On the Threshold of Gravitational Wave Astronomy

BEYOND 2010

Cape Town, February 5, 2010

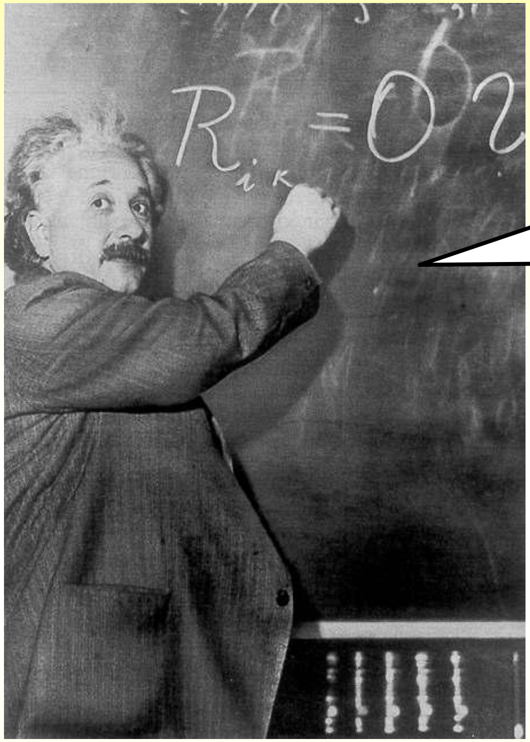
Peter Aufmuth

Max-Planck-Institut für Gravitationsphysik

(Albert-Einstein-Institut)

Leibniz Universität Hannover

Introduction



Gravitational waves are a necessary issue of General Relativity, but the effect is so small that, probably, they will never be detected.

Einstein 1916

Outline

(1) Basic information on GWs
(2) Interferometric GW detectors
(3) Results obtained in 2009
(4) Future of GW detection

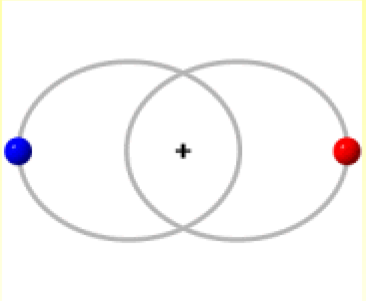
Gravitational Waves

(i) GR: mass/energy curves the geometry of spacetime
$\rightarrow$ spacetime is a deformable quantity
(ii) SR: any perturbation propagates at the most with *c*
$\rightarrow$ perturbations in the geometry of spacetime produce waves

e.g. super nova explosion

Gravitational wave, n. By accelerated masses produced transverse wave in the structure of spacetime, propagating with the velocity of light. They carry energy and angular momentum. Predicted by physicist $\rightarrow$ A. Einstein in 1916.

Existence of GW Confirmed

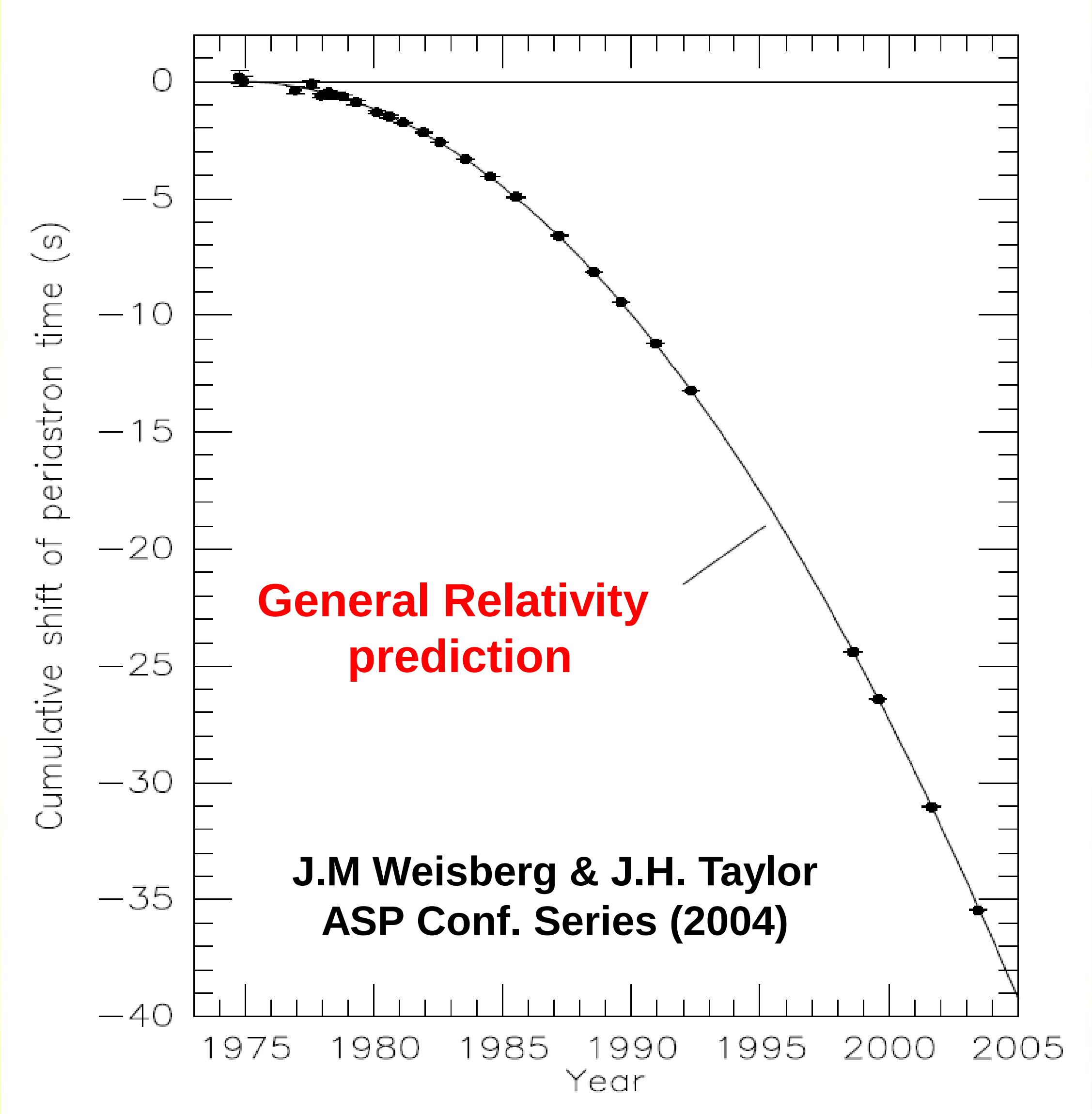


Binary systems of neutron stars or black holes, e.g., PSR B1913+16 :

