Gravitational Waves: Challenges and New Physics

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Graviton Group

GRAVITON GROUP

INPE

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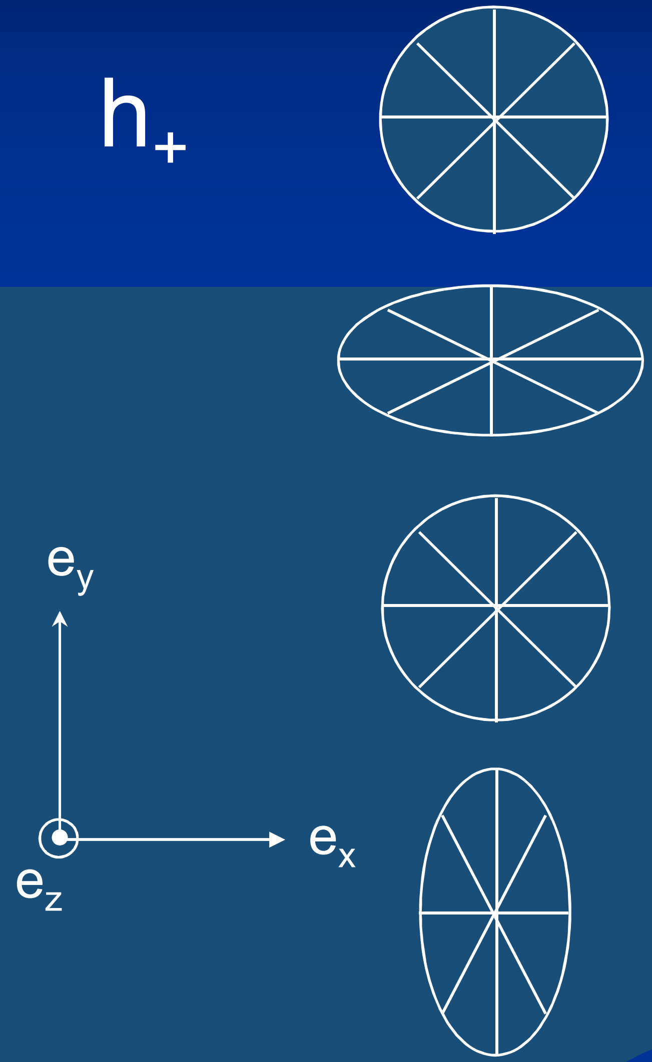
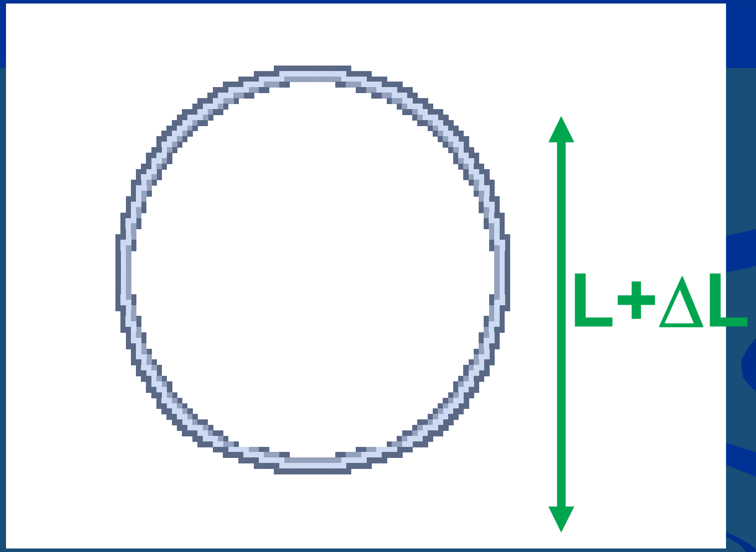
Gravitational Waves

- 1916 - Einstein proved mathematically, from his theory of General Relativity, that gravitational waves should exist.

- These gravitational waves, caused by the accelerated mouvements of masses, would be distortions of the ***spacetime*** which would be travelling in the Universe with the speed of light.

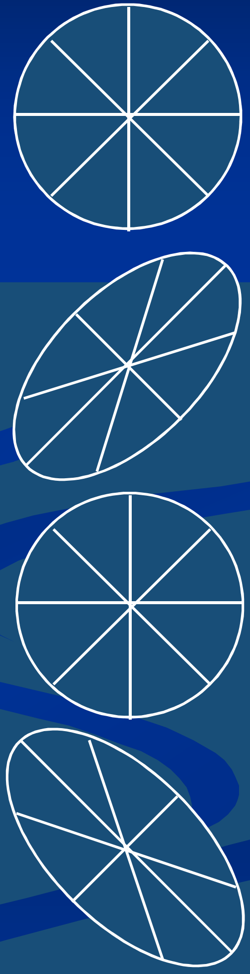
Two polarizations “+” and “x”





Deformation of a ring made of test particles

h_x



$$h = \Delta L / L = ((h_+)^2 + (h_x)^2)^{1/2}$$

Gravitational Waves (GWs): do they really exist?

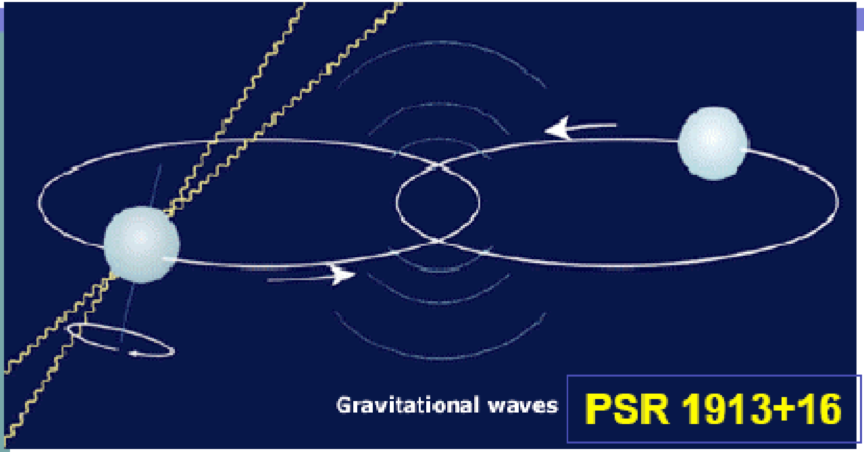
- Half century of theoretical debate (1916-1965);
- A direct detection hasn’t been confirmed yet after four decades (1965-2009) of observational search.

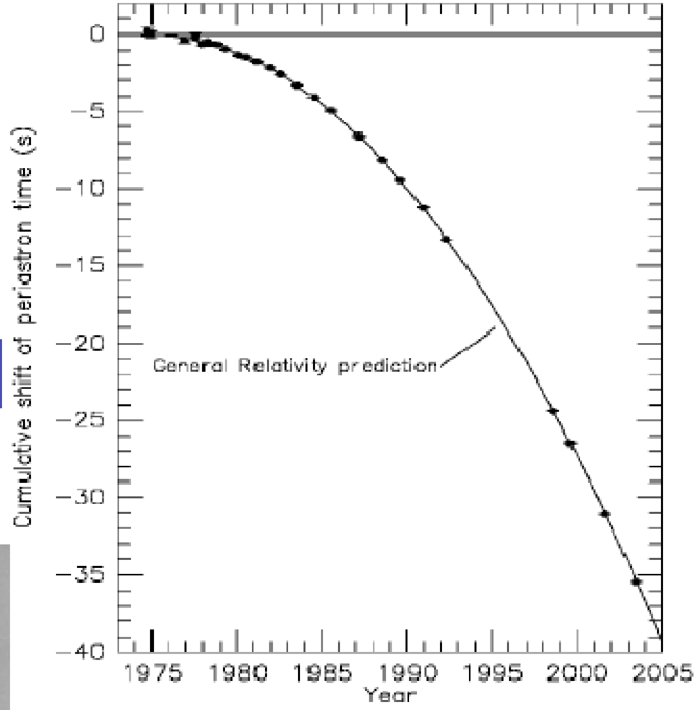
- A good evidence (an indirect observation):

  PSR 1913+16 (Taylor & Hulse 1974)

  (Sistem of two neutron stars with periods of 7h45min, in which one of them is a Pulsar)

First verification of GWs



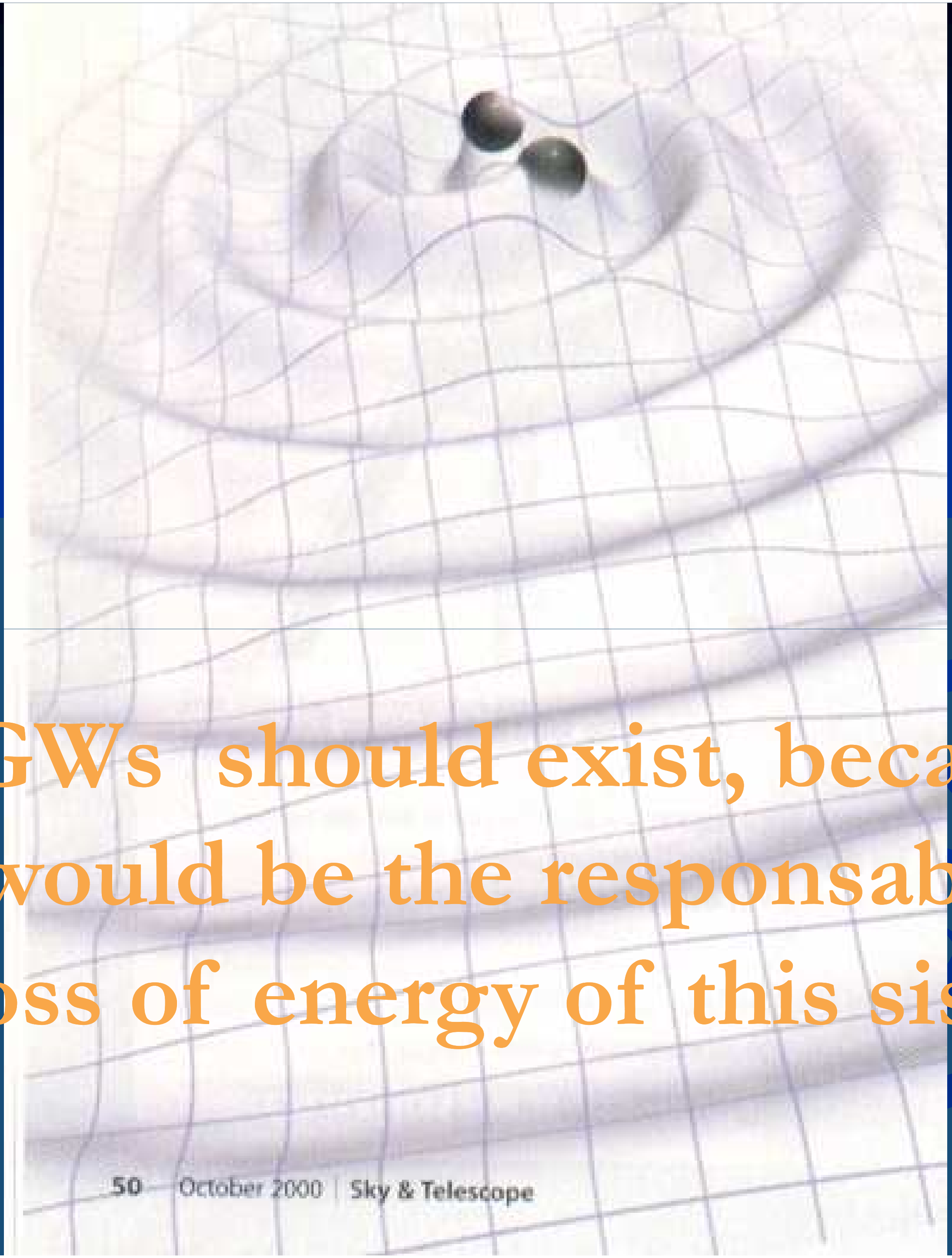


Nobel 1993

Hulse & Taylor

$$\frac{\dot{P}_{b,corrected}}{\dot{P}_{b,GR}} = 1.0013 \pm 0.0021$$

credit: Kostas Kokkotas



⇒ GWs should exist, because they would be the responsable for the loss of energy of this sistem.

$$\nabla . \mathbf{E}_g = -4\pi G\rho$$

Newton’s law (analogue to Gauss’ law)

$$\nabla . \mathbf{B}_g = 0$$

analogue to Gauss’ law for magnetism

$$\nabla \times \mathbf{E}_g = -\frac{1}{c}\frac{\partial \mathbf{B}_g}{\partial t}$$

analogue to Faraday’s law of induction

$$\nabla \times \mathbf{B}_g = \frac{1}{c}\left(-4\pi G \mathbf{J} + \frac{\partial \mathbf{E}_g}{\partial t} \right)$$

analogue to Ampère’s circuital law

with Maxwell’s correction

$\mathbf{E}_g$	is the static gravitational field (or gravitoelectric field);
$\mathbf{B}_g$	is the gravitomagnetic filed;
ρ	is mass density;
$\mathbf{v}_\rho$	is the velocity of the mass flow generating the gravitomagnetic field;
$\mathbf{J} = \rho\, \mathbf{v}_\rho$	is mass current density;
G	is the gravitational constant;
c	is the speed of propagation of gravity (the speed of light in general relativity).

For a test particle of mass m and instantaneous velocity $\mathbf{v}_m$, the net (Lorentz) force acting on it due to a GEM field is described by the “Lorentz” force equation in gravitation:

$$\mathbf{F}_m = m\left(\mathbf{E}_g + \frac{\mathbf{v}_m}{c} \times 2\mathbf{B}_g \right)$$

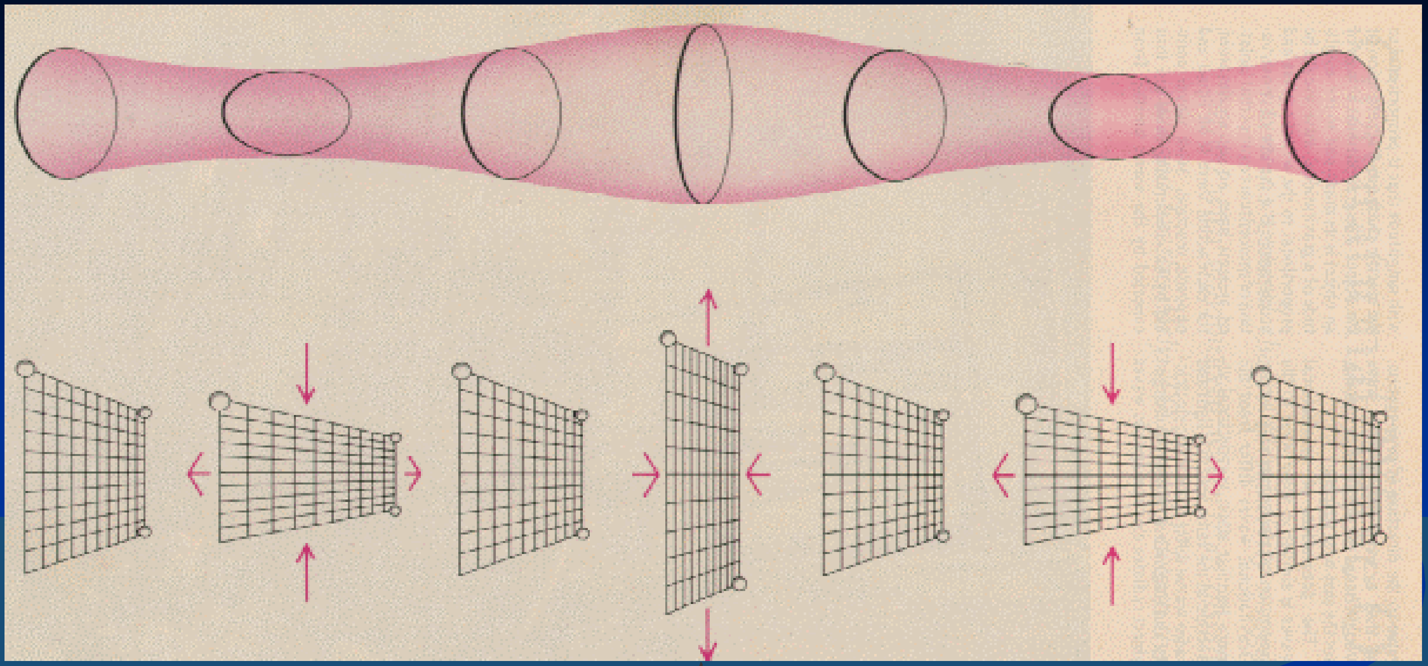
In vacuum:

$$\nabla \times \mathbf{E}_g = -\frac{1}{c}\frac{\partial \mathbf{B}_g}{\partial t}$$

$$\nabla \times \mathbf{B}_g = \frac{1}{c}\frac{\partial \mathbf{E}_g}{\partial t}$$

The changing gravitomagnetic field creates a changing gravitoelectric field through the analogue of Faraday’s law for gravitation. That gravitoelectric field, in turn, creates a changing gravitomagnetic field through the analogue of Maxwell correction to Ampère’s law for gravitation. This perpetual cycle allows these waves to propagate through space at velocity c.

