united nations
educational, scientific
and cultural
organization

international atomic
energy agency

the
abdus salam
international centre for theoretical physics

ICTP 40th Anniversary

H4.SMR/1574-11

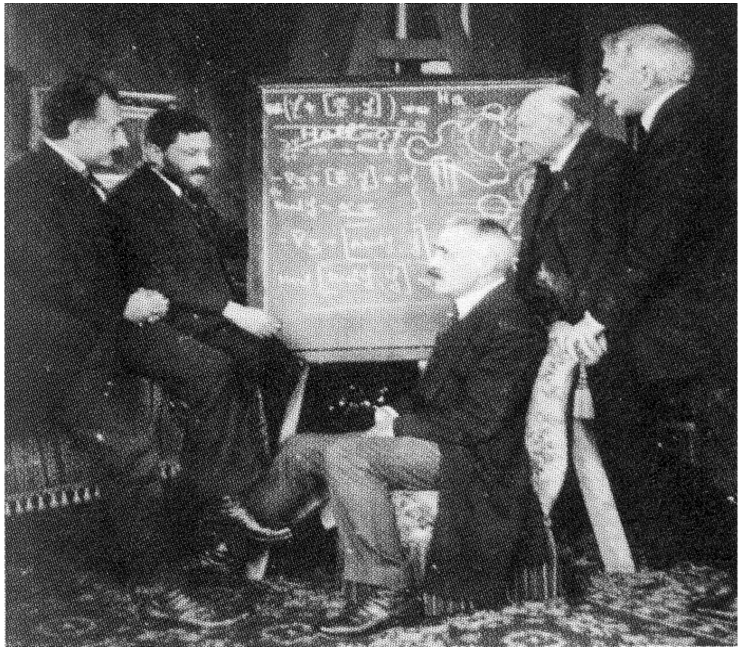
"VII School on Non-Accelerator Astroparticle Physics"

26 July - 6 August 2004

Searches for Gravitational Waves - II

Eugenio COCCIA

University of Rome "Tor Vergata"
& INFN Gran Sasso
Italy



Searches for Gravitational Waves II

Eugenio Coccia
University of Rome “Tor Vergata”
and INFN Gran Sasso

I

How to detect gw

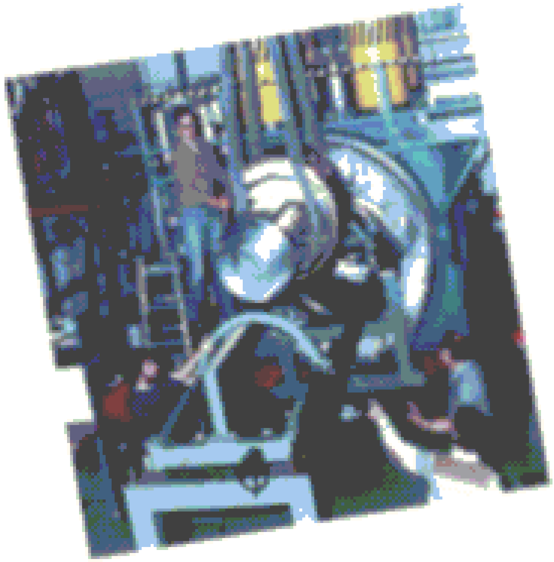
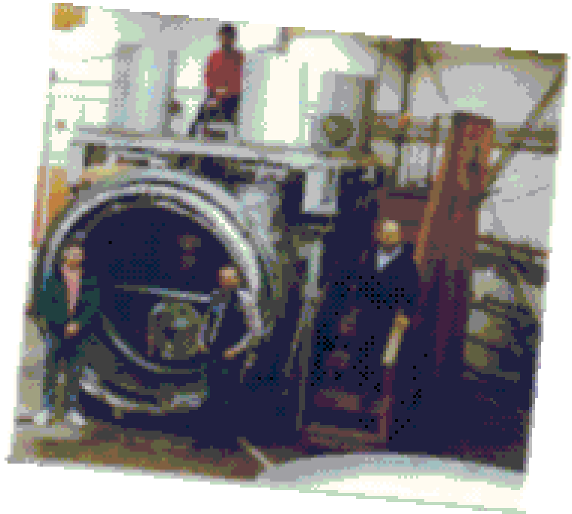
Detection principle and sensitivity of

Resonant masses and Interferometers

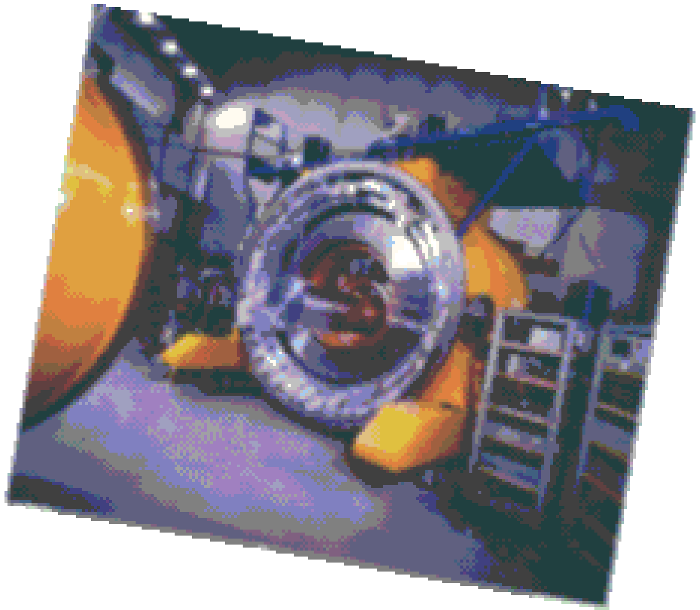
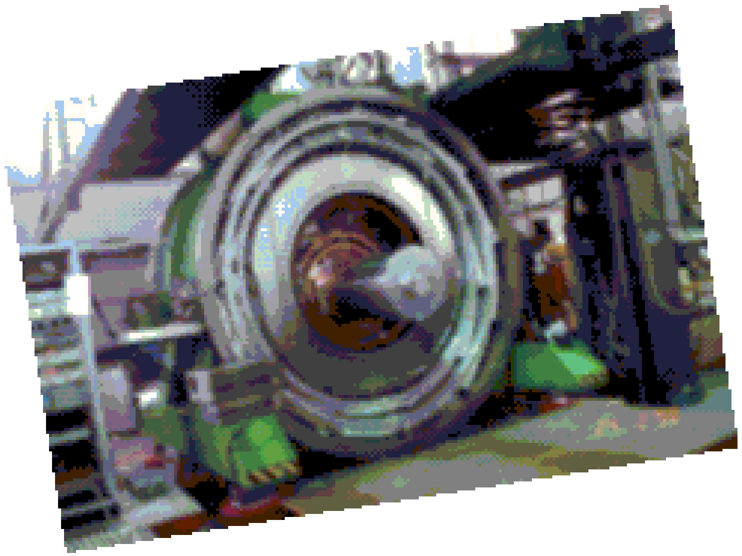
II

Results

Perspectives


ALLEGRO AURIGA EXPLORER NAUTILUS NIOBE

Bursts

IGEC, Phys. Rev. Lett. ***85,*** *5046 (2000)*
Class. Quant. Grav. ***18****, 43 (2001)*
Class. Quant. Grav. 19, 5449 (2002)

Continuous signals

Phys. Rev. D ***65,*** *022001(2002)*
Phys. Rev. D, ***65****,042003 (2002)*
Class.Quant.Grav. 20 (2003) S665-S676

Stochastic Background

Astron. Astrophys. ***351****, 811 (1999)*

more

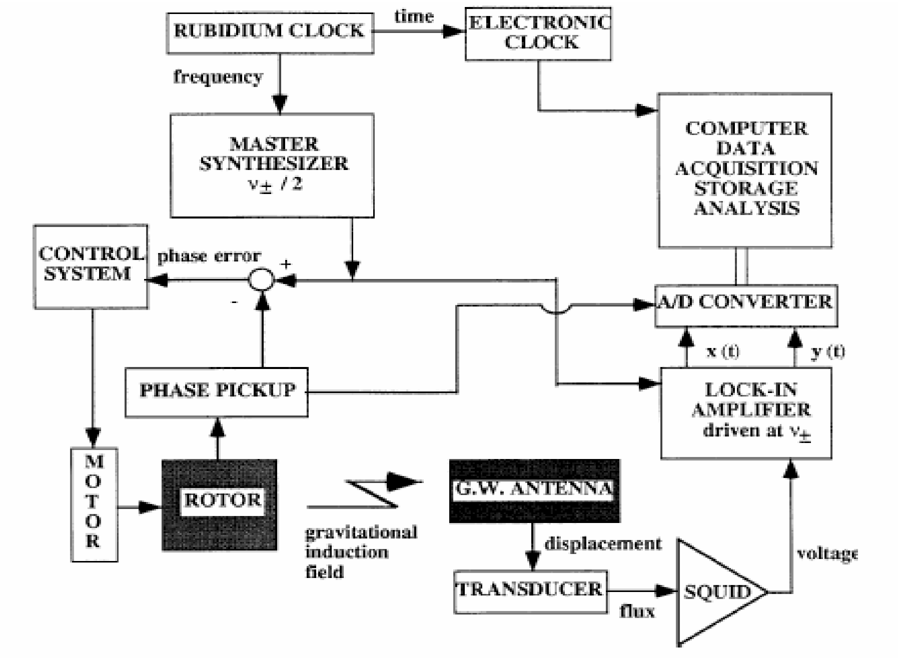
Search for correlation with GRB's
Astron. Astrophys. ***138****, 603 (1999)*
Phys. Rev. D ***66*** *102002 (2002)*

Gravitational near field
Eur. J. Phys. C ***5****, 651 (1998)*

Effect of cosmic rays
Phys. Rev. Lett. ***84*** *, 14 (2000)*
Phys. Lett. B ***499****, 16 (2001)*
Phys. Lett. B (2002)

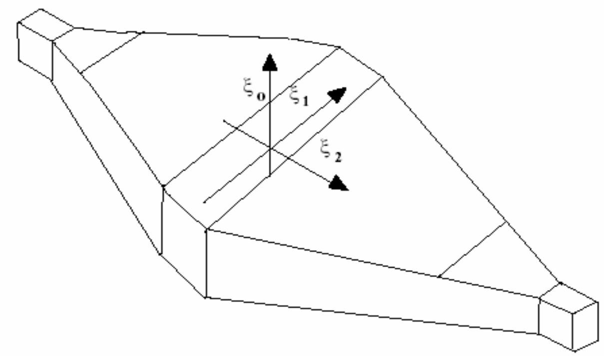
analysis of data

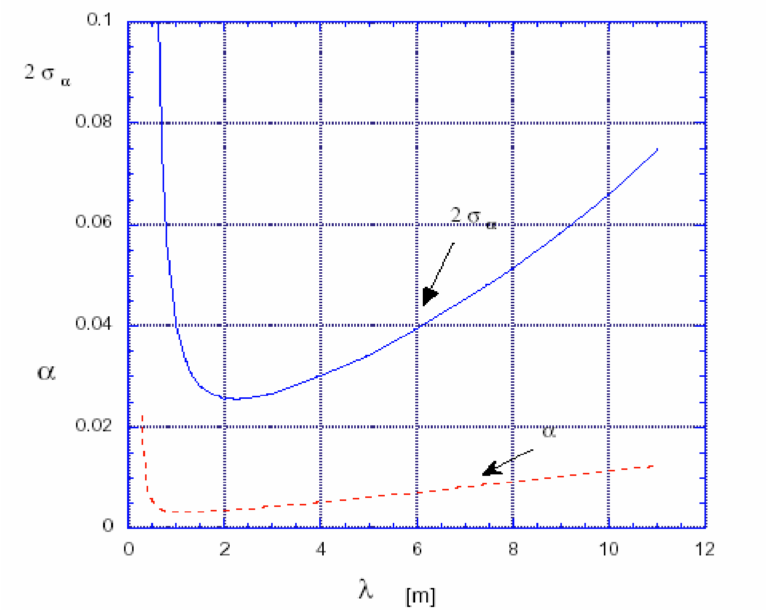
Detector calibration - Deviation from Newton law



$$V = -\frac{Gm}{r}\left(1 - \alpha e^{-r/\lambda}\right)$$

EXPLORER, J.of Phys. C (1999)





Detectable signals **today**

BURSTS: Black Hole ($M \sim 10 M_\odot$) formation, $10^{-4} M_\odot$ into GW

$$SNR = 6 \times 10^{3} \left(\frac{10\ kpc}{r}\right)^{2} \left(\frac{10^{-44}\ Hz^{-1}}{\tilde{h}^{2}}\right) \left(\frac{\Delta f}{1 Hz}\right)$$

SPINNING NEUTRON STARS: Non axisymmetric ($\varepsilon \sim 10^{-6}$) pulsar, $M \sim 1.4 M_\odot$

$$SNR \approx 30 \left(\frac{10\ kpc}{r}\right)^{2} \left(\frac{10^{-44}\ Hz^{-1}}{\tilde{h}^{2}}\right) \left(\frac{\varepsilon}{10^{-6}}\right) \left(\frac{T_{obs}}{1 y}\right)$$

COALESCING BINARIES: Inspiraling NS-NS system, $M \sim 1.4 M_\odot$

$$SNR \approx 10^{3} \left(\frac{10\ kpc}{r}\right)^{2} \left(\frac{10^{-44}\ Hz^{-1}}{\tilde{h}^{2}}\right) \left(\frac{\Delta f}{1\ Hz}\right)$$

STOCHASTIC BACKGROUND: 2 detectors, at distance $d << \lambda_{GW}$

$$\Omega_{GW} \approx 2 \times 10^{-3} \left(\frac{f}{900\ Hz}\right)^{3} \left(\frac{\tilde{h}_{1,2}}{10^{-22}\ Hz^{-1/2}}\right)^{2} \left(\frac{1 Hz}{\Delta f}\right)^{1/2} \left(\frac{1 y}{T_{obs}}\right)^{1/2}$$

•Because of the inherent weakness of GW signals, and the difficulty in distinguishing them from a myriad of noise sources, the direct detection of a gw burst require coincident detection by multiple detectors with uncorrelated noise.

$$n_c << N_1, N_2$$

•Background: expected number of coincidences <n>, during the observation time T

$$\langle n \rangle = \frac{N_1 N_2 \Delta t}{T}$$

This background can be *measured*: one shifts the time of occurrence of the events of one of the two detectors for a number of times, and takes the average

Number 514 (Story 1), 29 November 2000 by Phillip F. Schewe and Ben Stein

New Upper Limit on Gravity Wave Events in Our Galaxy

The International Gravitational Event Collaboration (IGEC) is the first ever network of cryogenic resonant-cylinder gravity wave detectors. It consists of five widely spaced detectors: one in the US (Baton Rouge), two in Italy (Legnaro and Frascati), one in Switzerland (at CERN), and one in Australia (Perth).

Searching for passing gravity waves is a delicate art since it involves sensing deformations much smaller than the size of an atomic nucleus in huge detectors meters or kilometers in size. In the resonant detector approach this means watching for longitudinal vibrations in chilled automobile-sized metal cylinders. In the interferometer approach (used at LIGO; see, for example, Update 442) the deformation is the change in the separation of distant mirrors attached to test masses. Gravity waves strong enough to be detected will most likely come from events such as the coalescence of black holes or neutron stars, and these are rare. IGEC reports now that in its first operational period it has observed no gravity waves. From this they calculate an upper limit of the order of one per year in the rate at which such gravity wave events occur in our galaxy.

GEC is not only striving to have the sensitivity to record gravity waves from events out to distances of 100 million light years but is also hoping to be able to locate the source of the waves in the sky.

IGEC

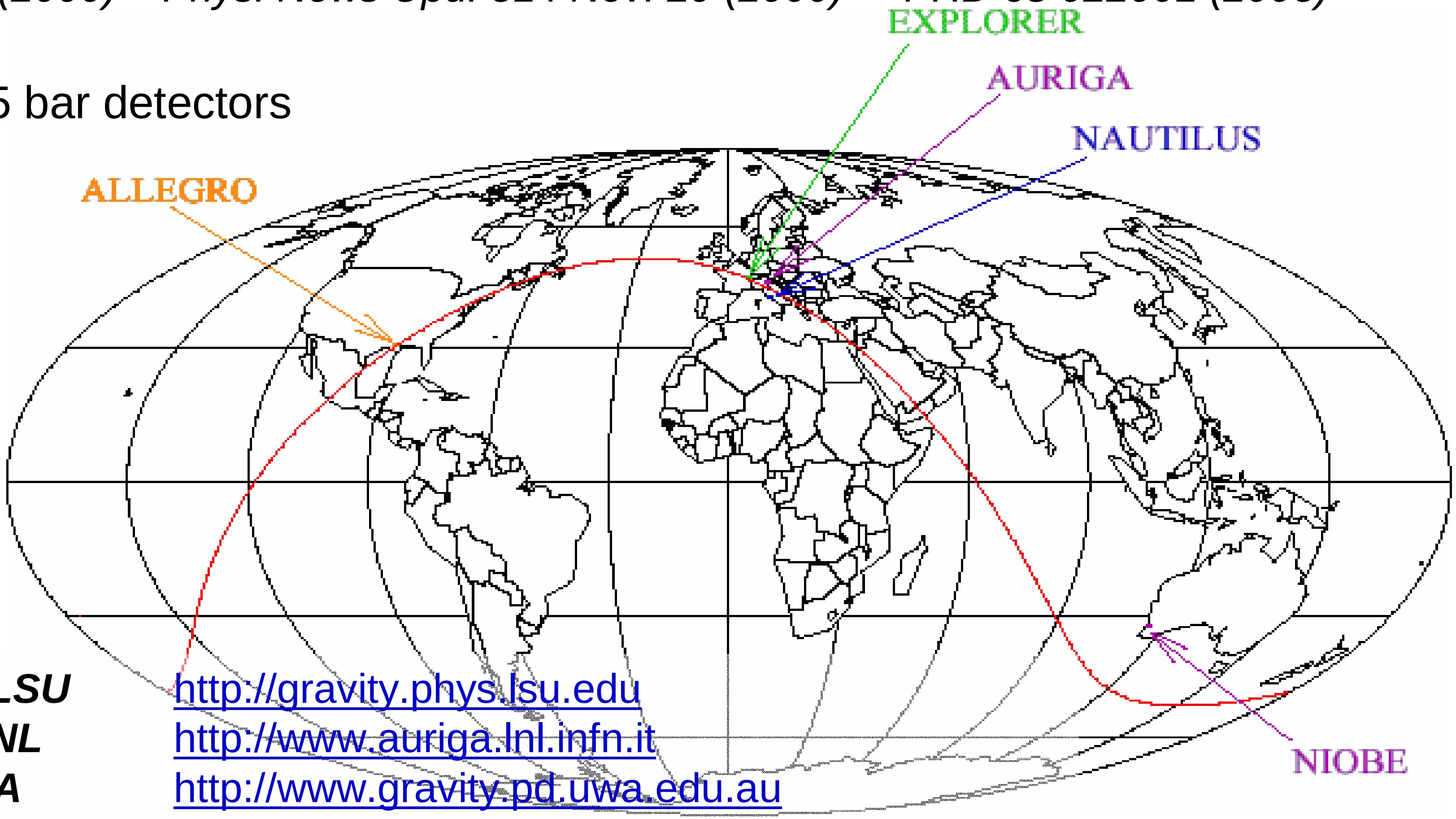
International Gravitational Event Collaboration

