探索超低溫世界的新領域
– 超低溫分子

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清華大學物理系

5/02/2007,

Department of Physics, NTHU

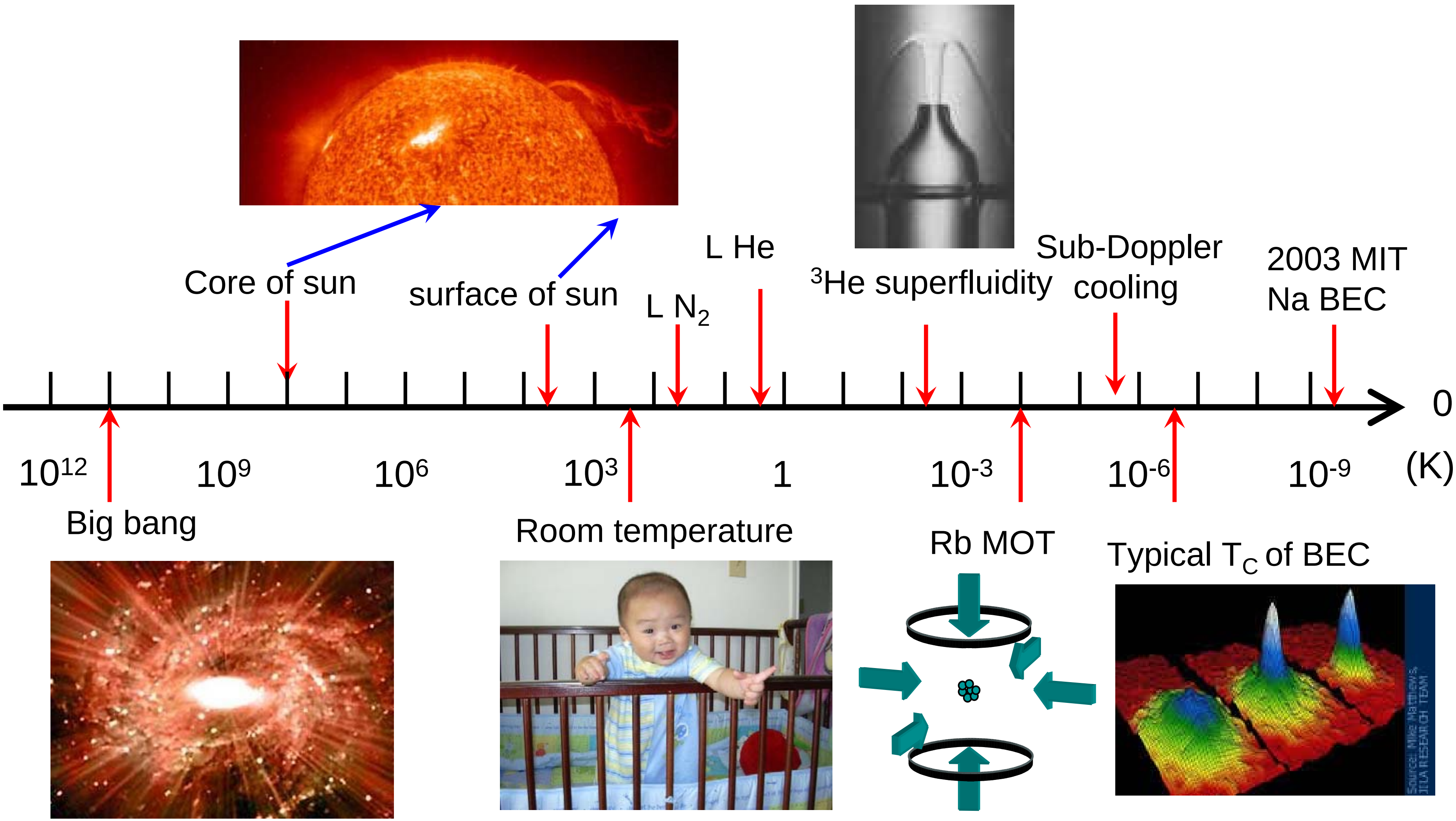
IAMS

研究：探險、探索、與欣賞

大綱

- 雷射冷卻與超冷原子回顧
- 為何要超冷分子？
- 如何冷卻分子？
- 我們如何邁向超低溫之路
- 展望

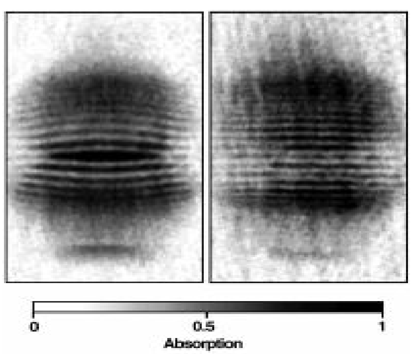
溫度地標

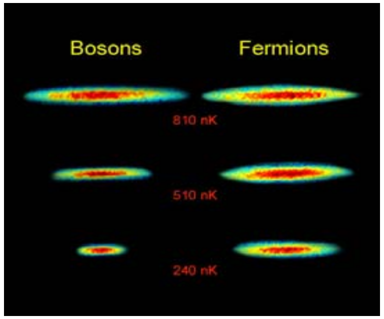


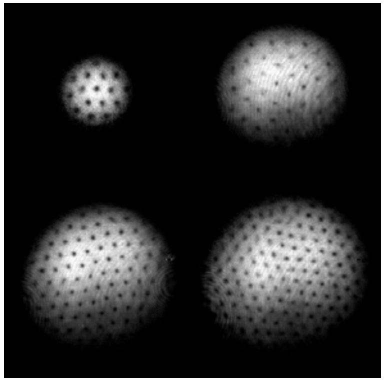
Core of sun
surface of sun
L N_2
L He
^{3}He superfluidity
Sub-Doppler cooling
2003 MIT Na BEC
0
10^{12}
10^9
10^6
10^3
1
10^{-3}
10^{-6}
10^{-9}
(K)
Big bang
Room temperature
Rb MOT
Typical T_C of BEC

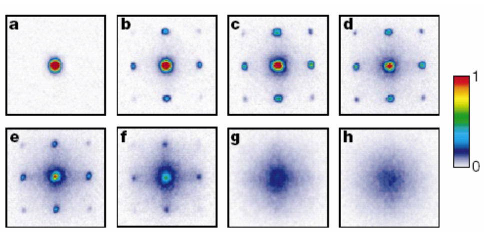
奇妙的超低溫世界

- **A wonderland where Quantum Mechanics governs**
  - Wave nature of matter $\lambda = h/\sqrt{2\pi m k_B T}$ ~1 μm for Na @ 100nk
  - Quantum statistics $f = \dfrac{1}{e^{(\varepsilon-\mu)/kT} \pm 1}$ - for boson, + for fermion
  - Uncertainty principle, zero-point energy
  - Ordered state for any system, third law of thermodynamics
  - Quantum phase transition

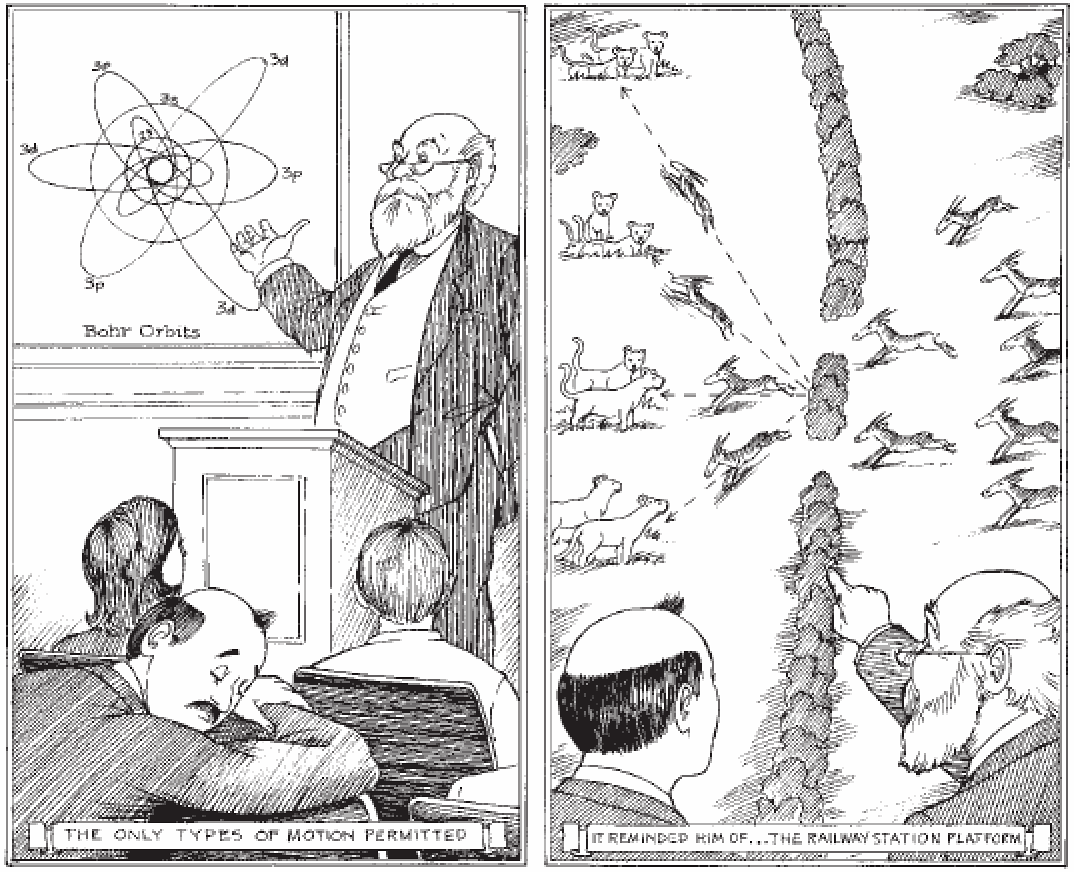








量子叢林: The Quantum Jungle



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

George Gamow, " *Mr. Tompkins in Wonderland*"

雷射冷卻與捕捉原子

- Cooling, velocity-dependent force: Doppler effect
- Trapping, position-dependent force: Zeeman effect

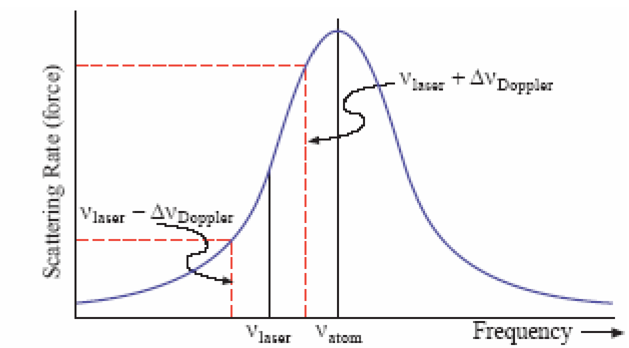
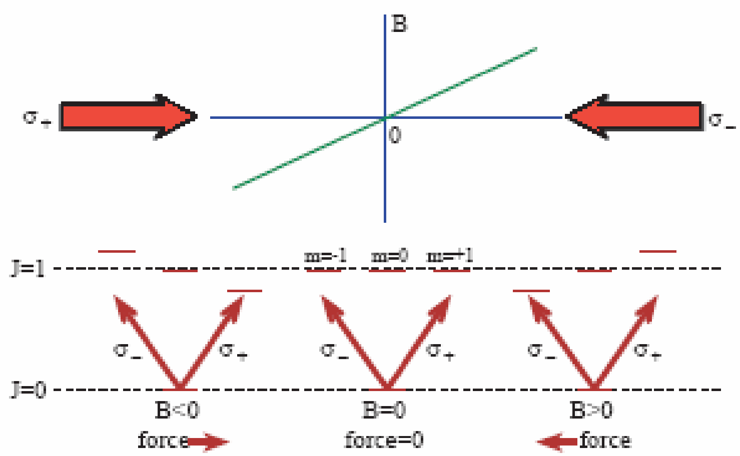
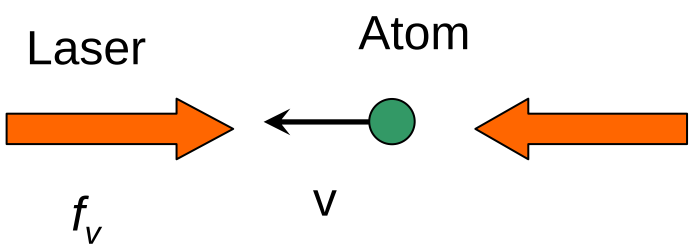
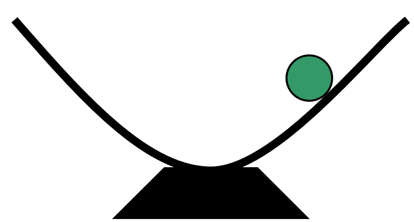


Figure 1. Atomic scattering rate versus laser frequency.

