Fundamental physics with infrastructures and technology of GW interferometers

Takayama 2014-05-26

The INFN is within the «what's next» investigations period -- for our community it translates in the question «what is the fundamental physics that GW detectors can pursue after the discovery of GWs ?»

The main answers are related to General Relativity tests (alternative theories of gravitation, dynamic in high-field regime..) are not taken into account in the present talk

Three ways of linking GW detectors to other INFN core fields

- GW measurement to constraint exotic equation of states of Neutron Stars core
- Side-Use of GW detectors or infrastructure to test fundaments of Quantum Mechanics – EPR paradox
- Propose new side-experiments – the measure of the Archimedes force of vacuum

What Next in Gravitational Wave research?

European Gravitational Observatory, Cascina (Italy), March 4 – 5 2014

Equation of state of matter at supranuclear density and Neutron Star structure

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and

INFN Sezione di Pisa

Relativistic equations for stellar structure

Static and sphericaly symmetric self-gravitating mass distribution

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu = e^{2\Phi(r)} c^2 dt^2 - e^{2\lambda(r)} dr^2 - r^2 (d\theta^2 + \sin^2\theta \, d\varphi^2)$$

$\Phi = \Phi(r)$, $\lambda = \lambda(r)$ metric functions

$$e^{\lambda(r)} \equiv \left[1 - \frac{2G\, m(r)}{c^2 r}\right]^{-1/2}$$

for the present case the Einstein's field equations take the form called the

Tolman – Oppenheimer – Volkov equations (TOV)

$$\frac{dP}{dr} = -G \frac{m(r)\rho(r)}{r^2} \left(1 + \frac{P(r)}{c^2 \rho(r)}\right) \left(1 + 4\pi \frac{r^3 P(r)}{m(r)\; c^2}\right) \left[1 - \frac{2Gm(r)}{c^2 \; r}\right]^{-1}$$

$$\frac{dm}{dr} = 4\pi r^2 \rho(r)$$

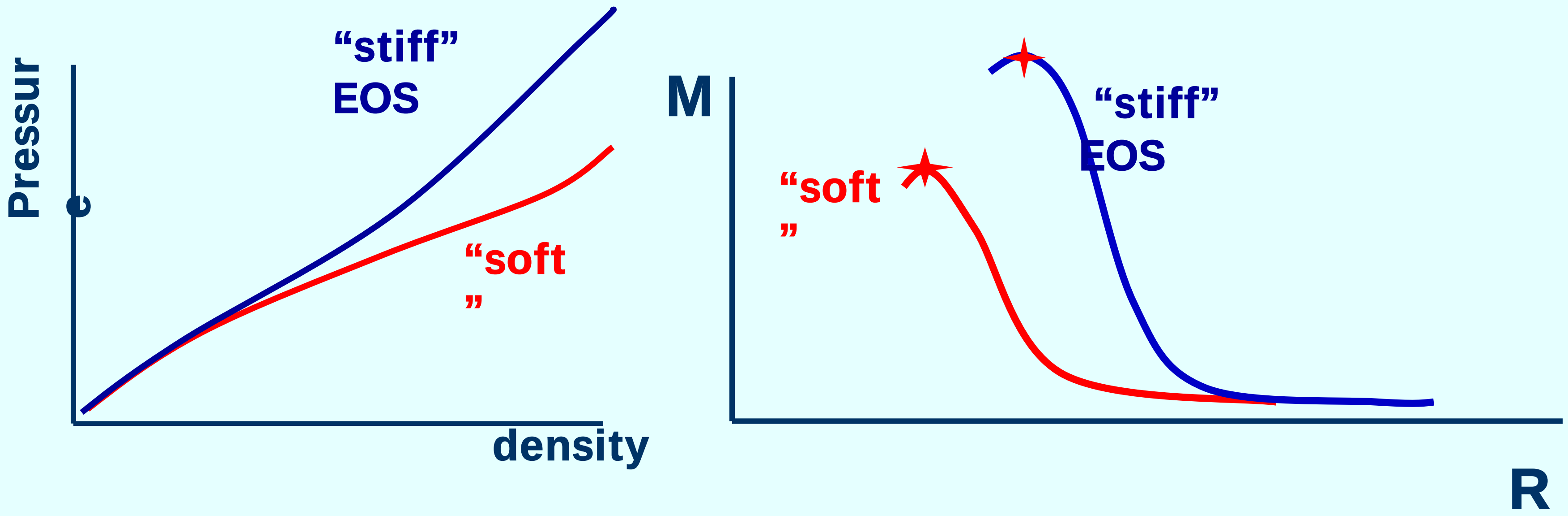
$$\frac{d\Phi}{dr} = -\frac{1}{\rho(r) c^2} \frac{dP}{dr} \left(1 + \frac{P(r)}{\rho(r) c^2}\right)^{-1}$$

One needs the **equation of state (EOS) of dense matter, P = P(ρ),** up to **very high densities**

