- 我們是哪一行
  - ✓ 我們的領域叫AMO
  - ✓ 我們的專長：光梳雷射物理、量子控制(雷射穩頻與物質波控制)

什麼是AMO?

美國物理協會有一個分支：

Damop: Division of atomic, molecular, and optical physics

光與原子分子的交互作用，以用途而言，分兩類

用光來控制原子分子的量子狀態

用原子分子來控制光的量子狀態

1997~2011，AMO這個小族群，有十二個人拿諾貝爾獎

- 1997: Laser cooling (Since 1986) (用光來製造冷原子)
  - ✓ S. Chu, B. Philips and C. Tonugui
- 2001: Bose-Einstein Condensation (since 1995) (用光使原子凝結)
  - ✓ C. Wiman, E. Cornell, W. Kettler
- 2005: High precision measurement and Comb laser (since 1999) (用原子控制光)
  - ✓ R. Clauber, T. Hansch, J. Hall
- 2011: Quantum manupilation and control (用光控制離子)
  - ✓

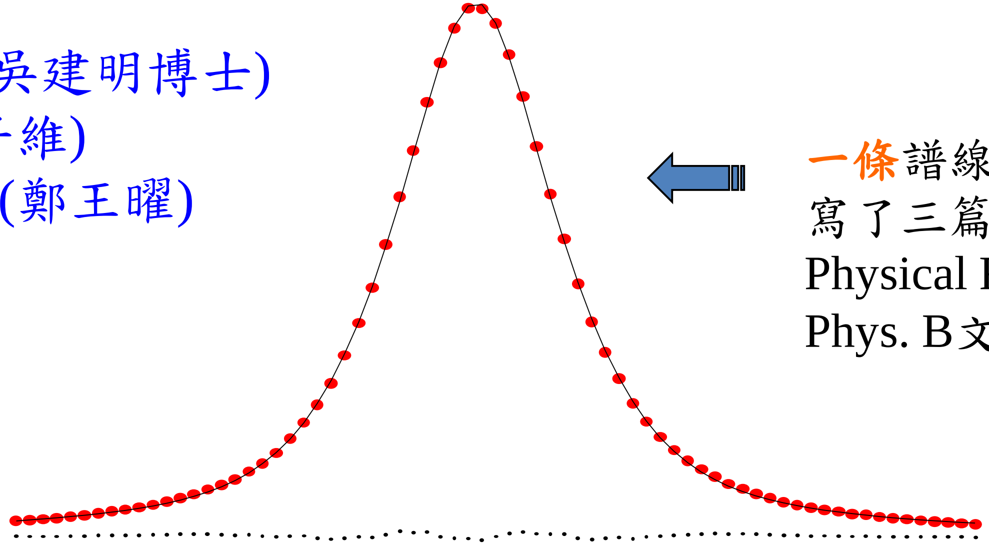
他們的雷射都需要穩頻！！！

我們在AMO這行的專長

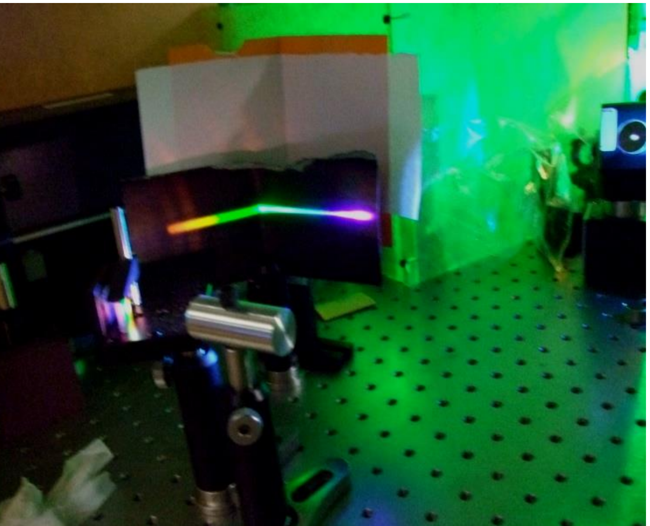
- ✓光梳雷射物理
- ✓量子控制(雷射穩頻與物質波控制)
- ✓原子分子光譜

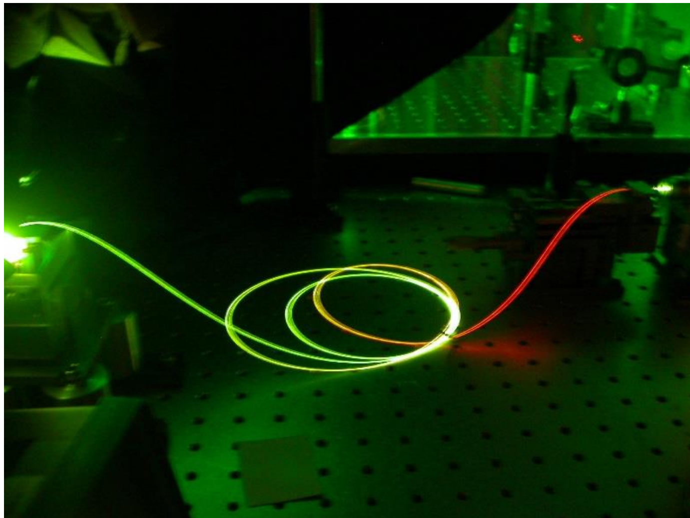
十三年磨劍--銫原子6S-8S超精細光譜之研究

Chien-Ming Wu (吳建明博士)
Tze-Wei Liu (劉子維)
Wang-Yau Cheng (鄭王曜)

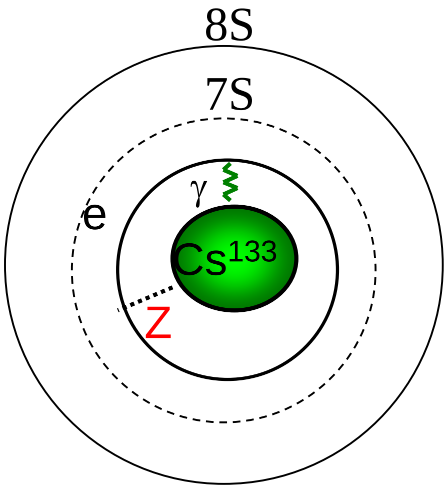


一條譜線，我們奮鬥十三年寫了三篇Optics Letters一篇Physical Review A 及二篇Appl. Phys. B文章



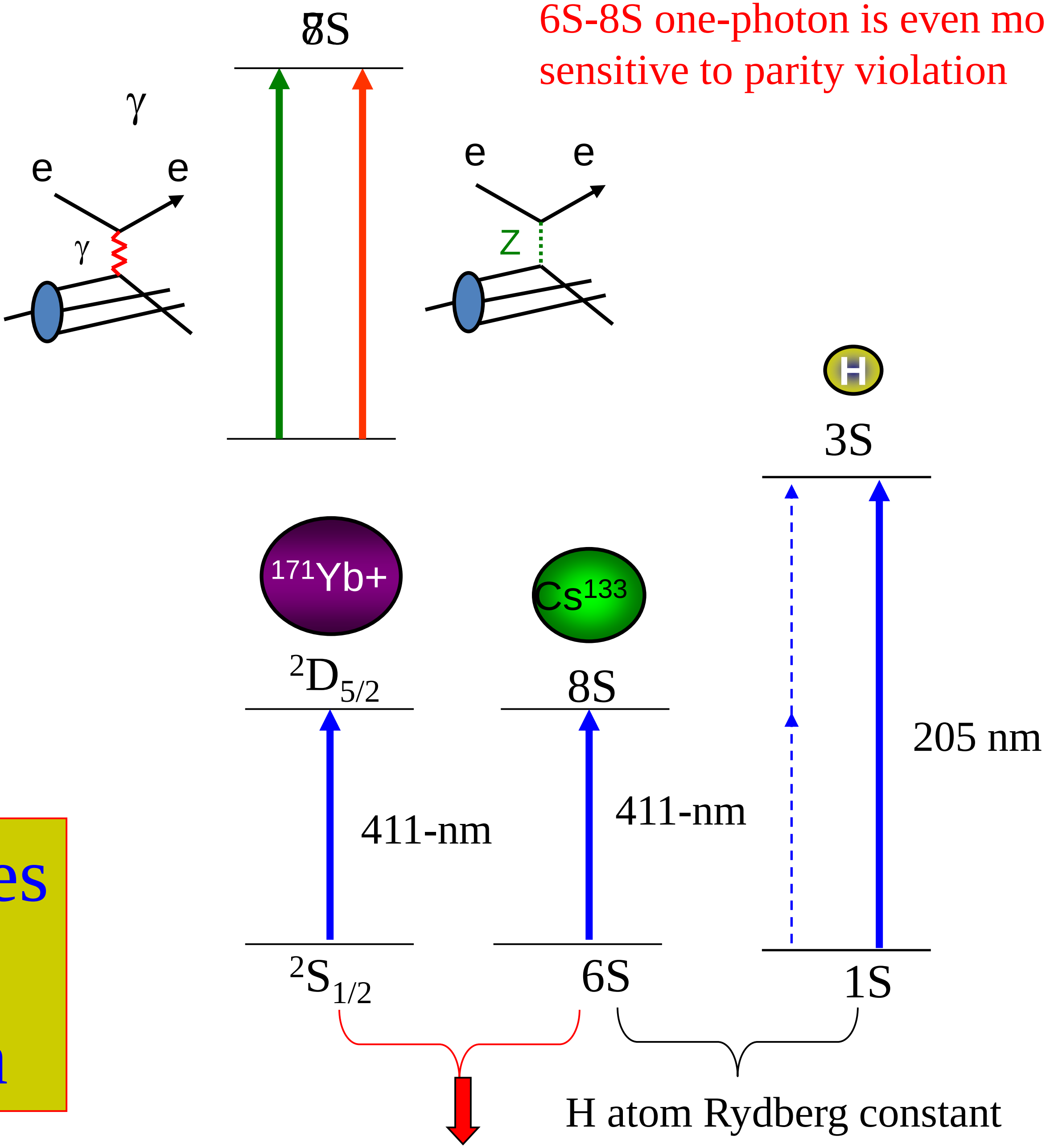


Unique features of Cesium atom



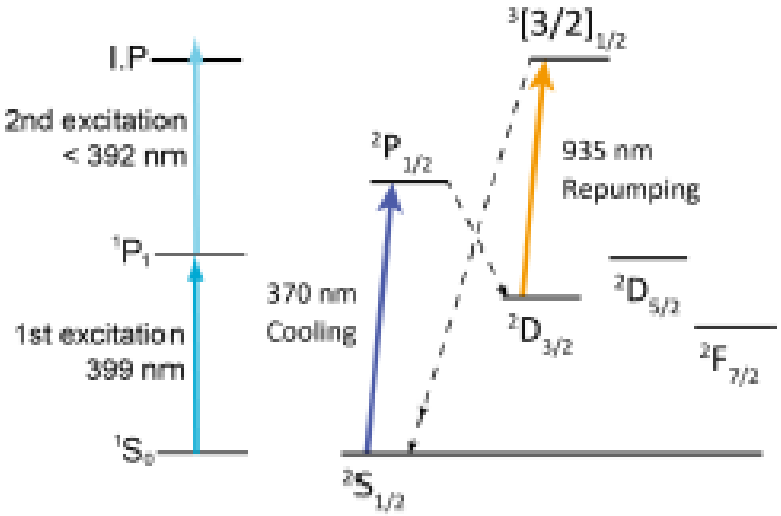
Heavy nuclear offers an excellent basis for testing electric-weak theory