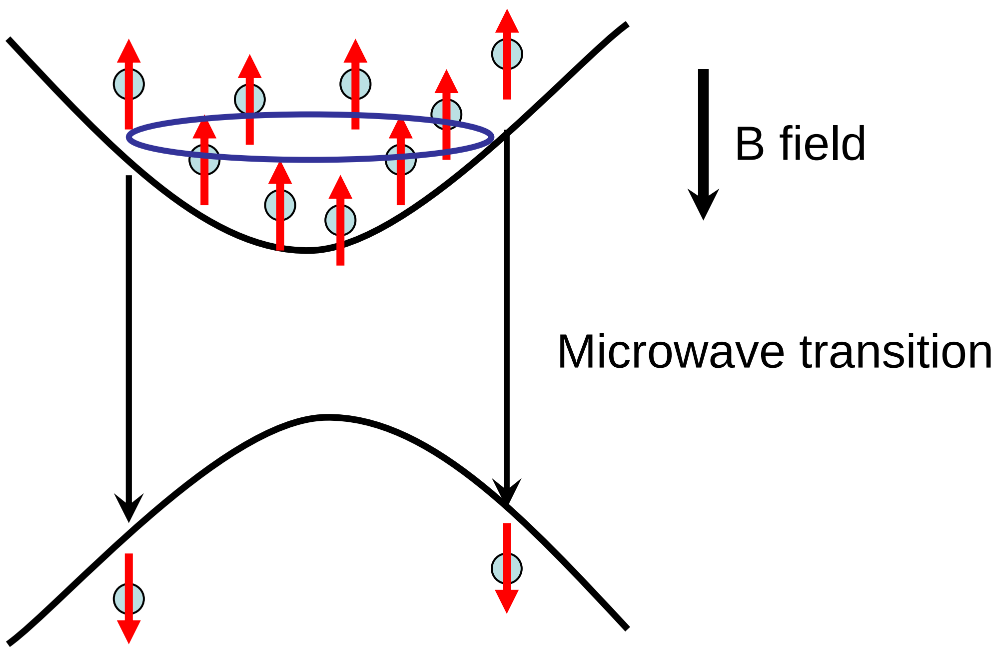




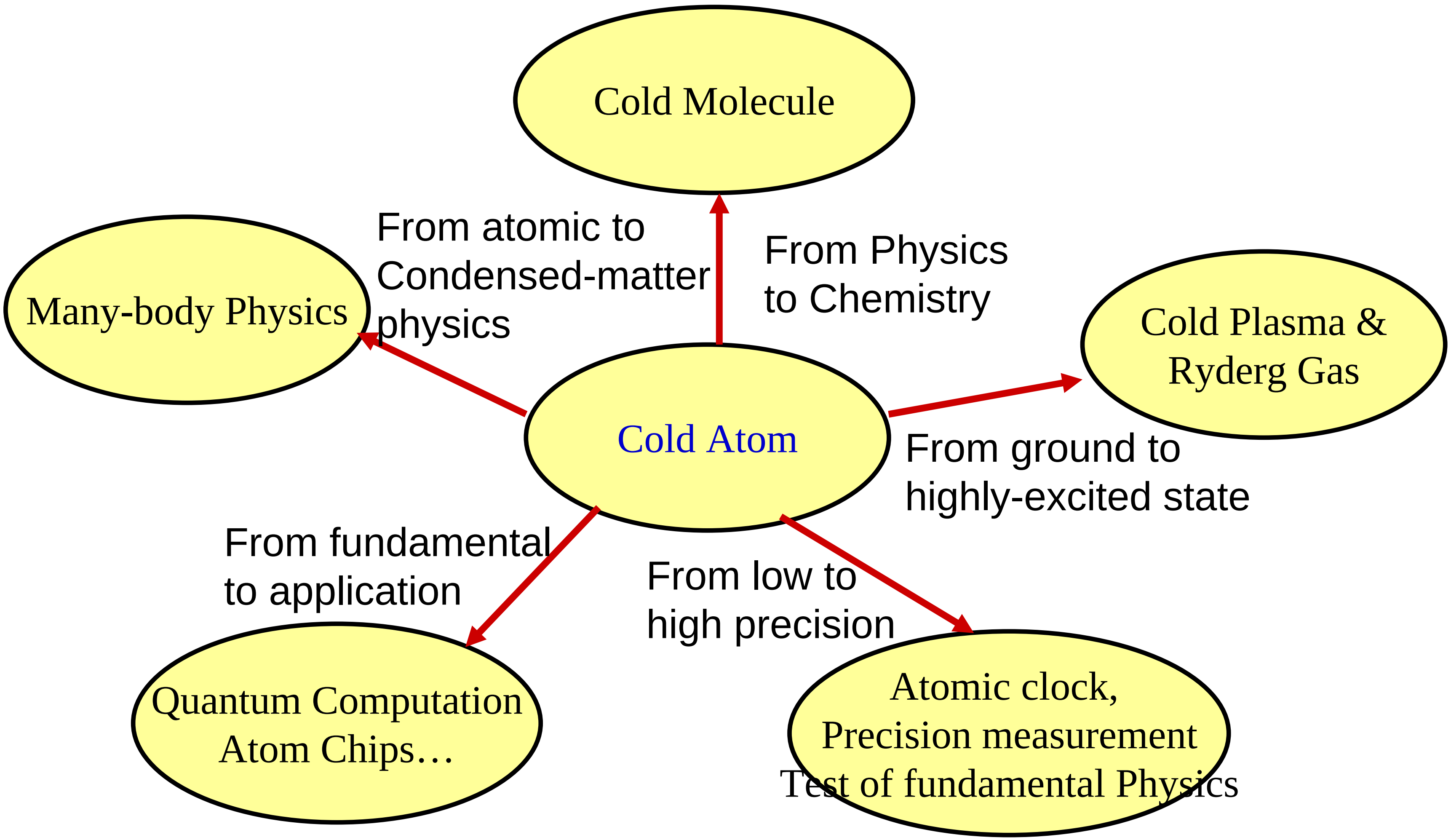


磁侷限與蒸發式冷卻法

$$U(r) = -\vec{\mu} \bullet \vec{B}(r)$$



超低溫世界研究趨勢



Fundamental research out of nano, bio, environmental, and energy related topics!

接下來你要玩什麼？

Wolfgang Ketterle 的一席話

- **…the major challenge for a young scientist is to make the right decision about which hill to climb**…

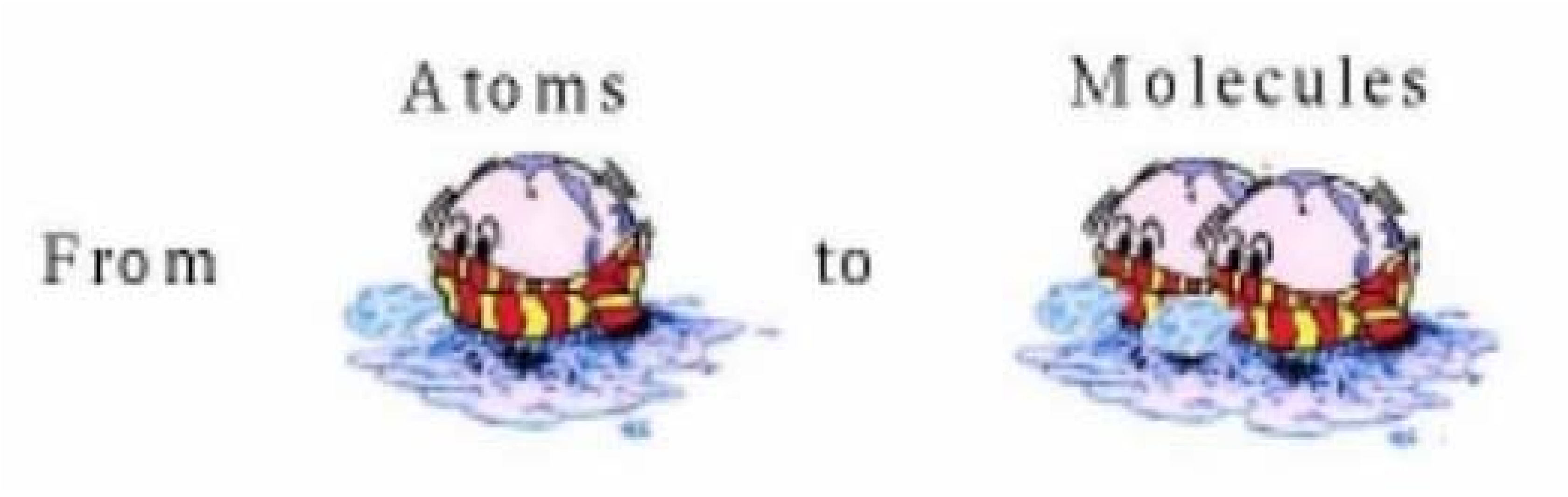
- There is something that nobody really know what is right and wrong and there is something that we definitely know what is right and wrong !

--- Bartlet, West Wing, NBC TV

- Anyway, you have to make a decision to pursue the direction at least you think it is right !

Decision !

- Life is a series of decision !



為何需要超冷分子?

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS B: ATOMIC, MOLECULAR AND OPTICAL PHYSICS

J. Phys. B: At. Mol. Opt. Phys. 39 (2006) doi:10.1088/0953-4075/39/19/E01

INTRODUCTORY REVIEW

Cold Molecules: a chemistry kitchen for physicists?

Olivier Dulieu[1], Maurice Raoult[1] and Eberhard Tiemann[2]

[1] Laboratoire Aimé Cotton, CNRS, Bât. 505, Campus d'Orsay, 91405 Orsay Cedex, France
[2] Department of Quantum Optics, Gottfried Wilhelm Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany

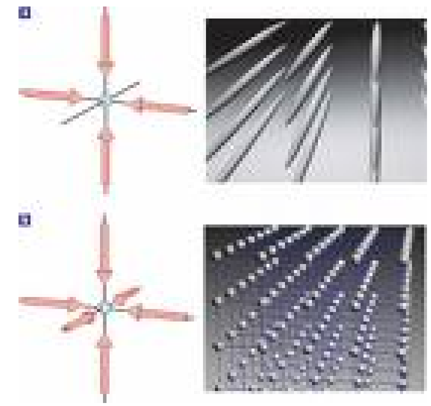
Three Main Motivations

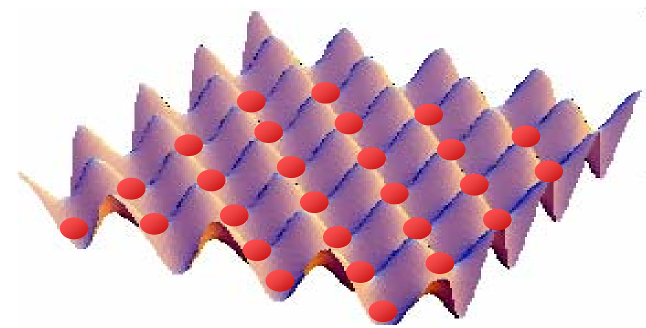
- Condensed Matter Physics with dipolar interaction: Quantum Simulation
  - 添加新花樣!
- Test of Fundamental Physics:

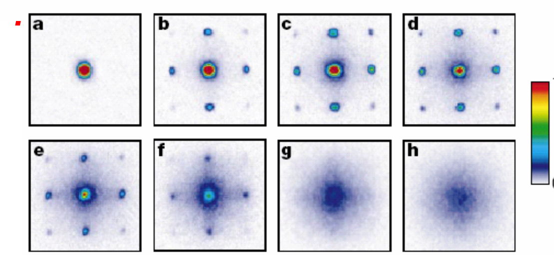
  e.g. search for electron dipole moment (test of time-reversal symmetry breaking)
  - 更精密量測、尋找新物理!
- Quantum information and computation
  - 量子力學的應用!

Condensed Matter Physics with Quantum Gases

- Cold atoms in optical lattices :simulation of condensed-matter physics.
- Lattice structure, potential depth, filling fraction, atom temperature, atomic states, atomic interaction, boson or fermion species …etc many parameters can be precisely controlled and tunable.
- Realization of Feynman's idea of quantum simulation, simulating one quantum system by another quantum system.







Superfluid-Insulator transition

Dipolar Gas : Adding a New Parameter!

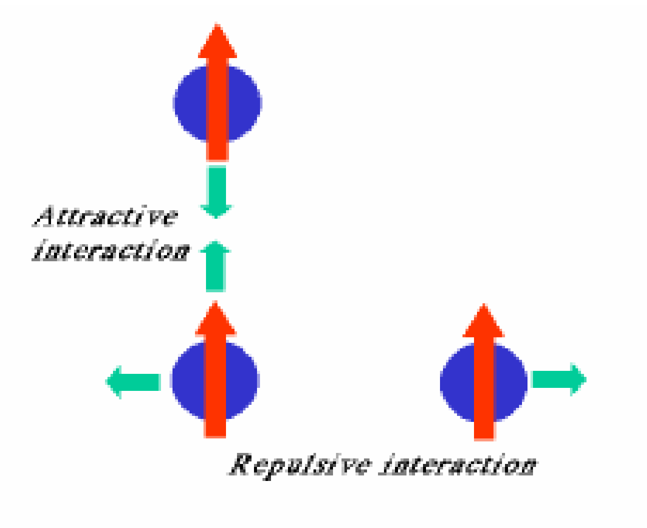
Dipole-dipole interaction

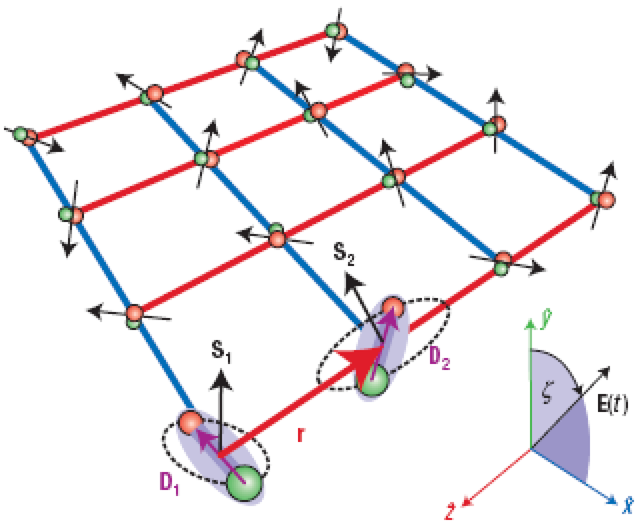
$$U_{dd} = \frac{\vec{d}_1 \cdot \vec{d}_2 - 3(\vec{d}_1 \cdot \hat{r})(\vec{d}_2 \cdot \hat{r})}{R^3}$$

- Relative long-range interaction
- Anisotropic interaction

Order of magnitude

∗ For ^{87}Rb, magnetic dipolar interaction strength is 0.006g.
∗ U_{dd} for 1 D is a factor of ~3000 more than that for 1 μ_B
∗ For d=1 Debye, n=10^{14} cm^{-3}, U_{dd}/k=700nK



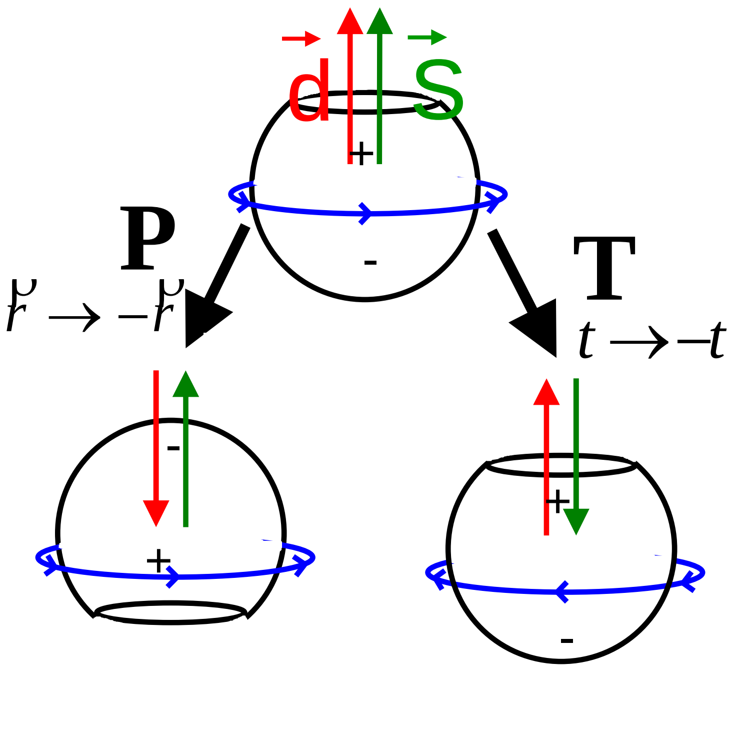


Test of Fundamental Physics

- Search for electron's dipole moment. An EDM violate T and P symmetry. Physics beyond Standard Model.
- Polar molecules enhance the EDM effect by strong internal field.
- Cold molecules allow higher precision and low systematic effect in EDM experiments.

