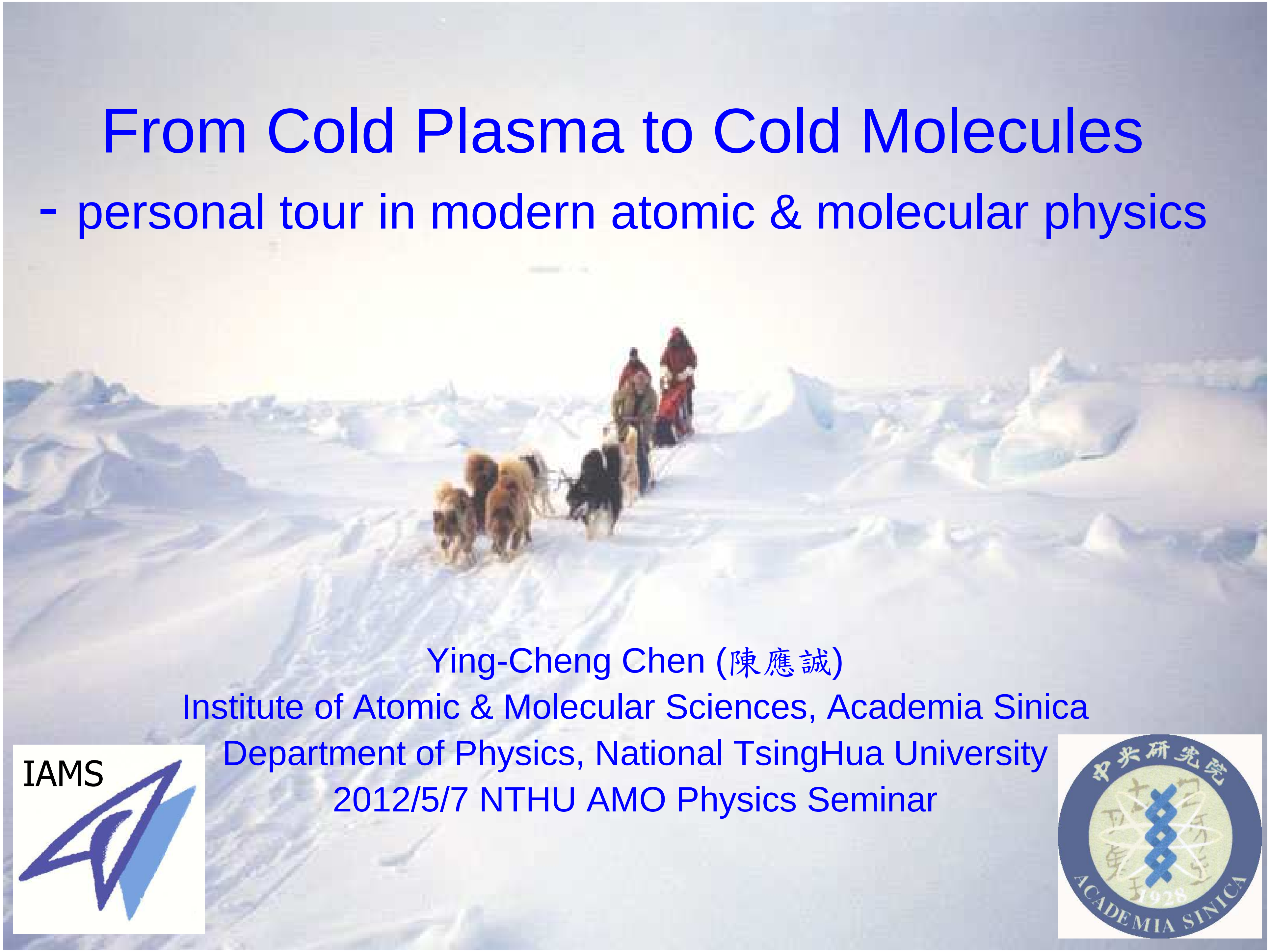
From Cold Plasma to Cold Molecules

- personal tour in modern atomic & molecular physics



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2012/5/7 NTHU AMO Physics Seminar

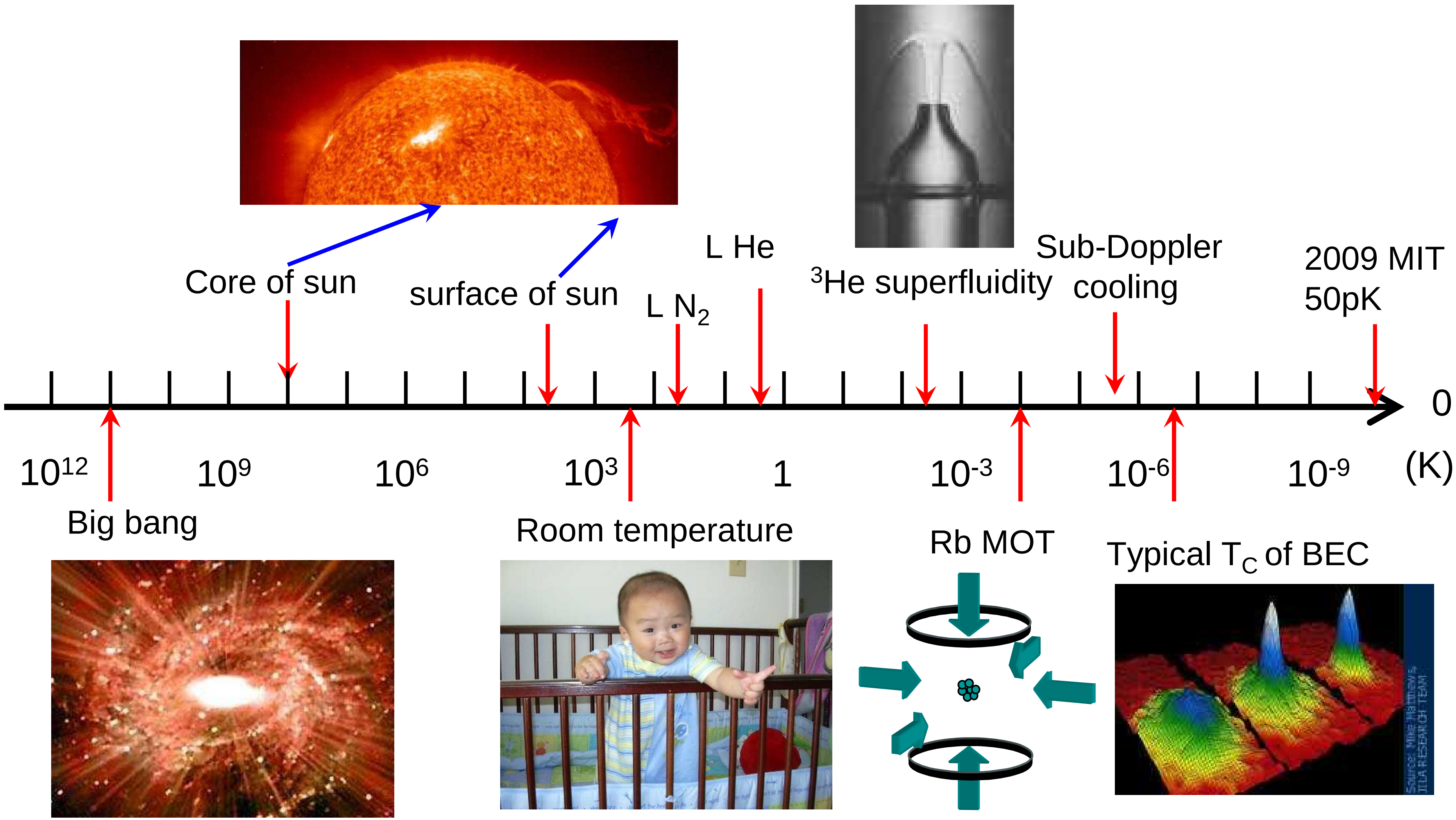
My personal story after
"Adventure in the Turtle island"
烏龜島探險記(1995清華物理系刊)之後

學習、研究與人生
一個探險、探索與欣賞的過程

studying, research & life: adventure, exploration & appreciation

- 教育是當你忘掉所有的細節,所剩下來的東西就是教育!
- 研究（或解習題）是你必須知道所有細節,不然你就做不下去!
- 演講是讓聽眾知道一點點細節,但其實比較像教育的東西！

Temperature Landmark



To appreciate something is a good motivation to learn something !

Modern Atomic, Molecular & Optical Physics

Precision measurement

Atomic clock
Test of particle physics (EDM)
Test of nuclear physics
(parity violation)
Test of general relativity
Variation of physical constants

Condensed-matter or Many-body physics

BEC/Degenerate Fermi gas/dipolar gas
Superfluidity/superconductivity
Quantum phase transition
BEC/BCS crossover
Quantum magnetism/
high Tc superconductivity

Core technology
Atom manipulation
Laser development

Quantum information science

Quantum control
Quantum teleportation
Quantum network
Quantum cryptography
Quantum computing

Extreme nonlinear optics

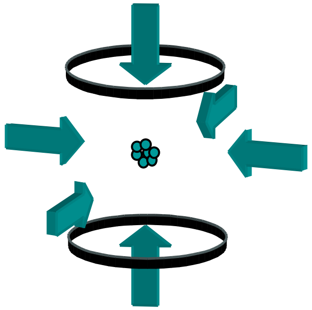
Atom/molecule under intense fields
High harmonic generation
Plasma physics
X-ray laser
Attosecond laser

Nano-photonics,opto-mechanics & Hybrid systems

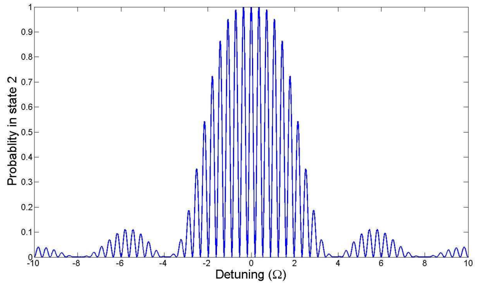
Laser cooling of mechanical oscillator
Coupling of cold atom with
mesoscopic(nano) object
Quantum limit of detection
Near field optics

Core Technology in AMO Physics

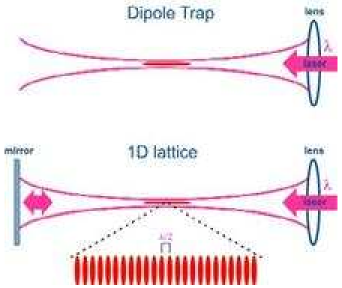
- The control ability of atoms, photons, and molecules.



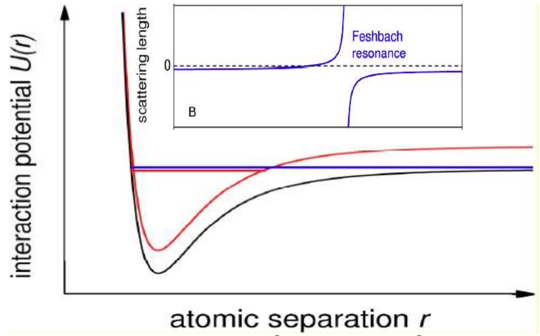
Laser cooling & trapping controls external degree of atoms.



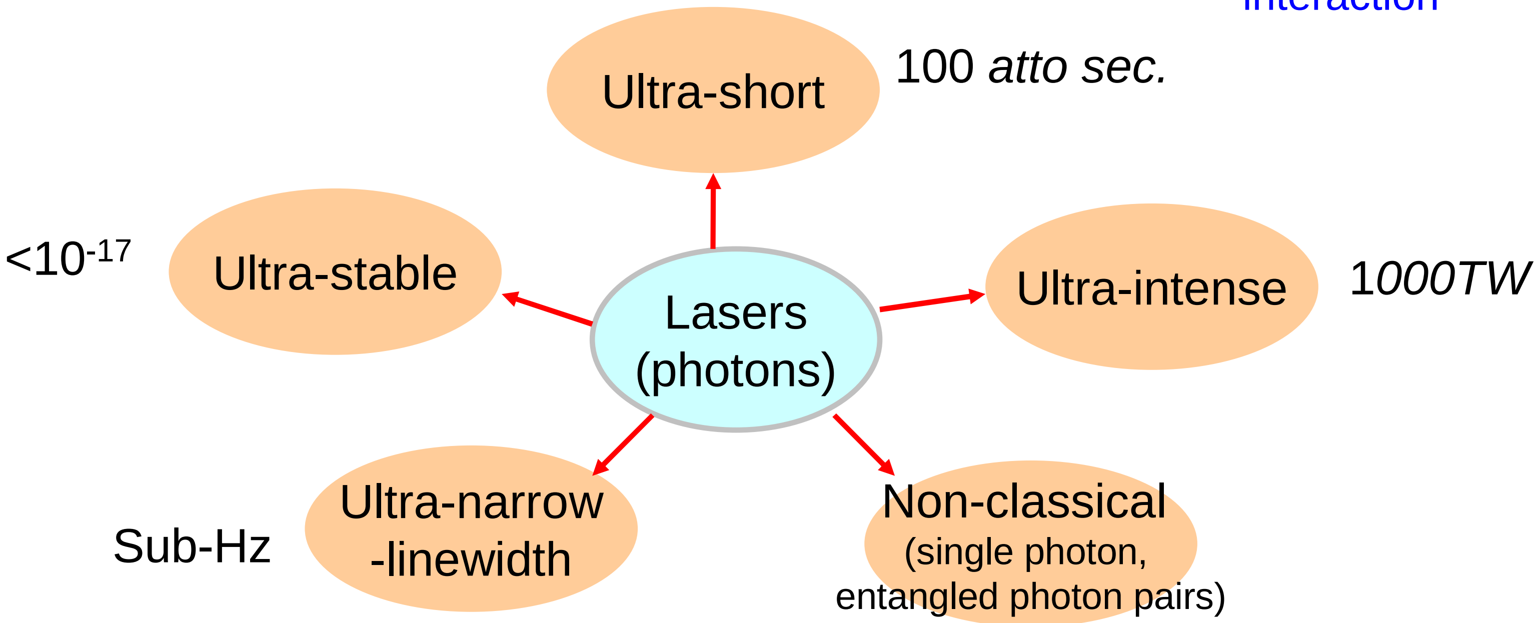
Electromagnetic excitations control the internal state of atoms



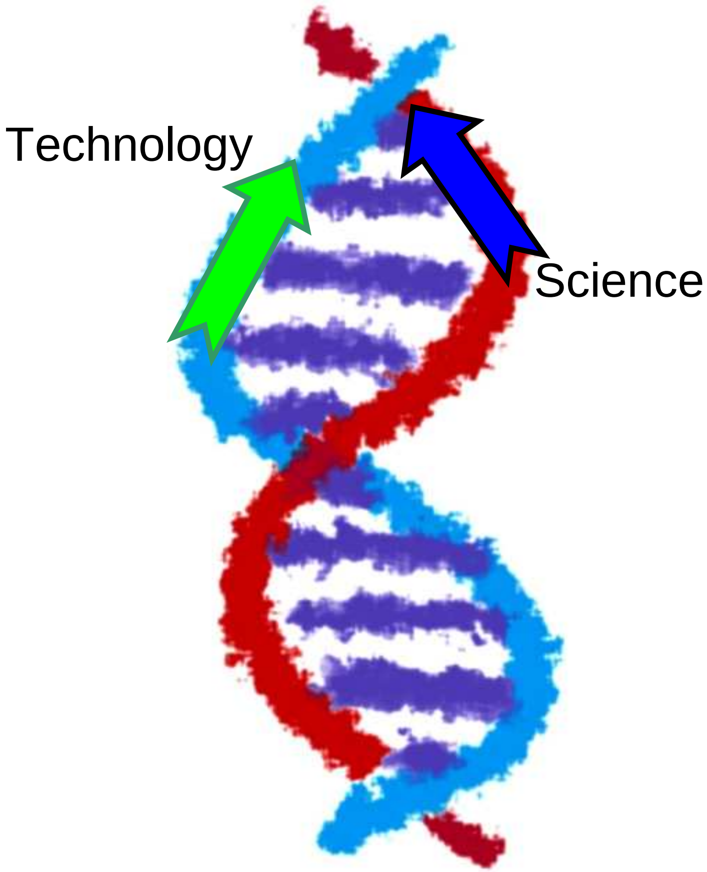
Optical lattices control the many-body environment



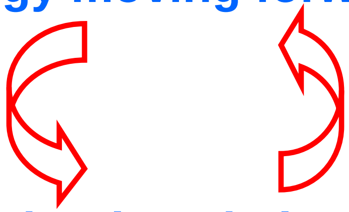
Magnetic-tuned Feshbach resonance controls atom-atom interaction



Double Helix of Science & Technology



Better understanding of science helps technology moving forward



Better technology helps to explore new science

It is a tradition in AMO physics to extend new technology to explore physics at new regime.

躬逢其盛！

20th ICAP, Innsbruck, Austria, July 2006, Norman Ramsey
"I wish I were 29 instead of 92 years old such that I could participate in the exciting advancement of atomic physics".

能作為一個物理學家是極大的恩典，
要配得上它，大多數人一生在作無聊
繁複的事！

Today's Talk

- Not just about physics, but more about learning processes, personal experiences and feelings !
- 分享那些迷惘與困惑、失敗與沮喪、狂喜與欣慰、感動與賞析的種種！
- What I really learn during these 14 years' exploration on the ultracold world !
- What I really want to teach to all students !

最需要教的並不是物理, 而是如何培養自己的能力!

- 有好奇心、健康的人生觀，要對某些事有熱情。
- 要問問題，要問別人更要問自己，嘗試獨力去尋找答案，有自我學習能力。
- 要有思辯邏輯、分析判斷能力，保持批判性思考，不要太輕易相信任何事。
- 有好的工作習慣，想清楚流程、記錄有用資訊、讓工作環境方便舒服、防呆、模組化、作數量級估計。
- 有解決問題能力，分段除錯、各個擊破。
- 勇敢解釋你已懂的也讓別人懂，培養表達能力並教學相長。
- 有面對壓力、挫折的勇氣。
- 相信自己，你可以辦的到，有志者事竟成！
- 擁有這些能力，面對不同主題一樣適用！

所有我眞正需要知道的．．．

最近我在家裏偶然看到一本平裝書一所有我眞正需要知道的在幼稚園時就學到了〔譯註〕一是Robert Fulghum的短文集。多年前它列名暢銷書單榜首時，不知怎麼漏過我的注意（但我妻子沒漏，書一定是她帶回家的）。

書中這一篇短文說明Fulghum的個人信條——他眞正需要知道的，他宣稱在幼稚園已學到了。

物理學家的信條是什麼呢？那些事是物理學家需要知道的？我仔細想過後整理了一張清單在這裡。您的優先順序可能不同——這是一張關心研究的理論學家所開列的單子。所列項目沒有一條是在幼稚園學到的，而事實上，沒有一項在我大學或研究所課程內。所有我眞正需要知道關於物理的事情我必須靠自己發掘。

一個物理學家的信條

※保存想法、上課及工作的筆記。記憶會衰退但寫下來的一直跟著你。年輕時你可能低空閃過，但當你到四、五十歲時，你的筆記——編了號，記了日期，附有索引並收集在夾子中——是在混日子和仍作有用工作間的重大區別。

※粗略的筆記只是漸漸隱去的影像。謄寫下來，不要等待。校訂你生產的東西，以例證說明，工整的書寫，最好能用文字處理工具。材料本身已夠艱深，任何使找回它們較順利的方法都有大幫助。

※如果值得記憶的，寫下來。在電話機旁擺本筆記簿，將每一項記錄編號並寫上日期

※翻閱文獻並讀與你相關的（你不是Feynman）。收集參考資料。清晰的甚至教學式的寫你自己的論文。

※花時間選擇你要學習的書籍。不好的書會令你沮喪，而好的則讓你高飛。搜索那能提供你直覺洞察力的並用你自己的文字寫下重要的章節及計算過程。解習題。

※決不停止學習。學習過程中組織你自己的練習。它們將爲更嚴肅的問題開道。

※不要給拉進大計畫除非你對其最終產品有一清楚的概念。

※去找大問題。沒人會在乎可以發表的瑣碎結果。

※花時間準備一個計畫——否則你會花太多時間做不需要做的事。

※展望未來。規畫你打算做的事——下個月、明年、長遠的未來。當你學到更多時再

作修正。

※學著嗅出好問題。尋找它們的技巧比解決它們更重要（雖然兩者均算數）。如果你能將令人困惑的數據轉換成適切的問題時你就搞定了。將半解的難題收起來留待後日。

※不懂時決不告訴自己懂了（你如何能知道F＝ma的意義除非你能清楚的定義F和m？）。如果你不懂，想辦法弄懂。請教朋友，查書還有訴諸常識。記筆記。

※如果到最後還是不懂，寫下你已有的。將來你有可能再繼續下去。

※花時間整理你心中和筆記裏的想法：趨勢與實質材料是一樣重要的。對歷史的認知將有助於識別趨勢。

※不要怕單調辛苦的工作。沒有痛苦，沒有收獲。

※但若計算過程越來越繁雜，可能大自然並沒打算要你用那個方法。尋找不同的路。

※一旦你了解一種推導，設法猜出它直觀的意義。理想狀況下，你只需記得觀念；數學可等以後再加進去。

※檢查單位(dimensions)和數量級。

※準備每一次的上課或演講。用文字。

※預演會議中十分鐘的報告。分發抽印本(preprints)。

※回信。

※如果你召集一個委員會，花時間想清楚應該有什麼樣的結果。每次開會前寫下你自己的會議事項。控制自己的發言時間，兩次會議之間設法使委員會活下去。

※從寫評論性（回顧性）論文中你會學到很多。不管該評論談的是什麼，徹底的工作使你成爲最前面的專家。同時，在此過程中你非常有可能再發現一兩個值得追擊的研究題目。

※公平的給予別人該得的(credit)。

※如果可能找位良師或益友，若找不到也別驚訝。良師益友不多，而且每個人都忙。或許你能爲別人扮演這個角色。

※招募聰明的年輕人。

※與同仁溝通。珍惜少數對你的工作真正關心的。

※花時間請教專家。他們不會在意而且可能很高興展現他們的博學。

尋找意氣相投的人。他們很稀少又離的很遠。再沒比這更可貴的。

※能作爲一個物理學家是極大的恩典。要配得上它。大多數人一生在作無聊繁複的事。

譯自　1993年五月號"今日物理"(Physics Today)% 63頁。

Personal Tour in Ultracold Research

- 1997-2002, TsingHua University, Prof. Ite A. Yu, PhD,
  - Coherence-induced phenomena, e.g. electromagnetically induced transparency, in cold atoms
  - Pursuit of rubidium Bose-Einstein condensation
- 2002-2003, Rice University, Prof. Randall Hulet, Postdoc,
  - Superfluidity and pairing in degenerate Fermi gases with lithium atoms
  - Optimization of evaporative cooling with Boson/Fermion mixtures
- 2004-2005, Rice University, Prof. Thomas Killian, Postodc,
  - Ultracold neutral plasma starting with strontium atoms
  - Photoassociation spectroscopy of strontium atoms
- 2005-2011, Ins. of Atomic & Molecular Sciences, Assistant Prof.
  - Cooling and trapping of SrF molecule
  - Low-light-level nonlinear optics with cold cesium atoms

原子物理的單純性與可驗證性

- 微觀現象可以很直接方式呈現在面前！
- 可直接和所學的簡單量子理論比對!
- 很“容易”可以操控它們！
- 可以高精密度的量測相關物理量！
- 所發展出來的工具可用於其它研究領域!

However, 實驗的複雜性與多自由度

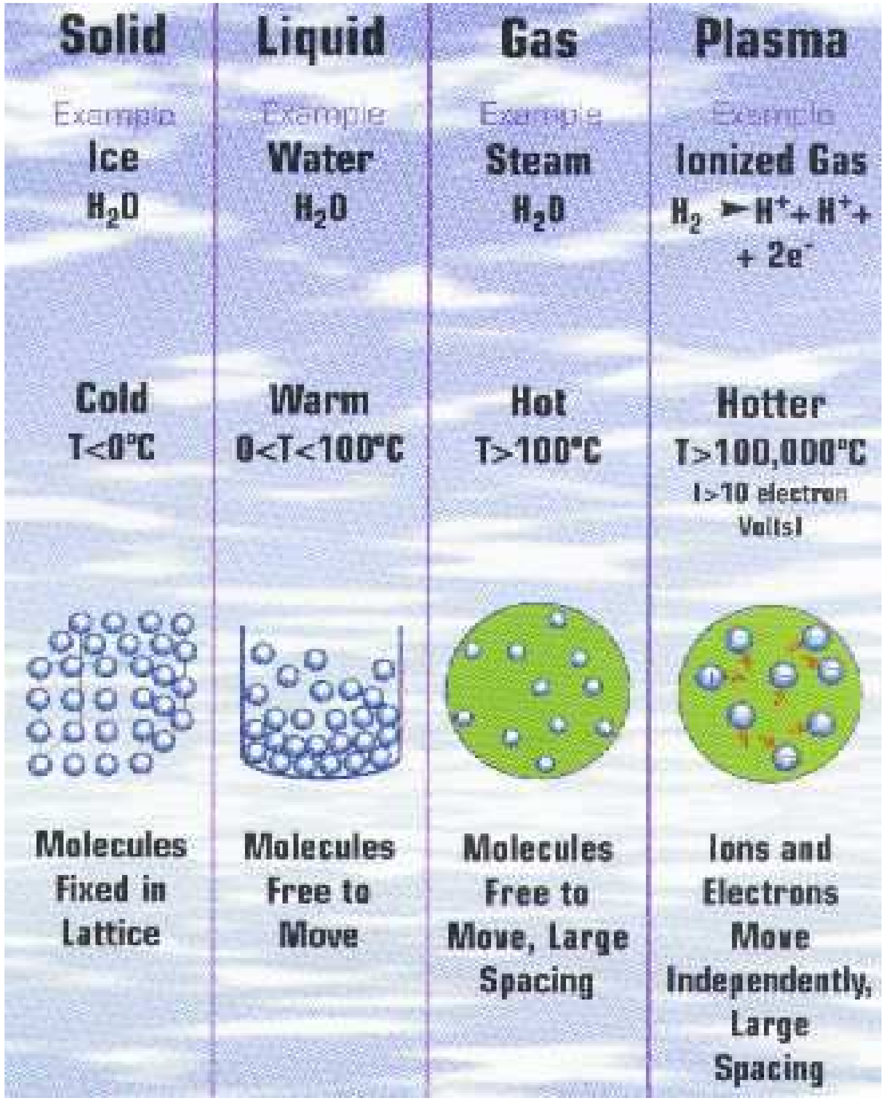
- 須知光電、真空、電子、機械、自動控制、數據分析等各種技術!
- 好幾台(N~5-10)Lasers,每一台都須鎖頻、像個baby須好好照顧!
- 上百個光學元件，每一個都有好幾個alignment自由度。
- 自動控制數十台儀器，每一個時序都須精準控制。
- 每一個控制都有其背後對應的物理判斷須知! 這往往是最需要時間累積知識與經驗的!
- 監控所有可能的訊號，確保所有事都像你想那樣正常運作!
- 最困難的是每一個東西須正常運作，實驗才能順利進行!
- 要做好一個實驗很難，但要弄壞一台儀器卻很容易!
- 每一個東西比別人好1.1倍，100個東西比別人可靠1.1^{100}=13781倍!
- 從工作中建立屬於你自己的“哲學”(Algorithm;Morphy’s law) e.g. 多維自由度之最佳化、先破壞才有建設、模組化、防呆、分段除錯、不要太相信儀器(連BNC線都可能有問題)…
- 原子分子與光學物理是讓人練就前述所述研究能力機會較多的一們領域！

What is plasma ?

