

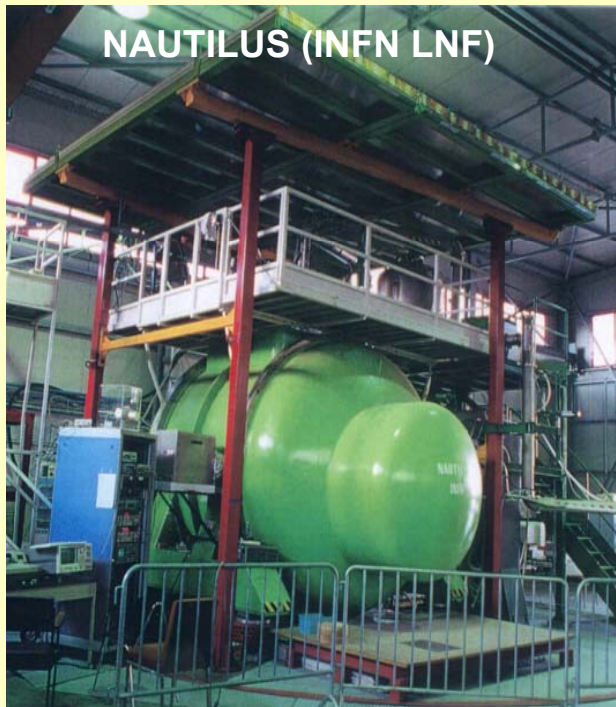
Current results of data analysis on Gravitational Wave Antennae

V.N.Rudenko
SAI MSU

*workshop “Metrology of Fundamental Constants”
Dubna, JINR, 1-4 December 2009*

Cryogenic Bar Detectors Sensitivity & Stability

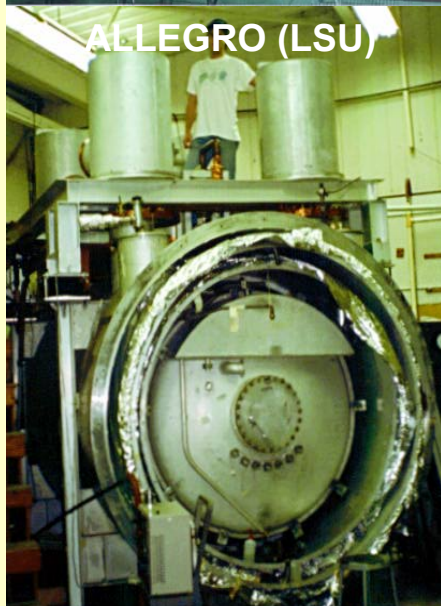
NAUTILUS (INFN LNF)



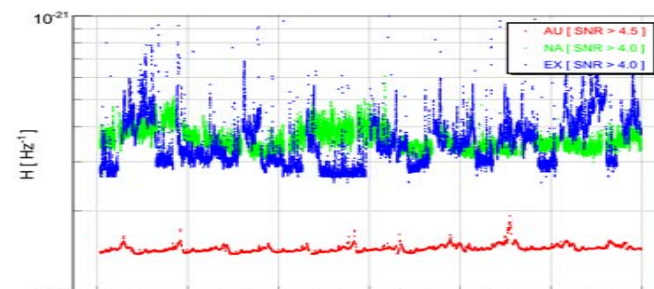
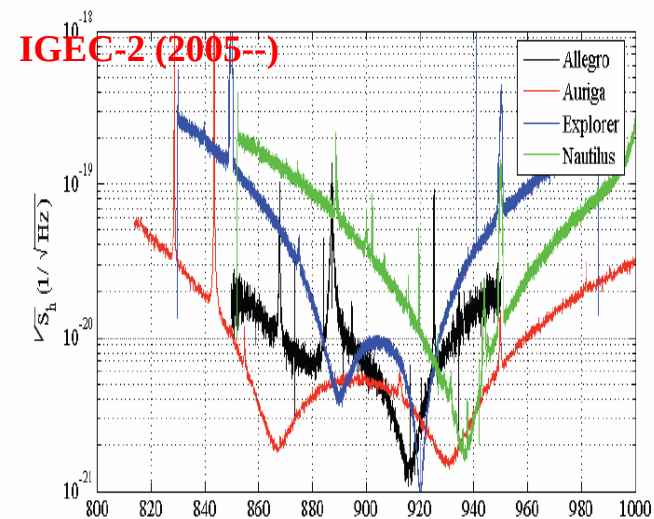
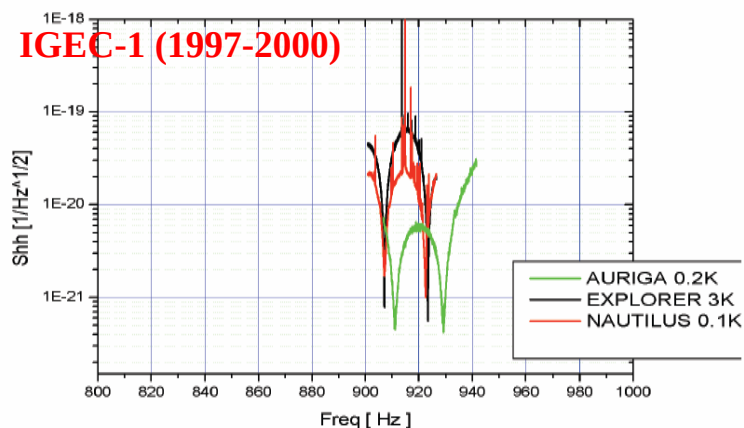
AURIGA (INFN LNL)



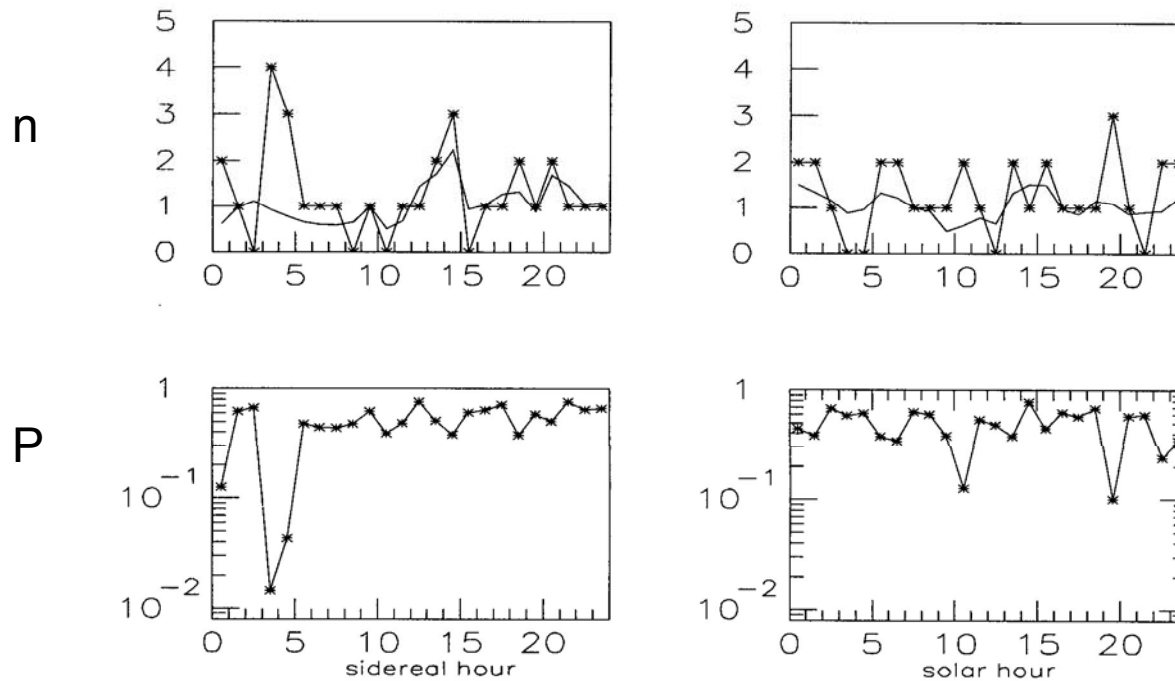
ALLEGRO (LSU)



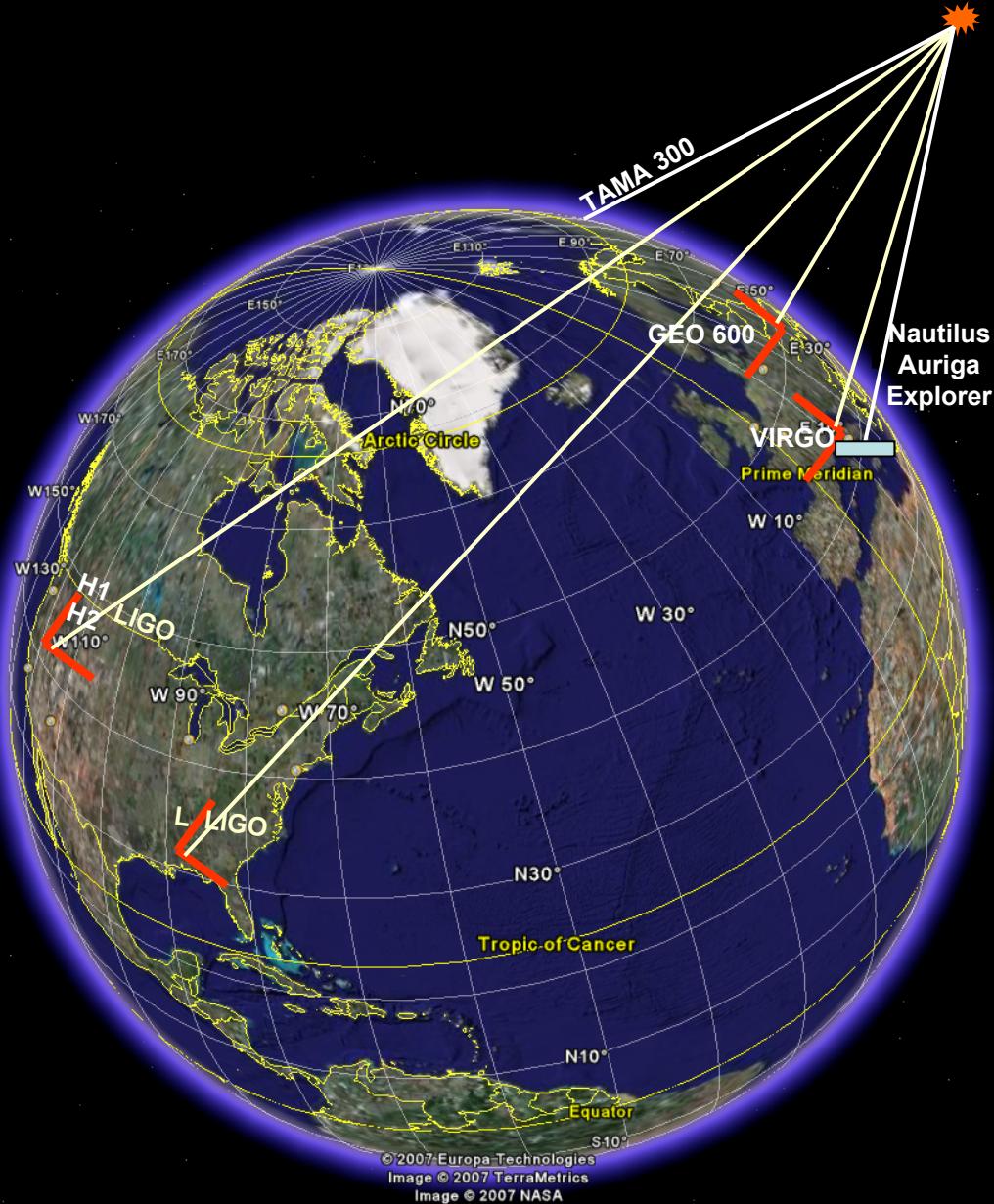
EXPLORER (INFN CERN)



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



Global network of Detectors



Coherent Analysis: why?

- Sensitivity increase
- Source direction determination from time of flight differences
- Polarizations measurement
- Test of GW Theory and GW Physical properties

Astrophysical targets

- Far Universe expansion rate Measurement
- GW energy density in the Universe
- Knowledge of Universe at times close to Planck's time

Ligo interferometrs



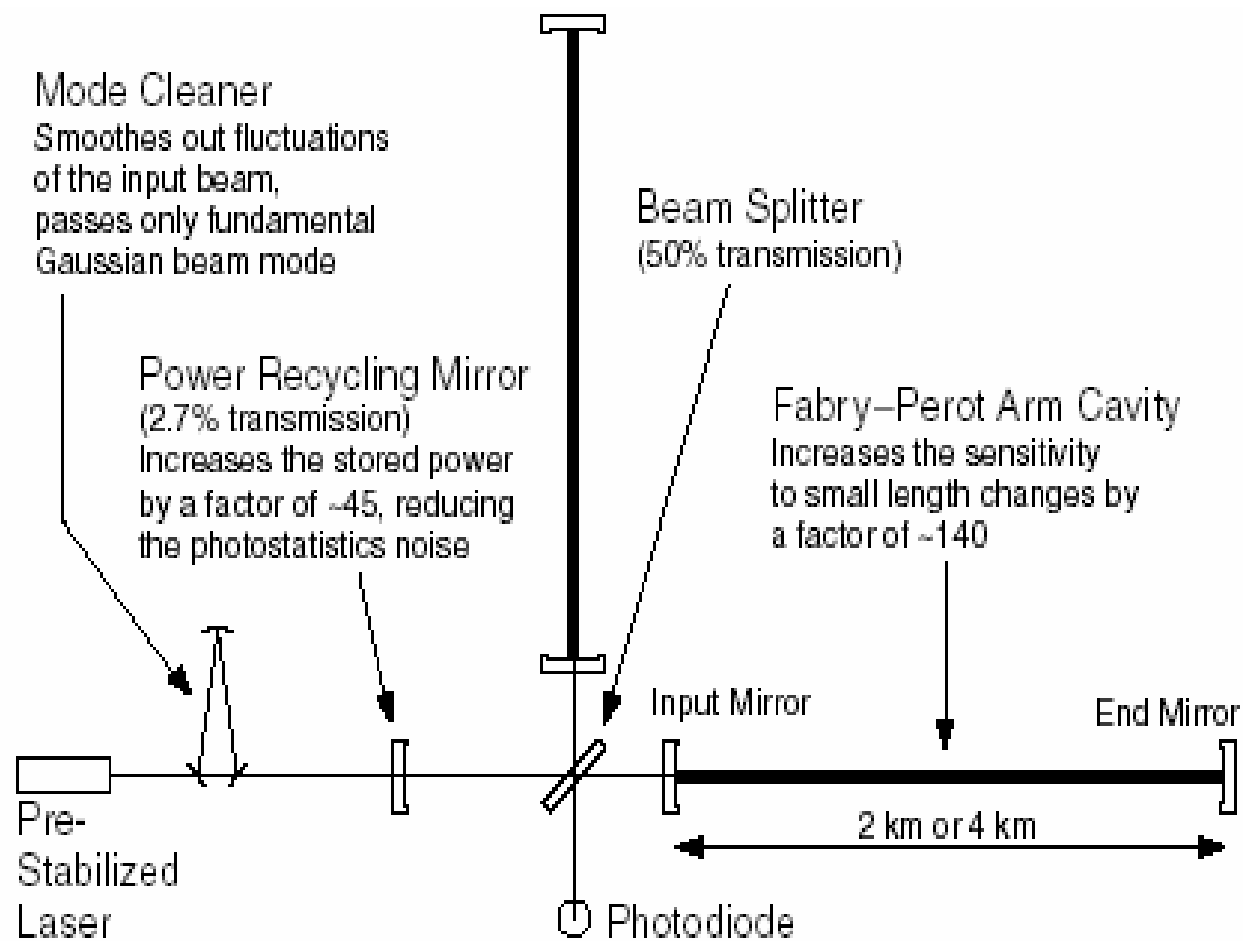


Figure 1. Simplified optical layout of a LIGO interferometer.

