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Analog Measurements of Acceleration Radiation

Or a new type of acceleration particle detector

W. G. Unruh

Analog Measurements of Acceleration radiation
or
A New type of acceleration particle detector

W.G.Unruh

Vanc. Aug15 2022

One of the most amazing aspects of modern Physics is the role of analogy-- mathematical analogy

Many different systems are described by the same or similar mathematics

Can one understand gravitational particle creation by use of other systems?

Black Hole evaporation

1974-- Hawking “predicted” that black holes were not black

but had a temperature

$$T = \frac{1}{8\pi M}\left(\frac{c^3\hbar}{k_B G}\right)$$

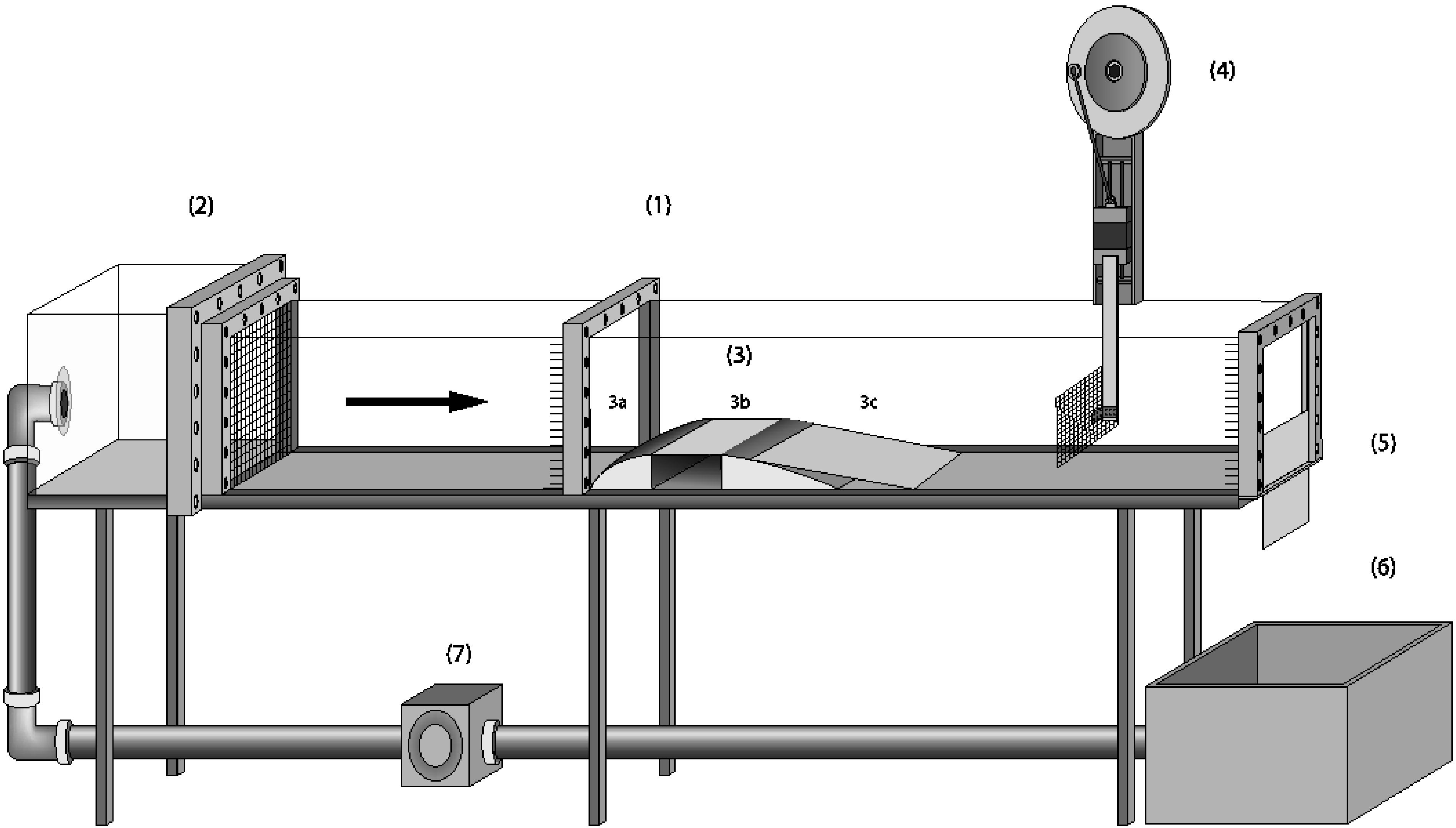
Solar mass black hole (a few km wide) has a Temp
Or about 10^{-5} K (1/100000 deg above absolute 0,)

1976—I showed that uniformly accelerated particle detectors (Internal states which are excited by field)

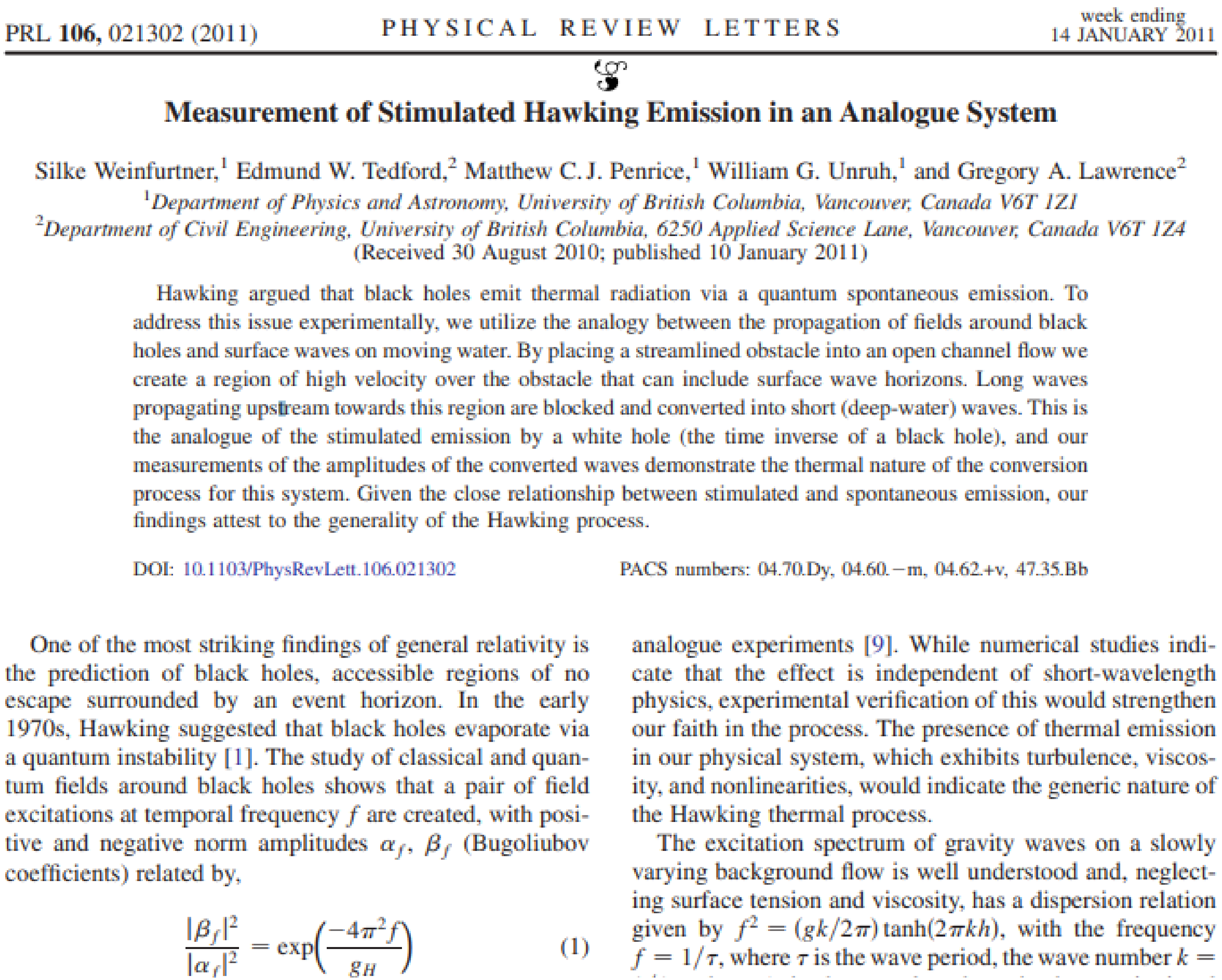
$$T = \frac{a}{2\pi}\frac{\hbar}{k_B c}$$

