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Cold Atom Sensors at ONERA: Developments and Prospects

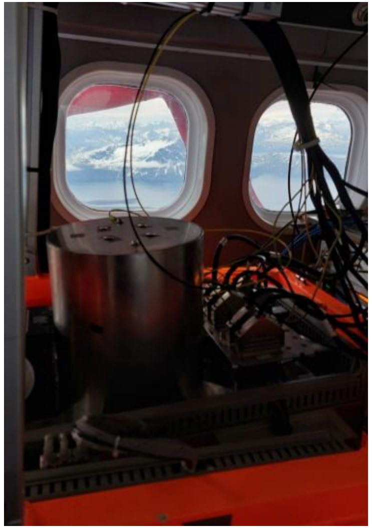
TQCI Seminar

November, 14th 2024

Alexis BONNIN

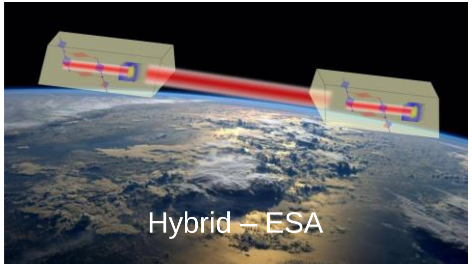
Quantum technologies at ONERA

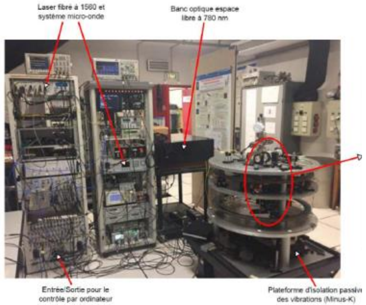
- ONERA is a French national lab devoted to research for aerospace and defense applications
- QTech (w3.onera.fr/qtech) is ONERA's lab for quantum technologies, around 5 domains: quantum communications, quantum optronics, quantum calculation, nanomaterials and components, and atomic sensors
- The atomic sensors team (6 permanent researchers) has been developing cold atom sensors for 2 decades



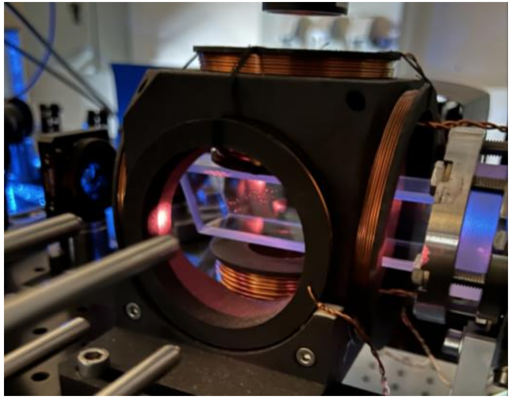
Cold atom sensors at ONERA

- ***Inertial sensors*** based on ***atom interferometry***
  - Gravimeter (mainly for onboard applications)
  - Towards spatial accelerometer
  - Towards Inertial Measurement Unit
  - Multi-species atom interferometry





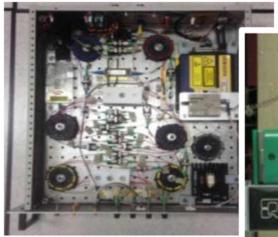
- ***Electromagnetic field sensors*** based on ***cold Rydberg atoms***
  - Spectroscopy in a Magneto-Optical Trap
  - Towards arrays of Rydberg atoms in optical tweezers



Inertial Sensors

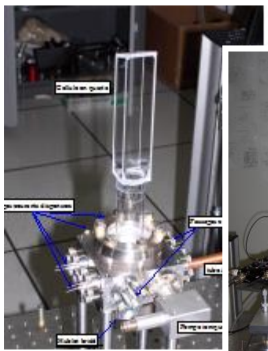
Generations of the “GIRAFE” cold atom gravimeter

