COLD MOLECULE AND PHOTOASSOCIATION

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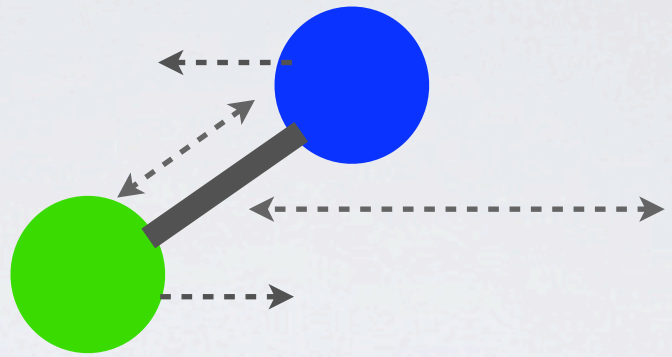
WHAT IS COLD MOLECULE?



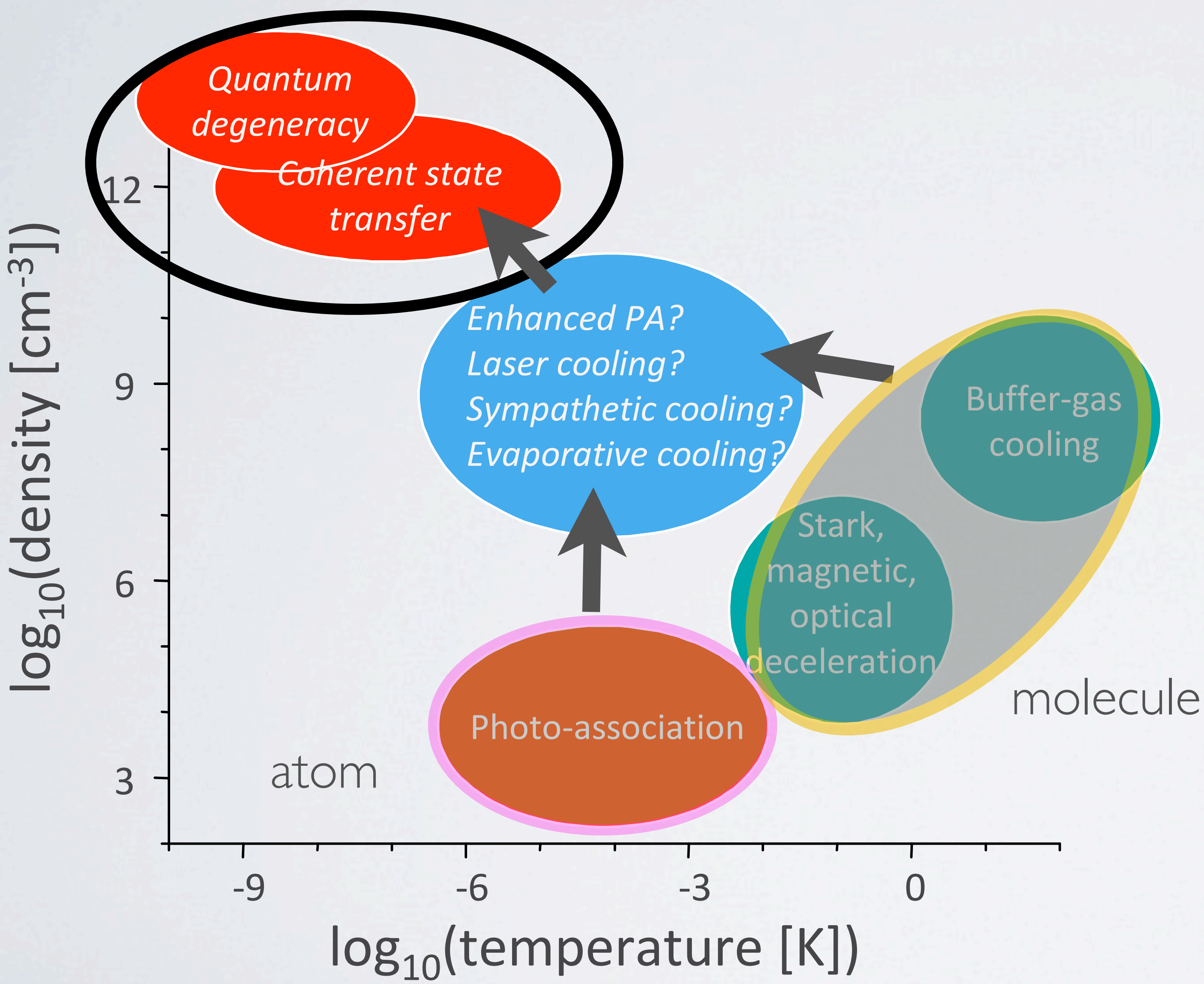
- A neutral bound system with more than one atom has a very low kinetic energy (translational, vibrational, rotational)
- K_2, KRb, Rb_2,Cs_2....

New problems in molecular system

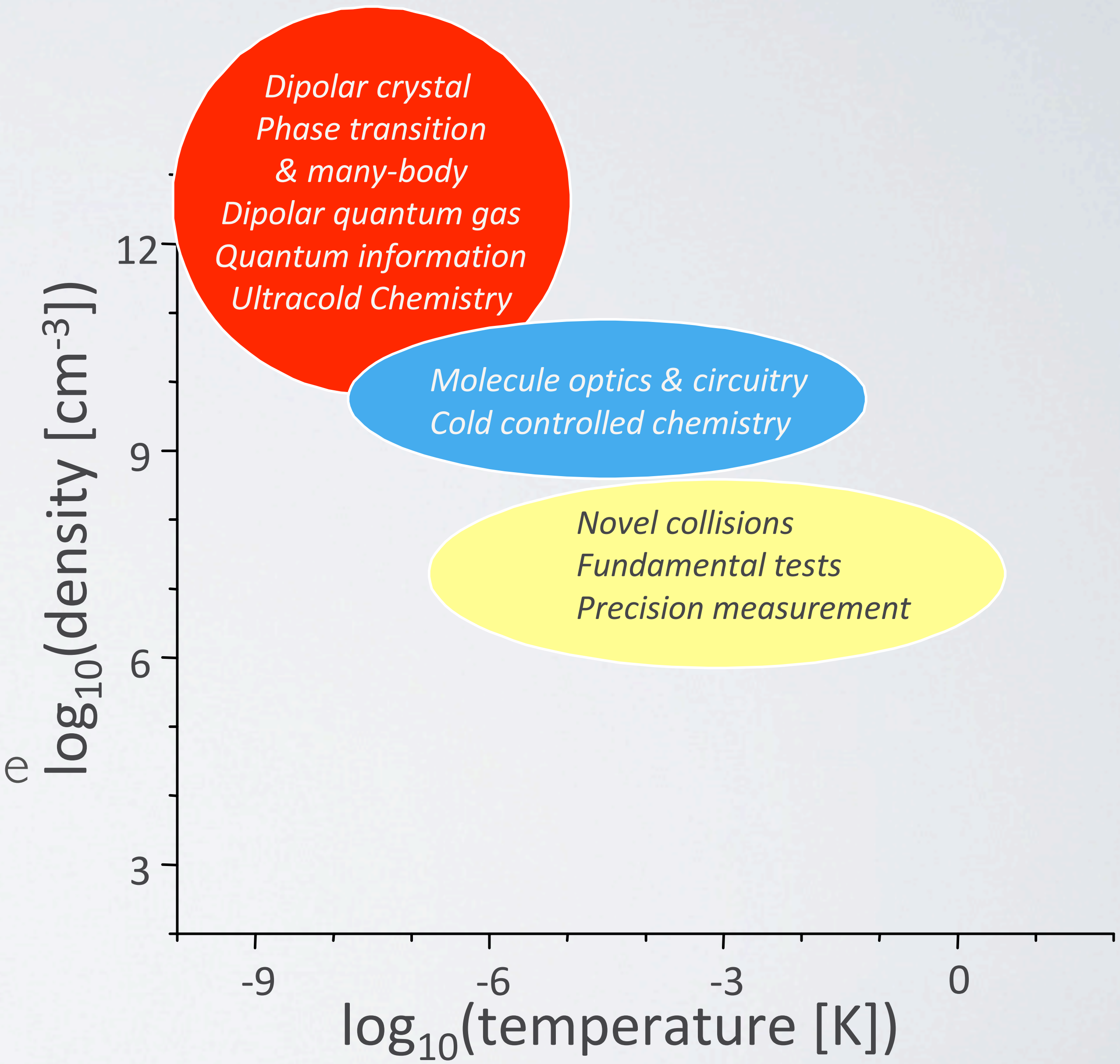
WHY COLD MOLECULE?

- Fundamental research: fundamental constant, EDM, PNC
- New era of chemistry: superchemistry
- Quantum simulator for solid state physics
- Quantum Computer.

TEMPERATURE, DENSITY AND COOLING



various cooling techniques



physics using cold molecule

TWO MAINSTREAMS IN COLD MOLECULE INDUSTRY

- Cool down a molecule
- Produce molecule from cold atoms

↓

Association: Perform chemistry using very cold ingredients

HEAT INCREASES INTERACTION, BUT WE ARE GOING TO COOL EVERYTHING

Heat helps chemical reaction, because:

1. higher collision rate

2. higher kinetic energy to penetrate chemical energy barrier

Then, why shall we go cold?

WHAT AND WHY "ULTRACOLD"

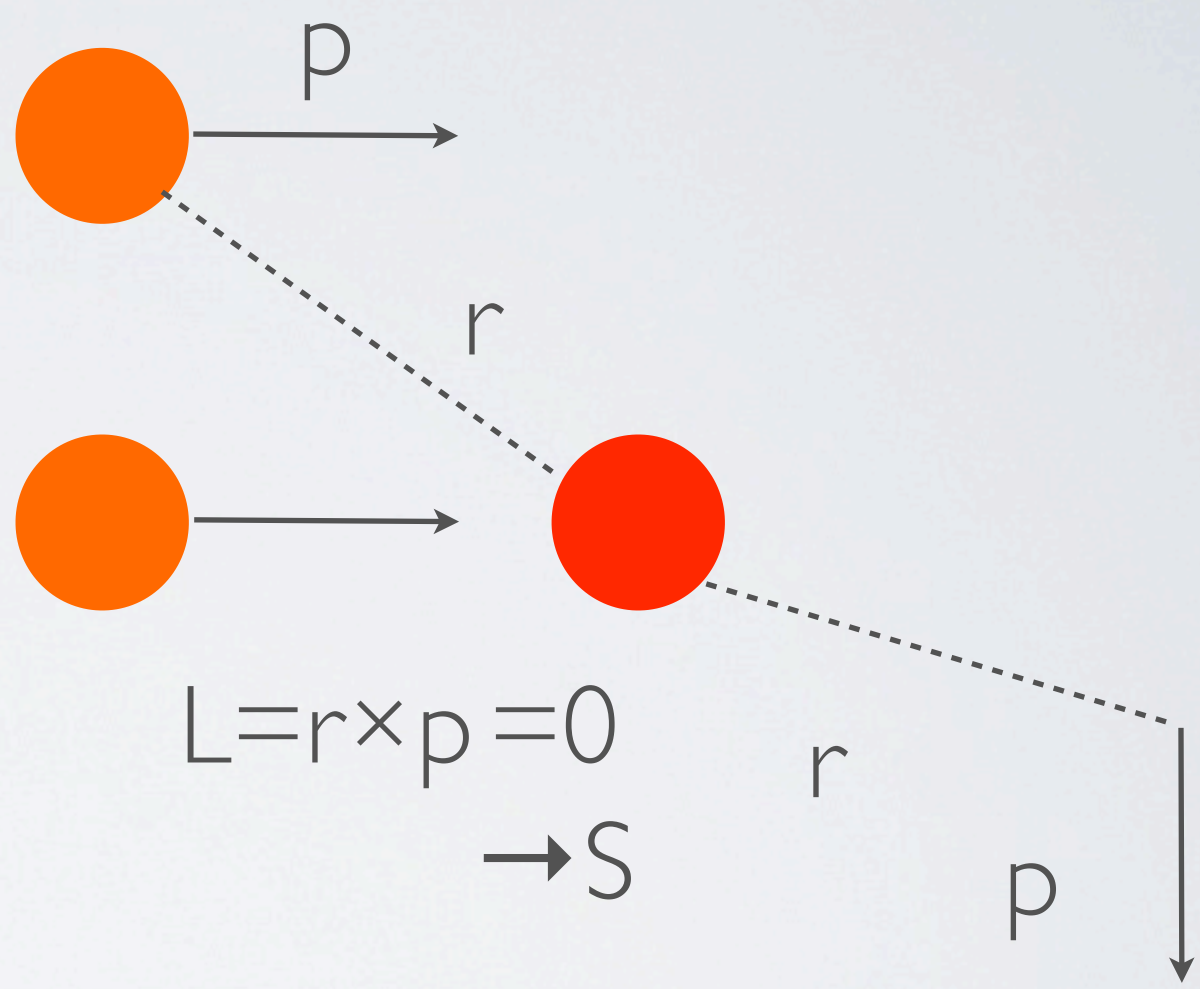
- The ingredients (atoms) must be cold to have cold products (molecules).
- "Ultracold" → S wave scattering → enhance inelastic collision and chemical reaction. (increase by 10^3) ↔ It contradicts with our experience in chemical practice.