Energy loss by means of GW radiation causes a shift of periastron time that is consistent at the

(0.13 ± 0.21) %

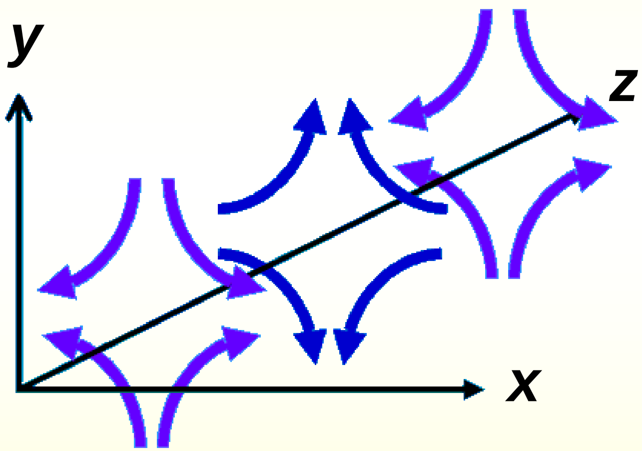
level with GR prediction

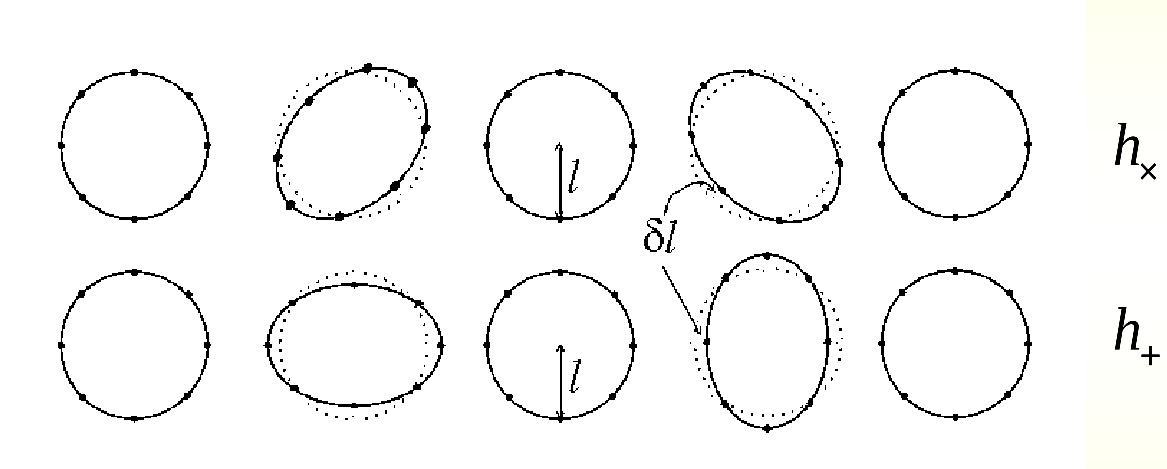


Action of a Gravitational Wave

GW produce tidal forces on free test masses
= change in the proper distance ds between two test particles:

$$ds^2 = -c^2 dt^2 + (1+h_+)dx^2 + (1-h_+)dy^2 + dz^2$$





two polarization modes

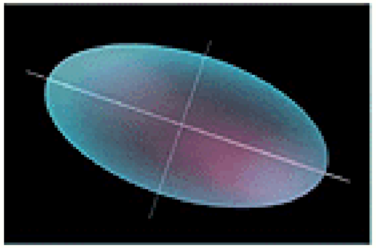
$$h = \frac{\delta\ell}{\ell}$$ **= amplitude or strain of the wave**

Quadrupole Formula

The metric perturbation in the wave zone ($r \gg \lambda/2\pi$) depends on the mass quadrupole moment Q of the source (Einstein 1918):

$$Q = \int \rho (x_i x_j - \frac{1}{3}\delta_{ij} r^2) \mathrm{d}^3 x$$

$$h_{ij} = \frac{2G}{c^4}\frac{1}{r}\frac{\partial^2}{\partial t^2}\left[Q_{ij}\left(t - \frac{r}{c}\right)\right]$$



$$1.6 \times 10^{-44} \, \frac{\mathrm{s}^2}{\mathrm{kg\,m}}$$

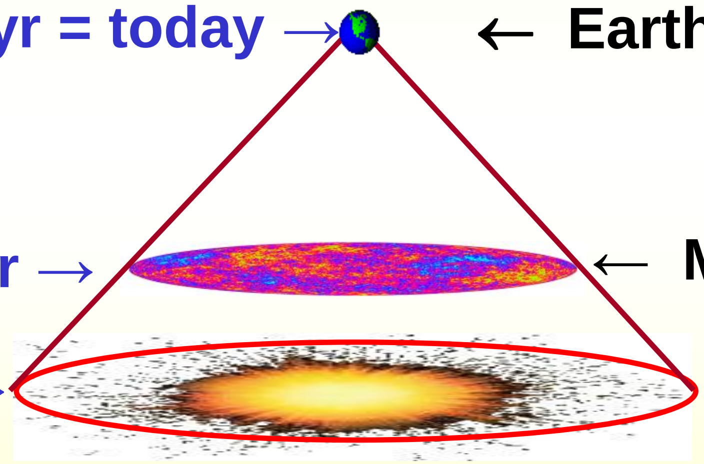
large quadrupole moments !
fast changes !

Typical amplitudes from astrophysical sources at the Earth:
$h \sim 10^{-20} \ldots 10^{-24}$.

Interaction with Matter

Problem: GW have nearly no interaction with matter.
Advantage: GW detectors explore the interior of stars.
GW are ideal carriers of information.

The whole Universe is transparent to GW !



