FIRST-QIPP / DYCE　夏期研修会2011～関西・関東学生チャプター合同研究会～
京都大学　時計台記念館　２F　国際交流ホールⅠ
2011年8月12日（金）～8月17日（水）

光格子時計の高精度周波数比較

東京大学大学院工学系研究科
ERATO 創造時空間プロジェクト、科学技術振興機構
理化学研究所、量子計測研究室

香取秀俊

Personal research background

- Finish D. thesis in ‘94 in Tokyo (Prof. Fujio Shimizu)
  - Ultracold **neutral** rare-gas atoms (Ar*,Kr*), atomic interactions…
- Post doc. in Walther’s group in MPQ, Garching (94.9-97.3)
  - Prof,. Shimizu’s suggestion: Do not join ion clock group.
  - Precise manipulation of a single ion in a linear (ring) trap
  - Excitement of the **Cirac-Zoller gate**; a step **toward QC**, as later realized in **Wineland’s** group and **Blatt’s** group
  - Spent nearly 2 years for terrible micro-motion compensation, QC seemed far away, …
- **Fruitful Gifts from Garching**
  - **Huge amount of time to read Dr. Wineland’s papers and his strategies**
  - **Never win the game as long as I follow his track**
  - **Glancing at In+ clock poster every day**
  - **We should work faster with many atoms to recover 20 years’ delay!**
- Simulating ion experiments with neutral atoms (97.4-present)
  - Narrowline cooling down to μK (1999) and “magic wavelength” optical trap (1999)
- Optical lattice clock proposal at FSM 2001

VOLUME 82, NUMBER 6 PHYSICAL REVIEW LETTERS 8 FEBRUARY 1999

Magneto-Optical Trapping and Cooling of Strontium Atoms down to the Photon Recoil Temperature

Hidetoshi Katori, Tetsuya Ido, Yoshitomo Isoya, and Makoto Kuwata-Gonokami
Cooperative Excitation Project, ERATO, Japan Science and Technology Corporation (JST), KSP D-842, 3-2-1 Sakado, Takatsu-ku Kawasaki, 213-0012, Japan
(Received 4 September 1998)

We report narrow-line laser cooling and trapping of strontium atoms down to the photon recoil temperature. ^{88}Sr atoms precooled by the broad $^1S_0$-$^1P_1$ transition at 461 nm were further cooled in a magneto-optical trap using the spin-forbidden transition $^1S_0$-$^3P_1$ at 689 nm. We have thus obtained an

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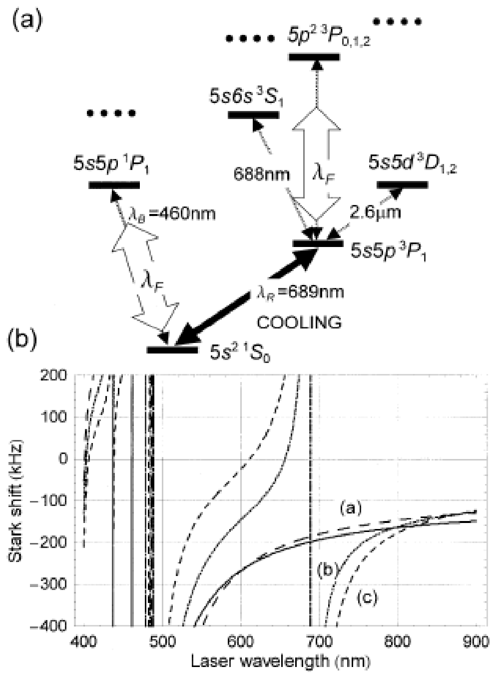
Journal of the Physical Society of Japan
Vol. 68, No. 8, August, 1999, pp. 2479-2482

Optimal Design of Dipole Potentials for Efficient Loading of Sr Atoms

Hidetoshi KATORI, Tetsuya IDO and Makoto KUWATA-GONOKAMI
Cooperative Excitation Project, ERATO, Japan Science and Technology Corporation (JST), KSP D-842, 3-2-1 Sakado, Takatsu-ku, Kawasaki 213-0012
(Received May 11, 1999)



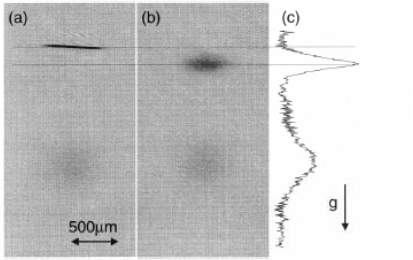
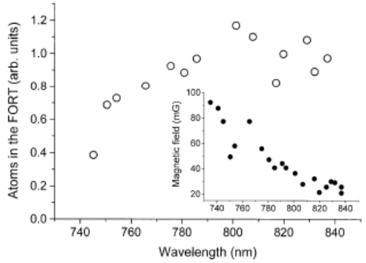
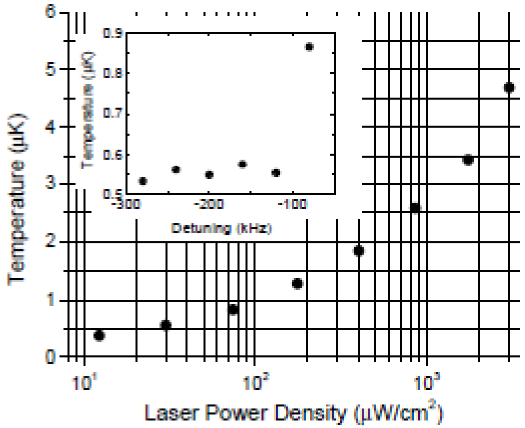


Fig. 3. Absorption image of a FORT (a), the expanded atomic cloud in a 6 ms flight (b), and a cross section of the image (b) along the vertical axis (c). The profile of the expanded atom cloud was fitted well by the Gaussian with $T = 1.2\,\mu$K. The weak round images in (a) and (b) below show atoms that were not captured in the FORT. The gravity directs toward the bottom.





achieve higher phase space density. Another interesting experimental possibility is applying sideband cooling between $5s^2\,{}^1S_0$ and $5s5p\,{}^3P_1$ states. Coupling these two states to upper $5s5p\,{}^1P_1$ and $5s6s\,{}^3S_1$ states, respectively, by an infrared laser may realize optical potentials with the same vibrational energy separation $\hbar\omega_m$ for both states simultaneously. Since ω_m can be larger than the linewidth γ_2 or $E_R/\hbar$, the well established scheme in a single ion cooling [22] can be applied to the ensemble of neutral atoms. In this case, the final state of the sideband cooling impressively depends on the quantum statistics of the isotopes, ^{88}Sr or ^{87}Sr, corresponding to BEC or degenerate Fermi gas, respectively.

Prospects: "magic lattice" and sideband cooling down to quantum degeneracy

2 essential experimental tools for transferring Paul trap tech. into neutrals.

Quantum Metrology

Study of measurement at quantum limited performance

Time / Frequency

Currently, NOT on temperature, weight, (voltage),… lack of quantum references

NOT limited by technical noises:

- Noise from electronics circuit, detectors, …
- Thermal noise

Time/frequency measurement is NOT limited by frequency counters but is limited by the quantum system itself (and their design).

精密計測の鉄則：
「測定値を時間・周波数の測定に置き換えること」

時間・周波数は物理計測の中で最も正確に計測可能な物理量

□ 1秒の定義の精度：15桁、国際原子時
□ 長さ計測；光速度一定、時間計測へ
□ 電圧計測；ジョセフソン効果、周波数計測へ
ー $K_J = 2e / h$=483597.9(GHz/V)；ジョセフソン定数

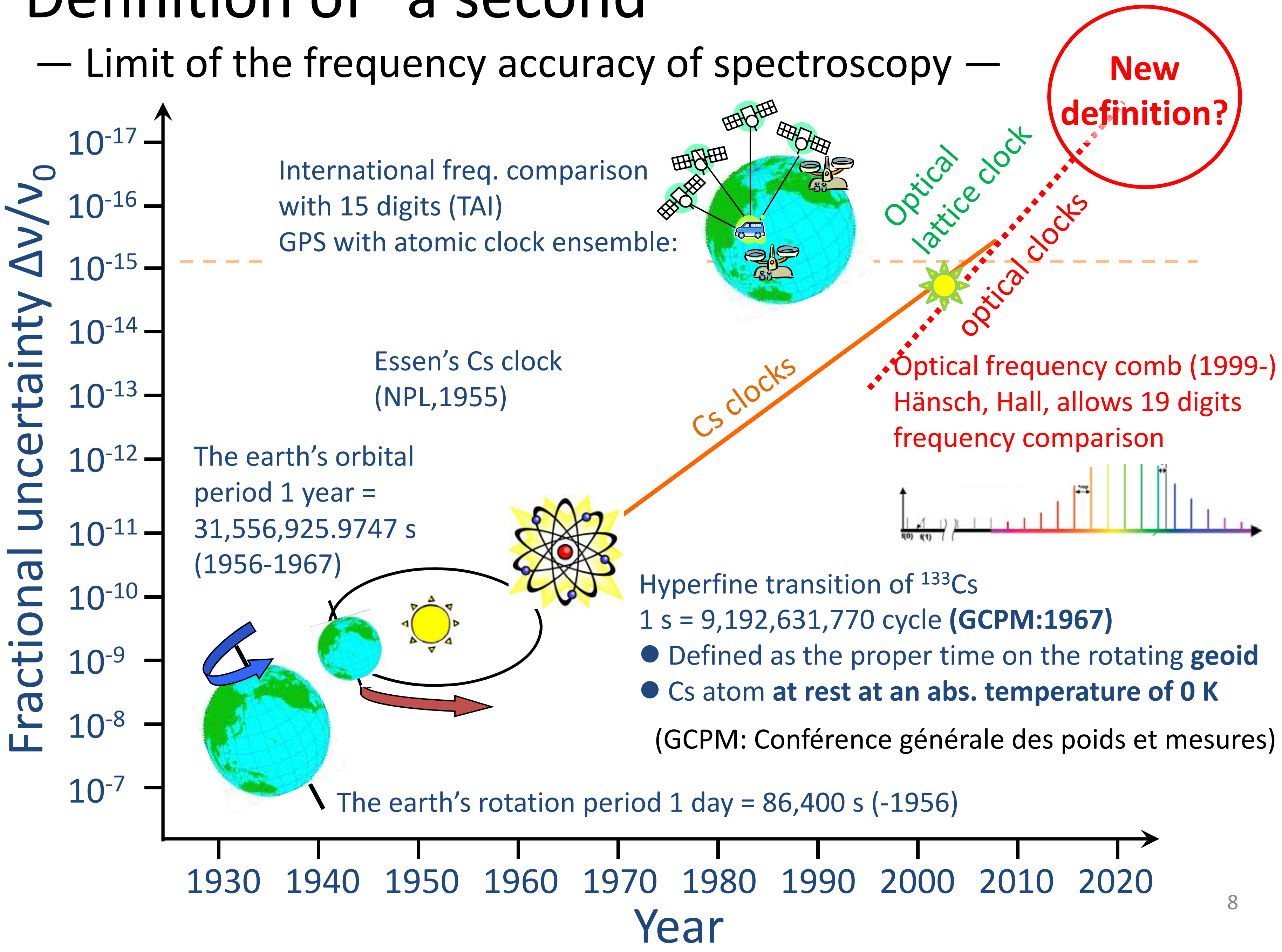
□ 光格子時計のアイディア
  ー 摂動を与えるプロトコルを周波数で定義する

内容

- 原子時計の実現：2状態間のエネルギー差を正確に測る方法
  - デーコヒーレンスの少ないqbitの実現
- 原子時計の安定度は量子射影ノイズで原理的に制限さえる
- 光格子時計の発明、「魔法波長」の発見
- 量子限界で動作する光格子時計の実現
- （原子時計の）時間比較でわかること

Definition of “a second”

— Limit of the frequency accuracy of spectroscopy —



International freq. comparison with 15 digits (TAI)
GPS with atomic clock ensemble:

Essen’s Cs clock (NPL,1955)

The earth’s orbital period 1 year = 31,556,925.9747 s (1956-1967)

Optical frequency comb (1999-)
Hänsch, Hall, allows 19 digits frequency comparison

Hyperfine transition of ^{133}Cs
1 s = 9,192,631,770 cycle **(GCPM:1967)**

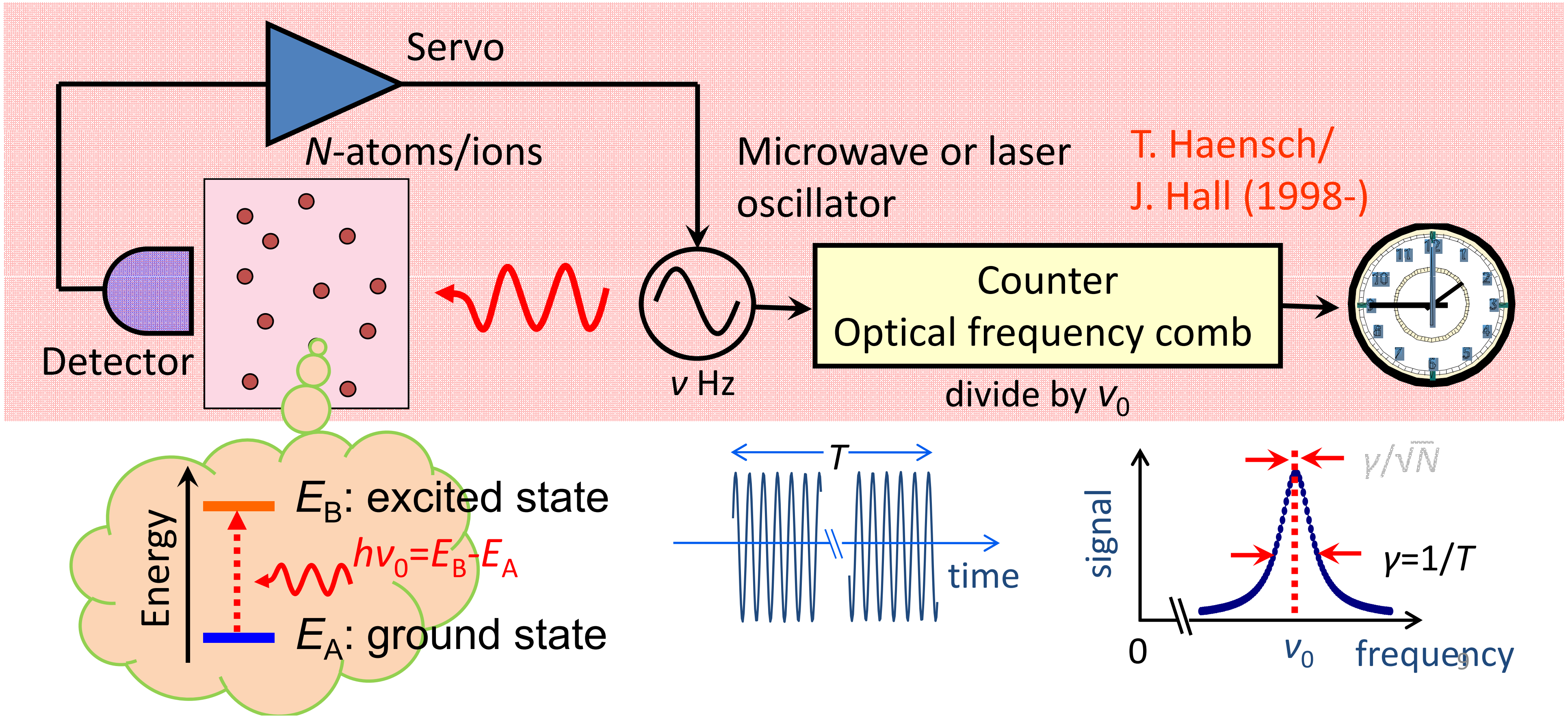
- Defined as the proper time on the rotating **geoid**
- Cs atom **at rest at an abs. temperature of 0 K**

(GCPM: Conférence générale des poids et mesures)

The earth’s rotation period 1 day = 86,400 s (-1956)

Building Atomic Clocks

- **Believe in the constancy of fundamental constant. (Is this true?)**
- Measure local oscillator frequency referencing the atomic transition
  - Excitation linewidth $\gamma \approx 1/T$ (Fourier limit for T interaction)
  - Data averaging for better statistics with N atoms
  - Uncertainty in frequency estimation (QPN): $\langle \delta\nu \rangle = \langle \Delta N \rangle / \left| \mathrm{d}(N p_B) / \mathrm{d}\nu \right| \le \frac{1}{T\sqrt{N}}$
- Servo control of flywheel oscillator (laser)