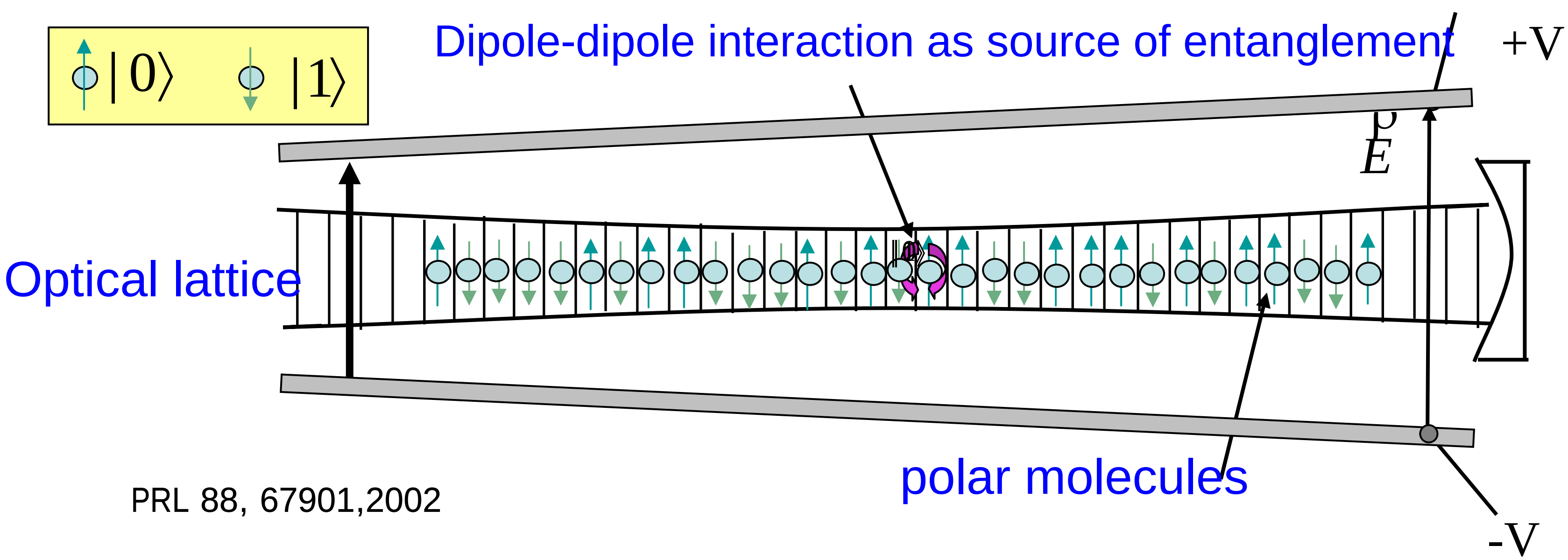
$$H = -(d\vec{E} + \mu\vec{B}) \bullet \vec{S} / S$$

S is total angular momentum.
E does not change sign under T-operation, wheras both *B* and *J* do.



Quantum Computation

- Superposition states, Quantum bit, Entanglement, Quantum gate, Operation time, Decoherence time…
- Strong dipole-dipole interaction between polar molecules as a source of entanglement to implement quantum gate and allow shorter gate operation time.
- Longer coherence time for cold molecules.



PRL 88, 67901,2002

Some By-products

- High-precision spectroscopy
- Cold molecular collisions and reactions.
- Precision determination of molecular potential by resonance spectroscopy.
- “SuperChemistry” :

Chemistry without entropy. Molecules prepared in pure quantum states.

Clear appearance of quantum effects in chemical reactions.

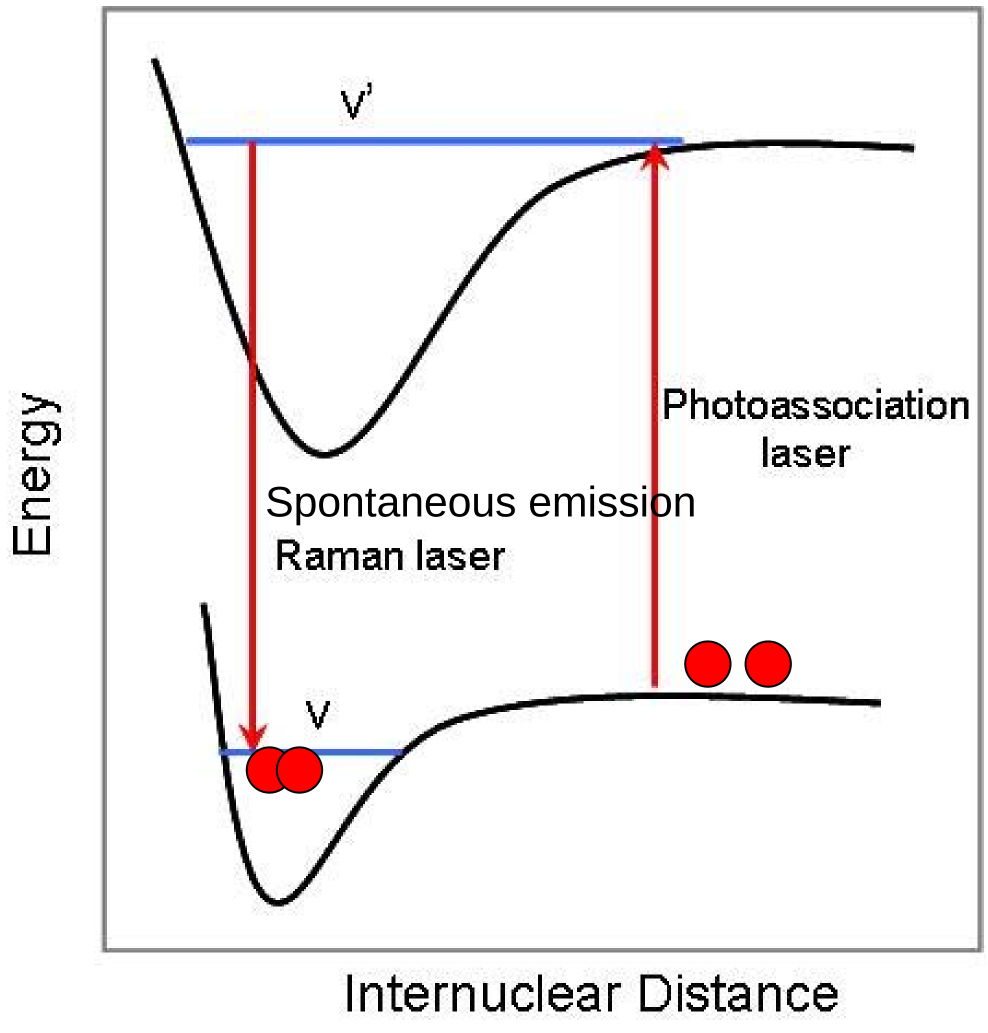
How to make cold molecules?

方法是人想出來的 ！

Methods to generate cold molecules

- **Indirect method** : making cold molecules from cold atoms
  - Photoassociation
  - Adiabatic passage in a Feshbach resonance
- **Direct Method** : making cold molecules directly from molecules
  - Helium buffer gas cooling
  - Stark deceleration of a molecular beam
  - Velocity selection by Stark guiding
  - Crossed molecular beam collision
  - Rotating nozzle
  - Optical Stark deceleration of a molecular beam
  - …

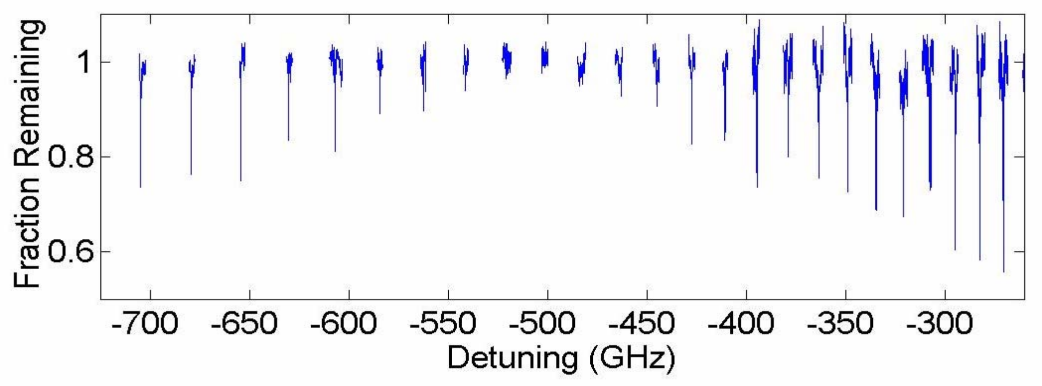
Photoassociation of Cold Atoms

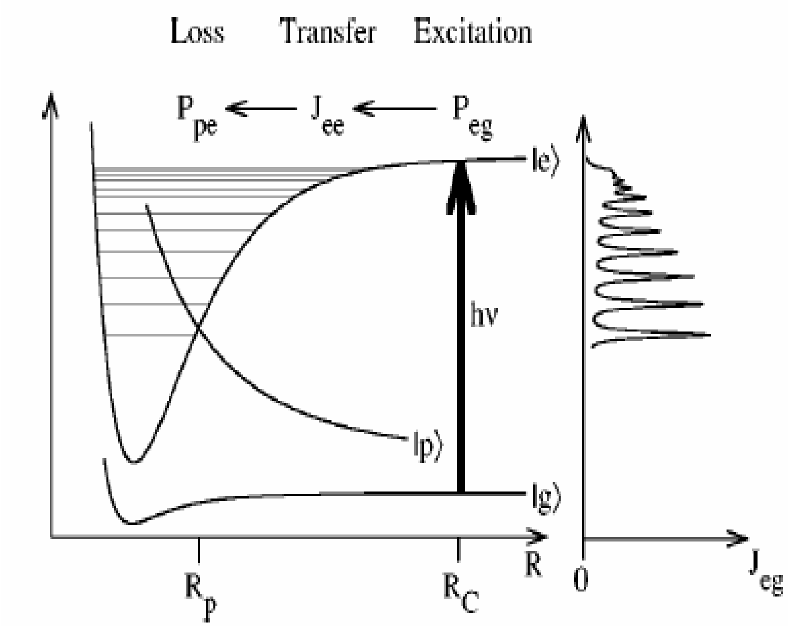


PRL 80, 4402, 1998
Science 287,1016, 2000
Physics/0501008

Photoassociation Spectroscopy: My touching moment !

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





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

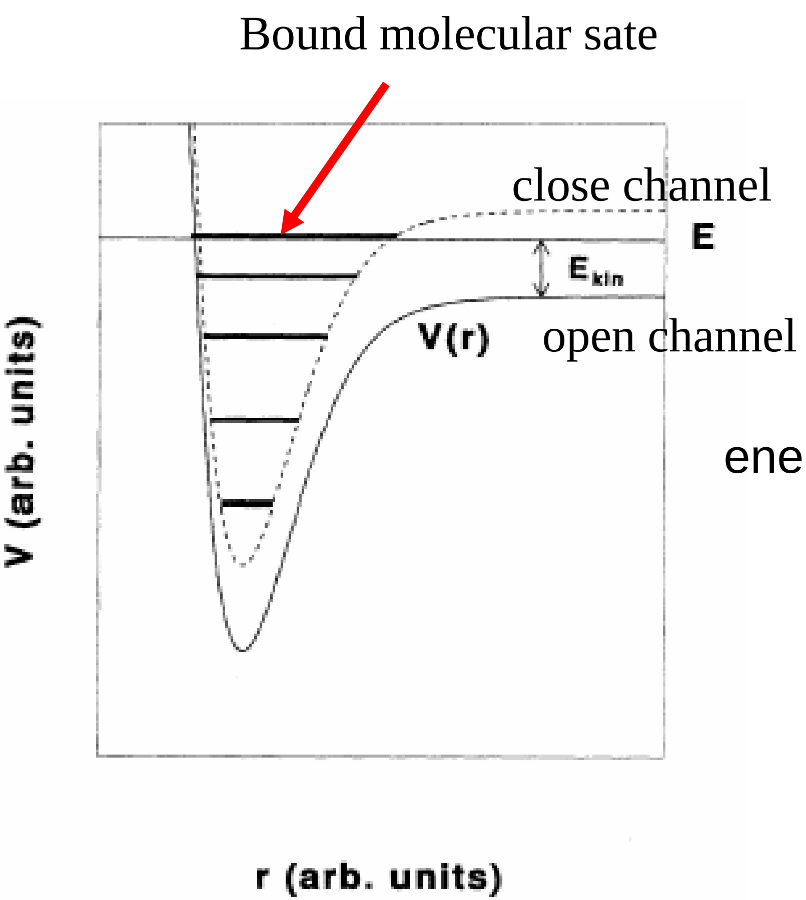
$$C_3 = \frac{3\hbar\lambda^3}{16\pi^3}\gamma$$

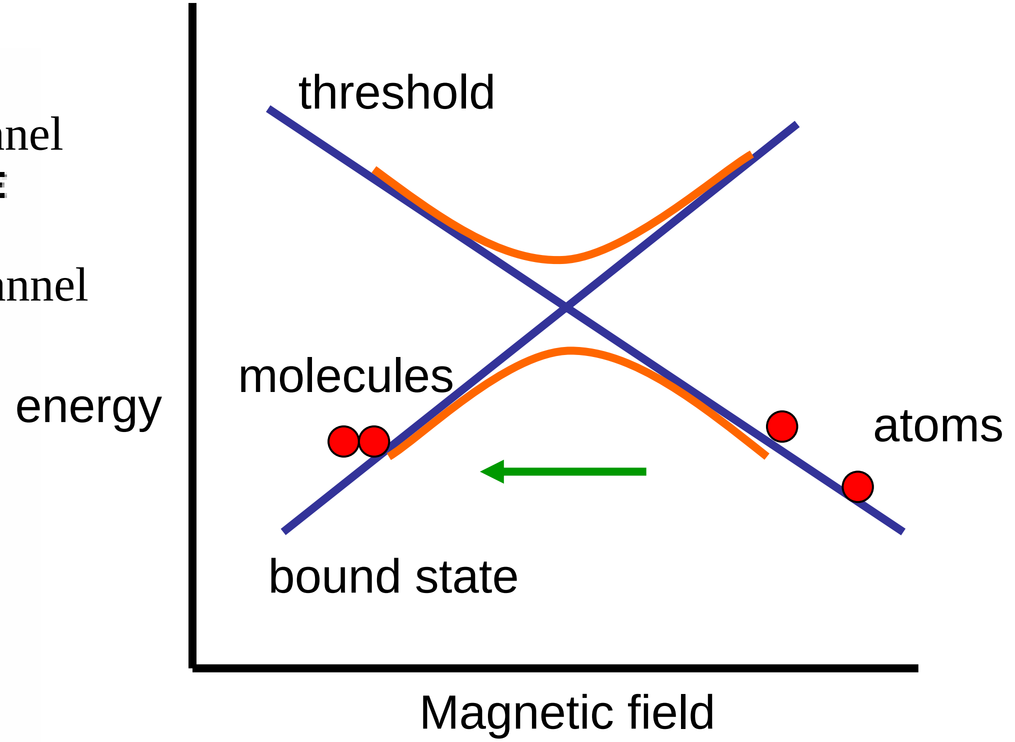
$$E(\upsilon) = D - X_0(\nu_D - \nu)^6$$

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

Allow one to determine atomic excited state lifetime and ground state collision property !