6S-8S one-photon is even more sensitive to parity violation



α variation, clock transition

H atom Rydberg constant



- Neutral Yb for photoionization
- Partial term scheme of Yb$^+$

- Isotope 171(I=1/2)
  - $m_F=0 \rightarrow m_F'=0$: no 1st-order Zeeman shift
  - Simple hyperfine structure: small system with simple light source

Clock transitions

411 nm: $^2S_{1/2} - {}^2D_{5/2}$ $\tau = 7$ ms Roberts *et al.*, PRA 60, 2867 (1999)
435 nm: $^2S_{1/2} - {}^2D_{3/2}$ $\tau = 52$ ms Tamm *et al.*, PRA 80, 043403 (2009)
467 nm: $^2S_{1/2} - {}^2F_{7/2}$ $\tau \sim 4000$ d Huntemann *et al.*, PRL 108, 090801 (2012)

一個離子，有三個躍遷被預
測是未來人類的時間標準

演講提要

1. 我們證明這條躍遷可用於雷射穩頻
(Optics Letters **32**, 563 (2007))

2. 我們做出手掌大小之光頻參考頻率並申請專利
(Optics Letters **36**, 76 (2011))

3. 我們利用此躍遷做出光頻率游標尺
(Applied Physics B **92**, 13 (2008); B **117**, 699 (2014))

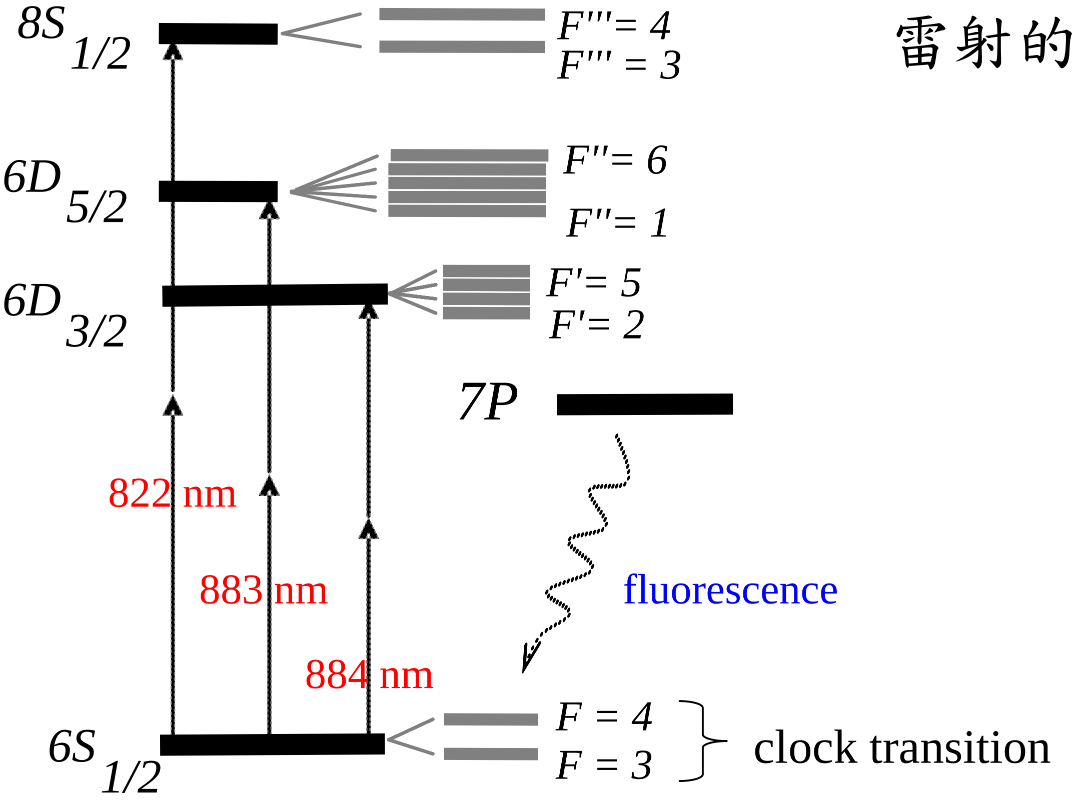
4. 我們量測這條躍遷之絕對頻率
(Optics Letters **38**, 3186 (2013))

5. 我們用量子干涉為工具，比較德國與台灣銫原子這條躍遷的差異 (Phys. Rev. A, **92**, 042504 (2015)

0. 演講中會提到的能階

Atomic Cs

*這些波長，都在Ti:sapphire 雷射的波長範圍

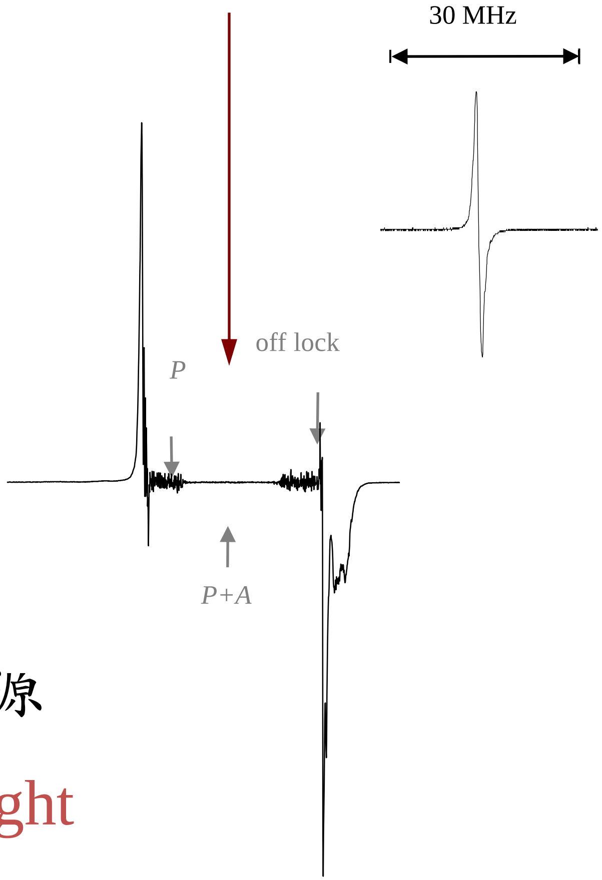


1. 我們證明這條躍遷可用於雷射穩頻

frequency instability 40 Hz
*Over 3.2*10^{14} Hz duty cycle*

cesium 6S-8S
dipole not allowed transition

Opt. lett. **32**, 563 (2007)

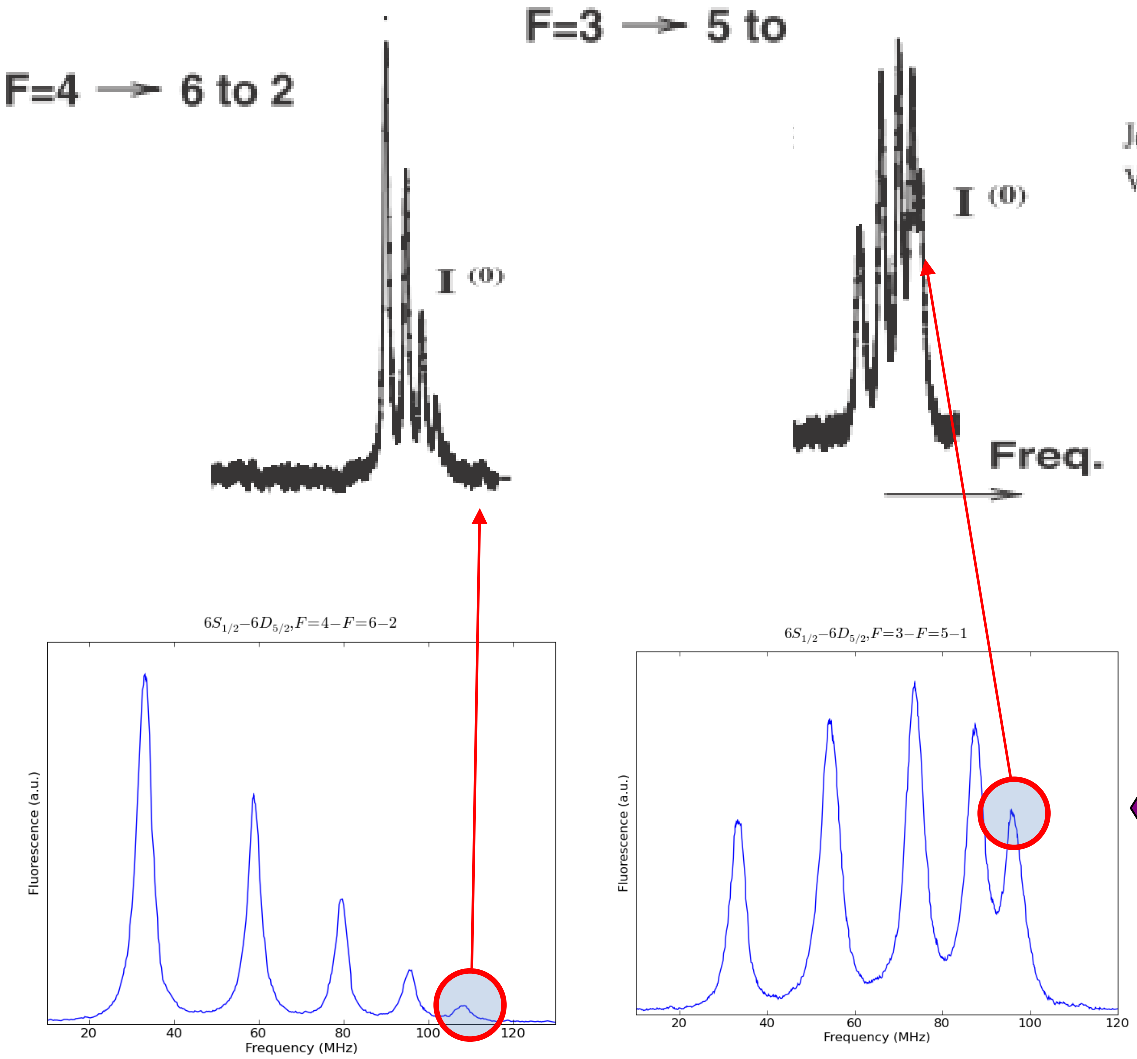


electronics for
feedback
control

超高同調性光源

Ultra-high Coherence light

Advantage for a intracavity scheme



Journal of the Physical Society of Japan
Vol. 74, No. 9, September, 2005, pp. 2487–2491

