Autour de la métrologie des fréquences au laboratoire PIIM

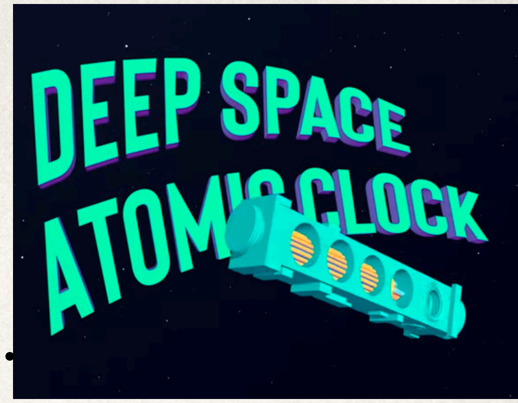
Caroline Champenois pour l'équipe CIML

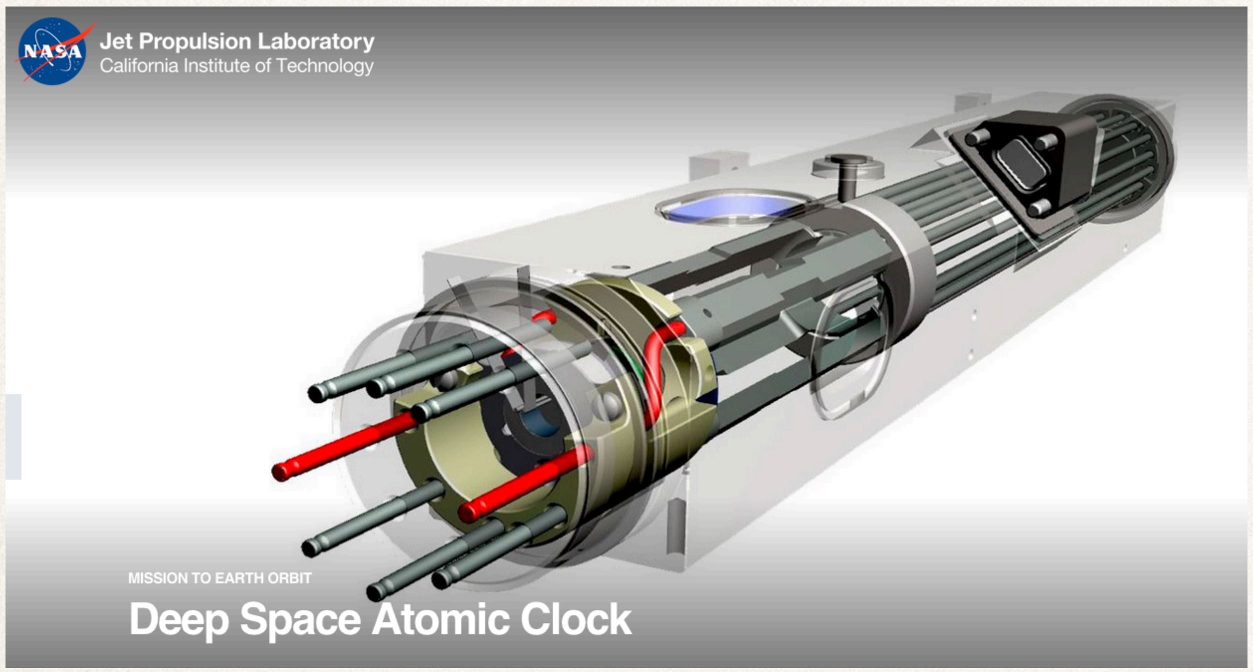
assemblée générale FIRST-TF, 10 octobre 2019

Expériences de spectroscopie laser sur des nuages d'ions refroidis par laser, en piège radiofréquence.

- recherche en amont pour l'amélioration des performances d'horloges micro-ondes basées sur un nuage d'ions piégés, en partenariat avec le CNES de 2006 à 2018.
- exploitation d'une raie noire produite par piégeage cohérent de population (CPT) à trois photons, observable dans la fluo d'un nuage d'ions piégés.

- cahier des charges d'une horloge micro-onde à ions pour la navigation lointaine. Travaux basés sur les prototypes développés par le JPL pour la NASA depuis 1996 (ou avant?).





Acronym: DSAC

Type: Instrument, Airborne/Ground, Technology Demonstration

Status: Current

Launch Date: June 22, 2019

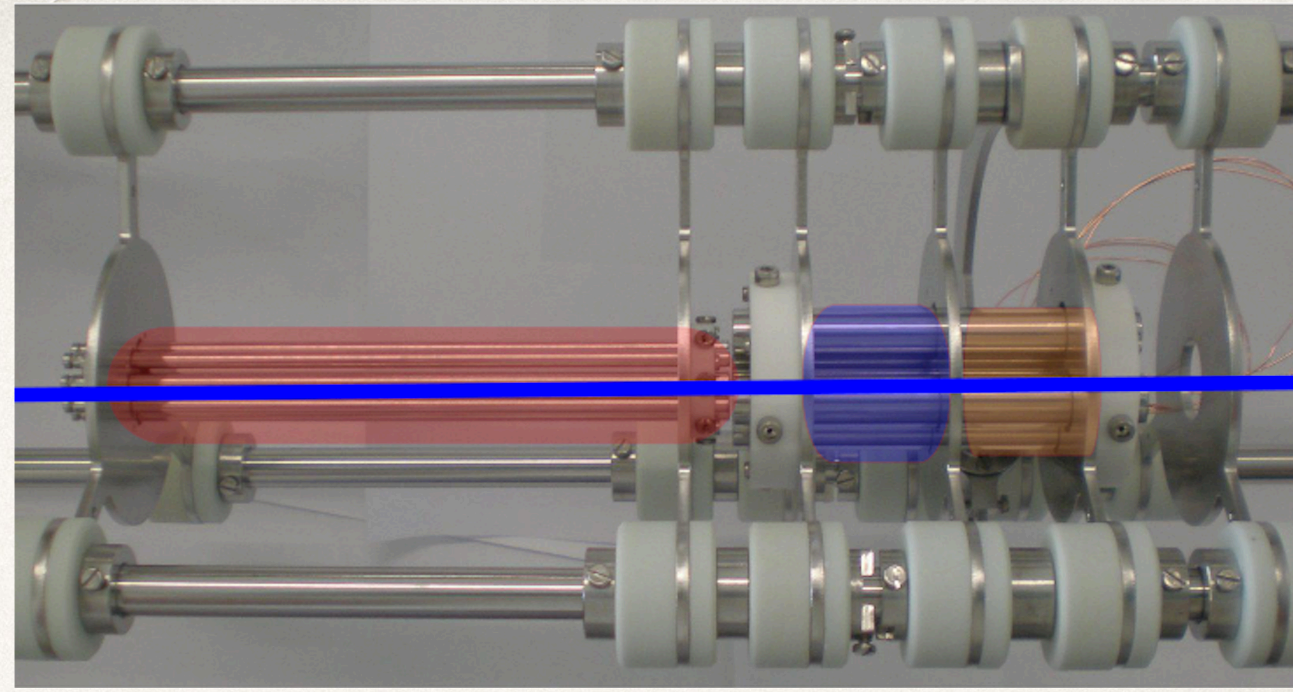
Destination: Earth Orbit

un double piège radiofréquence : un quadrupole en ligne avec un multipole (8, puis 12 et finalement 16 barreaux)

- **notre contribution** : étude du transport et de l'accumulation pour réduire la durée nécessaire au transport des ions entre les 2 parties du piège?
- **une démonstration qui reste à faire** : comparer expérimentalement les distributions de vitesse en quadrupole et multipole et identifier les contributions du mouvement thermique et du micro-mouvement (forcé par RF).

Le dispositif TADOTI :

- un piège quadrupolaire segmenté,   en ligne avec un octupole
- des ions Ca+ refroidis par laser
- une séparation entre les différentes parties du piège assurée par des tensions DC.