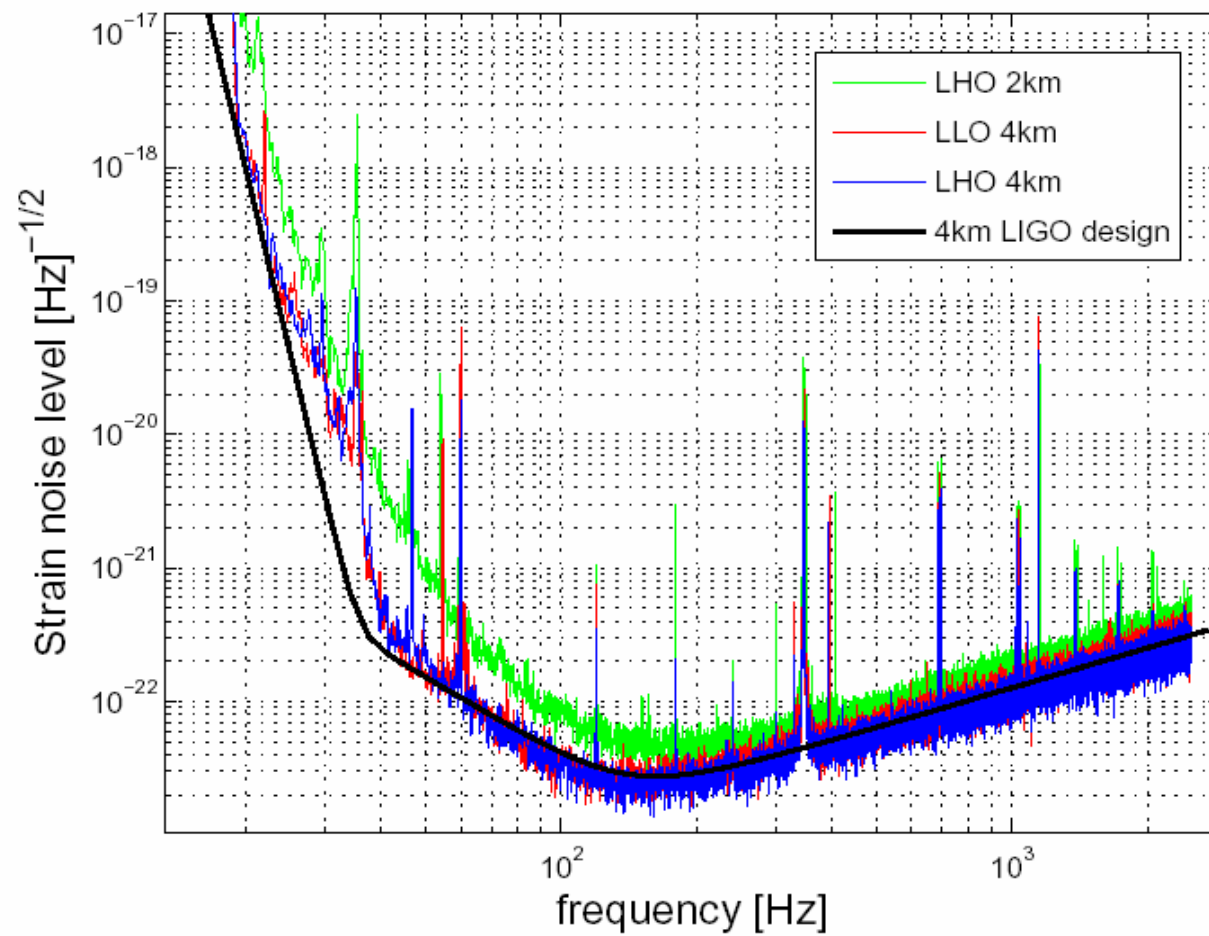
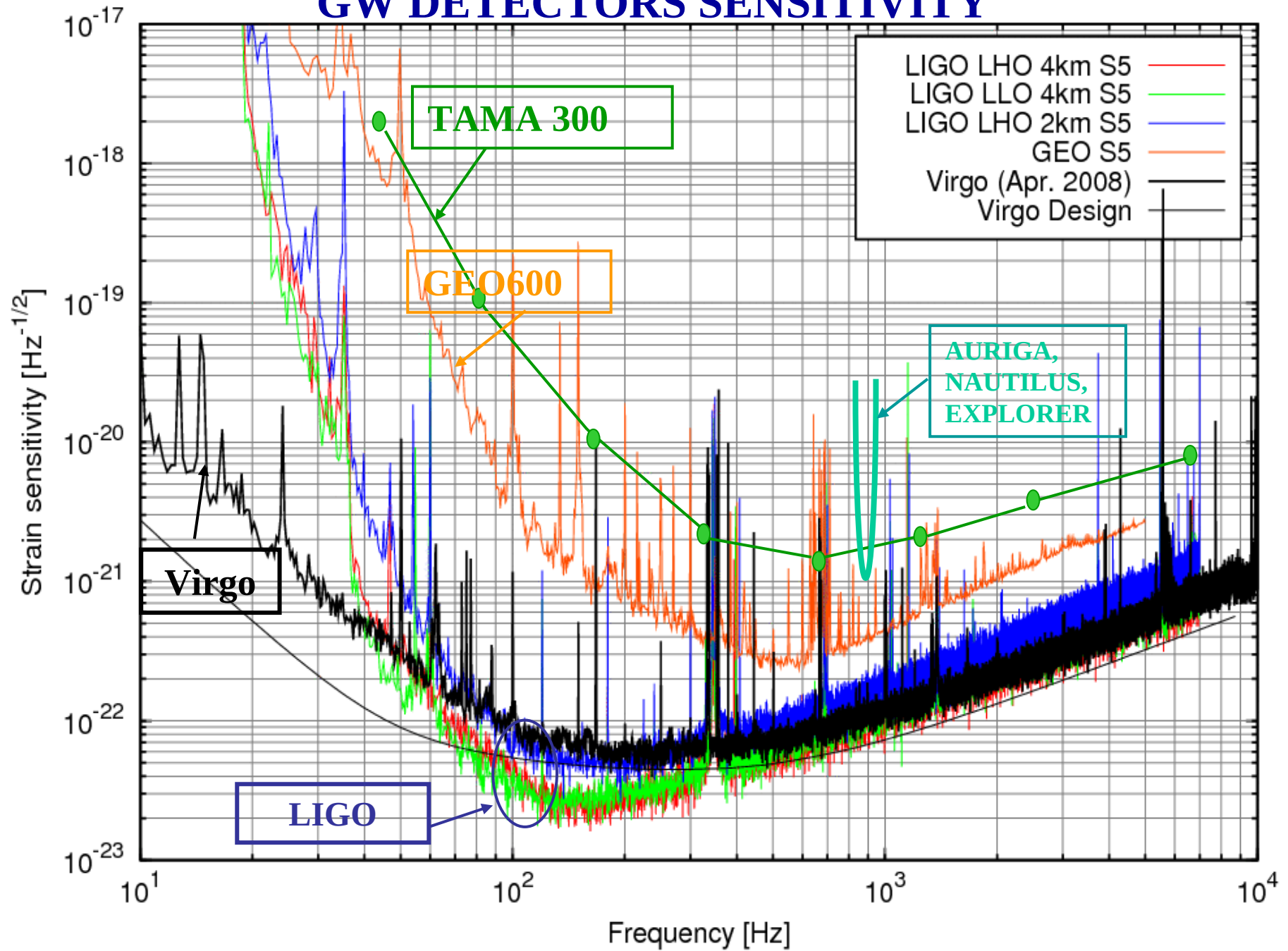


Figure 1. LIGO sensitivity during its 5th science run. The black solid curve shows the design sensitivity goal.

GW DETECTORS SENSITIVITY



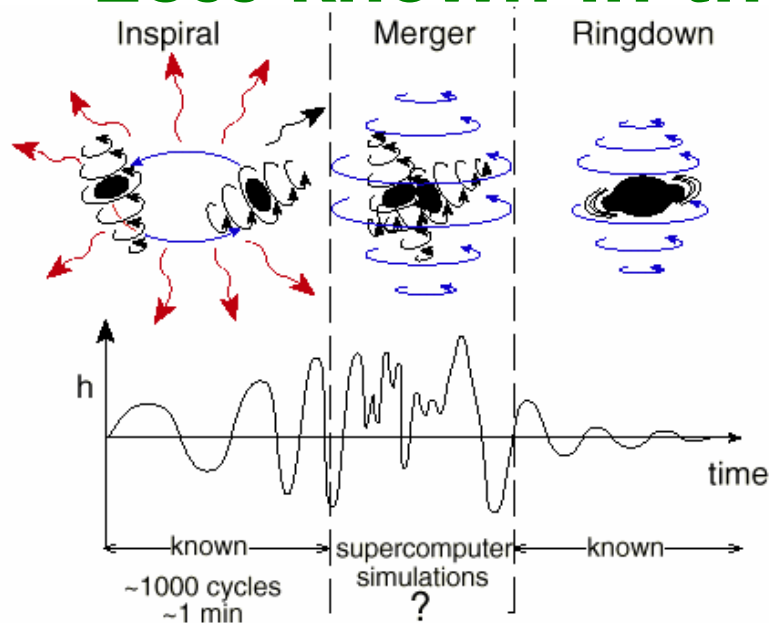
Frequency Range: (50 – 1500) Hz
Blind All Sky Searching

Sources:

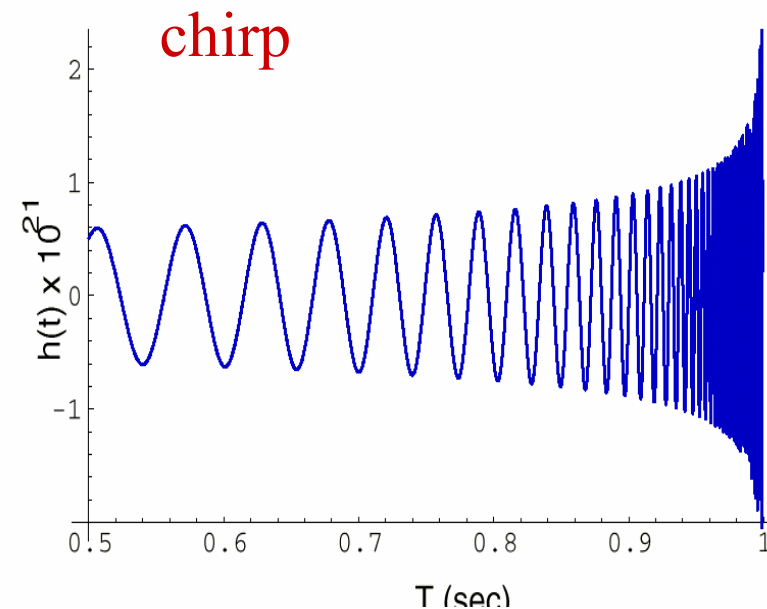
- compact binary systems evolution
(inspiral, merging, ring down)
 - supernova collapse events
 - continuous GW radiation (Pulsars)
 - stochastic GW background
- Triggered Search (Astro-gravity associations)

Coalescing Binaries

- **Source: coalescence of compact binary stars (BNS, BBH, NS/BH)**
 - **Waveform accurately modeled in the first and last phase**
 - **Allows matched filtering**
 - **Less known in the “merger” phase**

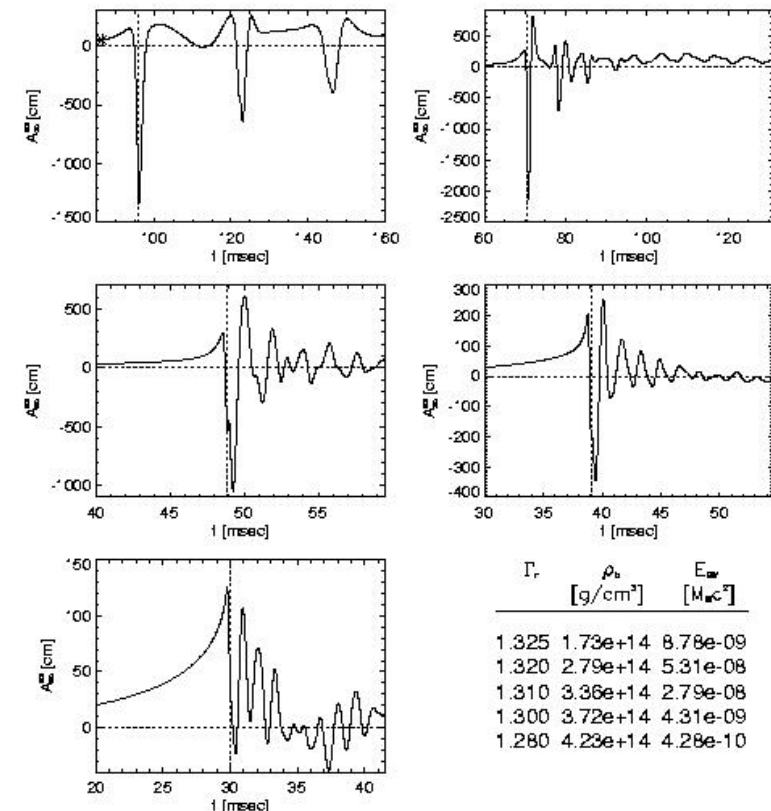
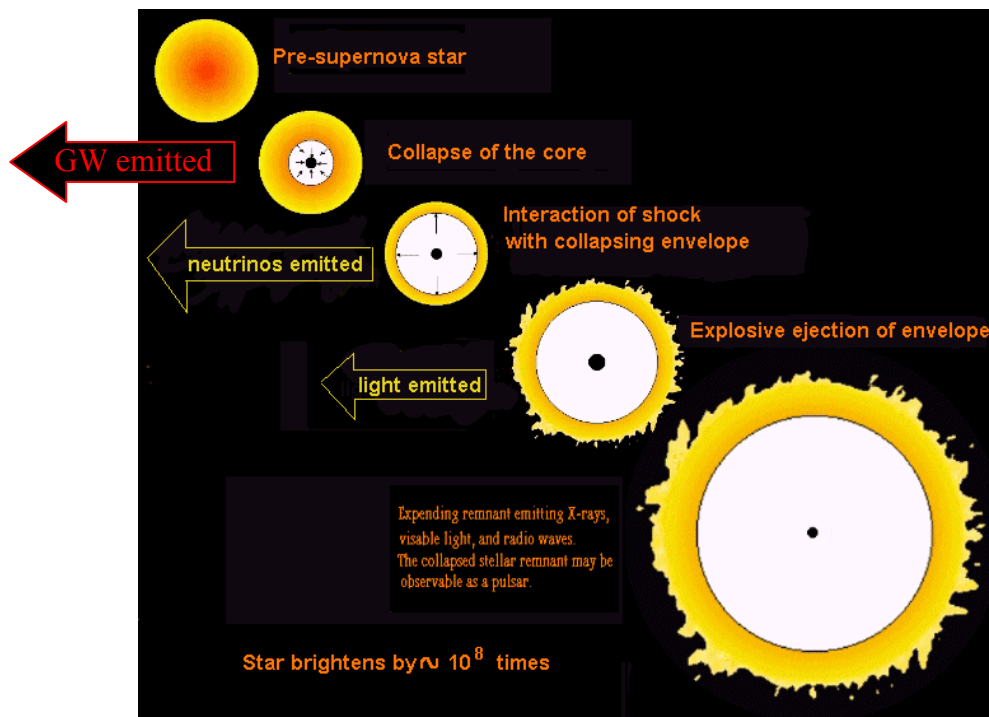


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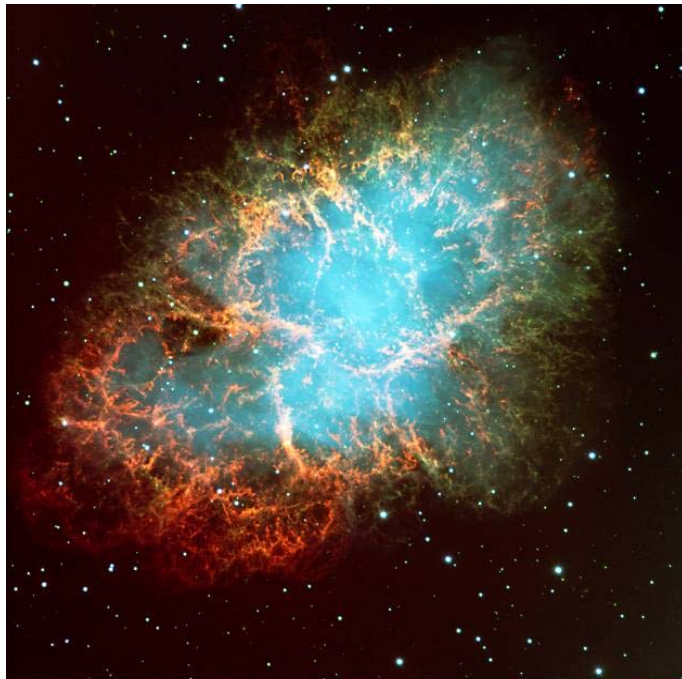
Bursts

- **Classical sources: supernovae**
 - **Waveform poorly known**
 - **Several events/year in the Virgo cluster**
 - **Possibly detectable only within our Galaxy**
- **Generally, whatever can cause short ($< 1\text{s}$) GW impulses**
 - **Include exotic things (strings) or classical things (NS, BH ringdowns)**



Pulsars

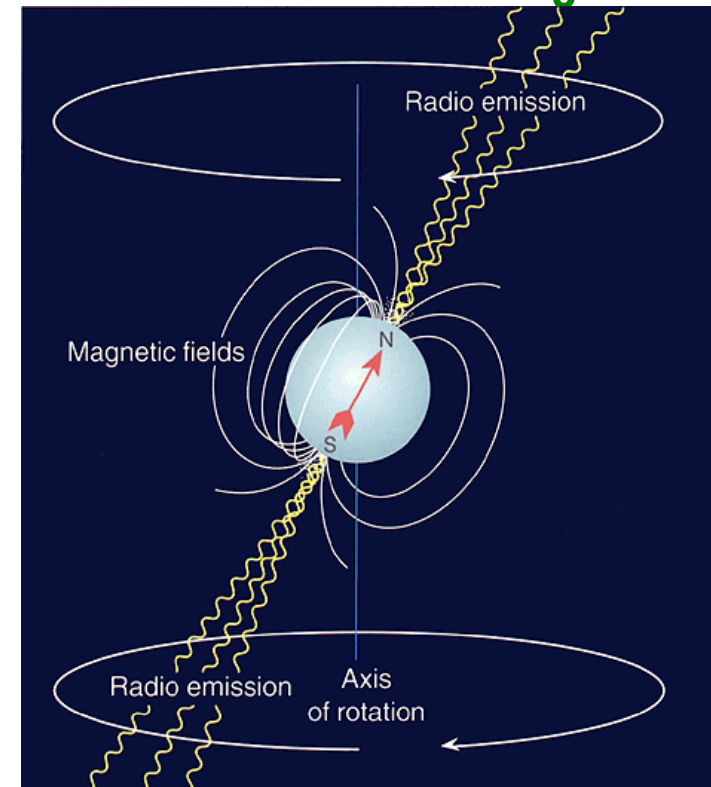
- **Distorted NS, emitting “lines” of GW radiation**
 - **Things greatly complicated by the Doppler effect**
 - **Contrary to intuition, by the far the most computing intensive search**
 - **Thousands of known potential sources in our Galaxy**
 - **Most probably below detection threshold**
 - **Many more yet unknown NS could generate a detectable signal**



The Crab Nebula in Taurus (VLT KUEYEN + FORS2)

