Quantum Sensing in Particle and Astroparticle Physics at DESY

Quantum Sensors, Fundamental Physics and Plans for the Future

Steven Worm
DESY Zeuthen and Humboldt-Universität zu Berlin

September 21, 2020

Outline

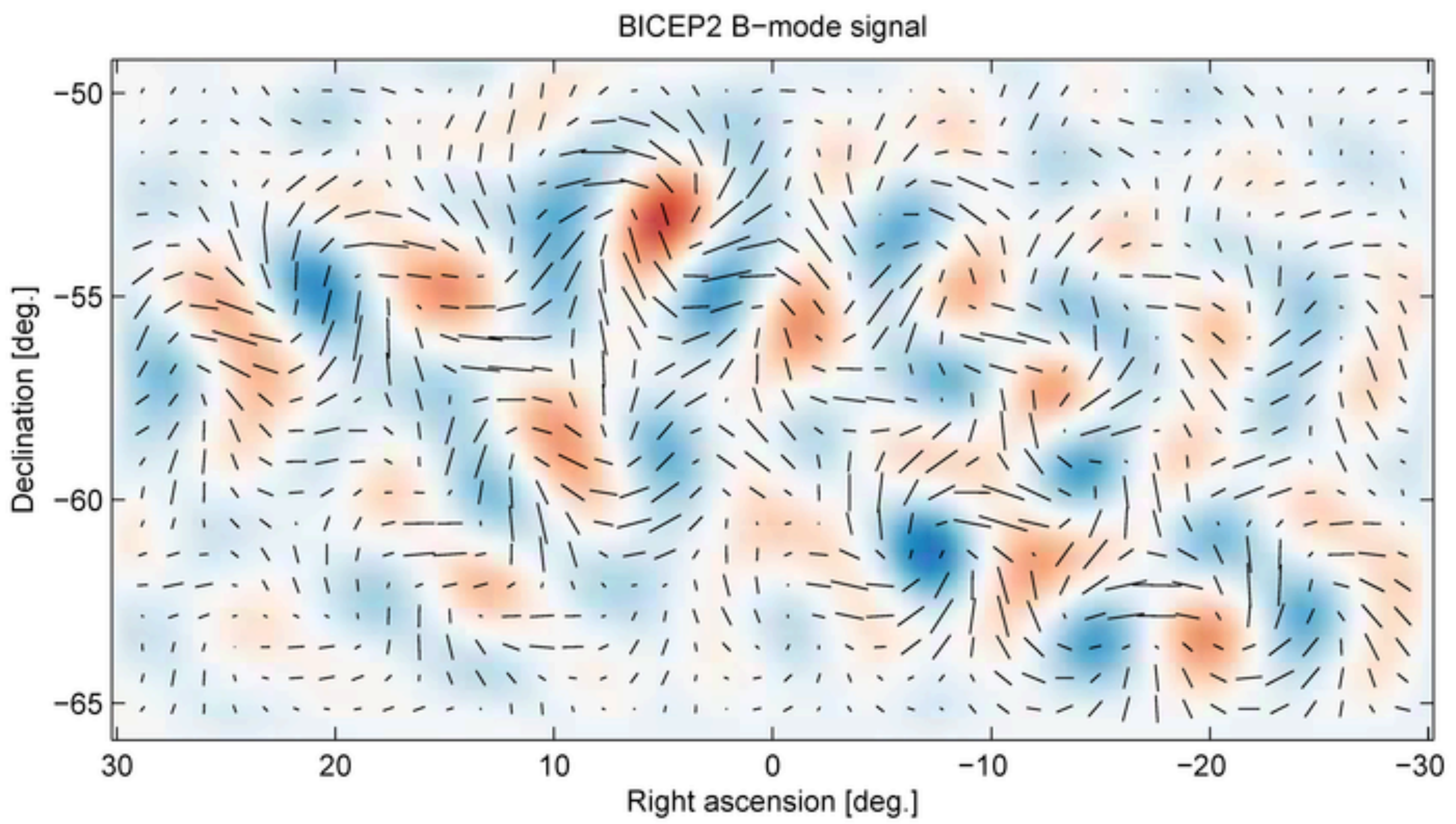
- Examples of Quantum Sensing from Astronomy and Astroparticle Physics
- Transition Edge Sensors (as bolometers, heterodyne receivers & at ALPS)
- Dark Matter with Quantum Sensors and ideas for Particle Physics
- Future plans, opportunities for collaboration

Herschel Space Observatory

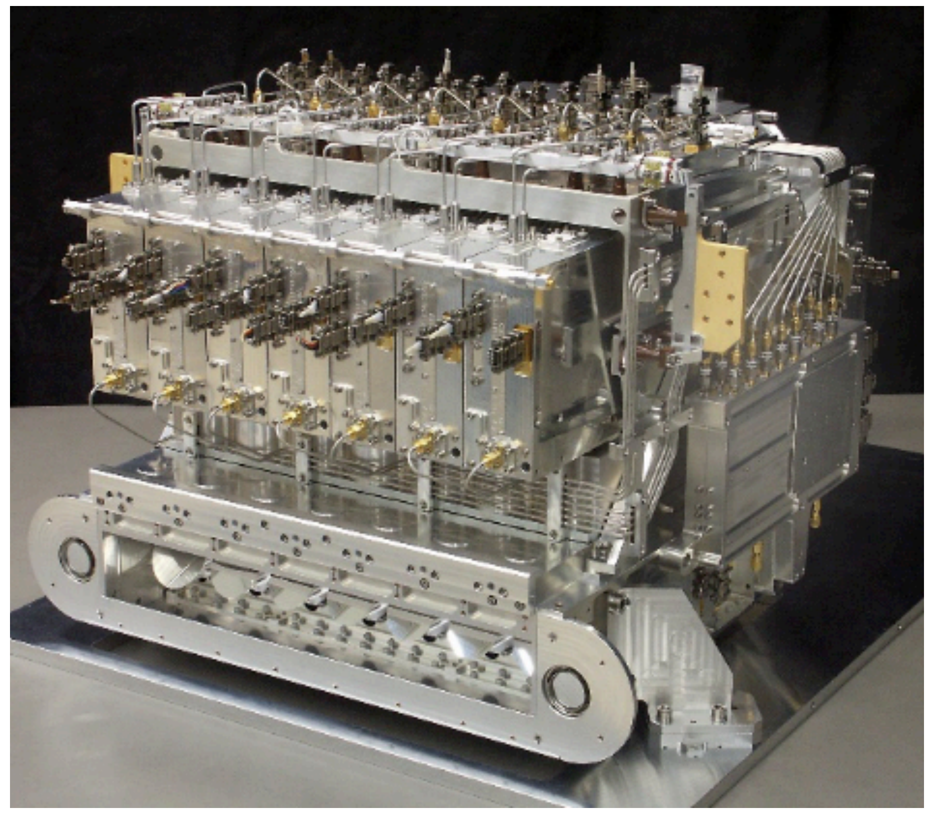
Quantum Instruments for Astronomy and Astrophysics

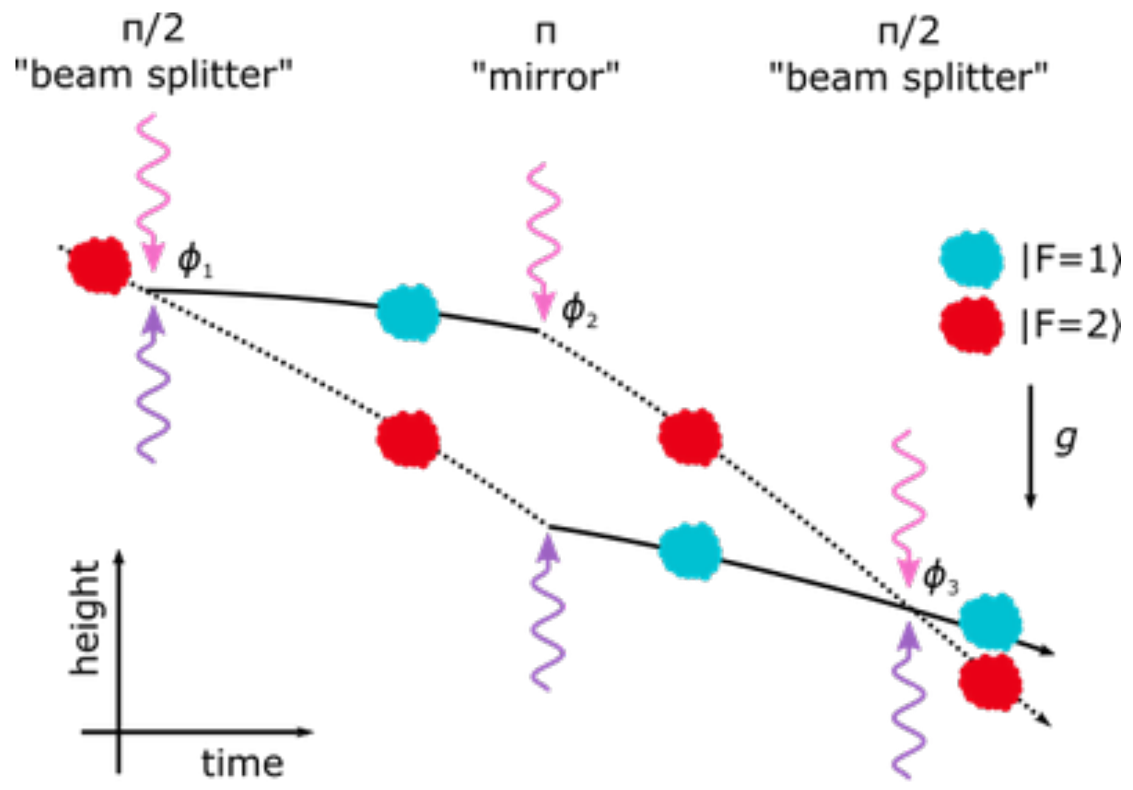
Ultra-low noise QS essential for modern Astronomy

- Astronomy/Astroparticle
  - Black hole imaging (microwave)
  - Polarization of CMB (mm wavelengths)
  - Galaxy formation in the early universe (far-infrared)
  - Star formation and extrasolar planets at (infrared)
  - Black-hole astrophysics (x-rays)
- Gravitational Wave Physics
  - Optical/laser interferometry (LIGO, Virgo)
  - Atomic interferometry (MAGIS, AION)
- Space Science
  - Solar planetary science
  - Ultra-sensitive astronomy
  - Earth observation

