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INO - CNR
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Raffreddamento laser di molecole

Andrea Fioretti
....

18 gennaio 2013
Area della Ricerca di Pisa

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SHORT STORY of AF

- Collaboration with C. Gabbanini since 1998 (IFAM, IPCF and INO)
- Last 3-years in Laboratoire Aimé Cotton, Orsay (Fr)

- Recent research activity at LAC on:
  - Monochromatic ion and electron beams from a cold atom source

    (collaboration with CNRS-Orsay, the private company Orsay Physics in Fuveau (FR) and the University of Pisa under a FP7-IAPP «Coldbeams»

  - Cold Rydberg atoms and cold plasma

  - Cold molecules

OUTLINE

- Introduction. Why cold molecules?

- Introduction. Methods of production of cold molecules

- Optical pumping and vibrational cooling

- Rotational cooling

- Conclusions and perspectives

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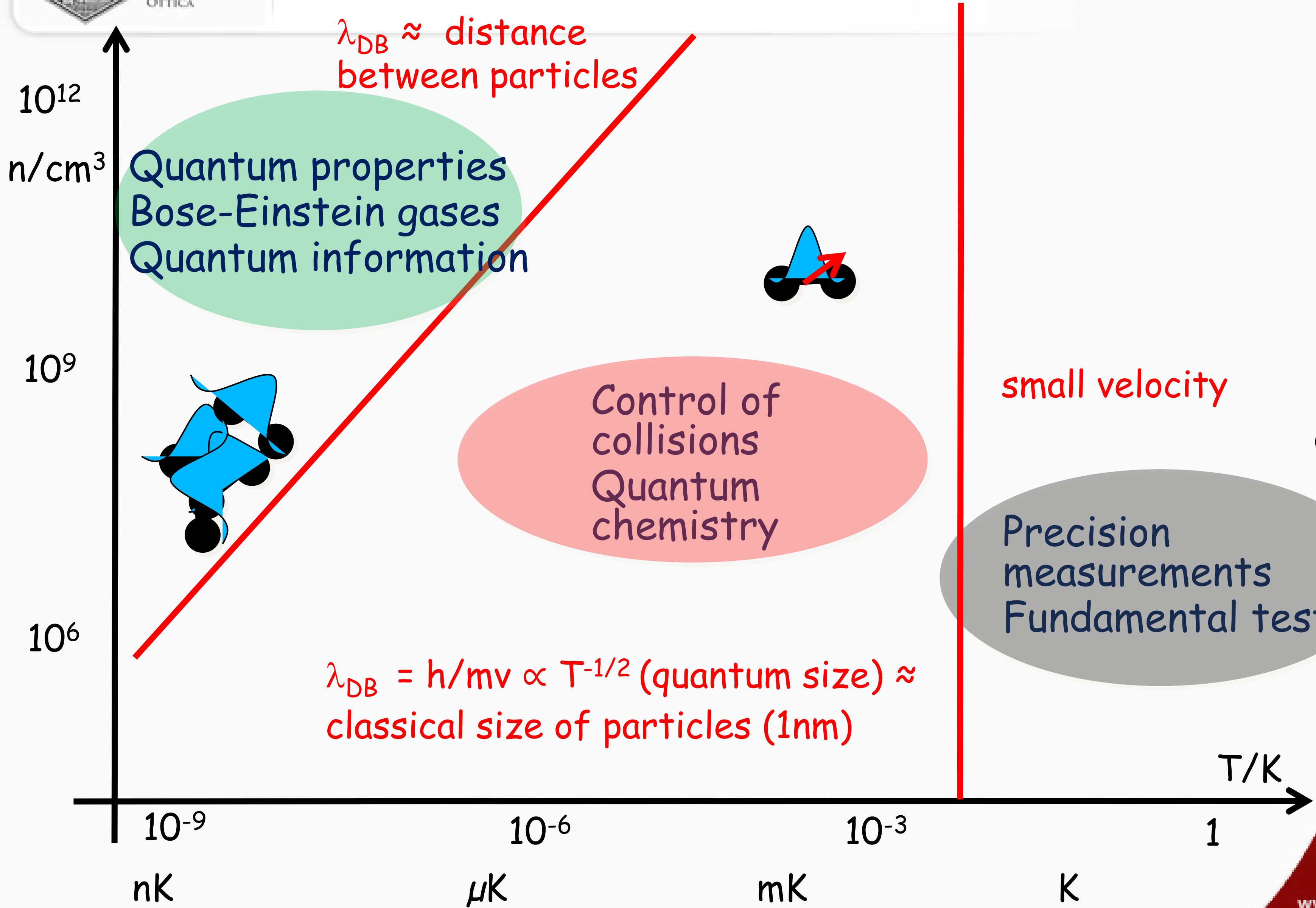
MOTIVATIONS FOR COLD MOLECULES



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MOTIVATIONS FOR COLD MOLECULES

- Precision measurements and fundamental tests

Improved measurement of the shape of the electron
E. A. Hinds group, Nature **473**, 493–496 (26 May 2011)
They use cold YbF molecules

- Quantum information with polar systems

Quantum computation with trapped polar molecules.
DeMille, D. , Phys. Rev. Lett. 88, 067901 (2002) (PROPOSAL with RbCs)
A coherent all-electrical interface between polar molecules and mesoscopic supercond. resonators.
André, A. *et al.* Nature Phys. **2**, 636–642 (2006) (PROPOSAL with CaBr)

- Quantum gases, many-body physics

A toolbox for lattice-spin models with polar molecules.
Micheli, A., Brennen, G. K. & Zoller, P. Nature Phys. **2**, 341–347 (2006)
(PROPOSAL with candidate polar molecules: CaF, CaCl and MgCl.)

- Cold collisions (instellar collisions, quantum collision regime, quantum degeneracy),… cold chemistry?
- …

Low-energy collisions of NH_3 and ND_3 with ultracold Rb atoms.
Żuchowski, P. S. & Hutson, J. M. Phys. Rev. A **79**, 062708 (2009)

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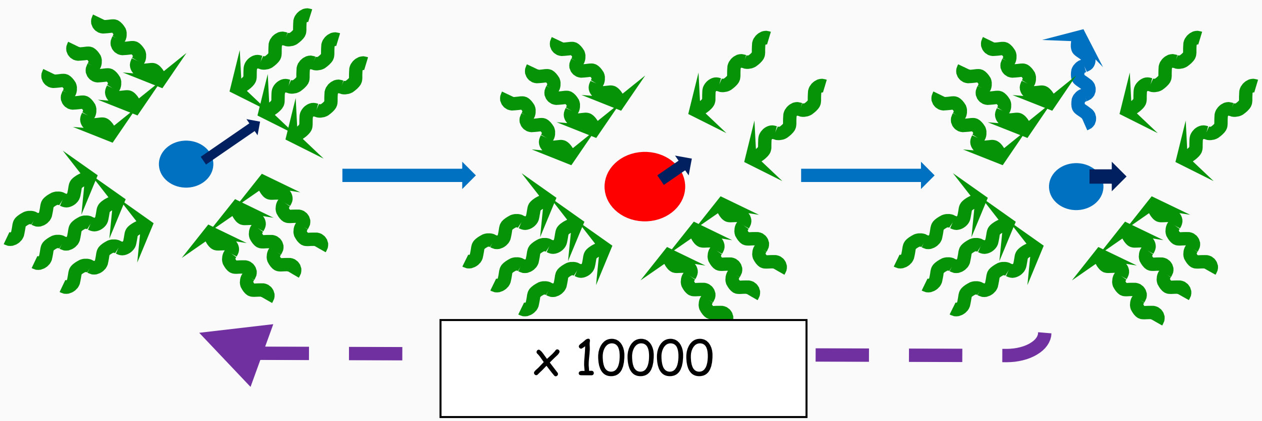
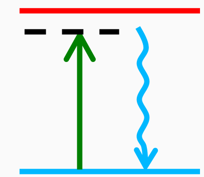
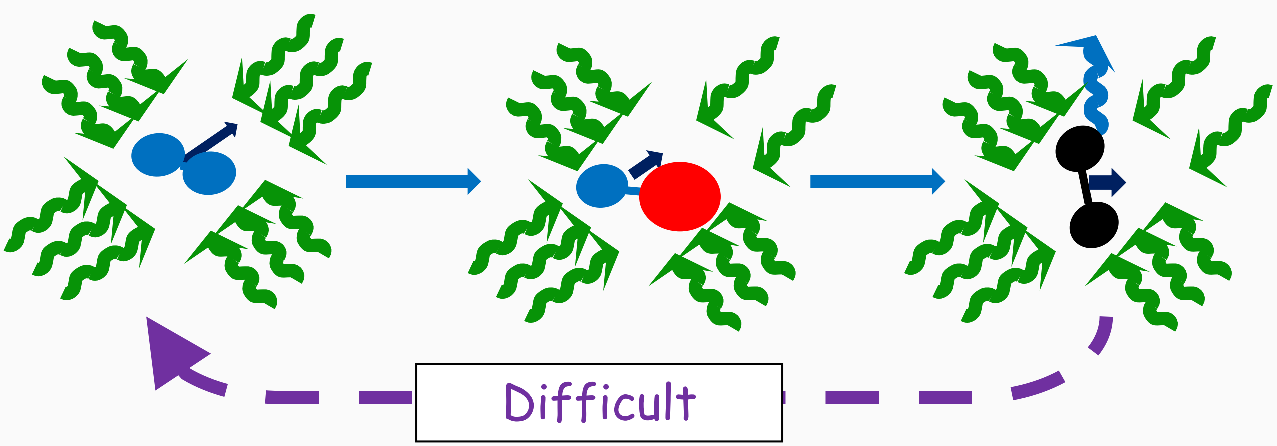
LASER COOLING OF MOLECULES: POSSIBLE?

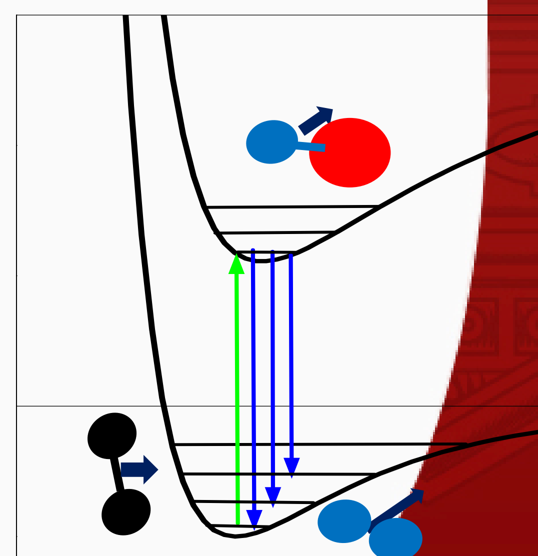
Laser cooling of atoms: many absorption-spontaneous emission cycles





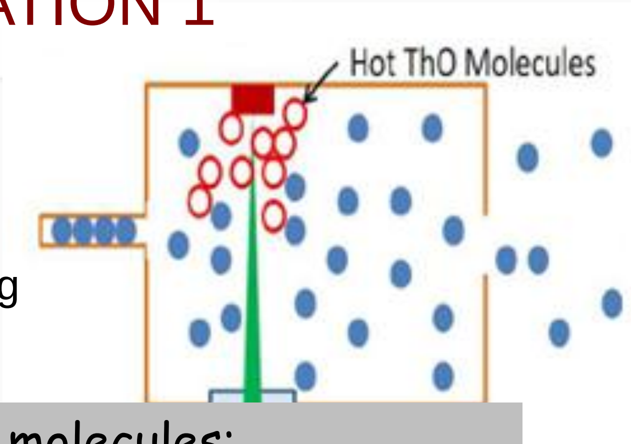
Laser cooling of molecules?





COLD MOLECULE FORMATION 1

from molecules



- Cryogenic method: Buffer gas cooling + magnetic trapping

  CaH, PbO, O_2,ND_3, … (Doyle, Harvard 1998)

Recent achievements in direct laser cooling of molecules:

- **Trasverse laser cooling and longitudinal slowing of SrF**

E. Shuman, J. Barry and D. DeMille, Nature (7317), 820 (2010).

- **2-D magneto-optical trapping of YO**

M.T. Hummon, M. Yeo, B.K. Stuhl, A.L. Collopy, Y. Xia and J. Ye, 2012

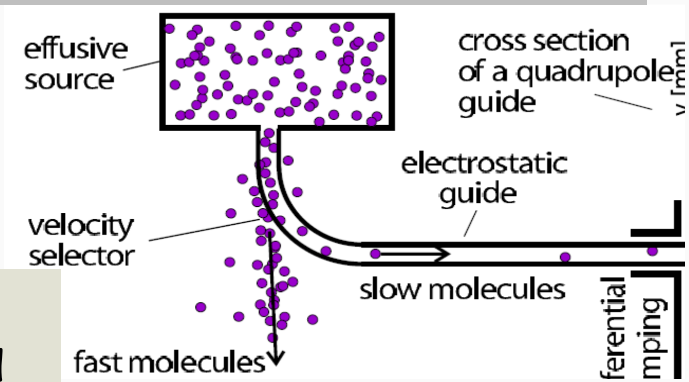
beam

han)

H_2

- Velocity filtering by molecule guiding

  H_2CO, CH_3F, H_2O, ... (G. Rempe 2004)



- Translational temperature ~ K-mK
- Vibrational and rotational temperatures ~ cold

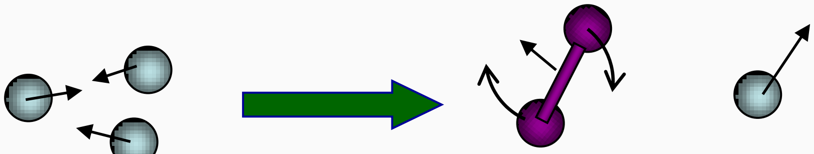
COLD MOLECULE FORMATION 2

from pre-cooled atoms

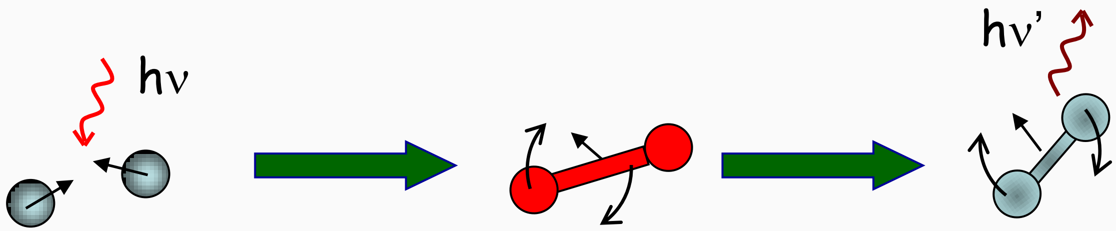
(Cs_2, K_2, Rb_2, RbCs, KRb, LiCs, NaCs…)

- Magneto-association (Feshbach resonance)

- 3-Body Collision



- Photo-association



- Temperature (speed) ~ atomic temperature ~ ultracold (nK-μK)
- Vibrational temperature ~ HOT
- rotational temperature ~ cold but several levels occupied

SUMMARY OF REQUIREMENTS

From molecules

- Motion

  Temperatures ~ mK-K

- Vibration and rotation:

  In general cold but **many** levels are occupied

From cold atoms

- Motion
  - Temperatures ~ nK-mK

- Vibration: very excited and/or many levels occupied
- Rotation: low but several levels occupied

AIM

Control and cool all degrees of freedom

EXTERNAL:

Motion, position

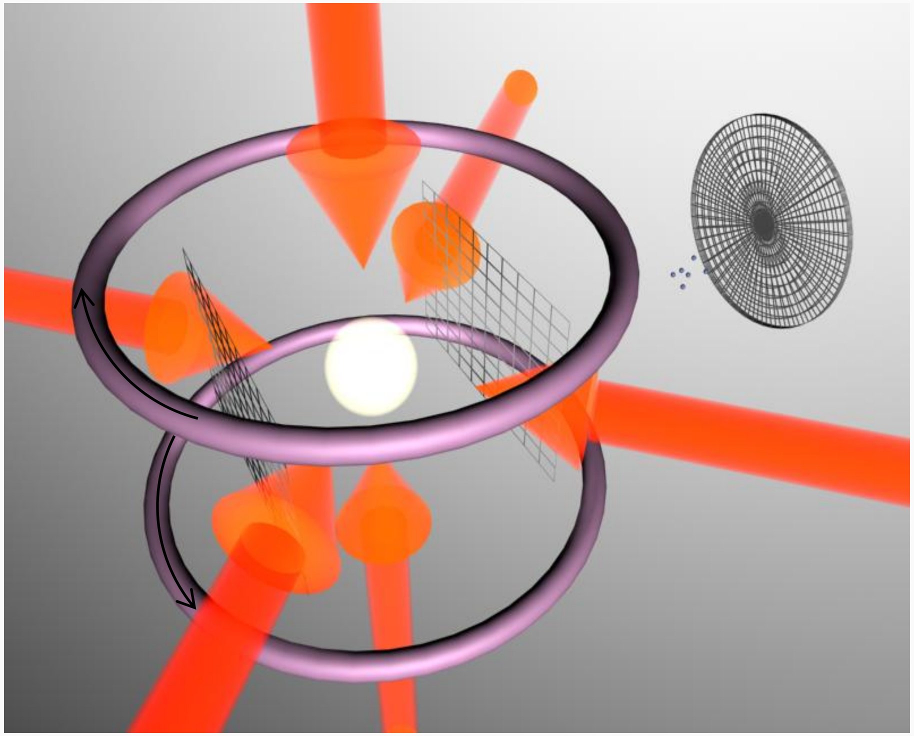
INTERNAL:

electronic state, vibrational, rotational and hyperfine level

EXPERIMENT

Work horse: a cesium magneto-optical trap MOT

N~ 5 $\cdot 10^7$ atomes, n $\sim 10^{11}$at/cm^3 , T~100µK



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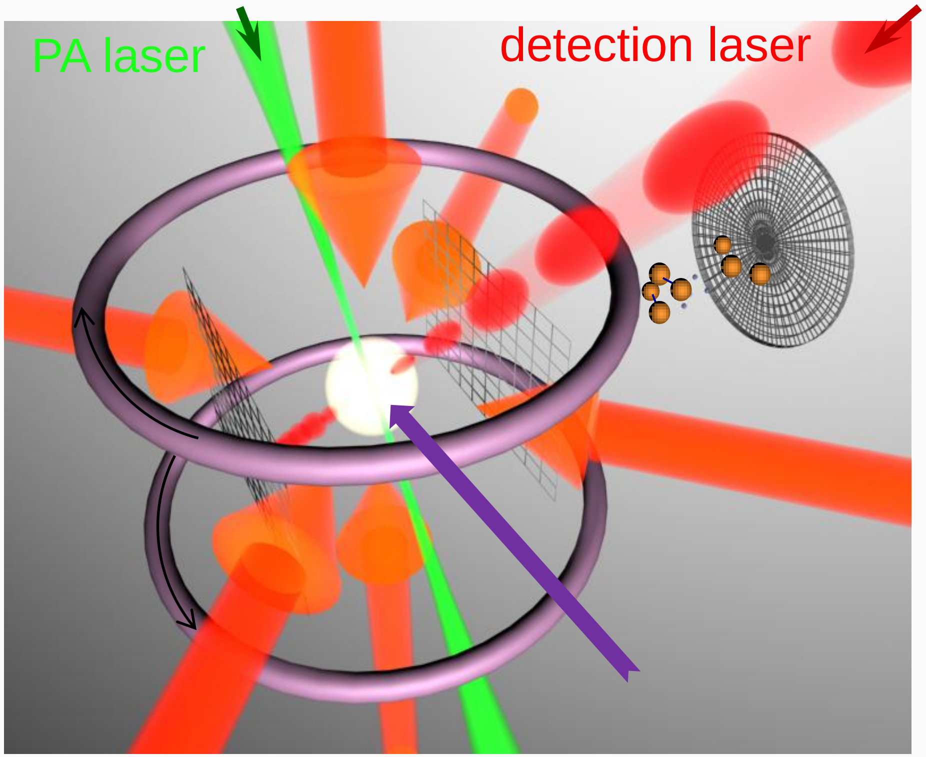
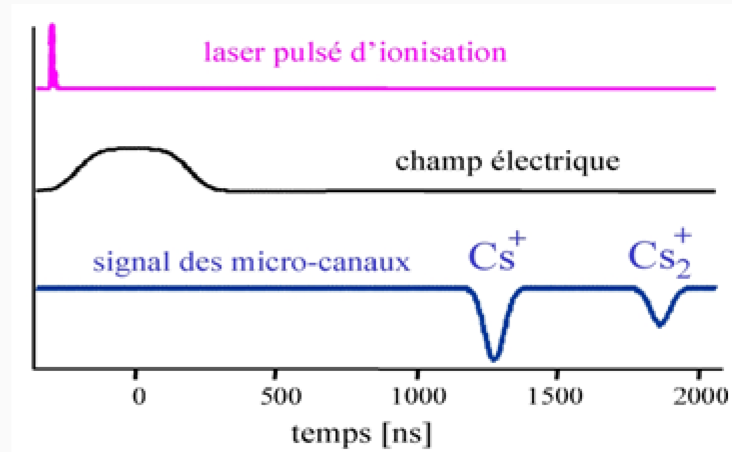
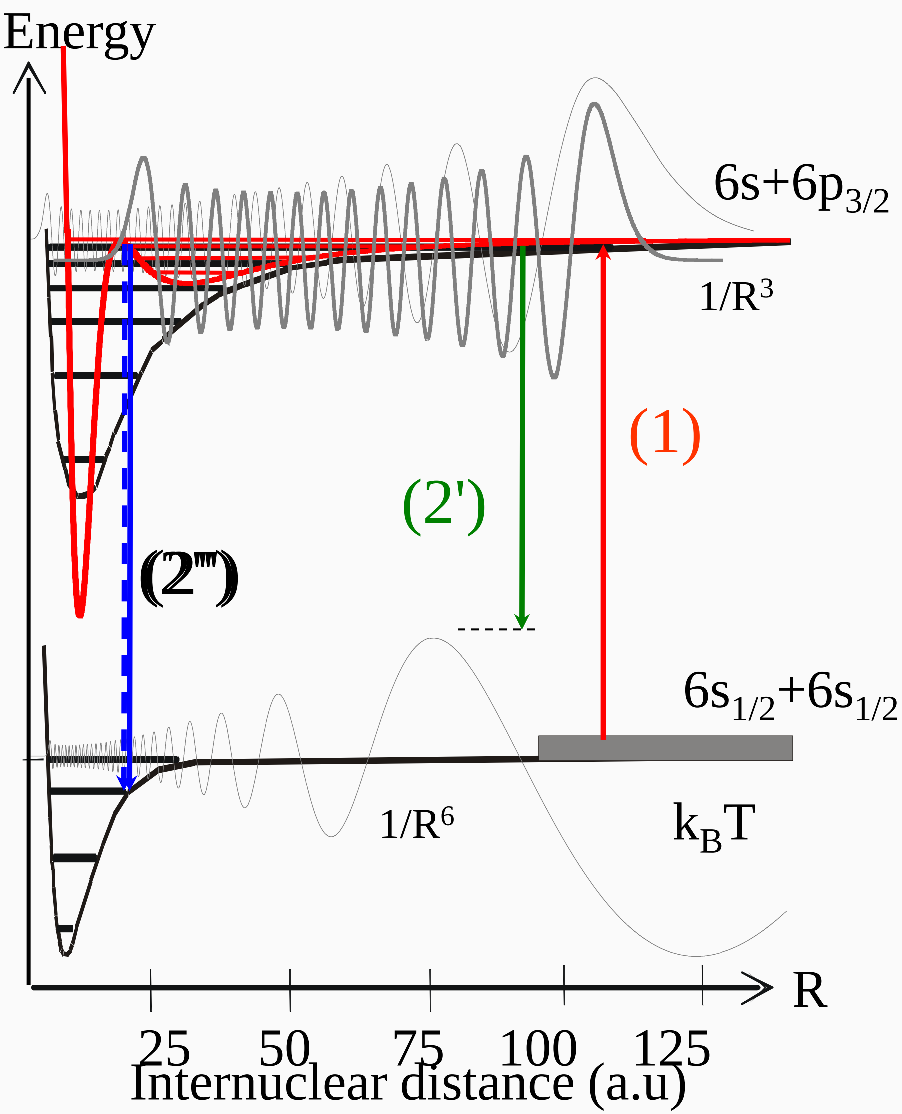




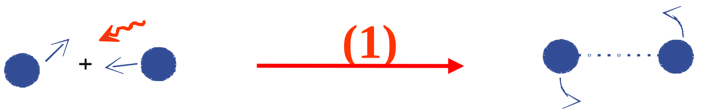
- MOT: diode lasers, cw, 852nm, 150mW, frequency stabilized <1MHz
- PA: Ti:Saphire cw, 852 nm, ~1W, linewidth ≤ 1MHz
- Detection (ionisation): pulsed laser 10 Hz-7ns, 5-10mJ/pulse

-Vibrational cooling: broadband (femtosecond) laser, 80MHz, 770 nm, 1W (but other choices are possible)

PHOTOASSOCIATION

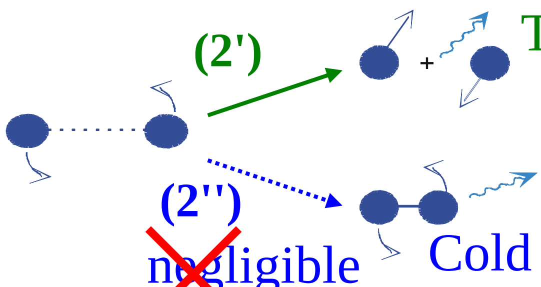


Photoassociation



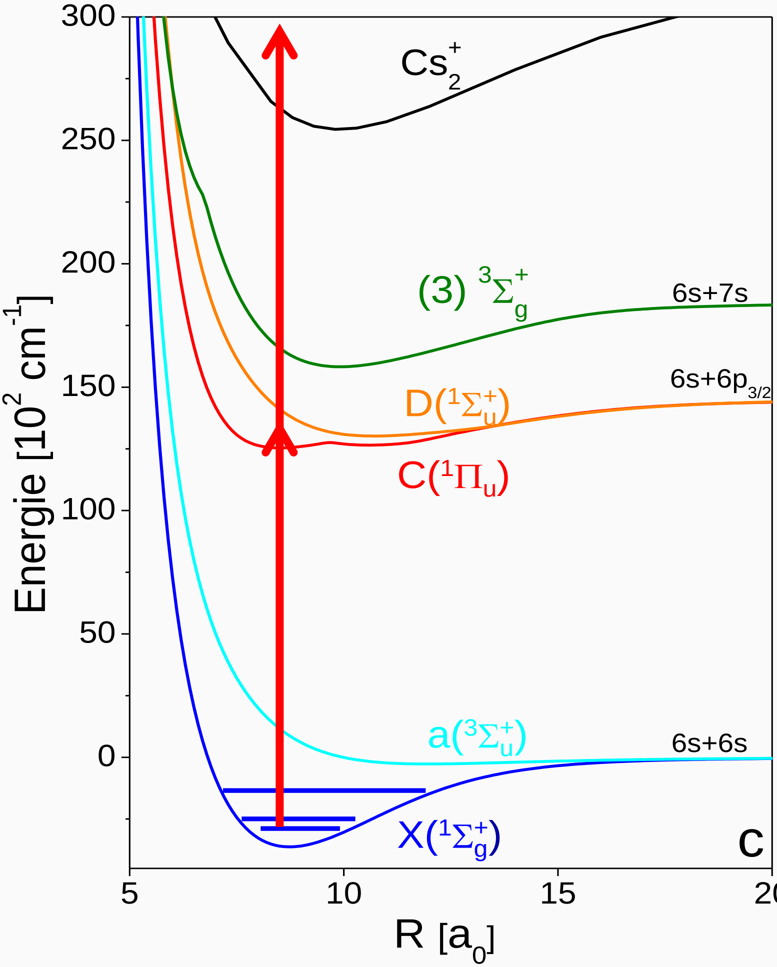
Resonant absorption of one photon by 2 colliding cold atoms (T~100µK)

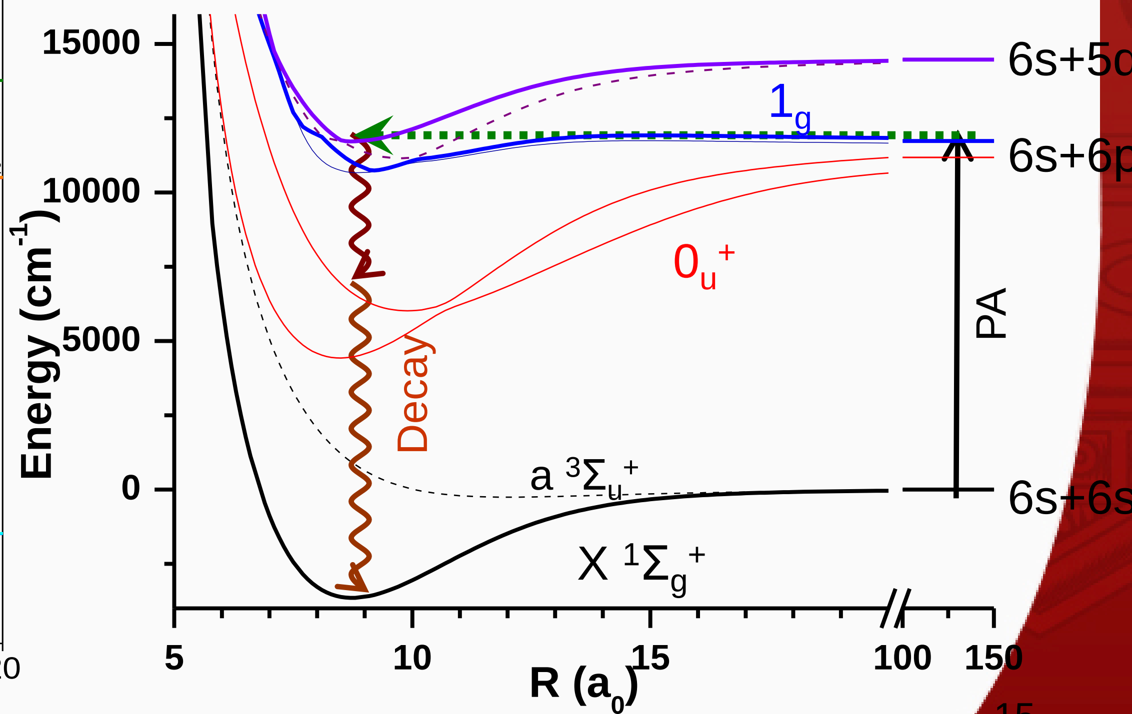
Emission



PA: FORMATION in the $X^1\Sigma_g^+$ state

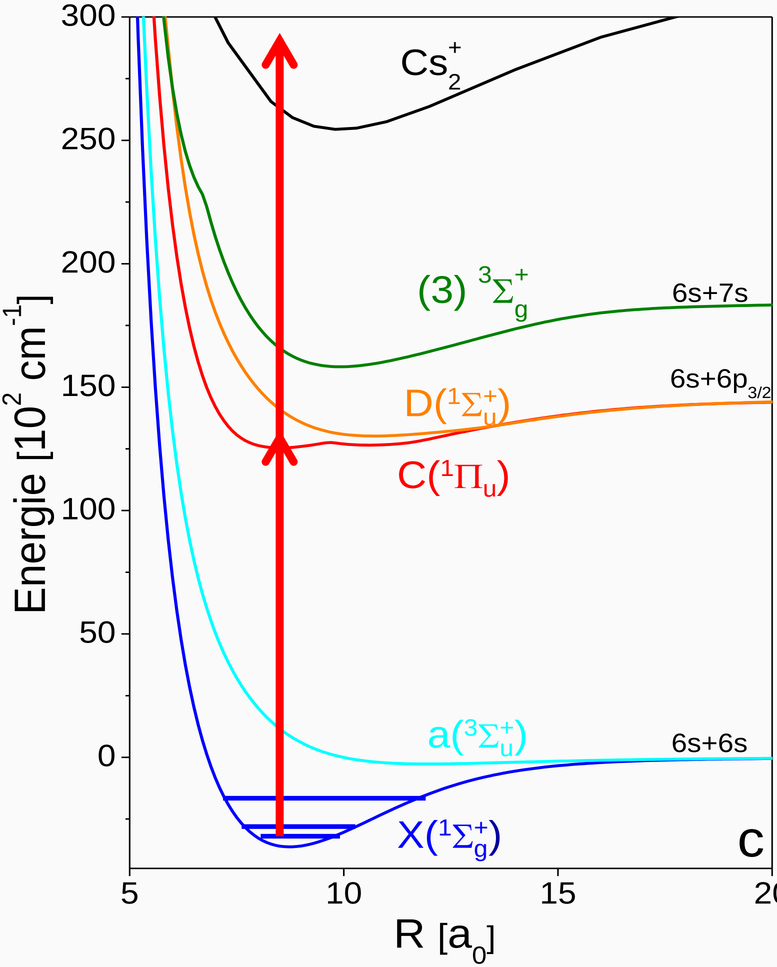
- Vibrationally selective detection: 2-photon ionization with resonant intermediate state (REMPI)

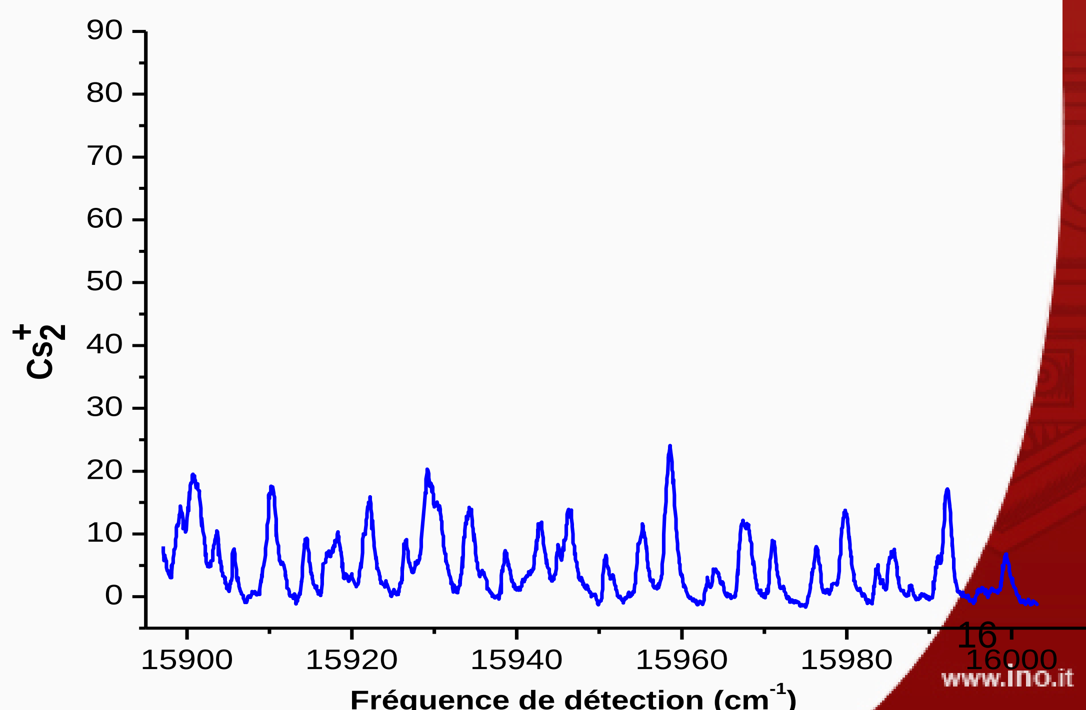




PA: DETECTION in the $X^1\Sigma_g^+$ state

- Vibrationally selective detection: 2-photon ionization with resonant intermediate state (REMPI)
- Scan of detection laser (pulsed)

