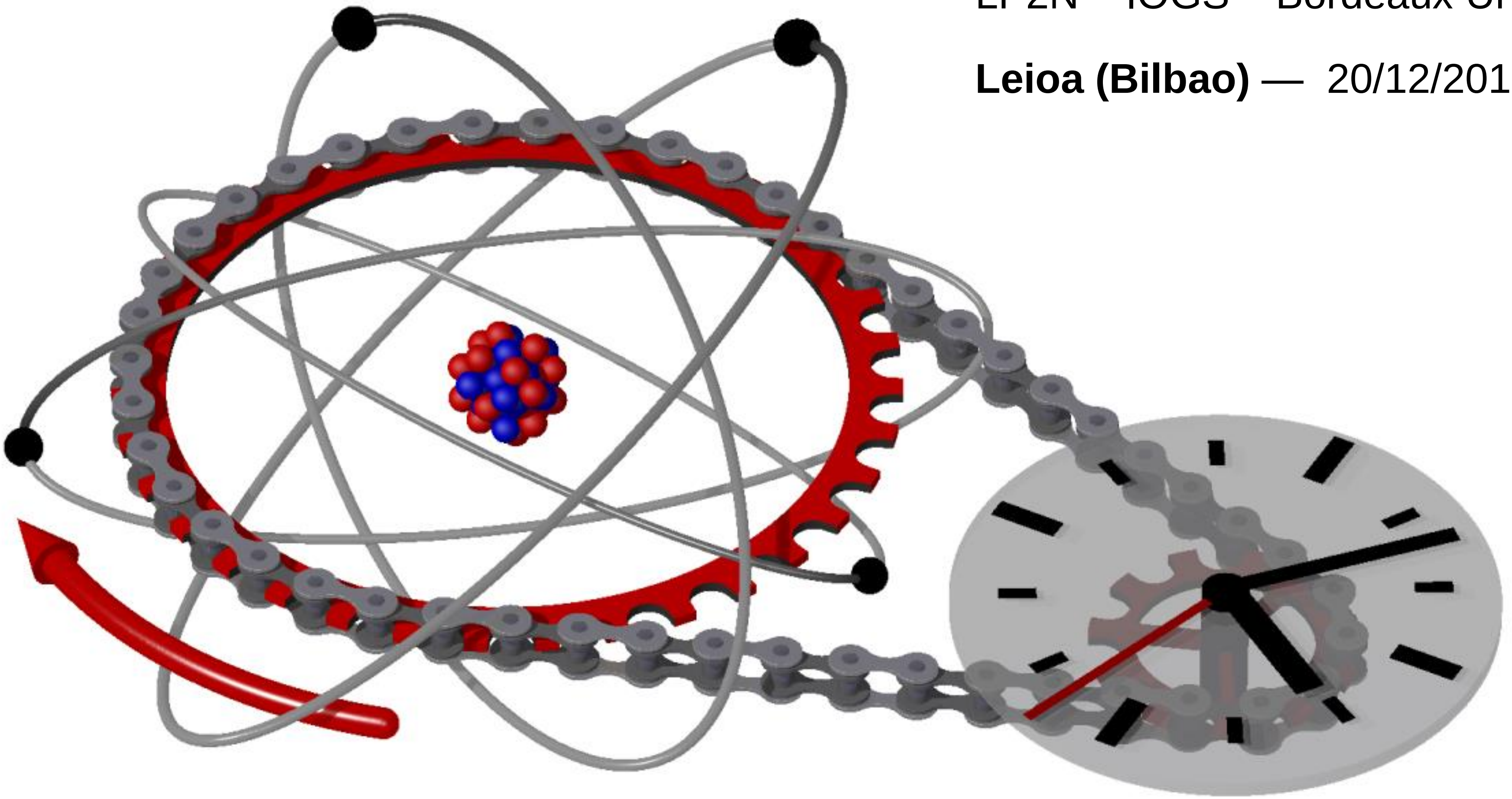
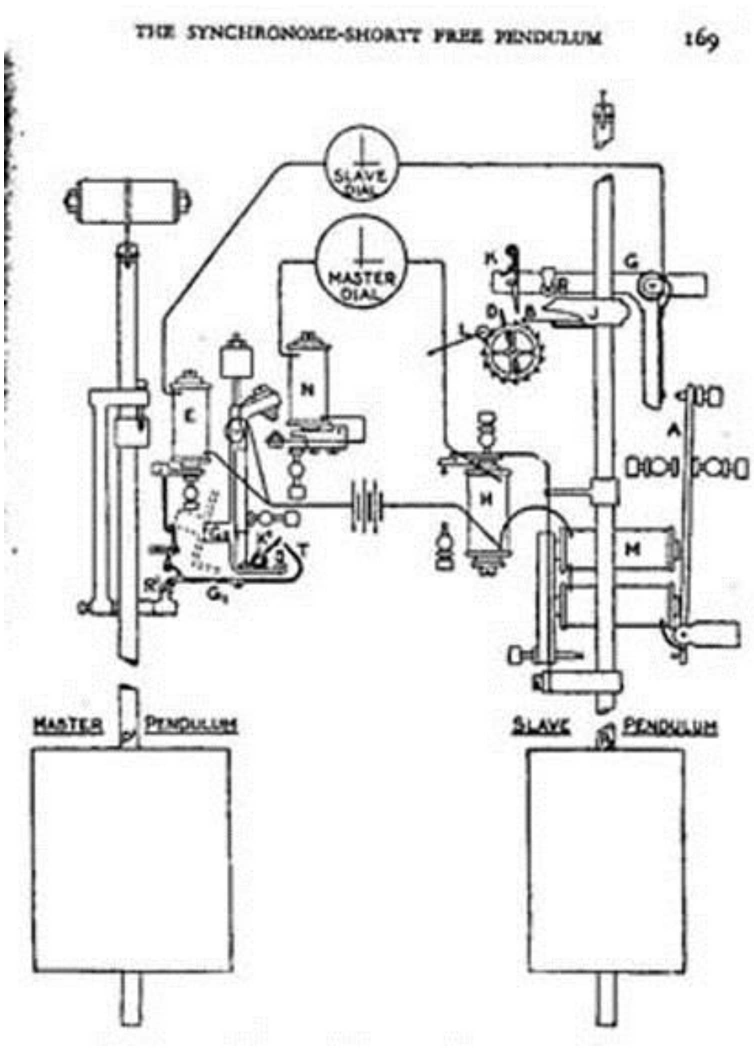
Atom interferometry with feedback and phase lock loops

A. Bertoldi
LP2N – IOGS – Bordeaux University

Leioa (Bilbao) — 20/12/2016

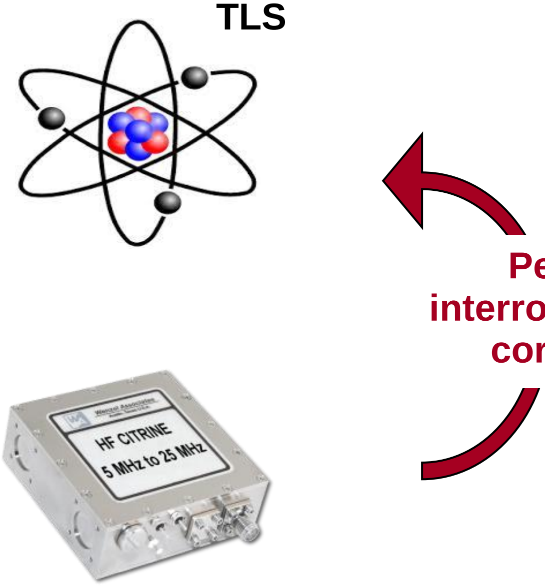


PLL and Shortt clock



P. Boucheron, *Just how good was the Shortt clock?*, The Bulletin of the National Association of Watch and Clock Collectors **27**, 165 (1985)

Atomic clock



TLS

Periodic interrogation and correction

LO + counter

Uncorrelated sampling

→√N scaling with # samples

Replace frequency lock with PLL:

problems & advantages

Outline

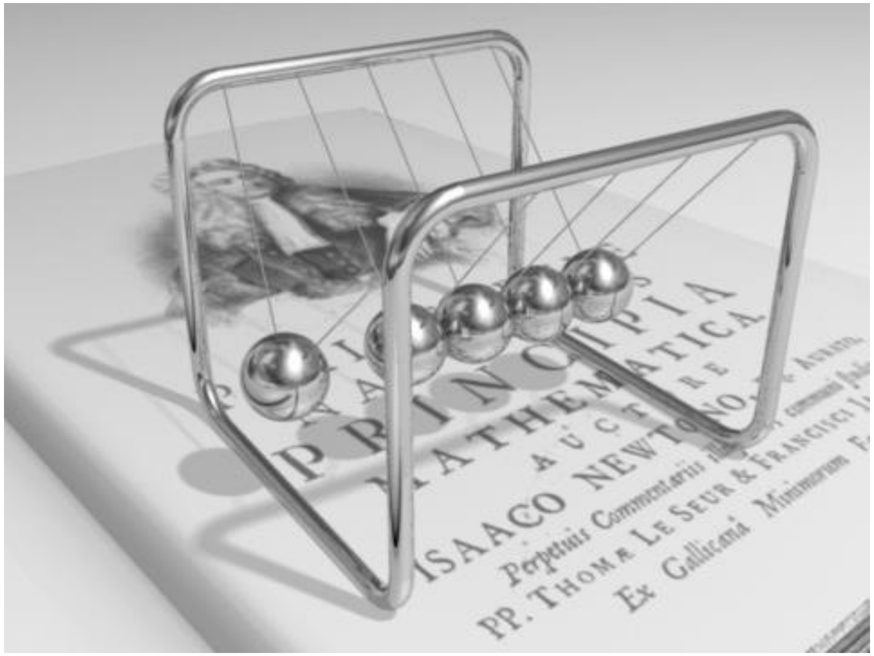
- **Measuring a phase**
  - ☐ classical and quantum case
  - ☐ phase wraps issue
  - ☐ adopted solutions

- **Coherence preserving measurements and feedback**
  - ☐ experimental setup
  - ☐ information retrieval vs. destructivity
  - ☐ quartz – quantum state PLL
  - ☐ atomic clock with PLL

- **Outlook**
  - ☐ PLL in inertial sensing and optical clocks

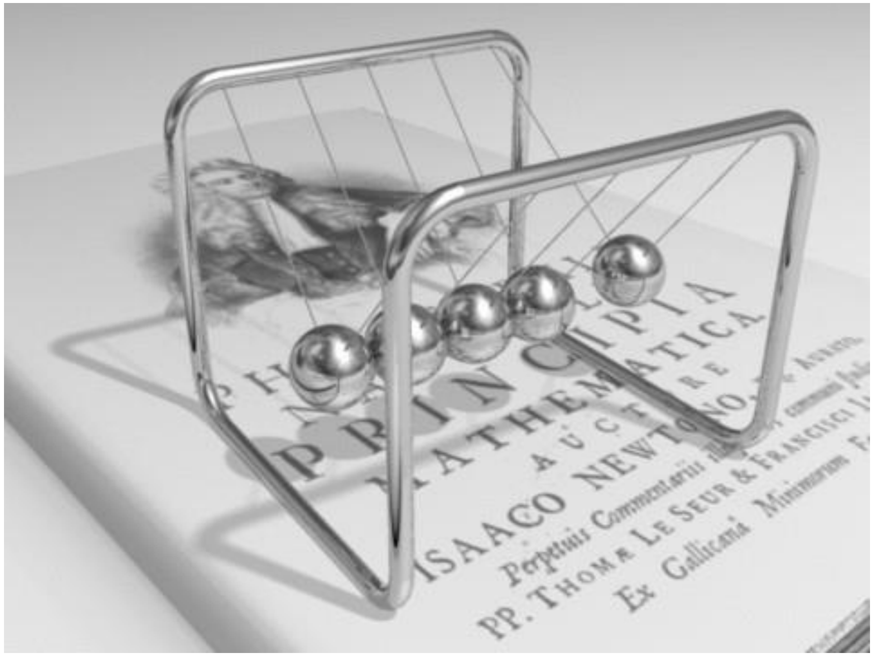
  - ☐ Cold atom experiments at LP2N - Bordeaux

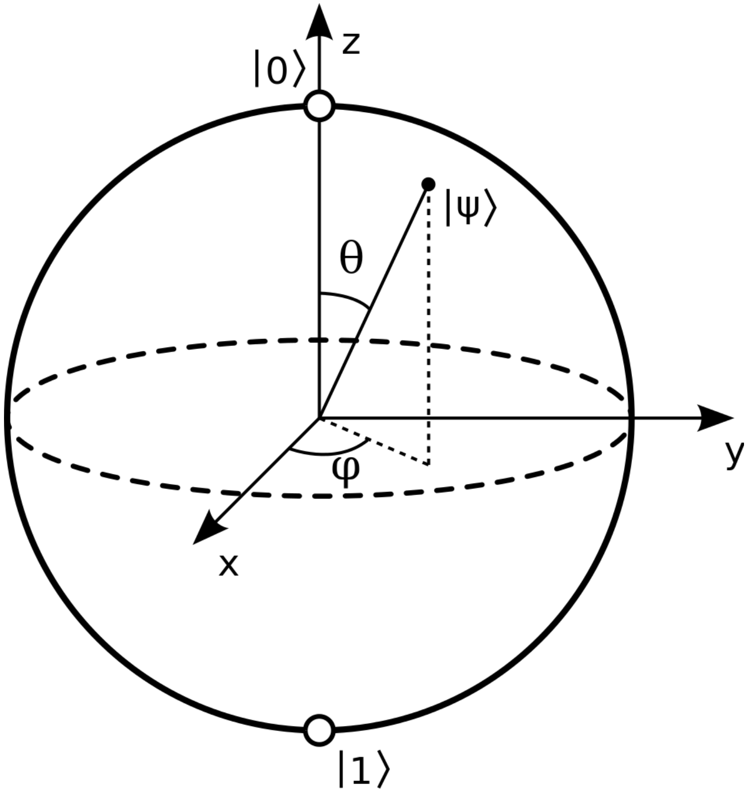
Phase measurement



Classical case: **- continuous readout**

Phase measurement





Classical case: **- continuous readout**

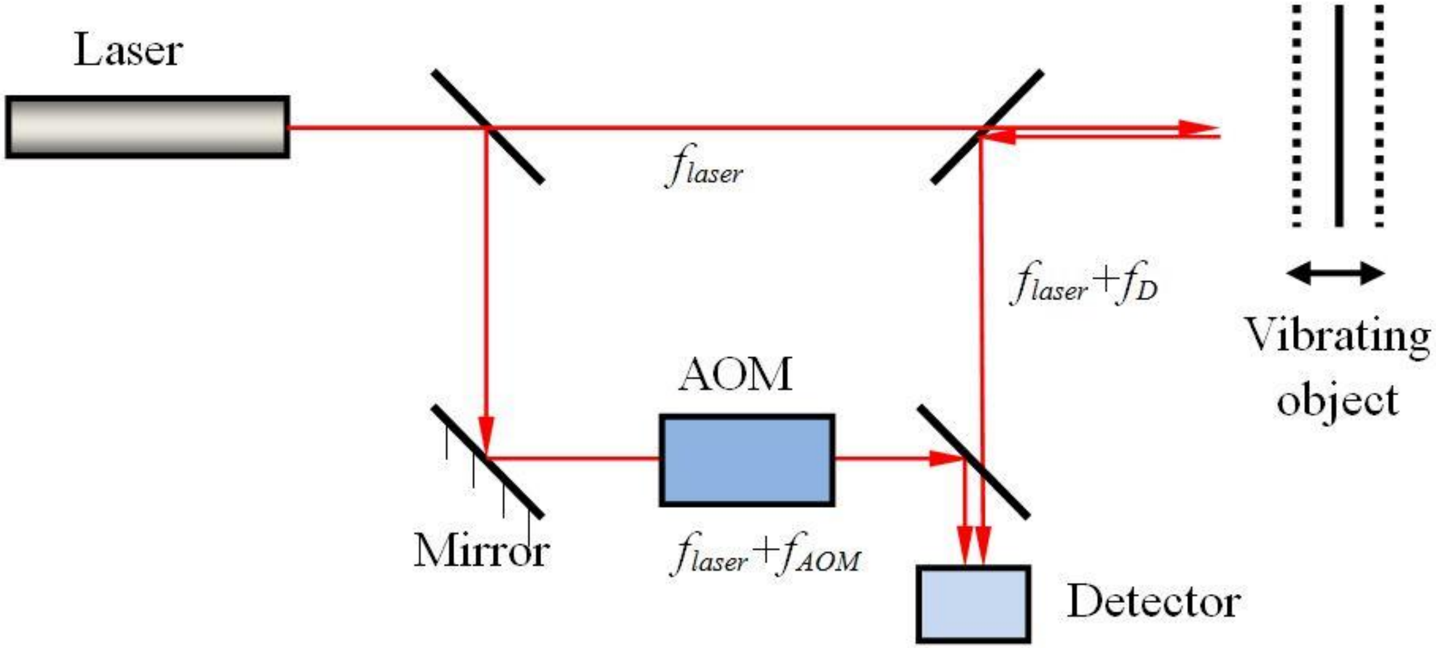
Quantum case:

- modifies the system (projection & destruct.)