Sources and Frequencies

Background radiation

Pulsars

Coalescing binaries:
NS – NS
NS – BH

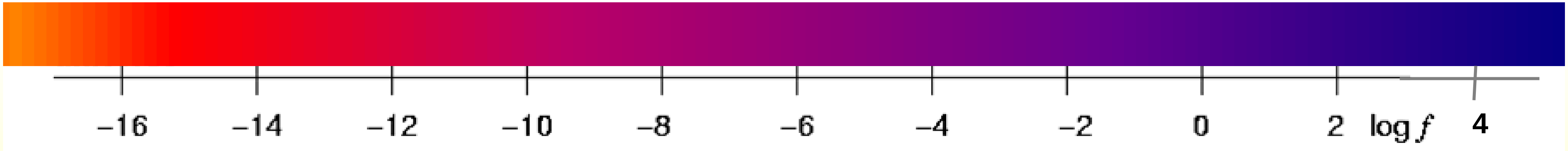
New physics:
Dark Matter ?

Phase transitions
in the early Universe

Quantum fluctuations
in the early Universe

Compact objects
+ supermassive
Black Holes

Supernovae
in the
Milky Way



"PLANCK"
Polarization
of CMB

Pulsar
timing

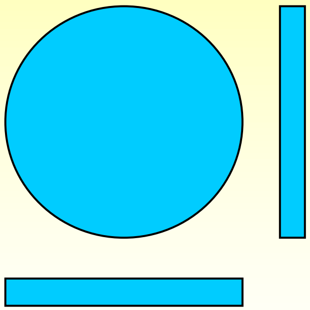
"LISA"

Interferometer

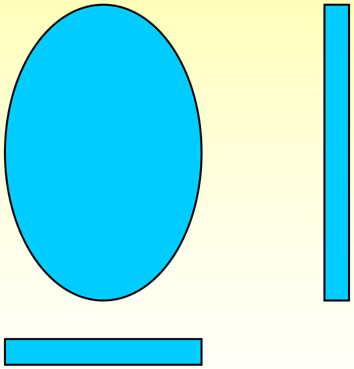
Resonance
antennas

GW Detectors

"before"



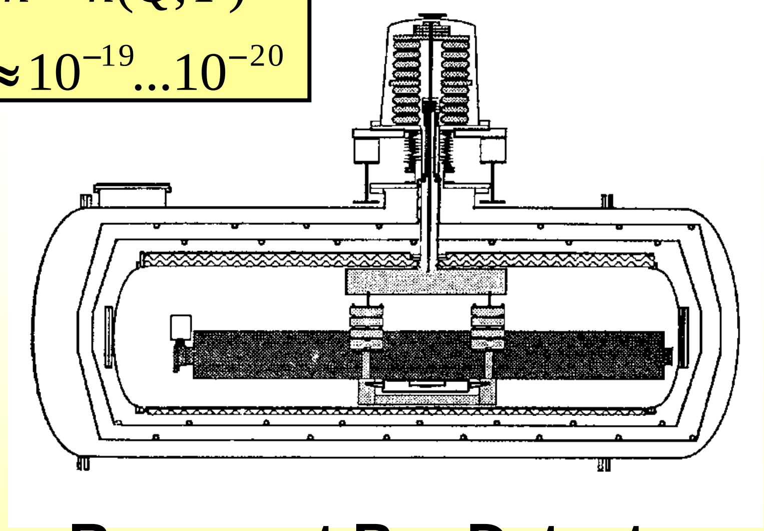
"after"