- The fourth state of matter.
- Assemblies of charged particles, neutrals and fields that exhibit .
- Debye length<system size

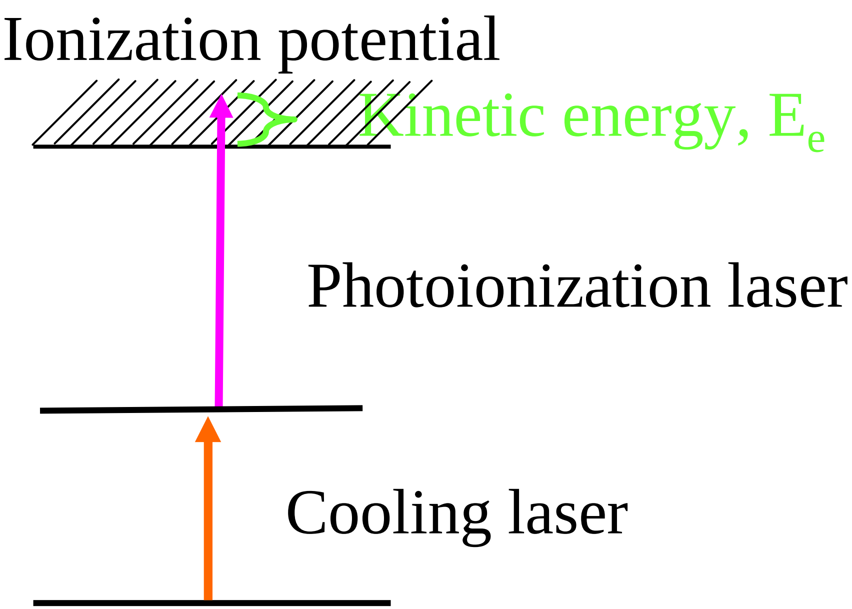
$$\lambda_D = \sqrt{\varepsilon_0 k_B T / n e^2} < L$$

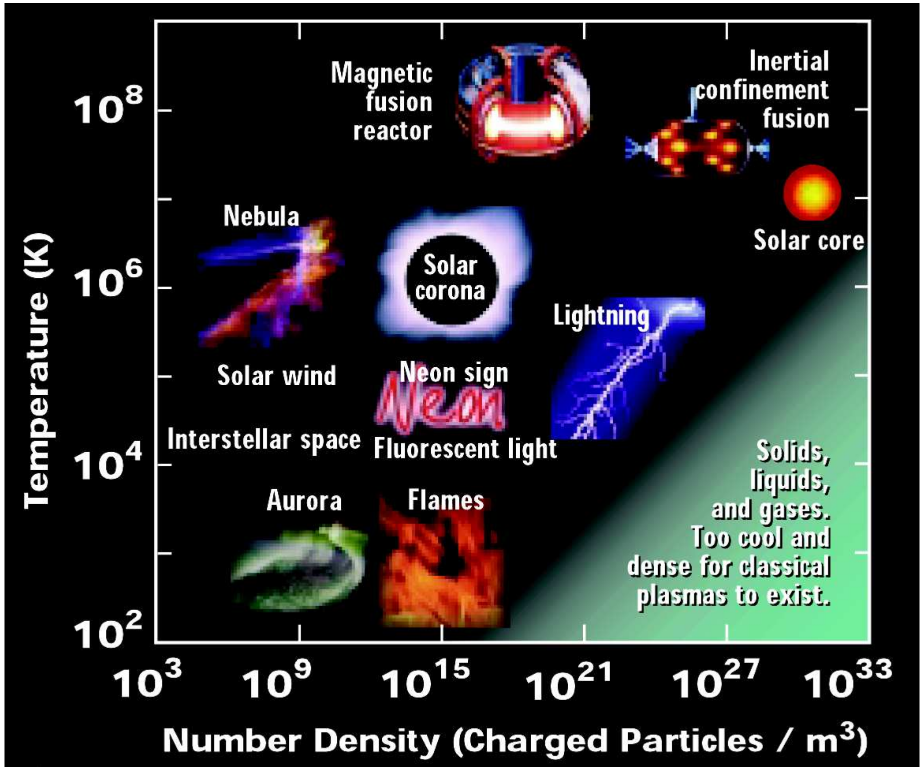
- 99% of the universe is in plasma state.



- 個人學術生涯之光明時期
- 人生有时轉個彎就峰迴路轉!

Cold plasma ?





- Initial electron kinetic energy, E_e, equals excess photon energy (0.1-1000 K)
- Ions created with mK energies
- Be careful, the cold plasma is not in a thermal equilibrium state !

- 製造出一奇特的物理環境並研究其下的有趣物理,在研究上總是可以引領話題,因為這 正是人類好奇心的一種顯現！

Time Scale of Plasma Dynamics

Electron plasma period : Time scale for electron sub-system to reach equilibrium, ~ 1ns

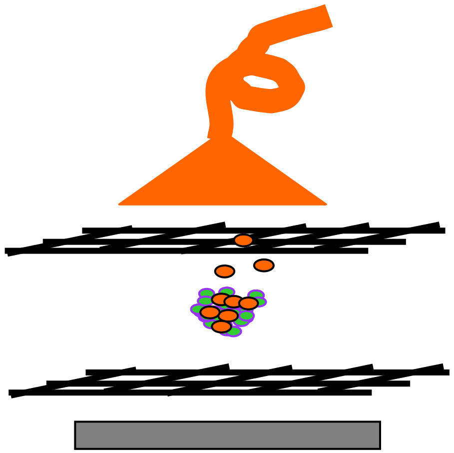
Ion plasma period : Time scale for ion sub-system to reach equilibrium, ~ hundreds of ns

Plasma expansion time : Time scale for plasma to expand due to electron pressure, ~ 1 μs - hundreds of μs

Electron-ion equilibrium time : Time scale for electron and ion to reach equilibrium, ~ 1 ms

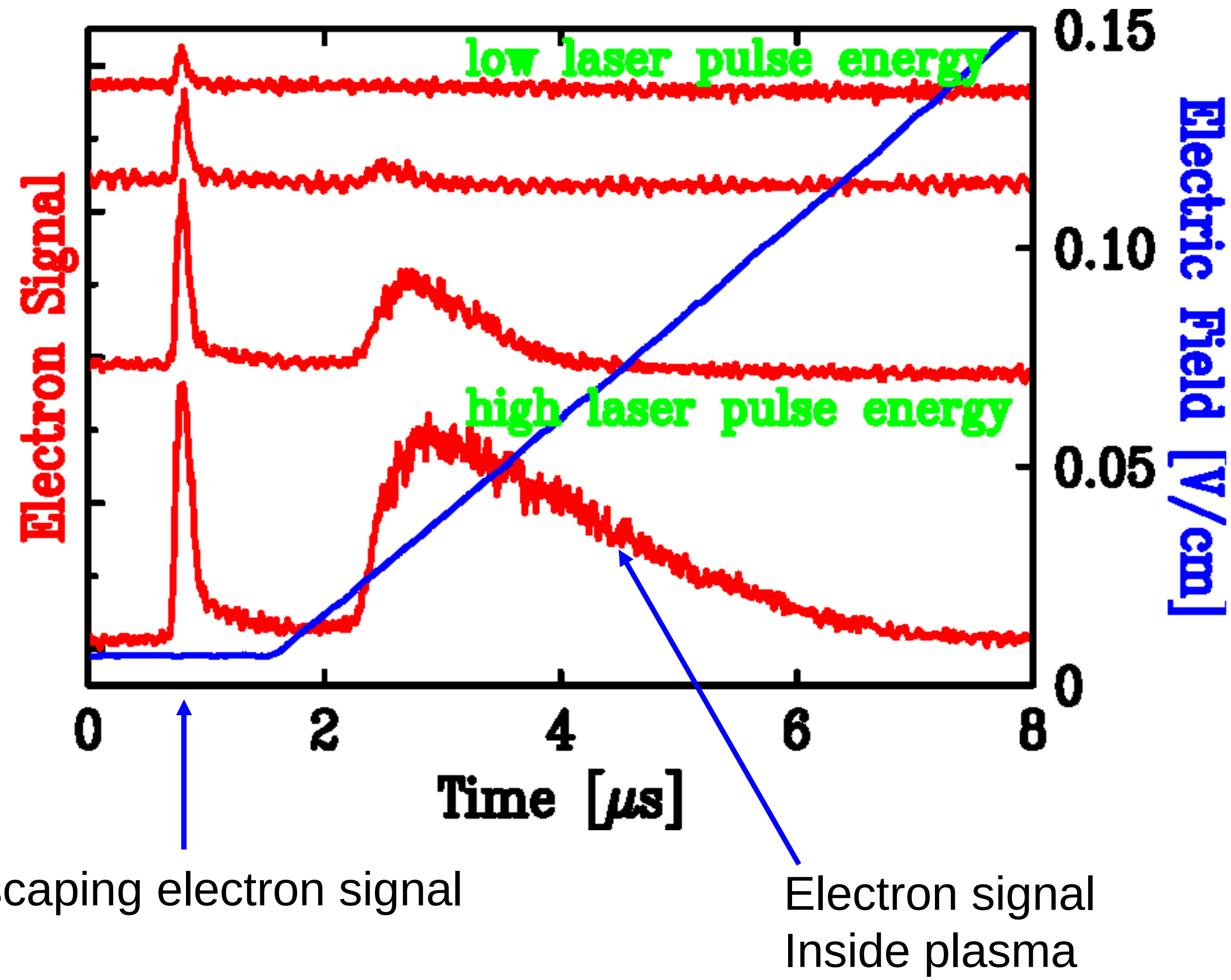
- 對物理系統之特徵時間(或其它物理量)要先有感覺,才抓得到大的圖像(big picture)

Electron Signals



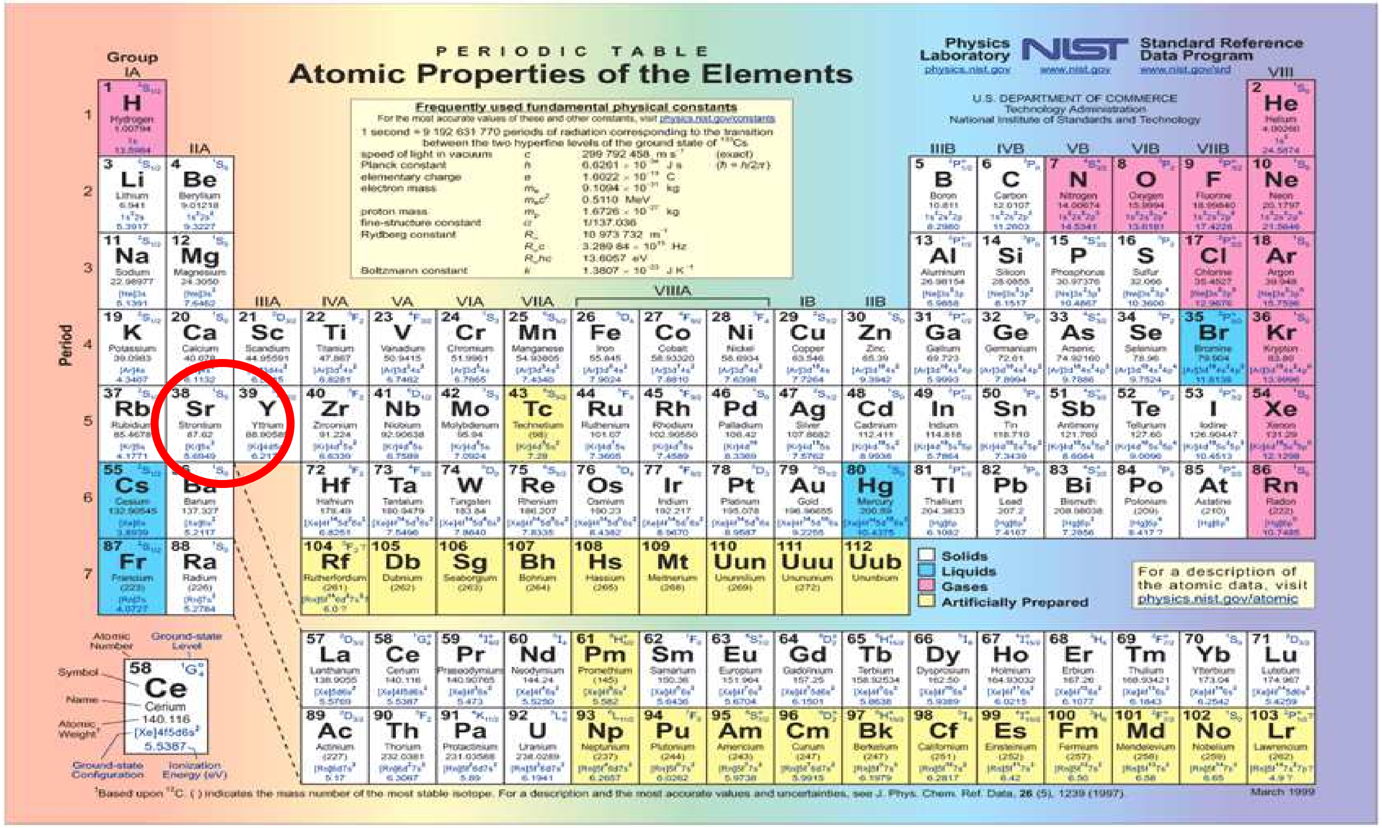
PRL, 83,4776(1999)

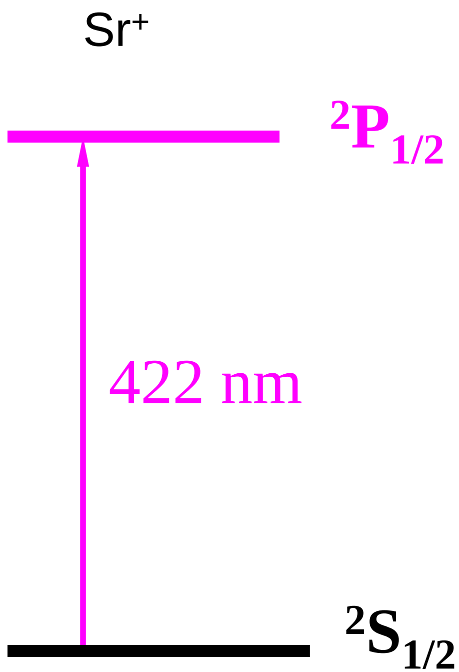
- Destructive method !



Charged Particle Detection:

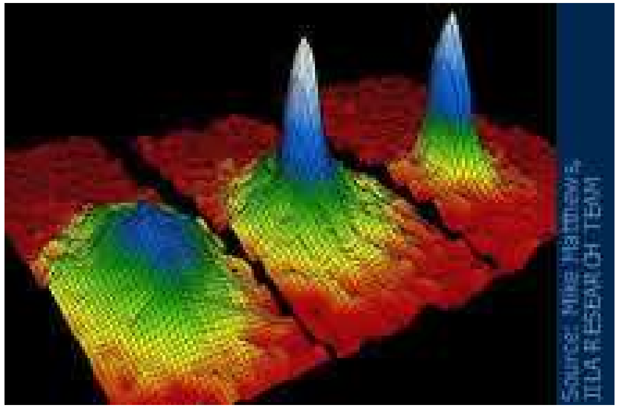
- time resolution limited by time of flight
- destructive (not an in situ probe)
- no spatial resolution
- little information on ions

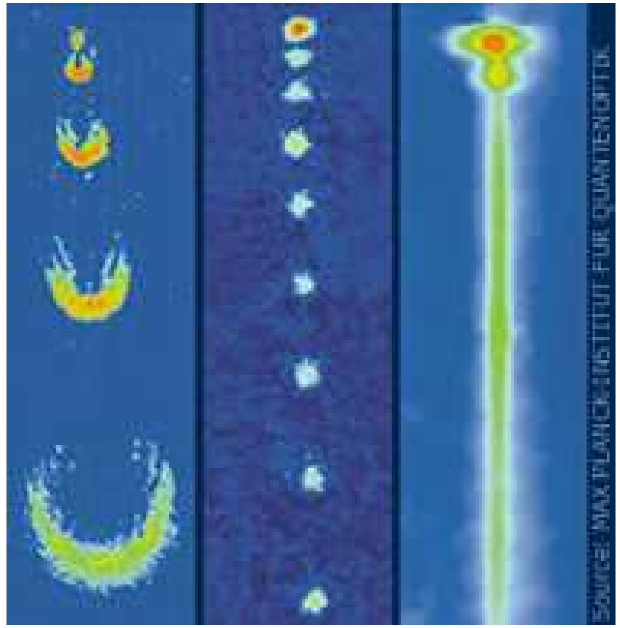


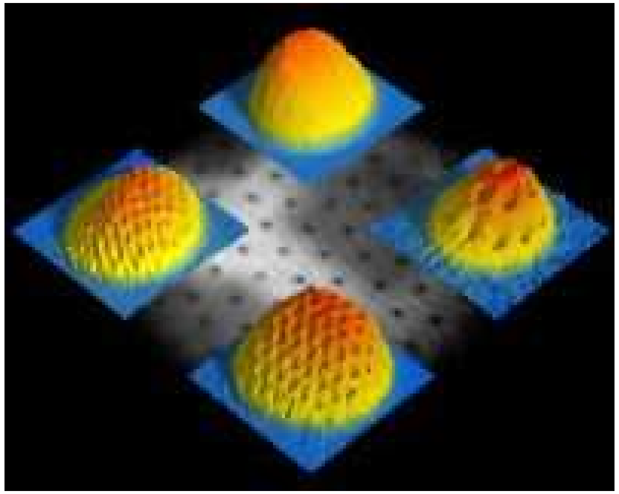


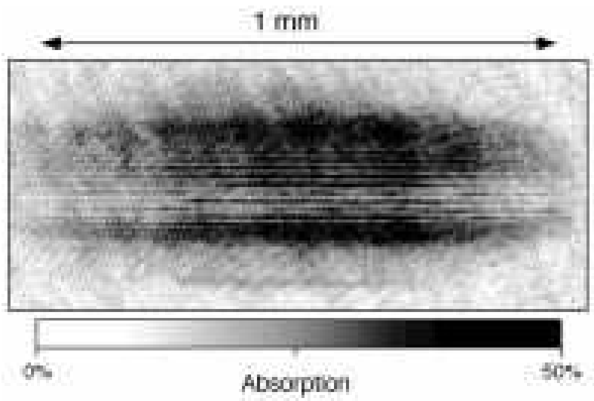
- 針對現有系統的缺點提出一個改善方案往往是創新的來源!
- 研究有一個好賣點是很重要!

Optical Imaging of Neutral Atoms



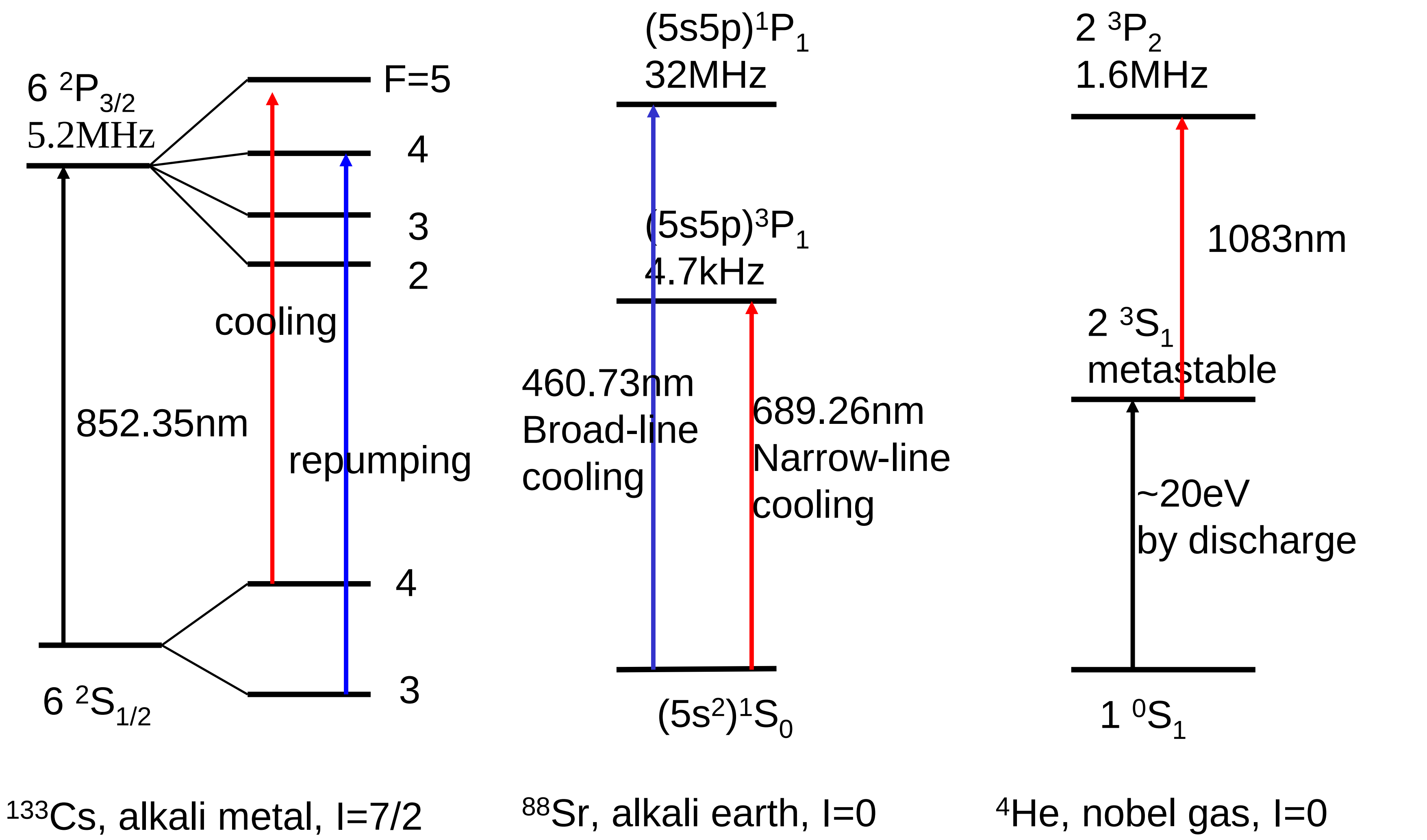






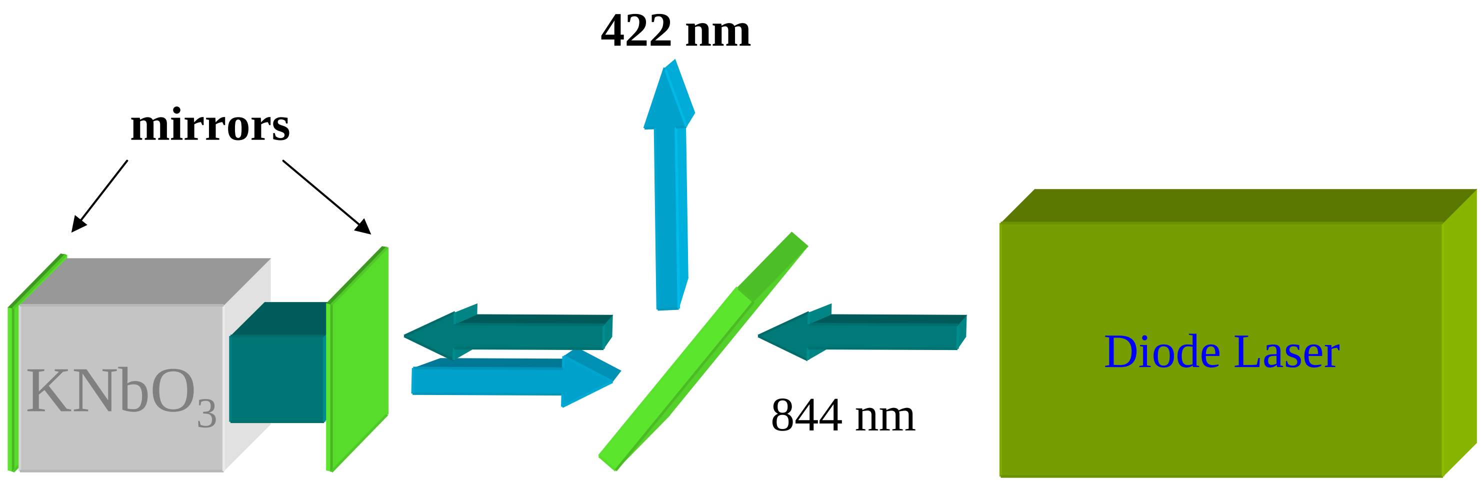
Atomic Species

- Different atomic specie has its unique feature, just like human being !



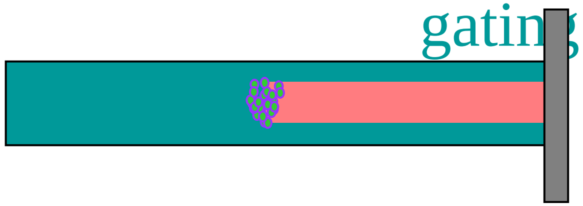
Building the laser !

- Well, it works finally although looks ugly !
- Two diode lasers died !
- Three crystal water damaged !
- Frustration !
- 細心與耐心！雷射就像個嬰兒要好好呵護！

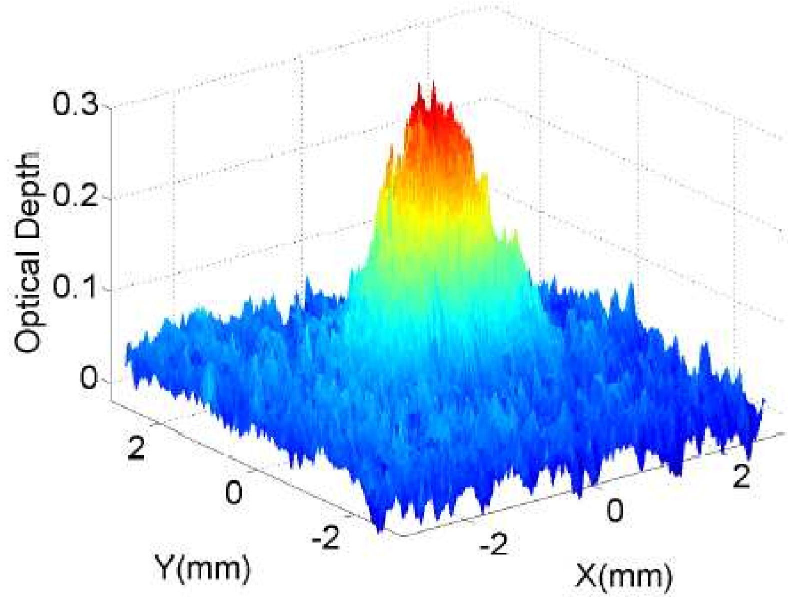


Absorption Imaging of the Plasma

Camera with
fast time
gating



- 第一張影像, 開香檳!

