A table-top gravitational wave detector based on Bose-Einstein condensates ?

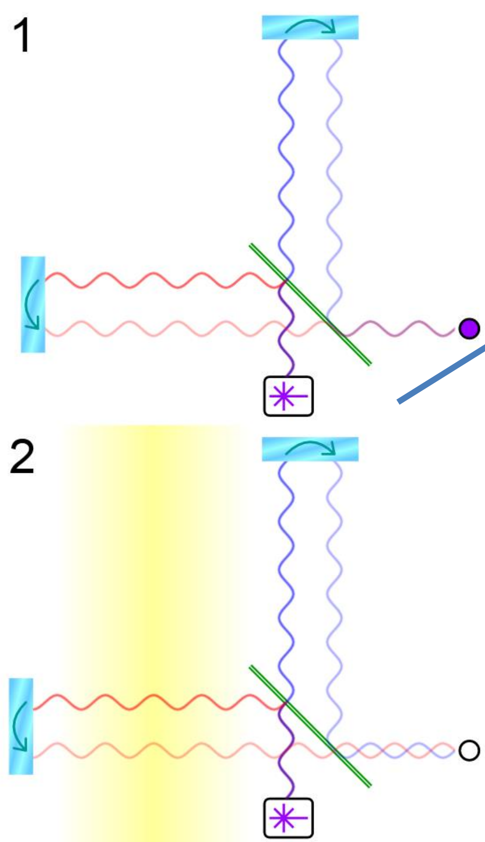
Mihail Antoniu Iliescu,

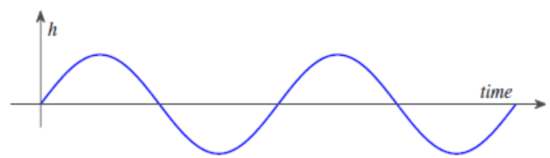
Hitchhiker's Advanced Guide to Quantum Collapse Models *Frascati, November 2022*

Interferometric Gravitational Wave detectors

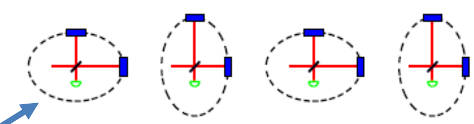
September 14th, 2015 - First GW detection with LIGO/VIRGO of a merge event of 36 and 29 solar masses black holes -> spinning black hole of 62 solar masses (3 SM radiated in GW @1 billion ly distance)

The ripple in spacetime changed the length of a 4 km LIGO arm with~10^{-18} m, 1/1000 the size of a proton

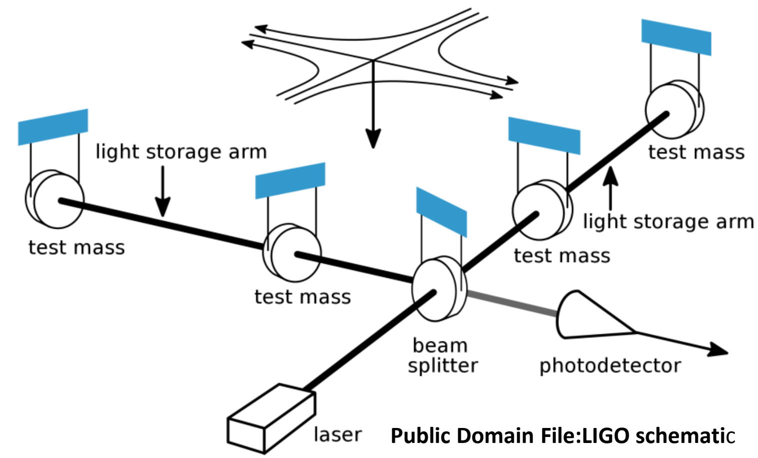




+ Polarized quadrupole radiation



B.P.Abbot et. al,Rep. Prog. Phys. 72 (2009) 076901



Public Domain File:LIGO schematic

$\Delta L(t)/L = F_+S_+(t) + F_xS_x(t) \equiv S(t)$
(L-arm length, F-direction coefficients, S-GW strain)