SCATTERING

Scattering of various partial wave

The collision complex can be decomposed according to the angular momentum. s, p, d ...

During the process of the collision, the angular momentum must be conserved.

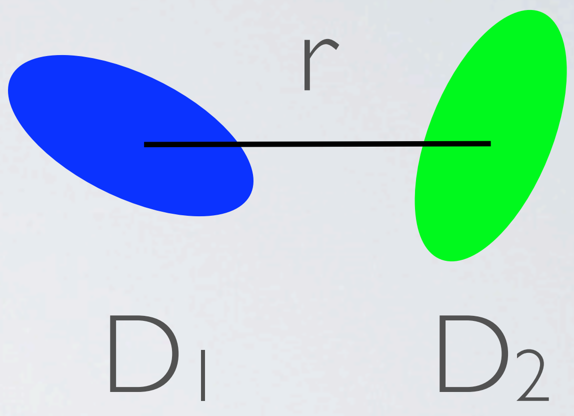


Head-to-Head collision

ULTRACOLD COLLISION

Dipole-Dipole interaction

$$V_d(\vec{r}) = \frac{\vec{D}_1 \cdot \vec{D}_2 - 3\left(\vec{D}_1 \cdot \hat{r}\right)\left(\vec{D}_2 \cdot \hat{r}\right)}{r^3}$$



Rank-2 Tensor: $\mathbf{T^{(2)}q}$

Wavefunction of the complex during collision: **|l,m>**

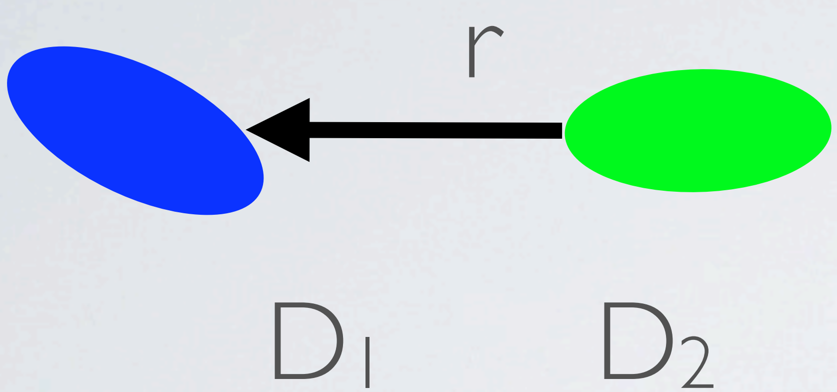
The potential is: **<l,m|T$^{(2)}$q|l,m> =0**

l=0, s-wave scattering

dipole-dipole interaction is vanished

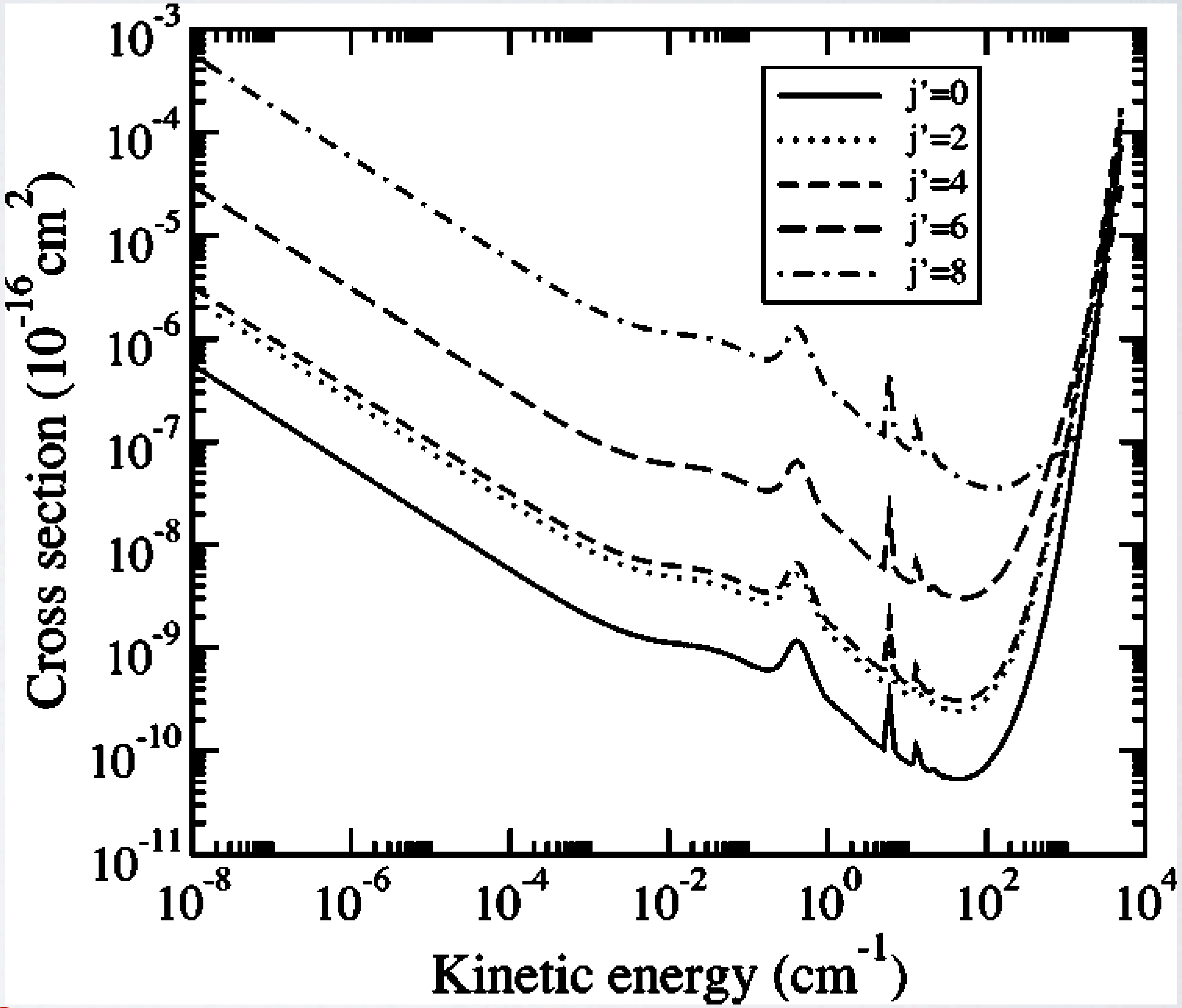
inelastic collision is enhanced

CROSS SECTION ENHANCEMENT



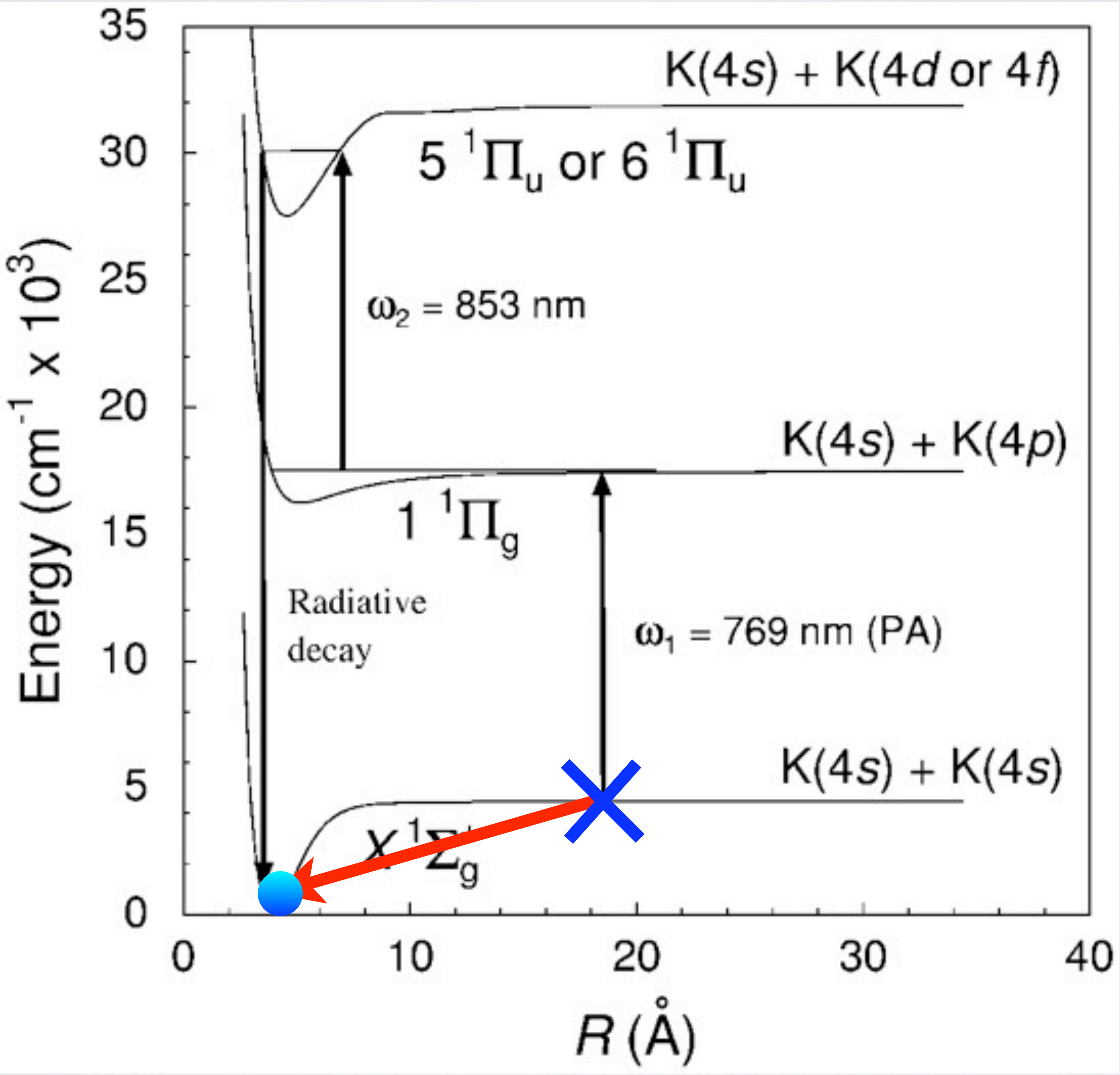
Head-to-Head collision
Averaged force is zero
No potential barrier

Furthermore, external field can be used to control the alignment, then the interaction of atoms



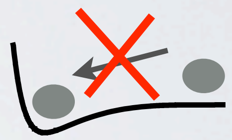
H_2 -Ar collision v.s temperature

OUR ULTIMATE GOAL : TO THE GROUND STATE

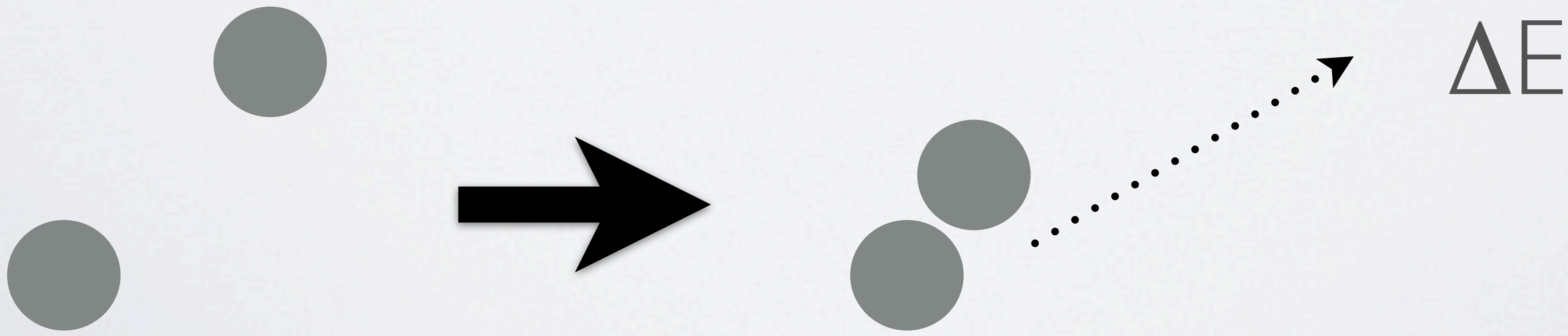


FROM COLD ATOMS TO COLD MOLECULES

- Energy conservation: How to remove internal energy?
- Vibration of neutral particles can not emit photons→ no radiative decay!