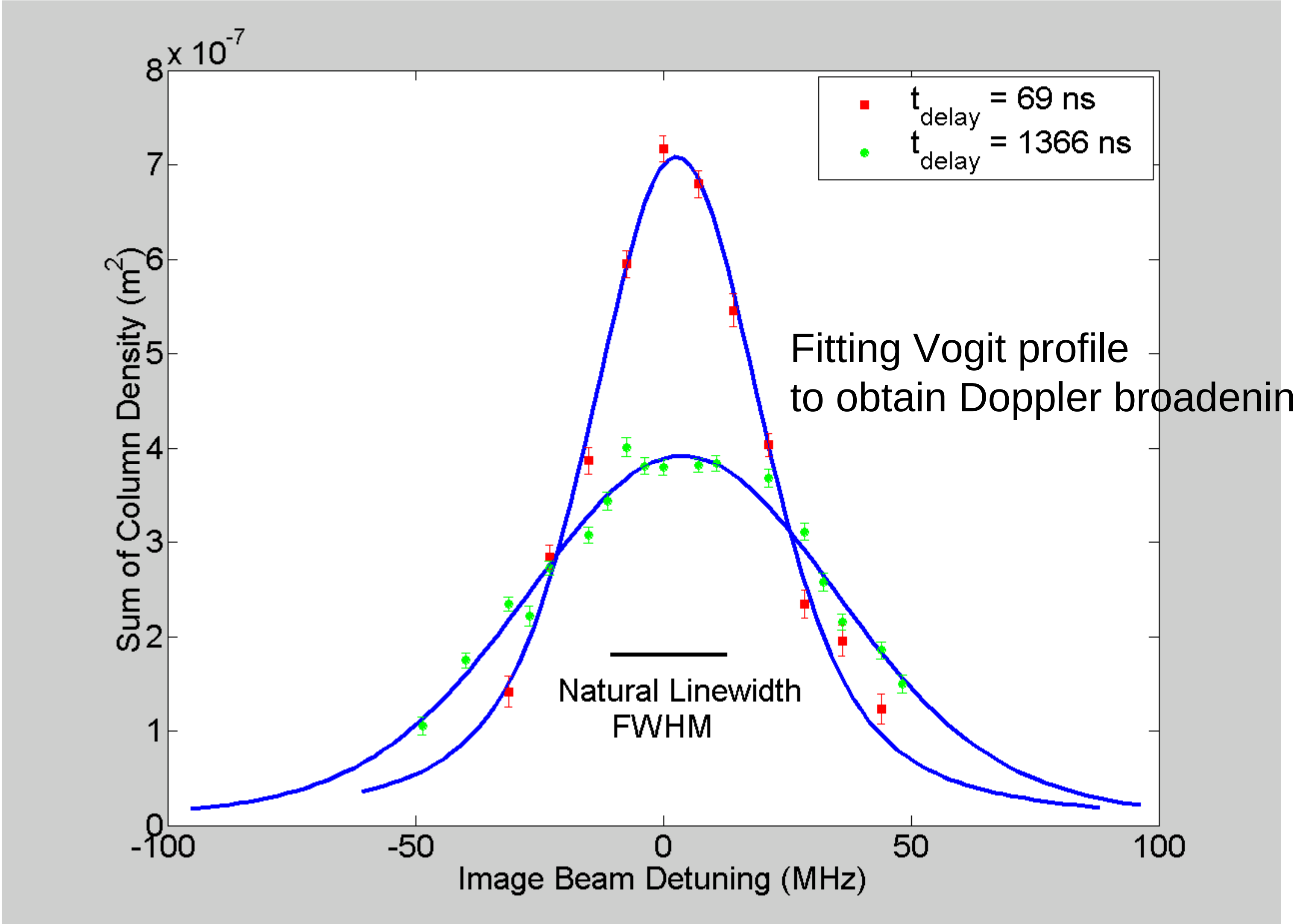


optical depth =
$Log(I_{plasma}(x,y)/I_{bg}(x,y))$

- 愛因斯坦：

  在已獲得知識的啟發下取得愉快的成就，幾乎是一件理所當然的事，任何一個夠聰明的學生都可以不太費勁的取得它。但是長期在黑暗中焦急的探索、強烈的渴望、信心的變化、及精力的消耗，最後終於進入光明，這一切只有那些有過這種經驗的人才能體會！

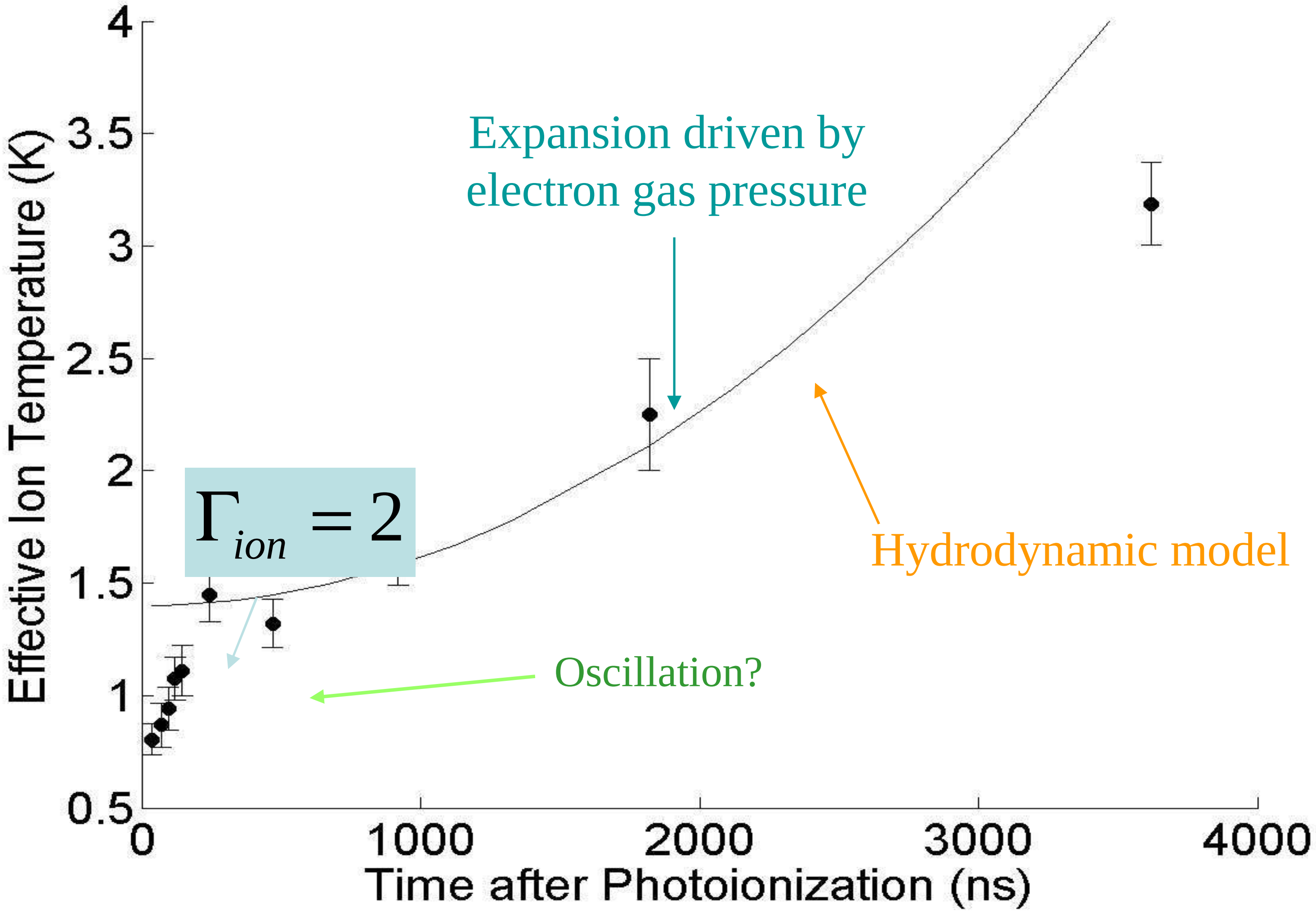
Ion Absorption Spectrum



Fitting Vogit profile
to obtain Doppler broadening !

- 學以致用才會感覺到真有學到東西！

Ion Effective Temperature

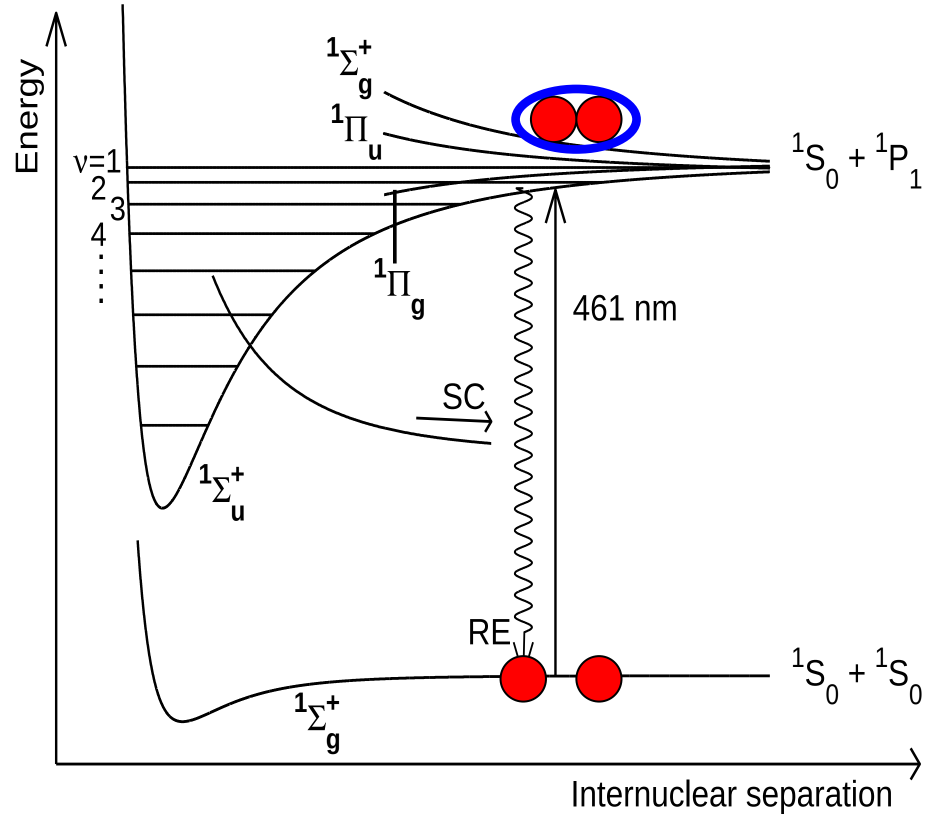


- 真的能利用自己建的系統開始看到一些物理，就是研究人最快樂的時候！

Photoassociative Spectroscopy (PAS)

- When two atoms collide, they interact on molecular potentials.
- A photon can excite colliding laser-cooled atoms to a bound molecular level.
- The molecule decays through a variety of means.
- The resulting atoms have increased kinetic energy and may leave the trap.
- When molecule are created, we see an increased decay rate for atoms in MOT.

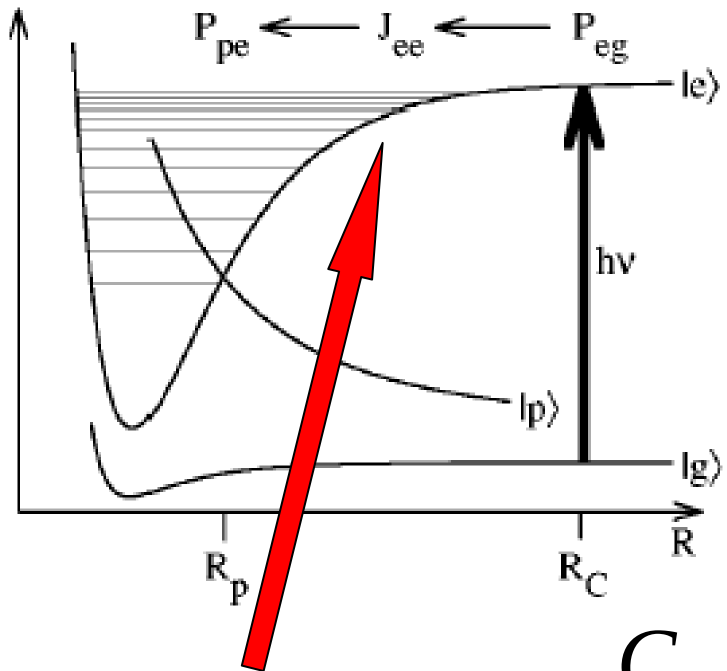
$$A + B + h\nu \rightarrow AB^*$$



What can we learn from the photoassociative spectroscopy?

Atomic and Molecular Constants

- The long range molecular potential has a resonant dipole-dipole form.
- From the position of the resonances, one can determine the C_3.
- With C_3, one can precisely determine the decay rate.



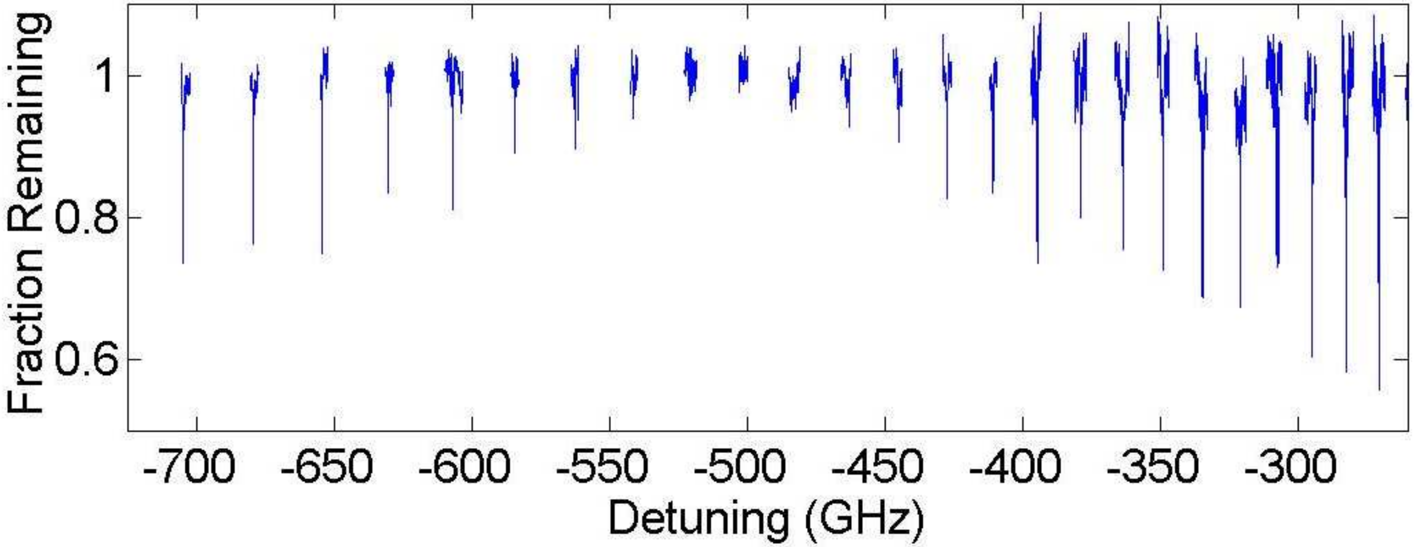
$$U(R) = D - \frac{C_3}{R^3}$$

$$C_3 = \frac{3\hbar\lambda^3}{16\pi^3\tau}$$

$$E(\upsilon, J) = D - X_0(\upsilon_D - \upsilon)^6$$

$$X_0 = \left[\frac{\Gamma(4/3)}{2\sqrt{2\pi}\,\Gamma(5/6)}\right]^6 \frac{h^6}{\mu^3 C_3^2}$$

"Seeing" the zero of a wavefunction: a touching moment

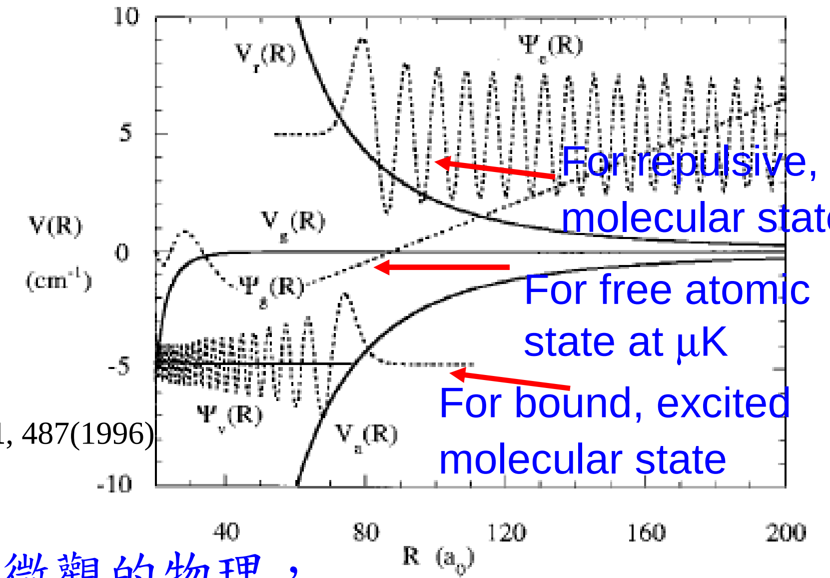


Frank-Condon factor

$$P_{ge} = \left|\Omega_{eg}(R_C)\right|^2 \left|\left\langle \Psi_e(R) \middle| \Psi_g(E,R) \right\rangle\right|^2$$

$$\cong \left|\Omega_{eg}(R_C)\right|^2 \frac{h\nu}{D_C} \left|\Psi_g(E,R_C)\right|^2$$

Ground-state wavefunction



Phys. Rev. Lett. 94, 083004(2005) & 95, 223002(2005);J. of NIST, **101**, 487(1996)

- 能透過親手所建的系統"看見"一些微觀的物理，正是讓人感動並且繼續不計勞苦往前走的動力！

- Thomas Killian, Professor
- Clayton Simien, Sampad Laha, Sarah Nagel,
  Priya Gupta, Yanni Natali, Pascal Mickelson, Aaron Saeno ,

2 diode lasers broken
3 crystals water damaged
Many long nights
data taking
…..
struggles.furstraition
hopeless,.happienss.…
Research!
Life !

A weakness in the AMO physics :

The control ability of molecules !

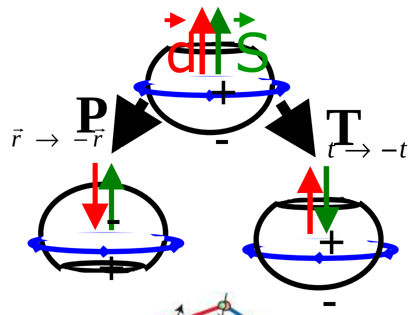
Why cold molecules for me ?

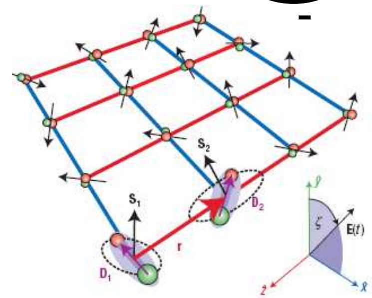
- **"…the major challenge for a young scientist is to make the right decision about which hill to climb**…". Wolfgang Ketterle (MIT)
- "There is something that we definitely know what is right and wrong but there is something that nobody really know what is right and wrong!" Bartlet, "West Wing". NBC TV series
- "Anyway, you have to make a decision to pursuit the direction at least you think that is right to you ! ", Ying-Cheng Chen.

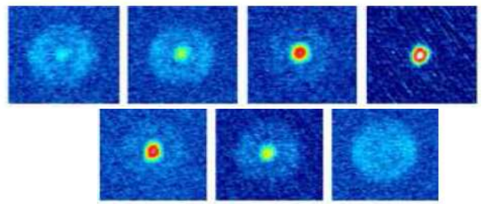
Cold molecules : Why ?

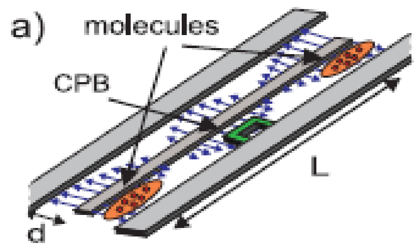
Full quantum control of internal and external degree of freedoms for precise experiments !

- Test of fundamental Physics.
  - Search for electron dipole moment…
- Quantum simulation with Dipolar Gases
  - Add new possibility in quantum simulation.
- Cold Chemistry
  - Chemistry with clear appearance of quantum effects
  - Controlled chemical reaction
- Quantum Information
  - Long coherence time and short gate operation time

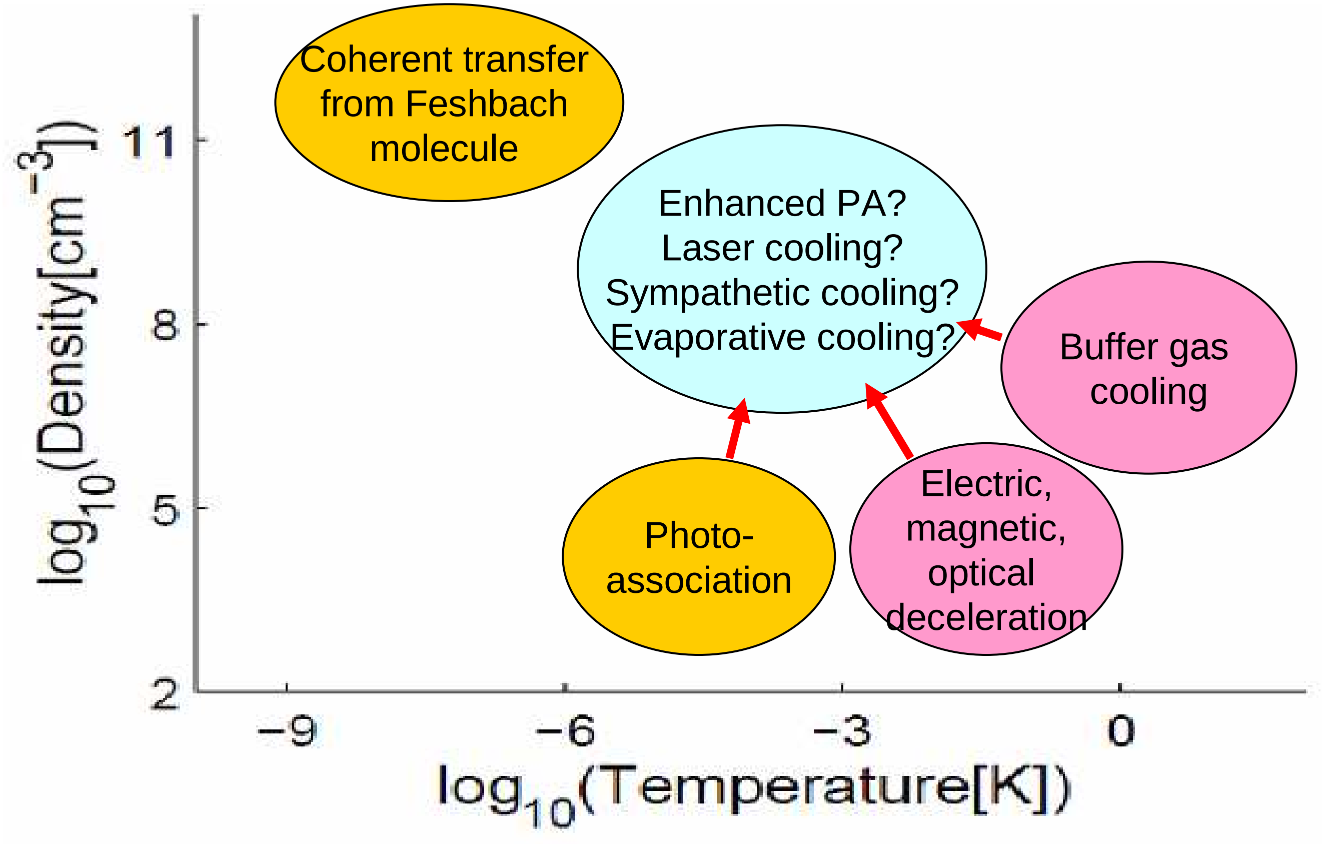


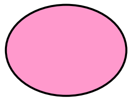




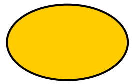


Cold molecules : How ?

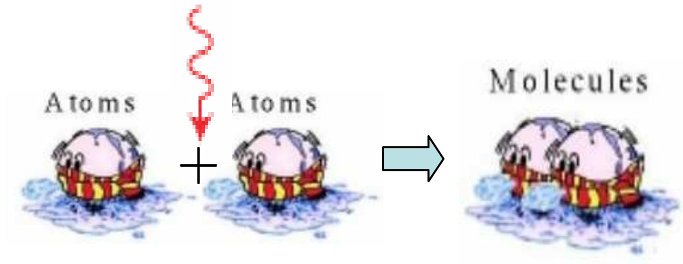




Direct approach

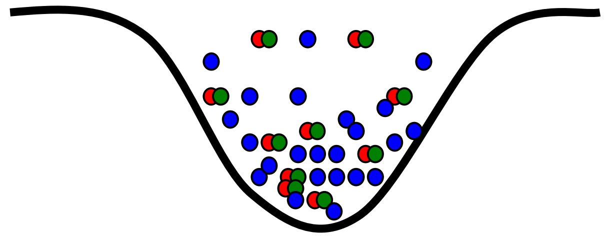


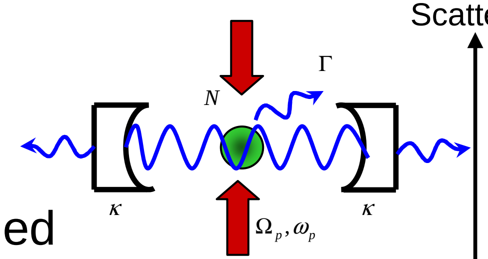
Indirect approach

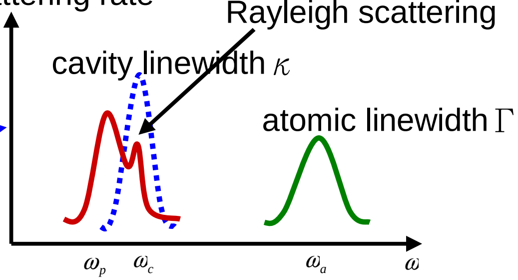


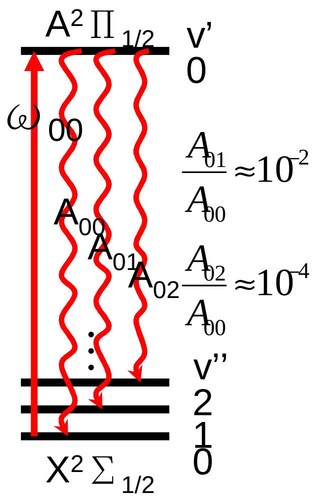
Quest of Second Stage Cooling to overcome the mK Barrier for Direct Approach

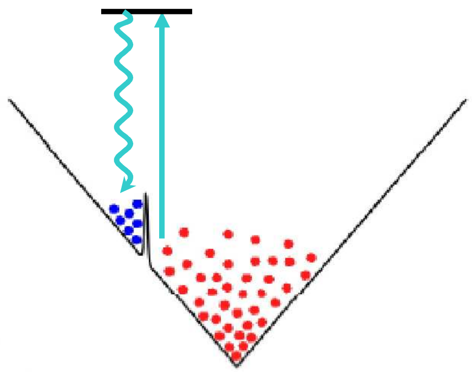
- Sympathetic cooling with ultracold atoms
  - Not so promising due to strong inelastic loss for DC traps
  - AC trap is necessary
- Cavity laser cooling
  - Haven't been demonstrated.
- Direct laser cooling
  - Under testing. Yale team claimed to cool SrF to 300 μ K in 1-D
  - Limited to a few species
- Single-photon (information) cooling
  - In combination with magnetic trapping
  - May be demonstrated soon
- ...





