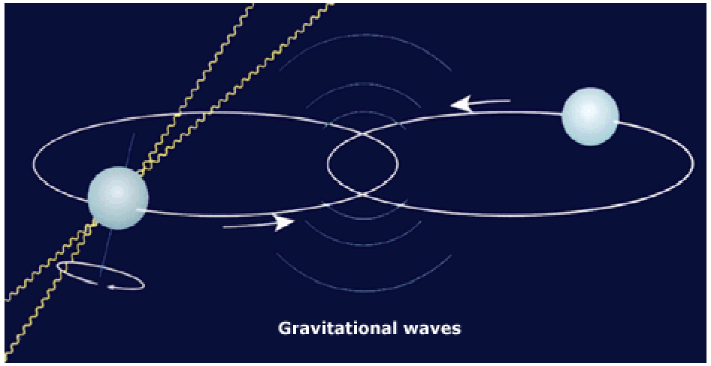
Virgo and the quest for low frequency sensitivity in GW detectors

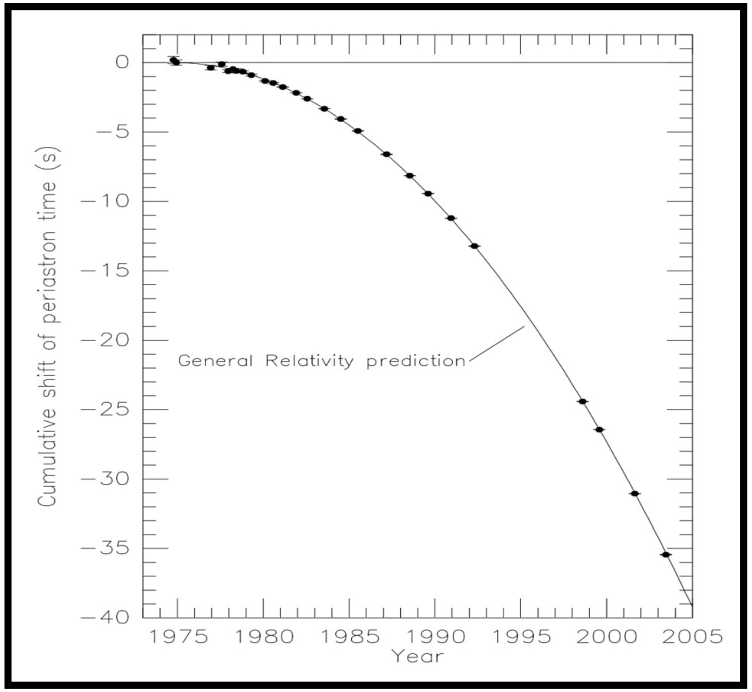
Adalberto Giazotto
INFN Pisa

What we found established when we entered in the GW business in 1982 and afterword?

1) Indirect Evidence of GW existence by Taylor and Hulse started in 1973

- PSR1913+16: 2 Pulsar system, 7 kpc from Earth

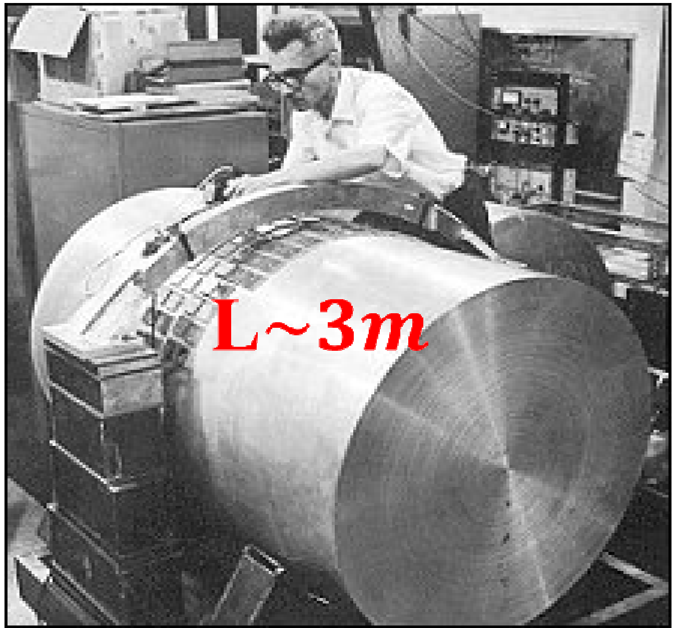




Orbital Period decrease changes Periaster time

2) Bar Detectors: JosephWeber was the first one to apply GR formalism for building GW-detector interaction:

$$F = \frac{1}{2} ML(\ddot{h}^{+} \sin^2\theta \cos 2\varphi + \ddot{h}^{X} \sin^2\theta \sin 2\varphi)$$



JOSEPH WEBER WITH GRAVITATIONAL WAVE DETECTOR

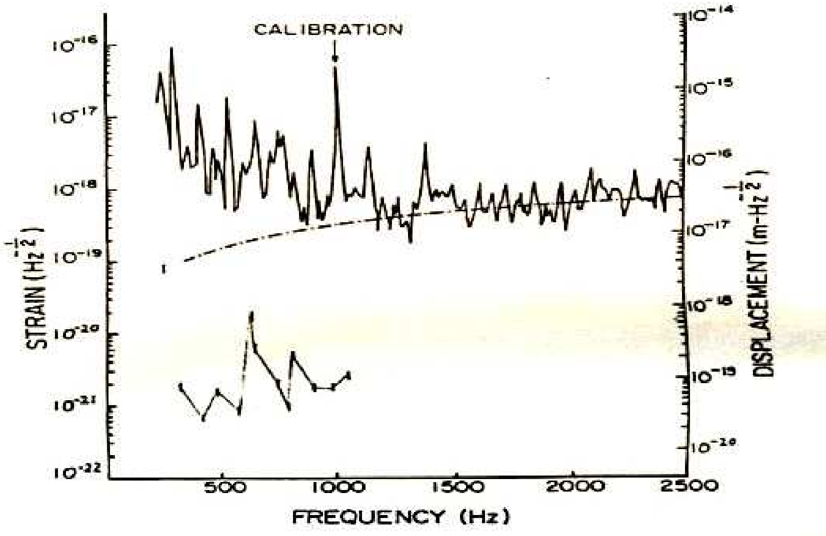
3) Two Interferometric Detectors

Caltec 40 m Fabry-Perot

Max Planck- Garching 30 m Delay line

Caltec 40 m

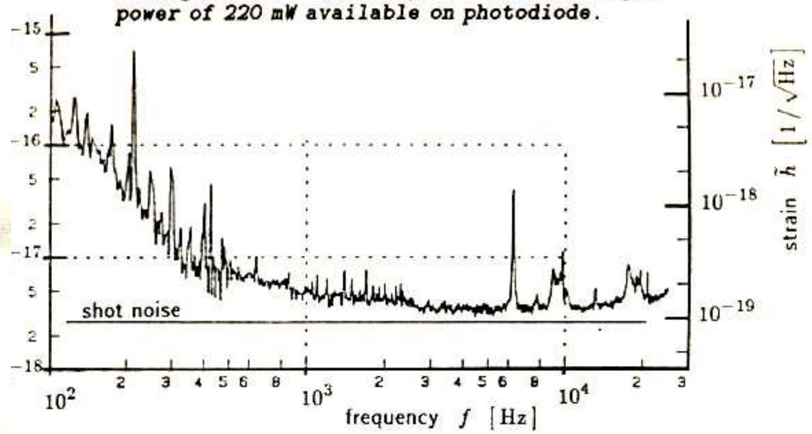
The CalTech Laser-Interferometric Gravitational Wave Detector



2. Noise spectrum of the detector, calibrated in strain (/√Hz

Max Planck 30 m

igure 1: Noise spectrum of 90 × 30 m interferometer, expressed as (linear) spectral density of strain $h = \delta\ell/\ell$ (axis on right hand side) or apparent displacement $\delta\ell$ (axis on left). Straight line: shot noise for maximum light power of 220 mW available on photodiode.



In 1985 Interferometers did not have any low frequency operation

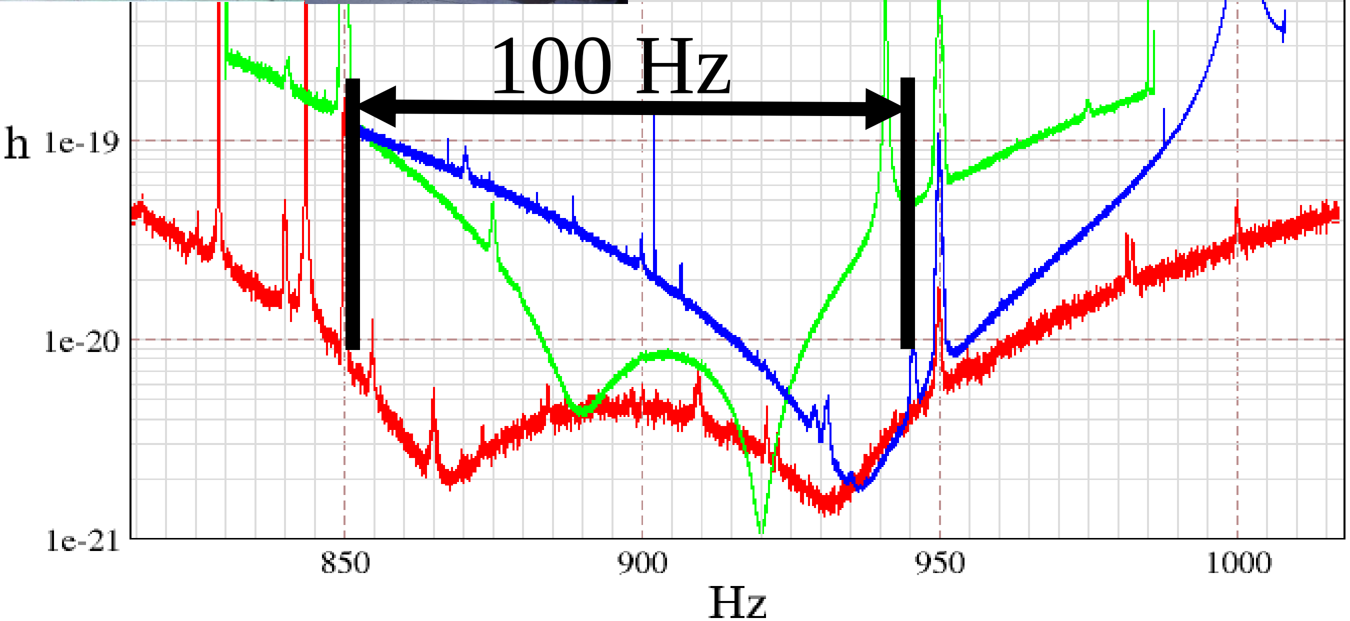
Even the more advanced Bar Detectors were missing low frequency

Auriga, Explorer and Nautilus

E. AMALDI, G. PIZZELLA,

I.MODENA, M. CERDONIO,

E. COCCIA

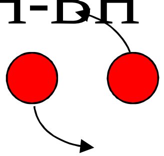


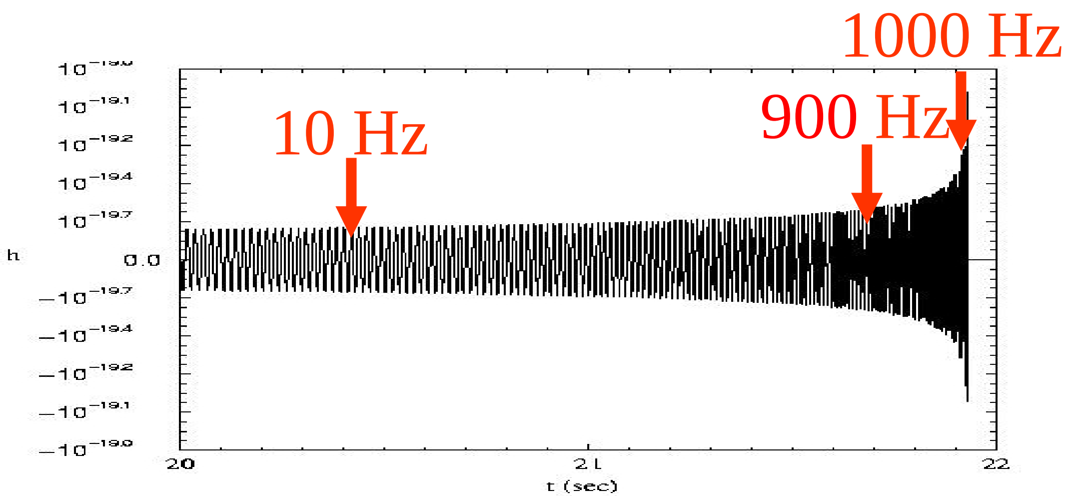
OUR TARGET WAS THEN THE CONSTRUCTION OF A VERY LARGE INTERFEROMETRIC DETECTOR SENSITIVE DOWN TO 10 Hz. Why?

