Wideband acoustic gravitational wave detectors at kHz frequencies: from AURIGA to DUAL

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AURIGA
www.auriga.lnl.infn.it

Caltech
Dec 12th 2005

LIGO-G050649-00-Z

as frequency increases > 1 kHz
signal amplitudes decrease, detector noises increase

but

gw sources in the kHz band

compact binaries mergers as "target signals"
out to > 100 Mpc (et alia…)

bars are kHz gw detectors (brief reminder)

SQL, bandwidth, antenna pattern, timing

AURIGA recent upgrades and performance

three modes operation and approaching the Standard Quantum Limit to widen the band

AURIGA and the Dec 27th 2004 SGR flare

DUAL

concept of a novel **wideband low spectral noise** acoustic gw detector based on massive resonators

QuickTime™ and a
Sorenson Video decompressor
are needed to see this picture.

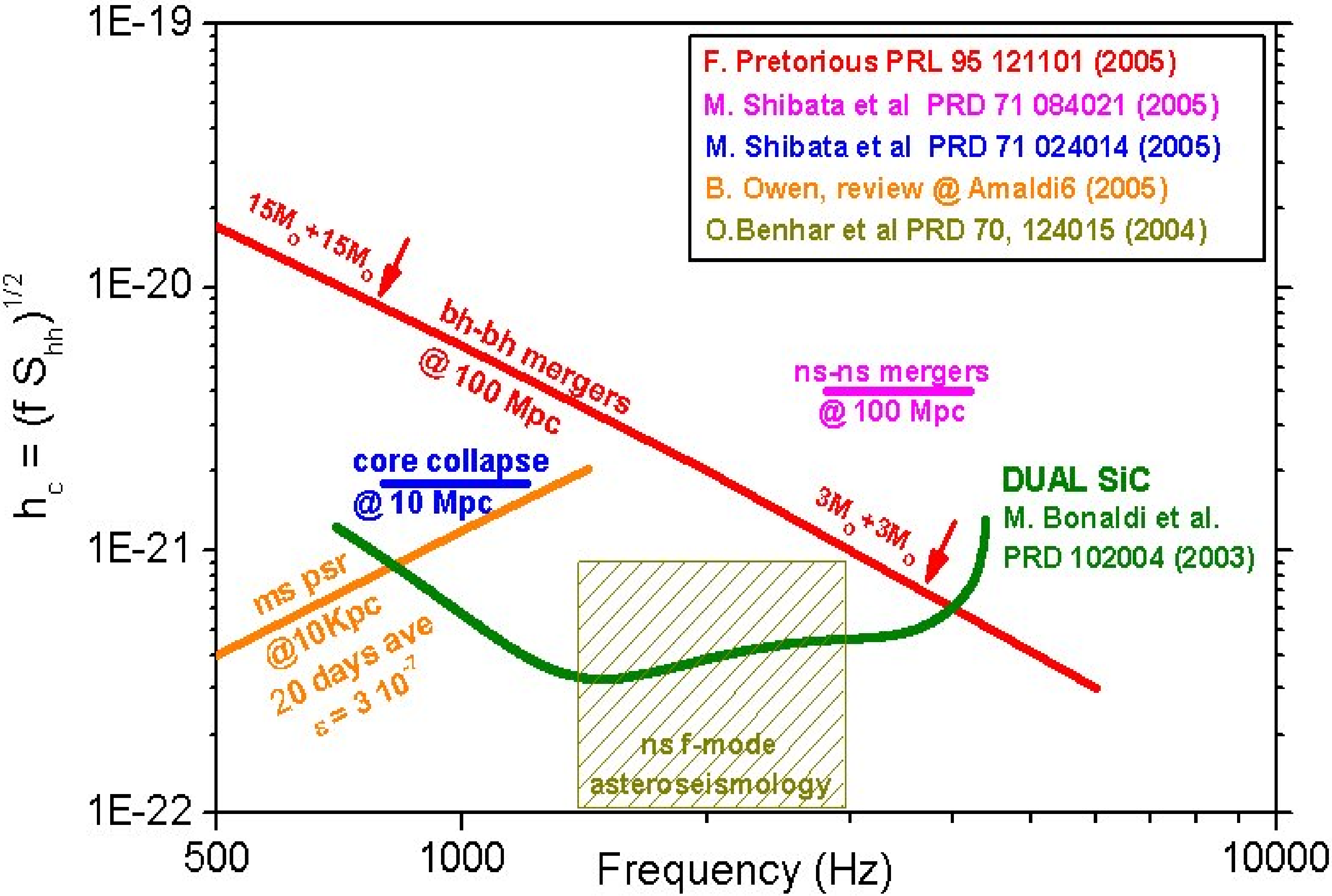
the “perfect” detection

@ 100 Mpc a ns-ns binary coalesces *(short GRB ?)*

LIGO Advanced sees the inspiral and predicts the time of plunge

DUAL gets at the right time the vibrations of the merged object somewhere 2 kHz to 5 kHz

(depending on EOS)



"characteristic" gw strength $h_c = hn^{1/2}$ for gw of amplitude h lasting n cycles
all sources at best orientation (DUAL is fairly isotropic)
expected rate> 3 ev/y for ns-ns mergers

gw sources in the kHz band for DUAL

(after recent progress in fully general relativistic simulations in 3-D with realistic nuclear Equation Of State)

cosmological (> 3 events/year: the "target" signals for DUAL)

- merging of binary neutron stars & vibrations of remnant
  quasi periodic oscillations @ 3-4 kHz depending on EOS
  formation of black-hole depending on EOS ***(Shibata PRL 2005)***
  both out to 100 Mpc ***(short GRBs as ns-ns mergers: Nature 2005)***
- merging of binary black-holes & vibrations of remnant
  15+15 M_O to 3+3 M_O out to 100 Mpc
  (Pretorious PRL 2005; Campanelli et al 2005)

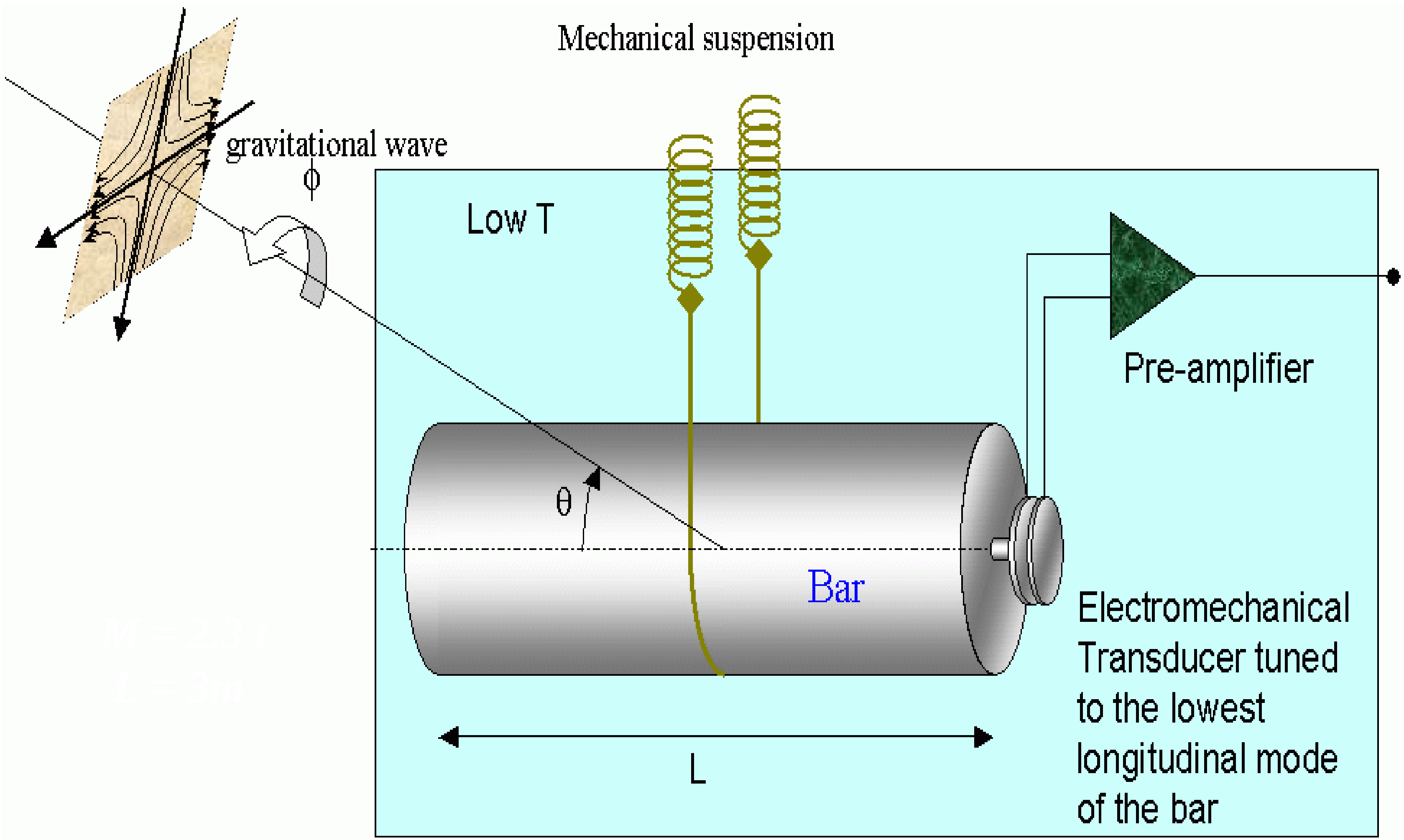
Virgo cluster (many events/year ?)

- (fast rotating) stellar core collapses *(supernovae)*
  "bar mode" instabilities @ 1 Khz out to 10 Mpc ***(Shibata PRD 2005)***

galactic

- fast rotating isolated ns *(ms PSR)* & accreting ns *(LMXB)*
  continuous emission, X-ray flares out to 10 kPc ***(Owen 2005)***
- "gravitational wave asteroseismology of neutron stars" ?
  (Kokkotas PRD 2004, Benhar PRD 2004, Tsui PRL 2005)

“bar” gw detectors



"bars" at the Standard Quantum Limit

detect few quanta of vibration in a 2.3 tons oscillator

need:

- wide detection bandwidth **$\Delta f \sim 100$ Hz**,
- large **$Q/T \sim 10^8$ K^{-1}**
- a quantum limited amplifier: SQUID, optical,...

$T \sim 0.1$ K, $Q \sim 10^7$

where are we ?

$f \sim 930$ Hz
$\Delta f \sim 100$ Hz
$Q \sim 5\ 10^6$

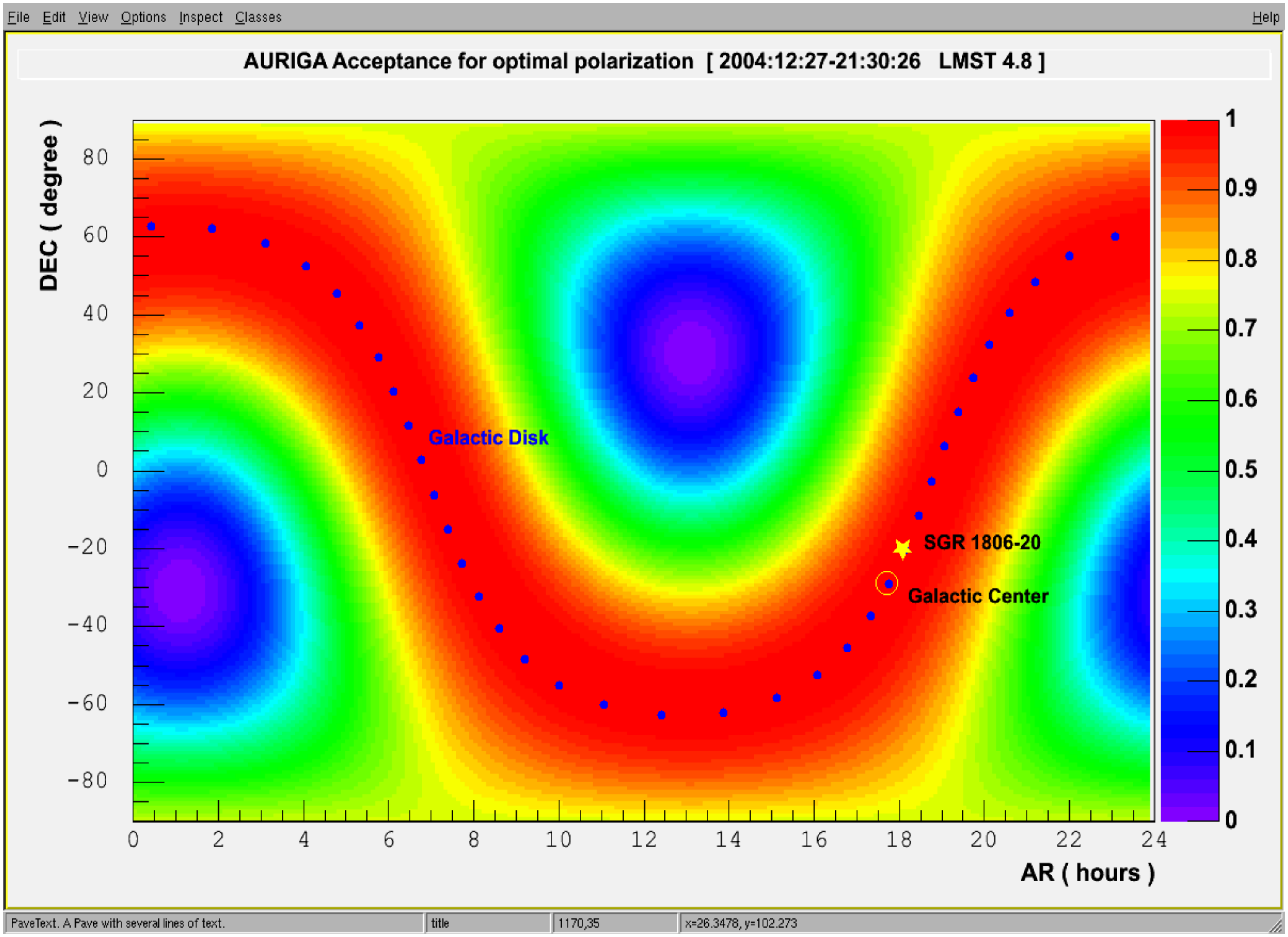
AURIGA @ 4.5 K $\Delta E_{absorbed} \sim 500$ quanta

