

OROLOGI ATOMICI: STATO DELL'ARTE

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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?





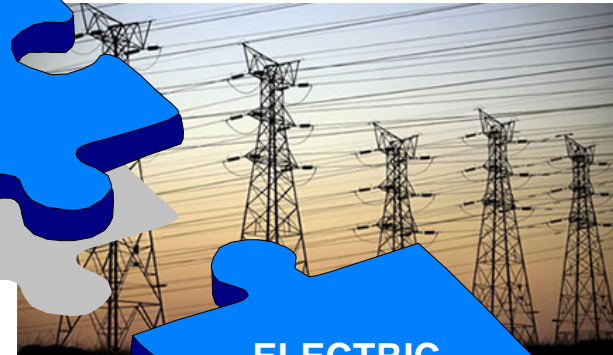
POSITIONING SYSTEMS

TELECOMMUNICATIONS



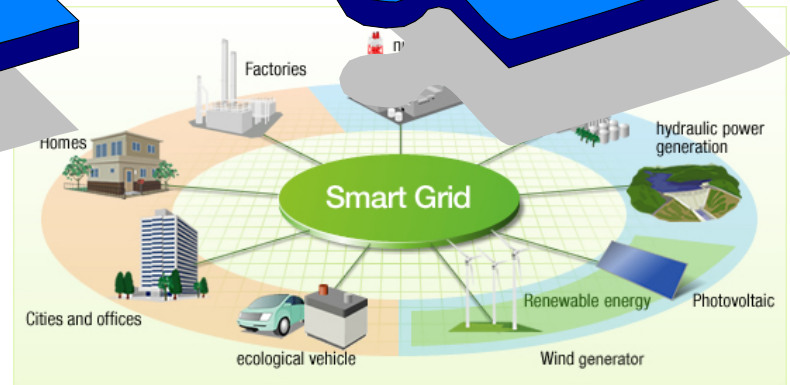
TRANSPORTS AND NAVIGATION

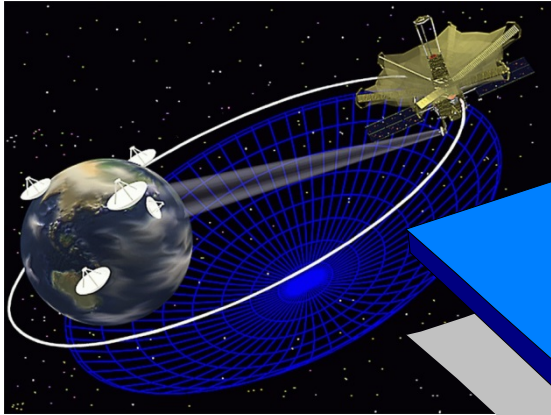
DATING



ELECTRIC POWER

E-COMMERCE





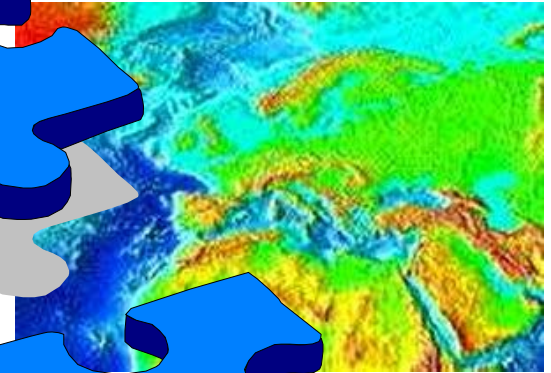
SPACE



EQUIPMENT

**FUNDAMENTAL
RESEARCH**

GEODESY



AGRICULTURE

DEFENCE



La convenzione del metro



ITALIA: INRiM a Torino





INRIM Atomic Frequency Standards Group



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)**

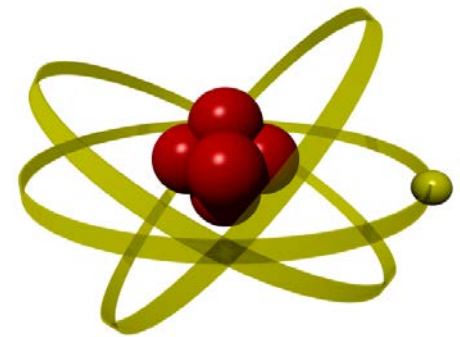
*Il secondo è la frazione $1 / 86\,400$
del giorno solare medio*

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

*Il secondo è la frazione $1 / 31\,556\,925,9747$
dell'anno tropico relativo al giorno
1 gennaio 1900 alle ore 12 UT*

- **Tempo atomico (dal 1967)**

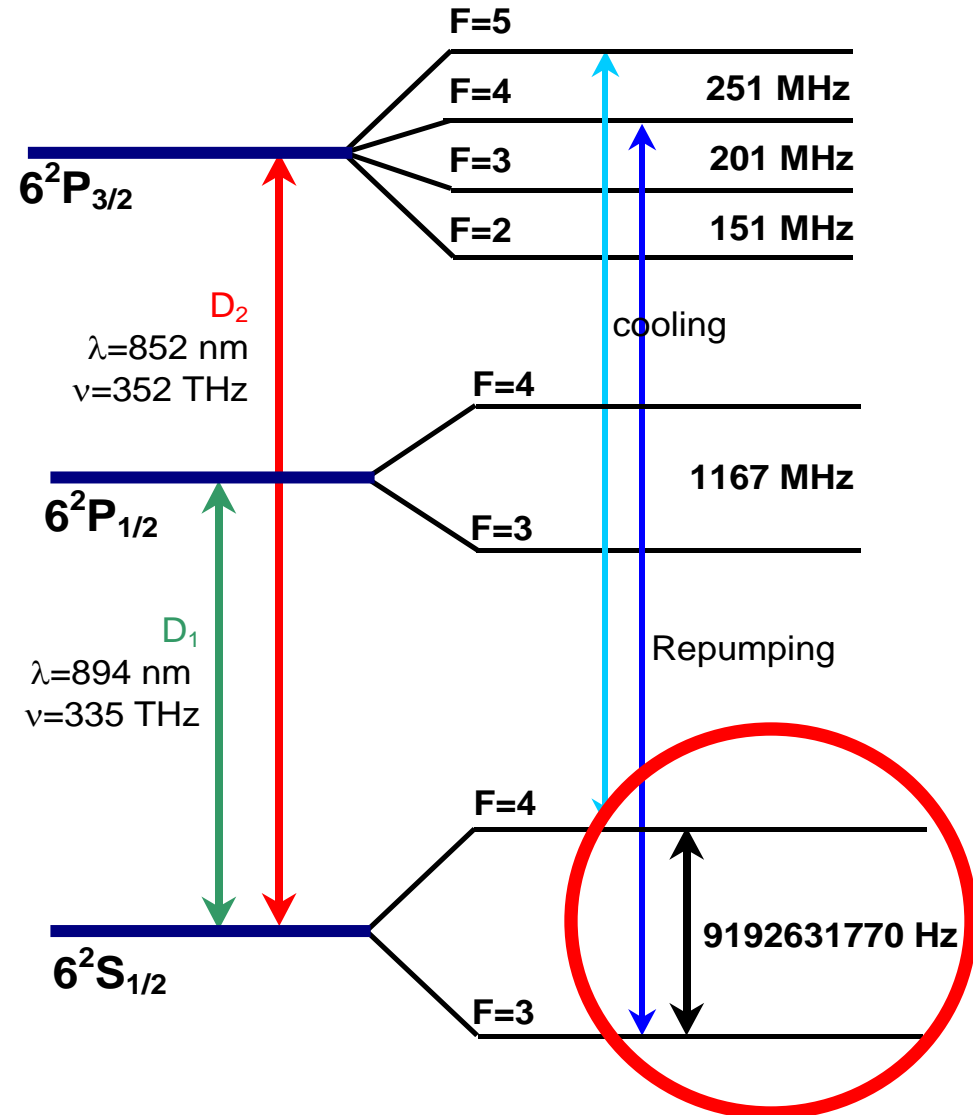
*Il secondo è la durata di $9\,192\,631\,770$
periodi della radiazione corrispondente
alla transizione tra i due livelli iperfini
dello stato fondamentale dell'atomo
di cesio 133.*



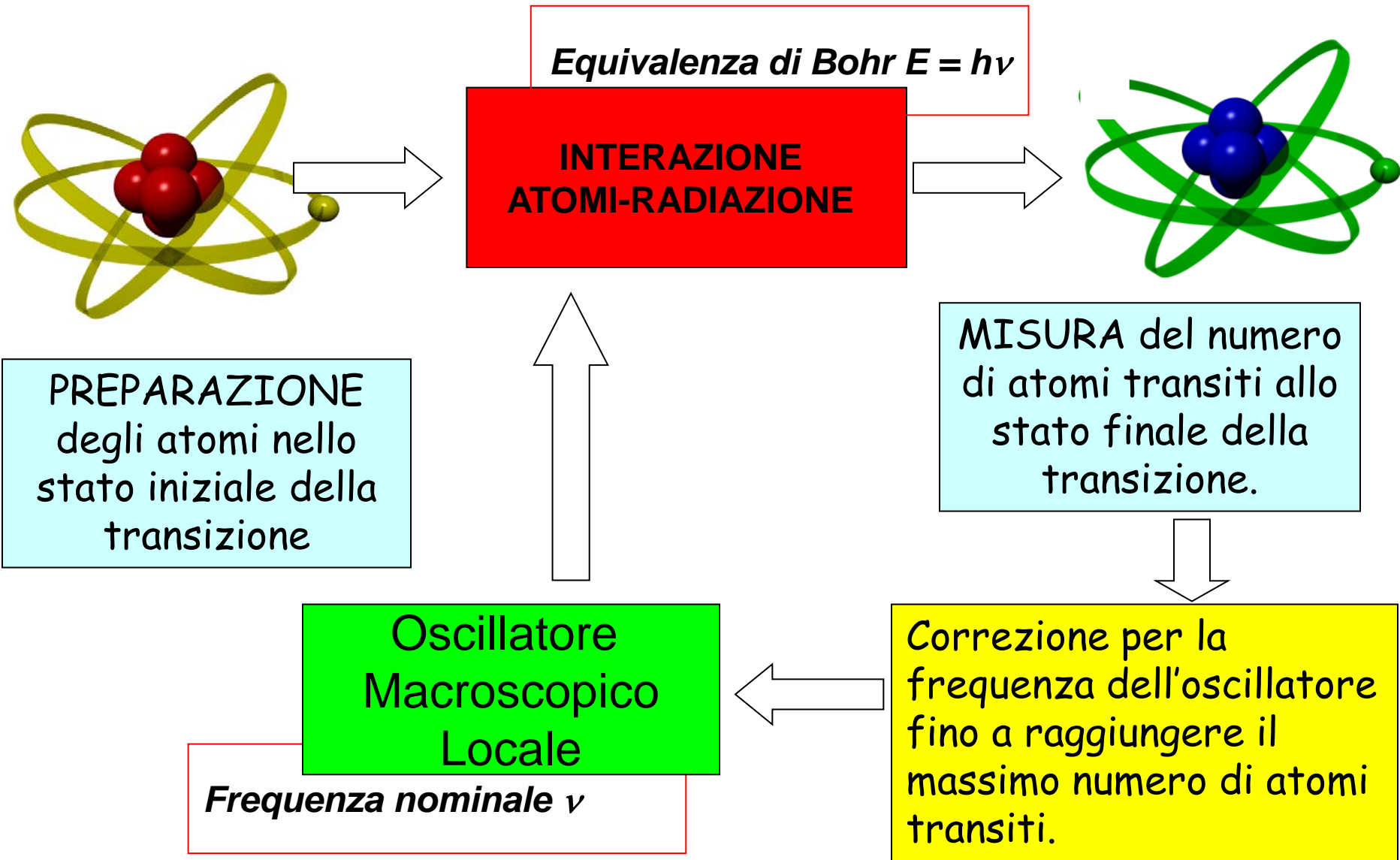
Il secondo SI

Tra tutte le possibili transizioni il secondo è definito come:

Il secondo è l'intervallo di tempo corrispondente a 9192631770 periodi di radiazione della transizione tra i due stati fondamentali dell'atomo di ^{133}Cs imperturbato.

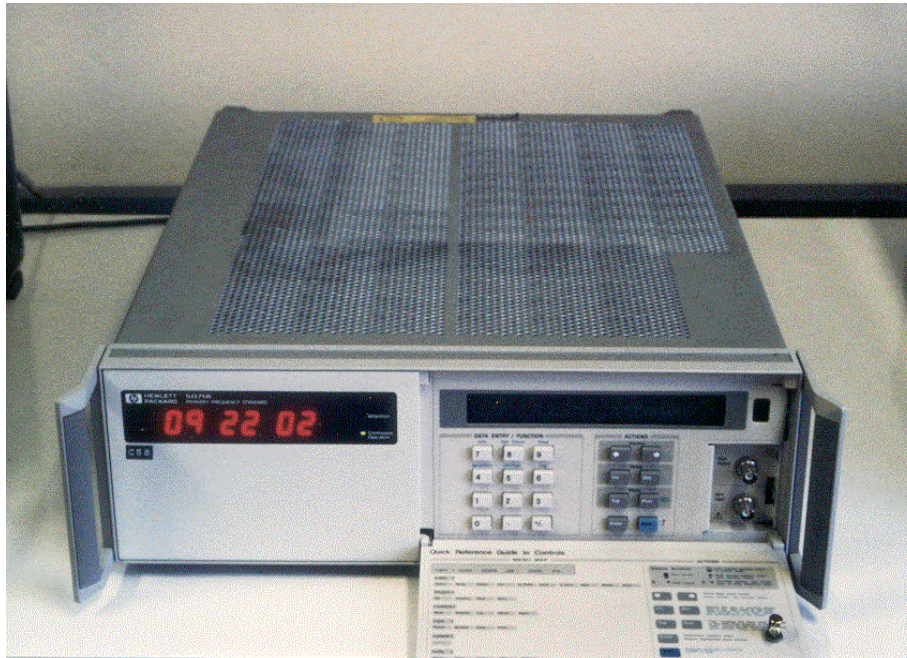


Orologi atomici: Principia



Orologi atomici commerciali:

- Cesio
- Idrogeno
- Rubidio

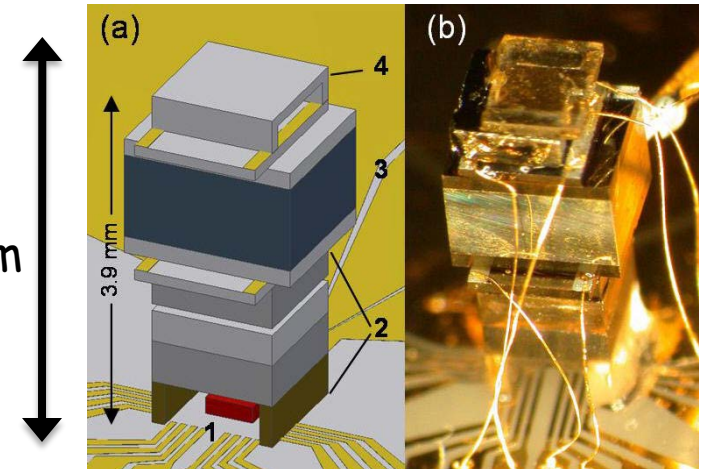


≈ 40 cm

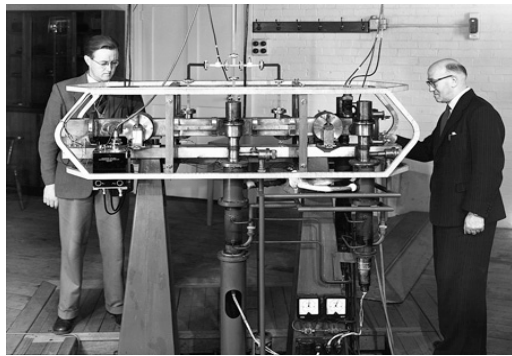
≈ 1 m



≈ 4 mm



Atomic clocks accuracy in the last 50 years

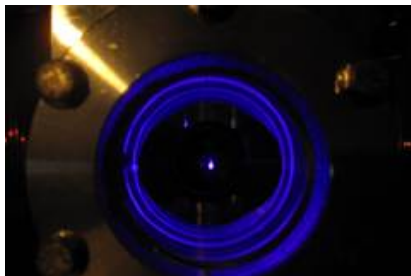


First Cs beam clock
(1955)



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

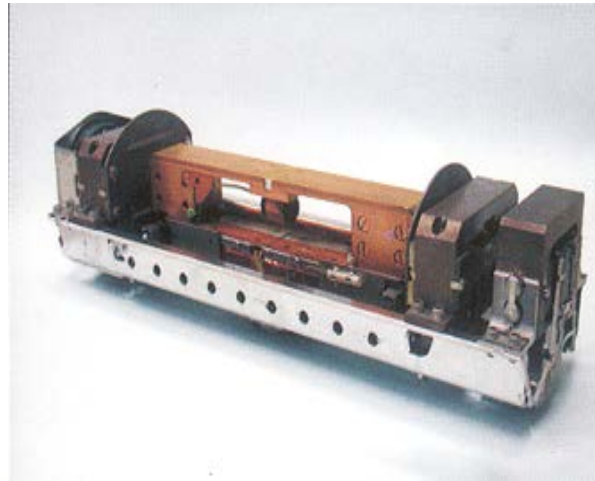
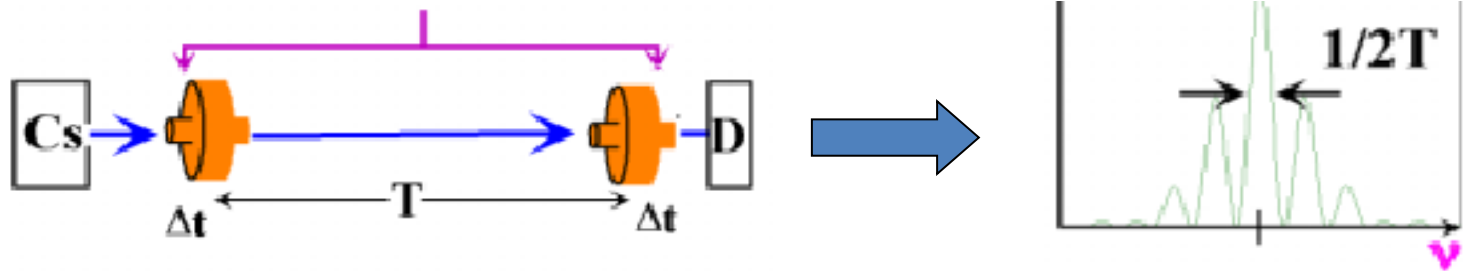
- 1) Aumentare il Tempo di interazione $\Delta\nu\Delta T > 1$
- 2) Ridurre l'effetto Doppler (riducendo l'energia cinetica degli atomi)
- 3) Scegliere Transizioni Atomiche migliori (frequenza maggiore, larghezza naturale minore, minore sensibilità ambiente esterno)

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"

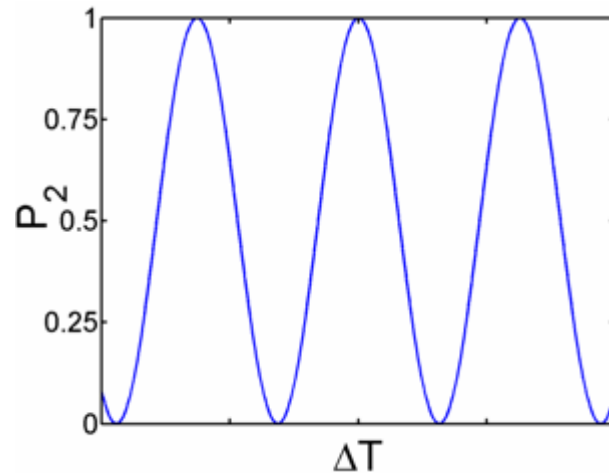
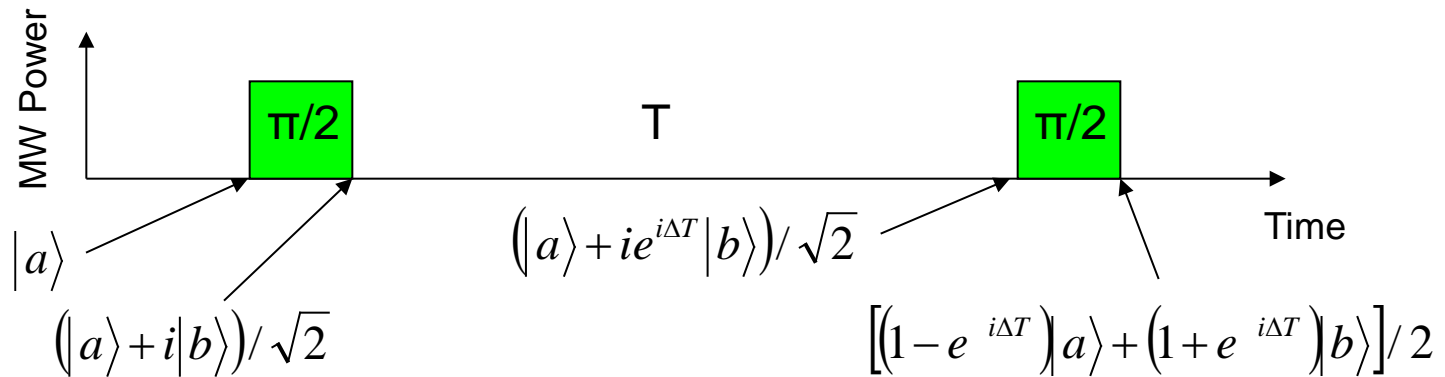
Hans G. Dehmelt Wolfgang Paul

"for the development of the ion trap technique"



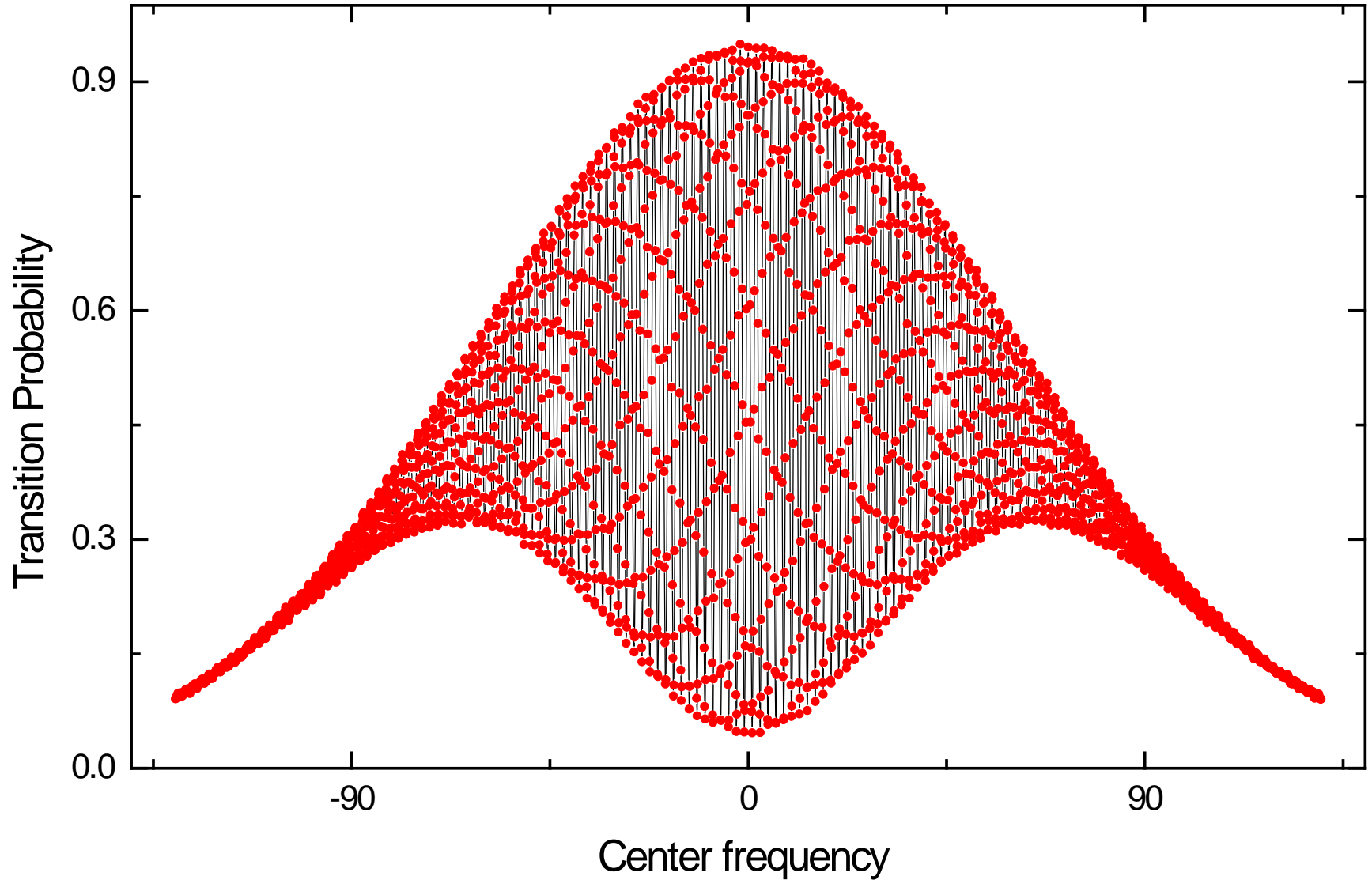
Ramsey spectroscopy of free atoms

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



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

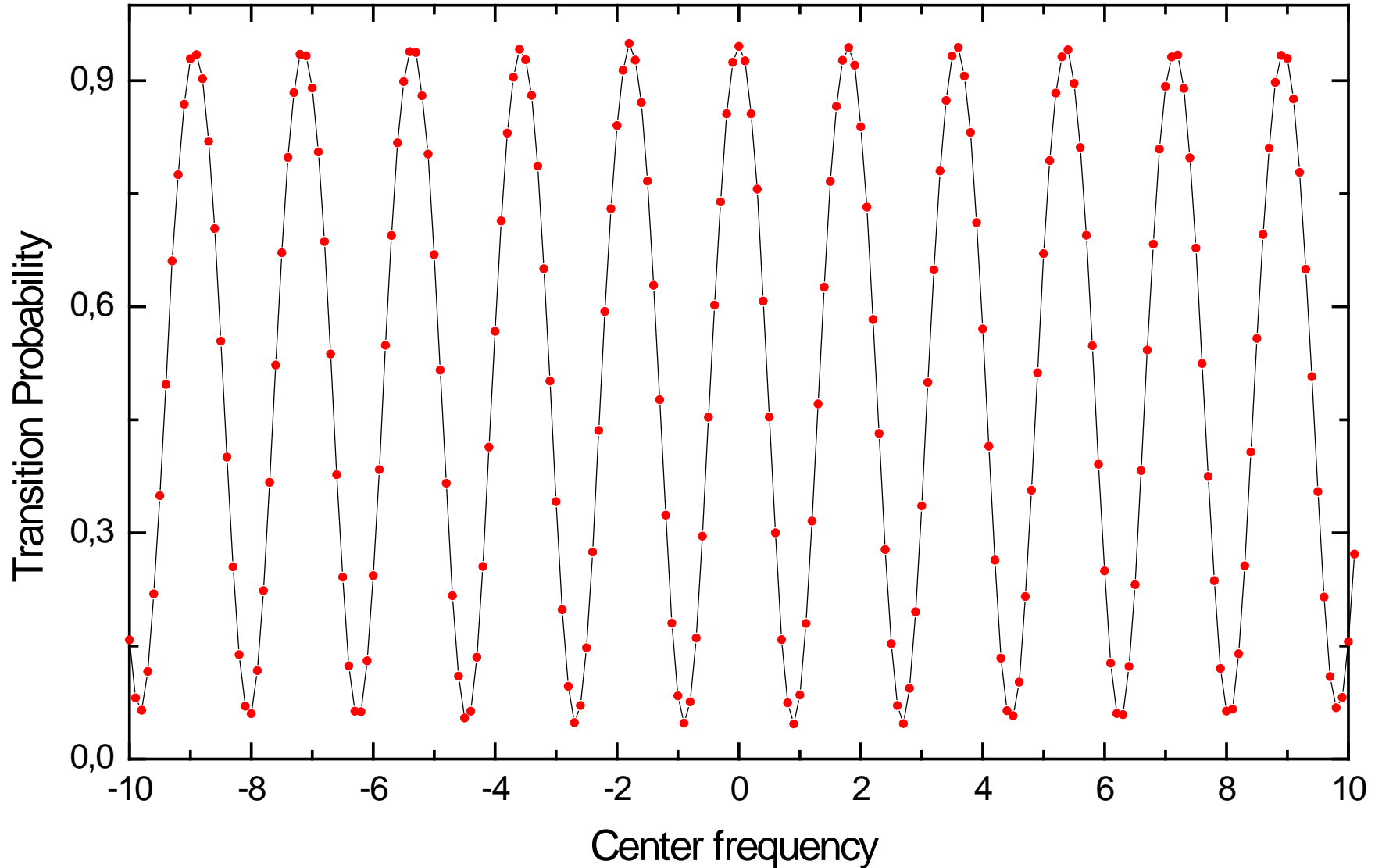
Ramsey fringes



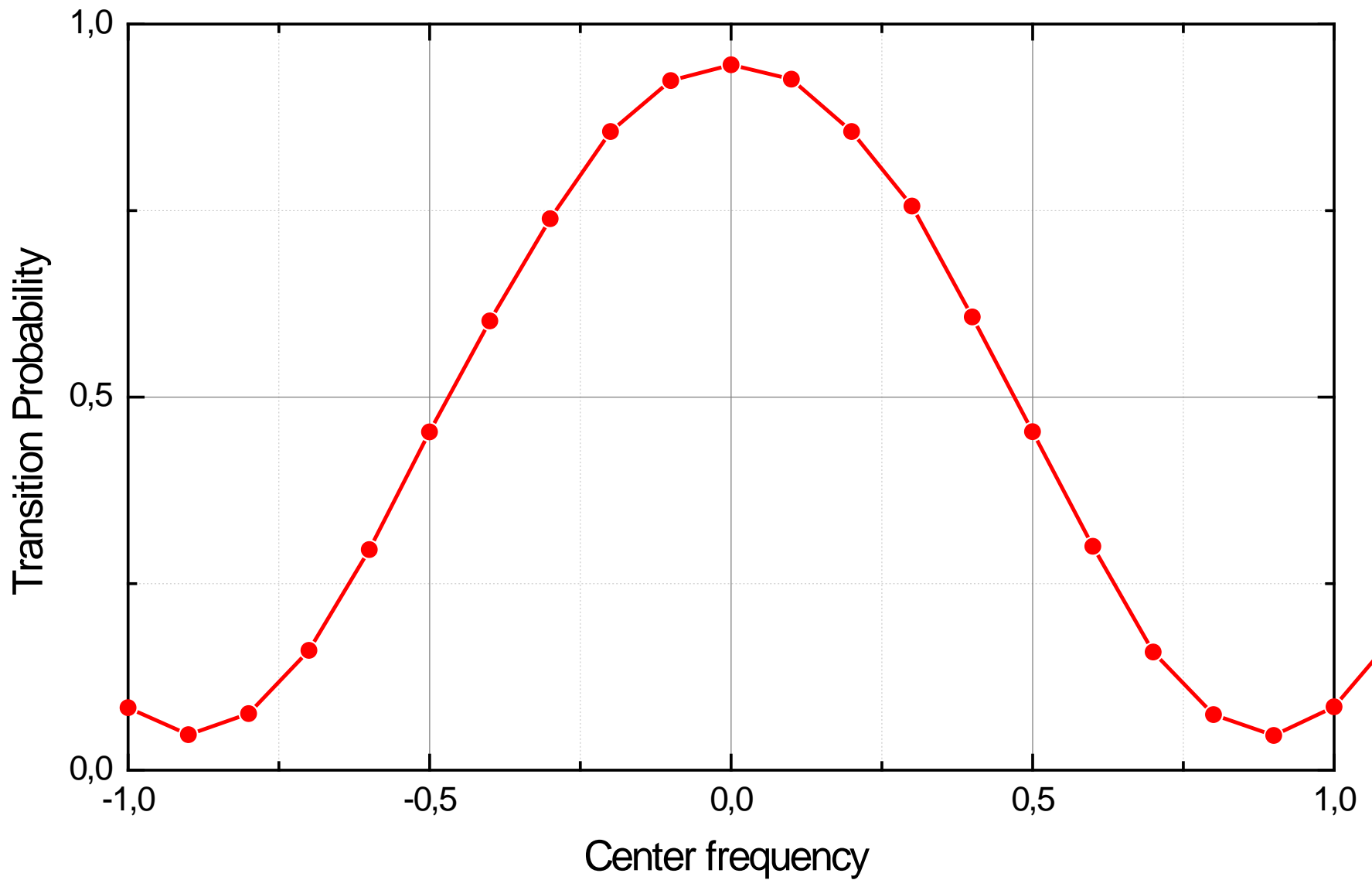
$$P(\omega - \omega_0) = \frac{4b^2}{\Omega^2} \sin^2 \frac{\Omega\tau}{2} \left\{ \cos \frac{\Omega\tau}{2} \cos \frac{(\omega - \omega_0)T}{2} - \frac{\omega - \omega_0}{\Omega} \sin \frac{\Omega\tau}{2} \sin \frac{(\omega - \omega_0)T}{2} \right\}^2$$

Central fringes

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

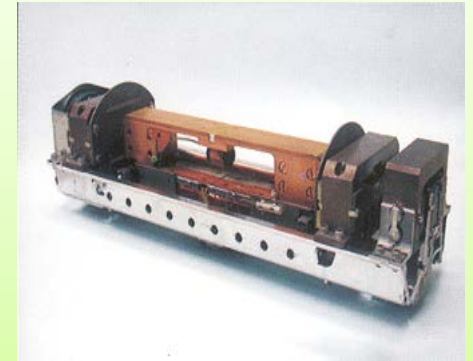
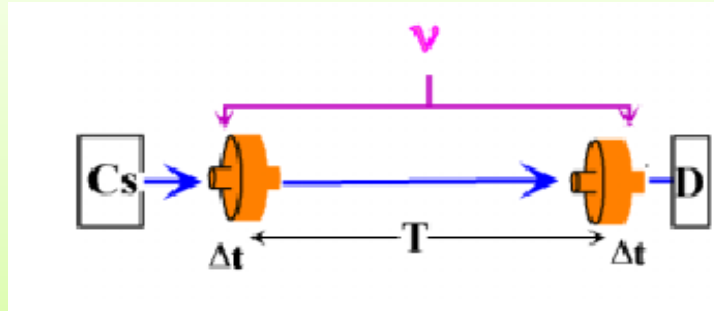


$$P(\omega) \simeq \frac{1}{2}[1 + \cos(\omega - \omega_0)T]$$

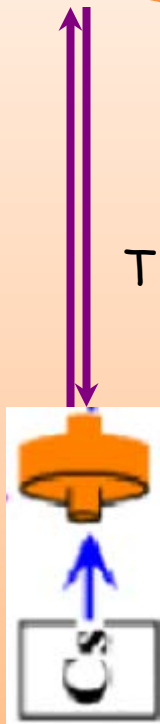


Ramsey fringes: different implementations

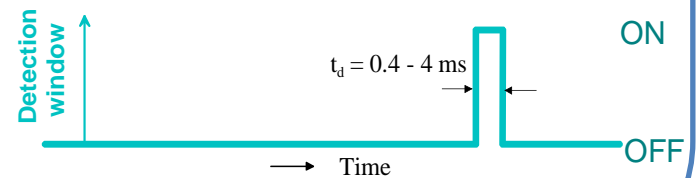
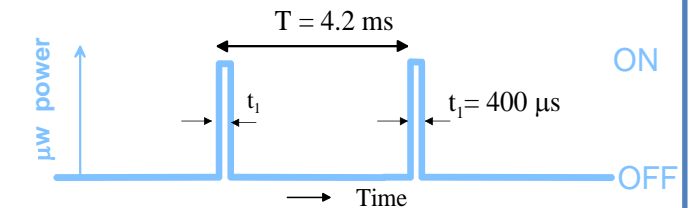
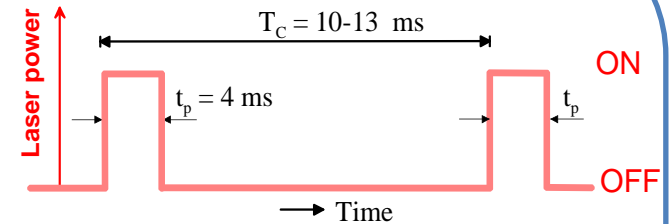
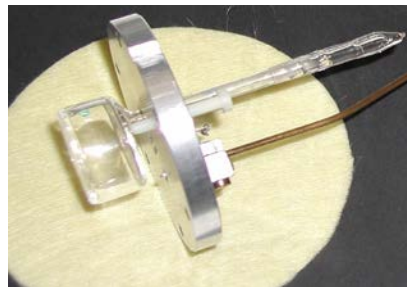
In an atomic beam
(spatial implementation)



