QUANTERA

ERA-NET Cofund in Quantum Technologies

# Mid Term Conference

**Granada, 13-14 November 2019**

# TAIOL

# Trapped Atom Interferometers in Optical Lattices

Franck Pereira dos Santos

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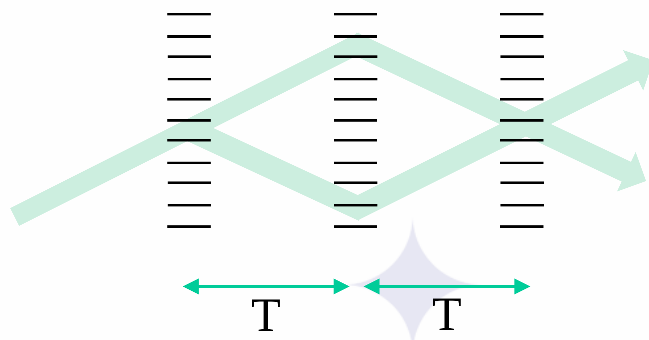
# TAIOL Consortium

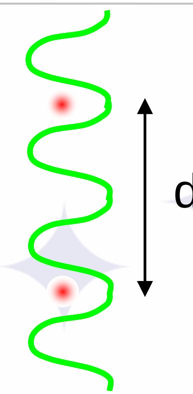
| Lab/Institute | | PI | Country |
|---|---|---|---|
| SYRTE/Paris Observatory | | Franck Pereira dos Santos | France |
| LP2N/IOGS | | Andrea Bertoldi | France |
| IQ/LUH | | Ernst Rasel | Germany |
| CNR-INO/LENS | | Marco Fattori | Italy |
| UW | | Jan Chwedeńczuk | Poland |

# Context

Two different types
of atom interferometers:

Free Fall Vs Trapped




| Configuration | Free fall | Trapped |
|---|---|---|
| Interferometer Phase | $kgT^2$ | $mgdT/\hbar$ |
| Max interferometer duration (on ground) | 2T < 1s | T ~ 10 s |
| Size | 1-10 m | mm - cm |
| Wavepacket separation | Up to tens of cm | ~ tens of μm |
| Acceleration sensitivity @1s | ~ $10^{-9}$g | ~ $10^{-6}$g |
| Maturity | High | Low |
| Main systematics | Light beamsplitters wavefronts | Trap/guide/atom interactions |

# Context

**Main objectives:**

Tackling the fundamental issues that have limited so far trapped atom interferometers

- ❑ Identify and demonstrate innovative techniques to enlarge the coherent separation of trapped atomic samples from few (tens of) microns up to millimeters.

- ❑ Operate trapped atom interferometers with sensitivities beyond state of the art

Challenge trapped atom interferometry in high-spatial-resolution measurement of forces such as Casimir Polder forces close to a surface and nano-g sensitivities in mm size devices.

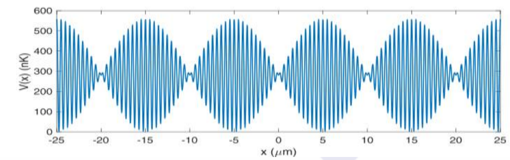
- ❑ Tackle the decoherence of the interferometric phase due to interactions through the use of:
  - ➢ atomic sources where the collisional cross section can be precisely tuned to zero
  - ➢ exploiting innovative sources of ultra-diluted/cold atomic samples.

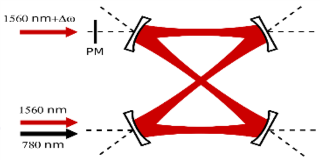
- ❑ Study and test new methods to enhance the phase sensitivity of the interferometers using quantum entanglement and chaos.