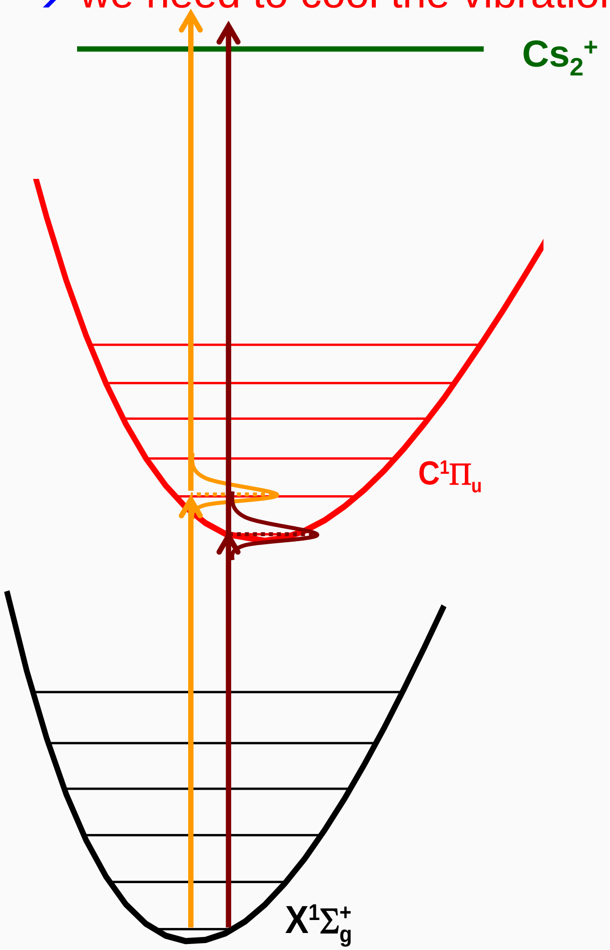


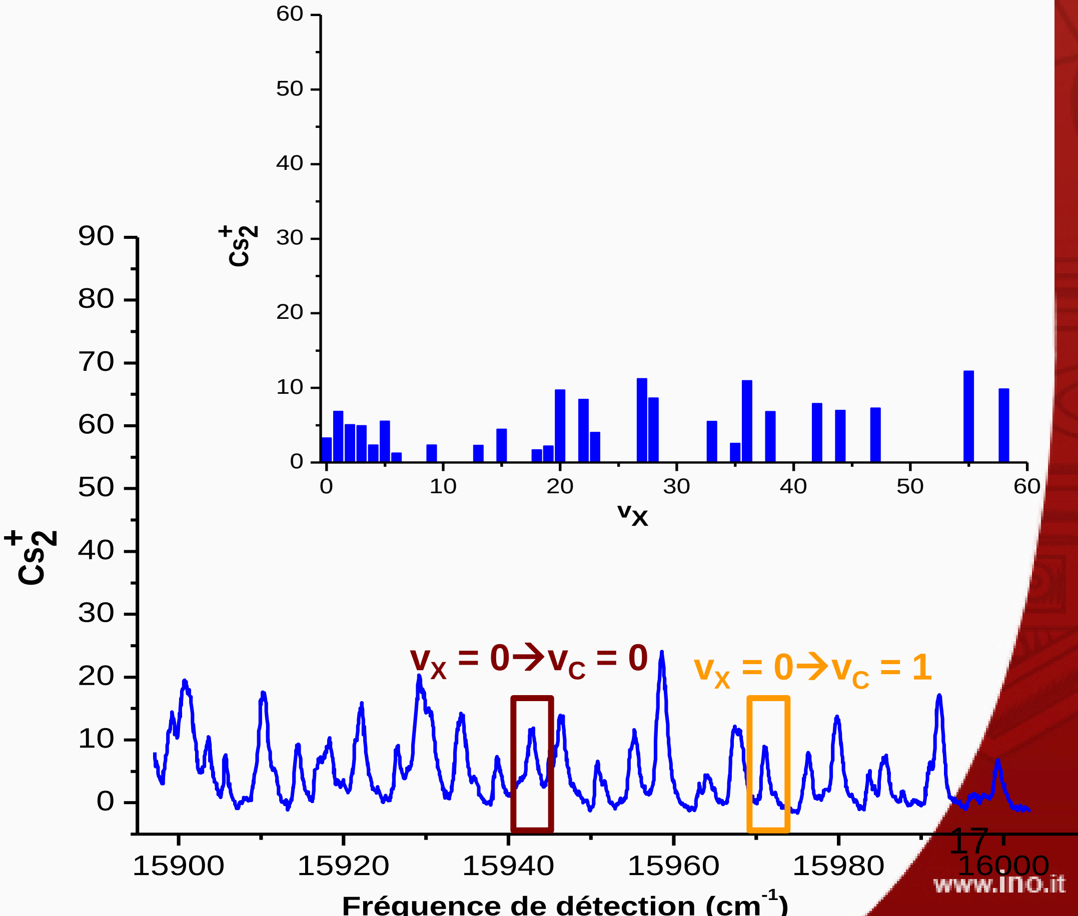


PA: DETECTION in the $X^1\Sigma_g^+$ state

→ several vibrational levels are populated

→ we need to cool the vibrational degree of freedom





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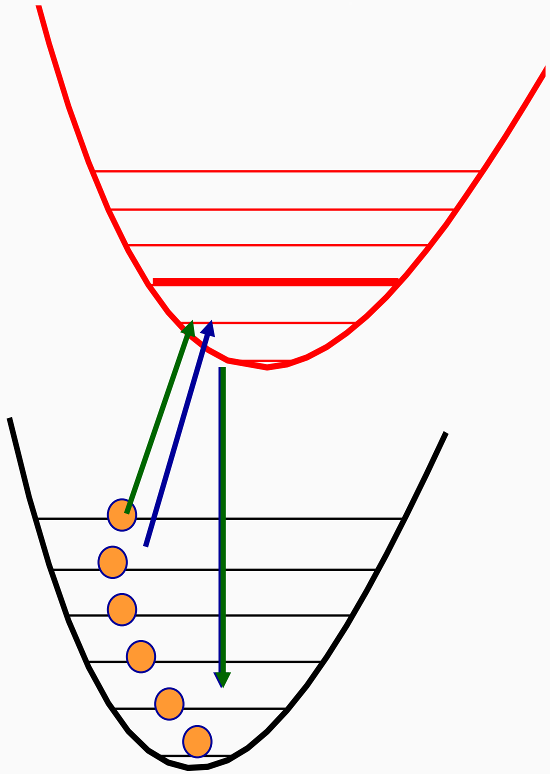
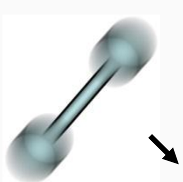
VIBRATIONAL COOLING 1: STIRAP method?

Very efficient to trasfer molecules already in a single level (i.e. Feshbach molecules): Cs_2, KRb, Rb_2

Not efficient to transfer molecules distributed over many levels



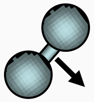
STIRAP



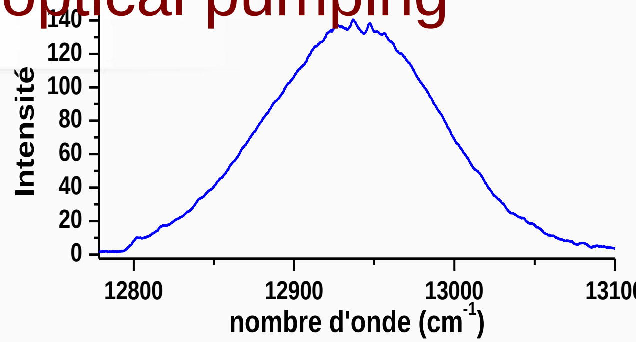
Traslationally cold
but
Vibrationally **HOT**

Our aim

Traslationally
and
Vibrationally
cold

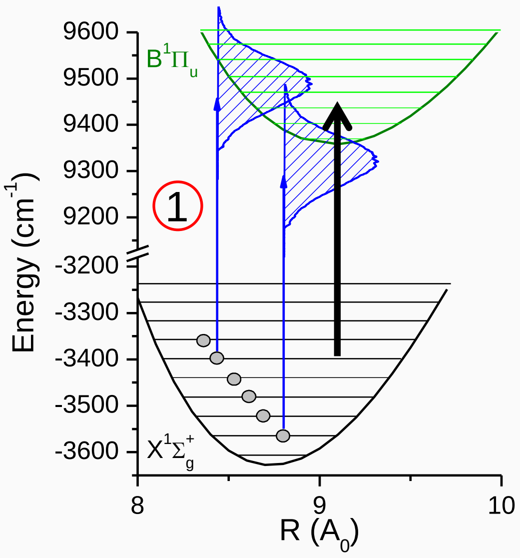


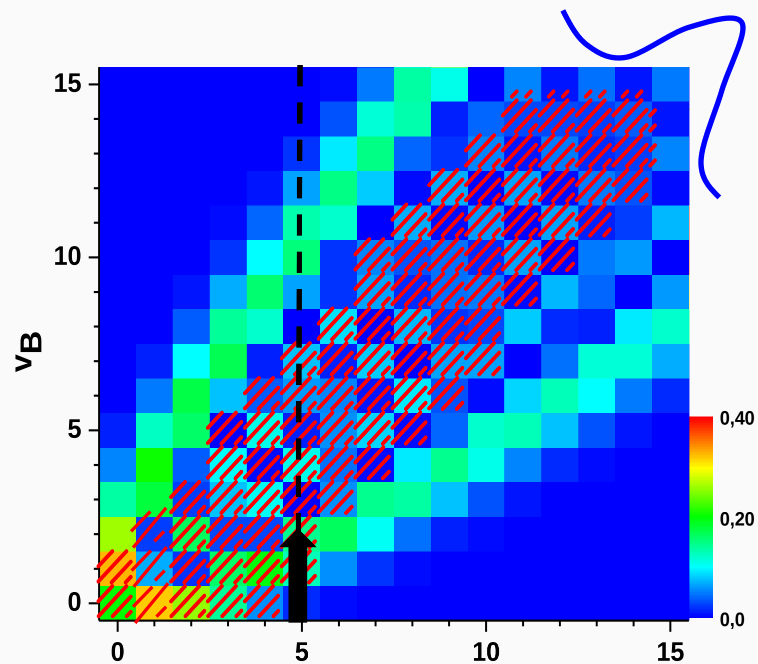
VIBRATIONAL COOLING 2: optical pumping



- Broadband laser(femtosecond laser: 200 cm^{-1})
  - →Excites all levels towards the target state B
  - →Excitation probability:

$$\Gamma_{v_X \to v_B} \propto FC[v_X][v_B] (D[v_X][v_B])^2 I_{laser}[v_X][v_B]$$





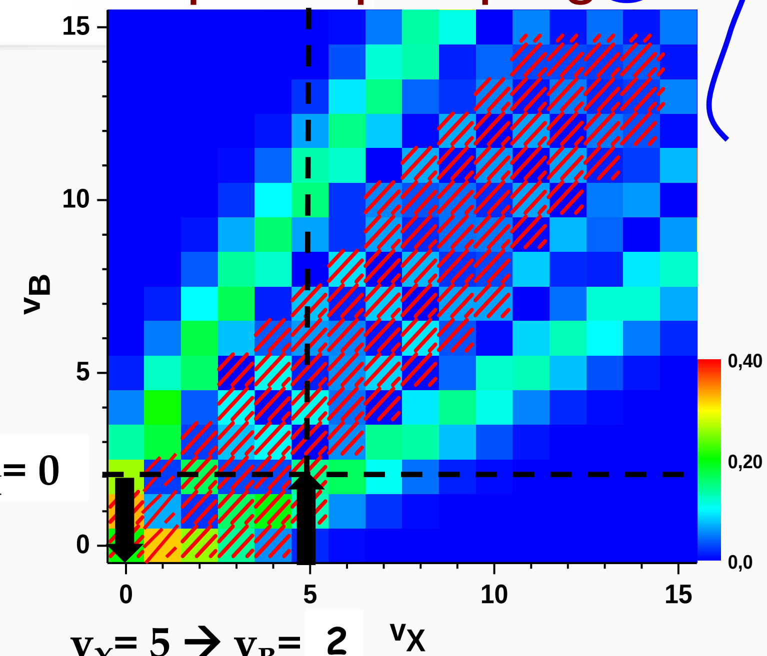
$v_X = 5 \to v_B = 2$

VIBRATIONAL COOLING 2: optical pumping

- Emission spontanée → Redistribution des molécules dans l'état X

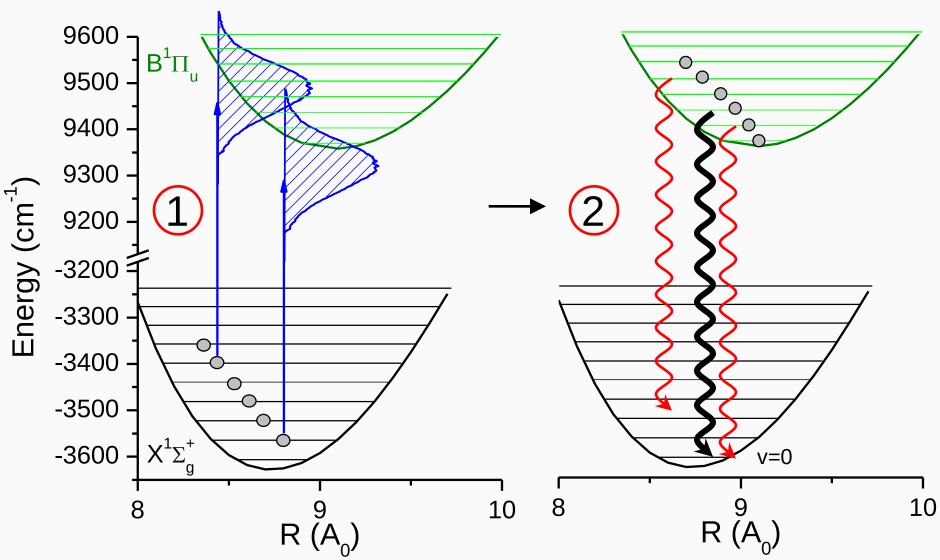
  →Probabilité de désexcitation :

$$\Gamma_{v_B \to v_X} \propto \boxed{FC[v_X][v_B]}(D[v_X][v_B])^2 \omega^3_{v_B \to v_X}$$

