Workshop on future instruments for gravity-based earthquake early warning

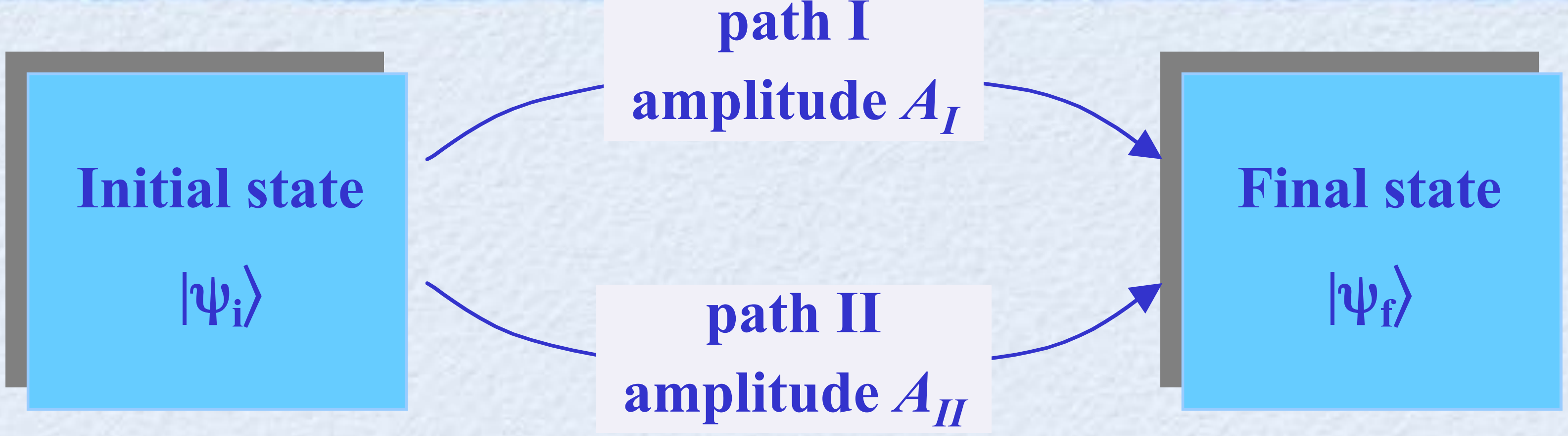
Gradiometers based on atom interferometers

Fiodor Sorrentino
INFN - Genova

Outline

- Brief recap on AI gravity sensors:
  - atom optics, ultracold atoms & atom interferometers
  - AI gravity gradiometers: seism CMRR & sensitivity limits
  - state of the art of atomic sensors
    - laboratory experiments
    - compact AI sensors: TRL
- Perspectives and potential improvements
  - medium-large scale experiments
  - atom optics progress
  - alternative schemes
    - trapped atoms
    - fiber links

Atom interferometry



Initial state

$|\psi_i\rangle$

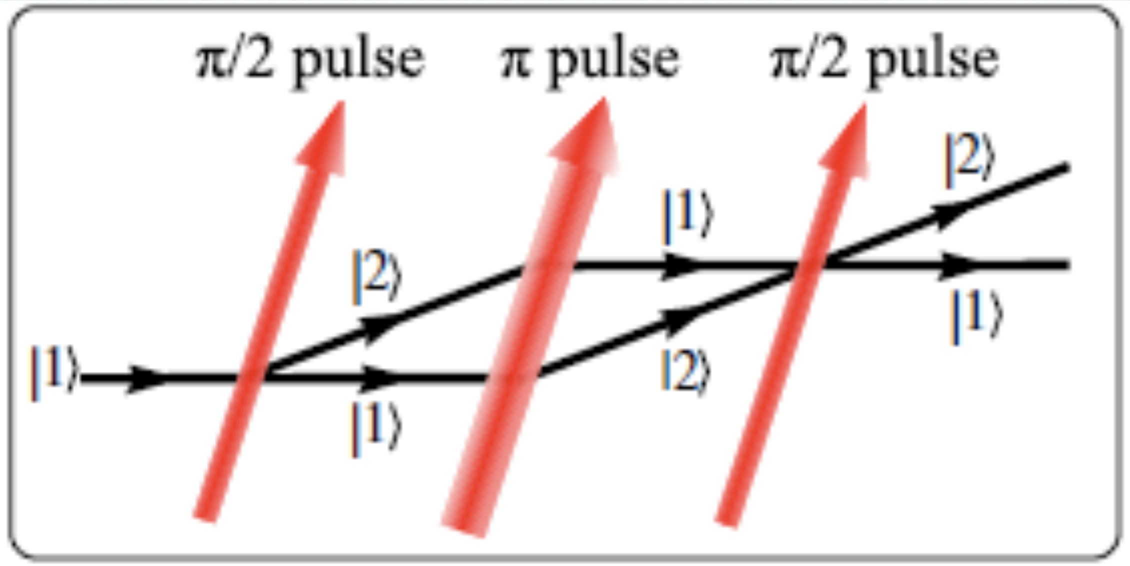
path I
amplitude A_I

path II
amplitude A_{II}

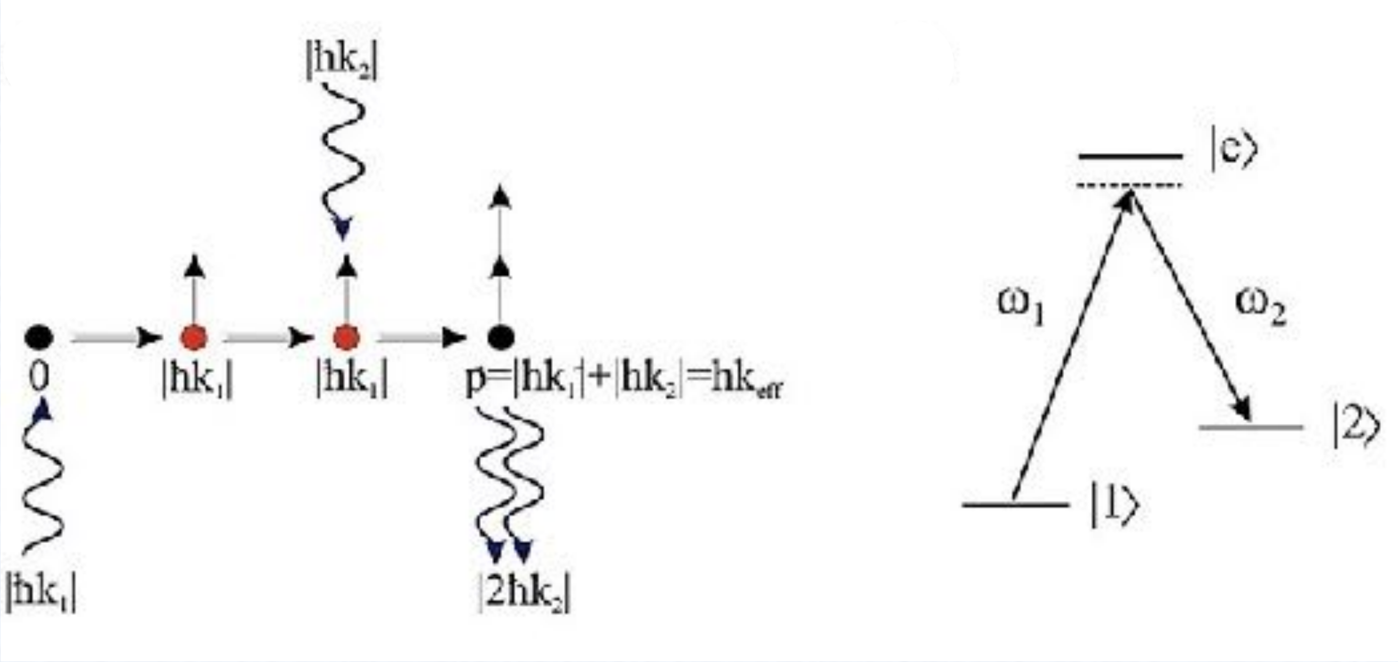
Final state

$|\psi_f\rangle$

Interference of de Broglie amplitudes

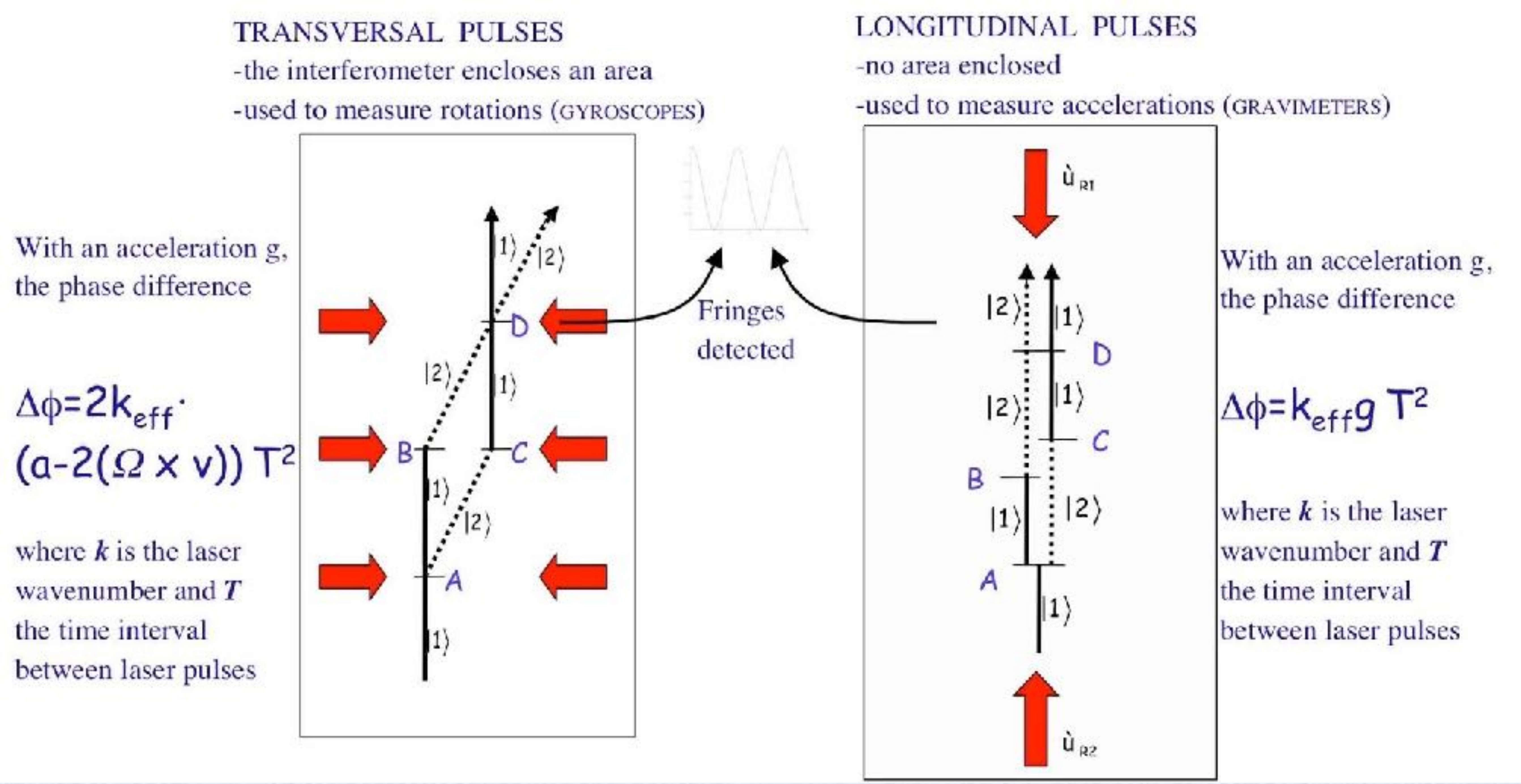


Light-pulse beam splitters
+ fluorescence detection



Output phase selectively sensitive to different effects (inertial, gravitational, external fields, laser phase/frequency, etc) via choice of quantum states

Light-pulse AI inertial sensors



TRANSVERSAL PULSES

-the interferometer encloses an area

-used to measure rotations (GYROSCOPES)

LONGITUDINAL PULSES

-no area enclosed

-used to measure accelerations (GRAVIMETERS)

With an acceleration g, the phase difference

$$\Delta\phi=2k_{eff}\cdot(a-2(\Omega\times v))\,T^2$$

where ***k*** is the laser wavenumber and ***T*** the time interval between laser pulses

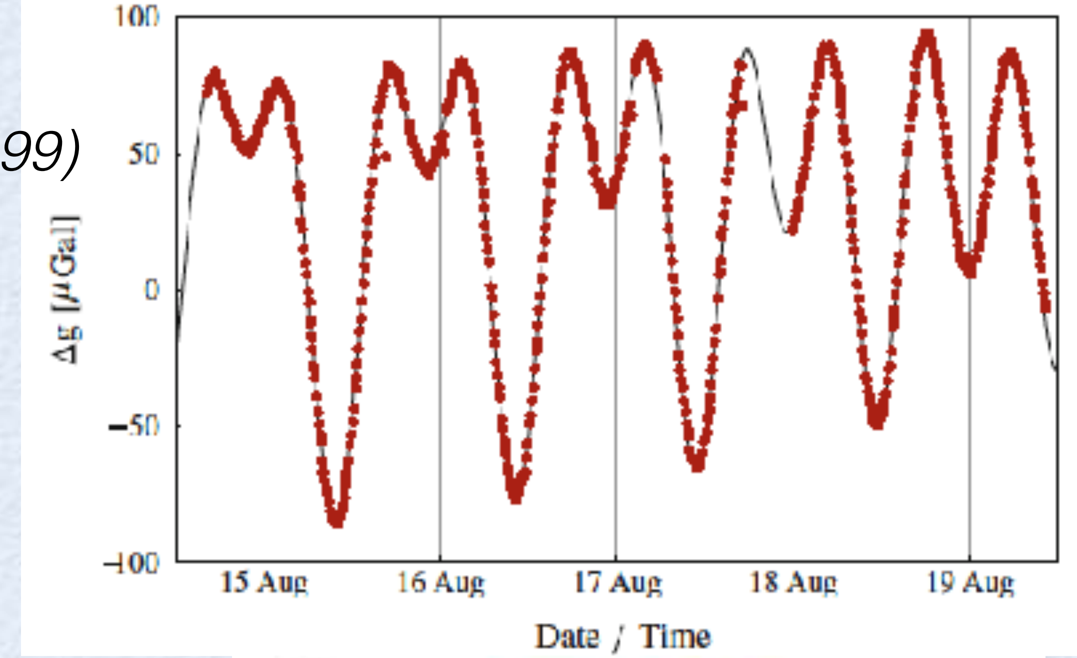
With an acceleration g, the phase difference