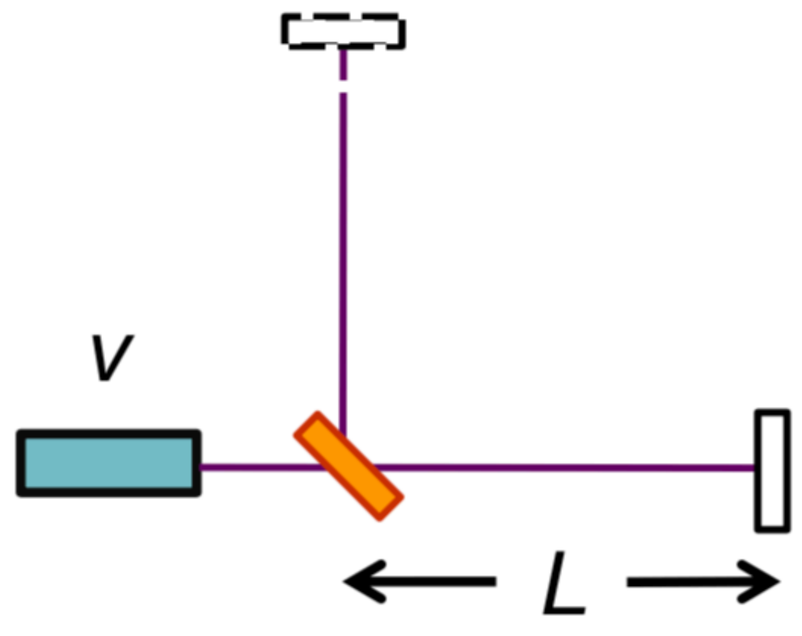


CMB Polarization


Herschel/HIFI Heterodyne



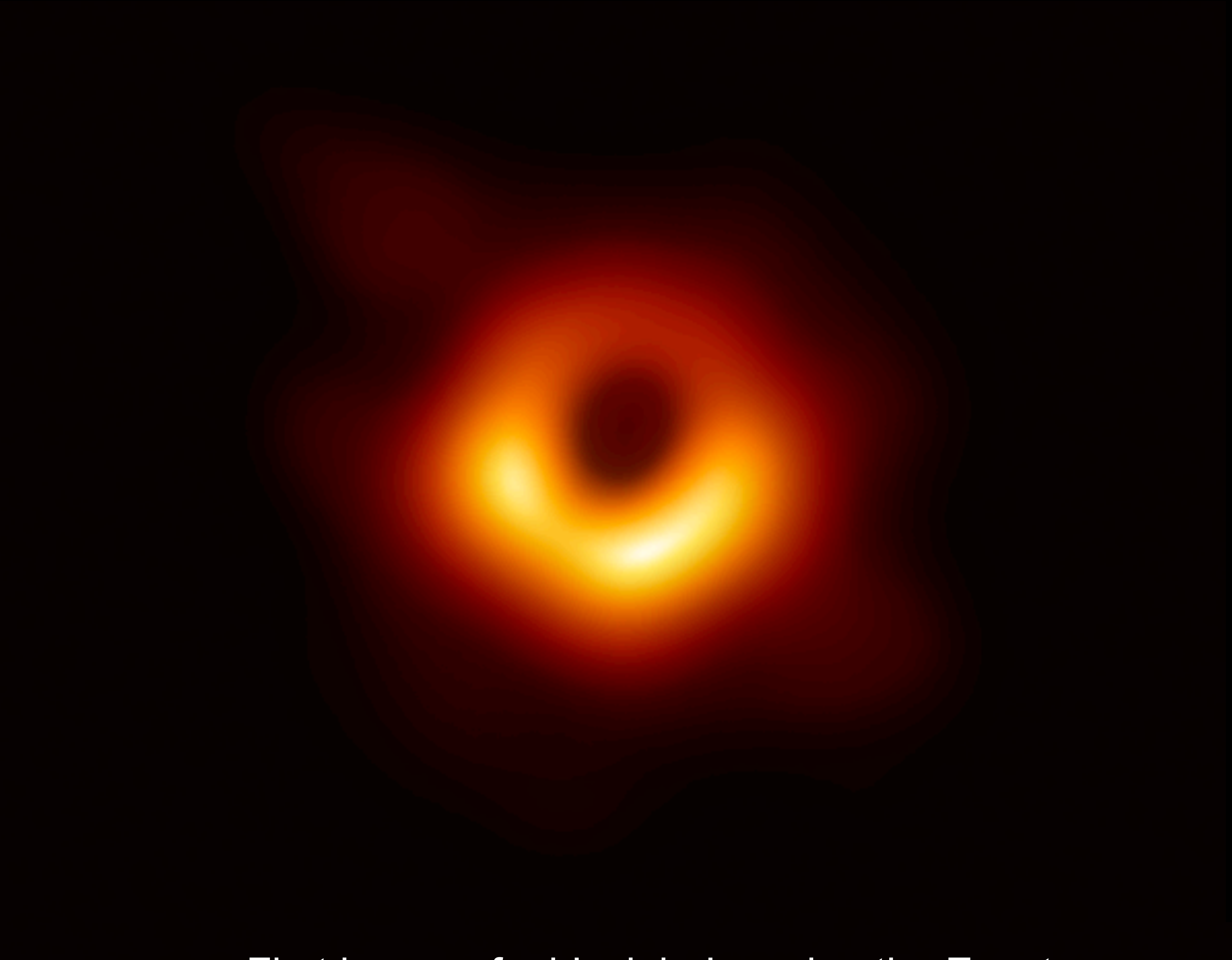
Atom Interferometry



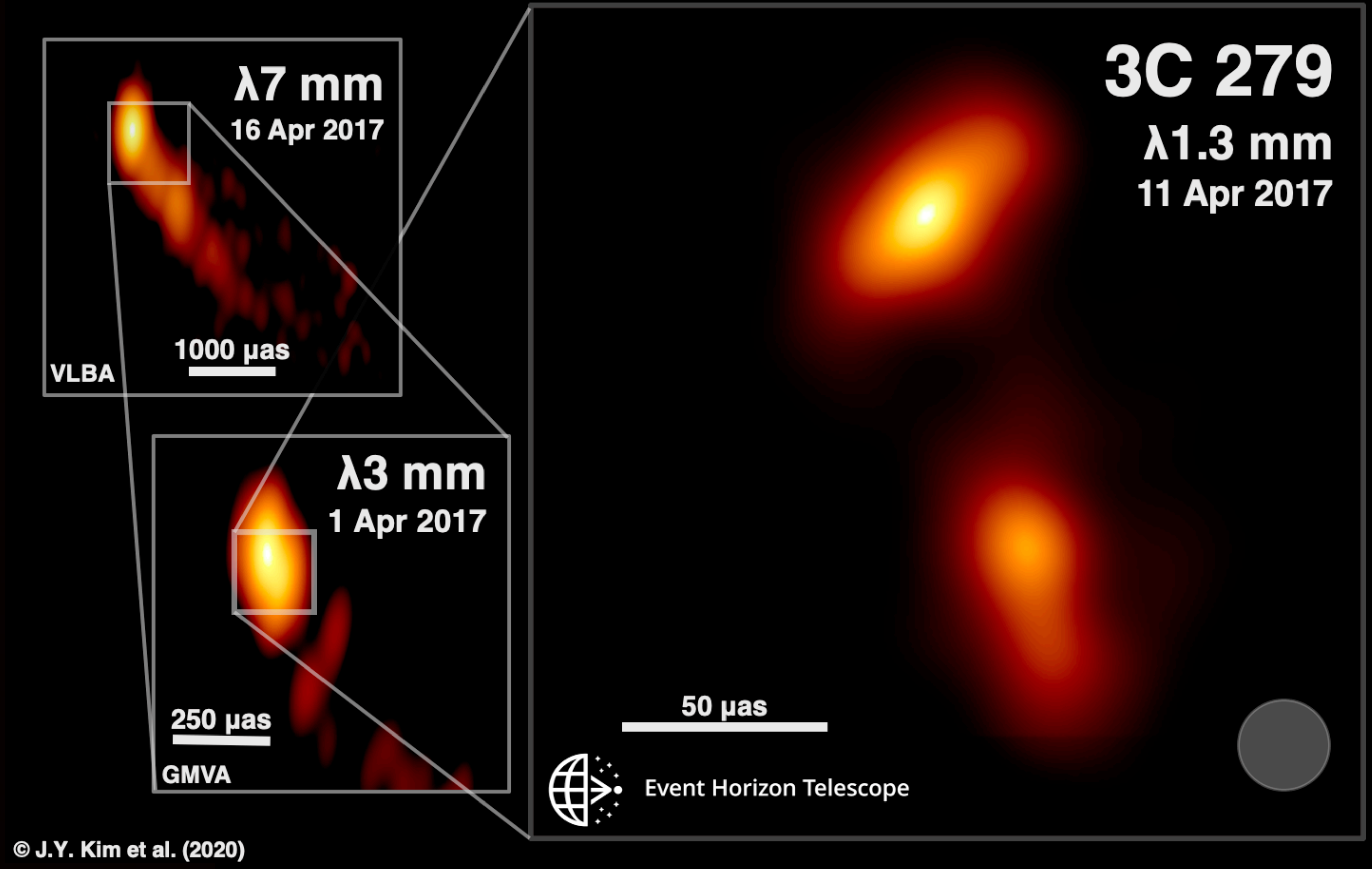
Laser Interferometry

Event Horizon Telescope

Superconducting electronics for sensitivity at 230 GHz (1.3mm)



First image of a black hole, using the Event Horizon Telescope (Galaxy M87) - 2019

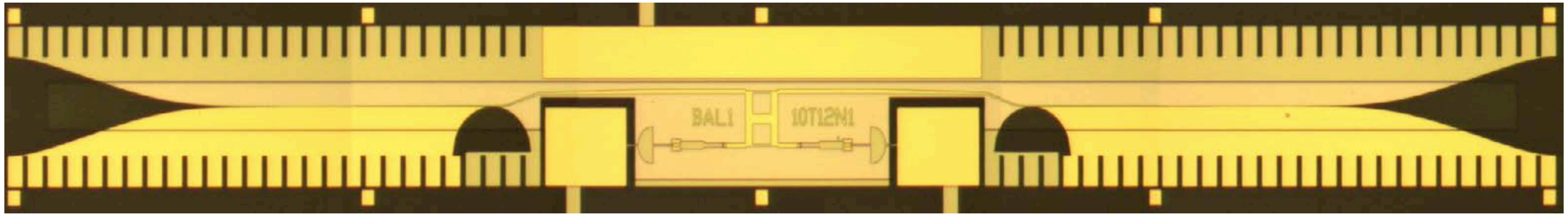


Event Horizon Telescope images of a black-hole powered jet (Quasar 3C 279) - 2020

Quantum Sensors in Astronomy: Millimeter and Sub-mm

Superconductor-Insulator-Superconductor (SIS) Receivers essential for sub-mm Astronomy

- Superconducting circuits allow phase coherent downconversion from THz to GHz frequencies
- Quantum devices (SIS receivers, mixers) based on coherent superconducting ground state
  - Operate very near quantum limit (noise temperature)
  - Gain on downconversion (non-classical)
  - Excellent response from 100 GHz to 1200 GHz
- 30+ years of observatories/instruments developed from this technology: ALMA, EVT, Herschel/HIFI
- Can’t buy commercially: developed in close collaboration with condensed matter groups, labs

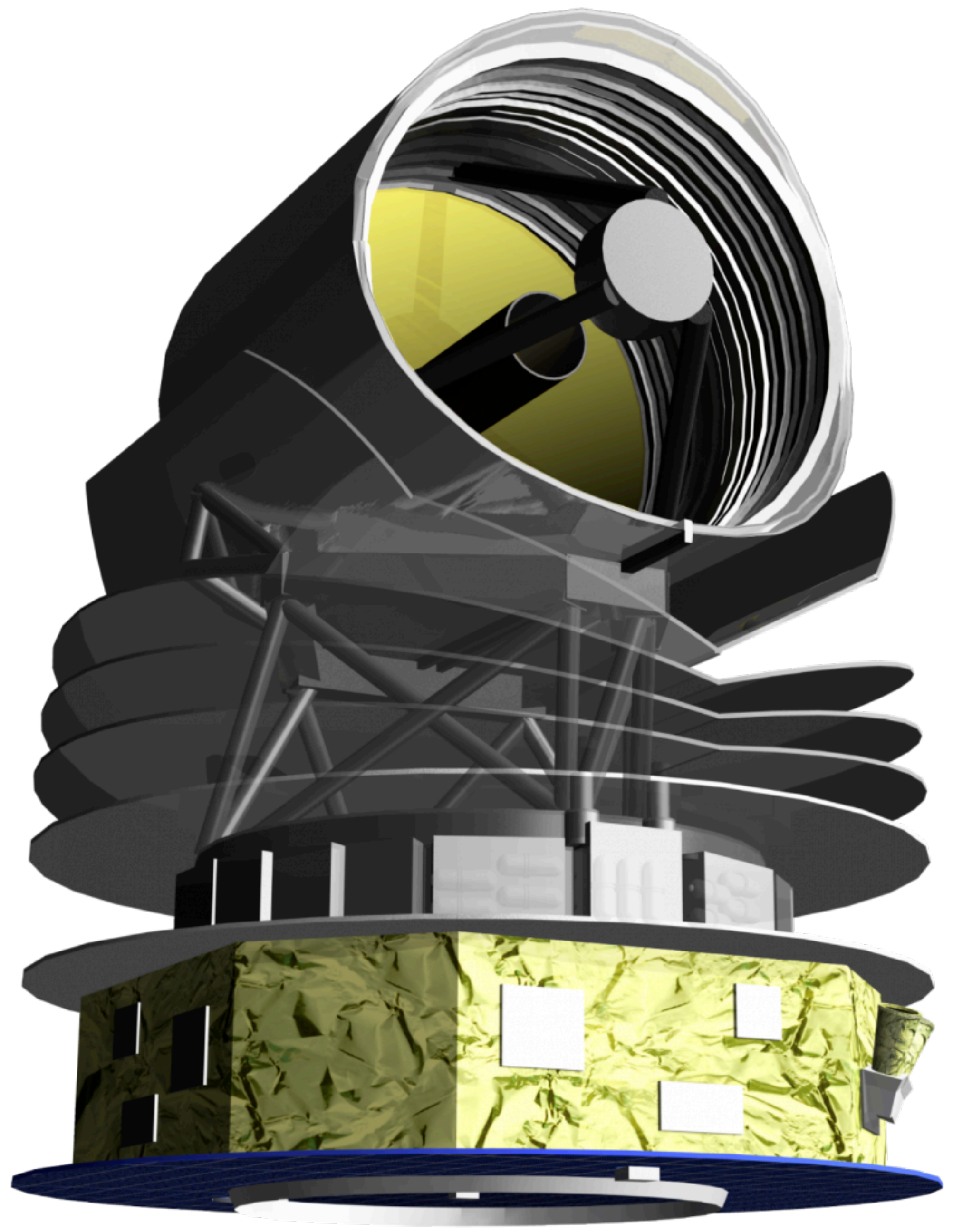


[Withington]