Servo

N-atoms/ions

Microwave or laser oscillator

T. Haensch/ J. Hall (1998-)

Detector

ν Hz

Counter

Optical frequency comb

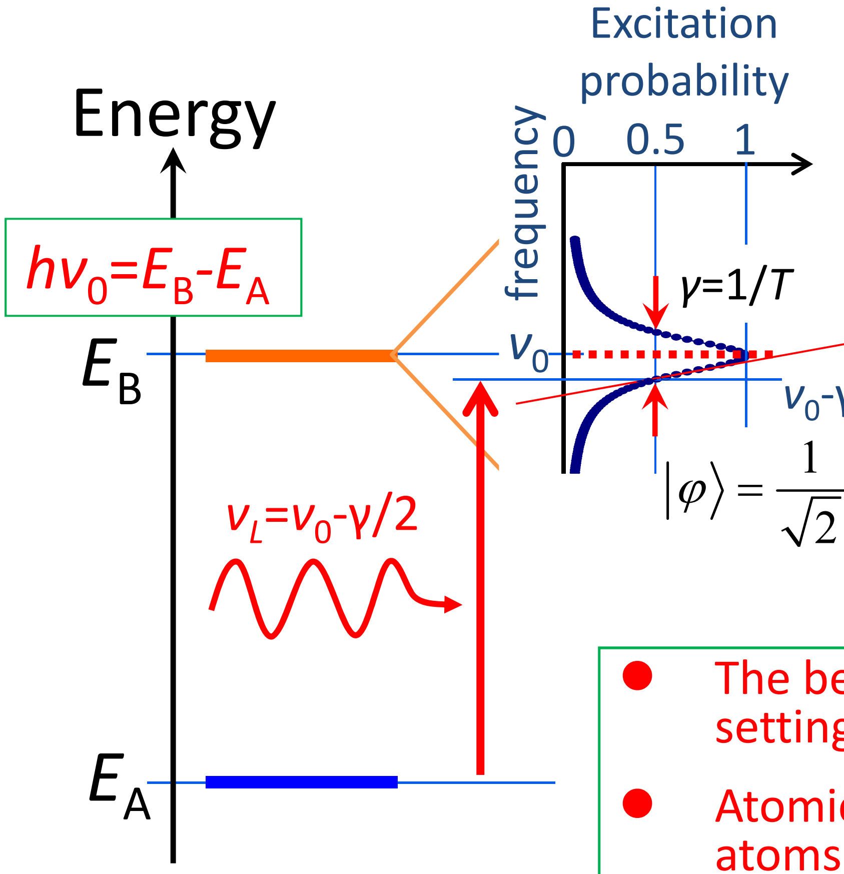
divide by ν_0

E_B: excited state

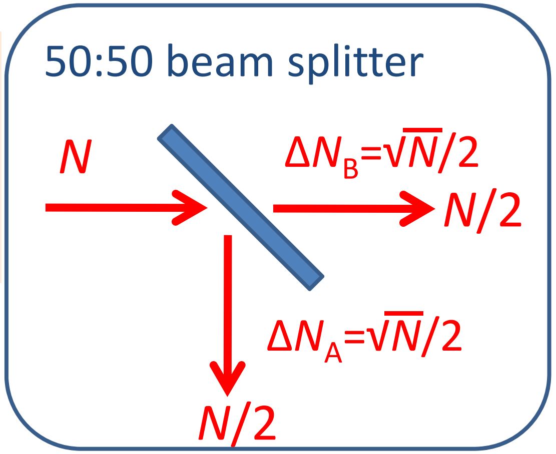
$h\nu_0 = E_B - E_A$

E_A: ground state

量子揺らぎとの戦い
原子によるレーザー周波数の最善の測定



$\delta\nu_c/\gamma$ (freq. fluct.)
$\approx \delta\kappa$
$\approx 1/\sqrt{N}$ (QPN)



$$|\varphi\rangle = \frac{1}{\sqrt{2}}\left(|a\rangle + |b\rangle\right)$$

*a*状態か*b*状態か確率半々の二項分布（ベルヌーイ試行）
→分散は$\frac{1}{2}(1-\frac{1}{2})N$ →偏差$\sqrt{N}/2$

- The best evaluation of the laser frequency is done by setting **$\nu_L=\nu_0-\gamma/2$**, where the **excitation probability is ½.**
- Atomic state can be projected on either A or B. For ***N*** atoms, $\Delta N_{A(\text{or } B)}=\sqrt{N}/2$, the same as photons through a beam splitter, causing quantum noise **$\Delta N_A/N=2/\sqrt{N}$.**
- **Shot (Projection) noise limit uncertainty: $\Delta\nu=\gamma/\sqrt{N}$, large *N* helps!**

W. M. Itano *et al., Phys. Rev. A* 47, 3554 (1993).

Strategies for making better clocks

Indicator: fractional uncertainty $\Delta\nu/\nu_0$

→ With a given measurement uncertainty $\Delta\nu \approx 10^{-3}$-$10^{-5}$ Hz, higher ν_0 wins, i.e., **optical clocks ($\nu_0 \approx 10^{15}$ Hz)** surpass **Cs clock at MW ($\nu_0 \approx 10^{10}$ Hz)** that provides SI-second/International atomic time.

Stability

- How fast can one achieve projected accuracy?
- Projection/Shot noise limited stability given by Allan deviation

Accuracy

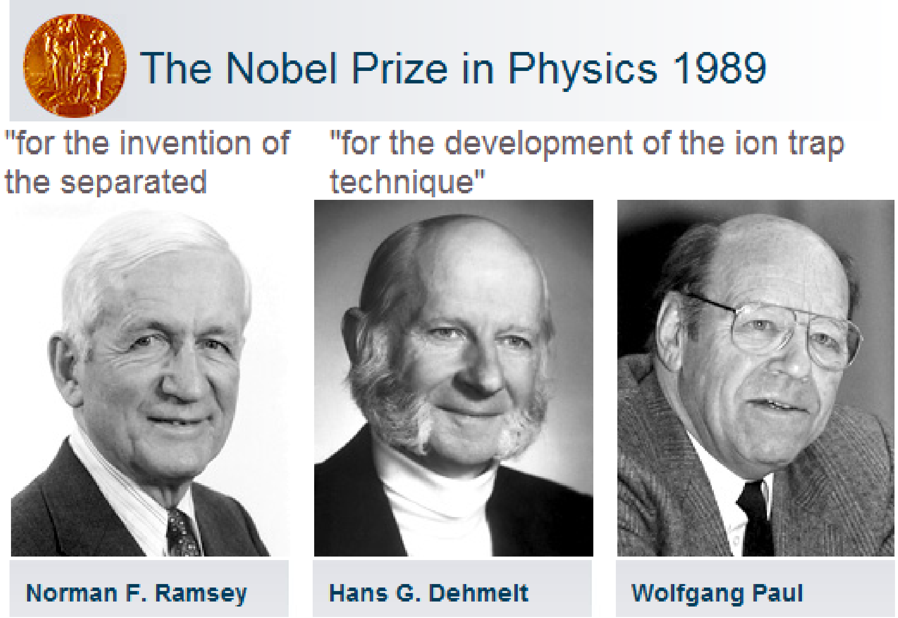
- How small is perturbation $\Delta\nu$ (EM field, Doppler, collisions,…) on unperturbed transition frequency?

In view of accuracy, an ion in a Paul trap would be a perfect clock, however, there is still a good reason to have better stability.

In view of the accuracy aspects of the clock…

Single atoms/ions held in field-free space would be ideal

For decades, singly trapped-ions (atoms) in **Paul** traps (“50-) have been considered to be the prime candidate for future optical atomic clocks as proposed by **Dehmelt** and others (“82)



The Nobel Prize in Physics 1989

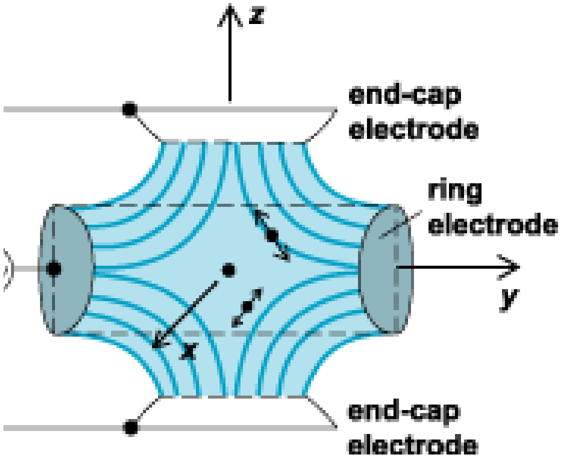
"for the invention of the separated

"for the development of the ion trap technique"

Norman F. Ramsey

Hans G. Dehmelt

Wolfgang Paul



e near the zero of the trapping

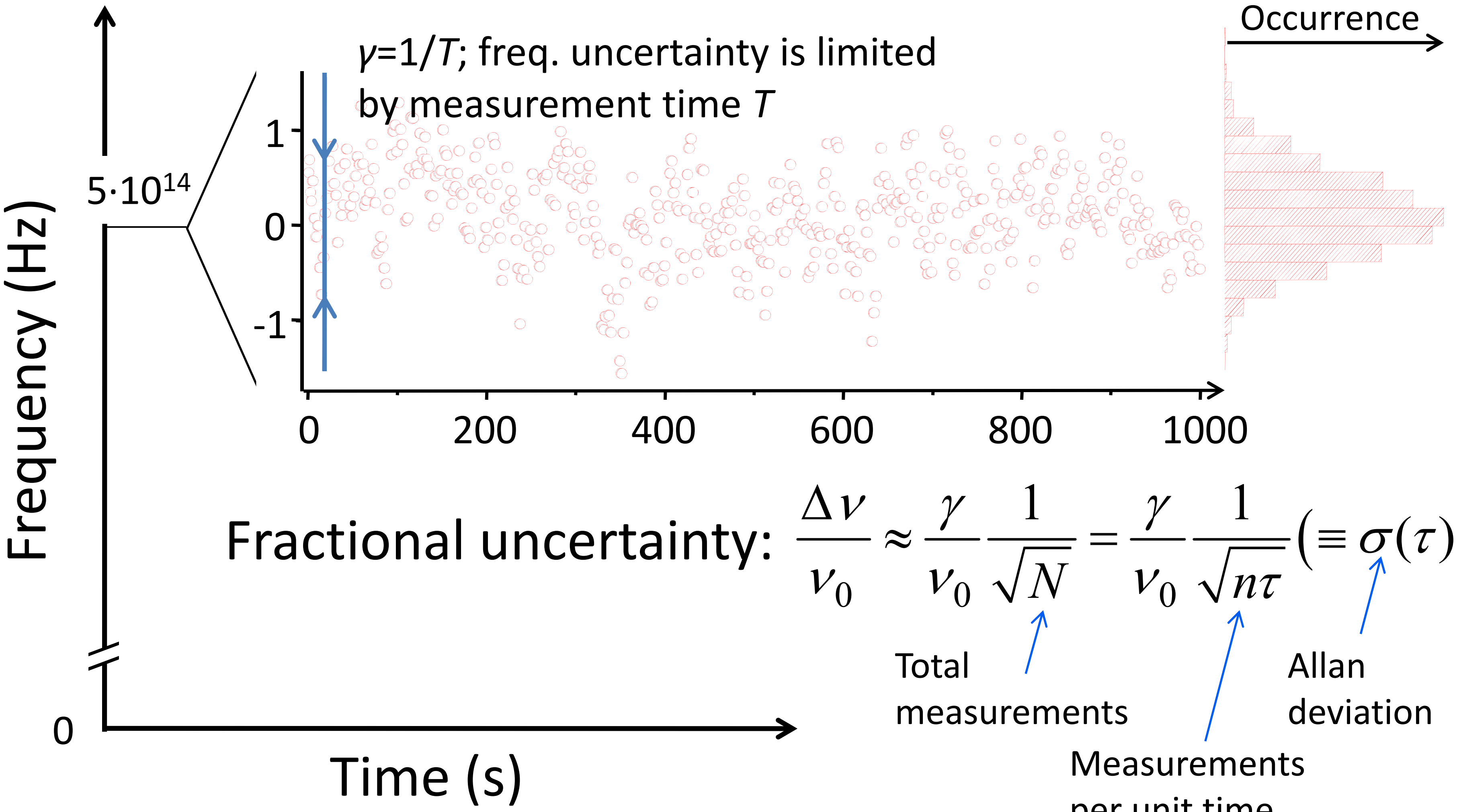
ized perturbation promises

clock accuracy $\Delta\nu/\nu_0 \approx 10^{-18}$, however **the stability is limited.**

Al+ ion optical clock with uncertainty of 7.0 × 10^{-18} (NIST group 2009.12)

Stability of a clock:

It takes some time to achieve good statistics



γ=1/*T*; freq. uncertainty is limited by measurement time *T*

Fractional uncertainty: $$\frac{\Delta\nu}{\nu_0} \approx \frac{\gamma}{\nu_0}\frac{1}{\sqrt{N}} = \frac{\gamma}{\nu_0}\frac{1}{\sqrt{n\tau}} \left(\equiv \sigma(\tau)\right)$$

Total measurements

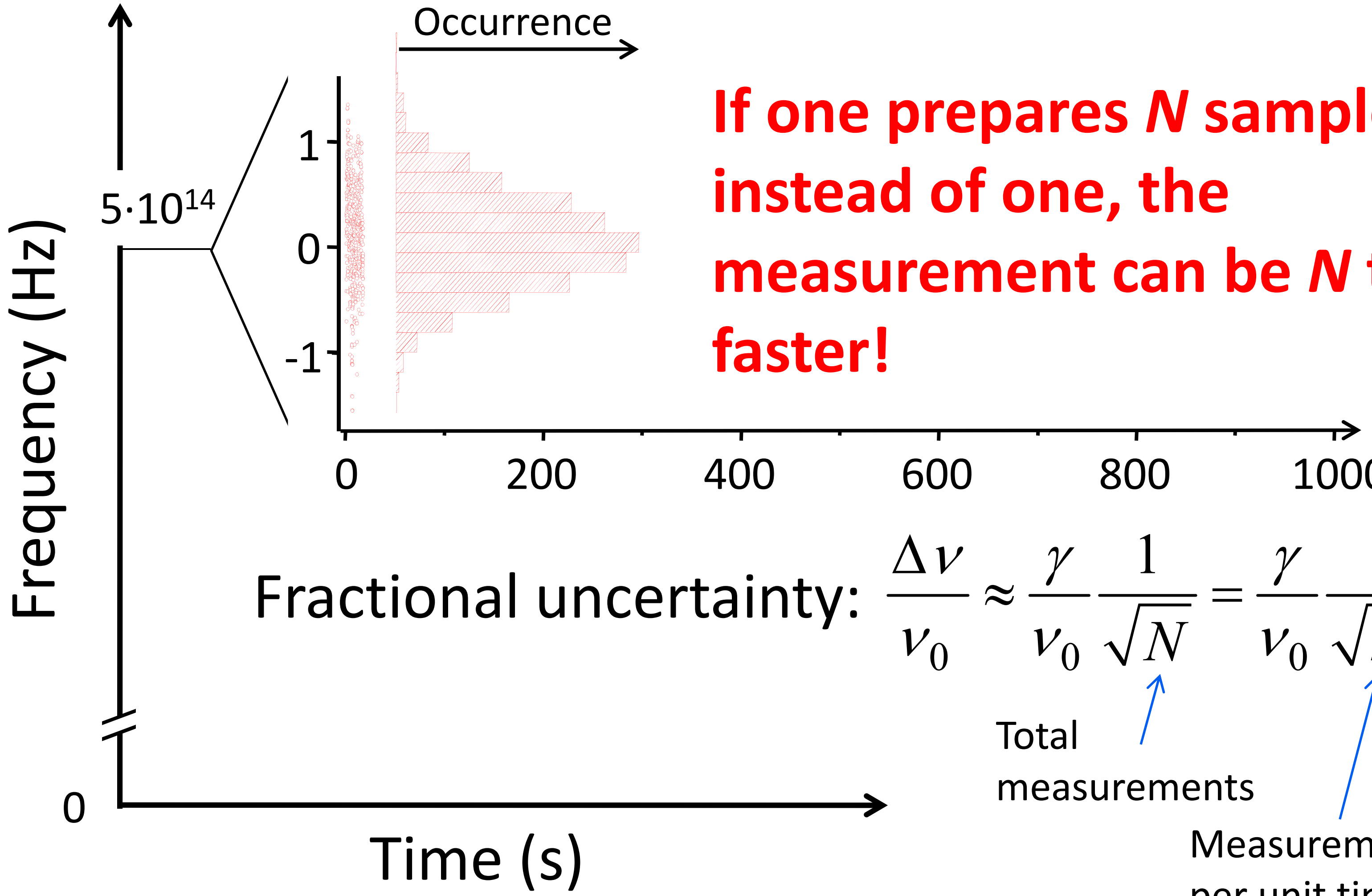
Measurements per unit time

Allan deviation

Significant speed up of the measurement can be achieved by increasing atom # measured in a unit time

Stability of a clock:

It takes some time to achieve good statistics



If one prepares *N* samples instead of one, the measurement can be *N* times faster!

