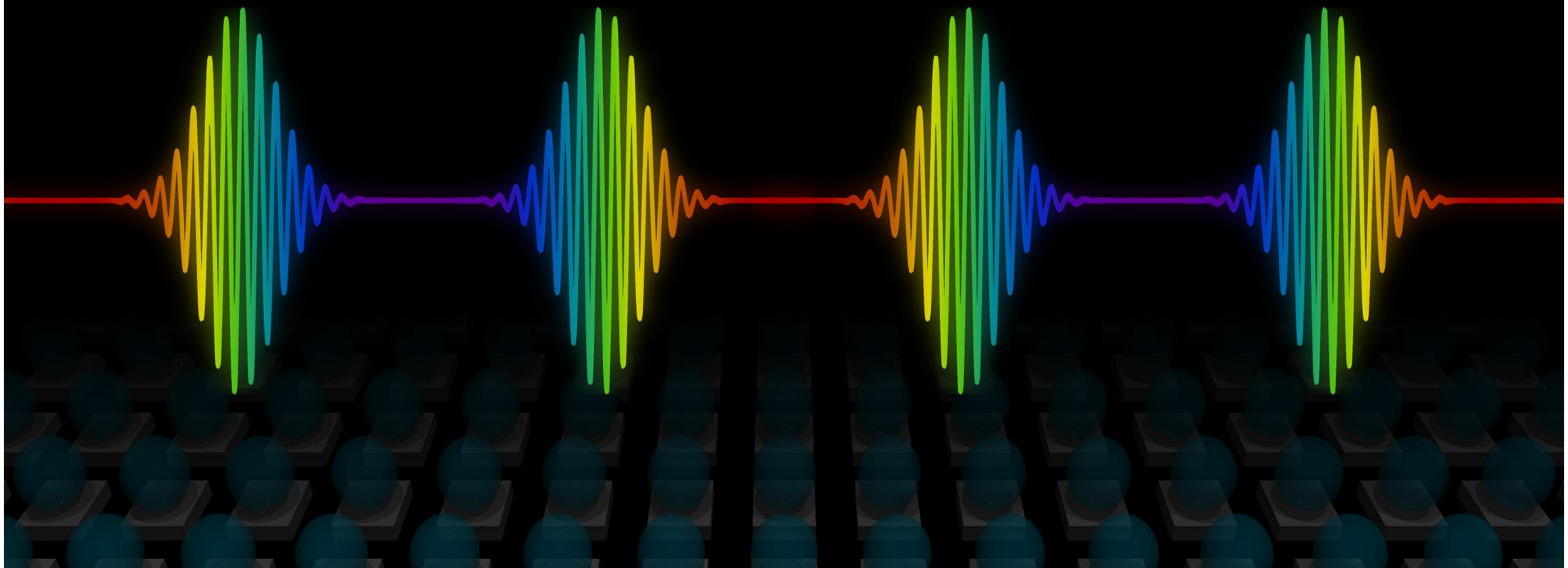
Light, atoms, time

Varenna, July 6th, 2019



Massimo Inguscio

CNR Consiglio Nazionale delle Ricerche
LENS European Laboratory for Nonlinear Spectroscopy
Dept. of Engineering University Campus Bio-Medico of Rome

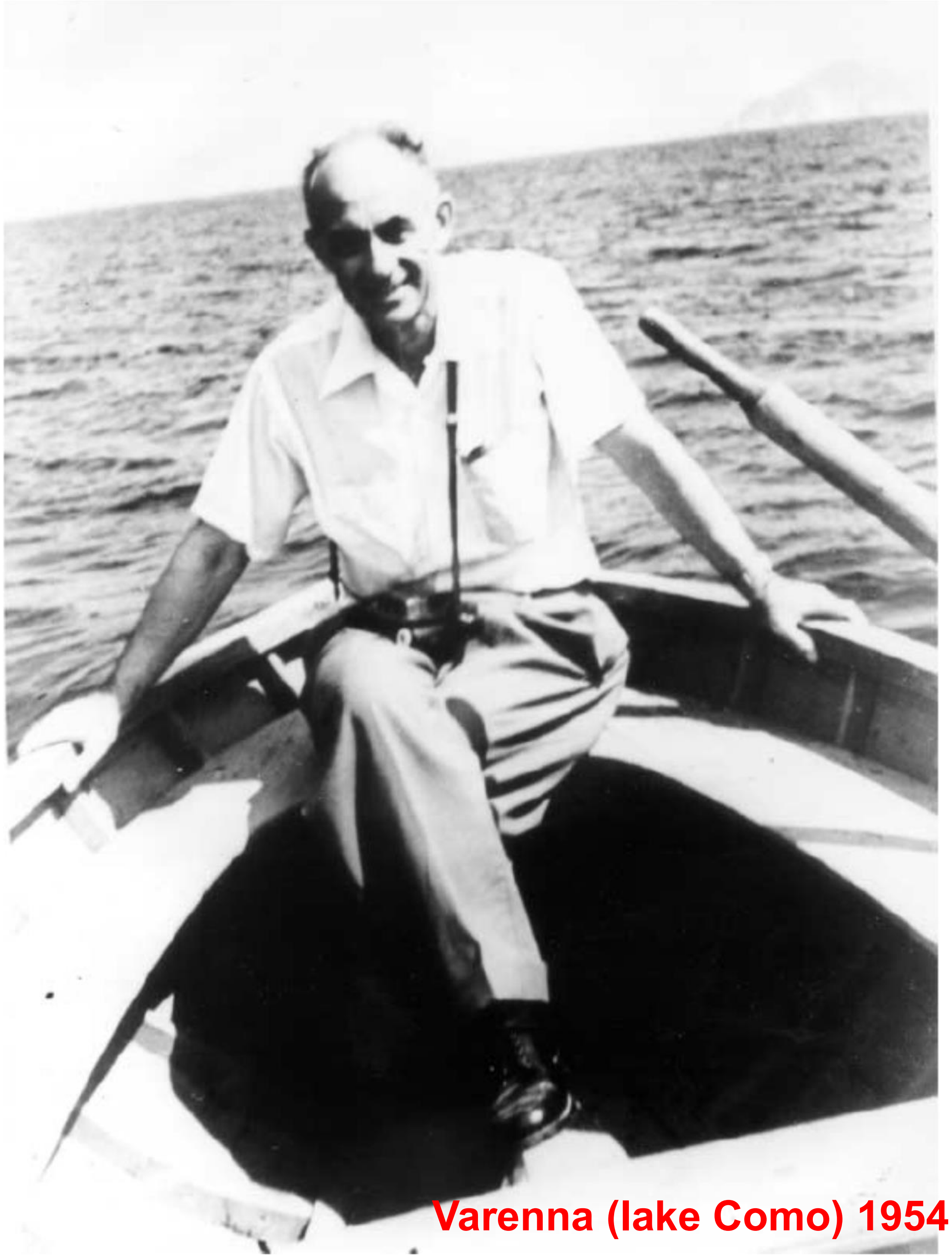
Quantum revolutions

We can not yet foresee the consequences that, in the scientific thought of tomorrow, the Heisenberg principle and to which technical results the statistical interpretation of mechanics can lead us ...

Gustavo Colonnetti,
President of CNR

Italian Constitution, 1947

Article 9: The Republic promotes the development of culture and scientific and technical research. Protects the landscape and the historical and artistic heritage of the nation.

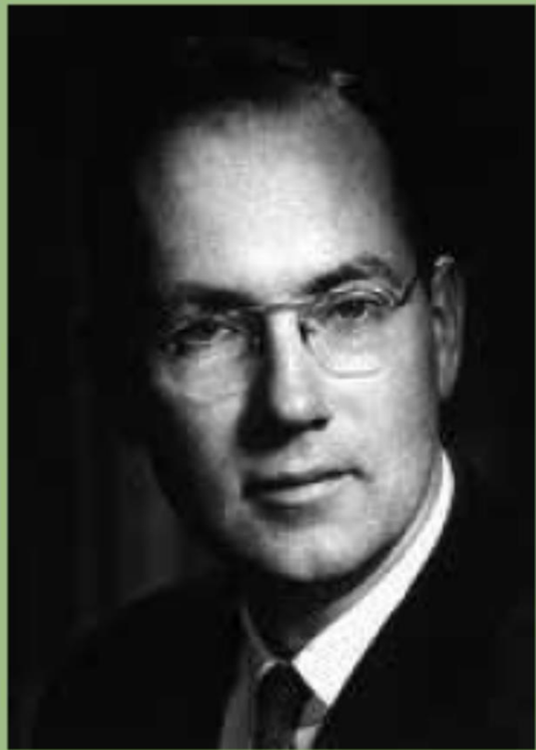


Varenna (lake Como) 1954

I. Rabi
Nobel Prize 1944

1955

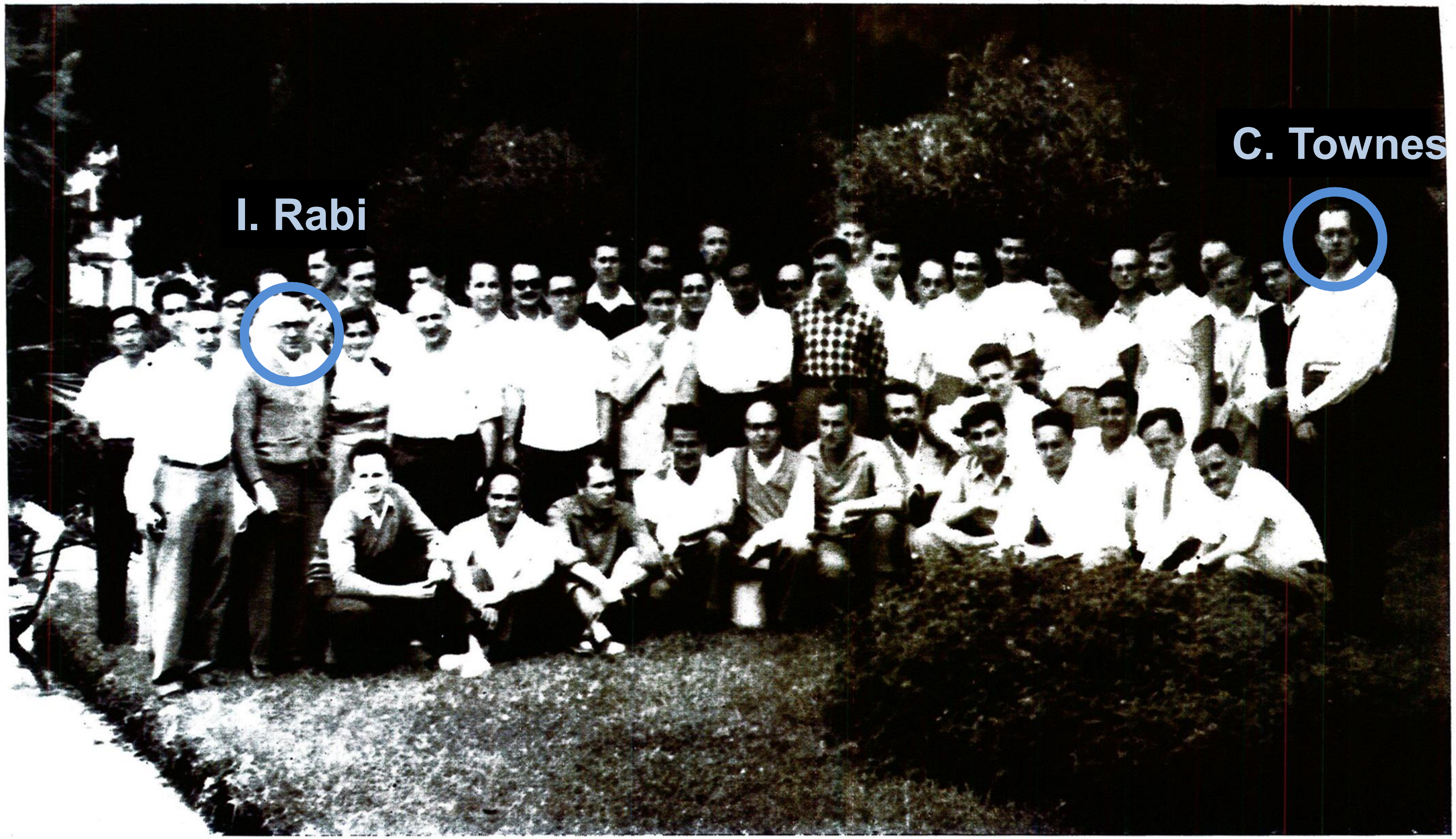
C. H.Townes
Nobel Prize 1964



1955, 1960, 1963

III Summer School on "Topics of Nuclear Structure" (Varenna, July 1955)

3° CORSO ESTIVO - VARENNA SUL LAGO DI COMO - VILLA MONASTERO - 17 Luglio - 6 Agosto 1955



III Summer School on “Topics of Nuclear Structure” (Varenna, July 1955)

RENDICONTI

DEL

CORSO CHE NELLA VILLA MONASTERO A VARENNA

DAL 17 LUGLIO AL 6 AGOSTO, 1955

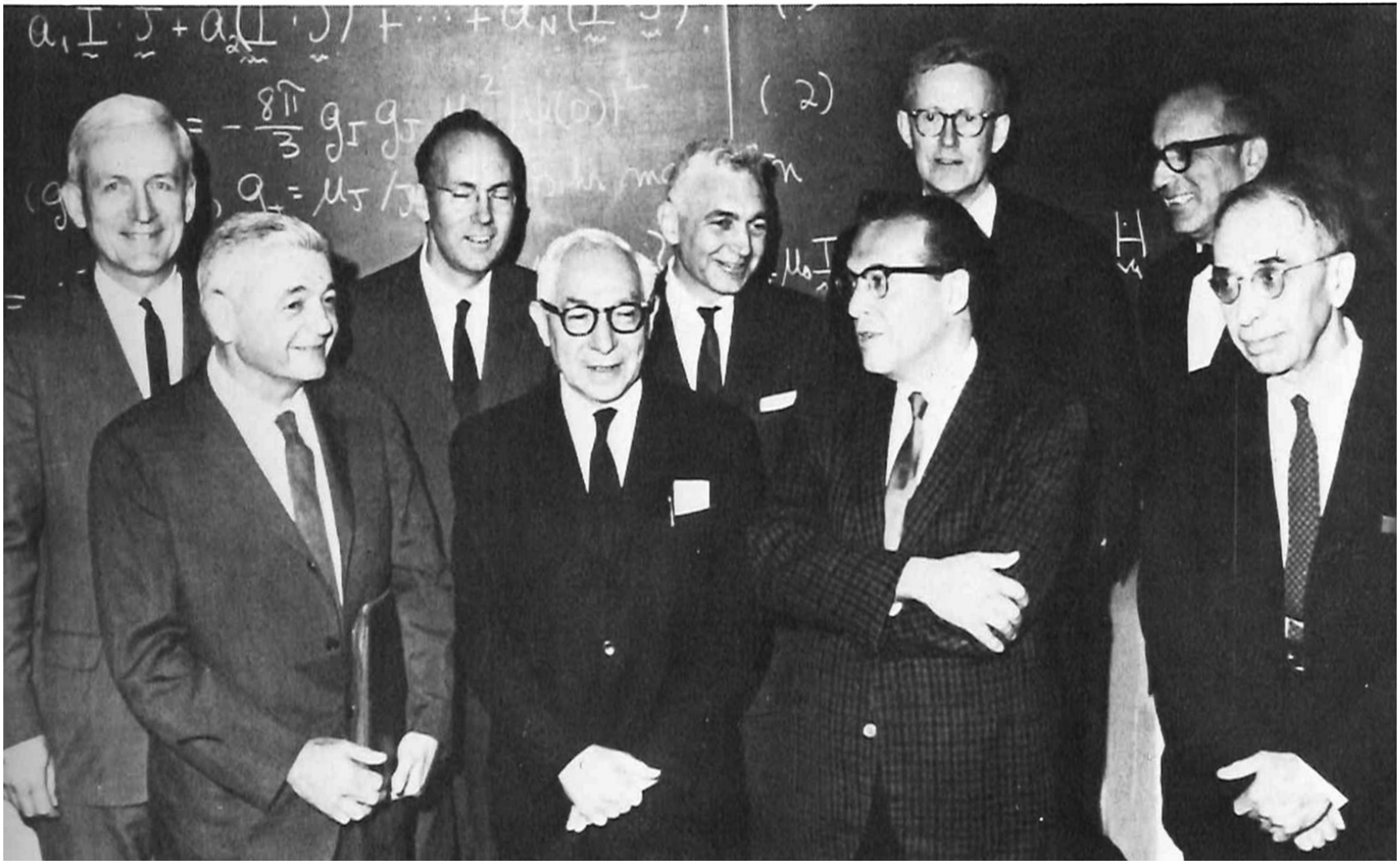
FU TENUTO A CURA

DELLA SCUOLA INTERNAZIONALE DI FISICA

DELLA SOCIETÀ ITALIANA DI FISICA

PARTE SECONDA. – **Momenti nucleari.**

Rabi's retirement from Columbia University in 1968 was an opportunity for some of his former students and friends to come together. From left, Norman Ramsey, Jerrold Zacharias, Charles Townes, Rabi, V. W. Hughes, Julian Schwinger, Edward Purcell, William Nierenberg, and Gregory Breit.



XXXI Summer School on "Quantum Electronics and Coherent Light" (Varenna, 1963)

ITALIAN PHYSICAL SOCIETY

PROCEEDINGS

OF THE

INTERNATIONAL SCHOOL OF PHYSICS
« ENRICO FERMI »

COURSE XXXI

C. H. TOWNES
Director of the Course

VARENNA ON LAKE COMO
VILLA MONASTERO
19th - 31st AUGUST 1963

Quantum Electronics and Coherent Light

Proceedings edited by
P. A. MILES

1964

XXXI Summer School on “Quantum Electronics and Coherent Light” (Varenna, 1963)

XXXI Summer School on “Quantum Electronics and Coherent Light” (Varenna, 1963)

CXL Summer School on “Bose-Einstein Condensation in Atomic Gases” (Varenna, July 1998)

ITALIAN PHYSICAL SOCIETY

PROCEEDINGS

OF THE

INTERNATIONAL SCHOOL OF

«ENRICO FERMI»

COURSE CXL

edited by M. INGUSCIO, S. STRINGARI and C.

VARENNA ON LAKE COMO

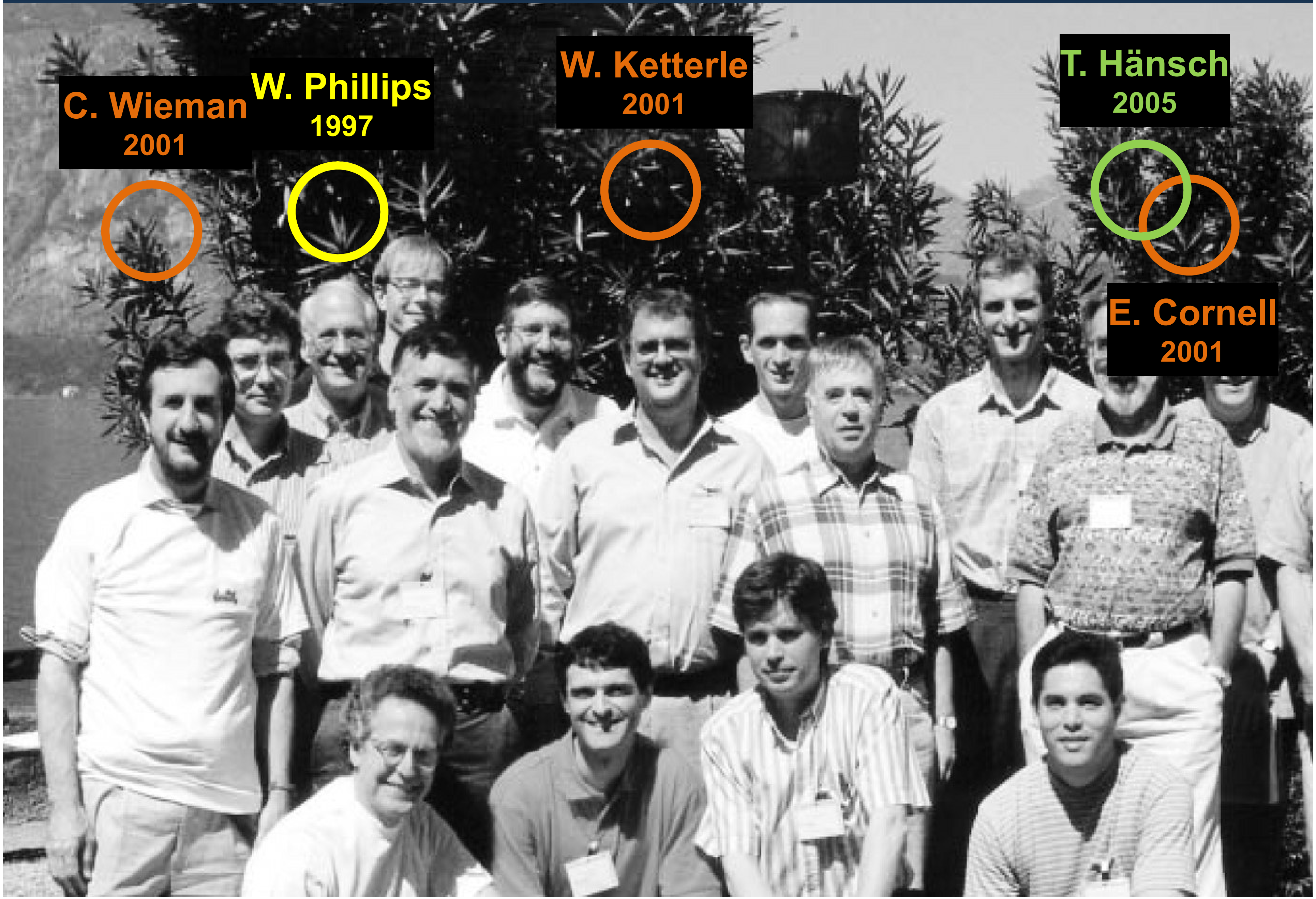
VILLA MONASTERO

7-17 July 1998

Bose-Einstein Conden.

Atomic Gases

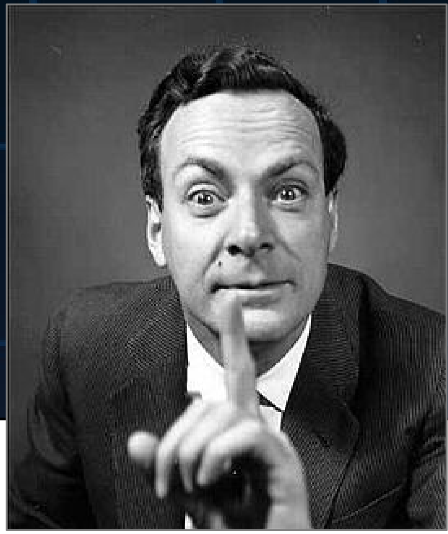
CXL Summer School on "Bose-Einstein Condensation in Atomic Gases" (Varenna, July 1998)



Atoms and light

It's all about atoms

What should you learn first?



