Status of Gravitational Wave Detection

Adalberto Giazotto

INFN Pisa and EGO

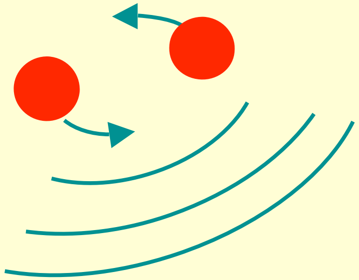
The Indirect Evidences of GW Existence

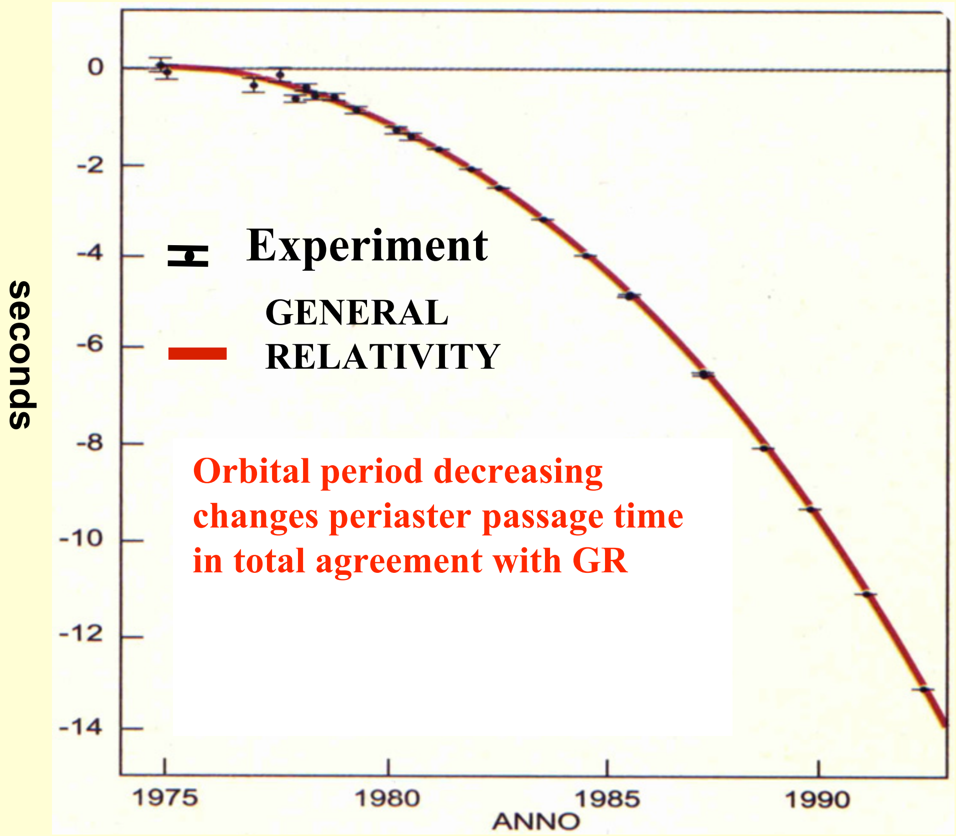
1974: First Discovery

Taylor and Hulse

Nobel Prize
1993

Coalescing Neutron Star System PSR 1913+16



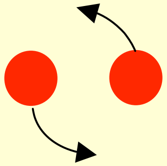


Orbital period decreasing changes periaster passage time in total agreement with GR

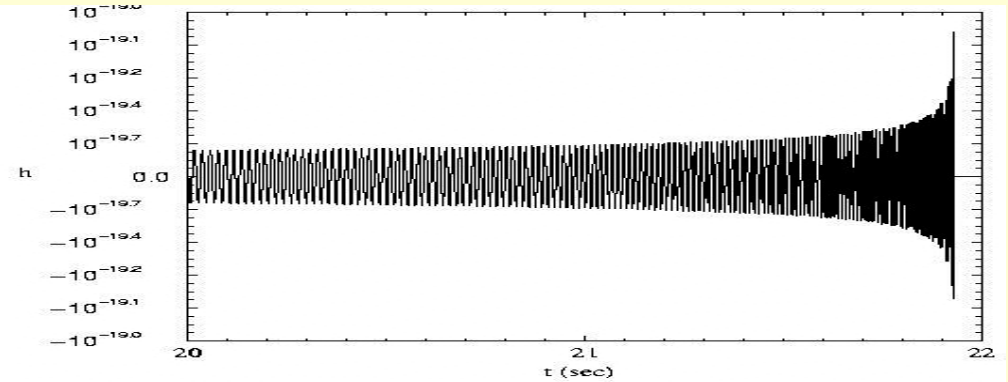
Now there are about 6 similar systems, and the “double pulsar” PSR J0737-3039 is already overtaking 1913 in precision. All agree with GR

Some Gw SOURCES

1) Coalescing Binary Systems: NS and Black Holes



Rate~0,01/year in a 100 Mly sphere.

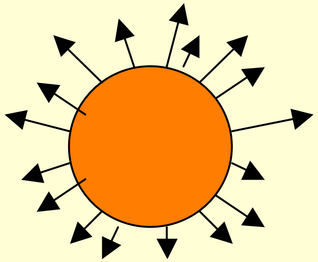


2)Supernovae Explosions:

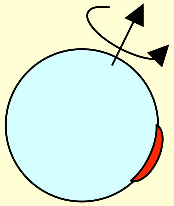
Explosions Rate:

Virgo Cluster ($h \sim 10^{-23}$) ~30/year

Milky Way ($h \sim 10^{-20}$) 1/30 years



3) Periodic Sources : For rotating Neutron Stars h very “Small” $h < 10^{-25}$. Very long Integration time (1 year) increases S/N.



4) Big-Bang Cosmological BKG (CB): Since $\alpha_{GRAV}=10^{-39}$ Big-Bang matter is mainly transparent to GW. In the Virgo bandwidth we may observe GW emitted after 10^{-24}s from time zero.

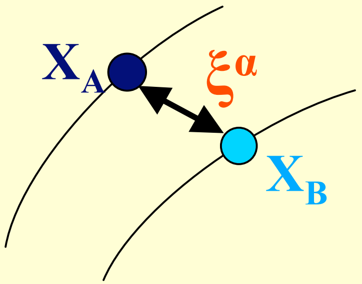
The Detection of Gravitational Waves

F.A.E.Pirani in 1956 first proposed to measure Riemann Tensor by measuring relative acceleration of two freely falling masses. If A and B are freely falling particles, their separation $\xi^\alpha=(x_A-x_B)^\alpha$ satisfies the **Geodesic Deviation equation:**

$$\boxed{\frac{D^2\xi_\alpha}{d\tau^2} \Rightarrow \frac{1}{2}\ddot{h}^{TT}_{\alpha\beta}\xi^\beta} \Longrightarrow$$

Riemann Force

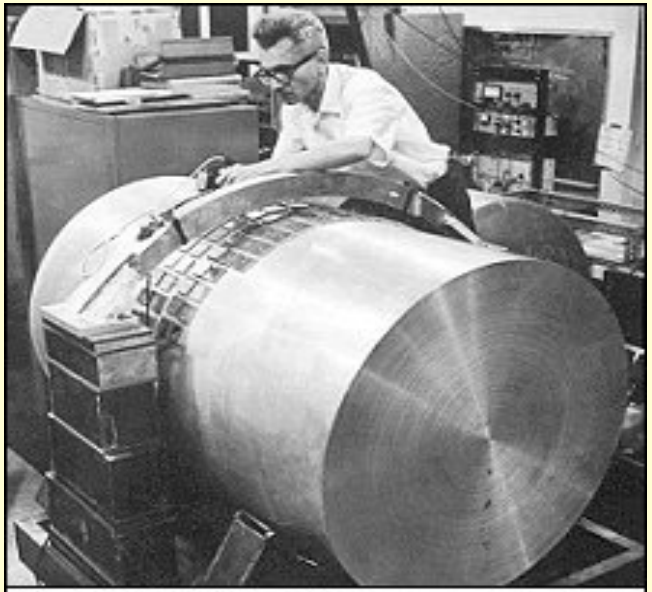
$$F_\alpha = \frac{1}{2}M\ddot{h}^{TT}_{\alpha\beta}\boxed{\xi^\beta}$$



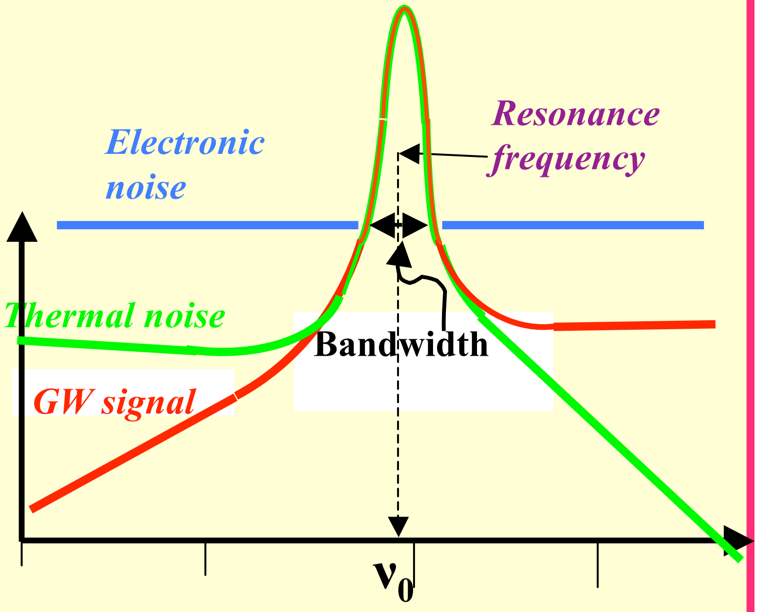
<u>The receiver is a device measuring space-time curvature</u> i.e. the relative acceleration of two freely falling masses or, equivalently, <u>their relative displacement</u>.

Early Detectors: Room Temperature Resonant Bars

In 1959 Joseph Weber was the first to build a GW detector working on the principles of Geodesic Deviation Equation.



JOSEPH WEBER WITH GRAVITATIONAL WAVE DETECTOR



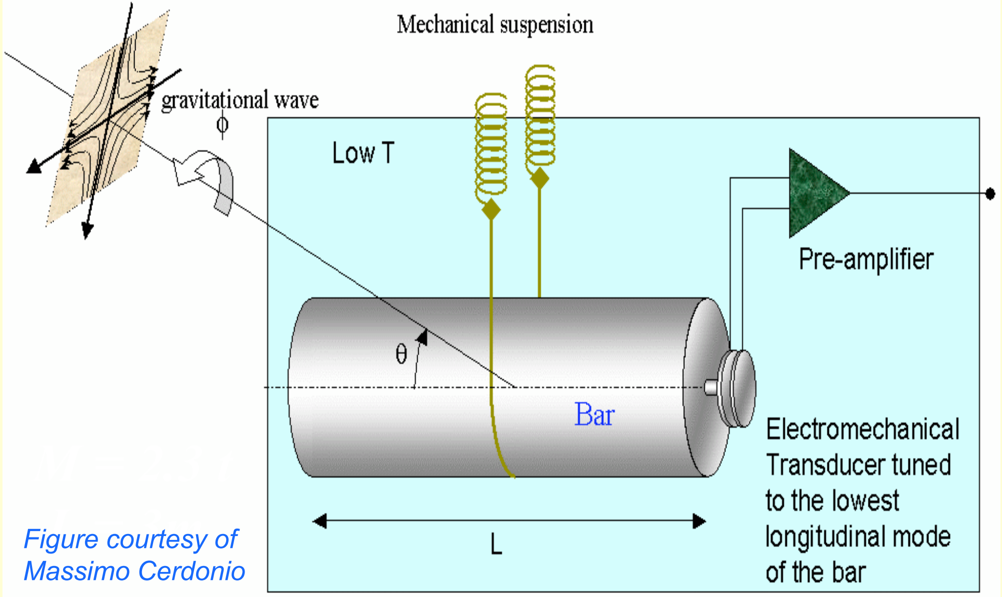
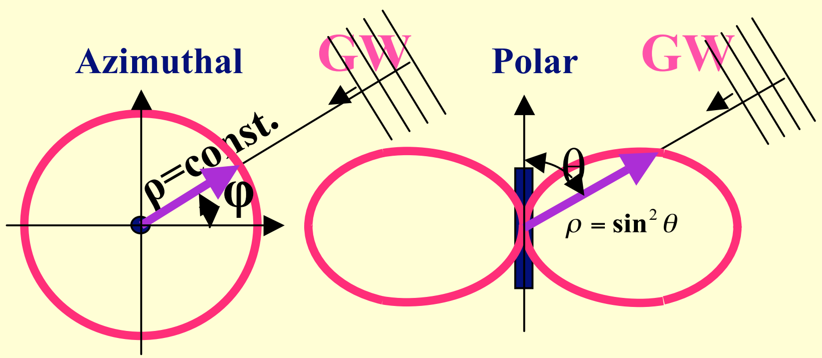
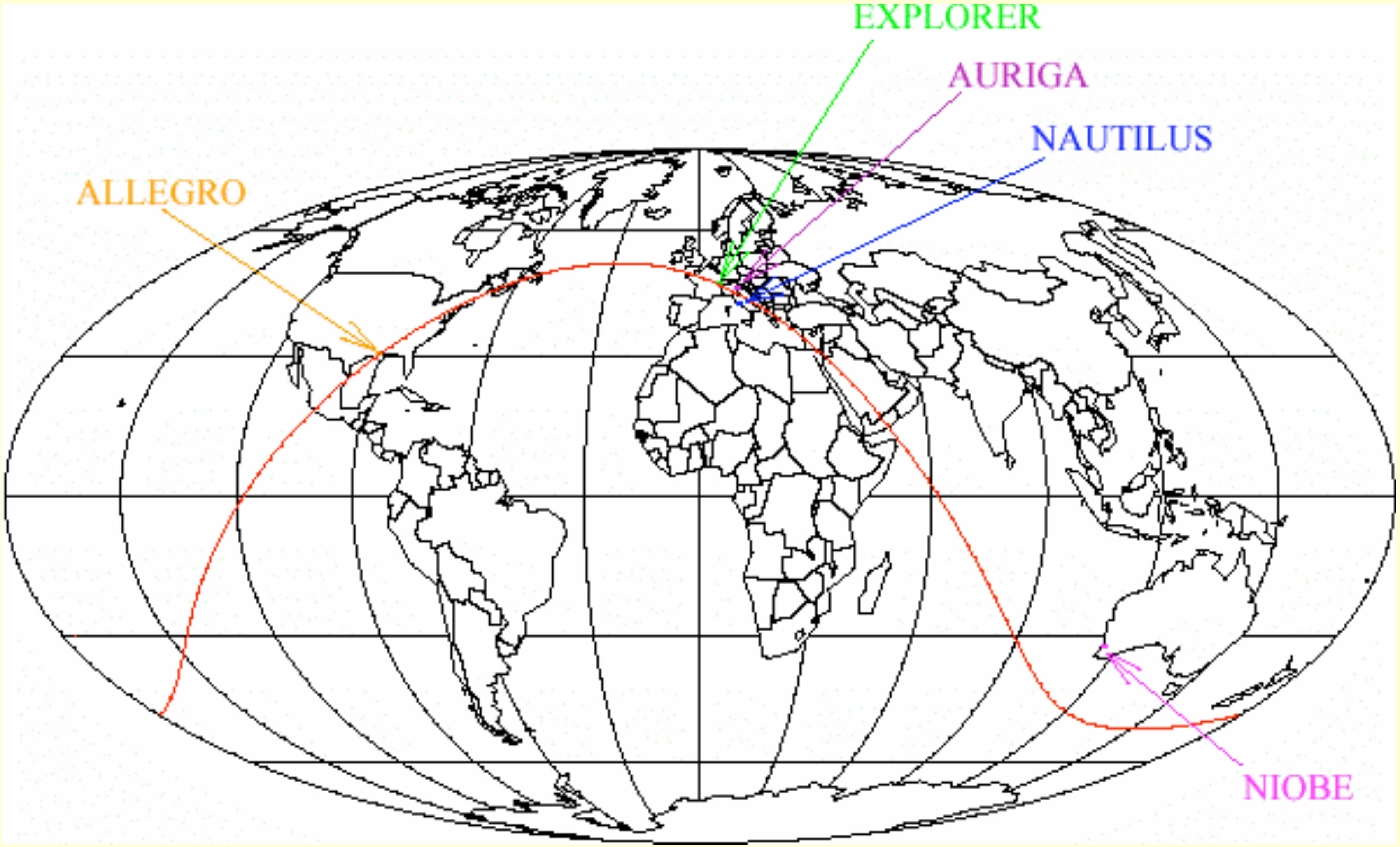


Figure courtesy of Massimo Cerdonio

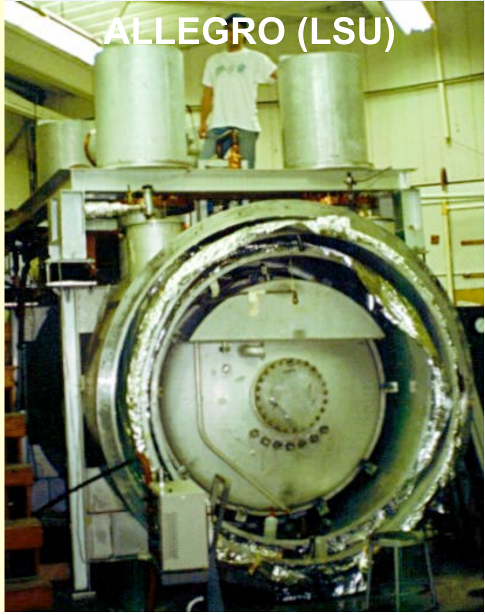
Antenna Pattern summed on polarizations



Cryogenic Bar Detectors



Cryogenic Bar Detectors

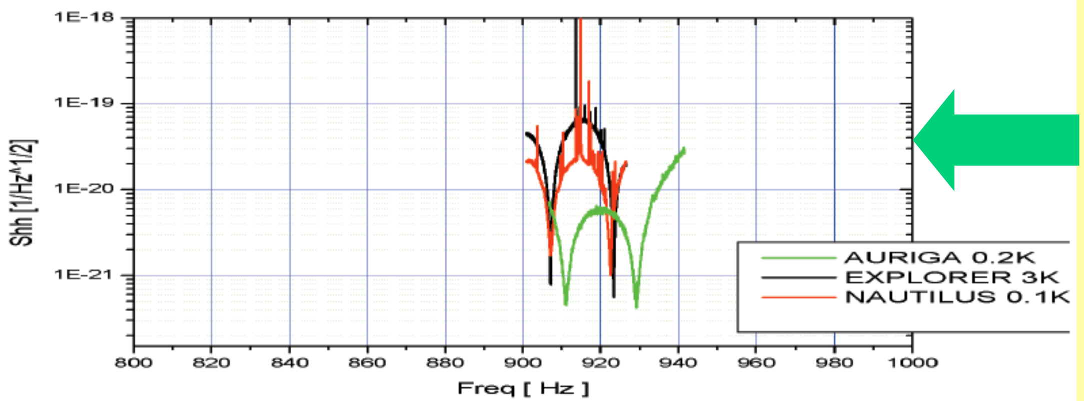


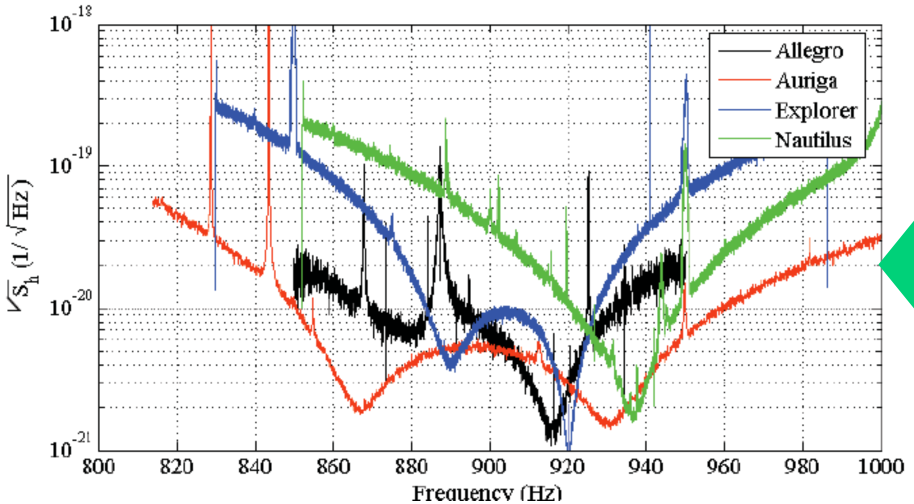
IGEC the Resonant Bar Detectors network

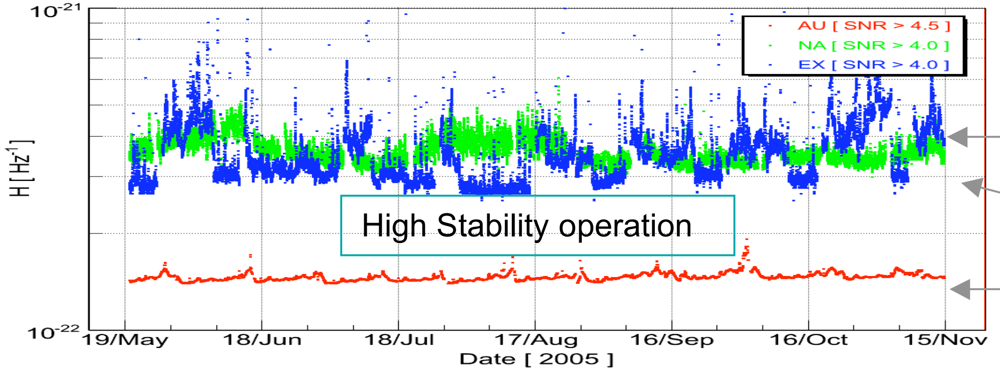
***I**nternational*
***G**ravitational*
***E**vent*
***C**ollaboration*
established 1997 in Perth

The First GW Detector Network

Cryogenic Bar Detectors Sensitivity, Stability& Duty Cycle







EXPLORER

NAUTILUS

AURIGA

IGEC-1 (1997-2000)

29 days of four-fold coinc.

178 days of three-fold coinc.

713 days of two-fold coinc.

Followed by a series of upgrades resumed operations

EXPLORER in 2000

AURIGA in 2003

NAUTILUS in 2003

ALLEGRO in 2004

NIOBE ceased operation

IGEC-2 (2005--)

First data analyzed covered May-November 2005 when no other observatory was operating

*Massimo Visco on behalf
of the IGEC2
Collaboration*

Rencontres de Moriond

*Gravitational Waves and
Experimental
Gravity*

March 11-18, 2007

***La Thuile, Val d'Aosta,
Italy***

Bar Detectors situation at Present

NIOBE (Perth) stopped operation and did not join IGEC-2

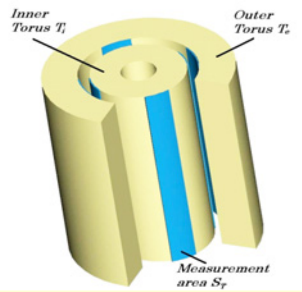
ALLEGRO (LSU) stopped operation in 2007

In 2006 INFN stopped R&D on Spherical Detectors and left running Auriga, Nautilus and Explorer on an annual evaluation. It is likely that at Virgo+ starting (6/2009) they will be shut down.

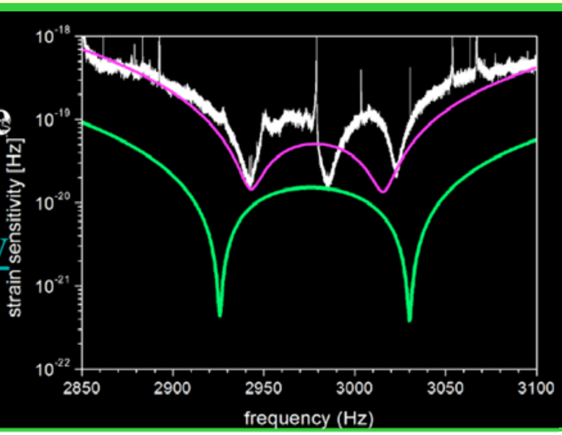
INFN left open R&D on DUAL

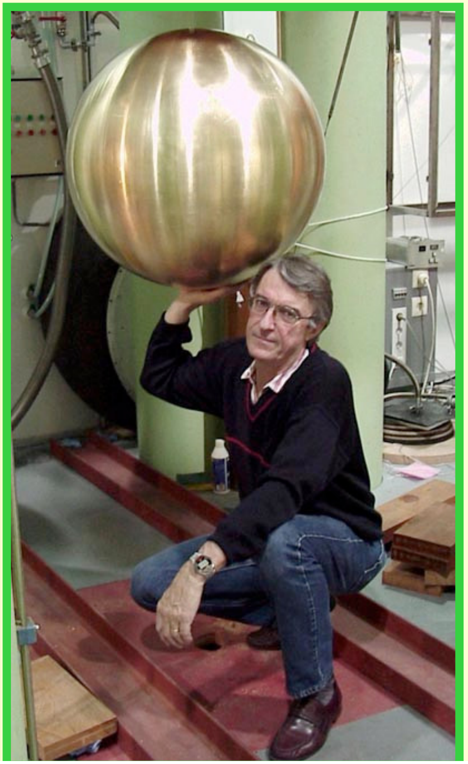
M.Cerdonio et al. Phys. Rev. Lett. 87 031101 (2001)

DUAL is a wide band high frequency detector with high bandwidth (5 kHz) and reduced Back Action.