Fractional uncertainty: $$\frac{\Delta\nu}{\nu_0} \approx \frac{\gamma}{\nu_0}\frac{1}{\sqrt{N}} = \frac{\gamma}{\nu_0}\frac{1}{\sqrt{n\tau}} \left(\equiv \sigma(\tau)\right)$$

Total measurements

Allan deviation

Measurements per unit time

Significant speed up of the measurement can be achieved by increasing atom # measured in a unit time

見えなかった新たな時間領域に光をあてる！

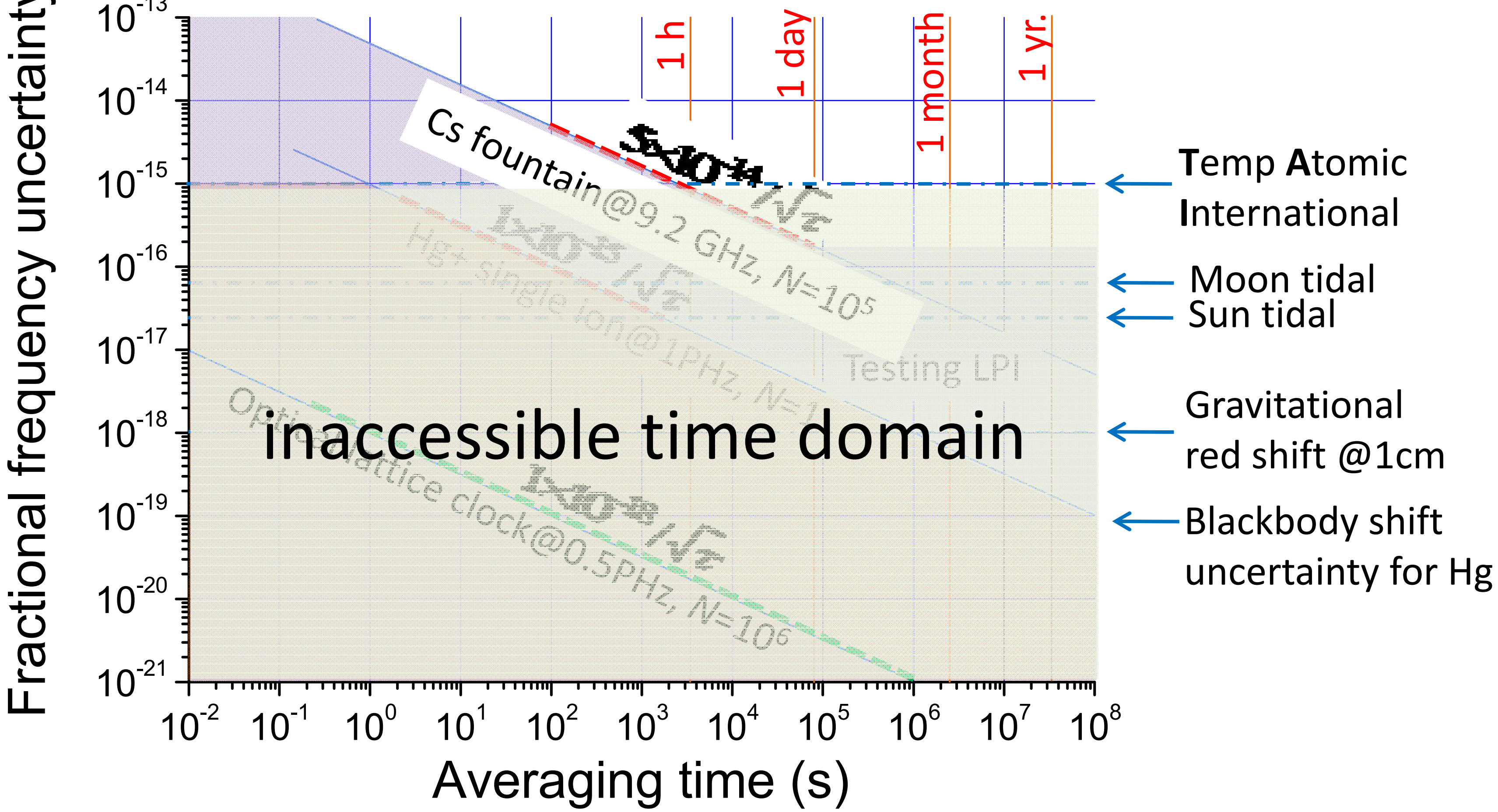
Clock stability, Allan variance:

$$\sigma(\tau)=\frac{\Delta\nu}{\nu_0}=\frac{\gamma}{\nu_0}\frac{1}{\sqrt{N}}=\frac{\gamma}{\nu_0}\frac{1}{\sqrt{n\tau/T_C}}$$

T_C: Cycle time

n/T_C: Observed atoms/cycle

τ: Averaging time



Our approach for novel atomic clock
― Engineering of the perturbation ―

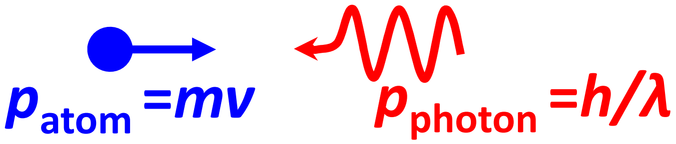
- Traditional approach: ultimate removal of the electromagnetic field from interrogated atoms
  - Quantum mechanical stability limit achieved for single-ion clocks
- Is application of well-engineered perturbation improve clocks?
  - Freeze atomic motion (within optical wavelength) to suppress Doppler shift similar to an ion in a Paul trap
  - Can one control perturbation with 18 digits?
  - **Concept of "Optical lattice clock"**
    （Proposal: Katori @Freq. Metr. Symp. 2001 ）

Whether one can make atomic clocks in presence of strong perturbation is a challenge to a tradition of atomic clocks over 50 yrs.

Manipulation of atomic motion by lasers

(Chu, Cohen-Tannoudji, Phillips, 1997 Nobel Prize)

1) Laser Cooling:

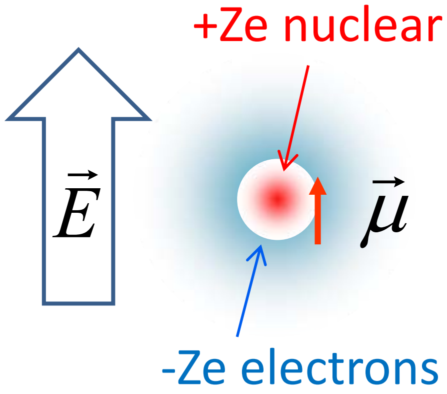

$p_{atom} = mv$ $p_{photon} = h/\lambda$

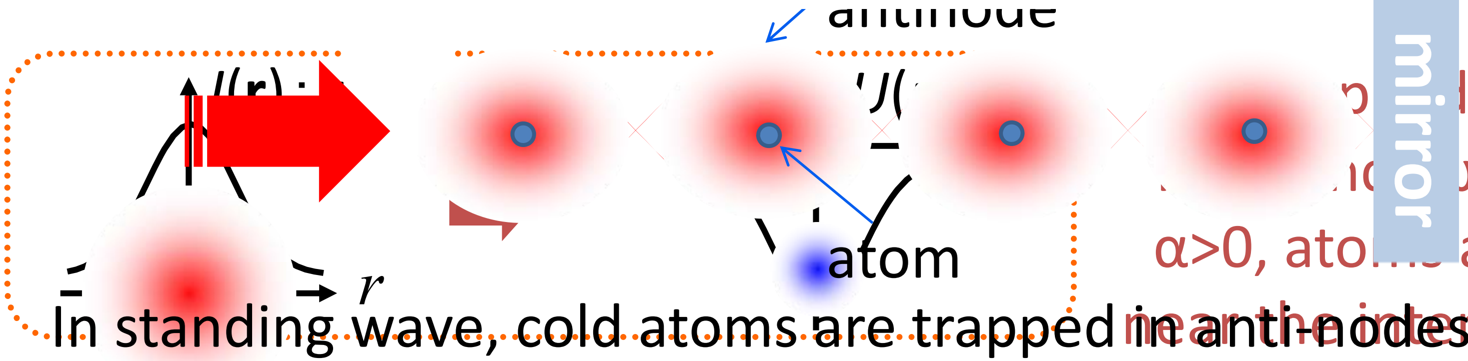
Atom's momentum is controlled by photons' momenta

→ cool atoms down to ~μK and below

2) Optical dipole trap:

Applying electric field, atoms are polarized.





ds on laser

o. For ω < ω_0

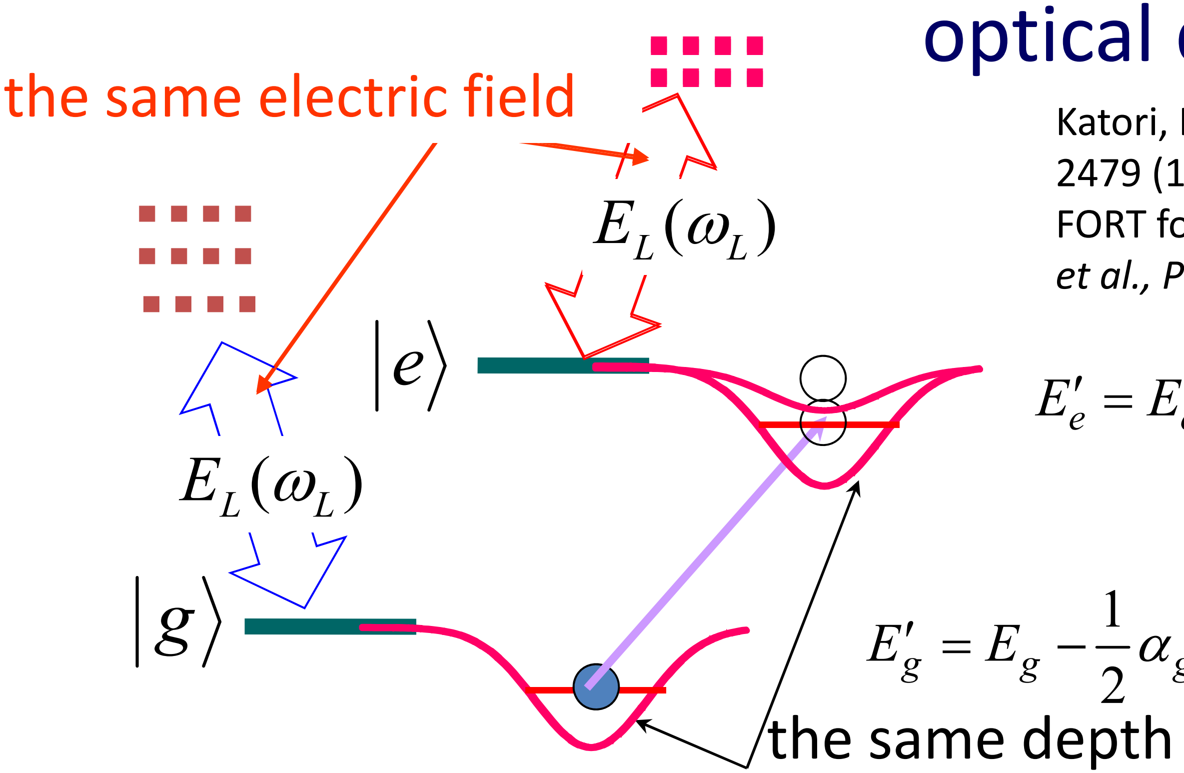
α>0, ato are confined

near the intensity maxima.

In standing wave, cold atoms are trapped in anti-nodes, where the light intensity is maximum: **OPTICAL LATTICE "array of atoms"**

Elimination of light field perturbation in optical dipole traps (1999)

Katori, Ido, & Gonokami, *J. Phys. Soc. Jpn*. **68**, 2479 (1999)
FORT for Rb C-QED experiment: J. McKeever *et al., Phys. Rev. Lett*. **90**, 133602 (2003).



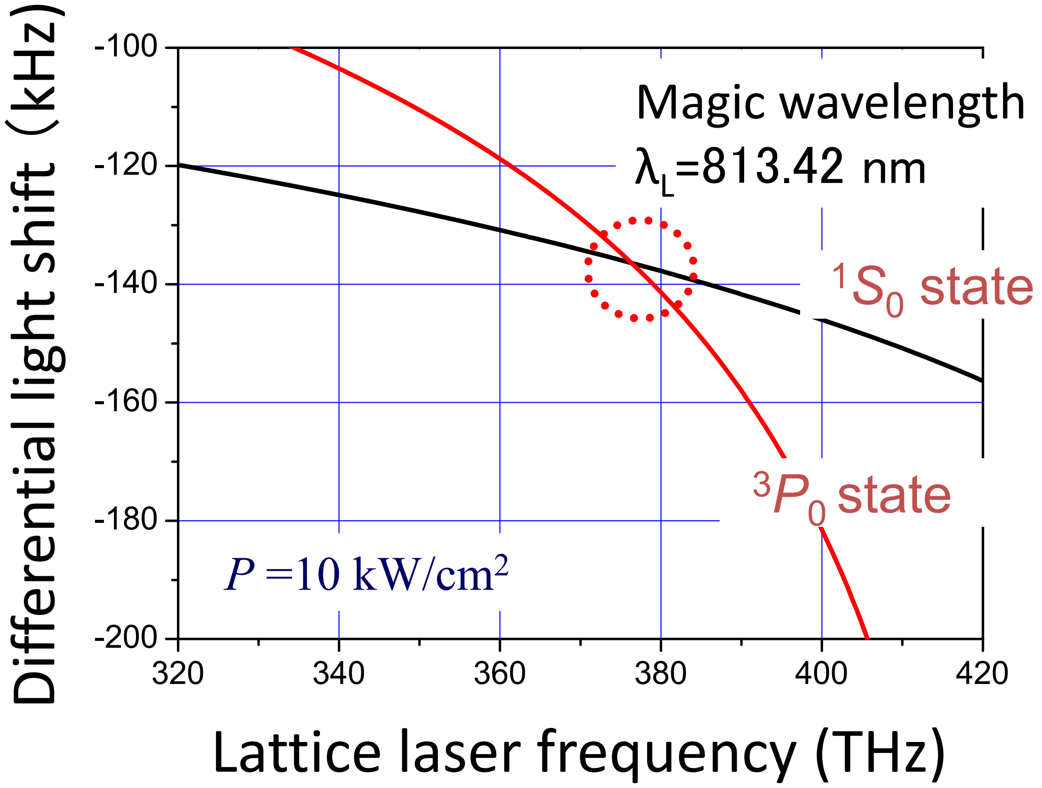
$$E'_e = E_e - \frac{1}{2}\alpha_e(\omega_L)\left|E_L(\mathbf{r},\omega_L)\right|^2$$

$$E'_g = E_g - \frac{1}{2}\alpha_g(\omega_L)\left|E_L(\mathbf{r},\omega_L)\right|^2$$

$$h\nu_{\text{atom}} = (E_e - E_g)$$

Light field perturbation can be eliminated, if the “differential polarizability” is ZERO:

Controlling light shift on the $^1S_0$-$^3P_0$ transition



Freq. dependence

$$\frac{d\nu_{ac}}{d\nu_L} = -1\times10^{-9}$$

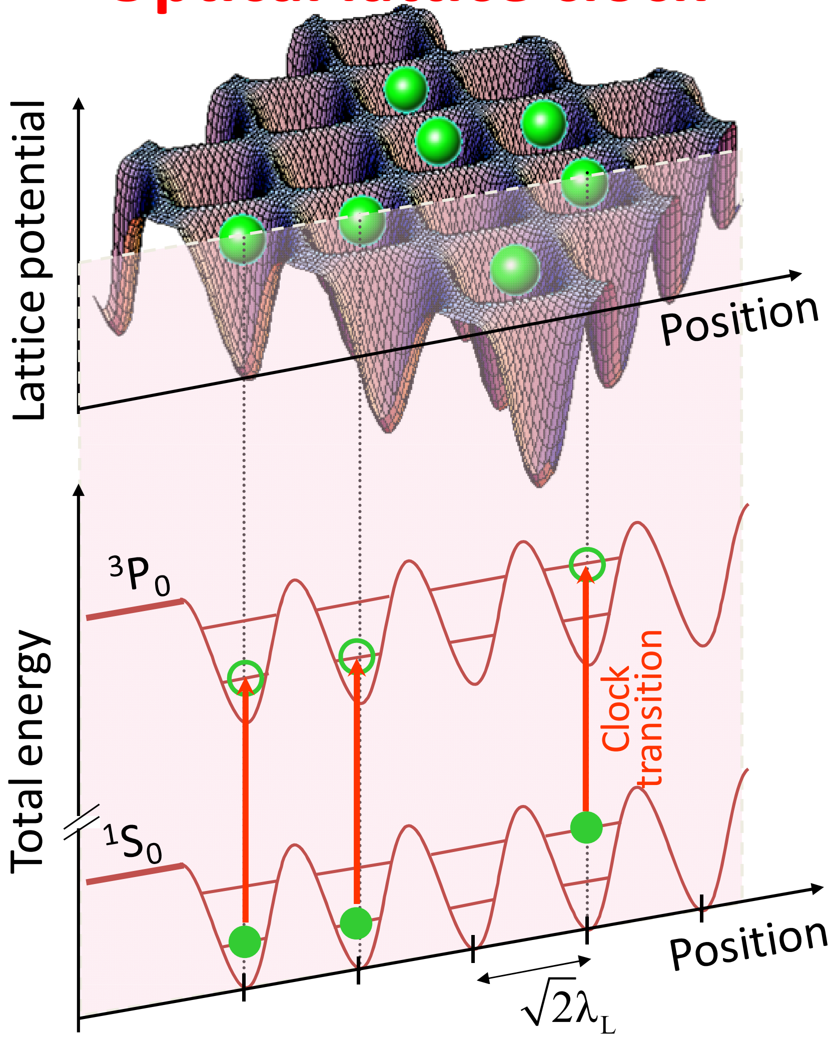
- 18-digits uncertainty can be guaranteed by sharing the "magic wavelength $\lambda = c/\nu_L$" by 9 digits

◎ Possibility of 18-digits accuracy clock by engineered perturbation

(Theory) Katori, Takamoto, Pal'chikov & Ovisannikov, Phys. Rev. Lett. 91,173005(2003).
(Experiment) M. Takamoto & H. Katori, Phys. Rev. Lett. 91, 223001(2003).

