GW-experiment:
current situation at Jan.2006

Gravitational Waves (GW)

Gravitational waves give fundamental informations on the Universe.

The four fundamental interactions coupling constants are:

Strong	E.M.	Weak	Gravitational
$a_s=1$	$e^2=1/137$	$G_F M^2=10^{-5}$	$GM^2=10^{-39}$

Some consequences of G smallness:

1)In stellar collapses Neutrinos undergo ~10^3interactions before leaving the collapsing star, GW<<1.

2)After Big-Bang , electromagnetic waves decouple from hot matter after 13000 years, neutrinos after 1s, GW only after Planck's Time (10^{-43}s) .

3) It is extremely difficult to detect them.

Linearization of Einstein equations

When gravity is "small" we may write $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$, where $h_{\mu\nu}$ is infinitesimal; to first order in $h_{\mu\nu}$ Riemann tensor and Einstein's equations become:

$$R_{iklm} = \frac{1}{2}\left(\frac{\partial^2 h_{im}}{\partial x_l \partial x_k} + \frac{\partial^2 h_{lk}}{\partial x_i \partial x_m} - \frac{\partial^2 h_{km}}{\partial x_i \partial x_l} - \frac{\partial^2 h_{il}}{\partial x_k \partial x_m}\right)$$

$$\Box \Psi_{\mu\nu} = \frac{8\pi G}{c^4} \tau_{\mu n}$$

Where $$\Psi_{mn} = h_{mn} - \frac{1}{2} d_{mn} h^l_l$$

and $\tau_{\mu\nu}$ is $T_{\mu\nu}$ expanded to first order in $h_{\mu\nu}$.

Considering that $t_{00} = r c^2$ **, where ρ is the matter density,**

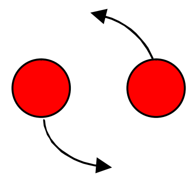
it follows $$\Psi_{ab} = -\frac{2G}{c^4 R_o}\left(\frac{\partial^2}{\partial t^2}\int r x_a x_b dV\right)_{t-R_0/c}$$ **R_0 is the source distance**

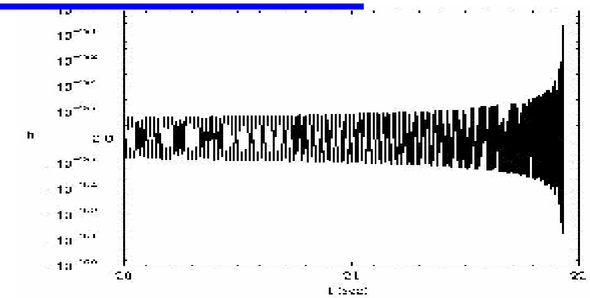
In the limit of weak gravity, GW amplitude is proportional to the second time derivative of the mass quadrupole moment.

GW SOURCES

1) Coalescing Binary Systems: NS and Black Holes

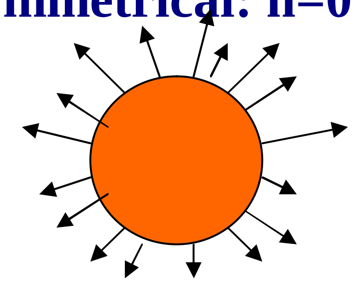
Rate: 1~2/year in a 50Mpc sphere.





2) Supernovae Explosions

Symmetrical: h=0



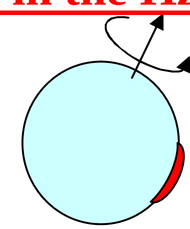
Explosions Rate:

Virgo Cluster (h~10^{-23}) 1~2/year

Galassia (h~10^{-20}) 1/30 years

3) Periodic Sources: 10^9 Galactic rotating Neutron Stars emitting in the Hz region

h< 10^{-25}



Earth Doppler shift

$$e^{iwt} \Rightarrow e^{iw(t-\vec{n}.\vec{R}/c)}$$

n is the SN direction
R the Earth radius

4) Cosmological BKG: Perhaps the most important signal: can give informations on Big–Bang at times close to Planck's time.

Þ Coincidence of two close detectors extremely sensitive.

THE GW RECEIVER

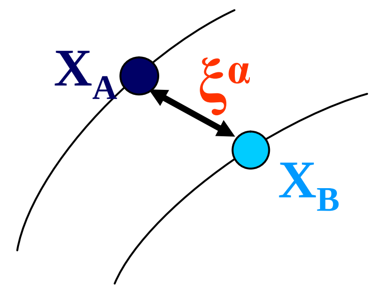
A particle moving freely under the action of a gravitational field has its x^μ coordinate satisfying the geodesic equation:

$$\frac{d^2 x^\mu}{d\tau^2} = \Gamma^\mu_{\nu\lambda}\frac{dx^\nu}{d\tau}\frac{dx^\lambda}{d\tau}$$

Where τ is the proper time

It is always possible to find a space-time trajectory in which $\Gamma^\mu_{\nu\lambda}=0$ at any time; along this trajectory a particle is freely falling.

Let's consider two freely falling particles A and B, their separation $\xi^\alpha=(x_A-x_B)^\alpha$ satisfies the geodesic deviation equation:



$$\frac{D^2 \xi^\alpha}{d\tau^2} + R^\alpha_{\beta\gamma\delta}\,\xi^\gamma\,\frac{dx^\beta}{d\tau}\frac{dx^\delta}{d\tau} = 0$$

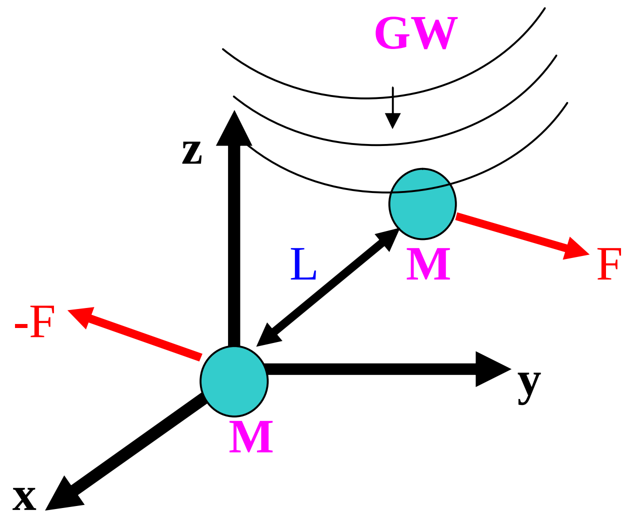
Where D^2 is the second covariant derivative:

$$\frac{D^2\xi^\alpha}{d\tau^2} = \frac{d^2\xi^\alpha}{d\tau^2} + \frac{d\Gamma^\alpha_{\beta\mu}}{d\tau}\xi^\beta\frac{dx^\mu}{d\tau} + \Gamma^\alpha_{\beta\mu}\frac{d}{d\tau}\left(\xi^\beta\frac{dx^\mu}{d\tau}\right) + \Gamma^\alpha_{\beta\mu}\left(\frac{d\xi^\beta}{d\tau} + \Gamma^\beta_{\varepsilon\nu}\xi^\varepsilon\frac{dx^\nu}{d\tau}\right)\frac{dx^\mu}{d\tau}$$

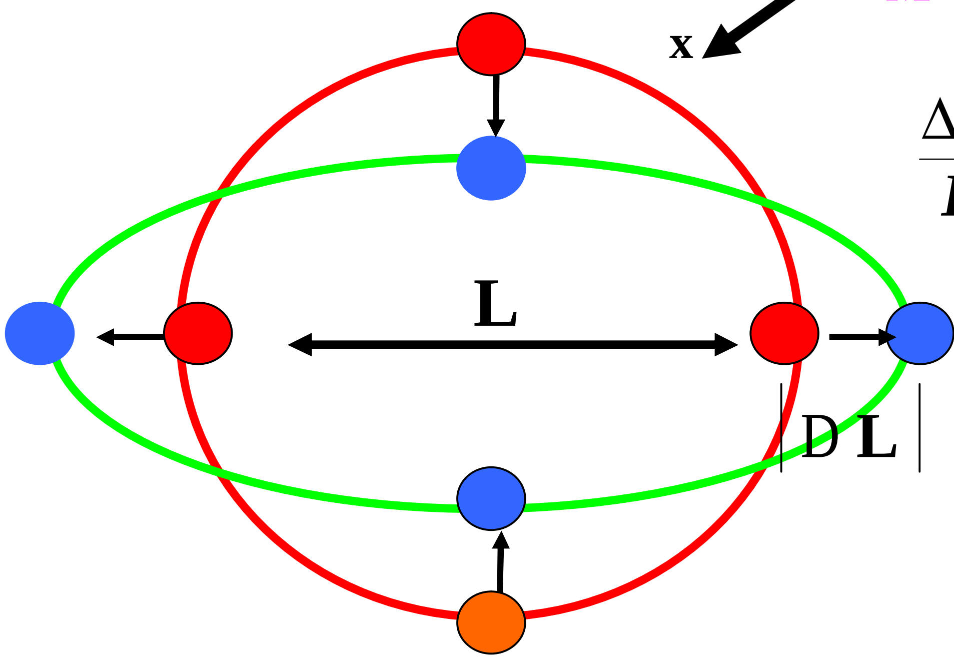
Gravitational Waves create tidal forces on the masses

Force increase with L until L<λ

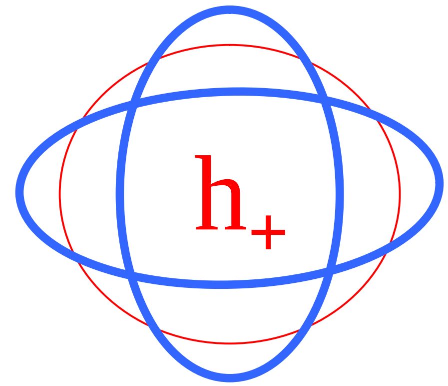
$$F_b = -\frac{1}{2} M L_a \frac{d^2}{dt^2} h^a_b$$

