Λ-enhanced gray molasses cooling of ^7Li

Séminaire du groupe atomes froids
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Introduction

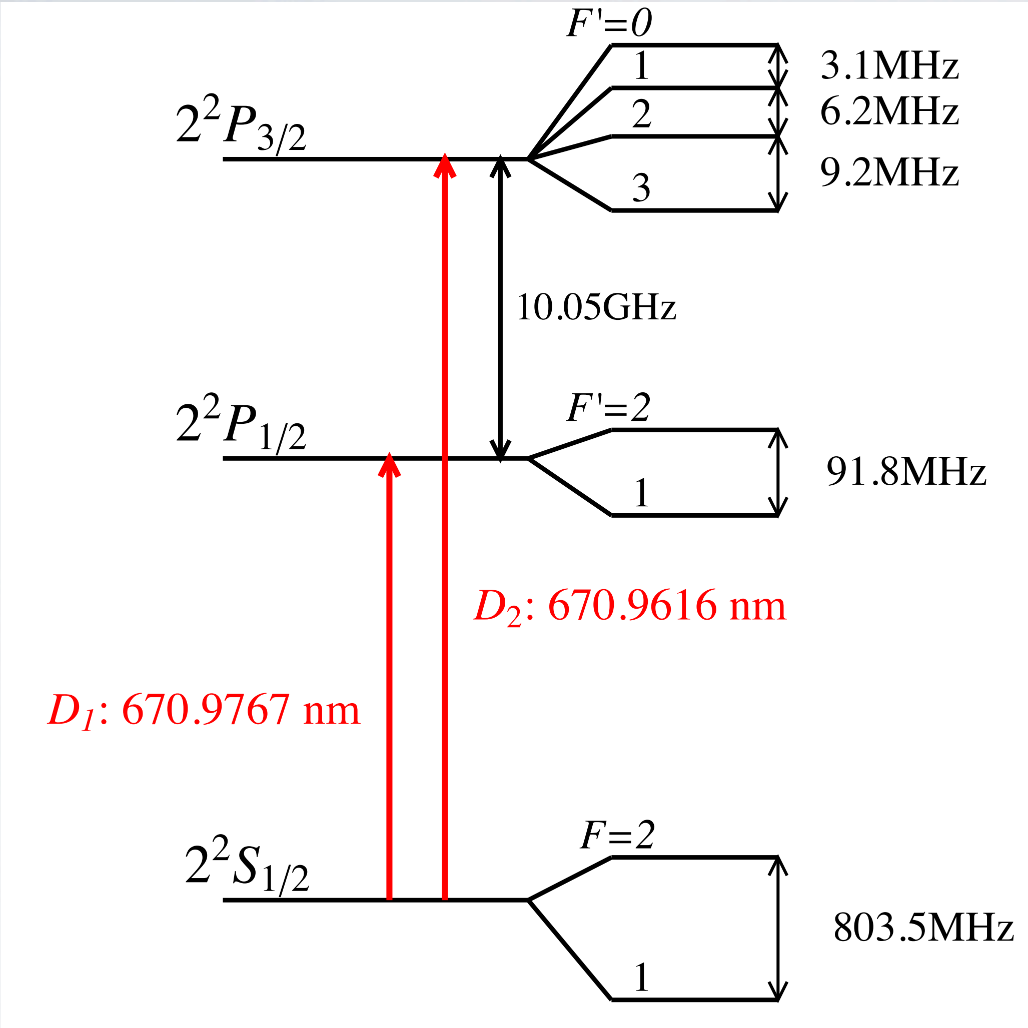
- Motivations for gray molasses in lithium
- First principles of gray molasses

1. Experimental results on the Lithium apparatus
   - Performances
   - Λ-enhancement

2. Study of the Λ-configuration
   - Model and the Bloch equations
   - Perturbative approach
   - Results and physical picture
   - Continued fractions

Conclusion

Motivations : features of ^{7}Li



- $\Gamma = 2\pi \times 6$MHz
- Doppler limit $T_D = \hbar\Gamma/2k_B = 150\mu K$
- Very small hyperfine splitting < Γ
- Inefficient sysiphus cooling
- MOT temperatures >300µK

Motivation for new sub-Doppler cooling schemes

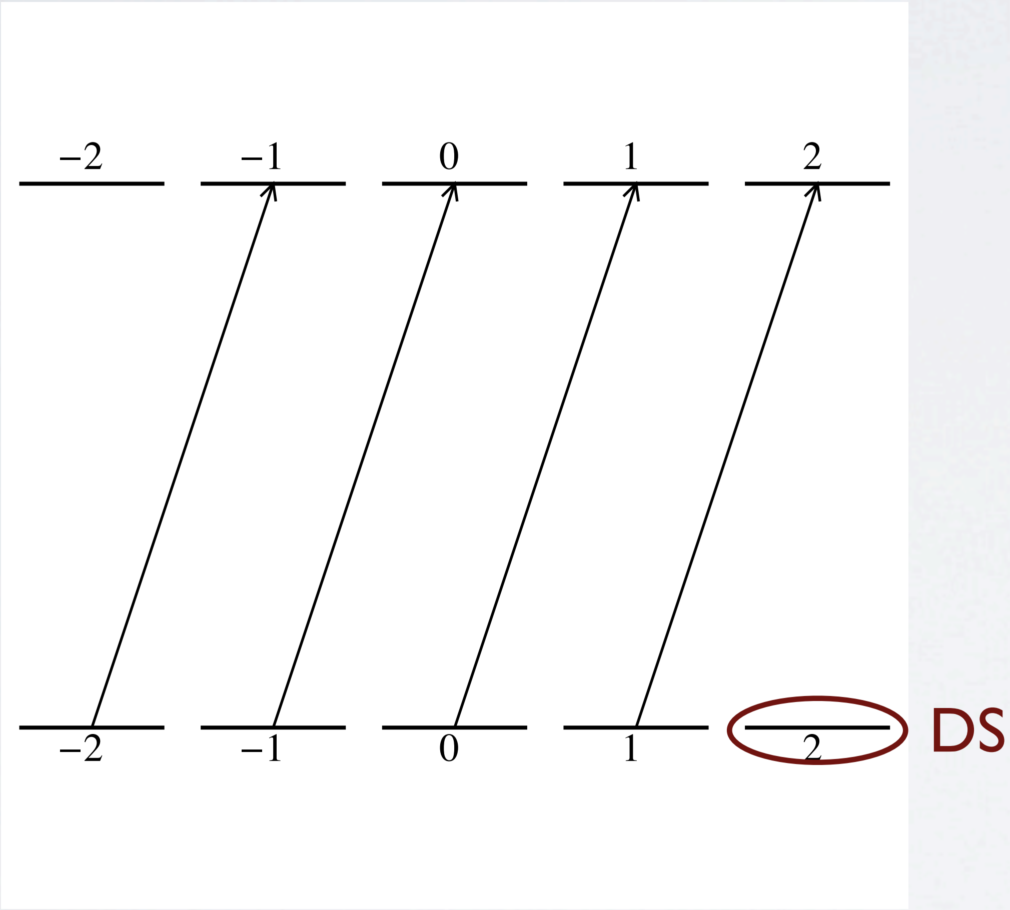
Gray molasses demonstrated by the Fermix team on potassium.

D. Rio Fernandes *et., al., EPL,* 100, 63001, (2012)

Gray molasses : first principles

Transitions : $F \rightarrow F' = F$ or $F \rightarrow F' = F - 1$

Dark state(s) unaffected by the light

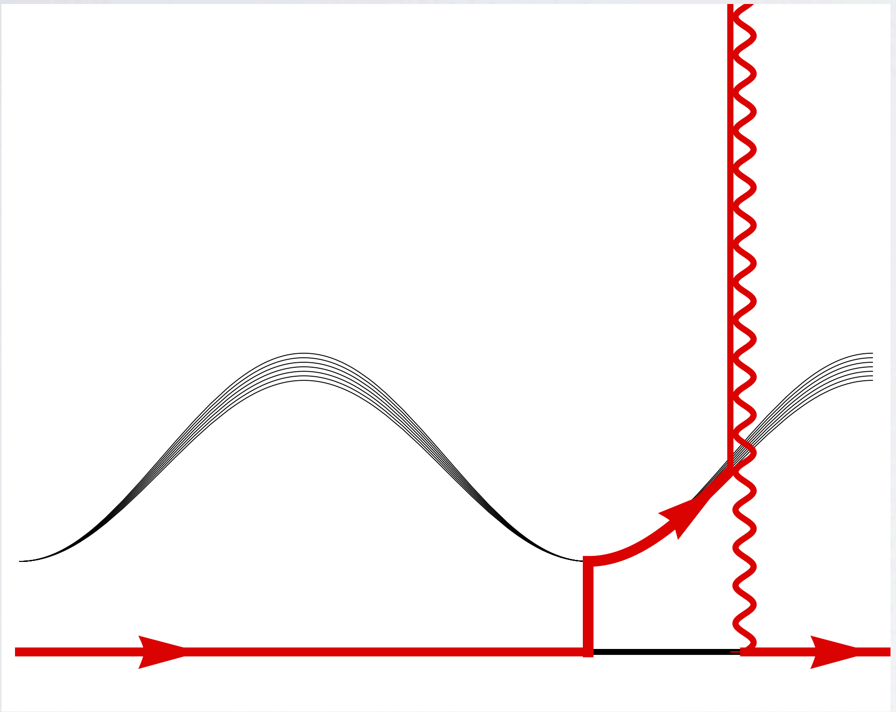


Example : addressed by σ^+ light

Notes de cours de C. Cohen-Tannoudji au collège de France
Weidemüller *et. al.,* EPL, 27, 109 (1994)
Grynberg and Courtois EPL, 27, 41 (1994)
Ol'Shanii and Minogin, Opt. Comm., 89, 393 (1992)