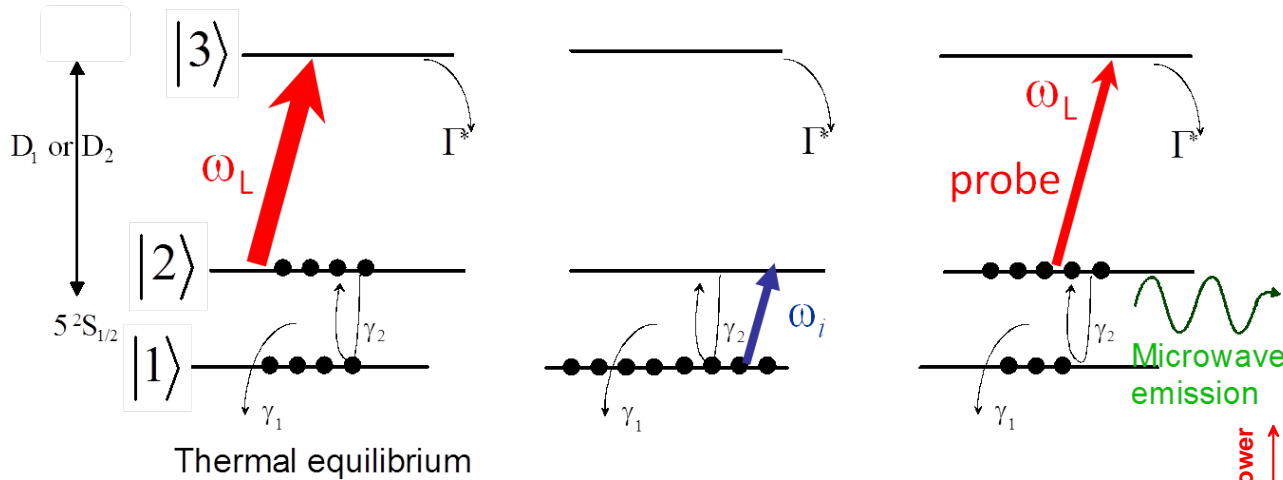
In an atomic fountain
(spatial implementation)



In an atomic vapour cell
(temporal implementation)

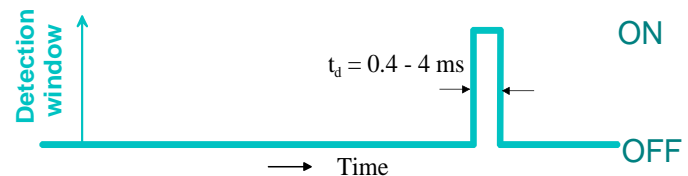
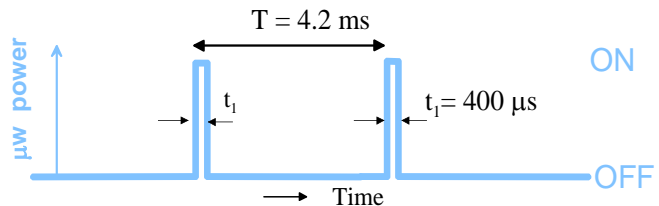
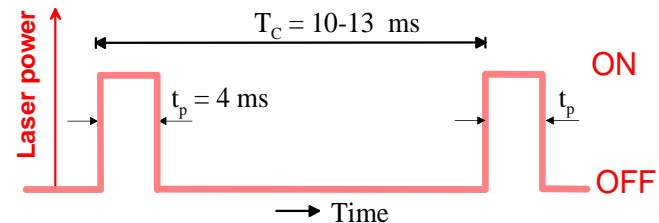


Ramsey fringes in a atomic vapour cell: The Pulsed Optically Pumped Clock

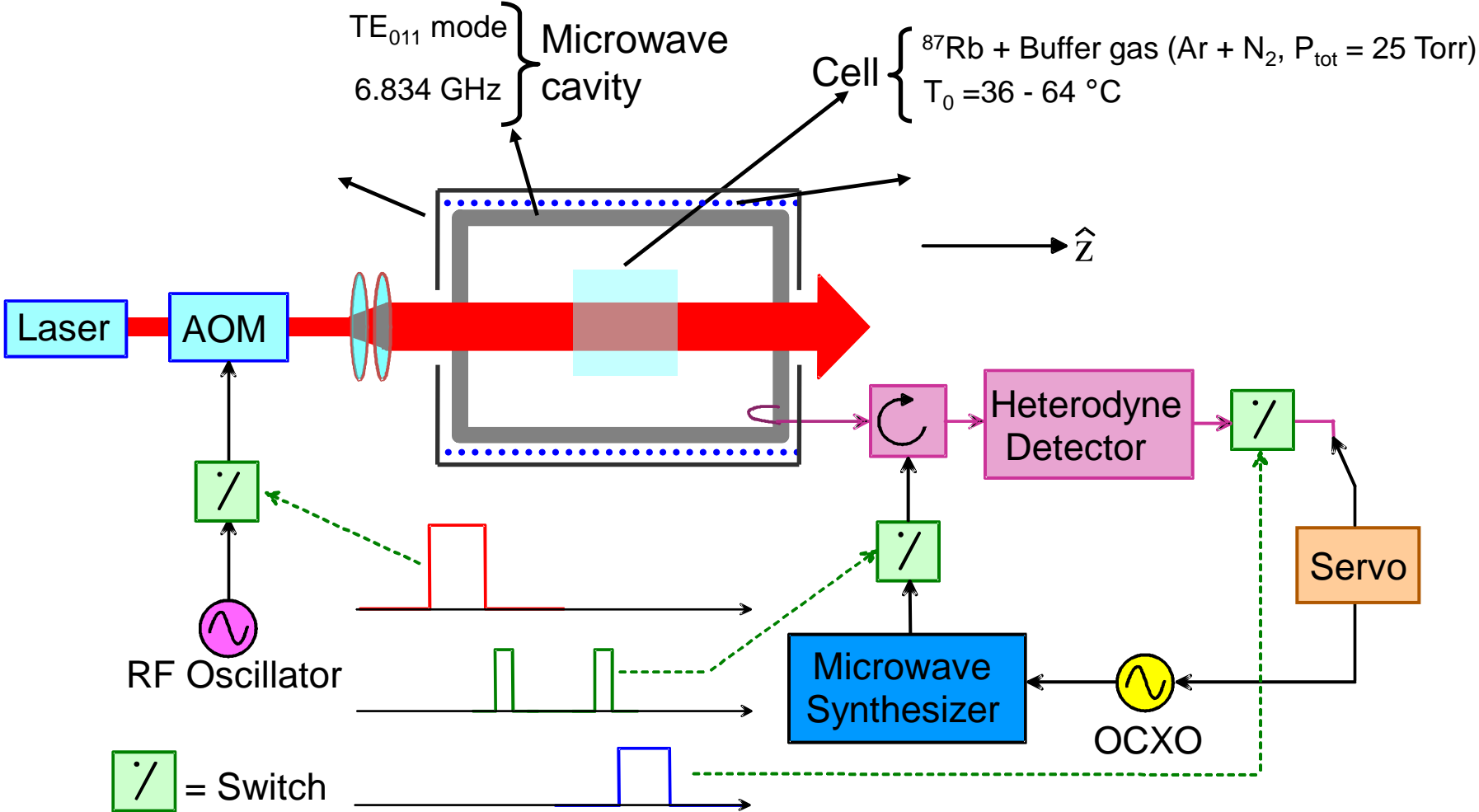


- ▶ ^{87}Rb + buffer gas
- ▶ three-level system
- ▶ timing limited by the cell:
 $T \approx 1/\gamma_2$

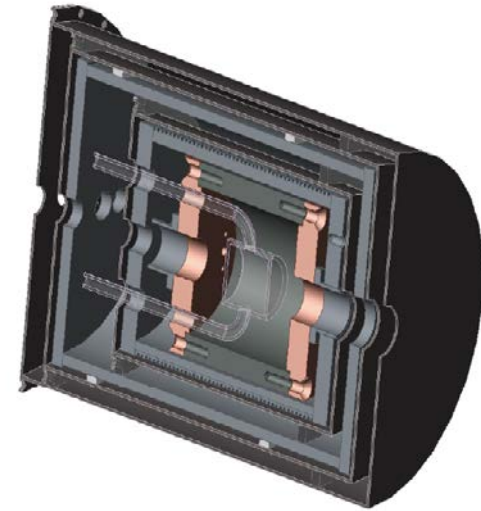
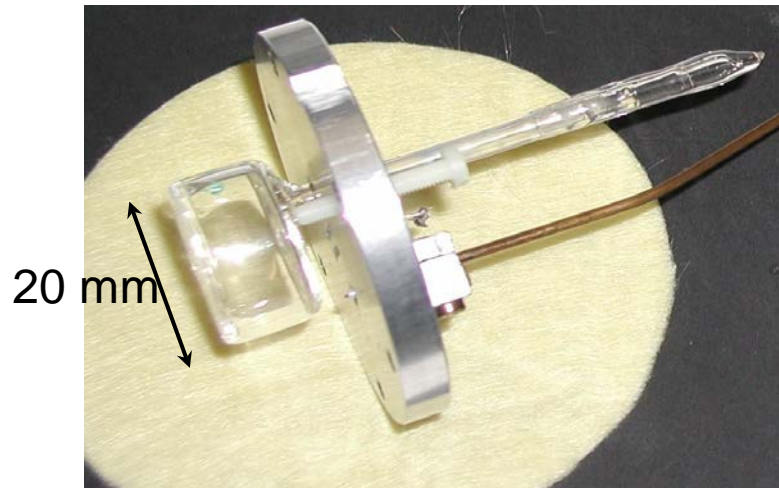
- preparation: laser optical pumping
- interrogation: microwave Ramsey scheme
- detection: microwave/laser probe detection



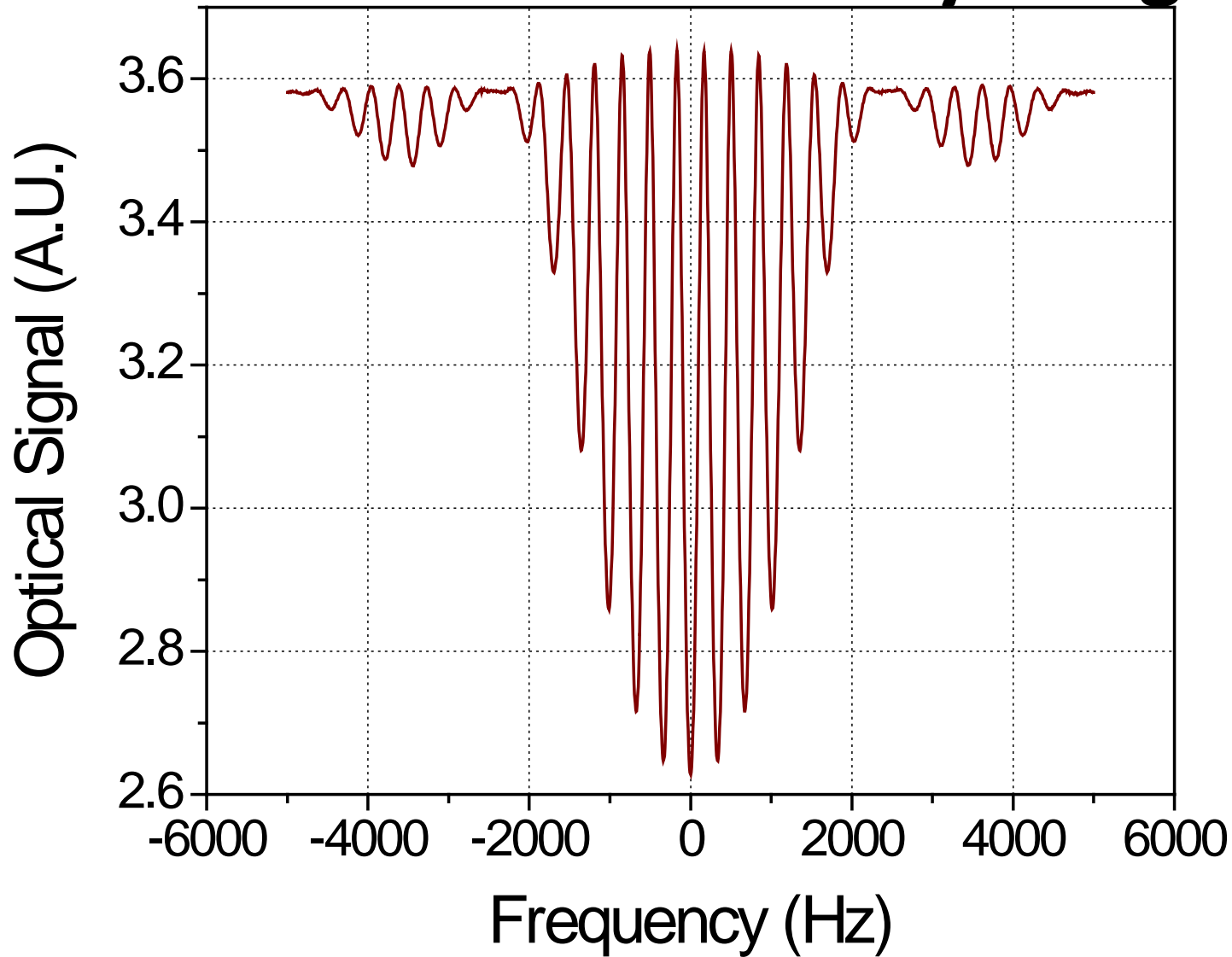
The POP clock: set up



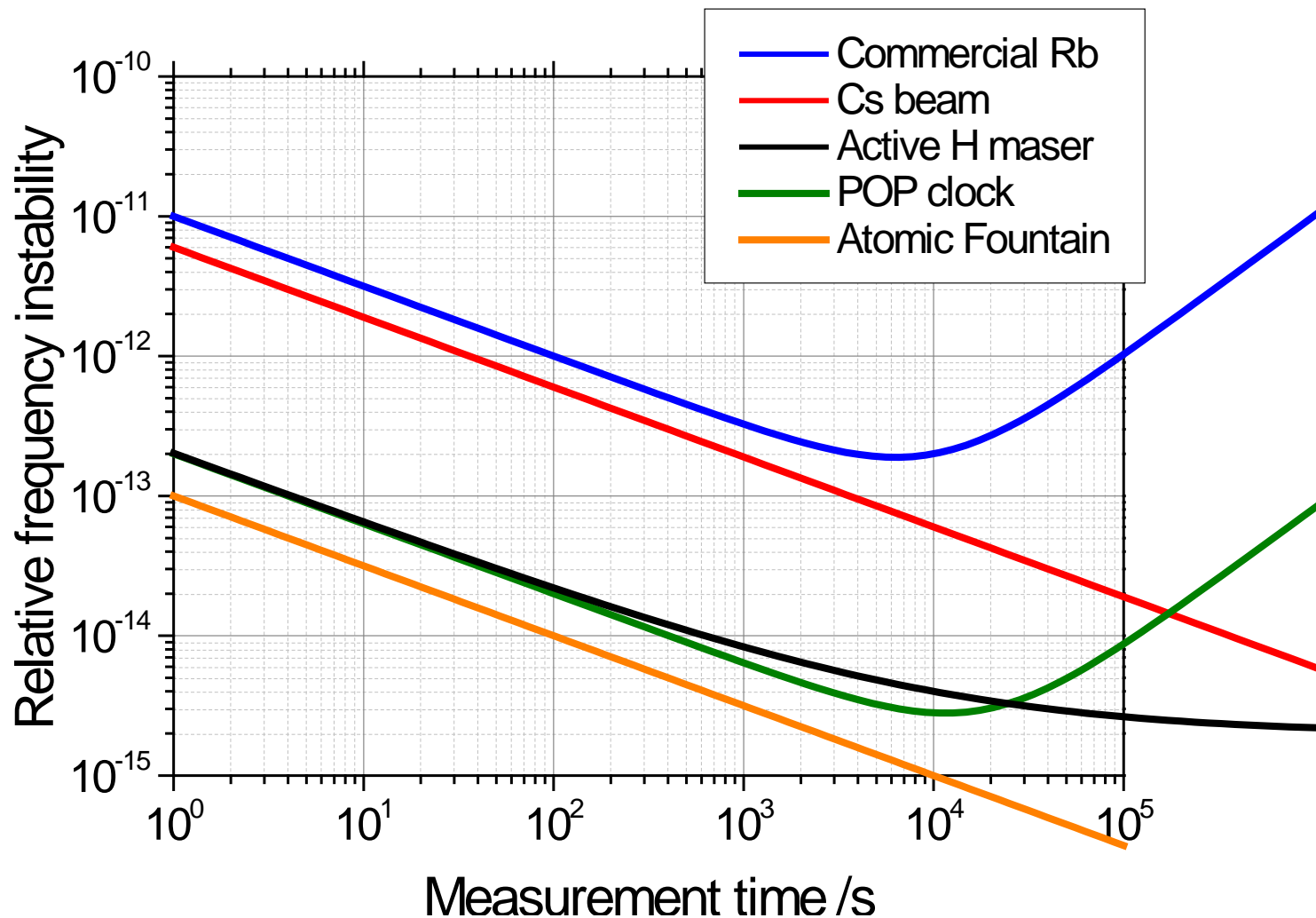
The POP clock: set up



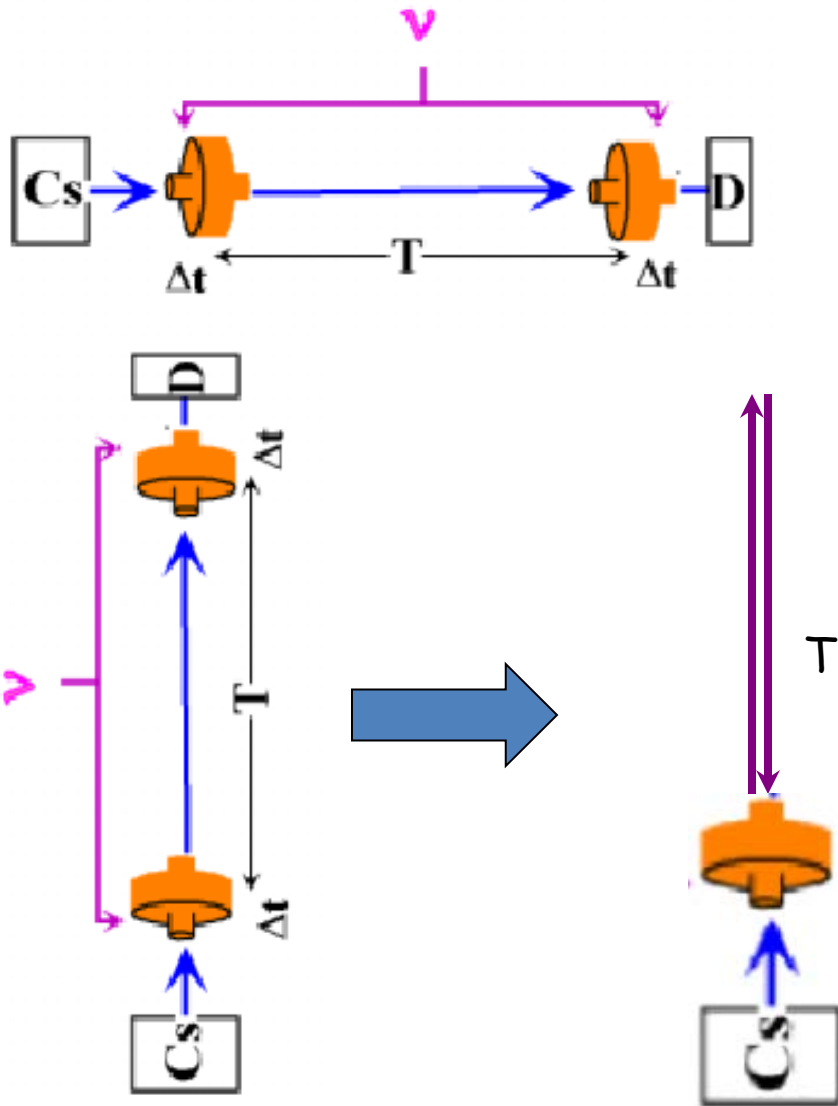
The POP clock: Ramsey Fringes



Atomic Clocks: frequency stability



L' idea di una fontana atomica



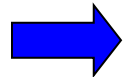
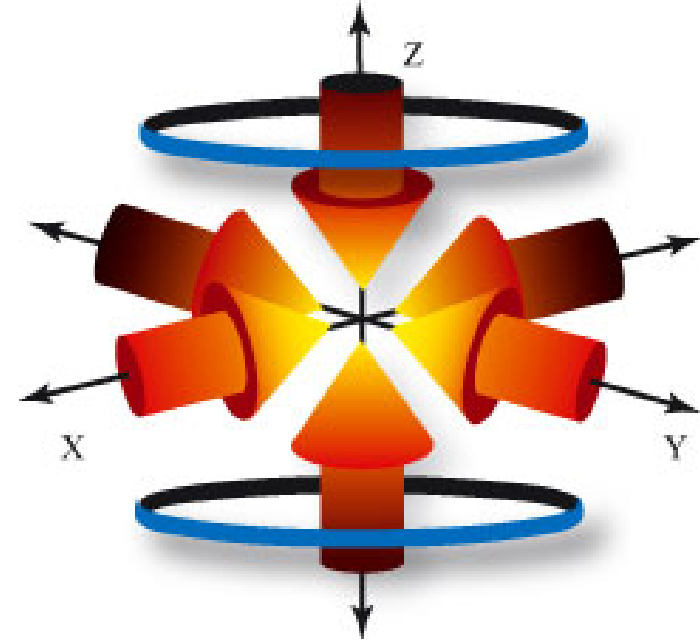
Zacharias, al MIT nel 1954, propose di aumentare T con un orologio a geometria verticale, con atomi in volo balistico: **una fontana atomica.**

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

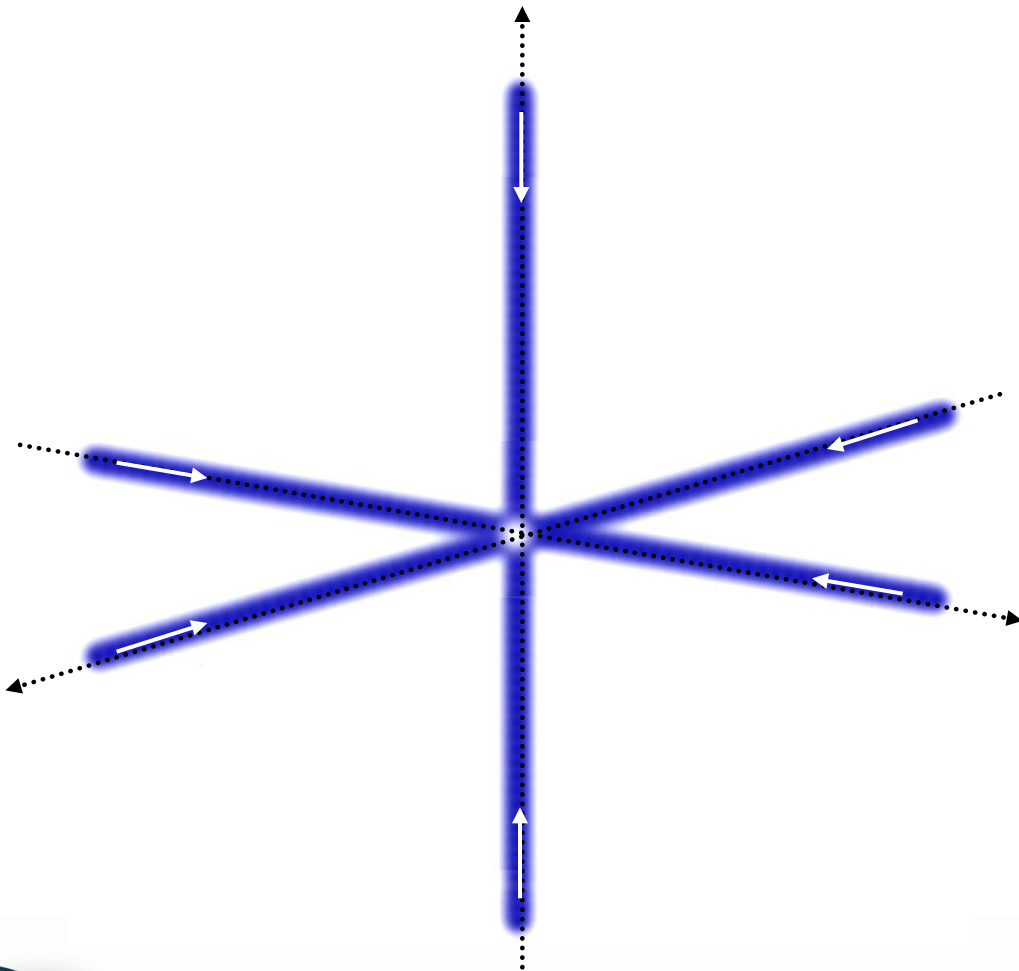


Stephen Chu, William Phillips, Claude Cohen-Tannoudj

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



Magneto-Optical Trap (MOT)



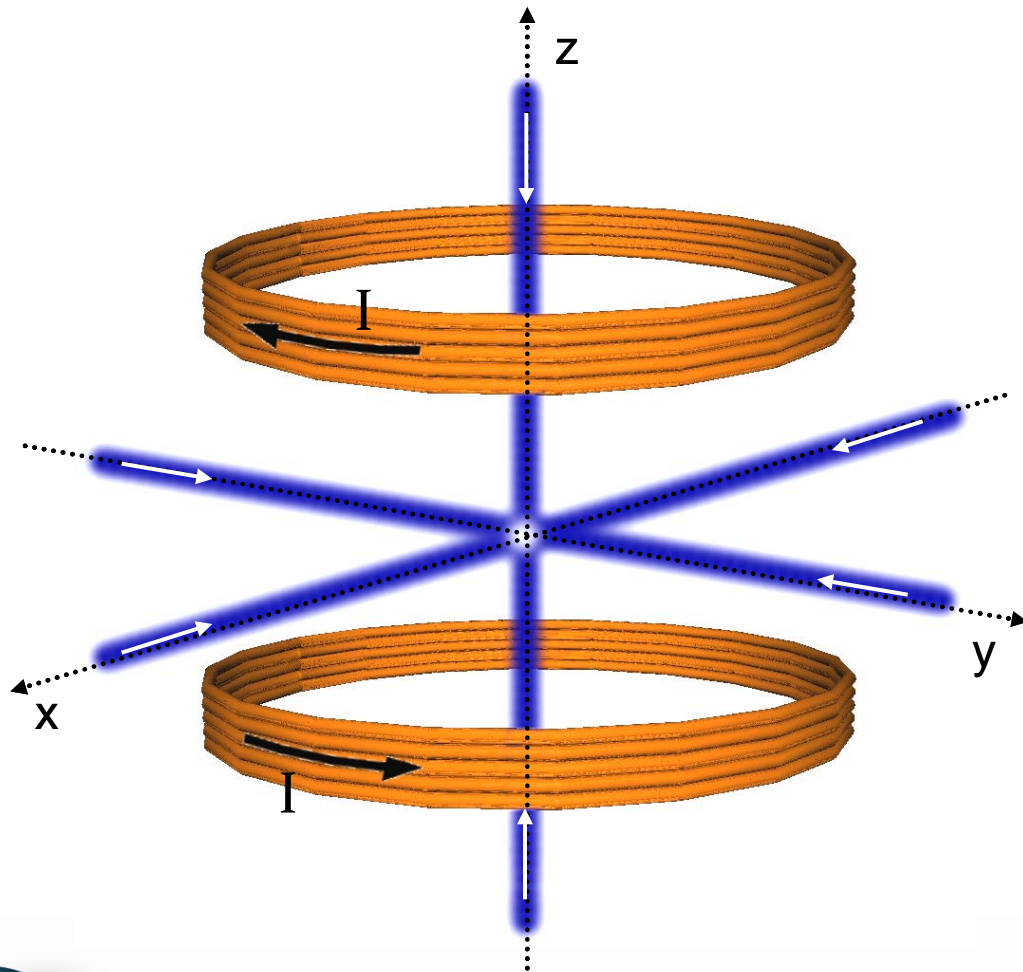
3 coppie di fasci contropropaganti:

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

→ **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:

$$F \approx -\beta v - kr$$

β : coefficiente di viscosità
 k : costante elastica
 Forza viscosa Forza 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**

Cs Fountain: how it works



INRIM, Fontane di Cesium 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

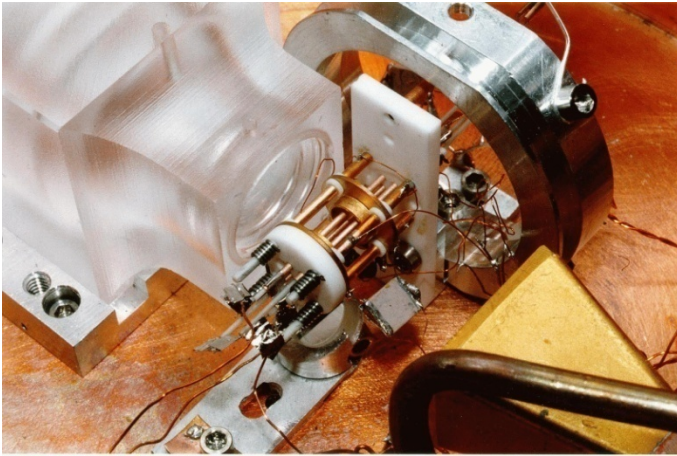
Sei laboratori hanno finora contribuito regolarmente alla generazione del Tempo Atomico Internazionale con fontane al Cesio: USA (2 fontane); Francia (3); **Italia (2)**; Germania (2); UK (2); Giappone (2)



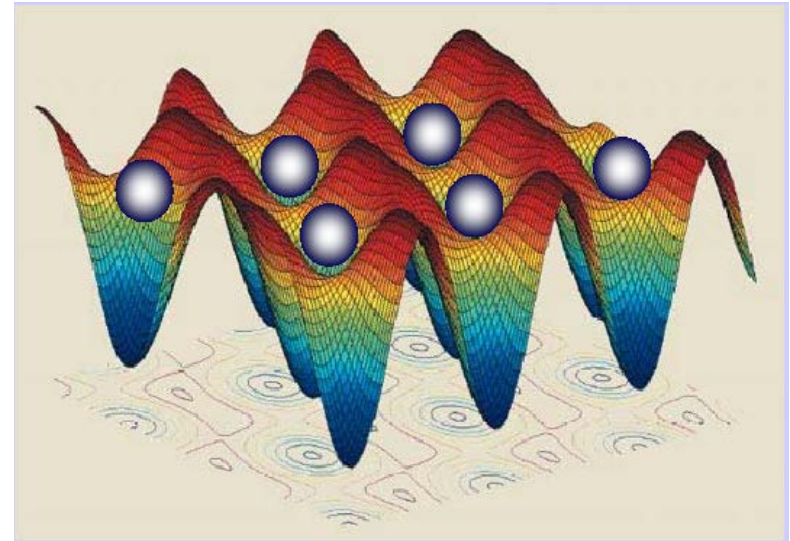
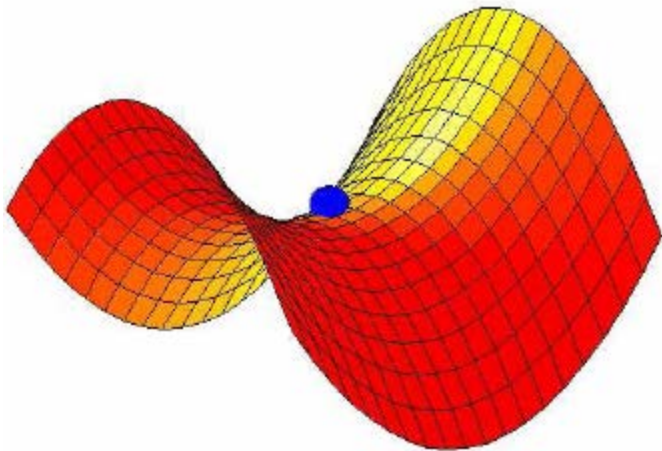
Meno Doppler & Più Interazione / 2

Trappole a ioni e reticoli ottici

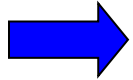
Trappole RF a singolo ione



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



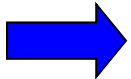
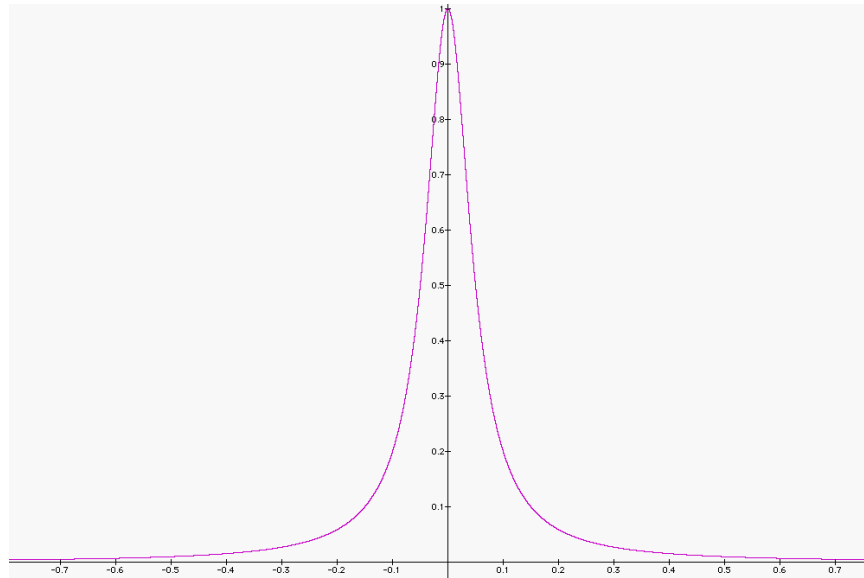
3) Scegliere Transizioni Atomiche migliori (frequenza maggiore, larghezza naturale minore, minore sensibilità ambiente esterno)



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

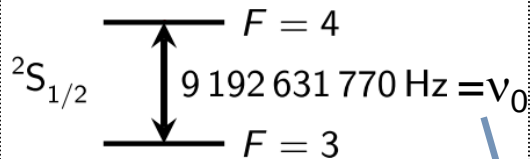
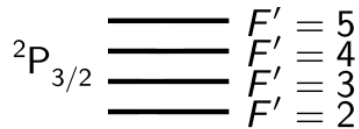
Campioni di
frequenza

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

Campioni di
frequenza ottici:

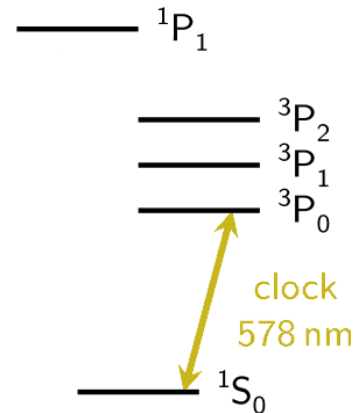
$$\nu_0 \sim 5 \times 10^{15} \text{ Hz}$$

