



ISTITUTO
NAZIONALE
DI RICERCA
METROLOGICA



LA LUCE, LA MISURA DEL TEMPO E GLI OROLOGI ATOMICI

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Sommario

- Metrologia di frequenza
- Orologi compatti (nuova generazione)
- Fontana atomica
- Orologi ottici
- Link Ottici
- Applicazioni scientifiche

Time and Frequency Metrology: who cares?



Utenti T&F



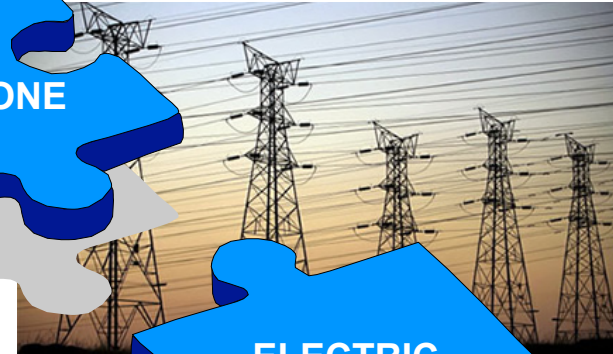
POSITIONING

TELECOMUNICAZIONI



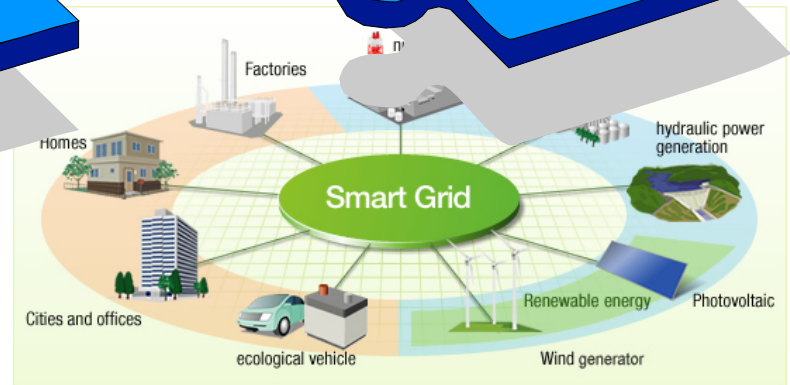
DATAZIONE

TRASPORTI

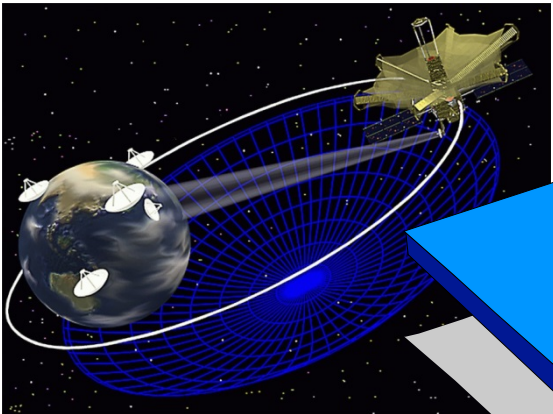


ELECTRIC POWER

E-COMMERCE

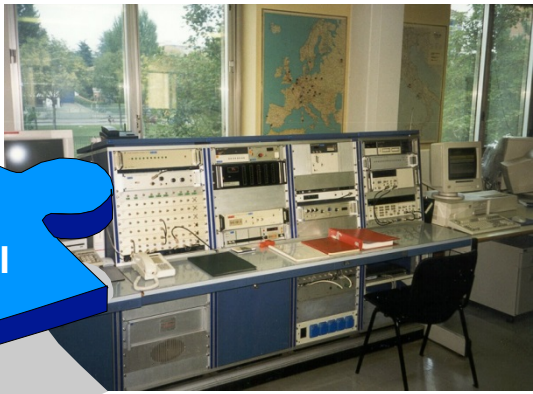


Utenti T&F



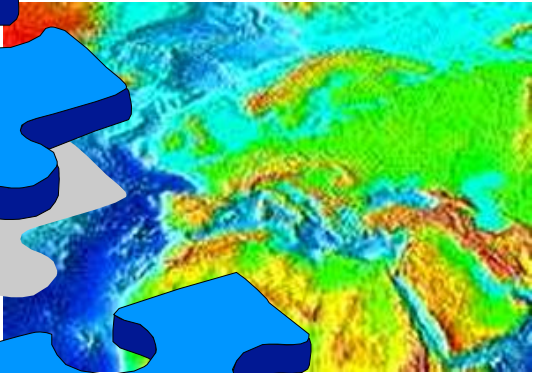
SPAZIO

STRUMENTI



**RICERCA
FONDAMENTALE**

GEODESIA

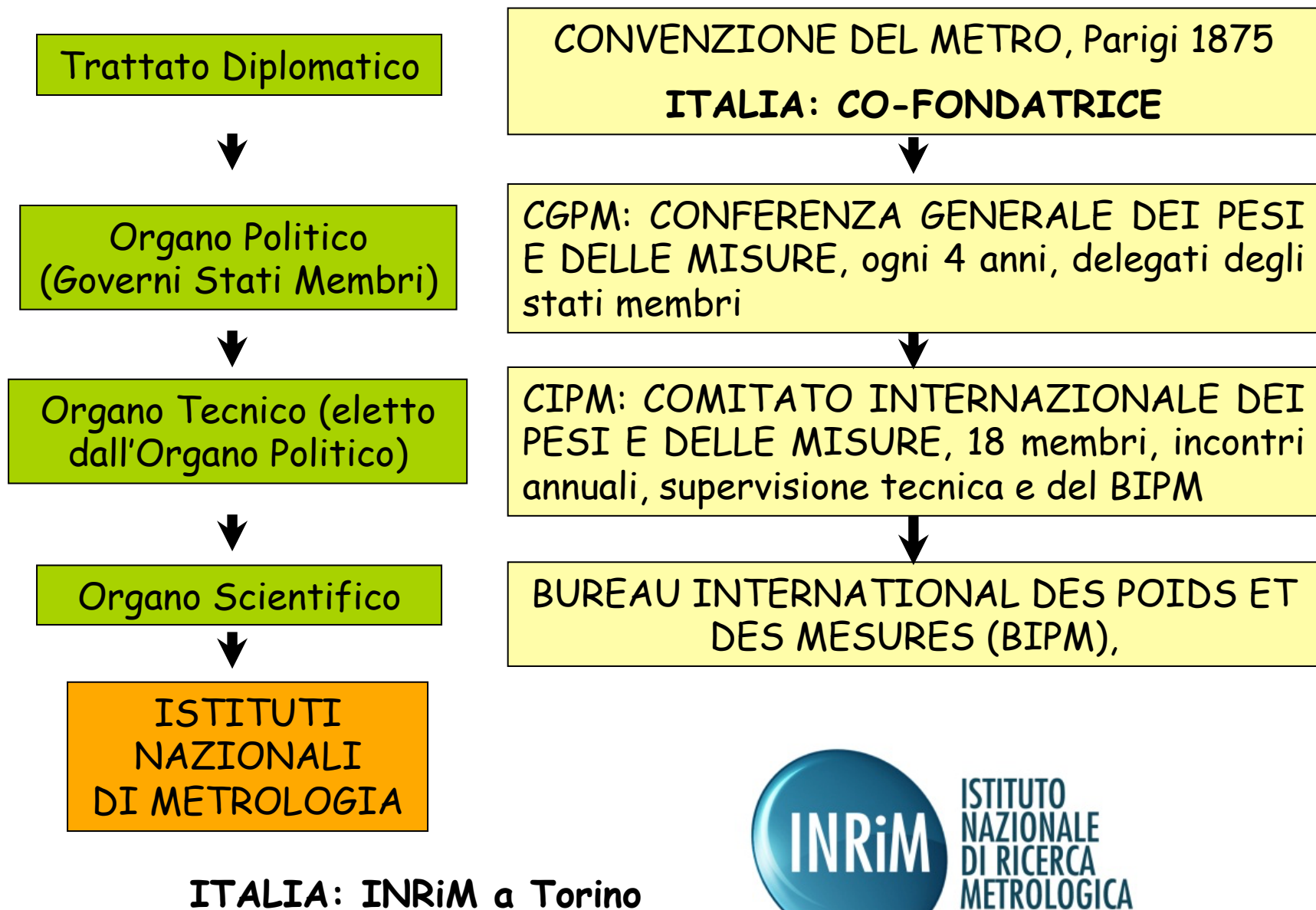


AGRICOLTURA

DIFESA



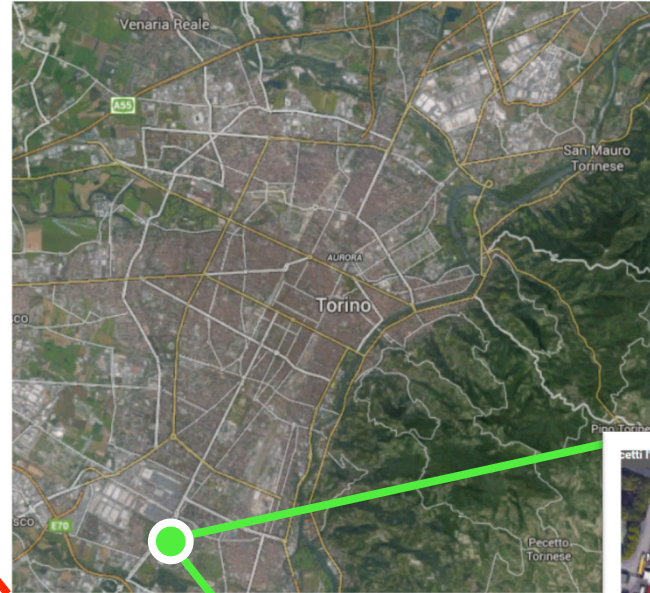
La convenzione del metro



ITALIA: INRiM a Torino



TORINO



- L'Istituto Metrologico Italiano
- 200 lavoratori + studenti/postdoc
- campus 120.000 m²
- 4° ente metrologico in Europa
- 5° Ente Pubblico di Ricerca in Italia
- Forte Rapporto con Università/Industria



Campione atomico di frequenza primario

- ❑ Un campione atomico di frequenza è un dispositivo capace di riferire la frequenza di un oscillatore macroscopico (un quarzo, un laser) a quella di un sistema quantistico semplice (atomo, ione o molecola).
 - ❑ Gli atomi sono tutti identici tra loro
 - ❑ La frequenza di risonanza non muta nel tempo
- ❑ Il campione si dice primario quando la frequenza di risonanza dell'atomo si può ricondurre alla sua frequenza imperturbata.



Il secondo : definizione (la metrologia non è una scienza statica)

- **Tempo solare medio (fino al 1960)**

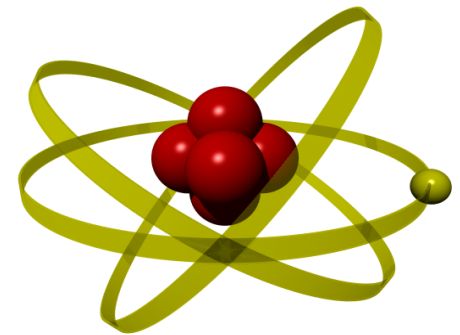
*Il secondo è la frazione $1 / 86400$
del giorno solare medio*

- **Tempo delle Effemeridi (dal 1960 al 1967)**

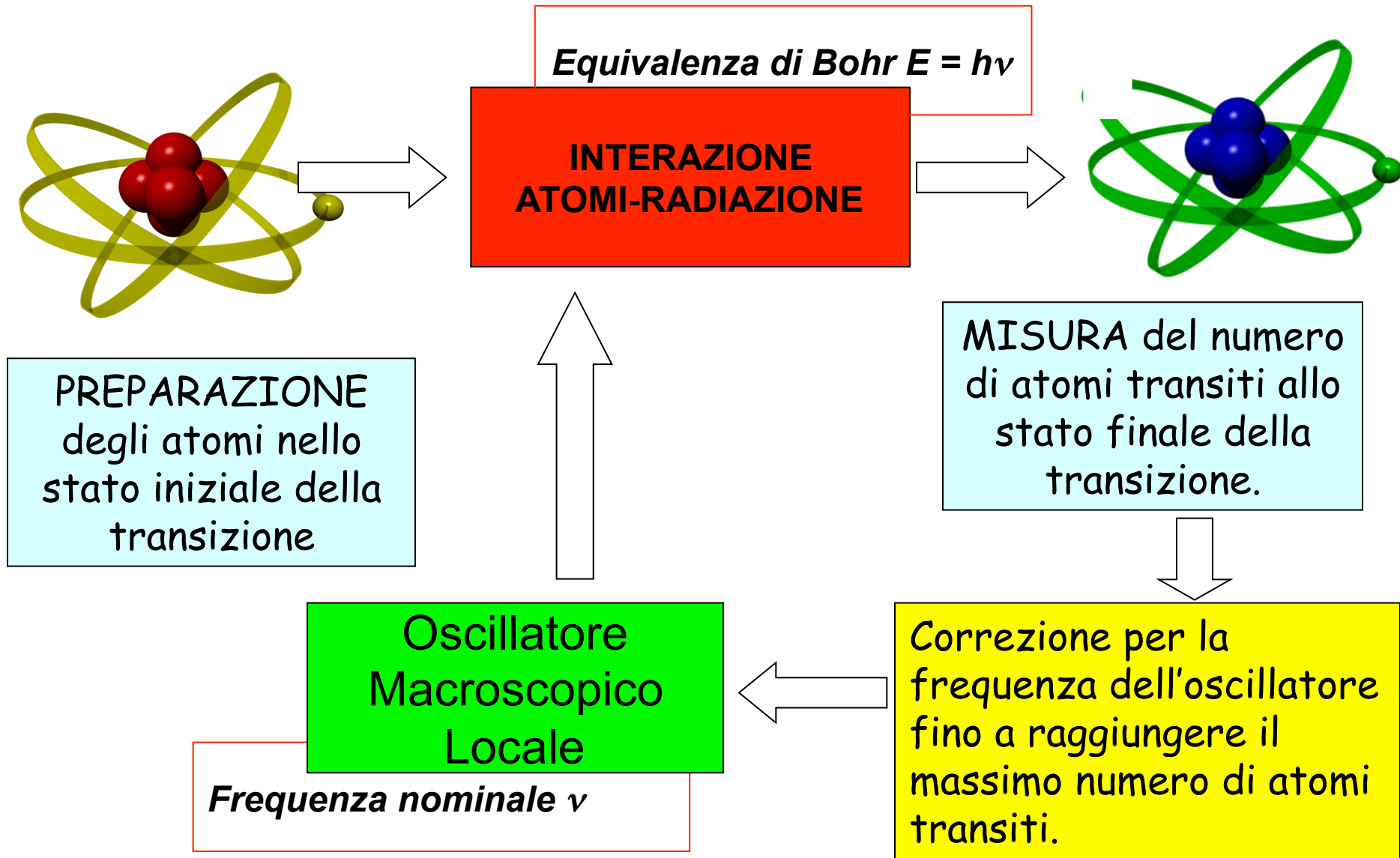
*Il secondo è la frazione $1 / 31556925,9747$
dell'anno tropico relativo al giorno
1 gennaio 1900 alle ore 12 UT*

- **Tempo atomico (dal 1967)**

*Il secondo è la durata di 9 192 631 770
periodi della radiazione corrispondente
alla transizione tra i due livelli iperfini
dello stato fondamentale dell'atomo
di cesio 133.*

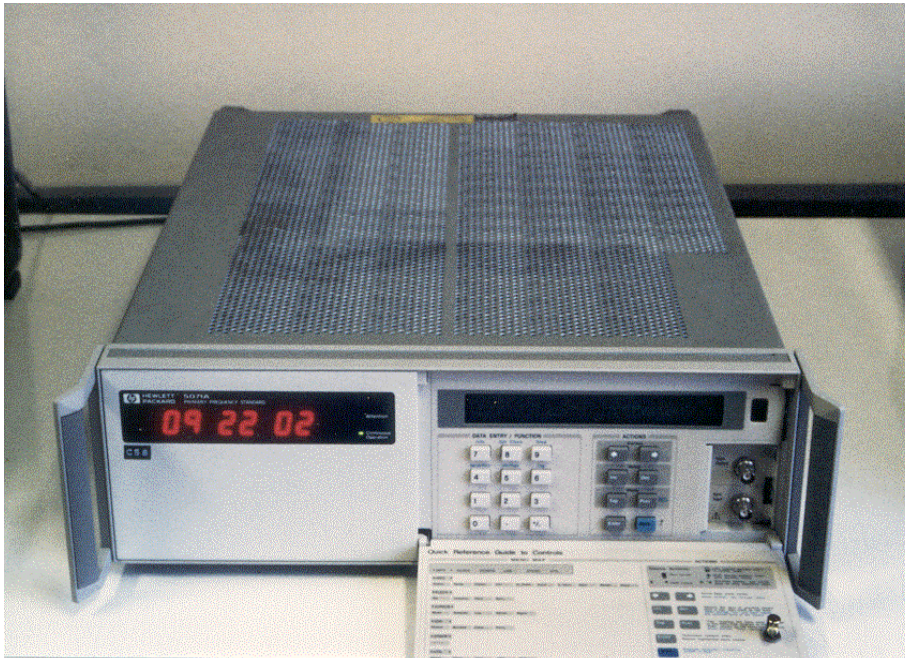


Orologi atomici: Principia



Orologi atomici commerciali:

- Cesio
- Idrogeno
- Rubidio

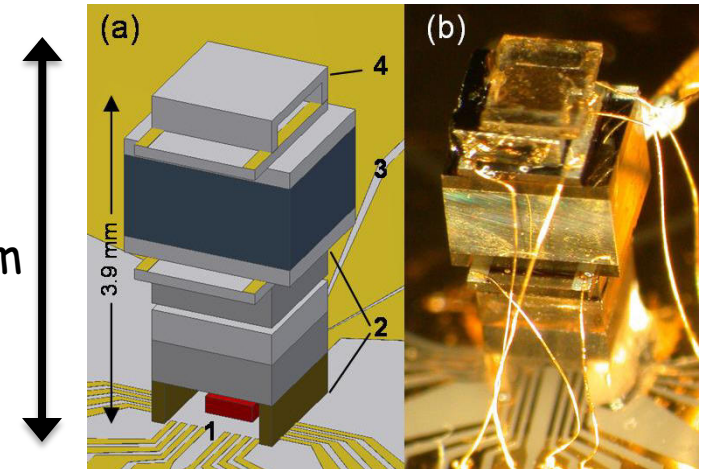


≈ 40 cm

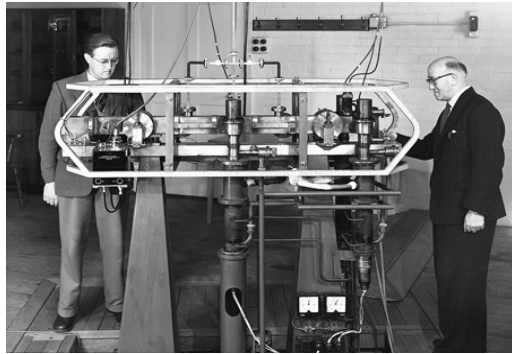
≈ 1 m



≈ 4 mm



Atomic clocks accuracy in the last 50 years

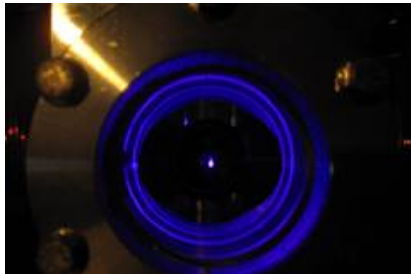


First Cs beam clock
(1955)

First Cs fountain
(1996)



Cs fountain clocks
(today)



Best optical clocks
(today)



Satellite techniques
(1 day averaging)

Optical links
(1 day averaging)



Per migliorare in generale gli orologi

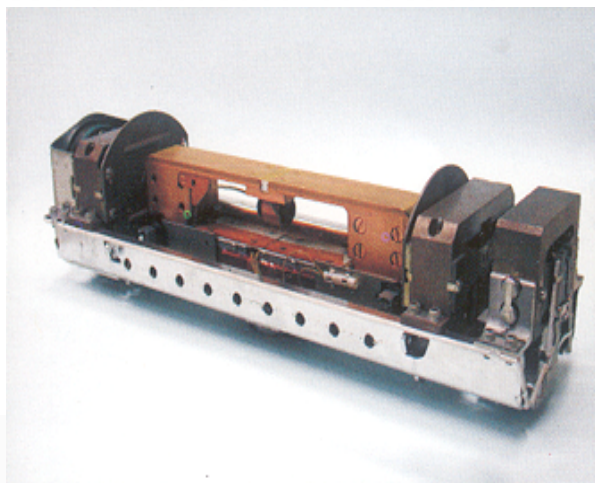
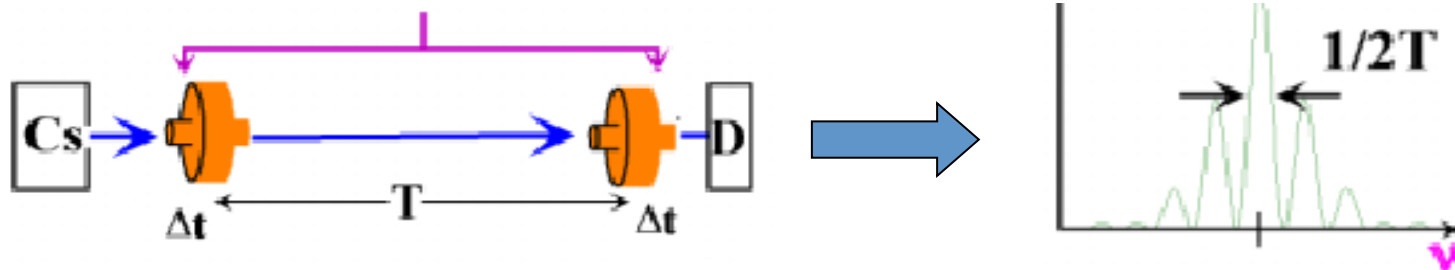
- 1) Aumentare il Tempo di interazione $\Delta\nu\Delta T > 1$
- 2) Ridurre l'effetto Doppler (riducendo l'energia cinetica degli atomi)
- 3) Scegliere Transizioni Atomiche migliori (frequenza maggiore, larghezza naturale minore, minore sensibilità ambiente esterno)

Orologi atomici: spettroscopia quantistica

Interazione tra atomi (Cesio) e e microonde (in cavità risonanti)