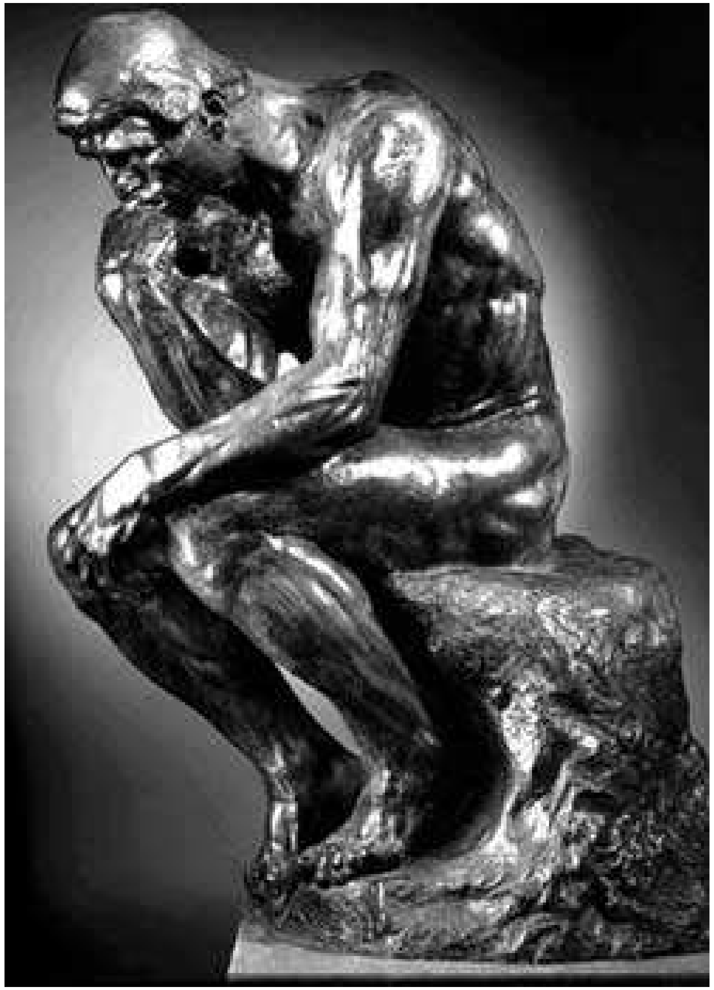






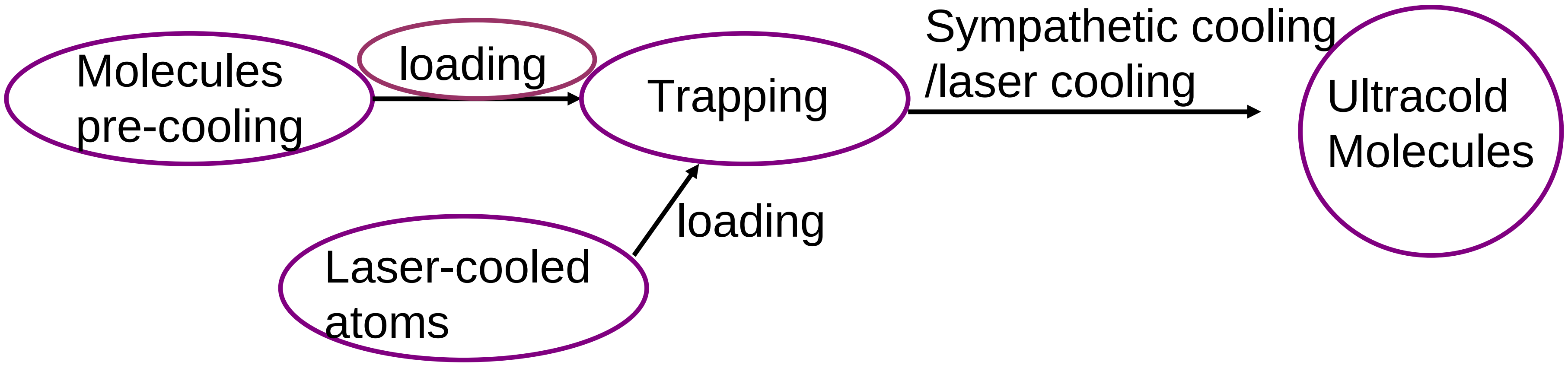
M.Raizen

What is our approach ?

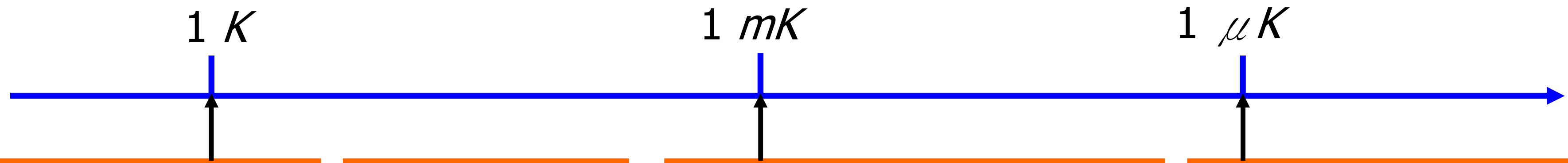


What are our considerations ?

- Choose the direct approach to make cold molecules in order to have more impacts in other fields as well. (a good choice ?)
- Generate a large number of molecules in the first stage.
- Build an AC trap in order to avoid the inelastic collision loss which is expected to be significant for polar molecules in static traps.
- Use sympathetic cooling with laser-cooled atoms in the ac trap to cool molecules down to *mK* regime or less.
- What advantages to take? What disadvantages to live with?



Routes Towards Ultracold Molecules

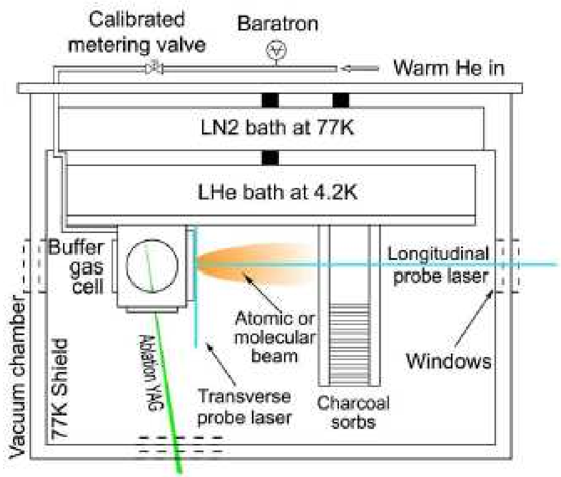


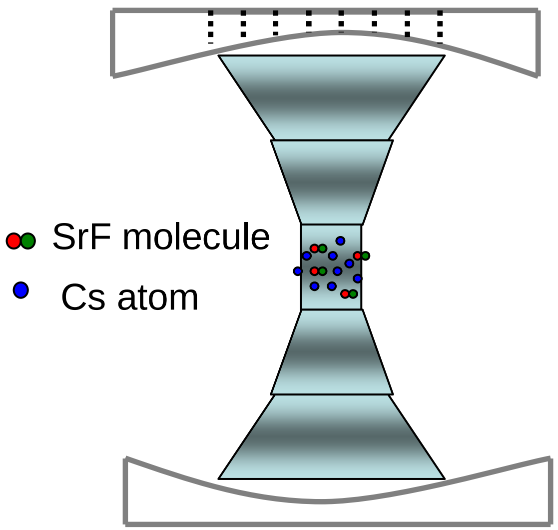
Buffer gas cooling plus ac electric guiding

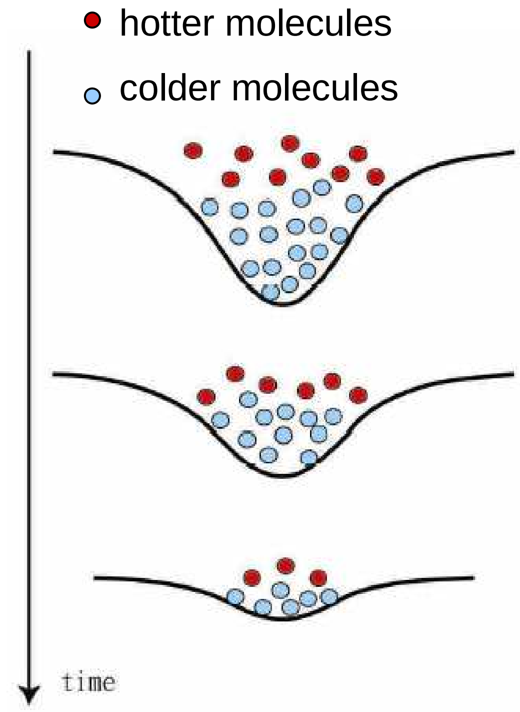
Dissipative damping & trap loading

Sympathetic cooling in a microwave trap by ultracold cesium atoms.

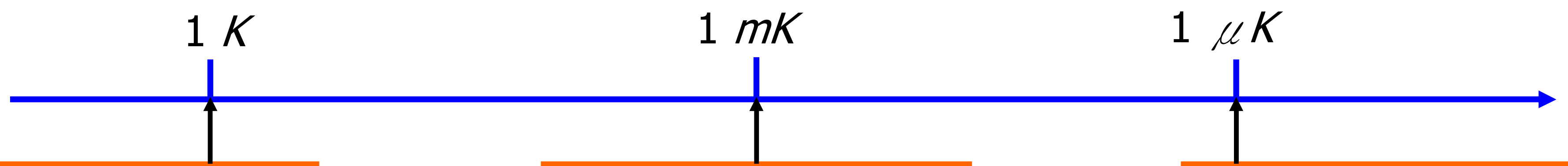
Evaporative cooling in a microwave trap.







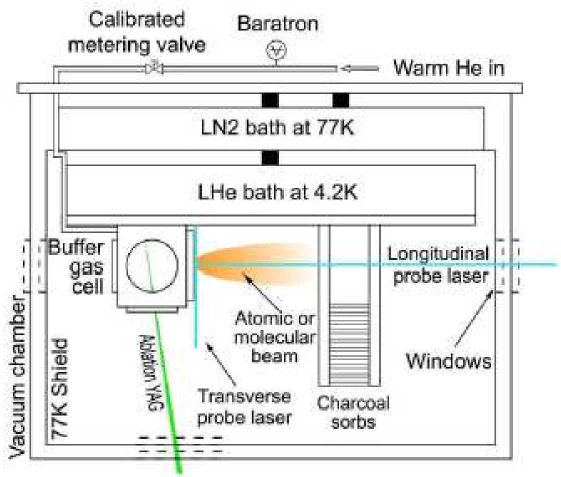
Recent Ideas

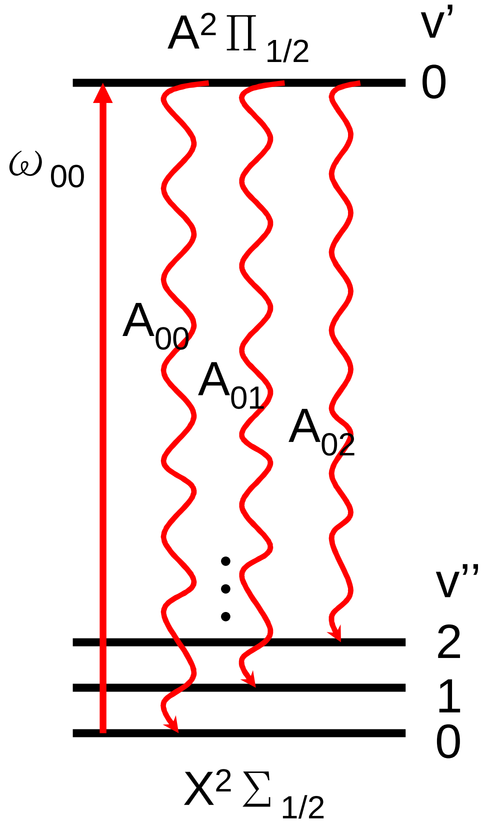


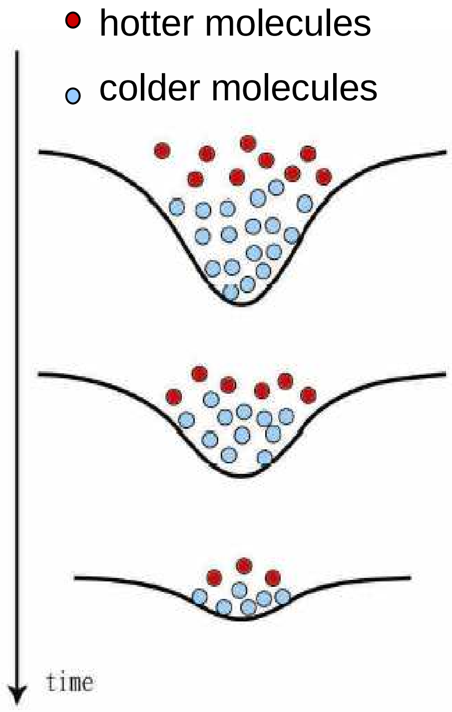
Buffer gas cooling plus magnetic guiding

Direct laser cooling

Evaporative cooling in an optical dipole trap.







What molecule? SrF, Why?

- Alkali-like electronic structure with strong transitions at visible wavelengths (651& 663nm). Easy to detect by diode lasers.
- Relatively complete spectroscopy data available.
- Large electric dipole moment, 3.47 D and many bosonic and fermionic isotopes . More possibilities in the future.
- Microwave trapping consideration. Available microwave high power amplifier at its rotational transition (2B~ 15 GHz).
- With nearly diagonal Frank-Condon array that allow direct laser cooling with reasonable number of lasers.
- Physicist favored molecules suitable for test of fundamental physics and quantum information science.
- Radical molecules. Disadvantages in molecule generation (laser ablation or high-temperature reaction).
- What advantages to take? What disadvantages to live with ?

Development of an intense SrF Molecular Beam

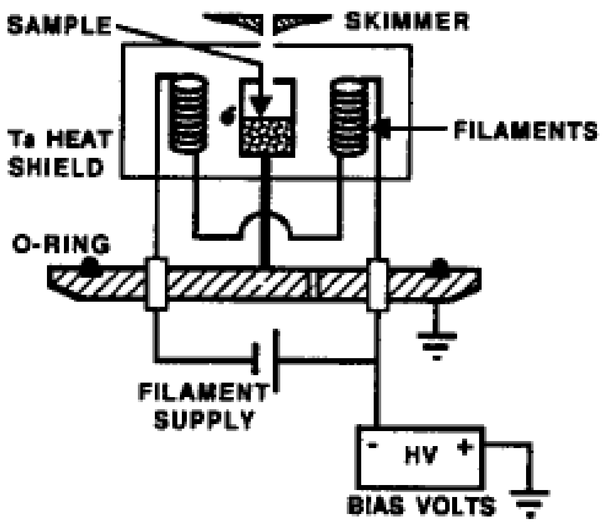
THE JOURNAL OF CHEMICAL PHYSICS VOLUME 48, NUMBER 8 15 APRIL 1968

Mass-Spectrometric Studies of Bonding in the Group IIA Fluorides

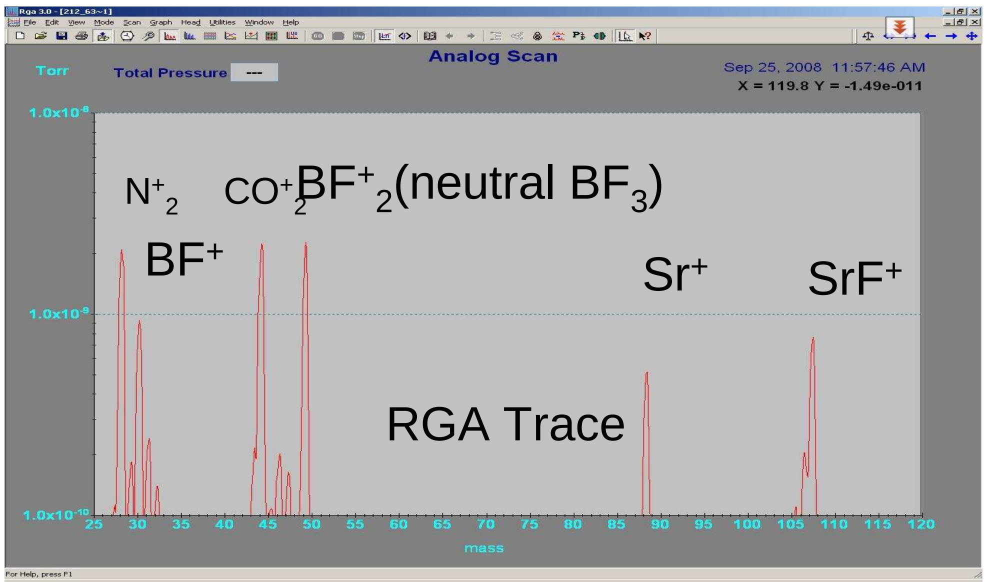
D. L. HILDENBRAND

Advanced Research Laboratories, Douglas Aircraft Company, Inc., Huntington Beach, California

2B+3 SrF_2(high-temperature~1500K)→BF_3+Sr+2SrF+BF



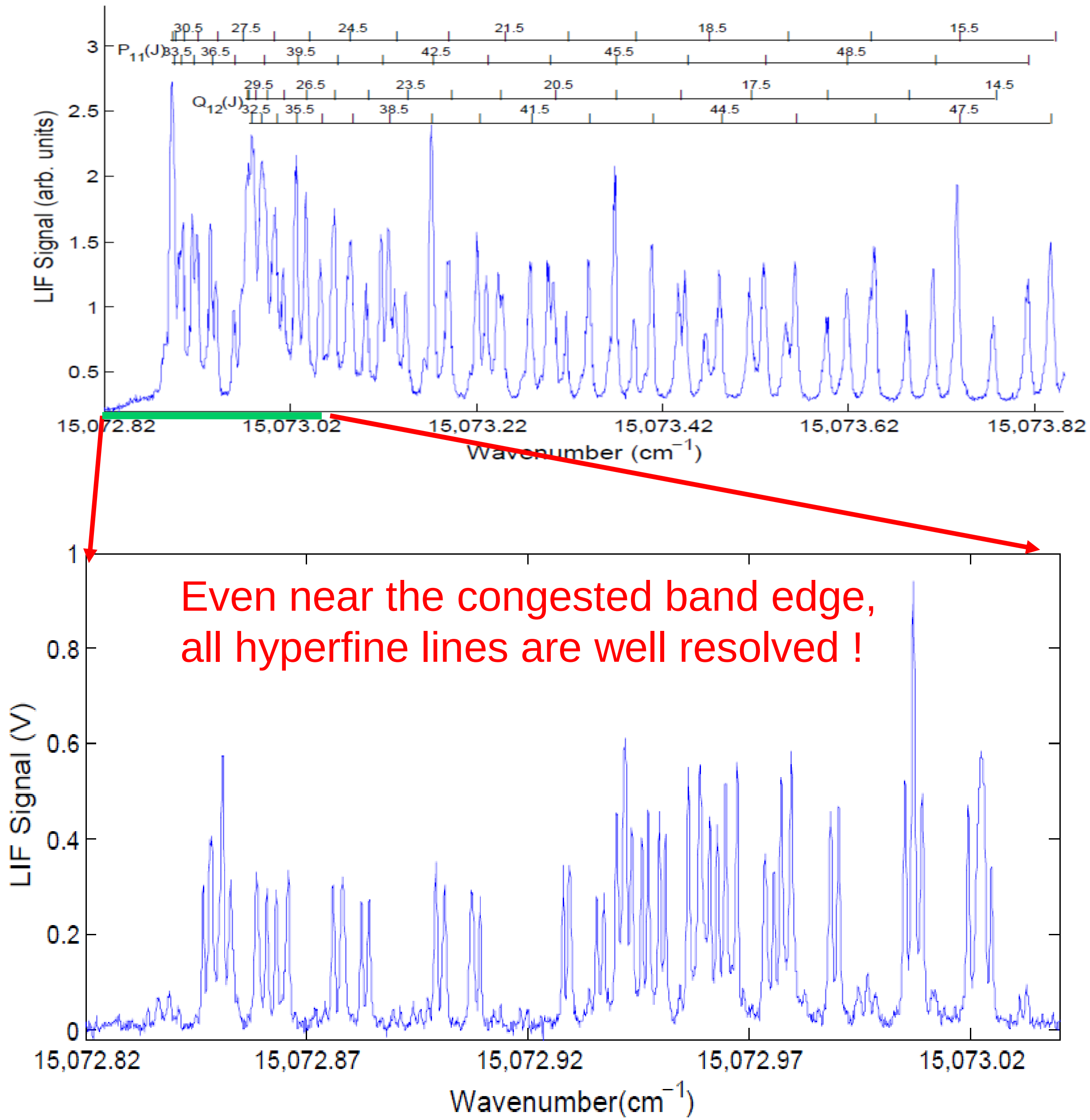
Electron-bombardment heating



May have important application in test of fundamental physics.

If one want to work with (cold) molecules then he need to learn some chemistry !

Typical Spectrum



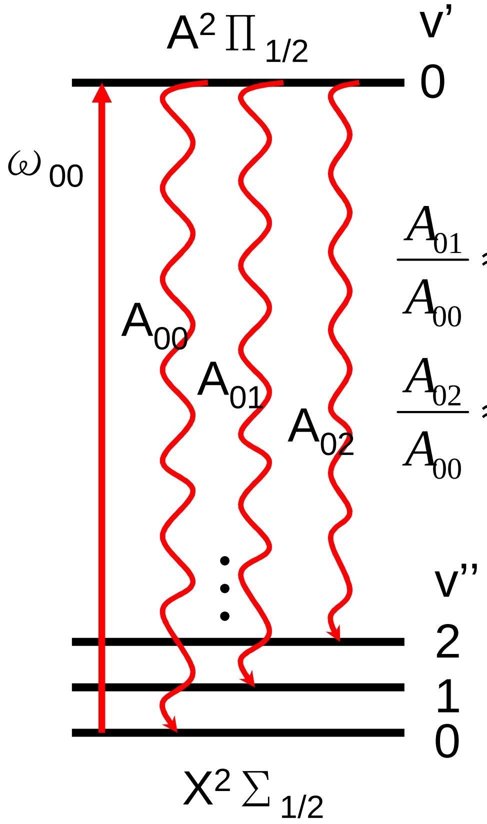
(0,0) vibrational band of $A^2\Pi_{1/2}$- $X^2\Sigma^+$ transition of ^{88}SrF

Laser intensity ~5 00mW/cm^2
FWHM linewidth ~ 130MHz
S/N ratio >200

Laser intensity ~ 5mW/cm^2
FWHM linewidth ~ 15 MHz
S/N ratio > 50
Hyperfine lines resolved
(I=1/2 for ^{19}F)

Direct Laser Cooling of SrF

- Try transverse cooling on SrF molecular beam first which is ~ 1K cold due to skimming.
- Repump the v''=1 population, the transition is closed to 10^{-4} level



$$\frac{A_{01}}{A_{00}} \approx 10^{-2}$$

$$\frac{A_{02}}{A_{00}} \approx 10^{-4}$$

$$\frac{m\bar{v}}{\hbar k} \sim 3600, T = 1K$$

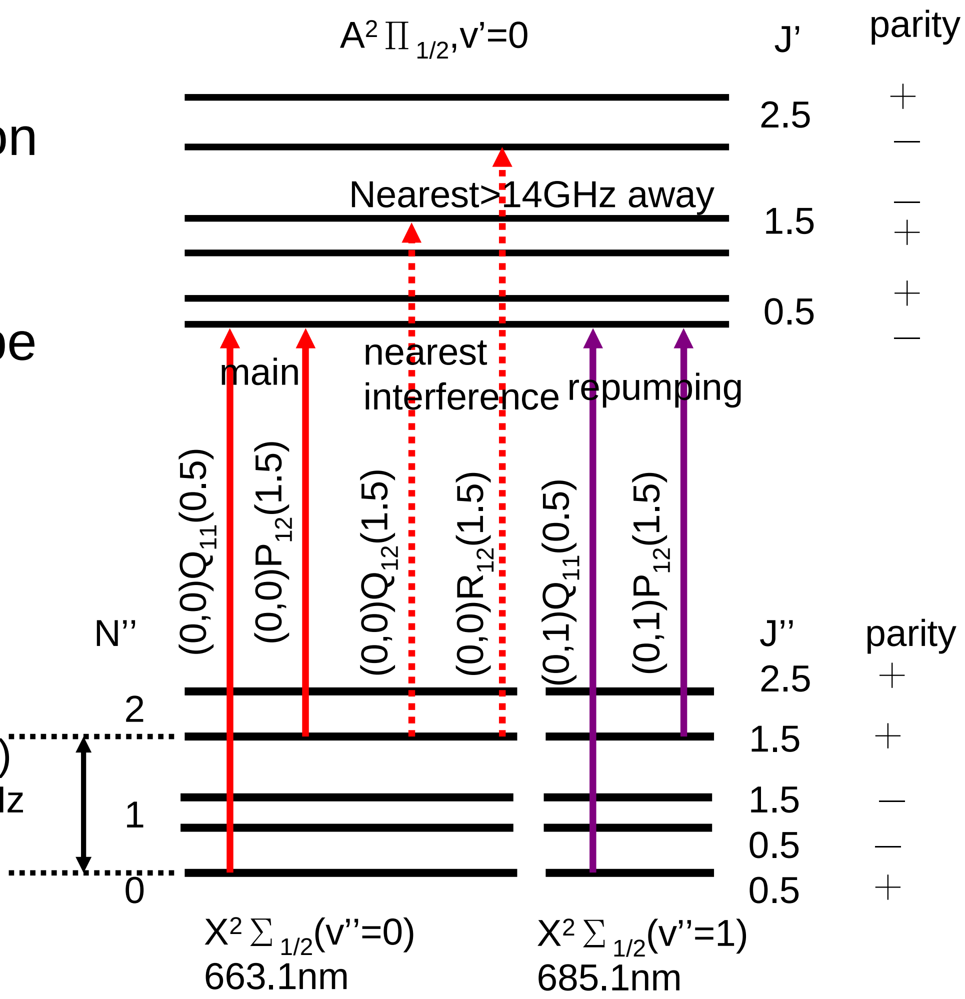
state	$X^2\Sigma$, v=0	v=1	v=2	v=3
$A^2\Pi$, v=0	0.9895	0.0103	1.33x10^{-4}	1.57x10^{-6}

