Cold atom gyroscope with 1 nrad.s^{-1} rotation stability

D. Savoie, I. Dutta, B. Fang, B. Venon, N. Miélec, R. Sapam, C. Garrido Alzar, R. Geiger and A. Landragin
LNE-SYRTE, Observatoire de Paris
IACI team

GPHYS 2016
06/07/2016

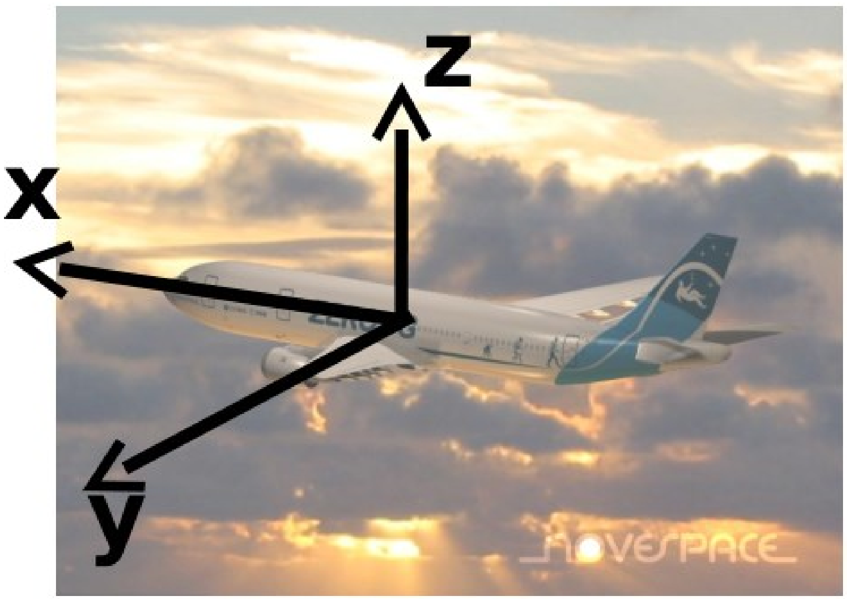
I. Dutta et al., Phys. Rev. Lett. **116**, 183003

Outline

- Application of cold atom inertial sensors for fundamental physics
- Principles of atom interferometry
- Cold atom gyroscope at SYRTE

Applications

- **Inertial Navigation**: onboard accelerometers or gyroscopes



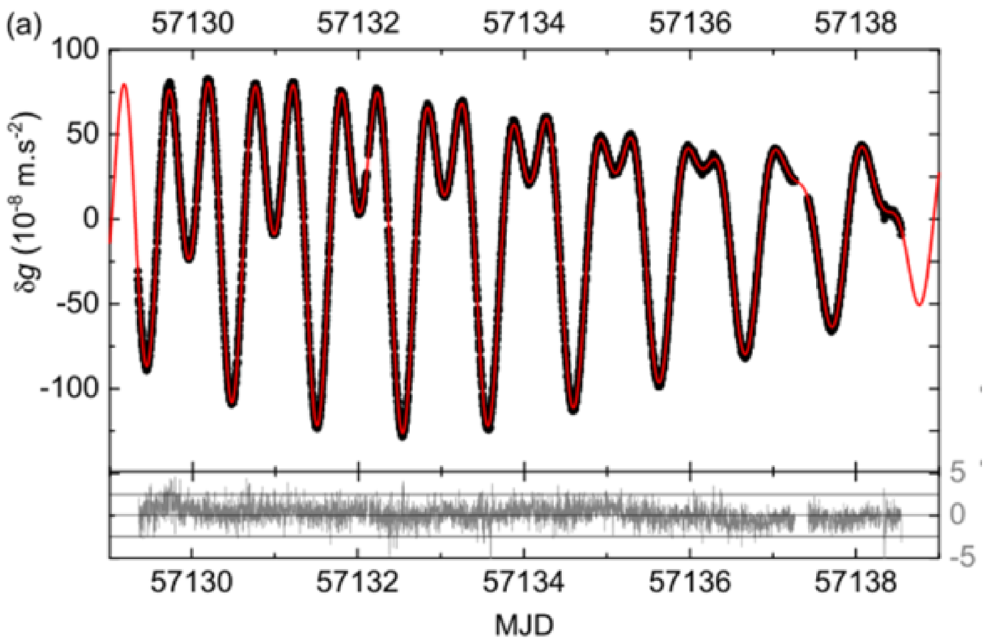
Inertial navigation :
Accelerometers and gyroscopes

Canuel et al, PRL (2006)
Geiger et al, Nature Comm. (2011)

Applications

- **Inertial Navigation**: onboard accelerometers or gyroscopes
- **Geosciences**: monitoring global phenomena through $\vec{\Omega}_{\mathrm{Earth}}(t)$, $\vec{g}(t)$

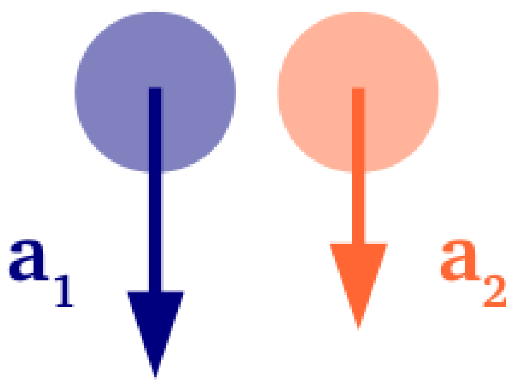
Fang et al, arXiv:1601.06082
Freier et al, arXiv:1512.05660



Geoscience:
Measurements of Earth rotation with gyroscopes
Measurement of gravity with gravimeters

Applications

- **Inertial Navigation**: onboard accelerometers or gyroscopes
- **Geosciences**: monitoring global phenomena through $\vec{\Omega}_{\mathrm{Earth}}(t)$, $\vec{g}(t)$
- **Fundamental physics** (e.g. test of equivalence principle, Lorentz invariance tests)



Zhou et al, PRL (2015)
Aguilera, CQG (2014)

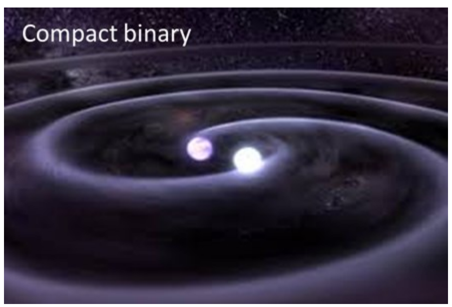
Example: weak equivalence principle test: simultaneous acceleration measurement with 2 types of atoms in free fall.