- *sin(φ)* as population imbalance

Phase wraps and solutions – classical case

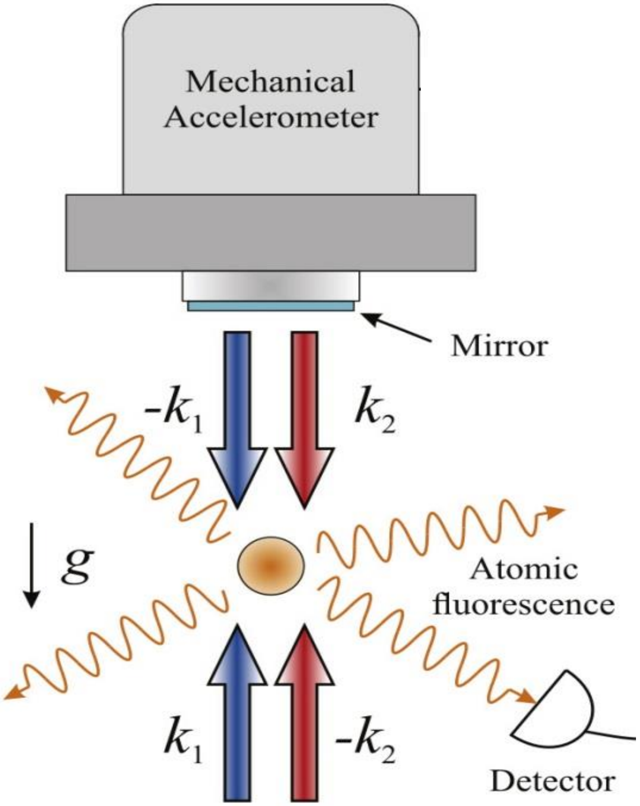
sin(φ) → φ unambiguous in [-π/2:+π/2]

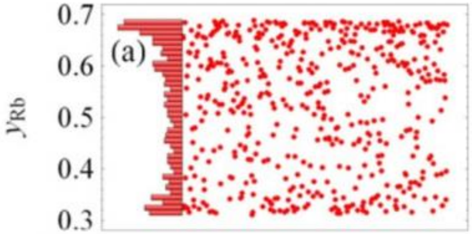


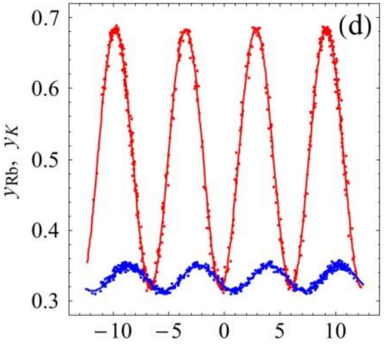
Laser Doppler vibrometers
Rothberg *et al.*, J. Sound and Vibr. **135**, 516 (1989)

Phase wraps and solutions – inertial sensing

$\sin(\varphi) \rightarrow \varphi$ unambiguous in $[-\pi/2:+\pi/2]$



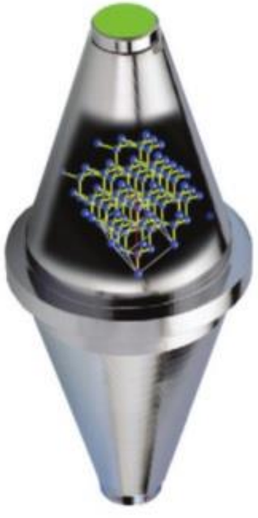

raw atomic signal


hybrid sensor output

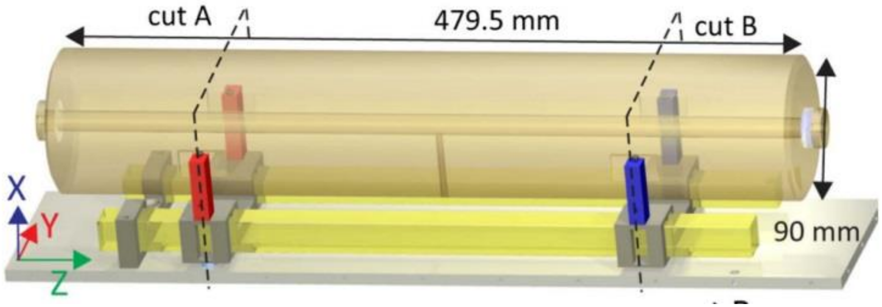
Coupling classical-atom gravimeter
Barrett *et al.*, New J. Phys. **17**, 085010 (2015)

Phase wraps and solutions

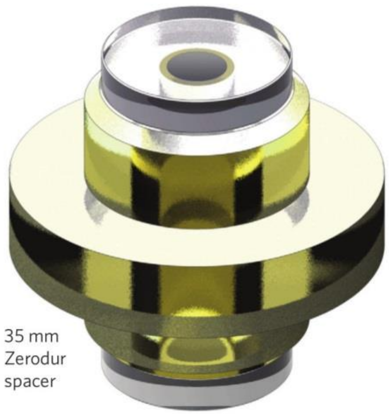
Standard approach in atom clocks & AI: improve LO !!



Single-crystal silicon cavity
Kessler *et al.*, Nat. Photon. **6**, 687 (2012)



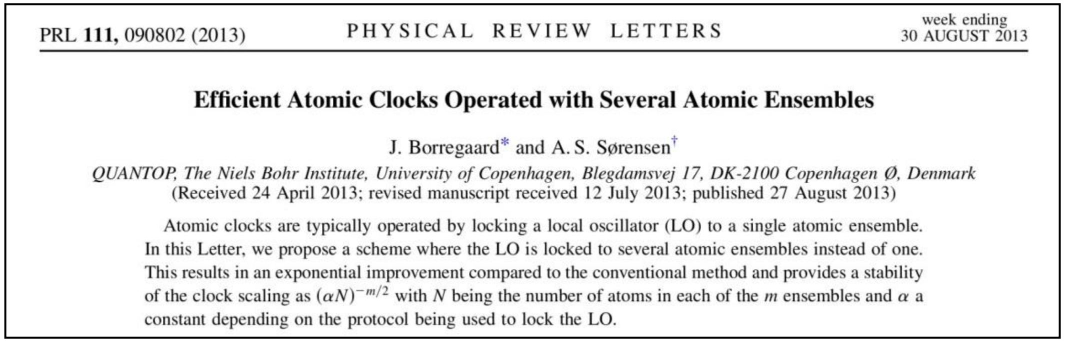
Long cavity at room temperature
Häfner *et al.*, Opt. Lett. **40**, 2112 (2015)



Mono-crystalline coating
Cole *et al.*, Nat. Photon. **7**, 644 (2013)

PTB, JILA, SYRTE, NIST, NPL …

Phase wraps and solutions



PRL **111,** 090802 (2013) PHYSICAL REVIEW LETTERS week ending 30 AUGUST 2013

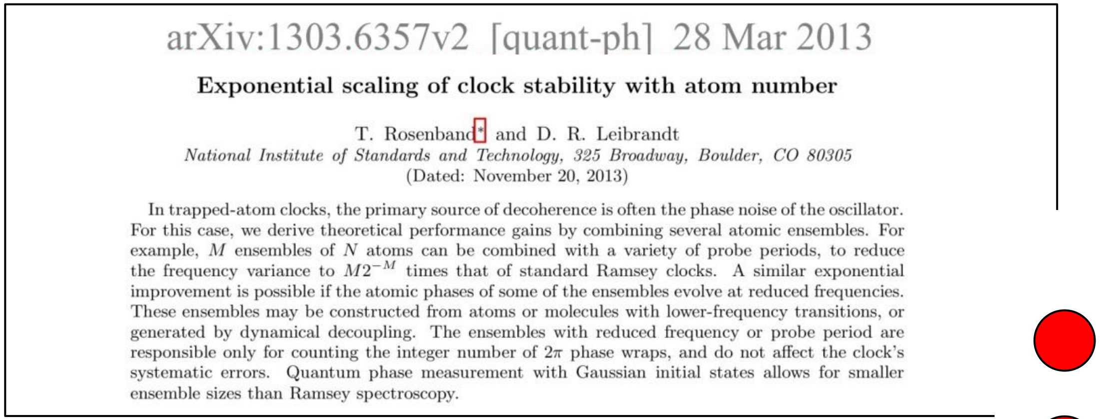
Efficient Atomic Clocks Operated with Several Atomic Ensembles

J. Borregaard* and A. S. Sørensen†

QUANTOP, The Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark

(Received 24 April 2013; revised manuscript received 12 July 2013; published 27 August 2013)

Atomic clocks are typically operated by locking a local oscillator (LO) to a single atomic ensemble. In this Letter, we propose a scheme where the LO is locked to several atomic ensembles instead of one. This results in an exponential improvement compared to the conventional method and provides a stability of the clock scaling as $(\alpha N)^{-m/2}$ with N being the number of atoms in each of the m ensembles and α a constant depending on the protocol being used to lock the LO.



arXiv:1303.6357v2 [quant-ph] 28 Mar 2013

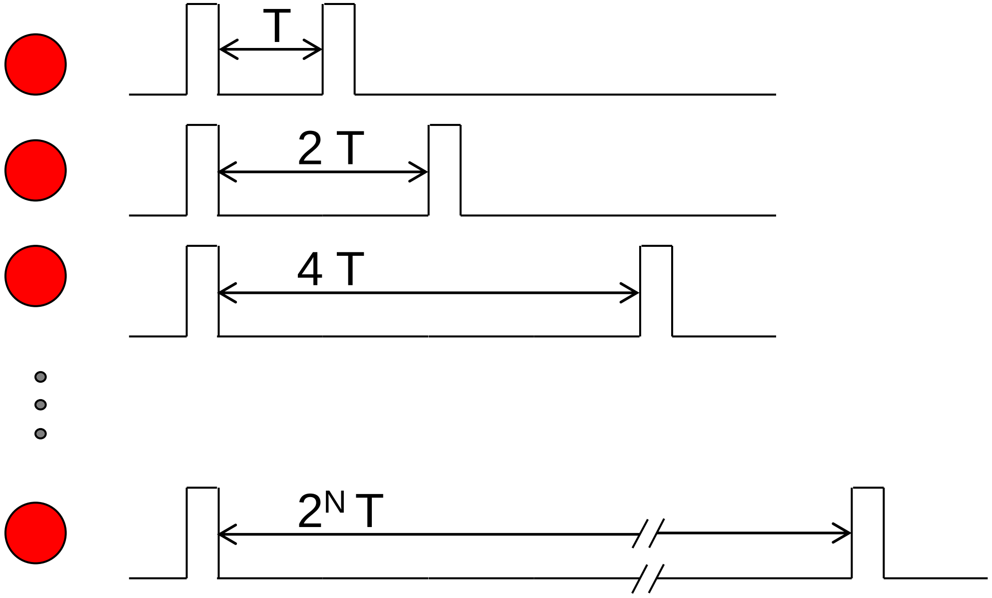
Exponential scaling of clock stability with atom number

T. Rosenband* and D. R. Leibrandt

National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305

(Dated: November 20, 2013)

In trapped-atom clocks, the primary source of decoherence is often the phase noise of the oscillator. For this case, we derive theoretical performance gains by combining several atomic ensembles. For example, M ensembles of N atoms can be combined with a variety of probe periods, to reduce the frequency variance to $M2^{-M}$ times that of standard Ramsey clocks. A similar exponential improvement is possible if the atomic phases of some of the ensembles evolve at reduced frequencies. These ensembles may be constructed from atoms or molecules with lower-frequency transitions, or generated by dynamical decoupling. The ensembles with reduced frequency or probe period are responsible only for counting the integer number of 2π phase wraps, and do not affect the clock's systematic errors. Quantum phase measurement with Gaussian initial states allows for smaller ensemble sizes than Ramsey spectroscopy.



Phase wraps and solutions

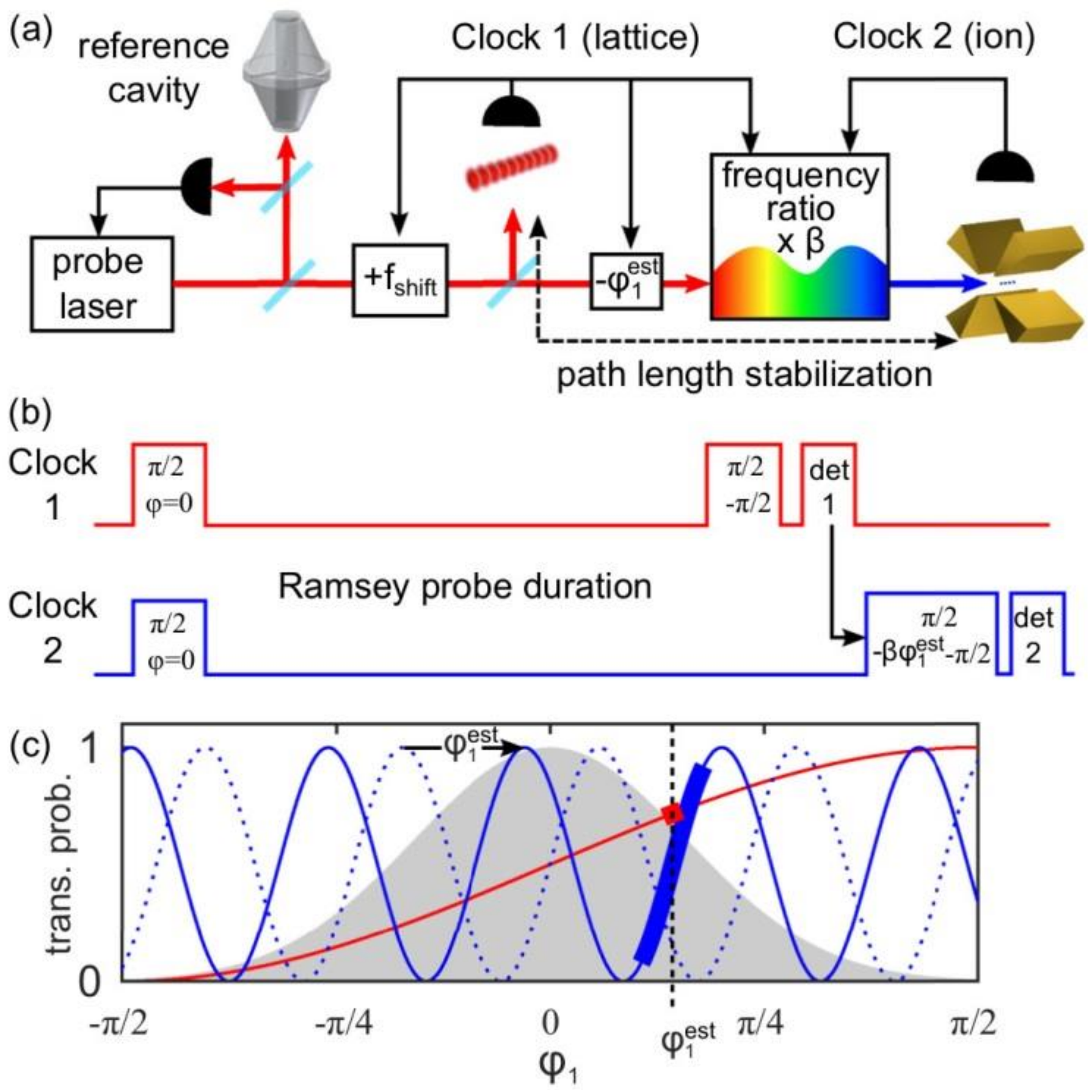
PHYSICAL REVIEW A **93**, 032138 (2016)

Probing beyond the laser coherence time in optical clock comparisons

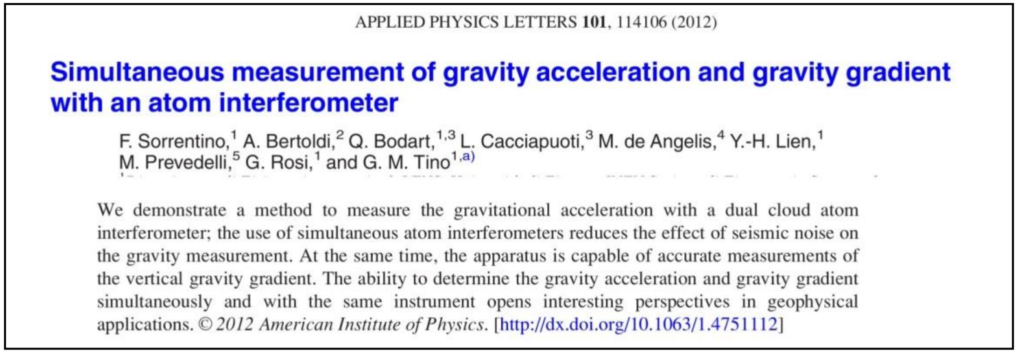
David B. Hume* and David R. Leibrandt
National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA

(Received 1 September 2015; revised manuscript received 8 January 2016; published 30 March 2016)

We develop differential measurement protocols that circumvent the laser r
clock comparisons by synchronous probing of two clocks using phase-lo
for probe times longer than the laser coherence time, avoids the Dick effec
measurement precision. We present protocols for such frequency comparisons
of the protocols with realistic noise sources. These methods provide a route to r
durations by more than an order of magnitude.