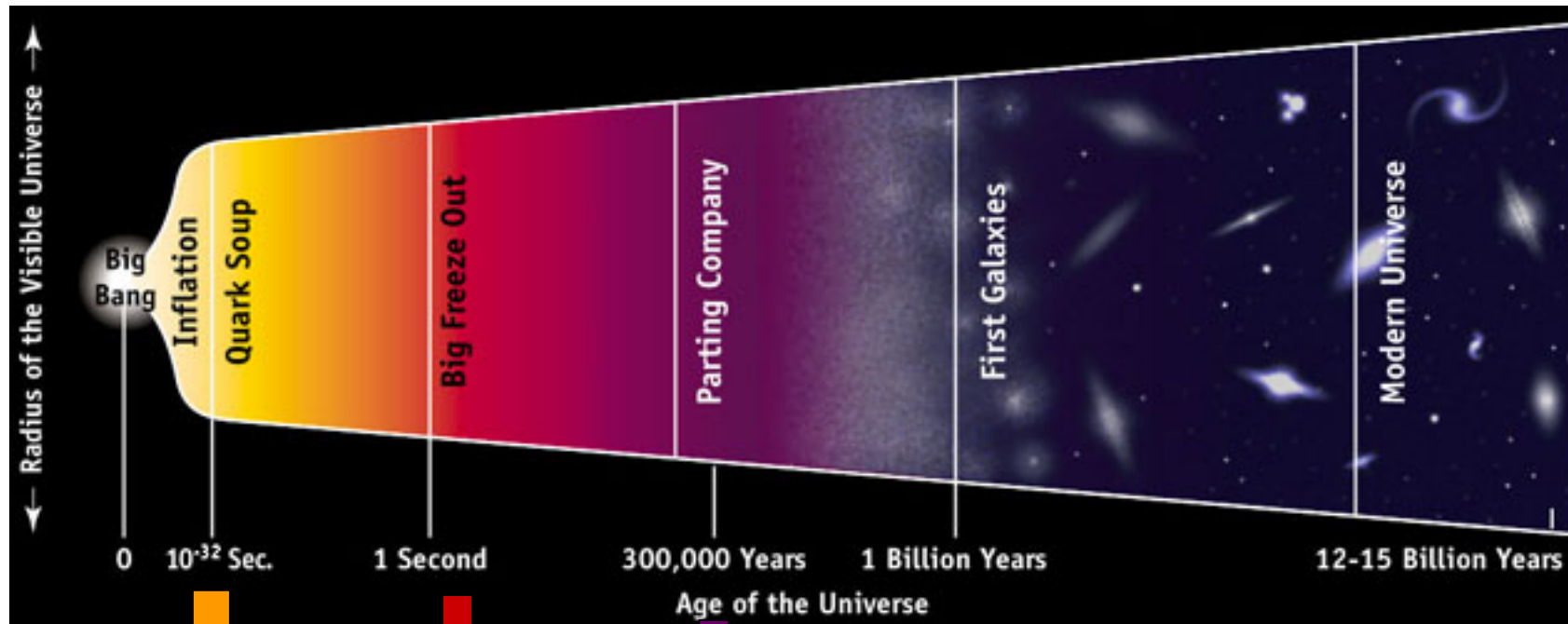
ESO PR Photo 40f/99 (17 November 1999)

© European Southern Observatory



Cosmological Stochastic Background

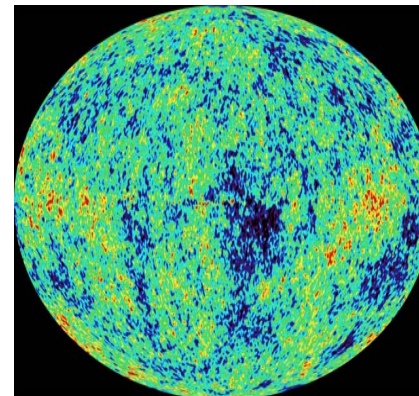
- **Potential access to very early Universe**



Relic gravitons

Relic neutrinos

CMBR



LIGO Scientific Runs (2000 – 2007)

S1 – (08-09) 2000 y. (noise 100 times projected level)

S2 , S3 - during 2003 y (bad seismic isolation)

**S4 - (02-03) 2005 y (duty cycle 70%, but selected 15,5
days data !)**

joint operation of 3 interferometers

S5 - (06. 2006 - 10.2007) results are published partly

Methods of data analysis

Non modeled Bursts Search

outputs of two GW detectors: vectors **a** , **b**

$$\text{total energy : } E = \left(\left| \bar{a} + \bar{b} \right|^2 = \bar{a}^2 + \bar{b}^2 + 2|\bar{a}||\bar{b}| \right)$$

normalized and integrated at the it is reduced to variables:

$$\text{Burst's Excess Power: } E_a \sim \sum_i (a_i / \sigma)^2, \quad E_b \sim \sum_i (b_i / \sigma)^2,$$

$$E > C_{thr}$$

Burst's Cross Power:

$$R = (E_a \cdot E_b / \sigma_a \sigma_b)^{1/2} \sim |a| \cdot |b| / \sigma_a \cdot \sigma_b \quad R > R_0$$

Sine-gaussian waveform

$$h_{rss} = \sqrt{\int h_+(t)^2 + h_\times(t)^2 dt}.$$

$$E_{GW} = \frac{d^2 c^3}{4G} (2\pi f_0)^2 h_{rss}^2$$

Wavelet transform

$$\psi_{a,b}(x) = \frac{1}{\sqrt{|a|}} \psi\left(\frac{x-b}{a}\right),$$

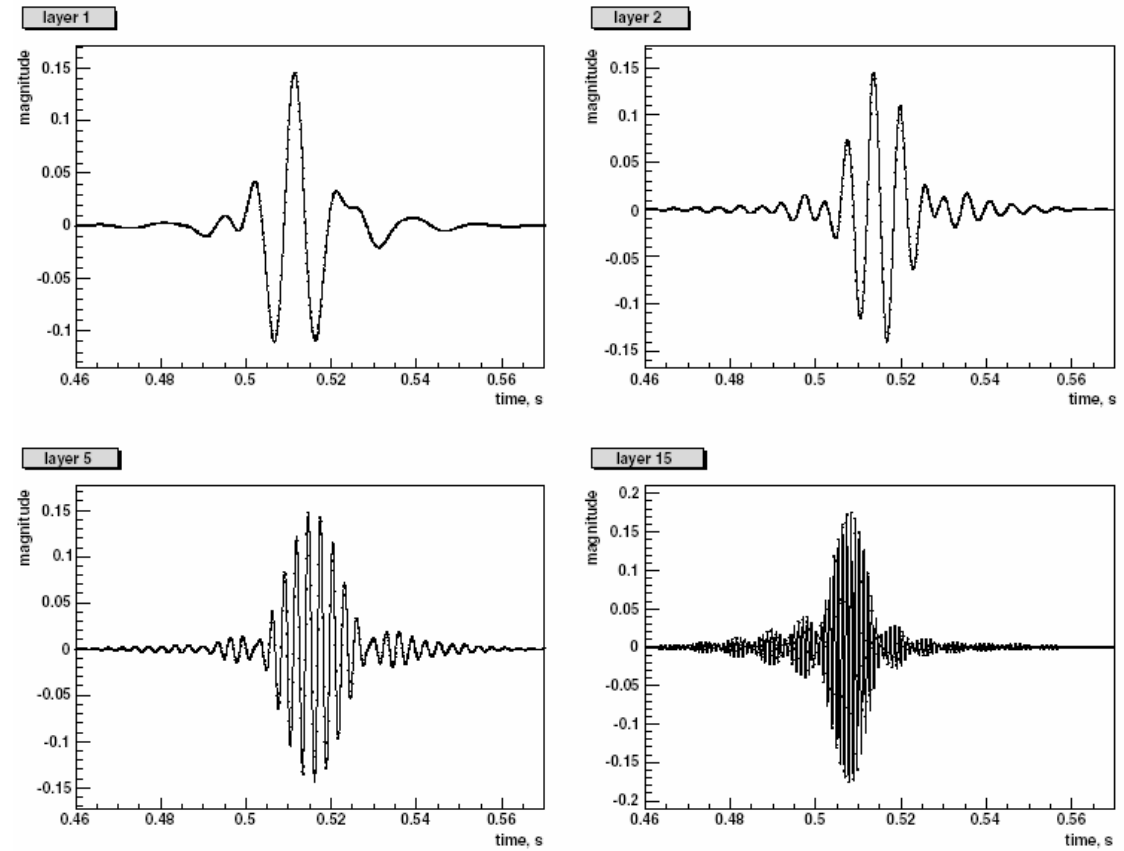


Figure 1. Wavelet function for SYMLET transformation (layer 1), wavelet packets (layers 2, 5, 15).

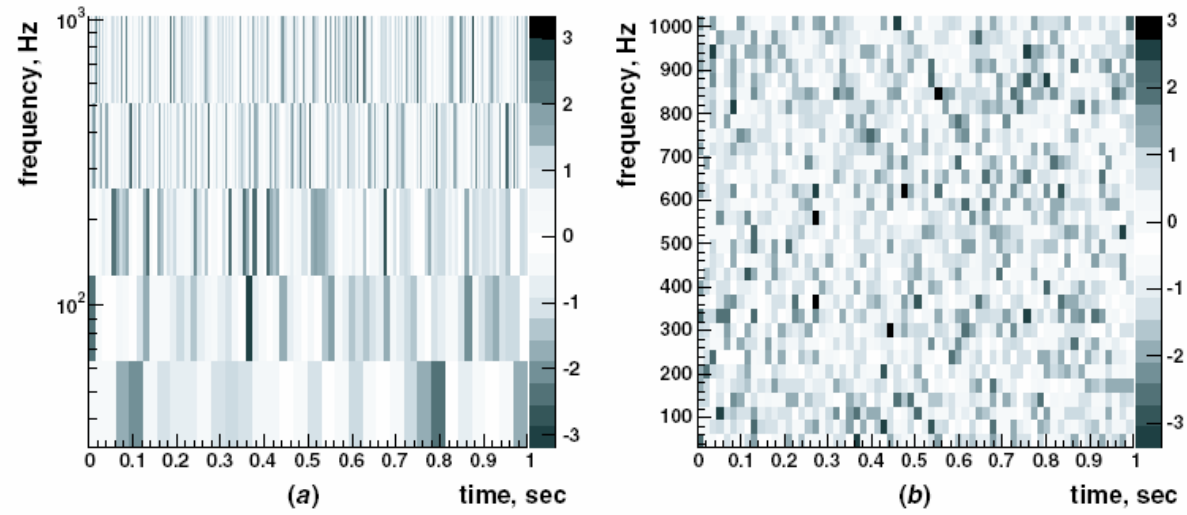


Figure 3. Wavelet amplitude scalograms for Gaussian noise produced with: (a) dyadic decomposition, $L = 6$ and (b) binary decomposition, $L = 5$. Only detail layers are shown.

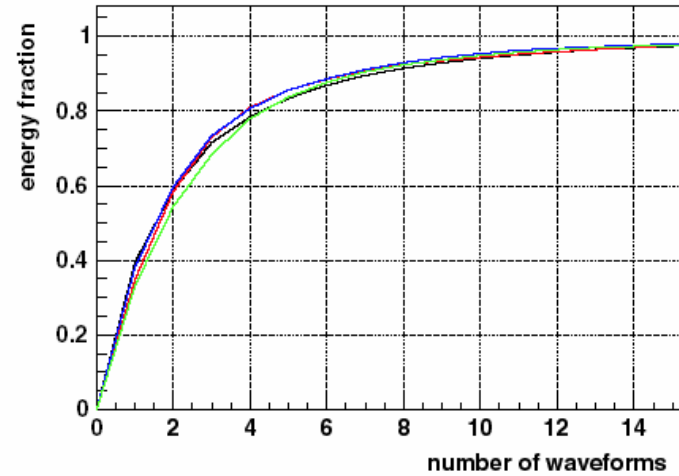


Figure 4. Approximation of the Lazarus black-hole merger waveforms with SYMLET-60 wavelet functions. Different curves correspond to the binary systems of 10, 20, 40 and 80 solar masses.

Excess power or **Wave Burst** algorithm :

$Z_g \rightarrow$ geometrical mean of 3 detector excess powers

(time shifted triggers)

$Z_g > 6.7$!

$Z_g > 20$, $\Gamma < 12$

are artifacts

$$r = \frac{\sum_{i=1}^N (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^N (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^N (y_i - \bar{y})^2}}.$$

Cross-Power statistic: $\Gamma \sim$ mean “r” of 3 detectors $H_1, H_2 \rightarrow R < 0$ rejected

(time shifted triggers)

$H, L \rightarrow \Gamma < 12$ rejected

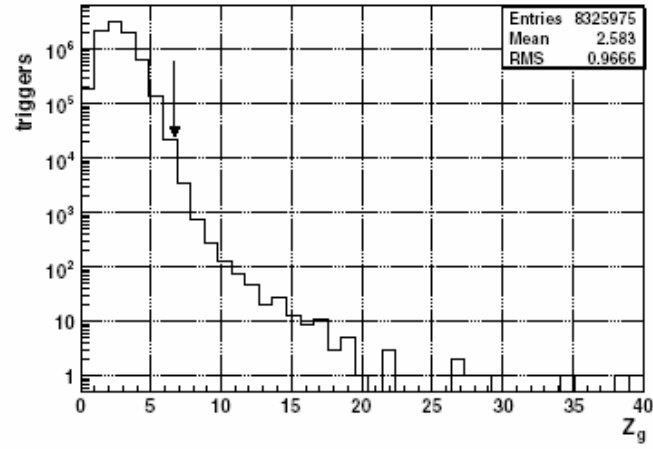


Figure 3. Distribution of Z_g values for all WaveBurst triggers. The arrow shows the location of the initial significance cut, $Z_g > 6.7$.

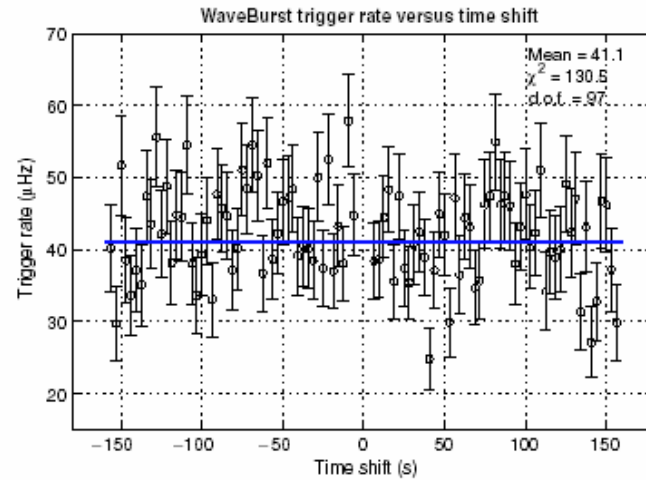


Figure 4. WaveBurst trigger rate as a function of the relative time shift applied between the Hanford and Livingston data streams. The horizontal line is a fit to a constant value, yielding a χ^2 of 130.5 for 97 degrees of freedom.

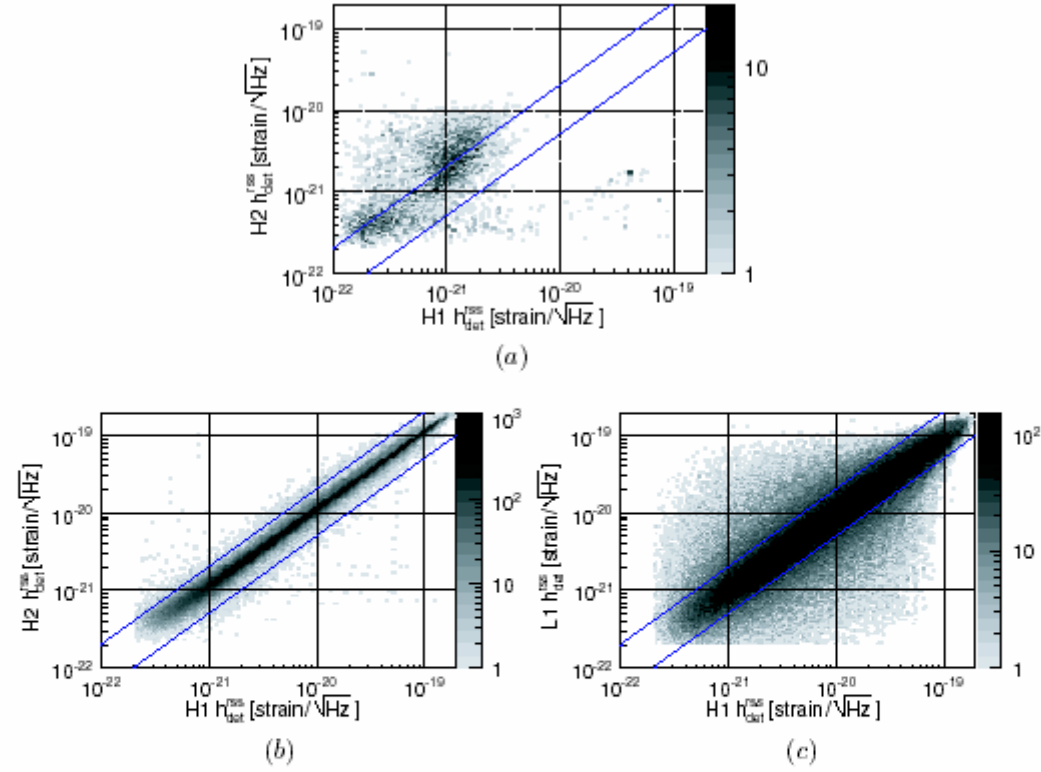


Figure 5. (a) A two-dimensional histogram, with bin count indicated by grayscale, of H2 versus H1 amplitudes reconstructed by WaveBurst for the tuning set of time-shifted triggers. (b) A two-dimensional histogram of H2 versus H1 amplitudes reconstructed for simulated sine-Gaussian signals with a wide range of frequencies and amplitudes from sources uniformly distributed over the sky (see section 7). In these plots, the diagonal lines show the limits of the H1/H2 amplitude consistency cut: $0.5 < \text{ratio} < 2$. (c) A two-dimensional histogram of L1 versus H1 amplitudes for the same simulated sine-Gaussian signals. Diagonal lines are drawn at ratios of 0.5 and 2 only to guide the eye; no cut is applied using this pair of interferometers.