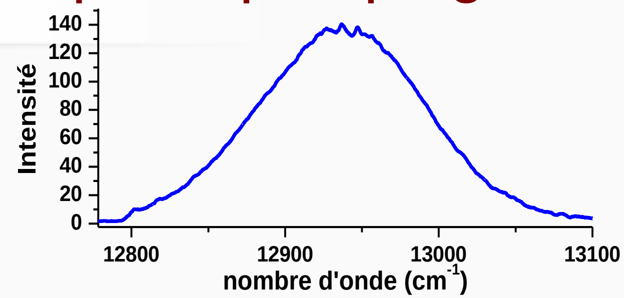


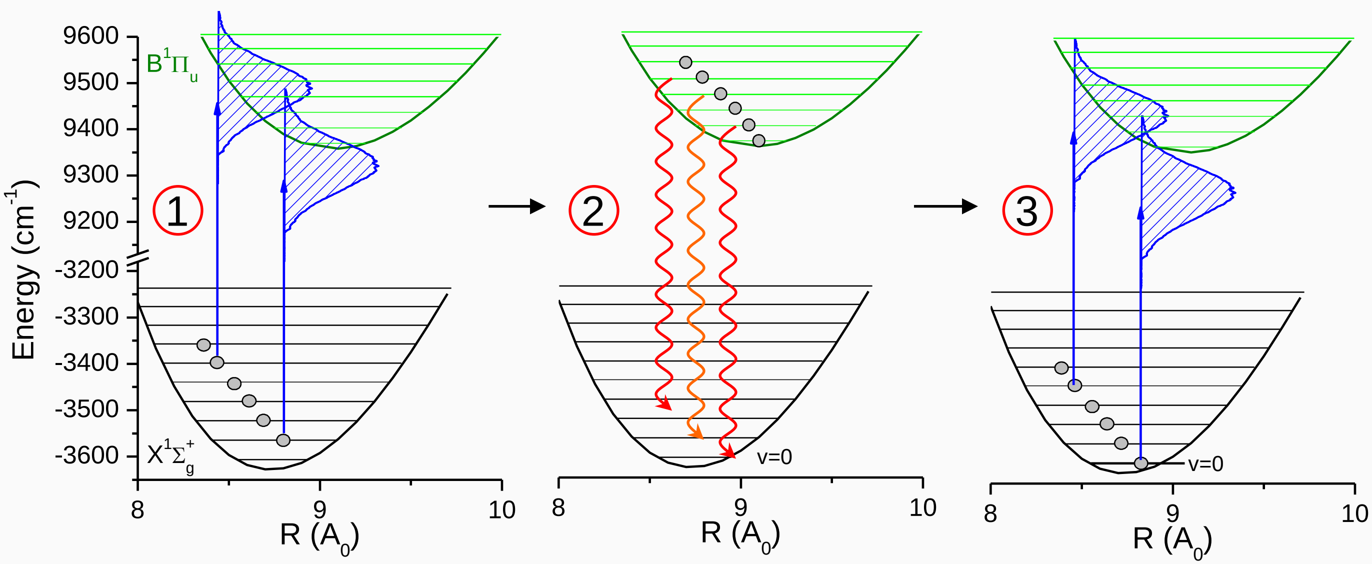
v_B=2 → v_X= 0

v_X= 5 → v_B= 2



VIBRATIONAL COOLING 2: optical pumping





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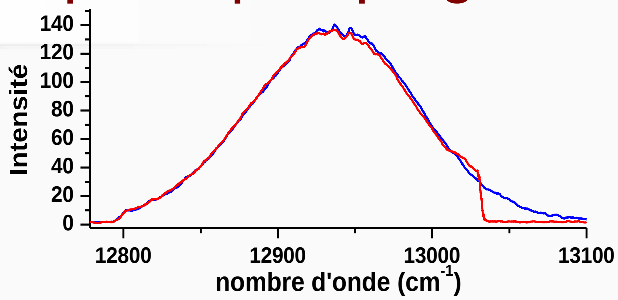
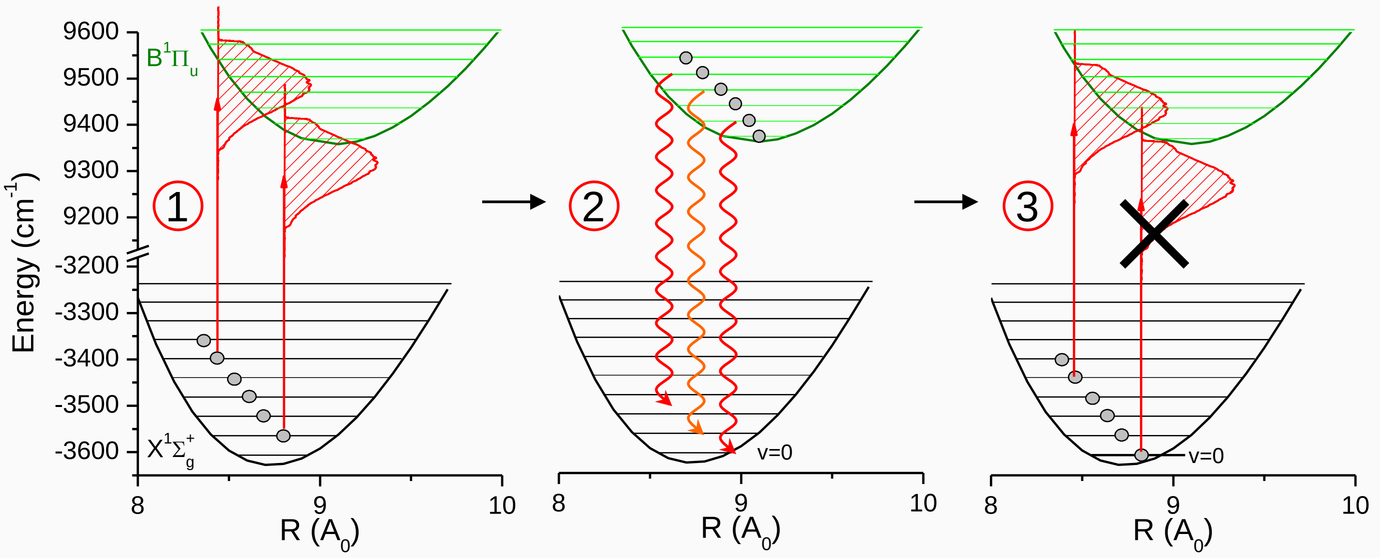


- Shaped broadband laser:
  no transition from v=0
  → **dark state**



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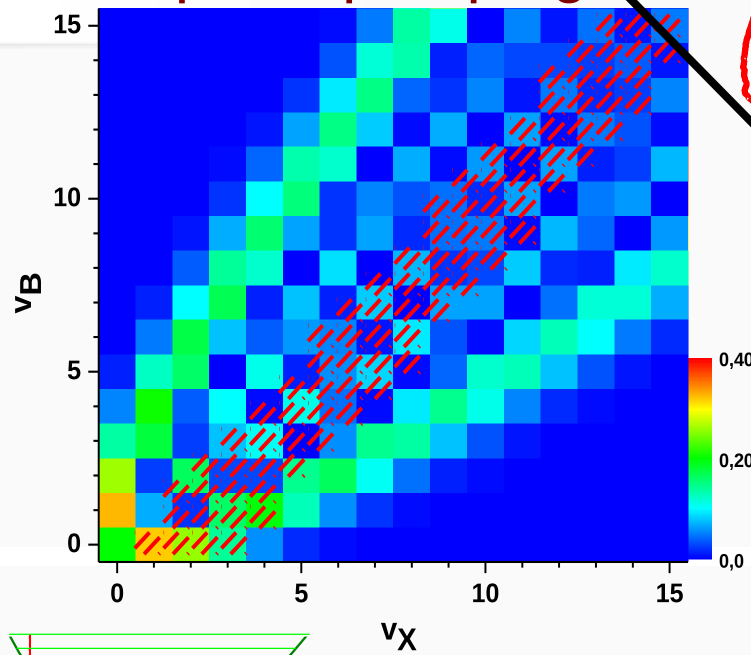

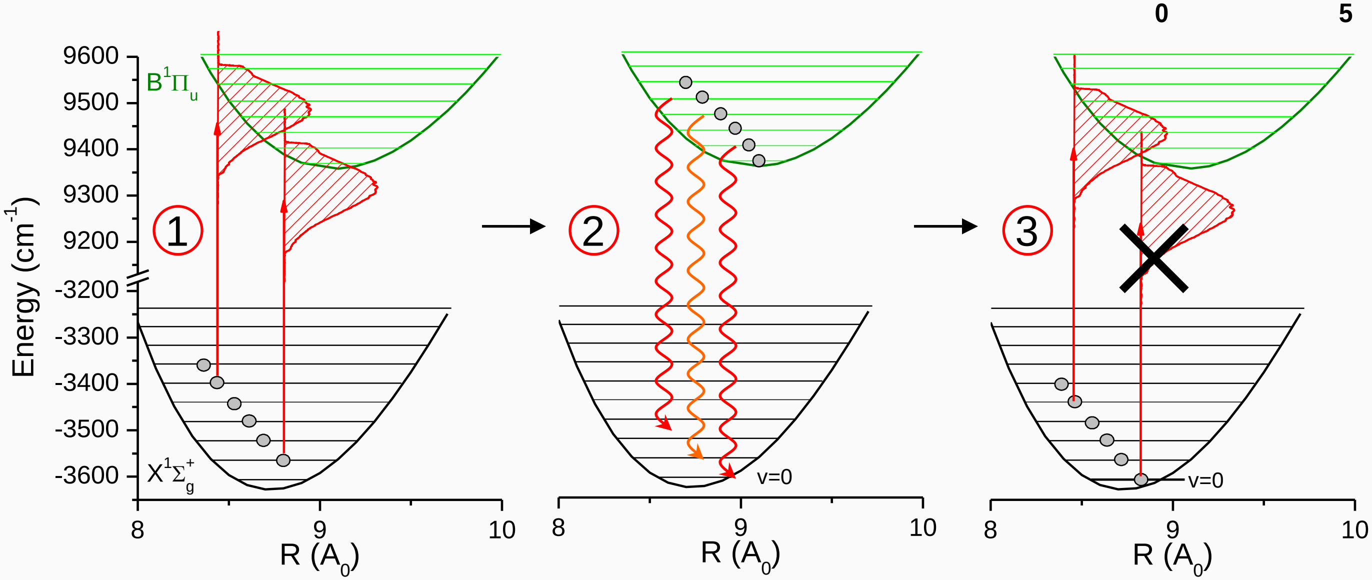

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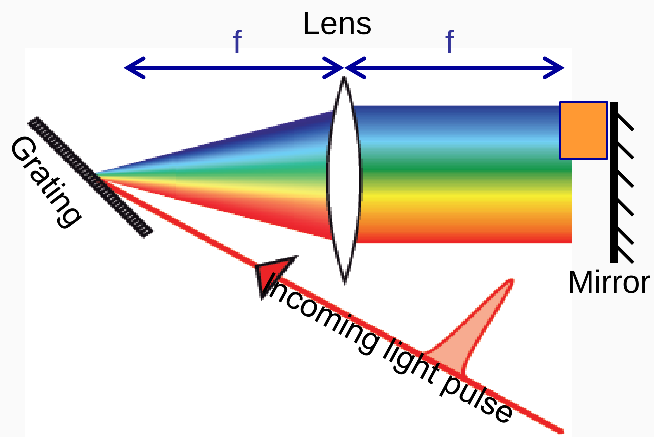
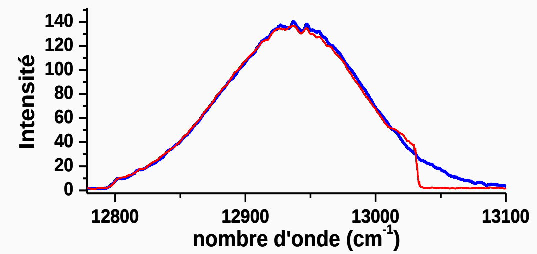
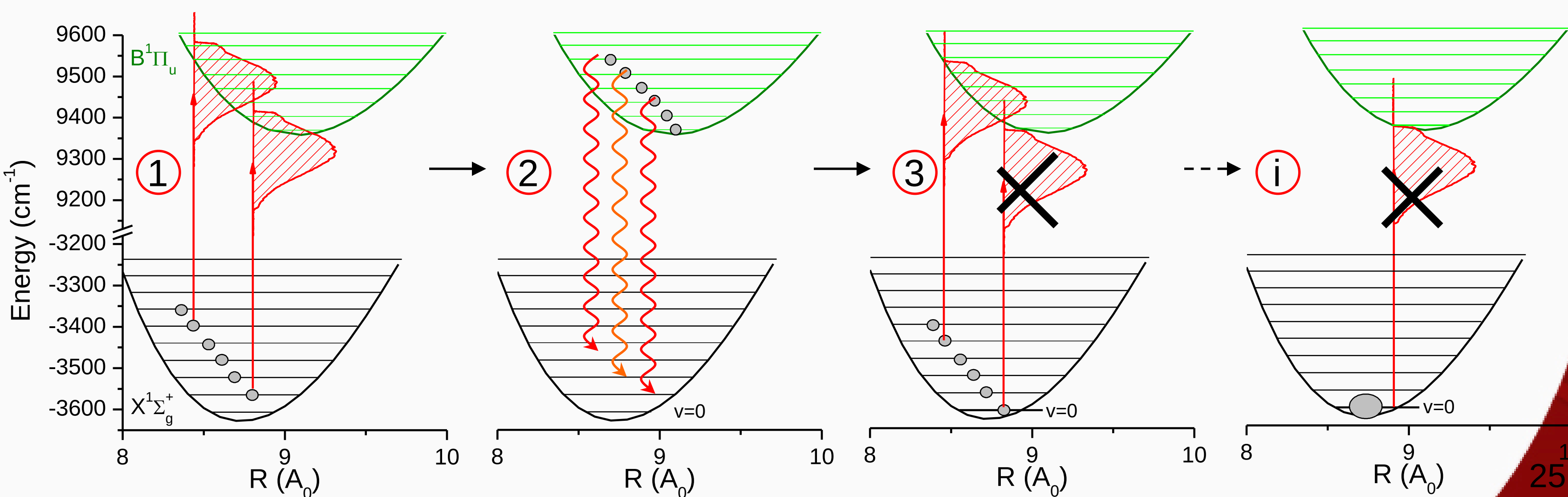
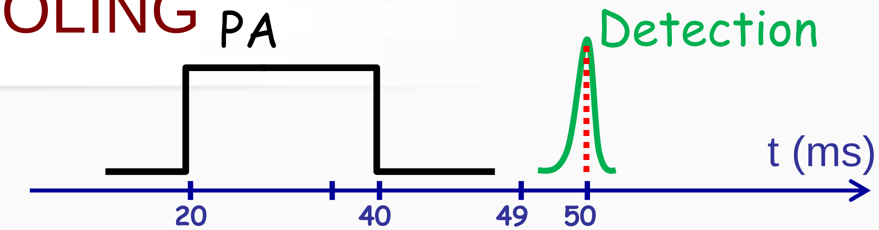


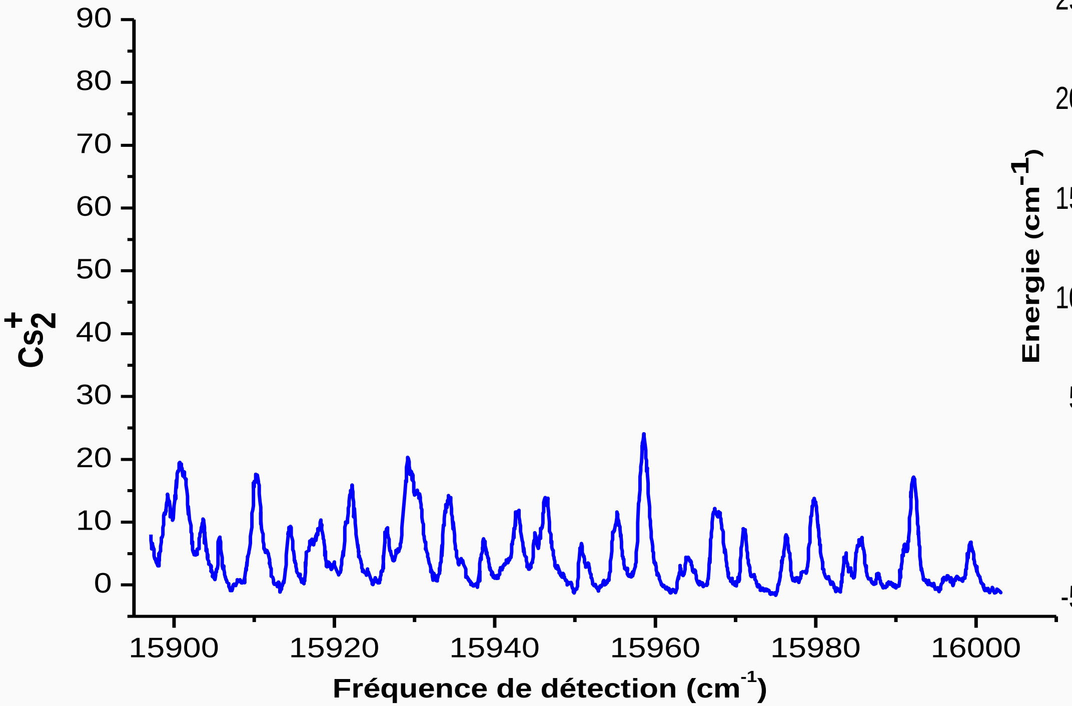


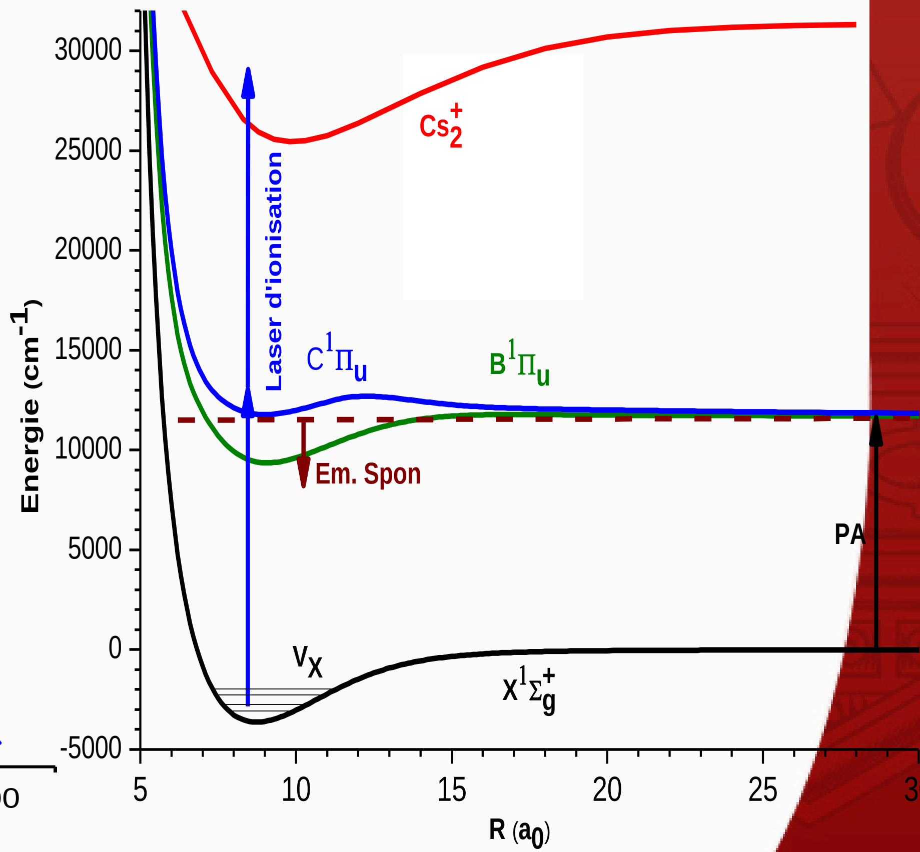


BEFORE VIBR-COOLING

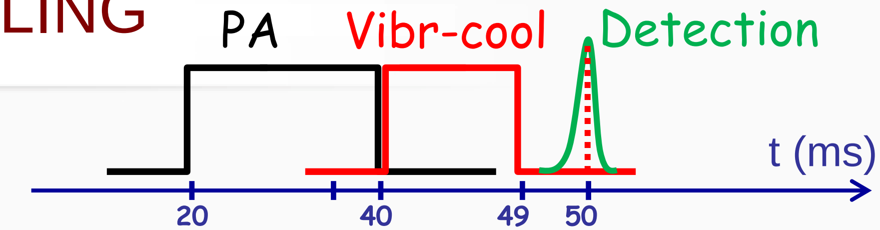


- Detection spectrum (via the C state)
  - → Molecules distributed over many vibrational levels