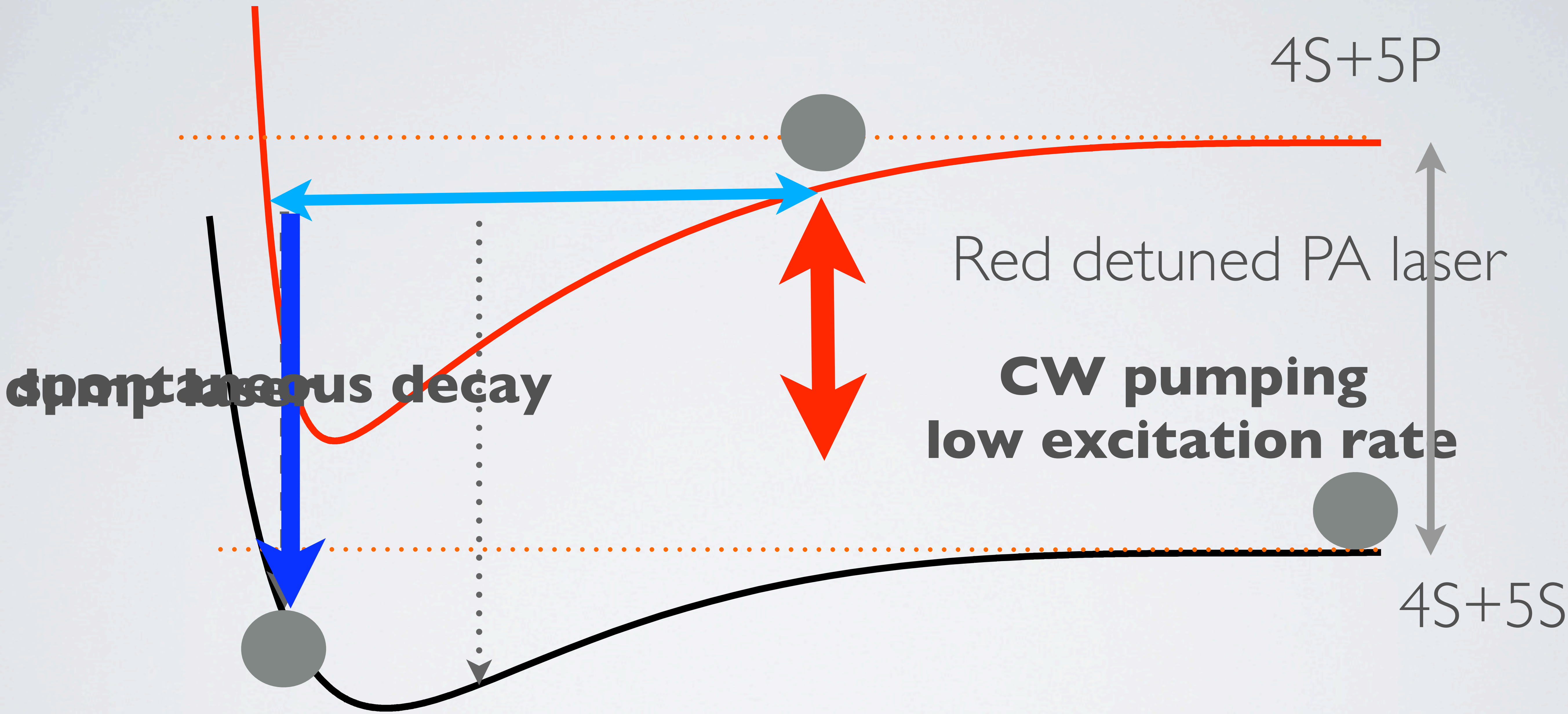
- The third party is needed: photon or particle(three-body collision)



AVAILABLE APPROACHES

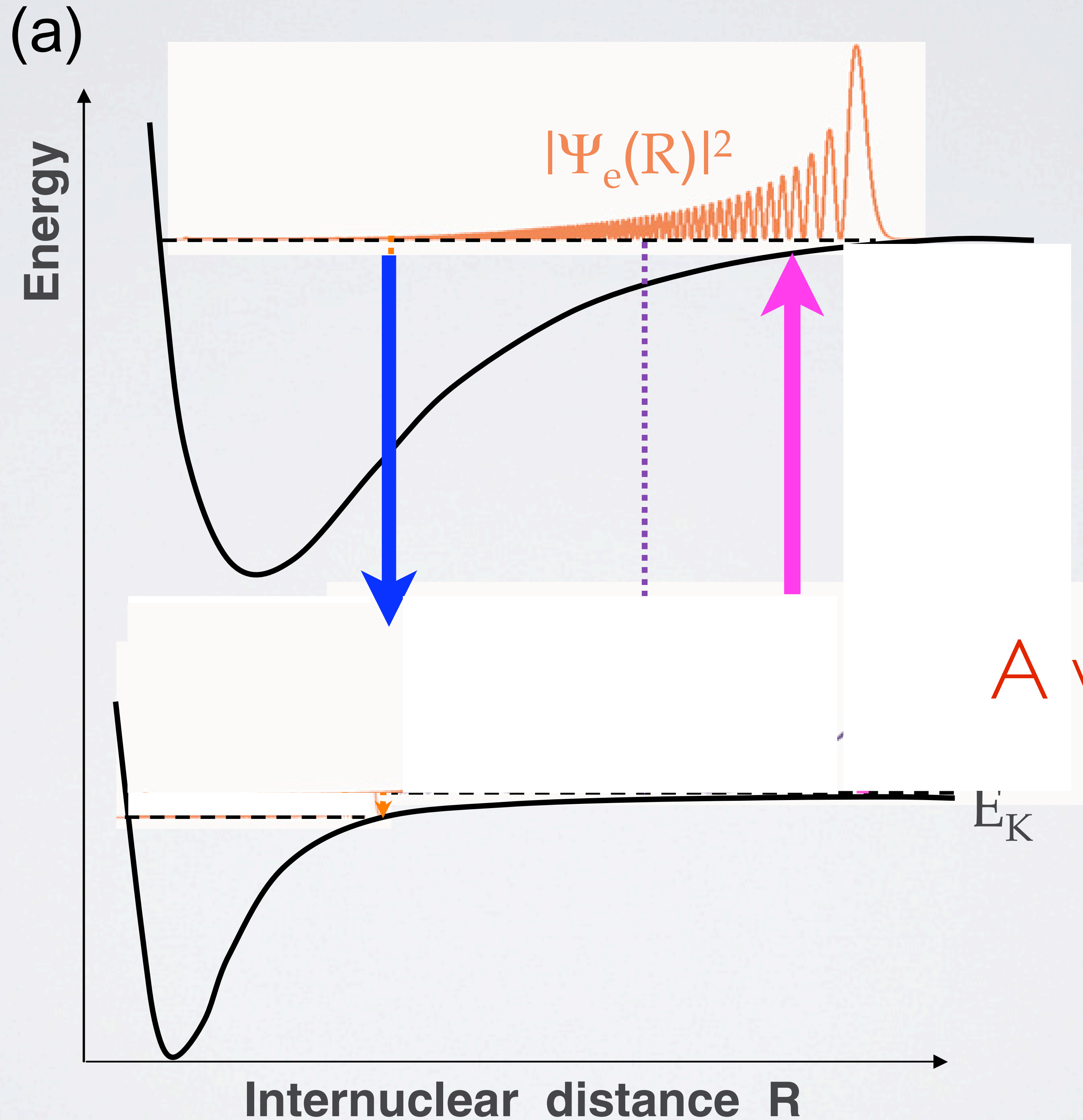
- Feshbach resonance : tuning interaction by external field, transfer kinetic energy to internal hyperfine(Adiabatic)
- Photoassociation : using photons to take out energy.(Adiabatic or Not)

PHOTOASSOCIATION



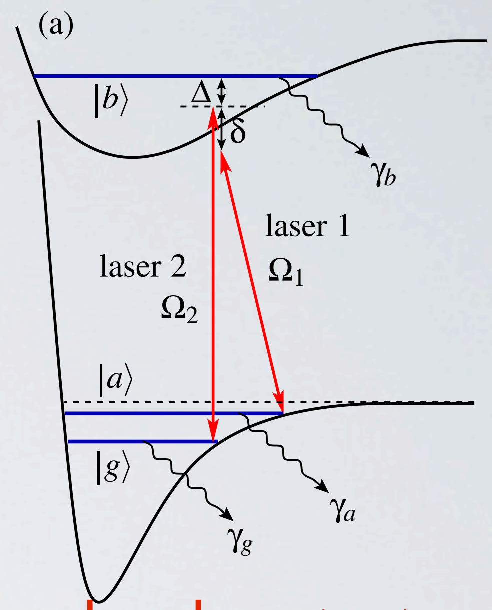
- Low rate, complicate laser system

A WEAKLY BOUND SYSTEM CAN INCREASE PA RATE



A weakly bound

STIMULATED RAMAN ADIABATIC PASSAGE: **STIRAP**



$|A\rangle=(a_1\,|1\rangle+a_2|3\rangle)e^{i\alpha t}$:coupled by laser 1

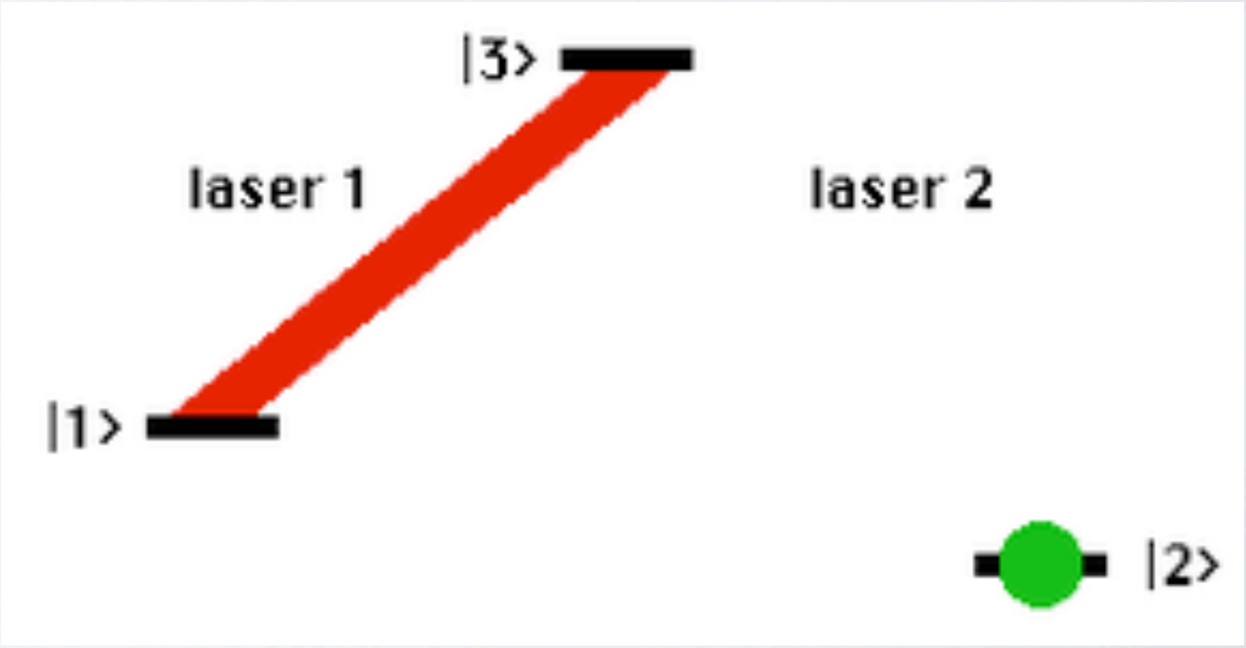
$|B\rangle=(b_1\,|2\rangle+b_2|3\rangle)e^{i\beta t}$:coupled by laser 2