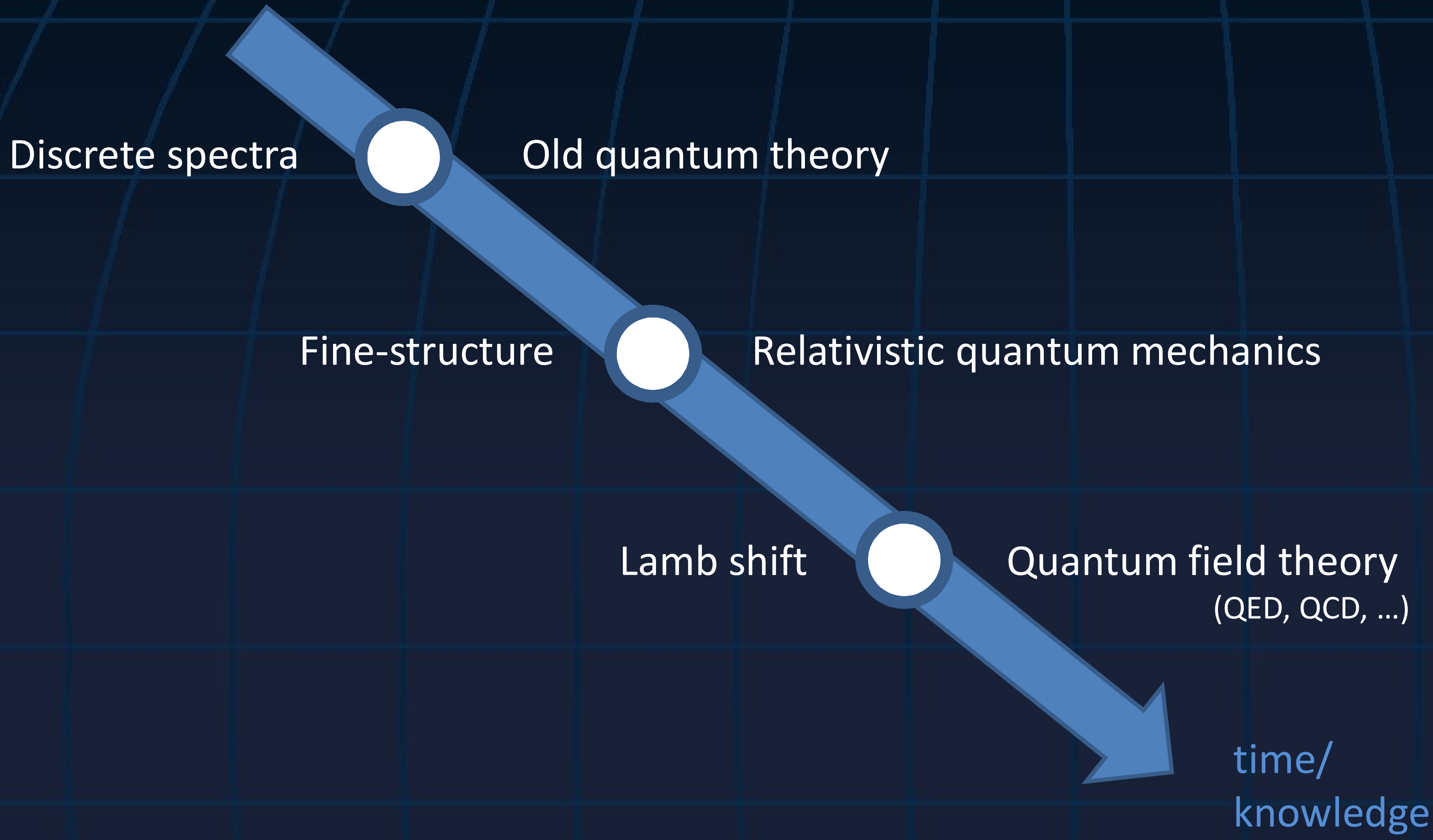
R. P. Feynman, *Lectures on Physics*
Volume 1, Chapter 1

1-2 Matter is made of atoms

If, in some cataclysm, all of scientific knowledge wer
one sentence passed on to the next generations of creatu
contain the most information in the fewest words?
hypothesis (or the atomic *fact*, or whatever you wish to
made of atoms—little particles that move around in pe

Spectroscopy

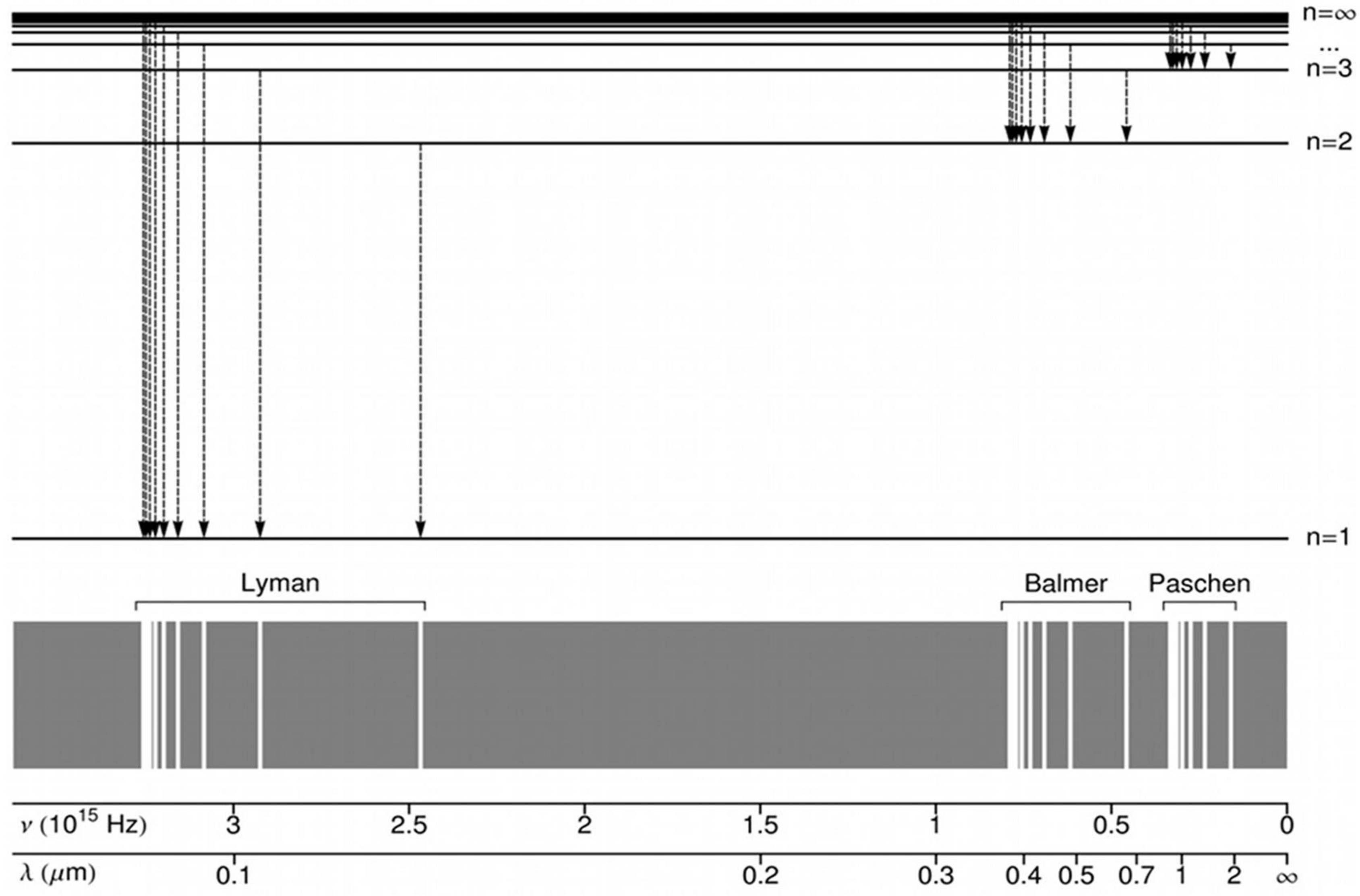
Atoms are our keys to the quantum world gates



Hydrogen

Hydrogen Balmer series

Hydrogen



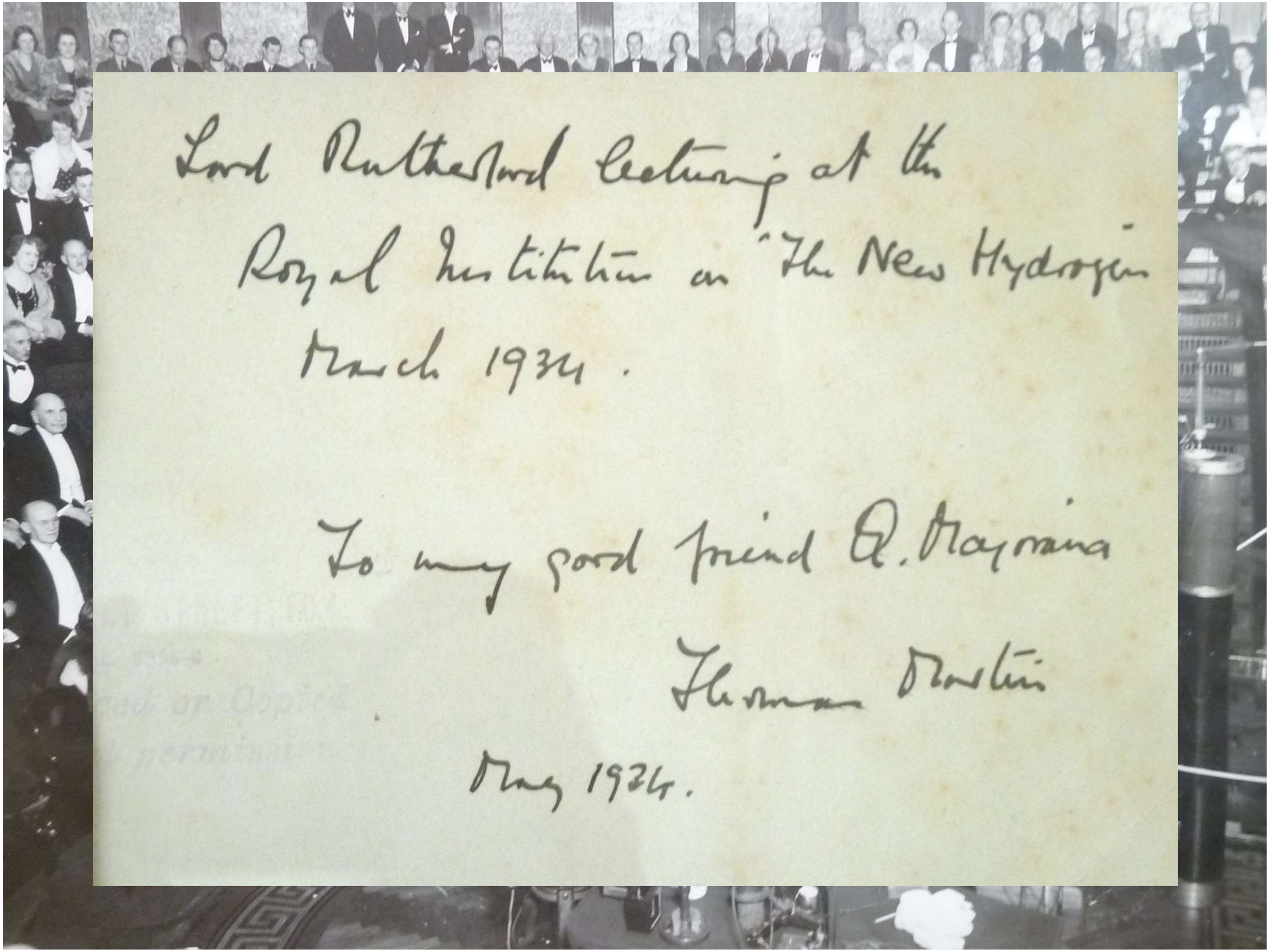
n=∞
...
n=3
n=2
n=1
Lyman
Balmer
Paschen
ν (10^15 Hz)
3
2.5
2
1.5
1
0.5
0
λ (μm)
0.1
0.2
0.3
0.4
0.5
0.7
1
2
∞

Fine structure

Fine structure doublet in sodium spectrum

↓

Relativistic quantum mechanics (Dirac)



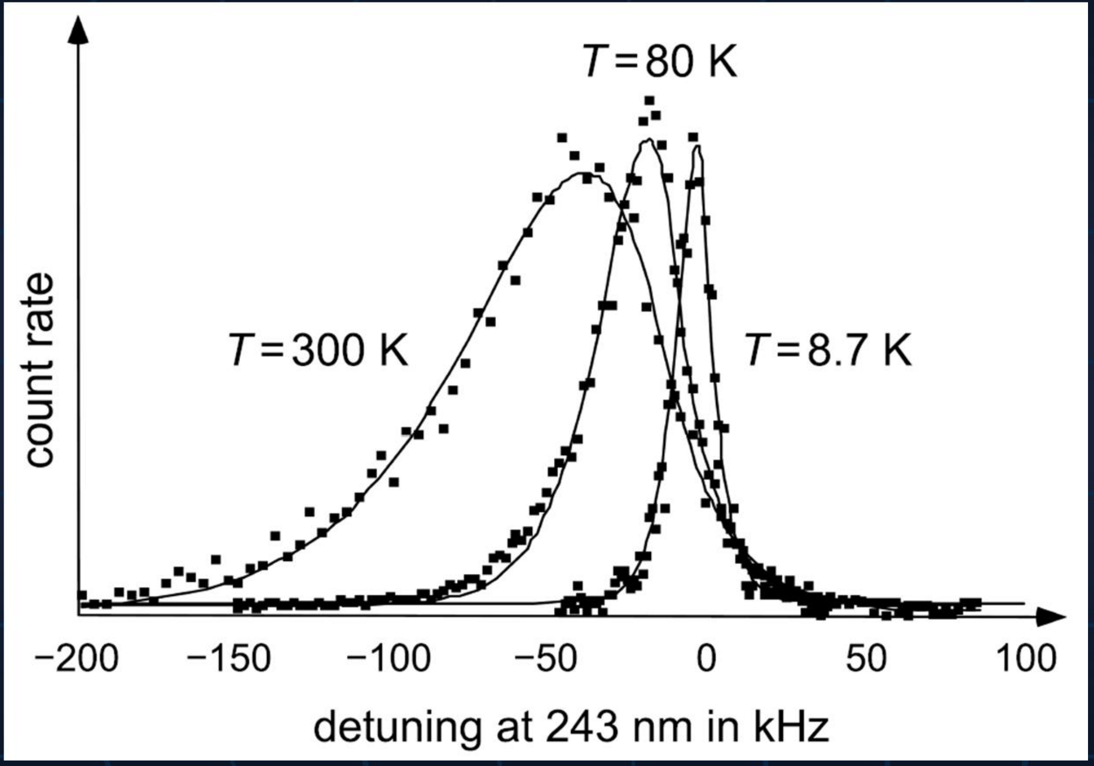
Lord Rutherford lecturing at the
Royal Institution on "The New Hydrogen"
March 1934.

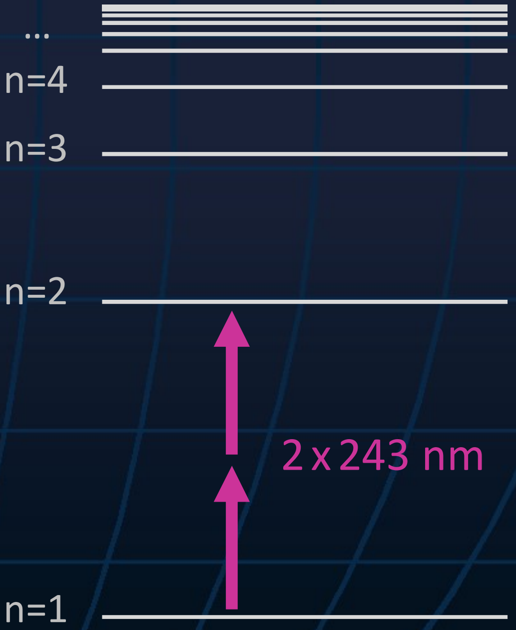
To my good friend E. Majorana

Thomas Martin

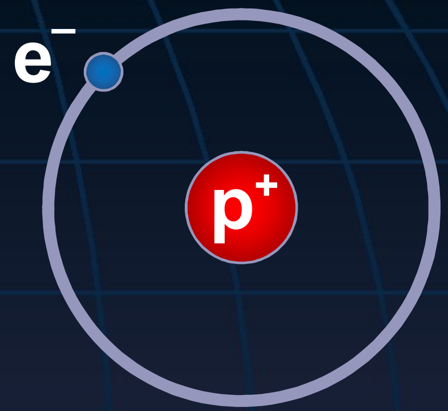
May 1934.

Spectroscopy of hydrogen 1s-2s (T. W. Haensch)





Hydrogen



High-precision spectroscopy

$$\delta\nu(1s - 2s) = 2\ 466\ 061\ 413\ 187\ 035\,(10)\ \mathrm{Hz}$$

↓

The Rydberg constant

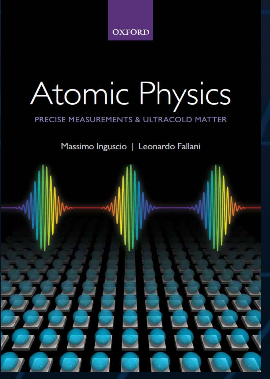
$$R_\infty = 10\ 973\ 731.568\ 539(55)\ \mathrm{m}^{-1}$$

$$E_n = -hcR_\infty \frac{1}{n^2}$$

Very precise measurements!
Very precise theory!

…but still ***there are*** surprises!

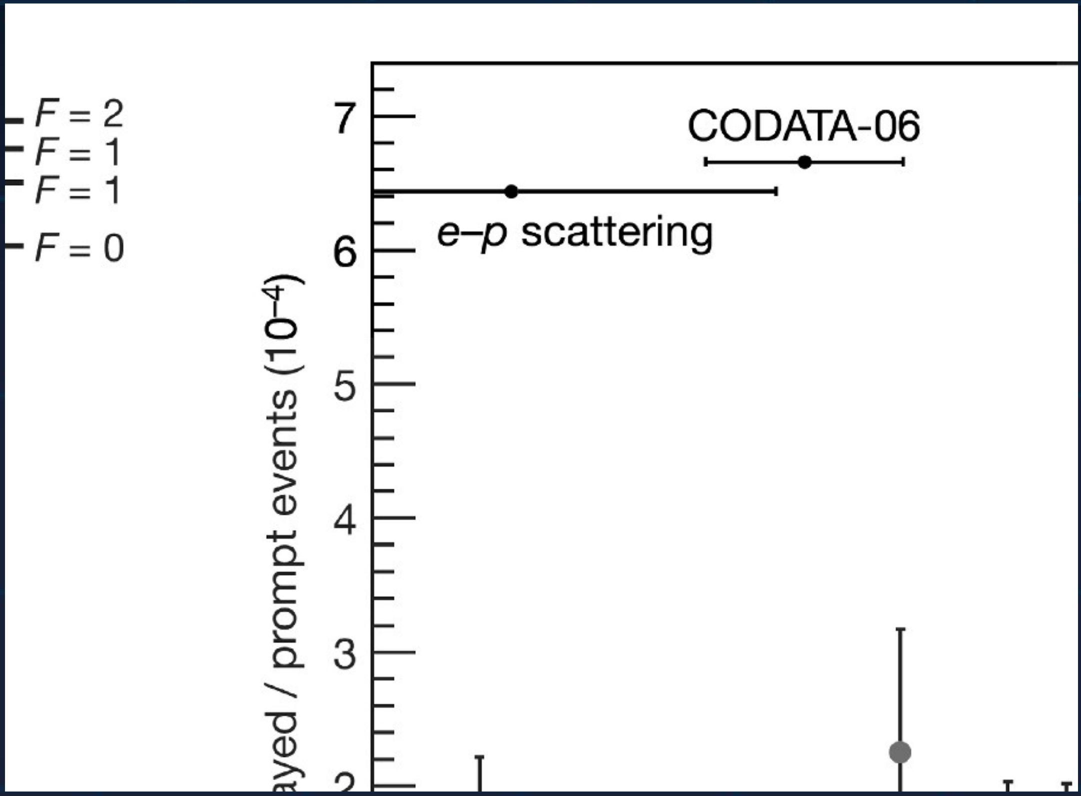
Massimo Inguscio & Leonardo Fallani
Atomic Physics: Precise Measurements and Ultracold Matter (Oxford, 2013)



Muonic hydrogen

Spectroscopy of Lamb shift in muonic hydrogen

What's the size of the proton?

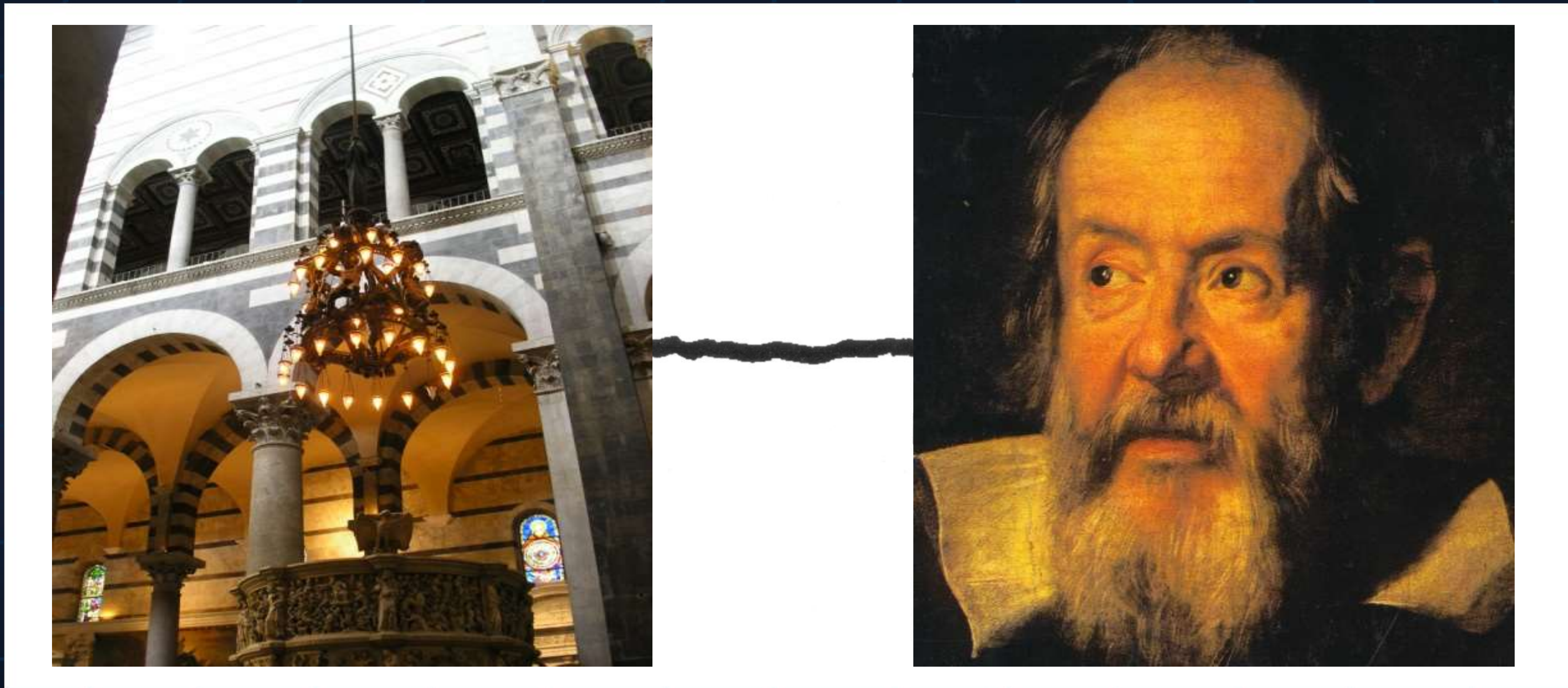


R. Pohl et al., Nature (2010)

Time and atomic clocks

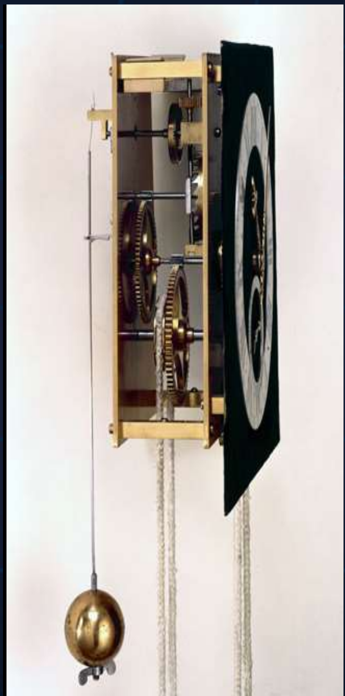
Measuring time

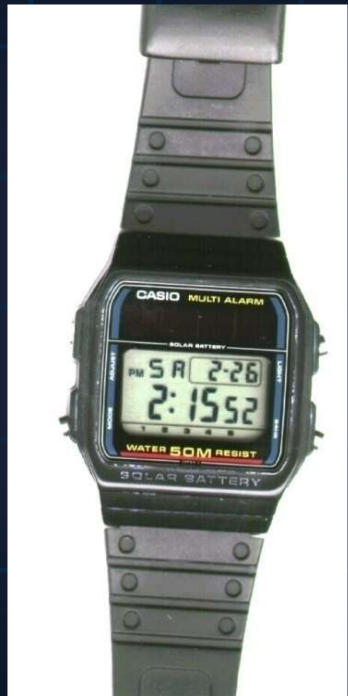
Measuring time = A good oscillator + A counter