The only existing Spherical Detector in commissionig phase is Minigrail (G. Frossati et al.) ([Kamerlingh Onnes Laboratory](), [Leiden University](), Nd)

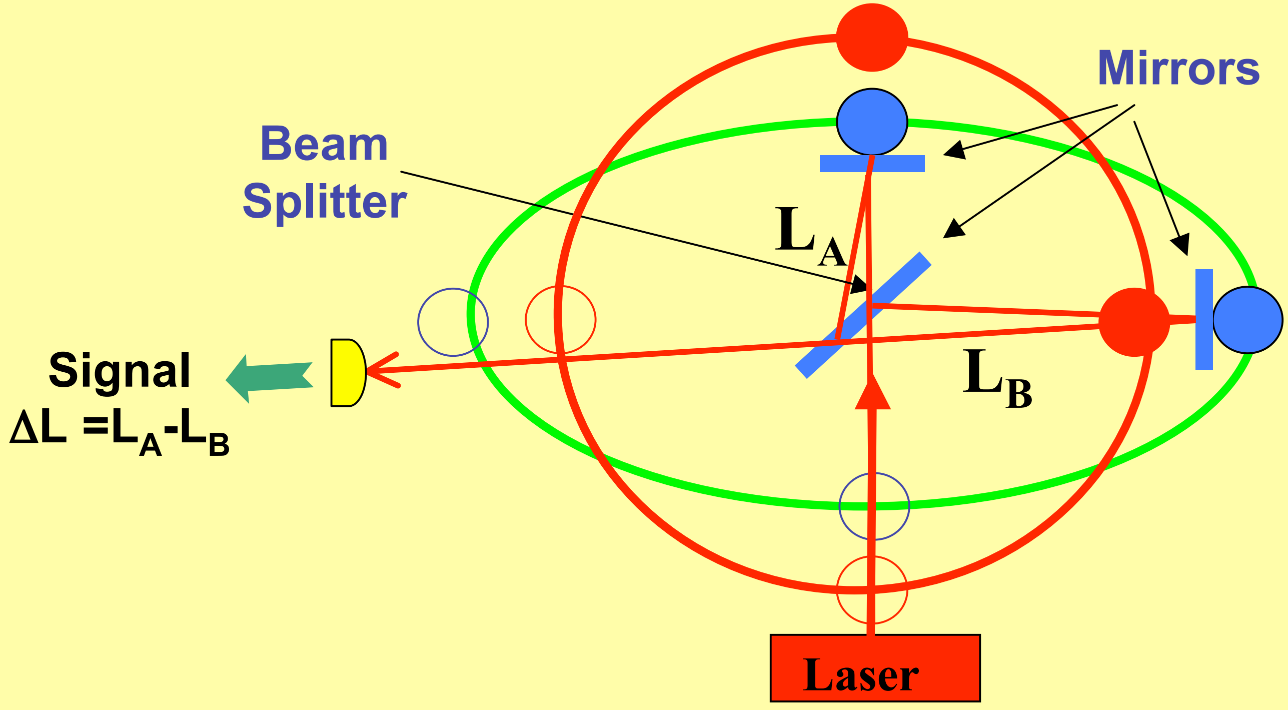




INTERFEROMETRIC DETECTORS

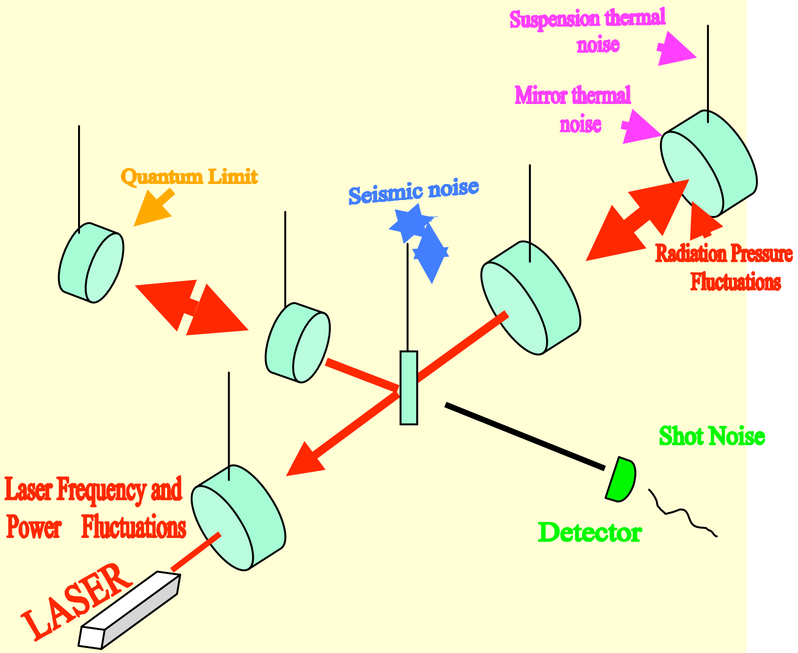
Large L ⟶ High sensitivity

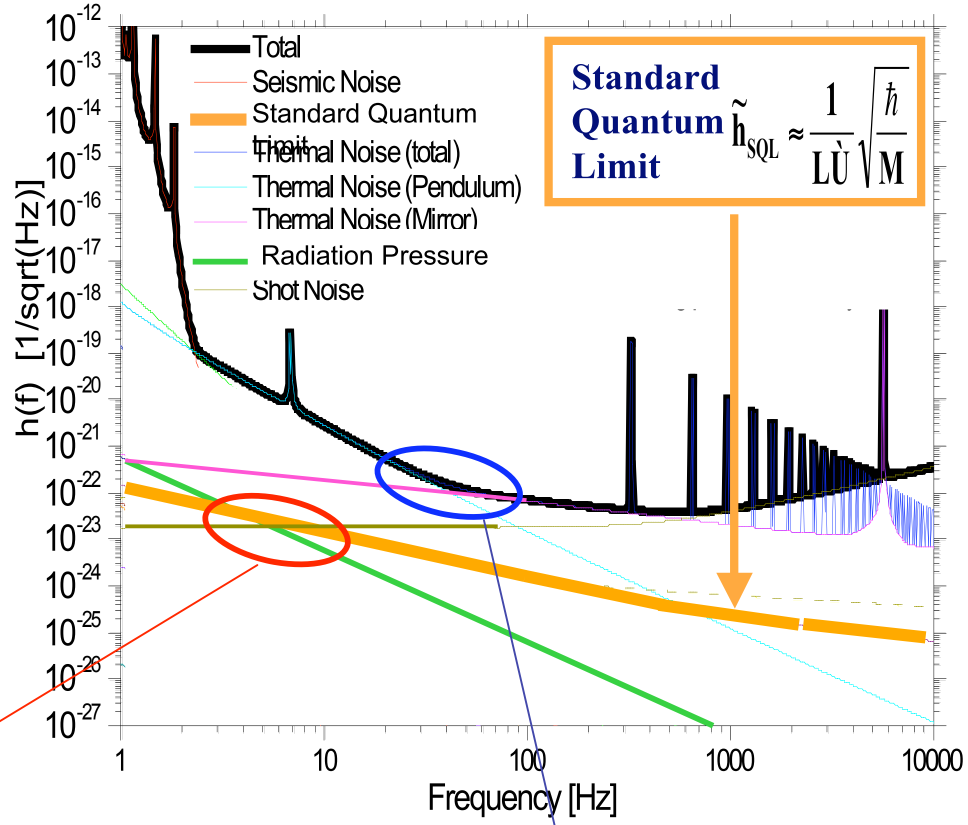
Very Large Bandwidth 10-10000 Hz



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

Interferometer Noises





Optical Noises can not be overcome with standard ITF but can with QND techniques

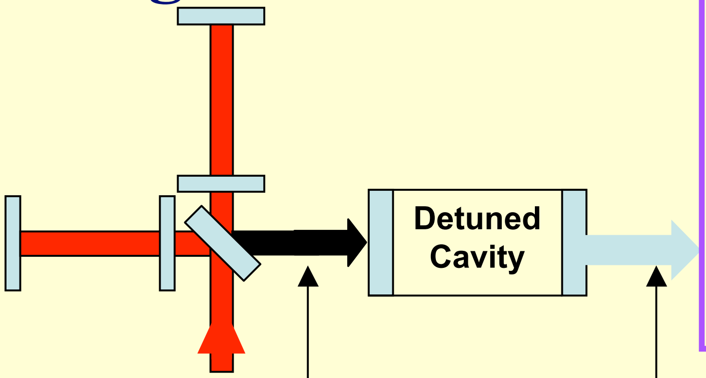
Thermal Noise, the more subtle, can perhaps be overcome bringing Mirrors close to -273 K^0

Modern Interferometers with QND Signal Readout

Uncertainty Principle:

$\Delta\varphi \,.\, \Delta N \sim 1$

We only measure φ, the only one containing the signal, hence we can ignore ΔN.



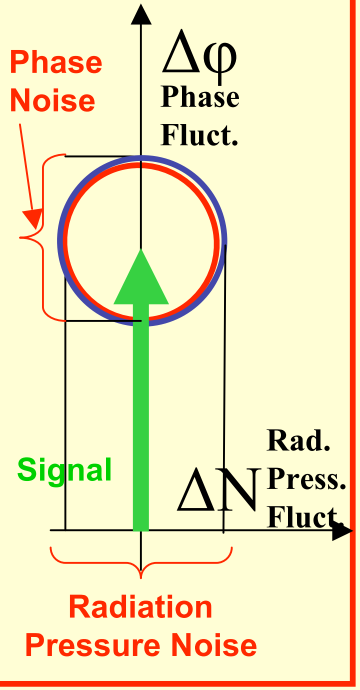
Optical Noise can be less than SQL:

$$\frac{4\pi}{\lambda} hL \geq \sqrt{K} + \frac{1}{\sqrt{K}}$$

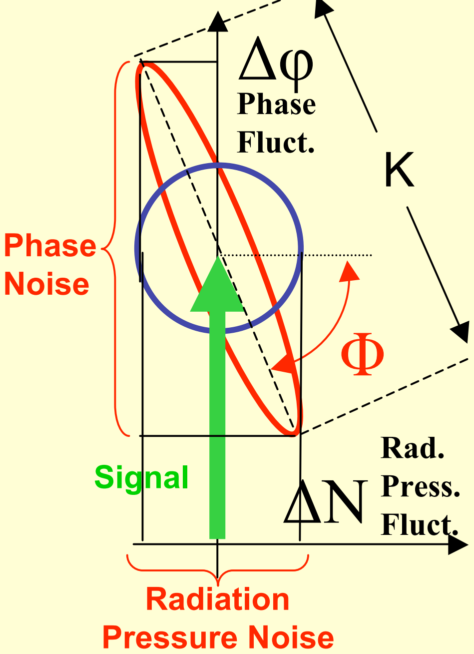
$$\Downarrow$$

$$\frac{4\pi}{\lambda} hL \geq \frac{1}{\sqrt{K}}$$

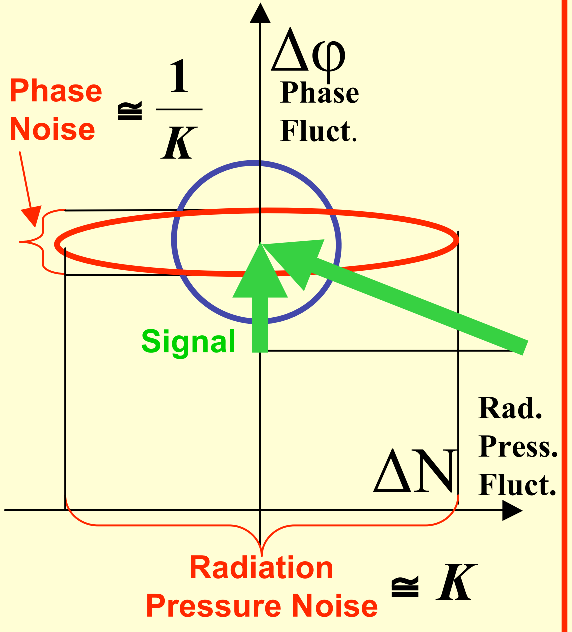
In a Fix Mirror ITF, Rad. Press. Fluct. can't move mirrors.



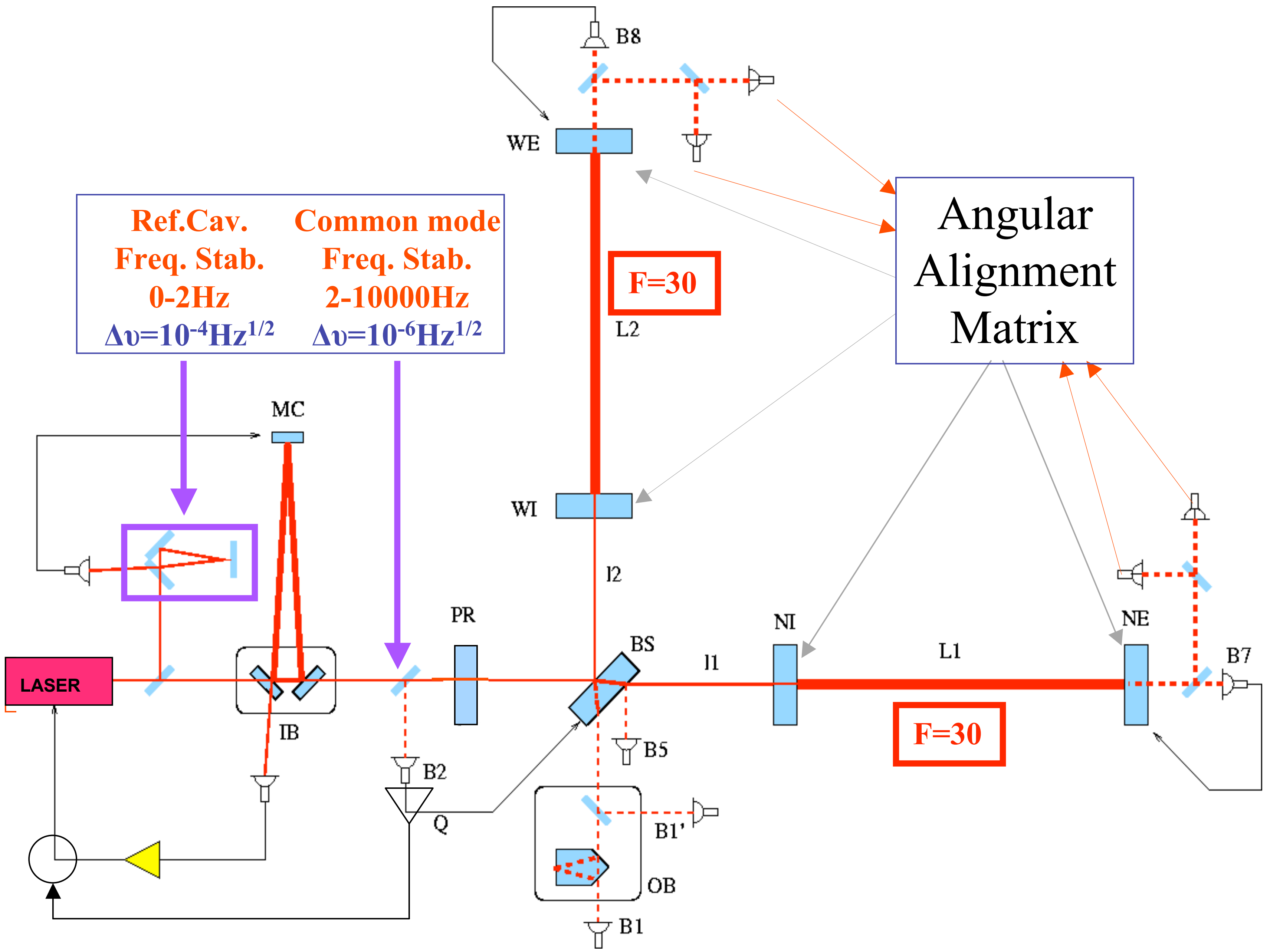
In a suspended Mirror ITF, Rad. Press. Fluct. move randomly mirrors, hence Phase noise is increased.



A Detuned Cavity can rotate in the Δφ, ΔN plane. Phase noise Δφ has been decreased at expenses of ΔN.



Virgo Diagram



Ref.Cav.
Freq. Stab.
0-2Hz
$\Delta\upsilon=10^{-4}\mathrm{Hz}^{1/2}$

Common mode
Freq. Stab.
2-10000Hz
$\Delta\upsilon=10^{-6}\mathrm{Hz}^{1/2}$

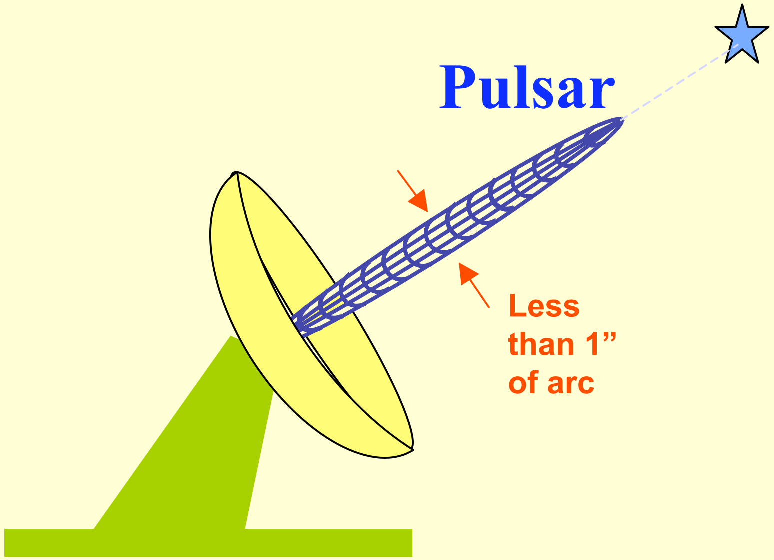
Angular
Alignment
Matrix

F=30

F=30

GW Detectors have a very appealing Antenna pattern

Radiotelescope Antenna Pattern

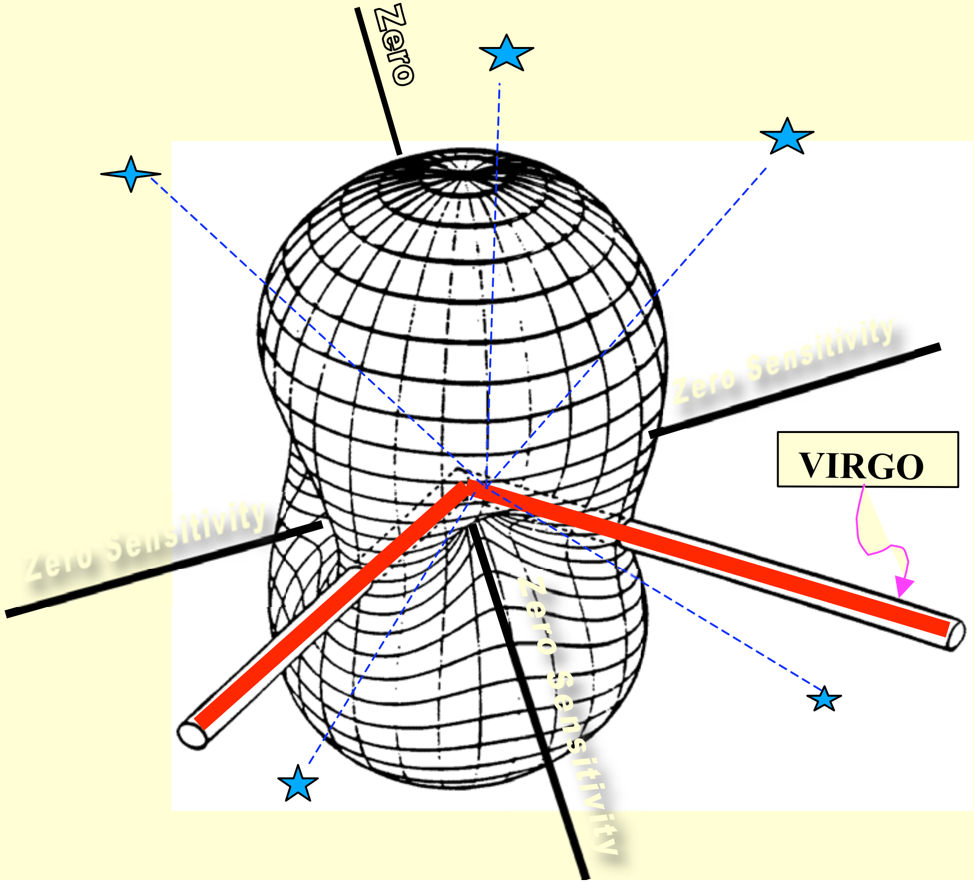


Sources are localyzed

"Geometrically "

Interferometric GW Detector Antenna Pattern

ALL sky seen at once.