If laser 1,2 are **coherent**,

then $|1\rangle$ and $|2\rangle$ are coupled into a coherent dark state

$|\text{coherent dark state}\rangle= (r_1\,|1\rangle+r_2|2\rangle)e^{i\gamma t}$

Population can be transfered between $|1\rangle$ and $|2\rangle$ with no access to $|3\rangle$, therefore no spontaneous decay

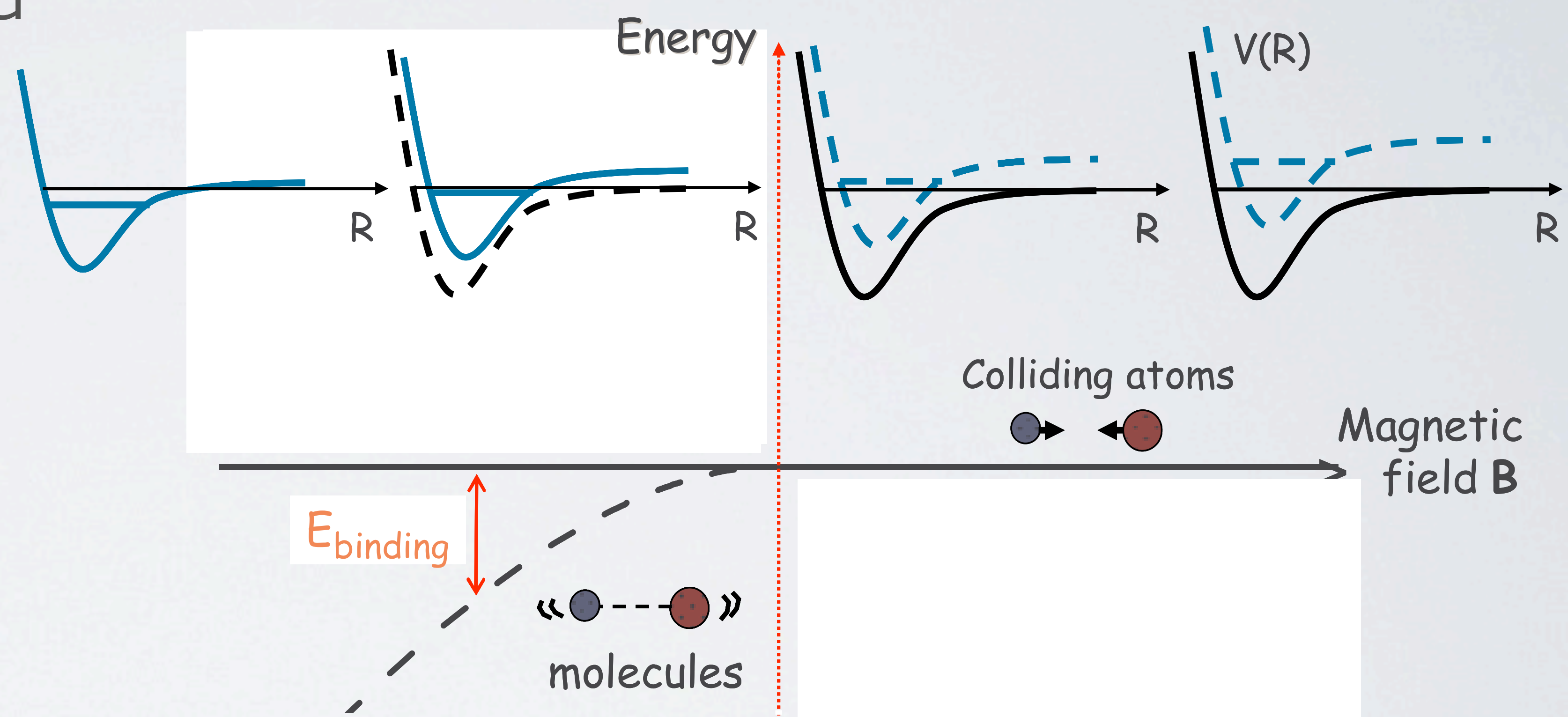


FESHBACH RESONANCE

Apply external field to shift energy level and tune the interaction between atoms

$K+U_{lowHF} \rightarrow U_{highHF}$

Free → Bound

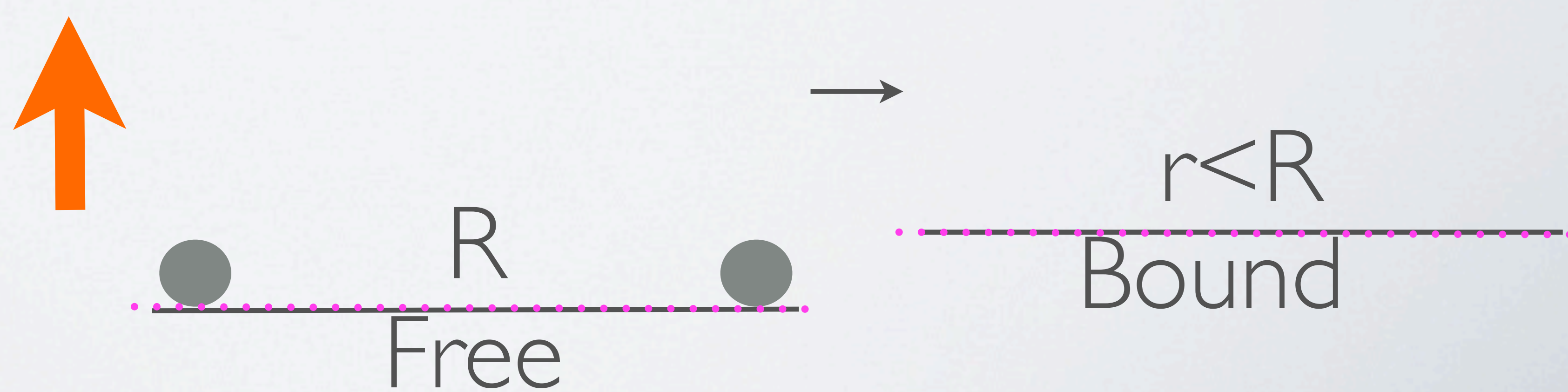


The external fields can be:

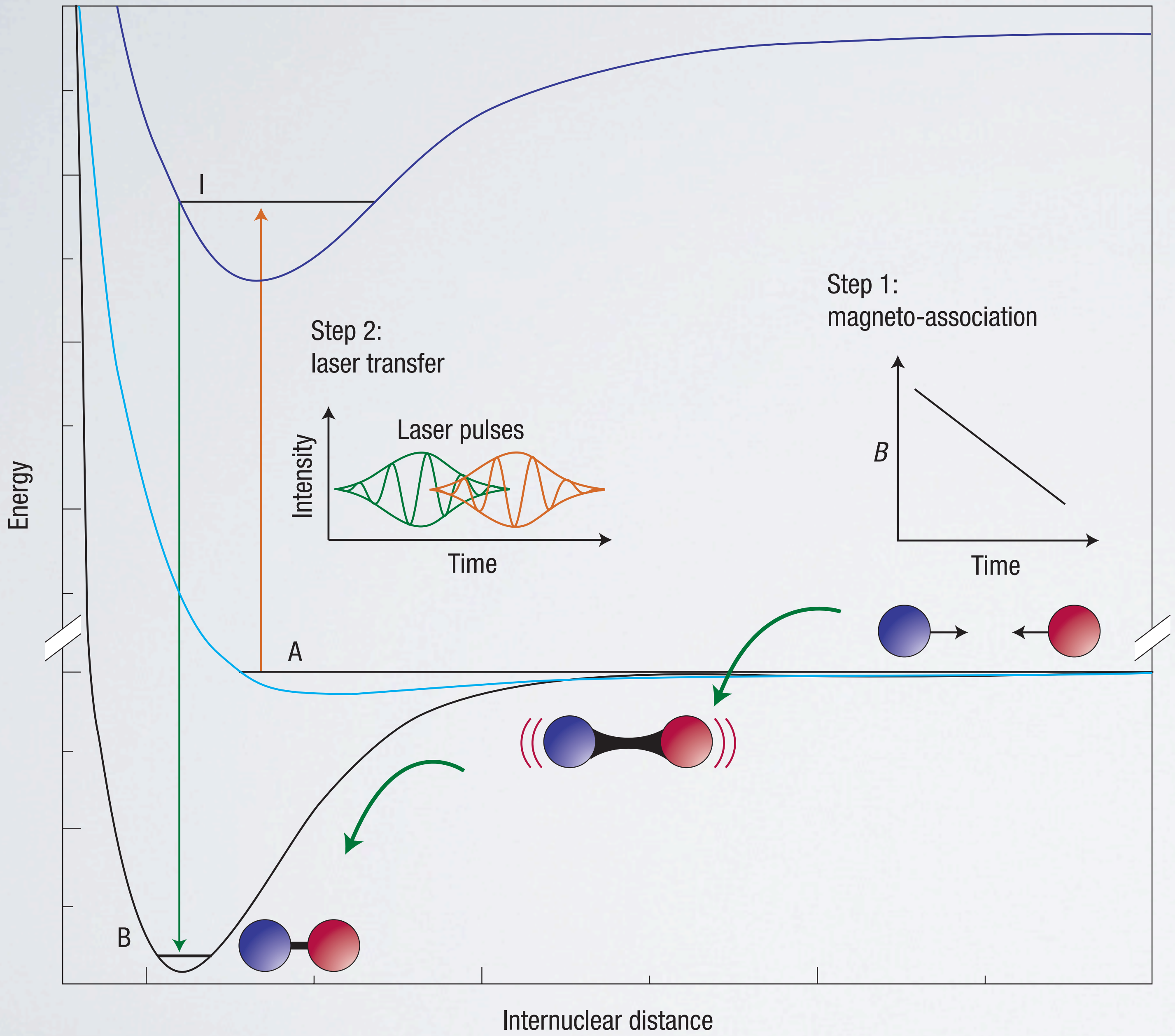
magnetic,

optical,

electrical



THE BEST SOLUTION SO FAR



- Feshbach resonance+STRAP (stimulated Raman adiabatic passage)
- Form a very large (R, and high ν) molecule, then remove vibrational energy by stimulation emission.
- CsRb and KRb have been successfully produced (Ni and et al, JILA,Science, 2008. Sage and et al, Yale, PRL, 2005)

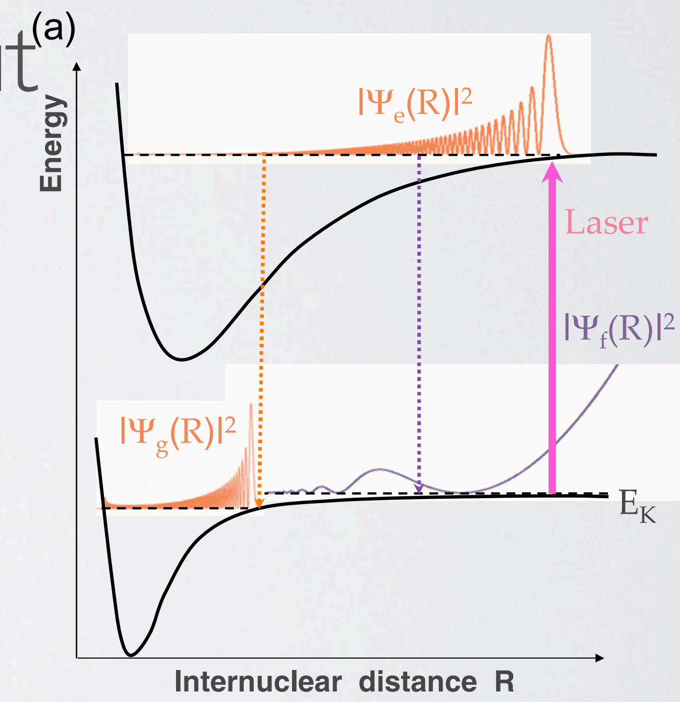
Very classical, and low rate……

A PROPOSAL TO INCREASE PA RATE

- Can we drive population in all levels using one laser?