Controlling light shift on the $^1S_0$-$^3P_0$ transition

"Optical lattice clock"



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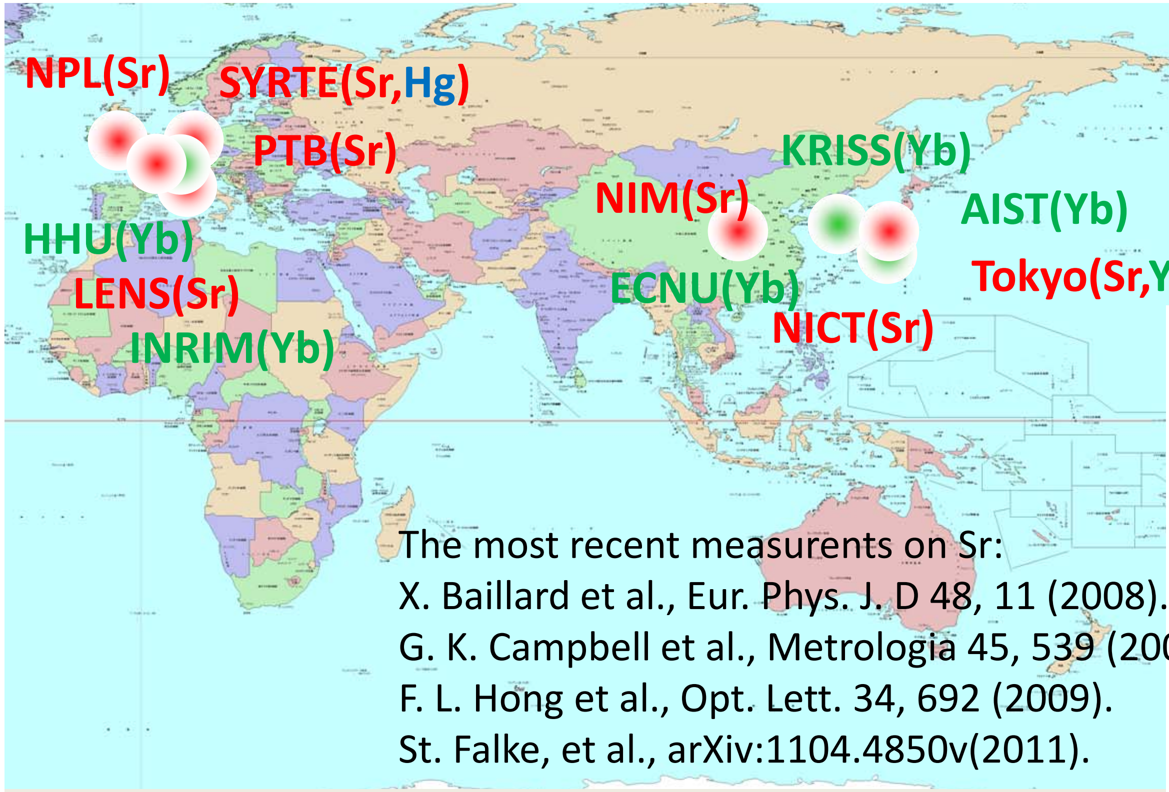
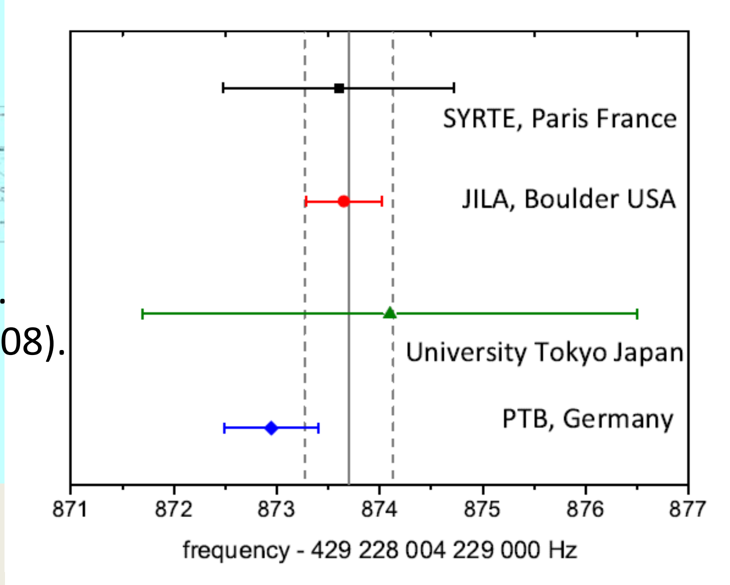
(Experiment) M. Takamoto & H. Katori, Phys. Rev. Lett. 91, 223001(2003).

Realization of Sr lattice clocks in the world and adoption as "the secondary representation as a second" in 2006.10



The most recent measurents on Sr:
X. Baillard et al., Eur. Phys. J. D 48, 11 (2008).
G. K. Campbell et al., Metrologia 45, 539 (2008).
F. L. Hong et al., Opt. Lett. 34, 692 (2009).
St. Falke, et al., arXiv:1104.4850v(2011).



RECOMMENDATION CIPM (2009.10)

f_{87Sr} = 429 228 004 229 873.7

with relative standard uncertainty of 1 x 10^{-15}

Equivalent to the uncertainty of the SI second! (or limited by SI)

Optical-optical comparison necessary for further evaluation.

CIPM: Comité International des Poids et Mesures

Essence of the lattice clock scheme:

Create **accurate time/freq. using less-accurate time/freq**. by sharing "magic wavelength" protocol, which relies on the fact that freq. is the most accurately controllable parameter in physics.

However, in reality, atoms are more complicated…

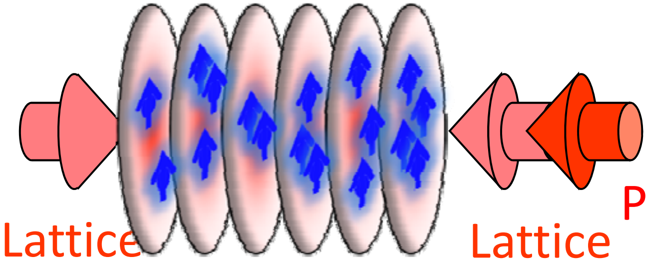
- Nuclear spin
- Coupling of atomic spin to light polarization
- Atom-atom interactions (collisions)
- Higher order atom-field effects
- Multipolar atom-field interactions …

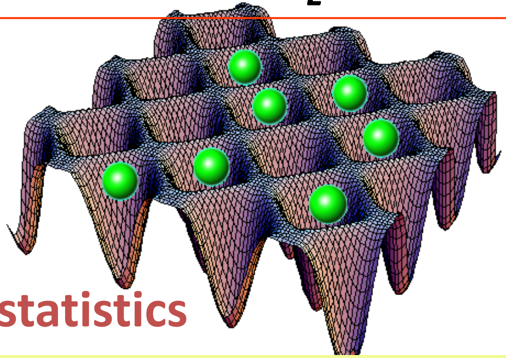
There provide interesting (many body) physics to work with…

Designing optical lattice clocks: many body physics

—"Lattice Geometry (polarization)" & "Quantum Statistics" —

Note: Optical lattice clocks use *J*=0 → *J*=0 transition to be insensitive to $\boldsymbol{\varepsilon}_L$
Fermions have half integer spin (*F*≠0) → sensitive to $\boldsymbol{\varepsilon}_L$
Bosons (may) have zero spin (*J*=0)→ insensitive to $\boldsymbol{\varepsilon}_L$





Quantum statistics

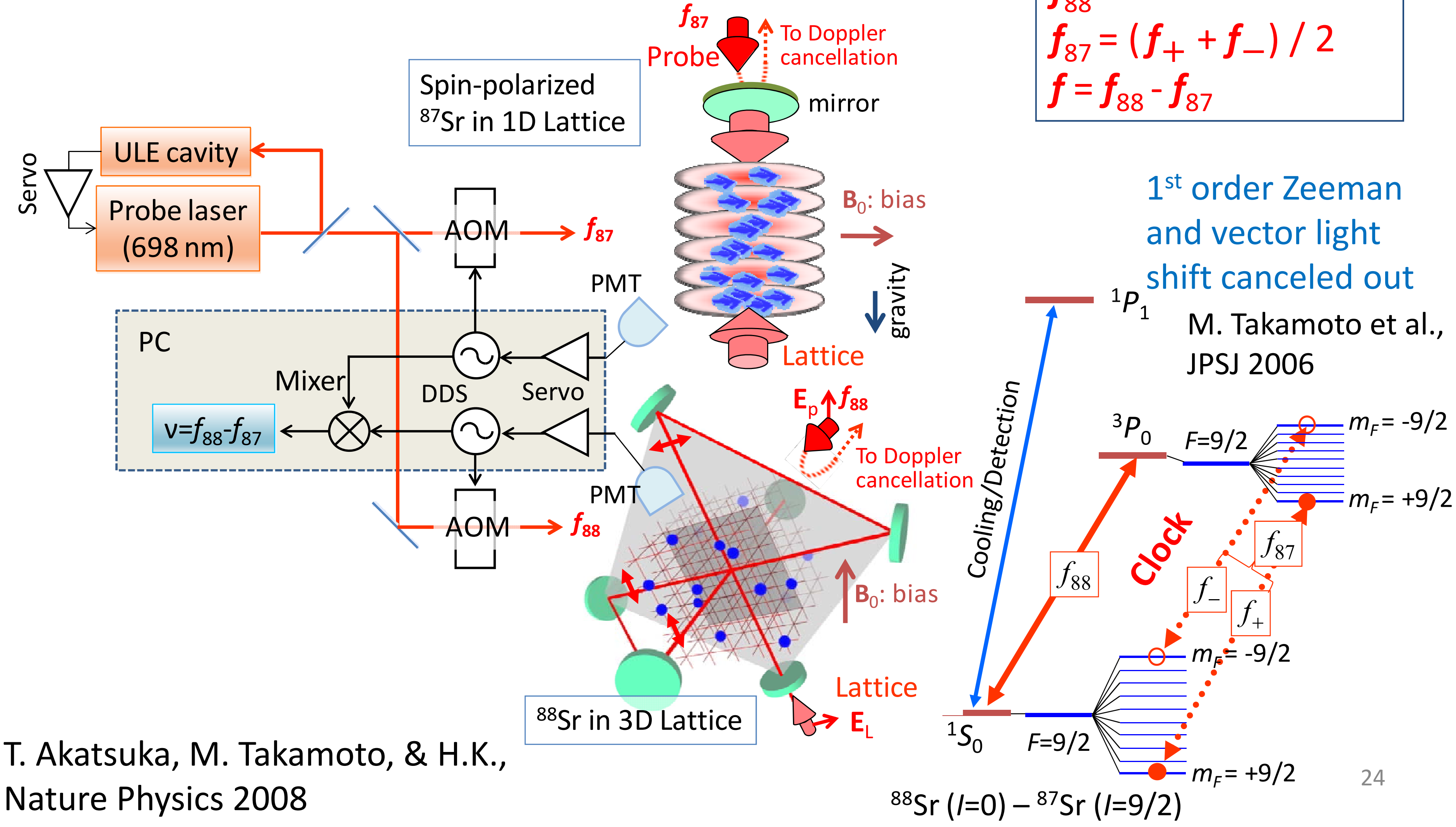
Lattice geometry

	Fermion (*F*≠0)	Boson (*J*=0)
1D (2D)	**◎Pauli blocking of collisions** (Spatially uniform polarization, vector light shift cancellation)	× Cold collisions unavoidable C Lisdat, et al., PRL 103, 090801 (2009)
3D	△vector shifts? (Local and non-uniform elliptical polarization)	**◎Single occupancy** **◎Better S/N？** (Larger # of atoms)

Vector light shift cancellation: Takamoto et al., JPSJ (2006)

T. Akatsuka, M. Takamoto, & H.K., Nature Physics 2008

Frequency comparison between optical lattice clocks with “**non-interacting**” bosons and fermions



$\boldsymbol{f}_{88}$

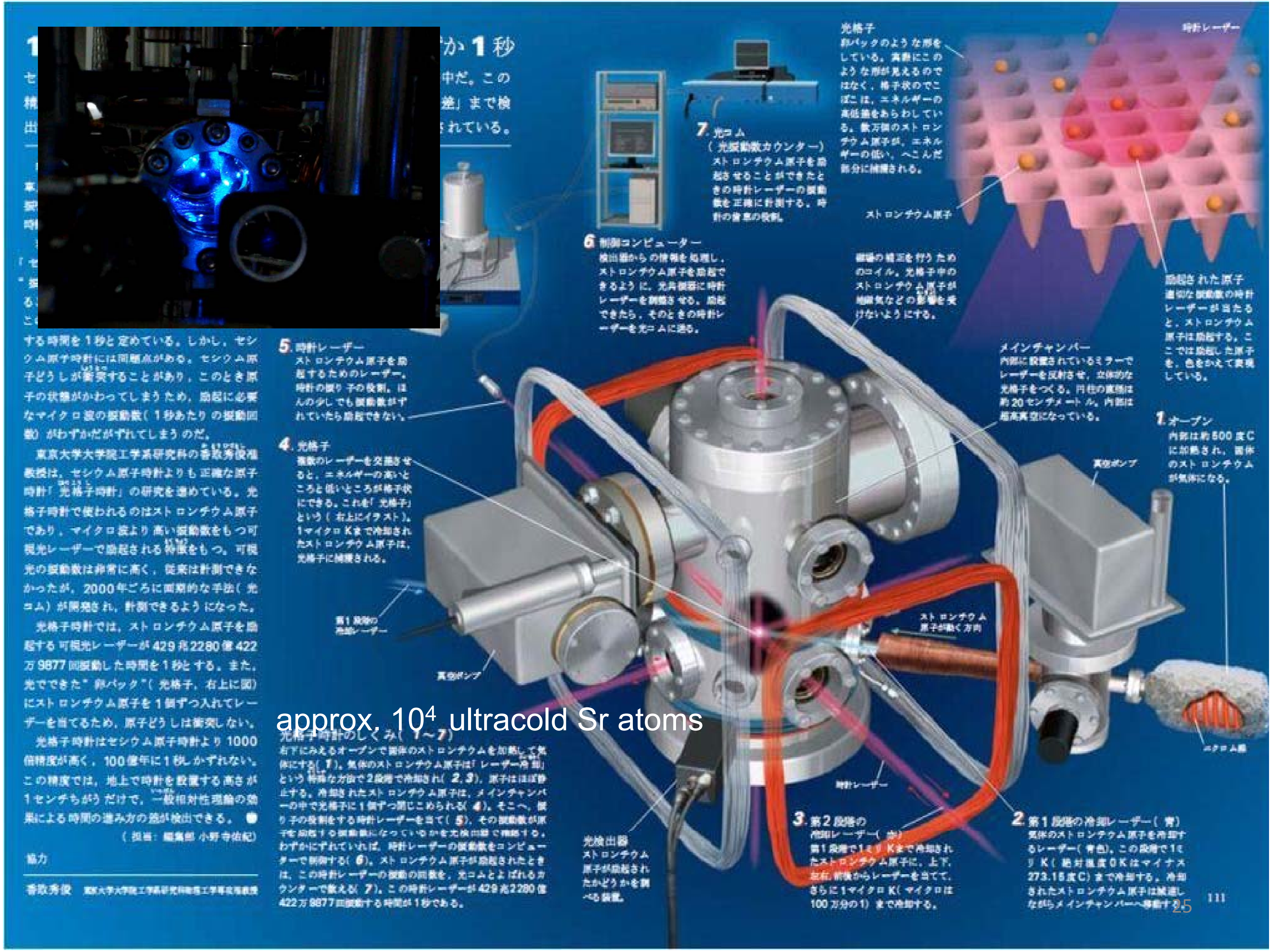
$\boldsymbol{f}_{87} = (\boldsymbol{f}_+ + \boldsymbol{f}_-) / 2$