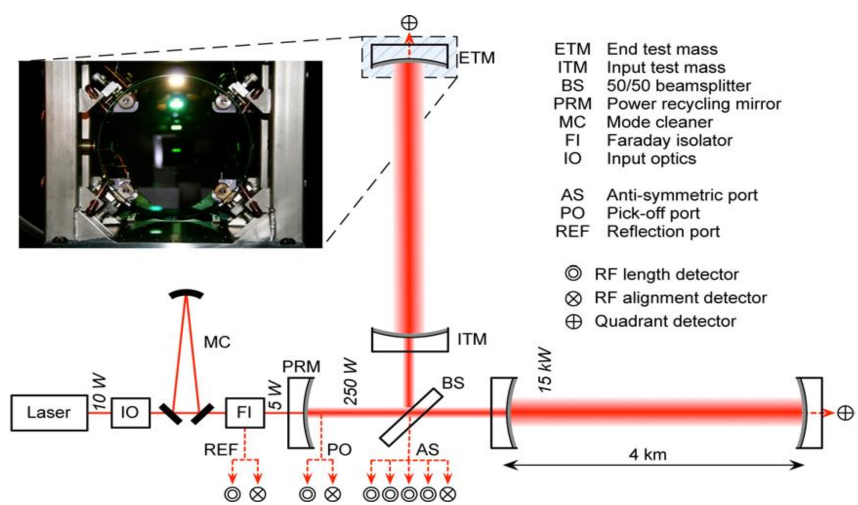
$\Delta\Phi \approx N \cdot \Delta L/\lambda = S \cdot R \cdot L/\lambda$
L-arm length, R-reflections

$S_{min} \approx \lambda / (L \cdot R\sqrt{N})$, ($\sqrt{N}$-shot noise)

Storage time=R·L/c ≤ ½ GW period

R~400 (100 Hz), N=2x10^{20} ph/10ms
(integration time)

$S_{min} \approx 10^{-23}$



B.P.Abbot et. al,Rep. Prog. Phys. 72 (2009) 076901

Current developments in Interferometric Gravitational Wave detectors

LIGO-VIRGO-KAGRA have a useful band between 10 Hz and 10 KHz

Access to lower band requires a space-born interferometer (NASA-ESA project LISA)

Enhanced sensitivity addressed by terrestrial projects like

- **Advanced LIGO/VIRGO (implemented)**
- **the next generation, 40 km-baseline Cosmic Explorer**
- **large underground facilities like Einstein Telescope**
- **large scale atom interferometers like ELGAR (16 + 16 km, 160 atom interferometric stations) (covers the mHz-Hz band gap between LIGO and LISA)**

Issues:

- **Huge infrastructures requiring big investments**
- **Cannot be deployed all around the globe**
- **Sensitivity lobes, require combined observation to narrow the source solid angle detection**
- **Hard to reach Real Time correlation with other observatories (gamma, optical, X-ray, neutrino) for investigating the first seconds evolution of hypernovae or similar events**

Can a GW interferometer be "table top"?

Storage time=R·L/c ≤ ½ GW period

Until now, most of the development addressed the baseline.
(length, number of reflections)

Can we act (efficiently) on the light propagation speed?

Developments in large group index materials

In 1991, the electromagnetic induced transparency (EIT) demonstrated an increase of the transmittance from exp(-20) to exp(-1) in a gas of Sr atoms; successively, in 1994 it was shown the resulting group velocity in a Pb gas was c/165.

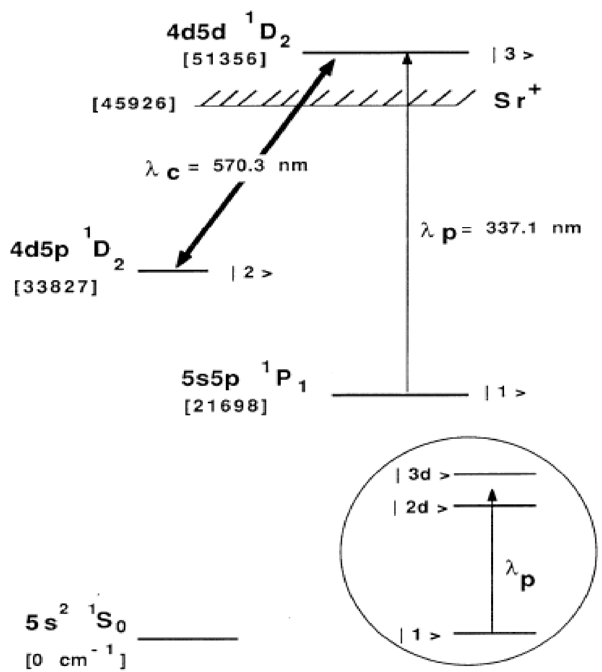


FIG. 1. Energy-level diagram of neutral Sr. Inset: Dressed-state picture.