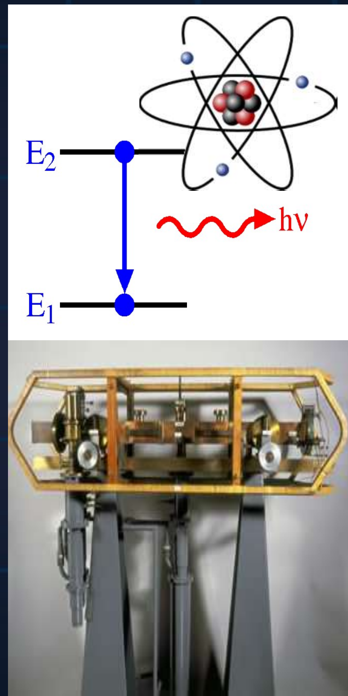


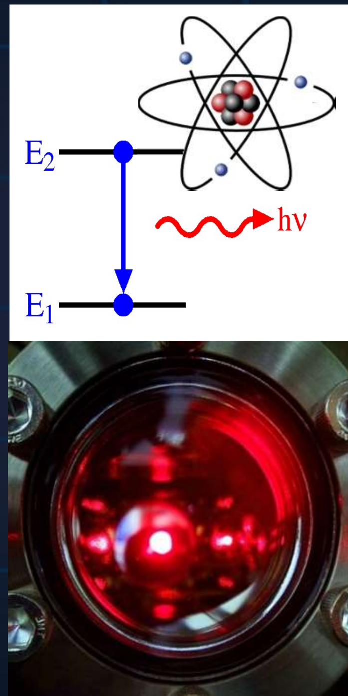
Counting time

~5000 a.C.	1656	1918	1955	~2010
sundial	pendulum clock	quartz clock	microwave atomic clock	optical atomic clock
1 osc. / day	1 osc. / second	32.768 osc. / second	9.192.631.770 osc. / second	518.295.836.590.863 osc. / second





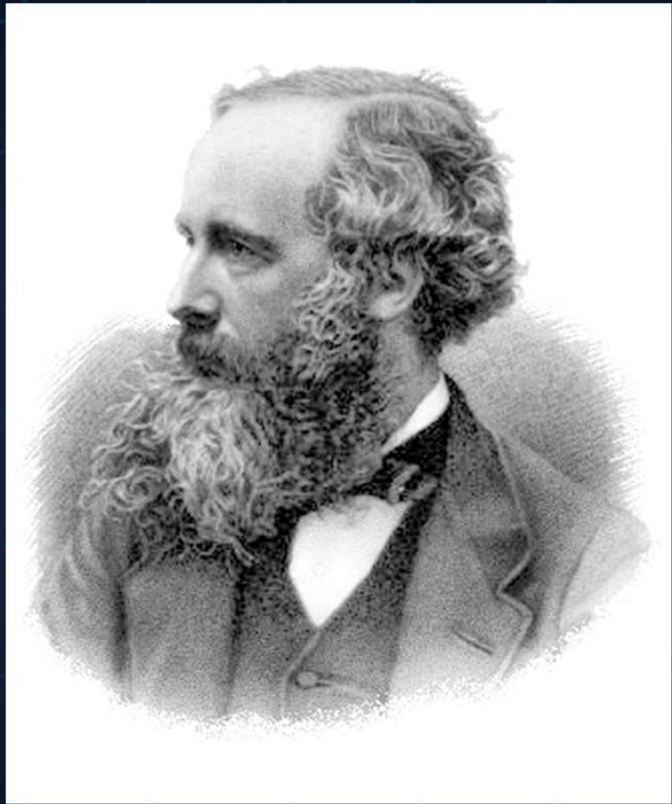




An atomic system of units

If, then, we wish to obtain standards of length, time, and mass which shall be absolutely permanent, we must seek them not in the dimensions, or the motion, or the mass of our planet, but in the wave-length, the period of vibration, and the absolute mass of these imperishable and unalterable and perfectly similar molecules.

J. C. Maxwell (1870)



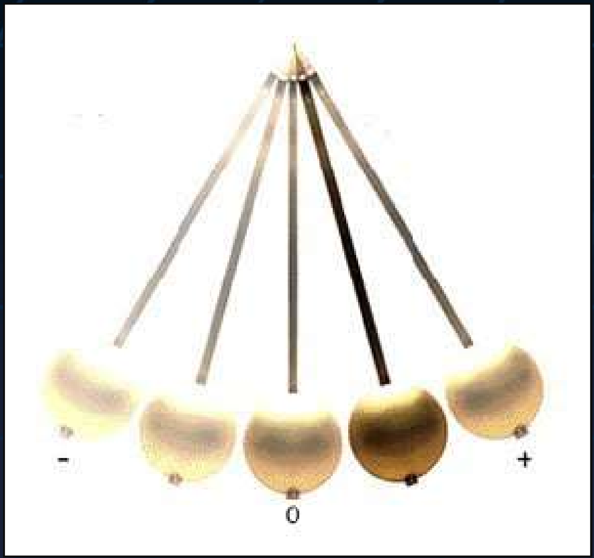
The International System of Units (SI)

The fundamental SI units (until May 30th 2019):

Length	**meter**	derived from time
Mass	**kilogram**	international prototype
Time	**second**	atomic transition frequencies
Current	**ampere**	force between wires
Temperature	**kelvin**	triple point of wate
Amount of subst		
Luminous intens		

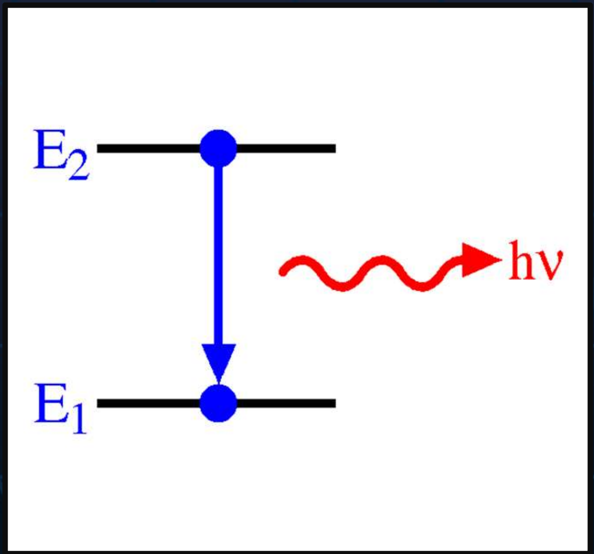
The most precise unit (~10^{-16})!
Why? It's quantum!!!

A good oscillator



Mechanical pendulum

f ≈ 1 Hz (1 oscillation/second)

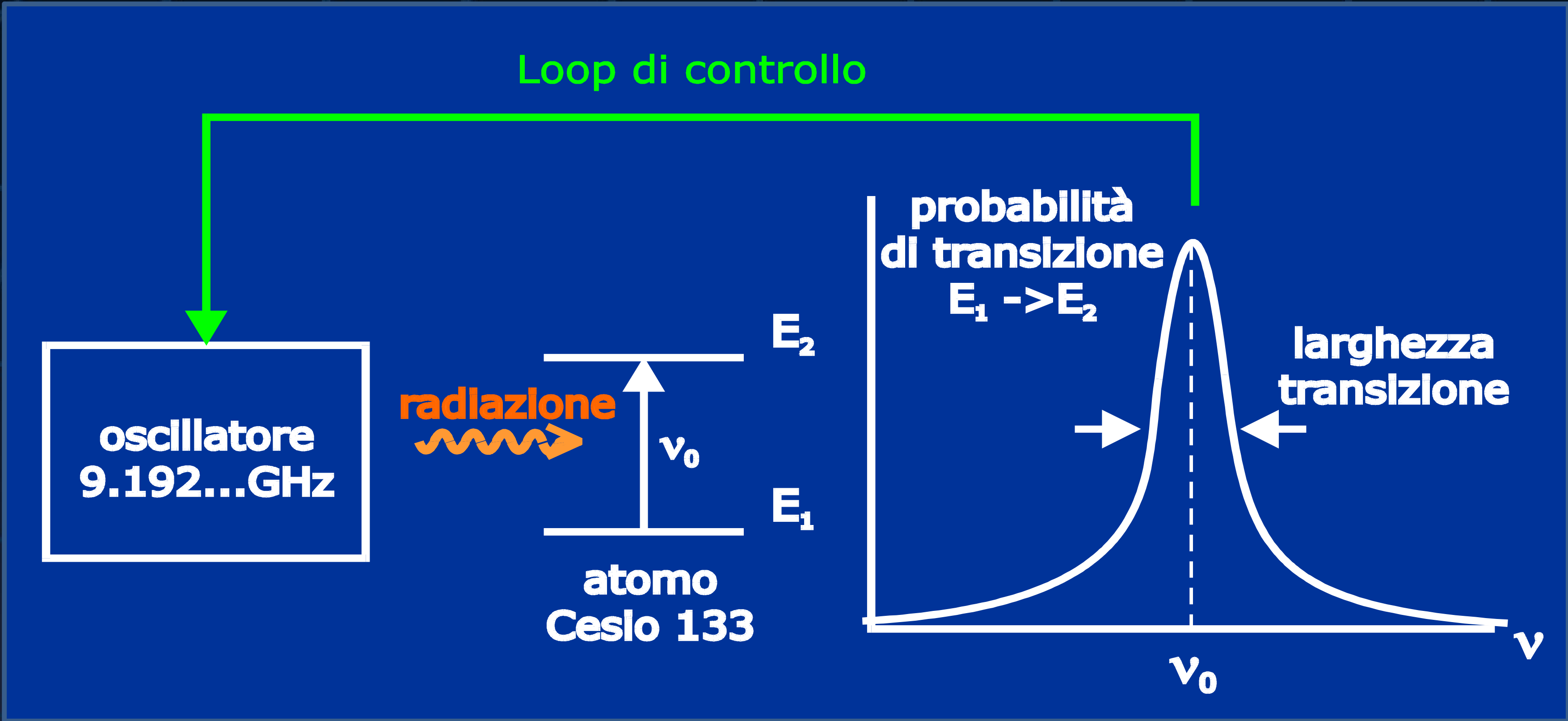


Transition between atomic levels

$f \approx 10^{10}$ Hz microwave clock
(10.000.000.000 oscillations/second)

$f \approx 10^{15}$ Hz optical clock
(1.000.000.000.000.000 oscillations/second)

Atomic clocks

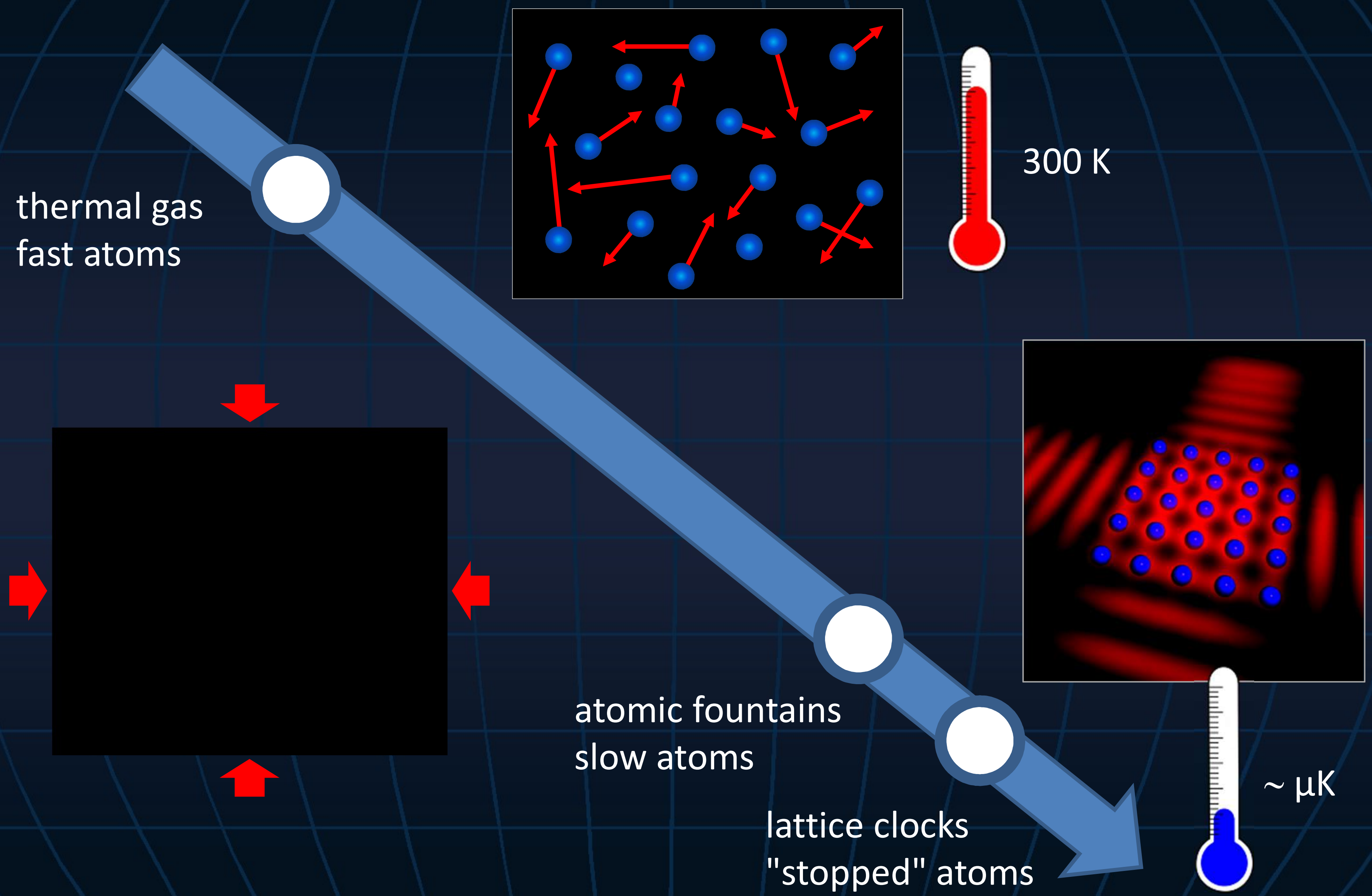


The precision increases with interrogation time: $\Delta\nu \sim \Delta t^{-1}$

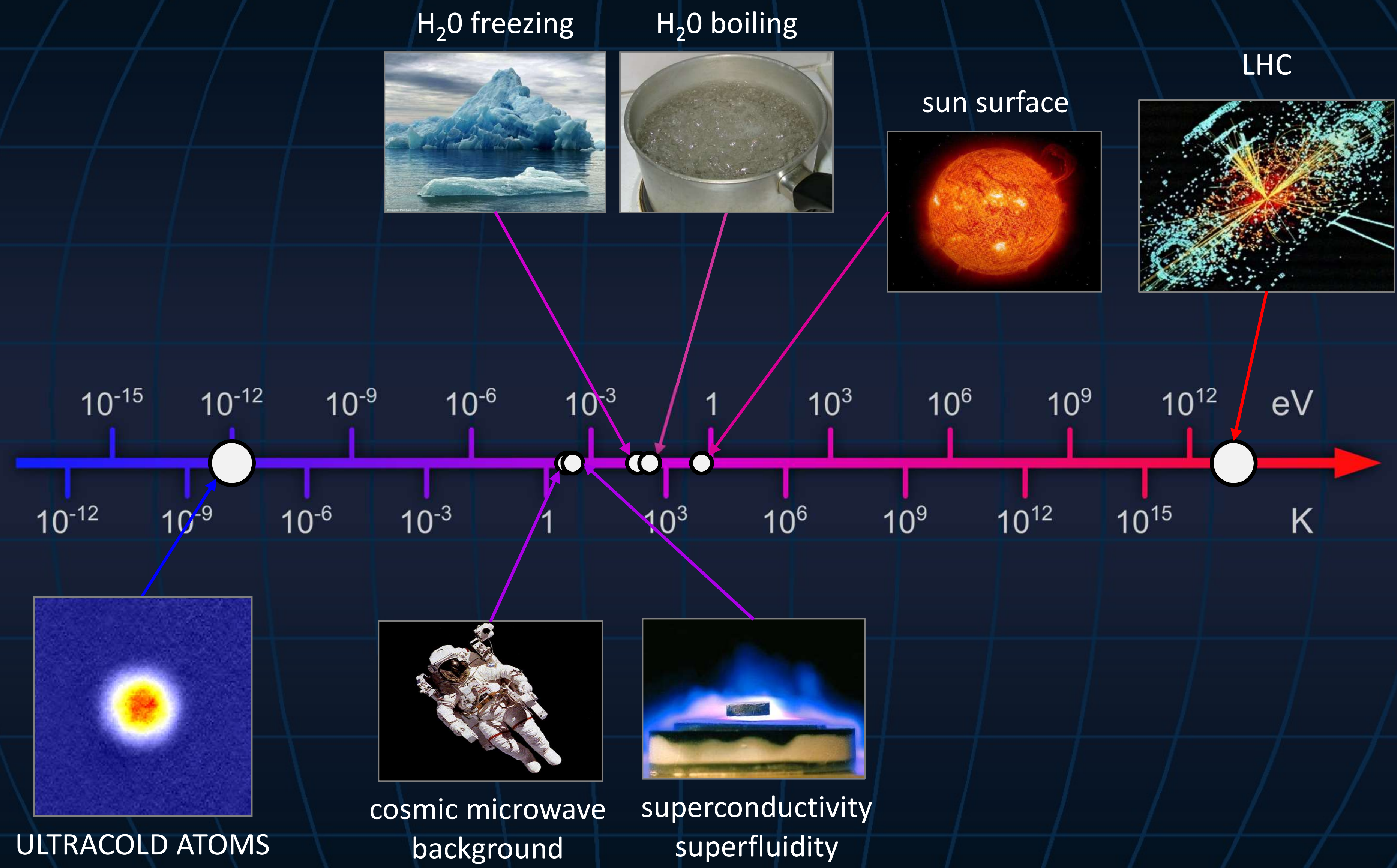
↓

Laser cooling

Laser cooling

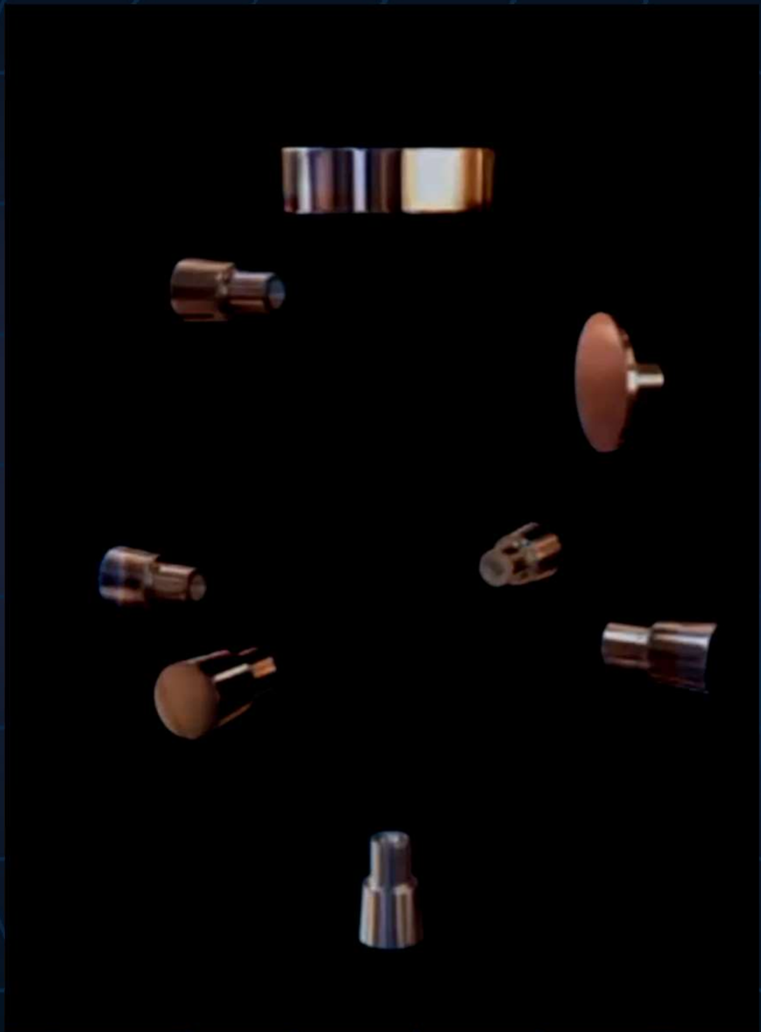


Temperature/energy scales



Microwave atomic clocks

Atomic fountain clocks



Hyperfine levels of ^{133}Cs

Accuracy of INRIM fountain clocks

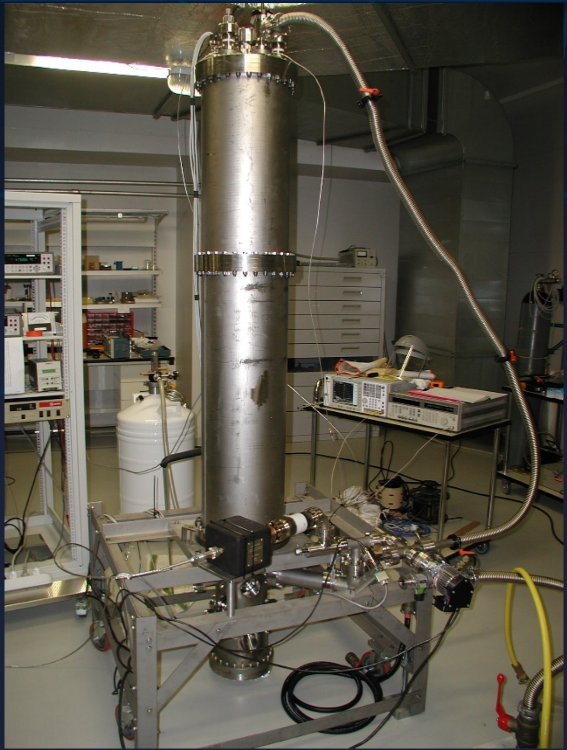
	ITCsF1 $\sigma_y(\tau) = 1.5\cdot10^{-13}\ \tau^{-1/2}$	**ITCsF2** $\sigma_y(\tau) = 1.5\cdot10^{-13}\ \tau^{-1/2}$
Zeeman	2E-16	8E-17
Collisions	3E-16	1E-16
Blackbody	3E-16	1E-17
Microwave	2E-16	1E-16
Redshift	1E-17	1E-17
Total	**5E-16**	**2E-16**