AURIGA @ 0.1 K $\Delta E_{absorbrd} \sim 10$ quanta

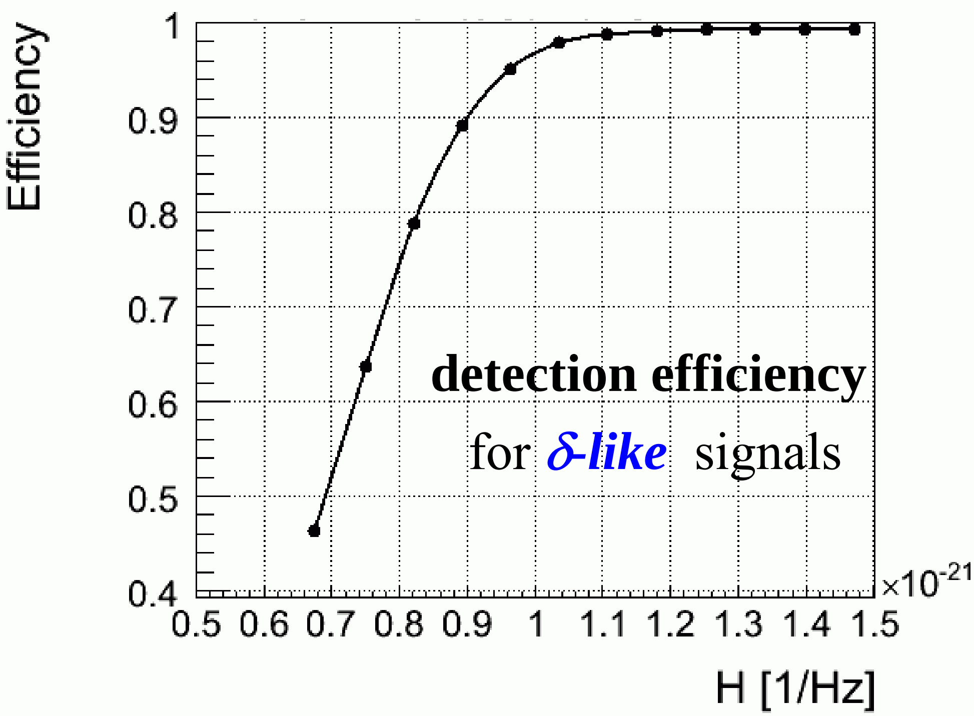
$$h_{SQL} \sim 3\ 10^{-21}$$

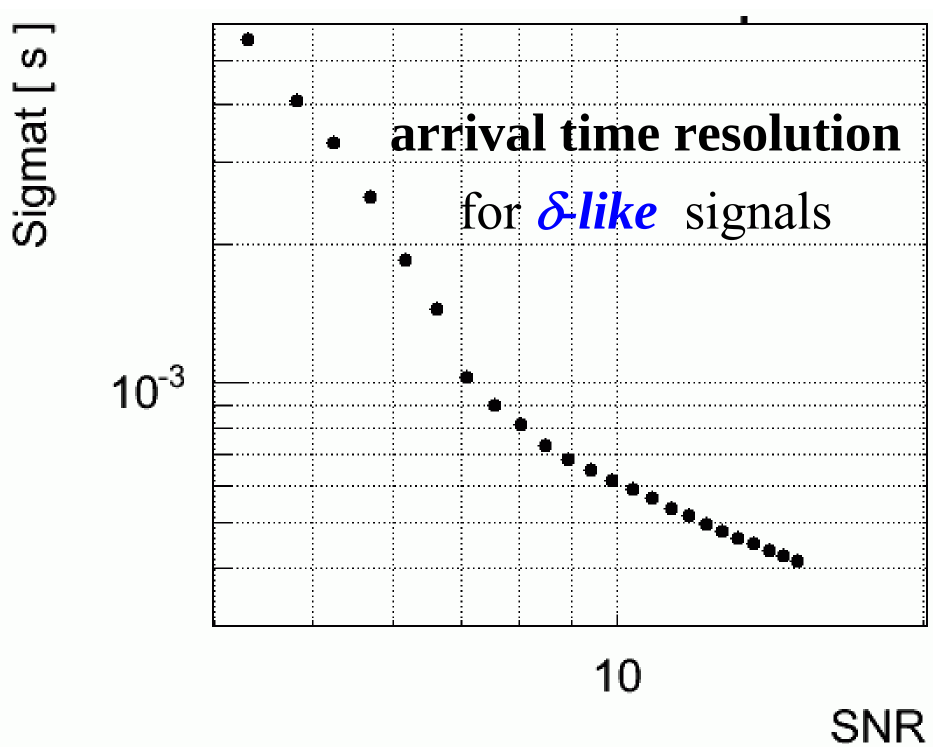
$sen^2\theta \cos 2\psi$

Antenna pattern



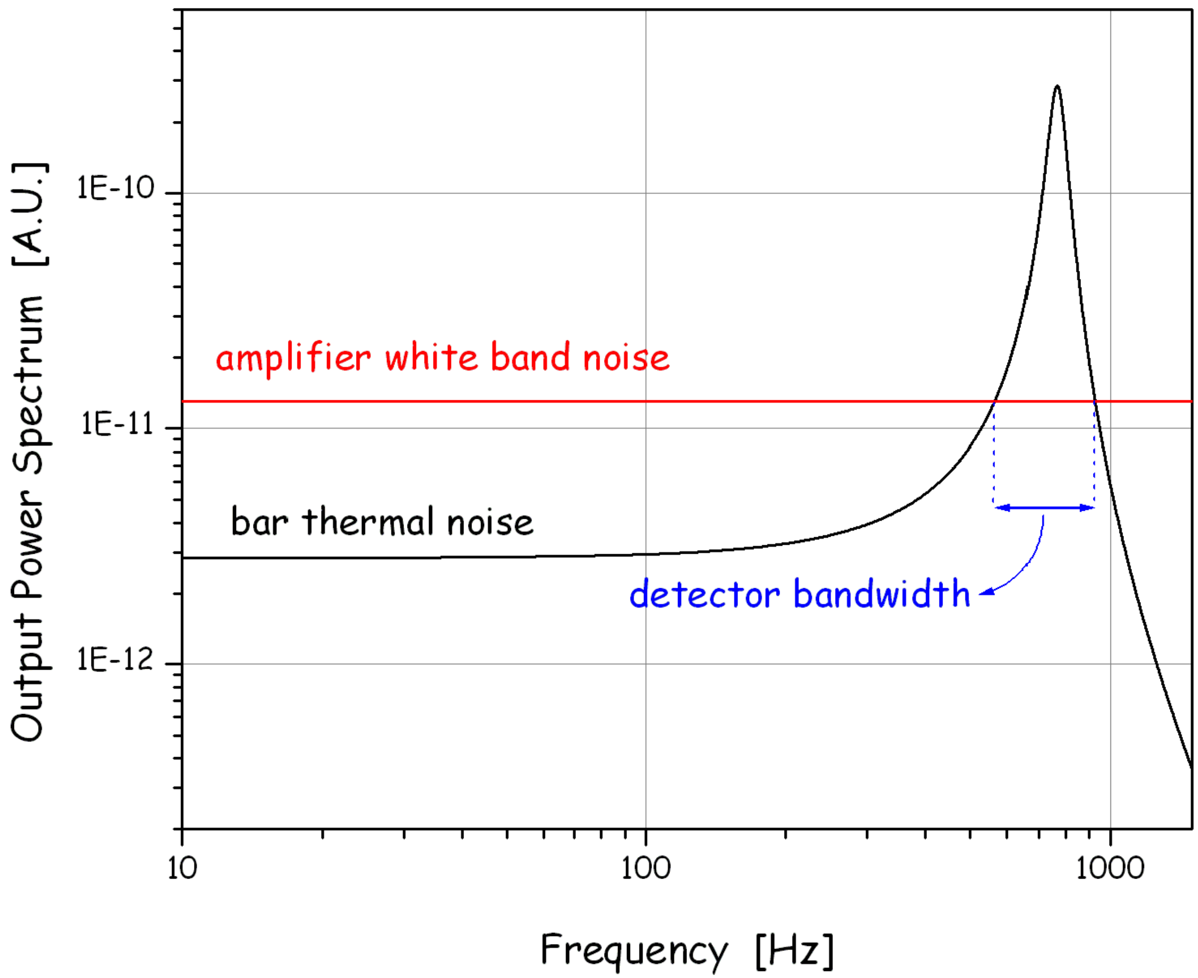
- **measure detection efficiency** by Monte Carlo injections of software signals
- *crucial to cross-validate detectors in a network*





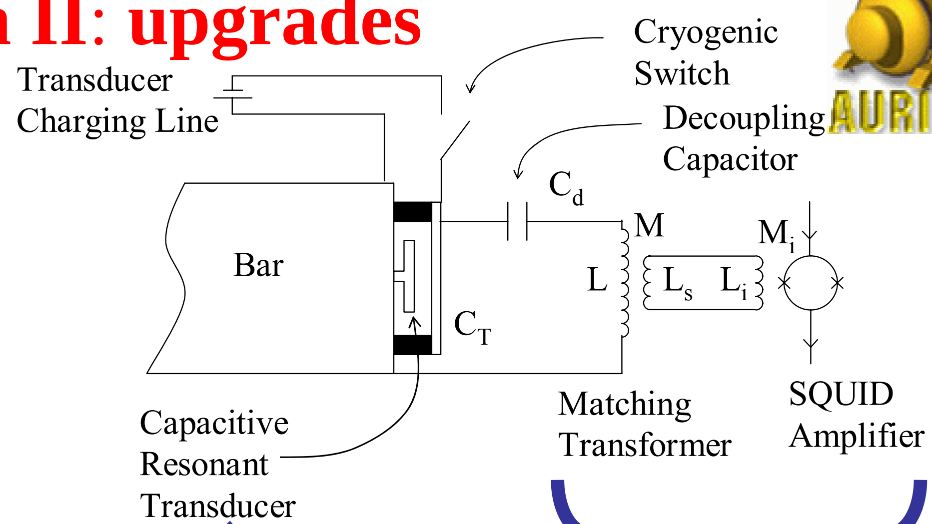
- **submillisecond arrival time resolution for SNR > 7**
- *crucial to check travel speed of the gw and to locate the source*

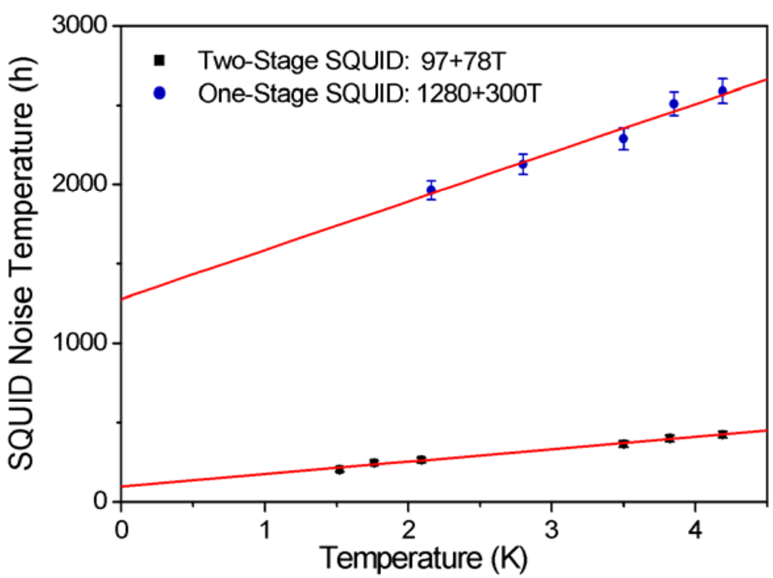
the bandwidth is potentially infinite

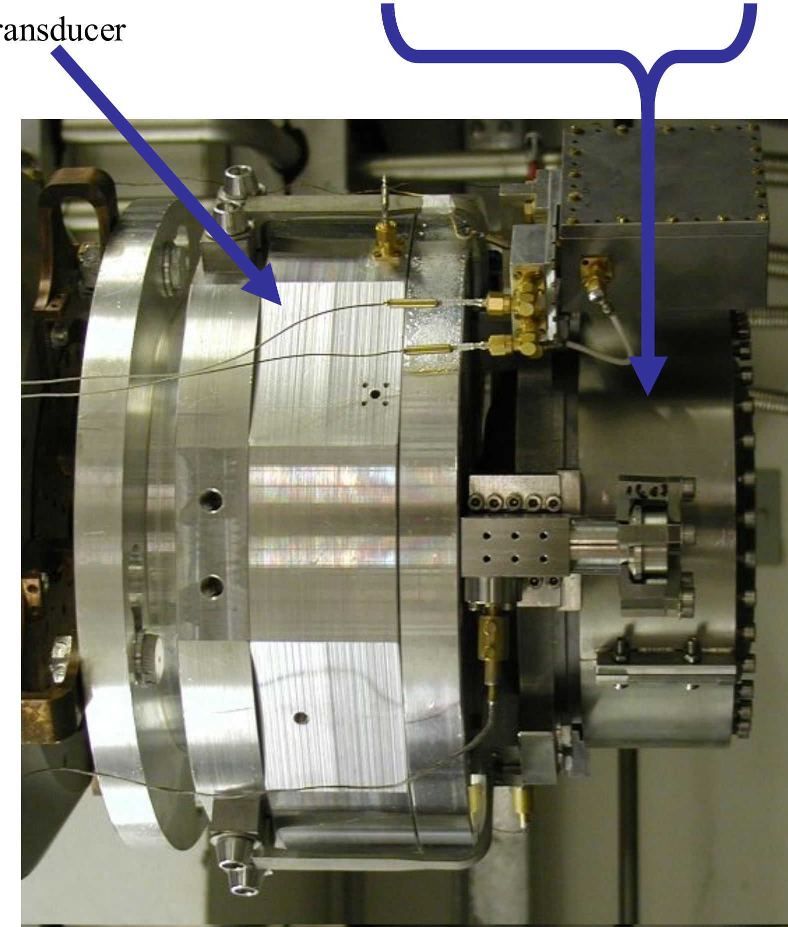


AURIGA run II: upgrades

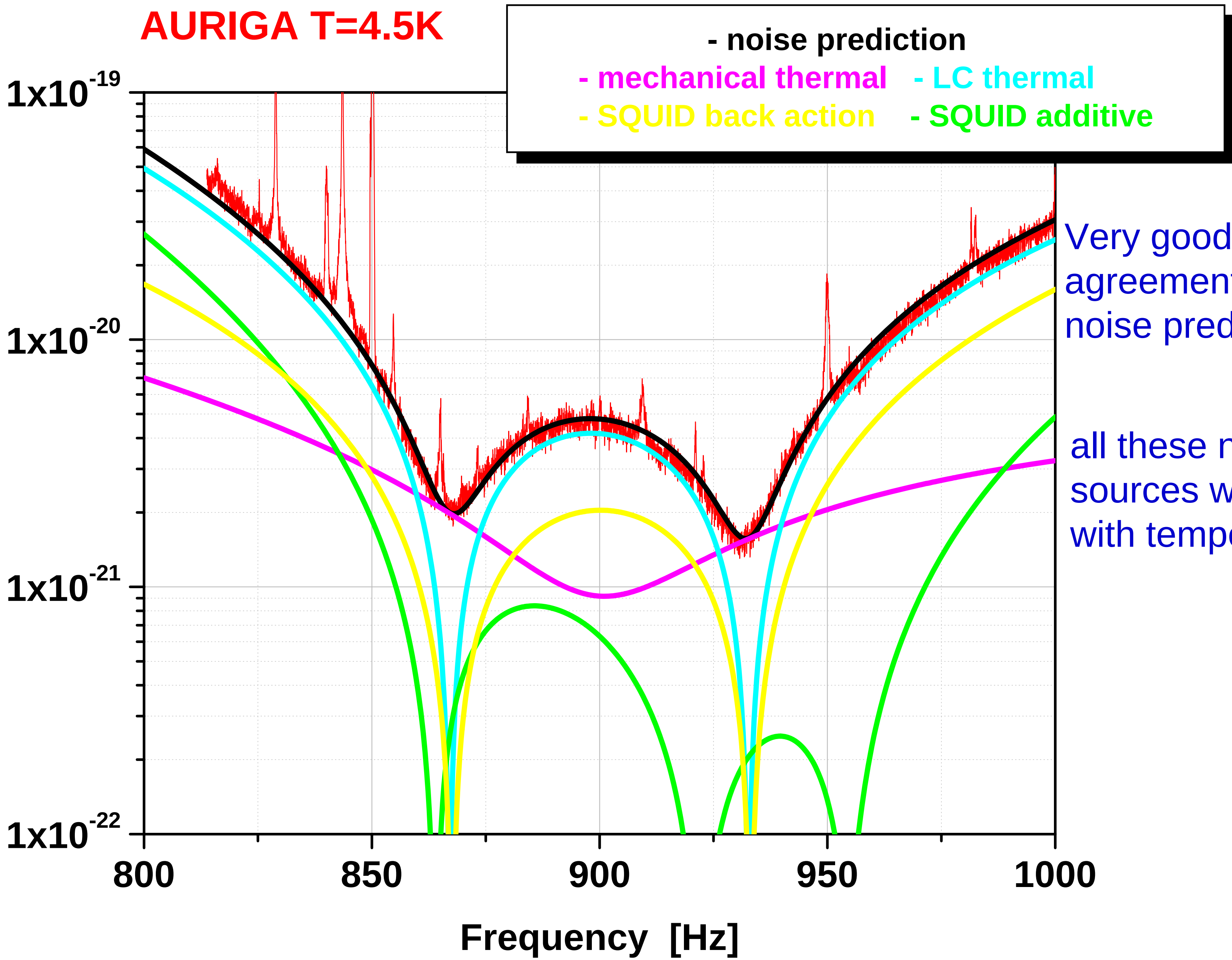
- **three resonant modes operation:**
  - two mechanical modes
  - one electrical mode
- transducer bias field 8 MV/m
- **new SQUID amplifier :**
  - double stage SQUID
  - ~500□ energy resolution at 4.5 K in the detector





