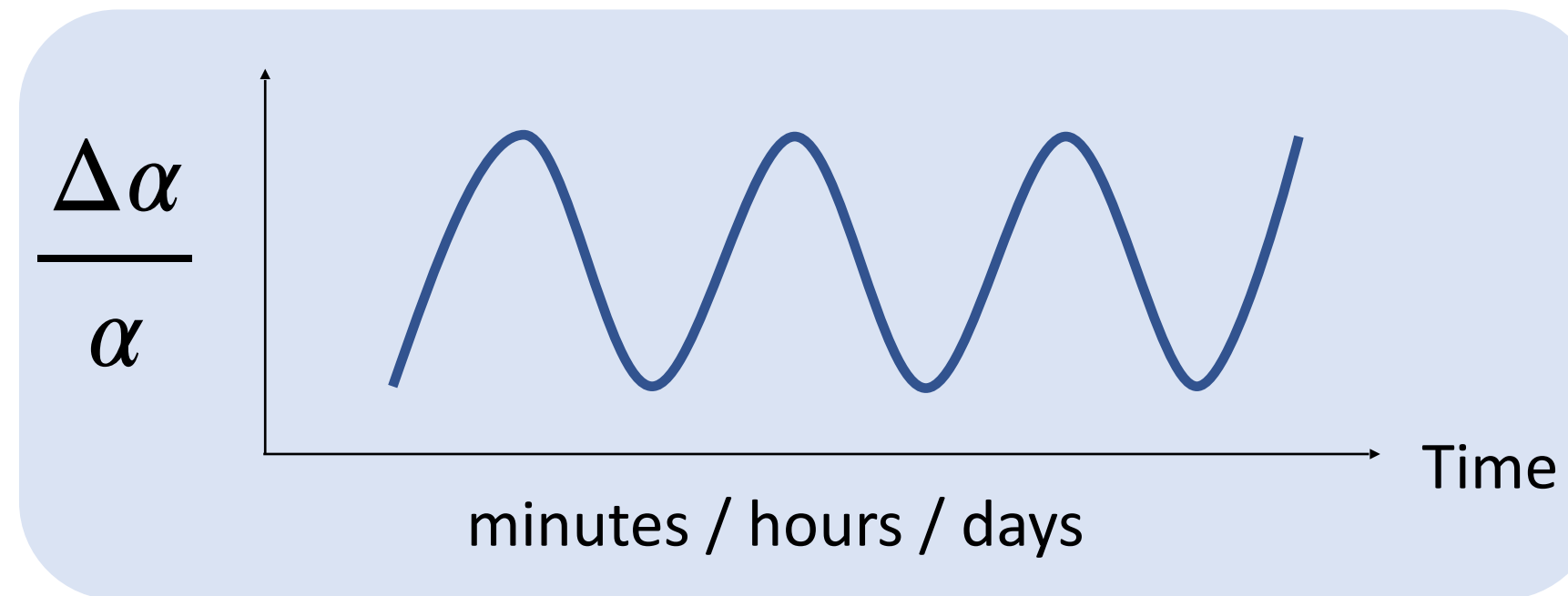
Search for Variations at Different Timescales

