



SAGE

Guglielmo M. Tino

Dipartimento di Fisica e Astronomia & LENS - Università degli Studi di Firenze

Istituto Nazionale di Fisica Nucleare (INFN)

Firenze, Italy

<http://coldatoms.lens.unifi.it/>

*Workshop on Atomic Experiments
for DM and Gravity Exploration
CERN, 22 July 2019*



Proposal title

SPACE ATOMIC GRAVITY EXPLORER

Acronym

SAGE

Lead Proposer

Prof. Guglielmo M. Tino

Dipartimento di Fisica e Astronomia and LENS Laboratory, Università di Firenze
Istituto Nazionale di Fisica Nucleare
Firenze (Italy)

In response to the Call for New Science Ideas in ESA's Science Programme

September 13, 2016

G. M. Tino et al., *SAGE: A Proposal for a Space Atomic Gravity Explorer*, Submitted. [arXiv:1907.03867](https://arxiv.org/abs/1907.03867)



new scientific ideas



New Scientific Ideas » Home

Home

Letter of Intent
submission

Proposal submission

ANNOUNCEMENT OF OPPORTUNITY FOR NEW SCIENCE IDEAS IN ESA'S SCIENCE PROGRAMME

9 February 2016

Through this Call the Director of Science solicits from the broad scientific community proposals for the competitive selection of new "Science Ideas", to be investigated in terms of feasibility and needed technology developments.

Direct link to this page:

<http://www.cosmos.esa.int/web/new-scientific-ideas>

Note (18 March 2016): the tentative date and place for the Briefing meeting have changed.

The Briefing meeting is now planned for 1st June 2016 in ESAC - Spain (still TBC)

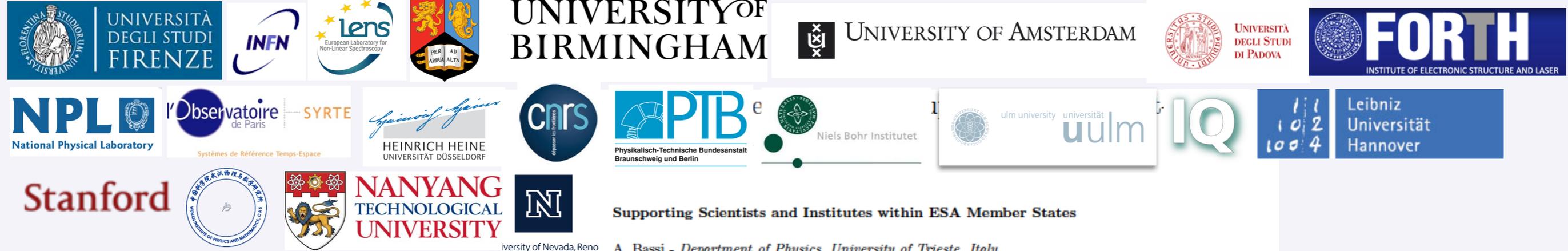
Interested parties planning to submit a proposal are required, as indicated below, to send a mandatory Letter of Intent by 9 May and will be invited to attend a briefing meeting on 8 June (date TBC).

The present Call is open to science ideas in all areas of Space Science. No limitations to the science goals addressed are imposed on the proposals.

This Call is not intended at replacing future Calls for Medium (M) or Large (L) missions, but aims at stimulating the emergence of new and innovative science ideas based on technologies not yet sufficiently mature, possibly to become potential candidates for future M or L mission Calls in the ESA Science Programme.

Documentation

- Letter of invitation from the Director of Science (pdf)
- Announcement - New Science Ideas (pdf)



Supporting Scientists and Institutes within ESA Member States

- A. Bassi - *Department of Physics, University of Trieste, Italy*
- G. Bianco - *Space Geodesy Centre, ASI, Matera, Italy*
- K. Bongs - *School of Physics and Astronomy, University of Birmingham, UK*
- P. Bouyer - *Laboratoire Photonique, Numérique et Nanosciences, Bordeaux, France*
- S. Capozziello - *Dipartimento di Fisica, INFN, Università di Napoli "Federico II", Italy*
- M. L. Chiofalo - *Dipartimento di Fisica, INFN, Università di Pisa, Italy*
- W. Ertmer - *Institute for Quantum Optics, Leibniz Universität Hannover, Germany*
- N. Gaaloul - *Institute for Quantum Optics, Leibniz Universität Hannover, Germany*
- P. Gill - *National Physical Laboratory, Teddington, Middlesex, UK*
- L. Iess - *Dipartimento di Ingegneria Meccanica e Aerospaziale, Università di Roma, Italy*
- C. Klempt - *Institute for Quantum Optics, Leibniz Universität Hannover, Germany*
- A. Peters - *Humboldt-Universität zu Berlin, Germany*
- N. Poli - *Dipartimento di Fisica e Astronomia, LENS, Università di Firenze, INFN, Italy*
- E. Rasel - *Institute for Quantum Optics, Leibniz Universität Hannover, Germany*
- G. Rosi - *Dipartimento di Fisica e Astronomia, LENS, Università di Firenze, INFN, Italy*
- A. Roura - *Institut für Quantenphysik, Universität Ulm, Germany*
- C. Salomon - *Laboratoire Kastler Brossel, Ecole Normale Supérieure, Paris, France*
- S. Schiller - *Institut für Experimentalphysik, Universität Düsseldorf, Germany*
- W. Schleich - *Institut für Quantenphysik, Universität Ulm, Germany*
- D. Schlippert - *Institute for Quantum Optics, Leibniz Universität Hannover, Germany*
- F. Schreck - *Van der Waals-Zeeman Institute, University of Amsterdam, The Netherlands*
- C. Schubert - *Institute for Quantum Optics, Leibniz Universität Hannover, Germany*
- F. Sorrentino - *Istituto Nazionale di Fisica Nucleare, Sezione di Genova, Italy*
- U. Sterr - *Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany*
- J. W. Thomsen - *Niels Bohr Institute, Copenhagen, Denmark*
- G. M. Tino - *Università di Firenze, LENS, INFN, Firenze, Italy*
- G. Vallone - *Department of Information Engineering, University of Padova, Italy*
- F. Vetrano - *University of Urbino, Italy*
- P. Villoresi - *Department of Information Engineering, University of Padova, Italy*
- W. von Klitzing - *IESL-FORTH, Crete, Greece*
- P. Wolf - *LNE-SYRTE, CNRS, Observatoire de Paris, France*

Supporting Scientists and Institutes outside ESA Member States

- X. Chen - *Peking University, Beijing, China*
- A. Derevianko - *Physics Department, University of Nevada, Reno, USA*
- P. Graham - *Stanford University, Stanford, CA, USA*
- J. Hogan - *Stanford University, Stanford, CA, USA*
- M. A. Kasevich - *Stanford University, Stanford, CA, USA*
- H. Katori - *University of Tokyo, RIKEN, Tokyo, Japan*
- X. Lu - *Zhejiang University, Hangzhou, China*
- L.-S. Ma - *East China Normal University, Shanghai, China*
- H. Müller - *University of California, Berkeley, CA, USA*
- N. R. Newbury - *NIST, Boulder, Colorado, USA*
- C. Oates - *NIST, Boulder, Colorado, USA*
- D. Wilkowski - *Nanyang Technological University, Singapore*
- J. Ye - *JILA, NIST, Boulder, Colorado, USA*
- N. Yu - *NASA JPL, California Institute of Technology, Pasadena, CA, USA*
- M. S. Zhan - *Wuhan Institute of Physics and Mathematics, CAS, Wuhan, China*



Proposal title



SPACE ATOMIC GRAVITY EXPLORER

Acronym

SAGE

Lead Proposer

Prof. Guglielmo M. Tino

- PRIMARY GOAL:**
- Observe Gravitational Waves in new frequency ranges with atomic sensors.
- SECONDARY GOALS:**
- Search for Dark-Matter
 - Measure the Gravitational Red Shift
 - Test the Equivalence Principle of General Relativity and search for spin-gravity coupling
 - Define an ultraprecise frame of reference for Earth and Space and compare terrestrial clocks
 - Investigate quantum correlations and test Bell inequalities for different gravitational potentials and velocities
 - Use clocks and links between satellites for optical VLBI in Space

September 13, 2016

The ESA–L3 Gravitational Wave Mission

Gravitational Observatory Advisory Team

Final Report

GOAT
ESA Gravitational Observatory Advisory Team
Final report to the SPC
<https://www.cosmos.esa.int/web/goat>

Committee members:

Pierre Binétruy	AstroParticule et Cosmologie (APC), Paris (F)
Philippe Bouyer	Laboratoire Photonique, Numérique et Nanosciences (LP2N), Bordeaux (F)
Mike Cruise	University of Birmingham, Emeritus (UK)
Reinhard Genzel	Max-Planck-Institut für extraterrestrische Physik (MPE), Munich (D)
Mark Kasevich	Stanford University (USA)
Bill Klipstein	JPL, Pasadena (USA)
Guido Müller	University of Florida, Gainesville (USA)
Michael Perryman	University College Dublin (IRL, adjunct), Chair
Bernard Schutz	Albert Einstein Institute, Golm (D) and University of Cardiff (UK)
Stefano Vitale	Università degli Studi di Trento (I)

Observers:

Masaki Ando (The University of Tokyo/JAXA)
Robin Stebbins (NASA)

ESA support:

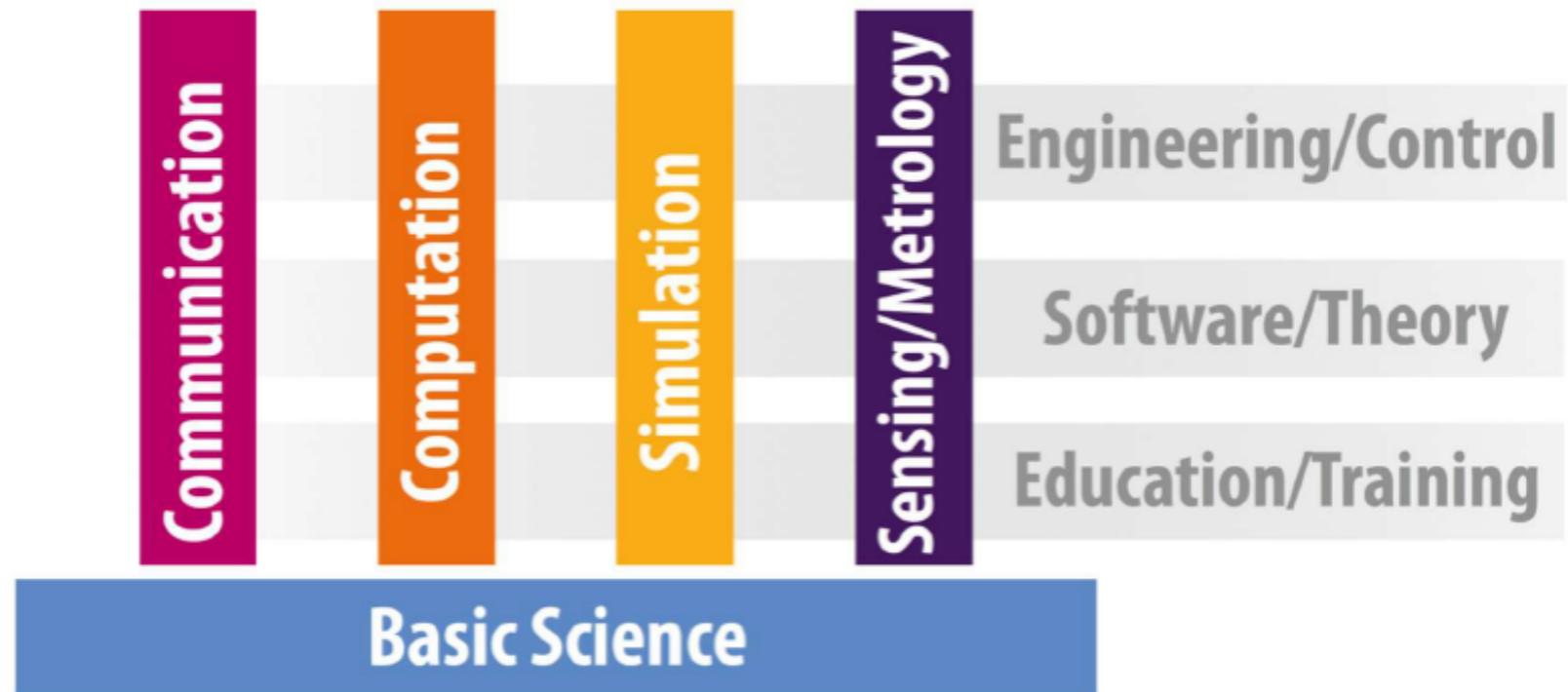
Luigi Cacciapuoti
Fabio Favata
Martin Gehler
Oliver Jennrich
Frédéric Safa

3.3.2 ESA Announcement of Opportunity for new science ideas

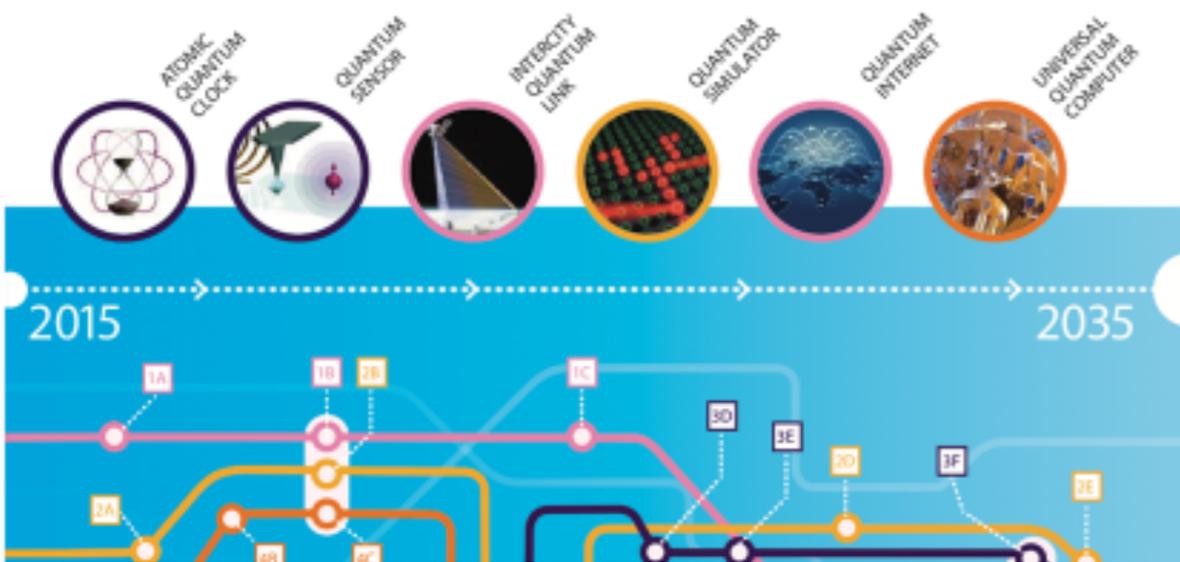
On 2016 February 9, the Director of Science issued an Announcement of Opportunity, soliciting from the broad scientific community proposals for the competitive selection of new ‘Science Ideas’, to be investigated in terms of feasibility and needed technology developments (www.cosmos.esa.int/web/new-scientific-ideas). The call aims at stimulating the emergence of new and innovative science ideas based on technologies not yet sufficiently mature, possibly to become potential candidates for future M or L missions in the ESA Science Programme.

The Committee considers that this call is well timed for nurturing the prospective Atom Interferometry concept. Thorough evaluation will allow this option to be assessed in parallel with the early phase of the L3 development cycle. The schedule announced calls for a Letter of Intent to be submitted by 2016 May 9, a briefing meeting at ESTEC on or around 2016 June 8, a proposal submission deadline of 2016 September 14, and a selection of proposals for study at the end of 2016.