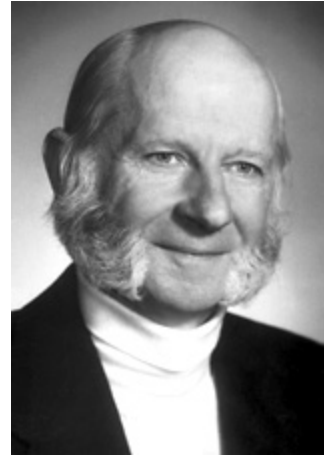
Doppio Passaggio (N. Ramsey):

Risonanza Magnetica Nucleare e interferometria quantistica, più precisione



Nobel Gallery/1

1989



Norman F. Ramsey

"for the invention of the separated oscillatory fields method and its use in the hydrogen maser and other atomic clocks"

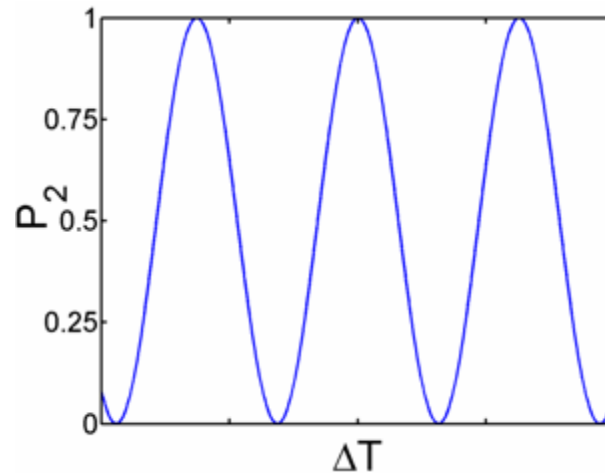
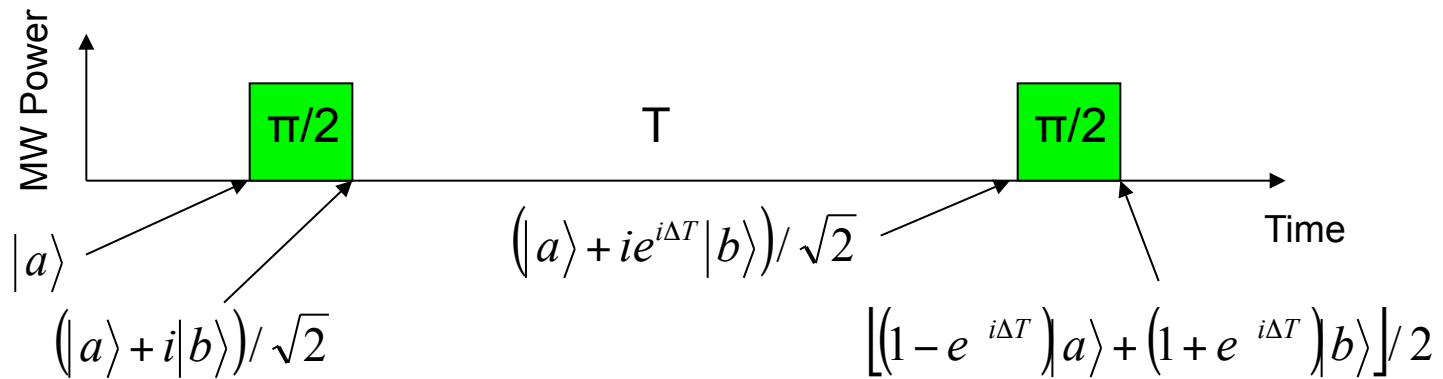
Hans G. Dehmelt Wolfgang Paul

"for the development of the ion trap technique"



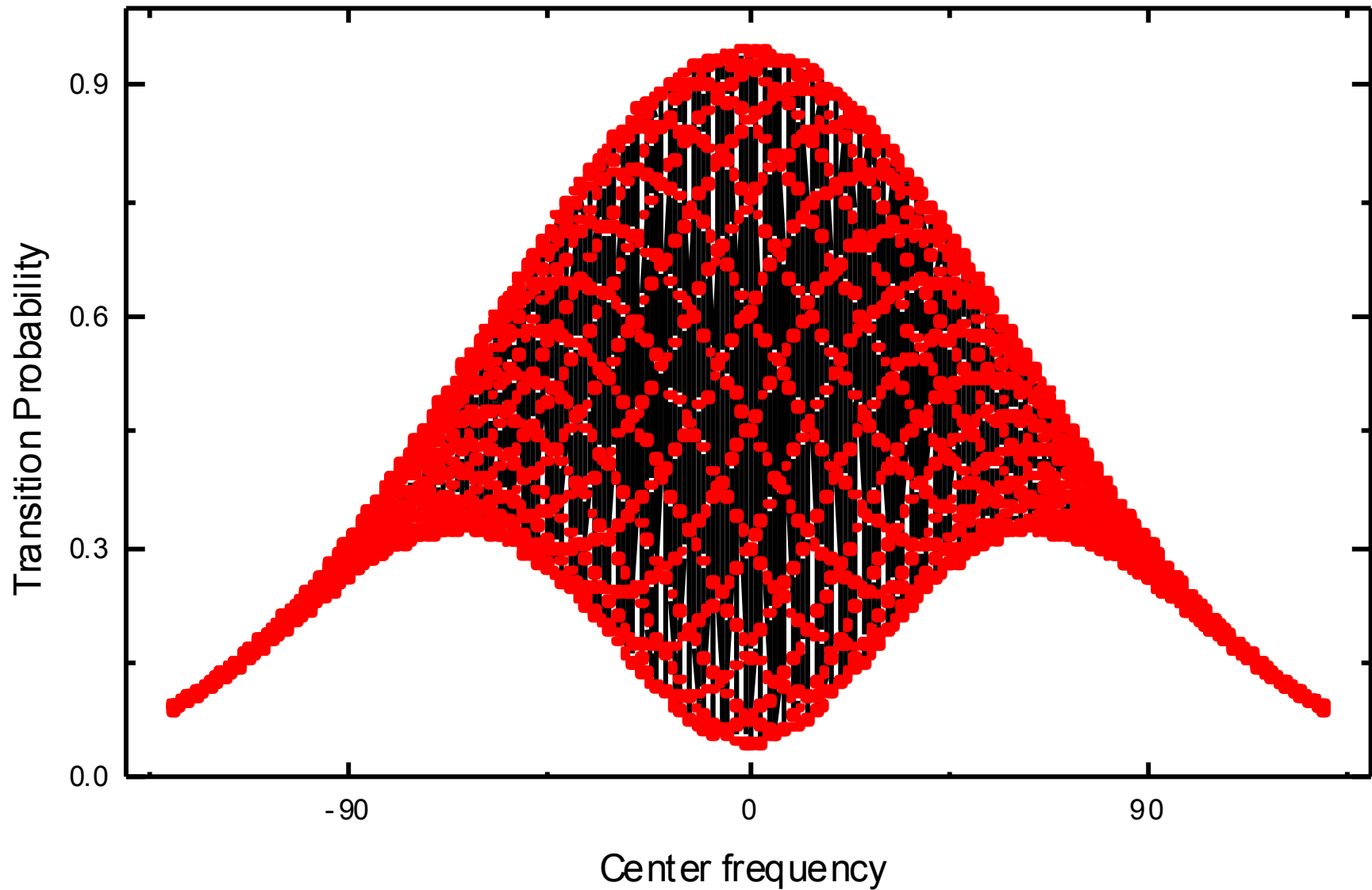
Ramsey spectroscopy of free atoms

$H = H_{\text{int}} + H_{\text{ext}} \rightarrow$ Spectroscopy of two-level Atoms



$$P_2 = \frac{1}{2}(1 + \cos(\Delta T))$$

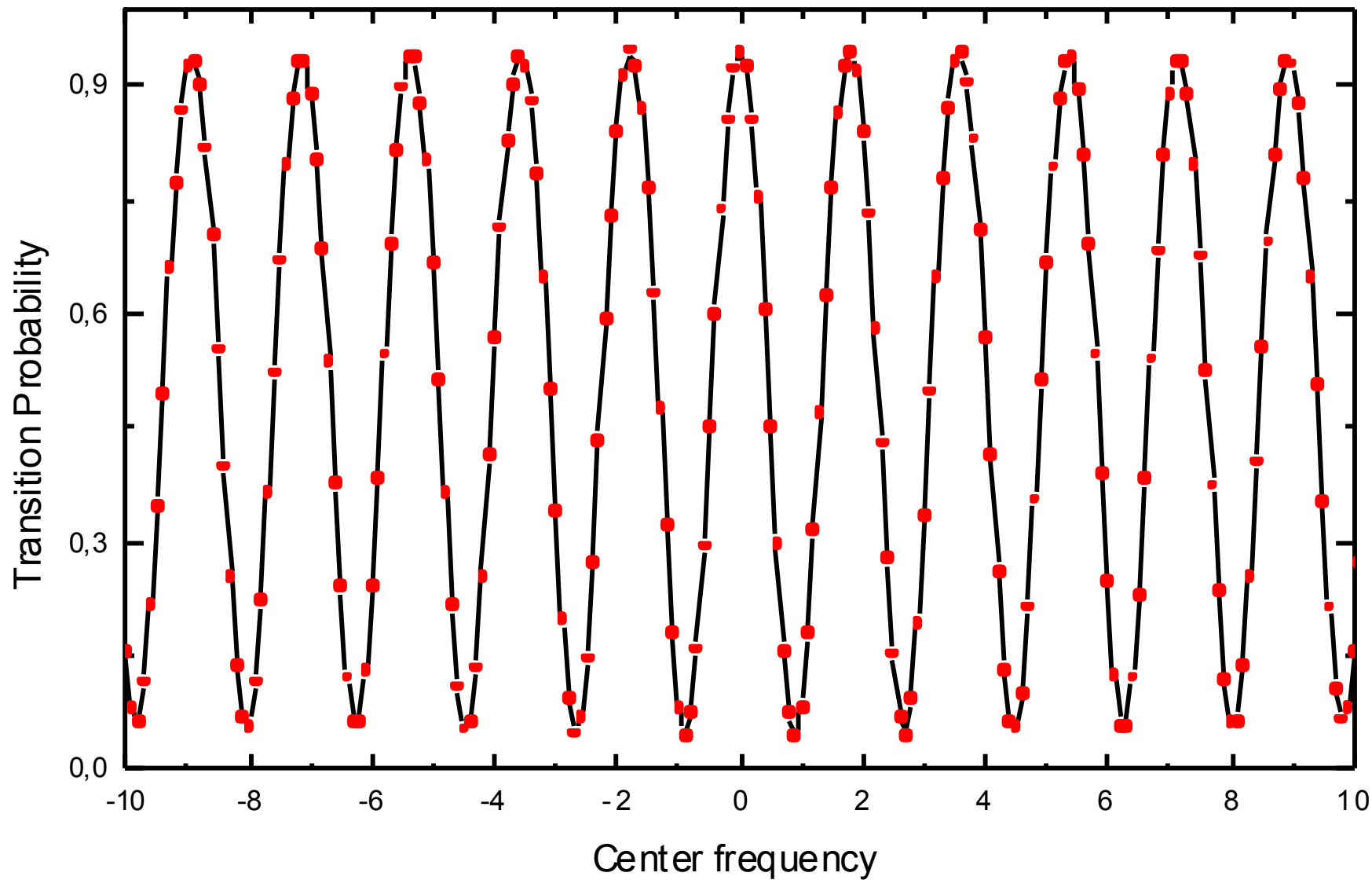
Ramsey fringes



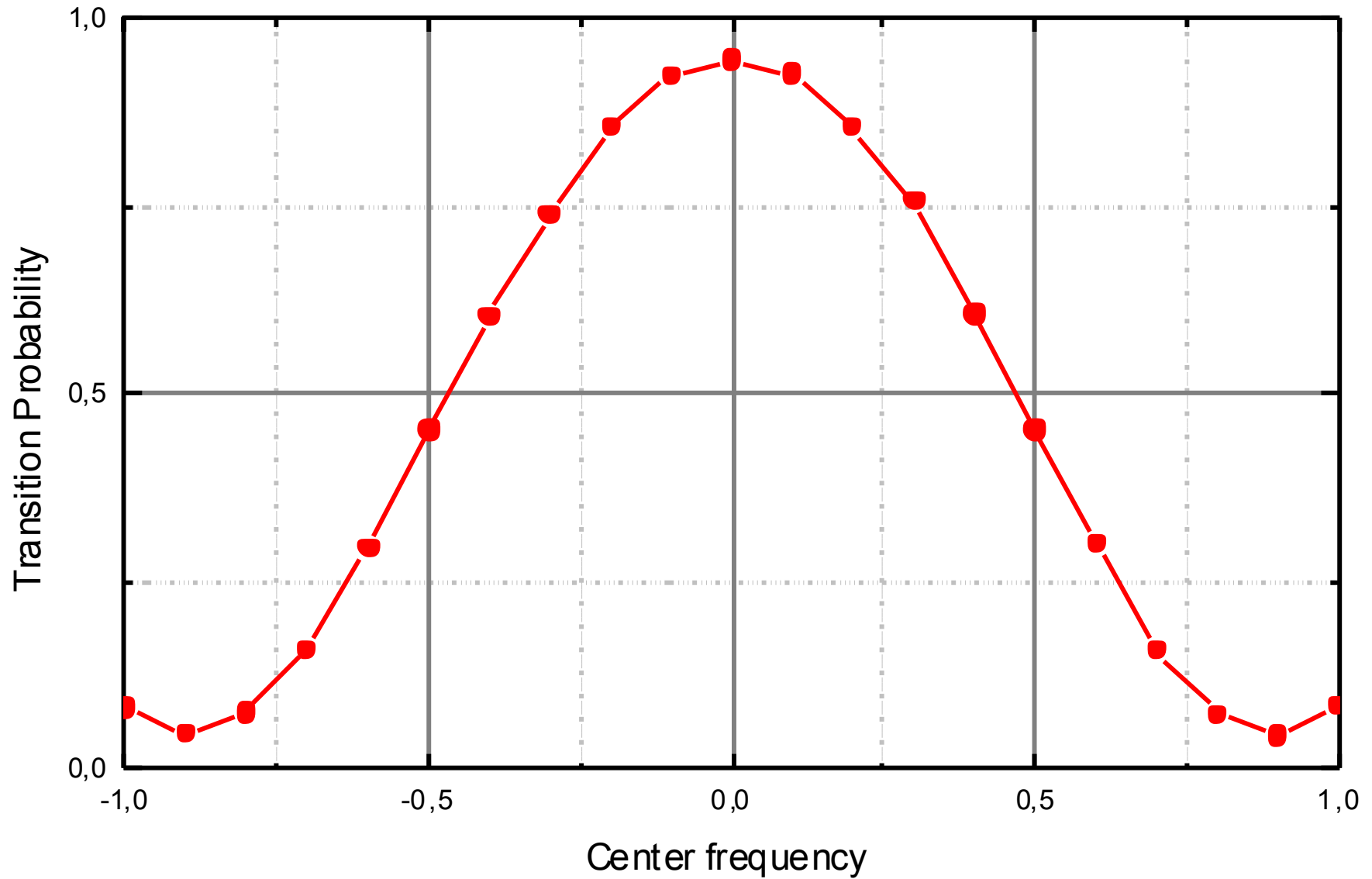
$$P(\omega - \omega_0) = \frac{4b^2}{\Omega^2} \sin^2 \frac{\Omega\tau}{2} \left\{ \cos \frac{\Omega\tau}{2} \cos \frac{(\omega - \omega_0)T}{2} - \frac{\omega - \omega_0}{\Omega} \sin \frac{\Omega\tau}{2} \sin \frac{(\omega - \omega_0)T}{2} \right\}^2$$

Central fringes

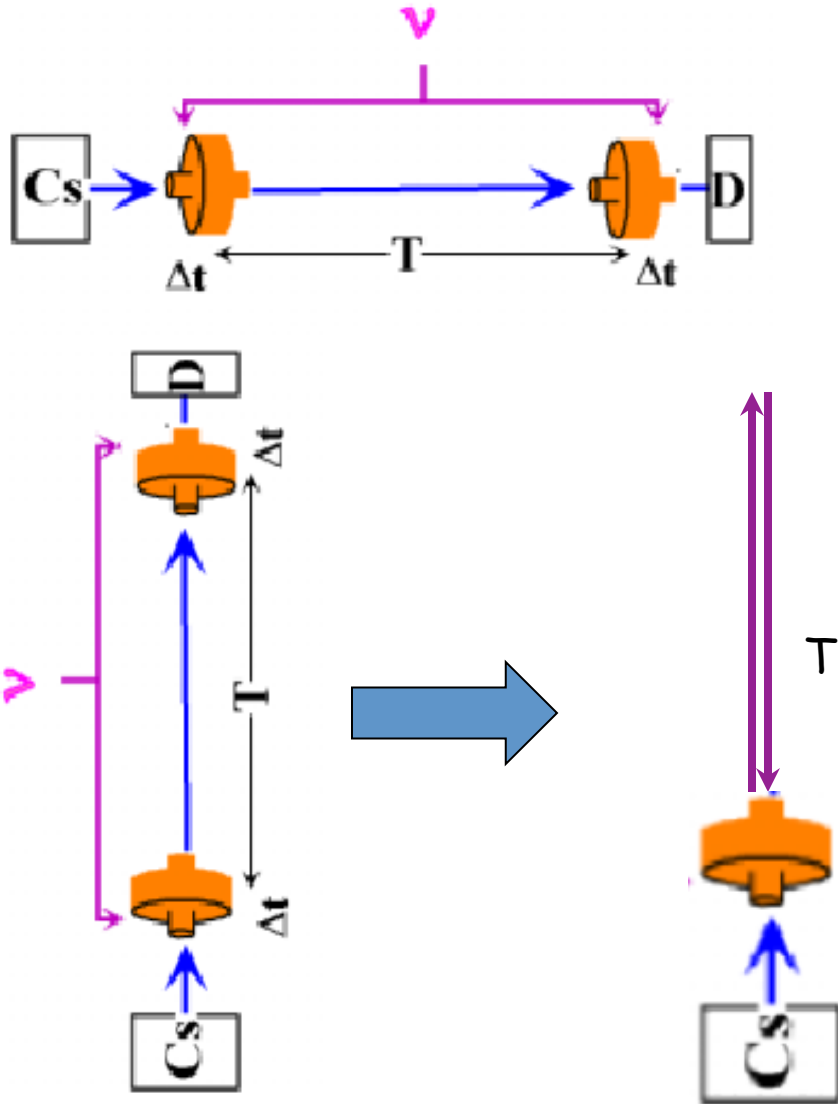
$$P(\omega) \simeq \frac{1}{2}[1 + \cos(\omega - \omega_0)T]$$



$$P(\omega) \simeq \frac{1}{2}[1 + \cos(\omega - \omega_0)T]$$



L'idea di una fontana atomica



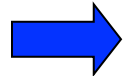
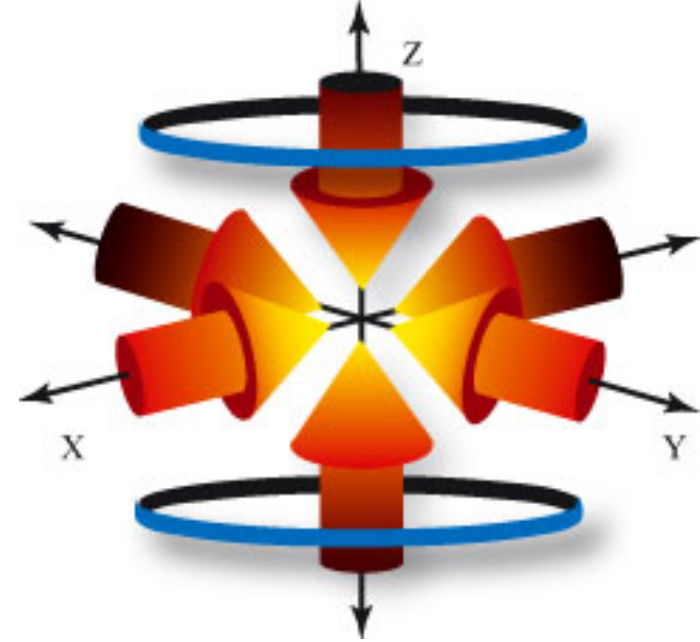
Zacharias, al MIT nel 1954, propose di aumentare T con un orologio a geometria verticale, con atomi in volo balistico: **una fontana atomica.**

MA, gli atomi di Cs a temperatura ambiente in volo si diffondono e non tornano indietro

Nel 1954, la fontana di Zacharias era utopica.