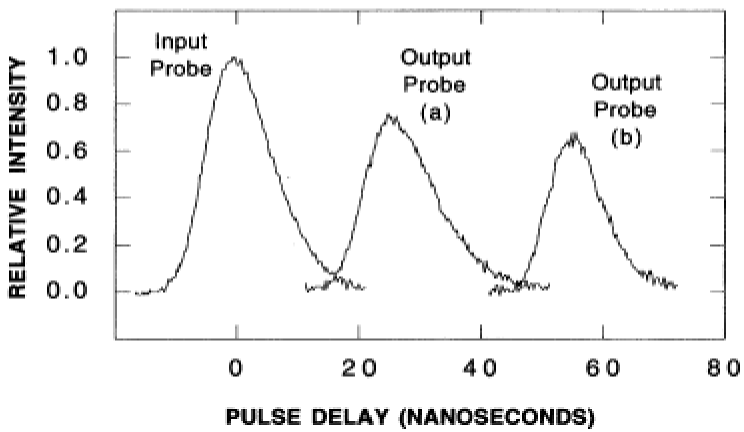


FIG. 2. Transmission vs pulse delay in a 10-cm-long ^{208}Pb cell [$N = (1.6 \times 10^{14}) \pm 30\%$ atoms/cm^3]. The pulse is shown at both the cell input and the cell output. For each pulse the peak probe Rabi frequency is 0.02 cm^{-1}. For pulse (a), as the probe pulse slips through the coupling laser pulse, Ω_c increases from 0.18 to a peak of 0.2 and then falls to 0.18 cm^{-1}. For pulse (b), Ω_c increases from 0.11 to 0.15 and then falls to 0.14 cm^{-1} (i.e., the probe spends most of its time on the rising edge of the coupling laser wave form). Pulse (b) corresponds to a group velocity of $c/v_g = 165$ and 55% energy transmission.

$$\tau_{\text{delay}} = L(1/v_g - 1/c)$$

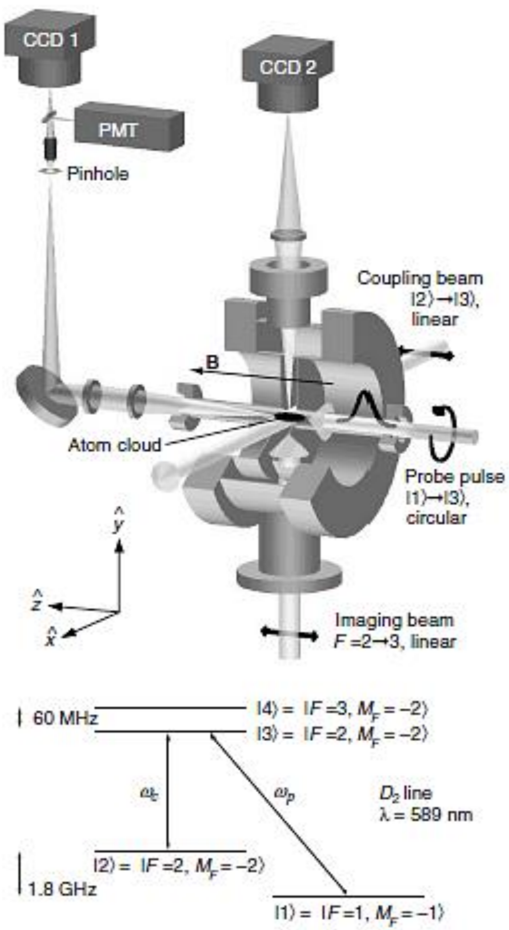
Original excitation scheme of K.-J. Boiler, A. Imamoglu, and S. E. Harris
Phys. Rev. Lett. 66, 2593 (1991)

First "slow light" A. Kasapi, M. Jain, G. Y. Yin, and S. E. Harris,
Phys. Rev. Lett. 74, 2447 (1995)

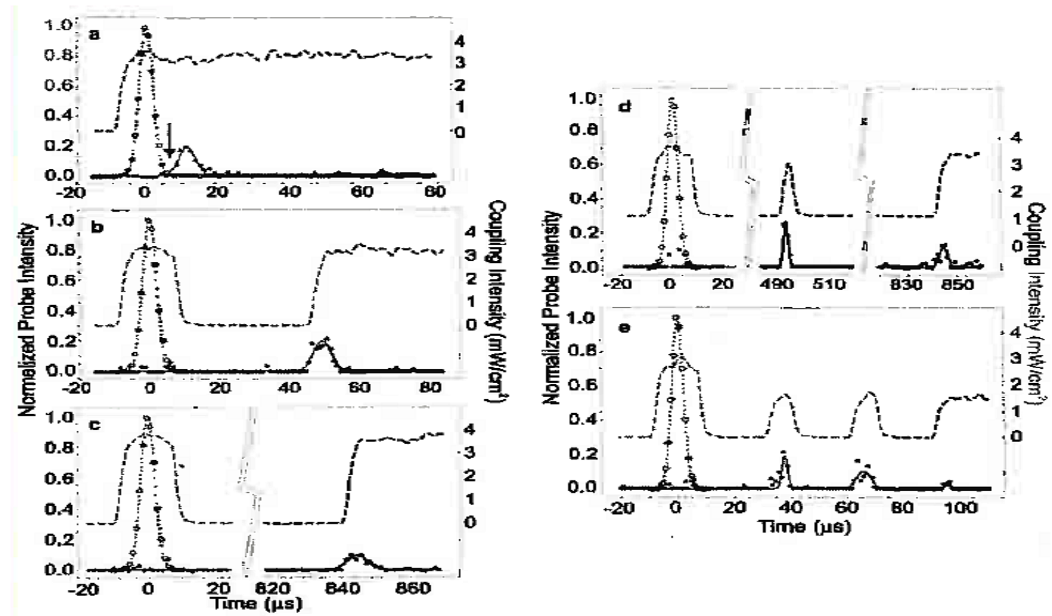
Developments in large group index materials