- State of the art with cold atoms : $\frac{\delta a}{a} = 10^{-8}$
- Perspective : $\frac{\delta a}{a} = 10^{-15}$

Applications

- **Inertial Navigation**: onboard accelerometers or gyroscopes
- **Geosciences**: monitoring global phenomena through $\vec{\Omega}_{\mathrm{Earth}}(t)$, $\vec{g}(t)$
- **Fundamental physics** (e.g. test of equivalence principle, Lorentz invariance tests)
- **Gravitational wave detection below 10 Hz**

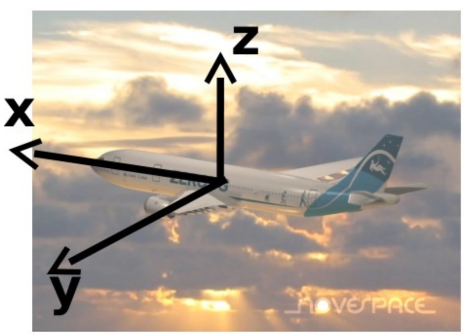
Dimopoulos et al, PRD (2008)
Chaibi et al, 2016 PRD (2016)



Gravitational wave detection:
Detection of GW of lower frequencies than Earth-based optical detectors

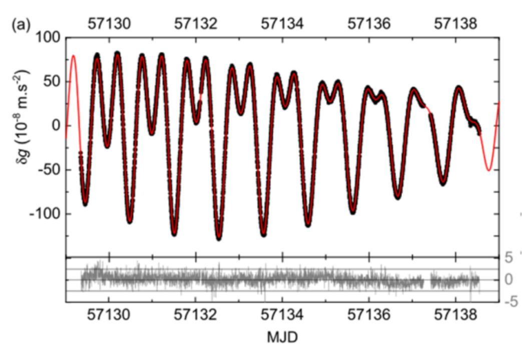
Applications

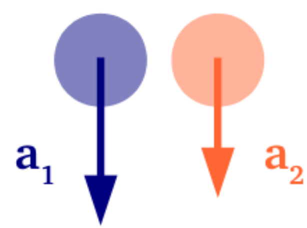
- **Inertial Navigation**: onboard accelerometers or gyroscopes
- **Geosciences**: monitoring global phenomena through $\vec{\Omega}_{\text{Earth}}(t)$, $\vec{g}(t)$
- **Fundamental physics** (e.g. test of equivalence principle, Lorentz invariance tests)
- **Gravitational wave detection below 10 Hz**



Canuel et al, PRL (2006)
Geiger et al, Nature Comm. (2011)

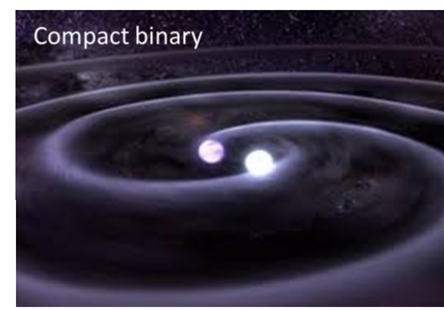
Fang et al, arXiv:1601.06082
Freier et al, arXiv:1512.05660



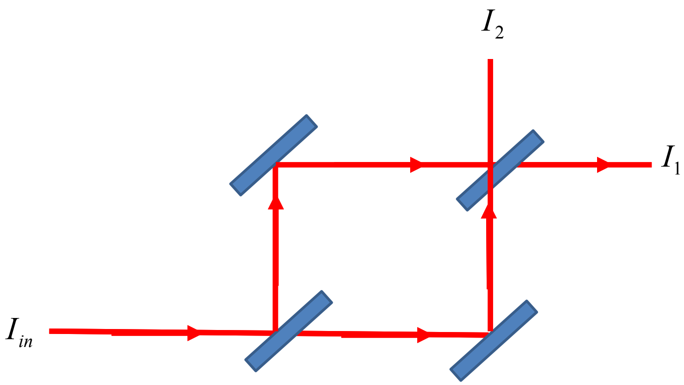


Zhou et al, PRL (2015)
Aguilera, CQG (2014)

Dimopoulos et al, PRD (2008)
Chaibi et al, 2016 PRD (2016)