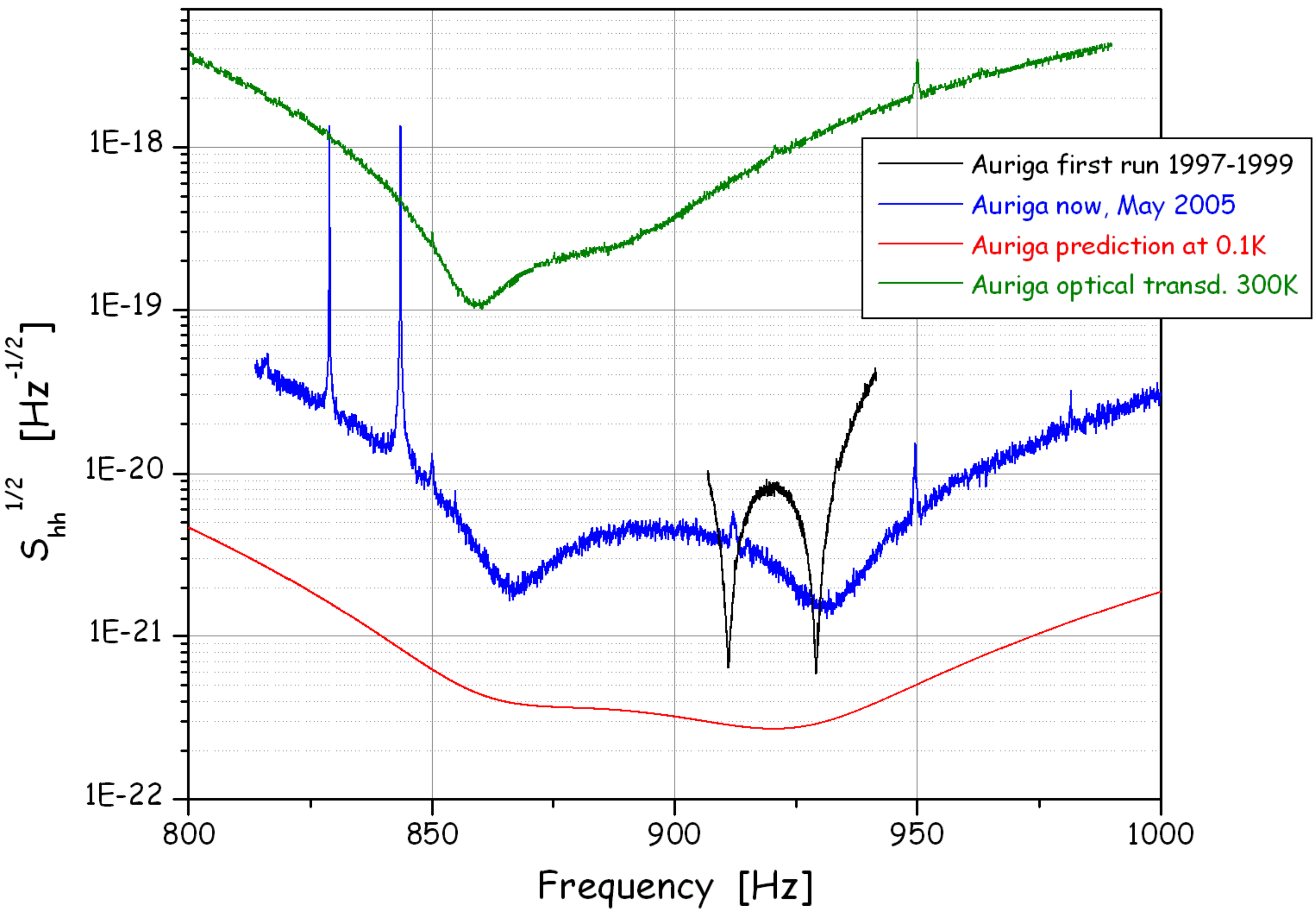


S_{hh} sensitivity
one-sided S_{hh}



Very good agreement with noise predictions

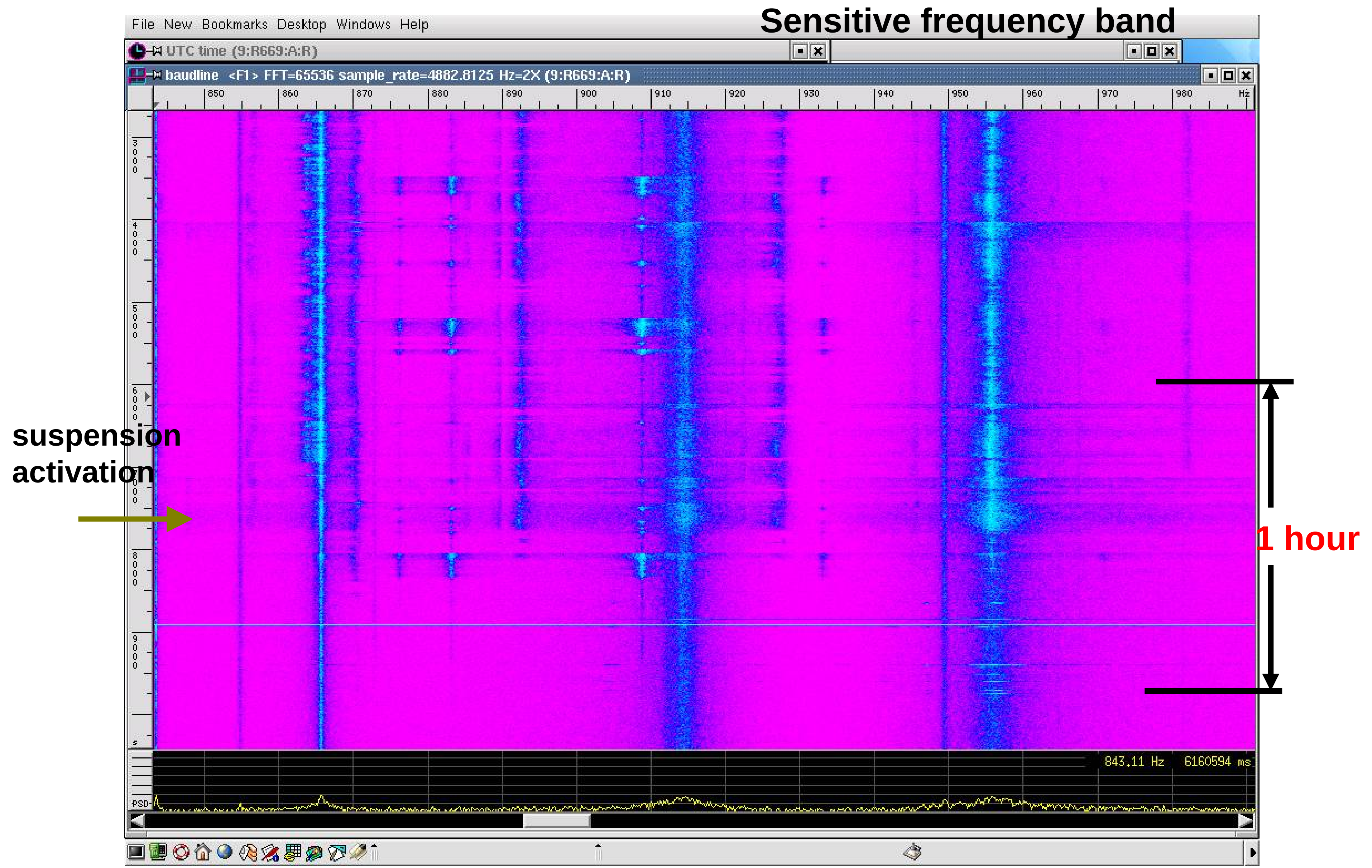
all these noise sources will scale with temperature



Auriga first run 1997-1999
Auriga now, May 2005
Auriga prediction at 0.1K
Auriga optical transd. 300K
1E-18
1E-19
1E-20
1E-21
1E-22
800
850
900
950
1000
Frequency [Hz]
$S_{hh}^{1/2}$ [$Hz^{-1/2}$]

AURIGA

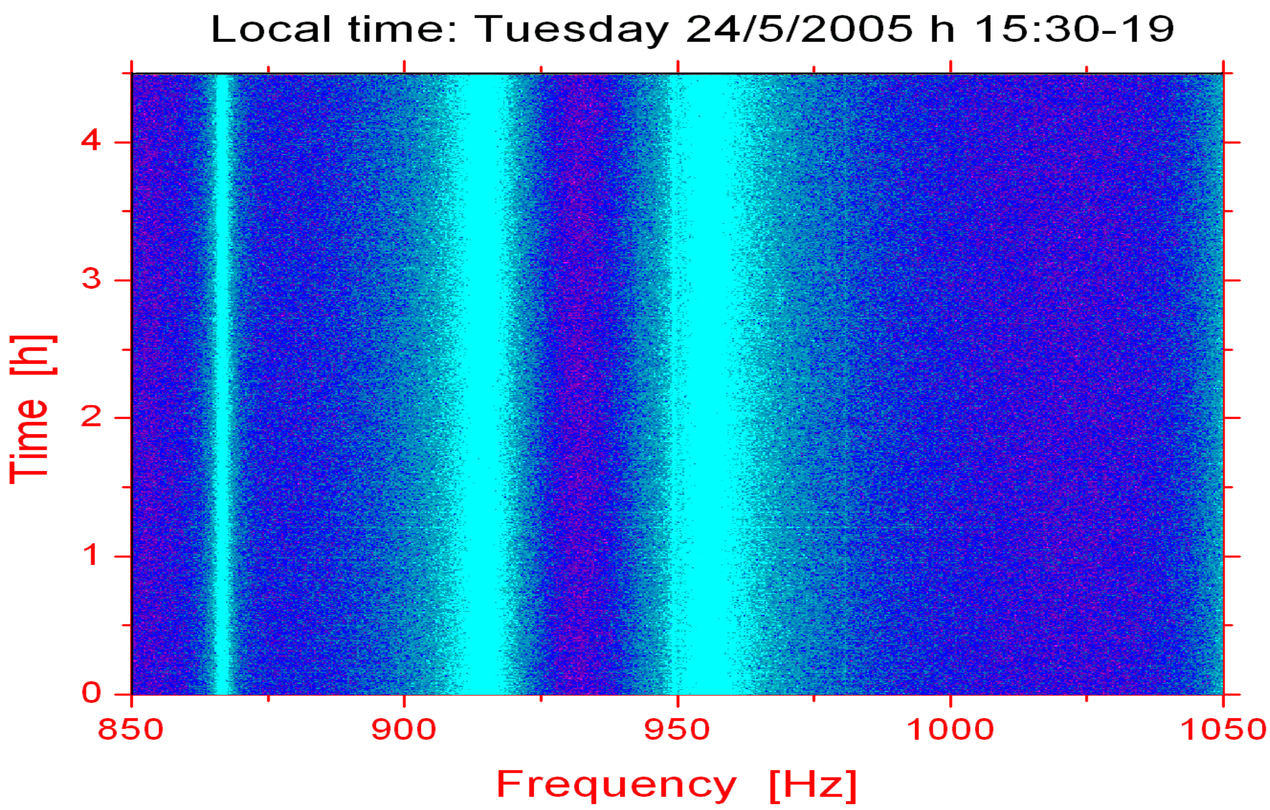
LF suspensions upgrade: on-line effect (May 19th)