Gray molasses : first principles

Dark state(s) unaffected by the light
Light frequency blue of the transition
Bright states light shifted and dressed



$$\mathcal{F} \propto -\mathrm{v}^3 + o(v^3)$$

Motional coupling from dark to bright states
Optical pumping from bright to dark

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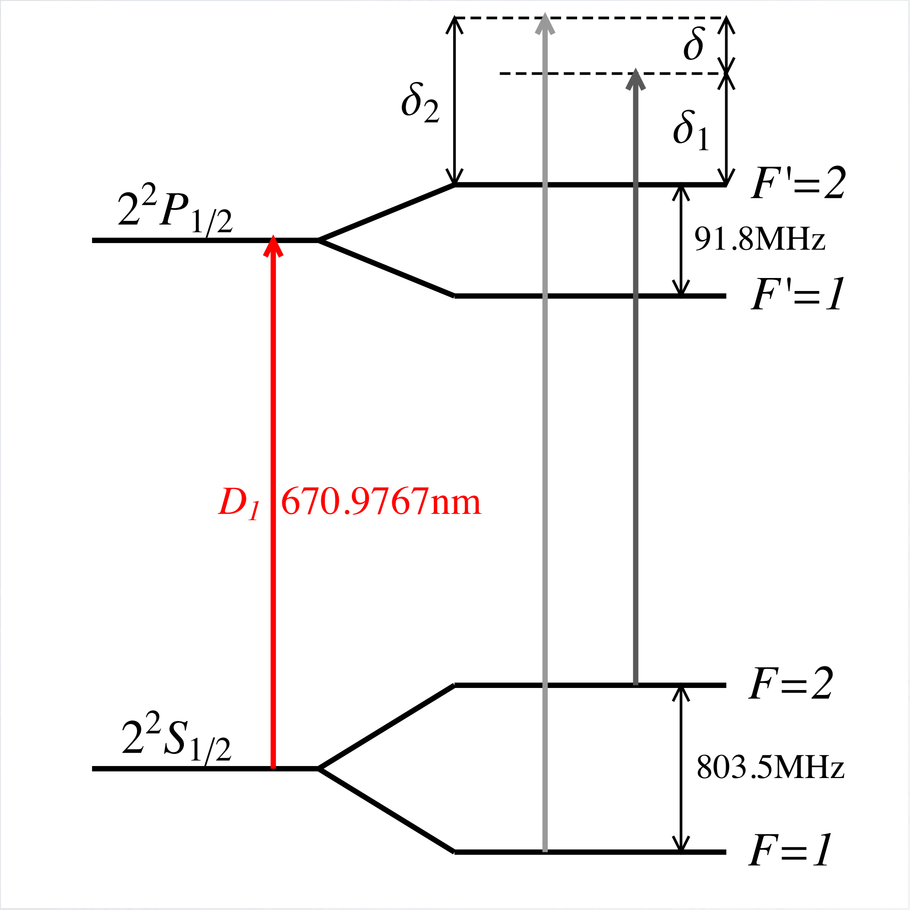
Ol'Shanii and Minogin, Opt. Comm., 89, 393 (1992)

Experimental implementation on ^{7}Li

- On $F=2 \rightarrow F'=2$
- 3 pairs of circularly polarized beams
- Intensity in the principal beam $\gtrsim 10\ I_{sat}$
- Necessity of a repumping beam on $F=1 \rightarrow F'=2$

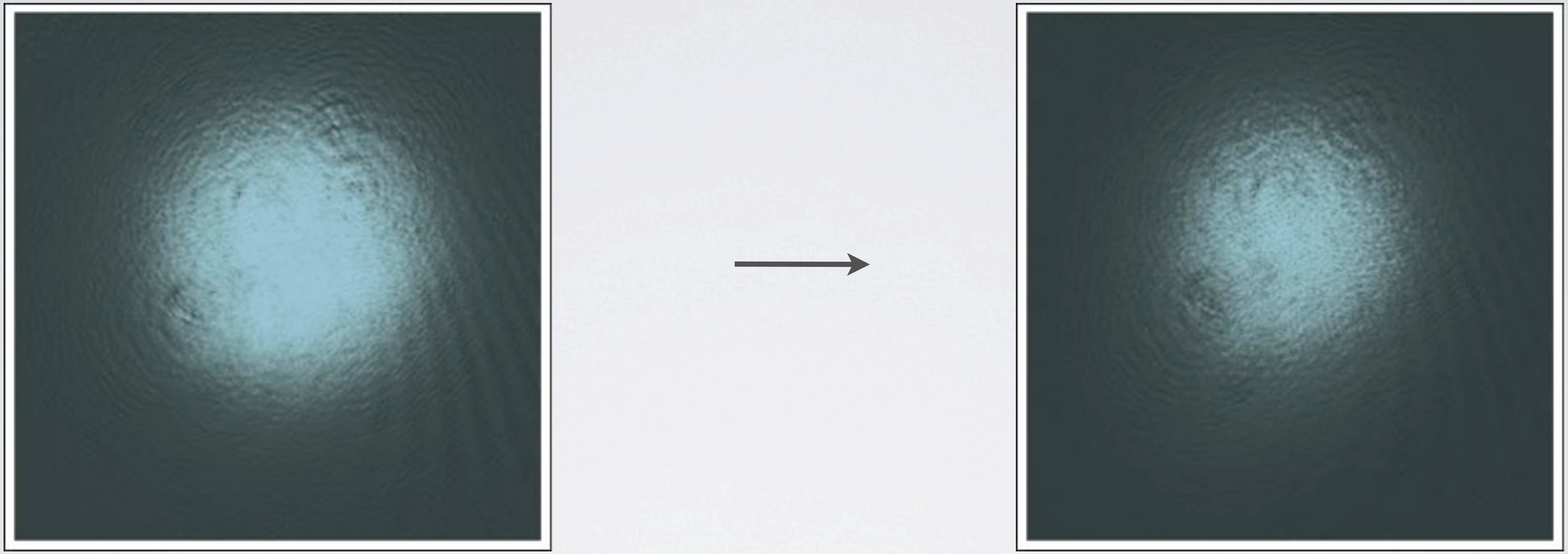


- Repumper generated by electro optic modulator (EOM)

Results on ^{7}Li

time of flight 1.5 ms

time of flight 6 ms

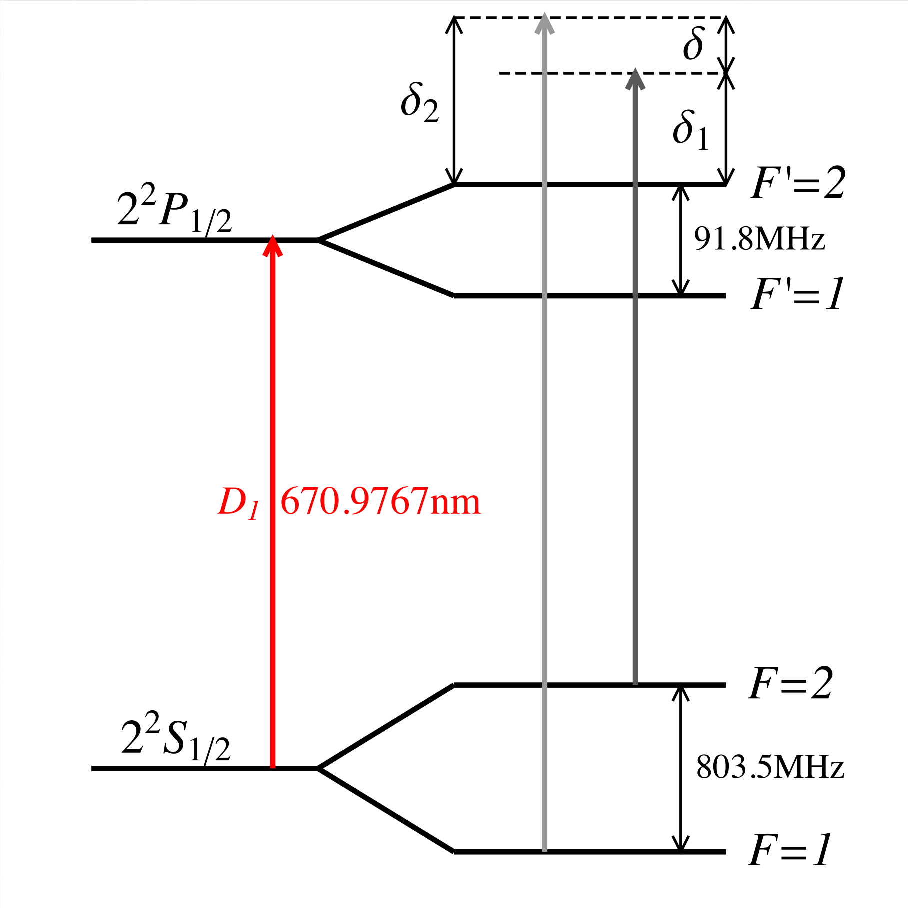


- 2 ms
- From a 600μK (C)MOT to 50μK
- After optical pumping, close to100% spin polarized for magnetic trapping.