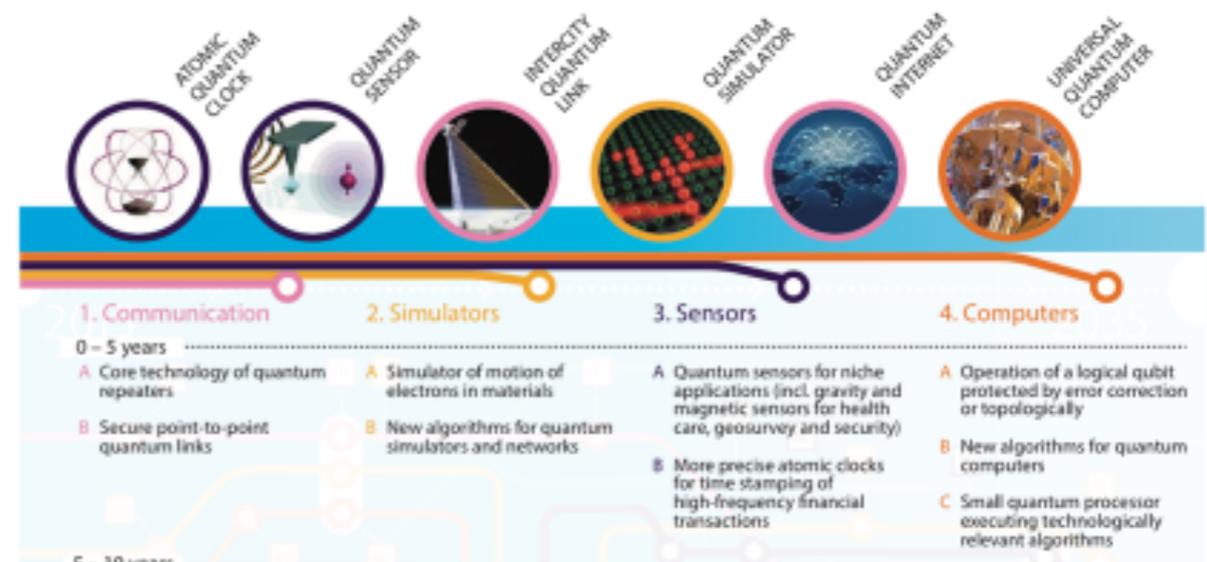
EUROPEAN QUANTUM FLAGSHIP PROGRAM



Quantum Manifesto



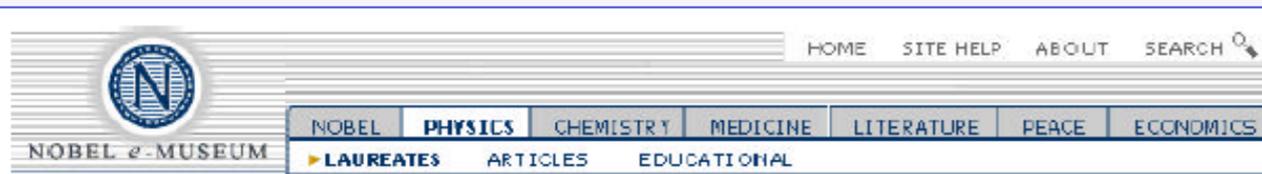
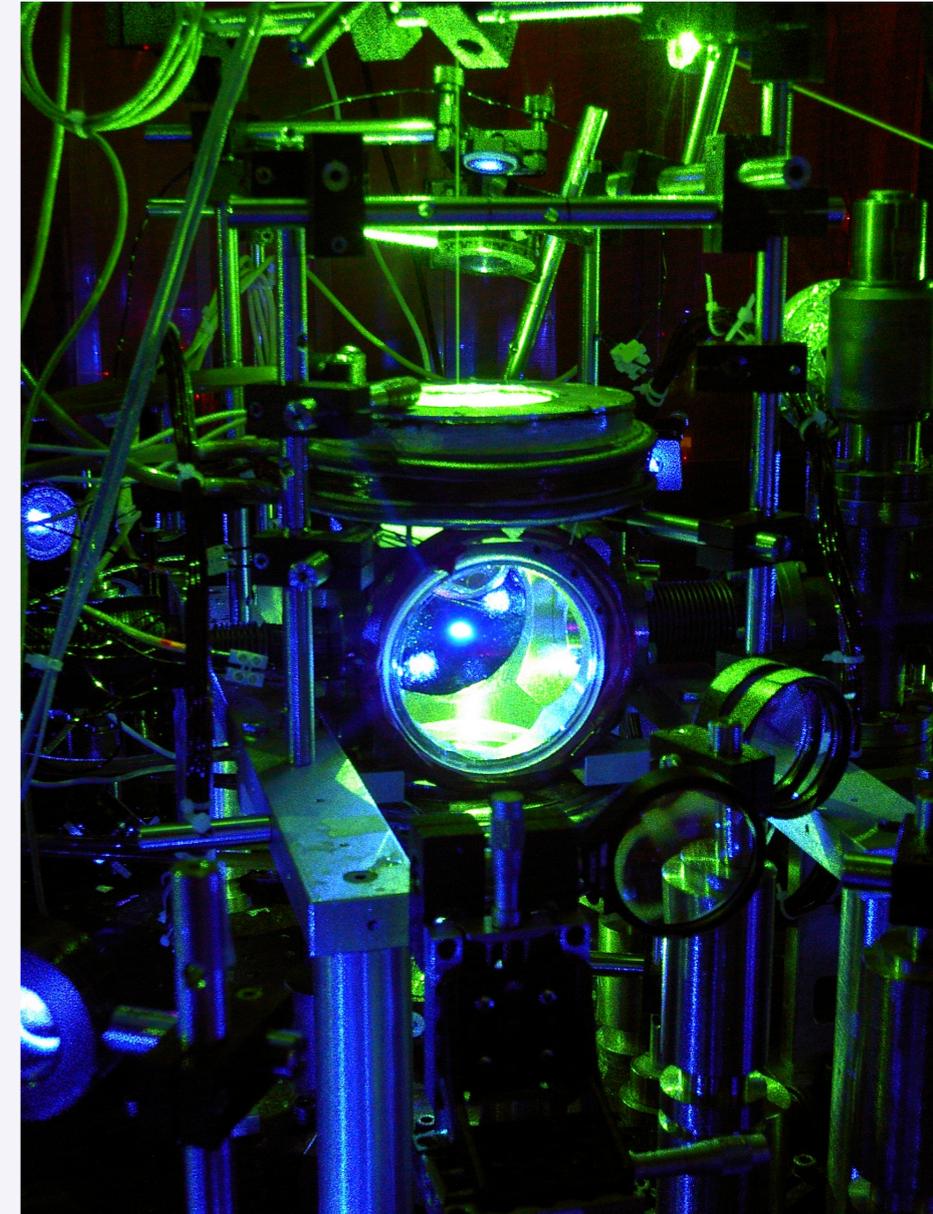
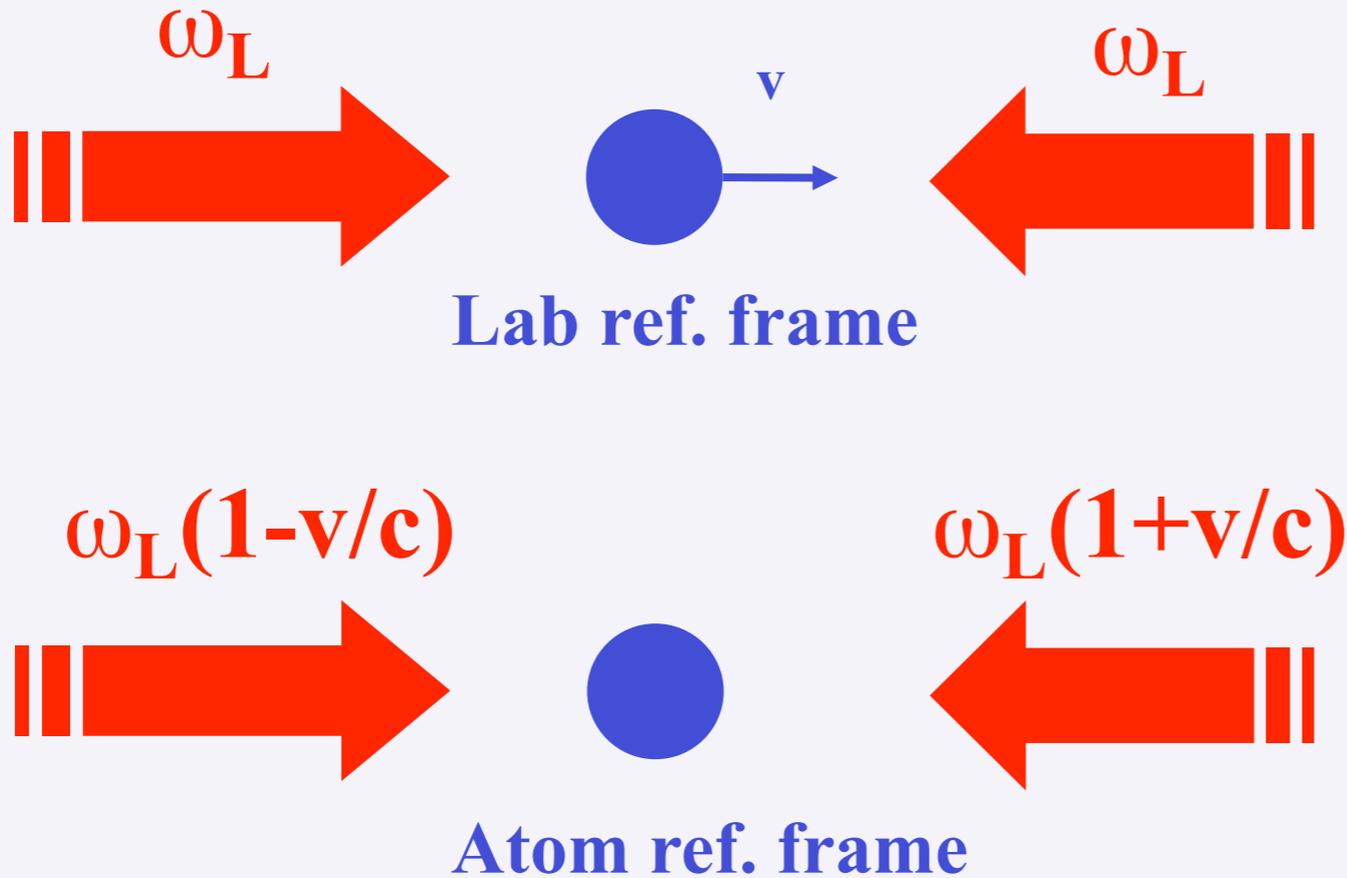
m Manifesto



Quantum Technology - Implementations for Space
9 November 2016

European Space Agency

Laser Cooled Sr Atoms



Web-Adapted Version of the Nobel Poster from the Royal Swedish Academy of Sciences

BACK

The Nobel Prize in Physics 1997



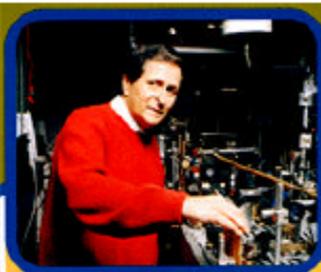
The Royal Swedish Academy of Sciences has awarded the 1997 Nobel Prize in Physics jointly to

Steven Chu, Claude Cohen-Tannoudji and William D. Phillips

for their developments of methods to cool and trap atoms with laser light.



Steven Chu
Stanford University, Stanford,
California, USA

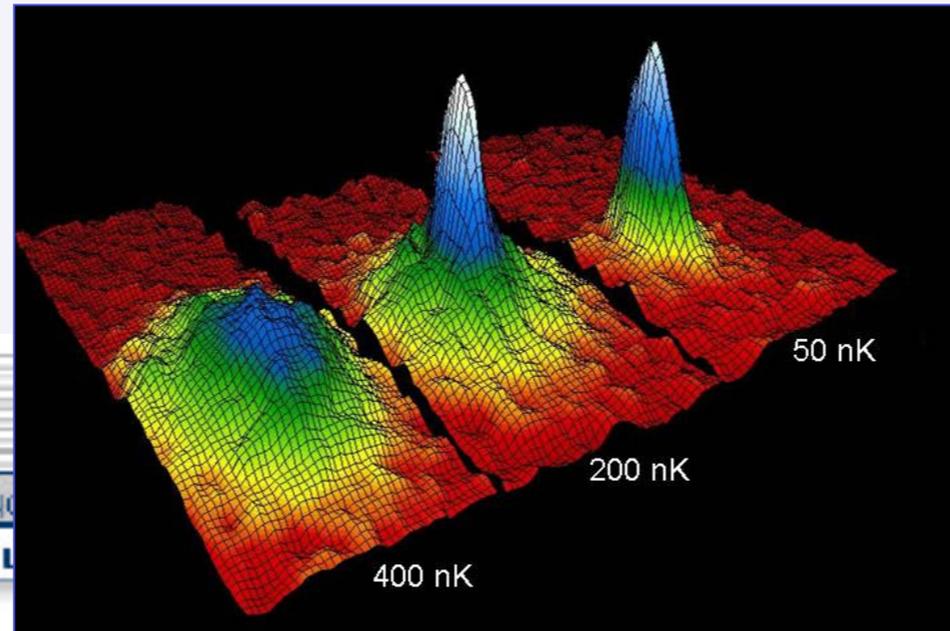


Claude Cohen-Tannoudji
Collège de France and École Normale
Supérieure, Paris, France



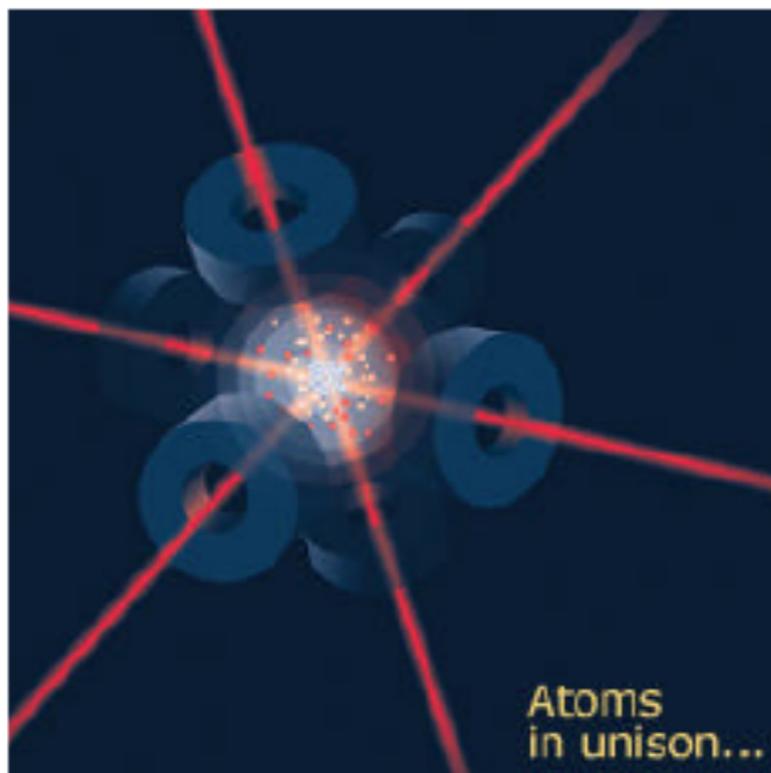
William D. Phillips
National Institute of Standards and
Technology, Gaithersburg, Maryland, USA

Bose-Einstein condensation in dilute gases of atoms



The Nobel Prize in Physics 2001

The Royal Swedish Academy of Sciences has awarded the Nobel Prize in Physics for 2001 jointly to Eric A. Cornell, Wolfgang Ketterle and Carl E. Wieman "for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates".



Eric A. Cornell
JILA and National Institute of Standards and Technology (NIST), Boulder, Colorado, USA.

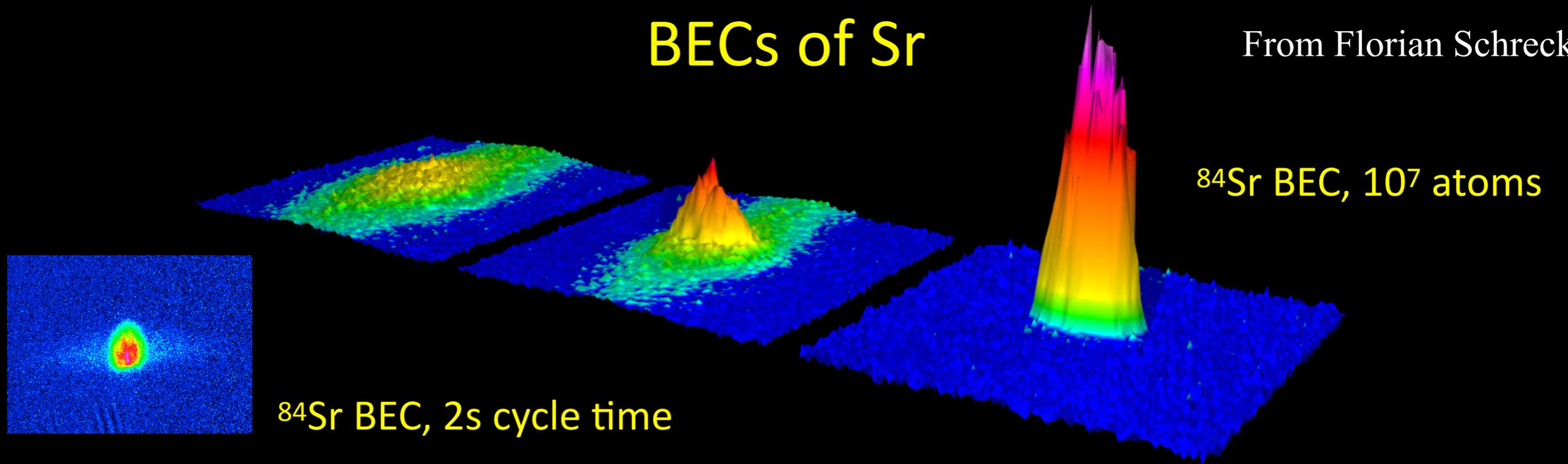
Carl E. Wieman
JILA and University of Colorado, Boulder, Colorado, USA.

Wolfgang Ketterle
Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts, USA.