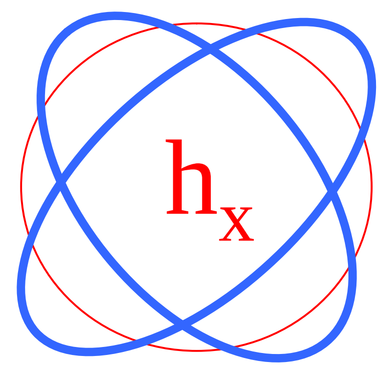


$$\frac{\Delta L}{L} \sim h < 10^{-22}$$



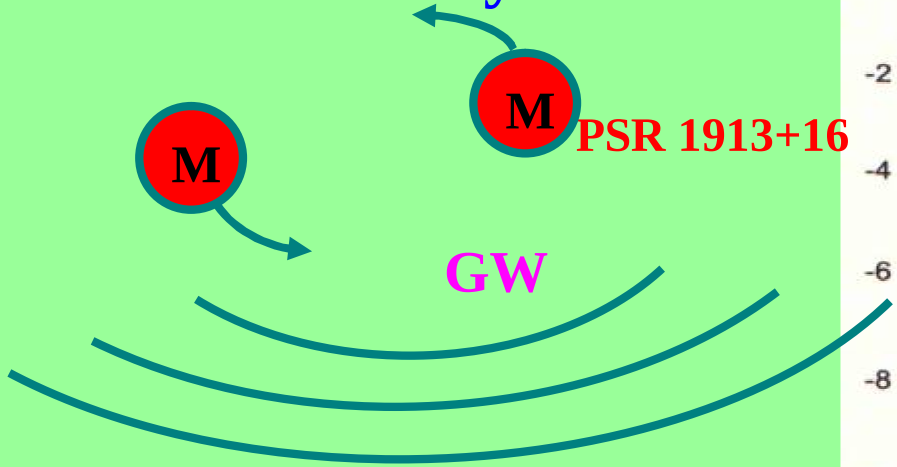
Effect of 2 Polarizations

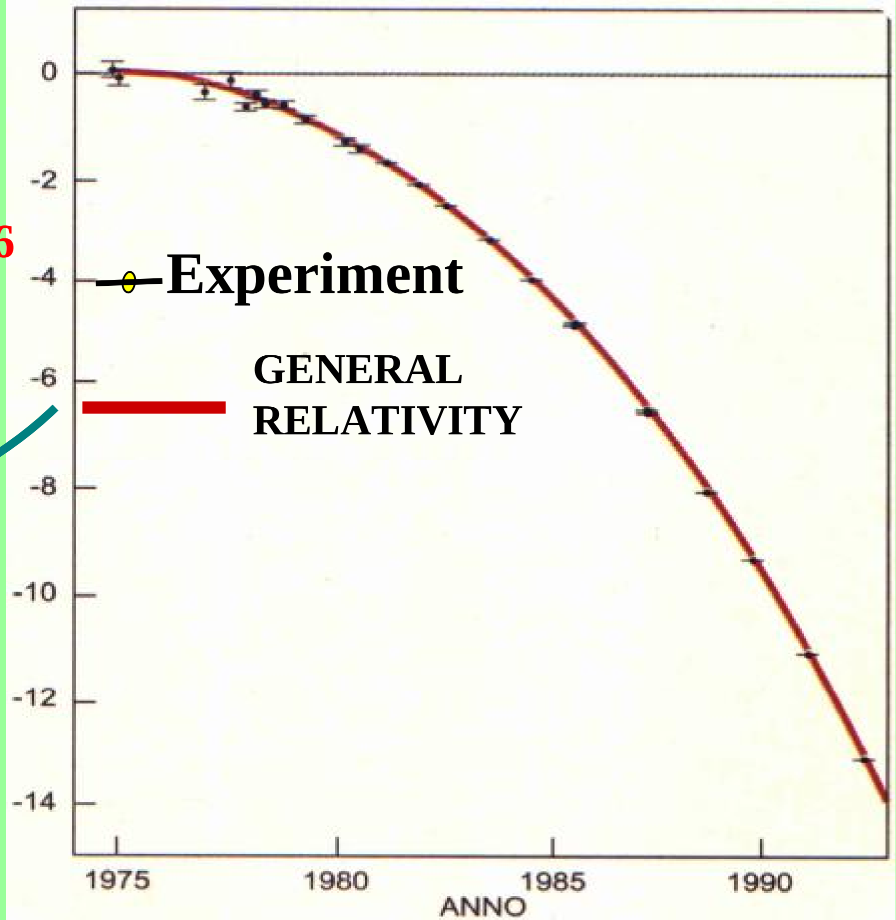




GW Existance demonstration

Neutron Star System



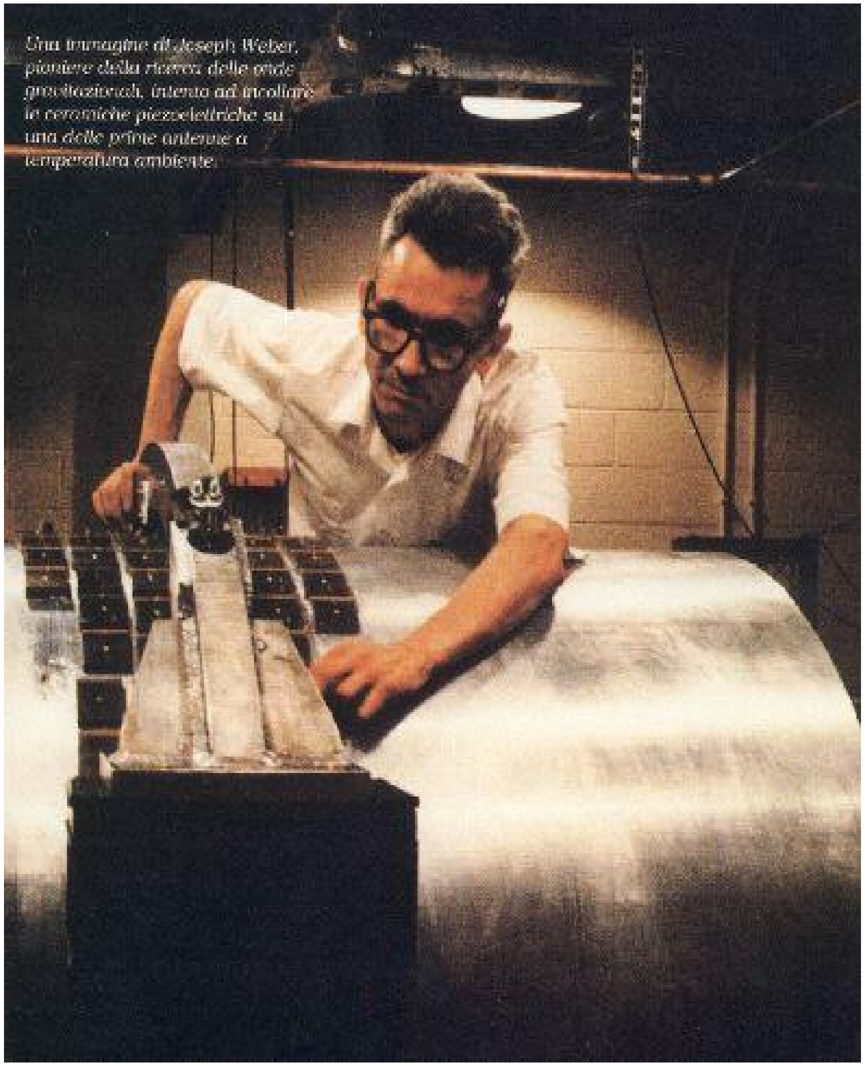


$$\dot{P}_{MEAS} / \dot{P}_{GTR} = 1.0023 \pm .0047$$

Taylor and Hulse
(Nobel 1993)

Orbital period decreasing changes periaster passage time in total agreement with GRT

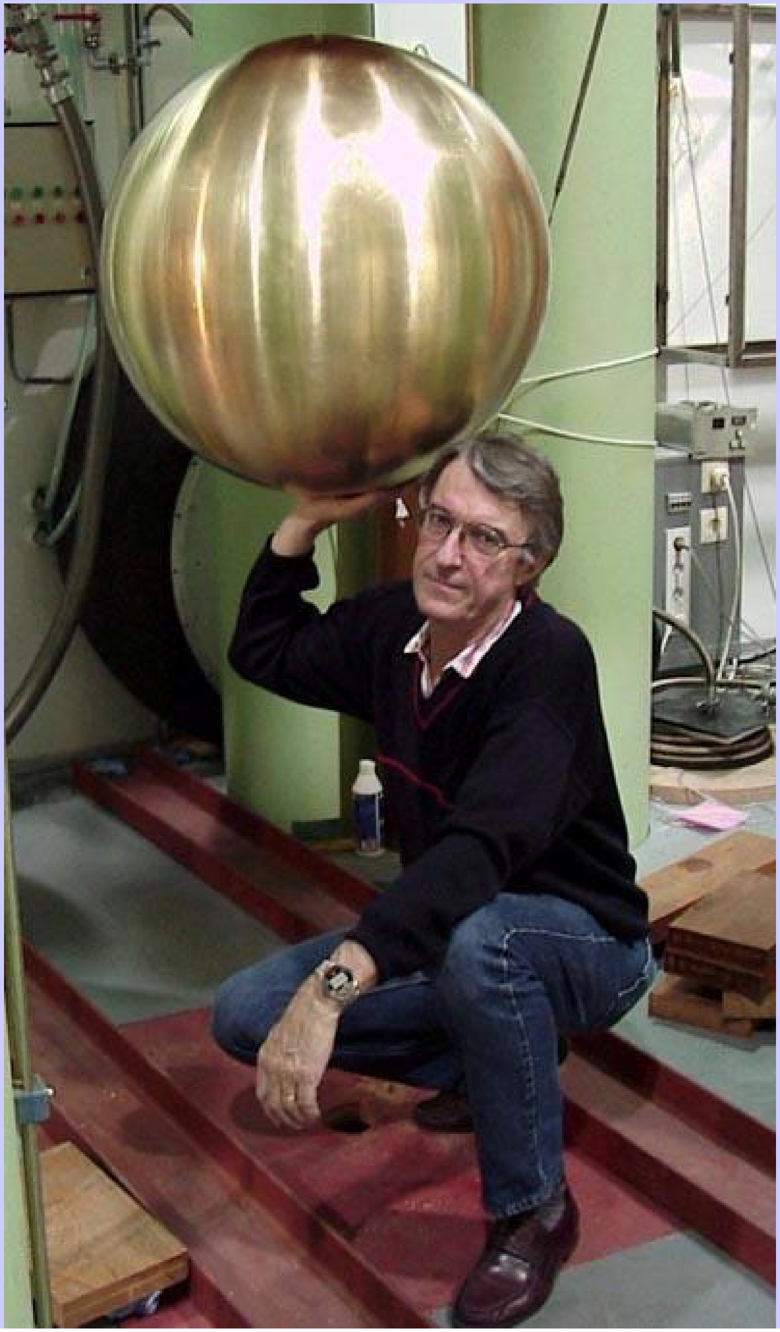
RESONANT DETECTORS:



Yesterday: J.Weber

Tomorrow

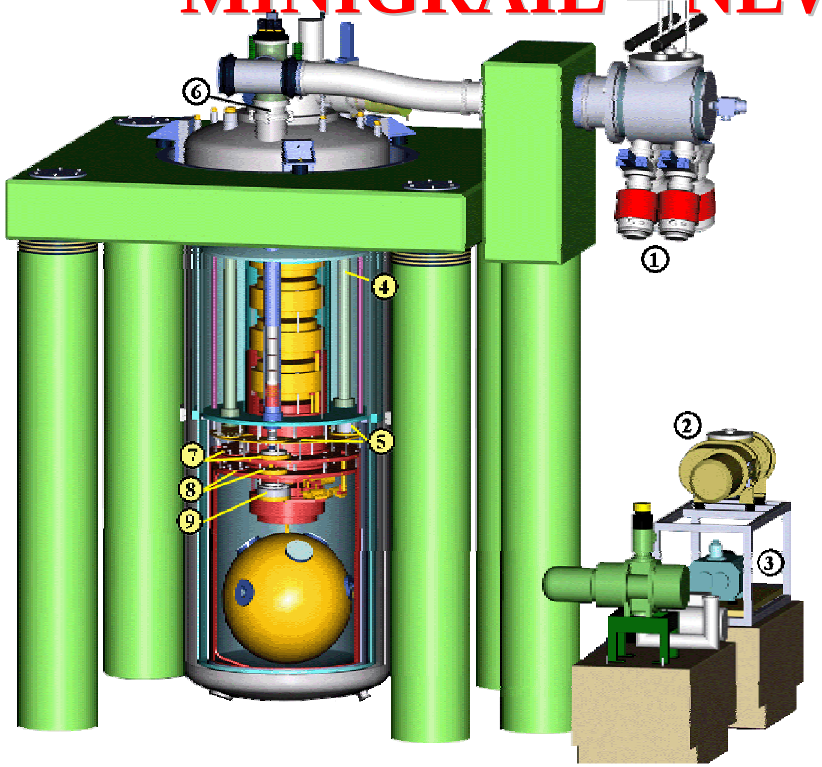
MINIGRAIL

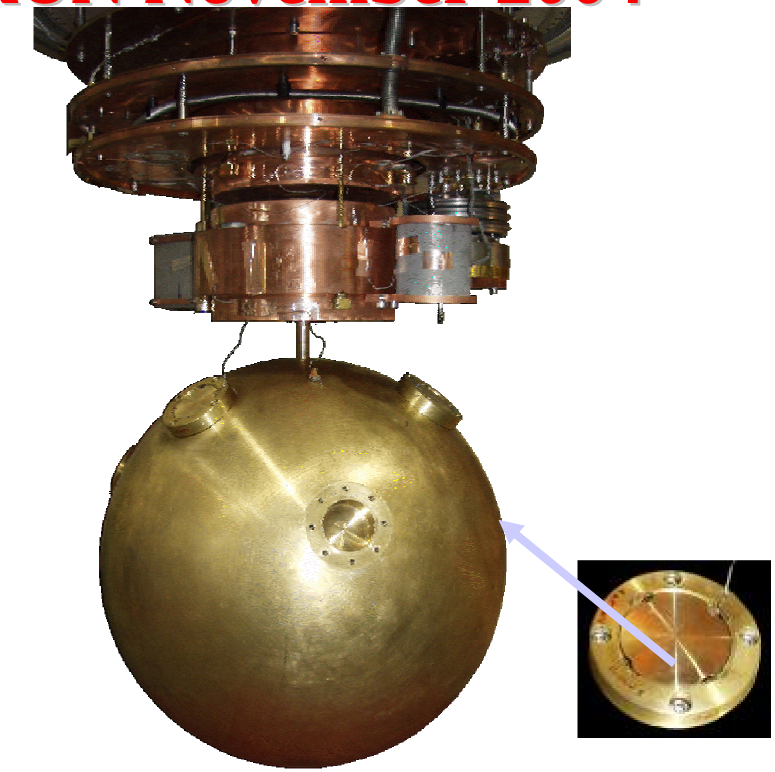


Spherical Detectors

Have the advantage of giving information on GW direction by measuring the amplitude of the 5 quadrupole sphere modes. The first working prototype is Minigrail in Leiden (G. Frossati et al.)