A Detector, of a field (say electromagnetic field) which is in it’s lowest energy state (vacuum) and for which a particle detector would see nothing, would, if accelerated, would see photons as if it were in a thermal bath of photons.

Closely related to Hawking’s discovery


(2)
(1)
(4)
(3)
3a
3b
3c
(5)
(6)
(7)

30 years later


PRL 106, 021302 (2011) PHYSICAL REVIEW LETTERS week ending 14 JANUARY 2011

Measurement of Stimulated Hawking Emission in an Analogue System

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(Received 30 August 2010; published 10 January 2011)

Hawking argued that black holes emit thermal radiation via a quantum spontaneous emission. To address this issue experimentally, we utilize the analogy between the propagation of fields around black holes and surface waves on moving water. By placing a streamlined obstacle into an open channel flow we create a region of high velocity over the obstacle that can include surface wave horizons. Long waves propagating upstream towards this region are blocked and converted into short (deep-water) waves. This is the analogue of the stimulated emission by a white hole (the time inverse of a black hole), and our measurements of the amplitudes of the converted waves demonstrate the thermal nature of the conversion process for this system. Given the close relationship between stimulated and spontaneous emission, our findings attest to the generality of the Hawking process.

DOI: 10.1103/PhysRevLett.106.021302 PACS numbers: 04.70.Dy, 04.60.−m, 04.62.+v, 47.35.Bb

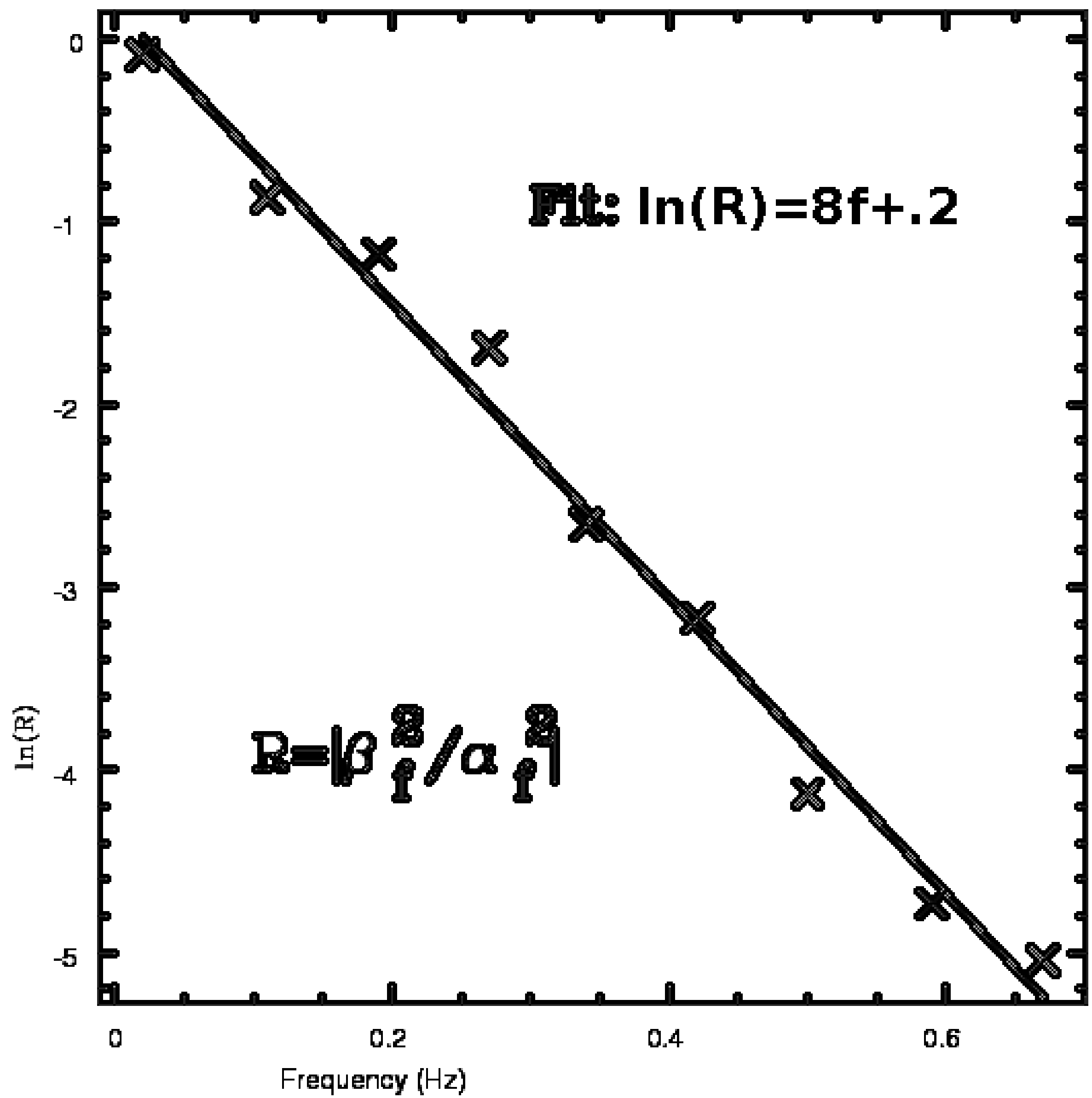
One of the most striking findings of general relativity is the prediction of black holes, accessible regions of no escape surrounded by an event horizon. In the early 1970s, Hawking suggested that black holes evaporate via a quantum instability [1]. The study of classical and quantum fields around black holes shows that a pair of field excitations at temporal frequency f are created, with positive and negative norm amplitudes α_f, β_f (Bugoliubov coefficients) related by,

$$\frac{|\beta_f|^2}{|\alpha_f|^2} = \exp\left(\frac{-4\pi^2 f}{g_H}\right) \quad (1)$$

analogue experiments [9]. While numerical studies indicate that the effect is independent of short-wavelength physics, experimental verification of this would strengthen our faith in the process. The presence of thermal emission in our physical system, which exhibits turbulence, viscosity, and nonlinearities, would indicate the generic nature of the Hawking thermal process.