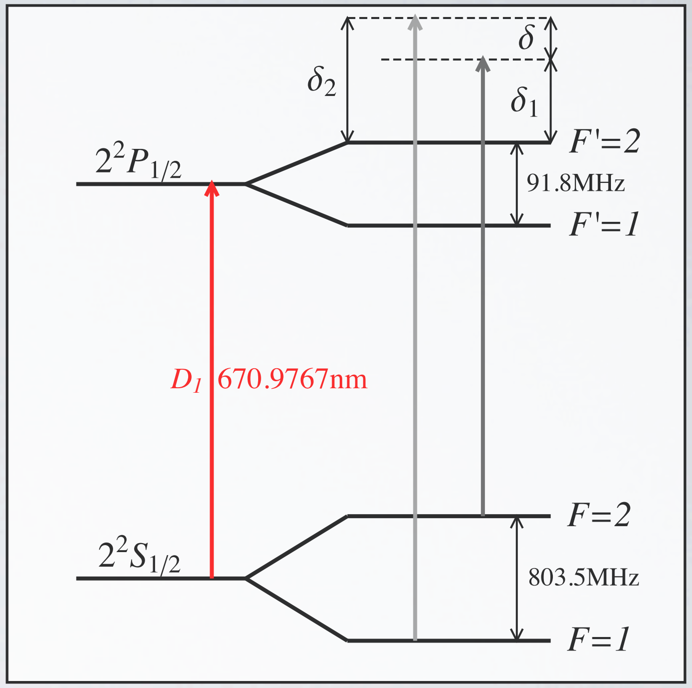
Results on ^{7}Li

Best parameters :

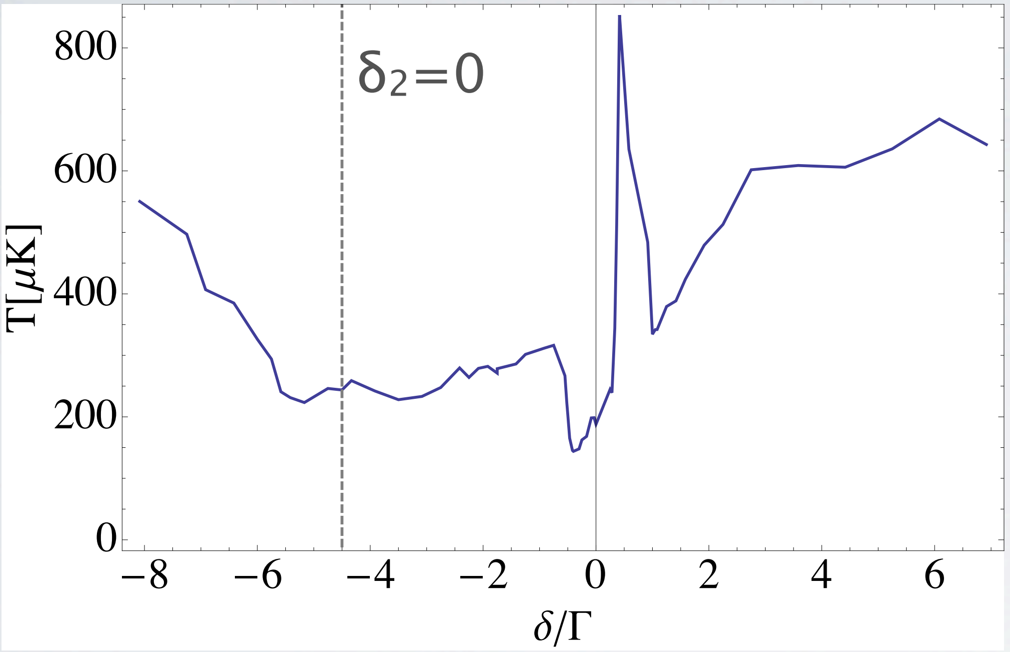
- $\delta_1 = 4.5 \times \Gamma = 27$ MHz
- $\delta_2 = \delta_1$ Raman condition
- Power ratio : $P_{repump} = 0.02 \times P_{principal}$



Λ-enhancement : results

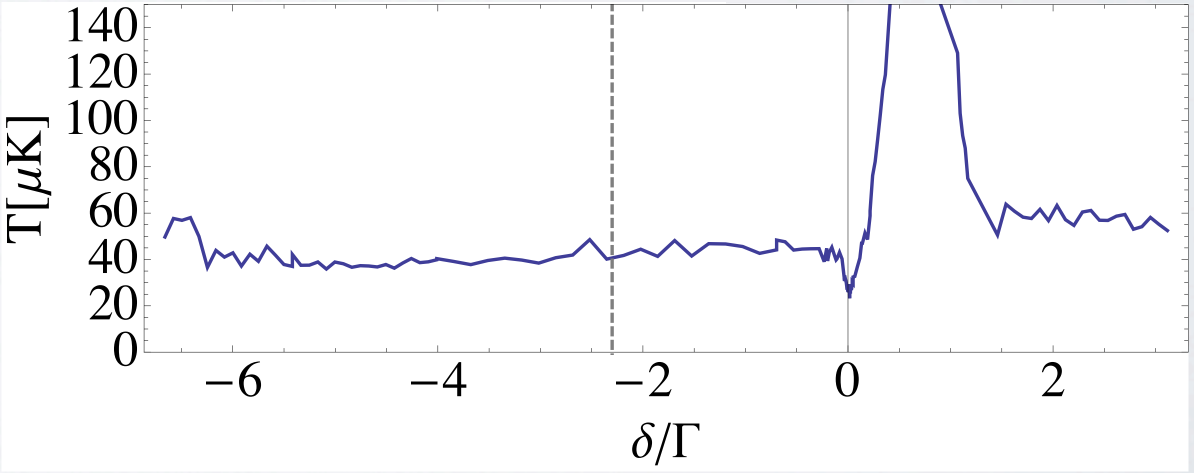


Temperature for all parameters fixed, varying δ_2



- Gain factor 2 in temperature
- Complex structure
- Strong heating blue of the Raman condition (RC)

Also in ^{40}K



Λ-enhancement

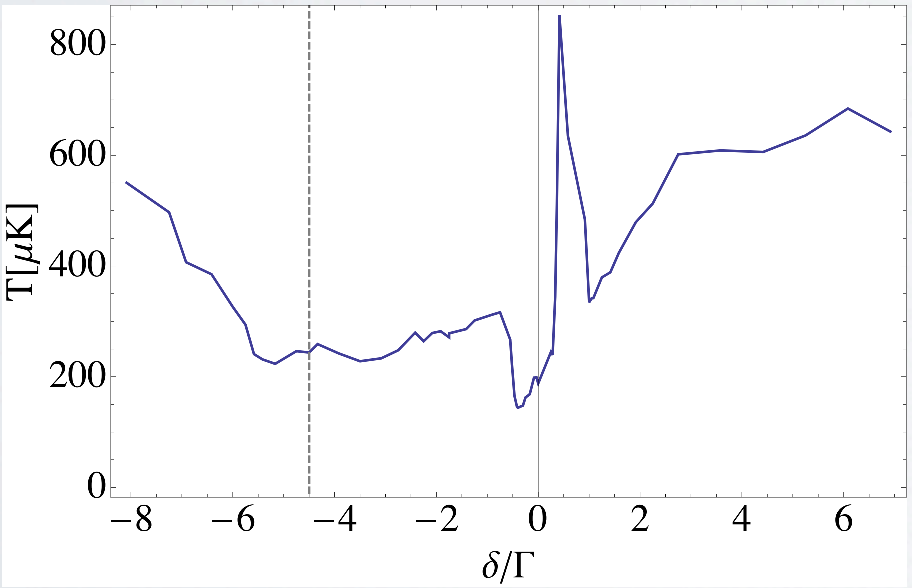
Why is the Raman condition the best configuration?

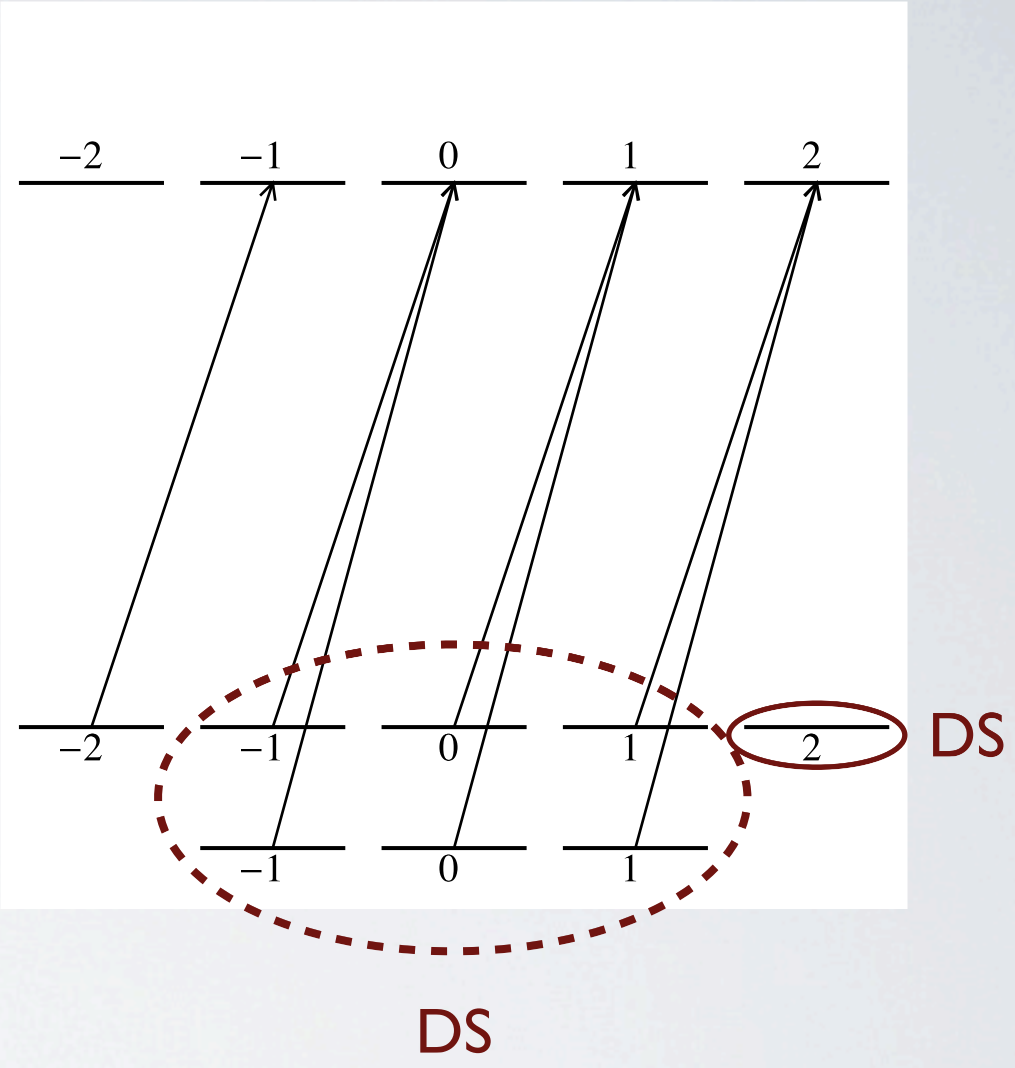
Gray molasses on ^{7}Li

Simplified situation : σ^+ light on $F=2 \rightarrow F'=2$

Repumper ➞ new dark states!