Quantum Sensors in Astronomy: TES Examples

SPICA (SAFARI)

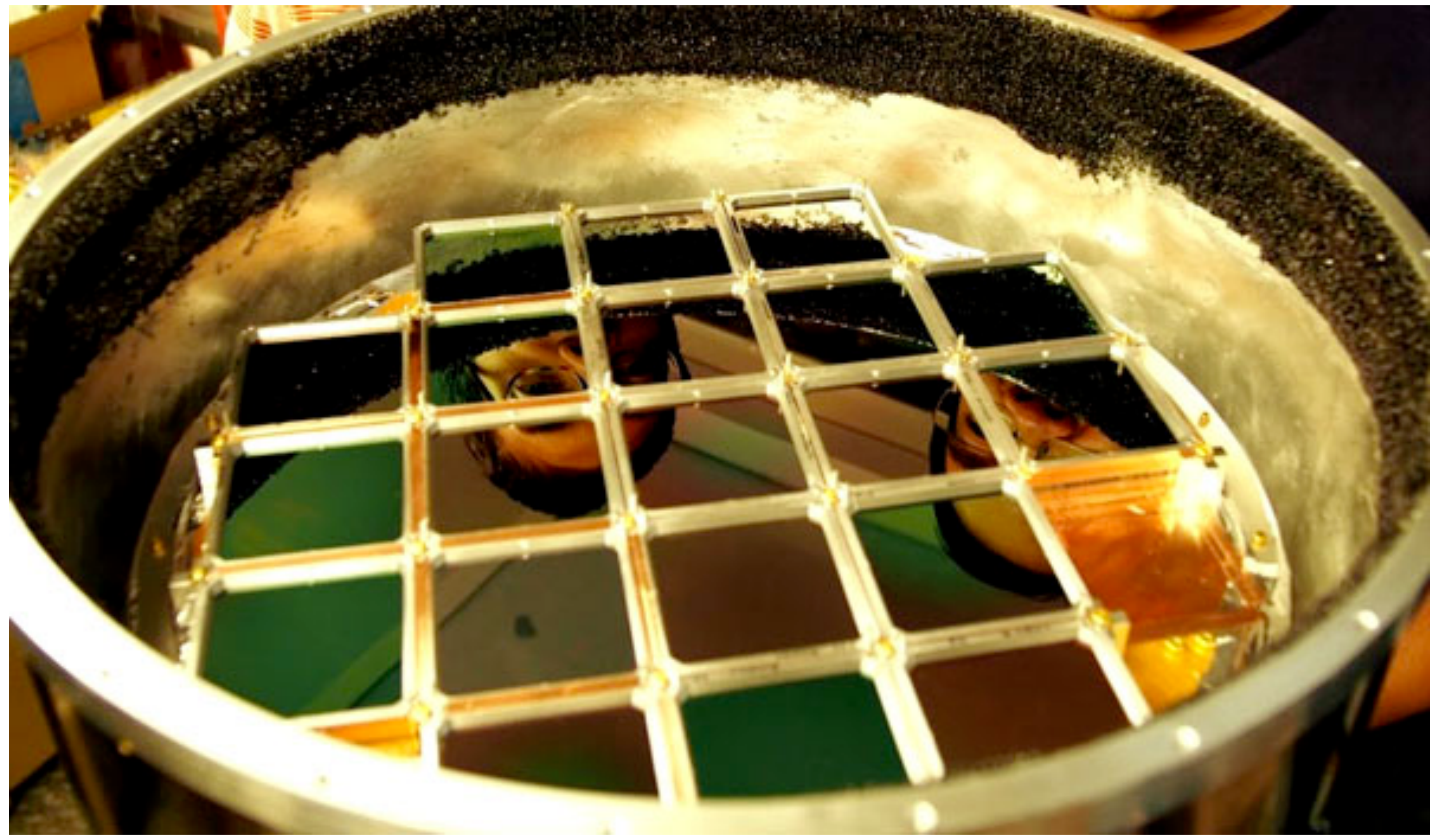
- ESA-JAXA mission operating at Lagrange Point L2
- Plan: extragalactic point-source spectroscopy, birth/evolution of stars
- Cooled 3.5 m telescope (<8K) to eliminate thermal radiation from mirror
- 3500 superconducting Transition Edge sensors (TES) operating at 50 mK
- NEP (weakest detectable signal) goal of 2×10^{-19} $WHz^{-1/2}$
- Readout and multiplexer based on superconducting SQUIDs



JAXA / SPICA Team

BICEP2 / Keck Array / BICEP3

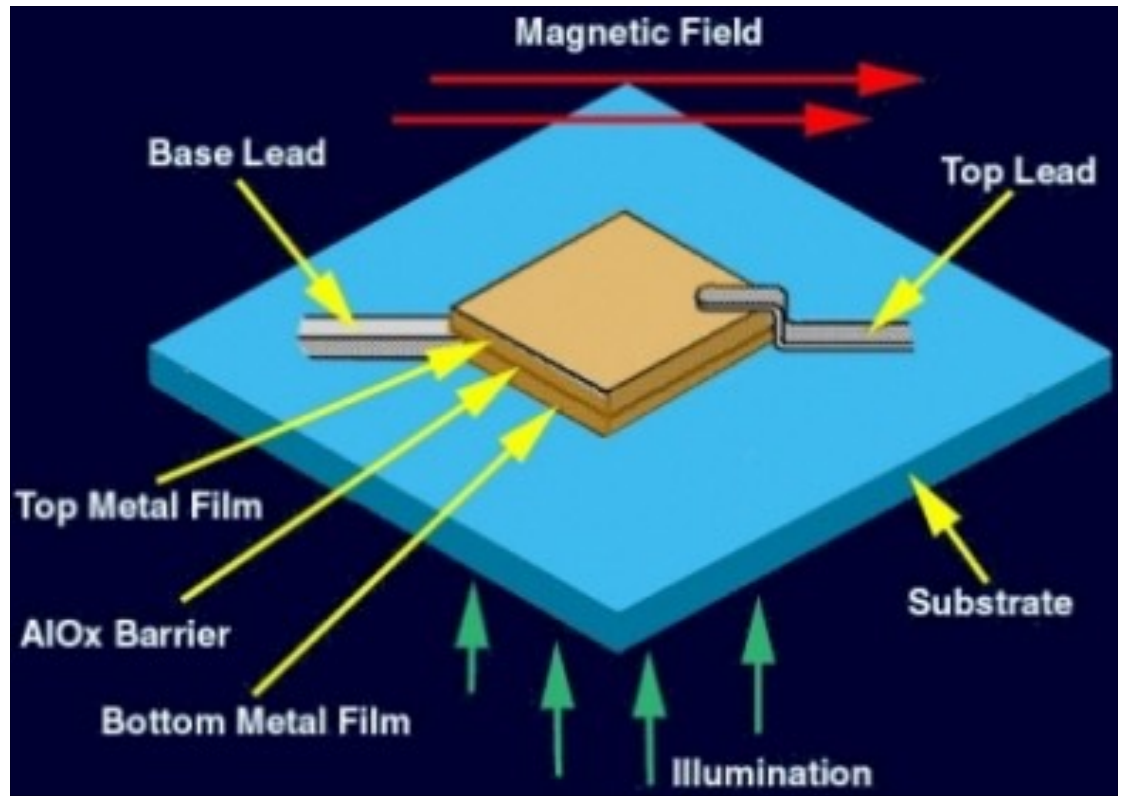
- Study Cosmic Microwave Background (B-modes)
- Study low-foreground region (from South Pole)
- Monolithic arrays of 2400 antenna-array coupled TES detectors
- Multicolor maps of 90–270 GHz, now adding 30-40 GHz
- Sensors fabricated at JPL, coupled to SQUID multiplexers from NIST



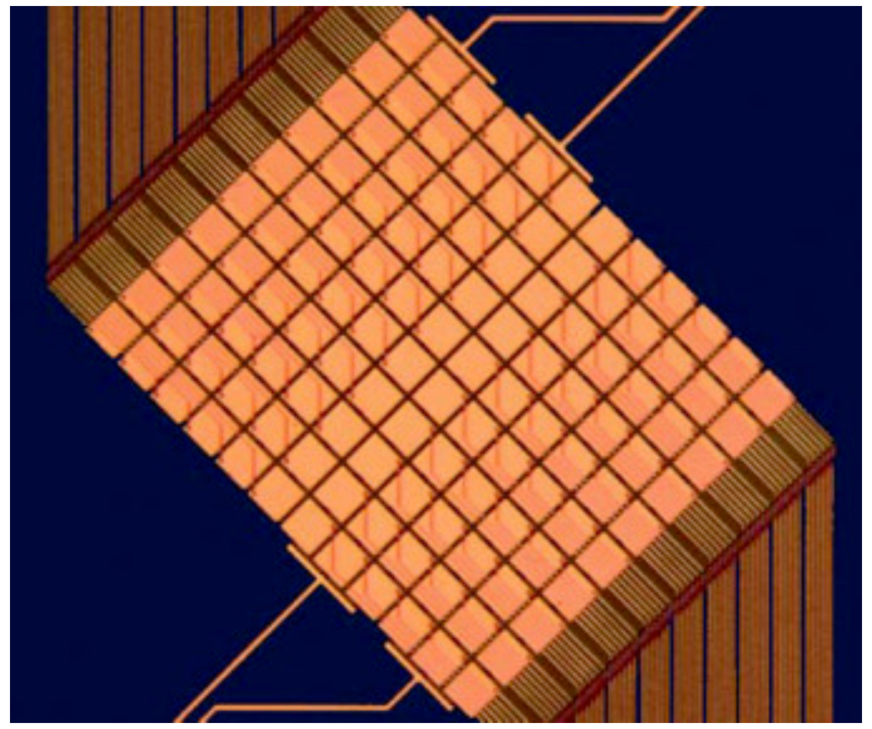
Quantum Sensors in Astroparticle: Next Steps

- Transition Edge Sensors (TES)
  - Exploit sharpness of superconducting phase transition, coupled to SQUID for readout
  - Cameras with high spectral resolution employed from radio to X-ray (SPT, ATHENA, BICEP)
- Superconducting Tunnel Junctions (STJ)
  - Exploit quantum tunnelling in a junction of two superconductors
  - Direct tunnel current measurement (non-Heterodyne): could give simultaneous fast photon counting and spectroscopy in IR, Vis, UV bands
  - Prototypes tested with ~100 pixels and resolving power of ~10
- 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
- Pixelated STJ or MKID for simultaneous imaging and spectrophotometry?
  - Goal of high pixel count (>1MP) and good resolving power (~1000)
  - Example use: Supernovae, Neutron star mergers, Pulsars
  - Exploit links to Quantum Computing? Improve existing technologies by about x1000?