MINIGRAIL – NEW RUN November 2004



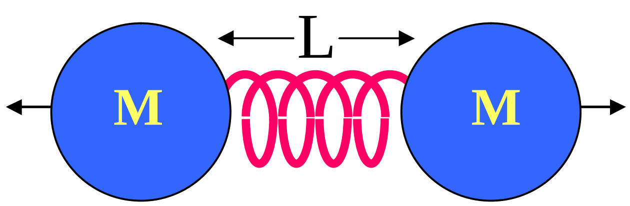


Ø 68 cm - 1.4 ton 3kHz

T=72mK

New cryogenic run with 3 capacitive transducers and SQUID read-out.

Cryogenic Bar Detectors

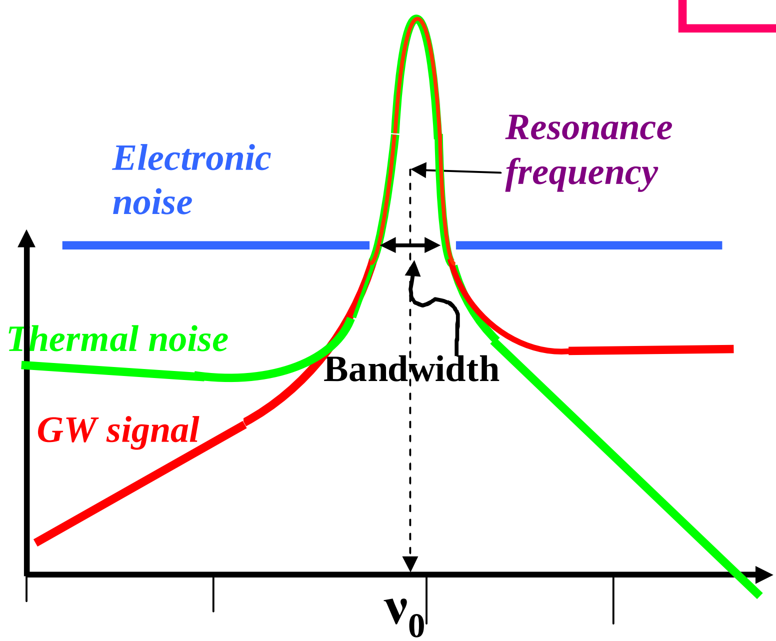


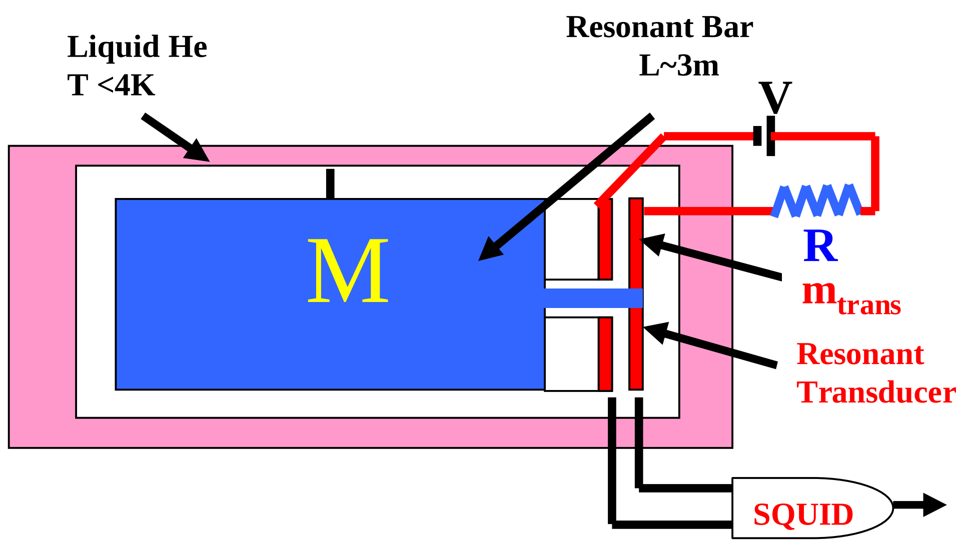
$$F_{Riemann} \approx \frac{1}{2} M\Omega^2 L\tilde{h}(\Omega)$$

$$F_{Thermal} \approx \sqrt{\frac{4KTM\Omega_0}{Q}}$$

$$\frac{S}{N} \approx L \frac{\Omega^2 \tilde{h}(\Omega)}{\sqrt{4K\Omega_0}} \sqrt{M\frac{Q(T)}{T}}$$

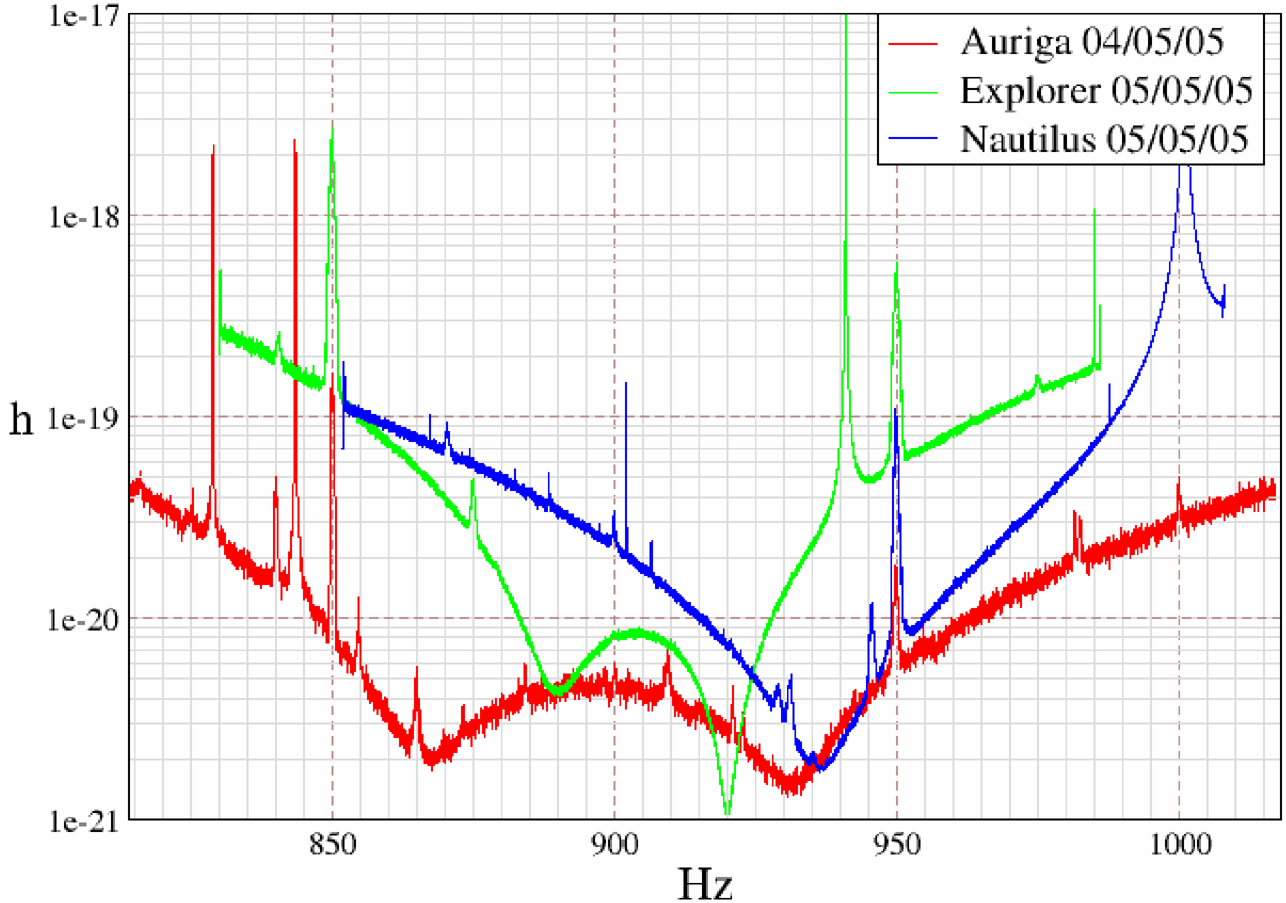
$$\Delta x(\Omega) \approx \frac{\Omega^2 L\tilde{h}(\Omega)/2}{-\Omega^2+\Omega_0^2+iM\frac{\Omega\Omega_0}{Q}} + \frac{\sqrt{\frac{4KT\Omega_0}{QM}}}{-\Omega^2+\Omega_0^2+iM\frac{\Omega\Omega_0}{Q}}$$





Resonant Bar Detectors:

Allegro, Auriga, Explorer and Nautilus

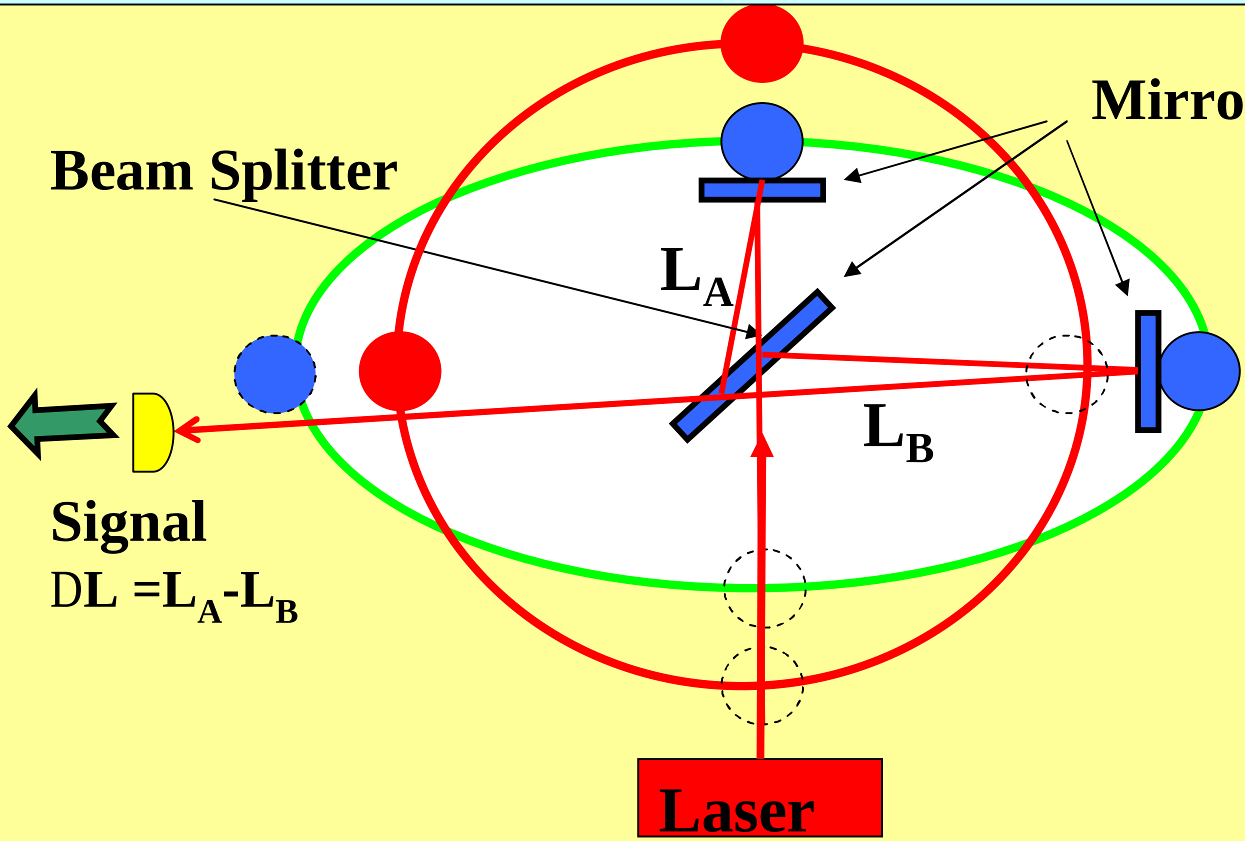


Auriga 04/05/05
Explorer 05/05/05
Nautilus 05/05/05
1e-17
1e-18
1e-19
1e-20
1e-21
h
850
900
950
1000
Hz