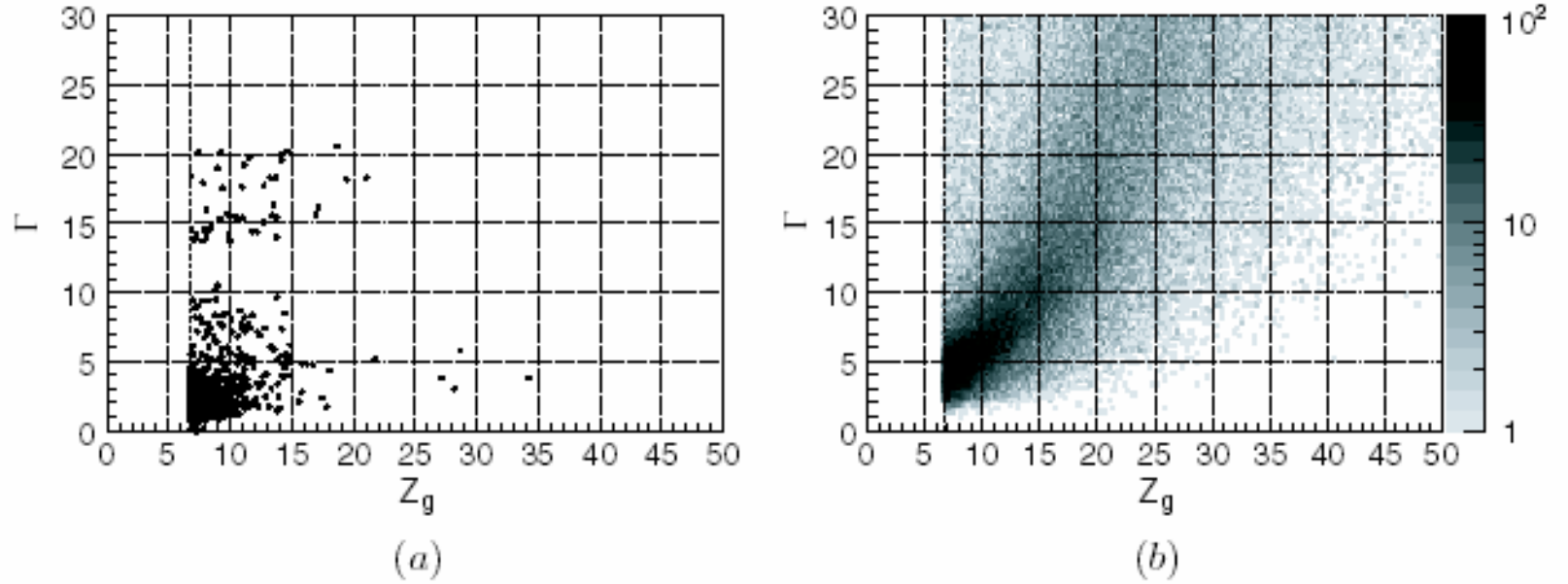


Figure 6. Plots of Γ versus Z_g , after the H1/H2 amplitude consistency cut but before any other cuts. (a) Scatter plot for all time-shifted triggers in the tuning set. (b) A two-dimensional histogram, with bin count indicated by grayscale, for simulated sine-Gaussian signals with a wide range of frequencies and amplitudes from sources uniformly distributed over the sky (see section 7). In both the plots, the vertical dashed line indicates the initial WaveBurst significance cut at $Z_g = 6.7$.

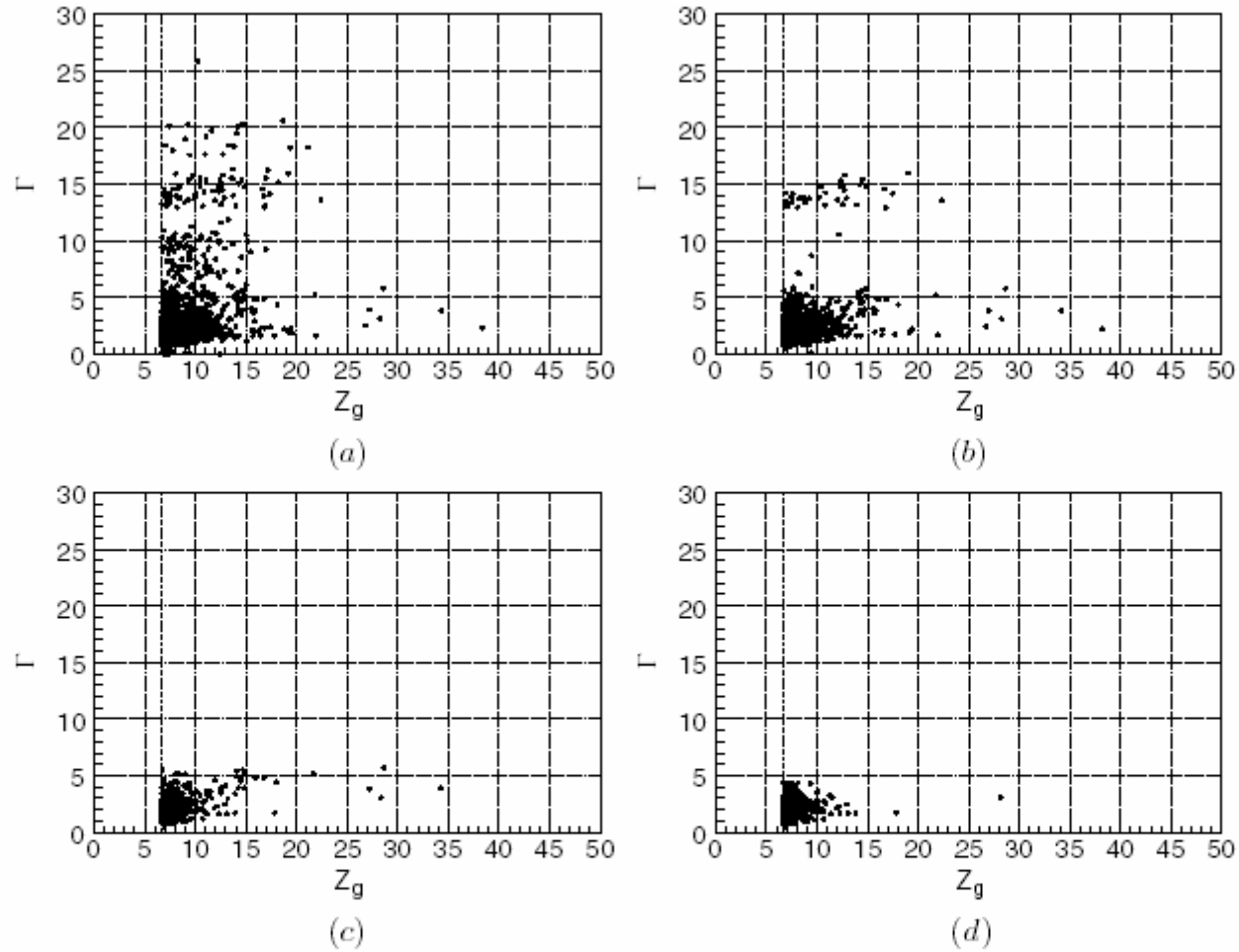


Figure 7. Scatter plots of Γ versus Z_g for the tuning set of time-shifted triggers. (a) All triggers; (b) after data quality cuts; (c) after data quality and H1–H2 consistency cuts (amplitude ratio and R_0); (d) after data quality, H1–H2 consistency, and auxiliary-channel vetoes.

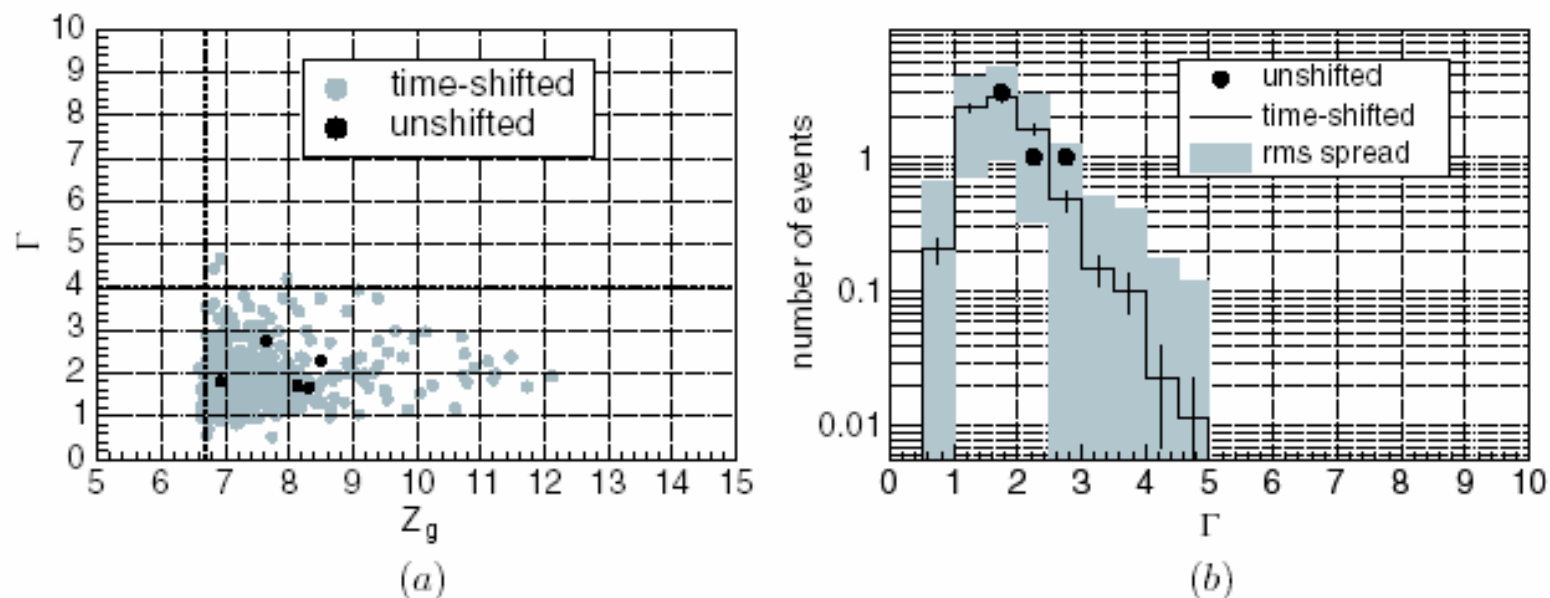


Figure 8. (a) Scatter plot of Γ versus Z_g for time-shifted triggers (gray circles) and unshifted triggers (black circles) after all other analysis cuts. The vertical dashed line indicates the initial WaveBurst significance cut at $Z_g = 6.7$. The horizontal dashed line indicates the final Γ cut. (b) Overlaid histograms of Γ for unshifted triggers (black circles) and mean background estimated from time-shifted triggers (black staircase with statistical error bars). The shaded bars represent the expected root-mean-square statistical fluctuations on the number of unshifted background triggers in each bin.

Table 1. Counts of time-shifted and unshifted triggers as cuts are applied sequentially. The column labeled ‘normalized’ is the time-shifted count divided by 77.4, representing an estimate of the expected background for the S4 observation time.

Cut	Time shifted		Unshifted count
	Count	Normalized	
Data quality	3153	40.7	44
H1/H2 amplitude consistency	1504	19.4	14
$R_0 > 0$	755	9.8	5
Auxiliary-channel vetoes	671	8.7	5
$\Gamma > 4$	3	0.04	0

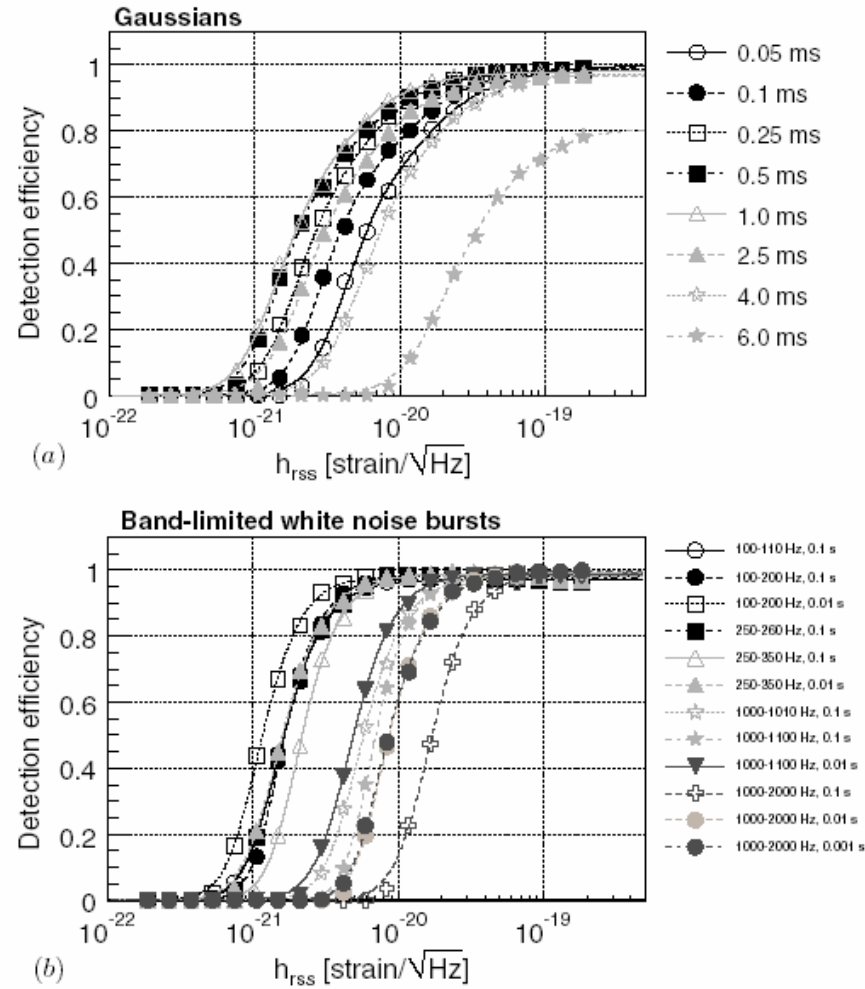


Figure 10. Efficiency curves for simulated gravitational-wave signals: (a) linearly-polarized Gaussian waves; (b) band-limited white-noise bursts with two independent polarization components. Note that four curves in the latter plot are nearly identical: 100–110 Hz, 0.1 s; 100–200 Hz, 0.1 s; 250–260 Hz, 0.1 s; and 250–350 Hz, 0.01 s. Statistical errors are comparable to the size of the plot symbols.

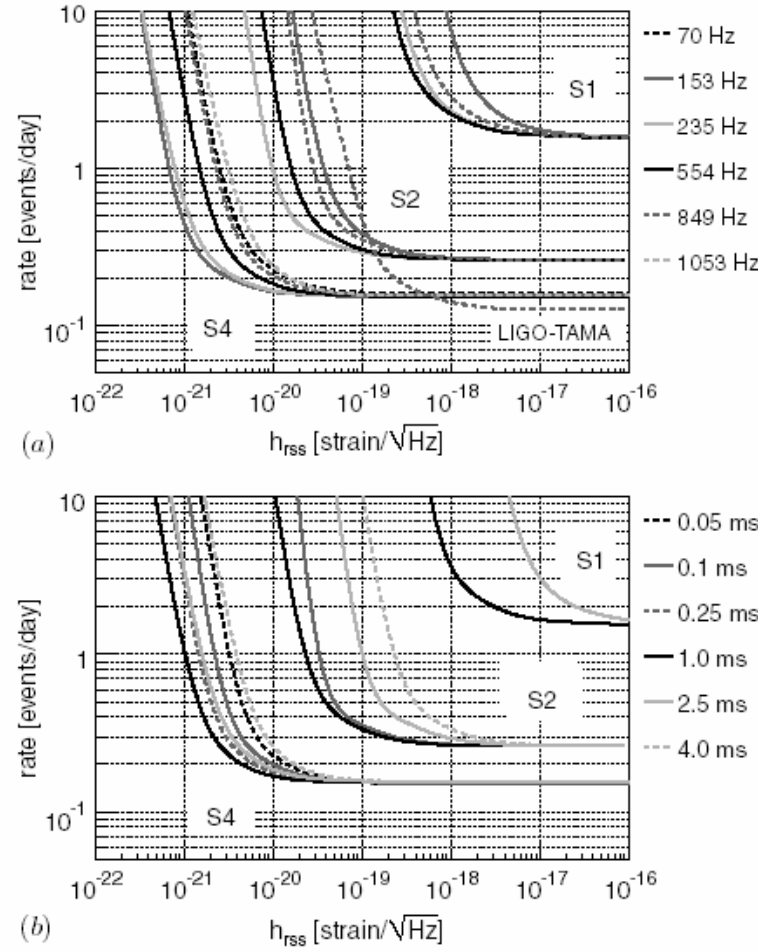


Figure 12. Exclusion diagrams (rate limit at 90% confidence level, as a function of signal amplitude) for (a) sine-Gaussian and (b) Gaussian-simulated waveforms for this S4 analysis compared to the S1 and S2 analyses (the S3 analysis did not state a rate limit). These curves incorporate conservative systematic uncertainties from the fits to the efficiency curves and from the interferometer response calibration. The 849 Hz curve labeled ‘LIGO-TAMA’ is from the joint burst search using LIGO S2 with TAMA DT8 data [8], which included data subsets with different combinations of operating detectors with a total observation time of 19.7 days and thereby achieved a lower rate limit. The h_{rss} sensitivity of the LIGO-TAMA search was nearly constant for sine-Gaussians over the frequency range 700–1600 Hz. (a) Sine-Gaussians with $Q = 8.9$. (b) Gaussians.