J Phy Chem A, 102,9482,1998

0.999867^{3600}=62%

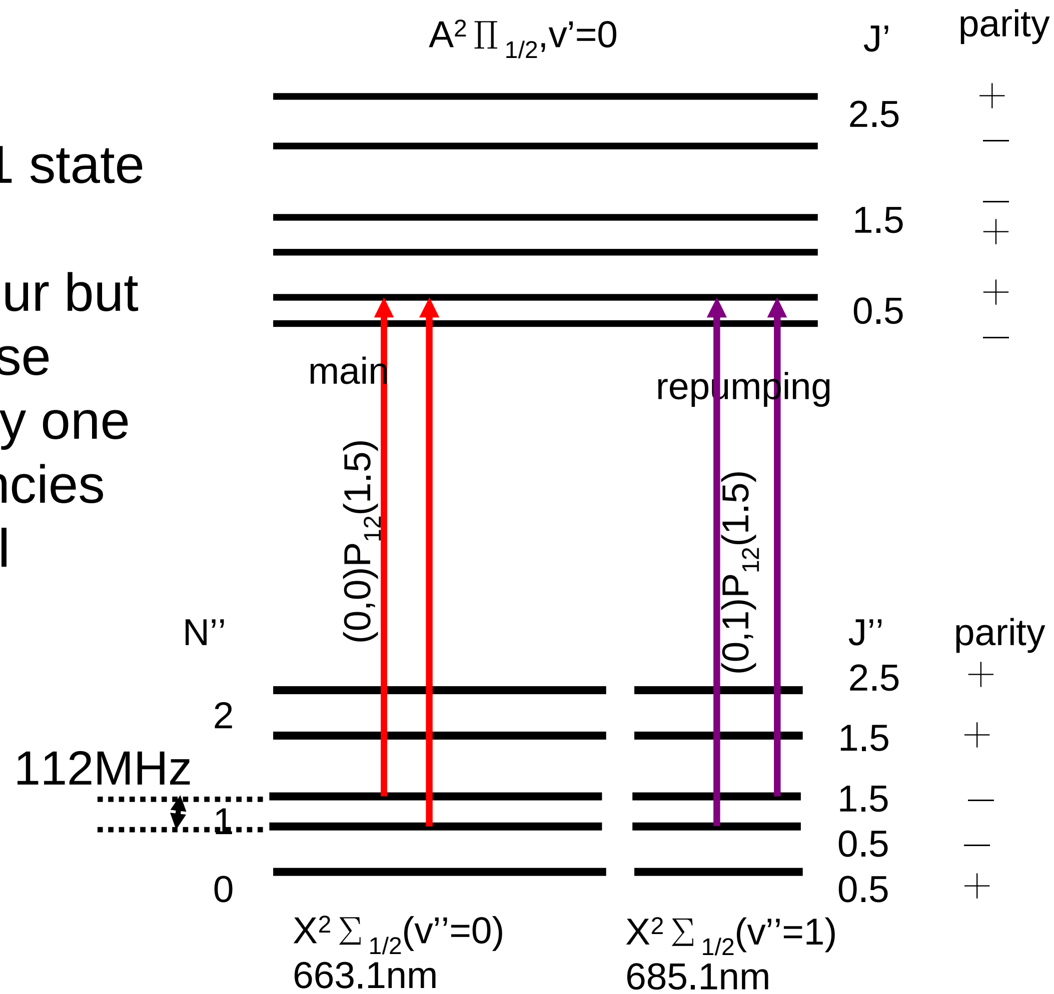
Rotational Transitions

- Need 4 lasers with two ~663nm and another two ~685nm to close the transition to 10^{-4}.
- Nearest transitions are >14 GHz away at least and can be negligible.
- Two lasers are ~ 45 GHz away for both two vibrational states.
- Similar to the D1 line cooling of alkali. (Opt.Com.135,269,1997)



Alternative scheme

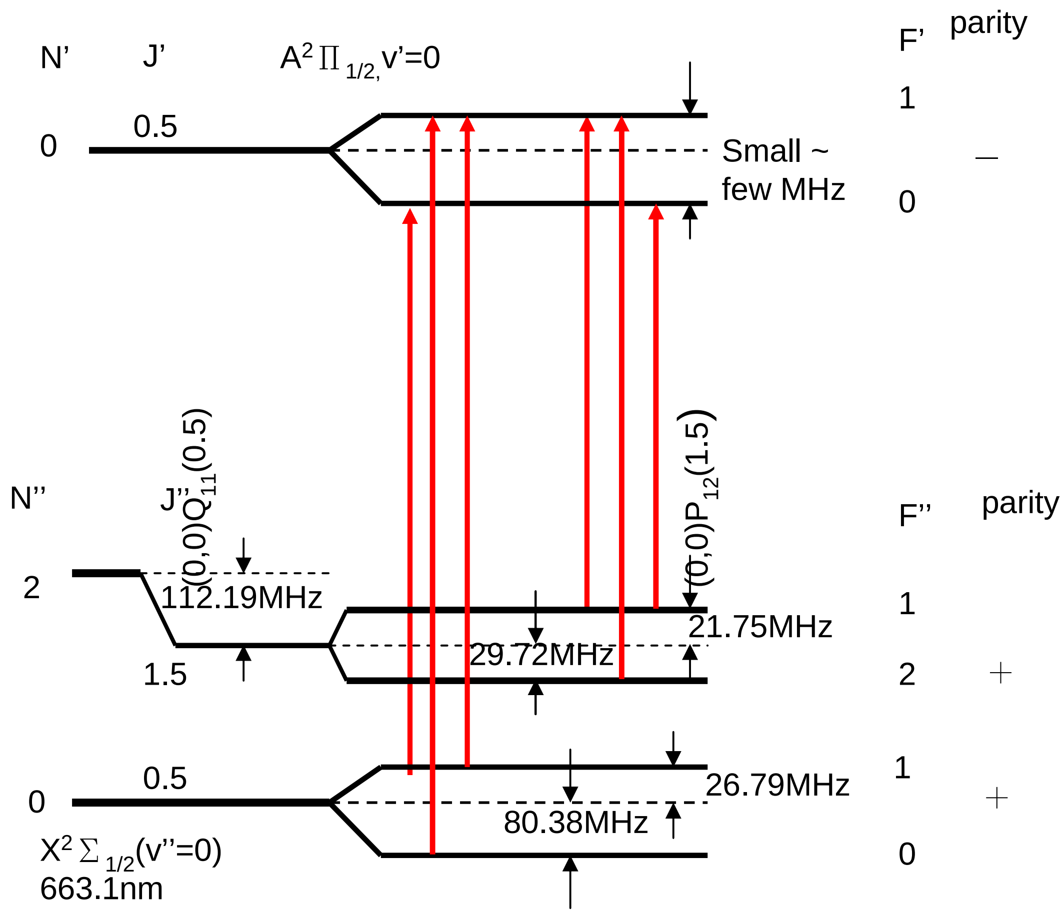
- One can choose to cool N''=1 state instead of N''=0 state
- The number of laser is still four but two sets of them are very close (~) 112MHz.One can use only one laser to generate two frequencies by acousto- or electric-optical modulators.



DeMille's team, PRL 2009

Hyperfine Transitions

- Each laser is needed to generate two beams with ~50-100MHz far apart by AOMs due to hyperfine splitting.
- In total, there are four frequencies required for each vibration state.
- Dark state in Zeeman sublevels can be avoid by inhomogeneous magnetic field.

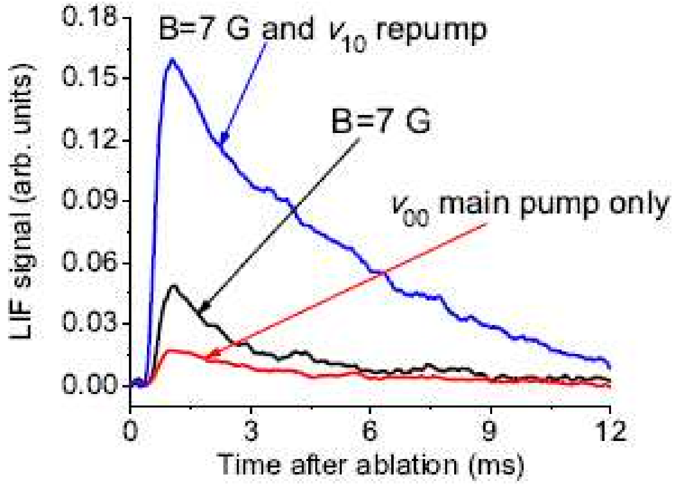


Competition

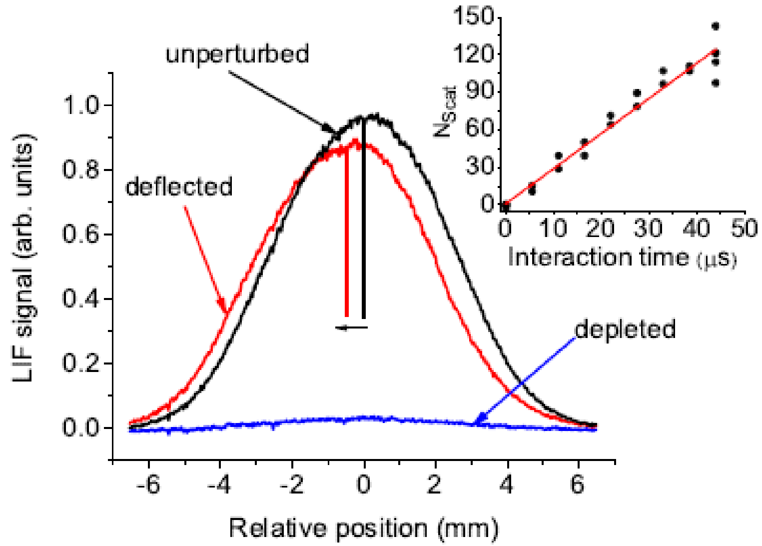
- DeMille's work on SrF arxiv://0909.2600 Setp 2009.

Radiative force from optical cycling on a diatomic molecule

E.S. Shuman, J.F. Barry, D.R. Glenn, and D. DeMille
Department of Physics, Yale University, PO Box 208120, New Haven, CT 06520, USA
(Dated: September 14, 2009)



Optical cycling $N_{scattering}$~140



Deflection of molecular beam

doi:10.1038/nature09443

Laser cooling of a diatomic molecule

E. S. Shuman[1], J. F. Barry[1] & D. DeMille[1]

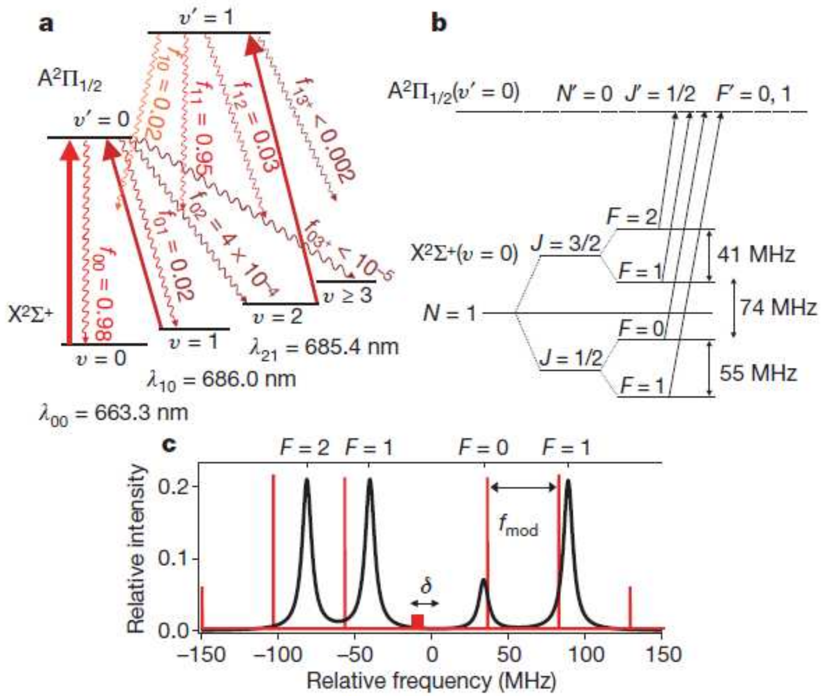
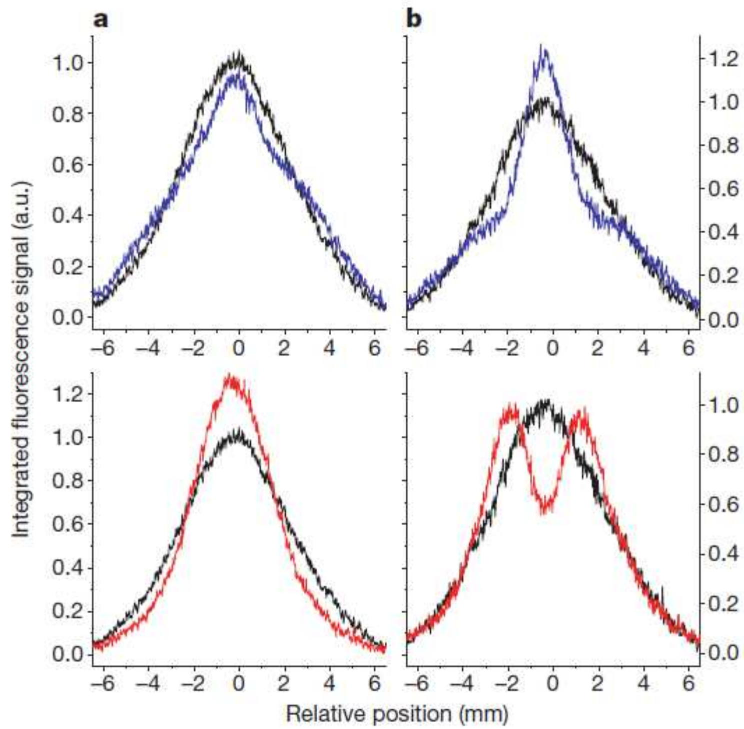


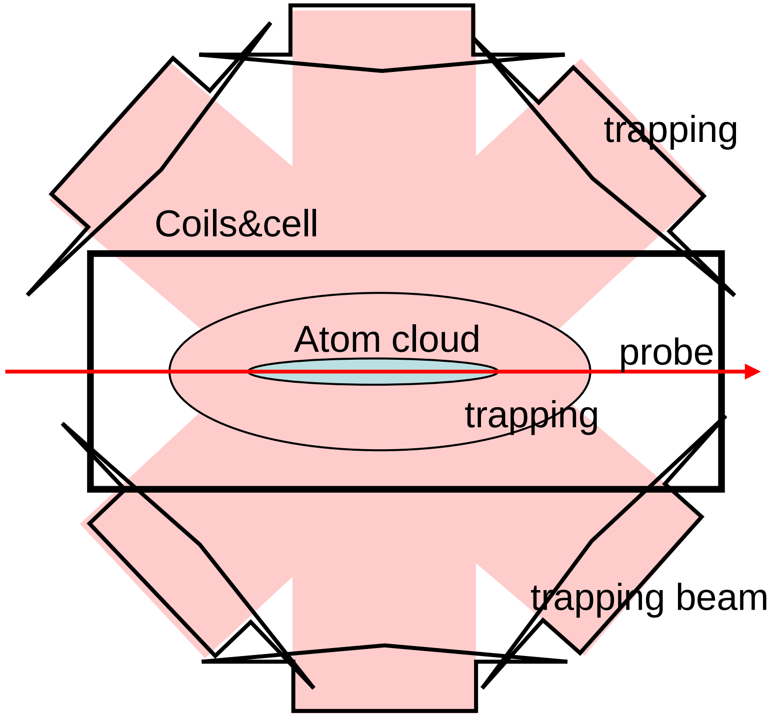
Figure 1 | Energy-level structure in SrF. a, Relevant electronic and

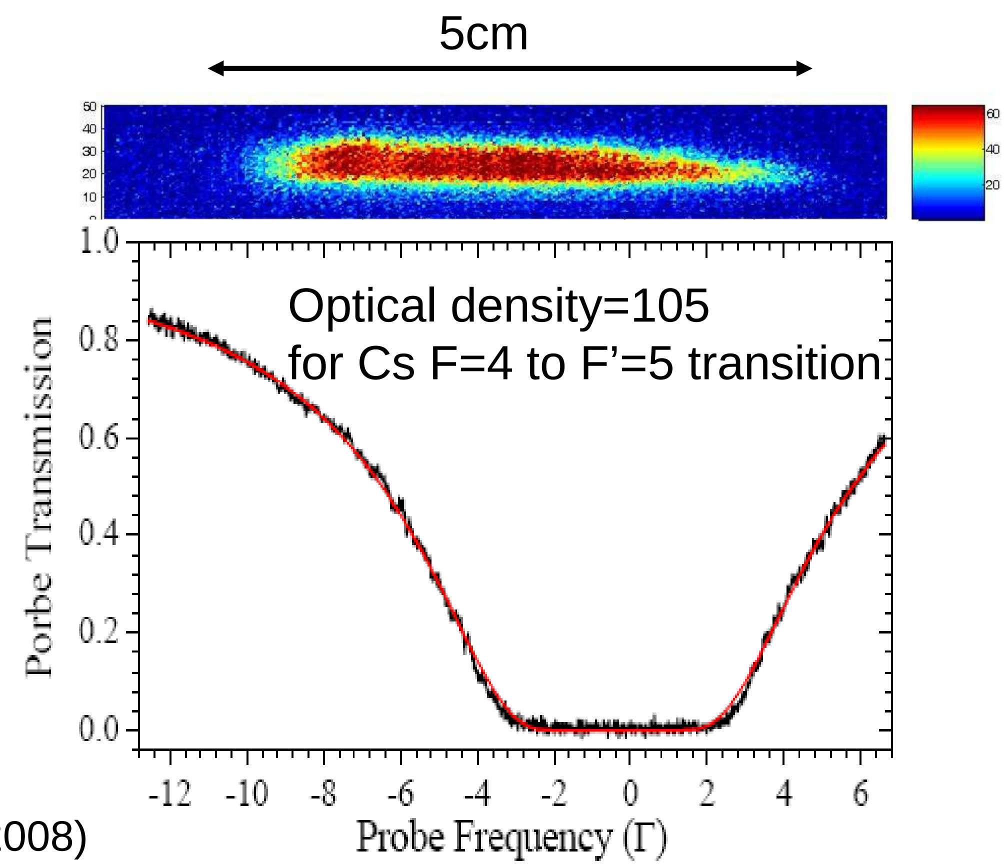


A detour in research
but back to my old track !

Optical Dense Atomic Medium

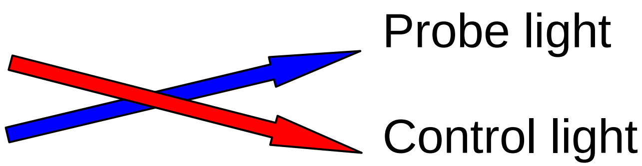
- Original designed fro molecular sympathetic cooling !
- Spin off to an independent project !
- 踏破鐵鞋無覓處，得來全不費工夫！



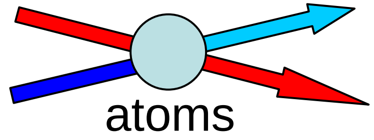


YW Lin et al. Optics Express. 16,3754(2008)

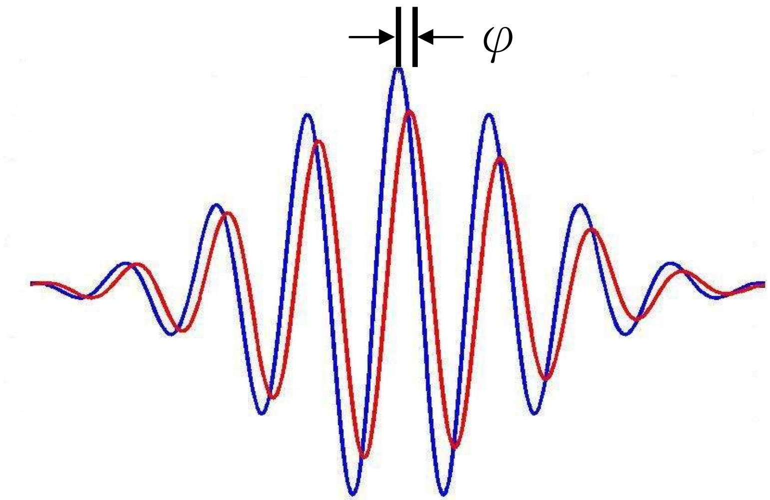
Pursuit of Holey Grail in Nonlinear Optics



Photon-photon has no coupling in free space, at least at low field strength where QED effect is not significant.



Photon can couple to photon via the media (e.g. atoms).



Without control light

With control light

Kerr effect: $n = n_0 + n_2 I$

XPM: Phase change of the probe pulse under the presence of control pulse and media.

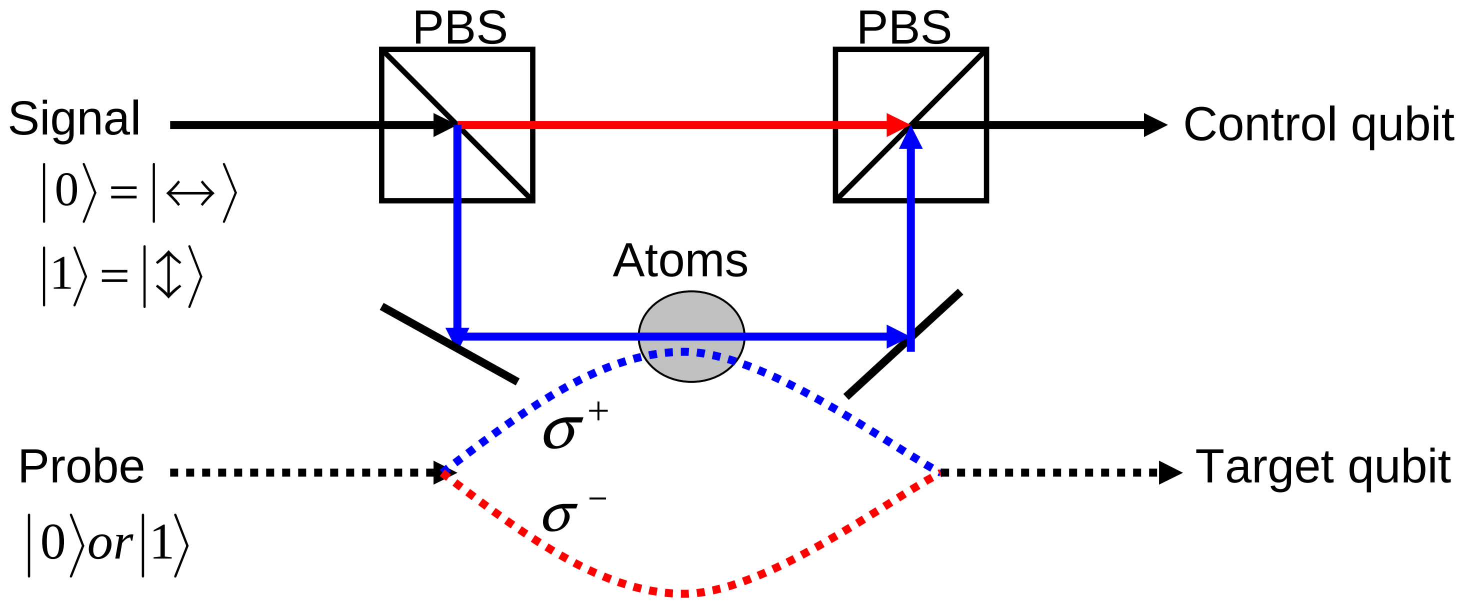
- One of the holey grail in nonlinear optics is to observe the π radian mutual phase shift for two single photon pulses with small absorption loss.

可能的應用

- 實現量子計算所須之量子閘
- 實現非破壞性量測
- 產生糾纏態光子對

Truth table for CNOT gate

$$|0_C 0_T\rangle \rightarrow |0_C 0_T\rangle; |0_C 1_T\rangle \rightarrow |0_C 1_T\rangle$$
$$|1_C 0_T\rangle \rightarrow |1_C 1_T\rangle; |1_C 1_T\rangle \rightarrow |1_C 0_T\rangle$$



For a good introductory article, see 陳易馨&余怡德 CPS Physics Bimonthly, 524, Oct. 2008

General Considerations in Achieving Few-Photon-Level XPM

- Large phase shift and low absorption (EIT-based XPM scheme)
- Tightly focusing
- Long interaction time
- Enough atom (optical) density

Atom-photon interaction $\propto \int dt(\vec{d} \bullet \vec{E}) \propto \int dt\left(\vec{d} \bullet n_{photon} \left(\frac{\hbar\omega}{2\varepsilon_0 V}\right)^{1/2} \hat{\varepsilon}\right)$

Longer interaction time

Choosing a transition which has a large transition dipole moment & Clebsch-Gordon coefficient !

Tightly focusing such that even with a few photon the electric field is still large enough!

- 技術極限在何處？先看清楚Big picture

Theoretical Limitation !?