Cs

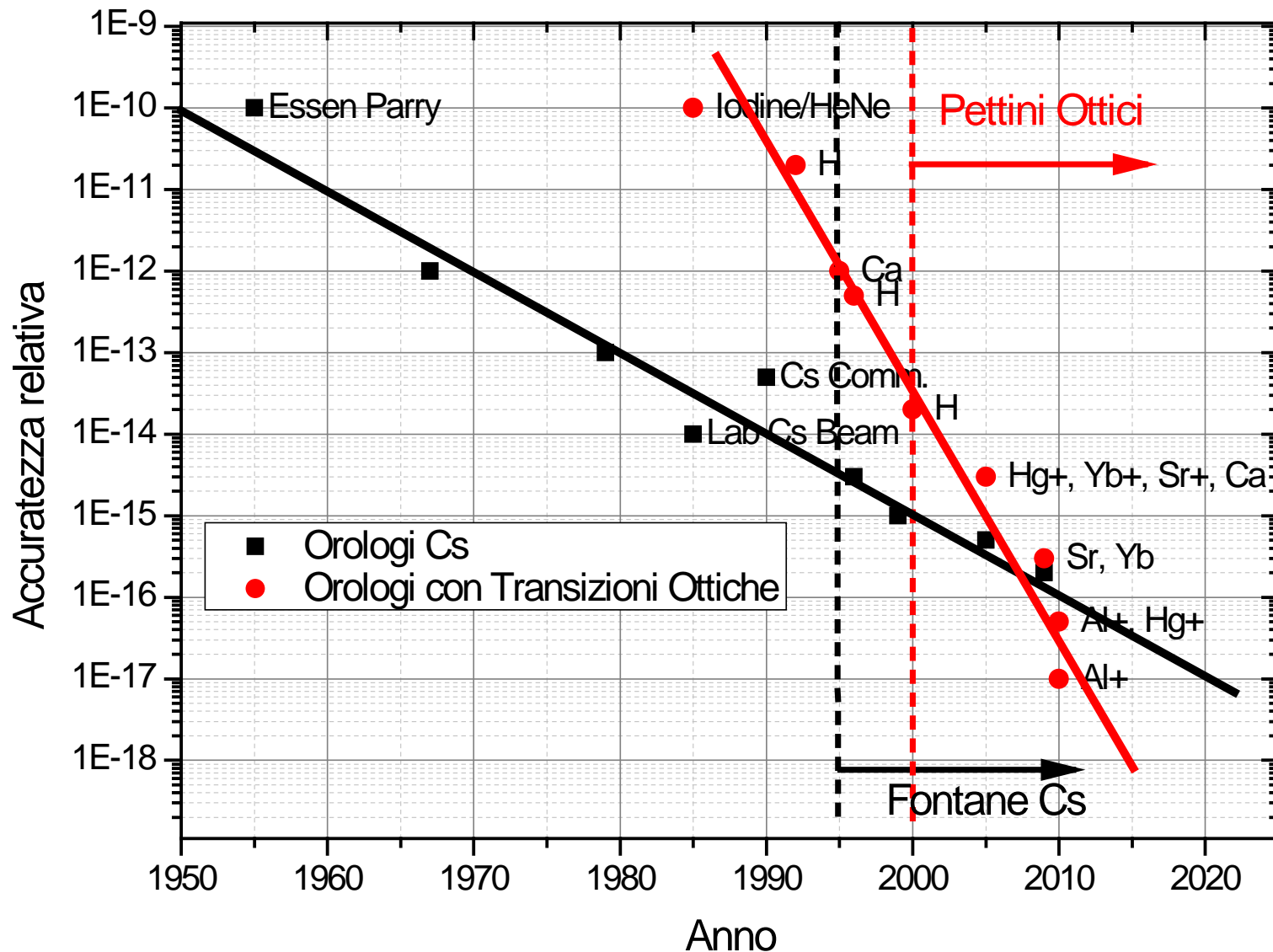


Definizione del
secondo

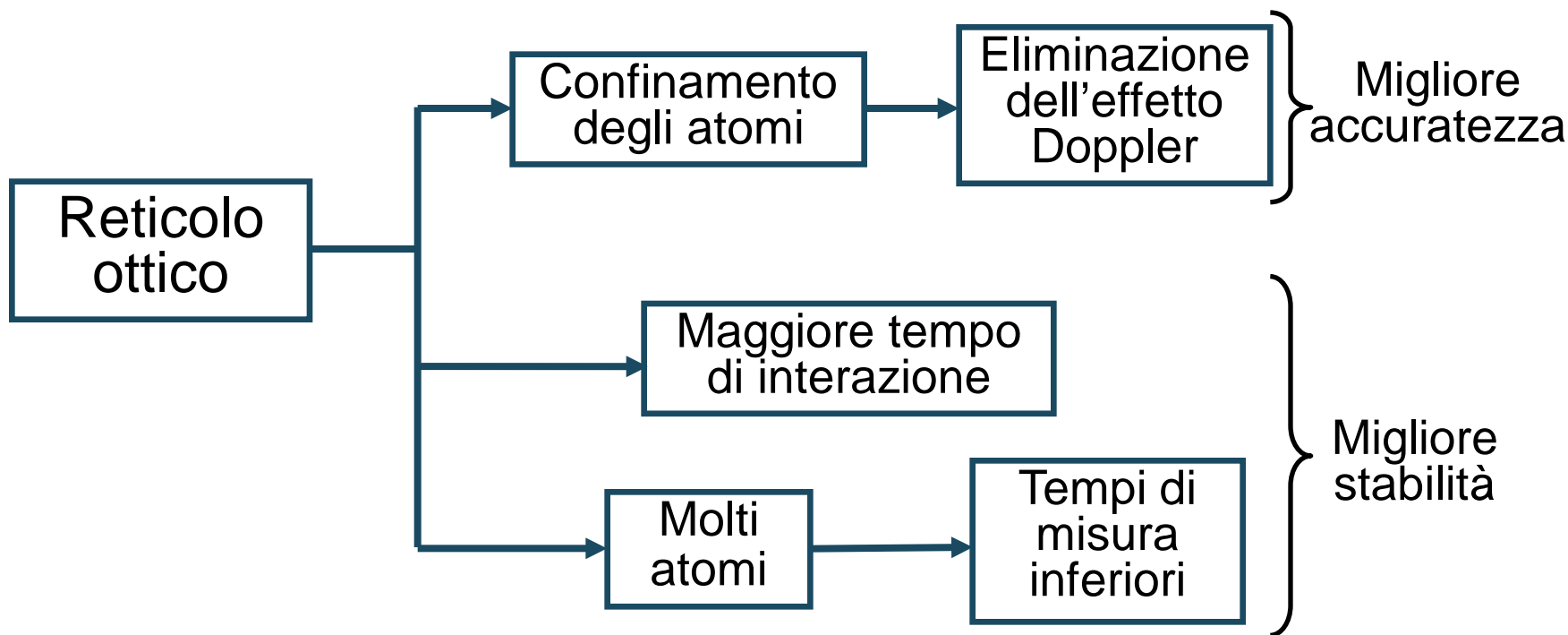
Yb



Dal Cesio agli orologi Ottici: Verso la ridefinizione del secondo



Vantaggi dell'intrappolamento in reticolo ottico



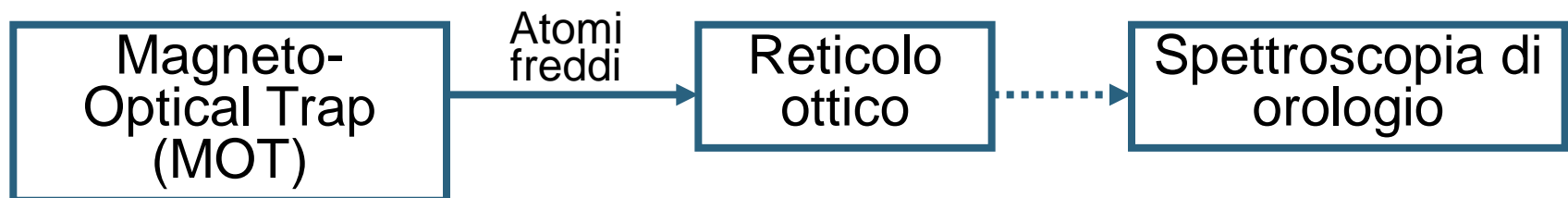
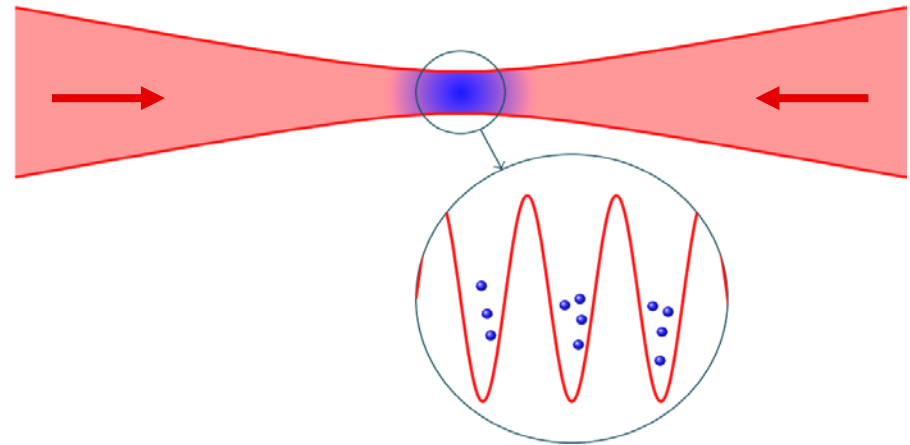
Reticolo ottico

Spettroscopia imperturbata:

- lunghezza d'onda "magica"

Intrappolamento:

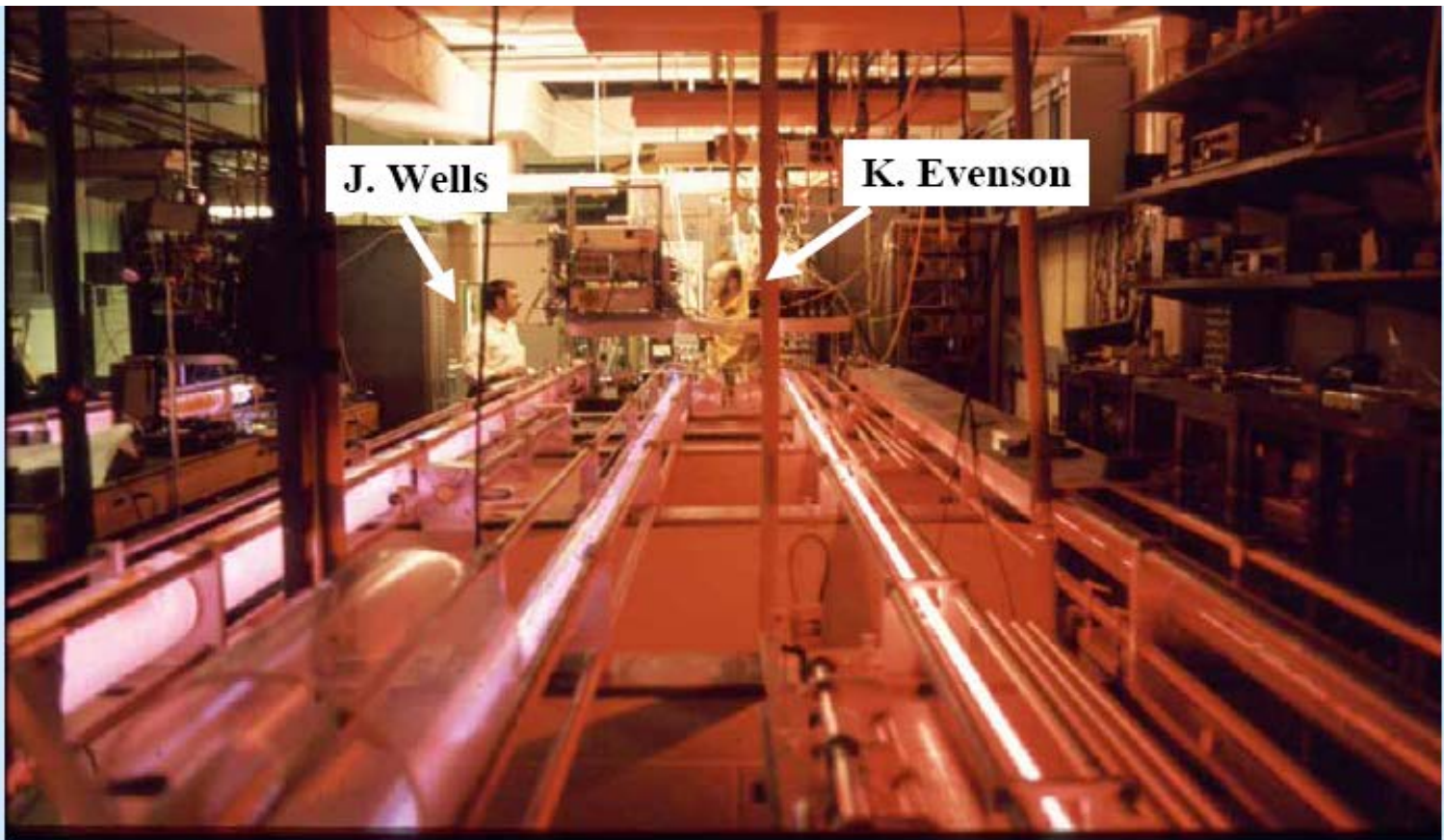
- necessità di raffreddare gli atomi



Anche i laser diventano orologi

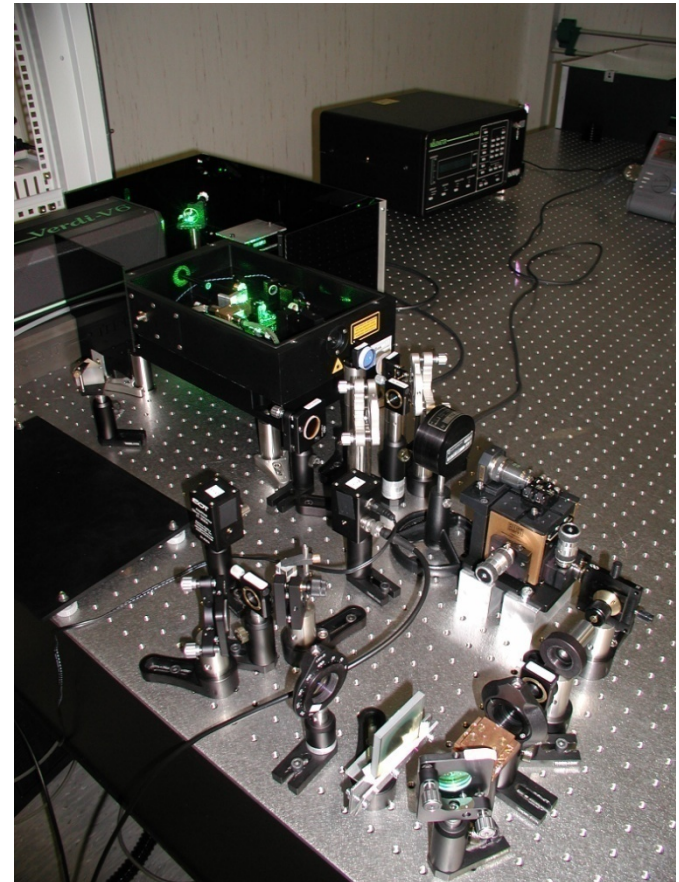
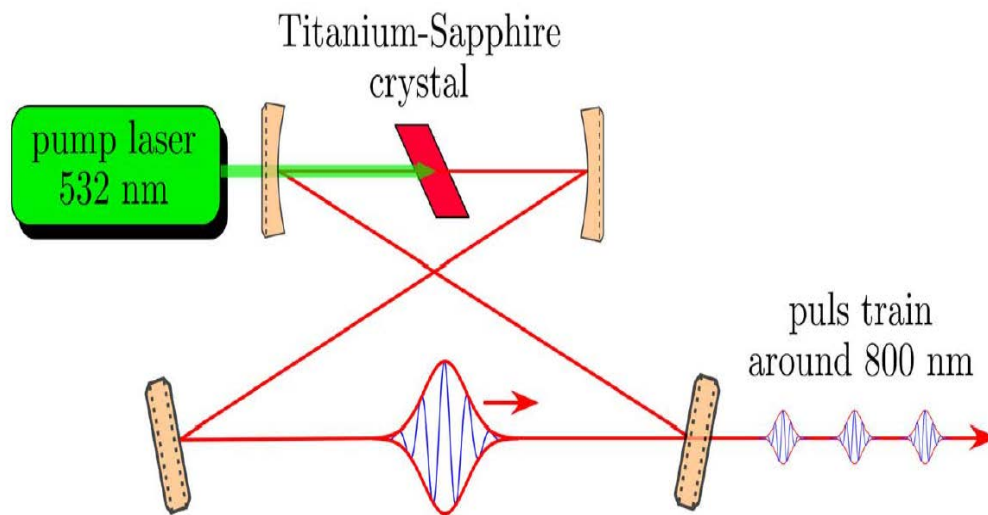
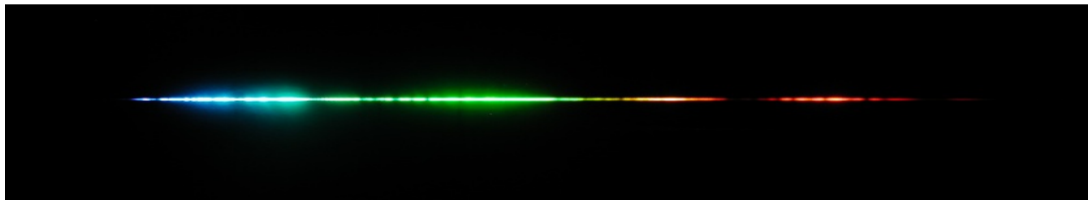
Fino alla fine del secolo scorso, lunghe catene di sintesi, che coinvolgevano svariati laser, erano l'unico metodo di misura accurato per frequenze ottiche

L'incertezza restava limitata a parti in 10^{-13} (al meglio)



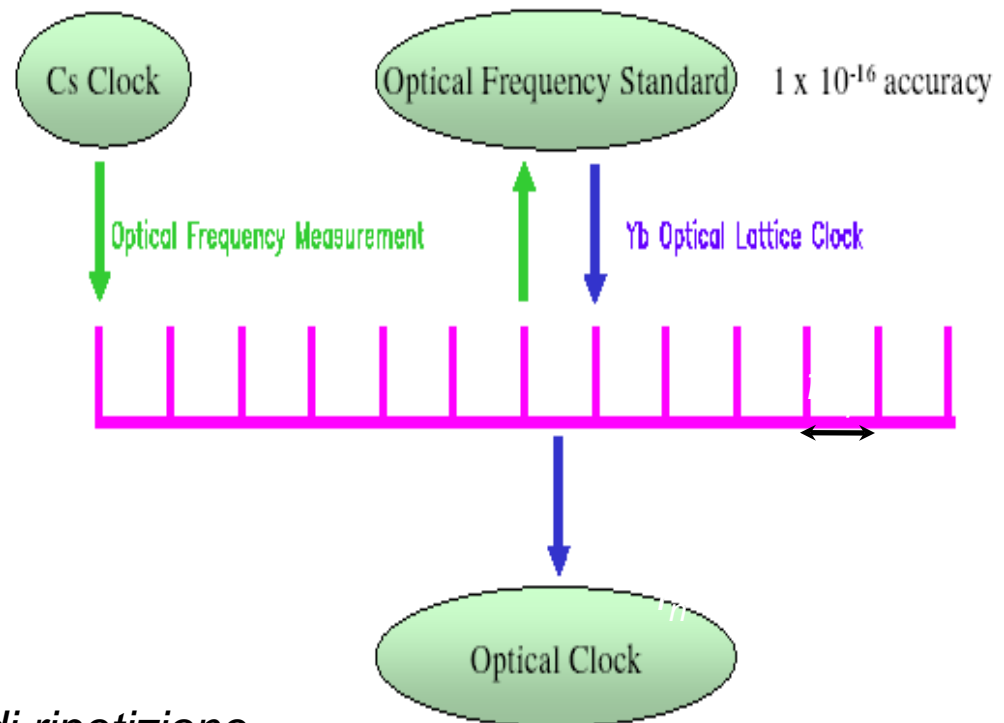
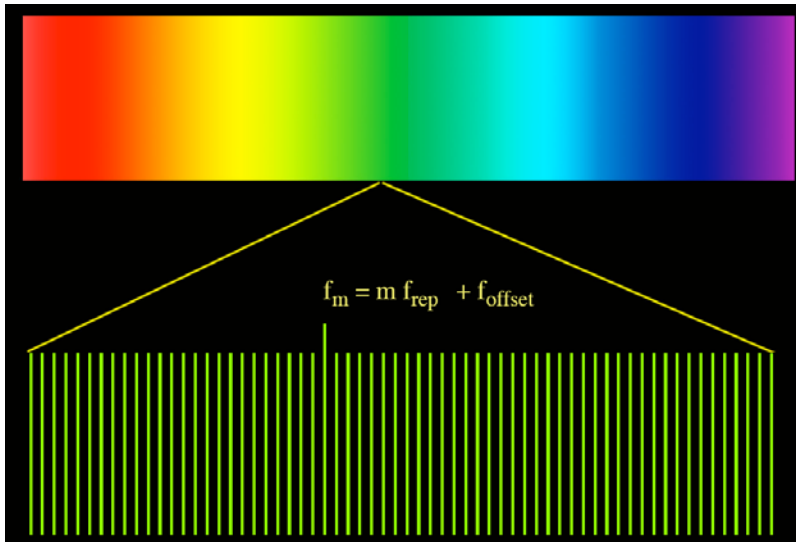
Anche i laser diventano orologi/2

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})



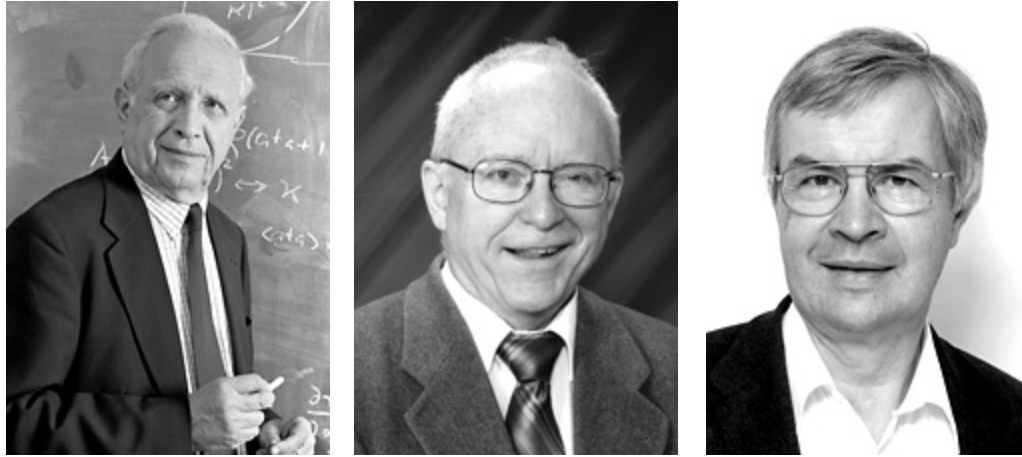
f_{rep} frequenza di ripetizione

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

Si misurano direttamente vs riferimento assoluto

A Nobel Gallery

2005



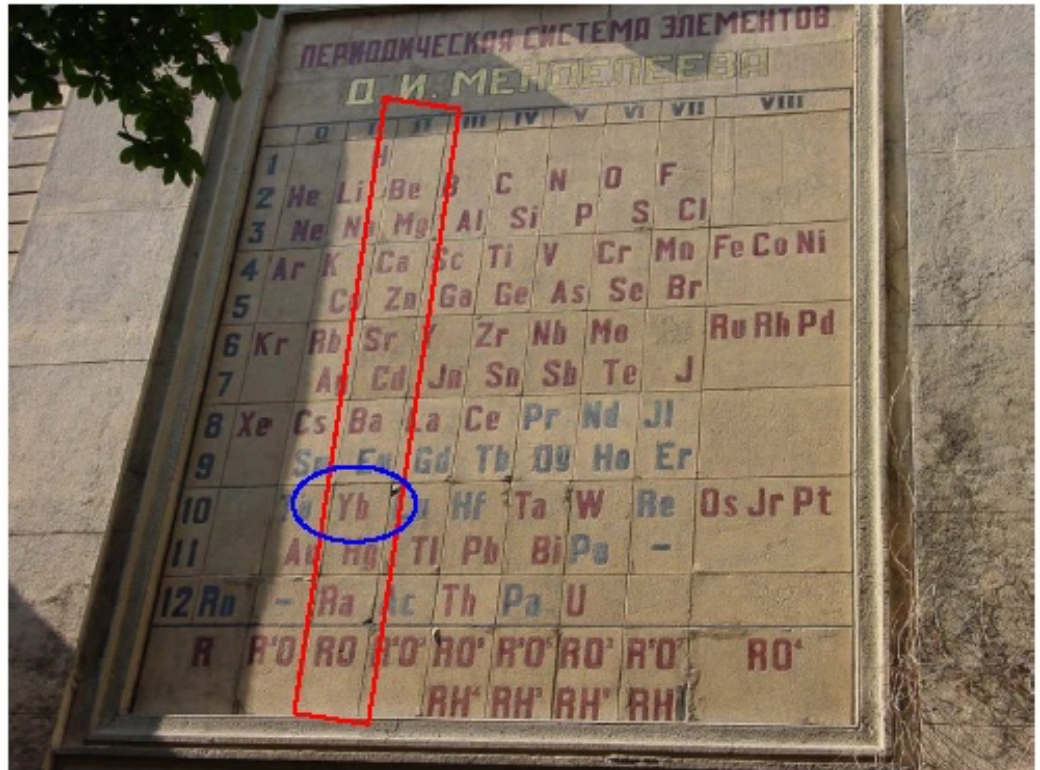
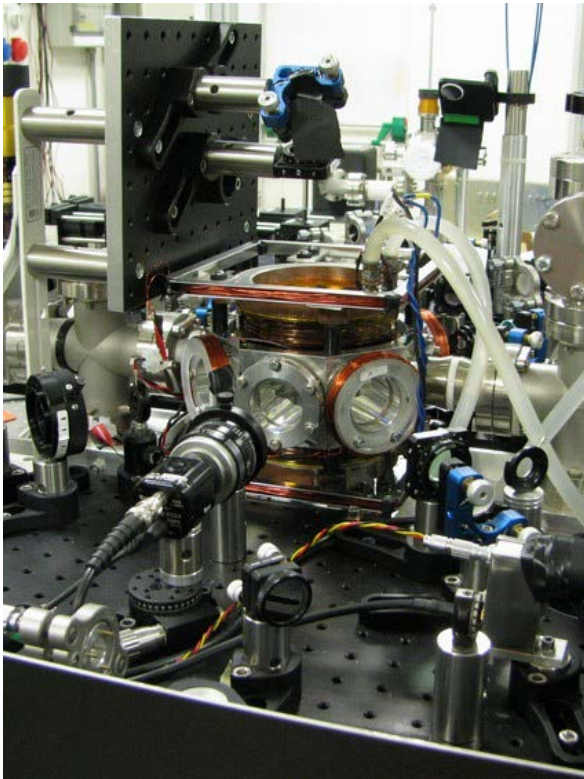
Roy J. Glauber

"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"

Orologio Ottico a Yb



Yb clock Main features

1. Level structure for laser cooling and trapping

First stage cooling $1S_0 - 1P_1$ @ 398.9 nm (28 MHz linewidth)

Second stage cooling $1S_0 - 3P_1$ @ 555.8 nm (180 kHz linewidth)

2. Clock $1S_0 - 3P_0$ transition @ 578 nm, 10 mHz linewidth

Lattice Magic Wavelength @ 759 nm

3. Accuracy $<10^{-16}$

Stability $<10^{-15}$ at 1s

Large abundance of stable bosonic and fermionic isotopes:

Different clock schemes

**Yb Lattice clock in the world:
NIST, UniDusseldorf, Japan AIST, INRIM...**

Blu Trap
399 nm

Yb @ 1 mK
(20 cm/s)



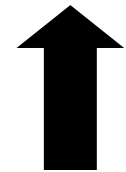
Green Trap
556 nm

Yb @ 20 μ K
(2 cm/s)

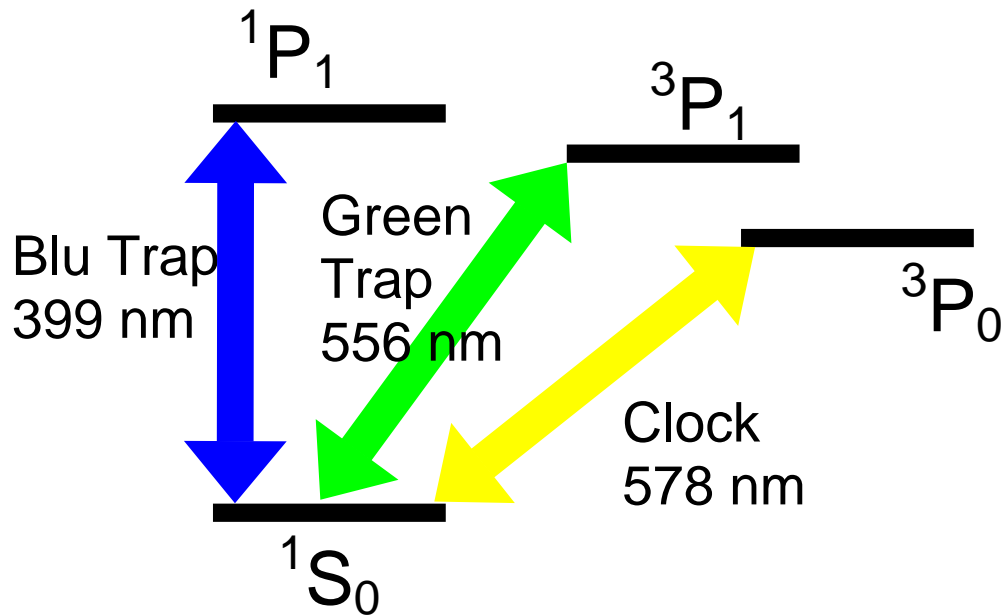


Lattice Trap
759 nm

Yb localized

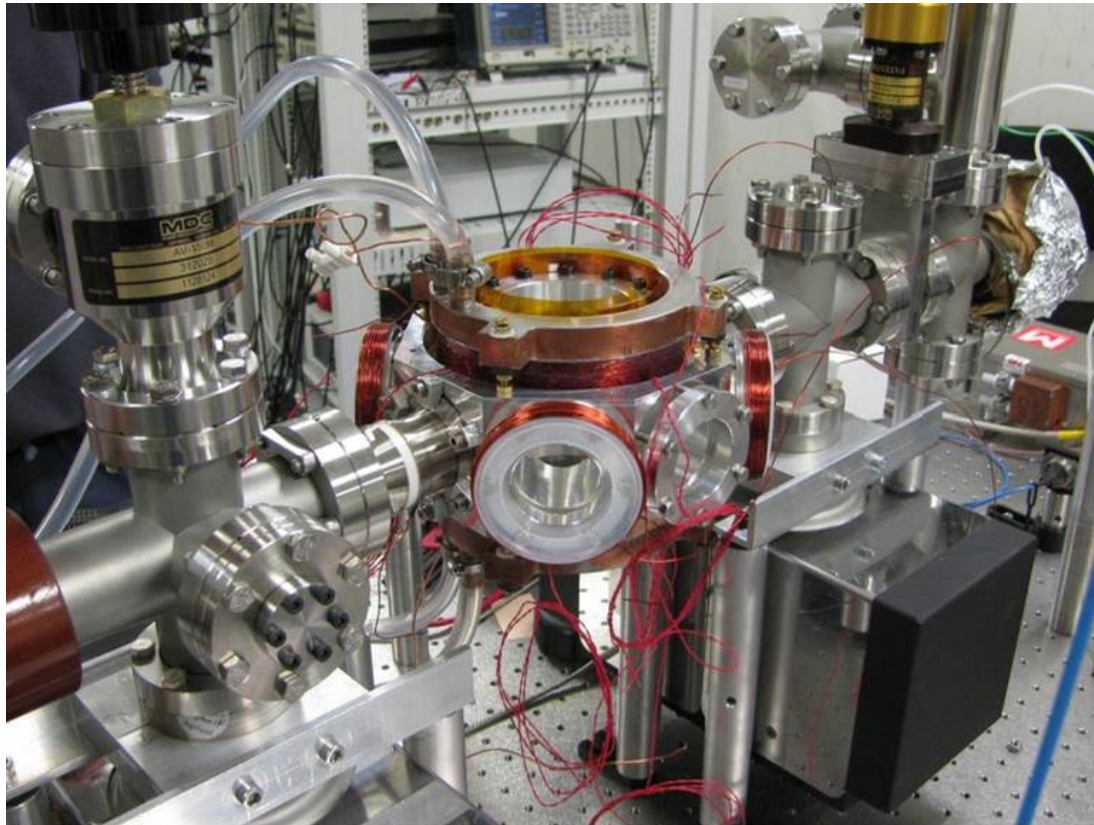


Clock
578 nm



Yb Lattice Clock at INRIM

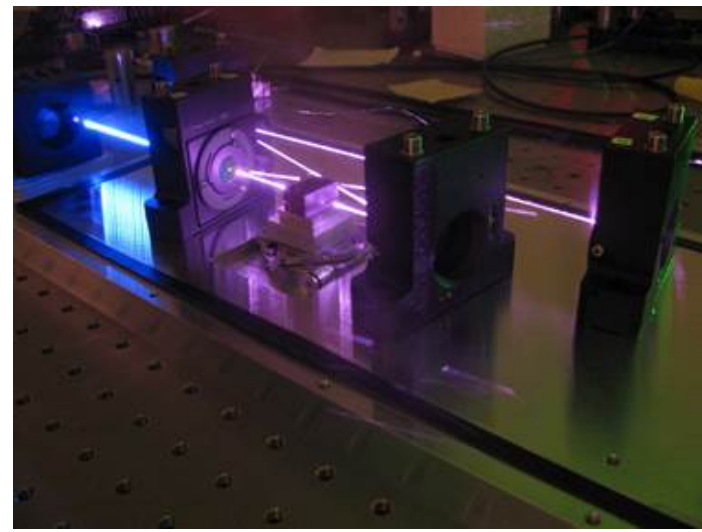
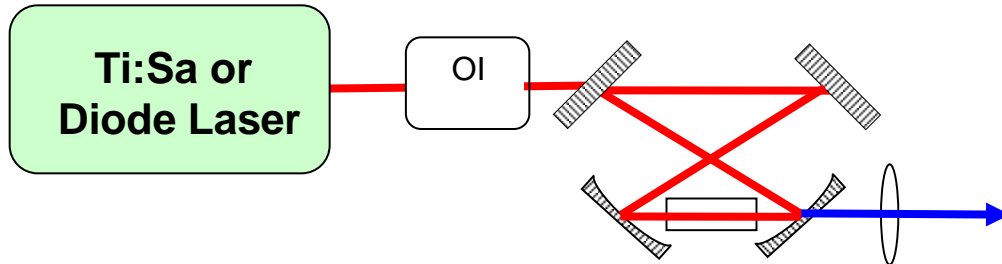
New chamber under operation



- Indium-sealed viewports
- Compact high efficiency oven
- Atomic beam shutter
- No Zeeman Slower (precooler laser only)
- Increased number of trapped atoms expected
- Better vacuum