# New beamsplitting tools

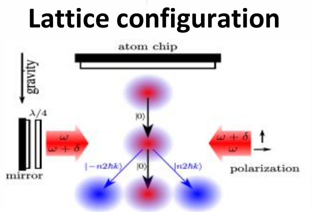
**Investigate several original approaches of mutual use: a toolbox of innovative methods**

- ✓ Explore different innovative Beat-Lattices (BLs), formed through the superposition of two lattices realized with similar optical wavelengths, for atom manipulation:
  Bloch oscillations, Selection of Wannier states,
  Double well interferometers with 10 μm separation …

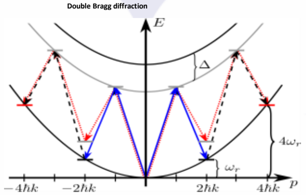



- ✓ Exploit the ultra-stable multi well potential defined by the spatial modes of a high finesse cavity to hold, split and recombine atoms over 100 microns distances

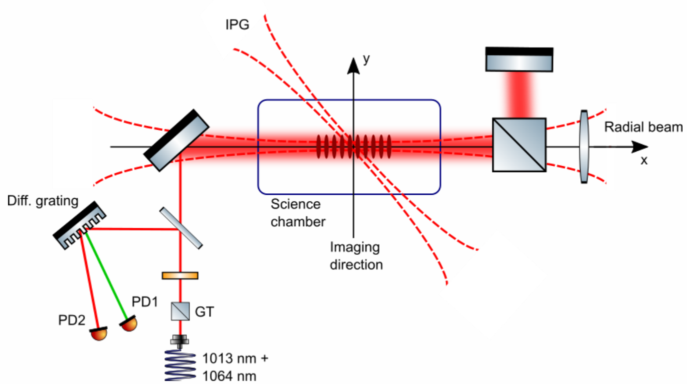



- ✓ Symmetric beam splitting techniques in a guide / dual lattice / quasi guide: combine symmetric double Bragg transitions + dual Bloch lattices



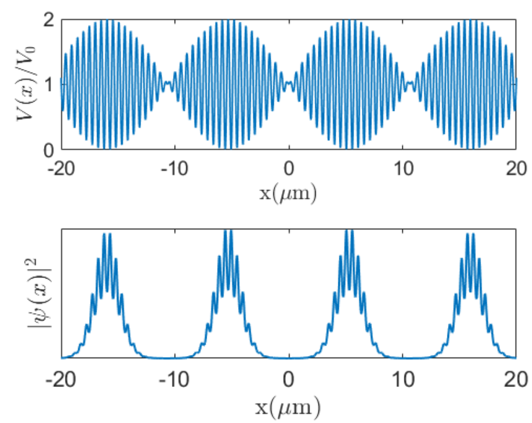
# Progress: Large spacing optical lattice at CNR-INO

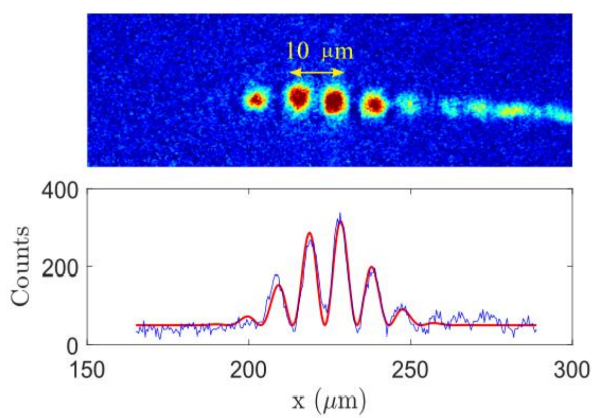
Optical setup for the production of the beat-note lattice