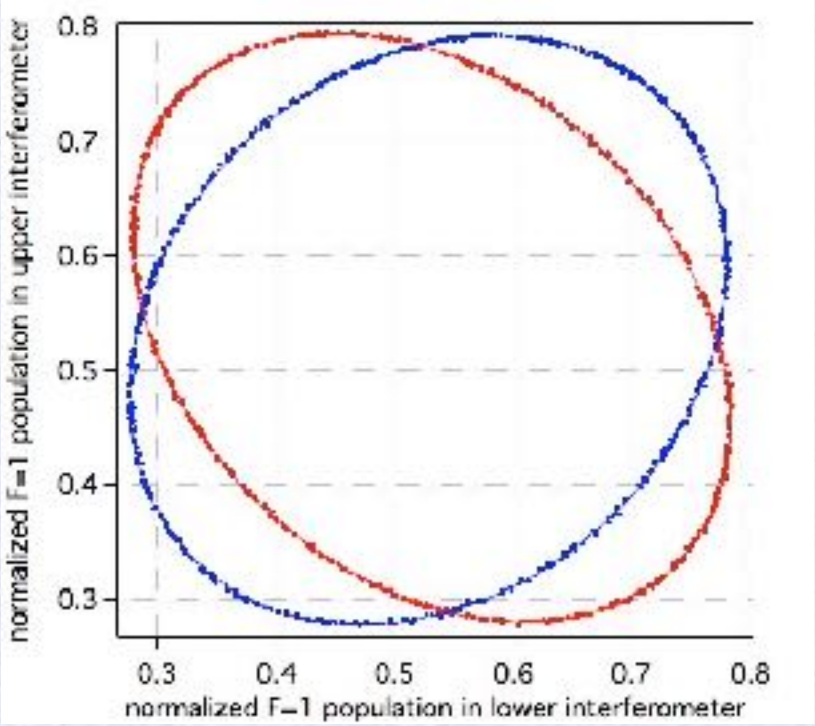
$$\Delta\phi=k_{eff}g\,T^2$$

where ***k*** is the laser wavenumber and ***T*** the time interval between laser pulses

Current performance

- Absolute gravimeters
  - resolution: 3×10^{-9} g in 1 second (SYRTE)
  - averaging down to 2×10^{-10} g after 30 min (SYRTE)
  - accuracy: $10^{-9}\div10^{-10}$ g, limited by tidal models
    - *A. Peters, K.Y. Chung and S. Chu, Nature 400, 849 (1999)*
    - *H. Müller et al., Phys. Rev. Lett 100, 031101 (2008)*
    - *M. Hauth et el., Appl. Phys. B 113, 49 (2013)*
    - *P. Gillot et al., Metrologia 51, L15 (2014)*
- Gravity gradiometers
  - 1 m fountain: differential acceleration sensitivity: 5×10^{-9} g in1 s (5×10^{-11} g after 10^4 s)
    - *F. Sorrentino et al., Phys. Rev. A 89, 023607 (2014)*
  - 10 m fountain: differential acceleration sensitivity: 5×10^{-10} g in1 s
    - *P. Asenbaum et al., Phys. Rev. Lett. 118, 183602 (2017)*
- Rotation sensors
  - sensitivity: 6×10^{-10} rad/s/√Hz
  - scale factor stability <5 ppm
  - bias stability <70 μdeg/h
    - *T. L. Gustavson et al., Class. Quantum Grav. 17, 2385 (2000)*
    - *D. S. Durfee et al., Phys. Rev. Lett. 97, 240801 (2006)*

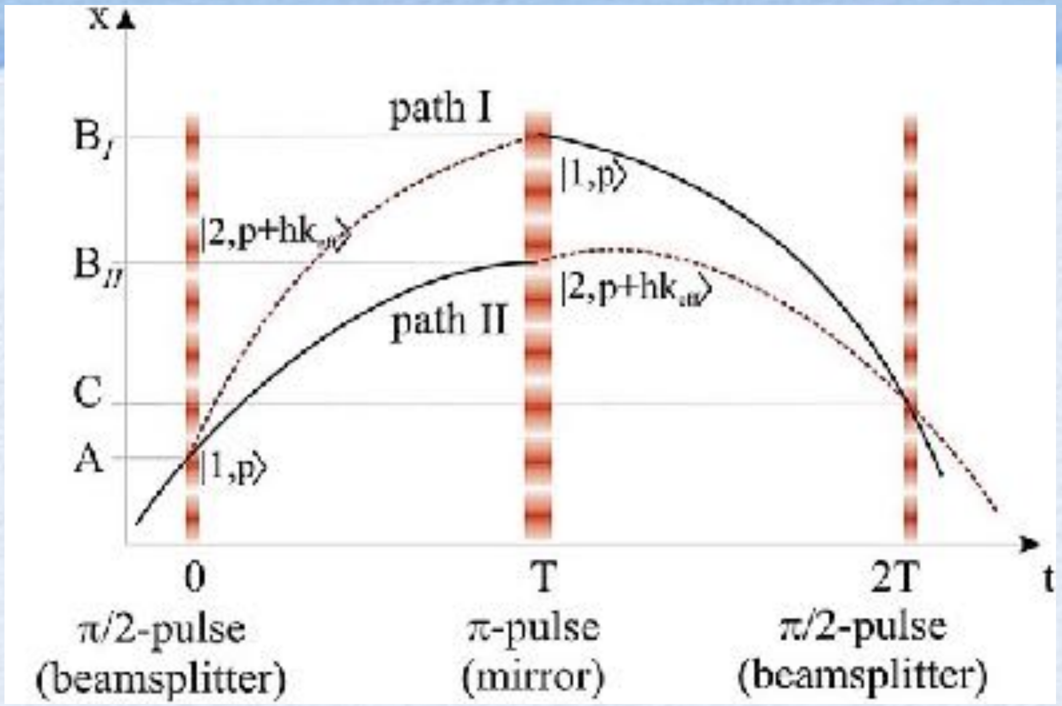




Sensitivity limits

- Short-term sensitivity in state-of-the art atom interferometers is usually limited by **quantum noise**
- For long integration times, and/or for major sensitivity improvements one should consider several effects
  - Acceleration noise
  - Laser wavefront
  - Atomic motion
  - Laser phase and frequency noise
  - Aliasing
  - External fields
  - Other technical noise sources

Quantum projection noise



Phase difference between the paths:

$$\Delta\Phi = k_e[z(0) - 2z(T) + z(1T)] + \Phi_e$$

$$k_e = k_1 - k_2$$

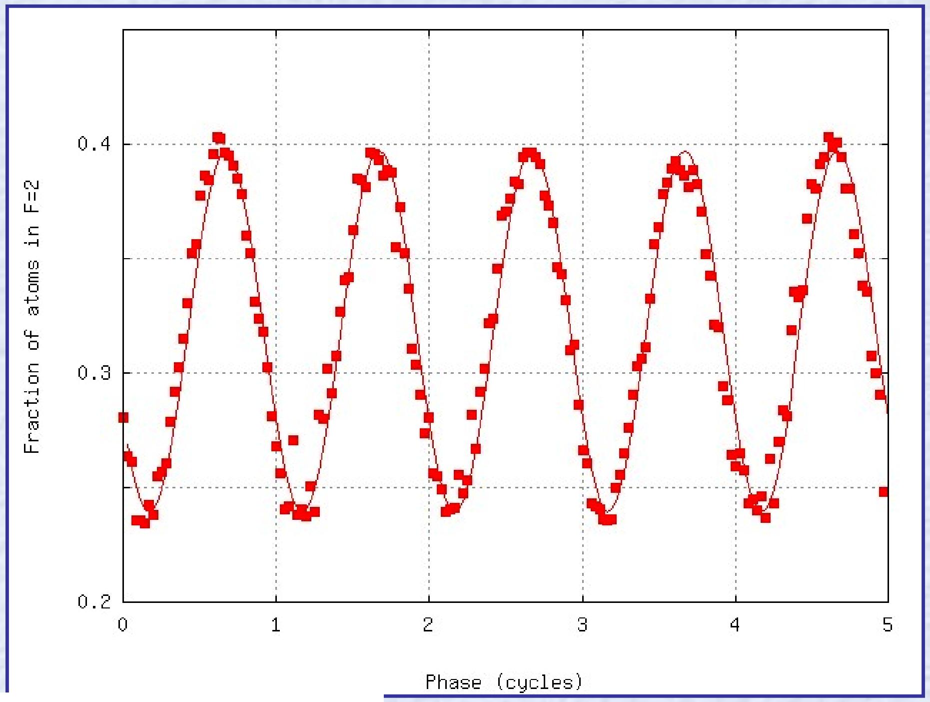
with $z(t) = -gt^2/2 + v_0 t + z_0$ & $\Phi_e = 0$

$$\rightarrow \Delta\Phi = k_e g T^2$$

Final population:

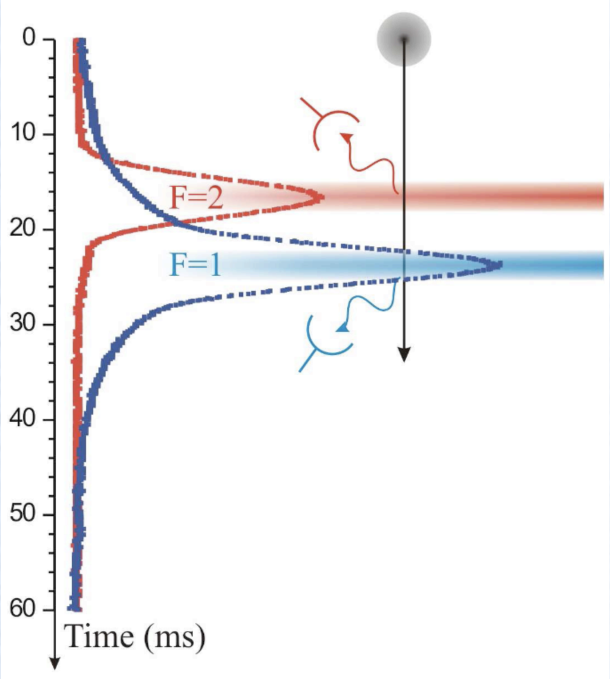
$$N_a = N/2(1 + cos[\Delta\Phi])$$

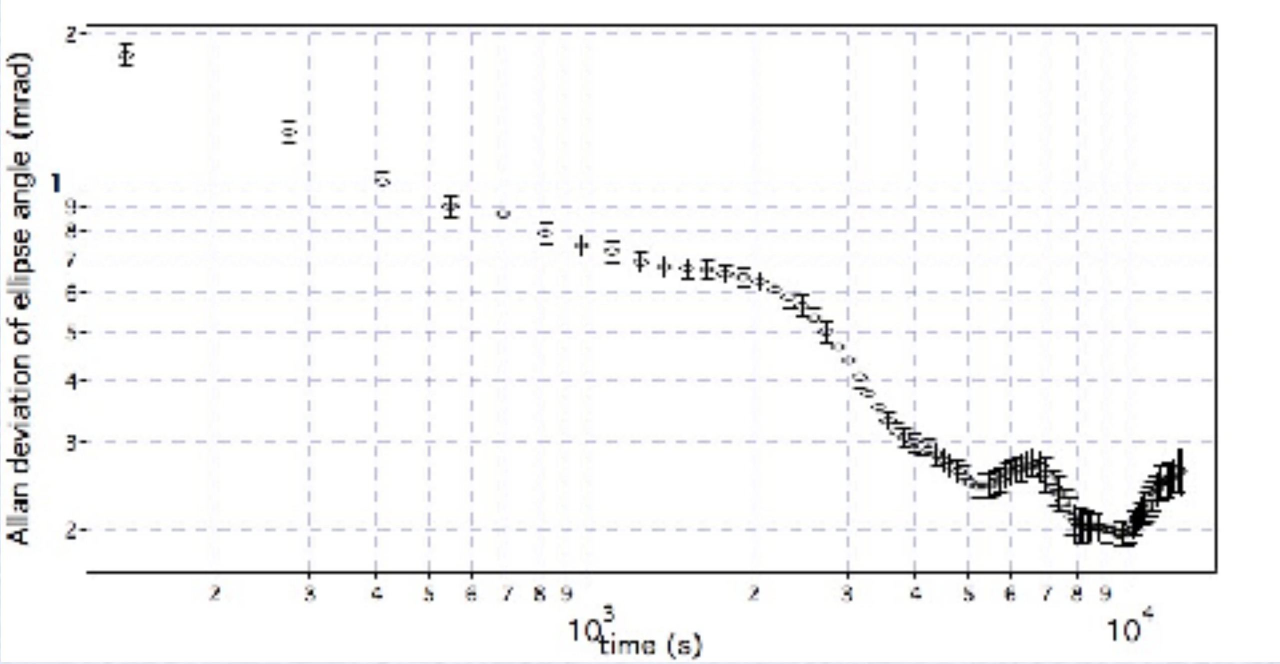
$$\delta\Phi \sim \frac{1}{\sqrt{(N_{at})}}$$