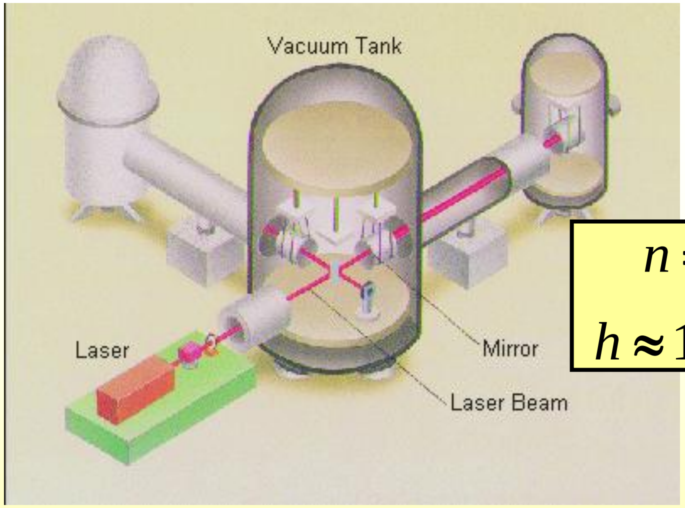
Gravitational Waves …

– deform a rigid body
– produce a differential length change

$$n = n(Q,T)$$
$$h \approx 10^{-19} \ldots 10^{-20}$$



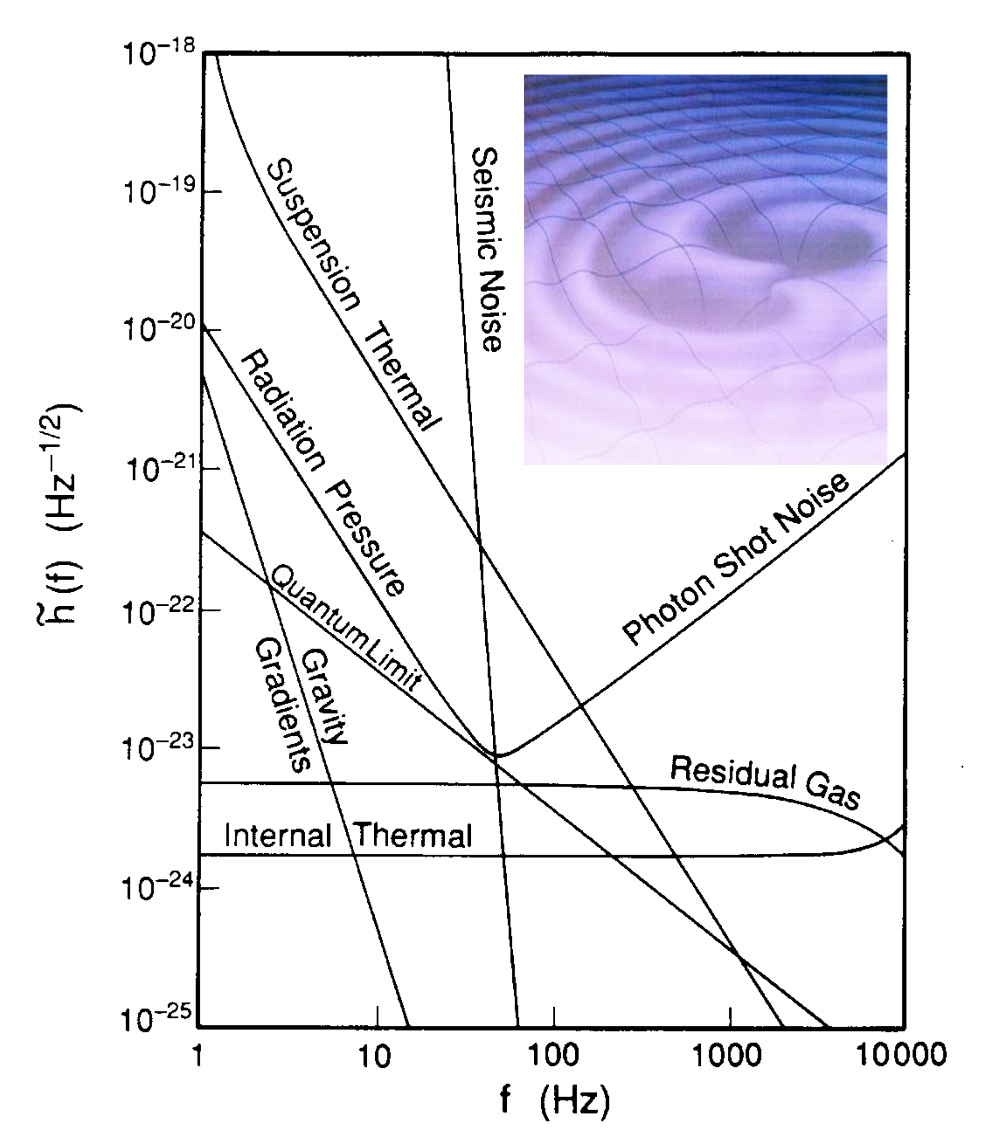
Resonant Bar Detector



$$n = n(L,P)$$
$$h \approx 10^{-21} \ldots 10^{-22}$$

Michelson Interferometer

Noise Sources & Technical Solutions

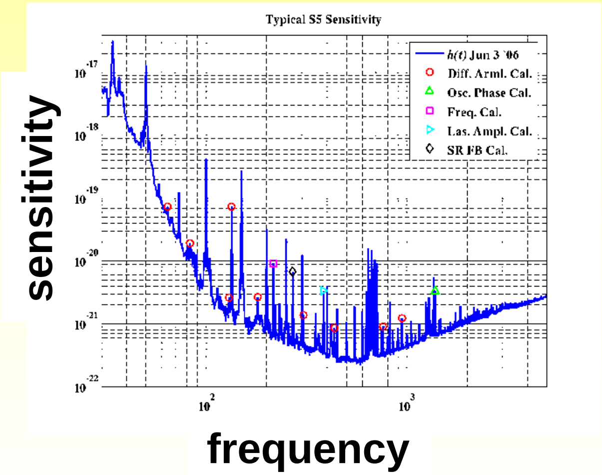


- UHV ($p \sim 10^{-9}$ Torr)
- Multiple-stage pendula
- Low-absorption materials
- Ultra-stable laser systems (frequency, amplitude)
- Power recycling
- Signal recycling
- Monolithic suspensions
- Squeezed light

More than 30 years of R&D

Sensitivity & Spectral Density

$\tilde{n}(f)$



$$s(t) = h(t) + n(t)$$

signal = GW + noise

noise as linear spectral density:

$$\tilde{n}(f) = \sqrt{S_n(f)} \frac{1}{\sqrt{\text{Hz}}}$$

typical sensitivity curve = remaining noise floor

$$\tilde{n}\sqrt{\Delta f} = n \quad \text{for} \quad \tilde{n} \approx \text{const.}$$

***S*(*f*) = power spectrum or power spectral density = *FT* of the autocorrelation function**

Amplitude spectral density:

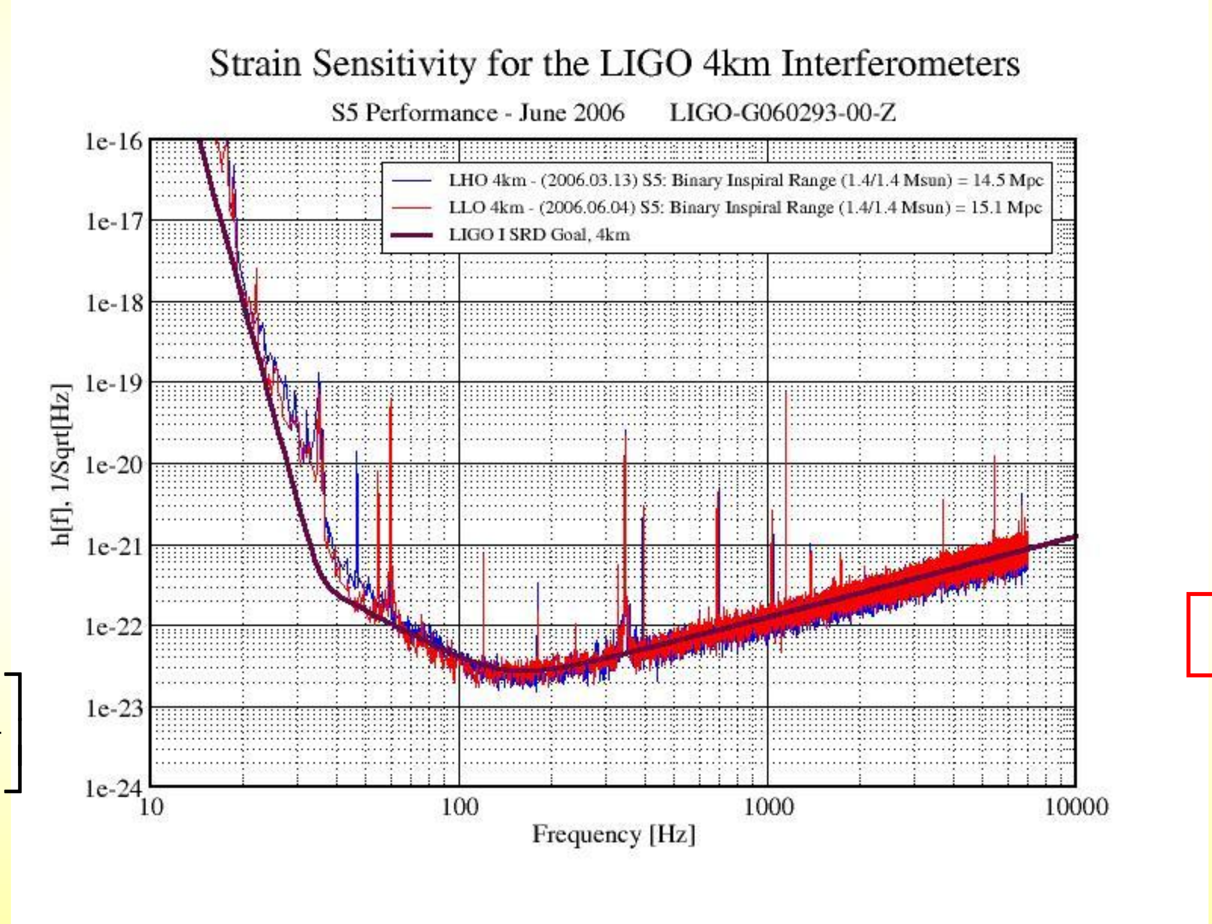
$$\tilde{h}(f) = \sqrt{S_h(f)} \frac{1}{\sqrt{\text{Hz}}}$$

1st Generation Sensitivity

Aim of first-generation interferometric detectors:

$$h \approx 10^{-21} \text{ for } \Delta f \approx 1\,\text{kHz}$$
$$\tilde{h} \approx 10^{-23} / \sqrt{\text{Hz}}$$

$$SNR = \frac{\tilde{h}}{\tilde{n}} \geq 5$$



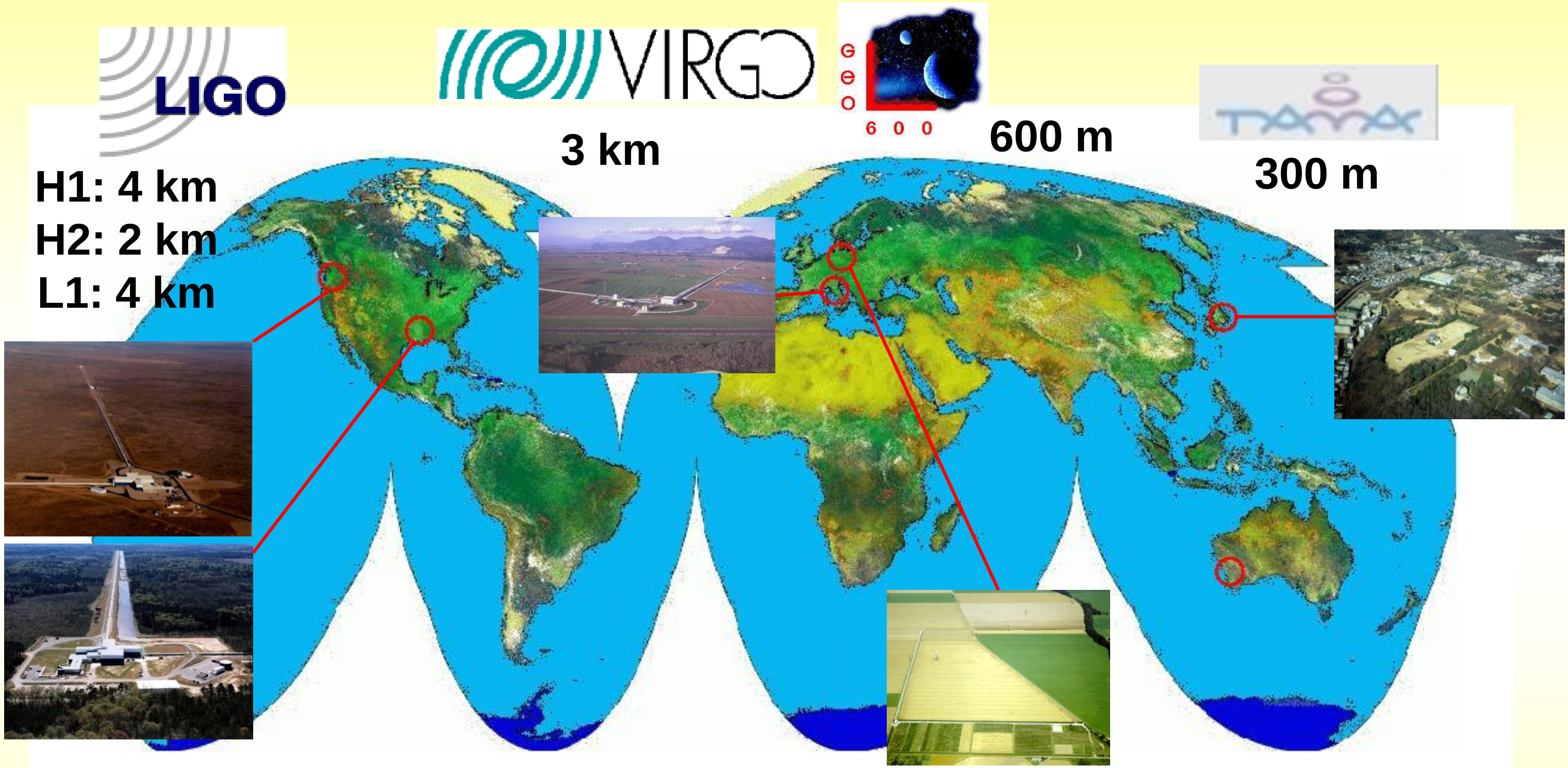
$$\tilde{n} \left[\frac{1}{\sqrt{\text{Hz}}}\right]$$