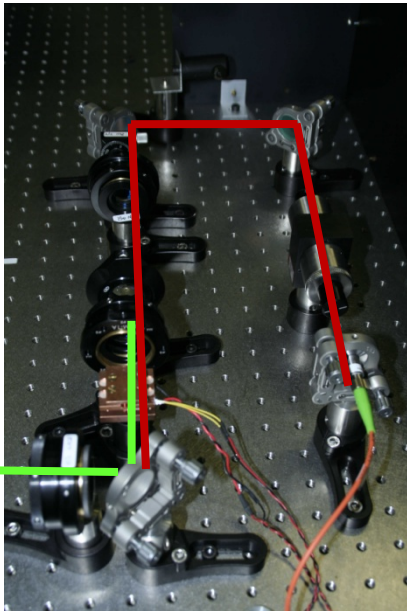
Cooling Radiations

399 nm Laser Generation

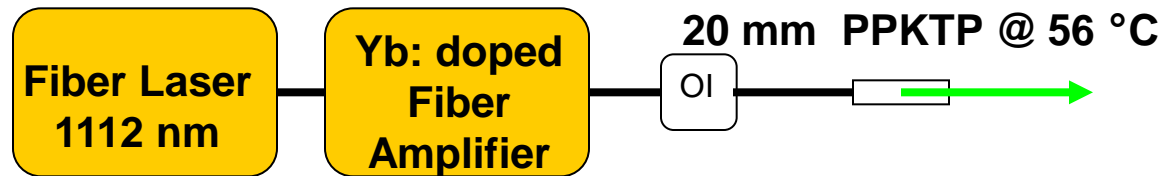


10 mm LBO enhancement cavity

600 mW @ 399 nm from 1 W @ 797.2 nm (Ti:Sa)

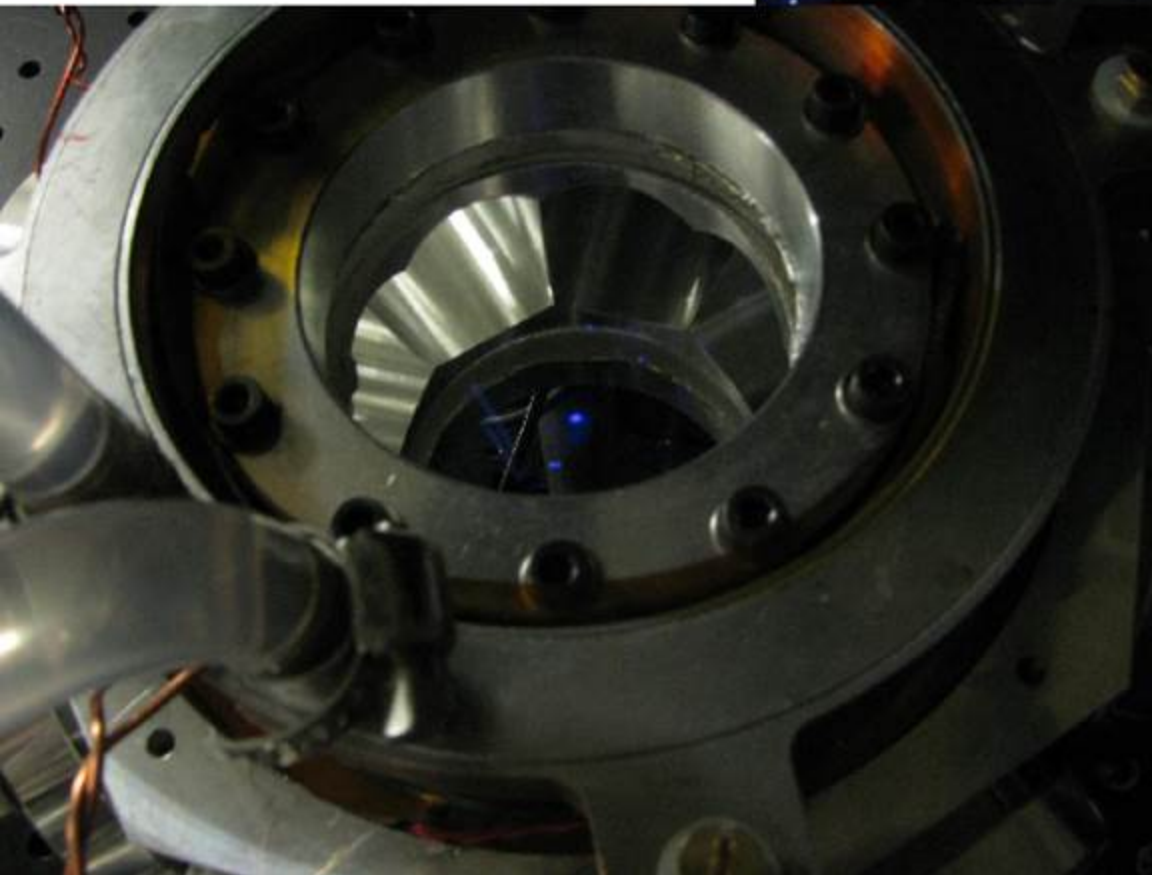
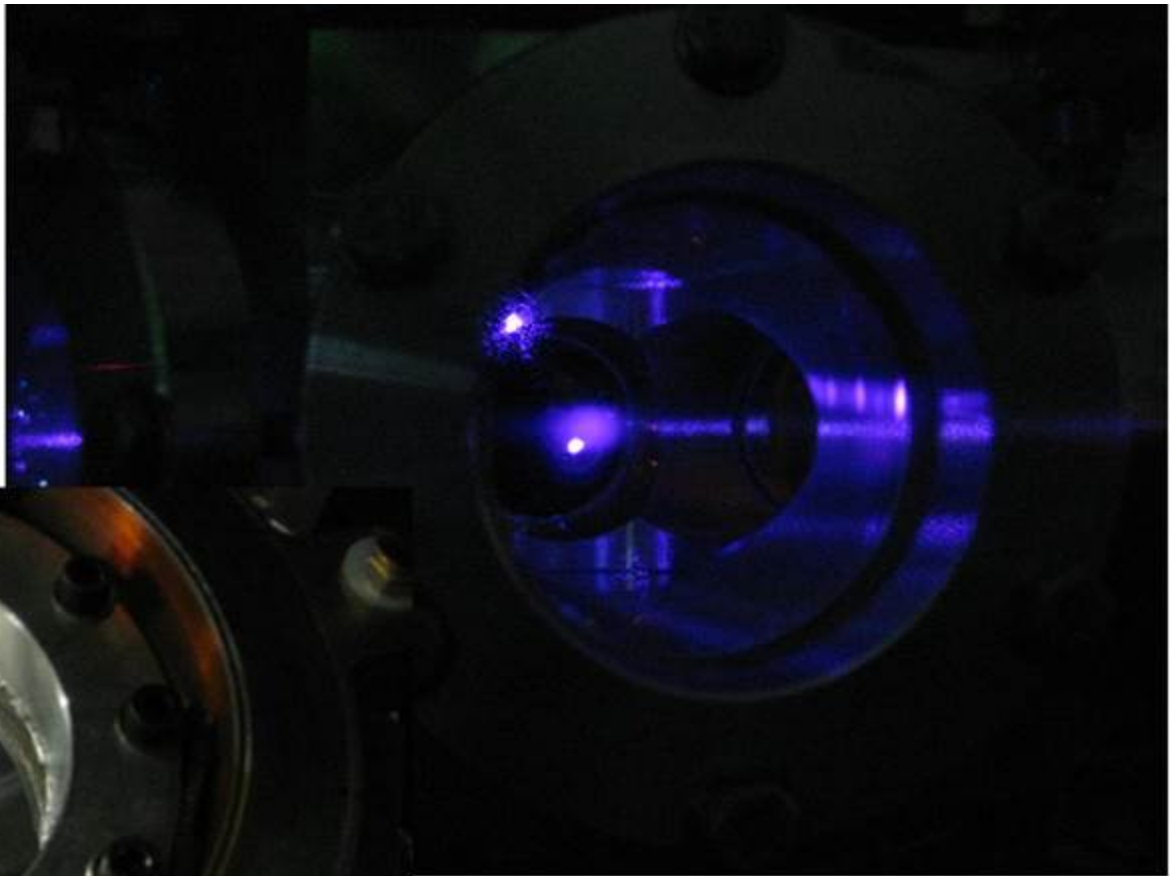


556 nm Laser Generation



15 mW @ 556 nm from 600 mW @ 1112 nm

399 nm Magneto Optical Trap



$$N_{\text{at}} \sim 10^7$$

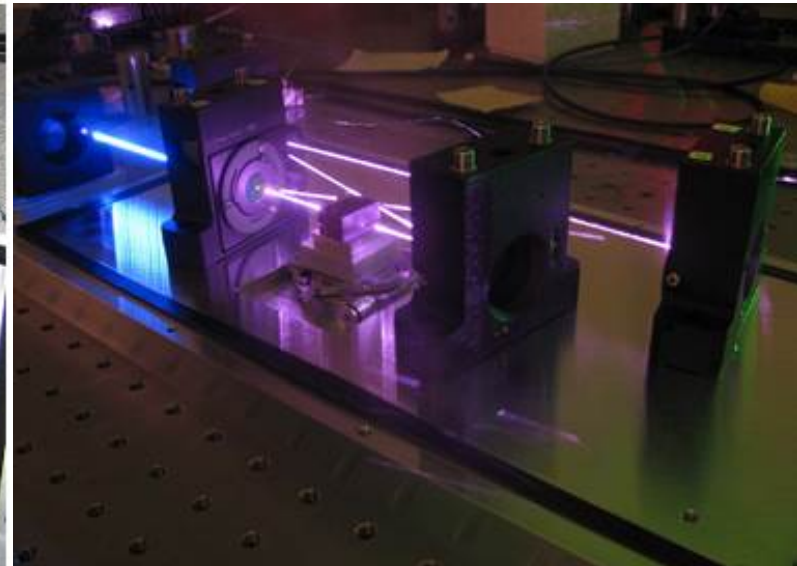
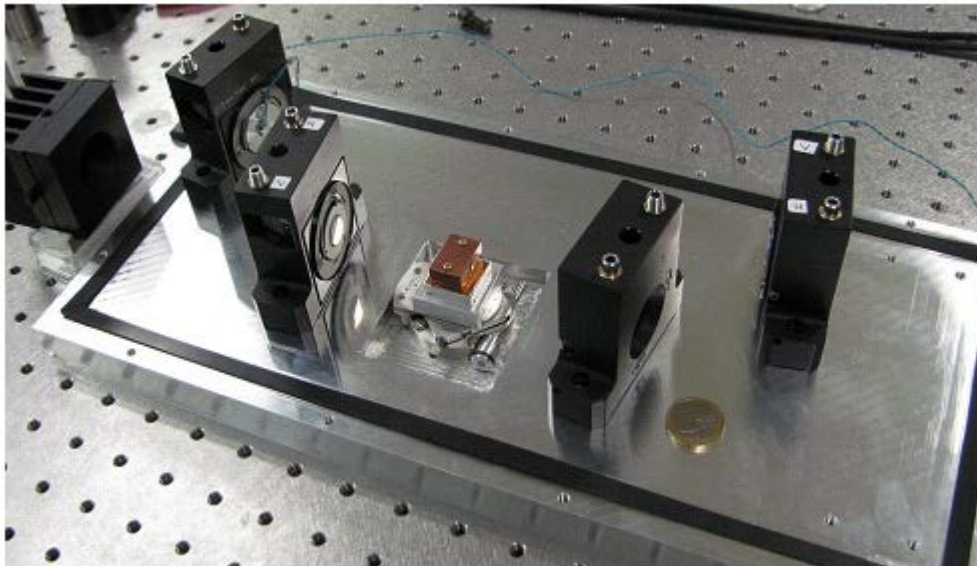
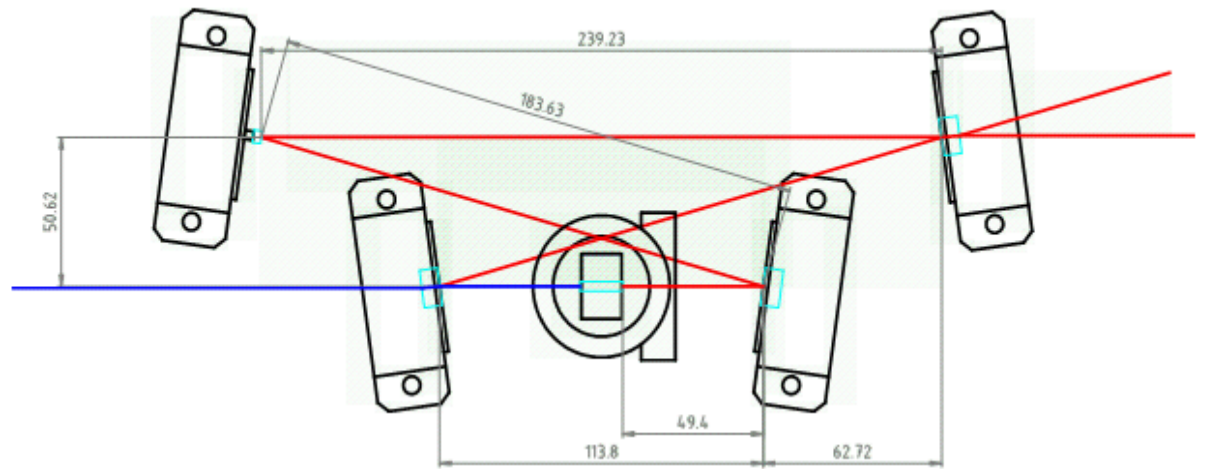
MOT load time 150 ms

T oven 400 °C

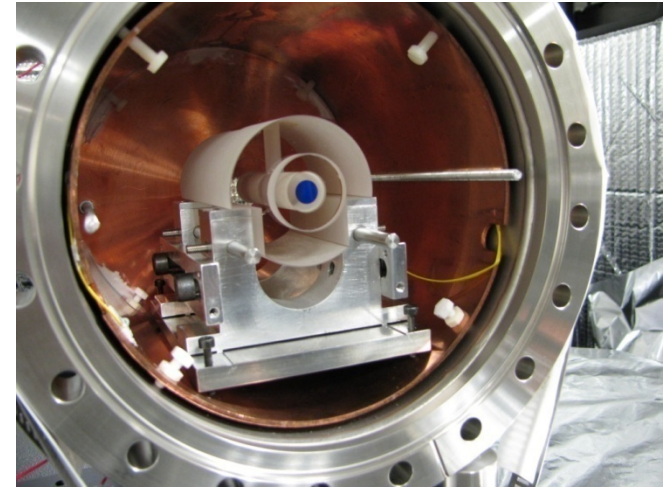
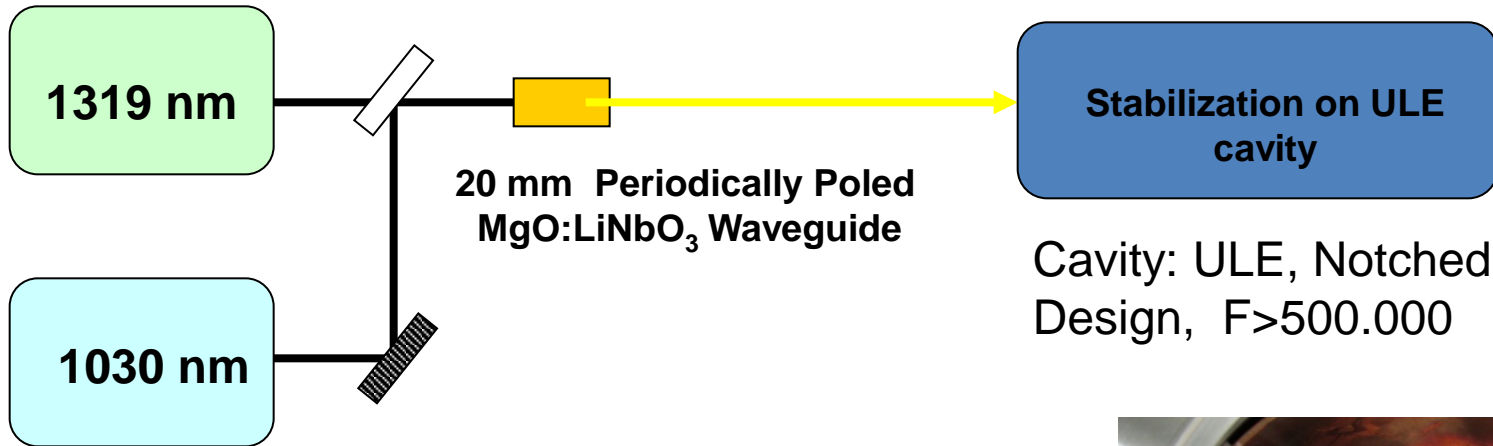
$b \sim 40 \text{ G/cm}$

Enhancement Cavity

To increase the output power, use a cavity to cycle first harmonic photons and enhance the SHG



Clock Laser Radiation



- ✓ up to 12 mW @ 578nm SFG
- ✓ Stabilized on notched ULE cavity
- ✓ Two independent cavities implemented

Reference Cavity Physical Package at INRIM

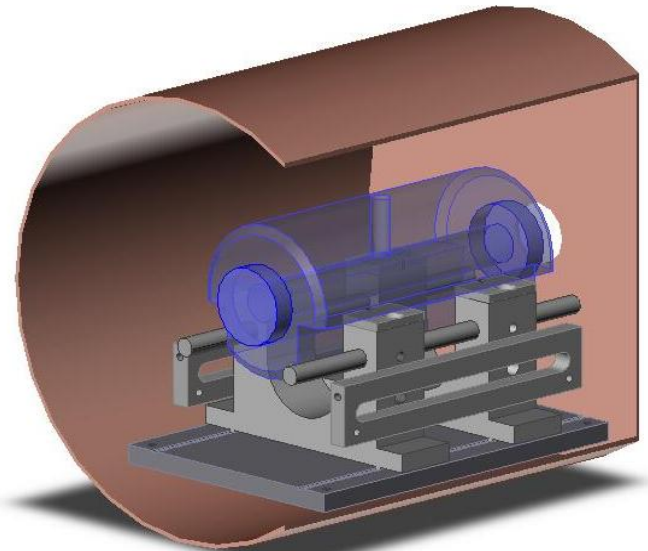
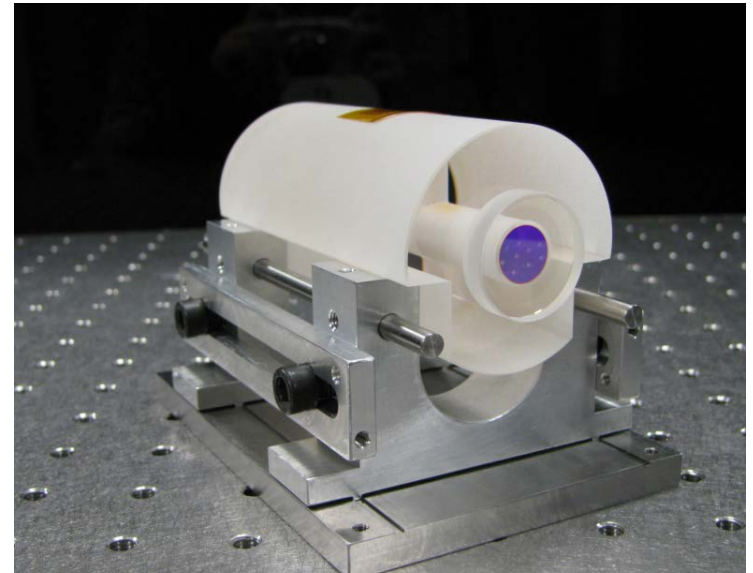
- Frequency stabilized with the Pound-Drever-Hall method against a stable Fabry-Pérot cavity
- The spacer is made in Corning Ultra Low Expansion Glass (ULE)
- FSR $\Delta\nu_{\text{FSR}} = 1.5 \text{ GHz}$
finesse $\mathcal{F} = 151\,000 \pm 1000$
linewidth $\Delta\nu = (9.93 \pm 0.06) \text{ kHz}$

Length 100 mm

Measured Zero CTE 21.5°C

Second Cavity $F = 250000$

$\Delta\nu = 6 \text{ kHz}$



Stabilizzazione della cavità^{1,2,3}

Frequenza di risonanza della cavità:
$$\nu = n \frac{c}{2L}$$

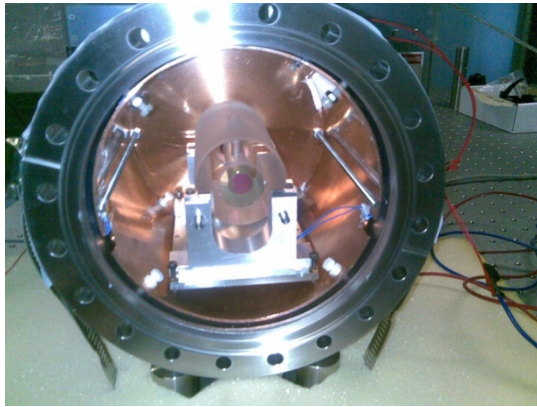
La cavità è isolata dall'ambiente

• Termicamente:

- **Specchi e distanziale in ULE[®] Corning:** attorno a T_C :

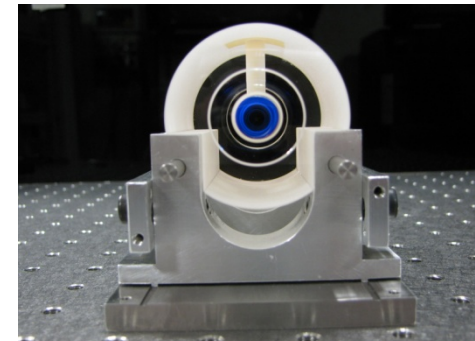
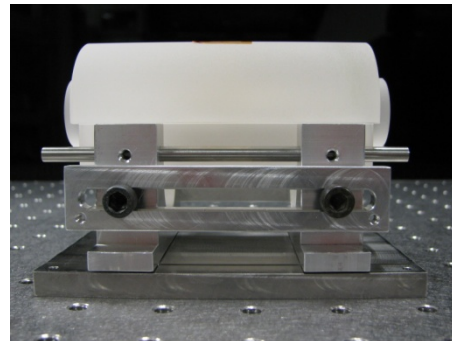
$$\frac{\Delta\nu}{\nu} = \frac{\Delta L}{L} \approx 10^{-9} (T - T_C)^2 \Rightarrow \frac{d}{dT} \frac{\Delta\nu}{\nu} \approx 10^{-9} (T - T_C)$$

- **Camera sotto vuoto:** $P = 6 \times 10^{-8}$ mbar
- **Rivestimento in Acciaio**
- **Schermo in Rame** separato dal rivestimento mediante viti in ceramica
- **Circuito di controllo** attivo della temperatura

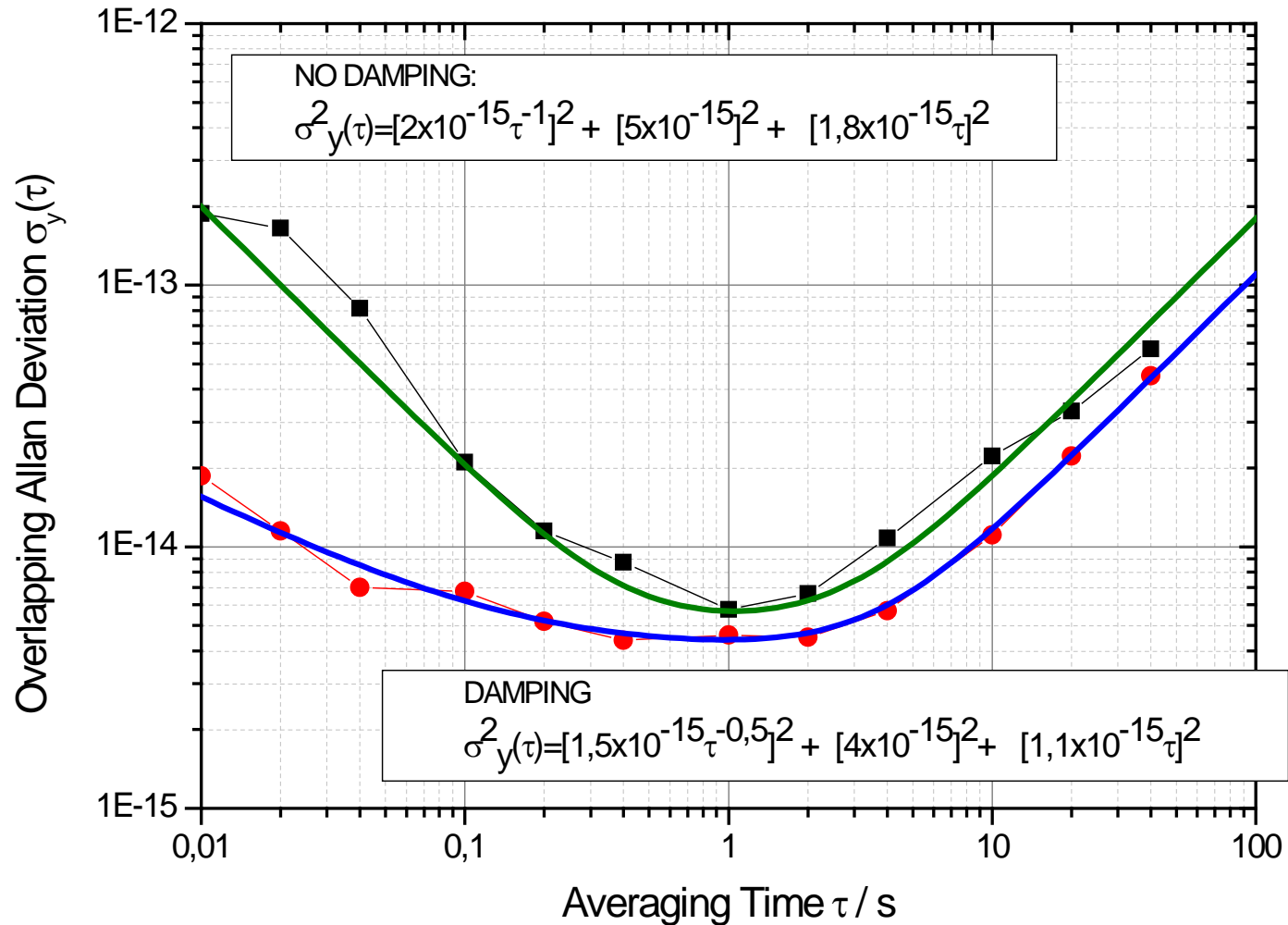


• Meccanicamente:

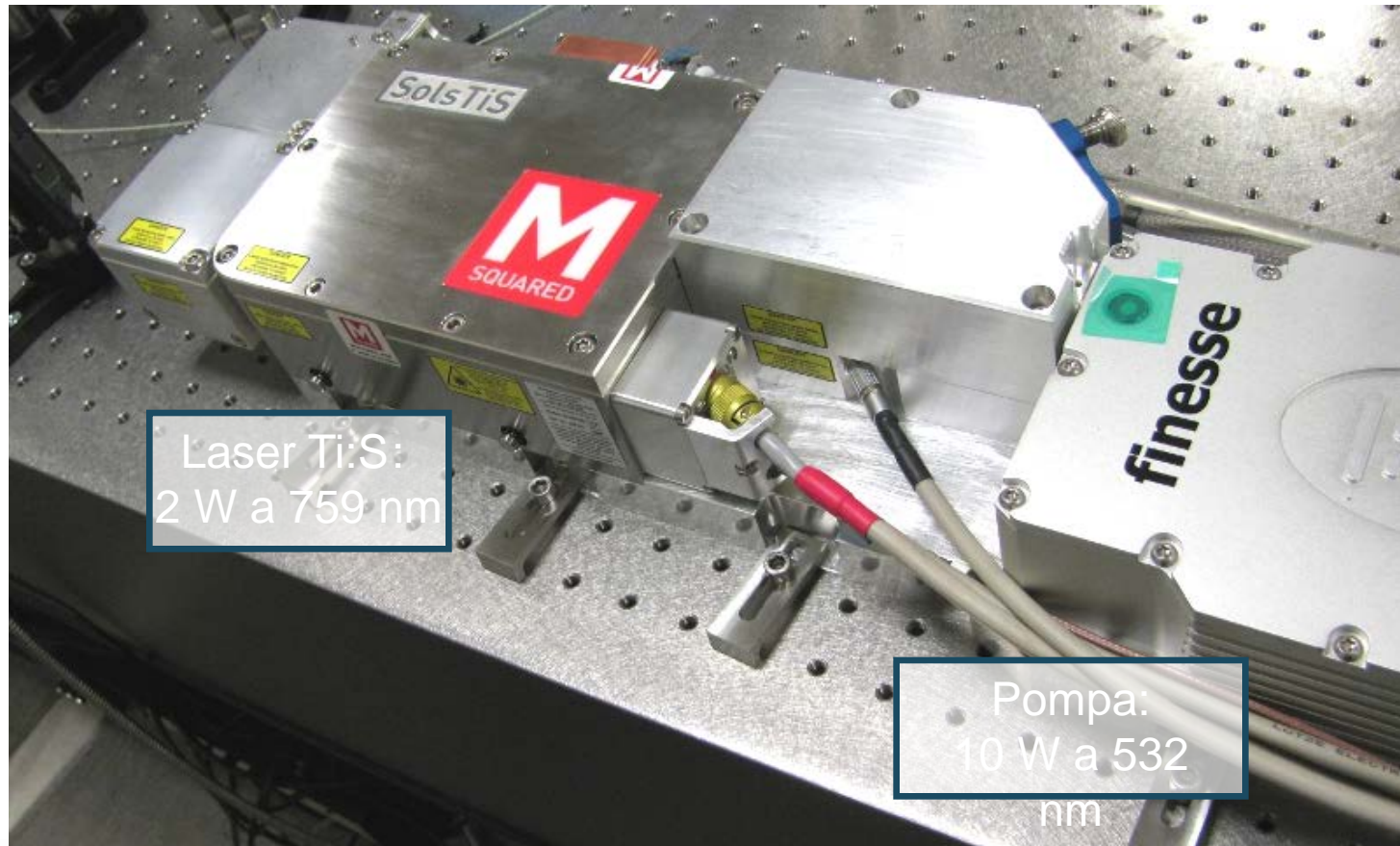
- Il **banco ottico** garantisce uno smorzamento delle vibrazioni a frequenze spettrali > 10 Hz
- **Appoggio sui punti di Airy** perché la cavità subisca la minima deformazione di L dovuta alle accelerazioni del sistema.



Two Independent locked 578 nm Laser

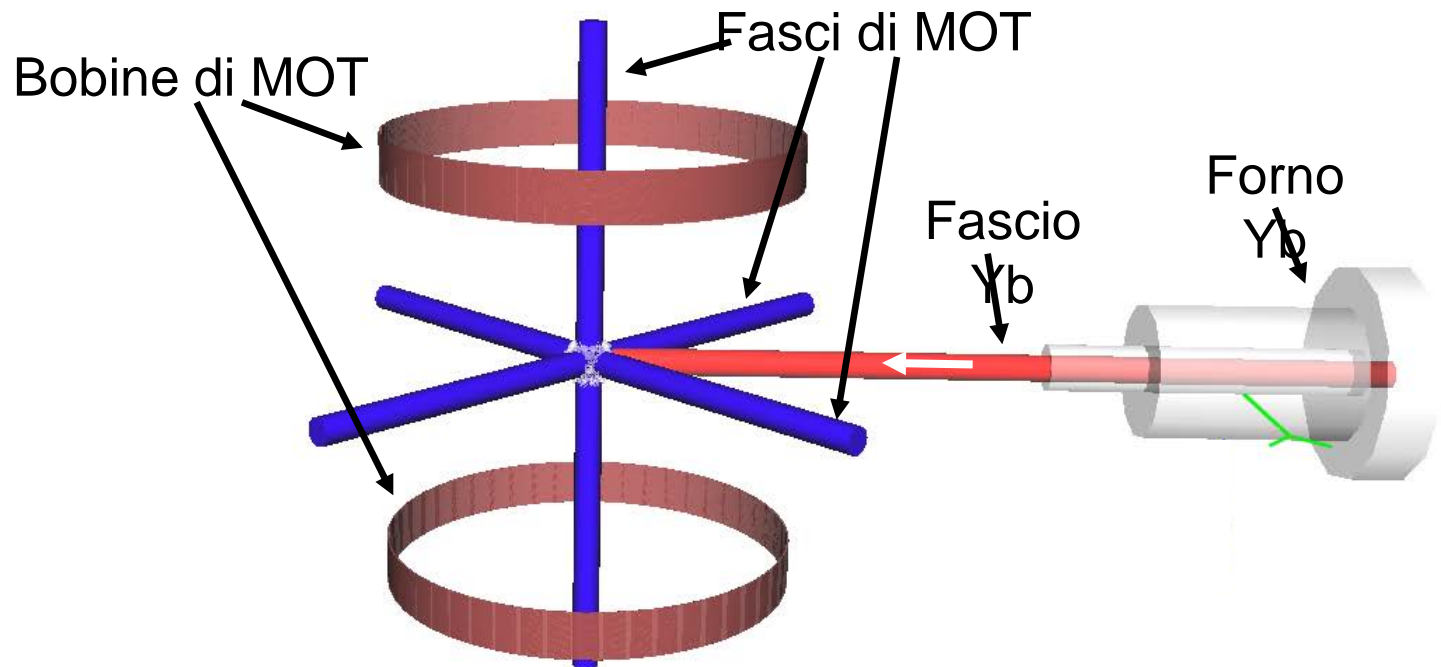


Laser di reticolo (759 nm)