- transport au sein du quadrupole de $8*10^4$ ions sur 20 mm en 100 μs avec une efficacité de 90% (100% pour des petits nuages)
- transport sur 70 mm, du quadrupole vers l'octupole, avec une efficacité supérieure à 80% pour des nuages plus petits que $3*10^4$ ions, durée : 650 μs.
- démonstration d'une technique d'accumulation pour former des gros nuages (>200 000 ions)

Fast accumulation of ions in a dual trap

M. R. Kamsap, C. Champenois, J. Pedregosa-Gutierrez, M. Houssin and M. Knoop

EPL, **110** (2015) 63002

PHYSICAL REVIEW A **92**, 043416 (2015)

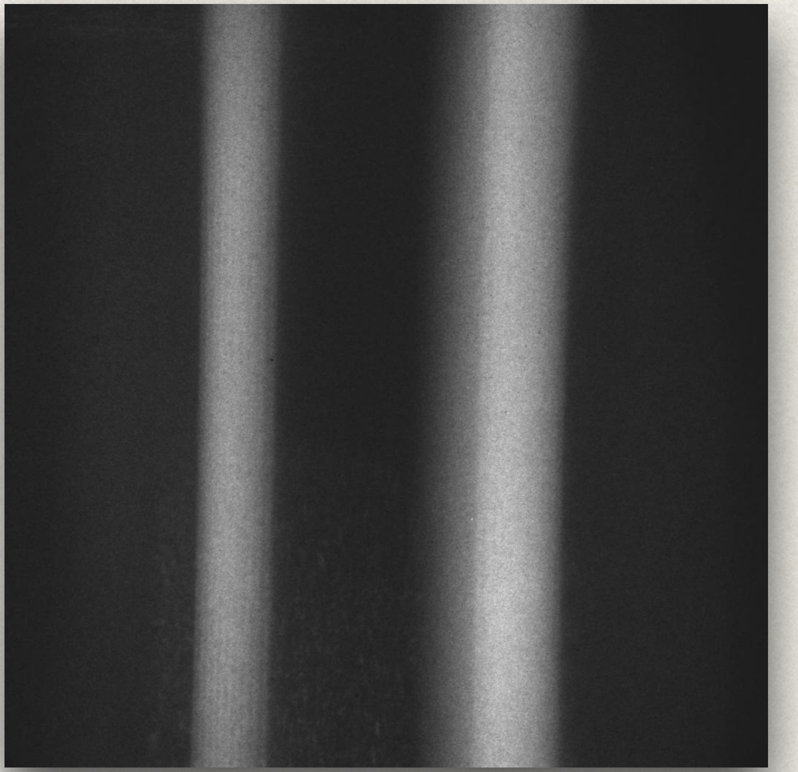
Fast and efficient transport of large ion clouds

M. R. Kamsap, J. Pedregosa-Gutierrez, C. Champenois,* D. Guyomarc'h, M. Houssin, and M. Knoop
Aix-Marseille Université, CNRS, PIIM, UMR 7345, 13397 Marseille, France
(Received 22 May 2015; revised manuscript received 27 July 2015; published 21 October 2015)

image de la fluorescence d'ions froids en octupole : mise en évidence de la brisure de symétrie

La confrontation expériences/simulations confirme trois minima locaux de potentiel, de profondeur de l'ordre de quelques Kelvin.

- quel impact sur des ions à 300 K?
- Est-il possible de compenser ces défauts pour construire un potentiel multipolaire? Oui!



J. Pedregosa *et. al*

REVIEW OF SCIENTIFIC INSTRUMENTS **89**, 123101 (2018)

Correcting symmetry imperfections in linear multipole traps

J. Pedregosa-Gutierrez,[1,a] C. Champenois,[1] M. Houssin,[1] M. R. Kamsap,[2] and M. Knoop[1]

JOURNAL OF MODERN OPTICS, 2018
VOL. 65, NOS. 5–6, 529–537
https://doi.org/10.1080/09500340.2017.1408866

Symmetry breaking in linear multipole traps

Perspectives :

- démonstration expérimentale de la compensation des défauts par adaptation de l'amplitude RF sur chaque barreau (thèse de M. Marchenay)
- caractérisation de la distribution de vitesses dans le cas compensé et le cas très dissymétrique.
- de la pertinence des multipoles pour la métrologie des fréquences en fonction de la température des ions…

Peut-on faire de la spectroscopie laser pertinente pour la métrologie des fréquences avec un nuage d'ions?

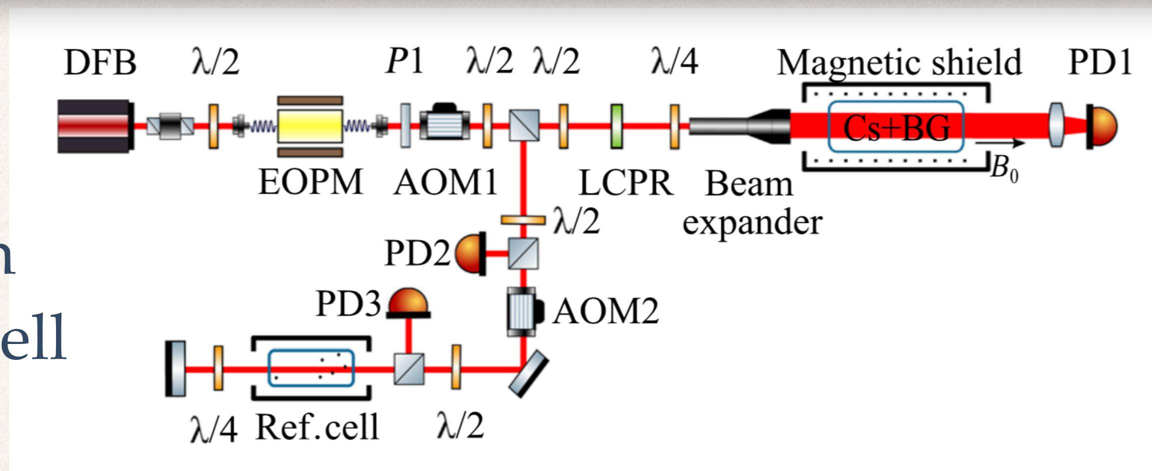
Coherent Population Trapping : a resource for microwave clocks based on the transition between two hyperfine sub-levels of Rb or Cs

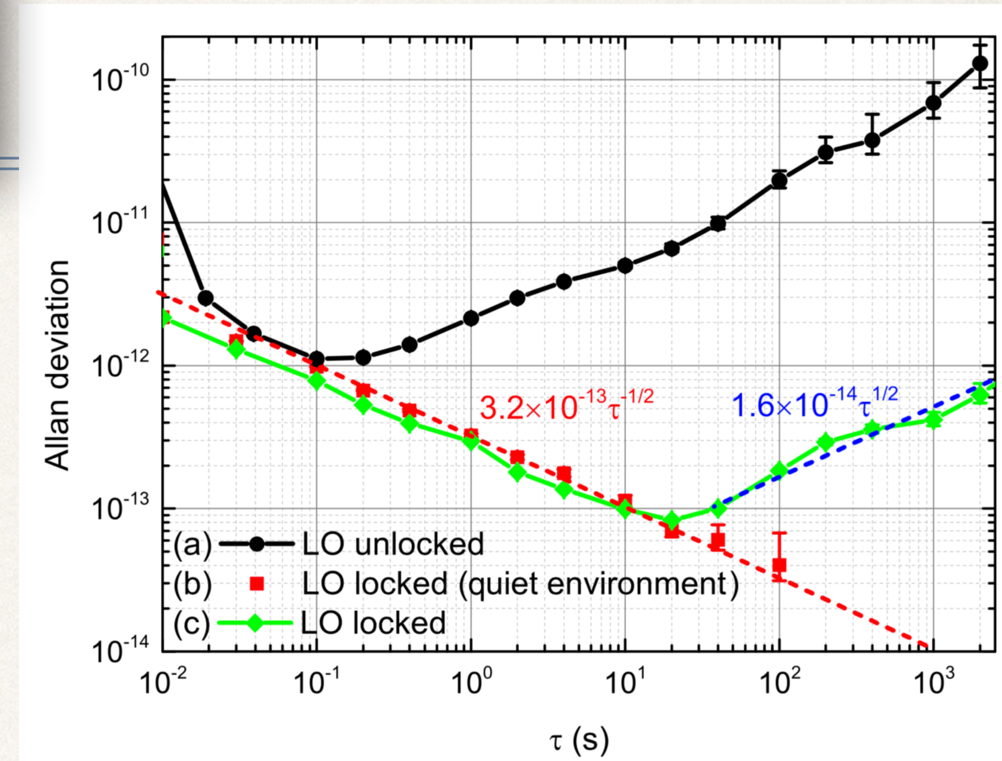
PHYSICAL REVIEW APPLIED **7,** 014018 (2017)

High-Performance Coherent Population Trapping Clock with Polarization Modulation

Peter Yun,[1,*] François Tricot,[1] Claudio Eligio Calosso,[2] Salvatore Micalizio,[2] Bruno François,[3] Rodolphe Boudot,[3] Stéphane Guérandel,[1] and Emeric de Clercq[1]