Participates to grey molasses





Model

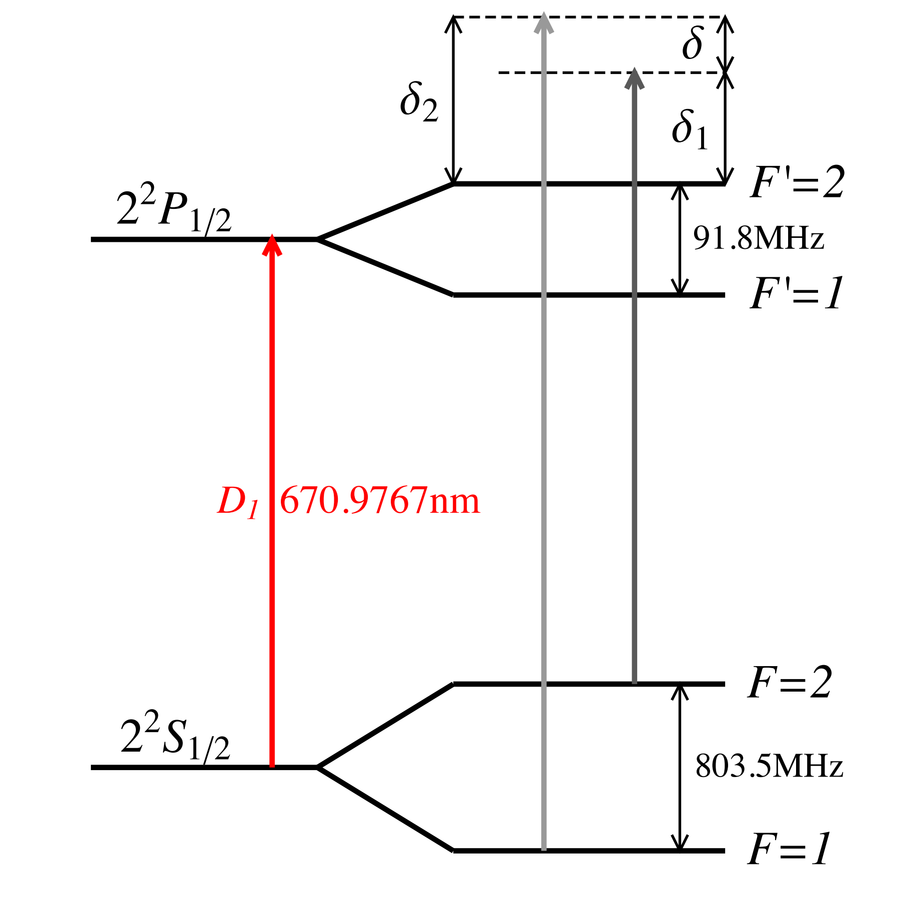
Goals:

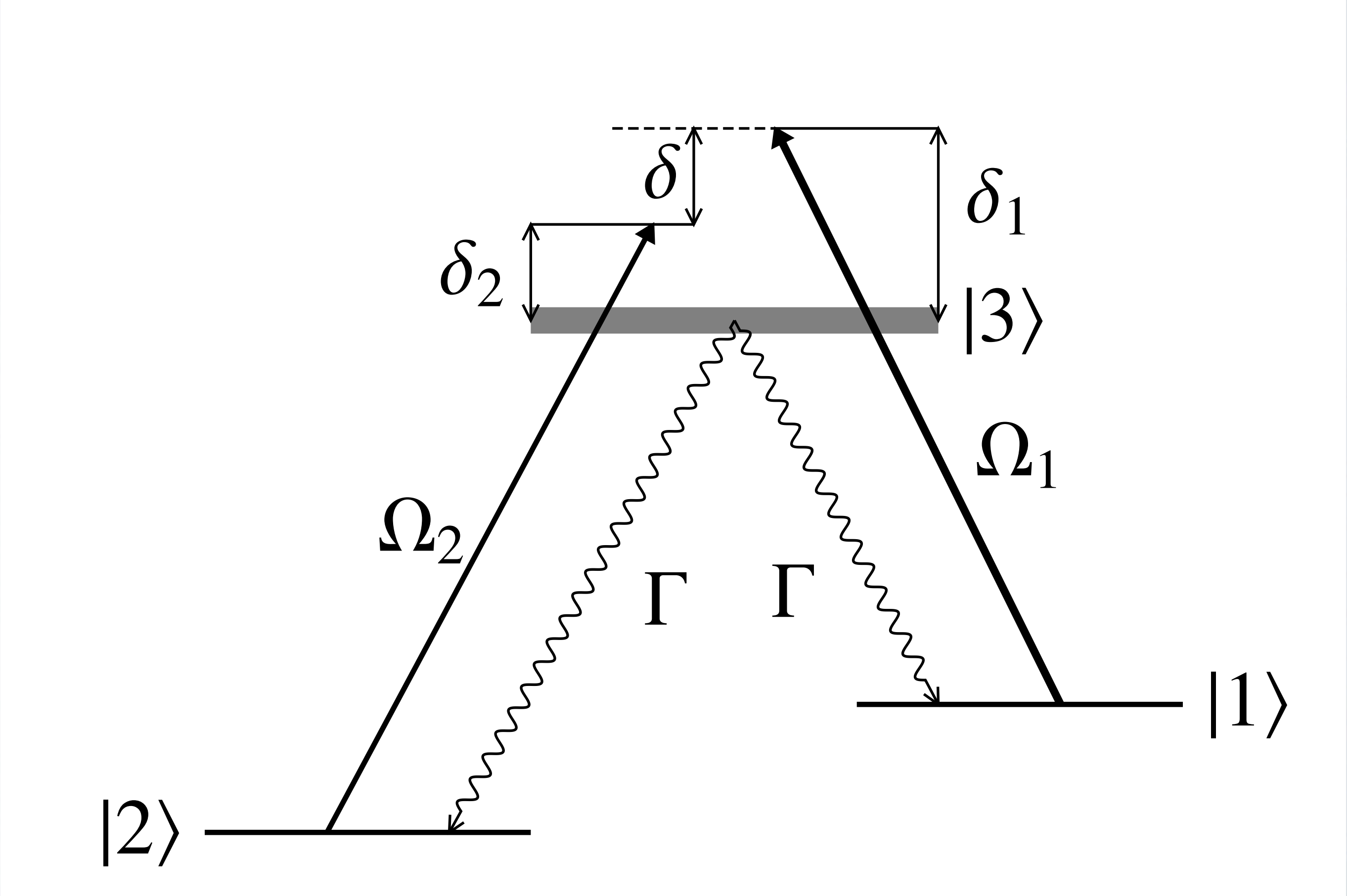
- Account for bi-chromatic effects
- Unravel main physical phenomena
- Be simple

R. Gupta, C. Xie, S. Padua, H. Batelaan, and H. Metcalf, *PRL*, 71, 3087, (1993).
N. Malossi *et. al., PRA*, 72, 051403, (2005).
D.V. Kosachev, Yu. V. Rozhdestvenskii, JETP, 79, 856 (1994).
M. Drewsen, *PRA*, 51, 1407, (1995).

Model chosen:

- Get rid of Zeeman degeneracy so lose gray molasses cooling
- Three level Λ system with standing waves





Model

- Light force as a Langevin force
- Velocity distribution subject to the Fokker Planck Equation with stationary solutions

$$\mathcal{P}_{st}(\mathrm{v}) \propto \frac{1}{\mathcal{D}(\mathrm{v})} \exp\left(m \int_0^{\mathrm{v}} \mathrm{dv}' \, \frac{\mathcal{F}(\mathrm{v}')}{\mathcal{D}(\mathrm{v}')} \right)$$

- F : mean force
- D : diffusion coefficient (fluctuations of the force)

- Enables one to derive a temperature in the small velocities limit equating with a Boltzmann distribution:

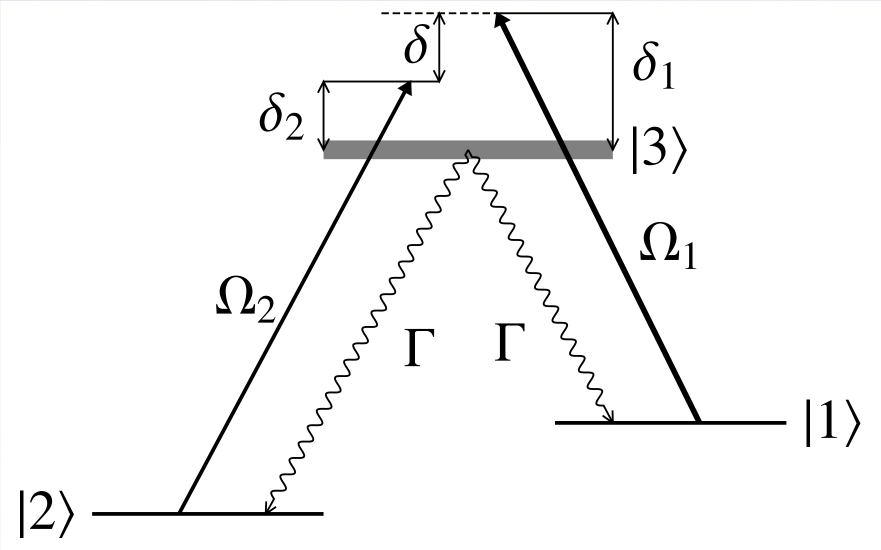
$$\alpha = \left(\frac{\partial \mathcal{F}}{\partial \mathrm{v}} \right)_{\mathrm{v}=0} \qquad k_{\mathrm{B}} T = -\frac{\kappa}{\alpha}$$