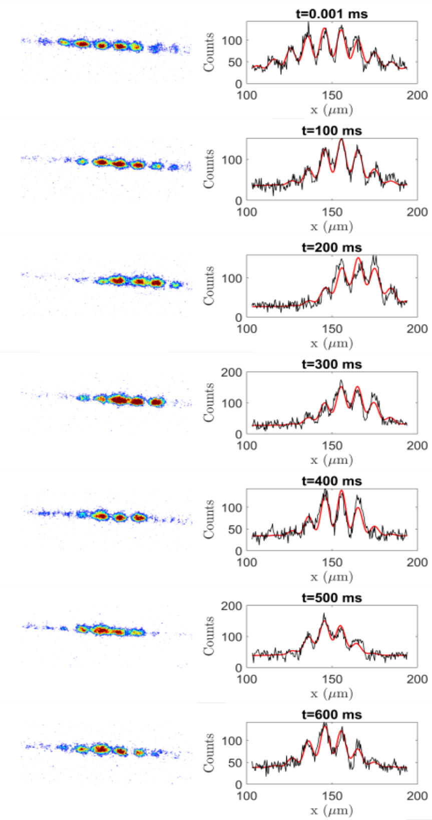

$$(n+1)\lambda_2 = n\lambda_1 \rightarrow d = \frac{n\lambda_1}{2}$$

$$\begin{cases} \lambda_1 = 1064 \text{ nm} \\ \lambda_2 = 1013 \text{ nm} \end{cases} \rightarrow d = 10.6\ \mu\text{m}$$