- Slow drifts



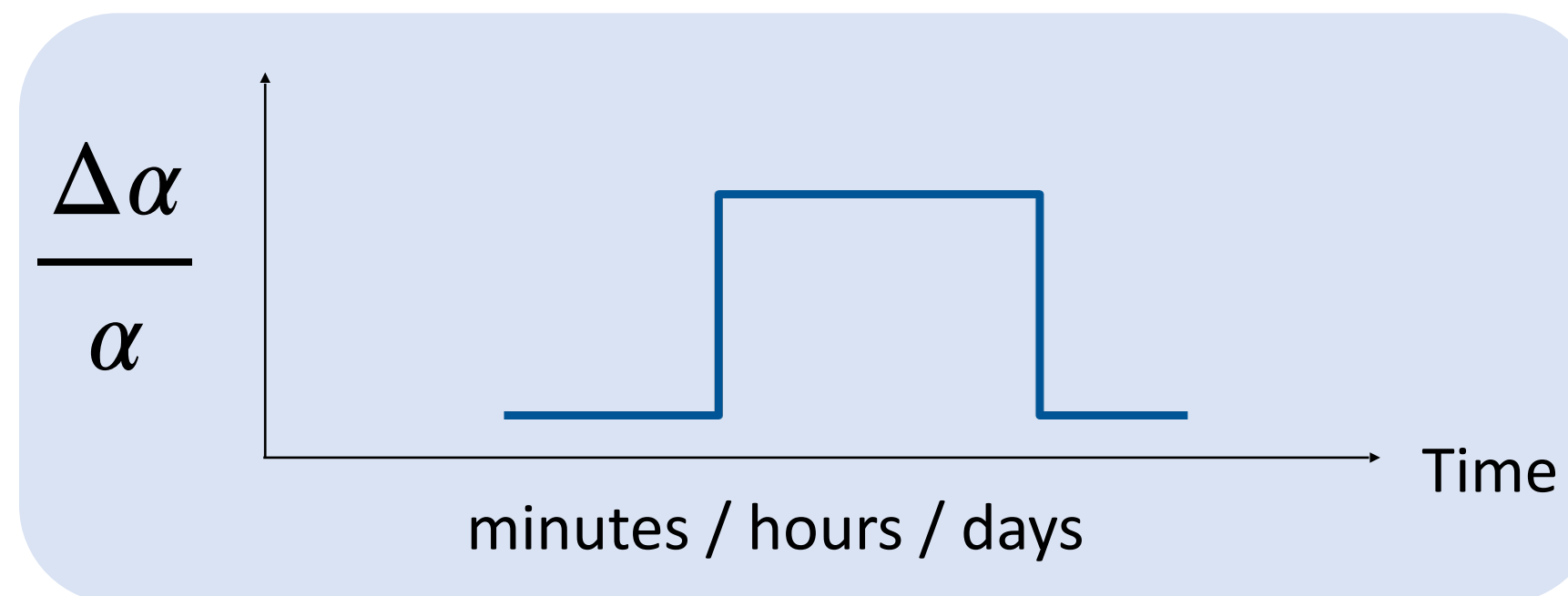
➡ New physics

- Oscillations



➡ Very light dark matter

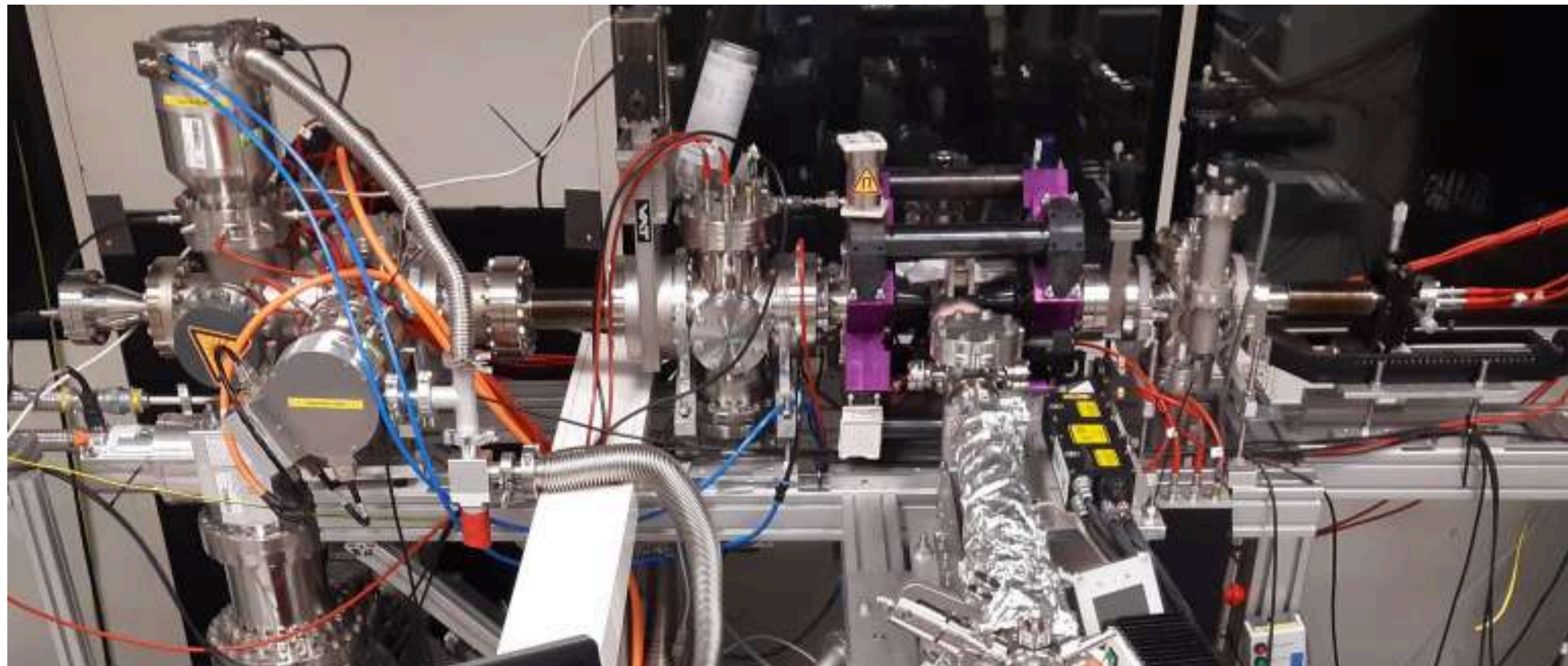
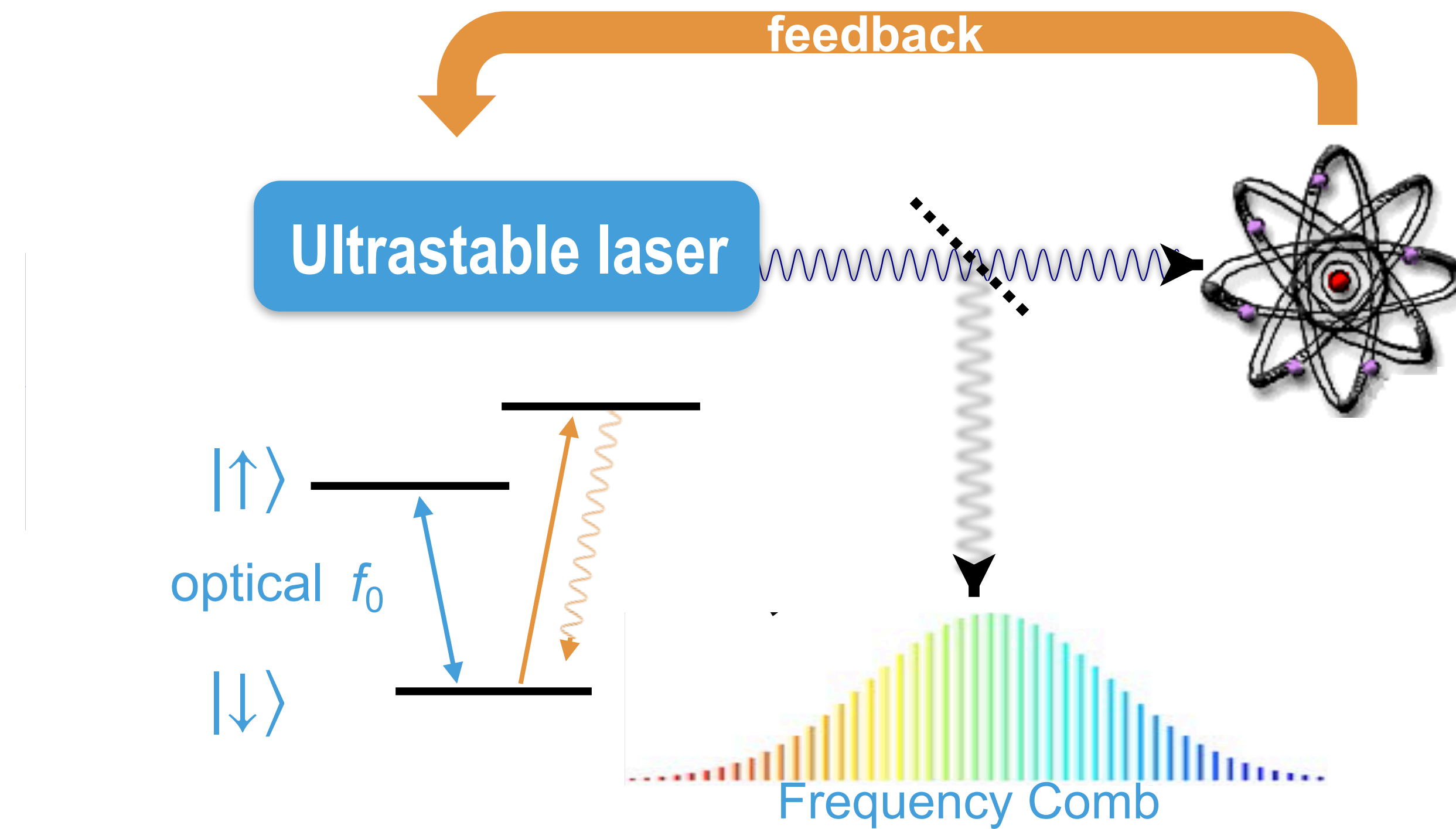
- Fast transients