INTERFEROMETRIC DETECTORS

Large L ⇨ High sensitivity

Very Large Bandwidth 10-10000 Hz

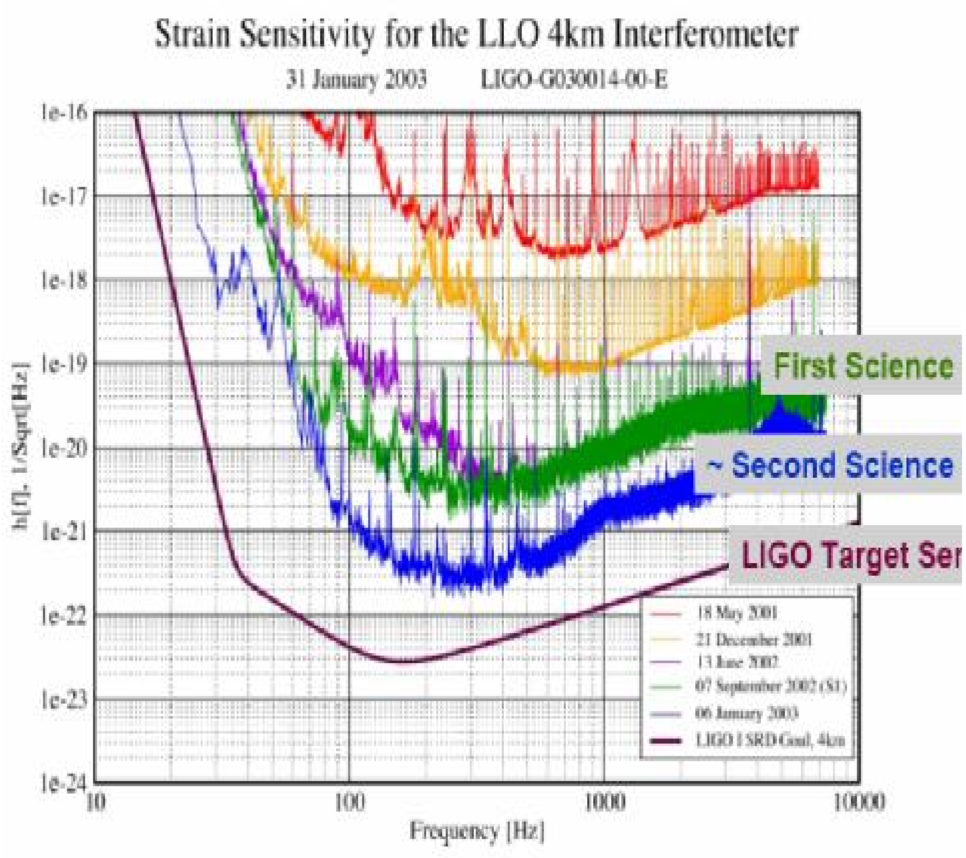


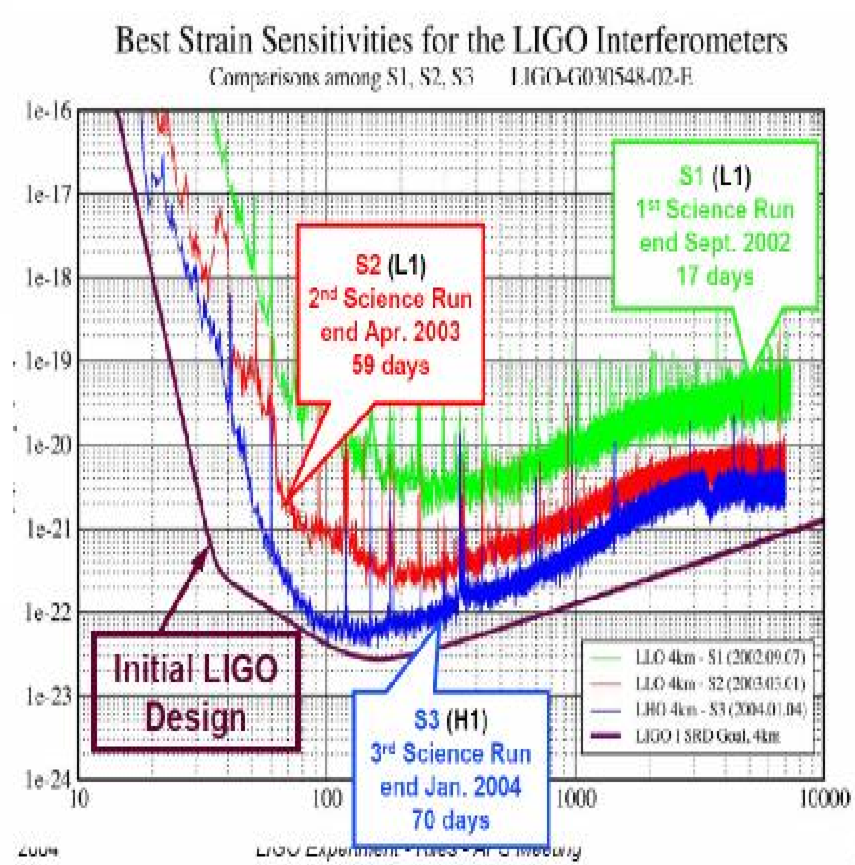
Displacement sensitivity can reach ~10^{-19}-10^{-20} m, then, for measuring $DL/L \sim 10^{-22}$ L_A and L_B should be km long.

LIGO


Hanford 4km+2km


Livingstone 4km


Strain Sensitivity for the LLO 4km Interferometer
31 January 2003
LIGO-G030014-00-E
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
10
100
1000
10000
Frequency [Hz]
First Science
~ Second Science
LIGO Target Ser
18 May 2001
21 December 2001
07 September 2002 (S1)
06 January 2003
LIGO I SRD Goal, 4km


Best Strain Sensitivities for the LIGO Interferometers
Comparisons among S1, S2, S3
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
10
100
1000
10000
S1 (L1)
1st Science Run
end Sept. 2002
17 days
S2 (L1)
2nd Science Run
end Apr. 2003
59 days
Initial LIGO
Design
S3 (H1)
3rd Science Run
end Jan. 2004
70 days
LIGO I SRD Goal, 4km


VIRGO

Detector Network and the birth of GW Astronomy

Coerent Analysis: why?

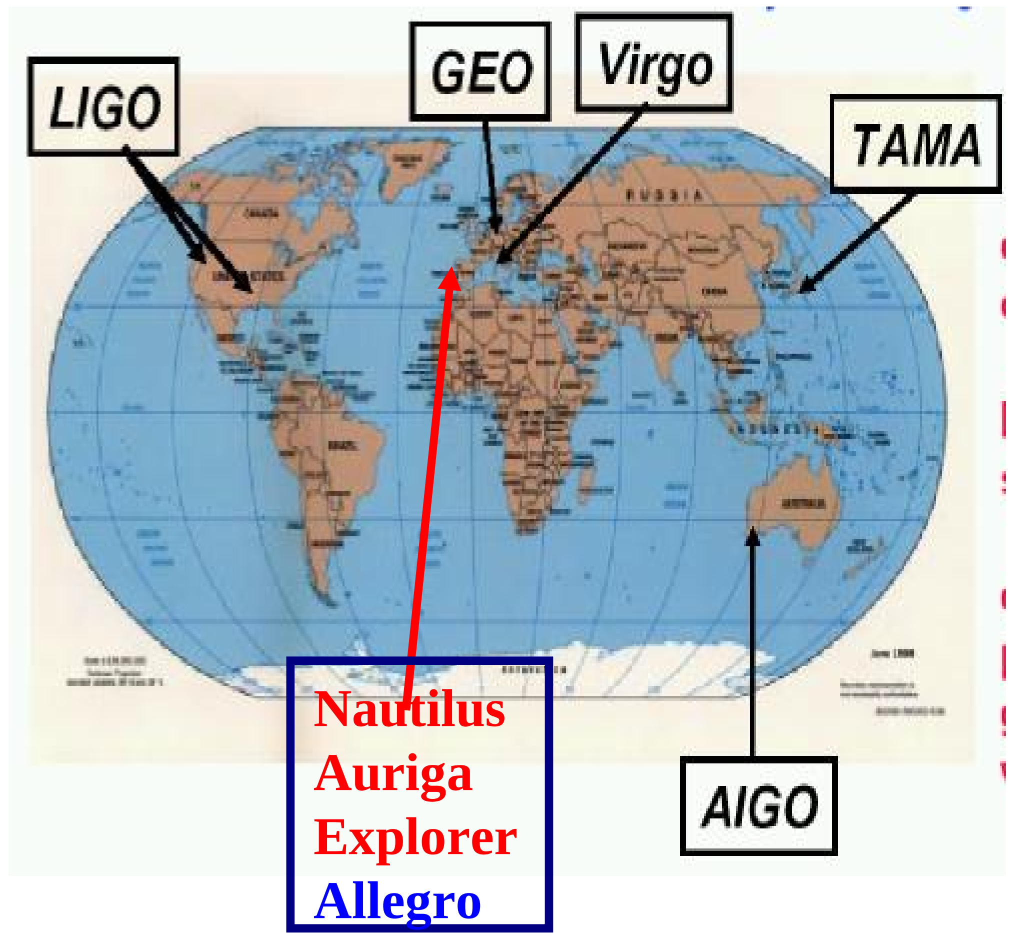
1)S/N increase

2)Source direction determination from time of flight differences

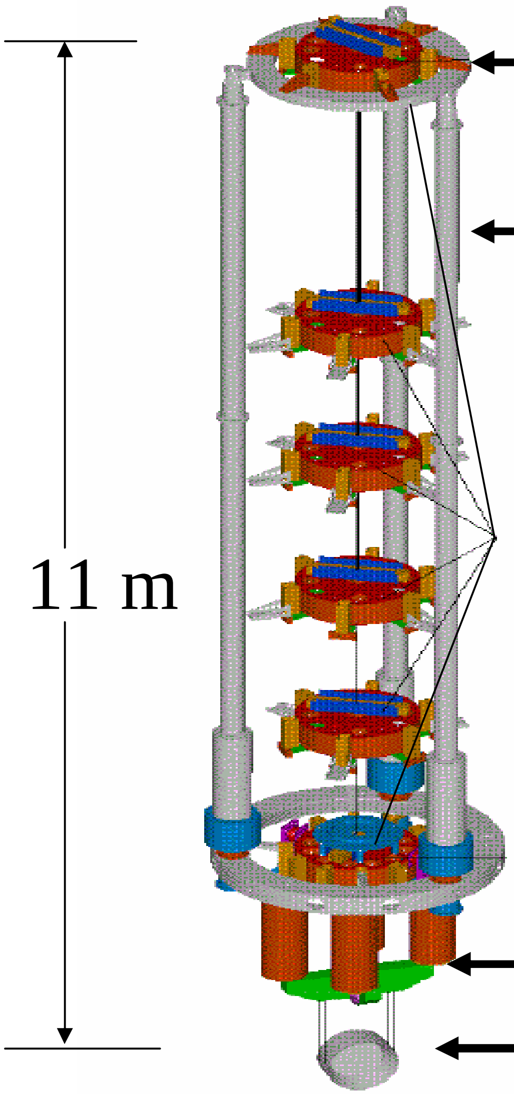
3)GW speed from time of flight differences

