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## Horloges atomiques et applications

Sebastien Bize

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Systèmes de Référence Temps-Espace

# Horloges Atomiques et Applications



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*L'optique à Paris  
17 novembre 2011  
Ecole Normale Supérieure, Paris*



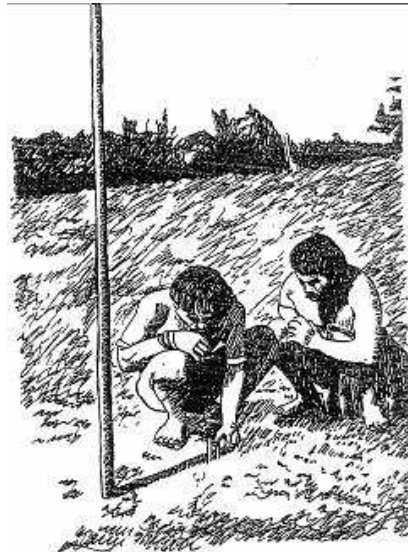
## Plan de l'exposé

- Généralités sur la mesure du temps
- Généralités sur les horloges atomiques
- Horloges de grande exactitude
  - Fontaines atomiques
  - Horloges optiques
  - Laser ultra stables
  - Méthodes de comparaison
- Tests fondamentaux à l'aide d'horloges

# Une manière universelle de percevoir le temps

- En observant la périodicité d'un phénomène naturel: la rotation de la Terre
  - La succession jour/nuit permet de compter les jours qui passent

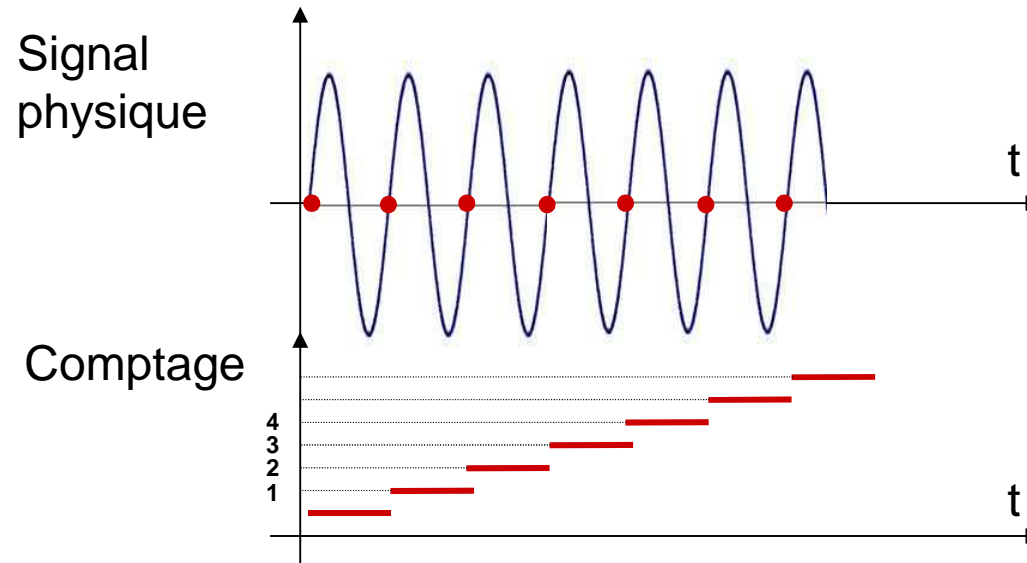
- De manière plus fine
  - Gnomon, cadran solaire



- Beaucoup plus fine
  - Jusqu'en 1967, la seconde du Système Internationale (SI) est basée sur le mouvement de la Terre
- Le principe de l'observation d'un phénomène périodique reste valable pour les horloges les plus modernes

# Principe de mesure d'une durée ou intervalle de temps

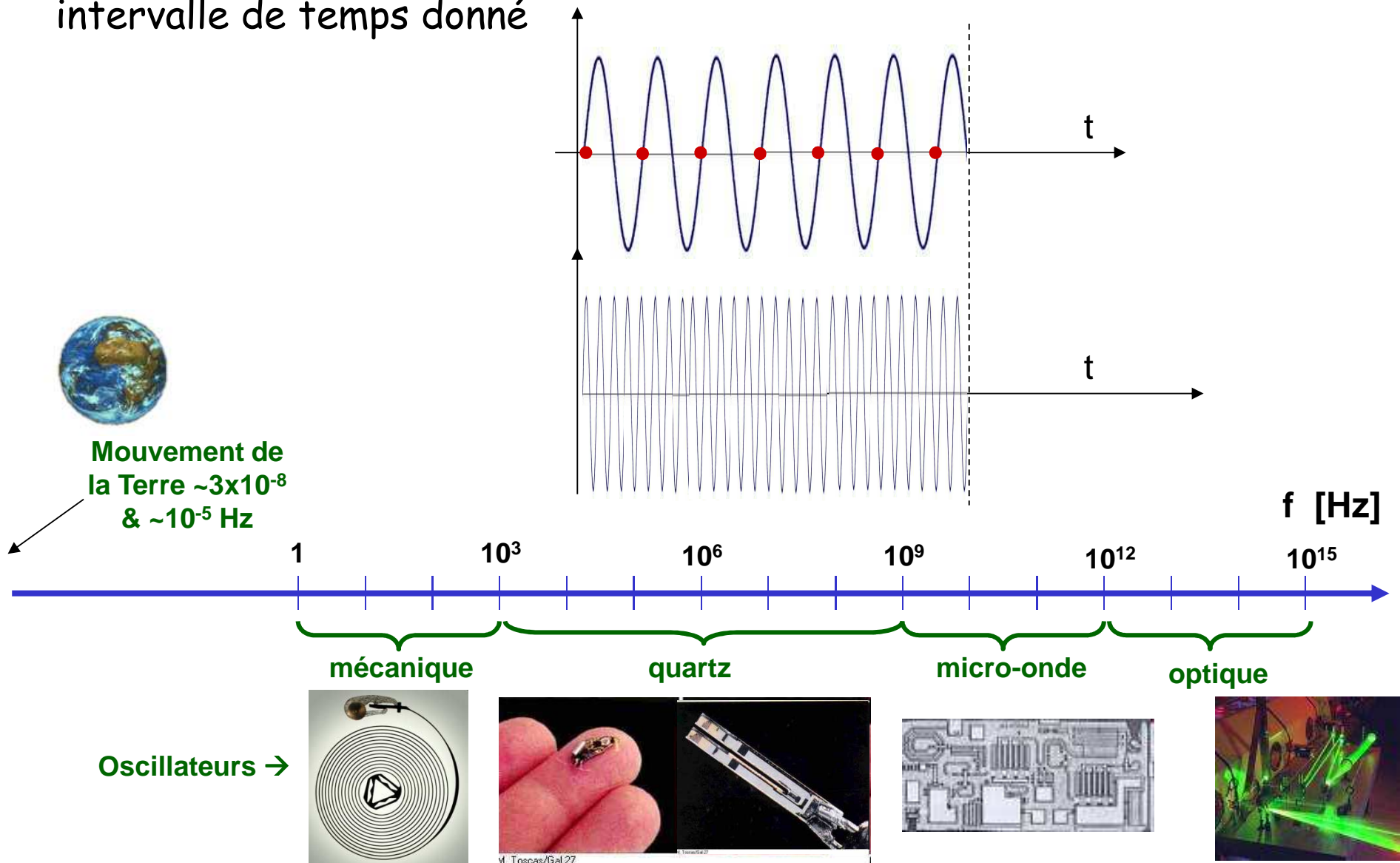
- Observation et comptage d'un phénomène périodique



- Qualité de mesure d'un intervalle de temps
  - → stabilité du phénomène périodique
  - → nombre de périodes mesurées

# Influence de la fréquence d'oscillation

- Une fréquence plus élevée permet une subdivision plus fine d'un intervalle de temps donné



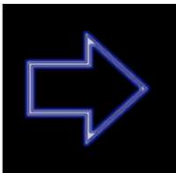
# Imperfection des oscillateurs

## ■ Problème



- La fréquence dépend de la géométrie, des dimensions et de beaucoup d'autres caractéristiques physiques
- Sujet au vieillissement, à l'usure, à l'influence de paramètres extérieurs
- → Pas de caractère universel

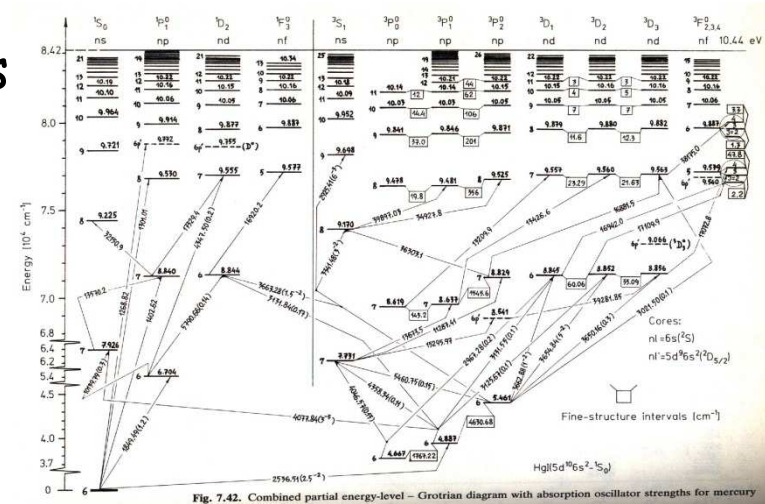
## ■ Solution



- Stabiliser la fréquence de l'oscillateur sur une référence « absolue » : une transition atomique