The excitation spectrum of gravity waves on a slowly varying background flow is well understood and, neglecting surface tension and viscosity, has a dispersion relation given by $f^2 = (gk/2\pi)\tanh(2\pi kh)$, with the frequency $f = 1/\tau$, where τ is the wave period, the wave number $k =$

Arxiv 1008.1911


Fit: ln(R)=8f+.2
R=|β f 2/α f 2|
ln(R)
Frequency (Hz)
0
-1
-2
-3
-4
-5
0
0.2
0.4
0.6

nature physics

ARTICLES

PUBLISHED ONLINE: 15 AUGUST 2016 | DOI: 10.1038/NPHYS3863

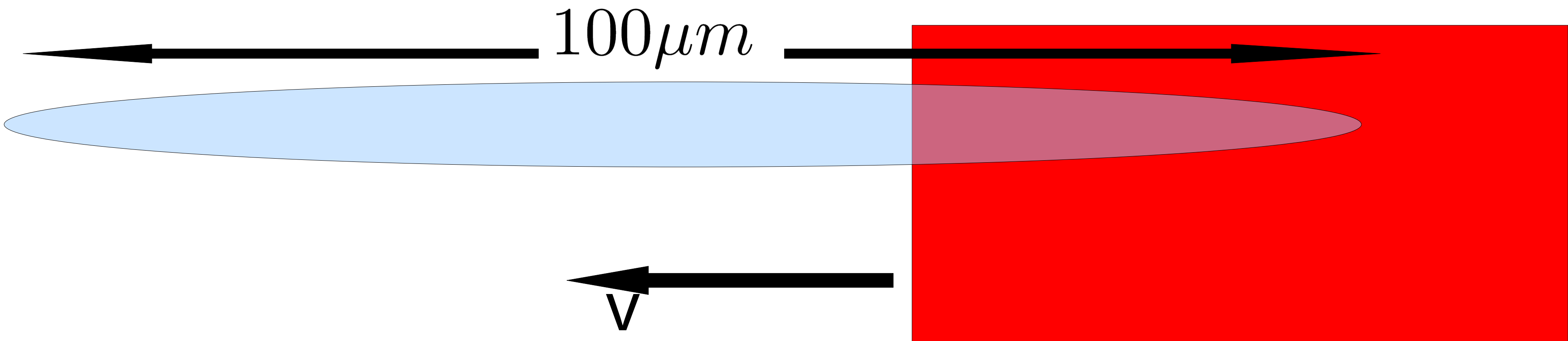
Observation of quantum Hawking radiation and its entanglement in an analogue black hole

Jeff Steinhauer

We observe spontaneous Hawking radiation, stimulated by quantum vacuum fluctuations, emanating from an analogue black hole in an atomic Bose–Einstein condensate. Correlations are observed between the Hawking particles outside the black hole and the partner particles inside. These correlations indicate an approximately thermal distribution of Hawking radiation. We find that the high-energy pairs are entangled, while the low-energy pairs are not, within the reasonable assumption that excitations with different frequencies are not correlated. The entanglement verifies the quantum nature of the Hawking radiation. The results are consistent with a driven oscillation experiment and a numerical simulation.

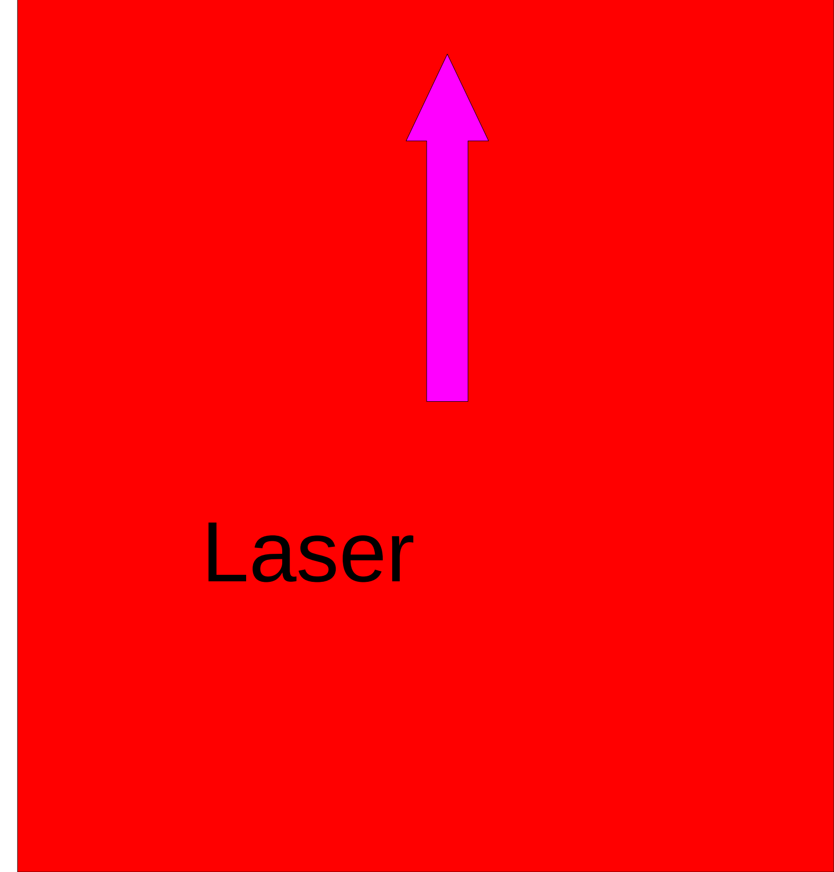
Steinhauer Aug 2016 (Nature Physics)