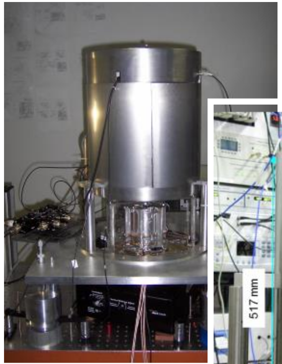
2005



2008

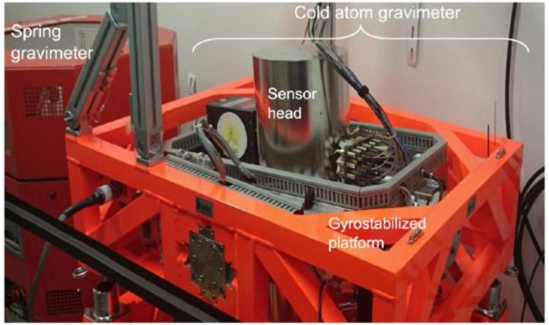
2010





2015

2016



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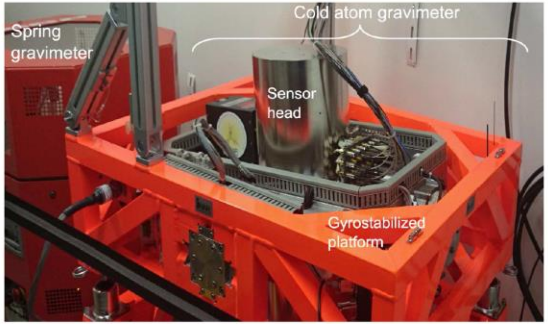
Generations of the “GIRAFE” cold atom gravimeter

2015

2016



industrial marine cold atom gravimeters

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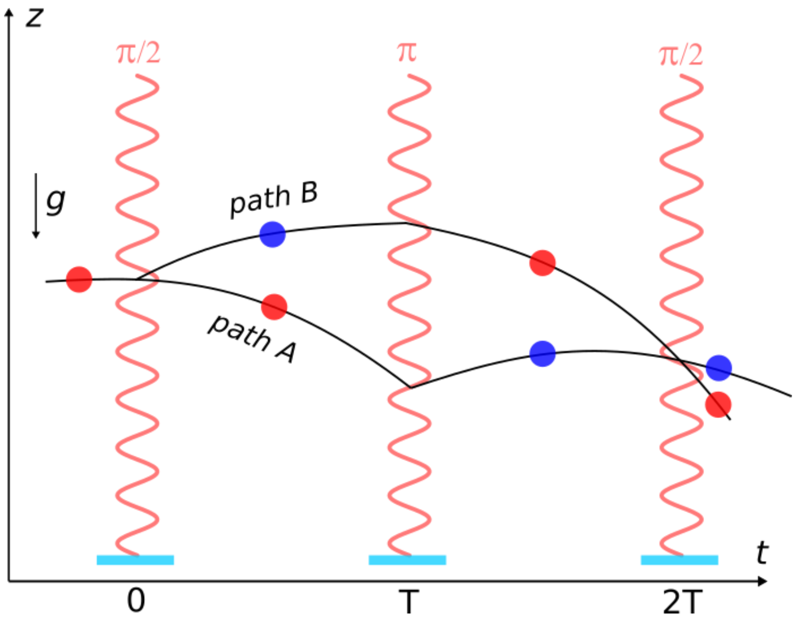
DGA DIRECTION GÉNÉRALE DE L'ARMEMENT

Sensor description (1/2)

. Source: cold atoms of ^{87}Rb ($T \sim 1\,\mu K \Leftrightarrow \sigma_v \sim 1\,cm.s^{-1}$)

. Atom interferometer: atomic wave-packets in free fall illuminated by 3 laser pulses



. Number of atoms detection by fluorescence

$$P = \frac{N_2}{N_1 + N_2} = P_0 + C\cos(\Delta\phi)$$

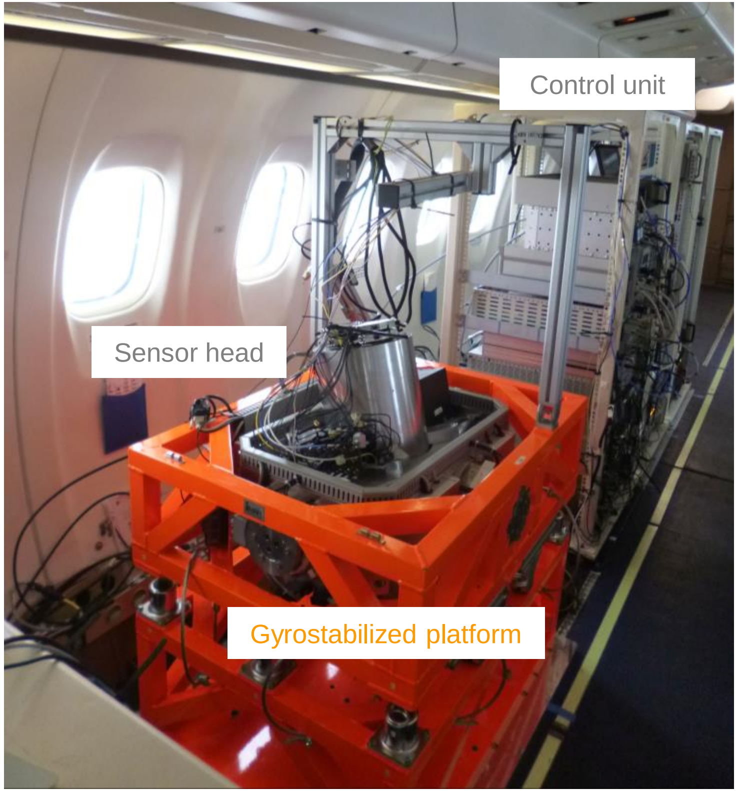
. Dephasing

$$\Delta\phi = \vec{k}\cdot\vec{g}\,T^2$$

laser wave-vector "interrogation time"

Sensitive, Stable and Accurate !