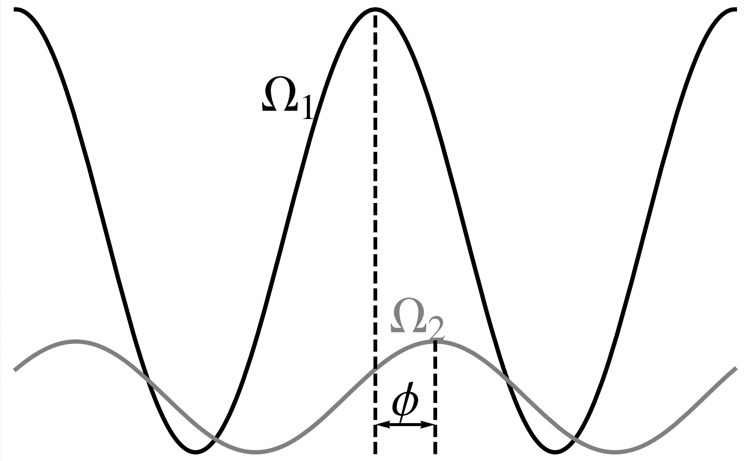
$$\kappa = \mathcal{D}(\mathrm{v} = 0)$$

- α is called the friction coefficient

Model

$$\hat{\mathcal{H}}_{\text{a.l.}} = \hbar\Omega_1 \cos(kz)\left(|1\rangle\langle 3| + h.c.\right) + \hbar\Omega_2\cos(kz+\phi)(|2\rangle\langle 3| + h.c.) + \hbar\delta_1 |1\rangle\langle 1| + \hbar\delta_2 |2\rangle\langle 2|$$





- Force

$$F = \left\langle -\nabla \hat{\mathcal{H}}_{\text{a.l.}} \right\rangle = -Tr\left[\hat{\rho}\,\hat{\mathcal{H}}_{\text{a.l.}}\right]$$

$$\mathcal{F}(\text{v}) = \frac{1}{\lambda}\int_0^{\lambda} dz \sin(kz)\left(\Omega_1 Re\rho_{13} + \Omega_2 Re\rho_{12}\right)$$

- Diffusion coefficient : we keep only the spontaneous emission

$$\mathcal{D} = \text{v}_{\text{rec}}^2 \Gamma \rho_{33}$$

Model

$$\mathcal{F}(\mathrm{v}) = \frac{1}{\lambda}\int_0^\lambda dz \sin(kz)\left(\Omega_1 Re\rho_{13} + \Omega_2 Re\rho_{12}\right)$$

$$\mathcal{D} = \mathrm{v}_{\mathrm{rec}}^2 \Gamma \rho_{33}$$

- Solutions of the optical Bloch equations (OBE)

$$i\frac{d}{dt}\rho = \frac{1}{\hbar}\left[\hat{\mathcal{H}}_{AL}, \rho\right] + i\left(\frac{d\rho}{dt}\right)_{\mathrm{spont.\,emis.}}$$

$$\mathrm{v} \ll \Gamma/k$$

$$\frac{d}{dt} \rightarrow \mathrm{v}\frac{d}{dz}$$

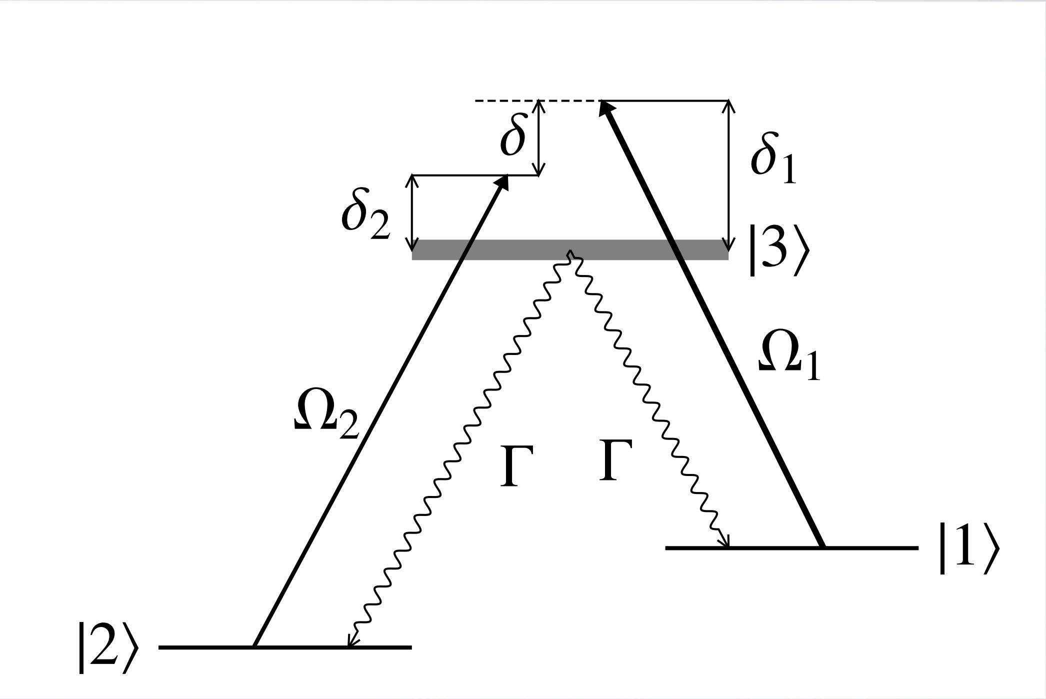
Solving methods :

- Perturbative approach
- Continued fractions

The perturbative approach

Focus on ^{7}Li
Experimental parameters :

- δ_1 = 4.5 x Γ = 27 MHz
- $I_{princip} \gtrsim 10\ I_{sat}$
- Power ratio : P_{repump}=0.02 x $P_{principal}$



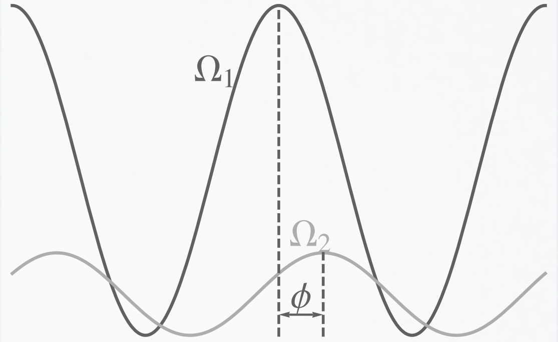
$$\Omega_1 = \Gamma\sqrt{I/2I_{\rm sat}} \geq 2\Gamma$$

$$\Omega_2/\Omega_1 \lesssim 0.02$$

$$\Omega_2 \ll \Gamma,\ \Omega_1$$

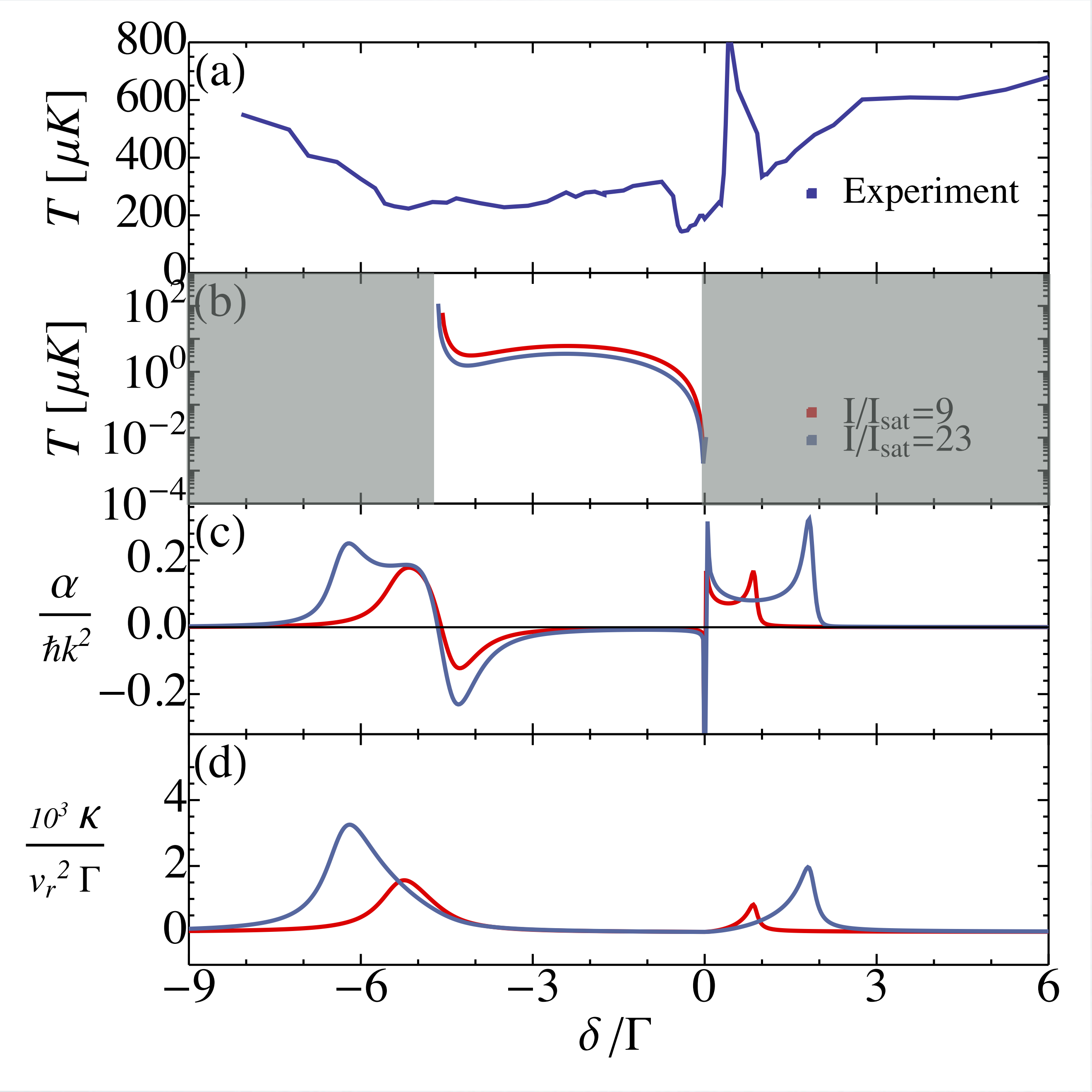
- Perturbative approach in powers of Ω_2
- Setting Φ=0

