DRD5 WG2: Atomic, nuclear and molecular systems in traps and beams

Exotic systems, Interferometers, Clocks

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With input from:
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Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

Physics enabled by atomic, nuclear and molecular systems

- Variation of fundamental constants (α and μ) → eg for Dark Matter
- Precision tests of Quantum Electrodynamics
- Atomic parity violation
- Time-reversal violation: electric dipole moments and related phenomena
- Tests of the CPT theorem, matter-antimatter comparisons
- Searches for exotic spin-dependent and spin-independent interactions
- General relativity and gravitation
- Lorentz symmetry tests
- …

[Search for New Physics with Atoms and Molecules, arXiv:1710.01833v3]

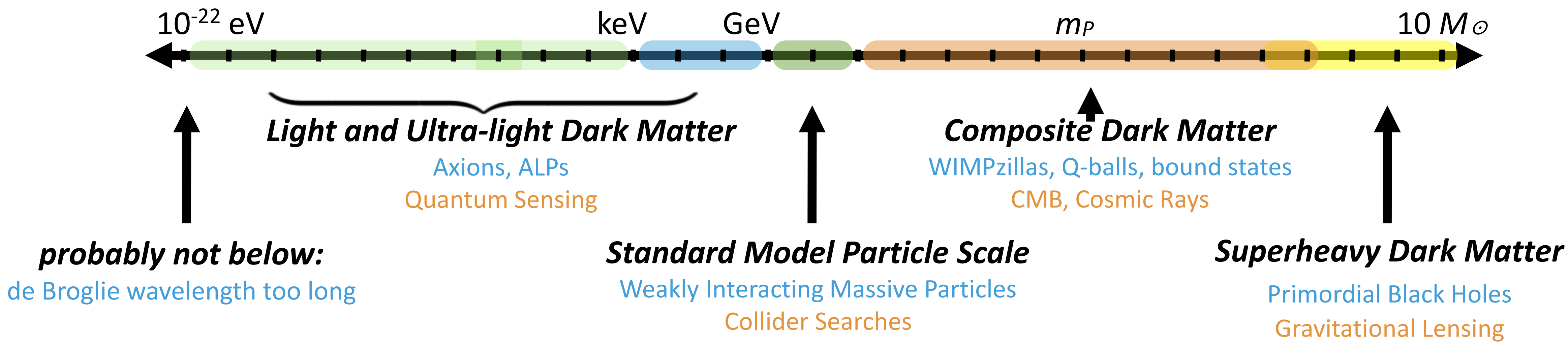
Work Package currently lists three groups:

- **Exotic systems:** Rydberg systems, exotic nuclei (King plots), …
- **Interferometry:** many groups active, such as AION, MAGIS, ELGAR, MIGA…
- **Clocks, networks:** metrology labs & many university groups, CASPEr, QSNET, …

- Are these the right groupings?
- Does it cover everything it should?
- What work packages make sense?
- How best to build a community, and show the added value?

Particle Physics Example: Mass Scales for Dark Matter

Why Quantum Sensing? Why Clocks? Light/Ultralight Dark Matter is one reason…



Example: Light Bosonic Dark Matter Couplings

Bosons

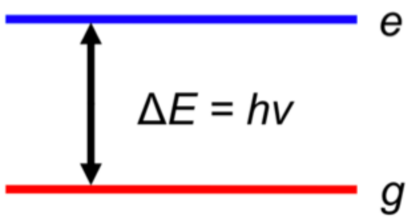
- **Scalar (Spin = 0)**
  Axions and other Goldstone Bosons
  - **Electro-magnetism**: $\left(\frac{a}{f_a}F\tilde{F}\right)$ $\left(\sim \frac{a}{f_a}\vec{E}.\vec{B}\right)$
  - **Nuclear Spin**: $\left(\frac{\partial_\mu a}{f_a}\bar{N}\gamma^\mu\gamma_5 N\right)$ General Axions
  - **Nuclear Force**: $\left(\frac{a}{f_a}G\tilde{G}\right)$ QCD Axions
- **Pseudoscalar (Spin = 1)**
  Investigate anomaly-free couplings
  - **Electro-magnetism**: $\left(\epsilon F' F\right)$ Kinetic Mixing
  - **Nuclear Spin**: $\left(\frac{F'_{\mu\nu}}{f_a}\bar{N}\sigma^{\mu\nu}N\right)$ Dipole Moment
  - **Nuclear Current**: $\left(gA'_\mu J^\mu_{B-L}\right)$ B-L

- 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 Methods for Testing Variations in α and μ

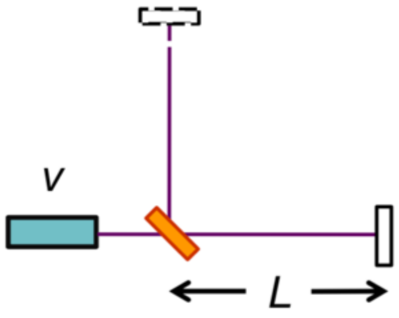
Methods for Testing $\Delta\alpha/\alpha$



Atomic spectroscopy (clocks)

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

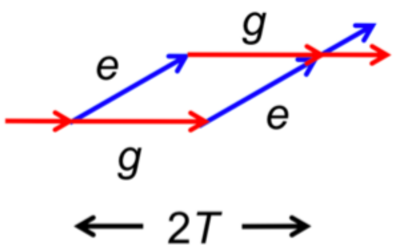
10^{-23} eV > m_ϕ > 10^{-16} eV



Laser interferometry (cavities)

$$\delta\Phi \propto \delta(\nu L) \propto \cos(m_\varphi t)$$

10^{-20} eV > m_ϕ > 10^{-15} eV



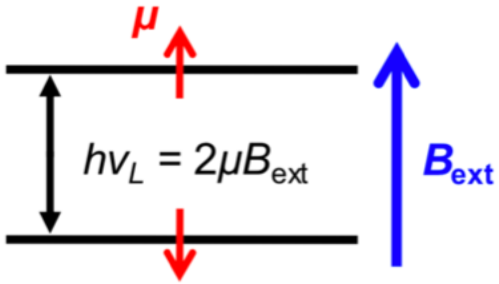
Atom interferometry

$$\boldsymbol{F}(t) \propto \boldsymbol{p}_\varphi \sin(m_\varphi t)$$

10^{-23} eV > m_ϕ > 10^{-16} eV

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

Co-magnetometry

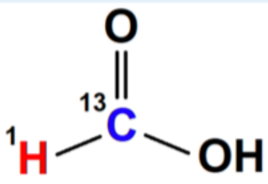


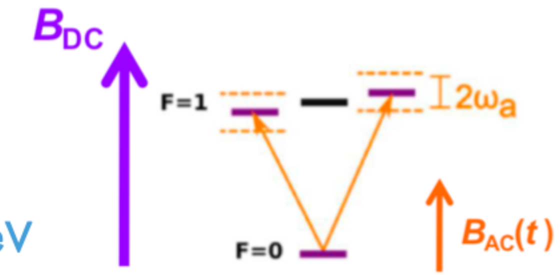
$$\delta(\nu_{L,1}/\nu_{L,2}) \propto \cos(m_a t)$$

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

10^{-23} eV > m_ϕ > 10^{-17} eV

Nuclear magnetic resonance (“sidebands”)



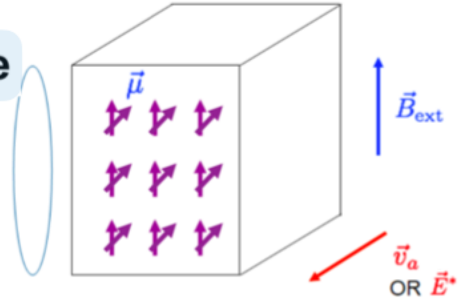


10^{-16} eV > m_ϕ > 10^{-13} eV

Nuclear magnetic resonance

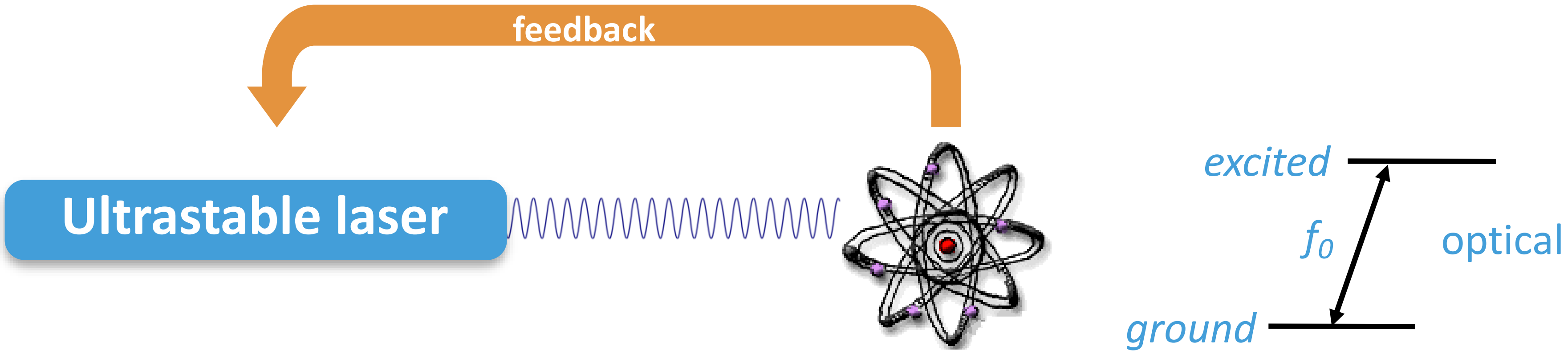
Resonance: $2\mu B_{ext} \approx m_a$

10^{-14} eV > m_ϕ > 10^{-7} eV



[Stadnik]

Optical Atomic Clocks



$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c}$$

$$\mu = \frac{m_p}{m_e}$$

Electron transition frequency stabilisation for timekeeping element

- Recent (2000) innovation of using high-frequency mode-locked laser for optical transitions
- Stabilisation technique led to Nobel Prize in Physics for Hall and Hänsch in 2005

***Ultra-sensitive**, e.g. to Dark Matter variations in fine structure constant α or proton/electron mass ratio μ*

Clock Transitions and Sensitivities

- Atomic transition scale set by Rydberg constant $R_\infty = \alpha^2 m_e c/4\pi\hbar$, also structure constant α and proton-to-electron mass ratio μ

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

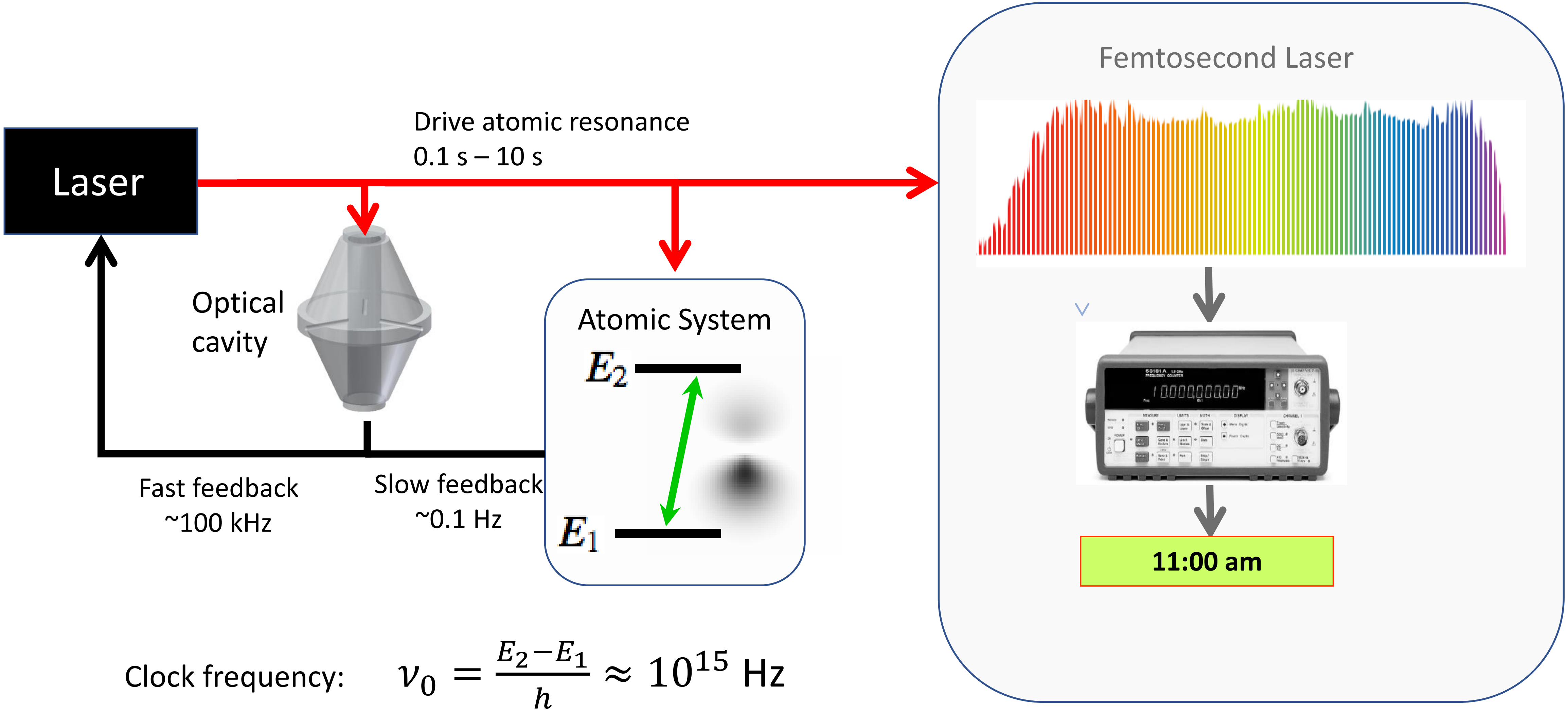
Clock	Kα	Kμ
Yb^+ (467 nm)	-5.95	0
Sr (698 nm)	0.06	0
Cs (32.6 mm)	2.83	1
CaF (17 μm)	0	0.5
N_2^+ (2.31 μm)	0	0.5
Cf^{15+} (618 nm)	47	0
Cf^{17+} (485 nm)	-43.5	0