Two years after, in 1997, the EIT was applied to Bose Einstein Condensates (BEC) with the spectacular result of propagating a 1 km long (in vacuum) light pulse in a Na BEC with a speed of 17 m/s, compressed and completely contained in 50 μm of condensate.
The experiment was later reproduced by D. F. Philips et al., Phys. Rev. Lett. 86, 783–786 (2001)

In a second step it was proved the light pulse (converted to matter wave, propagating as solitons) can be slowed down at will and even stopped for a short time (tens to hundreds of μs) then restarted, while conserving the full information in a "hologram pattern" which can also be altered/processed during the "freezing" time.



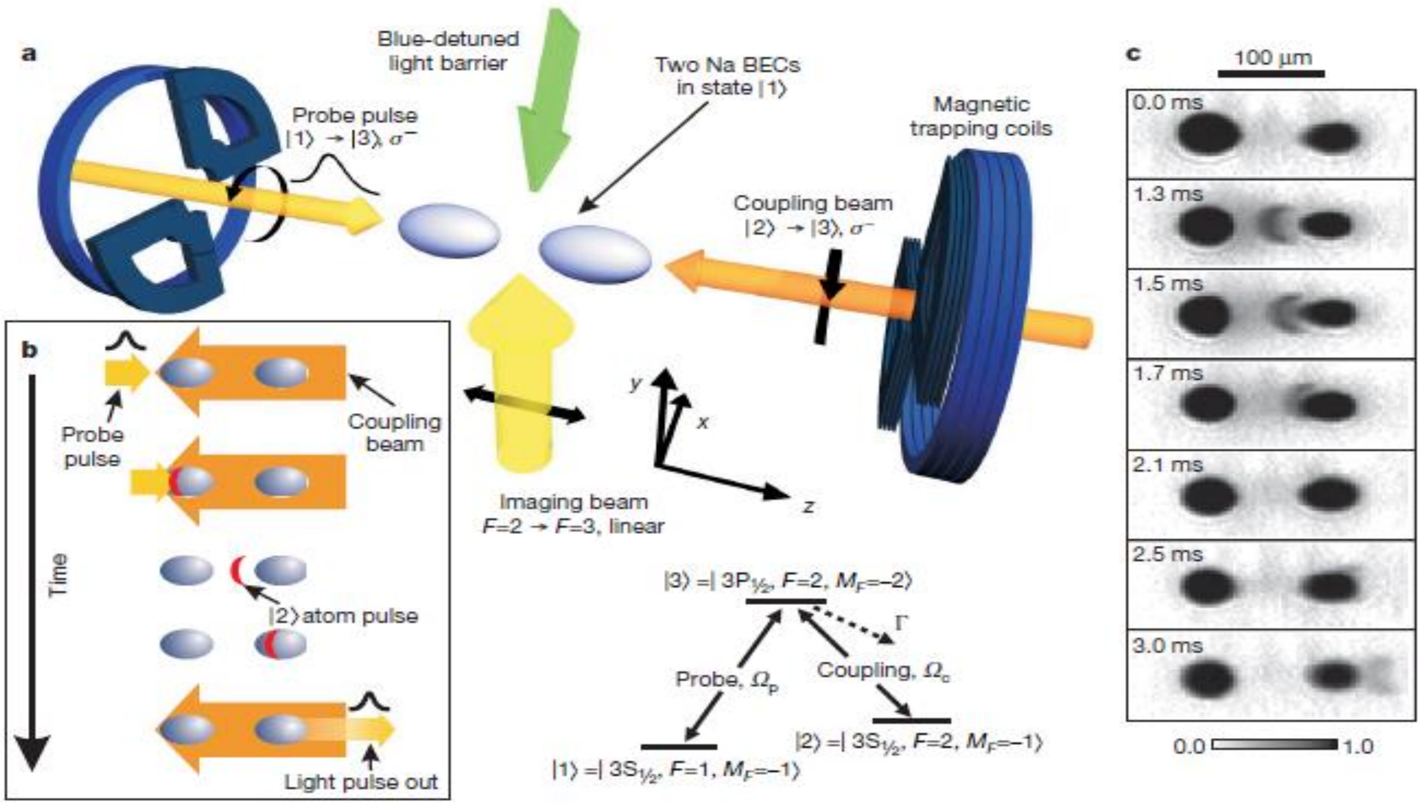
Setup and EIT excitation scheme used by
L. V. Hau, S. E. Harris, Z. Dutton, & C. H. Behroozi, Nature 397, 594–598 (1999).