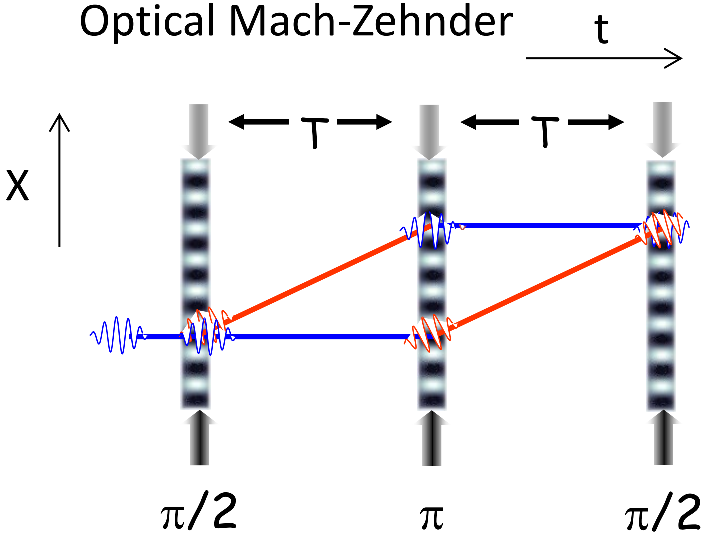


Principles of atom interferometry



Optical Mach-Zehnder

$$I_1 = \frac{1}{2}\left(1+\cos\left(\Delta\Phi\right)\right)I_{in}$$



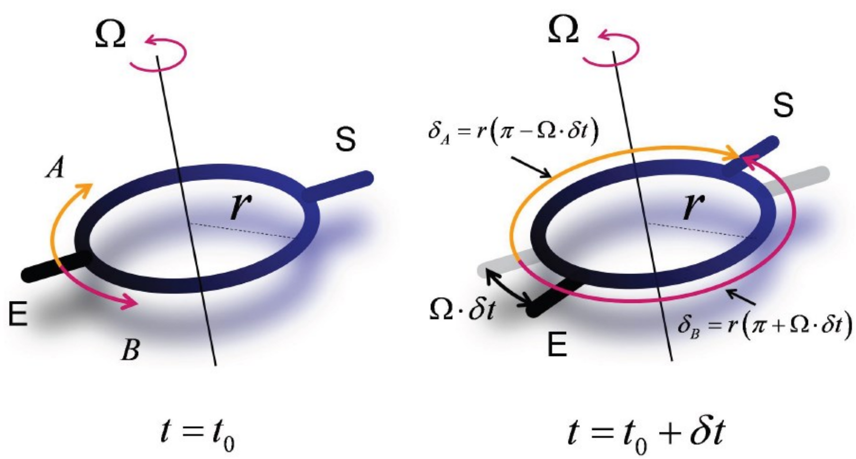
Atomic Mach-Zehnder

- Light -> Matter waves
- Mirrors and separators -> Light pulses
- Output channel intensity -> Transition Probability

$$P_{|f,p\rangle\rightarrow|e,p+\hbar k\rangle} = \frac{1}{2}\left(1+\cos\left(\Delta\Phi\right)\right)$$

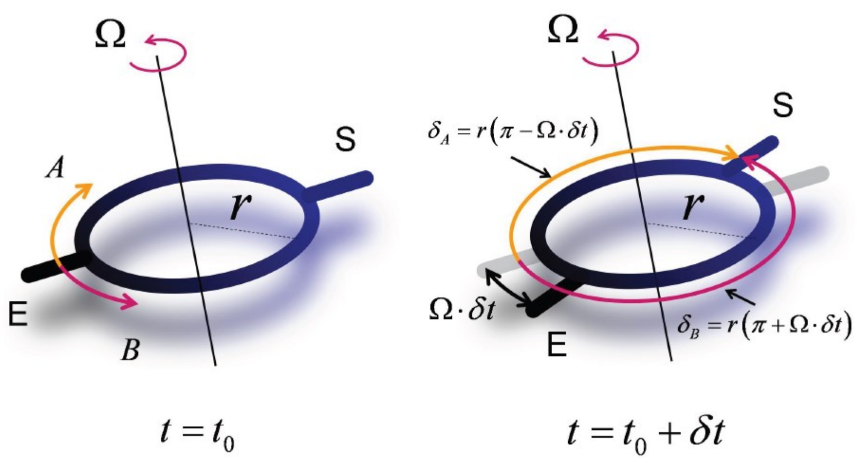
Why an atomic gyroscope ?

Sagnac effect



Why an atomic gyroscope ?

Sagnac effect



In general :

$$\Delta\Phi_{\Omega} = \frac{4\pi E}{hc^2}\vec{A}\vec{\Omega}$$

energy

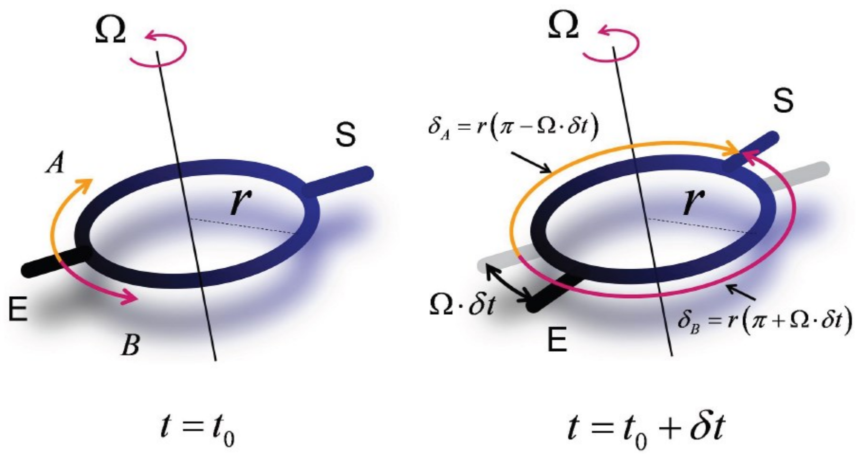
Physical area of the interferometer

With photons :

- A : cm² to m²
- $E \sim 1\text{eV}$

Why an atomic gyroscope ?

Sagnac effect



In general :

$$\Delta\Phi_{\Omega} = \frac{4\pi E}{hc^2} \vec{A}\vec{\Omega}$$

energy

Physical area of the interferometer

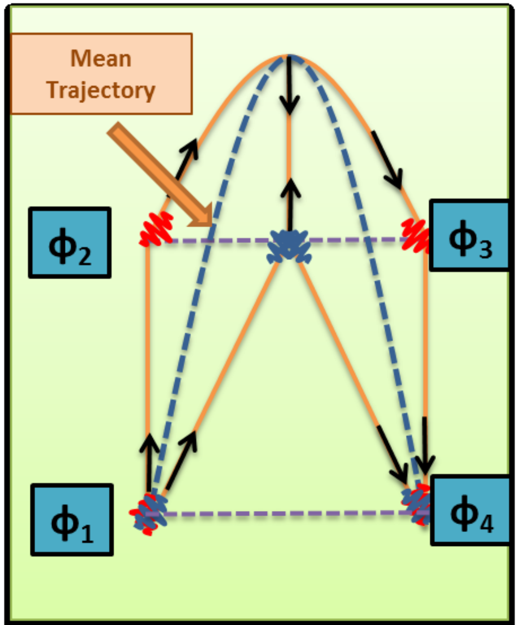
With photons :