laser power: 32 W/mm^2
Ti;S:~100 thousand USD

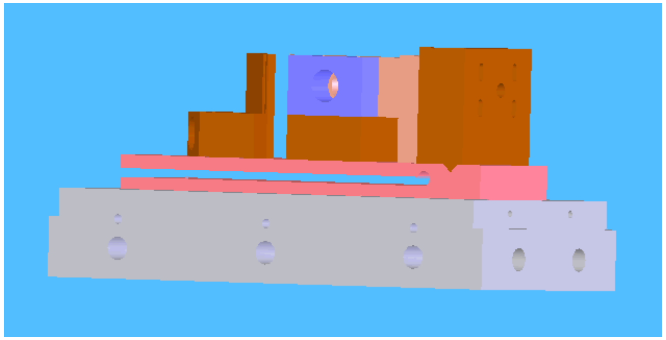
Opt. lett. **36**, 76 (2011)

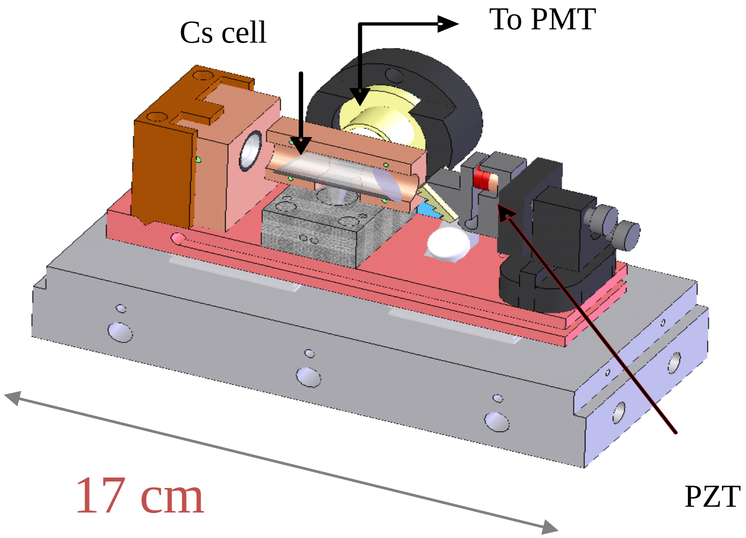
laser power: 0.2 W/mm^2
diode laser:~3 thousand USD
perfect beam overlapping

光梳雷射光譜實驗室(Laboratory for comb laser based spectroscopy)

2. 我們做出手掌大小之光頻參考頻率並申請專利

(Optics Letters **36**, 76 (2011))





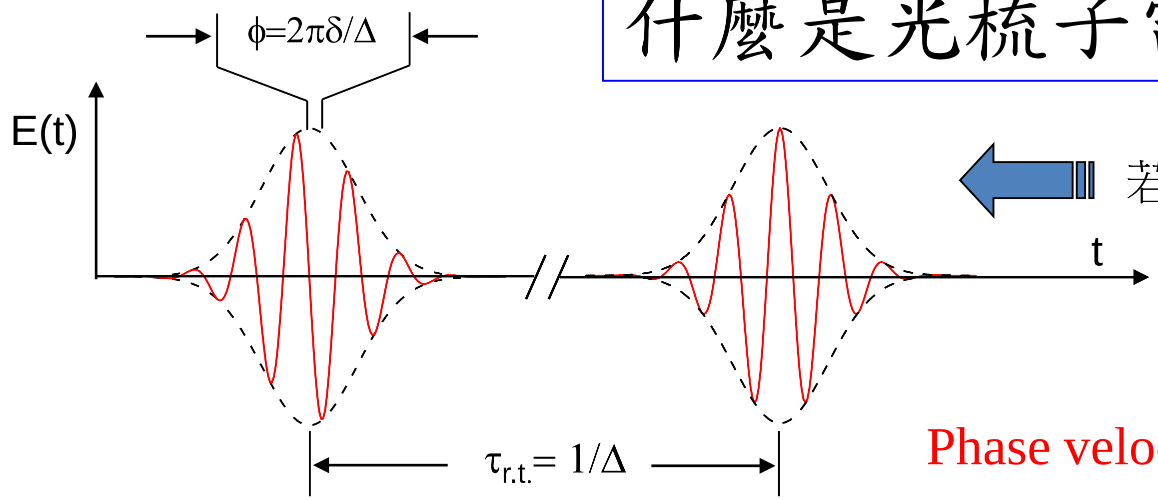
Extended-cavity
diode laser

USA pattern number
8,890,088

獲美國專利

這些穩頻雷射，加上光梳子雷射，
可成為光頻量測的游標尺

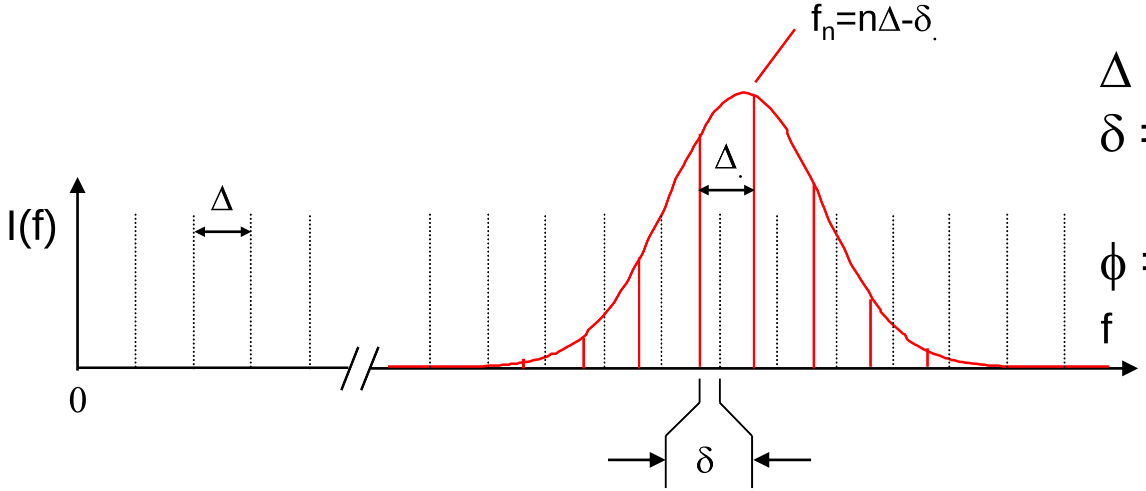
什麼是光梳子雷射？



若ϕ=constant可以有穩定干涉！

Phase velocity ≠ Group velocity

D. J. Jones, S. A. Diddams, J. K. Ranka, A. Stentz, R. S. Windeler, J. L. Hall, S. T. Cundiff, Science **288**, 635 (2000).



Δ = repetition rate=1/T

δ = Comb offset from harmonics of Δ

ϕ = Phase slip b/t carrier & envelope each round trip

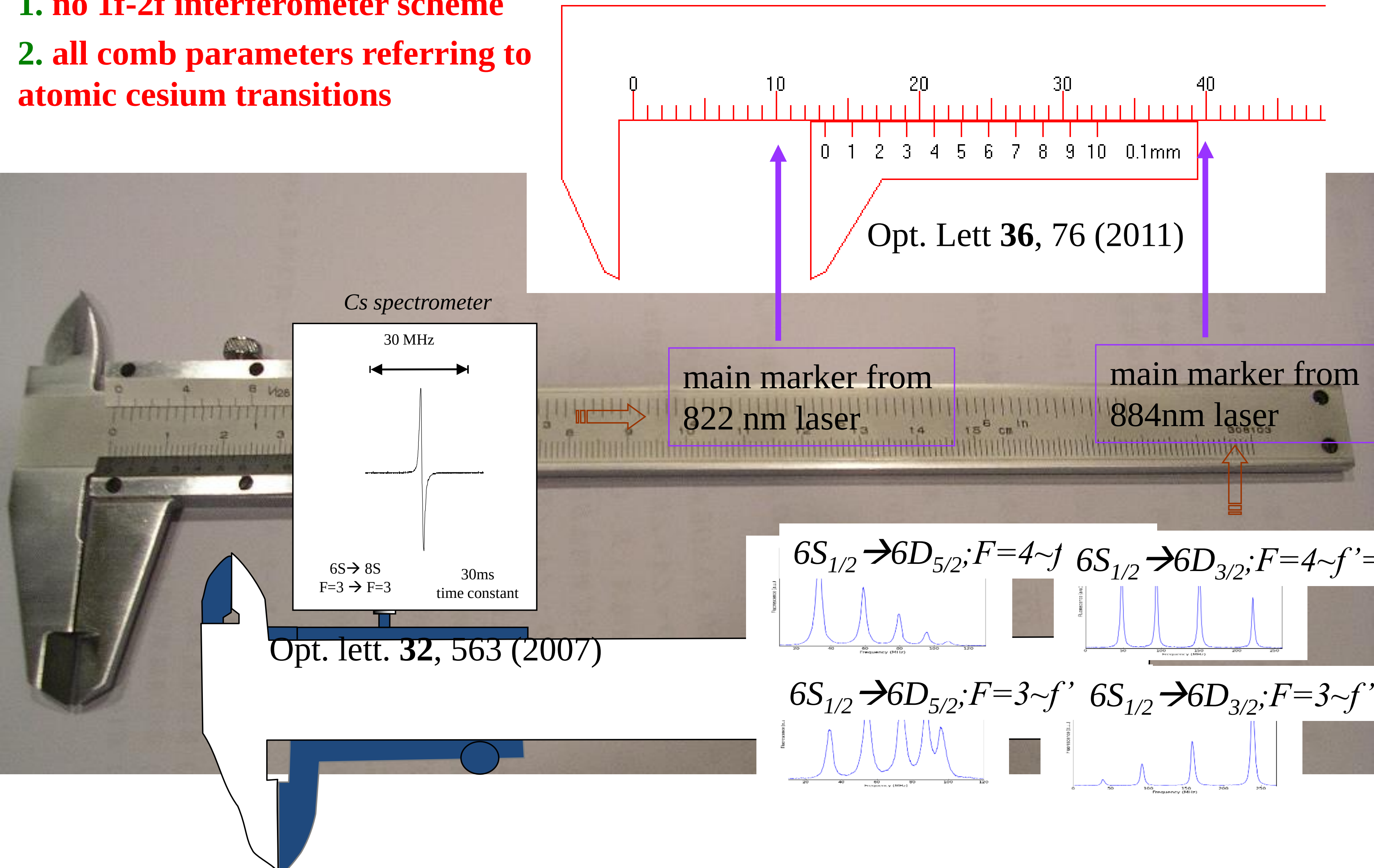
f

$$\text{Spontenous frequency } \delta \equiv \frac{d\phi}{dt} = \frac{1}{2\pi}\,\frac{\phi/\,pulse}{T}$$