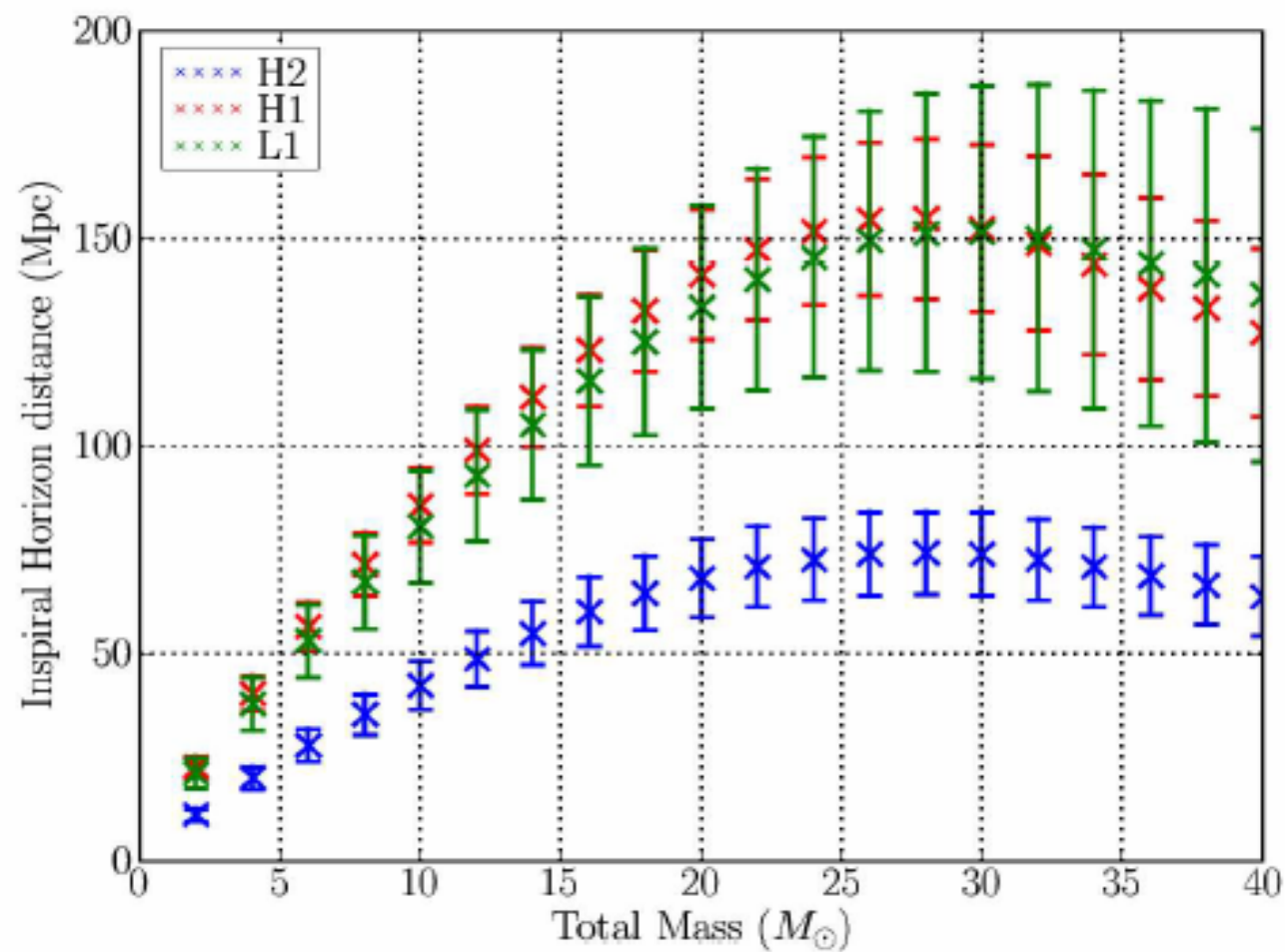


Figure 2. Typical horizon distance during the S5 run as a function of the total mass of the binary system. *Courtesy of the LSC.*

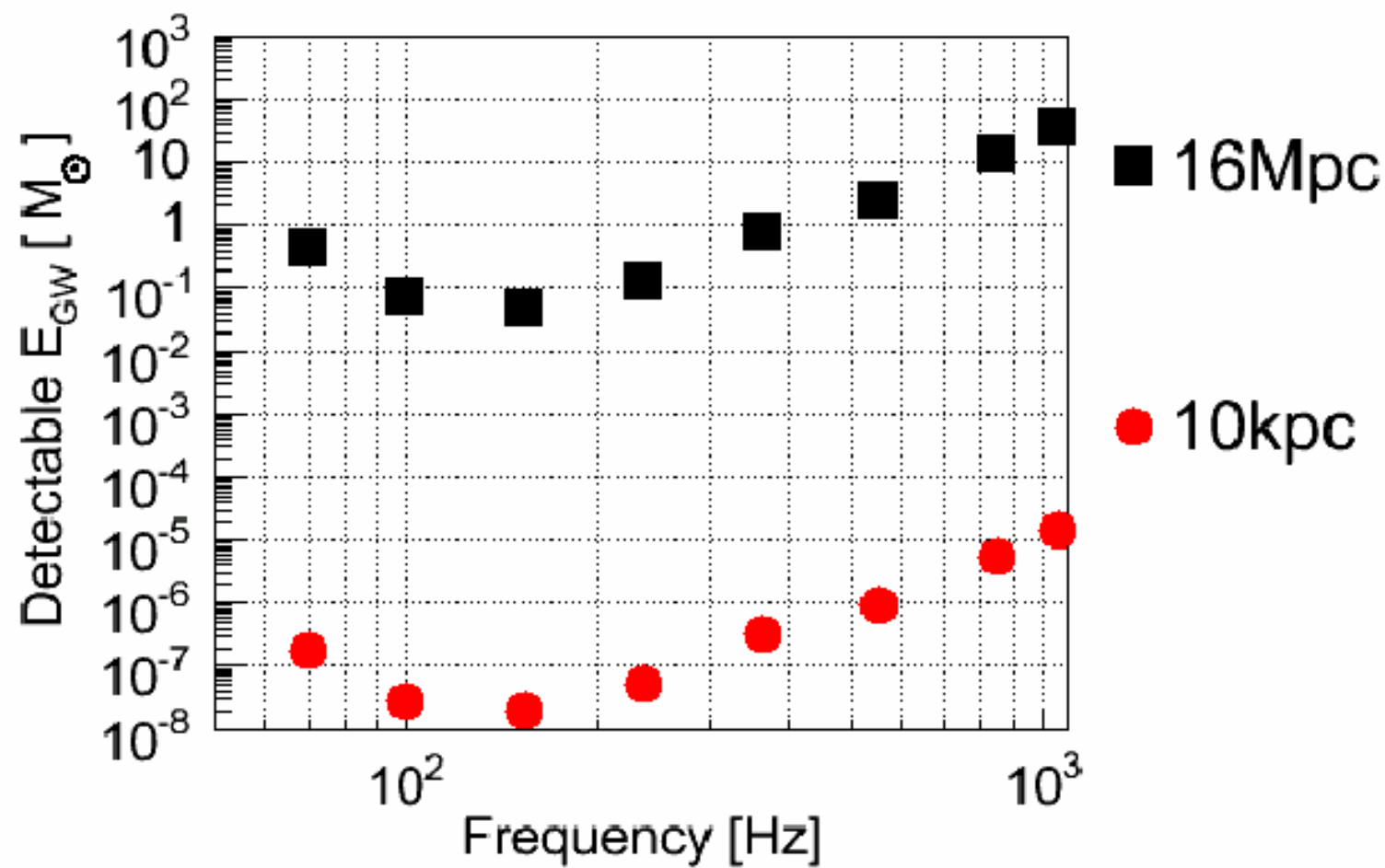


Figure 3. Energy in emitted in gravitational waves that would generate a sine-gaussian signal detectable with 50% efficiency, as a function of the frequency of the sine-gaussian waveform. *Courtesy of the LSC.*

Pulsars

$$h_0 = \frac{4\pi^2 G}{c^4} \frac{I \nu^2}{d} \epsilon \quad , \quad \epsilon = \frac{7.6 \times 10^5 \dot{\nu}^{1/2}}{\nu^{5/2}} .$$

↑
ellipticity

↑
If the spindown produced by GW

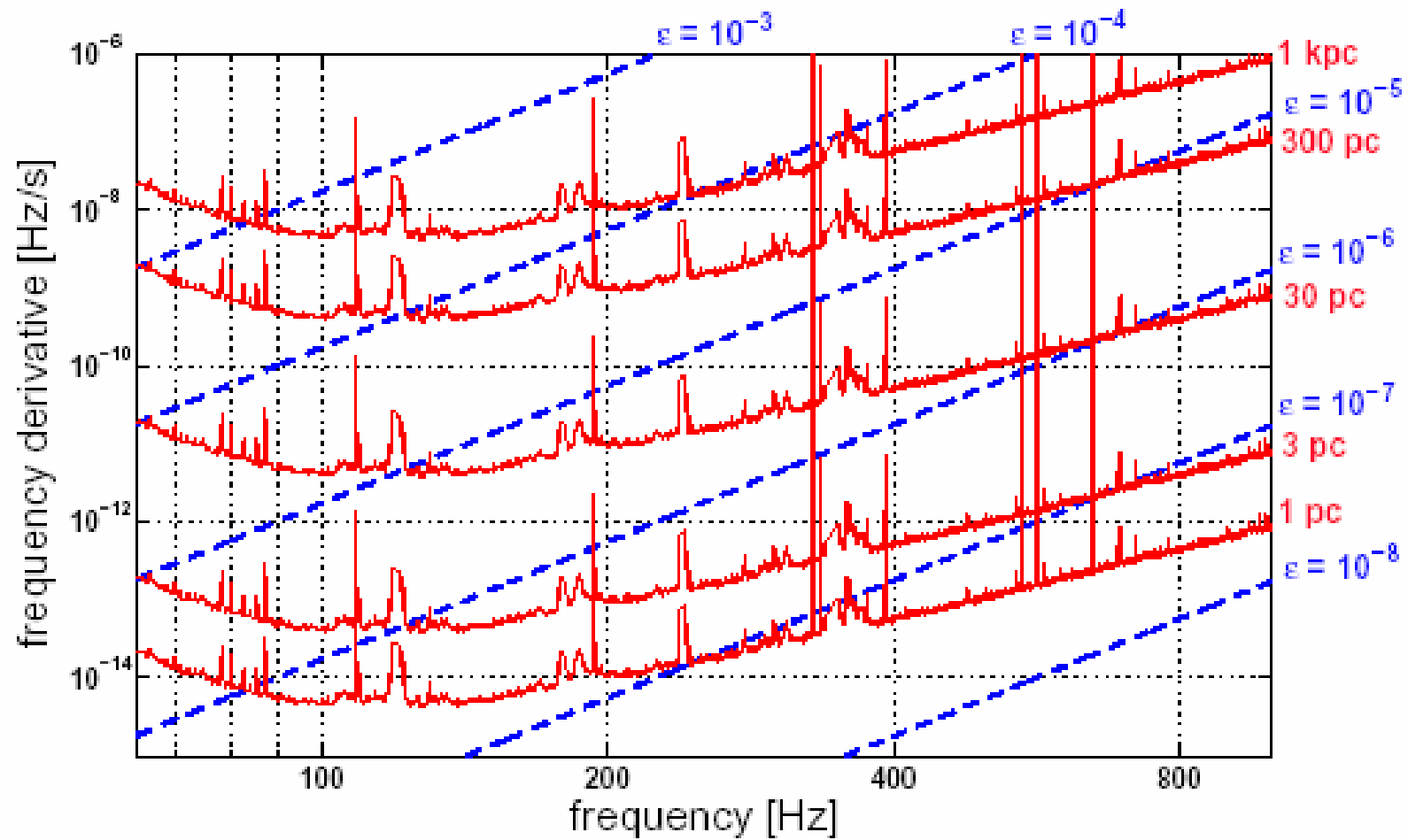


Figure 4. Solid curves: Frequency and frequency-derivative values of a signal that would be detectable by the S4 stack-slide search described in [31]. Dashed lines: lines of constant ellipticity.

Results S4 , S5 (preliminary)

Unmodeled bursts : upper limit $\rightarrow < 0.15 \text{ day}^{-1}$, $h_{\text{rss}} < 10^{-20} \text{ Hz}^{-1/2}$

Inspiral Bursts : upper limit $\rightarrow$ Event Rate: R

$R = (\text{Number of events/ year. galaxy})$

1 event per 20-300 years for NS binary

for $d_H \sim 60 \text{ Mpc}$

1 event per 20-2000 years for binary $\sim 5 M_0$

1 event per 3 – 30 years for binary $\sim 10 M_0$

Pulsars : $f \sim 150 \text{ Hz}$, $h \sim 10^{-25}$, $\varepsilon < 10^{-5}$

Stochastic background: $f \sim (50 - 100) \text{ Hz}$, $\Omega < 6.5 \cdot 10^{-5}$

result of S4

LIGO remarkable results

1. Limit on **GW** counterpart of **GRB 070201**

mono Gamma burst 0.1 sec, location ~ 700 kps (M31) (or ?)

no accompanied GW-signal at $E < 10^{-4} mc^2$

2. Beating the **spin-down limit on GW from Crab pulsar**

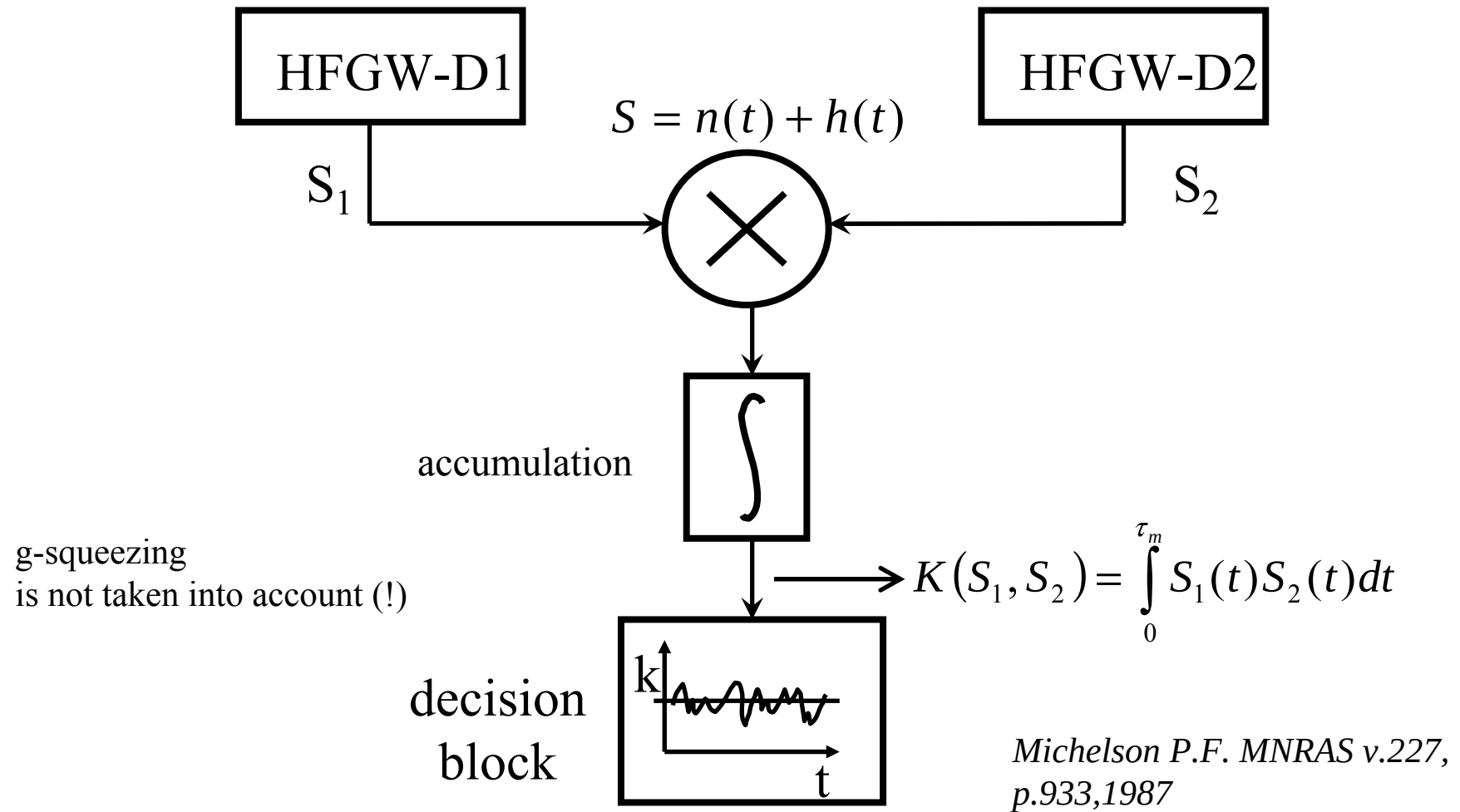
after S5 observable GW from PRS JO534-2200 is evaluated

*as $h < 3.4 \cdot 10^{-25}$ in 4 times less then the prior estimate -
“spin-down limit” – $h < 1.4 \cdot 10^{-24}$*

3. Experimental **upper limit to a stochastic GW background**

new limit $\Omega_{\text{gw}} < 7 \cdot 10^{-6}$ is less the

Detection of a correlated noise at Gaussian background



Sensitivity to the Relic Background

$$K(S_1, S_2) \approx \cdot \langle h_1, h \rangle \cdot + \cdot \langle n_1, n_2 \rangle$$

$$\langle h_1, h_2 \rangle \cdot \sim |h_\nu|^2 \cdot \Delta\nu \cdot \tau_m, - \cdot \text{signal}$$

$$\langle n_1, n_2 \rangle \cdot \sim |n_\nu|^2 \cdot \sqrt{\Delta\nu \cdot \tau_m}, - \cdot \text{noise}$$