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

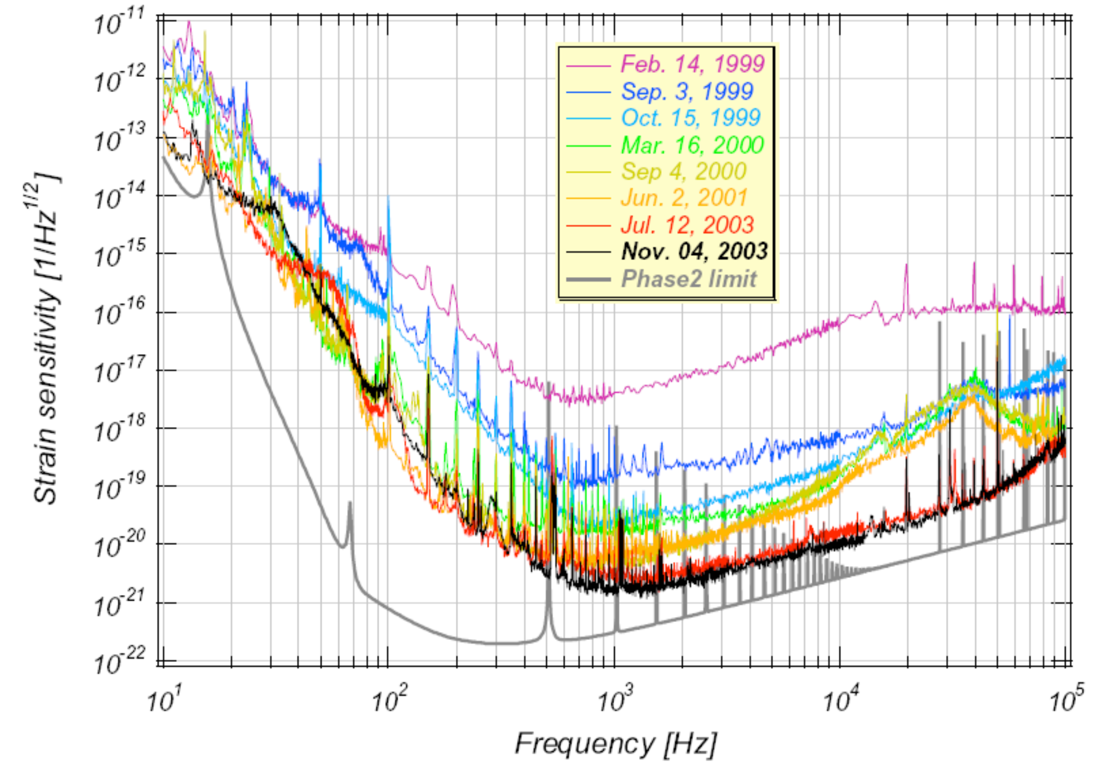
- Far Universe expansion rate Measurement

-GW energy density in the Universe

-Knowledge of Universe at times close to Planck’s time

TAMA 300m-Tokyo

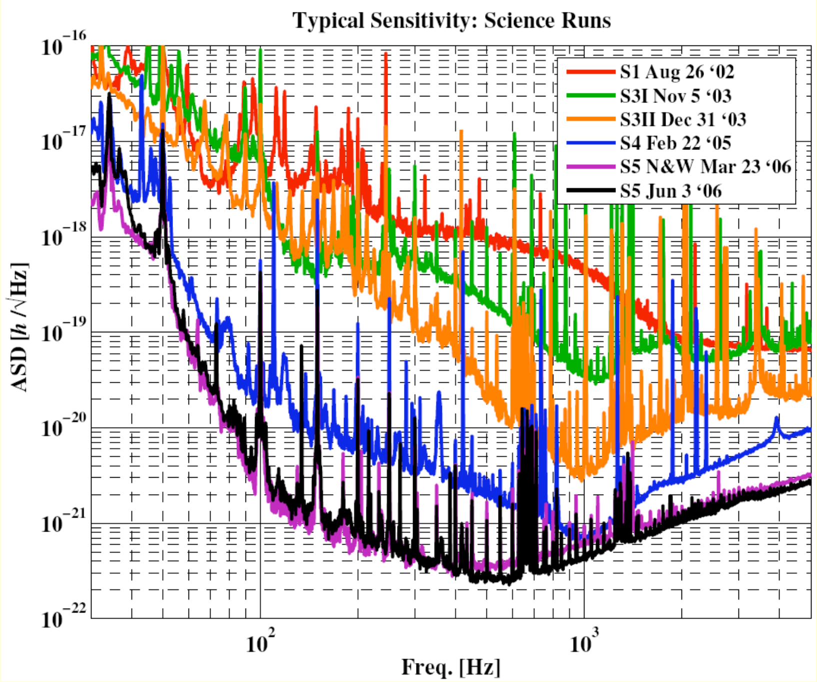
Progress of TAMA 300 Sensitivity



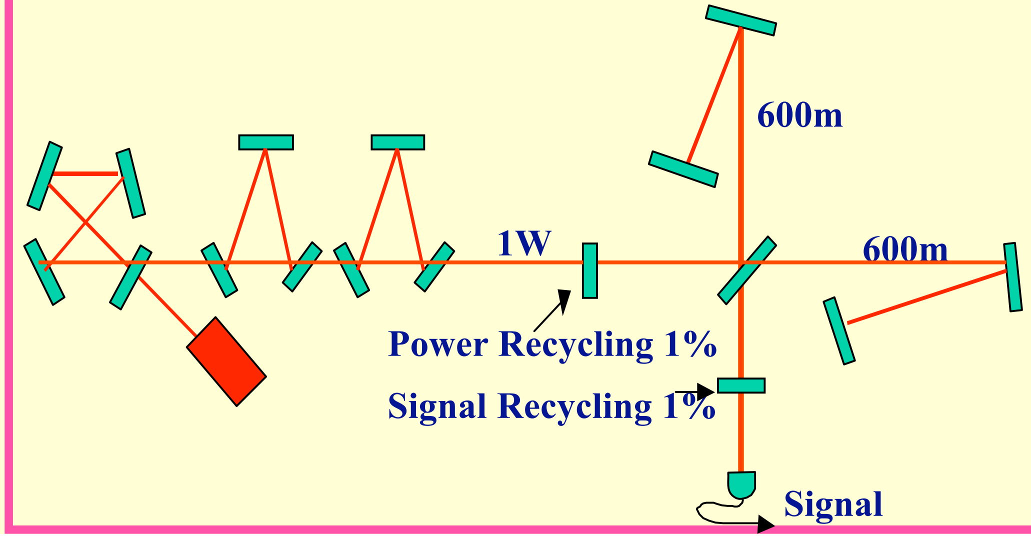
In 1999, TAMA is the first large ITF to start observations, in 2001 attained the world best sensitivity and made continuous observation more than 1000 hr with the highest sensitivity. Joint observations with LIGO/GEO during DT7-DT9

Best sensitivity : $h = 1.7 10^{-21} \ {}^{1}\!/\!_{\sqrt{Hz}} @ 1KHz$ Recycling gain of 4.5

GEO 600 m- Hannover



GEO 600 is a Dual Recycling Interferometer



600m

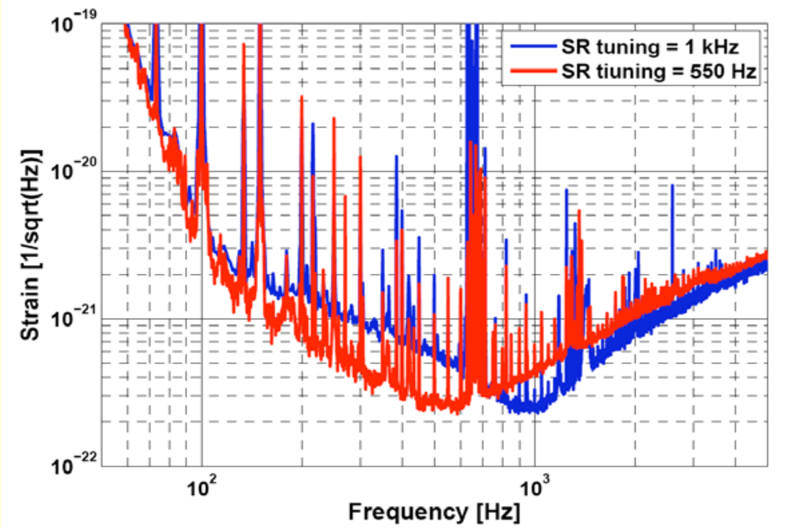
1W

600m

Power Recycling 1%

Signal Recycling 1%

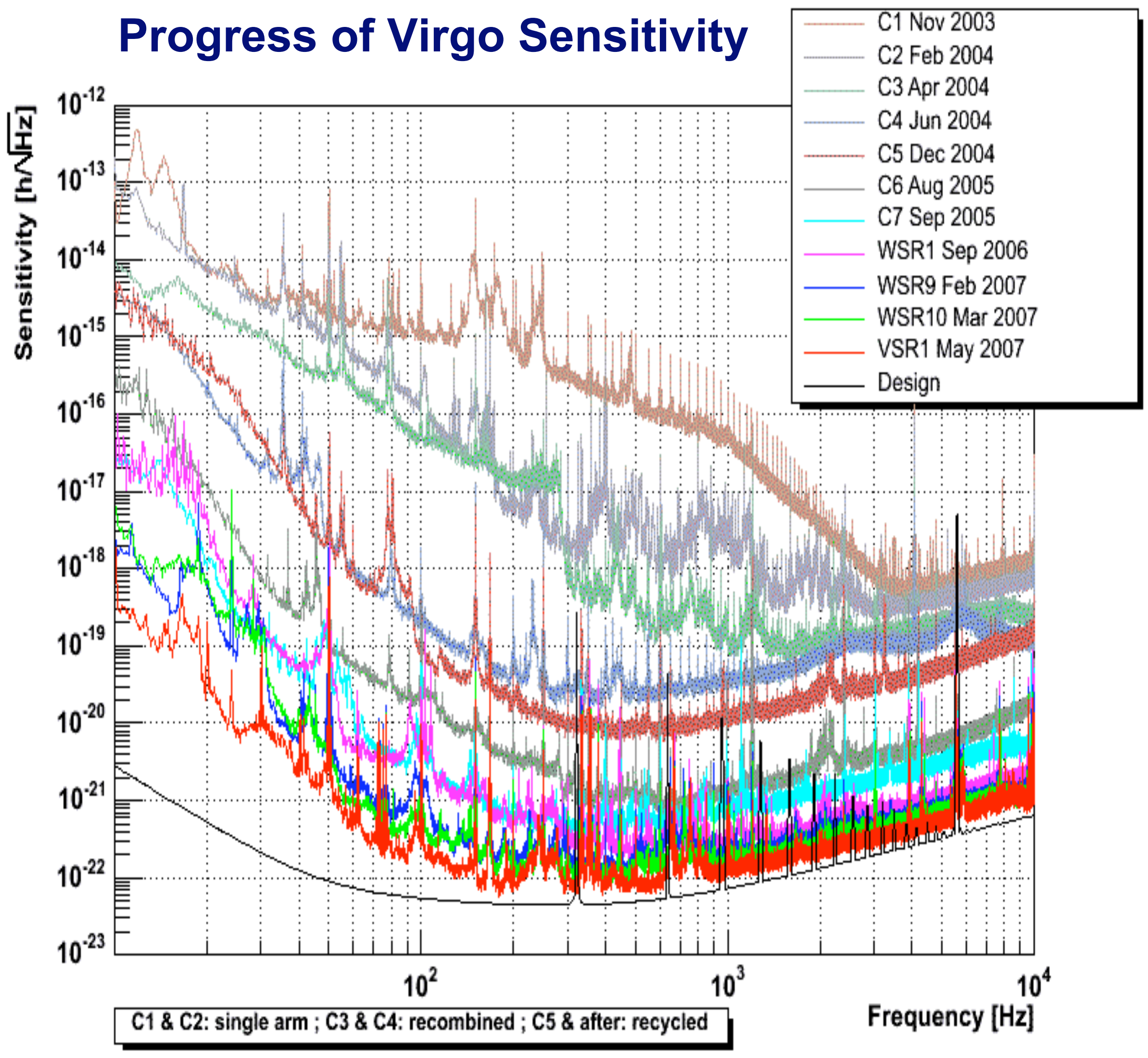
Signal



VIRGO

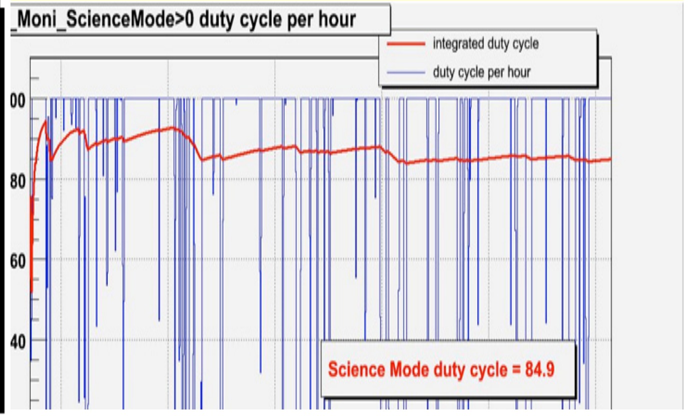
3 km-Cascina

Virgo Sensitivity, Duty Cycle and Stability First 5 weeks (started 18/5/2007) of Coincidence with LIGO/GEO



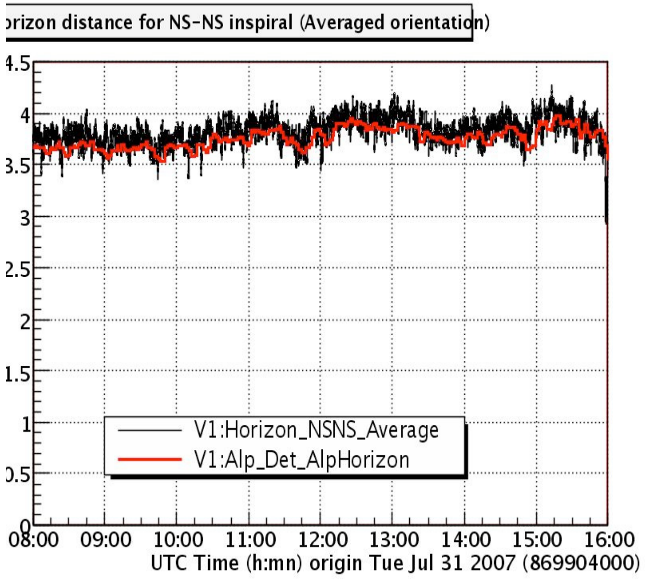
Progress of Virgo Sensitivity

C1 & C2: single arm ; C3 & C4: recombined ; C5 & after: recycled



_Moni_ScienceMode>0 duty cycle per hour

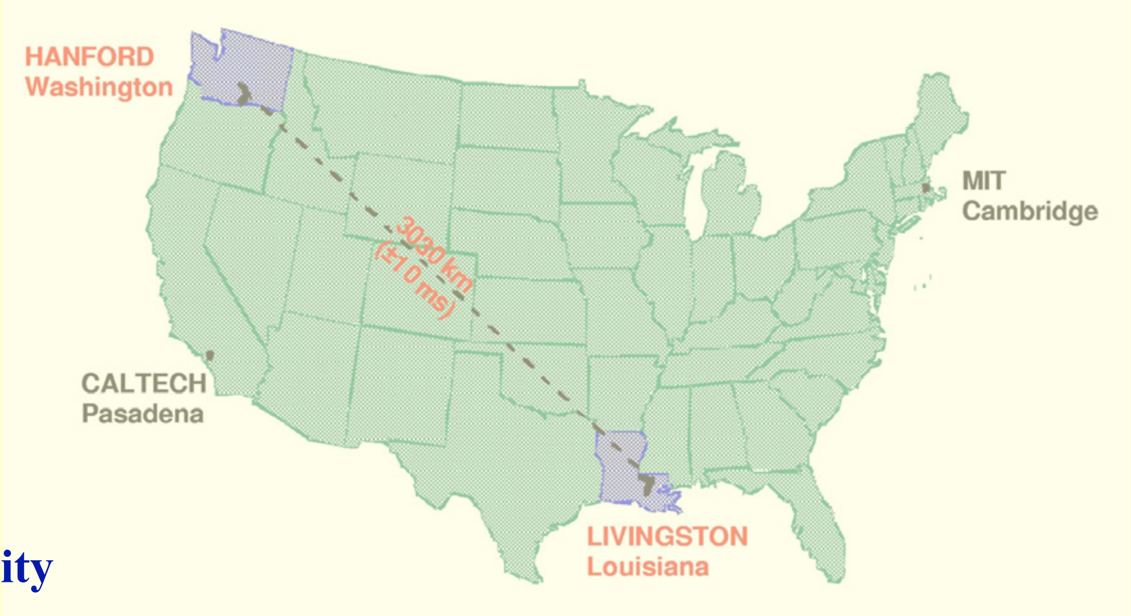
Science Mode duty cycle = 84.9



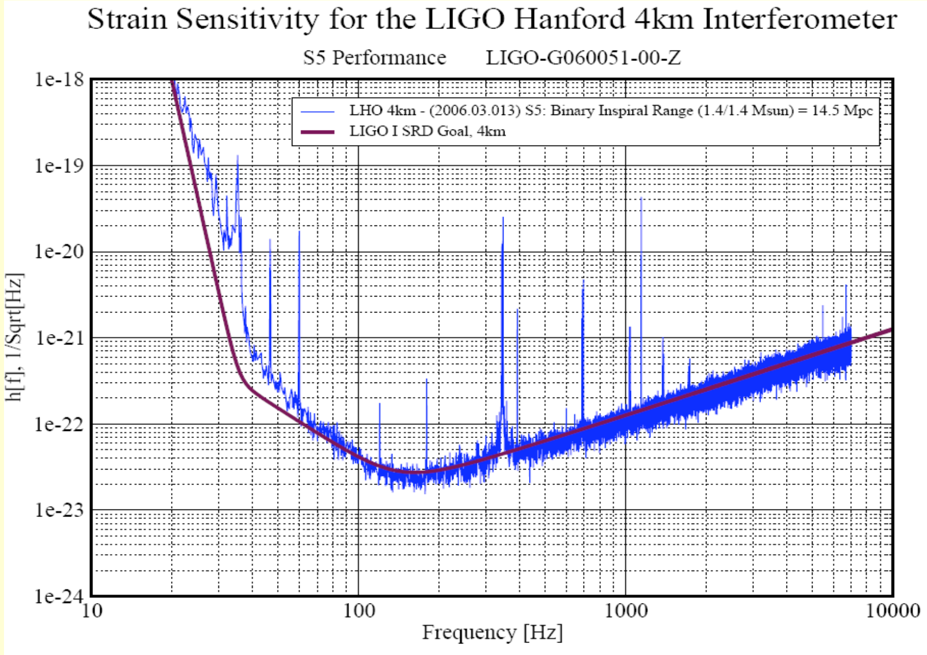
orizon distance for NS-NS inspiral (Averaged orientation)

LIGO

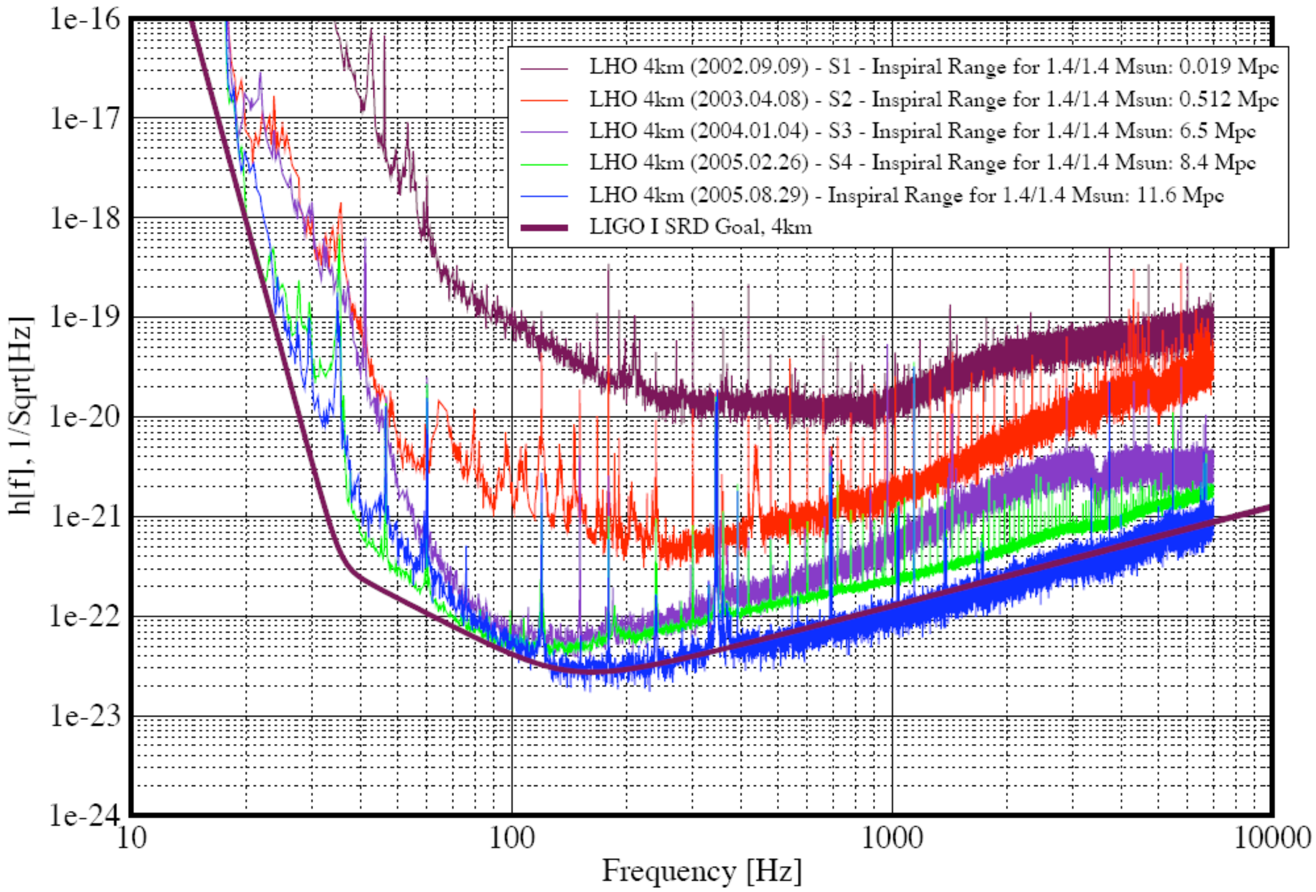
One Vacuum Tube with
2 ITF: 4 km and 2 km

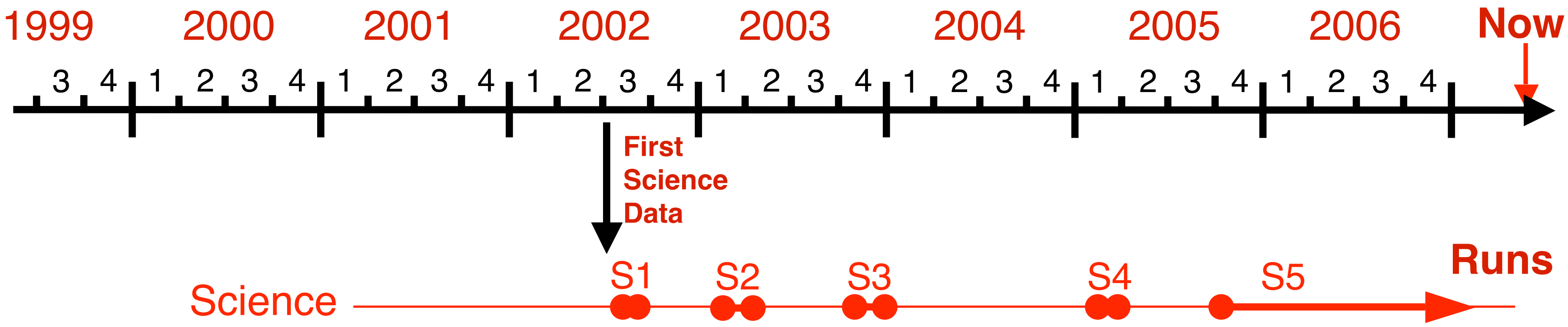


Present LIGO Sensitivity

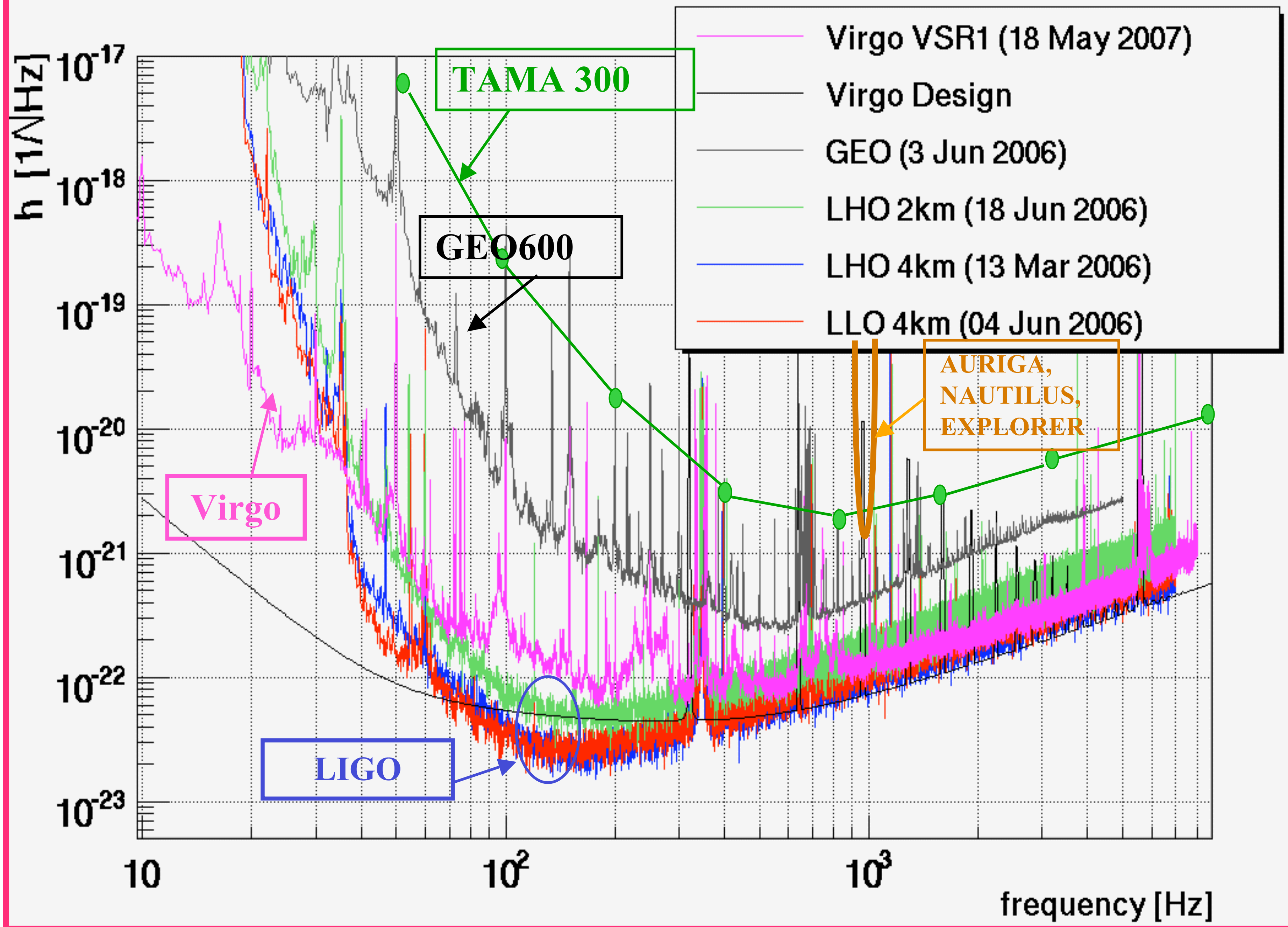


4 km Arms


LHO 4km (2002.09.09) - S1 - Inspiral Range for 1.4/1.4 Msun: 0.019 Mpc
LHO 4km (2003.04.08) - S2 - Inspiral Range for 1.4/1.4 Msun: 0.512 Mpc
LHO 4km (2004.01.04) - S3 - Inspiral Range for 1.4/1.4 Msun: 6.5 Mpc
LHO 4km (2005.02.26) - S4 - Inspiral Range for 1.4/1.4 Msun: 8.4 Mpc
LHO 4km (2005.08.29) - Inspiral Range for 1.4/1.4 Msun: 11.6 Mpc
LIGO I SRD Goal, 4km
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
h[f], 1/Sqrt[Hz]
10
100
1000
10000
Frequency [Hz]


1999
2000
2001
2002
2003
2004
2005
2006
Now
3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4
First Science Data
Science
S1
S2
S3
S4
S5
Runs

GW DETECTORS SENSITIVITY



GW DETECTION STATUS

IGEC: Network of Bar Detectors Started in 1997 (Auriga, Explorer, Nautilus, Allegro) for impulsive GW detection.