1) Large Bandwidth makes larger detection probability

2) Coalescing Binaries Detection

NS-NS NS-BH BH-BH

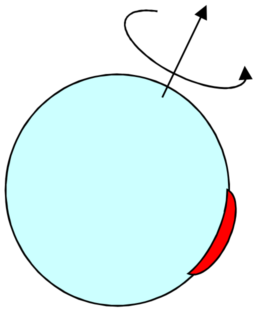




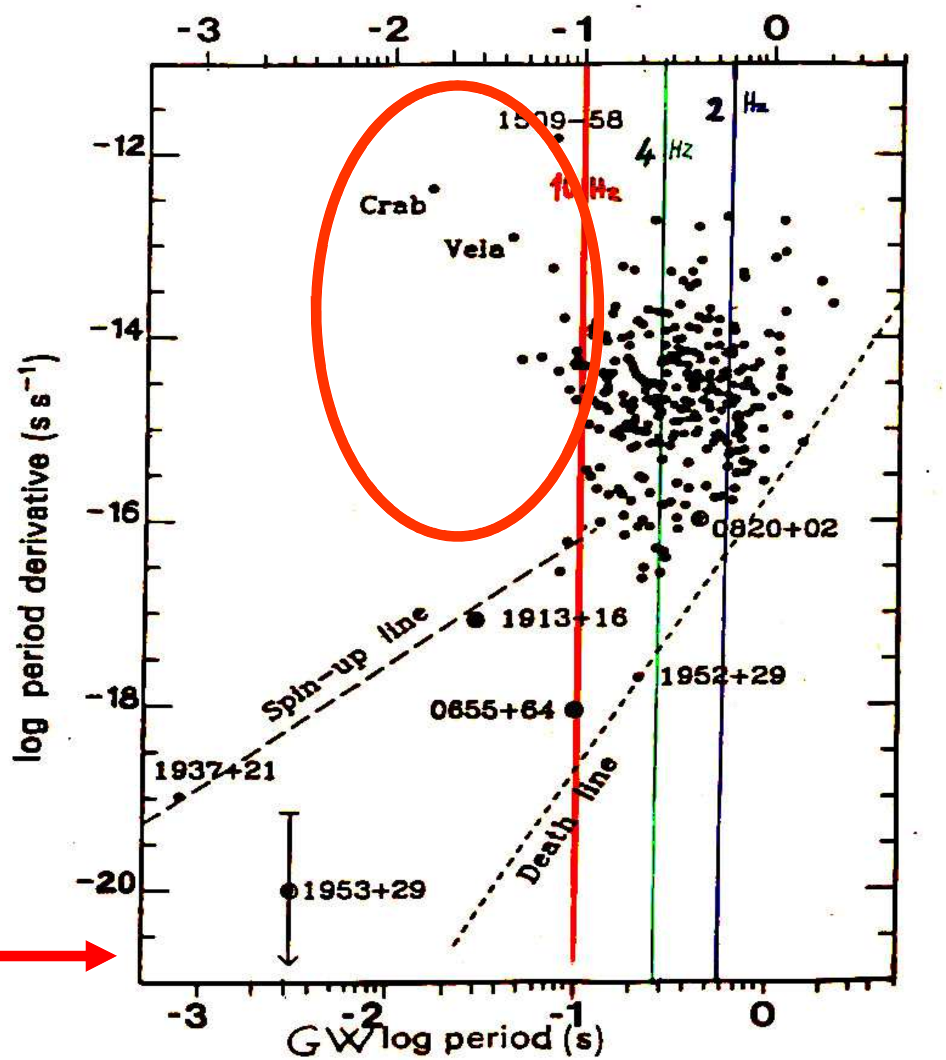
$$\text{Observation time increasing } \left[\frac{1000}{10}\right]^{8/3} \approx 800 \; times$$

3) PERIODIC SOURCES : Pulsar

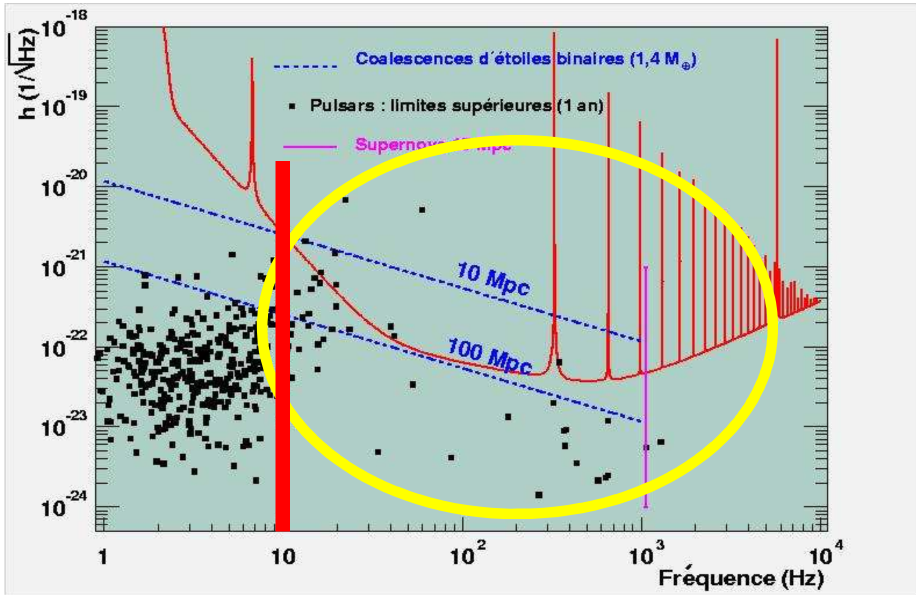
Galactic Neutron stars emit GW >10Hz



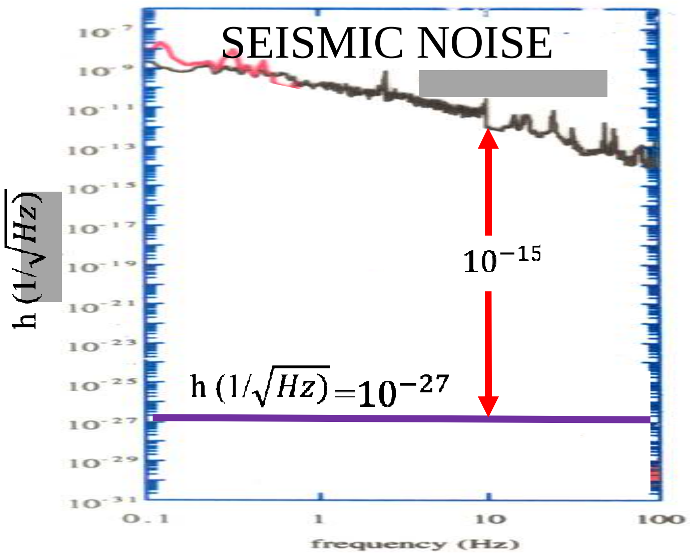
1980 Original Trasparency



Dick Manchester
Pulsar data taken
at Marrabra (AU)
Radiotelescope



But Going down to 10 Hz means that we had to suppress seismic noise in the mirror suspensions by at least 15 orders of magnitude.



1984 First Attempt

Ron Drever (Caltec) and Jim Hough (Glasgow) were attempting to create active inertial references. We started an experiment called IRAS (Interferometer for Seismic Noise Active Reduction)

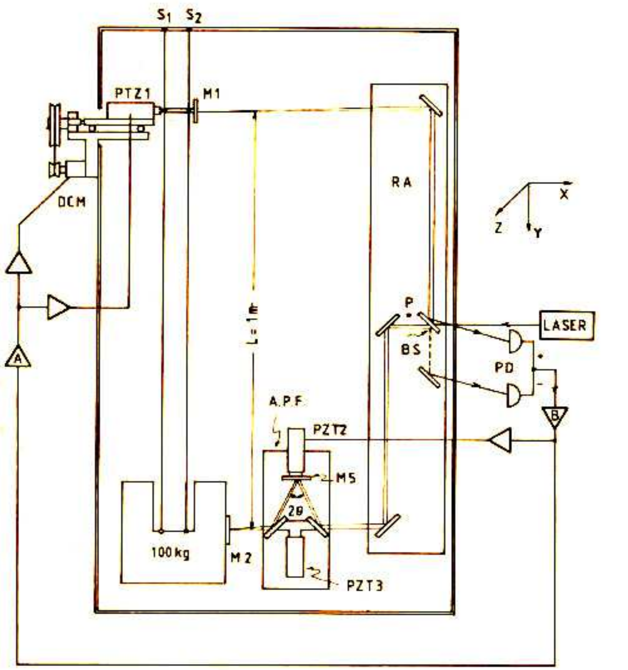


FIG. 3. Layout of the IRAS experiment including the interferometric system.

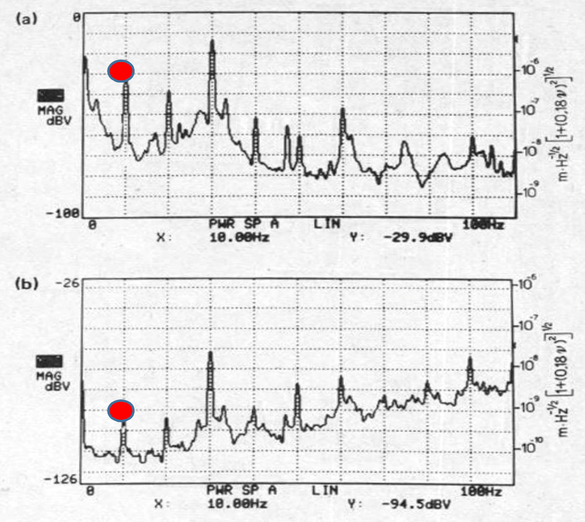


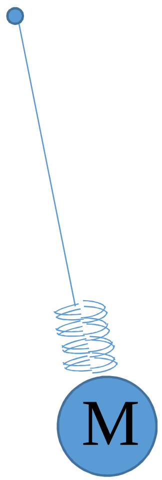
FIG. 6. The, RA locked-, open- (a), and closed- (b) loop frequency spectra for $0<\nu<100$ Hz.