A broad band laser!

- Can we pump up population only, without stimulating it down?



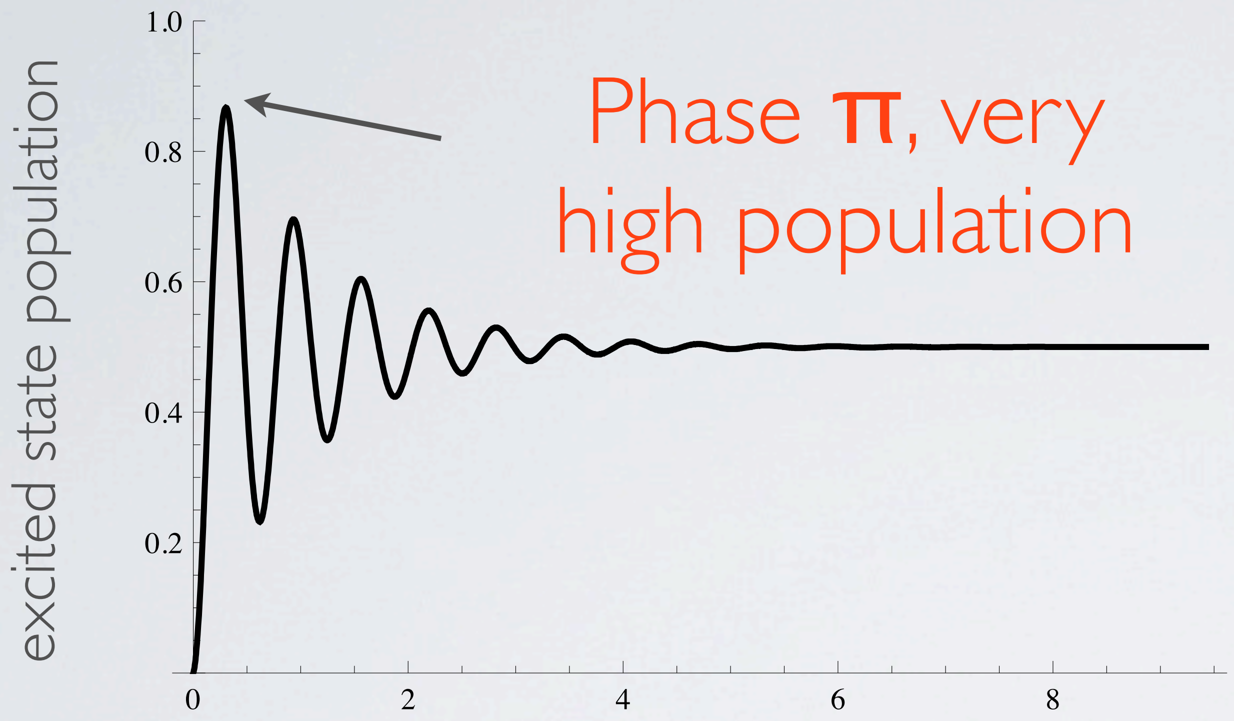
A pulse laser!

⇒*The femtosecond laser*

BANDWIDTH OF PUMP LASER

- The typical linewidth of molecular absorption without overlap with neighboring band → $\Delta\nu = 10^2 - 10^3\ cm^{-1}$
- By uncertainty principle (Fourier transform-limited), τ=femtosecond

MAXIMUM INVERSION USING Π

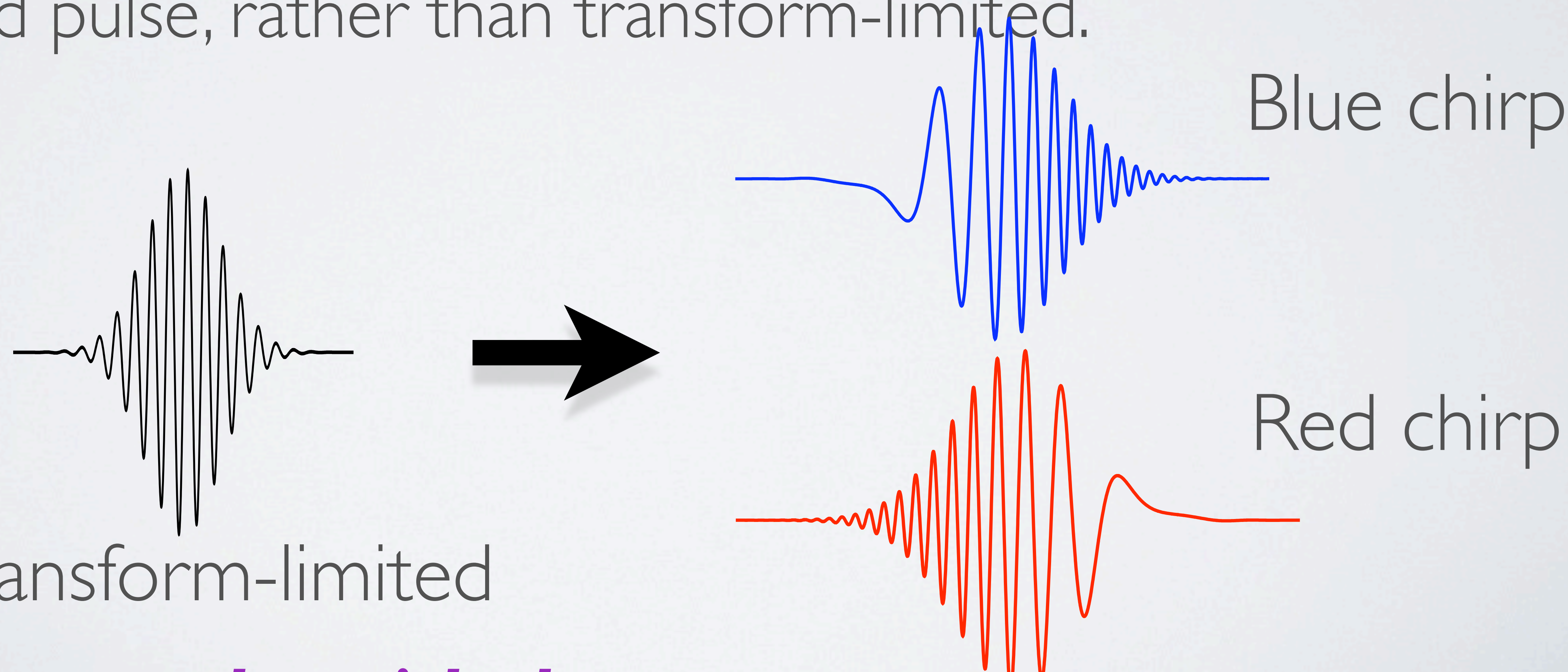


Rabi Oscillation

- Short pulse to perform **π** population transfer.
- **$\tau E_0 \mu / \hbar = \pi$**
  - Problems: very large $E_0 \sim 10^{12}$-10^{14} W/cm^2. Many subtle effects should be taken into account, such as multi-photon transition

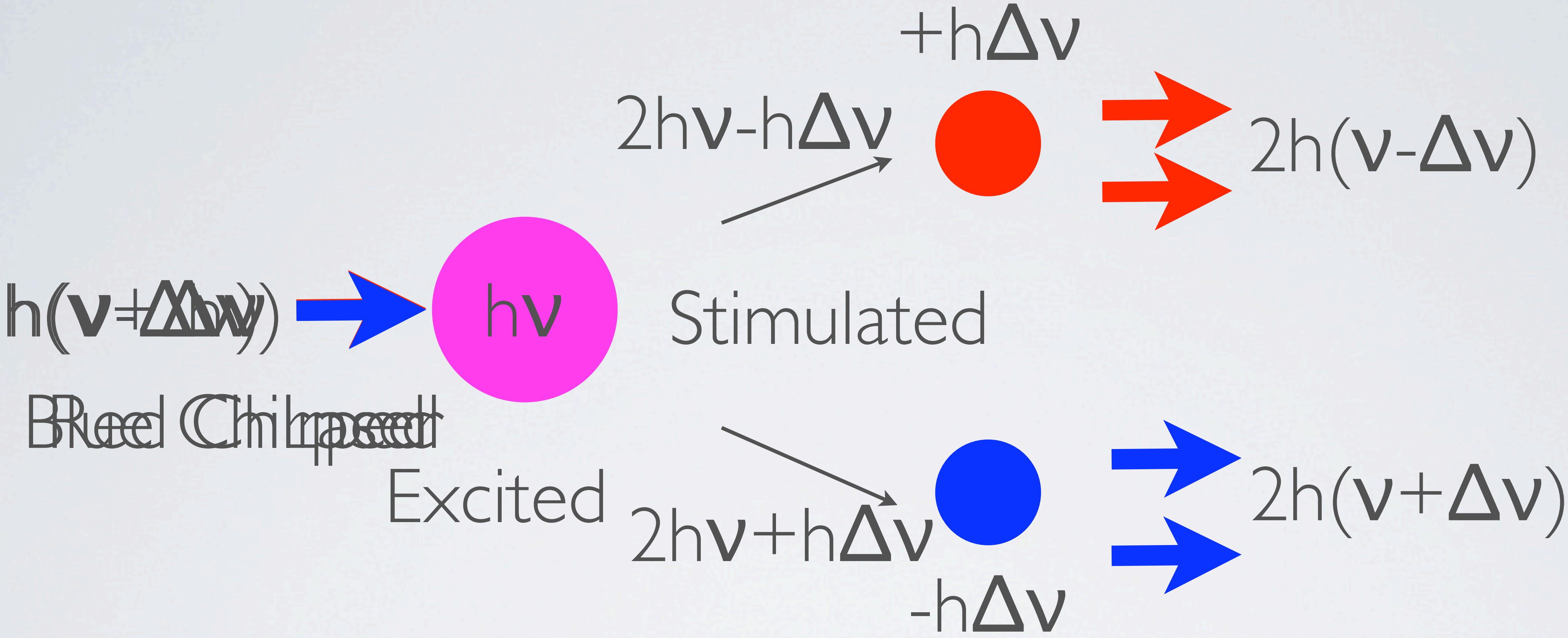
CHIRPED FEMTOSECOND LASER

- $\tau E_0 \mu/\hbar = \pi$, a longer τ can lower required E_0
- To maintain the same $\Delta\nu$ with a long τ ($>1/\Delta\nu$), we need a chirped pulse, rather than transform-limited.



Longer pulse with the same power spectrum

BLUE OR RED?