http://igec.lnl.infn.it

Results of the 1997-2000 Search for Burst GW by IGEC

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

Network of the 5 bar detectors almost **parallel**



***ALLEGRO* NFS-LSU** http://gravity.phys.lsu.edu

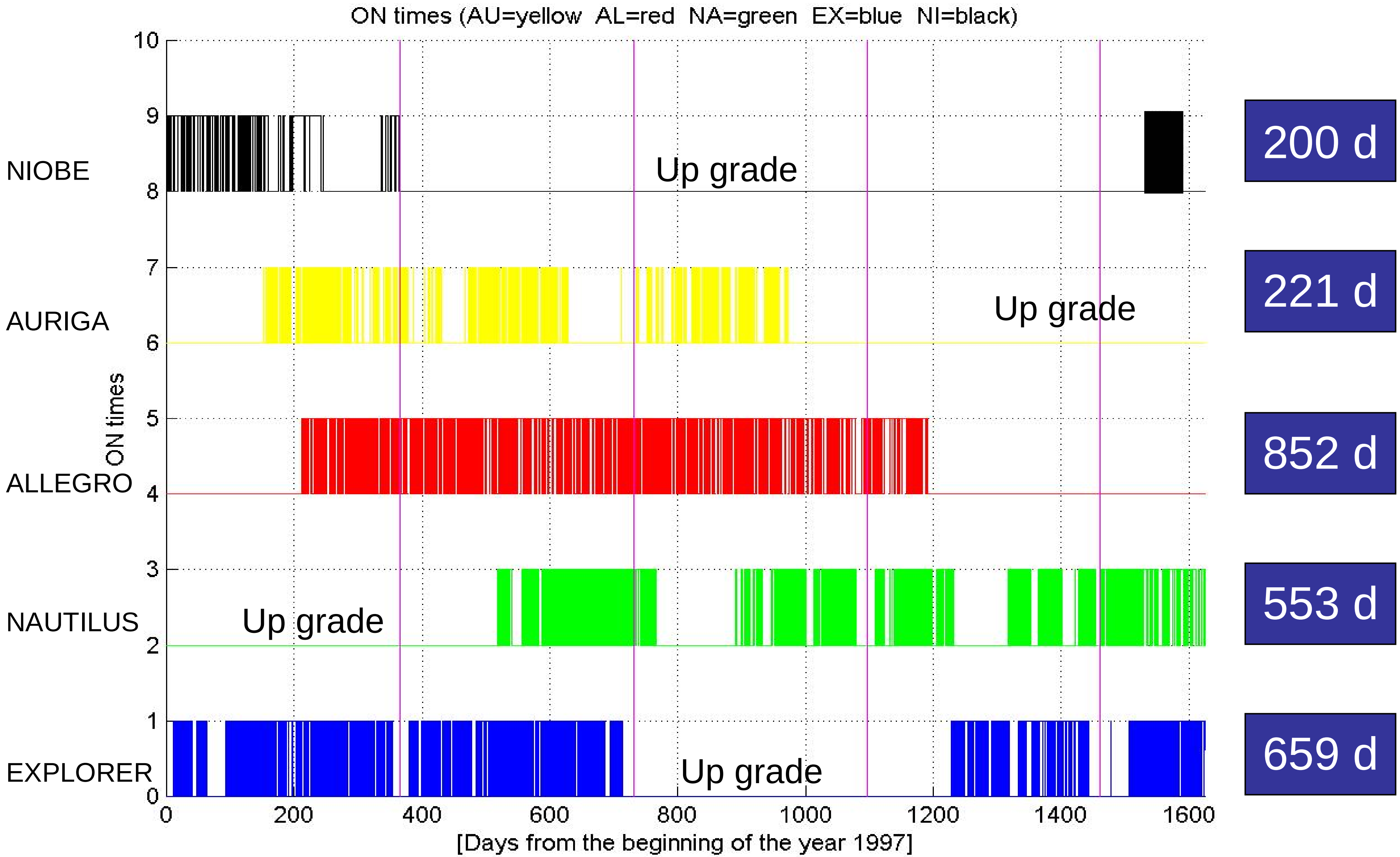
***AURIGA* INFN-LNL** http://www.auriga.lnl.infn.it

***NIOBE* ARC-UWA** http://www.gravity.pd.uwa.edu.au

***EXPLORER* INFN-CERN** http://www.roma1.infn.it/rog/rogmain.html

***NAUTILUS* INFN-LNF**

•ON times for the various detectors 1997-2001



IGEC

Detectors main features

	ALLEGRO	AURIGA	EXPLORER	NAUTILUS	NIOBE
Bar Material	Al5056	Al5056	Al5056	Al5056	Nb
Bar Mass [kg]	2296	2230	2270	2260	1500
Bar Length [m]	3.0	2.9	3.0	3.0	2.75
Freq. - [Hz]	895	912	905	908	694
Freq. + [Hz]	920	930	921	924	713
Q ± [1E6]	2	3	1.5	0.5	20
Bar Temp. [K]	4.2	0.25	2.6	0.1	5
Misalignment *	6°	5°	3°	2°	16°

* Angle between bar axis and the perpendicular to the Earth great circle closer to the five detectors.

- **almost parallel** detectors
- resonant **frequencies** span from **694 to 930 Hz**
- typical **frequency bandwidths** per each resonance ~ **1 Hz**
- typical **amplitude thresholds** for bursts search in 1997–1998 at resonances:

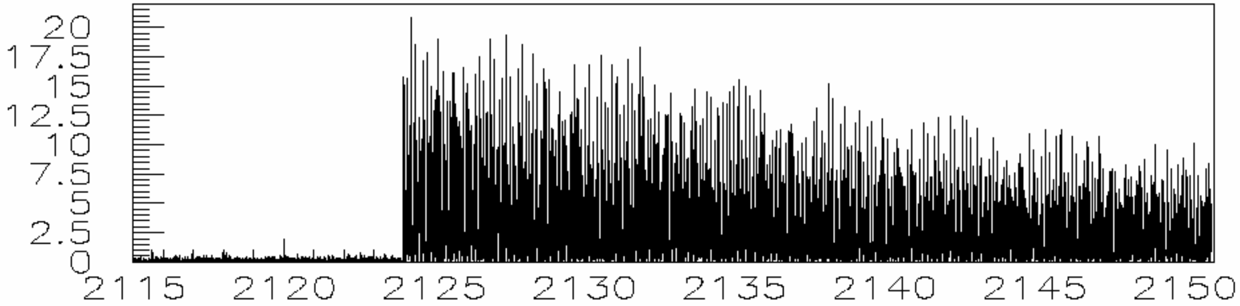
$H_{th} \sim 1.5 - 4 \times 10^{-21}$ /Hz *Fourier component of the g.w. burst amplitude*

$h_{th} \sim 1.5 - 4 \times 10^{-18}$ *strain g.w. amplitude for a conventional ~1ms burs*

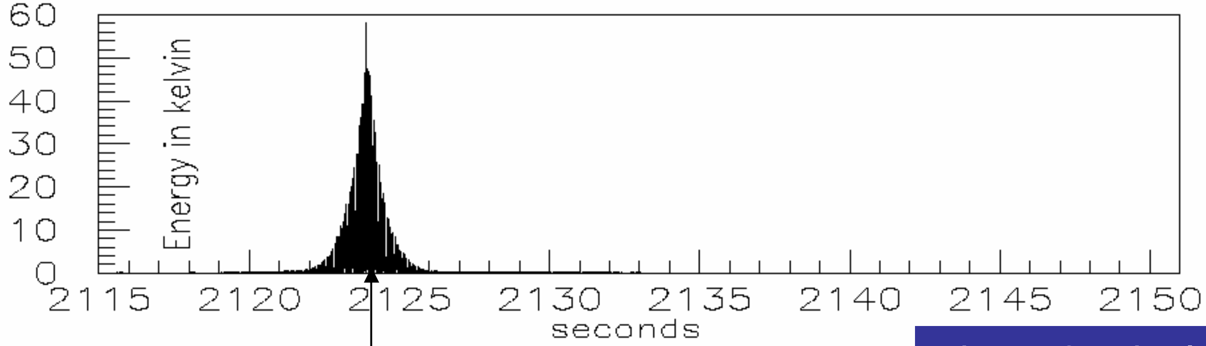
Burst event for a present bar: a millisecond pulse, a signal made by a few millisecond cycles, or a signal sweeping in frequency through the detector resonances. The burst search with bars is therefore sensitive to different kinds of gw sources such as a stellar gravitational collapse, the last stable orbits of an inspiraling NS or BH binary, its merging, and its final ringdown.

Real data: the arrival of a cosmic ray shower on NAUTILUS

Unfiltered signal (V^2)



The signal after filtering (kelvin)



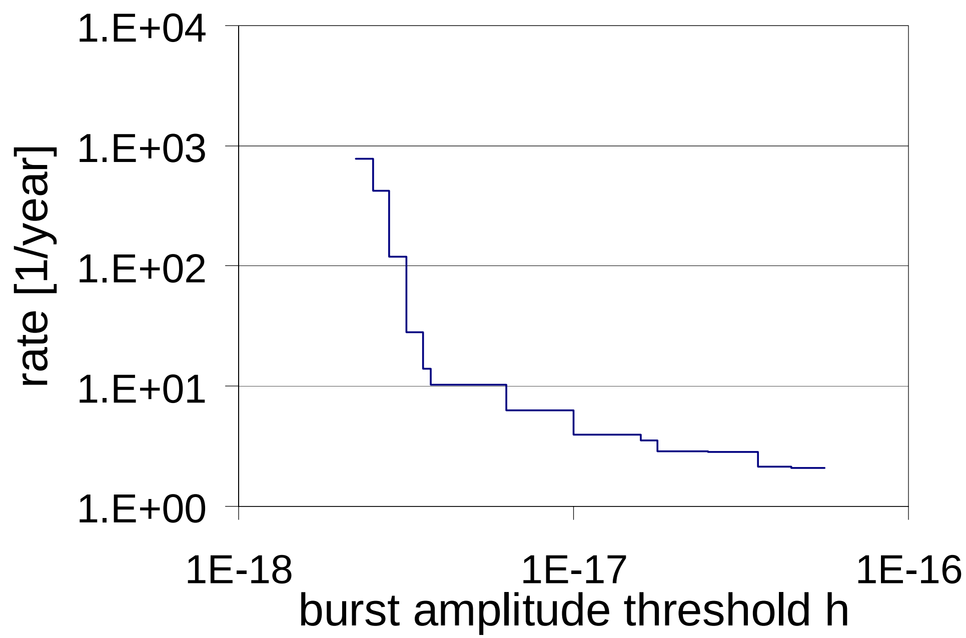
Time of arrival uncertainty ~ 1 ms

IGEC

UPPER LIMIT on the RATE of BURST GW
from the
GALACTIC CENTER DIRECTION

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

Current world record



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

Sensitivity to short bursts:

$$h_c \sim \frac{\tilde{h}_{peak}}{\sqrt{\Delta f}}$$

Detectors having the same burst sensitivity h_c

detector	*strain sens.*	Δf	h_c
EXPLORER	$2\ 10^{-21}\ Hz^{-1/2}$	40 Hz	$4\ 10^{-19}$
Equivalent	$6.4\ 10^{-21}\ Hz^{-1/2}$	400 Hz	$4\ 10^{-19}$

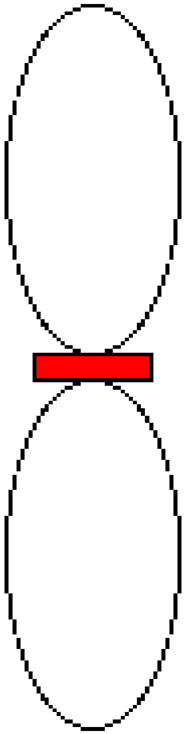
No detection of g.w. bursts above $h = 4\ 10^{-18}$

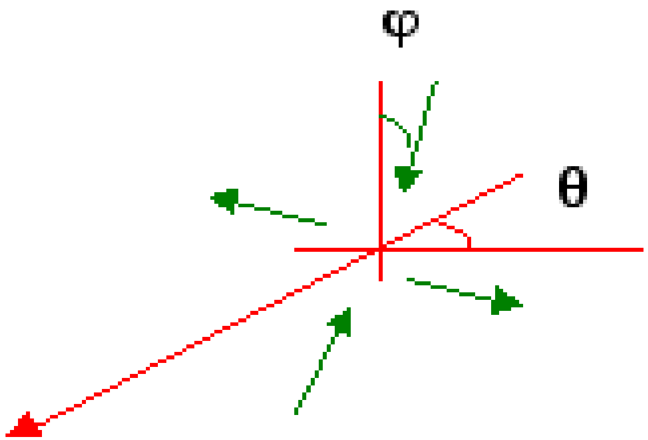
That is, 0.07 solar masses in the GC

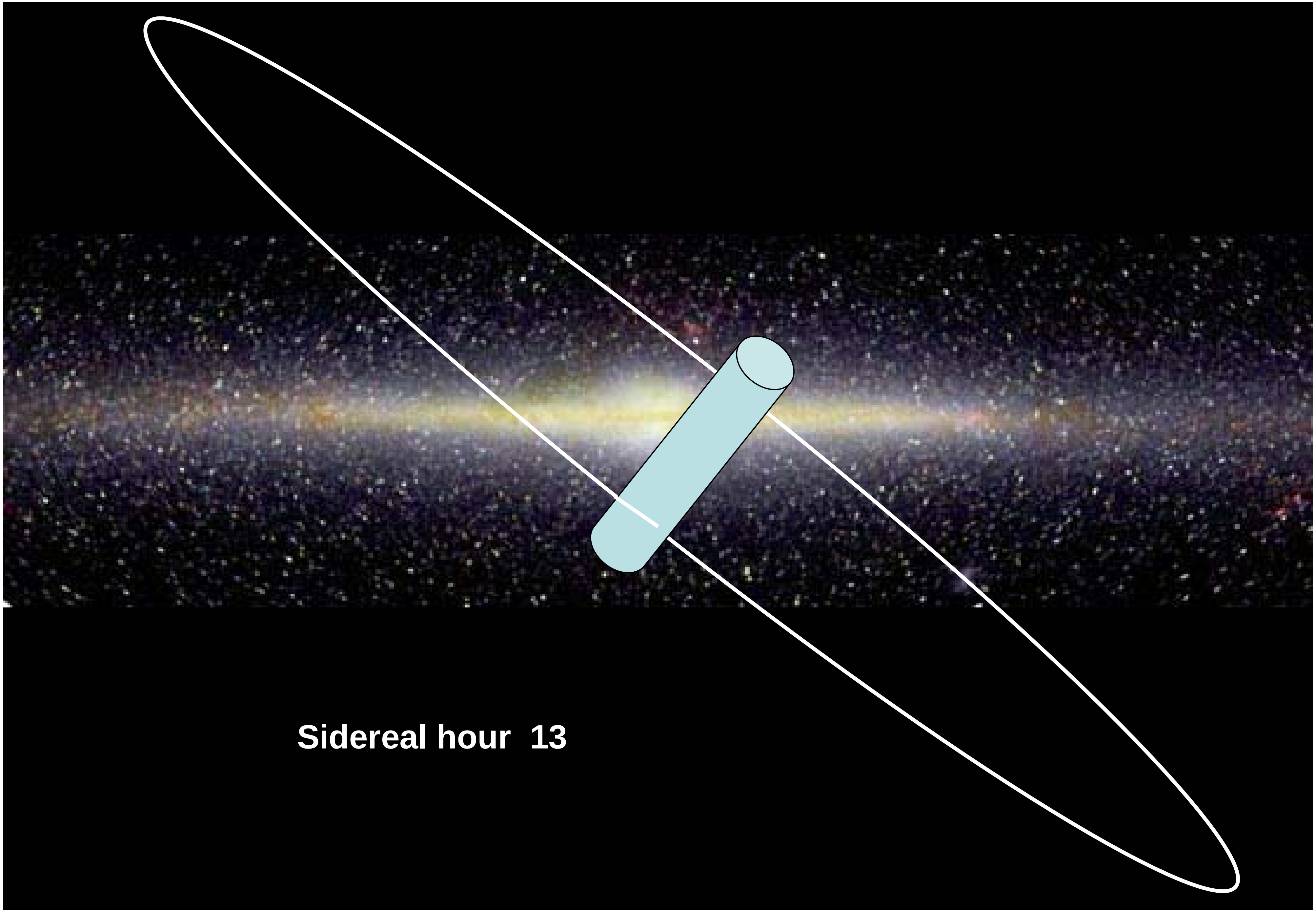
Three detectors in accidental coincidences 1 / 10^4 y