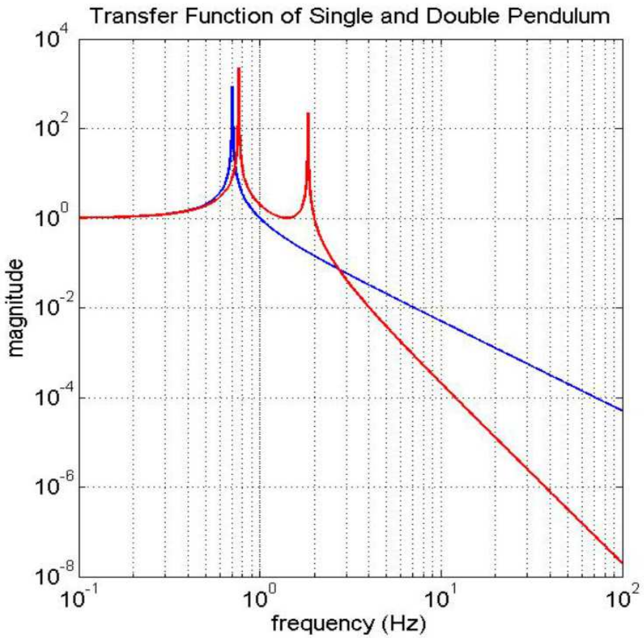
Pub.1985

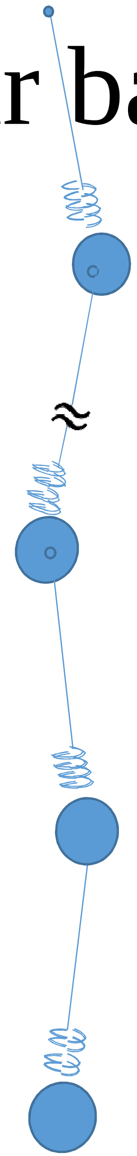
Attained Seismic noise Att. **$1,6\ 10^{-3}$**

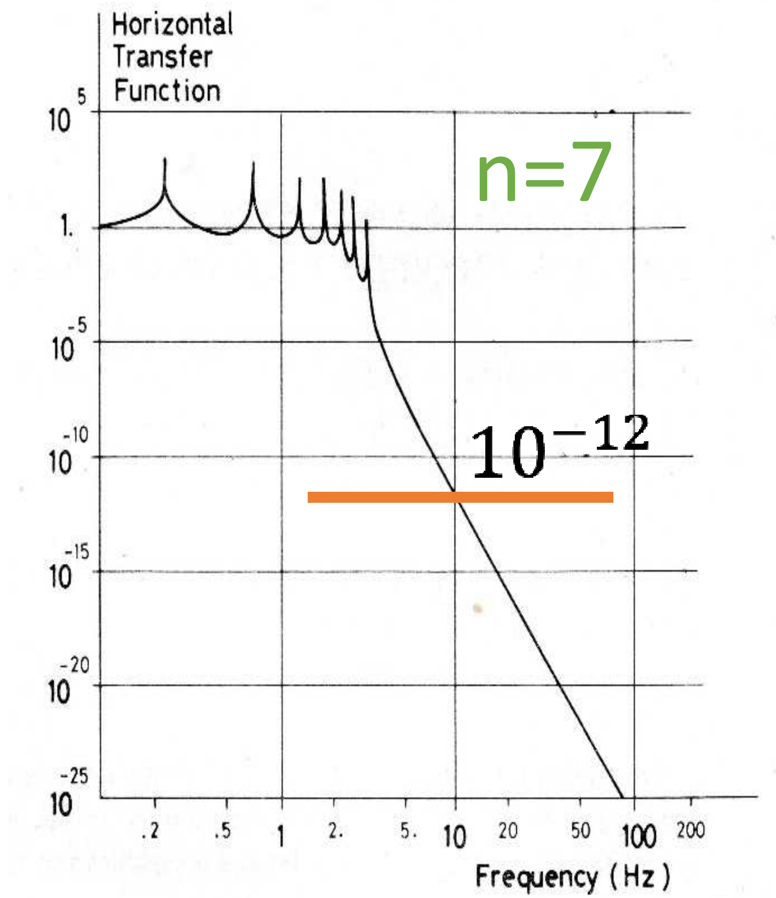
With such a low attenuation the only chance was to put many IRAS in cascade, thing Impossible. But this experiment was very important because showed that **a different method for killing Seismic noise had to be found**.

Our basic idea



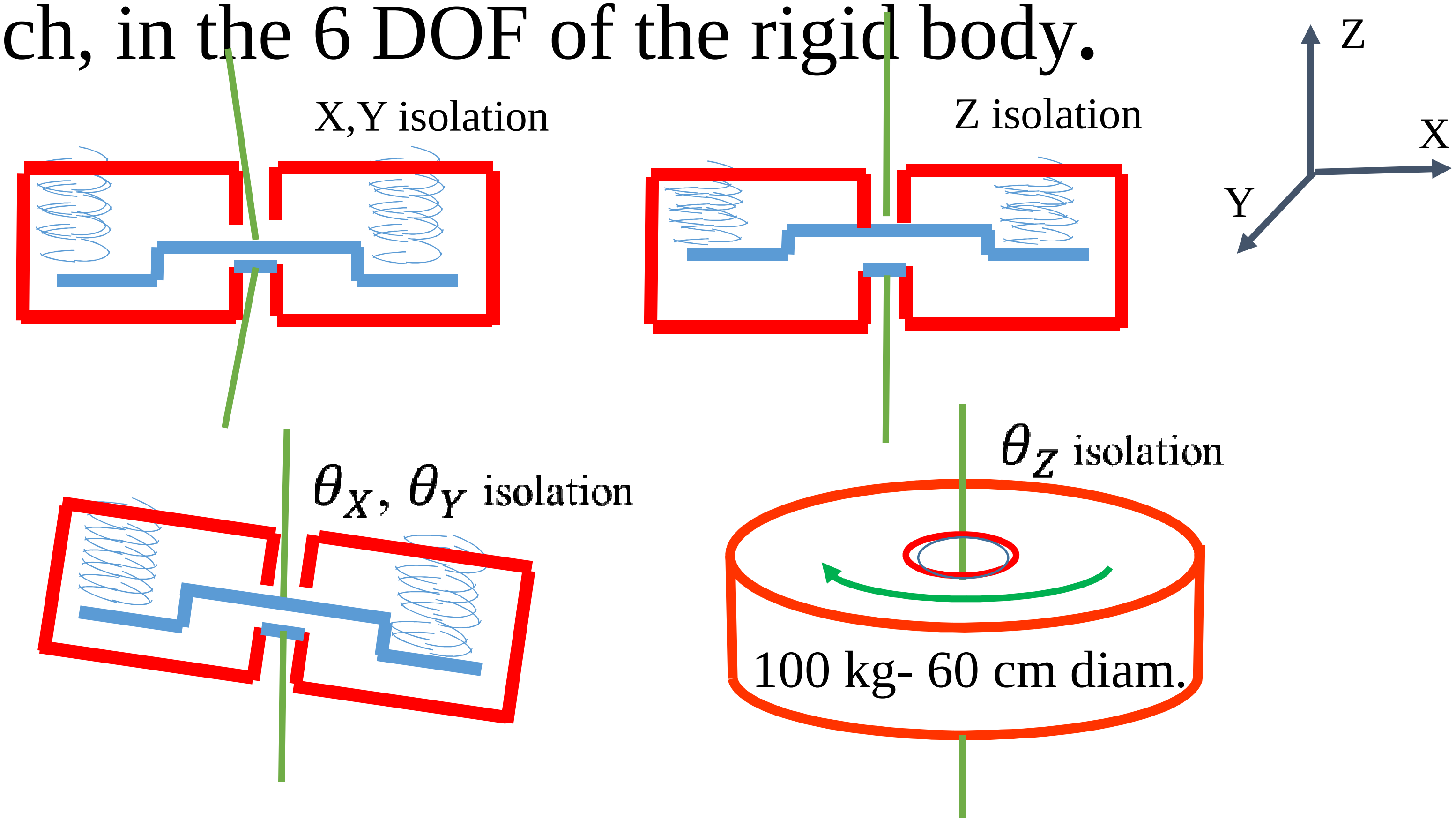






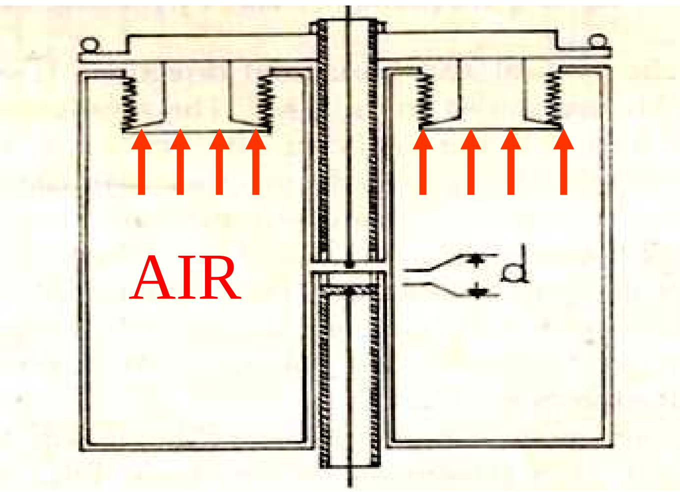
Toward a Solution

In 1985 we discovered that high seismic isolation requires a cascade of filters isolating, each, in the 6 DOF of the rigid body.



1987 Second Attempt and Steel Creep Problem

For Vertical attenuation Steel spring have Creep.i.e: Sliding of molecular structure. Creep produces Noise. Since Gas Spring are not affected by Creep, we created a gas spring mechanical filter attenuating in the 6 DOF of the rigid body and we built two chains of 7 filters under vacuum for measuring attenuation.



412 A. Giazotto, Interferometric detection of gravitational waves

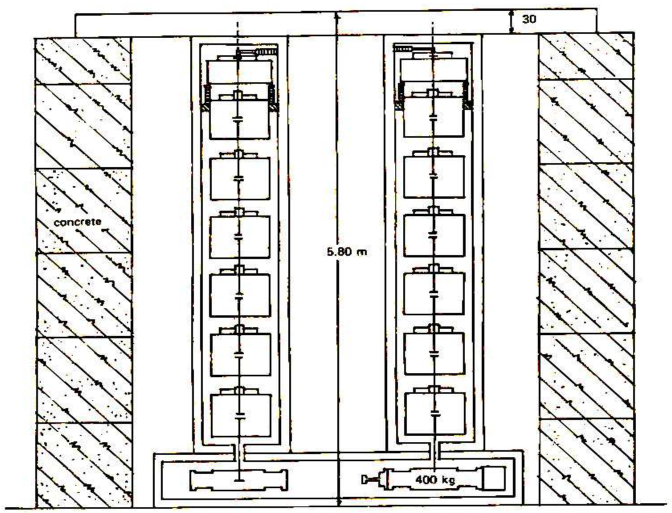
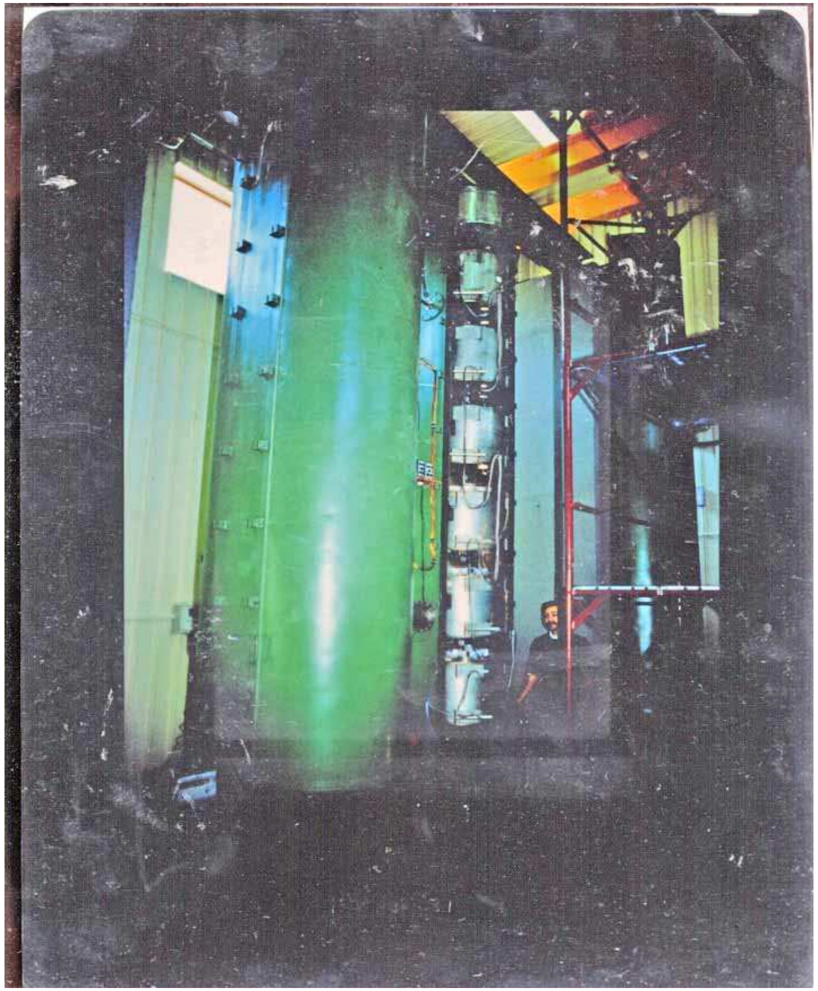