The art of taming light: ultra-slow and stopped light
Z. DuttonI , N. S. Ginsberg, C. Slowe & L. V. Hau
Nature 445, 623–626 (2007).

Developments in large group index materials

Successively, the coherent control of optical information with matter wave dynamics was demonstrated for a system with two condensates.



Information transfer between two BECs. Naomi S. Ginsberg, S. R. Garner & L. V. Hau Nature 445, 623–626 (2007).

Interferometry with BEC

Enhanced spectral sensitivity interferometers based on slow-light media were proposed soon after, while matter wave interference (non-transparent) was applied in space-born atomic interferometers, taking advantage of the longer BEC lifetime under microgravity.

One way to see this enhancement effect is to study the output of a Mach–Zehnder (M–Z) interferometer as shown in Fig. 1. When the optical path difference between the upper and lower routes through the M–Z interferometer is caused only by a medium with length L and refractive index n, the phase difference of the two beams passing through two different routes is given by

$$\Delta\phi = \frac{\omega}{c} nL, \tag{1}$$

where ω is the optical frequency of the incident light and c is the velocity of light in vacuum. The intensity transmission of such an M–Z interferometer is given by

$$T = \frac{1}{2}(1 + \cos \Delta\phi). \tag{2}$$

Note that $\Delta\phi$ can further be a function of transverse coordinates and $\Delta\phi$ appears also in the expressions

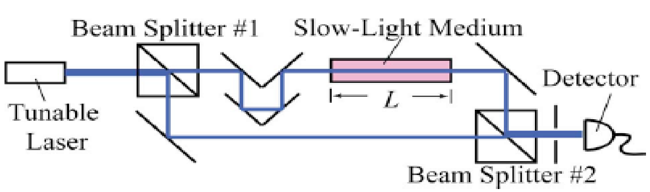
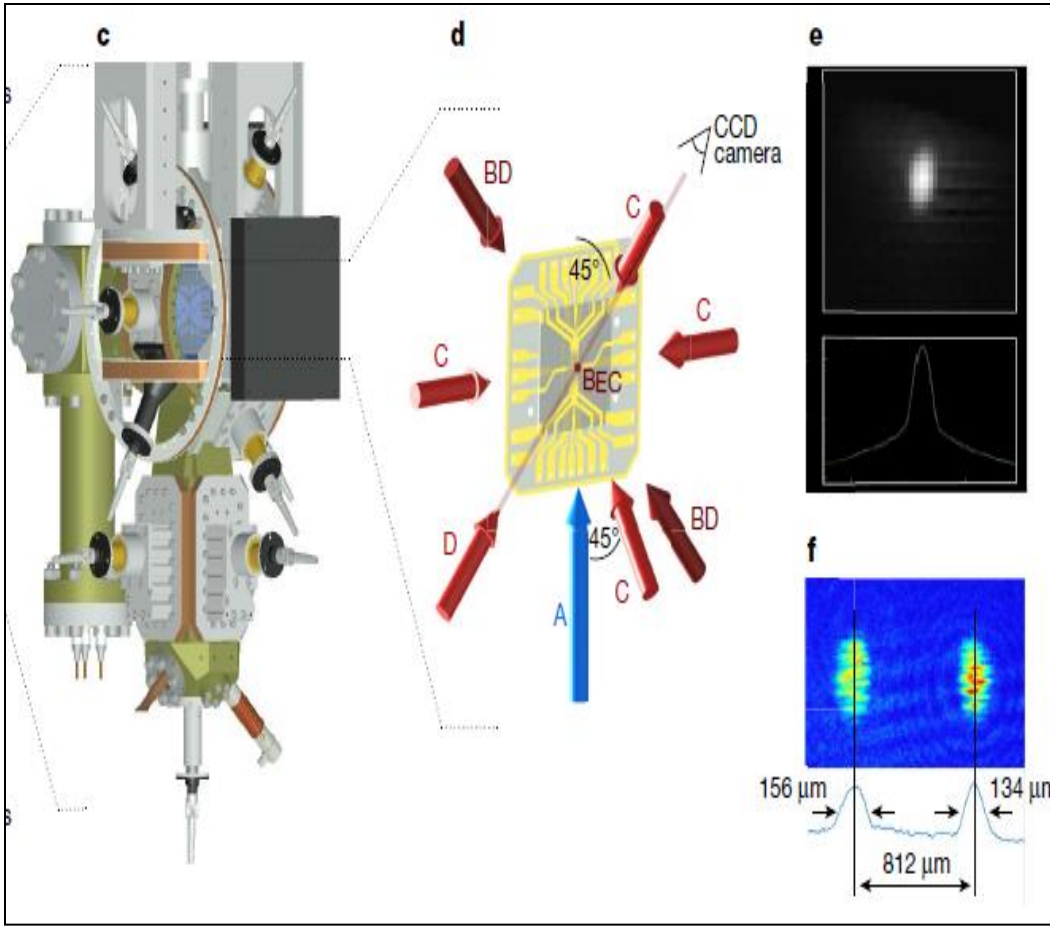


Fig. 1. (Color online) Schematic diagram of a Mach–Zehnder interferometer containing a slow-light medium in one arm.