AFTER VIBR-COOLING

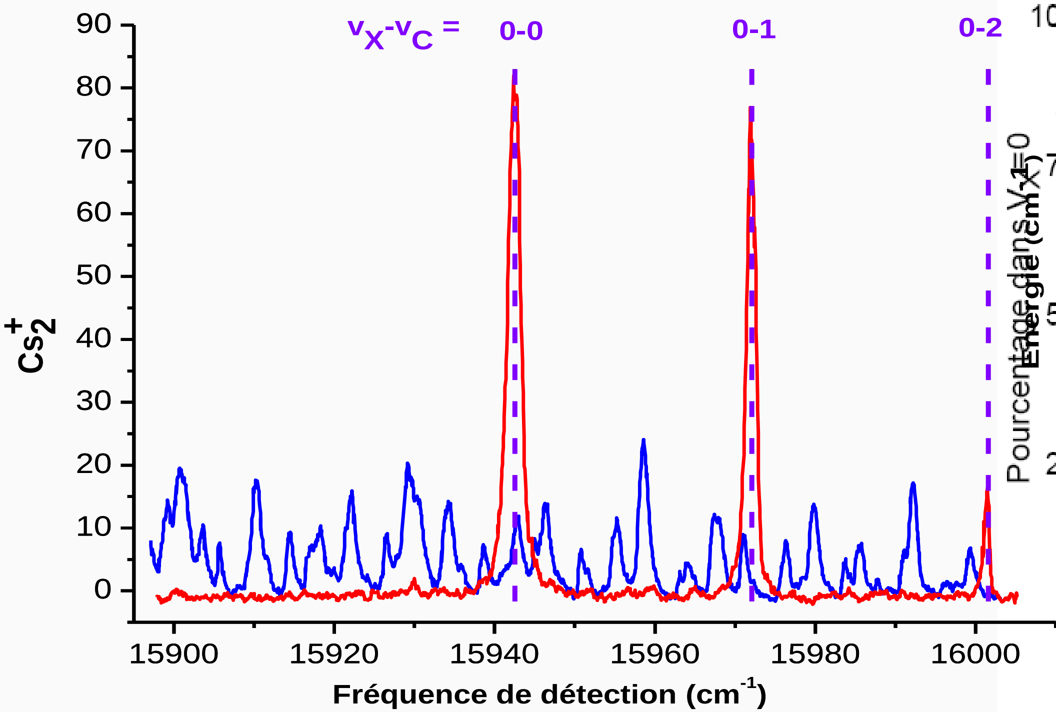


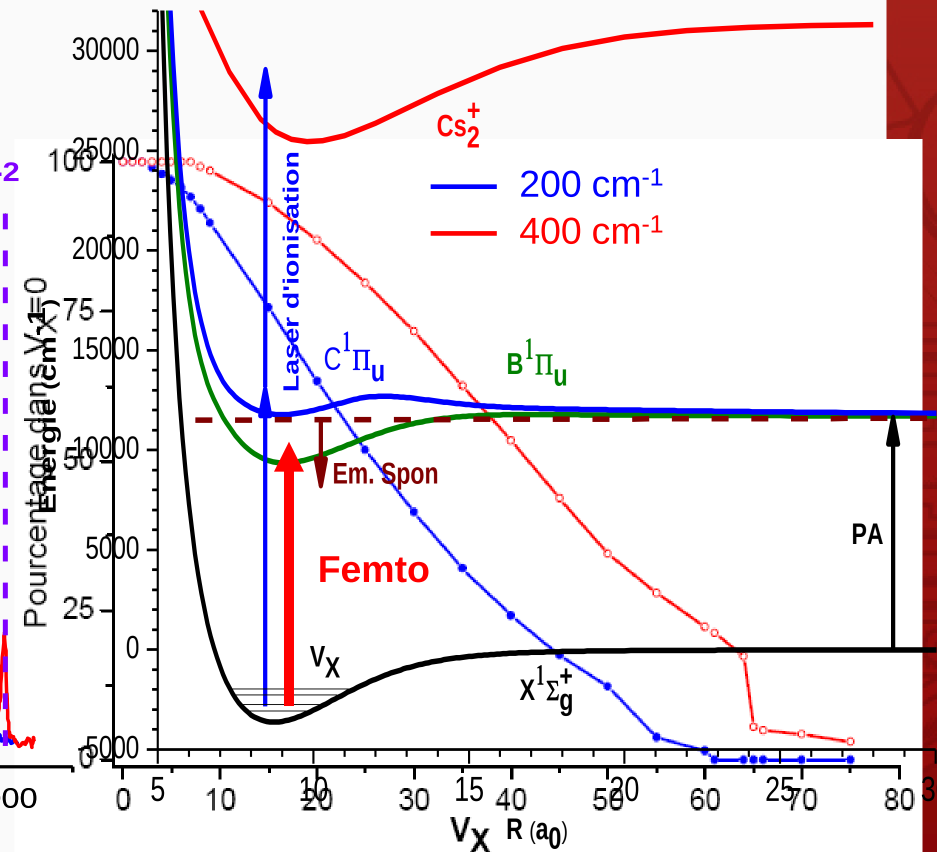
- With an optical pumping phase

Molecule pile up in the DARK state v=0

→Efficiency ~ 80 %

→limited also by spectral bandwidth of the laser





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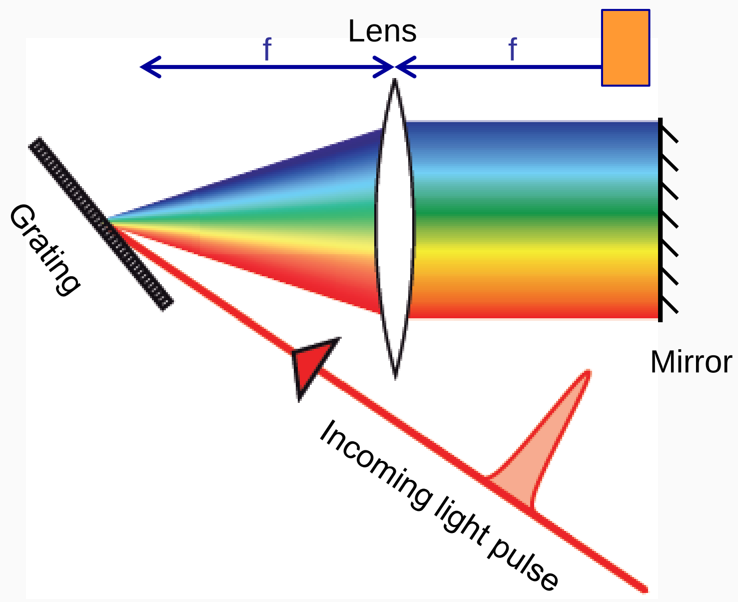
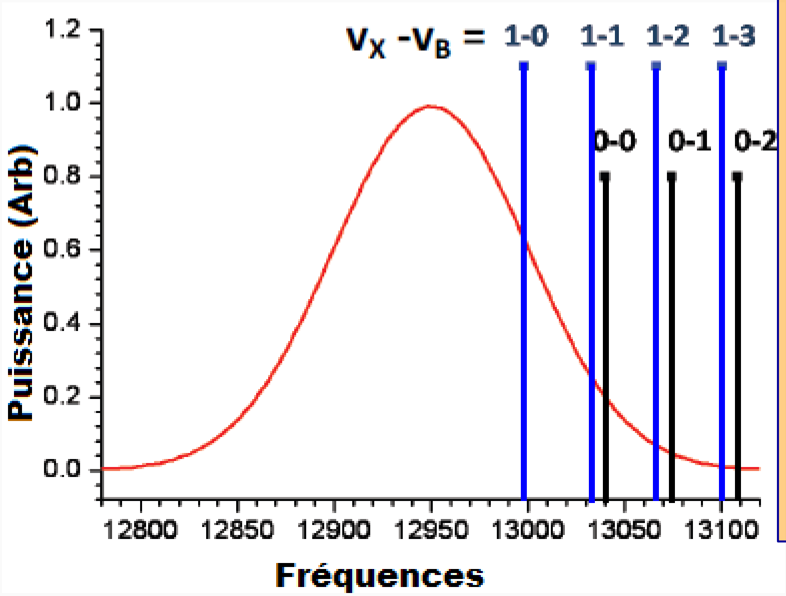
Pumping into a PRE-SELECTED LEVEL

How to accumulate molecules into another pre-selected level?

→ suppress ALL laser frequencies connecting the target level (example v=1) to excited states





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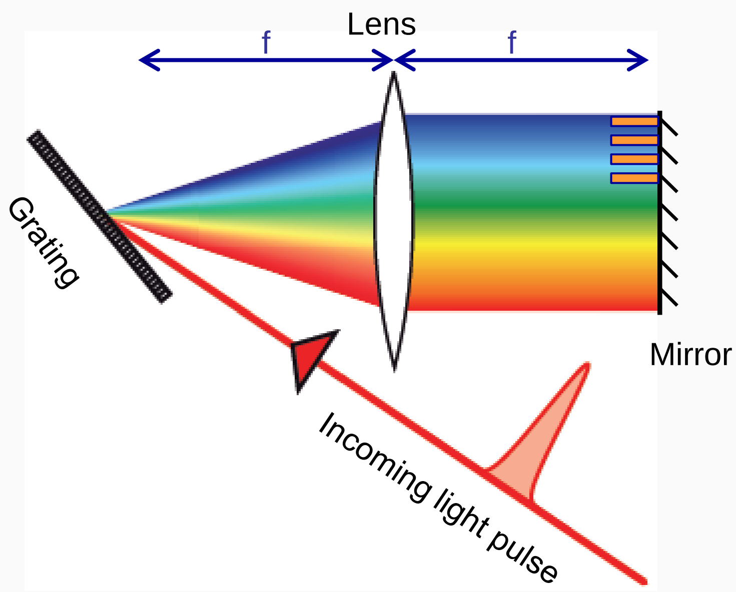

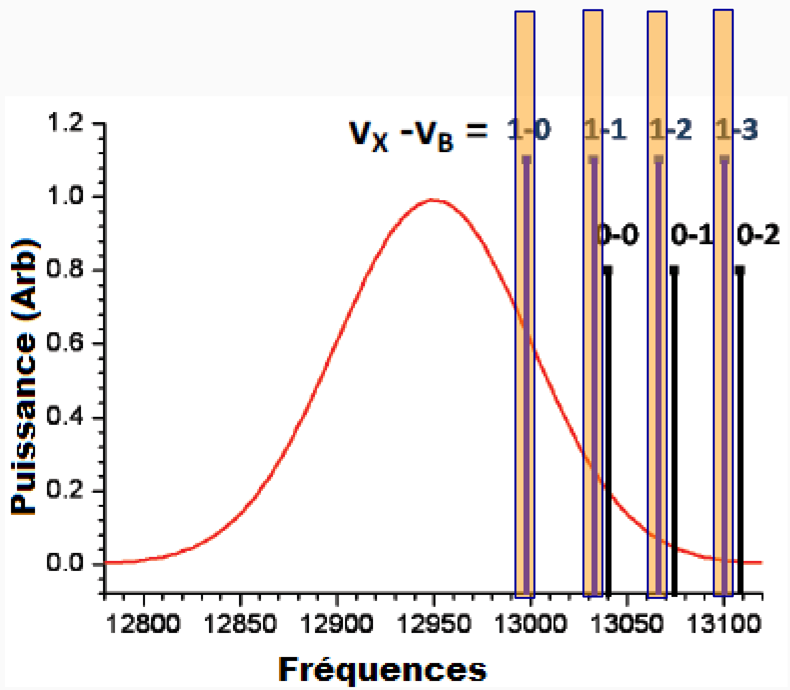

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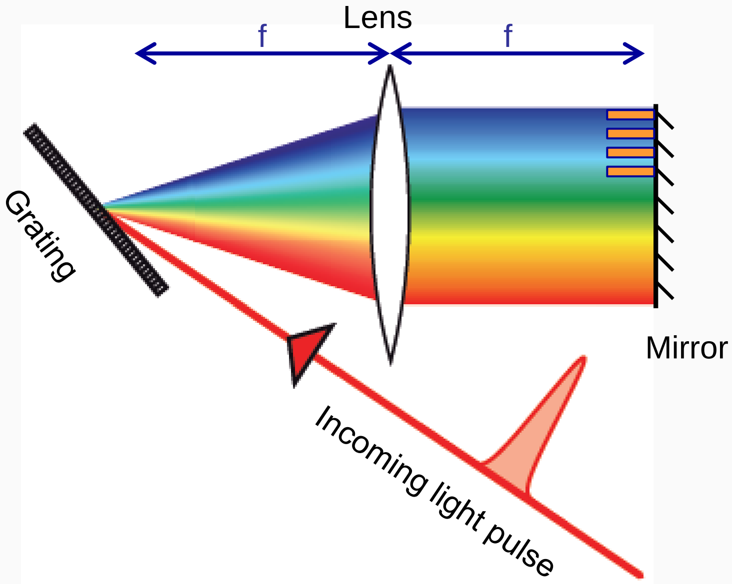
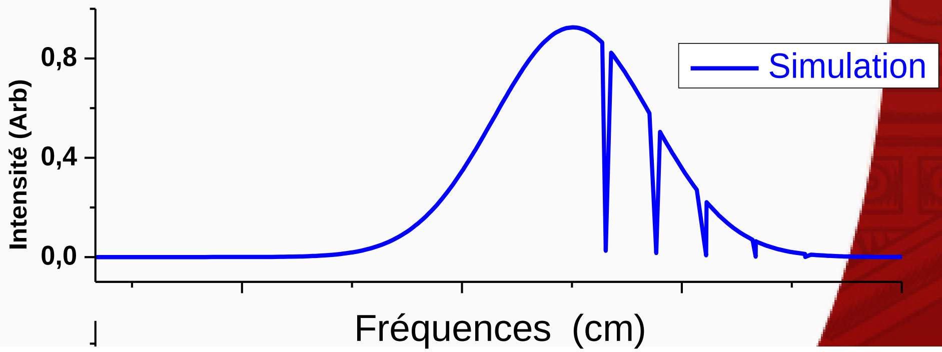




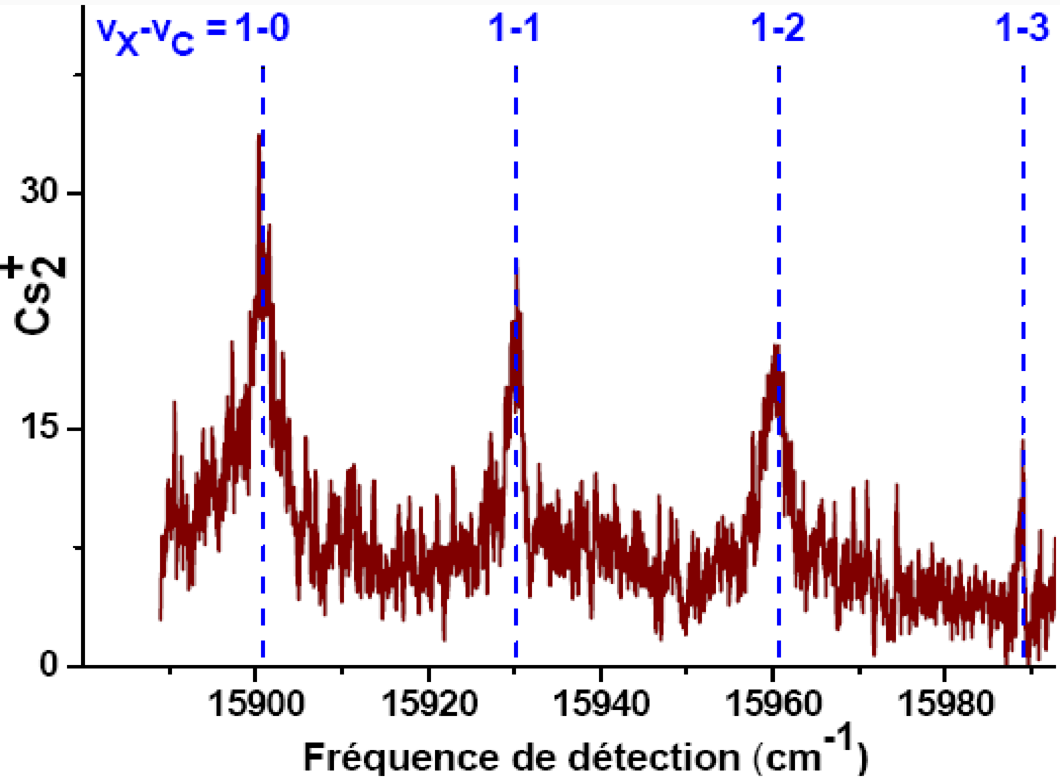
Pumping into a PRE-SELECTED LEVEL

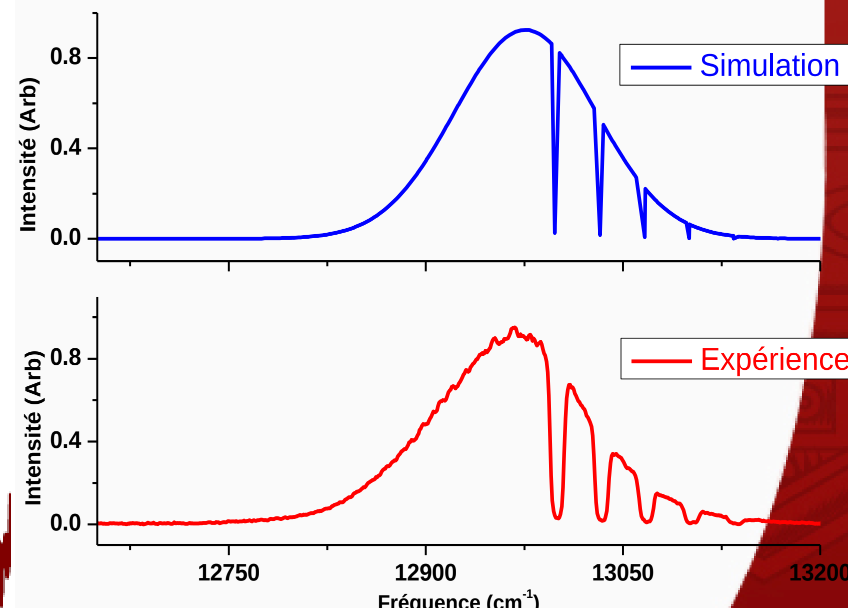
How to accummulate molecules into another pre-selected level?