- A : cm² to m²
- $E \sim 1\text{eV}$

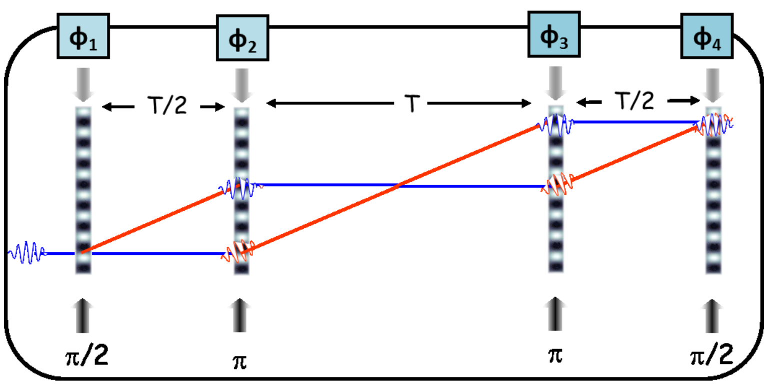
With atoms :

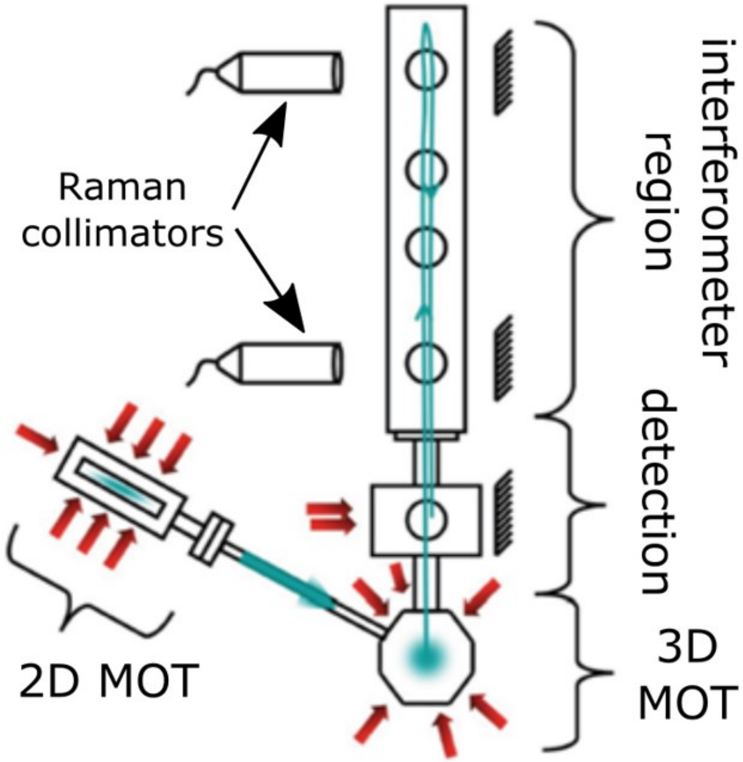
- A : mm² to cm²
- $E \sim 10^{11}\text{eV}$

4-pulse gyroscope



« Butterfly » configuration





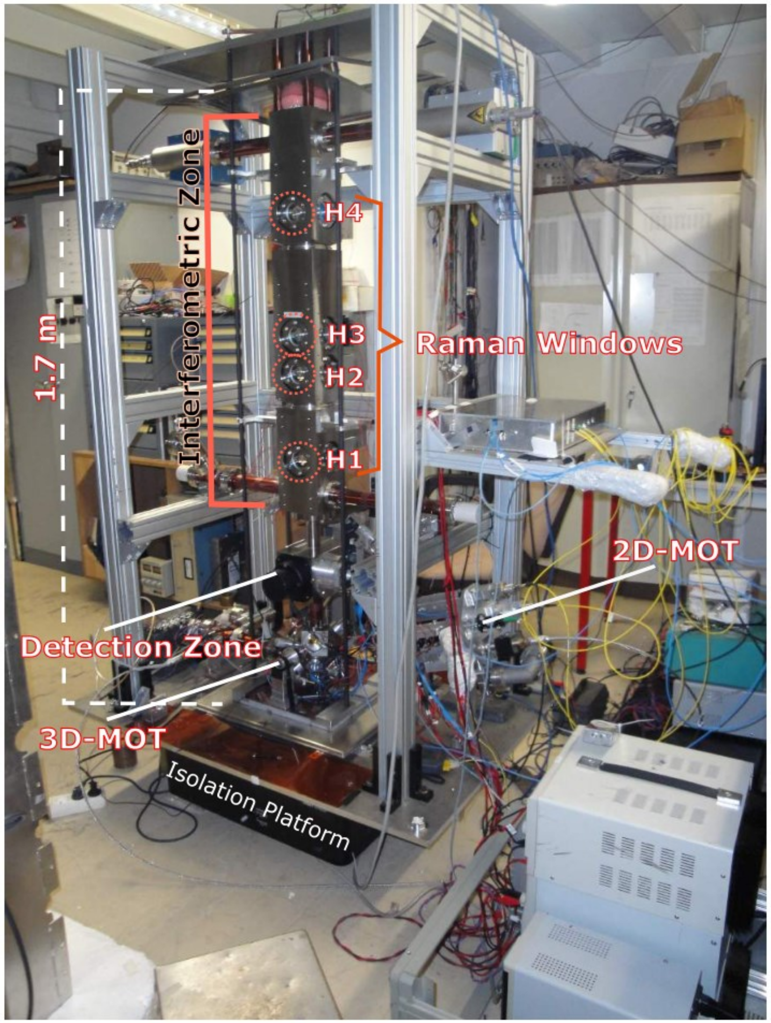
Sensitivity of the Gyroscope

$$\Phi_\Omega = \frac{1}{2}\vec{k}_{\text{eff}} \cdot \left(\vec{g} \times \vec{\Omega}\right) T^3$$