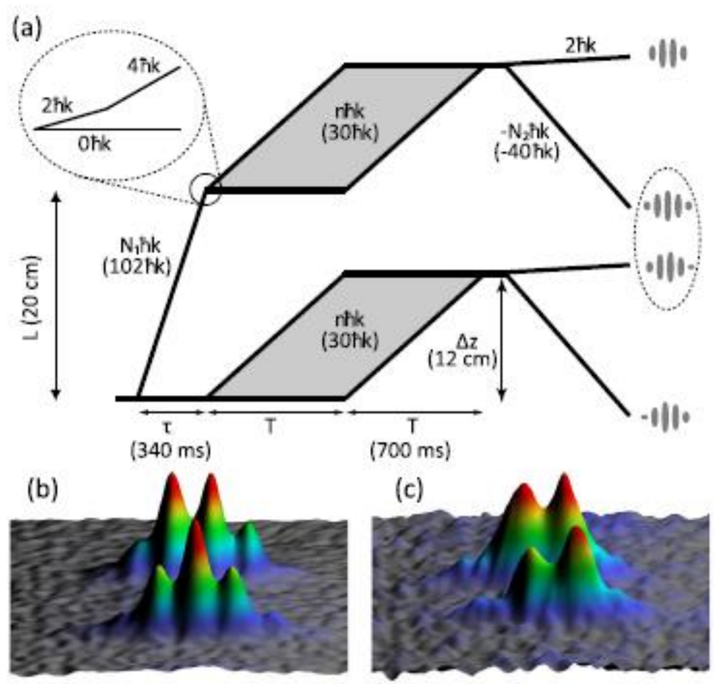


Z. Shi et al., *Optics Letters* 32, 917 (2007)

D. Becker et al., Nature 562, 391–395 (2018).

Interferometry with BEC

One of the most relevant application is the "Atomic gravitational wave interferometric sensor", proposed in 2008 by S. Dimopoulos et. al Phys. Rev. D 78, 122002 (2008), based on extracting the interference pattern of splitted BEC in free parabolic evolution, which subsequently recombine. The pattern is affected by the phase of the manipulating lasers, in turn subject to the GW induced phase shift. A first version of the apparatus was built in 2017 and demonstrated wave function sensitivity to tidal forces induced by spacetime curvature.



P. Asenbaum et al., Phys. Rev. Lett. 118, 183602 (2017).

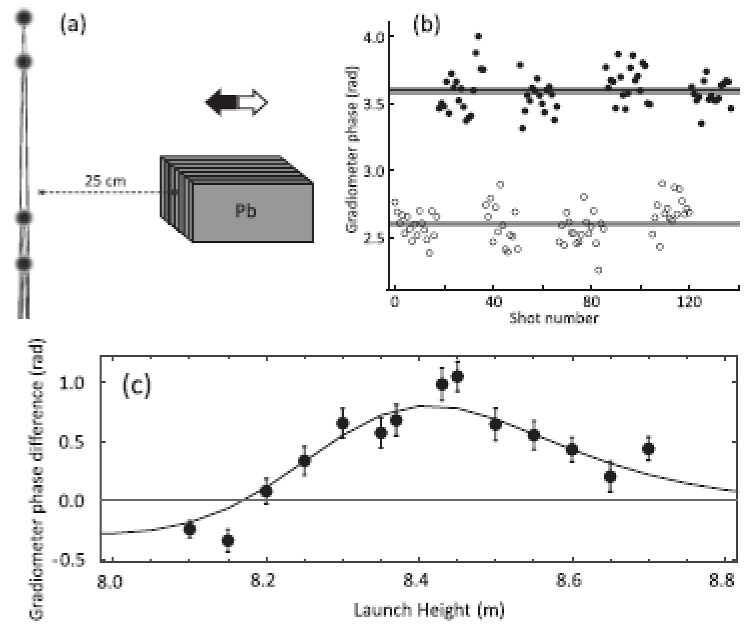


FIG. 2. (a) Schematic representation of the experimental setup for measuring the gravity gradient of seven lead bricks (total mass 84 kg). (b) Measured gradiometer phase of a sequence with $h = 8.45$ m, $L = 32$ cm, $n = 20$, and $T = 600$ ms ($\Delta z = 7$ cm), with (solid circles) and without (open circles) the bricks present. (c) Gradiometer phase difference (with and without bricks present) as a function of the launch height with $L = 10$ cm, $n = 30$, and $T = 900$ ms ($\Delta z = 16$ cm). The black, solid curve represents the full phase shift calculation.