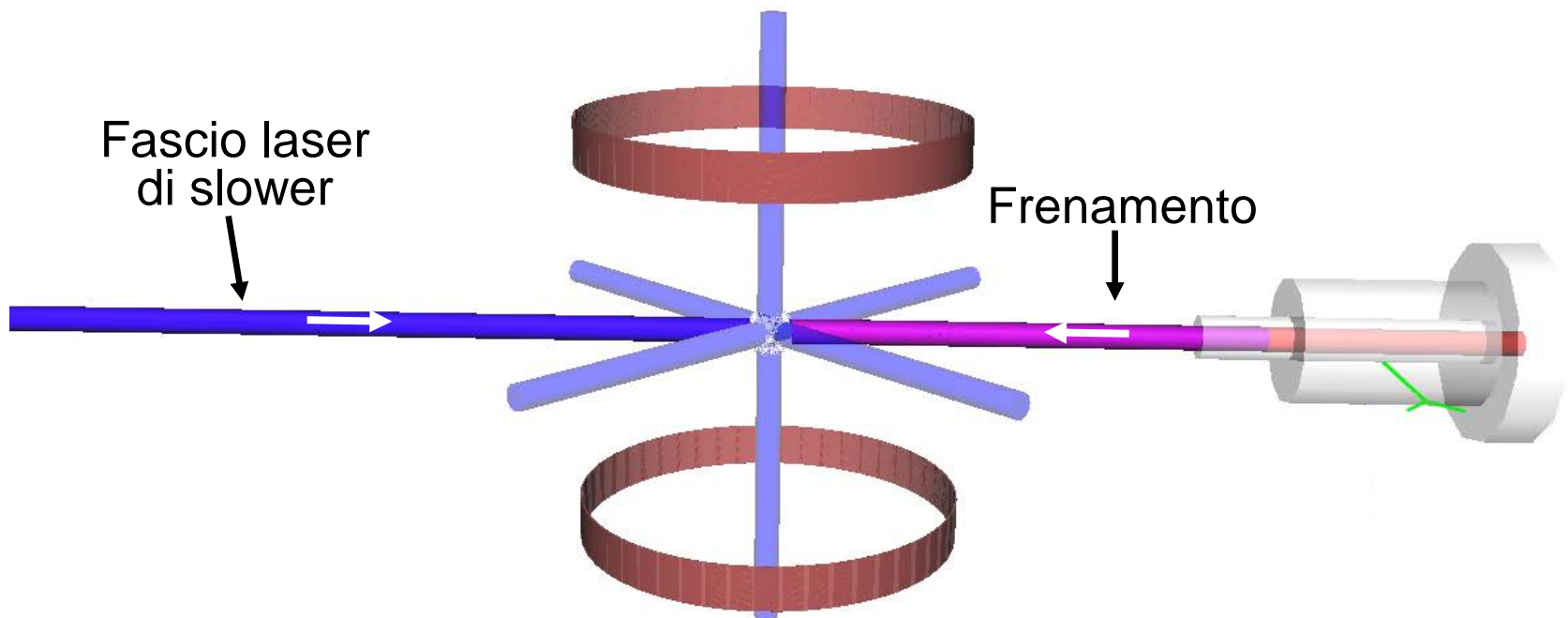


Schema della MOT blu

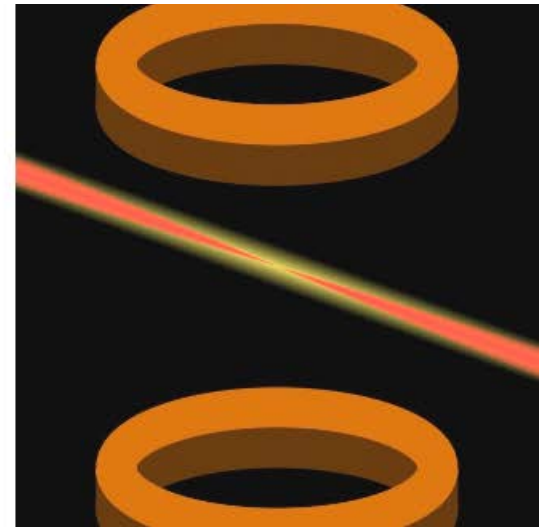
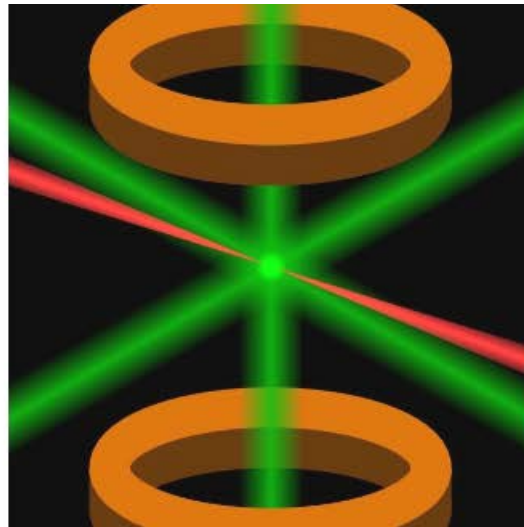
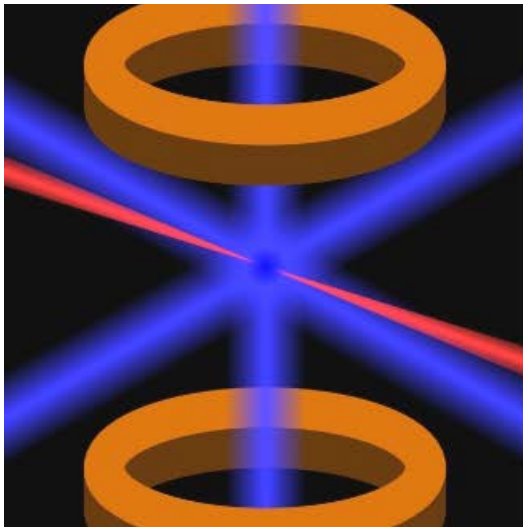
3D (1/2)



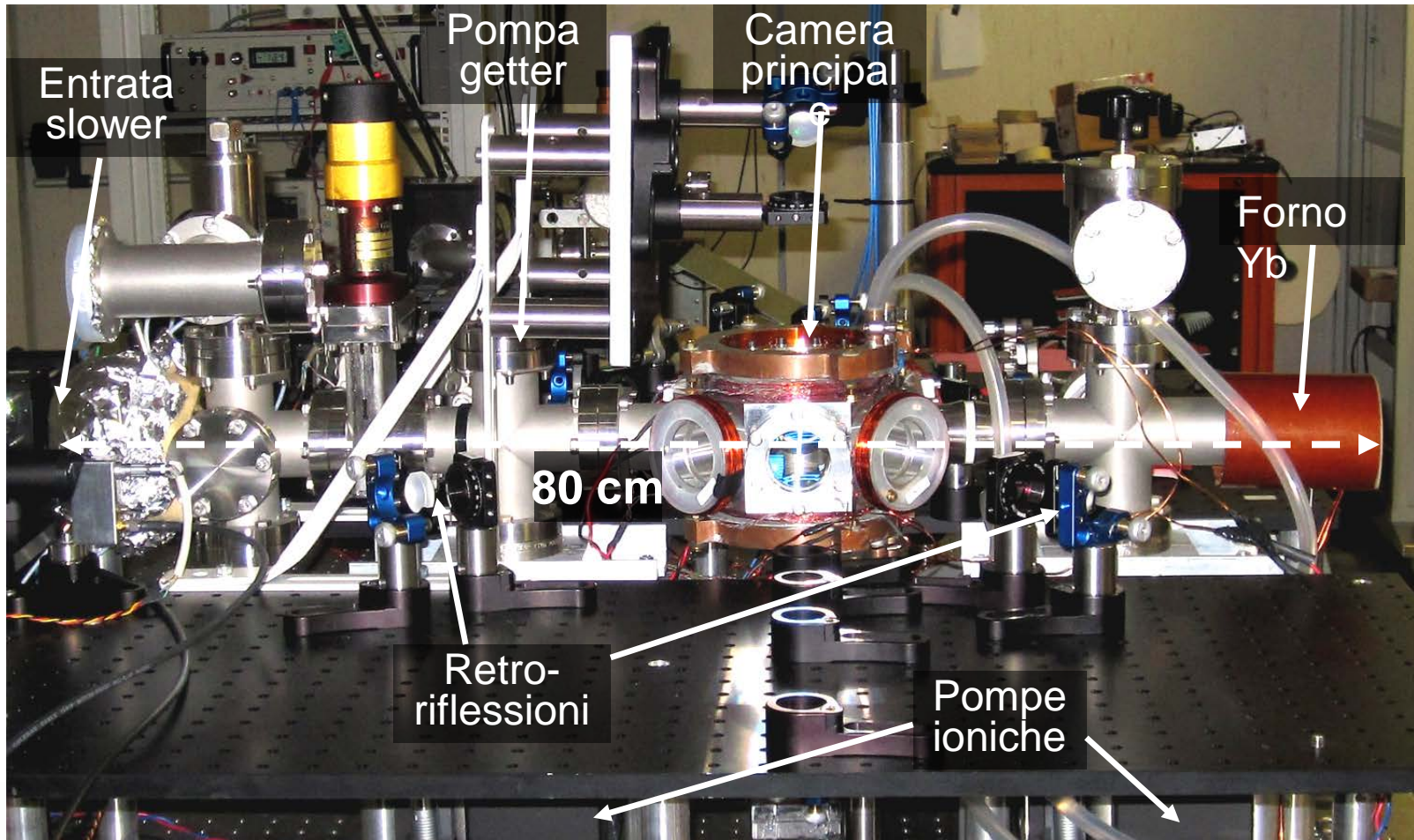
Schema della MOT blu: fascio laser di slower



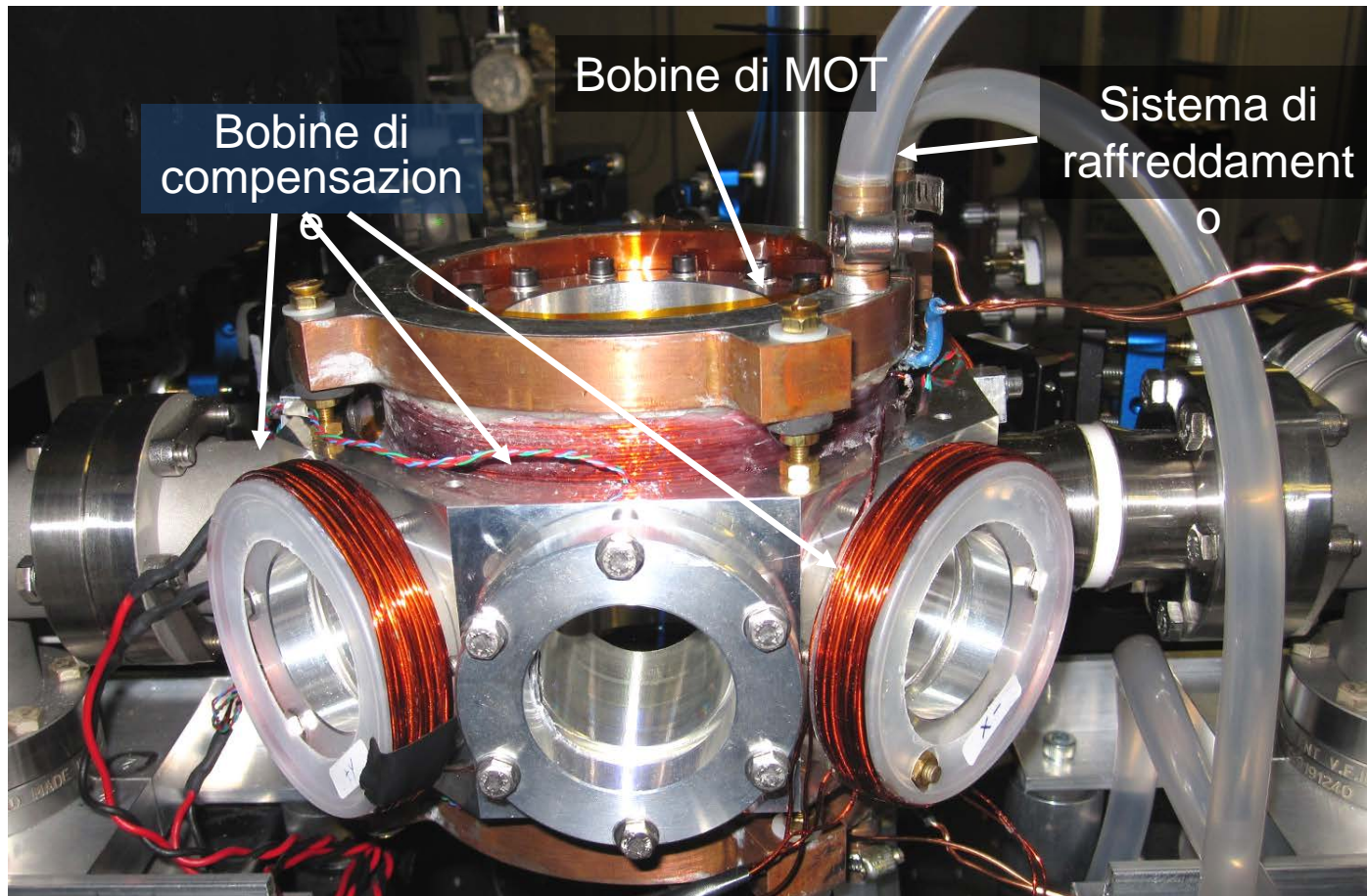
Sequenza di intrappolamento



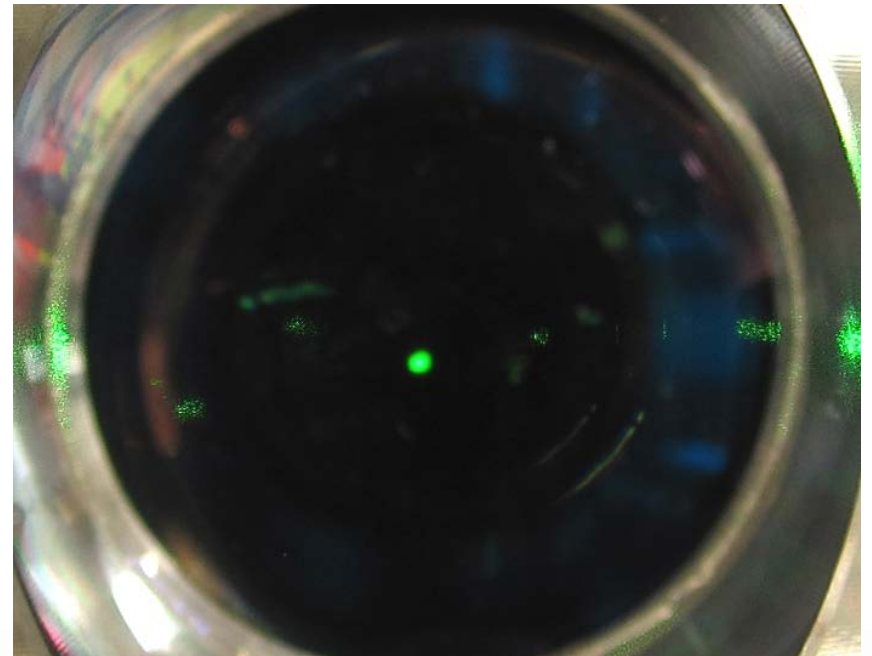
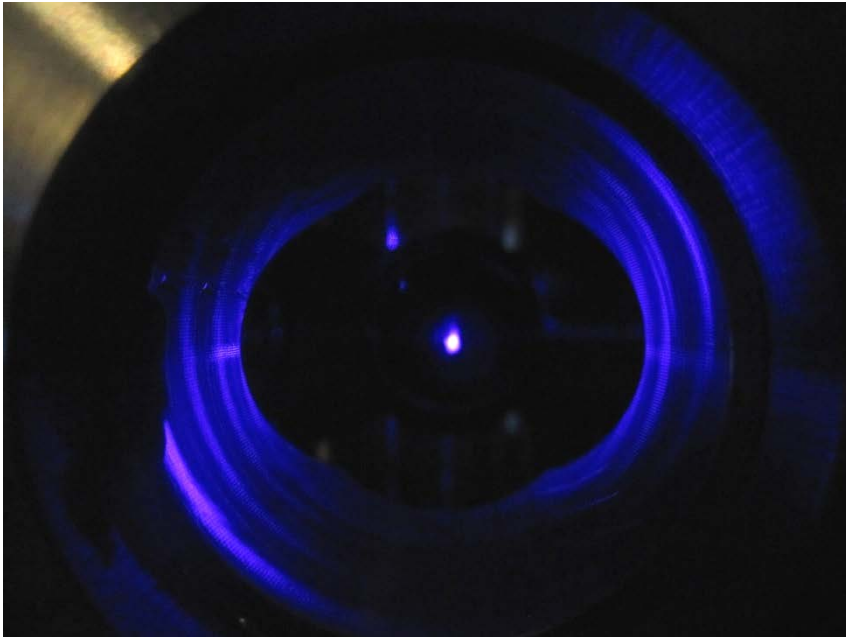
Apparato sperimentale



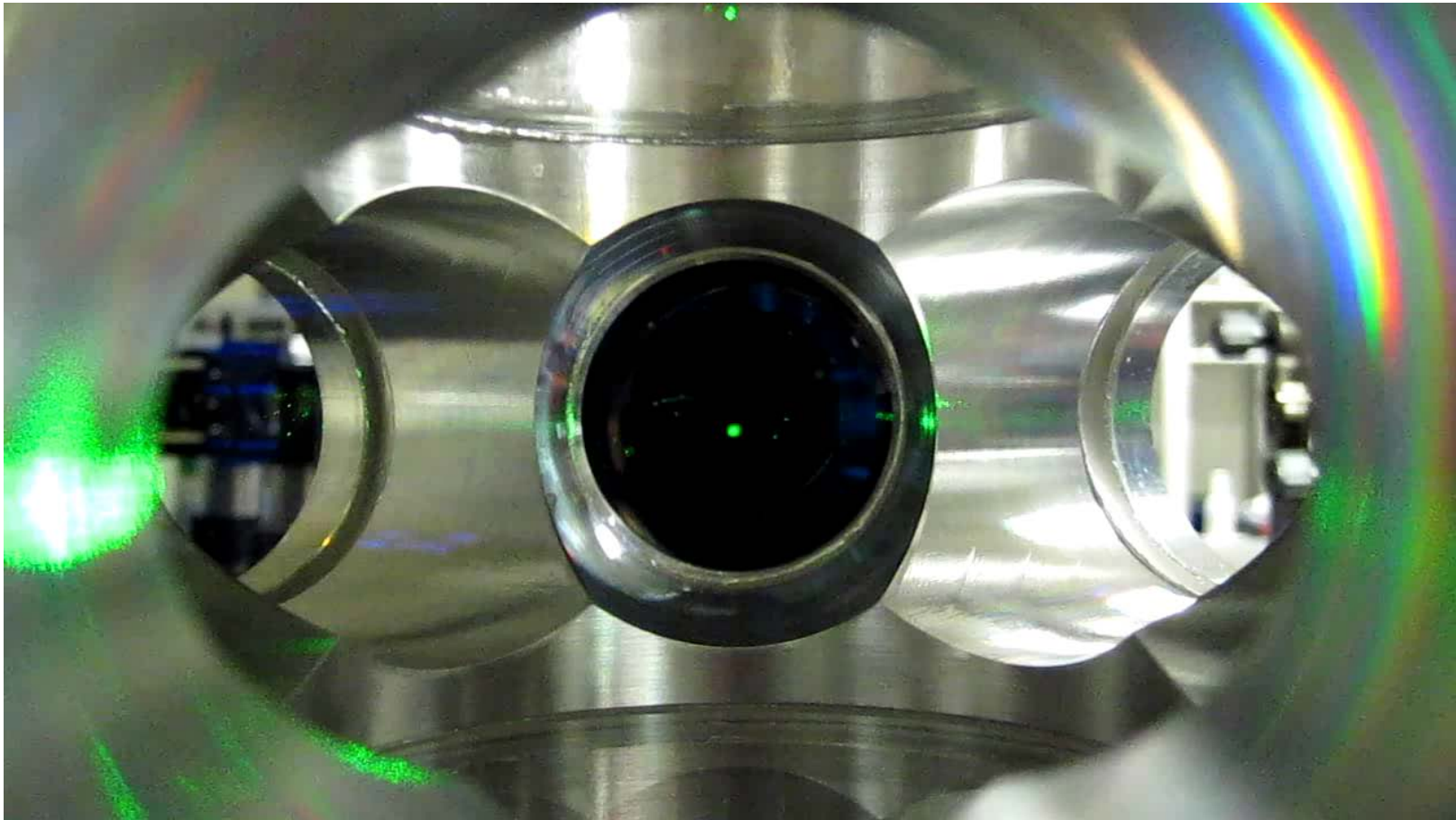
Bobine di MOT e di compensazione



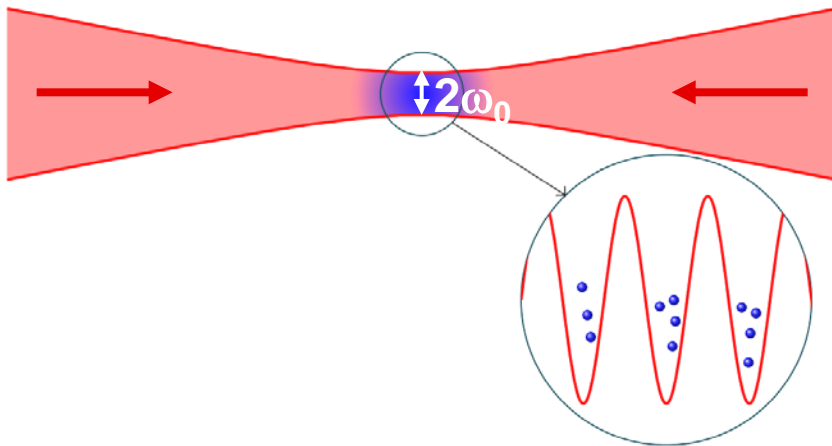
Realizzazione delle MOT



Realizzazione delle MOT



Realizzazione del reticolo ottico



Yb Loading

Blue MOT

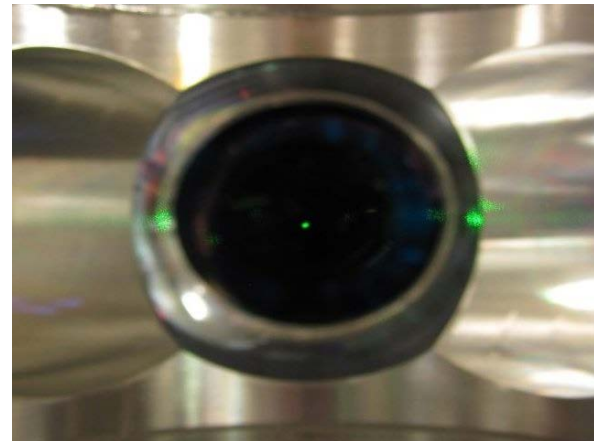
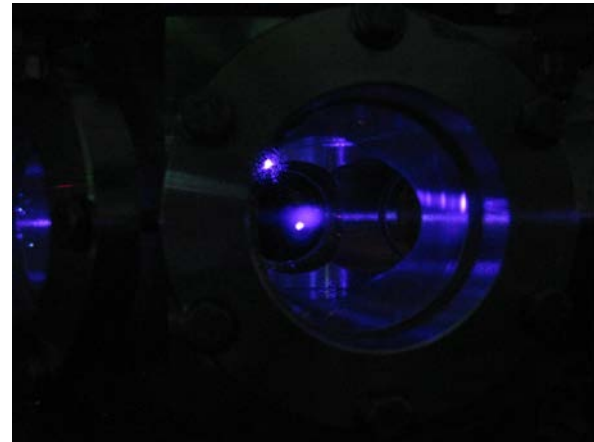
- .Up to 1×10^7 Yb171 Atoms
- .150 ms loading time
- .Oven temperature 400 °C
- .No Zeeman slower,

Green MOT

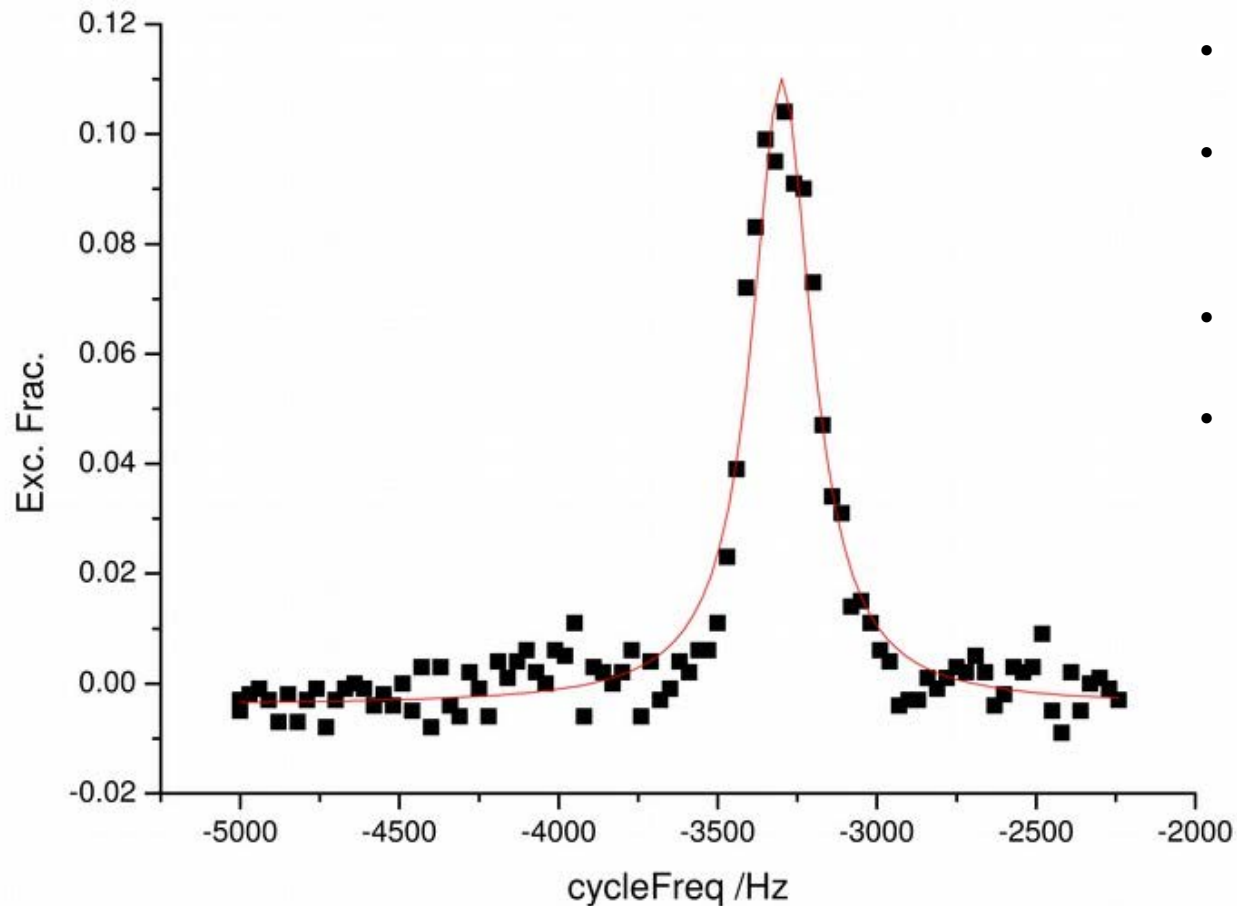
- .70% transfer efficiency
- .3 frequency stages
- .Atoms temperature 10 μ K

Lattice

- .Up to $3.6(3) \times 10^4$ atoms
- .Usually 1×10^4 atoms
- .3 s lifetime in the trap



First Clock Transition Excitation



- 2 pi transitions
- Zeemann splitting
~200 Hz/G
- Linewidth 230 Hz
- Work in progress
to optimize the
line and lock the
laser



So how good are optical clocks right now?

Reported uncertainty

Al⁺ ion quantum logic clock: 9×10^{-18}

Hg⁺ ion cryogenic ion clock: 2×10^{-17}

Sr⁺ ion quadrupole clock: 2.1×10^{-17}

Yb⁺ ion octupole clock: 7×10^{-17}

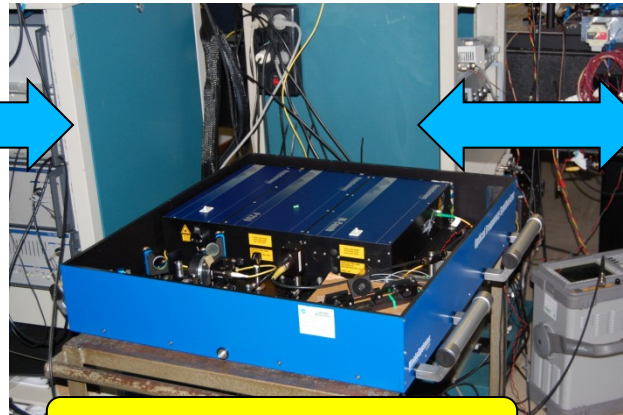
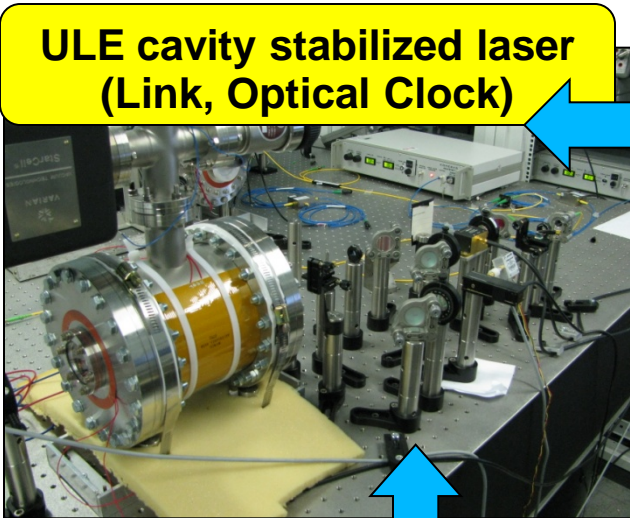
Sr neutral lattice clock: 1.5×10^{-16}

Yb neutral lattice clock: 3.4×10^{-16}

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

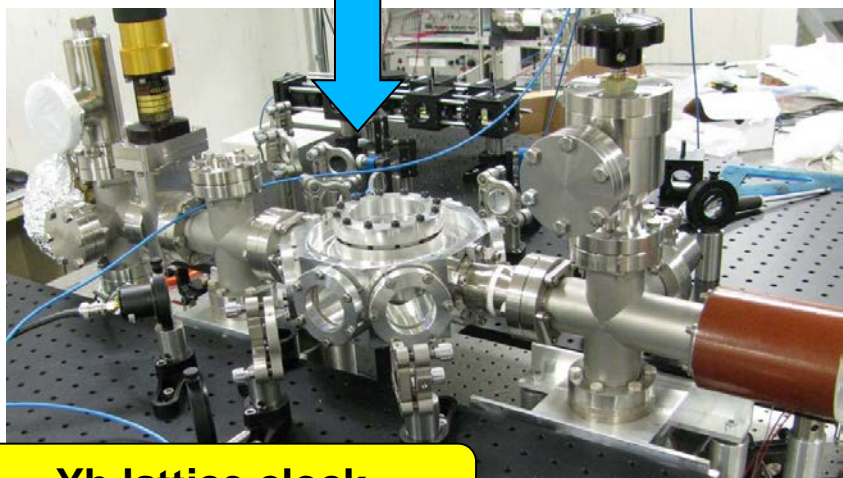


**Cryogenic
Cs Fountain
ITCsF2**



**Cs Fountain
ITCsF1**

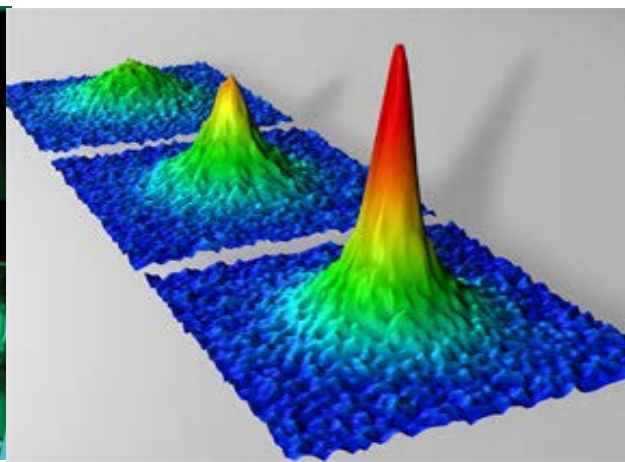
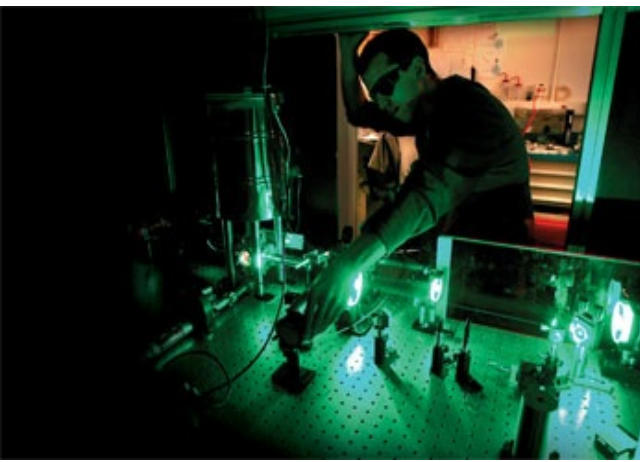
Cs Primary References



Yb lattice clock

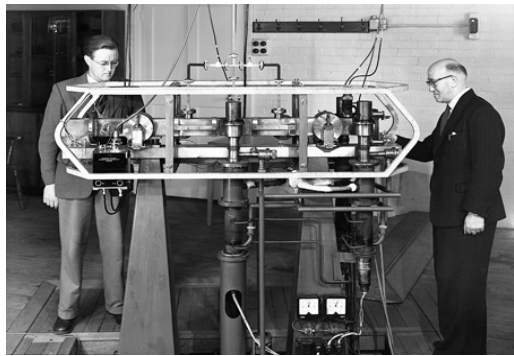
4 H-Masers





LINK E CONFRONTI IN FIBRA OTTICA

Atomic clocks accuracy in the last 50 years

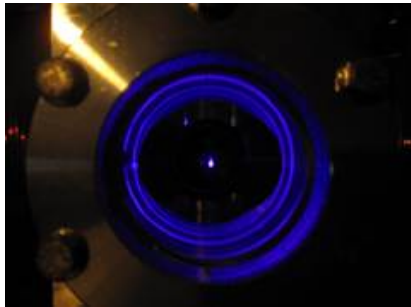


First Cs beam clock
(1955)

First Cs fountain
(1996)



Cs fountain clocks
(today)



Best optical clocks
(today)

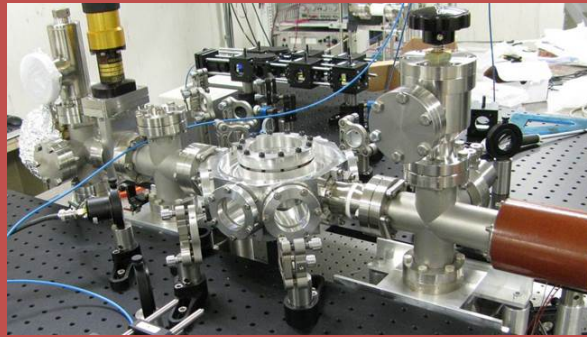


Satellite
techniques
(1 day averaging)

Optical links
(1 day averaging)

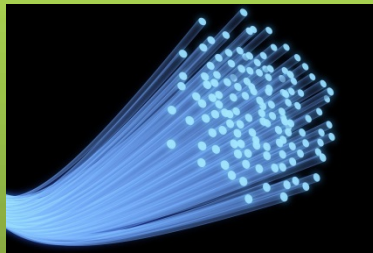


Accurate Time for all: How to?