Laser Cooling

Negli anni ottanta, si sviluppano le tecniche di **raffreddamento laser** per diverse specie di vapori atomici: per certi livelli particolare, la luce laser, a una certa frequenza e polarizzazione, rallenta gli atomi e li raffredda



Il Cesio si raffredda fino a velocità residue di 1 cm/s, cioè una temperatura $T \sim 1 \mu\text{K}$:

All'inizio degli anni novanta, l'idea di Zacharias poteva diventare realtà

Credits: <http://www.sparclabs.com>



Nobel Gallery/2

1997

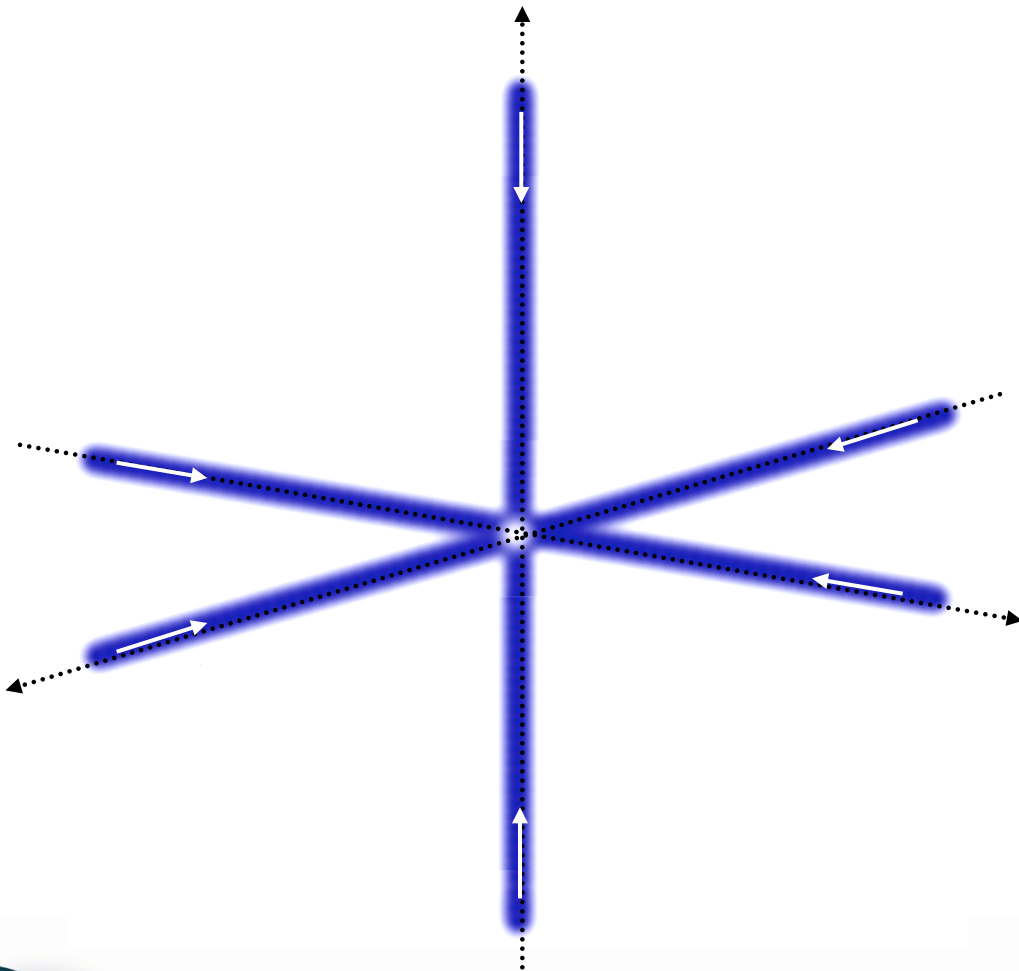


Stephen Chu, William Phillips, Claude Cohen-Tannoudj

"for development of methods to cool and trap atoms with laser light"



Magneto-Optical Trap (MOT)



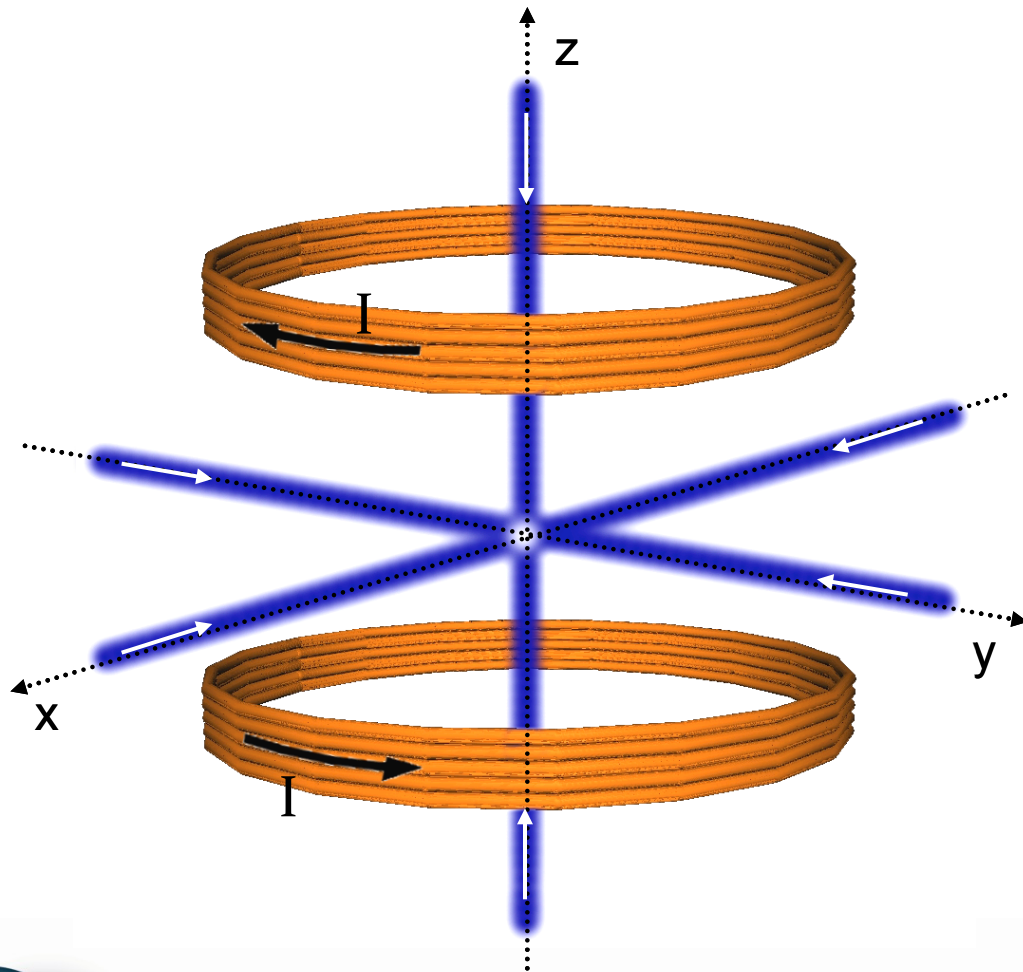
3 coppie di fasci contropropaganti:

$$\nu_{\text{laser}} < \nu_{\text{transizione}} = \nu_{\text{emissione}}$$

→ Perdita di energia



Magneto-Optical Trap (MOT)



3 coppie di fasci contropropaganti:

$$v_{\text{laser}} < v_{\text{transizione}} = v_{\text{emissione}}$$

→ Perdita di energia

Coppia di bobine, configurazione anti-Helmholtz:

- Gradiente di campo magnetico
- $\vec{B} = 0$ al centro della trappola

Espandendo l'espressione della forza in serie di Taylor:

$$F ; \underbrace{-\beta v}_{\text{Forza viscosa}} - \underbrace{kr}_{\text{Forza elastica}}$$

β : coefficiente di viscosità
 k : costante elastica



Fontana criogenica al Cesio INRIM ITCsF2



**Raffreddamento laser del Cs a $1 \mu\text{K}$;
Struttura Criogenica a 89 K;**

**Realizza in Italia la
definizione del
secondo**

**Contribuisce alla
realizzazione del
Tempo Atomico
Internazionale**

INRIM, Fontane di Cesio ITCsF1 e ITCsF2: Accuratezza

ITCsF1

$$\sigma_y(\tau) = 1.5 \cdot 10^{-13} \tau^{-1/2}$$

Accuratezza: $5 \cdot 10^{-16}$

	u ITCsF1	u ITCsF2
Zeeman	2E-16	8E-17
Collisioni	3E-16	1E-16
Corpo Nero	3E-16	1E-17
Microonda	2E-16	1E-16
Redshift	1E-17	1E-17
Totale	5E-16	2E-16

ITCsF2

$$\sigma_y(\tau) = 1.5 \cdot 10^{-13} \tau^{-1/2}$$

Accuratezza: $2 \cdot 10^{-16}$



Fontane atomiche attive nel mondo

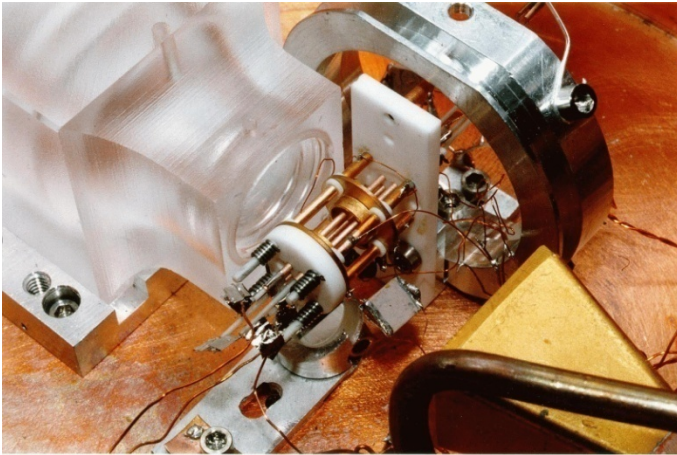
Sei laboratori hanno finora contribuito regolarmente alla generazione del Tempo Atomico Internazionale con fontane al Cesio: USA (2 fontane); Francia (3); **Italia (2)**; Germania (2); UK (2); Giappone (2)



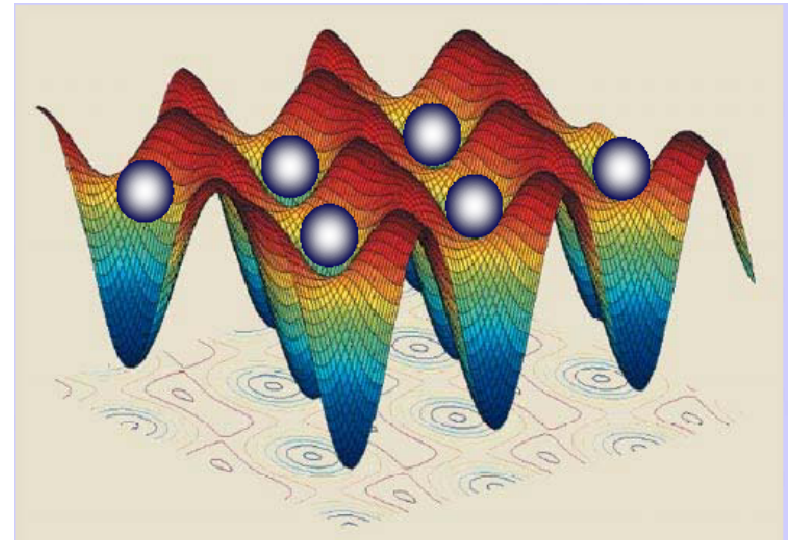
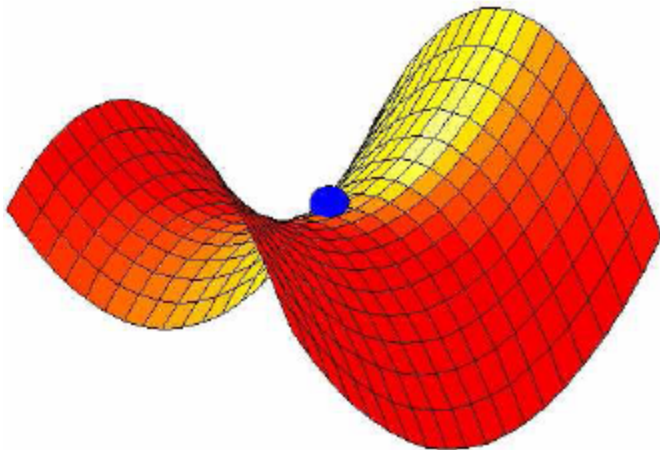
Meno Doppler & Più Interazione / 2

Trappole a ioni e reticoli ottici

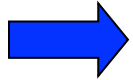
Trappole RF a singolo ione



Reticoli Ottici con Atomi Neutri
(Lunghezza d'onda "magica" senza
Light shift)



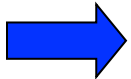
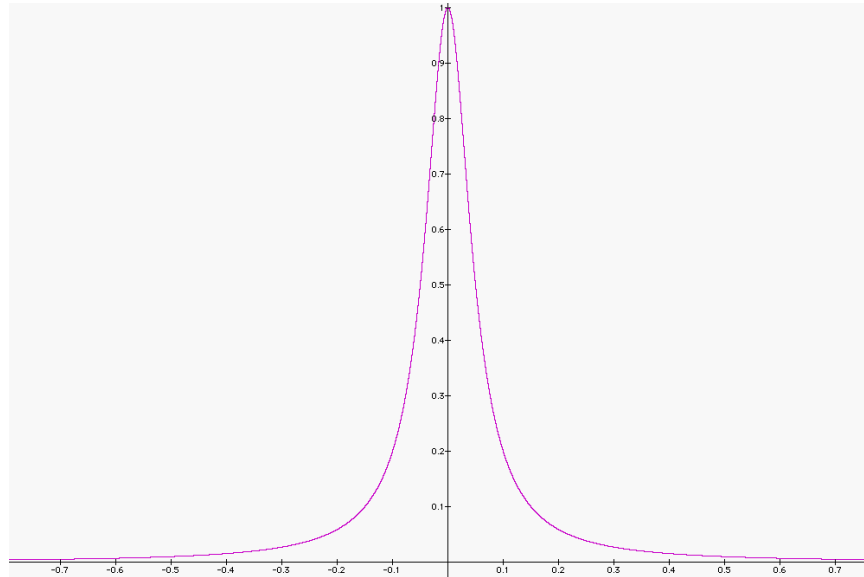
3) Scegliere Transizioni Atomiche migliori (frequenza maggiore, larghezza naturale minore, minore sensibilità ambiente esterno)



Aumentare fattore di qualità della riga $Q = \nu/\Delta\nu$

Q transizioni microonda (fontane) $\cong 10^{10}$

Q ottiche(microonda) $> 10^{15}$



**Da transizioni a microonda (Cs, Rb) a transizioni ottiche nel visibile:
OROLOGI OTTICI**

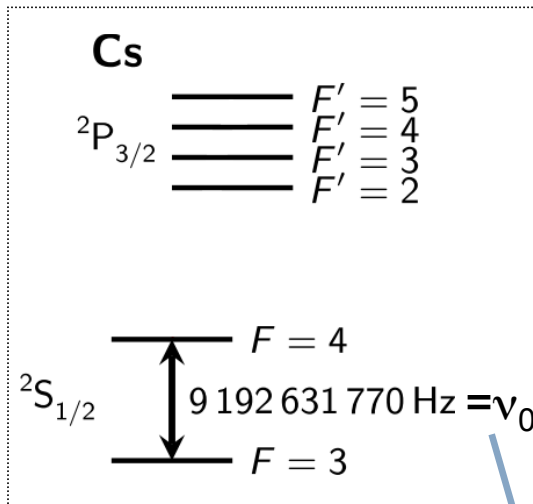
Dalle microonde all'ottico

Campioni di frequenza
a microonde:

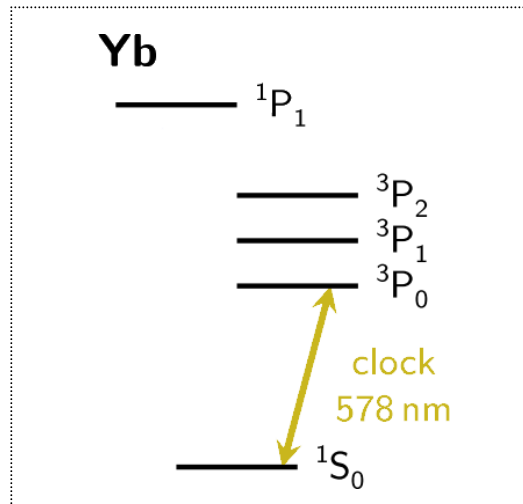
$$\nu_0 \sim 10^{10} \text{ Hz}$$

Campioni di frequenza
ottici:

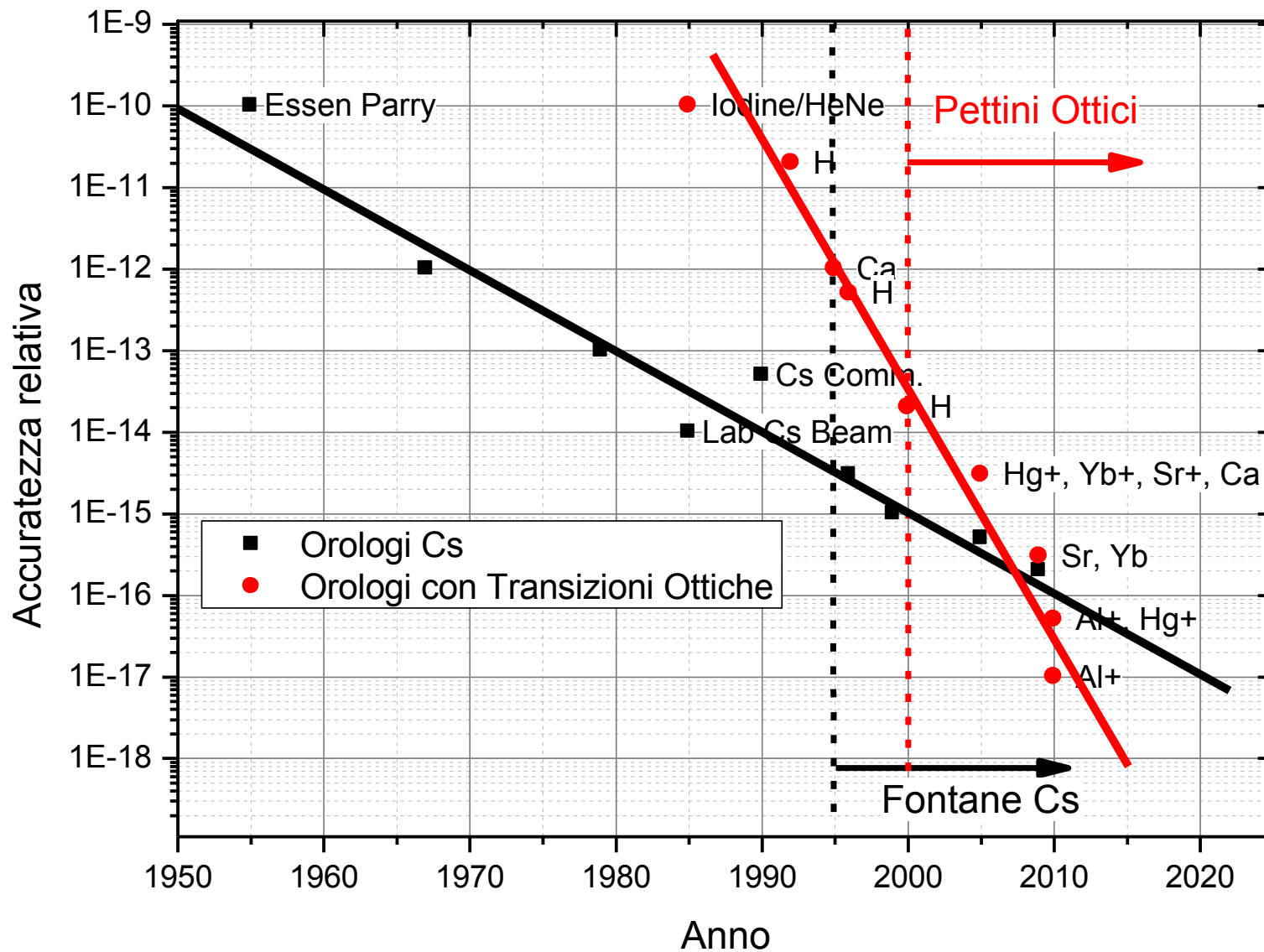
$$\nu_0 \sim 5 \times 10^{15} \text{ Hz}$$



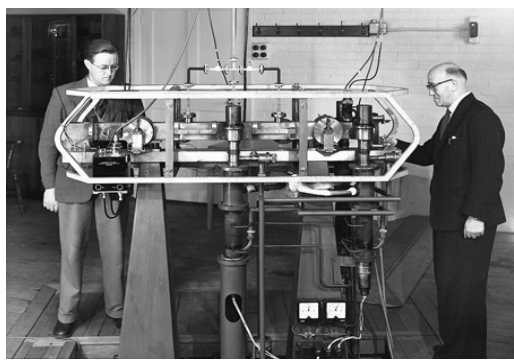
Definizione del
secondo



Dal Cesio agli orologi Ottici: Verso la ridefinizione del secondo



Acuratezza degli orologi atomici



Primo Cs a fascio
(1955)

Prima fontana Cs
(1996)

Fontane di Cs
(oggi)

Orologi ottici
(oggi)

10^{-8}

10^{-10}

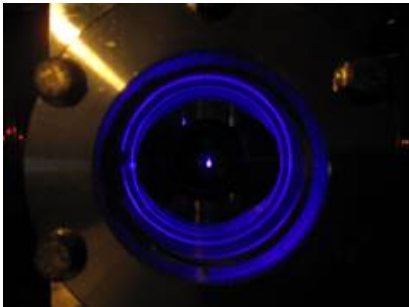
10^{-12}

10^{-14}

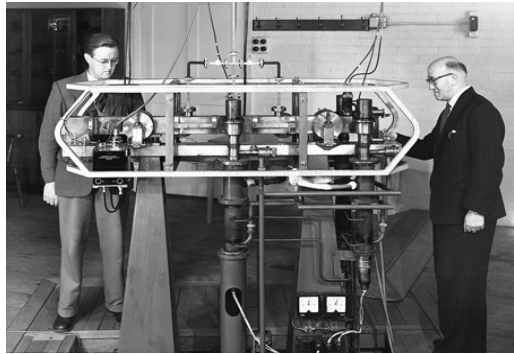
10^{-16}

10^{-18}

10^{-20}



Acuratezza degli orologi atomici

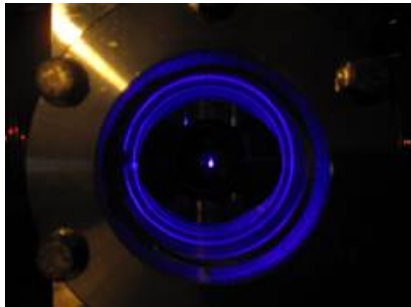


Primo Cs a fascio
(1955)



Prima fontana Cs
(1996)

Fontane di Cs
(oggi)



Orologi ottici
(oggi)



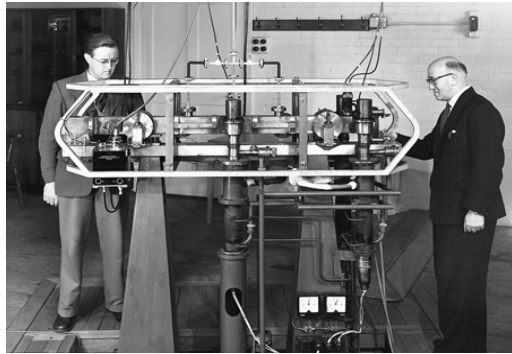
Tecnologie:

RAFFREDDAMENTO
LASER

PETTINI OTTICI DI
FREQUENZA

LASER COME
OROLOGI

Acuratezza degli orologi atomici

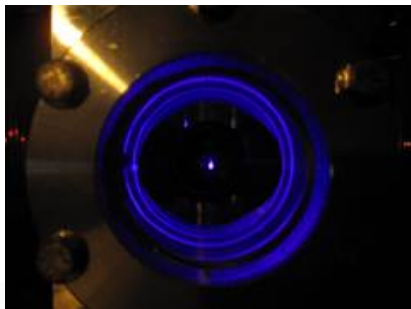


Primo Cs a fascio
(1955)



Prima fontana Cs
(1996)

Fontane di Cs
(oggi)



Orologi ottici
(oggi)



Tecnologie:

RAFFREDDAMENTO
LASER

PETTINI OTTICI DI
FREQUENZA

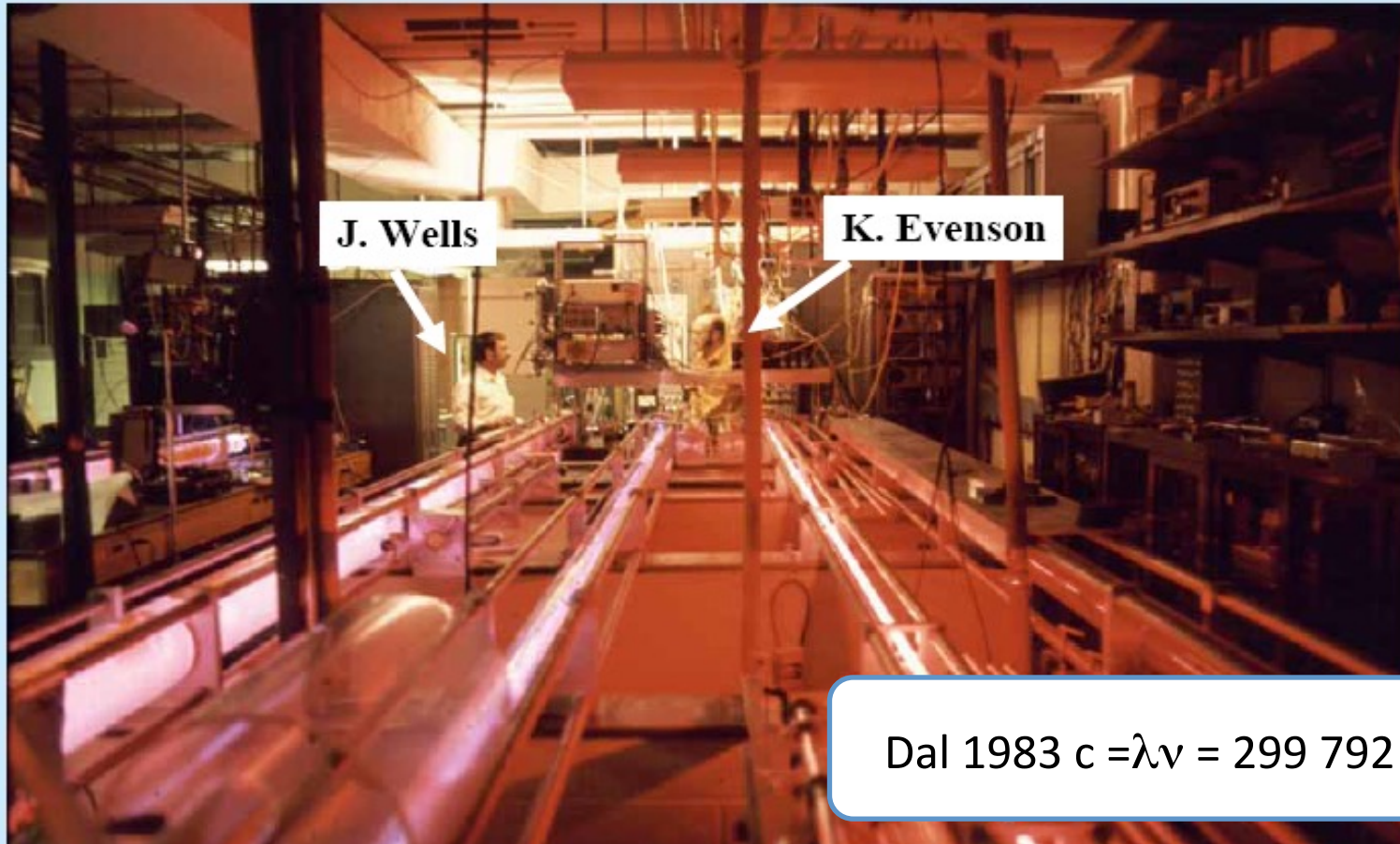
LASER COME
OROLOGI

**VERSO LA
RIDEFINIZIONE DEL
SECONDO!**

Anche i laser diventano orologi

The First NBS Optical Frequency Chain

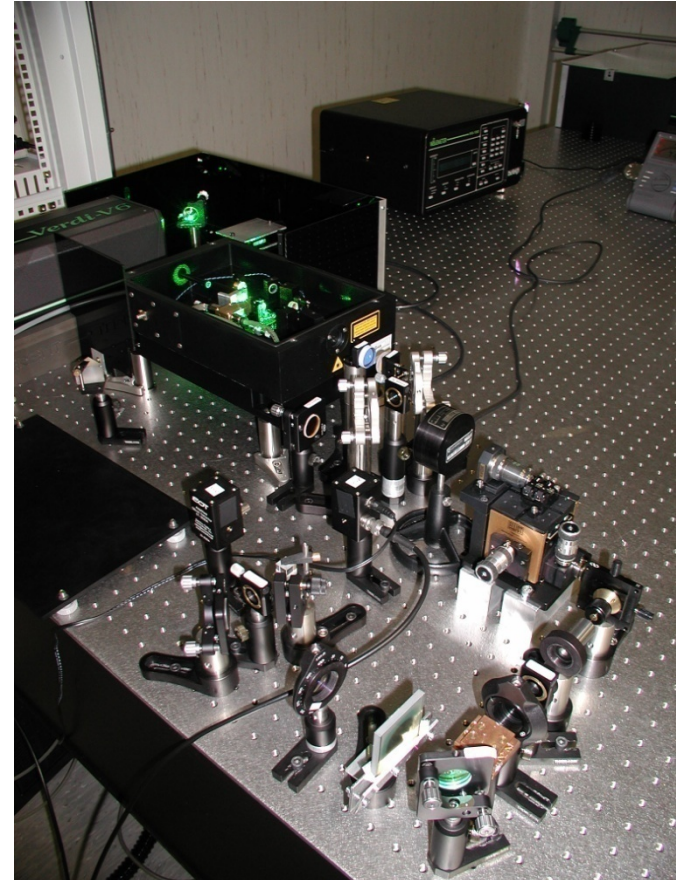
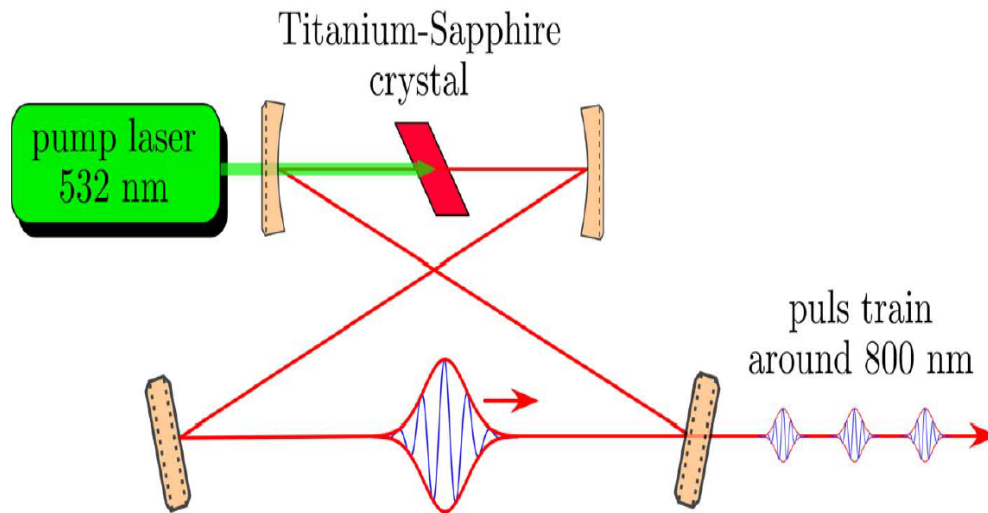
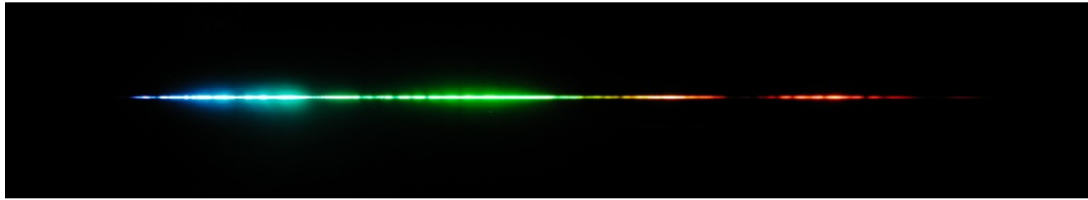
NBS (NIST): measurement of speed of light, 1972



Dal 1983 $c = \lambda\nu = 299\,792\,458$ m/s

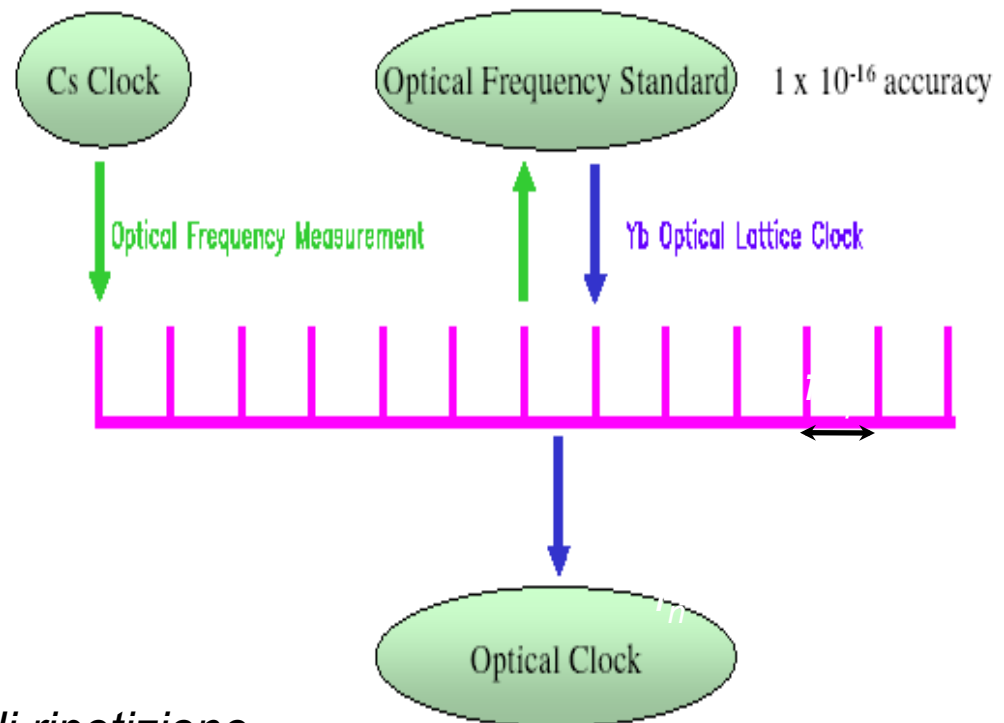
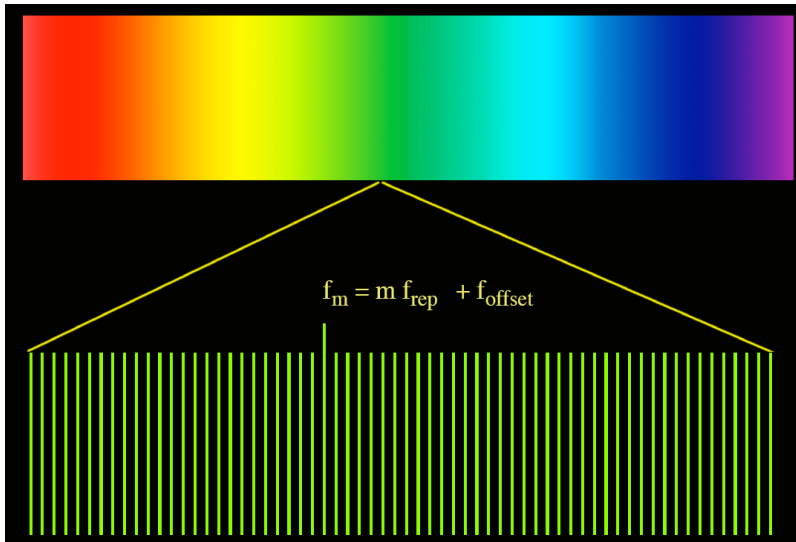
Anche i laser diventano orologi/2

La soluzione del problema della misura accurata delle frequenze ottiche con un Pettine di Frequenza generato da un Laser impulsato al femtosecondo



Anche i laser diventano orologi/3

Confronta una frequenza ottica (10^{14} Hz) direttamente con una microonda (10^{10} Hz) con incertezze $\ll 1$ mHz (incertezza relativa 10^{-18})

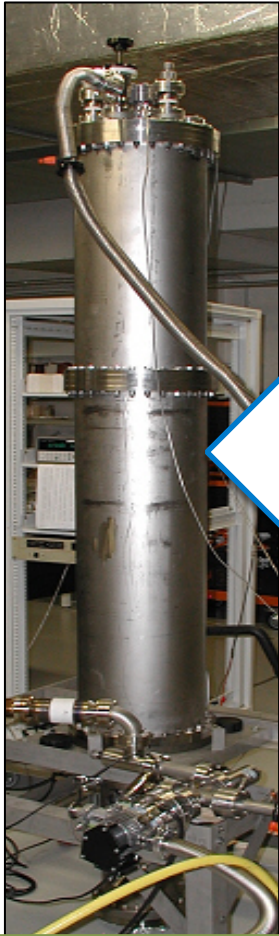


f_{rep} frequenza di ripetizione

f_{ceo} frequenza di offset (il pettine non parte da zero)

Si misurano direttamente vs riferimento assoluto

Il Pettine Ottico di Frequenza: Ponte tra secondo SI e misure ottiche

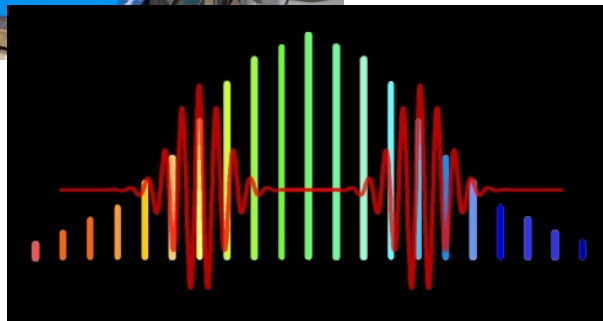


Orologi a Micronda

Pettine Ottico
di Frequenza



Orologi Ottici/
Misure Ottiche





Ted Haensch
Premio Nobel in Fisica 2005



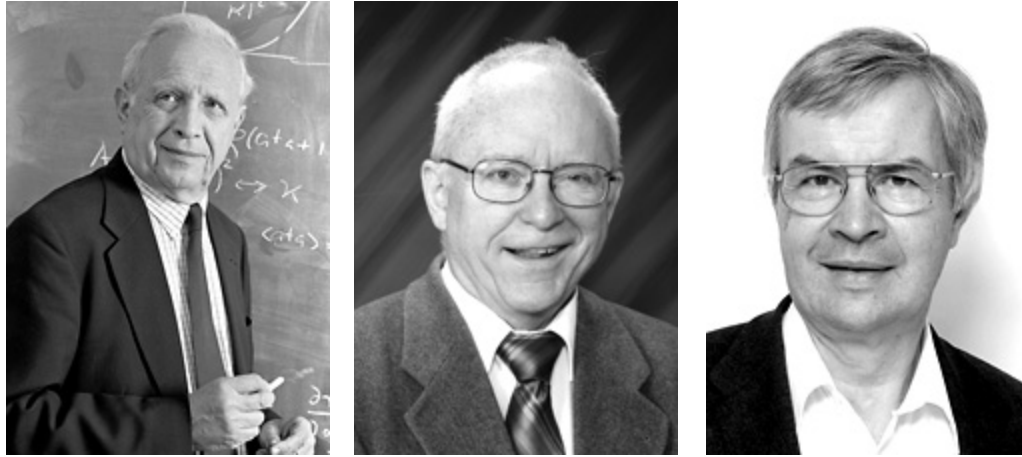
The headquarters of Menlo Systems in Martinsried outside Munich.

Nel 2001, fonda l'azienda
che produce i Pettini Ottici
Oggi impiega 80 ricercatori
Con un fatturato >4 Meuro



A Nobel Gallery

2005

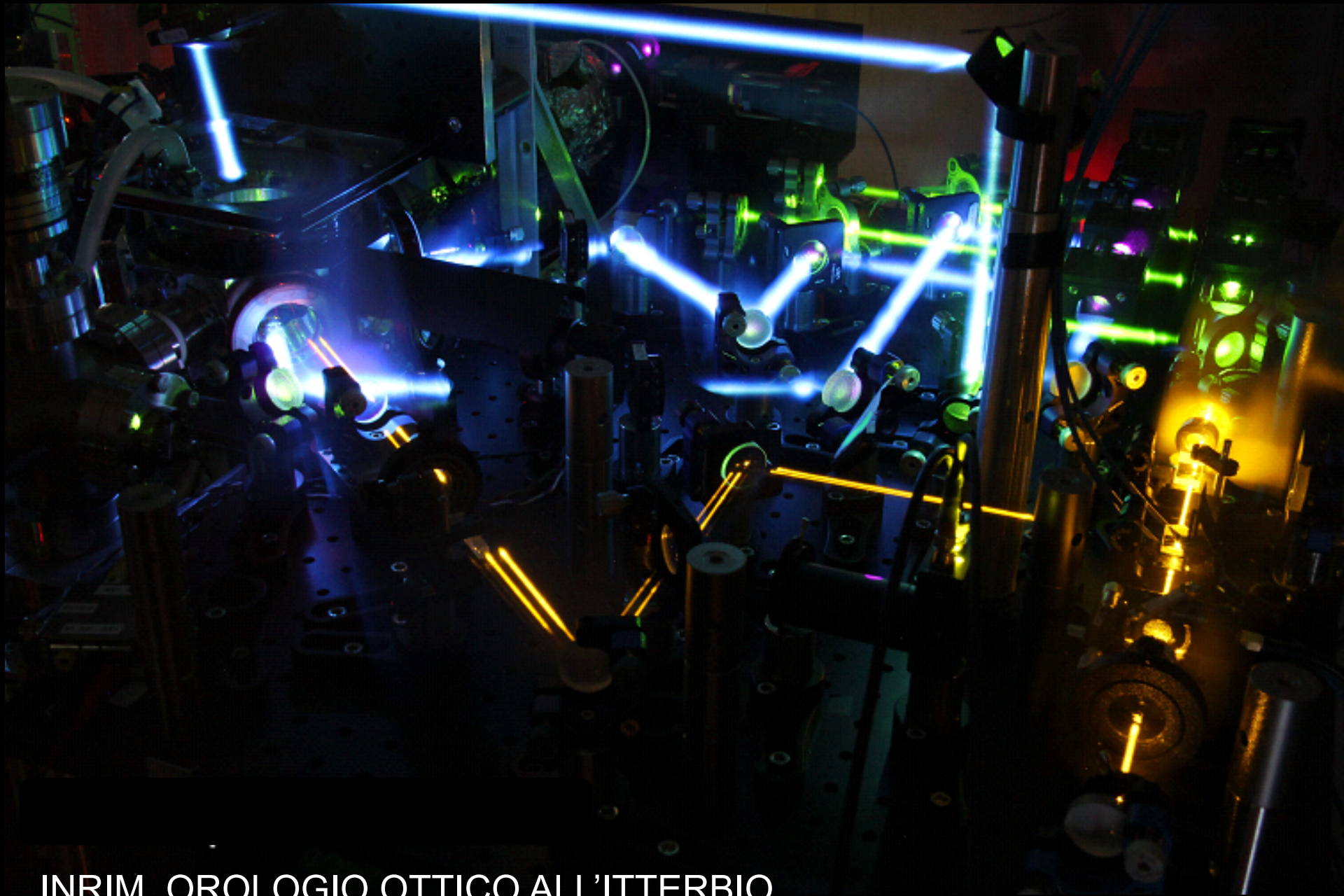


Roy J. Glauber

"for his contribution to the quantum theory of optical coherence"

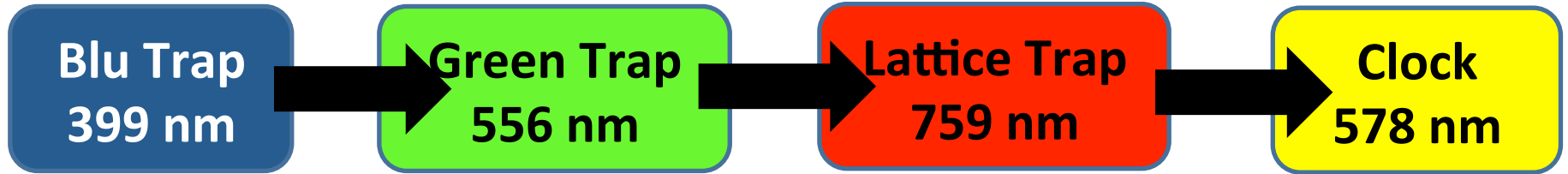
John L. Hall Theodor W. Hänsch

"for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"

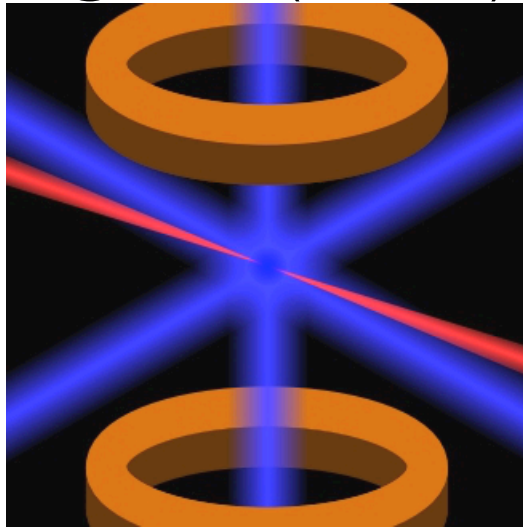


INRIM, OROLOGIO OTTICO ALL'ITTERBIO

Yb optical clock: operation cycle



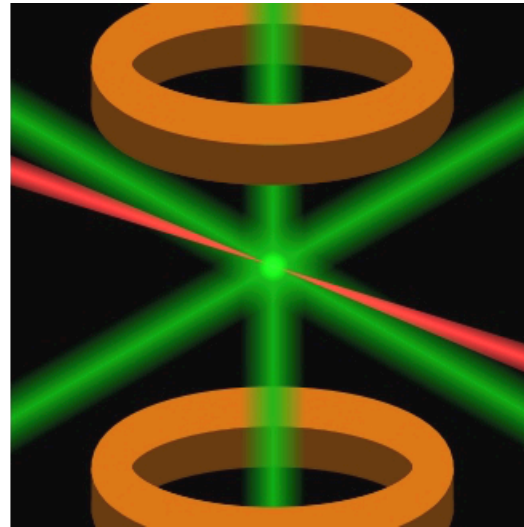
Yb @ 1 mK (20 cm/s)