The Oppenheimer-Volkoff maximum mass

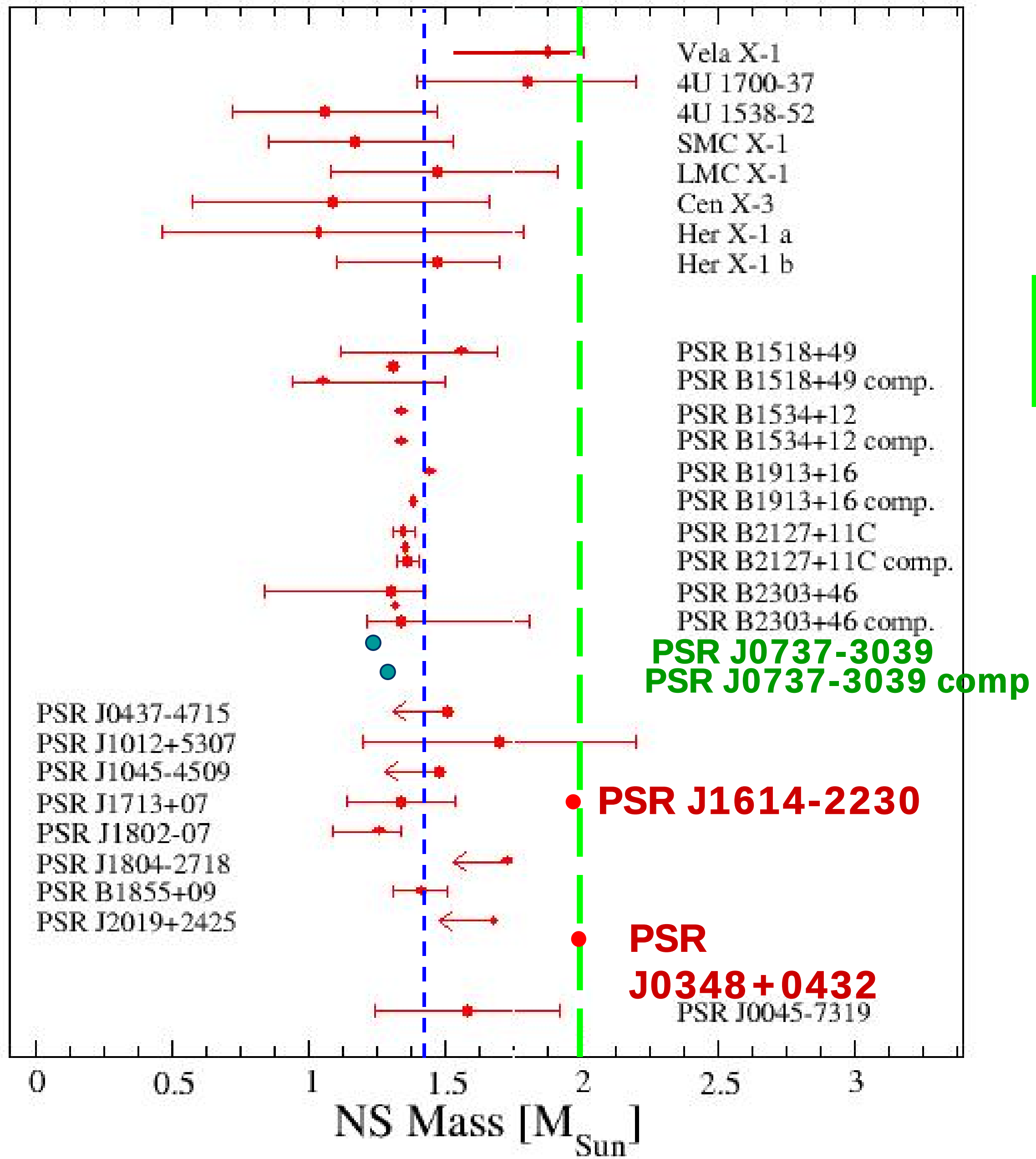
$M_{max} = (1.4 – 2.5)\ M_{\odot}$

EOS dependent



There is a maximum value for the gravitational mass of a Neutron Star that a given EOS can support. This mass is called the Oppenheimer-Volkoff mass

Measured Neutron Star Masses



$M_{max} \approx 2\ M_{\odot}$

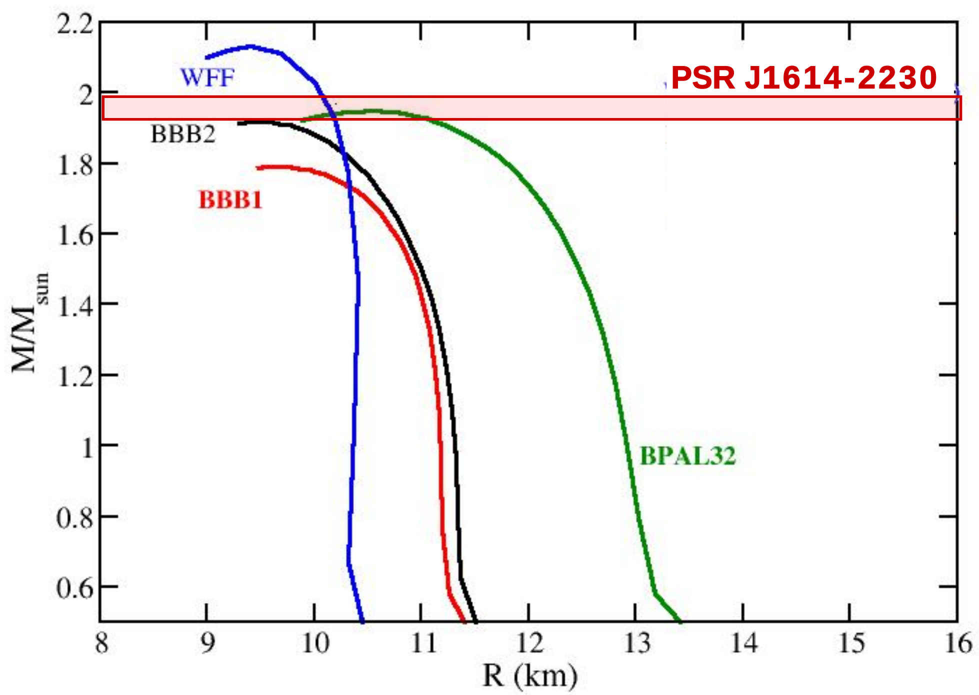
Very stringent constraint on the EOS

β-stable nuclear matter

$$p + e^- \leftrightarrow n + \nu_e$$

$$n \leftrightarrow p + e^- + \bar{\nu}_e$$

Mass-Radius relation for Nucleon Stars



Maximum mass configuration for Nucleon Stars

EOS	$M_G/M_\odot$	R(km)	n_c / n_0
BBB1	1.79	9.66	8.53
BBB2	1.92	9.49	8.45
WFF	2.13	9.40	7.81
APR	2.20	10.0	7.25
BPAL32	1.95	10.54	7.58
KS	2.24	10.79	6.30

WFF: Wiringa-Ficks-Fabrocini, 1988.
BPAL: Bombaci, 1995.
BBB: Baldo-Bombaci-Burgio, 1997.
APR: Akmal-Pandharipande-Ravenhall, 1988.
KS: Krastev-Sammarruca, 2006

$$M_{max} = (1.8 \text{ -- } 2.3)\ M_\odot$$

Hyperon Stars

Why is it very likely to have hyperons in the core of a Neutron Star?

- **The central density of a Neutron Star is "high": $n_c \approx (4 - 10)\, n_0$**
  $(n_0 = 0.17\ \mathrm{fm}^{-3})$

- **above a threshold density, $n_{cr} \approx (2 - 3)\, n_0$, weak interactions in dense matter can produce strange baryons (hyperons)**

$$n + e^- \rightarrow \Sigma^- + \nu_e$$

$$p + e^- \rightarrow \Lambda + \nu_e$$

etc.

A. Ambarsumyan, G.S. Saakyan, (1960)
V.R. Pandharipande (1971)

Hyperons in Neutron Stars: implications for the stellar structure

The presence of hyperons reduces the maximum mass of neutron stars: $\Delta M_{max} \approx (0.5 - 1.2)\ M_{\odot}$

Therefore, **to neglect hyperons always leads to an overstimate of the maximum mass of neutron stars**

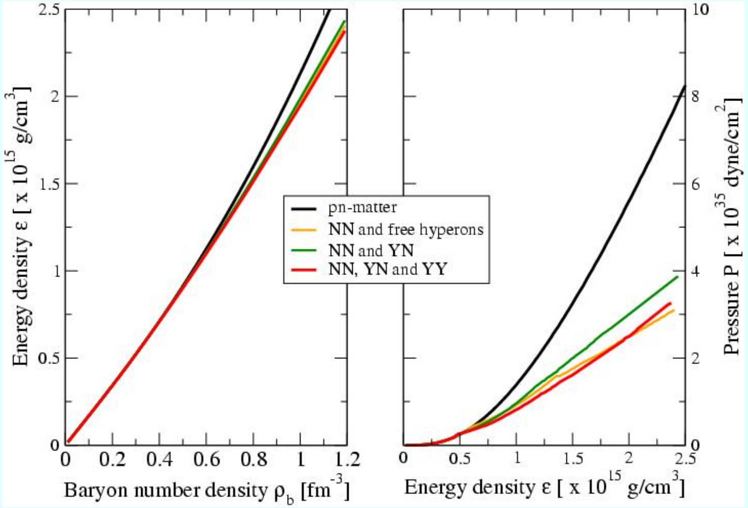
Microscopic EOS for hyperonic matter: "very soft" non compatible with measured NS masses