- Transitions have different sensitivities to variations in α or μ, given by K_α and K_μ
- Measure ratios of frequencies of two transitions ($R = \nu_1/\nu_2$)
- So for α and simple case of scalar field ϕ and linear coupling, ratio oscillates with frequency $f = m_\phi c^2/h$

$$\frac{dR}{R} = [K_{\alpha,1} - K_{\alpha,2}]\frac{d\alpha}{\alpha}$$

$$\propto [K_{\alpha,1} - K_{\alpha,2}]\cos(2\pi f t)$$

Principle of Optical Clocks



Clock frequency: $\nu_0 = \frac{E_2 - E_1}{h} \approx 10^{15}$ Hz

Ultralight dark matter : new limits

- Ultralight bosonic dark matter ($m \ll 10\,\mathrm{eV}$) expected to locally behave like a classical field

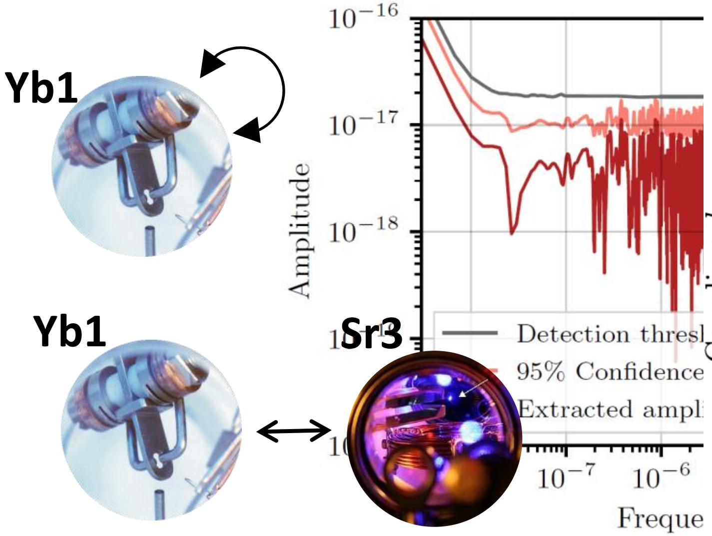
$$\varphi(t) \propto \sqrt{2\rho_{\mathrm{DM}}}/m_\varphi \cos(\omega t)$$

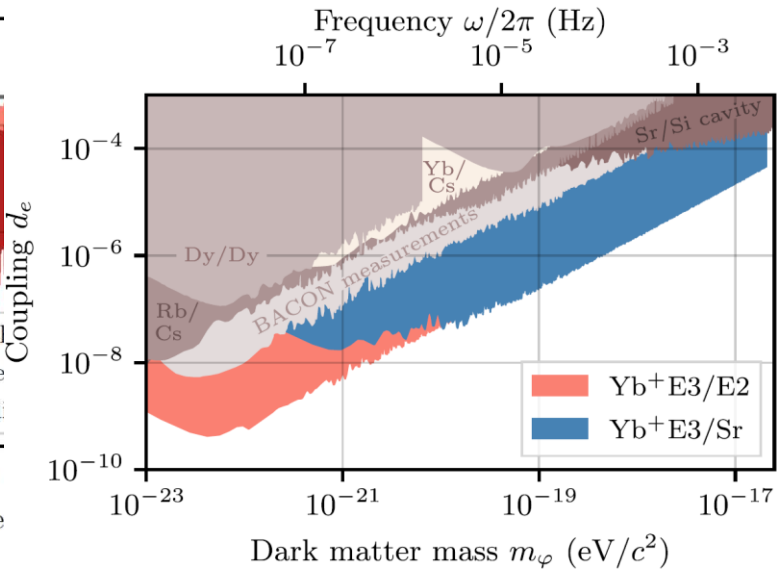
with a frequency given by the Compton frequency [1] $\omega = m_\varphi c^2/\hbar$

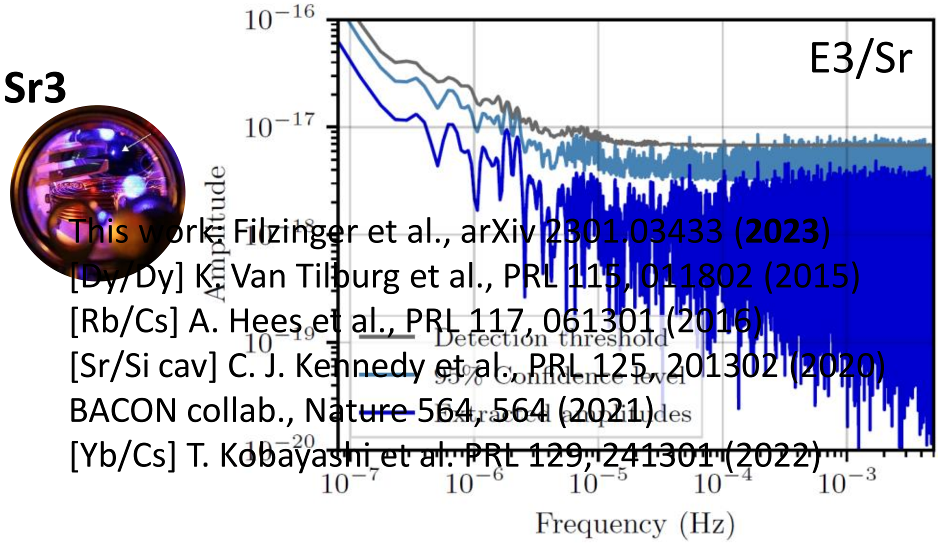
- A coupling d_e of such a dark matter field to photons $\mathcal{L} \supset \varphi \frac{d_e}{4\mu_0} F_{\mu\nu}F^{\mu\nu}$

would lead to coherent oscillations of the fine-structure constant [1]: $\alpha(\varphi) = \alpha(1 + d_e\varphi)$

- Can translate limits on oscillations in atomic clock comparisons into limits on dark matter couplings



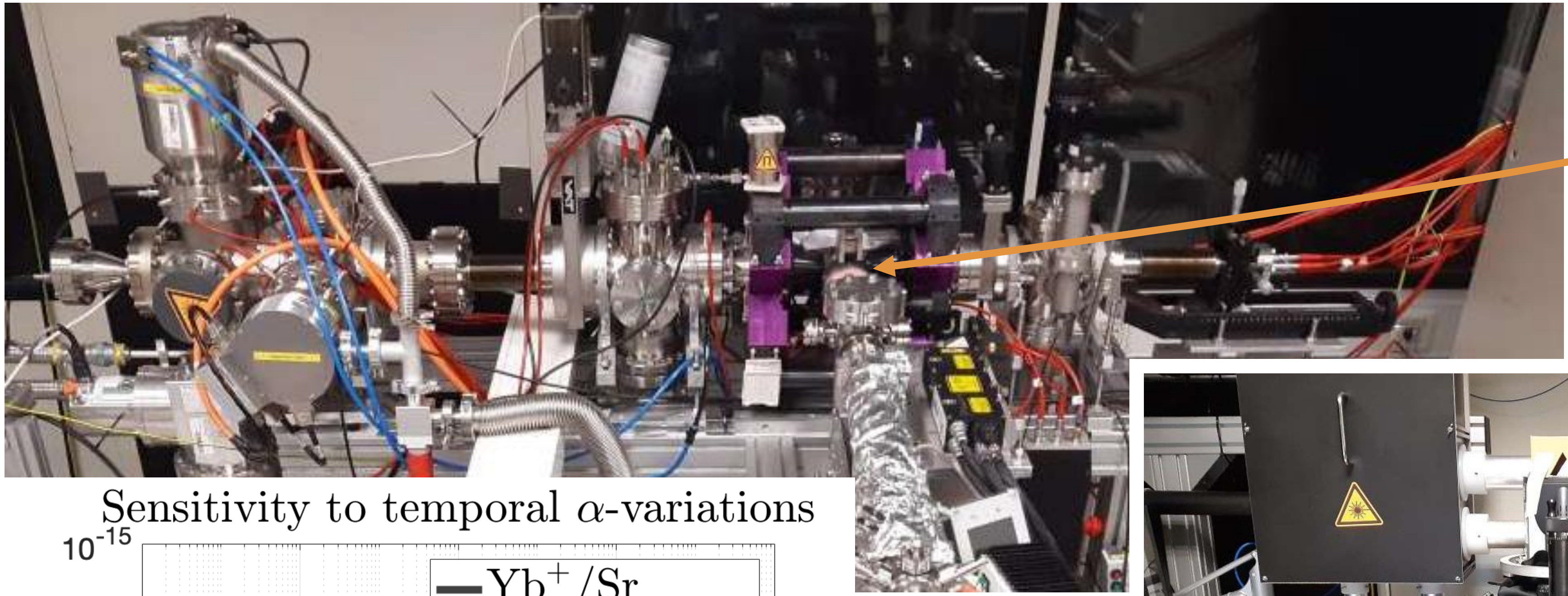




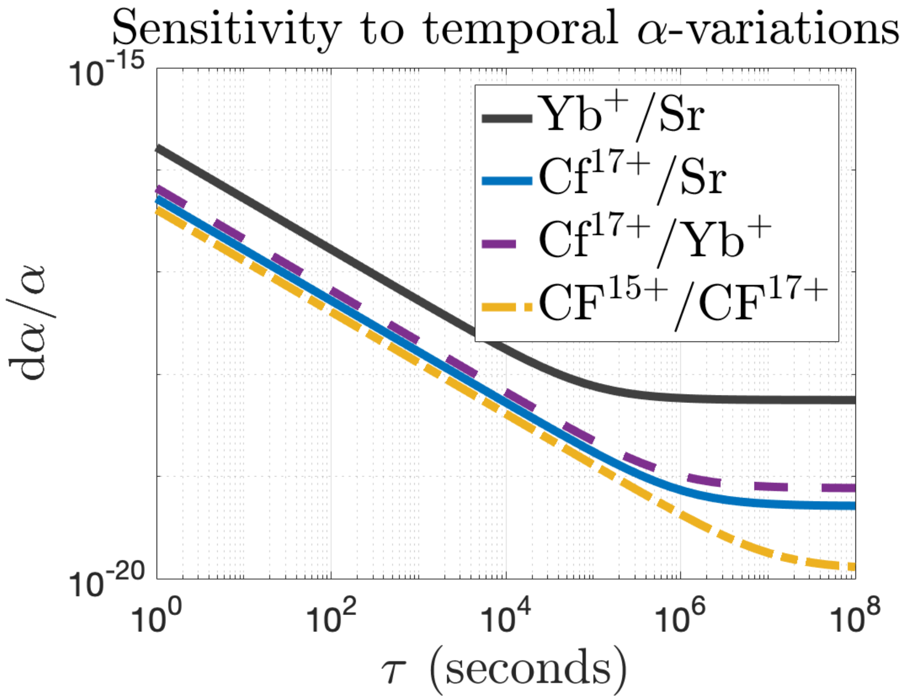
This work: Filzinger et al., arXiv 2301.03433 (**2023**)
[Dy/Dy] K. Van Tilburg et al., PRL 115, 011802 (2015)
[Rb/Cs] A. Hees et al., PRL 117, 061301 (2016)
[Sr/Si cav] C. J. Kennedy et al., PRL 125, 201302 (2020)
BACON collab., Nature 564, 564 (2021)
[Yb/Cs] T. Kobayashi et al. PRL 129, 241301 (2022)

[1] A. Arvanitaki et al., PRD 91, 015015 (2015)