Interferometry with BEC

The previous experiment represents one of the basis for the European Laboratory for Gravitation and Atom-interferometric Research (ELGAR proposal, 2020). ELGAR addresses the GW detection with a setup in which 160 ultra-cold matter waves, launched on local ballistic trajectories on two perpendicular 16-km long arms, are laser-splitted then made interfere. The phase shift induced by GW on the manipulating laser when traveling from a BEC to the next one will generate different interference patterns.
ELGAR is a first proposal of atom interferometry for GW, covering the band gap between LISA and LIGO.

Class. Quantum Grav. **37** (2020) 225017 B Canuel *et al*

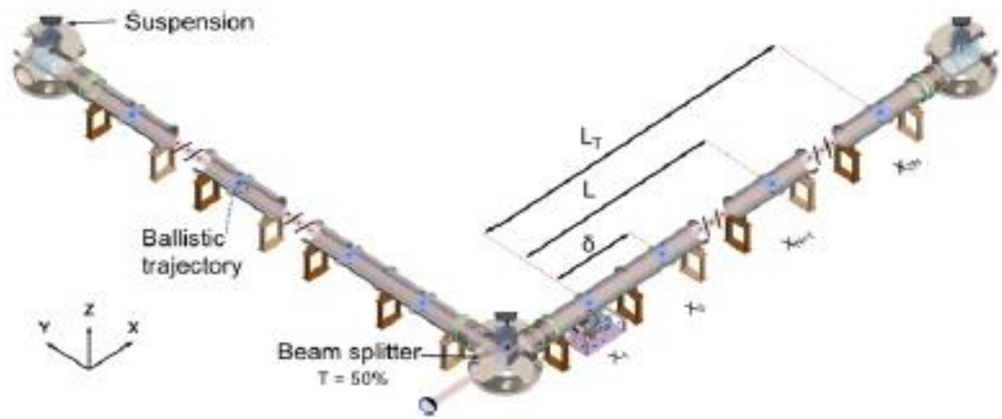


Figure 4. Schematic diagram of the proposed ELGAR infrastructure. Each arm of the detector of total length L_T is formed by N gradiometers of single baseline L. The gradiometers are spaced by a distance δ. The retro-reflection mirrors and the beam splitter are placed on suspension systems. The entire detector is inside a large steel vacuum vessel that maintains a base pressure of $\leqslant 1 \times 10^{-9}$ mbar. A vertical arm could be added at the same location or on a distributed site.

BEC lifetime

The above applications used the BEC themselves as interferometer due to their short lifetime (seconds to minutes under microgravity). Their functioning regime does not use EIT and requires ballistic setups, able to laser-target many launched BEC, spread over large distances, with similar constraints as LIGO for the mechanical stability of the stations and cleanness of the vacuum chamber.
A major innovation in the field arrived in June 2022, consisting in a new procedure, based on Bose-stimulated gain of atoms from a thermal bath, allowing maintaining a matter wave indefinitely. Moreover, the method consents achieving 1,000 times higher phase-space densities than previous works.