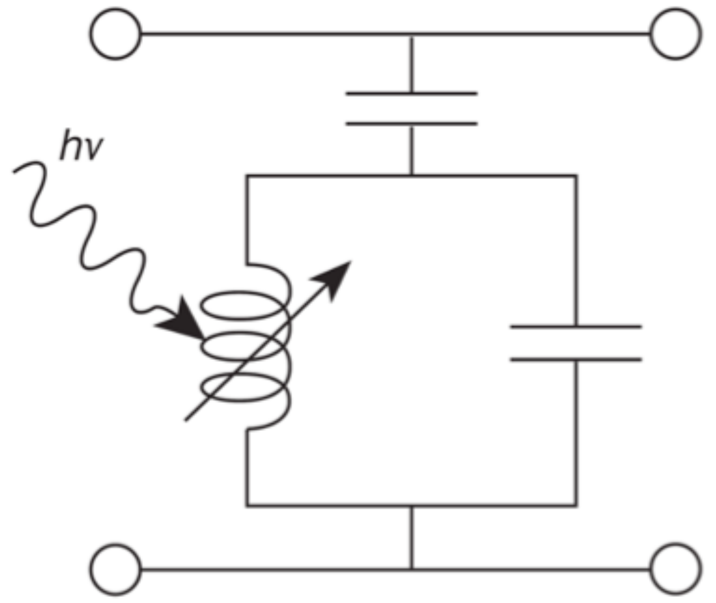
Opportunity for joint development: superconducting QS tech can evolve fast



Superconducting Tunnel Junction



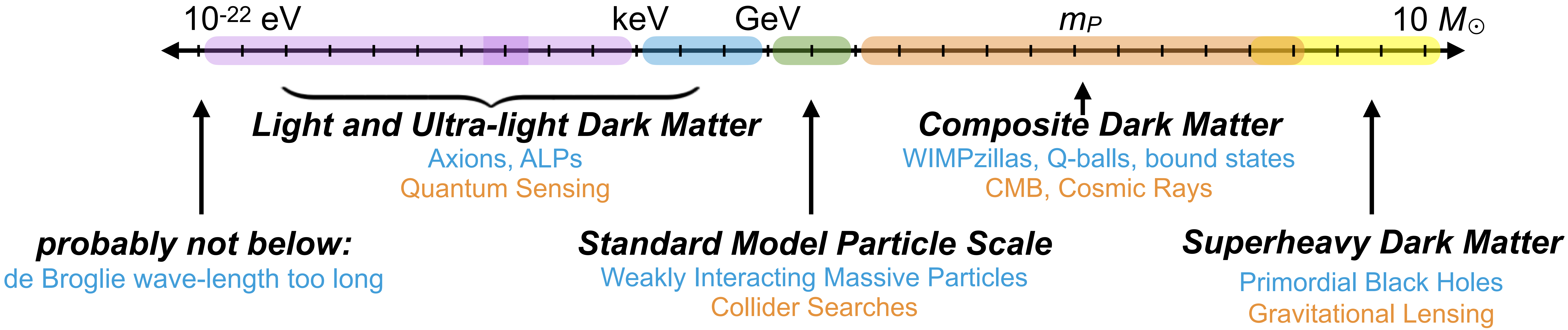
Array of 120 STJs from S-CAM3



MKID operating principle

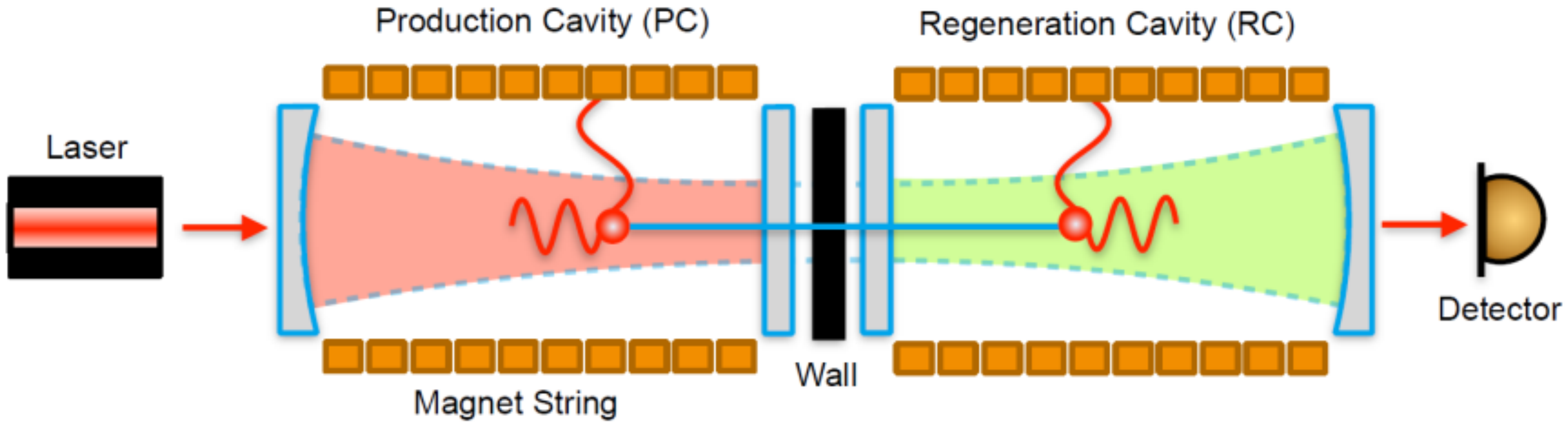
Particle Physics Example: Mass Scales for Dark Matter

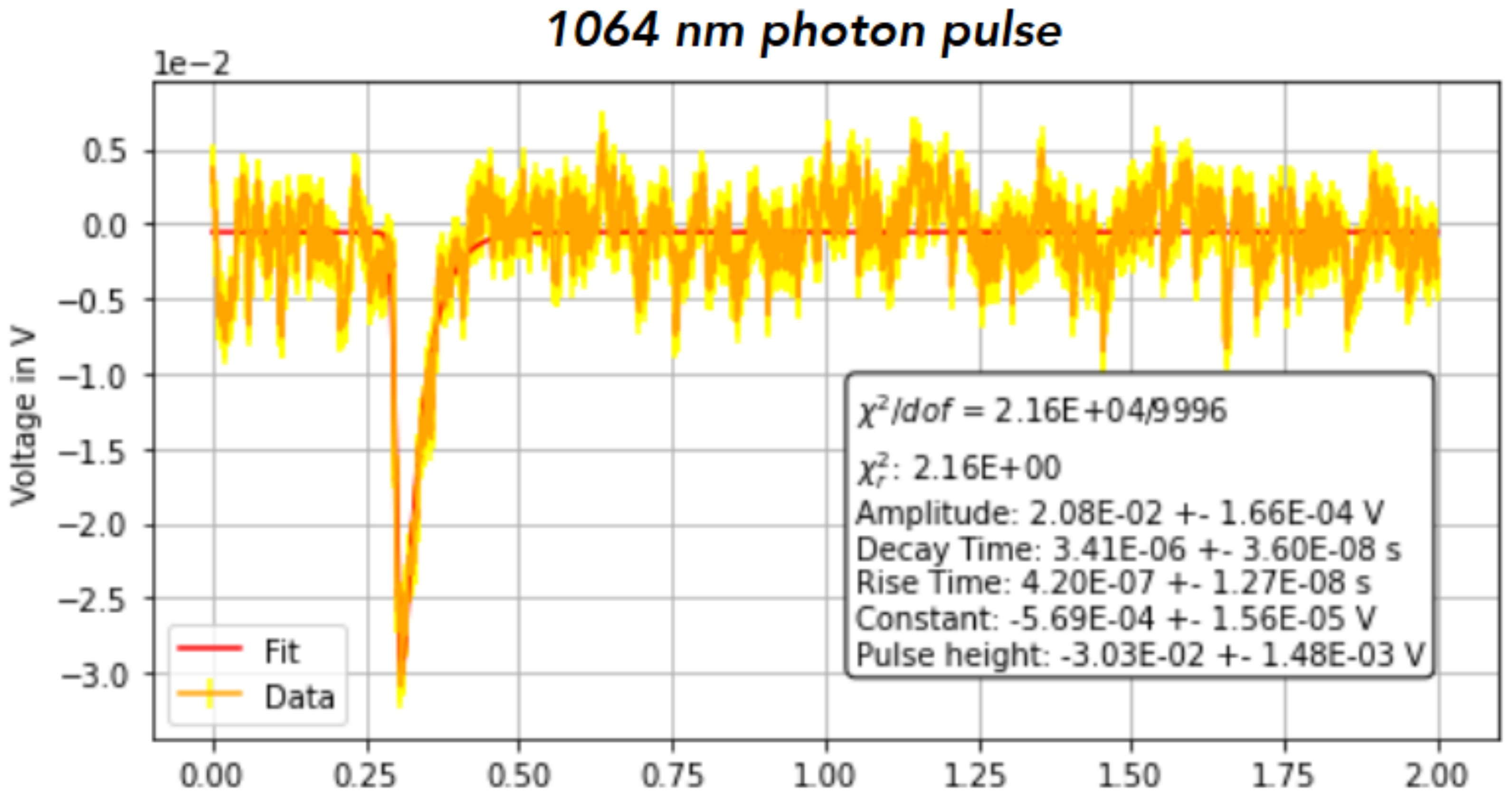
Quantum Sensing needed for Light/Ultralight Dark Matter



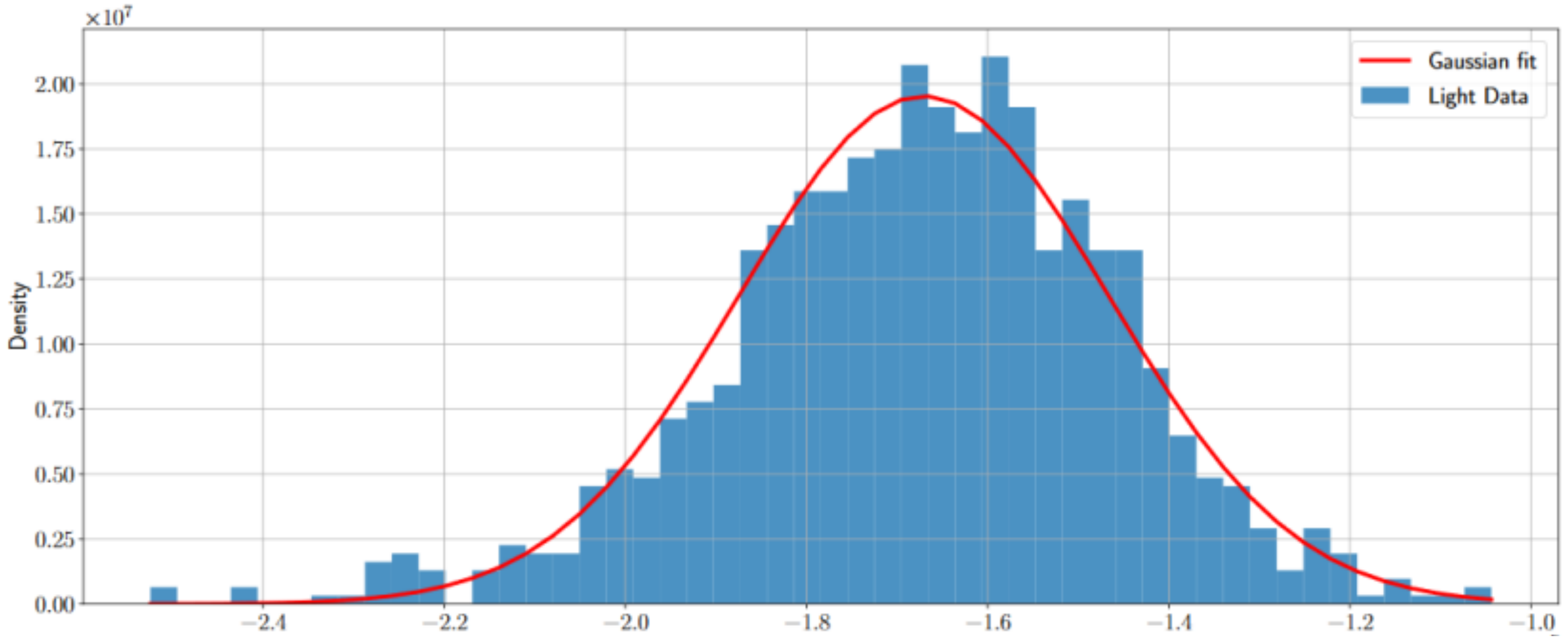
TES Detector for ALPS II

- 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





Time ($\times 10^{-4}$ s)



Pulse Integral ($\times 10^{-7}$ Vs)

ALPS
DESY.
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

[Januschek]

ALPS TES setup at DESY

Dilution refrigerator
(T≈20 mK)