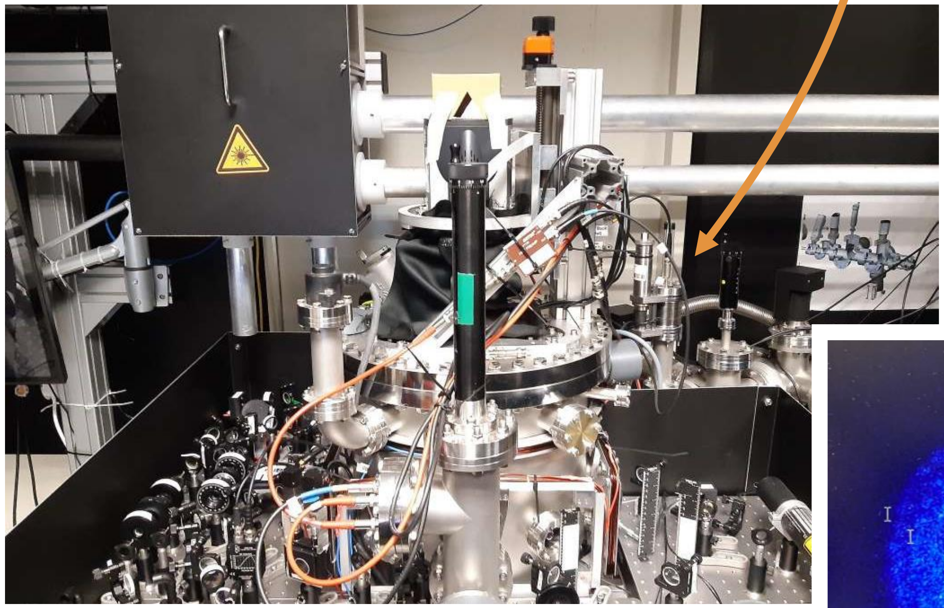
Highly Charged Ions: Production, cooling and trapping

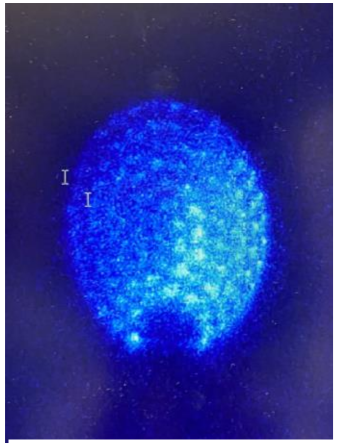


EBIT test stand @MPIK



Paul trap w/ optics



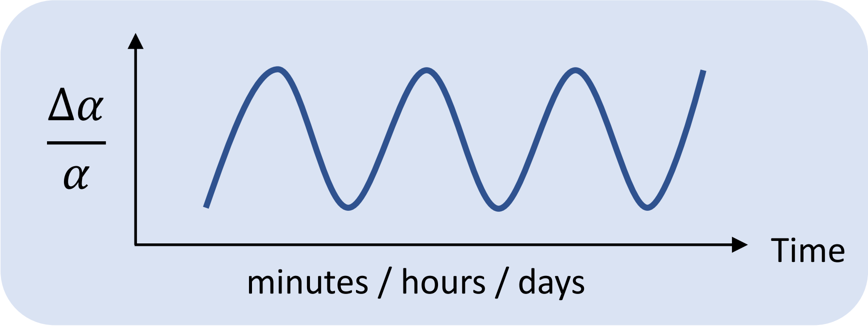


Be crystal with highly charged ion (Ar)

[MPIK: José R. Crespo López-Urrutia]

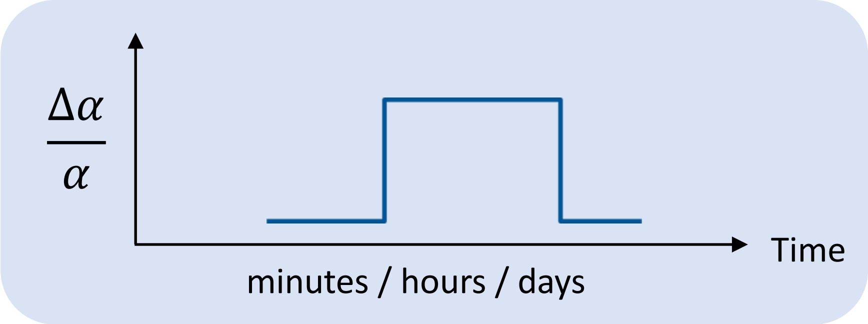
Need to look for variations on different time/lengthscales

- Oscillations



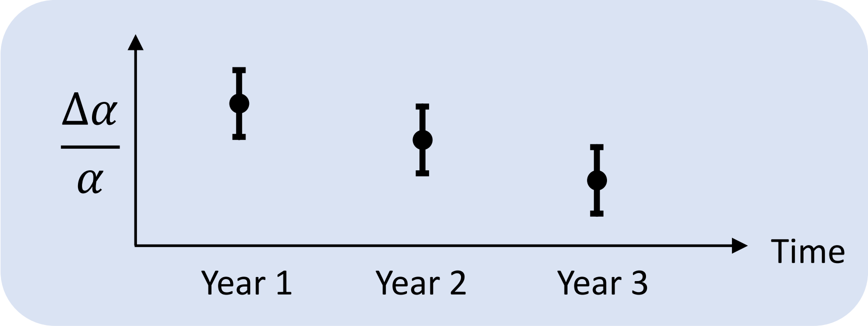
Very light DM

- Fast transients



DM- topological defects

- Slow drifts

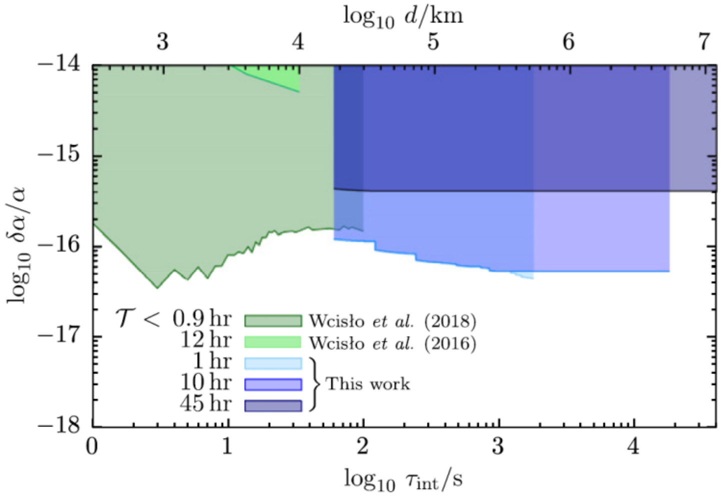


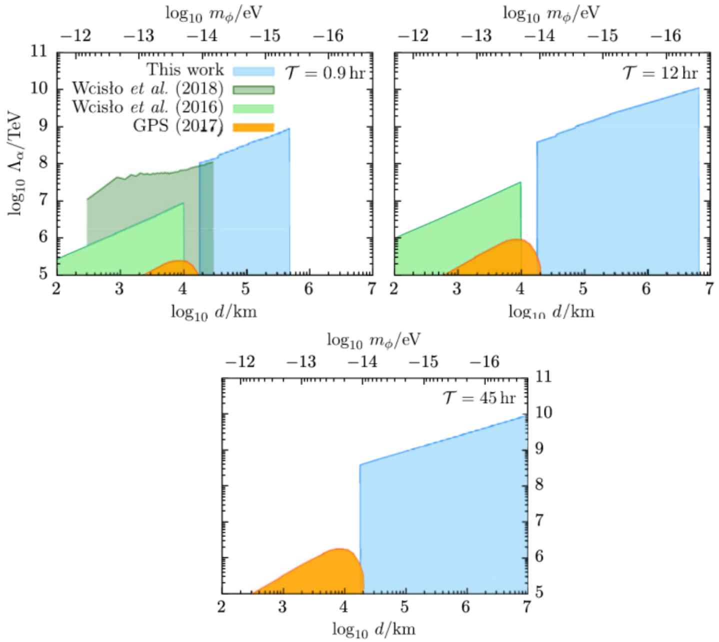
New physics, dark energy

Fast transients (optical fibre network)

- NPL-SYRTE-PTB: realising a “superdetector” connecting clocks with dark fibres [Roberts et al, New J. Phys. 22, 093010 (2020)]

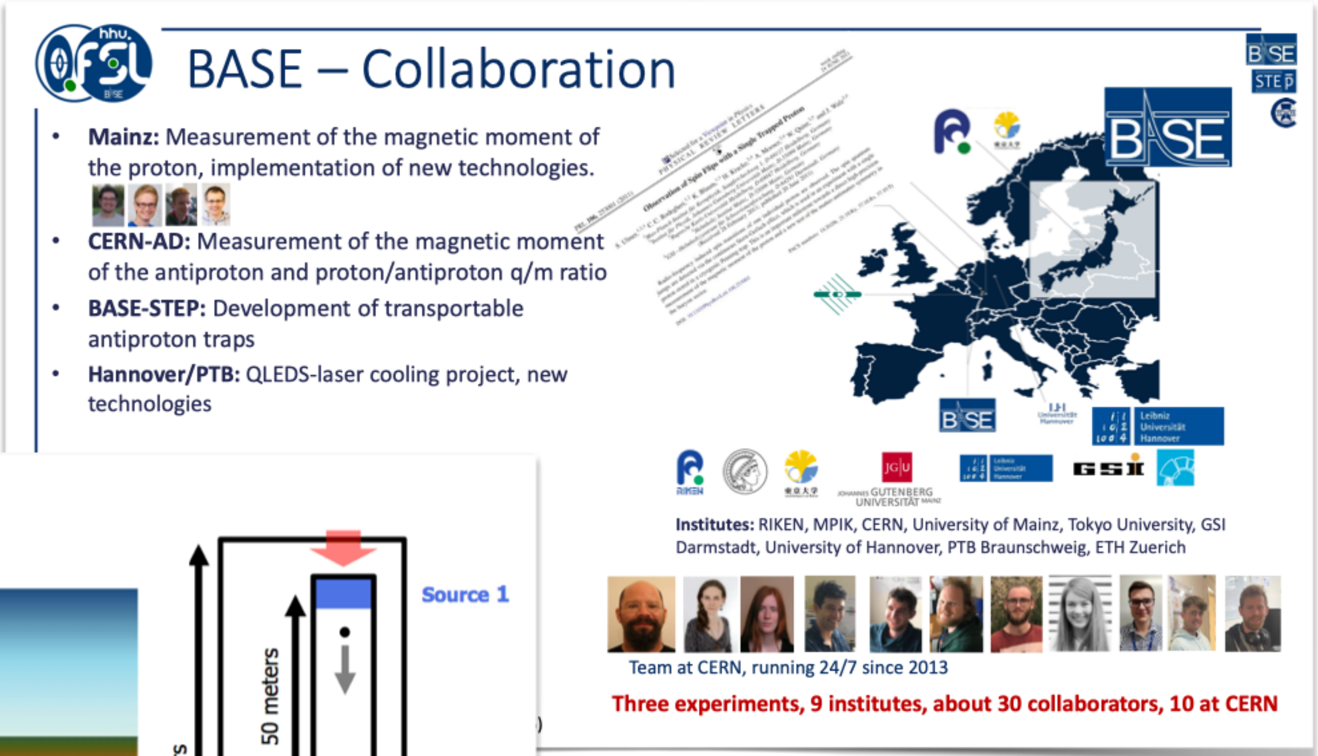
- Comparing clocks with different sensitivities to variations of α
- Clock-clock comparisons over optical fibres features excellent long-term stability
- Previously unconstrained parameter space for quadratic coupling
- Longer measurement time (40 days so far), nested networks

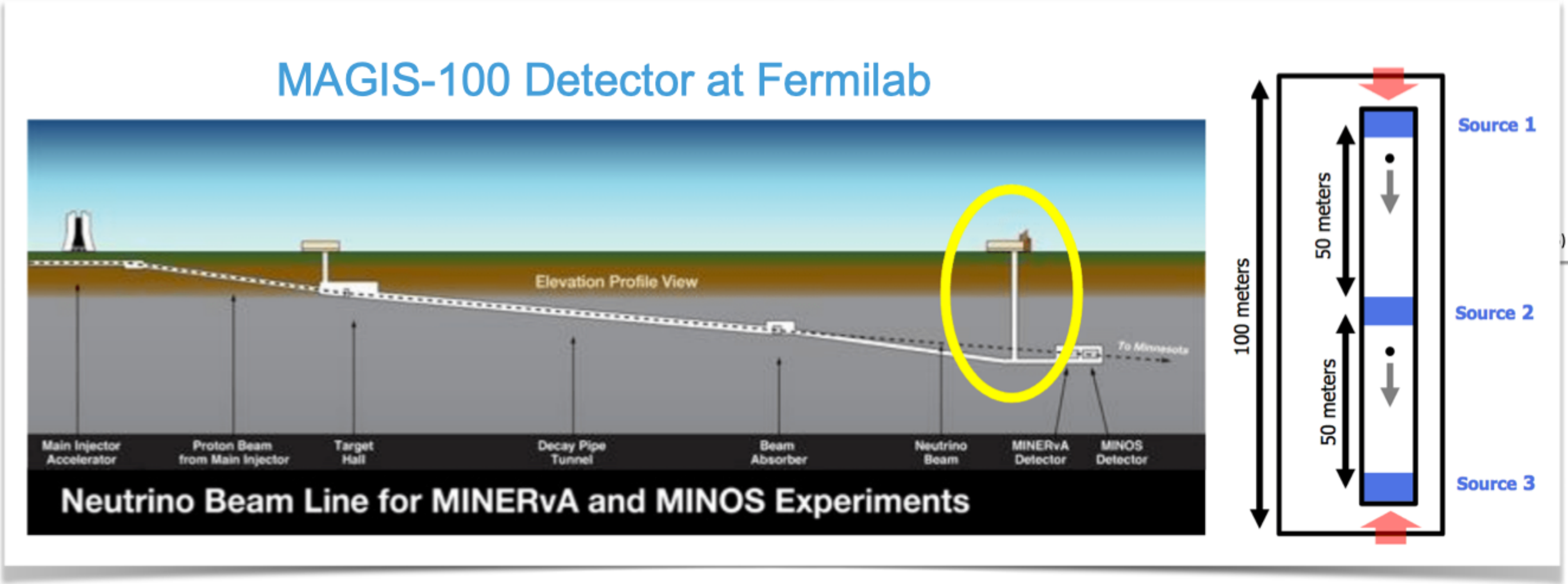




Quantum Experiment Examples: BASE, MAGIS, AION

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





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

AION

The Atom Interferometric Observatory and Network

exploration of ultra-light dark matter
and gravitational waves

Ideas for Milestones/Deliverables

- Networking links & dark fibre
- Portable clocks & free space links
- Control systems, up-time, reliability

- (Other ideas welcome!)