Contents:

BECs of Sr

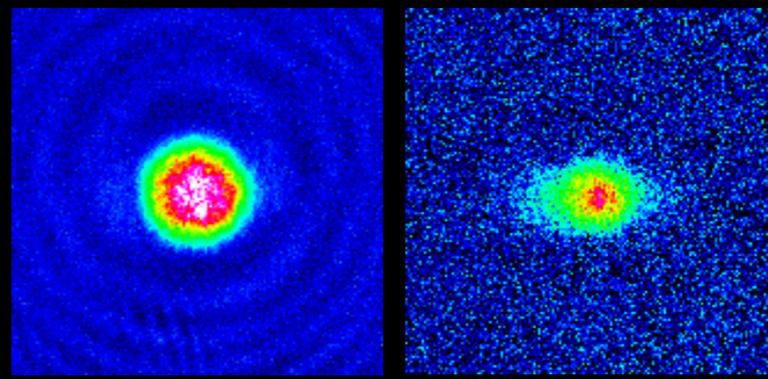
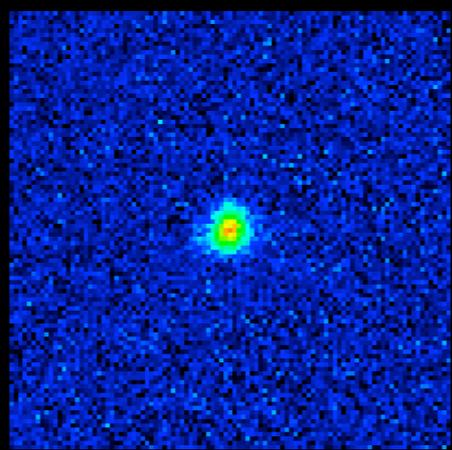
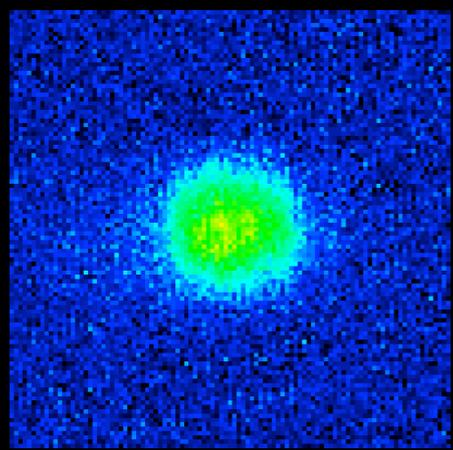
From Florian Schreck



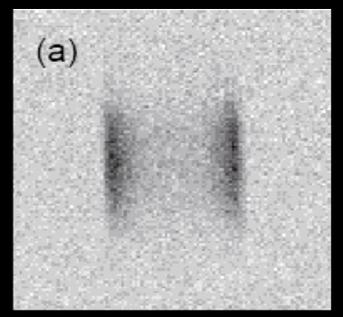
⁸⁶Sr BEC

⁸⁸Sr BEC

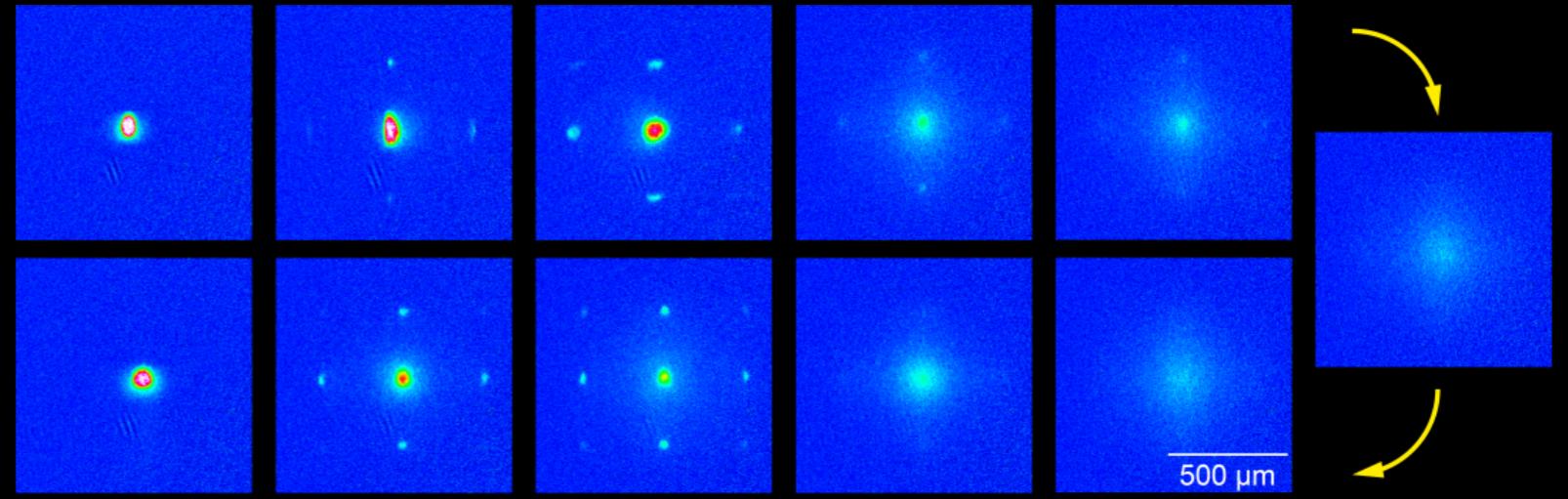
⁸⁴Sr + ⁸⁶Sr BEC



⁸⁴Sr₂ molecules



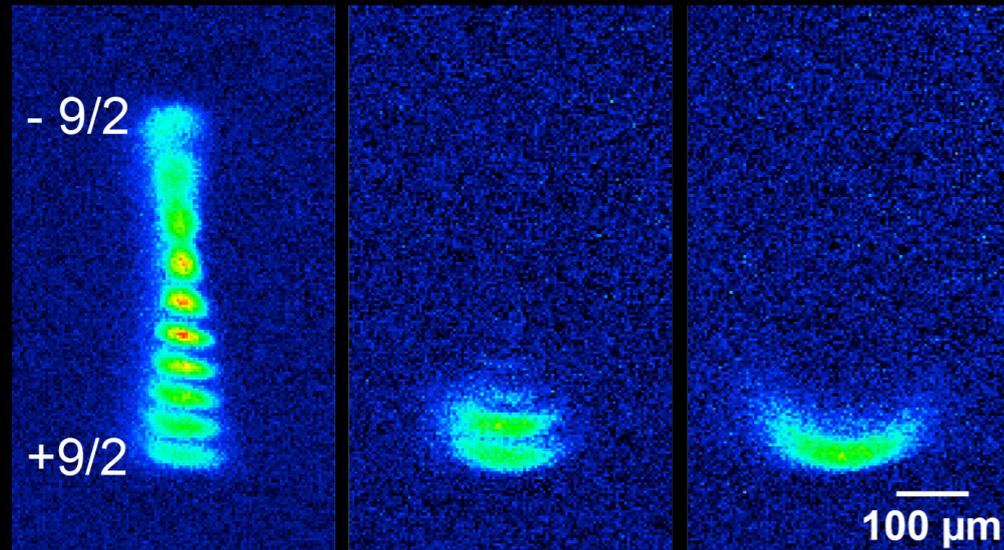
SF to MI transition with ⁸⁴Sr



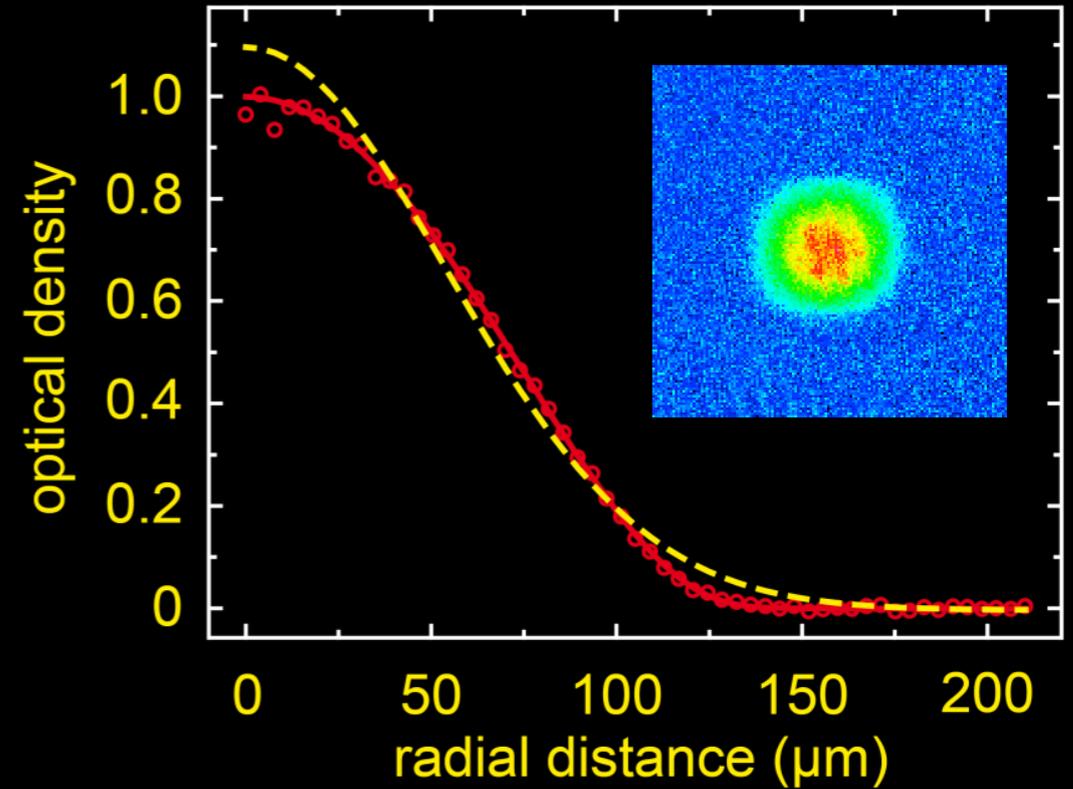
S. Stellmer, F. Schreck, T. Killian,
<http://arxiv.org/abs/1307.0601>

Degenerate Fermi gases of Sr

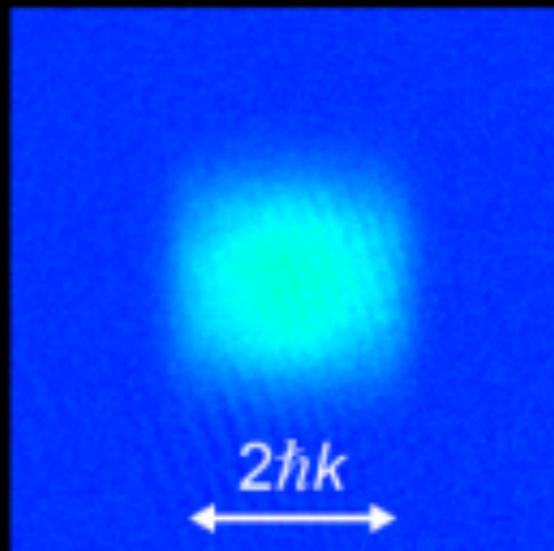
control of spin states in ^{87}Sr



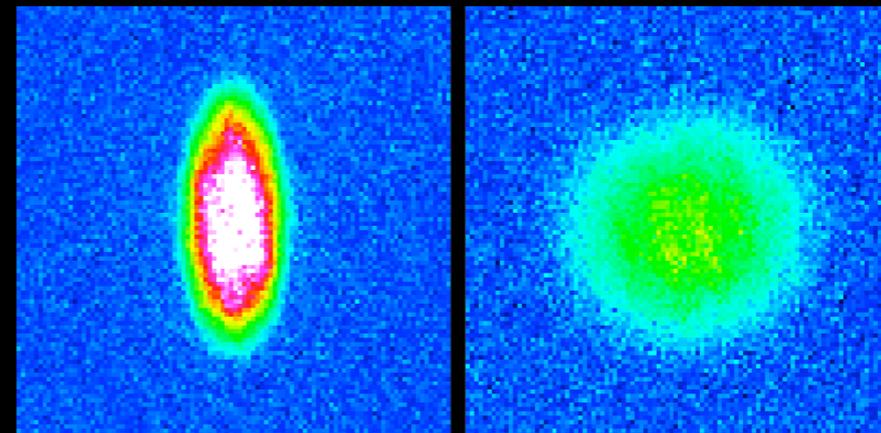
^{87}Sr Fermi gas, $T/T_F = 0.08$



^{87}Sr on a lattice



^{84}Sr BEC + ^{87}Sr Fermi gas



Optical clocks: Towards 10^{-18}

- **Narrow optical transitions**

$\delta\nu_0 \sim 1\text{-}100\text{ Hz}$, $\nu_0 \sim 10^{14}\text{-}10^{15}\text{ Hz}$

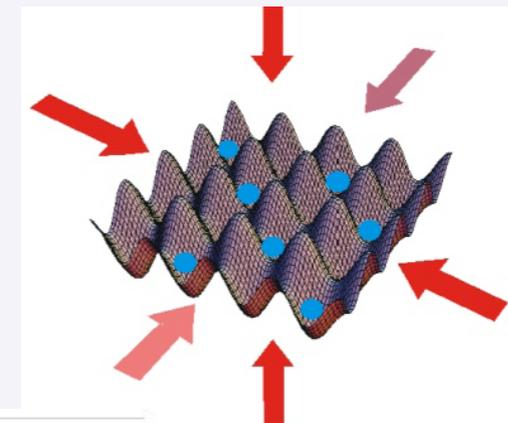
$$\sigma_y \approx \frac{\text{Noise}}{\pi Q \cdot \text{Signal}} \approx \frac{\Delta\nu}{\nu_0} \frac{1}{\sqrt{N_{\text{atom}}}} \sqrt{\frac{T_{\text{cycle}}}{2\tau_{\text{average}}}} \frac{1}{C_{\text{fringe}}}$$

- **Candidate atoms**

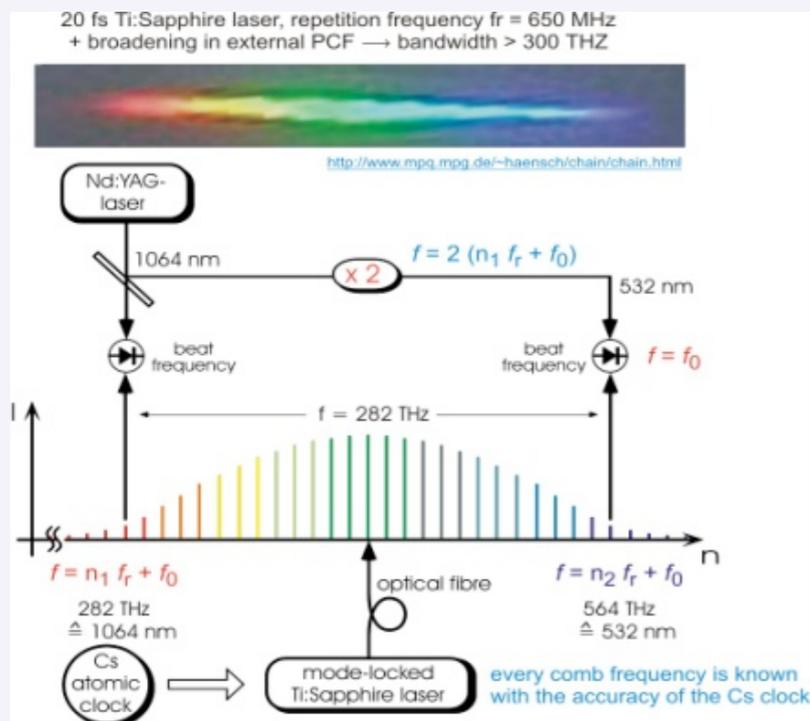
Trapped ions: Hg^+ , In^+ , Sr^+ , Yb^+ ,...



Cold neutral atoms: H, Ca, **Sr**, Yb,...