Another Way : Feshbach Resonance

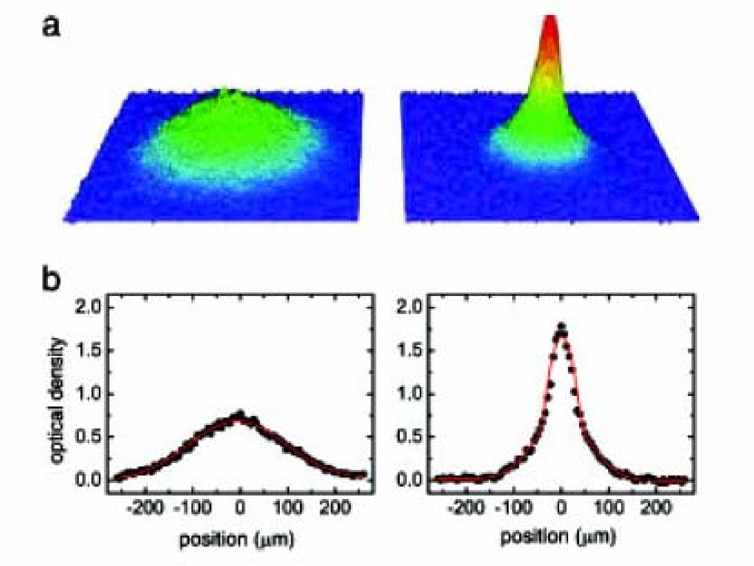




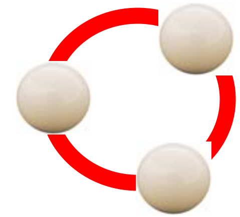
Nature, 412, 295, 2001

BEC of molecules has been realized this way !!!

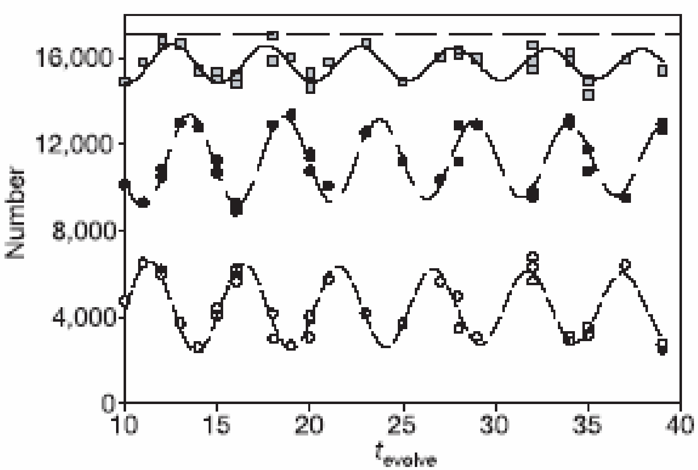
Fanscnating Phenomena of Ultracold Molecules



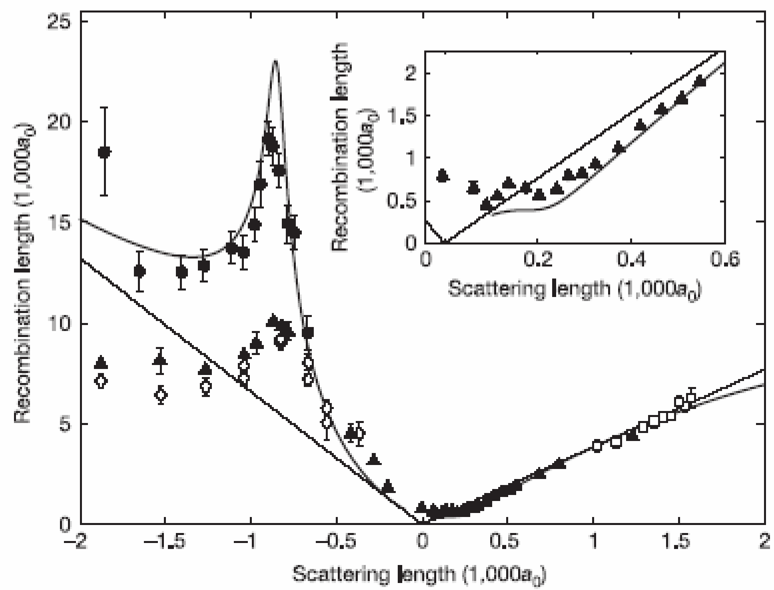
Bose-Einstein condensation, JILA



Efimov trimmer



Coherent conversion between atom and molecules, JILA



Innsbruck

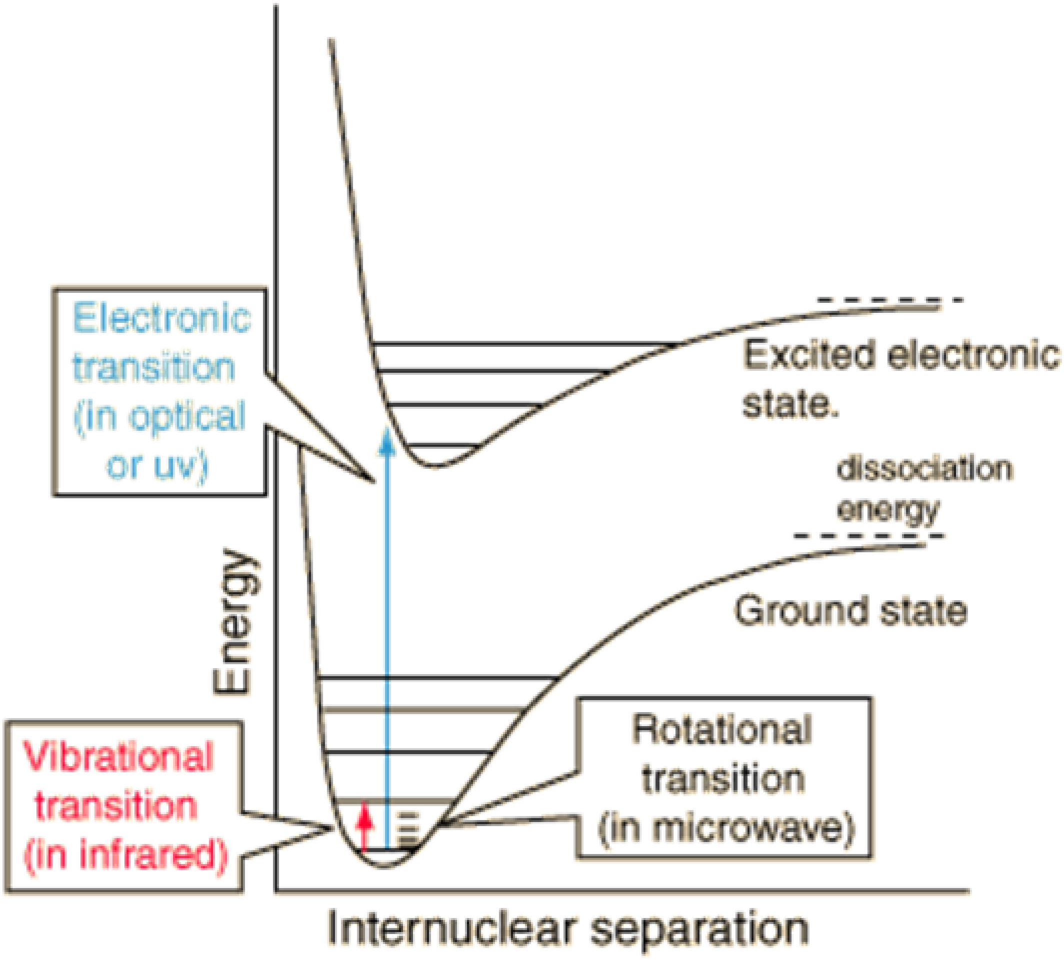
Limitation of Cold Molecule Produced from Cold Atoms

- Limited species
- Limited structure, mostly dimer
- Difficult to produce molecule in lowest vibrational ground state, molecule in higher vibration state is unstable to collision.

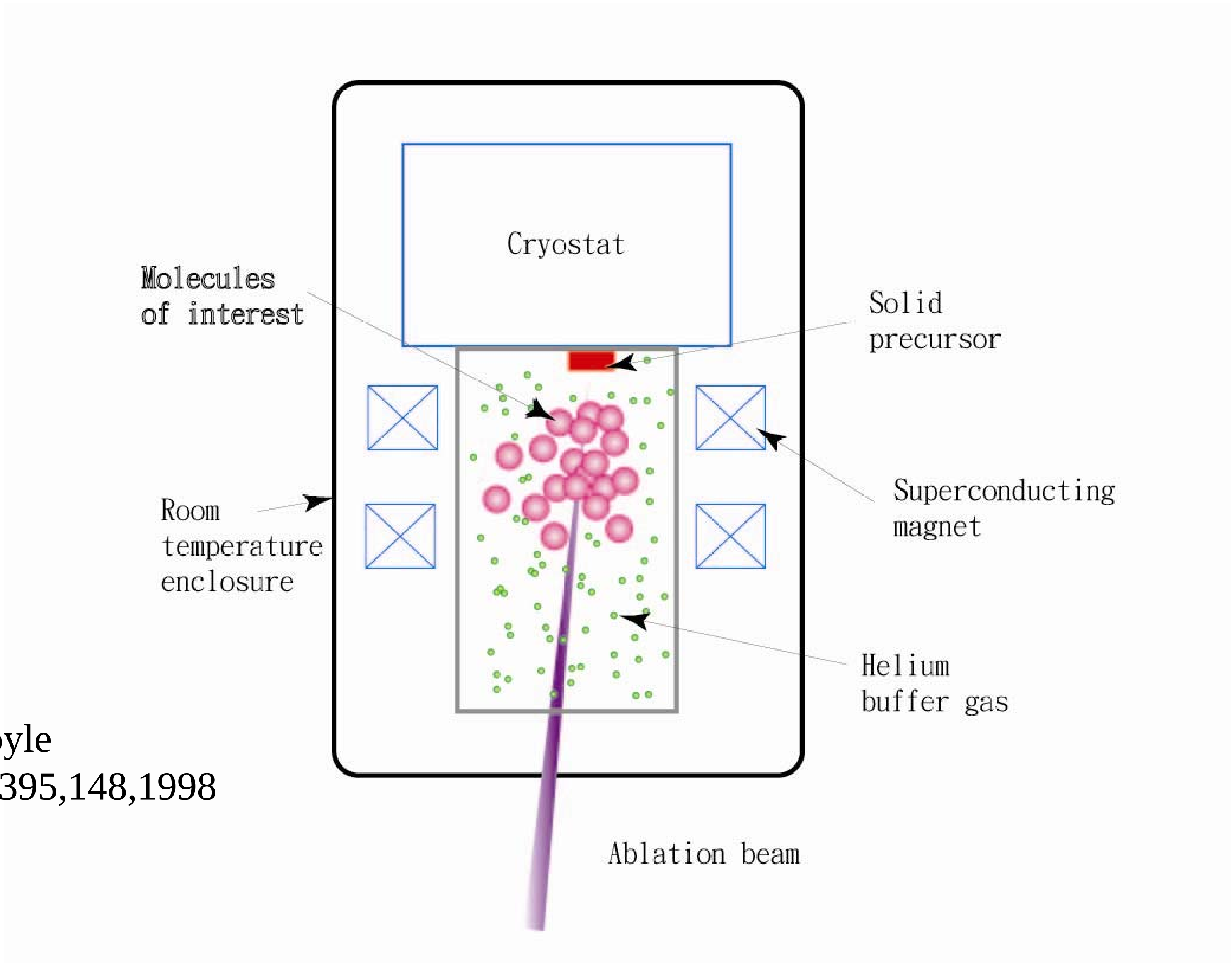
Cold Molecule Starting from Molecule ?

Laser Cooling of Molecule ?
Not so cool !