$$\rho_{ij} = \sum_{n,l} \rho_{i,j}^{(n,l)} (\Omega_2)^n (\mathrm{v})^l$$



- Solving recursively

The perturbative approach results



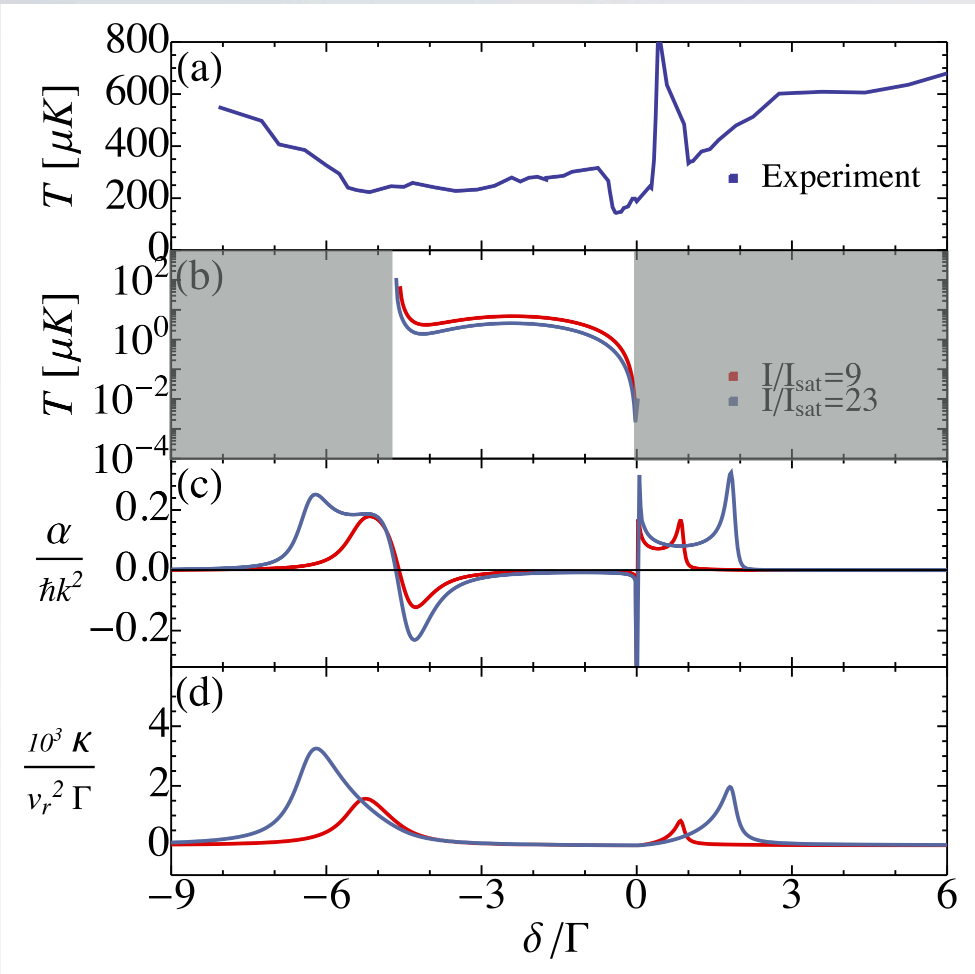
Experimental parameters :

- $\delta_1 = 4.5 \times \Gamma = 27$ MHz
- $I_{princip} \gtrsim 10\ I_{sat}$
- Power ratio : $P_{repump} = 0.02 \times P_{principal}$

$$\mathcal{F} = \alpha \mathrm{v} + o(\mathrm{v})$$

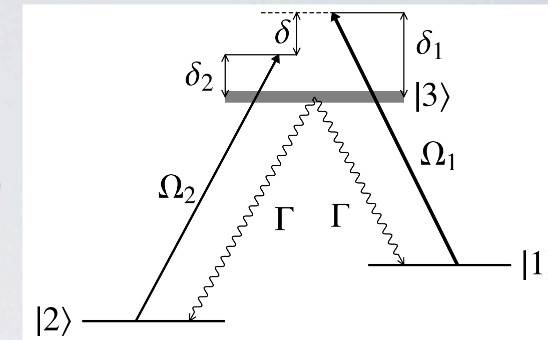
$$\mathcal{D} = \kappa + O(\mathrm{v})$$

Physical interpretation, the force



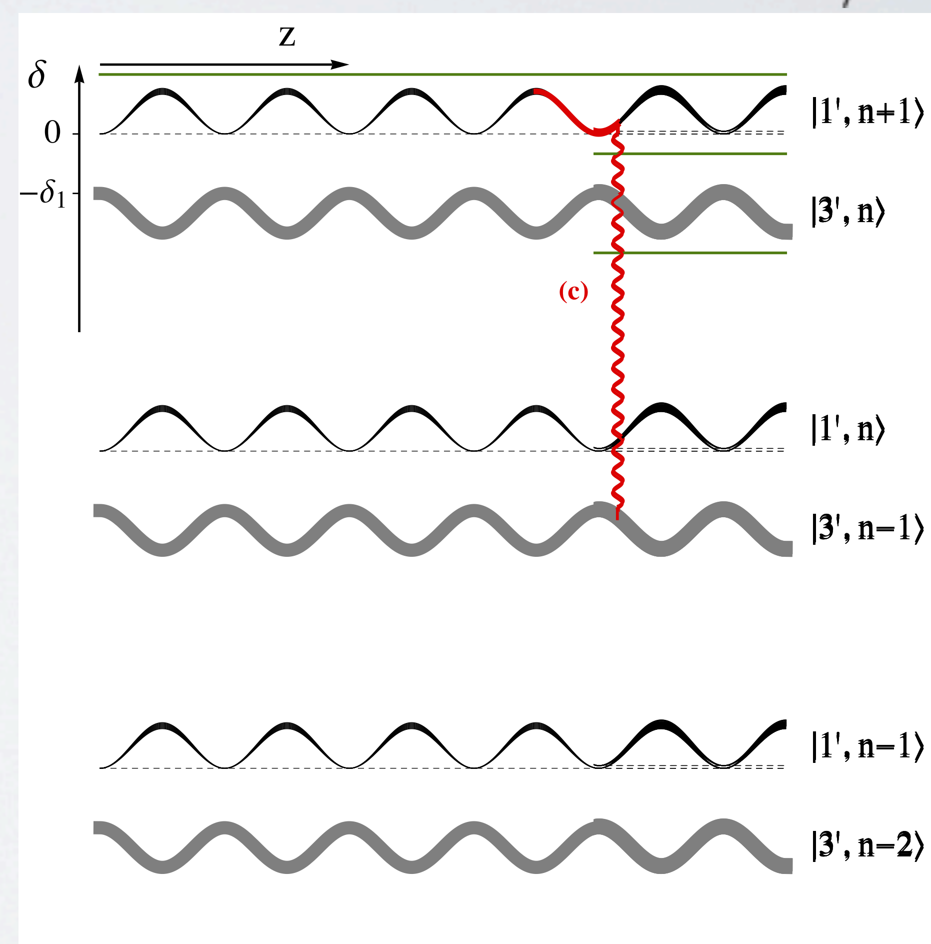
- Cascade of levels dressed by the strong principal transition

$$|1'\rangle \propto |1\rangle - i\Omega_1/\delta_1\,|3\rangle$$
$$|3'\rangle \propto -i\Omega_1/\delta_1\,|1\rangle + |3\rangle$$