$$h = \frac{\delta L}{L}$$

$$L = 4\,\text{km}$$

$$\delta L = 10^{-19}\,\text{m}$$

Operating Interferometric GW Detectors



LIGO Scientific Collaboration
and Virgo Collaboration

500 scientists from
> 50 institutions

Science Data Runs

S1 : LIGO & GEO600 – 17 days in Aug/Sept 2002

S2 : LIGO, TAMA300, ALLEGRO – 59 days Feb/April 2003

S3 : LIGO & GEO600 – 70 days Oct 2003/Jan 2004

S4 : LIGO & GEO600 – 29 days Feb/Mar 2005

S5 : LIGO – Nov 2005 – Oct 2007 + GEO May – Oct 2006

+ VSR1: Virgo May – Oct 2007

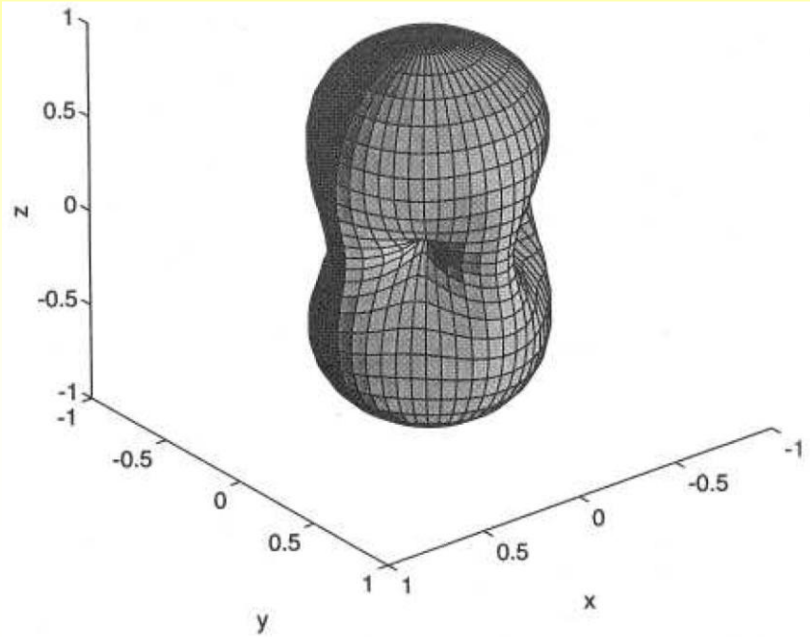
Astrowatch: GEO 2007 – 2009

S6/VSR2: enhLIGO + Virgo+

– since July 2009 to 2011

Up to now no detection, but better upper limits
First statements on astrophysical models and objects

GW Observables



Antenna pattern of an interferometric detector

E.g., GEO data acquisition (38 DOF, 250 control loops):
64 channels w/ 16384 Hz
64 channels w/ 512 Hz
1000 channels w/ 1 Hz

Amplitude, Polarization, Phase

$$h_{\mathrm{RSS}} = \sqrt{\int \left(|h_+(t)|^2 + |h_\times(t)|^2 \right) \mathrm{d}t} \; \left[\mathrm{Hz}^{-1/2}\right]$$

Root-sum-squared strain amplitude of a GW signal arriving at the Earth

$$h = F_+ h_+ + F_\times h_\times$$

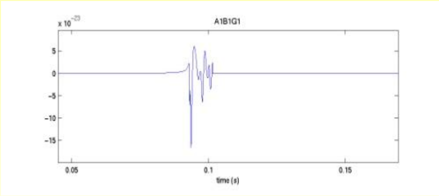
$$F = F(\theta, \phi, \psi)$$

Antenna pattern function (response) depending on the sky coordiantes of the source (θ, ϕ) and the orientation of the detector (ψ)

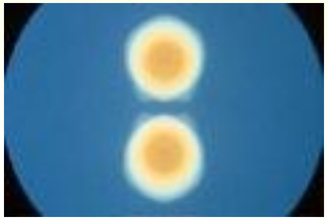
Data rate:
~ 80 GB/day

Sources, Signals, Data Analysis

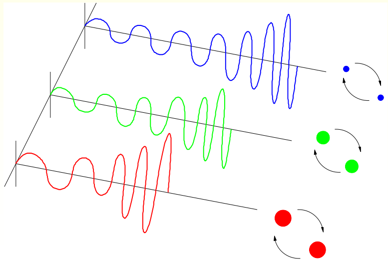
Supernovae in the Milky Way
Pulses



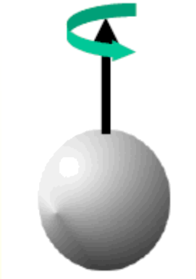
Coincidences between the detectors



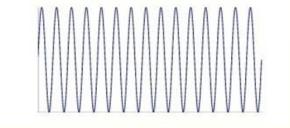
Merging compact binaries
“Chirps”