$\boldsymbol{f} = \boldsymbol{f}_{88} - \boldsymbol{f}_{87}$

1st order Zeeman and vector light shift canceled out

M. Takamoto et al., JPSJ 2006

T. Akatsuka, M. Takamoto, & H.K., Nature Physics 2008



か1秒

中だ。この

差」まで検

されている。

する時間を1秒と定めている。しかし，セシウム原子時計には問題点がある。セシウム原子どうしが衝突することがあり，このとき原子の状態がかわってしまうため，励起に必要なマイクロ波の振動数（1秒あたりの振動回数）がわずかだがずれてしまうのだ。

東京大学大学院工学系研究科の香取秀俊准教授は，セシウム原子時計よりも正確な原子時計「光格子時計」の研究を進めている。光格子時計で使われるのはストロンチウム原子であり，マイクロ波より高い振動数をもつ可視光レーザーで励起される特徴をもつ。可視光の振動数は非常に高く，従来は計測できなかったが，2000年ごろに画期的な手法（光コム）が開発され，計測できるようになった。

光格子時計では，ストロンチウム原子を励起する可視光レーザーが429兆2280億422万9877回振動した時間を1秒とする。また，光でできた"卵パック"（光格子，右上に図）にストロンチウム原子を1個ずつ入れてレーザーを当てるため，原子どうしは衝突しない。

光格子時計はセシウム原子時計より1000倍精度が高く，100億年に1秒しかずれない。この精度では，地上で時計を設置する高さが1センチちがうだけで，一般相対性理論の効果による時間の進み方の差が検出できる。●

（担当：編集部 小野寺佑紀）

協力

香取秀俊 東京大学大学院工学系研究科物理工学専攻准教授

光格子時計のしくみ（1〜7）

右下にみえるオーブンで固体のストロンチウムを加熱して気体にする（1）。気体のストロンチウム原子は「レーザー冷却」という特殊な方法で2段階で冷却され（2，3），原子はほぼ静止する。冷却されたストロンチウム原子は，メインチャンバーの中で光格子に1個ずつ閉じこめられる（4）。そこへ，振り子の役割をする時計レーザーを当て（5），その振動数が原子を励起する振動数になっているかを光検出器で確認する。わずかにずれていれば，時計レーザーの振動数をコンピューターで制御する（6）。ストロンチウム原子が励起されたときは，この時計レーザーの振動の回数を，光コムとよばれるカウンターで数える（7）。この時計レーザーが429兆2280億422万9877回振動する時間が1秒である。

1. オーブン
内部は約500度Cに加熱され，固体のストロンチウムが気体になる。

2. 第1段階の冷却レーザー（青）
気体のストロンチウム原子を冷却するレーザー（青色）。この段階で1ミリK（絶対温度0Kはマイナス273.15度C）まで冷却する。冷却されたストロンチウム原子は減速しながらメインチャンバーへ移動する。

3. 第2段階の冷却レーザー（赤）
第1段階で1ミリKまで冷却されたストロンチウム原子に，上下，左右，前後からレーザーを当てて，さらに1マイクロK（マイクロは100万分の1）まで冷却する。

4. 光格子
複数のレーザーを交差させると，エネルギーの高いところと低いところが格子状にできる。これを「光格子」という（右上にイラスト）。1マイクロKまで冷却されたストロンチウム原子は，光格子に捕獲される。

5. 時計レーザー
ストロンチウム原子を励起するためのレーザー。時計の振り子の役割。ほんの少しでも振動数がずれていたら励起できない。

6. 制御コンピューター
検出器からの情報を処理し，ストロンチウム原子を励起できるように，光共振器に時計レーザーを調整させる。励起できたら，そのときの時計レーザーを光コムに送る。

7. 光コム（光振動数カウンター）
ストロンチウム原子を励起させることができたときの時計レーザーの振動数を正確に計測する。時計の歯車の役割。

光格子
卵パックのような形をしている。実際にこのような形が見えるのではなく，格子状のでこぼこは，エネルギーの高低差をあらわしている。数万個のストロンチウム原子が，エネルギーの低い，へこんだ部分に捕獲される。

励起された原子
適切な振動数の時計レーザーが当たると，ストロンチウム原子は励起する。ここでは励起した原子を，色をかえて表現している。

地磁気の補正を行うためのコイル。光格子中のストロンチウム原子が地磁気などの影響を受けないようにする。

メインチャンバー
内部に設置されているミラーでレーザーを反射させ，立体的な光格子をつくる。円柱の直径は約20センチメートル。内部は超高真空になっている。

光検出器
ストロンチウム原子が励起されたかどうかを調べる装置。

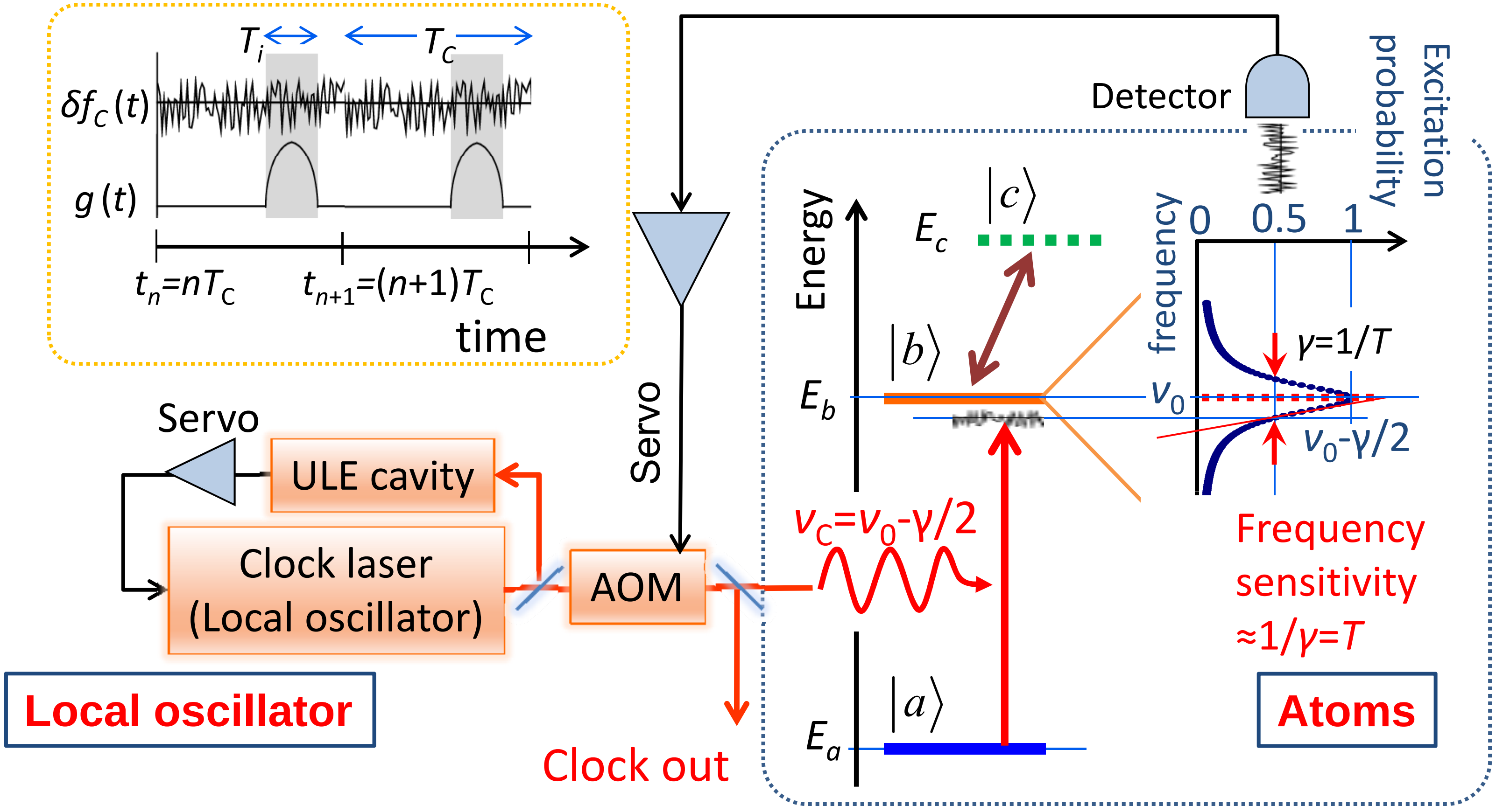
111

approx. 10^4 ultracold Sr atoms

ディック(Dick) 効果･その除去

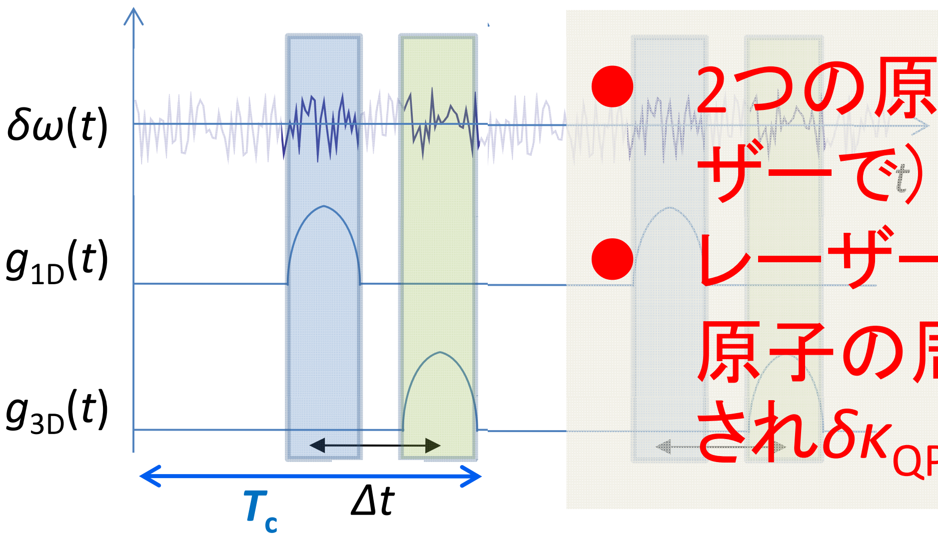
- 光時計：原子の共鳴周波数を基準にして、レーザー周波数を制御したい。
- ところが、レーザーの周波数変動の一部しかサンプルしていない。速いレーザーノイズ成分がダウンコンバートされて、制御信号にノイズが加わる（Dick効果）。励起確率$\boldsymbol{\kappa}$ に $\boldsymbol{\delta\kappa_{\mathrm{Dick}}}$ 分のノイズが加わる。
- 光格子時計で、量子ノイズを $\boldsymbol{\delta\kappa_{\mathrm{QPN}} \approx 1/\sqrt{N}}$ に改善したのに、今度はレーザーノイズ由来のディック効果に道を阻まれた。

G. J. Dick, et al., in 22nd PTTI Meeting 1990.



Synchronous interrogations of atoms to reduce the noise of a probe laser and the Dick effect

Sequential interrogation

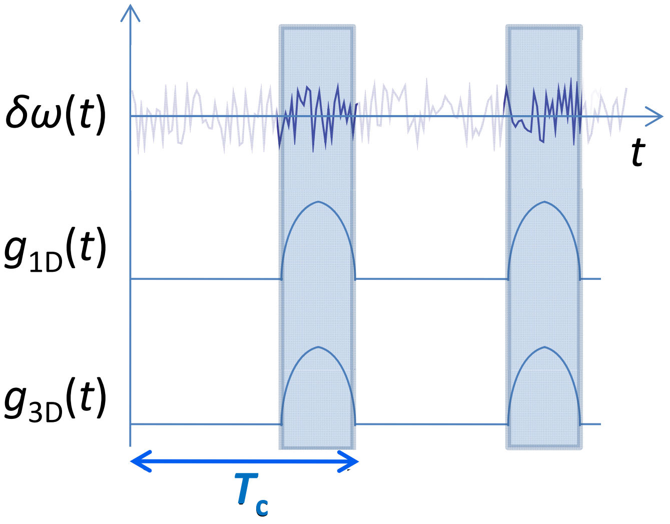


- $\delta\omega(t)$: frequency fluctuation of probe laser
- $g(t)$: sensitivity (to frequency fluctuation of probe laser) function of atoms
- Population fluctuation $\delta\kappa$ after interrogation :

$$\delta\kappa_{1D} = \kappa\int_{T_c} g_{1D}(t)\,\delta\omega(t)\,dt$$

$$\delta\kappa_{3D} = \kappa\int_{T_c} g_{3D}(t)\,\delta\omega(t-\Delta t)\,dt$$

- 2つの原子の遷移を(ノイズをもつレーザーで)同相でプローブする
- レーザーノイズの効果$\delta\kappa_{\mathrm{Dick}}$は、2つの原子の周波数差の測定では同相除去され$\delta\kappa_{\mathrm{QPN}}$だけ残る



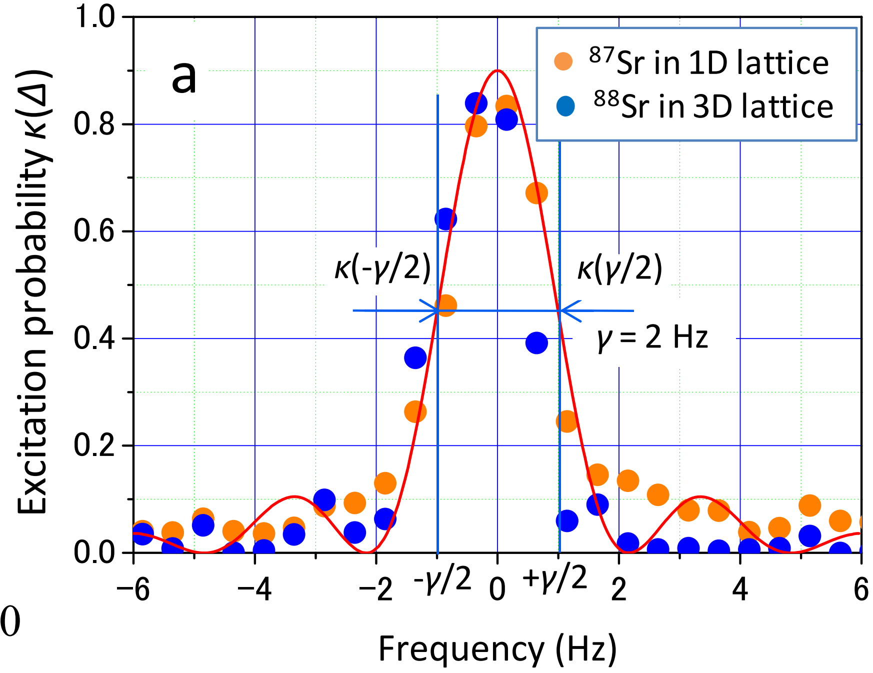
Synchronous interrogation:

Both atoms observe laser noise as a common mode noise

If $g_{1D}(t)=g_{3D}(t)$,
the frequency fluctuation of probe laser would be rejected between two clocks.

S. Bize, et al., IEEE Trans. Ultrason., Ferroelectr., Freq. Contr. 47, 5 (2000)
J. Lodewyck, et al., New Jour. Phys. 12, 065026 (2010).
cf. C. W. Chou et al., Phys. Rev. Lett. 106, 160801 (2011).