Microwave atomic clocks

Atomic fountain clocks

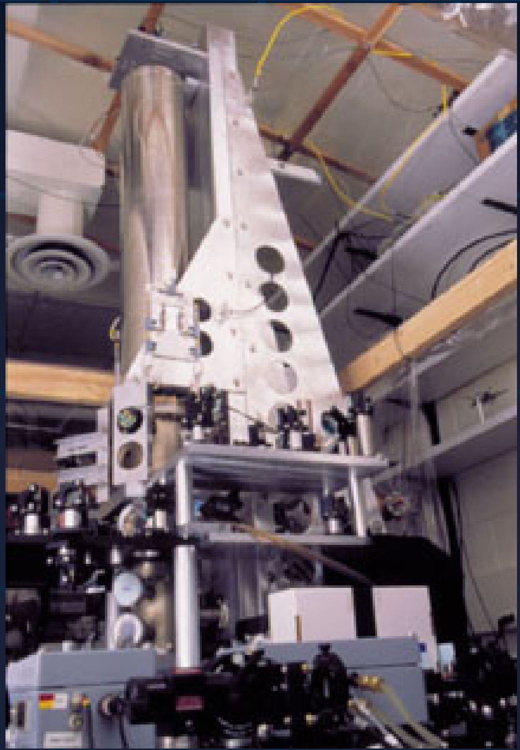
15 atomic fountains in operation at INRIM, PTB, NIST, SYRTE, USNO, Penn St, NPL, Neuchatel, JPL, NIM, NMIJ, NICT, Sao Carlos, …

~10 report to BIPM with accuracy of a few 10^{-16} realizing the **International Atomic Time** (TAI)



INRIM (Italy)

PTB (Germany)



NIST (USA)

Microwave atomic clocks

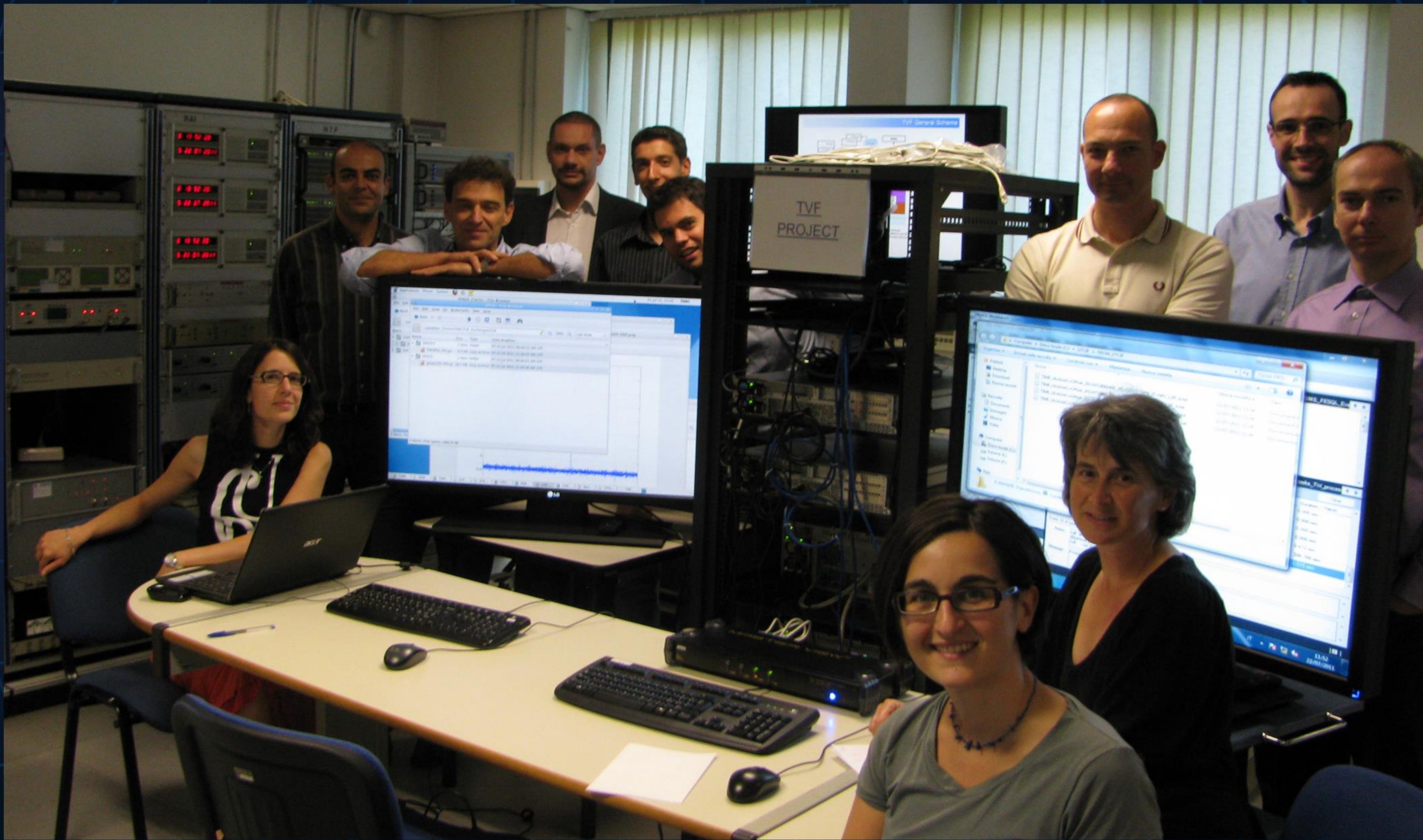
At the basis of satellite-based navigation systems

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

GALILEO Time Validation Facility

...to GALILEO

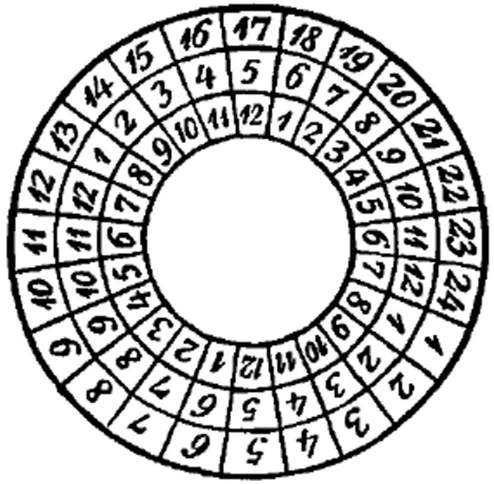
GALILEO Time Validation Facility @ INRIM



J.W. GOETHE
VIAGGIO IN ITALIA

CERCHIO COMPARATIVO
dell'ora italiana e tedesca, nonché dell'orario italiano per la seconda metà di settembre

Mezzogiorno



Mezzanotte

La notte cresce di mezz'ora ogni mezzo mese

Mese	Giorno	È notte secondo il nostro orario alle	Qui è perciò mezzanotte alle
Ag.	1	8½	3½
»	15	8	4
Sett.	1	7½	4½
»	15	7	5
Ott.	1	6½	5½
»	15	6	6
Nov.	1	5½	6½
»	15	5	7

D'ora in poi l'ora rimane fissa ed è

	notte	mezzanotte
Dic. Genn.	alle 5	alle 7

Il giorno cresce di mezz'ora ogni mezzo mese

Mese	Giorno	È notte secondo il nostro orario alle	Qui è perciò mezzanotte alle
Febbr.	1	5½	6½
»	15	6	6
Marzo	1	6½	5½
»	15	7	5
Aprile	1	7½	4½
»	15	8	4
Maggio	1	8½	3½
»	15	9	3

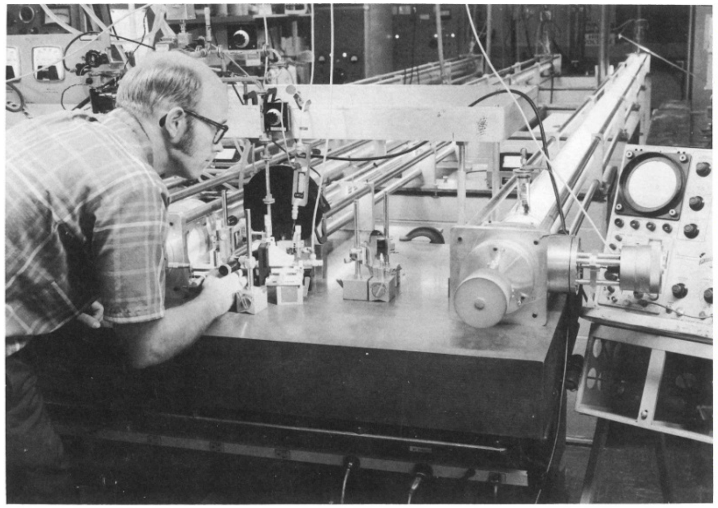
D'ora in poi l'ora rimane fissa ed è

	notte	mezzanotte
Giugno Luglio	alle 9	alle 3

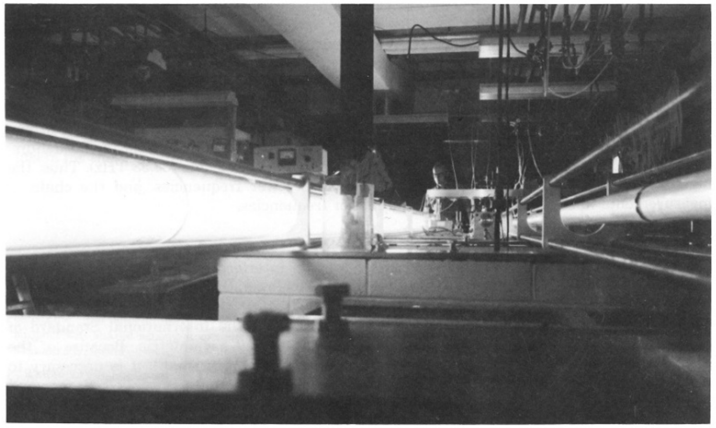
Dear Massimo, As you see in this book it is pre-Inguscio!
The last entry is 1976 — and you came here in 1977.

months later, absolute frequency measurements were extended to still higher values (again reported as "highest cw frequency measurements as yet reported"), using the CO_2 laser [38]. These measurements led in turn to the He-Ne laser cited in ref. [36] above [39].

It is too bad the "new" meter is not in here, or the first ν measure of visible light, or those fun things we did when you were here.
I hope you will again get some time to spend with us again!
Best Wishes,
Ken.



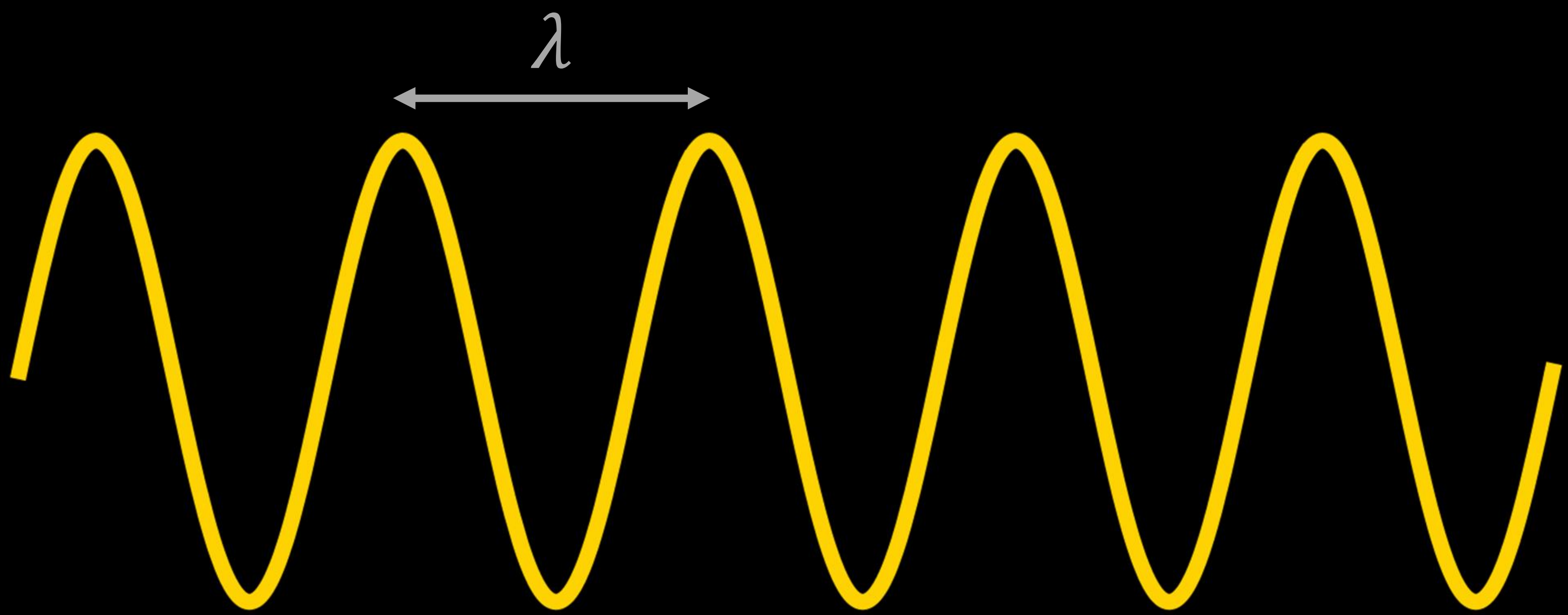
Laser research at NBS Boulder has improved the determination of the speed of light by 100-fold. Kenneth M. Evenson is adjusting lasers used in the project.



Laser used in the speed-of-light determination.

Kenneth Evenson

NBS (now NIST)
Boulder Colorado



$$c = \lambda \nu$$

Meter: 1/ 299 792 458 seconds

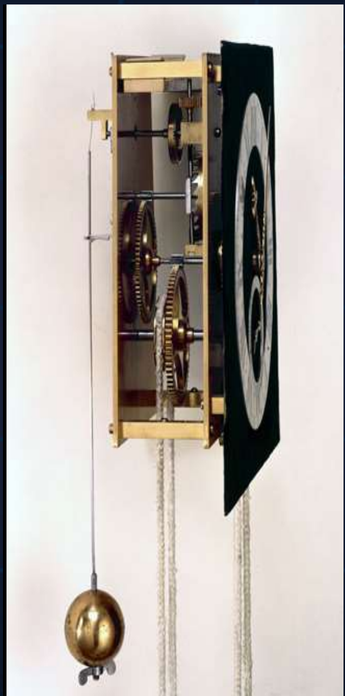
Optical atomic clocks

Counting time

~5000 a.C.
sundial

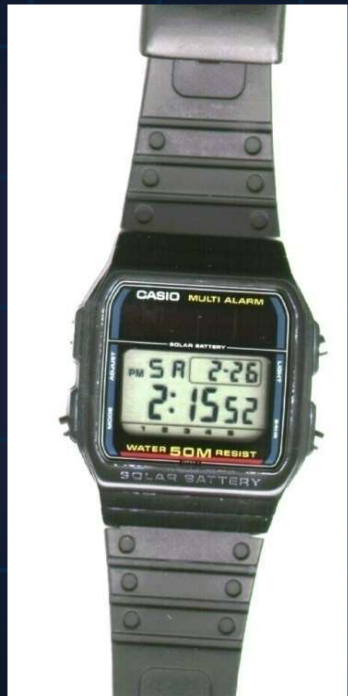
1
osc. / day

1656
pendulum clock



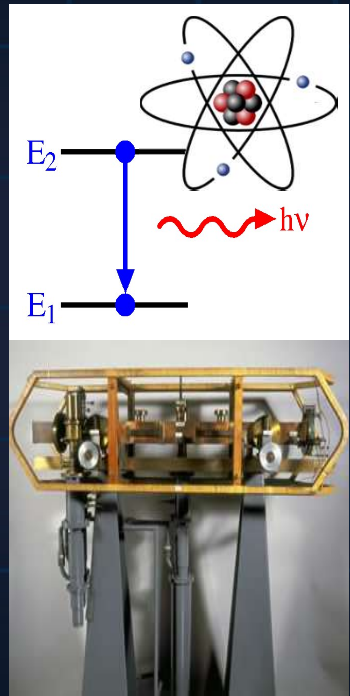
1
osc. / second

1918
quartz clock



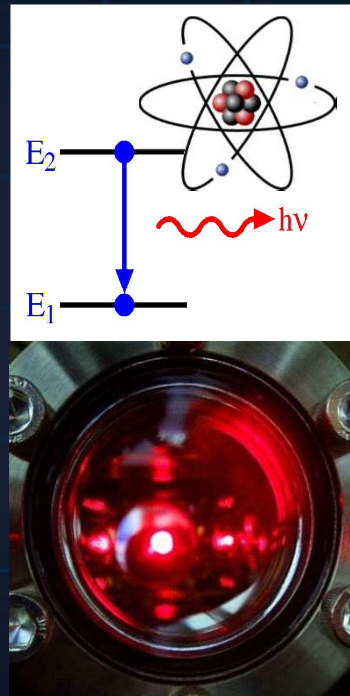
32.768
osc. / second

1955
microwave atomic clock



9.192.631.770
osc. / second

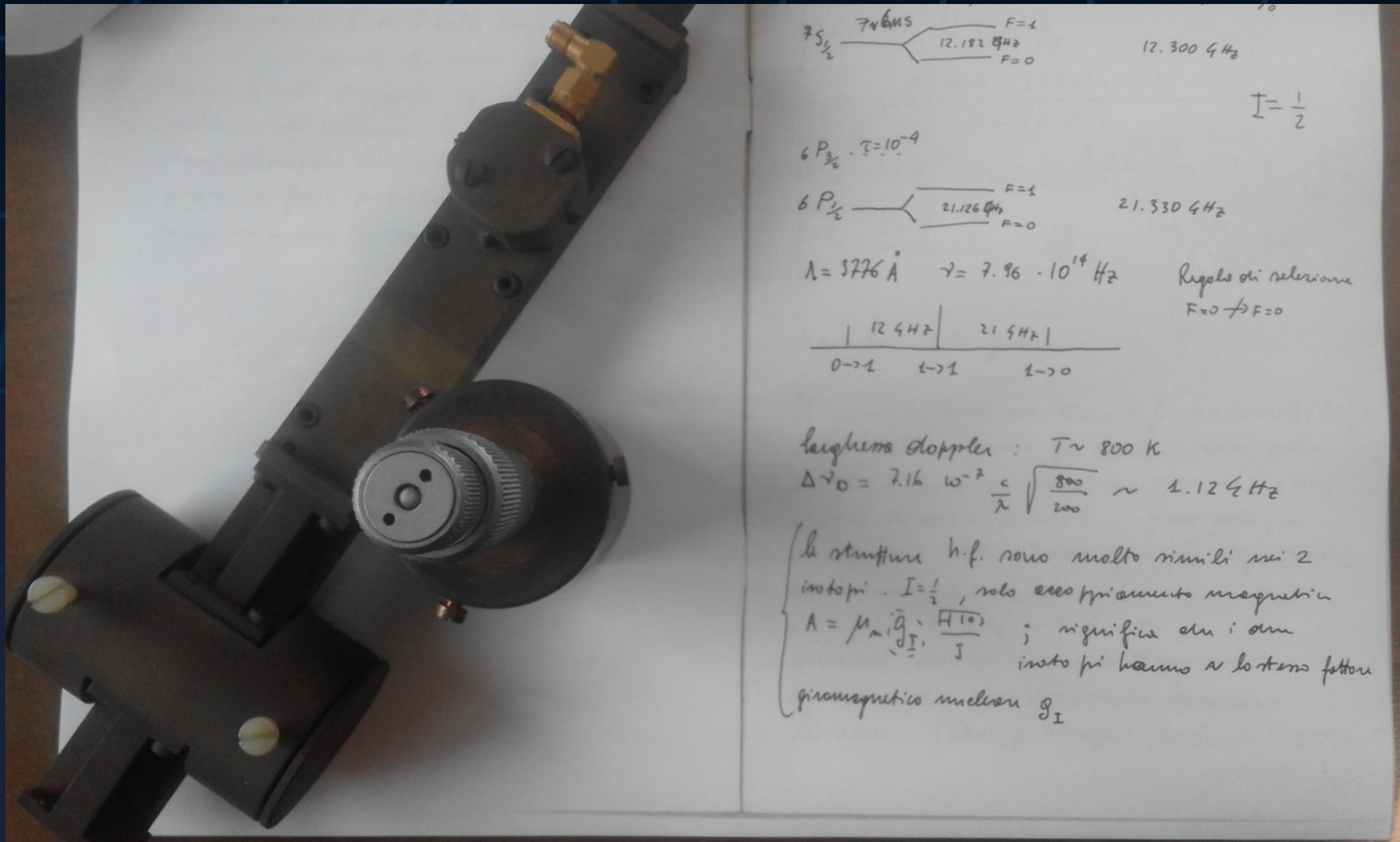
~2010
optical atomic clock



518.295.836.590.863
osc. / second

Increasing the clock frequency

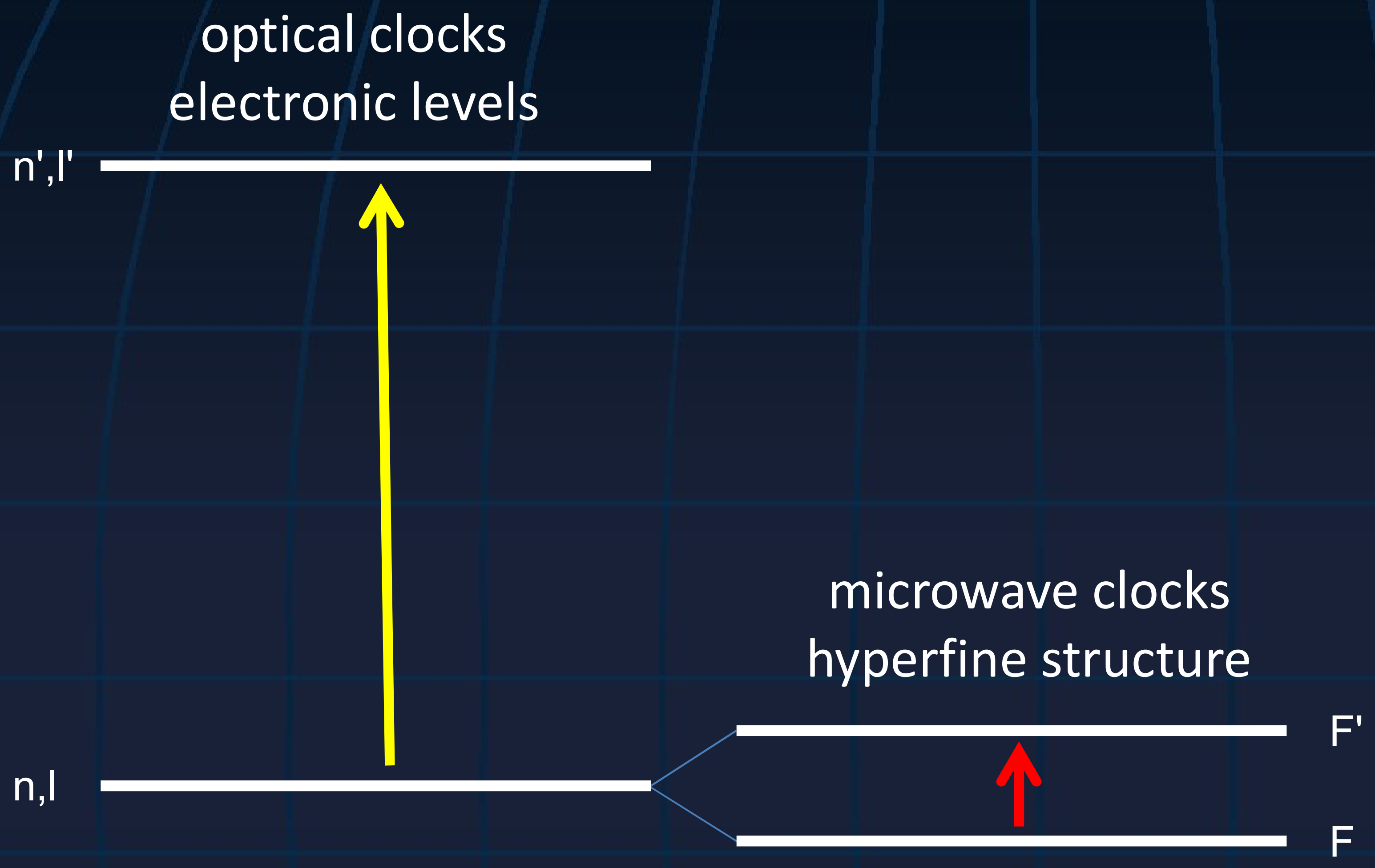
From Caesium to Thallium: 9 to 21 GHz…



1973 – IEN Galileo Ferraris (now INRiM)