welding the "wings"
to position AURIGA on the pillars

May 19th 2005
AURIGA on the dampers

the three modes of AURIGA as they keep clean and stable in time

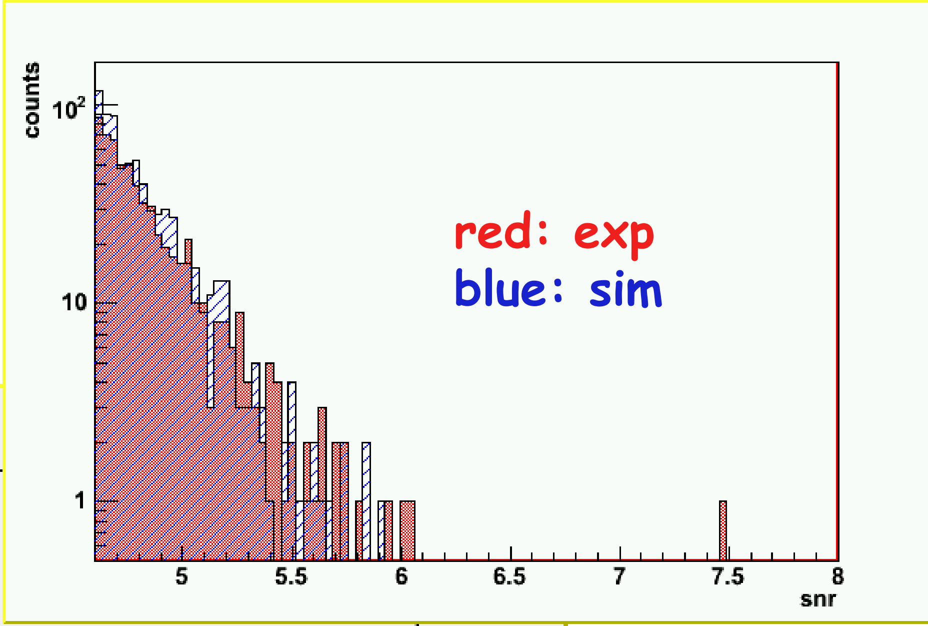


AURIGA II run

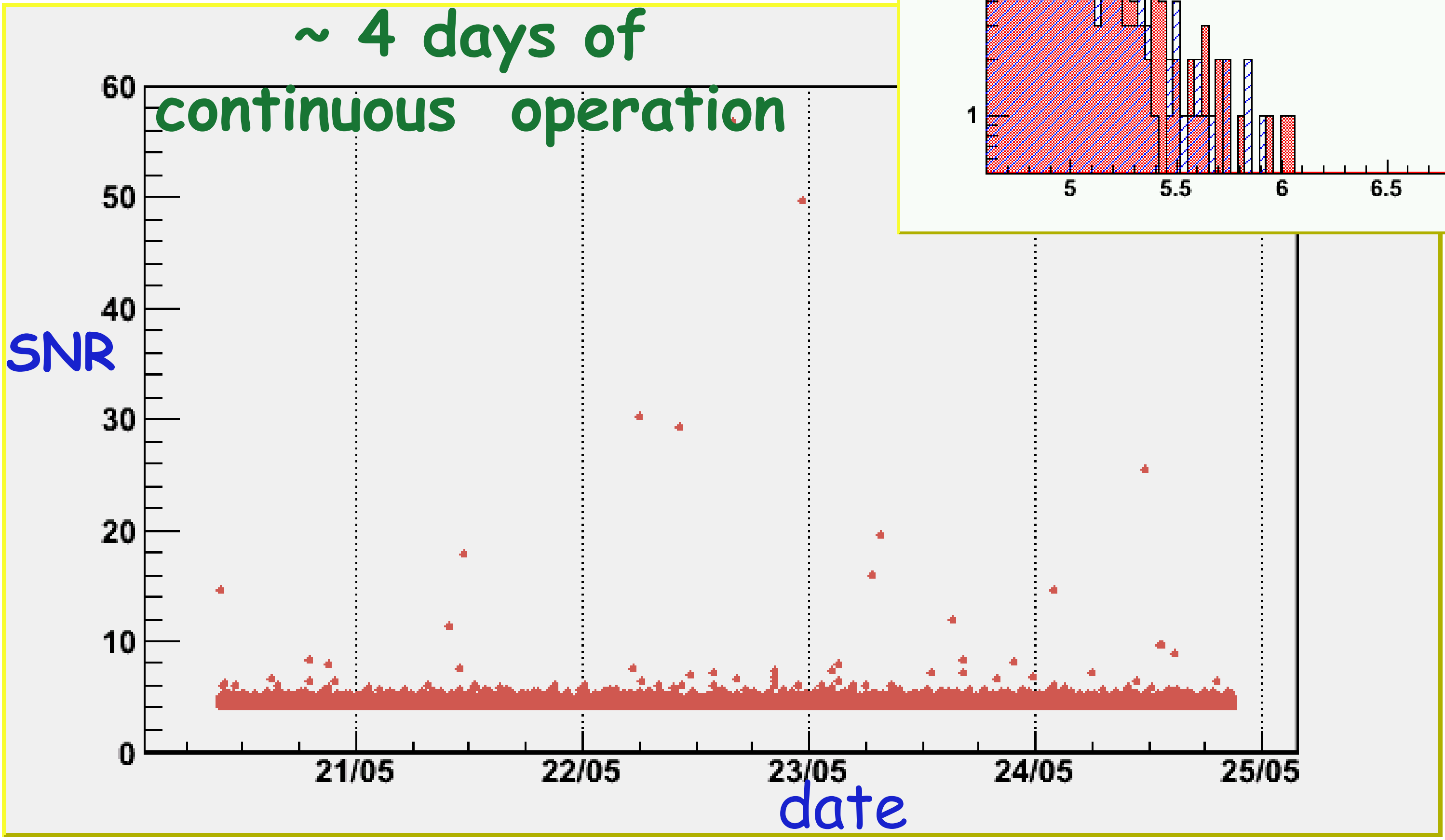
stationary gaussian operation of a wideband "bar" detector

- the 3 modes thermal at 4.5 K
- $S_{hh}^{1/2} < 4\ 10^{-21}\ Hz^{-1/2}$ over 90 Hz band (one sided)
- ~ 100% operation for acquisition of usable data
  (except 3hours/month > He transfer)
- veto time intervals under out-of-band triggers to select against epochs of external disturbances
- reduce (for bursts) to ***stationary gaussian*** operation over ~ 98 % duty cycle

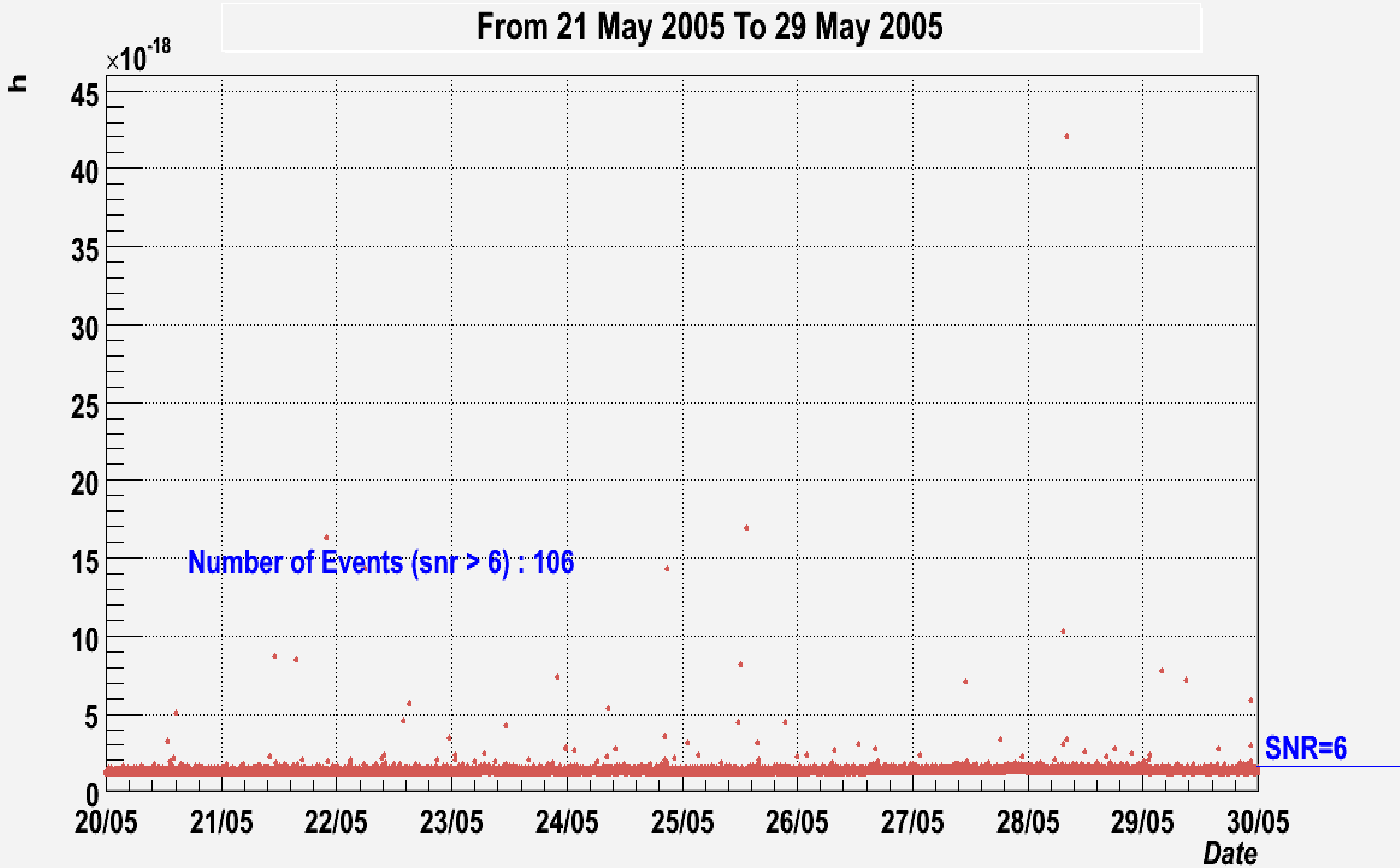
P.Falferi et al, “3-modes detection…”
Phys.Rev.Letters 2005
M.Bonaldi et al,“AURIGA suspensions…”
Rev. Sci. Instr. 2005
A.Vinante et al, “Thermal noise in a…”
Rev. Sci. Instr. 2005



~ 4 days of continuous operation



duty cycle ~ 98%



From 21 May 2005 To 29 May 2005
×10^-18
h
45
40
35
30
25
20
15
10
5
0
Number of Events (snr > 6) : 106
SNR=6
20/05
21/05
22/05
23/05
24/05
25/05
26/05
27/05
28/05
29/05
30/05
Date

current astrophysical observations

AURIGA alone:

- upper limits related to astronomical triggers
  - L.Baggio et al. (*giant flare of SGR1806-20)*, **PRL 95**, 081103 (2005)
- search for quasi-periodic gw from NS in binary systems (LMXB)

AURIGA in network:

- IGEC-2 network of the 4 operating resonant bars
  - search for bursts gw, long term observations
- AURIGA-LIGO
  - burst gw search (methodological phase)
- VIRGO&INFN bars network
  - burst and stochastic background search (methodological phase)
- AURIGA-TAMA (just started)

The Dec. 27th 2004 giant flare of the soft gamma ray repeater SGR1806-20

- on a ~ 10 kpc distance scale in the direction of Sagittarium
- 100 times more energetic than any other
- after peaking with ms rise time, decayed to 1/10 intensity in ~ 300 ms

a catastrophic instability involving global crustal failure in a "magnetar", which possibly triggers the excitation of *f-* and *p-modes* in the neutron star

the excited mode damps out by gw emission, the energetics of which would be ~ 100 times larger of that of the X-rays flare

AURIGA and the flare

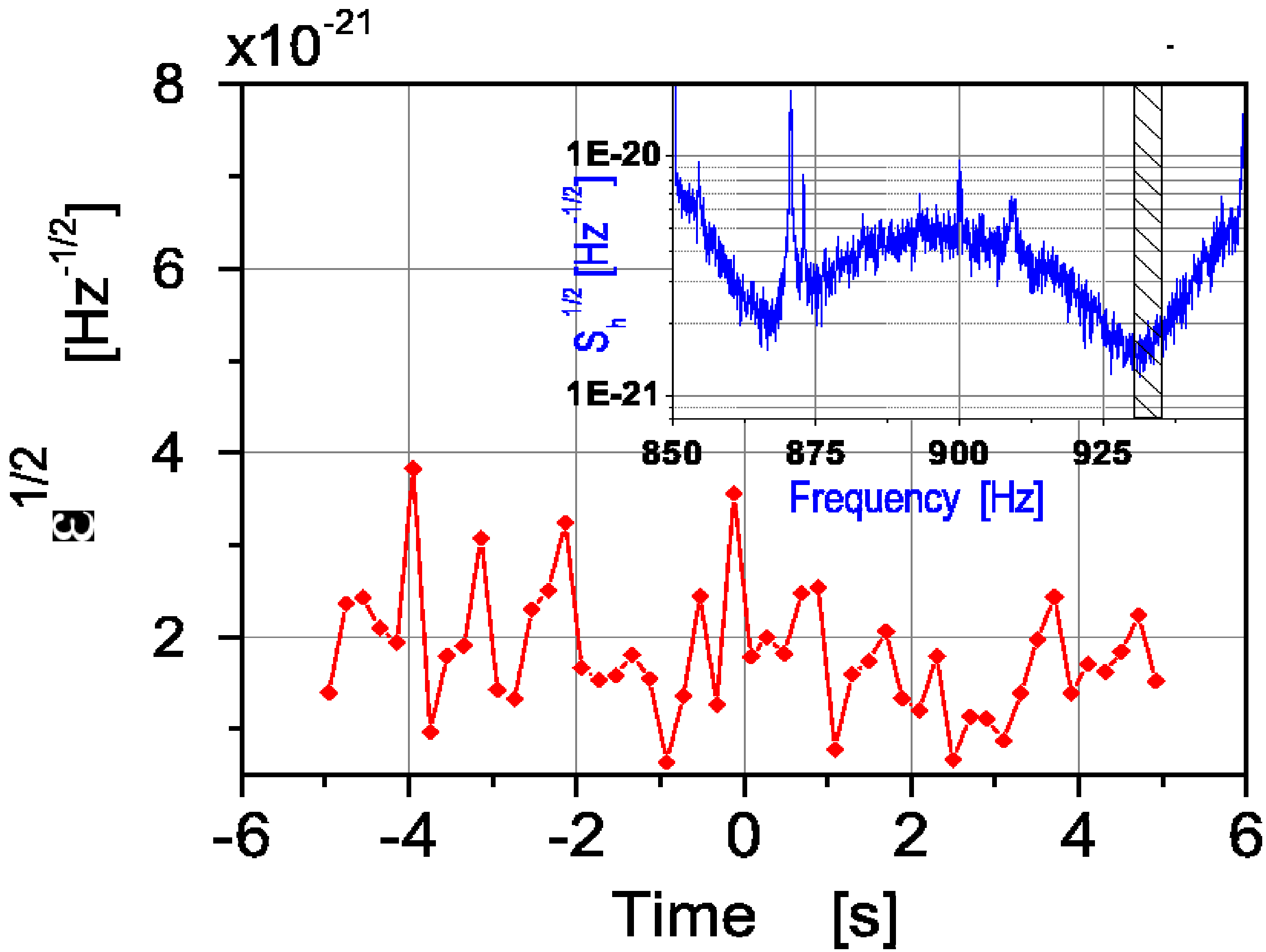
- was optimally oriented towards 1806-20 at the flare time
- was performing as a stationary gaussian detector
- was covering a ~ 100 Hz band in which neutron star f- and p-modes *may* fall

we test if, at the flare time, gw emission is found, as a damped sinusoidal wave train at any frequency f within AURIGA band, with damping time τ_s

- divide the band in sub-bands of width $\Delta f \sim 1/\tau_s$ around each f
- integrate for a time $\Delta t \sim \tau_s$ the output energy $\mathcal{E}$ in the sub-band
- check the statistics of the time series $\mathcal{E}(t)$ in each sub-band f
- test for any excess in $\mathcal{E}(t)$ at the flare peak time t_p

we take τ_s = *100 ms* as ~ 1/3 of the observed flare decay

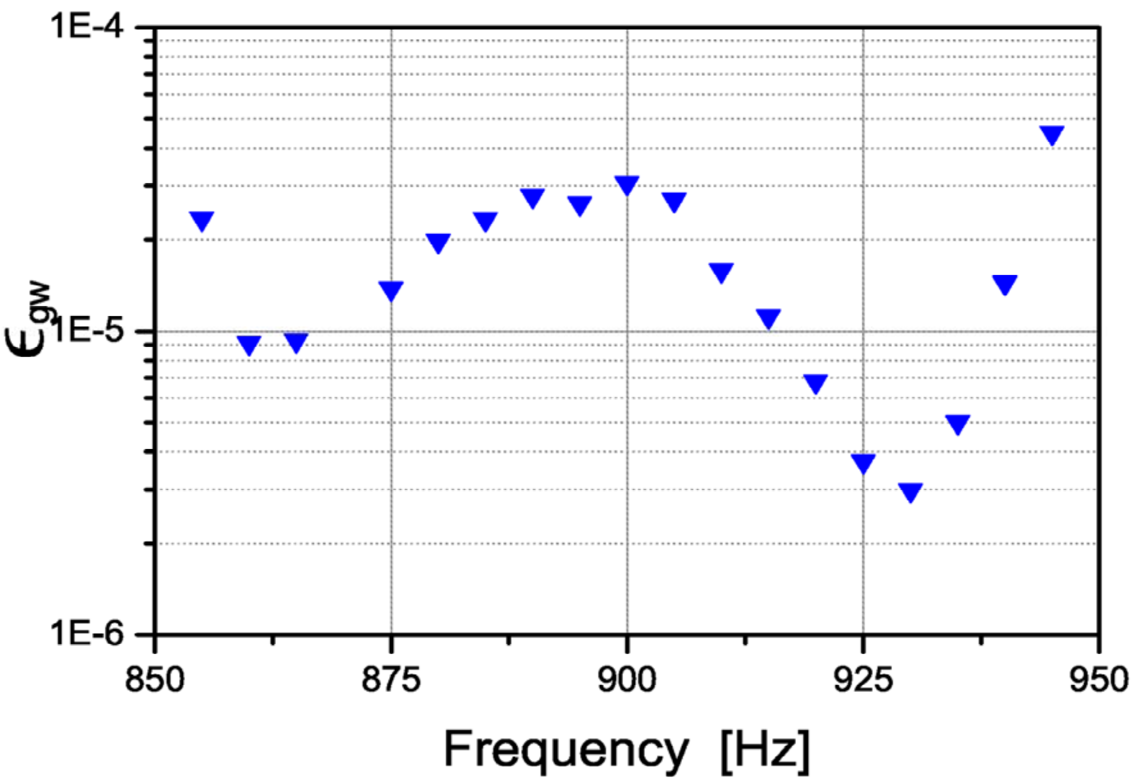
Baggio *et al.* (AURIGA collaboration) Phys.Rev.Letters **95** 081103 (2005)