Need for extra pressure at high density

Improved NY, YY two-body interaction

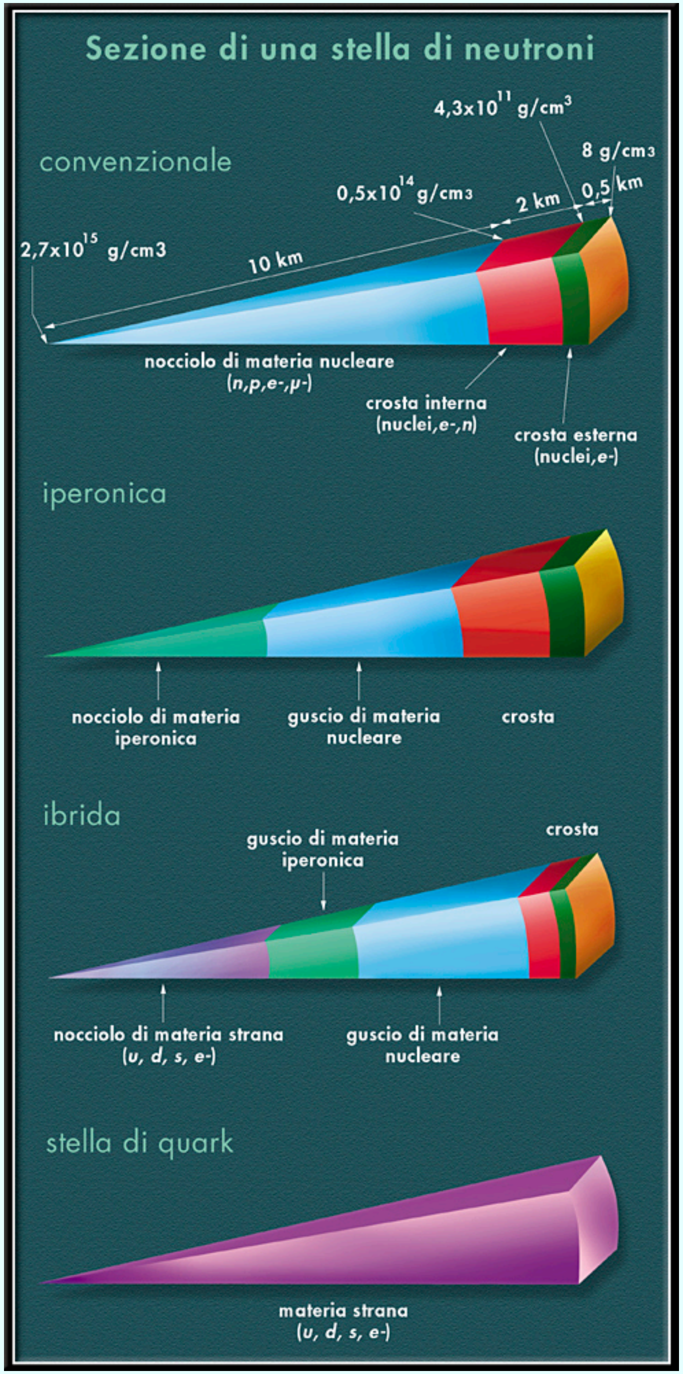
Three-body forces*: NNY, NYY, YYY

More experimental data from hypernuclear physics



(*) A preliminary study: **I. Vidana, D. Logoteta, C. Providencia, A. Polls, I. Bombaci, EPL 94 (2011) 11002**

“Neutron Stars”



I. Bombaci, A. Drago, INFN Notizie, n. 13, 15

Nucleon Stars

Hyperon Stars

Hybrid Stars

Strange Stars

Maximum ellipticity and maximum "mountain" height for different kind of "Neutron Stars"

Nucleon stars	$\varepsilon_{max} \approx 10^{-8} \div 10^{-6}$	$R\ \varepsilon_{max} \approx 10^{-2} \div 1\ \ \text{cm}$
Strange stars	$\varepsilon_{max} \approx 10^{-4}$	$R\ \varepsilon_{max} \approx 1\ \ \text{m}$
quark stars	$\varepsilon_{max} \approx 10^{-2}$	$R\ \varepsilon_{max} \approx 100\ \ \text{m}$

The detection of GW from neutron stars and the measurement of the ellipticity could contribute to understand the composition of the neutron stars and their equation of state.

In Search of Superluminal Quantum Communications: Recent Experiments and Possible Improvements.

Bruno Cocciaro*,

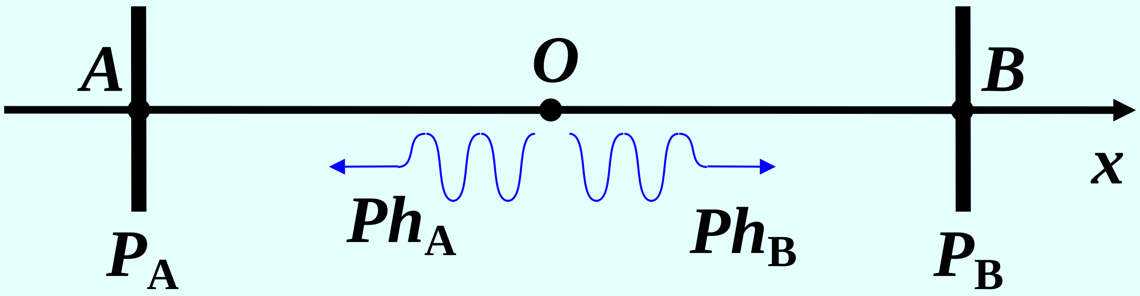
Sandro Faetti[+] ,

Leone Fronzoni[+].

+ Department of Physics, University of Pisa.

* High school XXV Aprile, Pontedera (Pisa).

The EPR Paradox (Einstein, Podolski, Rosen)



Ph_A e Ph_B: photons emitted at point O in the entangled state

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|HH\rangle + e^{i\phi}|VV\rangle\right)$$

H,V = horizontal and vertical polarization.

QUANTUM MECHANICS IS NON LOCAL: a measurement of polarization of photon Ph_A at point A leads to the collapse of state $|\psi\rangle$ and sets the polarization of photon Ph_B at point B even for "space like" events (Action at a distance ?).

- Superluminal communications (Bell[1], Eberhard[2], Bohm and Hiley[3]) The wave function collapse occurs locally and propagates at a distance through superluminal messengers (**tachyons**).

Causal paradoxes ? $\Longrightarrow$ **No, if a tachyons preferred frame (*PF*) exists (!)**

$\vec{V} = \vec{\beta} c$ **: velocity of *PF* with respect to the laboratory.**

$V_t = \beta_t c$ **: tachyon's velocity in the *PF*.**

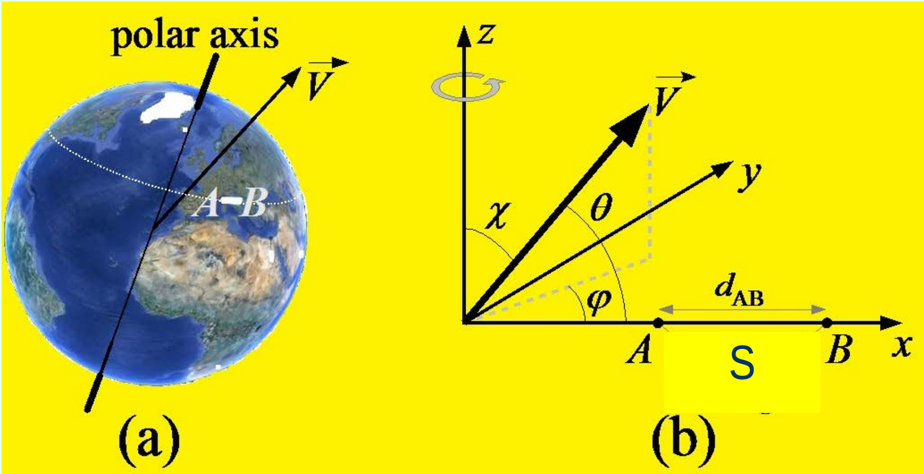
Tachyons preferred reference frame. The two polarizers are placed in points *A* and *B* and distances d_A e d_B from the emitting point *S*

Photons will cross polarizers at times $t_A = d_A / c$ e $t_B = d_B / c$. The time required by a tachyon emitted by *A* (or *B*) to reach *B* (or *A*) is $T = (d_A + d_B) / V_t$. If $T > |t_A - t_B| = |(d_A - d_B)/c|$, the first photon which passes through a polarizer will have no sufficient time to "advice" the other photon before it encounters the other polarizer and substantial deviations from the predictions of *QM* should be observed.