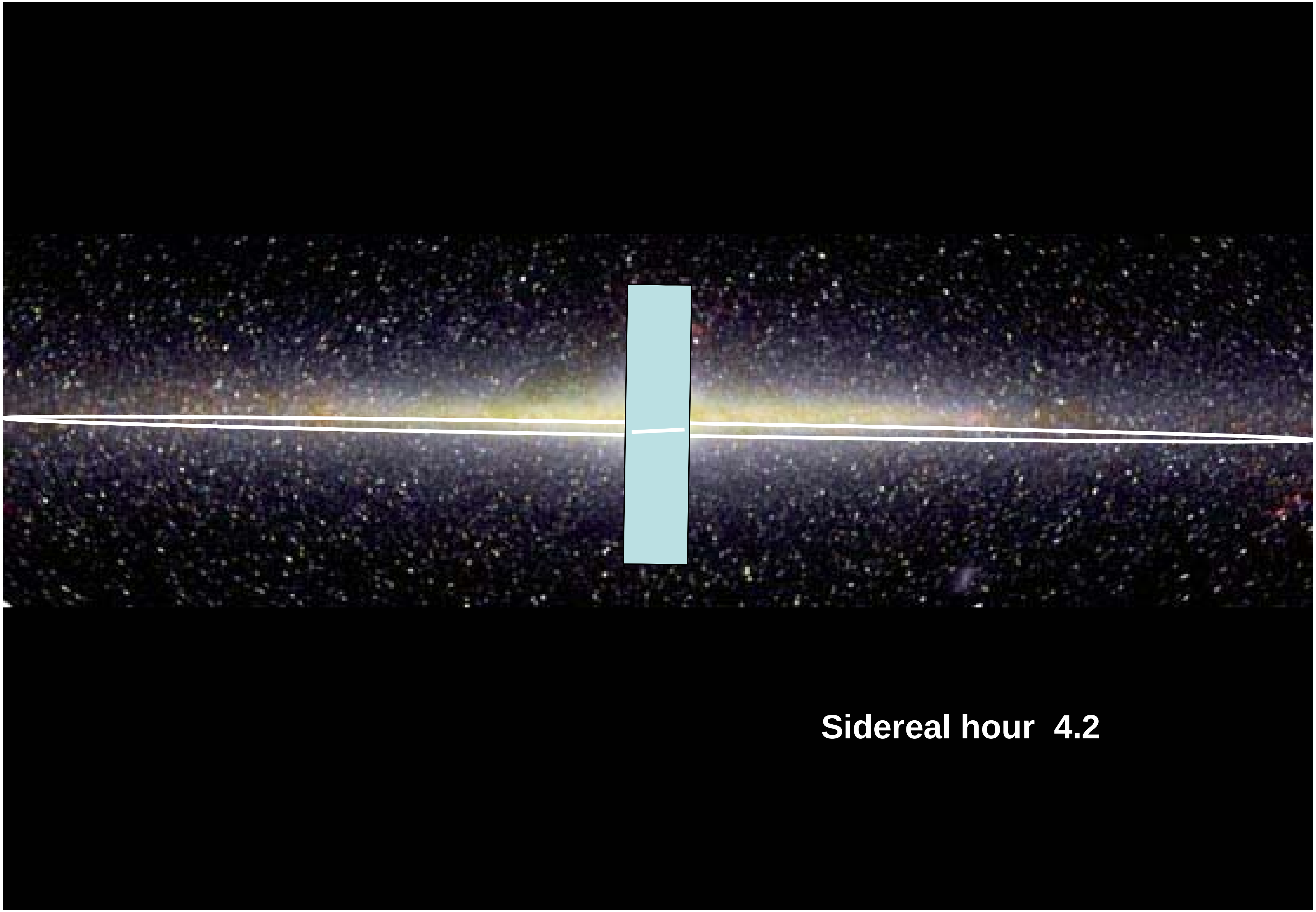
The cross section of a bar detector depends on the wave propagation direction and polarization

$$\sigma_c = \frac{8}{\pi}\frac{G}{c^3} M v_s^2 \left[\sin^4(\theta)\cos^2(2\varphi)\right]$$

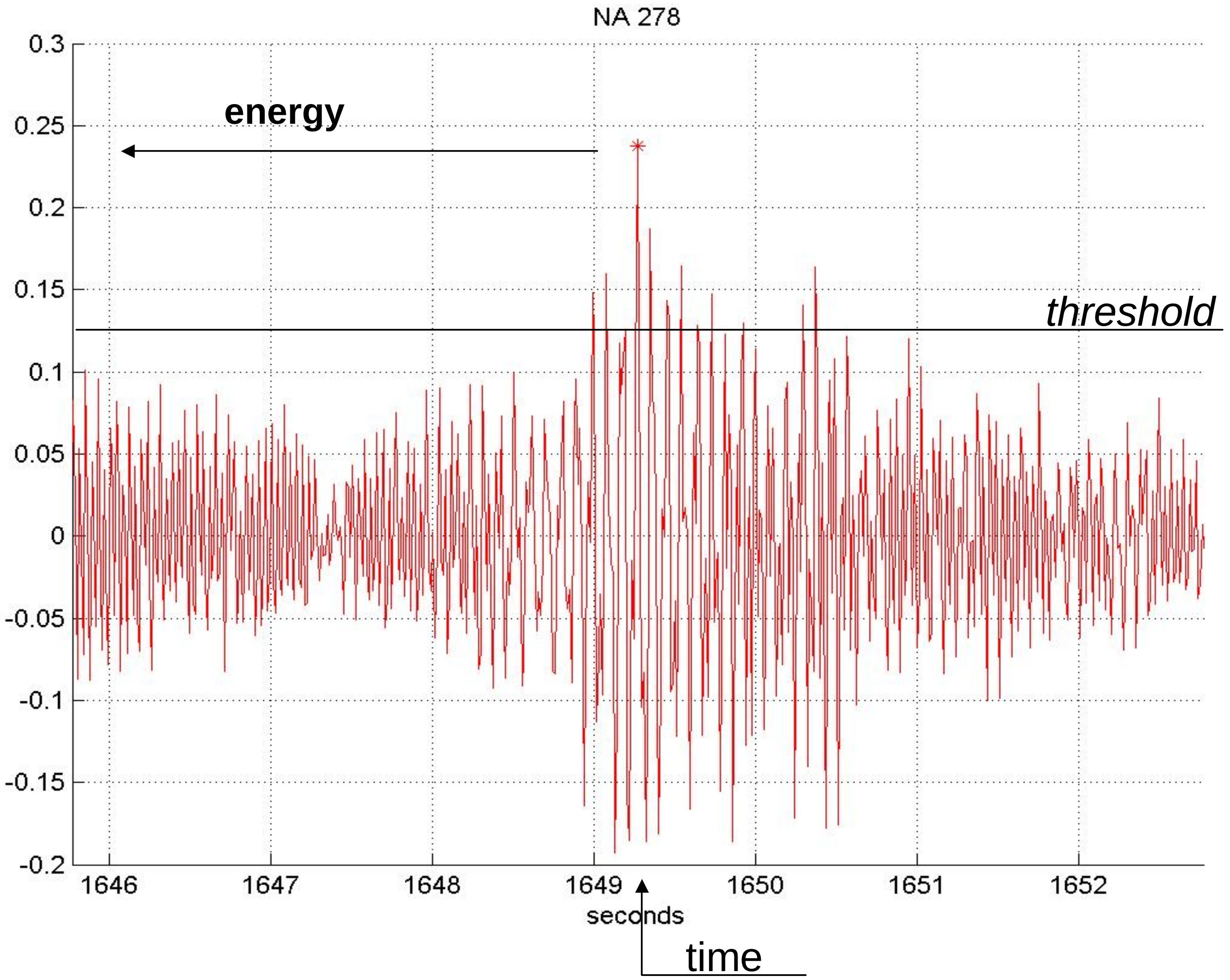




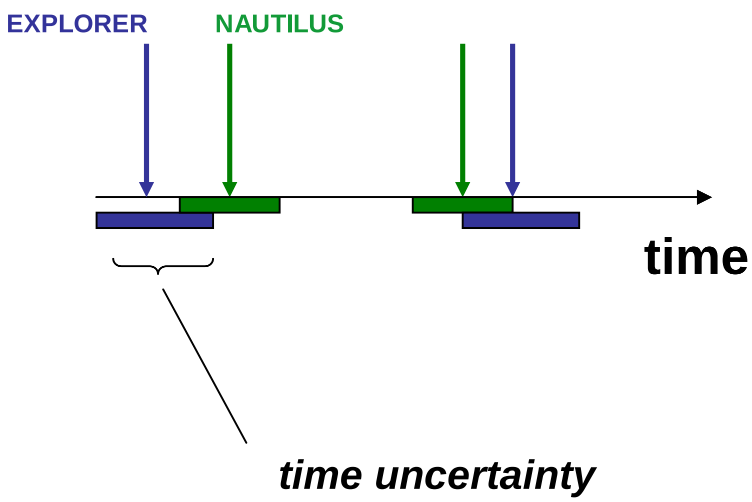

Sidereal hour 13


Sidereal hour 4.2

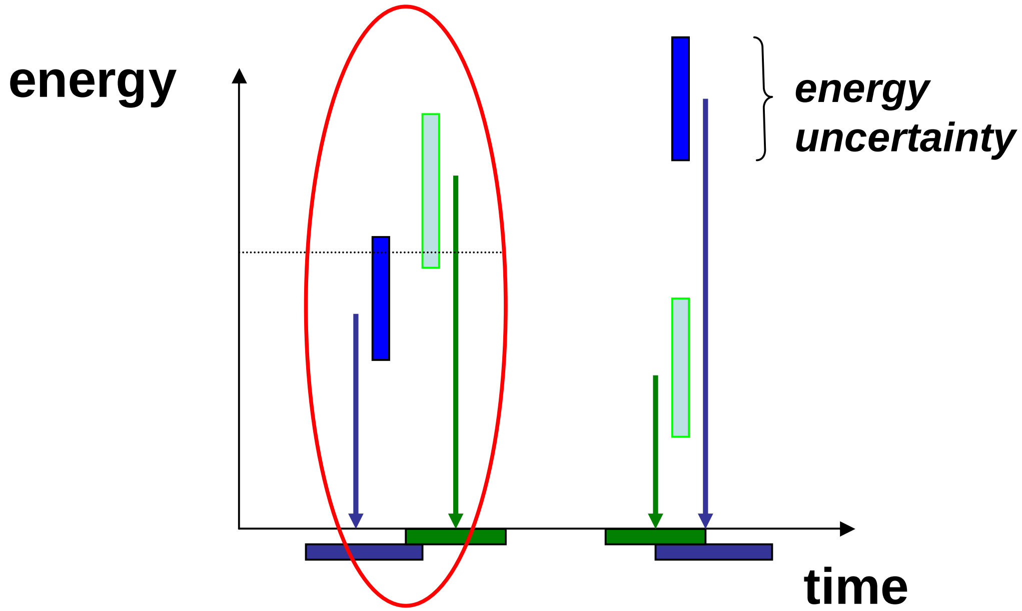
Definition of ***event***



Time coincidence



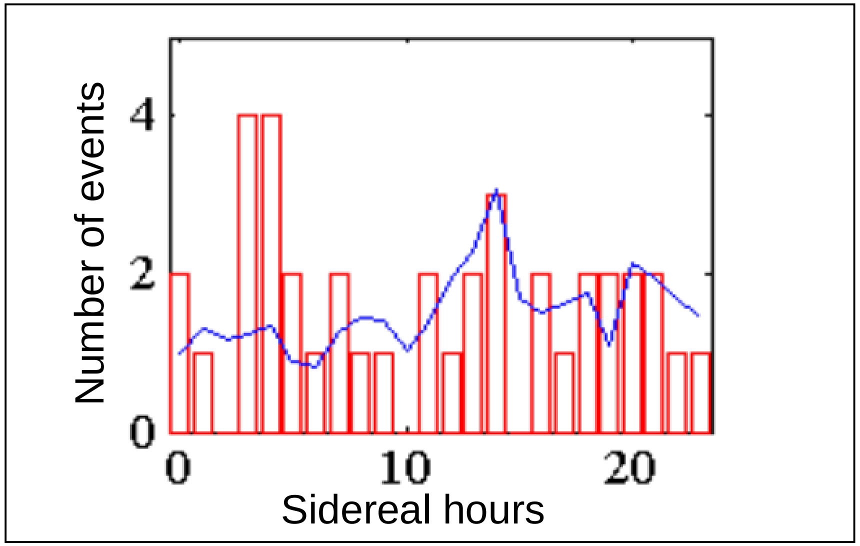
Time coincidence + energy filter (*G. Pizzella*)

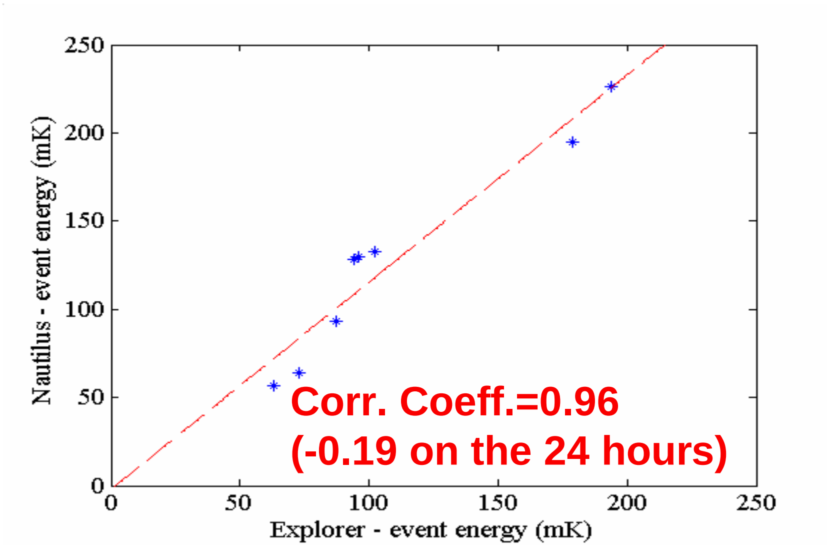


EXPLORER-NAUTILUS 2001 data analysis

*ROG Coll.: CQG **19**, 5449 (2002)*

During 2001 EXPLORER and NAUTILUS were the only two operating resonant detectors, with the best ever reached sensitivity.





Comments, analysis and studies

*L.S.Finn: CQG **20**, L37 (2003)*

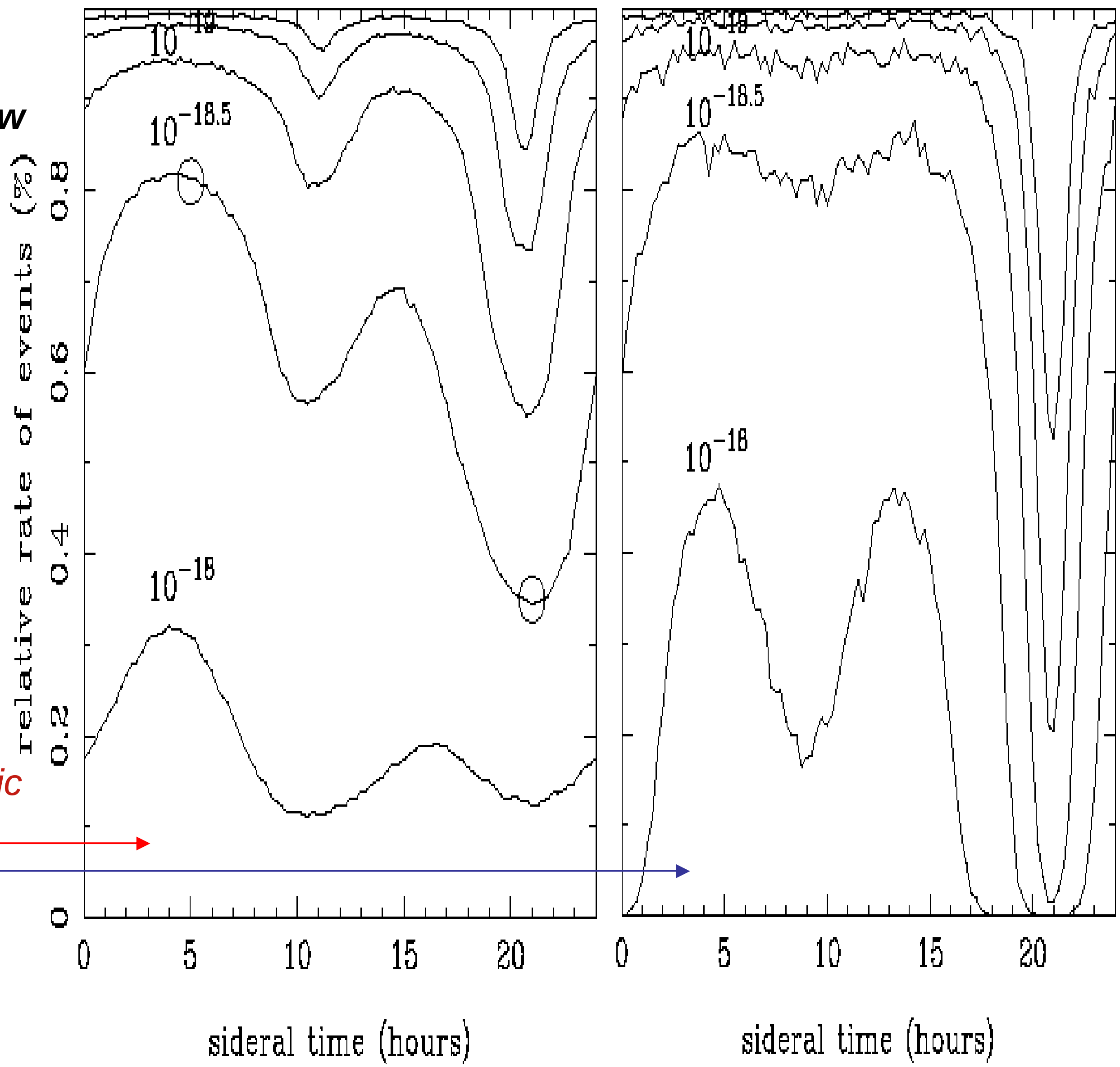
P.Astone, G.D'Agostini, S.D'Antonio: CQG 20, 365 (2003) Proc. of GWDAW 2002, gr-qc/0304096

ROG Coll.:CQG 20, 395 (2003); Proc. of GWDAW 2002, gr-qc/0304004

E. Coccia, F. Dubath, M.Maggiore gr-qc 0405047

G. Paturel, Yu.V. Barishev
Sidereal time analysis as a tool for study of the space distribution of gw sources. Astro-ph/0211604v1, A&A 398, 377 (2003)

The expected rate of events on EXPLORER for sources on the galactic disc and on the GC



Poisson probabilities

n. of hours, around 4	n_c	<n>	P(%)
2	7	1.69	0.18
4	8	3.45	2.5
6	10	5.01	3.2
8	13	6.2	1.1

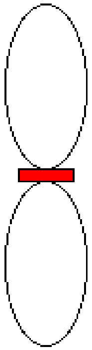
GW are described by a symmetric and traceless tensor h_{ij}

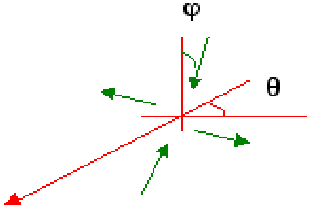
information:

h_+ h_x **H** δ h_s

ampl. of the 2 pol. states; source direction; scalar field (=0 in GR)

A resonant mass detector is characterized by those eigenmodes having the appropriate (quadrupole) symmetry