LIGO collaboration



Why have they not been detected yet ?

Because they are hard to be detected .

Why are they so hard to be detected ?

Gravitational Waves

- Two polarizations ("+" and "x") according to General Relativity
- Wave frequencies: 10^{-18} Hz to 10^{10} Hz
- Very tiny amplitudes: $h = \Delta L/L < 10^{-19}$
- Energies associated to $\Delta L \sim 10^{-19}$ m amplitudes:

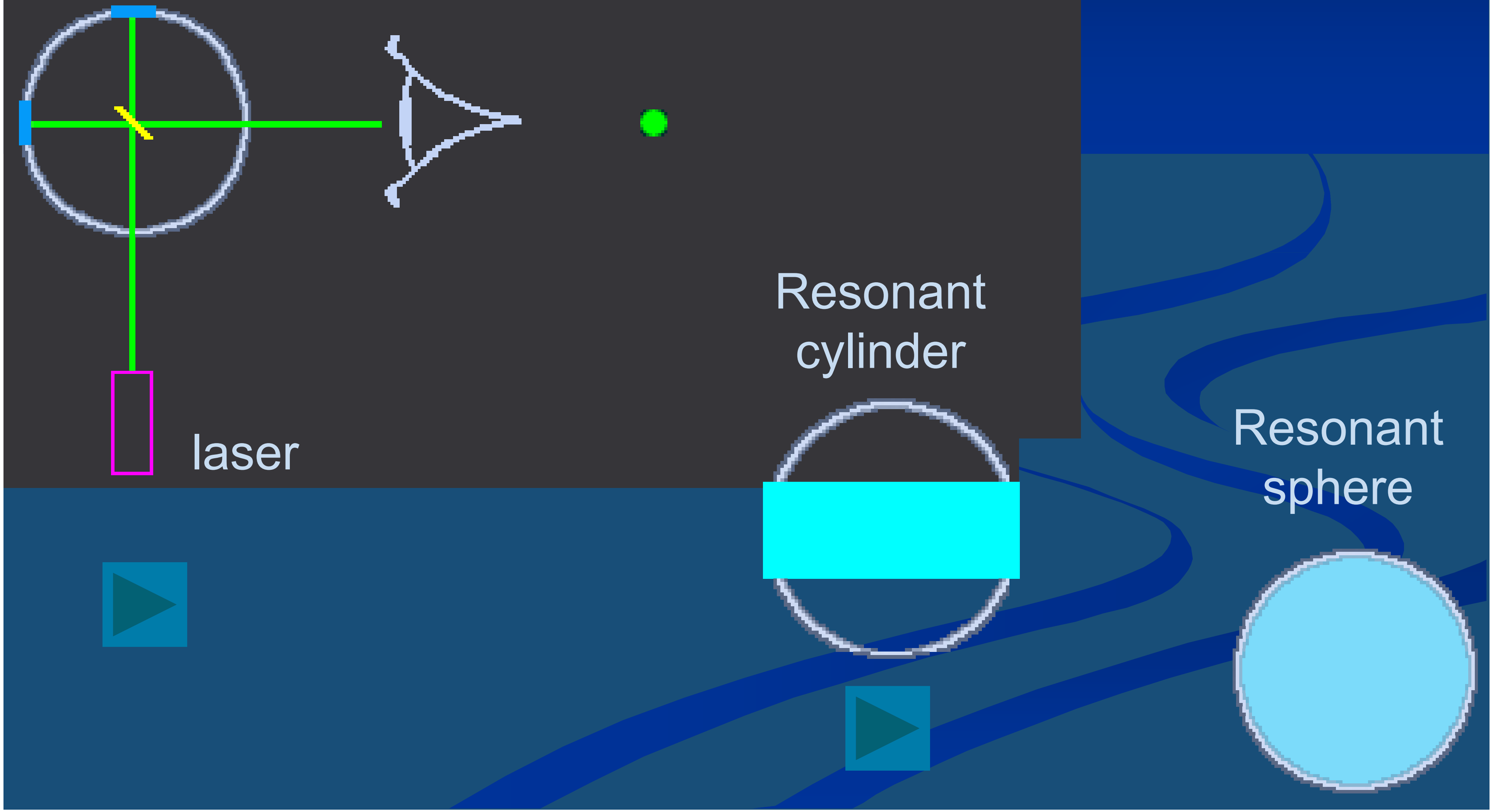
for the Schenberg detector → $\sim 6 \times 10^{-28}$ Joules

or 290 gravitons !

This is 10^{-9} times the energy of a photon of light !

by Arlette de Waard

Gravitational Wave Detectors



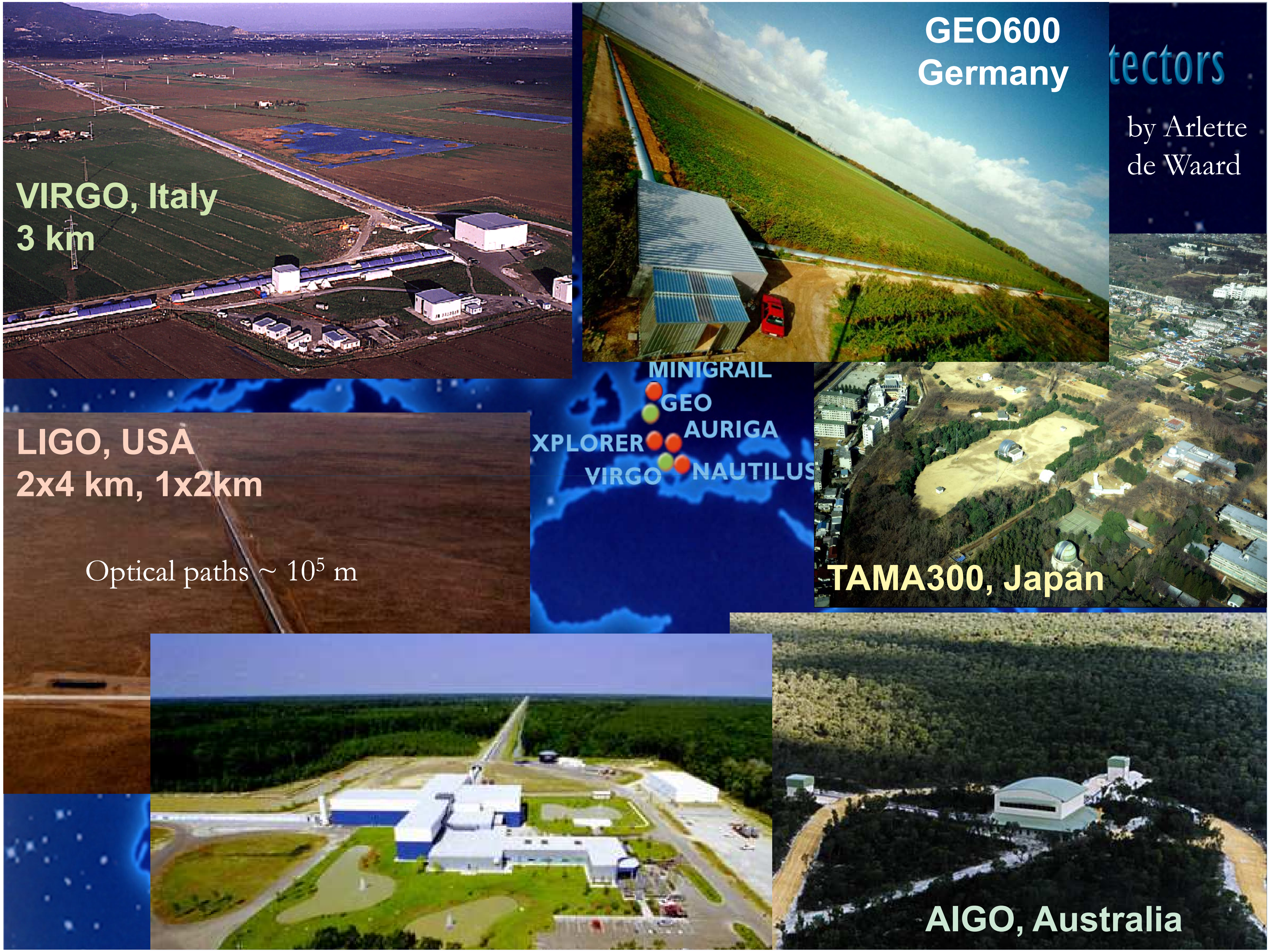
laser

Resonant cylinder

Resonant sphere

tectors

by Arlette de Waard



VIRGO, Italy
3 km

GEO600
Germany

LIGO, USA
2x4 km, 1x2km

Optical paths ~ 10^5 m

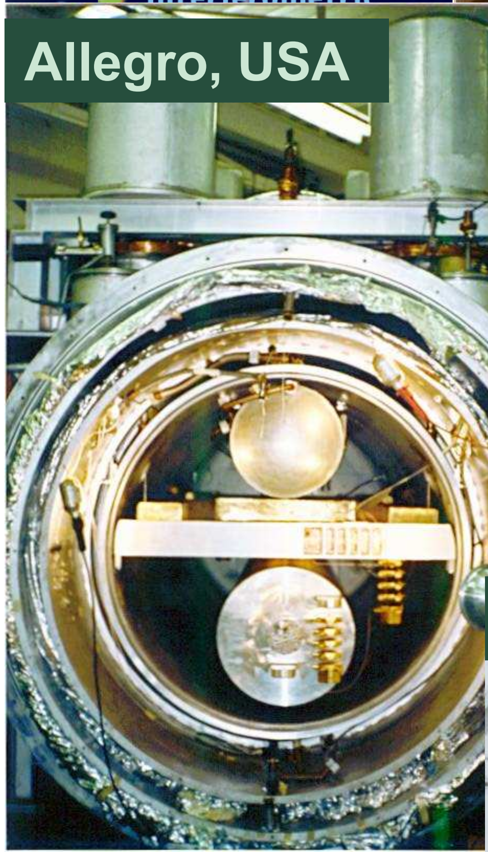
TAMA300, Japan

AIGO, Australia

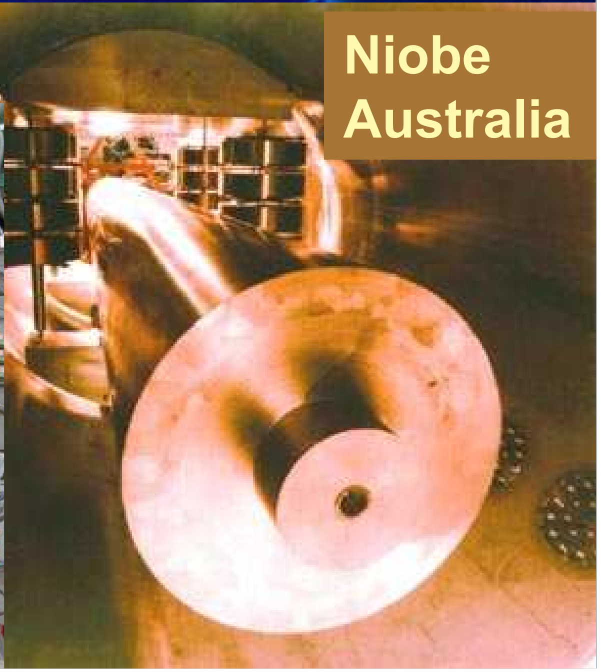
by Arlette de Waard


Explorer
Switzerland


Auriga, Italy


Allegro, USA

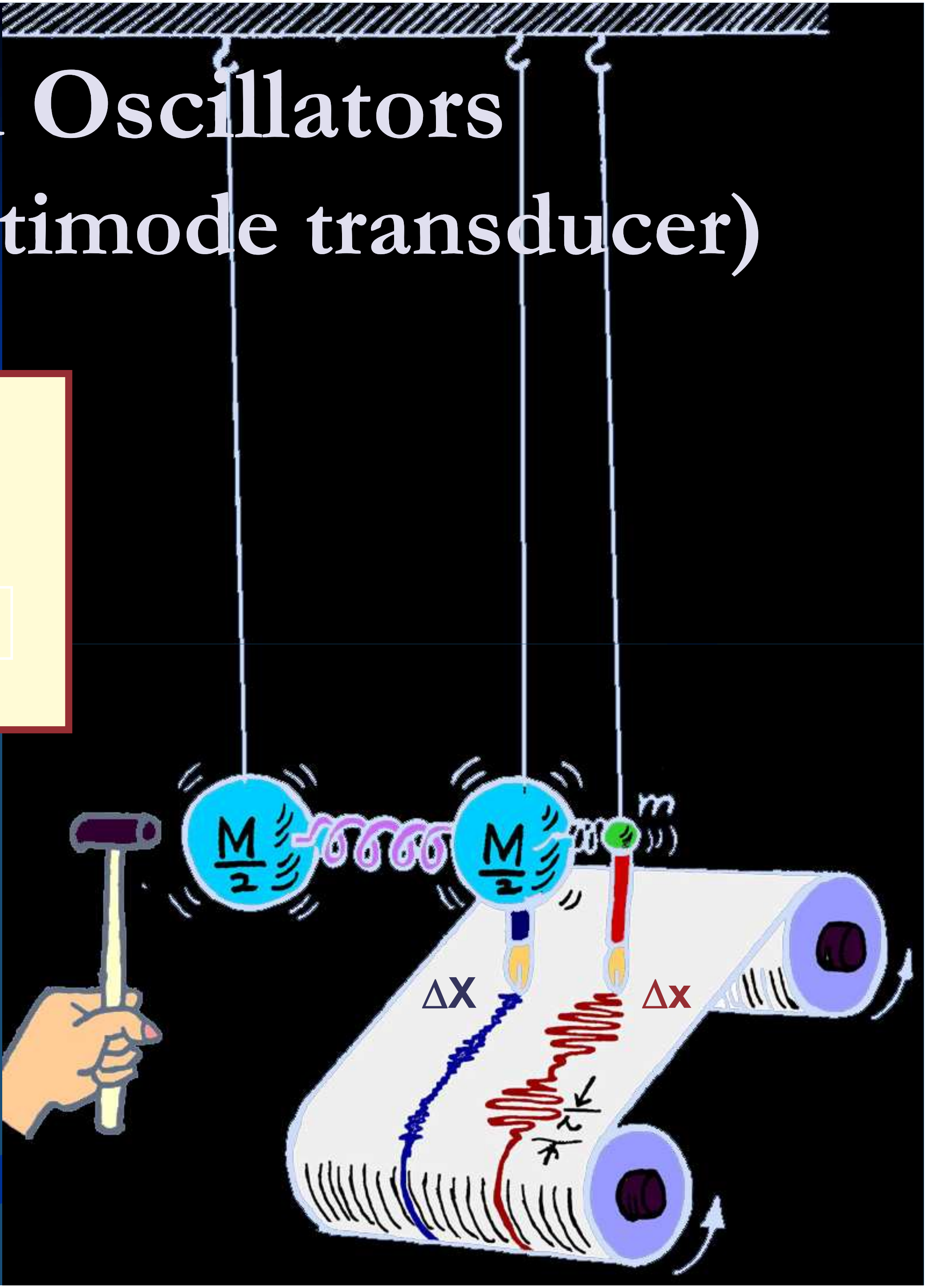

Nautilus, Italy


Niobe
Australia

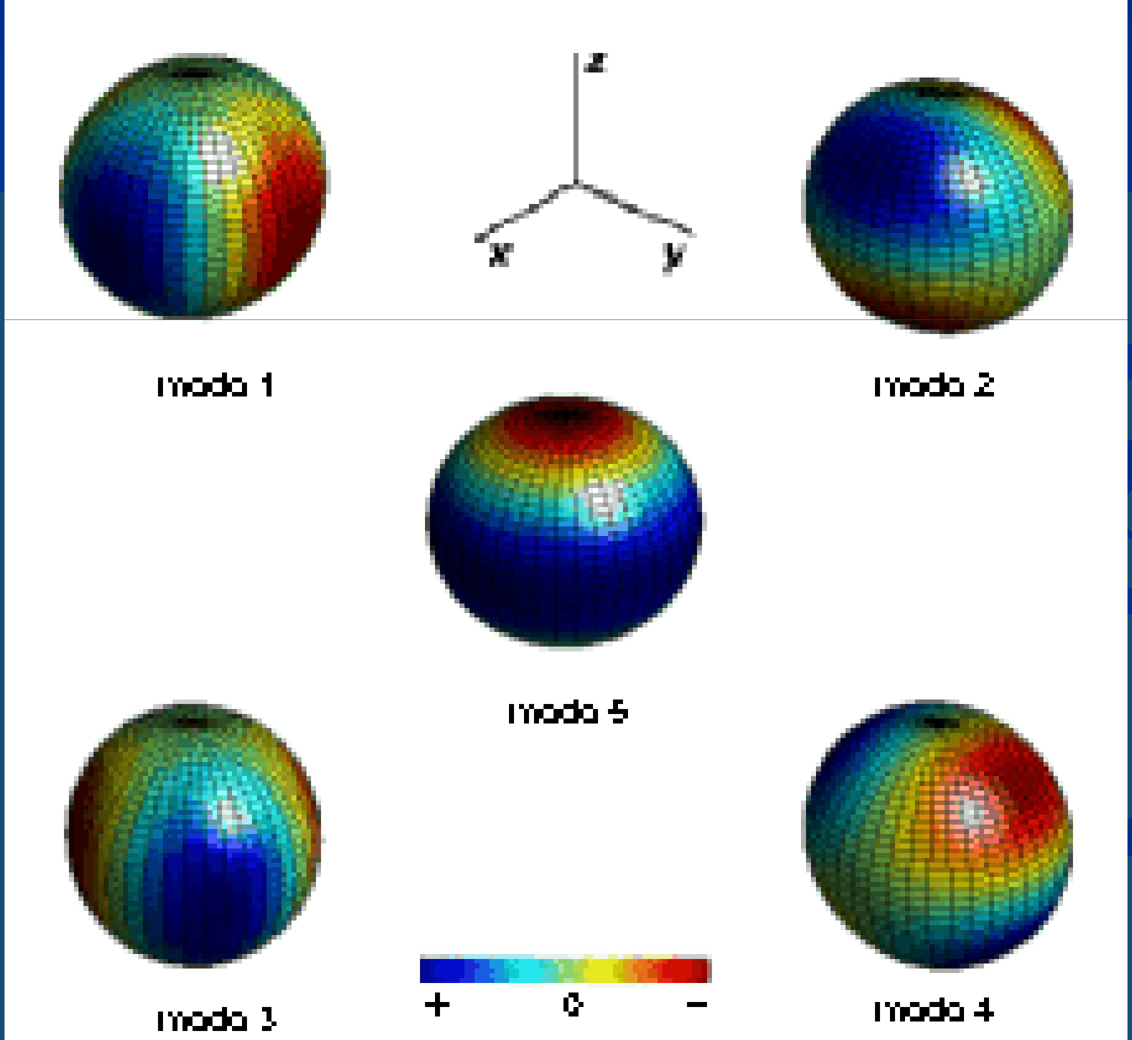
Coupled Oscillators
(antenna + multimode transducer)