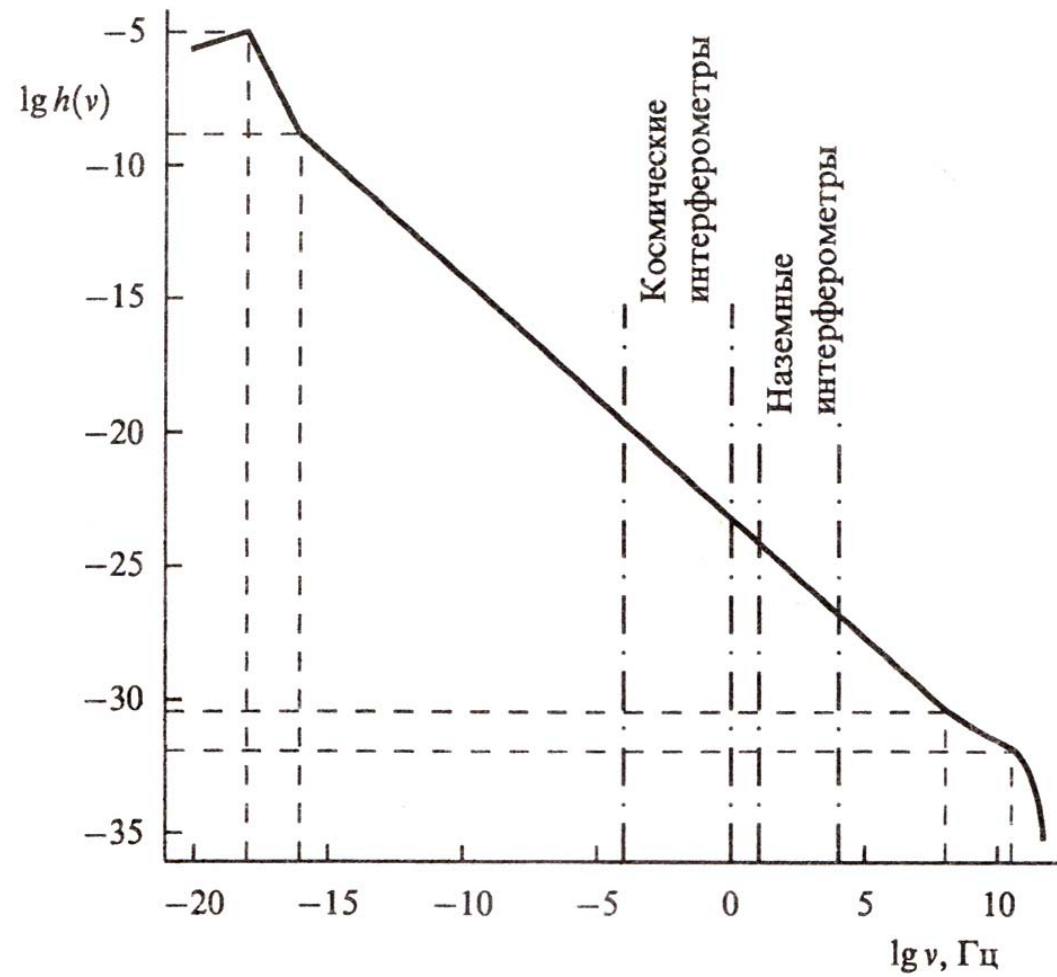
$$\langle h_1 h_2 \rangle \cdot \sim \cdot \frac{|n(\nu)|^2}{\sqrt{\Delta\nu \cdot \tau_m}}$$

$$\Delta\nu \sim \cdot \frac{c}{2L} \cdot \frac{1}{F} \cdot \sim \cdot 500 \cdot \text{Hz}$$

$$|n(\nu)|_{\Delta\nu=1\text{Hz}} \sim \cdot 10^{-20} \quad \Rightarrow \quad \langle |h|^2 \rangle^{1/2}_{\min} \cdot \geq \cdot 10^{-24} \div 10^{-25}$$

$$\tau_m = \cdot 10^7 \text{ s}$$

squeezing was not considered



Grishchuk's estimate of the relic graviton spectrum.

b)

Grishchuk's cosmological gravitons

very early Universe evolution: $dS = a^2(\eta)[d\eta^2 + (\delta_{ij} + h_{ij})dx^i dx^j]$, $d\eta = \frac{c}{a(\eta)} dt$

$a(\eta)$ – scale factor, $h = \sum h_n(\eta) \sim \frac{1}{a(\eta)} \{u_n(\eta) \cdot + \cdot v_n(\eta)\}$, $\mu_n(\eta) = a(\eta) \cdot h_n(\eta)$

parametric graviton creation $\mu_n'' + \mu_n \cdot (n^2 - \frac{a''}{a}) = 0$, (a'' / a) - cosmological pump

squeezed quadratures — $u_n \exp(j\theta) \cdot \cosh \cdot r_n \dots, v_n \exp[-j(\theta_n - 2\Phi_n)] \cdot \sinh \cdot r_n$

LIGO estimate of the Stochastic GW Background

$$\Omega_{gw}(f) = \frac{f}{\rho_c} \frac{d\rho_{gw}}{df}$$

$$\Omega_{gw}(f) = \Omega_{\alpha} \left(\frac{f}{100 \text{ Hz}} \right)^{\alpha}$$

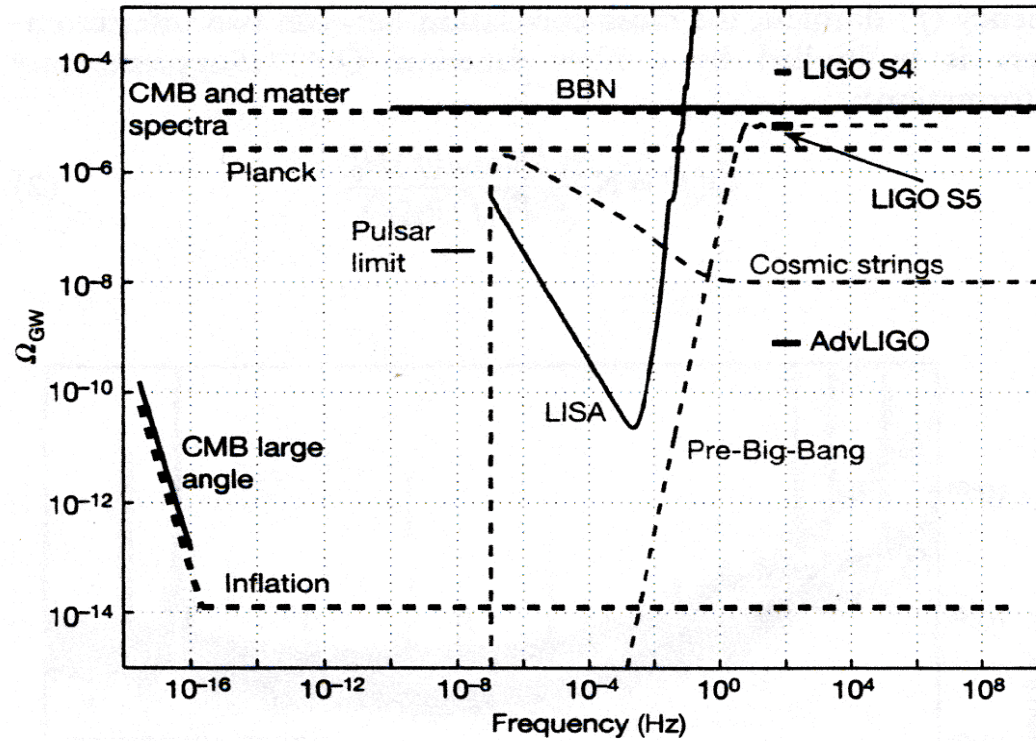
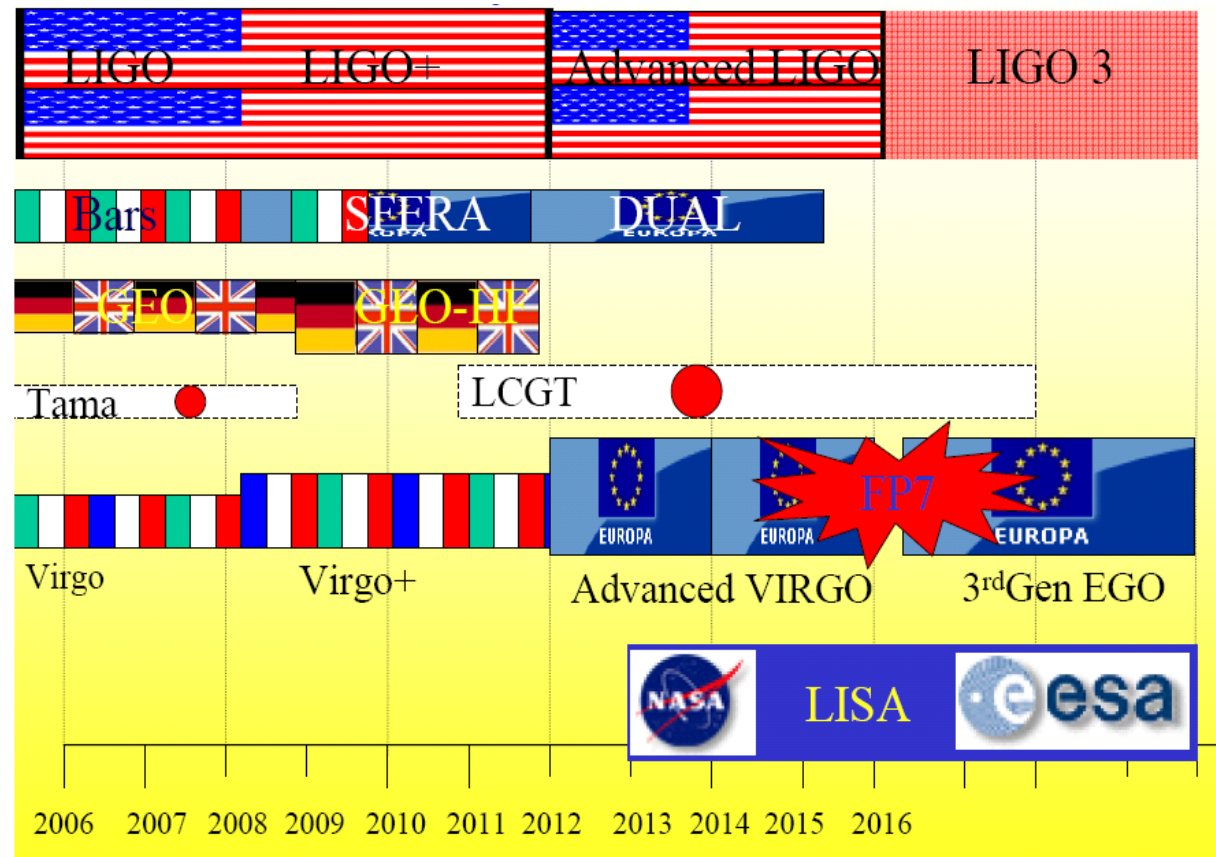


Figure 2 | Comparison of different SGWB measurements and models. The 95% upper limit presented here, $\Omega_0 < 6.9 \times 10^{-6}$ (LIGO S5), applies in the frequency band 41.5–169.25 Hz, and is compared to the previous LIGO S4 result²² and to the projected Advanced LIGO sensitivity²⁵. Note that the corresponding S5 95% upper bound on the total gravitational-wave energy density in this band, assuming frequency independent spectrum, is 9.7×10^{-6} . The indirect bound due to BBN^{1,6} applies to $\Omega_{\text{BBN}} = \int \Omega_{\text{GW}}(f) d(\ln f)$ (and not to the density $\Omega_{\text{GW}}(f)$) over the frequency band denoted by the corresponding horizontal line, as defined in equation 3. A similar integral bound (over the range 10^{-15} – 10^{10} Hz) can be placed using CMB and matter power spectra⁷. Projected sensitivities of the satellite-based Planck CMB experiment⁷ and LISA gravitational-wave detector²⁶ are also shown. The pulsar bound²⁷ is based on the fluctuations in the pulse arrival times of millisecond pulsars and applies at frequencies around 10^{-8} Hz. Measurements of the CMB at large angular scales constrain the possible redshift of CMB photons due to the SGWB, and therefore limit the amplitude of the SGWB at largest wavelengths (smallest frequencies)⁶. Examples of inflationary^{9,10}, cosmic strings^{4,5,15,16}, and pre-Big-Bang^{11–13} models are also shown (the amplitude and the spectral shape in these models

Future development plans



green - comm & oper. 2d-detector generation

white - upgrade periods



-
- **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.

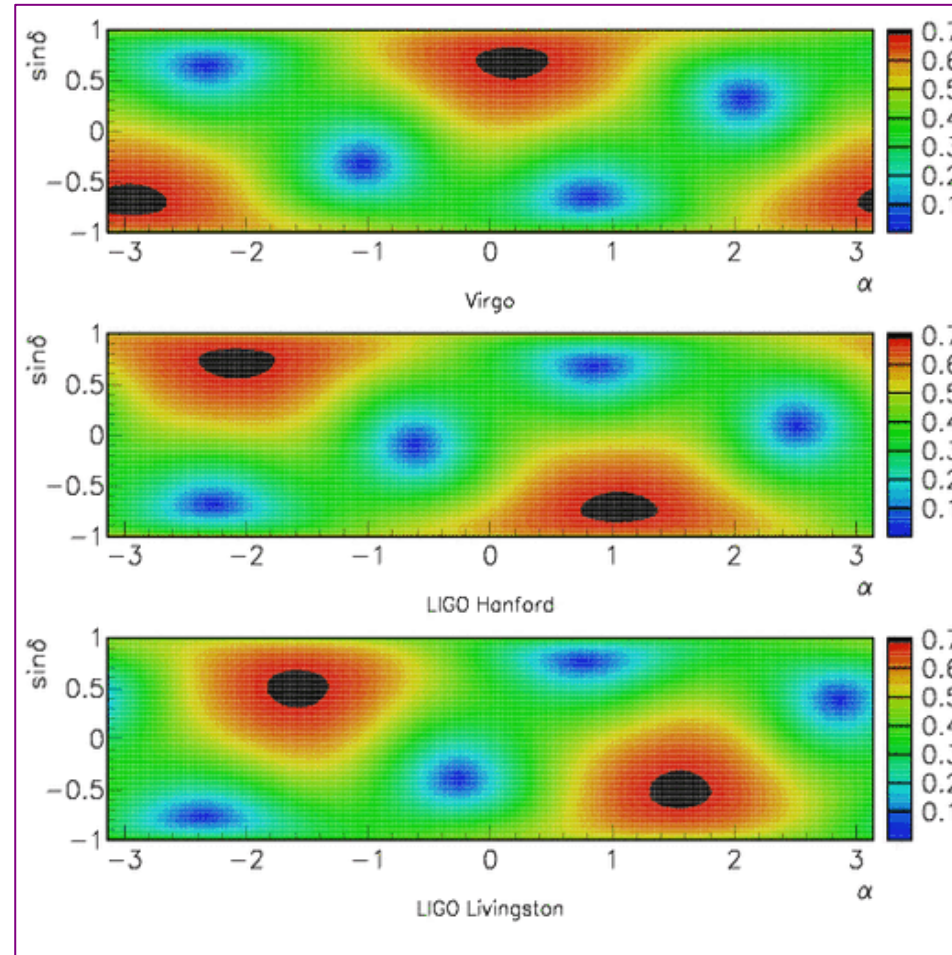


Fig. 2. The detection probability as function of the sky position when averaged over Earth daily rotation. The LIGO Hanford and Livingston show a good overlap while Virgo appears to be complementary making triple coincidences less probable.

GW-experiment: News

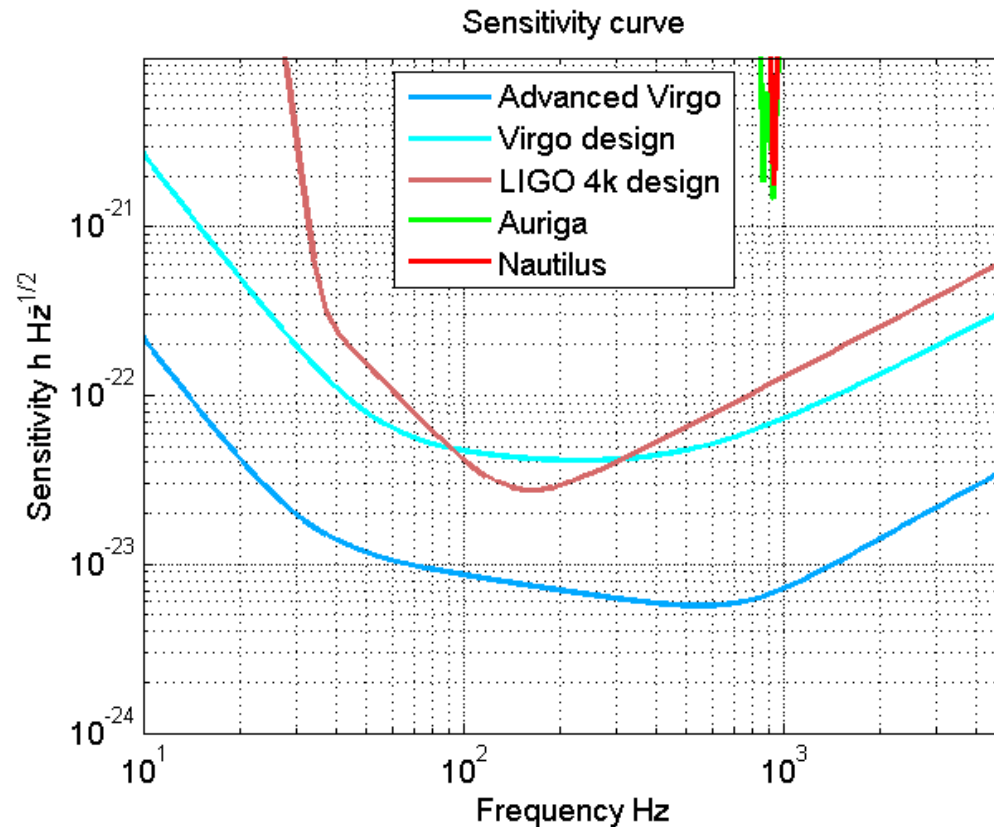


Fig. 1. Advanced Virgo sensitivity curve compared with Virgo and LIGO design and current bar sensitivity. Violin modes are not displayed for clarity