800 ms interrogation time -> 11 cm^2 Sagnac area

1 $rad.s^{-1}$ rotation rate signal -> $4{,}6x10^6$ rad phase shift in the AI

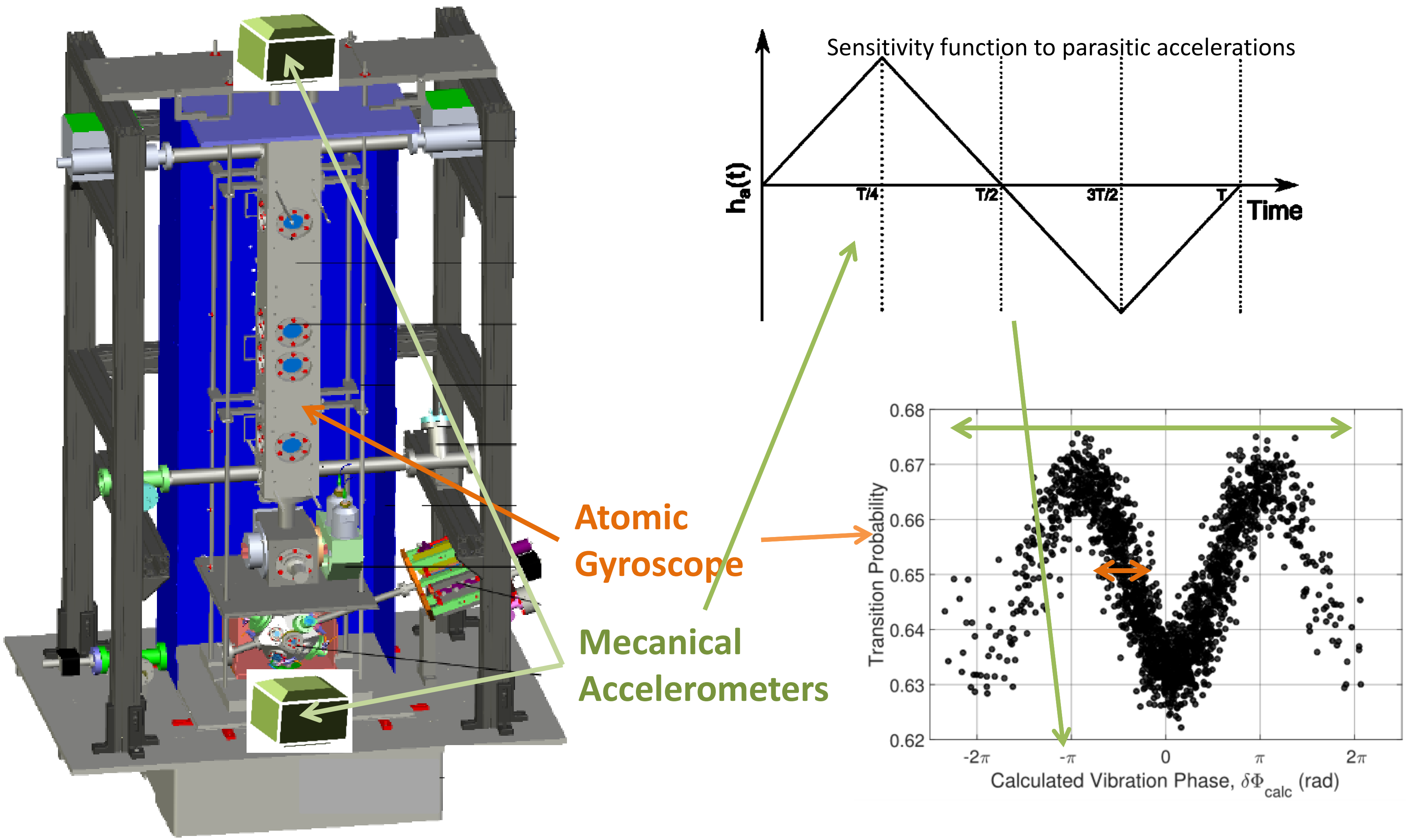
The SYRTE cold atom gyroscope



I. Dutta, PhD Thesis

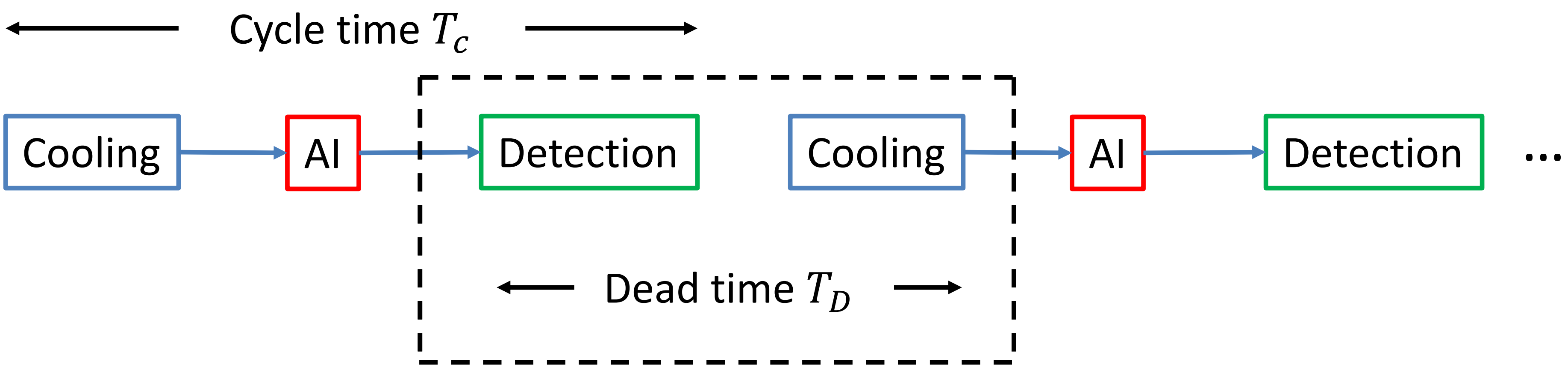
- Long interrogation time -> large area : 11 cm²
- Big scale factor : 1 rad/s ->$4{,}6\times10^{6}$ rad (Earth rotation rate: $7{,}3\times10^{-5}$ rad/s)
- Allows no-dead-time operation
- A few 10^{7} Cs atoms at 1,2 µK launched at 5 m/s