BLUEFORS

SQUID electronics

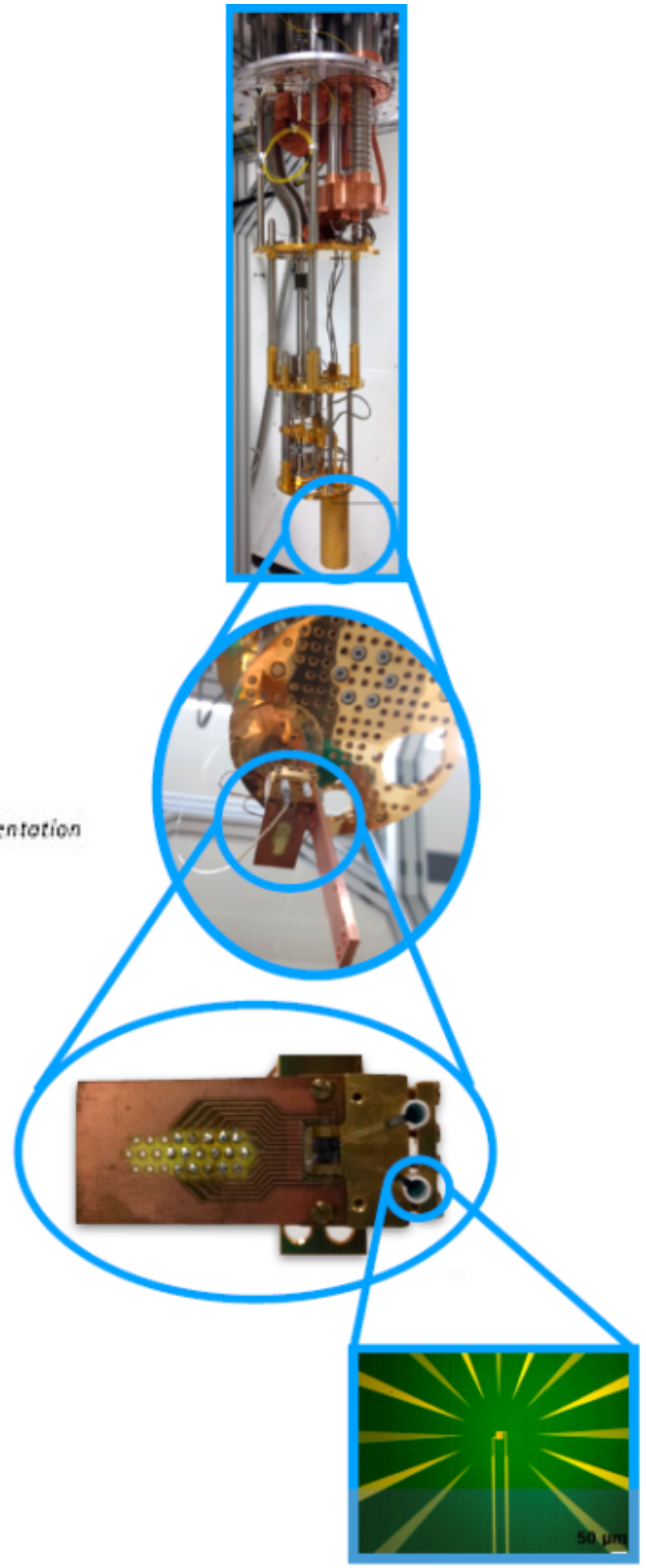
MAGNICON
physical research and instrumentation

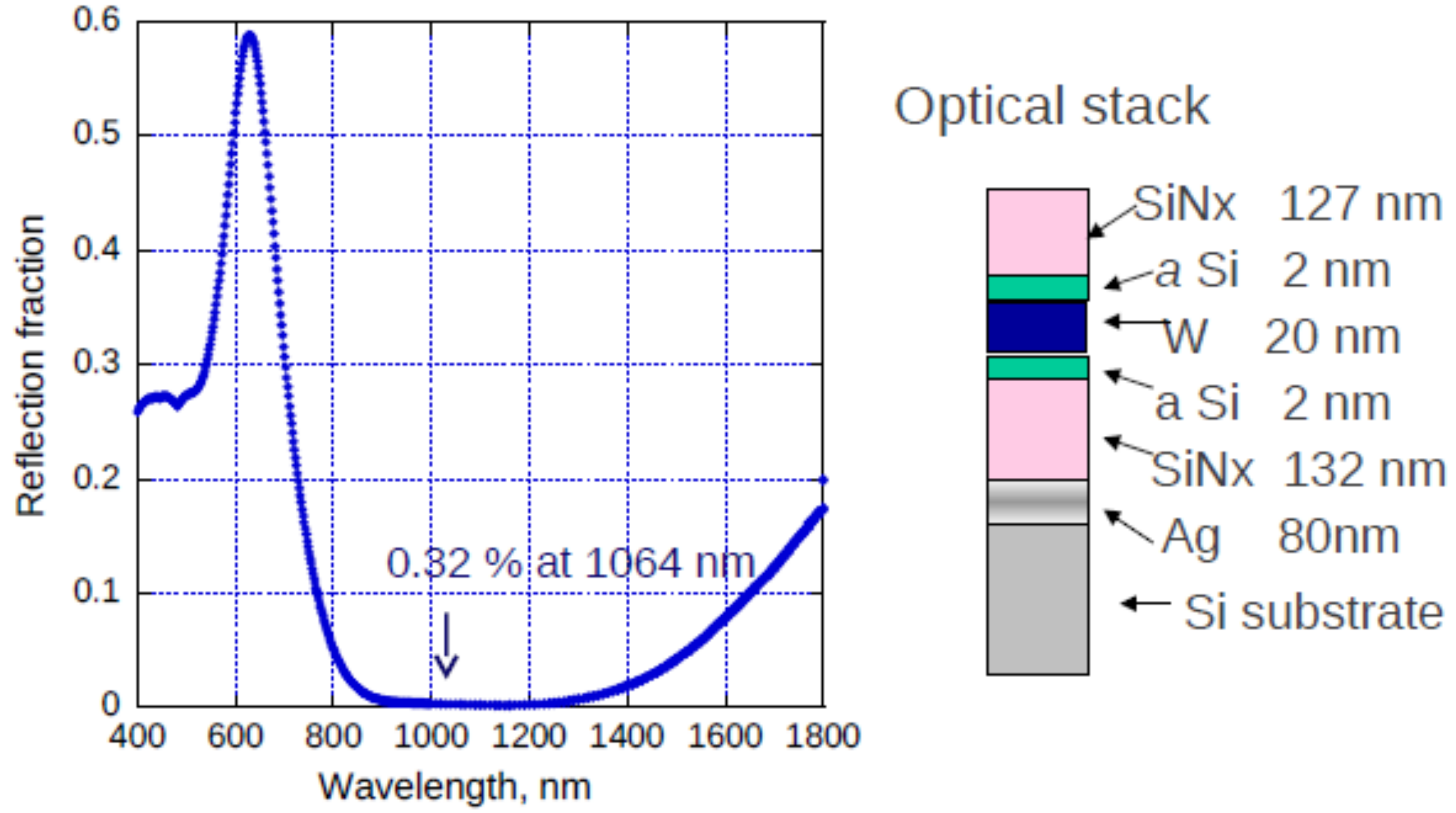
SQUIDs

PTB
Messen ▪ Forschen ▪ Wissen

TES (1064 nm)