4)GW Polarization measurement

5)GW Tensorial character Determination

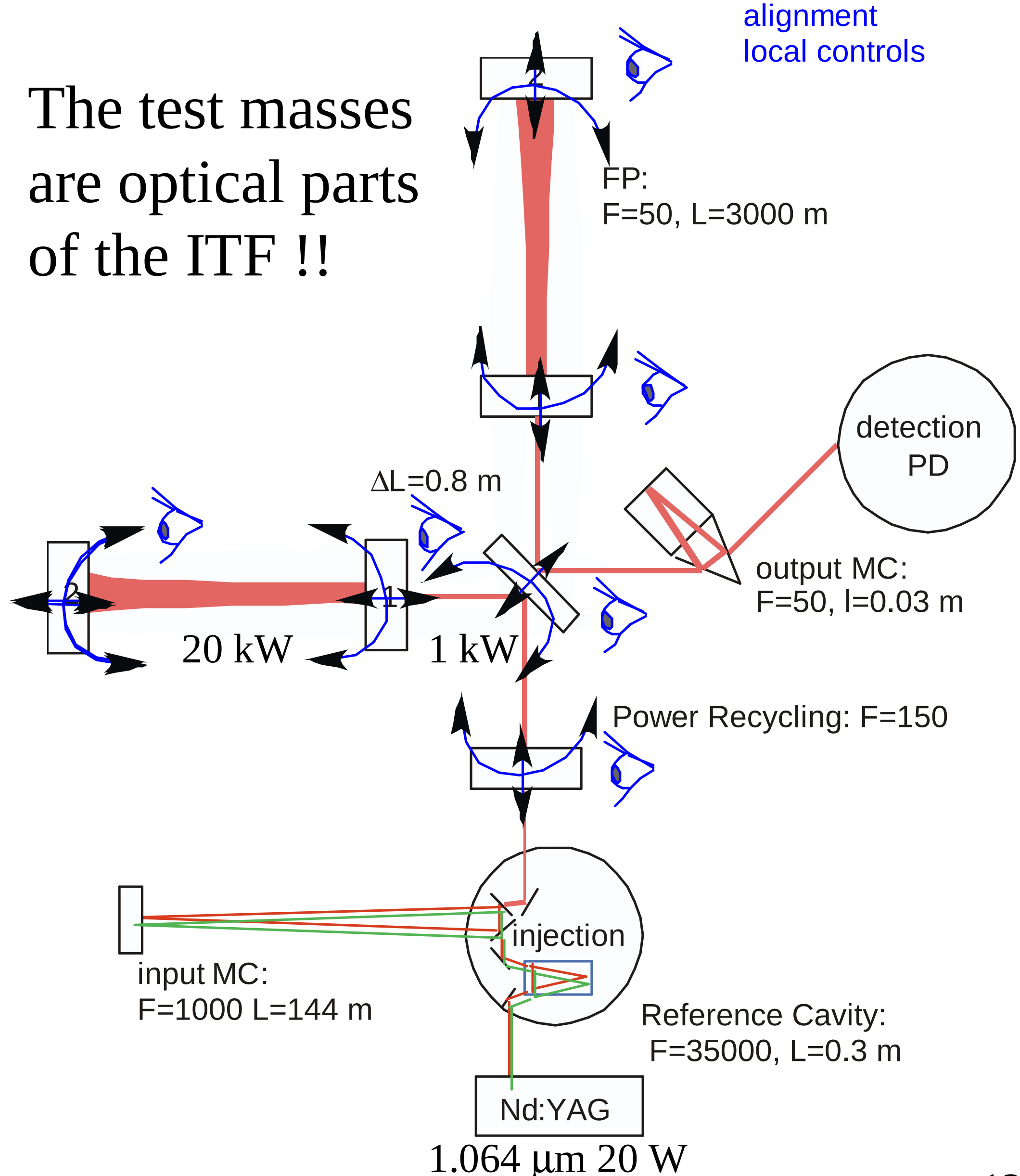


SA meter

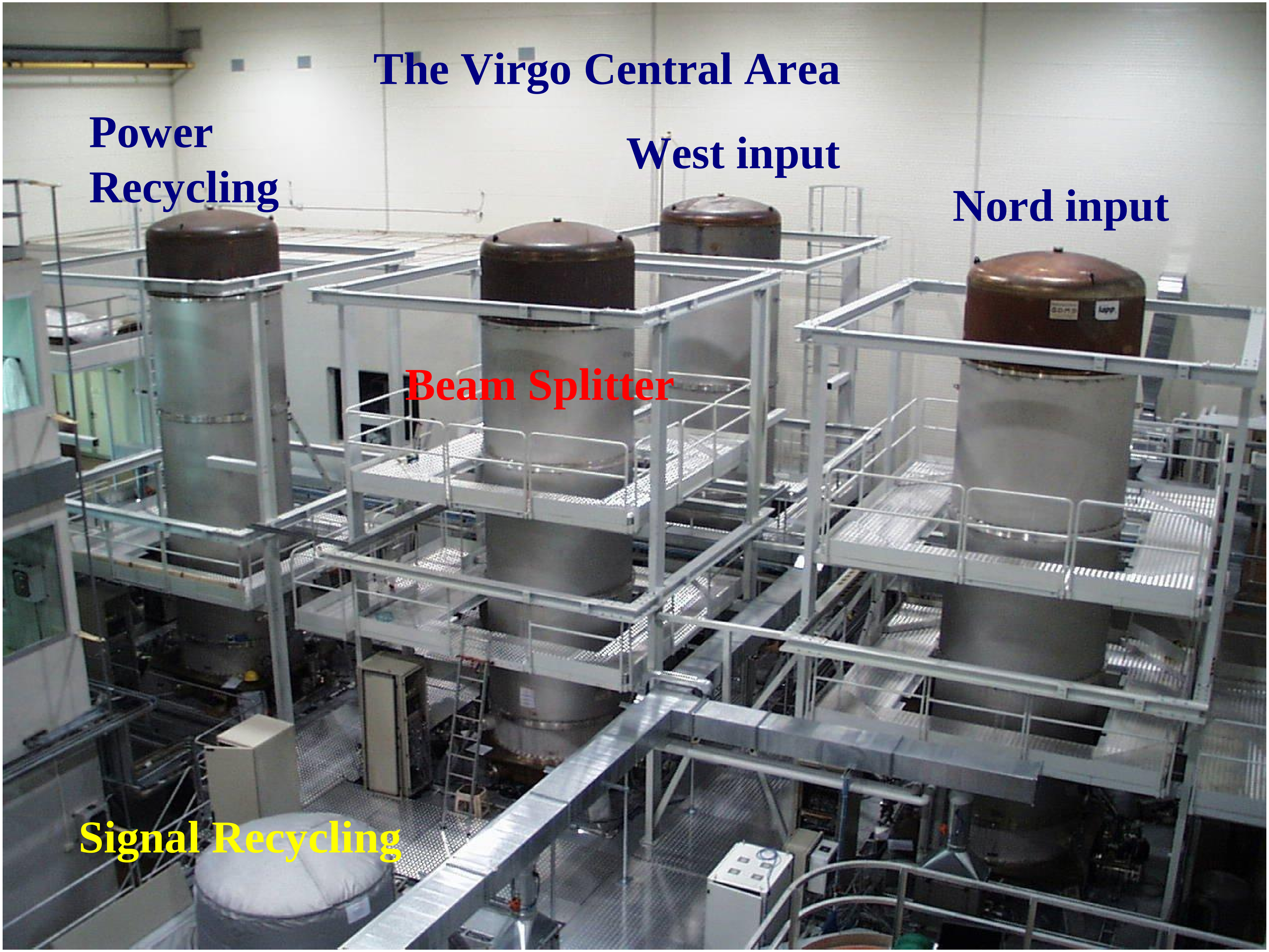


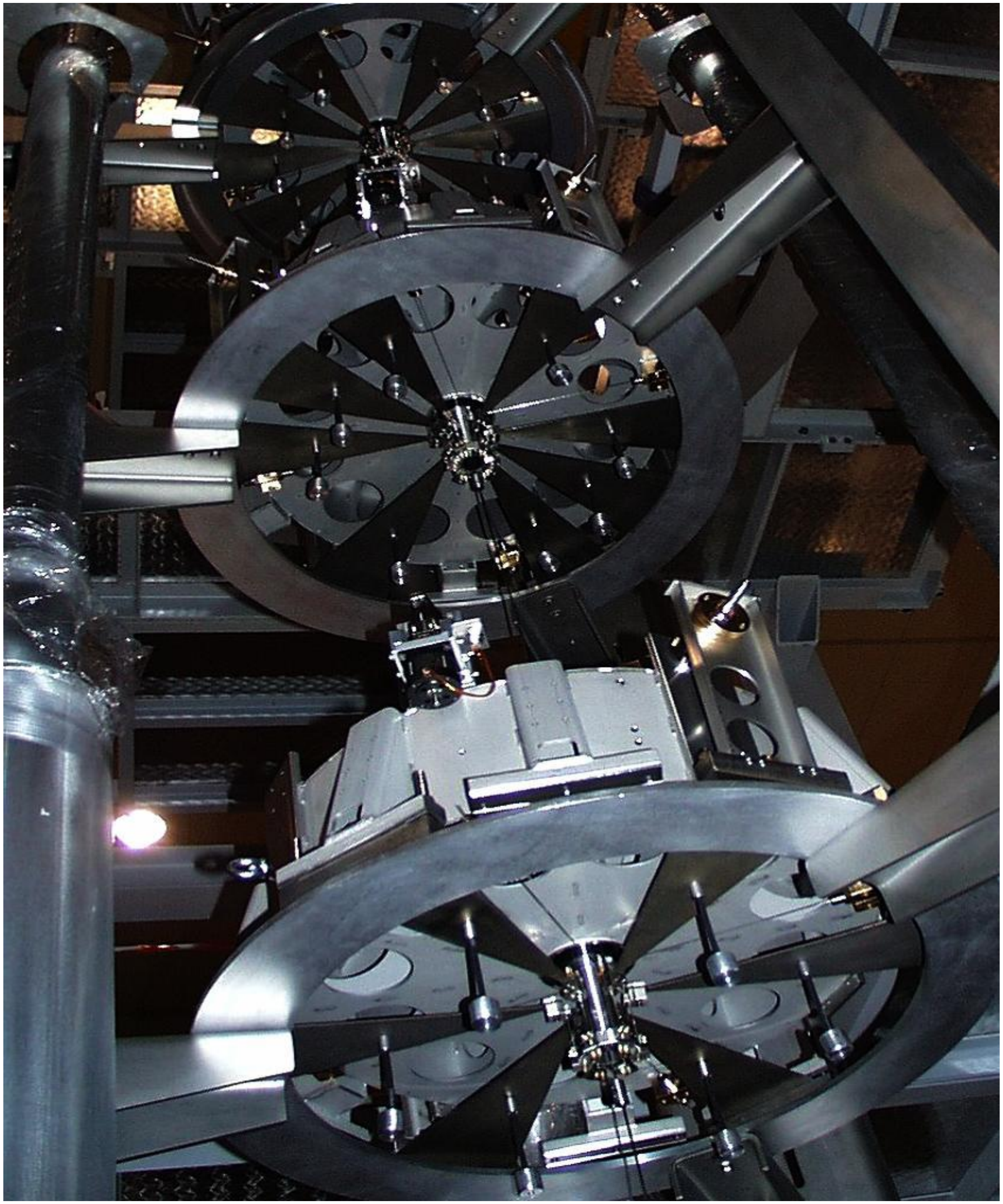
$$A = 10^{-14}$$
$$@10Hz$$

The test masses are optical parts of the ITF !!

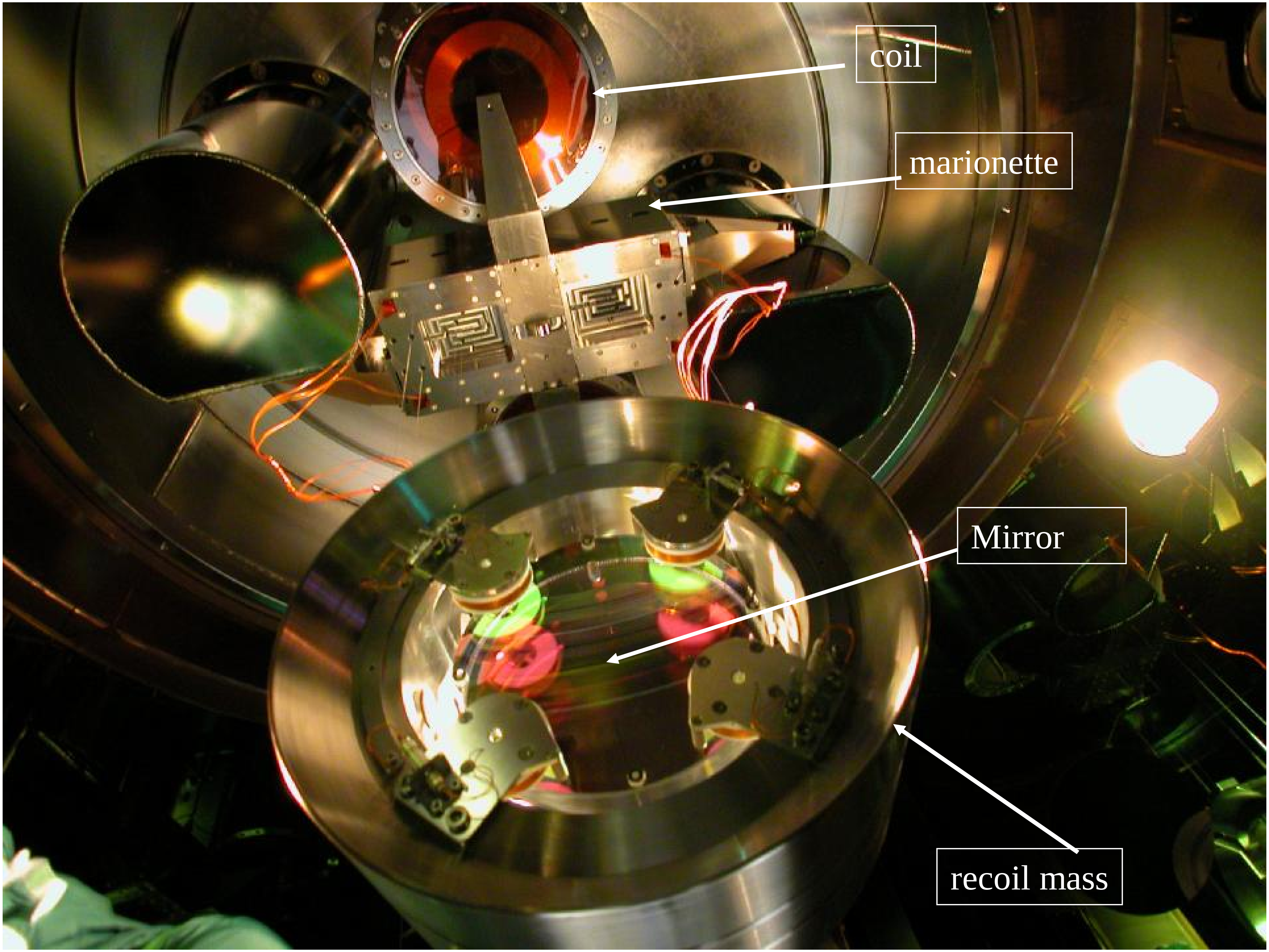


v12


The Virgo Central Area
Power
Recycling
West input
Nord input
Beam Splitter
Signal Recycling