- **Direct optical- μ wave connection by optical frequency comb**



The Nobel Prize in Physics 2005

Roy J. Glauber, John L. Hall, Theodor W. Hänsch

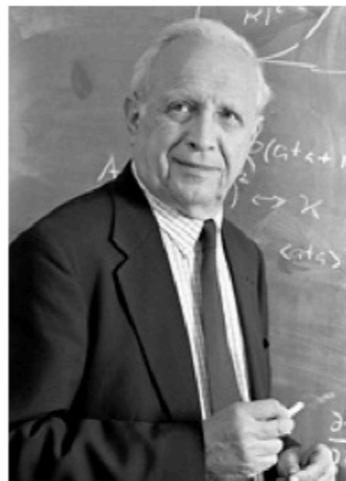
The Nobel Prize in Physics 2005

Nobel Prize Award Ceremony

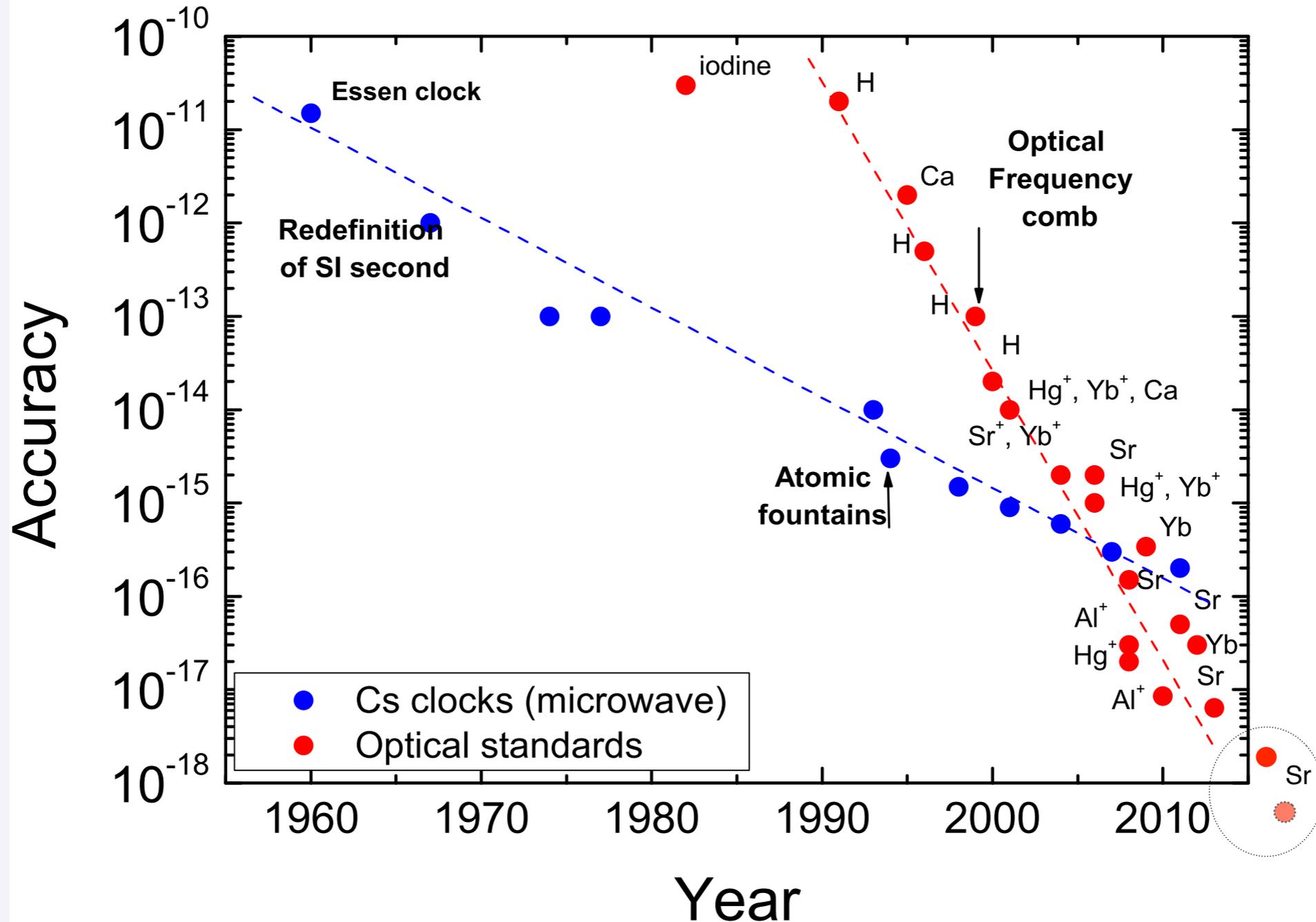
Roy J. Glauber

John L. Hall

Theodor W. Hänsch

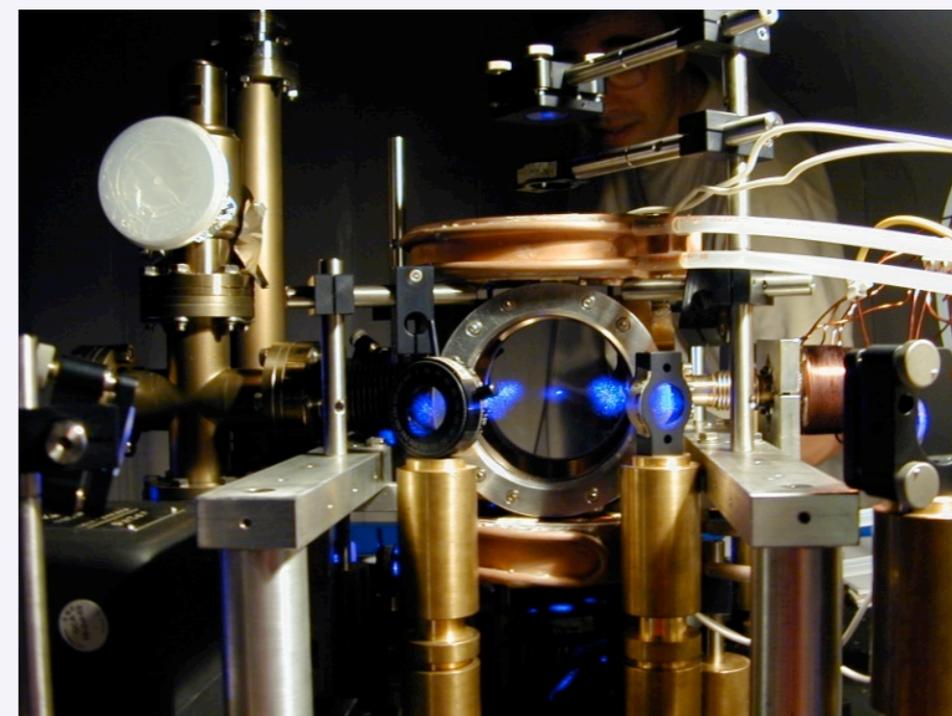
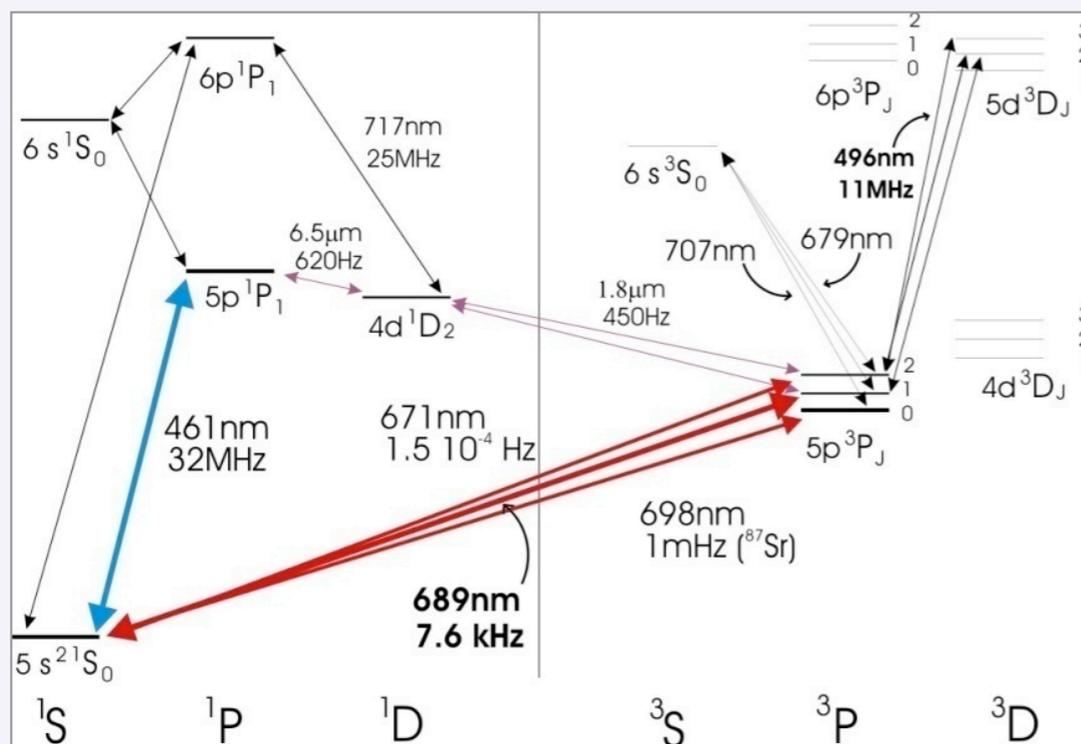


Microwave vs. optical clocks



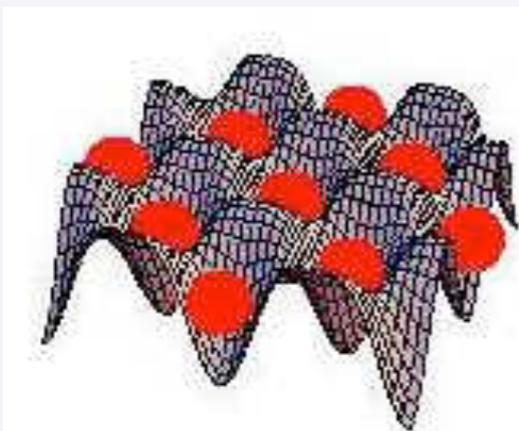
N. Poli, C. W. Oates, P. Gill and G. M. Tino, *Optical atomic clocks*,
Rivista del Nuovo Cimento Vol. 36, N. 12 (2013) - arXiv:1401.2378

Ultracold Sr for new atomic clocks and interferometers



- Optical clocks using visible intercombination lines

- New atomic sensors for fundamental physics tests



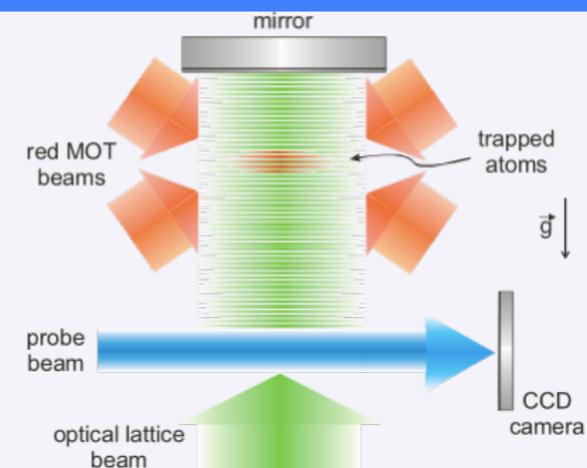
- A cold atom Cesium clock in space
- Fundamental physics tests
- Worldwide access

G. Ferrari, P. Cancio, R. Drullinger, G. Giusfredi, N. Poli, M. Prevedelli, C. Toninelli, G.M. Tino, *Precision Frequency Measurement of Visible Intercombination Lines of Strontium*, Phys. Rev. Lett. 91, 243002 (2003)

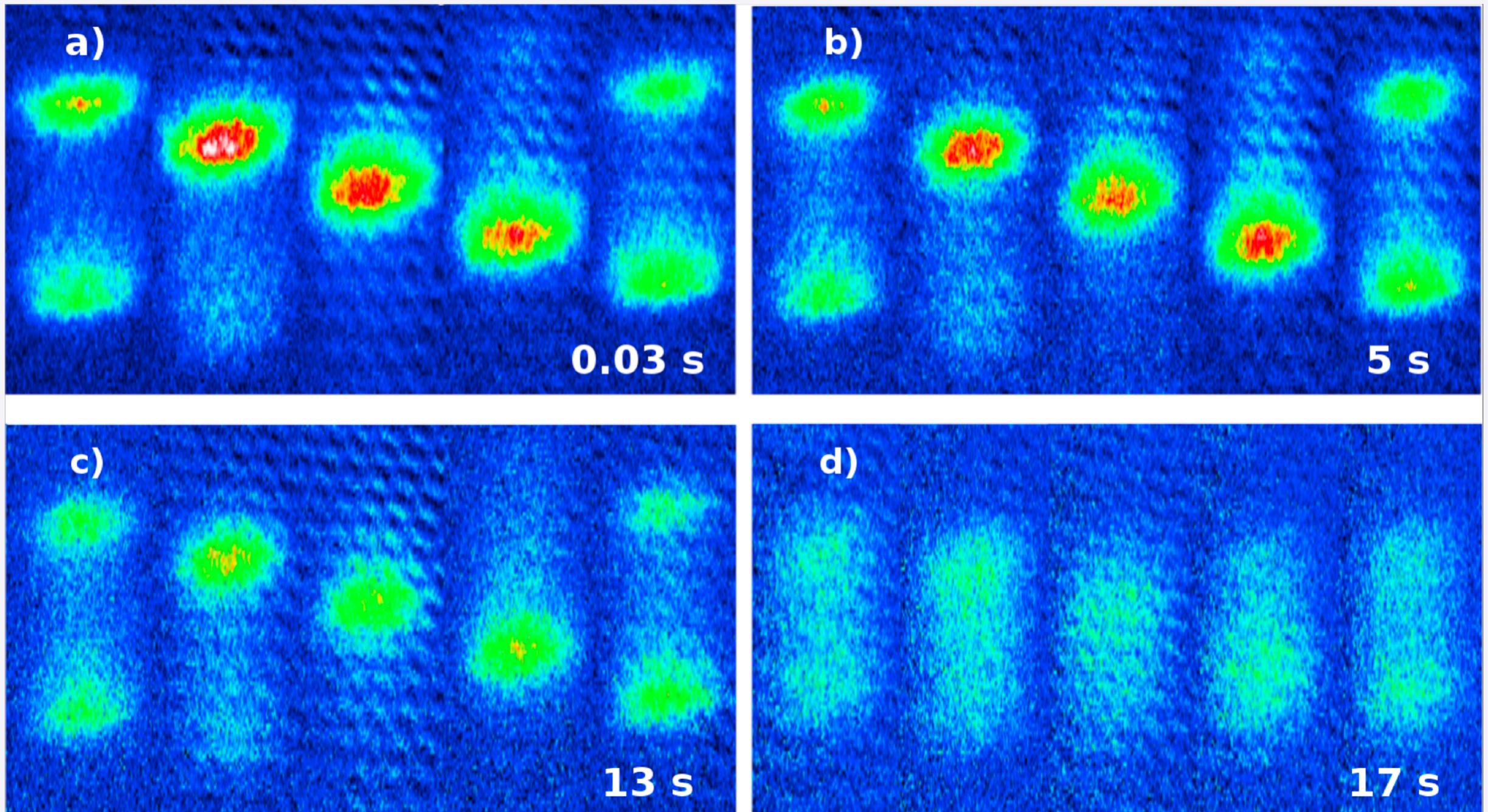
G. Ferrari, N. Poli, F. Sorrentino, and G. M. Tino, *Long-lived Bloch oscillations with bosonic Sr atoms and application to gravity measurement at micrometer scale*, Phys. Rev. Lett. 97, 060402 (2006)

N. Poli, M. Schioppo, S. Vogt, St. Falke, U. Sterr, Ch. Lisdat, G. M. Tino, *A transportable strontium optical lattice clock*, Appl. Phys. B 117, 1107 (2014)

V. Ivanov, A. Alberti, M. Schioppo, G. Ferrari, M. Artoni, M. L. Chiofalo, G. M. Tino, *Coherent Delocalization of Atomic Wave Packets in Driven Lattice Potentials*, Phys. Rev. Lett. 100, 043602 (2008)



Bloch oscillations of ^{88}Sr atoms



N. Poli, F.Y. Wang, M.G. Tarallo, A. Alberti, M. Prevedelli, G.M. Tino,
*Precision Measurement of Gravity with Cold Atoms in an Optical Lattice
and Comparison with a Classical Gravimeter,*
Phys. Rev. Lett. **106**, 038501 (2011)

Executive summary

The SAGE proposal is in the field of Fundamental Physics. The scientific objective is to investigate Gravitational Waves and other fundamental aspects of gravity as well as the connection between gravitational physics and quantum physics using new quantum sensors, namely, optical atomic clocks and atom interferometers based on ultracold Strontium atoms.

Combining quantum sensing and quantum communication, SAGE is based on recent impressive achievements in quantum technologies for optical clocks, atom interferometers, microwave and optical links. This call provides a unique opportunity to investigate in detail the fascinating idea of this ultimate multi-purpose gravity explorer based on all the most advanced achievements in the field.

We consider a multi-satellite configuration with payload/instruments including Strontium optical atomic clocks, Strontium atom interferometers and satellite-to-satellite/satellite-to-Earth laser links.

SAGE main scientific goals are:

PRIMARY GOAL:

- Observe Gravitational Waves in new frequency ranges with atomic sensors.

SECONDARY GOALS:

- Search for Dark-Matter
- Measure the Gravitational Red Shift
- Test the Equivalence Principle of General Relativity and search for spin-gravity coupling
- Define an ultraprecise frame of reference for Earth and Space and compare terrestrial clocks
- Investigate quantum correlations and test Bell inequalities for different gravitational potentials and relative velocities
- Use clocks and links between satellites for optical VLBI in Space

Although the technology for such a mission is not mature yet, it takes advantage of developments for the ACES (Atomic Clock Ensemble in Space) mission and the results of ESA studies for SOC (Space Optical Clock), SAI (Space Atom Interferometer), STE-QUEST, GOAT and ongoing national projects in this frame.

Supporting scientists and institutes from ESA member states as well as from USA, China, Japan, Singapore are listed in the final section of the proposal.