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Concept of an International Fiber Network:

as investigated in the CLONETS consortium (2020-2022)

Coordinator: **GEANT** – runs also CERN LCG network

Transatlantic connections of LCG are run by ESnet

GÉANT

Time and frequency distribution in the GÉANT network

Guy Roberts
Senior Network Architect, GÉANT

NDN, Reykjavik
14 Sept 2022

CloNetS DS
Clock Network Services Design Study

1 NETHERLANDS
- GEANT VERENIGING

2 FRANCE
- CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS
- RENATER
- UNIVERSITÉ SORBONNE PARIS NORD
- IXBLUE

3 ITALY
- INSTITUTO NAZIONALE DI RICERCA

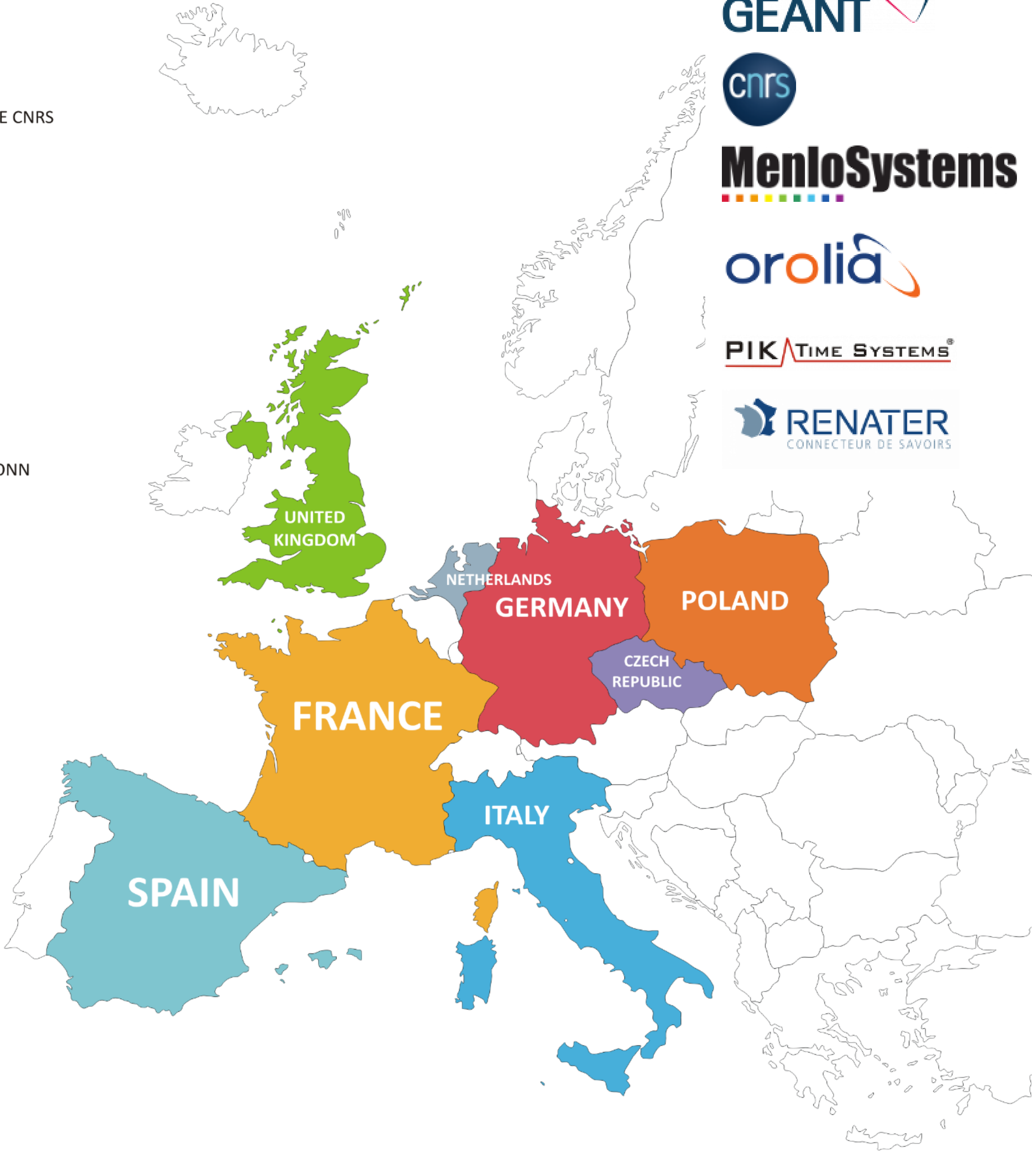
4 GERMANY
- PHYSIKALISCH-TECHNISCHE BUNDESANSTALT
- MENLO SYSTEMS GmbH
- TECHNISCHE UNIVERSITAET MUENCHEN
- RHEINISCHE FRIEDRICH-WILHELMS-UNIVERSITAT BONN

5 UNITED KINGDOM
- UNIVERSITY COLLEGE LONDON

6 CZECH REPUBLIC
- CESNET, z.s.p.o.
- USTAV PRISTROJOVE TECHNIKY AV CR, v.v.i.

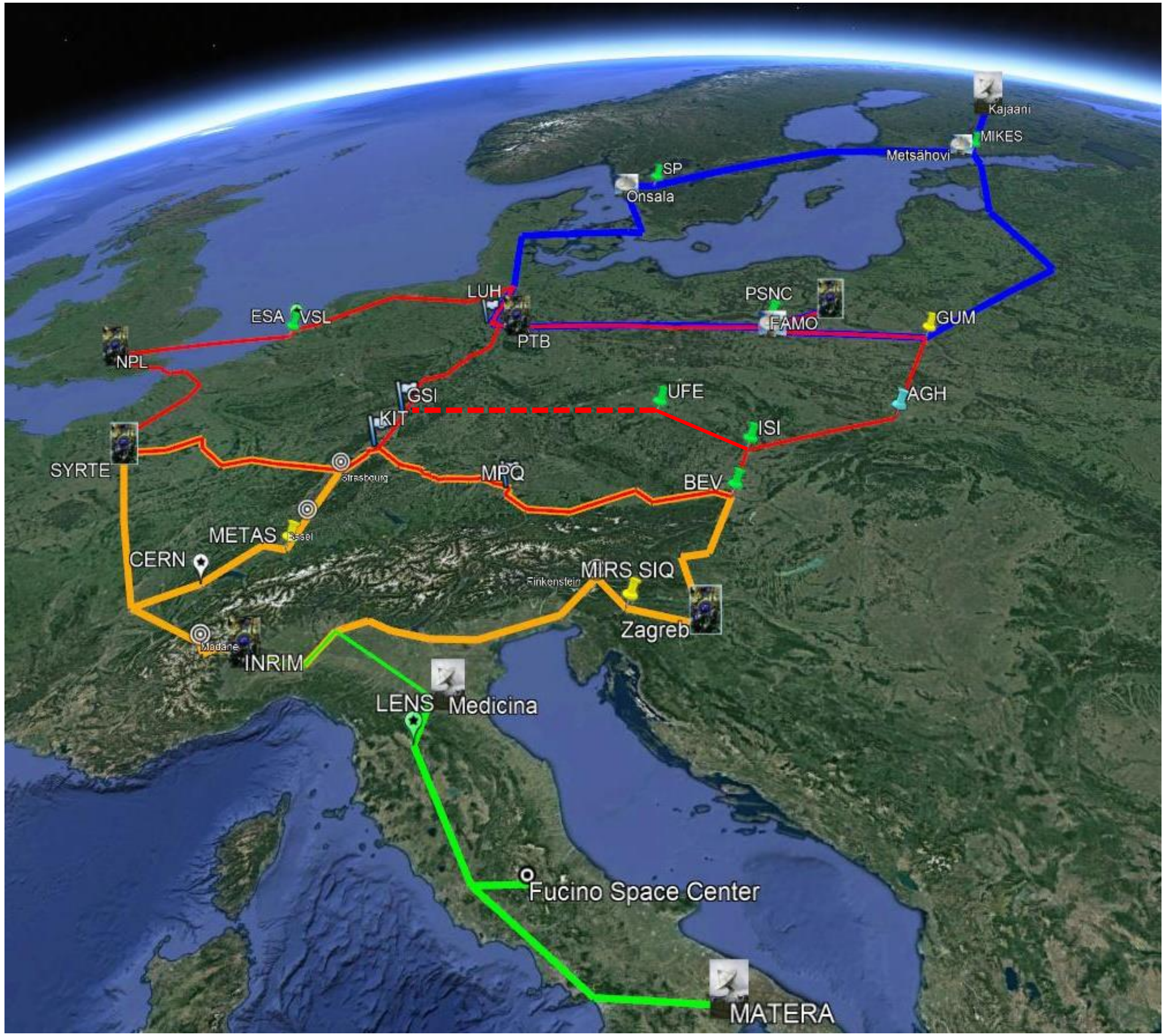
7 POLAND
- POZNANSKIE CENTRUM SUPERKOMPUTEROWO-SIECIOWE
- PIKTIME SYSTEMS sp. z o. o.
- AKADEMIA GORNICZO-HUTNICZA IM. STANISLAWA STASZICA W KRAKOWIE