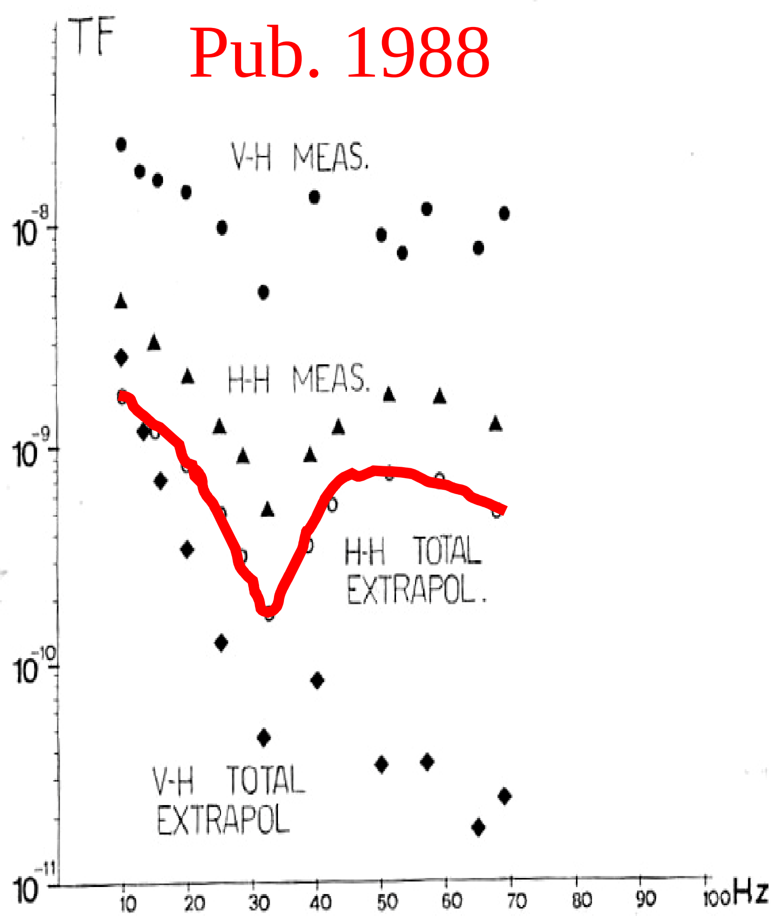
Fig. 11.4. Schematic diagram of the seismic noise attenuator (from Del Fabbro et al. [1988b]). The two attenuators, composed of a 7-fold three-dimensional harmonic oscillator, are able to give isolation in the vertical direction as well. The 400 kg test masses contained in the vacuum chamber are also shown. This device is able to attenuate the seismic noise in the vertical direction by a factor of $\leq 2 \times 10^{-8}$ at 10 Hz.

With Gas Spring chains we obtained seismic noise attenuation **10^{-9}@10 Hz**, the highest value ever reached on Earth but

Yet Not Enough



A. Giazotto, Interferometric detection of gravitational waves



THIS FIRST SUCCESS JOINED UP WITH THE PARTICIPATION OF ALAIN BRILLET , TOP CNRS OPTICS EXPERT, TO VIRGO.

IN 1987 FRANCE AND ITALY JOINED TOGETHER FOR THE BIRTH OF VIRGO

12 Maggio 1987
INFN PI/AE 87/1

Proposta di

Antenna interferometrica a grande base per la ricerca di Onde Gravitazionali

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Angela DI VIRGILIO
Adalberto GIAZOTTO
Hans KAUTZKY
Vinicio MONTELATICI
Diego PASSUELLO

Universita' di Napoli

Fabrizio BARONE
Riccardo BRUZZESE
Antonello CUTOLO
Luciano DI FIORE (INFN)
Massimo LANDINI
Maurizio LONGO
Leopoldo MILANO
Salvatore SOLIMENO

CNR Frascati

Franco BORDONI
Franco FULIGNI
Valerio IAFOLLA

Universita' di Salerno

Innocenzo PINTO

Gravitation et cosmologie Relativiste (Orsay-Paris)
CNRS-Univ. Pierre et Marie Curie

J.L. BOULANGER
Alain BRILLET
Oliver CREGUT
C. Nary MAN
Alain MARRAUD
David SHOEMAKER
Philippe TOURRENC
Jean-Yves VINET

UNIVERSITÀ DEGLI STUDI DI PISA
DIPARTIMENTO DI FISICA

Istituto Nazionale di Fisica Nucleare
Sezione di Pisa

The Discovery of NO CREEP Steel

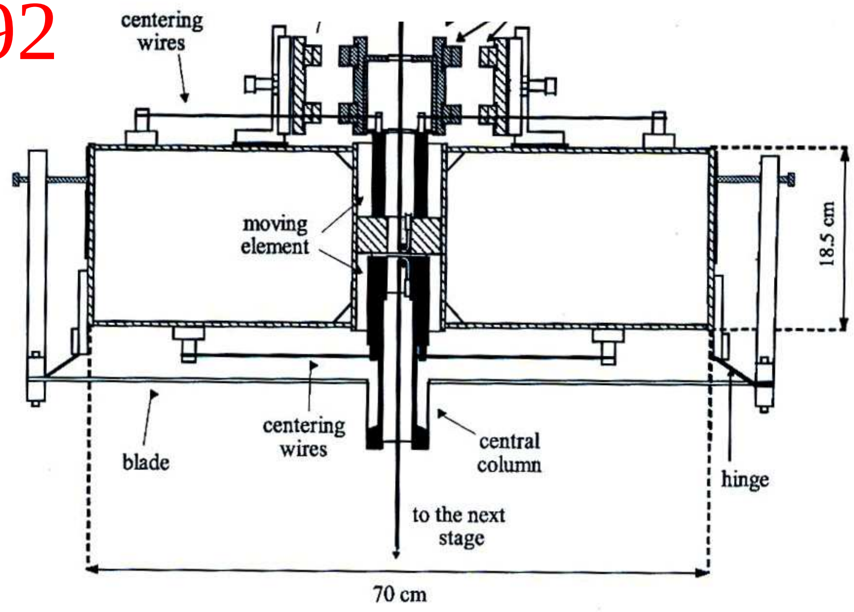
After long studies of different kinds of Steel (R. De Salvo), we pointed toward cannon steel. Cannons mouth dilate but after explosion recover primitive diameter. This is

MARAGING STEEL

This discovery brought us toward the good solution

Third Attempt: The use of MARAGING STEEL

About 1992



Gas Springs were too unstable under temperature variations. For this reason we created a mechanical filter satisfying the following requirements:

1) Mechanical restoring force in place of gas

2) No Creep with MARAGING STEEL

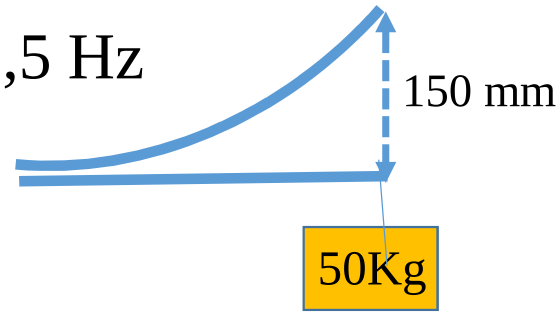
3) Almost insensitive to temperature variations

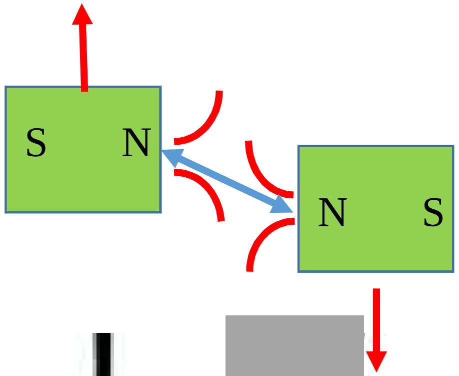
4) High momentum of inertia according to the three rotation axis

5) Extremely low vertical frequency, down to 100 mHz, by using magnetic antispring

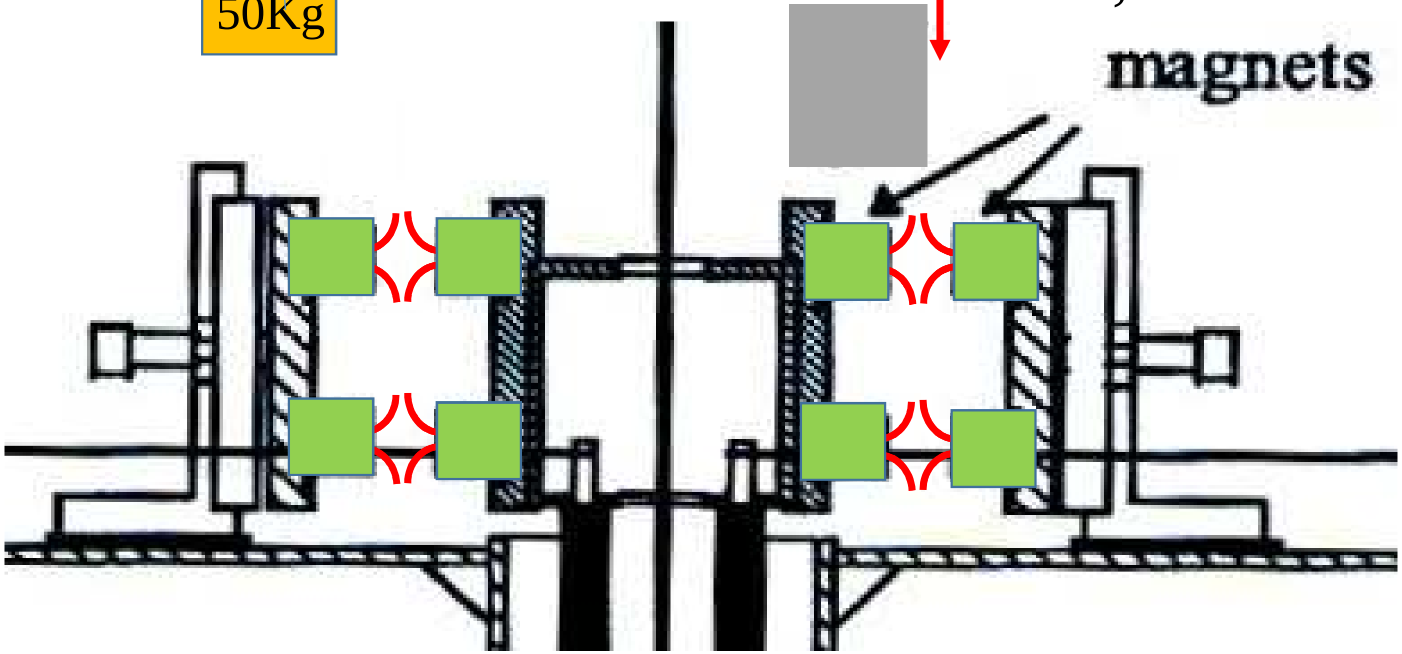
How to make vertical springs softer?
TUNABLE MAGNETIC ANTISPRING