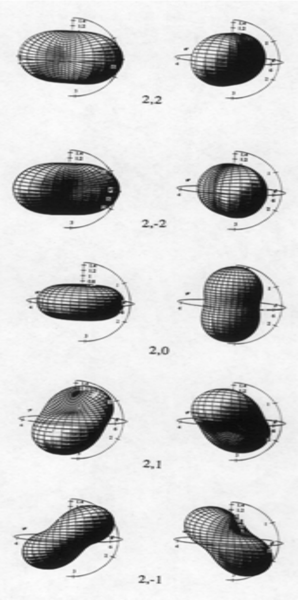




cylindrical bar

only one quadrupole mode interacts strongly with GWs

The cross section is dependent on the wave propagation direction. The *single* output is a (unknown) combination of the components (*same for an interferometer*)



sphere

five degenerate quadrupole modes (described using the basis of the five spherical harmonics Y_{2m} with m=±2,±1,0;
the same basis can be used to express h_{ij} in the equivalent spherical components h_m)

The cross section is omnidirectional

The five outputs determine the five parameters:

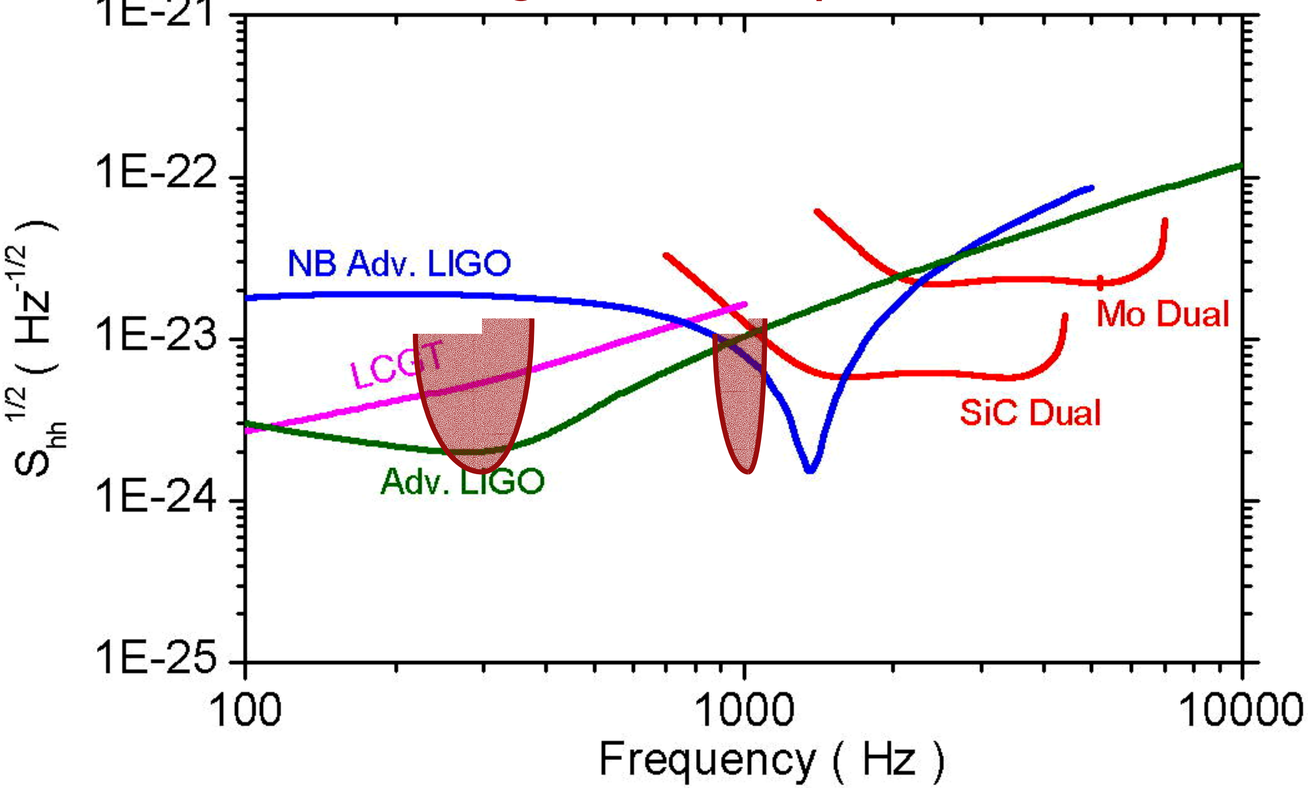
h_+ h_x **H** δ h_s

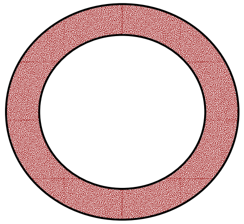
G. Frossati, E. Coccia
Cryogenics (1994)

R&D for spherical detectors

- Started on MiniGrail by ROG-Leiden
- Funded by INFN, MIUR, EU, EGO
- 3 y of design study

Goal: Large hollow sphere





D = 4.8 m;
f_1=300 Hz;
f_2=1000 Hz;
SQL

Collapses and chirps @ 200Mpc
$\Omega_{gw} \sim 10^{-9}$

DUAL: wideband high freq gw detector

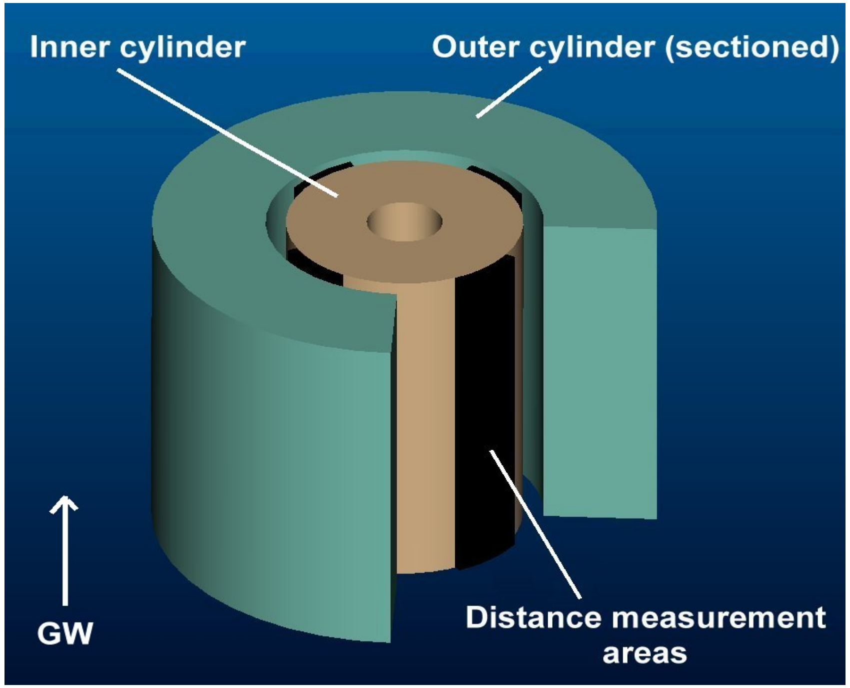
*PRL **87** 031101 (2001)* *PRD **68** 102004 (2003)*

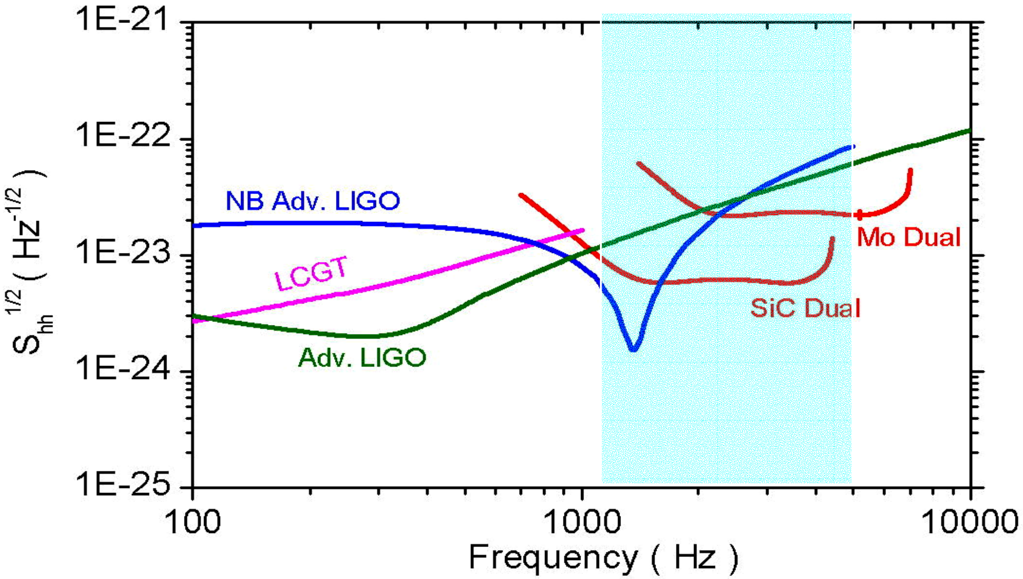
2 nested resonant masses:

***Selective** readout of differential deformation* **between** *the lowest quadrupolar modes*

⇒ gw signals add

⇒ back action noises subtract





T~0.1 K , Standard Quantum Limit

Mo Dual	16.4 ton	height 2.3 m	Ø 0.94m
SiC Dual	62.2 ton	height 3 m	Ø 2.9m

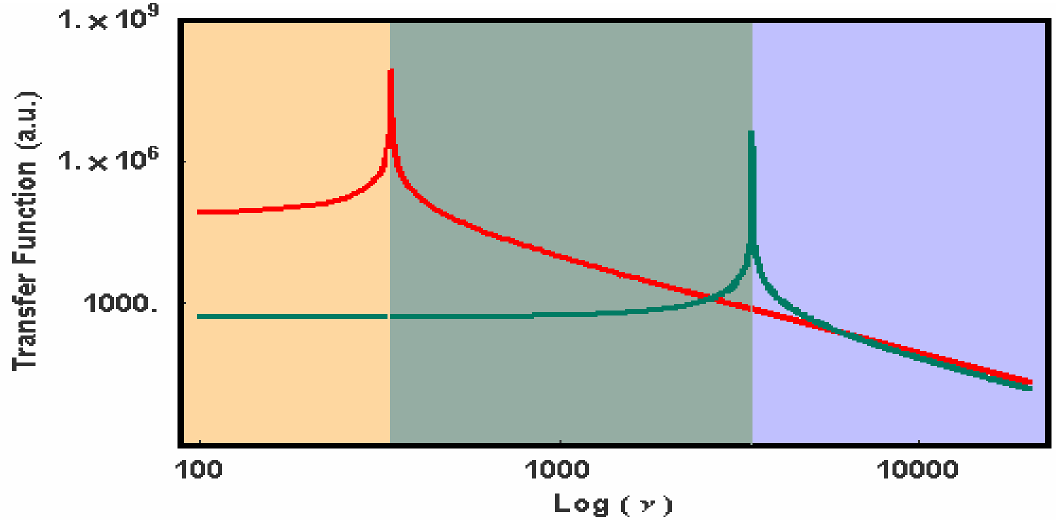
Possible sources:

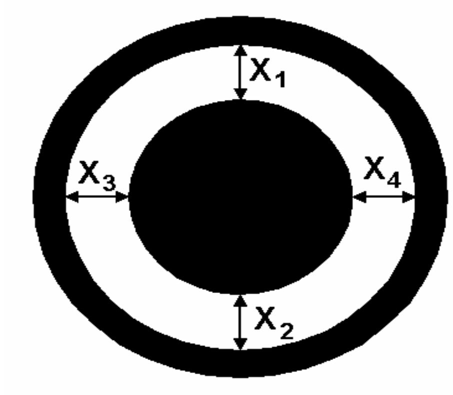
- LMXB
- BH and NS mergers and ringdown
- NS vibrations and instabilities
- EoS of superdense matter

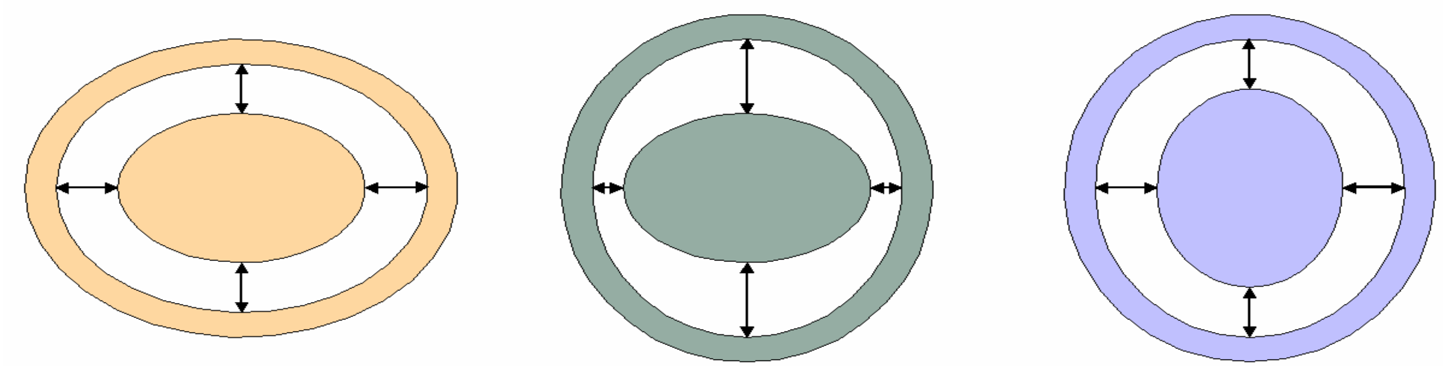
DUAL: wideband high freq gw detector

concept

distance measurement between two concentric bodies = h measurement



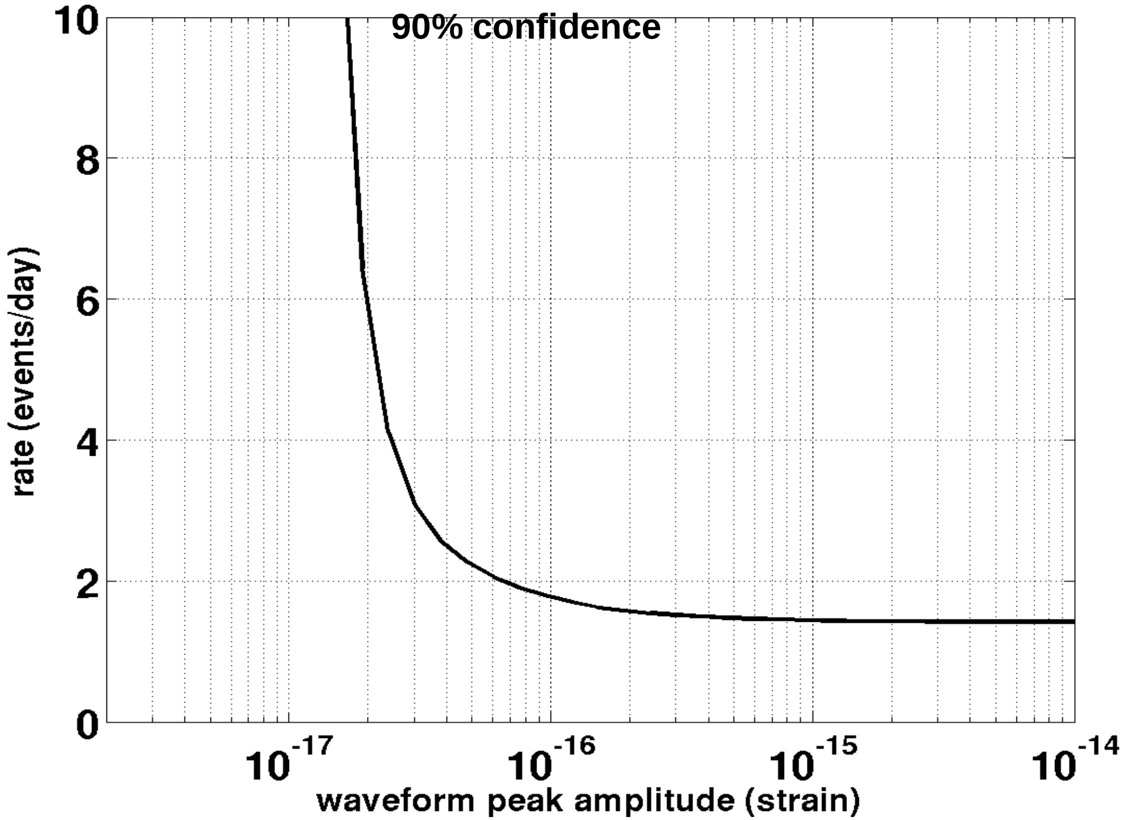




Burst Upper Limit from S1

1ms gaussian bursts

Result is derived using 'TFCLUSTERS' algorithm

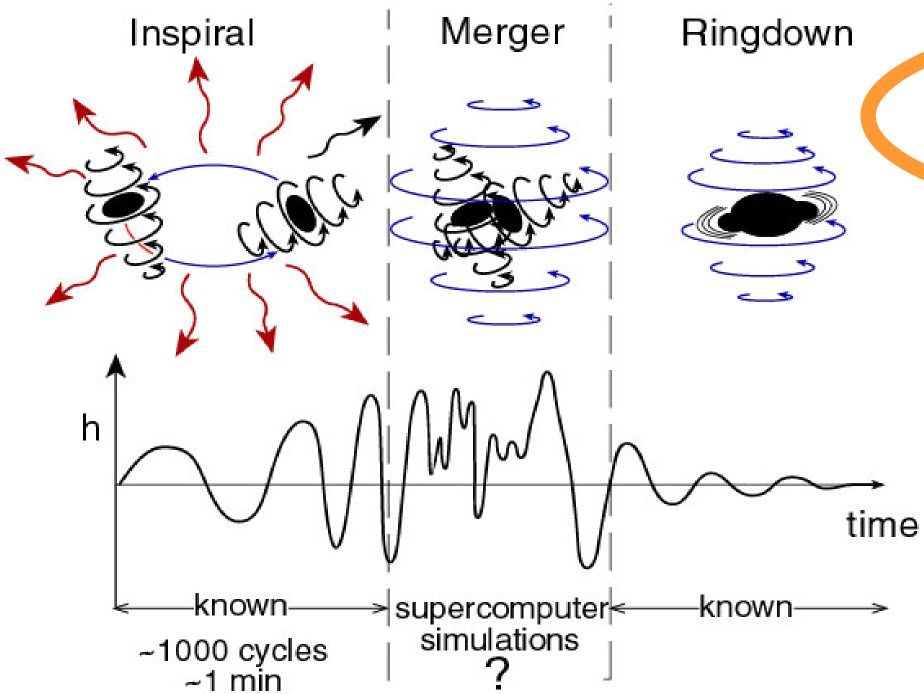


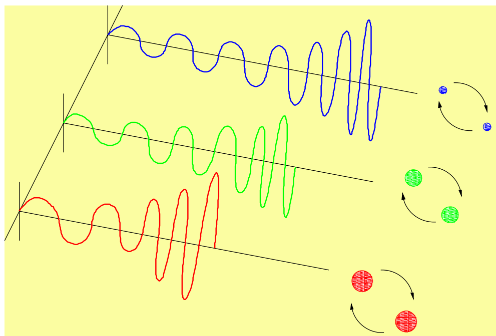
Upper limit in *strain* compared to earlier (cryogenic bar) results:

- **IGEC 2001 combined bar upper limit: < 2 events per day having $h=1x10^{-20}$ per Hz of burst bandwidth. For a 1kHz bandwidth, limit is < 2 events/day at $h=1x10^{-17}$**

- **Astone *et al.* (2002), report a 2.2 σ excess of one event per day at strain level of h ~ $2x10^{-18}$**

Compact binary collisions





- Neutron Star – Neutron Star
  - **waveforms are well described**
- Black Hole – Black Hole
  - **need better waveforms**
- Search: *matched templates*

"chirps"

Optimal Filtering

frequency domain

- Transform data to frequency domain : $\tilde{h}(f)$
- Generate template in frequency domain : $\tilde{s}(f)$
- Correlate, weighting by power spectral density of noise:

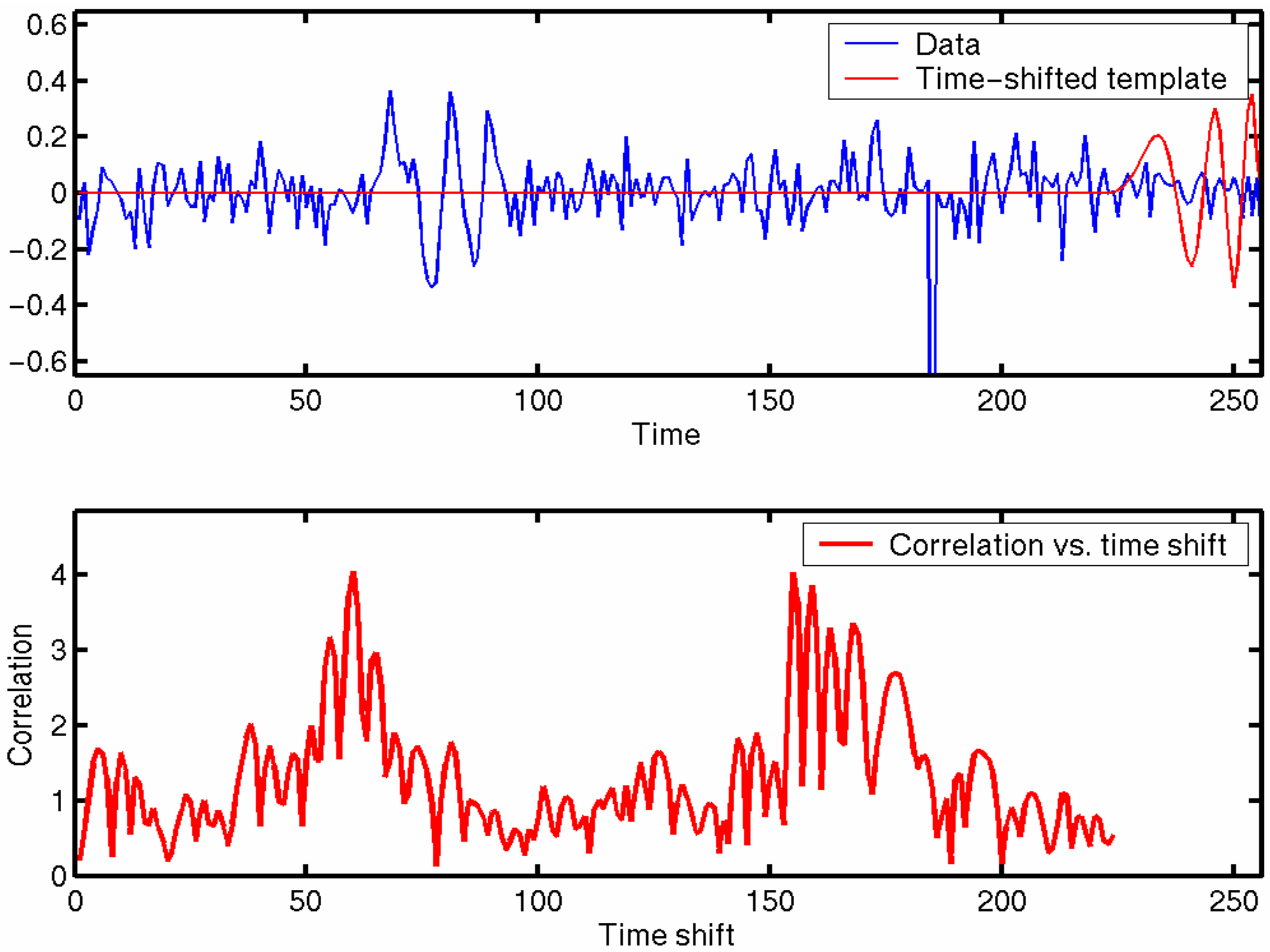
$$\frac{\tilde{s}(f)\ \tilde{h}^*(f)}{S_h(|f|)}$$

Then inverse Fourier transform gives you the filter output at all times:

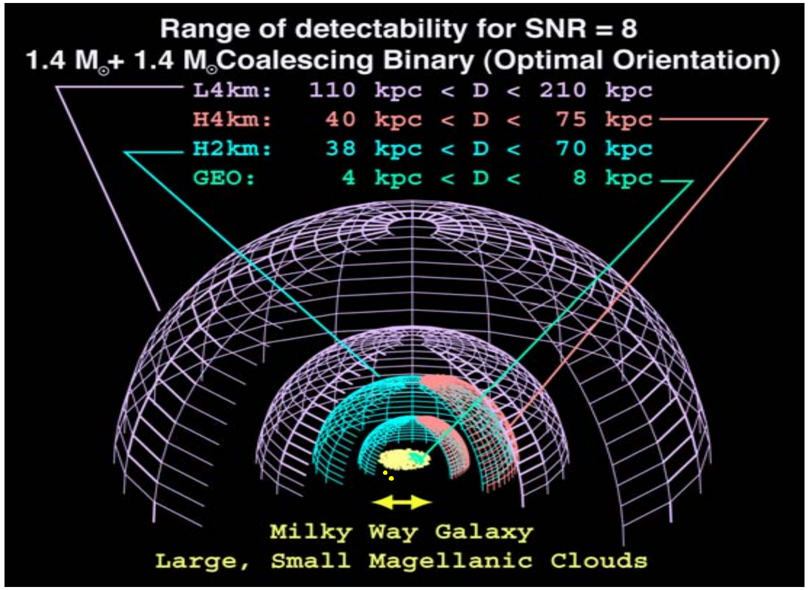
$$z(t) = 4\int_0^\infty \frac{\tilde{s}(f)\ \tilde{h}^*(f)}{S_h(|f|)}\ e^{2\pi i f t}\ df$$

Find maxima of $|z(t)|$ **over arrival time and phase**
Characterize these by *signal-to-noise ratio* (SNR) and *effective distance*

Matched Filtering



Results of Inspiral Search



Upper limit

binary neutron star

coalescence rate

LIGO S1 Data

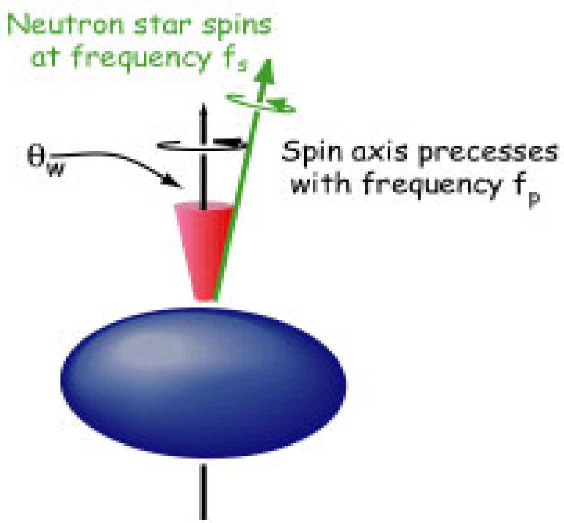
R < 160 / yr

- Previous observational limits
  - Japanese TAMA → R < 30,000 / yr
  - Caltech 40m → R < 4,000 / yr
  - Theoretical prediction R < 2×10^{-5} / yr

Detectable Range for S2 data will reach Andromeda!

Detection of Periodic Sources

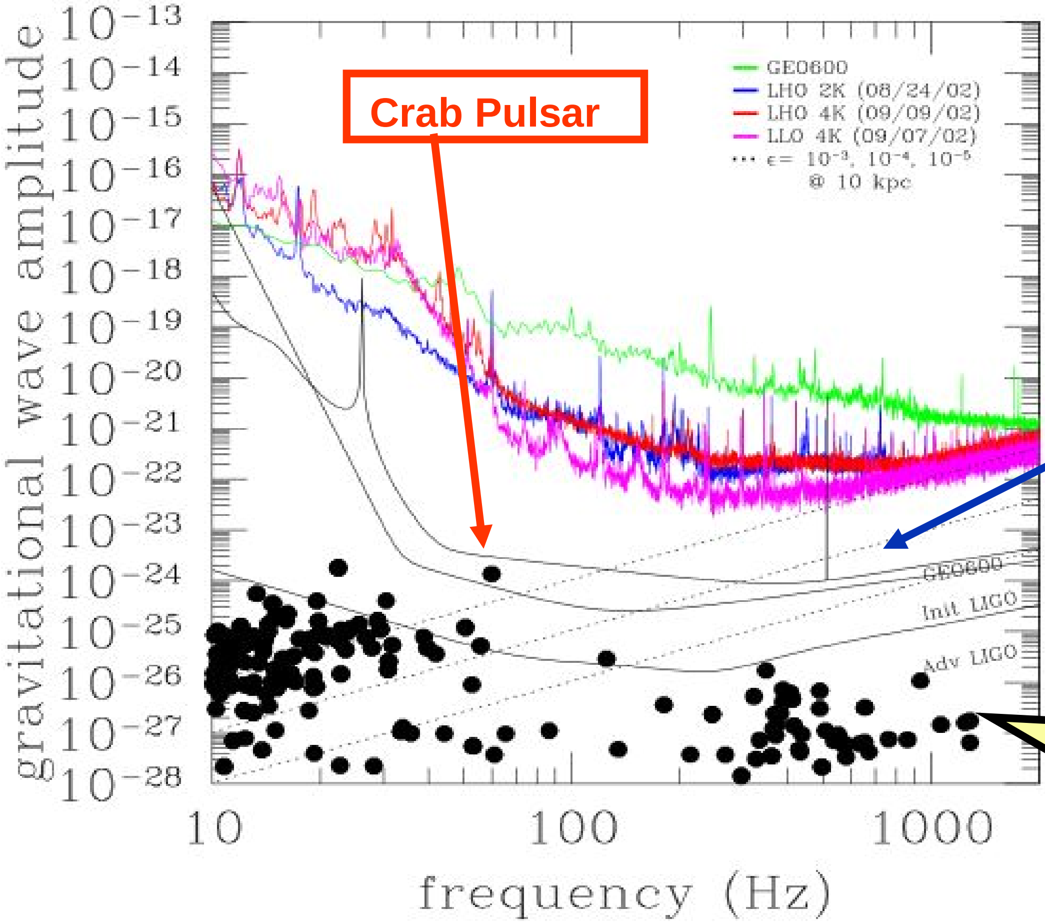
- Pulsars in our galaxy: *“periodic”*
  - search for observed neutron stars
  - all sky search (computing challenge)



- **Frequency modulation of signal due to Earth’s motion relative to the Solar System Barycenter, intrinsic frequency changes.**

- **Amplitude modulation due to the detector’s antenna pattern.**

Directed searches



NO DETECTION EXPECTED

at present sensitivities

$$\langle h_0 \rangle = 11.4 \sqrt{S_h(f_{GW})/T_{OBS}}$$

Limits of detectability for rotating NS with equatorial ellipticity $\varepsilon = \delta I/I_{zz}$: 10^{-3}, 10^{-4}, 10^{-5} @ 8.5 kpc.

PSR J1939+2134
1283.86 Hz

Two Search Methods

Frequency domain

- Best suited for large parameter space searches
- Maximum likelihood detection method + frequentist approach

Time domain

- Best suited to target known objects, even if phase evolution is complicated
- Bayesian approach

First science run --- use both pipelines for the same search for cross-checking and validation

Results: Periodic Sources

- No evidence of continuous wave emission from PSR J1939+2134.
- Summary of 95% upper limits on h:

IFO	Frequentist FDS	Bayesian TDS
GEO	$(1.94\pm0.12)\times10^{-21}$	$(2.1\pm0.1)\times10^{-21}$
LLO	$(2.83\pm0.31)\times10^{-22}$	$(1.4\pm0.1)\times10^{-22}$
LHO-2K	$(4.71\pm0.50)\times10^{-22}$	$(2.2\pm0.2)\times10^{-22}$
LHO-4K	$(6.42\pm0.72)\times10^{-22}$	$(2.7\pm0.3)\times10^{-22}$

- **Best previous results for PSR J1939+2134:**
  $h_o < 10^{-20}$ (Glasgow, Hough et al., 1983),

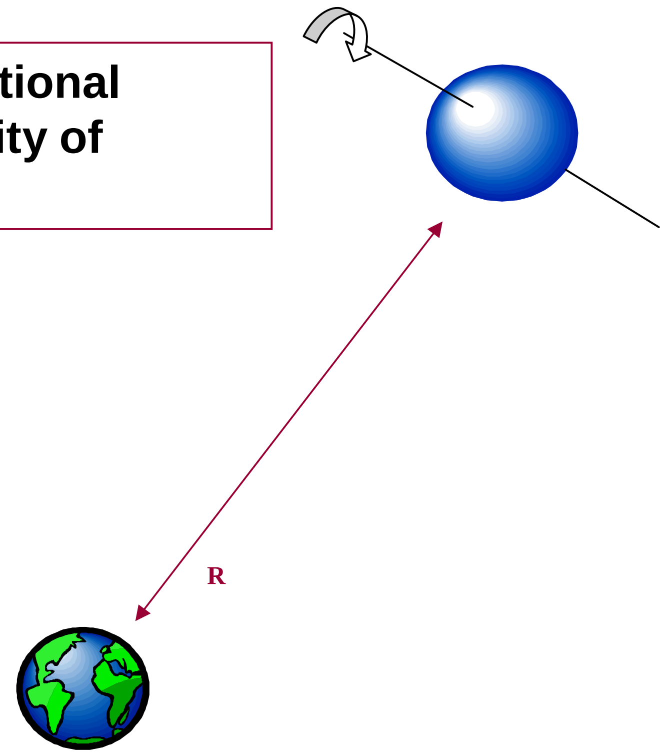
Upper limit on pulsar ellipticity

J1939+2134

moment of inertia tensor

gravitational ellipticity of pulsar

$$h_0 = \frac{8\pi^2 G}{c^4} \frac{I_{zz} f_0^2}{R} \varepsilon$$



$h_0 < 3\ 10^{-22} \rightarrow \varepsilon < 3\ 10^{-4}$

($M=1.4M_{sun}$, r=10km, R=3.6kpc)

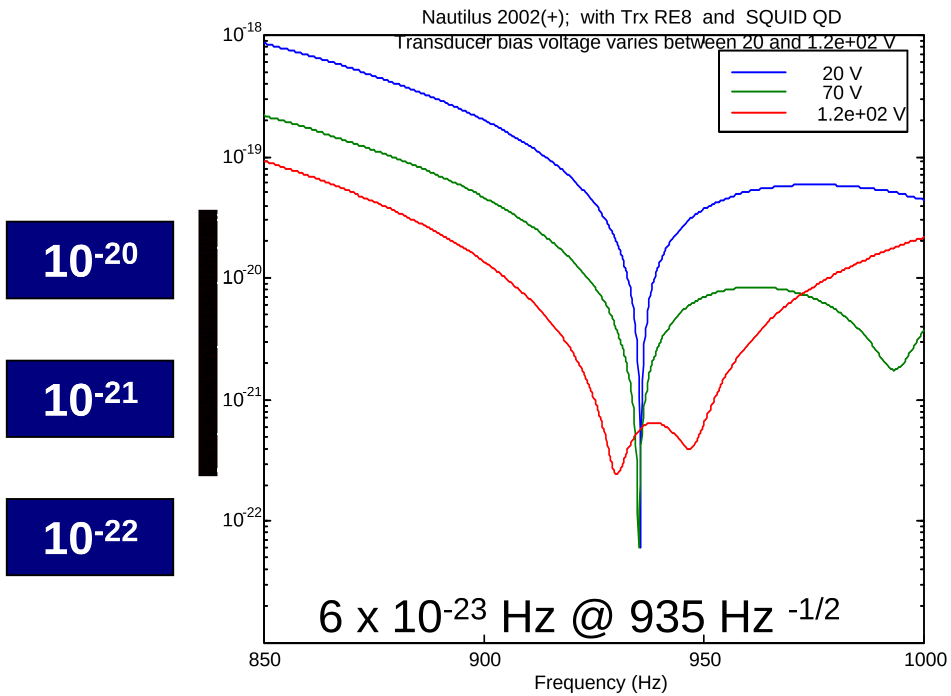
- **assuming emission due to deviation from axisymmetry:**

NAUTILUS
INFN Frascati Nat. Labs

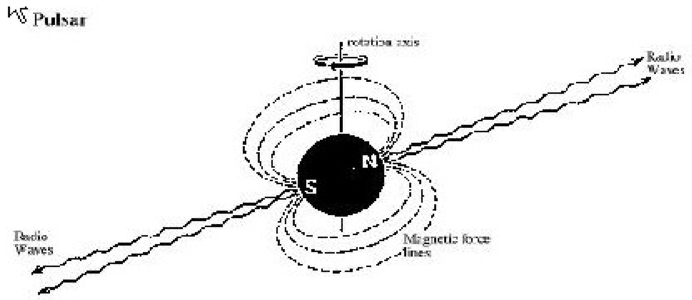
2002: Tuning of the Nautilus antenna at 935 Hz for a possible detection of GW from the pulsar associated with SN1987A

If the observed pulsar spindown is due to GW emission, we expect $h=4.7\times10^{-26}$ on Earth.