Cs in a room temperature cell



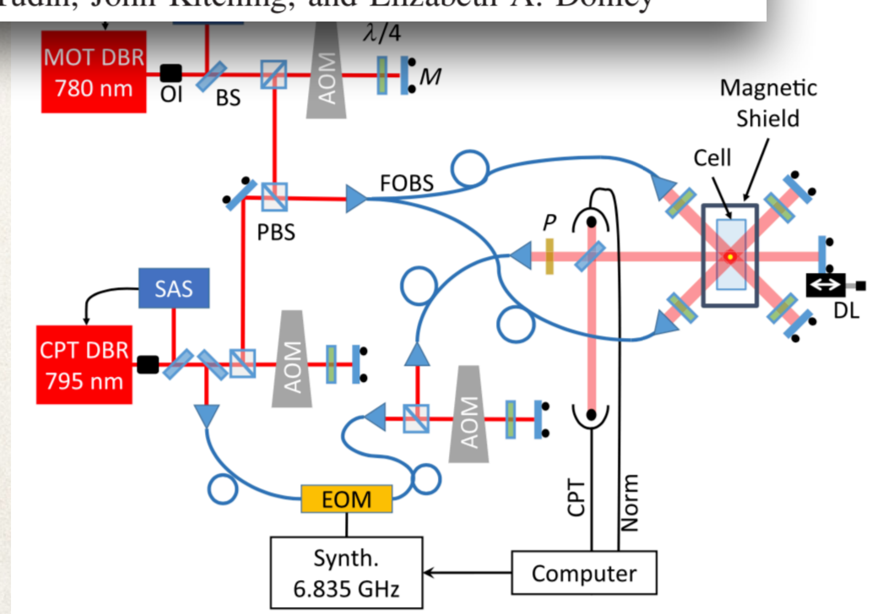


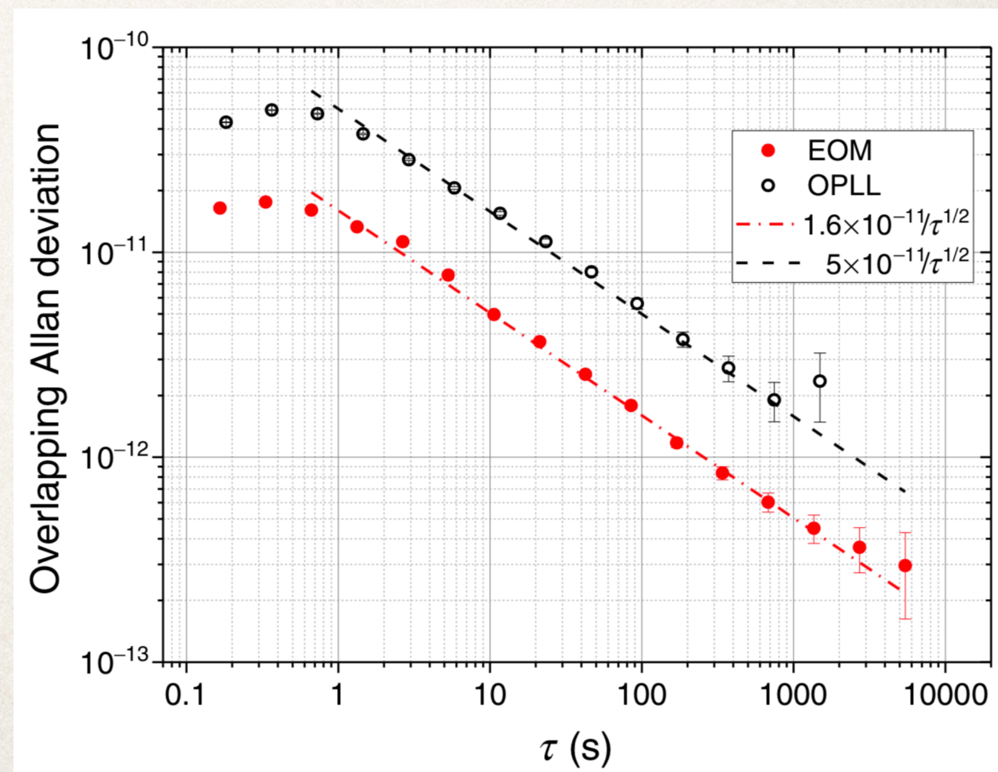
PHYSICAL REVIEW APPLIED **8,** 054001 (2017)

Low-Drift Coherent Population Trapping Clock Based on Laser-Cooled Atoms and High-Coherence Excitation Fields

Xiaochi Liu, Eugene Ivanov, Valeriy I. Yudin, John Kitching, and Elizabeth A. Donley[*]

Rb in a MOT





From two- to three-photon CPT

- occurs in any N-scheme with 3 stable or metastable states
- can be understood like a laser-mediated two-photon CPT because one of the transition has to be weak.

$$\Delta_R = \Delta_B - \Delta_C - \delta_C$$

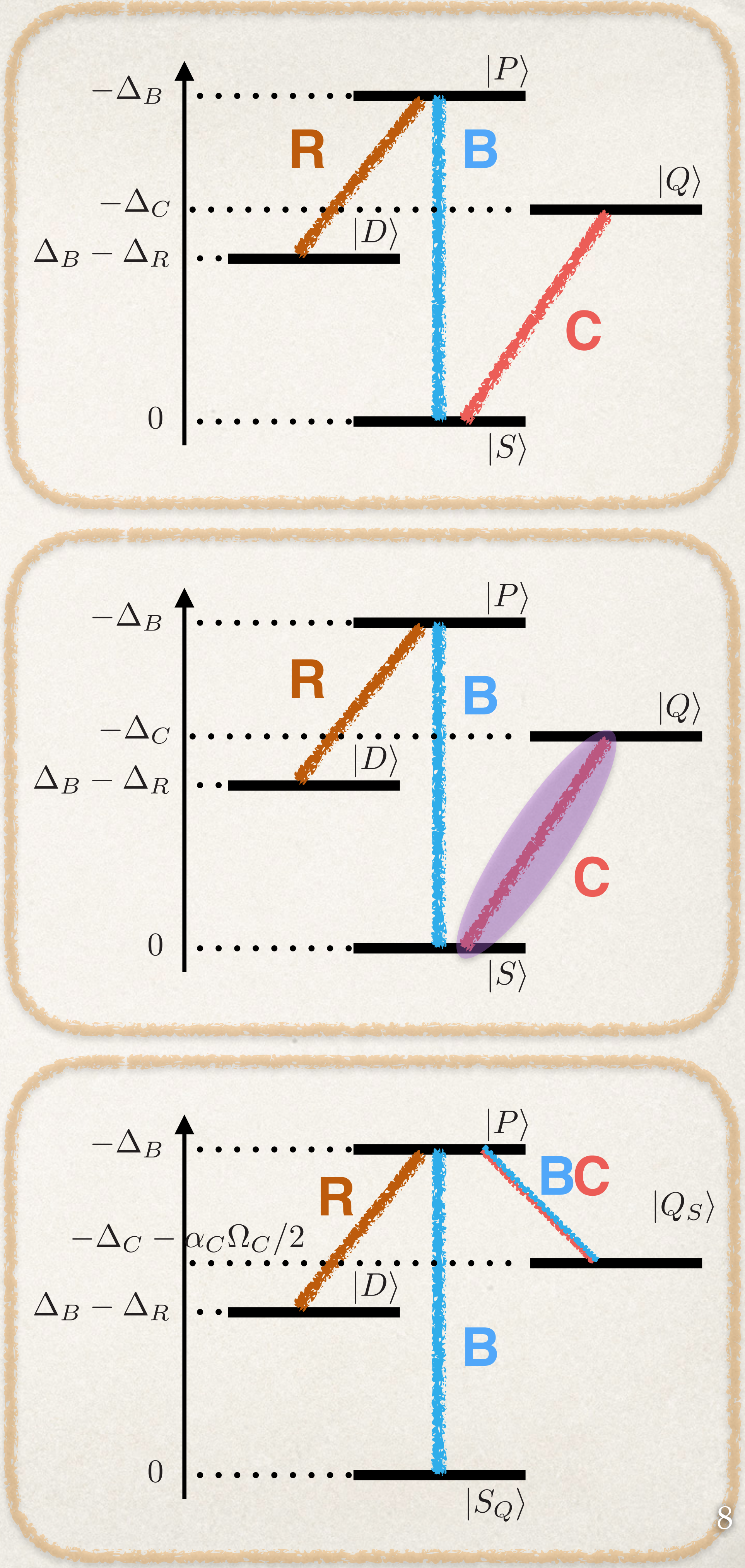
- can be Doppler free by fulfilling the phase matching condition

$$\mathbf{k}_B - \mathbf{k}_C - \mathbf{k}_R = \mathbf{0}$$

- occurs in Ca+ where it is referenced to the magnetic dipole transition $D_{3/2} \rightarrow D_{5/2}$ with frequency 1,82 THz.