the time origin corresponds to the arrival time of the flare peak t_p at the AURIGA site

upper limits
on ***emitted gw energy*** as fraction of solar mass
over the sub-band at ***frequency f*** of ***width Δf***

models predict $\varepsilon_{gw} \sim 5\ 10^{-6}$



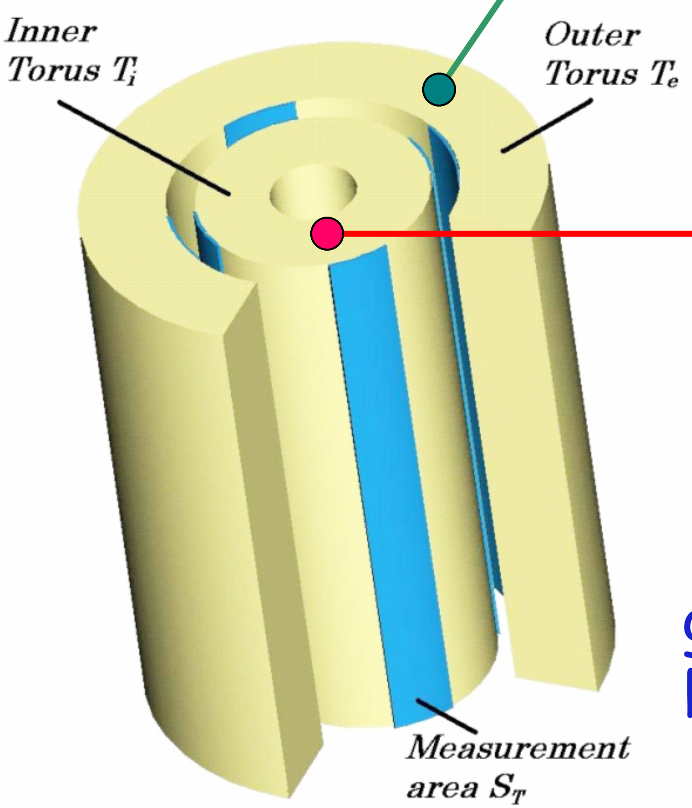
DUAL

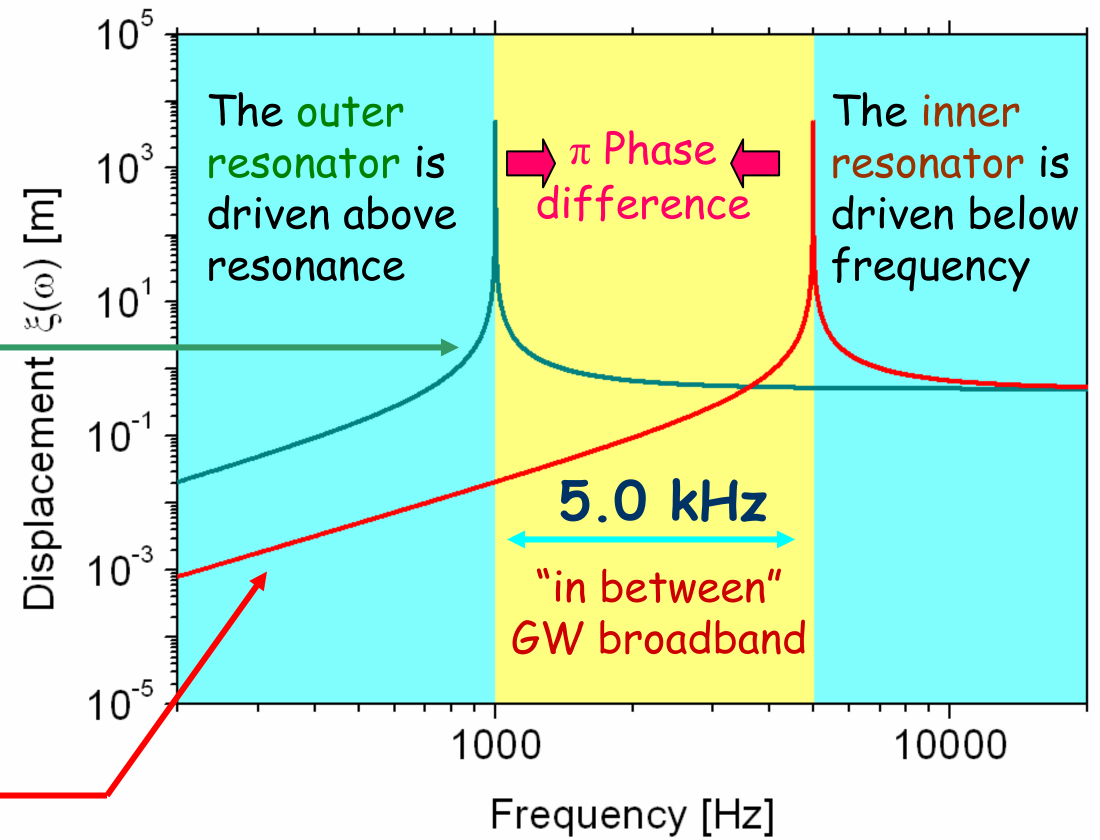
how to open wide, many kHz, the band of an acoustic detectors

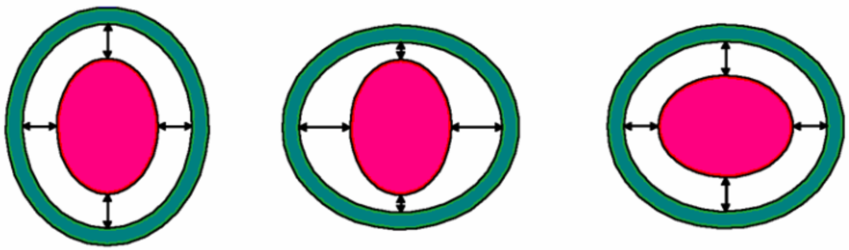
the DUAL R&D collaboration:
Firenze, Legnaro, Padova, Trento, Urbino

DUAL
the concept

read the differential deformations of two nested resonators

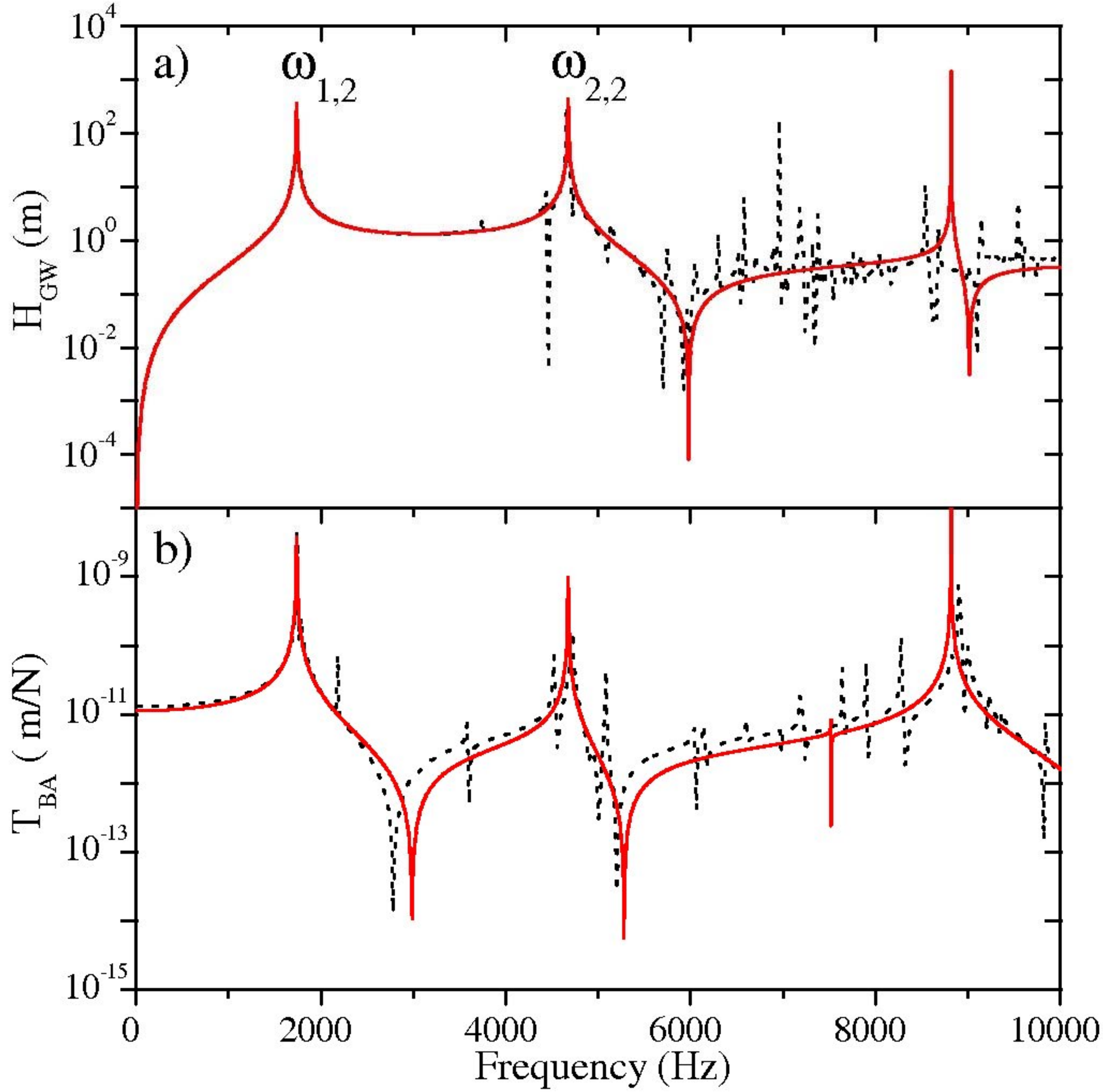






gw signal adds up
back-action subtracts out

SNR enhanced



a)
ω1,2
ω2,2
b)
10^4
10^2
10^0
10^-2
10^-4
HGW (m)
10^-9
10^-11
10^-13
10^-15
TBA (m/N)
0
2000
4000
6000
8000
10000
Frequency (Hz)

the new ideas of the DUAL detector

1 –the “dual” concept : read displacement between two massive resonators with a non-resonant read-out

M. Cerdonio et al. Phys. Rev. Lett. 87 031101 (2001)

avoid resonant bandwidh limit and thermal noise contribution by the resonant transducer

2 - selective readout: only the motion corresponding to GW sensitive normal modes is sensed

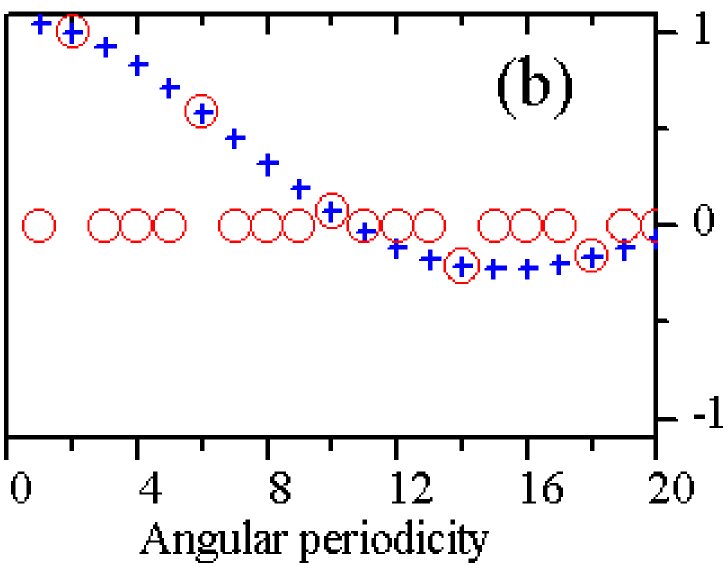
M. Bonaldi et al. Phys. Rev. D 68 102004 (2003)

reduce overall thermal noise by rejecting the contribution of non-gw sensitive modes

Mode selection strategy

Geometrically based mode selection

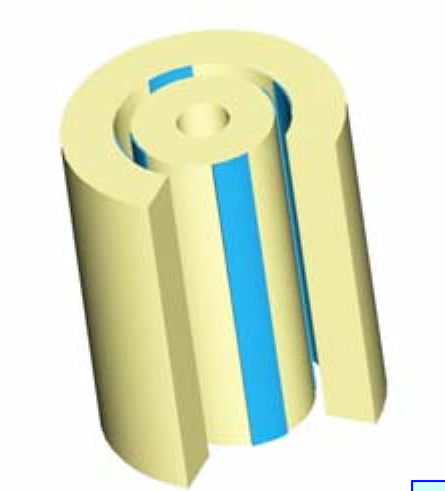
Bandwidth free from acoustic modes not sensitive to GW



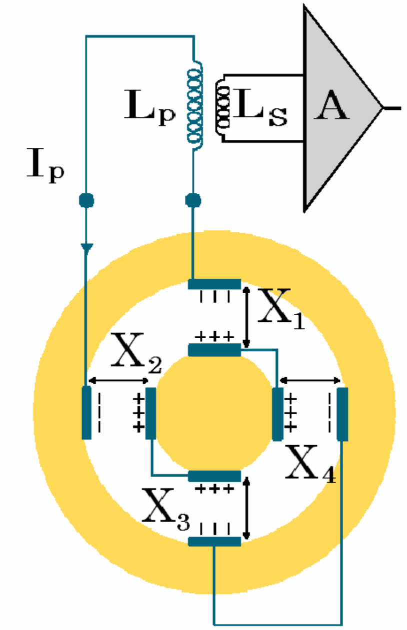
2-D Quadrupolar filter:
$X = X_1 + X_3 - X_2 - X_4$

Large interrogation regions

Reject high frequency resonant modes which do not carry any GW signal



Capacitive transducer design



Also FFP optical scheme
F. Marin et.al, Phys. Lett. A 309, 15 (2003)

DUAL R&D : 3 main research topics

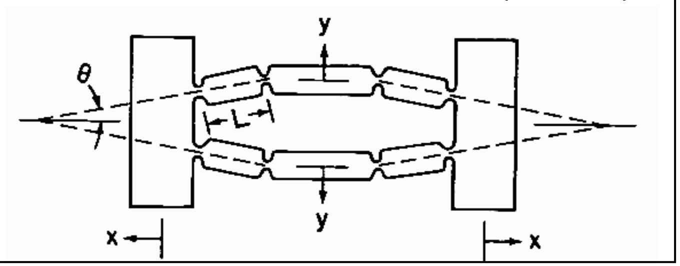
	Current technology	DUAL requirements
readout system:		
• mechanical amplification	resonant 15 x 100 Hz BW	not resonant 10x 4 kHz BW
• displacement sensitivity and wide sensing area	5×10^{-20} m	5×10^{-22} (100x)
test masses:		
• underground operation	not necessary	define requirements
• high cross section (□ v_s^{2-3})	Al 5056	Mo, SiC, Sapph. (50 x)
detector design		
• seismic noise control	external passive	+ embedded active

Readout system for DUAL: mechanical amplification stage

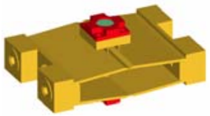
- Broadband amplification up to 5.0 kHz
- Displacement gain factor about 10
- Negligible intrinsic thermal noise
- Compliance