Phase wraps and solutions

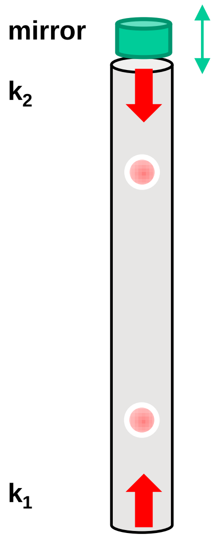


APPLIED PHYSICS LETTERS **101**, 114106 (2012)

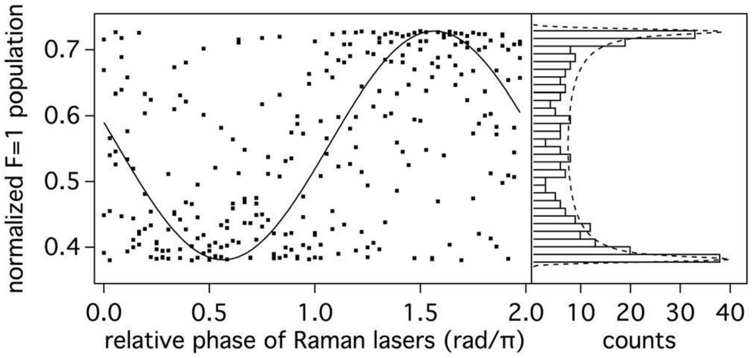
Simultaneous measurement of gravity acceleration and gravity gradient with an atom interferometer

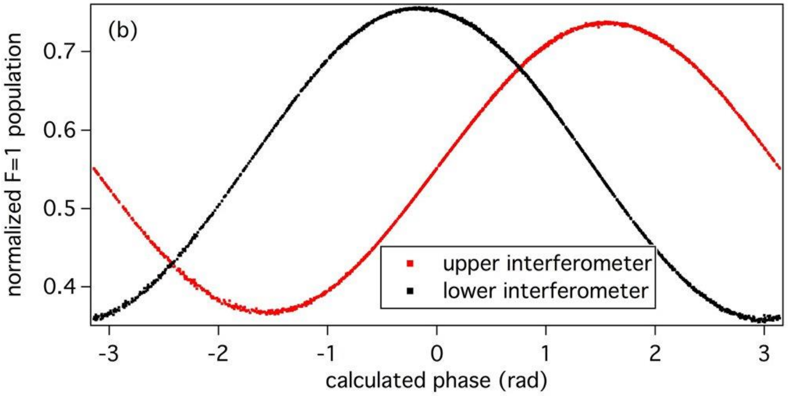
F. Sorrentino,[1] A. Bertoldi,[2] Q. Bodart,[1,3] L. Cacciapuoti,[3] M. de Angelis,[4] Y.-H. Lien,[1]
M. Prevedelli,[5] G. Rosi,[1] and G. M. Tino[1,a)]

We demonstrate a method to measure the gravitational acceleration with a dual cloud atom interferometer; the use of simultaneous atom interferometers reduces the effect of seismic noise on the gravity measurement. At the same time, the apparatus is capable of accurate measurements of the vertical gravity gradient. The ability to determine the gravity acceleration and gravity gradient simultaneously and with the same instrument opens interesting perspectives in geophysical applications. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4751112]



Atomic fountain
2 atom interferometers





Outline

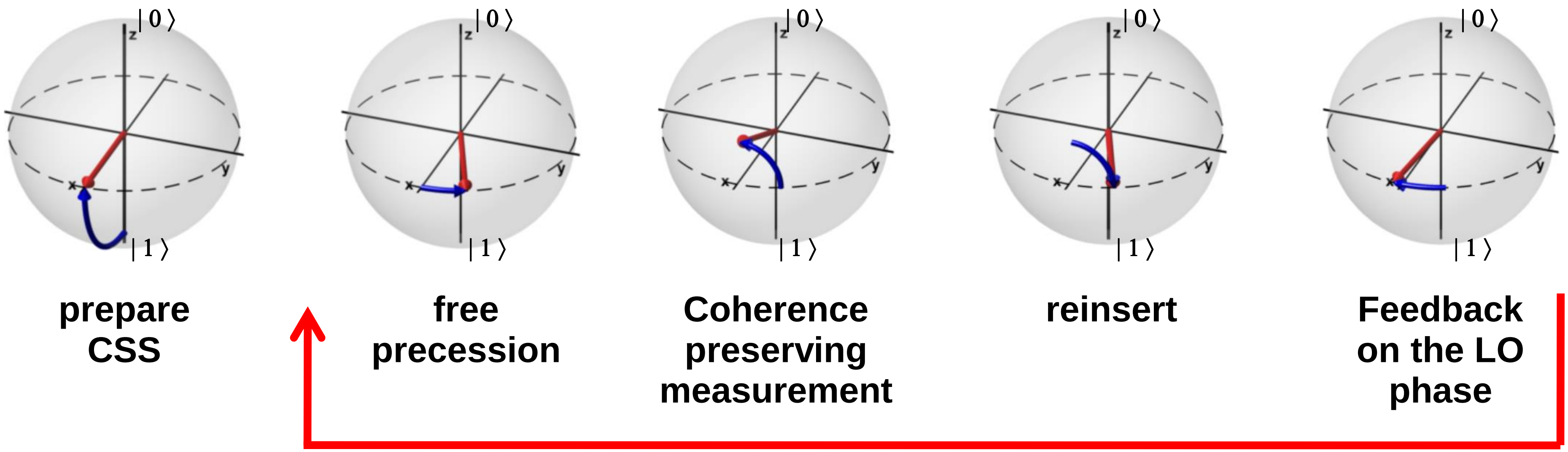
- Measuring a phase
  - ☐ classical and quantum case
  - ☐ phase wraps issue
  - ☐ adopted solutions

- **Coherence preserving measurements and feedback**
  - ☐ experimental setup
  - ☐ information retrieval vs. destructivity
  - ☐ quartz – quantum state PLL
  - ☐ atomic clock with PLL

- Outlook
  - ☐ PLL in inertial sensing and optical clocks

  - ☐ Cold atom experiments at LP2N - Bordeaux

Our solution: PLL



$\pi/2$ (y) — **prepare CSS**

T — **free precession**

$\pi/2$ (x) — **Coherence preserving measurement**

$-\pi/2$ (x) — **reinsert**

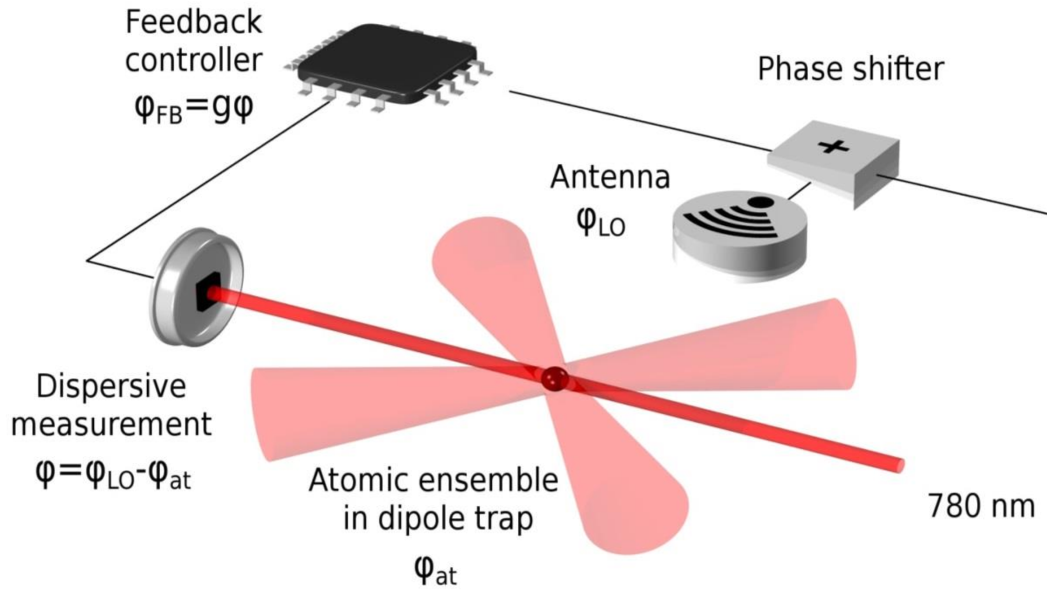
Feedback on the LO phase

N Cycles

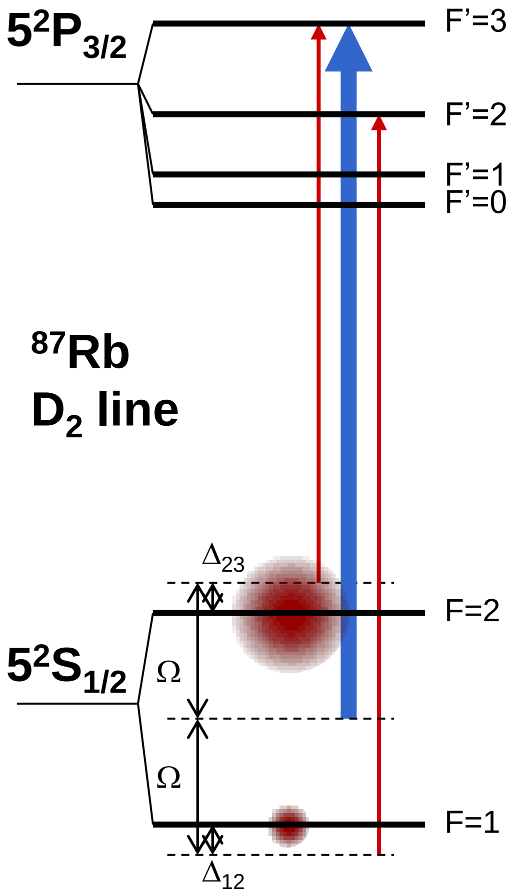
PRX **5**, 021011 (2015)

builds on:
Shiga *et al.*, New J. Phys. **14**, 023034 (2012)

Experimental setup and detection scheme



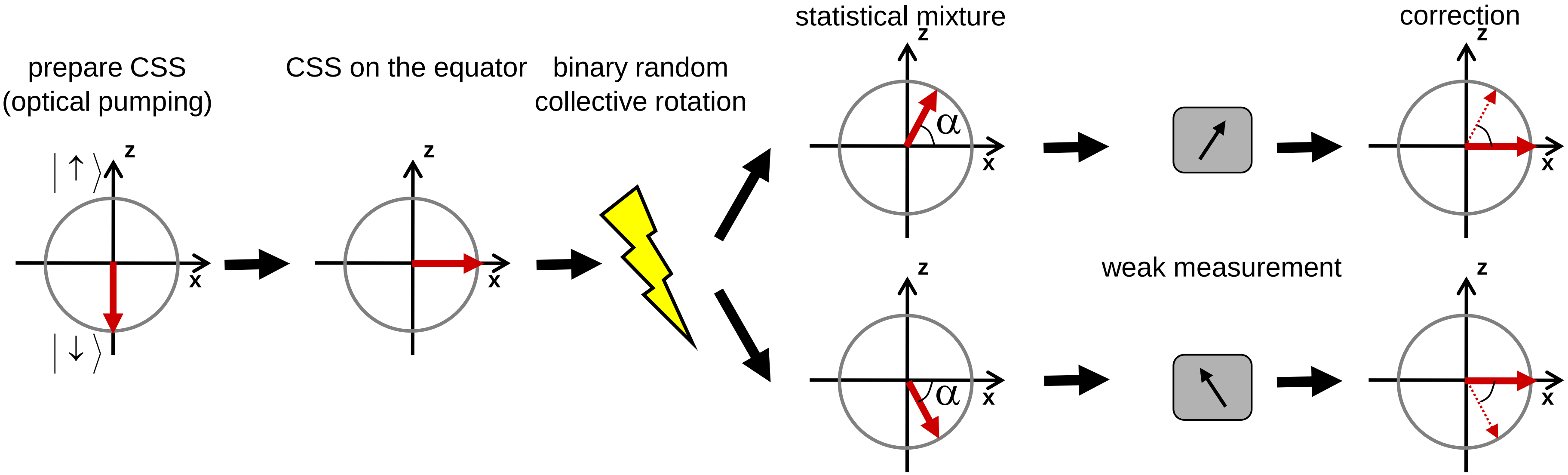
5x10^5 atoms @ 10 μK in the ODT



Frequency modulation spectroscopy

- strong carrier 1 mW (phase reference)
- weak sidebands (atomic signals)
- very short probe pulses (50 ns – 2 ms)

Information retrieval / destructivity trade-off



prepare CSS (optical pumping)

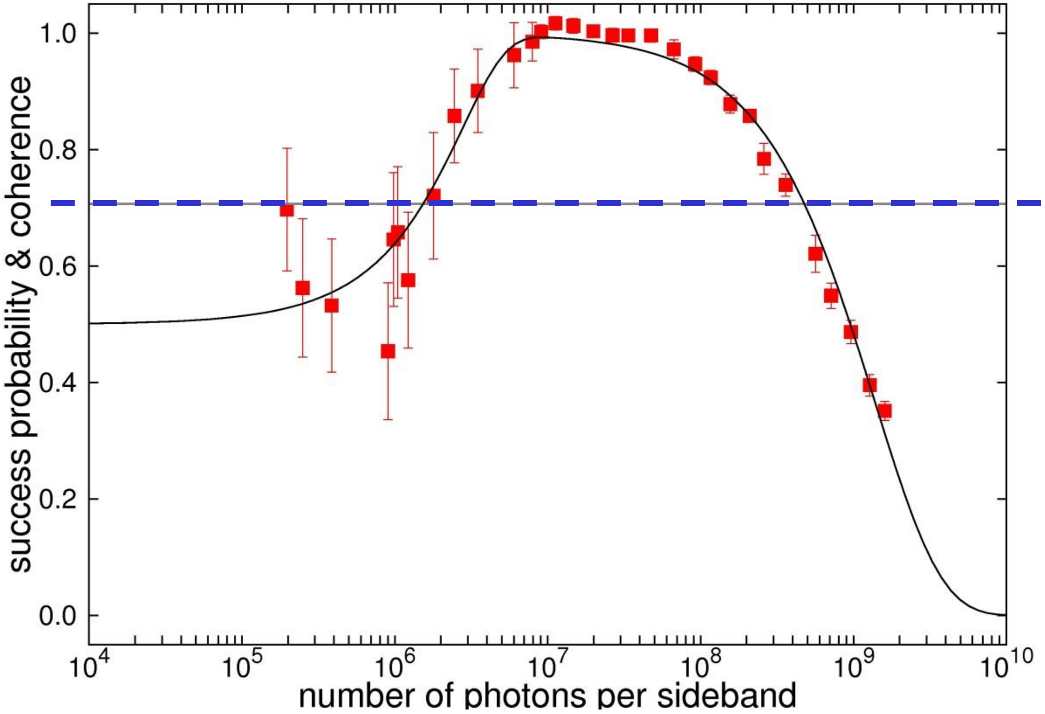
CSS on the equator

binary random collective rotation

statistical mixture

weak measurement

correction



Best pulse: 9.1×10^6 photons

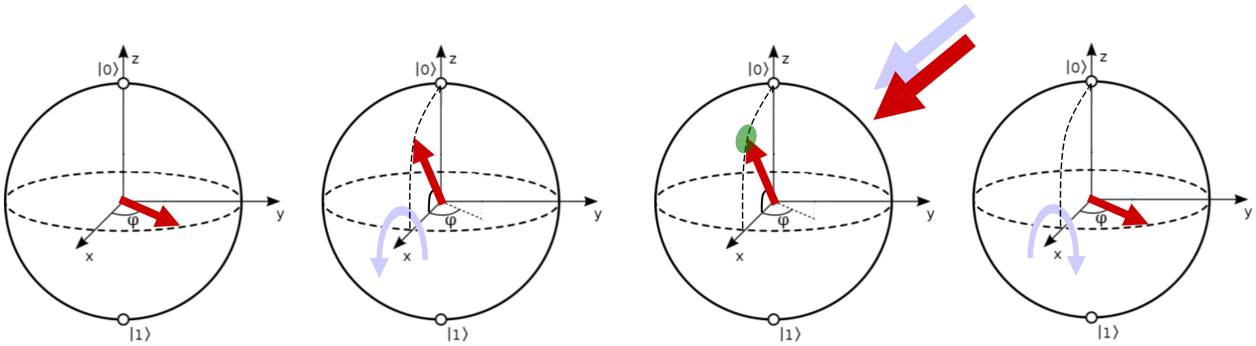
Feedback increases coherence from 0.707 to 0.993(1)