- Thanks for attention !
but
sorry for a taking your time

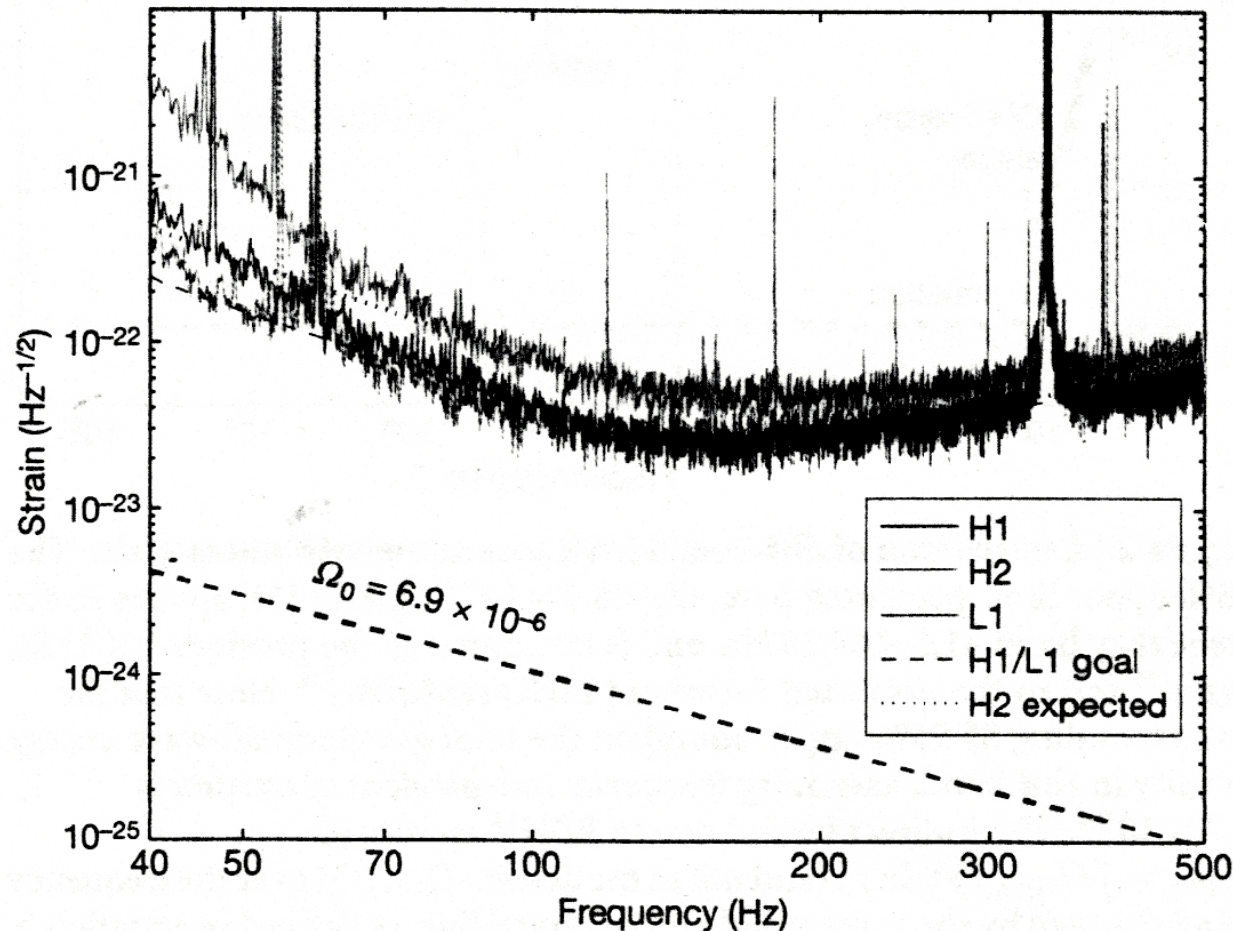


Figure 1 | Sensitivities of LIGO interferometers. LIGO interferometers reached their design sensitivity in November 2005, resulting in interferometer strain noise at the level of 3×10^{-22} r.m.s. in a 100 Hz band around 100 Hz. This figure shows typical strain sensitivities of LIGO interferometers during the subsequent science run S5. Also shown is the strain amplitude corresponding to the upper limit on the gravitational-wave energy density presented in this paper (grey dashed line). Note that this upper limit is ~ 100 times lower than the individual interferometer sensitivities, which illustrates the advantage of using the cross-correlation technique in this analysis.

ROOM-TEMPERATURE GRAVITATIONAL BAR-DETECTOR WITH CRYOGENIC LEVEL OF SENSITIVITY¹

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Received 30 October 1995

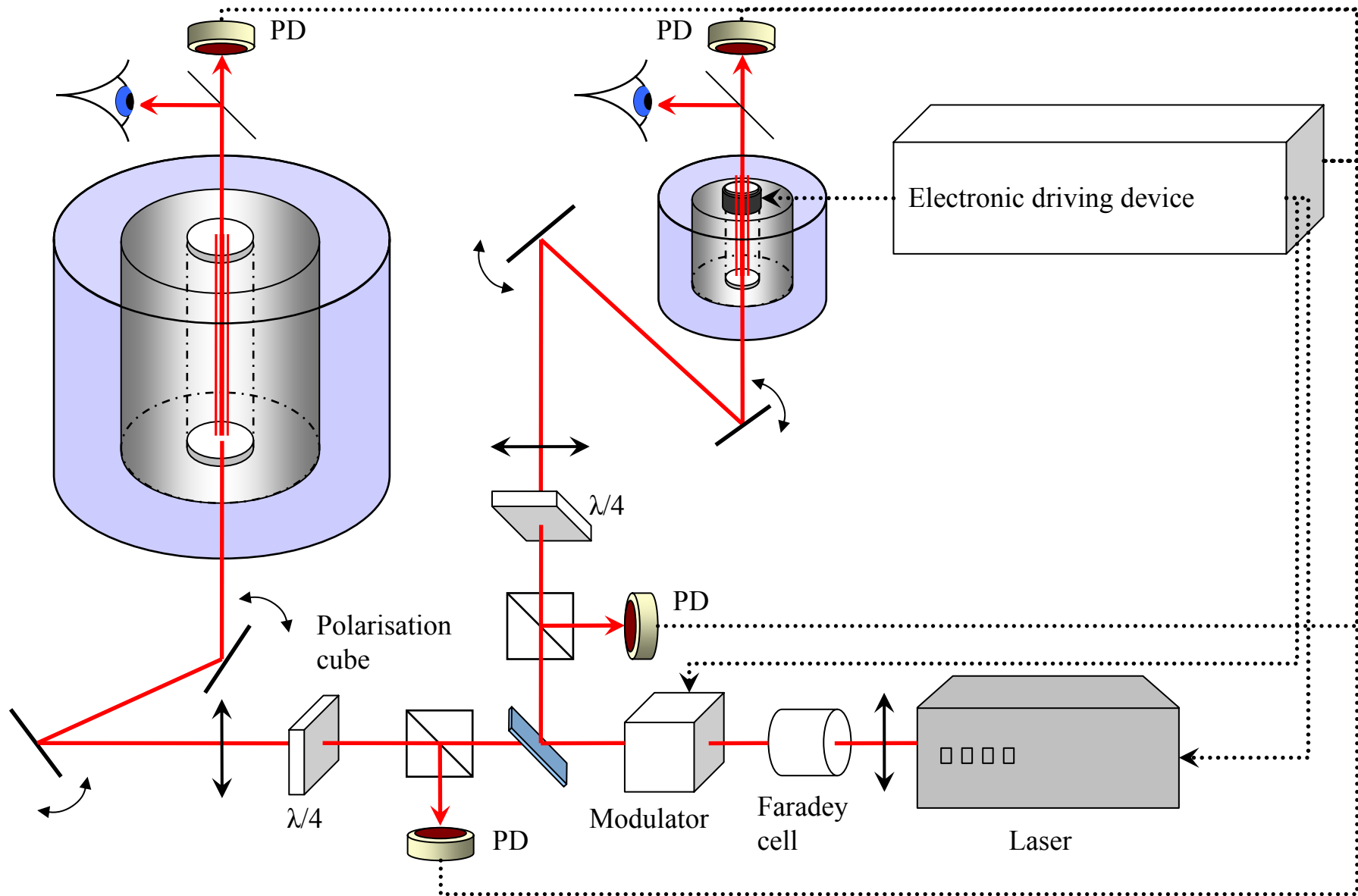
A possibility of achieving a sensitivity level of $h \simeq 10^{-18}$ in terms of metric perturbation for a room-temperature gravitational bar antenna is discussed. Two modern types of transducers with extremely small back action are analyzed: a tunnel current probe and an optical readout system. A small back action of the transducers allows one to increase the transducer coupling with the bar acoustic mode through a displacement transformer and results in a sensitivity improvement.

Program:	start 2005 - OGRAN project as a collaboration:
Search for “rare events” in the Galaxy and close environment	INR RAS, ILP SB RAS, SAI MSU
~ 100 Kpc	“room temperature opto-acoustical GW detector”
$h \sim 10^{-18}$	installation in the deep BNO INR underground
	Treaties with INFN Tor Vergata and LNGS

Argumentation of the OGRAN sensitivity and a perspective of improvement

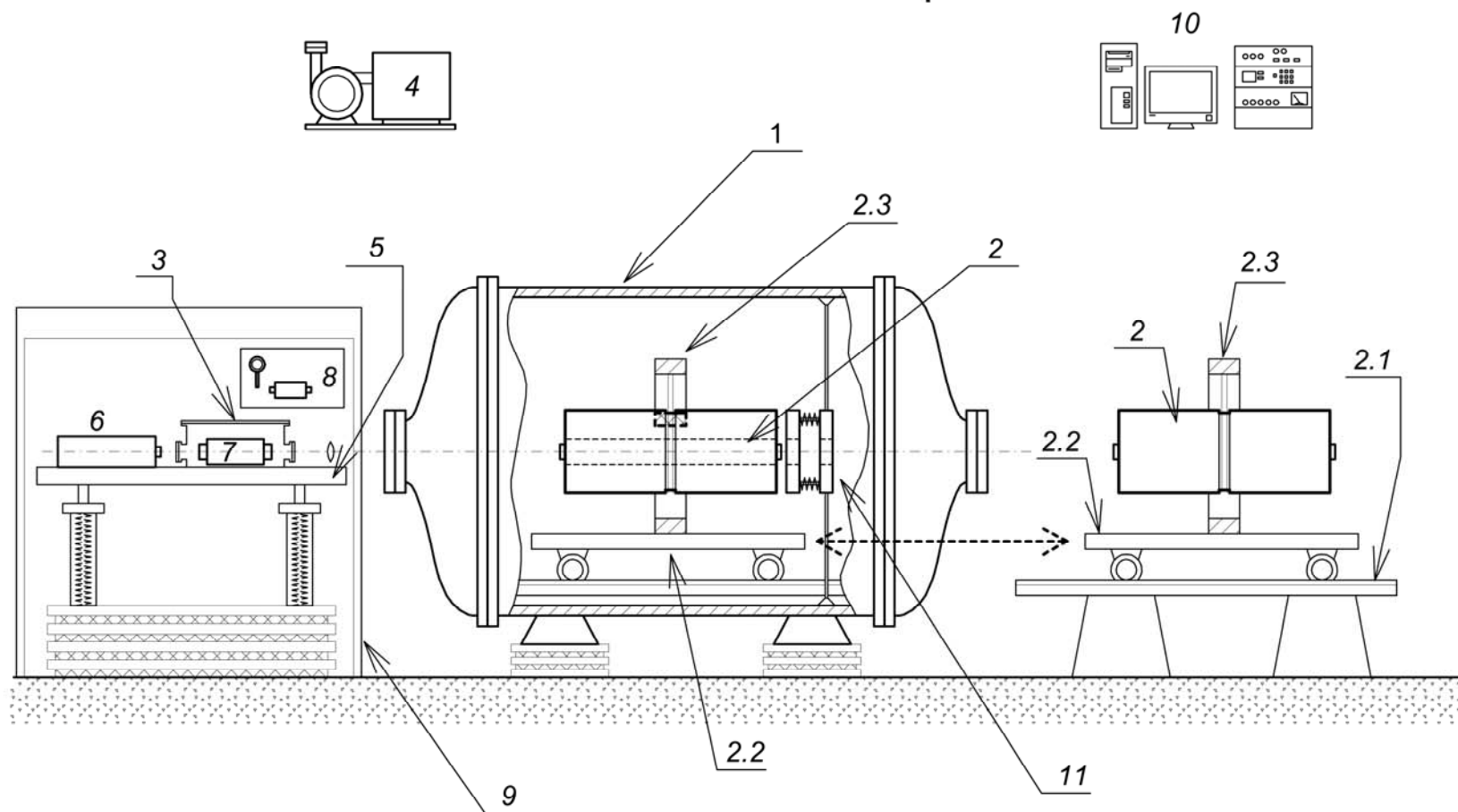
- Main issues:
- Due to the optical readout with small back action noise it is possible to achieve the sensitivity level $h \sim 10^{-19} \div 10^{-20} \text{ Hz}^{-1/2}$ without cooling the bar.
- With the bar cooled up to $T=10 \text{ mK}$ one can reach the sensitivity $h \sim 10^{-23} \text{ Hz}^{-1/2}$ in the bandwidth $\Delta f \sim 100 \text{ Hz}$

Principal scheme of the OGRAN setup



Composition of the OGRAN setup

ПРИНЦИПИАЛЬНАЯ СХЕМА РАСПОЛОЖЕНИЯ ЭЛЕМЕНТОВ ГРАВИТАЦИОННОЙ АНТЕННЫ



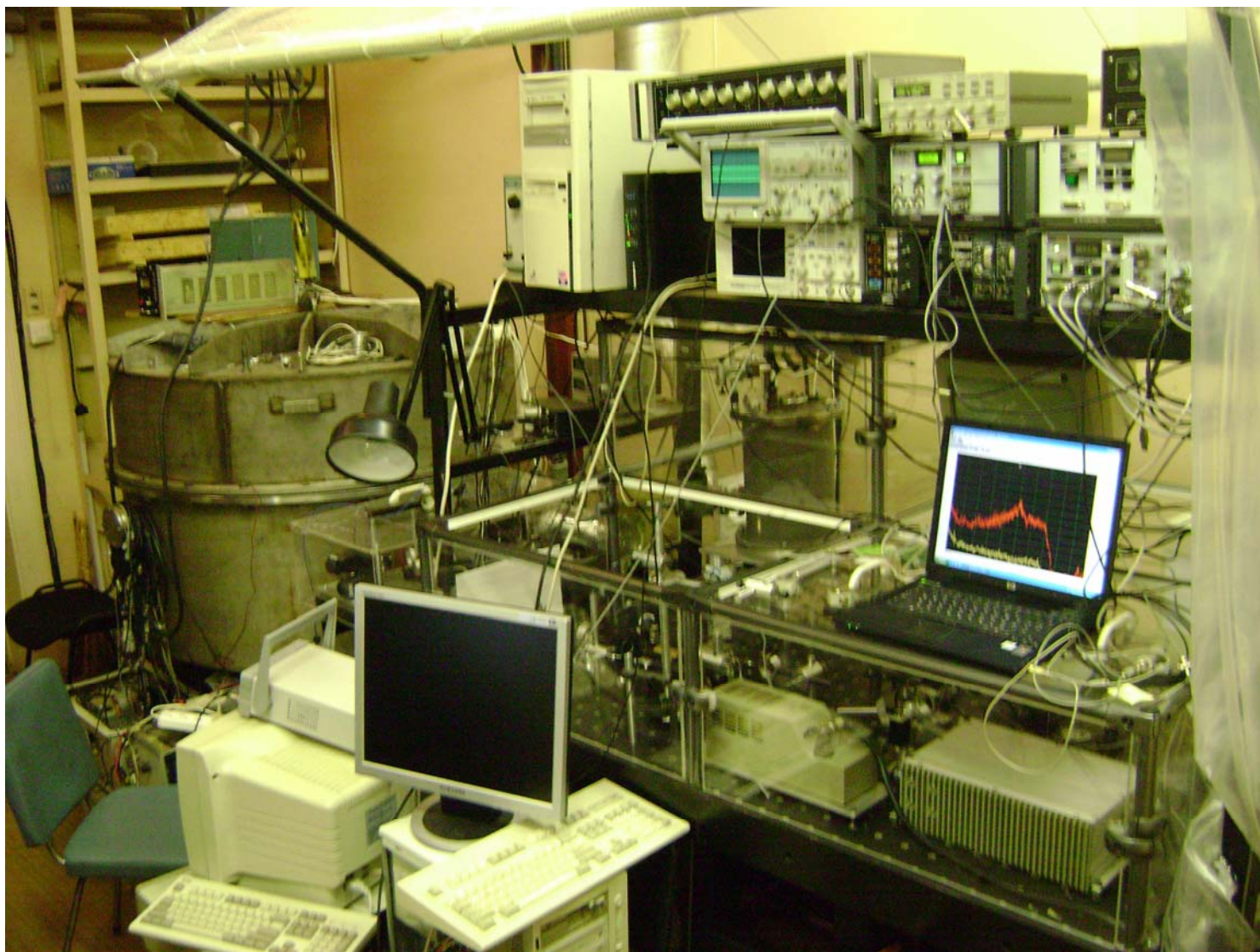
OGRAN bar (2,3 T) at the anti seismic suspension