Increasing the clock frequency

From microwave to optical: ~10 GHz to ~500 THz…

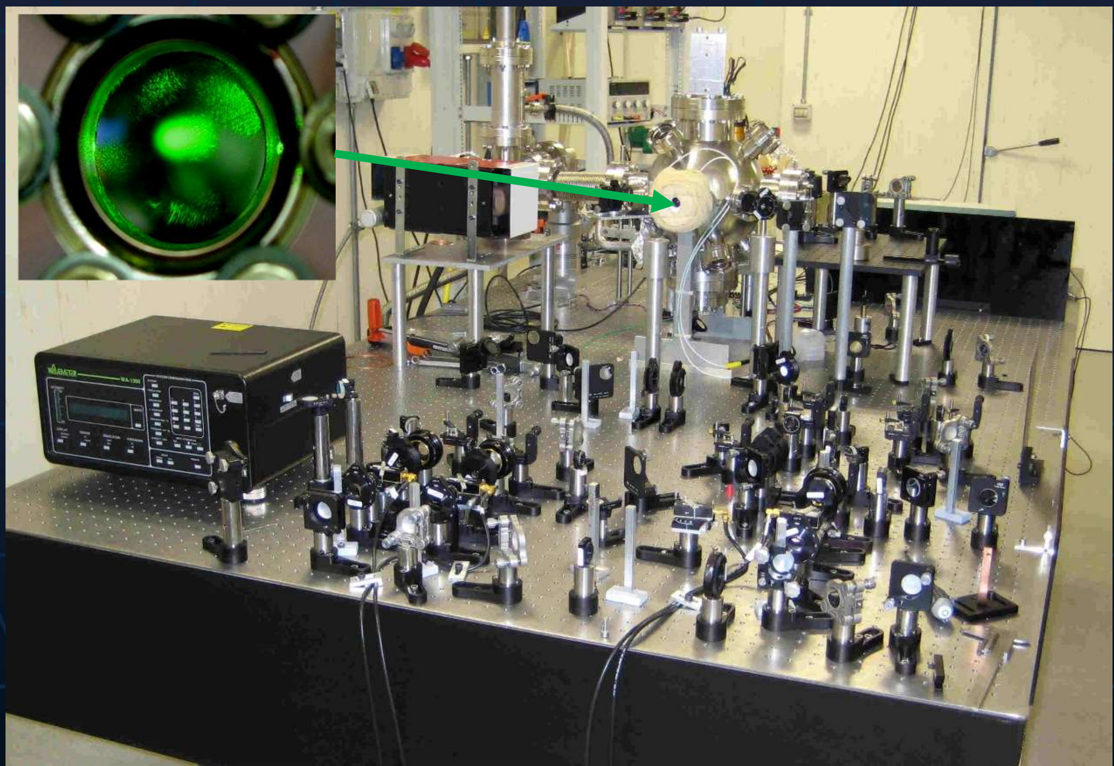


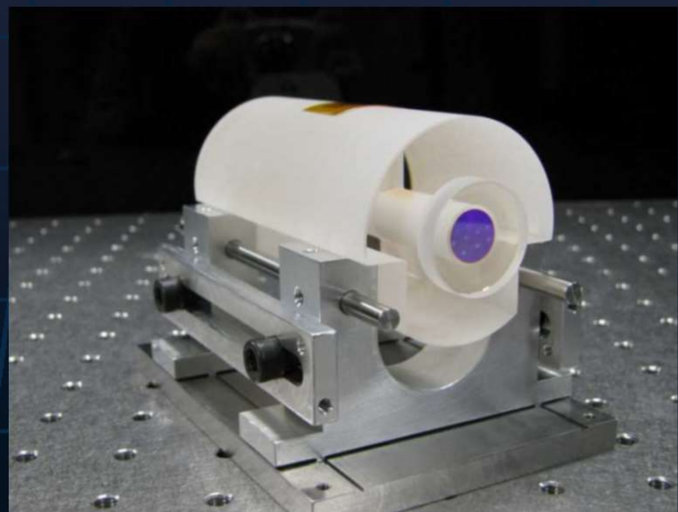
Optical atomic clocks

Ticking time with ultrastable light linked to an atomic frequency

Electronic levels of Yb

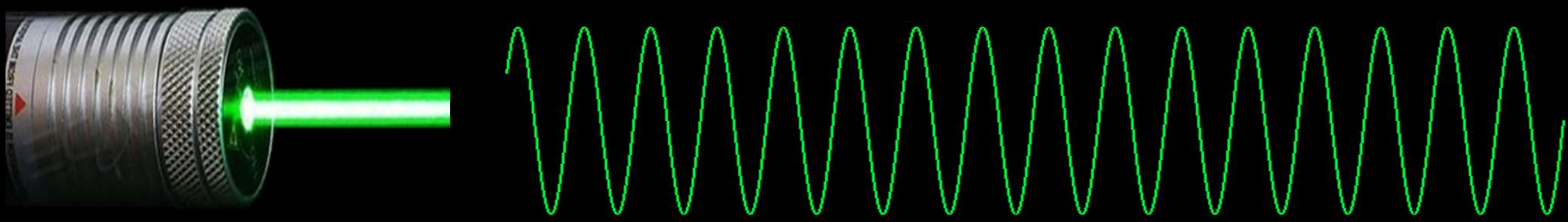
Ultranarrow optical transition!!



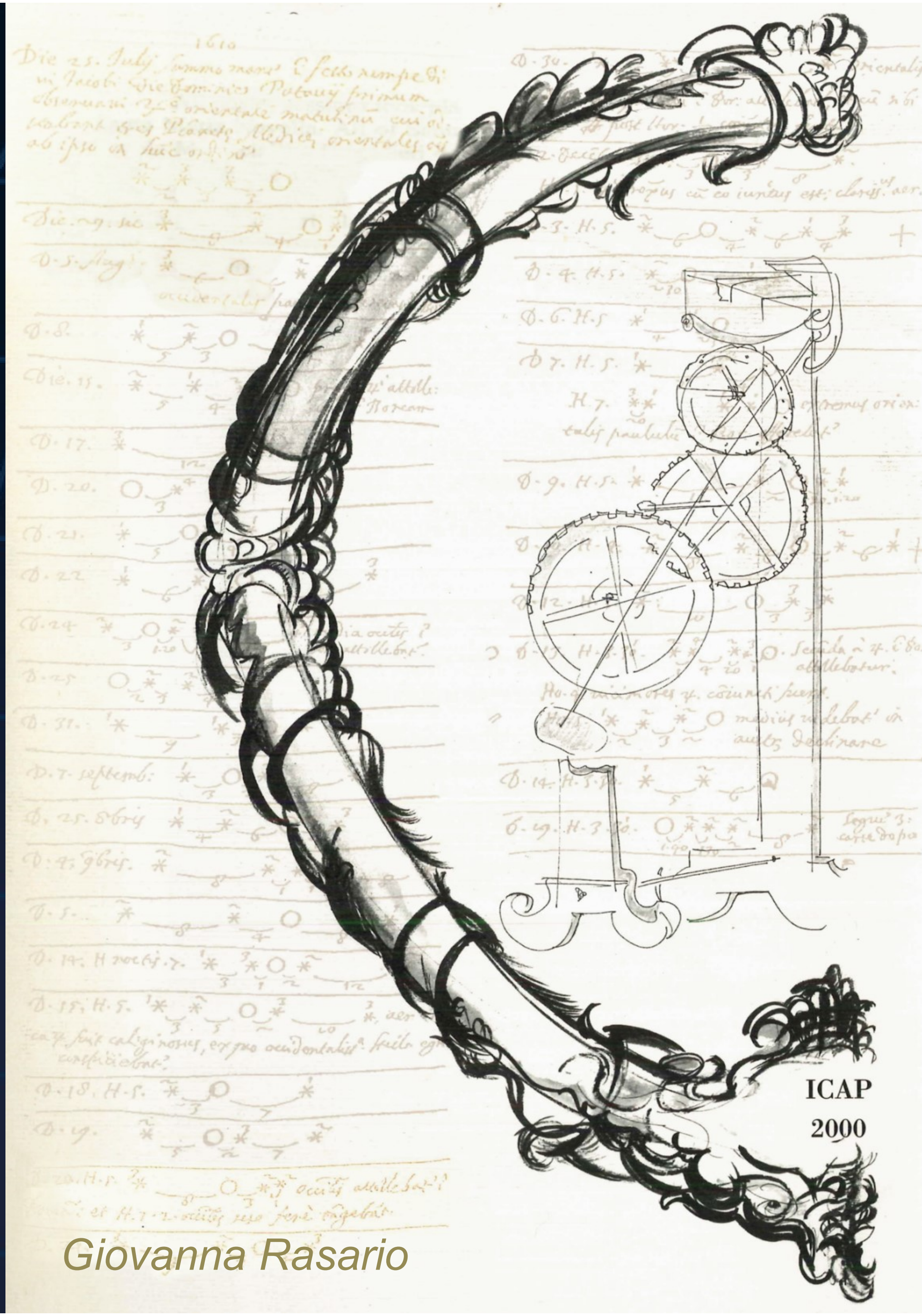


Optical atomic clocks

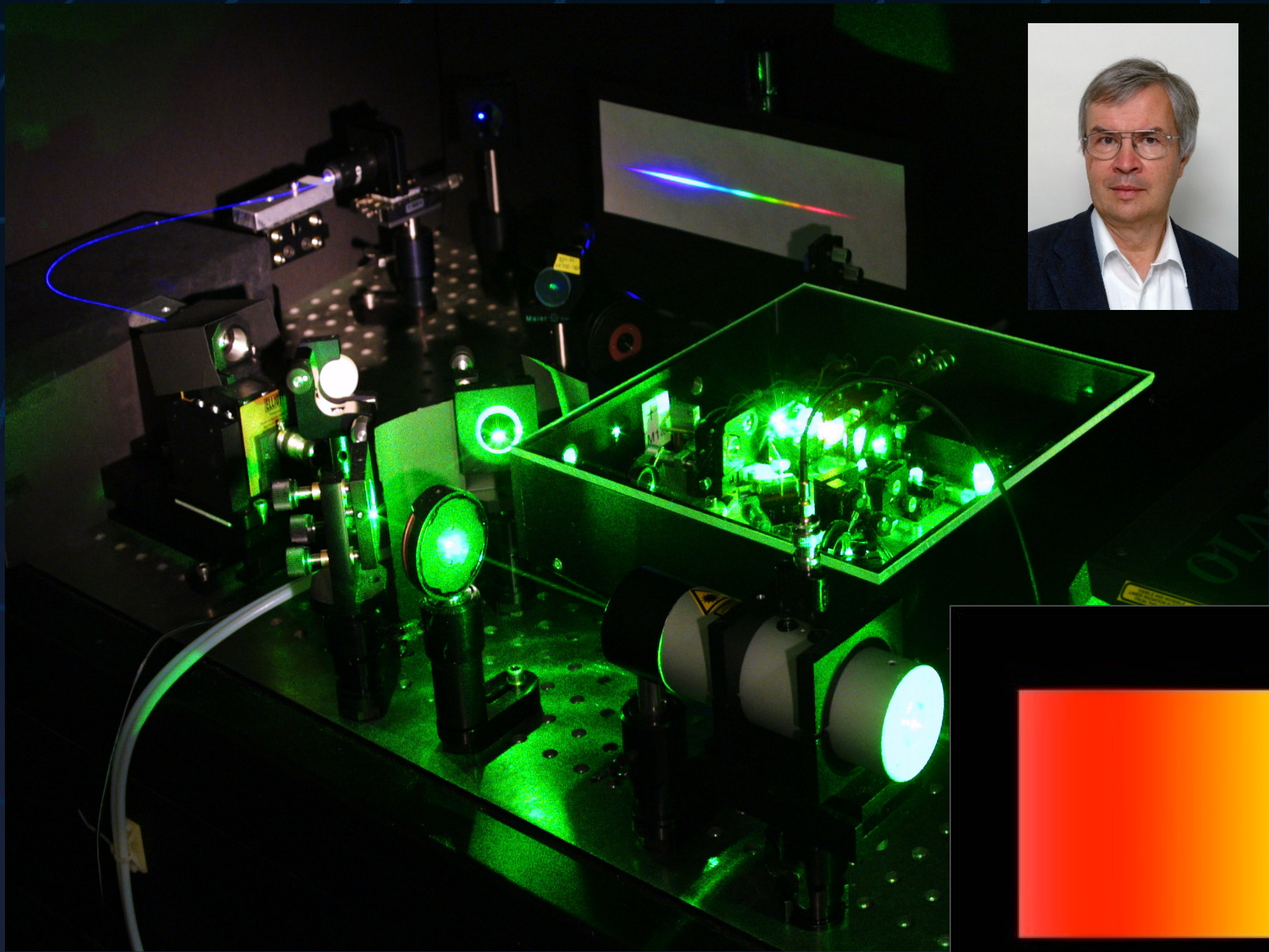
Measuring time = counting oscillations of light

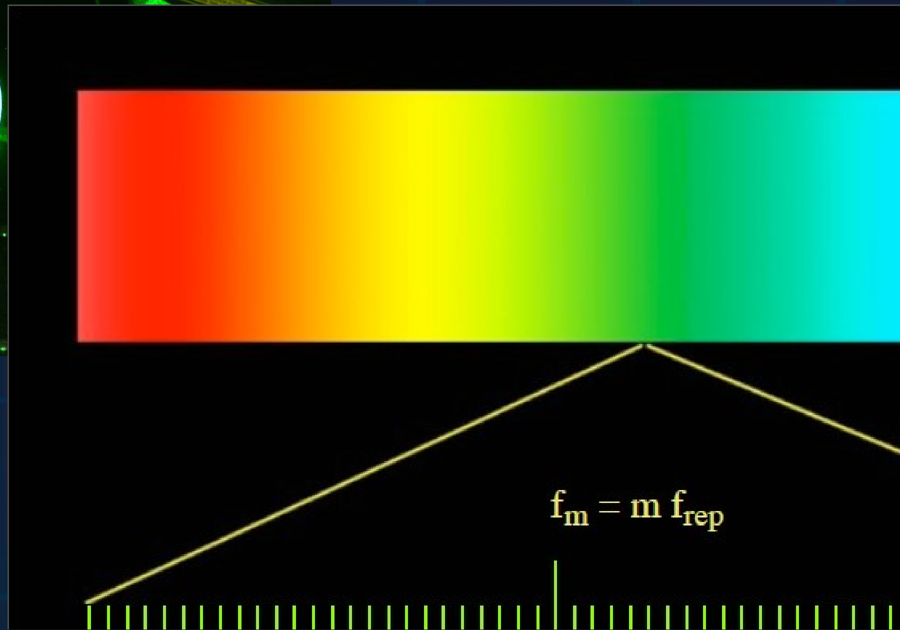


518 295 836 590 863   osc. / secondo


ICAP
2000
Giovanna Rasario

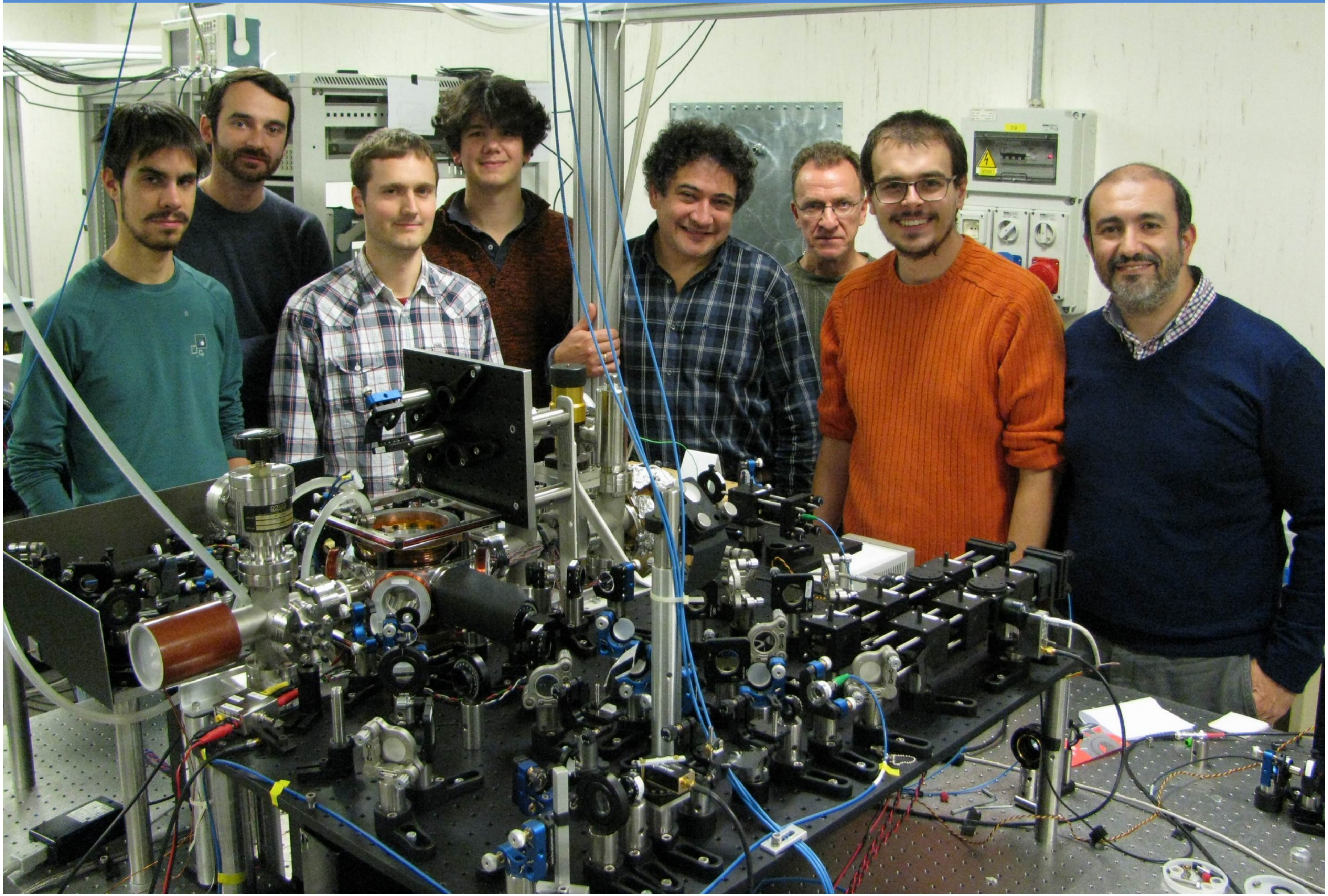
A counter for light





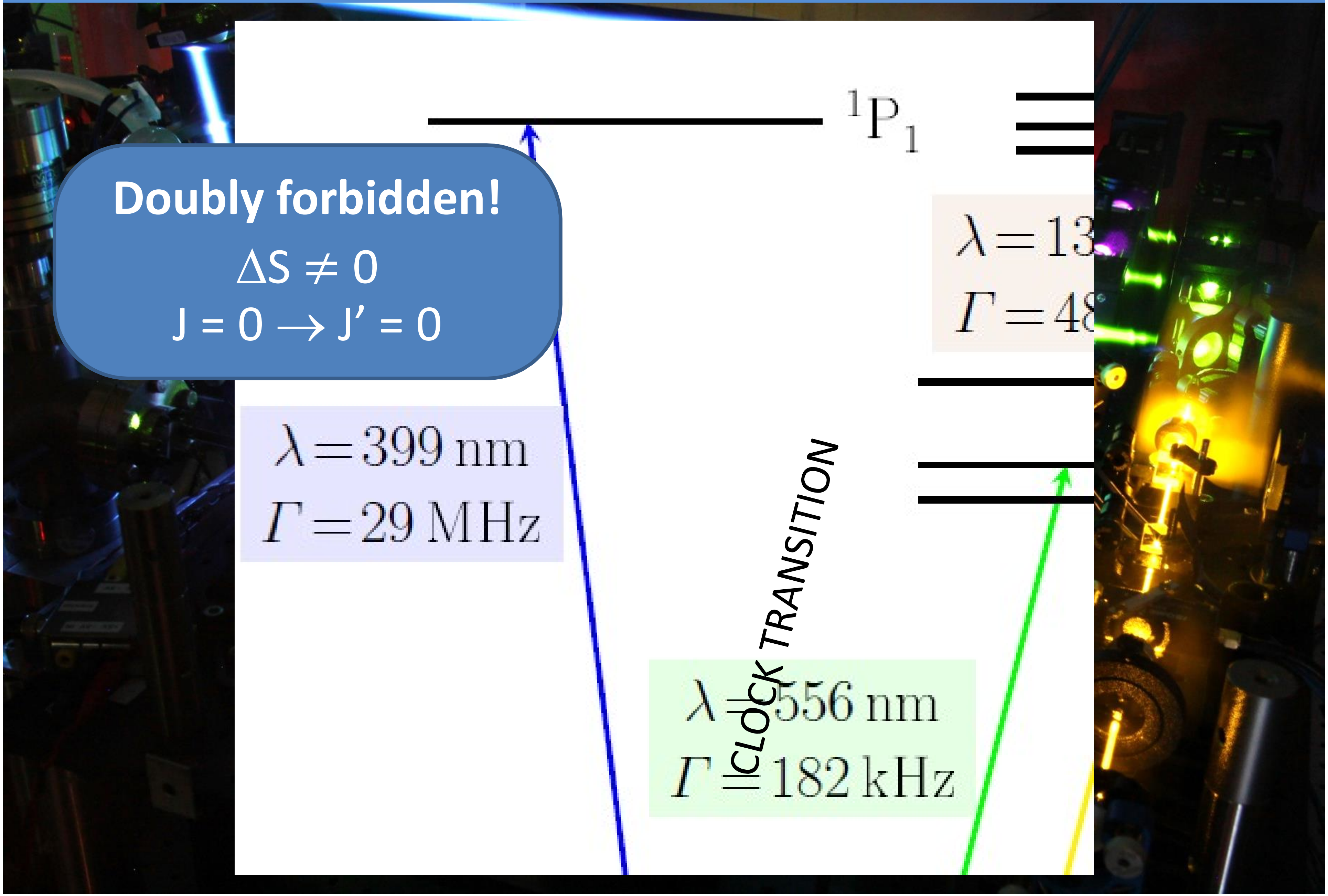
The optical frequency comb:
a frequency ruler of laser lines