→ suppress ALL laser frequencies connecting the target level (example v=1) to excited states

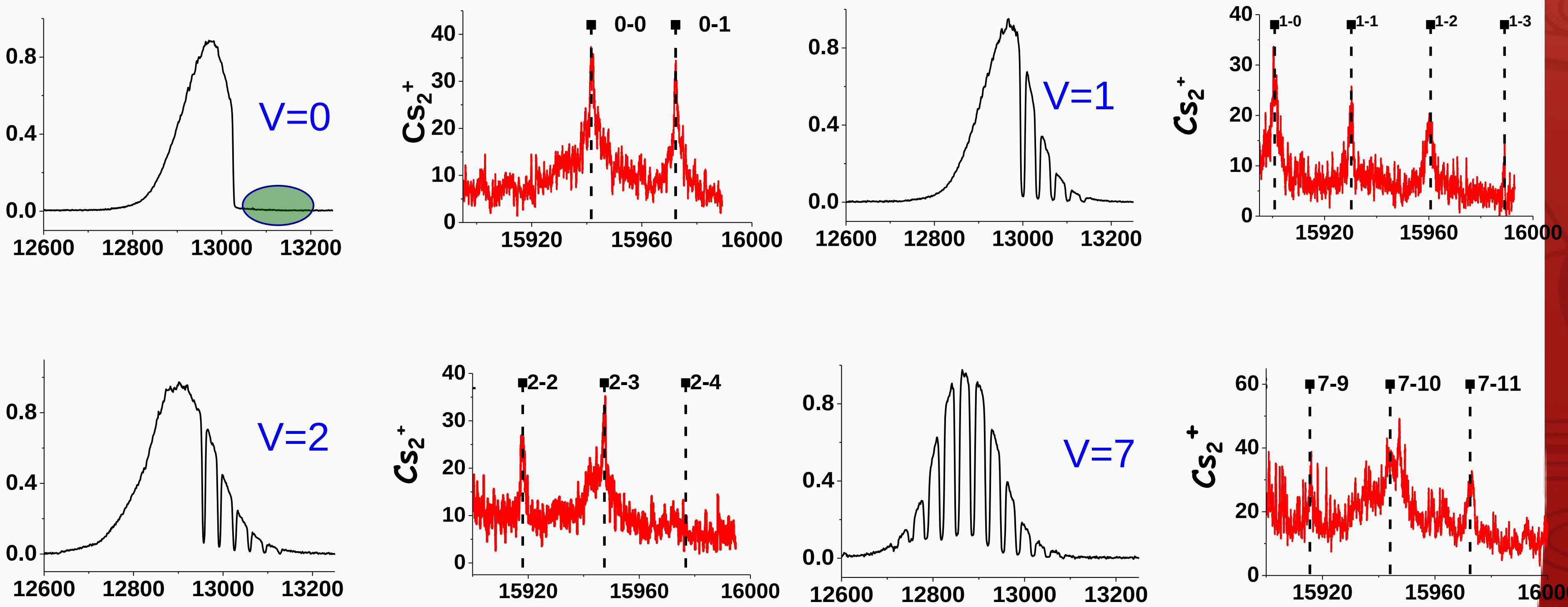
→different option to spectrally shape the laser

1) Liquid Crystal Spatial Light Modulator LC-SLM (collaboration with B. Chatel, Toulouse)
2) mechanical mask
3) micro-mirror array





Pumping into a PRE-SELECTED LEVEL



Efficiency ~ 50 % limited by :

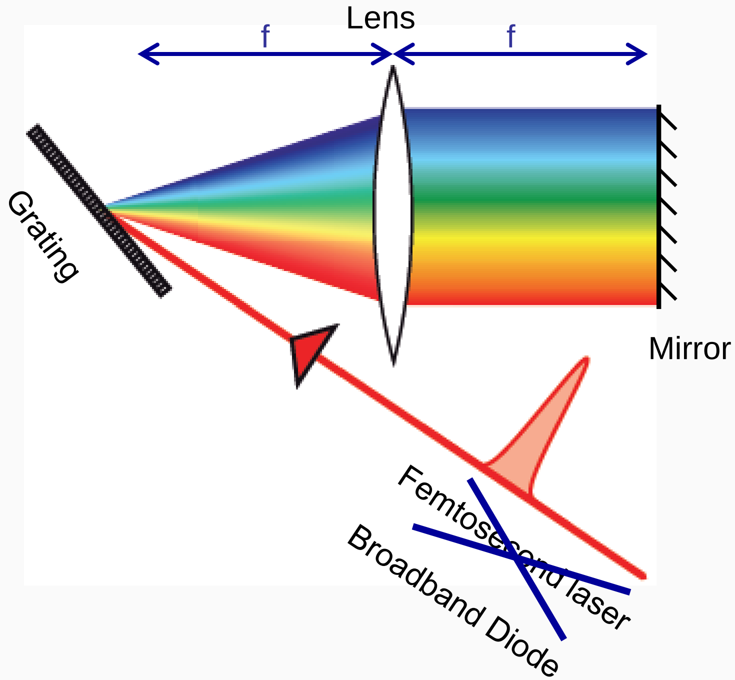
- Laser bandwidth
- SLM extinction ratio ~ 97%

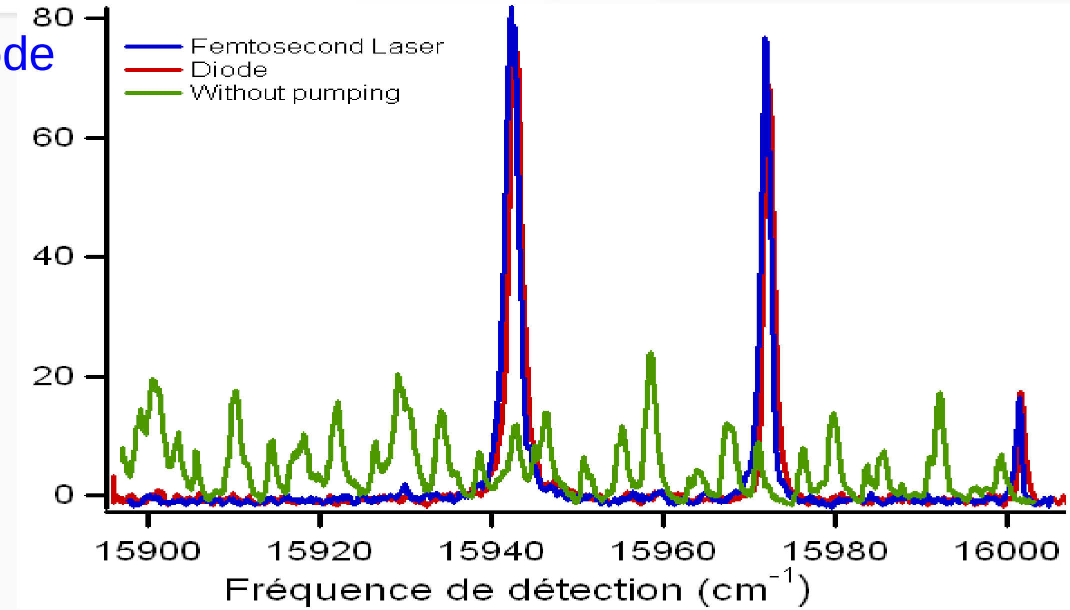
SLM resolution ~ 0,06nm = 0,8cm^{-1}@852nm

Vibrational spacing ~ 40cm^{-1}

VIBR-COOLING WITH INCOHERENT LIGHT

femtosecond laser → broadband diode





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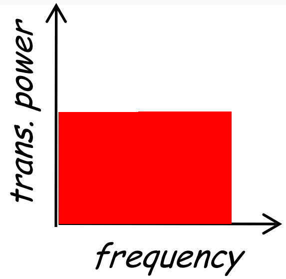
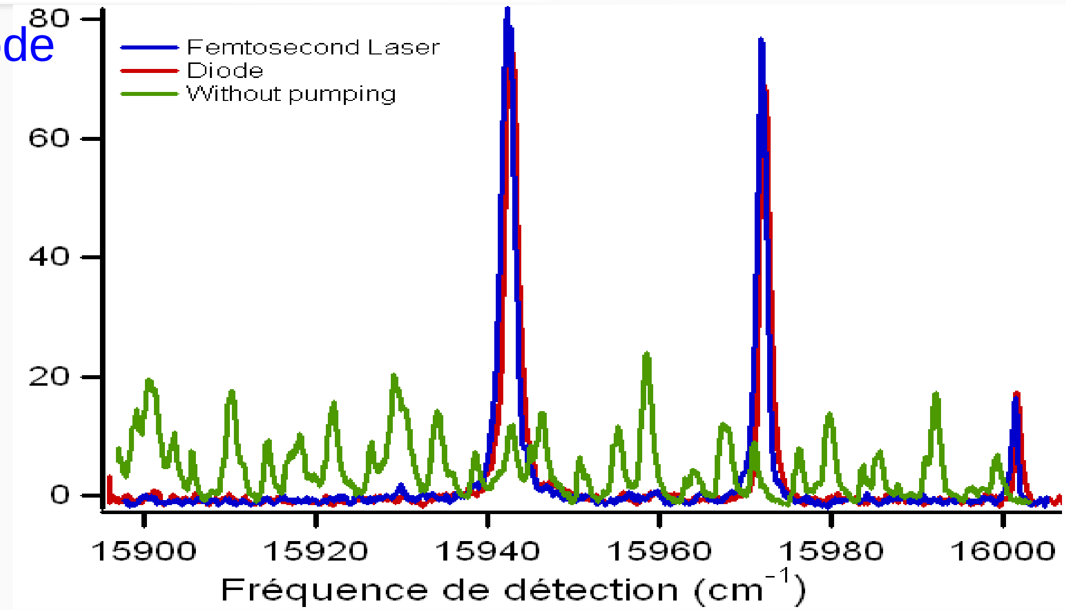
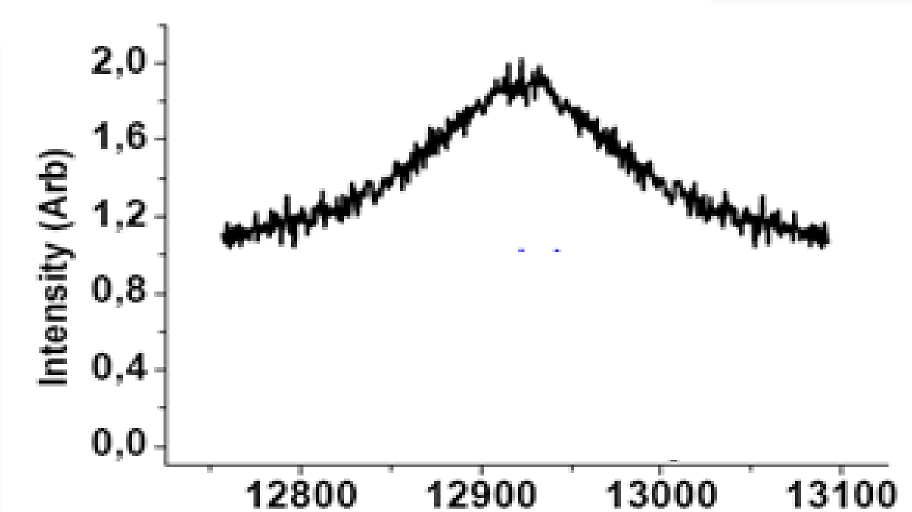
VIBR-COOLING WITH INCOHERENT LIGHT

femtosecond laser → broadband diode

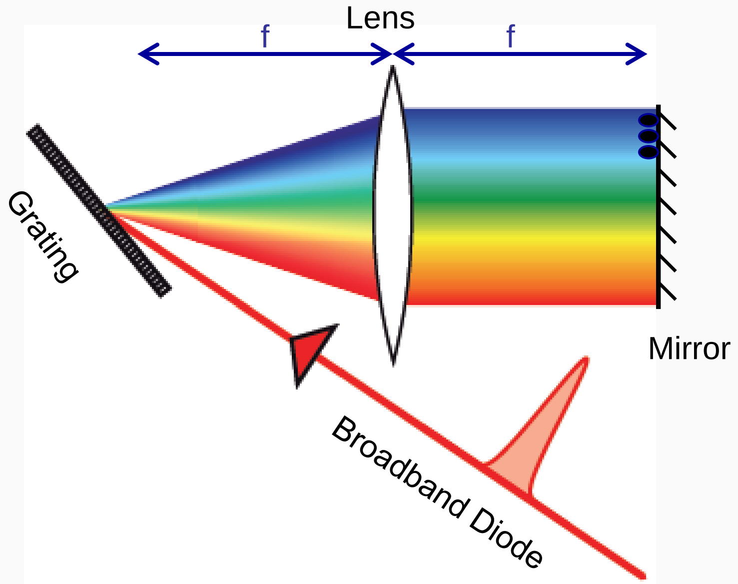


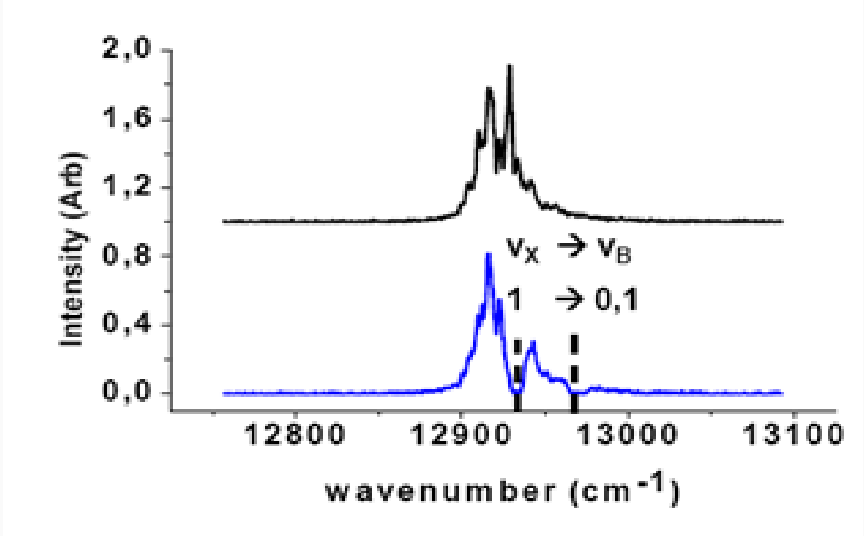




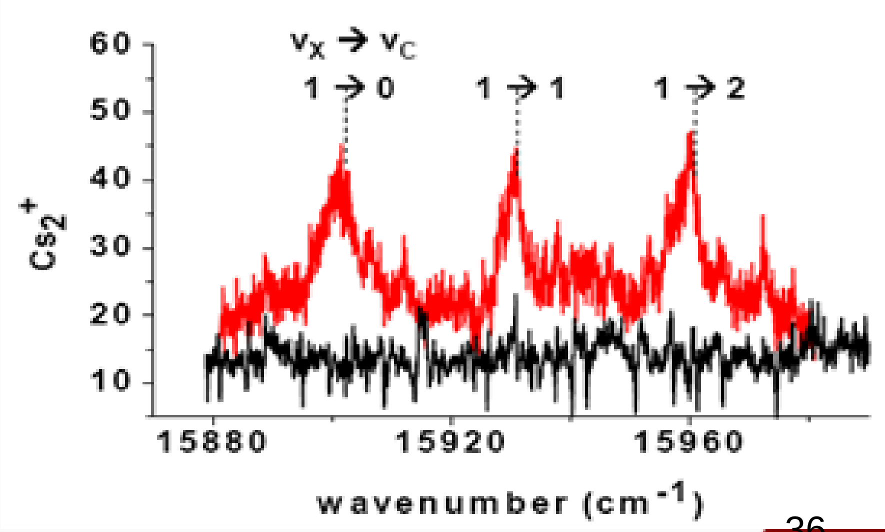
VIBR-COOLING WITH INCOHERENT LIGHT

femtosecond laser → broadband diode





Mehanical mask for v=1
with extiction ratio 100%



OUTLINE

- Introduction. Why cold molecules?
- Introduction. Methods of production of cold molecules
- Optical pumping and vibrational cooling
- Optical pumping into a preselected level
- Rotational cooling
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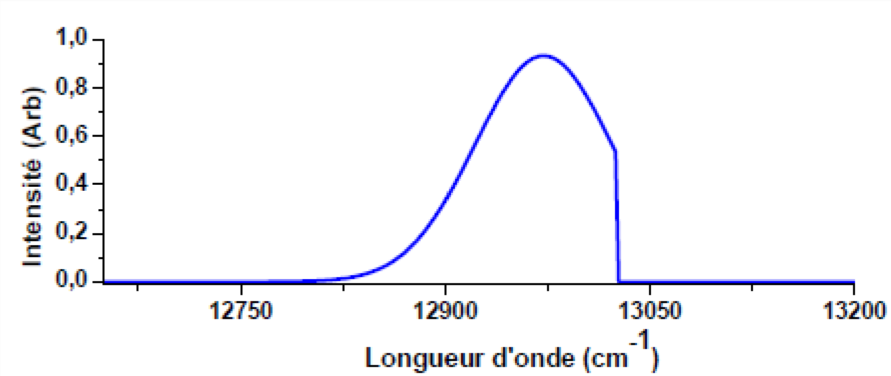
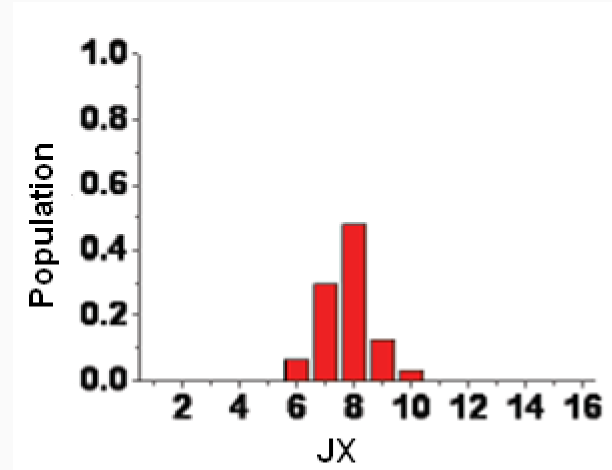
ROTATIONAL COOLING 1: simulation