K=3000 N/m
1,5 Hz

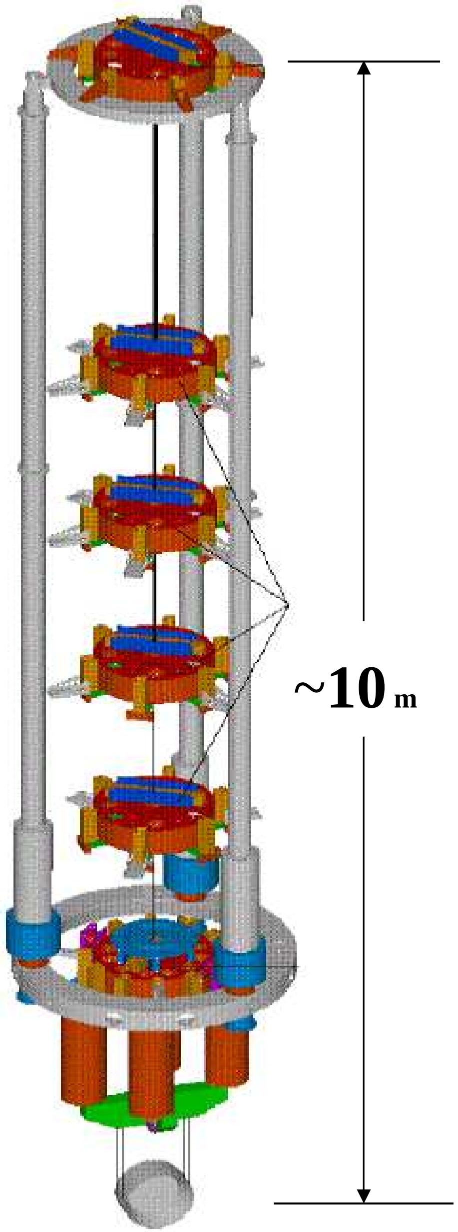


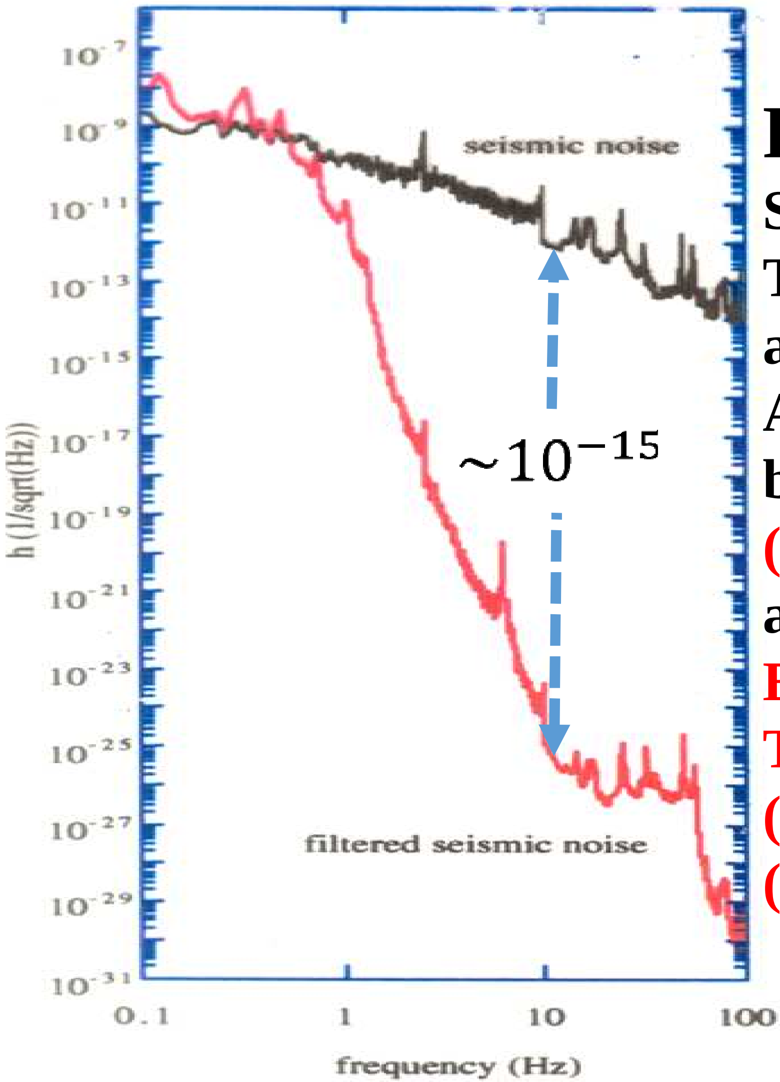


With Magnetic Antispring
K=30 N/m
0,15 Hz

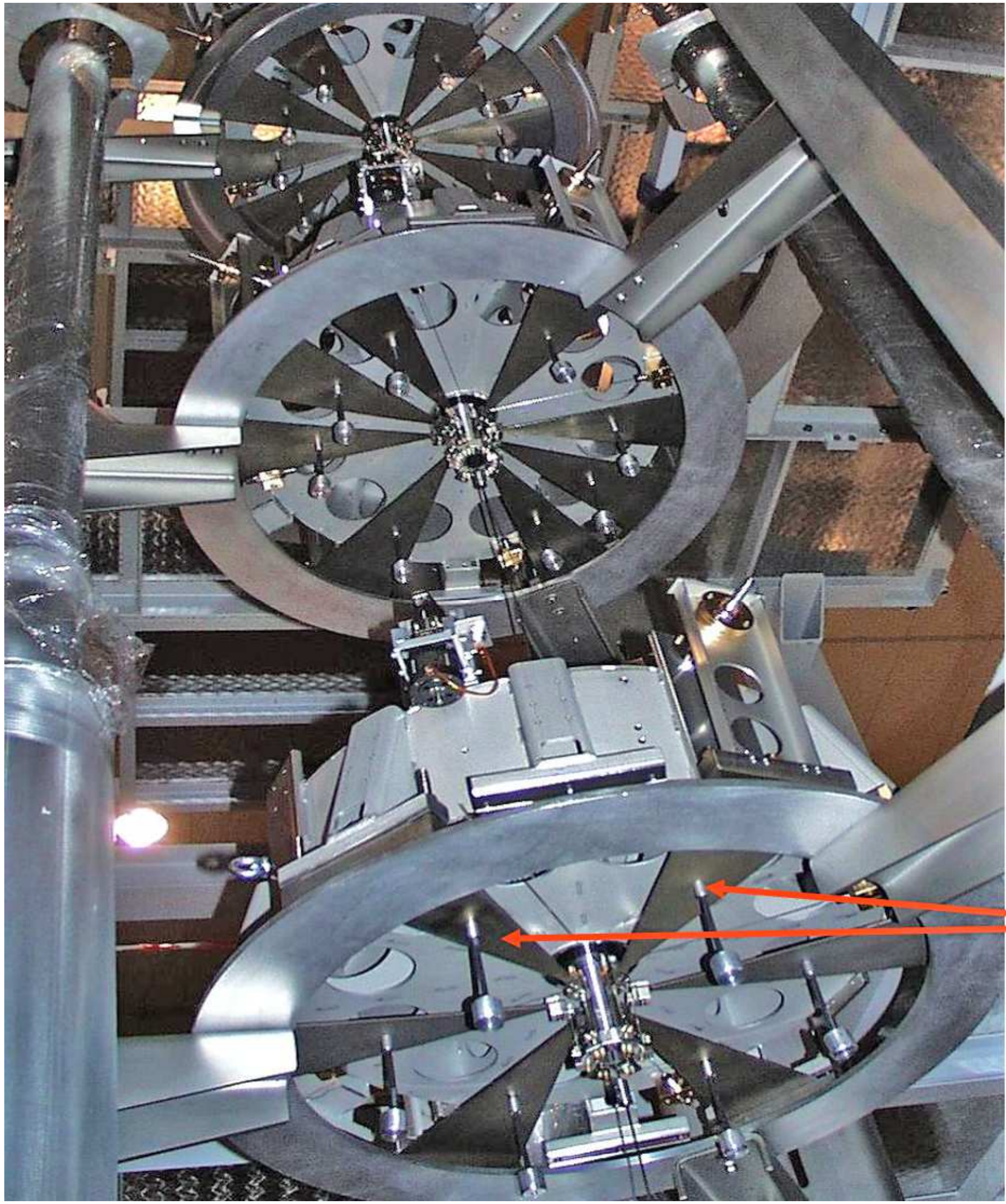


Vert. n=6 , Hor. n=8



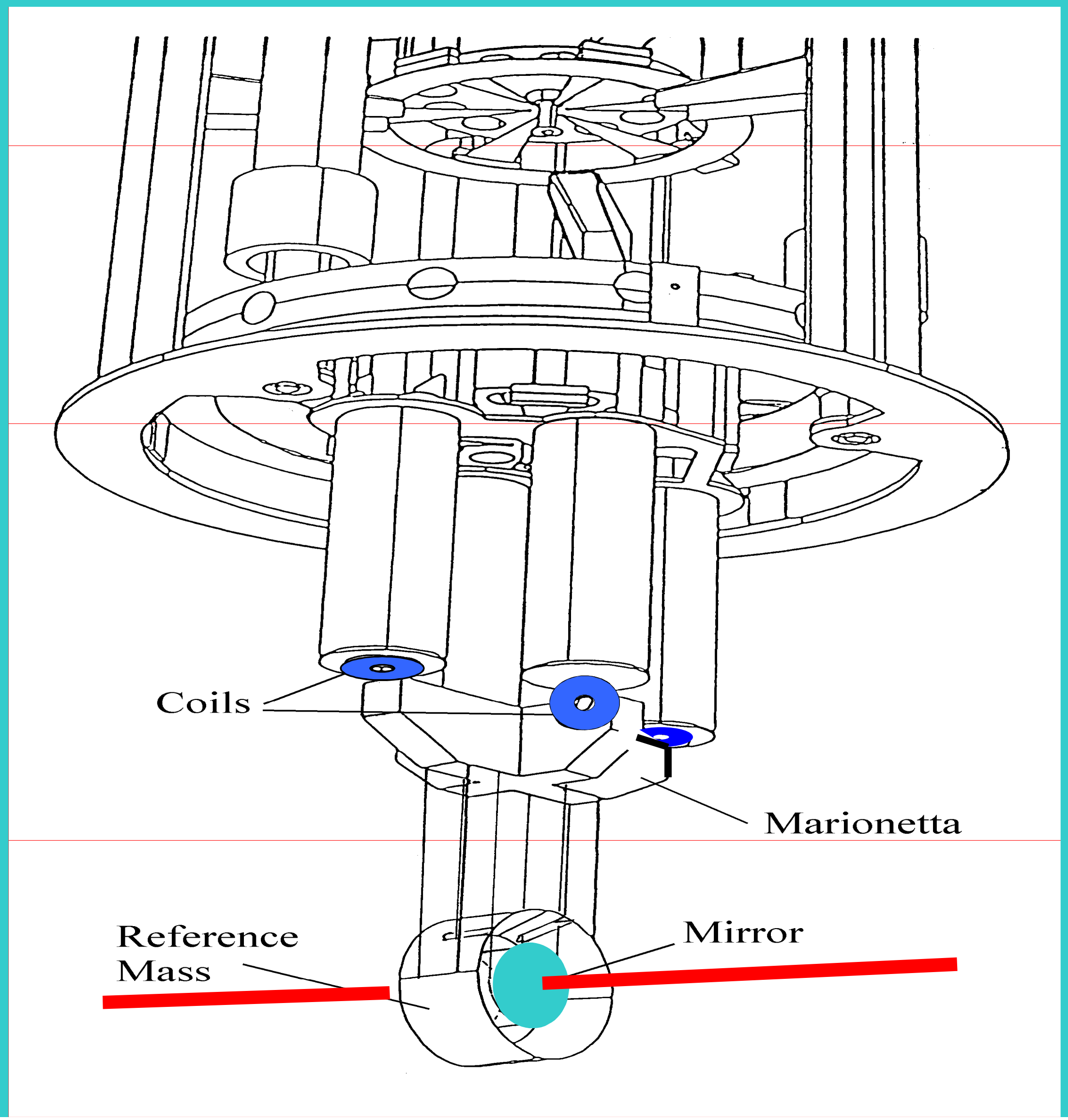


PASSIVE
SUPERAT-
TENUATORS
are today
ADOPTED
by KAGRA
(3Km)
and
EINSTEIN
TELESCOPE
(10 Km)
(in design)