- **Blue MOT**

Up to 1×10^7 Yb¹⁷¹ Atoms
150 ms loading time
Oven temperature 400 °C

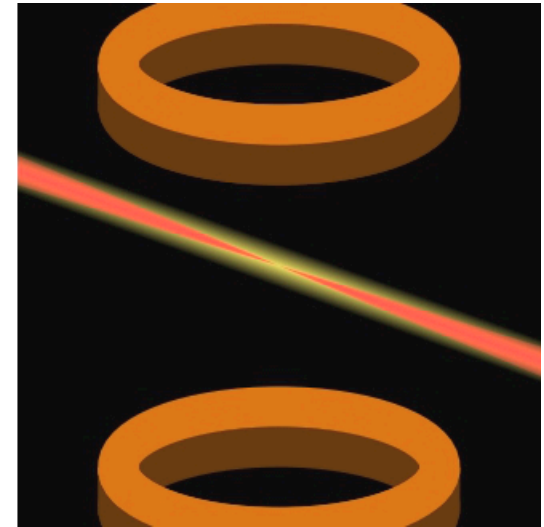
Yb @ 10 μ K (1 cm/s)



- **Green MOT**

70% transfer efficiency
3 frequency stages
Atoms temperature 10 μ K

Yb localized @ 5 μ K



- **Lattice and Clock**

Up to 4×10^4 atoms
Usually 1×10^4 atoms
3 s lifetime in the trap



Orologio ottico all'Yb: ciclo operativo

BlueTrap
399 nm

Green Trap
556 nm

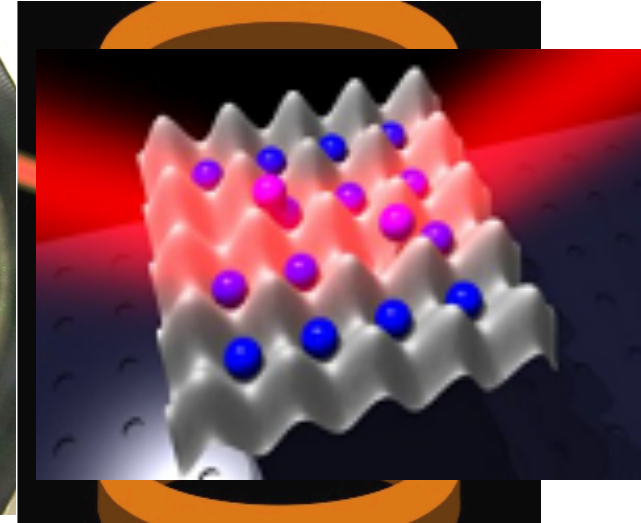
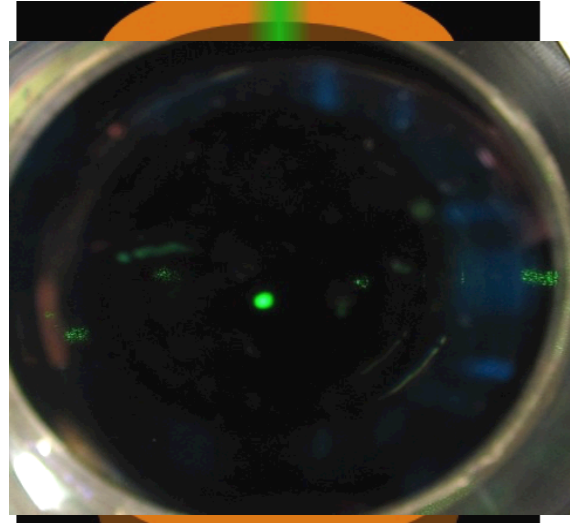
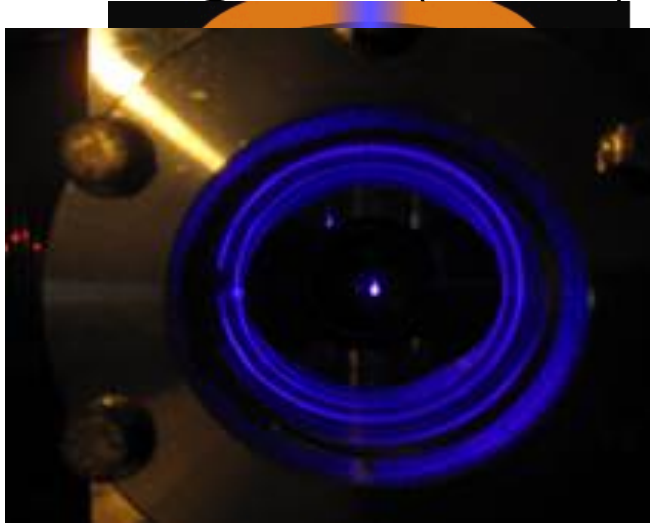
Reticolo
759 nm

Orologio
1S0-3P0
578 nm

Yb @ 1 mK (20 cm/s)

Yb @ 10 μ K (1 cm/s)

Yb in reticolo @ 5 μ K

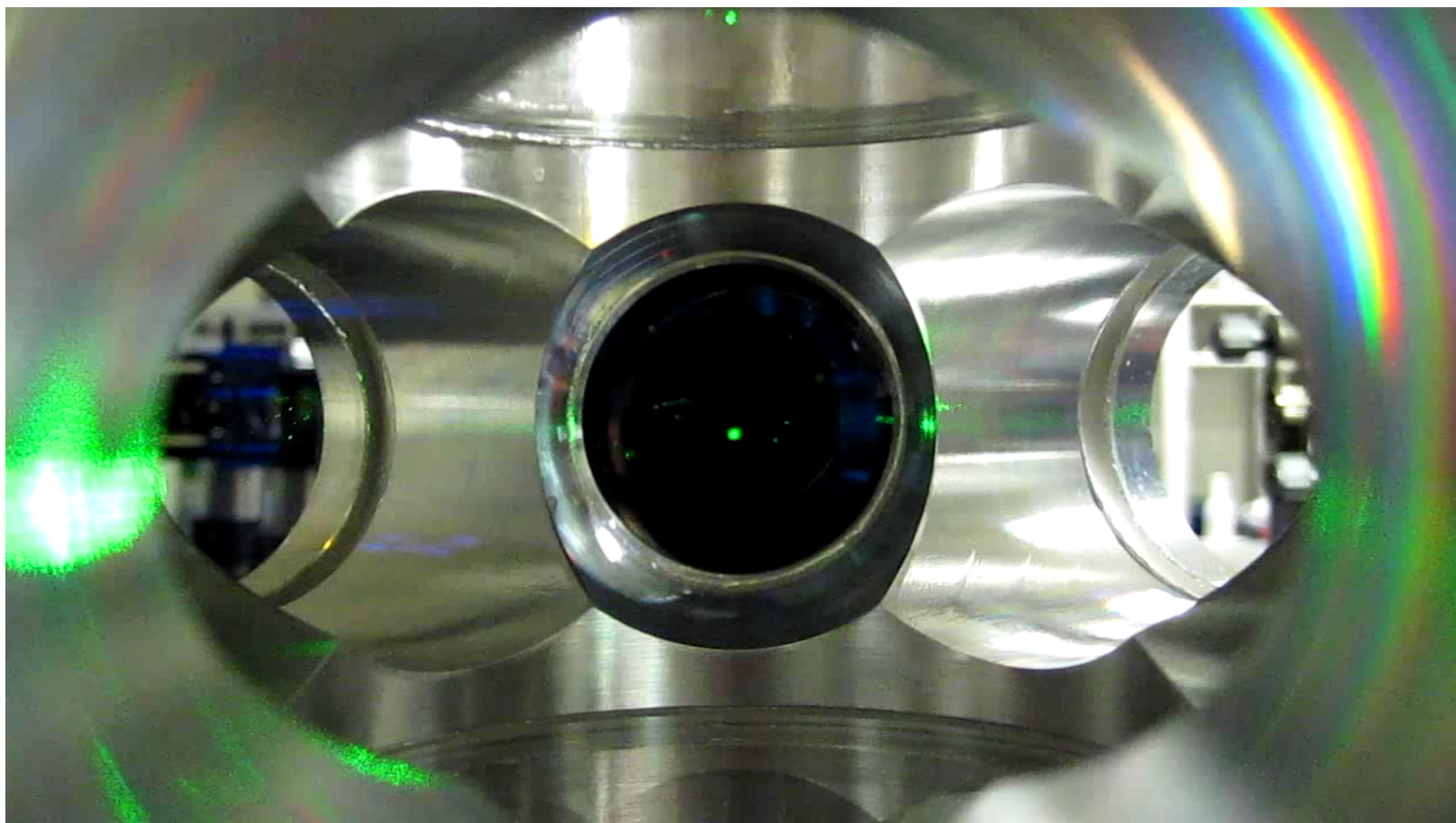


- **Blue MOT**
10⁷ Atomi 171Yb
150 ms tempo di carica
Temperatura Atomi 1 mK

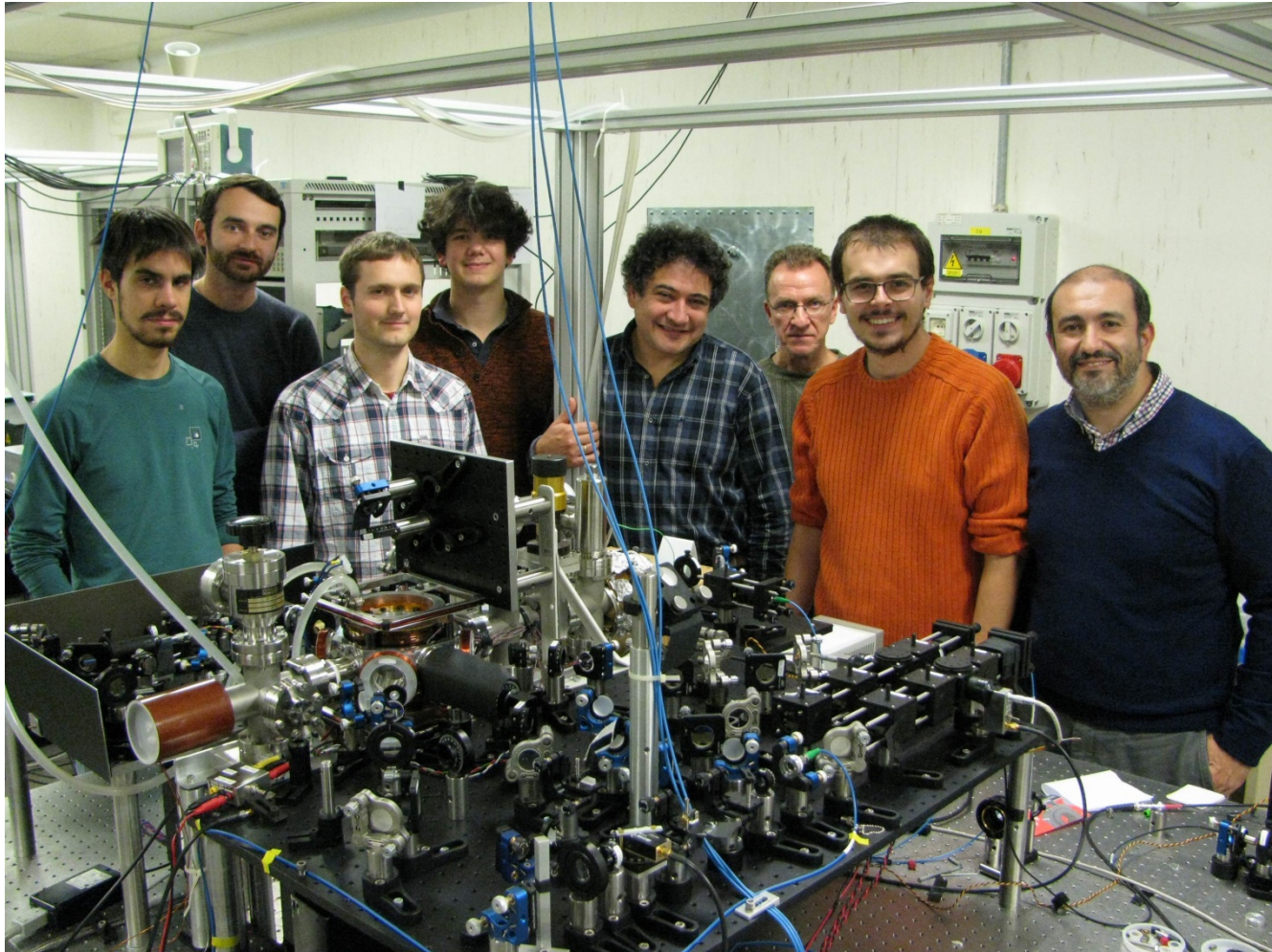
- **Green MOT**
70% efficienza di transfer
Temperatura Atomi 10 μ K

- **Lattice e Orologio**
4x10⁴ atomi
3 s vita della trappola di reticolo

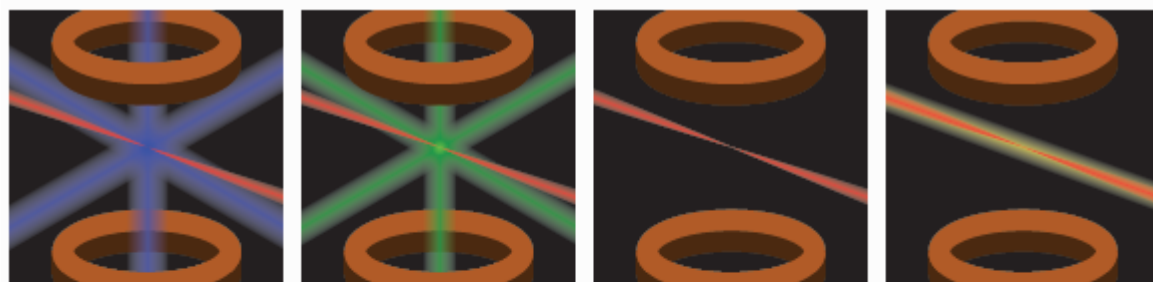
Realizzazione delle MOT



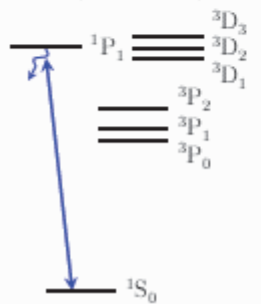
Orologio a Yb in reticolo all'INRIM



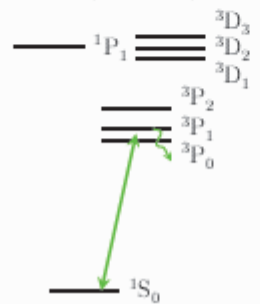
Yb clock cycle



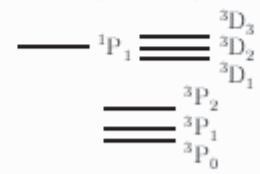
Blue Trap
 1×10^6 atoms
 (150 ms)



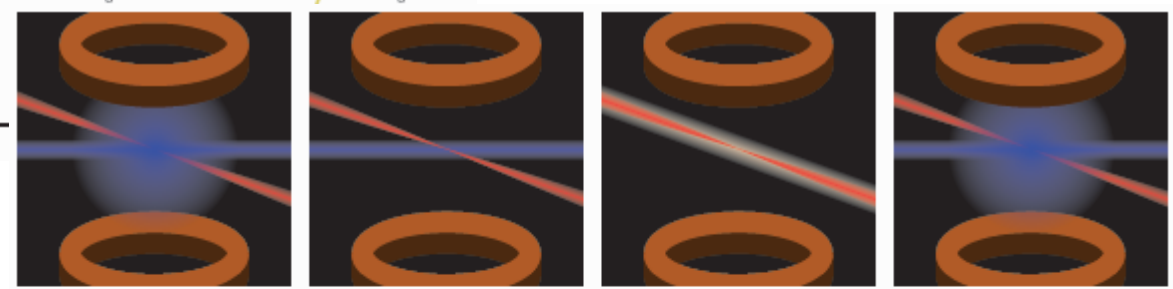
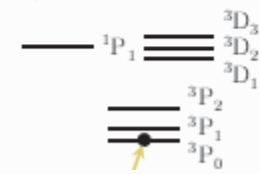
Green Trap
 5×10^5 atoms
 (60 ms)



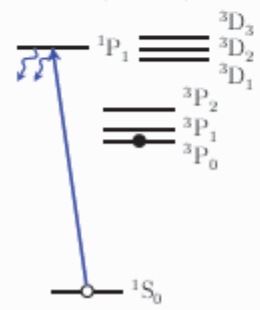
Lattice
 1×10^4 atoms
 (50 ms)



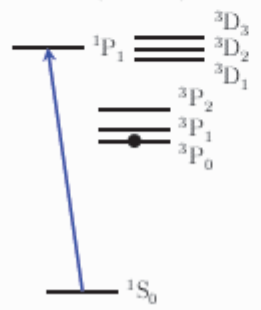
Clock pulse
 Rabi
 (50 ms–100 ms)



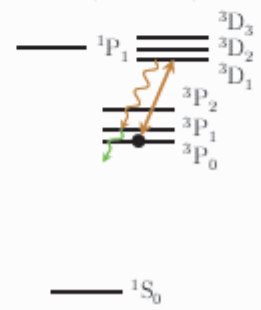
Detection
 Ground state
 (2 ms)



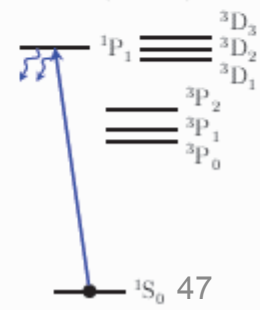
Detection
 Background
 (2 ms)



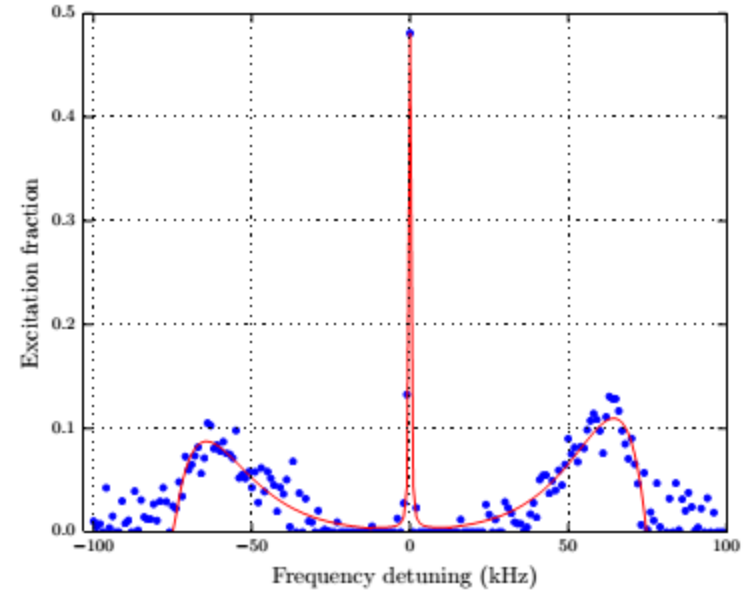
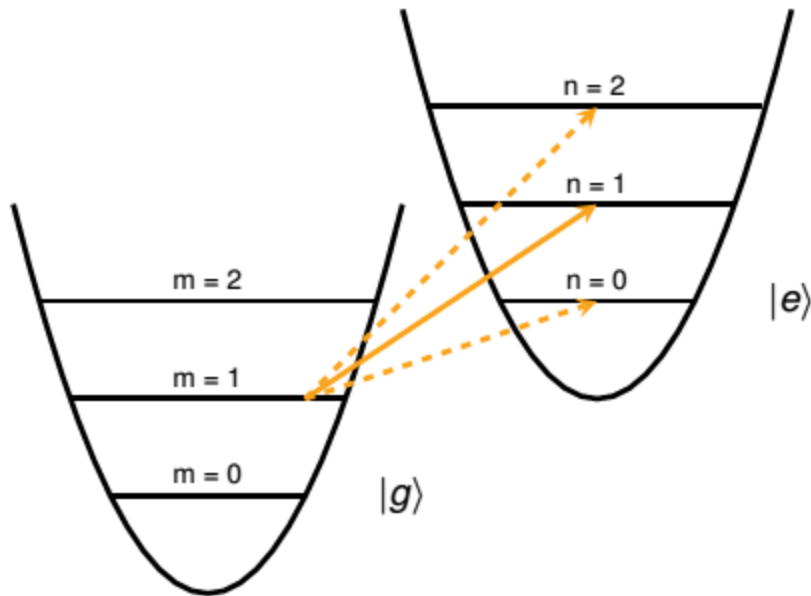
Repump
 to Ground
 (10 ms)



Detection
 Excited state
 (2 ms)