8 SPAIN
- OROLIA
- UNIVERSIDAD DE GRANADA



https://clonets-ds.eu

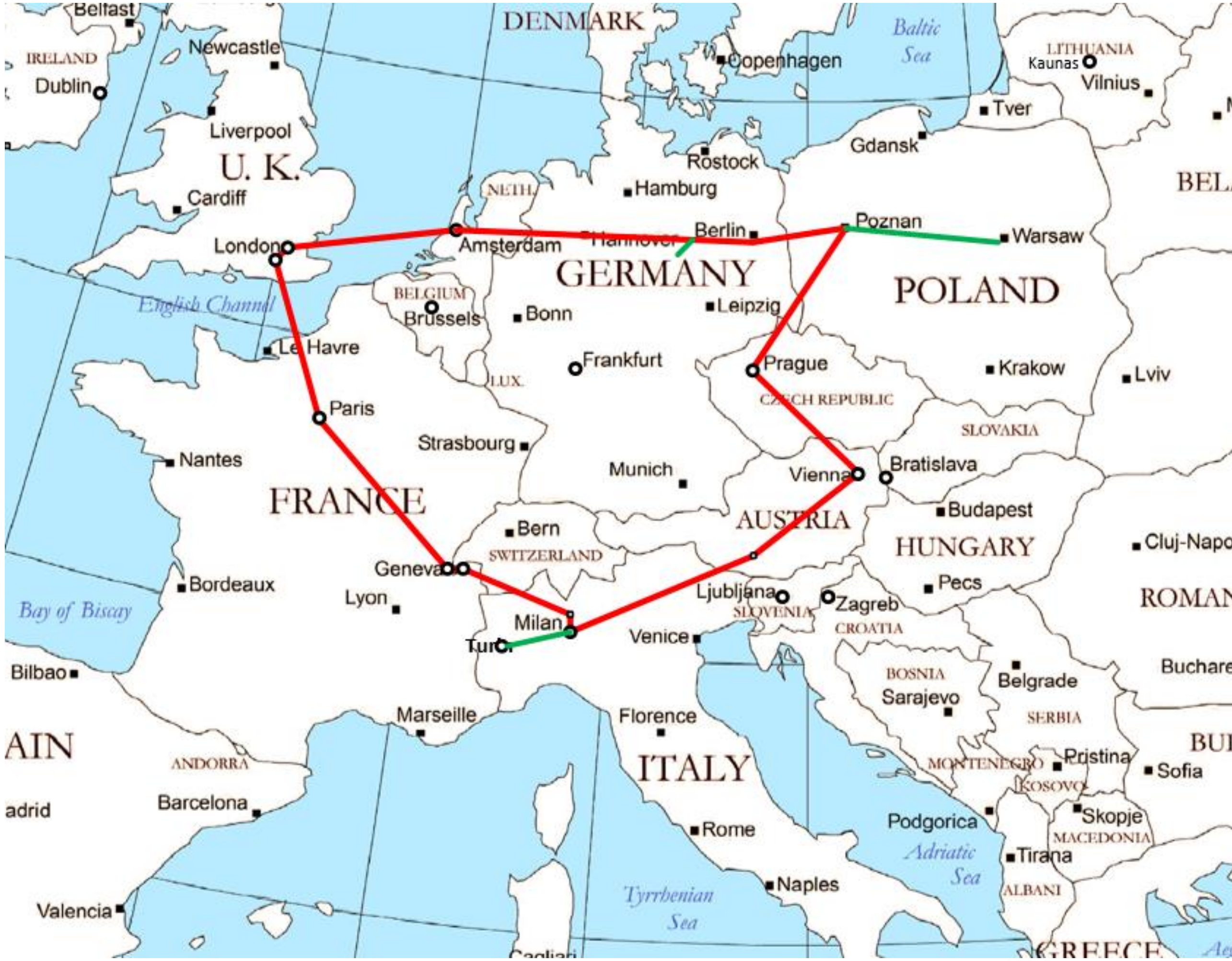
Ring topology across Europe



The network should rely

- on already existing national infrastructure if available
- and on NREN/GEANT for missing links and cross border connections
- National existing point-to-point connections should be considered as “in-kind” contribution to CLONETS-DS
- The operational responsibility should remain at the national level
- Fiber links should interconnect at dedicated Points of Presence (dPoP)

- In this scenario we have estimated the engineering cost of building a T/F ring on the reference ring below.
- The solution uses dedicated fibre for time/frequency
- Cost **over 10 years** includes dark fibre IRU, regenerators, amplifiers and maintenance.



Preferred solution: dark fibre ring

Cost: around 19.5 Million Euros over 10 years

Ideas for Milestones/Deliverables

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- Portable clocks & free space links
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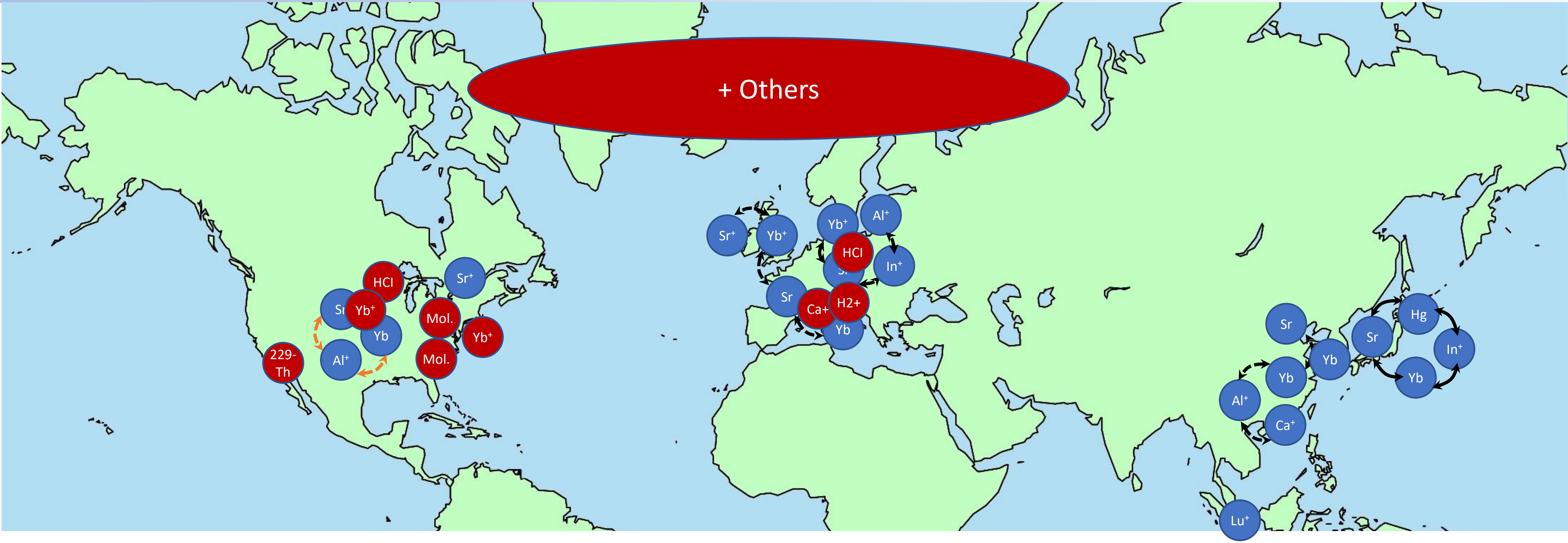
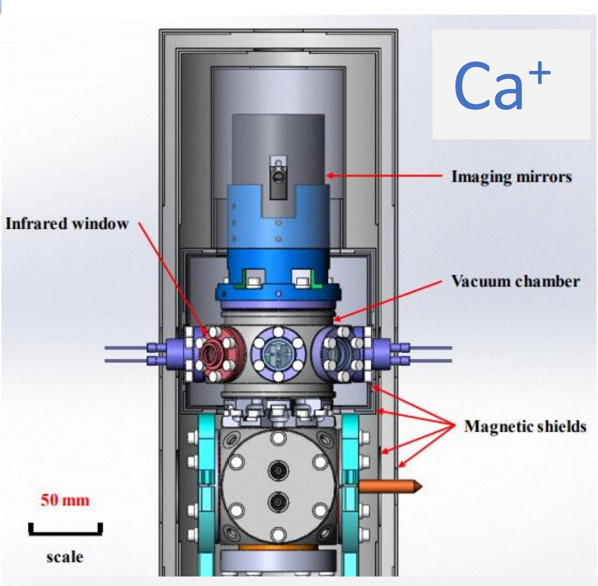
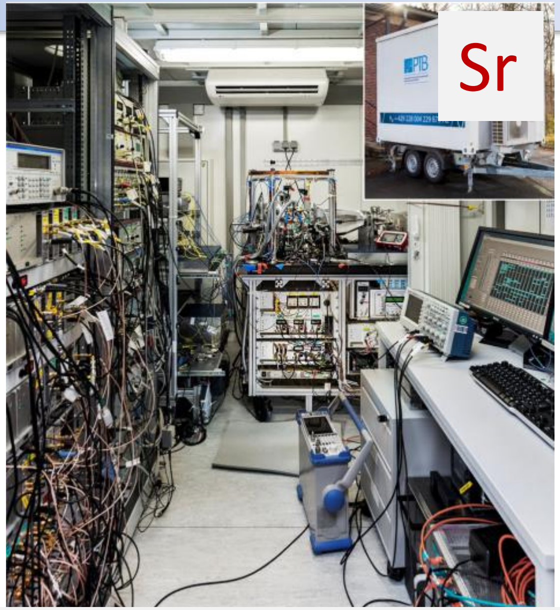
Clock networks



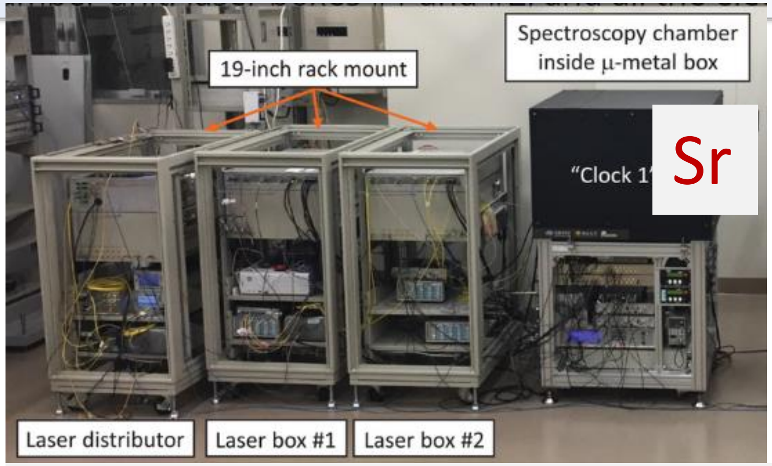
Transportable clock efforts



Zeng et al., arXiv:2303.07566 (2023)

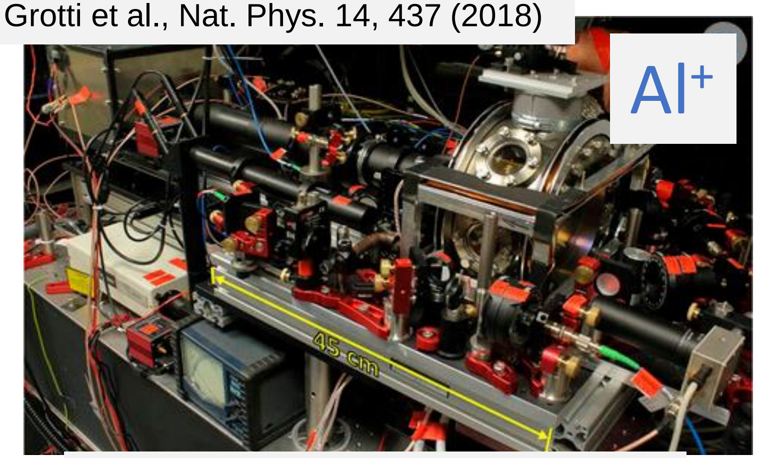


Grotti et al., Nat. Phys. 14, 437 (2018)

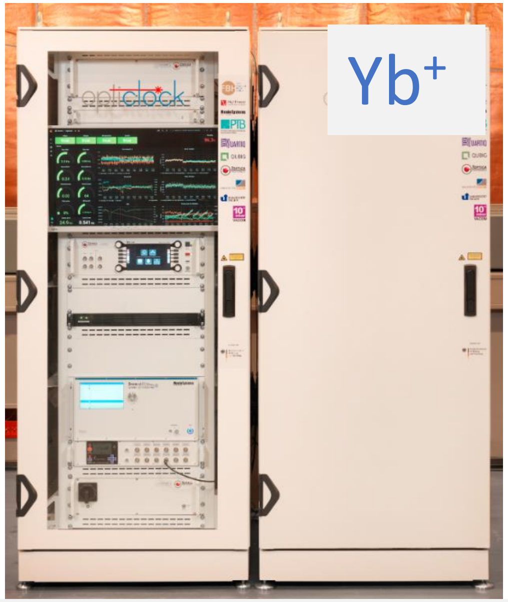


Ohmae et al., Adv. Quant. Tech. 4, 2100015 (2021)

NIST Transportable Yb-lattice clock
Fasano PhD thesis (2021)

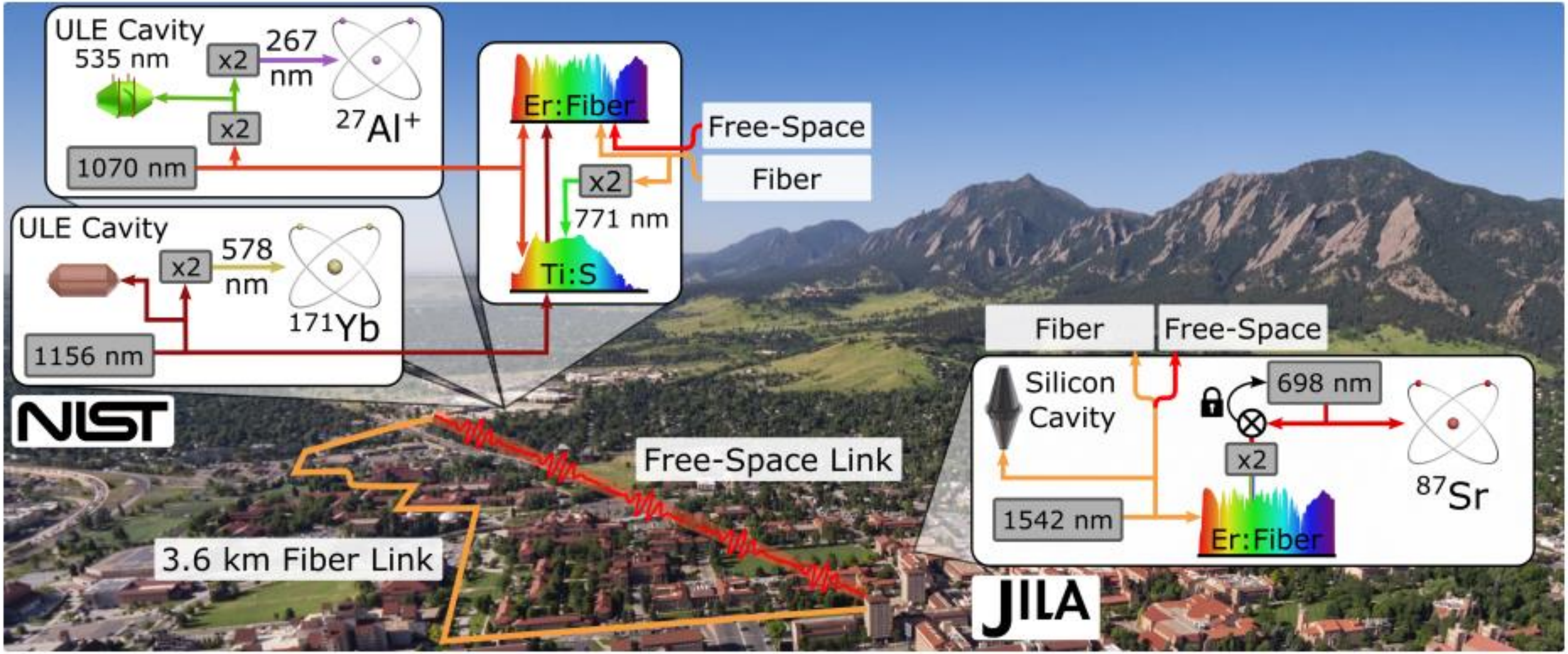


Hannig et al., RSI 90, 053204 (2019)