3. 我們利用此躍遷做出光學游標尺

(Applied Physics B **92**, 13 (2008); B **117**, 699 (2014))

1. **no 1f-2f interferometer scheme**
2. **all comb parameters referring to atomic cesium transitions**



Opt. Lett **36**, 76 (2011)

Cs spectrometer

main marker from 822 nm laser

main marker from 884nm laser

Opt. lett. **32**, 563 (2007)

$6S_{1/2} \rightarrow 6D_{5/2}; F=4\sim f$

$6S_{1/2} \rightarrow 6D_{3/2}; F=4\sim f'=$

$6S_{1/2} \rightarrow 6D_{5/2}; F=3\sim f'$

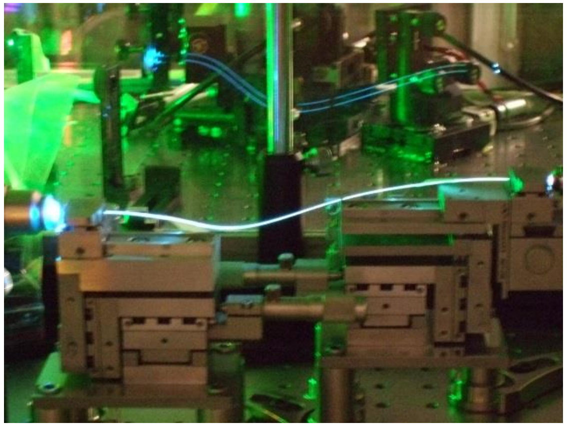
$6S_{1/2} \rightarrow 6D_{3/2}; F=3\sim f'$

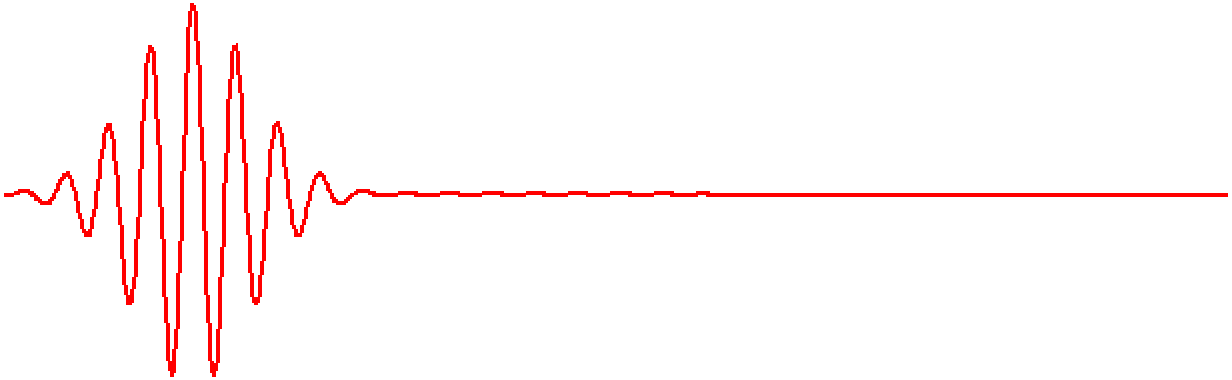
雷射被用了五十年了

在基礎科學上，還需要新雷射嗎？

從"時間"的觀點來看:

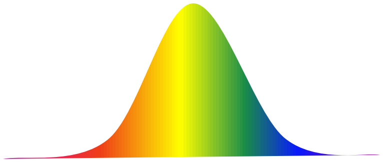
- 超短脈衝的相位被控制著
  - 高瞬間功率
（一萬個燈泡的光，集中在幾根頭髮大小）
  - 10^{-15} 秒的瞬間

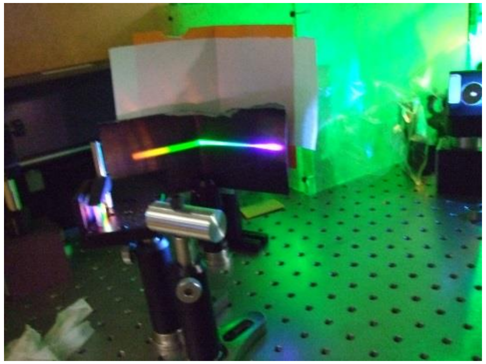




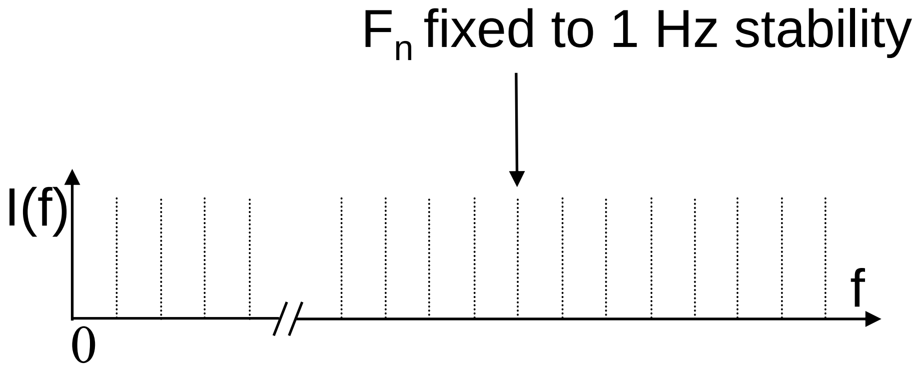
從"頻率"的觀點來看:

- 寬頻



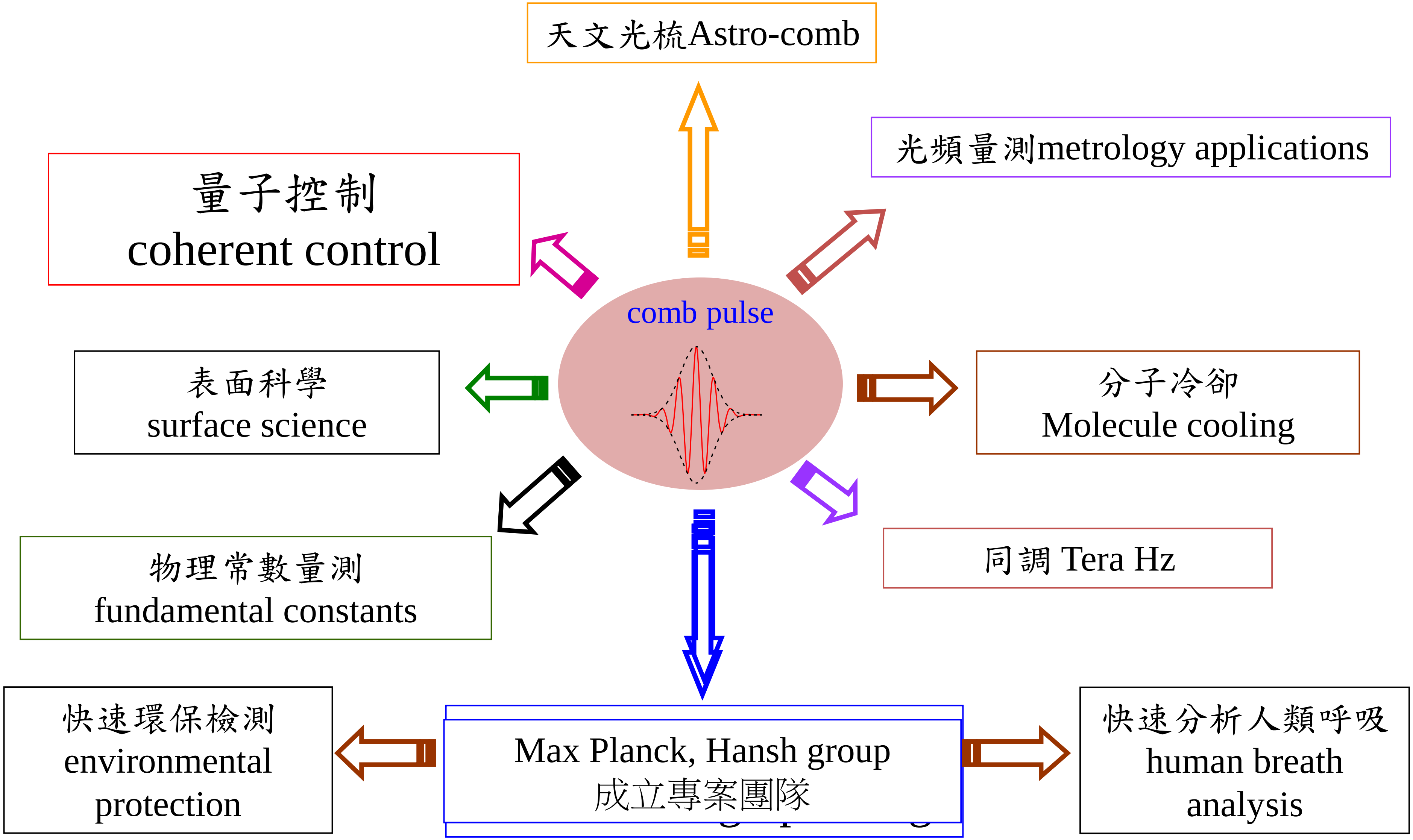


- 高解析



快速光譜

光梳雷射如何開啟一扇科學之窗



天文光梳Astro-comb

光頻量測metrology applications

量子控制
coherent control

comb pulse

表面科學
surface science

分子冷卻
Molecule cooling

物理常數量測
fundamental constants

同調 Tera Hz

快速環保檢測
environmental
protection

Max Planck, Hansh group
成立專案團隊

快速分析人類呼吸
human breath
analysis

其實，我們還不能說我們做了一個光頻率游標尺

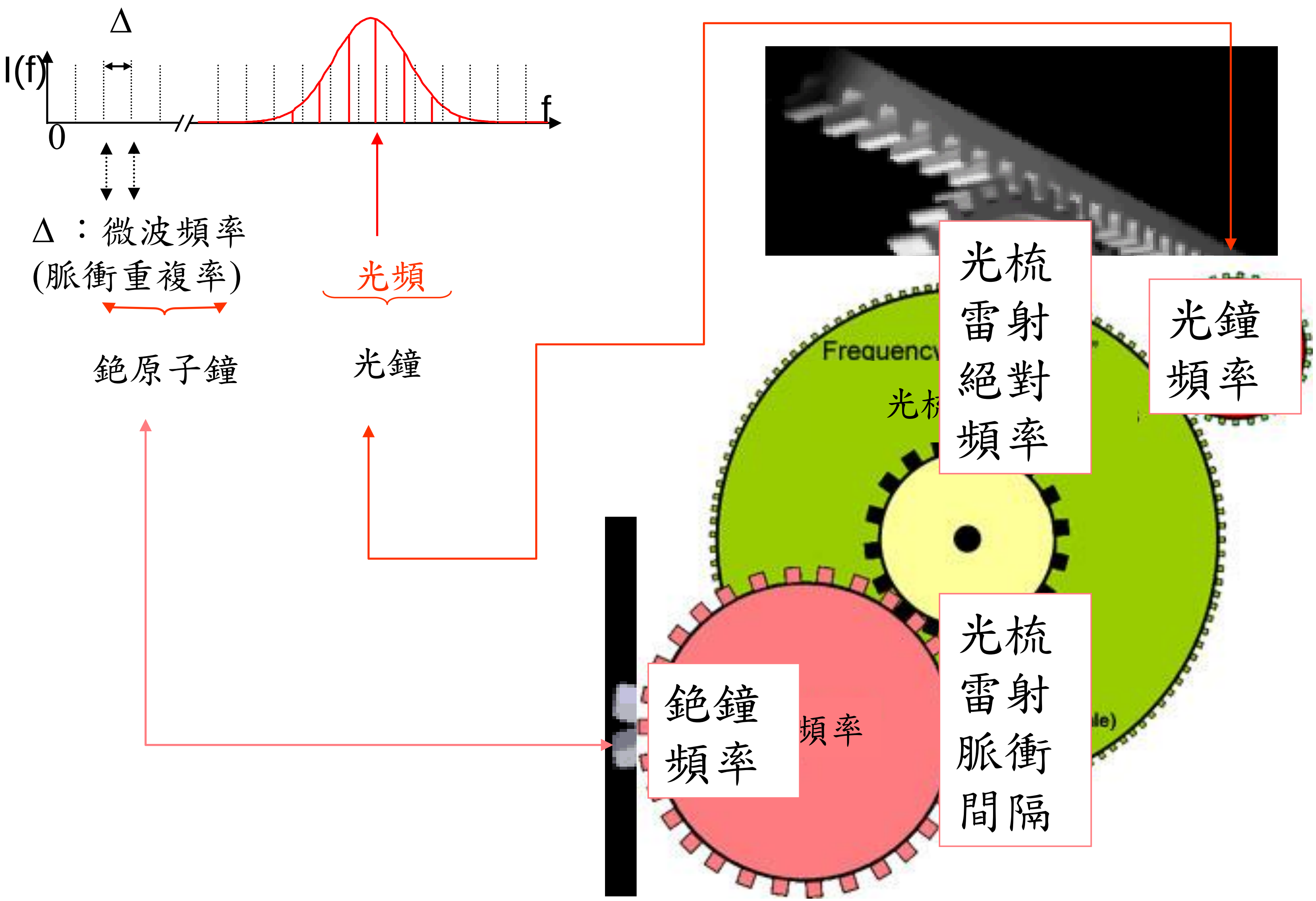
除非我們知道每個刻度的絕對頻率

4. 我們量測這條躍遷之絕對頻率
(Optics Letters **38**, 3186 (2013))

利用自參考法之光梳雷射量測參考雷射之絕對頻率

Opt. Lett. **38**, 3186 (2013)

光梳雷射在"鐘"之間，扮演什麼角色？



Δ ：微波頻率
(脈衝重複率)

銫原子鐘

光頻

光鐘

光梳雷射絕對頻率

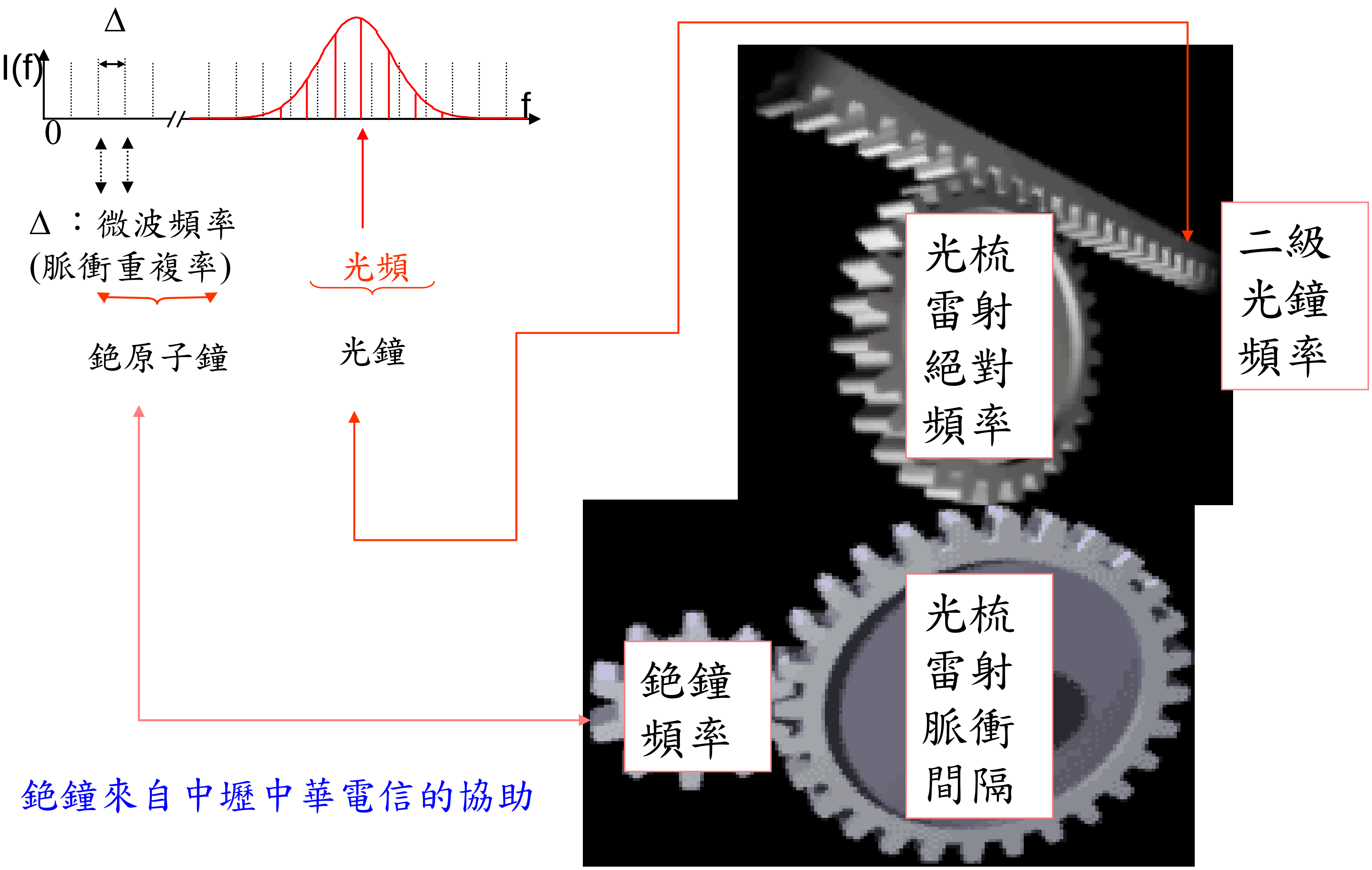
光鐘頻率

光梳雷射脈衝間隔

銫鐘頻率

我們做了什麼好事一(Opt. Lett. **38**, 3186 (2013))

→量出銫原子8S能階的絕對頻率(822-nm)



Δ ：微波頻率
(脈衝重複率)