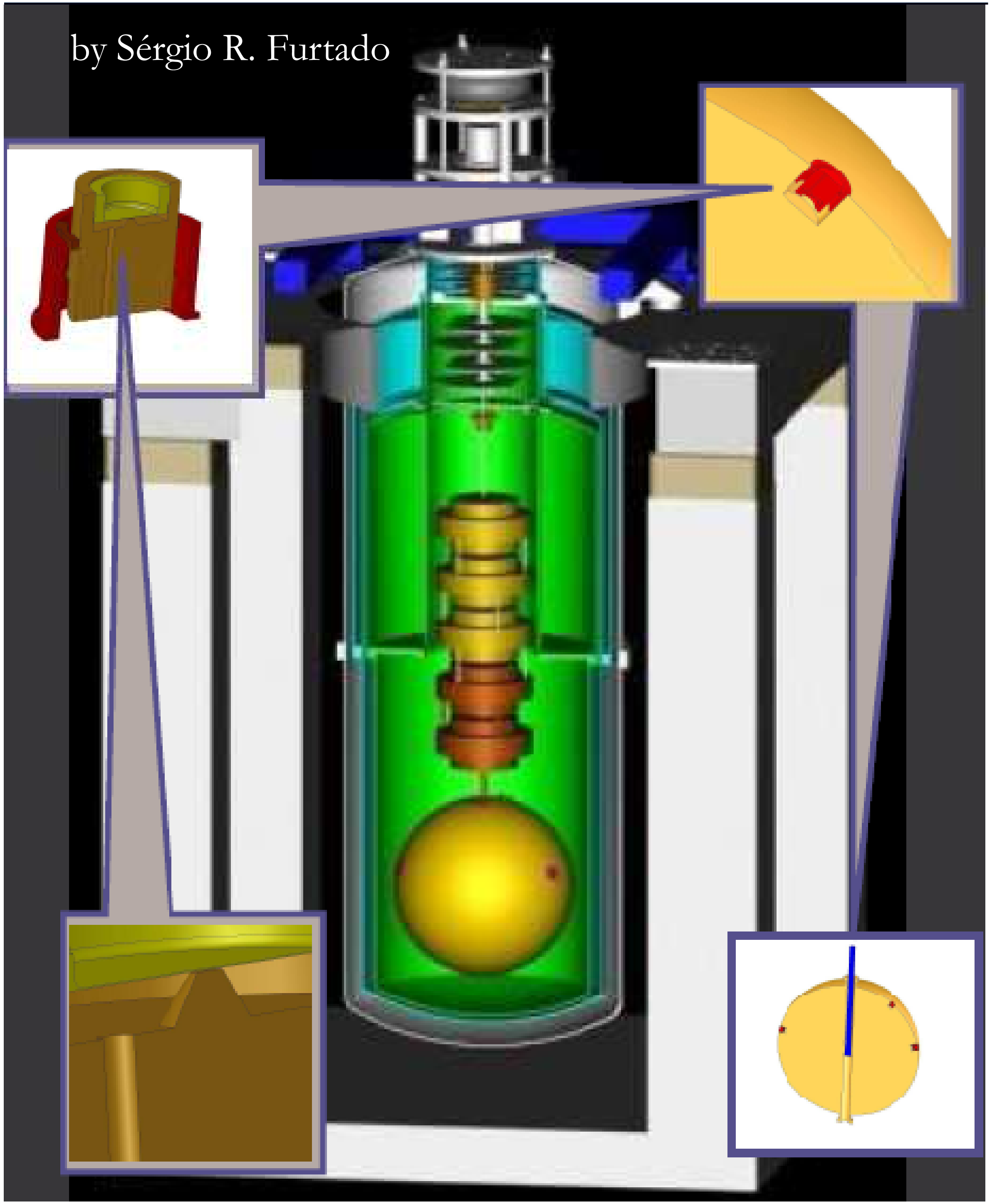
$$\Delta x = \sqrt{\frac{M}{m}}\,\Delta X$$

Ho Jung Paik



Quadrupole modes of the Mario Schenberg detector's sphere





287 kg is the effective mass for each sphere's quadrupole mode;

(5 x 287 kg = 1435 kg

> 1150 kg = M_{sphere})

287 kg, 53 g and 10 mg

amplitude gain ~ 5300

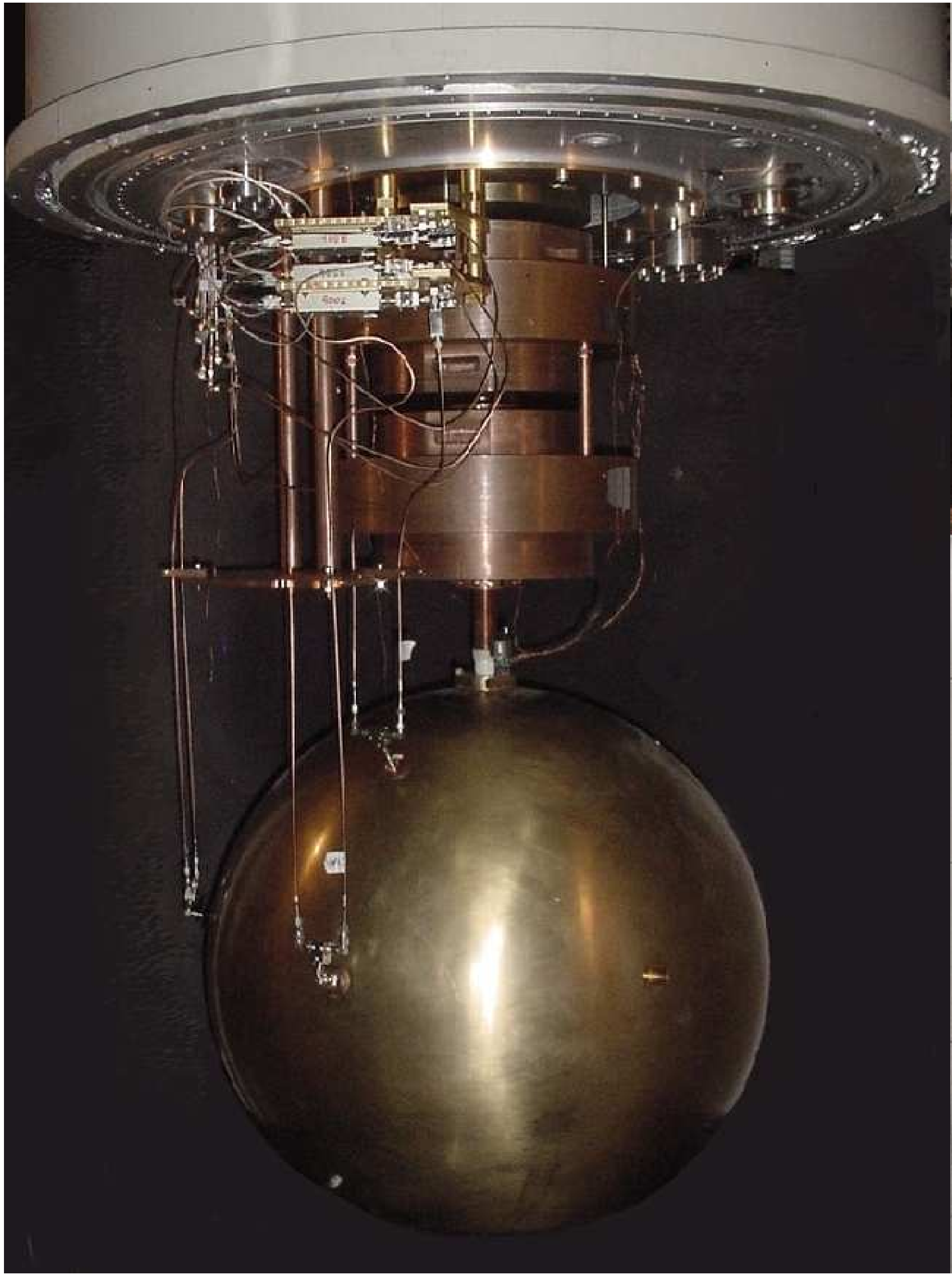
f_o ~ 10 GHz

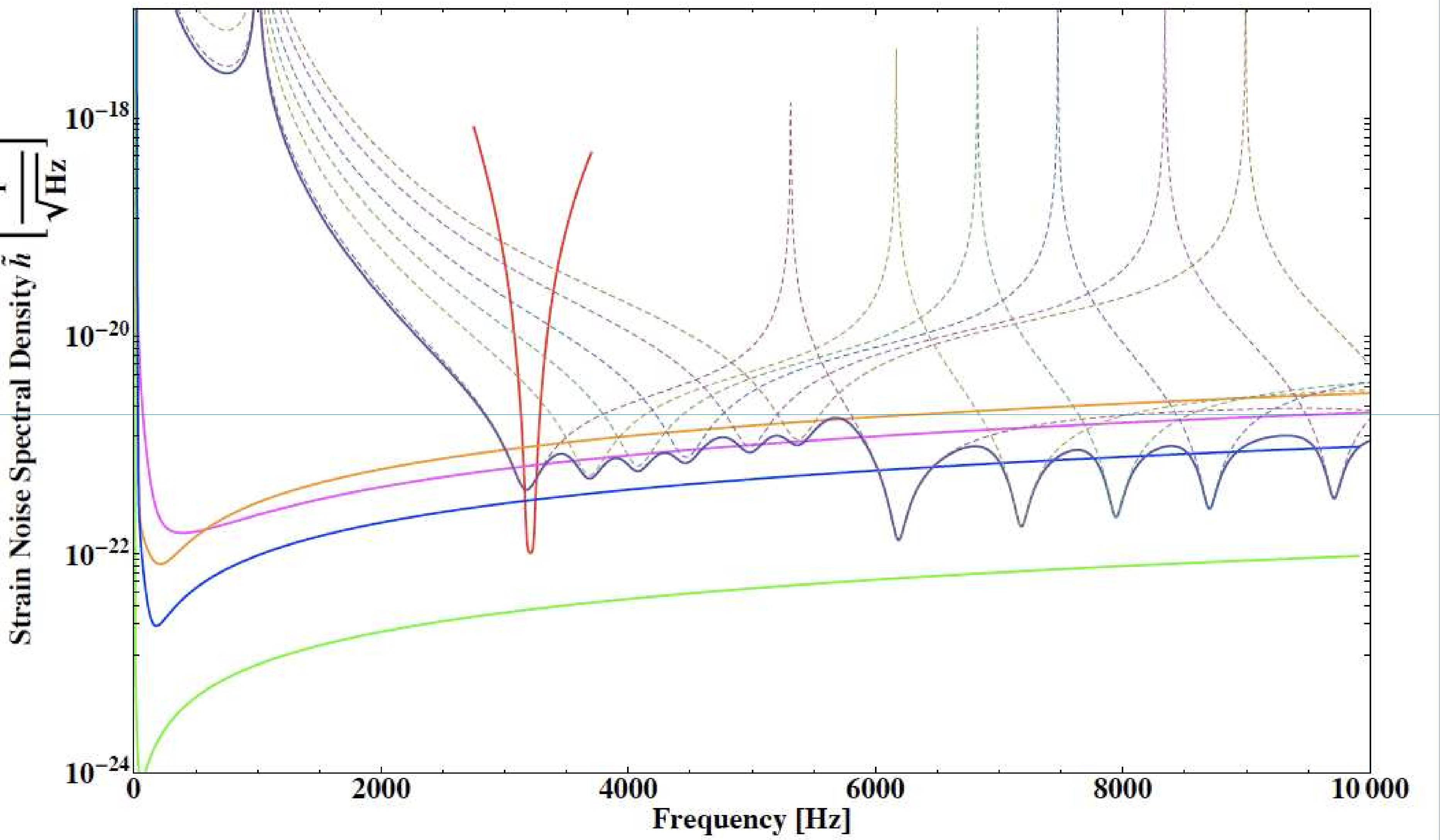
df/dx ~ 1 GHz / micron

or

non-resonant

with df/dx ~ 5 THz / micron





by Guilherme L. Pimentel

From the output of six 6 transducers tuned to the quadrupole modes

$$\Psi(\theta, \phi, \omega) = \sum_{i}^{5} \underbrace{a_i\,(\omega)}\;\underbrace{\Psi_i\,(\theta, \phi)}_{\text{spherical harmonics}}$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$h_{xx} + h_{yy} + h_{zz} = 0$$

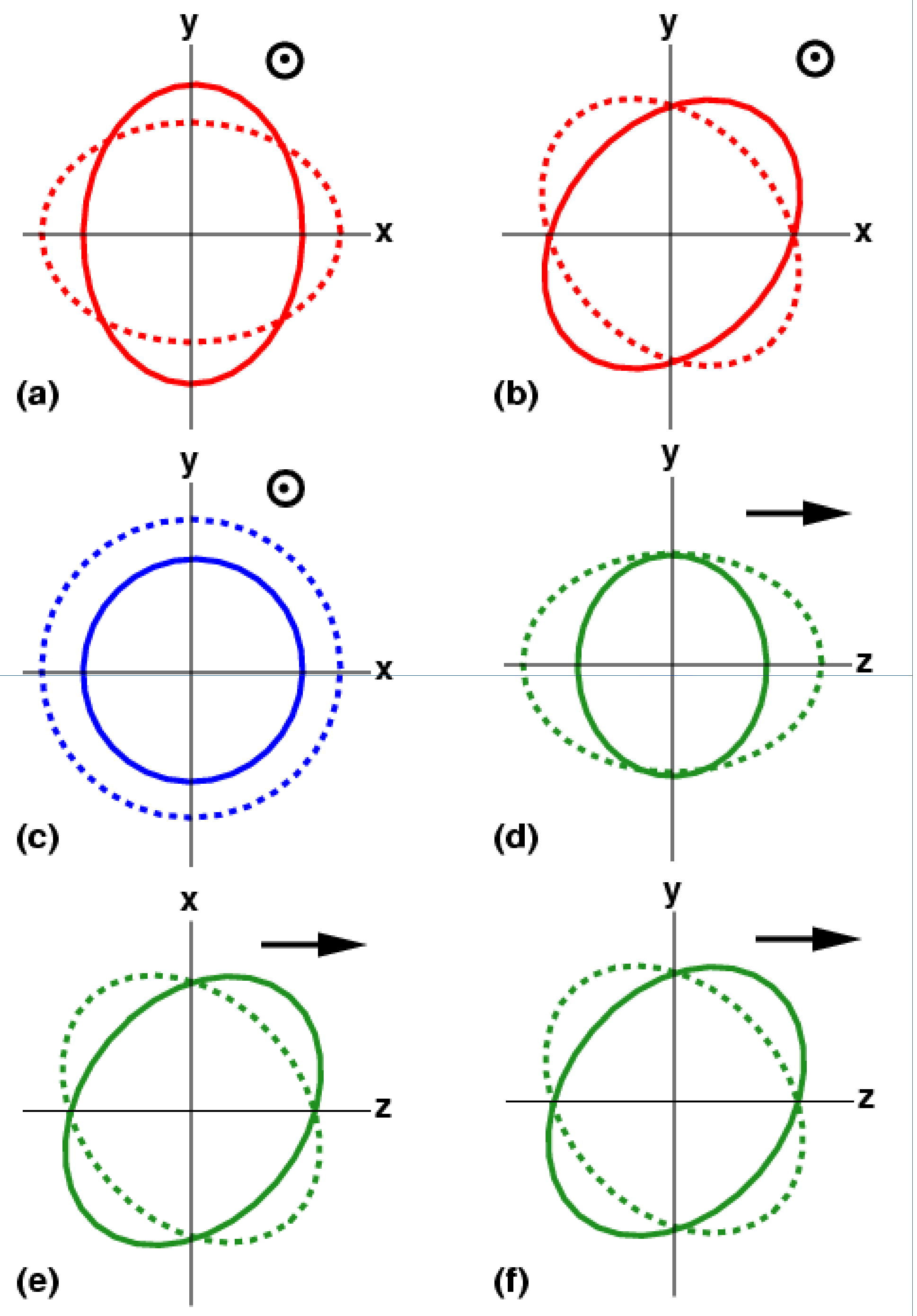
$$Ih = \begin{bmatrix} h_{xx} & h_{xy} & h_{xz} \\ h_{yx} & h_{yy} & h_{yz} \\ h_{zx} & h_{zy} & h_{zz} \end{bmatrix}$$