SAGE

Gravitational waves detection with atom interferometry

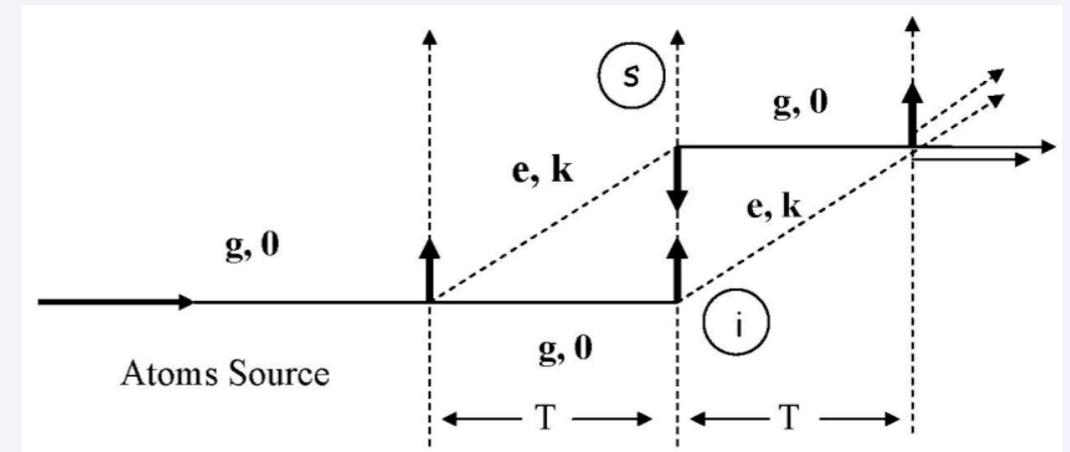
Main ideas

- Detection of GWs by matter waves
- Drastic reduction of critical noise sources
- Addressing new interesting frequency ranges

Gravitational waves detection with atom interferometry

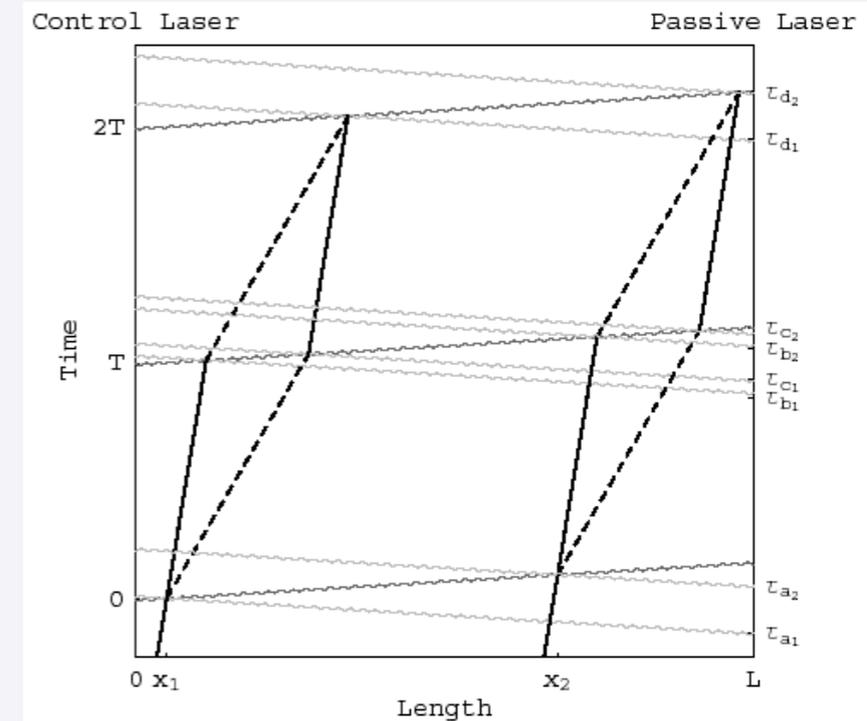
- *Single atom interferometer*

G.M. Tino and F. Vetrano, *Is it possible to detect gravitational waves with atom interferometers?* *Class. Quantum Grav.* 24, 2167 (2007)

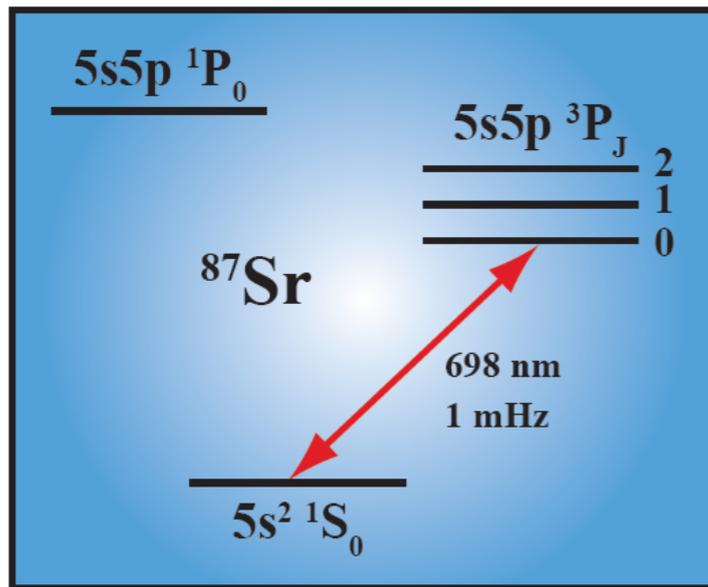


- *Differential scheme*

S. Dimopoulos, P. W. Graham, J. M. Hogan, M. A. Kasevich, S. Rajendran, *Atomic gravitational wave interferometric sensor*, *Phys. Rev. D* 78, 122002 (2008)



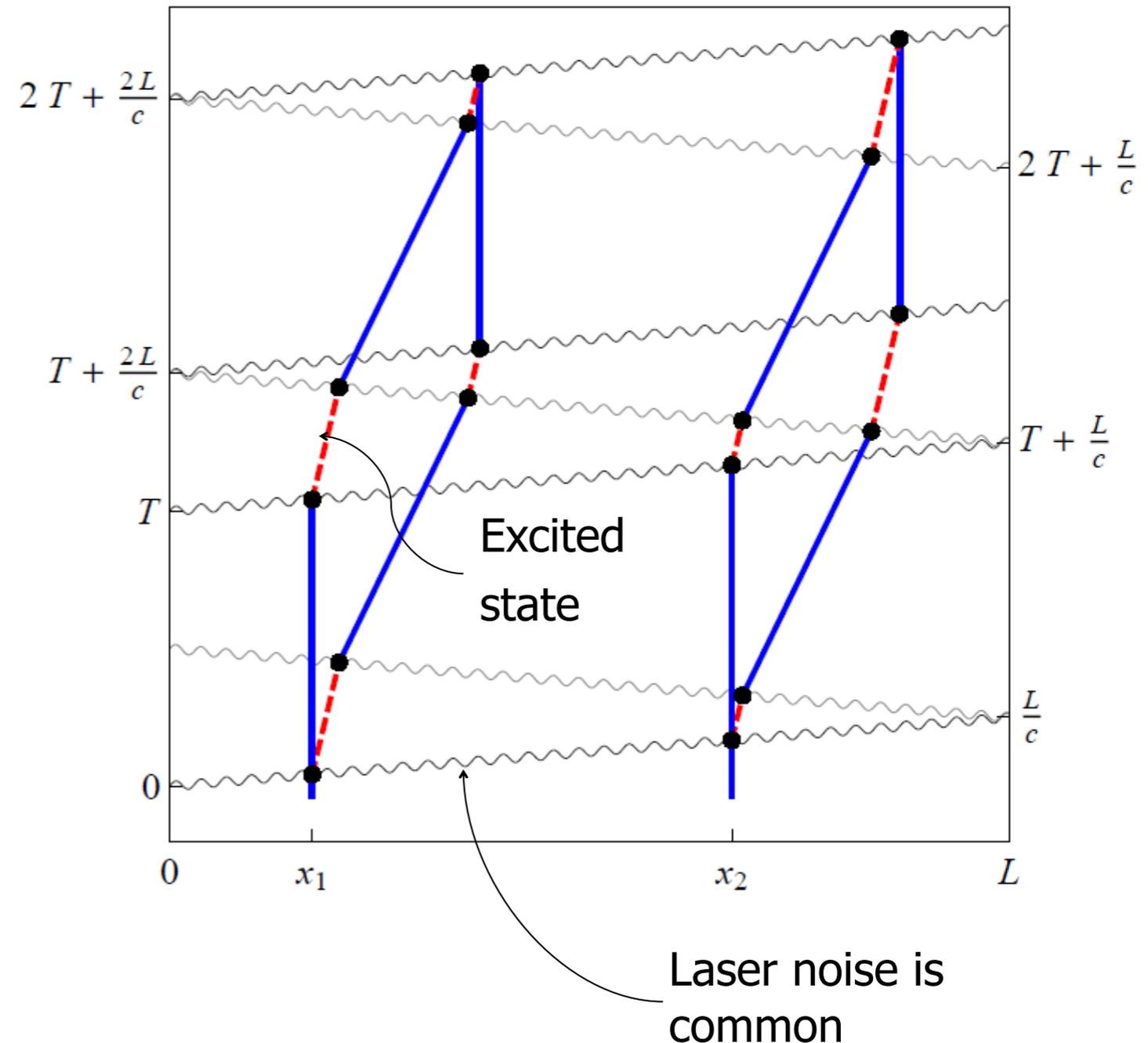
Laser frequency noise insensitive detector



Clock transition in candidate atom ^{87}Sr

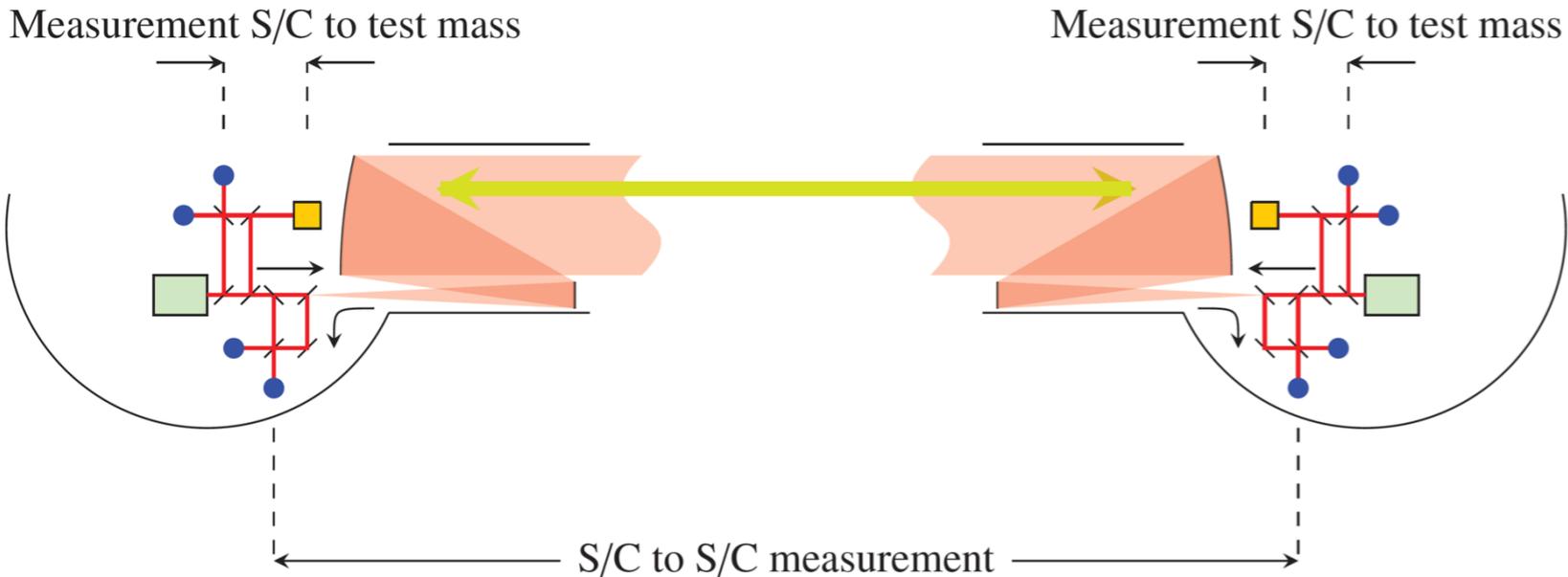
- Long-lived single photon transitions (e.g. clock transition in **Sr**, Ca, Yb, Hg, etc.).
- Atoms act as clocks, measuring the light travel time across the baseline.
- GWs modulate the laser ranging distance.

Enables 2 satellite configurations

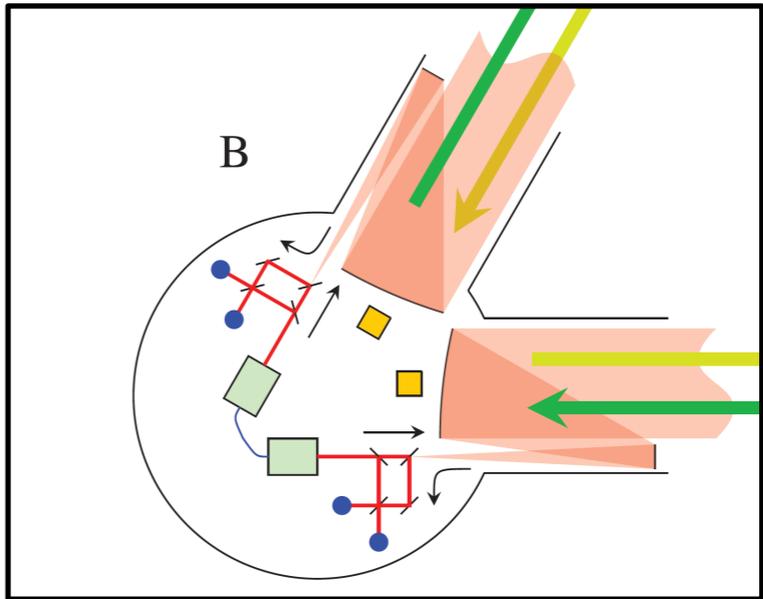


GW detector architecture

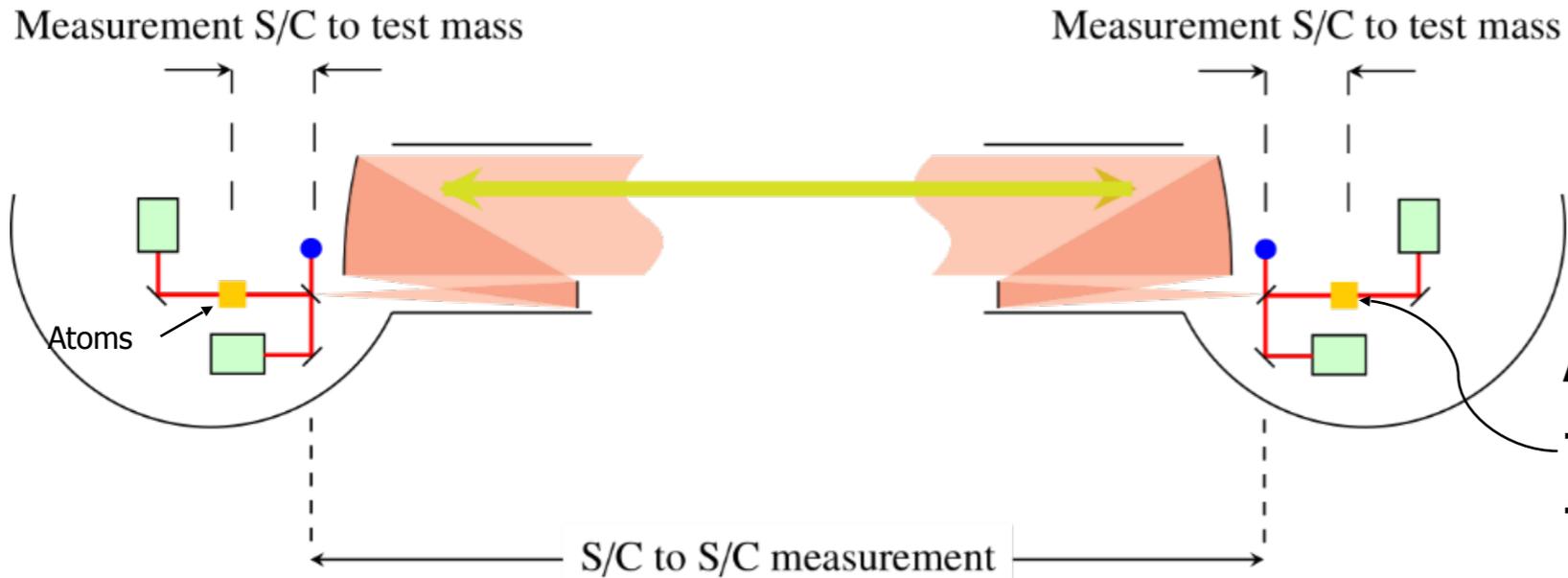
LISA:



Second baseline needed for phase reference:



Atom interferometer:

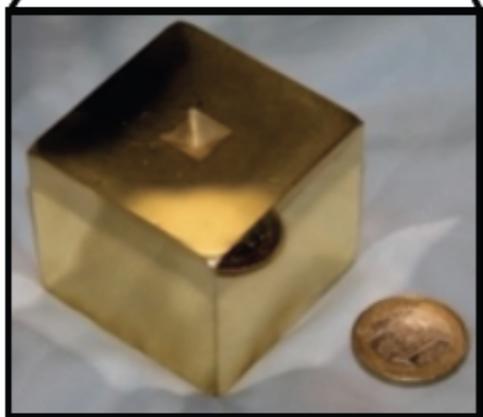
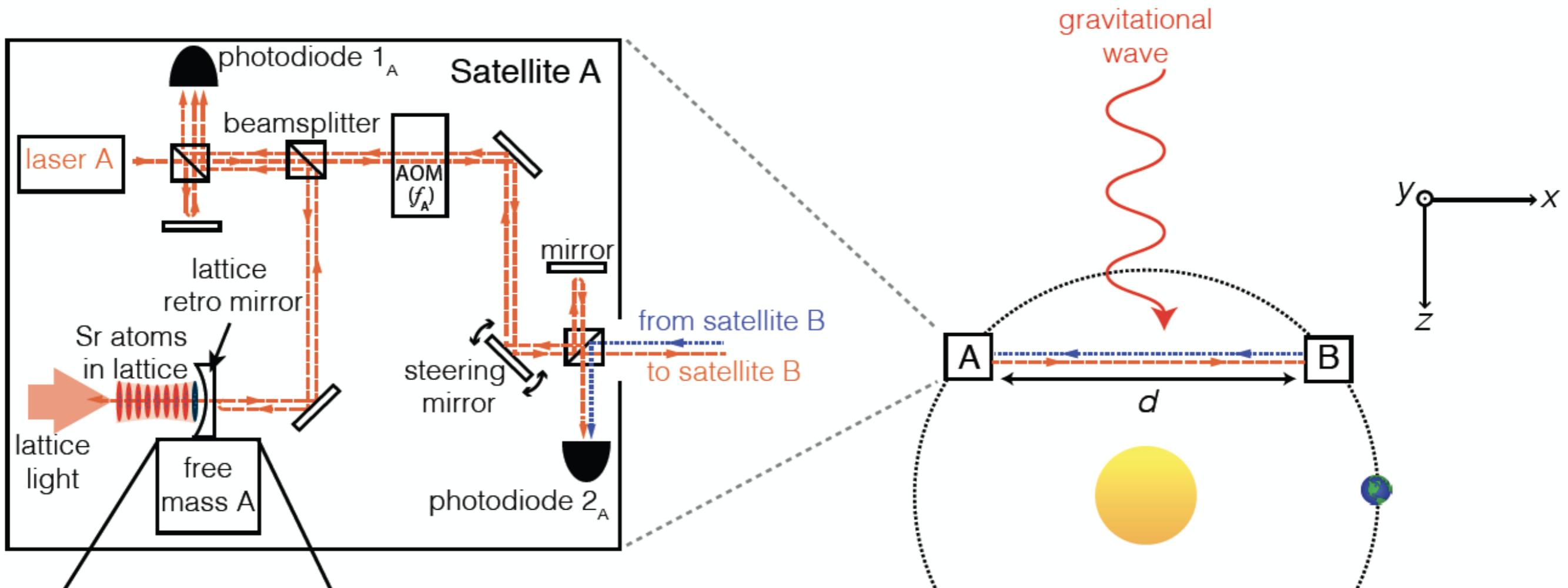


Atom test mass

- Provides laser phase reference
- Provides inertial reference



Gravitational wave detection with clocks



$$\sigma(\tau) = \frac{\delta\nu}{\nu_o} \Big|_{\tau} = \frac{\sqrt{\Delta_A}}{\nu_o \sqrt{2\pi\tau N}}$$

from J. Ye

Gravitational wave detection

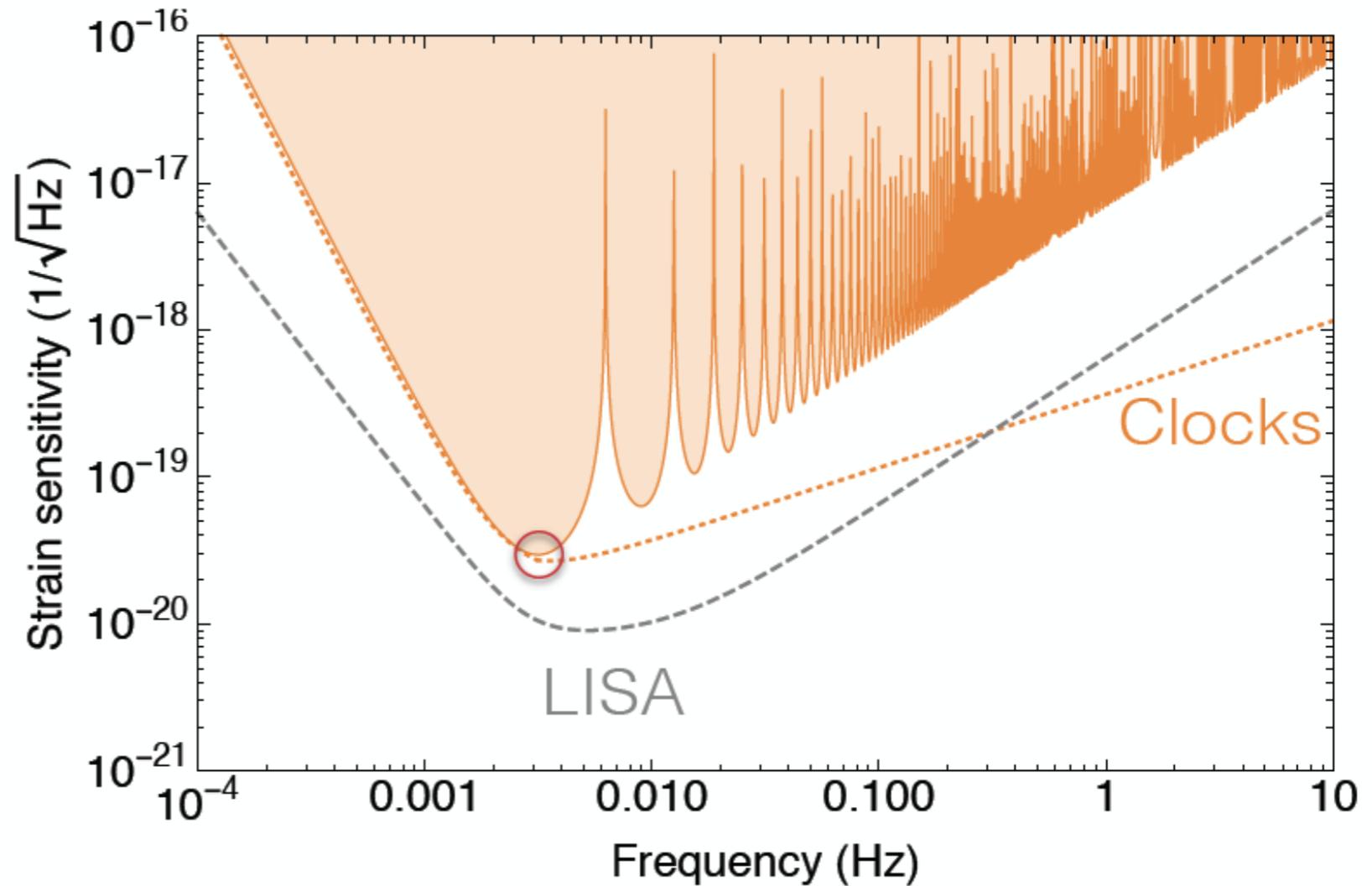
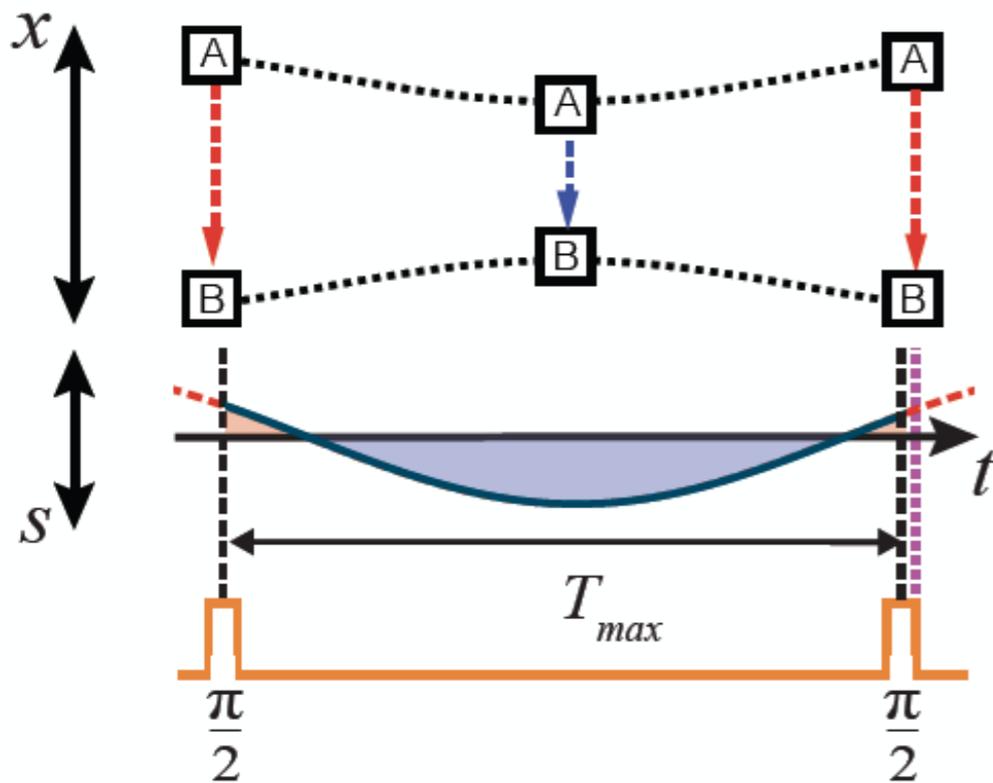
Clock based detector

$d = 5 \times 10^{10}$ m arm length

$N = 7 \times 10^6$ Sr atoms per clock

160 s coherence time

Long Ramsey sequence:



from J. Ye

Gravitational wave detection

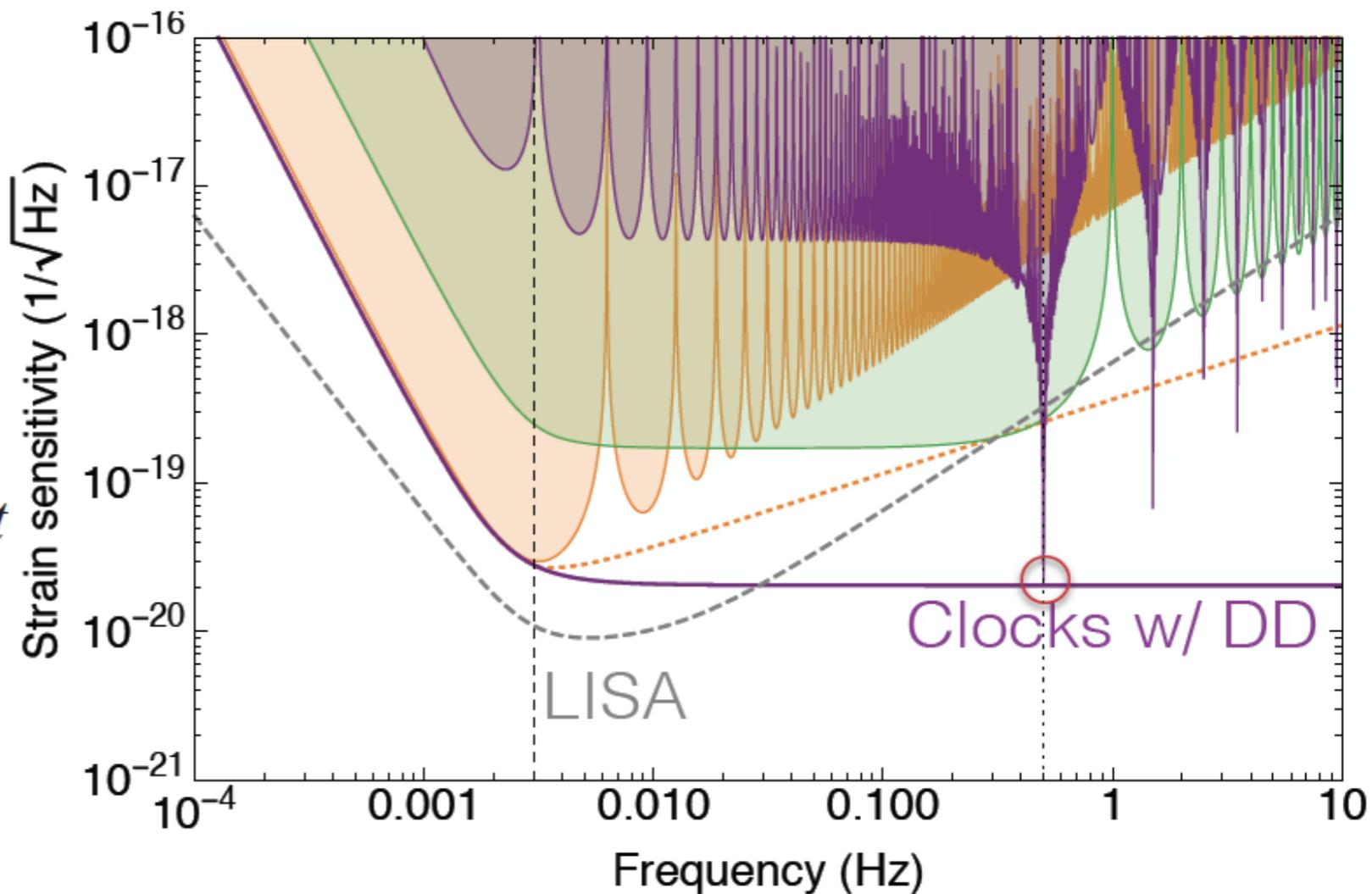
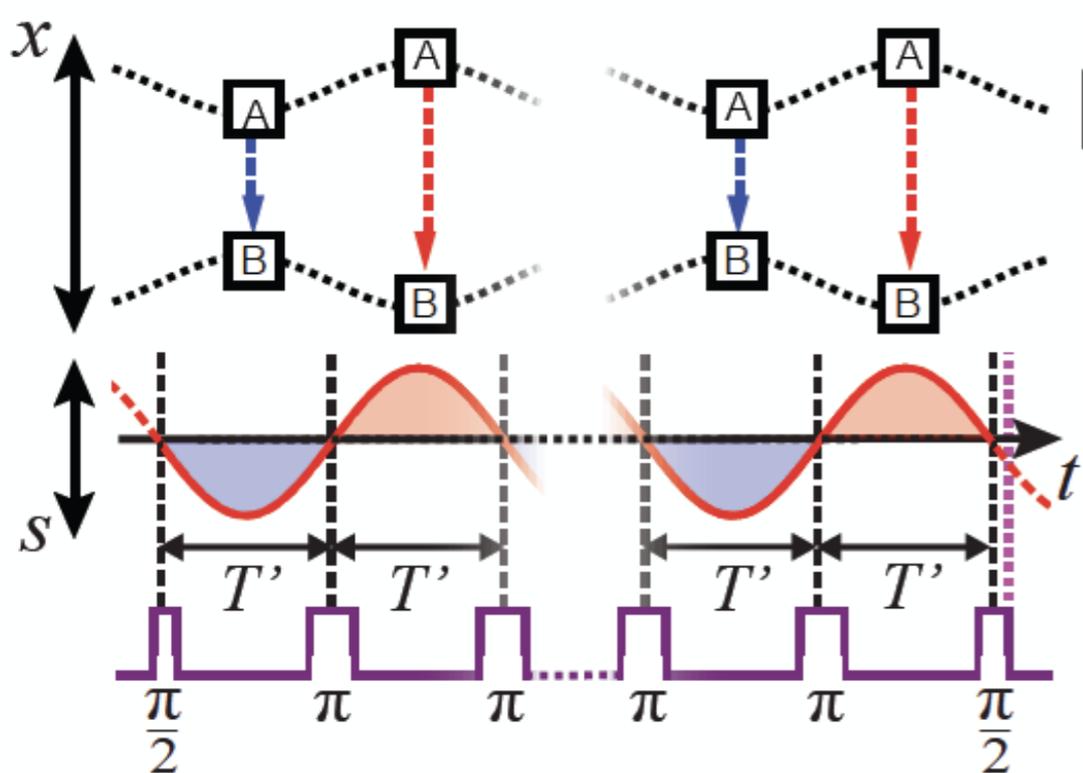
Clock based detector