1: J. S. Bell in P. C. W. Davies and J. R. Brown, "The Ghost in the Atom", Cambridge University Press (1986)
2: P. H. Eberhard, *A realistic model for Quantum Theory with a locality property*, in W. Shommers (Ed.), "Quantum Theories and Pictures of Reality", W. Schommers, ed., Springer Verlag, Berlin (1989).
- *Restoring Locality with Faster-Than-Light Velocities*, Lawrence Berkeley Lab., LBL-34575, (Aug. 1993).
3: D. Bohm and B. J. Hiley, "The undivided universe", Routledge (1993)

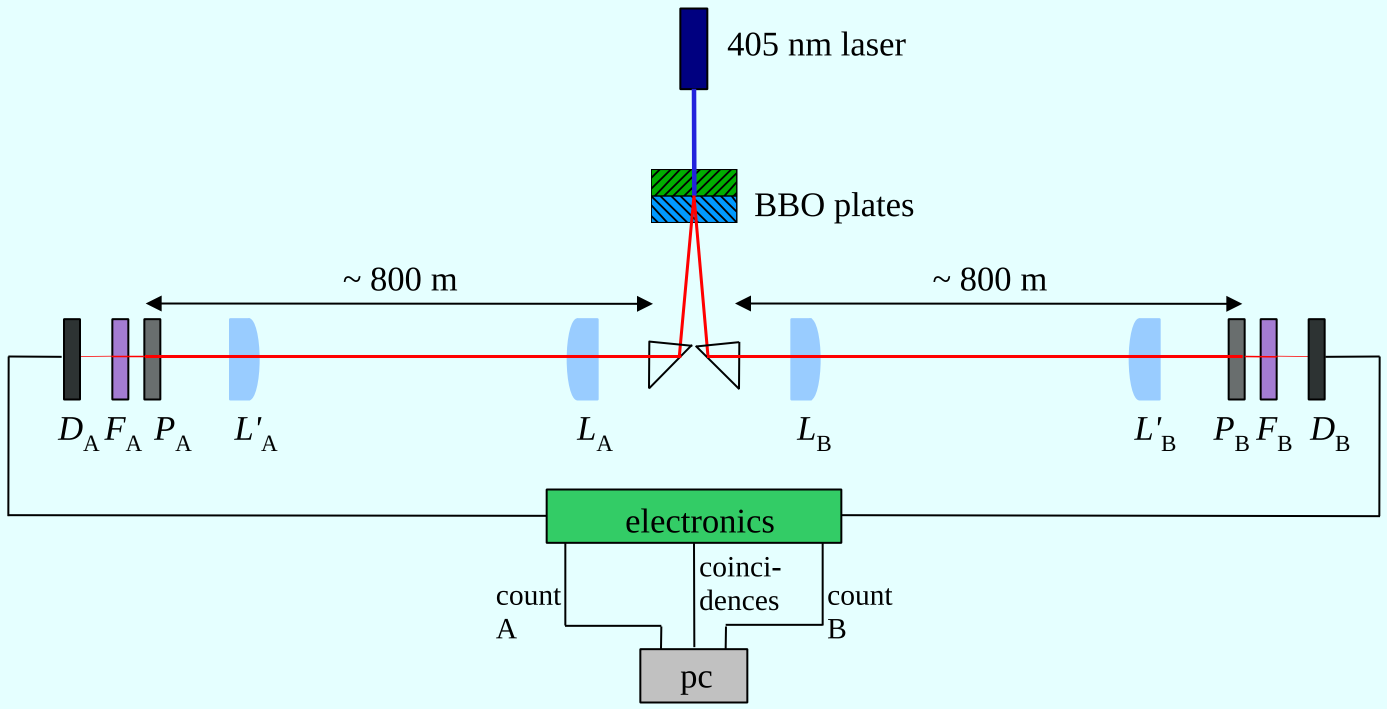
Search for deviations from QM correlation when the experiment is at rest or with tachions frame speed orthogonal to the line joining the two detectors

If the reference frame speed is orthogonal to the line joining the two detectors then two events in coincidence in the laboratory frame will be in coincidence also in the tachions frame→ the tachions have no more time to advice the photon prior to reach the other detector



If the segment AB is oriented east-west there are at least 2 «moments» each day when the condition is satisfied

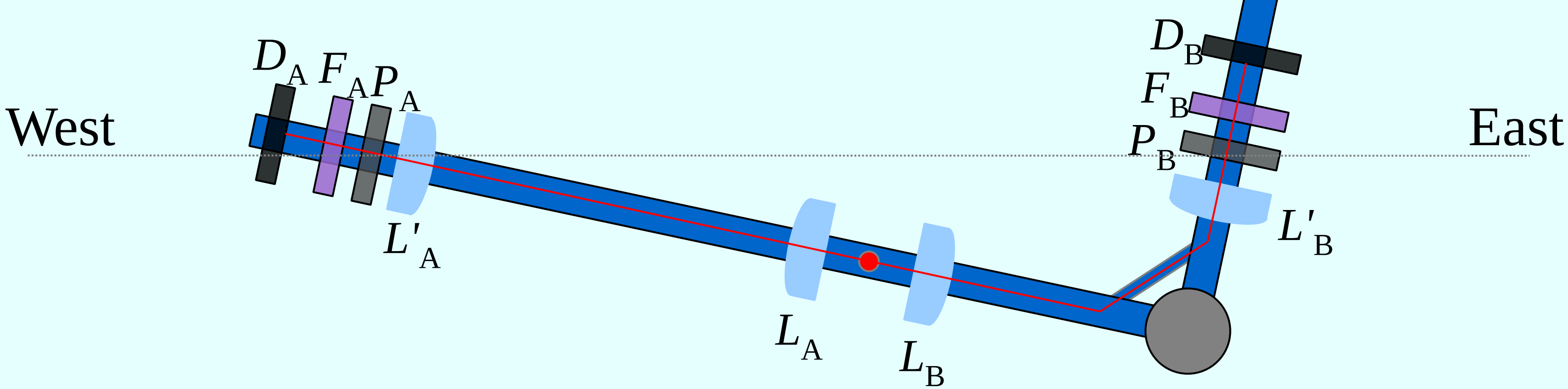
Schematic view of the experimental apparatus



L_A, L'_A, L_B, L'_B = plano-convex lenses with focal length f = 7.5 m and diameter ϕ = 15 cm;
P_A, P_B = polarizing plates;
F_A, F_B = bandpass optical filters ($\Delta\lambda$ = 10 nm);
D_A, D_B = Detectors (avalanche photodiodes + electronics).