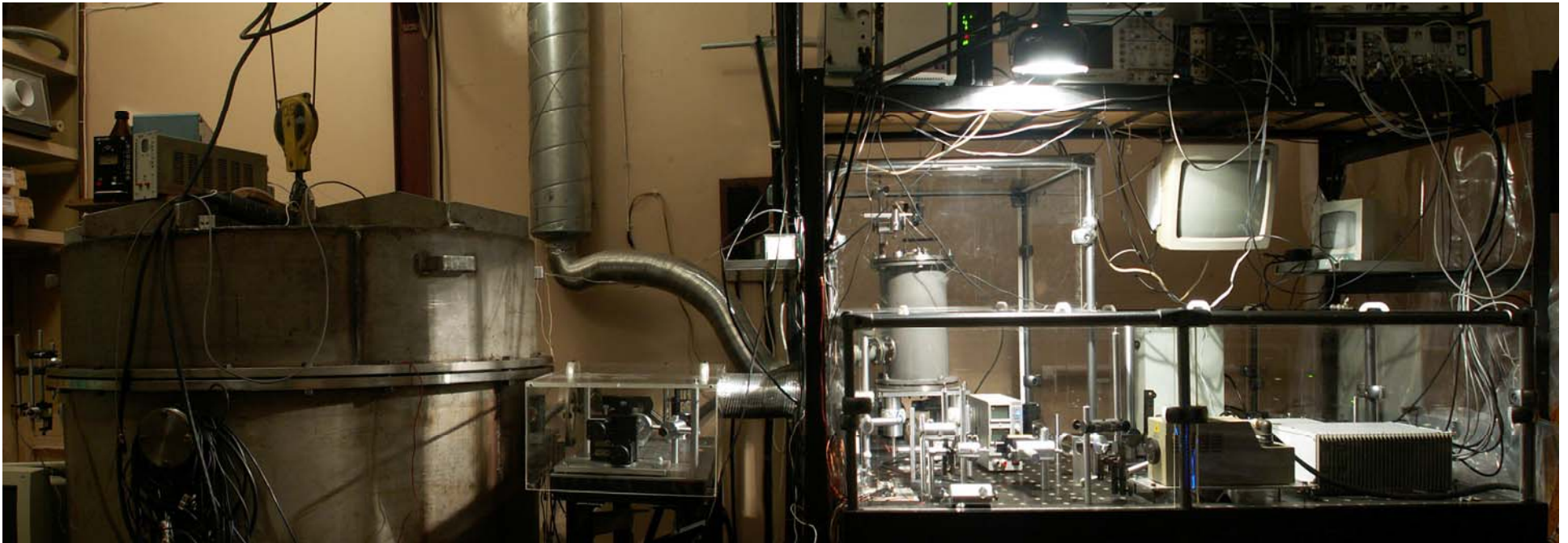
OGRAN chamber general view



Pilot setup

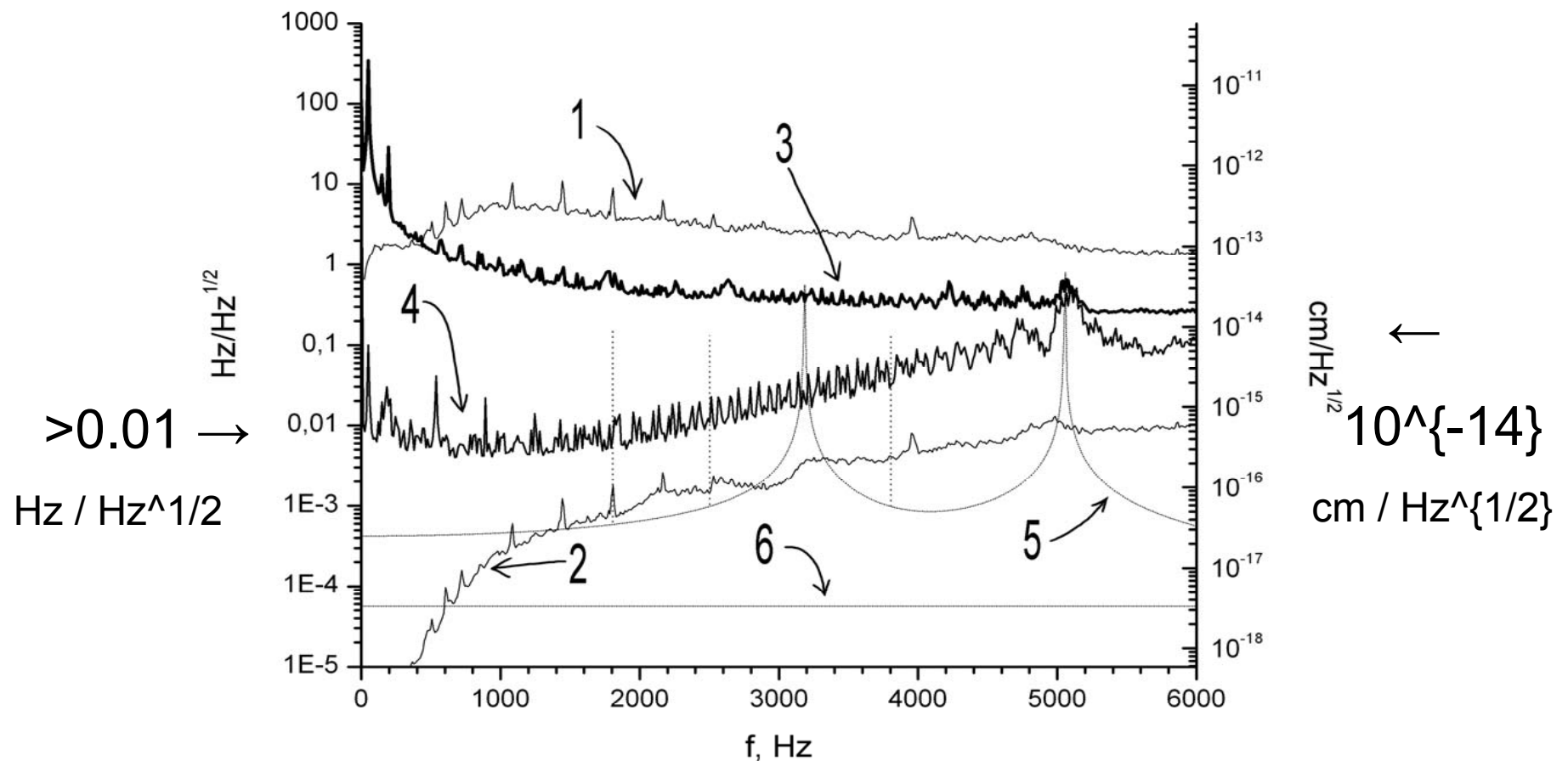


General view of the pilot model



BNO RAS: underground chamber for OGRAN install



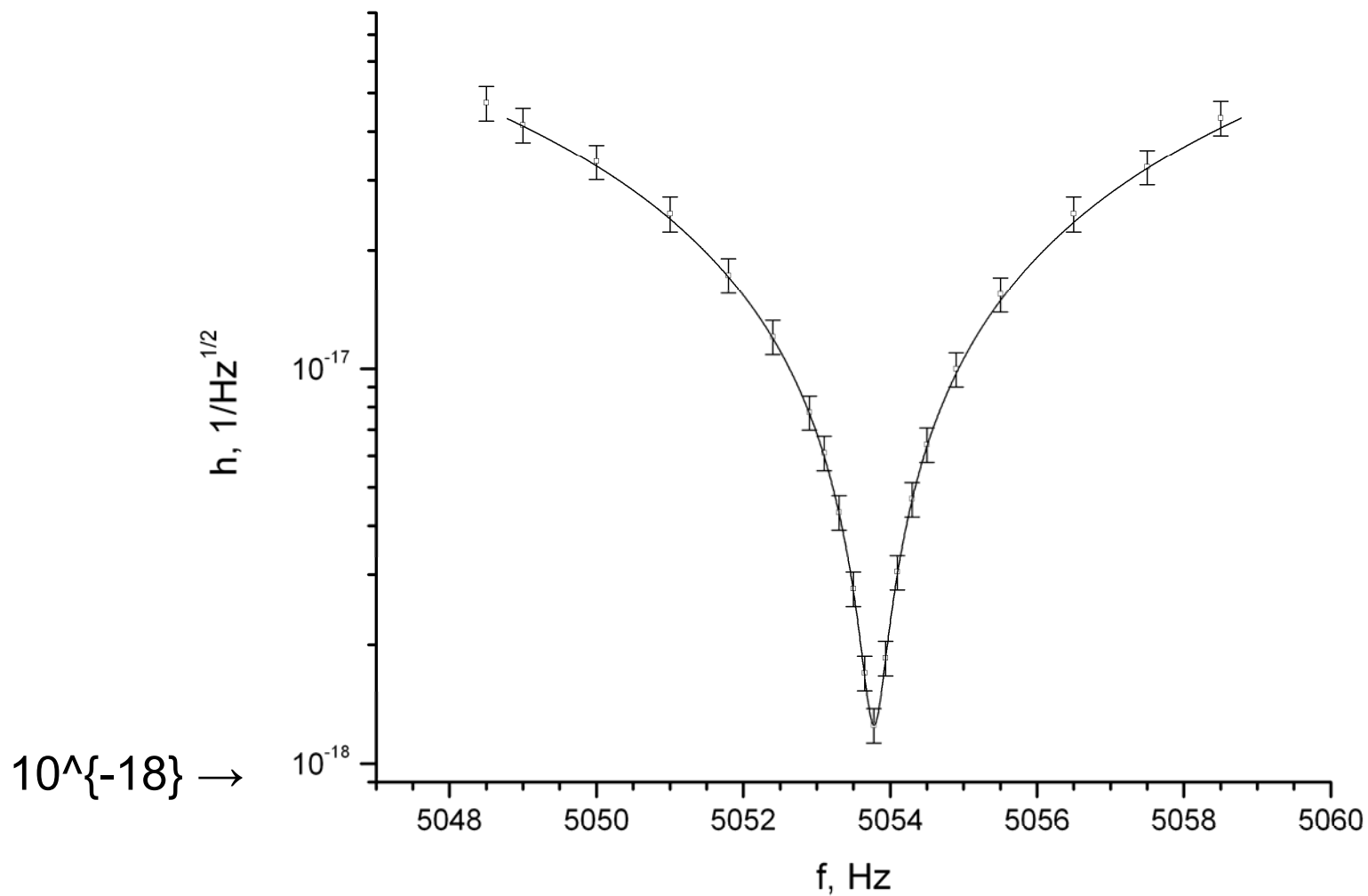


Noise spectral density:

1 - free laser noise; 2 – expected locked laser noise (theory)

3 – locked reference cavity noise; 4. locked detector cavity noise;

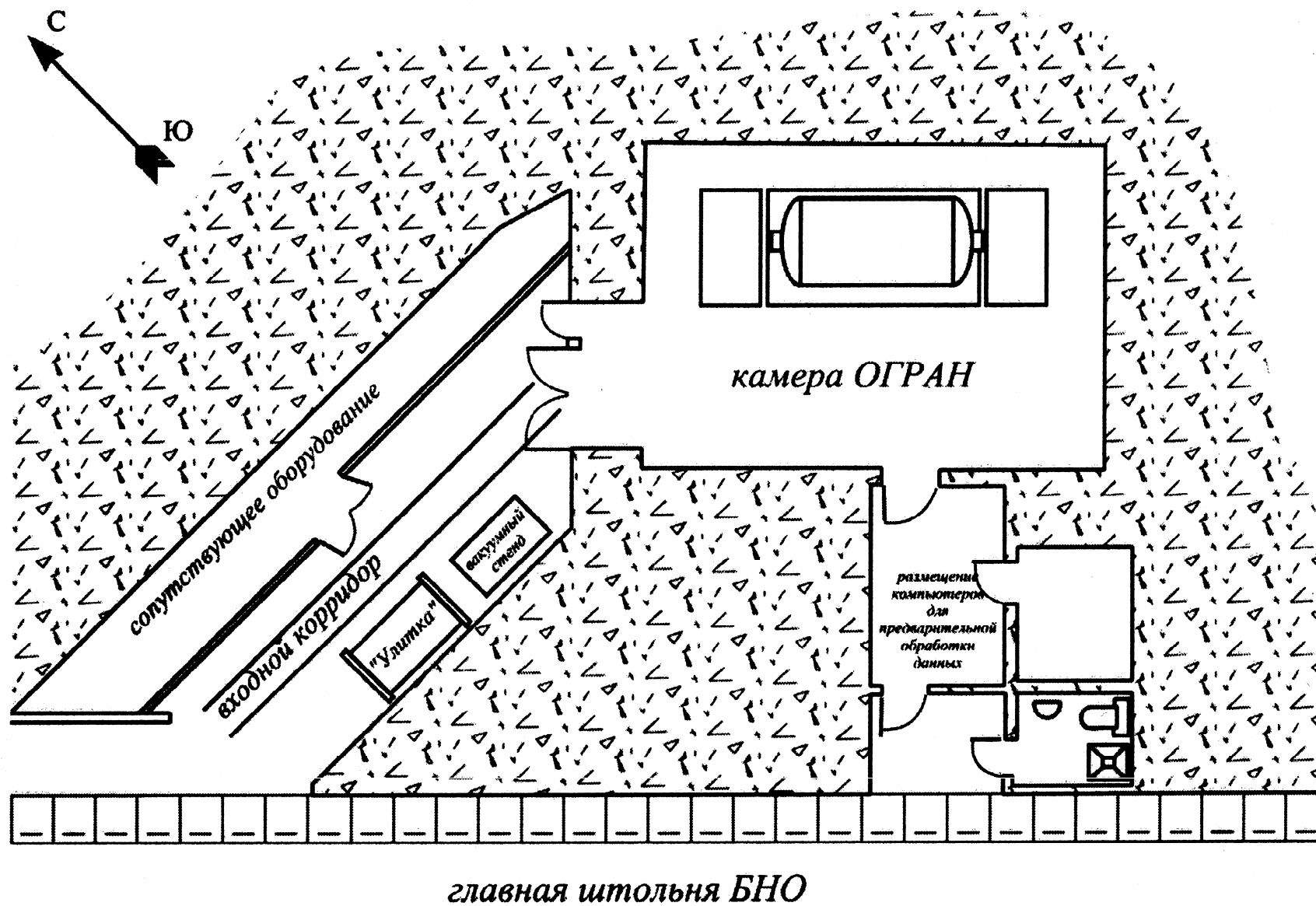
5. thermal noise; 6. optical shot noise

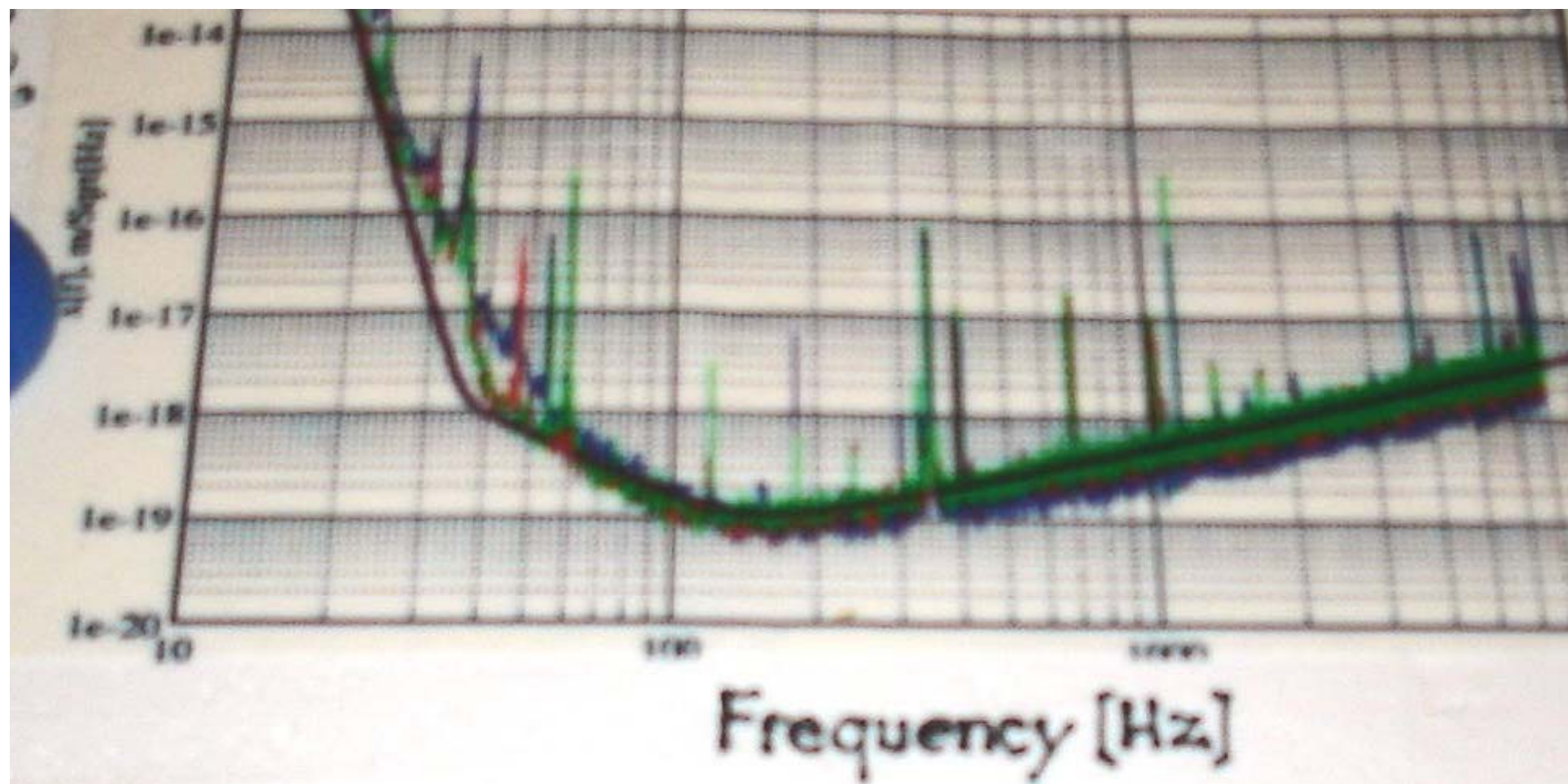


Pilot model sensitivity
reduced to the large detector parameters (2.5 T, 2,3 m)

OGRAN underground Lab disposition

(mark 1400 m along the tunnel)





WE DID IT !

Displacement Sensitivity of the LIGO Interferometers

Performance for S5 - May 2007 LIGO-G070367-00-E