Sensor description (2/2) $(1\, mGal = 1 \times 10^{-5}\, m.s^{-2})$



. Falling distance (14 mm)
  2T = 40 ms

. Sensor head (22x52 cm)

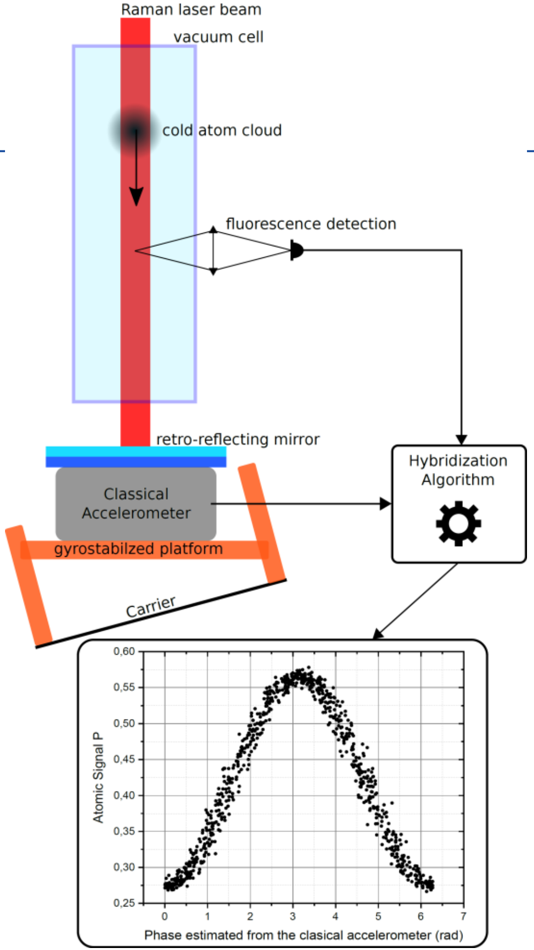
. Gyrostabilized (0.1 mrad)

. Static accuracy (0.07 mGal)

. Sensitivity < 0.75 $mGal.Hz^{-1/2}$

. Repetition rate (10Hz)

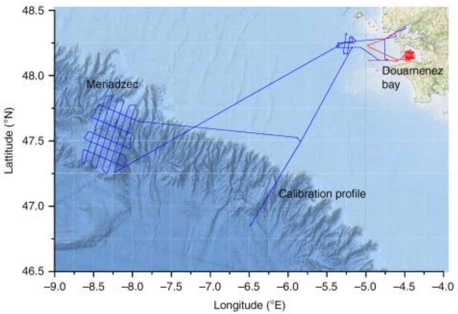
. Hybridization with a classical Accelerometer (Qflex)
    high dynamic range (60 g)
    high measurement bandwidth