Virgo arms are not East-West oriented

In Air



Lower bonds on tachion speed

$$\beta_{t,\min} = \sqrt{1 + \frac{\left(1-\beta^2\right)\left[1-(\Delta\rho)^2\right]}{\left[\Delta\rho + \beta\sin(\chi)\sin\left(\frac{\pi}{T}\delta t\right)\right]^2}}$$

β = V/c = preferred frame velocity,

T = sidereal day,

$$\Delta\rho = \frac{\Delta d}{d_{AB}} << 1$$

(Δd = difference of optical paths), δt = acquisition time ($\delta t << T$),

χ = angle between AB and polar axis

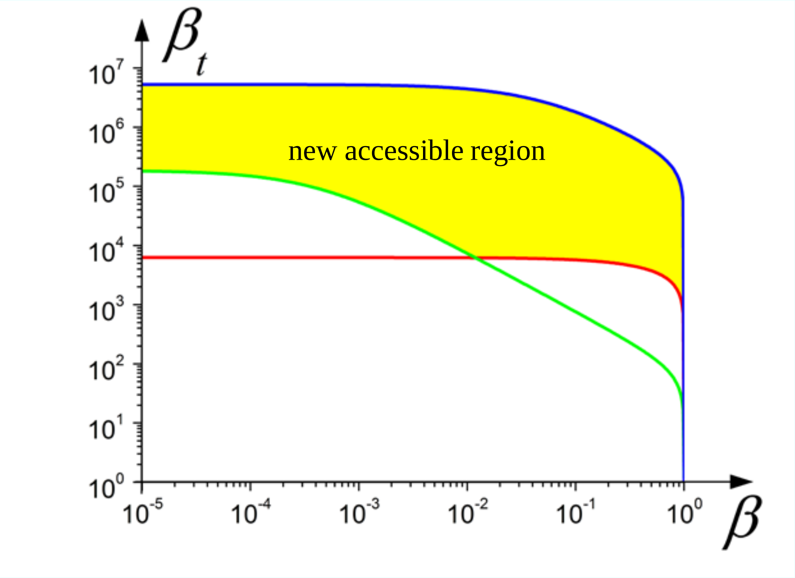


Figure: present and expected limits on tachion speed

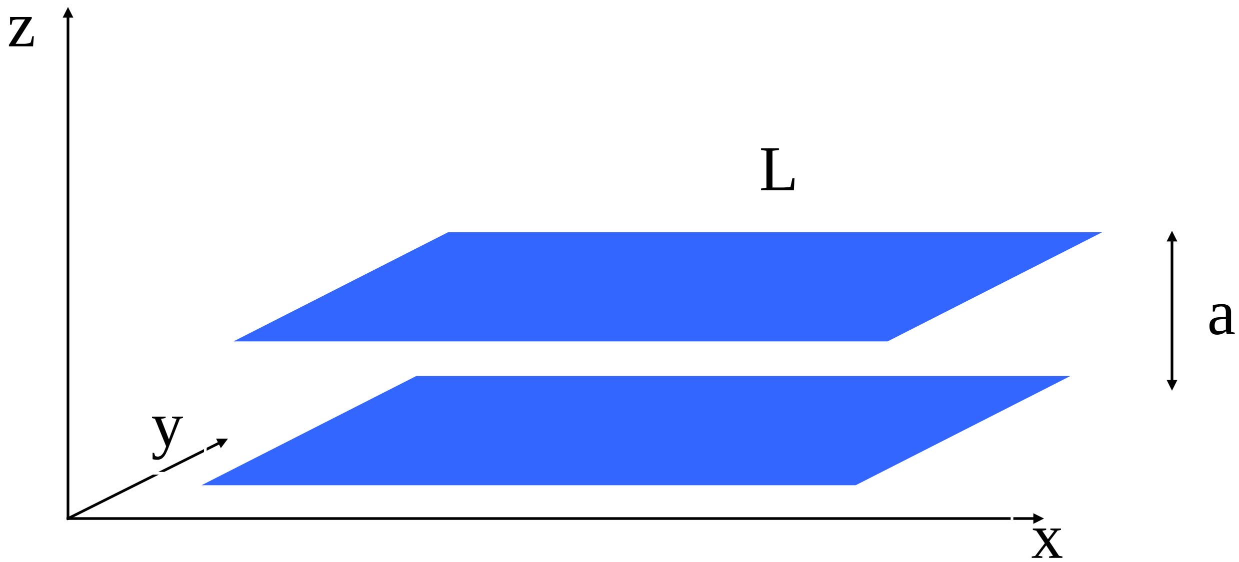
Towards measuring the Archimedes force of vacuum

INFN_Virgo sez Napoli & Laboratorio di Fisica della Gravitazione Fed. II Napoli
INFN_Virgo sez Pisa
INFN_Virgo sez Roma1

⋮

E. Calloni - Takayama 26-05-2014

The Casimir effect is a macroscopic manifestation of vacuum fluctuations. It is derived considering the zero point e.m. energy contained in a Casimir cavity, i.e. in the volume defined by two perfectly reflecting parallel plates



$$E = \sum \frac{1}{2}\hbar\omega$$

If the plates are perfectly reflecting the modes that can oscillate must have discrete wavenumbers on vertical axes $k_z = n\pi/a$ while all values are allowed for k_x e k_y

$$E = \frac{hcL^2}{2} \sum_{n=-\infty}^{n=\infty} \int \frac{d^2k}{(2\pi)^2} \sqrt{k^2 + \left(\frac{n\pi}{a}\right)^2} \longrightarrow \infty$$

The regularization is made by determing the Casimir Energy as the <u>change</u> in energy (in the same volume) when the plates are at distance “a” with respect to the plates having a→infinity

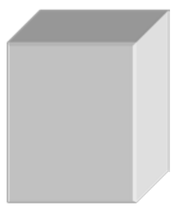
$E_{reg} = E(a) - E(\infty)$

- **Casimir Energy** $$E_{reg} = -\frac{\pi^2 L^2 hc}{720 a^3}$$
- **Casimir Pressure** $$P_C = \frac{1}{L^2}\frac{\partial U}{\partial a} = -\frac{\pi^2 hc}{240 a^4}$$ $= 1.3\times10^{-3}\ N/m^2 (1\mu m/a^4)$

First prediction: Casimir 1948
First measure (force): Sparnay 1956
Presently tested (force) with an accuracy of 0.5% (Mohideen: 2005)
(No problems in QFT in flat space-time)

Scientific motivations and goal of the experiment

- The scientific problem addressed is within the interaction of vacuum fluctuations with gravity -- cosmological constant problem : “why the universe exhibits a vacuum energy density much smaller than the one resulting from application of quantum mechanics and equivalence principle?



$$\sum \frac{1}{2}\hbar\omega \quad \Longrightarrow \quad \infty$$

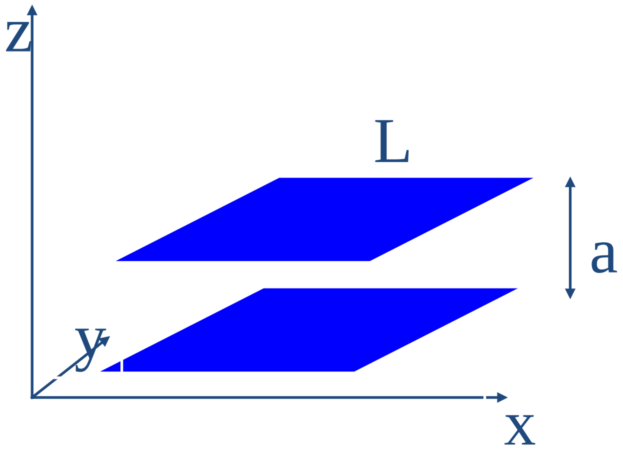
The first calculation of the radius of the universe as expected by applying general relativity and a energy density as foreseen by zero point fluctuations - with a cut off to highest frequencies/wavelenghts equal to the electron radius – dates back to Pauli – 1931 that found

R = 31 km !

Many remarkable and important theoretical attemps since then but not an experiment:
Does vacuum fluctuations gravitate or not?