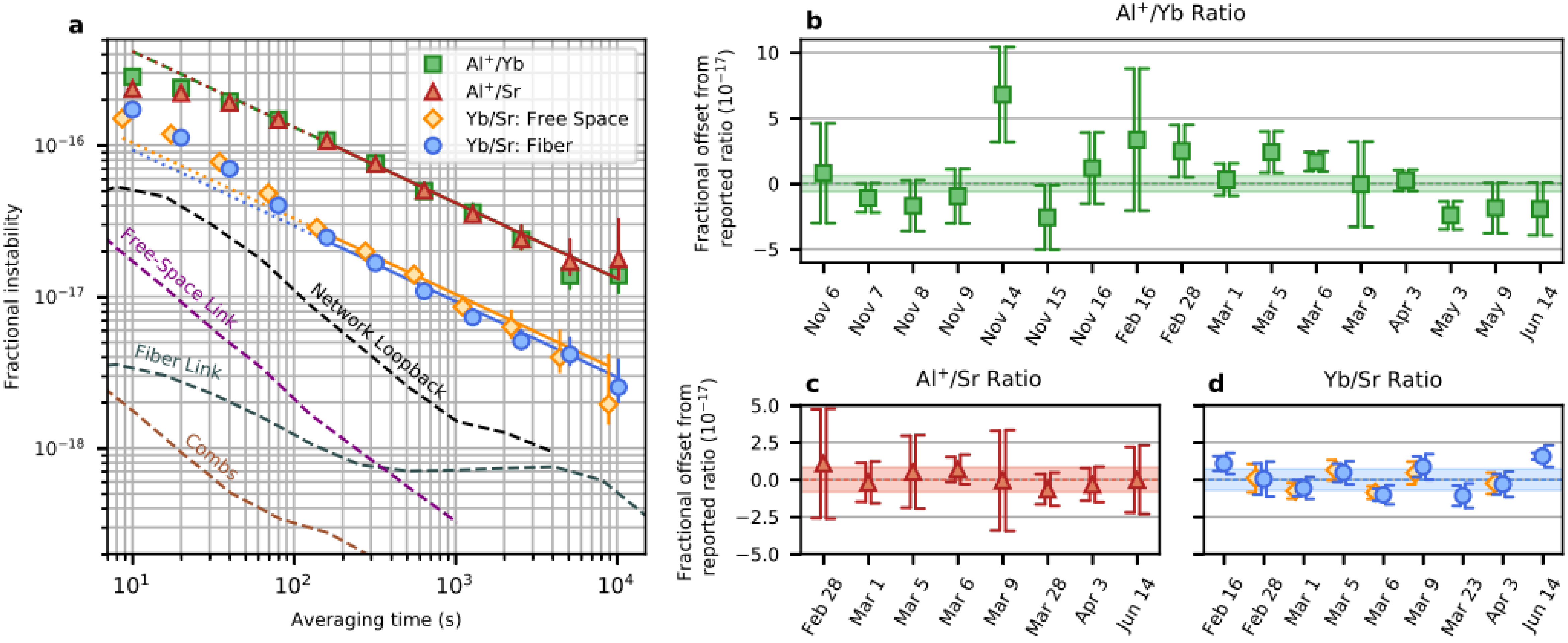
Stuhler et al., Measurement: Sensors 18, 100264 (2021)

Boulder Atomic Clock Optical Network



Beloy *et al.,* Nature 591, 564 (2021)

BACON Measurement Campaign



Beloy *et al.*, Nature 591, 564 (2021)

BACON results

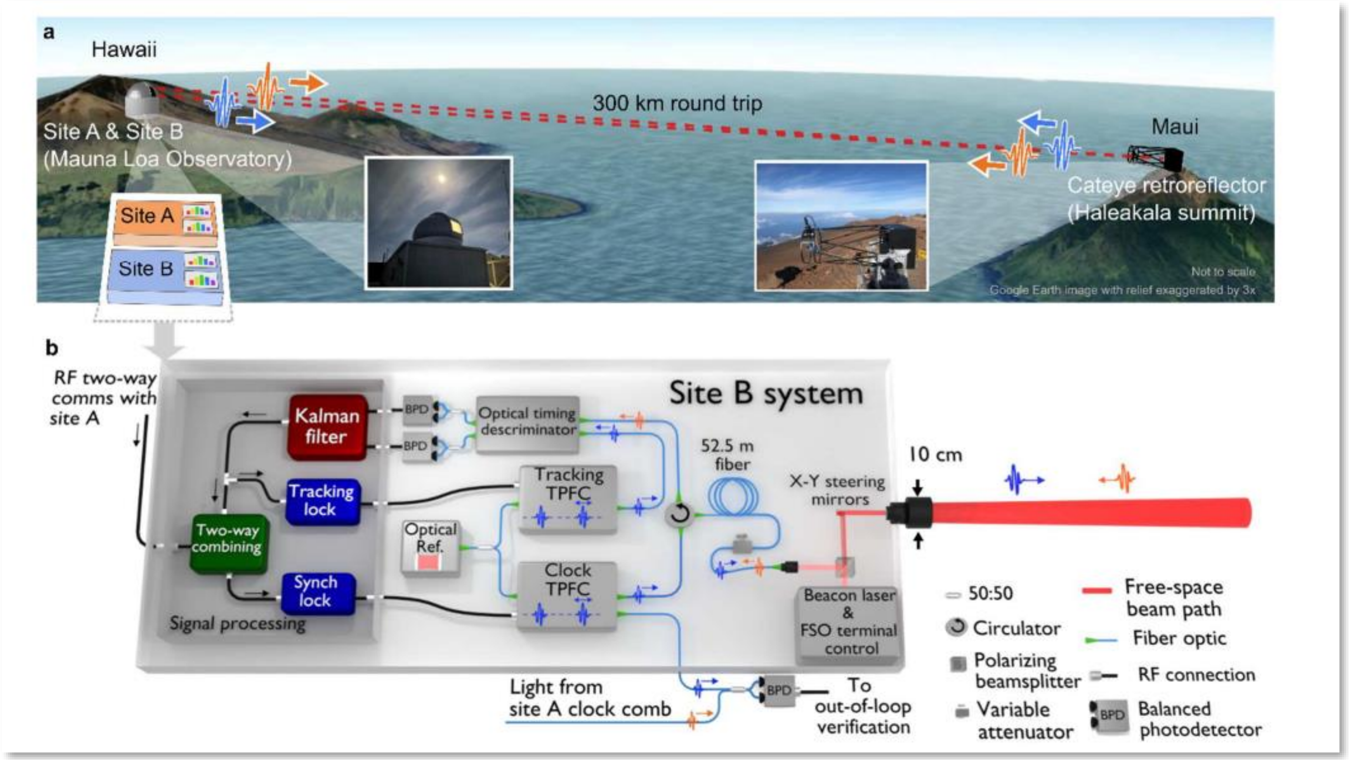
$$\frac{\nu_{Al+}}{\nu_{Yb}} = 2.162\,887\,127\,516\,663\,703(13) \qquad \frac{\Delta R_{Al+/Yb}}{R_{Al+/Yb}} = 5.9 \times 10^{-18}$$

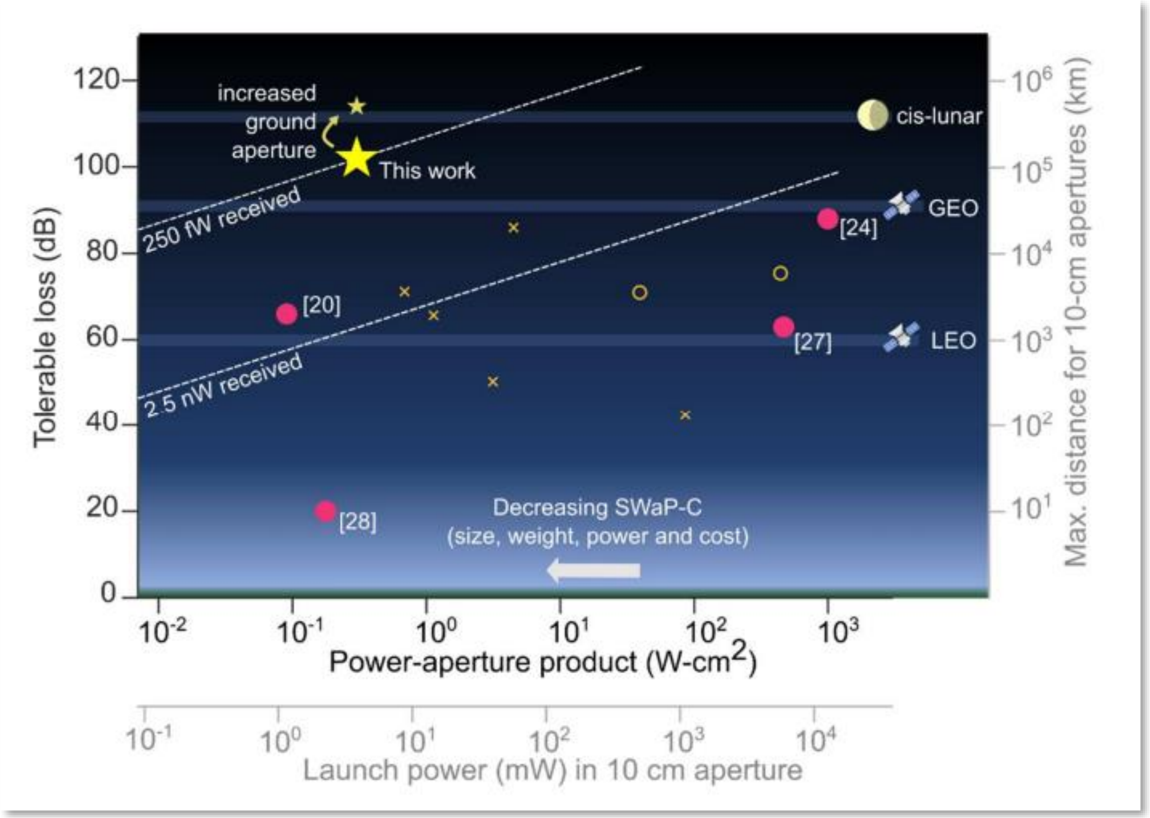
$$\frac{\nu_{Al+}}{\nu_{Sr}} = 2.611\,701\,431\,781\,463\,025(21) \qquad \frac{\Delta R_{Al+/Sr}}{R_{Al+/Sr}} = 8.0 \times 10^{-18}$$

$$\frac{\nu_{Yb}}{\nu_{Sr}} = 1.207\,507\,039\,343\,337\,848\,2(82) \qquad \frac{\Delta R_{Yb/Sr}}{R_{Yb/Sr}} = 6.8 \times 10^{-18}$$

Beloy *et al.*, Nature 591, 564 (2021)

Work towards longer distance networks





Quantum-limited performance over 300 km

Caldwell et al., arXiv:2212.12541 [physics.ins-det] (2022)