- ***The Blue Chirped pulse can remove energy** (proposed by J. Cao et al, PRL 1998)*
- just like Raman cooling

CHIRP EXPERIMENT

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Coherent Control of Ultracold Molecule Dynamics in a Magneto-Optical Trap by Use of Chirped Femtosecond Laser Pulses

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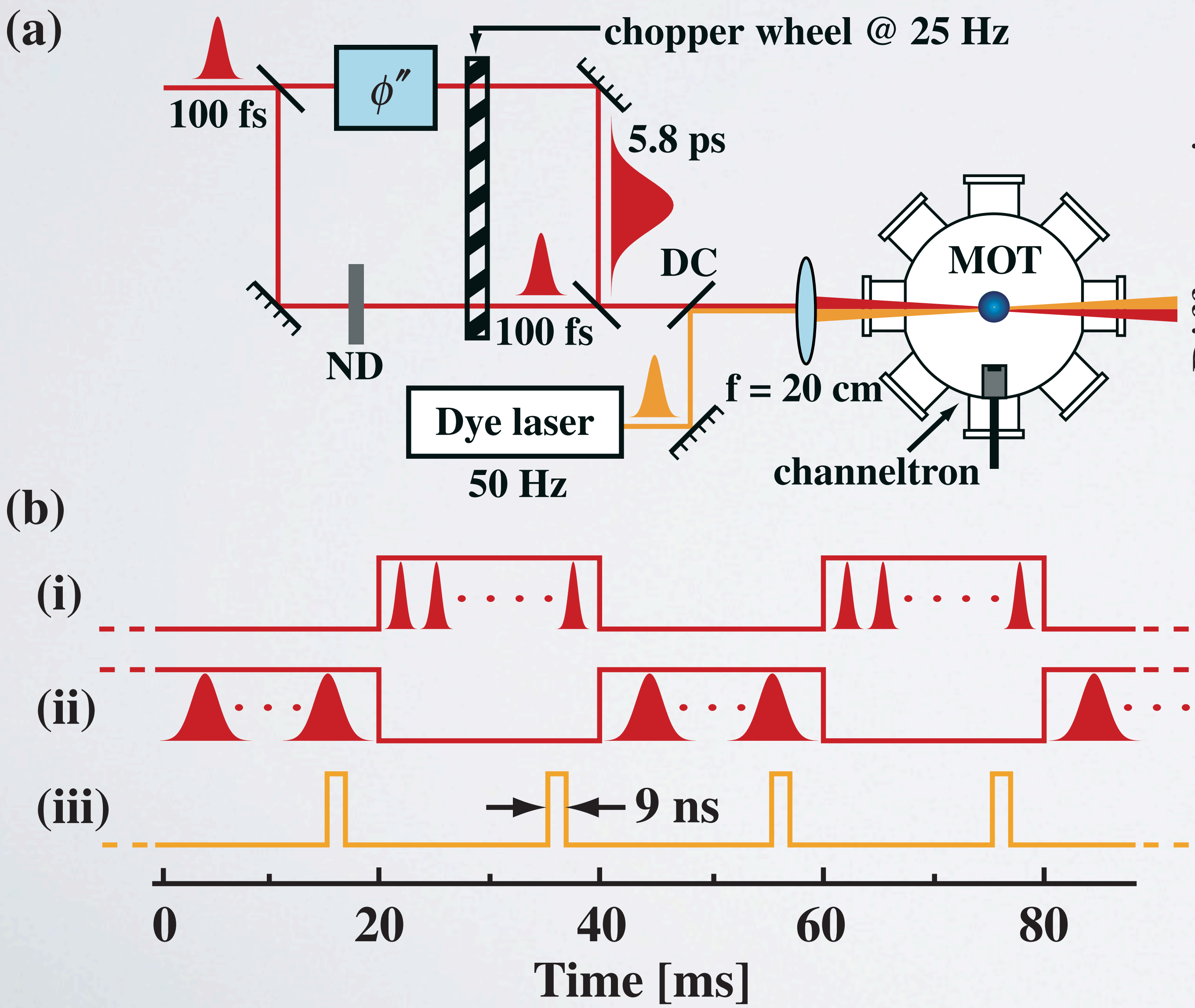
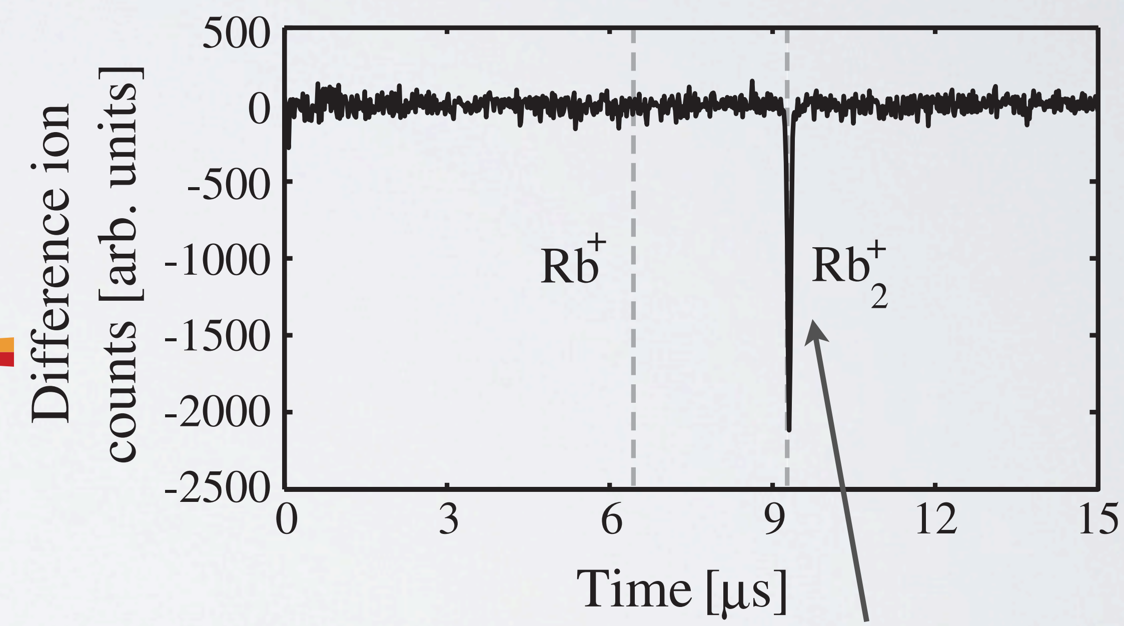
dispersive glass





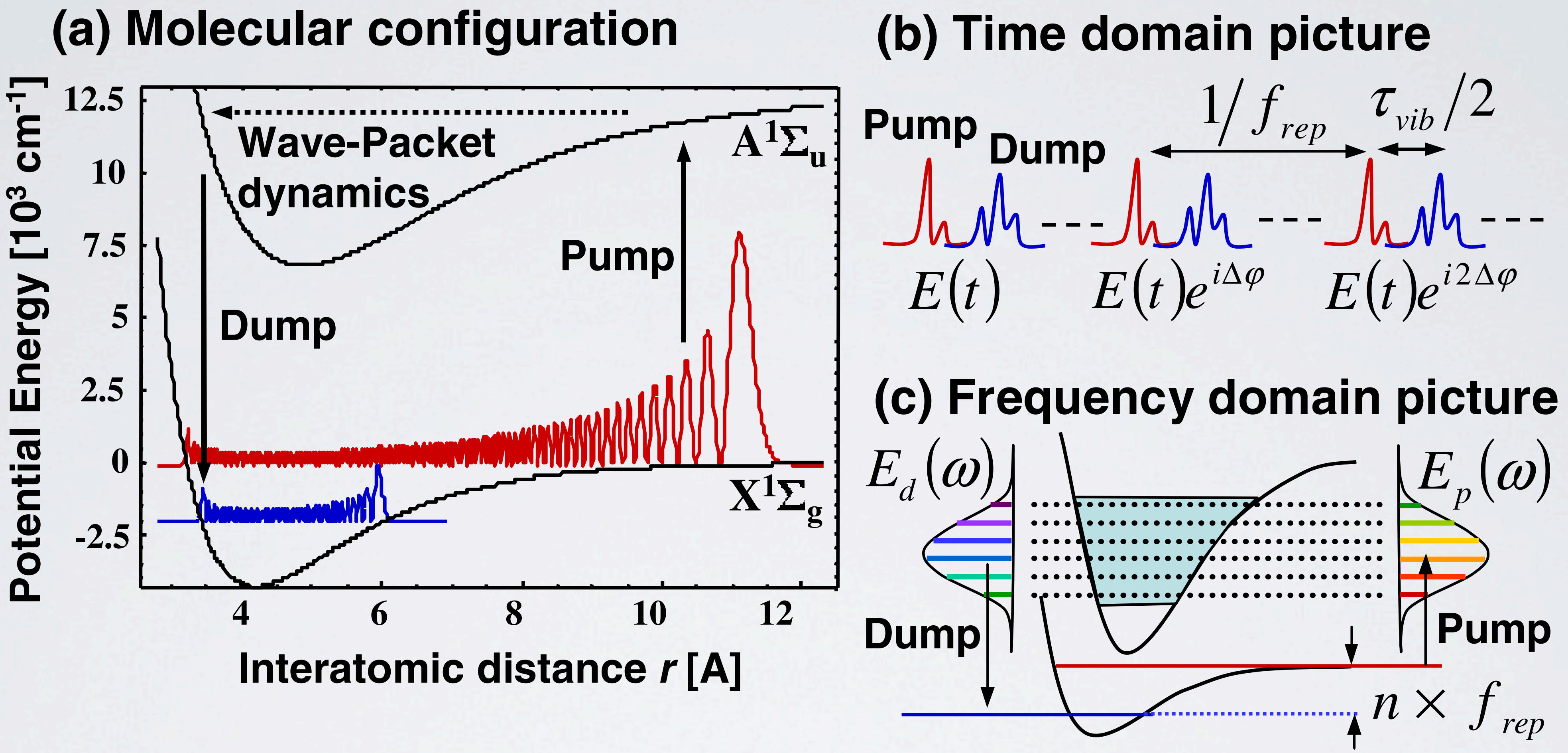
The rate decreased !!

Very sad!!

(fs laser, not comb, no stabilization)

COMB LASER

CONTROL PHASE OF WAVE PACKET USING COHERENCE BETWEEN PULSES



- The phase of the final products from each pulse is fixed, due to the coherent nature of comb laser.

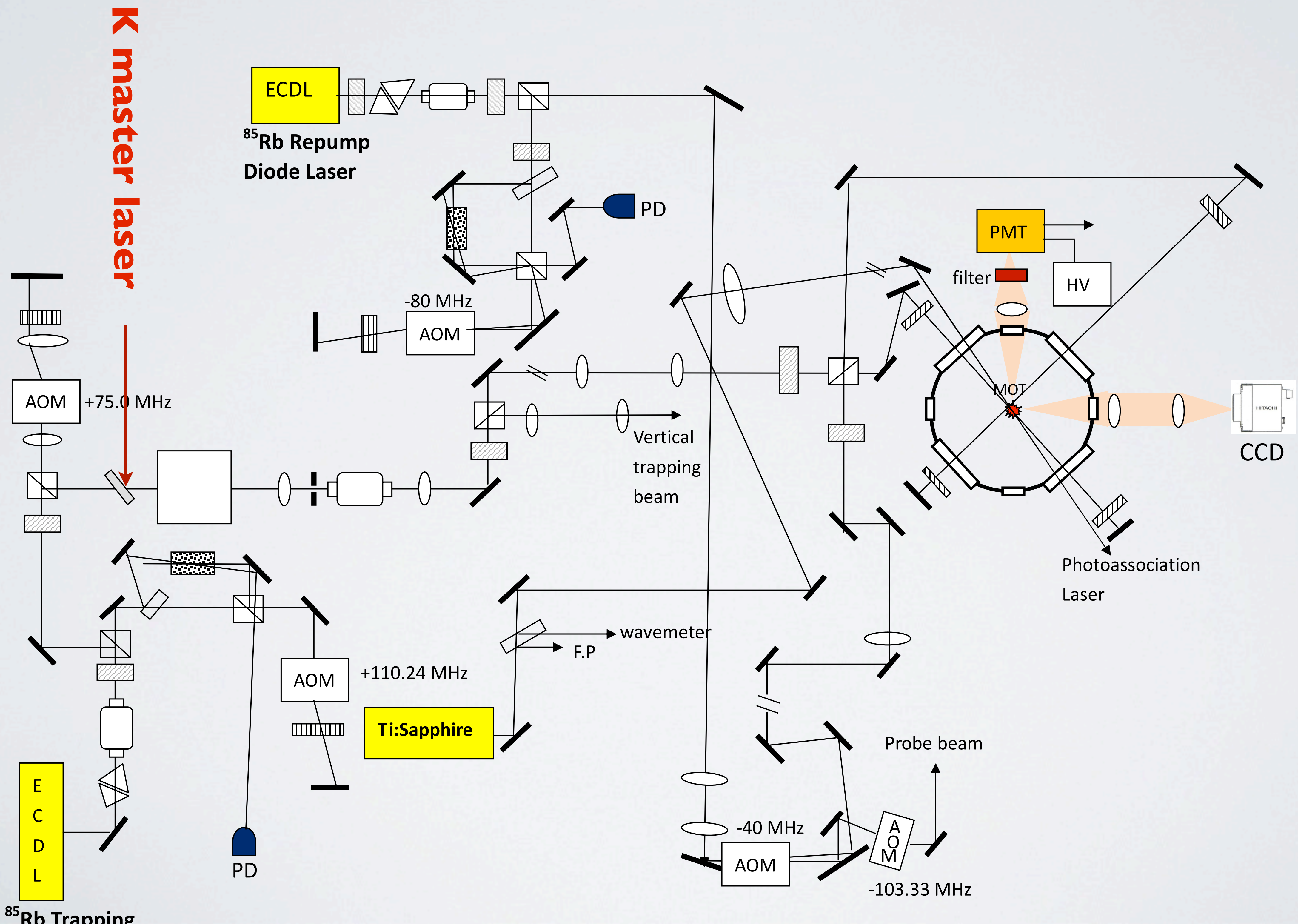
- $|\Phi>_f = e^{i\theta}|\Phi> + e^{i2\theta}|\Phi> + e^{i3\theta}|\Phi>$.... interference of grating