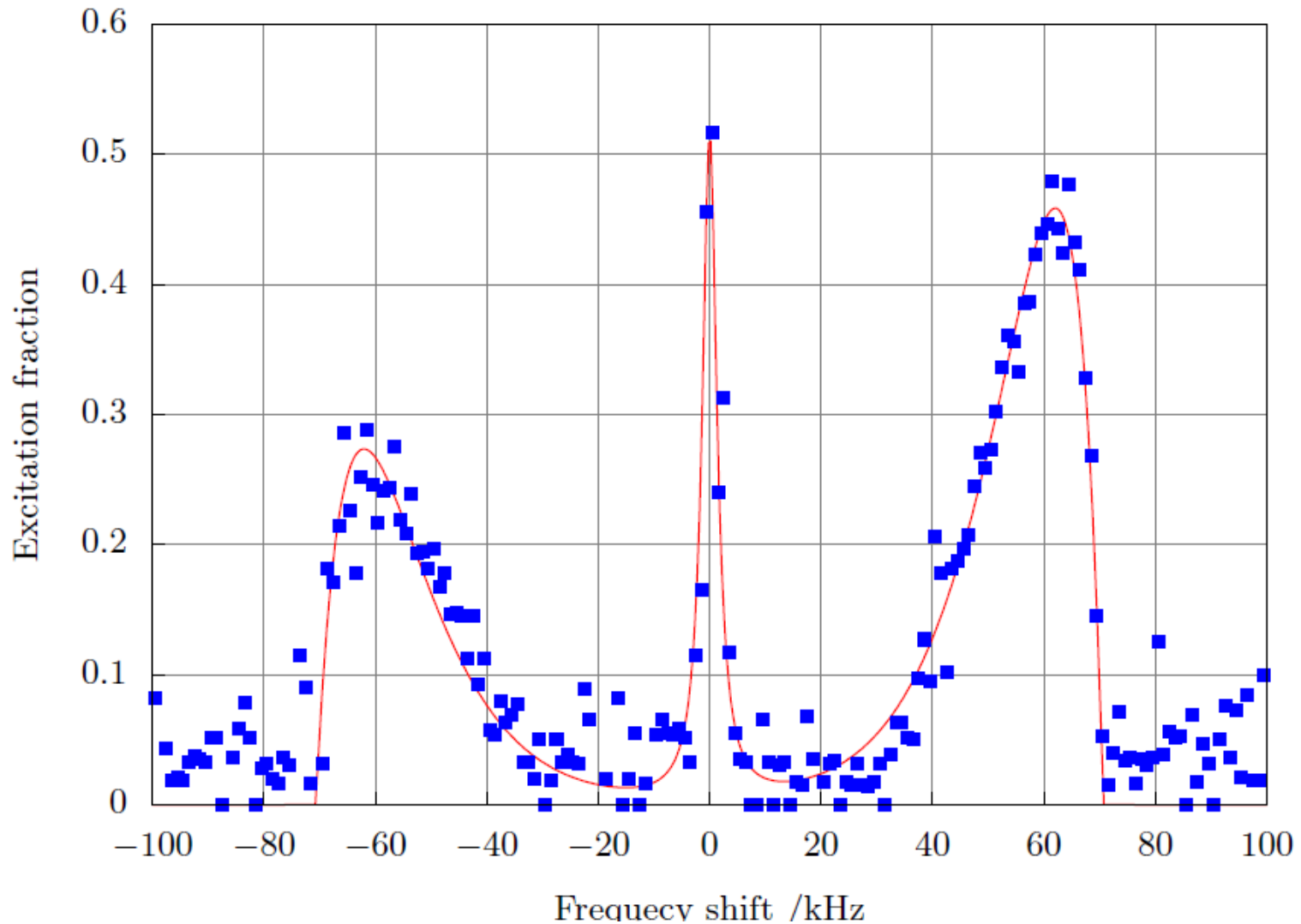


Sideband Spectroscopy



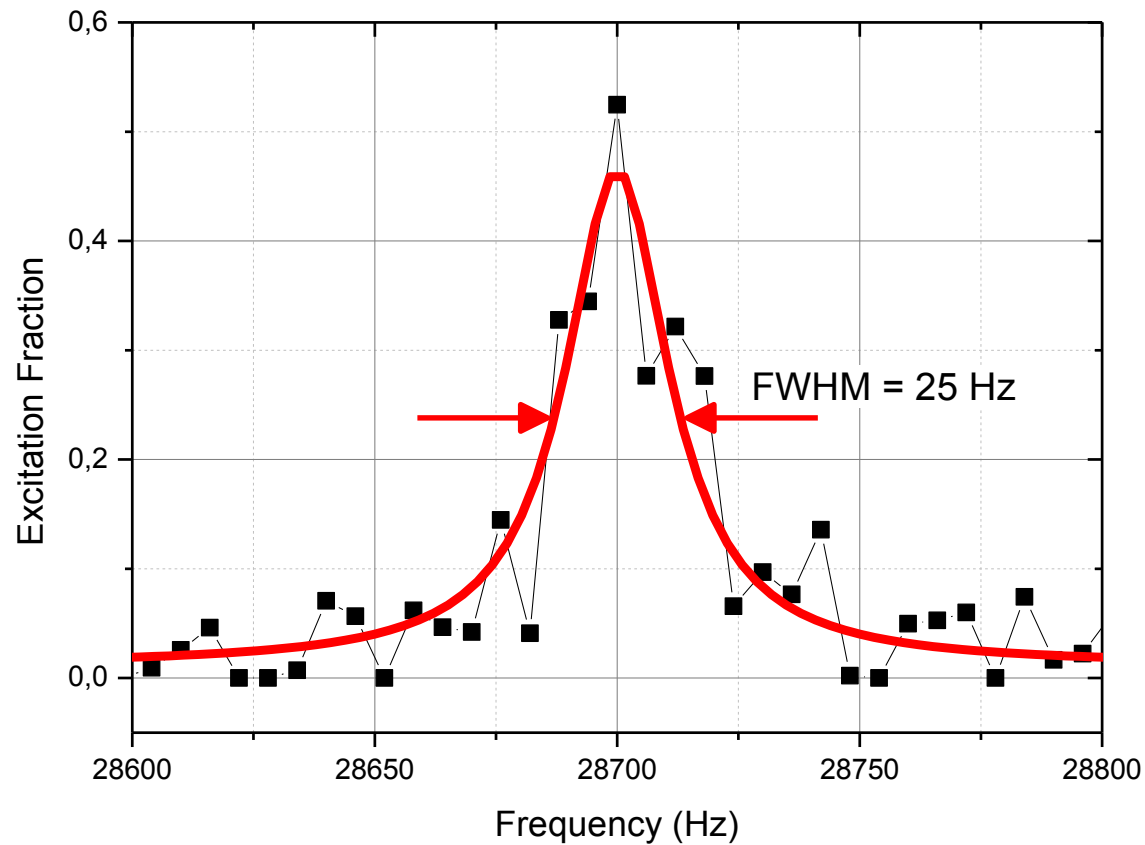
- $\nu_z = 74.7(7)$ kHz
- Profondità del reticolo $U_0 = 340(6)E_R$
- $T_z = 13.66(13)$ μK

Sideband Spectroscopy

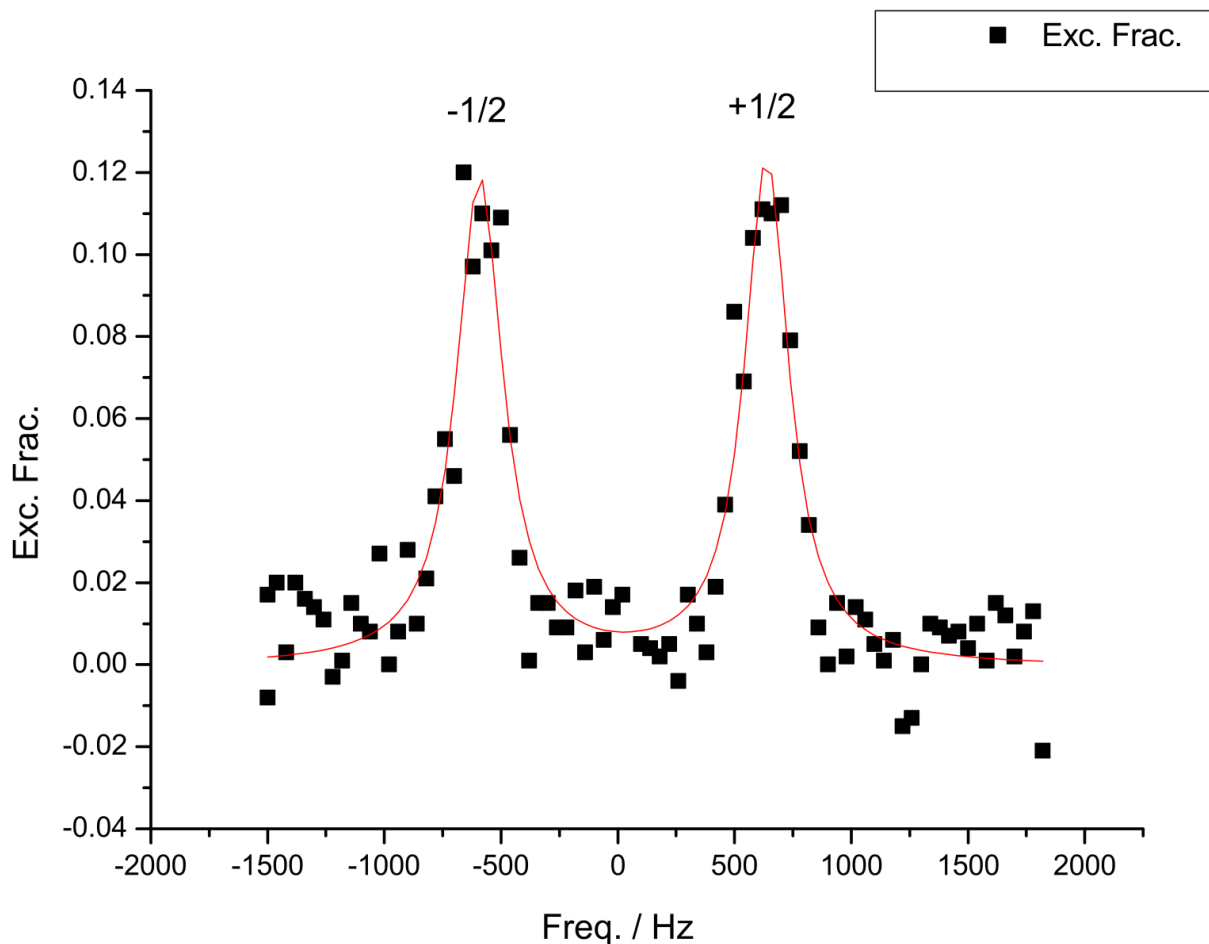


Probe laser: 100 ms @100 μ W - Sidebands @70 kHz (\sim 300 Er) - Asimmetry: T \sim 5 μ W

Clock Spectroscopy



Clock Spectroscopy/2



- 2π transitions only (Yb171 has spin 1/2)
- Zeeman splitting ~ 200 Hz/G
- Linewidth often broaden >100 Hz

So how good are optical clocks right now?

Reported uncertainty

Al⁺ ion quantum logic clock: 4×10^{-18}

Hg⁺ ion cryogenic ion clock: 4×10^{-17}

Sr⁺ ion quadrupole clock: 4×10^{-18}

Yb⁺ ion octupole clock: 4×10^{-18}

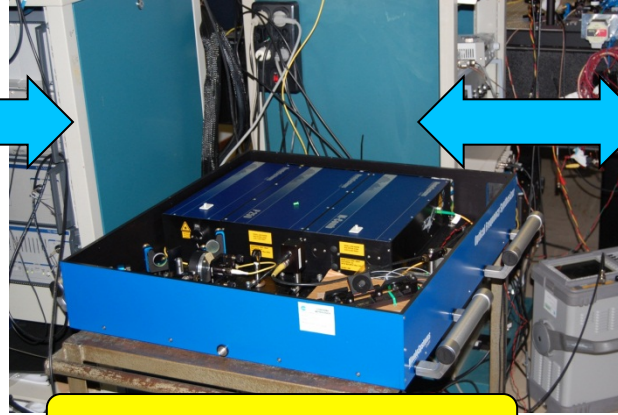
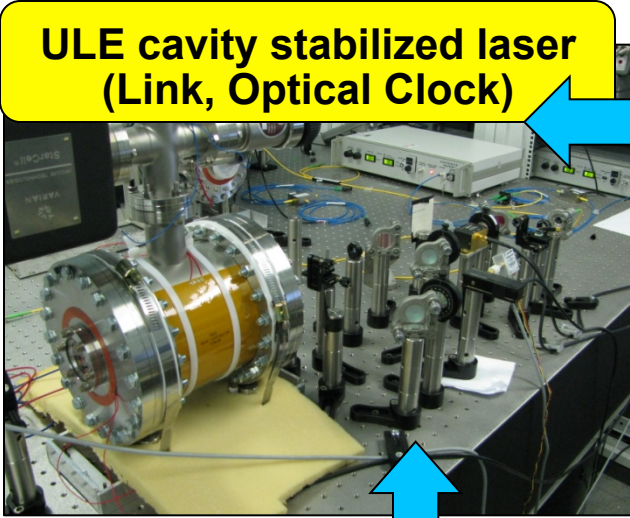
Sr neutral lattice clock: 5×10^{-18}

Yb neutral lattice clock: 5×10^{-18}

Cs fountain clock systematic unc: 2×10^{-16} (best)

But its work in progress & other systems under
evaluation.....

**ULE cavity stabilized laser
(Link, Optical Clock)**



Femtosecond comb

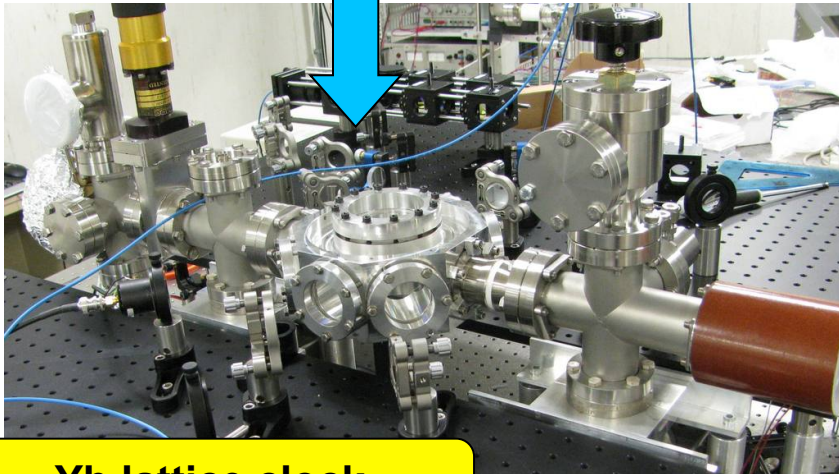


**Cryogenic
Cs Fountain
ITCsF2**



**Cs Fountain
ITCsF1**

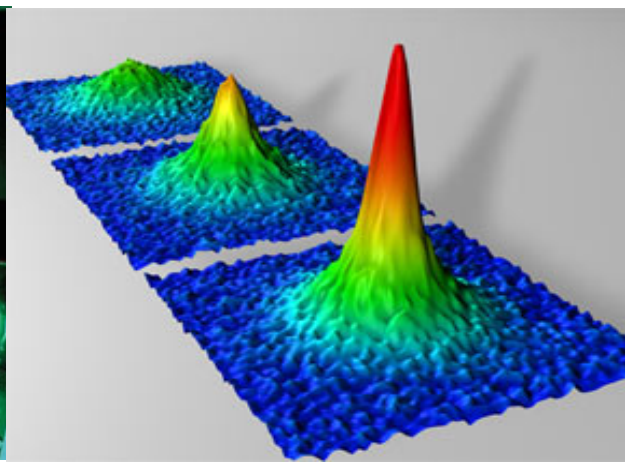
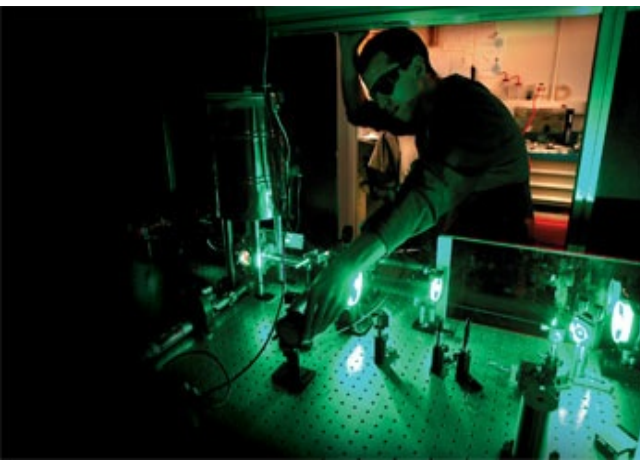
Cs Primary References



Yb lattice clock

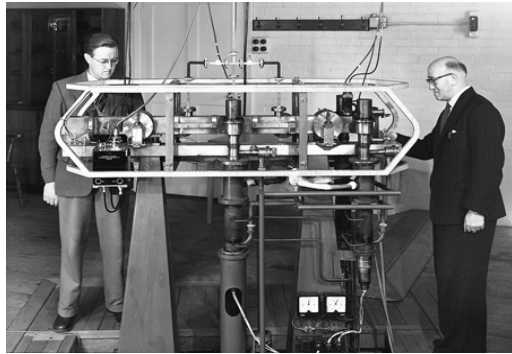
4 H-Masers





LINK E CONFRONTI IN FIBRA OTTICA

Atomic clocks accuracy in the last 50 years

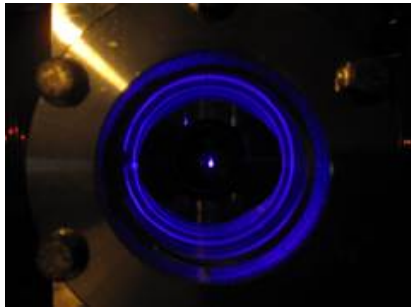


First Cs beam clock
(1955)

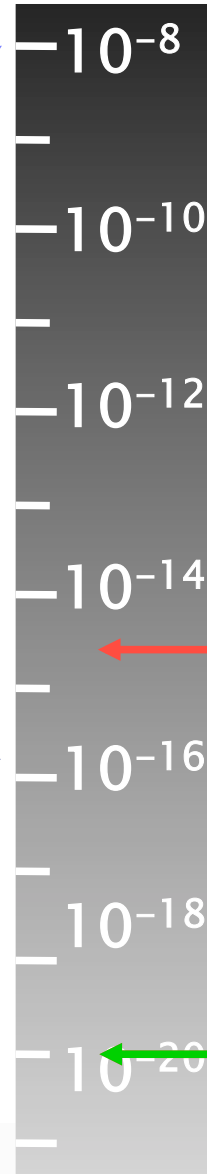
First Cs fountain
(1996)



Cs fountain clocks
(today)



Best optical clocks
(today)

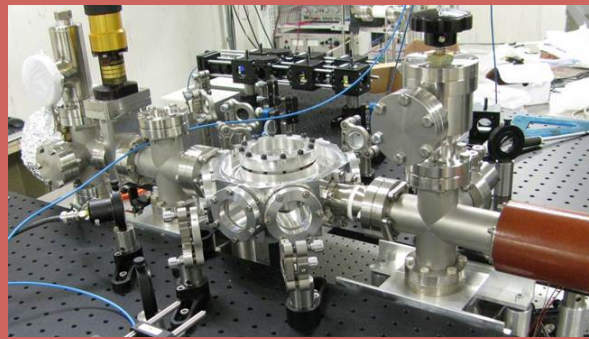


Satellite techniques
(1 day averaging)

Optical links
(1 day averaging)

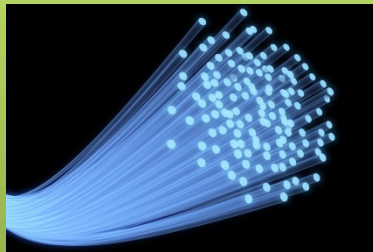


Accurate Time for all: How to?



National Metrological Institutes (Atomic Clocks)

Optical Fiber Techniques



Satellite Techniques



USERS

Fiber Link: how it works

ULTRASTABLE
TRANSFER LASER

1542 nm,
 $\Delta\nu < 10$ Hz

FPC

BIDIRECTIONAL
FIBER

Faraday
Mirror

Optical
Filter

Faraday
Mirror

AOM1

AOM2



PLL

FIBER NOISE
COMPENSATION

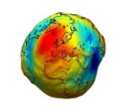


CLOCK A



CLOCK B





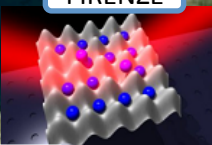
MILANO

FREJUS

TORINO



FIRENZE



BOLOGNA



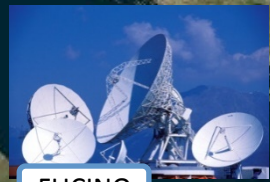
ROMA



NAPOLI



FUCINO



MATERA

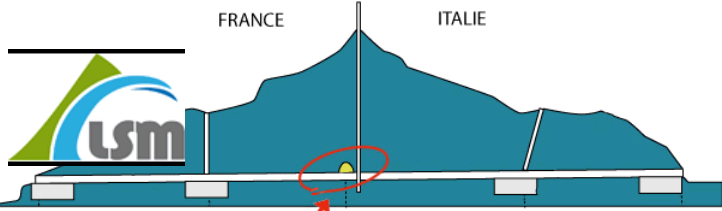


LIFT impact on academic research

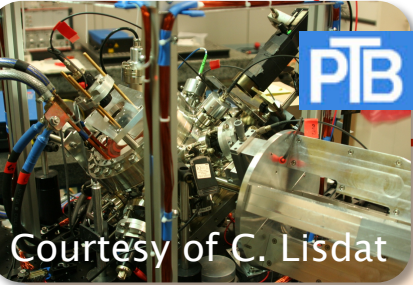
Frejus Tunnel

Relativistic Geodesy

FRANCE ITALIE



PTB



Courtesy of C. Lisdat

Florence

Atomic and molecular spectroscopy



INO
ISTITUTO NAZIONALE
DI OTTICA



Courtesy of P. De Natale

Bologna



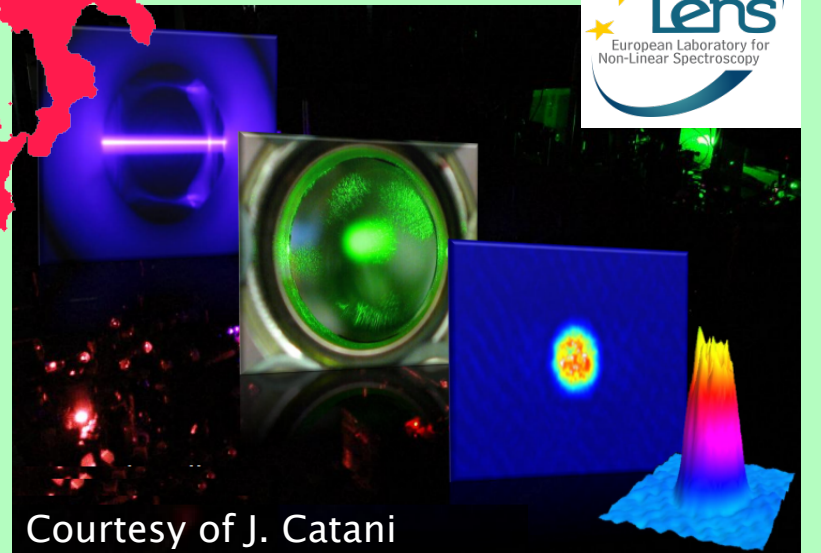
564 m x 640 m
Telescopes array.