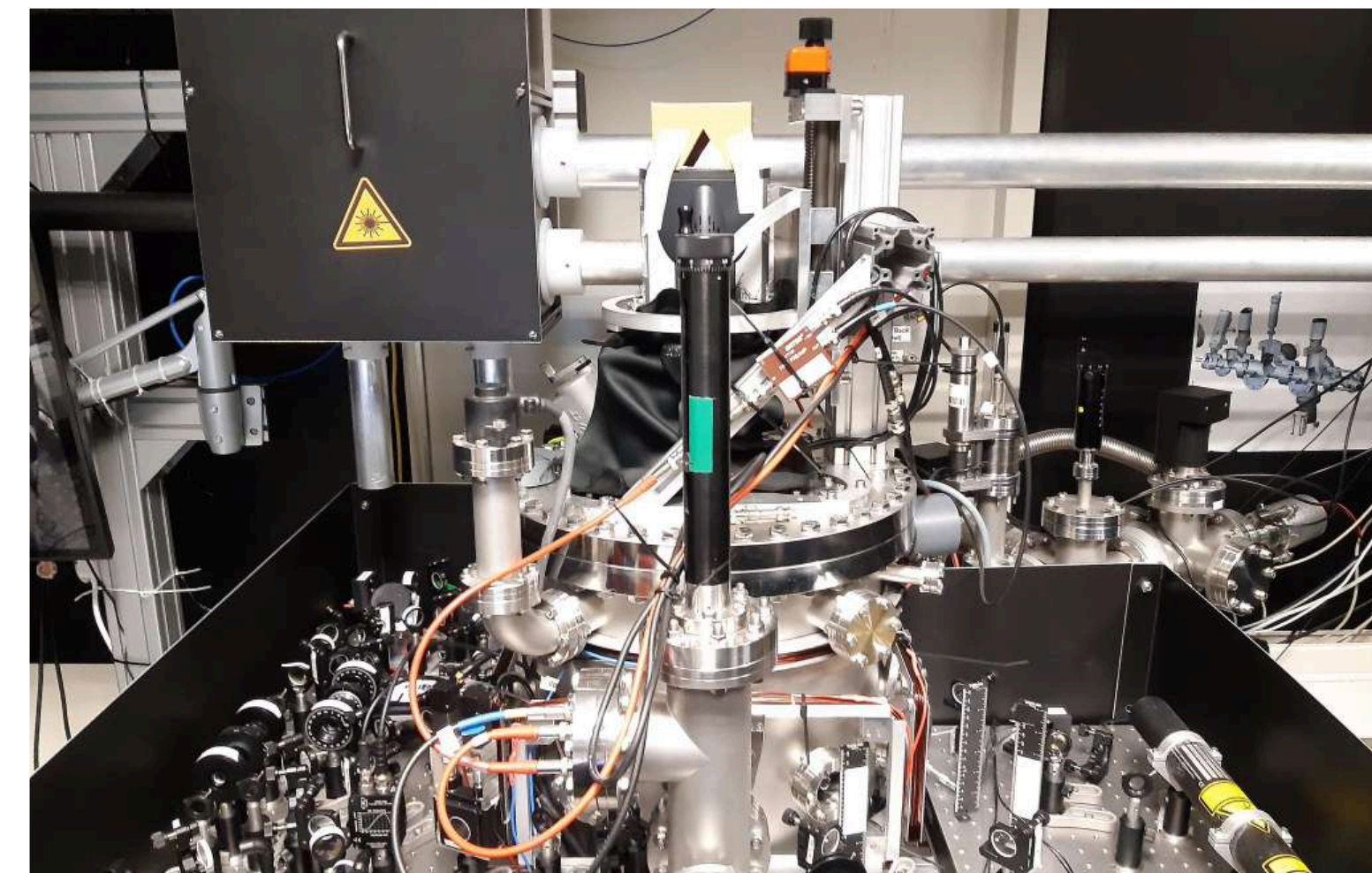
➡ Dark matter - topological defects

Optical Atomic Clocks w/ HCl

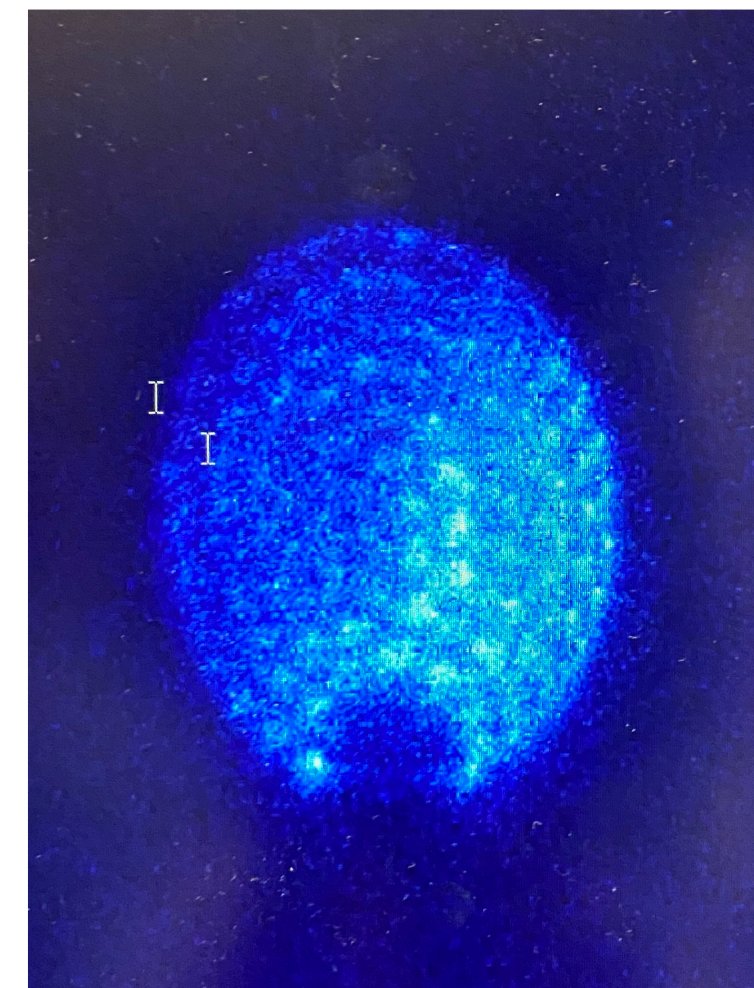
- Ultra-stable laser excites atomic transitions
- Establish feedback loop → a clock
- Frequency comb: optical → countable microwave
- Fluorescence-monitor 3-state system
- Laser/sympathetic cooling with a second ion (eg Be)
- Highly charged ions (HCl) for best sensitivity to $\Delta\alpha/\alpha$



EBIT test stand @MPIK



Paul trap w/ optics



Be crystal with HCl (Ar)

Quantum Experiment Examples: BASE, MAGIS, AION