Laser cooling of atom:
directly from 300K to 10 μK



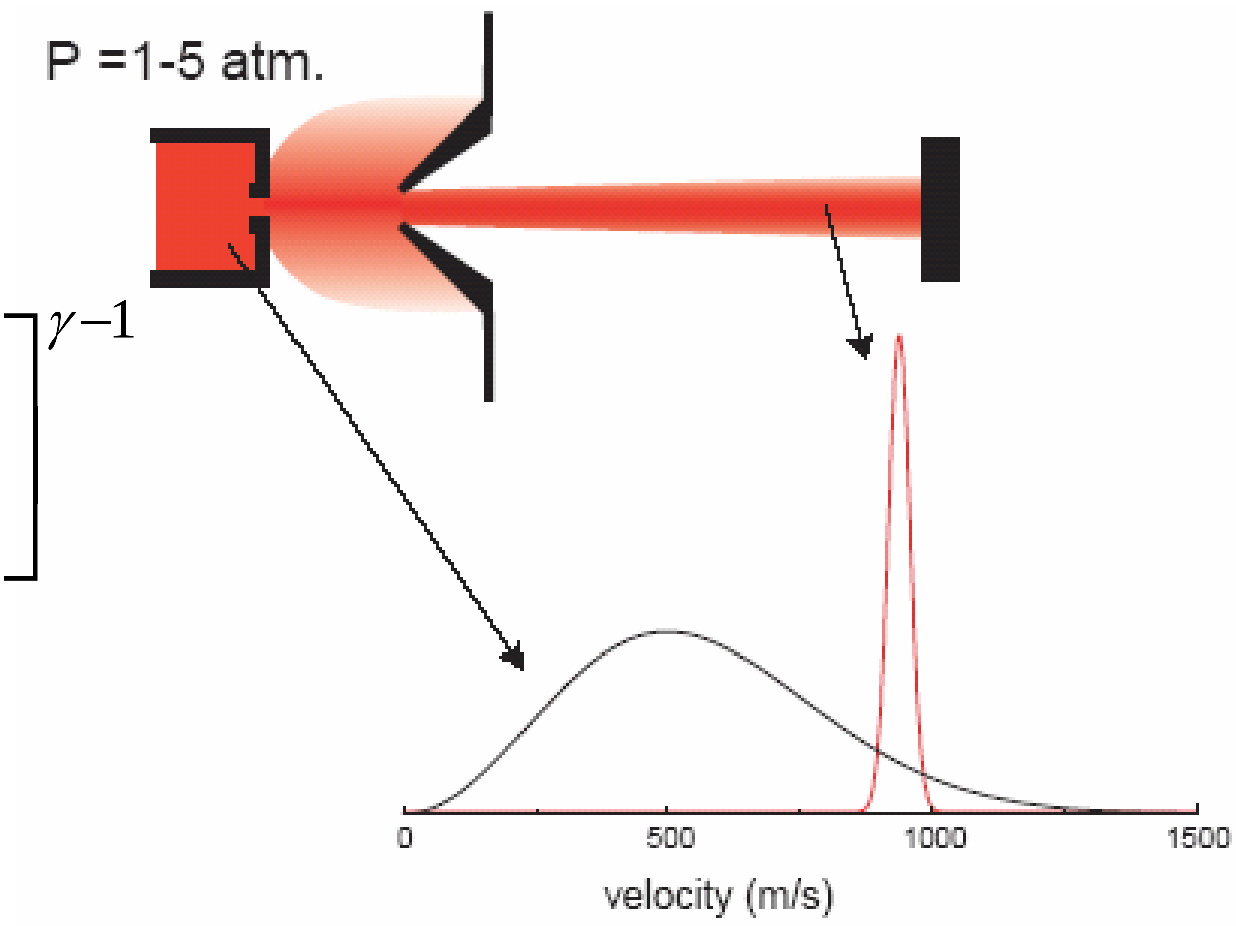
Helium Buffer Gas Cooling



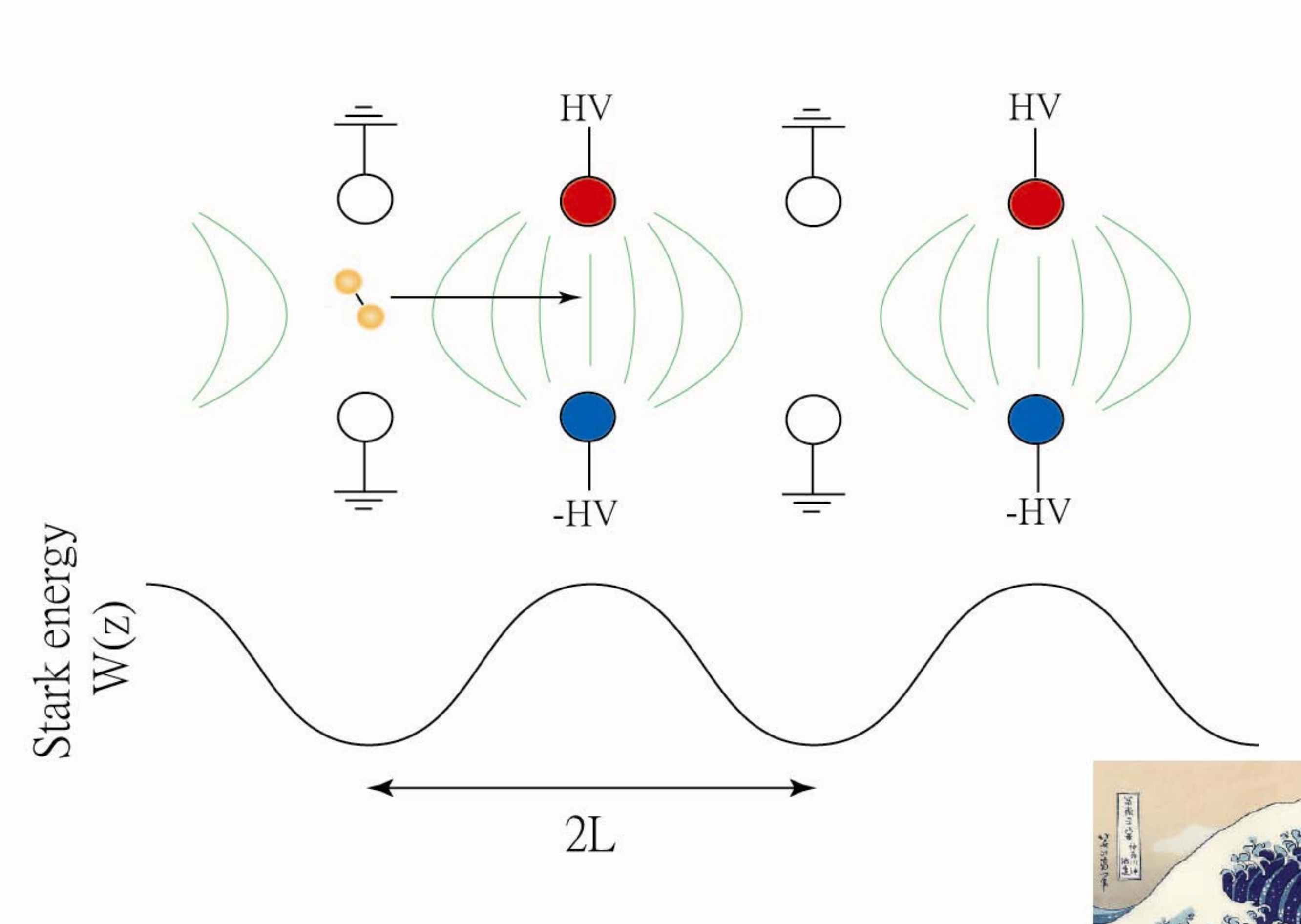
John Doyle
Nature, 395,148,1998

Supersonic Jet

$$T = T_0 \left[\frac{n}{n_0} \right]^{\gamma - 1}$$

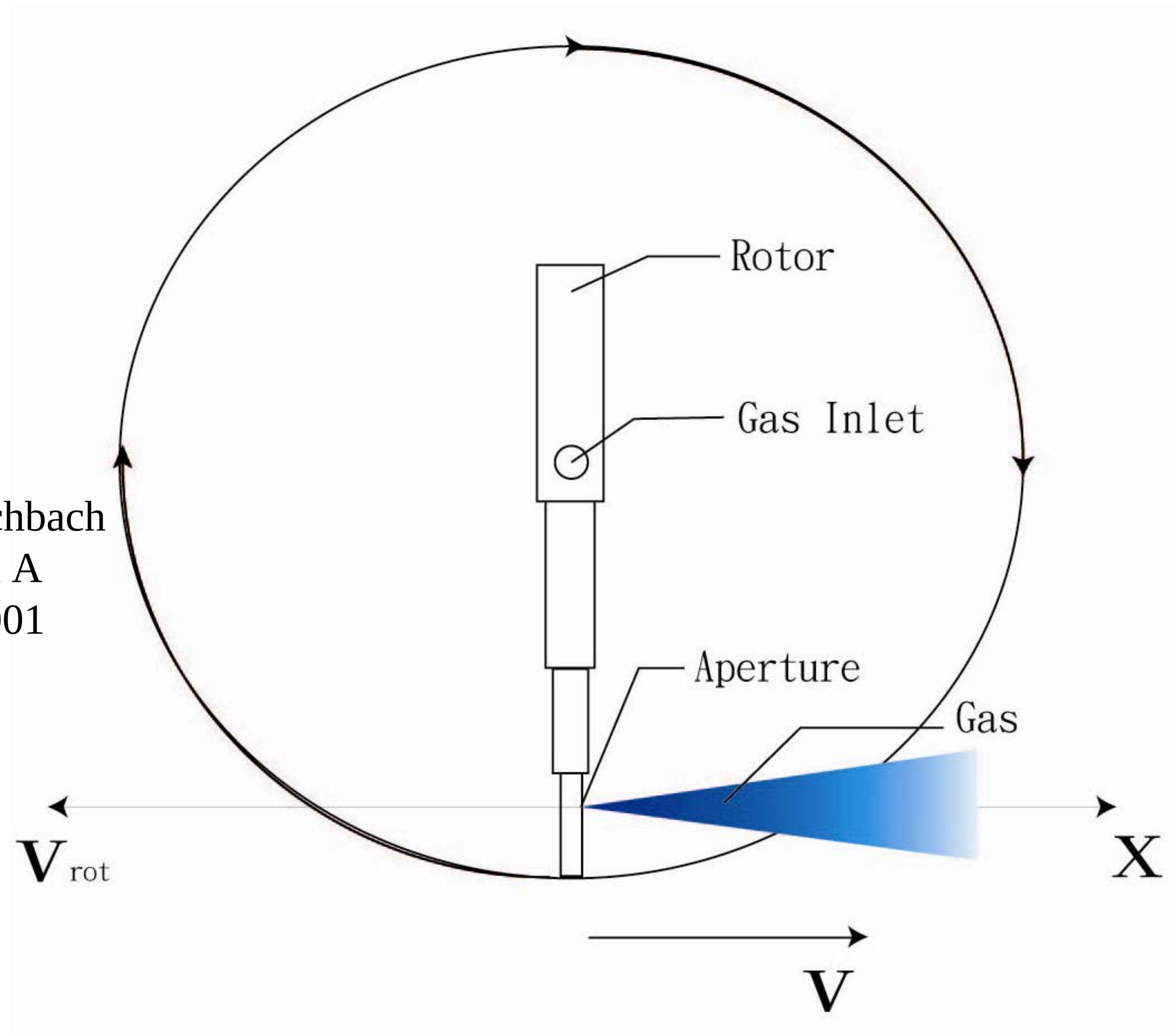


Stark Deceleration



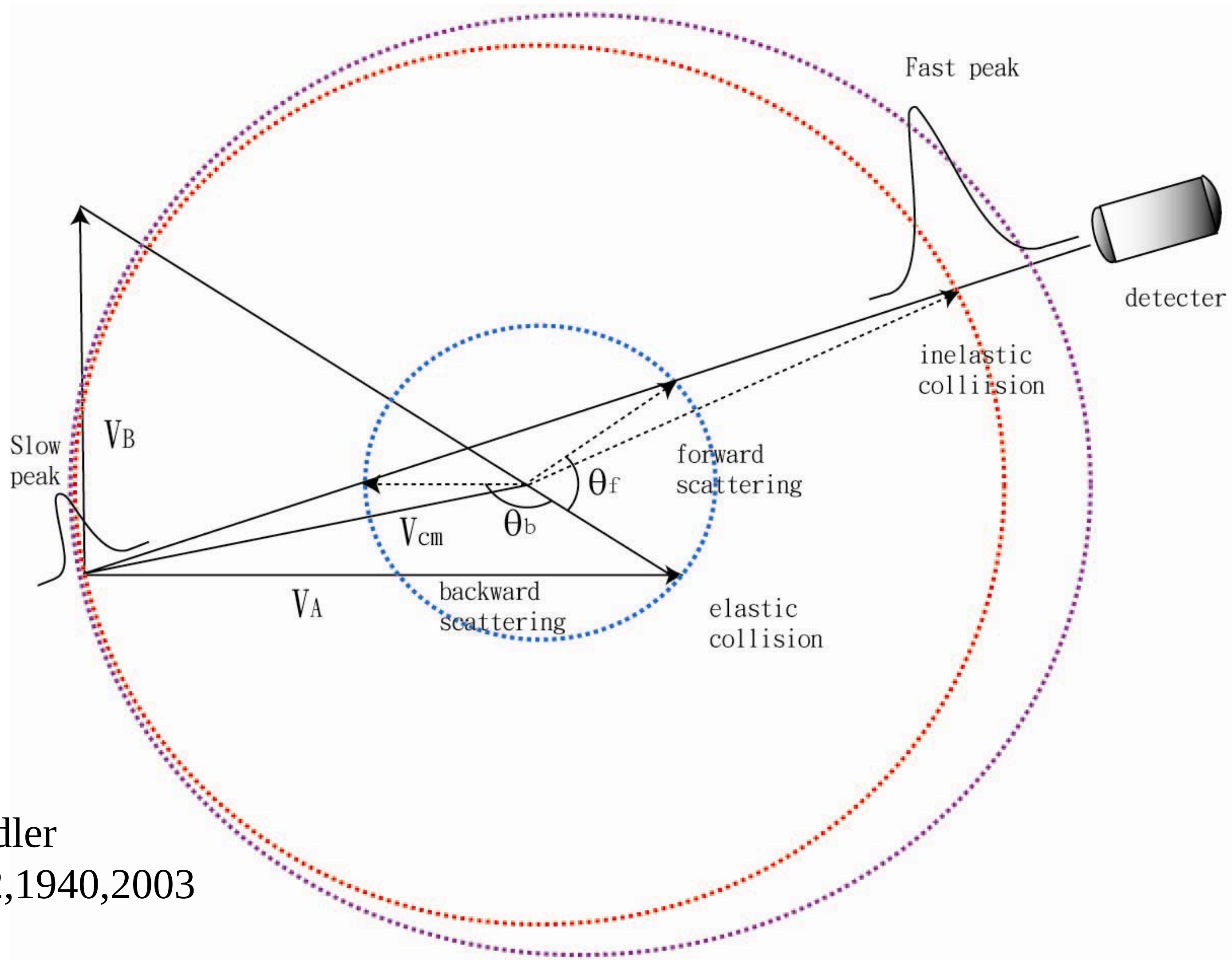
Gehard Mejier
PRL 83,1558,1999

Rotating Supersonic Jet



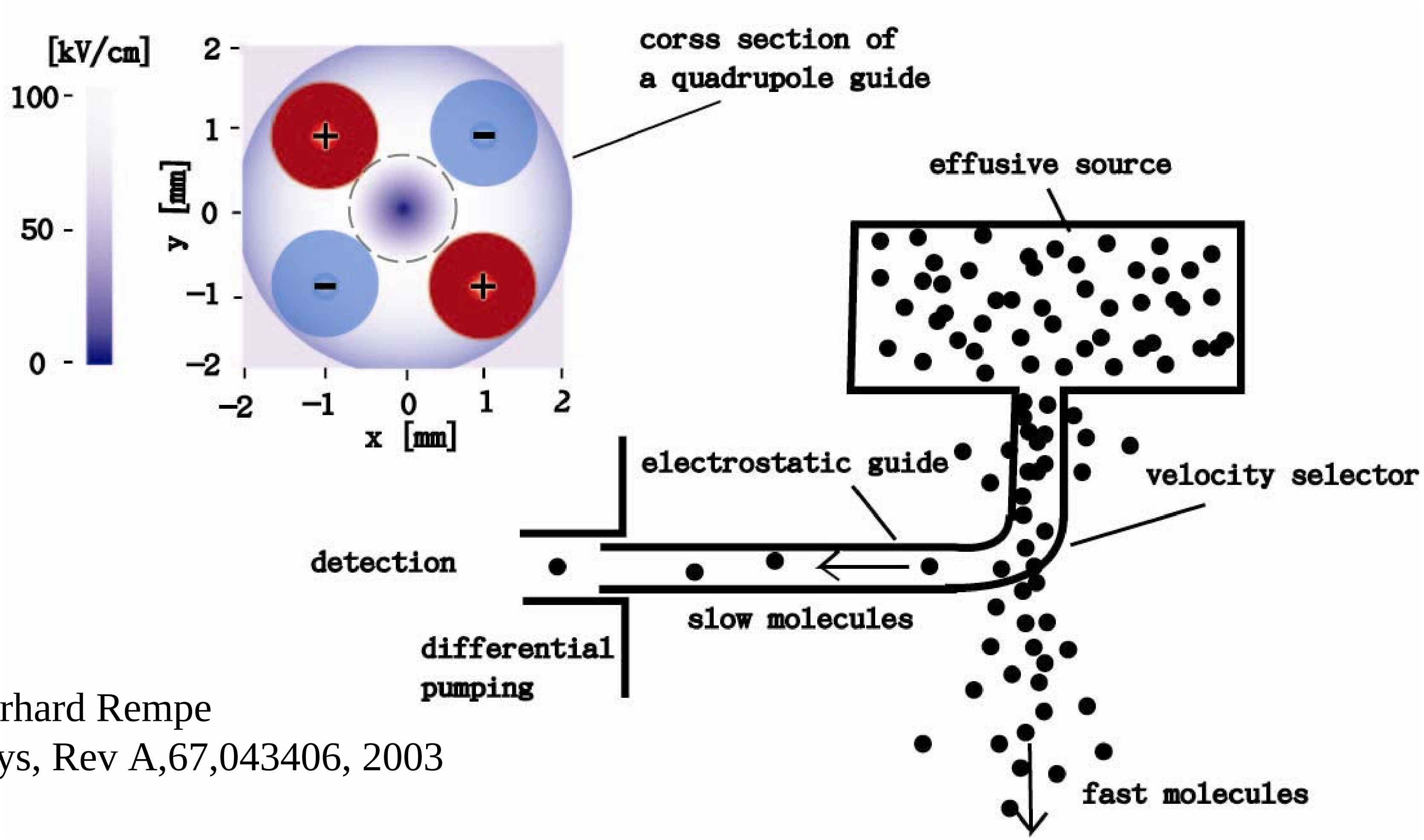
Dudley Herschbach
J. Phys Chem A
105, 1626, 2001

Crossed Molecular Beam Collision



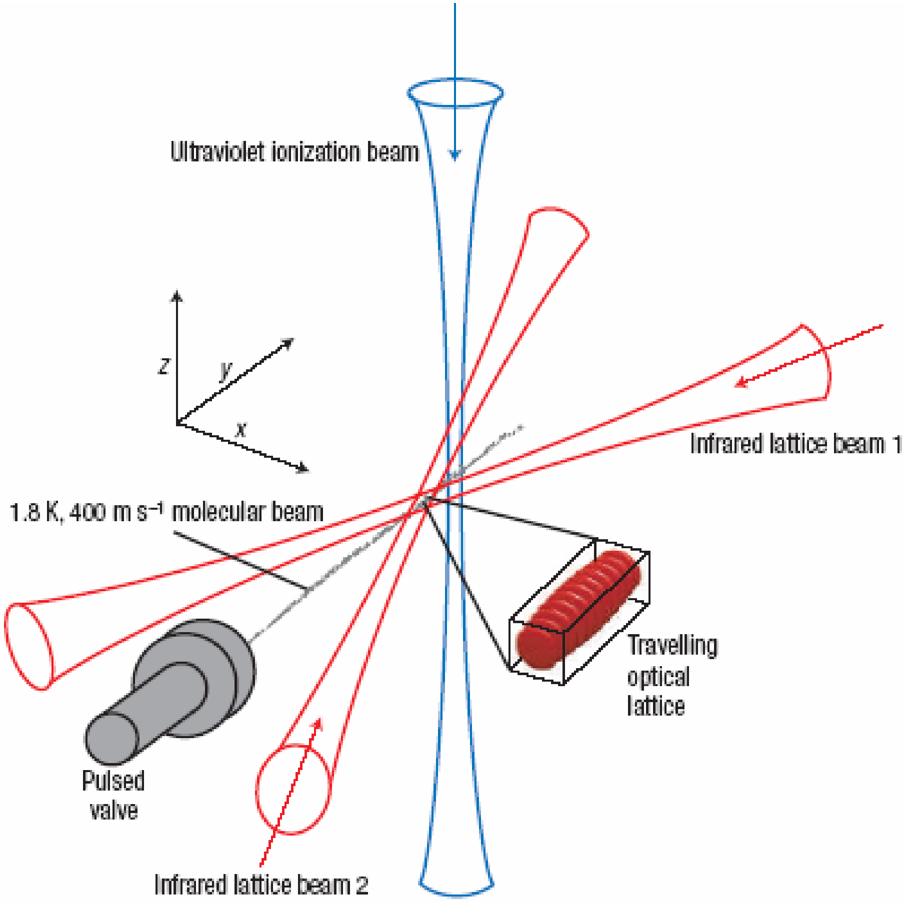
David Chandler
Science, 302,1940,2003

Stark Guiding



Gerhard Rempe
Phys, Rev A,67,043406, 2003

Optical Stark Deceleration



P.F. Barker at.al. Nature Physics, 2, 465 (2006)

Still many other “crazy” idea!

What is our approach ?

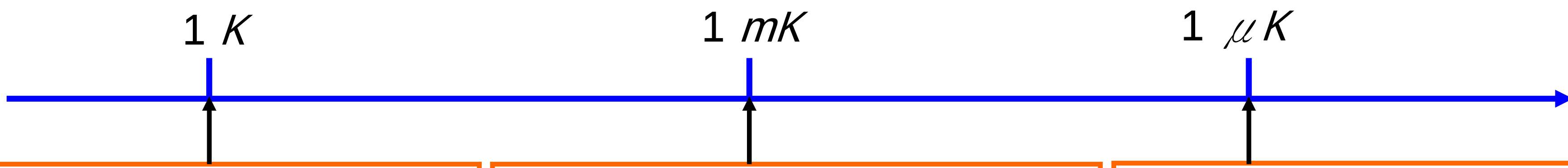