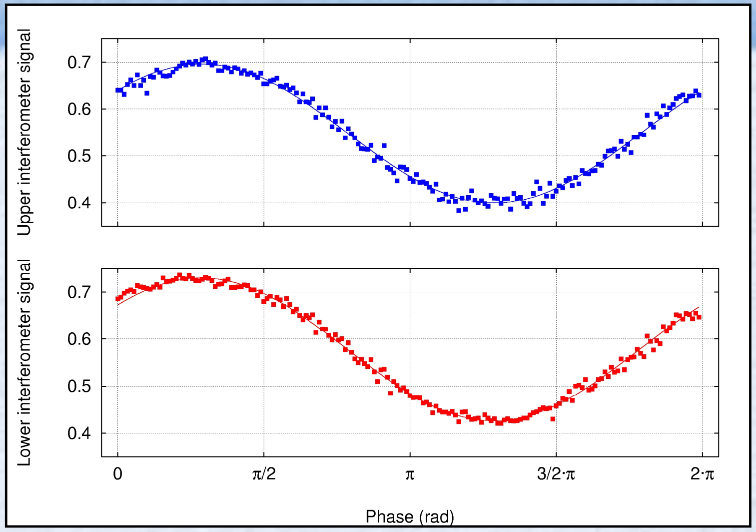
$T = 150$ ms $\rightarrow 2\pi = 10^{-6}$ g

S/N=1000 → Sensitivity 10^{-9} g/shot

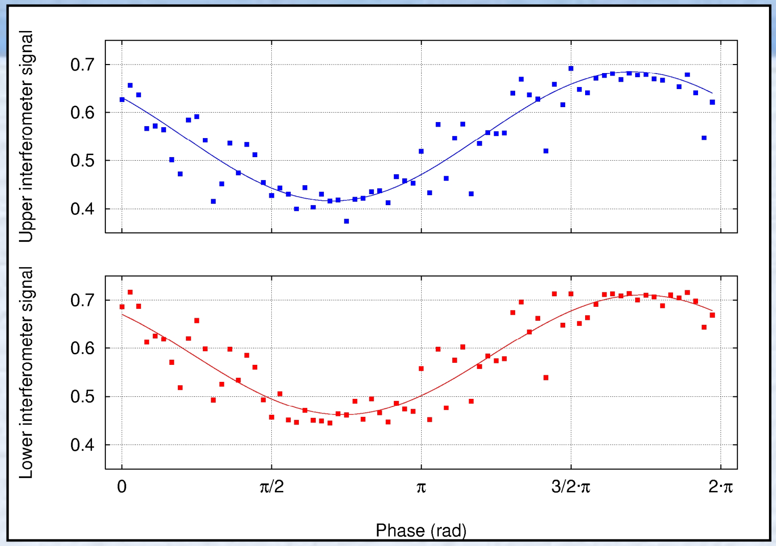




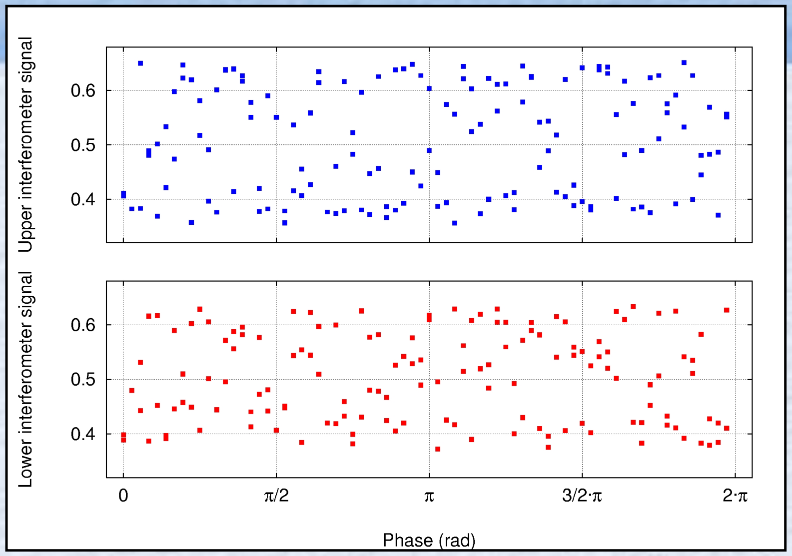
Acceleration noise



T=5 ms
$\text{resol.} = 2.3 \times 10^{-5} \text{g/shot}$

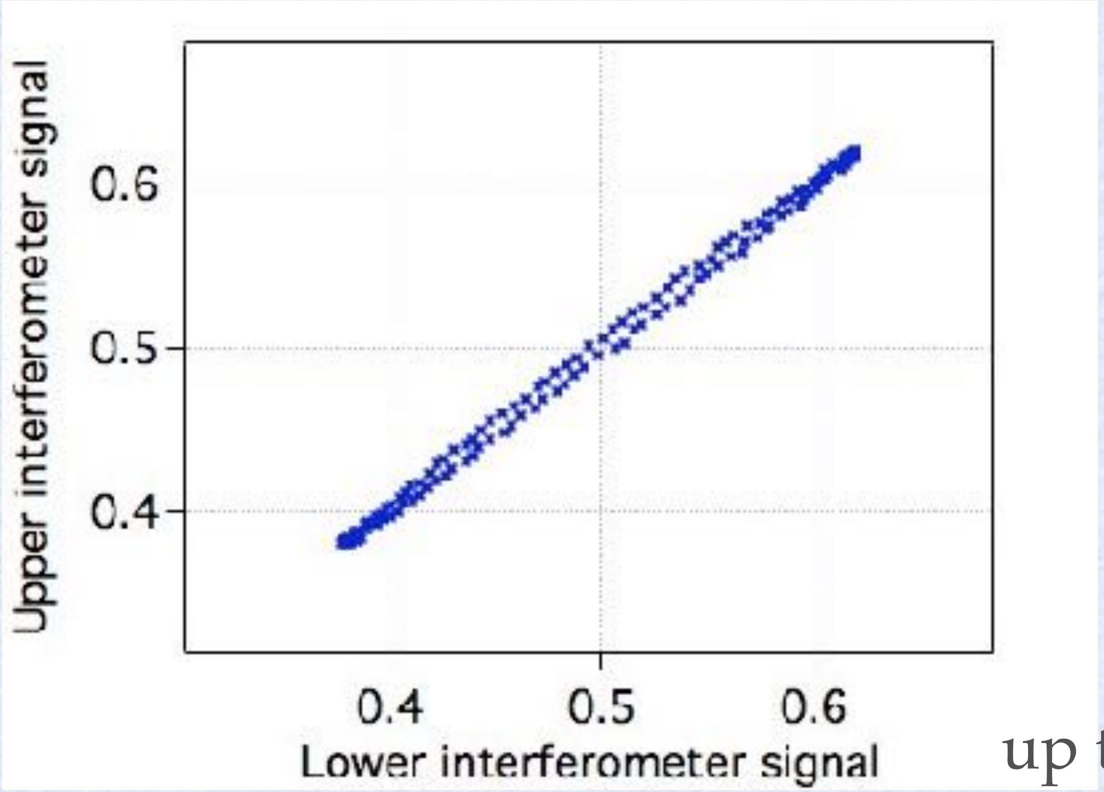


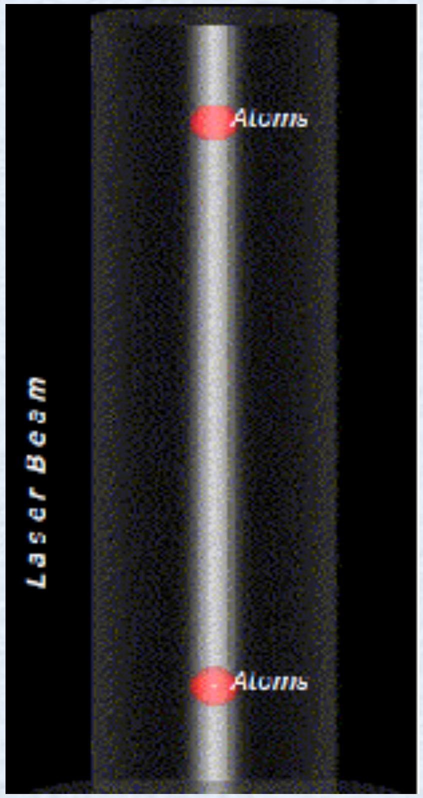
T=50 ms
$\text{resol.} = 1.0 \times 10^{-6} \text{g/shot}$