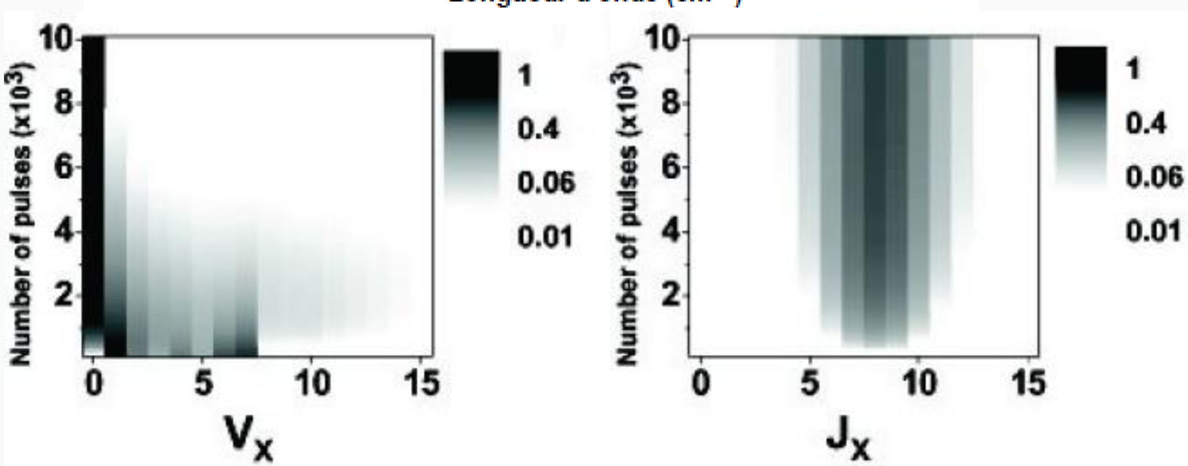
➢Rotational distribution:

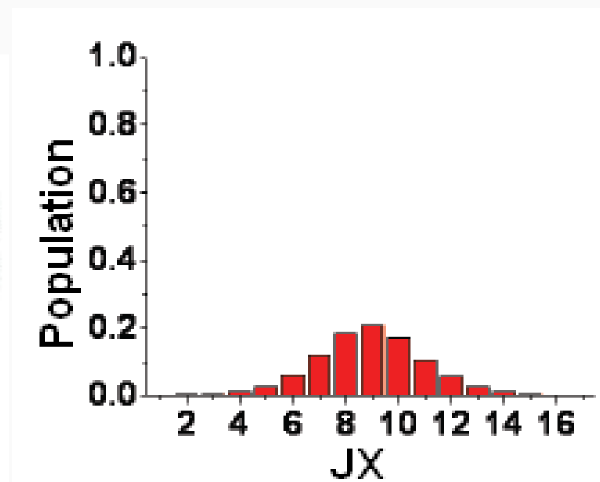
- after photoassociation

- after vibrational cooling









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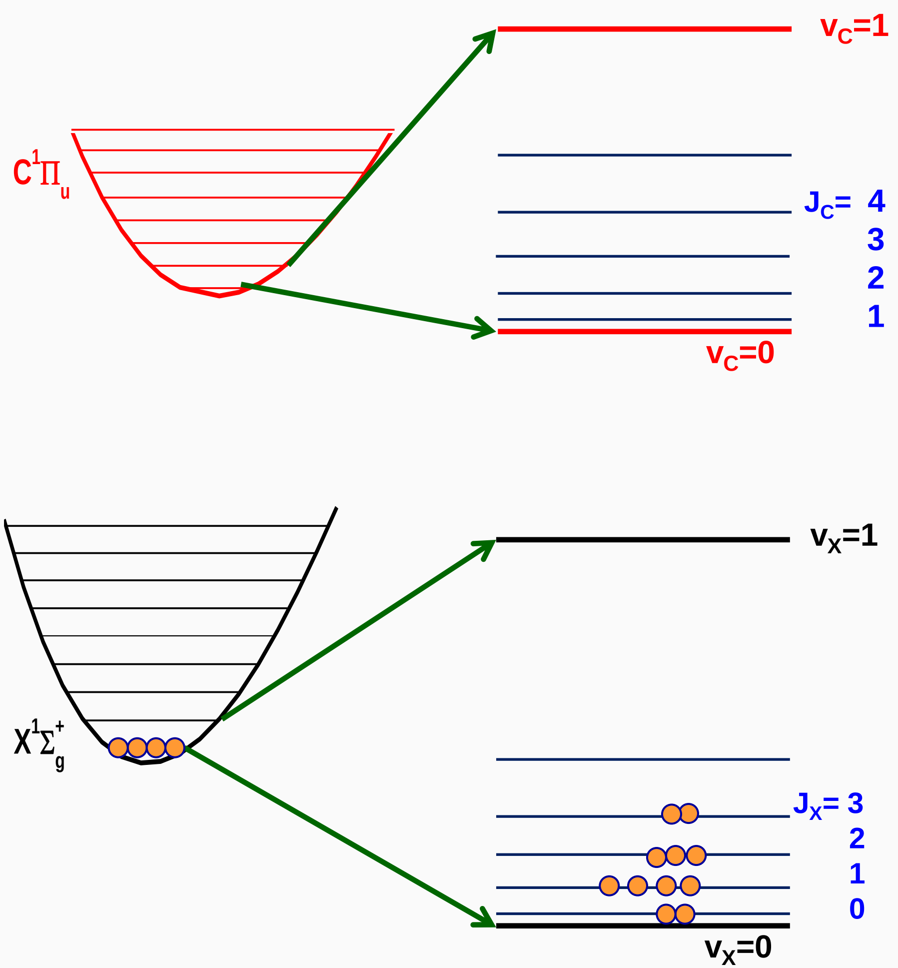
ROTATIONAL COOLING 2: detection



- for each vibrational level, several rotational levels are populated
- In Cs_2 (X state), the rotational separation **(~ 600 MHz)** is less than the detection laser linewidth used for the REMPI **(> 5 GHz)**
- A narrow bandwidth laser is required for detection

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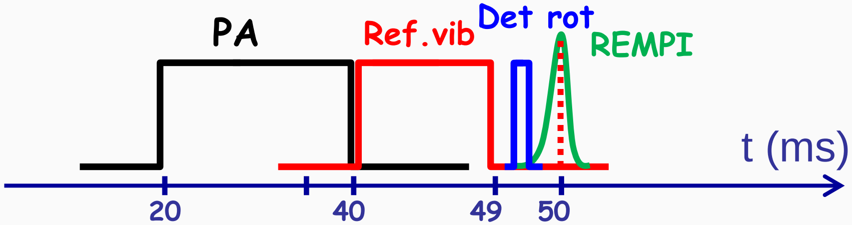
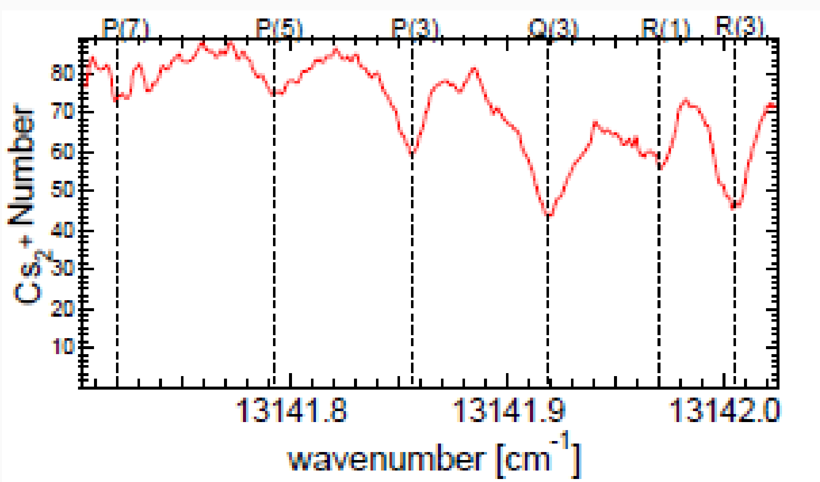
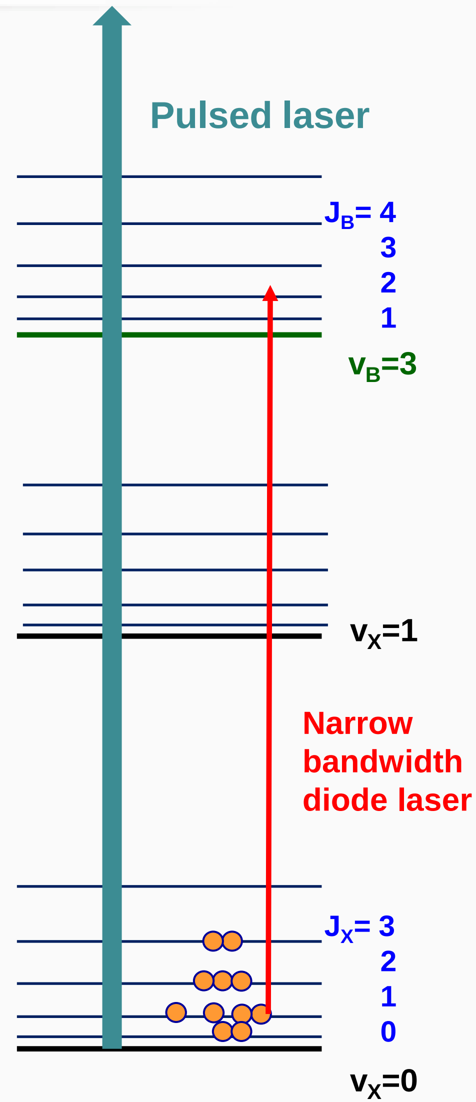
ROTATIONAL COOLING 2: detection



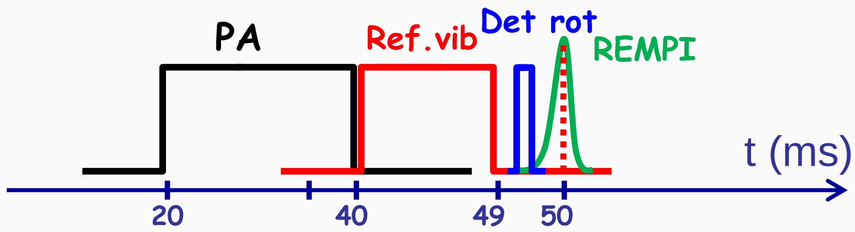
Two possibilities:

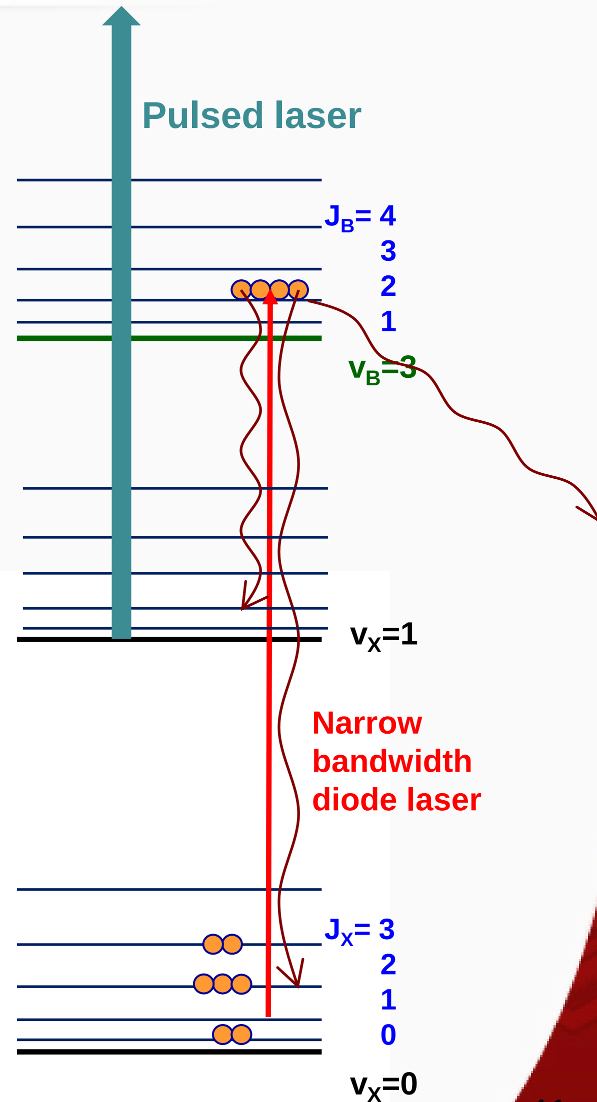
1) Depletion spectroscopy
2) Spontaneous-decay-induced double resonance





ROTATIONAL COOLING 2: detection





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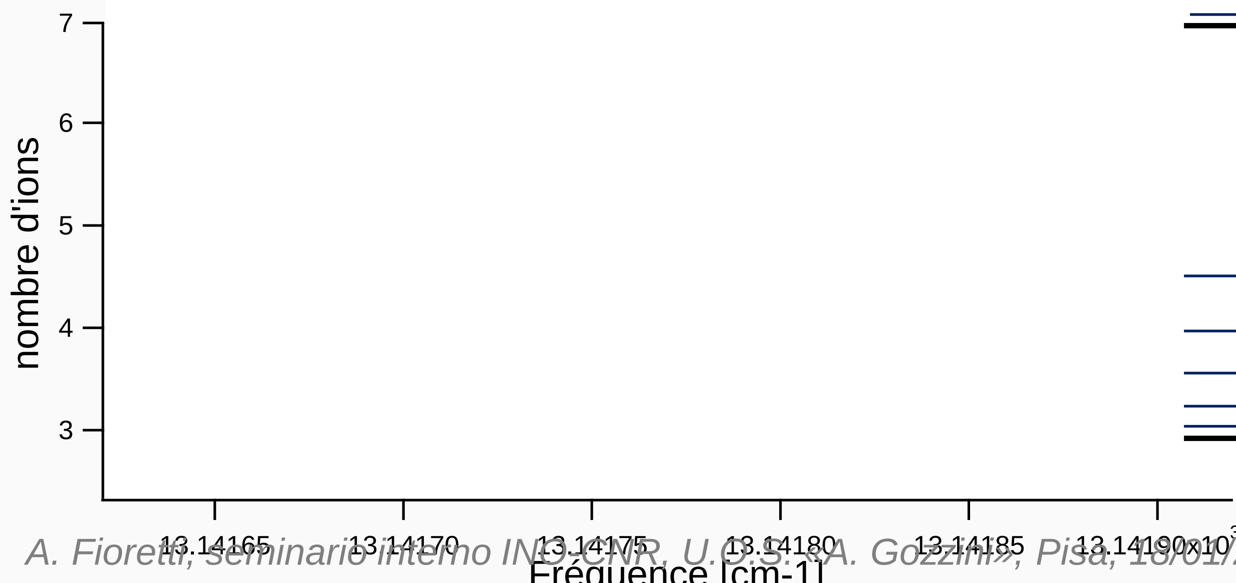
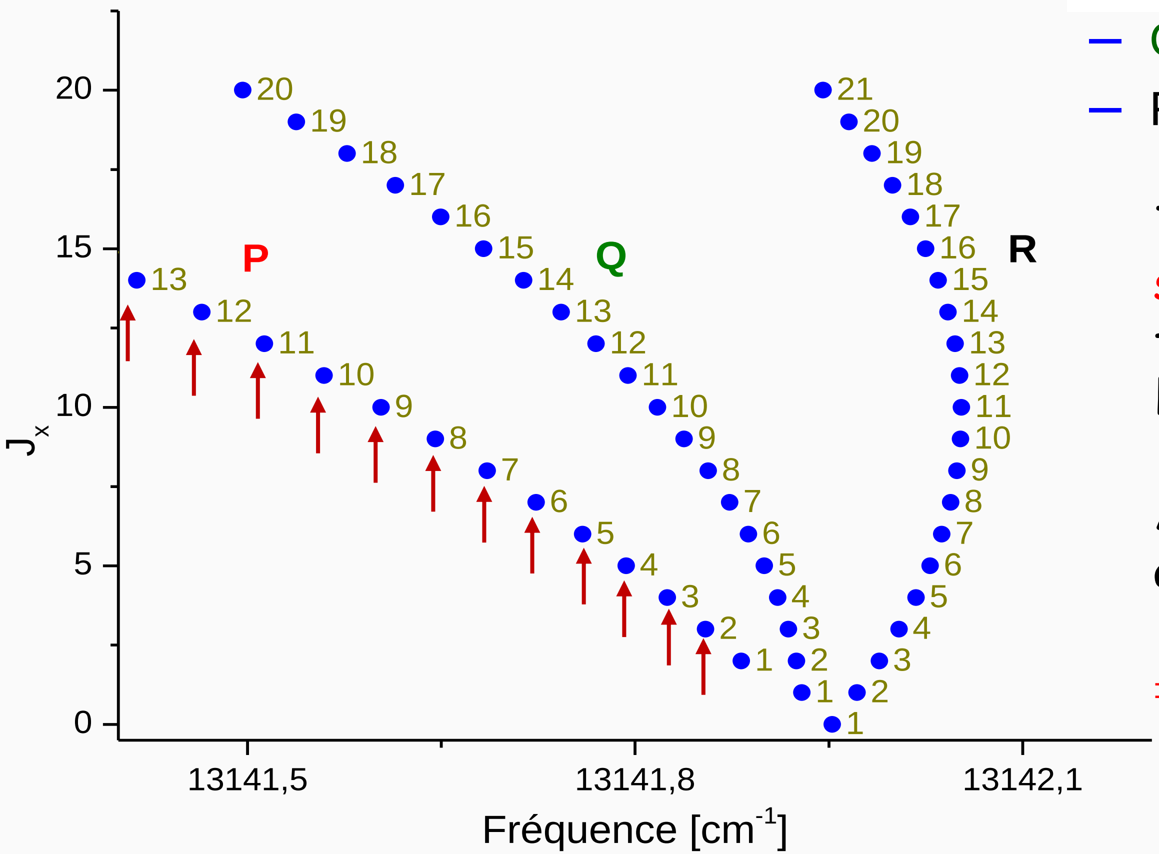