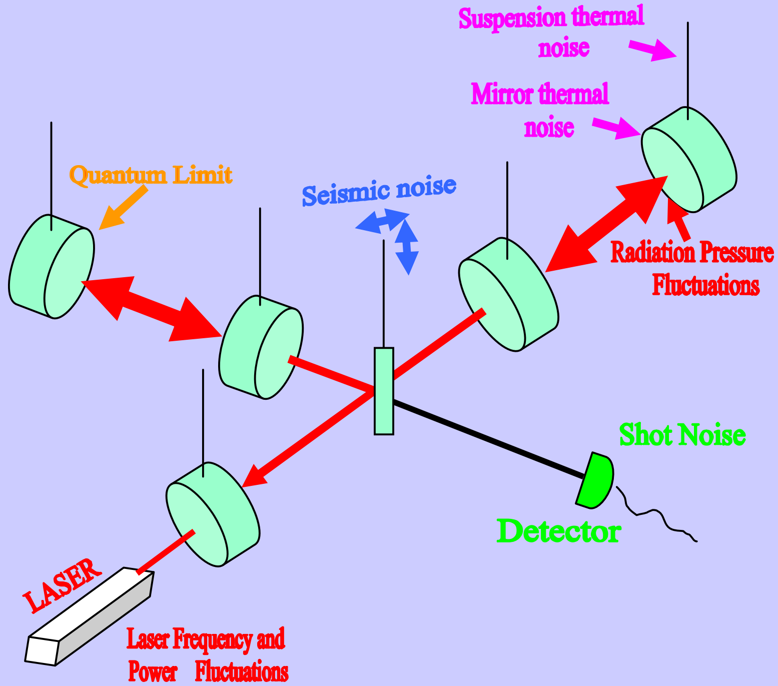
Superattenuator Mechanical Filters

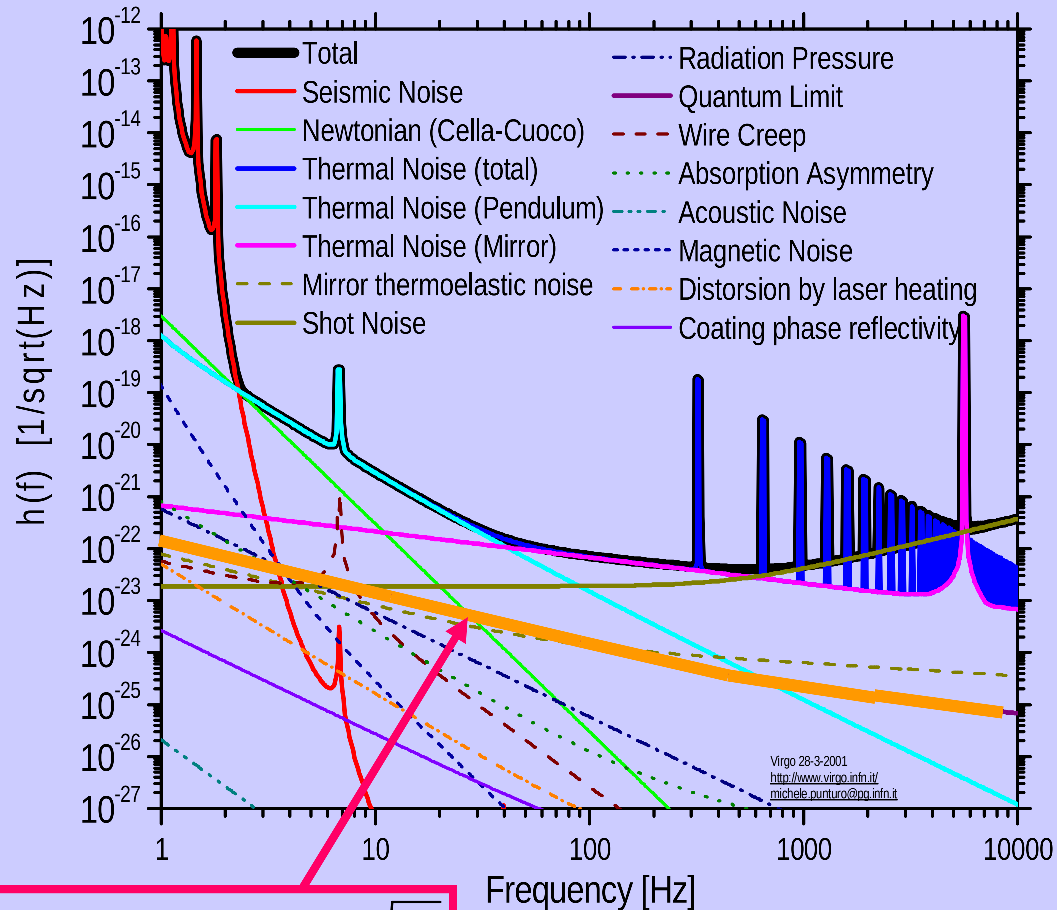

coil
marionette
Mirror
recoil mass

NORTH terminal building

Detection Bench before being suspended to a Superattenuator

Interferometer Noises

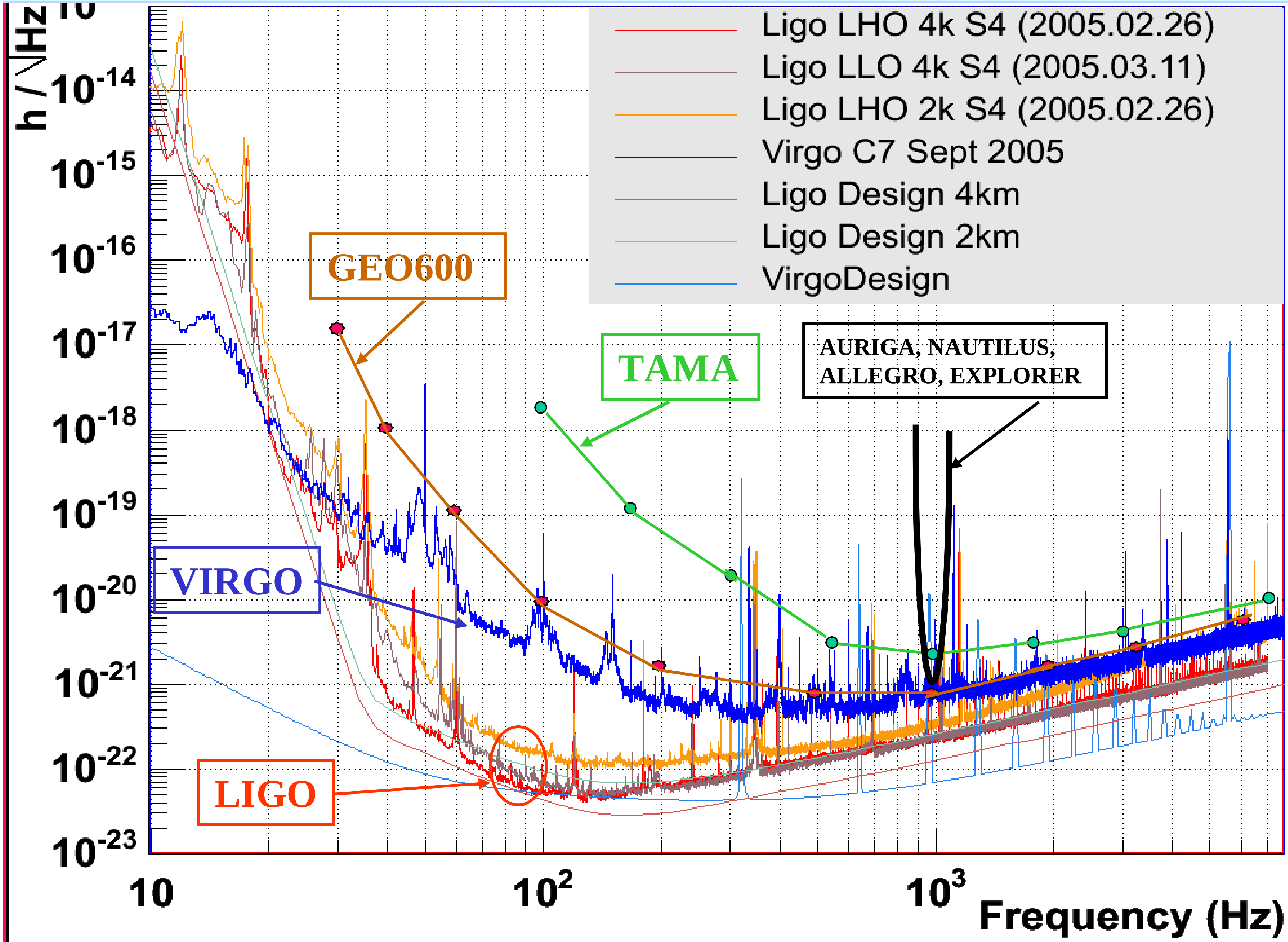




Standard Quantum Limit

$$\tilde{h}_{SQL} \approx \frac{1}{L\Omega}\sqrt{\frac{\hbar}{M}}$$

Sensitivity Comparison: Virgo-Bar-Tama-Geo600-Ligo



•

- **Letter of intent**
- **for the construction of**
- **A second Gravitational Wave Interferometer**
- **in Europe**
- The Italian laboratories of the Virgo Collaboration.
- Firenze – Urbino, Frascati, Napoli, Perugia, Pisa, Roma 1
- **Preamble**
- This Letter of Intents is a contribution to the “Roadmap” discussion set up by INFN as a response to a European Union invitation. It is expected that similar discussions shall take place in other countries. This Letter of Intents is meant to be open to interested groups, either now or in view of a discussion at European level.

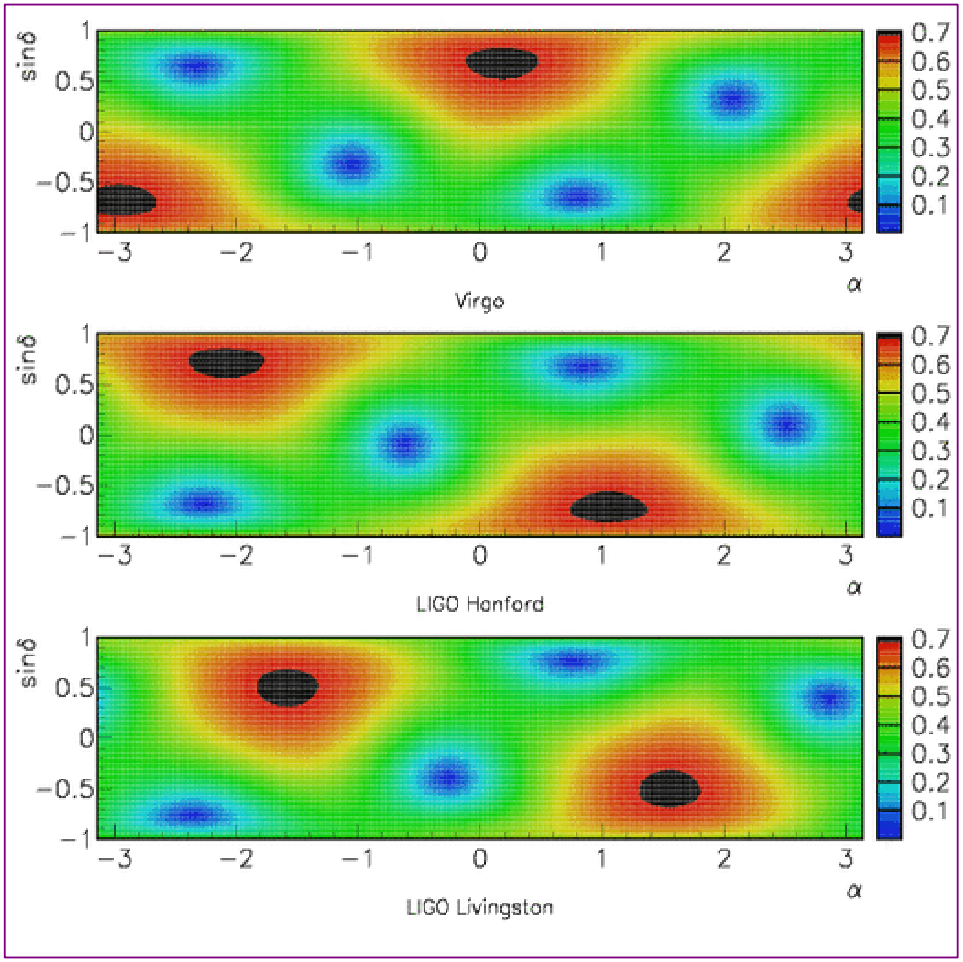


Fig. 2. The detection probability as function of the sky position when averaged over Earth daily rotation. The LIGO Hanford and Livingston show a good overlap while Virgo appears to be complementary making triple coincidences less probable.