2台（^{88}Sr/^{87}Sr）の時計の同期比較



$$\nu = f_{88} - f_{87}$$

$$\approx \beta(\kappa^{88} + \delta\kappa^{88}_{\mathrm{Dick}} + \delta\kappa^{88}_{\mathrm{QPN}})$$

$$- \beta(\kappa^{87} + \delta\kappa^{87}_{\mathrm{Dick}} + \delta\kappa^{87}_{\mathrm{QPN}}) + \nu_0$$

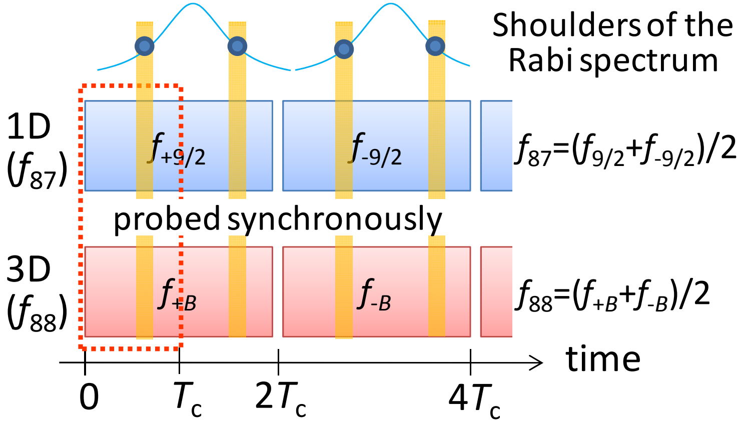
$$\approx \beta\left[(\kappa^{88} - \kappa^{87}) + (\delta\kappa^{88}_{\mathrm{QPN}} - \delta\kappa^{87}_{\mathrm{QPN}})\right] + \nu_0$$

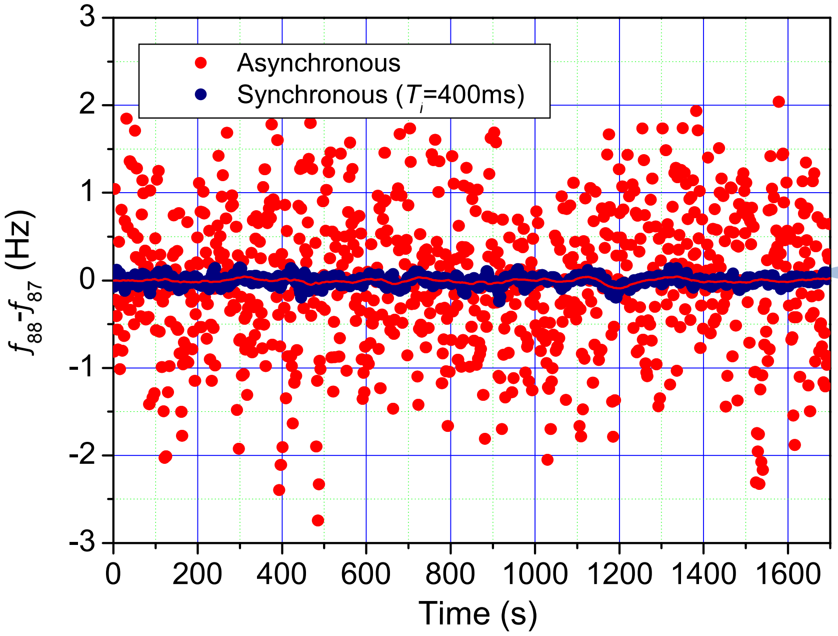
βは、射影測定から得られた励起確率κ（揺らぎ$\delta\kappa$）を周波数変化へ変換する係数。ν_0は同位体シフト。
$\Delta\kappa=\kappa^{88}$-$\kappa^{87}\rightarrow 0$となるように、ν_0にサーボをかける

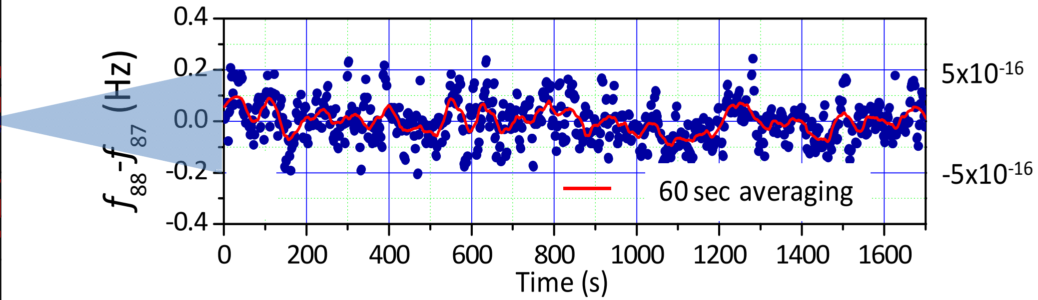
^{87}Sr-^{88}Sr comparison near the “Quantum Limit”

Common mode rejection of laser noise by synchronous operation

Slowly drifting environmental B field is removed.



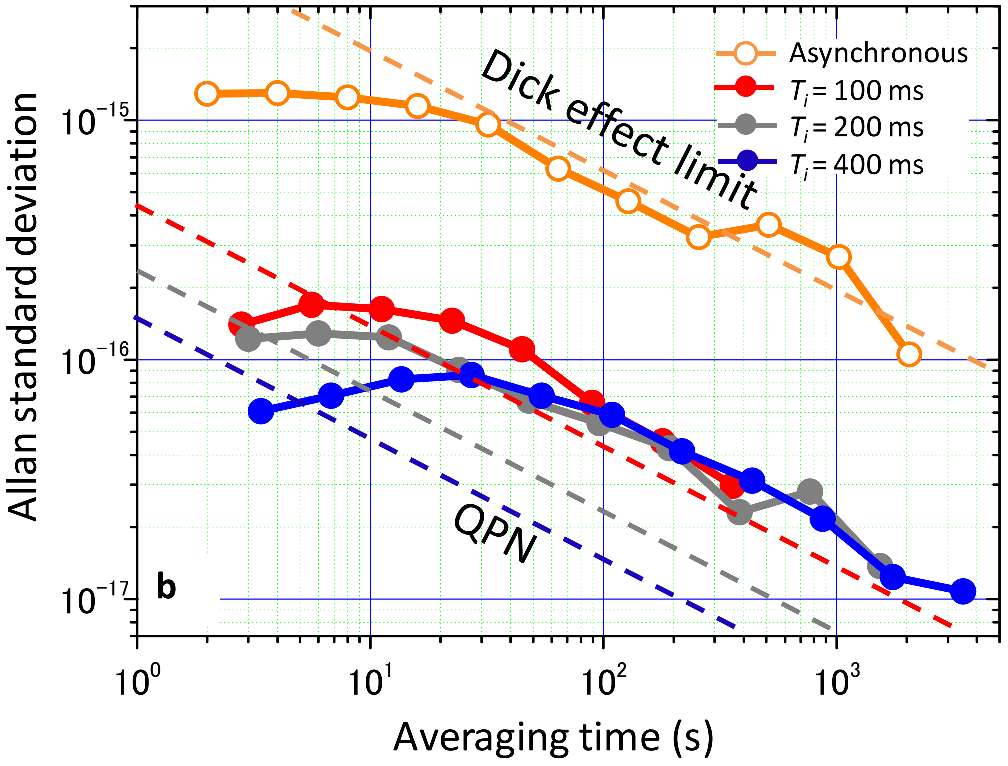


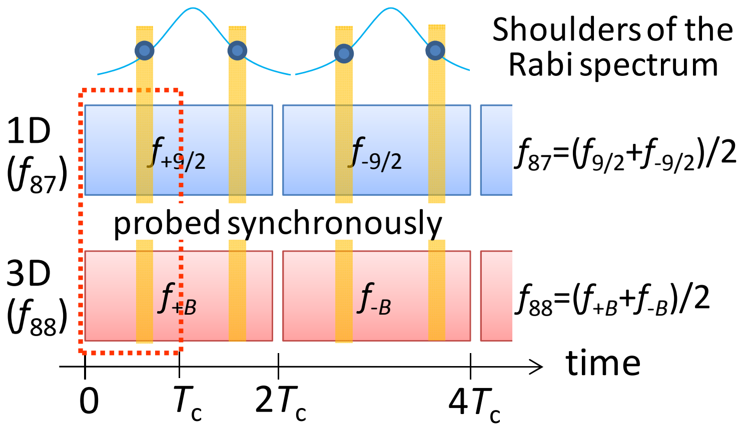


A fractional frequency difference of a few times 10^{-16} is visible within tens of seconds

^{87}Sr-^{88}Sr comparison near the “Quantum Limit”

Common mode rejection of laser noise by synchronous operation





← Moon tidal

← Sun tidal

← Black body radiation shift (ΔT<0.3K)

← Gravitational red shift
for 10 cm height dif.

M. Takamoto, T. Takano, and H. Katori,
Nature Photon. 5, 288 (2011).

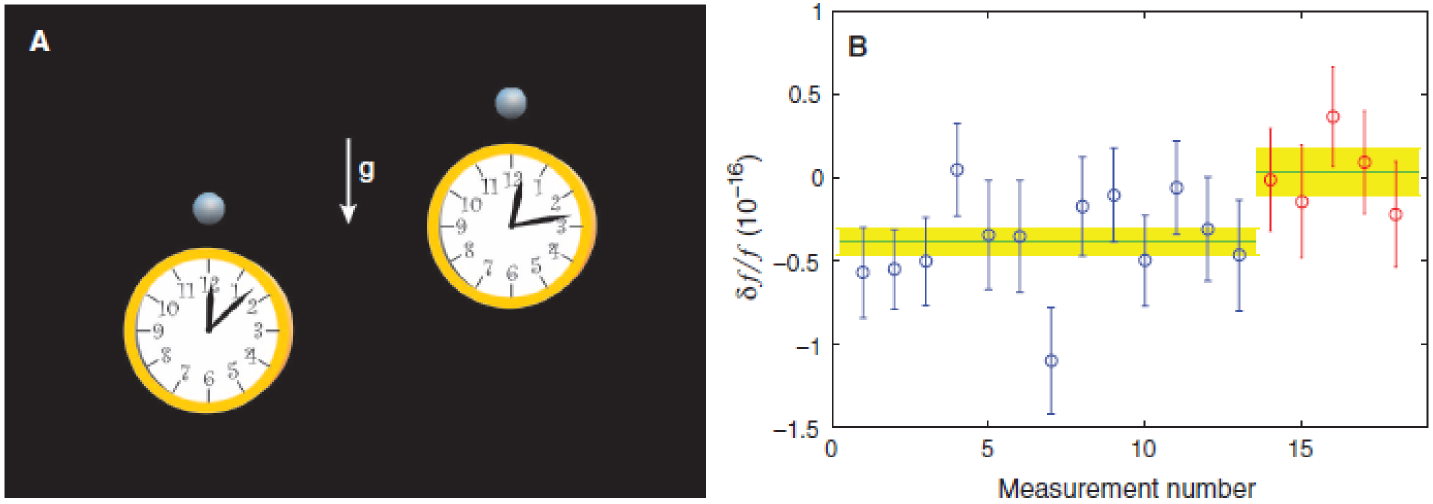
First demonstration of the *N* ≈1,000 shot noise limit in optical clocks.

M. Takamoto, T. Takano, and H. Katori, Nature Photon. 5, 288 (2011).

1630 24 SEPTEMBER 2010 VOL 329 SCIENCE

Optical Clocks and Relativity

C. W. Chou,* D. B. Hume, T. Rosenband, D. J. Wineland



33 cm

重力があると時計は
ゆっくり進む

$$\frac{\delta f}{f_0} = \frac{g\Delta h}{c^2} \Rightarrow 1.1\times 10^{-17} / 10\ \mathrm{cm}$$

1.6×10^{-17} uncertainty for 40,000 s (≈ 11 hours) averaging time
Optical lattice clock can do it in 15 min!

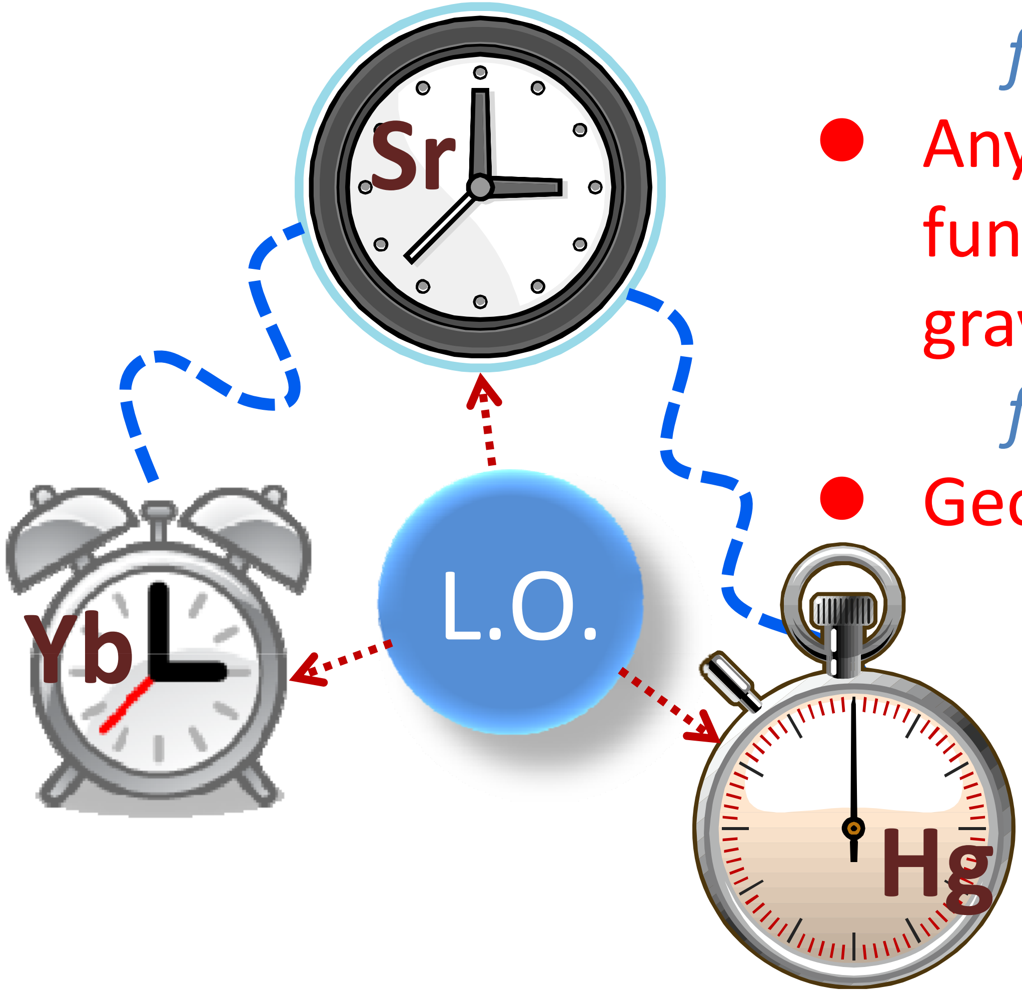
Physical effects that may contribute to a flicker floor @1×10^{-17}

Contributor	**Parameter to be controlled**	**^{87}Sr atoms in 1D lattice**	**^{88}Sr atoms in 3D lattice**
Lattice scalar light shift	Lattice laser frequency	Δf = 4 MHz (I = 13 kW/cm^2)	Δf = 6 MHz (I = 7.9 kW/cm^2)
Probe light shift	Laser intensity	Negligible (I = 0.7μW/cm^2)	$\Delta I/I$ = 0.3% (I = 74 mW/cm^2)
Blackbody shift at 300 K	Environmental temperature	ΔT = 0.1 K ($T \approx$ 296 K)	ΔT = 0.1 K ($T \approx$ 294 K)
Second-order Zeeman shift	Environmental magnetic field	ΔB_0 = 371 nT (B_0 = 0.23 mT)	ΔB_m = 103 nT (B_m = 0.83 mT)
First-order Doppler shift	Relative motion of lattice and lasers	v =3 nm/s	v =3 nm/s

Cryogenic environment necessary!

1×10^{-17} for T_i = 400 ms

Networking optical clocks finds new physics



—Clocks & Gravity

- Constancy of constants?

  $f[\mathrm{Hg}(Z^2\alpha(t)^2)]/f[\mathrm{Sr}(Z^2\alpha(t)^2)]$
- Any coupling between fundamental constants and gravity?

  $f[\mathrm{Hg}(\alpha(U_g))]/f[\mathrm{Sr}(\alpha(U_g))]$
- Geoid search

How does synchronous scheme benefit to these endeavors?