No evidence of a significant GW signal

LIGO-GEO600: GW from Pulsar (28 known)- ε < 10-5 – 10-6 (no mountains > 10 cm)- $\tilde{h}$ upper limits: 2.10^{-24}@200Hz, 5.10^{-24}@400Hz, 10^{-23}@1KHz

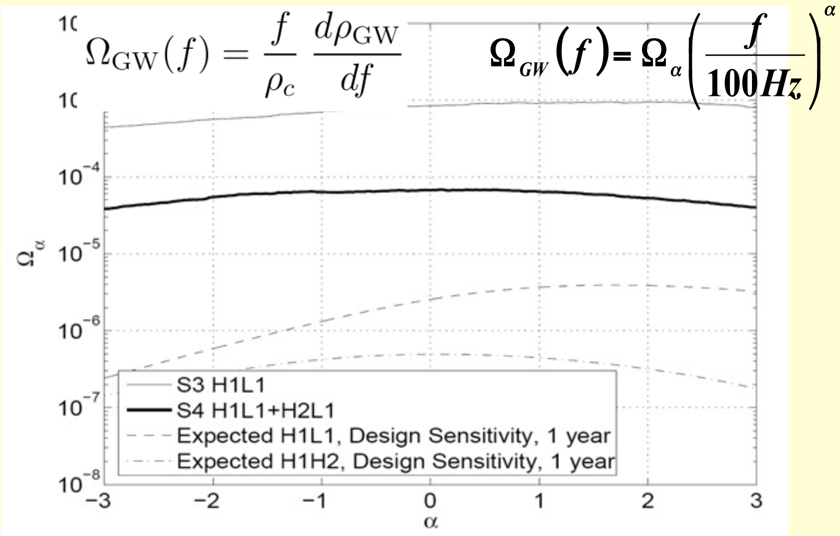
No evidence of a significant GW signal

LIGO,GEO600,TAMA: Up. lim.: Coalescing NS-NS <1 event/(gal.year) $2 < M_0 < 6$

Coalescing BH-BH <1 event/(gal.year) $10 < M_0 < 80$

No evidence of a significant GW signal

LIGO: Stockastic BKG



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

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

Virgo, LIGO, GEO 600:
May 18th 2007 started common data taking and coherent analysis; main target impulsive events ???

CLIO: The First Cryogenic Interferometer for GW Detection

Construction of CLIO

Acheved Pressure

- 100m Arm -

6×10^{-5} Pa

by a 800 litter Turbo

- Cryostat -

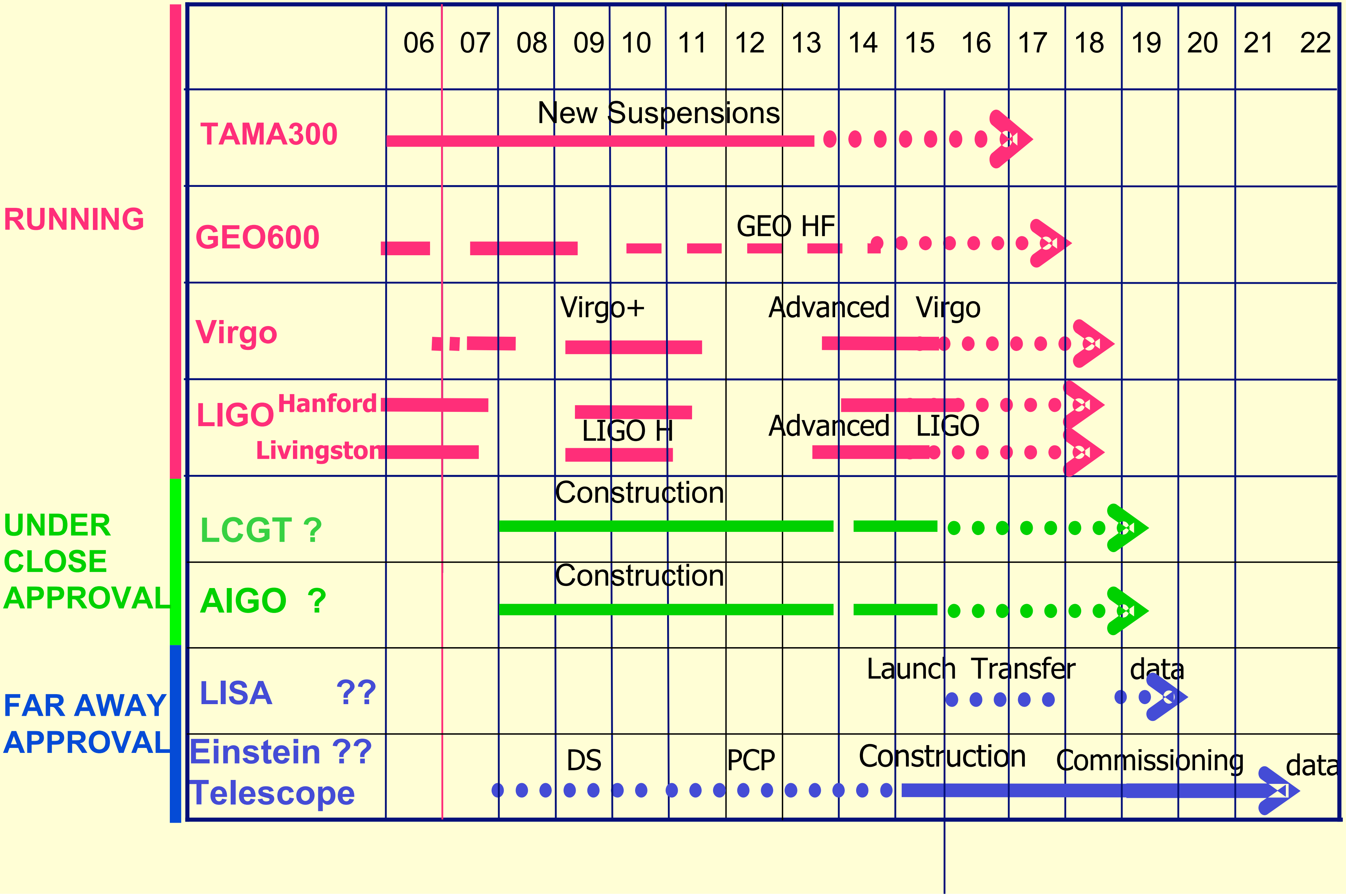
2×10^{-6} Pa

by Cryostat itself

“Status of TAMA 300” N.Kanda & the TAMA collab.

19

The Future



06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22

RUNNING

TAMA300 — New Suspensions

GEO600 — GEO HF

Virgo — Virgo+ — Advanced Virgo

LIGO Hanford / Livingston — LIGO H — Advanced LIGO

UNDER CLOSE APPROVAL

LCGT ? — Construction

AIGO ? — Construction

FAR AWAY APPROVAL

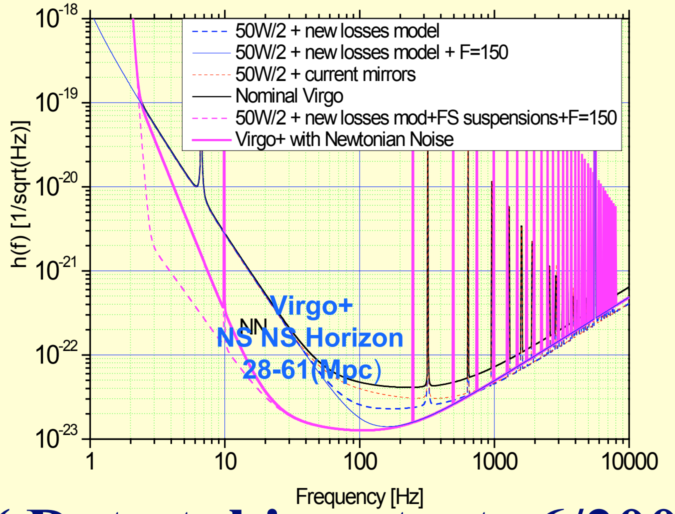
LISA ?? — Launch Transfer — data

Einstein ?? Telescope — DS — PCP — Construction — Commissioning — data

Virgo+

1) Cure low freq. Noise
2) Fused silica suspens
3) Increase arm finesse
4) Higher power laser

Final Decision to be made late 2007



Henanced Ligo

1) DC readout
2) Higher laser power
3) Output modecleaner

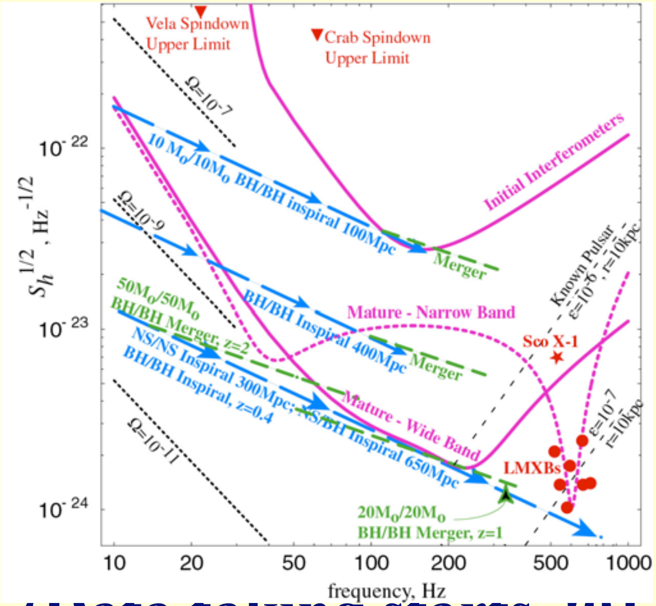
A factor of 2 improv. in sensitivity (8 in event rate)

(Data taking starts 6/2009)

Advanced Virgo

1)Larger mirror
2)Improved coatings
3)Higher laser power
4)DC readout

R&D underway
Design decisions late 2007

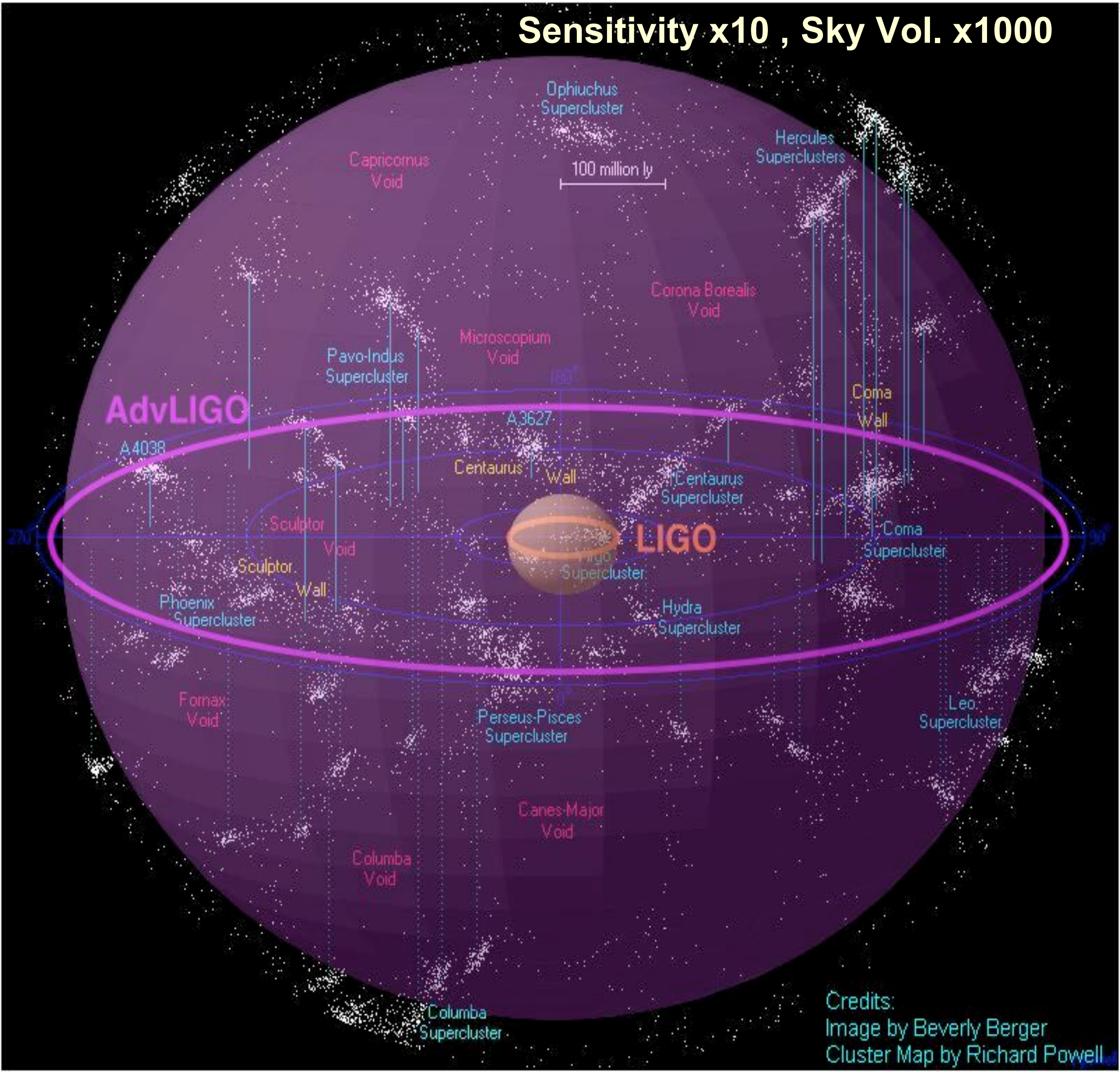


(Data taking starts 2014)

Advanced Ligo

1)Active anti-seismic system operating to down to 10 Hz
2)Lower thermal noise suspensions and optics
3)Higher laser power
4)More sensitive and more flexible optical configuration

Sensitivity x10 , Sky Vol. x1000

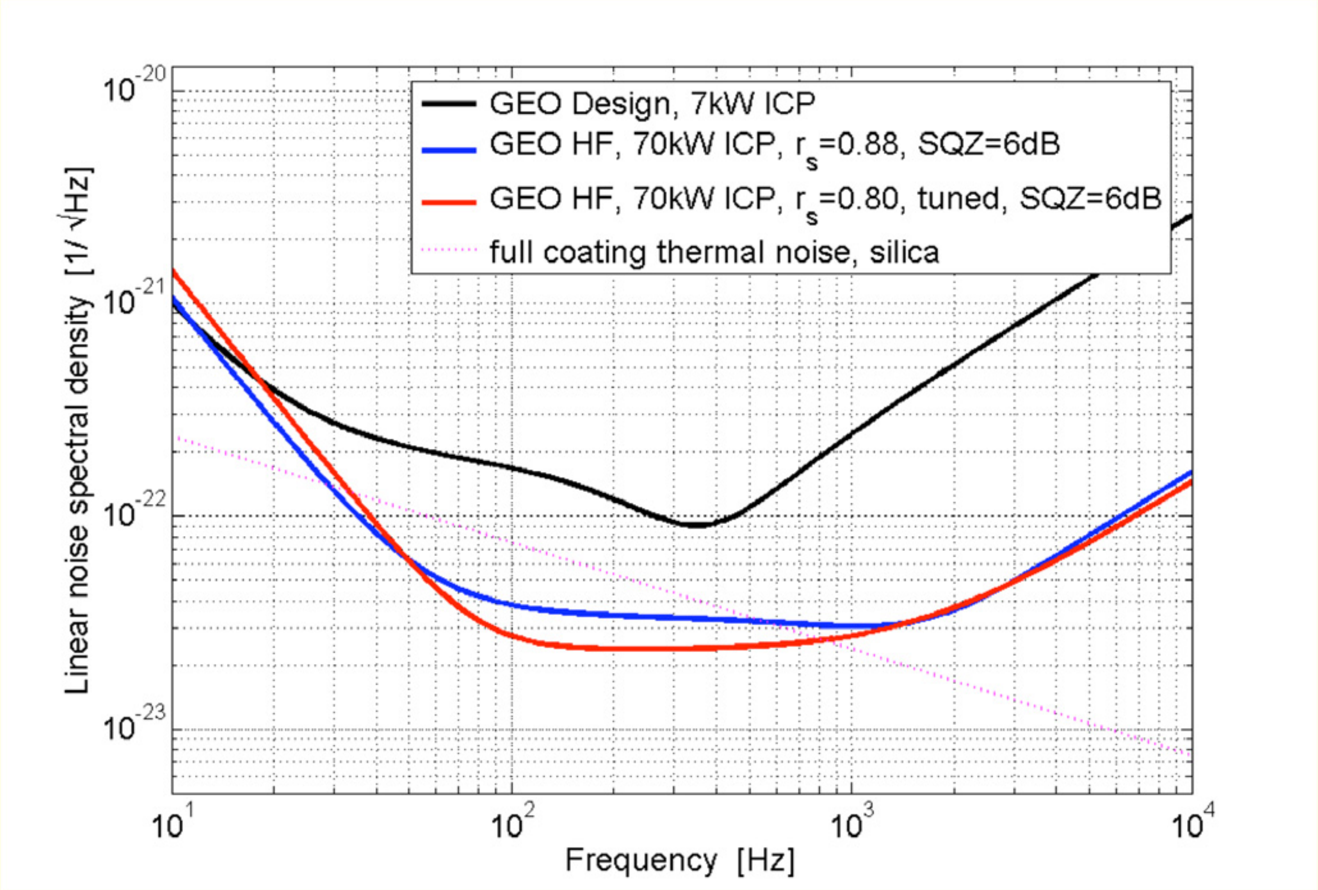


Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

Parameter	*LIGO*	*Advanced LIGO*
Input Laser Power	10 W	180 W
Mirror Mass	10 kg	40 kg
Interferometer Topology	Power-recycled Fabry-Perot arm cavity Michelson	Dual-recycled Fabry-Perot arm cavity Michelson
GW Readout Method	RF heterodyne	DC homodyne
Optimal Strain Sensitivity	3 x 10^{-23} / rHz	Tunable, better than 5 x 10^{-24} / rHz
Seismic Isolation	$f_{low} \sim 50$ Hz	$f_{low} \sim 10$ Hz
Mirror Suspensions	Single Pendulum	Quadruple pendulum

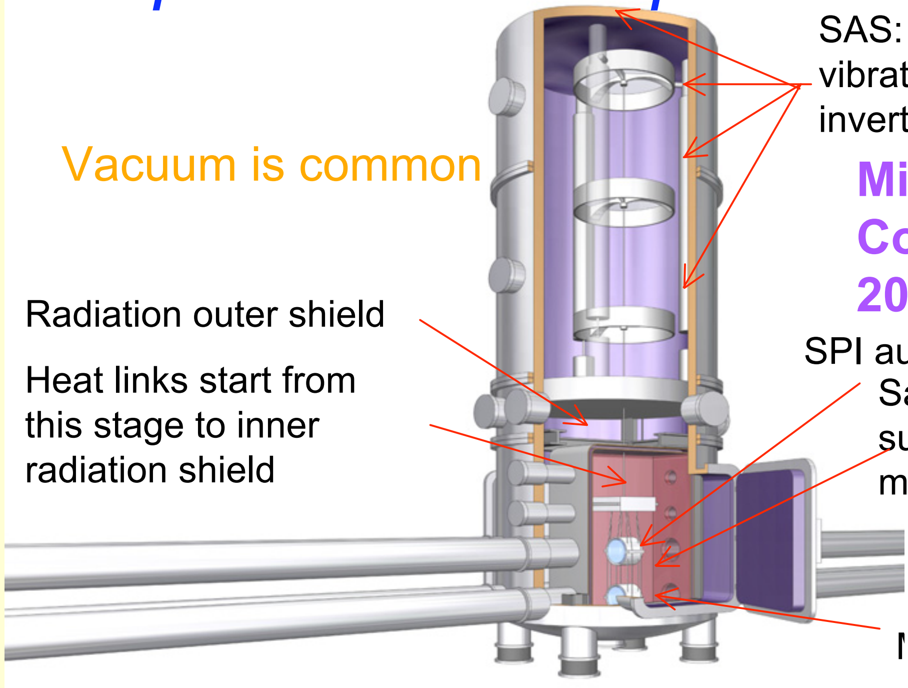
GEO 600

- Emphasize high frequencies--length less important
- Pioneer advanced techniques for other large interferometers
- Tuned signal recycling and squeezing?



LCGT: A CRYOGENIC INTERFEROMETER

Suspension Conceptual Design



SAS: 3 stage anti-vibration system with inverted pendulum

Vacuum is common

Mirrors Cooled at 20 K

Radiation outer shield

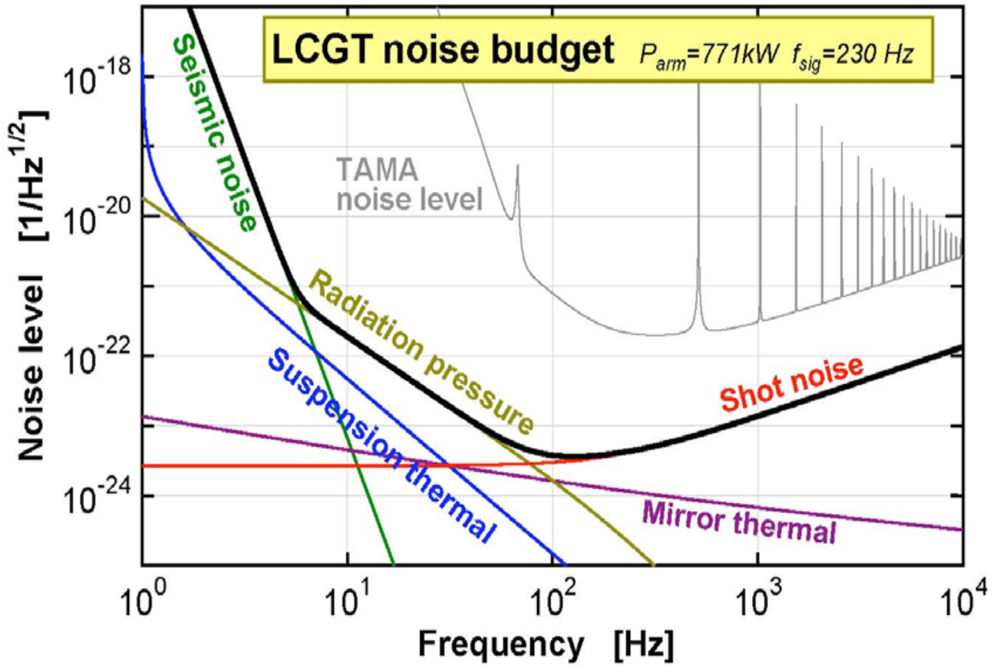
Heat links start from this stage to inner radiation shield

SPI auxiliary mirror

Sapphire fiber suspending main mirror

COST US$ 135M

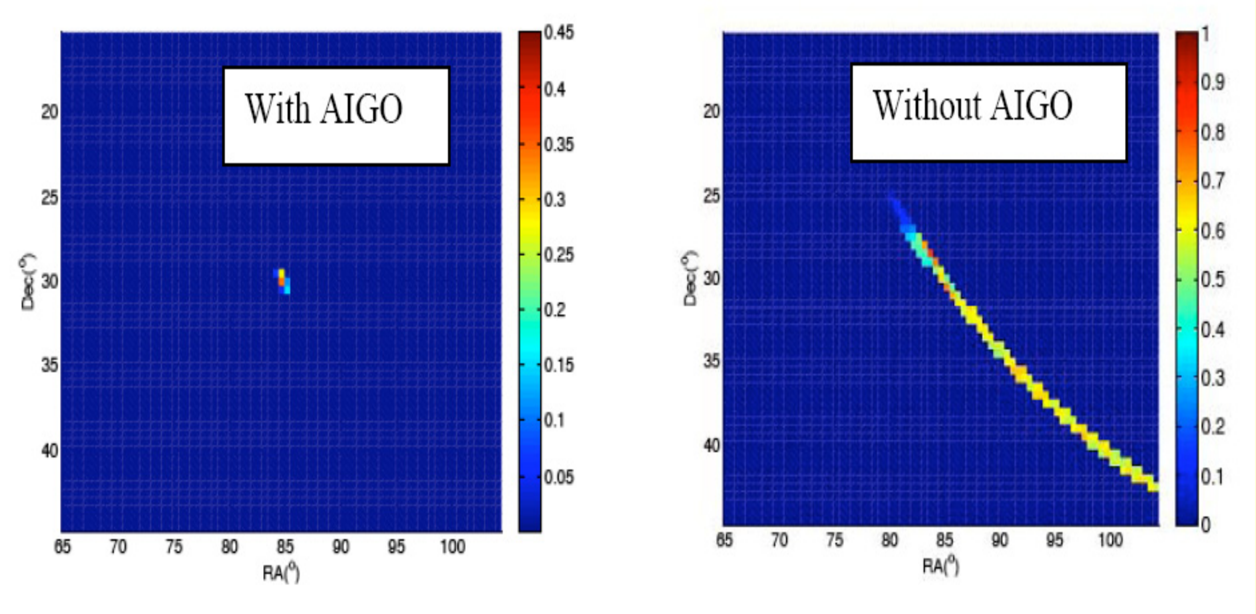
Does not include salaries & maintenances of facilities.