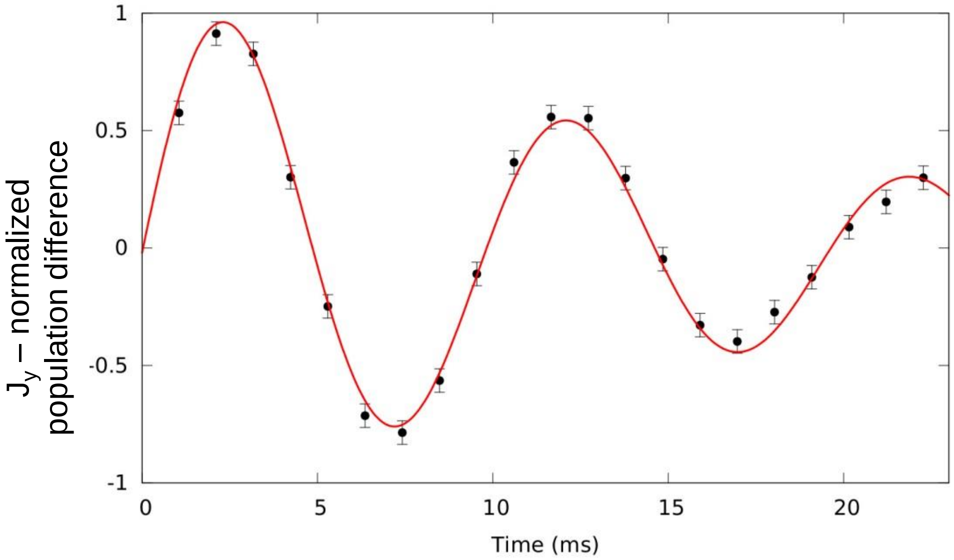
Phys. Rev. Lett. **110**, 210503 (2013)
Phys. Rev. A **89**, 063619 (2014)

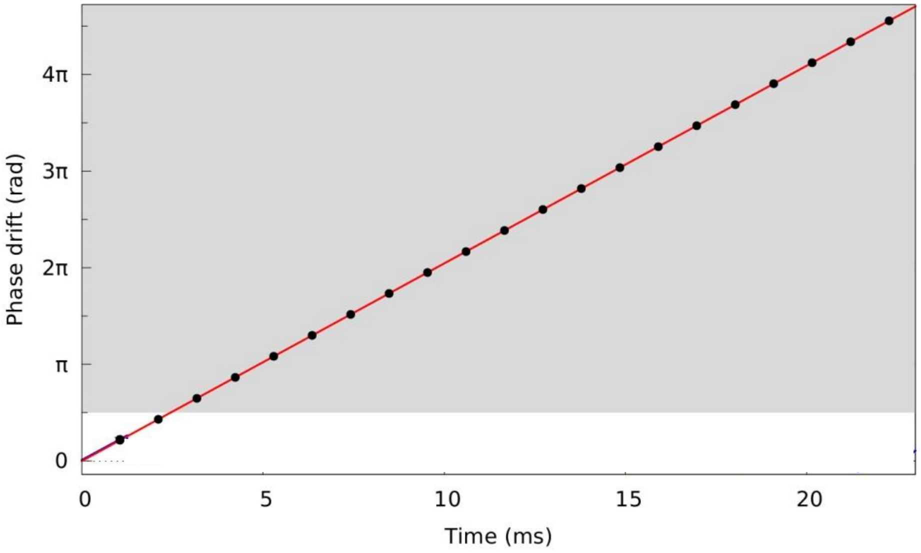
Probe LO phase noise using atomic state

100 Hz frequency offset on LO

repeated coherence preserving measurement of the relative phase





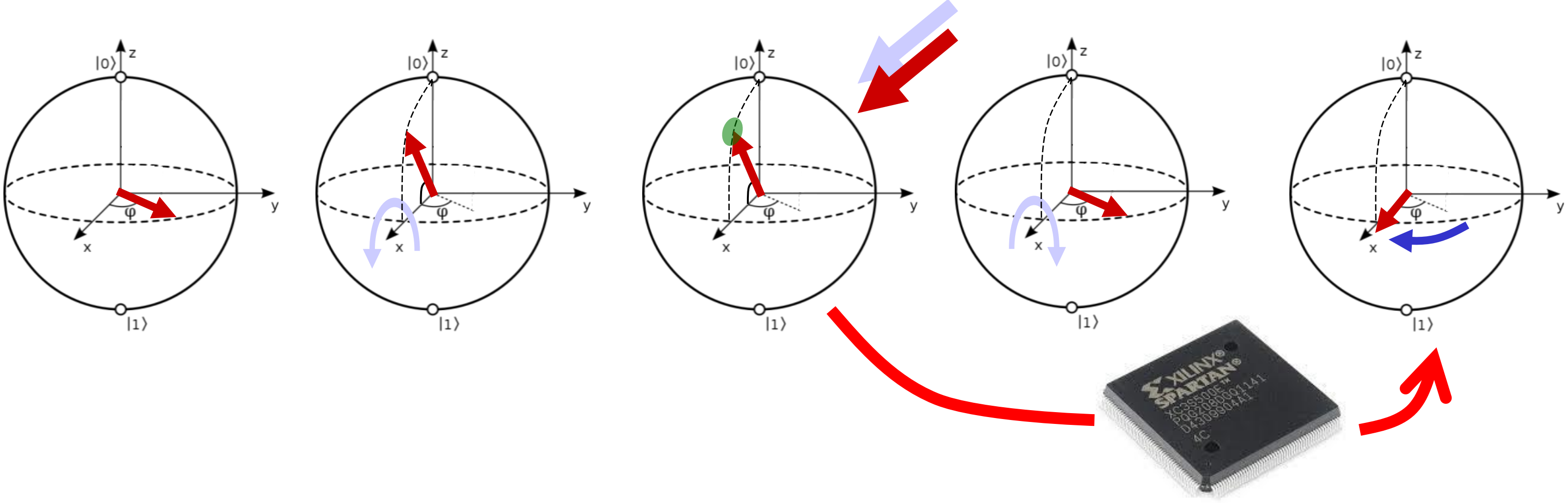


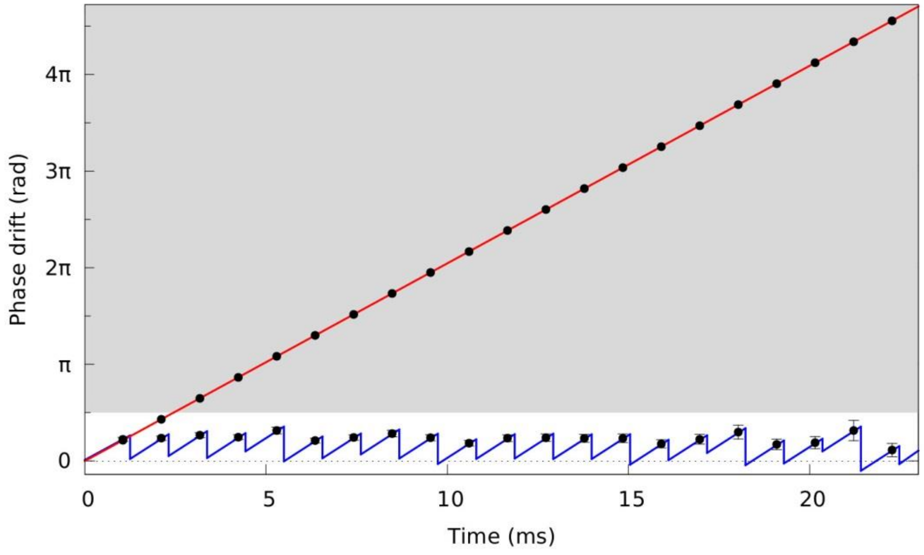
Phase lock of a LO to a quantum state

100 Hz frequency offset on LO

repeated coherence preserving measurement of the relative phase

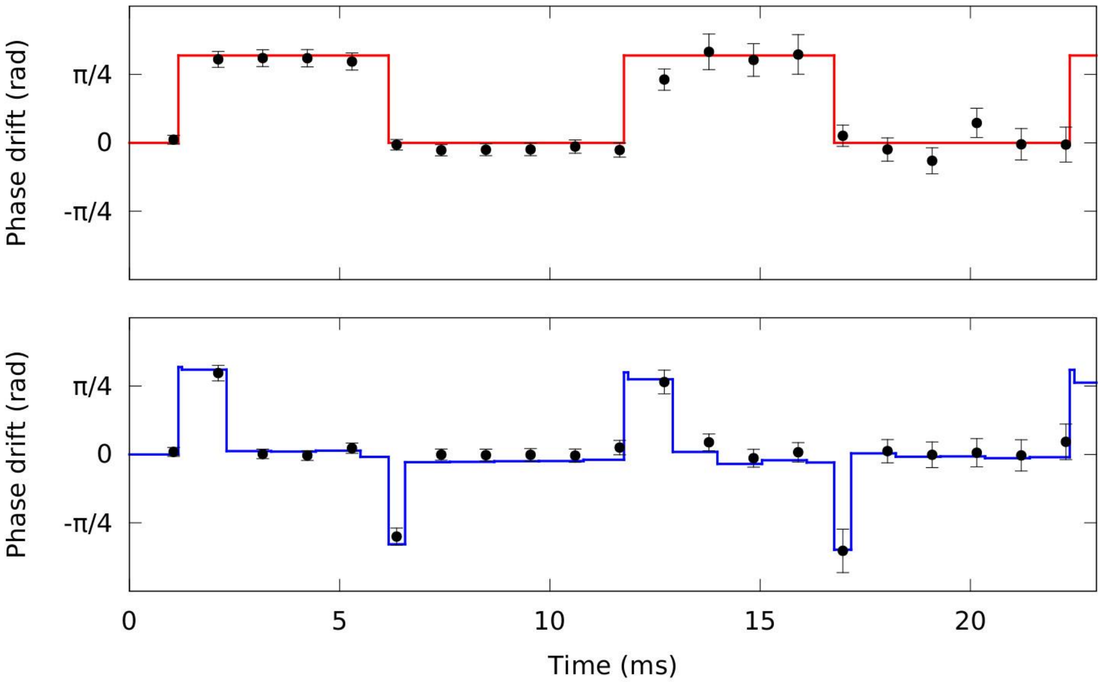
phase feedback on the LO with 6-bit phase shifter





PRX **5**, 021011 (2015)

Correcting phase jumps

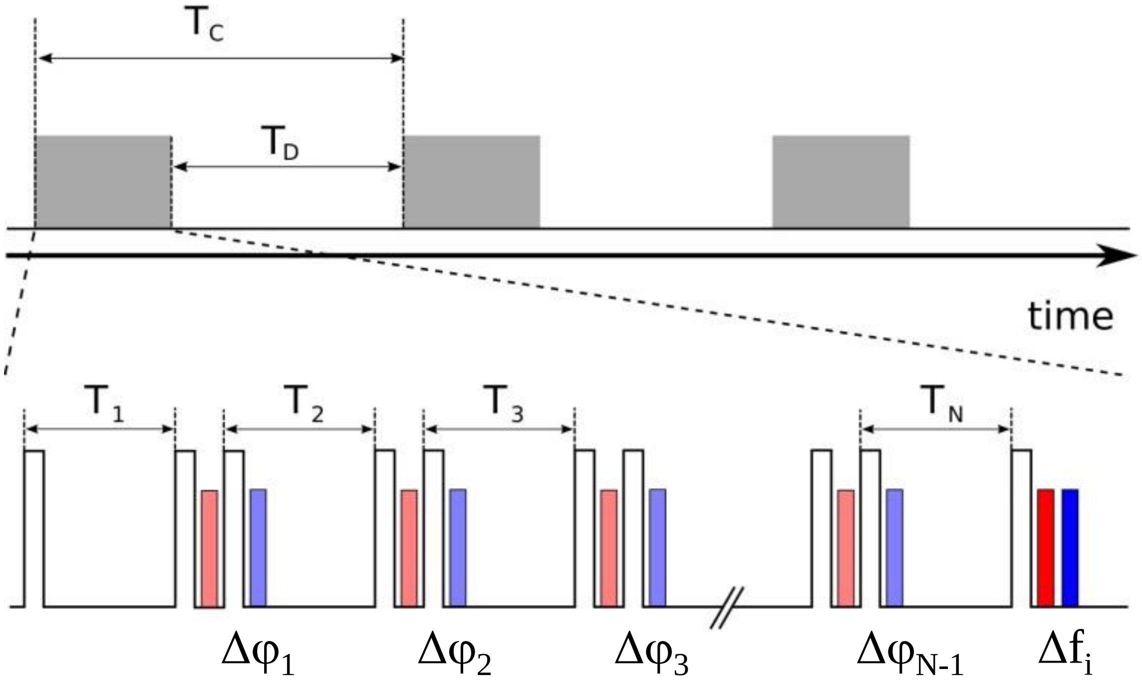


OPEN LOOP to monitors the relative phase evolution (π/3 jumps)

CLOSED LOOP phase jumps corrected 150 µs after their detection

Release of mechanical stress in ultra-stable cavities

Atomic clock with PLL



Clock cycle:

1. atomic state preparation

2. N-cycles of coherence preserving measurement of J_z and phase correction on the LO

(reduces Dick effect)

3. final destructive measurement, calculation of the total differential phase cumulated on the extended interrogation time, frequency correction on the LO

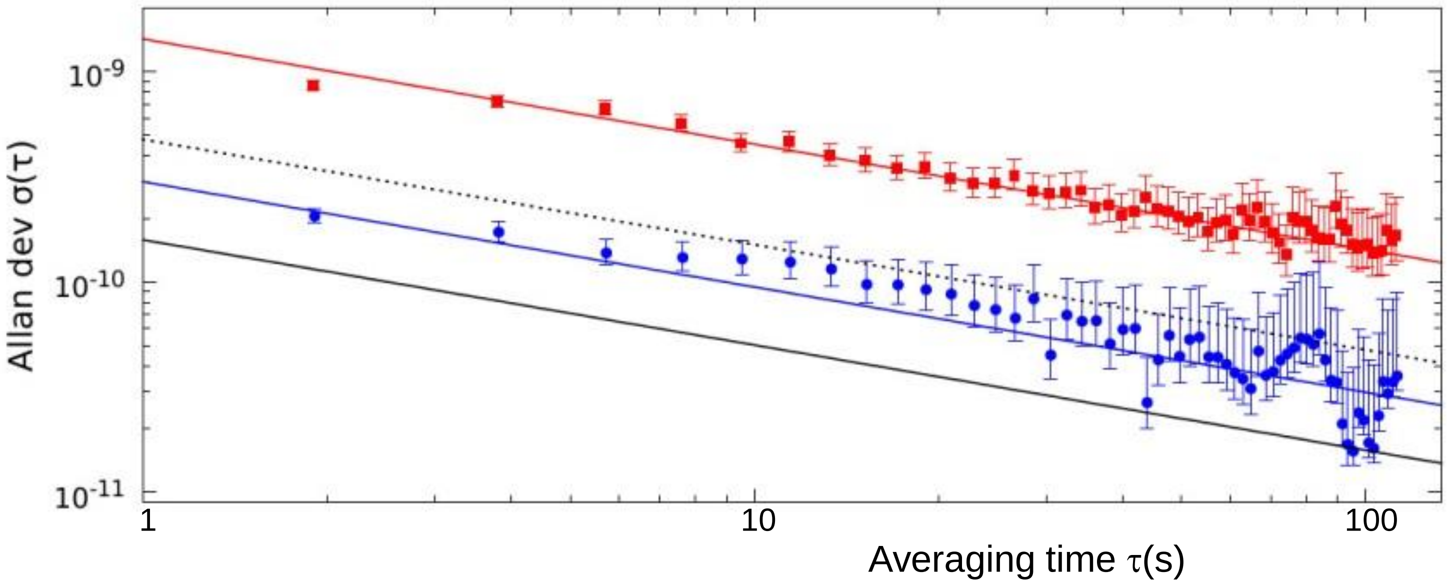
$$\Delta f_i = \Delta f_{i-1} + \frac{\left(\Delta\varphi_N - \sum_k^{N-1} \Delta\varphi_k\right)}{N \times T}$$

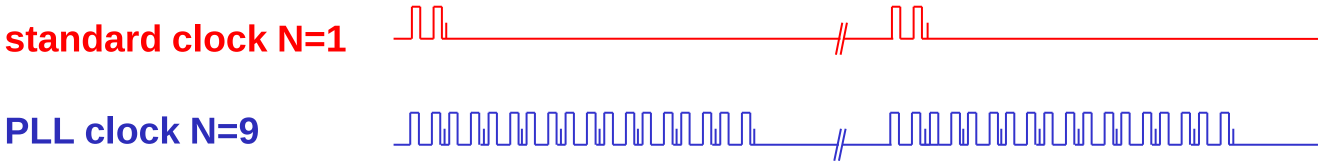
Atomic clock with PLL: stability enhancement