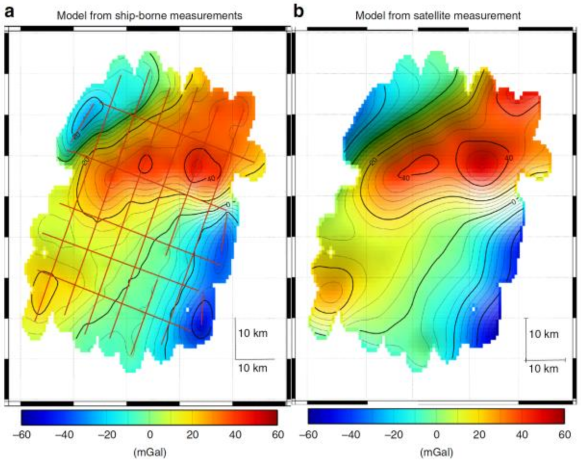


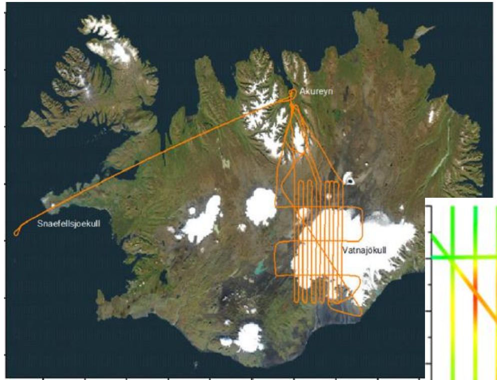
On-board gravity surveys

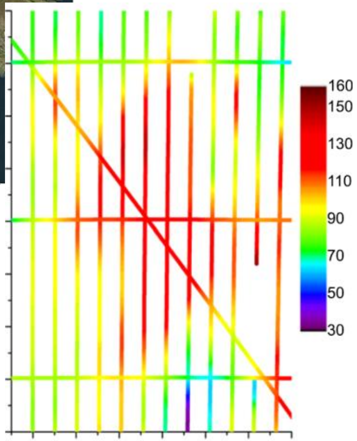
- 5 marine surveys (Atlantic)
- 4 airborne surveys (Iceland 2017, France 2019, France 2022, Iceland & Greenland 2023)

Bidel et al., Nat. Com. ***9****, 627 (2018)*
Bidel et al., J. of Geodesy ***94****:20 (2020)*
Bidel et al., JGR-Solid Earth ***128****, 4 (2023)*









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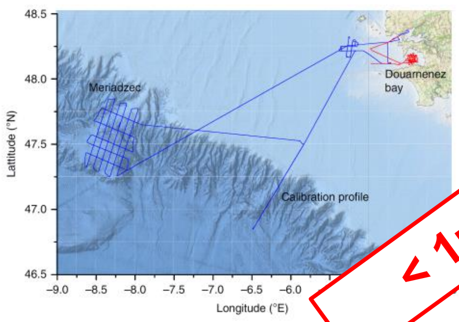
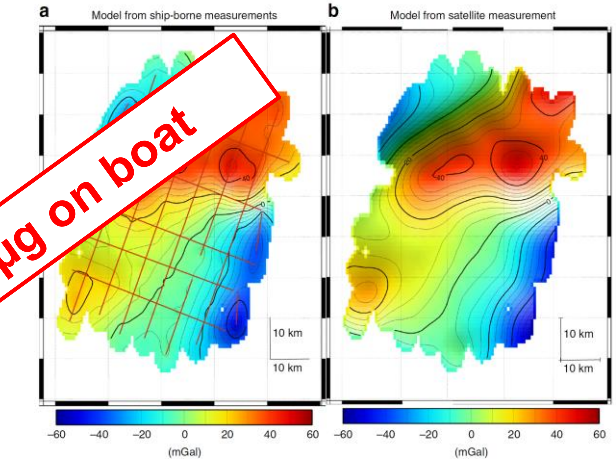
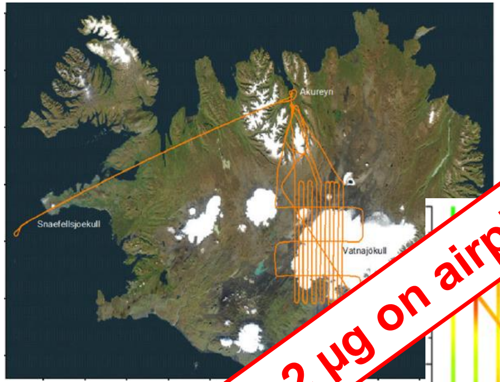
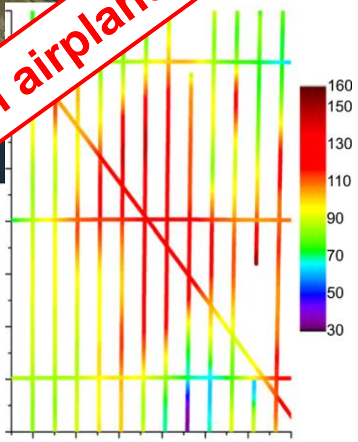




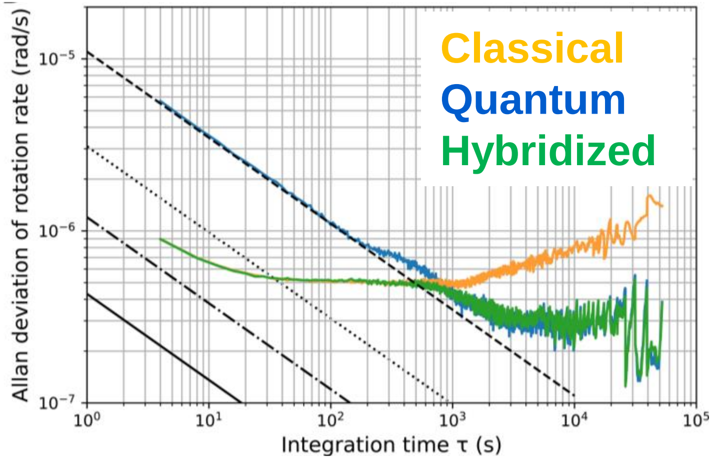




Inertial sensors developments in the lab

- Towards hybridized **I**nertial **M**easurement **U**nit
  - vertical acceleration (GIRAFE)
  - horizontal acceleration ($3.3\ \mu g/\sqrt{Hz}$)
  - 1st rotation measurement (1 axis) : interfering magnetically launched atoms