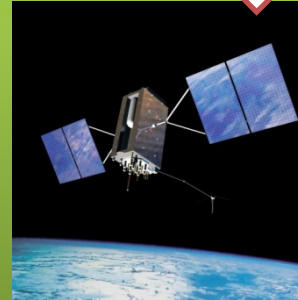


National Metrological Institutes (Atomic Clocks)

Optical Fiber
Techniques

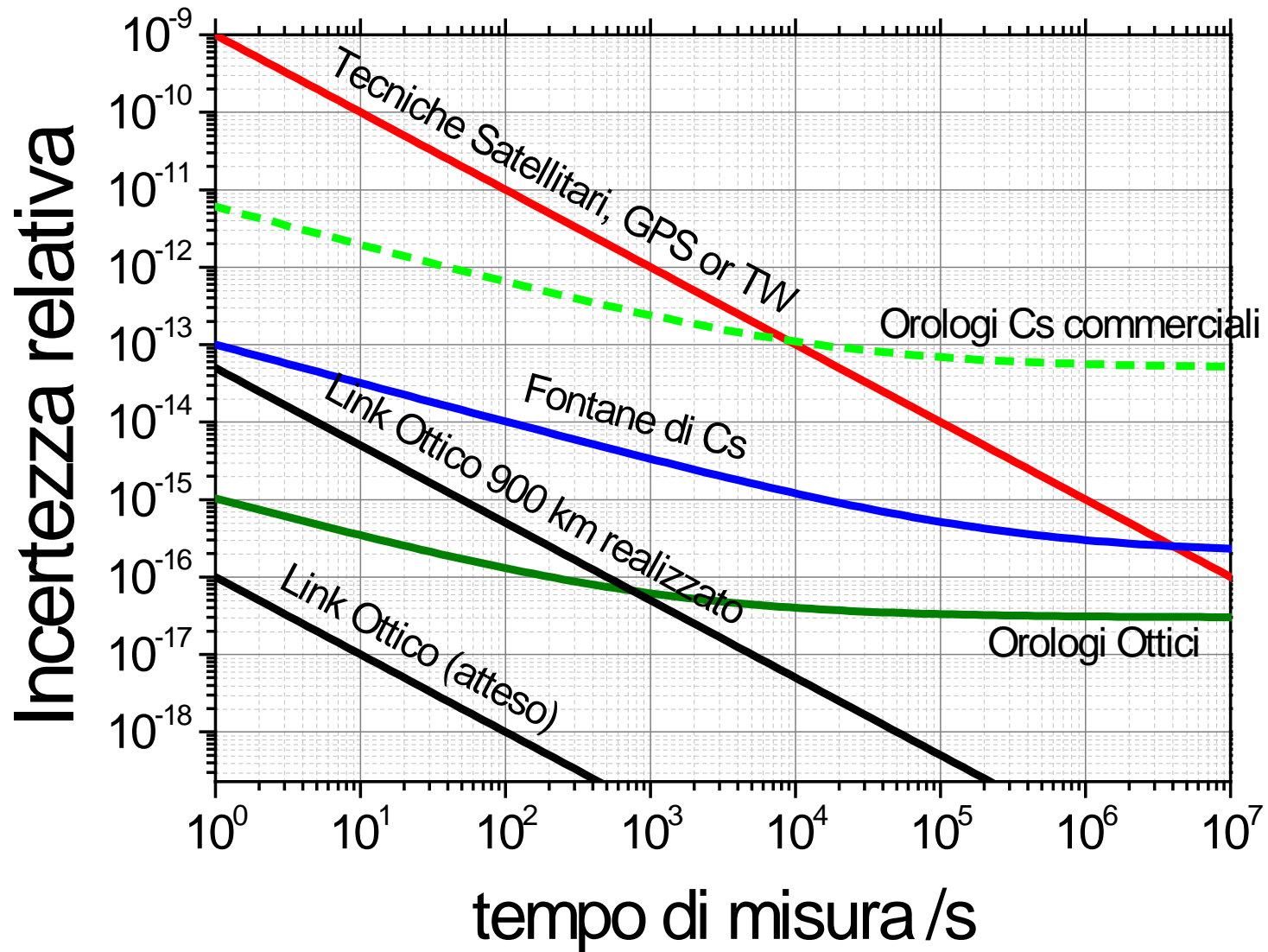


Satellite
Techniques



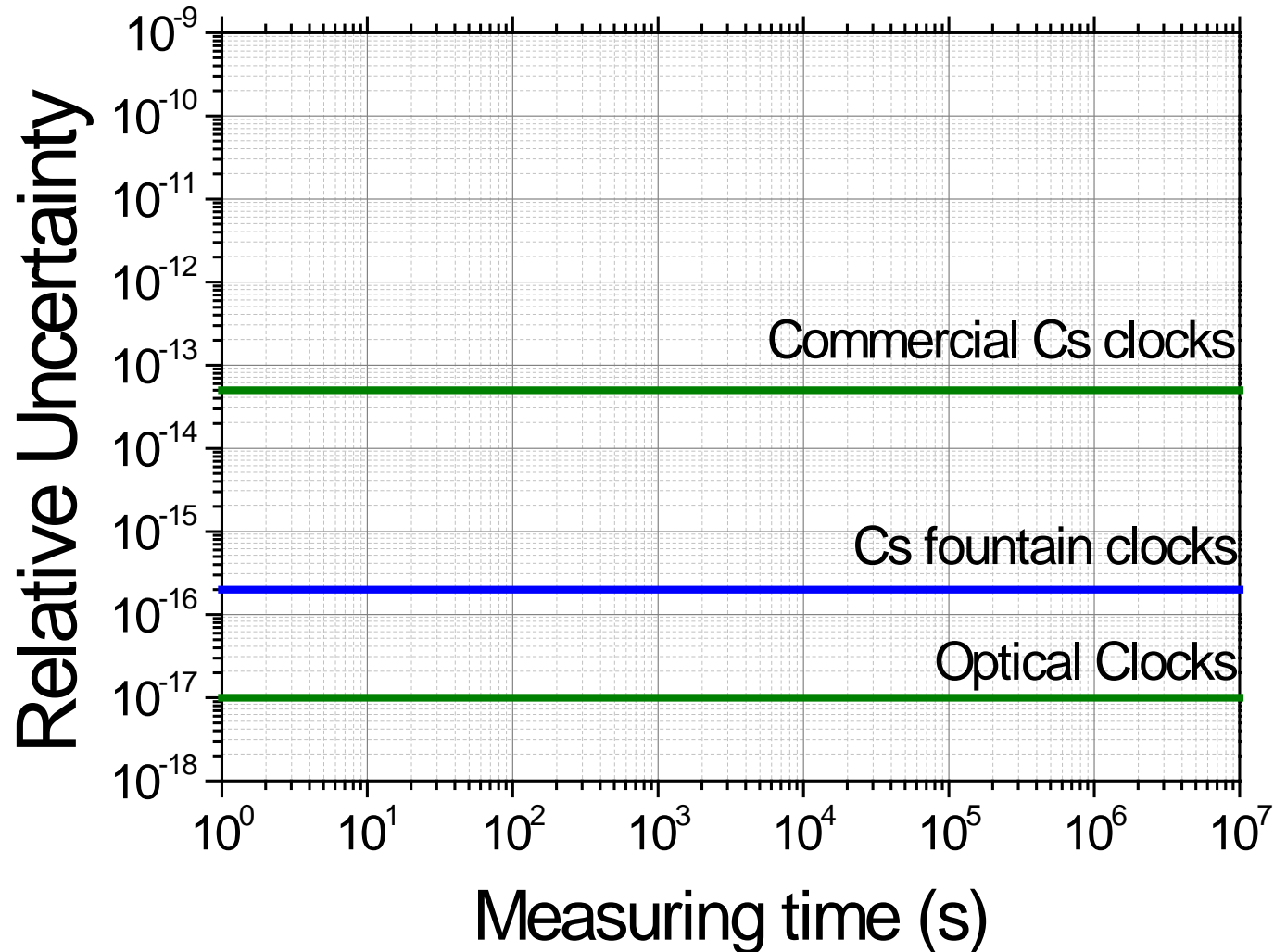
USERS

Prestazioni del Link Ottico



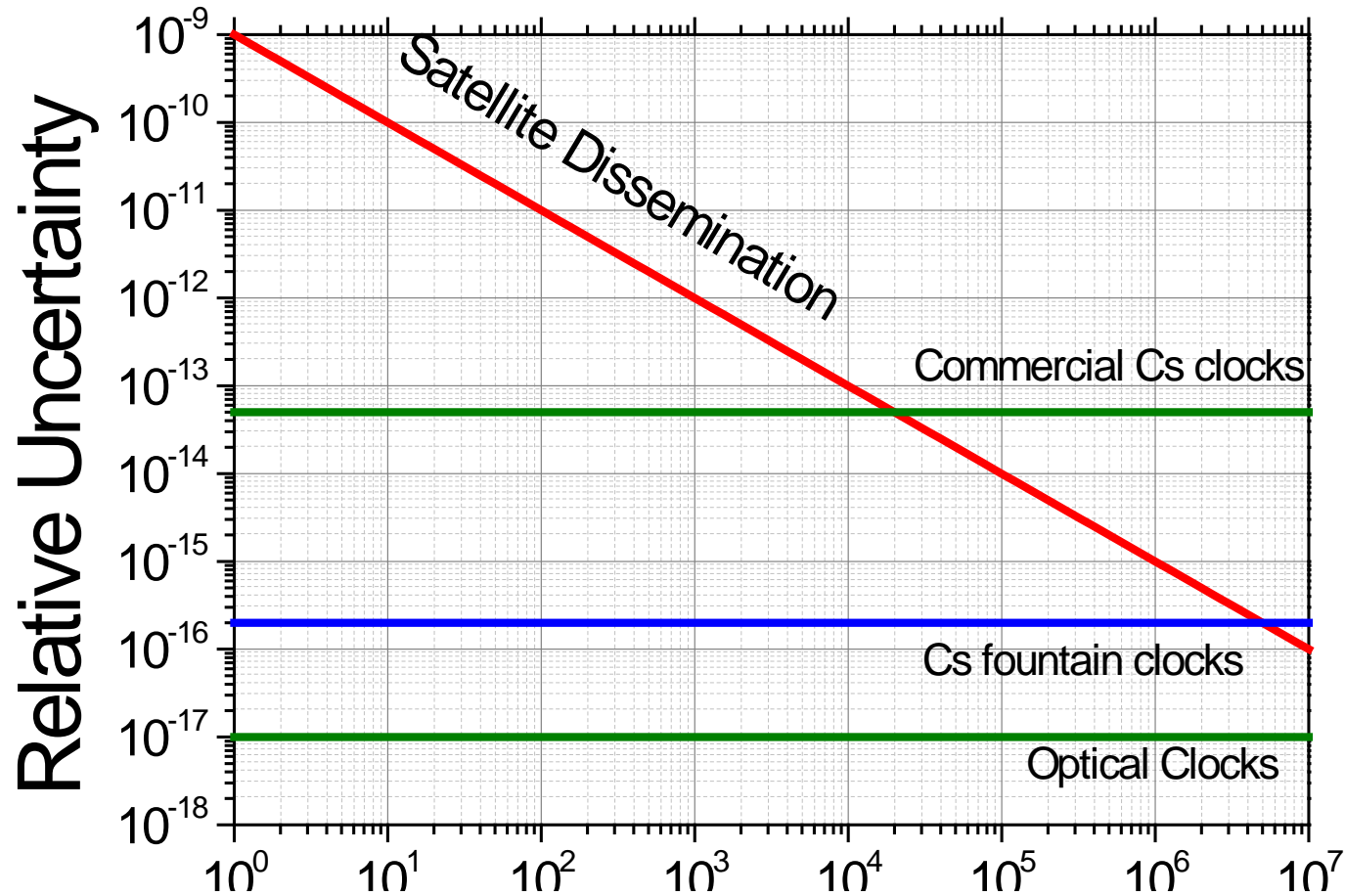
Spreading Accurate Time

From NMI to users



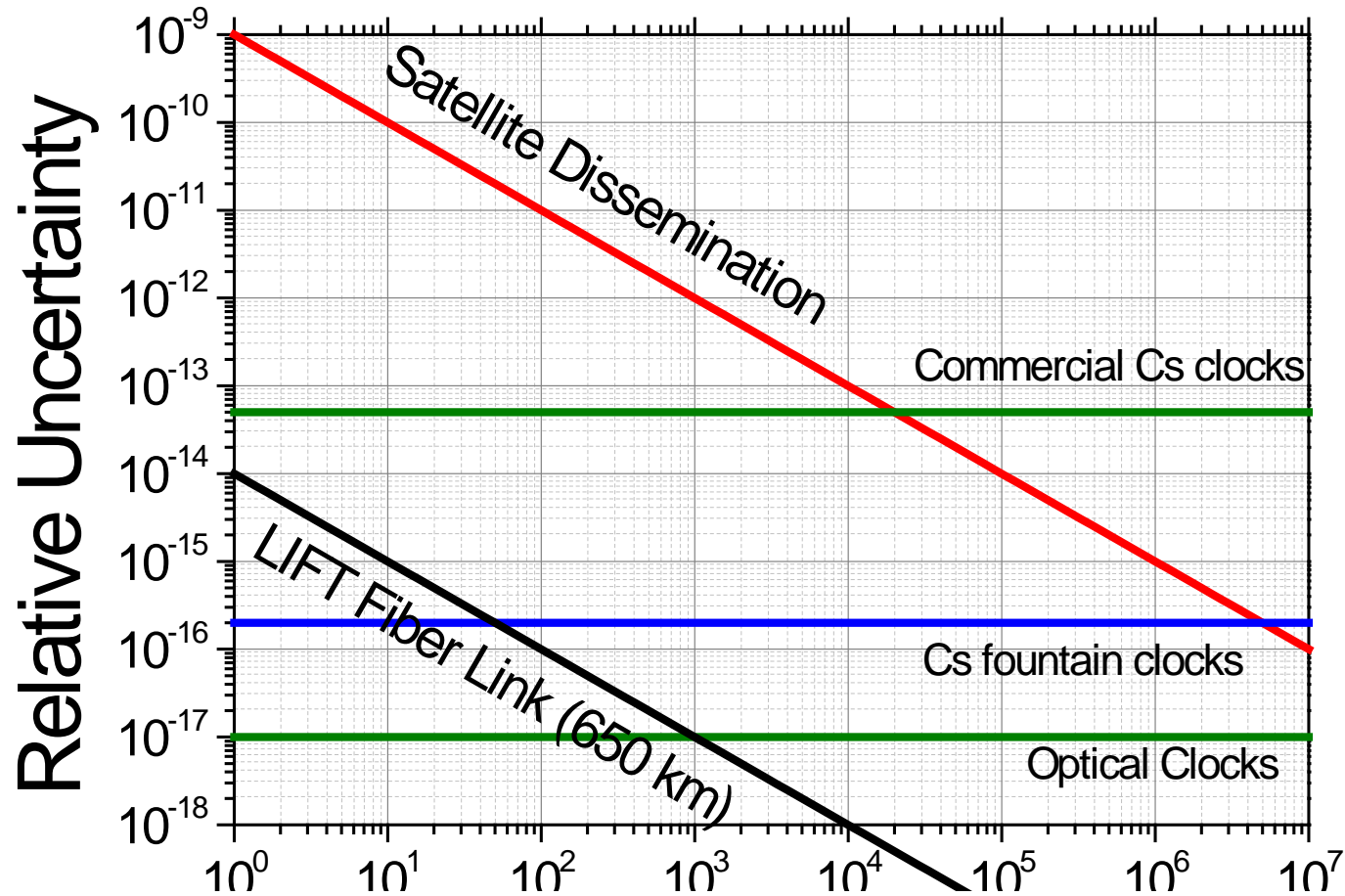
Spreading Accurate Time

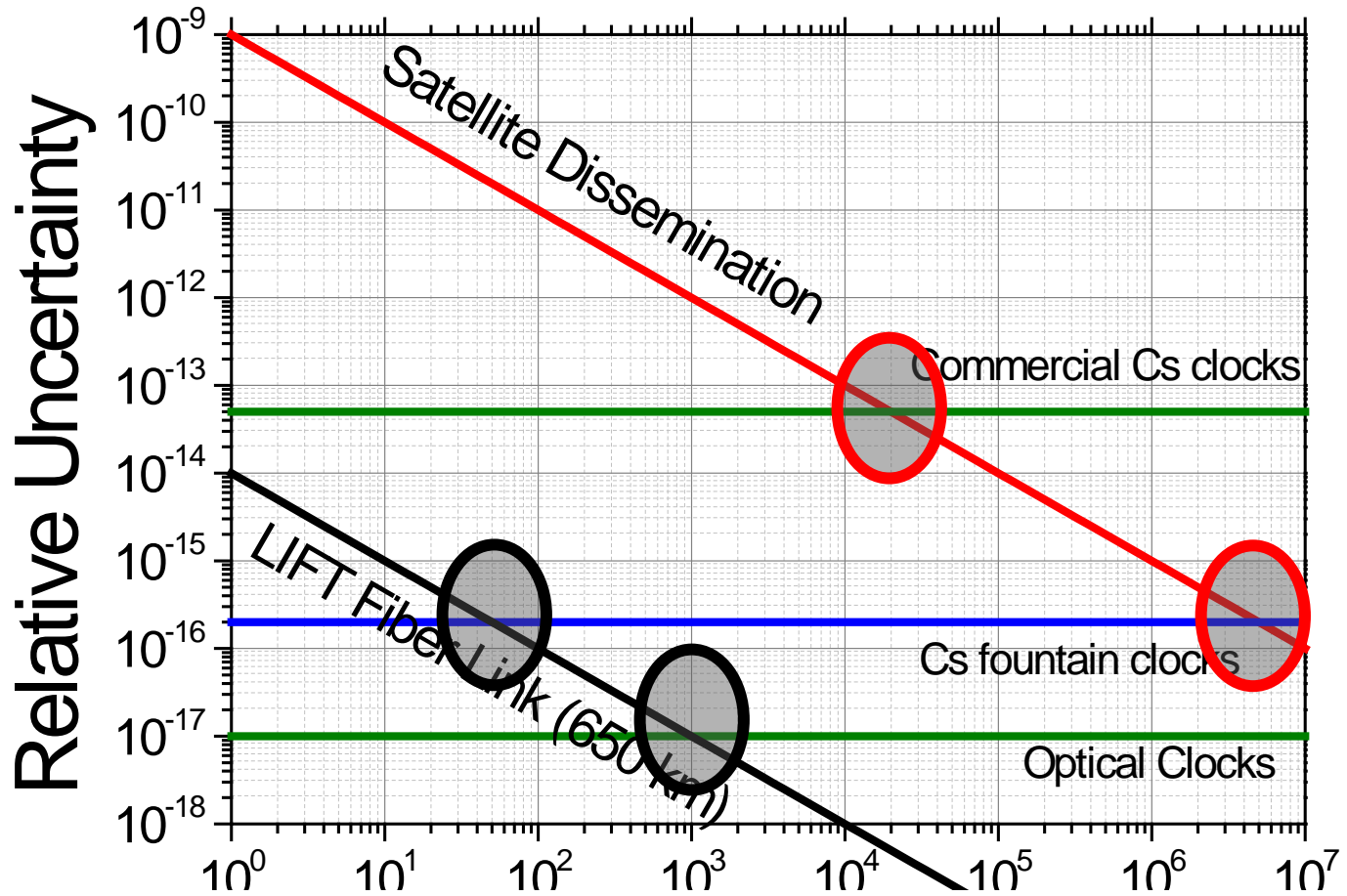
From NMI to users



Spreading Accurate Time

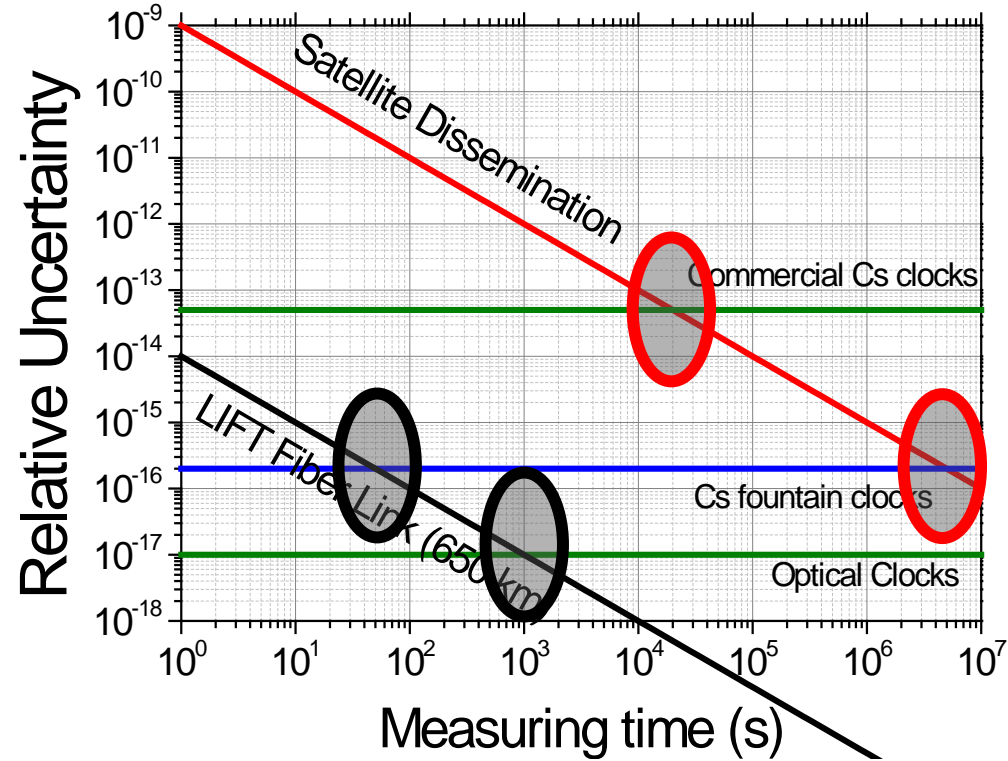
From NMI to users





Spreading Accurate Time

From NMI to users



Satellites:

>4 h to spread a Commercial Cs
>20 days to spread Cs Fountains
>100 days for optical clocks

Fiber Links:

Always better than Commercial Cs
100 s to spread Cs fountains
1000 s for Optical Clocks



Fiber Link: how it works

ULTRASTABLE
TRANSFER LASER

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

FPC

BIDIRECTIONAL
FIBER

Faraday
Mirror

Optical
Filter

Faraday
Mirror

AOM1

PLL

AOM2

FIBER NOISE
COMPENSATION



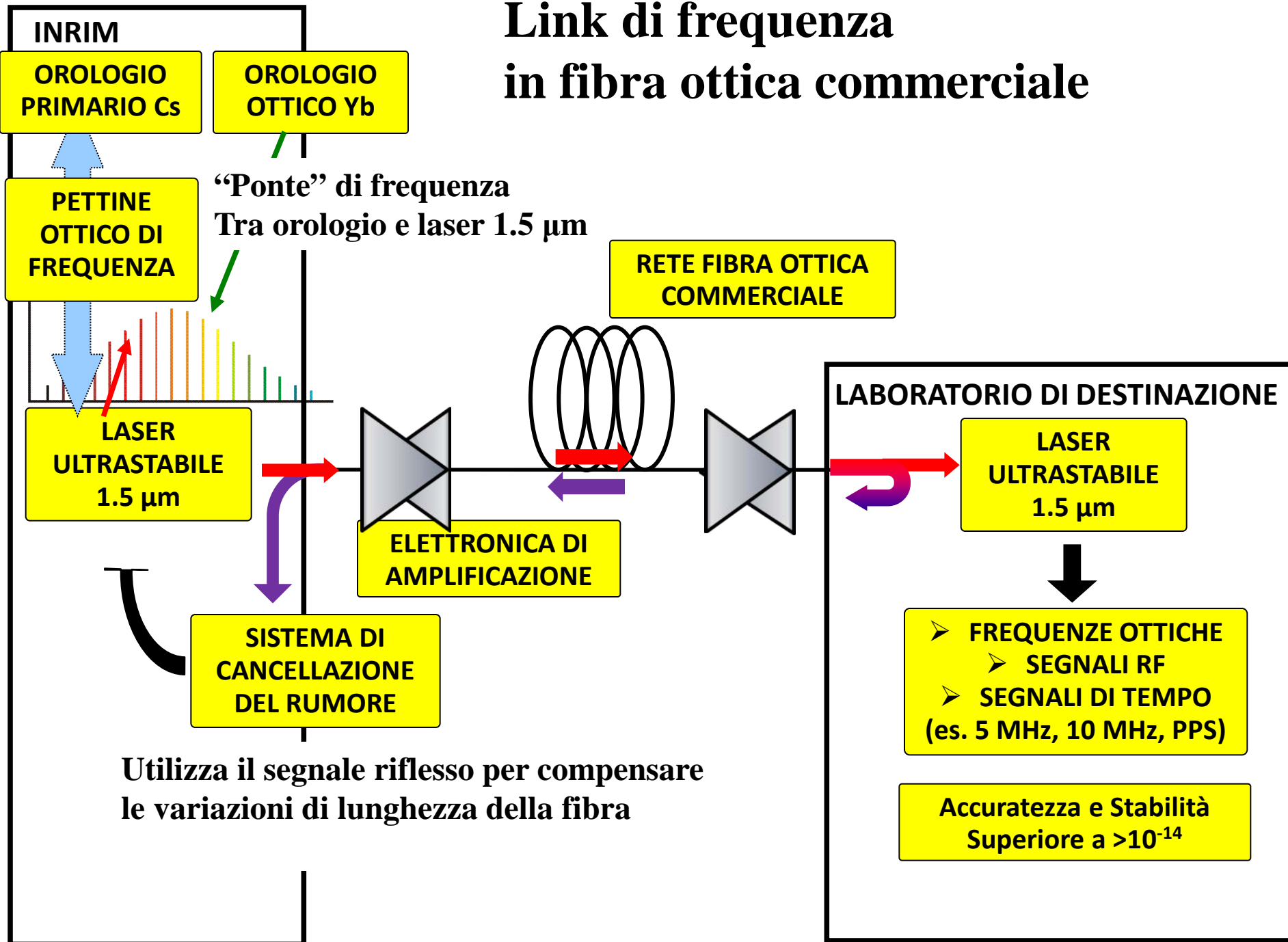
CLOCK A



CLOCK B



Link di frequenza in fibra ottica commerciale



LIFT

Link Italiano per la Frequenza e il Tempo





LIFT OPTICAL FIBER LINK



LIFT OPTICAL FIBER LINK

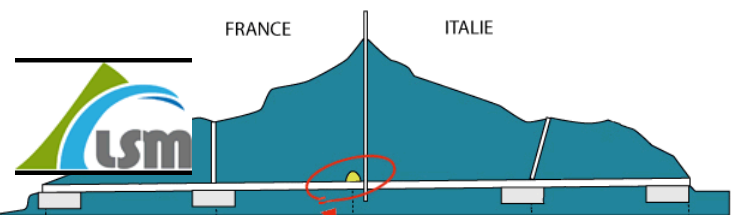
LIFT users



LIFT impact on academic research

Frejus Tunnel

Relativistic Geodesy



PTB

Courtesy of C. Lisdat

Florence

Atomic and molecular spectroscopy



INO
ISTITUTO NAZIONALE
DI OTTICA



Bologna



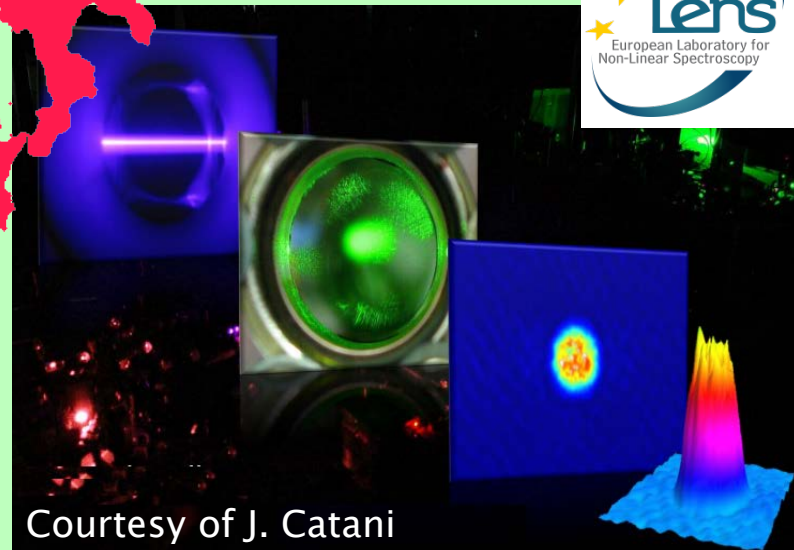
564 m x 640 m
Telescopes array.



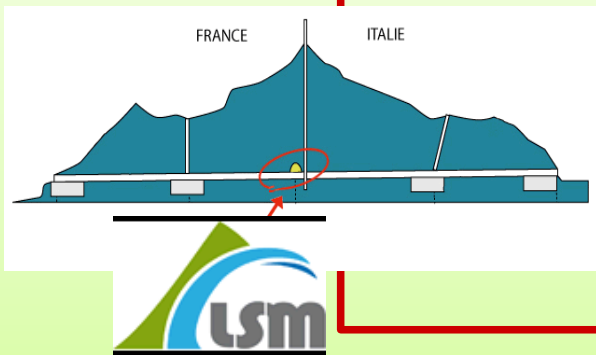
32-m dish for
Very Long Baseline
Interferometry



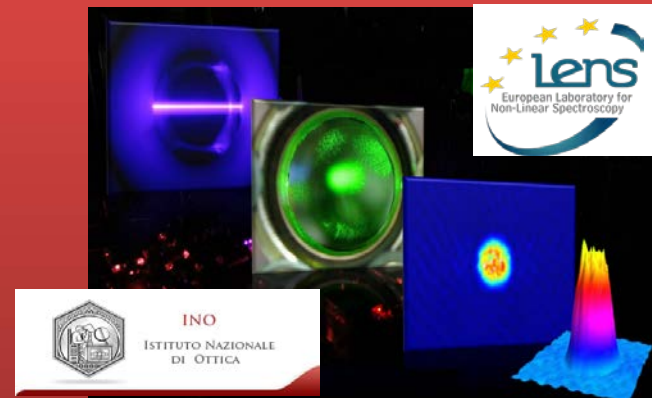
BEC with Yb atoms



Frejus: Relativistic Geodesy



Firenze: Atomic Physics



Bologna Radio-astronomy VLBI



Cagliari

INAF

ISTITUTO NAZIONALE
DI ASTRONOMIA
NATIONAL INSTITUTE
FOR ASTROPHYSICS

Noto

Matera

Space Geodesy



Development Of Atomic Clocks for Space



Milano



Roma



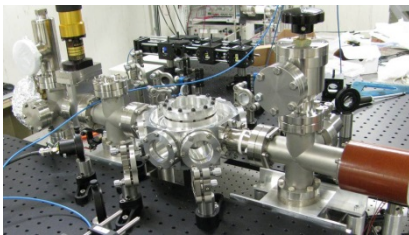
**Acrtivities based on
Galileo (Ground Segment)**



Testing Einsteins's geodetic motion INRIM-ASI-ISS triangle (July 2016- January 2018)



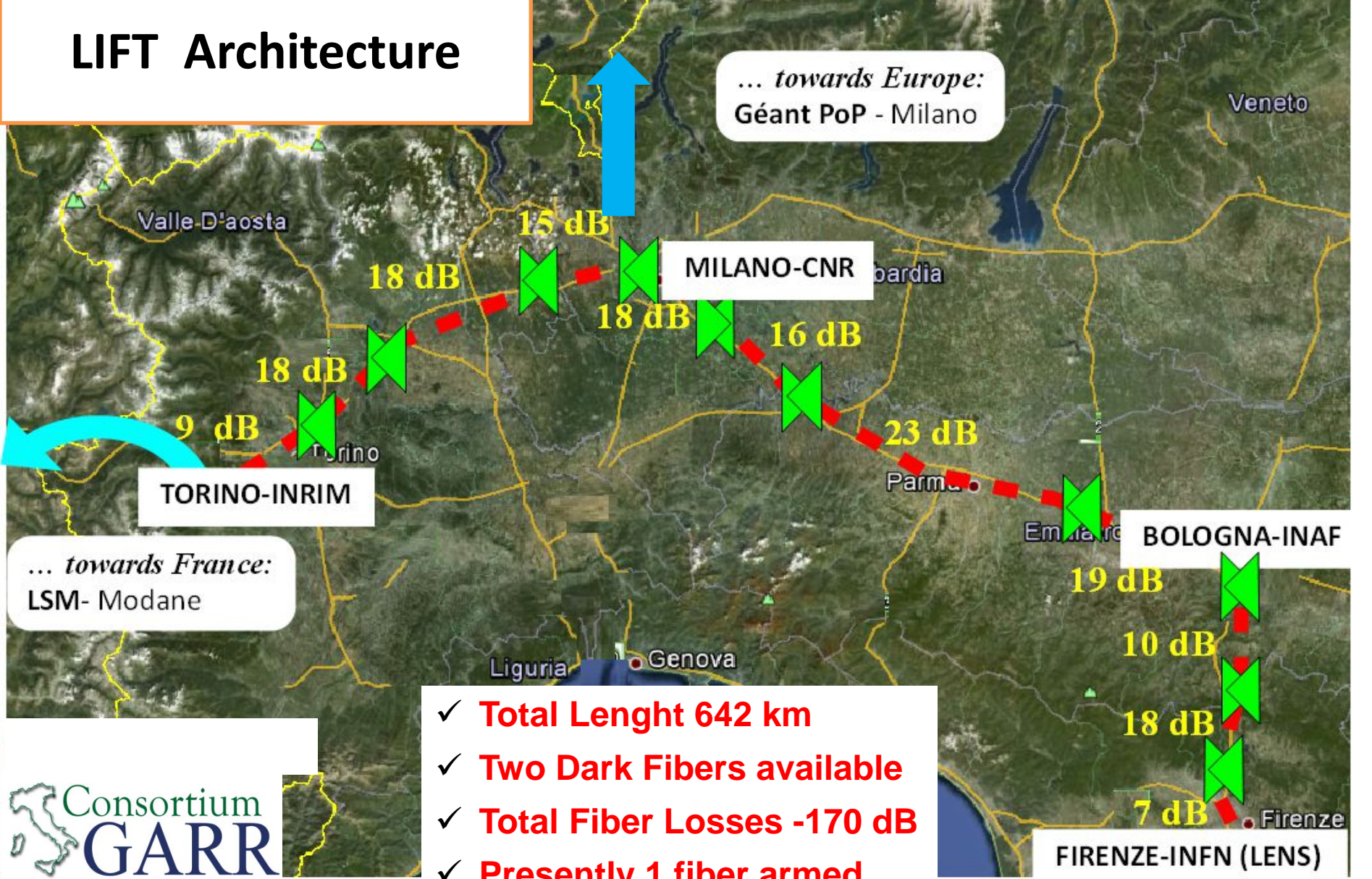
High accurate
Atomic clocks



Space Geodesy
Center Bepi Colombo



LIFT Architecture



- ✓ **Total Length 642 km**
- ✓ **Two Dark Fibers available**
- ✓ **Total Fiber Losses -170 dB**
- ✓ **Presently 1 fiber armed**
- ✓ **9 b-EDFA are used**



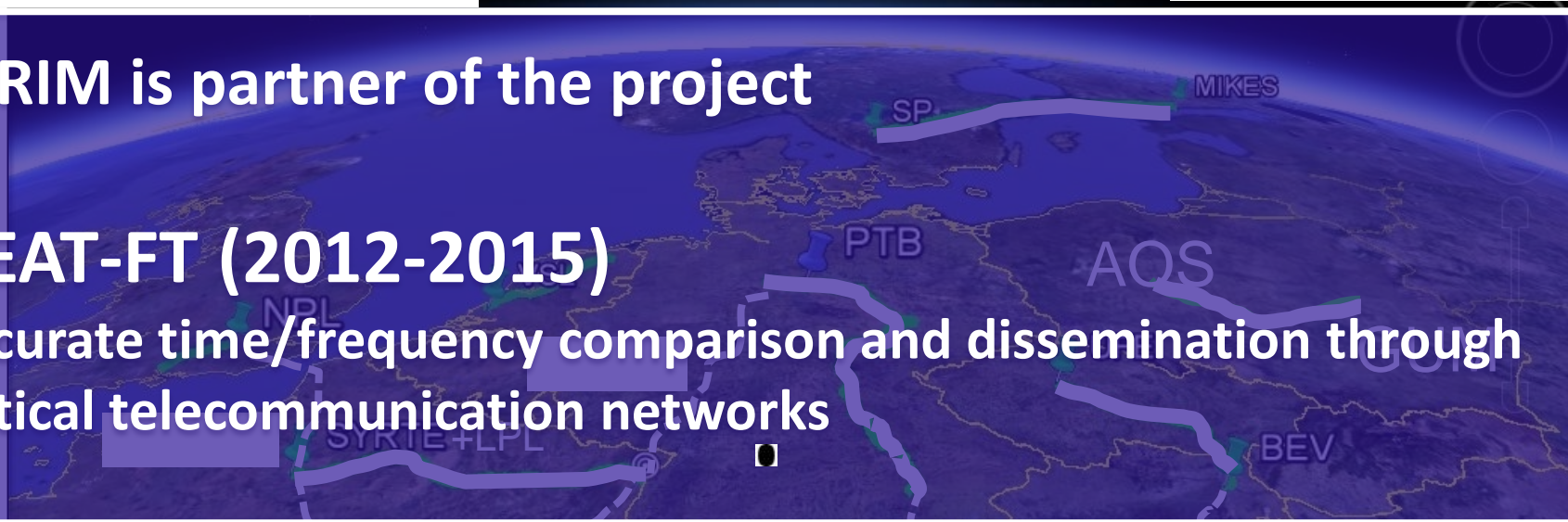


The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

INRIM is partner of the project

NEAT-FT (2012-2015)

Accurate time/frequency comparison and dissemination through optical telecommunication networks