Weighing the vacuum

The idea is to weigh a rigid Casimir cavity when the vacuum energy is modulated by changing the reflectivity of the plates. The forces along z are



$$\begin{cases} F_{\sup} = F_C \\ F_{\inf} = -F_C\left(1+\delta\phi\right) + \dfrac{\left|E_C\right|}{c^2} g \end{cases}$$

$$\delta\phi = \frac{g \cdot a}{c^2}$$ ⇔ difference of gravitational potential between the plates

$$\vec{F}_{tot} = \frac{\left|E_C\right|}{c^2} g \;\; \hat{z}$$

The total force is directed upward an it is equal to the weigh of the vacuum displaced

Something a bit more subtle

A simple summation of the lower force and upper force on the plates would bring to a somewhat unespected result:

$$F_{cas} = -L^2 \frac{\pi\hbar c}{240a^4}$$

$$F_{\inf} + F_{\sup} = F_{cas}\left(1+\delta\phi\right) + \frac{|E_C|}{c^2} g - F_{cas} = 4\frac{|E_C|}{c^2} g$$

$$E_{cas} = -L^2 \frac{\pi\hbar c}{720a^3}$$

The lower vacuum «photons» must exert a bigger force because the force will be red-shifted when reaching the same level of upper plate → the sum must be done taking into account the red-shift

$$\begin{cases} F_{\sup} = F_C \\ F_{\inf} = -F_C\left(1+\delta\phi\right) + \frac{|E_C|}{c^2} g \end{cases} \Longleftrightarrow \vec{F}_{tot} = \frac{|E_C|}{c^2} g \ \hat{z}$$

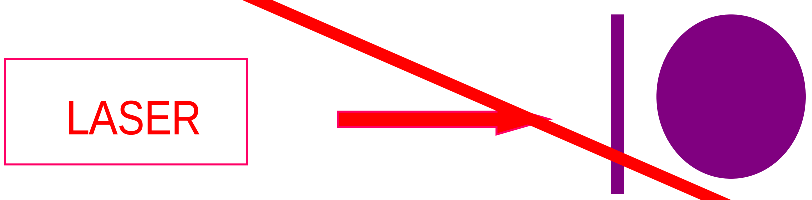
E. Calloni et.al. Phys. Letters A, 297, 328-333, (2002)

S. A. Fulling et al. Phys. Rev. D76:025004 (2007)
K.A. Milton et al. J. Phys. A 41:164052 (2008)
G. Bimonte, E. Calloni et. al. Phys.Rev.D76:025008, (2007)

On interpretation of Tolman-Ehrenfest effect:

C. Rovelli, M. Smerlak Class. Quant. Grav. 28 (2011) 075007 , arXiv:1005.2985
Hal M. Haggard and Carlo Rovelli, arXiv:1302.0724

Experimental problem: modulate Casimir energy without exchanging too much energy with the system (to not destroy the possibility of measurement and control) and measure it.



The energy E sent to the film is about 5x10^(5) J

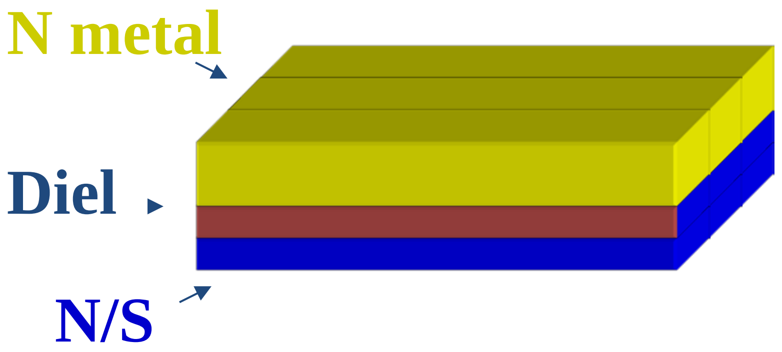
The variation of casimir energy ΔE_{cas} is about 2.5x10^(-19) J

The efficiency is $\varepsilon = \Delta E_{cas}/E = 10^{(-14)}$

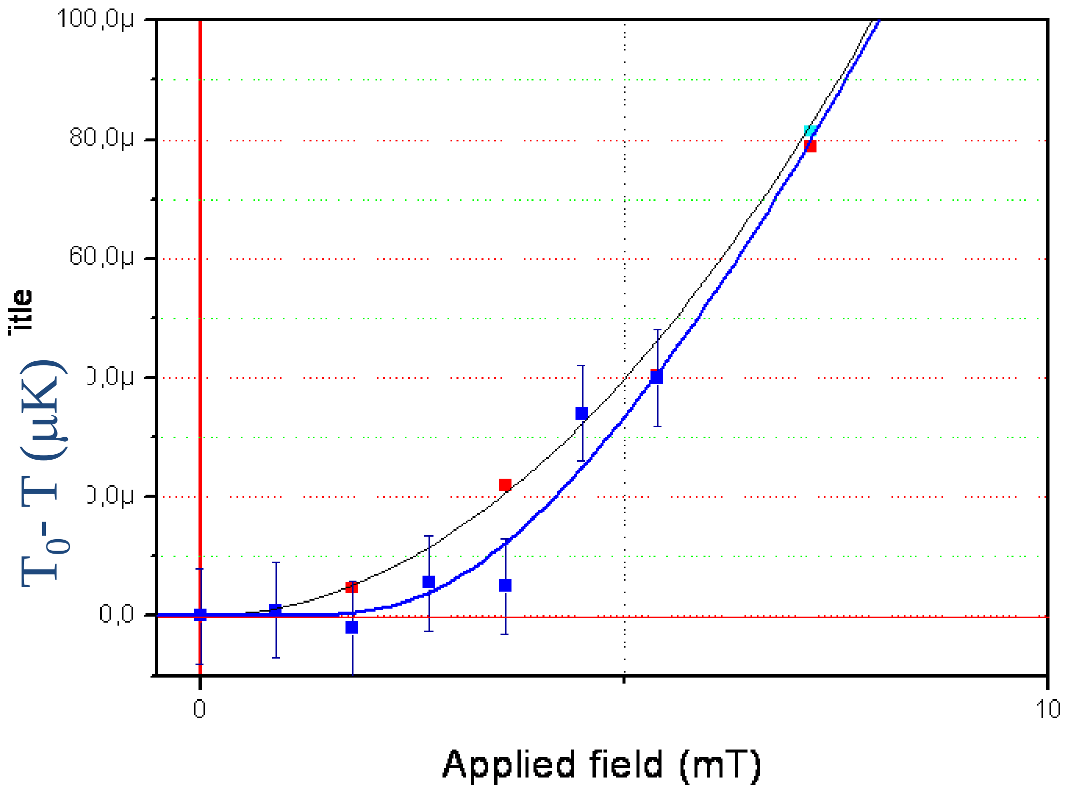
Thanks U. Mohideen for discussion

Use of superconductors

- The condensation energy is very small so it can be expected that the variation of Casimir energy at the transition for a superconductor inside a cavity can be of the same order, or even dominates, the total transition energy



Results and references on energy modulation



The data are not in contrast with the theory and the region of energy of different behaviour is the expected one