BASE: Quantum experiments for magnetic moment of antiproton, q/m ratio, antiproton trap at CERN



BASE – Collaboration

- Mainz:** Measurement of the magnetic moment of the proton, implementation of new technologies.

- CERN-AD:** Measurement of the magnetic moment of the antiproton and proton/antiproton q/m ratio

- BASE-STEP:** Development of transportable antiproton traps
- Hannover/PTB:** QLEDS-laser cooling project, new technologies



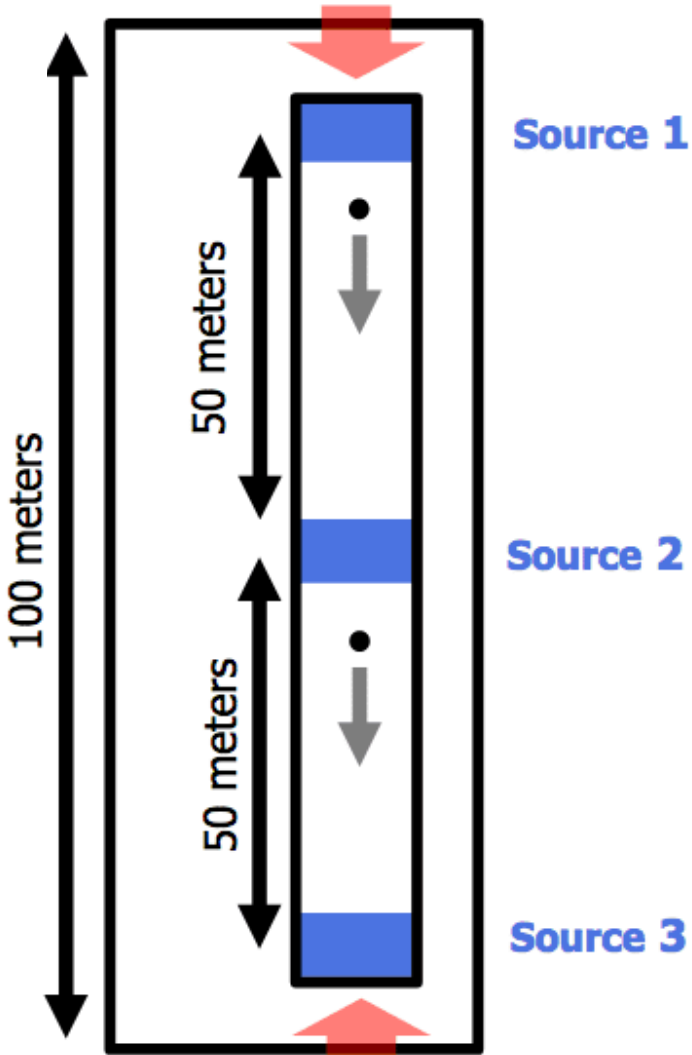
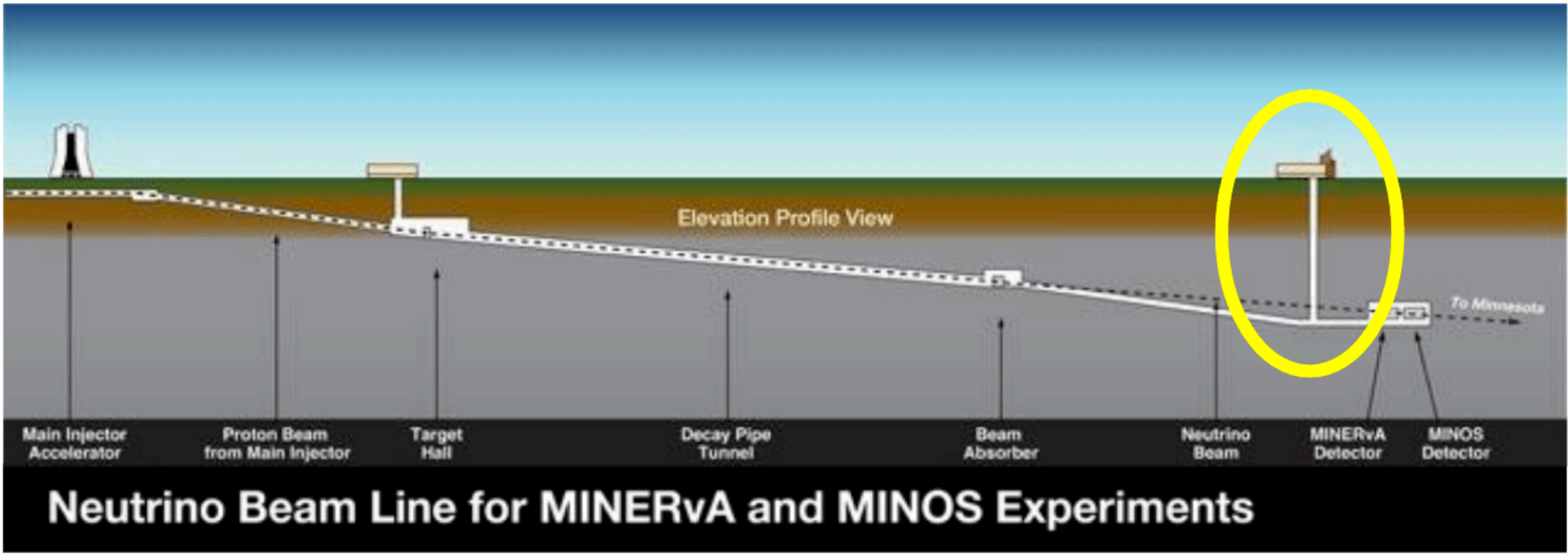
Institutes: RIKEN, MPIK, CERN, University of Mainz, Tokyo University, GSI Darmstadt, University of Hannover, PTB Braunschweig, ETH Zuerich