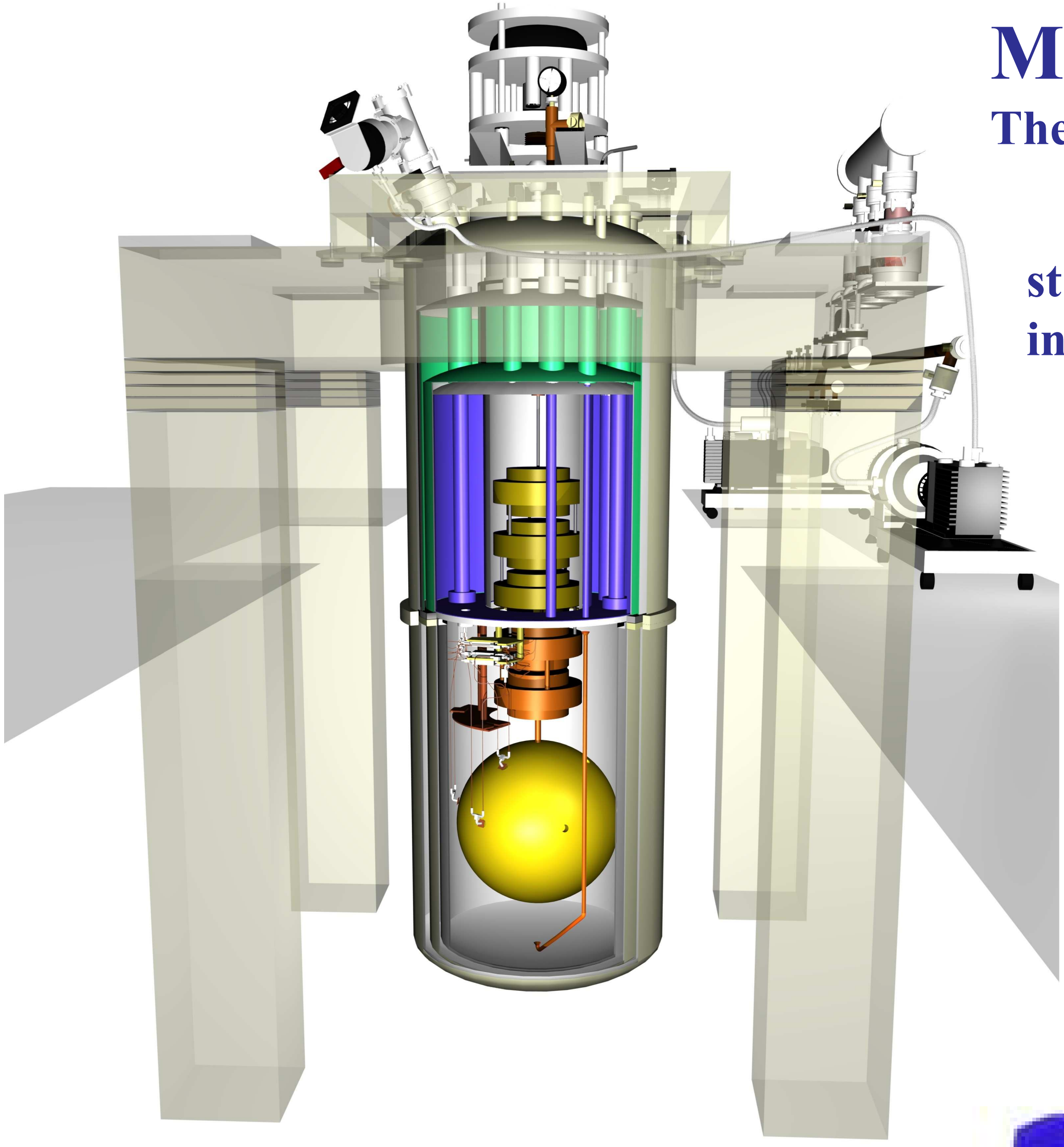
5 independent

components

Test of General Relativity and other Theories of Gravitation

- **Polarizations**
- **Speed**
- **Quantization**





Mario SCHENBERG

The Gravitational Wave Detector

(Brazil)

started commissioning operation in the 8th of September, 2006.

It involves a
collaboration
between

INPE
ITA
IFSP
UNICAMP
UNIFESP
USP, among others,

and it has been
supported by

FAPESP

Gravitational Wave Detectors

(V. Fafone)

Astron. Astrophys. 216, 325–332 (1989)

ASTRONOMY
AND
ASTROPHYSICS

First gravity wave coincidence experiment between resonant cryogenic detectors: Louisiana-Rome-Stanford

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Summary. The results of a coincidence search for short bursts of gravitational radiation with cryogenic resonant-mass detectors are reported. No significant excess of coincidences at zero time delay were found. The data have been used to set an improved observational upper limit on the flux of impulsive gravitational waves that may be impinging on the Earth.

Key words: gravitational waves – detectors, gravitational waves – coincidence experiment

employs a resonant capacitive transducer (Rapagnani, 1982) matched to a d.c. SQUID amplifier (Carelli, 1985).

The performance of the three detectors during this coincidence experiment did not reach the design goals or previously achieved levels by the Stanford detector in either sensitivity or in non-Gaussian disturbance level (Boughn, 1982). Despite this situation, the limit that we are able to set on the rate of gravity wave pulses impinging on the Earth is better than that set by any previous observations.

Analysis of LIGO data for gravitational waves from binary neutron stars

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We report on a search for gravitational waves from coalescing compact binary systems in the Milky Way and the Magellanic Clouds. The analysis uses data taken by two of the three LIGO interferometers during the first LIGO science run and illustrates a method of setting upper limits on inspiral event rates using interferometer data. The analysis pipeline is described with particular attention to data selection and coincidence between the two interferometers. We establish an observational upper limit of $\mathcal{R}<1.7\times10^2$ per year per Milky Way Equivalent Galaxy (MWEG), with 90% confidence, on the coalescence rate of binary systems in which each component has a mass in the range $1–3\ M_\odot$.

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I. INTRODUCTION

The Laser Interferometer Gravitational-Wave Observatory (LIGO) is an ambitious US initiative to detect gravitational waves from astrophysical sources such as coalescing neutron stars and black holes, spinning neutron stars, and supernovas. The LIGO detectors are laser interferometers with light propagating between large suspended mirrors in two perpendicular arms. They measure the strain (differential fractional change in arm lengths) produced by gravitational waves from astrophysical sources by monitoring the relative optical phase between light paths in each arm [1]. LIGO comprises three detectors housed at two geographically distinct locations: in Hanford, WA, there are two interferometers, one with arms 4 km long (which is referred to as H1 in this article) and one with arms 2 km long (H2); in Livingston, LA there is one interferometer with arms 4 km long (L1). The LIGO interferometers [2,3] form part of a worldwide network of gravitational-wave detectors which includes the British-German GEO 600 detector [4], the French-Italian

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PHYSICAL REVIEW D 77, 062002 (2008)

Search for gravitational waves from binary inspirals in S3 and S4 LIGO data

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1550-7998/2008/77(6)/062002(13)

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We report on a search for gravitational waves from the coalescence of compact binaries during the third and fourth LIGO science runs. The search focused on gravitational waves generated during the inspiral phase of the binary evolution. In our analysis, we considered three categories of compact binary systems, ordered by mass: (i) primordial black hole binaries with masses in the range $0.35M_\odot < m_1, m_2 < 1.0M_\odot$, (ii) binary neutron stars with masses in the range $1.0M_\odot < m_1, m_2 < 3.0M_\odot$, and (iii) binary black holes with masses in the range $3.0M_\odot < m_1, m_2 < m_{\max}$ with the additional constraint $m_1 + m_2 < m_{\max}$, where $m_{\max}$ was set to $40.0M_\odot$ and $80.0M_\odot$ in the third and fourth science runs, respectively. Although the detectors could probe to distances as far as tens of Mpc, no gravitational-wave signals were identified in the 1364 hours of data we analyzed. Assuming a binary population with a Gaussian distribution around $0.75 - 0.75M_\odot$, $1.4 - 1.4M_\odot$, and $5.0 - 5.0M_\odot$, we derived 90%-confidence upper limit rates of $4.9\ \mathrm{yr}^{-1}L_{10}^{-1}$ for primordial black hole binaries, $1.2\ \mathrm{yr}^{-1}L_{10}^{-1}$ for binary neutron stars, and $0.5\ \mathrm{yr}^{-1}L_{10}^{-1}$ for stellar mass binary black holes, where L_{10} is 10^{10} times the blue-light luminosity of the Sun.

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PHYSICAL REVIEW D **79**, 022001 (2009)

Einstein@Home search for periodic gravitational waves in LIGO S4 data

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1550-7998/2009/79(2)/022001(29)

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A search for periodic gravitational waves, from sources such as isolated rapidly spinning neutron stars, was carried out using 510 h of data from the fourth LIGO science run (S4). The search was for quasimonochromatic waves in the frequency range from 50 to 1500 Hz, with a linear frequency drift $\dot{f}$ (measured at the solar system barycenter) in the range $-f/\tau < \dot{f} < 0.1 f/\tau$, where the minimum spin-down age τ was 1000 yr for signals below 300 Hz and 10 000 yr above 300 Hz. The main computational work of the search was distributed over approximately 100 000 computers volunteered by the general public. This large computing power allowed the use of a relatively long coherent integration time of 30 h, despite the large parameter space searched. No statistically significant signals were found. The sensitivity of the search is estimated, along with the fraction of parameter space that was vetoed because of contamination by instrumental artifacts. In the 100 to 200 Hz band, more than 90% of sources with dimensionless gravitational-wave strain amplitude greater than 10^{-23} would have been detected.

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Gravitational wave burst search in the Virgo C7 data

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Abstract
A search for gravitational wave burst events has been performed with the Virgo C7 commissioning run data that have been acquired in September 2005 over 5 days. It focused on unmodeled short duration signals in the frequency range 150 Hz to 2 kHz. A search aimed at detecting the GW emission from the merger and ring-down phases of binary black hole coalescences was also carried out. An extensive understanding of the data was required to be able to handle a burst search using the output of only one detector. A 90% confidence level upper limit on the number of expected events given the Virgo C7 sensitivity curve has been derived as a function of the signal strength, for unmodeled gravitational wave searches. The sensitivity of the analysis presented is, in terms of the root sum square strain amplitude, $h_{rss} \simeq 10^{-20}\ \mathrm{Hz}^{-1/2}$. This can be interpreted in terms of a frequentist upper limit on the rate $\mathcal{R}_{90\%}$ of detectable gravitational wave bursts at the level of 1.1 events per day at a 90% confidence level. From the binary black hole search, we obtained the distance reach at 50% and 90% efficiency as a function of the total mass of the final black hole. The maximal detection distance for non-spinning high and equal mass black hole binary system obtained by this analysis in C7 data is $\simeq 2.9 \pm 0.1$ Mpc for a detection efficiency of 50% for a binary of total mass 80 $M_\odot$.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

Virgo [1] is a 3 km long arm power-recycled Michelson interferometer located near Pisa, Italy, whose goal is to detect gravitational waves (GW) emitted by astrophysical sources extending out past the Virgo cluster. The commissioning of the detector started in 2003 and regular data taking campaigns have been organized after each important milestone. The last commissioning run (C7) took place in September 2005 and lasted for 5 days. The best achieved sensitivity was $h \simeq 7 \times 10^{-22}\ \mathrm{Hz}^{-1/2}$ at 300 Hz. The Virgo design sensitivity at this frequency is expected to be better by an order of magnitude assuming that 10 W enters into the interferometer. However, during the C7 run, Virgo was running with a reduced light power, 0.7 W, because the backscattering in the mode-cleaner cavity of the light reflected by the recycling mirror

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First joint gravitational wave search by the AURIGA–EXPLORER–NAUTILUS–Virgo Collaboration

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Abstract

We present a methodology of network data analysis applied to the search for coincident burst excitations over a 24 h long data set collected by AURIGA, EXPLORER, NAUTILUS and Virgo detectors during September 2005. The search of candidate triggers was performed independently on each of the data sets from single detectors. We looked for two-fold time coincidences between these candidates using an algorithm optimized for a given population of sources and we calculated the efficiency of detection through injections of templated signal waveforms into the streams of data. To this end we have considered the

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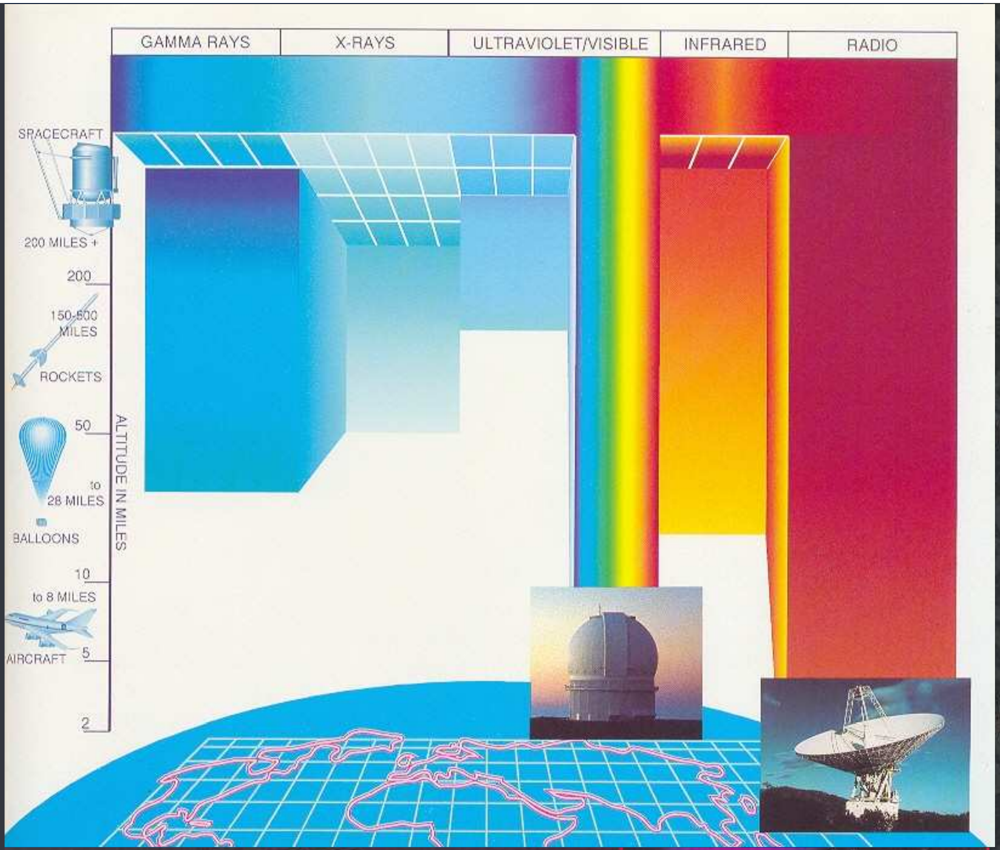
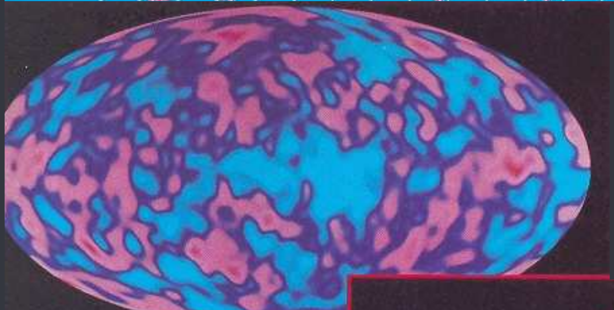
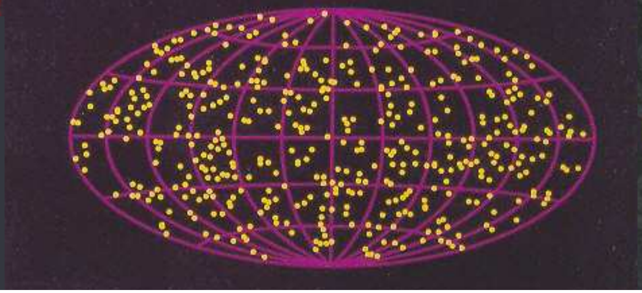
0264-9381/08/205007+20$30.00