Evaluate it & Decide it

Be brave !

Be open to learn new thing!

- One major thing need to learn to be a leader !

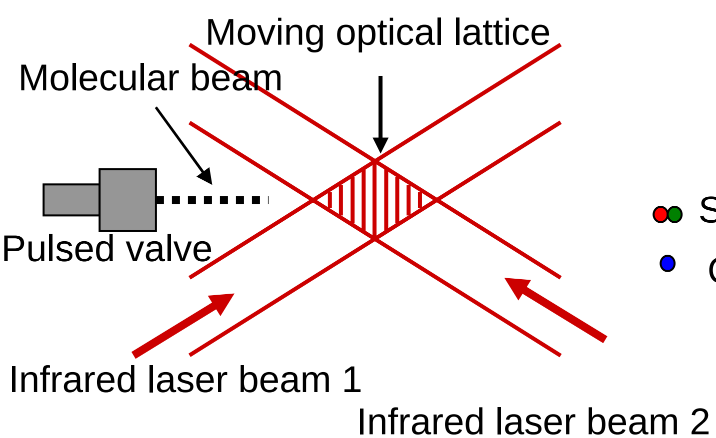
Routes Toward Ultracold Molecules

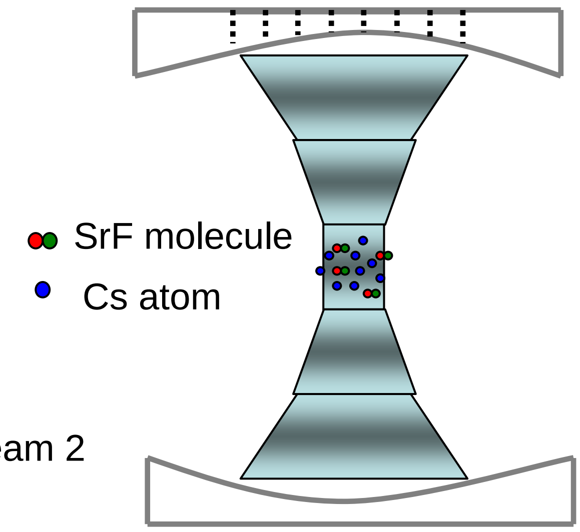


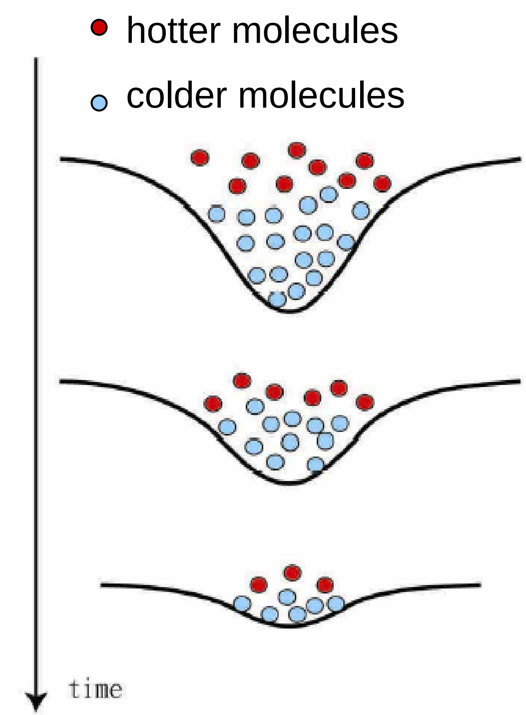
Optical Stark deceleration of a SrF molecular beam.

Sympathetic cooling of molecules to *mK* in a microwave trap by ultracold cesium atoms.

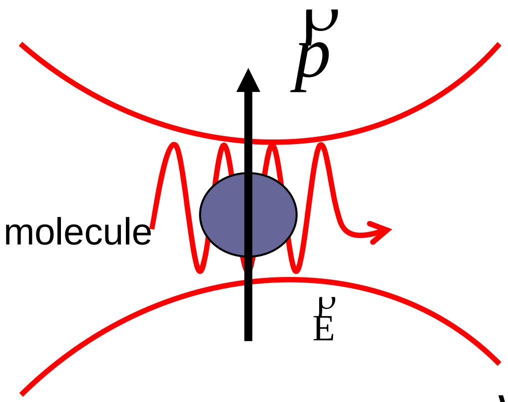
Evaporative cooling to *μK* in a microwave trap.







Optical Dipole Force



Far-detuned laser field

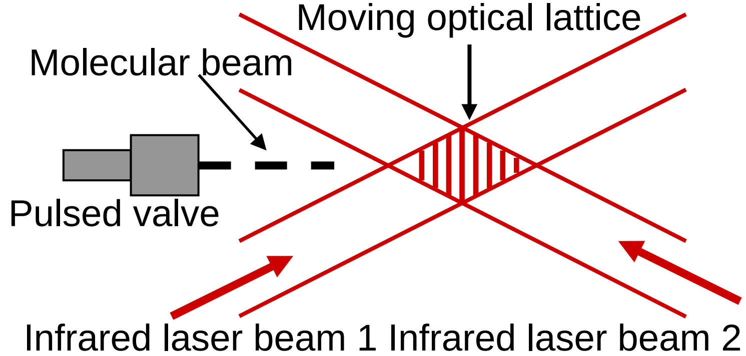
$$\vec{p} = \alpha \vec{E},$$

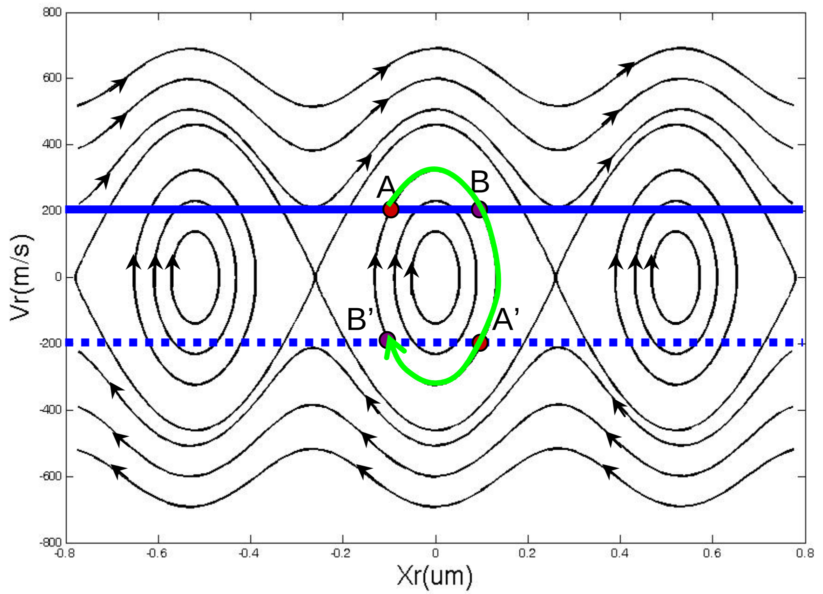
$$U = -\langle \vec{p} \bullet \vec{E} \rangle = -\frac{1}{2}\alpha E^2 = -\frac{\alpha}{2\varepsilon_0} I(\vec{r},t)$$

Where α is polarizability, which is ~1-10$\times 10^{-40}$ Cm^2V^{-1}.