2008

Bimonte G et al. 2005 Nuclear Physics B **726** 3 441-463

Bimonte, G et al 2005. 10.1103/PhysRevLett.94.180402 2005

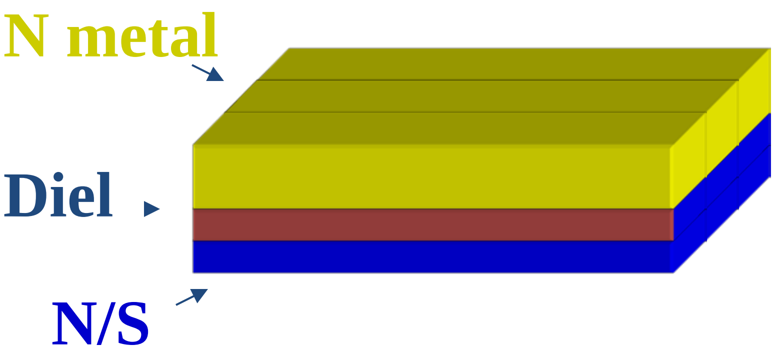
Bimonte G. *et al* 2008 *J. Phys. A: Math. Theor.* **41** 164023

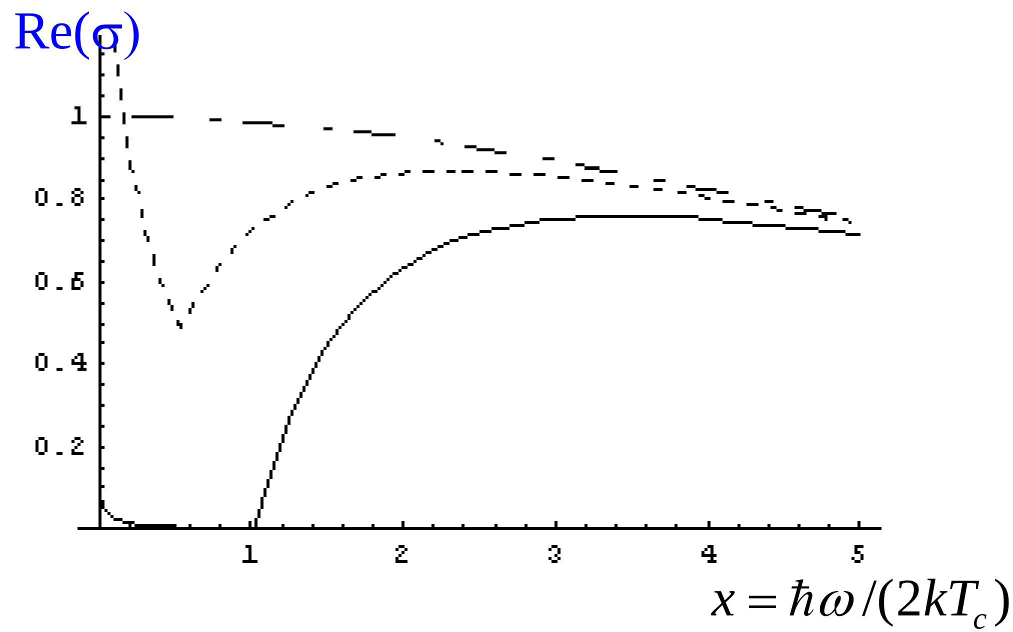
Allocca A et al 2012 Jour. Of. Supercond. And Novel Magnetism. **25**, 8, 2557-2565

The change in energy can be calculated following the Casimir energy calculation in case of real plates with complex conductivity σ

$$\Delta E_C = -\Delta\eta_E \frac{\hbar c \pi^2}{720} \frac{A}{L^3}$$

$\Delta\eta_E$ modulation factor with respect perfect reflectivity





$$\Delta\eta_E = \frac{\Delta E_C}{E_C} \approx \frac{kT_C}{h\nu_C} = \frac{kT_C}{hc/L} \approx 10^{-6}$$

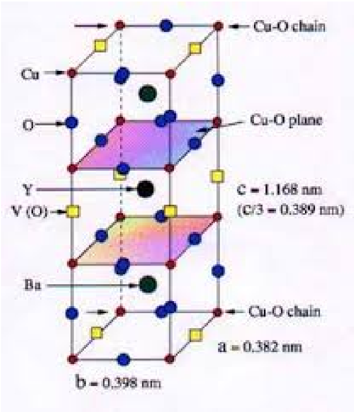
Plot of real part of conducibility σ normalized to zero frequency Drude conducibilty σ_0 for different temperatures:

— · - T = Tc (Drude) .... T/Tc = 0.9 ——T/Tc = 00.3

The conducibility changes only in the very low frequency region (microwave) so the modulation depth (if Tc is of the order of 1 K) is expected to be small for small T_c…

The experimental proposal → use of high Tc layered superconductors

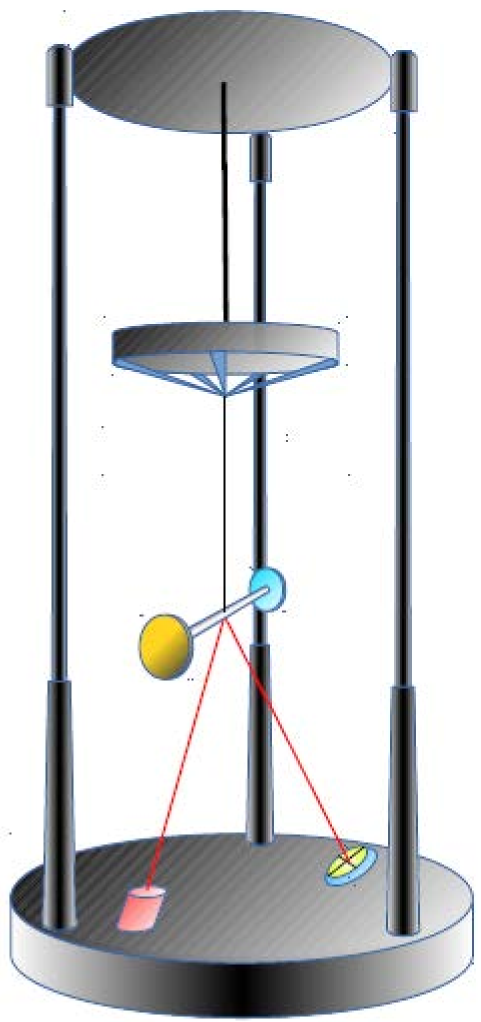
1) Use high_Tc layered superconductors as natural multi Casimir-cavities
2) Profit of the fact that in normal state the plane (that will become superconducting) is a very poor conductor → high variation of Casimir energy at the transition



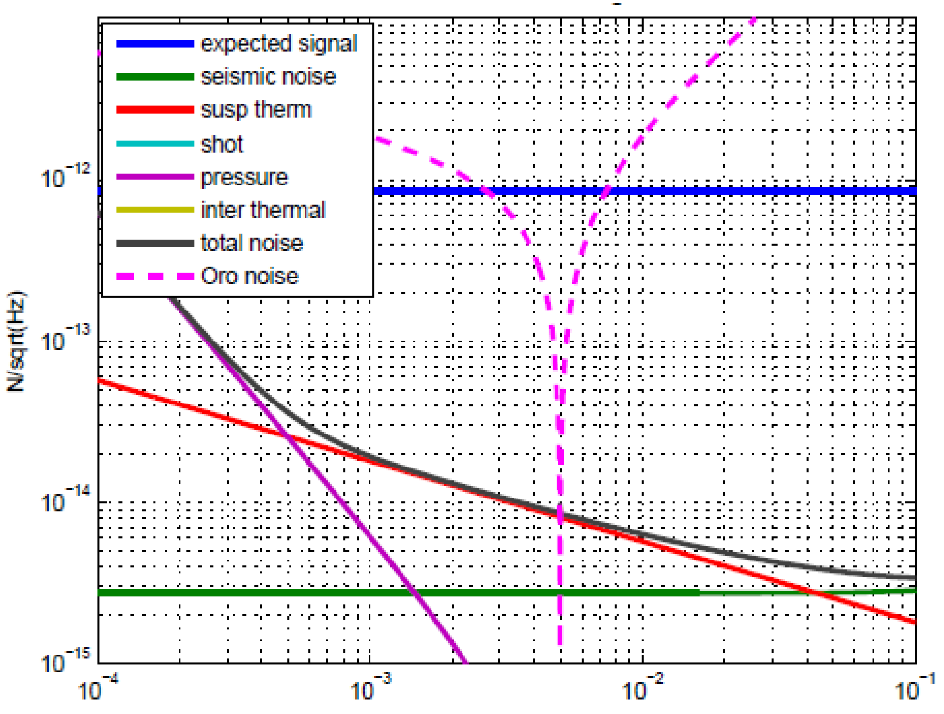
State of the art in the knowledge of Casimir energy in layered superconductors