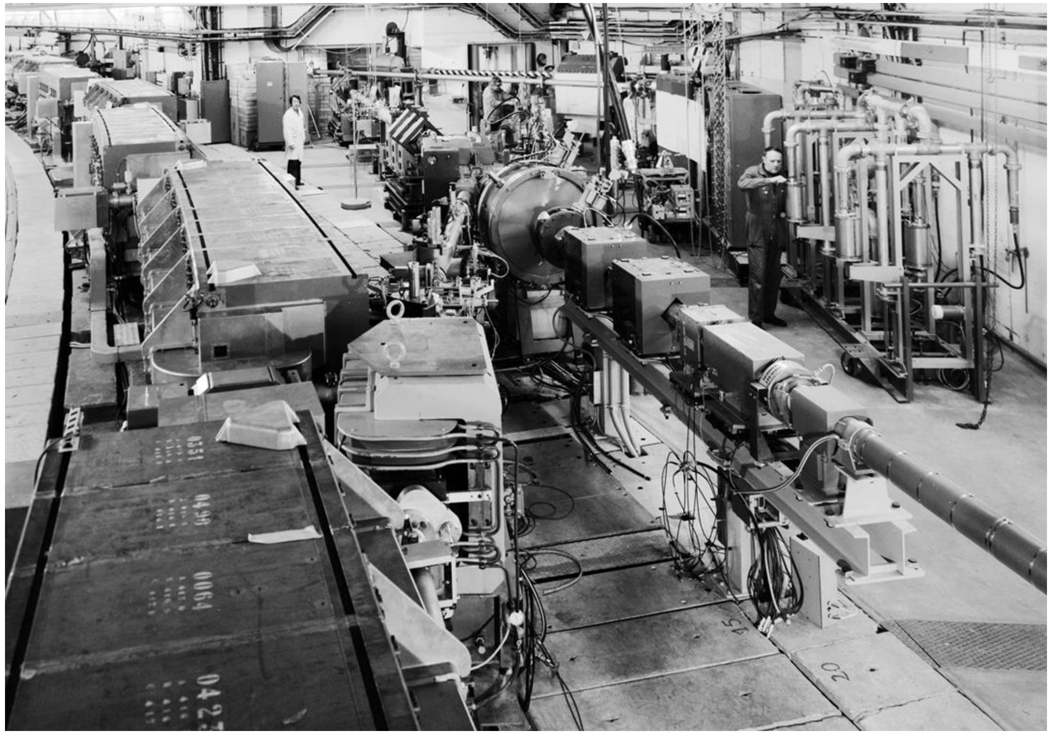
See also: Shen, Q. et al. Nature 610, 661 (2022)

Ideas for Milestones/Deliverables

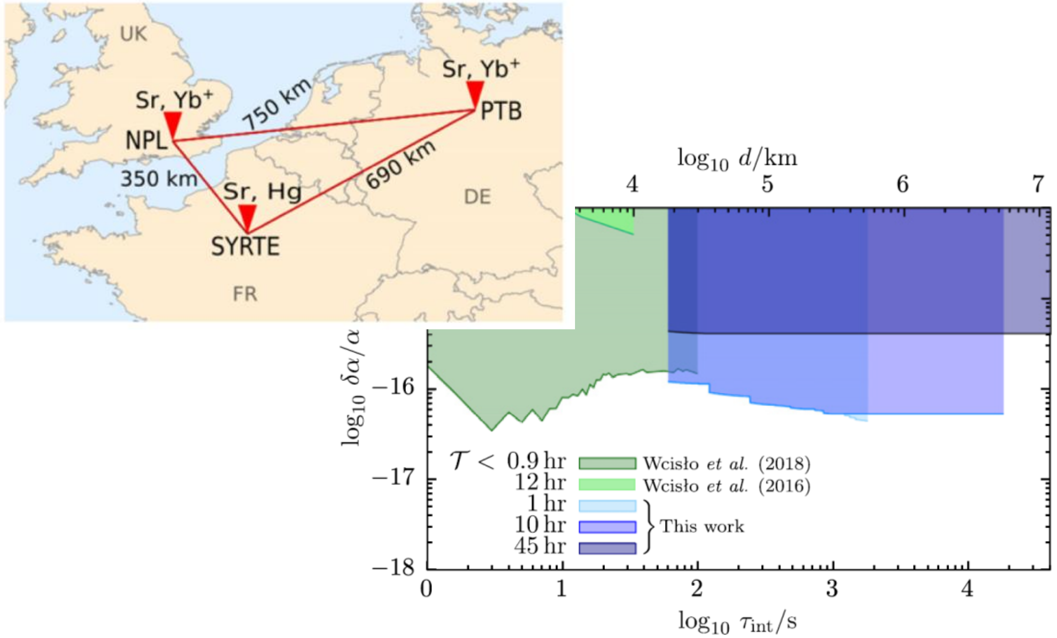
- Networking links & dark fibre
- Portable clocks & free space links
- Control systems, up-time, reliability

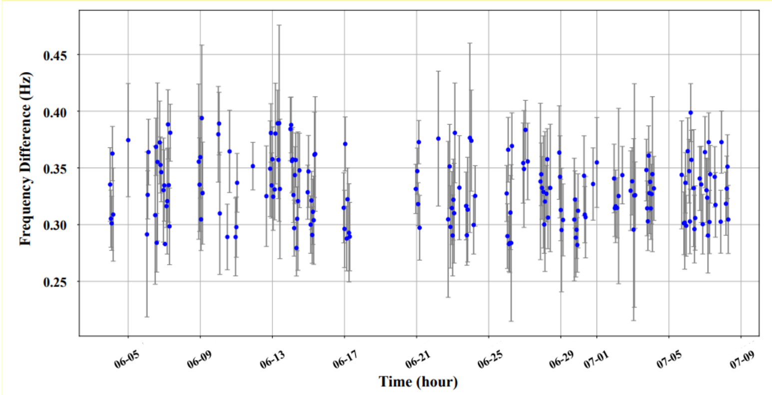
Reliability and Control Systems

- PS Accelerator: running for > 50 years



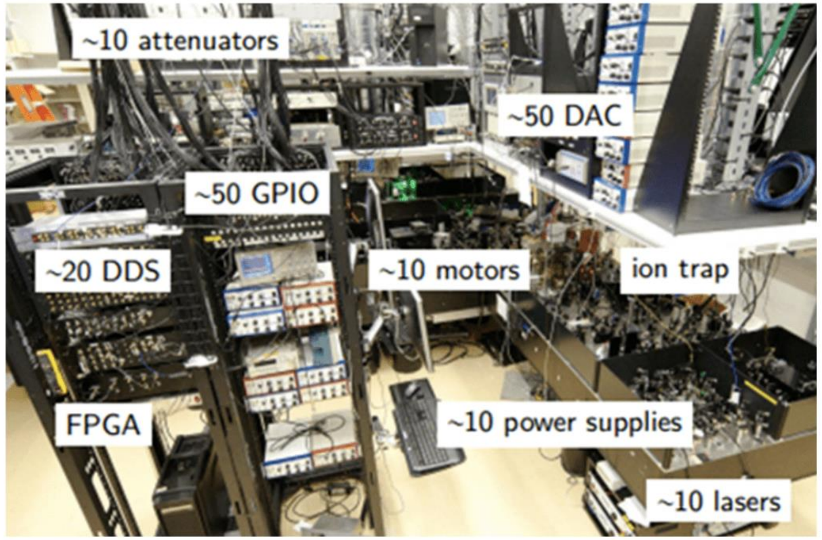
- Ultralight Dark Matter w/ clocks: ~2 weeks?



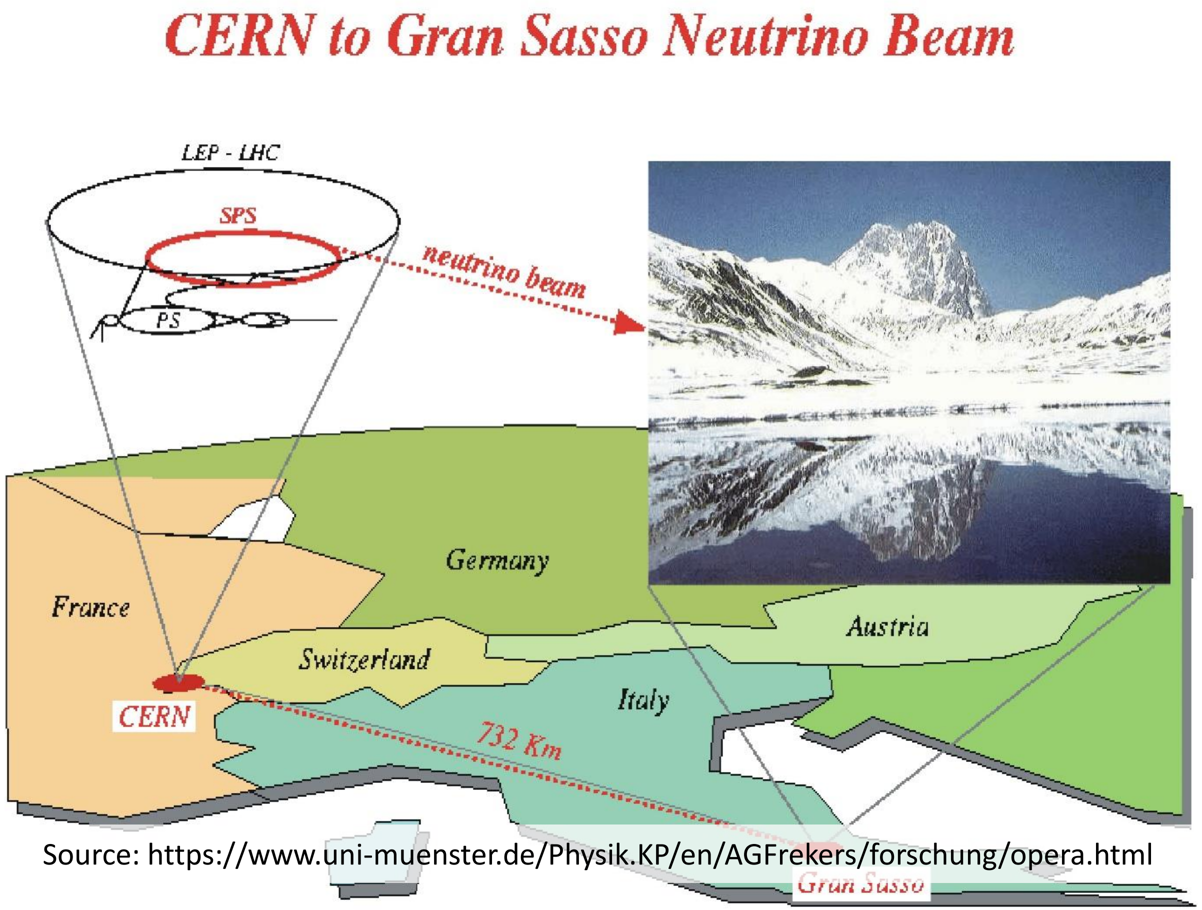


Control systems for Cold Atoms experiments

ARTIQ (Advanced Real-Time Infrastructure for Quantum physics) is a leading-edge control system for quantum information experiments. It was initiated and developed in partnership with the Ion Storage Group at NIST, and is now used and supported by a growing number of research institutions worldwide. While ARTIQ is currently mostly used by atomic physics groups, its applicability reaches beyond ion trapping.



Sometimes timing is essential

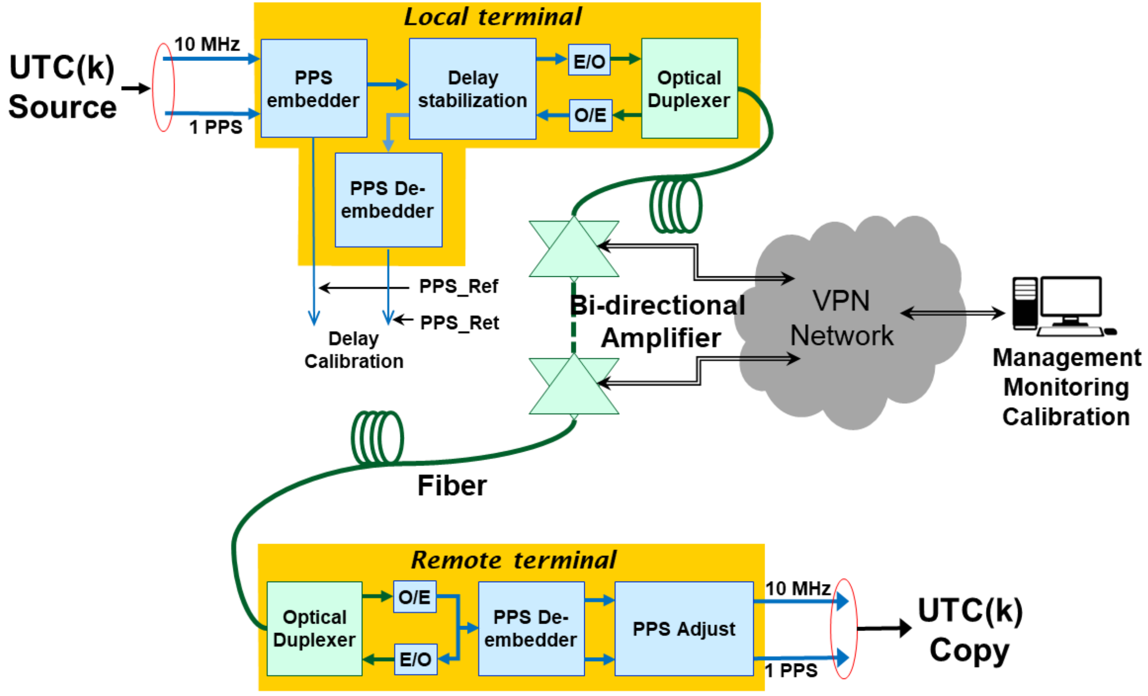


Source: https://www.uni-muenster.de/Physik.KP/en/AGFrekers/forschung/opera.html

Fig. 2: Sketch of the 732 km distance from CERN in Geneva to Gran Sasso (near Rome).