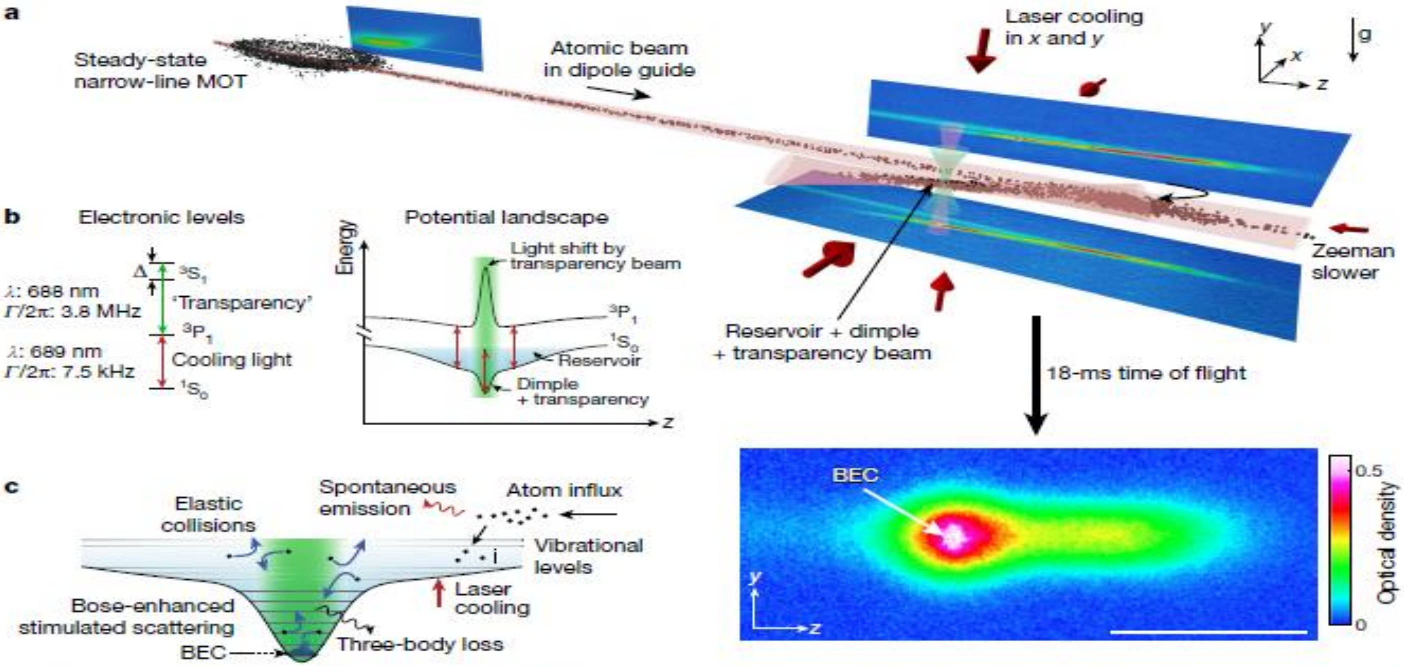
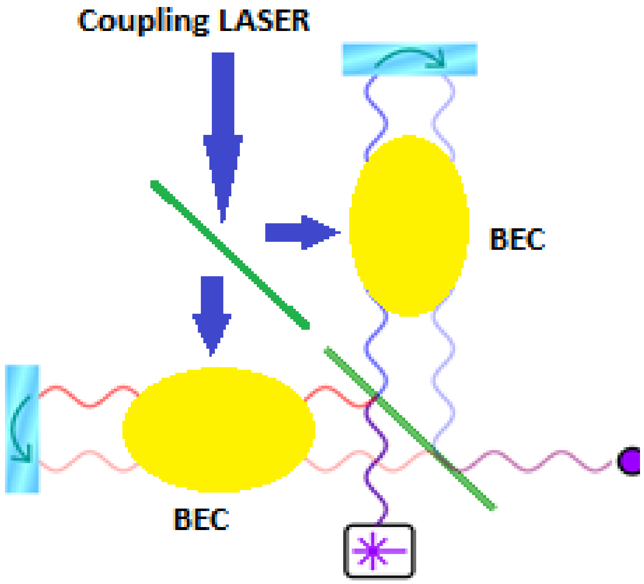


Fig. 1 | Experimental setup and scheme. a, ^{84}Sr atoms from a steady-state narrow-line magneto-optical trap (MOT) are continuously outcoupled into a guide and loaded into a crossed-beam dipole trap that forms a large reservoir with a small, deep dimple. Atoms accumulate in the laser-cooled reservoir and densely populate the dimple, in which a BEC forms in steady state. After time-of-flight expansion, the BEC shows as an elliptical feature in the centre of an absorption image. The scale bar denotes 1 mm. **b**, By off-resonantly addressing the $^3P_1$–$^3S_1$ transition using a 'transparency' laser beam, we produce a strong, spatially varying light shift on the $^3P_1$ electronic state, rendering atoms locally transparent to laser-cooling photons addressing the $^1S_0$–$^3P_1$ transition. This enables condensation in the protected dimple region. **c**, Schematic of the potential landscape from both reservoir and dimple trap, and of the dominant mechanisms leading to BEC atom gain and loss.

C-C. Chen, R. G. Escudero, J. Minář, B. Pasquiou,S. Bennetts & F. Schreck, Continuous Bose–Einstein condensation Nature 606, 683–698 (2022).

A Michelson interferometer with BEC

Given the cited recent developments, the idea to be investigated is straightforward and consists in placing two transparent, stable BEC on both arms of a Michelson interferometer. Single BEC configurations can be studied, as well.



Pros: a long storage time can be obtained with μm-long BEC. Given the currently reached limits (mm-long and >10^7 atoms), a low number of reflections can be used, reducing a lot the mirror's constraints, size and the associated noise. The ultra-high vacuum system for a cm-long setup will also be significantly reduced.

Cons: BEC themselves are subject to many instabilities coming from the cooling trap, evaporation, fluctuations in the coupling laser, etc.

To be studied and optimized (unknowns at the current date): the precision of the "refilling" procedure, the working regime (pulsed, continuous), the influence of non-condensed atoms and how efficiently can be removed from the light path, the density function under the influence of the GW.

The study is in a very preliminary phase and was submitted as LOI , while a proposal will be developed after a more detailed investigation.