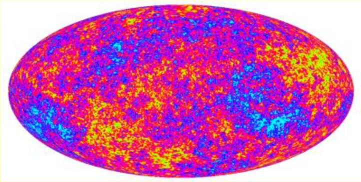
Matched filtering
Template bank



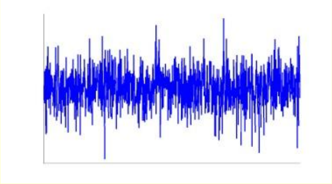
Pulsars
Neutron Stars
Periodic signals



Maximum likelihood
Monte-Carlo



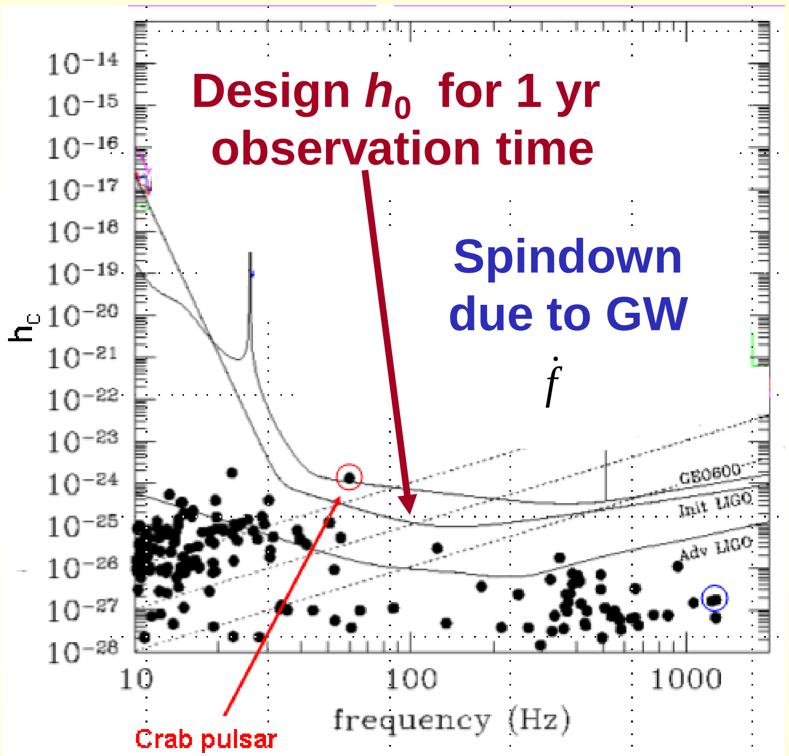
Cosmic background
Stochastic signals



Correlation between two detectors

Rotating Neutron Stars

Quasi-periodic signal at twice the rotation frequency of NS



Einstein@Home

All-sky search in S5

f = 50 … 1100 Hz

Sensitive to NSs of ellipticity

$\varepsilon \sim 10^{-6}$ @ r = 500 pc

NSs within r : 10^4 … 10^5

No detection

Portrait of galactic NS spinning down due to GW:

Birth rate < 1/30 yr

Ellipticity $\varepsilon < 10^{-6}$

Spin period T > 10 ms

PRL 102 (2009) 111102

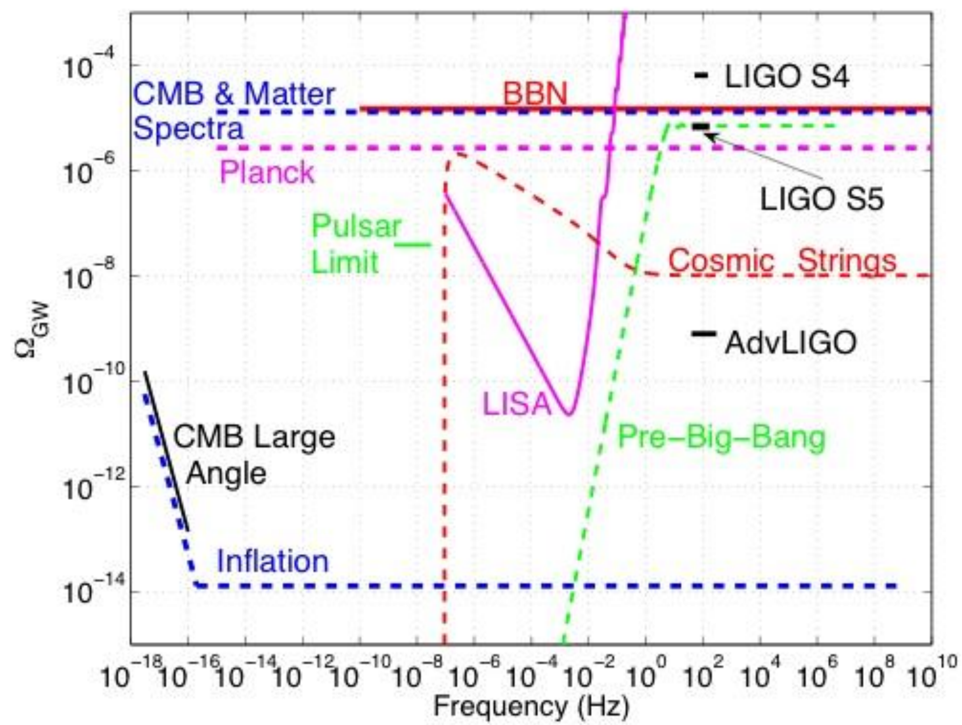
Stochastic Background

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

$d\rho_{GW}$ = energy density of GW in the frequency range f to $f + df$
ρ_{crit} = critical energy density of the Universe

$$\Omega_{GW}(@100\,\mathrm{Hz}) < 6.9 \times 10^{-6}$$
$$(95\%\ \mathrm{confidence})$$

rules out models with large EOS parameter and models with small string tension



Comparison of different models with GW measurements

$$10^{-14} \approx \Omega_{GW}(f) < 10^{-5}$$

Nature 460 (2009) 990

Test of Matrix Theory

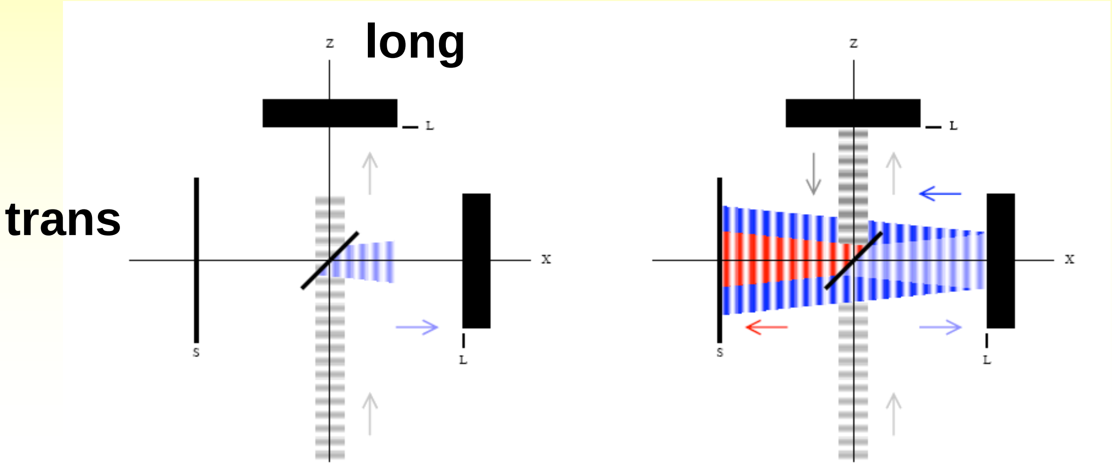
Holographic 2+1D theory predicts frequency independent noise:

$$S_{\mathrm{H}} = R/2$$

$$\Delta x = \sqrt{LR}$$

R **= fundamental length (compactification radius, width of 2D sheet)**
Δ*x* = indeterminacy in transverse position (BS-M)