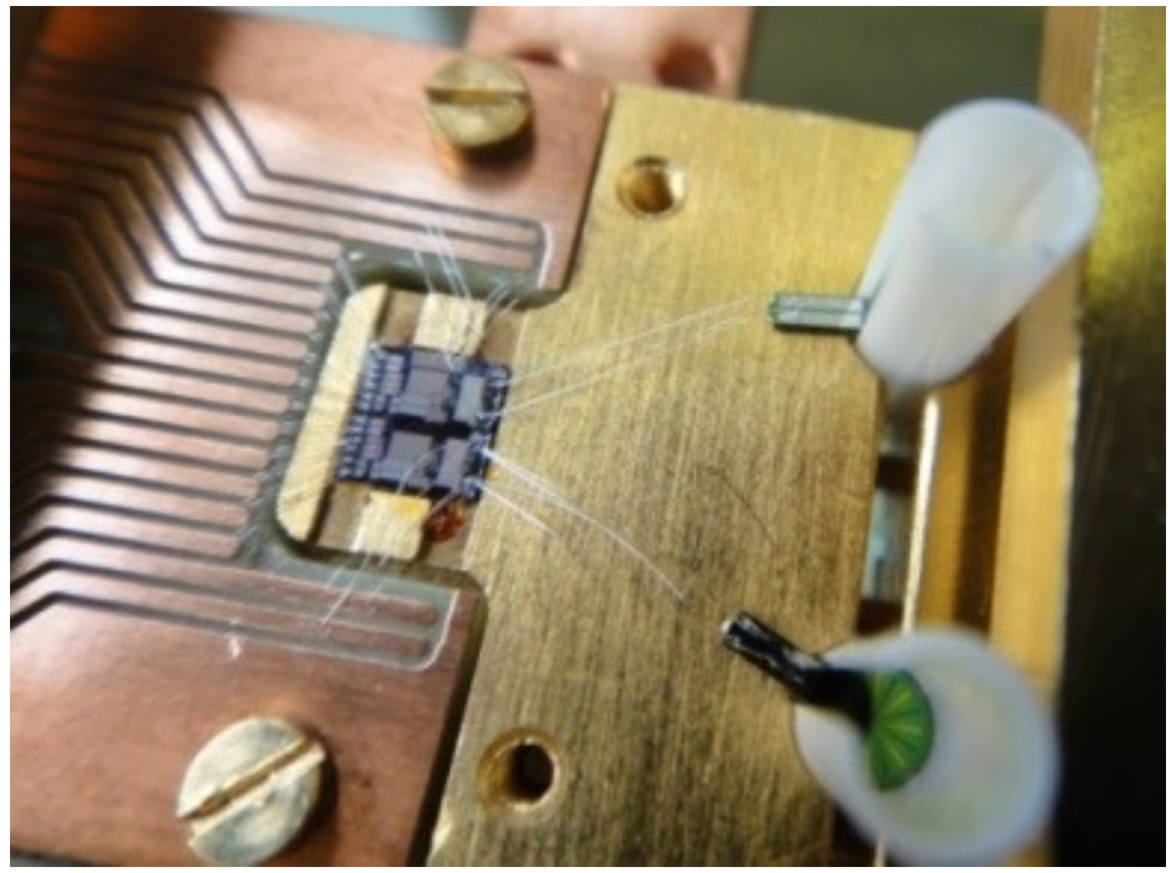
NIST

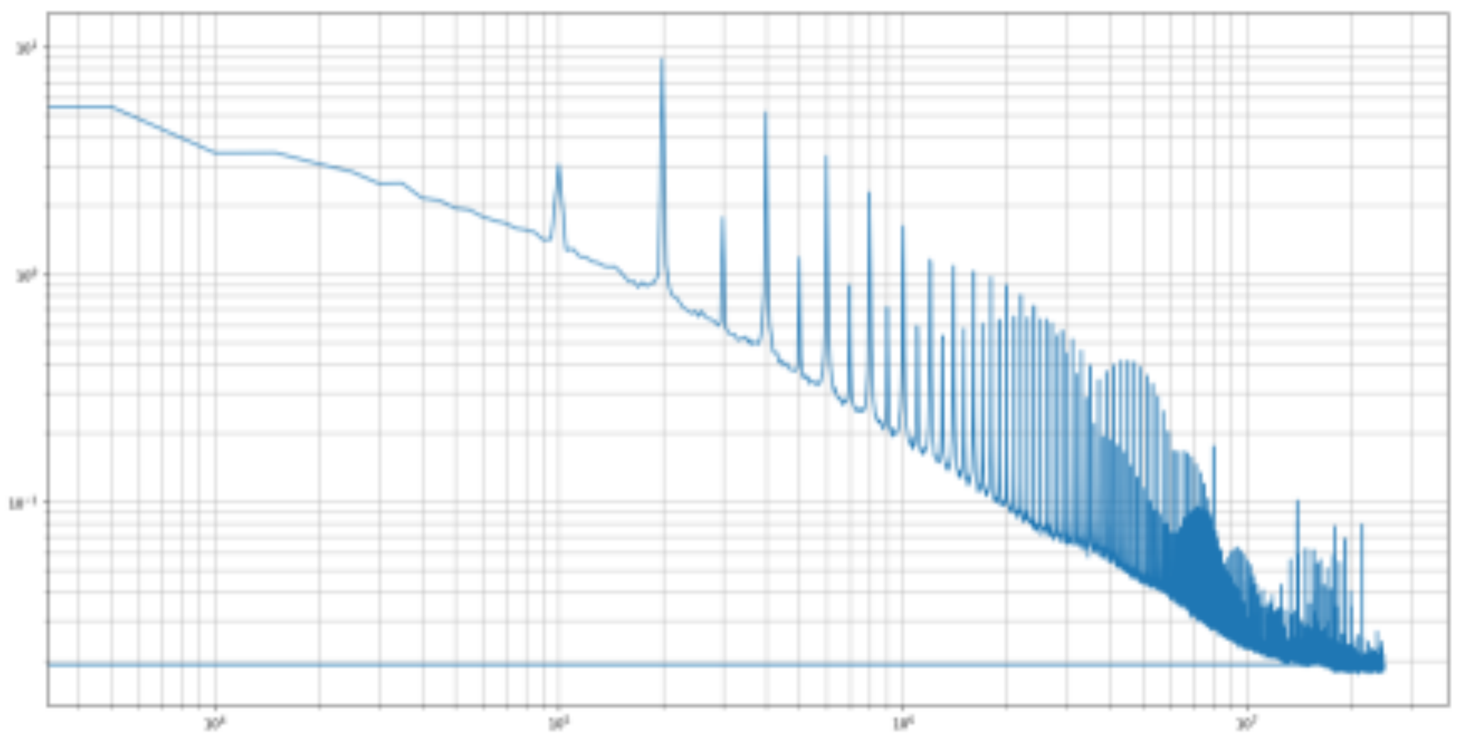


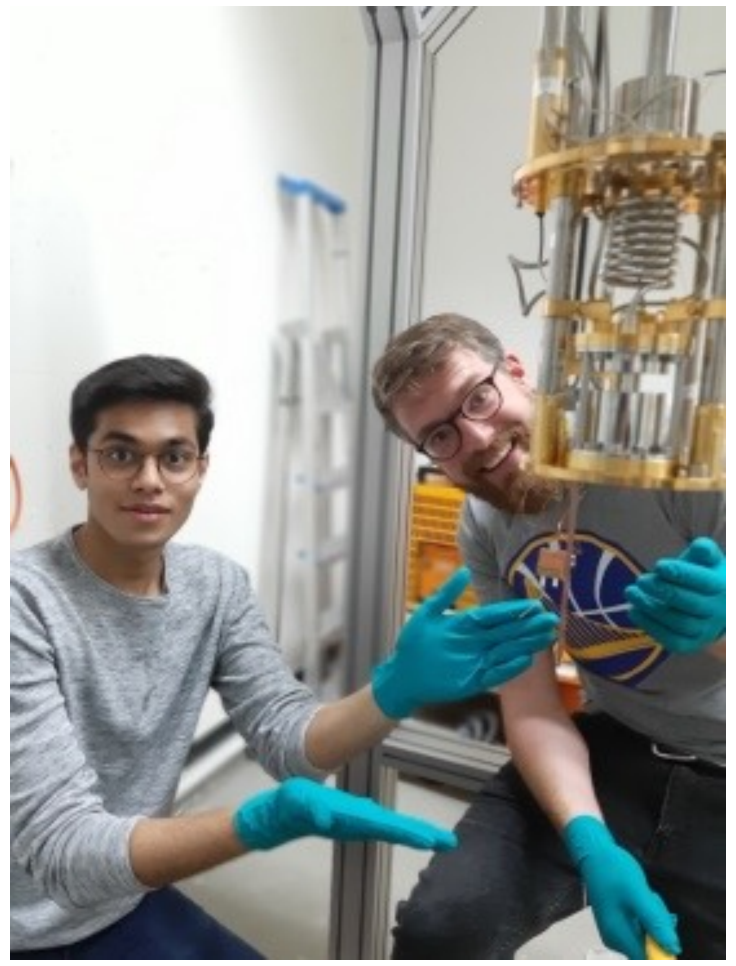


DESY Experience with TES Detectors and Plans

- TES detectors commissioned to search for new particles
  - Experience with cryogenic TES setup & operation (first ADR, now DR)
  - Noise reduction challenging, but successful; resolution of ≈10% for 1064 nm photons
  - Extremely low intrinsic dark counts; < $7.7 \times 10^{-6}\ s^{-1}$ 1064 nm photon-like events (<1/day)
  - ALPS data taking at TES lab in HERA-West in 2022
- R&D and Plans
  - Second cryostat for TES R&D and ALPS II planned at HERA-North
  - Plans: develop chips with two sensors for veto capability (with NIST, PTB), low background TESs for other wavelengths, search for dark matter search based on TES dark counts







Example: 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

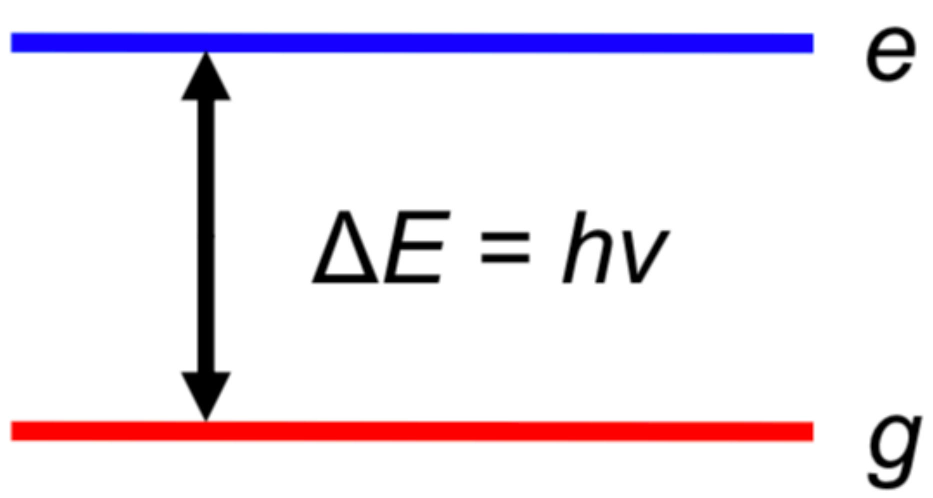
Bosons

Scalar (Spin = 0) Axions and other Goldstone Bosons

Pseudoscalar (Spin = 1) Investigate anomaly-free couplings

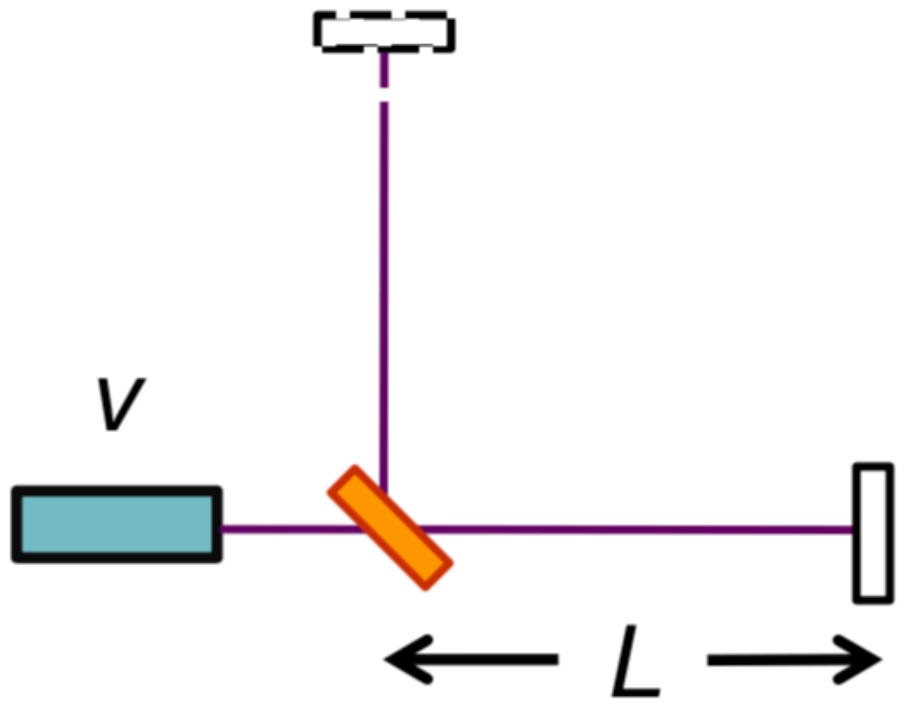
Scalar: Electro-magnetism	Scalar: Nuclear Spin	Scalar: Nuclear Force	Pseudoscalar: Electro-magnetism	Pseudoscalar: Nuclear Spin	Pseudoscalar: Nuclear Current
$\left(\frac{a}{f_a} F\tilde{F}\right)$ $\left(\sim \frac{a}{f_a} \vec{E}.\vec{B}\right)$	$\left(\frac{\partial_\mu a}{f_a} \bar{N}\gamma^\mu\gamma_5 N\right)$	$\left(\frac{a}{f_a} G\tilde{G}\right)$	$\left(\epsilon F^{'} F\right)$	$\left(\frac{F^{'}_{\mu\nu}}{f_a} \bar{N}\sigma^{\mu\nu} N\right)$	$\left(g A^{'}_{\mu} J^{\mu}_{B-L}\right)$
	General Axions	QCD Axions	Kinetic Mixing	Dipole Moment	B-L

Quantum Methods for Testing Δα/α



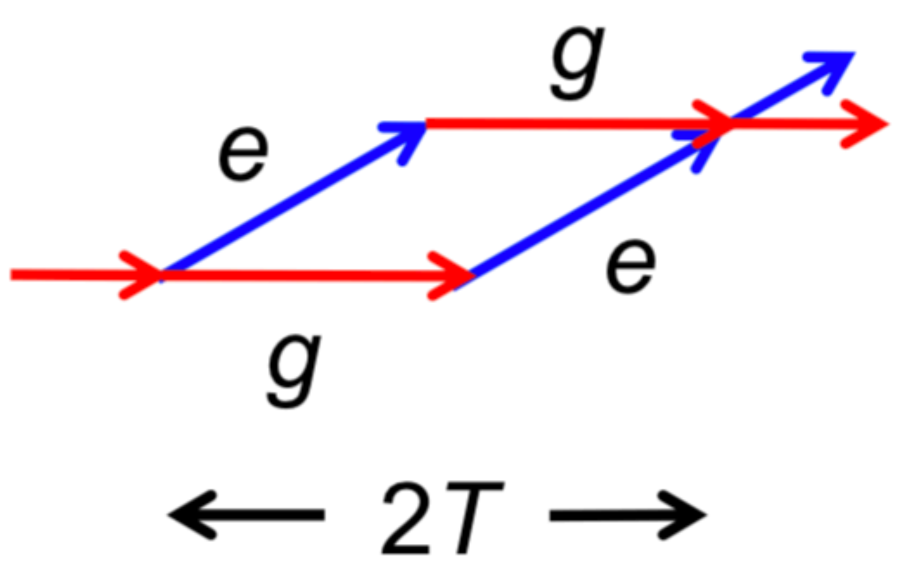
Atomic spectroscopy (clocks)

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



Laser interferometry (cavities)

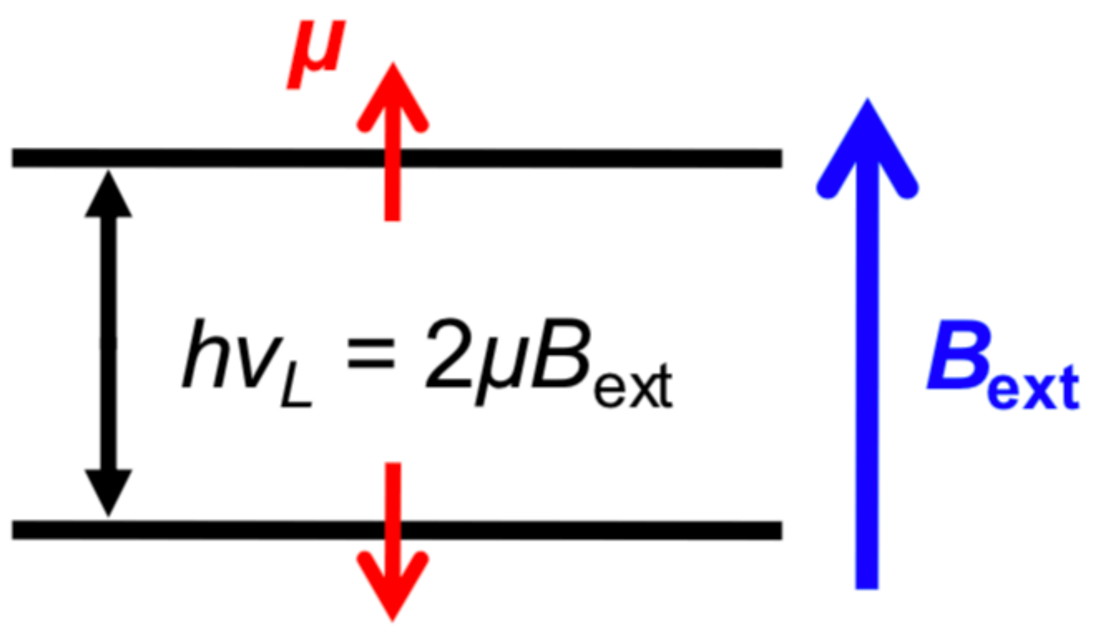
$\delta\Phi \propto \delta(\nu L) \propto \cos(m_\varphi t)$ 10^{-20} eV < m_φ < 10^{-15} eV