- Probed by transition from state $|2\rangle$

$v \ll \Gamma/k$



$\Phi=0$

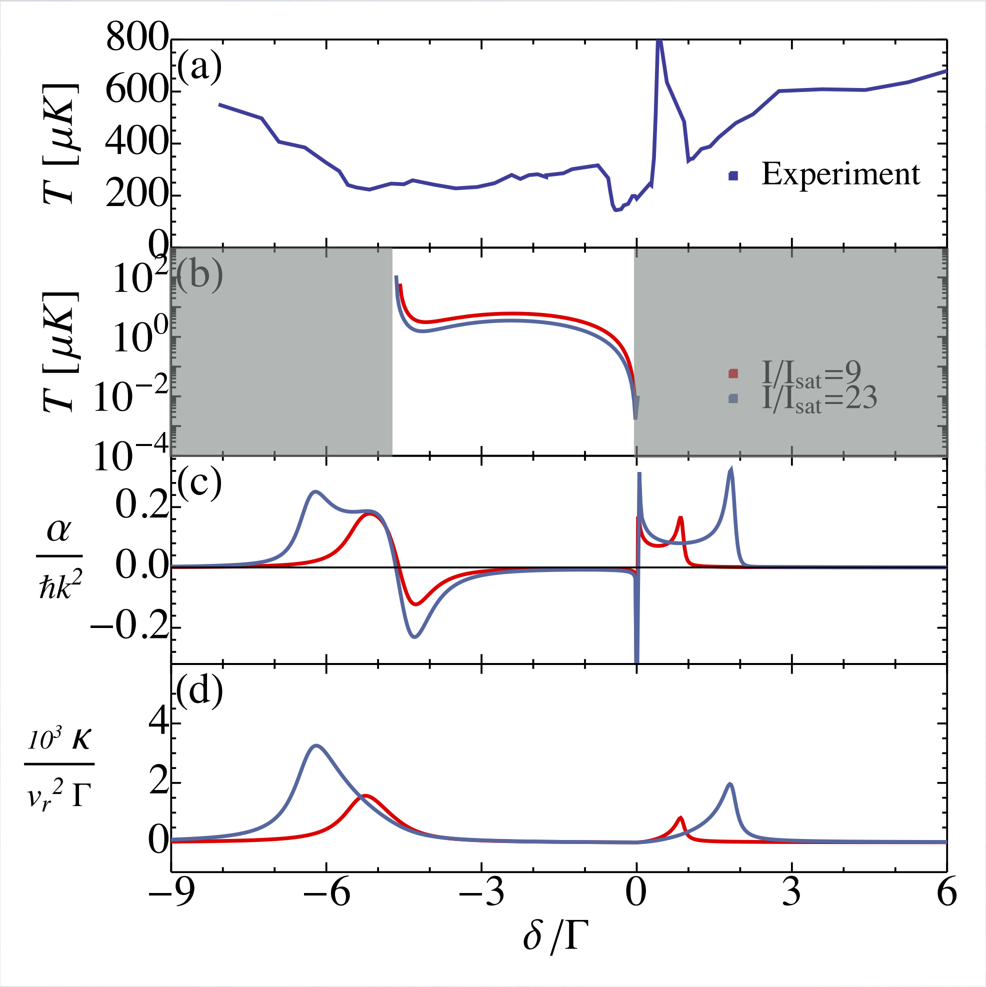
(a) $\delta_2<0$ heating

(b) $0<\delta_2<\delta_1$ cooling

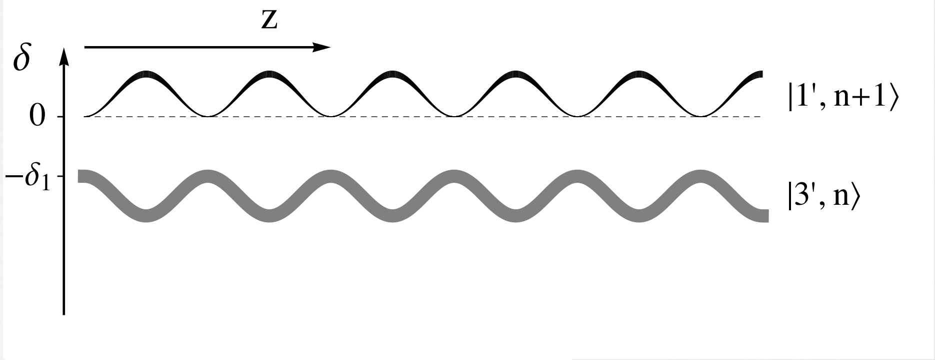
(c) $\delta_1<\delta_2$ heating

Two sign changes, one around the Raman condition

Physical interpretation, the diffusion coefficient



- Maximum scattering when resonant with either $|1'\rangle$ or $|3'\rangle$
- No scattering at the Raman condition $\delta_2=\delta_1$: dark state : $|\mathrm{DS}\rangle \propto \Omega_1\,|2\rangle - \Omega_2\,|1\rangle$

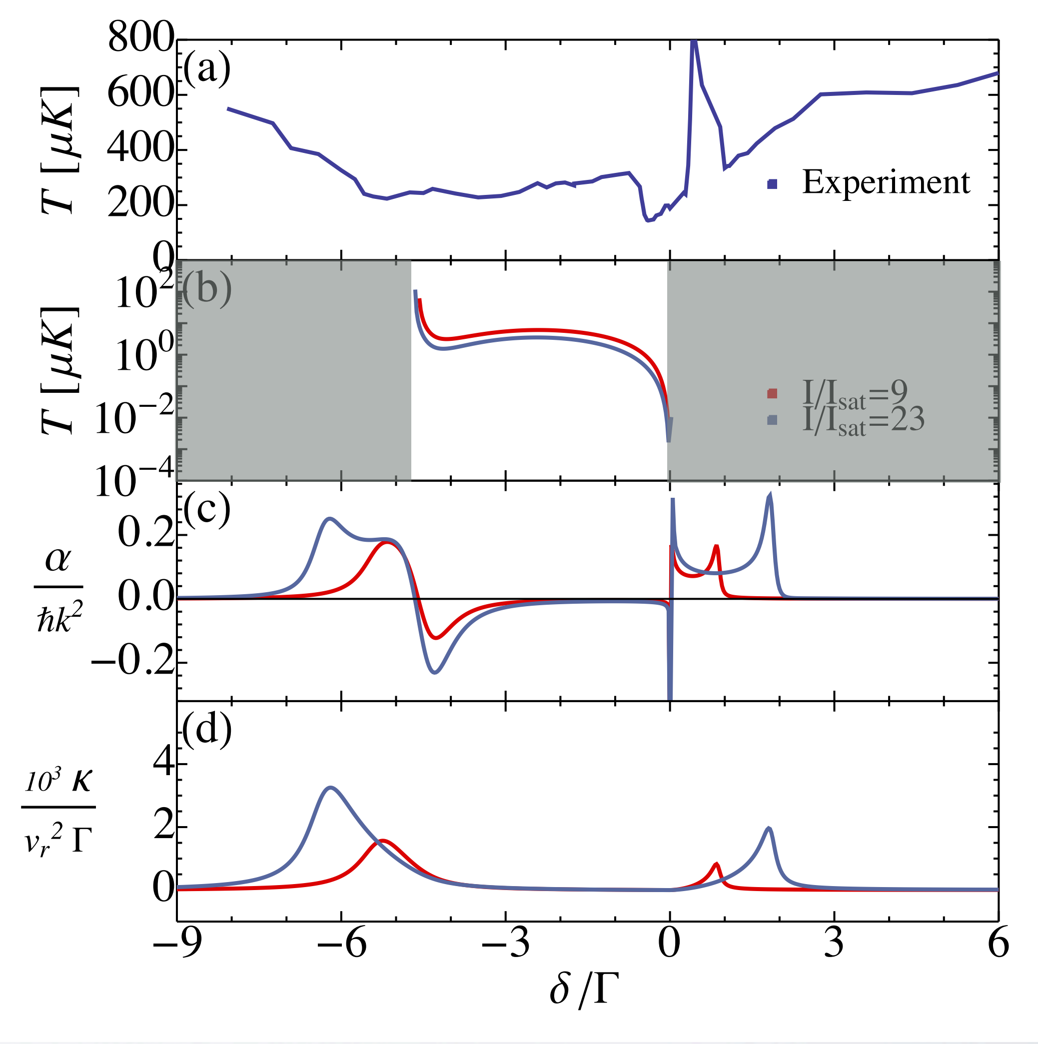


Summary the perturbative approach

- Cooling when red of the Raman condition
- The best cooling is at the Raman condition where the diffusion drops
- Connects to the addition of a dark state to the gray molasses
- Sign change at the RC is well described

DRAWBACKS

- Φ ≠ 0 in our gases !
- Divergence of α at the Raman condition
- T→0 is not physical



The continued fractions approach

$$\rho_{ij} = \sum_{n=-\infty}^{n=+\infty} \rho_{ij}^{(n)} e^{inkz}$$

- Solving recursively from top to bottom

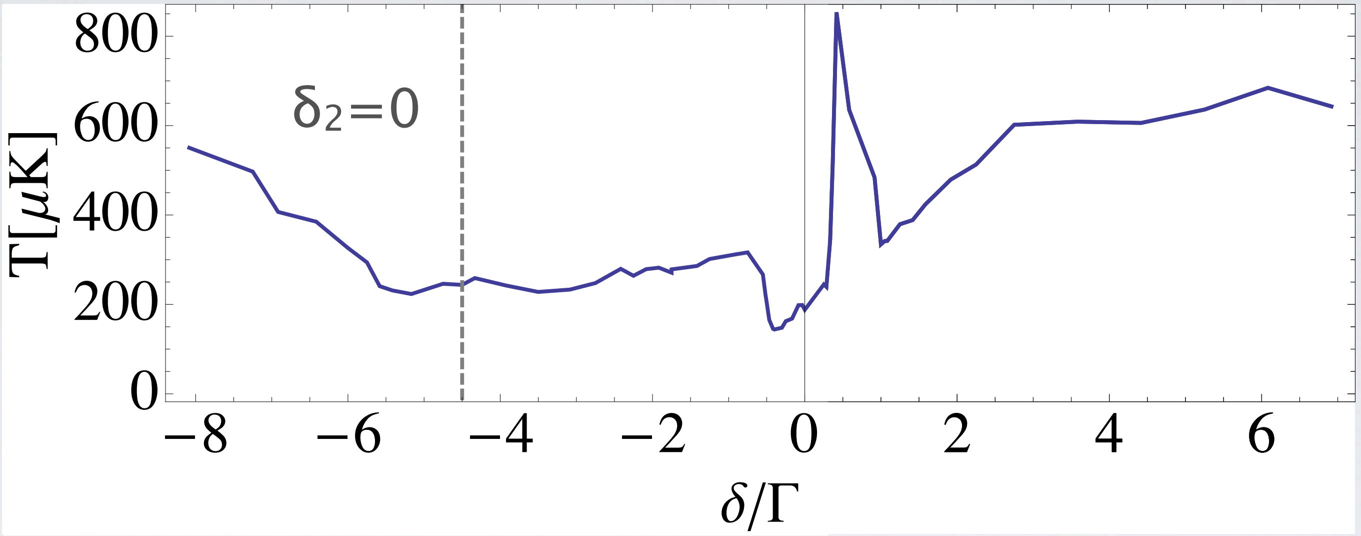
- Versatile tool: we can get F(v) for all v for any set of parameters.
- Account for a relative phase randomly distributed by averaging over Φ:

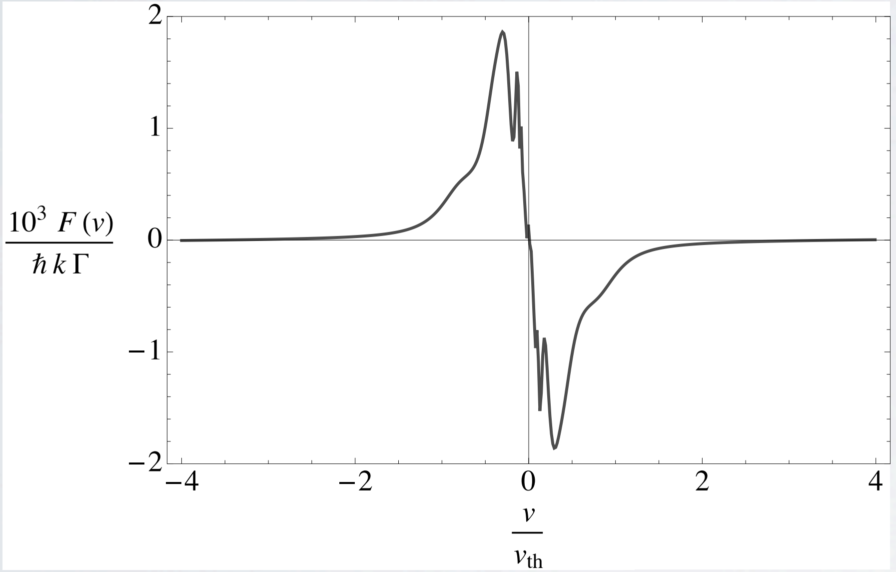
$$\langle \mathcal{F}(\mathrm{v}) \rangle_\phi = \frac{1}{2\pi} \int_0^{2\pi} \mathcal{F}(\mathrm{v}, \phi)\, d\phi$$

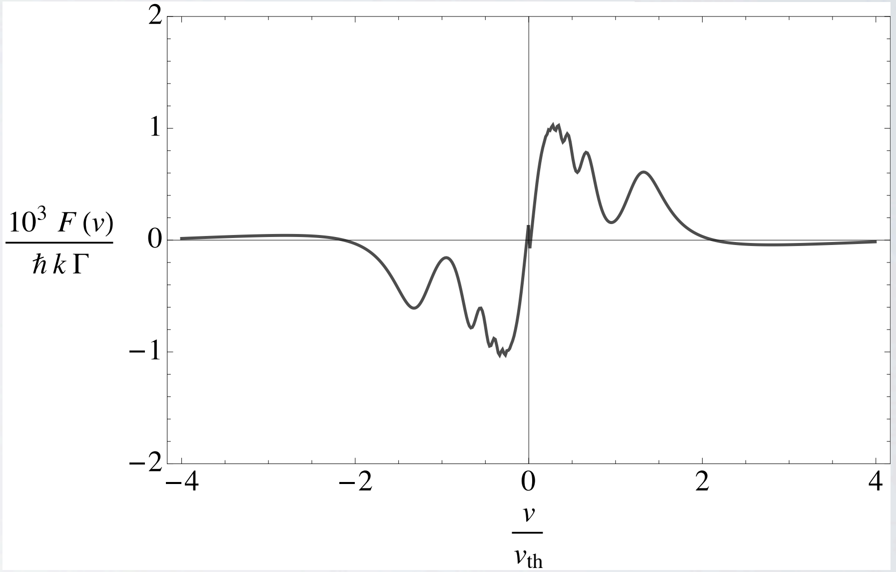
- We calculate only F(v) and not the diffusion coefficient
- Qualitative check if the physical picture holds for Φ

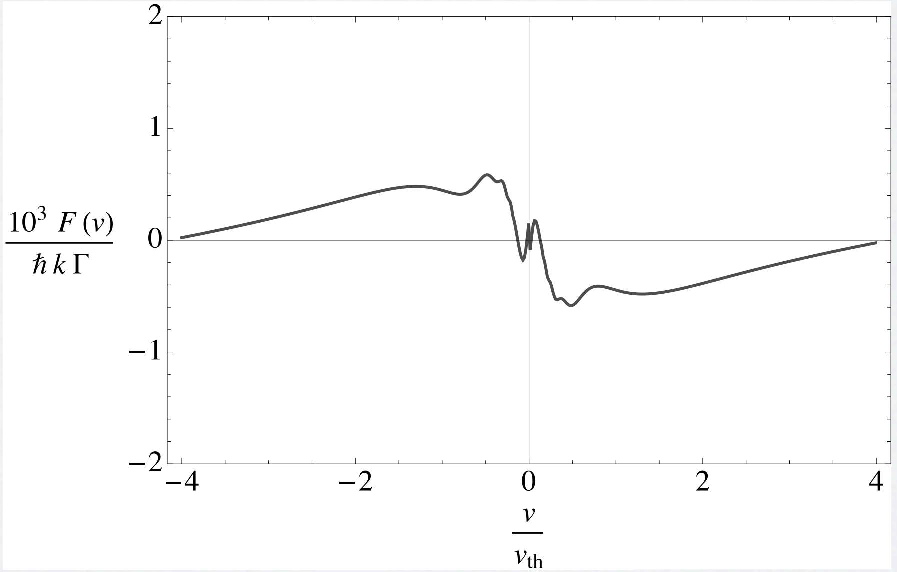
D.V. Kosachev, Yu. V. Rozhdestvenskii, JETP, 79, 856 (1994)
D. V. Kosachiov, Yu. V. Rozhdestvensky, and G. Nienhuis, J.O.S.A.B 14, 535-543 (1997)

The continued fractions approach, results









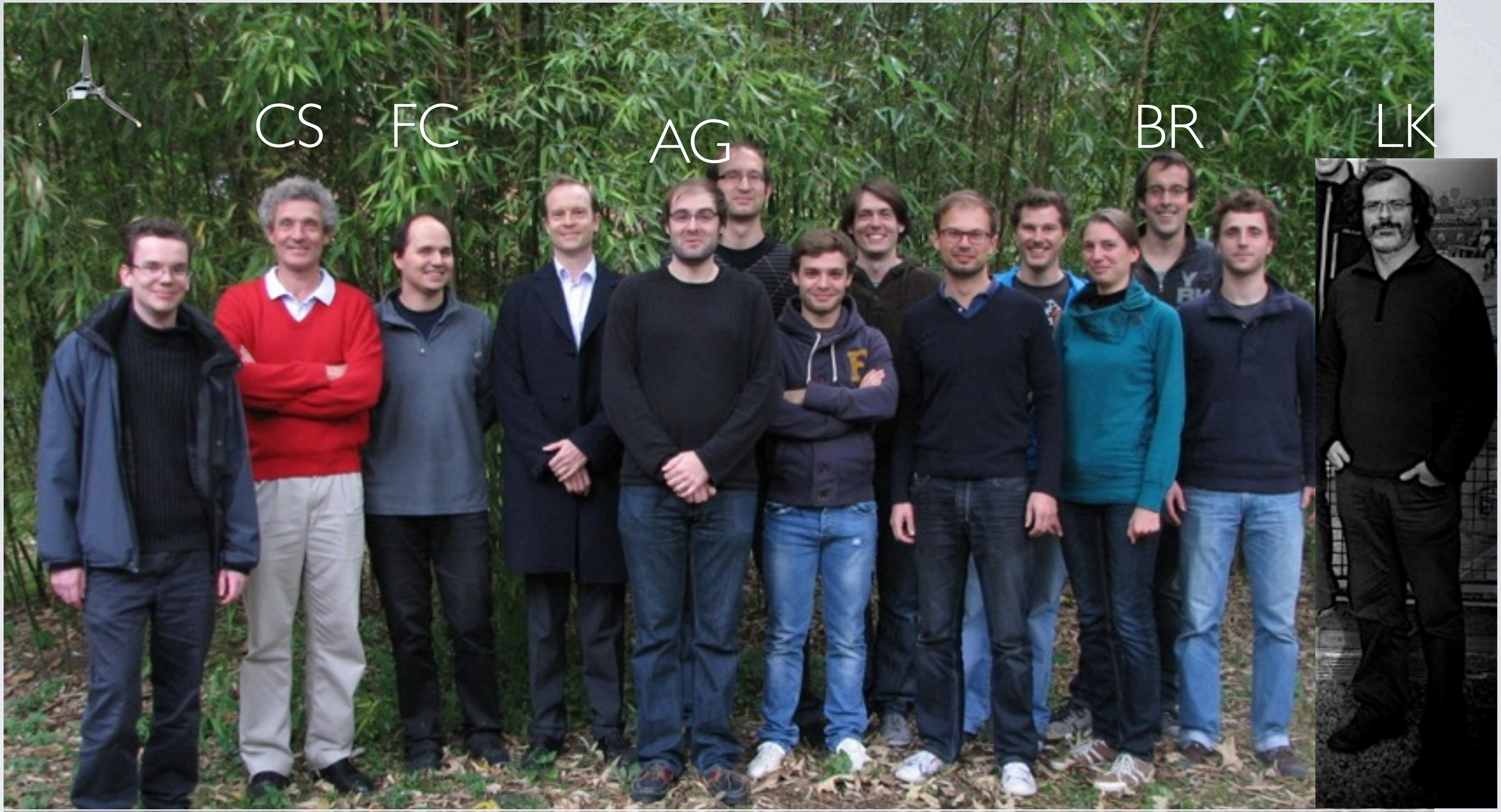
Summary of the continued fractions approach

- Qualitative confirmation of the picture obtained at Φ=0,
- Qualitative match with experimental data

Conclusion

- Gain of a factor ~10 in temperature with no losses
- Non-trivial force, repumper-dependent
- Long lived dark state at Raman condition completing the gray molasses

- Efficient sub-Doppler cooling of ^{7}Li
- Enhancement of gray molasses by Λ-configuration thanks to Raman coherence



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