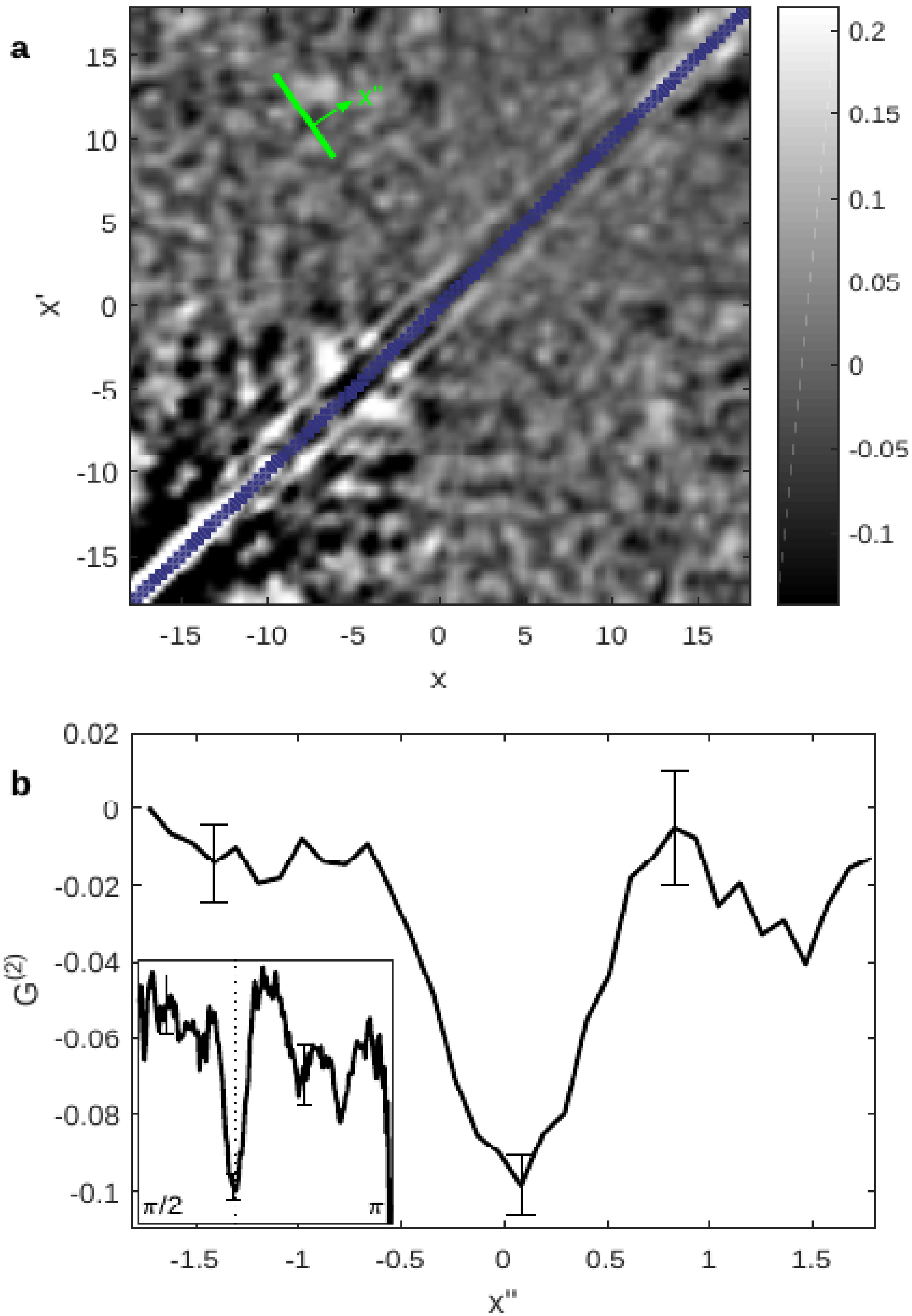
Create a potential jump for BEC (Waterfall)



Laser de-tuned from resonance.-- Decreases energy of atoms in laser field.

Sharp jump in potential of atoms

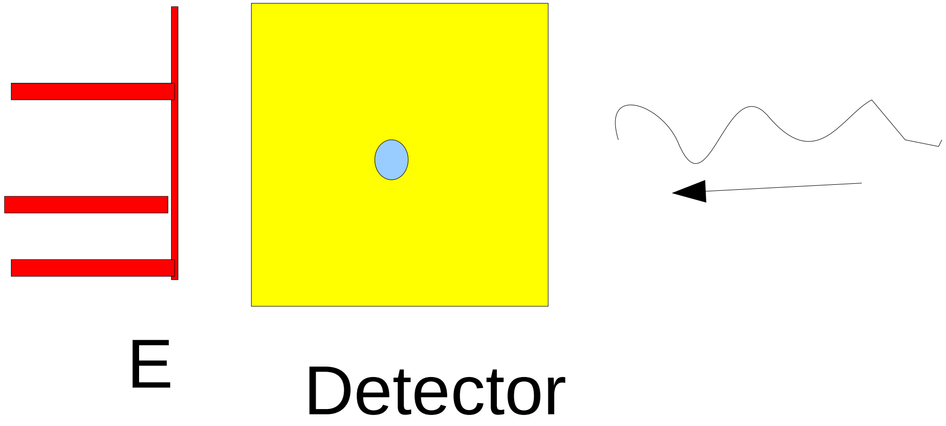


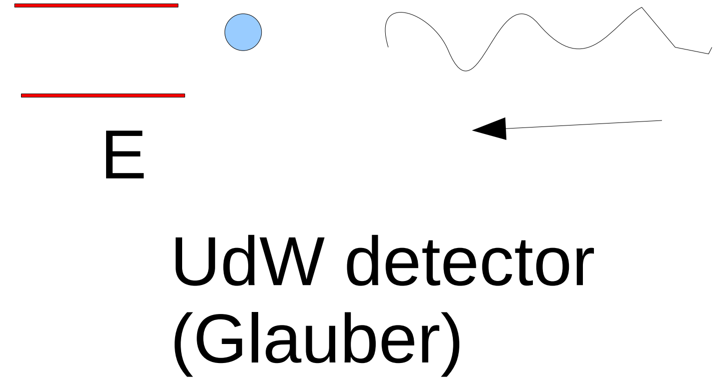


Density-Density corr.

note the faint corr.
of density to left and right
of horizon

Cross section across
line





If detector starts in ground state and is found in excited state, it has detected a particle.

If particle is accelerated (constant) particle detector responds exactly as if in a thermal bath in a gravitational field

$$T = \frac{\hbar}{2\pi k_B c} a$$

Can this be measured in an analog system?

Problems:

a) constant acceleration means that the velocity rapidly approaches the velocity of light/sound.
Need many such timescales (1/coupling-const squared)
Hard to keep detector in lab.

b) Effect depends not only on acceleration but also on Relativistic time dilation (no time dilation, no thermal effect and no time independence)

c) Analogs have non-trivial dispersion relations--acceleration takes one (rapidly) into regime of altered dispersion relation.

Bell & Leinaas (1983-85) Unruh (1994)

Circular (orbital) acceleration is also constant magnitude
Velocity constant, so relation between dilated time and relativistic time is constant.
Can remain in linear dispersion relation regime
Detector can remain in lab.

Nuclear Physics B284 (1987) 488–508
North-Holland, Amsterdam

THE UNRUH EFFECT AND QUANTUM FLUCTUATIONS OF ELECTRONS IN STORAGE RINGS

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J M LEINAAS

Rogaland College, Stavanger, Norway

Received 20 June 1986

The quantum fluctuation of electron orbits in ideal storage rings is a sort of Fulling-Unruh effect (heating by acceleration in vacuum) To spell this out, the effect is analyzed in an appropriate comoving and so accelerating and rotating co-ordinate system The depolarization of the electrons is a related effect, but is greatly complicated by spin-orbit coupling This analysis confirms the standard result for the polarization, except in the neighbourhood of a narrow resonance