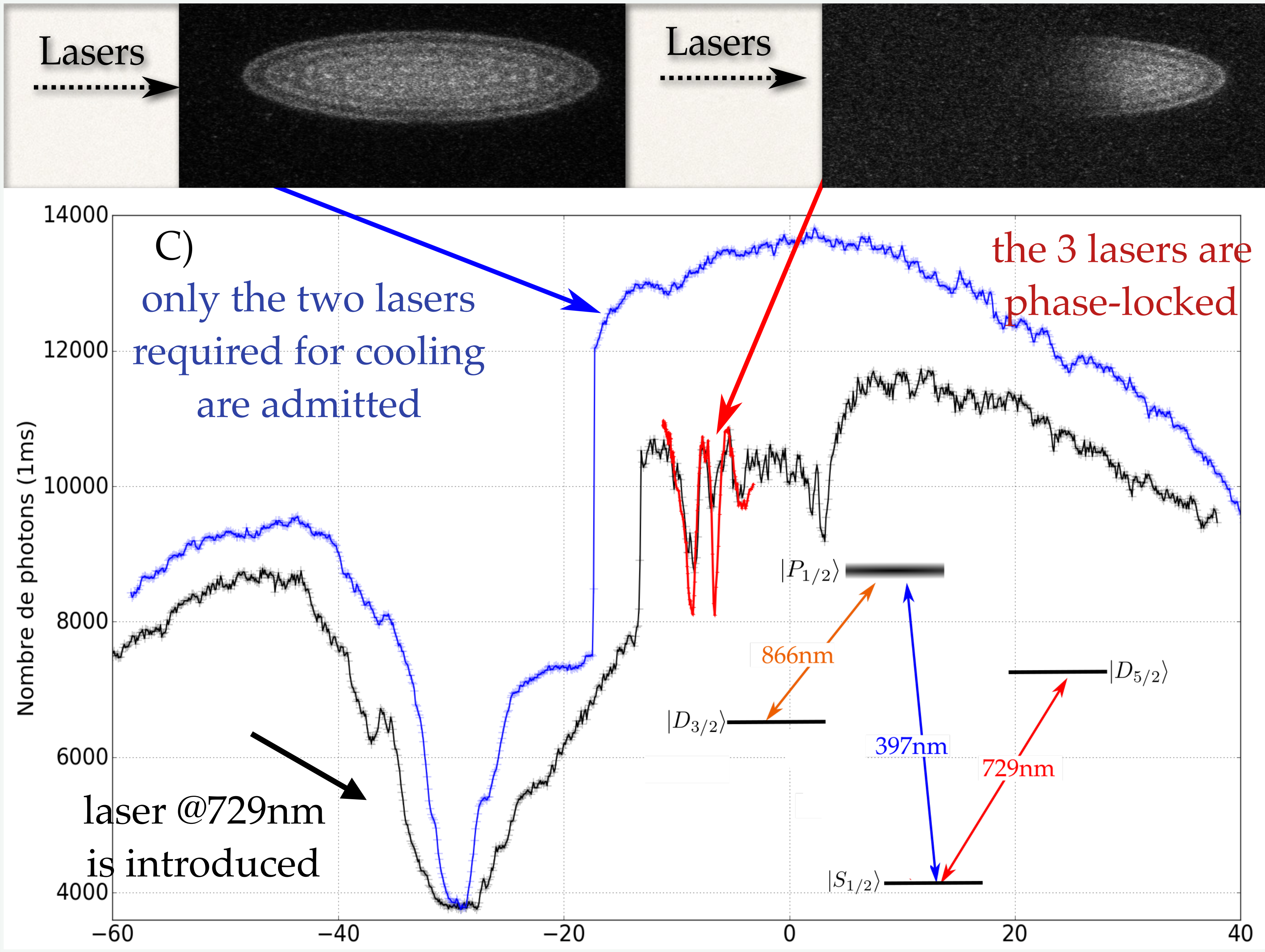
$$\omega_R + \omega_C - \omega_B + \delta_C = \omega_{THz}$$

C. Champenois, G. Morigi and J. Eschner, PRA **74** (2006) 053404

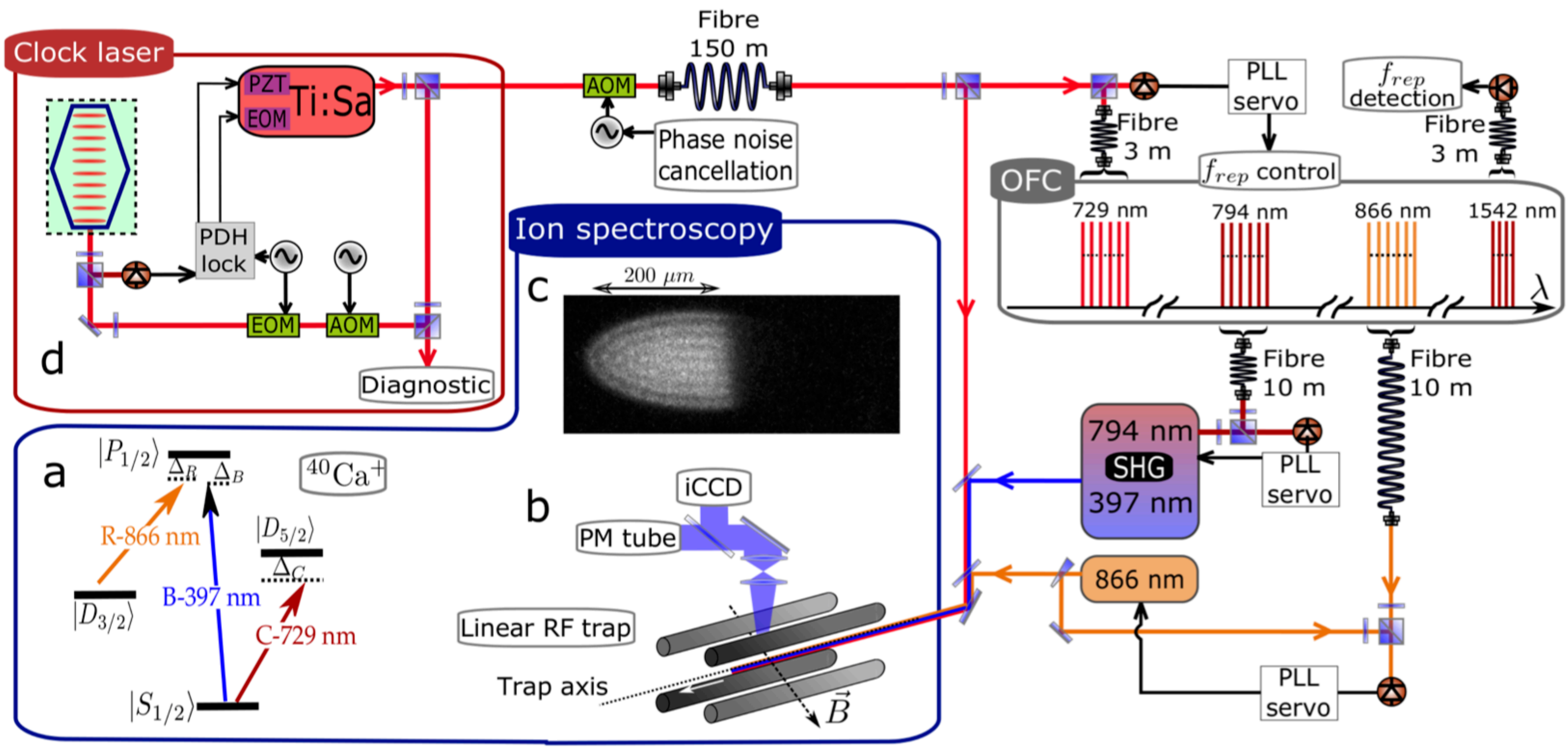


Observation of a three-photon CPT in a cloud of laser-cooled trapped Ca+ ions, stored in a linear quadrupole trap.

- from 60 to 2000 ions in a 0.9 Gauss B-field
- the three involved lasers are the
  - 397 nm cooling laser
  - 866 nm repumping laser
  - 729 nm ultra-stable laser exciting the E2-quadrupole transition.
- they co-propagate along the trap axis.
- the 866-laser frequency is scanned