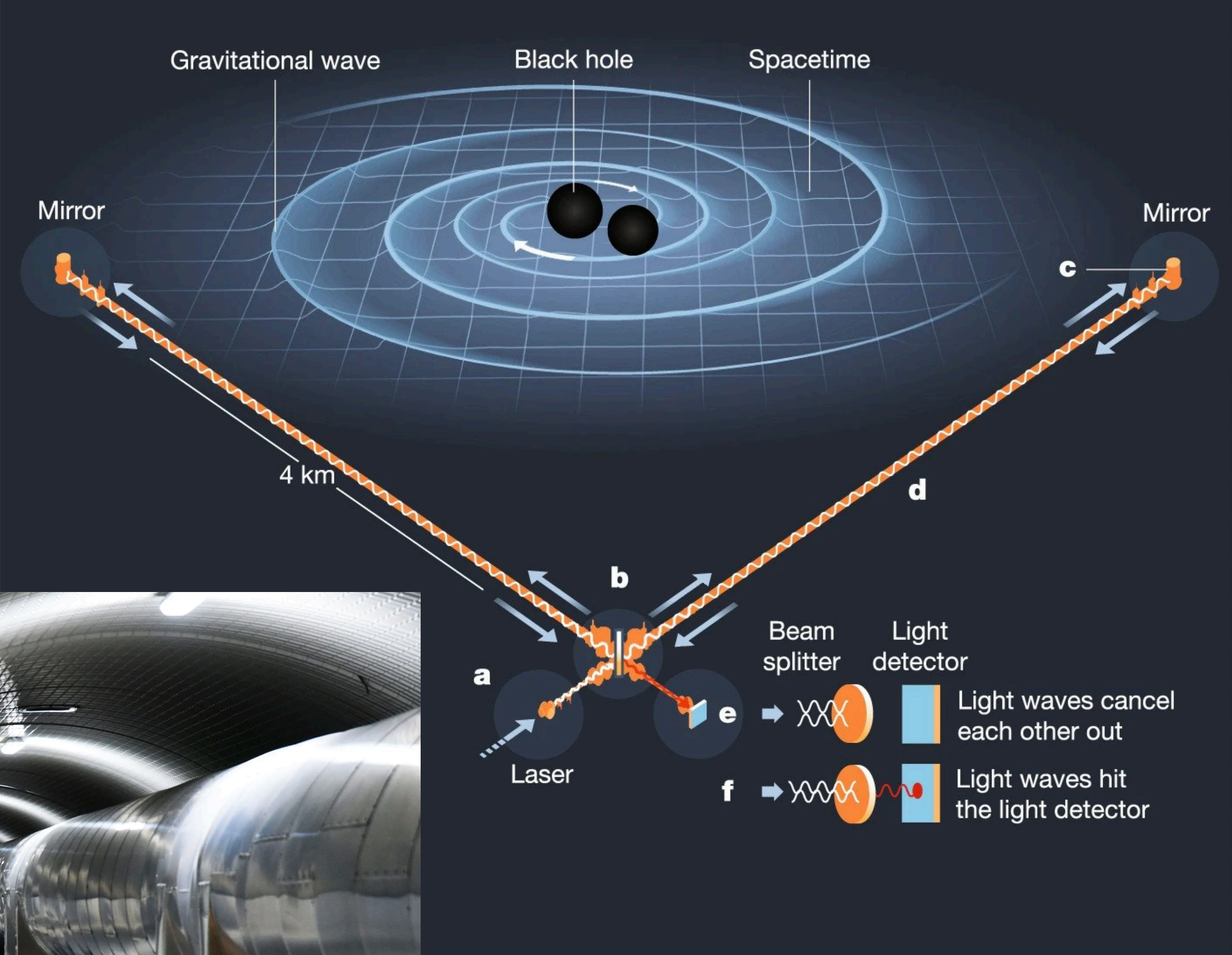
Team at CERN, running 24/7 since 2013

Three experiments, 9 institutes, about 30 collaborators, 10 at CERN

MAGIS-100 Detector at Fermilab



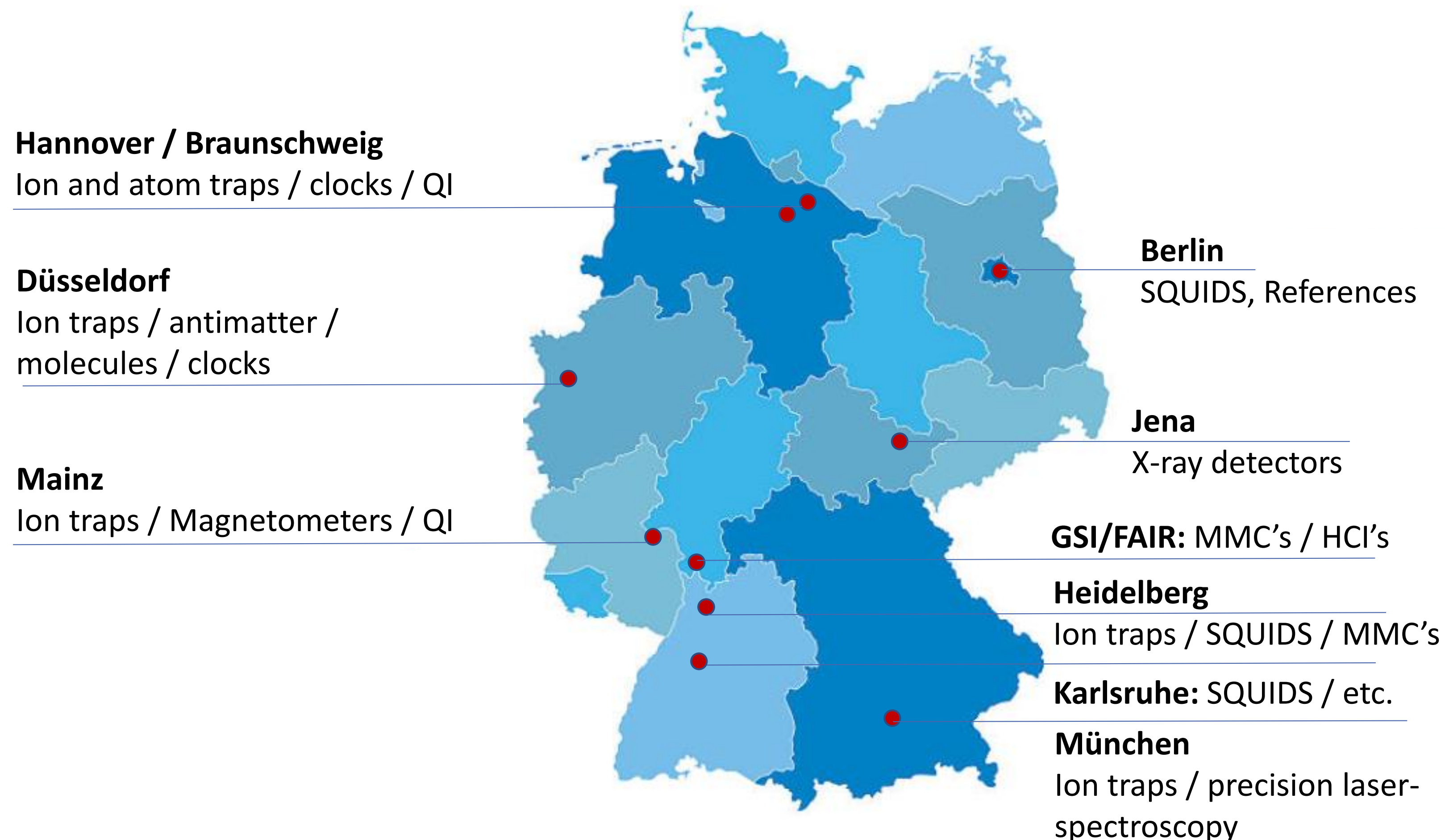
MAGIS-100, AION: 100m atom interferometer experiments planned for FNAL, CERN