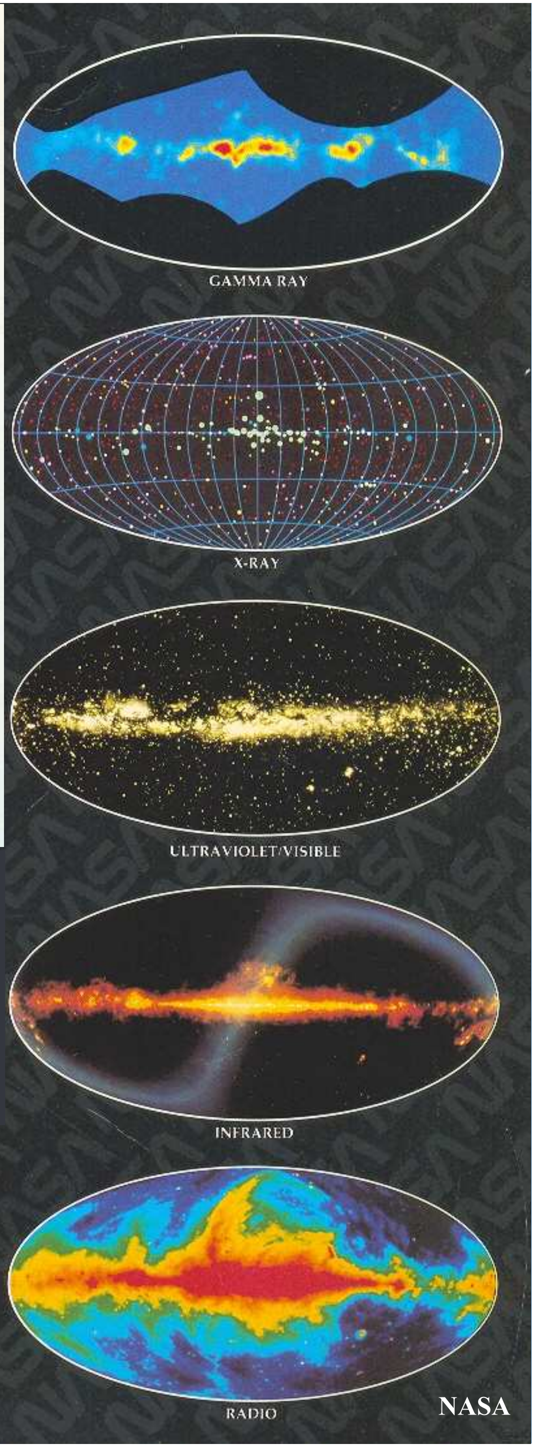
Gravitacional spectrum

(a new window to observe the Universe)



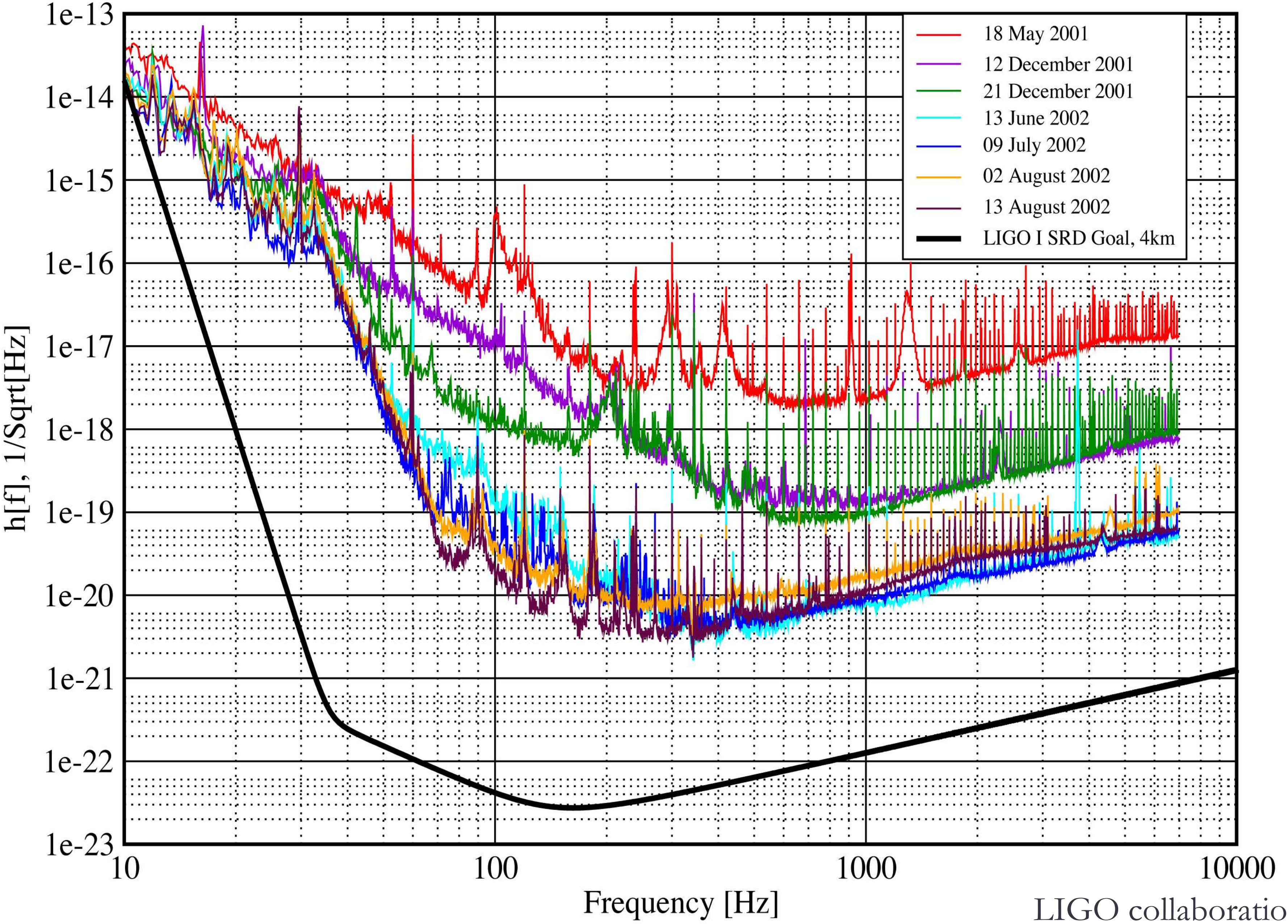




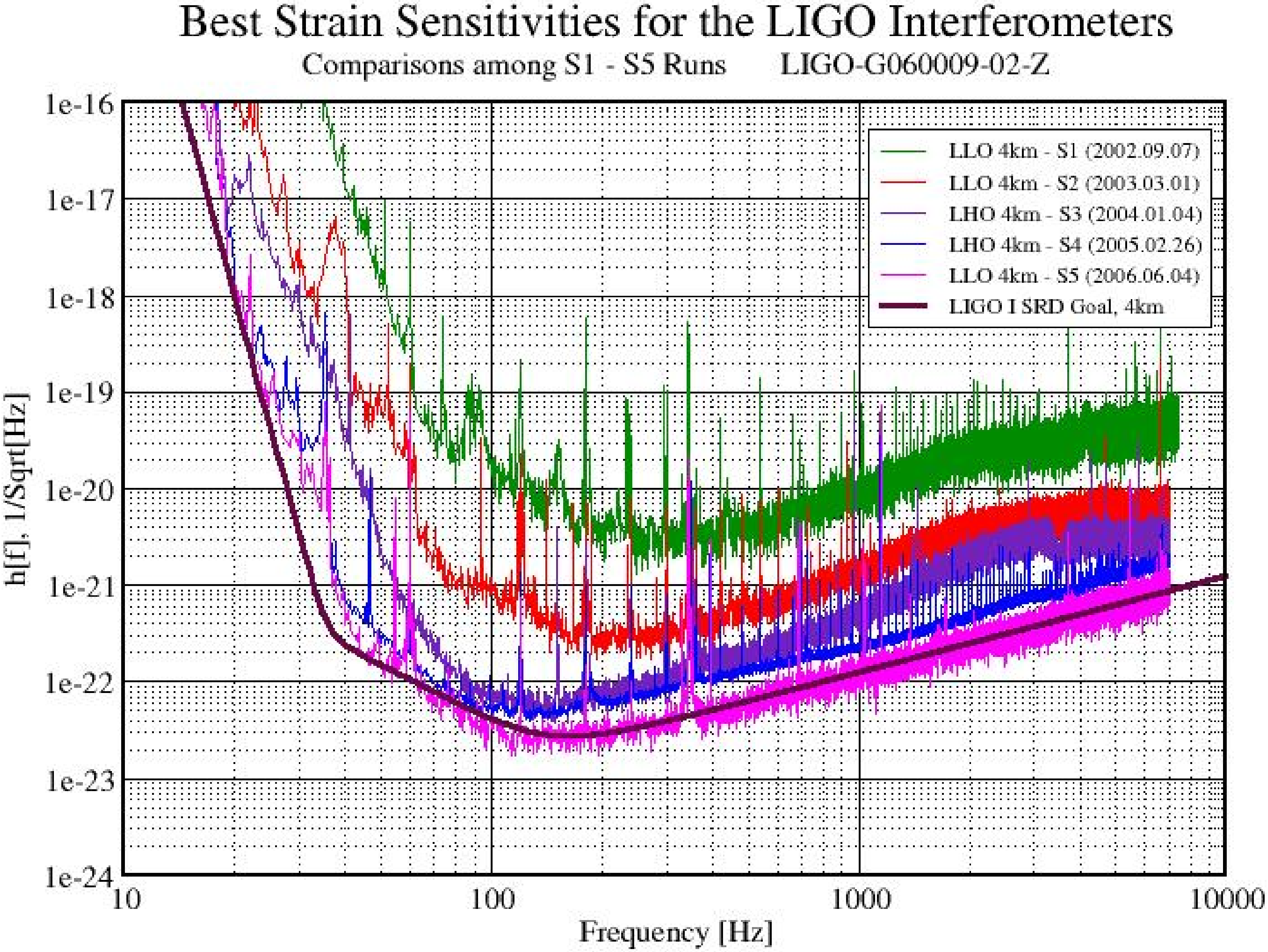


Strain Sensitivities for the LIGO Livingston 4km Interferometer, E7 to S1

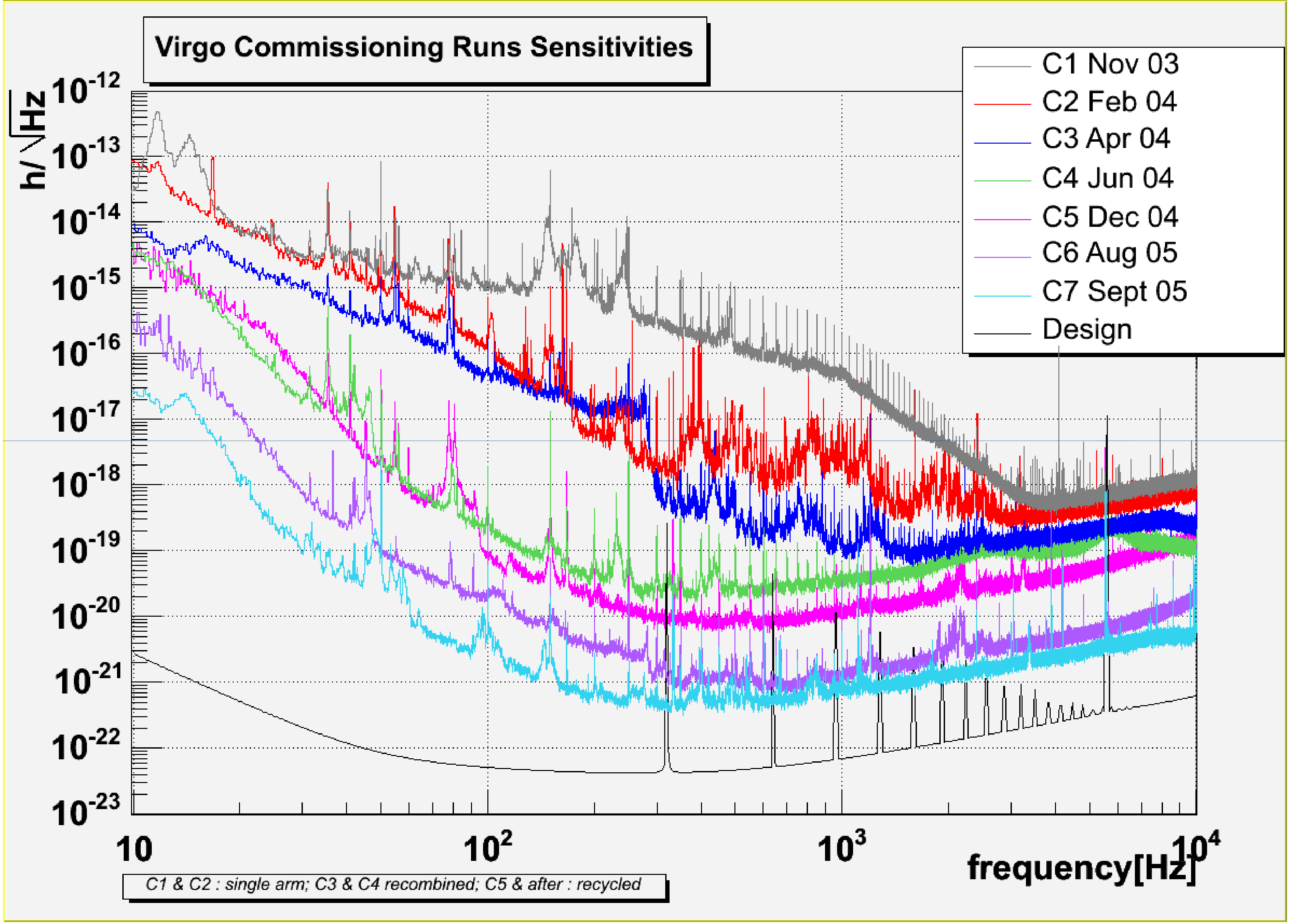
18 May 2001 - 13 August 2002 LIGO-G020451-00-E