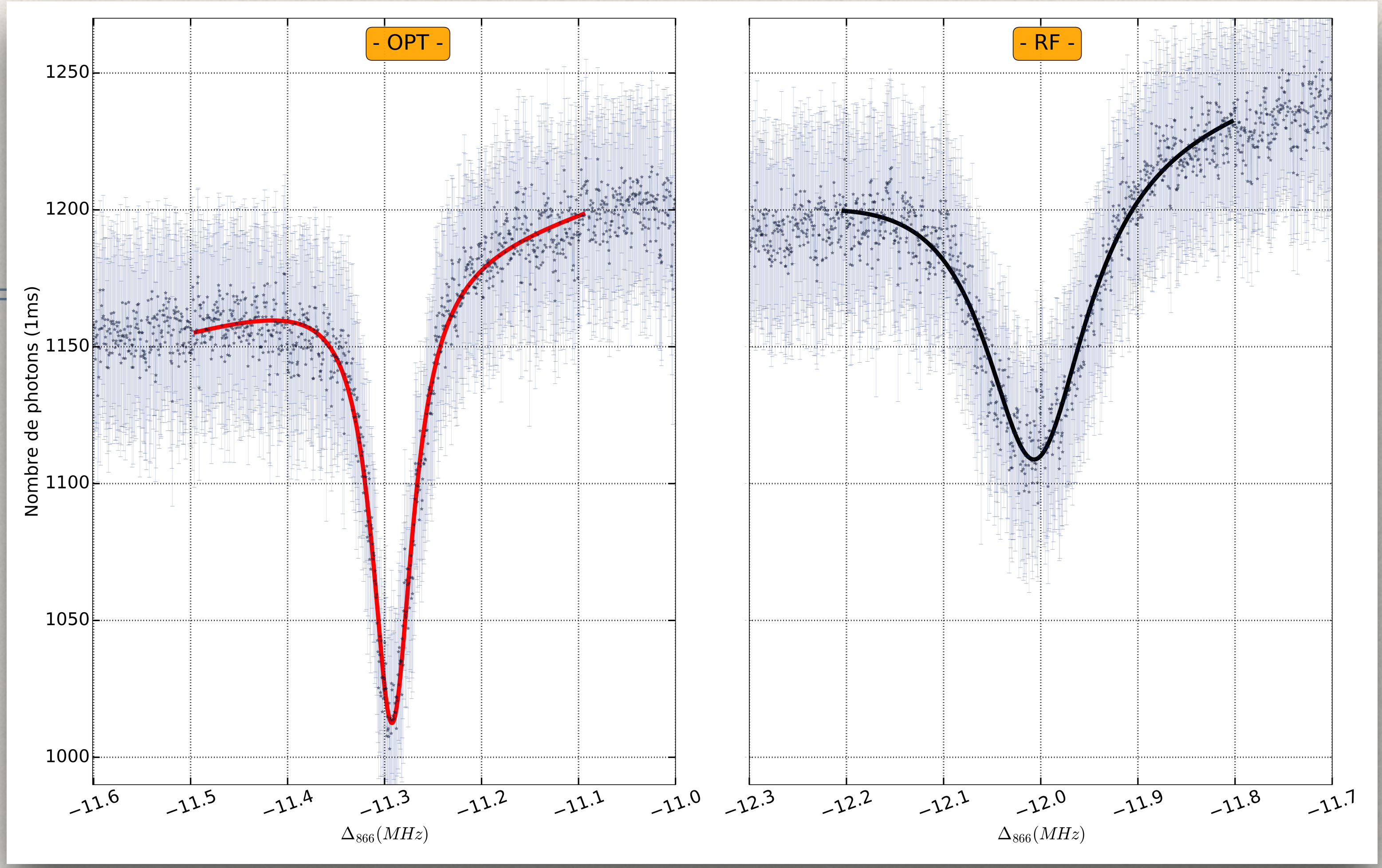
An (offset-free) Optical Frequency Comb (OFC) for simultaneous phase-lock of the three lasers



The partial trapping in the dark state keeps the ion cloud cold by sympathetic cooling

impact of phase coherence on the dark line

- the 397 and 866 lasers are locked on the Optical Frequency Comb.
- OFC is locked either on the ultra-stable laser at 729 nm or on an RF signal disciplined by GPS.



contrast falls from 22% to 13%
line-width increases from 50 (+/-2) kHz to 140 (+/-10) kHz.

more about the phase-lock loop system in Collombon *et. al* Optics Letters 44 (2019) 859

Another benefit from simultaneous phase-lock on the same OFC

- the three-photon resonance condition implies

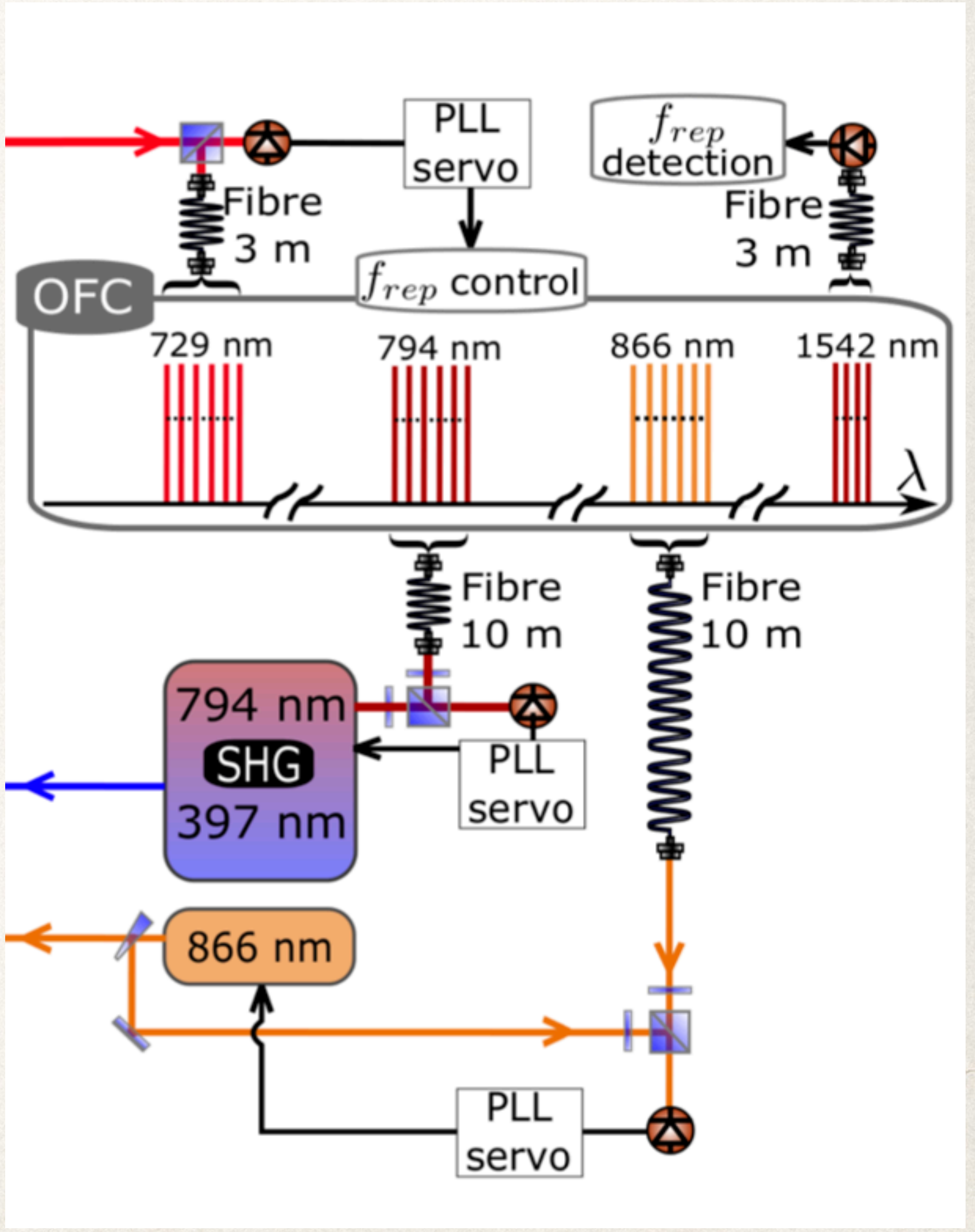
$$f_{866} + f_{729} - f_{397} + \delta_C = f_{THz}$$