光頻

銫原子鐘

光鐘

光梳
雷射
絕對
頻率

二級
光鐘
頻率

銫鐘
頻率

光梳
雷射
脈衝
間隔

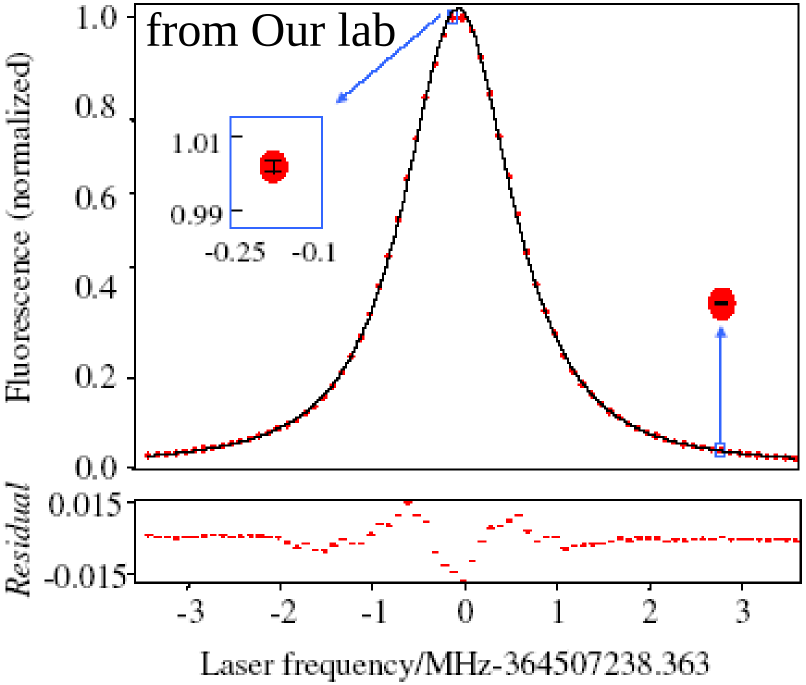
銫鐘來自中壢中華電信的協助

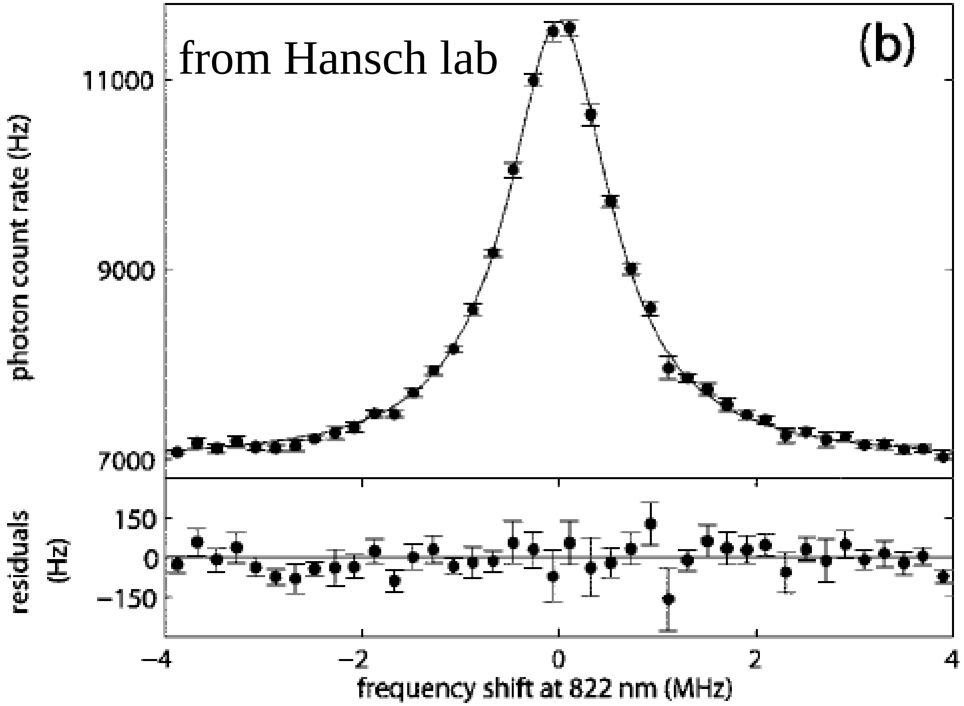
我們巧妙的利用光梳雷射與
銫原子雙光子量子干涉

沒人這樣量光頻過

與諾貝爾獎得主 Ted Hansch實驗室
量得的值不符合

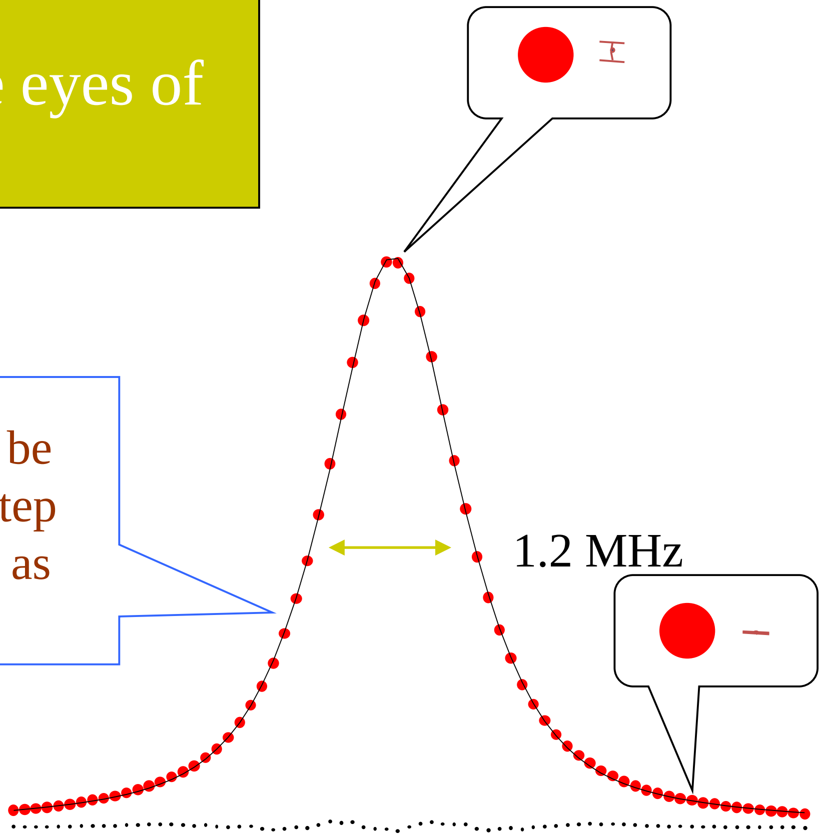
同一條譜線，我們解析度好一個數量級





Why it is a pretty composition in the eyes of a spectroscopist?

Center uncertainty: 300 Hz



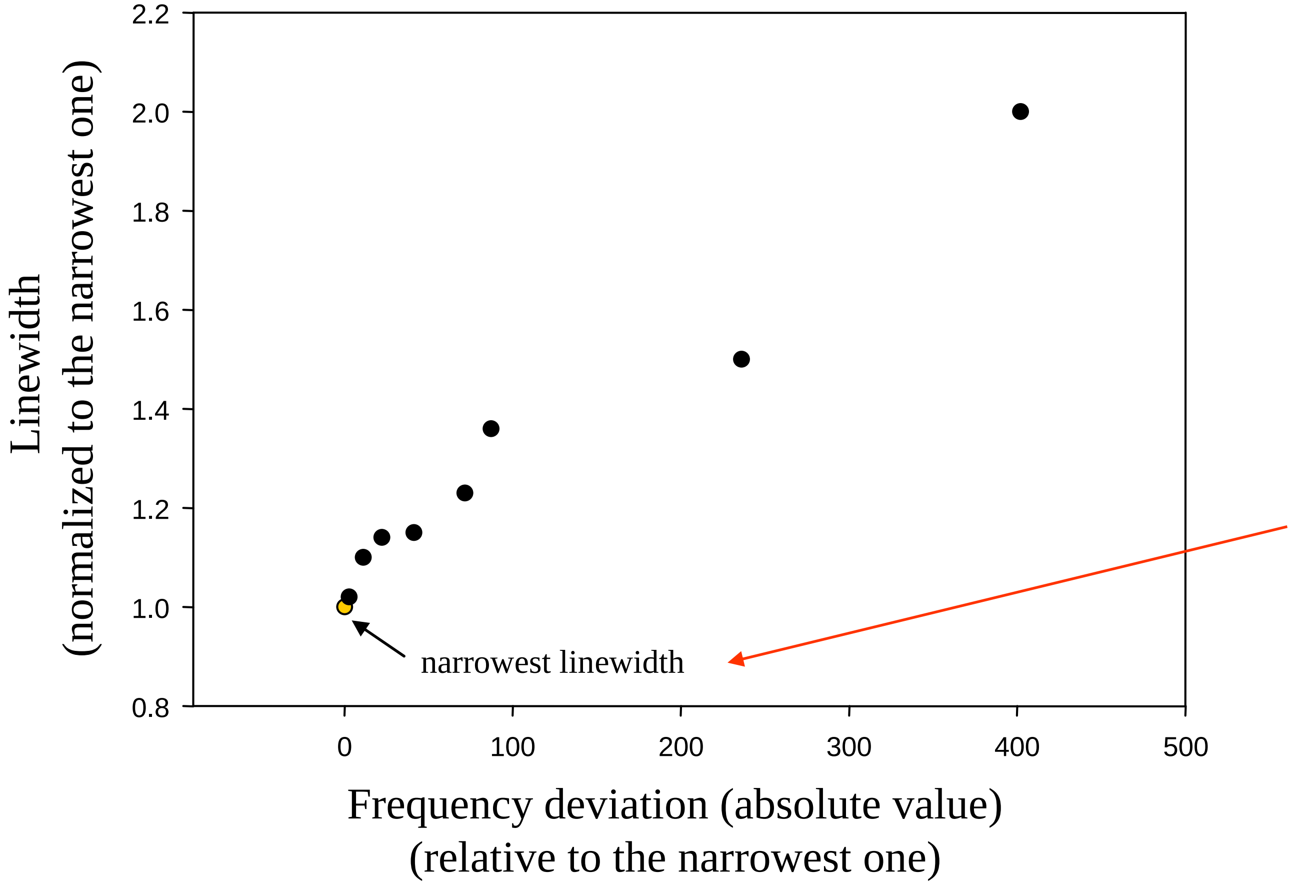
The spectrum could be performed step-by-step for each step as tiny as one wish

high symmetric fitting residual

10^{-2} fitting residual

我們做了什麼好事二(Opt. Lett. **38**, 3186 (2013))

我們發現一個物理現象，可能可以解釋誰的值比較合理



這個值
才對!!

這件事引起二個震驚：

1. 在真空度10^{-7}~10^{-8} torr底下，
銫原子為何還對環境這麼敏感？

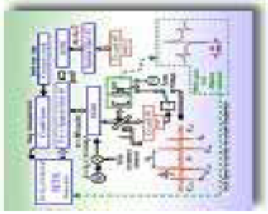
2. 二級光鐘的推行有希望

Absolute frequency of cesium 6S-8S 822 nm two-photon transition by a high-resolution scheme

Published in Optics Letters, Vol. 38 Issue 16, pp.3186-3189 (2013)

by Chien-Ming Wu, Tze-Wei Liu, Ming-Hsuan Wu, Ray-Kuang Lee, and Wang-Yau Cheng

（美國光學學會專文介紹我們的實驗，收錄於 2013 年八月，Spotlight on Optics）



Spotlight summary: Optical frequency measurements made a giant step forward 13 years ago when Ted Haensch and Jan Hall and their colleagues showed how to use a mode-locked laser to count optical frequencies. This Nobel-prize winning research made it possible to measure laser frequencies with mind-boggling precision. Scientists were suddenly able to spend less time babysitting lasers and to spend more time on atomic physics -- perfecting the science of stabilizing lasers to atomic transitions. The world record in this game is held by NIST, where a fractional frequency instability of only 1.6 x 10^{-18} has been demonstrated.