AIGO

- Project prospectus completed 2006
- AIGO concept plan submitted to Minister for Science Oct 2006
- AIGO International Advisory Committee appointed

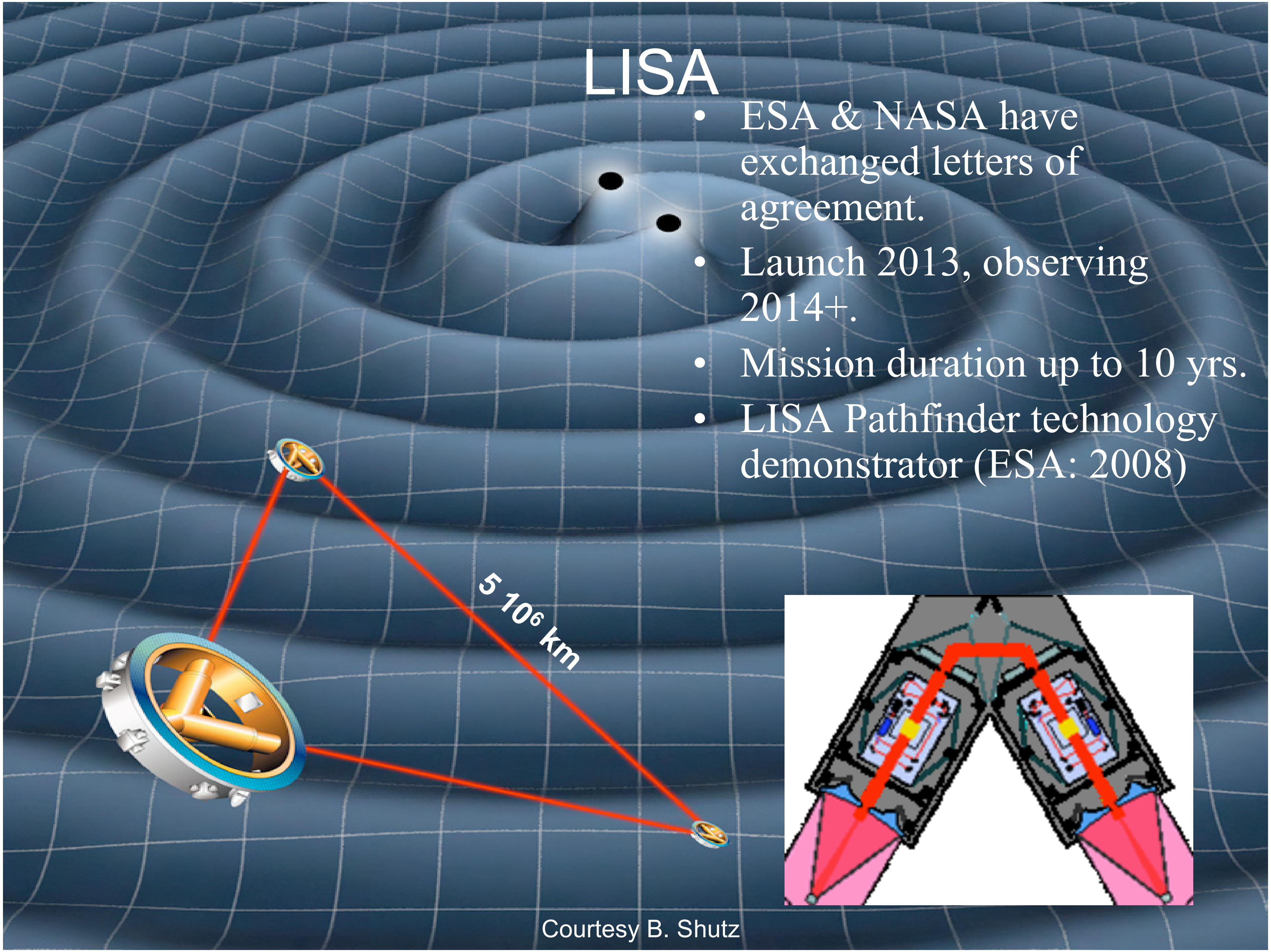
- AIGO provides strong science benefits e.g. host galaxy localization
- 5km baseline sensitive to inspirals in the range ~ 250Mpc
- Australian Consortium welcomes new partners in this project



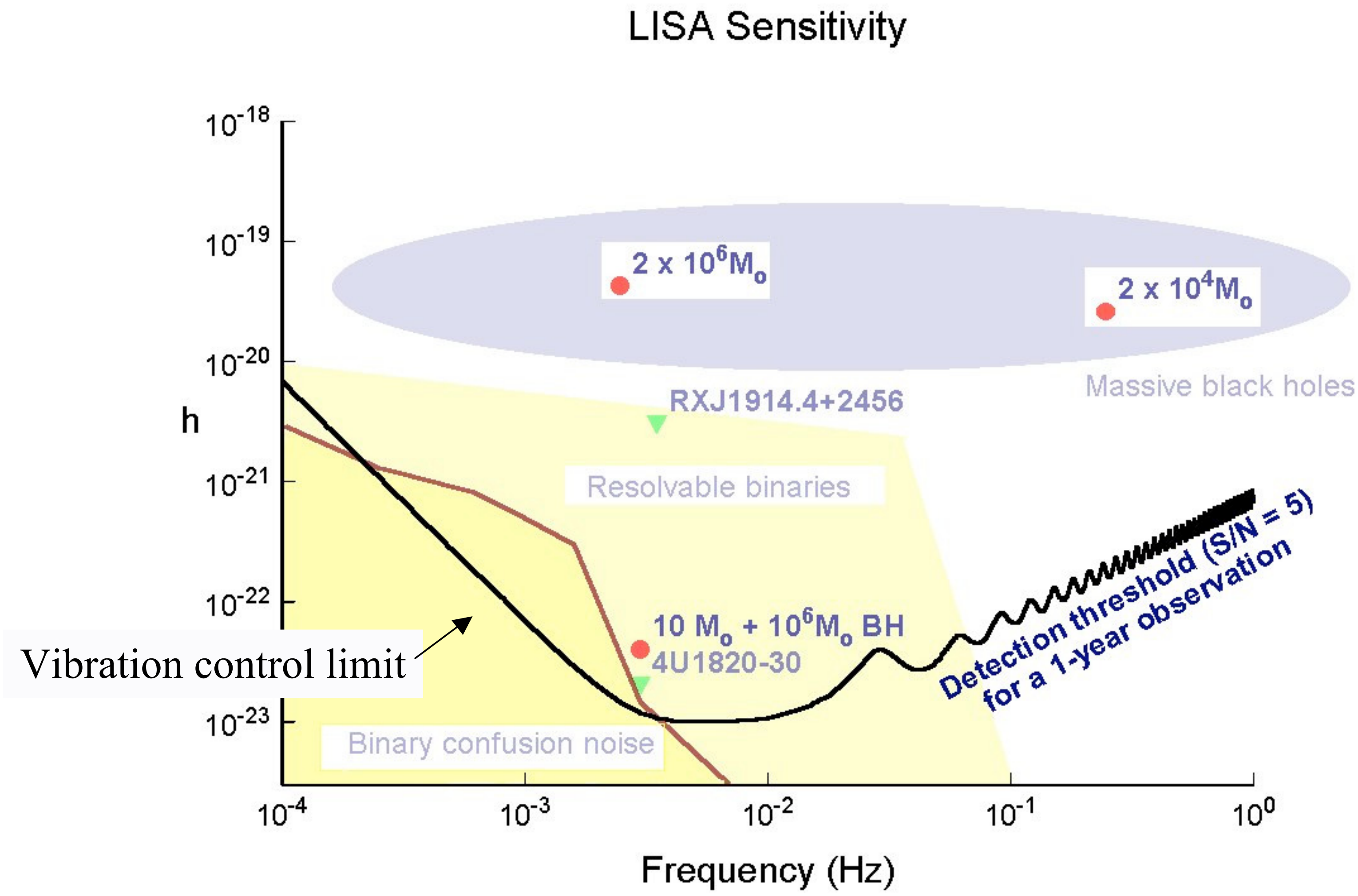
Interferometers Under Far Away Approval

LISA

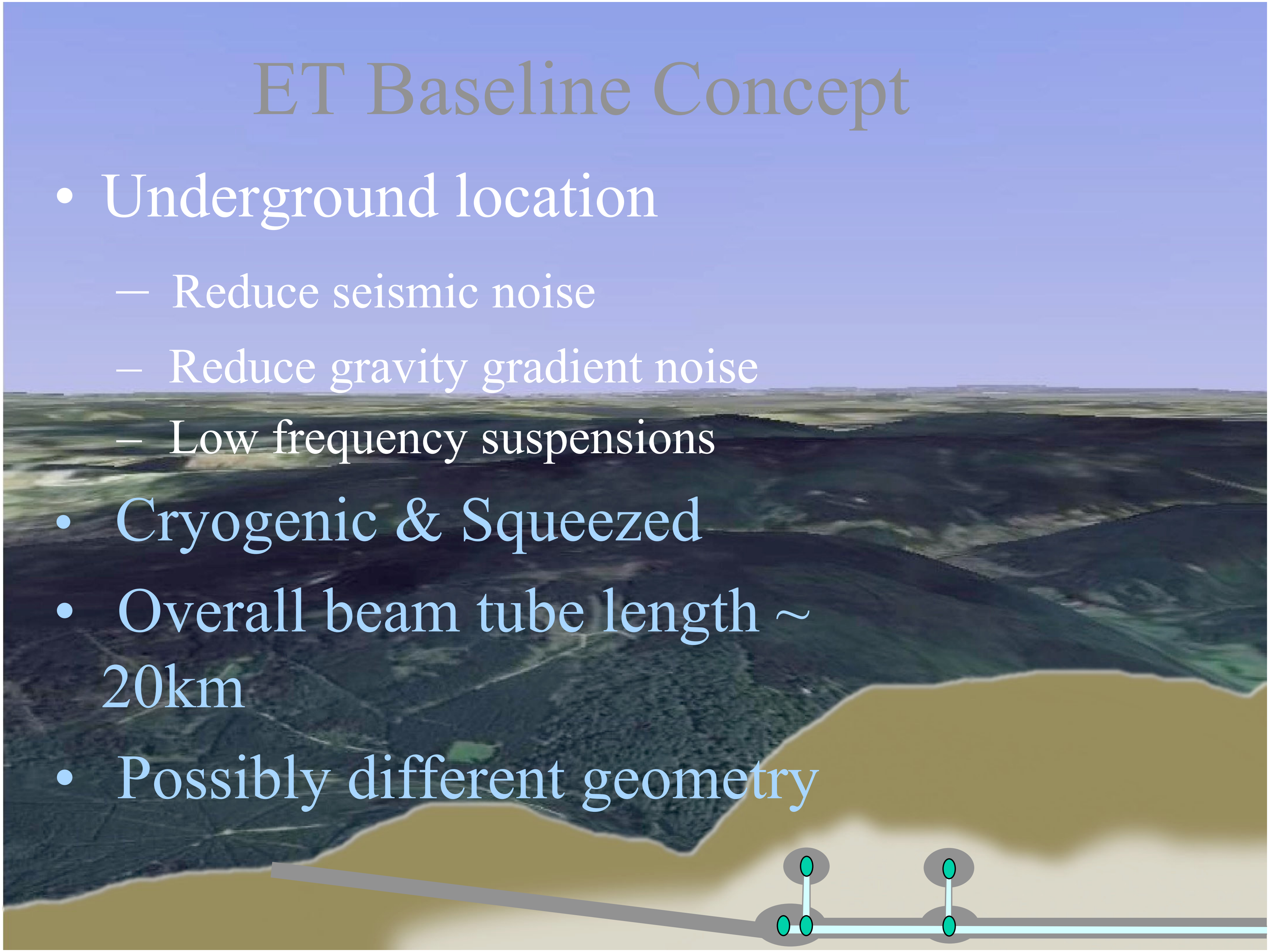
- ESA & NASA have exchanged letters of agreement.
- Launch 2013, observing 2014+.
- Mission duration up to 10 yrs.
- LISA Pathfinder technology demonstrator (ESA: 2008)



Courtesy B. Shutz


LISA Sensitivity
h
10^-18
10^-19
10^-20
10^-21
10^-22
10^-23
10^-4
10^-3
10^-2
10^-1
10^0
Frequency (Hz)
2 x 10^6 M_o
2 x 10^4 M_o
Massive black holes
RXJ1914.4+2456
Resolvable binaries
10 M_o + 10^6 M_o BH
4U1820-30
Binary confusion noise
Detection threshold (S/N = 5) for a 1-year observation
Vibration control limit

ET Baseline Concept



- Underground location
  - Reduce seismic noise
  - Reduce gravity gradient noise
  - Low frequency suspensions
- Cryogenic & Squeezed
- Overall beam tube length ~ 20km
- Possibly different geometry

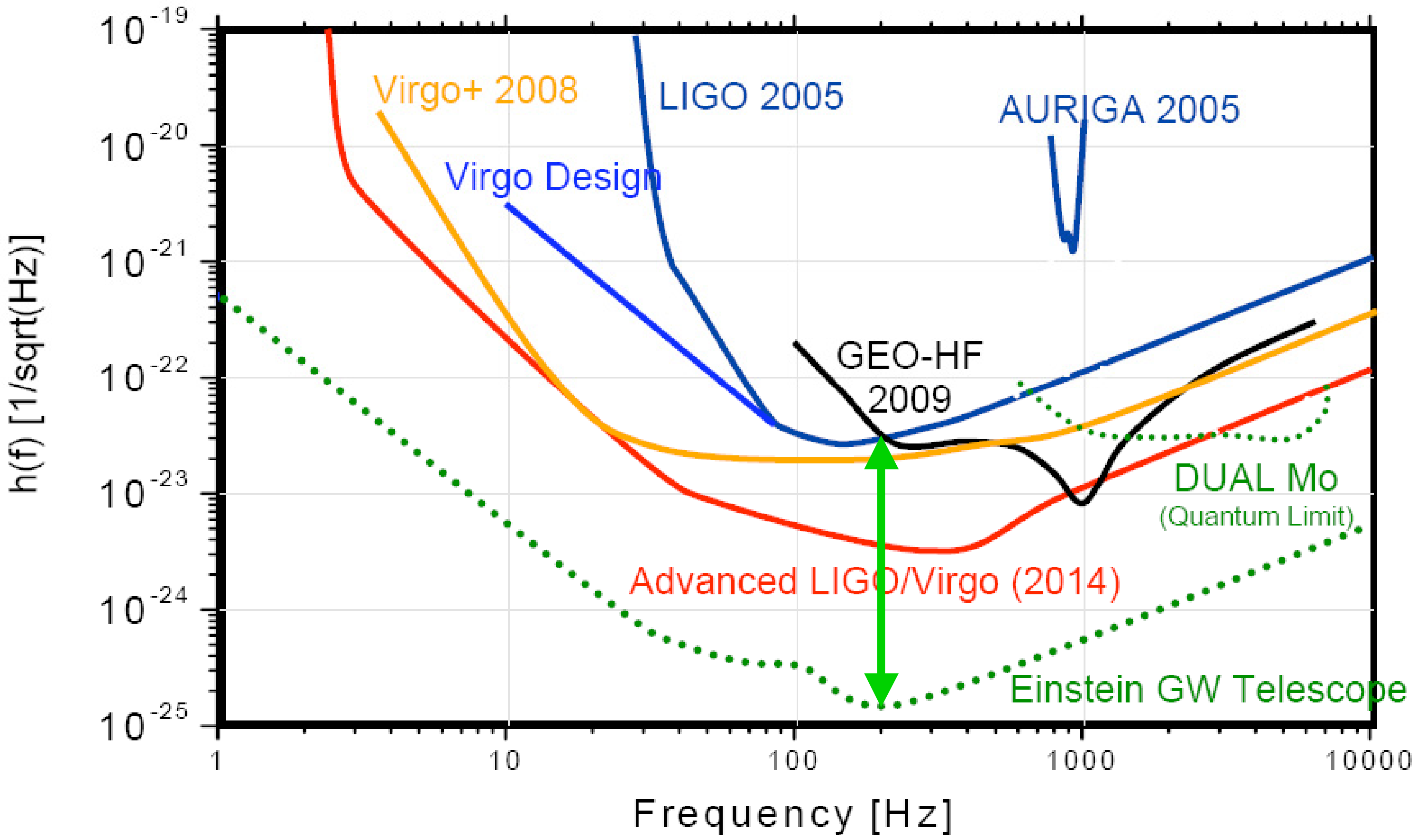
Einstein Telescope Configuration

1)ET will be the only surviving project. Virgo and LIGO will not have enough sensitivity for making a Network with ET

2)ET will be formed by at least 4 interferometers, well spaced. For solving the “Inverse Problem” 4 variables have to be measured:2 angles and 2 polarizations.

3)Possibly the ET network should have highly spaced interferometers. A wise decision could be in the same spirit as ESO whose telescopes are not in Europe. ET network should be scattered in best sites for better solving the “Inverse Problem”

Einstein Gravitational-Wave Telescope (ET)



Harald Lück

for the European Gravitational-Wave Community

Some Final Considerations

- Bar detectors have grown up, by means of a fantastic technological effort, to enormous and unexpected sensitivity and operation stability. Their operation was so good as to create the first GW network.
- The big steps forward in the last decade has been in the Interferometers technology. They reached design sensitivity above 100 Hz and stability is so good (unespectedly) that we have created an efficient network. Advanced LIGO and Virgo will open the very low frequency region.
- Class Einstein, after what we have lorned by the big machine, seems feasable with a very high probability of success. 1 Day of data of ET is equivalent to 10^6 days of data taking with Virgo or LIGO. This seems to be the right way to go for starting GW astronomy.

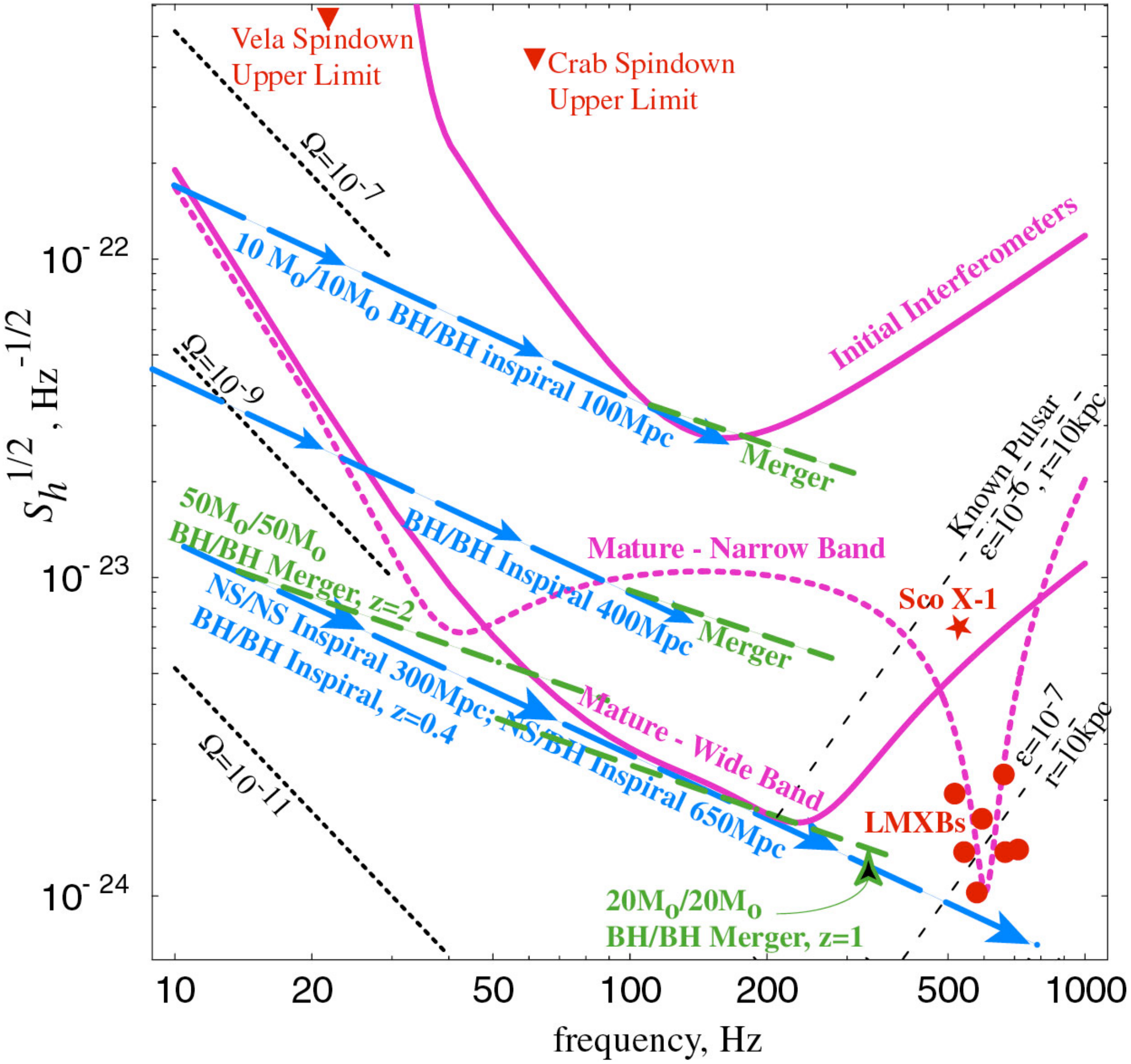
So Gravity waves do exist and Astrophysical phenomena involve:

enormous masses and big accelerations → According to GR: Copious emission of GW

amazing matter density → $\alpha_{GRAV}=10^{-39}$: Matter easily traversed by GW

Gravitational Waves are then odd objects by means of which we may start a new Astronomy:

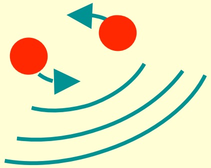
GW Astronomy.