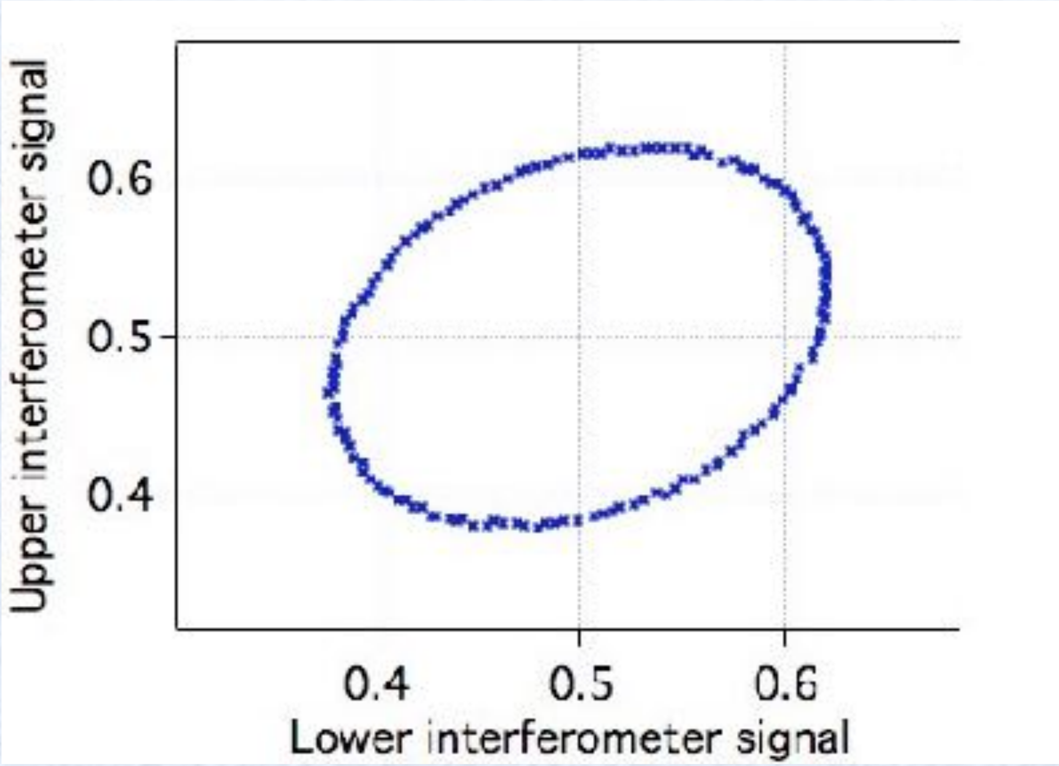


T=150 ms
$\text{resol.} = 3.2 \times 10^{-8} \text{g/shot}$

$$\Delta\Phi = k_e g T^2$$



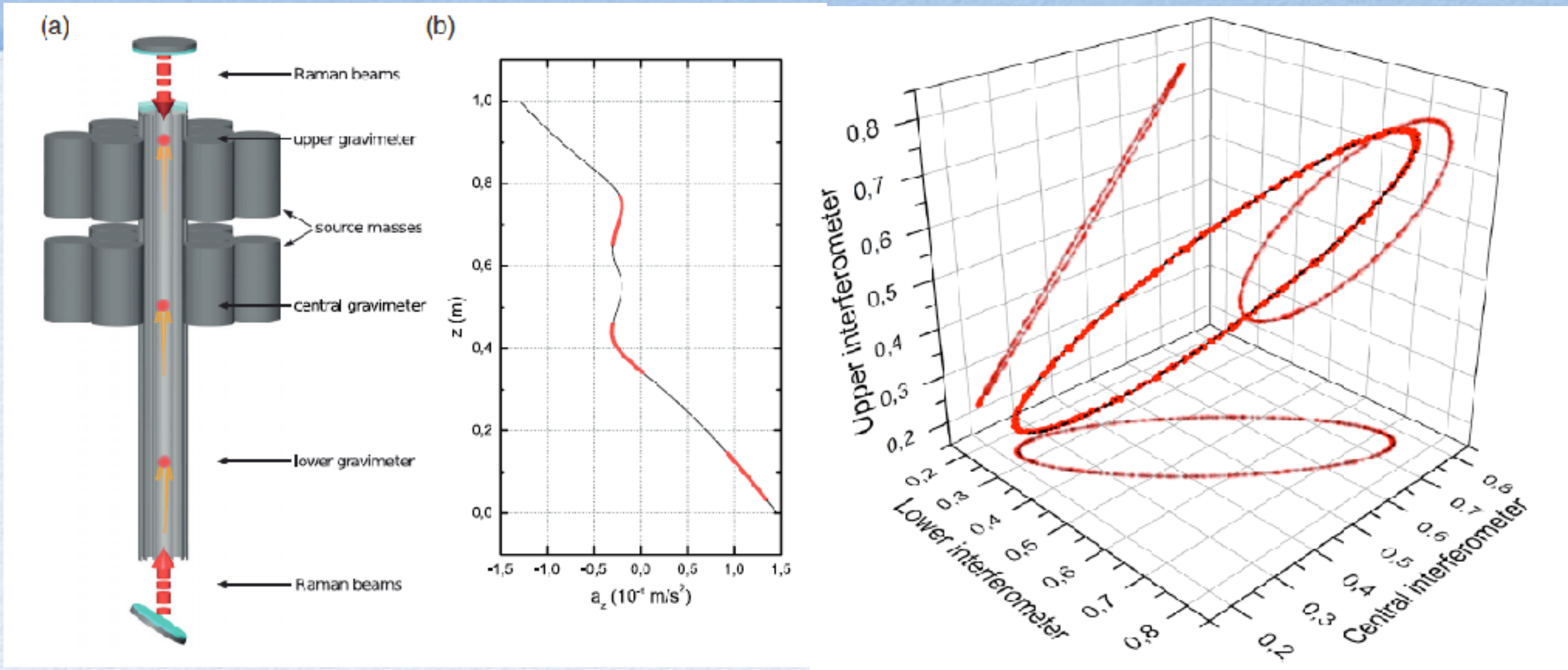




up to 140 dB CMRR with 1 m separation

G. T. Foster et al., Opt. Lett 27, 951 (2002)

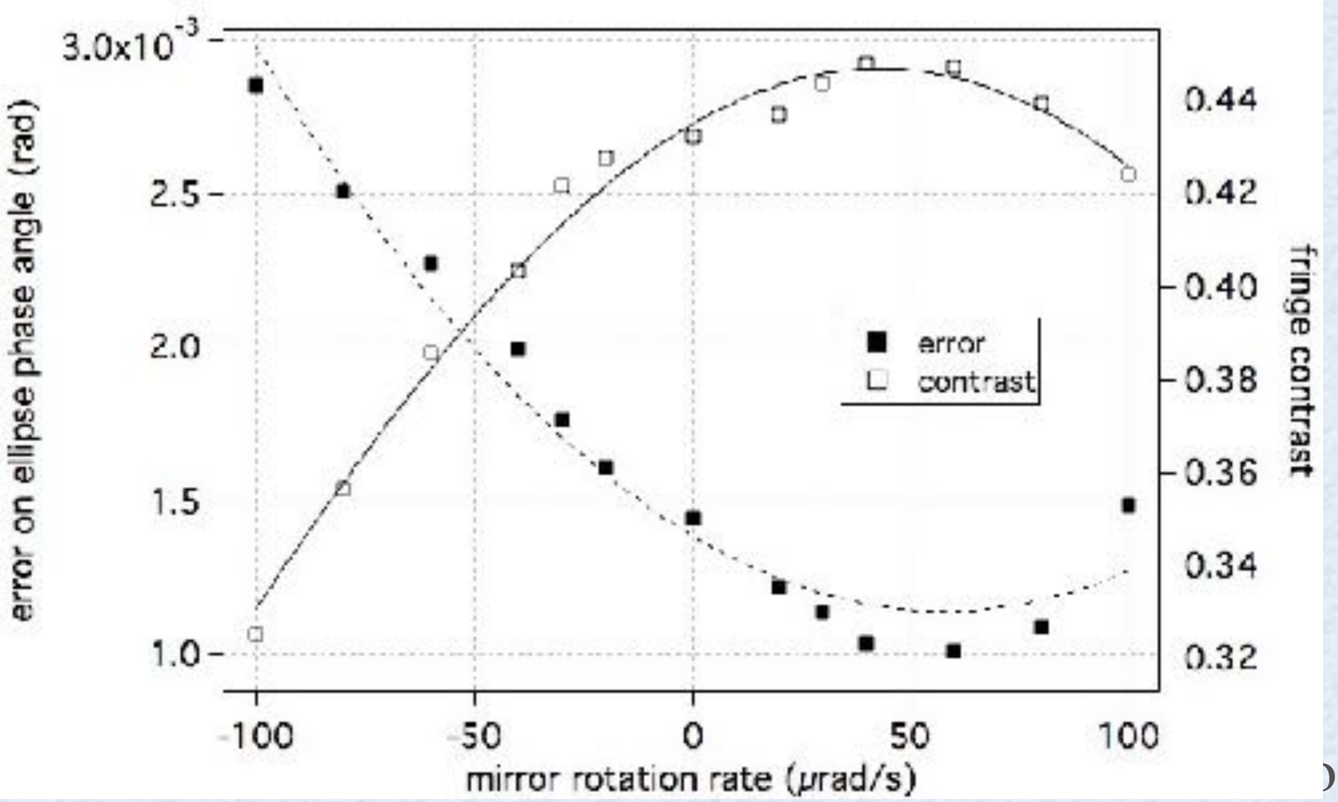
Multiple samples



- Use three atomic clouds to measure the vertical derivative of vertical gravity gradient
  - *G. Rosi et al., Phys. Rev. Lett. 114, 013001 (2015)*
- Scalable to arbitrary large number of samples
- Simultaneous, correlated AI can improve g measurements as well
  - *F. Sorrentino et al., Appl. Phys. Lett. 101, 114104 (2012)*
- Multiple, correlated AIs to mitigate NN
  - *W. Chaibi et al, Phys. Rev. D 93, 021101 (2016)*
- See talk by R. Geiger

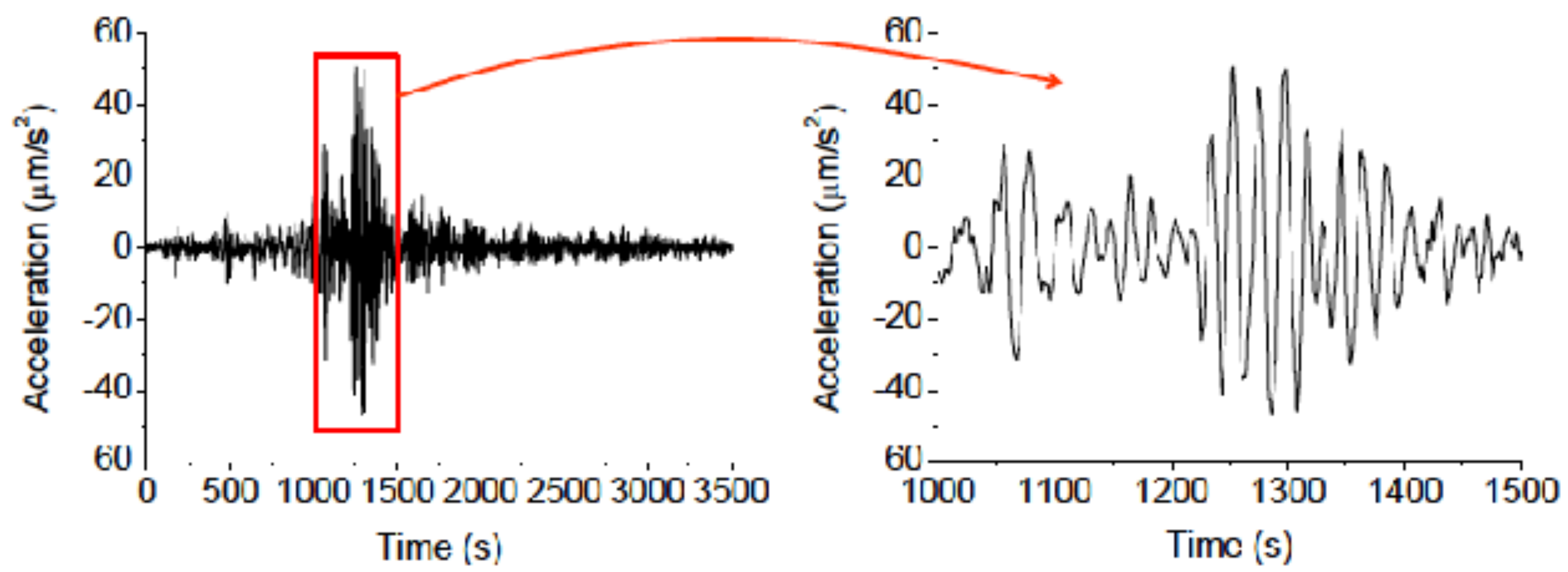
Atomic motion

- AI phase is affected by residual atomic motion
- Velocity spread due to finite temperature
- Shot to shot jitter in initial position and mean velocity
- Atomic motion couples with
  - laser wavefront distribution
  - Coriolis acceleration & higher order inertial effects
  - gravitational and magnetic gradients
- Coupled constraints on atomic temperature, launching velocity, and wavefront jitter
- Limits are particularly stringent for very long baseline (space GW detectors)
- For ground applications, nK temperatures and lambda/100 wavefront errors would be ok

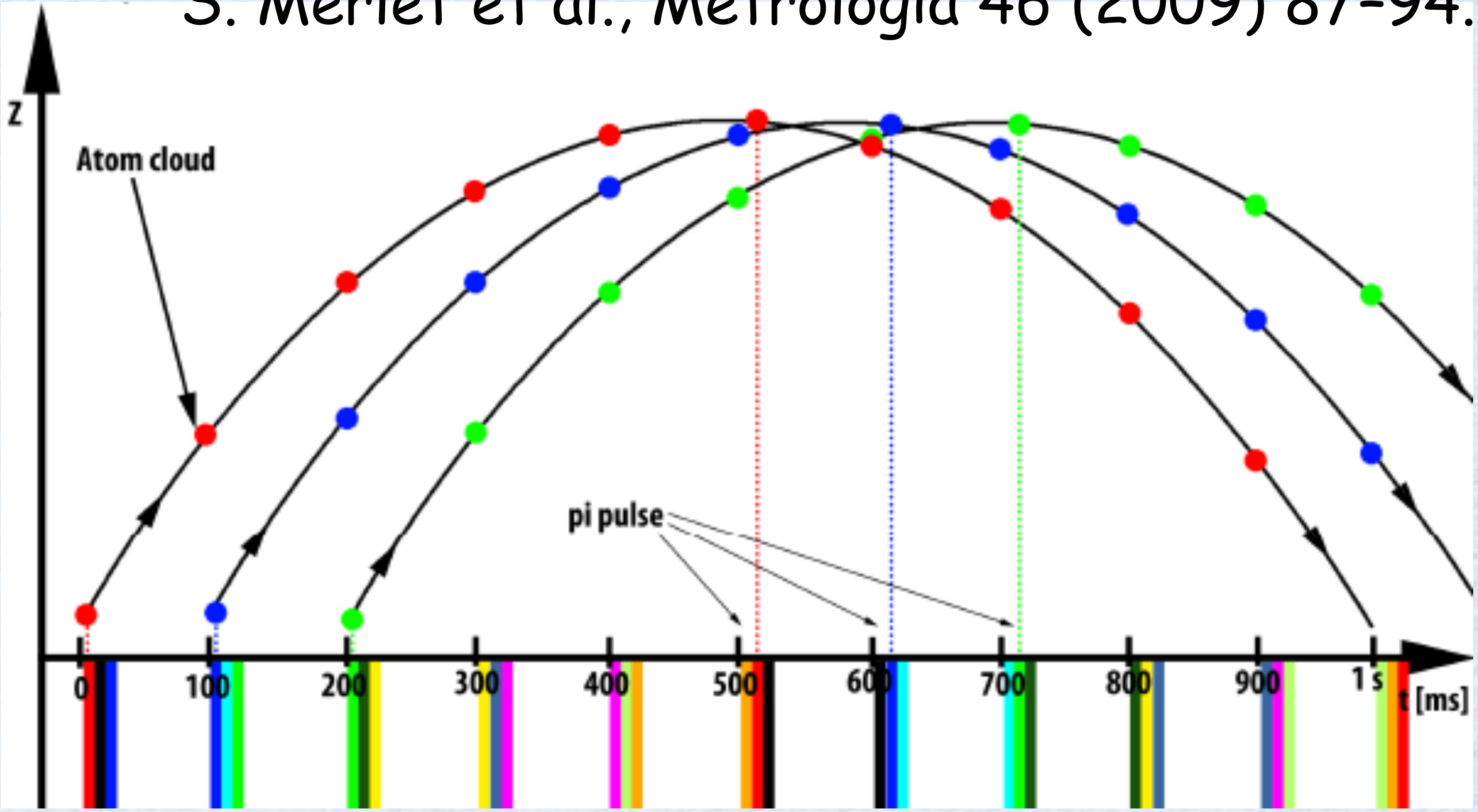


Bandwidth & aliasing

- Sensitivity ~ T^2
- Bandwidth ~ T^{-1}
- Highly sensitive gravimeters detect earthquakes
  - T~50 ms
  - rep rate ~ 5 Hz
- Improving *T* without loosing bandwidth
  - interleaved interferometers
  - main limit: Doppler separation of different channels
  - see e.g. *I. Dutta et al., PRL 116,183003 (2016)*