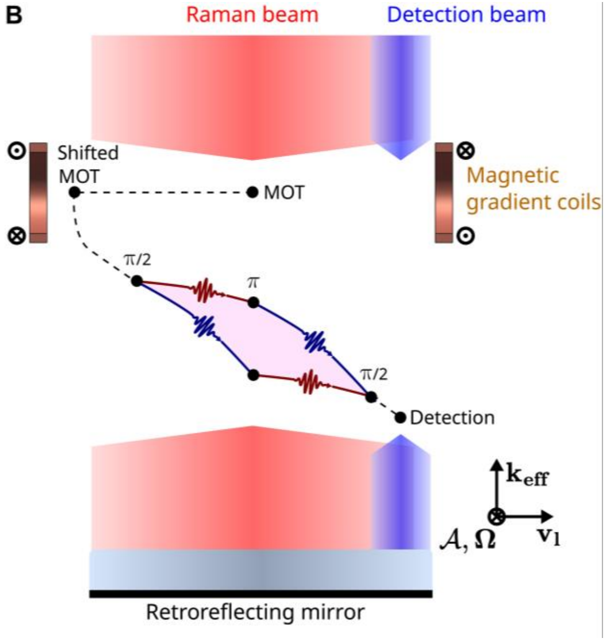
Perrin et al., Phys. Rev. A, ***100****, 053618 (2019)*
Bernard et al, Phys. Rev. A, ***105****, 033318, (2022)*



Salducci et al., Science Advances, ***10****, 44 (2024)*

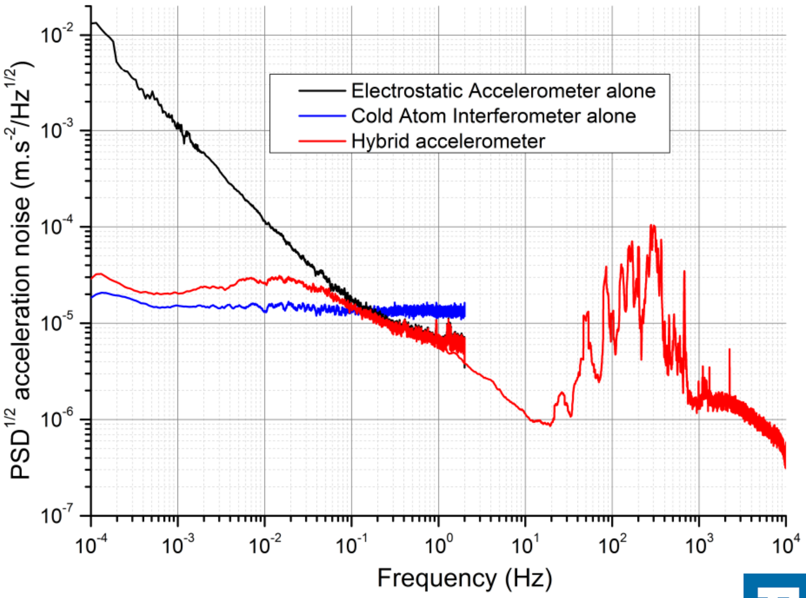
Scale factor stability : 700 ppm

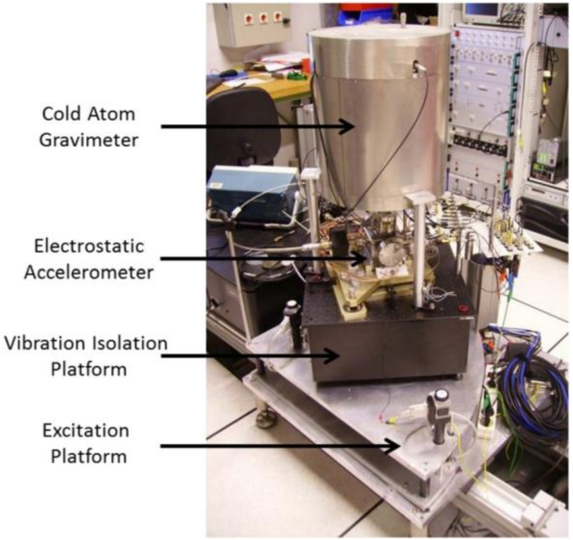
Bias stability : $4 \times 10^{-7} rad/s$



Inertial sensors developments in the lab

- Towards spatial accelerometers : Hybridized cold atom technology with ONERA's electrostatic space accelerometers