GW-experiment: News

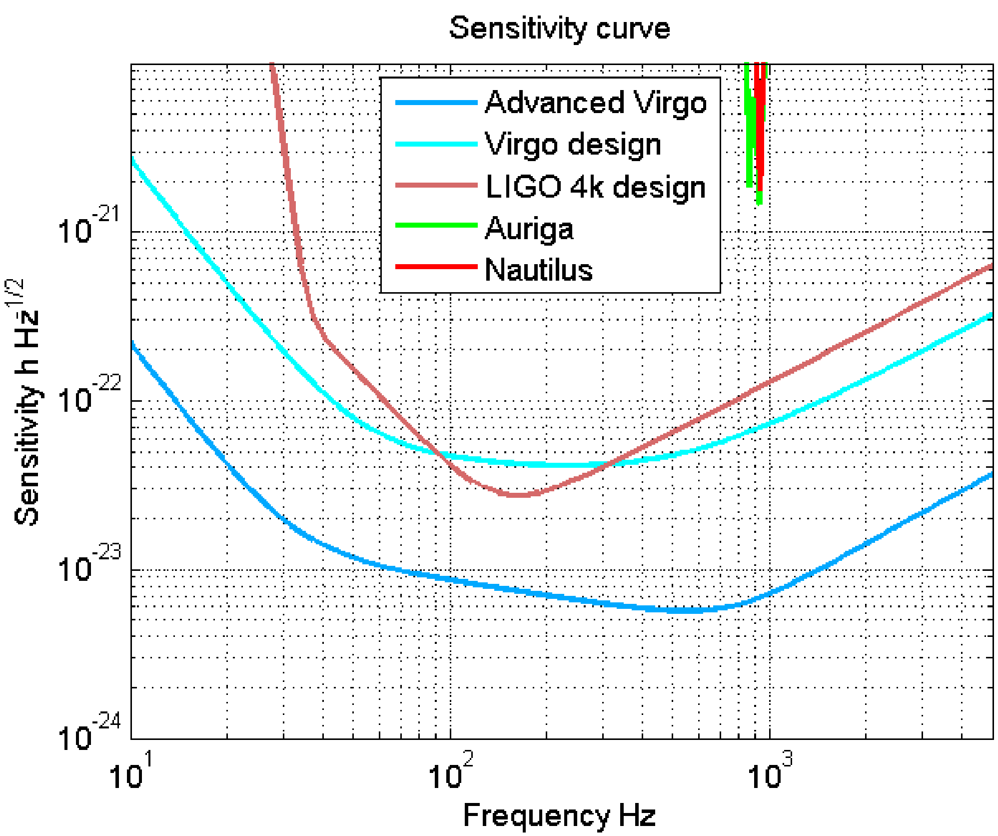
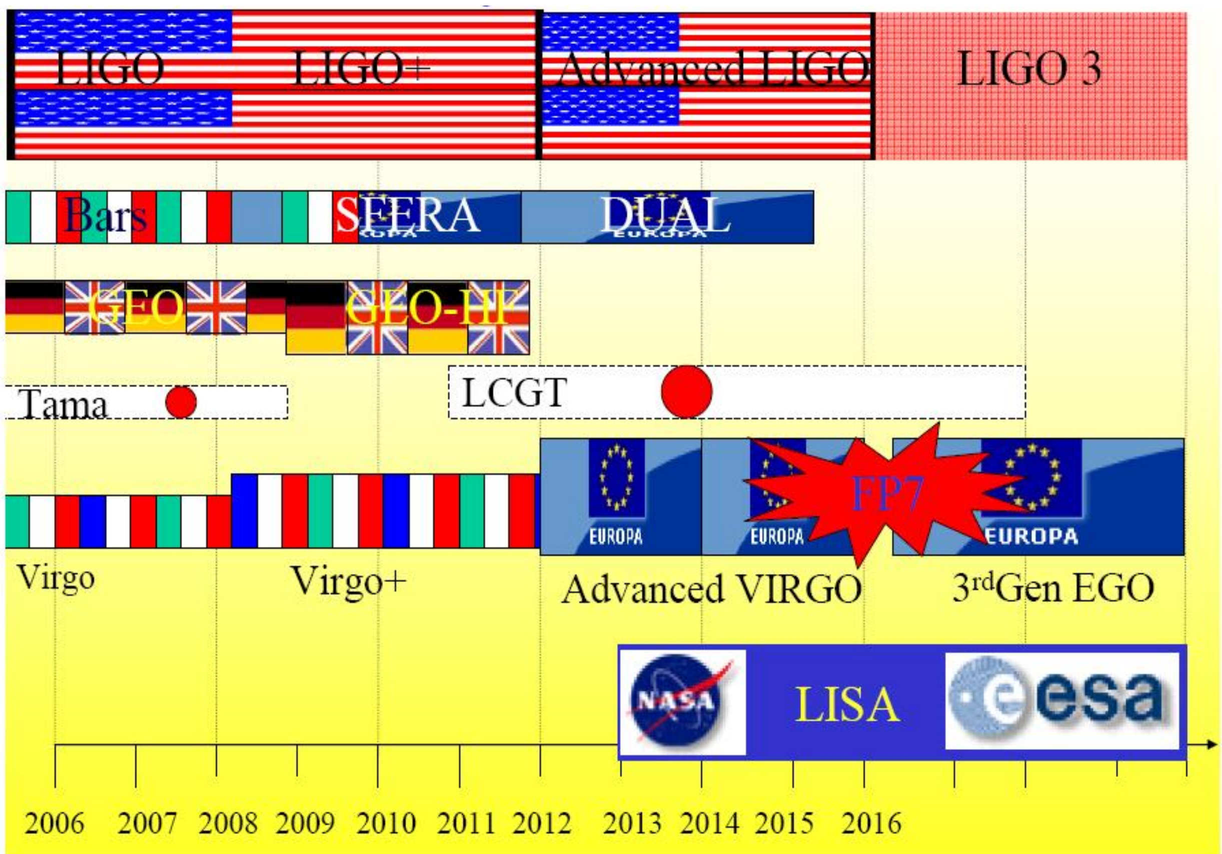


Fig. 1. Advanced Virgo sensitivity curve compared with Virgo and LIGO design and current bar sensitivity. Violin modes are not displayed for clarity

Future development plans



green - comm & oper. 2d-detector generation

white - upgrade periods

Explorer-Nautilus coincidences
in 1998 during activity

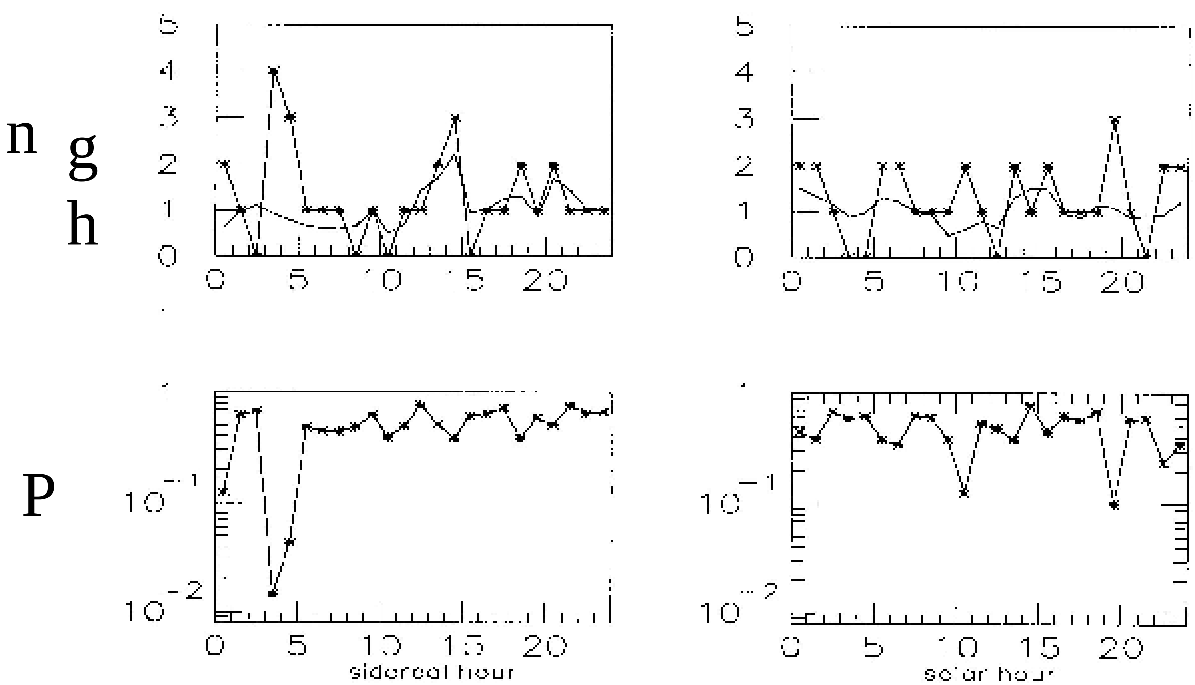
BH-candidate XTE J1550-564

and

Magnetar SGR 1900+14

I.Modena , G.Pizzella

Excess of coincidences in the Galactic Disc
Explorer-Nautilus, data 2001 year.

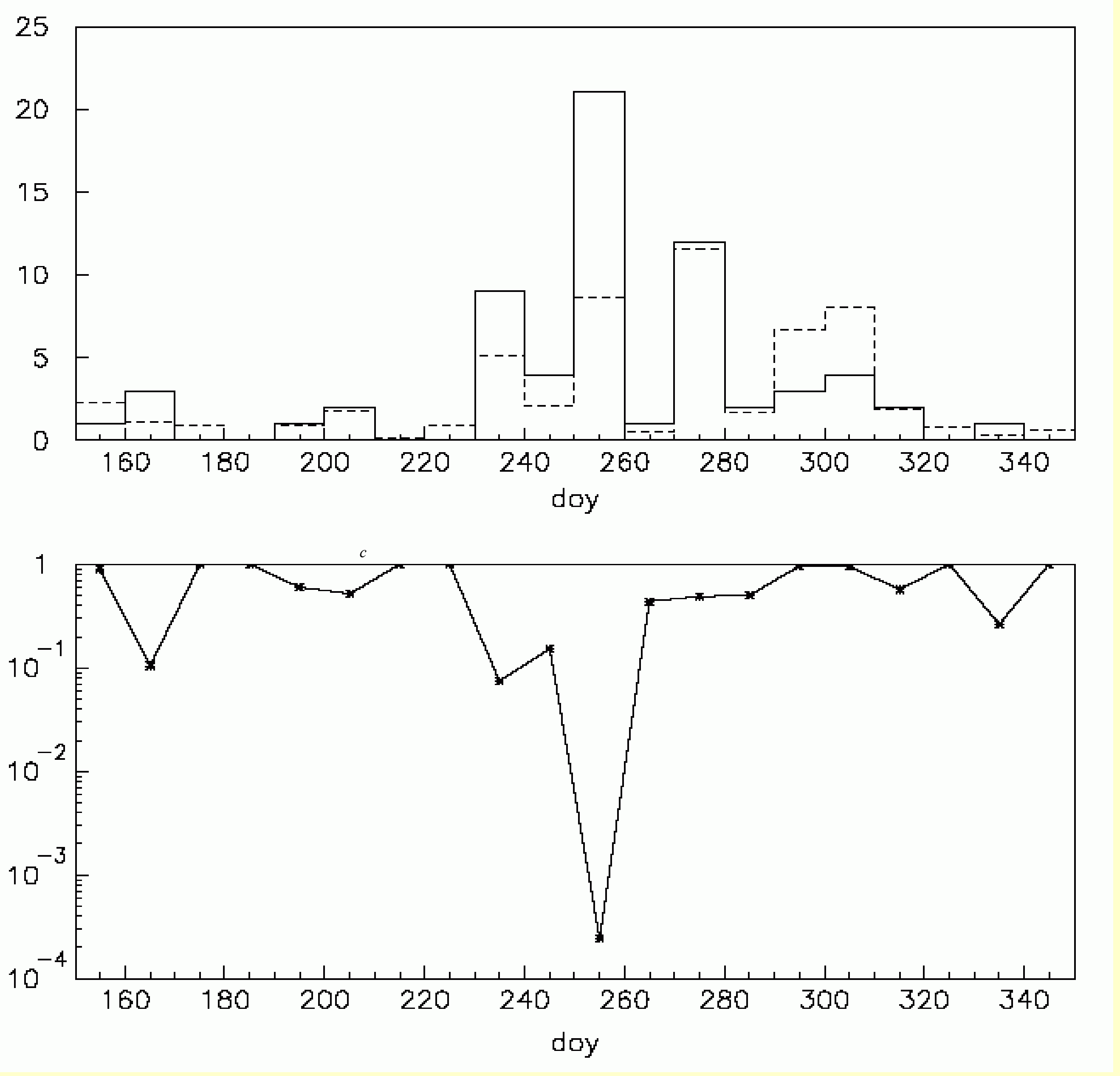


Exp.- Naut.