1) The unique esperiment to demonstrate that Casimir energy does play a role in the superconducting transition (i.e. it sums to the Helmholtz free energy as expected) has been done by our group on type I superconductor
2) Approximate theory for high_Tc superconductor (plasma sheet no dissipation – zero temperature) – Kempf hypothesis: in layered susperconductors the contribution to free energy is comparable to total condensation energy

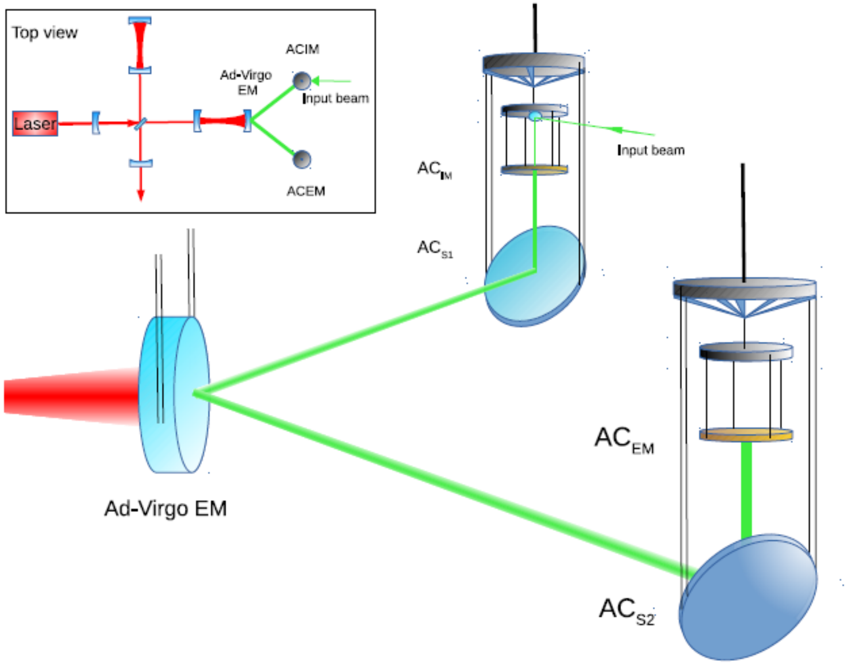
Scheme with balance and local detection



- ❑ Seismically isolated balance
- ❑ Temperature modulation around Tc
- ❑ Balance tilt possibly read with an optical lever

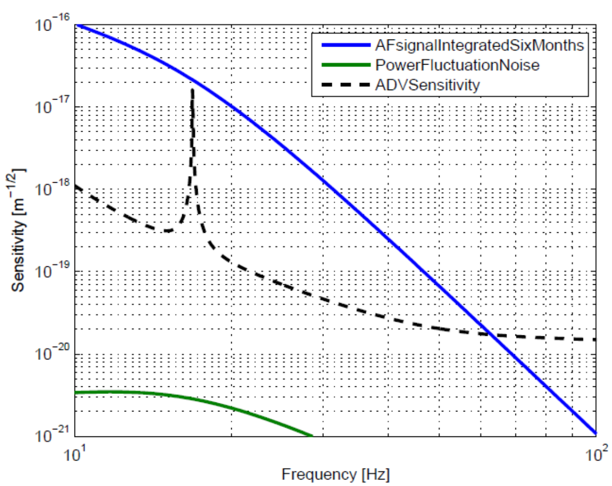


Signal and Sensitivity: expected signal amplitude for a fixed modulation frequency **(blue curve)** - total noise for interferometric detection (black curve) and optical lever (pink dashed curve)

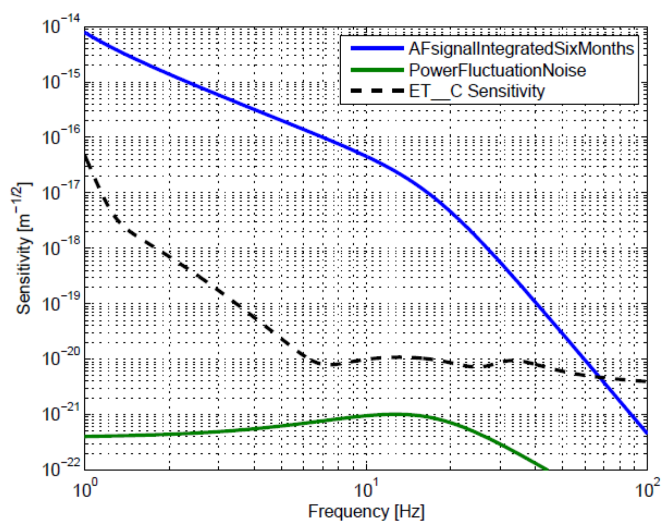


Use of GW detectors

The force is exerted on the GW detector test mass GE_EM via radiation pressure: (an optical spring, the cavity being done with AF_IM as input mirror, GW_EM as remittal mirror and AF_EM as end mirror): signal calculated under Kempf hypothesis



Sensitivity with Adv_Virgo



Sensitivity with ET

A curious citation

In the framework of quantum engineering propulsion for the futures spacecrafts our result has been cited in the paper:

"A gedanken spacecraft that operates using the quantum vacuum (Dynamic Casimir Effect) "

Foundations of physics 34, pag 477 (2004)

our result is proposed "..to make lighter and modulate the weight of the future spacecrafts….."

Is the author of this paper a visionary ?

↕

R. L. Forward – J. Maclay

R. L. Forward realized the first prototype
of interferometric gravitational wave detector !
1972 (Malibu laboratiores – California)

Conclusion

- Theory of vacuum fluctuations in gravitational field
- Modulation of vacuum energy in layered Supercondutoring systems

- **Improvement of seismic performances at low frequency**
- **Improvements of low temperature high quality optical material s**

Calloni et.al. Phys. Letters A, 297, 328-333, (2002) – Bimonte et al. CQG 21 647 (2004) - Bimonte et al. PRD 74, 085011 (2006) - Bimonte, et. al. PRD 76:025008 (2007) – Bimonte et al. PRD 77, 044026 (2008) – Bimonte et al. PRL 94, 180402 (2005) – Bimonte et al. Nucl Phys B 726 441 (2005) – Bimonte et al. J. Phys. A: Math. Theor. 41 (2008) 164023 - Allocca et al. J. Supercond. Nov. Mag 25 2557 (2012)

Towards measuring the Archimedes force of vacuum
E.Calloni, M.De Laurentis, R. De Rosa, F. Garufi, L. Rosa, L, Di Fiore,G. Esposito, C.Rovelli, P. Ruggi, F. Tafuri
arXiv:1401.6940 accepted with revision PRD