With the pulse energy of 200 mJ for a typical Q-switched Nd:YAG laser of 8 ns that is focus to 50 μm, the trap depth can up to **100-1000 *K*** !!!

Deceleration of a Molecular Beam by Moving Optical Lattices: Principle





$$\frac{d^2x}{dt^2} = -\frac{F_{//}}{m}\sin[q(x - v_L t) + \phi]$$

$$q = k_{1x} + k_{2x}; v_L = (\omega_2 - \omega_1)/q$$

$$\theta \equiv q(x - v_L t) + \phi$$

$$\tau \equiv t\omega_0; \omega_0 \equiv \sqrt{F_{//}q/m}$$

$$v_r \equiv (v - v_L)/v_n; v_n \equiv \sqrt{F_{//}/mq}$$

$$\frac{d\theta(\tau)}{d\tau} = v_r(\tau)$$

$$\frac{dv_r(\tau)}{d\tau} = -\sin[\theta(\tau)]$$

A pendulum problem in the moving lattice frame!

Advantages of optical Stark deceleration

1. Molecules in all kind of states (high-field-seeking and low-field-seeking states), including the absolute ground state, can be decelerated by this method.
2. The system is easily to be integrated with the trap.
3. A large fraction of molecules (up to 30%) can be bring to stop if intense laser is used.

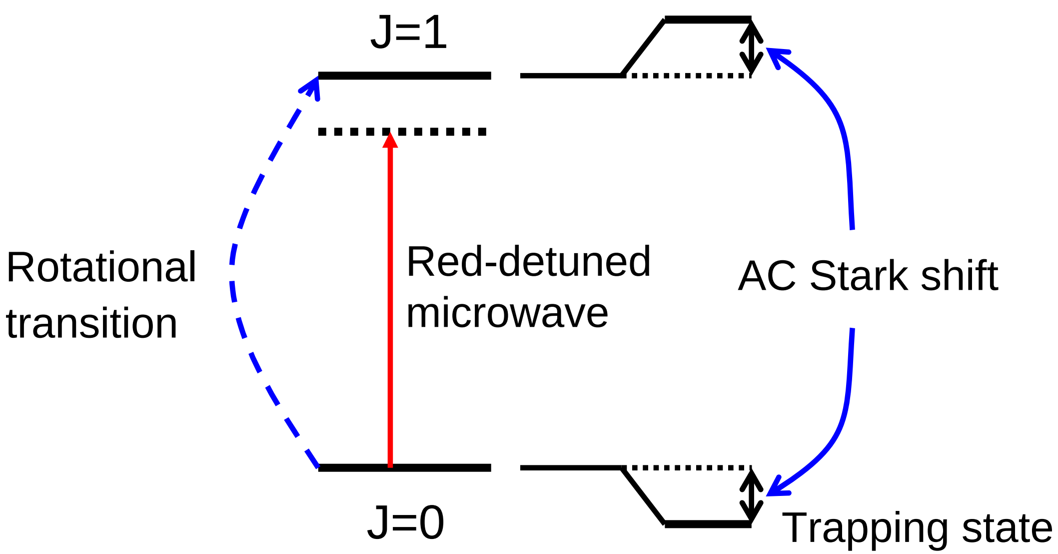
Summary

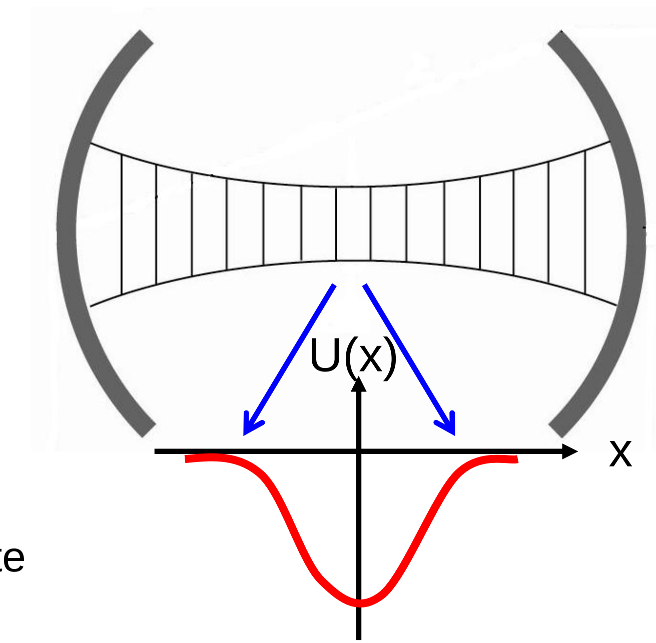
One single longitudinal mode Q-switched Nd:YAG (Spectra Physics GCR-290) laser with two AOMs will be used to form the moving optical lattices.

Laser induced fluorescence will be used to detect the molecules and its velocity distribution. A pulsed dye laser (Continuum ND6000) with wavelength ~ 642nm will be used to excite SrF $X\ ^2\Sigma^+$, v=0 $\rightarrow$ $A\ ^2\Pi_{1/2}$, v=1 and deteced at ~ 663nm by $A\ ^2\Pi_{1/2}$, v=1 $\rightarrow$ $X\ ^2\Sigma^+$, v=1 transition.

Velocity distribution after optical stark deceleration can be detected by a PMT at a certain distance away from the lattice. Delay time between deceleration and pulsed dye laser on will be varied.

Principle of Microwave Trap



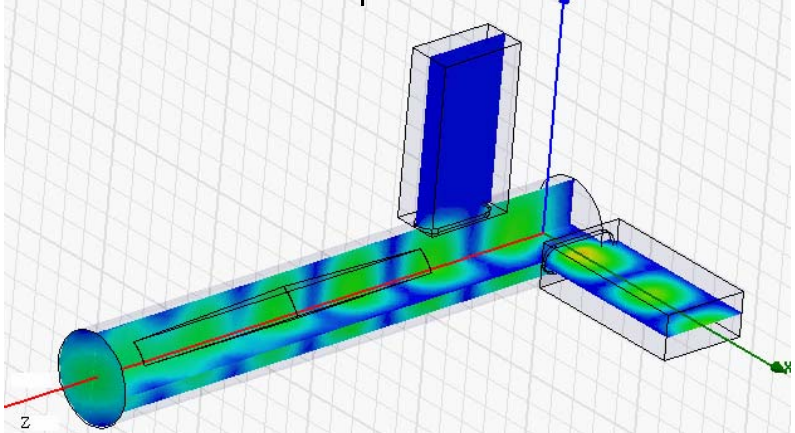


Why trapping molecules ?
- To accumulate more molecules
- Allow long storage time to perform further cooling, e.g. sympathetic or evaporative cooling
- For further spectroscopic or collision study

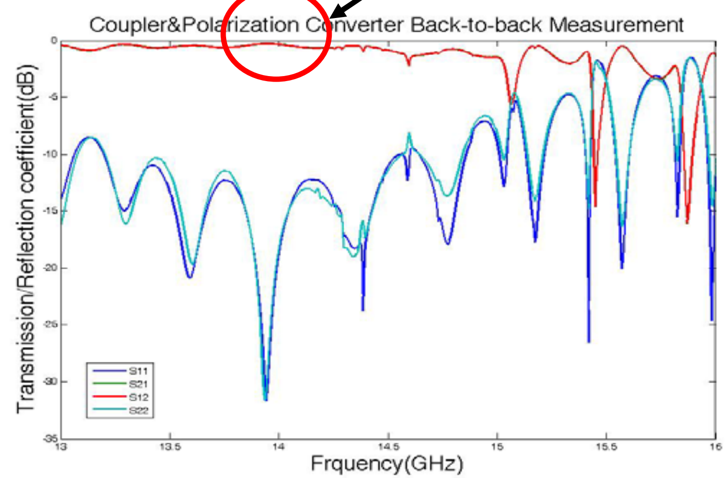
Advantages of microwave trap
- Large trap depth (~ 1K)
- Large trap volume (~ 1cm^3)
- Molecules in the absolute ground states can be trapped and thus immune to inelastic collisions loss.

Microwave Components

1, Rectangular to circular waveguide converter
+ linear to circular polarization converter



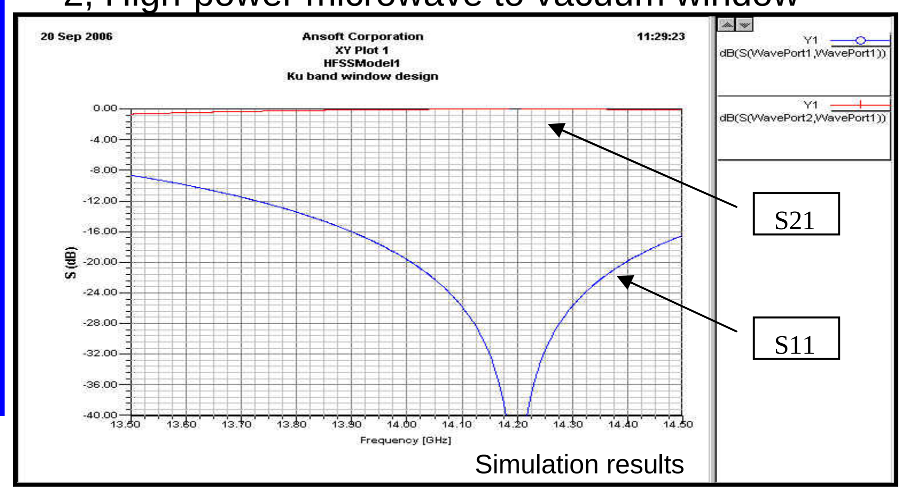
Good transmission in back-to-back measurement means good coupling efficiency in rectangular to circular converter and good conversion efficiency in linear to circular polarization converter !



Features

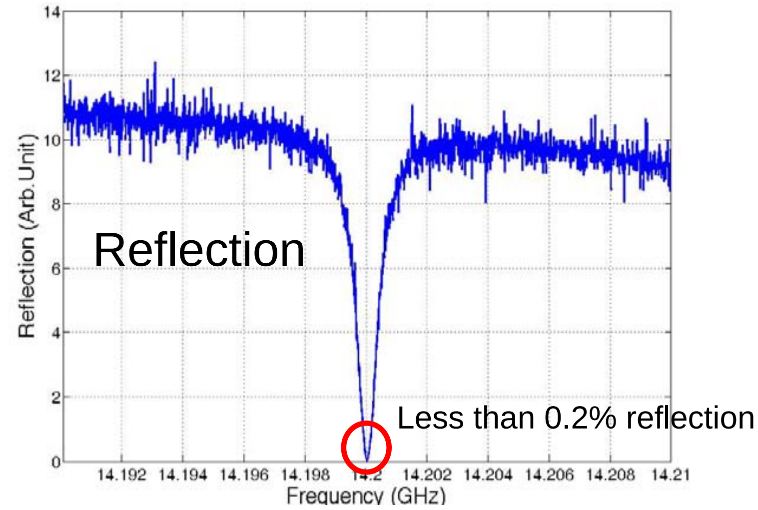
1. Dual function for rectangular to circular converter one as mode coupler and the other as return isolation.
2. Off axis position for rectangular waveguides offers better mutual isolation.
3. All metal design in linear to circular polarization converter offers high power operation capability.
4. High power window allows to operate the microwave trap inside the ultrahigh vacuum environment in order to have long trap lifetime.

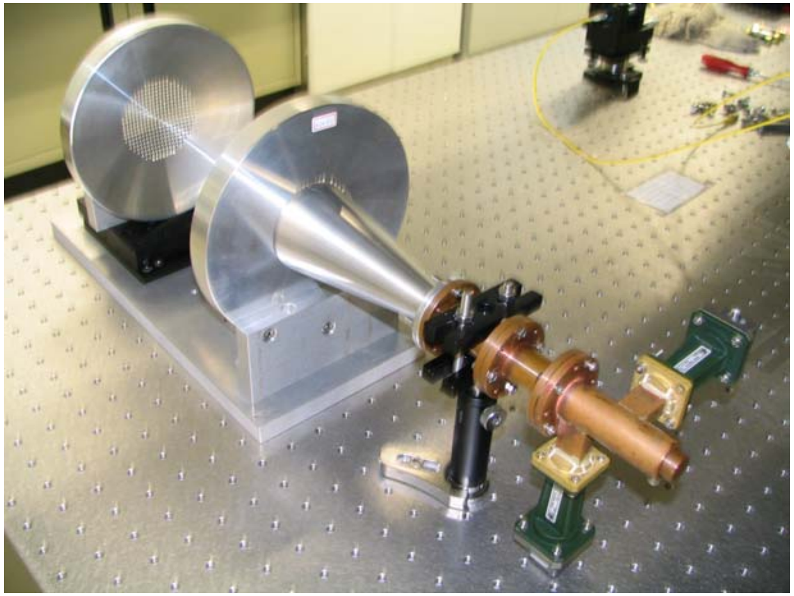
2, High-power microwave to vacuum window

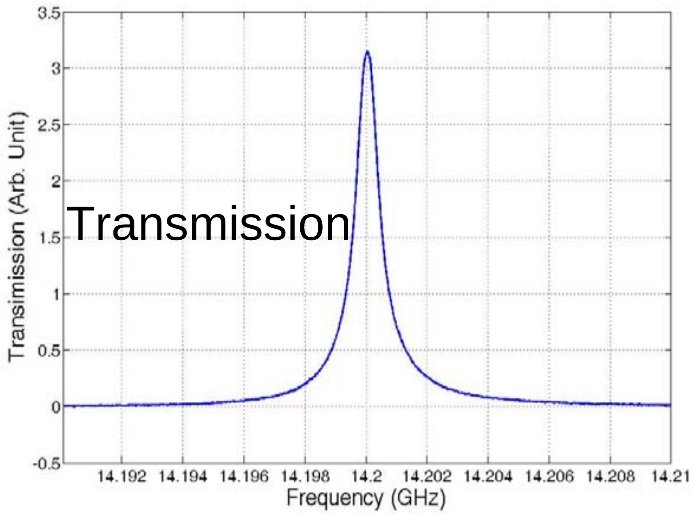


Optimum Coupling

- To efficiently couple microwave power into the open cavity, a hole pattern is first estimated by analytic results following by a systematic empirical variation on the design parameters.
- We can couple better than 99.8% power into the cavity.