Ultra-stable lasers have applications in geodesy, interferometry, metrology, time-keeping, and communication. They are also used to challenge scientific ideas on a very fundamental level, in areas ranging from testing QED calculations in simple atoms, looking for parity non-conservation, and searching for possible variations in the values of fundamental constants.

For some of these applications, it is not enough to have a stable laser. Its absolute frequency must also be known. As of right now, the amazing stability of NIST-class lasers is not routinely available. The clockwork required for absolute frequency measurements, while available commercially, is not always convenient to have on hand. So it is important to have well-known "secondary" frequency standards that can be conveniently and inexpensively reproduced in nearly any laser lab where an absolute frequency needs to be measured.

The paper by Wu et al. is an impressive example of one such secondary standard. They measured the absolute frequency of the Cs 6S-8S transition at 822 nm. Their approach is a variation of modulation transfer spectroscopy using cw lasers. They use a semiconductor laser at 822 nm to excite the two-photon transition and measure the fluorescence cascade photons in the blue. The cw laser frequency is measured using a self-referenced fs-laser-based frequency comb.

While the methods are somewhat routine, their result is astonishing. Finding that their measurements disagreed with high accuracy results in the literature, Wu et al. measured the 6S-8S transition frequency in 10 different Cs vapor cells. In former times, research groups made their own cells, repeatedly distilling and purifying Rb or other elements before sealing them off. But nowadays it is simply more convenient to buy cells from one of many different vendors. It has long been believed that commercial vapor cells were clean enough to allow accurate spectroscopy at the 10 kHz level, corresponding to a fractional frequency uncertainty of 3 x 10^{-11}. The surprising result from Wu's work is that the 6S-8S transition varies by hundreds of kHz in their cells. Cells with the largest shifts correlated with broader line widths, up to nearly a factor of 2. This is not pressure broadening due to Cs in the cell--that has been taken out in their work. The shift and width are due, evidently, to impurities in the cell. Without a reasonable theory to guide them, they chose to quote their measured transition frequency from the cell with the narrowest line width -- the transition width that was closest to the natural linewidth.

This work has significant implications. Not only is every commercial vapor cell suddenly suspicious, but measurements that used a Rb or Cs or I2 or other vapor cell as a secondary frequency reference are called into some doubt, Wu's work included. Cell-based spectroscopy, when used as a secondary frequency standard, is in the uncomfortable situation of having potentially large and unknown uncertainties. A high-accuracy measurement in an ultrapure and collision-free environment is certainly warranted. Atomic theory also has a near-term opportunity to explain what Wu et al. have measured, and to guide future measurements in this field.

The need for reliable secondary frequency standards is not going away. Wu's results are a challenge to the field of spectroscopy. Cell manufacturers may need to develop some way of testing and validating their products. But until this is resolved, it looks like spectroscopists have a little more work to do.

--Scott Bergeson

以上便是我們獲得有庠科技論文獎的原因(非常少數，因基礎科學獲獎)

第十二屆 有庠科技獎評審委員會

劉炯朗先生

主任委員

- 中研院院士
- 前國立清華大學校長

吳茂昆先生

評審委員兼奈米科技審查小組召

- 國立東華大學校長
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黃秉鈞先生

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- 國立臺灣大學機械工程學系教授
- 臺大新能源中心主持人

Acknowledgement:

National Science Council (國科會)

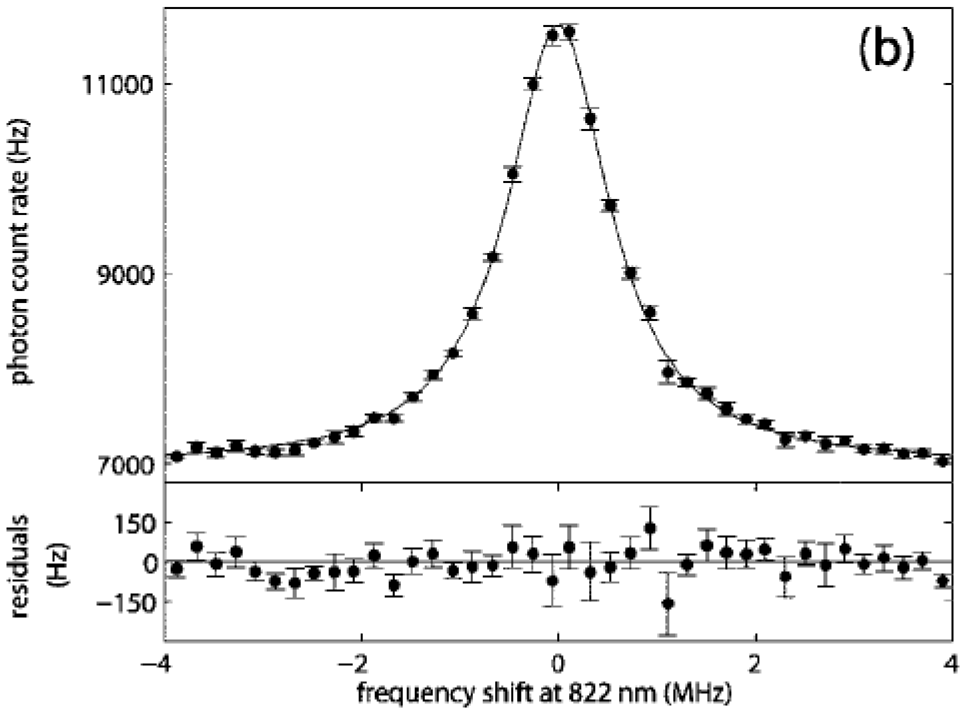
Ministry of Science and Technology (科技部)

Telecommun. Labs. (中華電信研究所)

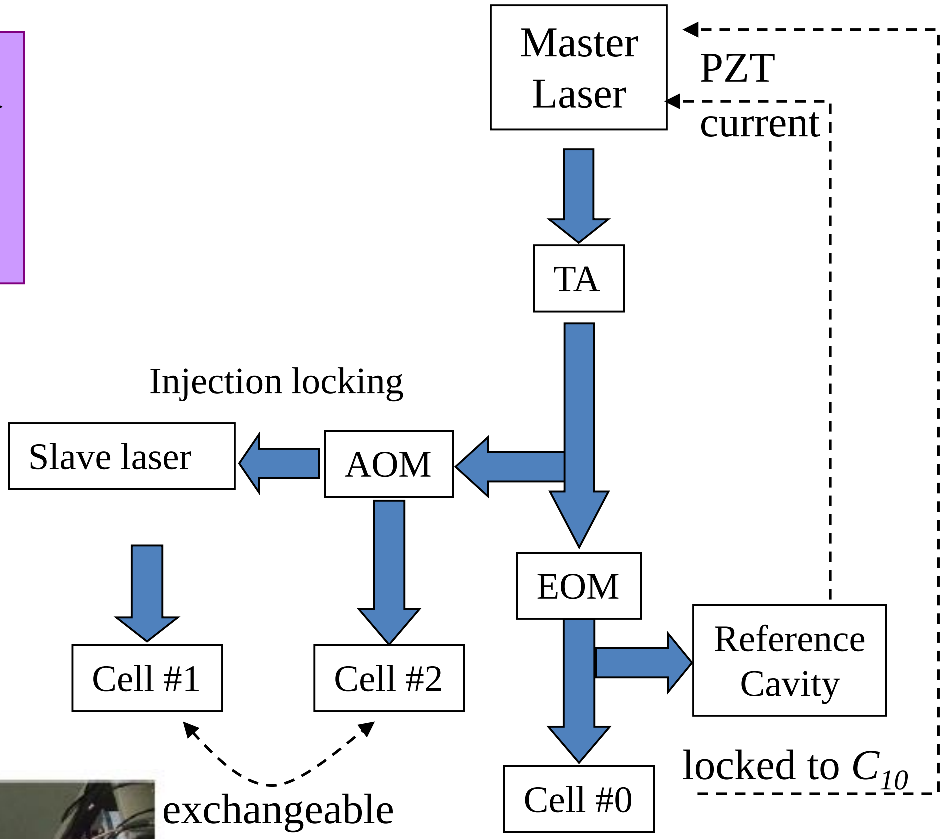
探索銫原子6S-8S的躍遷，

故事還沒有結束。。。

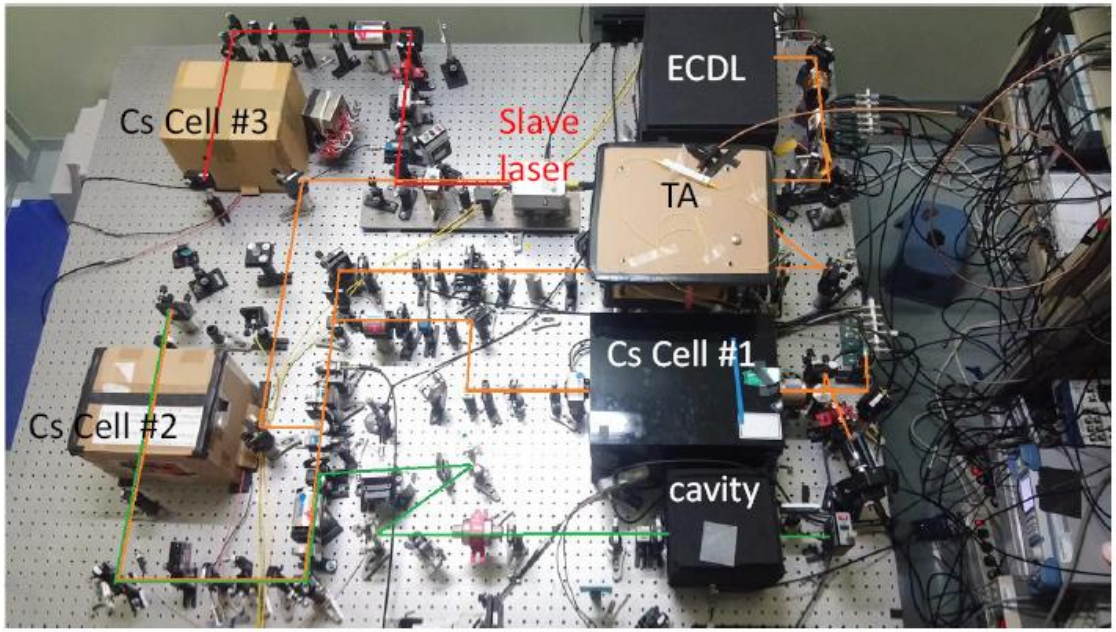
Max Planck Institute for Quantum Optics
Ted Hansch group下的T. Udem寄來
他們在2007年文章裡使用的銫原子