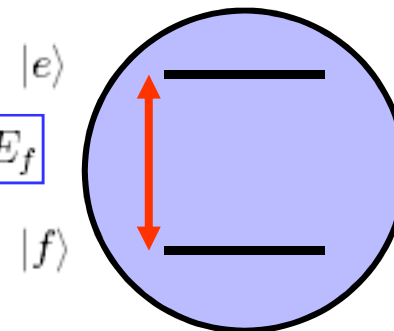
# L'atome : une référence universelle et (quasi) parfaite

- L'atome a des niveaux d'énergie quantifiés



- A la différence d'énergie entre deux niveaux correspond une fréquence via la relation de Planck

$$\hbar\omega_{ef} = h\nu_{ef} = E_e - E_f$$

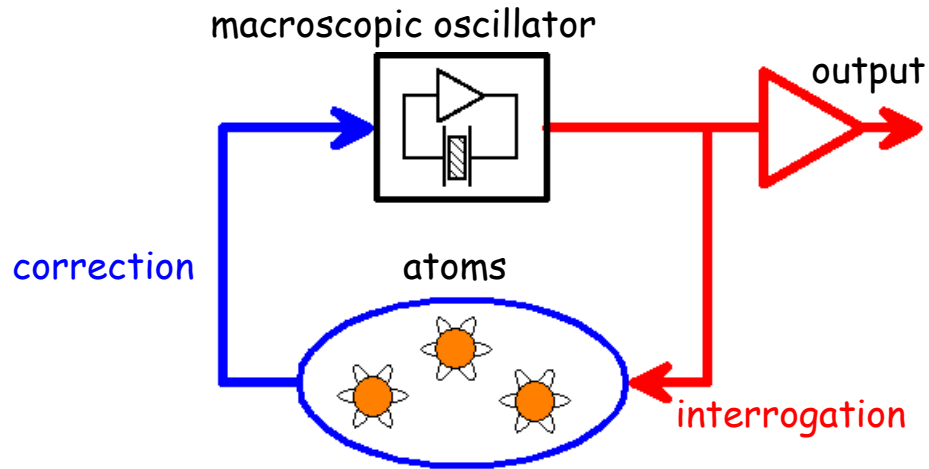


- Les fréquences de Bohr d'un atome non perturbé sont parfaitement stables et universelles. Elles ne dépendent *a priori* que des constantes fondamentales.
- Deux atomes de la même espèce sont « identiques »
- « Ils ne s'usent pas »



# Principle of atomic clocks

## Building blocks of an atomic clock



$$\omega(t) = \omega_{ef} \times (1 + \varepsilon + y(t))$$

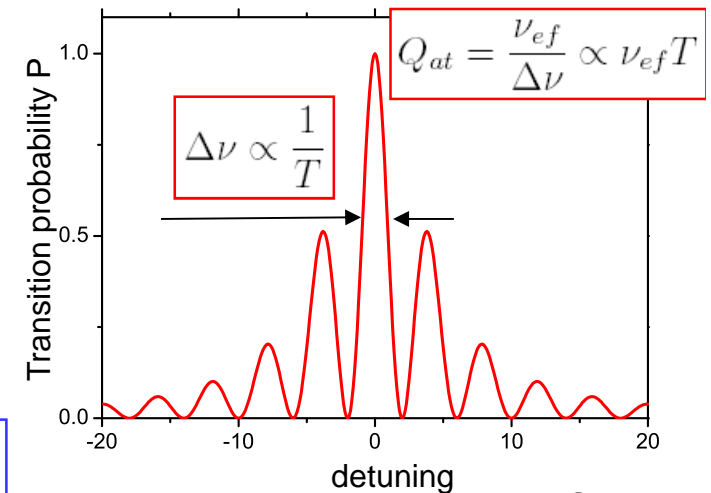
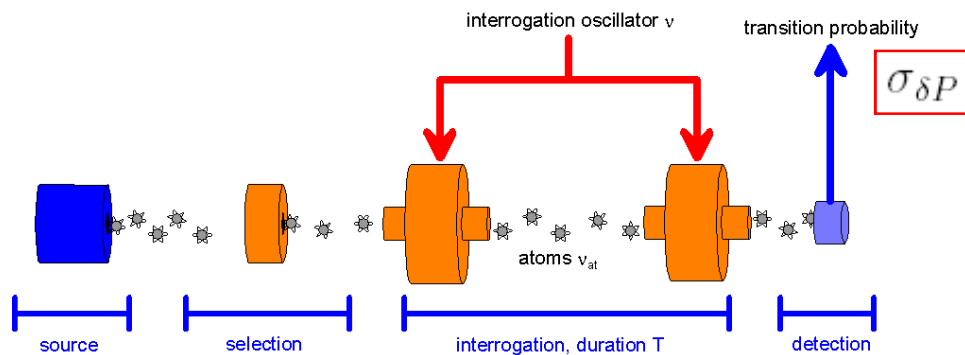
$\varepsilon$ : fractional frequency offset

Accuracy: overall uncertainty on  $\varepsilon$

$y(t)$ : fractional frequency fluctuations

Stability: statistical properties of  $y(t)$ , characterized by the Allan variance  $\sigma_y^2(\tau)$

Can be done with microwave or optical frequencies, with neutral atoms, ions or molecules



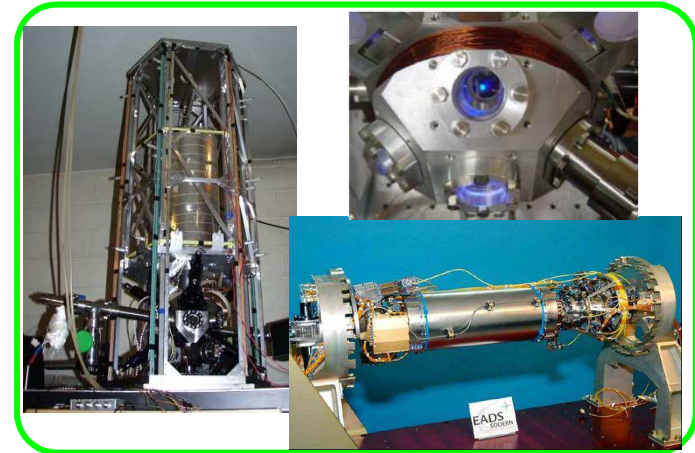
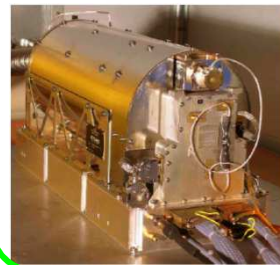
Fractional frequency instability:

$$\sigma_y(\tau) \propto \frac{\sigma_{\delta P}}{Q_{at}} \sqrt{\frac{T_c}{\tau}}$$

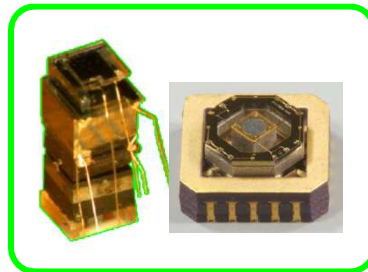
# Une grande variété d'horloges atomiques...

Performances

*Horloges commerciales :  
industrie, laboratoires, GNSS, ...*



*Horloges de laboratoire :  
Métrologie et physique  
fondamentales*



*Horloges miniatures :  
Industrie, récepteurs GPS/GALILEO*

Volume

1 cm<sup>3</sup>

1 dm<sup>3</sup>

1 m<sup>3</sup>

## ...pour de nombreuses applications

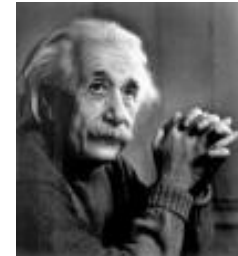
### Métrologie fondamentale

- Échelles de temps atomique, temps légal (horloge parlante 36 99, réseau hertzien, NTP, ...)
- Redéfinition des unités



### Tests de physique fondamentale

- Relativité Générale : décalage gravitationnel vers le rouge
- Invariance locale de Lorentz et de position
- Variation des constantes fondamentales



### Navigation et Positionnement

- 1ns  $\Leftrightarrow$  30 cm
- Global Navigation Satellite Systems (GNSS): GPS (USA), GLONASS (Russie), GALILEO (Europe), BEIDOU/COMPASS (Chine), GINSS (Inde)



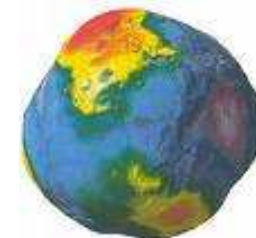
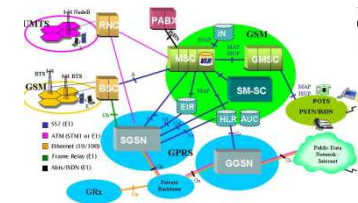
### Synchronisation des réseaux de télécommunication