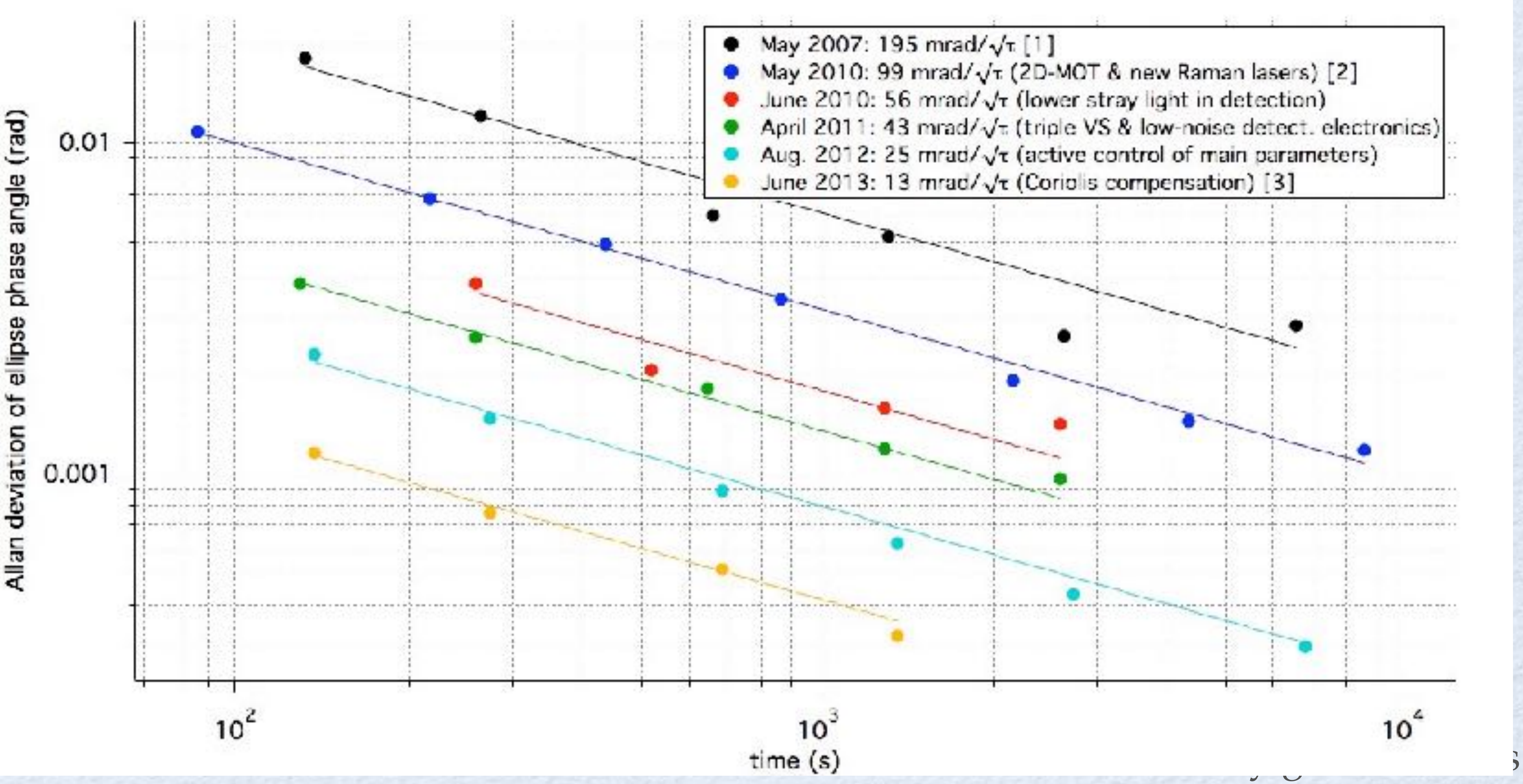
S. Merlet et al., Metrologia 46 (2009) 87–94.



Technical noise sources

- magnetic fields
- stray light
- photon shot noise
- tilt noise

[1] G. Lamporesi et al., Phys. Rev. Lett 100, 050801 (2008)
[2] F. Sorrentino et al., New J. Phys. 12, 095009 (2010)
[3] F. Sorrentino et al., Phys. Rev. A 89, 023607 (2014)



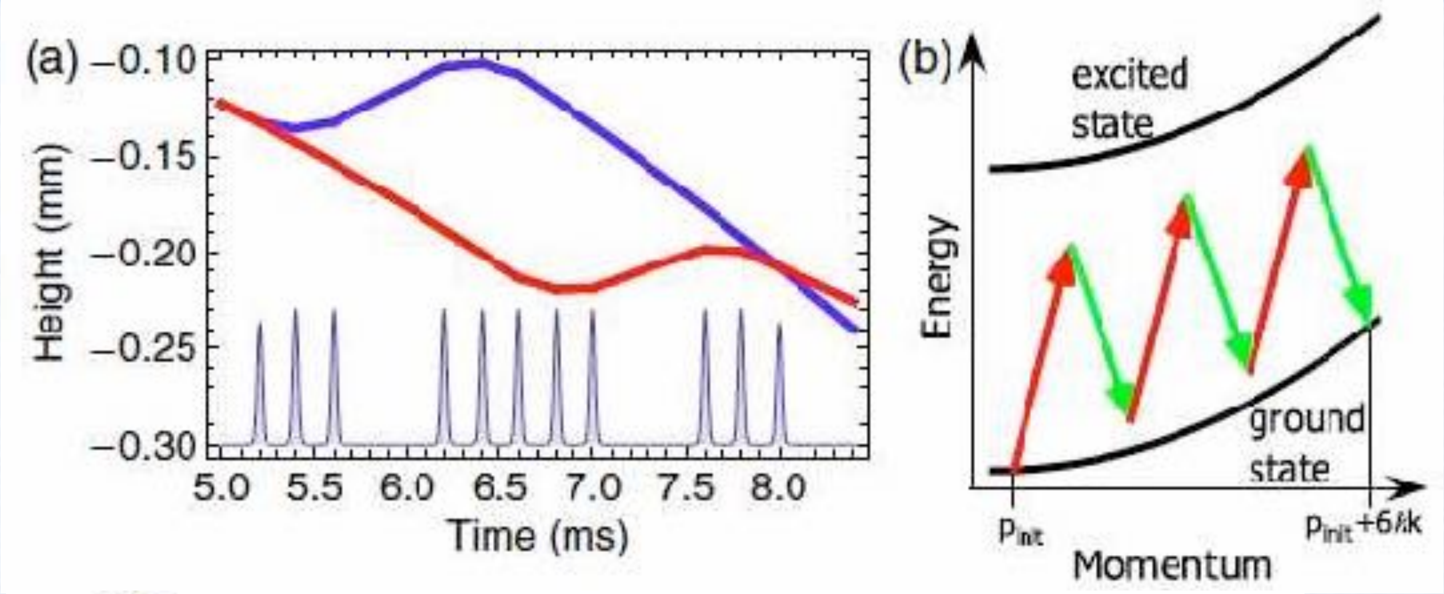
Potential improvements

Single-shot, quantum noise limited gradiometer sensitivity

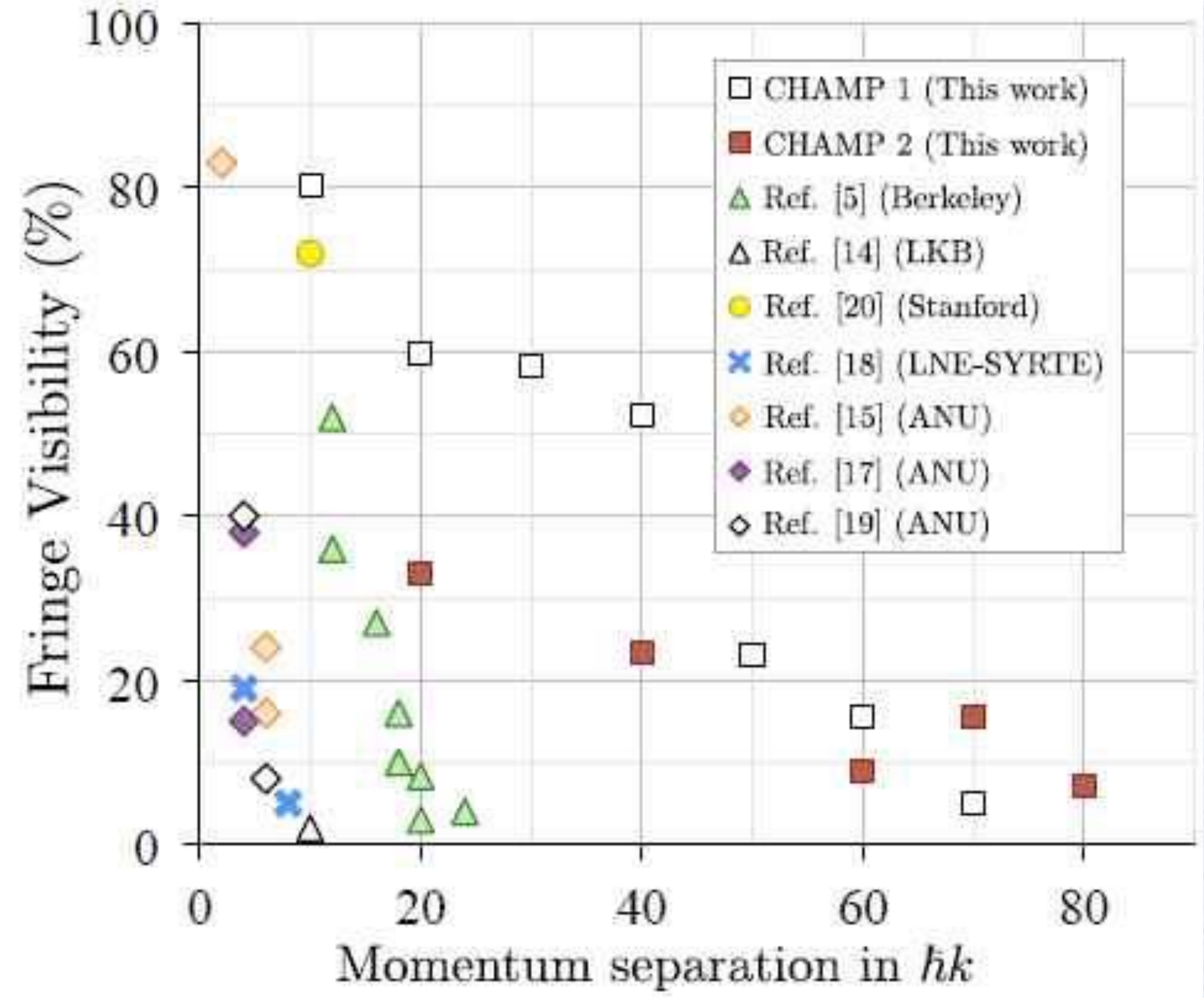
$$\delta\nabla g = \frac{\delta\phi}{nkLT^2}$$

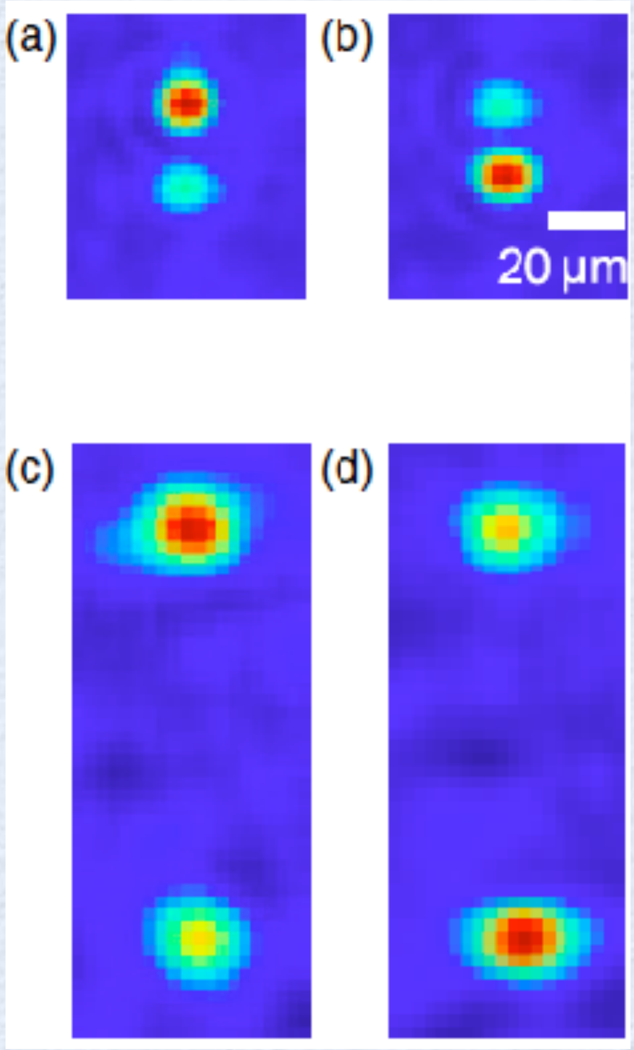
- Increasing the scale factor
  - Large momentum transfer splitters (increase *nk*)
  - Large scale AI (increase *T*)
  - Long baseline (increase L)
- Reducing phase noise
  - High flux atomic sources (reduce quantum noise)
  - Squeezing (phase noise below standard quantum limit)
- Choice of atomic species
- Interferometer topology