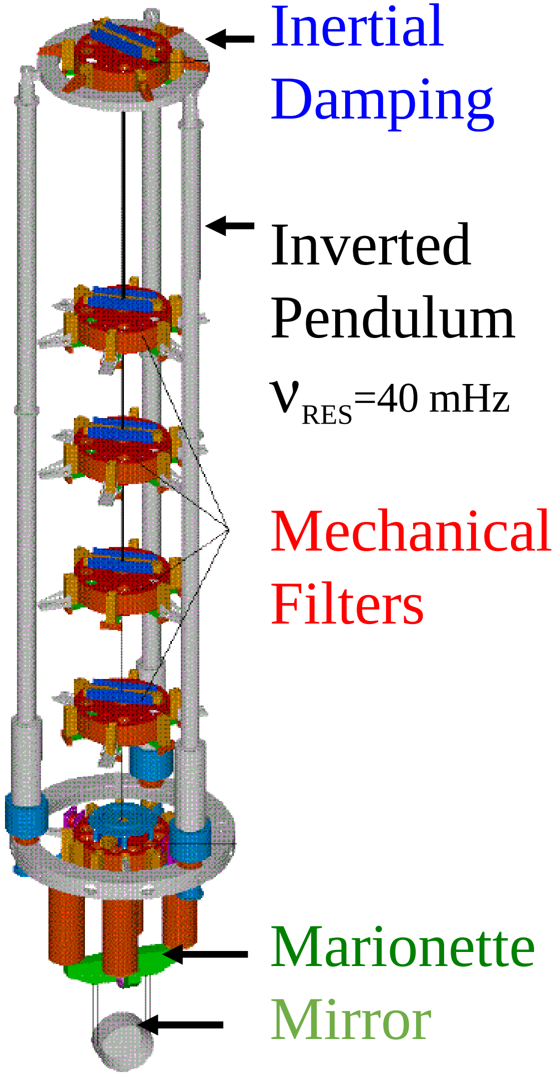


MARAGING
STEEL
BLADES

Superattenuatore: Filtro 7-Marionetta-Specchio



A Further Unknown : THE CONTROL OF VIRGO



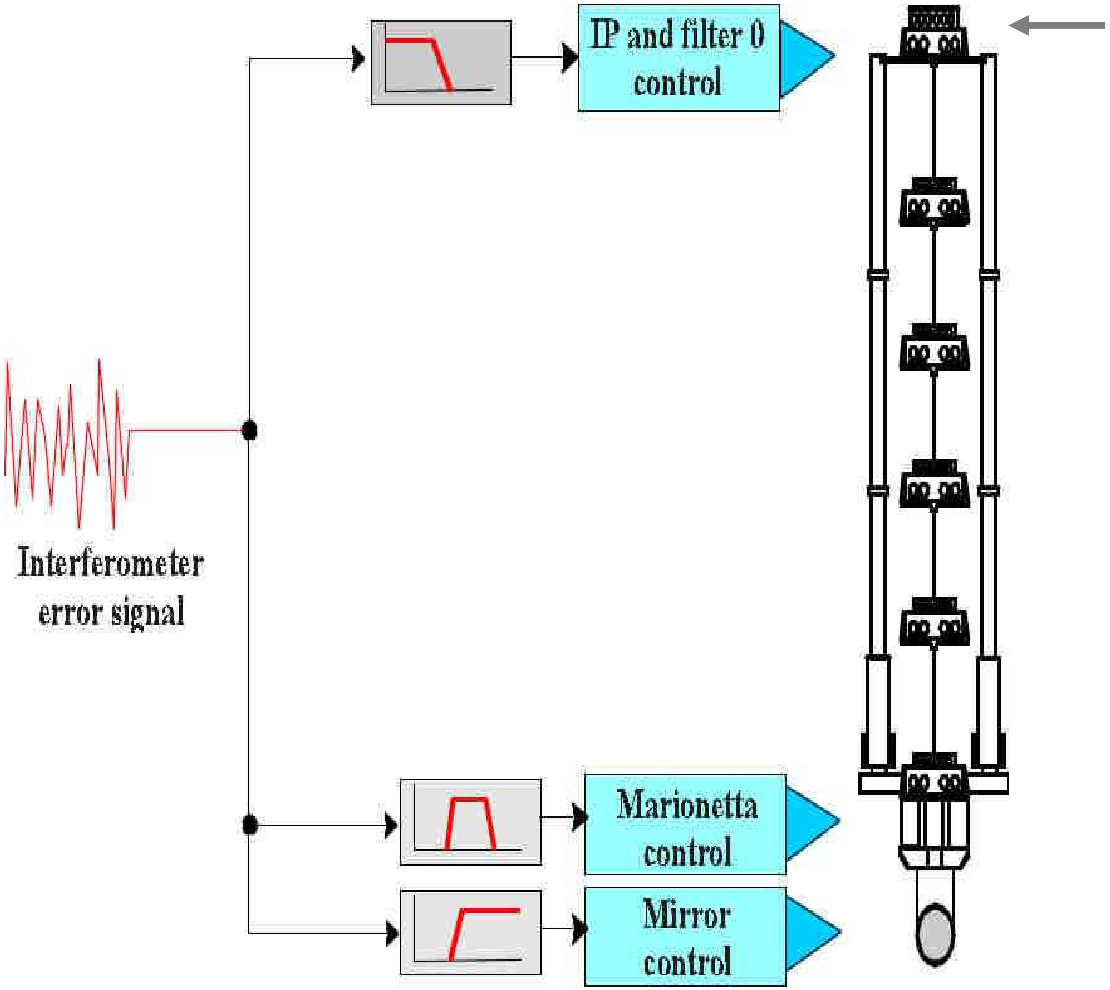
INVERTED PENDULUM (40 mHz)

Overall height 10 m

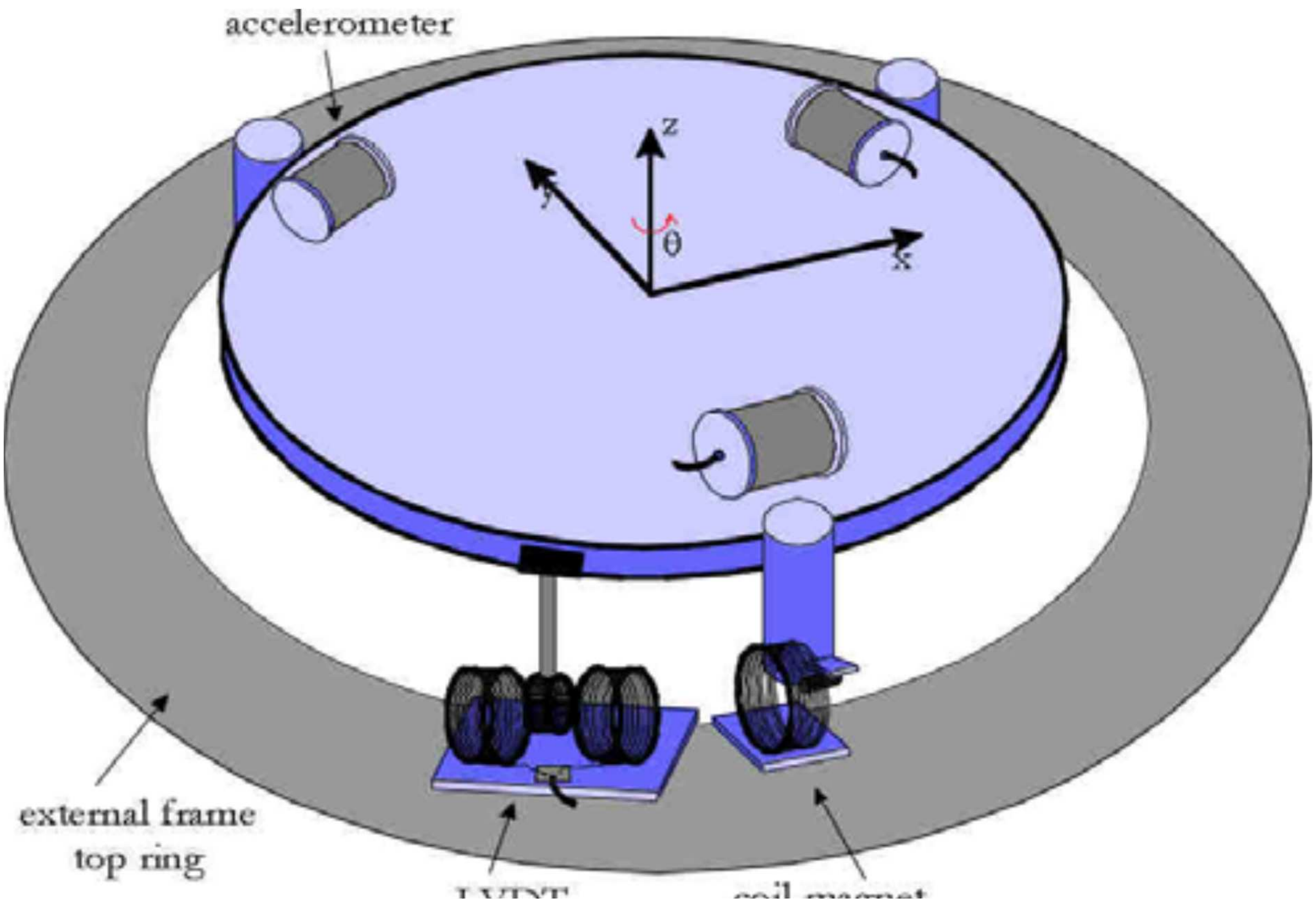
The idea was to inject Control Signals in 3 points:

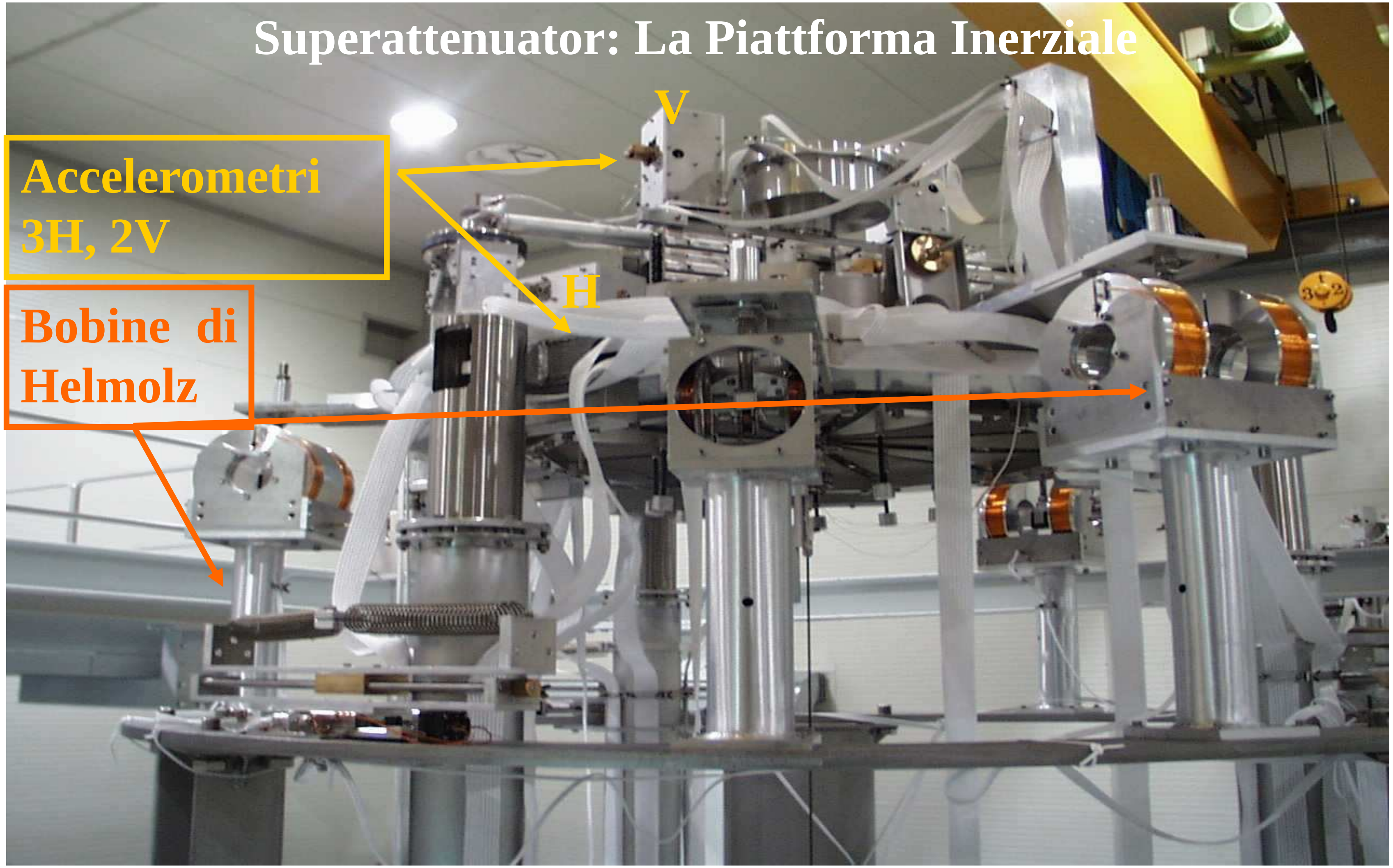
1) Low frequency on top
2) Medium frequencies to Marionetta
3) High Frequencies to Mirrors

1994 With SA we can make suspensions Hierarchical + Inertial Controls



Accelerometers for Inertial control


accelerometer
z
y
θ
x
external frame
top ring



1994, the low frequency problem, at least as far as seismic noise is concerned, was solved.