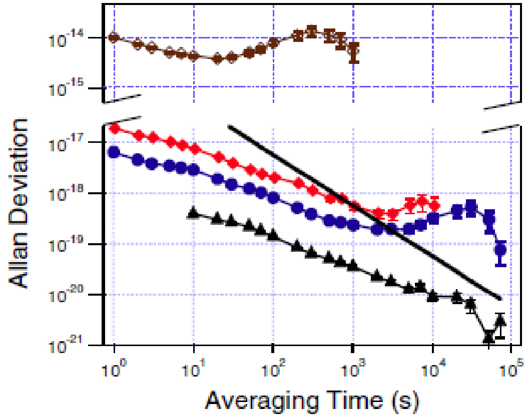
Optical frequency links in the world

PRL 99, 153601 (2007) PHYSICAL REVIEW LETTERS week ending 12 OCTOBER 2007

Coherent Optical Phase Transfer over a 32-km Fiber with 1 s Instability at 10^{-17}

Seth M. Foreman,[1] Andrew D. Ludlow,[1] Marcio H. G. de Miranda,[1] Jason E. Stalnaker,[2] Scott A. Diddams,[2] and Jun Ye

USA, Boulder



LETTERS

Coherent optical link over hundreds of metres and hundreds of terahertz with subfemtosecond timing jitter

I. CODDINGTON[1], W. C. SWANN[1], L. LORINI[2], J. C. BERGQUIST[1], Y. LE COQ[3], C. W. OATES[1], Q. QURAISHI[1], K. S. FEDER[4], J. W. NICHOLSON[4], P. S. WESTBROOK[4], S. A. DIDDAMS[1] AND N. R. NEWBURY[1]*

Europe

H. Jiang et al., J. Opt. Soc. Am. B 25, 2029 (2008).

SYRTE-LPL: 86x2 km

A. Pape et al., Opt. Express 18, 21477 (2010).

PTB-IQ(LUH): 73 km

O. Lopez et al., Opt. Express 18, 16849 (2010).

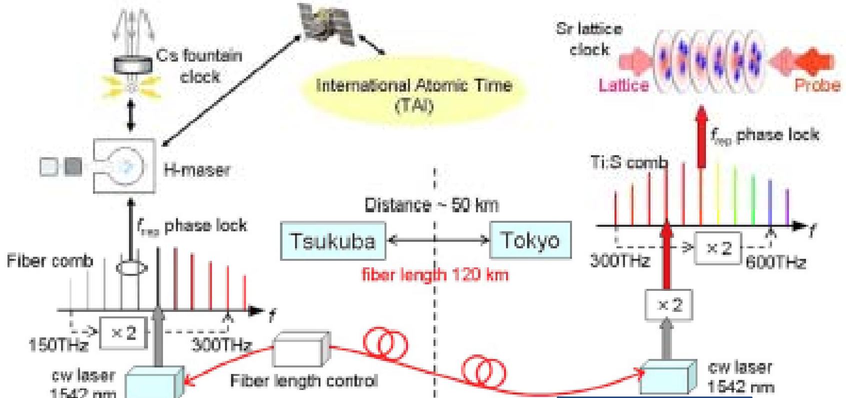
Use of Internet fiber

H. Schnatz et al., IEEE Trans. Ultrason. Ferroelectr. Freq. Control 57, 175 (2010).

MPQ-PTB: 900 km as presented by Predehl on Monday

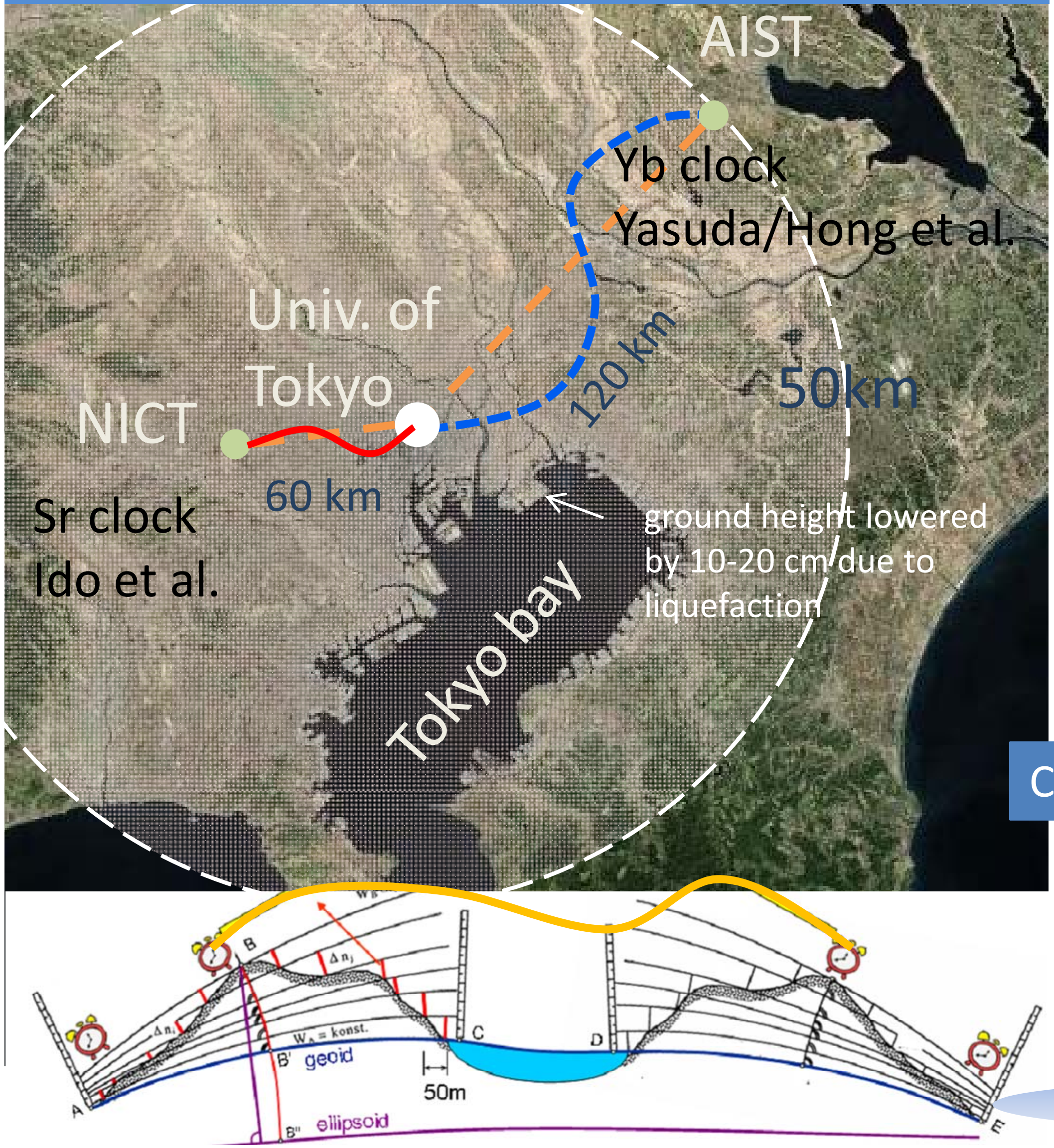
F. L. Hong et al., Opt. Lett. 34, 692 (2009).

AIST-U. of Tokyo: 120 km



Japan

Relativistic geodesy with optical lattice clock & fiber network in Tokyo area

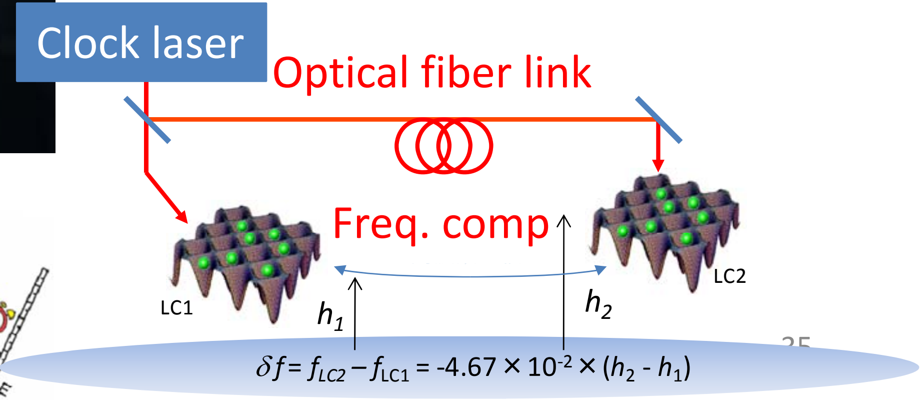


Gravitational red shift as a tool to explore geodesy

Geoid: equipotential surface of gravity (Average sea level of Tokyo bay in case of Japan)

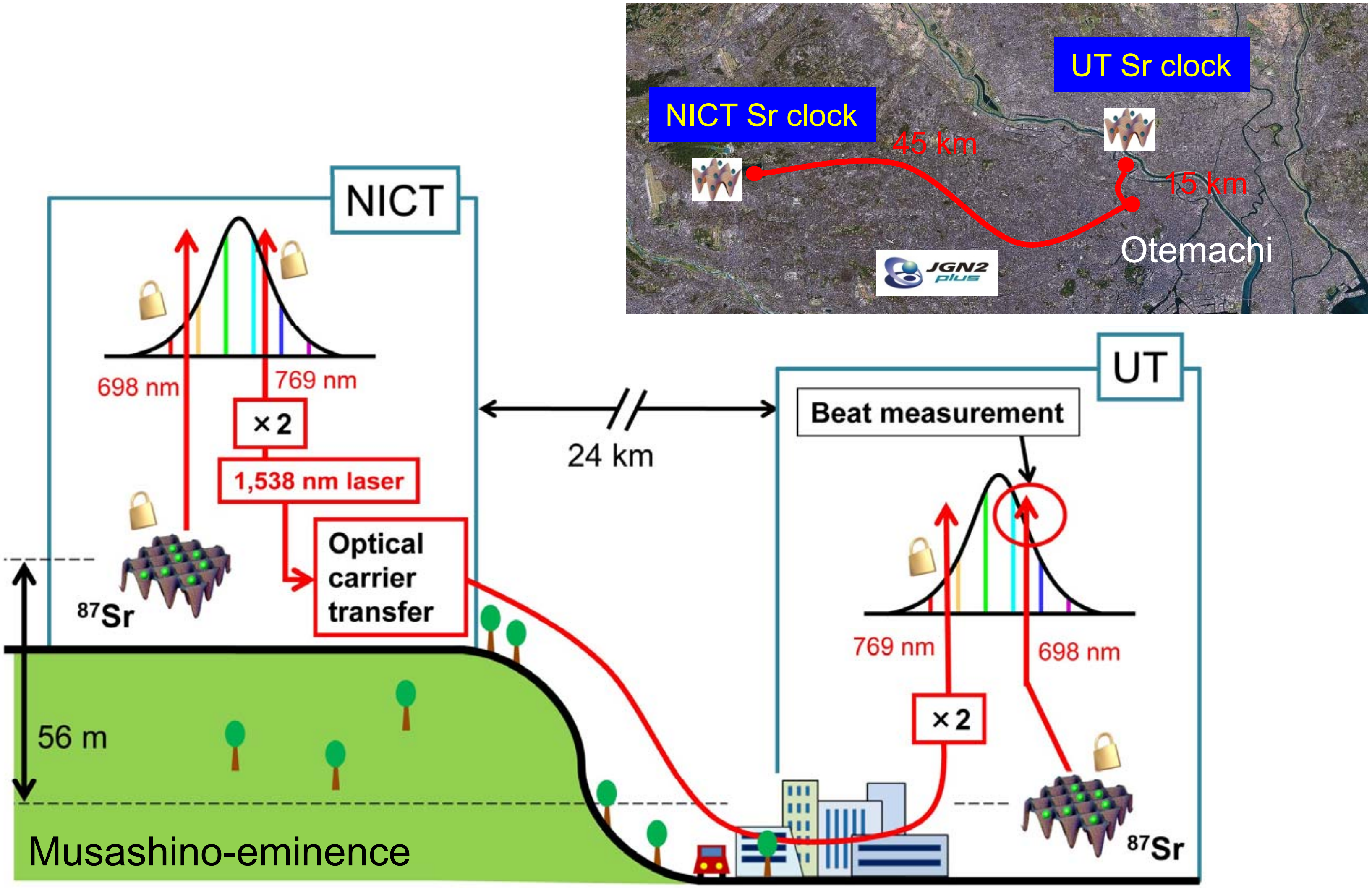
$$\Delta f/f = g\Delta h/c^2$$

- Geoid heights are mapped with 30-50 cm, or 3-5x10^{-17}.
- Frequency link between two sites determine differential geoid height.
- The earth is too soft to share accurate time over long distance!

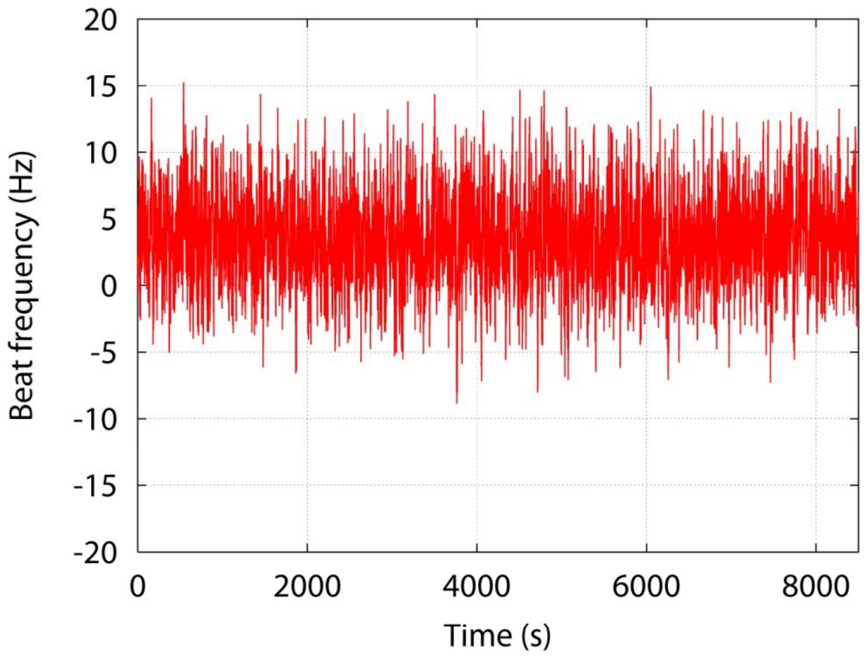


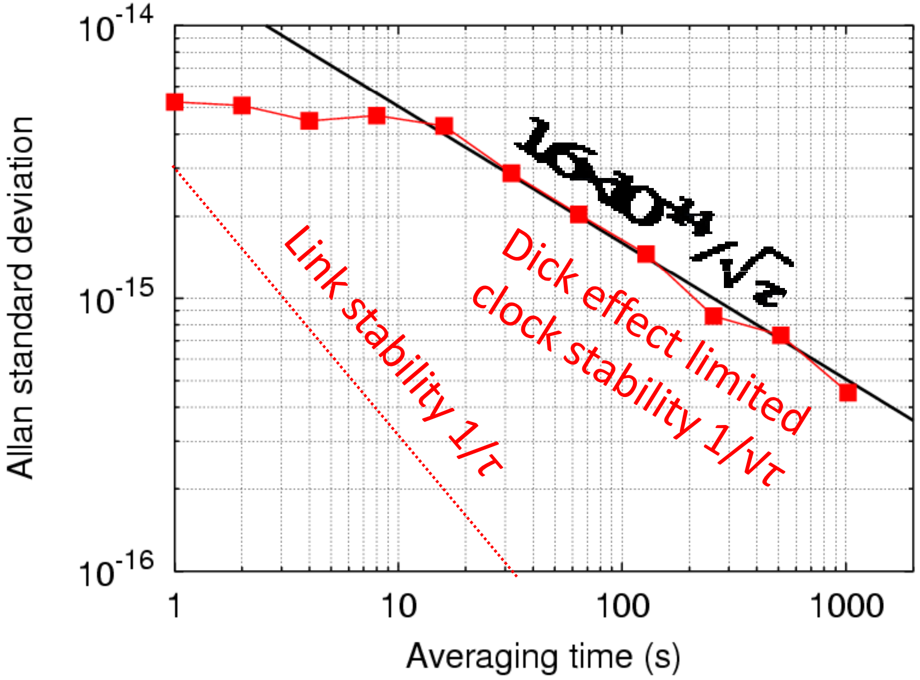
$\delta f = f_{LC2} - f_{LC1} = -4.67 \times 10^{-2} \times (h_2 - h_1)$

Frequency comparison of two optical lattice clocks of 24 km apart with 60 km fiber



Frequency difference and stability between UT-NICT optical lattice clocks





- The frequency difference is mainly attributed to the gravitational red shift of 2.6 Hz

Sr(NICT) - Sr(UT) = 3.66 ± 0.31Hz

- $5\text{x}10^{-16}$@1000s achieved
- Real time probing of the gravitational red shift
- After correcting systematic shifts, $\dfrac{\nu_{\mathrm{NICT}} - \nu_{\mathrm{UT}}}{\nu_0} = 0.9(7.3)\times10^{-16}$

By reducing clock uncertainty down to $1\text{x}10^{-17}$, the geoid height can be the major uncertainty

New Limits on Coupling of Fundamental Constants to Gravity Using ^{87}Sr Optical Lattice Clocks

$\alpha = e^2/hc$

S. Blatt,[*] A. D. Ludlow, G. K. Campbell, J. W. Thomsen,[†] T. Zelevinsky,[‡] M. M. Boyd, and J. Ye
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Department of Physics, University of Colorado, Boulder, Colorado, 80309-0440,
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LNE-SYRTE, Observatoire de Paris, 61, Avenue de l'Observatoire, 75014, Paris,
M. Takamoto, F.-L. Hong,[¶] and H. Katori
Department of Applied Physics, Graduate School of Engineering, The University of Tokyo, Bunkyo-ku,
V. V. Flambaum
School of Physics, The University of New South Wales, Sydney, New South Wales 2052,

Are fundamental constants constant? or coupled to the Gravity? Compare different clocks.