Partners: PTB-Germany (Coordinator), BEV (Austria), INRIM (Italy), MIKES (Finland), NPL (United Kingdom), OBSPARIS (France), SP (Sweden), UFE (Czech Republic), VSL (The Netherlands), CESNET (Czech Republic), AGH (Poland)

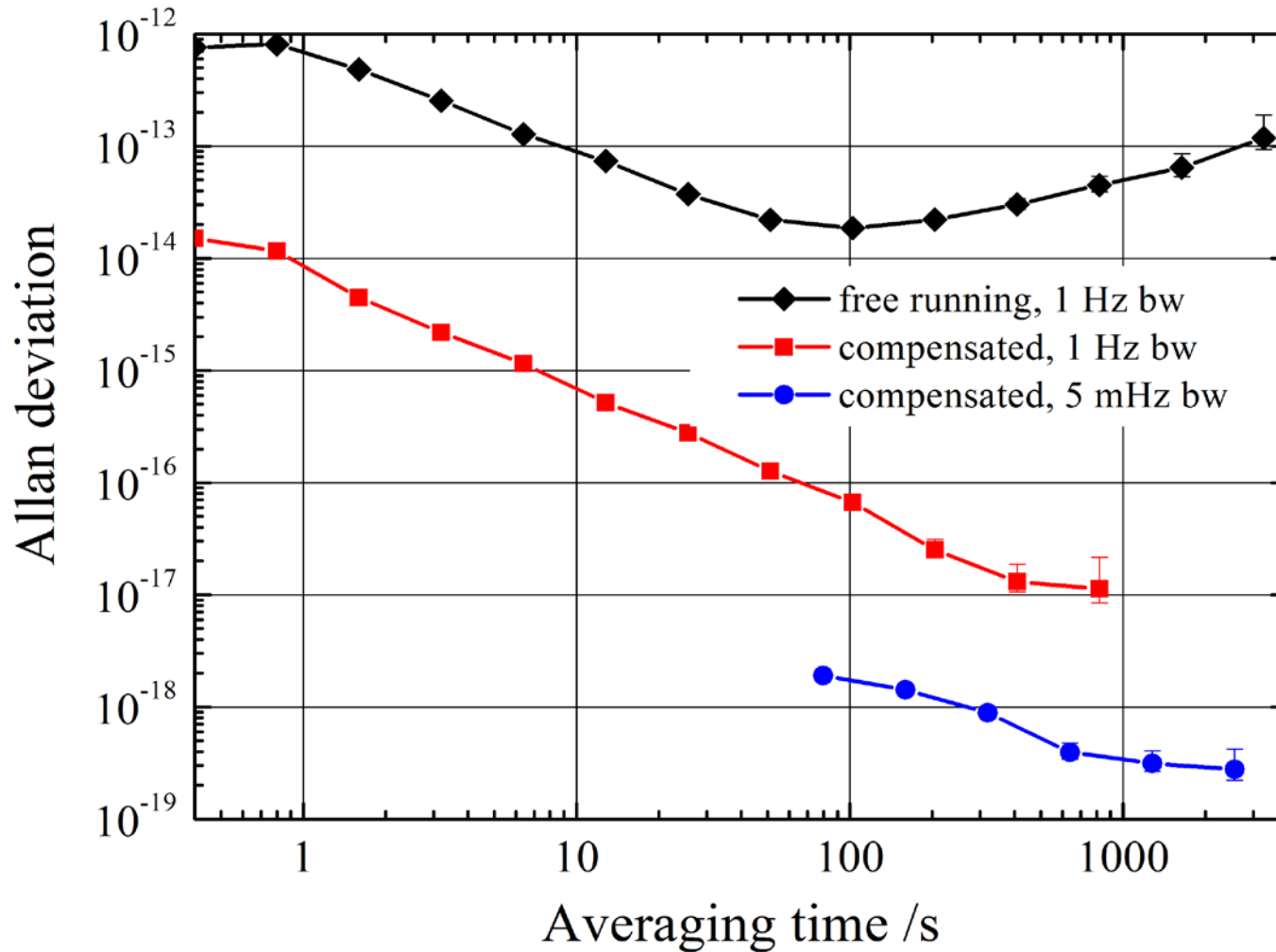


Link instability

$$\sigma_y^2(t_a) = \frac{3h_3 f_h^2}{8\pi^2} \frac{1}{t_a^2}$$



Link instability

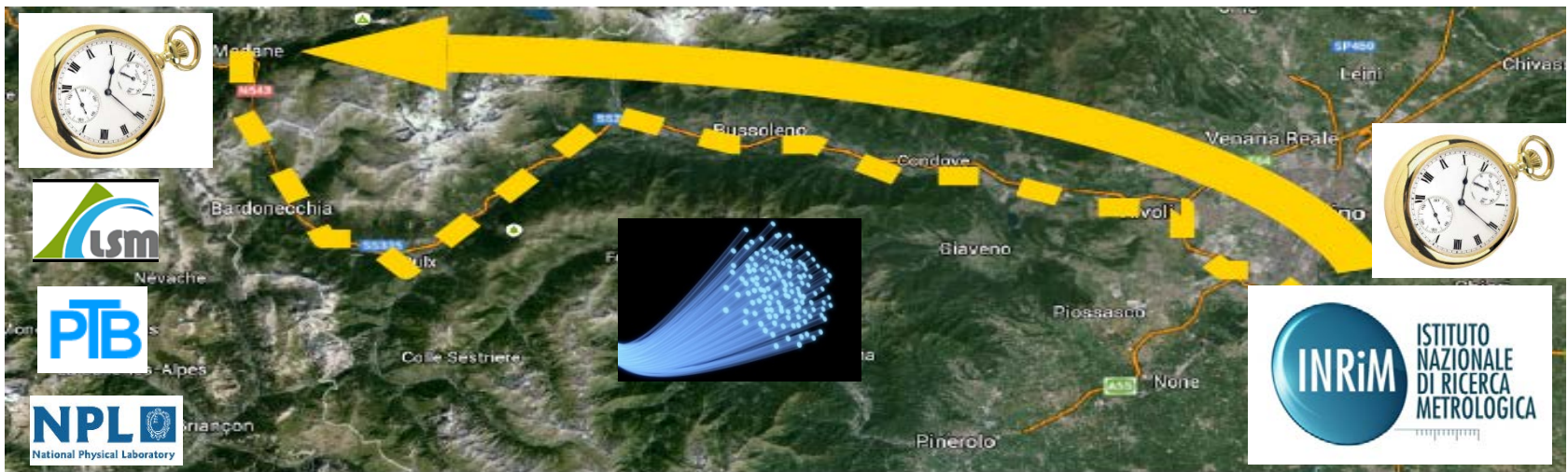
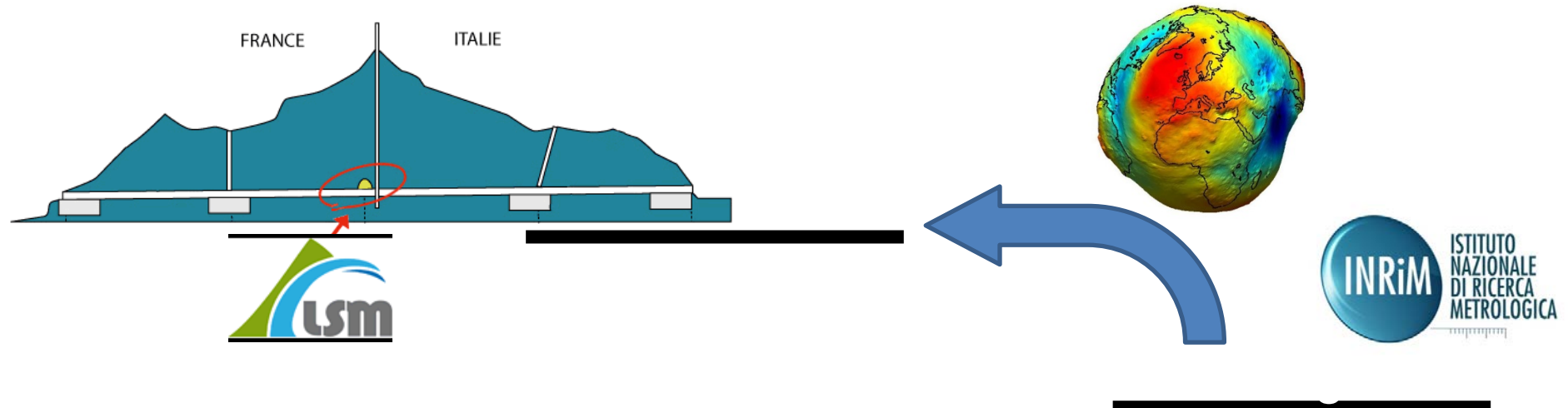


There is not an offset between delivered and original signal at the 5×10^{-19} level

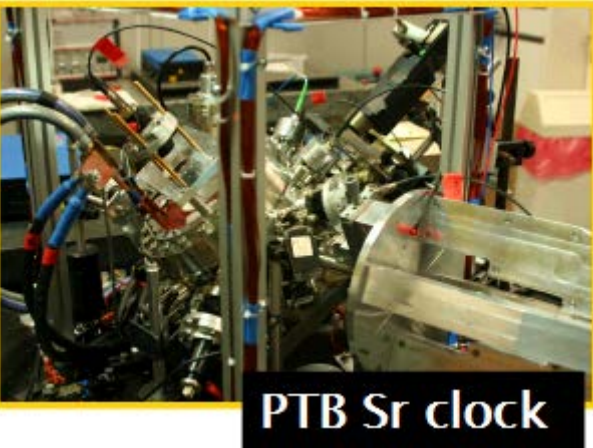
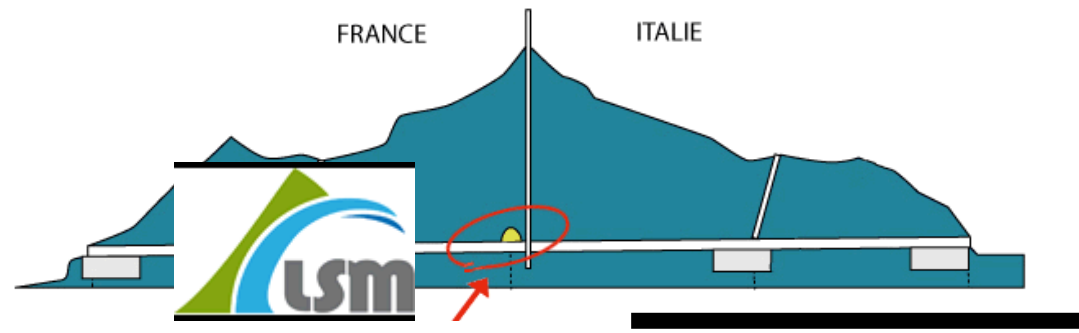


Relativistic Geodesy

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 Gravitazionale



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

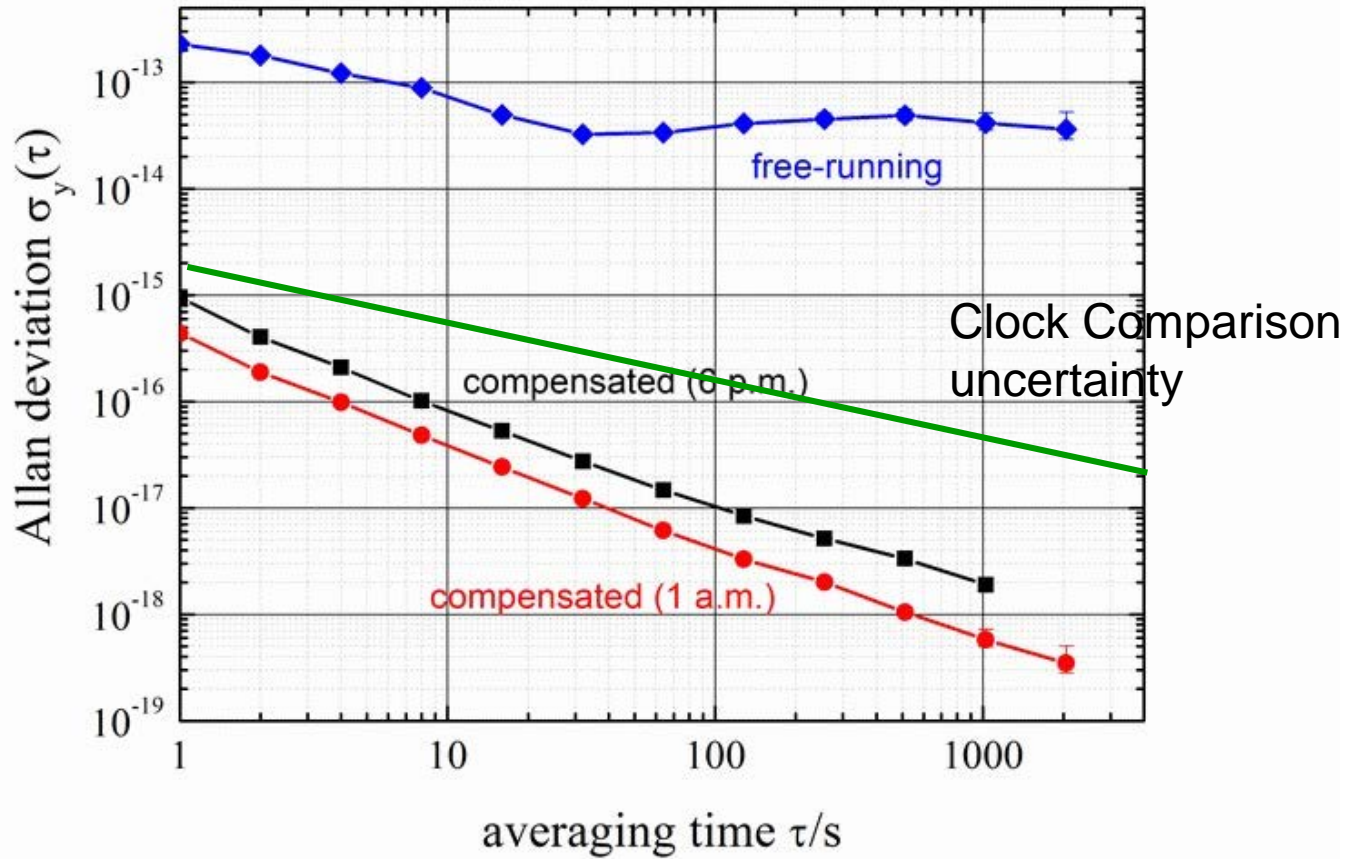
Nel limite di campo debole $W/c^2 \ll 1$, c velocità della luce, W_0 riferimento di potenziale):

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

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



Link Performances



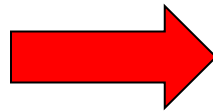
Local Position Invariance

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**

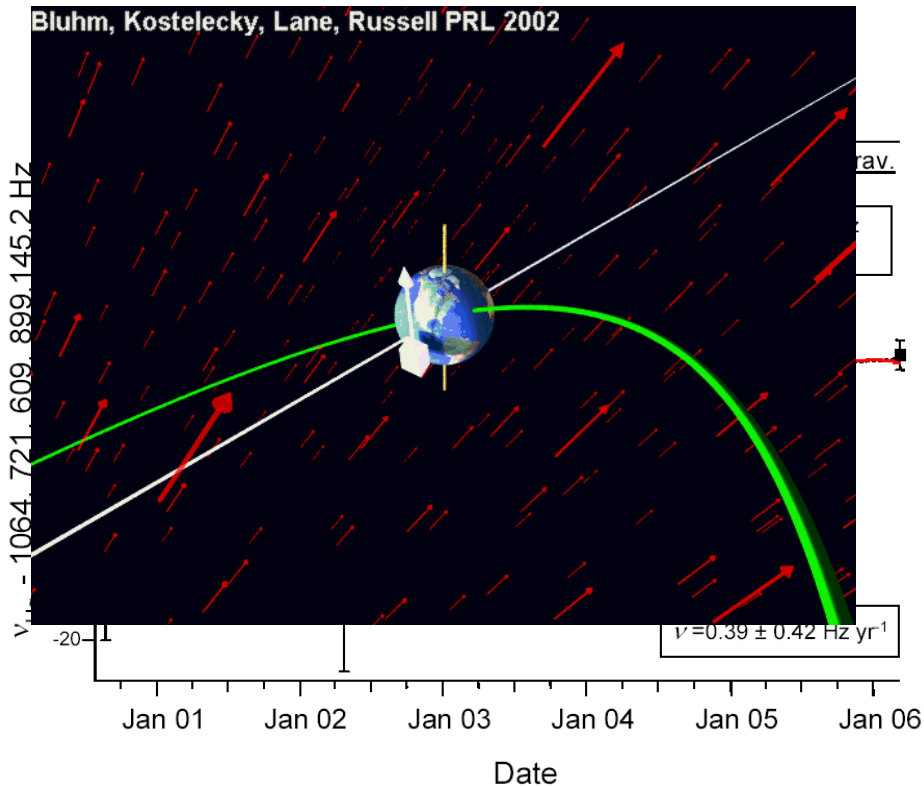


$$\beta_A = \beta_B$$

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

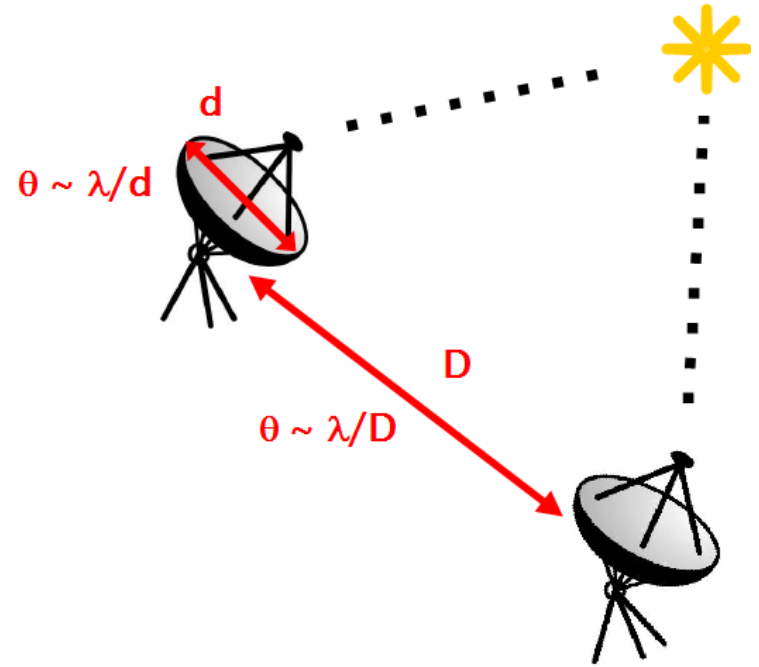


Radioastronomia e VLBI

(Very Large Baseline Interferometer)



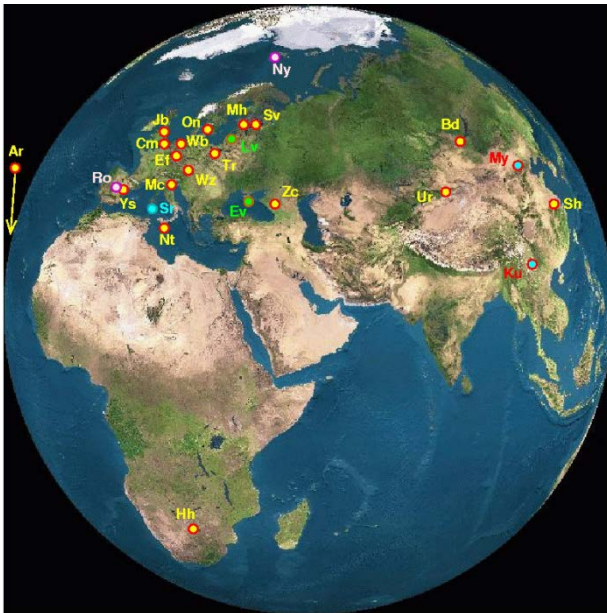
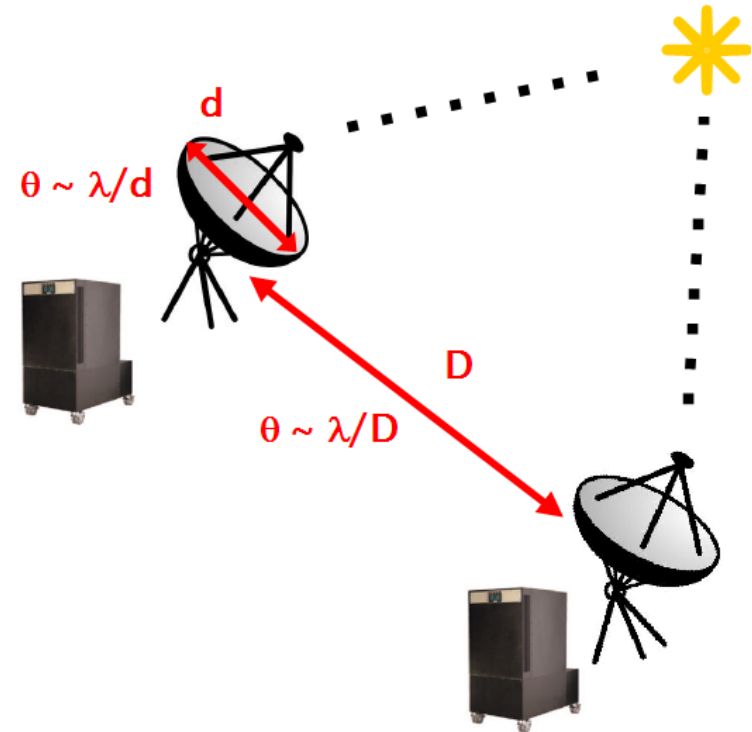
Radiotelescopi a IRA-INAf di Medicina



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



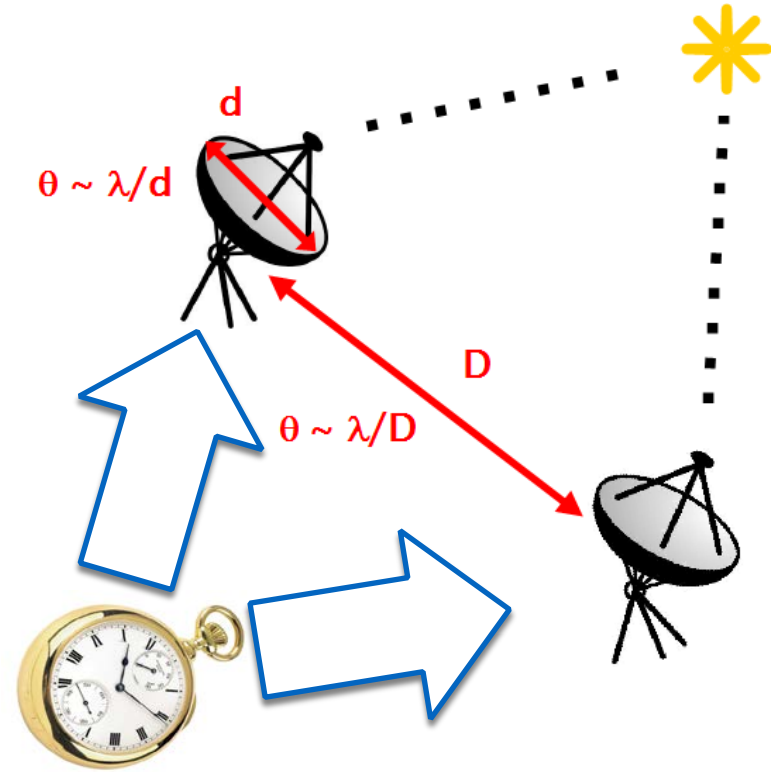
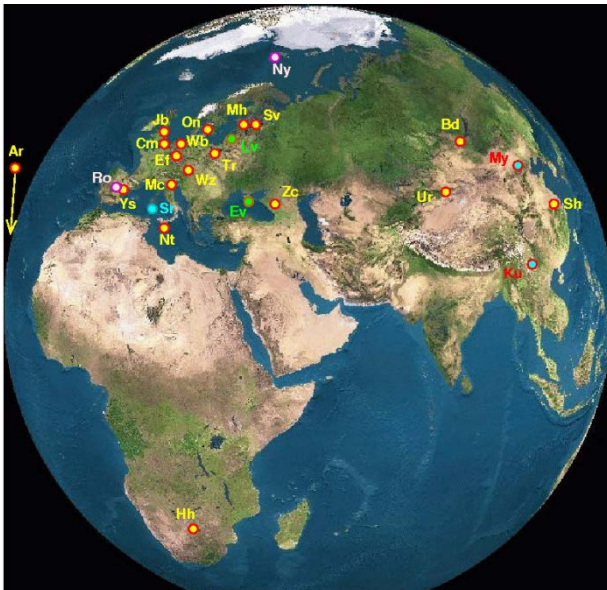
VLBI e orologi atomici



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

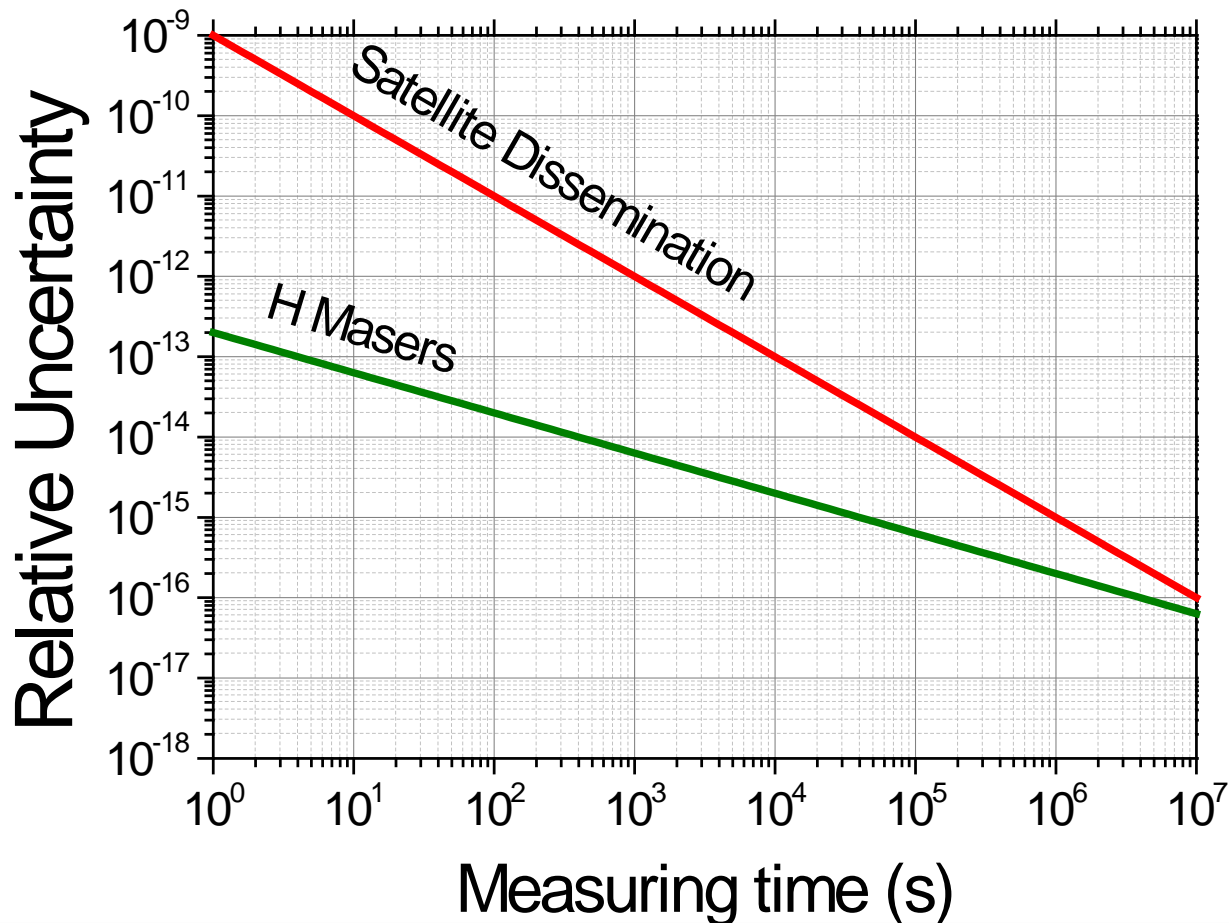


VLBI e orologi atomici



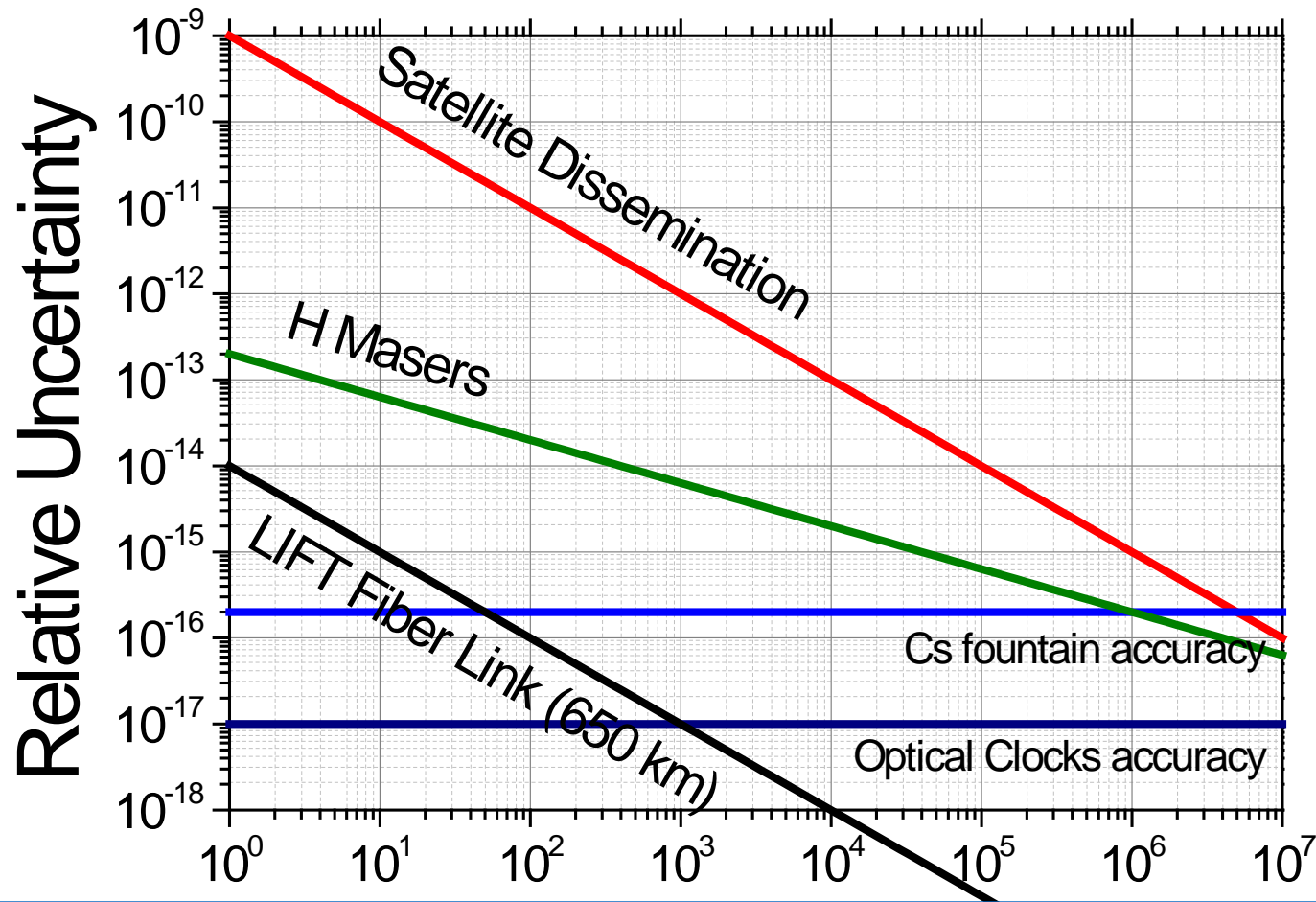
Perché non usare
un common clock?





La disseminazione del common clock via satellite per VLBI è sempre peggio di Maser separati





La nuova disseminazione del common clock con fibra ottica puo' funzionare!