ROTATIONAL COOLING 3: cooling

- Selection rules: ΔJ=0, ± 1 and parity
  - **P : J lowering transitions**
  - ~~Q : J constant transitions~~
  - ~~R : J raising transitions~~

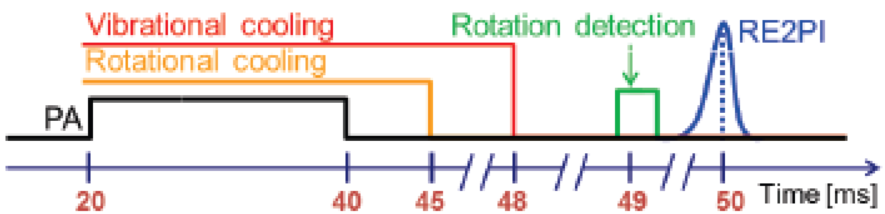


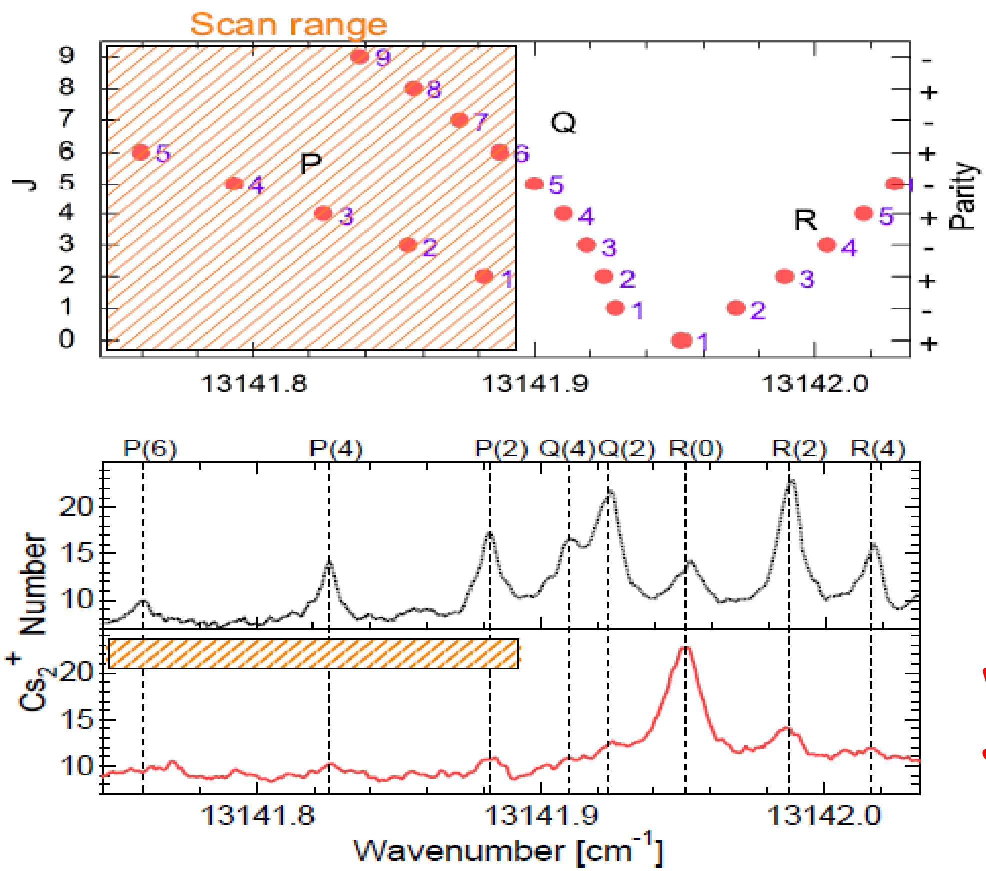
The cesium rotational structure is too narrow for shaping a broadband laser with a grating

Any rotational pumping will affect also the vibration

⇒ *A narrow linewidth laser is required!*

ROTATIONAL COOLING 3: cooling in v=0, J=0!





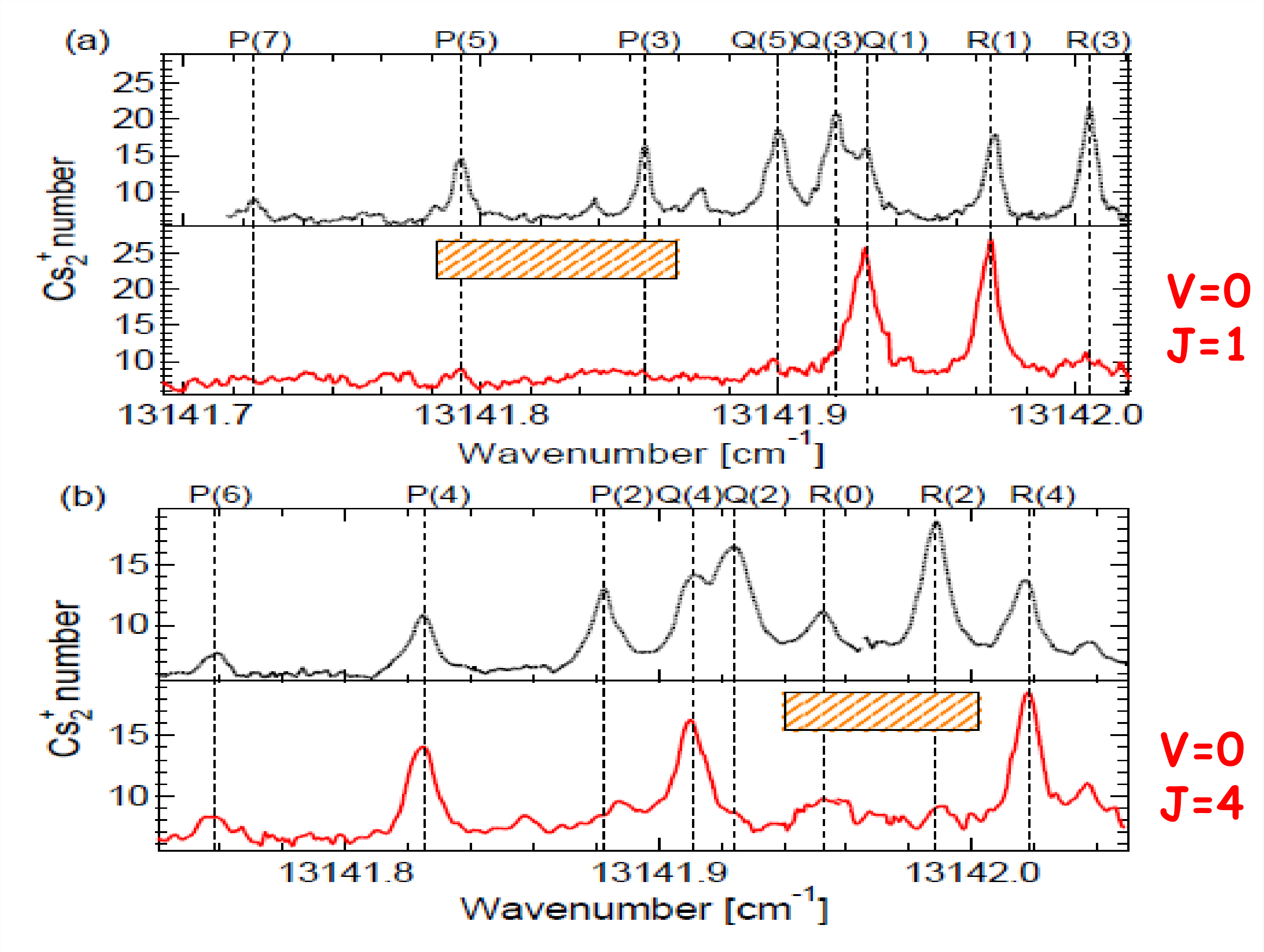
V=0
J=0

Rotational cooling obtained by the frequency scanning of a diode laser ($\Delta t \approx 100\mu s$)

Efficiency of rotational pumping ≈ 40%

Optimization is possible

ROTATIONAL COOLING 4: cooling in v=0, J≠0!



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CONCLUSIONS

- Optical manipulation of the internal degrees of freedom (electronic, vibrational and rotational) of the cesium dimer has been obtained.

- Laser cooling into the absolute (v=0, J=0) level as well as into other pre-selected levels have been obtained

Vibrational cooling: M. Viteau *et al.*, Science **321**, 232 (2008)
Vibr. cooling into a pre-selected level: D. Sofikitis *et al.*, New Journal of Physics, **11** (2009)
Vibr. cooling with laser diodes: D. Sofikitis *et al.*, Phys. Rev. A **80**, 051401, (2009)
State trasfer: R. Horchani *et al.*, Phys Rev. A **85**, 030502 (2012)
Rotational cooling: I. Manai *et al.*, Phys. Rev. Lett. **109**, 183001 (2012)

- Optical (incoherent) pumping offers an alternative approach to coherent transfer (STIRAP) towards the attainment complete control of external and internal degrees of freedom in simple molecules from laser cooled atoms

An ultracold high-density sample of rovibronic ground-state molecules in an optical lattice
J. G. Danzl, M. J. Mark, E. Haller, M. Gustavsson, R. Hart, J. Aldegunde, J. M. Hutson, and H.-C. Nägerl, Nature Physics 6, 265 (2010)

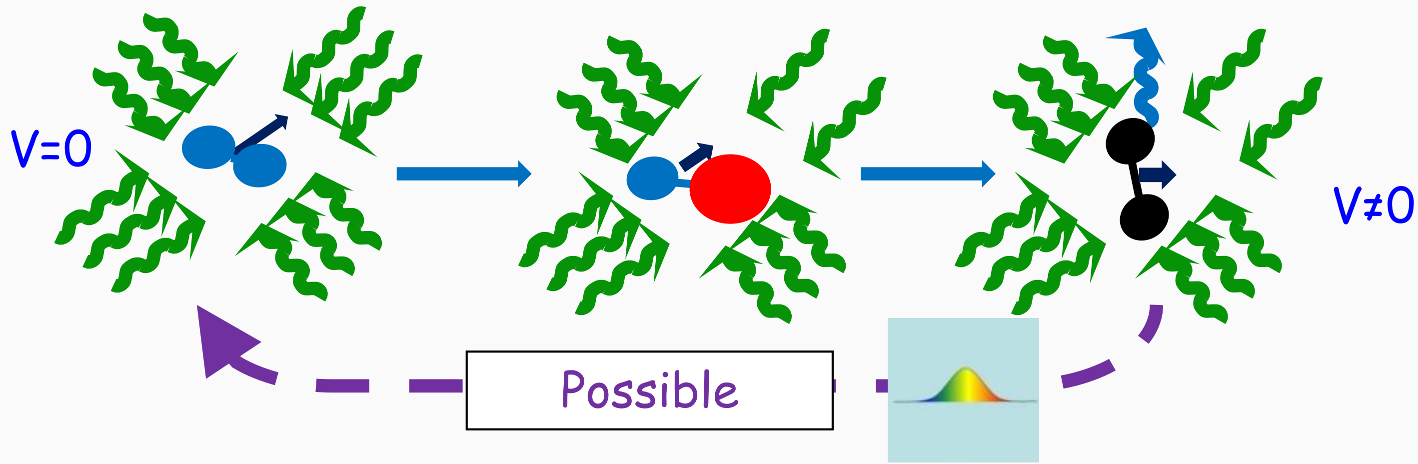
PERSPECTIVES

1)This method can be extended to more general (and interesting) molecules: laser sources (diodes, supercontinuum) and spectroscopic knowledge needed!

- Example: NaCs (N. Bigelow group, Optics Express, Vol. 20, No. 14, (2012))
- RbCs possible (INO-PISA)

2) State distillation of molecular samples is possible

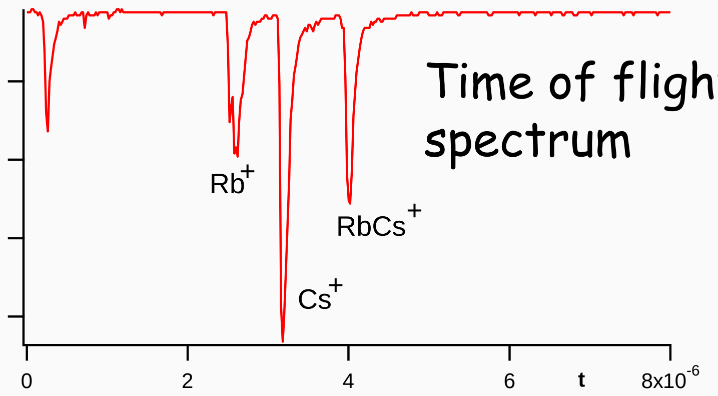
3) Direct laser cooling/trapping of molecules could be extended

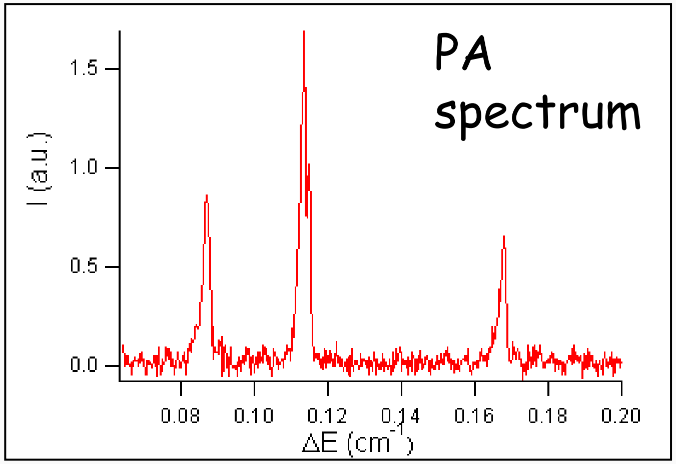


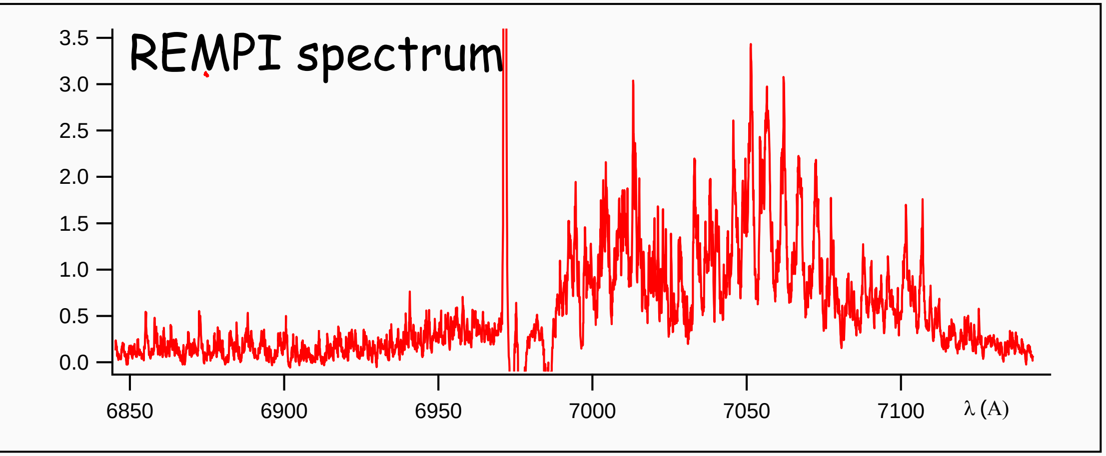
PERSPECTIVES at INO-Pisa

RbCs double MOT in operation, PA and cold molecule production, PA spectroscopy under way, vibrational cooling should be possible.

More laser sources needed!



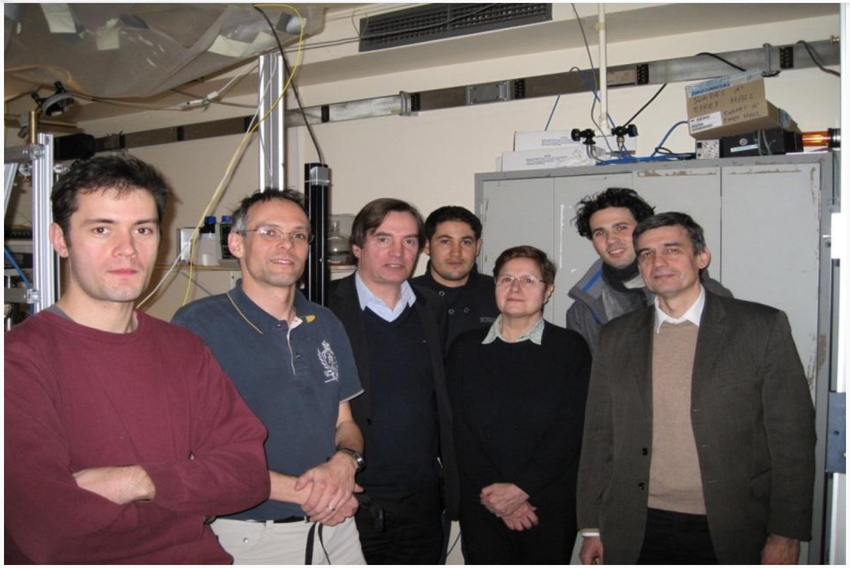




Δ_{PA}=-8.1 cm^{-1}

λ_{dye} ~ 700-712 nm

THE CREW



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- Isam Manai
- Ridha Horchani
- Hans Lignier
- Daniel Comparat
- Pierre Pillet
- + former PhD students

Theory LAC

- Nadia Bouloufa
- Olivier Dulieu

Visitors

- Marin Pichler
- Maria Allegrini
- Andrea Fioretti
- Goran Pichler
- Emiliya Dimova
- Lirong Wang
- + others

Thank you for your attention !

Collaboration

- Béatrice Chatel
- Sébastien Weber

(LCAM, Toulouse, France)