Hybrid measurement with vibration sensors



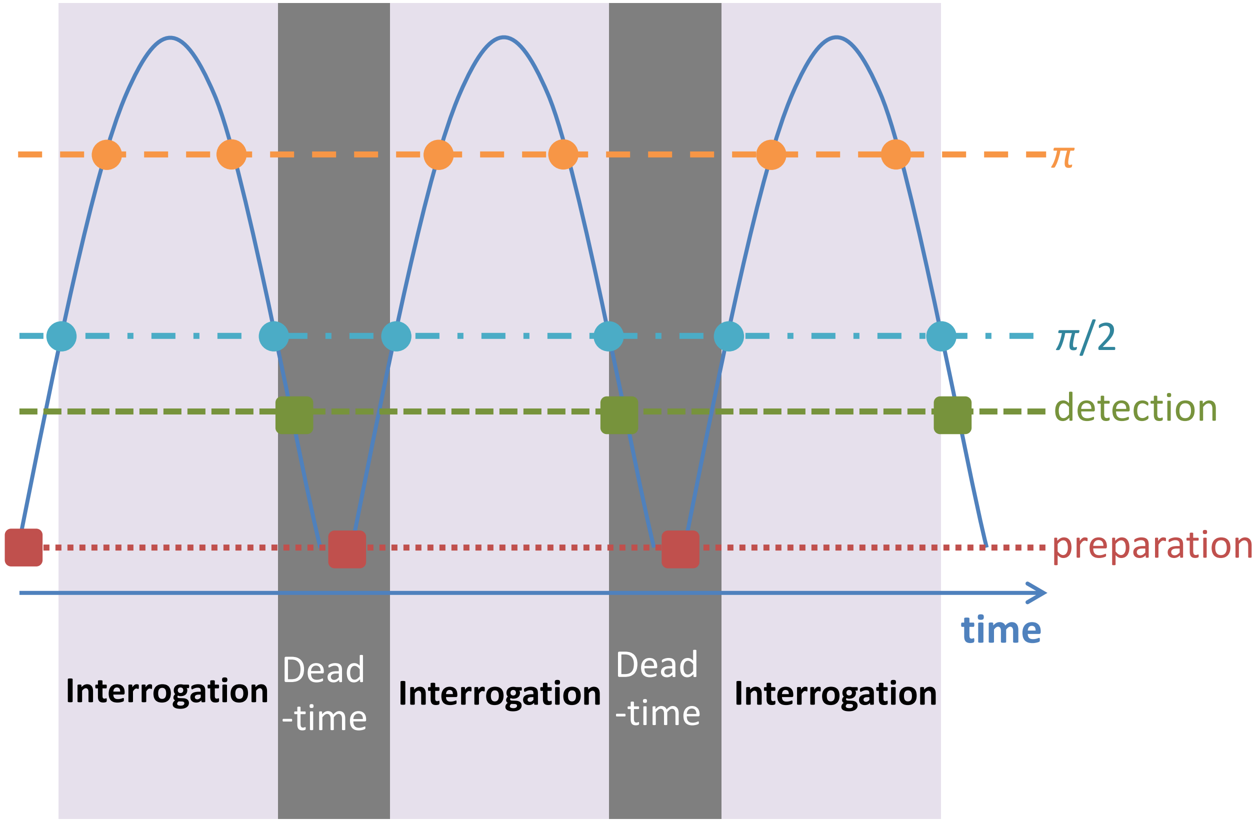
Continuous measurements

- Sequential operation of cold atom interferometers

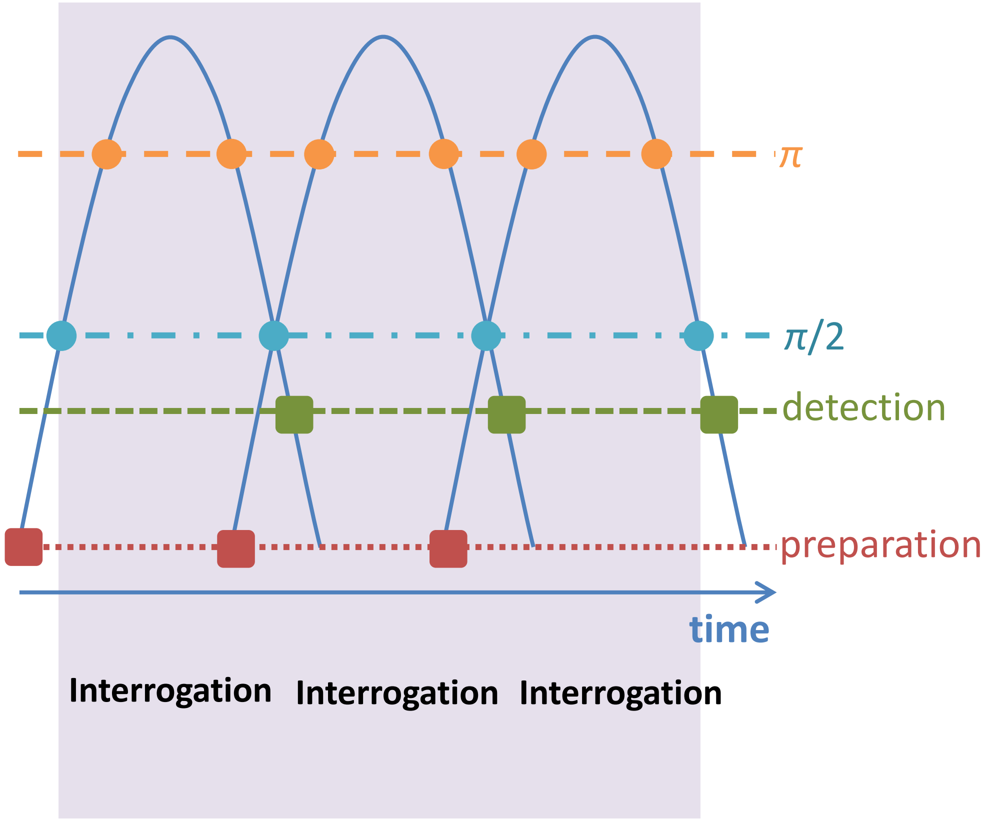


Leads to loss of information

Usual measurement cycle

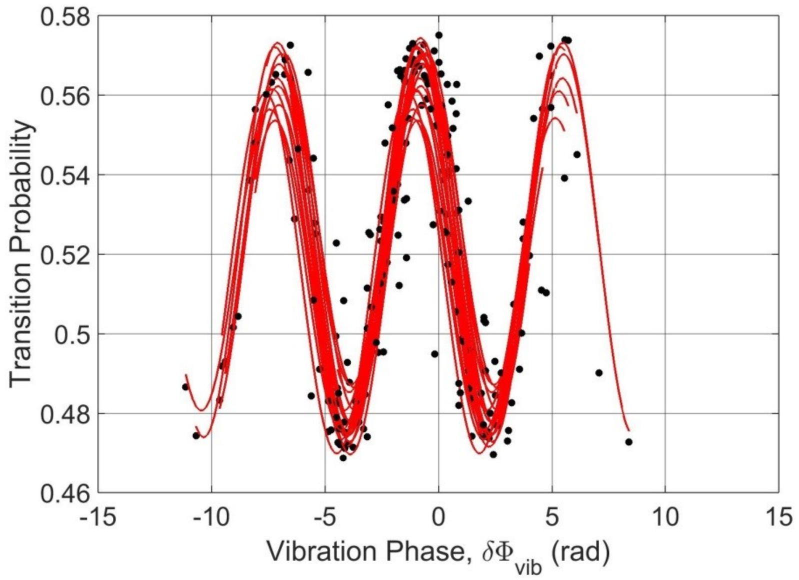