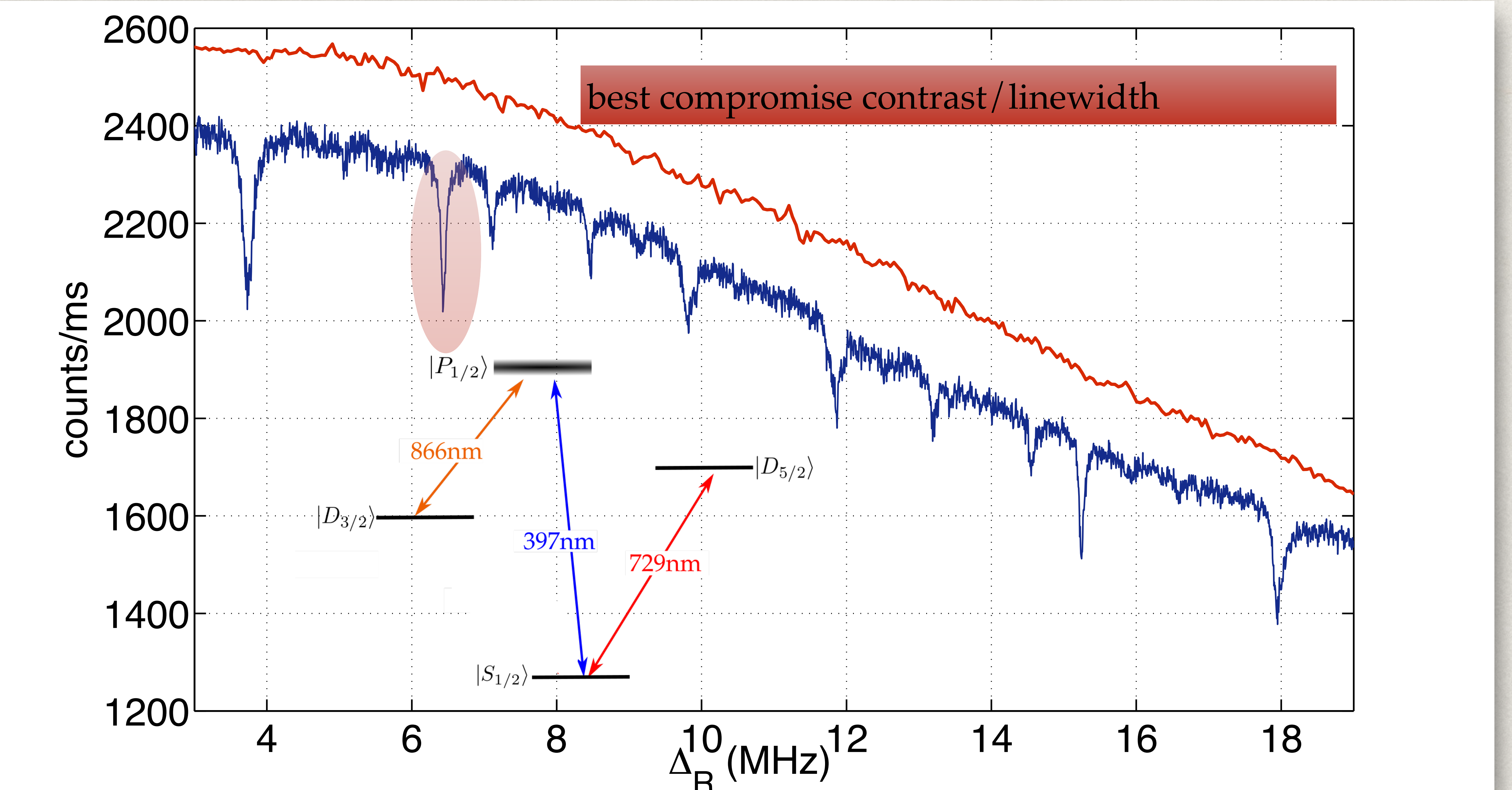
- two orders of magnitude reduction of the THz-frequency uncertainty

$$f_{THz} = (N_{866} + N_{729} - 2 * N_{794}) * f_{rep} + f^{i}_{beat} + f^{j}_{AOM}$$

$$f_{rep} = 80\ MHz \quad \text{with} \quad \sigma_{rep} \simeq 1.5\ mHz$$

$$(N_B - N_R - N_C) \times \sigma_{rep} \simeq 34\ Hz$$





a zoom around the 3-photon CPT dark lines

laser induced fluorescence **without** and **with** the 729 nm ultra-stable laser

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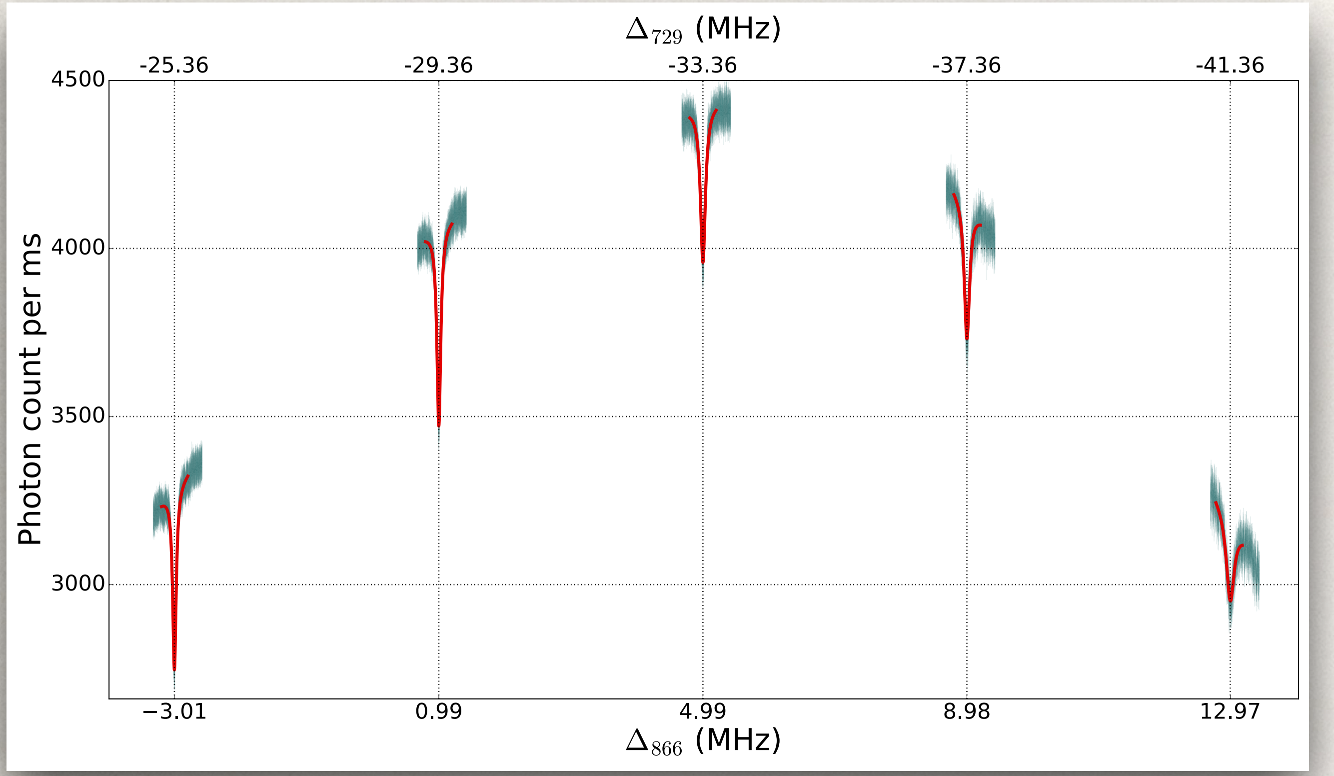
Rq : the trapping from the metastable state can not be discrimated.

Checking on the three-photon resonance condition for one dark line



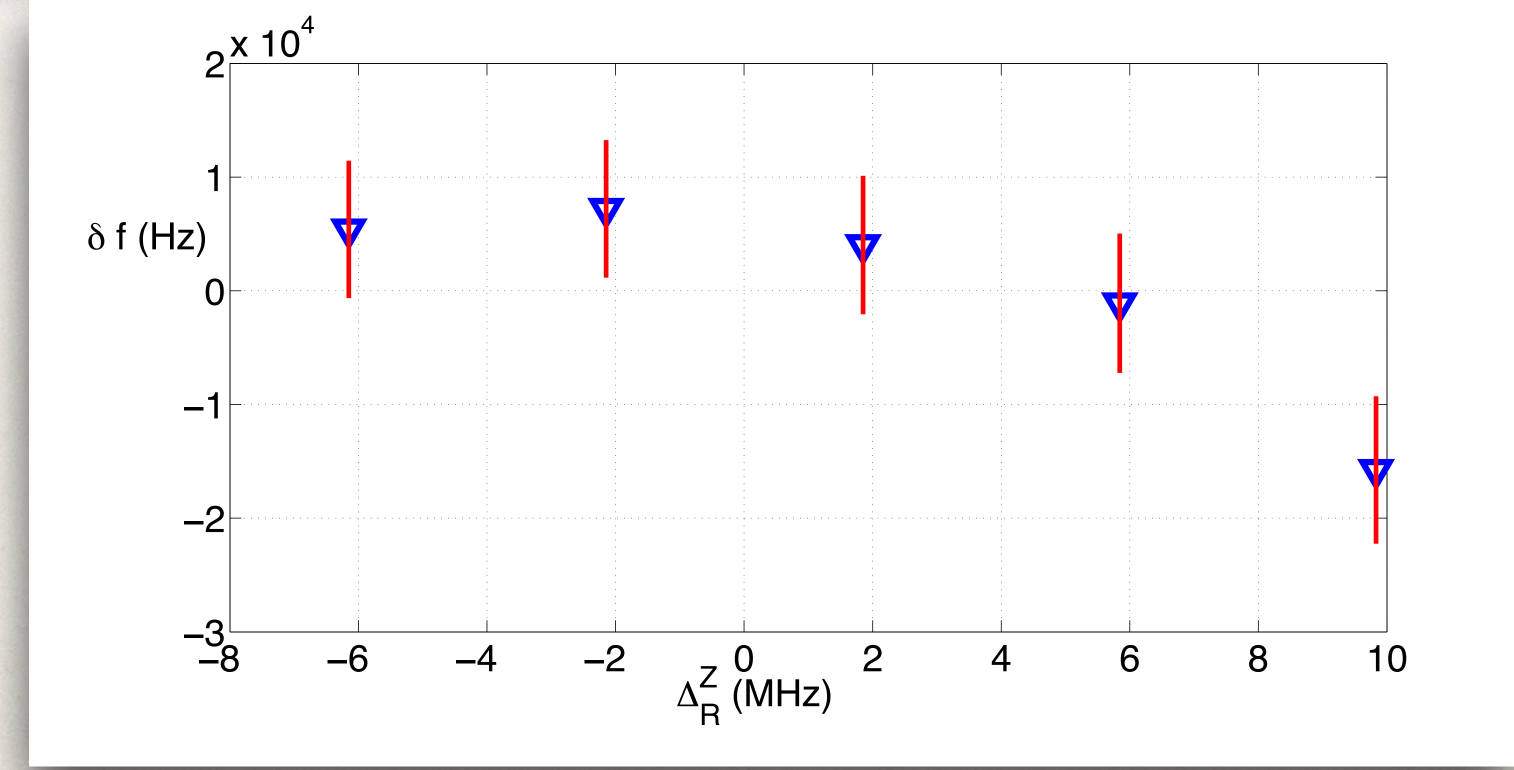
$$f_{THz} = (N_{866} + N_{729} - 2 * N_{794}) * f_{rep} + f_{beat}^{866}$$