5. 我們用量子干涉為工具，比較德國與台灣銫原子這條躍遷的差異 (Phys. Rev. A, 2015, accepted)


Master Laser
PZT
current
TA
Injection locking
Slave laser
AOM
EOM
Reference Cavity
Cell #1
Cell #2
exchangeable
Cell #0
locked to C_{10}

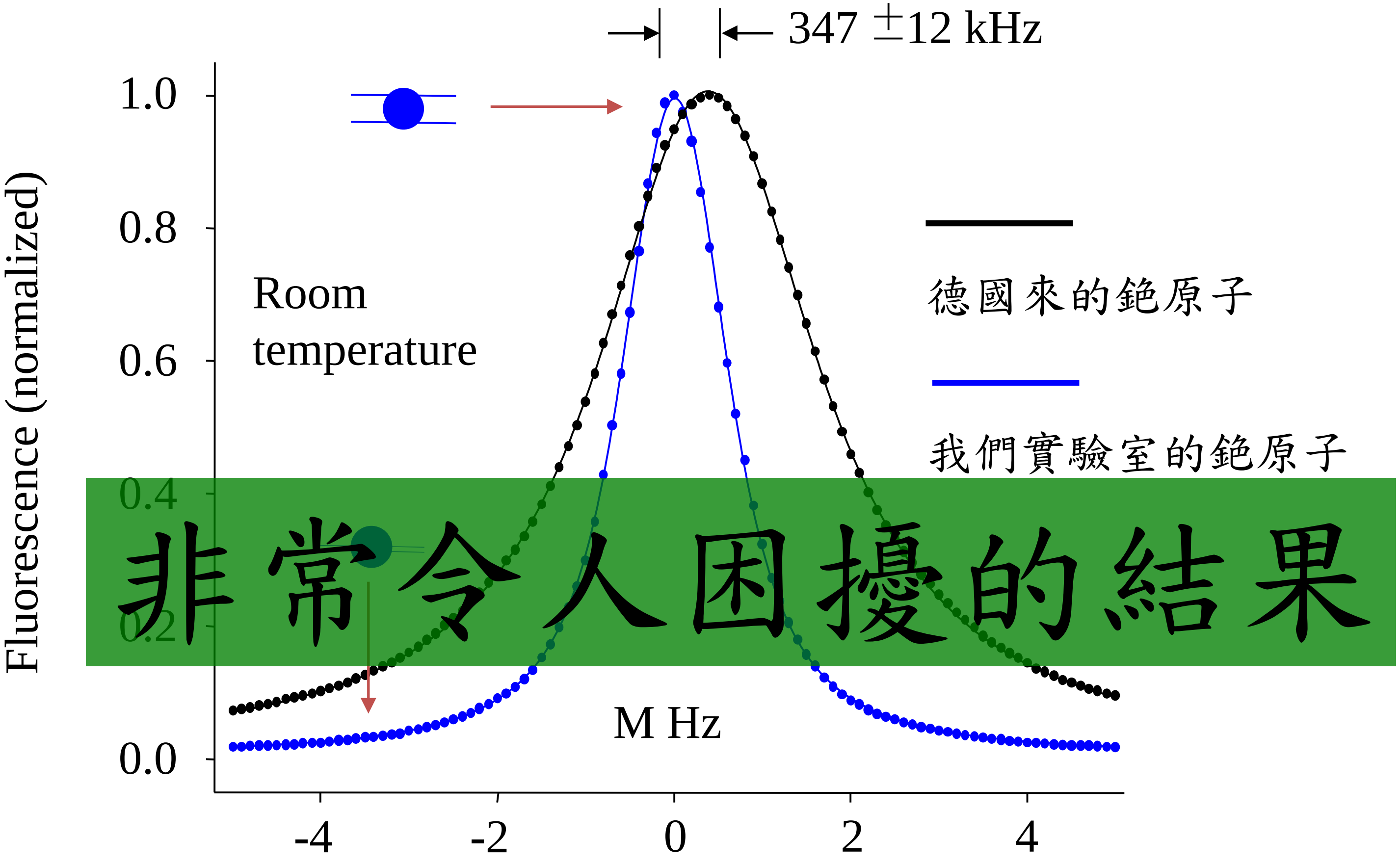
同時(simultaneously)量測



PHYSICAL REVIEW A **00**, 002500 (2015)

Quantum interference in two-photon spectroscopy for laser stabilization and cesium-cell comparison

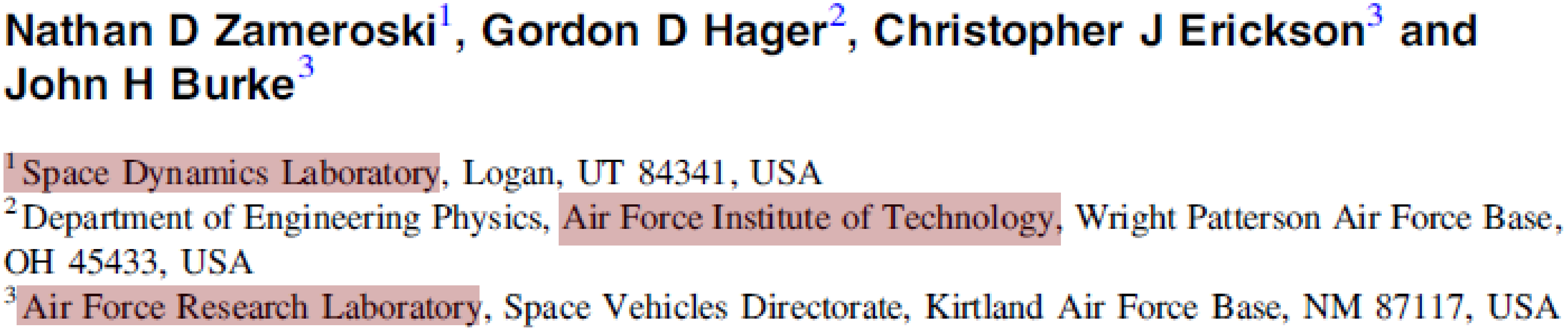
Chien-Ming Wu,[1,3] Tze-Wei Liu,[1,2,3] and Wang-Yau Cheng[3,*]



非常令人困擾的結果

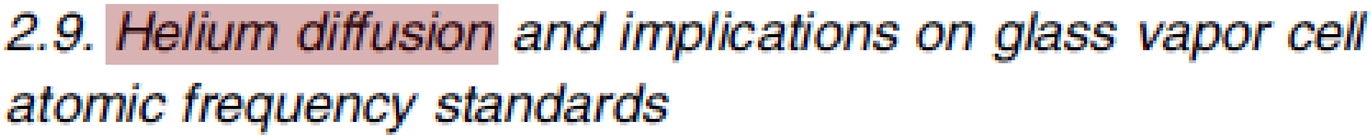
美國空軍的研究員認為。。。

Journal of Physics B, Vol. **47**, 225205 (2014)



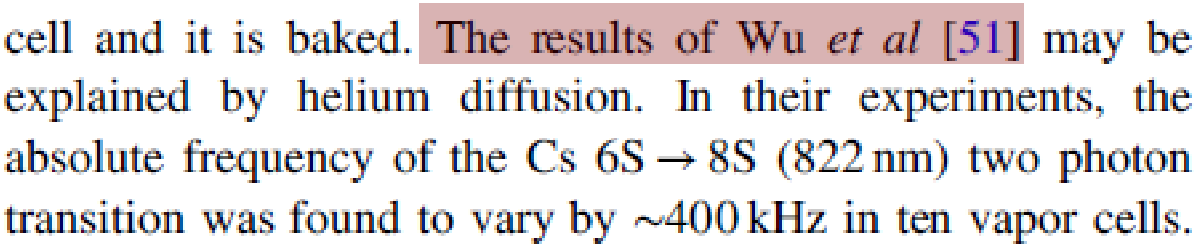
Nathan D Zameroski[1], Gordon D Hager[2], Christopher J Erickson[3] and John H Burke[3]

[1] Space Dynamics Laboratory, Logan, UT 84341, USA
[2] Department of Engineering Physics, Air Force Institute of Technology, Wright Patterson Air Force Base, OH 45433, USA
[3] Air Force Research Laboratory, Space Vehicles Directorate, Kirtland Air Force Base, NM 87117, USA



2.9. Helium diffusion and implications on glass vapor cell atomic frequency standards

……



cell and it is baked. The results of Wu *et al* [51] may be explained by helium diffusion. In their experiments, the absolute frequency of the Cs 6S → 8S (822 nm) two photon transition was found to vary by ~400 kHz in ten vapor cells.

大氣中有0.0002%的氦氣，滲透進去玻璃內
然後被我們精密的實驗量到了

我們實驗室，吳淑蓉同學，負責驗證這個可能性

(希望她對繼續做研究有興趣)

勸君惜取少年時

中央大學物理系光梳雷射光譜實驗室徵人啟事

Laboratory for comb laser based spectroscopy

有興趣參觀或加入實驗室，可連絡

鄭王曜老師：TEL: 65308 (lab); 65337 (office);email: wycheng@ncu.edu.tw
吳淑蓉學姊：TEL: 65308 (lab); kelly50125@hotmail.com
陳可翰學長：TEL: 65308 (lab); krazzymood@hotmail.com
陳伯緯學長：TEL: 65308 (lab); paulxxxtw@gmail.com

對於完全沒基礎的人，我們願意從頭教你．

認真的學生可以學到什麼？

✓**進階的電子電路**

- 回授電路　　鎖相迴路　　Lockin
- 各式電路設計(電流供應器、頻率產生器、PCB lay out技術等)

✓**光電元件的使用**

✓**雷射物理(大部分雷射我們自組)**

✓**原子分子光譜與量子力學的更加認識**

✓**量子光學計算(我們非常歡迎單純想做計算的人)**

- 量子干涉的發生條件　　連立微分方程的解
- 光梳雷射與物質交互作用的模型建立

我們之前的成果(2005~2015)

- ✓二級光鐘與電子電路設計(Review of Scientific Instrument, 2005)
- ✓新光頻標準(Optics Letters, 2007)
- ✓新穎光梳雷射 (Applied Phys. B, 2014,2008)
- ✓超高解析光譜(Optics Letters, 2011)
- ✓原子躍遷雷射絕對頻率量測(Optics Letters, 2013)
- ✓雙光子量子干涉理論與實驗(Physical Review A, 2015)
- ✓超冷原子(建構中)

歡迎對我們實驗室有興趣的同學加入!!