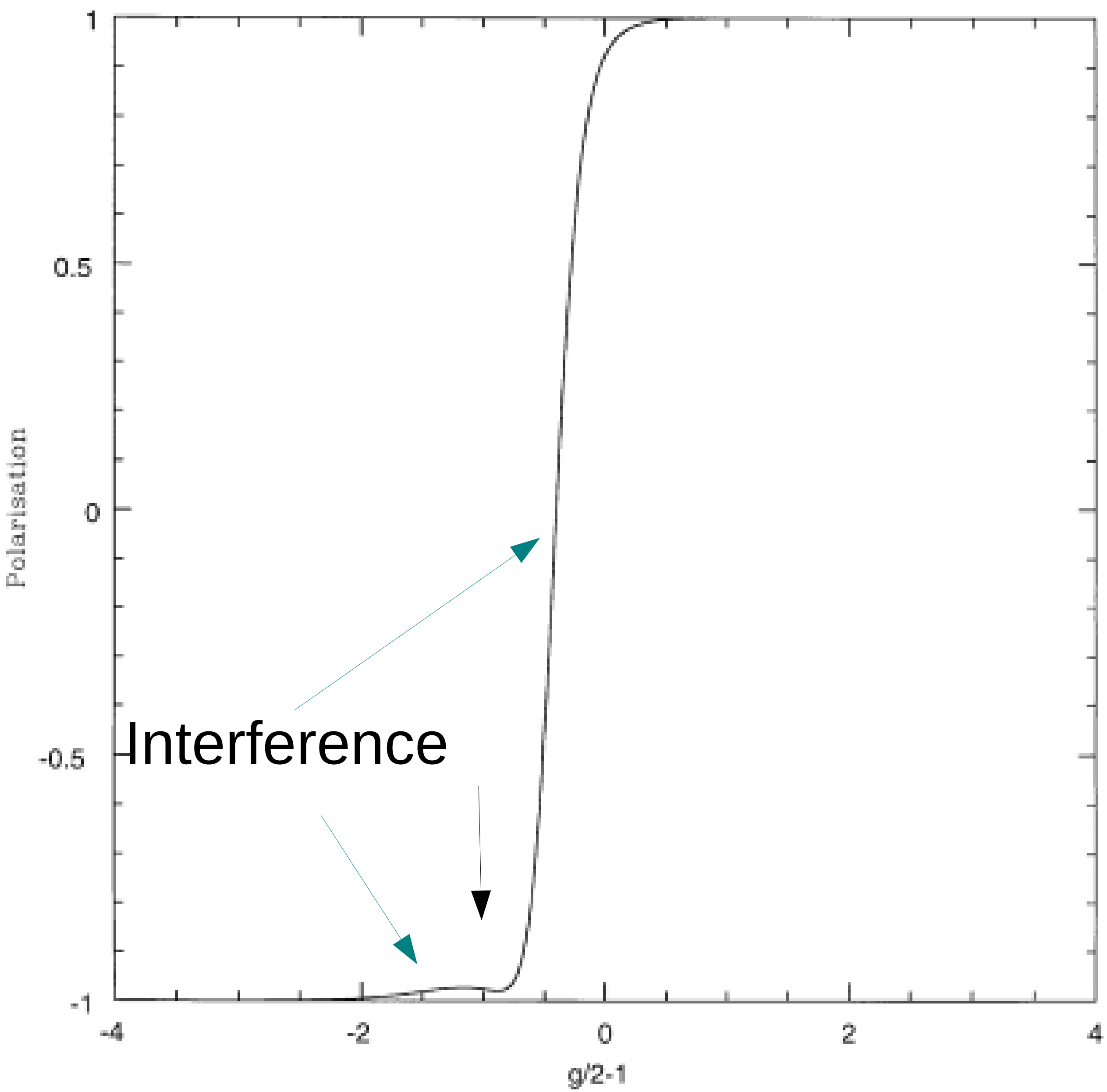
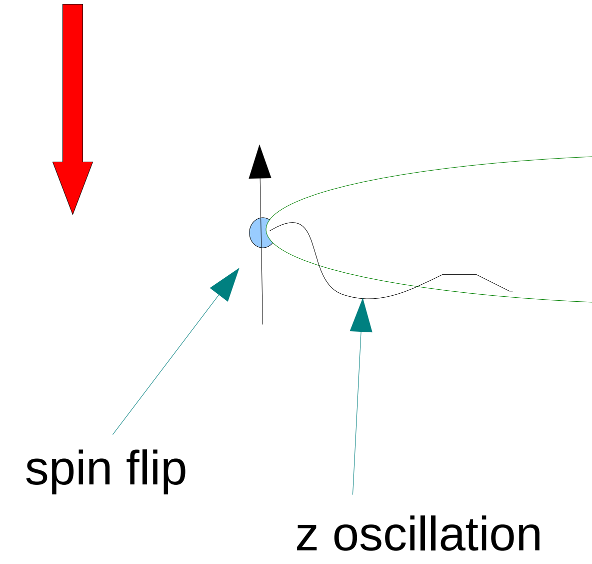


Fig. 1. Polarisation of an electron vs. the g factor.



2 Thermometers
Same field

Effective temperature of scalar field as seen by circularly accelerating particle

J.S. Bell, J.M. Leinaas / Electrons as accelerated thermometers 143

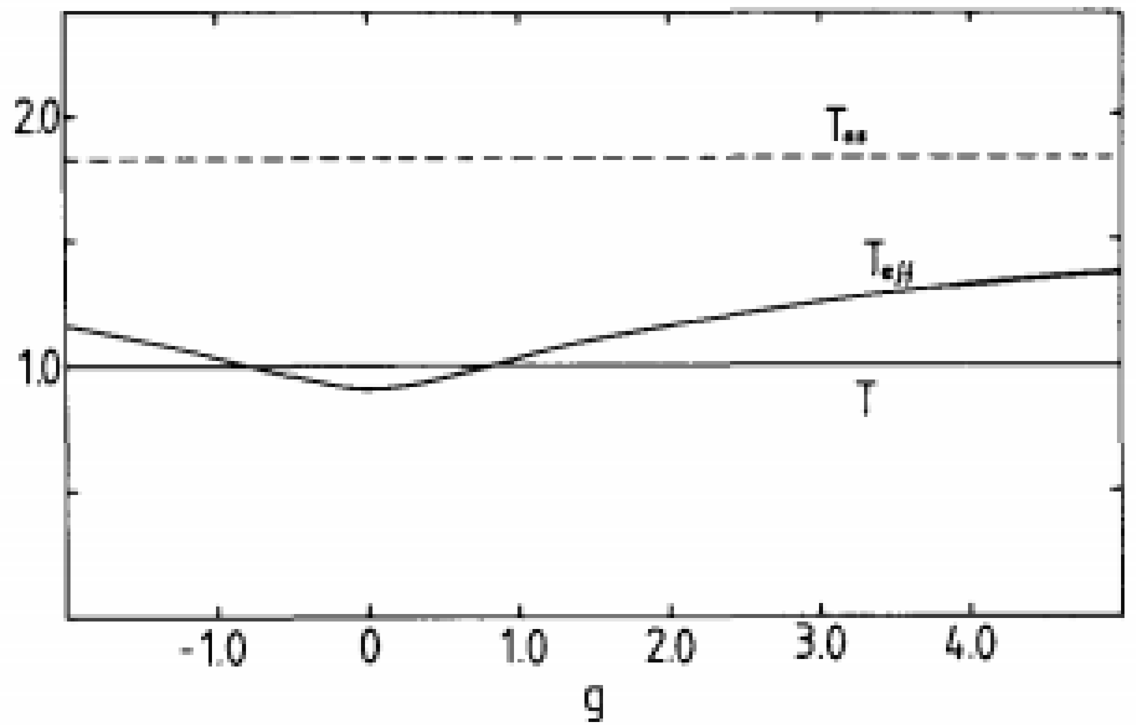


Fig. 2. The effective temperature for circulating scalar particles, T_{eff} is shown as a function of the energy splitting, measured in terms of g. It is shown on the scale where the temperature $T = \hbar a/2\pi kc$, with a as the acceleration, is put equal to unity. T_{as} is the asymptotic value of T_{eff} for $|g| \to \infty$.

Often claimed that temperature is due to horizon.
No horizon for circular acceleration.

How to measure in analog system?

Detector needs to be accelerated-- dragged through the fluid
Dragging likely to excite the fluid just where the detector is.