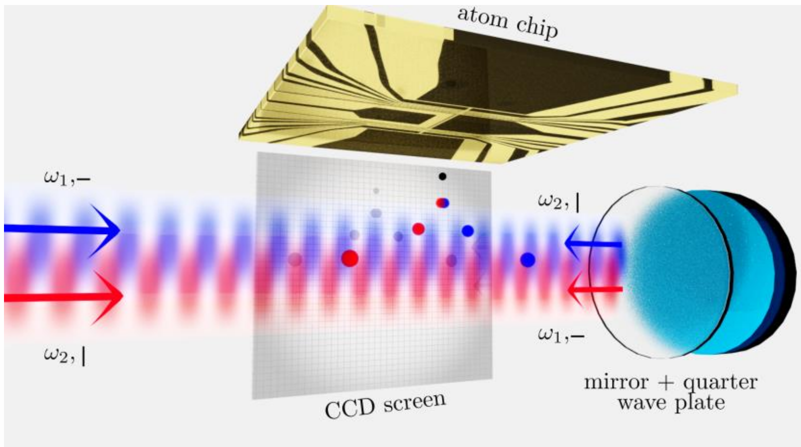



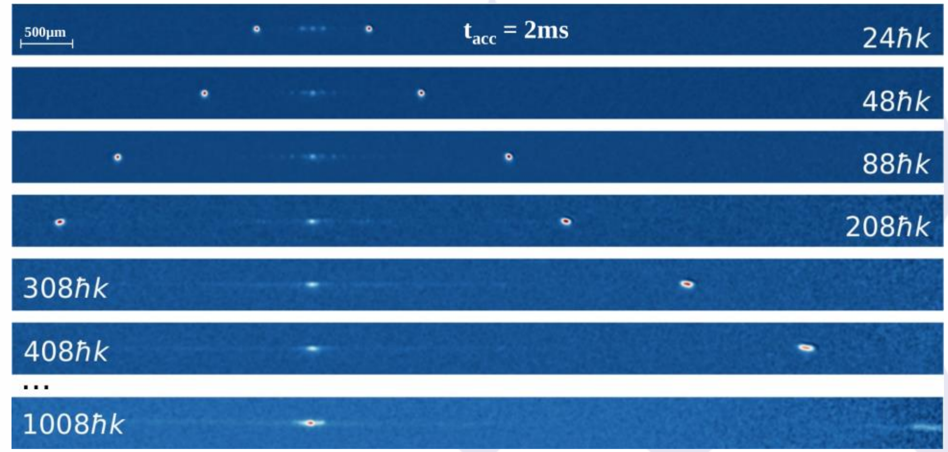

Bloch-like dynamics
Coherence time ~ 1 s



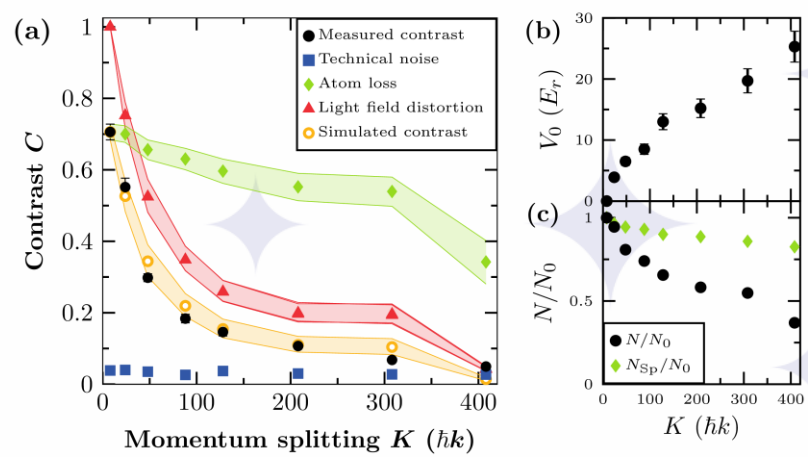

$\nu = 1$ Hz $\rightarrow F \sim 10^{-4}$g on 10 $\mu m$

# Progress: Twin-lattices in LUH



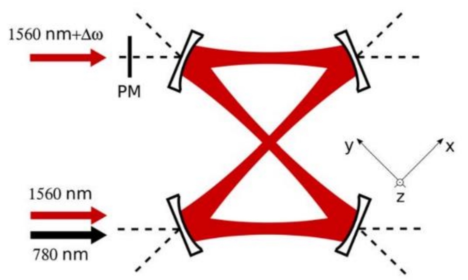




**Contrast measurement and model**



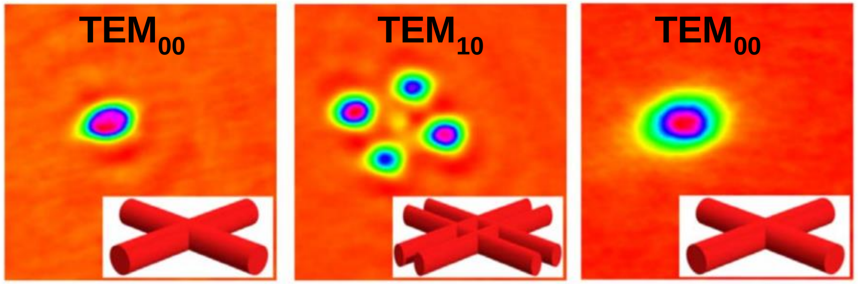

- Retro-reflective configuration with two frequencies and mirror
- Counter-accelerate with Bloch oscillations in twin lattice
- Record atom interferometer with up to 1632 photon recoils @ $K = 408\ \hbar k$
- Next step: apply the scheme guided in dipole trap

# Progress : towards cavity aided interferometry at LP2N




Thermal atoms
separated and recombined
using two transverse modes
of the resonator