NAUTILUS can reach this sensitivity (SNR=1) with 1 month integration time if its spectral sensitivity at 935 Hz is $h=6\times10^{-23}\ Hz^{-1/2}$

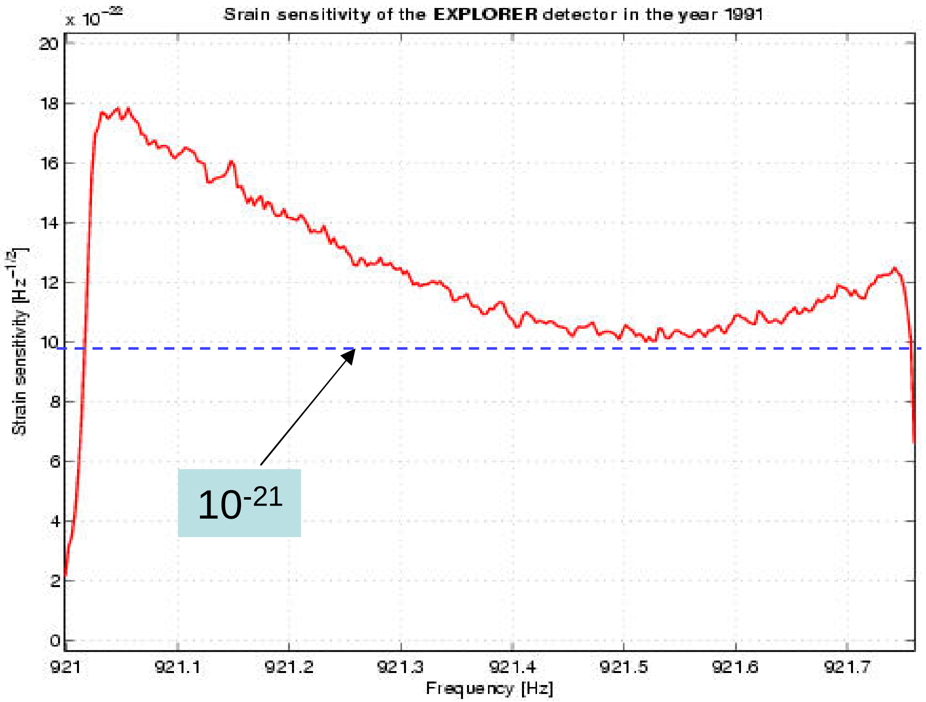


Continuous waves



Limit for signals in the GC, using 95 days of EXPLORER data
$h_c=3\cdot10^{-24}$, in the range 921.32 - 921.38 Hz (Astone et al. *PRD, 2002*)

Overall Sky Search

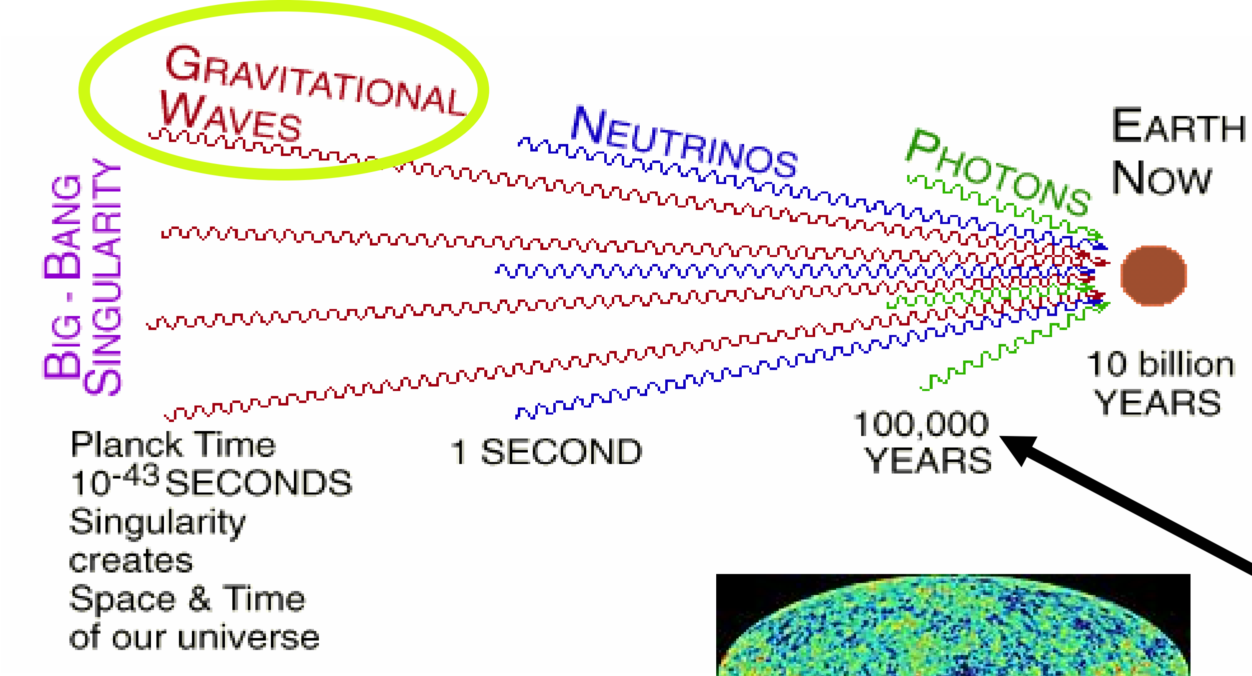


•Phase I: over 2 days of EXPLORER 1991 data in collaboration with A. Krolak and collaborators put an upper limit of $h_c=2\cdot10^{-23}$. (10^8 points, by choosing spin-down parameter and position randomly) (CQG, proc. GWDAW 2002)

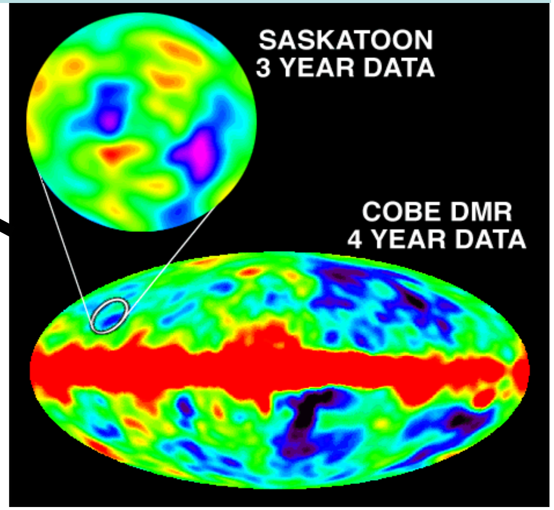
www.astro.uni.torun.pl/~kb/all-sky and www.roma1.infn.it/rog

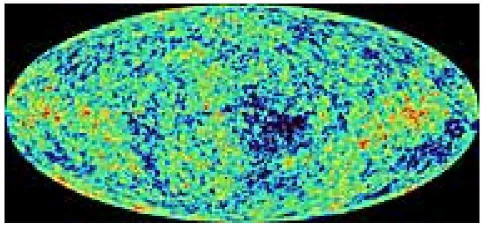
Signals from the Early Universe

stochastic background



Cosmic Microwave background





WMAP 2003

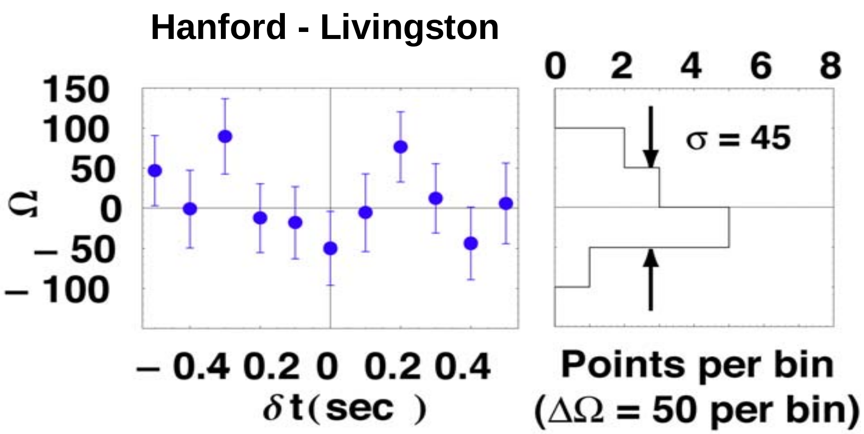
Stochastic Background

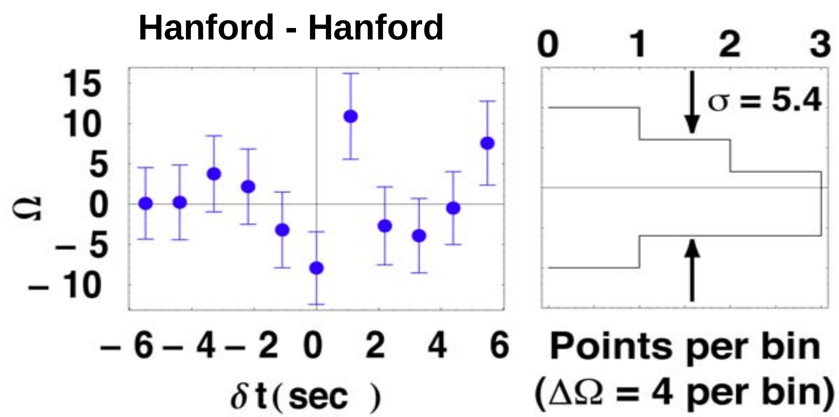
- Strength specified by *ratio of energy density in GWs to total energy density* needed to close the universe:

$$\Omega_{GW}(f) = \frac{1}{\rho_{critical}} \frac{d\rho_{GW}}{d(\ln f)}$$

First LIGO Science Data

- Detect by *cross-correlating* output of two GW detectors:



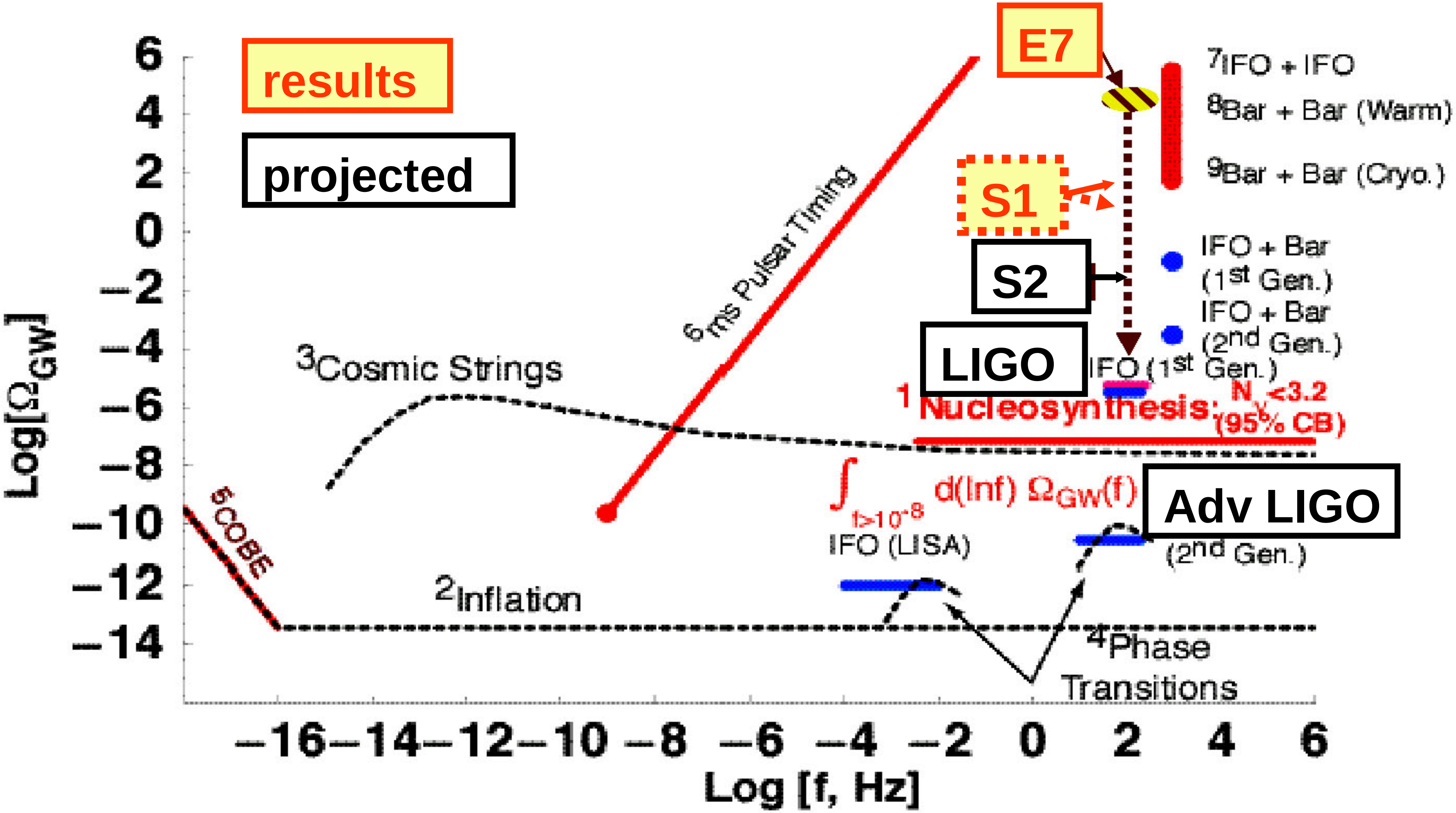


Limits: Stochastic Search

Interferometer Pair	90% CL Upper Limit	T_{obs}
LHO 4km-LLO 4km	Ω_{GW} (40Hz - 314 Hz) < 72.4	62.3 hrs
LHO 2km-LLO 4km	Ω_{GW} (40Hz - 314 Hz) < 23	61.0 hrs

- Non-negligible LHO 4km-2km (H1-H2) instrumental cross-correlation; currently being investigated.
- Previous best upper limits:
  - *Measured:* Garching-Glasgow interferometers : $\Omega_{GW}(f) < 3\times10^5$
  - *Measured*: EXPLORER-NAUTILUS (cryogenic bars): $\Omega_{GW}(907Hz) < 60$

Stochastic Background



Stochastic Background

Crosscorrelation of EXPLORER and NAUTILUS data

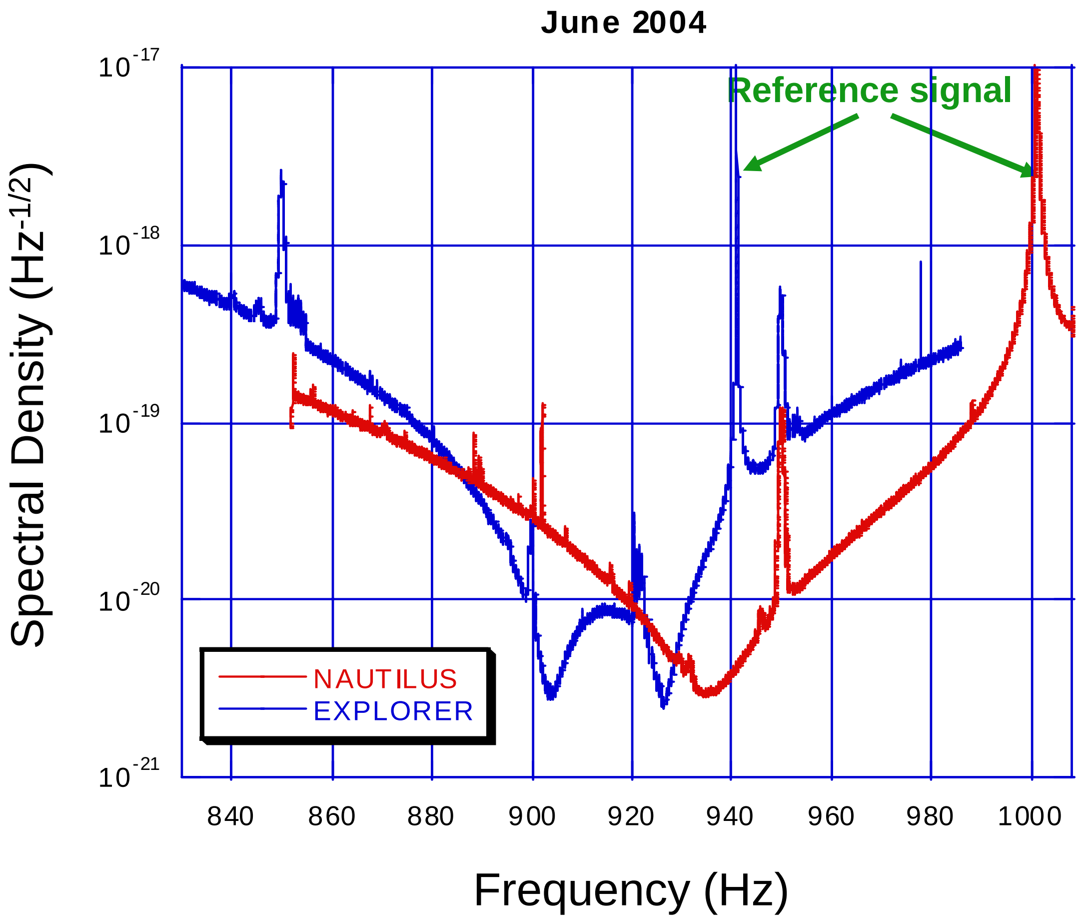
ROG Coll.: Astron. and Astrophys, 351, 811-814, (1999)