32-m dish for
Very Long Baseline
Interferometry

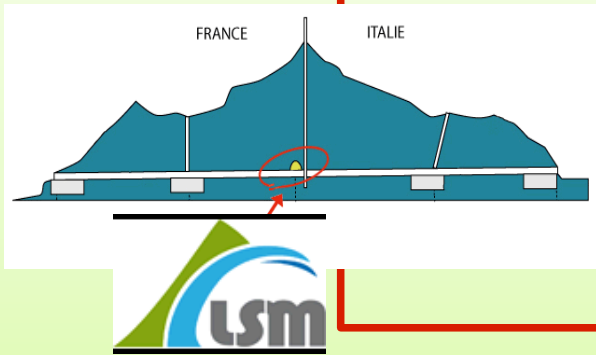


BEC with Yb atoms

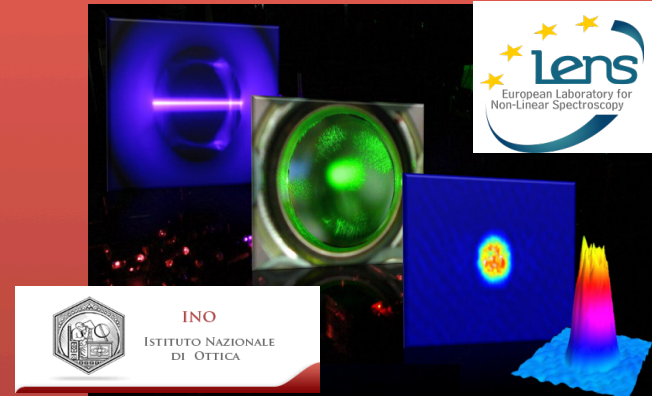


Courtesy of J. Catani

Frejus: Relativistic Geodesy



Firenze: Atomic Physics



Bologna Radio-astronomy VLBI



Caqliari

INAF

ISTITUTO NAZIONALE
DI ASTRONOMIA
NATIONAL INSTITUTE
FOR ASTROPHYSICS

Noto

Matera

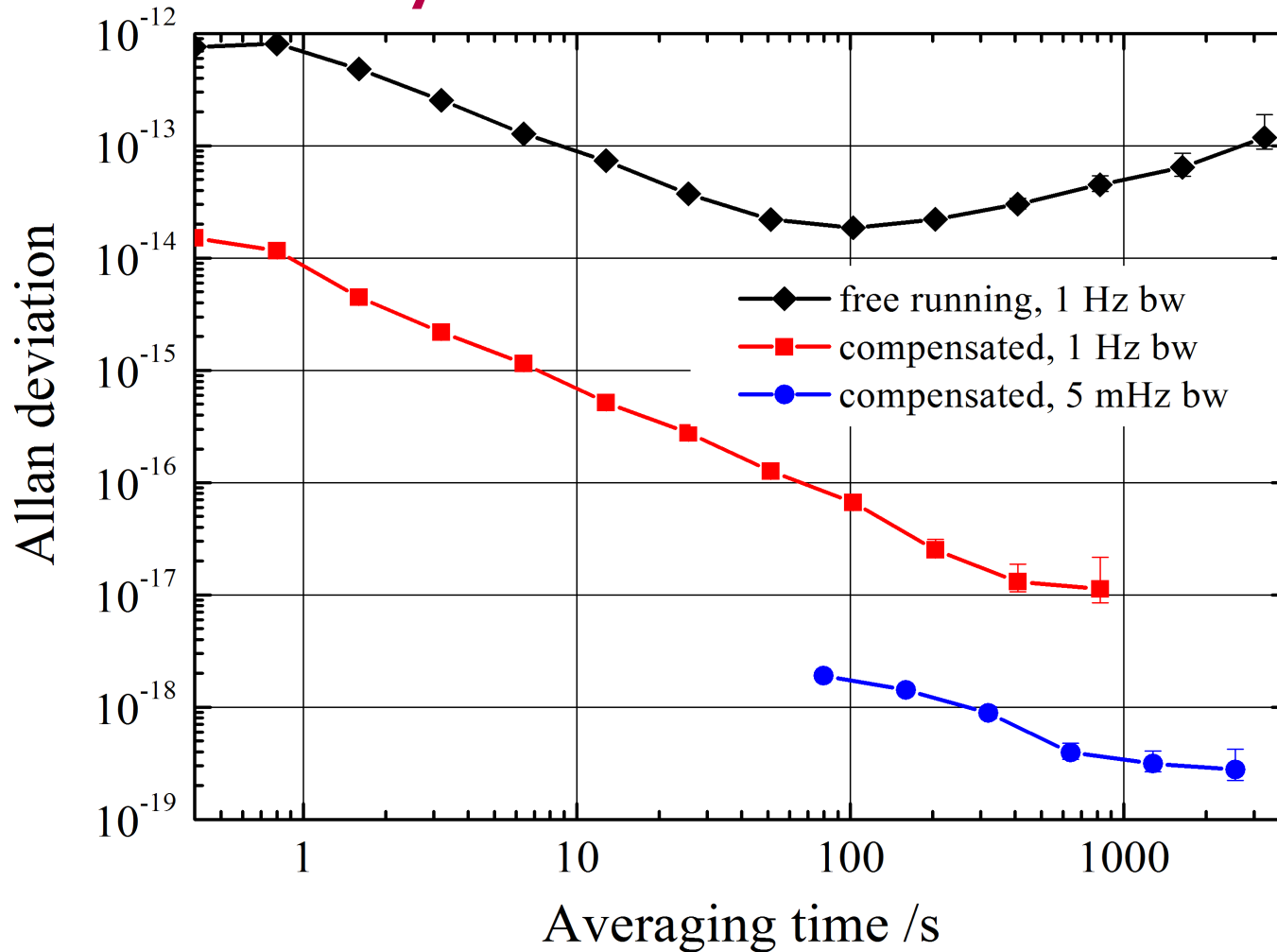


Space Geodesy





Link instability

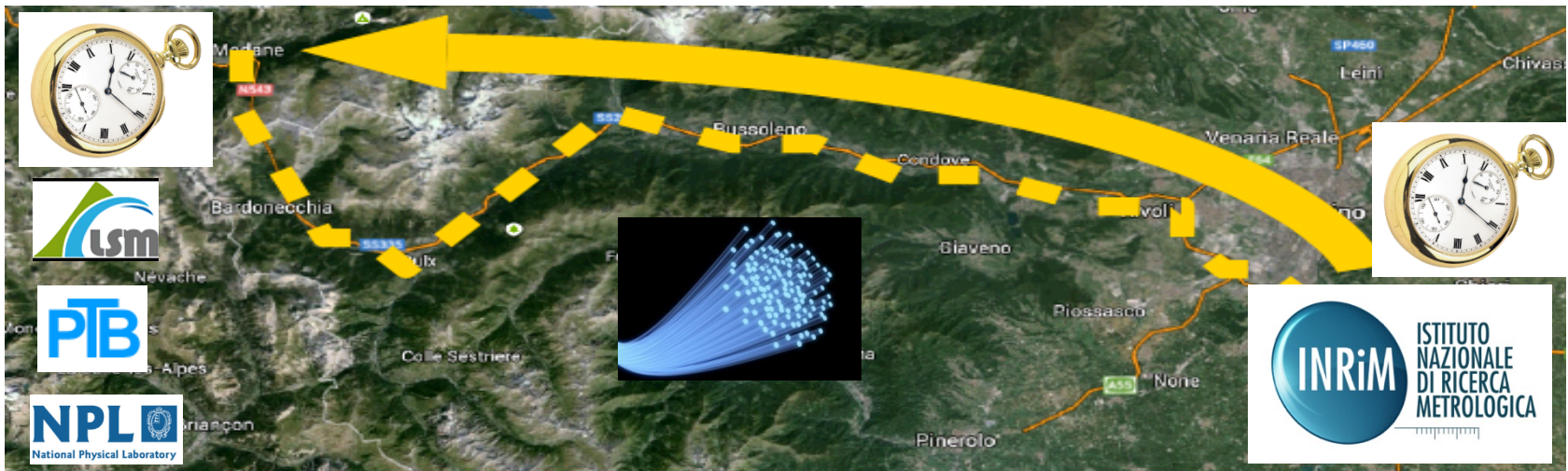
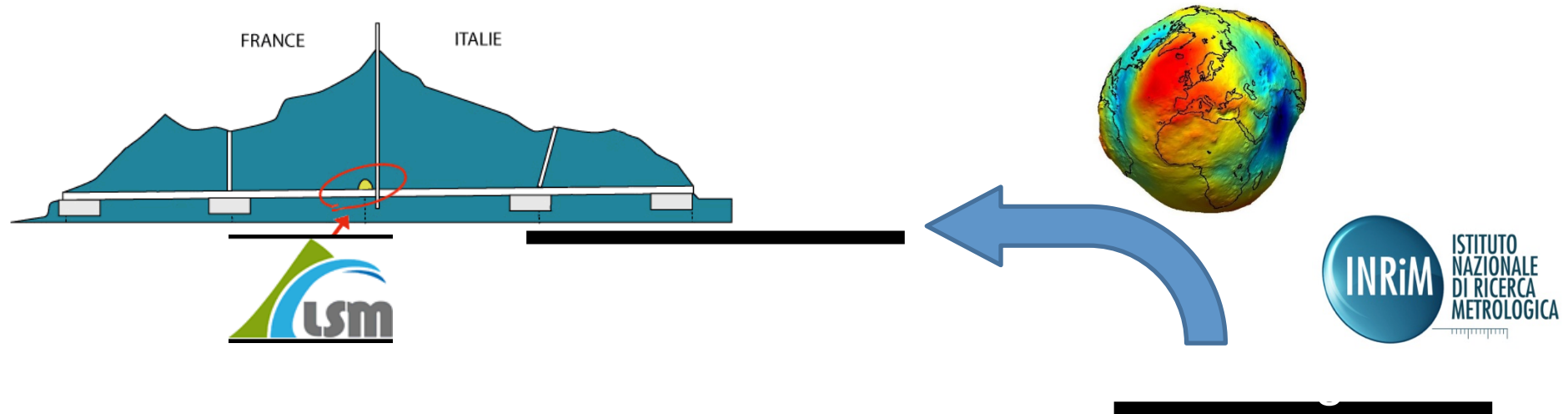


There is not an offset between delivered and original signal at the 5×10^{-19} level

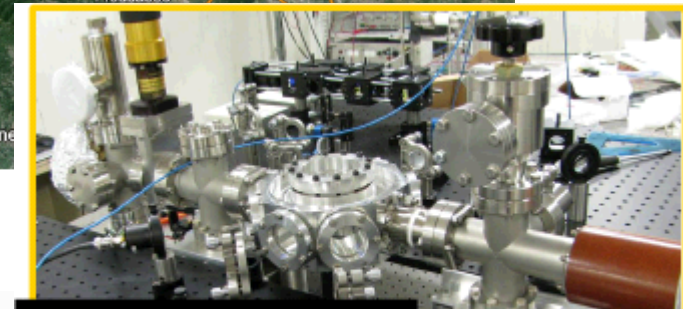
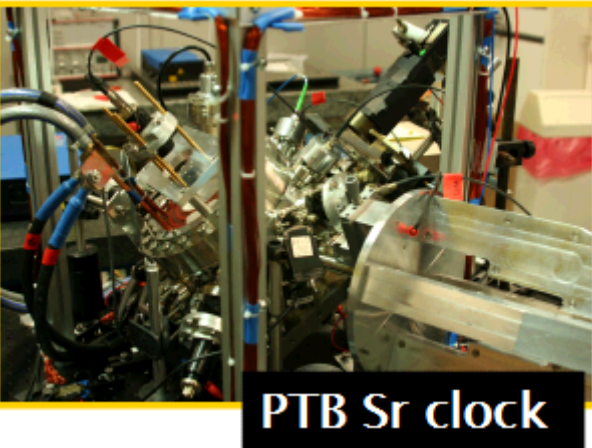
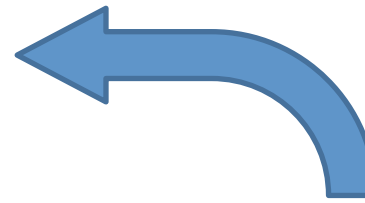
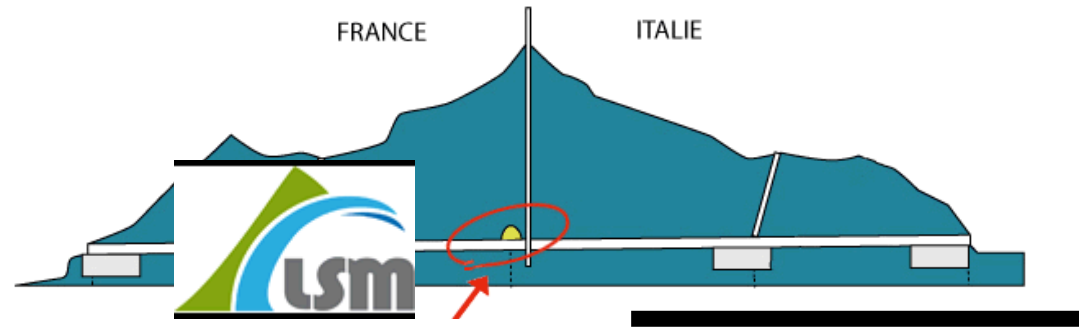


Relativistic Geodesy

General Relativity: on Earth, clock shift $\sim 10^{-16}/\text{m}$ over the Geoid.
Investigation on Geoid changes at 10 cm level (10^{-17})



Overall



Red-shift Gravitationale



Relatività Generale :

Un potenziale gravitazionale W deforma la metrica spaziotemporale e sposta la frequenza di un orologio ν rispetto a ν_0 su un potenziale di riferimento W_0

Nel limite di campo debole $W/c^2 \ll 1$, c velocità della luce, W_0 riferimento di potenziale):

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

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

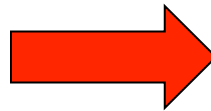
Local Position Invariance

In campi gravitazionali deboli, il principio di equivalenza di Einstein (EEP) porta l'invarianza locale di posizione (LOCAL POSITION INVARIANCE, LPI):

SPECIE ATOMICHE DIVERSE RISENTONO DELLO STESSO RED SHIFT GRAVITAZIONALE

$$\frac{\nu_A}{\nu_B} = \frac{\nu_{A0}}{\nu_{B0}} \left[1 + (\beta_A - \beta_B) \frac{W}{c^2} \right]$$

**RELATIVITA'
GENERALE**

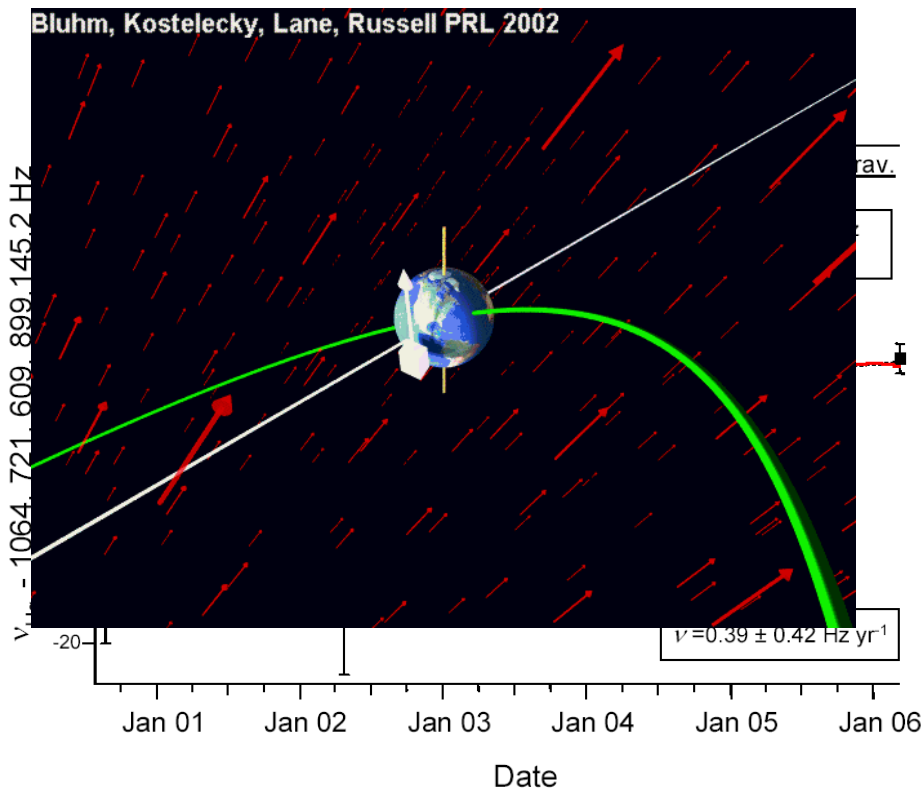


$$\beta_A = \beta_B$$

Test LPI

$$\frac{\nu_A}{\nu_B} = \frac{\nu_{A0}}{\nu_{B0}} \left[1 + (\beta_A - \beta_B) \frac{W}{c^2} \right]$$

$$\beta_A - \beta_B = 0 \quad ?$$



Mg-Cs (IEN-1992)

$$|\beta_{Mg} - \beta_{Cs}| \leq 7 \cdot 10^{-4}$$

Cs-H (PTB-2002)

$$|\beta_{Cs} - \beta_H| \leq 7 \cdot 10^{-5}$$

Cs-Hg⁺ (NIST-2007)

$$|\beta_{Cs} - \beta_{Hg^+}| \leq 3.5 \cdot 10^{-6}$$

Cs-H (NIST-2007)

$$|\beta_{Cs} - \beta_H| \leq 1.4 \cdot 10^{-6}$$

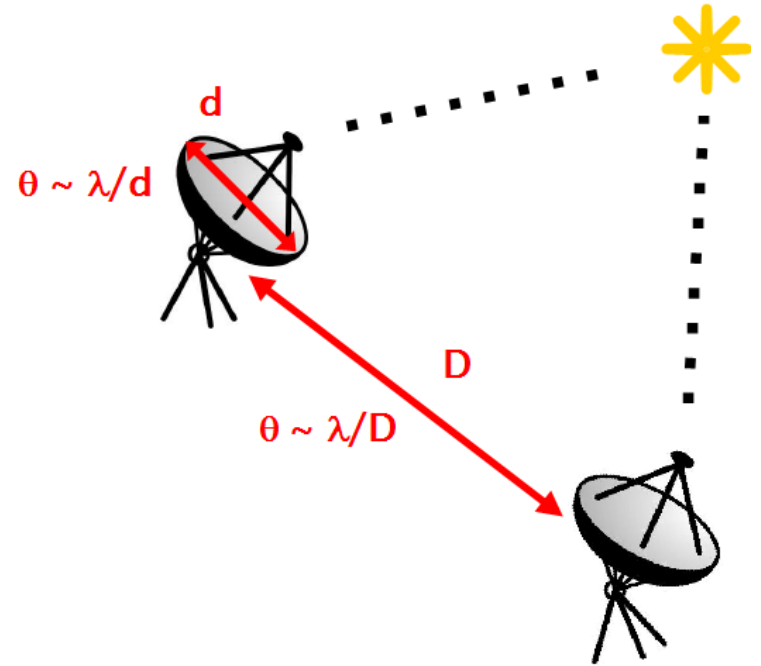
Timing per Radioastronomia



Radioastronomia e VLBI (Very Large Baseline Interferometer)



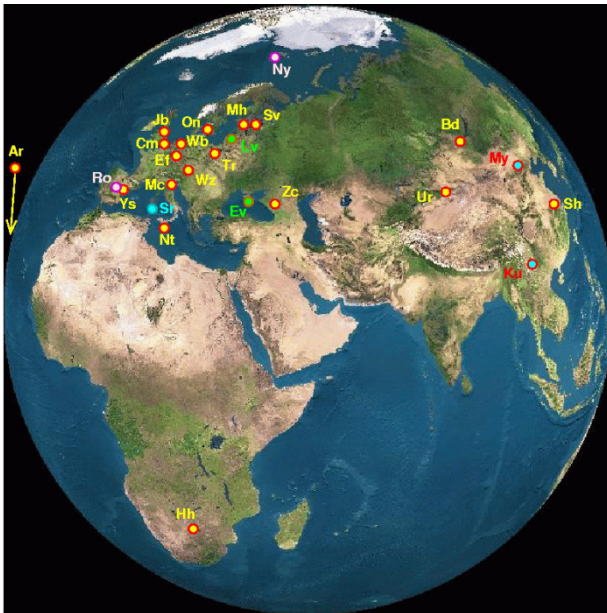
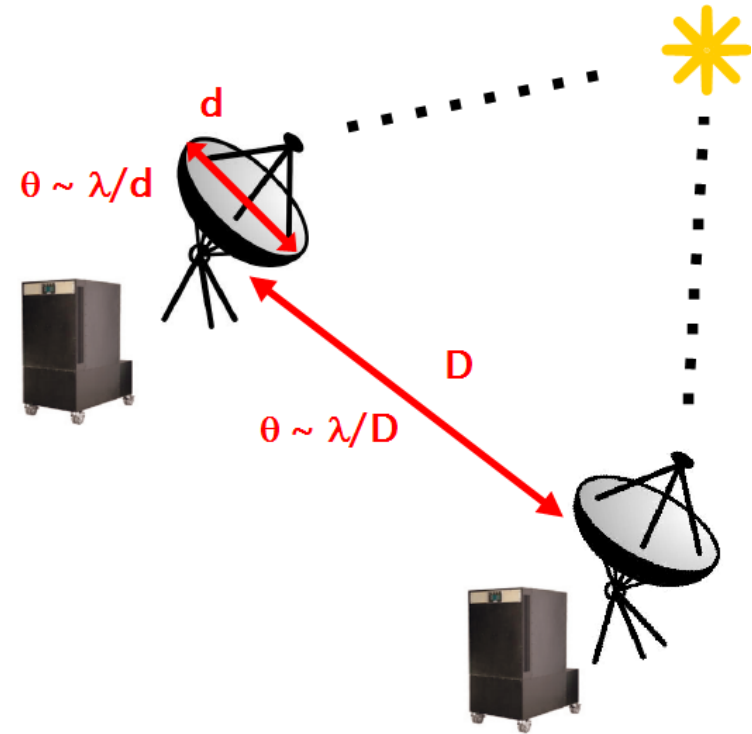
Radiotelescopi a IRA-INAf di Medicina



Antenne remote aumentano la
risoluzione angolare di un fattore D/d (Es. 900
 $0 \text{ km} / 30 \text{ m} = 300.000$)
ma le osservazioni
devono essere sincrone