### Astronomie

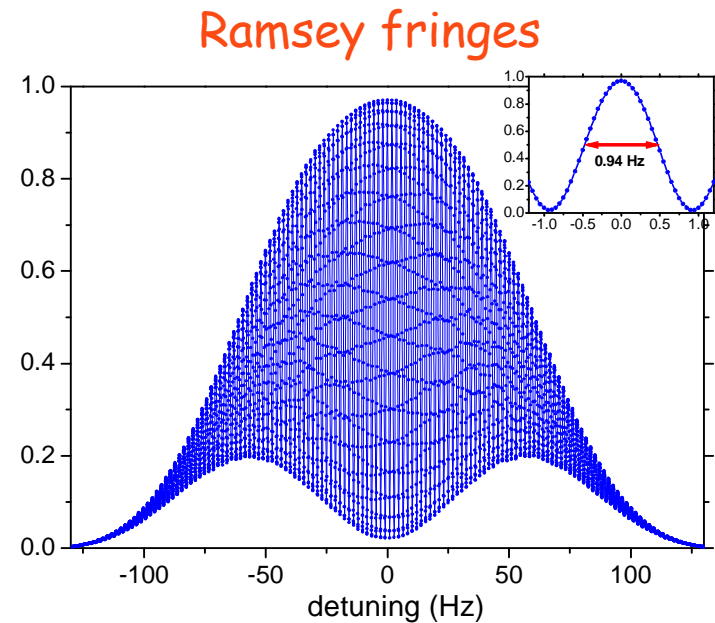
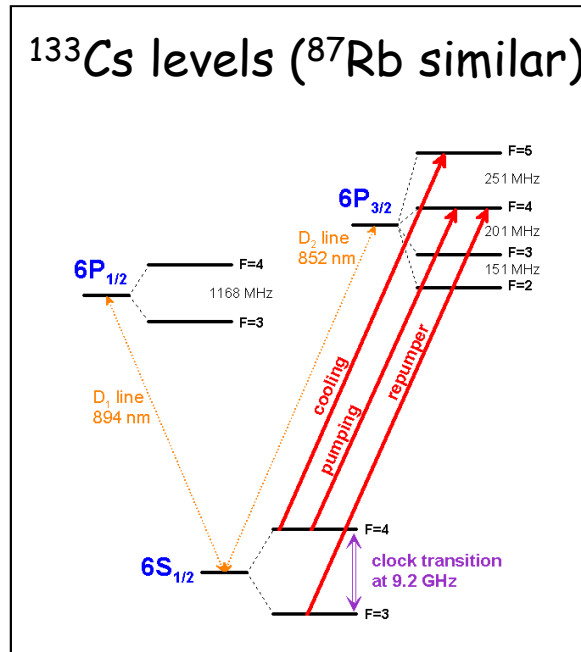
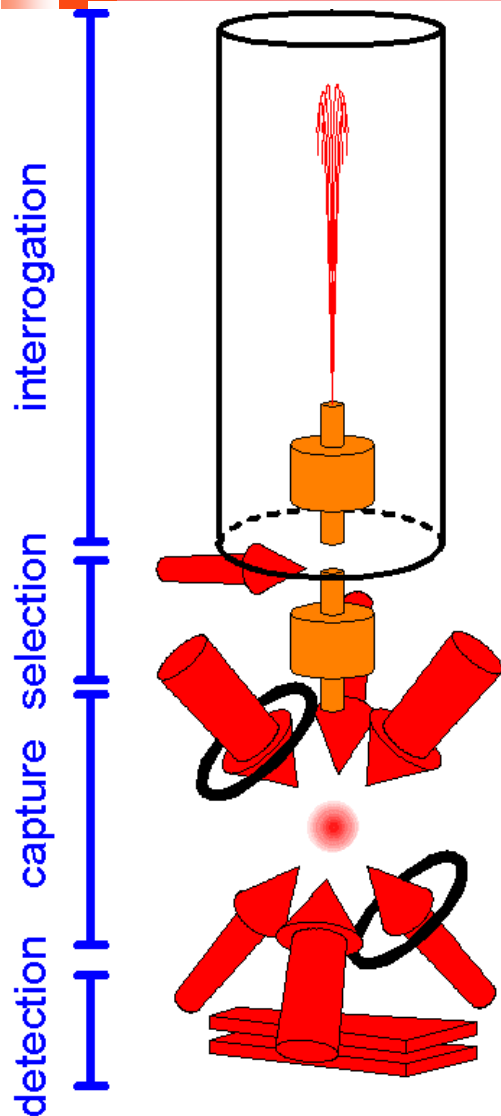
- Very Long Baseline Interferometry (VLBI), Astrocomb

### Géophysique

- Rotation de la Terre
- Cartographie de potentiel de gravitation



# Atomic fountain clocks



Atomic quality factor:

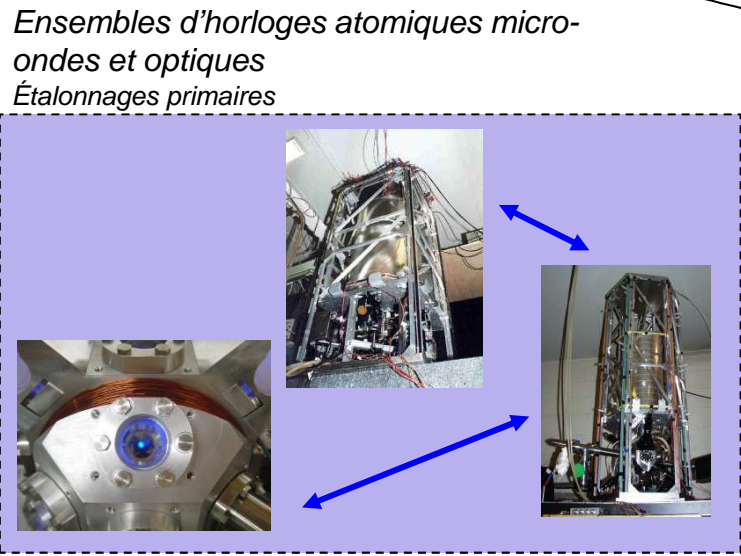
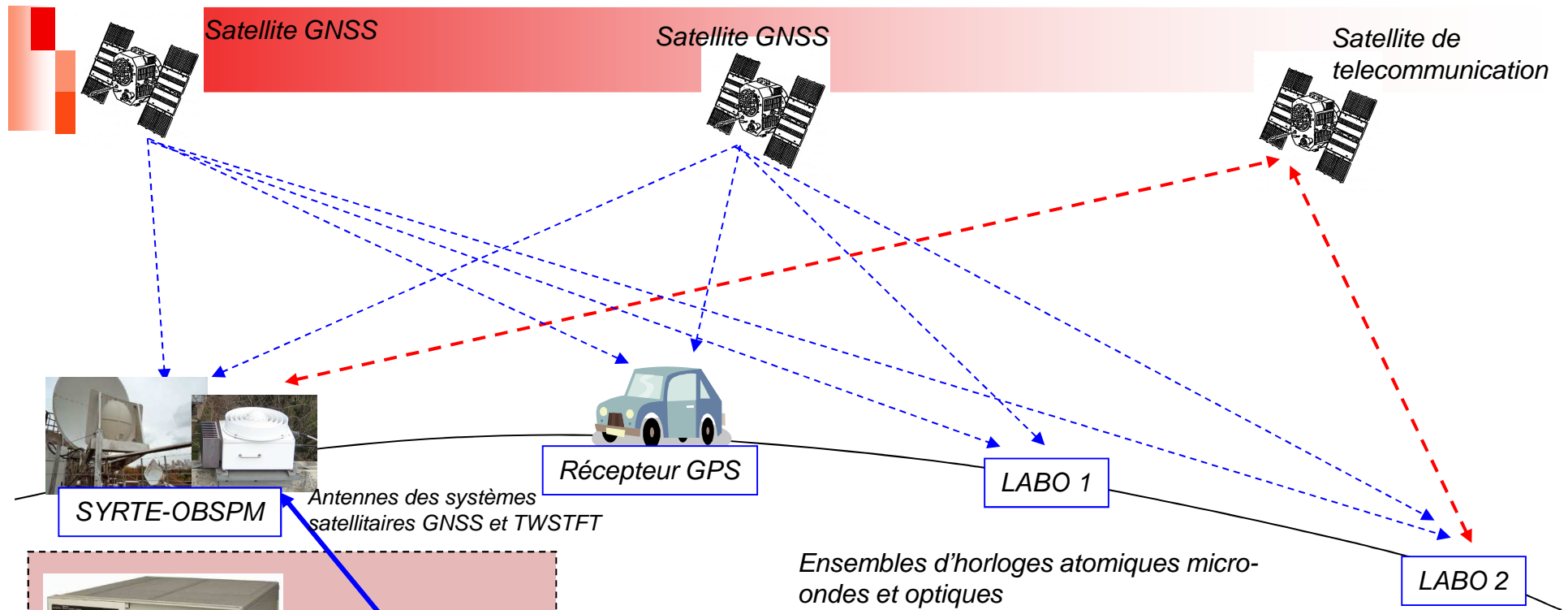
$$Q_{at} = \nu_{ef} / \Delta\nu \simeq 9.8 \times 10^9$$

Best frequency stability (~ Quantum Projection Noise limited):  $1.6 \times 10^{-14}$  @1s

Best accuracy:  $2.4 \times 10^{-16}$

## ■ Second of the International System of Units (SI)

« The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium-133 atom »