Study and compensate for satellite rotations

Zahzam et al., Remote Sens., ***14***, *3273 (2022)*

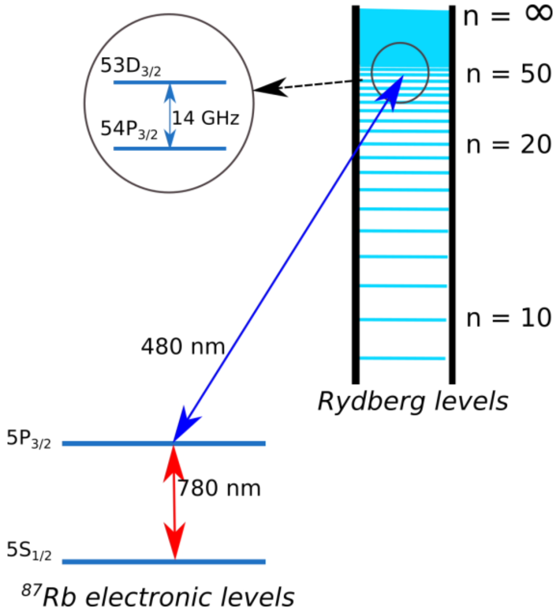
Electromagnetic Field Sensor

E-field sensing with cold Rydberg atoms (1/2)

- Electromagnetic sensing with Rydberg atoms is a very active field of research !
  Most of sensors are based on Electromagnetically Induce Transparency in room vapor cells

  C. T. Fancher et al,''Rydberg Atom Electric Field Sensors for Communications and Sensing''
  IEEE Transactions on Quantum Engineering, vol. 2, pp. 1-13, 2021

  D H Meyer et al, Assessment of Rydberg atoms for wideband electric field sensing,
  J. Phys. B: At. Mol. Opt. Phys. 53 034001, 2020



- Some key properties of Rydbarg states ($n \gg 1$)

  - very large electric moment → sensitivity

  - transition frequencies from MHz to THz → tunability

  - Long lived atomic states ($\tau \sim 100\ \mu s$)
    → precision spectroscopy and coherent manipulation

E-field sensing with cold Rydberg atoms (2/2)

- What cold atoms can bring ?

  - Reduced Doppler effect → resolution, sensitivity

  - Stability, long interrogation time for precision measurements (e.g. calibrating blackbody shifts in optical lattice clocks)

  - Control of the external degree of freedom → spatial resolution, THz imaging

  - Accuracy ?

  - But higher complexity and low instantaneous bandwidth (need development of new experimental techniques !)

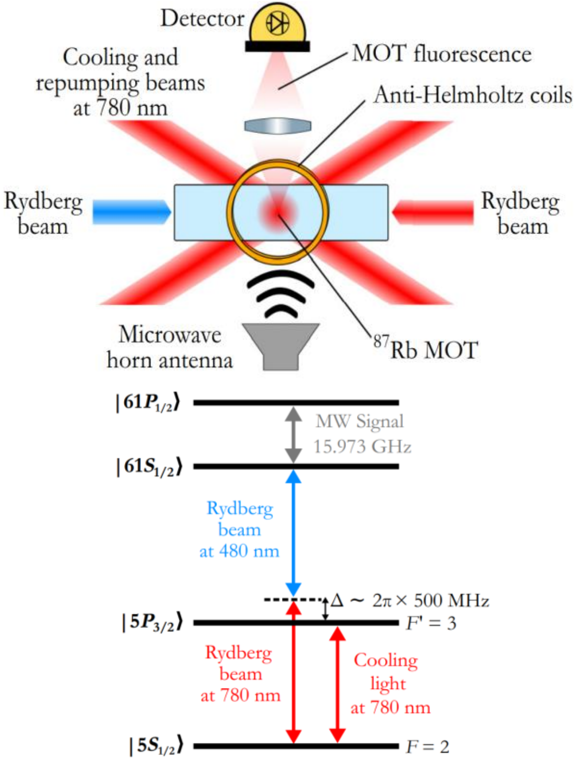
  - Quantum metrology with non-classical states !