LIGO collaboration

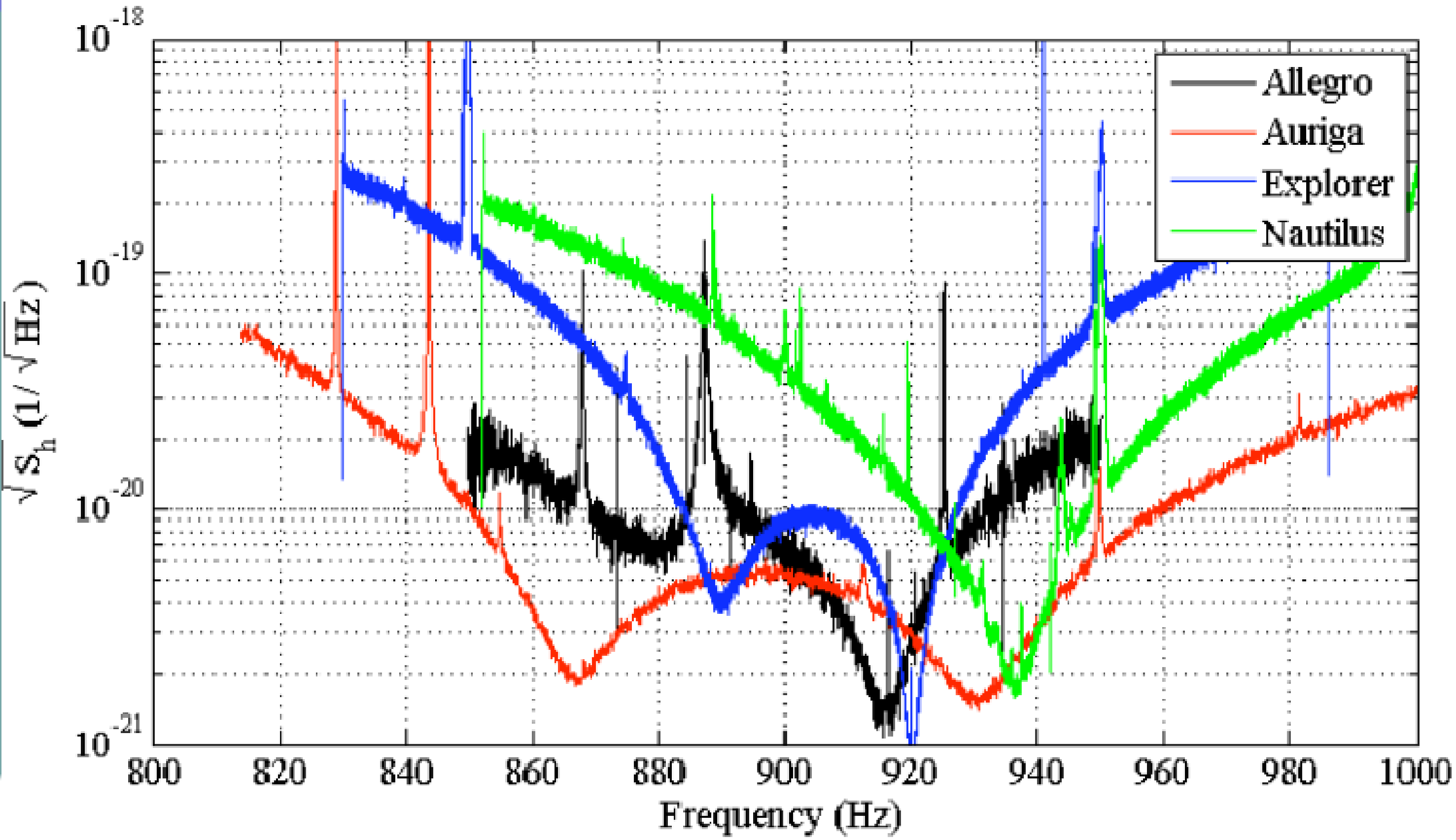


LIGO collaboration



C1 & C2 : single arm; C3 & C4 recombined; C5 & after : recycled

Sensitivity of Resonant Detectors



credit: Kostas Kokkotas

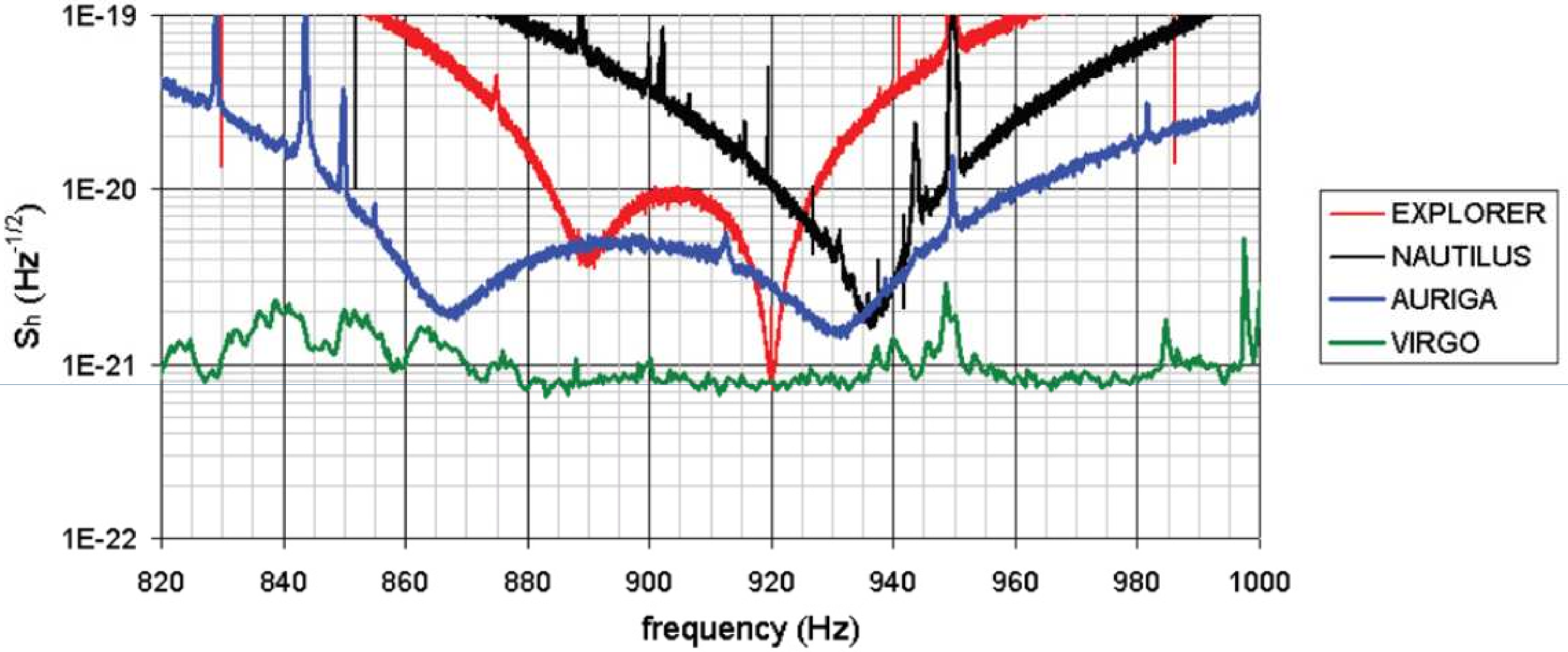
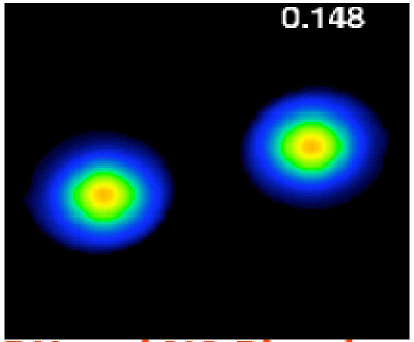
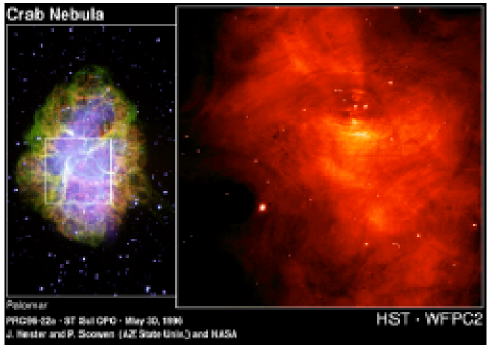


Figure 1. Typical spectral density of calibrated noise for the three resonant bar detectors during 2005 and for the Virgo interferometer in September 2005.

GW sources for Interferometric and Acoustic Detectors



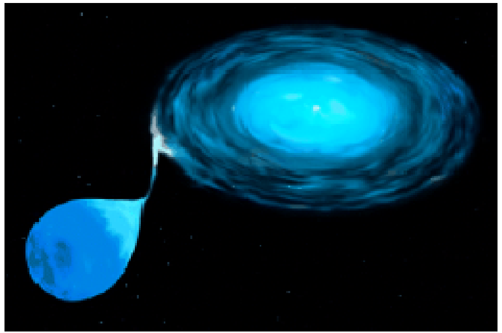
BH and NS Binaries



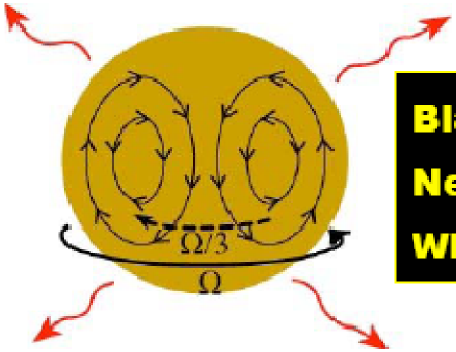
Supernovae, BH/NS formation

$$L_{GW} \sim \left(\frac{M}{R}\right)^5$$

$$h \sim \varepsilon \cdot \left(\frac{M}{r}\right) \cdot \left(\frac{M}{R}\right)$$



Spinning neutron stars in X-ray binaries

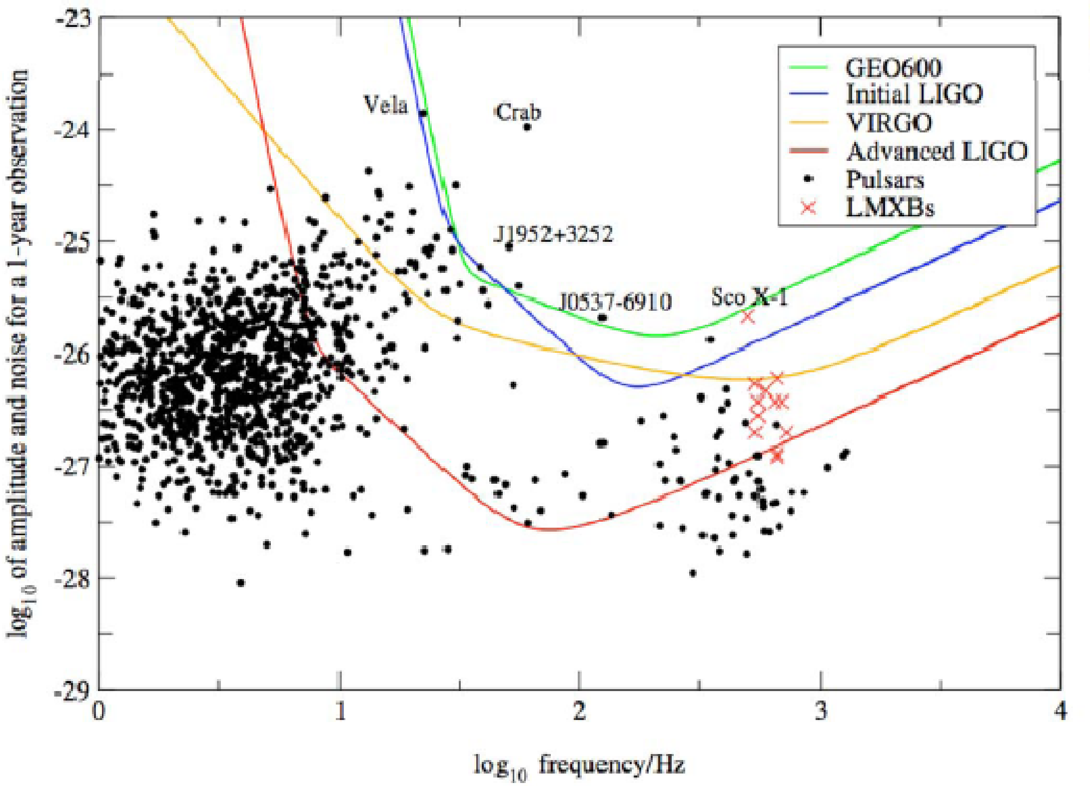


Young Neutron Stars

Black Holes : $M/R=0.5$
Neutron Stars : $M/R\sim0.2$
White Dwarfs : $M/R\sim10^{-4}$

credit: Kostas Kokkotas

Slowdown of radio pulsars



Upper limits on GW emission from triaxial NS can be used to decide which pulsars to target

credit: Kostas Kokkotas

+ stochastic sources

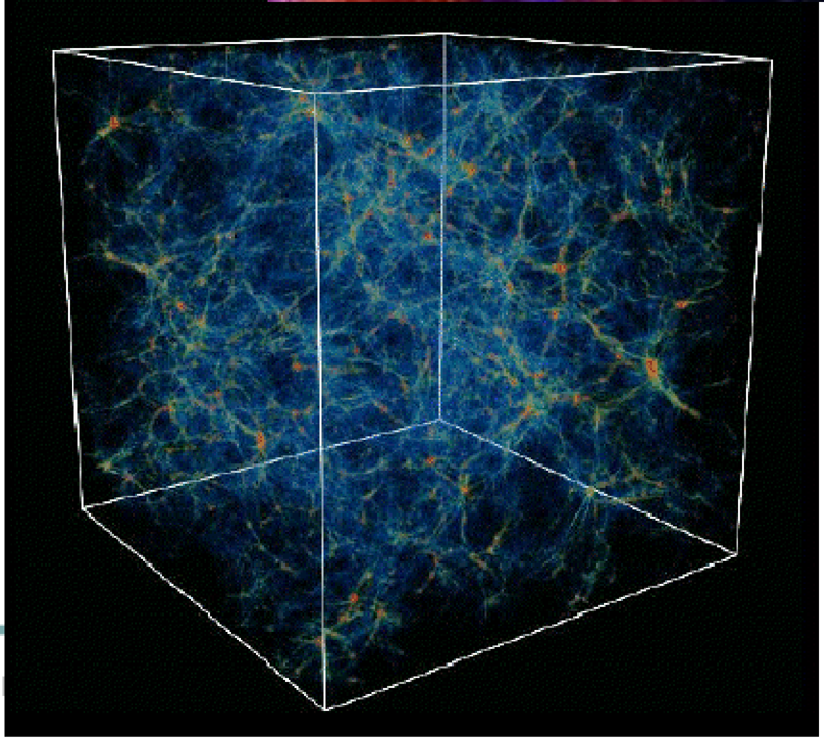
(contribute to a noisy background)