Atom interferometry

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

Quantum Methods for Testing Δμ/μ



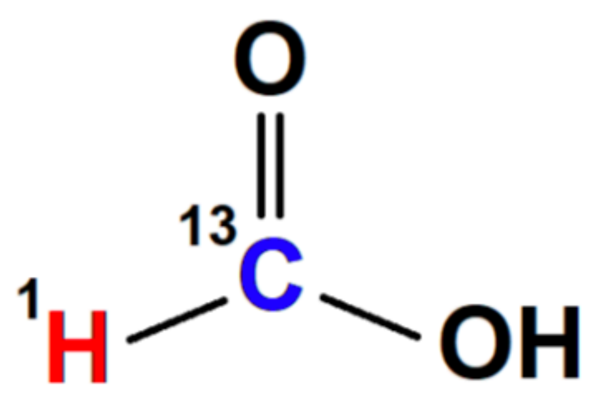
Co-magnetometry

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

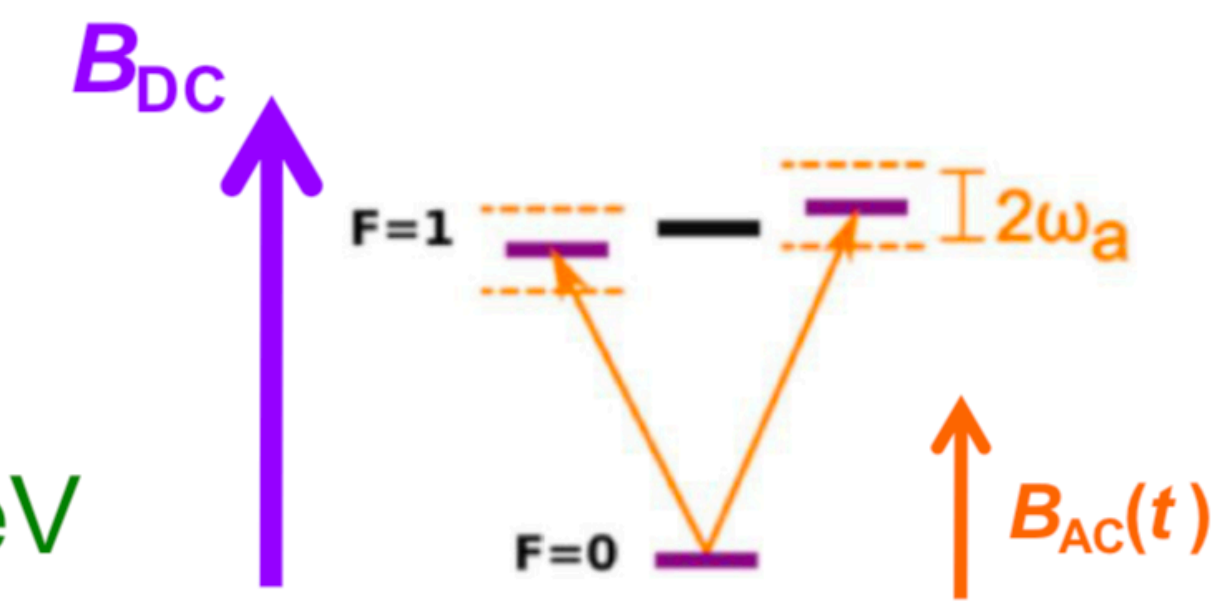
$$\text{or } \hat{\boldsymbol{\sigma}} \cdot \boldsymbol{p}_a \sin(m_a t)$$

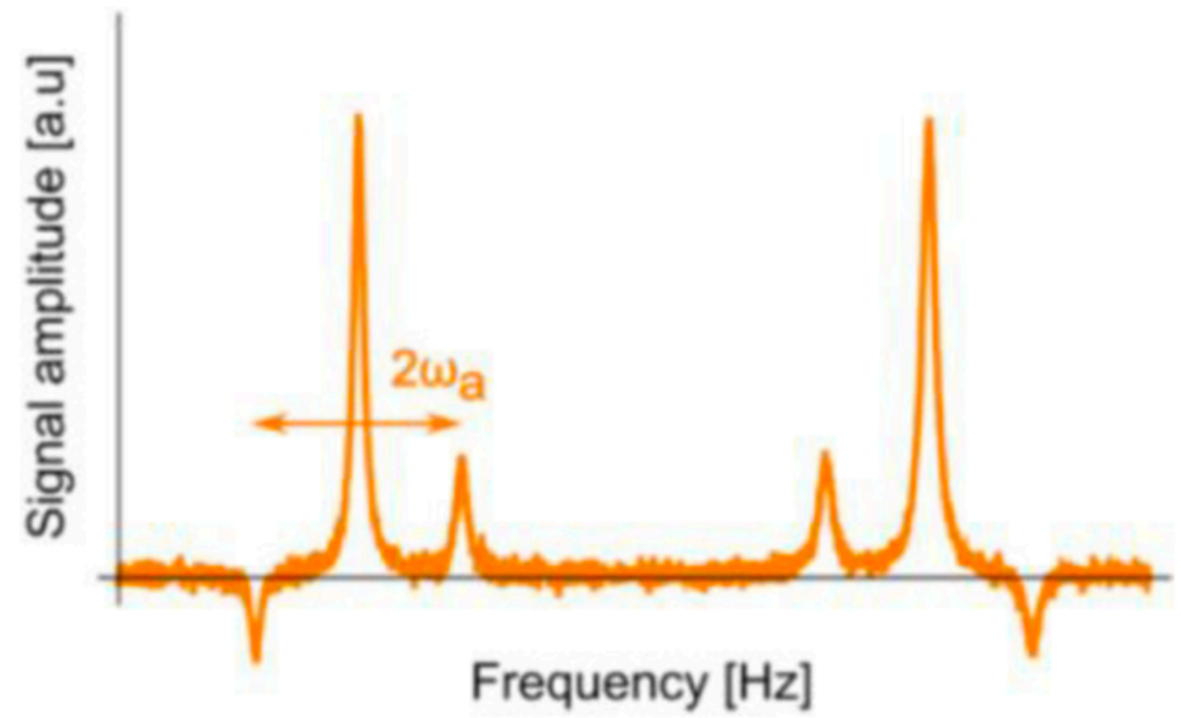
10^{-23} eV < m_a < 10^{-17} eV

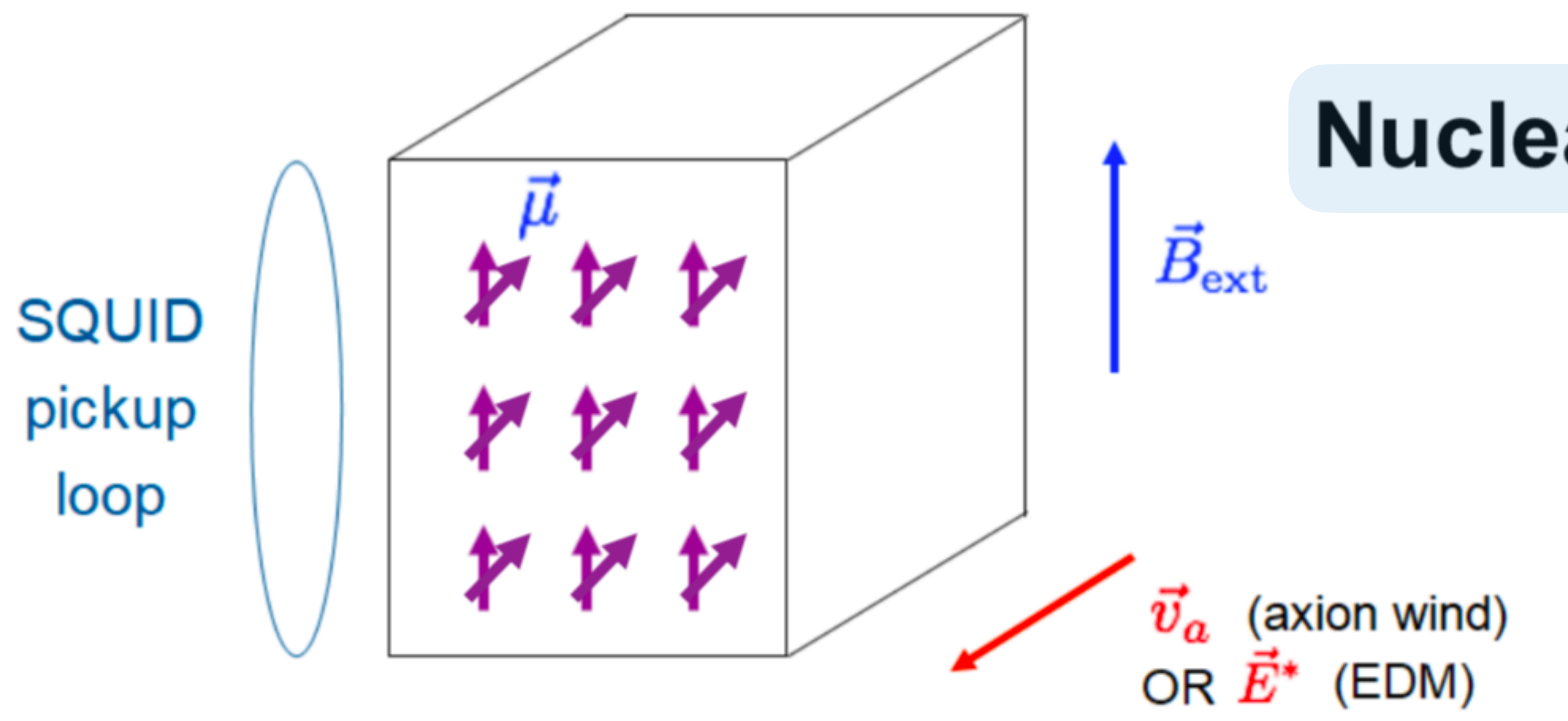
Nuclear magnetic resonance ("sidebands")