Leverage type amplifier

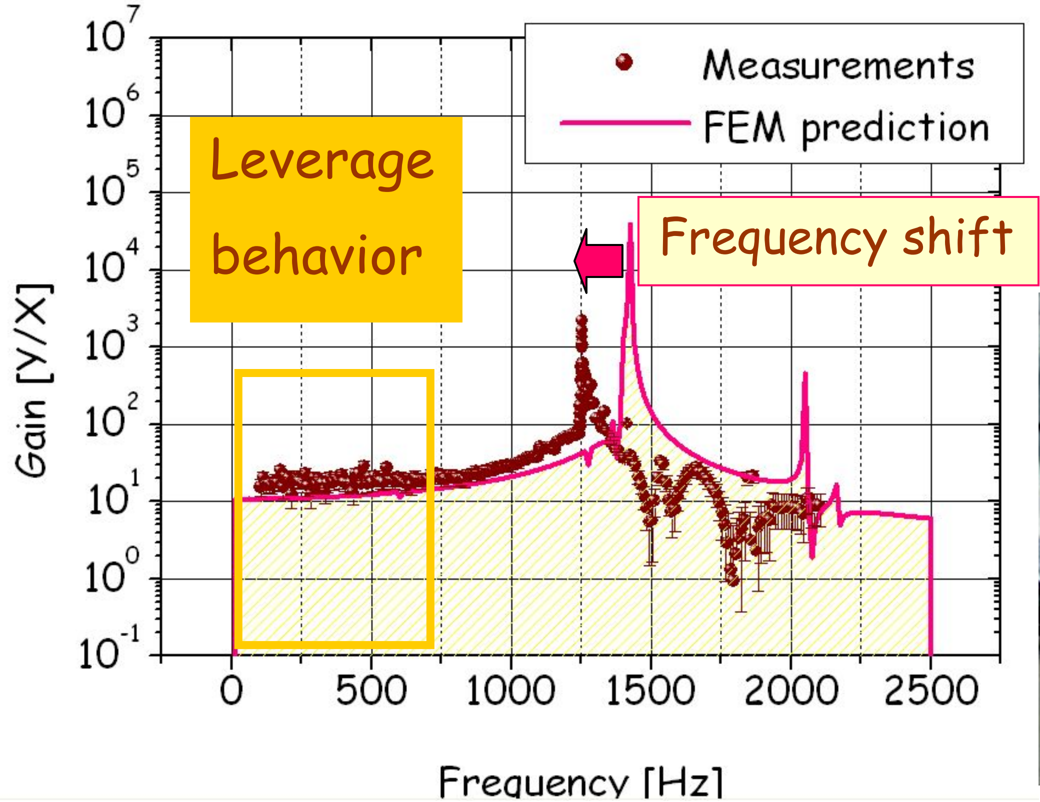
H.J. Paik, proceedings First AMALDI Conference (1995)

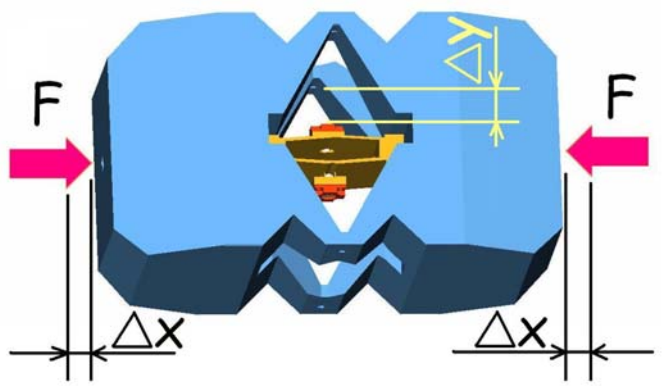


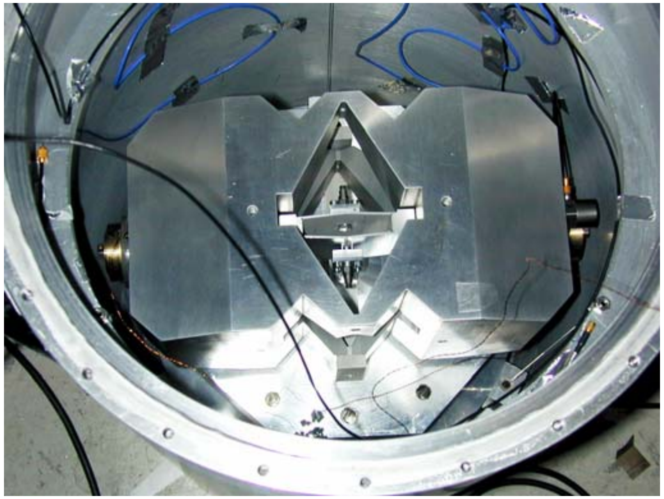
Mechanical gain measurements



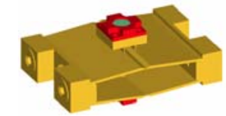
direct gain = Δy/Δx





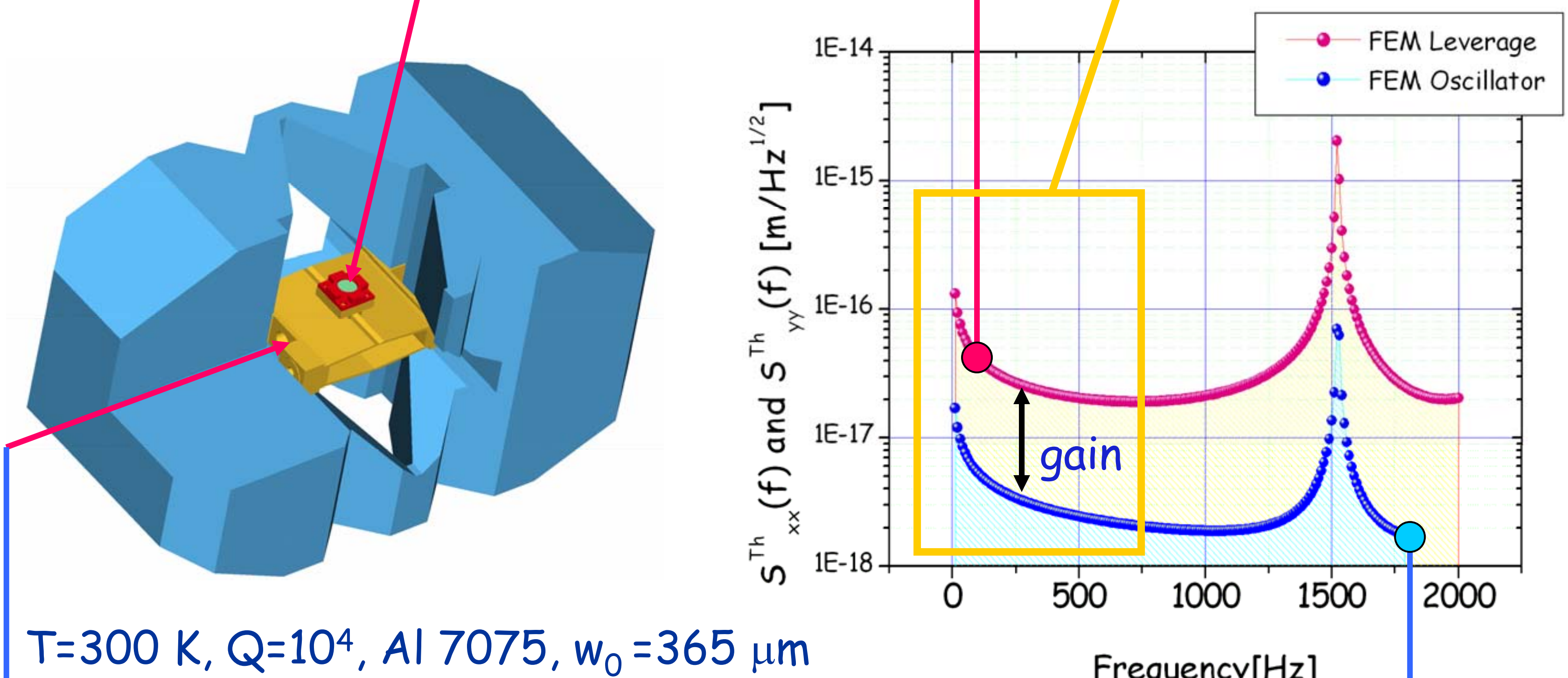


Next step: measure the thermal noise



ANSYS Prediction by using Fluctuation Dissipation Theorem

Leverage behavior: scaling with gain



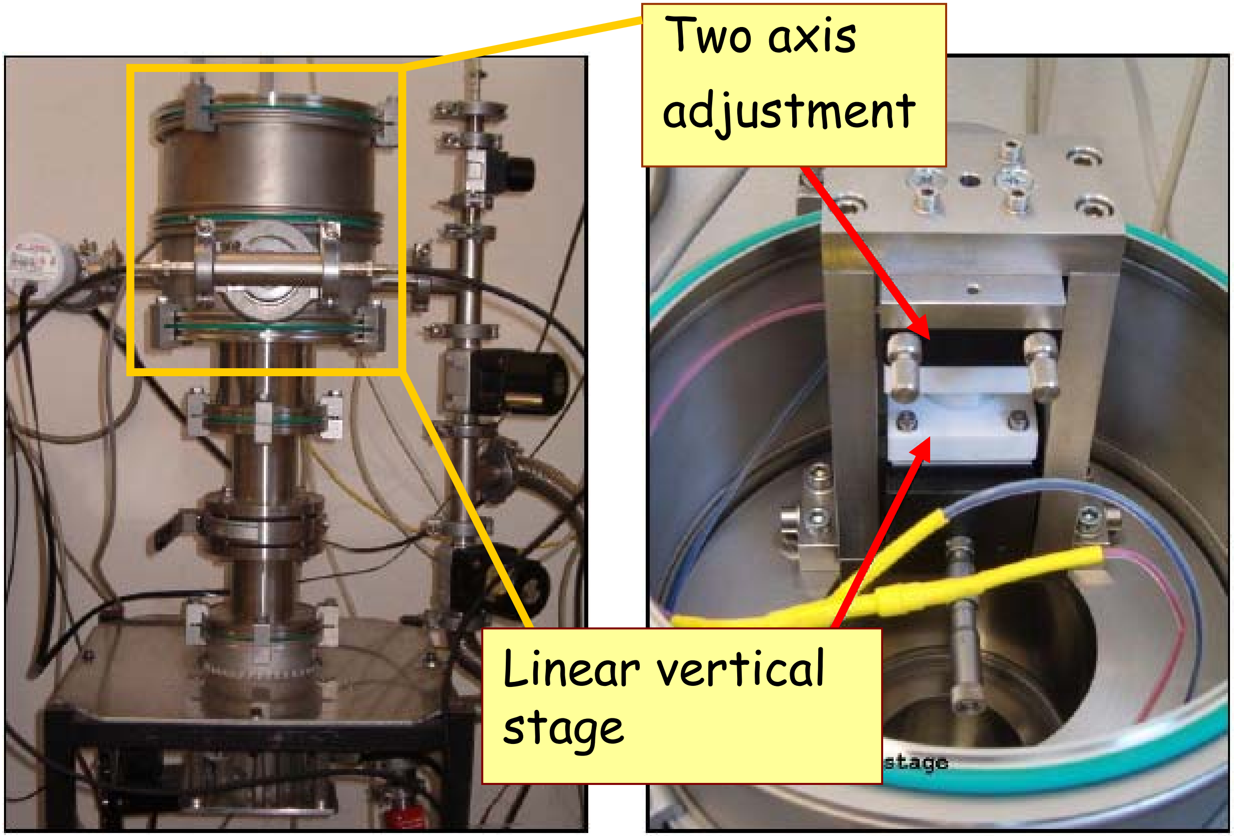
T=300 K, Q=10^4, Al 7075, w_0 =365 μm

- Bias voltage in the 100 MV/m range

  - surface finishing effect
  - electrodes conditioning procedure
  - effect of dielectric films

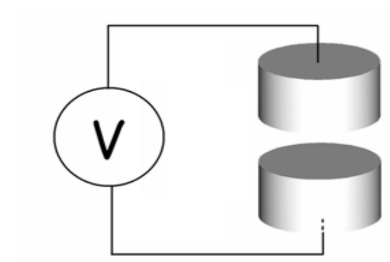
Goal: 10^8 V/m

Achieved: 10^7 V/m



Apparatus for High voltage breakdown study

Measurement of V.B. of aluminum polished surfaces of cylindrical samples



M. Bonaldi, F. Penasa,

Trento Phys. Dept.

Progress towards a wide area optical readout

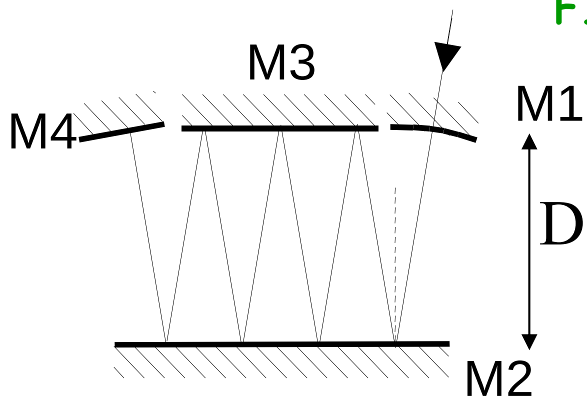
usual cm-long cavities have small spot size (□1mm)

higher order acoustic modes of the real system contribute to the noise

To average out the noise, we need a spot size > **10 cm** !!!!

Folded Fabry-Perot: FFP

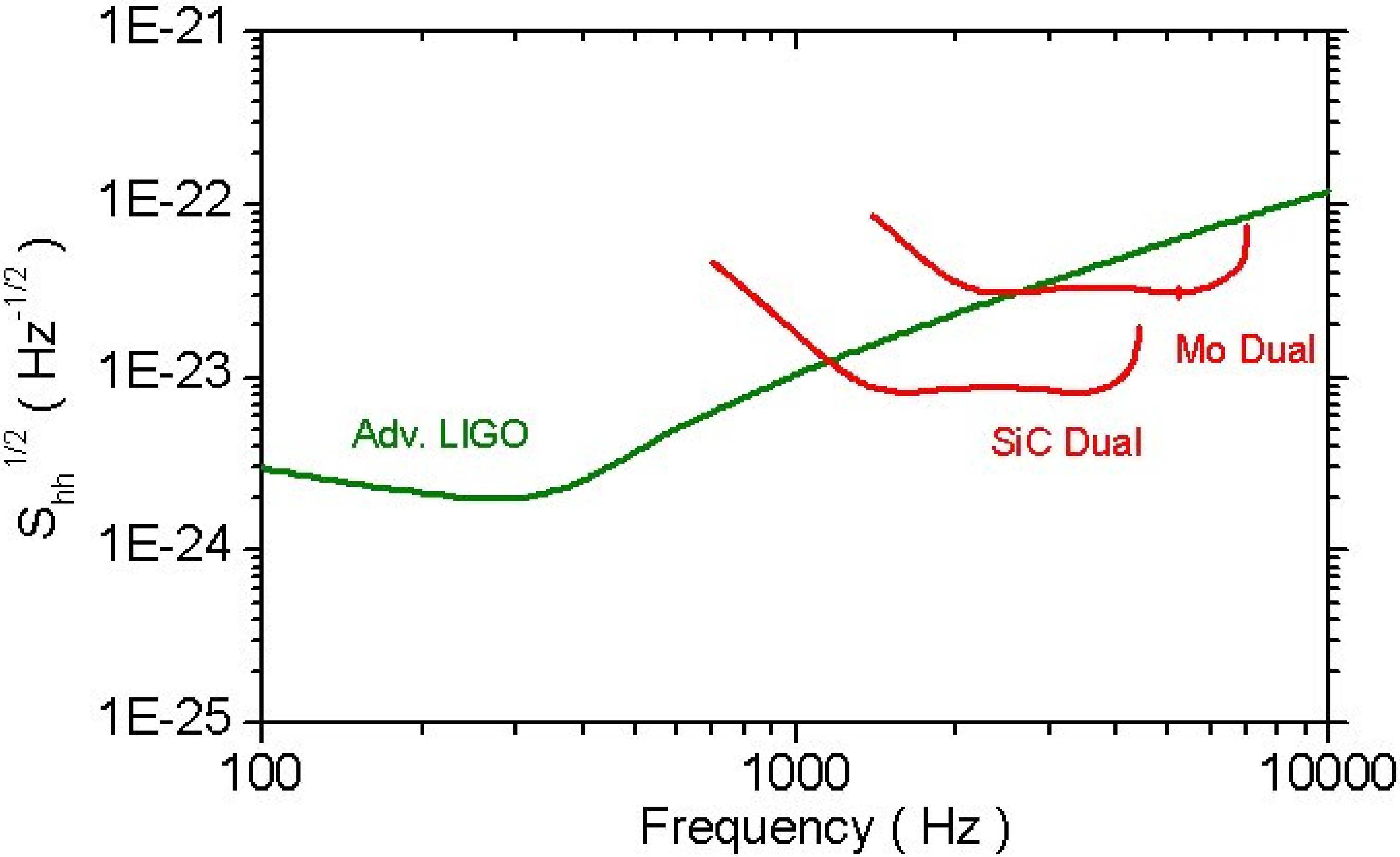
F.Marin *et al* Phys. Lett. A 309, 15 (2003)



effective increase of spot size

relative shot noise limited displacement sensitivity: constant
relative freq. noise due to Brownian noise $\propto 1/N$
relative freq. noise due to rad pressure noise $\propto 1/N^2$
+ spatial correlation effects

sensitivities at SQL (Dual & Advanced ifos)