Ensemble d'horloges commerciales  
 Comparaisons et algorithmes d'échelle de temps  
 Horloge parlante  
 Diffusion Temps Légal Français

# Motivations for developing optical clocks

Stability of an atomic clock :

$$\sigma_y(\tau) \propto \frac{\sigma_{\delta P}}{Q_{at}} \sqrt{\frac{T_c}{\tau}}$$

$$Q_{at} = \frac{\nu_{ef}}{\Delta\nu} \propto \nu_{ef} T$$

Quantum limited stability :

$$\sigma_y(\tau) = \frac{1}{\pi Q_{at}} \times \frac{1}{\sqrt{N_{det}}} \times \sqrt{\frac{T_c}{\tau}}$$

Microwave transition :  $\nu_{ef} \sim 10$  GHz, optical transition :  $\nu_{ef} = c/\lambda \sim 10^{14}$  Hz

Example #1: cycle  $T_c \sim 1$  s, linewidth  $\sim 1$  Hz et  $\sigma_{\delta p} \sim 10^{-4}$  :

Microwave :  $\sigma_y = 10^{-14}$  @1s

Optical :  $\sigma_y = 10^{-18}$  @1s

In practice, best reported stabilities

$\sigma_y = \sim$  few parts in  $10^{15}$  @1s

Example #2: cycle  $T_c \sim 1$  s, linewidth  $\sim 1$  Hz et  $N_{det} \sim 1$  (1 atom !):

Optical :  $\sigma_y = 3 \times 10^{-15}$  @1s

→ Better stability implies better resolution to evaluate systematic shifts

→ Many systematic shifts are much smaller as compared to microwave clocks

→  **$10^{-17}$  or better is within reach provided a solution is found for the effects of external motion**

$$\delta\omega_{Doppler} = \vec{k} \cdot \vec{v} \sim \omega \times \frac{v}{c}$$

$$\frac{\delta\omega_{Doppler}}{\omega} \sim \frac{v}{c}$$

# Motional effects on confined atoms: Lamb-Dicke regime

- Consider an atom spatially confined to much less than the wavelength of the incoming photon

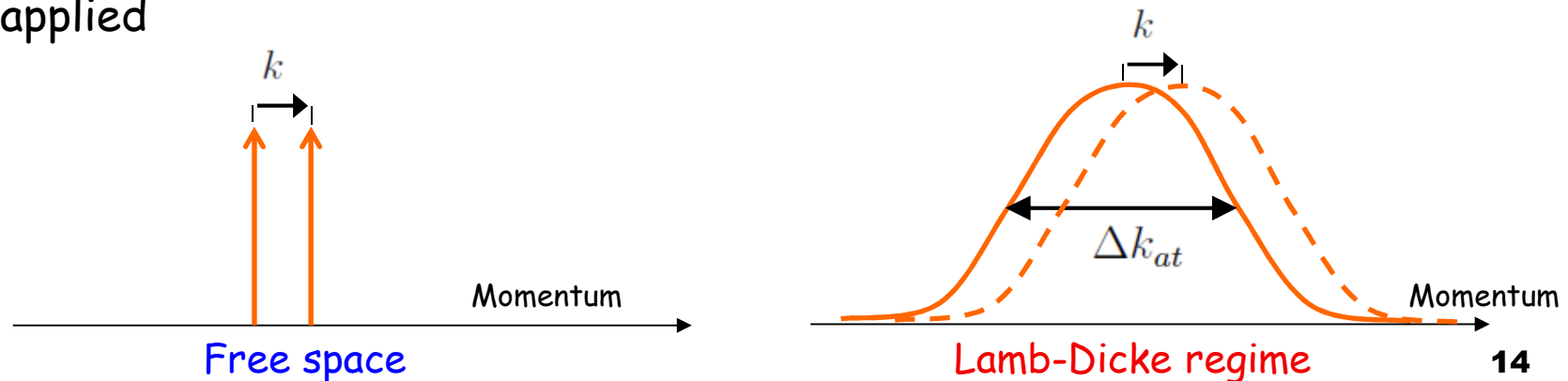
$$\Delta x_{at} \ll \frac{\lambda}{4\pi}$$

- In momentum space, the atomic wave-function is such that:

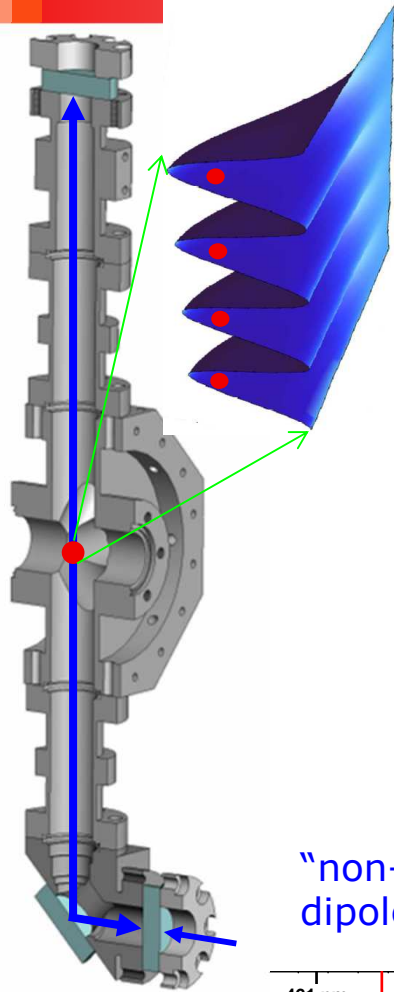
$$\Delta p_{at} \cdot \Delta x_{at} > \hbar/2 \quad \text{or} \quad \Delta k_{at} \cdot \Delta x_{at} > 1/2$$

- This implies that:  $\Delta k_{at} > \frac{1}{2\Delta x_{at}} \gg \frac{2\pi}{\lambda} = k$  or  $\Delta k_{at} \gg k$

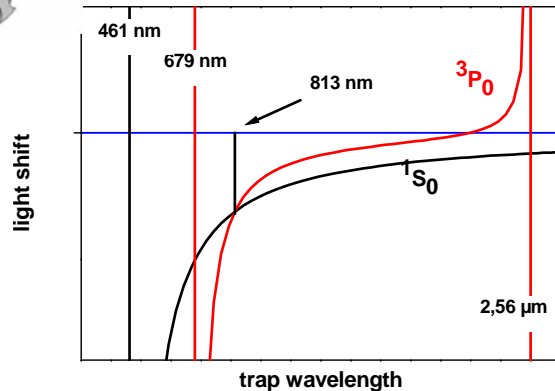
- the size of the wave-function in momentum space is large compared to the photon momentum
- The shift in momentum space implied by momentum conservation induces a minor modification of the wave-packet
- Small shift of the resonant frequency when the energy conservation is applied



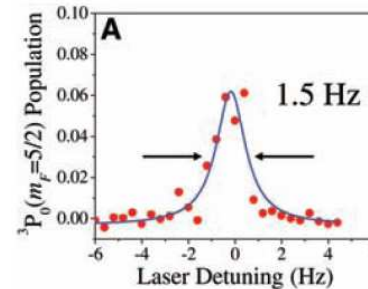
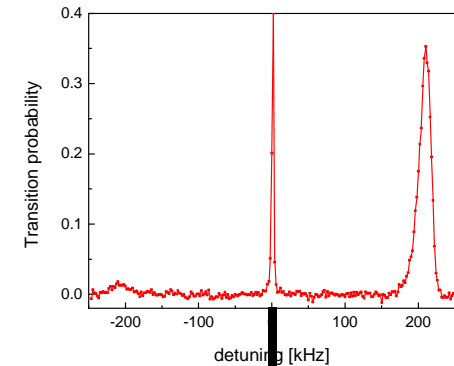
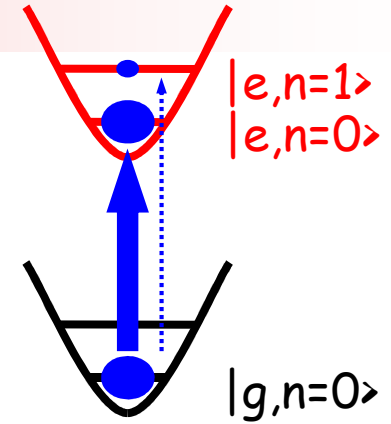
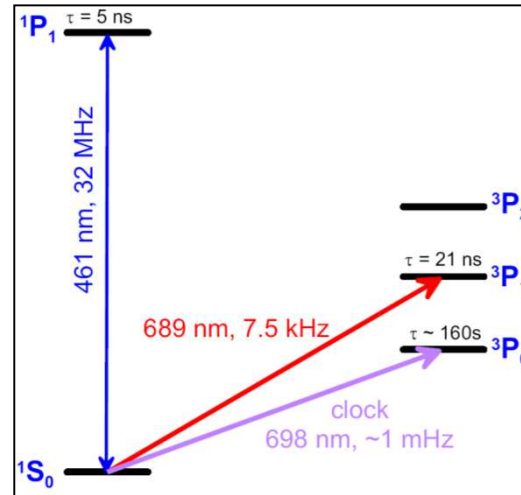
# Optical lattice clocks



"non-perturbing"  
dipole lattice trap



$^{87}\text{Sr}$  (Yb, Hg similar)