Yb optical clock at INRIM

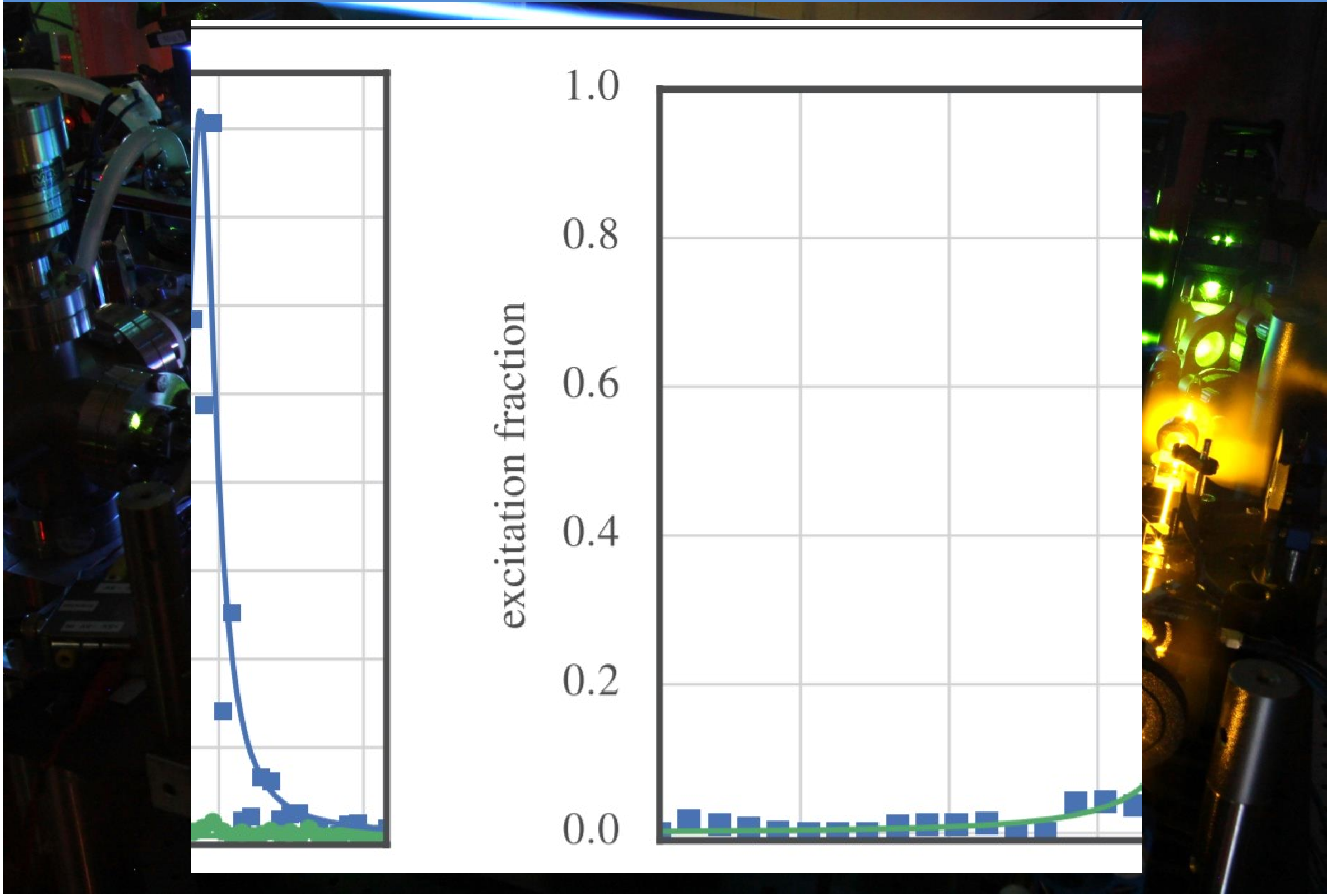


*M. Pizzocaro et al., Metrologia **54**, 102 (2017)*

Yb optical clock at INRIM



Yb optical clock at INRIM



Yb optical clock at INRIM

Absolute frequency measurement of ^{171}Yb clock transition

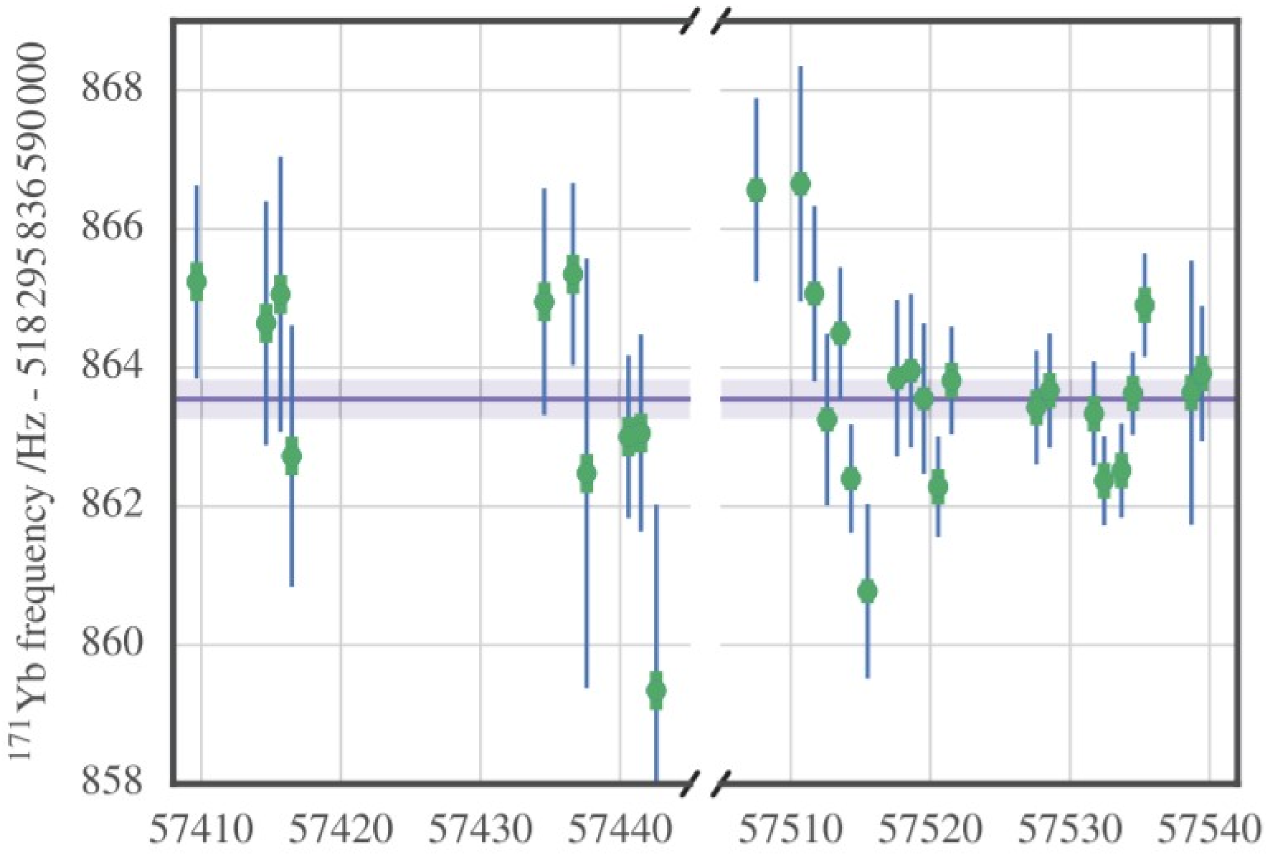
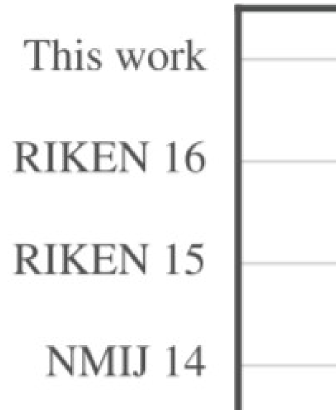


Table 2. Unce

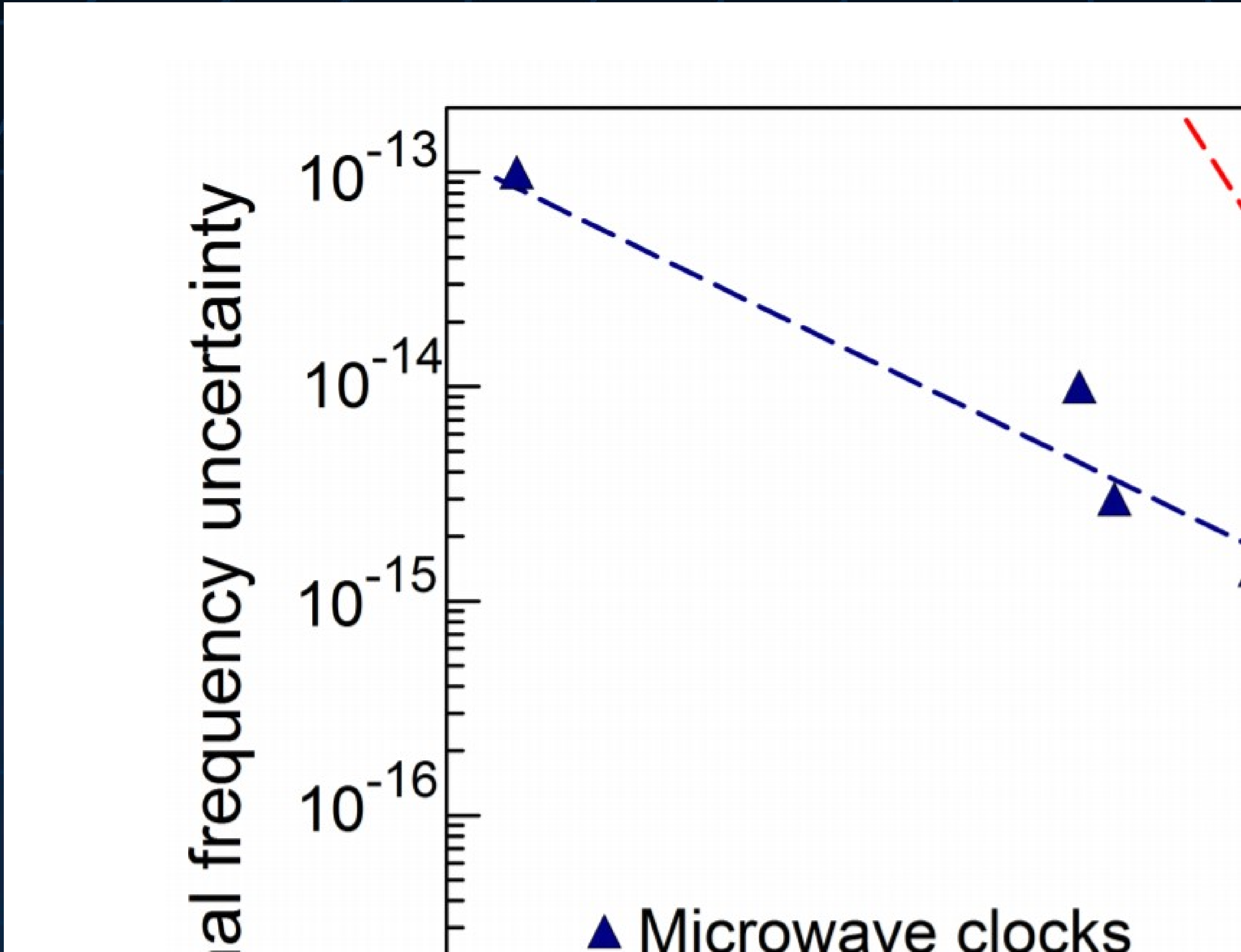
Contribution
ITCsF2
Statistics
Yb
Comb
Grav. redshift
Fiber link
Synchronization
Total



aign run from January
cy of ^{171}Yb relative to

*M. Safronova et al., RMP **90**, 025008 (2018)*

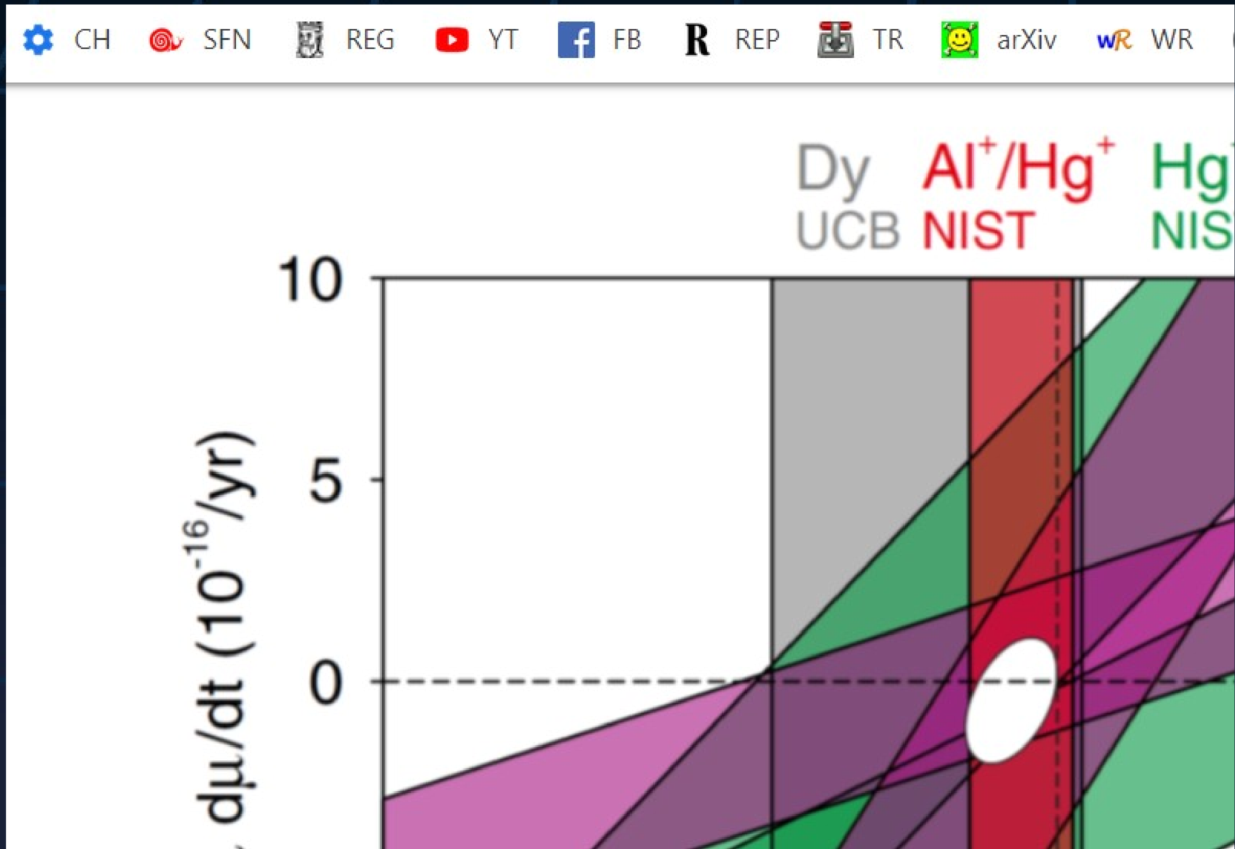
Uncertainty of atomic clocks



M. Safronova et al., RMP (2018)

Are fundamental constants constant?

Comparison btw different atomic clocks at different measurement times



Bounds on the drift of the proton/electron mass ratio μ and fine structure constant α:

Combining this mea
previous experiments,
owing limits to the pre

13 years ago... Fermions in Varenna (2006)

ITALIAN PHYSICAL SOCIETY

PROCEEDINGS

OF THE

INTERNATIONAL SCHOOL OF

"ENRICO FERMI"

COURSE CLXIV

edited by M. INGUSCIO, W. KETTERLE and C.

Directors of the Course

VARENNA ON LAKE COM(

VILLA MONASTERO

20 – 30 June 2006

Ultra-cold Fermi (

2007

IOS Press

tà Italiana di Fisica

ZIONALE DI FISICA «E. FERMI»

VARENNA SUL LAGO DI COMO

Quantum degenerate gases and the mixtures of ytterbium atoms

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PRL **98,** 030401 (2007) PHYSICAL REVIEW LETTERS week ending 19 JANUARY 2007

Degenerate Fermi Gases of Ytterbium

Takeshi Fukuhara,[1] Yosuke Takasu,[2] Mitsutaka Kumakura,[1,3,4] and Yoshiro Takahashi[1,3]

[1]*Department of Physics, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan*
[2]*Department of Electronic Science and Engineering, Graduate School of Engineering, Kyoto University, Kyoto 615-8510, Japan*
[3]*CREST, Japan Science and Technology Agency, Kawaguchi, Saitama 332-0012, Japan*
[4]*PRESTO, Japan Science and Technology Agency, Kawaguchi, Saitama 332-0012, Japan*

(Received 8 July 2006; published 17 January 2007)

Evaporative cooling was performed to cool fermionic ^{173}Yb atoms in a crossed optical dipole trap. The large elastic collision rate leads to efficient evaporation and we have successfully cooled the atoms to 0.37 ± 0.06 of the Fermi temperature, that is to say, to a quantum degenerate regime. In this regime, a plunge of evaporation efficiency was observed as a result of Fermi degeneracy.

DOI: 10.1103/PhysRevLett.98.030401 PACS numbers: 03.75.Ss, 32.80.Pj, 34.50.−s

PRL 98, 030401 (2007) PHYSICAL REVIEW LETTERS week ending 19 JANUARY 2007

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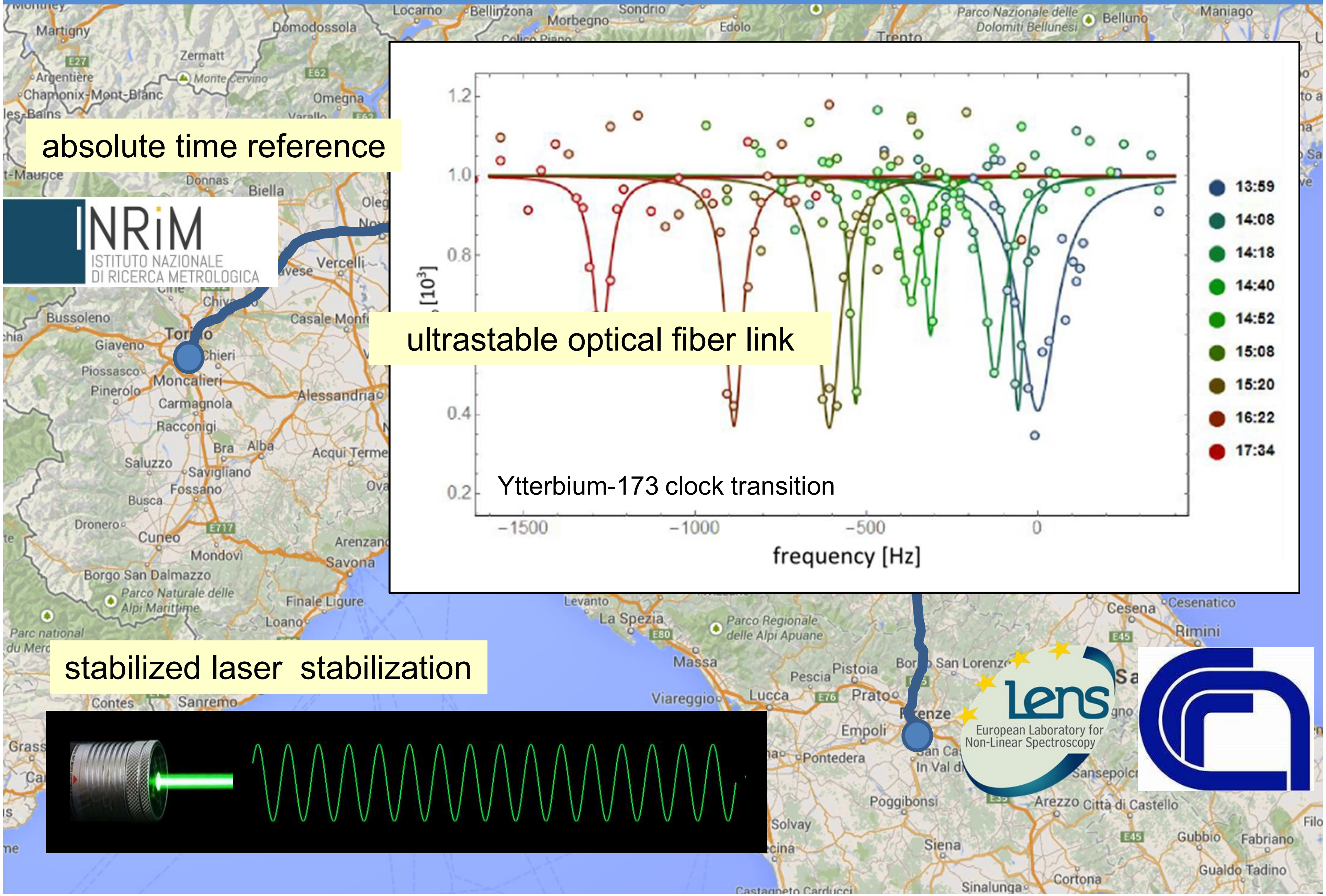
“Ultracold Fermi Gases” Varenna, June 2006

Linking clocks:
communicating time, sensing and beyond

Optical fiber link

- Time/freq. dissemination
- Radioastronomy
- Ultracold atoms physics
- Aerospace
- Finance
- Quantum technologies (QKD)

“Absolute” time dissemination



Matera

Matera

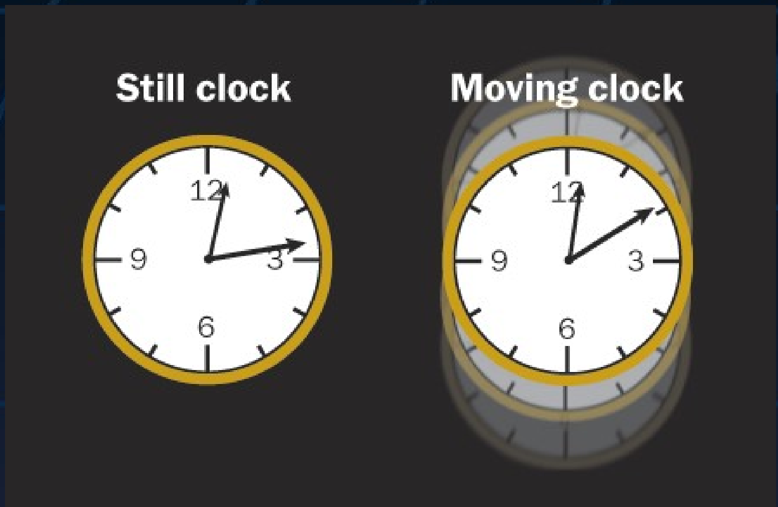
The enigma of the hour

Giovanna Rasario «Giorgio De Chirico, un filo di Arianna»