Al+/Hg+ : $\dot{\alpha}/\alpha < (-1.6 \pm 2.3)\times 10^{-17}$ / yr.

$f_{Sr}=F[\alpha \qquad]$,
$f_{Cs}=G[\alpha \qquad]$
$f_{Sr}/f_{Cs}=H[\alpha \qquad]$?

Use of elliptical orbit of the earth as a modulator of sun's gravitational potential. Testing LPI through measuring f_{Sr}/f_{Cs} for 3yrs
→ No coupling observed within measurement uncertainty; This work can be further improved by measuring $f_{Sr}/f_{Hg,Yb}$

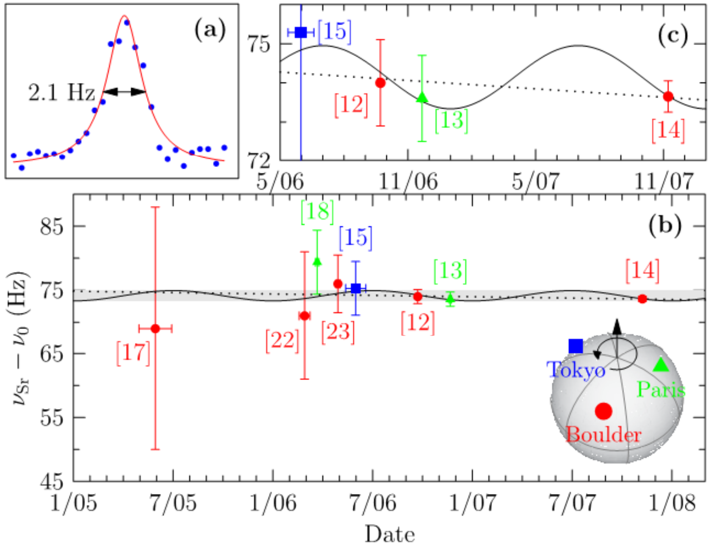
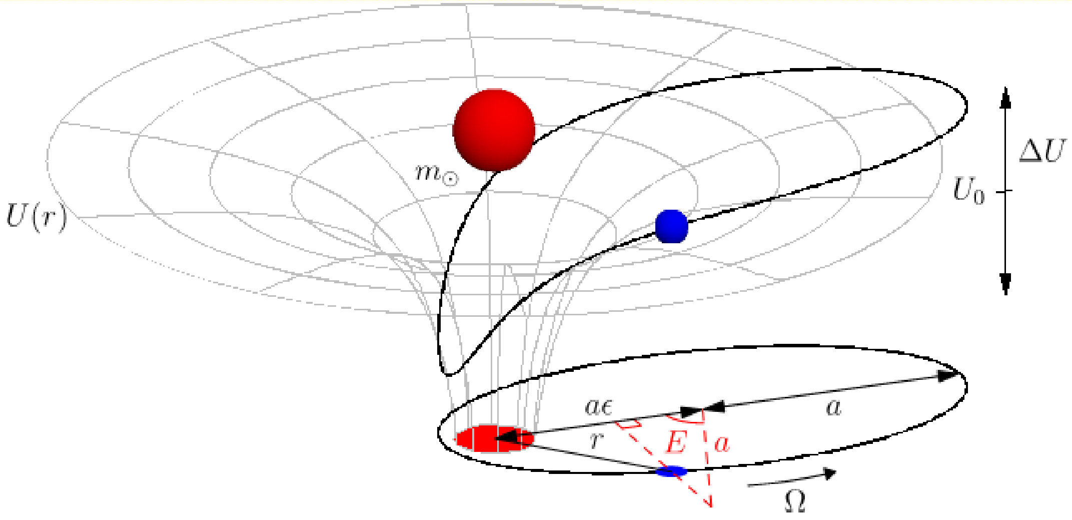
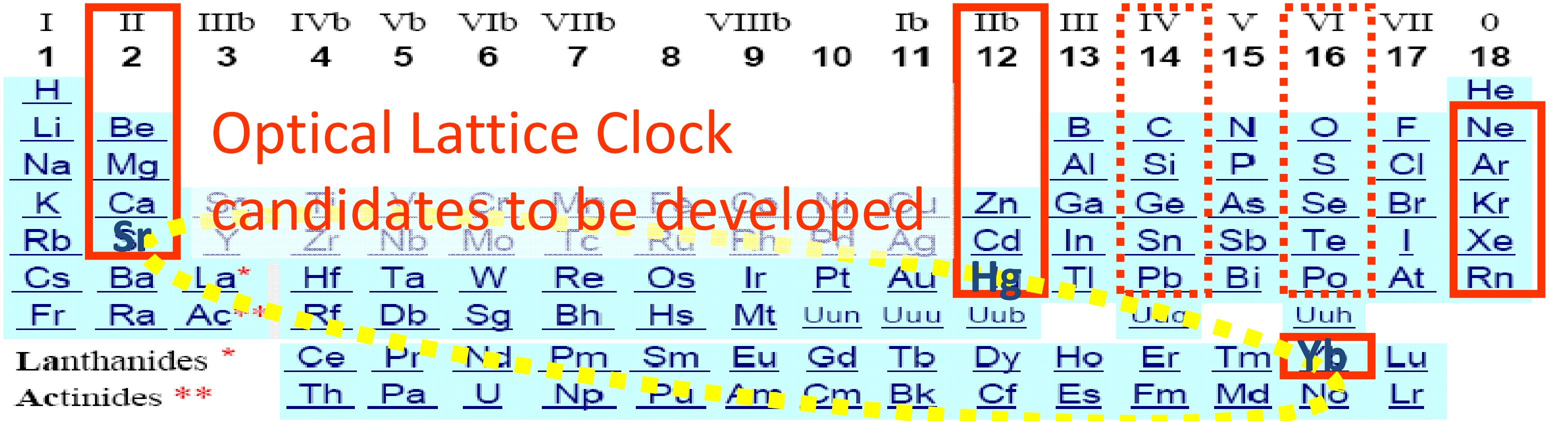


FIG. 1 (color online). (a) Spectrum of the ^{87}Sr $^1S_0$-$^3P_0$ clock transition with quality factor 2×10^{14}. (b) Measurements of the clock transition from JILA (circle), SYRTE (triangle), and U. Tokyo (square) over the last 3 years. Frequency data are shown relative to $\nu_0 = 429\,228\,004\,229\,800$ Hz. Weighted linear (dotted line) and sinusoidal (solid line) fits determine a yearly drift rate and an amplitude of annual variation. (c) Zoom into the four most recent measurements, showing agreement within 1.7 Hz and determining both drift and annual variation.



Do fundamental constants vary in time? Compare clocks.



Exploring the constancy of physical constant, α=*e*²/*hc*, at the limit:

- Dirac theory for H-like atom:

$$E_{n,j} = -\frac{Z^2 Ry}{n^2}\left[1+\frac{\alpha^2 Z^2}{4n^2}\left(\frac{4n}{j+1/2}-3\right)+O(\alpha^4 Z^4)\right]$$

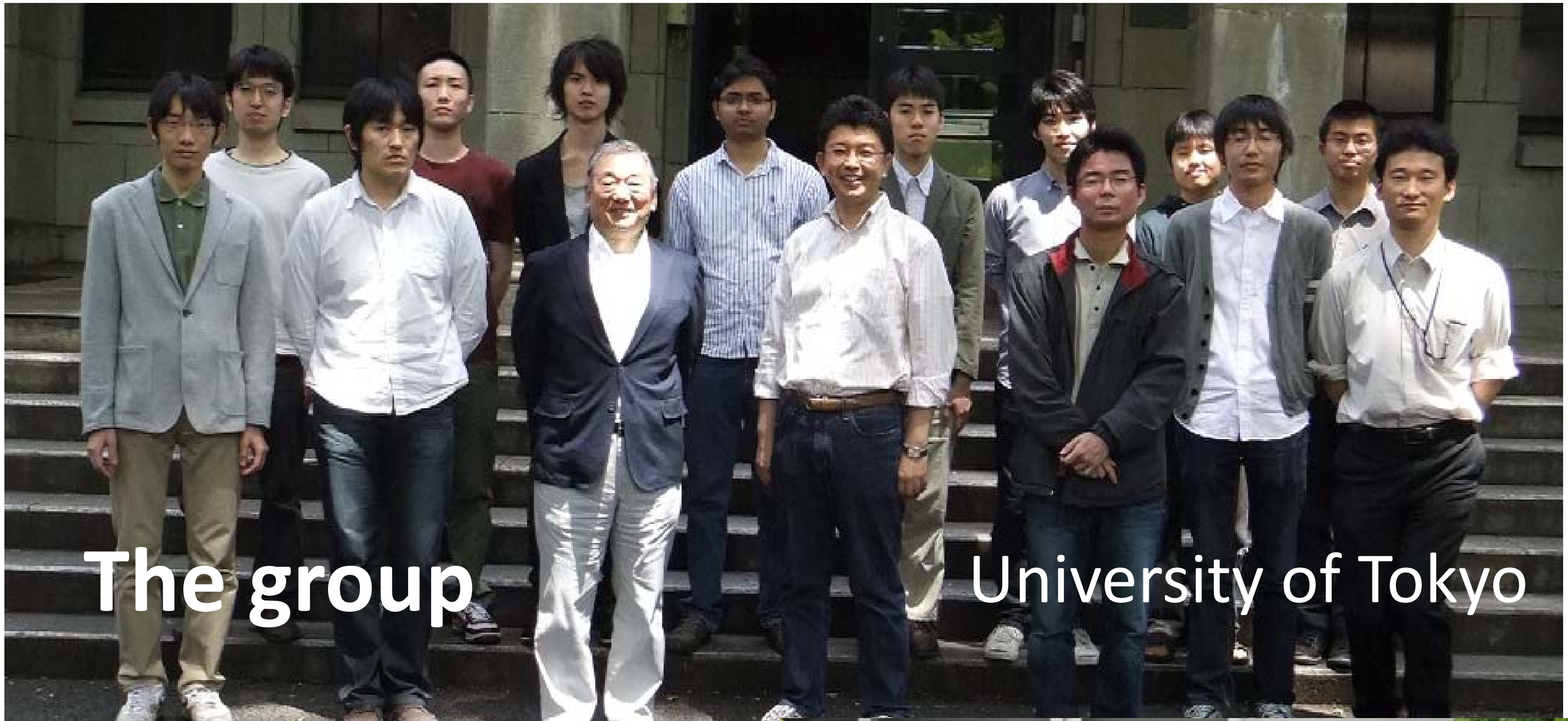
- Relativistic correction $\sim\alpha^2 Z^2$; larger for heavier atoms
- Any atomic transition can be expressed as: $\boxed{\nu = A\cdot Ry\cdot F_{\mathrm{rel}}(\alpha)}$

$$\Rightarrow \frac{\nu^{(X)}(t)}{\nu^{(0)}(t)} = \frac{A^{(X)}\cdot Ry\cdot F_{\mathrm{rel}}^{(X)}(\alpha)}{A^{(0)}\cdot Ry\cdot F_{\mathrm{rel}}^{(0)}(\alpha)} \propto \frac{F_{\mathrm{rel}}^{(X)}(\alpha(t))}{F_{\mathrm{rel}}^{(0)}(\alpha(t))}$$

: Frequency ratio of two atomic clocks may vary.

- Astrophysical (5-11Gyr): QSO spectrum (Murphy 2001) $\dot{\alpha}/\alpha = (7.2\pm1.8)\times10^{-16}/\mathrm{yr.}$
- Terrestrial limit (2Gyr): Oklo reactor $\dot{\alpha}/\alpha < 1\times10^{-18}/\mathrm{yr.}$
- Laboratory searches (1-2yr):Al+/Hg+ (NIST2008) $\dot{\alpha}/\alpha < (-1.6\pm2.3)\times10^{-17}/\mathrm{yr.}$
- Sr/Yb/Hg lattice clocks at 10^{-18} will reveal: $\dot{\alpha}/\alpha < 10^{-18}/\mathrm{yr.}$

The group


University of Tokyo

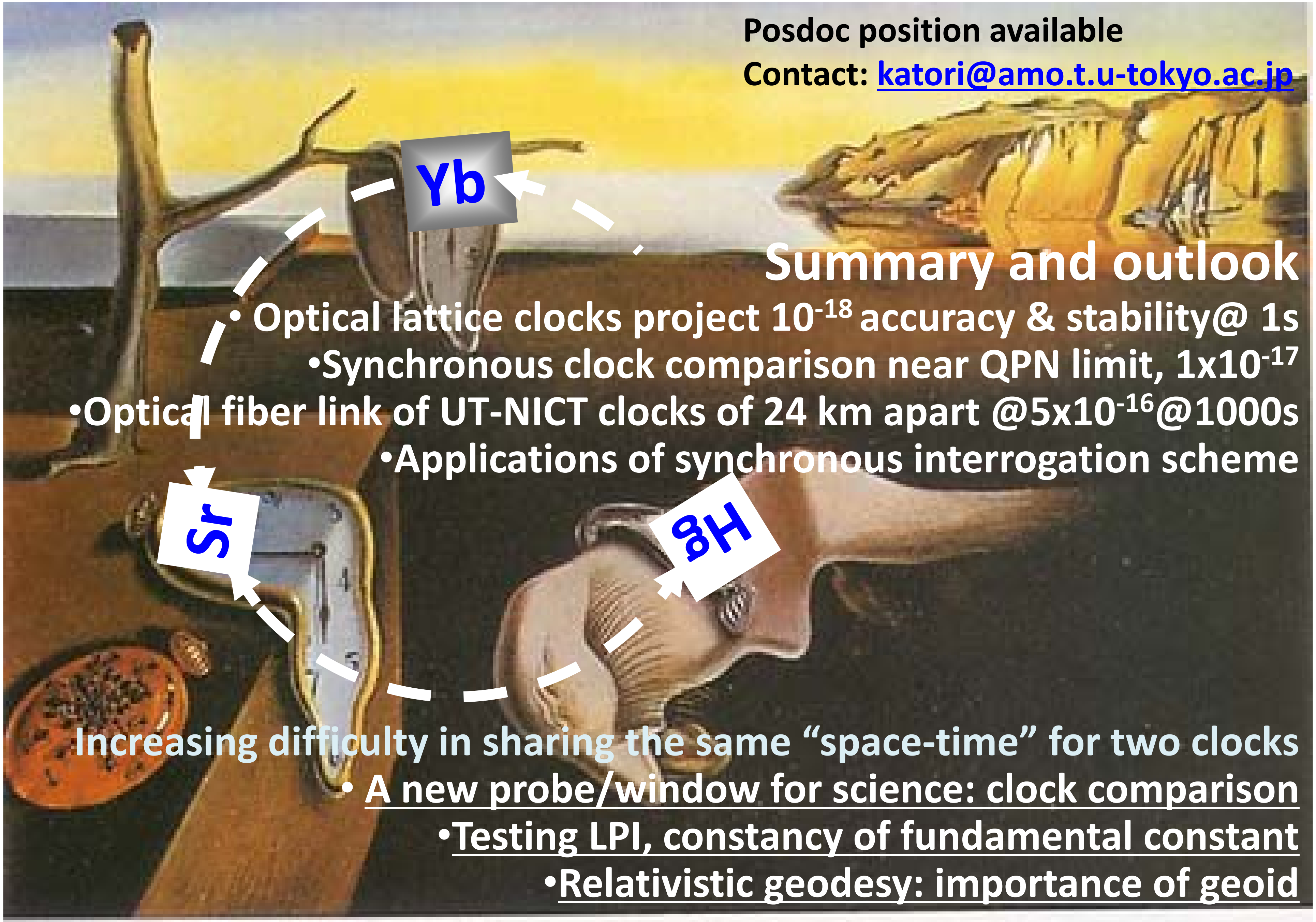
Univ. of Tokyo/ERATO(10-16)

H. Katori, M. Takamoto(RA), T. Takano(RA), D. Yu(PD), K. Hashiguchi(D I. Ushijima(D), O. Nonaka(M), K. Yamanaka(M), H. Kubo(M), N. Ohtani(M), T. Oita, M. Ohya

NICT group: Frequency comparison
A. Yamaguchi, M. Fujieda, M. Kumagai, H. Hachisu, S. Nagano, Y. Li, T. Ido

Posdoc position available

Contact: katori@amo.t.u-tokyo.ac.jp



Summary and outlook

- Optical lattice clocks project 10^{-18} accuracy & stability@ 1s
- Synchronous clock comparison near QPN limit, 1×10^{-17}
- Optical fiber link of UT-NICT clocks of 24 km apart @5×10^{-16}@1000s
- Applications of synchronous interrogation scheme

Increasing difficulty in sharing the same “space-time” for two clocks

- A new probe/window for science: clock comparison
- Testing LPI, constancy of fundamental constant
- Relativistic geodesy: importance of geoid

The Persistence of Memory, 1931 : Salvador Dalí