PHYSICAL REVIEW A **73**, 062305 (2006)

Single-photon Kerr nonlinearities do not help quantum computation

Jeffrey H. Shapiro
Massachusetts Institute of Technology, Research Laboratory of Electronics, Cambridge, Massachusetts 02139, USA
(Received 3 February 2006; published 7 June 2006)

PHYSICAL REVIEW A **81**, 043823 (2010)

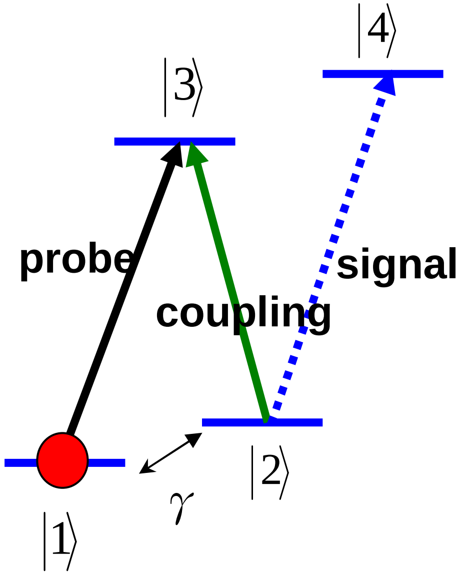
Impossibility of large phase shifts via the giant Kerr effect with single-photon wave packets

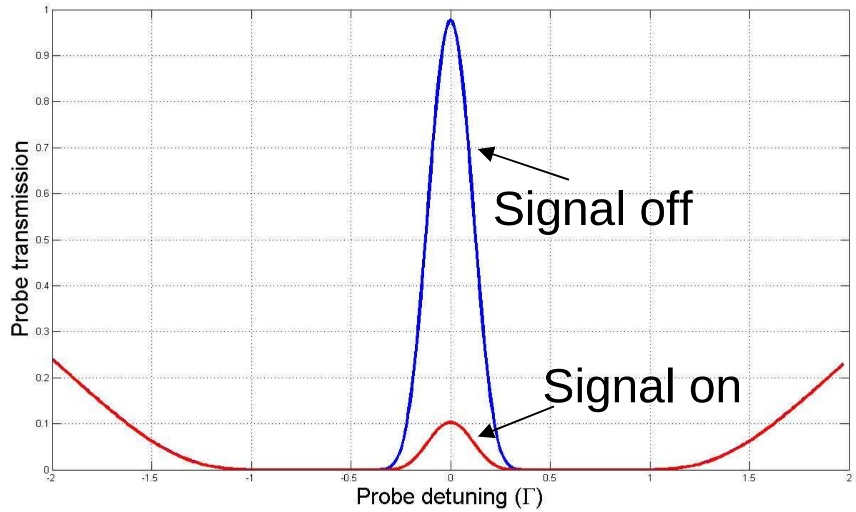
Julio Gea-Banacloche
Department of Physics, University of Arkansas, Fayetteville, Arkansas 72701, USA
(Received 30 November 2009; published 16 April 2010)

- 理論極限在哪裡？須深入探究！

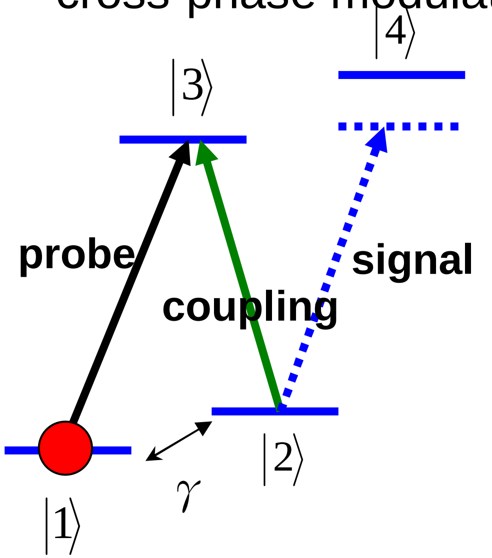
EIT-based Nonlinear Optics: N-type System

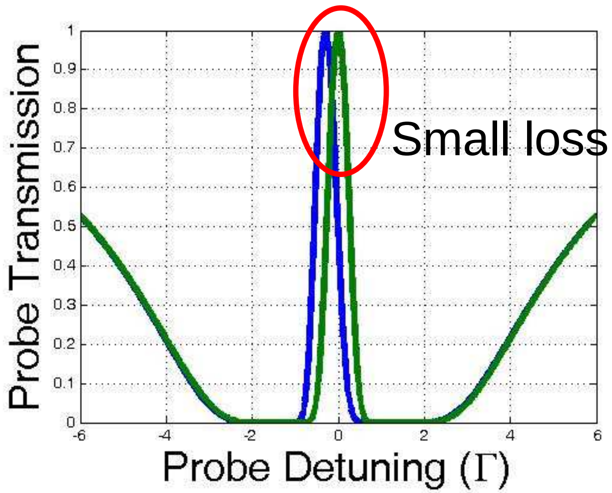
Photon switching

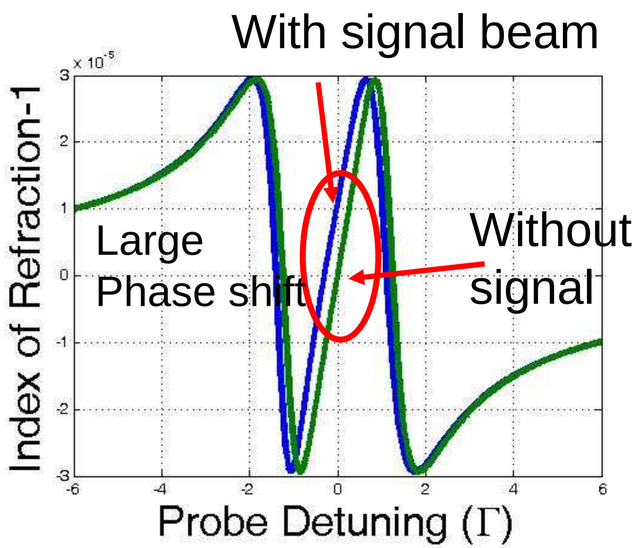




cross-phase modulation



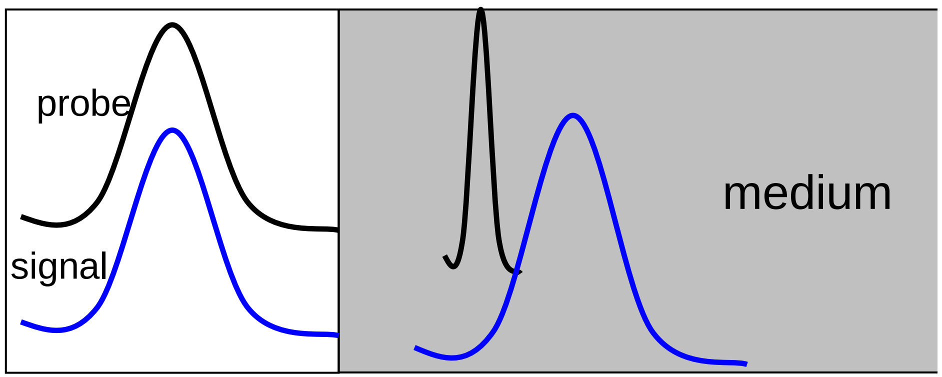


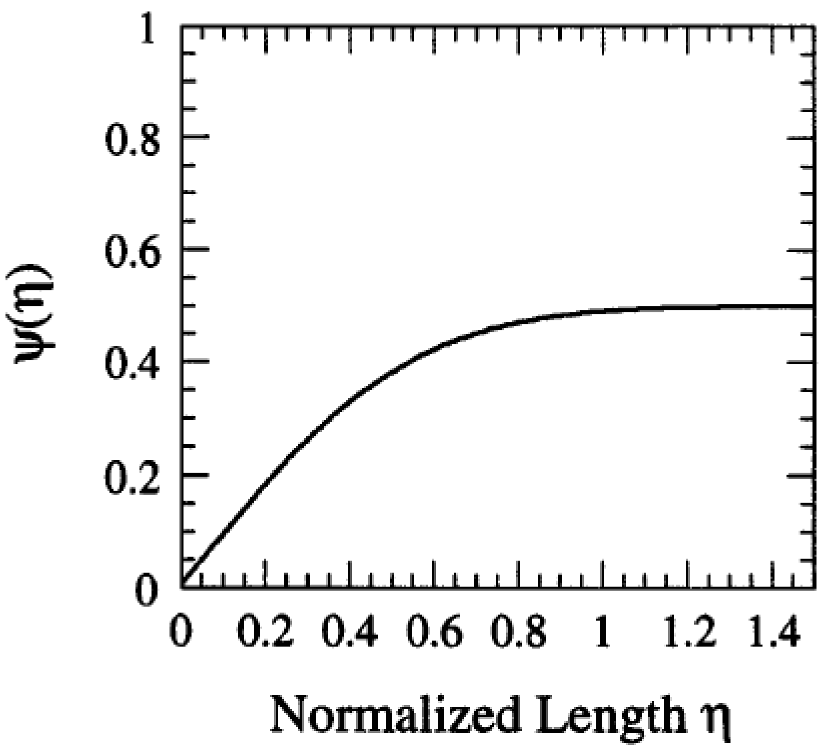


Schmidt & Imamoglu Opt. Lett. 21,1936,1996

Limitation with N-type system

- Probe is a slow light but the signal isn’t. This limit the atom-photon interaction time.
- There is a maximum phase shift of 0.1rad for single photon pulse for N-type even focusing the beams down to $3\lambda^2/2\pi$ level.

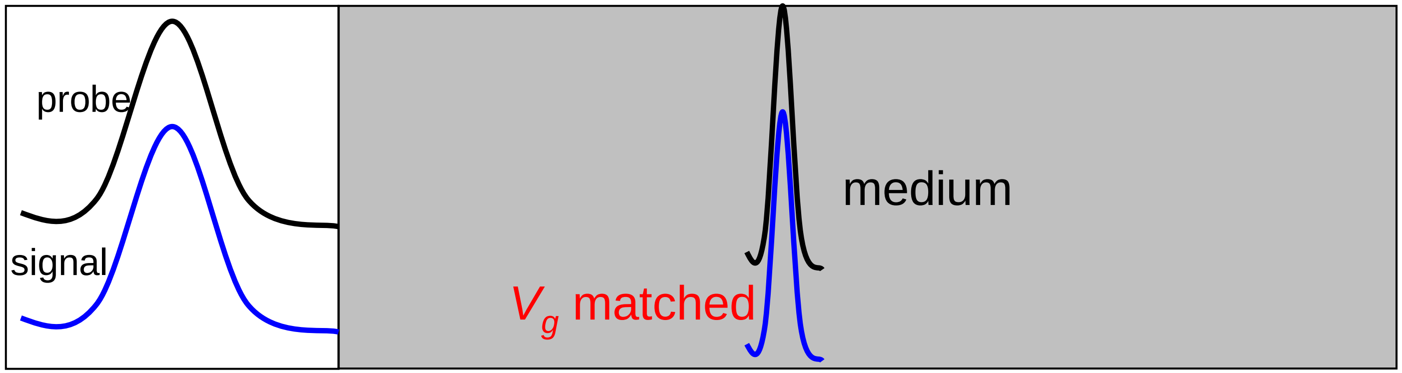


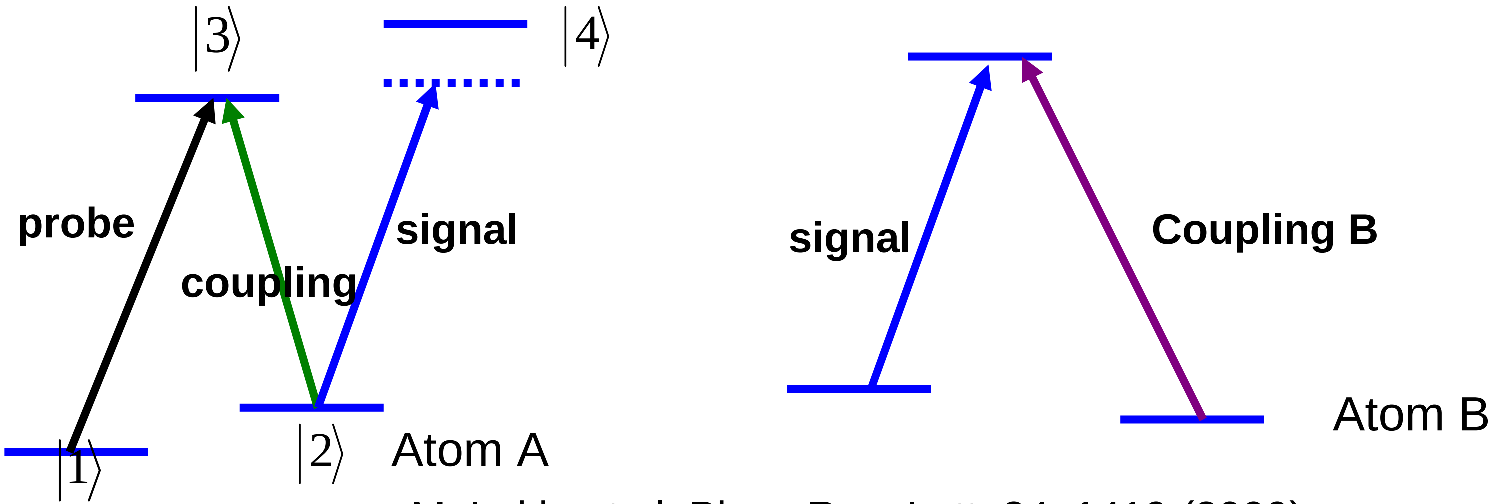


S.E. Harris & L.V. Hau, PRL, 82,4611,1999

XPM with Double Slow Light

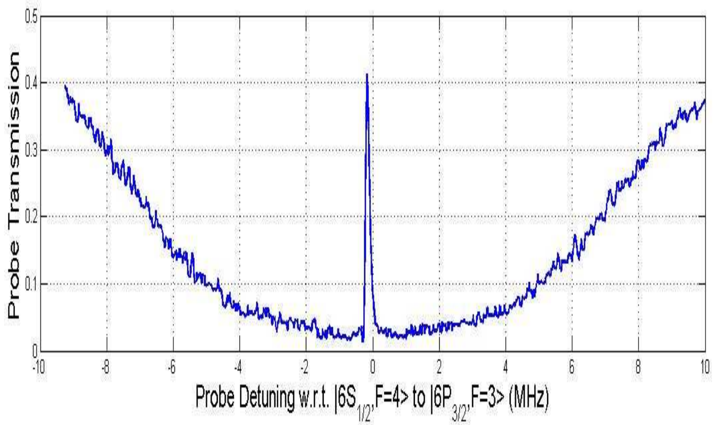
- Group-velocity-matched double slow light for both probe and signal using two atomic species for longer interaction time.

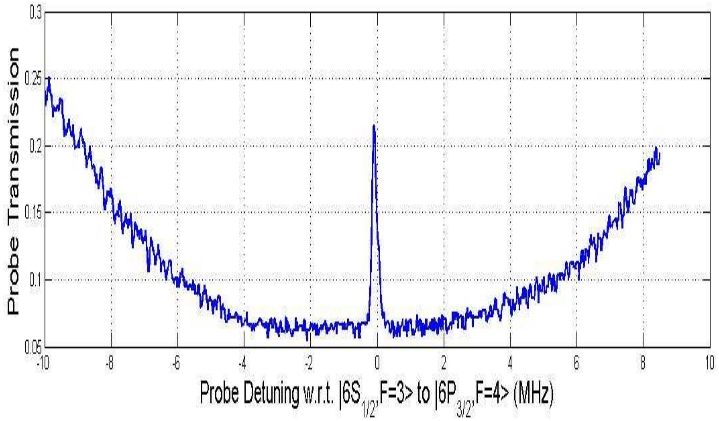


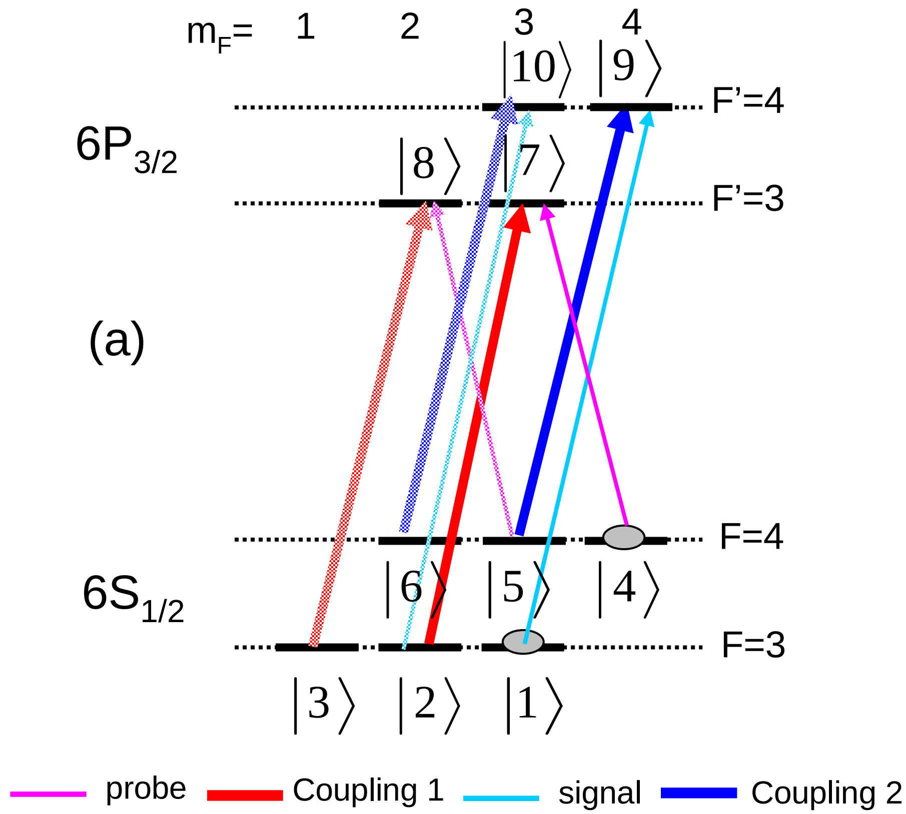


M. Lukin et al. Phys. Rev. Lett. 84, 1419 (2000).

The idea really works :
The happiest moment in research !



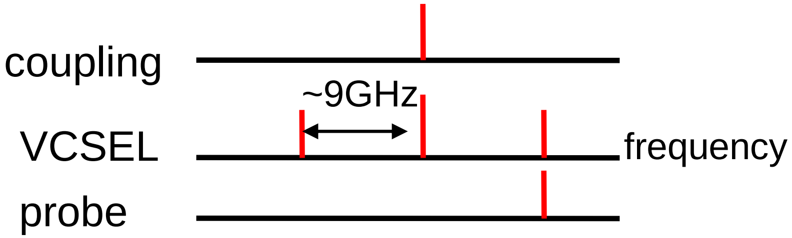




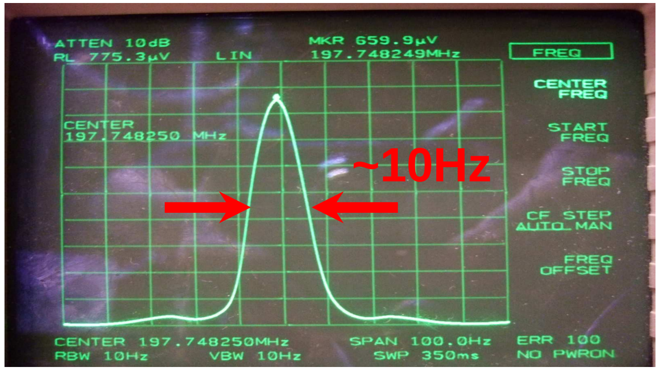
- An early (4 am) Saturday morning around May 2009 !
- 急於知道想法是否能成功的意念是可讓人廢寢忘食！
- 英雄” 所見略同 ！

After many efforts !