Large momentum transfer beam splitters



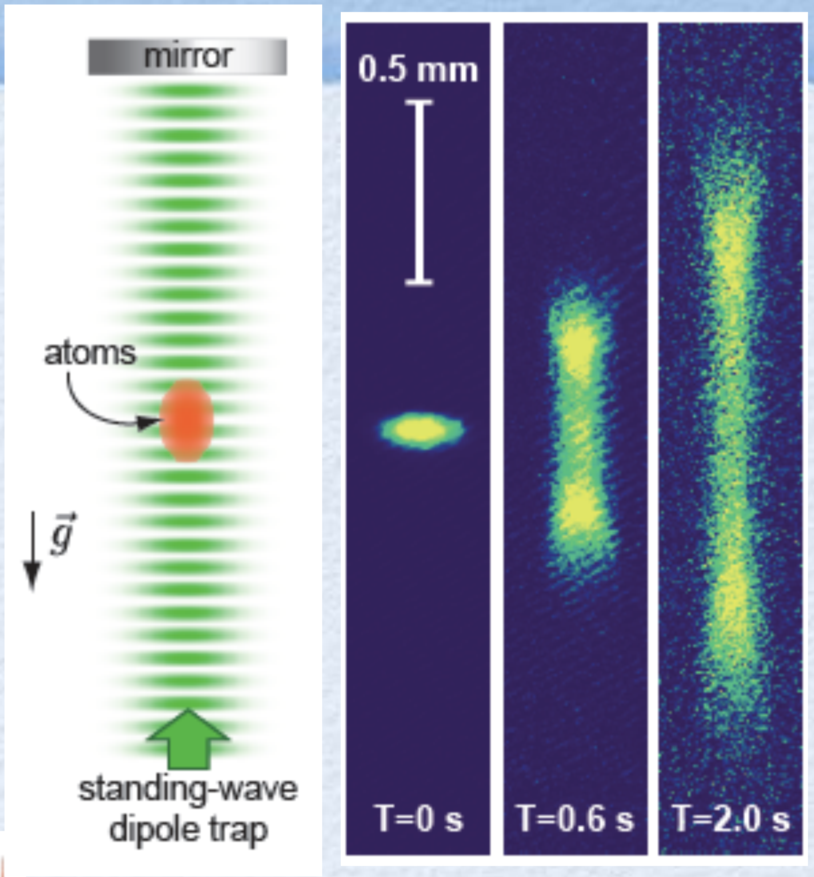
- H. Müller et al., PRL **102**, 240403 (2009)
- S.-W. Chiow et al., PRL **107**, 130403 (2011)
- G. D. McDonald et al., PRA **88**, 053620 (2013)

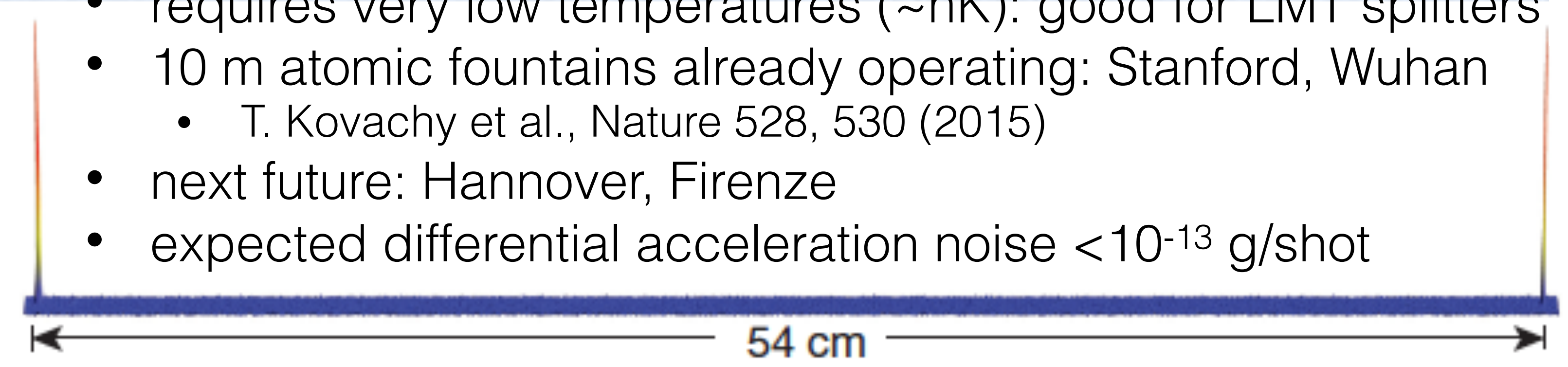


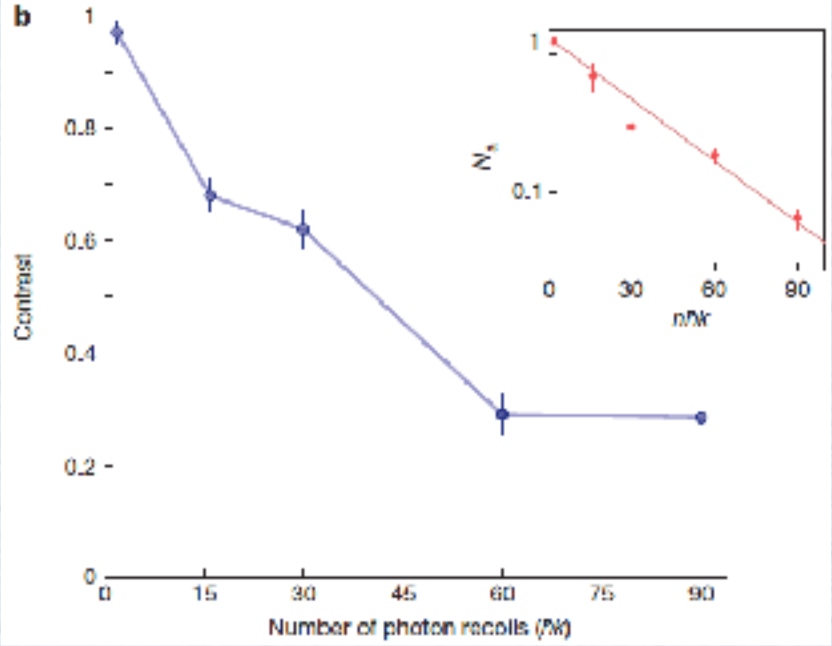


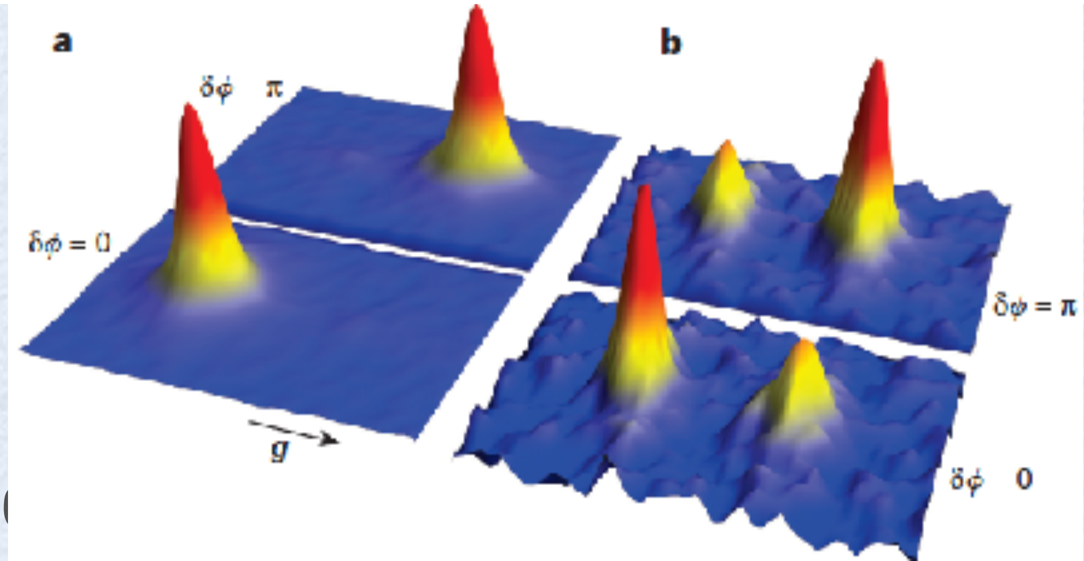
Long interaction time

- Microgravity: in principle $T>10$ s
- Increasing T on Earth
  - trapped atoms (Sr)
    - up to 15000 coherent photon recoils
    - decoherence time >500 s
      - *G. Ferrari et al., PRL 97, 060402 (2006)*
      - *V. V. Ivanov et al., PRL 100, 043602 (2008)*
      - *F. Sorrentino et al., Phys. Rev. A 79, 013409 (2009)*
      - *M. Tarallo et al., PRA 86, 033615 (2012)*
  - free fall
    - requires large vertical size
    - requires very low temperatures (~nK): good for LMT splitters
    - 10 m atomic fountains already operating: Stanford, Wuhan
      - T. Kovachy et al., Nature 528, 530 (2015)
    - next future: Hannover, Firenze
    - expected differential acceleration noise $<10^{-13}$ g/shot