J. High Energ. Phys. **2012,** 93 (2012). https://doi.org/10.1007/JHEP10(2012)093

Fiber-based dissemination of UTC



- Instability ≈ 10 ps over 275 days
- Repeatability < 30 ps

L. Sliwczynski *et al.*, IEEE Communications Magazine, **58**, 67-73, (2020)

The White Rabbit Project

The **White Rabbit Project** is a multilaboratory, multicompany and multinational collaboration to develop new technology that provides a versatile solution for control and data acquisition systems. The project was started within an effort to renovate the current CERN control and timing system. Since then, it has expanded beyond this initial application. One of the reasons for such expansion is the open source paradigm used in the project for the development of hardware, gateware and software. Another reason is the compatibility with standards.

The **White Rabbit Network** is based on existing IEEE standards while extending these standards in a backward-compatible way if needed to meet CERN's requirement. Technically, the White Rabbit Network is a Bridged Local Area Network with VLANs (IEEE 802.1Q) that uses Ethernet (IEEE 802.3) to interconnect switches and nodes, and the Precision Time Protocol (PTP, IEEE 1588-2008) to synchronise them.

The **main features** of the White Rabbit Network are:

- sub-nanosecond accuracy and picoseconds precision of synchronization
- connecting thousands of nodes
- typical distances of 10 km between network elements
- Gigabit rate of data transfer
- fully open hardware, firmware and software
- commercial availability from many vendors

Conclusions and Next Steps for WP2

- Many ongoing activities!
  - Which ones benefit from global coordination?
  - Are there technical challenges many groups/collaborations are facing?
  - What is the added value of RDq?

- Need to work on the text… input welcome!

- Suggestions for milestones greatly appreciated

Submission 1: European Network of Clocks (Barontini et al)

- Motivates clock networks, proposes three pillars of activity
- First two pillars motivate increased sensitivity and diversity
- Third pillar suggests a fiberoptic network for comparison
- 49 signatories from 12 countries (open signup)

Pillar 1:	**Reduce the uncertainty in clock measurements**. Continued research and development into techniques to reduce the instability and inaccuracy of clock frequency measurements.
Pillar 2:	**Develop new types of clocks with enhanced sensitivities**. There are many aspects of new physics that can be probed by searching for variations in fundamental constants such as the fine structure constant, α and the proton-to-electron mass ratio, μ. Certain clock transitions are particularly well-suited to searches for variations in α, such as highly charged ions and nuclear transitions. Variations in μ, however, are better probed with rotational or vibrational transitions in molecules. Transitions in highly charged ions present also enhanced sensitivity to violations of Lorentz invariance.
Pillar 3:	**Use optical fibres to link a large number of diverse clocks in a network**. Comparing a large number of clocks with different sensitivities creates an extremely powerful detector for searches of new physics. A network makes it possible to compare two or more clocks in different locations, which opens up a wider range of physics that can be tested as well as optimally exploiting the resources and expertise spread across different institutes.

A European network of clocks for detecting new physics

Proposal for the ECFA Roadmap

The extreme precision of atomic, molecular and nuclear clocks can be exploited to detect signatures of physics beyond our best established theories: the standard model of particle physics and the Lambda cold dark matter model of cosmology. Optical atomic clocks have already reached fractional frequency uncertainties close to 10^{-18}. Clocks based on highly charged ions, molecules or nuclear transitions hold the promise to reach and even surpass such precision, offering in addition enhanced sensitivity to probing new physics.

New physics can change the rates at which the clocks "tick". To measure a change in a clock's frequency, there must be a reference frequency that it can be measured against, preferably with comparable or lower uncertainty. In practice, to detect new physics we need to measure two or more ultra-precise clocks relative to each other by recording frequency ratios between them. Notably, clocks in different laboratories (and even different countries) can be linked and compared via optical fibres, with phase-noise cancellation in the links resulting in negligible additional uncertainty being introduced into the measurement.

A geographically distributed network of diverse clocks, connected by optical fibre links could thus be used as a detector with unprecedented precision to:

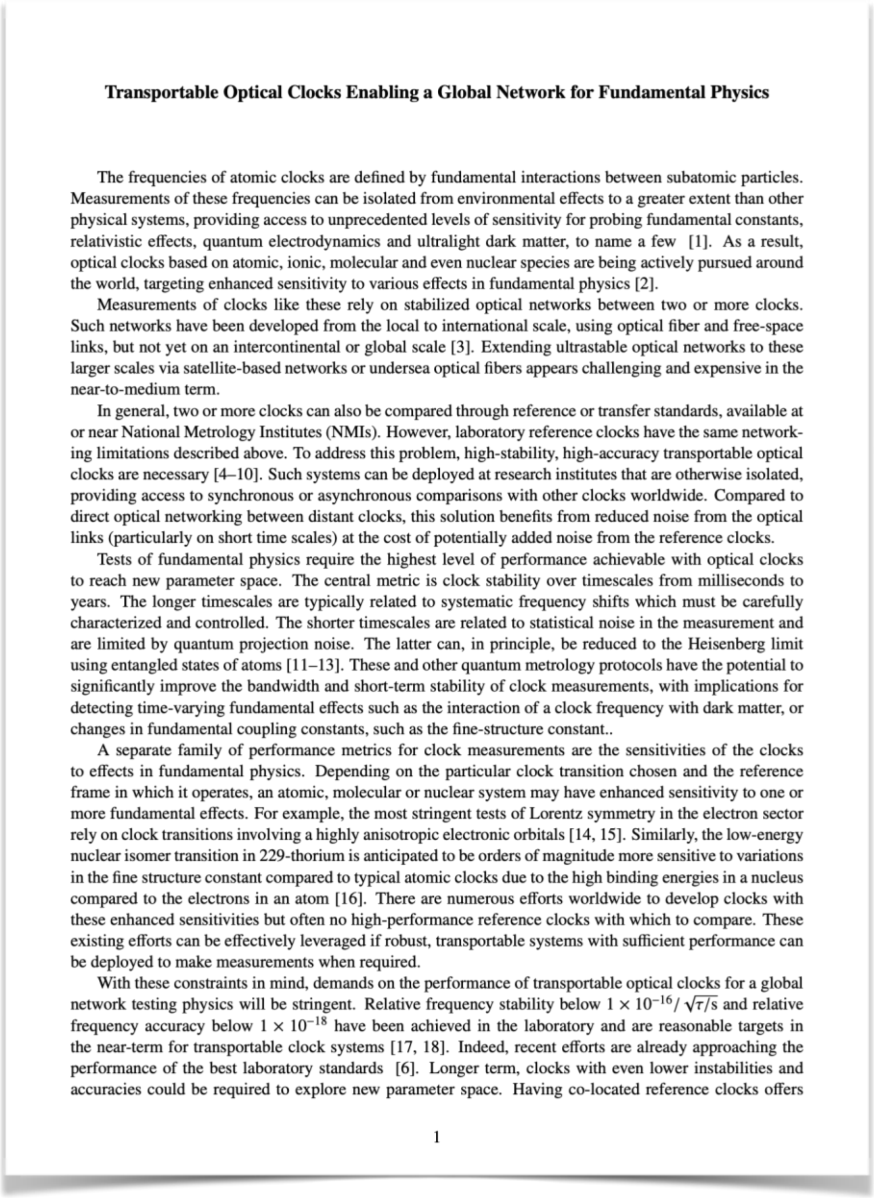
- Look for variations in fundamental constants, which could themselves be indicators of
  - Ultralight dark matter models
  - Quintessence-like models of dark energy
  - Generic hidden sector scalar fields
  - Kaluza-Klein models
  - Dilaton field models
  - Soliton models
  - Transient phenomena due to cosmic strings, domain walls, and kinks of a scalar field
- Look for violations of Lorentz Invariance and Local Position Invariance
- Test quantum gravity
- Test grand unification theories
- Probe space-time correlations, providing additional information, such as the speed and directionality of phenomena linked to new physics
- Detect transient events linked to macroscopic dark objects, such as topological defects, Q-balls and dark stars
- Improve the limit from a single pair of clocks by a factor sqrt(N), by having N pairs of clocks making the same measurements.
- Provide independent confirmation of measurements and rejection of false positives by having independent clocks detecting the same signal

Submission 2. Transportable Optical Clocks (Hume et al)

- Portable reference clock, for fundamental physics studies
  - Can do much of the same physics as with a networked approach, and is also extremely useful to characterise a network
  - Discussions just starting, with many interested institutes (NIST coordinated submission, no author list yet)

- Requirements
  - Excellent stability & accuracy: *optical* clock
  - Portable and compact
  - High up-time
  - Economical
  - Easy to set up and to operate, reliable
  - Specific ion (standardisation) not so important

- Suggested targets for transportable clock systems (near-term):
  - Relative frequency stability < $1\times10^{-16} / \sqrt{\tau/s}$
  - Relative frequency accuracy < 1×10^{-18}



Transportable Optical Clocks Enabling a Global Network for Fundamental Physics

The frequencies of atomic clocks are defined by fundamental interactions between subatomic particles. Measurements of these frequencies can be isolated from environmental effects to a greater extent than other physical systems, providing access to unprecedented levels of sensitivity for probing fundamental constants, relativistic effects, quantum electrodynamics and ultralight dark matter, to name a few [1]. As a result, optical clocks based on atomic, ionic, molecular and even nuclear species are being actively pursued around the world, targeting enhanced sensitivity to various effects in fundamental physics [2].

Measurements of clocks like these rely on stabilized optical networks between two or more clocks. Such networks have been developed from the local to international scale, using optical fiber and free-space links, but not yet on an intercontinental or global scale [3]. Extending ultrastable optical networks to these larger scales via satellite-based networks or undersea optical fibers appears challenging and expensive in the near-to-medium term.

In general, two or more clocks can also be compared through reference or transfer standards, available at or near National Metrology Institutes (NMIs). However, laboratory reference clocks have the same networking limitations described above. To address this problem, high-stability, high-accuracy transportable optical clocks are necessary [4–10]. Such systems can be deployed at research institutes that are otherwise isolated, providing access to synchronous or asynchronous comparisons with other clocks worldwide. Compared to direct optical networking between distant clocks, this solution benefits from reduced noise from the optical links (particularly on short time scales) at the cost of potentially added noise from the reference clocks.

Tests of fundamental physics require the highest level of performance achievable with optical clocks to reach new parameter space. The central metric is clock stability over timescales from milliseconds to years. The longer timescales are typically related to systematic frequency shifts which must be carefully characterized and controlled. The shorter timescales are related to statistical noise in the measurement and are limited by quantum projection noise. The latter can, in principle, be reduced to the Heisenberg limit using entangled states of atoms [11–13]. These and other quantum metrology protocols have the potential to significantly improve the bandwidth and short-term stability of clock measurements, with implications for detecting time-varying fundamental effects such as the interaction of a clock frequency with dark matter, or changes in fundamental coupling constants, such as the fine-structure constant..

A separate family of performance metrics for clock measurements are the sensitivities of the clocks to effects in fundamental physics. Depending on the particular clock transition chosen and the reference frame in which it operates, an atomic, molecular or nuclear system may have enhanced sensitivity to one or more fundamental effects. For example, the most stringent tests of Lorentz symmetry in the electron sector rely on clock transitions involving a highly anisotropic electronic orbitals [14, 15]. Similarly, the low-energy nuclear isomer transition in 229-thorium is anticipated to be orders of magnitude more sensitive to variations in the fine structure constant compared to typical atomic clocks due to the high binding energies in a nucleus compared to the electrons in an atom [16]. There are numerous efforts worldwide to develop clocks with these enhanced sensitivities but often no high-performance reference clocks with which to compare. These existing efforts can be effectively leveraged if robust, transportable systems with sufficient performance can be deployed to make measurements when required.

With these constraints in mind, demands on the performance of transportable optical clocks for a global network testing physics will be stringent. Relative frequency stability below $1 \times 10^{-16}/\sqrt{\tau/s}$ and relative frequency accuracy below 1×10^{-18} have been achieved in the laboratory and are reasonable targets in the near-term for transportable clock systems [17, 18]. Indeed, recent efforts are already approaching the performance of the best laboratory standards [6]. Longer term, clocks with even lower instabilities and accuracies could be required to explore new parameter space. Having co-located reference clocks offers

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