Proposed by Pe'er and et al, JILA, PRL, 2007

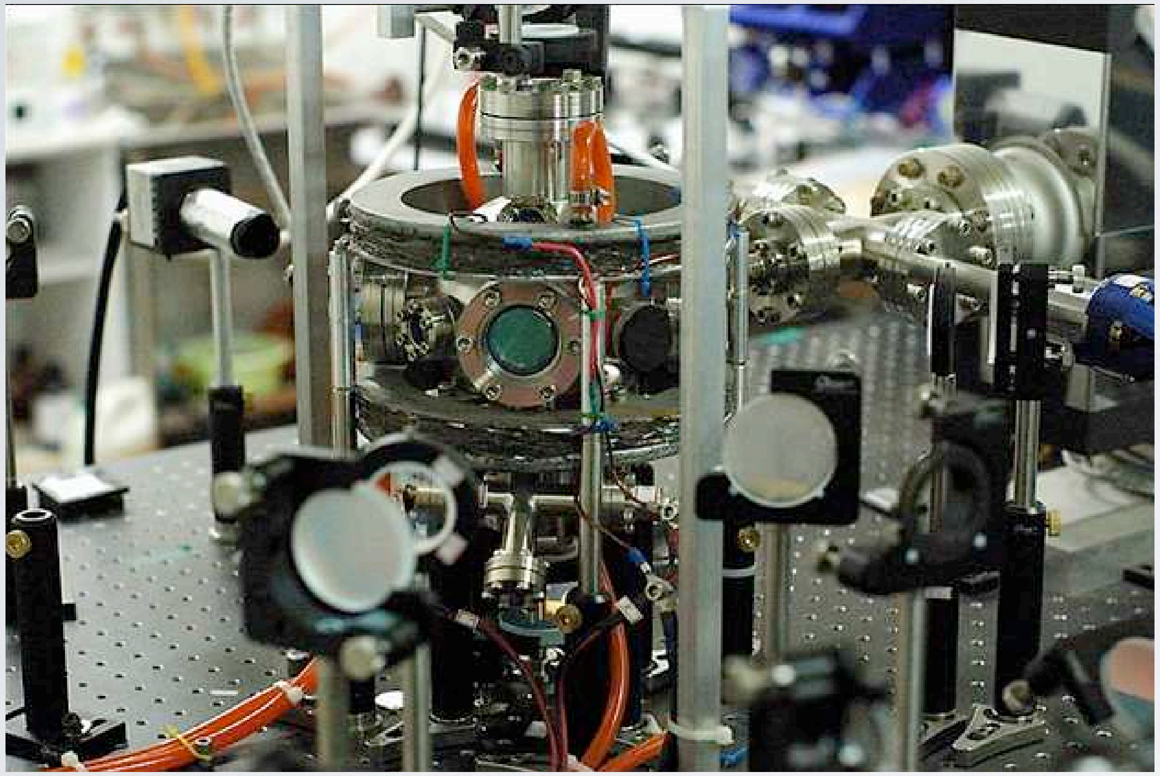
OUR APPROACH

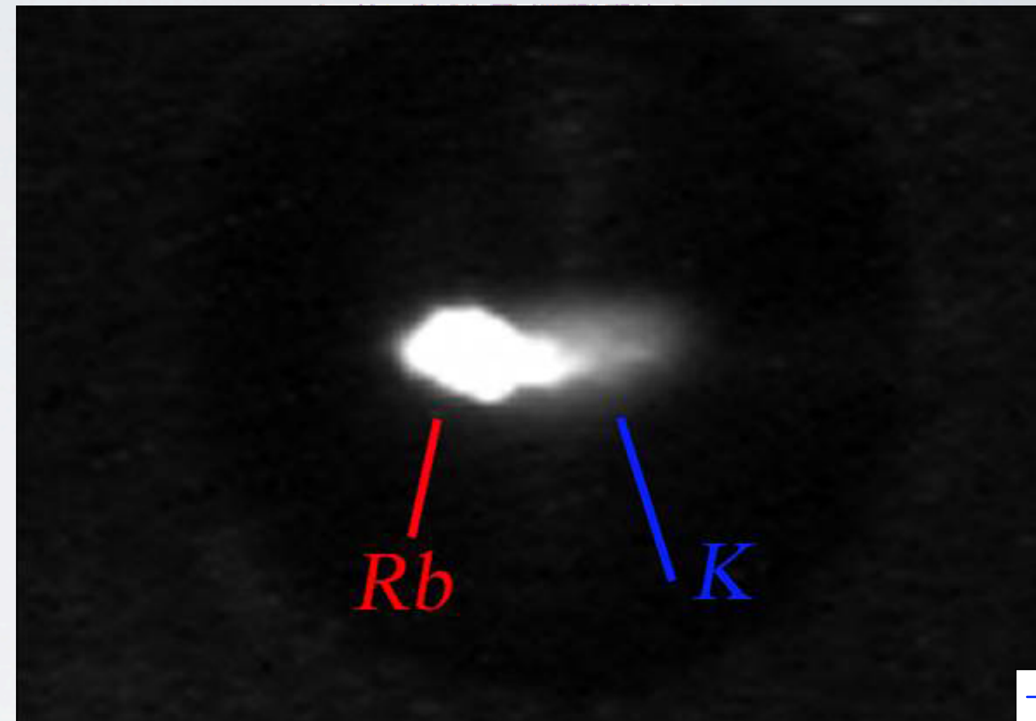
- KRb mixture
- Polarization Gradient cooling
- Dipole trap
- FechBach resonance combination
- Photo-association (pulsed coherent Raman)

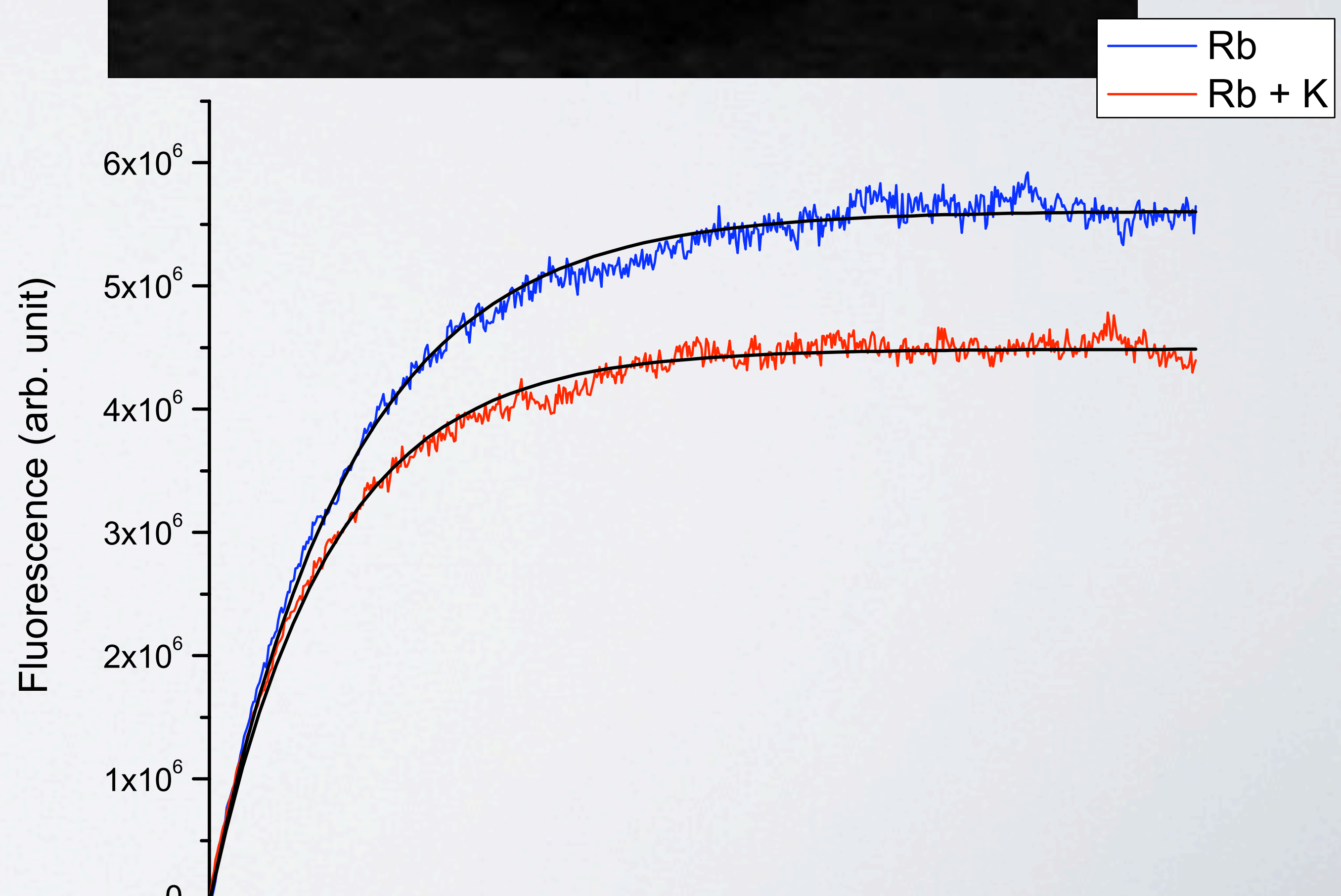
LASER SYSTEM FOR DOUBLE SPECIES COOLING SYSTEM



K AND RB MIXTURE







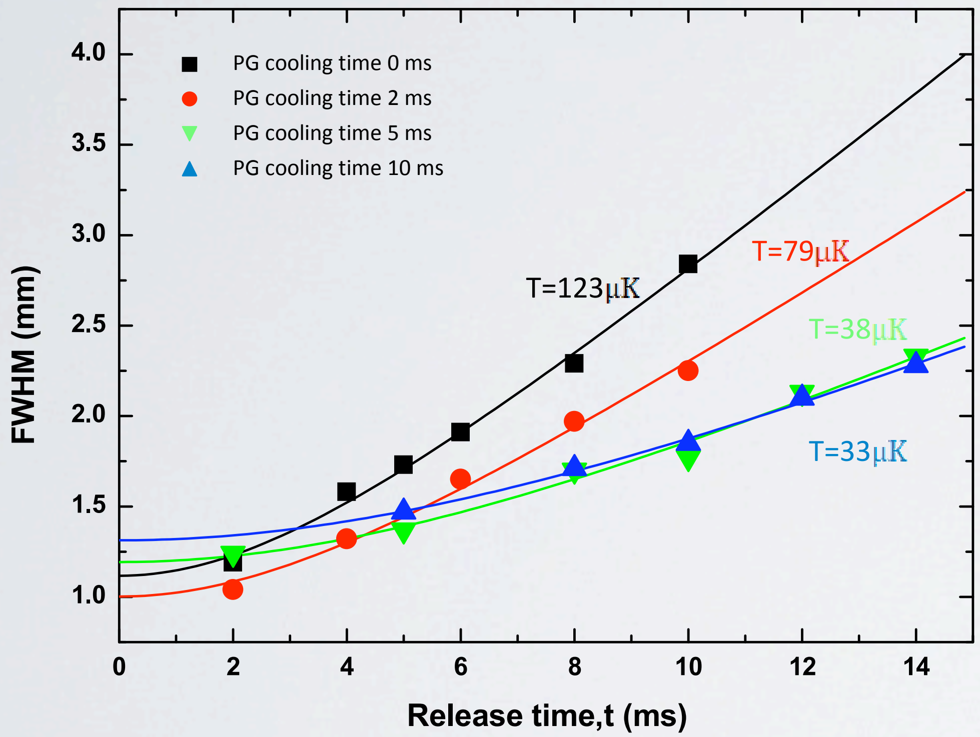
$$\frac{dN_K}{dt} = L - \gamma N_K - \beta n_K N_K - \boxed{\beta' n_{Rb}} N_K$$