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







Nuclear magnetic resonance

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

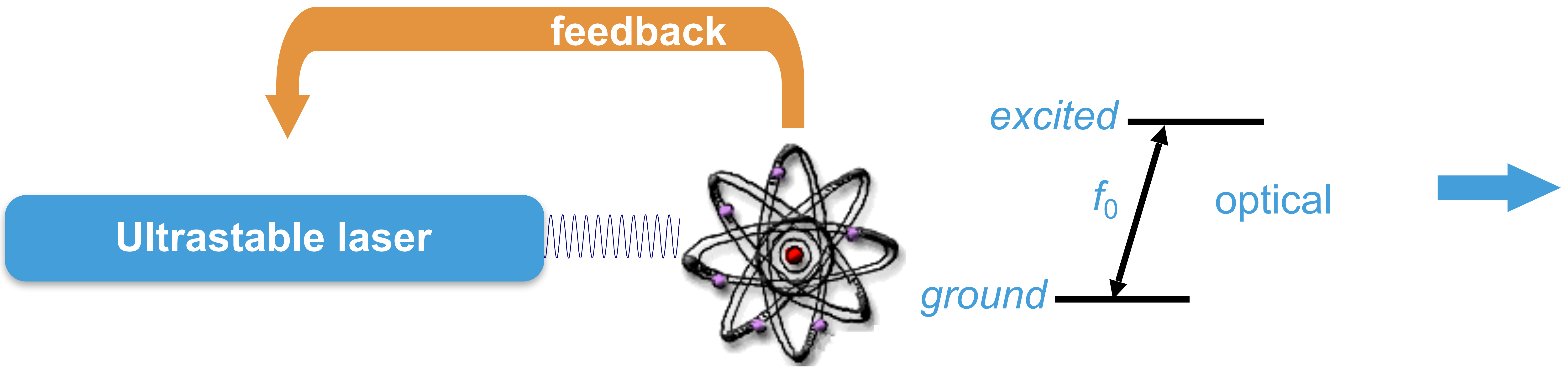
10^{-14} eV < m_a < 10^{-7} eV

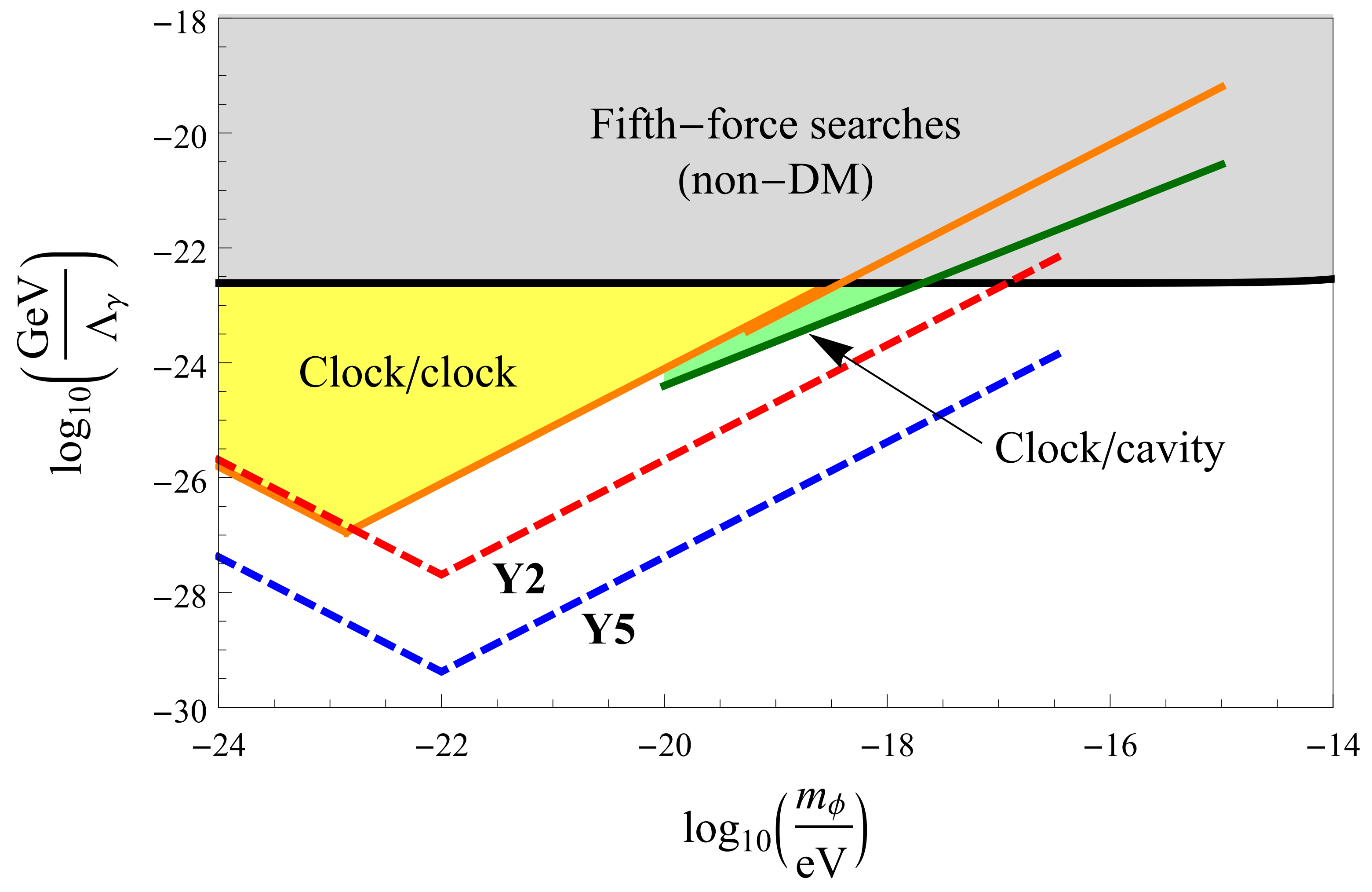
[Stadnik]

Quantum Sensors and the Search for Dark Matter

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

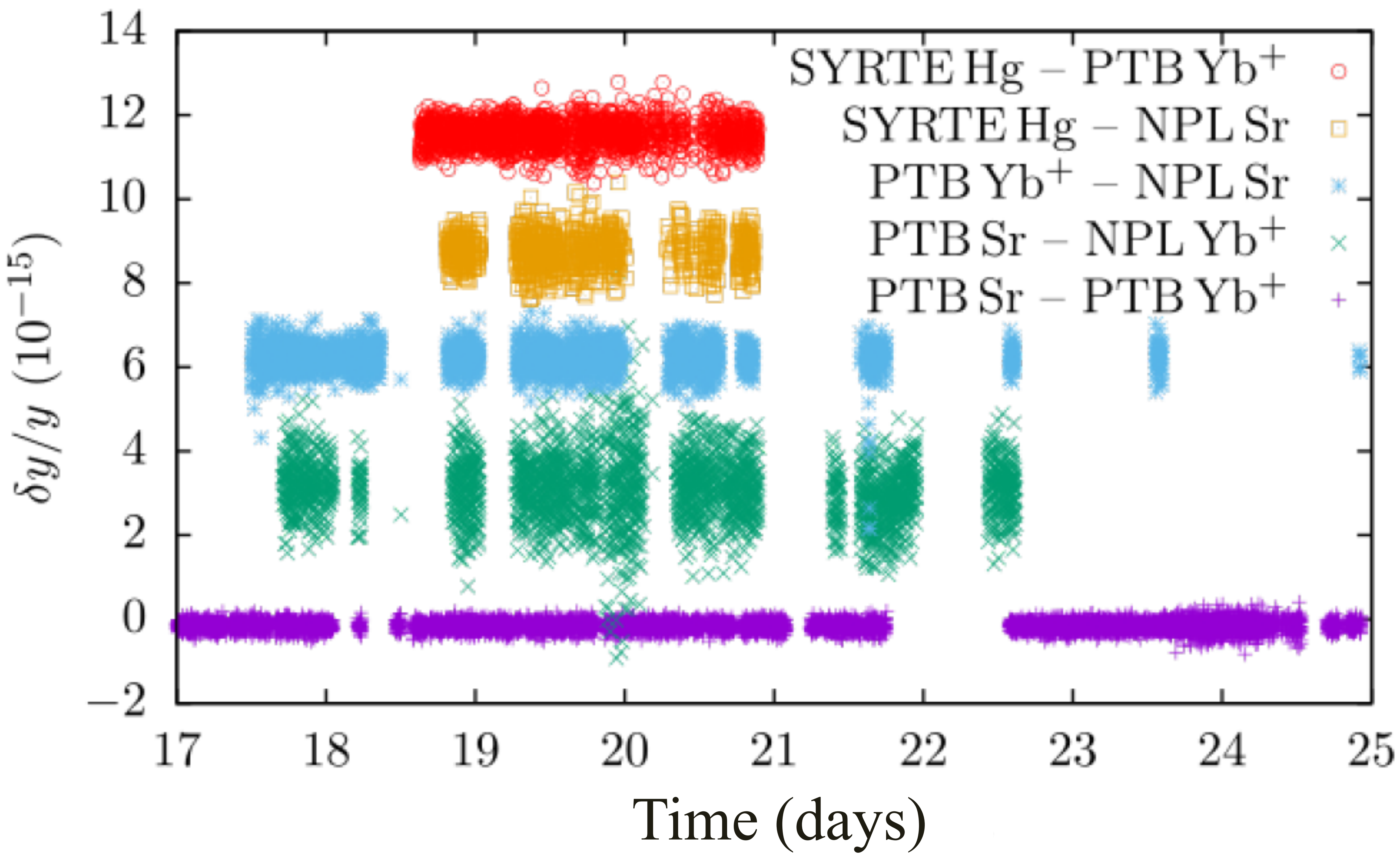
- Example: Optical Atomic clocks as enabling technology
  - Electron transition frequency as timekeeping element, using high-frequency mode-locked laser for optical transition
  - Frequency uncertainties ranging from 10^{-17} to 10^{-18} seconds
  - Reaching precision of better than one second in the age of the universe
  - Ultra-sensitive, e.g. to Dark Matter variations in fine structure constant α
  - Clever choice of element/isotope and transition determines sensitivity

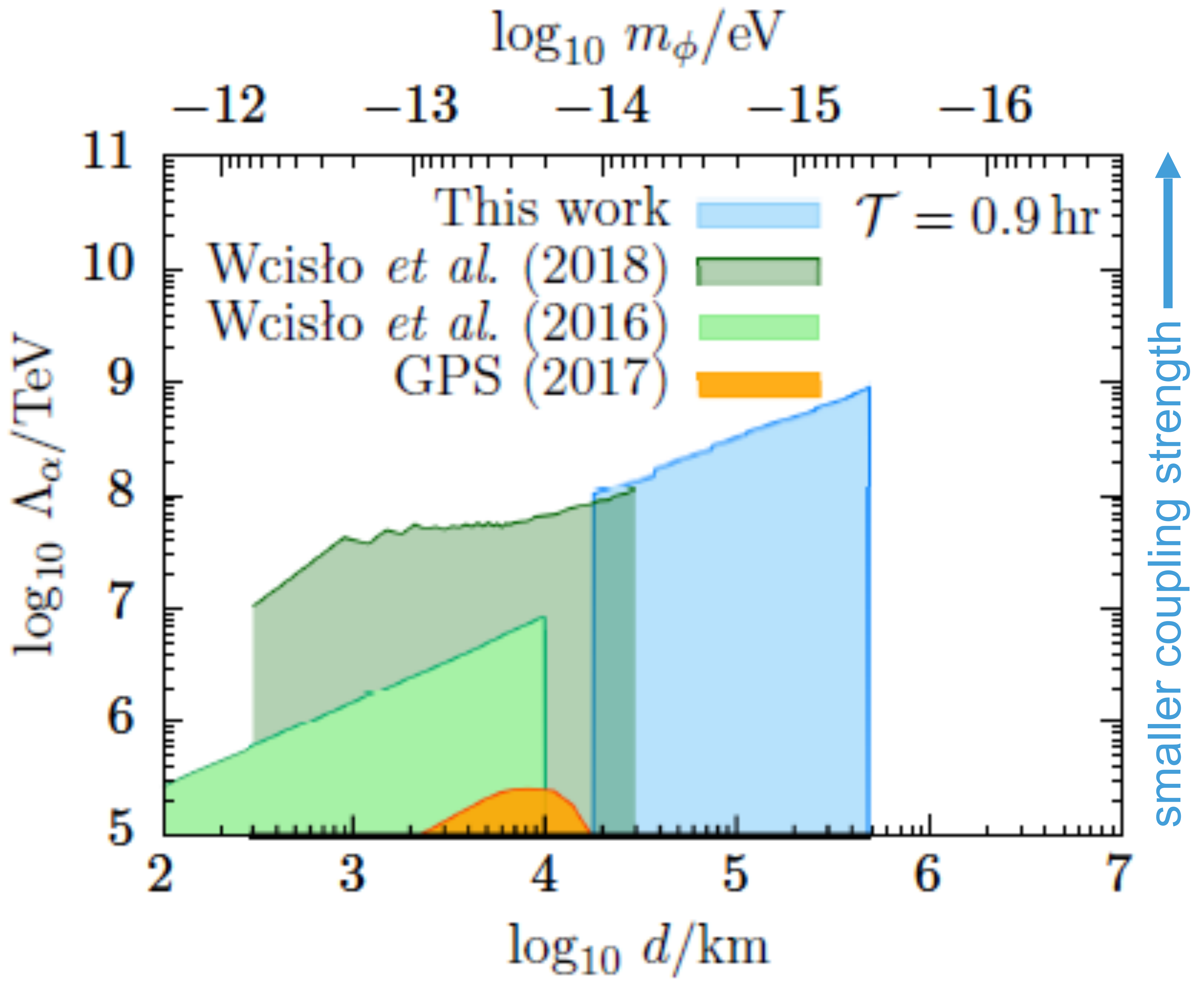




International Clock Comparison Data

- Constraints on energy scale, Λ_α of dark matter interactions
- Results for T = 0.9, 12, 45 hours
- Collaboration between PTB, SYRTE and NPL





[B.M. Roberts *et al.* arXiv:1907.02661]

Conclusion

Game-changing new technology for Astronomy, Particle and Astroparticle

- Quantum Sensing essential for modern Astroparticle/Astronomy
  - Mainstream applications incl. Transition Edge Sensors (as bolometers, heterodyne receivers)
  - New ideas coming up, with opportunities for collaboration
- Important new direction for Particle Physics, e.g. to extend search for Dark Matter
  - ALPS experiment leading the implementation at DESY
  - Lots of new, cross-disciplinary ideas for linking QS to DESY science
- Strong funding prospects world-wide for applications of quantum technology
  - USA announced ~$1Billion for 12 new Quantum Research centers
  - UK funding Quantum Sensors for Fundamental Physics - strong links to DESY