Gravitational Waves

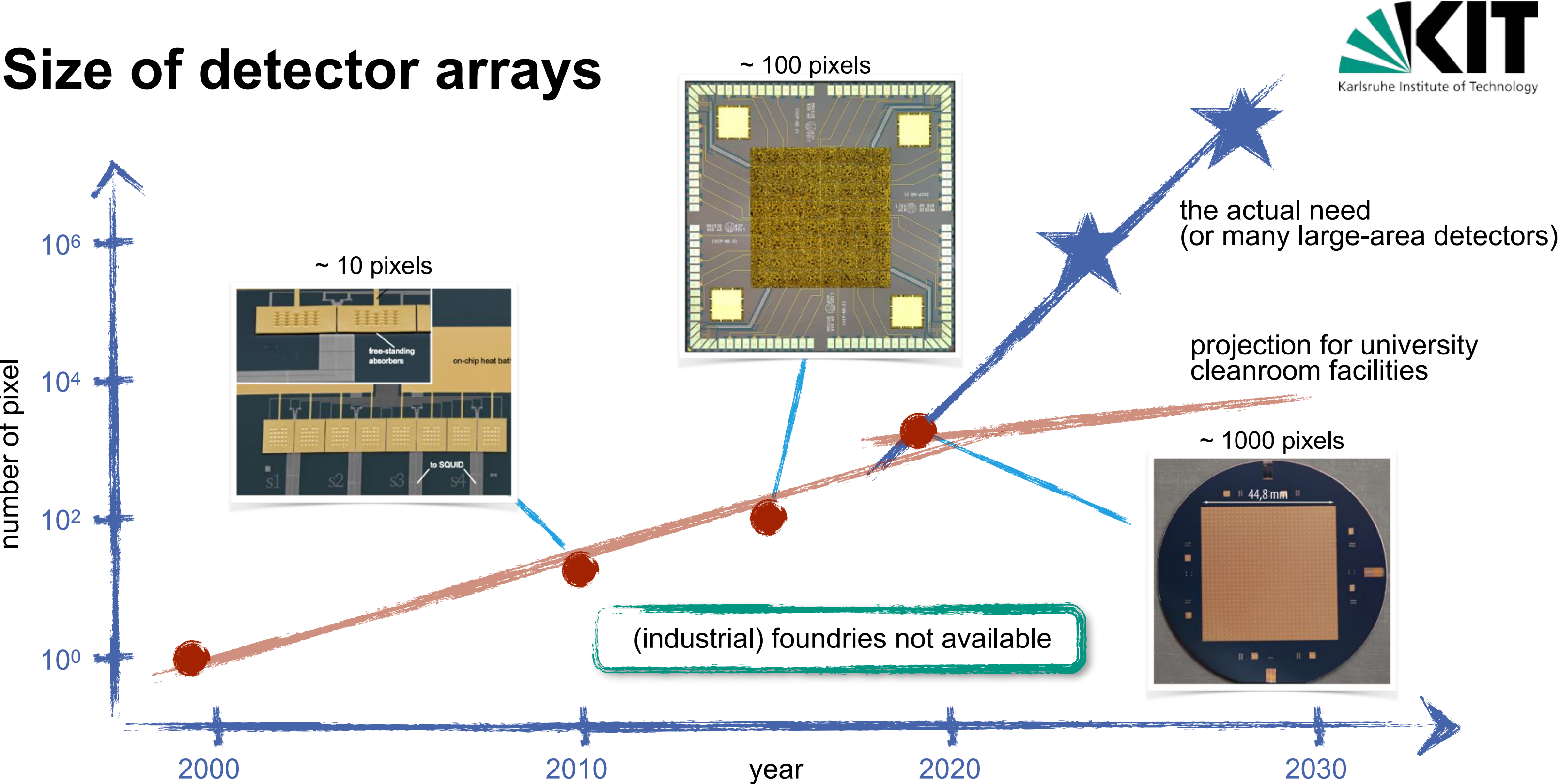
Quantum Technologies: Existing Groups

- Lots of active groups, many world-class activities and growing capabilities
- Diverse funding, goals, and locations; more collaboration would help