12 hours of data

Δf = 0.1 Hz

S_{12}< 1 x10^{-44} Hz^{-1}

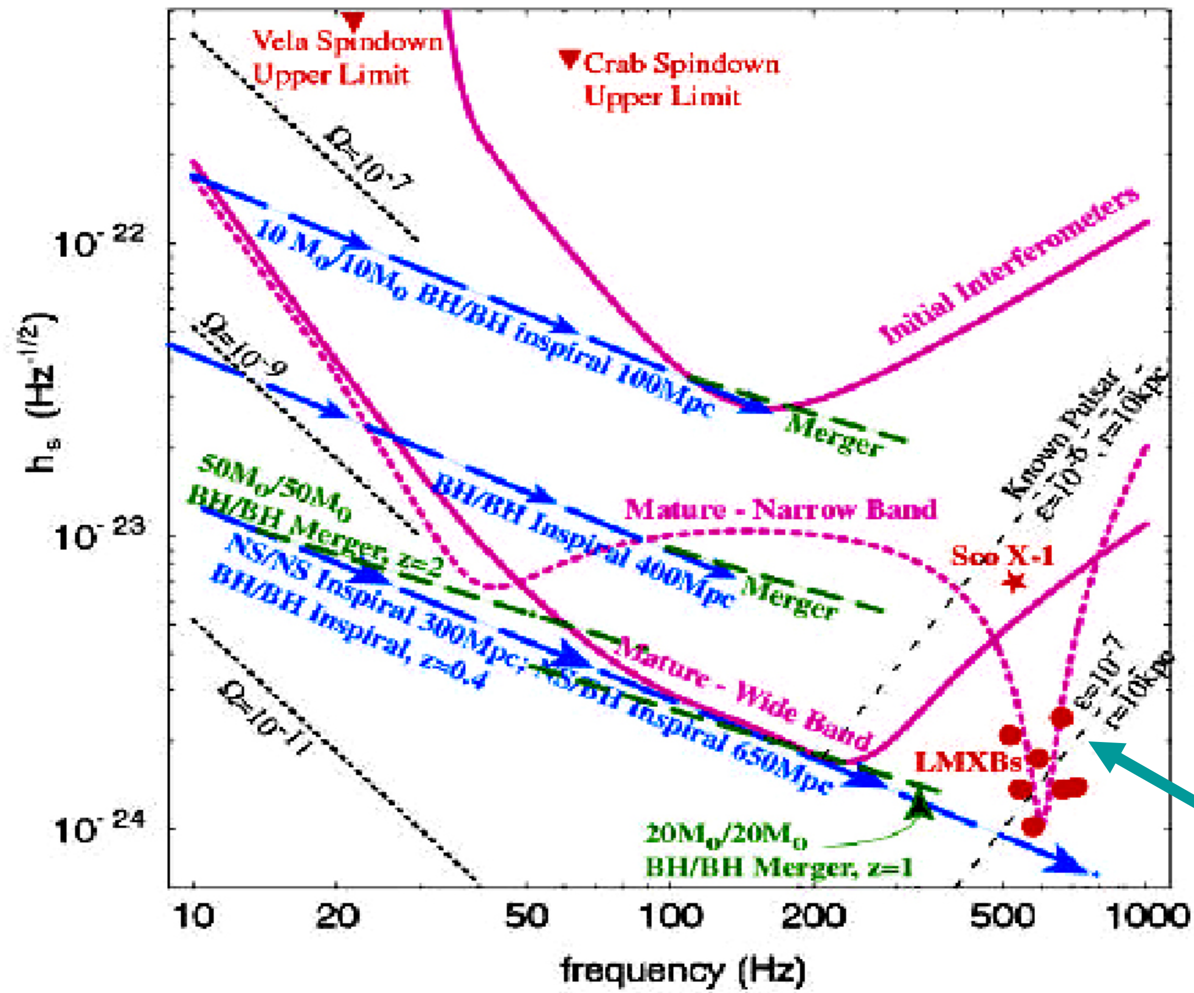
Ω_{GW} (920.2 Hz) < 60



Will optimize overlapping bandwidth by acting on the bias E field.
Potential common band is ~ 30 Hz = 300 x that exploited in `99.

If T_{obs} = 4 months $\Rightarrow$ Ω_{GW} < 0.4

Advanced LIGO



2007 +

Enhanced Systems

- **laser**
- **suspension**
- **seismic isolation**
- **test mass**

Improvement factor in rate

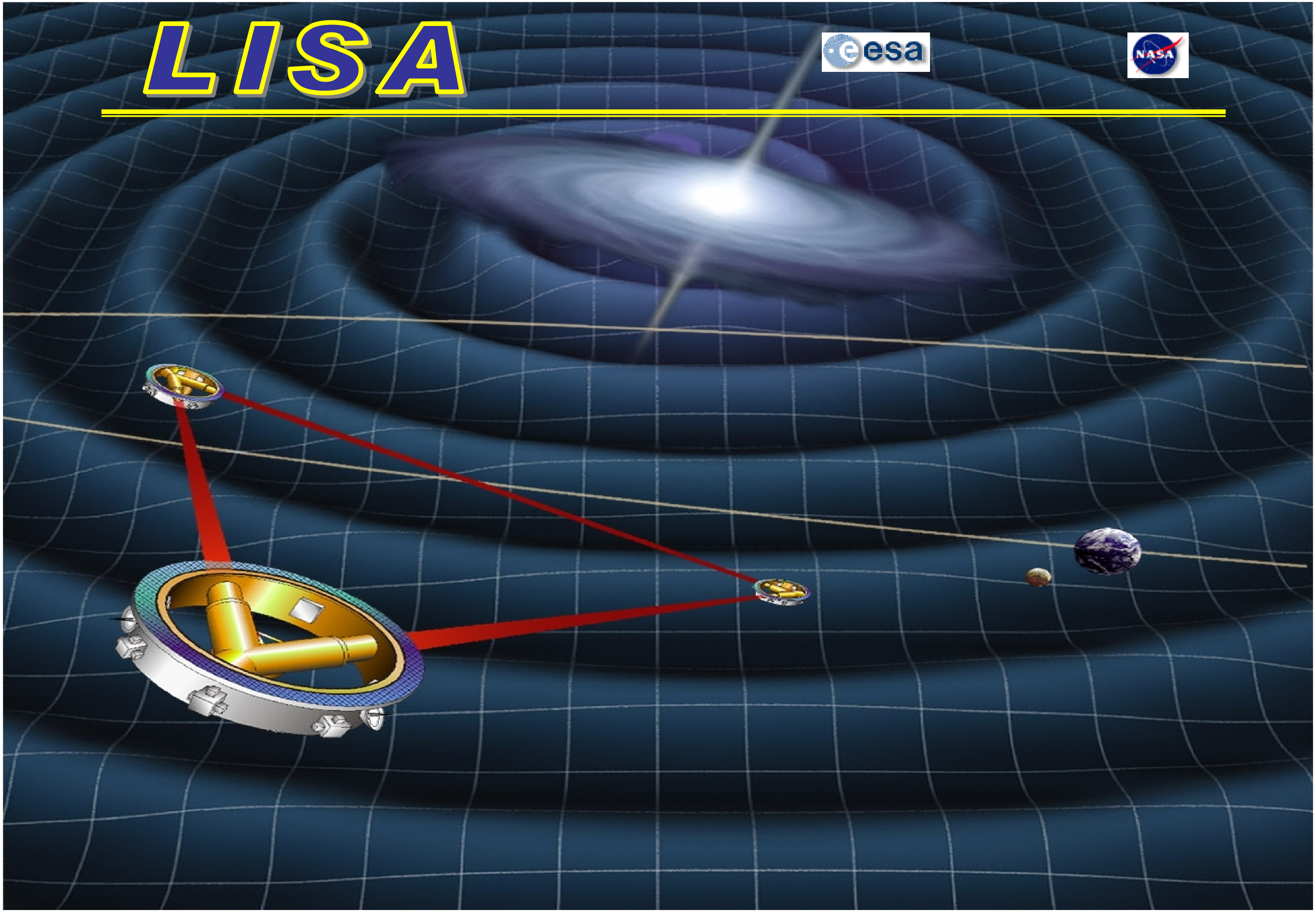
~ 10^4

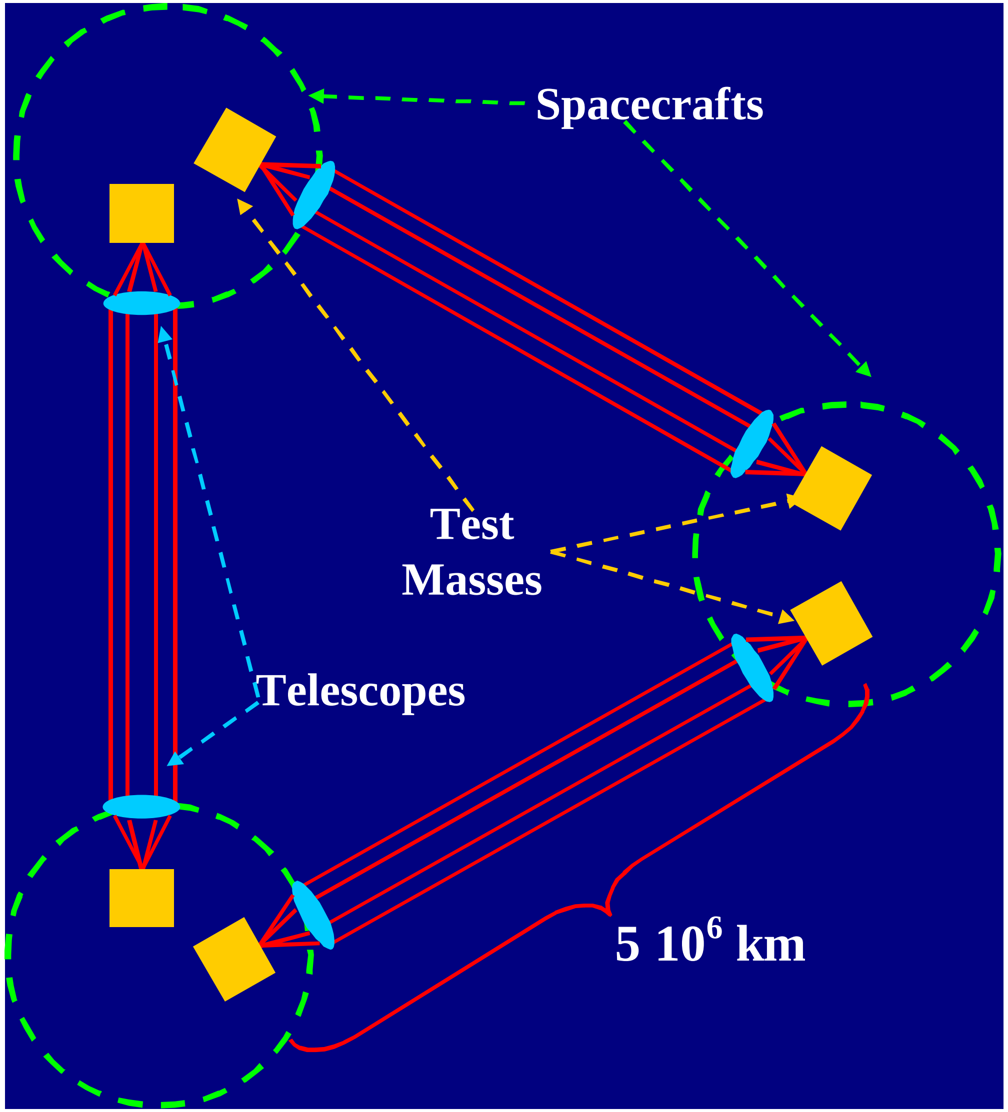
+

narrow band optical configuration

Gravitational Waves: Interferometers

- Terrestrial and Space Based Interferometers are being developed
- Ground based interferometers in U.S.(LIGO), Japan (TAMA) and Germany (GEO) have done initial searches & Italy (Virgo) is beginning commissioning.
- New Upper limits already reported for neutron binary inspirals, a fast pulsar and stochastic backgrounds
- Sensitivity improvements are rapid -- second data run was 10x more sensitive and 4x duration
- Enhanced detectors will be installed in ~ 5 years, further increasing sensitivity
- Gravitational waves should be detected within the next decade !


LISA
esa
NASA



3 pairs of "free falling" test masses

(3 10^{-15} ms^{-2} Hz$^{-1/2}$ @ 0.1 mHz)

3 "test-mass follower" shielding spacecraft

2 semi-independent 5 10^6 km Michelson Interferometers with Laser Transponders

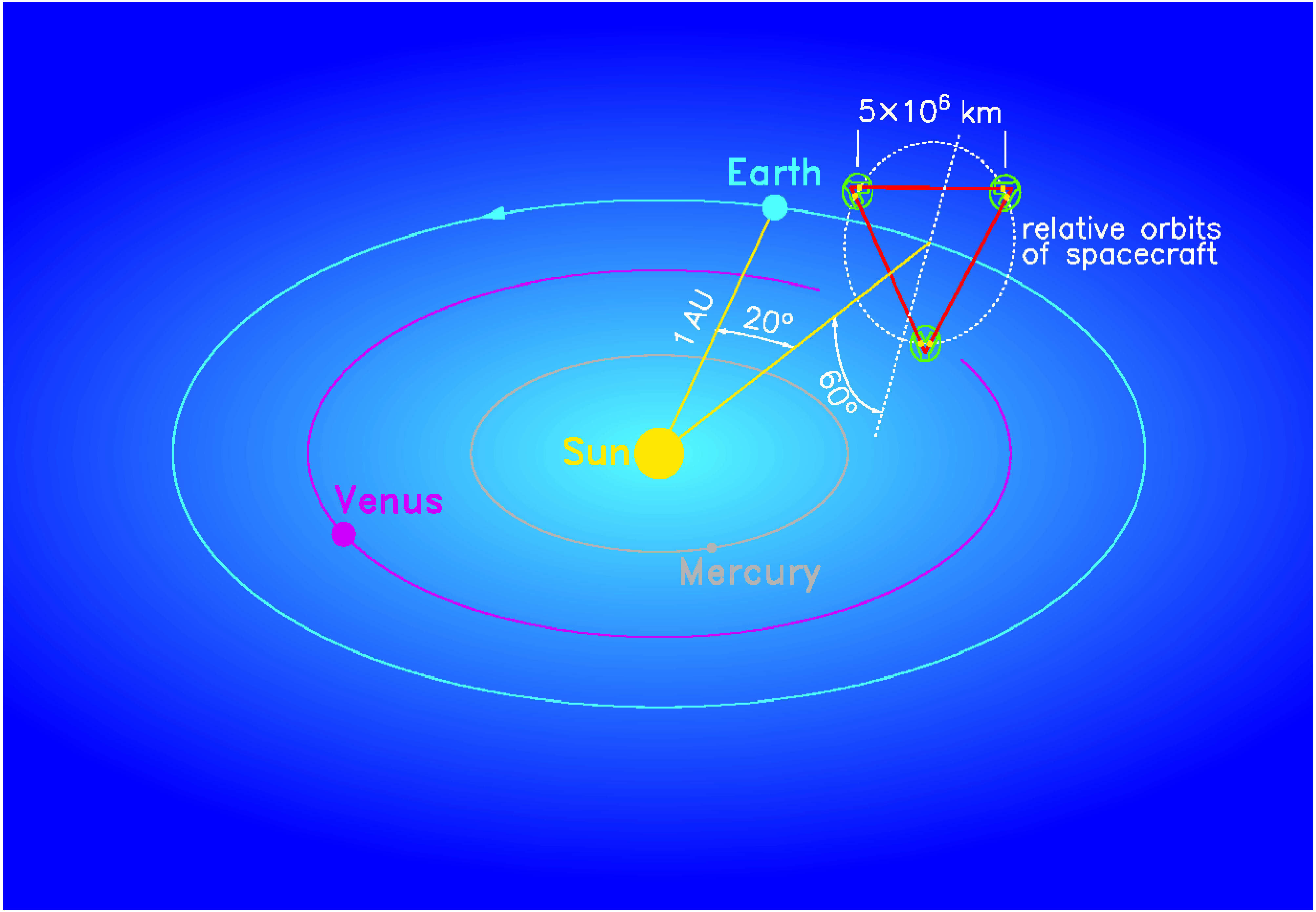
(40 pm Hz$^{-1/2}$)