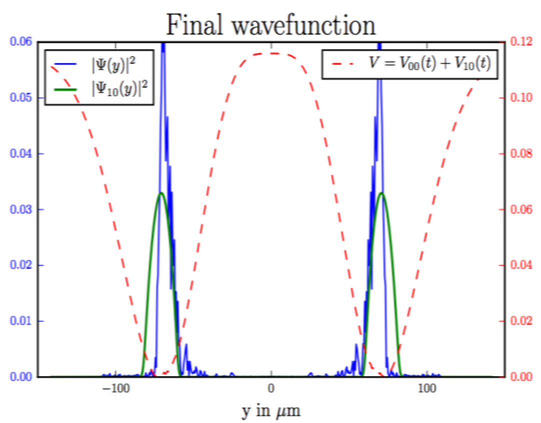
BUT incoherent process

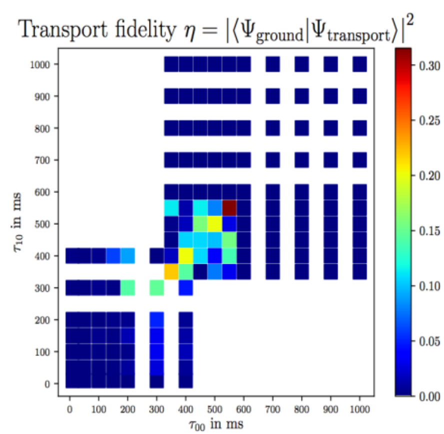



**Next step: repeat the experiment with Bose-condensed samples**

## Numerical simulation at LUH

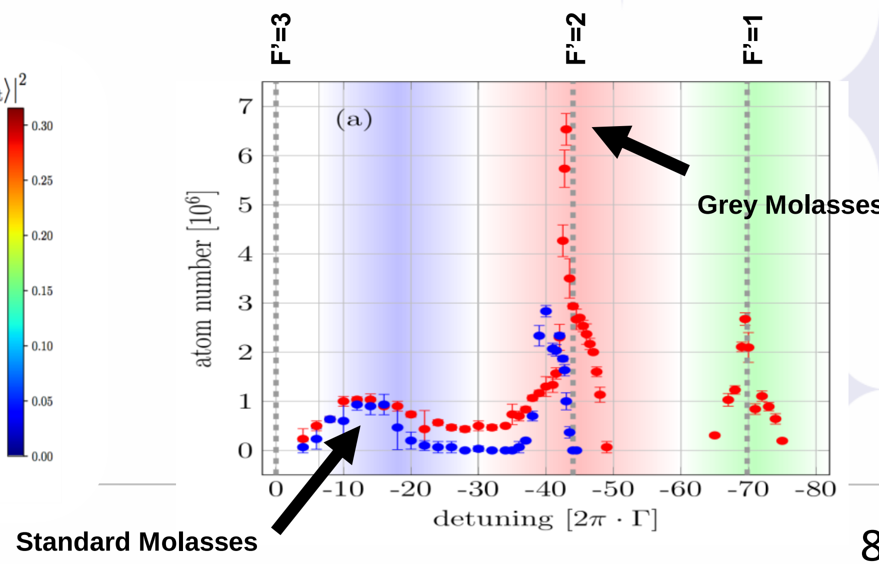
Determination of optimized intensity ramps
for the pumped modes to maintain the coherence.




## Improvement of BEC production at LP2N

$^{87}$Rb Loading in a telecom ODT
via Dark State Cooling



# Tackle decoherence and noise sources

- ✓ Study of decoherence/noise sources that compromise the sensitivity of TAIs
  Major sources of decoherence: potential inhomogeneity & atomic interactions

- ✓ Tune collisional scattering lengths (39K atoms in the absolute ground state F=1, $m_F$=1 using a broad magnetic Feshbach resonance)

- ✓ Use of atom chip BECs delta-kick cooled to extremely low temperatures/momentum distributions and extremely low densities/residual interaction energies

- ✓ Development of vibration isolation systems with optimized performances in the frequency ranges that mainly affect the performances of TAIs.

- ✓ **Definition of optimal strategies to characterize the optical potentials and guide experimentalists in the choice of the optical components and systems**

# Progress : development of a simulator at LUH

Based on position space description of light-pulse interaction

Straigtforward but not traditional

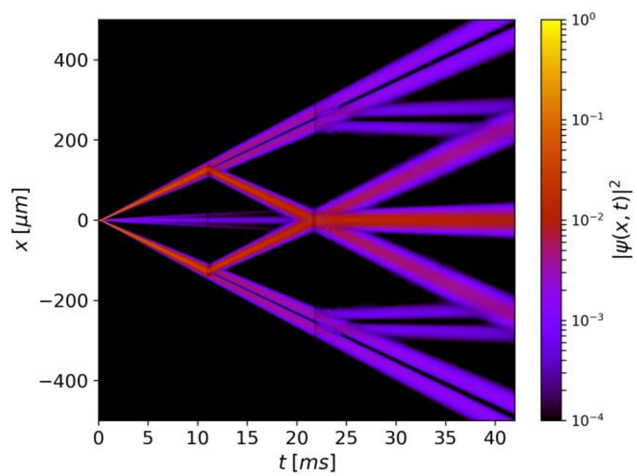
(based on expanding the wavefunction in momentum eigenstates)

$$i\hbar\,\dot{g}\,(z,t)=\left[-\frac{\hbar^2}{2m}\,\frac{\partial^2}{\partial z^2}+V(z,t)\right]g(z,t)$$

✓ V(z,t) can be as general as needed
to describe light distortions and other real-life problems