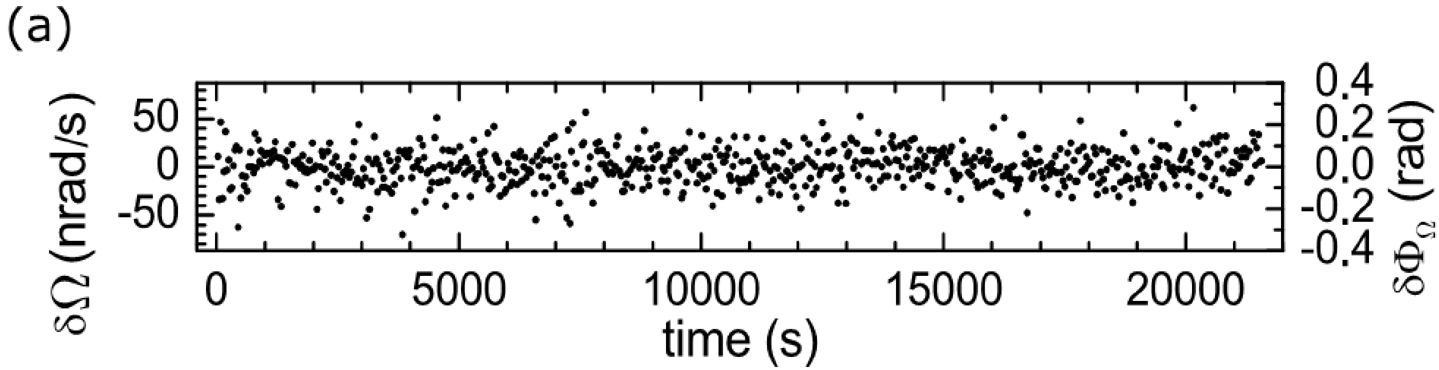
Continuous Measurements
On our experiment



Rotation measurement

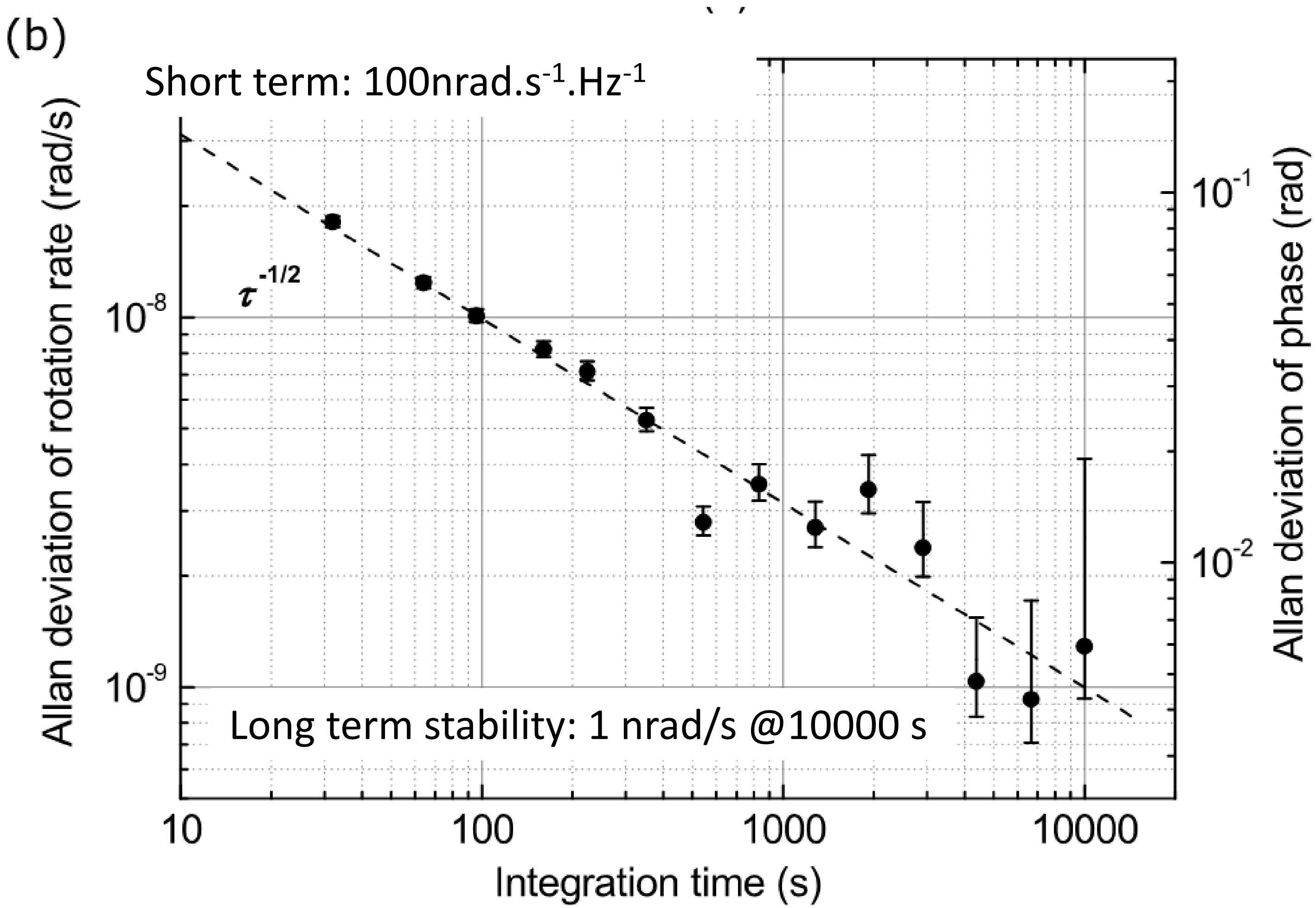
Fit by packet with the estimated vibration phase -> the useful signal is the phase offset of the fit of each packet