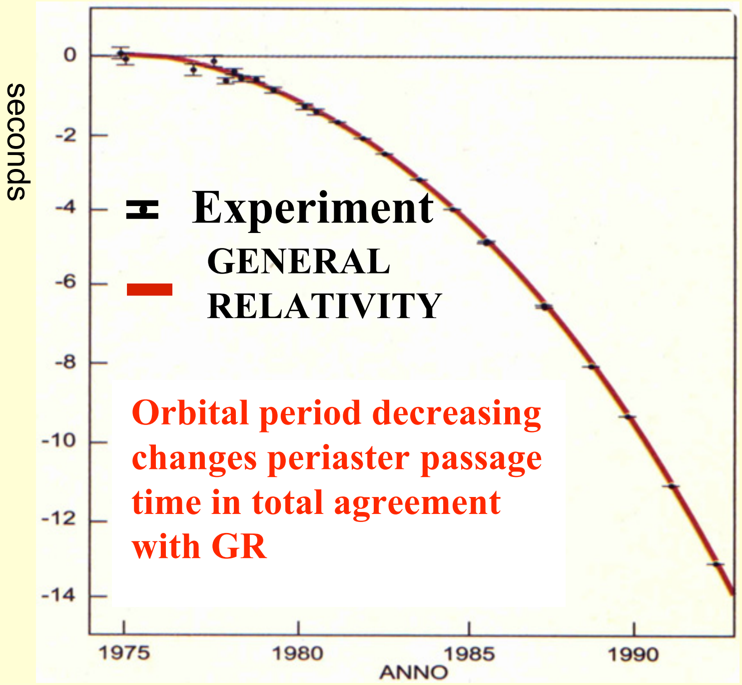

Vela Spindown
Upper Limit
Crab Spindown
Upper Limit
Ω=10-7
Ω=10-9
Ω=10-11
10 Mo/10Mo BH/BH inspiral 100Mpc
Merger
Initial Interferometers
BH/BH Inspiral 400Mpc
Merger
Mature - Narrow Band
Mature - Wide Band
50Mo/50Mo
BH/BH Merger, z=2
NS/NS Inspiral 300Mpc; NS/BH Inspiral 650Mpc
BH/BH Inspiral, z=0.4
20Mo/20Mo
BH/BH Merger, z=1
Known Pulsar
ε=10-6, r=10kpc
ε=10-7
r=10kpc
Sco X-1
LMXBs
10-22
10-23
10-24
10
20
50
100
200
500
1000
frequency, Hz
Sh1/2, Hz-1/2

The Indirect Evidences of GW Existence

1974:First Discovery by Taylor and Hulse (Nobel Prize 1993)

Coalescing Neutron Star System PSR 1913+16





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

Further evidences

PSR J0737-3039:

The binary Neutron Star system PSR J0737-3039 was discovered in 2003.

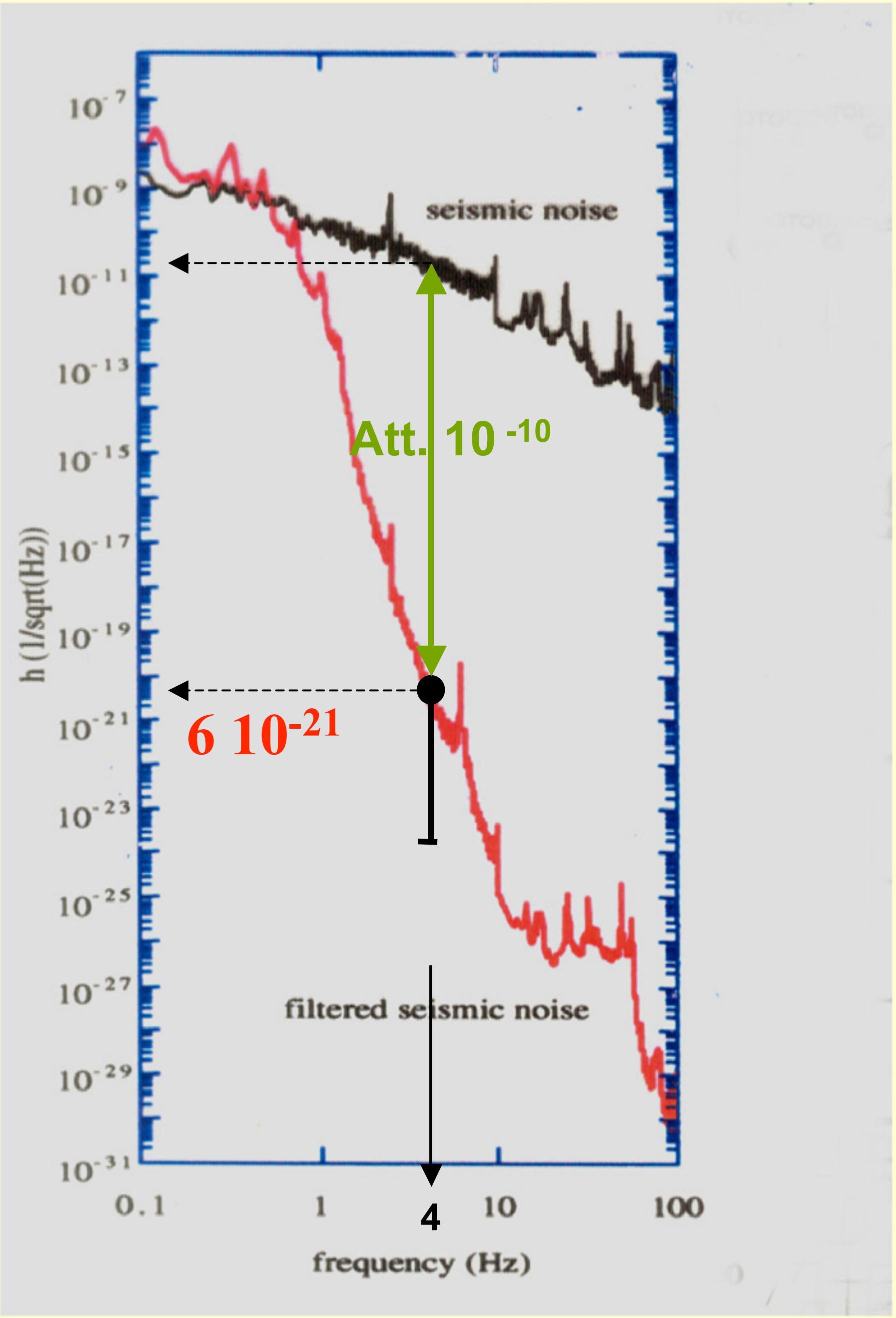
The system is doing exactly what GR theory predicts.

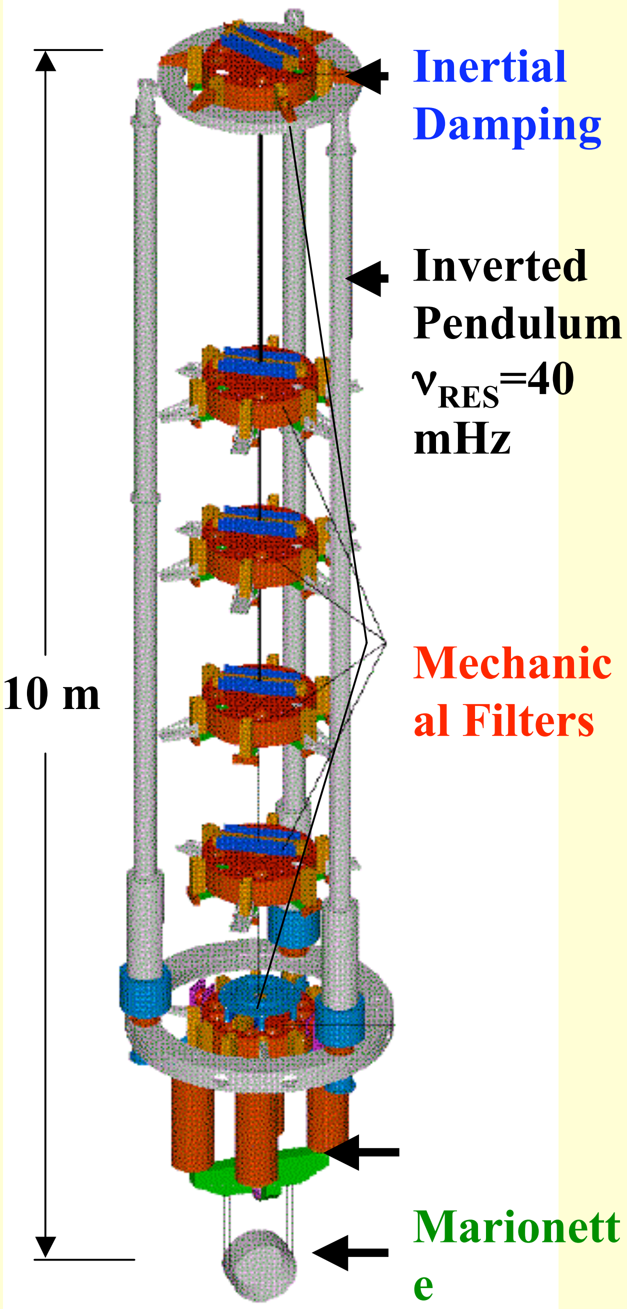
T. Strohmayer:

White Dwarf very tight Binary System (80000 km). The system's orbital period is 321.5 seconds and is decreasing by 1.2 milliseconds every year

in complete agreement with GR theory

Virgo Superattenuator





Inertial Damping

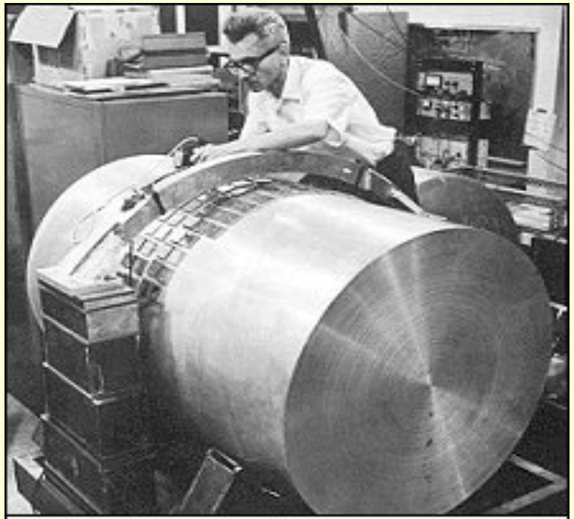
Inverted Pendulum
ν_{RES}=40 mHz

Mechanical Filters

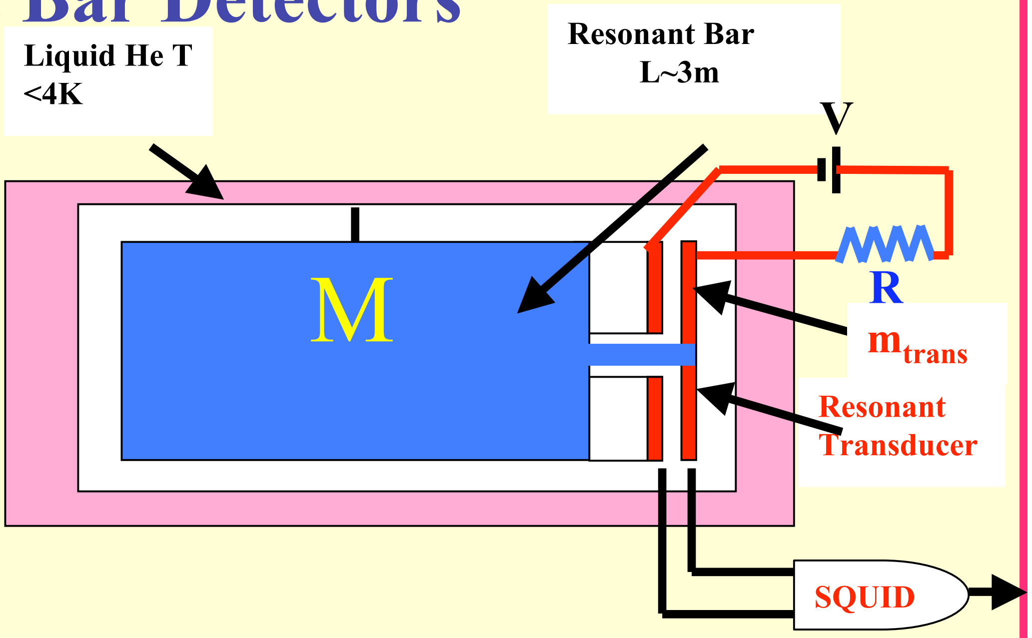
Marionette

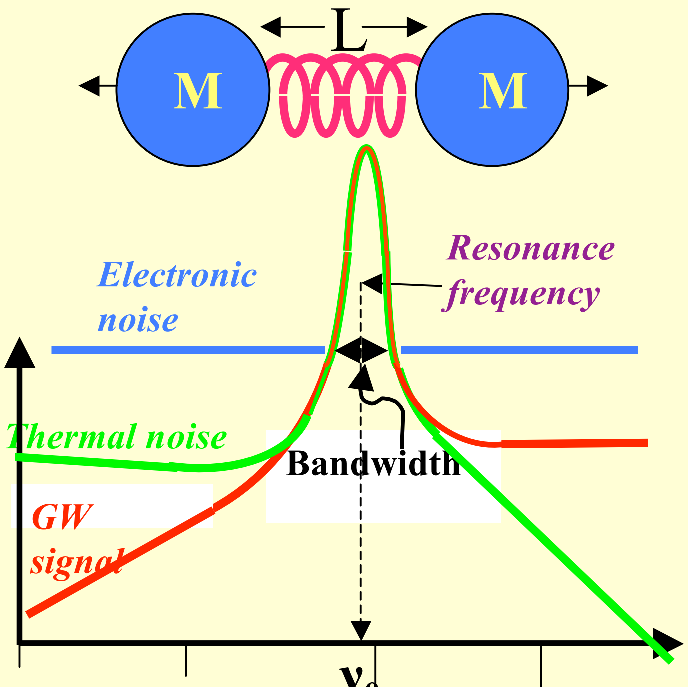
Cryogenic Bar Detectors

In 1959 J.W. was the first to propose a GW detector working on the principles of Geodetic Deviation Equation

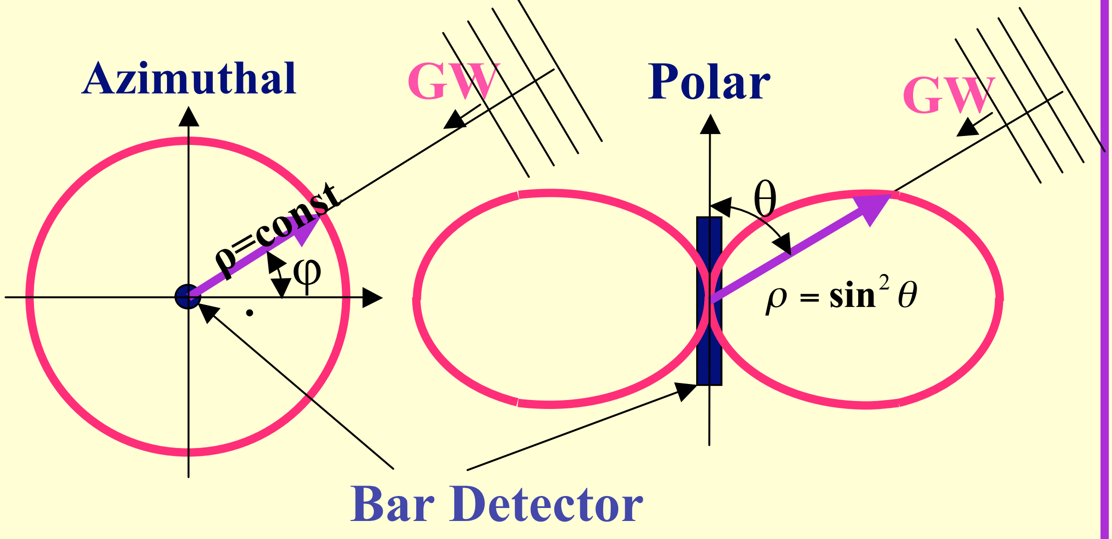


JOSEPH WEBER WITH GRAVITATIONAL WAVE DETECTOR

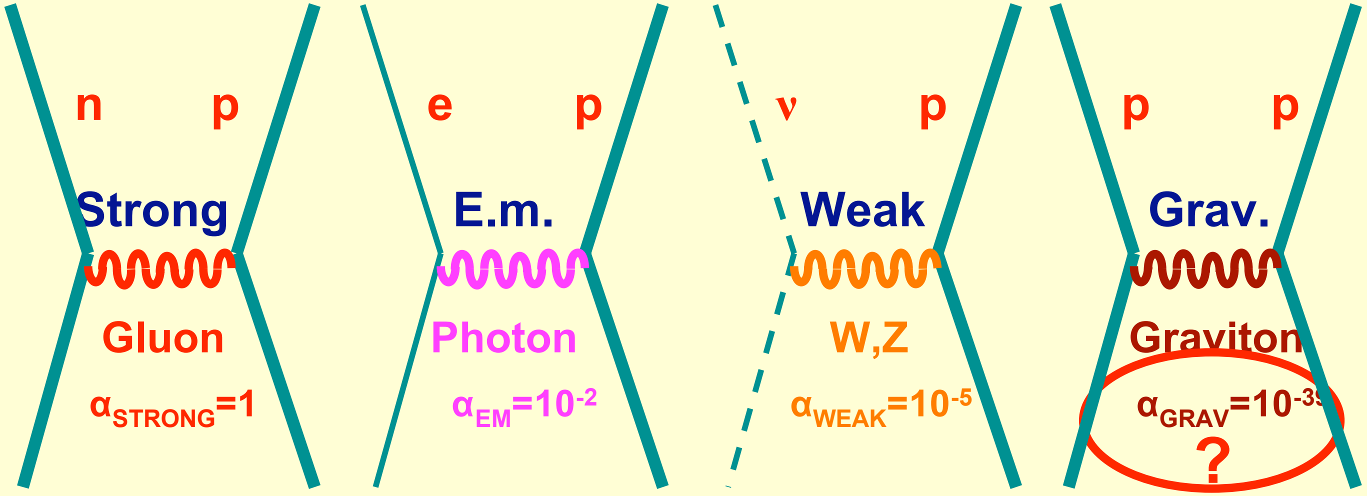




Antenna Pattern summed on polarizations



Why is Gravity so Appealing



n p

Strong

Gluon

$\alpha_{STRONG}=1$

e p

E.m.

Photon

$\alpha_{EM}=10^{-2}$

ν p

Weak

W,Z

$\alpha_{WEAK}=10^{-5}$

p p

Grav.

Graviton

$\alpha_{GRAV}=10^{-39}$

?

Why is Gravitational Coupling Constant amazingly small?

Three ingredients for a New Astronomy

1)Smallness of $\alpha_{GRAV}=10^{-39}$ means that interaction of Gravitational Waves (GW) with matter is extremely small.

2) General Relativity Theory (GR) predicts the existence of GW and shows that an accelerated mass emits GW.

3)Taylor and Hulse showed observationally that GW exist and their rate of emission follows “EXACTLY” GR predictions

The Generation of GW

Einstein eq.s

$\Psi_{\mu\nu}=(8\pi G/c^4)\,\tau_{\mu\nu}$

$\Psi_{\mu\nu}=h_{\mu\nu}-\frac{1}{2}\delta_{\mu\nu}h^{\lambda}_{\lambda}$

The GW Generator

$$h^{TT}_{\alpha\beta} = -\frac{2G}{c^4 R_o}\left(\frac{\partial^2}{\partial t^2}\int\rho\left(x_\alpha x_\beta\right)^{TT} dV\right)_{t-R_0/c}$$

R_0 source distance.
ρ source density.

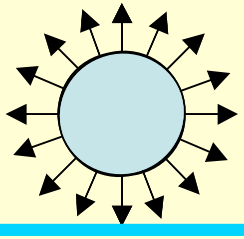
GW are produced by the second time derivative of the source Quadrupole Momentum of the mass distribution

$$h^{TT}_{\mu\nu} = h^{TT}_{11}\begin{pmatrix}0&0&0&0\\0&1&0&0\\0&0&-1&0\\0&0&0&0\end{pmatrix} + h^{TT}_{12}\begin{pmatrix}0&0&0&0\\0&0&1&0\\0&1&0&0\\0&0&0&0\end{pmatrix} = h^{+}e^{+}_{ik} + h^{X}e^{X}_{ik}$$

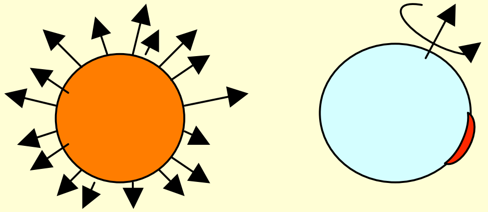
GW along X_3

The polarizations e^{+}_{ik} and e^{x}_{ik} are exchanged with a π/4 rotation around x_3 axis i.e. GW are spin 2 massless field

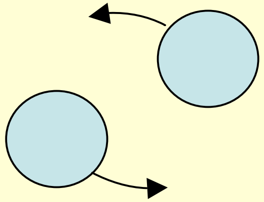
Symmetrical h=0



Low Asymmetry



Max. Asymmetry

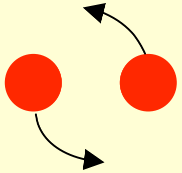


GW Sources

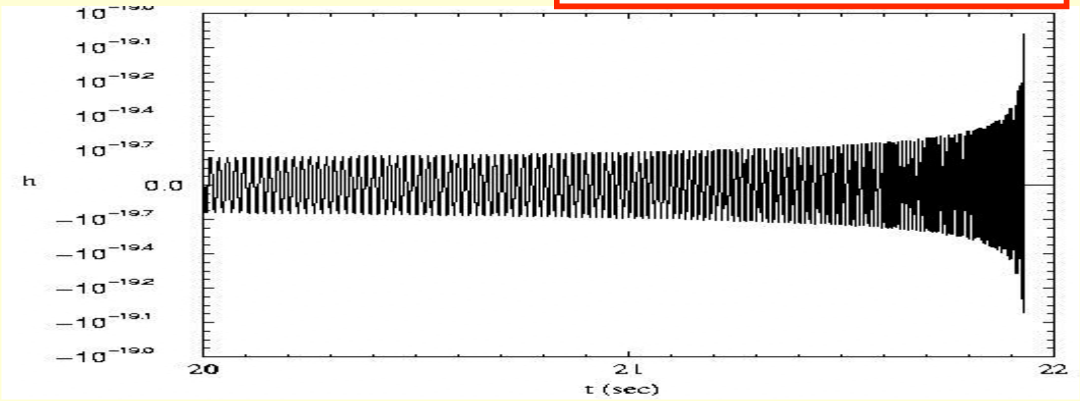
1) Coalescing Binary Systems: NS and Black Holes

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

Maximal Asymmetry → "Large" h



"known" waveform →



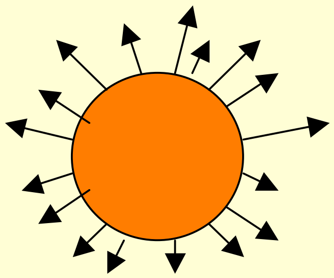
2) Supernovae Explosions

Low Asymmetry: "Small" h

Explosions Rate:

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

Galassia ($h \sim 10^{-20}$) 1/30 years



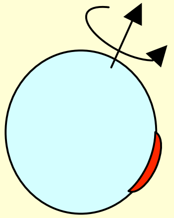
3) Periodic Sources: 10^9 Galactic rotating Neutron Stars emitting in the Hz regionVery Low Asimmetry: Very “Small” h but very long Integration Time