CONSEQUENTLY IN 1994, FRANCE AND ITALY APPROVED VIRGO CONSTRUCTION

ACCORD
concernant la Réalisation de l'Antenne de Détection des Ondes Gravitationnelles VIRGO

Le Centre national de la Recherche scientifique, Etablissement Public à caractère Scientifique et Technologique - ci-après désigné par les initiales CNRS et dont le siège social est sis 3, rue Michel-Ange, F75794 Paris Cedex 16, représenté par son Directeur Général, M. François Kourilsky,

et

l'Istituto Nazionale di Fisica Nucleare, institut publique pour la recherche scientifique - ci-après désigné par les initiales INFN et dont le siège social est sis via Enrico Fermi 40, I 00044 Frascati, représenté par son Président, M. Luciano Maiani,

ci-après désignés les Parties ;

CONSIDÉRANT que la détection des ondes gravitationnelles offrira

dans le domaine de la physique fondamentale

- une preuve directe de l'existence des ondes gravitationnelles ;
- un mode d'investigation des caractéristiques tensorielles du champ gravitationnel ;

dans le domaine de l'astronomie et de l'astrophysique

- un nouveau moyen d'observation des objets lointains, en sus des ondes électromagnétiques et des neutrinos ; il s'agira d'un instrument unique pour la détection des phénomènes très énergétiques tels que l'effondrement des supernovae et des binaires serrées ;

CONSIDÉRANT qu'une collaboration dans ce domaine existe déjà depuis de nombreuses années entre scientifiques français et italiens ;

- 1 -

conseguenza il presente Accordo sarà modificato tramite una clausola aggiuntiva.

ARTICOLO 14 - CONTROVERSIE

Le Parti risolveranno amichevolmente ogni controversia che potrebbe risultare dalla interpretazione o dalla applicazione del presente Accordo.

ARTICOLO 15 - SCALA DEI TEMPI

La data di acquisizione del sito costituisce il tempo zero della scala dei tempi previsti per la realizzazione del progetto (Allegato B). Nel frattempo la progettazione e la realizzazione di prototipi di sottosistemi nonché altre attività definite dal Consiglio VIRGO, sono o potranno essere condotte senza relazione temporale con l'acquisizione del sito.

ARTICOLO 16 - ENTRATA IN VIGORE

Il presente Accordo entrerà in vigore dopo essere stato approvato dalle Autorità competenti delle Parti.

ARTICOLO 17 - DURATA

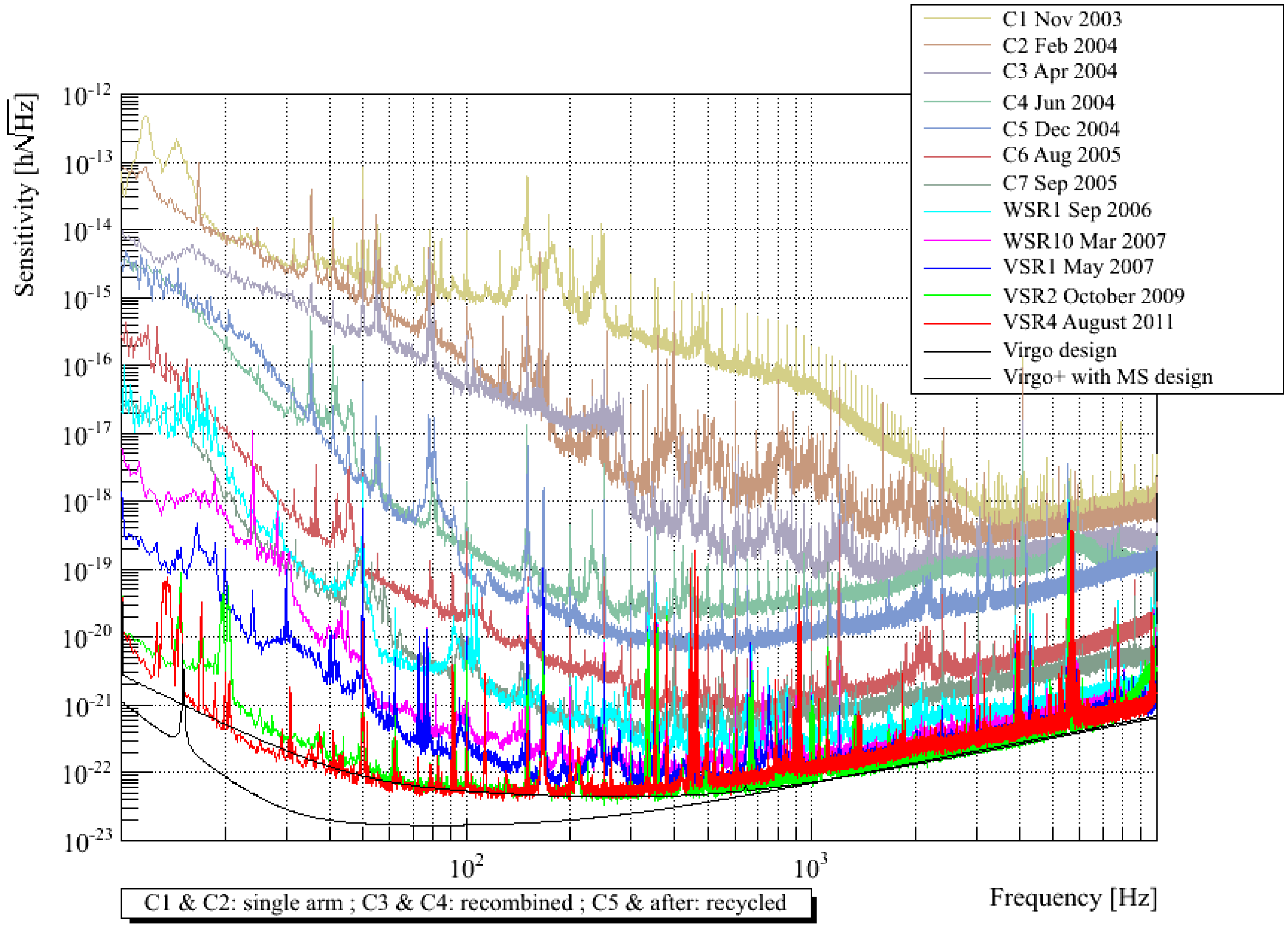
A meno che decidano di comune accordo di mettere fine alla loro collaborazione, le Parti si impegnano a partarla avanti, oltre alla fase di costruzione, per una durata minima di gestione di cinque anni, conformemente a quanto previsto dall'articolo 1. del presente Accordo.

ARTICOLO 18 - DISPOSIZIONI FINALI

Il presente Accordo é redatto in quattro esemplari originali, due in versione francese e due in versione italiana, entrambe facenti ugualmente fede.

Pisa li, 27 Juin 1994

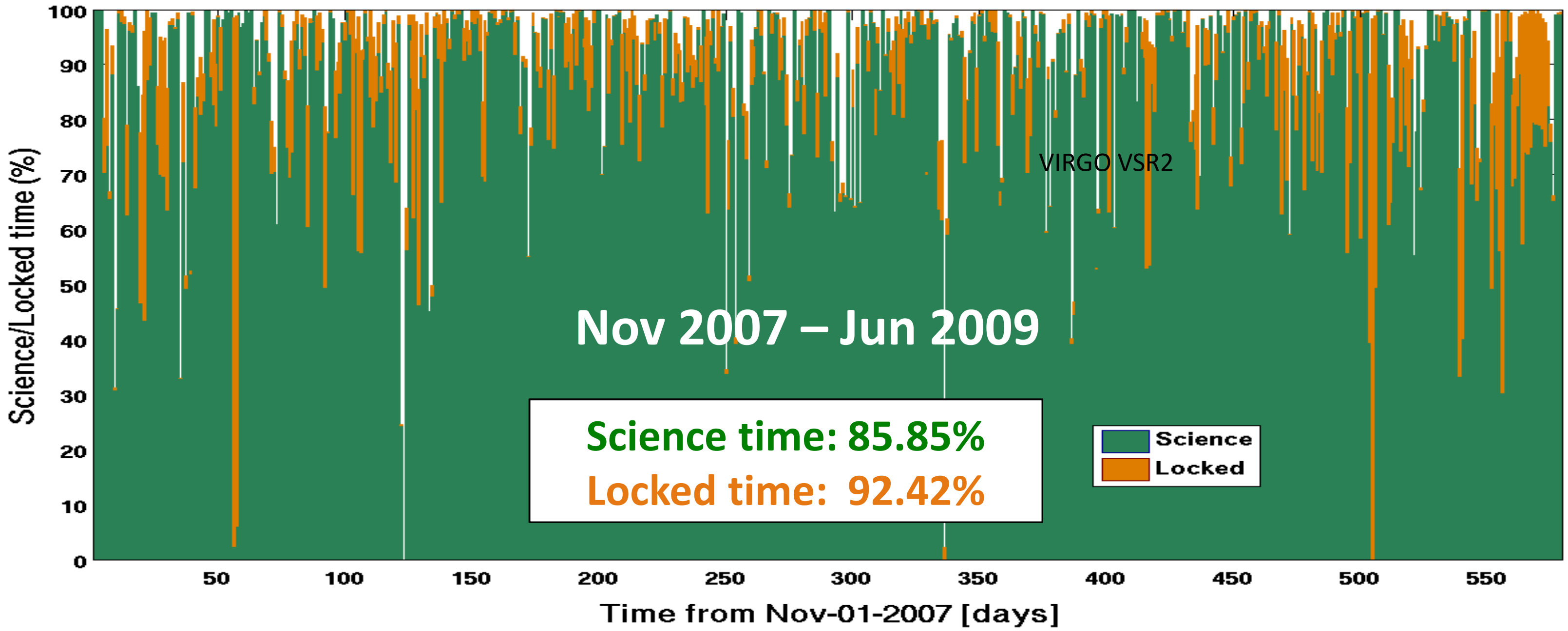
Per il CNRS	Per l'INFN
François KOURILSKY Direttore Generale	Prof. Luciano MAIANI Presidente



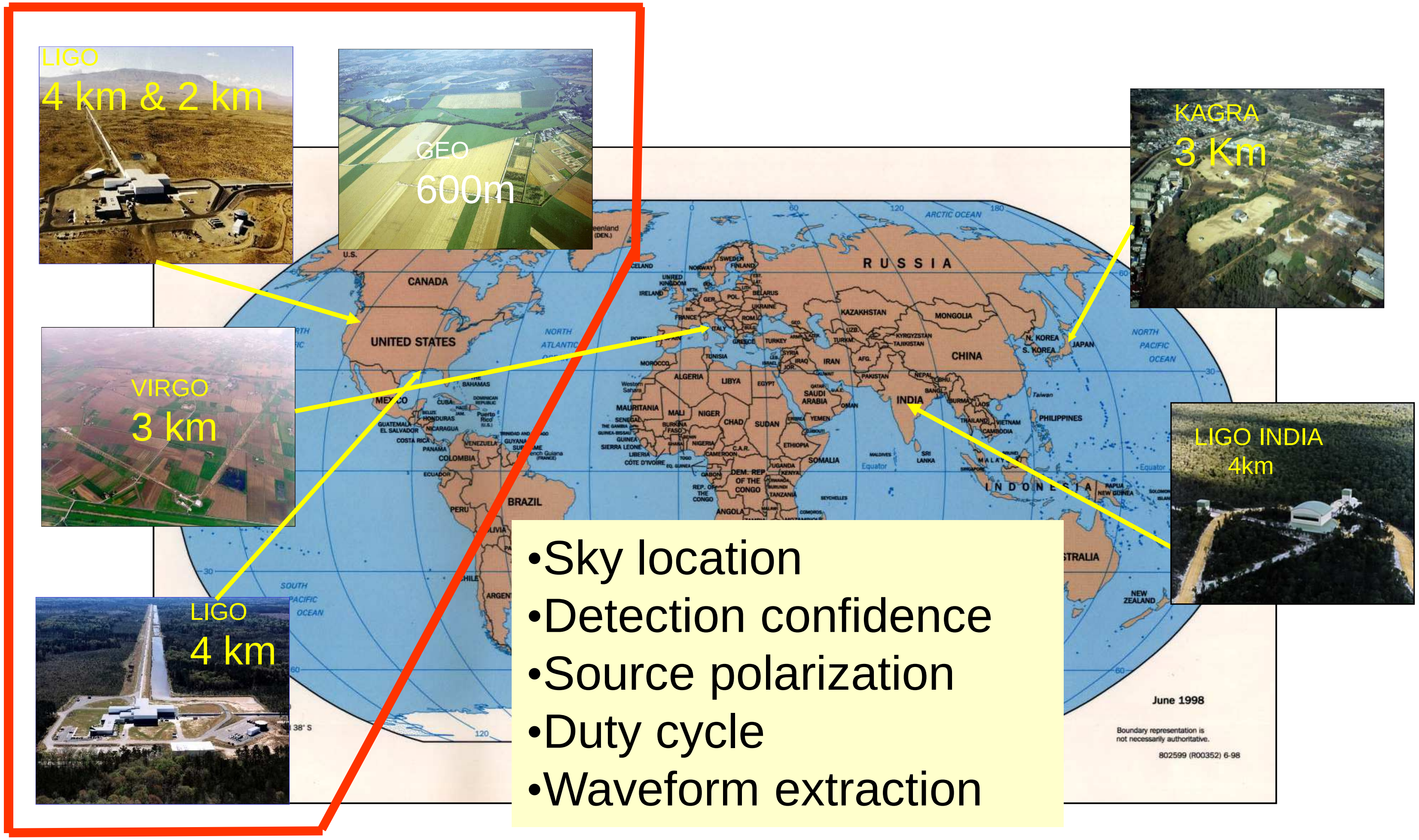
Sensitivity [h/√Hz]
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{2}
10^{3}
Frequency [Hz]
C1 & C2: single arm ; C3 & C4: recombined ; C5 & after: recycled
C1 Nov 2003
C2 Feb 2004
C3 Apr 2004
C4 Jun 2004
C5 Dec 2004
C6 Aug 2005
C7 Sep 2005
WSR1 Sep 2006
WSR10 Mar 2007
VSR1 May 2007
VSR2 October 2009
VSR4 August 2011
Virgo design
Virgo+ with MS design