Experimental realization

- white frequency noise on the LO, φ_{rms}=430 mrad @ 10 ms

- Ramsey interrogation time T=1 ms





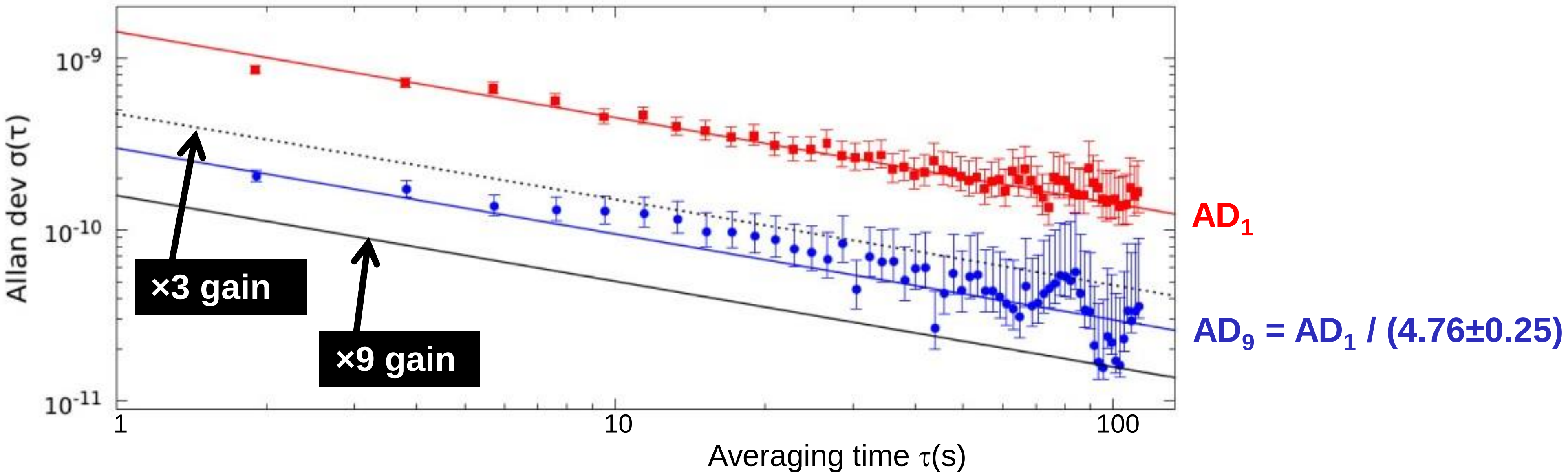
PRX **5**, 021011 (2015)
& EU patent

Atomic clock with PLL: stability enhancement

Experimental realization

- white frequency noise on the LO, φ_{rms}=430 mrad @ 10 ms

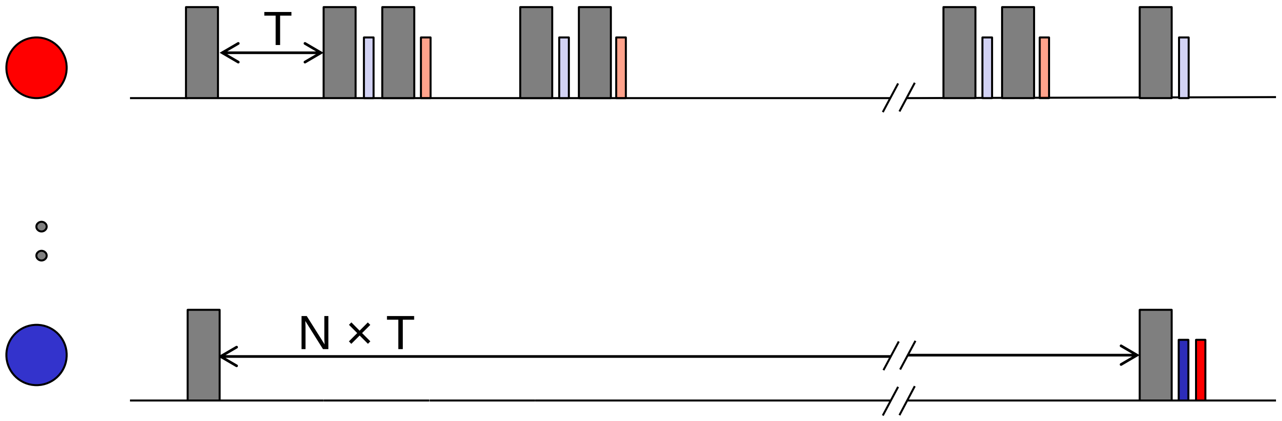
- Ramsey interrogation time T=1 ms



Clock operation with (partially) correlated measurements

PRX **5**, 021011 (2015)
& EU patent

Atomic clock with PLL: accuracy



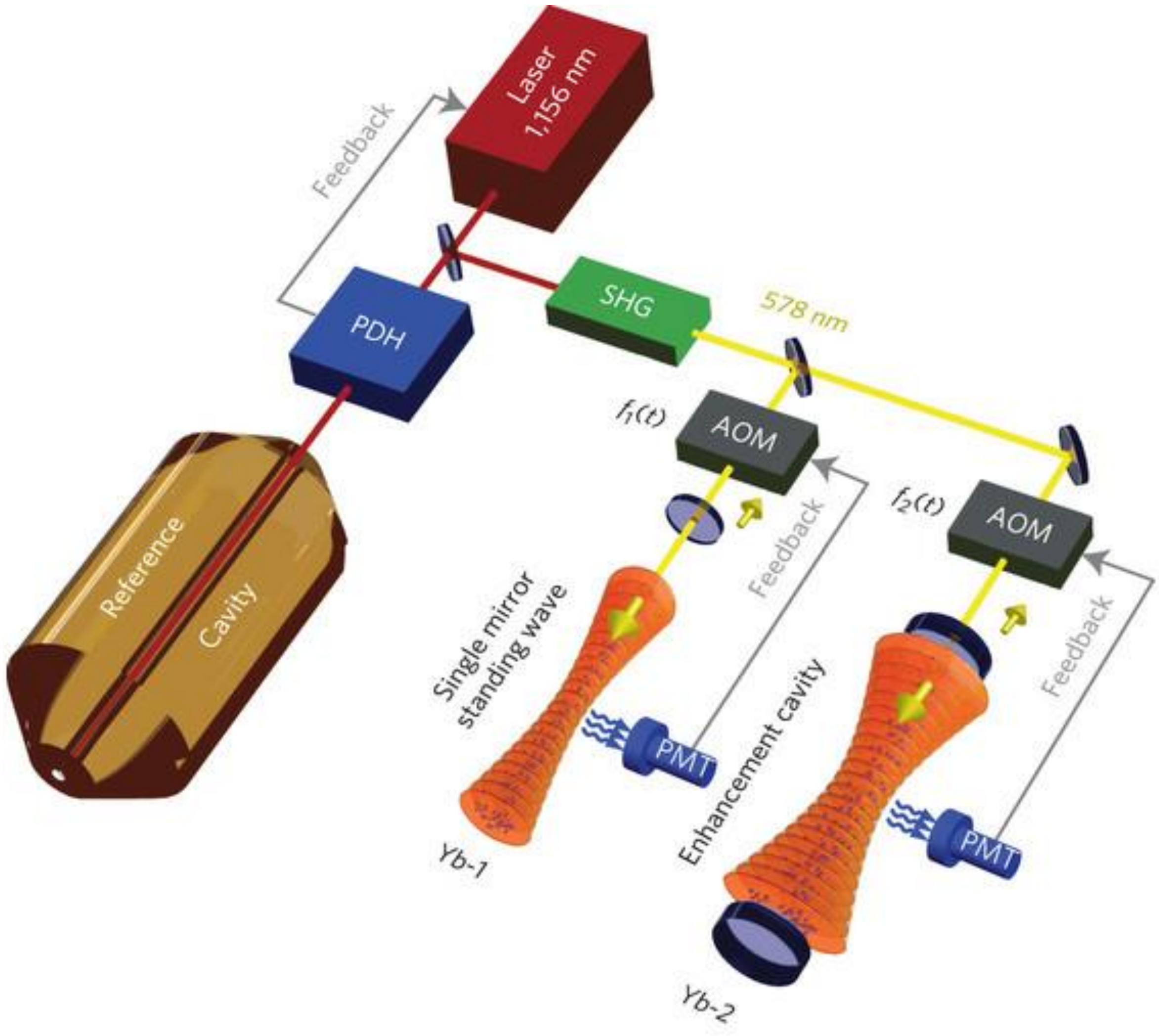
Two systems:

1. to pre-stabilize the LO

2. to address systematics, using pre-stab. LO

PRX **5**, 021011 (2015)
& EU patent

Atomic clock with PLL: accuracy



Schioppo *et al.*, Nature Photon. (2016)

Spectroscopic measurement improved using two combined atomic ensembles

Outline

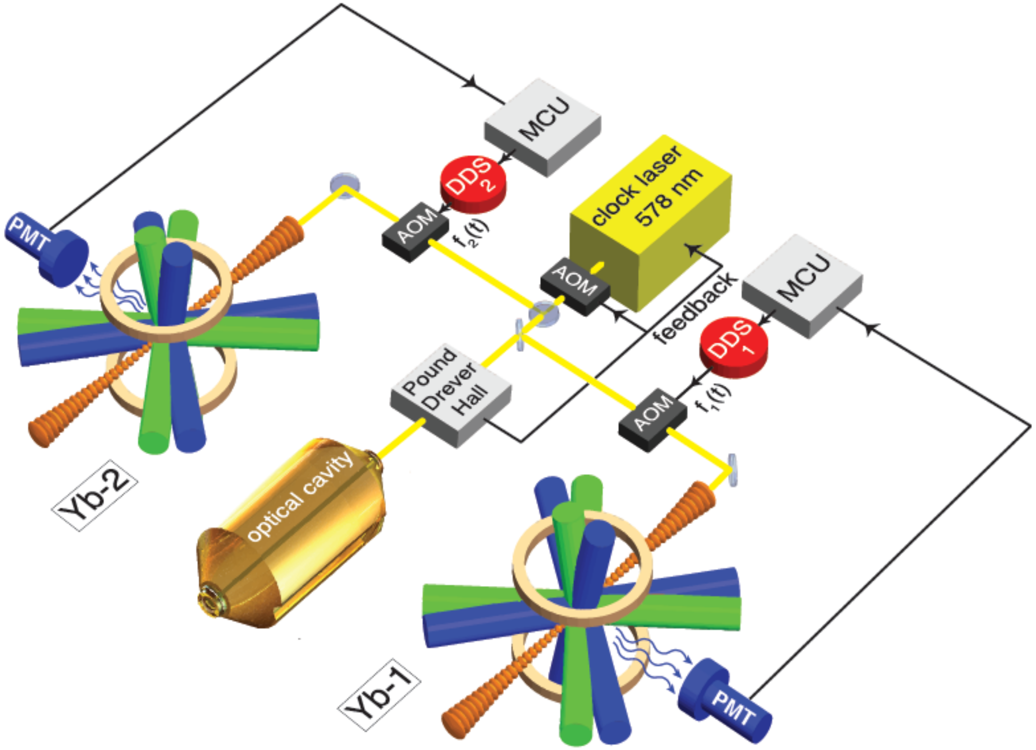
- Measuring a phase
  - ☐ classical and quantum case
  - ☐ phase wraps issue
  - ☐ adopted solutions

- Coherence preserving measurements and feedback
  - ☐ experimental setup
  - ☐ information retrieval vs. destructivity
  - ☐ quartz – quantum state PLL
  - ☐ atomic clock with PLL

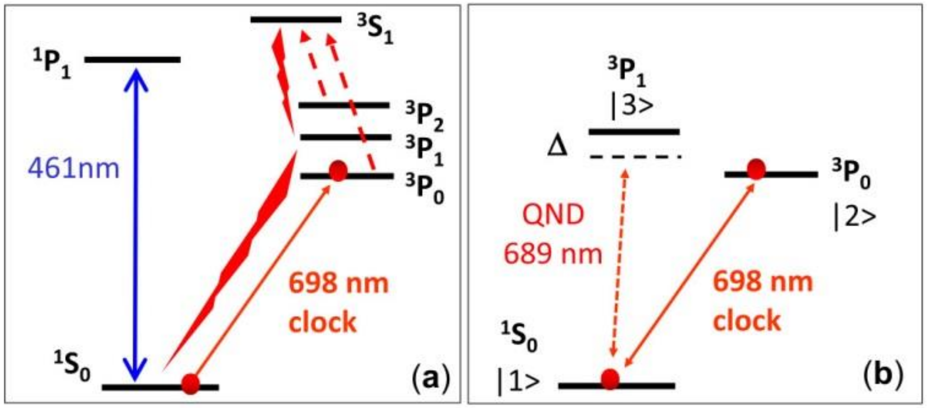
- **Outlook**
  - ☐ PLL in inertial sensing and optical clocks

  - ☐ Cold atom experiments at LP2N - Bordeaux

Atomic clock with PLL



Optical clock @ 10^{-18} instability
Hinkley *et al.*, Science **341**, 1215 (2013)



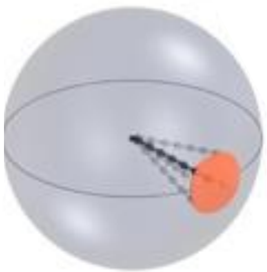
QND probe for alkaline-Earth atoms
Polzik and Ye, Phys. Rev. A **93**, 021404(R) (2016)

+ EOM as phase actuator

Atomic clock with PLL & spin squeezing

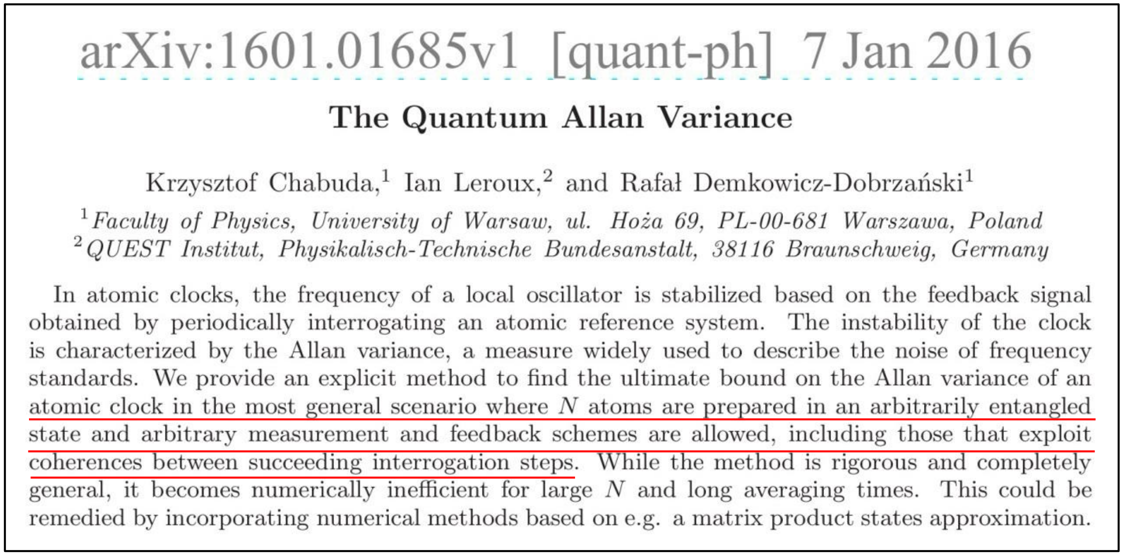
Atomic clock sensitivity:

$$\sigma_{y,\mathrm{det}} = \frac{1}{\omega_{\mathrm{LO}}}\frac{1}{\mathrm{SNR}}\frac{1}{T}\sqrt{\frac{T_C}{\tau}}$$



Coherent spin state
$\Delta J_z \times \Delta J_y = N/2$
$\Delta J_z = \Delta J_y = \sqrt{(N/2)}$