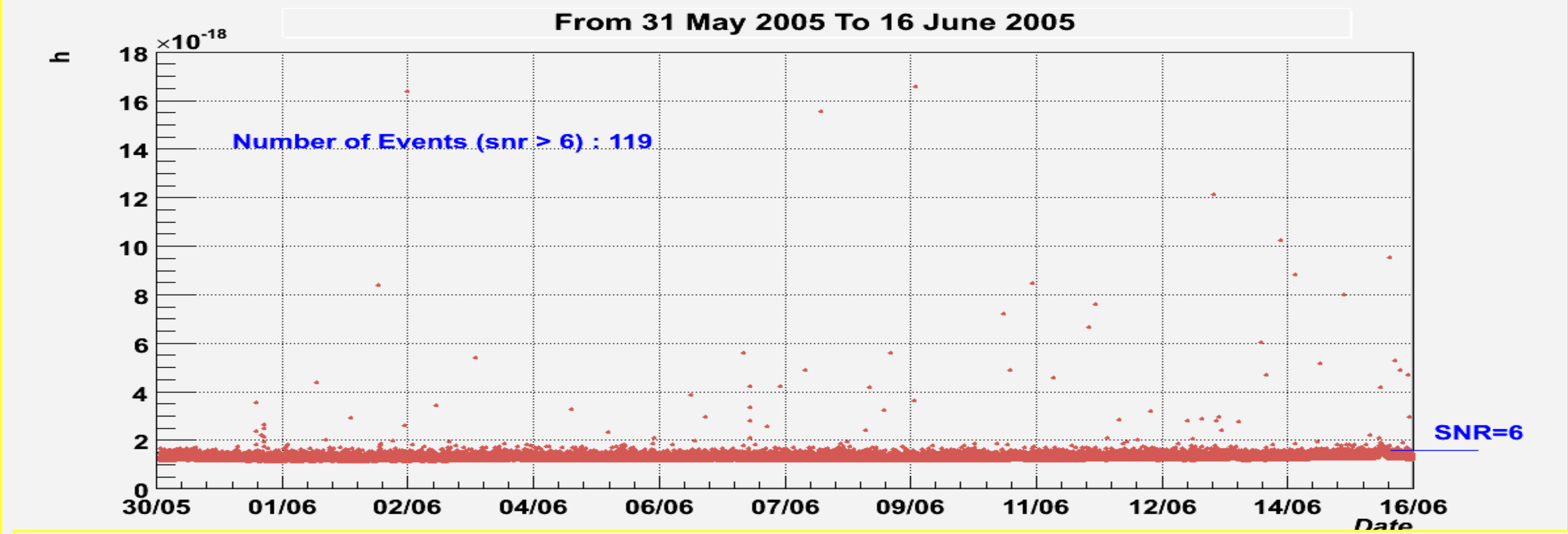
Mo Dual 16.4 ton height 3.0m ∅ 0.94m

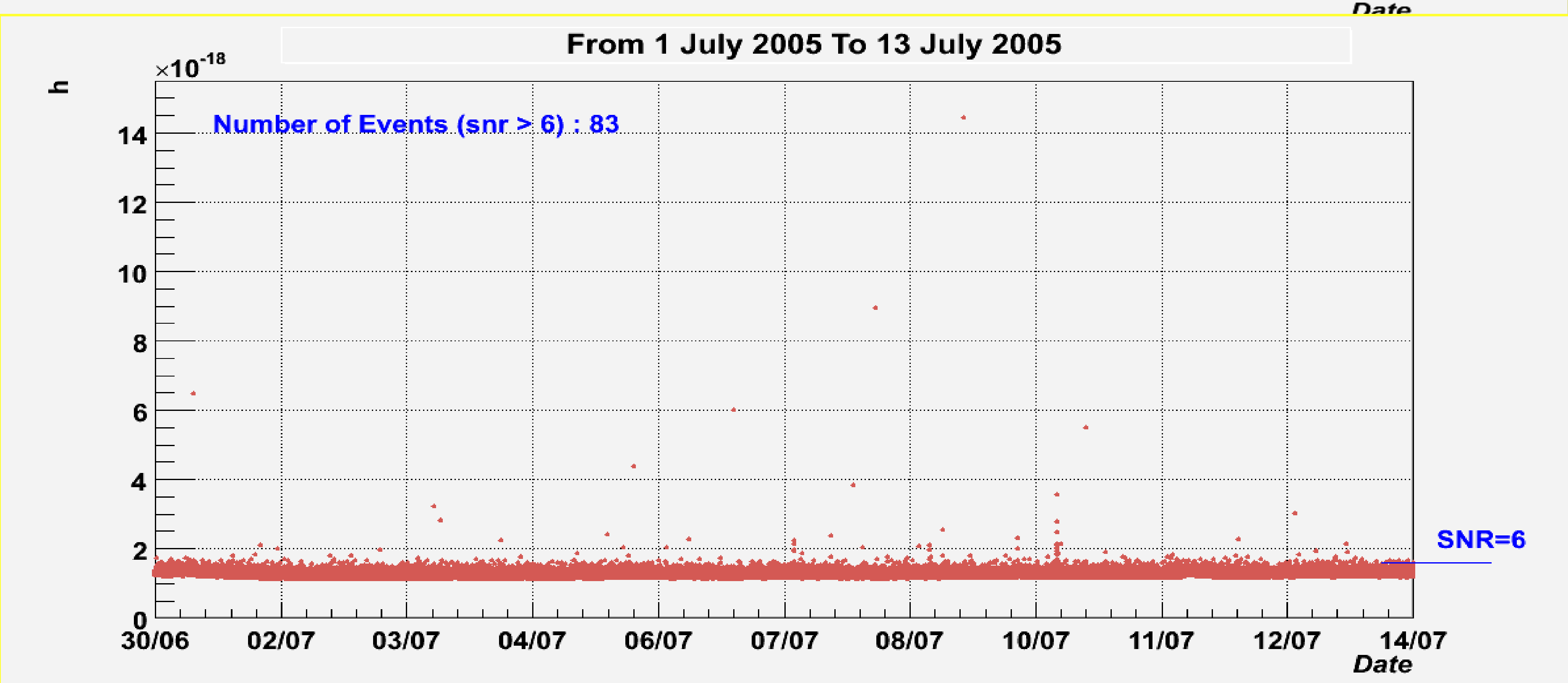
SiC Dual 62.2 ton height 3.0m ∅ 2.9m

M. Bonaldi et al.
Phys. Rev. D 68 102004 (2003)

$Q/T=2\times10^8\ K^{-1}$

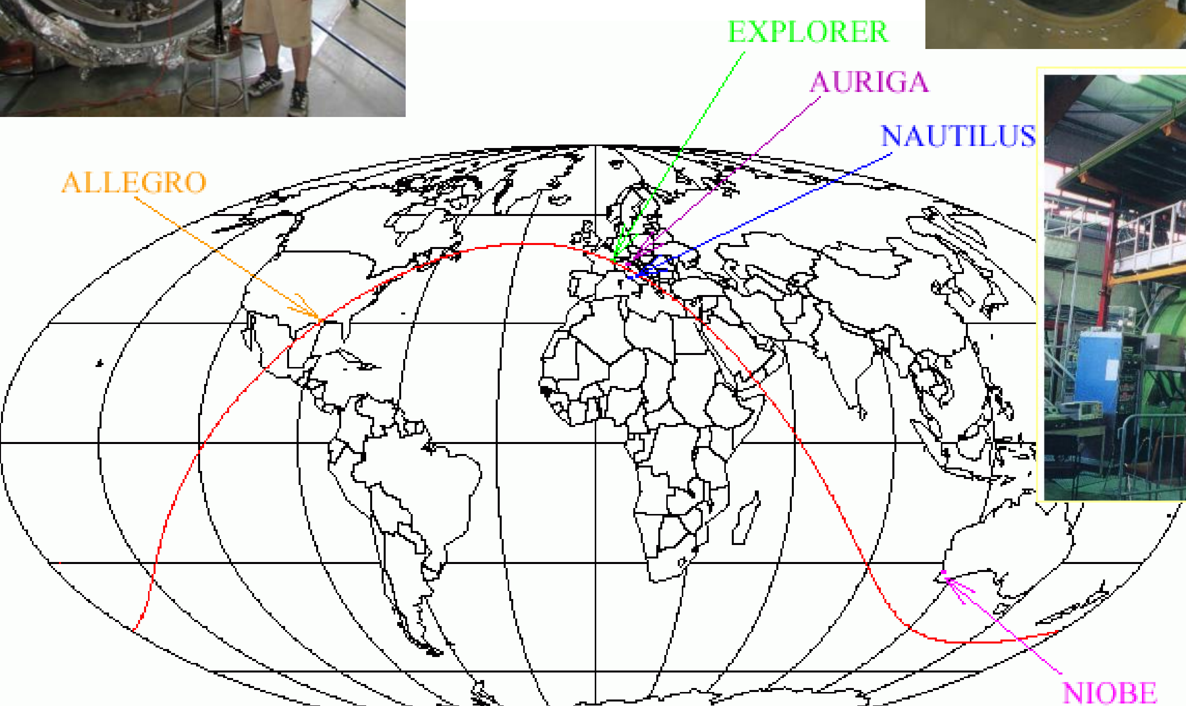
Antenna pattern: like 2 IFOs colocated and rotated by 45°


From 31 May 2005 To 16 June 2005
h
×10^-18
18
16
14
12
10
8
6
4
2
0
Number of Events (snr > 6) : 119
SNR=6
30/05
01/06
02/06
04/06
06/06
07/06
09/06
11/06
12/06
14/06
16/06
Date


From 1 July 2005 To 13 July 2005
h
×10^-18
14
12
10
8
6
4
2
0
Number of Events (snr > 6) : 83
SNR=6
30/06
02/07
03/07
04/07
06/07
07/07
08/07
10/07
11/07
12/07
14/07
Date

the "bar" network: Int.Gravit.Event Collaboration

IGEC-1 1997-2000 data



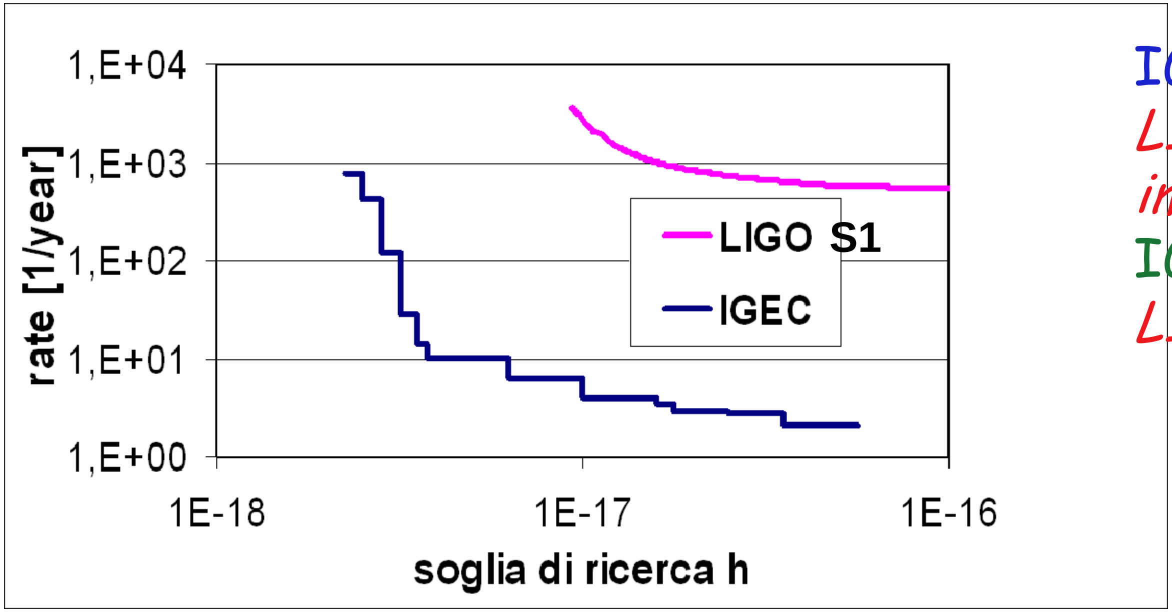
IGEC-2
Dec 04 onward

very encouraging: 3-4 detectors in coincidence most of the time (much more than IGEC-1)

Upper limit for burst GWs with random arrival time and measured amplitude ≥ search threshold