$d = 5 \times 10^{10}$ m arm length

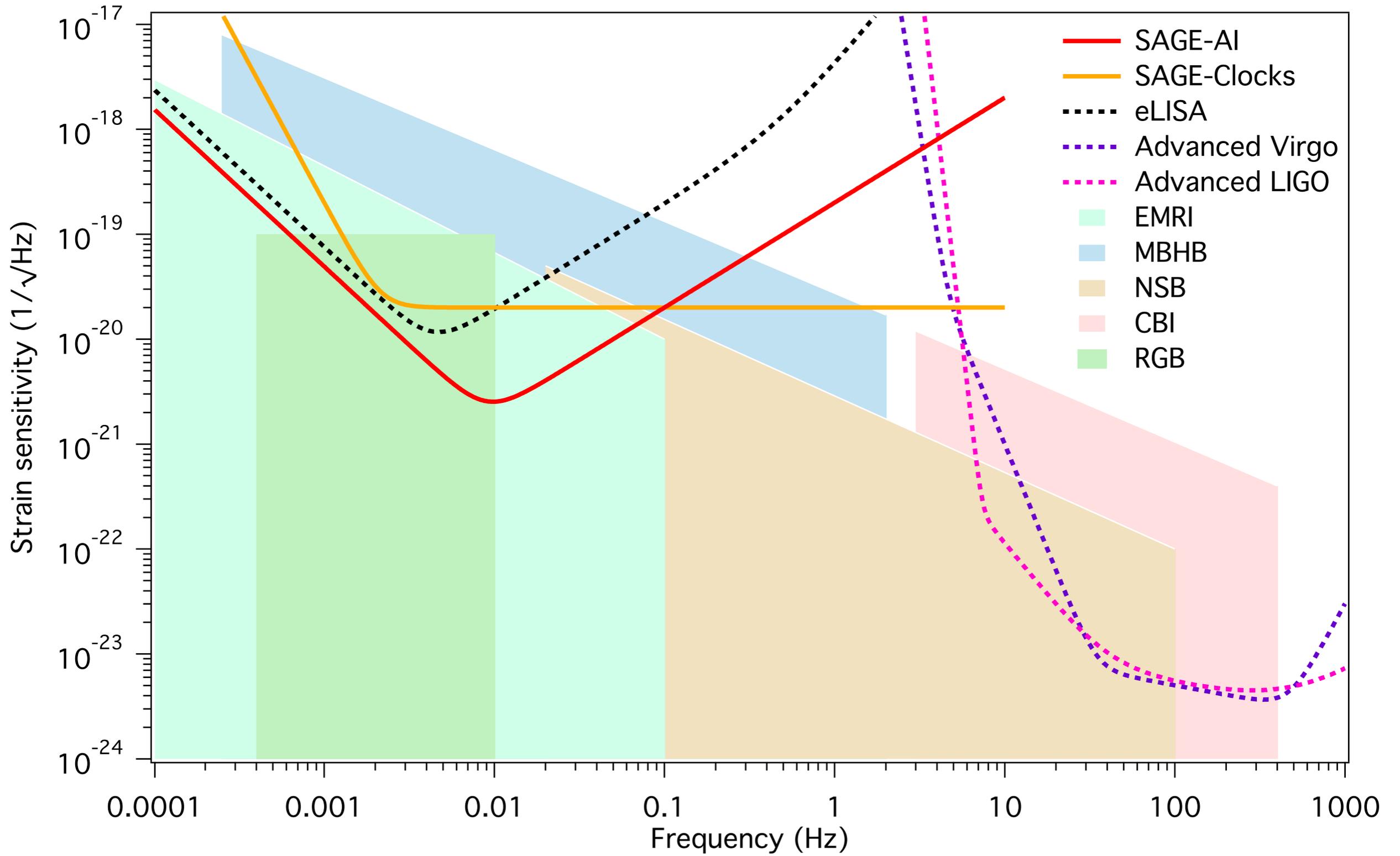
$N = 7 \times 10^6$ Sr atoms per clock

160 s coherence time

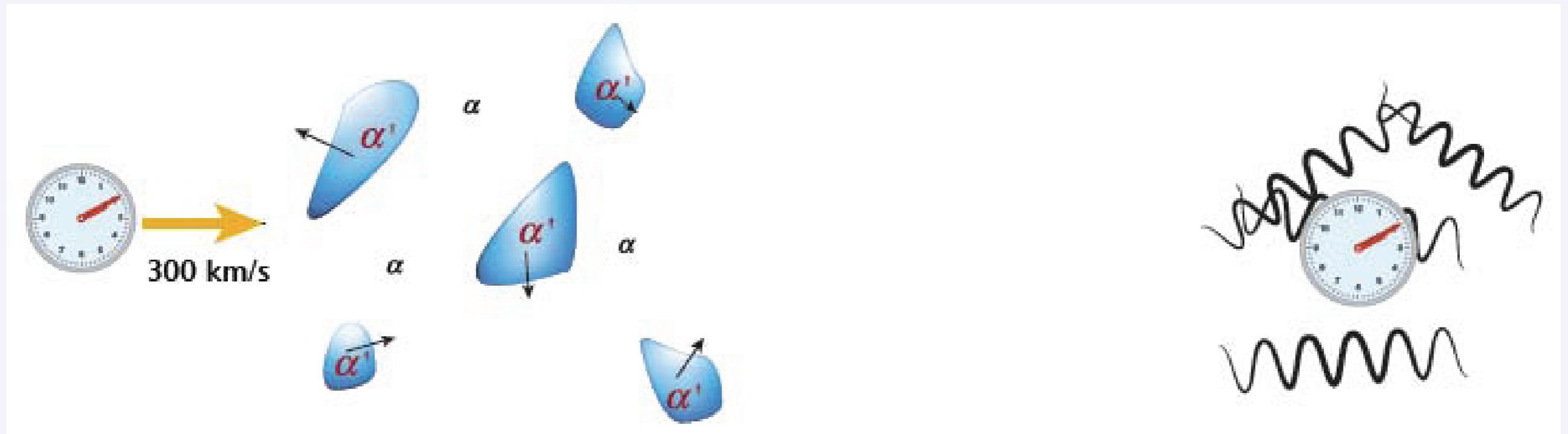
Dynamical decoupling
sequence:



from J. Ye



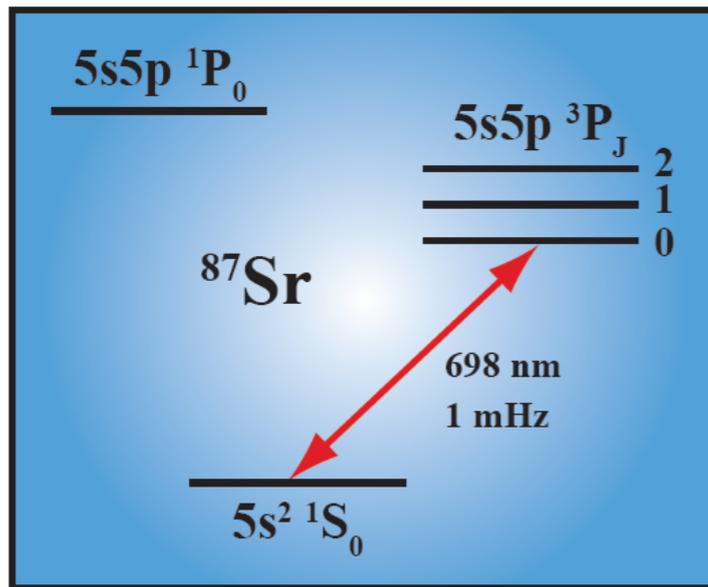
Search for Dark-Matter



(Left) An atomic clock sweeps through the DM. DM is assumed to be composed of extended objects (or clumps). If there is a difference of fundamental constants (such as the fine-structure constant in the figure) inside and outside the clumps, the clumps can cause the clock to slow down or speed up [A. Derevianko and M. Pospelov. Hunting for topological dark matter with atomic clocks. *Nature Phys.*, 10:933, 2014].

(Right) Ultralight fields can lead to oscillating fundamental constants at the field Compton frequency. By Fourier-transforming a time series of clock frequency measurements, one could search for peaks in the power spectrum and potentially identify DM presence [A. Arvanitaki, J. Huang, and K. Van Tilburg. Searching for dilaton dark matter with atomic clocks. *Phys. Rev. D*, 91(1):015015, 2015].

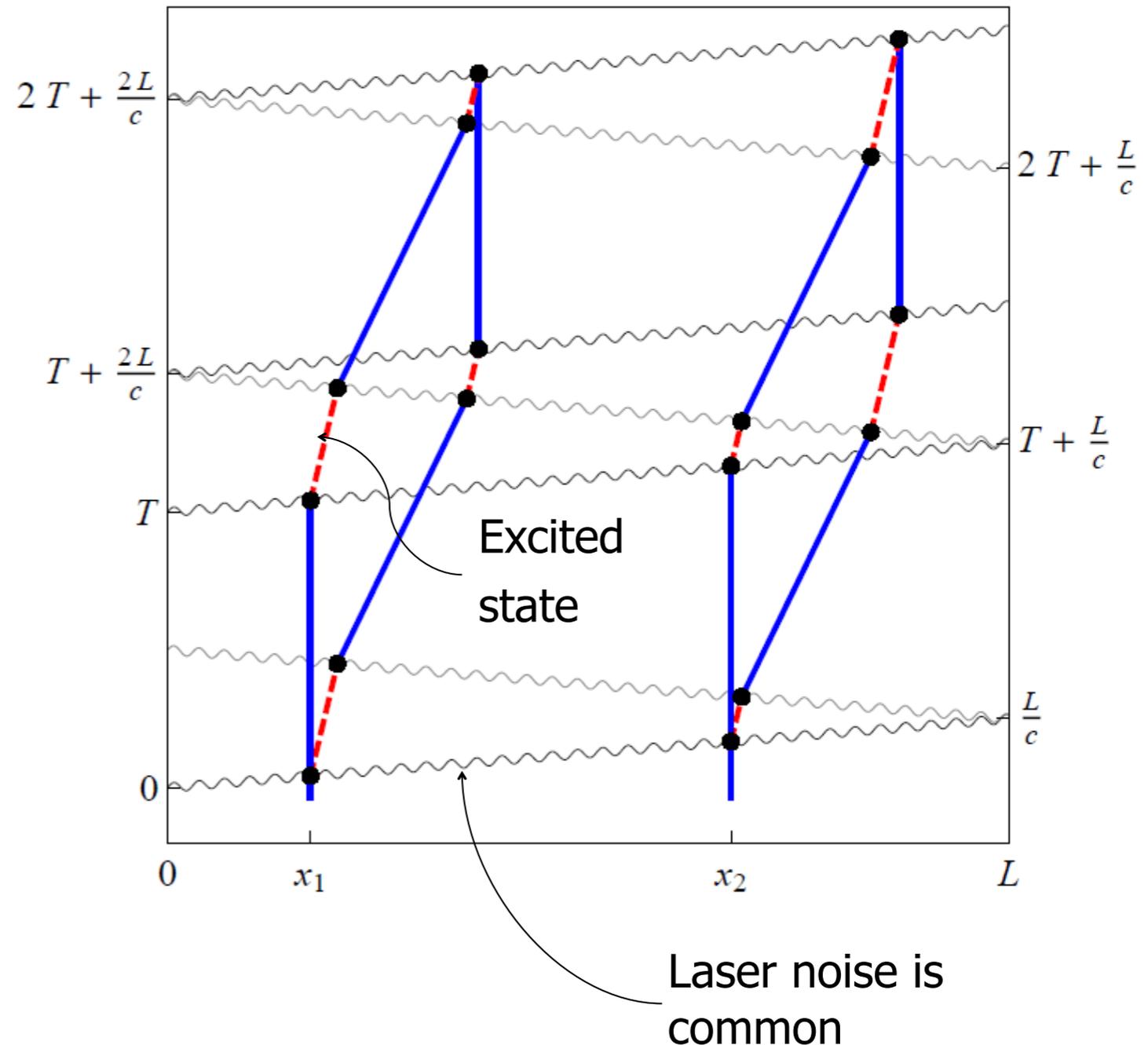
Laser frequency noise insensitive detector



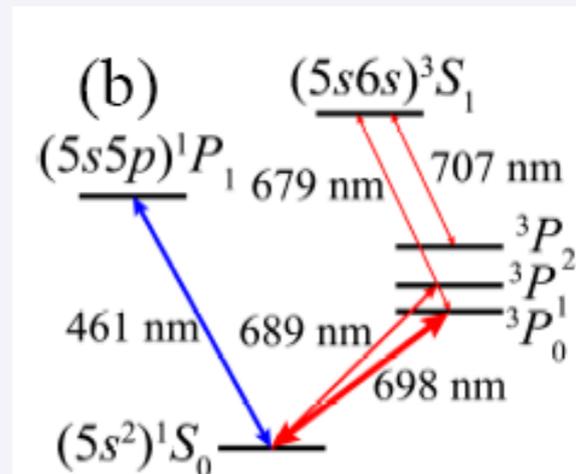
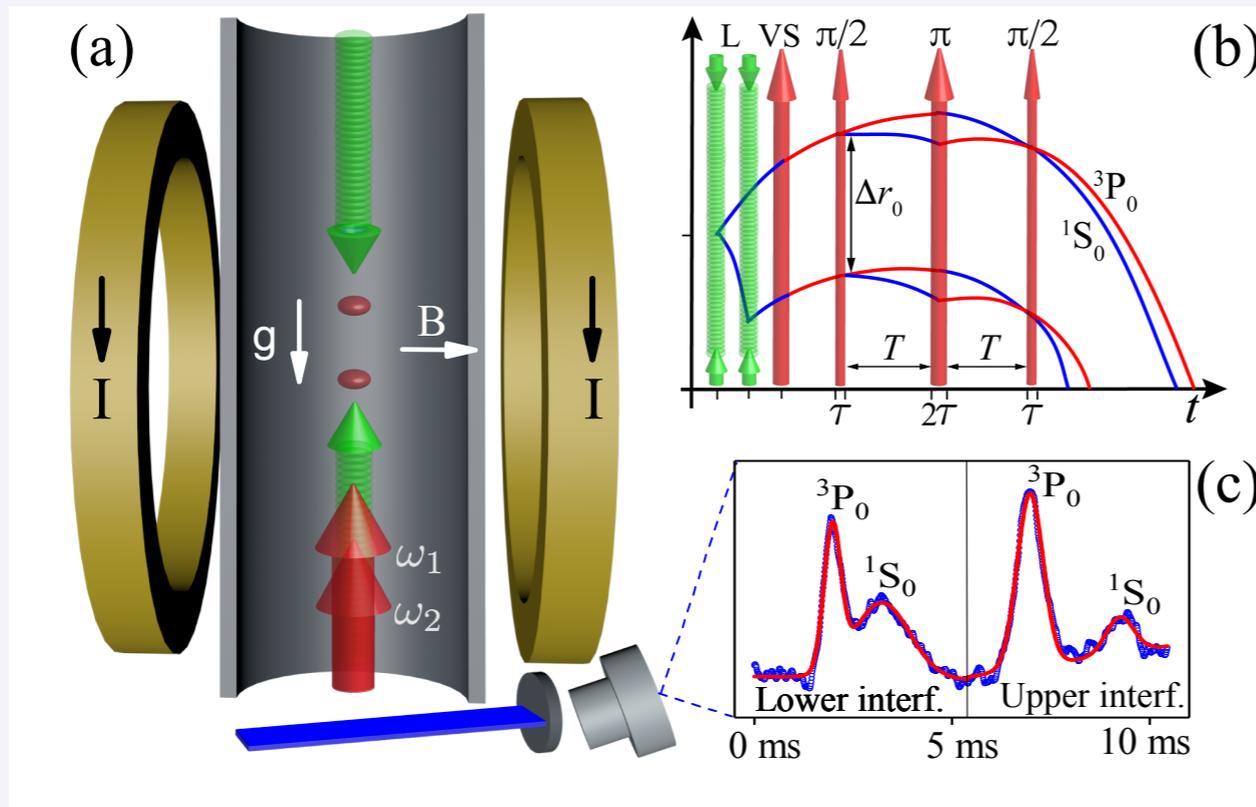
Clock transition in candidate atom ^{87}Sr

- Long-lived single photon transitions (e.g. clock transition in **Sr**, Ca, Yb, Hg, etc.).
- Atoms act as clocks, measuring the light travel time across the baseline.
- GWs modulate the laser ranging distance.

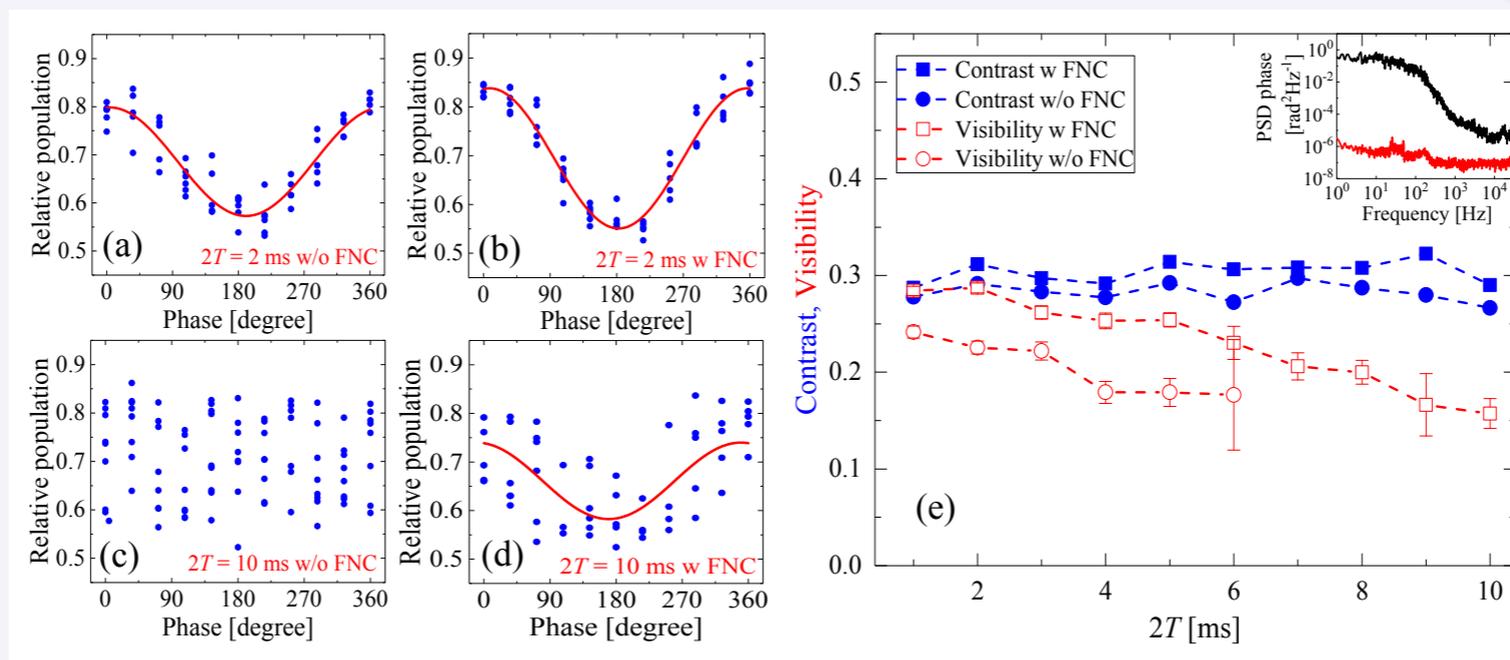
Enables 2 satellite configurations



Atom interferometry with the Sr optical clock transition



- ^{88}Sr isotope
- $B=300\text{ G} \rightarrow \Delta\nu=20\ \mu\text{Hz}$
- Rabi frequency $\Omega \sim 1\text{kHz}$



Liang Hu, Nicola Poli, Leonardo Salvi, Guglielmo M. Tino,
Atom interferometry with the Sr optical clock transition,
Phys. Rev. Lett. 119, 263601 (2017) - [Editors' Suggestion]

*Atom interferometry
with the Sr optical clock transition*

SAGE
Pathfinder
Successful !!