Squeezed state
$\Delta J_z < \sqrt{(N/2)}$



arXiv:1601.01685v1 [quant-ph] 7 Jan 2016

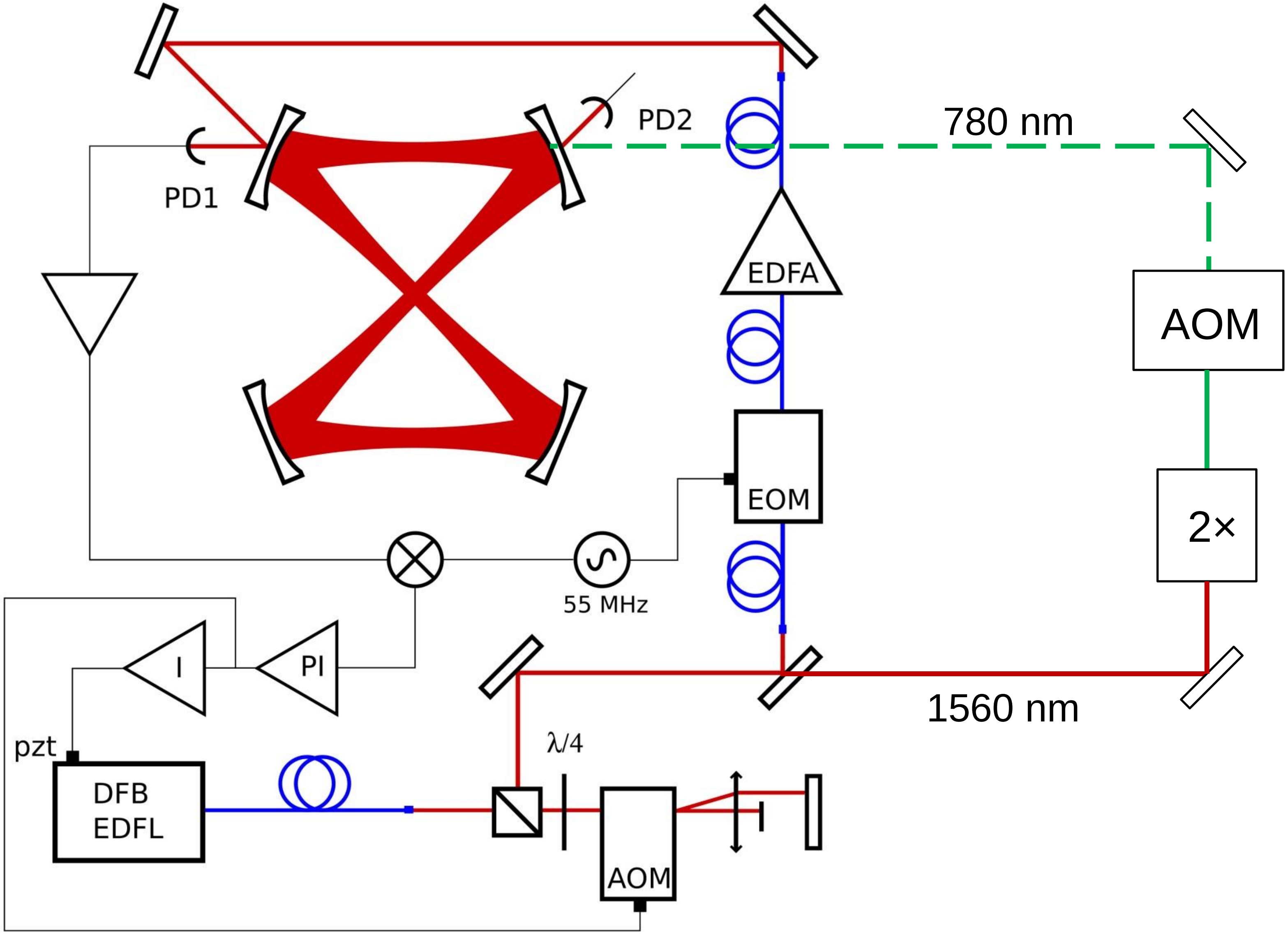
The Quantum Allan Variance

Krzysztof Chabuda,[1] Ian Leroux,[2] and Rafał Demkowicz-Dobrzański[1]

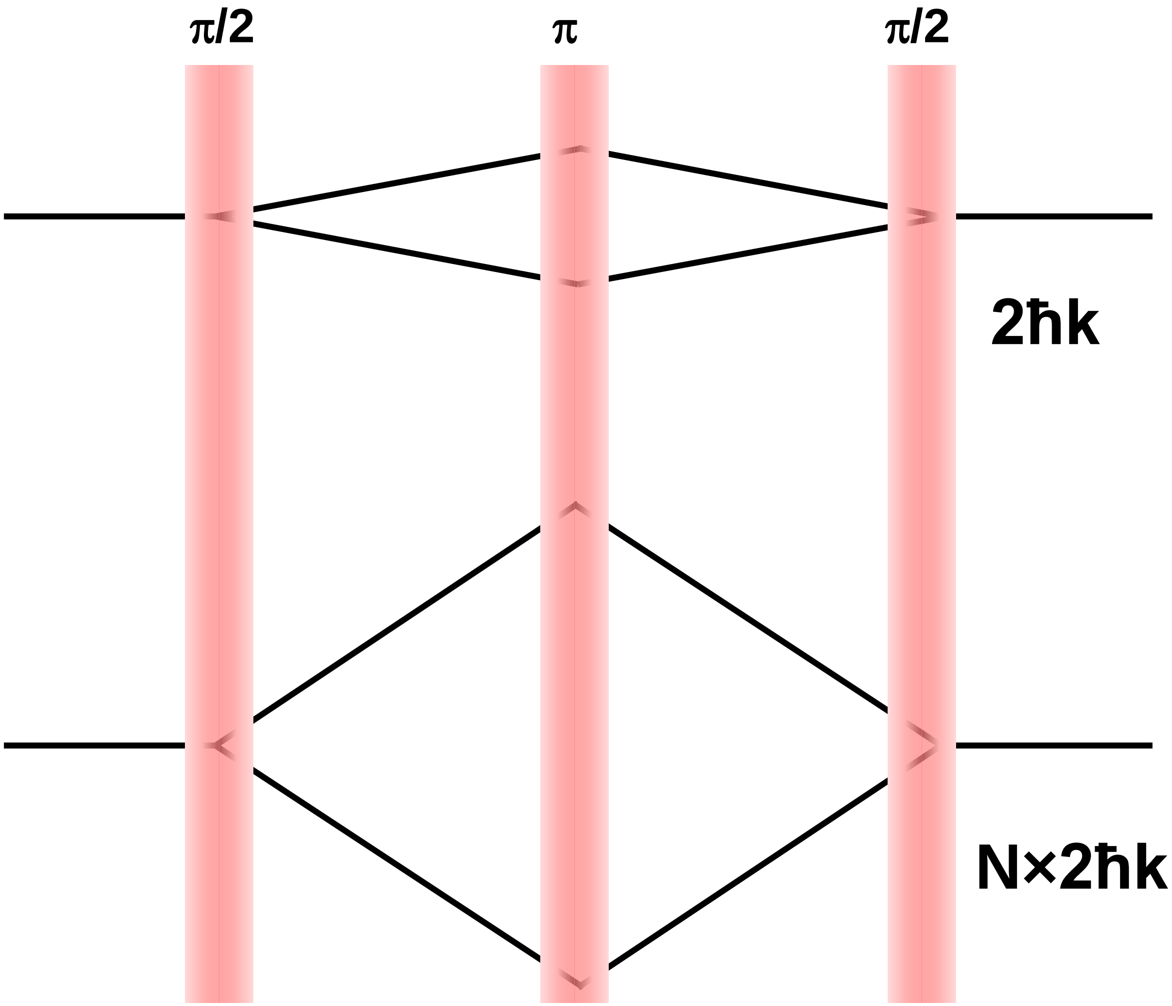
[1] *Faculty of Physics, University of Warsaw, ul. Hoża 69, PL-00-681 Warszawa, Poland*
[2] *QUEST Institut, Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany*

In atomic clocks, the frequency of a local oscillator is stabilized based on the feedback signal obtained by periodically interrogating an atomic reference system. The instability of the clock is characterized by the Allan variance, a measure widely used to describe the noise of frequency standards. We provide an explicit method to find the ultimate bound on the Allan variance of an atomic clock in the most general scenario where N atoms are prepared in an arbitrarily entangled state and arbitrary measurement and feedback schemes are allowed, including those that exploit coherences between succeeding interrogation steps. While the method is rigorous and completely general, it becomes numerically inefficient for large N and long averaging times. This could be remedied by incorporating numerical methods based on e.g. a matrix product states approximation.

Atomic clock with PLL & spin squeezing



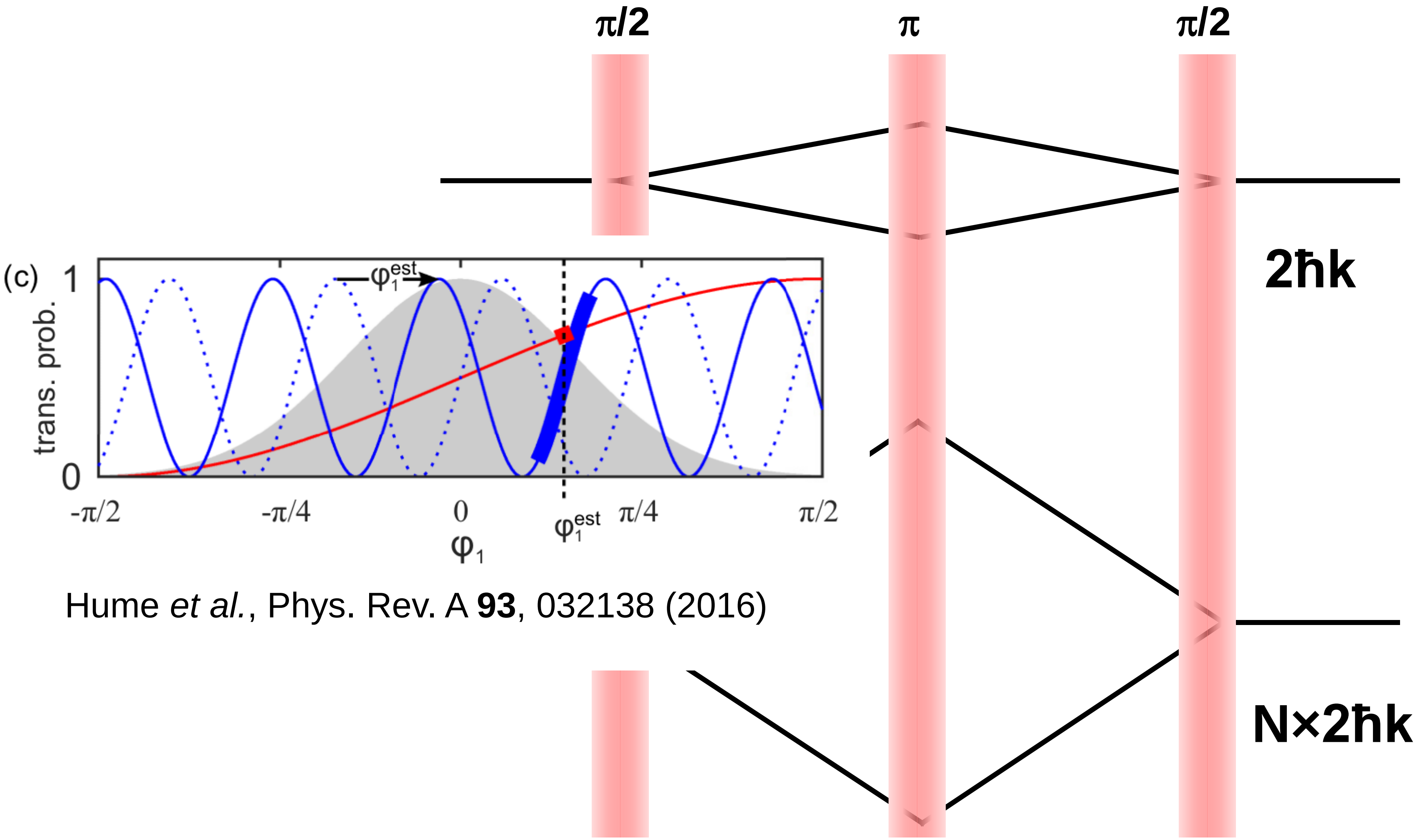
Coupled sensors using Large Momentum Transfer (LMT)



Two simultaneous sensors with different path separation
→ scaled up sensitivity

- **Low sensitivity sensor in the linear regime**
- **High sensitivity sensor out of the phase inversion region**

Coupled sensors using Large Momentum Transfer (LMT)

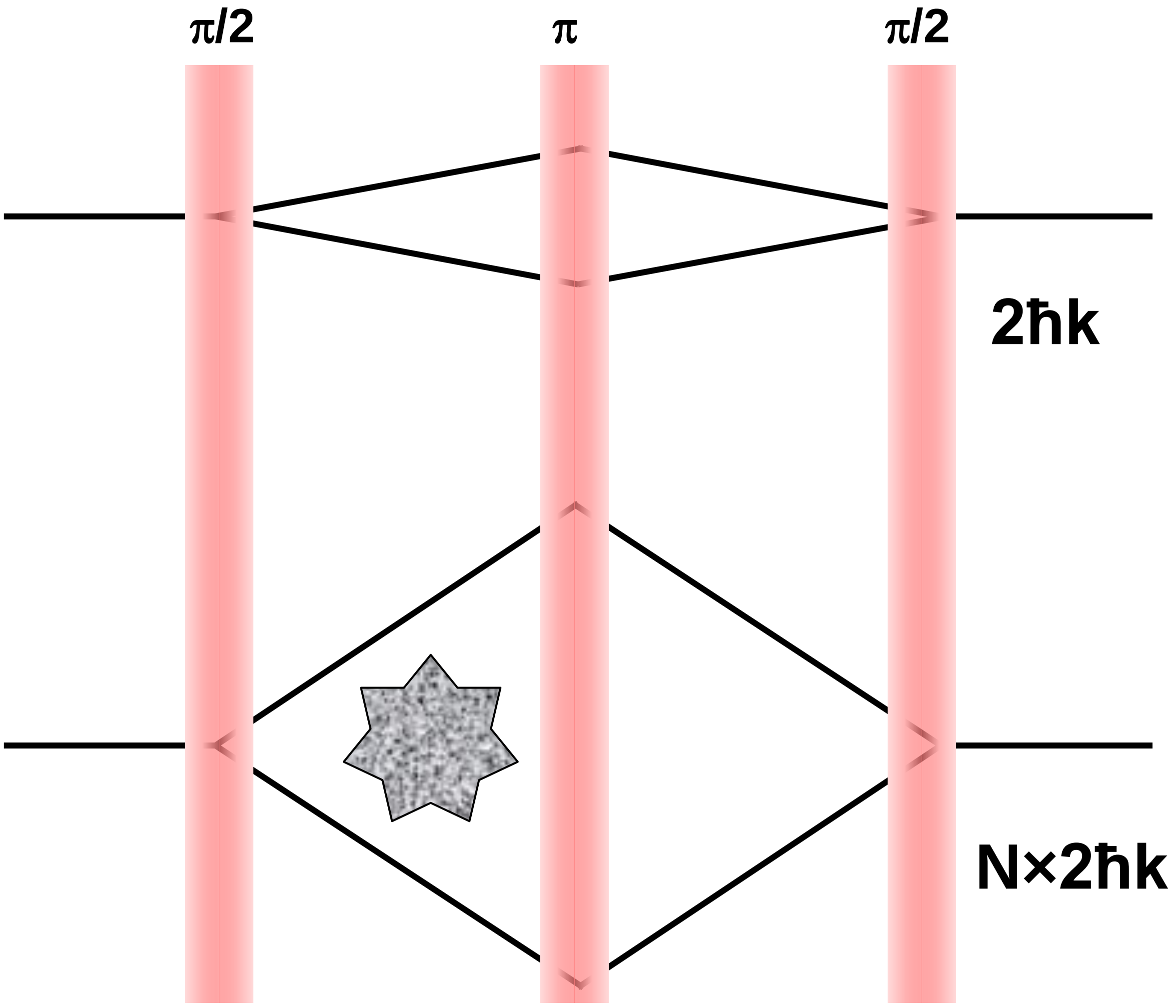


Hume *et al.*, Phys. Rev. A **93**, 032138 (2016)