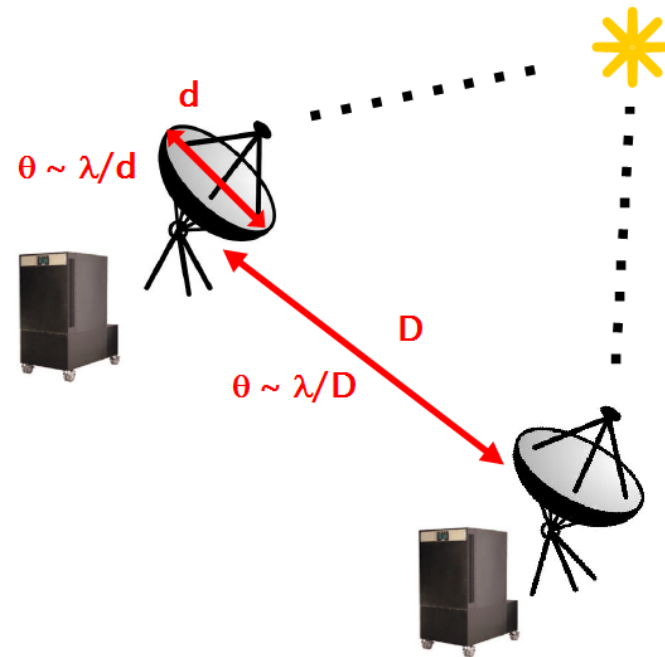
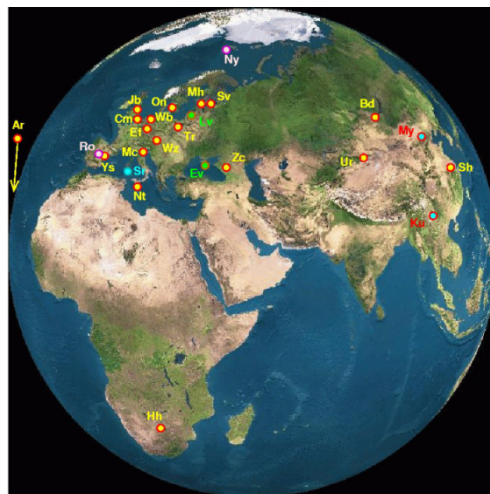


VLBI e orologi atomici



La sincronizzazione necessaria solo se si usano orologi atomici ultrastabili come i Maser all'Idrogeno

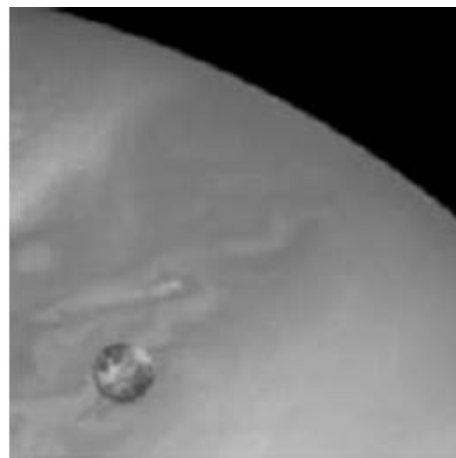
VLBI e orologi atomici



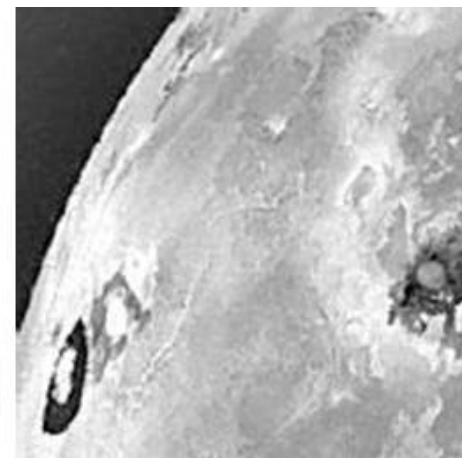
1' (minuto d'arco)
Radiotelescopio 140 m



1'' (secondo d'arco)
Array 8 km



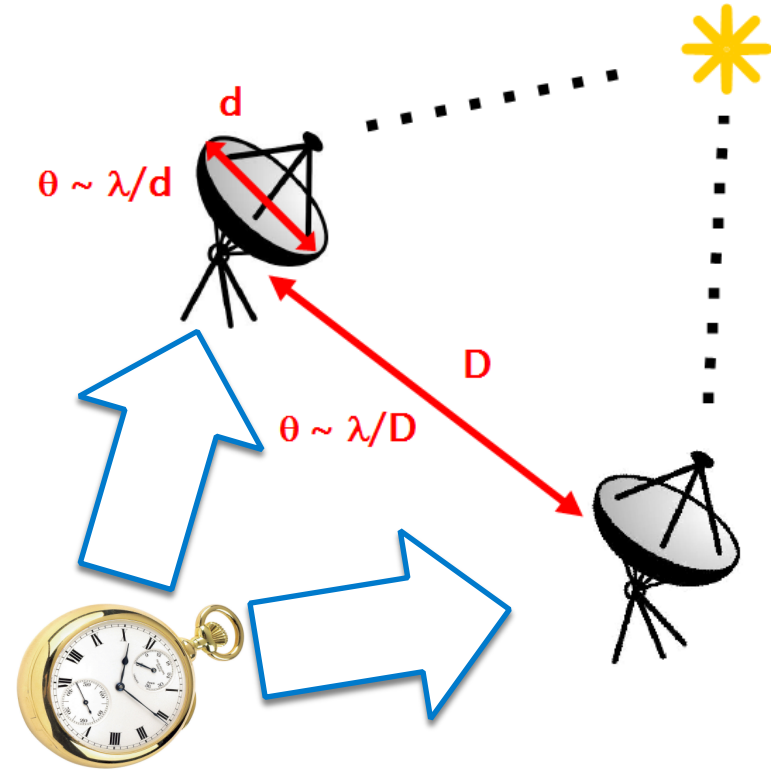
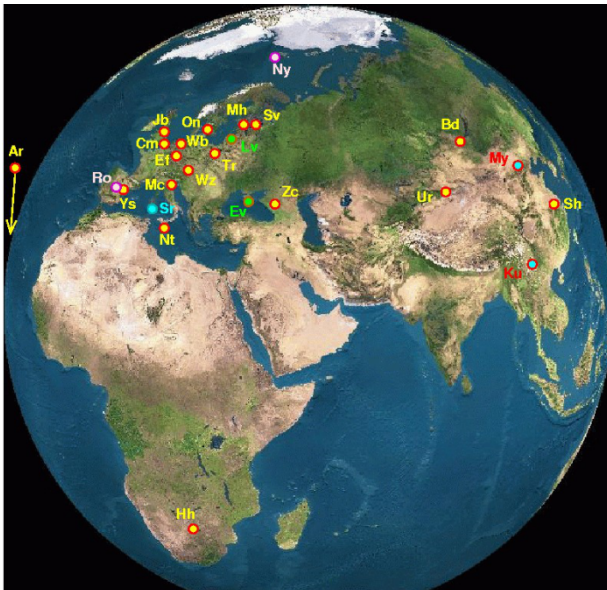
0,05''
Large Array 160 km



0,001''
VLBI 8000 km

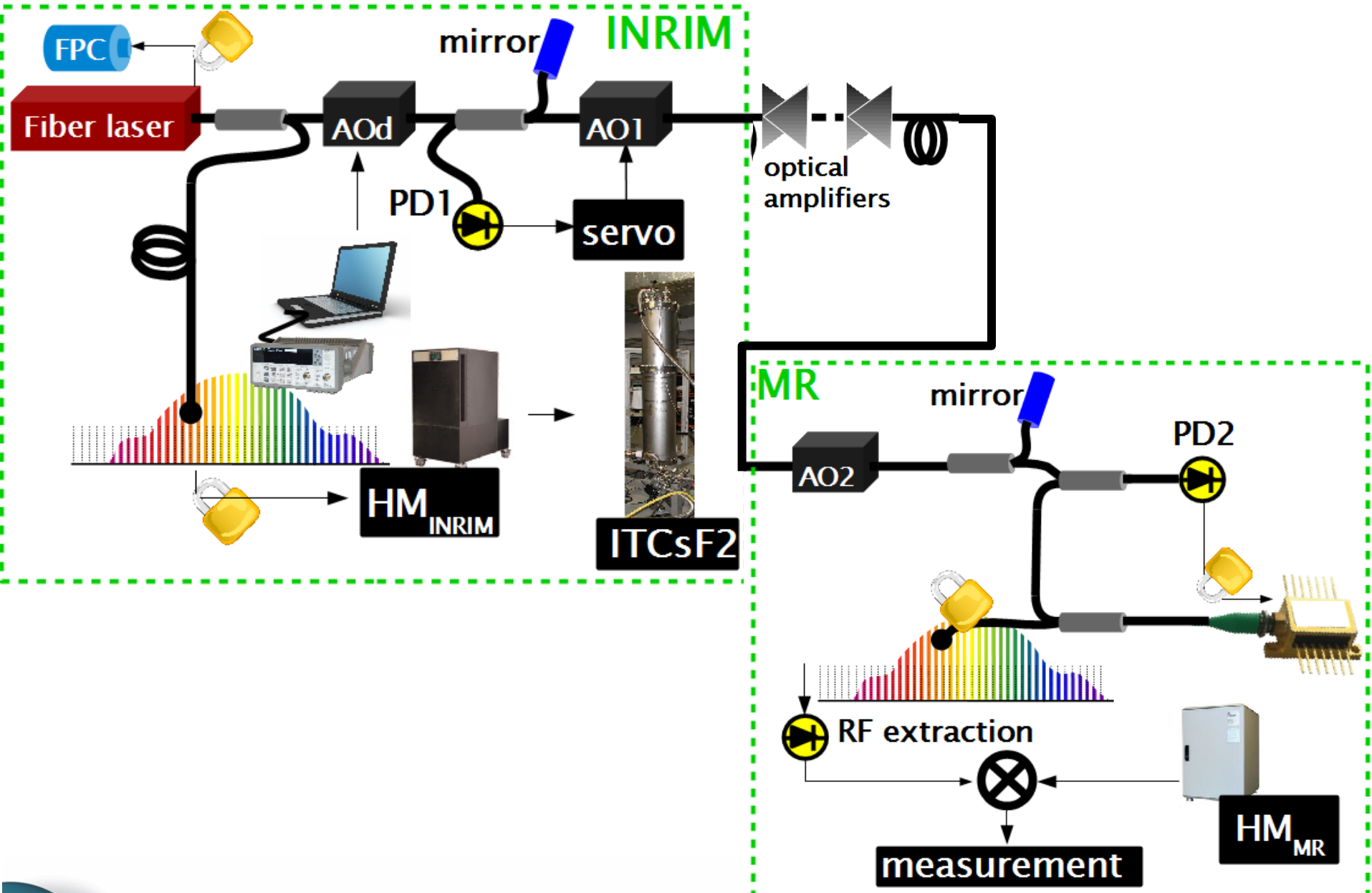


VLBI e orologi atomici



Perché non usare
un common clock?

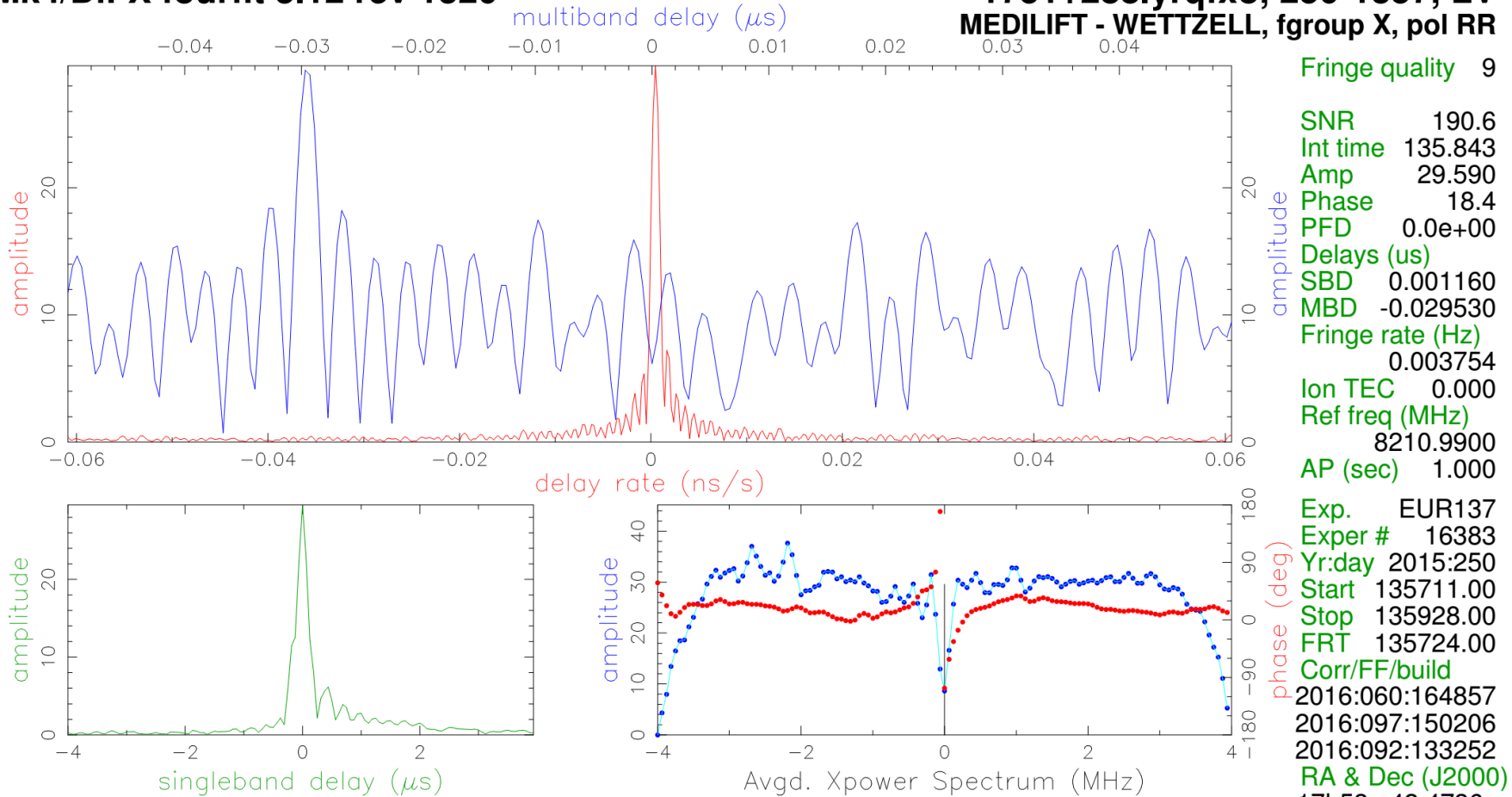
Fiber Link from INRIM to Medicina: set-up



MediLIFT Geodetic VLBI Fringes

Mk4/DiFX fourfit 3.12 rev 1320

1751+288.yrqfxo, 250-1357, LV
 MEDILIFT - WETTZELL, fgroup X, pol RR



Fringe quality 9

SNR 190.6
 Int time 135.843
 Amp 29.590
 Phase 18.4
 PFD 0.0e+00
 Delays (us)
 SBD 0.001160
 MBD -0.029530
 Fringe rate (Hz)
 0.003754
 Ion TEC 0.000
 Ref freq (MHz)
 8210.9900
 AP (sec) 1.000

Exp. EUR137
 Exper # 16383
 Yr:day 2015:250
 Start 135711.00
 Stop 135928.00
 FRT 135724.00
 Corr/FF/build
 2016:060:164857
 2016:097:150206
 2016:092:133252
 RA & Dec (J2000)
 17h53m42.4736s
 +28°48' 4.939"

Amp. and Phase vs. time for each freq., 23 seqs, 6 APs / seq (6.00 sec / seq.), time ticks 10 sec





EMPIR



The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States



-  Ministero
-  Istruzione
-  Università
-  Ricerca

- Characterization of the maser in Matera
- Calibration of ACES ground-to-satellite optical links
- Geodesy VLBI with common clock
Medicina/Matera



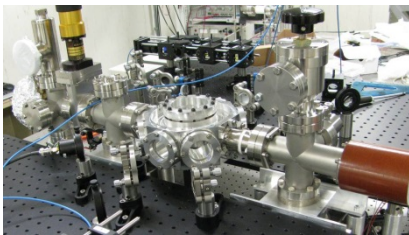
Testing Einstein's geodetic motion

INRIM-ASI-ISS triangle

(July 2016- January 2018)



High accurate
Atomic clocks



Microwave Link
Torino-ISS



Optical Link
Matera-ISS

Optical Link
Torino-Matera



Space Geodesy
Center Bepi Colombo



Conclusioni/1

- La metrologia di frequenza, con gli orologi atomici, è una disciplina di viva e proficua interazione con la fisica atomica e fondamentale (spettroscopia ad alta risoluzione, raffreddamento laser, interazioni fondamentali)
- L'accuratezza dei campioni atomici di frequenza offre la possibilità di eseguire test e misure a supporto della fisica fondamentale
- Prospettive:
Più orologi, più accuratezza, Link Ottici, Orologi nello Spazio:
Test migliori e nuovi Test



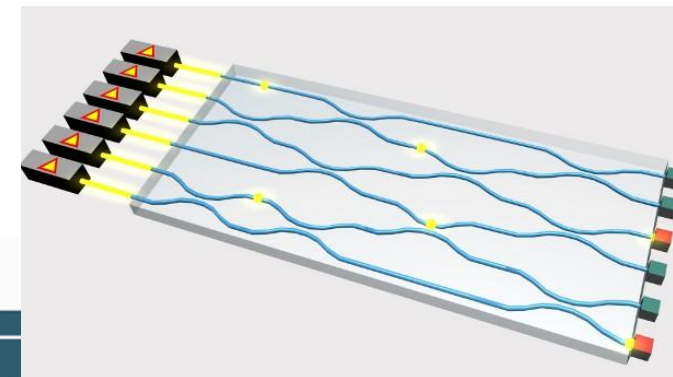
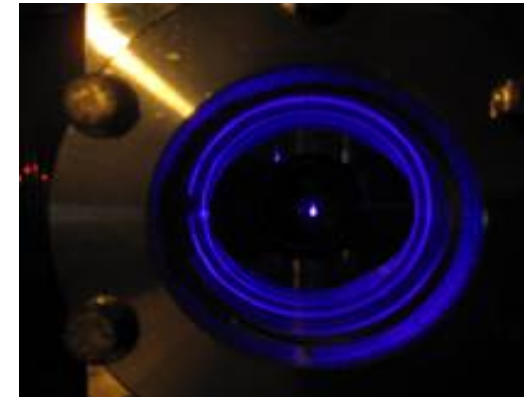
Conclusioni/2

- All'INRIM sono state sviluppate tecniche di raffreddamento laser degli atomi per la spettroscopia ad alta risoluzione
- E' operativo un campione primario di frequenza a fontana con accuratezza relativa di 2×10^{-16} .
- Orologio ottico a Yb in sviluppo.
- Link ottici in Italia e in Europa
- Test accurati di fisica fondamentale

Sono disponibili Tesi di Laurea/Dottorato

TESI DISPONIBILI

- Light-shifts measurements in optical lattice clock with an enhancement cavity
- A new optical lattice clock with control of the blackbody-radiation shift
- UV spectroscopy in Hg for a new measurement of the Boltzmann constant
- Dual Comb Spectroscopy Techniques: High Precision Fast Spectroscopy
- Fibre link and Radioastronomy
- Quantum Key Distribution over a fiber quantum backbone
- Coherent laser Time Transfer

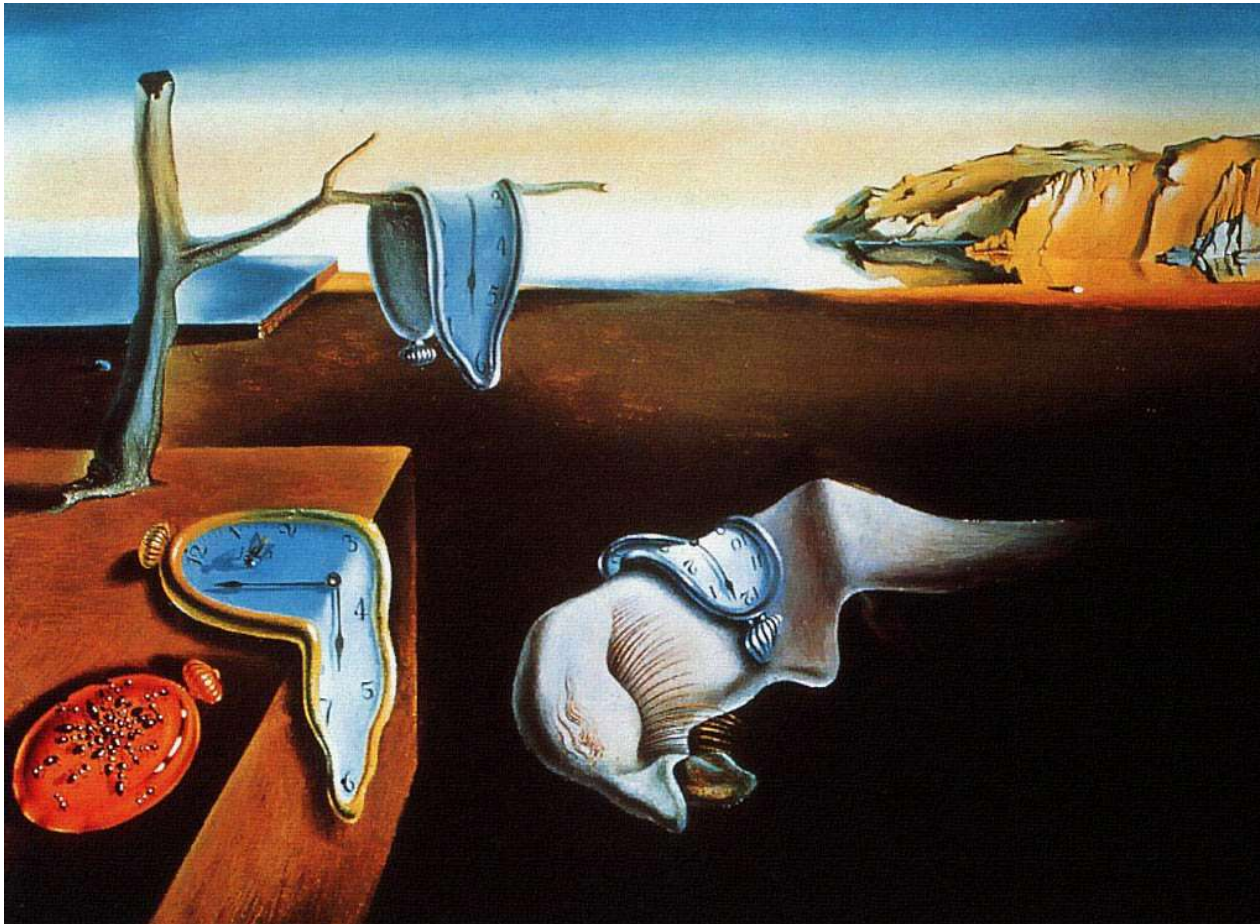


INRiM Atomic Frequency Standards Group



Il tempo e la relatività:

S. Dalì, 1931, *La Persistenza della memoria*



ma anche il paradigma dei quanti...

Salvador Dalì, 1954,

La Disintegrazione della Persistenza della memoria