Atomic quality factor:  $\sim 2.8 \times 10^{14}$

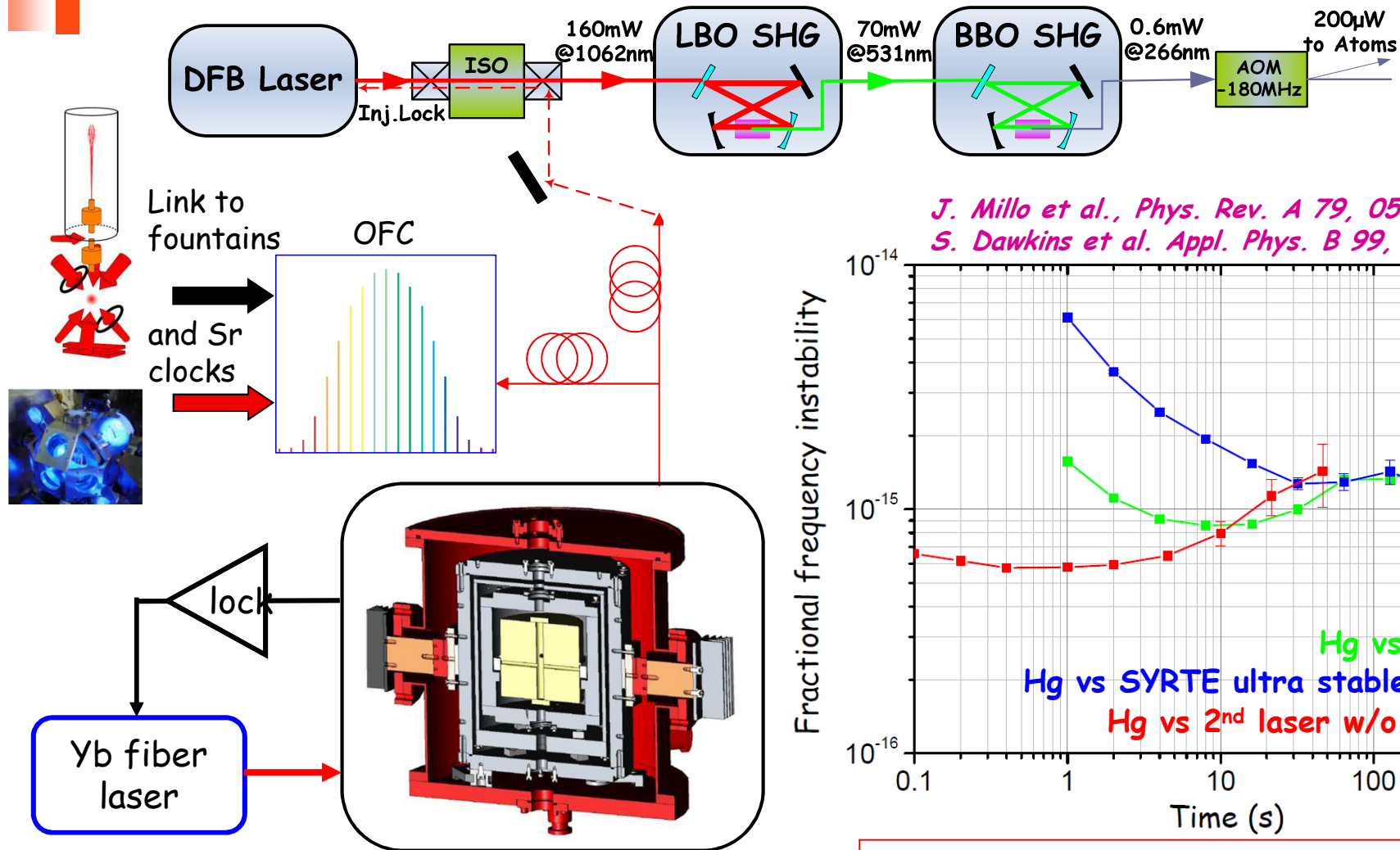
Best frequency stability:  $\sim 2 \times 10^{-15}$  @ 1s

Best accuracy :  $\sim 1.4 \times 10^{-16}$

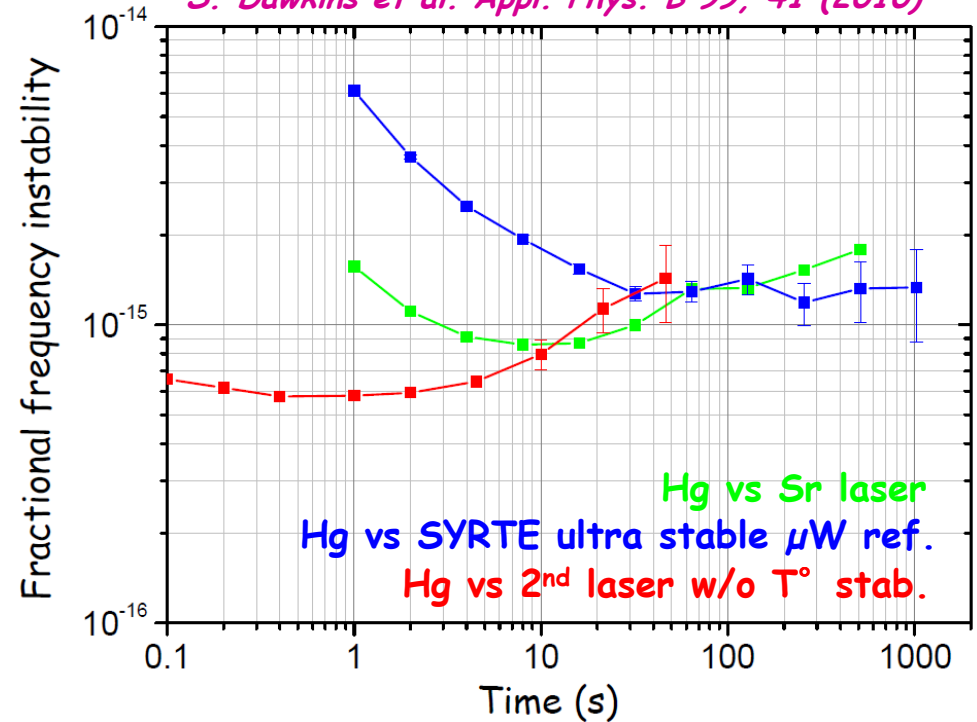
→ Large room for improving stability and accuracy



# Ultra stable probe light @265.6 nm



*J. Millo et al., Phys. Rev. A 79, 053829 (2009)*  
*S. Dawkins et al. Appl. Phys. B 99, 41 (2010)*



- Vertically mounted, low vibration sensitivity
- 10cm length, Finesse  $\sim 850000$
- FS mirrors for thermal noise  $< 10^{-15}$
- Heavy passive thermal shielding ( $\tau > 4$  days)

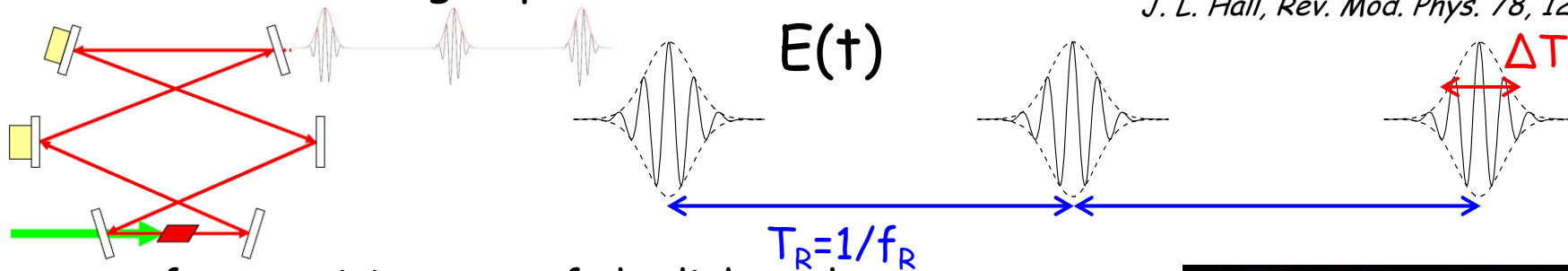
- → Flicker floor  $\sim 4 \times 10^{-16}$  each
- → Linewidth  $\sim 170$  MHz
- →  $\sim -20$  mHz/s drift ( $-7 \times 10^{-17}/s$ )
- → Months continuous operation