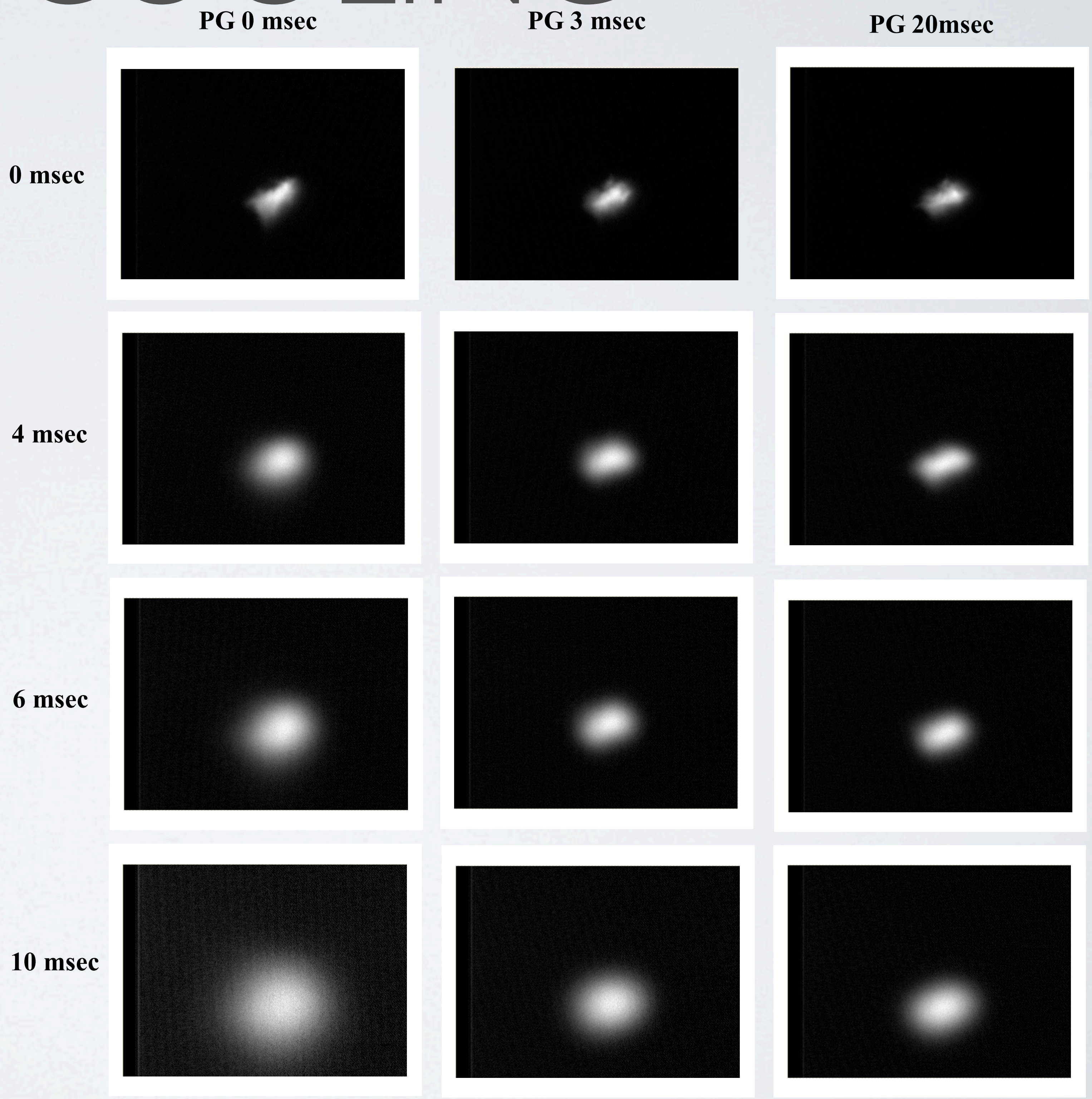
$$N_K = N_0\{1 - exp[-(\gamma + \beta n_K + \boxed{\beta' n_{Rb}})t]\}$$

$$\downarrow$$

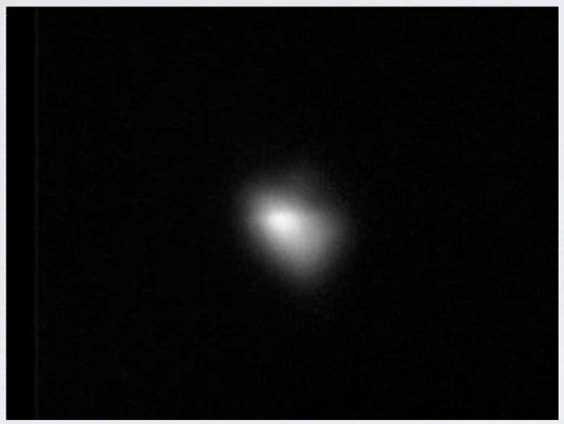
$$N_0 = L/(\gamma + \boxed{\beta n_{Rb}} + \beta' n_K)$$

A LITTLE BIT COLDER USING PG COOLING

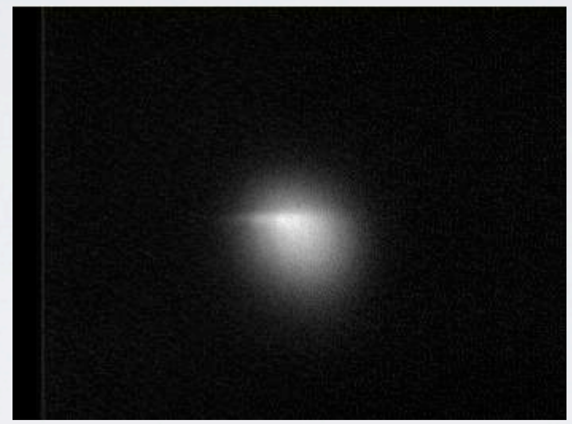




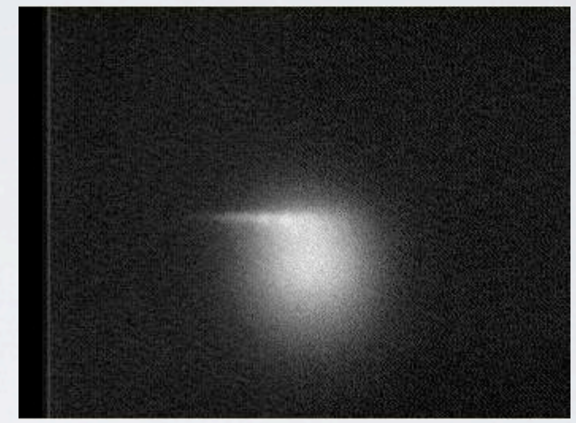
DIPOLE TRAP FOR ULTRACOLD ATOM



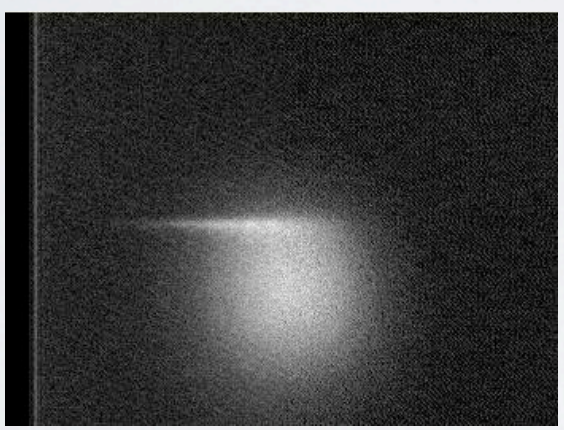
release time 0 ms



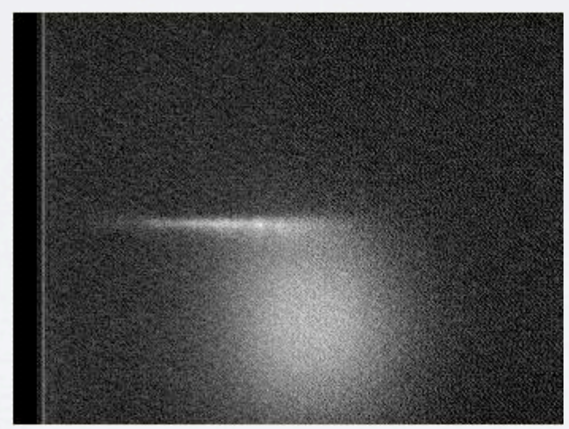
release time 5 ms



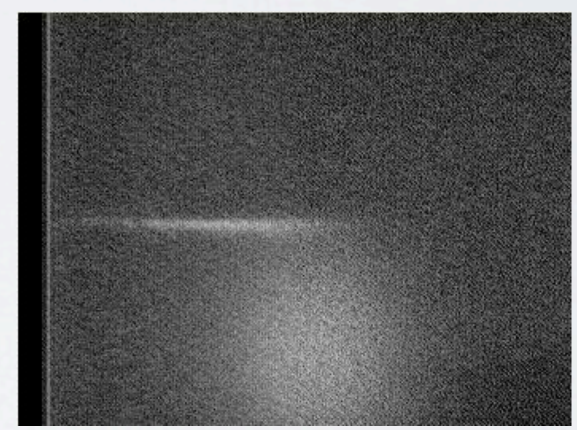
release time 10 ms



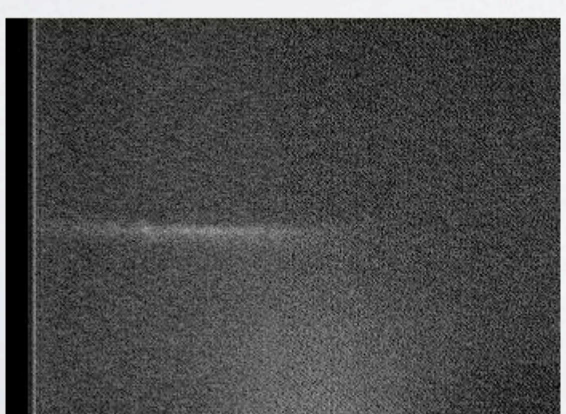
release time 15 ms



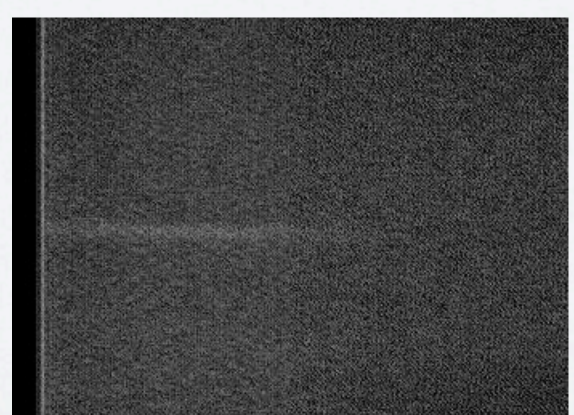
release time 20 ms



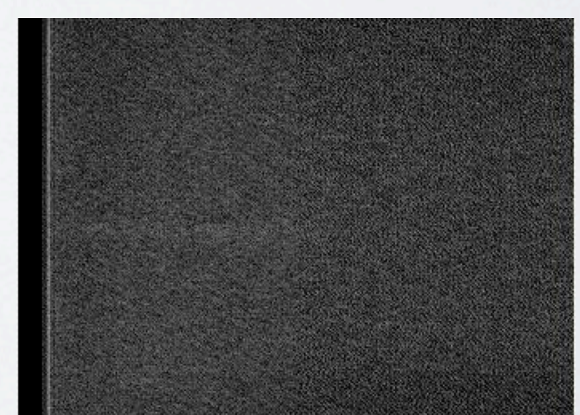
release time 25 ms



release time 30 ms



release time 40 ms



release time 50 ms

CONCLUSIONS

- JILA experiment (KRb) is very successful, but the laser system of two cw lasers, one comb laser, and one ionization laser is very complicate.
- Direct comb driving PA is attractive and promising. Although, the oxford experiment discouraged. How to optimize pulse shape and spectrum is still unclear. There is a long way to go.