Quantum Technologies: New Infrastructures

Size of detector arrays



national level



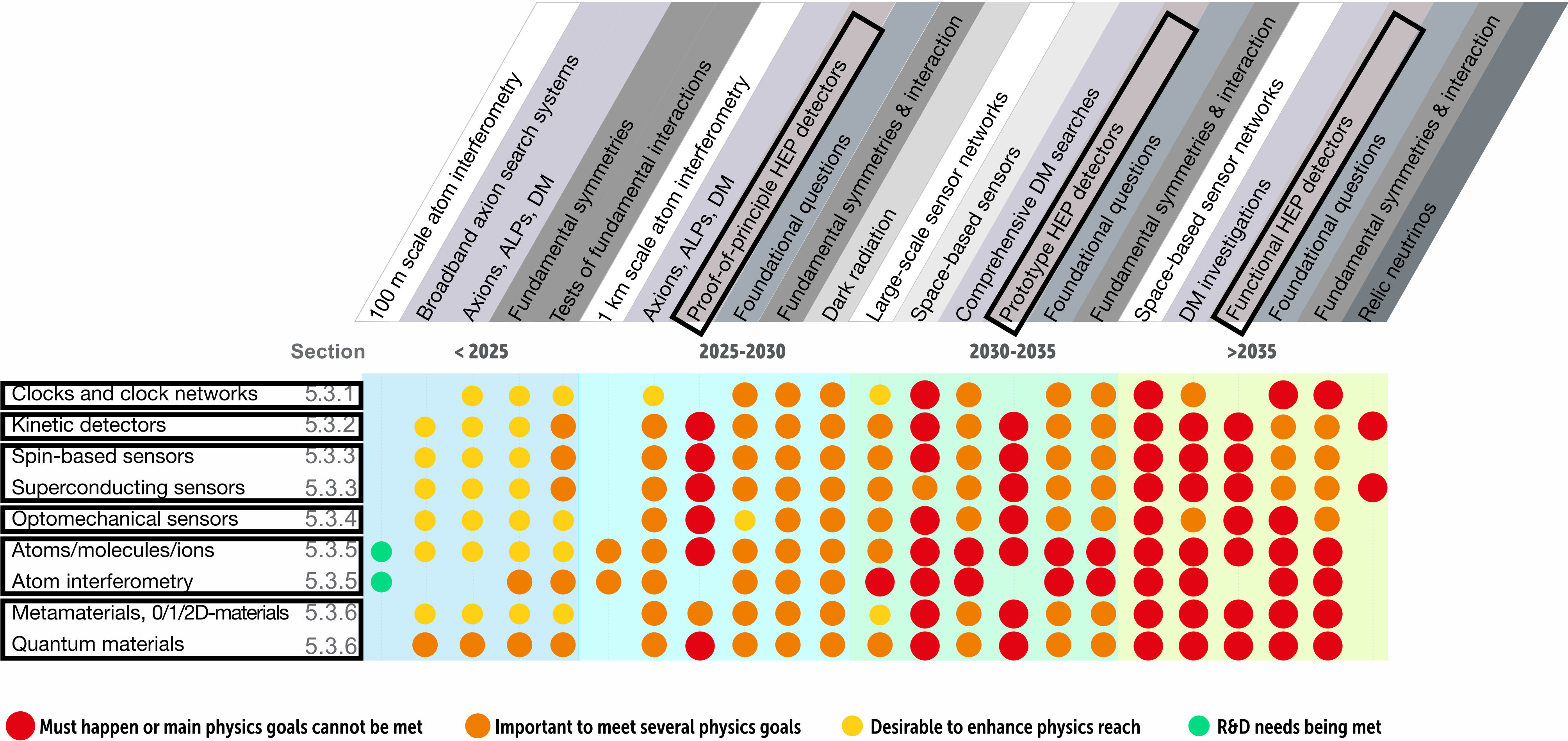
international level



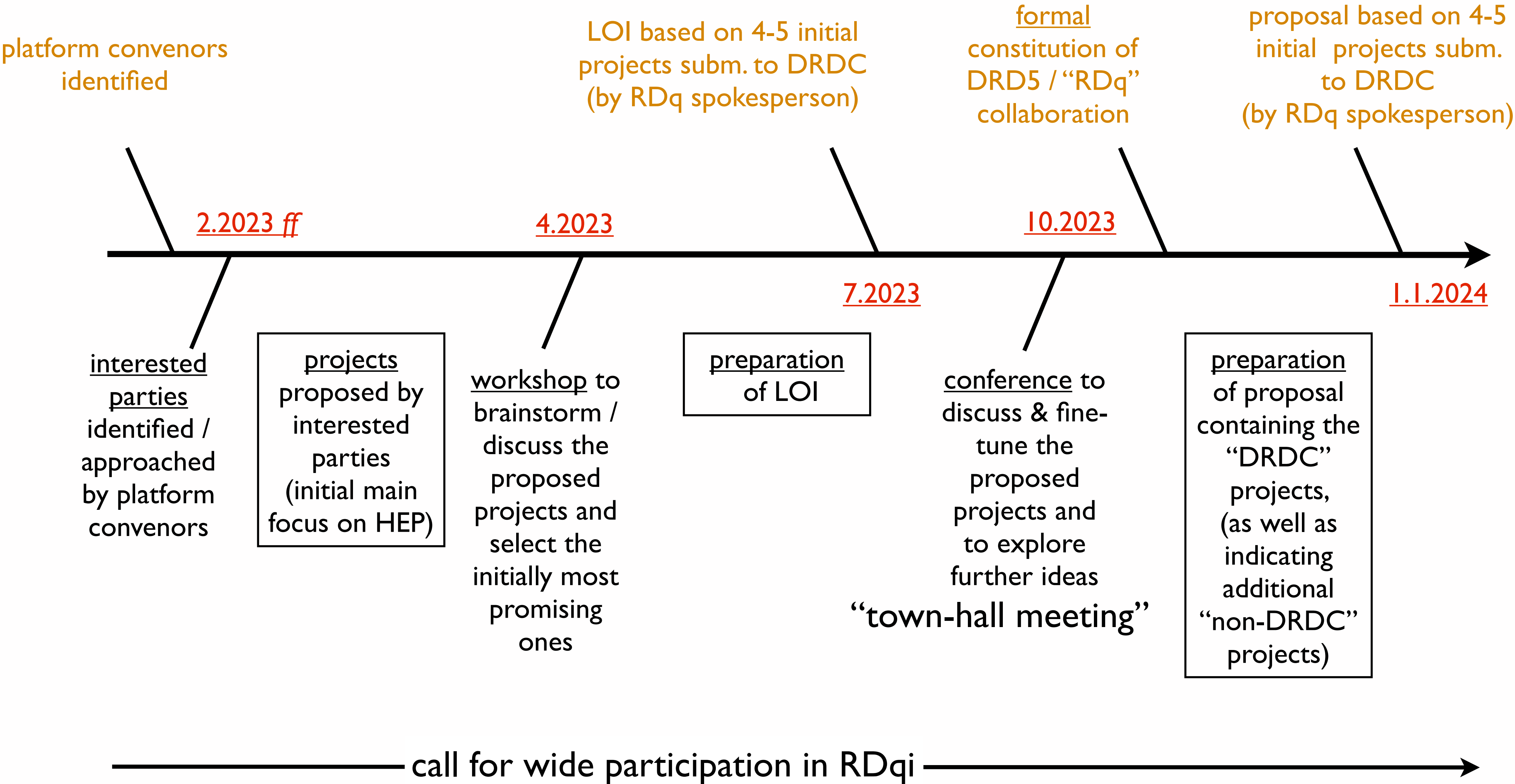
- On the horizon: test cryostats for cryogenic sensors (DESY, KIT), Helmholtz Distributed Detector Lab (DDL)
- New Collaborations: Consortium for Cryogenic Detectors and Superconducting Electronics (CDS)

ECFA Roadmap and DRD5 (RDq)

- RECFA Detector R&D Roadmap 2021: Chapter 5, Quantum and Emerging Technologies Detectors



DRD5 Timeline



DRD5 Working Groups and Conveners

Clocks and Clock Networks

David Hume	david.hume@nist.gov
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Superconducting and Spin-Based Sensors

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Optomechanical Sensors

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Atoms, Molecules, Ions, Interferometry

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Metamaterials, 0-1, 1-, 2-D Materials

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A few more to be added...

Quantum Detectors and ErUM-Pro?

- Previous grant round provided funding for detectors, instruments, methods & technologies in:

- Particle physics
- Ground-based astronomy and astroparticle
- Neutron, photon, or charged particle sources
- +others

**Bundesministerium
für Bildung und Forschung**
**Richtlinie
zur Förderung von
ausgewählten Schwerpunkten der Erforschung
von Universum und Materie im Themengebiet „Teilchen“**

Vom 25. August 2020

1 Förderziel, Anwendungszweck, Rechtsgrundlage

1.1 Förderziel und Anwendungszweck

Das Bundesministerium für Bildung und Forschung (BMBF) beabsichtigt, Vorhaben zur Forschung und Entwicklung im Themengebiet „Teilchen“ zu fördern. Grundlage hierfür ist das Rahmenprogramm „Erforschung von Universum und Materie – ErUM“¹. Die Förderung ist auf Grundlagenforschung der Elementarteilchenphysik sowie der Hadronen- und Kernphysik unter Einsatz ausgewählter Großgeräte gerichtet, an denen der Bund sich maßgeblich beteiligt.