Sept. 1998

n-coincidences

P- chance probability



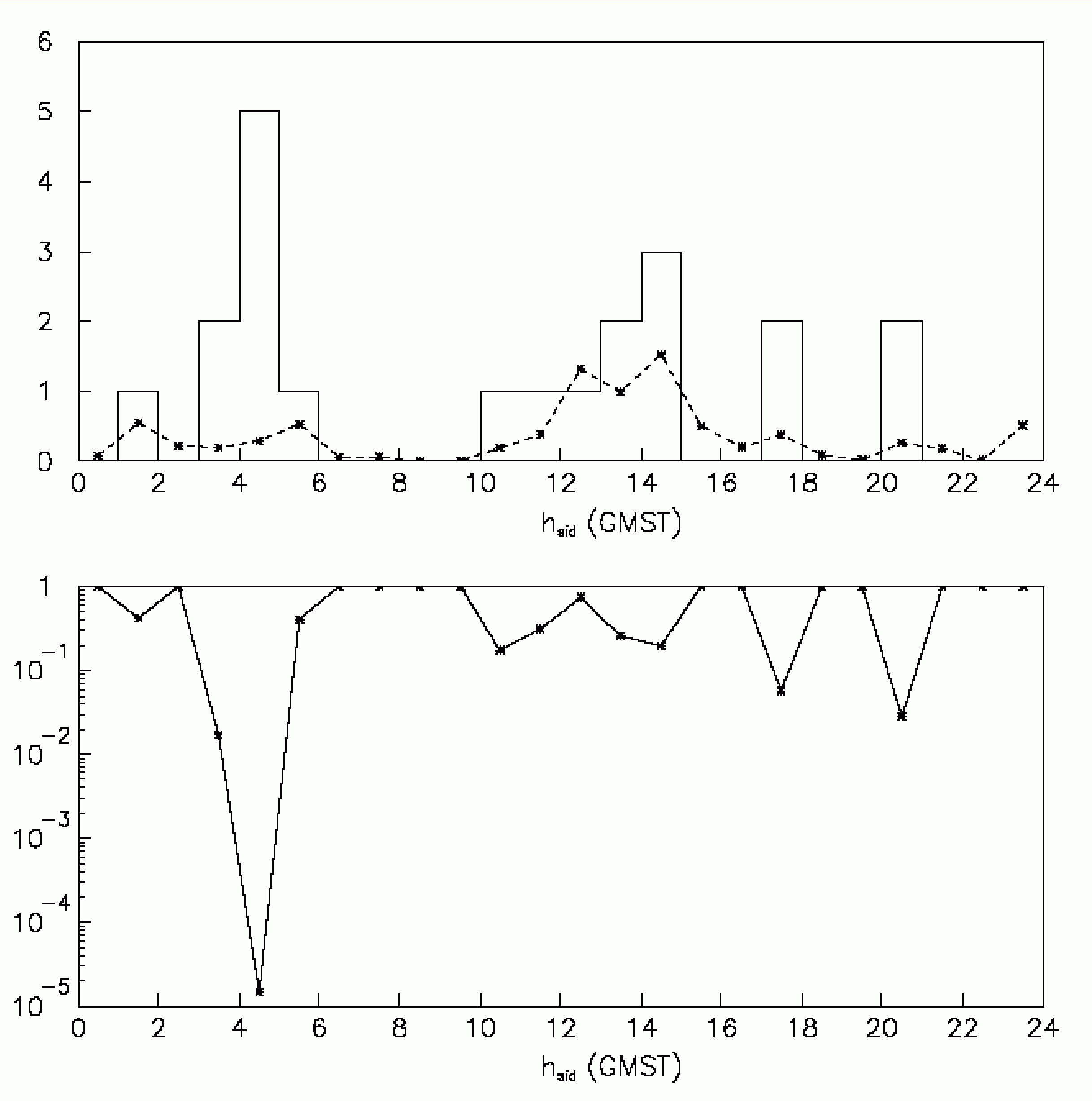
Exp-Naut.

7-17 Sept.
1998

siderial time

n

P



Aug. 28 - 27 Sept 1998.

Exp- Naut. coincidence excess

XTE J1550-564

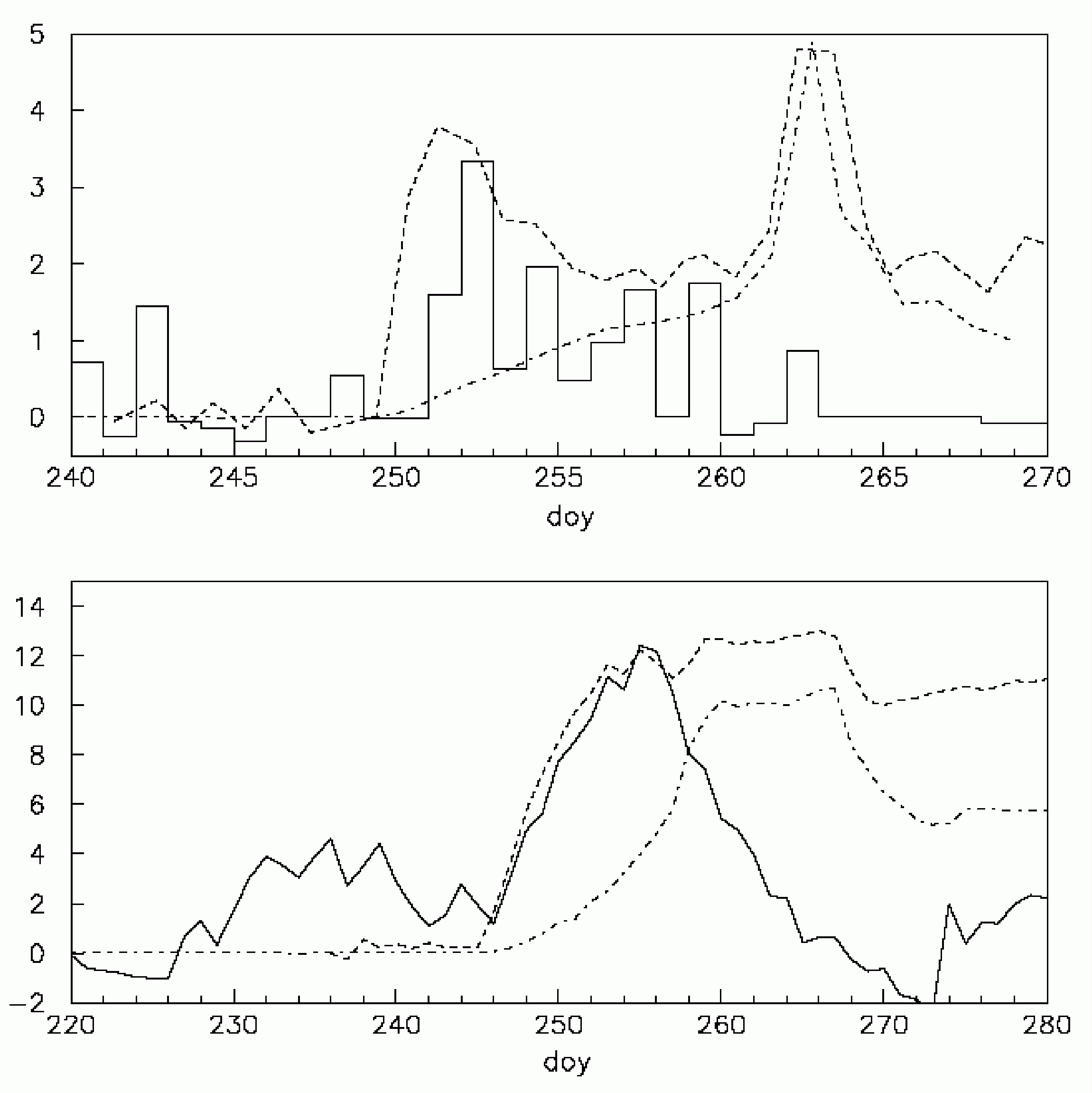
X-ray light curves

2-12 keV,

20-100 keV

averaged curve

1 day step

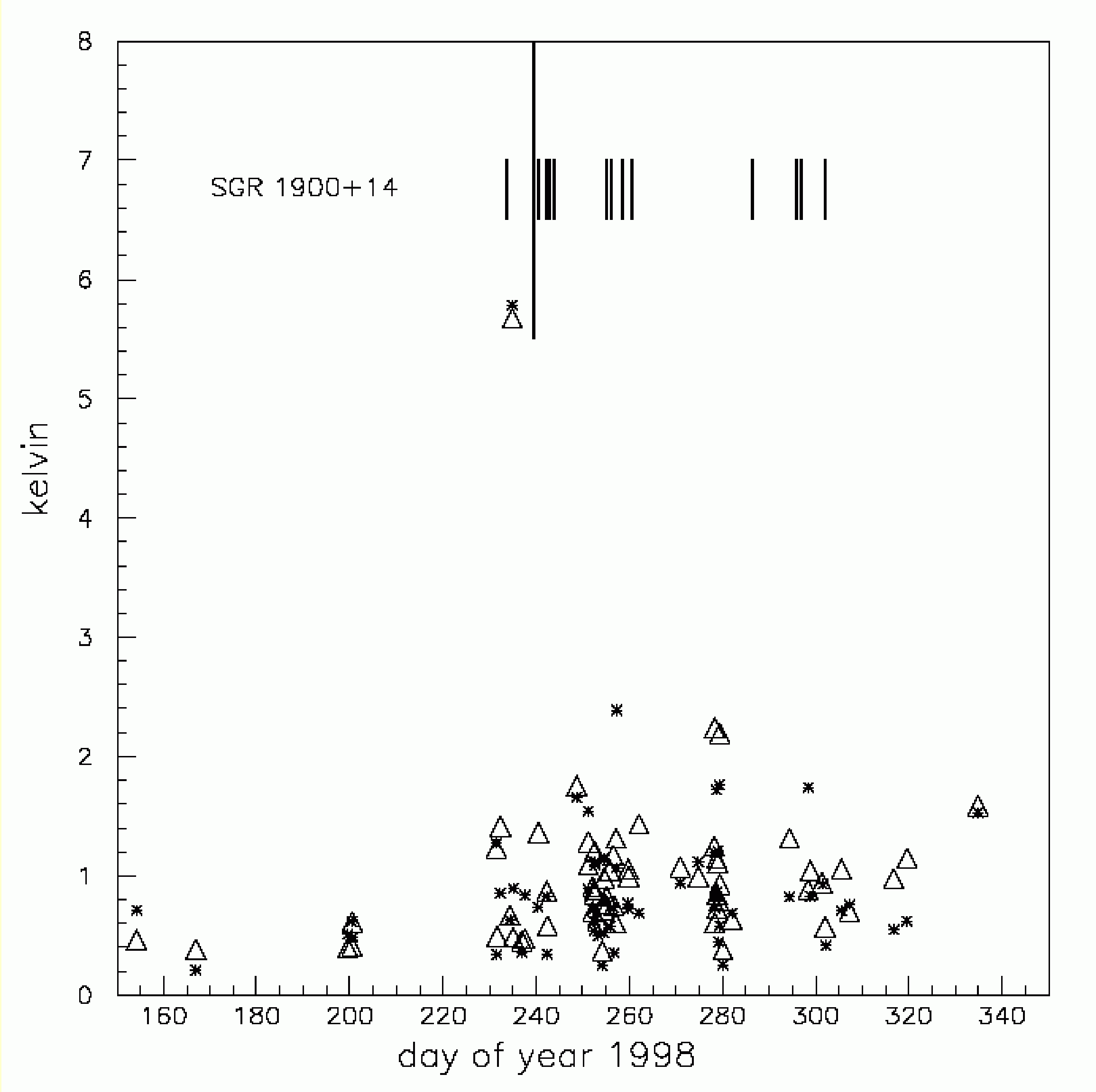


Exp.-Naut.

SGR1900+14

gaint flare

Aug. 27 1998



The Universe knowledge is lacking a lot: GW astronomy