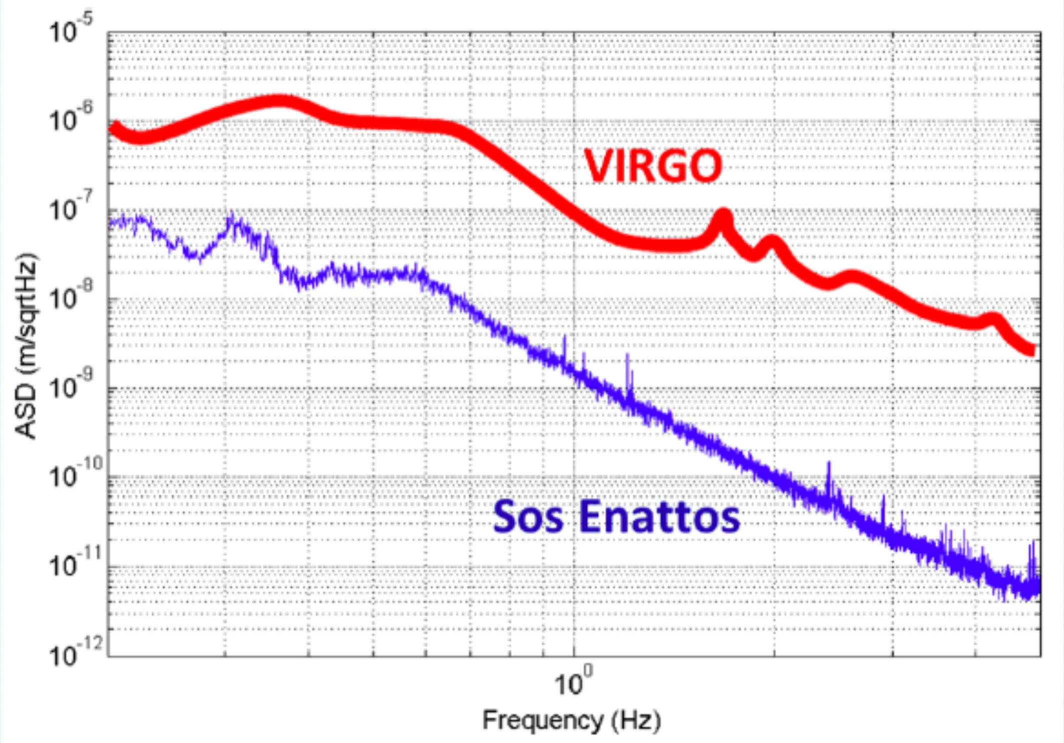


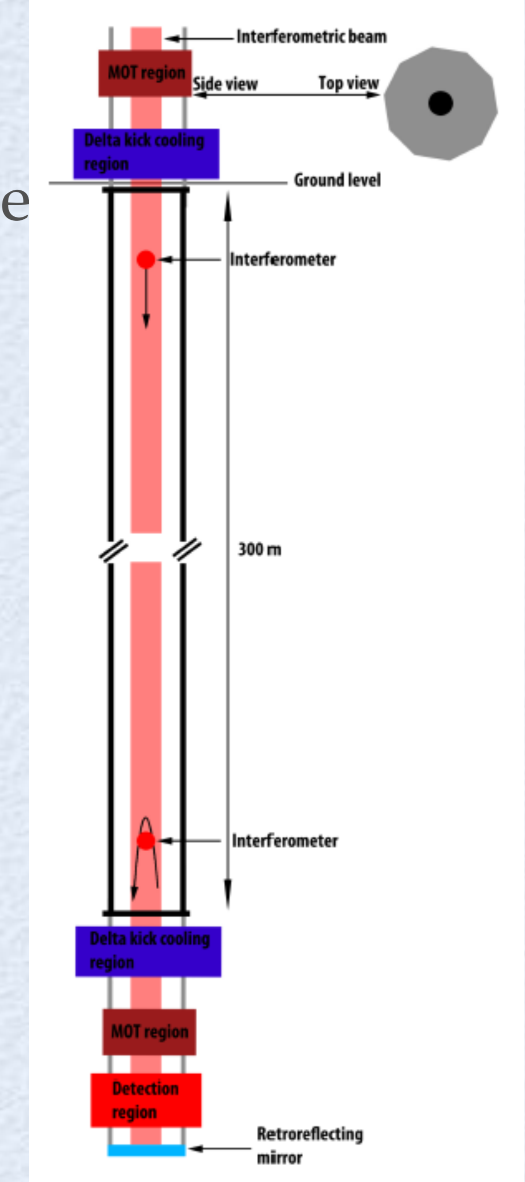




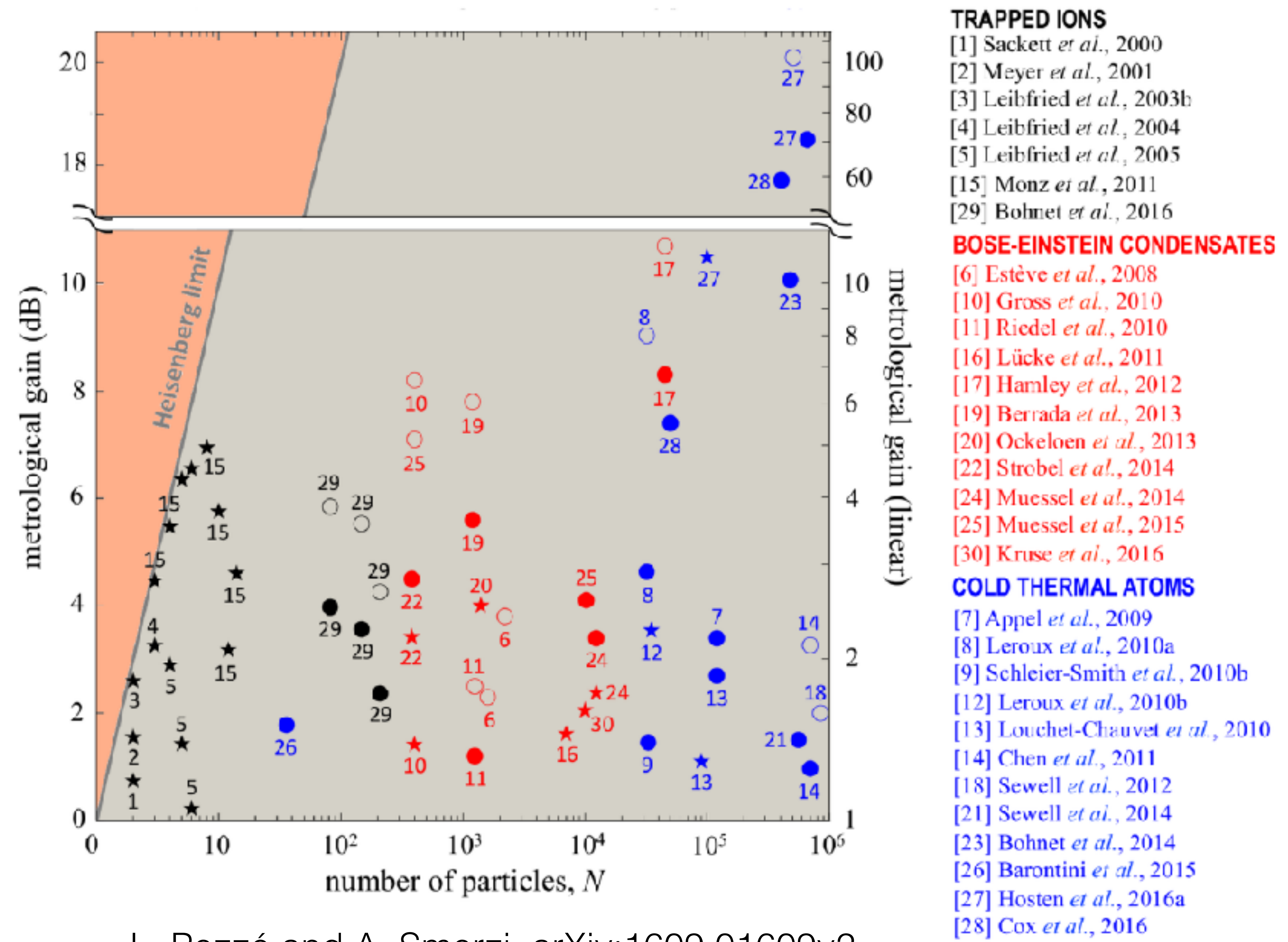
Long baseline

- CMRR for seismic noise will be maintained when increasing the baseline L
- proportional improvement on gradiometer sensitivity, different projects to reach L~1 km
  - long horizontal baseline L (MIGA, see talk by R. Geiger)
  - long vertical baseline: large L and large T
    - MAGIA Adv: plan to install a differential atom interferomete in a decommissioned carbon mine in Sardinia
    - vertical shafts available up to 500 m
    - microseism in Sardinia is extremely low





Squeezing



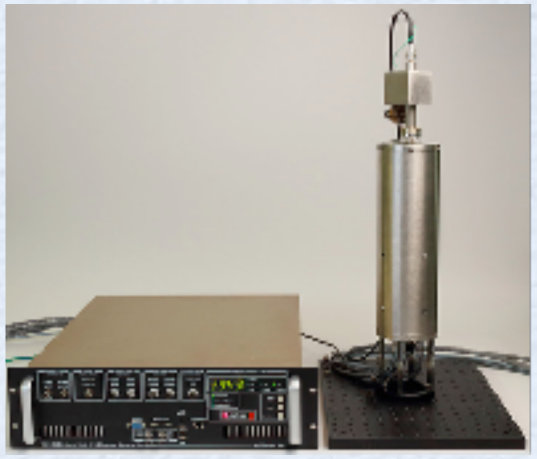
L. Pezzé and A. Smerzi, arXiv:1609.01609v2

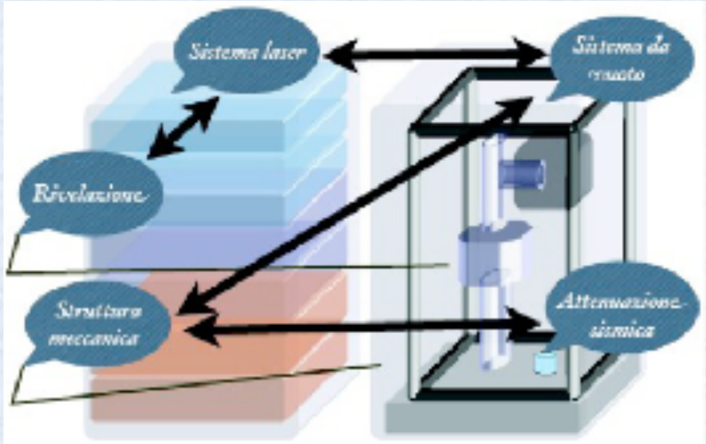
Summary on AI gradiometer sensitivity

- Best demonstrated performance of a gravity gradiometer:
  - small scale instrument (MAGIA, 1 m fountain, 30 cm baseline): ~30 E @ 20 s [*F. Sorrentino et al., Phys. Rev. A 89, 023607 (2014)*]
  - medium scale instrument (Stanford 10 m tower, 30 cm baseline): ~3 E @ 20 s [*P. Asenbaum et al., Phys. Rev. Lett. 118, 183602 (2017)*]
- Differential acceleration sensitivity of a large vertical gradiometer
  - interaction time *T*
  - *n* photon recoils
  - 10^6 atoms at QPN -> phase noise 1 mrad/shot
  - contrast C
  - distance between atomic clouds L
- Realistic projection for
  - medium baseline, long T: L=10 m, n=30, T=1.5 s, C=0.6 -> 0.2 mE @ 10 s
  - long baseline, long T: L=300 m, n=100, T=3 s, C=0.6 -> 0.6 µE @ 10 s
- Substantial improvement expected with squeezing (long term plan)

Technology readiness

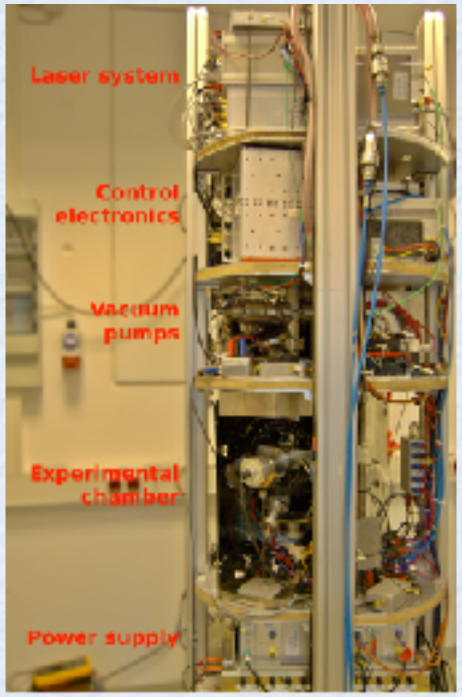
- Commercial atomic gravimeters & gradiometers
  - MuQuans (France)
  - AOSense (USA)
  - AtomSensors (Italy)

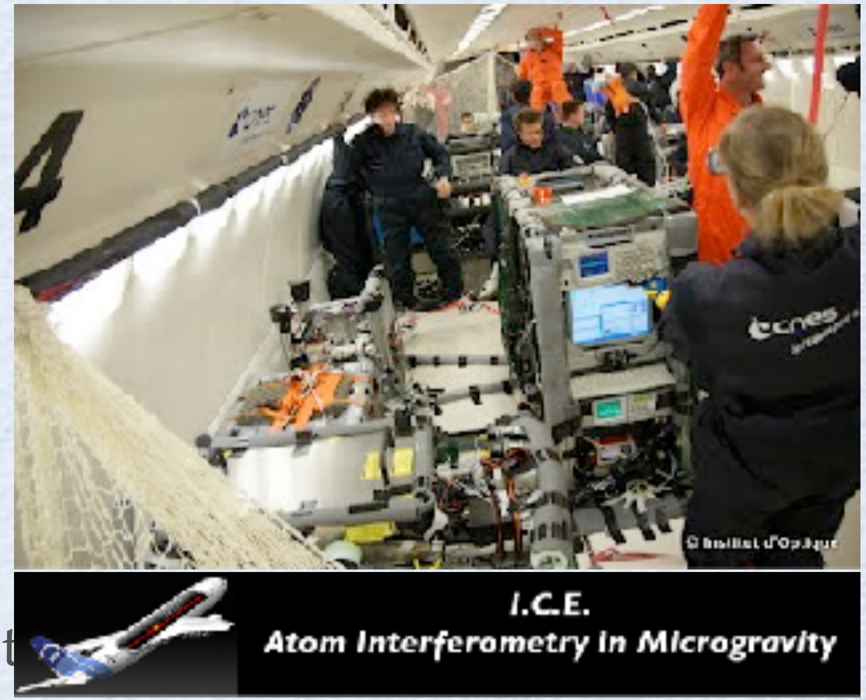




- Prototypes for microgravity
  - I.C.E. (CNES)
  - QUANTUS/MAIUS (DLR)
  - S.A.I. (ESA)

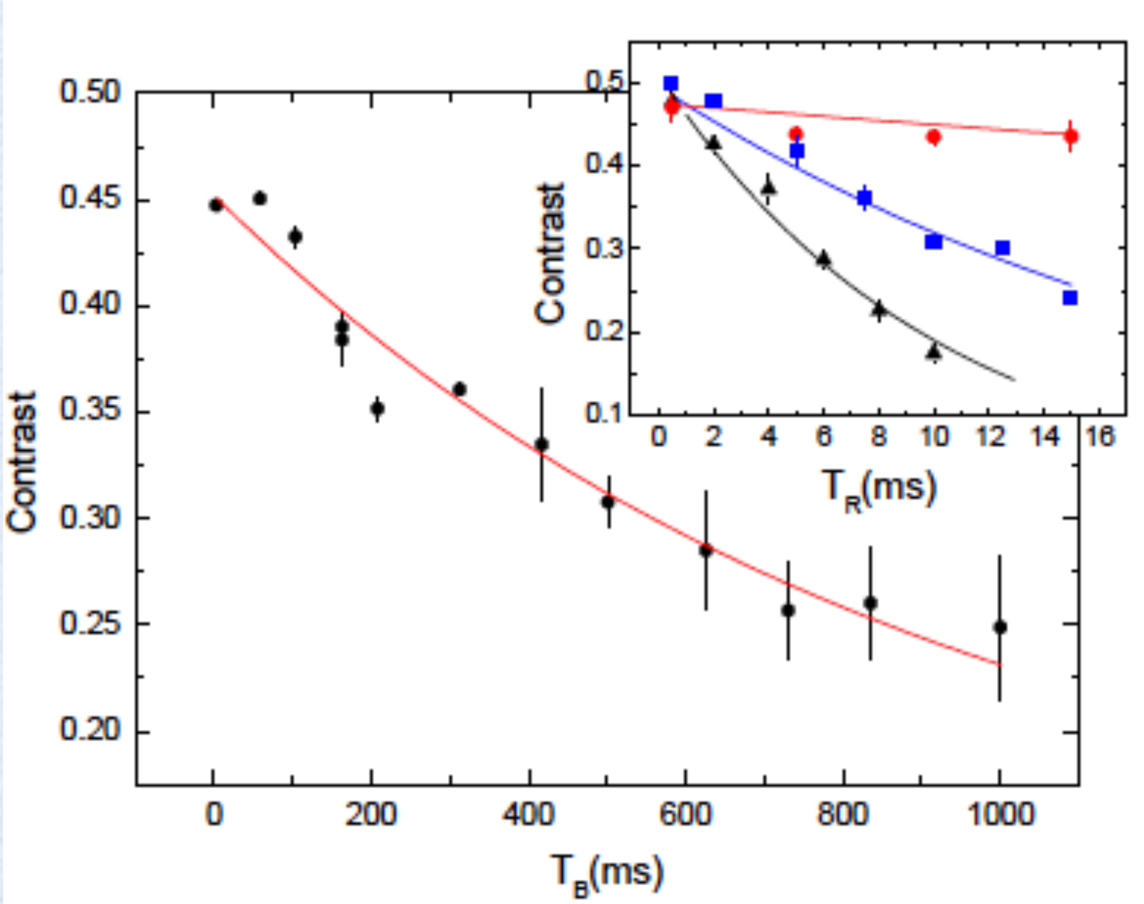
G. Tino et al., Precision Gravity Tests with Atom Interferometry in Space, Nuclear Physics B 243, 203 (2013)