ROBUSTNESS

- Excellent robustness (and very good duty cycles) obtained by 1st generation detectors
- Not just sensitive instruments, but reliable ones!



NETWORK OF INTERFEROMETERS



- Sky location
- Detection confidence
- Source polarization
- Duty cycle
- Waveform extraction

NETWORK

Memorandum of Understanding

between

VIRGO

on one side

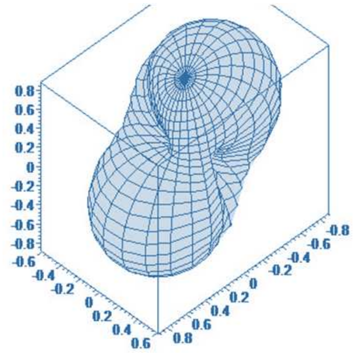
and the

Laser Interferometer Gravitational Wave Observatory (LIGO)

on the other side

Purpose of agreement:

The purpose of this Memorandum of Understanding (MOU) is to establish and define a collaborative relationship between VIRGO on the one hand and the Laser Interferometer Gravitational Wave Observatory (LIGO) on the other hand in the use of the VIRGO, LIGO and GEO detectors based on laser interferometry to measure the distortions of the space between free masses induced by passing gravitational waves.



LIGO, Virgo, GEO exchanging data since 2007.

MoU being renewed.

OBSERVATIONAL RESULTS

O(100) PAPERS ON ASTROPHYSICS/COSMOLOGY/ ASTROPARTICLE PHYSICS

PHYSICAL REVIEW D **82,** 102001 (2010)

Search for gravitational waves from compact binary coalescence in LIGO and Virgo data from S5 and VSR1

PHYSICAL REVIEW D **87,** 022002 (2013)

Search for gravitational waves from binary black hole inspiral, merger, and ringdown in LIGO-Virgo data from 2009–2010

PHYSICAL REVIEW D **81,** 102001 (2010)

All-sky search for gravitational-wave bursts in the first joint LIGO-GEO-Virgo run

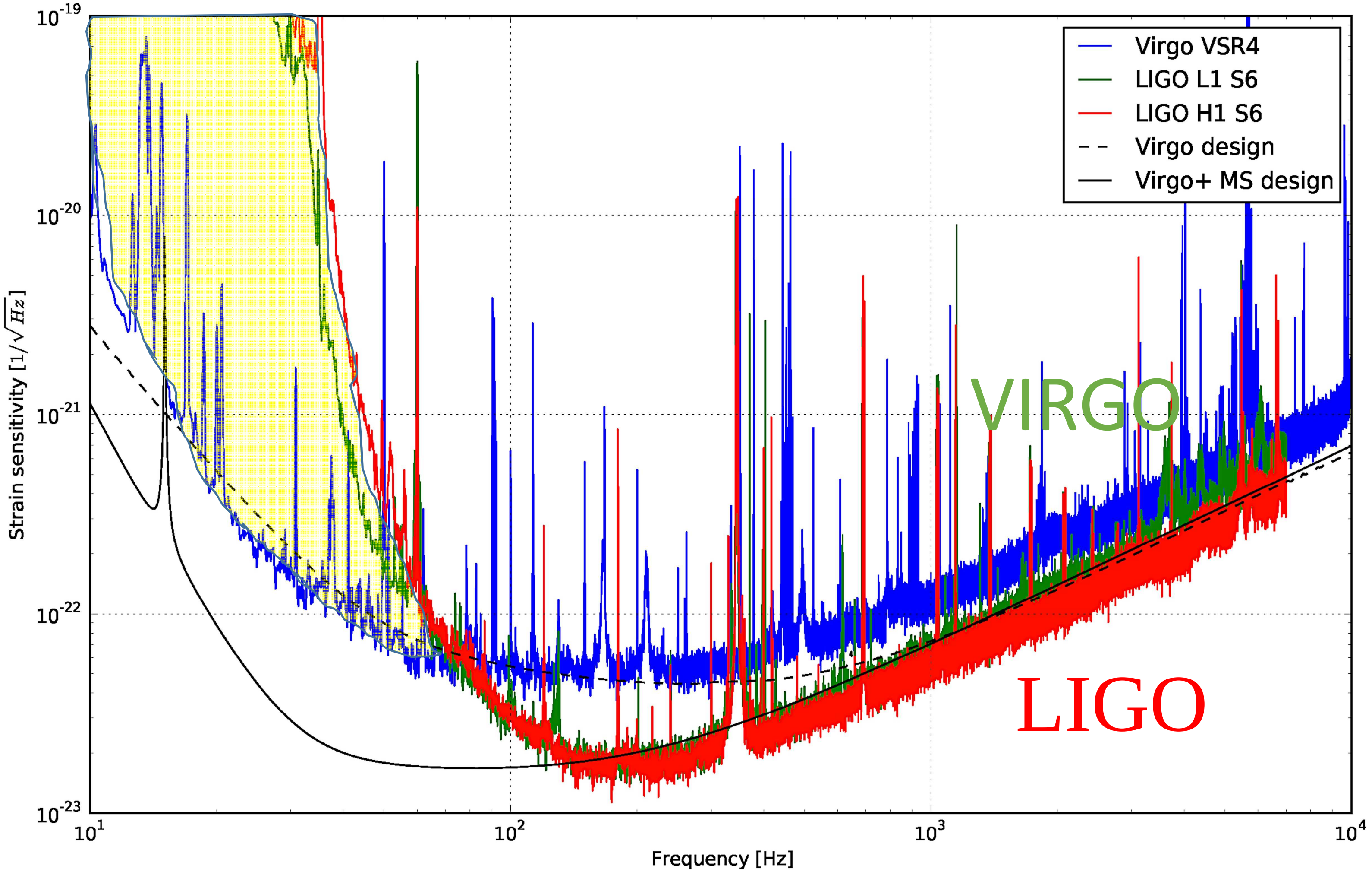
The Astrophysical Journal. 736:93 2011 August 20

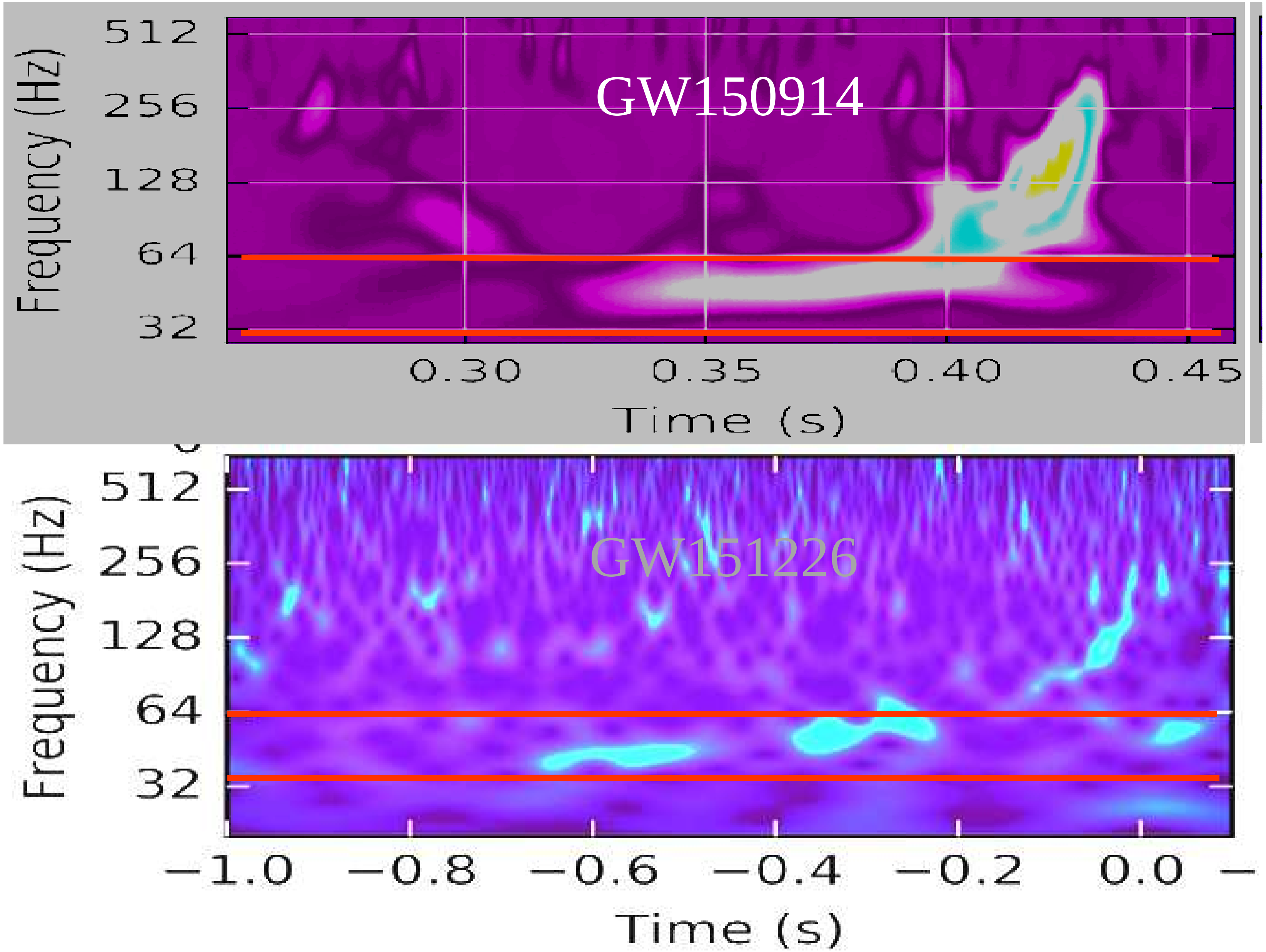
BEATING THE SPIN-DOWN LIMIT ON GRAVITATIONAL WAVE EMISSION FROM THE VELA PULSAR

THE UPPER LIMIT SET ON THE PULSAR EMISSION ALLOWS TO LIMIT THE ELLIPTICITY TO O(10^{-8}): WE ARE MEASURING THE STAR RADIUS ASYMMETRY WITH AN ACCURACY OF ~0.7 mm

But No Detection Of Gravitational Waves

Sensitivity of LIGO-Virgo Runs 2005-2009




GW150914
512
256
128
64
32
Frequency (Hz)
0.30
0.35
0.40
0.45
Time (s)
GW151226
512
256
128
64
32
Frequency (Hz)
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Time (s)