Measurement of acceleration radiation harder than Hawking

Joerg Schmiedmeyer, I at workshop Silke Weinfurtner had organized at Nottingham about 3 years ago-- in hallway after the talks. “Could we use a laser to measure this?” “Sure”

Out of that, with help of a whole group of people, came
a) A New detector (or rather a transducer or transformer)
b) a new interferometer (in frequency space rather than real space.)

a) New detector: A laser spot. A laser beam is swept over the BEC. The density of BEC (sound wave) at the laser spot gives a phase shift to the laser beam (proportional to the integrated density across the BEC and the polarizability of the atoms.) The density as a function of time at the laser spot is transfered into the phase of the laser beam (Coherent beam at some well defined frequency). Thus measurement of photons in laser beam is measurement of phonons in BEC.

No two level, or multi-level system.-- Broad band transducer and thus detector. Detection of photons far easier than detection of phonons.

b) The polarizability of material depends on resonances.

If we shake a harmonic oscillator at frequency below resonance the displacement is proportional to the force and in phase with the force.

If we shake a Harmonic oscillator at a frequency above the resonance, the displacement is opposite to the force (180^0 phase shift).

If “oscillator” is dipole moment of atom, then below freq, dipole moment is in phase of E field, making E field larger (higher refractive index). If above freq, dipole moment is opposite to E field-- decreases E field-- lower refractive index.

i) effect of below resonance-- positive phase shift by atoms-- light goes slower. Also, energy $\vec{d} \cdot \vec{E} > 0$ lower. Attracts medium-- optical tweezers.

ii) If frequency higher than resonance, refractive index smaller, Light goes faster, negative phase shift (proportional to density)

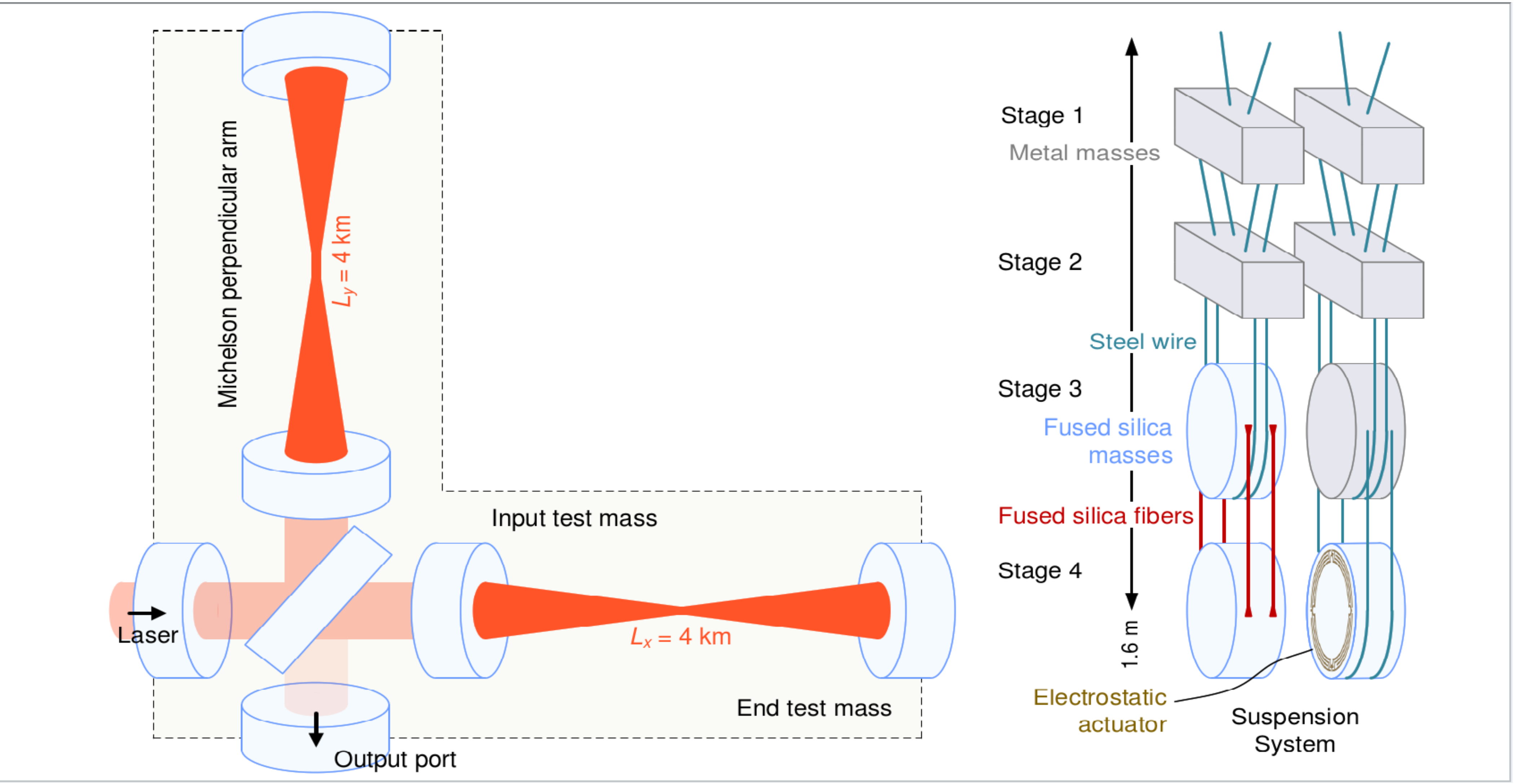
dipole energy higher, repels the matter (anti-tweezers).

Split beam, not spatially, but in frequency. If we have two laser beams, one at frequency higher than resonance, and one lower

i) Can balance the forces on the medium, so background strong laser field does not exert net force on the atoms.

ii) The effect of density fluctuation gives opposite effects in the two beams.

LIGO:



Interferometer

Gravity wave moves end masses in opposite directions. -- output sensitive to difference in lengths.

BEC analog for circular acceleration.