✓ Big Bang,

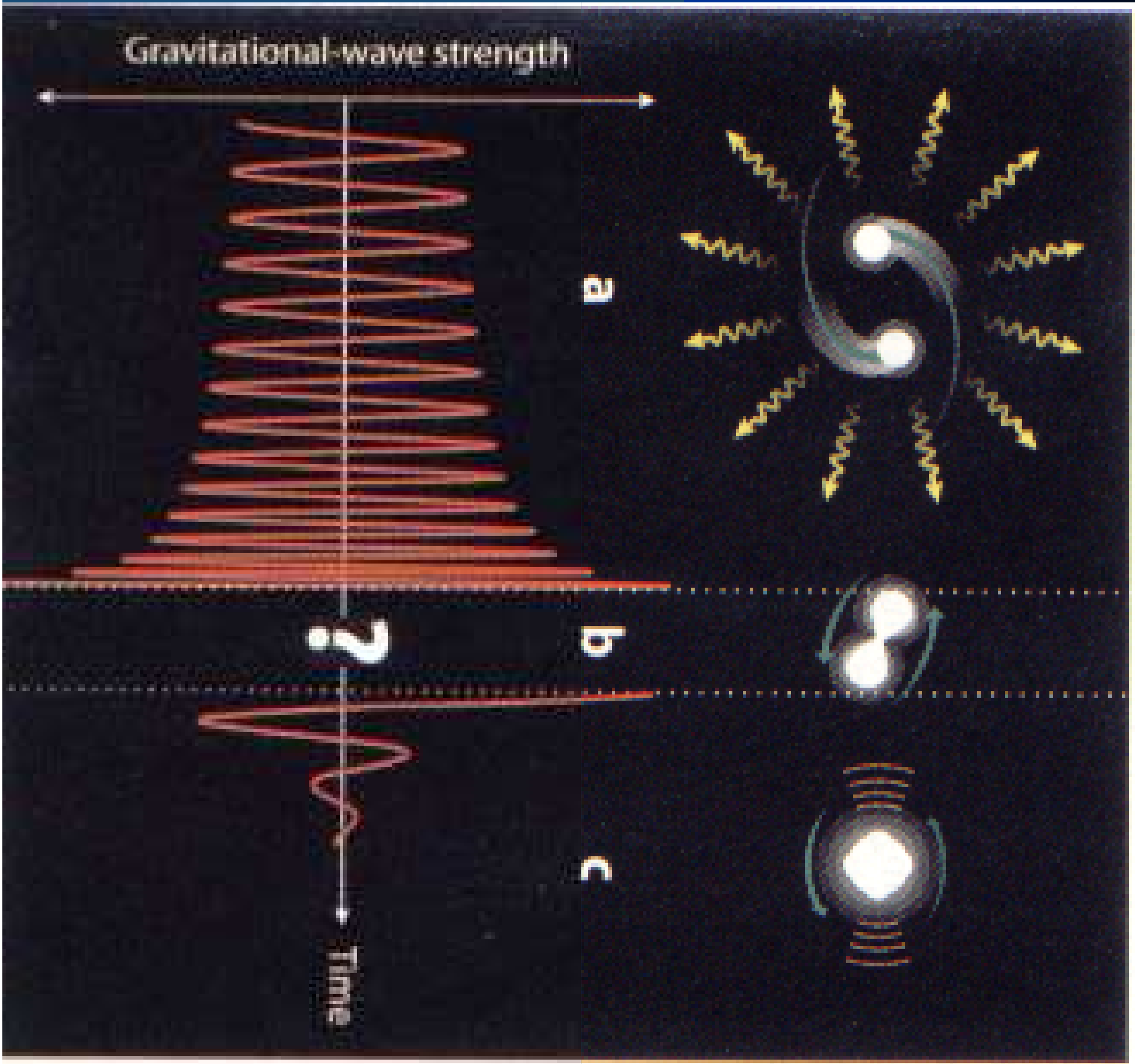
✓early expansion of the Universe,

✓cosmic strings,

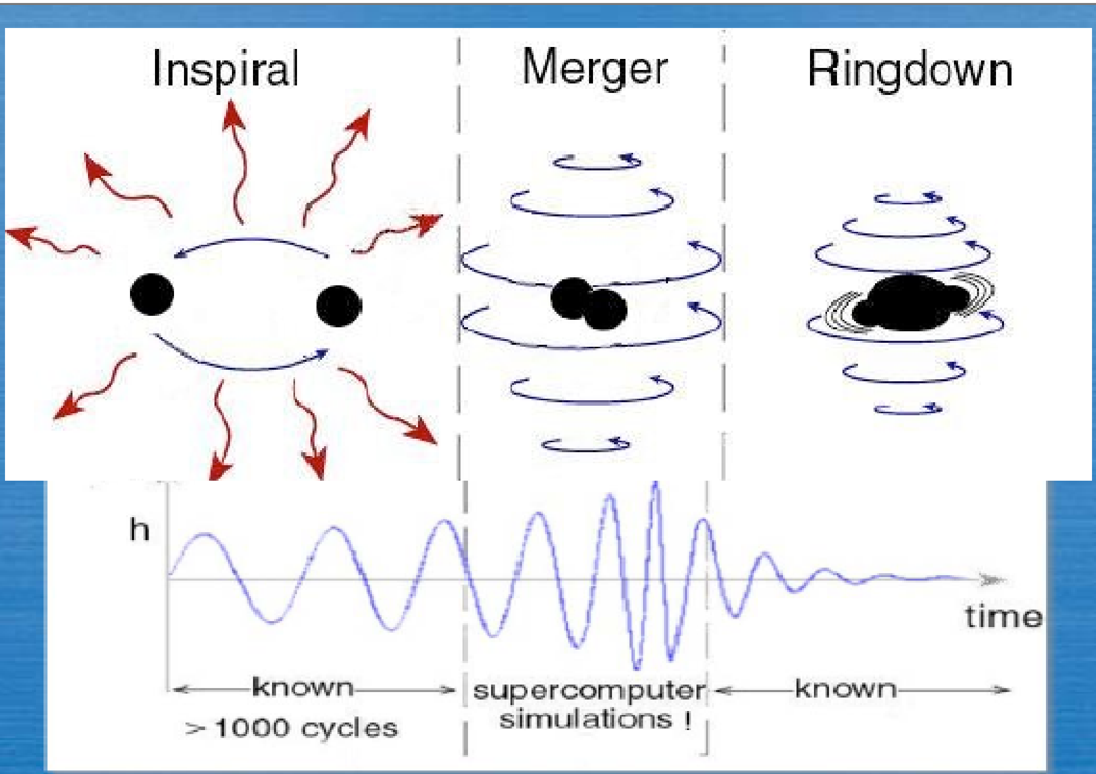
✓unresolved sources...



credit: Kostas Kokkotas


Gravitational-wave strength
a
b
?
c
Time

The emerging picture...



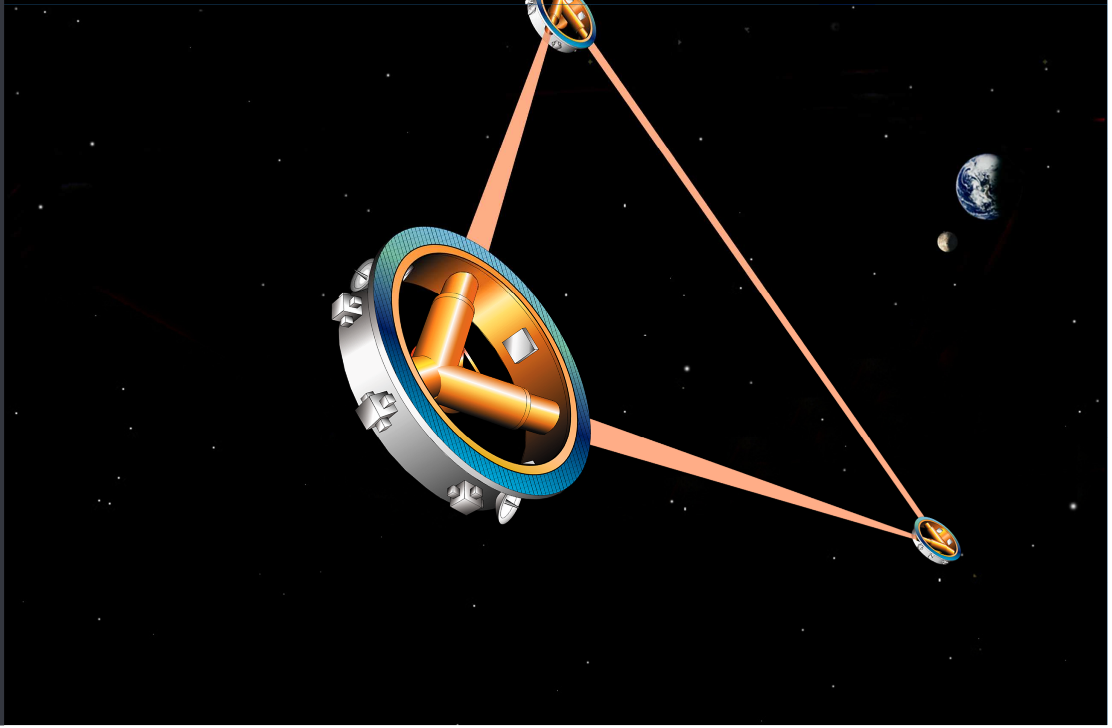
credit: Kostas Kokkotas

Space Interferometers:

LISA, ALIA and BBO

http://lisa.jpl.nasa.gov/

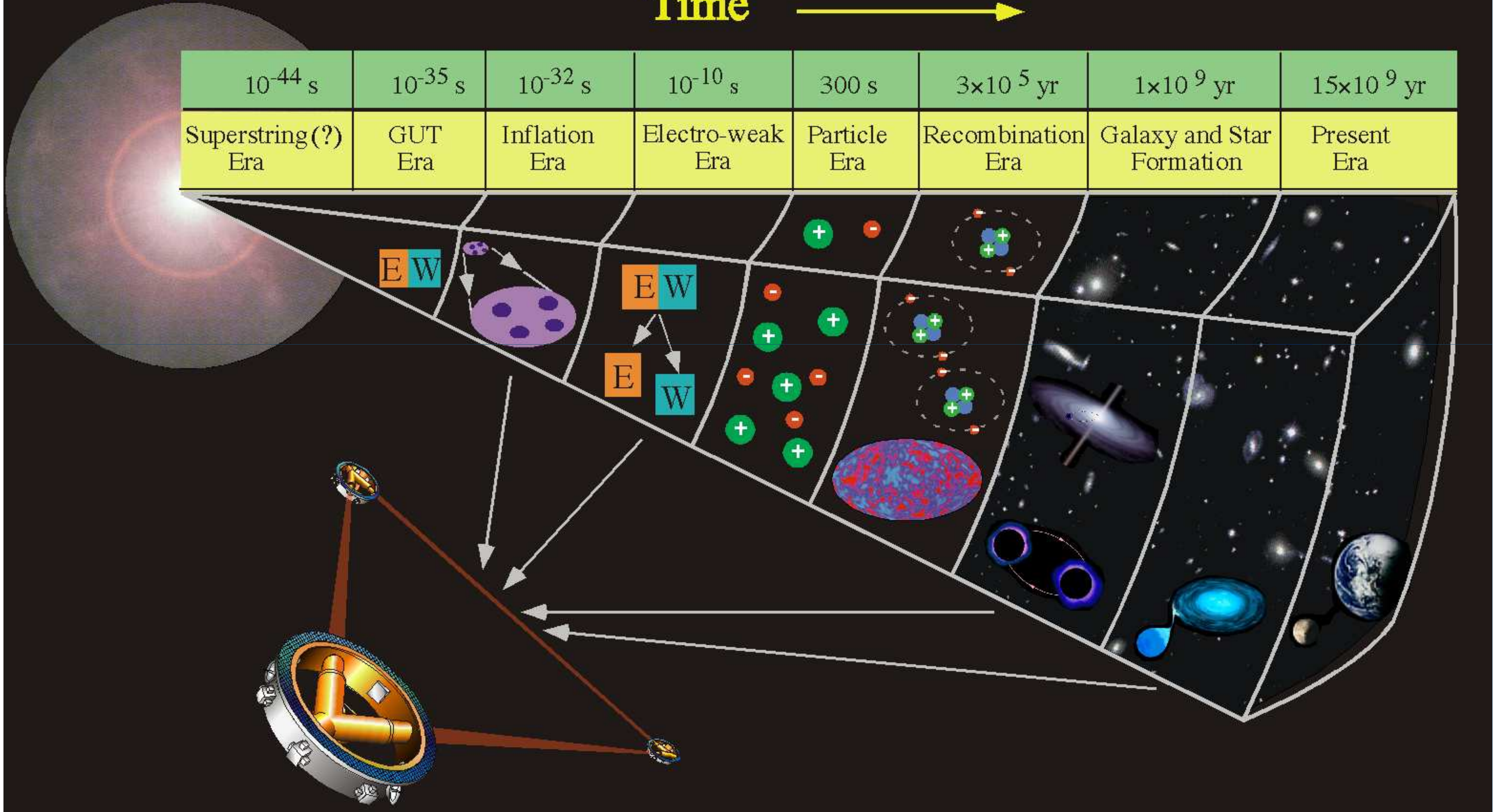
http://www.esa.int/esaSC/120376_index_0_m.html



http://lisa.jpl.nasa.gov/

Big Bang

Time →



10^{-44} s	10^{-35} s	10^{-32} s	10^{-10} s	300 s	3×10^{5} yr	1×10^{9} yr	15×10^{9} yr
Superstring (?) Era	GUT Era	Inflation Era	Electro-weak Era	Particle Era	Recombination Era	Galaxy and Star Formation	Present Era

■ **GRAVITATIONAL WAVES**

Although gravitational waves have never been directly observed, theory predicts that they can be detected because they stretch and squeeze the space they travel through. On striking a spherical mass (*a*), a wave first stretches the mass in one direction and squeezes it in a perpendicular direction (*b*). Then the effects are reversed (*c*), and the distortions oscillate at the wave's frequency (*d* and *e*). The distortions shown here have been greatly exaggerated; gravitational waves are usually too weak to produce measurable effects.

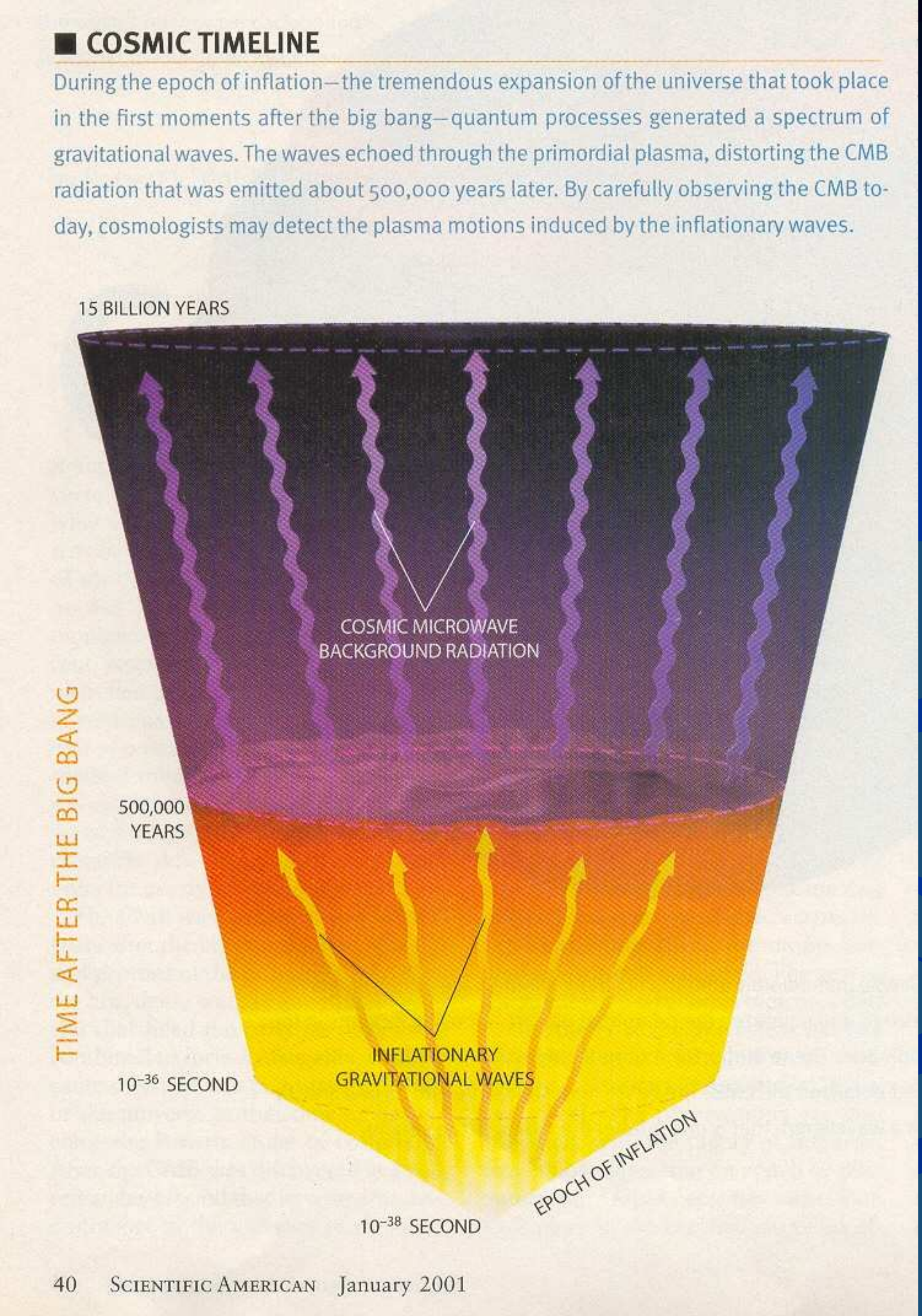
■ **DISTORTED UNIVERSE**

The fantastically rapid expansion of the universe immediately after the big bang should have produced gravitational waves. These waves would have stretched and squeezed the primordial plasma, inducing motions in the spherical surface that emitted the CMB radiation. These motions, in turn, would have caused redshifts and blueshifts in the radiation's temperature and polarized the CMB. The figure here shows the effects of a gravitational wave traveling from pole to pole, with a wavelength that is one quarter the radius of the sphere.