is compared with

$$f(3D_{3/2} - 3D_{5/2}) = 1.819\ 599\ 021\ 534(8) Hz$$

with the Zeeman shift included

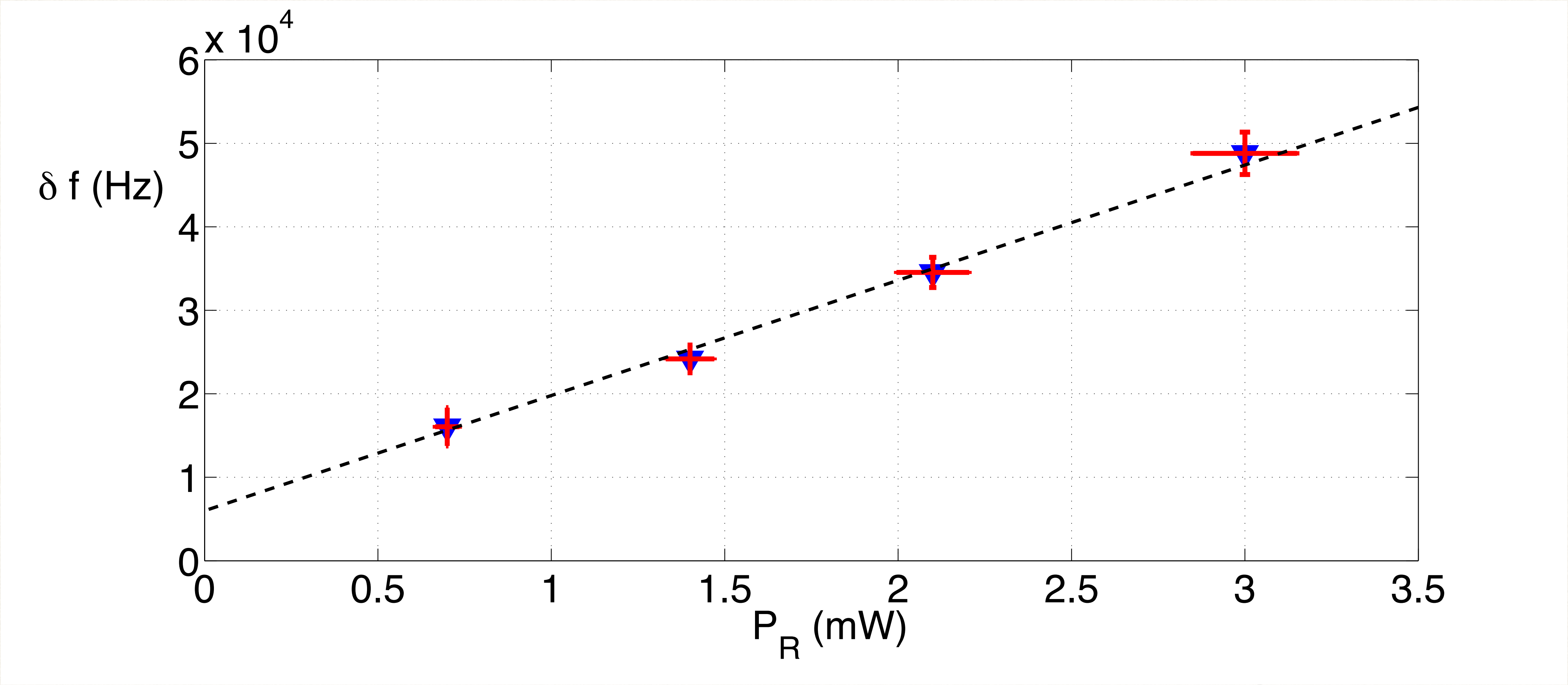
Phys. Rev. A **77** (2008) 012508
Phys. Rev. Lett. **120** (2018) 253601



The frequencies match with an error of the order of 10 kHz over a range of 16 MHz.

Champenois *et al.* PRA **74**, 053404 (2006)

The only observed power-induced shifts are due to laser coupling on the 866 nm transition (R-laser)



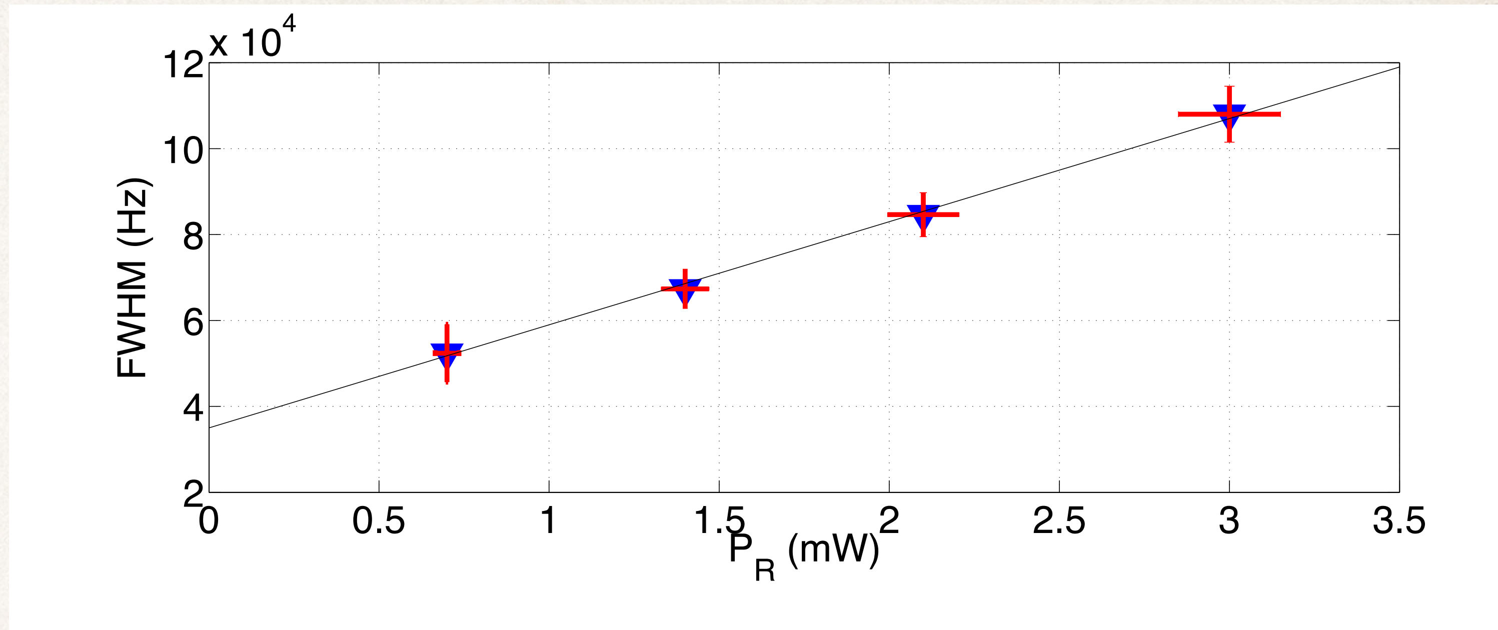
- From CPT-clock previous studies, we can extrapolate that the observed shift results from different contributions : *i.e.* light-shift from neighbour transitions and coherence relaxation induced shift, proportional to the one-photon detuning
  (cf Zanon-Willette *et al* PRA **84**, 062502 (2011))

Collombon *et al.* PRApplied **12**, 034035 (2019)

What about the line-width and contrast?