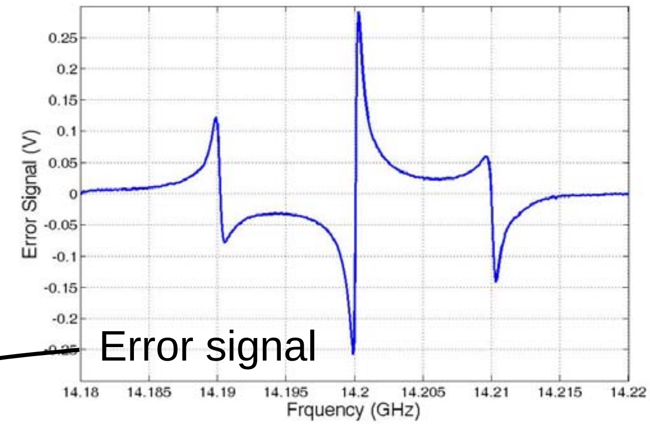


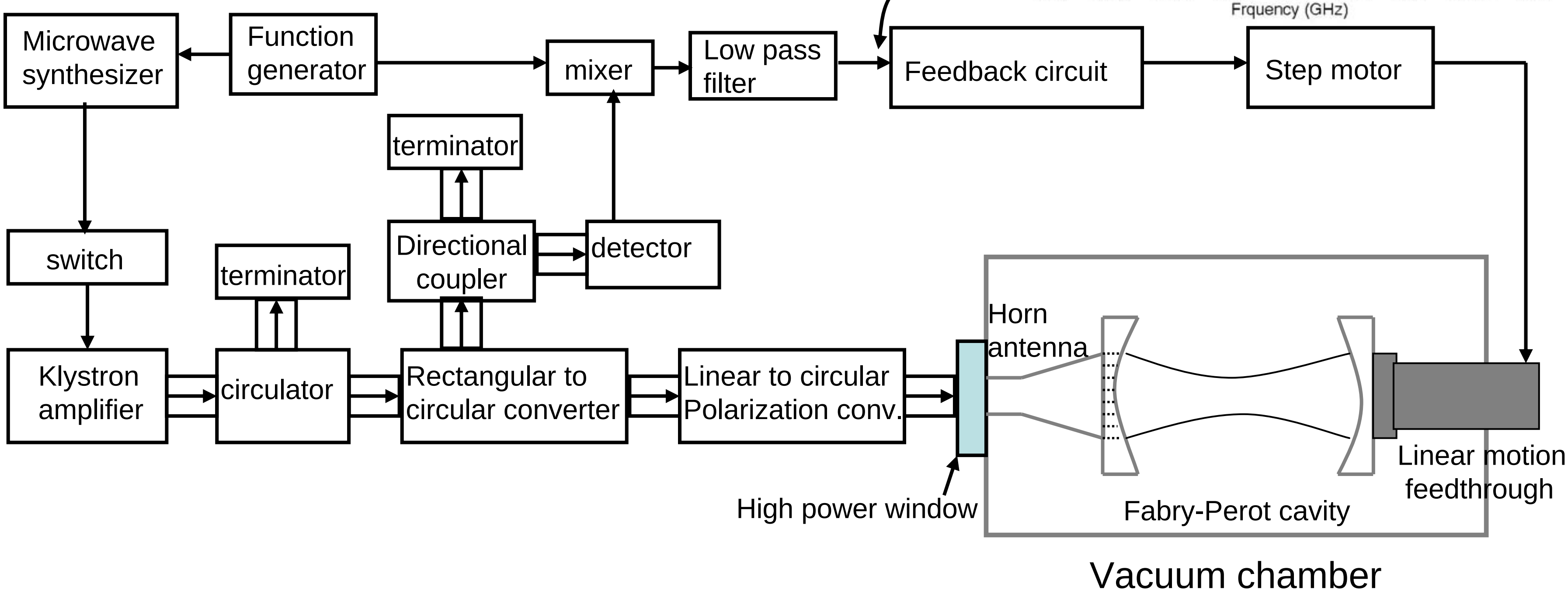




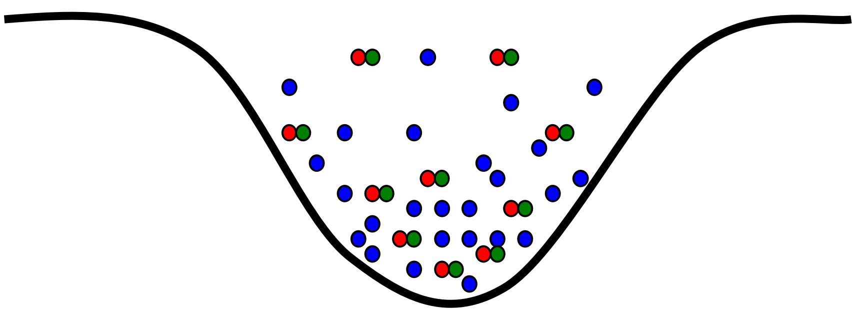
Microwave Trap : Setup

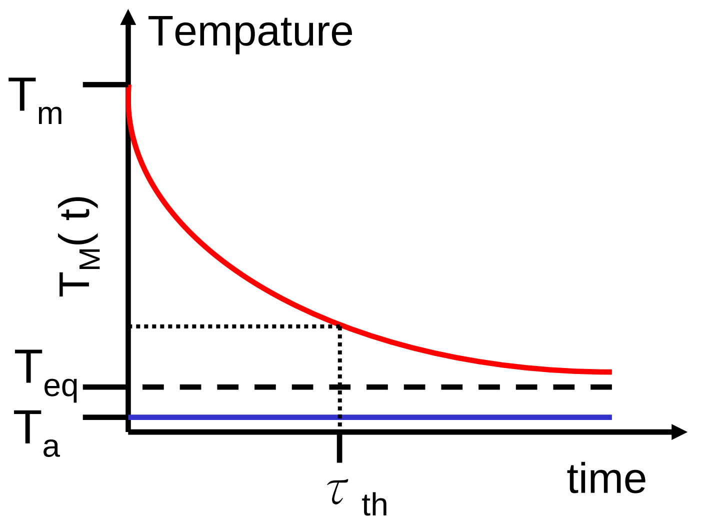
- Prototype microwave trap has been built and test. High power capability is taking into considerations.
- High power version within ultrahigh vacuum environment is under integration.
- Trapping of ultracold cesium atoms will be test first.





Sympathetic Cooling of Molecules by Ultracold Atoms in a Trap



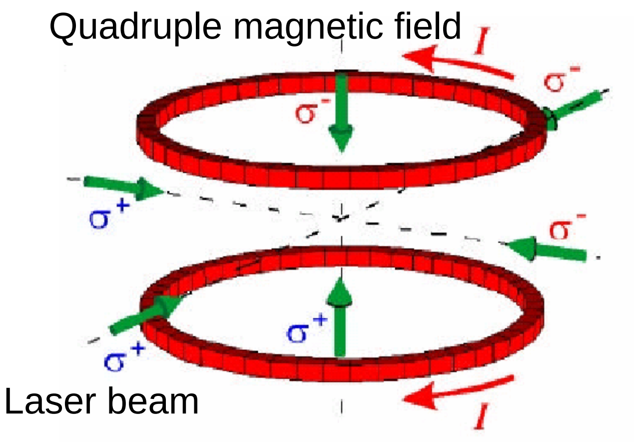


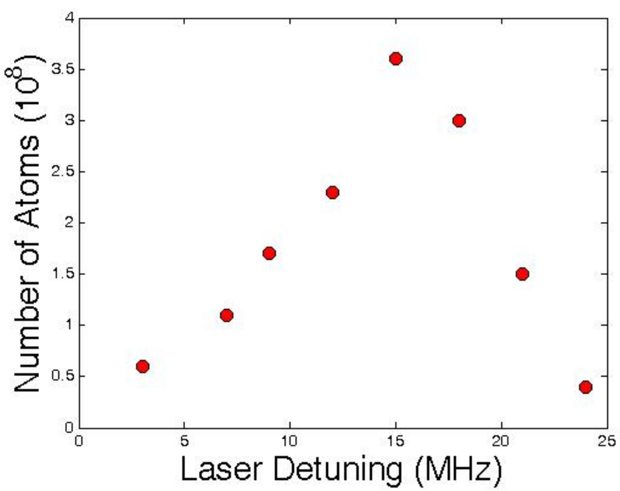
- Equilibrium temperature $T_{eq} = \dfrac{N_a T_a + N_m T_m}{N_a + N_m}$
- Thermalization time $\tau_{th} = \dfrac{3 N_a N_m}{2(N_a + N_m)\xi\gamma}$
- Collision rate $\gamma = n_{pa} n_{pm} \sigma_{am} \bar{v} c(T_a, T_m)$

c: a geometry factor and $\xi = 2M_a M_m / (M_a + M_m)^2$

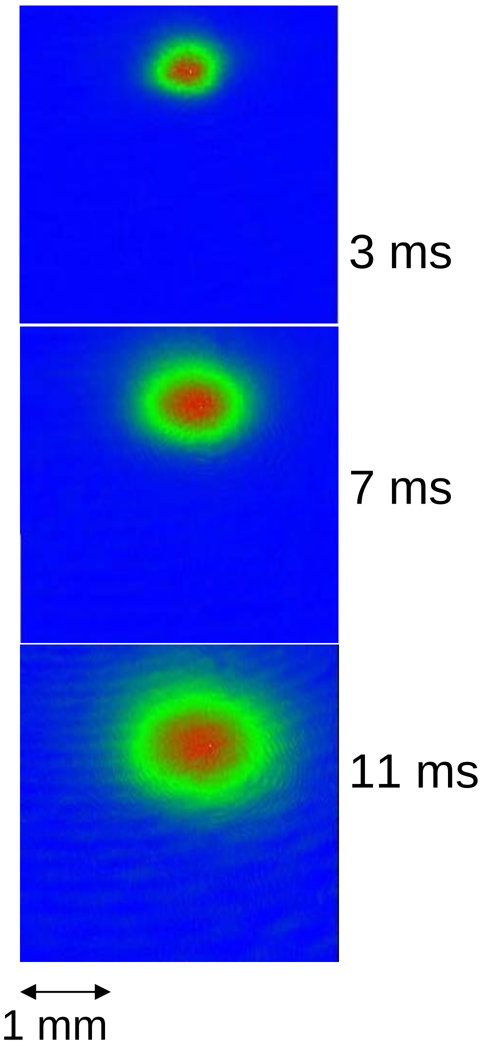
Larger number of cold atoms,
colder atom temperature
and higher atom density
implies
lower molecule temperature
and shorter thermalization time.

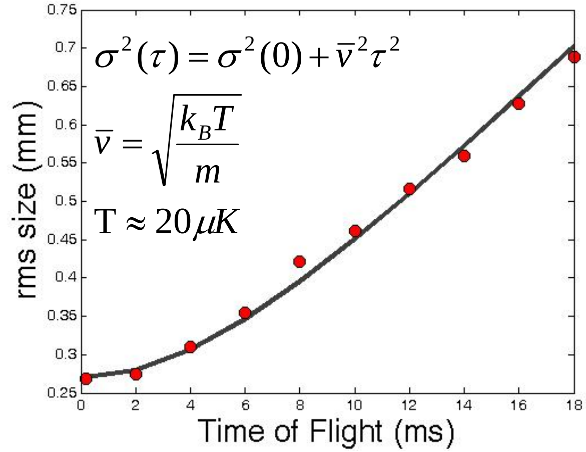
A Cesium Magneto-Optical Trap





Time of flight measurement
for temperature determination





Summary

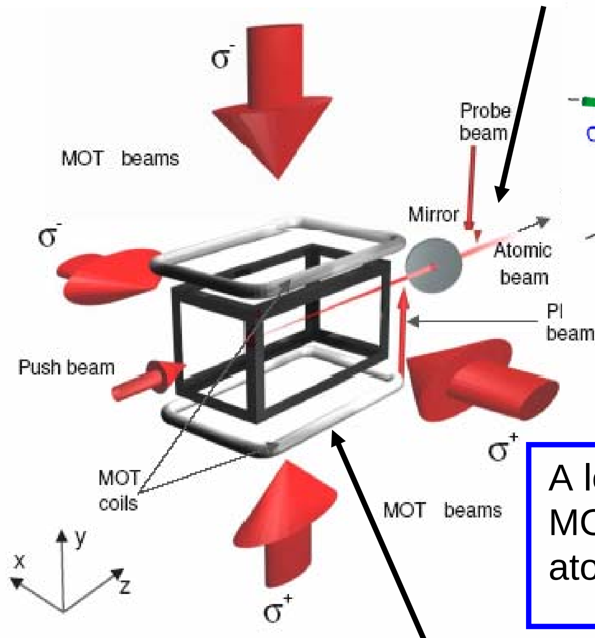
1. A maximum number of atom of ~4×10^8 and a minimum temperature of 20 μK has been achieved at pressure~5×10-9 torr
2. To get even larger number of cold atom but keep at better pressure, we will go for a cesium MOT with an atomic beam based on 2D MOT setup.
3. To get even colder temperature, the stray field will be careful compensated by microwave spectroscopy.

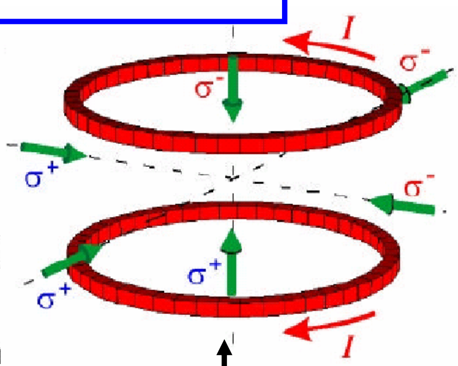
A Large Number Cs MOT

Summary

1. A slow atomic beam based on a 2-dimensional MOT setup can produce beam flux ~2×10^{10} /s with a mean velocity ~ 15m/s, a velocity width ~4 m/s and a small divergence of ~30 mrad. This allow ultrafast loading of atoms larger than 10^{10} in less than 1s.
2. The differential pumping tube allows trapping large number of atoms but still enjoy ultrahigh vacuum ~ 10^{-11} torr.
3. One can easily overlap the MOT with the open cavity microwave trap. This will allow sympathetic cooling of molecules in the microwave trap.

A differential pumping hole and tube allows maintaining ultrahigh vacuum in the 3-D MOT.





A low power 3-dimensional MOT can easily trap all the atoms in the atomic beam

2-dimensional MOT as a slow atomic beam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