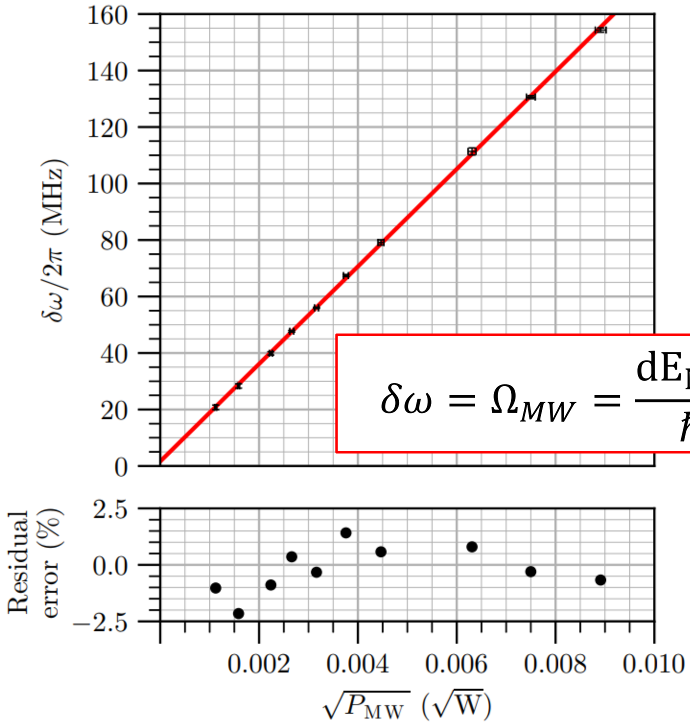
SYRTE l'Observatoire de Paris | PSL
SYstèmes de Référence Temps-Espace

LABORATOIRE Aimé Cotton

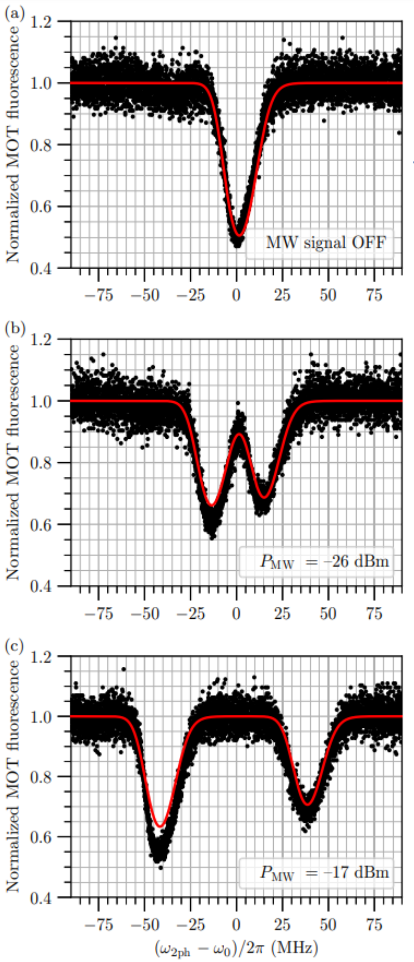
"Rydberg spin-squeezing"
Bornet et al., Nature ***621****, 728–733 (2023)*
Eckner et al., Nature ***621****, 734–739 (2023)*
Hines et al., Phys. Rev. Lett. ***131****, 063401 (2023)*