# Output of a mode-locked Laser

## Ideal train of light pulses in time domain

*T. W. Hänsch, Rev. Mod. Phys. 78, 1297 (2006)*

*J. L. Hall, Rev. Mod. Phys. 78, 1279 (2006)*

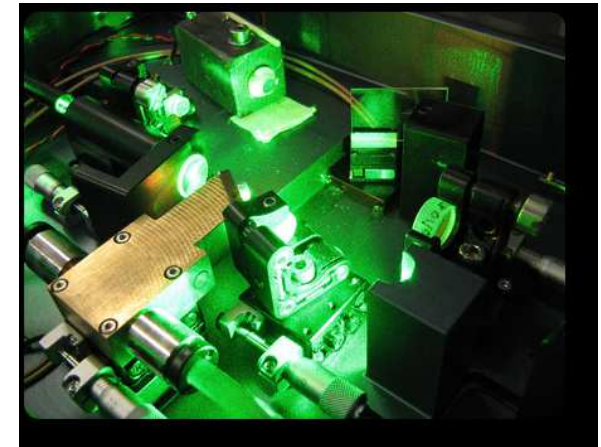
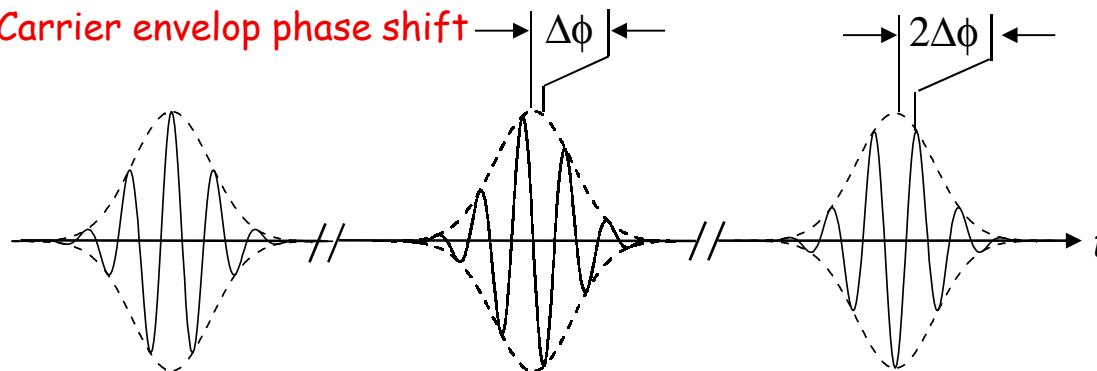


□  $f_R$ : repetition rate of the light pulses

## Pulse train inside the laser cavity with:

$$v_g \neq v_\phi$$

Carrier envelop phase shift

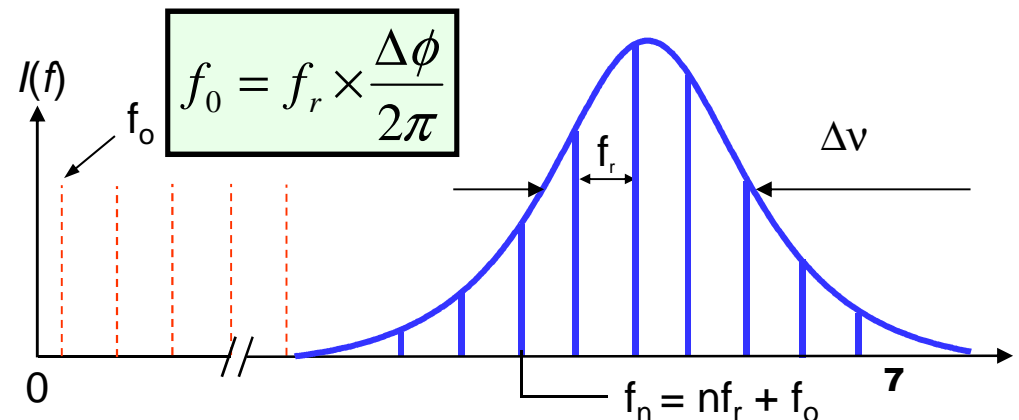


## Frequency domain

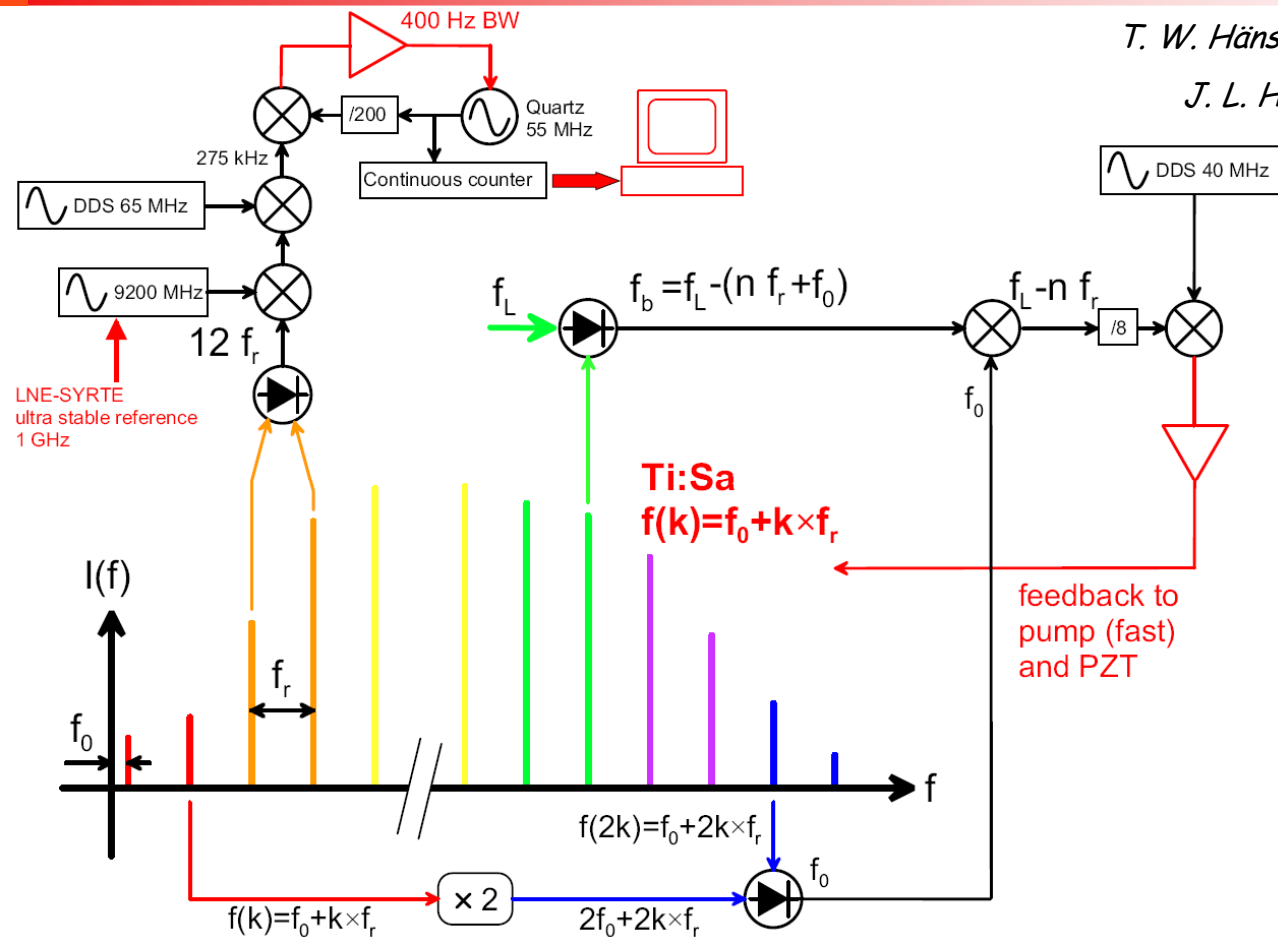
□ Components are phase coherent

□ Fourier limit:  $\Delta T \cdot \Delta \nu \geq 1/4\pi$

□ Comb shifted by  $f_0$



# Optical frequency combs



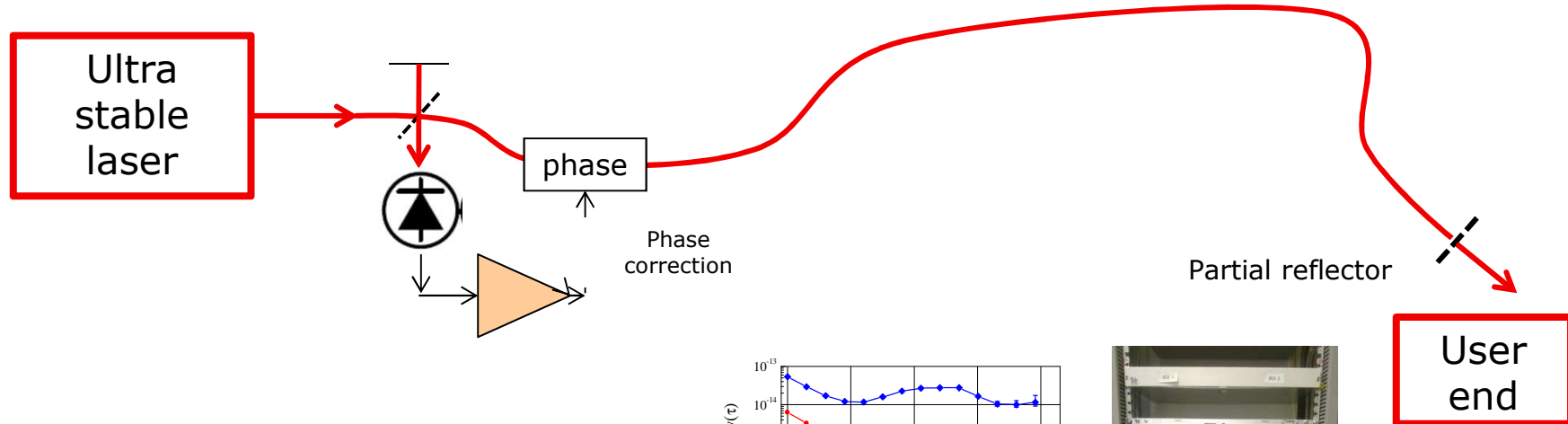
*T. W. Hänsch, Rev. Mod. Phys. 78, 1297 (2006)*