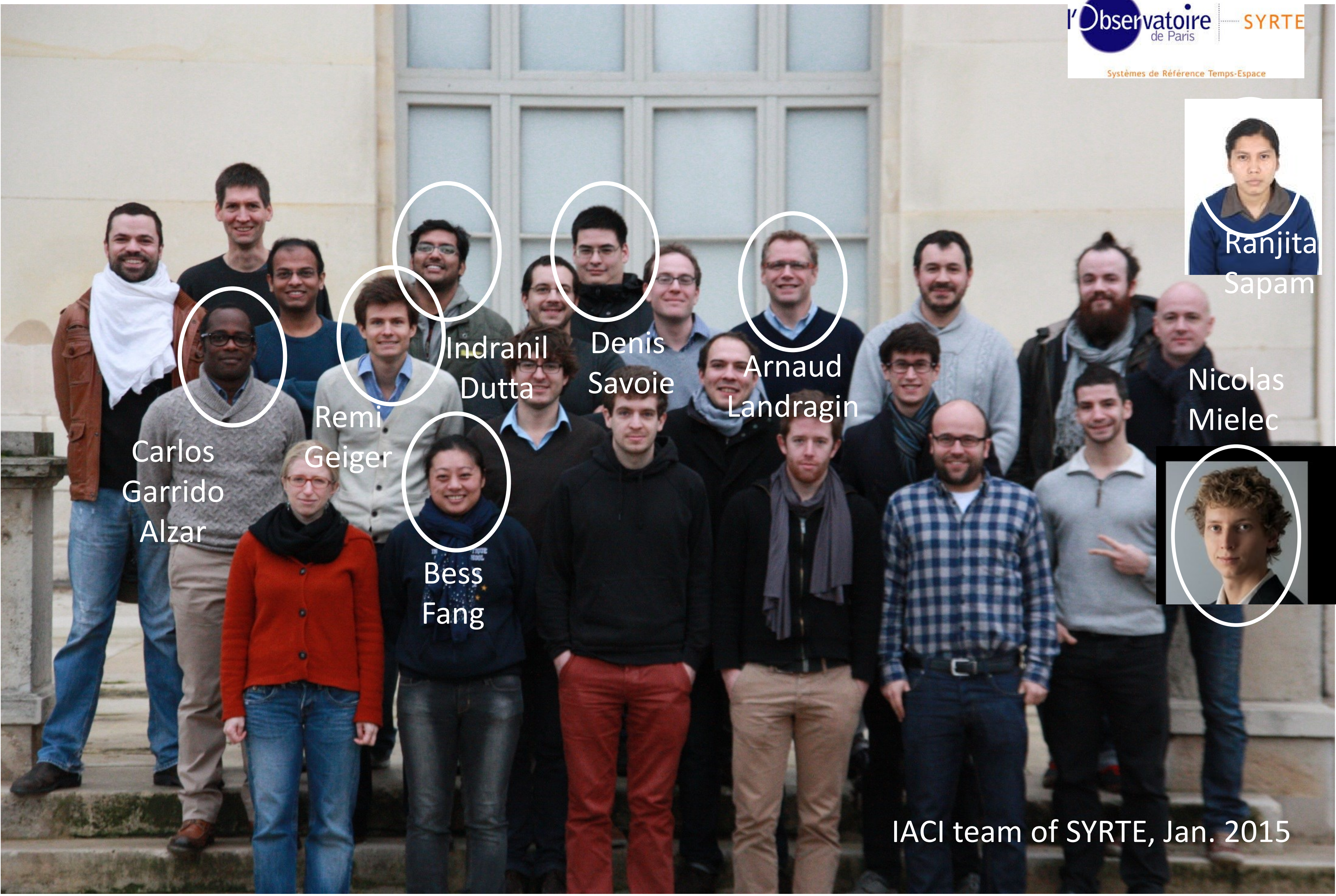
Performances

I. Dutta et al., Phys. Rev. Lett. **116**, 183003



Conclusion

- Cold-atom interferometers can be used for various applications
- We demonstrated a continuous measurement in an AI
- We operated a cold atom gyroscope with a stability of 1 nrad/s : state of the art
- Perspective for fundamental physics:
  - Use the experiment as an horizontal accelerometer to test Lorentz invariance



IACI team of SYRTE, Jan. 2015

Thank you for your attention