Die Großgeräte der naturwissenschaftlichen Grundlagenforschung sind ein wesentlicher Bestandteil der Forschungsinfrastruktur. Mit dieser Fördermaßnahme wird gemäß dem BMBF-Aktionsplan „ErUM-Pro“² die Gestaltung der Forschungsinfrastrukturen anhand der forschungspolitischen Prioritäten des Bundes umgesetzt. An den Großgeräten der naturwissenschaftlichen Grundlagenforschung werden Technologien an den Grenzen des Machbaren mit weitreichenden Anwendungen genutzt. Sie ermöglichen wissenschaftliche Spitzenleistungen bei der Erforschung von Universum und Materie und sind Ausgangspunkt für Innovationen in Deutschland. Die nur an Großgeräten mögliche Forschung leistet damit einen wichtigen Beitrag zur „Hightech-Strategie 2025“ und trägt dazu bei, die hervorragende Position Deutschlands im globalen Wettbewerb weiter auszubauen. Die Leistungsfähigkeit und das Anwendungsspektrum der Großgeräte sollen daher im Sinne der Hightech-Strategie kontinuierlich erweitert werden.

Mit der Durchführung der Vorhaben soll ein wirksamer Beitrag zur Festigung und zum weiteren Ausbau der im internationalen Vergleich hervorragenden Position der Wissenschaft in Deutschland im ErUM-Themengebiet „Teilchen“ geleistet und der Bildungs- und Forschungsstandort Deutschland nachhaltig gestärkt werden.

- ✓ Targeted at national/international facilities and infrastructures → [update list?](#)
 - ✓ Well-aligned with strategy process & roadmaps → [need to communicate ECFA-DRD plans to BMBF](#)
 - ✓ Supports cross-thematic cooperation between universities and non-university research institutions
 - ✗ Does not support "blue sky" R&D, small experiments, or most future facilities
-
- Might work for sensor development → [need link to DRD5](#)
 - Not a good fit for small-scale “table-top” experiments → [possible connection to infrastructures](#)

Thank you



Contact

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