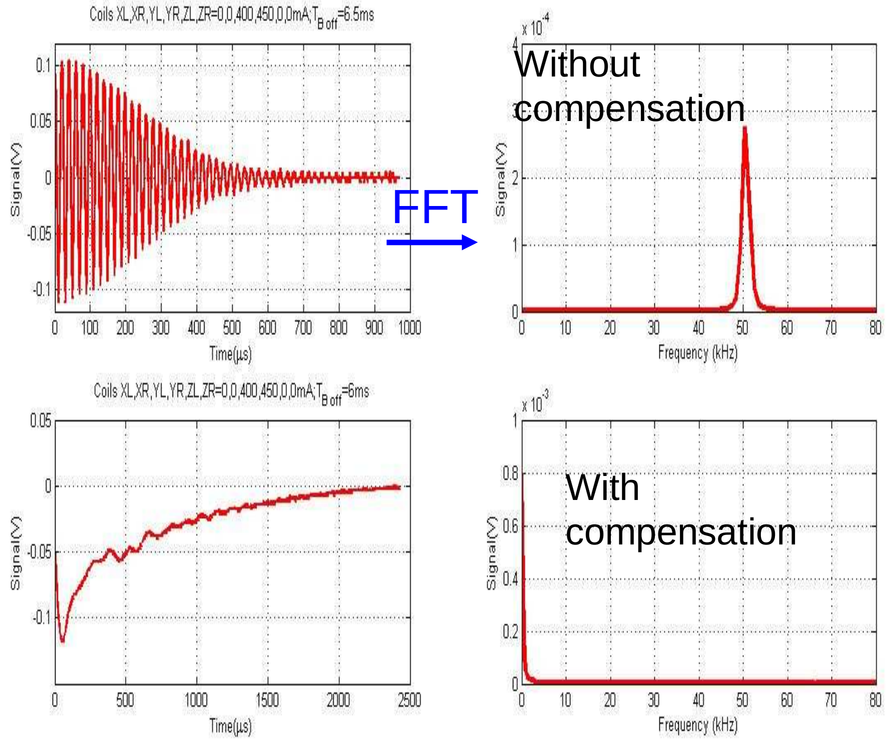
Reduction of mutual laser linewidth



Beatnote between coupling & probe laser

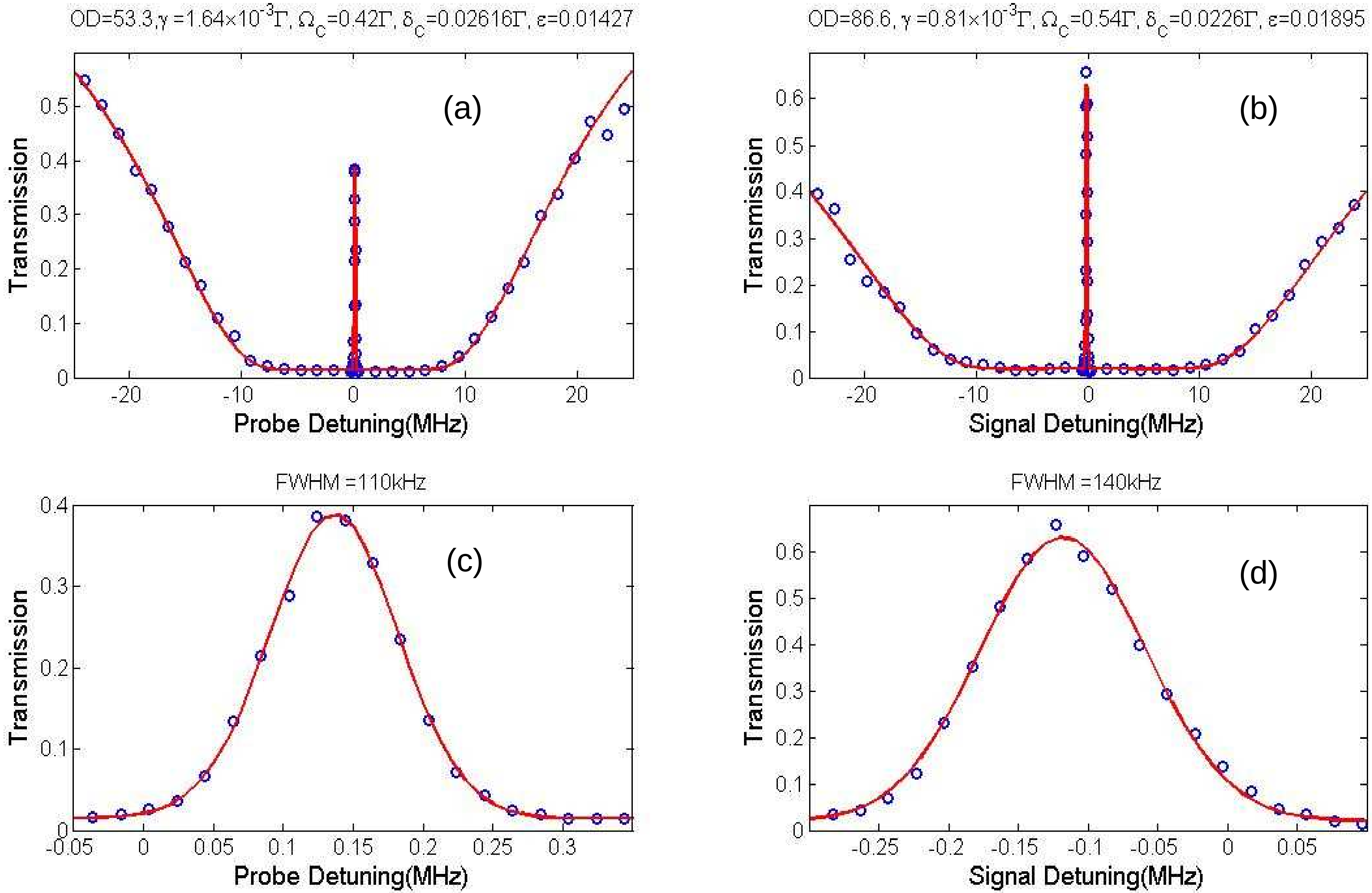


Reduction of stray magnetic field inhomogeneity & eddy current

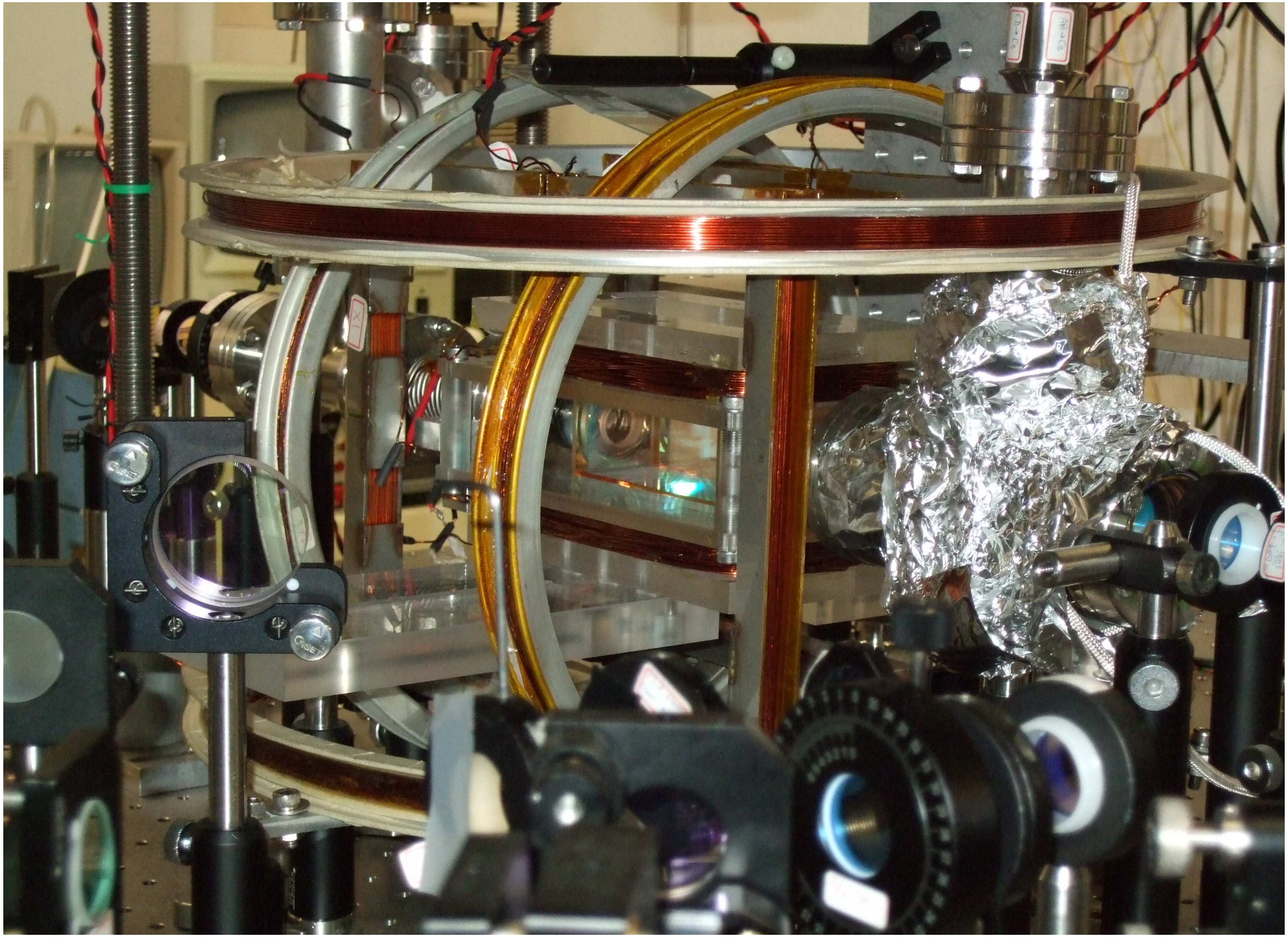


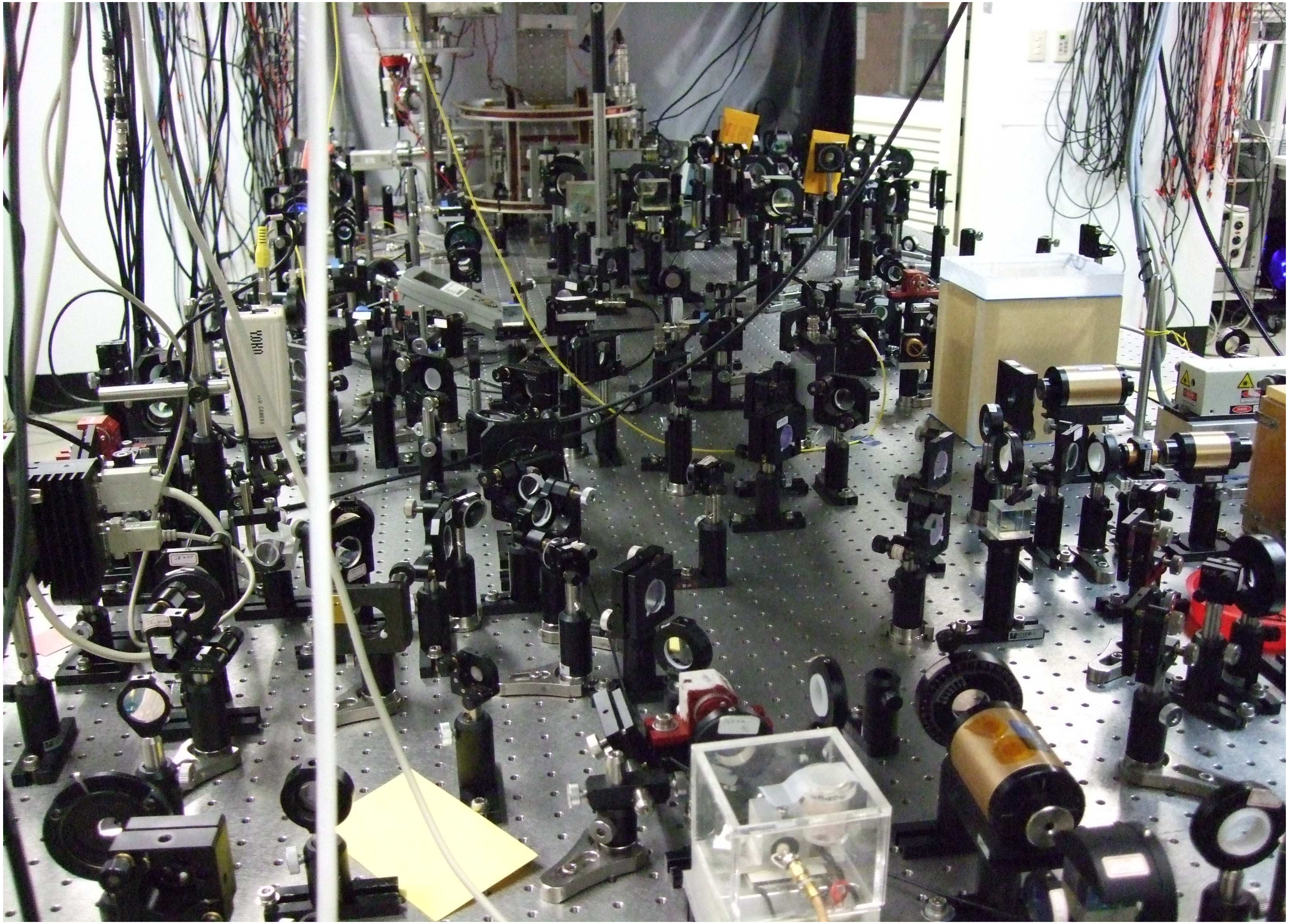
δ B<3mG limited by 60Hz AC magnetic field!

- 除了有好想法外，有些硬功夫還是要下的，才能確保優勢。
- 魔鬼藏在細節裡 ！



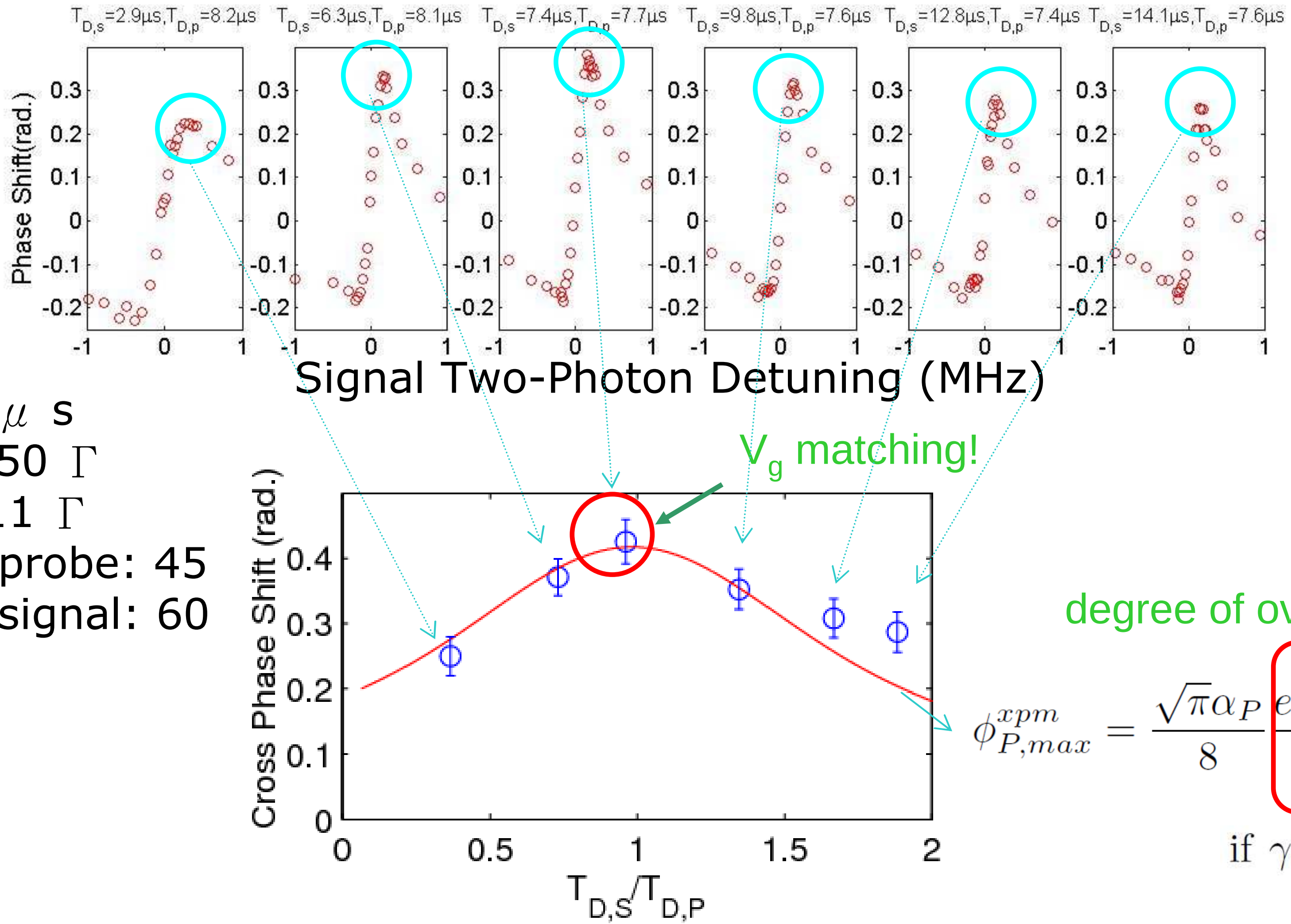
- 漂亮的數據總是讓人很有成就感的!
- 成就感來自於“我們可以做得這麼好”





Observation of enhancement due to group-velocity matching

Increasing the group delay of signal pulse



$T_{D,P}$: 8 μ s
Ω_{c1}: 0.50 Γ
Ω_S: 0.11 Γ
OD for probe: 45
OD for signal: 60

degree of overlapping

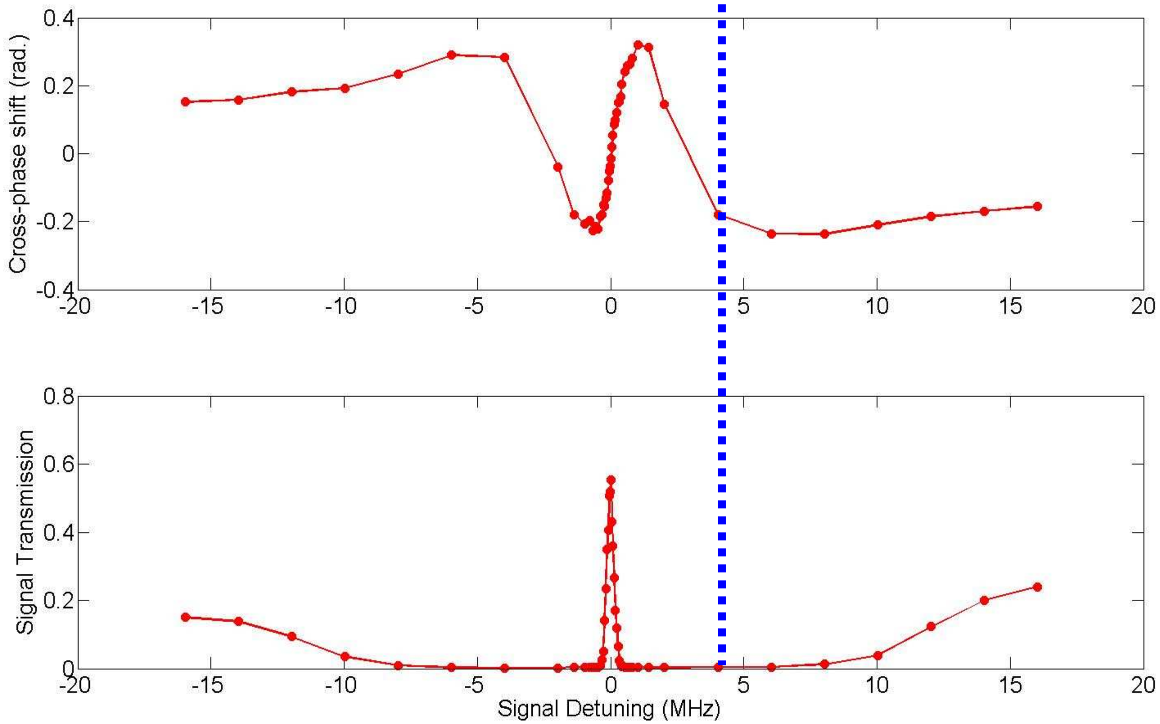
$$\phi^{xpm}_{P,max} = \frac{\sqrt{\pi}\alpha_P}{8} \frac{erf(\zeta_P)}{\zeta_P} \frac{\Omega_S^2}{\Omega_{C1}^2}$$

if $\gamma\Gamma << \Omega_{C2}^2$

• Phys. Rev. Lett. 106,193006(2011)

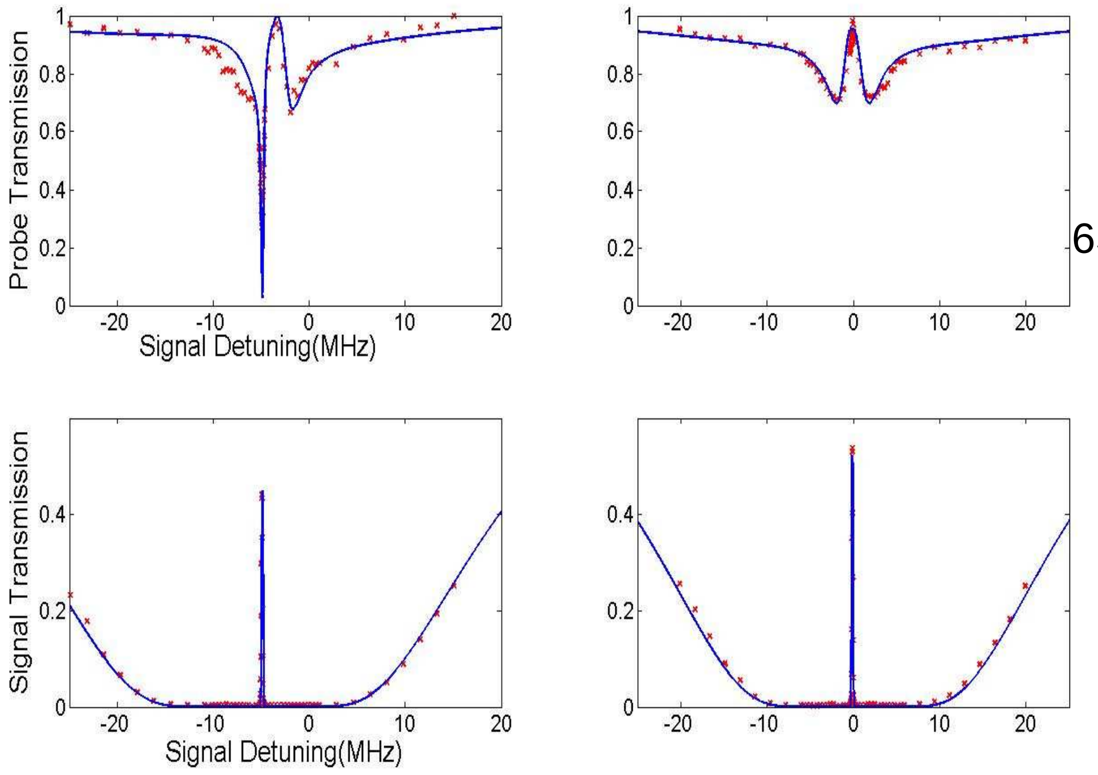
Why still worse than the N-type limit?

- The signal decay by its own $\chi^{(1)}$ due a the two-photon detuning of the signal for the XPM.
- Can one keep both EIT on their two-photon resonances ($\chi^{(1)}$~0) but still obtain the non-zero $\chi^{(3,xpm)}$?

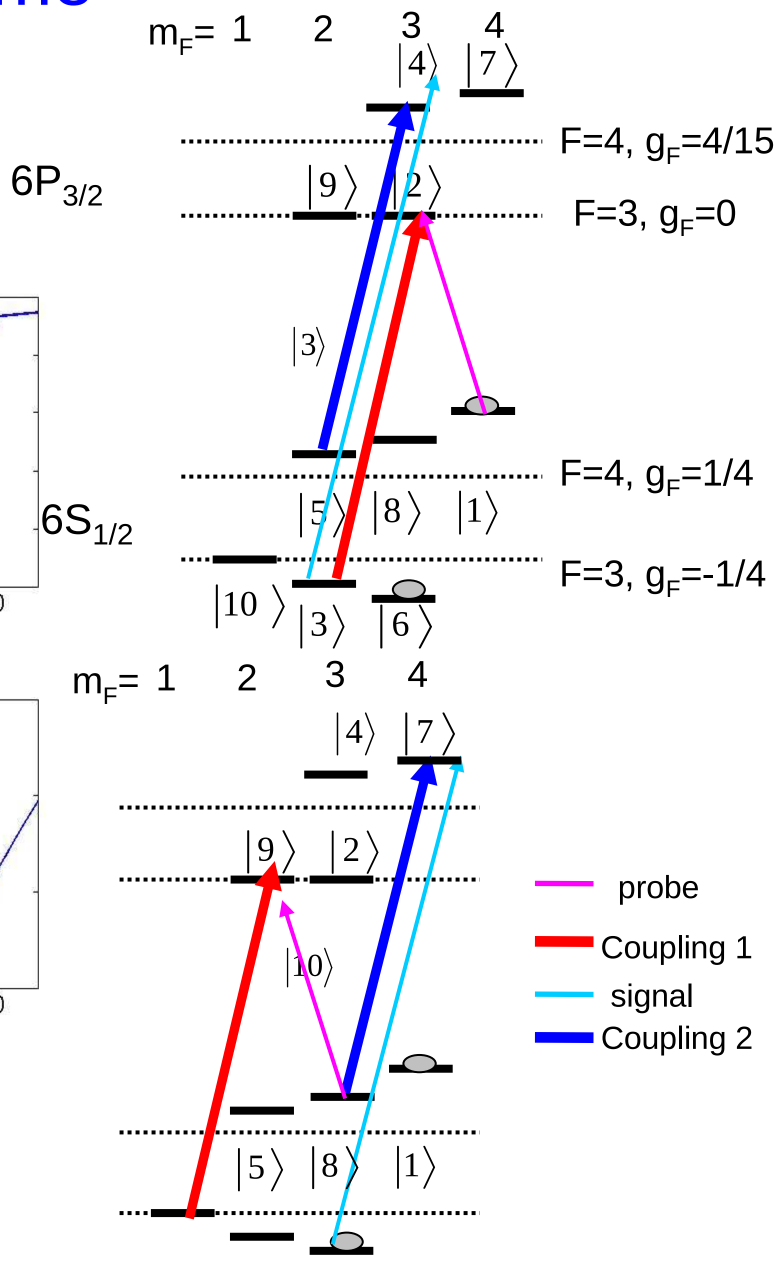


- 問出對的問題很重要 ！

New Scheme

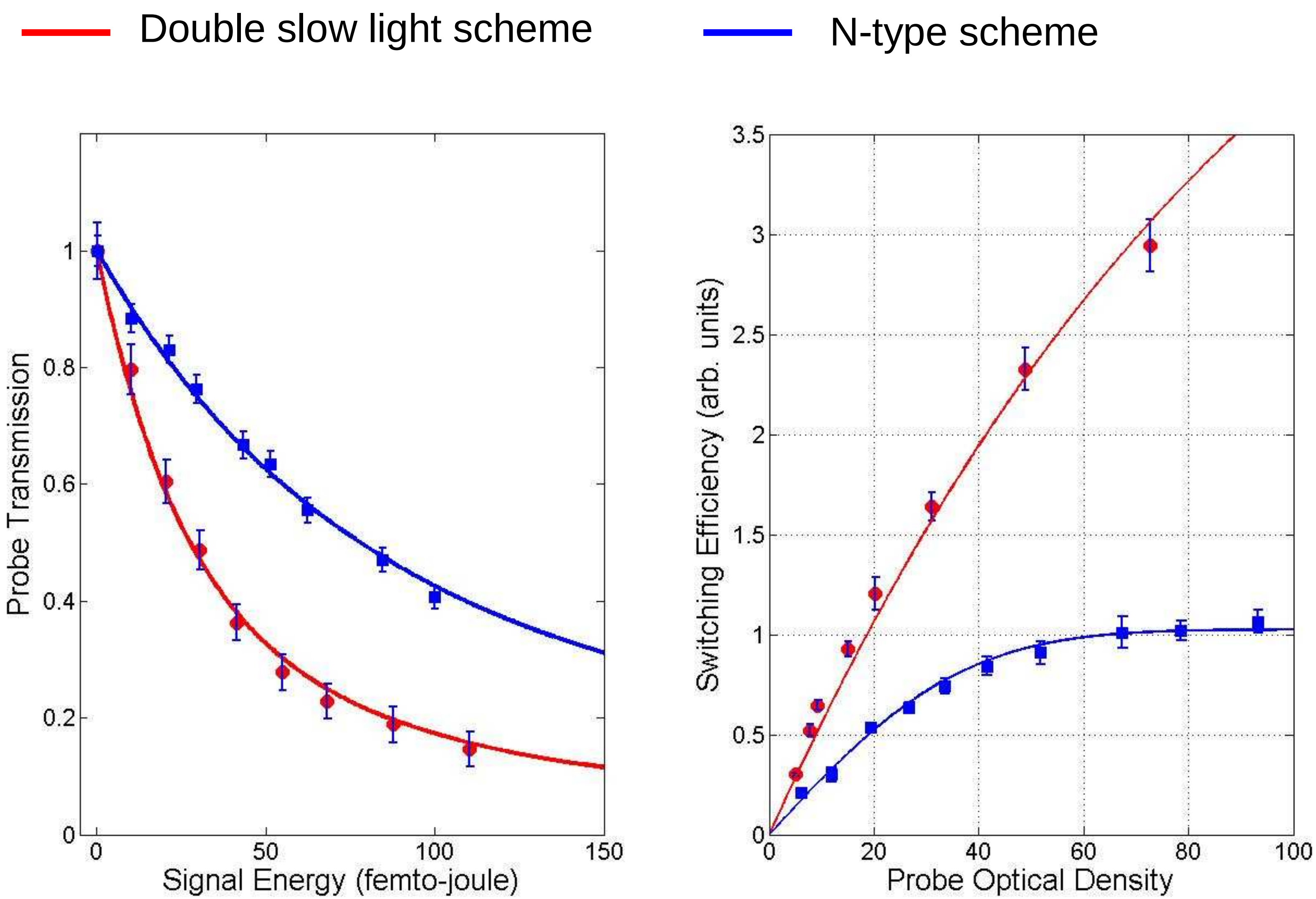


Probe Transmission
Signal Detuning(MHz)
Signal Transmission
Signal Detuning(MHz)



m_F= 1 2 3 4
6P3/2
F=4, g_F=4/15
F=3, g_F=0
6S1/2
F=4, g_F=1/4
F=3, g_F=-1/4
m_F= 1 2 3 4
probe
Coupling 1
signal
Coupling 2

Overcome the N-type Limit



培養自己的能力

- 有好奇心、健康的人生觀，要對某些事有熱情。
- 要問問題，要問別人更要問自己，嘗試獨立去尋找答案。
- 要有思辯邏輯、分析判斷能力，保持批判性思考，不要太輕易相信任何事。
- 有好的工作習慣，想清楚流程、記錄有用資訊、讓工作環境方便舒服、防呆、作數量級估計。
- 有解決問題能力，分段除錯、 各個擊破。
- 勇敢解釋你已懂的也讓別人懂，培養表達能力並教學相長。
- 有面對壓力、挫折的勇氣。
- 相信自己，你可以辦的到，有志者事竟成！

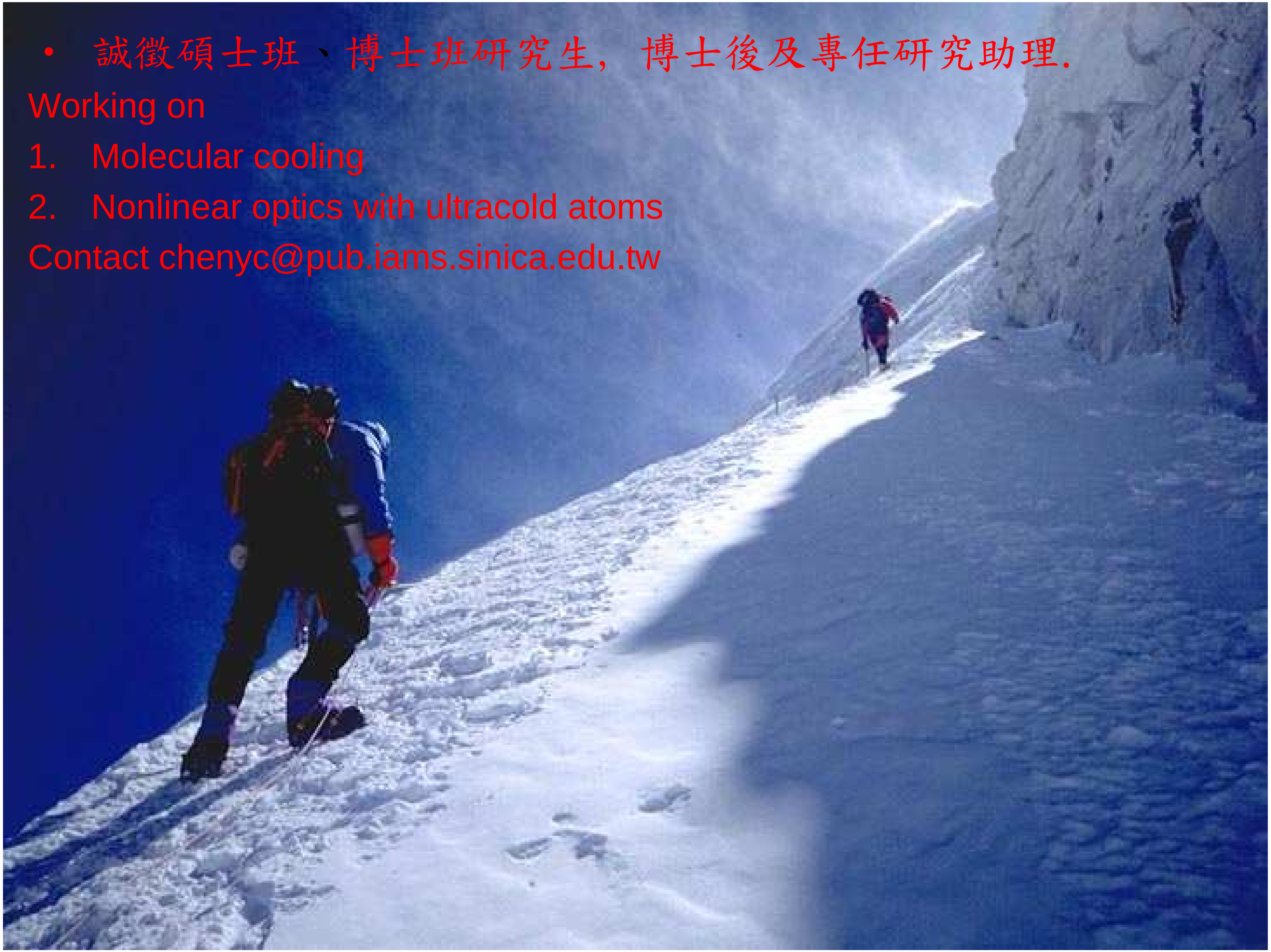
能作為一個物理學家是極大的恩典，要配得上它，大多數人一生在作無聊繁複的事！

- 誠徵碩士班、博士班研究生，博士後及專任研究助理.