ILLUSTRATIONS BY SLIM FILMS

by Robert R. Caldwell
and Marc Kamionkowski

Scientific American



■ COSMIC TIMELINE

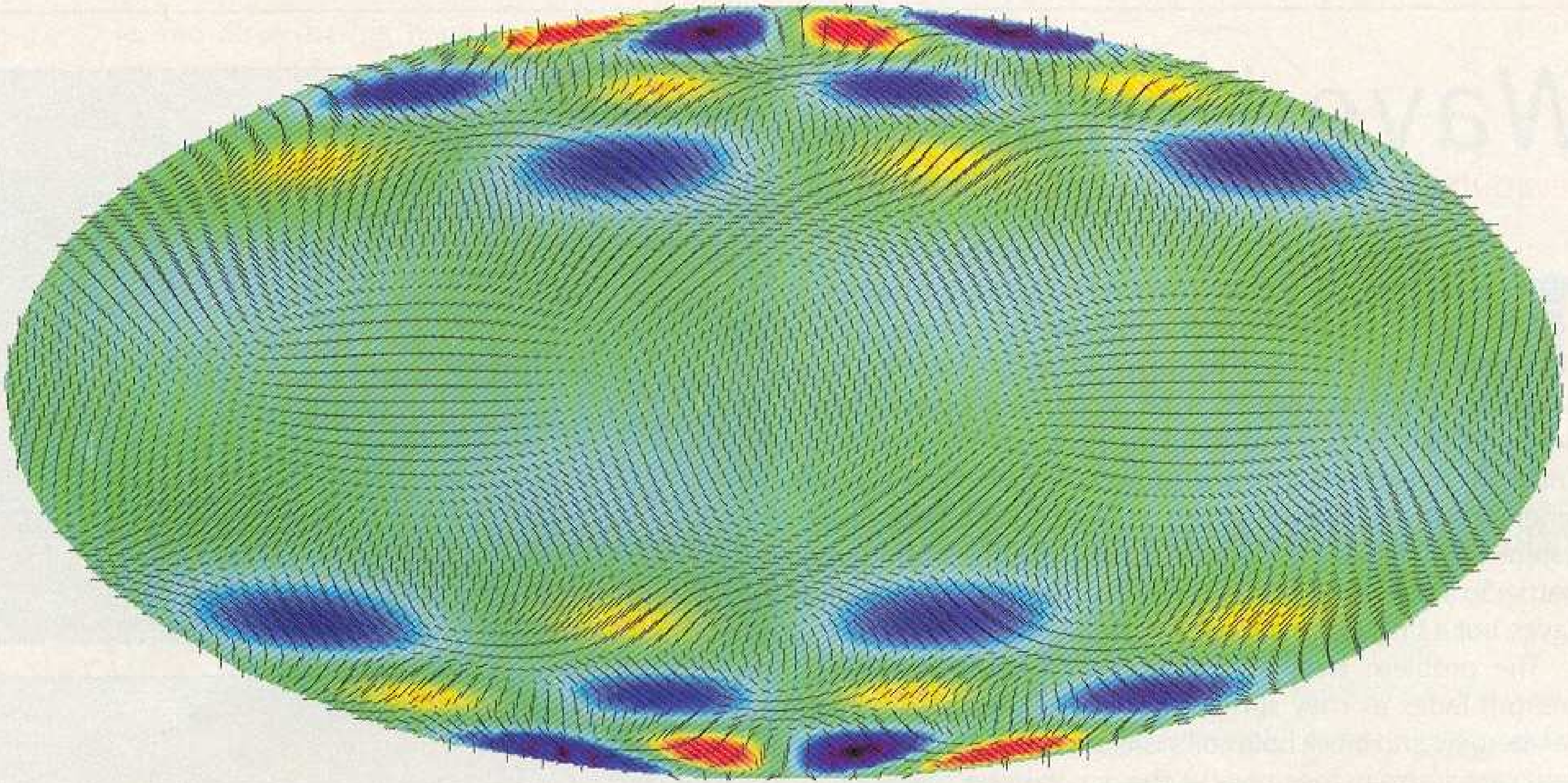
During the epoch of inflation—the tremendous expansion of the universe that took place in the first moments after the big bang—quantum processes generated a spectrum of gravitational waves. The waves echoed through the primordial plasma, distorting the CMB radiation that was emitted about 500,000 years later. By carefully observing the CMB today, cosmologists may detect the plasma motions induced by the inflationary waves.

by Robert R. Caldwell
and Marc Kamionkowski

Scientific American

by Robert R. Caldwell
and Marc Kamionkowski

Scientific American



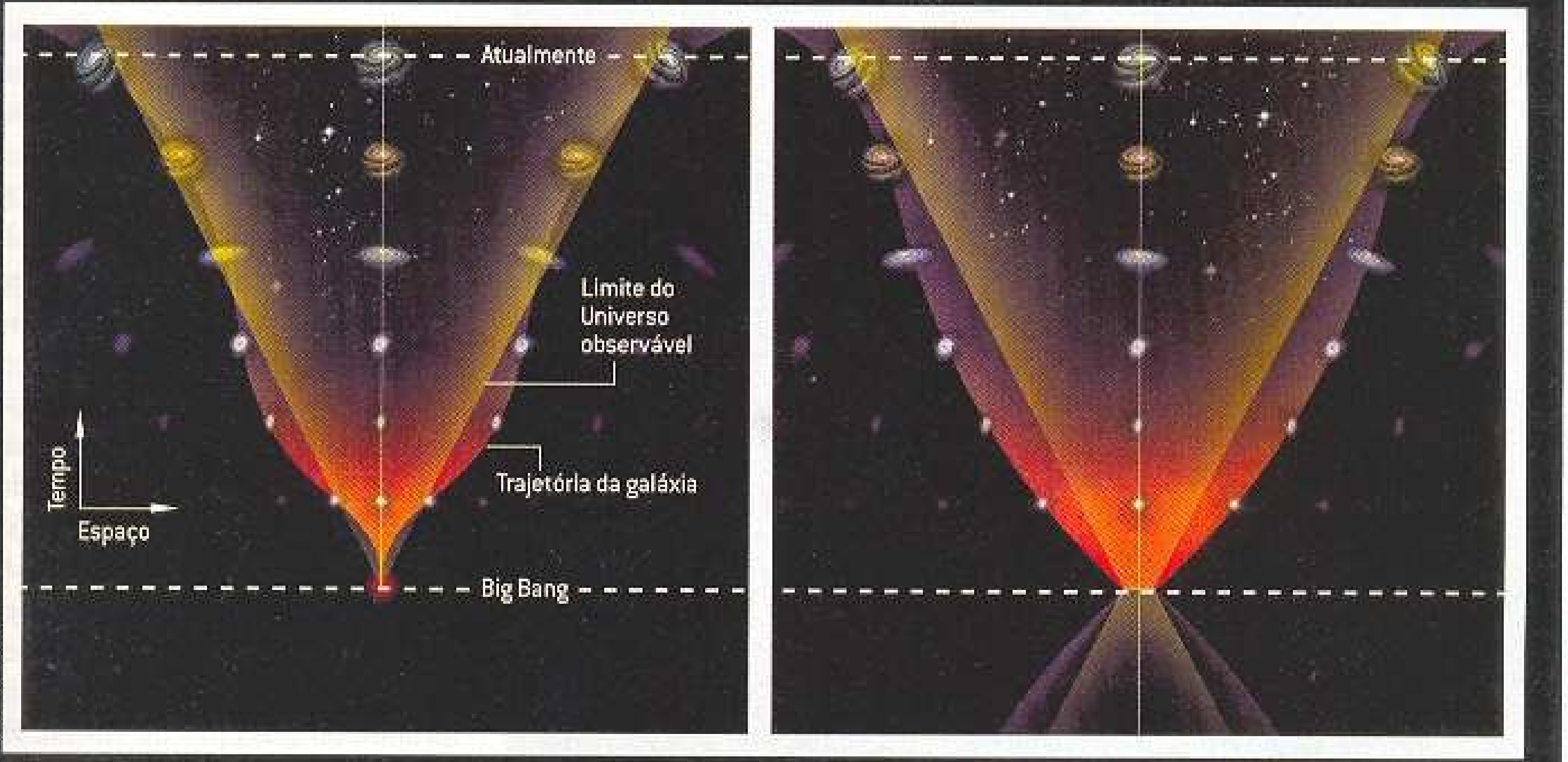
■ RELIC IN THE RADIATION

Inflationary gravitational waves would have left a distinctive imprint on the CMB. The diagram here depicts the simulated temperature variations and polarization patterns that would result from the distortions shown in the bottom illustration on page 39. The red and blue spots represent colder and hotter regions of the CMB, and the small line segments indicate the orientation angle of the polarization in each region of the sky.

Gabriele Veneziano, 2004
Scientific American Brasil

DUAS VISÕES DO PRINCÍPIO

Em nosso Universo em expansão, as galáxias se afastam rapidamente umas das outras, a uma velocidade proporcional à distância entre elas: duas galáxias separadas por uma distância de 500 milhões de anos-luz se afastam a uma velocidade duas vezes maior do que duas galáxias separadas por uma distância de 250 milhões de anos-luz. Por isso, todas as galáxias que vemos devem ter se originado em um mesmo ponto e ao mesmo tempo – o Big Bang. A conclusão é válida mesmo quando a expansão cósmica passou por períodos de aceleração e desaceleração; em diagramas de espaço-tempo (*abaixo*), as galáxias seguem trajetórias sinuosas que as levam para dentro e para fora da região observável do espaço (*triângulo amarelo*). No entanto, a situação torna-se incerta no instante exato em que as trajetórias das galáxias (ou suas predecessoras) começaram a divergir.



Na cosmologia do Big Bang convencional, que se baseia na teoria da relatividade geral de Einstein, a distância entre quaisquer duas galáxias era zero há um tempo finito. O tempo perde significado antes desse instante.

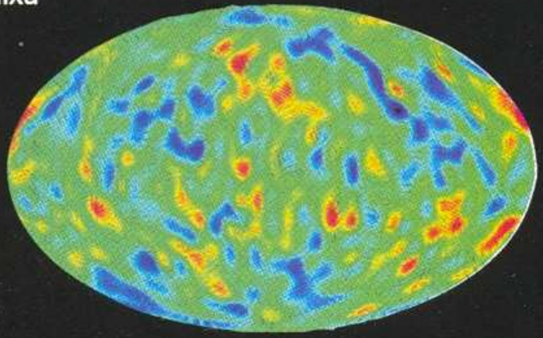
Nos modelos mais sofisticados, que incluem efeitos quânticos, quaisquer duas galáxias devem ter surgido a uma certa distância mínima uma da outra. Esses modelos abrem a possibilidade de um Universo pré-Big Bang.

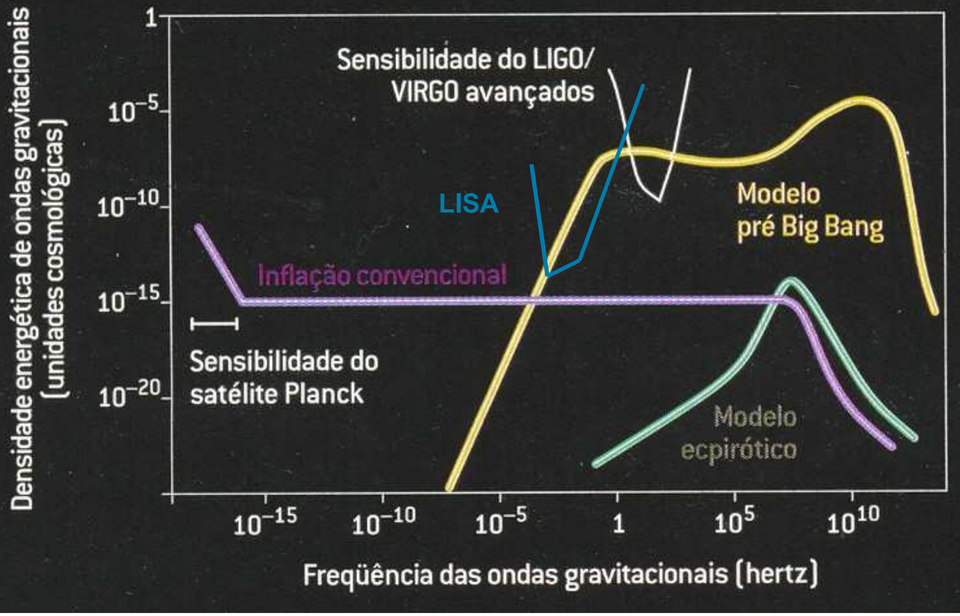
SAMUEL VELASCO

Gabriele Veneziano, 2004
Scientific American Brasil

EFEITO DE FUNDO

Observar o Universo pré-Big Bang pode parecer uma tarefa sem futuro, mas uma forma de radiação poderia sobreviver desde aquela época: a radiação gravitacional. Essas variações periódicas na campo gravitacional poderiam ser detectadas indiretamente, por seu efeito na polarização do fundo cósmico de microondas (*vista simulada, abaixo*), ou diretamente, em observatórios terrestres. Os cenários pré-Big Bang e ecpirótico prevêem mais ondas gravitacionais de alta freqüência e menos de baixa freqüência do que os modelos convencionais de inflação (*abaixo*). Medidas existentes de vários fenômenos astronômicos não conseguem fazer a distinção entre esses modelos, mas futuras observações do satélite Planck, assim como dos observatórios LIGO e VIRGO, devem ser capazes disso.





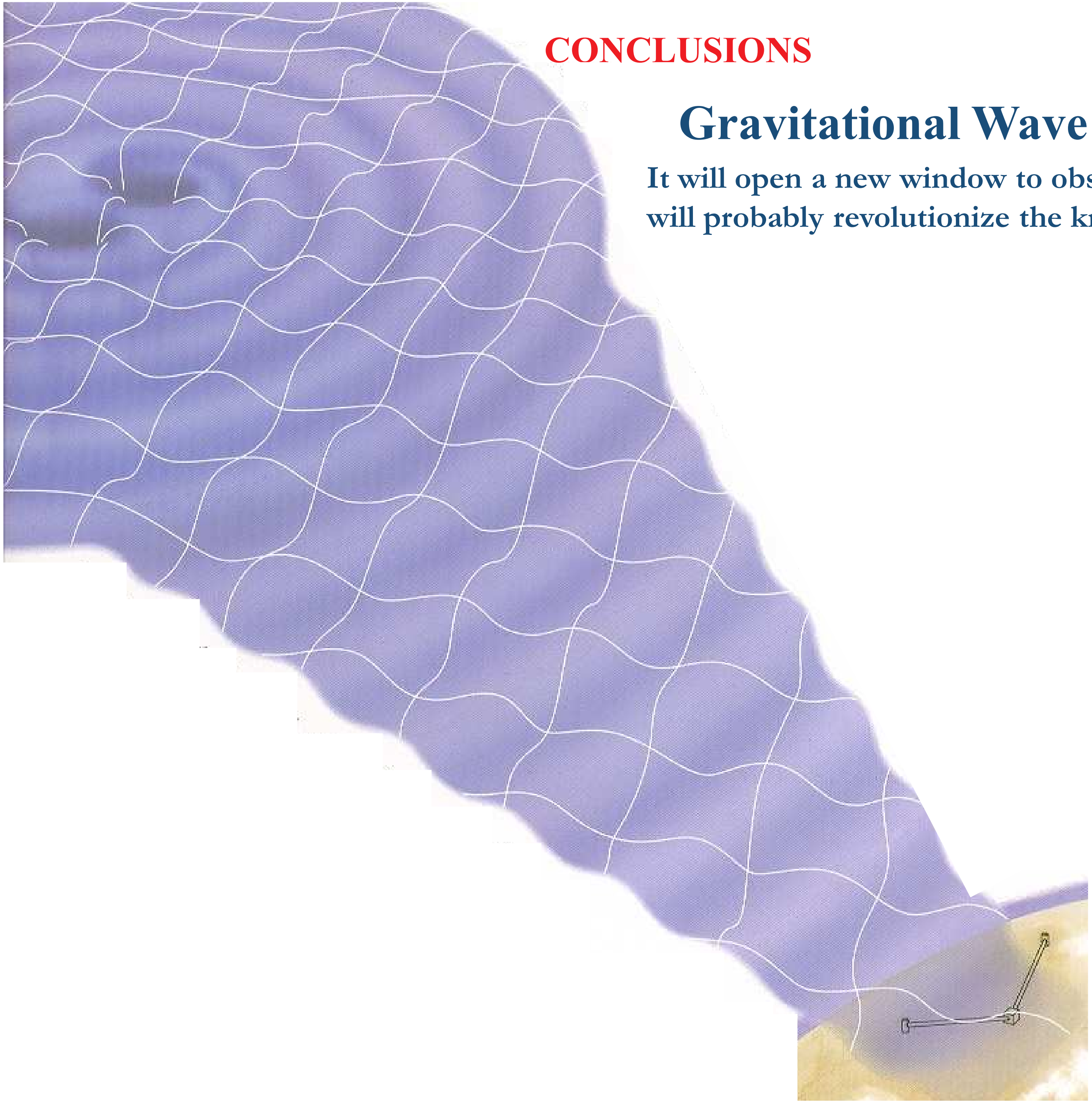
Exotic events, anticipated from theory, which may be confirmed when gravitational wave astronomy becomes a reality:

- Binaries formed by primordial black holes (MACHOS?),
-Cosmic strings,
- Cosmic bubbles,
- Boson stars,
- Quark stars (strange stars) (test of QCD),
- Phenomena not yet known or anticipated, and surprises.

If nature has more dimensions than the four of spacetime, gravity will have “transit” in these extra dimensions, and special effects on the intensity, propagation and polarization of gravitational waves may occur different from the ones anticipated by the General Relativity. The study of these effects on the gravitational waves would be, therefore, a tool for the investigation of extra dimensions in the Universe and to formulate an auto consistent theory of quantum gravity.

Universal GW Radio Broadcast
(100 MHz FM)

Carrier produced by a rotating 10^{-4} solar mass black hole and modulated by a controlled accretion flow.



CONCLUSIONS

Gravitational Wave Astronomy

It will open a new window to observe the Universe, which will probably revolutionize the knowledge we have of it.

CONCLUSIONS

The sources of gravitational waves can be:

- galactic,
- extragalactic,
- cosmological,
- from previous universes.

The spectrum goes from 10^{-18} Hz to 10^{10} Hz.

If extra-dimentions exist, gravitational wave have transit in them.

The probability of new revolutionary discoveries is very high.

Because spherical antennas are able to determine the origin of the signal in the sky and its polarizations, they will probably play an important rule on these new discoveries.

Thank you !