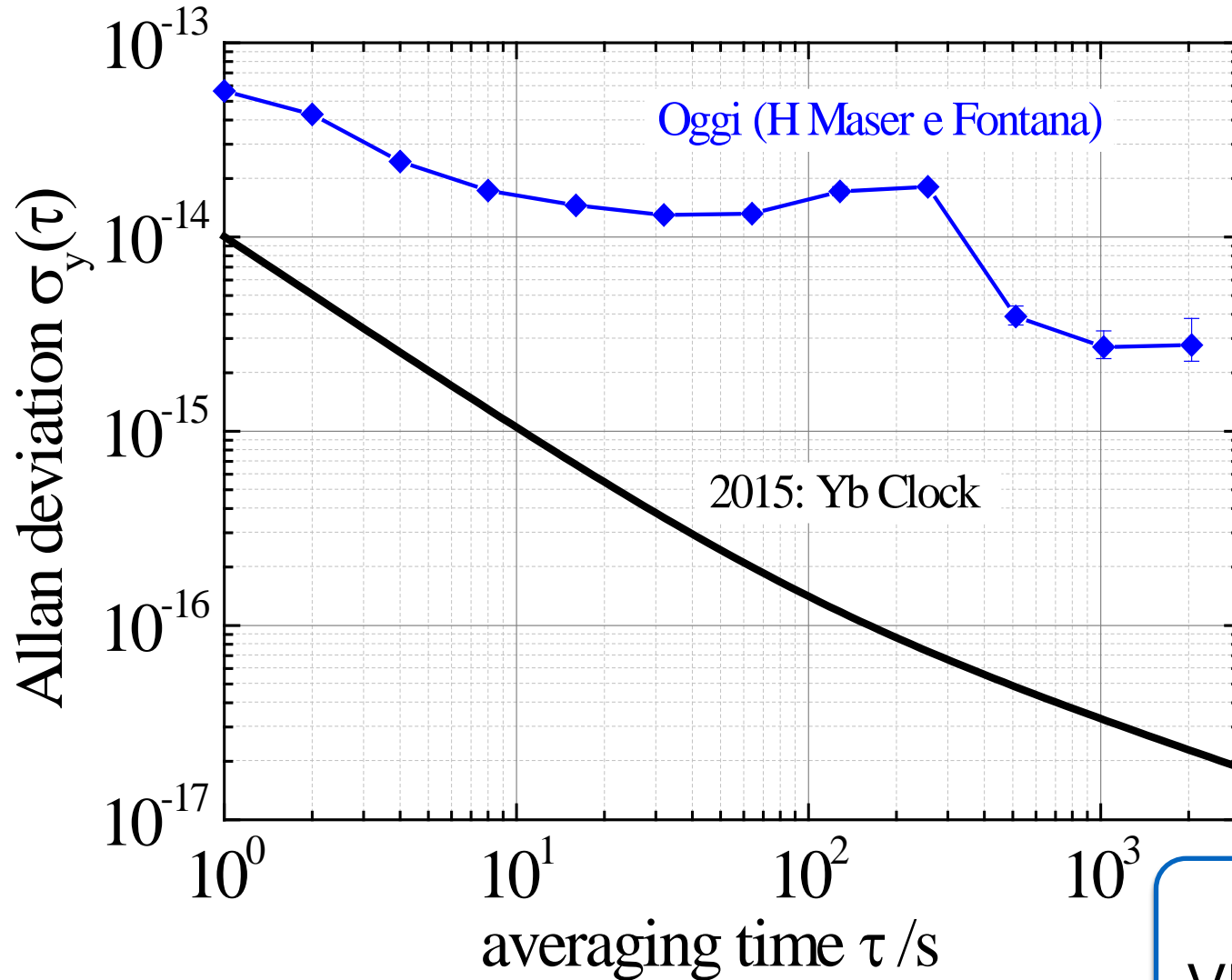


Remote calibration of H-Maser at Medicina-radiotelescopes

Introduction
642-link development
First results
Applications/VLBI



Maser INRIM trasferito in fibra a Medicina

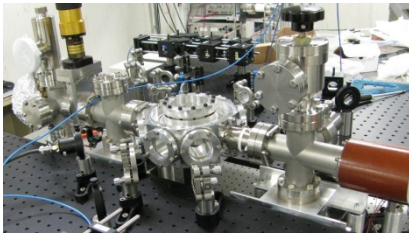


**IDONEO PER
VLBI AVANZATO!**

Testing Einsteins's geodetic motion INRIM-ASI-ISS triangle (July 2016- January 2018)



High accurate
Atomic clocks



Space Geodesy
Center Bepi Colombo





Pianeti Extrasolari e Metrologia di Frequenza

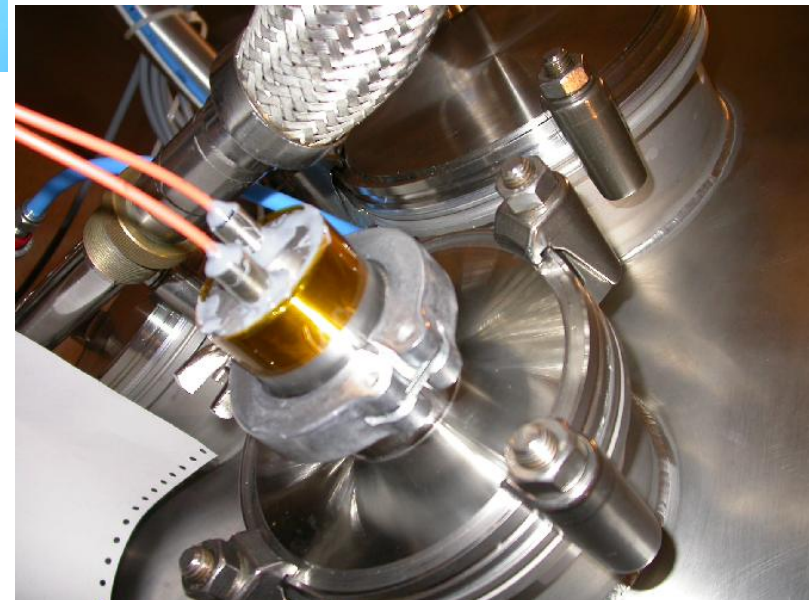


HARPS

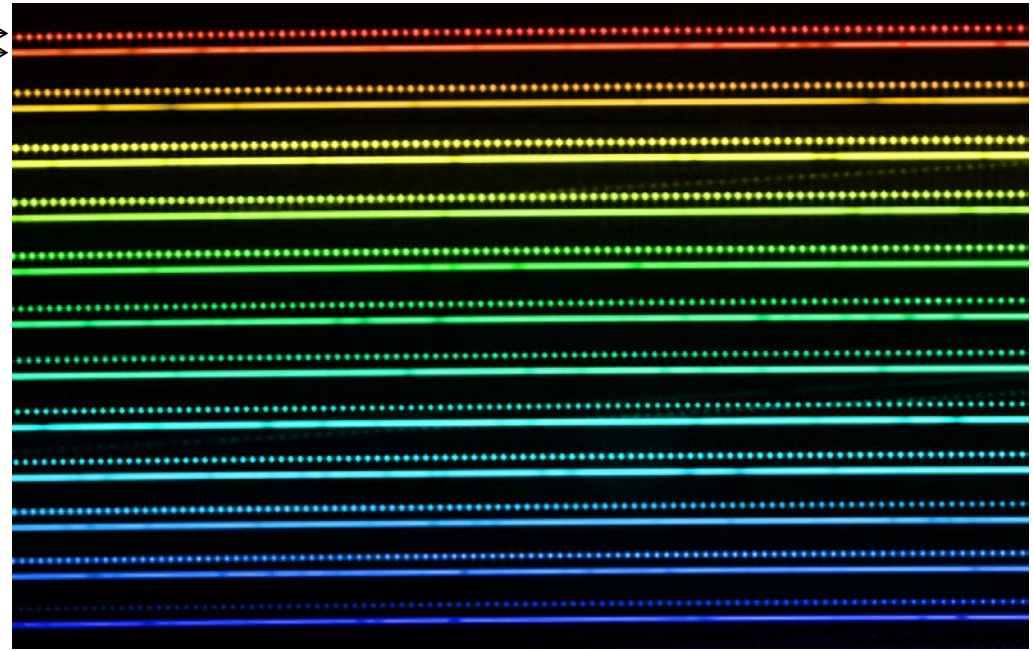
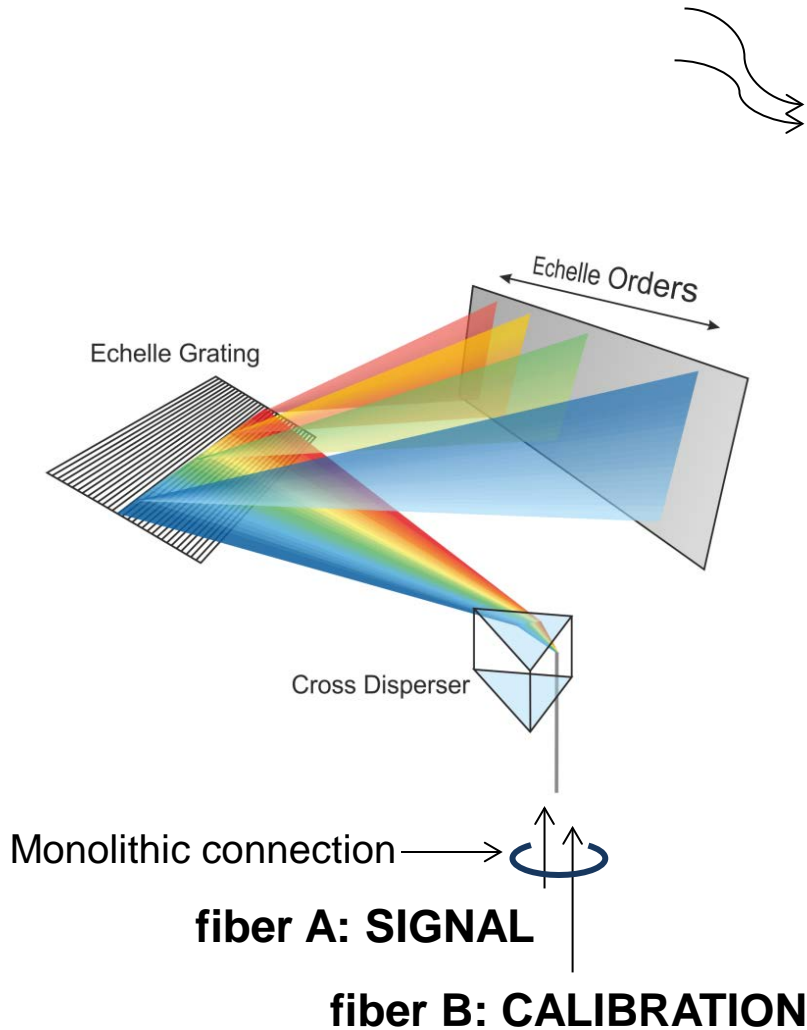
High Accuracy Radial velocity Planet Searcher

HARPS è un facility di ESO per misurare la velocità radiale con la migliore accuratezza possibile

Uno spettrometro raccoglie la luce delle stelle con una fibra ottica da un telescopio, mentre una seconda fibra porta un riferimento di frequenza nel visibile (lampada Th-Ar)



Echelle spectrograph calibration

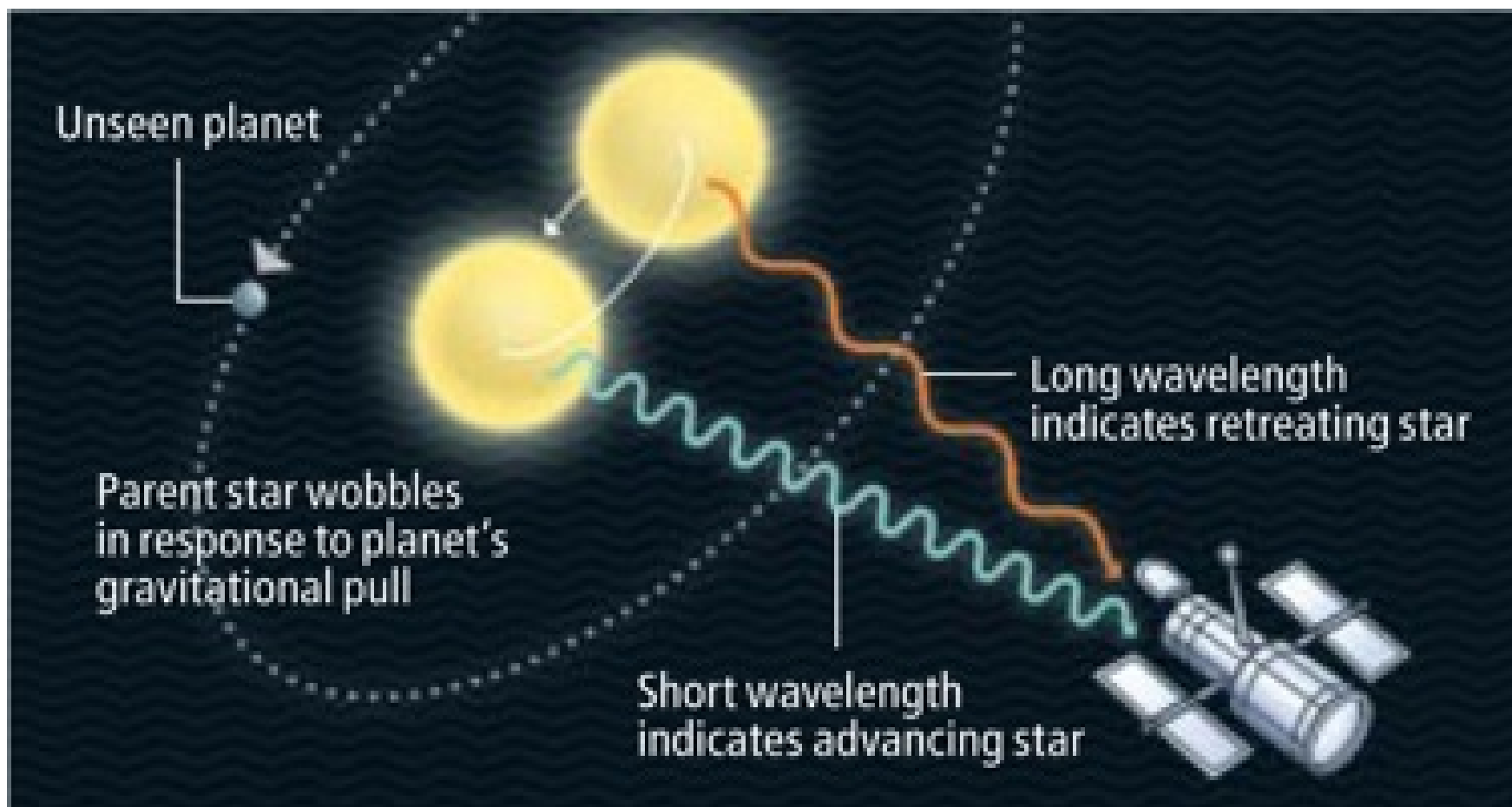


Source of image: ESO press release
The color range is for illustrative purposes only.

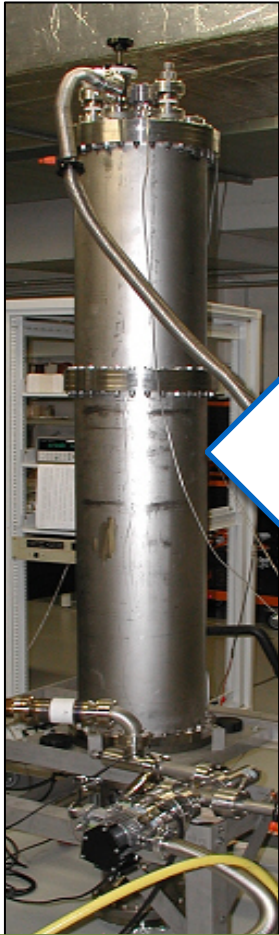




HARPS
PLANET HUNTER



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

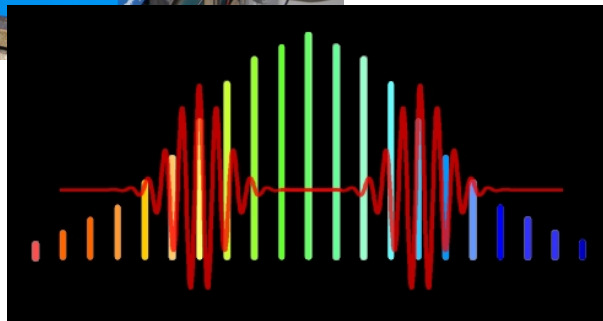


Orologi a Micronda

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



Comb vs. Thorium-Argon calibration



	Thorium-Argon	Frequency comb
LINE SPACING	Irregular	perfectly regular, adjustable
LINE INTENSITIES	Irregular	Low fluctuations line-to-line, Spectral envelope programmable
LINE POSITIONS	Fixed	Tunable
ABSOLUTE FREQUENCY	Known to ~ 10 m/s	Given by atomic clock
SHORT-TERM REPEATABILITY	Some 10 cm/s	2.5 cm/s demonstrated 1 cm/s appears feasible
LONG-TERM REPEATABILITY	Drifts through aging of lamp (\sim m/s)	No drift





The «Astrocomb»

Credits to:
Rafael Probst
Tilo Steinmetz
Ronald Holzwarth

MenloSystems



A spectrograph for exoplanet observations calibrated at the centimetre-per-second level

Tobias Wilken, Gaspare Lo Curto, Rafael A. Probst, Tilo Steinmetz, Antonio Manescau, Luca Pasquini, Jonay I. González Hernández, Rafael Rebolo, Theodor W. Hänsch, Thomas Udem & Ronald Holzwarth

Nature 485 (7400): 611--614 May 2012



Le Costanti Fondamentali sono costanti?

Molte teorie oltre il modello standard “vivono” in N dimensioni con $N > 4$
Esempio: Teorie di Kaluza-Klein (KK) e quindi teorie di corda; teorie di membrana

IN TUTTI I MODELLI OLTRE LO STANDARD, le costanti extra-dimensionali sono fissate, ma le costanti dell'universo 4-dimensionale variano nello spaziotempo.

La ricerca di una variazione delle costanti fondamentali è un test diretto per una teoria oltre il modello standard.

Anche molte teorie proposte per spiegare Dark Energy/ Dark Matter, presuppongono l'esistenza di campi scalari che causano variazioni delle costanti



$m_p, g_{(i)}$ non sono parametri fondamentali nel Modello Standard, ma si dimostra che sono legati al parametro fondamentale m_q/Λ_{QCD} , $m_q=(m_u+m_d)/2$ (m_u, m_d massa del quark up e down)

Si dimostra che qualsiasi transizione atomica di frequenza ν_{at} dipende da una combinazione di solo 3 costanti fondamentali $\alpha, m_q/\Lambda_{\text{QCD}}, m_e/\Lambda_{\text{QCD}}$, Λ_{QCD} costante di scala di QCD.

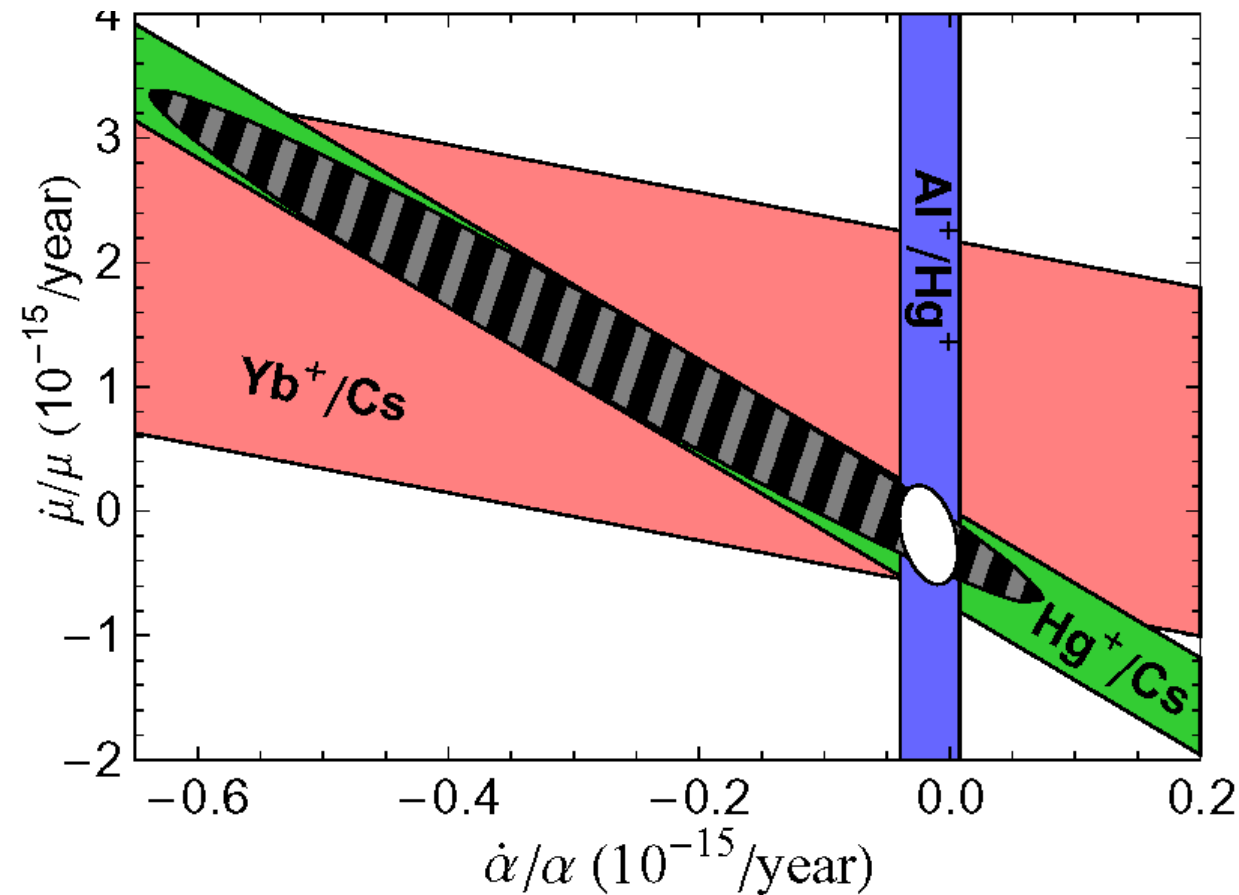
I coefficienti di sensibilità per varie transizioni atomiche sono stati calcolati

V. V. Flambaum et al., PR D69, 115006 (2004)

V. V. Flambaum and A. F. Tedesco, PR C73, 055501 (2006)

$$\delta \ln \left(\frac{\nu_{\text{at}}}{R_{\infty} c} \right) \cong K_{\alpha}^{\text{at}} \frac{\delta \alpha}{\alpha} + K_e^{\text{at}} \frac{\delta(m_e / \Lambda_{\text{QCD}})}{m_e / \Lambda_{\text{QCD}}} + K_q^{\text{at}} \frac{\delta(m_q / \Lambda_{\text{QCD}})}{m_q / \Lambda_{\text{QCD}}}$$

Confronto Hg^+/Cs & Yb^+/Cs & Hg^+/Al^+



$$\frac{\dot{\alpha}}{\alpha} = (2 \pm 2) \times 10^{-17} / \text{anno}$$

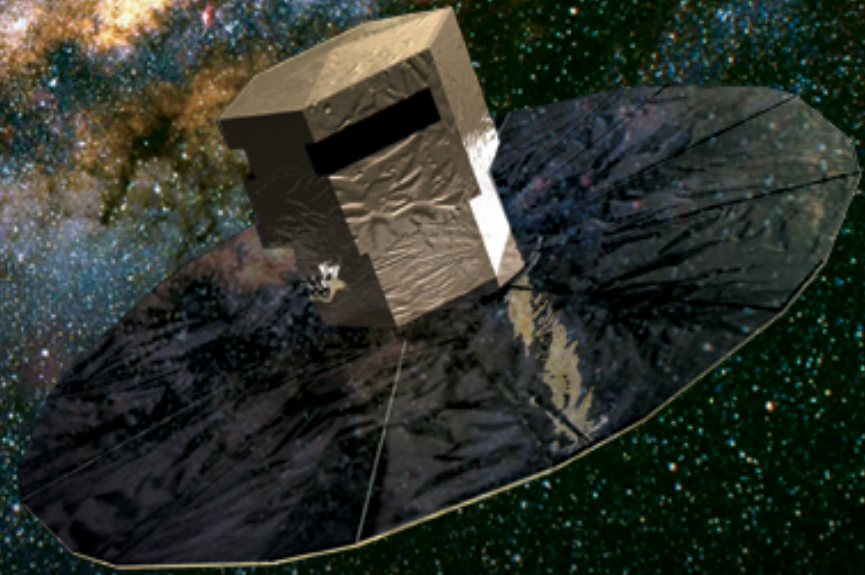
$$\frac{\dot{\mu}}{\mu} = (-2 \pm 4) \times 10^{-16} / \text{anno}$$

$$\mu = \mu_{\text{Cs}} / \mu_{\text{B}} = g_p m_e / m_p$$

Orologi Atomici vs Spettri Quasar?

Constant	Limit (yr ⁻¹)	Z	Method
α	$<0.4 \times 10^{-16}$	0	Clock comparisons
	$<0.5 \times 10^{-16}$	0.15	Oklo reactor
	$<3.4 \times 10^{-16}$	0.45	¹⁸⁷ Re decay
	$(6.4 \pm 1.4) \times 10^{-16}$	3.7	Quasar spectra
	$<1.2 \times 10^{-16}$	2.3	Quasar spectra
α_W	$<1 \times 10^{-11}$	0.15	Oklo reactor
m_e/m_p	$<3 \times 10^{-15}$	2-3	Quasar spectra

Timing per Gaia



GAIA: prestazioni astrometriche basate sulla datazione a bordo delle singole misure

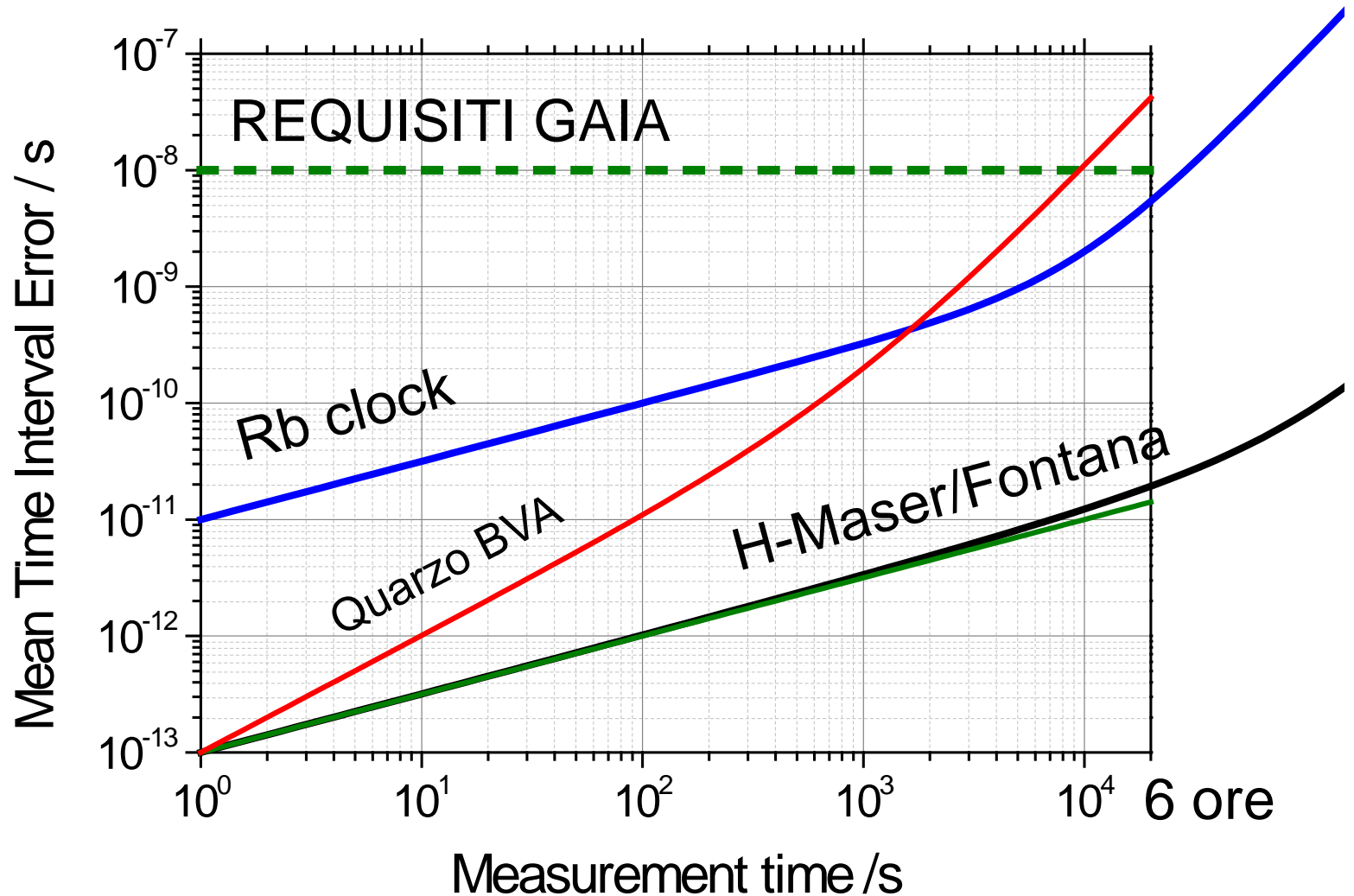
GAIA timing: per un'astrometria accurata, deve essere riferito alla scala di tempo internazionale, lo Universal Coordinate Time (UTC)

Misure sul GAIA payload :
Datazione con un orologio atomico al Rubidio a bordo

L'orologio Rb genera On Board Time,
Un modello relativistico trasforma OBT nel tempo terrestre

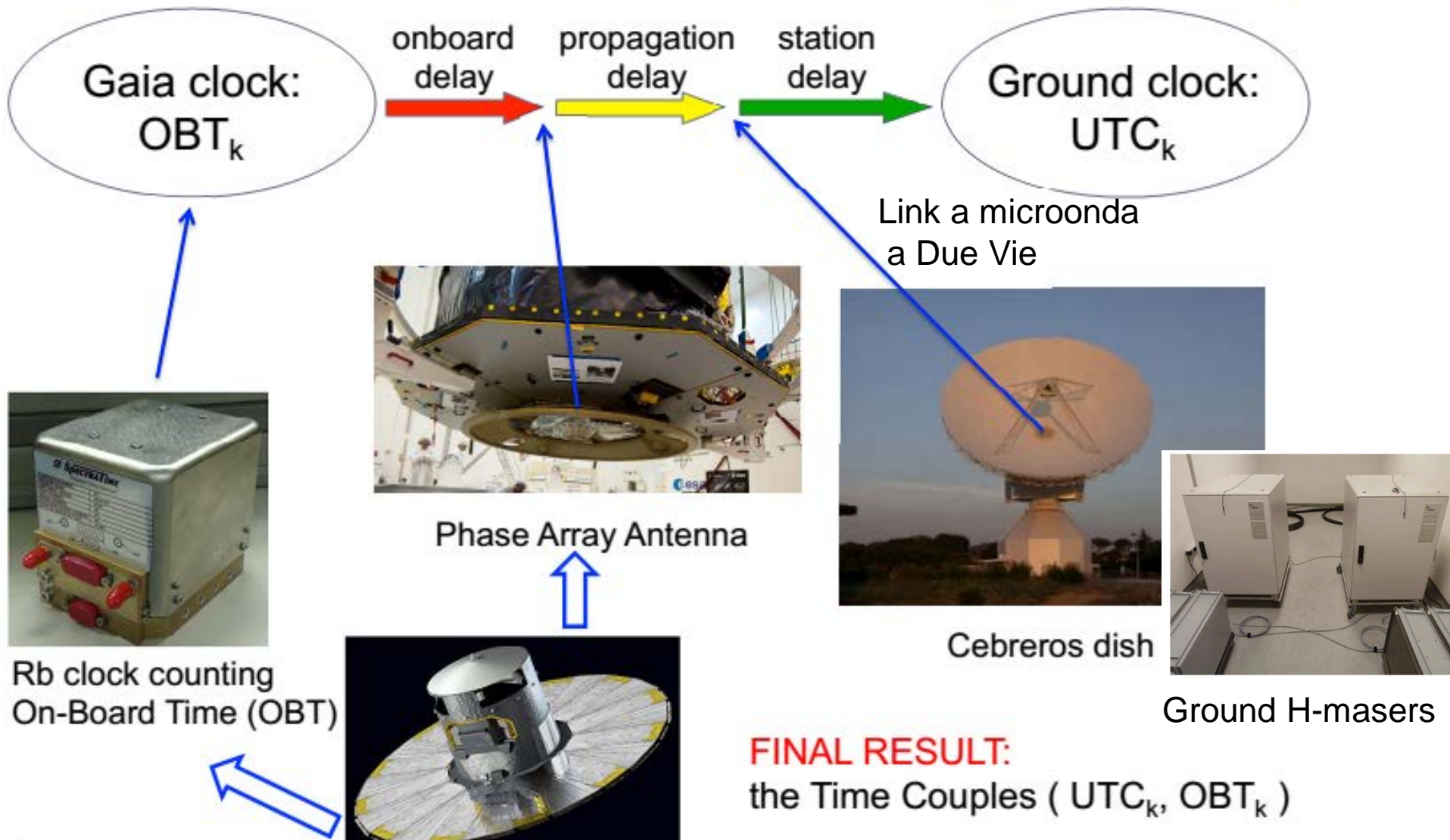
Requisiti dell'orologio:

- 1) Rotazione del Satellite: 360° in 6 ore (21'660 s)
- 2) Sensibilità alla posizione angolare: circa $1 \mu \text{ arcsec}$
- 3) 360° contiene $1.296 \times 10^{12} \mu \text{ arcsec}$
- 4) Time error: $21'660 \text{ s} / 1.296 \times 10^{12} = 16.7 \text{ ns}$
- 5) **Stabilità dell'Orologio: almeno 10 ns in 6 ore**
(MTIE, Maximum Time Interval Error)



Un orologio al quarzo non basta, ci va un orologio atomico.
 Il Rb basta, ed è anche il più compatto (3 kg) in assoluto
 (ottimo per lo spazio!)

Clock calibration: observational data (simplified)



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

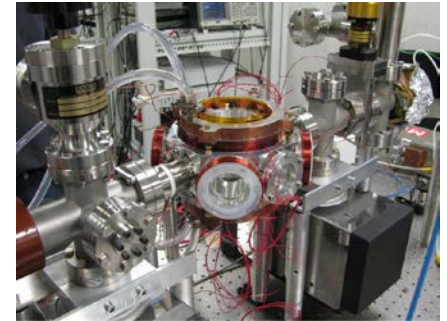
- All'INRIM sono state sviluppate tecniche di raffreddamento laser degli atomi per la spettroscopia ad alta risoluzione
- E' operativo un campione primario di frequenza a fontana con accuratezza relativa di 2×10^{-16} .
- Orologio ottico a Yb in sviluppo.
- Link ottici in Italia e in Europa
- Test accurati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

Sono disponibili Tesi di Laurea/Dottorato

TESI DISPONIBILI

Sperimentali;

Propedeutici: Meccanica Quantistica; Applicazioni di Elettromagnetismo



1) “Accuratezza di un orologio all’Ytterbio in reticolo ottico alla lunghezza d’onda magica”

L’orologio a Ytterbio va caratterizzato in accuratezza, ovvero occorre misurare gli effetti di interazione collisionale e quelli tra atomo e radiazioni elettromagnetiche. E’ previsto l’uso della fontana atomica con un optical comb per la misura assoluta di frequenza.

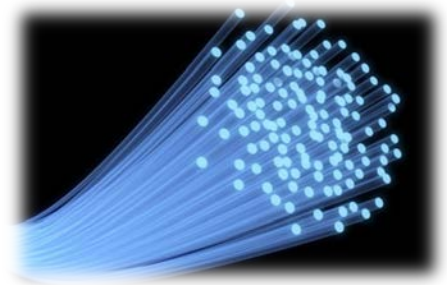
La tesi offre la possibilità di imparare una larga gamma di tecniche proprie della fisica atomica: generazione di radiazioni laser, ottica, raffreddamento atomico, spettroscopia ad alta risoluzione, fisica atomica di un atomo complesso.

Le tecniche laser in particolare sono di interesse sia accademico che applicativo in ambiti di ricerca fuori dal mondo della ricerca pubblica

In questa fase, si apprende anche in modo approfondito la fisica delle collisioni tra atomi freddi e dell’interazione laser-atomo.

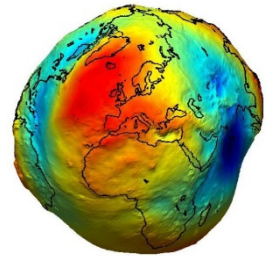


2) "Applicazioni di fisica fondamentale con link in fibra ottica"



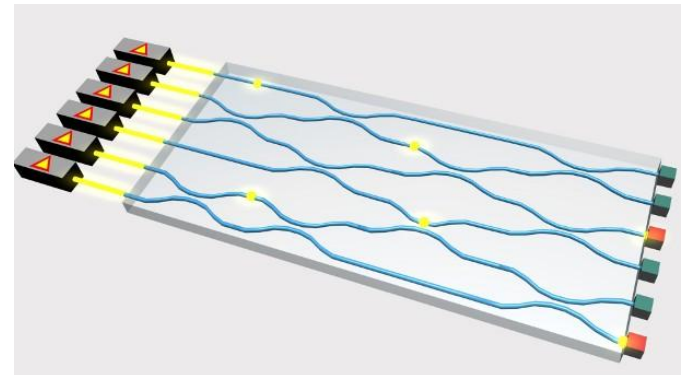
2a) Link ottici e radioastronomia: caratterizzazione e utilizzo del Link Torino-Medicina per l'utilizzo in ambito radioastronomico

2b) Tecniche innovative per trasferimento RF su fibra ottica (interferometri in fibra ottica e optoelettronica per generazione E rivelazione di segnali e compensazione del rumore di fase)



2c) Analisi e modellizzazione di effetti relativistici nei link ottici di frequenza (Geodesia Relativistica)

2d) Sviluppo di un amplificatore ottico basato su scattering Brillouin per disseminazione coerente di frequenza



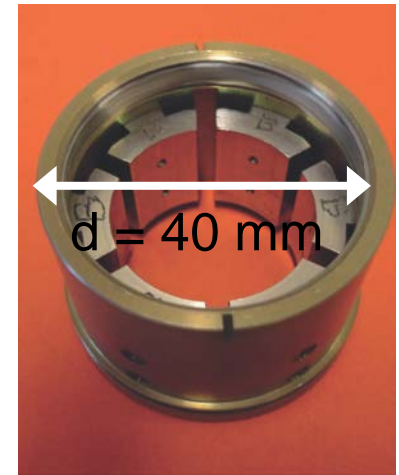
2e) Ottica integrata e Link Ottici



3) POP clock: Sviluppo e caratterizzazione di un campione atomico di frequenza al Rb a pompaggio ottico impulsato.

Argomenti di studio:

- nuovi set up sperimentali
- fenomeni di rallentamento della luce (CPT, $c/20$)
- trasferimento del rumore del laser al segnale di orologio (limite shot noise)
- studio della rotazione magneto-ottica e proprietà fisiche del mezzo



Magnetron
microwave
cavity



INRIM Atomic Frequency Standards Group



Grazie per l'attenzione!