*J. L. Hall, Rev. Mod. Phys. 78, 1279 (2006)*

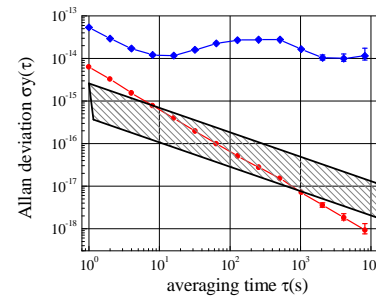
- The Optical Frequency Comb can be used in many different ways depending on the goal
- Reliable optical frequency combs are now available
- → Essential for making optical clocks useful

# Coherent optical fiber link

- "Easy" manipulation/measurement of optical carrier signals opens to possibility of new and better frequency and time transfer methods
- Coherent fiber link: the transmitted signal is the phase of the optical carrier
  - Largely surpasses existing satellite methods
  - Adapted to the new generation of optical clocks
- Principle of the link: heterodyne Michelson interferometer



- Feasibility very well established



# Fundamental Tests using Atomic Clocks

- General Relativity (GR) is one the corner stone of modern physics
- Description of space and time in relation with gravity is key to GR
- ➔ Clocks and highly stable oscillators (frequency related to the length macroscopic objects) are useful tools to test GR
- GR and the Equivalence Principle (EP) is questioned by unification theories
- Examples of GR/EP tests with clocks

- Test for variation of fundamental constants with time and gravitational potential

$$\nu_A = R_\infty c \times f_A \left( \alpha, \frac{m_e}{\Lambda_{\text{QCD}}}, \frac{m_q}{\Lambda_{\text{QCD}}}, \dots \right)$$

*Electroweak interaction (QED)*

*Strong interaction (QCD)*

$$\frac{\nu_A}{\nu_B} = \frac{f_A \left( \alpha, \frac{m_e}{\Lambda_{\text{QCD}}}, \frac{m_q}{\Lambda_{\text{QCD}}}, \dots \right)}{f_B \left( \alpha, \frac{m_e}{\Lambda_{\text{QCD}}}, \frac{m_q}{\Lambda_{\text{QCD}}}, \dots \right)}$$

- Measurement of the gravitational redshift

# Stability of constants tested with clocks

$$\frac{d}{dt} \ln \left( \frac{\nu_{\text{Rb}}}{\nu_{\text{Cs}}} \right) = (-2.0 \pm 1.2) \times 10^{-16} \text{ yr}^{-1} = -0.49 \frac{d}{dt} \ln(\alpha) - 0.025 \frac{d}{dt} \ln(m_q / \Lambda_{\text{QCD}})$$

$$\frac{d}{dt} \ln \left( \frac{\nu_{\text{H}}}{\nu_{\text{Cs}}} \right) = (-32 \pm 63) \times 10^{-16} \text{ yr}^{-1} = -2.83 \frac{d}{dt} \ln(\alpha) + 0.039 \frac{d}{dt} \ln(m_q / \Lambda_{\text{QCD}}) - \frac{d}{dt} \ln(m_e / \Lambda_{\text{QCD}})$$

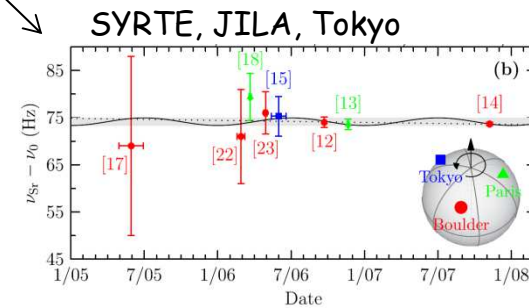
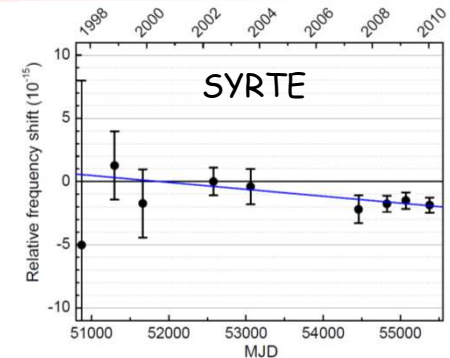
$$\frac{d}{dt} \ln \left( \frac{\nu_{\text{Sr}}}{\nu_{\text{Cs}}} \right) = (-7 \pm 18) \times 10^{-16} \text{ yr}^{-1} = -2.77 \frac{d}{dt} \ln(\alpha) + 0.039 \frac{d}{dt} \ln(m_q / \Lambda_{\text{QCD}}) - \frac{d}{dt} \ln(m_e / \Lambda_{\text{QCD}})$$

$$\frac{d}{dt} \ln \left( \frac{\nu_{\text{Hg}^+}}{\nu_{\text{Cs}}} \right) = (3.7 \pm 3.9) \times 10^{-16} \text{ yr}^{-1} = -6.03 \frac{d}{dt} \ln(\alpha) + 0.039 \frac{d}{dt} \ln(m_q / \Lambda_{\text{QCD}}) - \frac{d}{dt} \ln(m_e / \Lambda_{\text{QCD}})$$

$$\frac{d}{dt} \ln \left( \frac{\nu_{\text{Dy}}}{\nu_{\text{Cs}}} \right) = (-4 \pm 3.9) \times 10^{-8} \text{ yr}^{-1} = 1.5 \times 10^7 \frac{d}{dt} \ln(\alpha) + 0.039 \frac{d}{dt} \ln(m_q / \Lambda_{\text{QCD}}) - \frac{d}{dt} \ln(m_e / \Lambda_{\text{QCD}})$$

$$\frac{d}{dt} \ln \left( \frac{\nu_{\text{Yb}^+}}{\nu_{\text{Cs}}} \right) = (-7.8 \pm 14) \times 10^{-16} \text{ yr}^{-1} = -1.95 \frac{d}{dt} \ln(\alpha) + 0.039 \frac{d}{dt} \ln(m_q / \Lambda_{\text{QCD}}) - \frac{d}{dt} \ln(m_e / \Lambda_{\text{QCD}})$$

$$\frac{d}{dt} \ln \left( \frac{\nu_{\text{Hg}^+}}{\nu_{\text{Al}^+}} \right) = (4.6 \pm 6.7) \times 10^{-17} \text{ yr}^{-1} = -2.9 \frac{d}{dt} \ln(\alpha)$$



Least squares fit



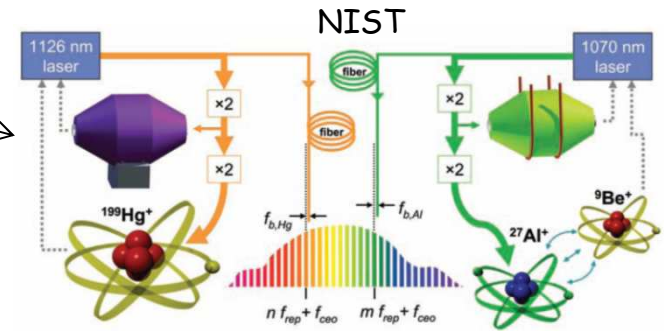
$$\frac{d}{dt} \ln(\alpha) = (-0.18 \pm 0.23) \times 10^{-16} \text{ yr}^{-1}$$

$$\frac{d}{dt} \ln(m_q / \Lambda_{\text{QCD}}) = (83 \pm 48) \times 10^{-16} \text{ yr}^{-1}$$

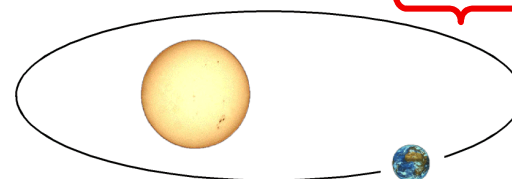
$$\frac{d}{dt} \ln(m_e / \Lambda_{\text{QCD}}) = (1.9 \pm 4.4) \times 10^{-16} \text{ yr}^{-1}$$

INDEPENDENT OF COSMOLOGICAL MODELS

- Test as a function of gravitation potential
  - Exploiting the ellipticity of Earth orbit