Affected by Earth Doppler shift

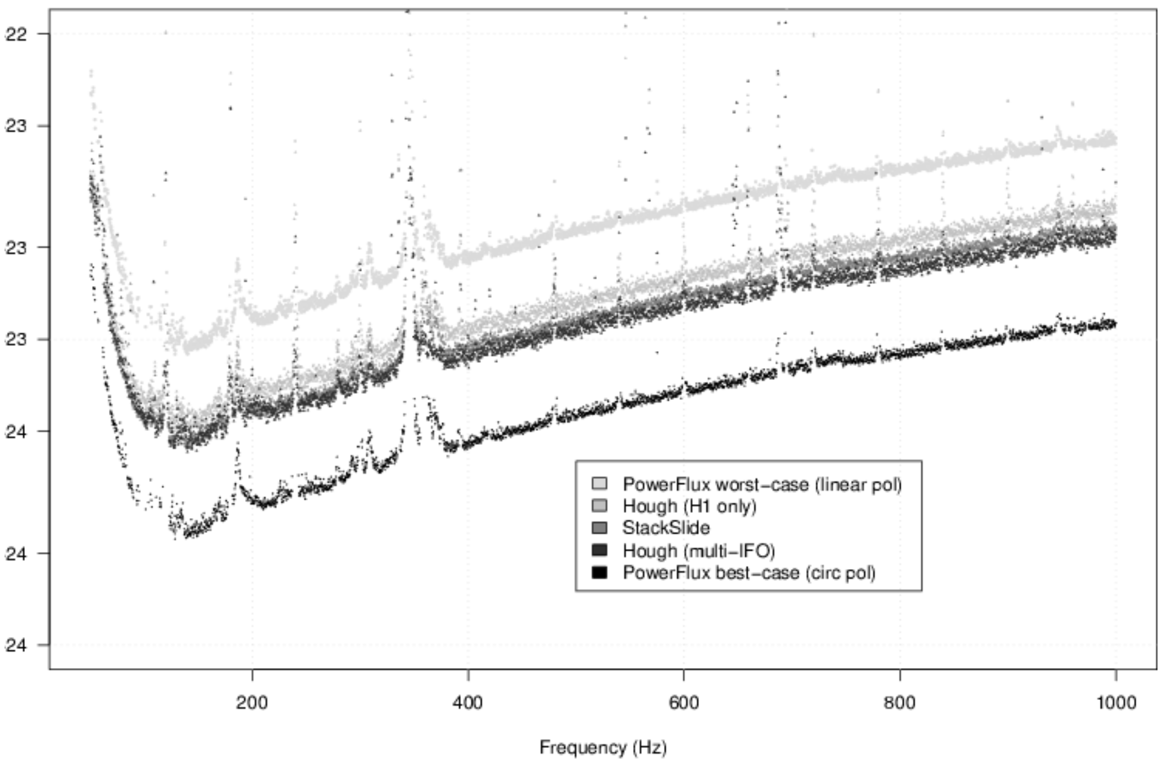
$$e^{i\omega t} \Rightarrow e^{i\omega(t-\vec{n}\cdot\vec{R}/c)}$$

n is the NS direction
R the Earth radius

$h < 10^{-25}$

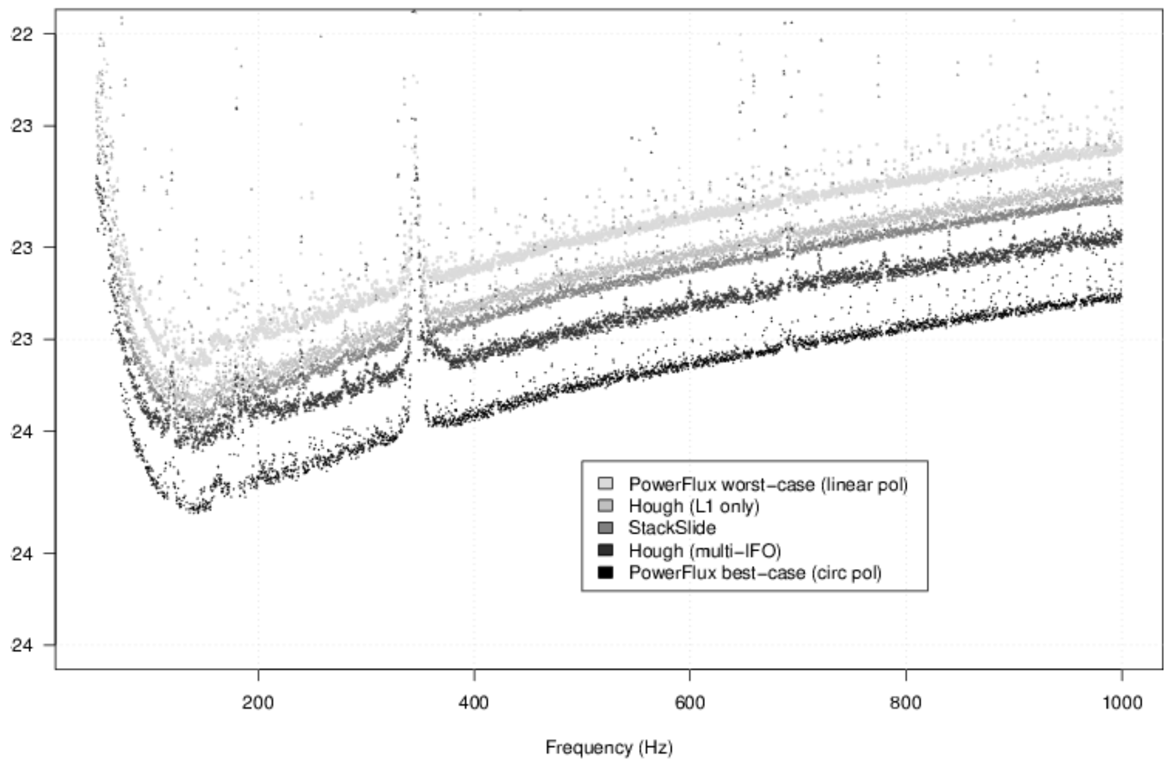


4) Big-Bang Cosmological BKG (CB): In the Virgo bandwidth we may observe GW emitted after 10^{-24}s from time zero. GW are the only way to investigate Bing-Bang close to time zero. Detection of CB requires Coincidence of two close detectors extremely sensitive.



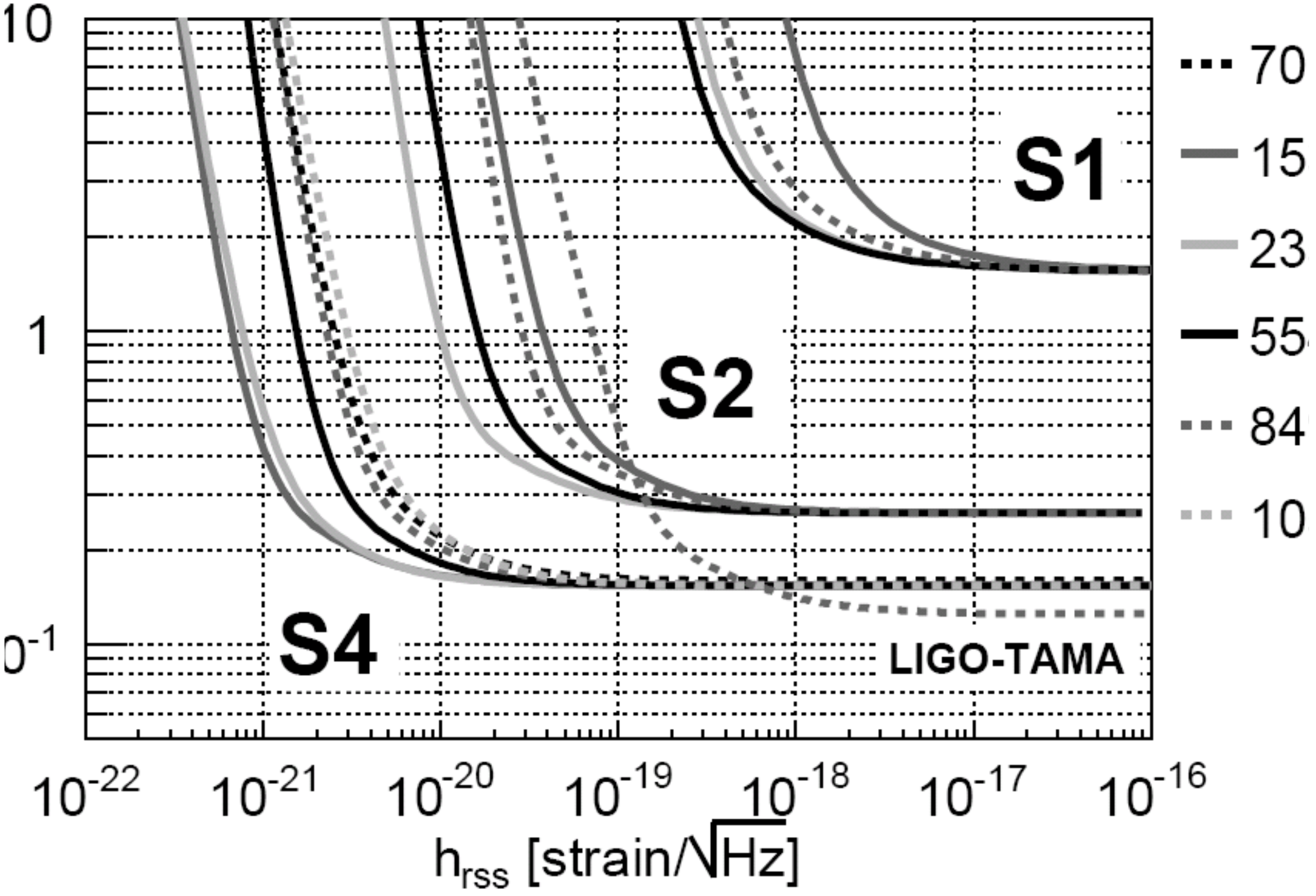
Periodic sources: upper limits

This is the Hanford all sky upper limit for periodic sources strain (95% confidence level), obtained for the Hanford observatory. The plot compares several search method, documented in the S4 paper LIGO-P060010-05-Z



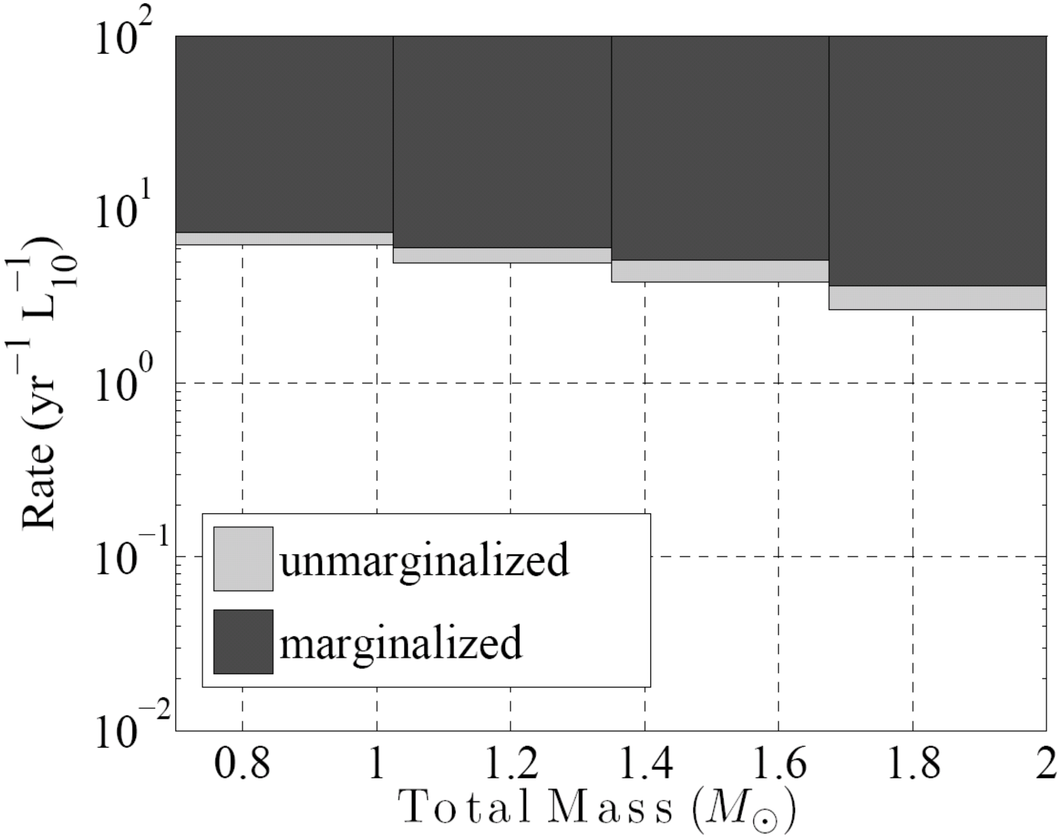
Periodic sources: upper limit

The same of the previous figure, for the Livingston observatory.



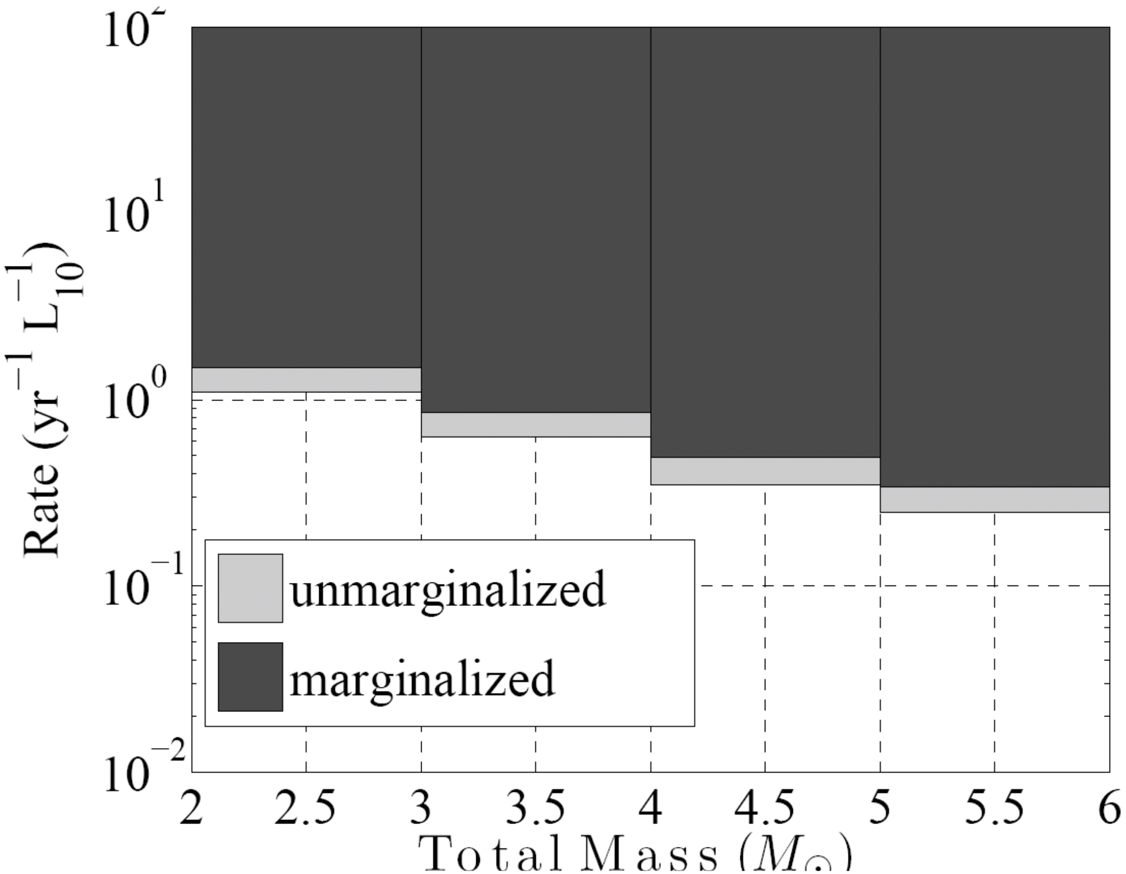
Upper limits: bursts

Exclusion diagrams (rate limit at 90% confidence level, as a function of signal amplitude) for sine-Gaussian simulated waveforms for the 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 hrss sensitivity of the LIGO-TAMA search was nearly constant for sine-Gaussians over the frequency range 700–1600 Hz.



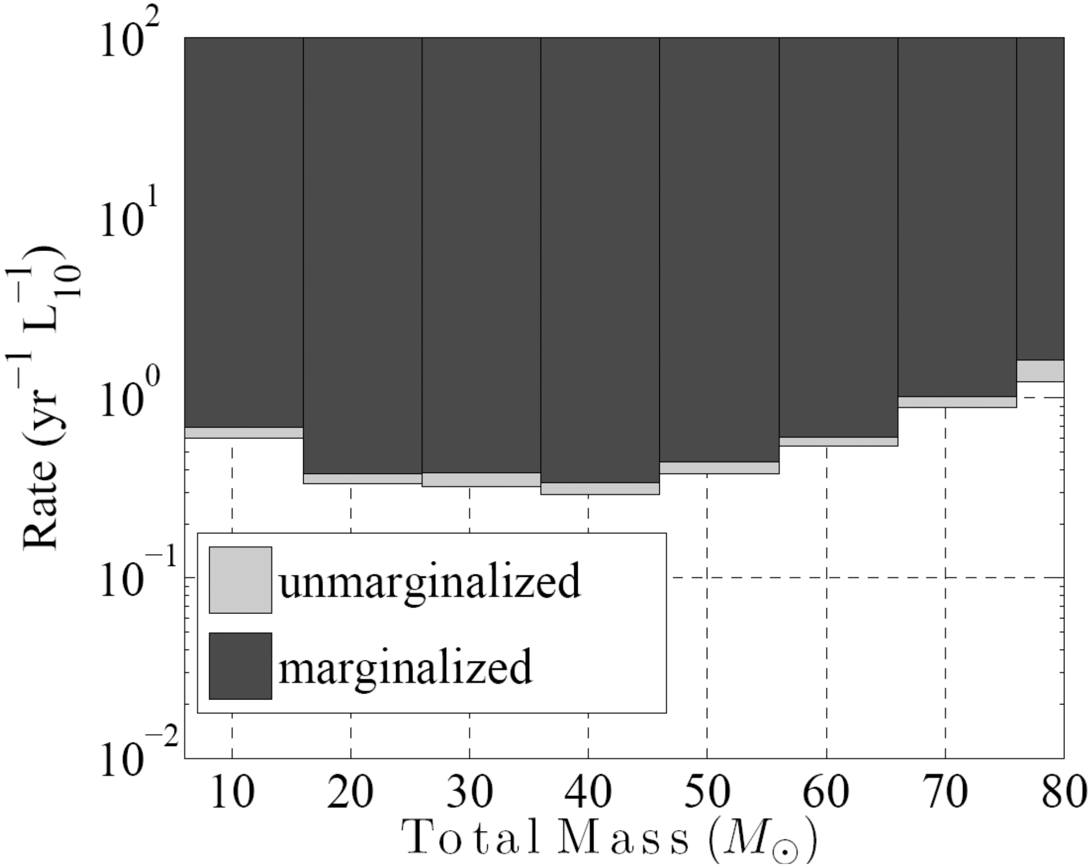
Upper limit: inspirals

Upper limits on the binary inspiral coalescence rate per year and per L10 as a function of total mass of the binary, for Primordial Black Hole binaries. The darker area shows the excluded region after accounting for marginalization over estimated systematic errors. The lighter area shows the additional excluded region if systematic errors are ignored.



Upper limits: inspirals

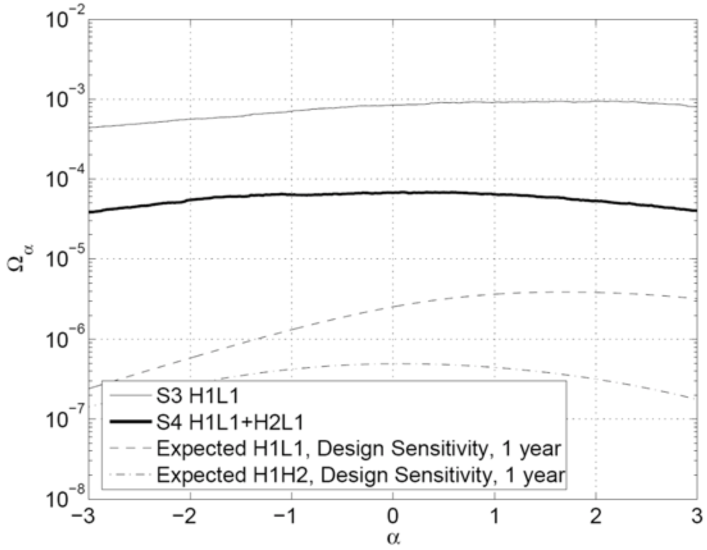
Same as the previous figure for Binary Neutron Stars



Upper limits: inspirals

Same as the previous figure for Binary Black Holes

$$\Omega_{\rm GW}(f) = \frac{f}{\rho_c}\,\frac{d\rho_{\rm GW}}{df}$$



Upper bounds: stochastic backgorund

90% Upper Limit on GW spectrum at 100 Hz (see the model on the right) as a function of α for S3 H1L1 and S4 H1L1+H2L1 combined, and expected final sensitivities of LIGO H1L1 and H1H2 pairs, assuming LIGO design sensitivity and one year of exposure.

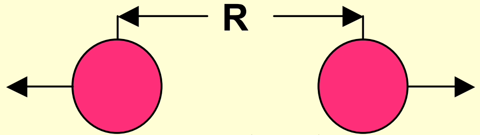
Model:

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

Three ingredients for a new Astronomy

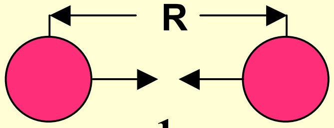
Forces Between two Protons

Electrostatic Repulsion



$$F = \frac{1}{100}\frac{1}{R^2}$$

Gravitational Attraction



$$F = \frac{1}{1000000000000000000000000000000000000000}\frac{1}{R^2}$$

1)Smallness of $\alpha_{GRAV}=10^{-39}$ means that interaction of Gravity with matter is extremely small.

2)Einstein in his General Relativity showed that:

-Accelerated masses emit GW.

-In presence of masses, the Space-Time (ST) is curved.

-Gravitational Waves are ripples in the ST traveling at speed of light.

Gravitational Waves in Curved Space-Time

3)Taylor and Hulse demonstrated, indirecly, that GW exist and their rate of emission follows “EXACTLY” General Relativity predictions

The Detection of Gravitational Waves

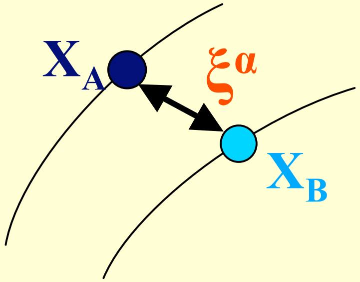
F.A.E.Pirani in 1956 first proposed to measure Riemann Tensor by measuring relative acceleration of two freely falling masses.

If A and B are freely falling particles, their separation $\xi^\alpha=(x_A-x_B)^\alpha$ satisfies the **Geodesic Deviation equation**:

$$\frac{D^2\xi_\alpha}{d\tau^2} \Rightarrow \frac{1}{2}\ddot{h}^{TT}_{\alpha\beta}\xi^\beta$$

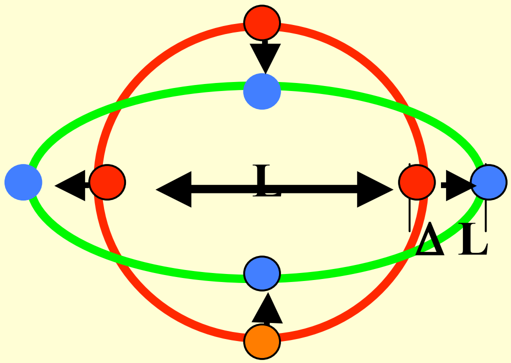
Riemann Force

$$F_\alpha = \frac{1}{2}M\ddot{h}^{TT}_{\alpha\beta}\boxed{\xi^\beta}$$



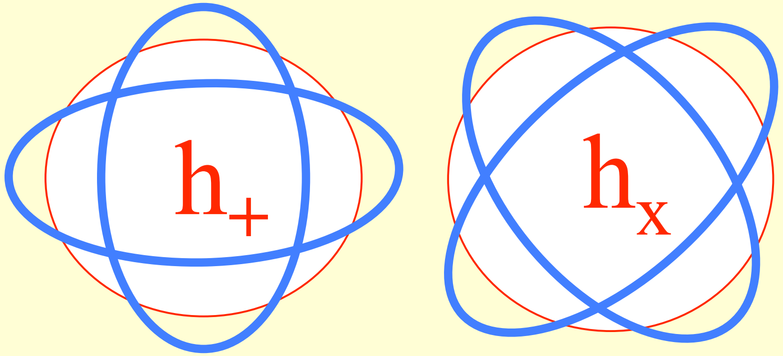
The receiver is a device measuring space-time curvature i.e. the relative acceleration of two freely falling masses or **their relative displacement**.