Our cold Rydberg sensor - Linearity



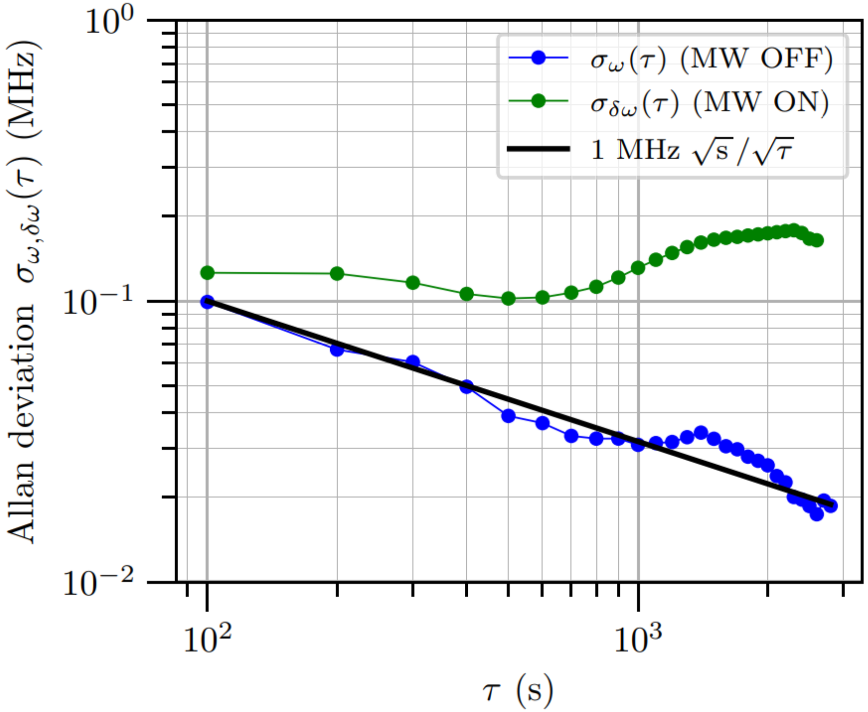


$$\delta\omega = \Omega_{MW} = \frac{dE_{MW}}{\hbar}$$



*Duverger et al, Physical Review Applied, **22**, 044039 (2024)*

Our cold Rydberg sensor - Stability



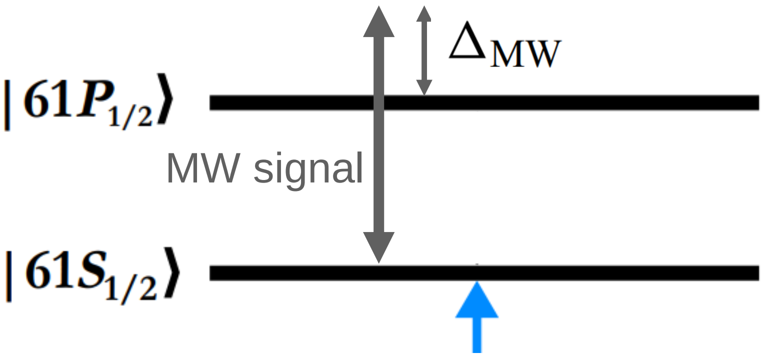
equivalent to about 5 $\mu V/cm$

*Duverger et al, Physical Review Applied, **22**, 044039 (2024)*

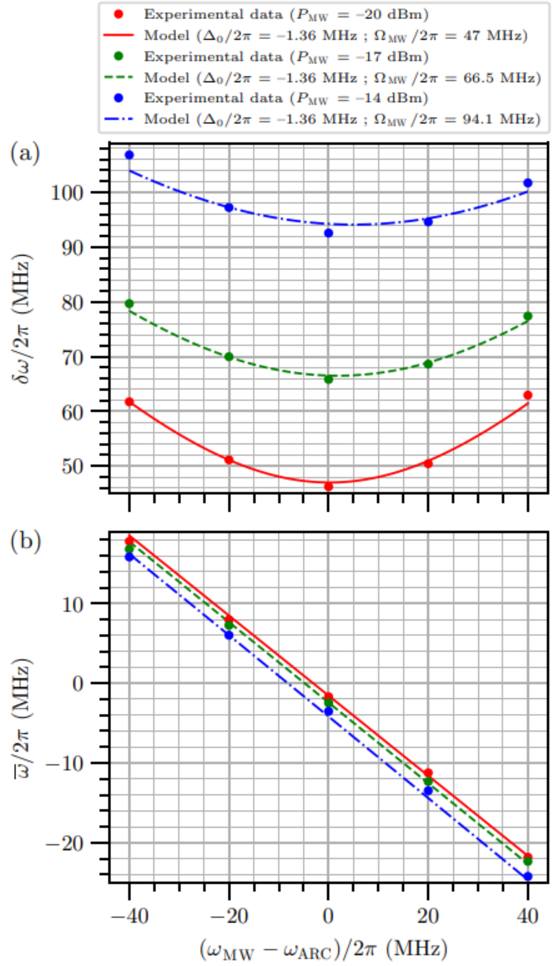
Our cold Rydberg sensor –
Measuring Amplitude and Frequency

$$\omega_{\pm} = \omega_0 - \frac{\Delta_{MW}}{2} \pm \frac{1}{2}\sqrt{\Omega_{MW}^2 + \Delta_{MW}^2}$$

$$\begin{cases} \delta\omega = \omega_{+} - \omega_{-} \\ \overline{\omega} = \frac{1}{2}(\omega_{+} + \omega_{-}) - \omega_0 \end{cases}$$



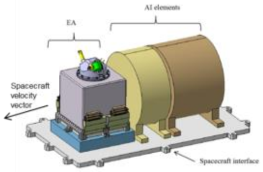
Need to account for the ''light'' shifts of neighboring states



Duverger et al, Physical Review Applied, ***22***, *044039 (2024)*

Perspectives

- Multi-species atom interferometry (improve performance, no dead-time, …)
- Towards strapdown gravimetry (ADEQUADE)
- Space accelerometers for geodesy (Hybrid, BEC source, CARIOQA)



- Cold Rydberg atoms in optical tweezers, hybridization with ‘hot’ vapor sensor ? (PEPR CARAMELS, ADEQUADE)

Thanks !

- ***ONERA-DPHY-SLM-Cold Atom Team***

Ingénieurs-chercheurs	*Technicien*	*Collaborateur extérieur*	*Contrat de projet*	*Doctorants*
A.Bresson Y. Bidel N. Zahzam A. Bonnin S. Schwartz	C. Blanchard	M. Cadoret (MdC CNAM)	A.Mainos	N. Marquet C. Salducci R. Duverger R. Granier M. Landru S. Darmon

Funding for PostDocs !

- ***Collaborations : academics and industrials***

- ***Supports***