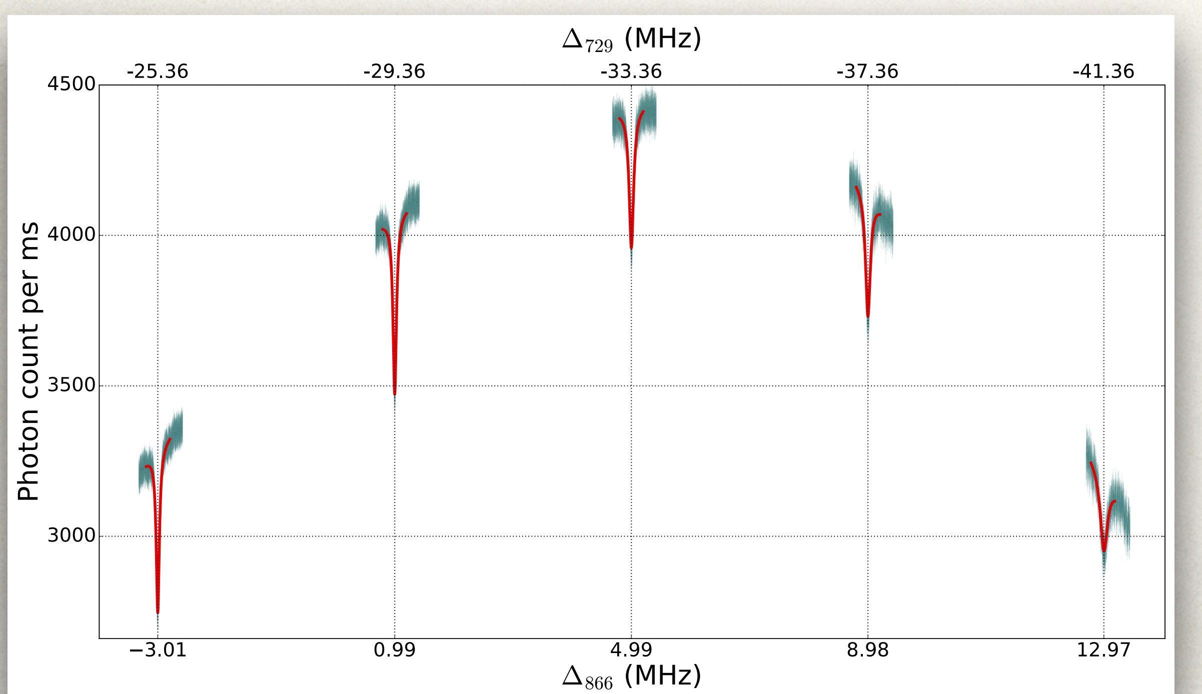
Power independent broadening includes

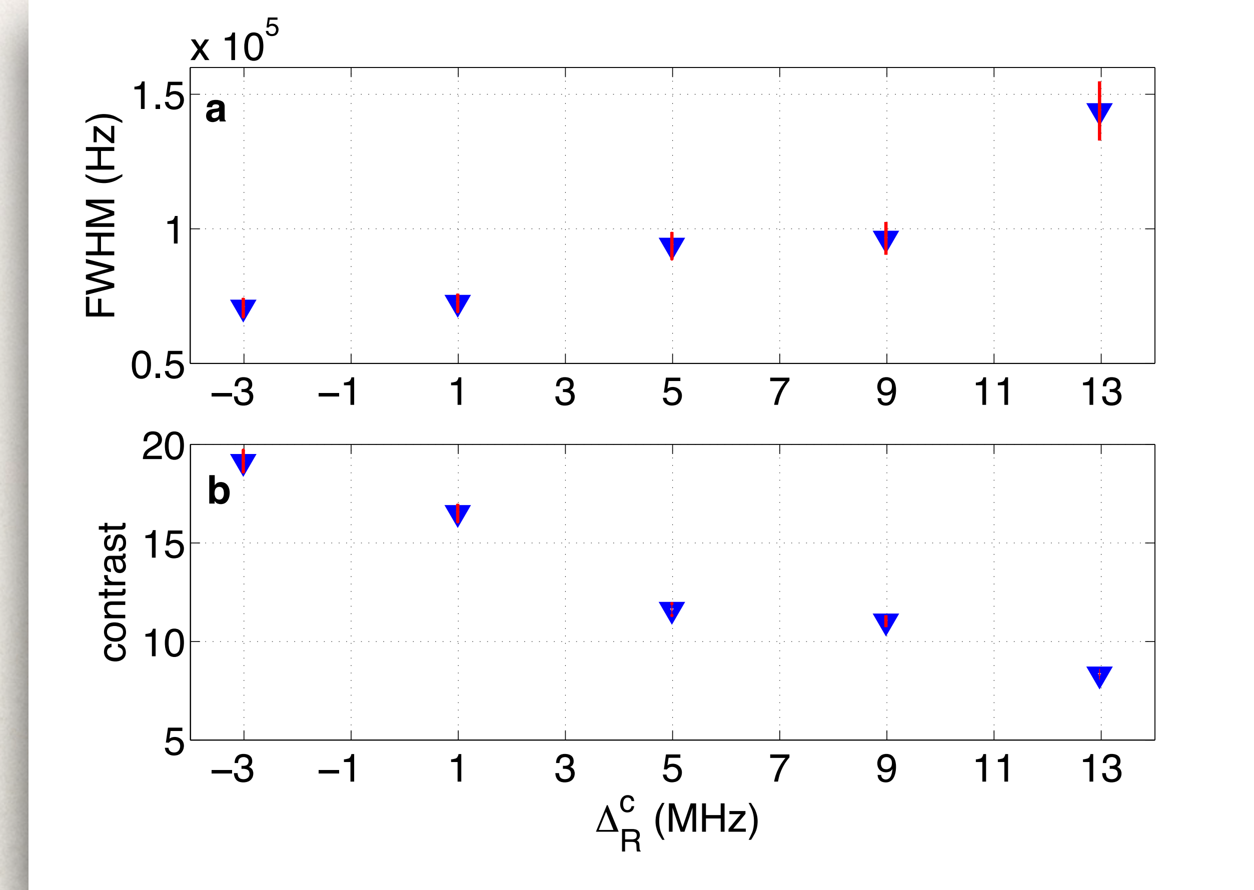
- Zeeman effect through B-field fluctuations (for at least 20 kHz)
- Doppler effect (for 20 kHz if a 10 mK sample is assumed)



Frequency shift to the THz-reference frequency, line-width and contrast are optimal in the same range of one-photon detunings.

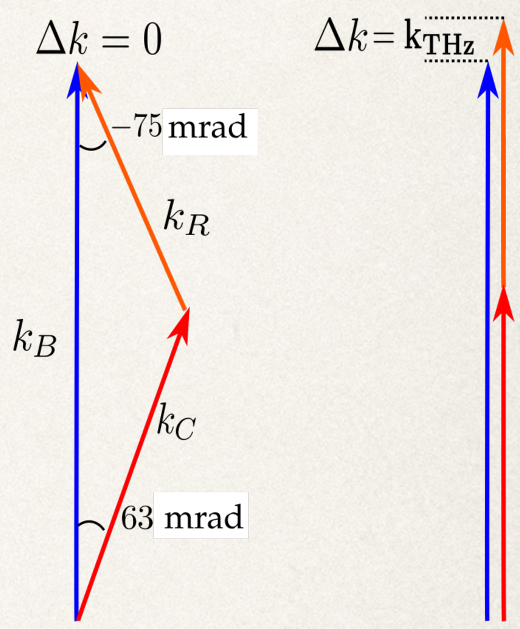
The maximum observed contrast is 25%.





Perspectives

- Doppler-free geometry by propagation of the two red lasers out of trap-axis.



- Better control of the bias magnetic field by a new set of 3D-Helmoltz coils

- Better control of the magnetic field fluctuations by another set of 3D-Helmoltz coils+sensor

- connection to the Refimeve+ network for an optical absolute frequency reference to compare to.

Champenois *et al.* PRL **99**, 013001 (2007)

To answer what questions?

- To propose a THz-frequency reference based on trapped atomic ions, but the production of a THz radiation from the three optical waves remain a challenge.

- To use ion clouds for high precision measurements?

- a midway path between microwave frequency references based on ion clouds and optical frequency references based on single ions, based on a robust protocol thanks to sympathetic cooling and Doppler free configurations.

- the large signal to noise ratio allows the resolution to be increased to the 10^{-11} range by averaging data over seconds even with a kHz line-width.

the people involved all along the years

- the group members in Marseille :

M. Knoop, G. Hagel ,M. Houssin, J. Pedregosa, M. Vedel and F. Vedel

- the students who made and will make it happen

M. Kamsap

M. Collombon

C. Chatou

M. Marchanay