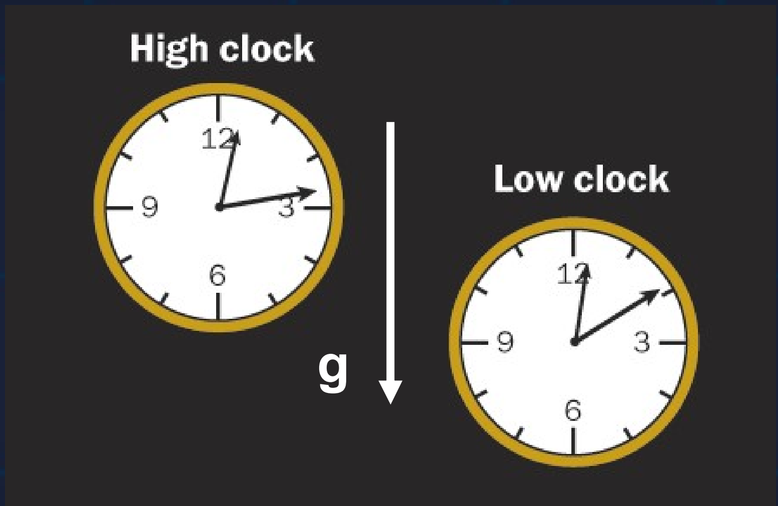
A relative time

Absolute time does not exist *(A. Einstein, 1905-1915)*

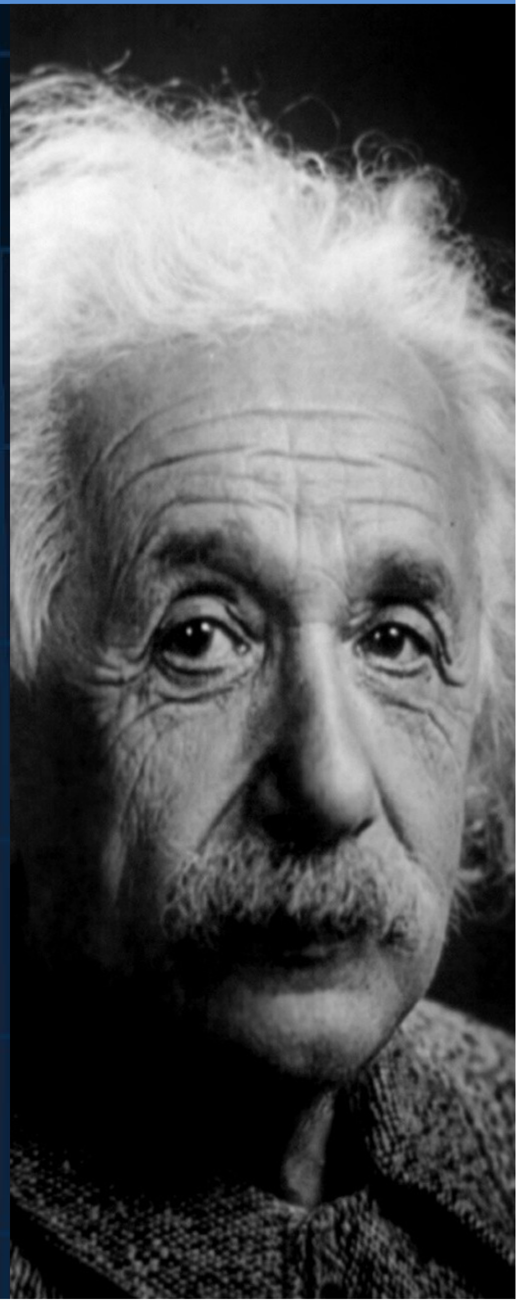
Time dilation because of motion and gravity



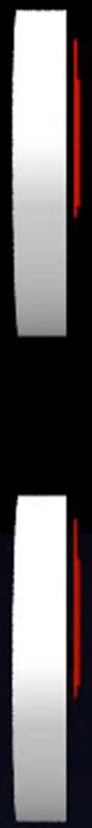
$$\frac{\delta f}{f} = \frac{v^2}{2c^2}$$



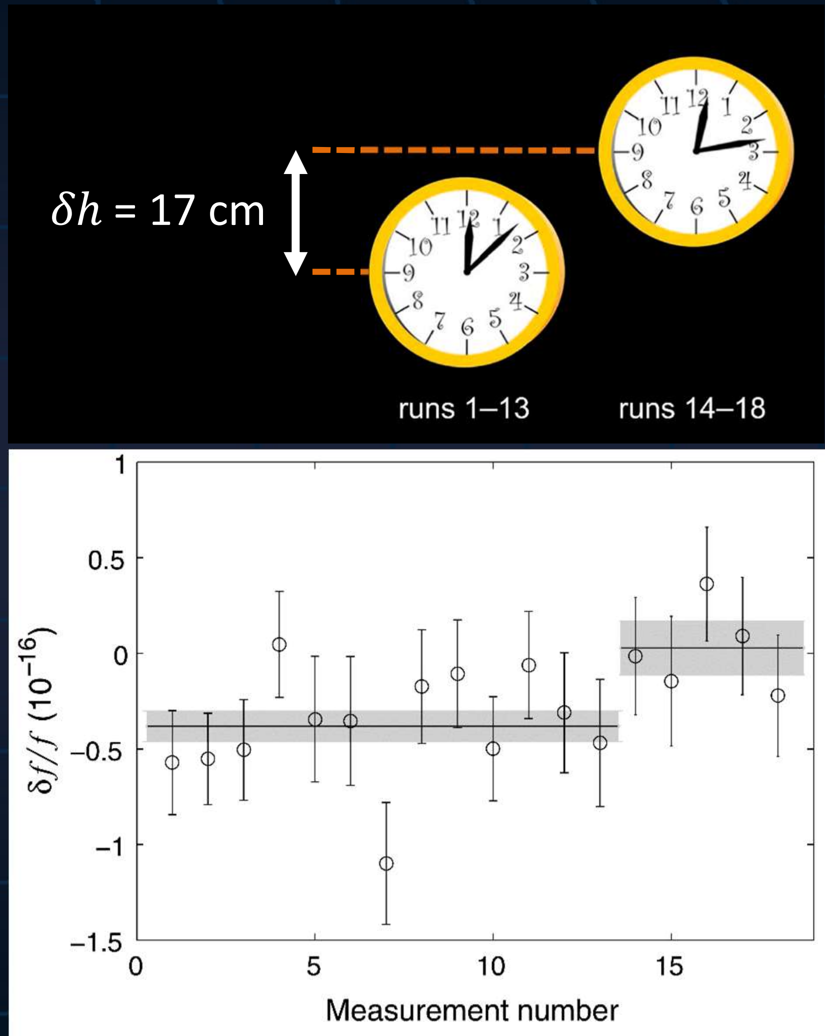
$$\frac{\delta f}{f} = \frac{g}{c^2}\delta h$$



A relative time

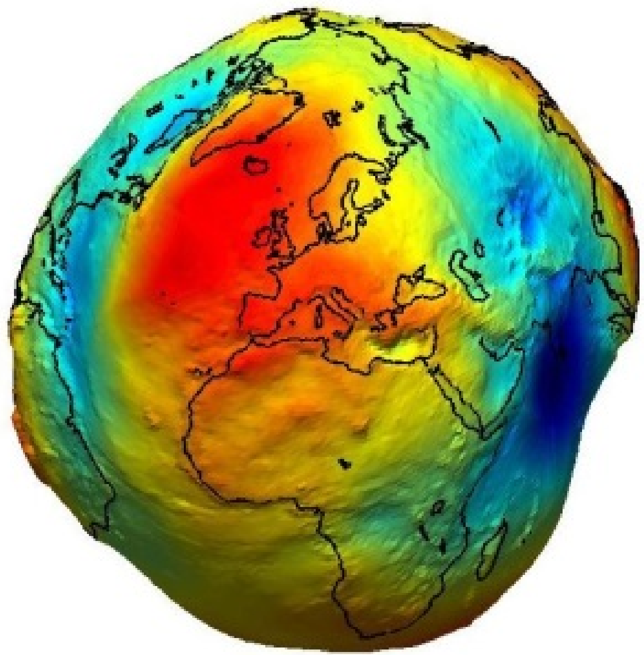


Gravitational redshift: 10^{-16} / m



D. Wineland Al^+ ion clock (NIST, Boulder)

Clocks and gravitational redshift



In the weak field approximation (as in the Solar System), two clocks placed at two different locations with different gravitational potential W, have a frequency offset:

$$\frac{\nu_0 - \nu(\bar{r})}{\nu_0} = \frac{W(\bar{r}) - W_0}{c^2}$$

On Earth (W_0 is the Geoid potential):

$$\frac{\nu_0 - \nu(\bar{r})}{f_\nu} \approx \frac{g_0}{c^2} m^{-1} = 1.09 \times 10^{-16} m^{-1}$$

Clocks comparisons at different gravity potentials

IEN G. Ferraris
1977

IL NUOVO CIMENTO Vol. 37 B, N. 2 11 Febbraio 1977

Evidence for the Earth Gravitational Shift by Direct Atomic-Time-Scale Comparison (*).

L. Briatore
Istituto di Fisica Generale dell'Università - Torino
Laboratorio di Cosmogeofisica del CNR - Torino

S. Leschiutta
Istituto Elettrotecnico Nazionale «Galileo Ferraris» - Torino

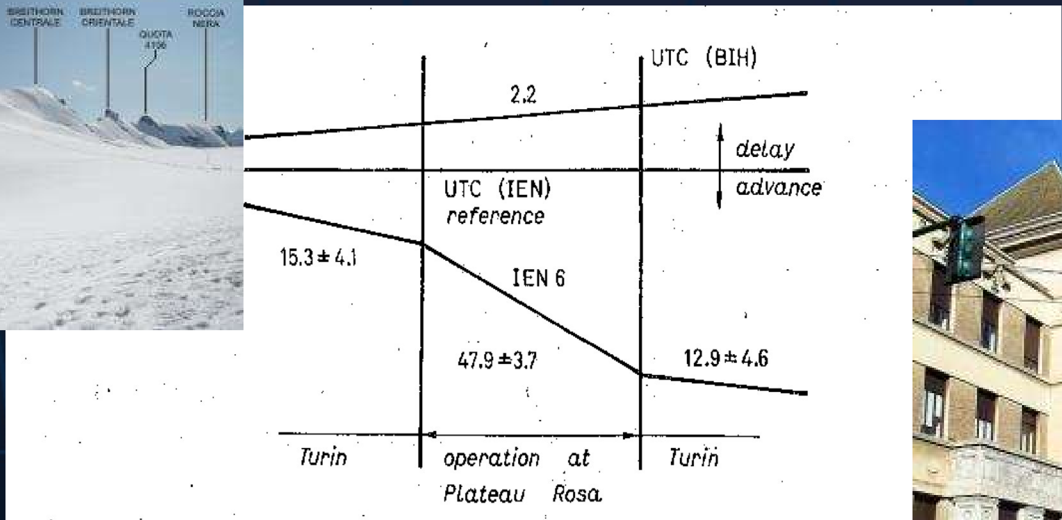
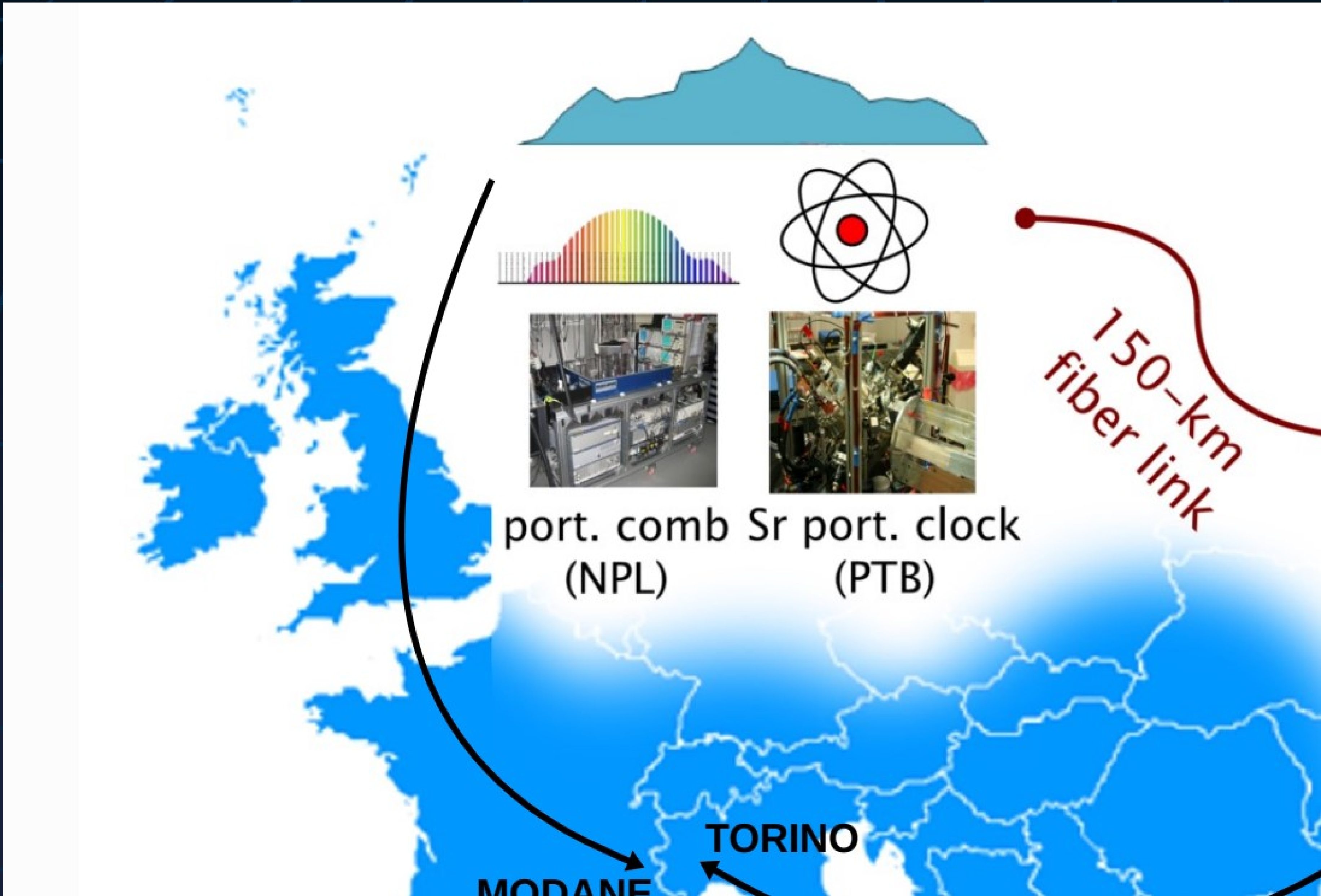


Fig. 3. – Schematic drawing of the least-square-fitted relative behaviours UTC (IEN) and UTC (BIH) for the periods concerned. The slopes are UTC (IEN) and are given in ns/d.

J. Grotti et al., Nature Phys. ***14****, 437 (2018)*

Relativistic geodesy on the Alps



J. Grotti et al., Nature Phys. ***14****, 437 (2018)*

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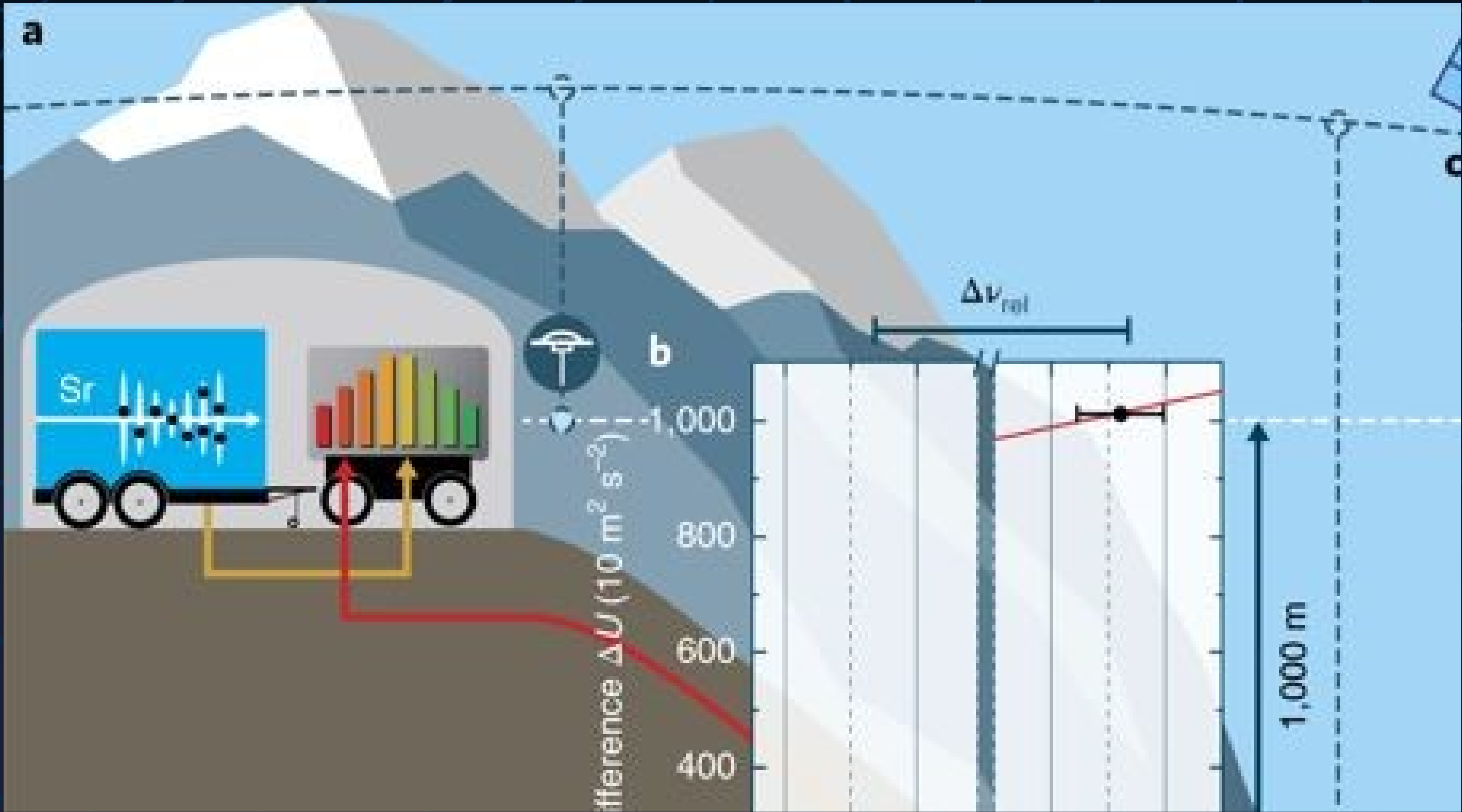


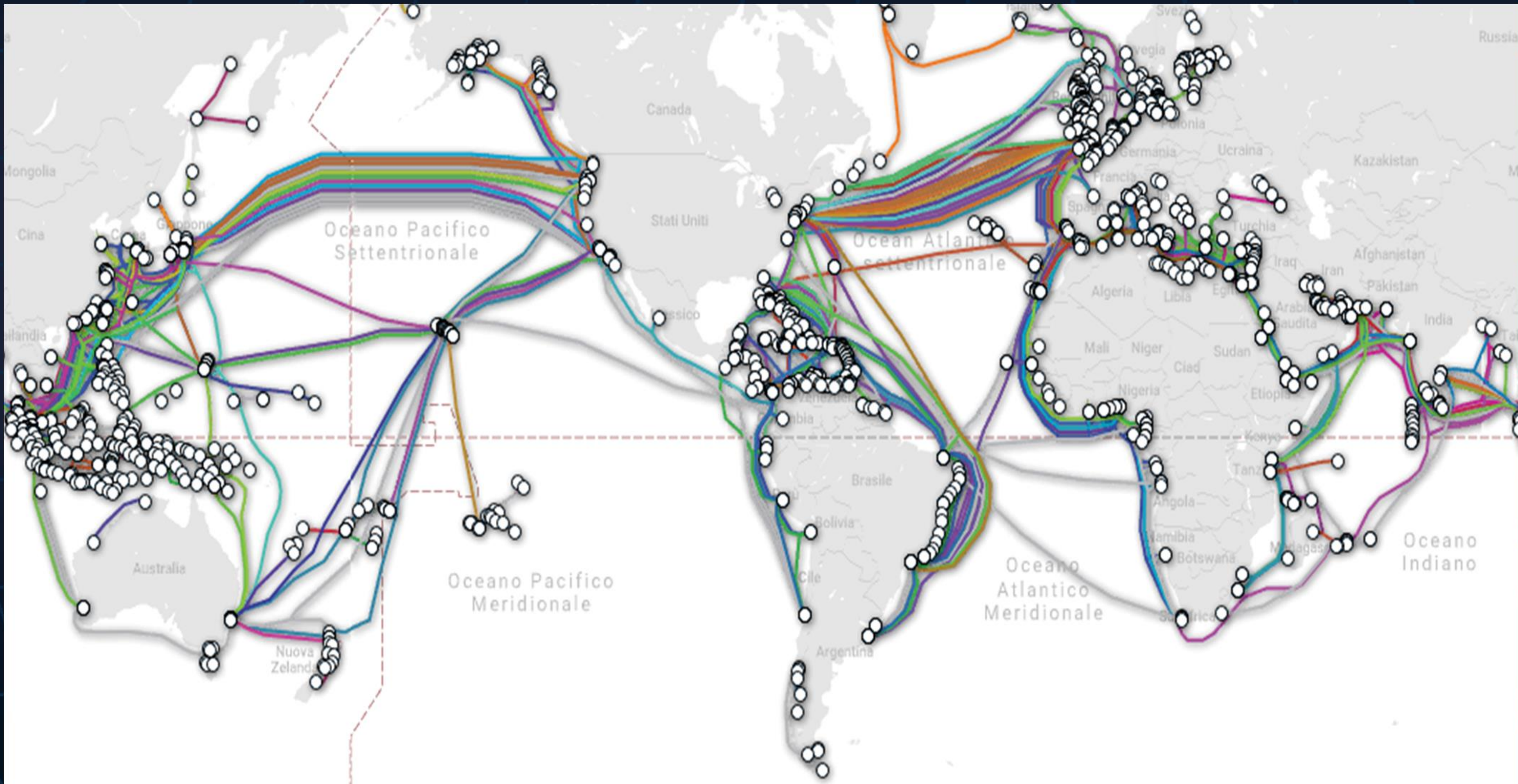
First demonstration of chronometric levelling with transportable optical clocks

Frejus tunnel – Turin gravitational potential difference: 10.034 (174) $m^2\ s^{-2}$

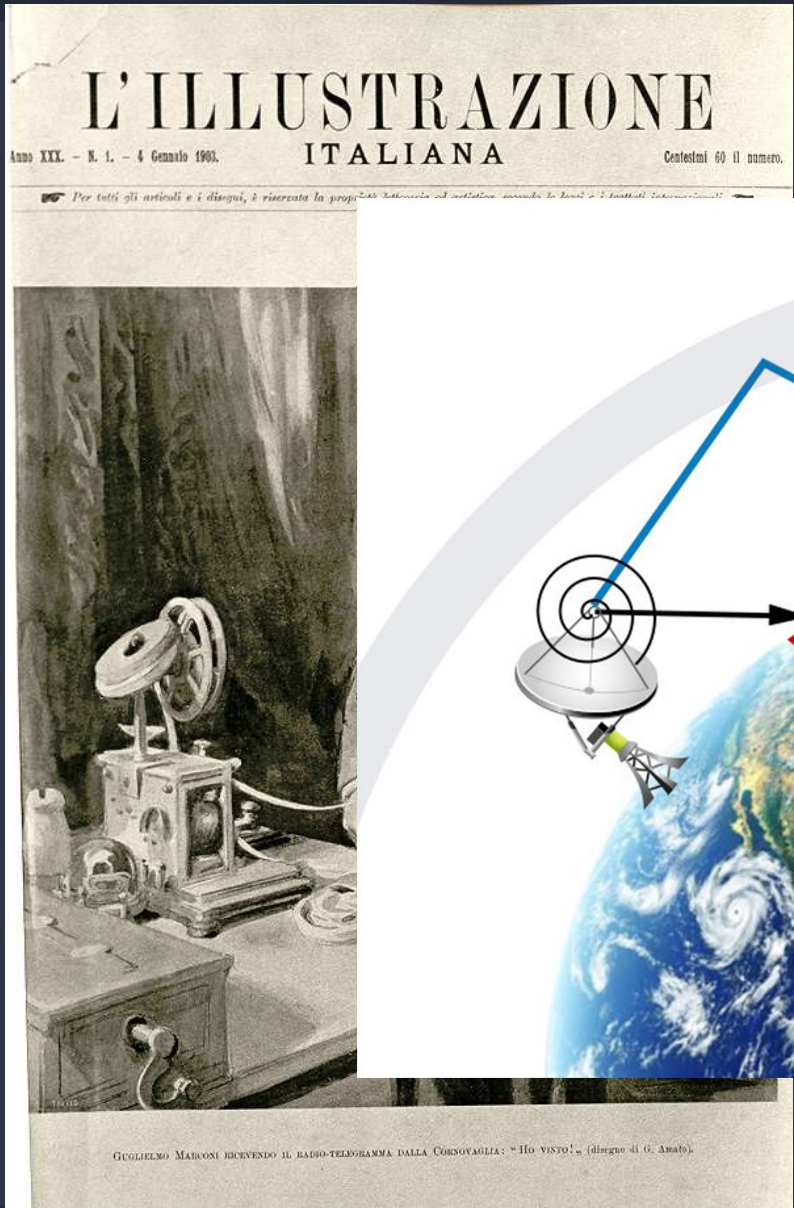
Optical fiber link for earthquake detection

Submarine earthquakes are very hard to detect
(submarine seismometers scarce, expensive and difficult to operate)

Can we use the current 1 Mkm-long submarine optical fiber network?