Two simultaneous sensors with different path separation
→ scaled up sensitivity

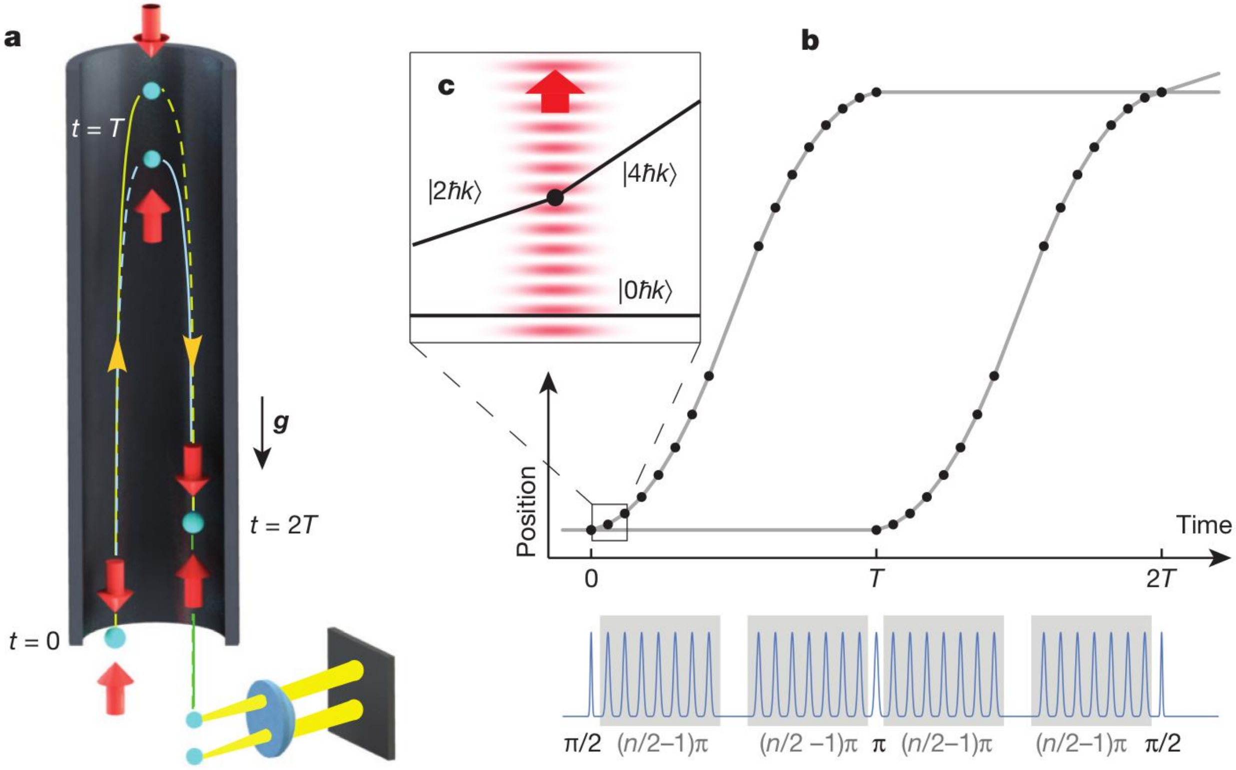
- **Low sensitivity sensor in the linear regime**
- **High sensitivity sensor out of the phase inversion region**

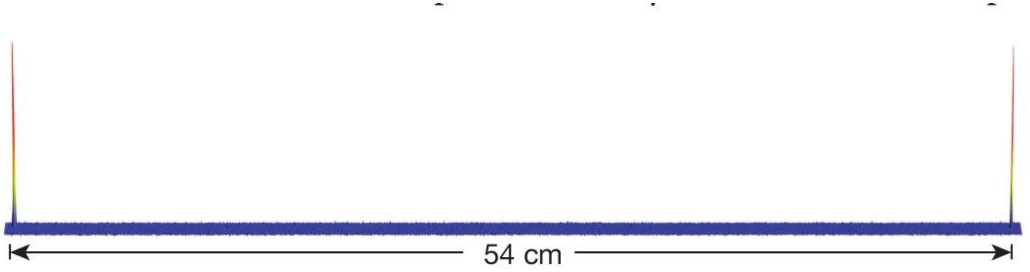
Coupled sensors using LMT



Retrieve phase when large separation required to encircle an obstacle (e. g. Gravitational Aharonov-Bohm Experiment, Hohensee *et al.*, Phys. Rev. Lett. **108**, 230404 (2012))

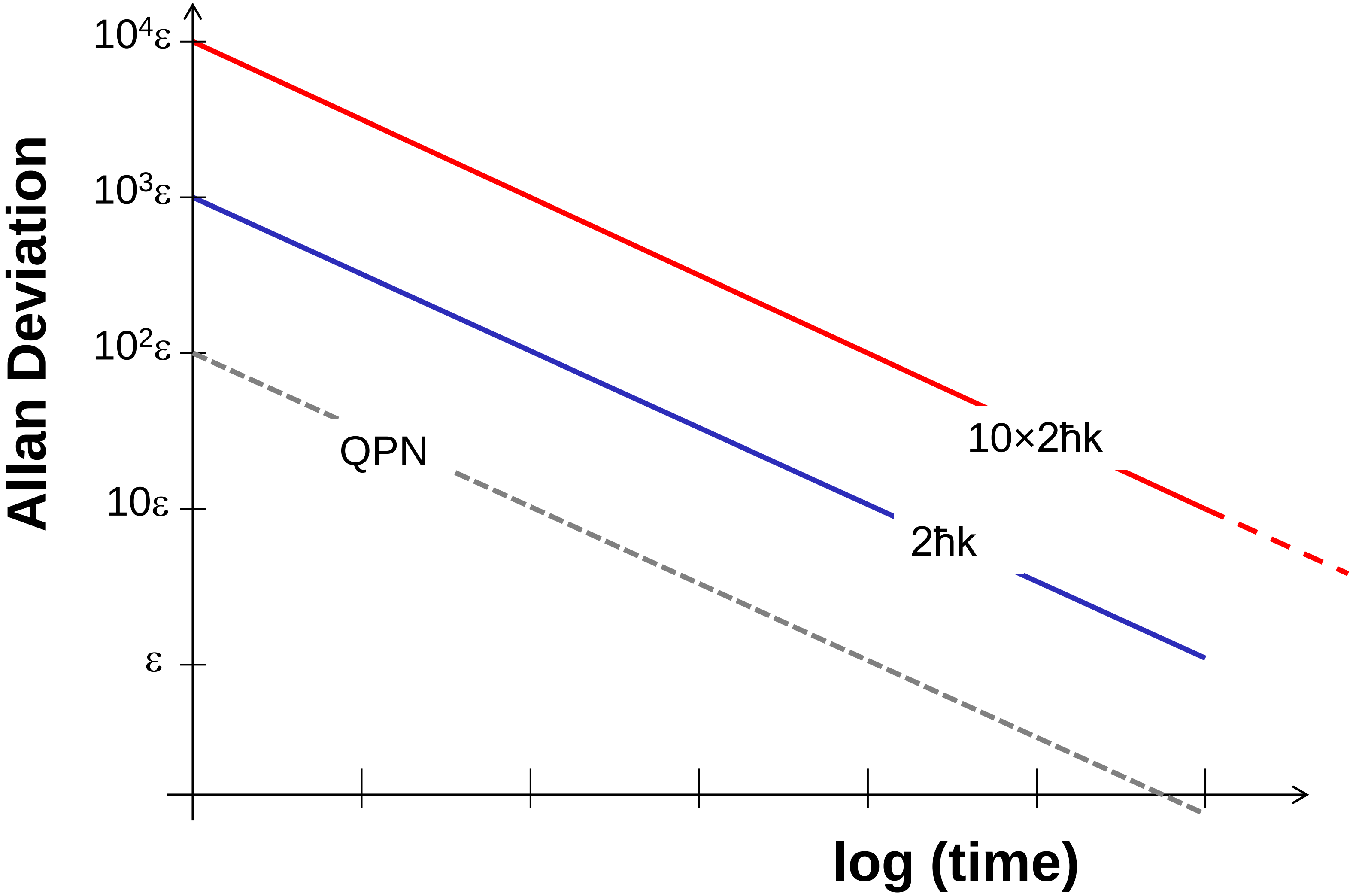
Coupled sensors using LMT





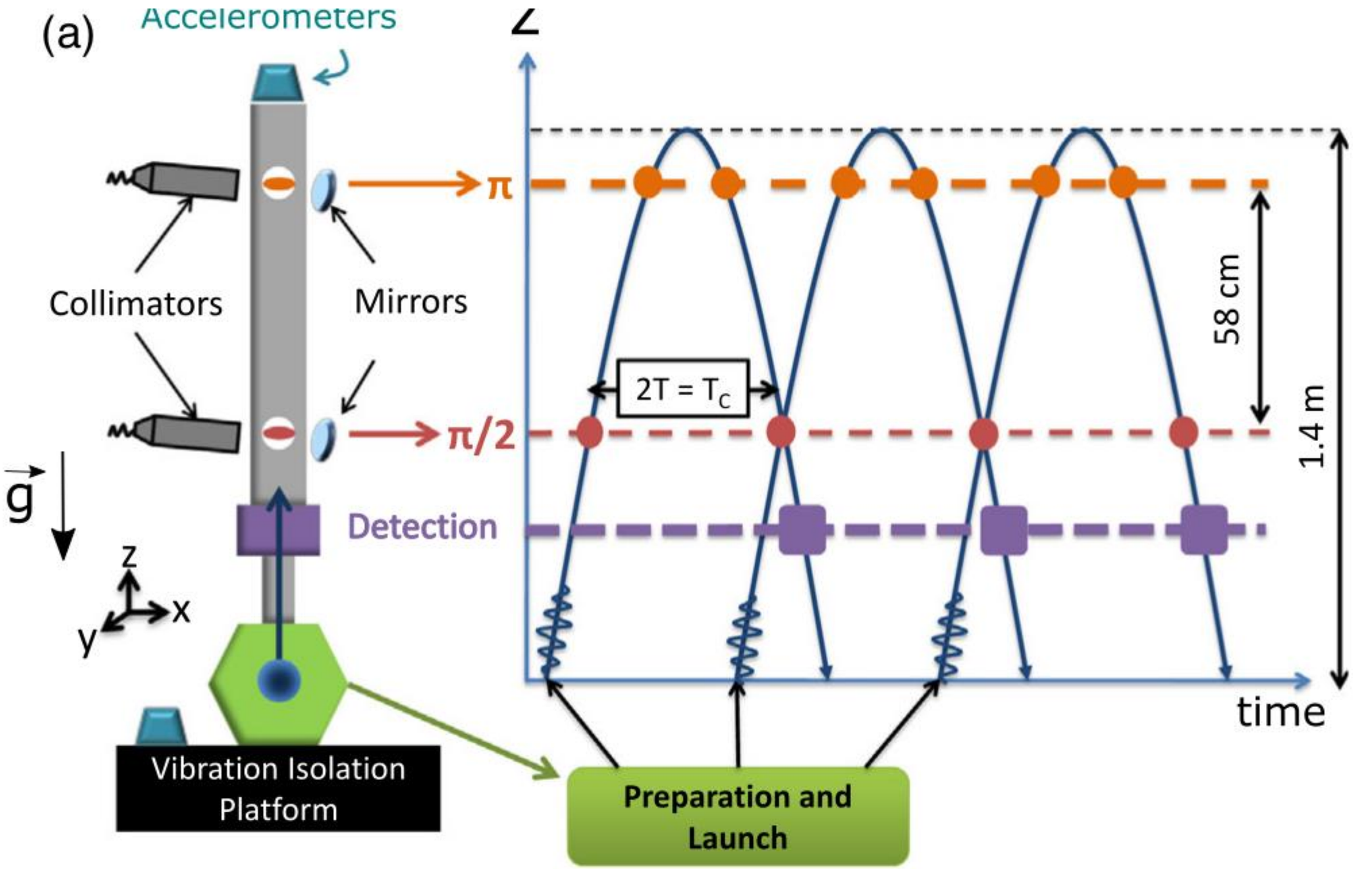
Demonstrate coherence in a wide separation AI
Kovachi *et al.*, Nature **528**, 530 (2015))
→ **Comment** Stamper-Kurn, Marti & Muller, arXiv:1607.01454

Coupled sensors using LMT



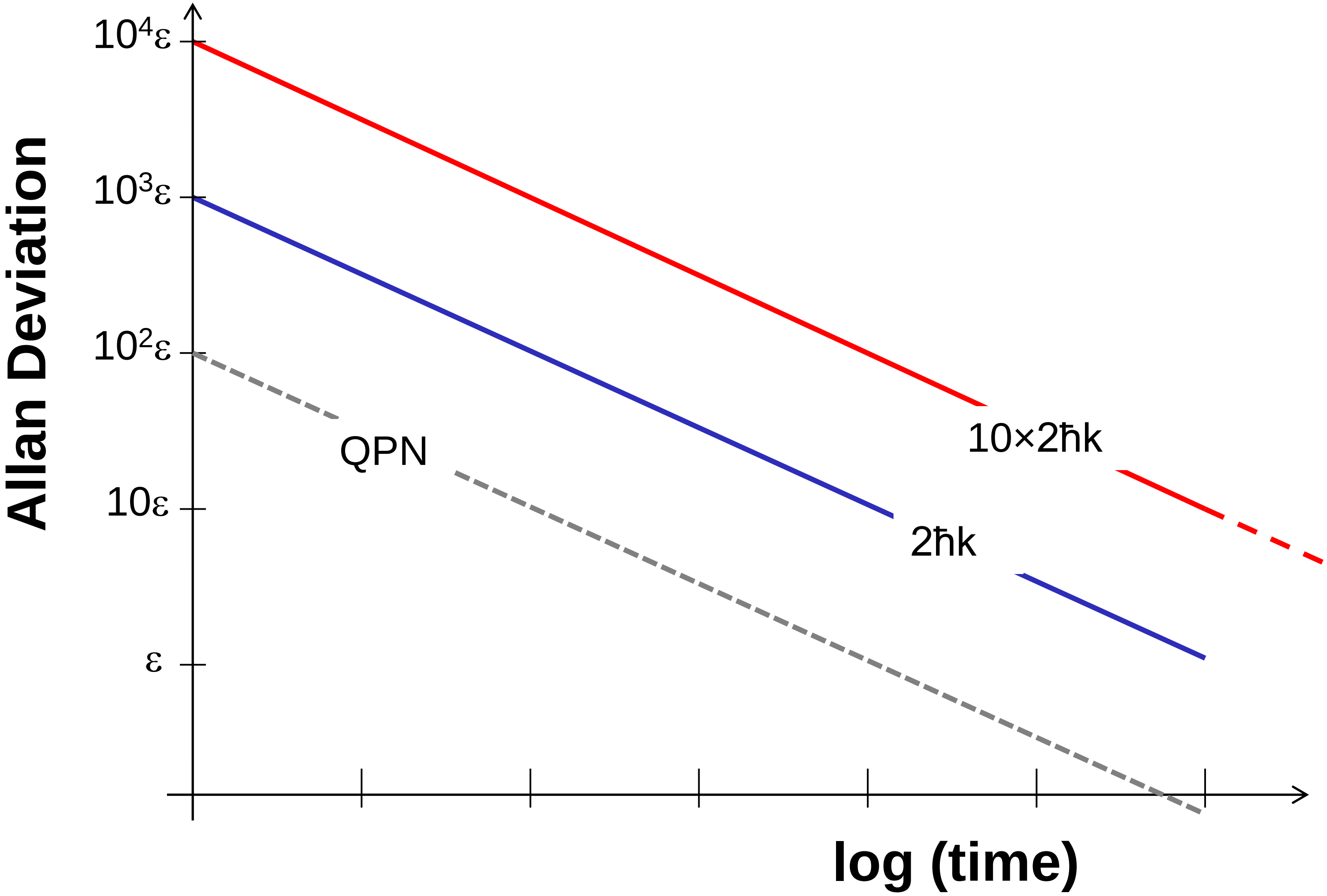
Sensitivity scaling like 1/√t in normal interferometer operation

Coupled sensors using LMT



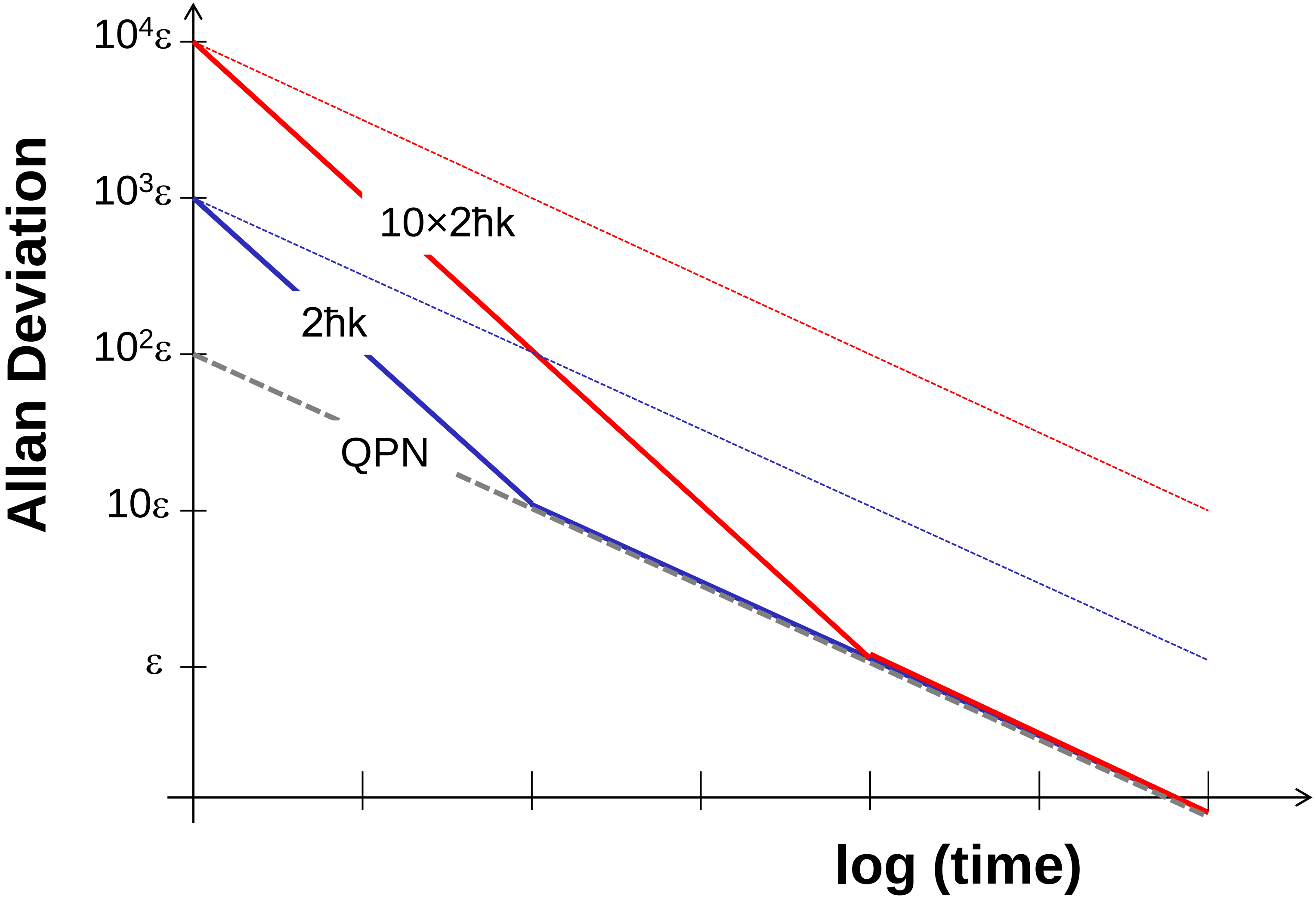
Sensitivity scaling like 1/t in interleaved interferometer operation
Biedermann *et al.*, Phys. Rev. **111** 170802 (2013)
Dutta *et al.*, Phys. Rev. **116** 183003 (2016)