Working on

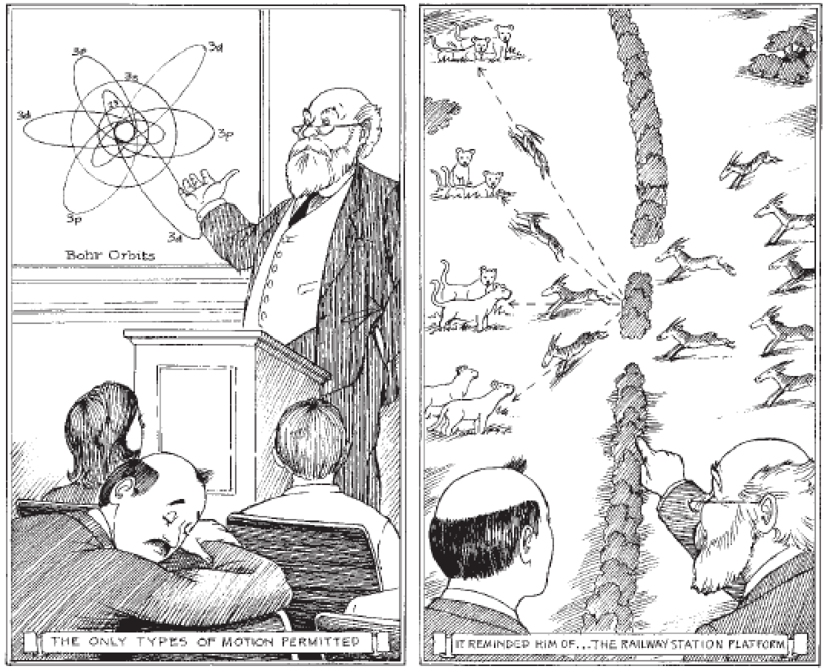
1. Molecular cooling
2. Nonlinear optics with ultracold atoms

Contact chenyc@pub.iams.sinica.edu.tw

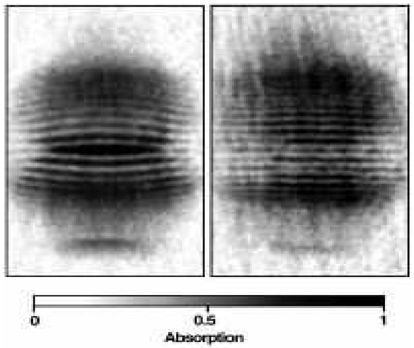


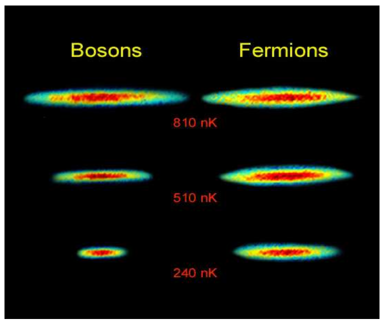
奇妙的超低溫世界-量子叢林

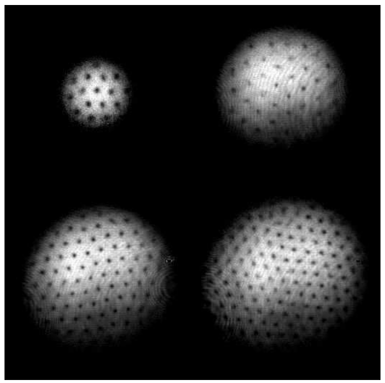
- 量子力學統治下的奇妙世界
  - 物質的波特性
  - 量子統計
  - 測不準關係、零場能
  - 熱力學第三定律有序態
  - 量子相變

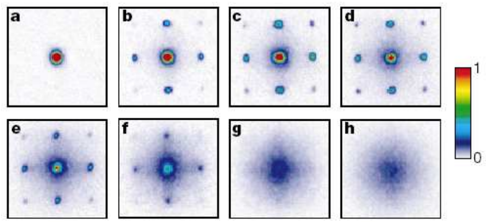


Quantum dreaming: Mr Tompkins' short attention span delivered him to a strange other world.









屈原：天問

遂 古 之 初 ， 誰 傳 道 之 ？ 上 下 未 形 ， 何 由 考 之 ？
冥 昭 瞢 闇 ， 誰 能 極 之 ？ 馮 翼 惟 像 ， 何 以 識 之 ？
明 明 闇 闇 ， 惟 時 何 為 ？ 陰 陽 三 合 ， 何 本 何 化 ？
圜 則 九 重 ， 孰 營 度 之 ？ 惟 茲 何 功 ？ 孰 初 作 之 ？
斡 維 焉 繫 ？ 天 極 焉 加 ？ 八 柱 何 當 ？ 東 南 何 虧 ？
九 天 之 際 ， 安 放 安 屬 ？ 隅 隈 多 有 ， 誰 知 其 數 ？
天 何 所 沓 ？ 十 二 焉 分 ？ 日 月 安 屬 ？ 列 星 安 陳 ？
出 自 湯 谷 ， 次 于 蒙 汜 。 自 明 及 晦 ， 所 行 幾 里 ？
夜 光 何 德 ， 死 則 又 育 ？ 厥 利 維 何 ， 顧 菟 在 腹 ？
…

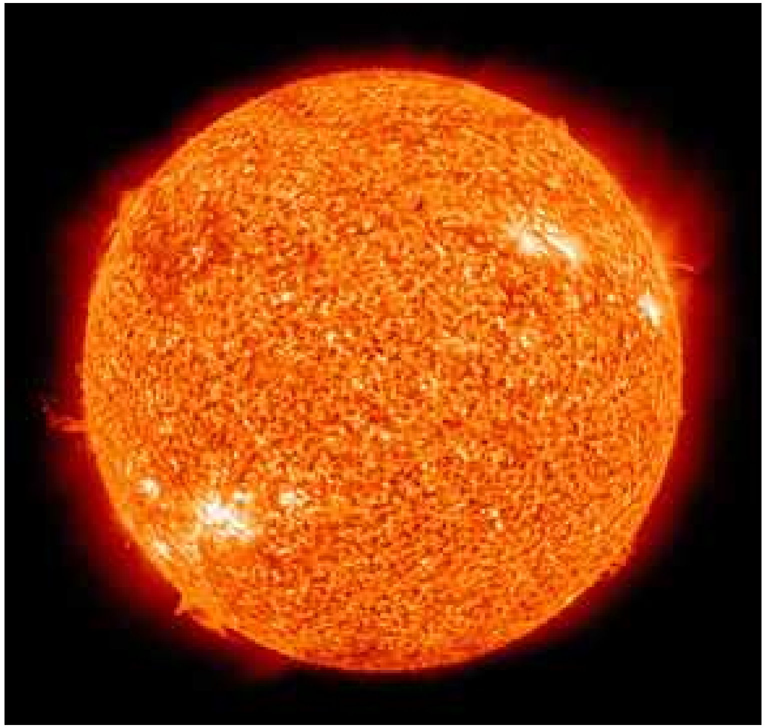
請問遠古開始之時，誰將此態流傳導引？ 天地尚未成形之前，又從哪裡得以產生？ 明暗不分渾沌一片，誰能探究根本原因？ 迷迷濛濛這種現象，怎麼識別將它認清？ 白天光明夜晚黑暗，究竟它是為何而然？陰陽參合而生宇宙，哪是本體哪是演變？ 天的體制傳為九重。有誰曾去環繞量度？ 這是多麼大的工程。是誰開始把它建築？ 天體軸繩繫在哪裡？天極不動設在哪裡？ 八柱撐天對著何方？東南為何缺損不齊？平面上的九天邊際，抵達何處聯屬何方？ 邊邊相交隅角很多，又有誰能知其數量？ 天在哪裡與地交會？黃道怎樣十二等分？ 日月天體如何連屬？眾星在天如何置陳？ 太陽是從暘谷出來。止宿則在蒙汜之地。打從天亮直到天黑，所走之路究竟幾里？ 月亮有著什麼德行，竟能死了又再重生？ 月中黑點那是何物，是否兔子腹中藏身？ ....

保持好奇心，有趣的科學問題無所不在，
深入探究將會帶你展開一段驚奇的旅程！

太陽在燒什麼?

- 為什麼可以燒出這麼多能量?還燒這麼久?

  一個每日高掛在我們頭上的科學問題！
- 原子核融合反應



$${}_1^1H + {}_1^1H \rightarrow {}_1^2D + e^+ + \nu_e + 0.42MeV$$

$$e^+ + e^- \rightarrow 2\gamma + 1.02MeV$$

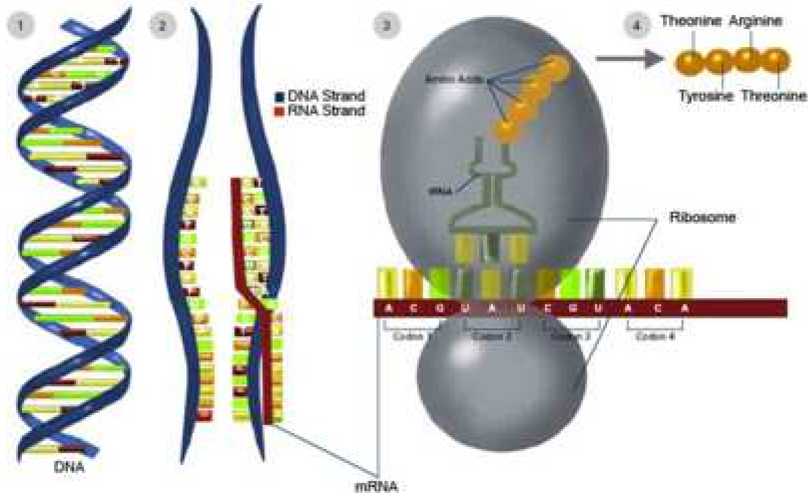
$${}_1^2D + {}_1^1H \rightarrow {}_2^3He + \gamma + 5.49MeV$$

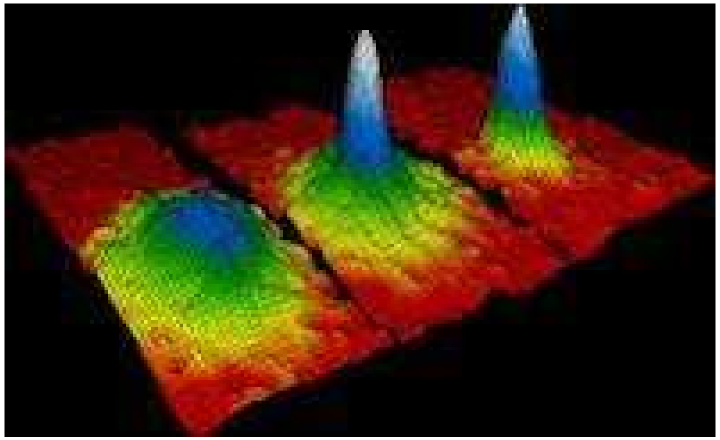
$${}_2^3He + {}_2^3He \rightarrow {}_2^4He + 2{}_1^1H + 12.86MeV$$

$$1MeV \sim 10^{10}K$$

My story about joining ultracold research

- Mango tree, Gene’s language & curiosity.
- Culture difference between different fields !
- Ultracold research: the wonderland of quantum physicists !





- 要有好奇心 ！ 要問自己問題 ！
- 勇於去嘗試 !即使最後並未繼續至少沒遺憾!
- 基於自己的興趣自然會找到屬於自己的路!

Laser Cooling & Trapping of Atoms

- Why laser can cool atom ?
- It makes a revolution to atomic physics and the impact has gone far beyond atomic physics.
- It is so convenient that one can have μK atomic samples to play with just in about 30 minutes everyday.
- I deeply appreciates its powerfulness after I played with molecules !

$$\Delta\vec{p} = \vec{p}' - \vec{p} = \hbar(\vec{k}_i - \vec{k}_s) \Rightarrow \vec{p}' = \vec{p} + \hbar(\vec{k}_i - \vec{k}_s)$$

$$\Delta K = K' - K = \hbar(\omega_i - \omega_s) = \frac{(\vec{p}'^2 - \vec{p}^2)}{2m} = \hbar(\vec{k}_i - \vec{k}_s)\cdot\vec{v} + \frac{\hbar^2(\vec{k}_i - \vec{k}_s)^2}{2m}$$

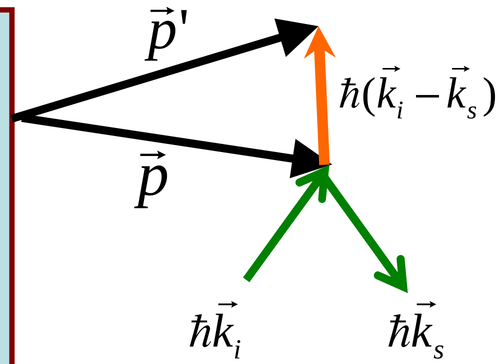
always positive but small, recoil heating

Criteria of laser cooling

If $\left\langle(\vec{k}_i - \vec{k}_s)\bullet\vec{v}\right\rangle_{avg} < 0$ and if $\left|\left\langle(\vec{k}_i - \vec{k}_s)\cdot\vec{v}\right\rangle_{avg}\right| > \left\langle\frac{\hbar(\vec{k}_i - \vec{k}_s)^2}{2m}\right\rangle_{avg}$

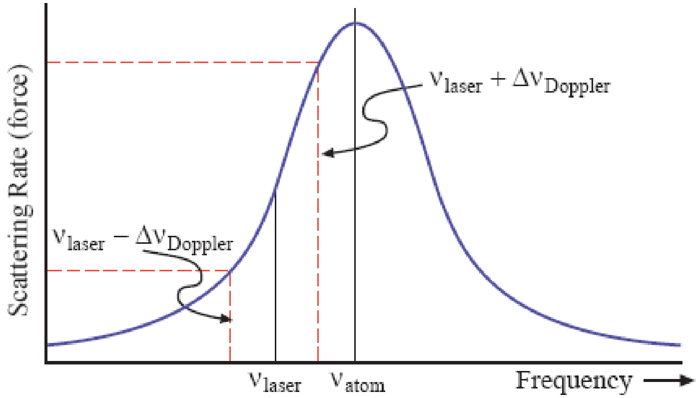
then $<\Delta K>_{avg} < 0$ or $<\omega_i> << \omega_s>$ the kinetic energy decreases,

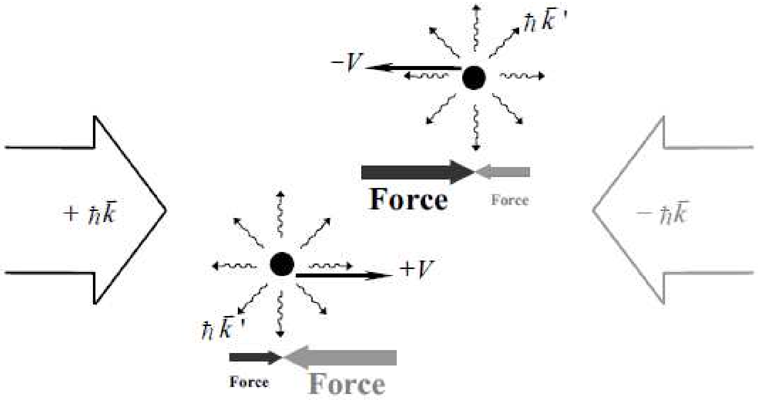
where avg stands for averaging over photon scattering events.



A laser cooling scheme is thus an arrangement of an atom-photon interaction scheme in which atoms absorb lower-energy photons and emit higher-energy photons on average!

Doppler Cooling

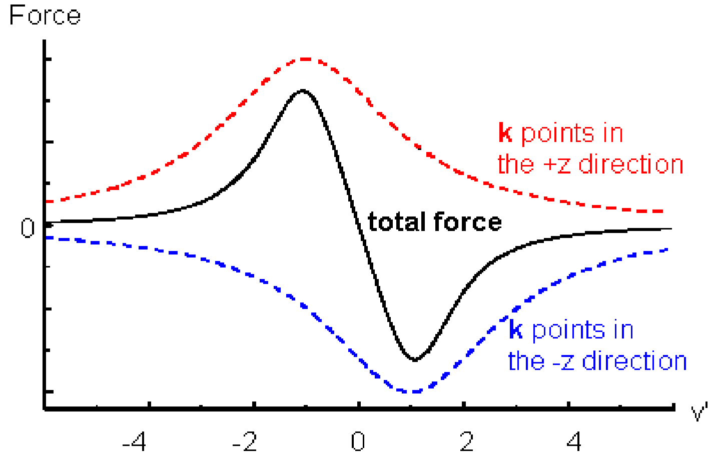




$$\vec{F} = \vec{F}_+ + \vec{F}_-$$

$$\vec{F}_\pm = \pm \frac{\hbar \vec{k} \Gamma}{2} \frac{I / I_s}{1 + I / I_s + [2(\delta \mp kv)/\Gamma]^2}$$

$$F \approx \frac{8\hbar k^2 \delta \frac{I}{I_s} \vec{v}}{\Gamma(1 + I/I_s + (2\delta/\Gamma)^2)^2} \equiv -\beta \vec{v}, if \, (\frac{kv}{\Gamma})^4 << 1$$



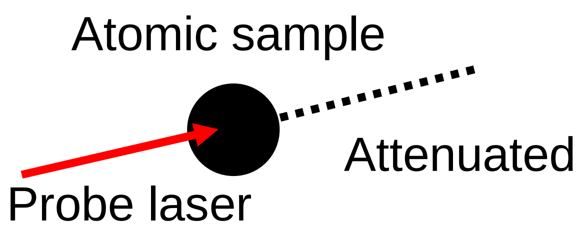
$$\Delta K = K' - K = \hbar(\omega_i - \omega_s) \approx \hbar(\vec{k}_i - \vec{k}_s) \bullet \vec{v}$$

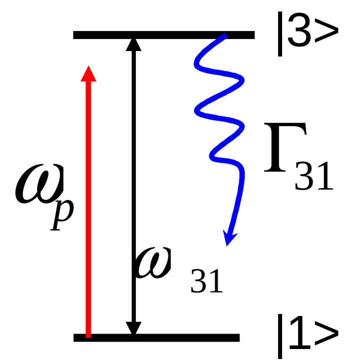
$$\langle \vec{k}_i \bullet \vec{v} \rangle = -\beta v^2 < 0 \; for \, \delta < 0; \langle \vec{k}_s \bullet \vec{v} \rangle = 0; \langle \omega_i \rangle < \langle \omega_s \rangle$$

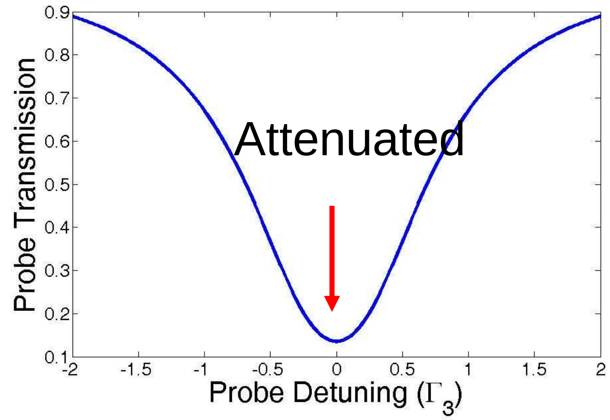
$$\Delta K < 0$$

- Doppler cooling ： 速度空間的一種回饋機制最終鎖定在速度約為零的附近 ！
- Q: 最終溫度為何?

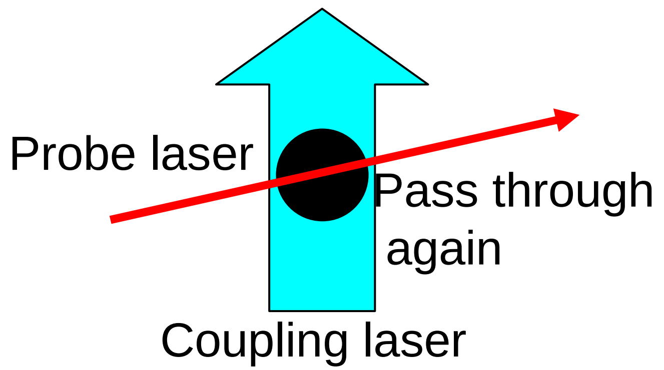
Electromagnetically induced transparency

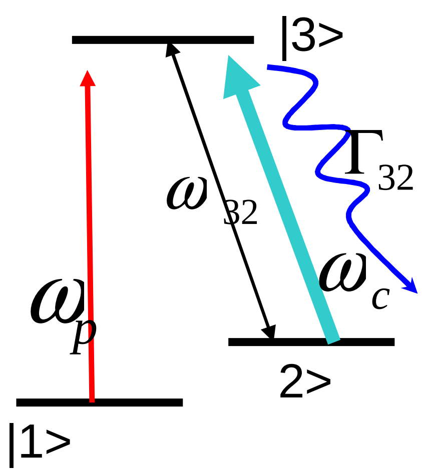


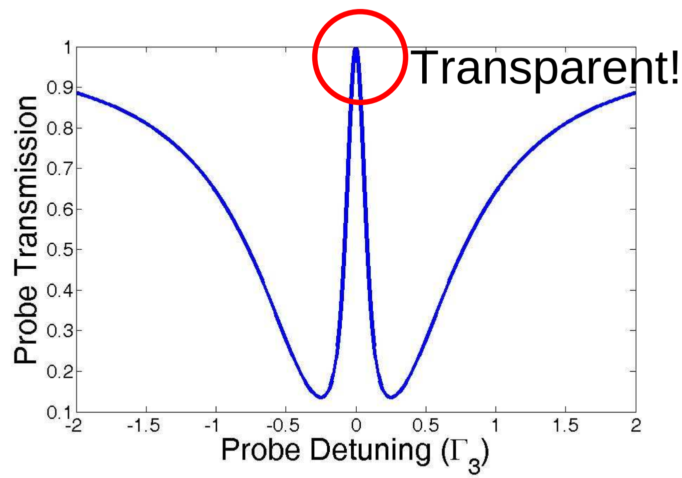




Optical density=2





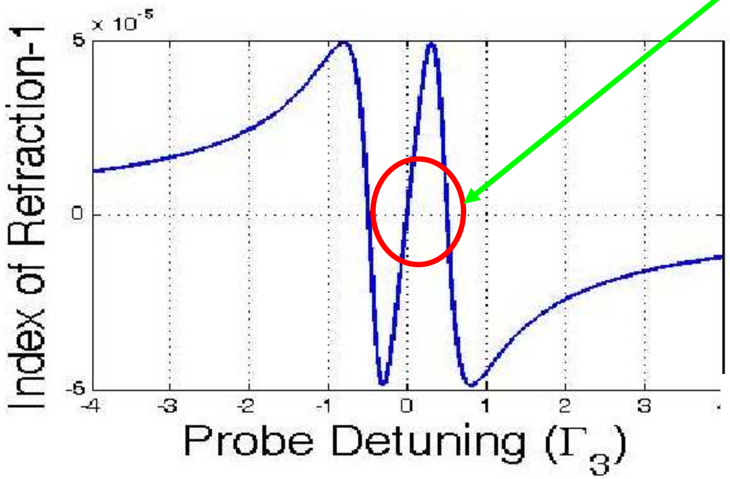


$$\delta_c = 0, \Omega_c = 0.5\Gamma_3, \gamma = 0$$

Slow Light :慢光

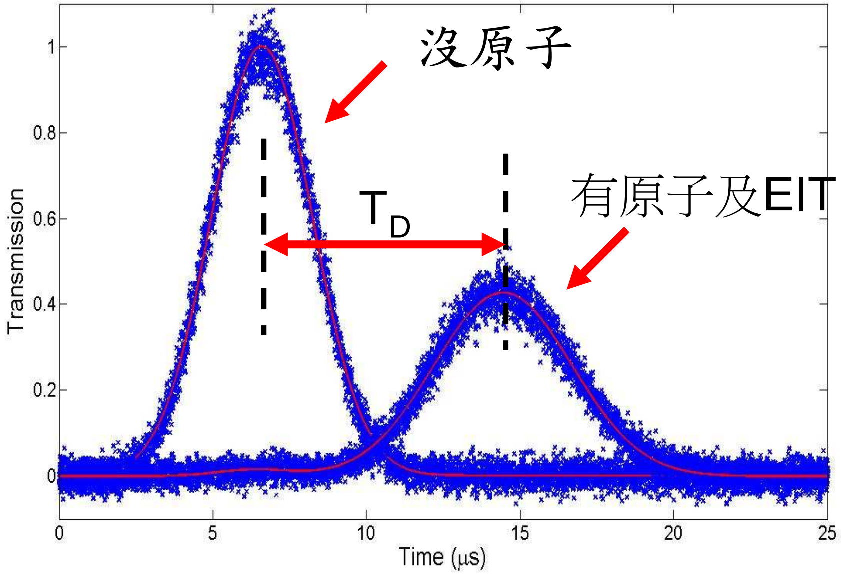
$$\omega_p(k_p) = ck_p / n(\omega_p)$$

$$v_g = \frac{d\omega_p}{dk_p}\Big|_{\delta_p=0} = \frac{1}{dk_p \big/ d\omega_p \,\big|_{\delta_p=0}} = \frac{c}{n + \omega_p (dn / d\omega_p)\,\big|_{\delta_p=0}}$$

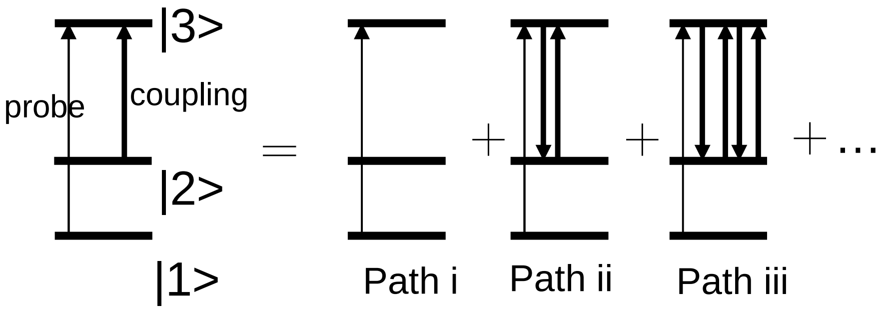


原子團長～2cm，光延遲～8μs

→光群速度＝2500 m/s



EIT & Quantum Interference



$$A_{tot}^2 = \left| A_i + A_{ii} + A_{iii} + \cdots\cdots \right|^2$$

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The Study of Coherence-Induced Phenomena Using Double-Sided Feynman Diagrams

Jung-Jung Su and Ite A. Yu*

$$r \equiv ba \xrightarrow{\Omega_c} bc \xrightarrow{\Omega_c} ba = \frac{-i\Omega_c}{2} \frac{-1}{[i(-\Delta_p + \Delta_c) - \gamma]} \frac{-i\Omega_c}{2} \frac{-1}{[i(-\Delta_p) - \Gamma/2]}.$$

$$\hat{\rho}_{ba} = \sum_{n=0}^{\infty} \hat{\rho}_{bb}^{(0)} \frac{-i\Omega_p}{2} \frac{-1}{i(-\Delta_p) - \frac{\Gamma}{2}} r^n = \hat{\rho}_{bb}^{(0)} \frac{-i\Omega_p/2}{(i\Delta_p + \frac{\Gamma}{2}) + (\frac{\Omega_c}{2})^2/[i(\Delta_p - \Delta_c) + \gamma]}.$$

- 被收錄於Jacob B. Khurgin ”Slow light: Science and Applications” 一書當成教材.
- 不要只是人云亦云！Show給我看！
- 是有價值的終究會被Recognized ！