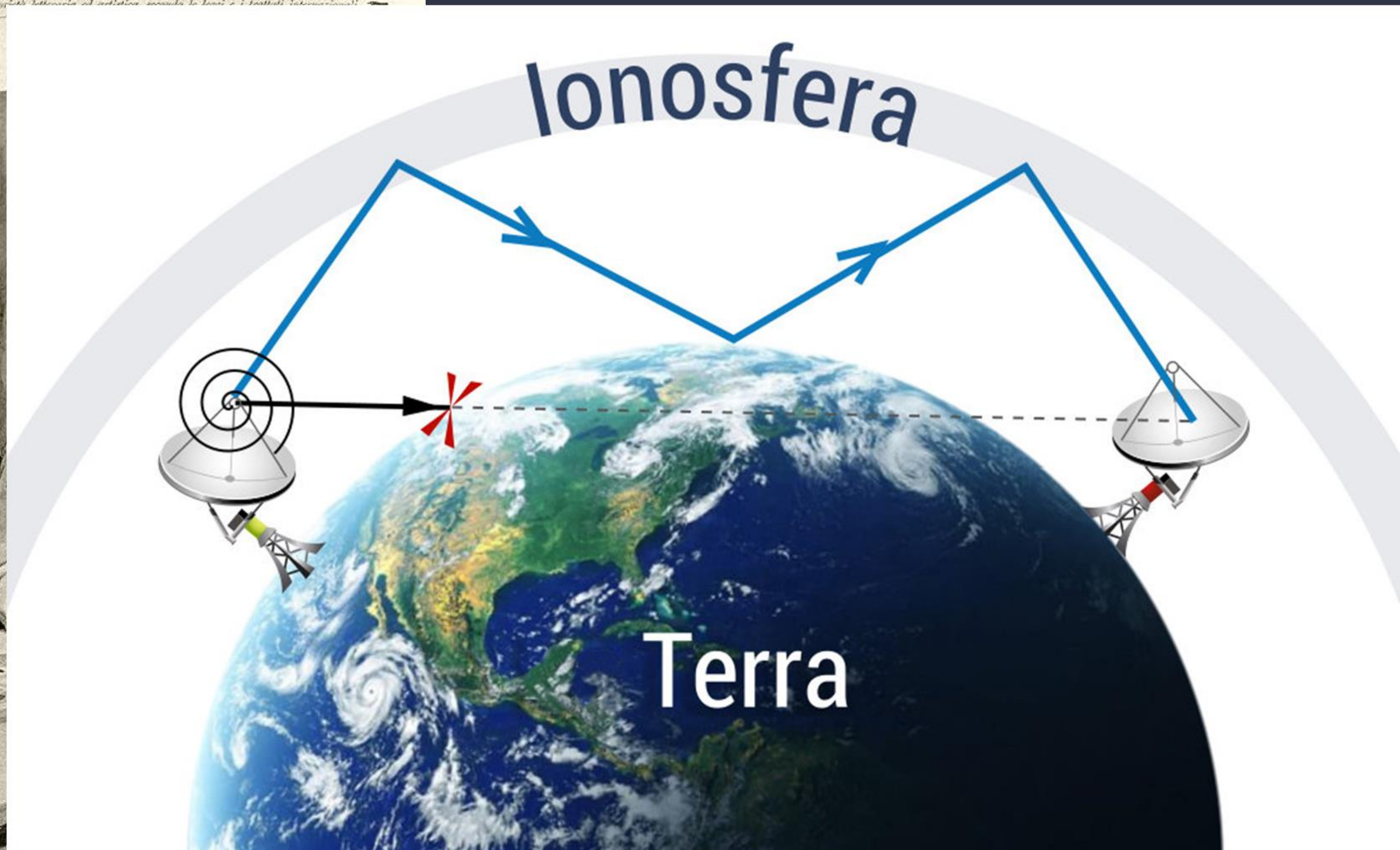
Marconi ... radiowaves


L'ILLUSTRAZIONE ITALIANA

Anno XXX. – N. 1. – 4 Gennaio 1903. Centesimi 60 il numero.

Per tutti gli articoli e i disegni, è riservata la proprietà [illegible]

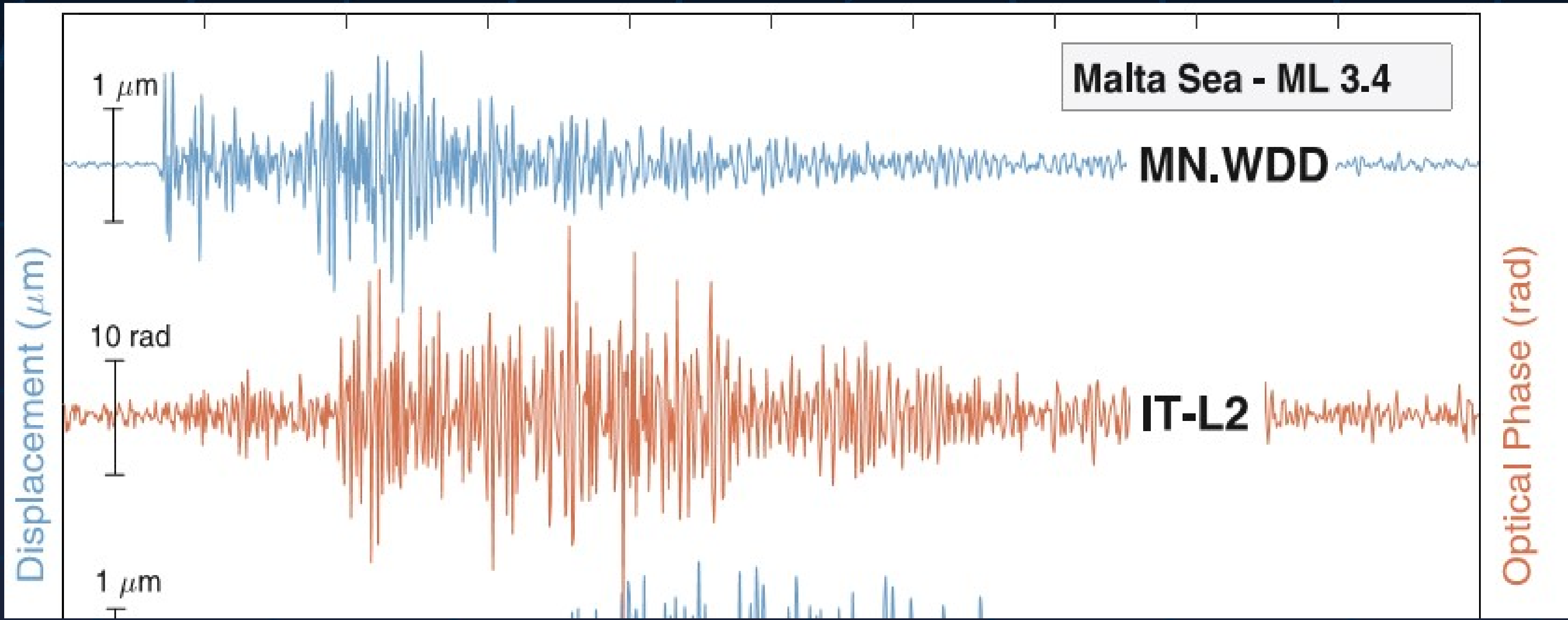
Guglielmo Marconi ricevendo il radio-telegramma dalla Cornovaglia: "Ho visto!" (disegno di G. Amato).



Optical fiber link for earthquake detection

Detection of submarine earthquakes (magnitude 3.4 e 5.1)

Blue: conventional seismometer
Red: optical fiber link error signal



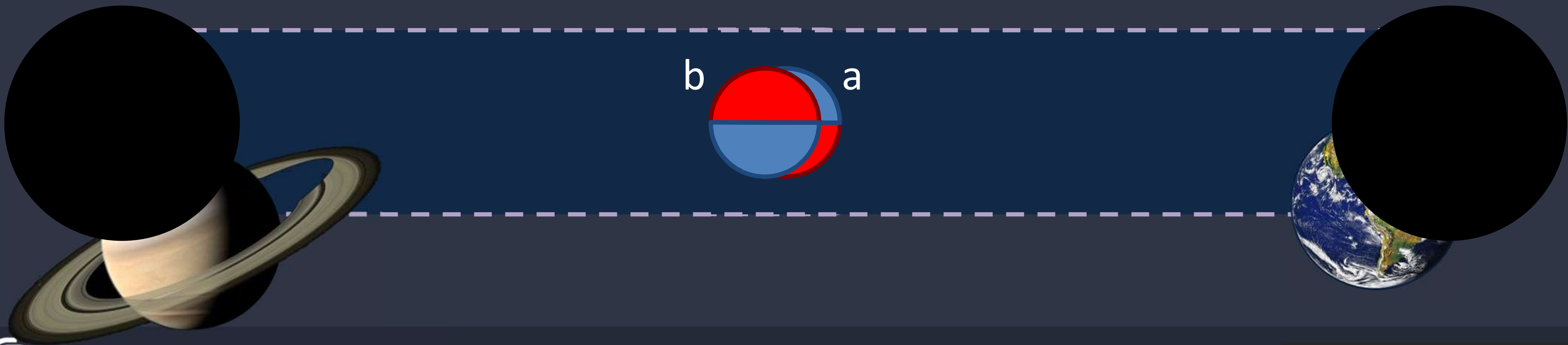
G. Marra et al., Science 361 (2018)

Quantum Communication

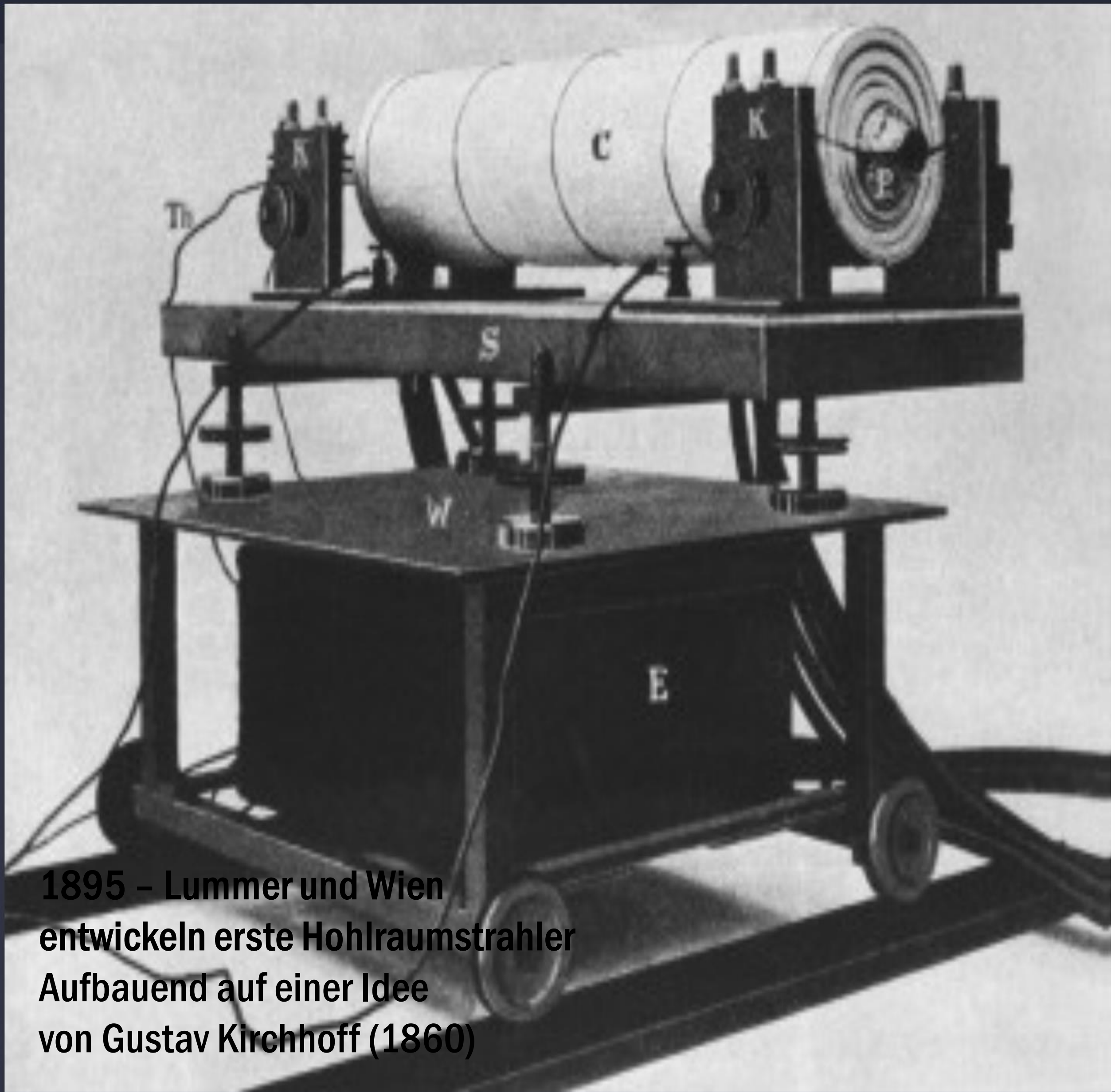
Entanglement:

$$|\,\underset{a}{\bullet}\,\underset{b}{\bullet}\,\rangle = \alpha\,|\,\underset{a}{0}\,\underset{b}{1}\,\rangle + \beta\,|\,\underset{a}{1}\,\underset{b}{0}\,\rangle$$

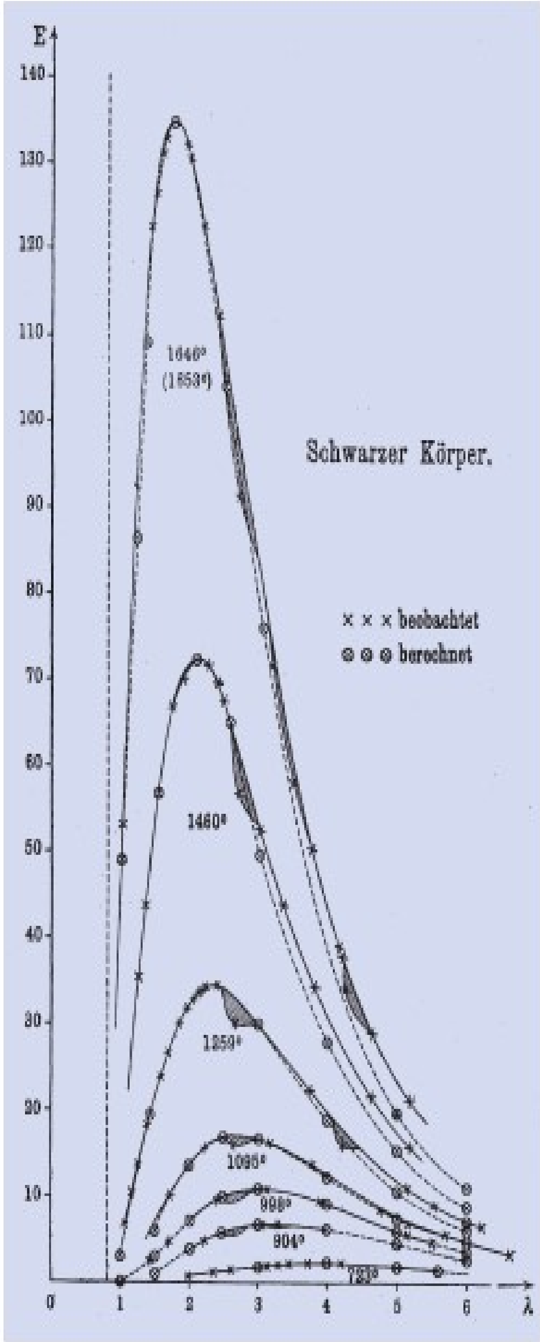
Two quantum systems can be correlated independently of their distance

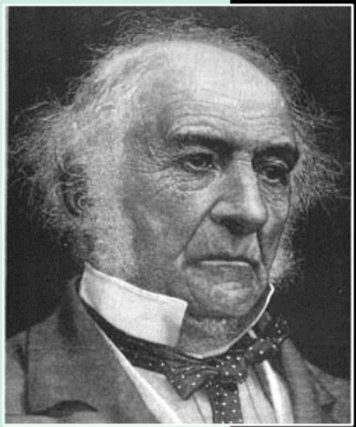



Light bulb used in
Menlo Park,
Christmas week, 1879
1



1895 – Lummer und Wien
entwickeln erste Hohlraumstrahler
Aufbauend auf einer Idee
von Gustav Kirchhoff (1860)

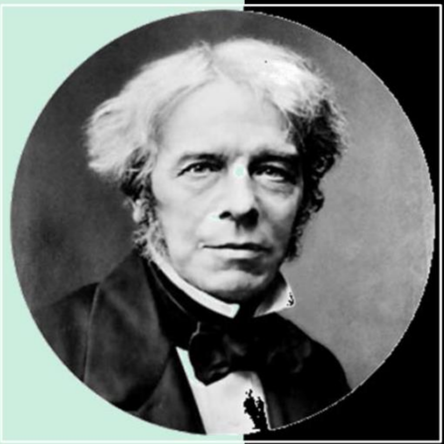




“But, after all, what good is it (generating electric current)?”

William Gladstone

British Chancellor of the Exchequer

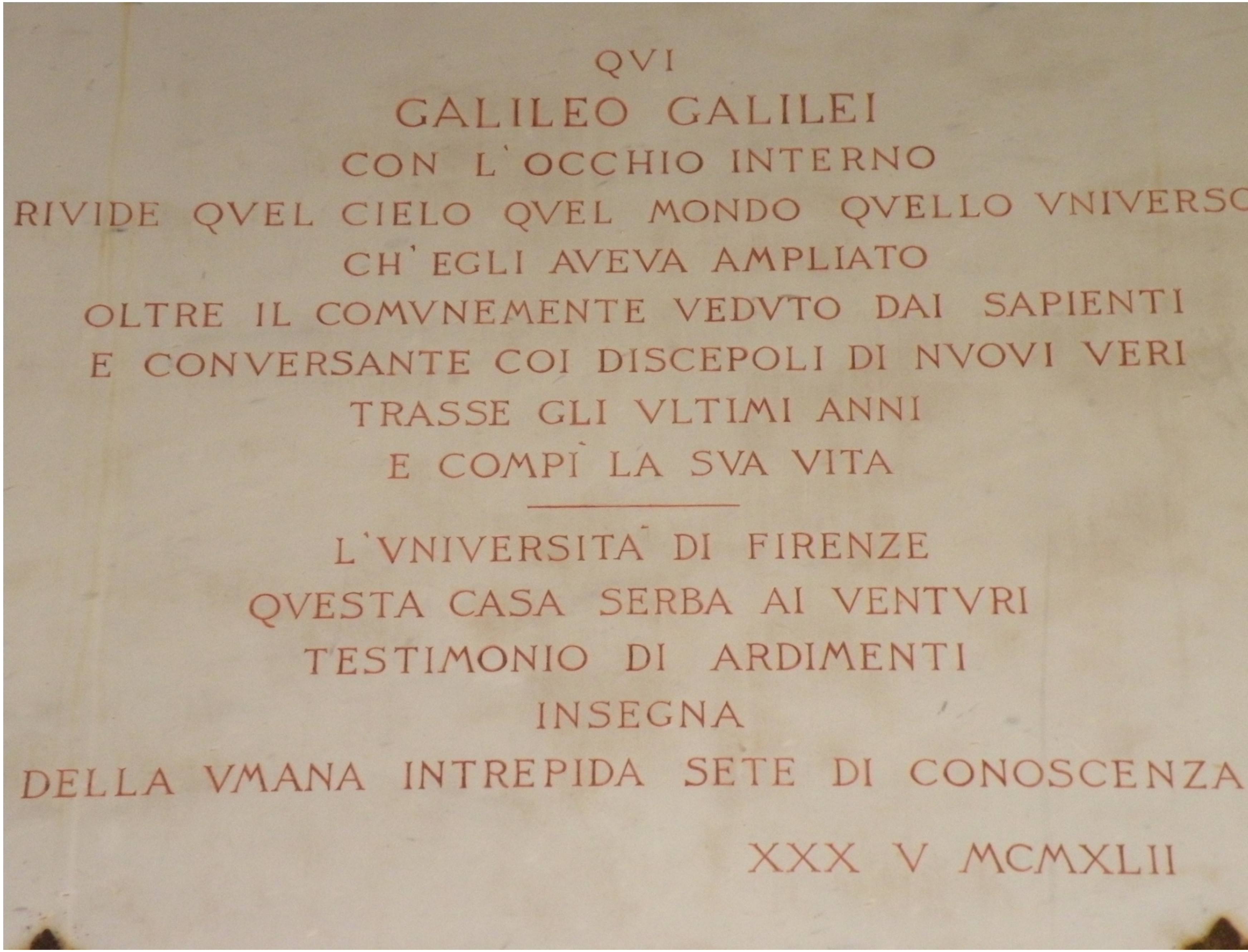


“Why sir, one day you will tax it.”

Michael Faraday

Galileo Galilei's telescope

1609: Galileo discovers the Jupiter's moons



QVI
GALILEO GALILEI
CON L'OCCHIO INTERNO
RIVIDE QVEL CIELO QVEL MONDO QVELLO VNIVERSO
CH'EGLI AVEVA AMPLIATO
OLTRE IL COMVNEMENTE VEDVTO DAI SAPIENTI
E CONVERSANTE COI DISCEPOLI DI NVOVI VERI
TRASSE GLI VLTIMI ANNI
E COMPÌ LA SVA VITA

L'VNIVERSITÀ DI FIRENZE
QVESTA CASA SERBA AI VENTVRI
TESTIMONIO DI ARDIMENTI
INSEGNA
DELLA VMANA INTREPIDA SETE DI CONOSCENZA

XXX V MCMXLII

Here
Galileo Galilei,
with his internal eye,
looked again at that sky, that world, that universe
that he had expanded
beyond what was commonly seen by the men of wisdom.
And, discussing with his disciples about the new truths,
he spent the last years of his life,
and here he passed away.

The University of Florence
offers this house for the future people,
as a testimony of daring,
as an emblem
of the intrepid human thirst for knowledge

30th May 1942


WHAT NEXT?