Coupled sensors using LMT



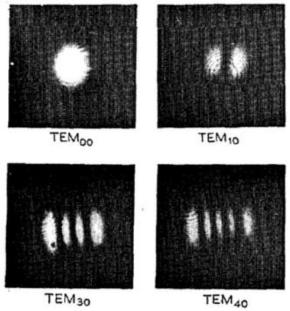
Sensitivity of the large area AI improves by √N once the QPN floor is reached

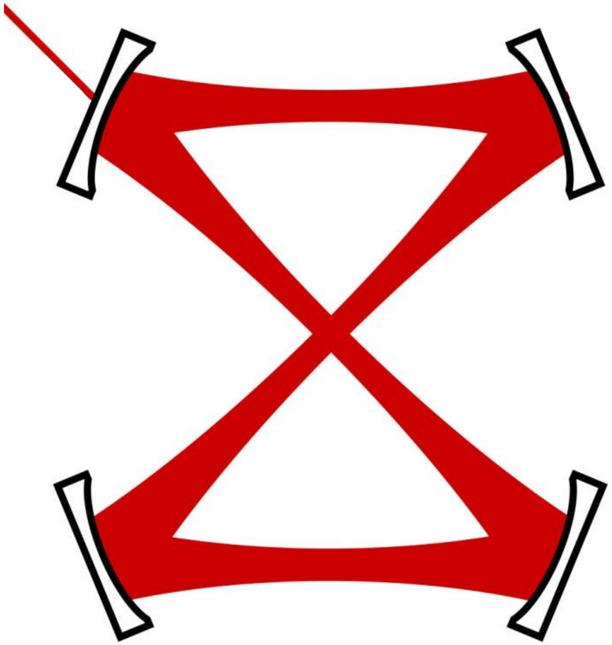
Coupled sensors using LMT

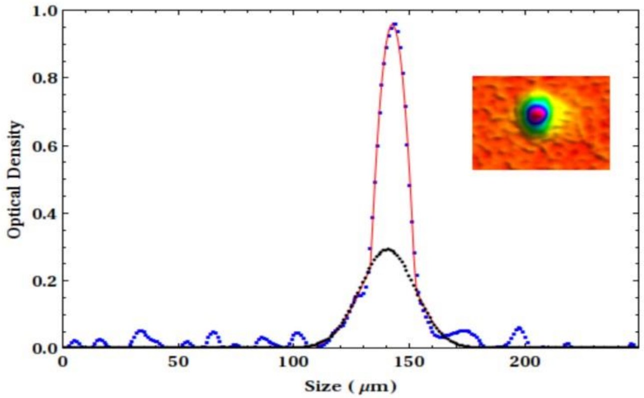


Sensitivity of the large area AI improves by N once the QPN floor is reached

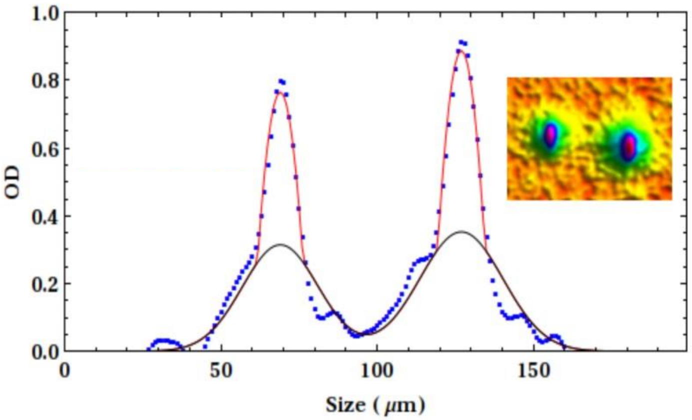
BEC in the higher cavity modes







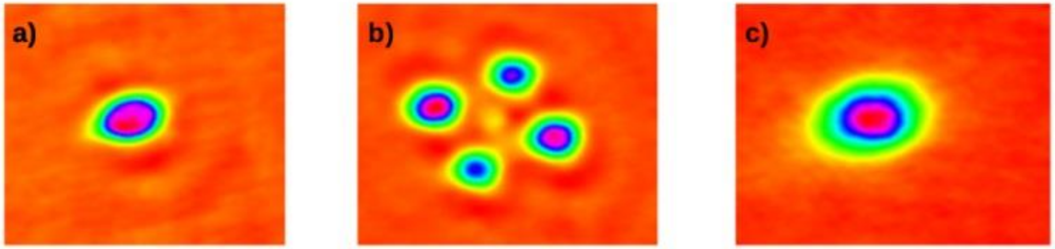
BEC in TEM$_{00}$



double BEC in TEM$_{01}$

Non degenerate cavity, selective injection of TEM$_{nm}$ mode using phase masks

Higher cavity modes and splitting



TEM_{00} TEM_{10} TEM_{00}

- Controlled cavity mode switch, maintaining trapping condition
- thermal atoms
- optimized trajectory with OCT?
- coherent splitting & recombination?

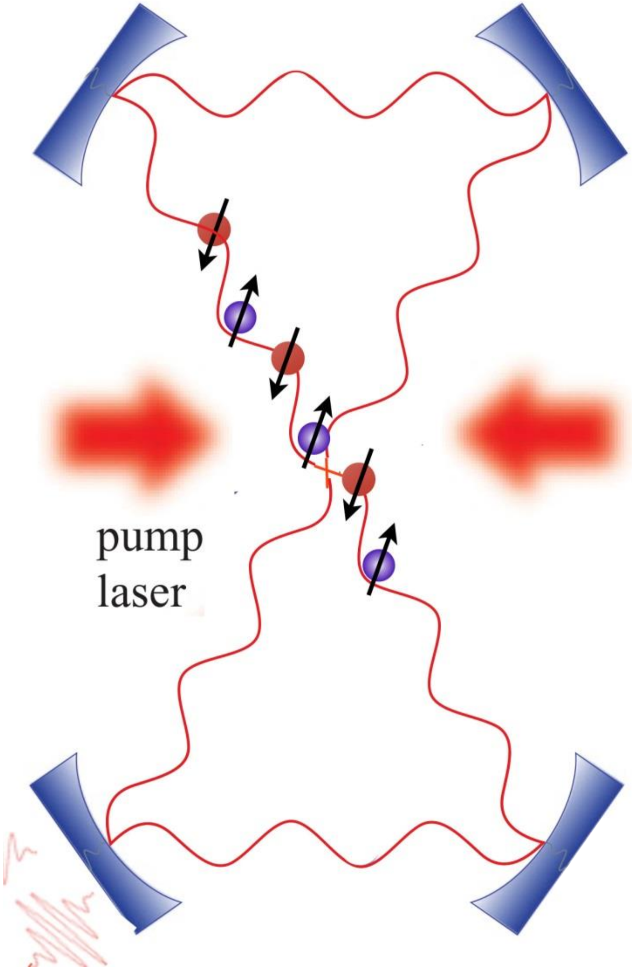
Emergent phenomena – crowd on the millennial bridge

Nature **438**, 43 (2005)

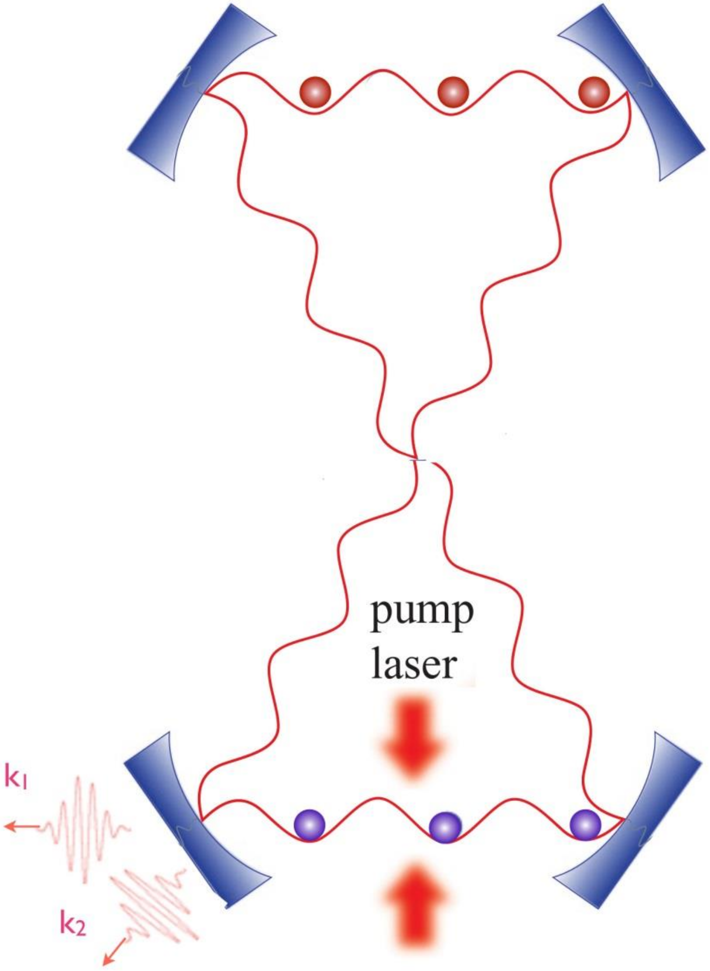
Emergent phenomena – crowd on the millennial bridge

Nature **438**, 43 (2005)

Emergent phenomena – pumped BEC in running wave cavity

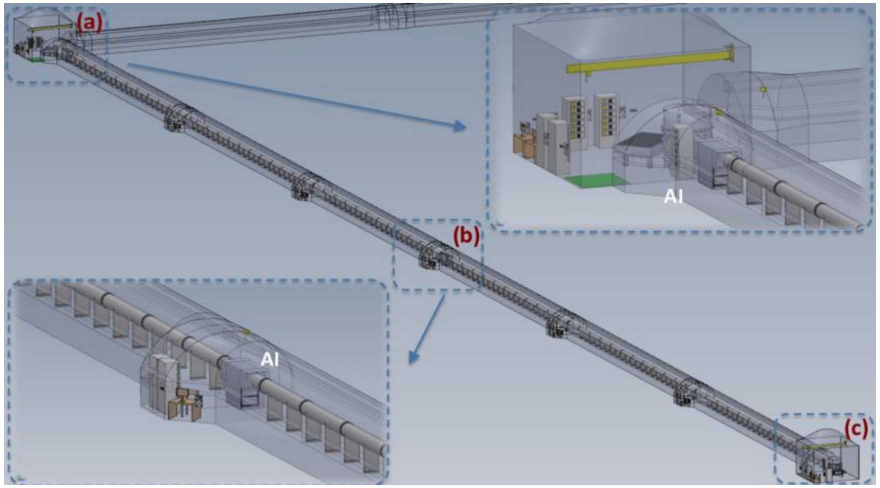


Controlled emergent crystallization; Brazovskii transition



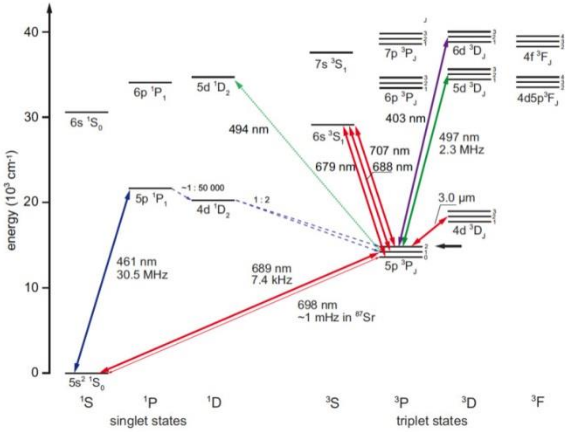
Long range, cavity mediated interactions and crystallization

Cold Atoms in Bordeaux



MIGA – underground array of AIs; demonstrator for GW detection; NN reduction protocols

ICE – airborne WEP test & soon micro-gravity simulator



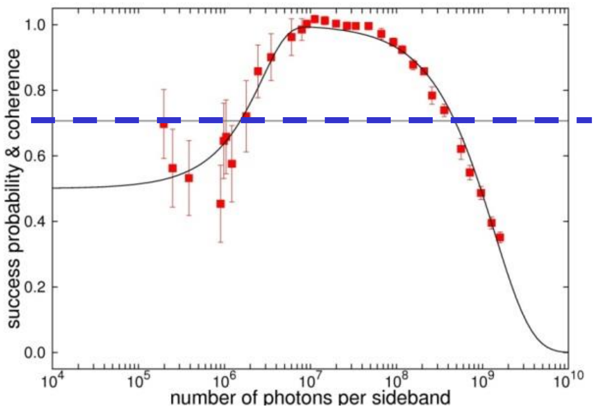
ALCALINF – single photon AI; decoherence in AI

IxATOM – AI based inertial navigation

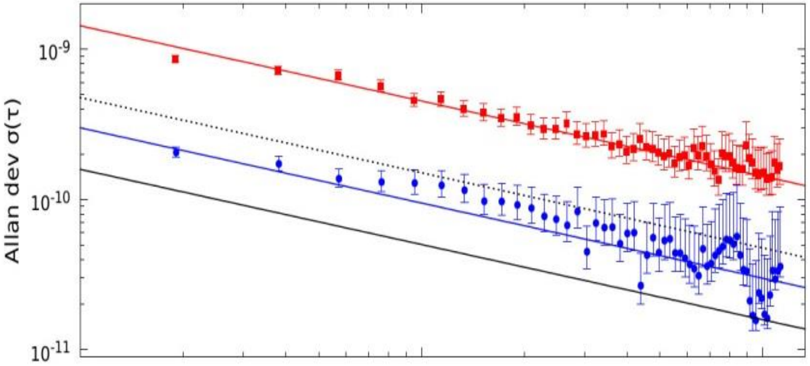
AUFRONS – atoms in nano-potentials

Postdocs & PhD positions available

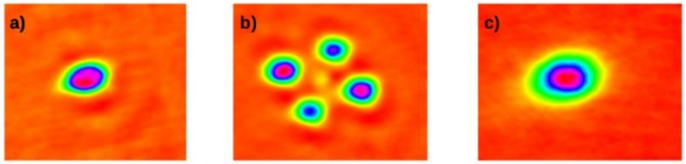
Summary



Coherence preserving measurements on CSS, and trade-off between information retrieval and destructivity



Phase lock of a LO to an atomic state
& Atomic clock with phase lock



BEC in higher cavity modes, and mode switching; emergent phenomena

People

LP2N

P. Bouyer
A. Bertoldi
D. Naik
G. Kuyumjyan

Previous PhDs & postdocs:

D. Pandey (@ Uni Bonn – D)
R. Kohlhaas (@SRON - NL)
E. Cantin (@ SYRTE – F)
T. Vanderbruggen (@Koheron – F)

Collaborations

A. Landragin (SYRTE – F)
M. Prevedelli (Univ. Bologna – I)
T. Freegarde (Univ. Southampton - UK)

EMRP
European Metrology Research Programme
Programme of EURAMET
The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union