Liang Hu, Nicola Poli, Leonardo Salvi, Guglielmo M. Tino,
Atom interferometry with the Sr optical clock transition,
Phys. Rev. Lett. 119, 263601 (2017) - [Editors' Suggestion]

SAGE

Tests of General Relativity and the Einstein Equivalence Principle

- Test of UFF and spin-gravity coupling using bosonic and fermionic Sr isotopes
- Test of LPI through the gravitational redshift

SAGE

Investigate quantum correlations and test Bell inequalities for different gravitational potentials and different relative velocities

Description of the proposed experiment and physical quantities to observe

- Quantum correlations and the test of the violation of the Bell Inequality are based on an entangled photon pairs source on the satellite.
- Polarization entanglement is the first choice due to its realization simplicity and easy measurement setup (essentially waveplates, polarizers and single photon detectors).
- One photon of the pair is measured locally after a suitable delay and the other is sent to the other satellite using the same optical channel realized for the GW detector and at distances up to 5000-30000 km.
- Other possible degrees of freedom for entanglement generation is the so called time-bin entanglement.



from P. Villoresi

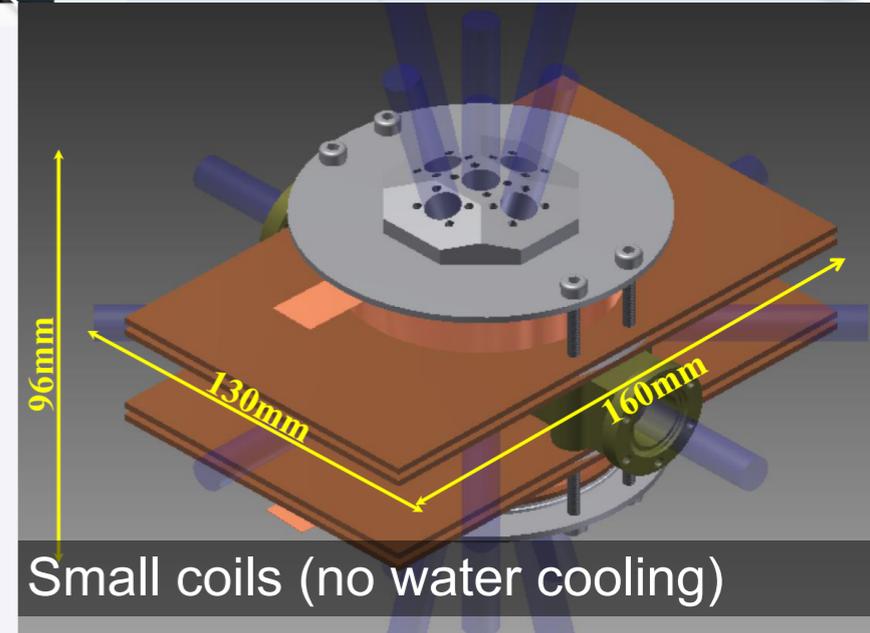
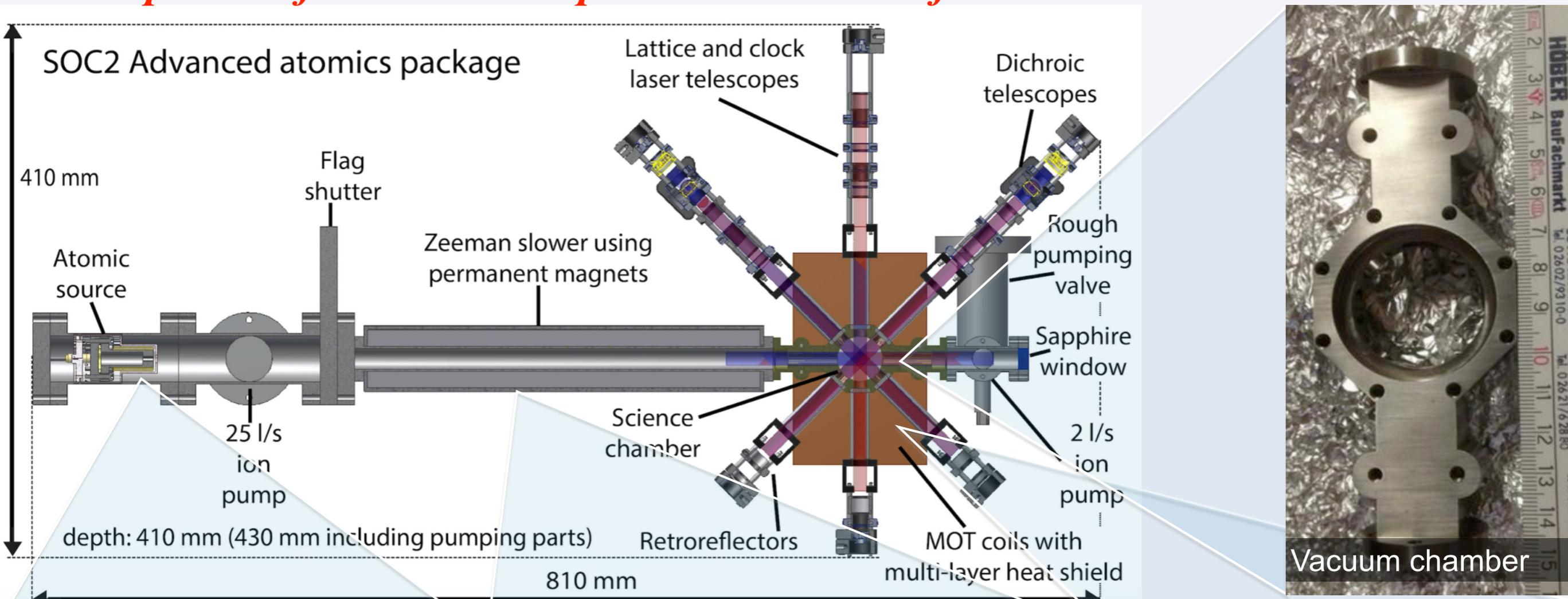


SAGE

Other Objectives and Applications

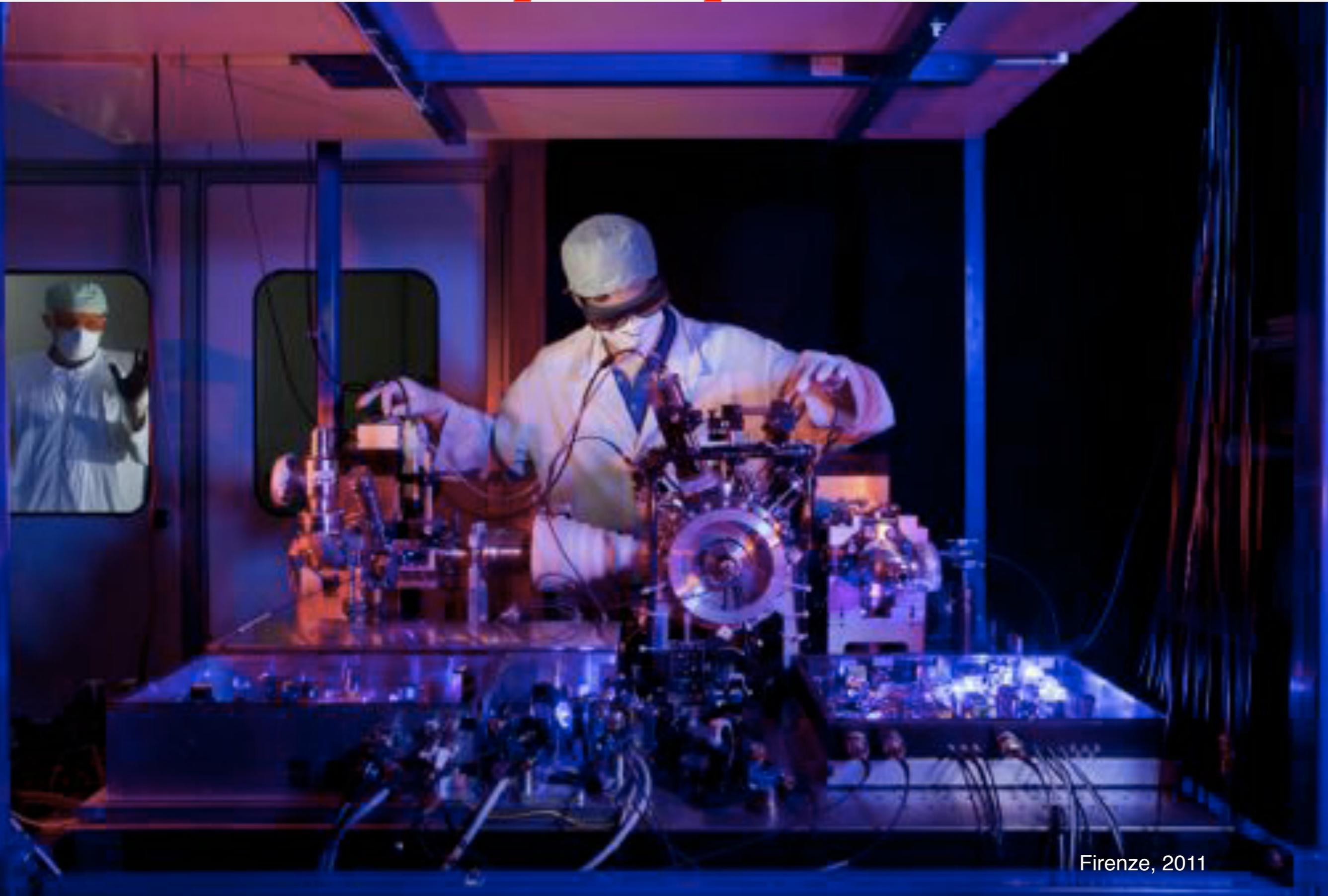
- *Define an ultraprecise frame of reference for Earth and Space and compare terrestrial clocks*
- *Use clocks and links between satellites for optical VLBI in Space*

Development of a strontium optical lattice clock for the SOC mission on the ISS



K. Bongs et al., *Development of a strontium optical lattice clock for the SOC mission on the ISS*, C. R. Physique 16, 553–564 (2015)

SOC – Space Optical Clock



Firenze, 2011

SAGE: ESA Conclusions and Actions Plan

- The experiment proposed by the team led by G. Tino (SAGE) in the area of precision clocks and atom interferometry needs significant maturation of the technology, as already analysed by the Gravitational Wave Observatory Team (GOAT) in 2016.

2nd Block of actions

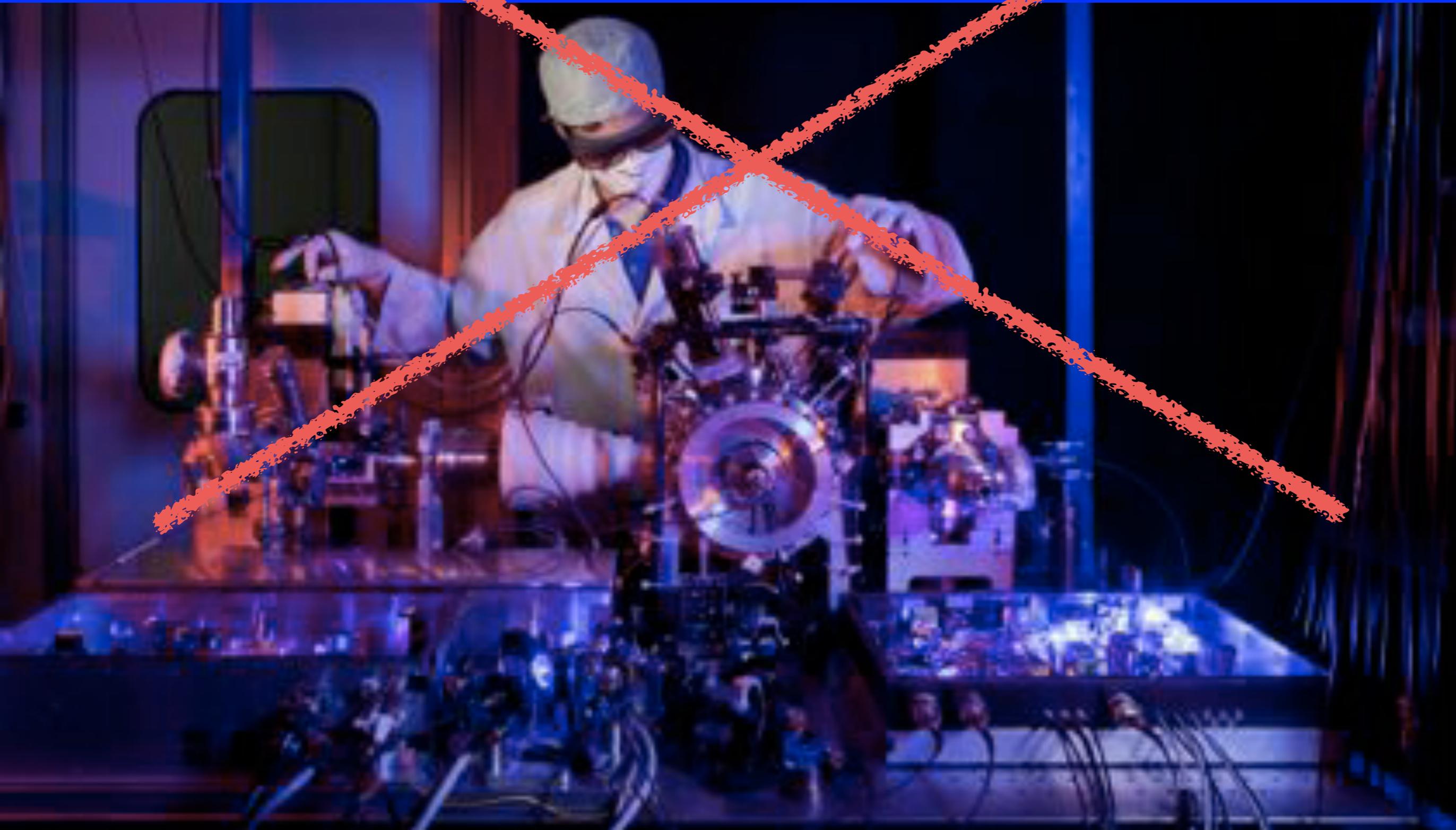
- The idea presented by Guglielmo Tino (SAGE) should follow the route recommended by the GOAT, i.e., the team needs to define and achieve milestones for their key technology items (clocks, cold atoms and inertial sensors) based on clearly understood performance requirements for the relevant experiments (detection of gravitational waves was mentioned during the presentation) with clear demonstration of achievements on ground and prove that these perform better than competing technologies/concepts for the various experiments (to the levels possible in laboratory experiments).
- ESA SCI-F will meet with the SAGE Team and other ESA experts as needed, to clarify the pathways already set for technology progress in areas relevant for clocks, cold atoms and inertial sensors and analyse the status of the technology for SAGE-like experiments.

Workshop on Quantum Physics - Follow up of the Call for “new science ideas” in the Science Programme
Trento University, 6-7 June 2017

ESA participation: Luigi Cacciapuoti, Luigi Colangeli, Peter Falkner, Fabio Favata, Martin Gehler, Martin Linder, Paul McNamara.
Stefano Vitale (member of ESA GOAT and SSC), Mike Cruise (member of ESA GOAT and SSC)

SAGE: SPACE ATOMIC GRAVITY EXPLORER

*Strontium Atomic Interferometers and Clocks
in Space for Fundamental Physics and Applications*



*? AEDGE: Atomic Experiments
for Dark Matter and Gravity Exploration
Strontium Atomic Interferometers and Clocks
in Space for Fundamental Physics and Applications ?*