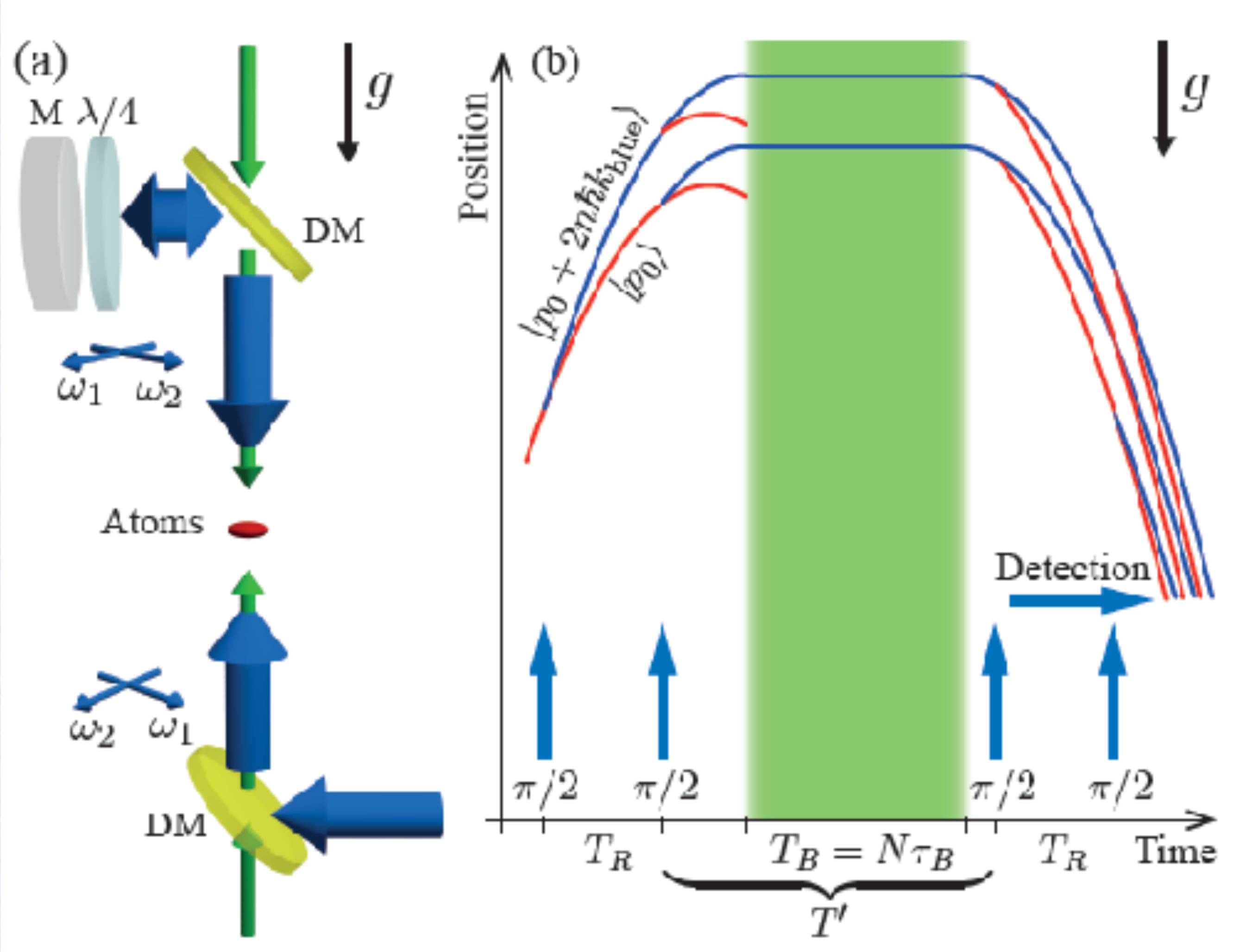




Combination of trapping & free fall

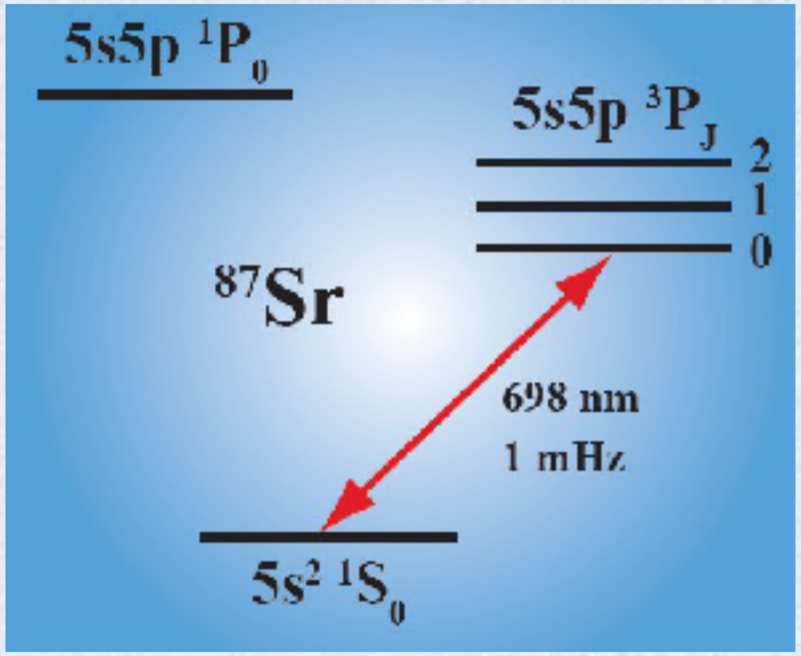
- LMT splitter + free fall to spatially separate interferometer arms
- Proof of principle demonstration with Rb
  - limited to T~0.1 s due to decoherence
  - R. Charrière et al., PRA 85, 013639 (2012)
- Up to T=1 s using Sr
  - X. Zhang et al., PRA 94, 043608-1 (2016)

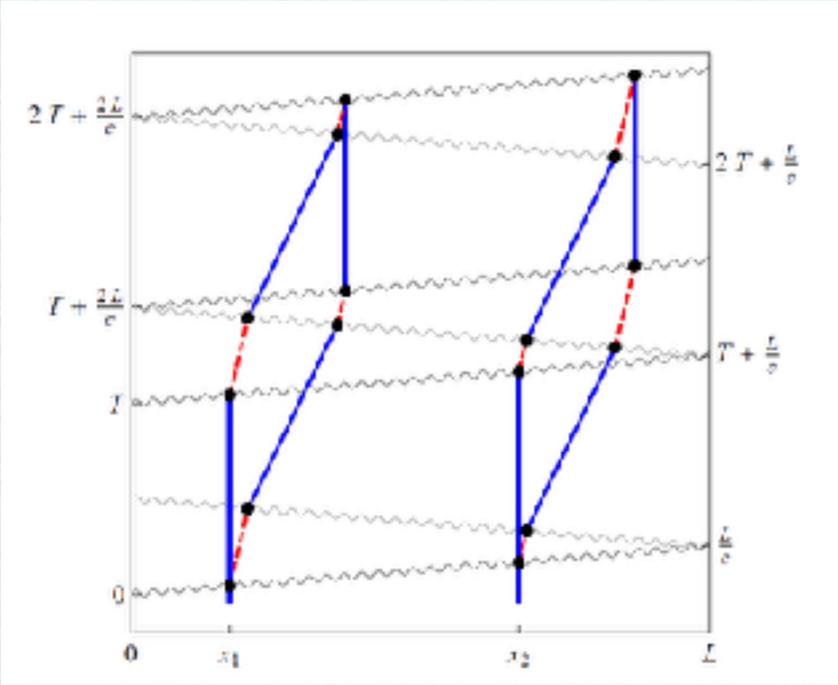


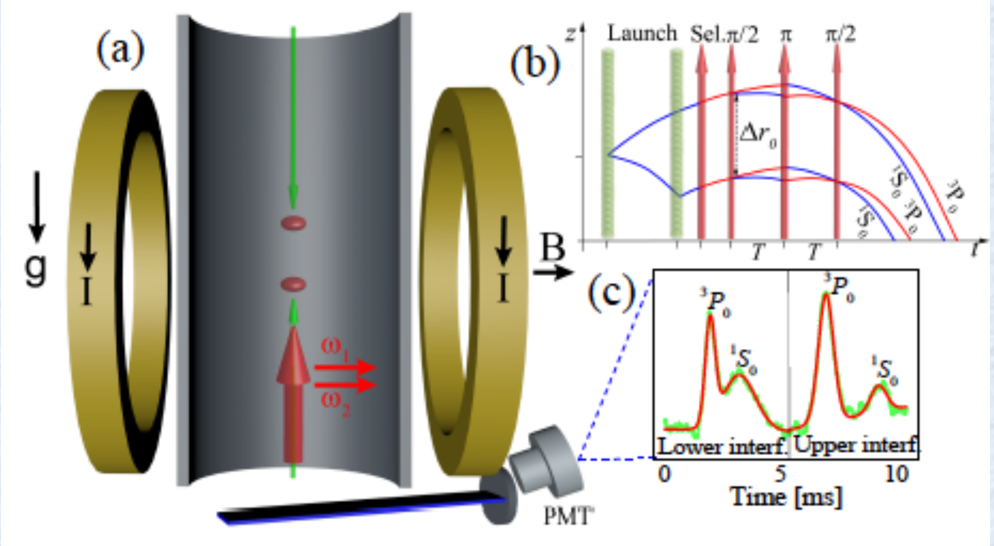


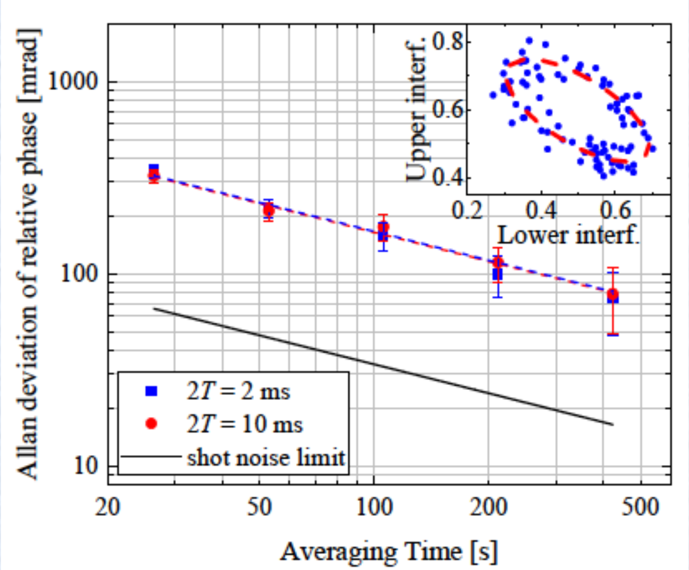
Single photon interferometry with Sr

- Cancellation of frequency noise in long-baseline interferometry
- Proposed for GW detection in space
  - *P. W. Graham et al., PRL 110, 171102 (2013)*
- Experimentally demonstrated on small baseline
  - *L. Hu et al., PRL 119,* ***263601*** *(2017)*



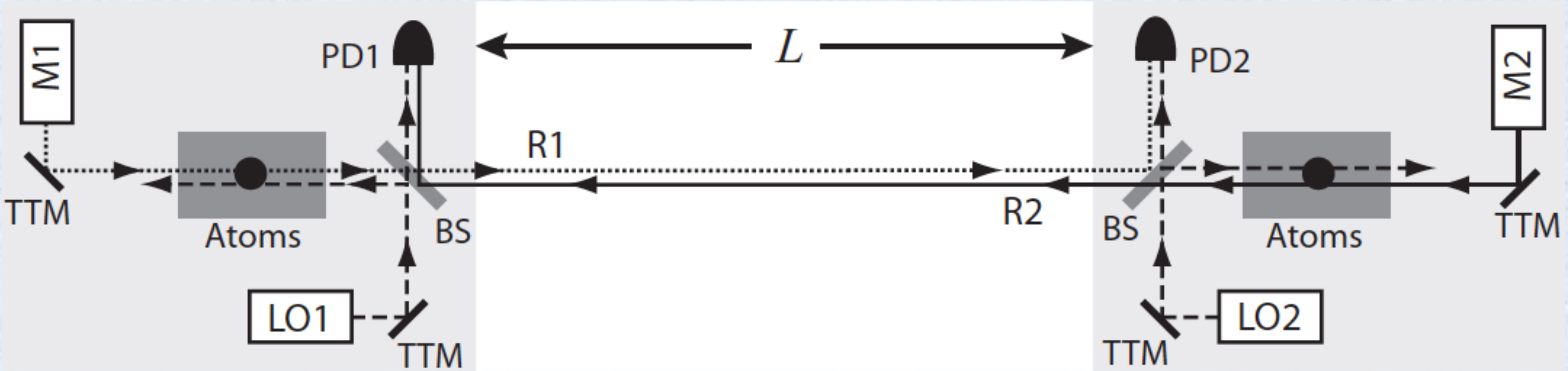






Fiber network

- Fiber Linked Atom-Interferometry Gravity Sensors (FLAGS)
  - *F. Sorrentino et al., to be published*
- gradiometer via coherent link between distant AI gravimeters
  - already proposed for GW detection with free-space links [*J. M. Hogan and M. A. Kasevich, Phys. Rev. A 94, 033632 (2016)*]
- two-way phase noise cancellation is routinely applied to optical frequency dissemination with residual phase noise at the level of ~0.1 rad rms over ~100 km
- trade off phase noise for much longer gradiometer arm
- in principle sub-mE/√Hz at reach with medium/small AI setups using state of the art technologies
- scalable to a network of many coherent AI gravity sensors



Conclusions

- State of the art of AI gravity gradiometers
  - demonstrated sensitivity at ~10 E/√Hz level
  - compact (mobile) sensors already available
- Further improvements expected in near future
  - long baseline
  - long T
  - squeezing
- realistic projection at
  - ~mE/√Hz level with mid-size sensors (10 m fountain)
  - ~μE/√Hz level with large scale antennas (1 km baseline)
- promising schemes for 10÷100 improvement over current sensitivity with small-scale sensors