Interferometric Unruh detectors for Bose-Einstein condensates

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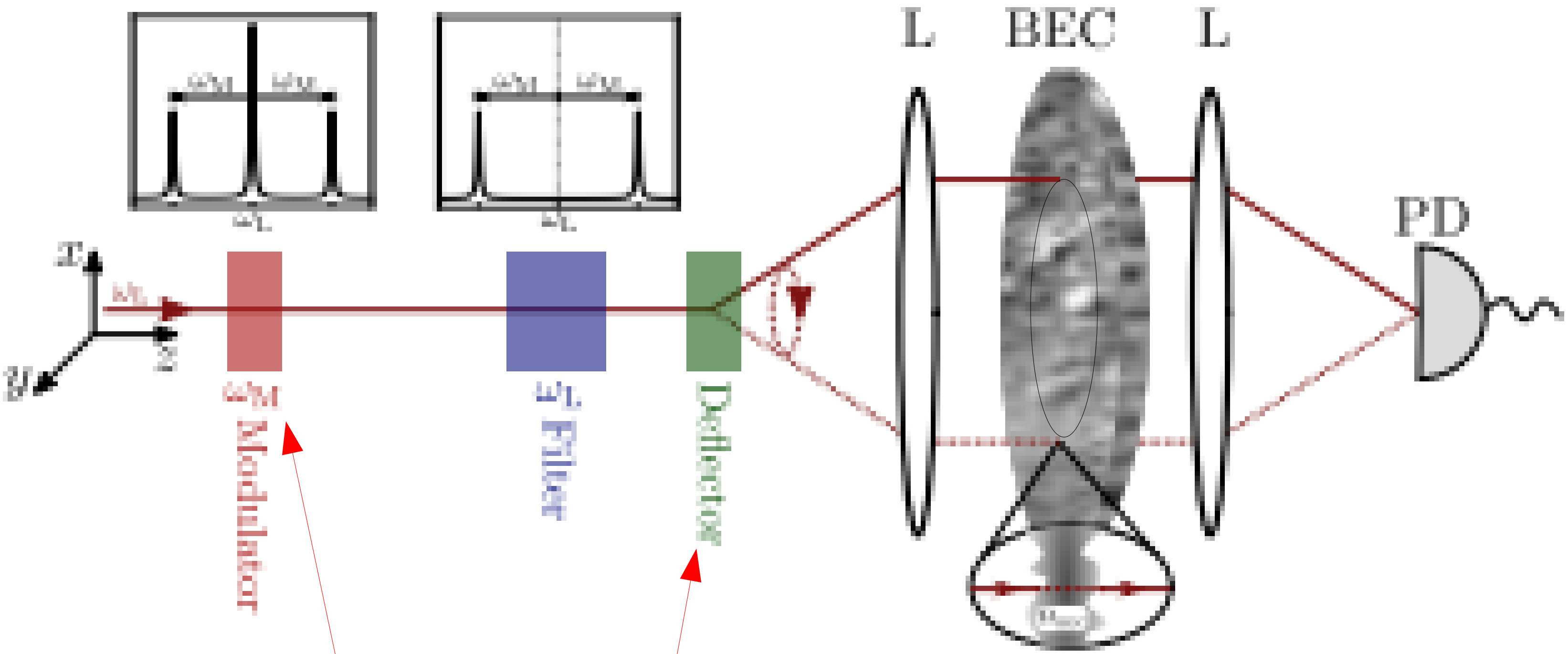
(Dated: July 15, 2020)

The Unruh effect predicts a thermal response for an accelerated detector moving through the vacuum. Here we propose an interferometric scheme to observe an analogue of the circular Unruh effect using a localized laser coupled to a Bose-Einstein condensate (BEC). Quantum fluctuations in the condensate are governed by an effective relativistic field theory, and as demonstrated below the coupled laser field acts as an effective Unruh-DeWitt detector thereof. The effective speed of light is lowered by 11 orders of magnitude to the sound velocity in the BEC. For detectors traveling close to the sound speed, observation of the Unruh effect in the analogue system becomes experimentally feasible.

Arxiv:2007.07160 July 2020

Phys Rev Lett. 125, 213603(2020)

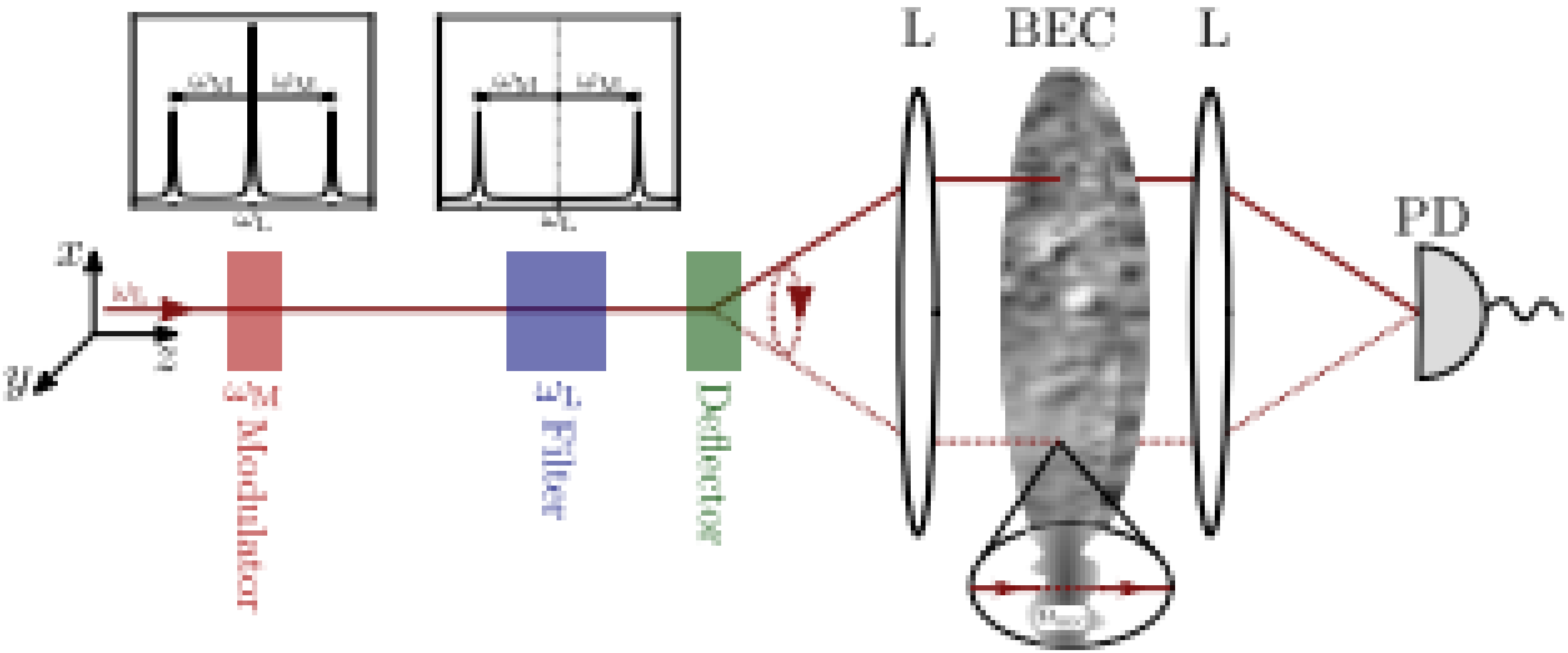


Laser beam modulated
(Beam splitter in freq space)

BEC Dinner plate
1x100 micron

Deflector puts beam in circular orbit
Beam interacts with BEC-- changes
index of refraction due to density fluct.

Opposite signs of refractive
index if freq chosen correctly



Half Silvered mirror

Circular interaction
with BEC phase shift
opposite in the two colour beams

ψ EM field before and after BEC

$$\psi(t,z) = \Bigg((e^{-i(\omega_0+\Omega)(t-z)}(\alpha\delta(\nu) + \int_{-\Delta}^{\Delta} +A_\nu \frac{e^{-i\nu(t-z)}}{\sqrt{\omega_0+\Omega+\nu}} d\nu)$$

$$+e^{-i(\omega_0-\Omega)(t-z)}(\alpha + \int_{-\Delta}^{\Delta} +B_\nu \frac{e^{-i\nu(t-z)}}{\sqrt{\omega_0-\Omega+\nu}})d\nu)\Bigg)$$

$$+\mathbf{HC}$$

$$\psi(t,z) = \Bigg(e^{-i(\omega+\Omega)(t-z)+\phi(t-z)}(\alpha\delta(\nu) + \int_{-\Delta}^{\Delta} +A_\nu \frac{e^{-i\nu(t-z)}}{\sqrt{\omega_0+\Omega+\nu}} d\nu)$$

$$+ e^{-i(\omega-\Omega)(t-z)-\phi(t-z)}(\alpha\delta(\nu) + \int_{-\Delta}^{\Delta} B_\nu \frac{e^{-i\nu(t-z))}}{\sqrt{\omega_0-\Omega+\nu}} d\nu)\Bigg)$$

$$+\mathbf{HC}$$

$\phi =$ Phase shift by index of refraction through by BEC

$$\phi = \epsilon(\omega_0 \pm \Omega)|\Psi(t, x(t), y(t))|^2$$

$$\epsilon(\omega_0 - \Omega) = -\epsilon(\omega_0 + \Omega)$$

Ψ Gross Piatevski field of BEC

D_ν Annihilation operators of the linear pert. around the const background of BEC along path of laser spot