Goal: GW at

0.1 mHz – 0.1 Hz

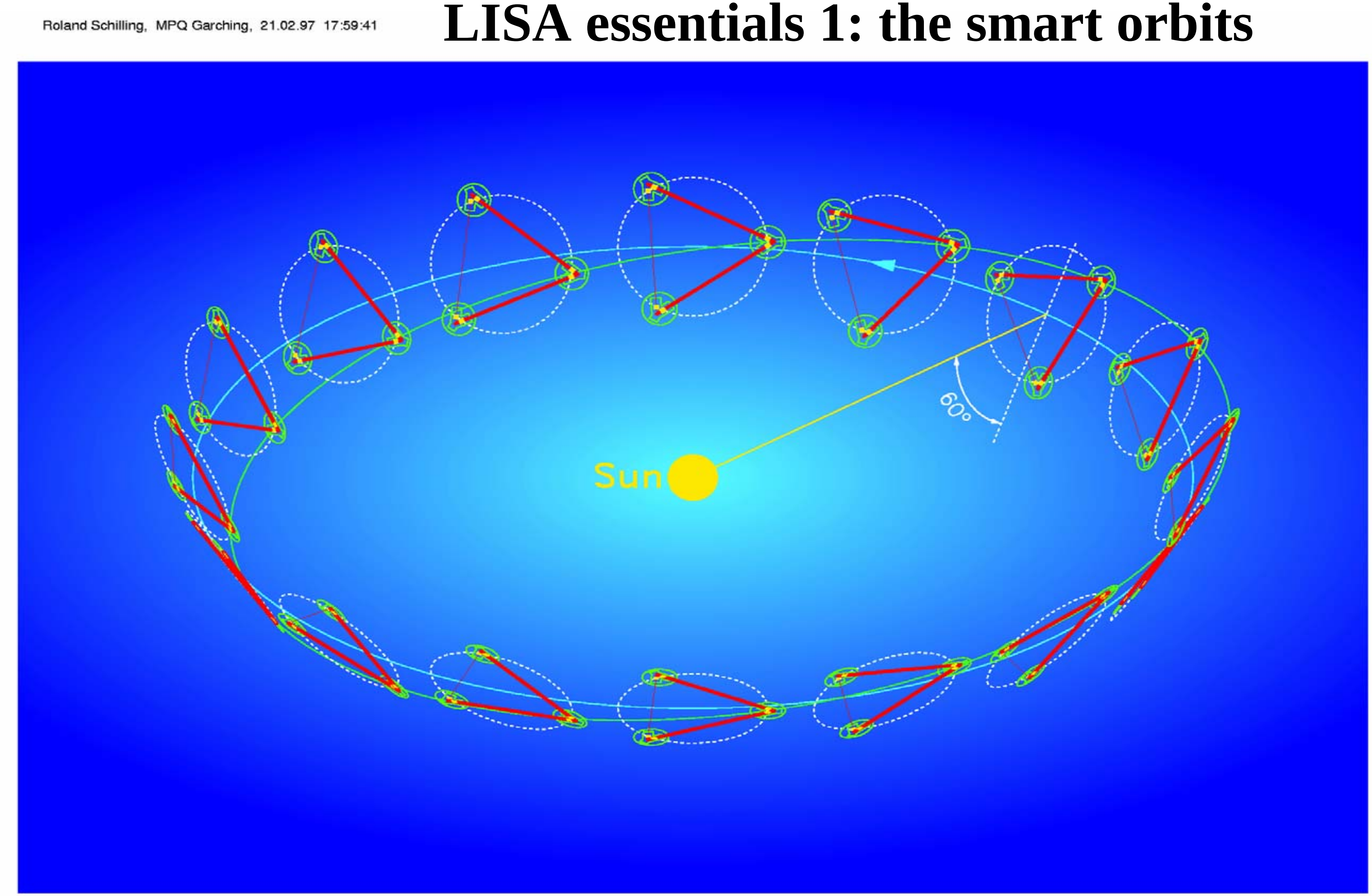
Sensitivity

4 10^{-21} Hz$^{-1/2}$ @ 1 mHz

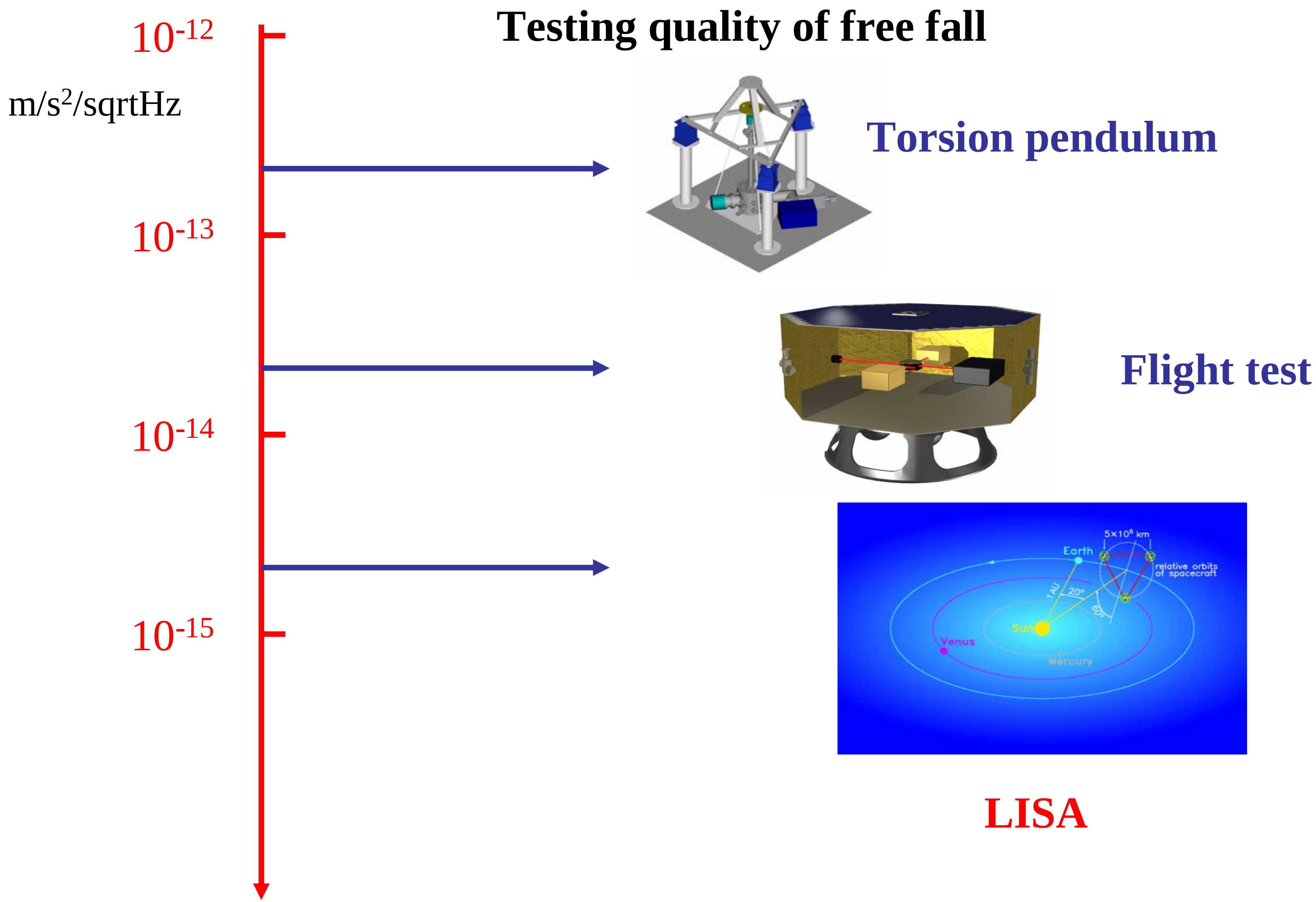


5×10^6 km
Earth
relative orbits
of spacecraft
1 AU
20°
60°
Sun
Venus
Mercury

LISA essentials 1: the smart orbits

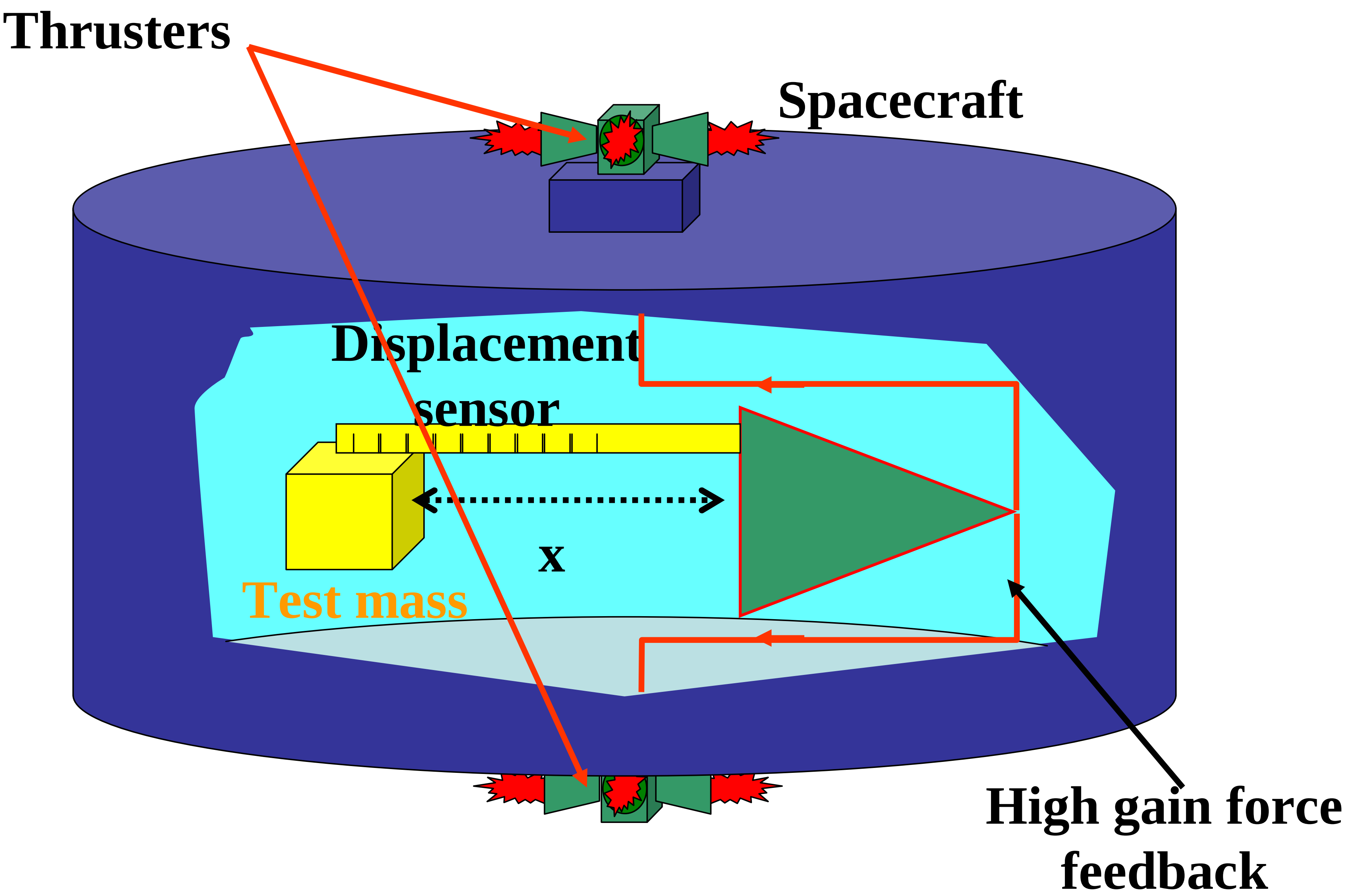


Keeping spacecraft formation and exploring the sky



Testing quality of free fall
10-12
m/s2/sqrtHz
10-13
10-14
10-15
Torsion pendulum
Flight test
5×10^6 km
Earth
relative orbits of spacecraft
1 AU
20°
60°
Sun
Venus
Mercury
LISA

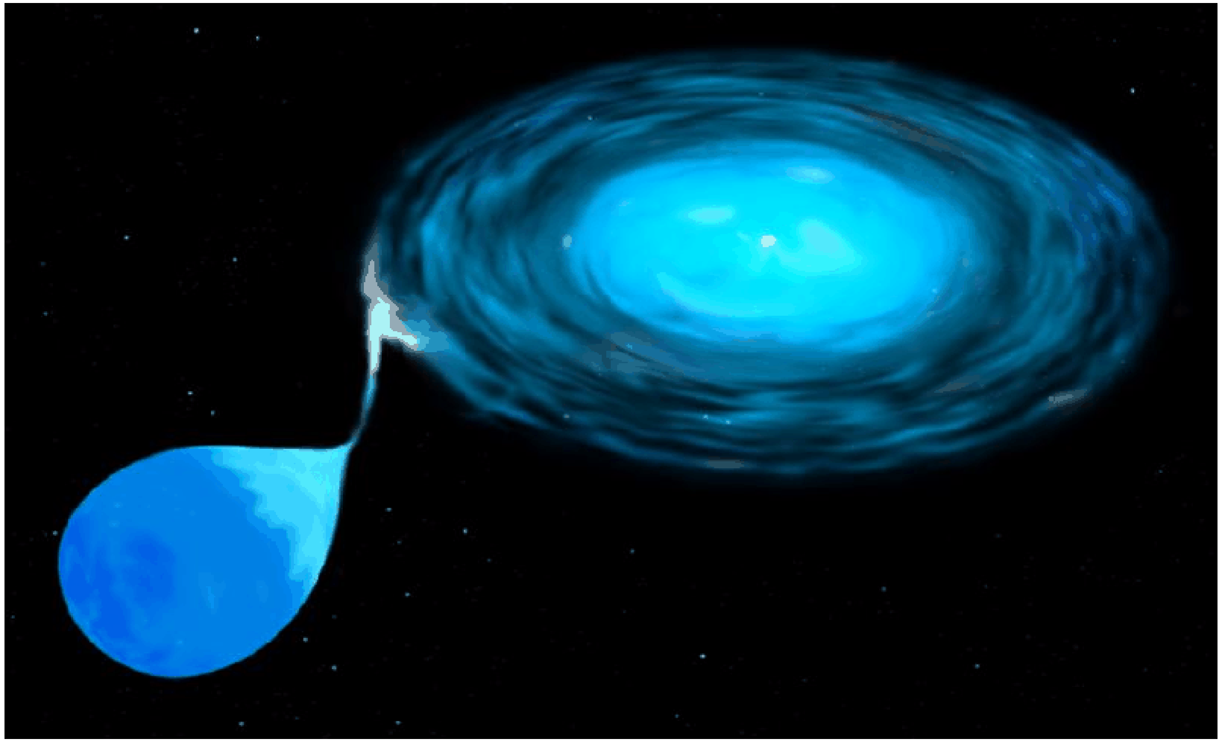
Keeping the spacecraft with the proof-mass

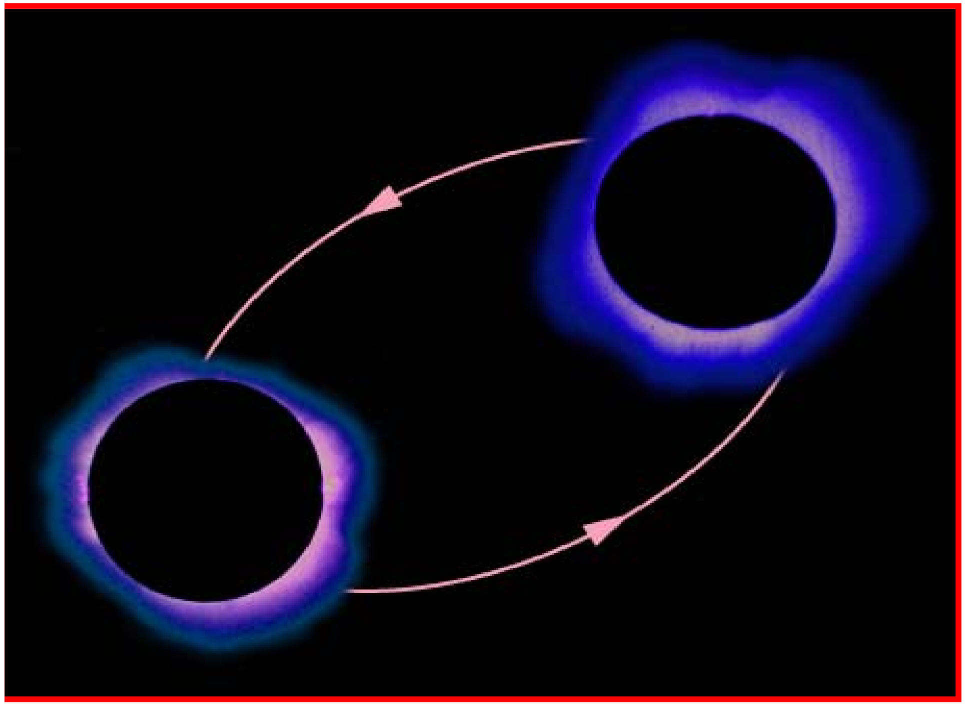


Galactic Binaries

SNR up to 500 in 1 year. Angular esolution 10^{-3} – 10^{-2} srad at SNR ≈10

Some are standard candles: everything known about the signal.





Massive black hole binaries from merging galaxies cores

SNR up to 2000 in one year at z ≈1 – 3

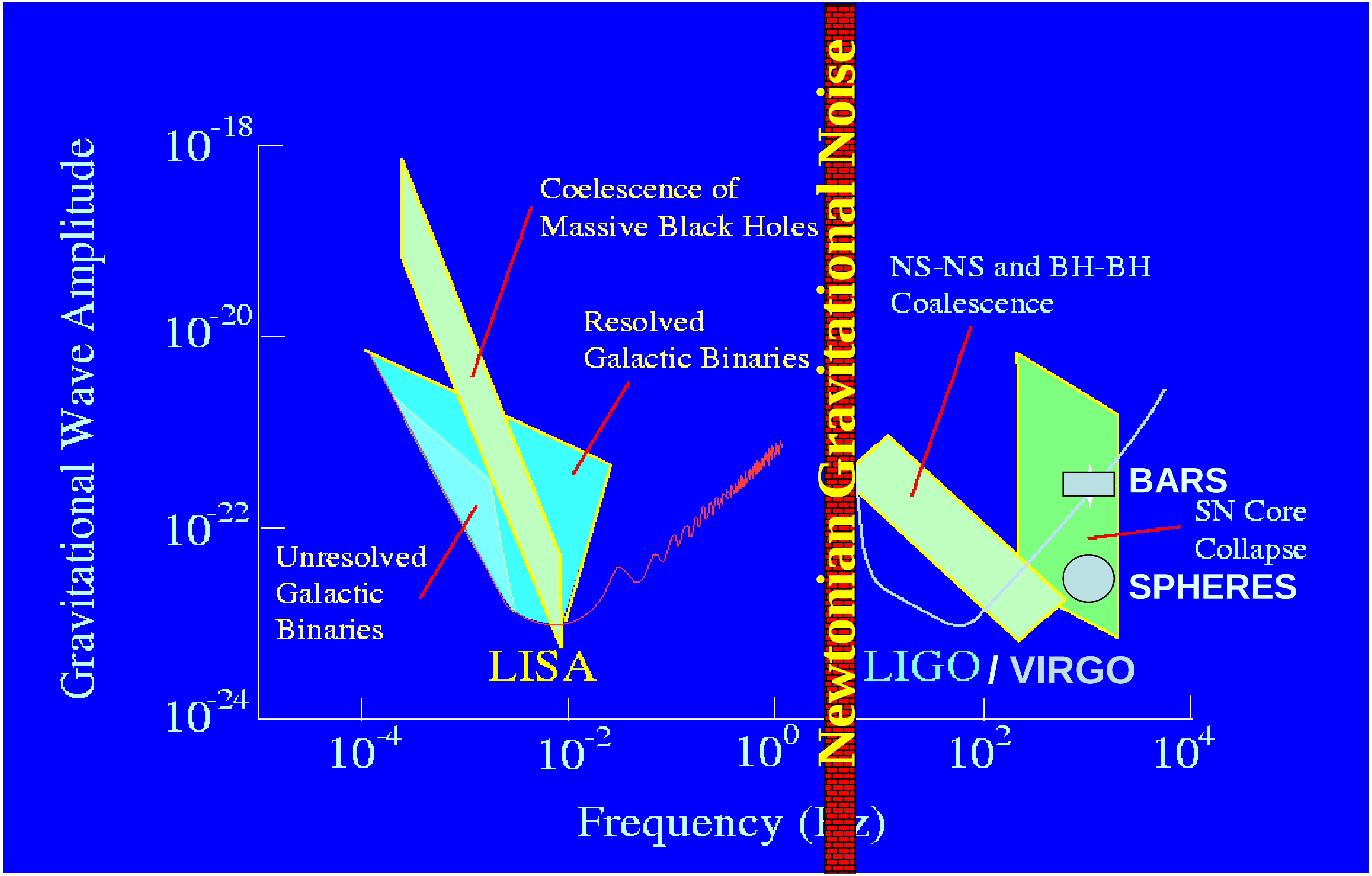
Angular resolution down to 10^{-5} srad.

The plan:

ESA(/NASA) technology demonstration mission 2006

LISA NASA/ESA collaborative mission 2012

2013: enjoy listening to black-holes



Gravitational Wave Amplitude
10^-18
10^-20
10^-22
10^-24
Coelescence of
Massive Black Holes
Resolved
Galactic Binaries
Unresolved
Galactic
Binaries
LISA
Newtonian Gravitational Noise
NS-NS and BH-BH
Coalescence
BARS
SN Core
Collapse
SPHERES
LIGO / VIRGO
10^-4
10^-2
10^0
10^2
10^4
Frequency (Hz)