***PRL 85** 5046 (2000) – Phys. News Upd. 514 Nov. 29 (2000) - PRD **68** 022001 (2003)*)

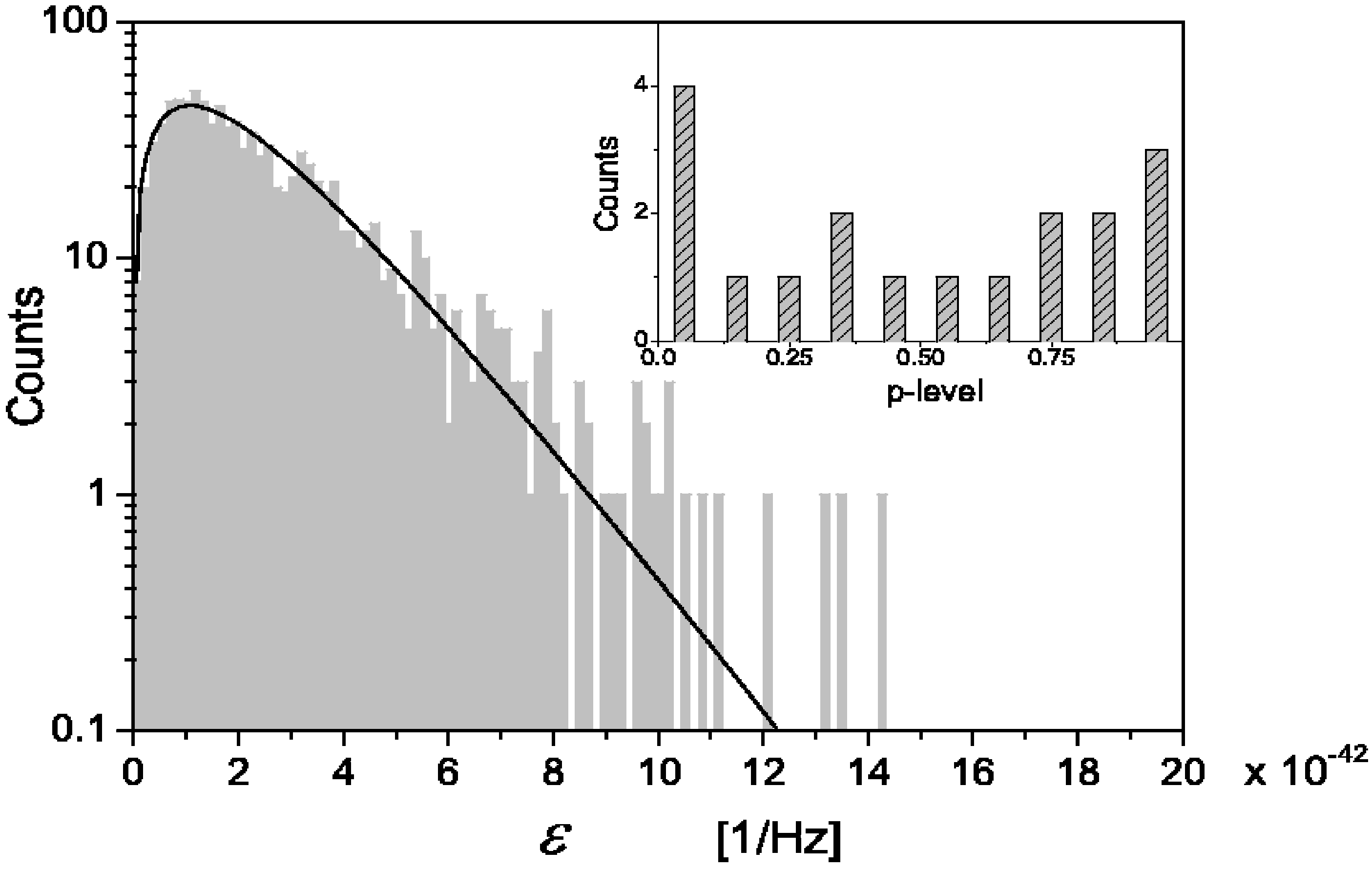
UPPER LIMIT on the RATE of GW bursts
from the
GALACTIC CENTER



IGEC-1 results
LIGO S2, S3 & S4 improve considerably
IGEC-2 will be comparable
LIGO S5 will overcome

$h \sim 2\ 10^{-18}$ ⟺ **$\Delta E \sim 0.02\ M_{sun}$** converted into gw at the Galactic Center

AURIGA gaussianity -100s to +100s around flare time



comments on
AURIGA & the flare

- stationary operation allows relevant searches even with a single detector
- obtained an upper limit about neutron stars dynamics, which is relevant as it invades part of the parameter region of existing models
- stronger upper limits could be put with optimal search methods *(I did not discuss this point > see PRL paper)*

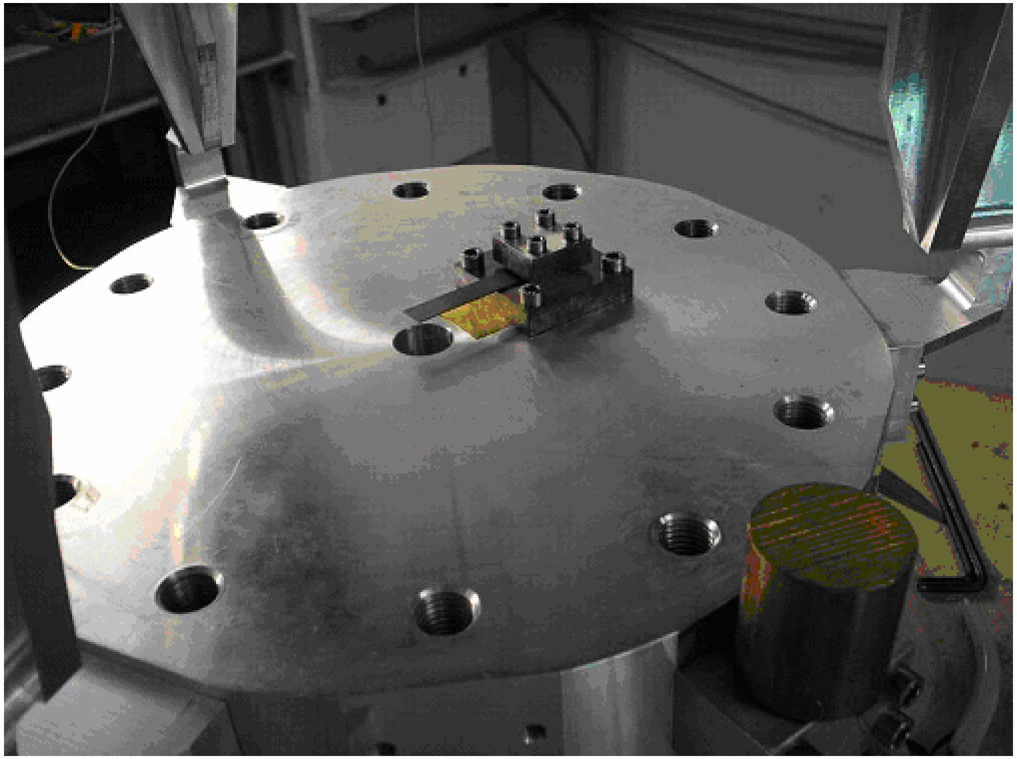
World-wide gravitational wave network

GWIC http://gwic.gravity.psu.edu/ ***is helping with steps toward a world-wide network including the large interferometers and (more recently) bars. So far, bi-lateral exchanges***

- GEO - LIGO continuing exchange & joint papers
- LIGO- TAMA exchange data for S2 data (60 days Spring 03). Small joint working group to coordinate the joint analysis
- Virgo and LIGO exchanging environmental data, and Virgo preparing for future gravitational data exchange
- AURIGA- LIGO exchanged 15 days of S3 data and are tuning tools
- AURIGA+EXPLORER+NAUTILUS+VIRGO are developing methods for joint analysis of bursts and stochastic
- EXPLORER+NAUTILUS and TAMA exchange data
- AURIGA and TAMA are preparing for data exchange

Test mass material characterization

Low temperature measurements of the Q factor of ceramic materials



J.P. Zendri,

Laboratori Legnaro

DUAL is based on

a deep revision of the resonant detector design

and

a R&D on readout systems

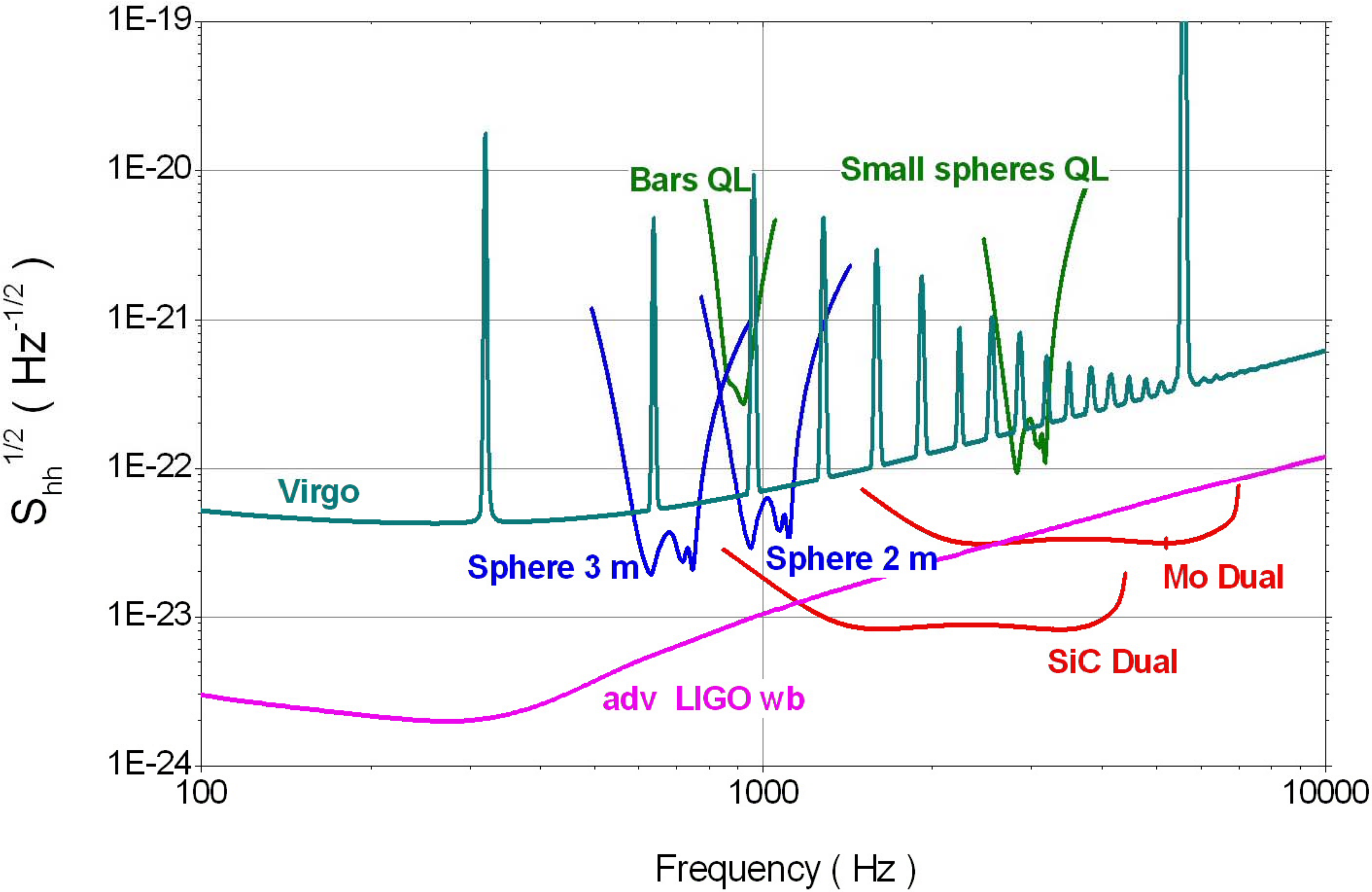
currently funded by: INFN, EGO, EC (ILIAS)

timeline

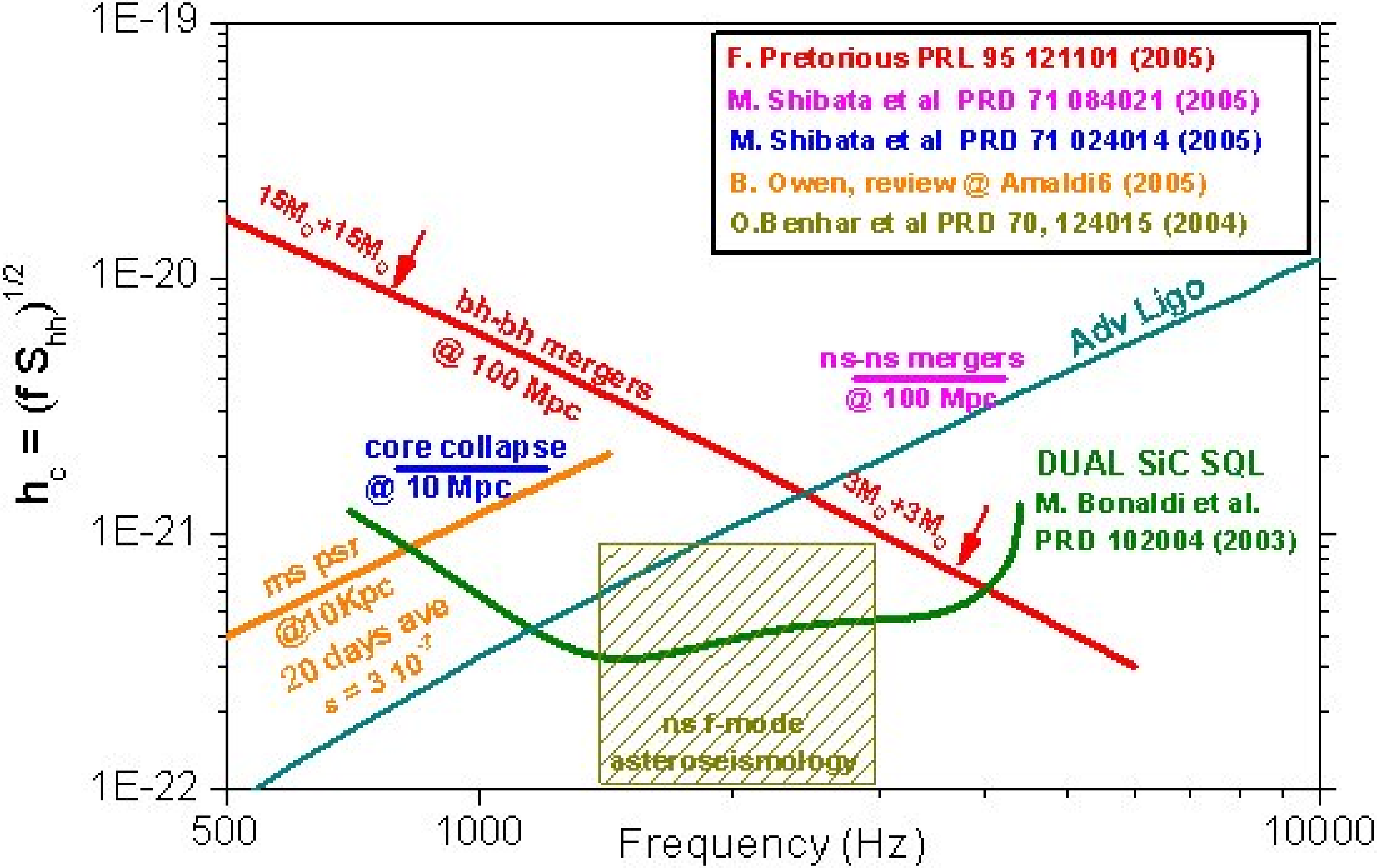
R&D + design : 2005 – 2008 (500 k€)
construction: 2009 – 2013 (15 M€- apply to "Ideas" in FP7)

FP7 new "Ideas" programme: at last fundamental science (all)…!!!

"Enhance the dynamism, creativity and excellence of European research at the frontier of knowledge. <…> Open to proposals from individuals and groups without constraint on size, composition or participation in the projects"



1E-19
1E-20
1E-21
1E-22
1E-23
1E-24
$S_{hh}^{1/2}$ ($Hz^{-1/2}$)
100
1000
10000
Frequency (Hz)
Virgo
Bars QL
Small spheres QL
Sphere 3 m
Sphere 2 m
Mo Dual
SiC Dual
adv LIGO wb



F. Pretorious PRL 95 121101 (2005)
M. Shibata et al PRD 71 084021 (2005)
M. Shibata et al PRD 71 024014 (2005)
B. Owen, review @ Amaldi6 (2005)
O.Benhar et al PRD 70, 124015 (2004)
15M☉+15M☉
bh-bh mergers
@ 100 Mpc
3M☉+3M☉
ns-ns mergers
@ 100 Mpc
Adv Ligo
core collapse
@ 10 Mpc
DUAL SiC SQL
M. Bonaldi et al.
PRD 102004 (2003)
ns psr
@10Kpc
20 days ave
ns f-mode
asteroseismology
1E-19
1E-20
1E-21
1E-22
500
1000
10000
Frequency (Hz)