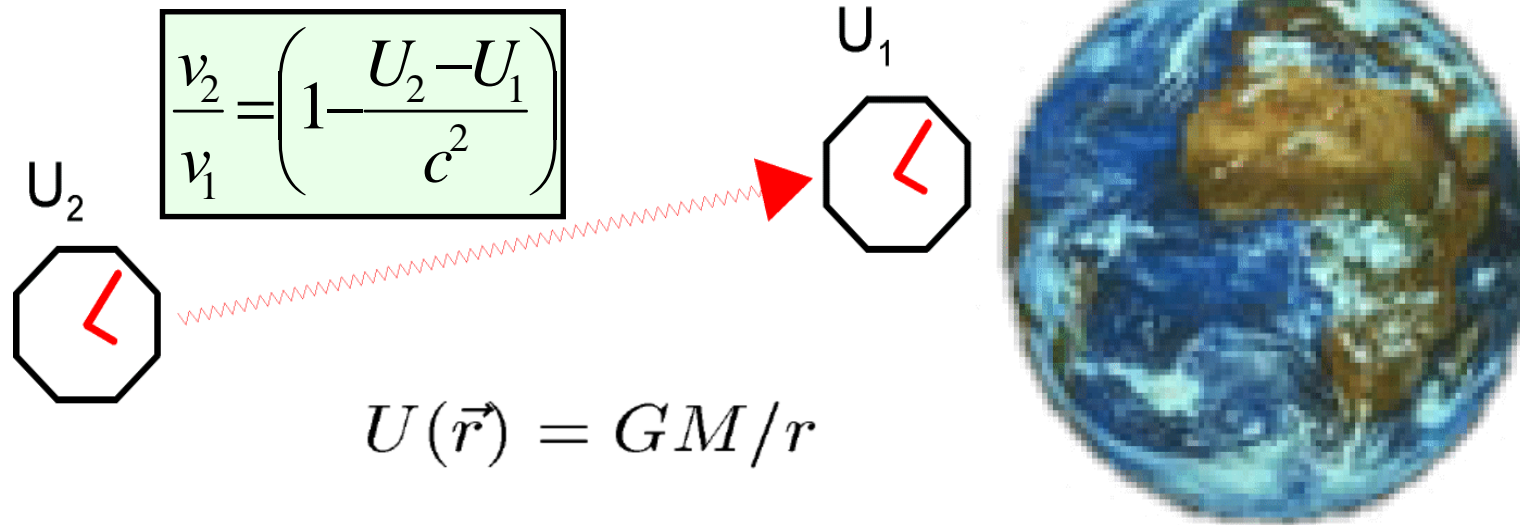


$$\frac{\Delta U(t)}{c^2} \approx - \frac{GM_{\odot}}{c^2 a} \epsilon \cos[\Omega(t - t_{\text{perihelion}})]$$



$\sim 1.6 \cdot 10^{-10}$

# A striking effect in General Relativity: the Gravitational Redshift



Potential of the Earth at its surface:  $7 \times 10^{-10}$

Gradient at Earth surface:  $\sim 10^{-16} \text{ m}^{-1}$

Surface to GNSS satellite ( $R=29600 \text{ km}$ ) difference:  $\sim 5.5 \times 10^{-10}$

Surface to ISS ( $h=450 \text{ km}$ ) difference:  $\sim 4.6 \times 10^{-11}$

Redshift measurement with a  $7 \times 10^{-5}$   
uncertainty: *GPA, R. Vessot et al. (1976)*

# ACES: Atomic Clocks on the ISS

Atomic Clock Ensemble in Space

*proposed by LKB and SYRTE*

*PI: C. Salomon, A. Clairon, Ph. Laurent*

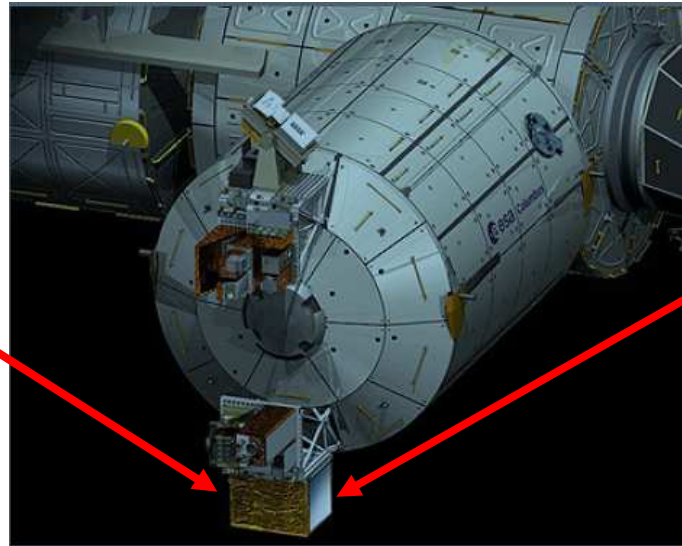


PHARAO

H-MASER



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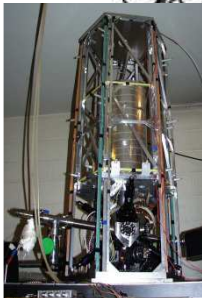


$\mu$ wave-link  
two-ways

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two-ways

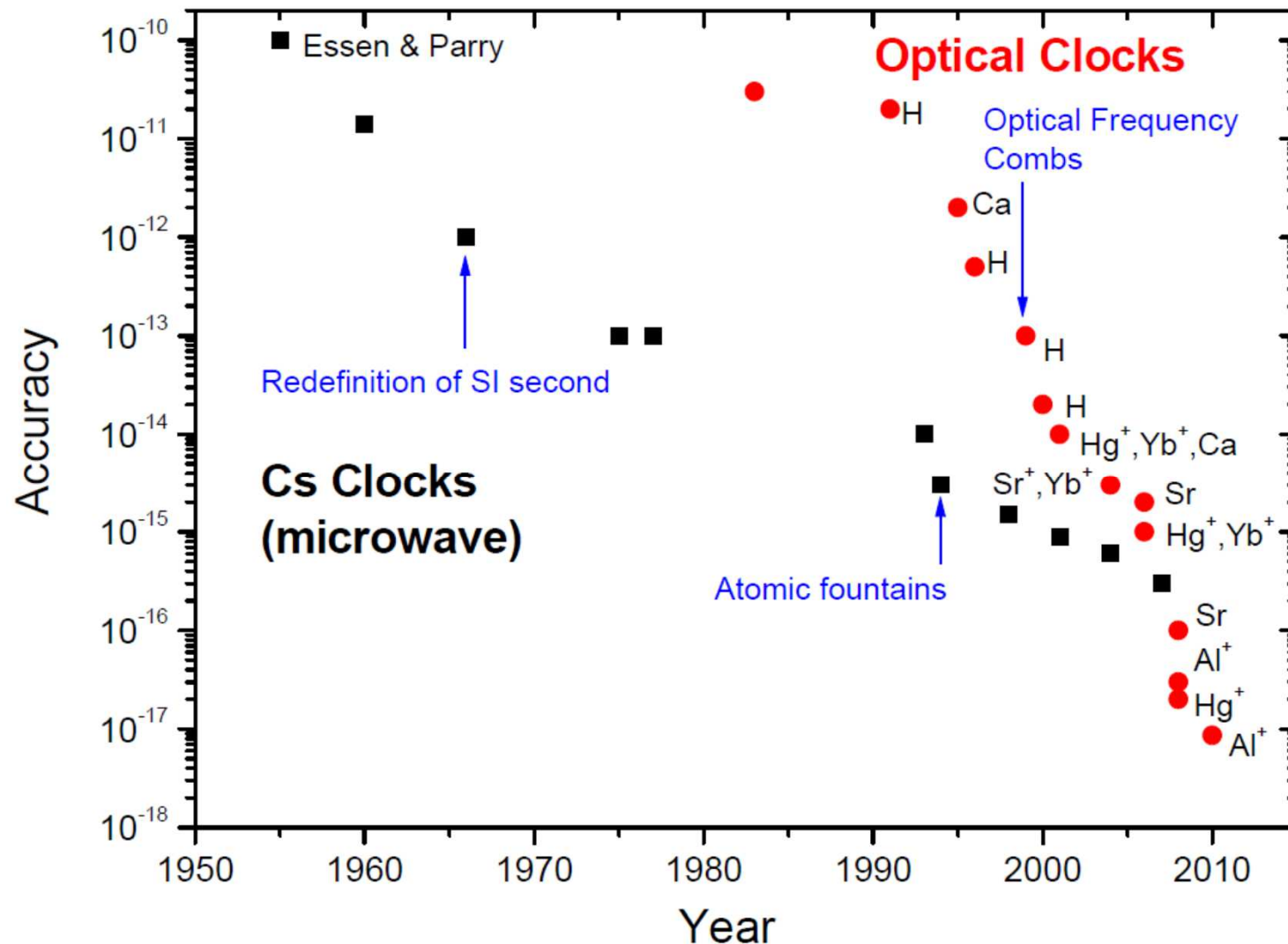
- A cold atom Cs standard in space
- Worldwide access
- Fundamental physics tests

Flight Model under development  
Launch: ~2015-2016 by japanese HTV  
Mission duration: 18 months





# Improvement of clock accuracy with time



- Several optical clock transitions are recognized by BIPM as secondary representations of the SI second
- In the future, optical clocks will offer a large number of possibilities for a redefining the SI second and testing fundamental physical laws.

# Nombreuses applications des horloges atomiques

## Métrologie fondamentale

- Échelles de temps atomique, temps légal (horloge parlante 36 99, réseau hertzien, NTP, ...)
- Redéfinition des unités



## Tests de physique fondamentale

- Relativité Générale : décalage gravitationnel vers le rouge
- Invariance locale de Lorentz et de position
- Variation des constantes fondamentales



## Navigation et Positionnement

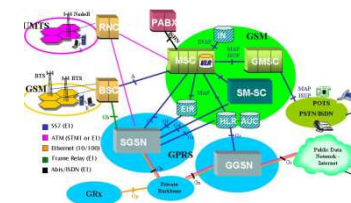
- 1ns  $\Leftrightarrow$  30 cm
- Global Navigation Satellite Systems (GNSS): GPS (USA), GLONASS (Russie), GALILEO (Europe), BEIDOU/COMPASS (Chine), GINSS (Inde)



## Synchronisation des réseaux de télécommunication

## Astronomie

- Very Long Baseline Interferometry (VLBI), Astrocomb



## Géophysique

- Rotation de la Terre
- Cartographie de potentiel de gravitation