Effect of Riemann Force

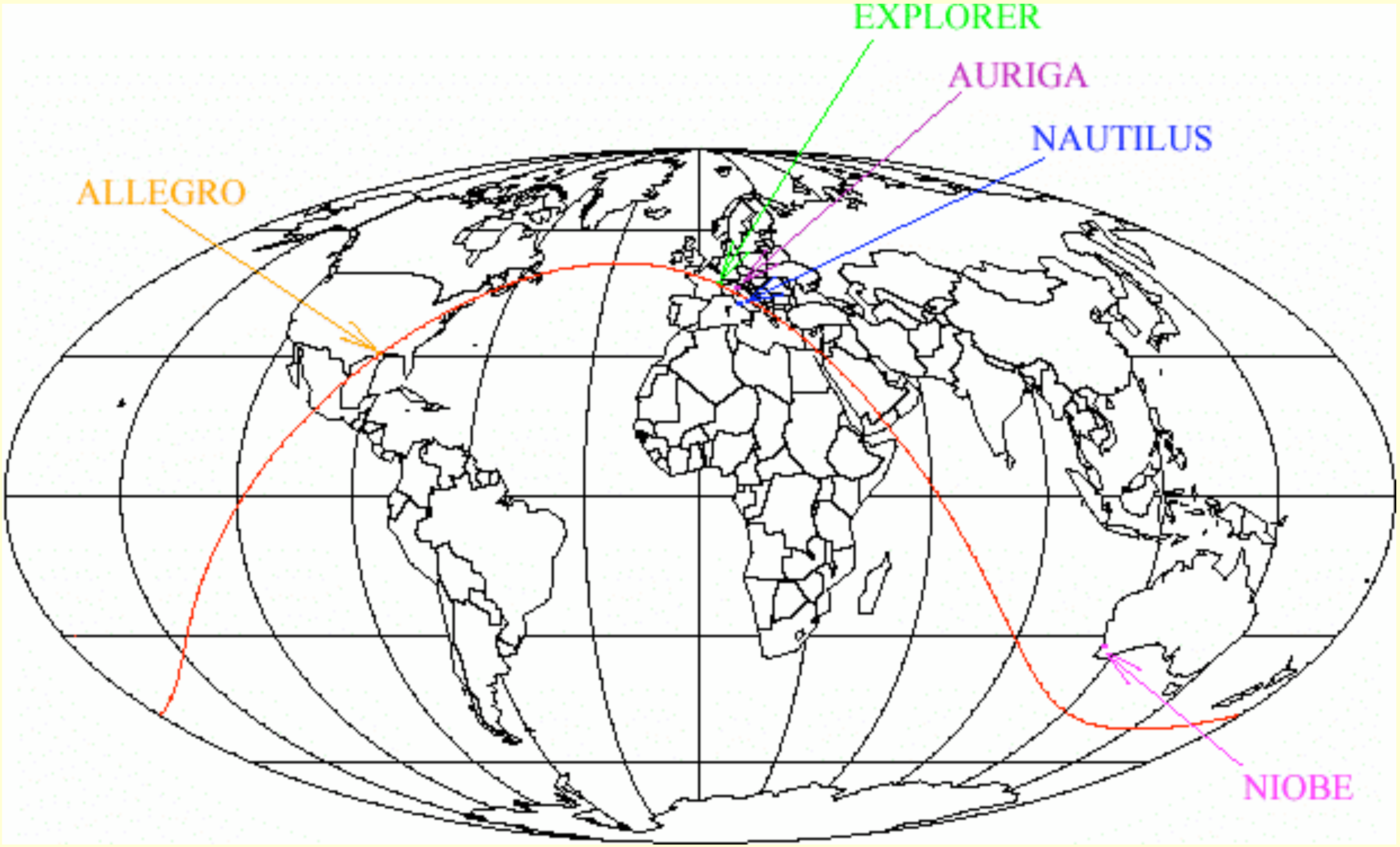


$$\frac{\Delta L}{L} \sim h < 10^{-22}$$

Effect of 2 Polarizations



Cryogenic Bar Detectors

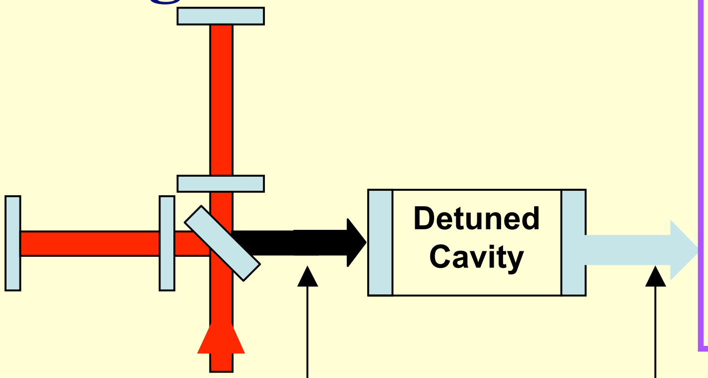


Modern Interferometers with QND Signal Readout

Uncertainty Principle:

$\Delta\varphi \,.\, \Delta N \sim 1$

We only measure φ, the only one containing the signal, hence we can ignore ΔN.

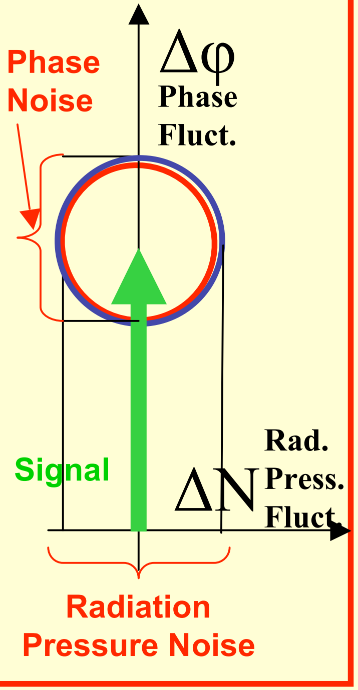


Optical Noise can be less than SQL:

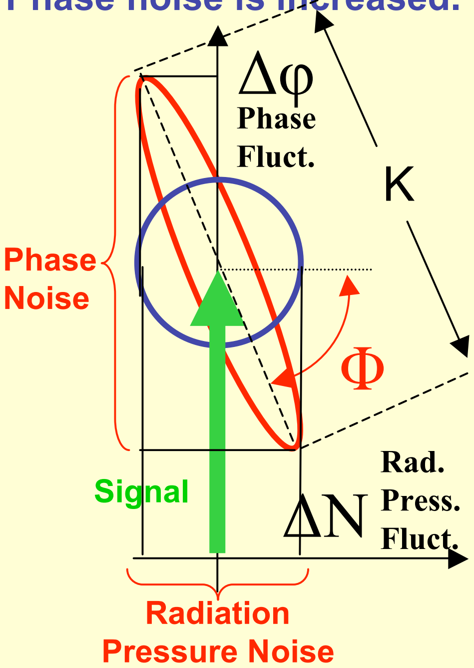
$$\frac{4\pi}{\lambda} hL \geq \sqrt{K} + \frac{1}{\sqrt{K}}$$

$$\frac{4\pi}{\lambda} hL \geq \frac{1}{\sqrt{K}}$$

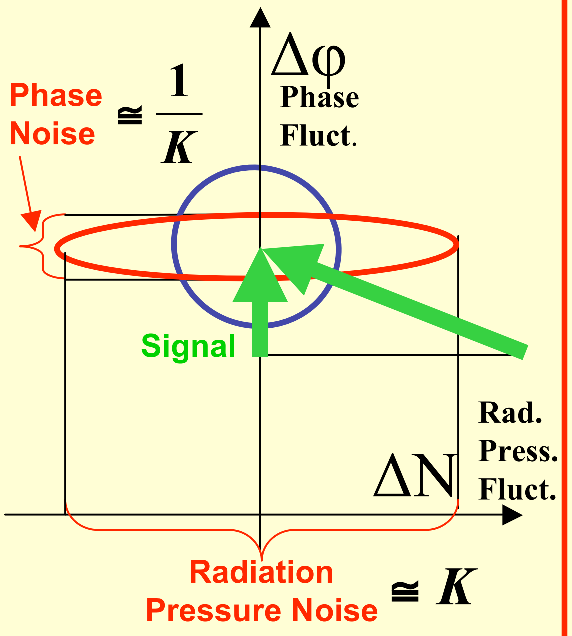
In a Fix Mirror ITF, Rad. Press. Fluct. can't move mirrors.



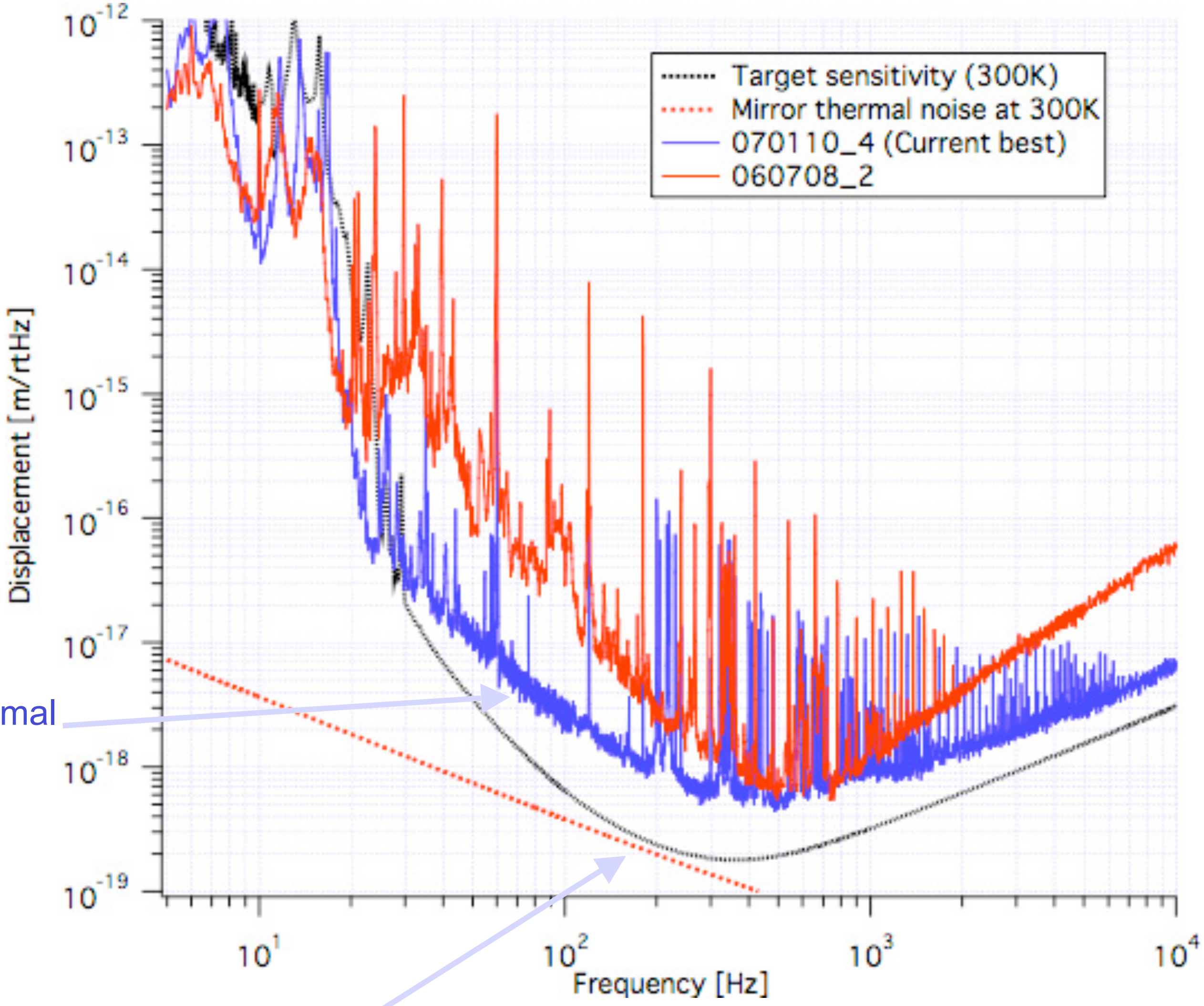
In a suspended Mirror ITF, Rad. Press. Fluct. move randomly mirrors, hence Phase noise is increased.



A Detuned Cavity can rotate in the Δφ, ΔN plane. Phase noise Δφ has been decreased at expenses of ΔN.



Current sensitivity of CLIO



After reaching thermal limit, start cooling

Mirror thermal noise(300K)

1970

The first Interferometer for GW detection was built by Robert Forward (Hughes Lab)

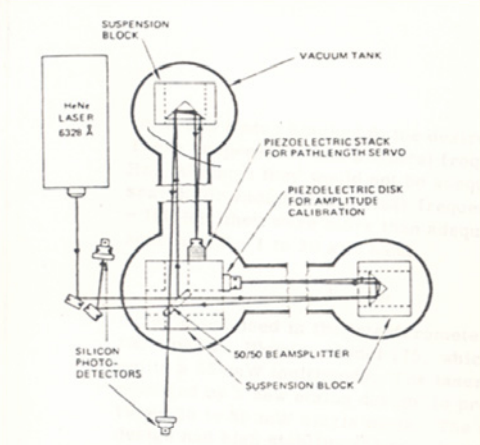


FIG. 7. Schematic of folded optical path.

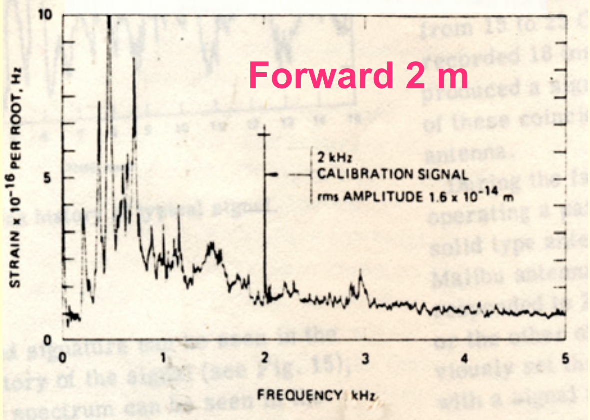


FIG. 14. Strain sensitivity of interferometer antenna.

1980

The Max Planck 30 m Delay Lines Interferom.

Problem: Too much Diffused Light

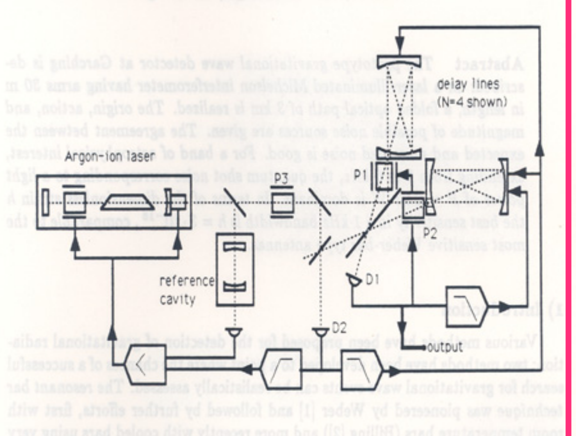


Figure 1 : A schematic view of the interferometer

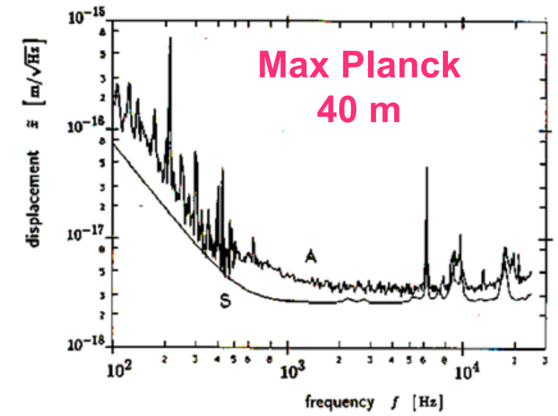
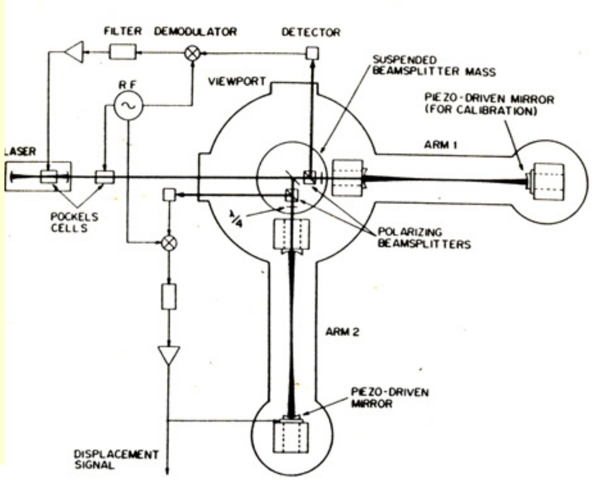
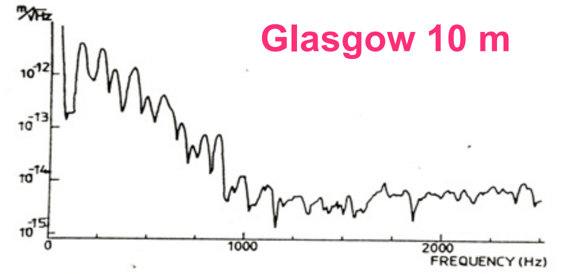


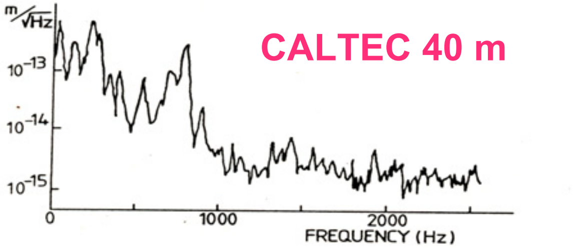
Figure 4 : The interferometer noise spectrum.
A: measured, S: predicted.

Break Through : 1981

The 10 m Glasgow and 40 m CALTEC Fabry Perot Interferometers

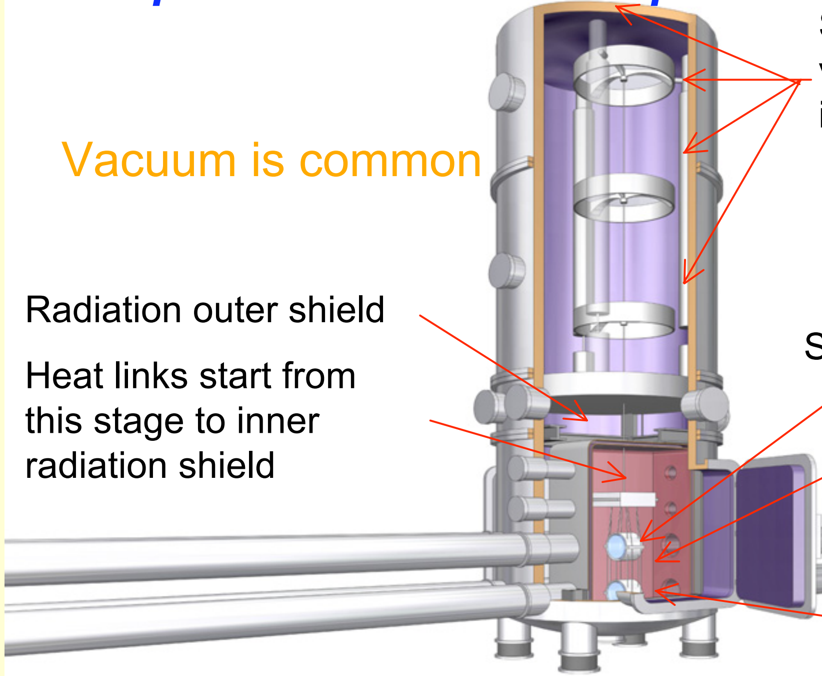






LCGT: A CRYOGENIC INTERFEROMETER

Suspension Conceptual Design



SAS: 3 stage anti-vibration system with inverted pendulum

Vacuum is common

Radiation outer shield

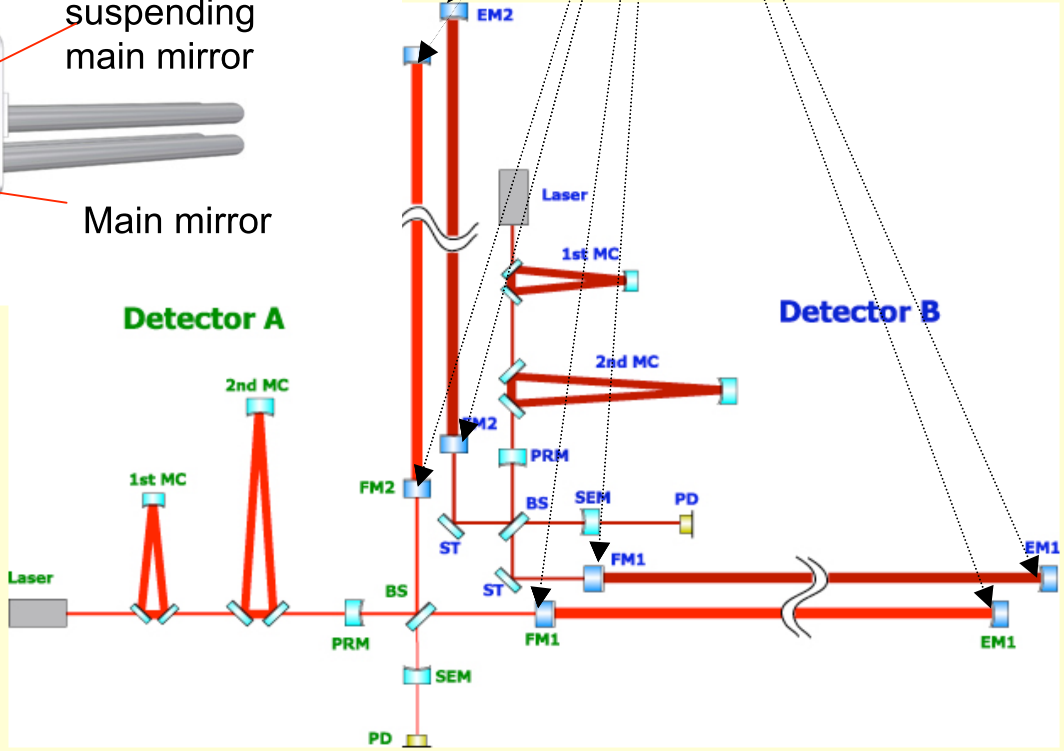
Heat links start from this stage to inner radiation shield

SPI auxiliary mirror

Sapphire fiber suspending main mirror

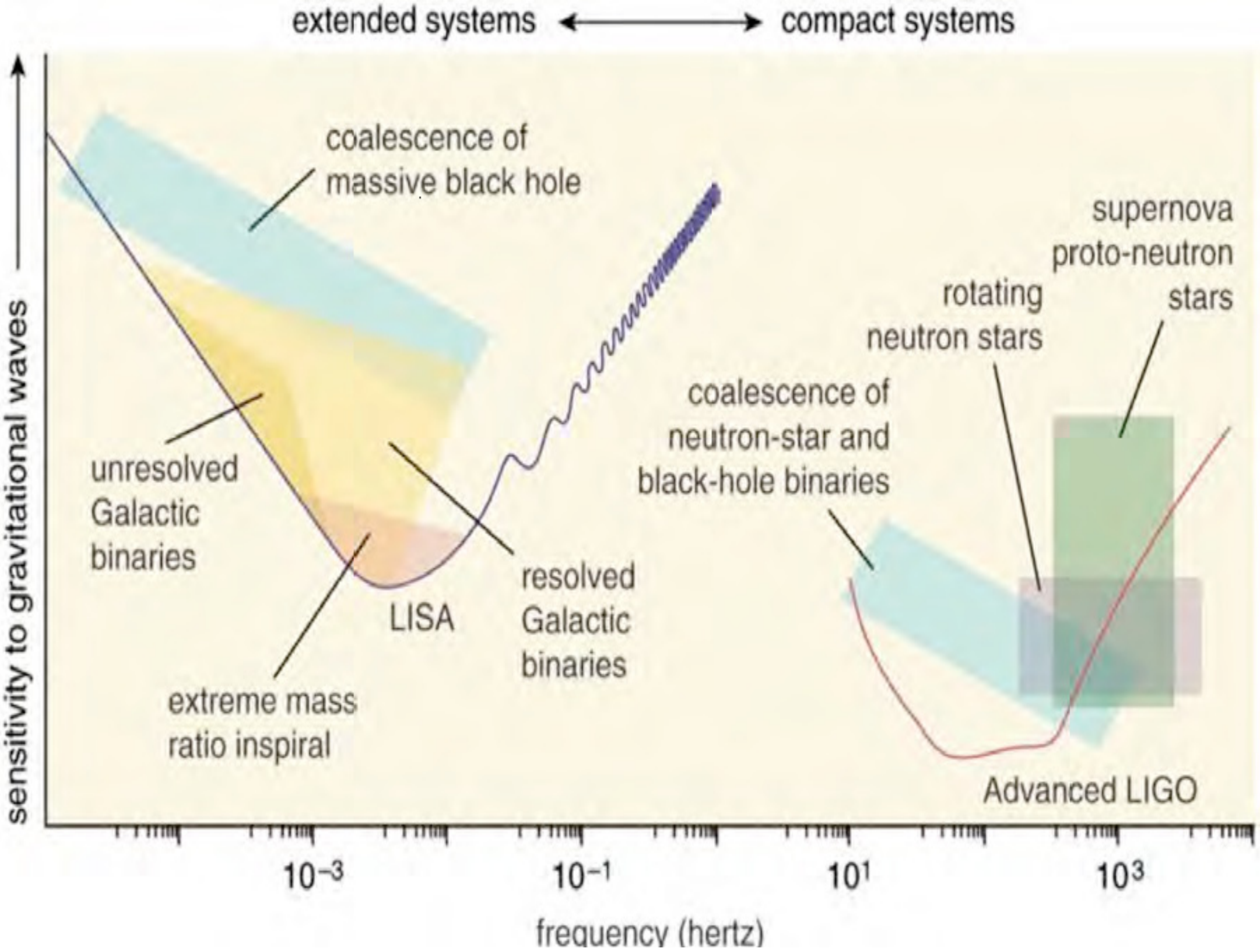
Main mirror

Mirrors Cooled at 20 K



COST US$ 135M

Does not include salaries & maintenances of facilities.


extended systems
compact systems
sensitivity to gravitational waves
coalescence of massive black hole
unresolved Galactic binaries
extreme mass ratio inspiral
LISA
resolved Galactic binaries
supernova proto-neutron stars
rotating neutron stars
coalescence of neutron-star and black-hole binaries
Advanced LIGO
10−3
10−1
101
103
frequency (hertz)