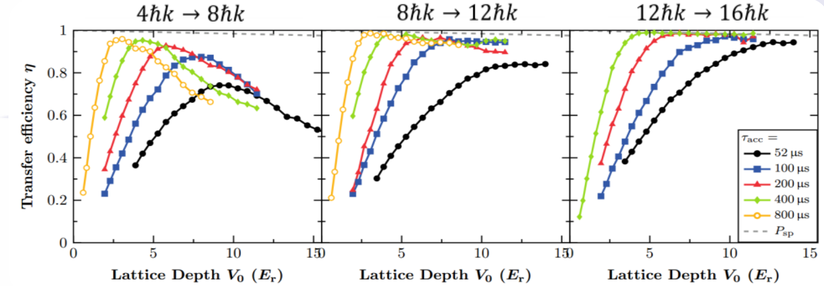
✓ Exact (numerical) solutions possible
with efficient and flexible solvers

Simulation of
Bragg double diffraction
interferometer

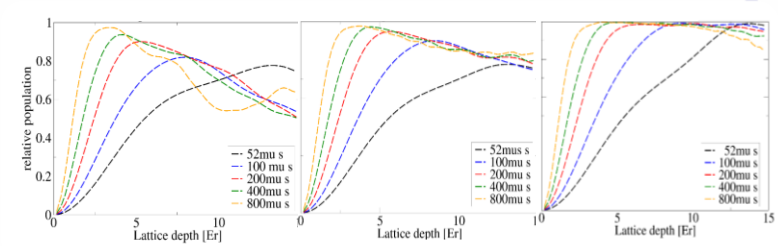



**Comparing simulator with experiments**

EXPERIMENTS



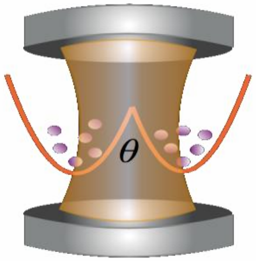

SIMULATOR

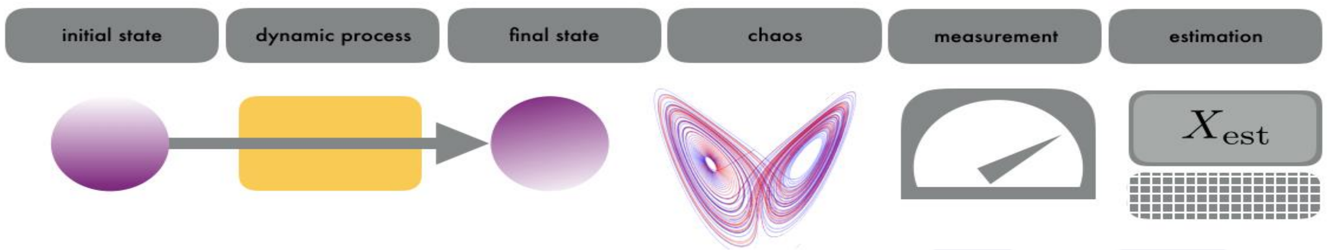



Excellent agreement
Good understanding of sources
limiting the beamsplitter efficiency

# Enhancing phase sensitivity

✓ New techniques to readout the interferometric phase of a trapped interferometer exploiting chaotic dynamics




**PROGRESS: Theoretical analysis by UW**
Performance of an atom-light coupled sensor built with a double-well BEC immersed into an optical cavity.
Atom-light coupling leads to very strong scaling of the sensitivity with the number of photons and atoms.

✓ Use tuning capability of the inter-particle interaction for accurate interferometric measurements with sub-shot noise resolution: use of Feshbach resonances to first enhance the interaction for the creation of quantum entangled states and later to switch it off

# Dissemination

**Scientific production**

7 peer-reviewed papers
(4 accepted, 2 submitted, 1 under preparation)

19 presentations at international conferences

3 deliverables (reports)

TAIOL website: syrte.obspm.fr/taiol

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Thank you for your attention

CONTACT

Franck Pereira dos Santos

franck.pereira@obspm.fr

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