Before

Unitarity

After

$$X_\nu \approx \frac{A_\nu - B_\nu}{\sqrt{2}}\Theta(\nu) \qquad \tilde{X}_\nu = (1 - \frac{1}{2}\mu^2)X_\nu + i\mu D_\nu + \frac{1}{2}\mu^2 Y_\nu^\dagger$$

$$Y_\nu \approx \frac{A_{-\nu} - B_{-\nu}}{\sqrt{2}} \qquad \tilde{Y}_\nu = (1 + \frac{1}{2}\mu^2)Y_\nu + i\mu D_\nu^\dagger + \frac{1}{2}\mu^2 X_\nu^\dagger$$

$$D_\nu \qquad \tilde{D}_\nu = D_\nu + i\mu X_\nu + i\mu Y_\nu^\dagger$$

"Two Mode squeezed state"

A_ν, B_ν annihil ops at $\omega_0 \pm \Omega + \nu$

$$X_\nu \approx \frac{A_\nu - B_\nu}{\sqrt{2}}\Theta(\nu) \qquad \tilde{X}_\nu = (1 - \frac{1}{2}\mu^2)X_\nu + i\mu D_\nu + \frac{1}{2}\mu^2 Y_\nu^\dagger$$

$$Y_\nu \approx \frac{A_{-\nu} - B_{-\nu}}{\sqrt{2}} \qquad \tilde{Y}_\nu = (1 + \frac{1}{2}\mu^2)Y_\nu + i\mu D_\nu^\dagger + \frac{1}{2}\mu^2 X_\nu^\dagger$$

$$D_\nu \qquad \tilde{D}_\nu = D_\nu + i\mu X_\nu + i\mu Y_\nu^\dagger$$

X_ν damped Y_ν amplified

D_ν remains same amplitude.-- But extra noise from X_ν Y_ν

BEC quantum density fluctuations converted (and amplified) into light beams
Light quantum fluctuations converted into BEC fluctuations.
(Back action without damping).

Unlike LIGO, signal is quantum rather than classical.
If BEC large enough, back-action travels away from interaction to not bother us again.

Using “reasonable parameters” thermal signal just detectable.

Detector is NOT two-level system. It is broad-band. BEC signal is transformed into light-signal over whole bandwidth of BEC frequencies.

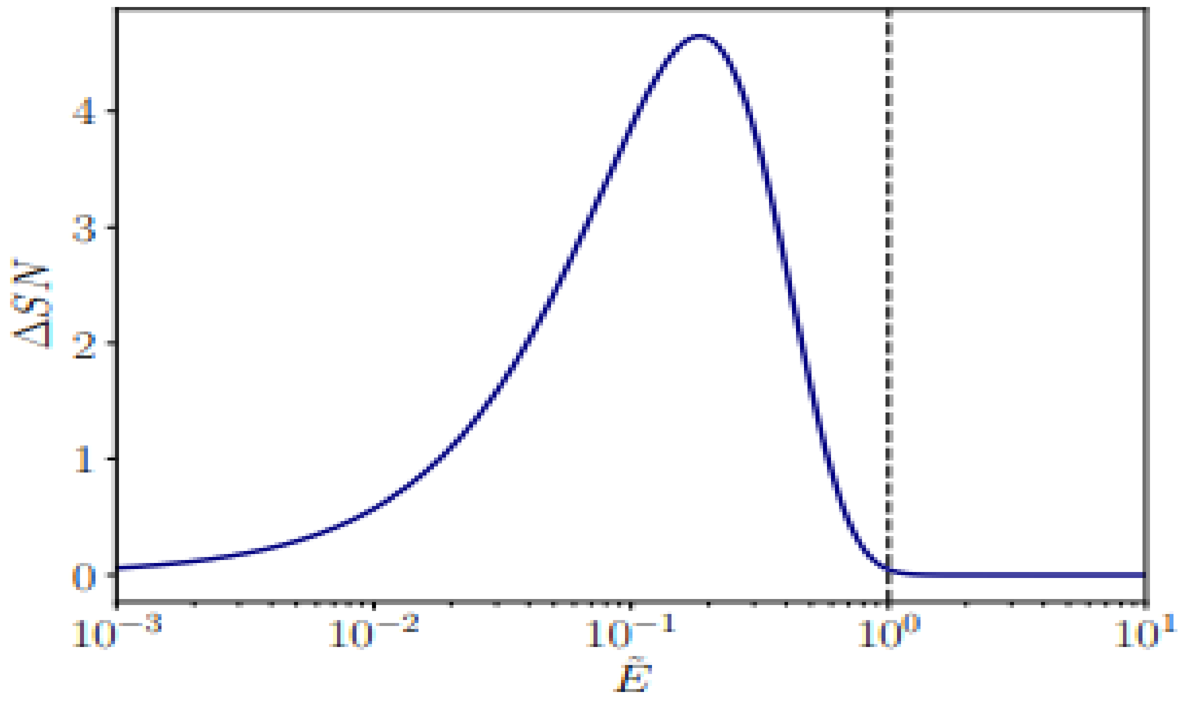


FIG. 2. Signal-to-noise ratio ΔSN as a function of dimensionless energy $\tilde{E} = \hbar\omega/\mu$ for ^{133}Cs and $N = 10^6$ experimental realizations. The experimental parameters chosen are the scattering rate $\Gamma_{sc} \approx 0.1\,\mathrm{Hz}$, beam width $r_0 = 3\,\mu\mathrm{m}$, chemical potential $\mu \approx 2\pi\hbar\, 9.5\,\mathrm{Hz}$, healing length $\xi \approx 2\,\mu\mathrm{m}$, density $\rho_0 = 10^3\,\mu\mathrm{m}^{-2}$, scattering length $a_s = 25\mathrm{pm}$, radial confinement $a_\perp = 1\mu\mathrm{m}$, and the observer trajectory radius $R = 10\,\mu\mathrm{m} \approx 5\xi$ and velocity $v = 0.95c_s$ leading to $T_\mathrm{U} \approx 60\,\mathrm{pK}$. Note that the signal vanishes for $\tilde{E} \to 0$, due to the suppression of density perturbations $\delta\rho$ at long wavelength. The signal to noise ratio within the whole phononic band (below the dashed black line) given by Eq. (17) for $B_\mathrm{m} = 1\,\mathrm{Hz}$ is $\overline{\Delta SN} \approx 5.8$.

Parameters difficult but not absurd

Within the next year or two should get at least indication that the parameters are achievable together.

Hope that in addition to measurement of Black Hole radiation in Analog system, will also have first measurement of acceleration radiation.

In addition we hope to contribute to technical development of measurements on BEC (eg, continuous measurement of density fluctuations, rather than one-shot measurement, use of frequency space interferometer on BEC.)

Watch This Space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