Michelson Interferometer



The wavefunction which scatters first has more time to acquire a large transverse uncertainty

GEO600 sensitive enough to measure this noise and to decide on holographic theories

C.J. Hogan, M.G. Jackson
hep-th/0812.1285 (2009)

Gravitational Collapse

Core-collapse supernovae (IIa) or compact binary mergers

$$h_{\mathrm{RSS}} \sim 6\times10^{-21}\left(\frac{E_{\mathrm{GW}}}{10^{-7}M_\odot}\right)^{1/2}\left(\frac{1\,\mathrm{ms}}{T}\right)^{1/2}\left(\frac{1\,\mathrm{kHz}}{f_0}\right)\left(\frac{10\,\mathrm{kpc}}{d}\right)$$

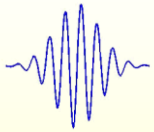
All-sky search in the first year of S5 data

No detection

$$h_{\mathrm{RSS}}^2 = \int_{-\infty}^{\infty} |h(t)|^2\,\mathrm{d}t$$

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

Test of algorithms by injection of simulated waveforms like Gaussians and sine-Gaussians



$h_{\mathrm{RSS}} \sim 6\mathrm{x}10^{-22} \ldots 10^{-21}\ \mathrm{Hz}^{-1/2}$

$Rate_{90\%} < 3.75$ /yr

GW energy needed for a 153 Hz sine-Gaussian

d = 10 kpc → $E = 1.9\mathrm{x}10^{-8}\ M_\odot c^2$

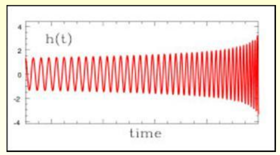
d = 16 Mpc → $E = 0.05\ M_\odot c^2$

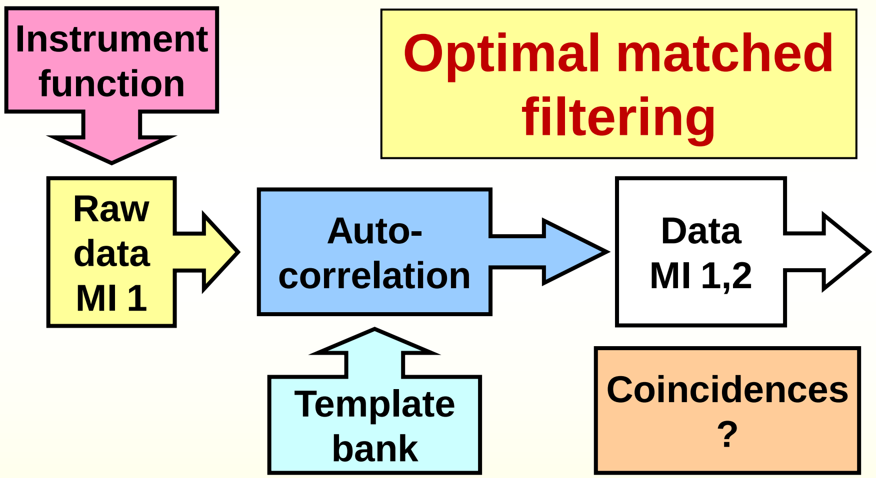
PR D 80 (2009) 102001

Binary Star Systems

Inspiral and ringdown waveforms are accurately known
7000 templates cover total masses $2M_\odot \ldots 35M_\odot$

$$h = h(m_1, m_2, d)$$





Analysis of first year of S5 data

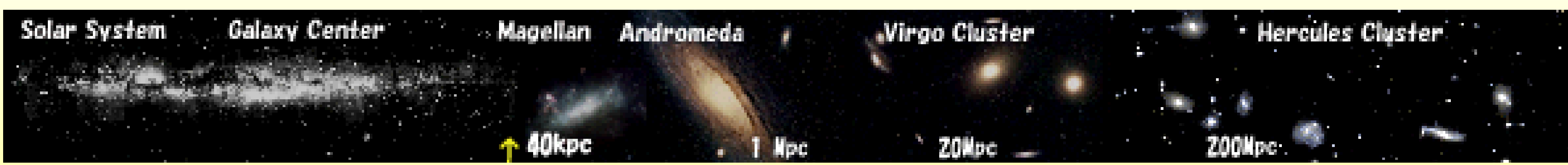
No detection

d(S/N = 8) ~ 30 … 35 Mpc
for BNS inspirals
$Rate_{90\%} < 1.4\mathrm{x}10^{-2}\mathrm{yr}^{-1}L_{10}^{-1}$

L_{10}: blue luminosity of typical galaxy

PR D 80 (2009) 047101

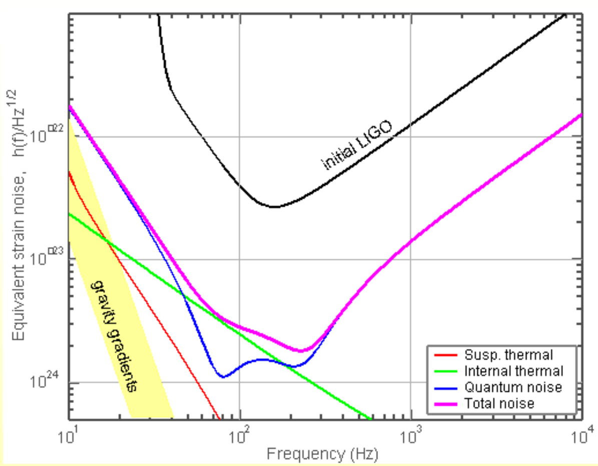
1st gen ↓   2nd gen ↓



Future of LIGO

Enhanced LIGO
new high-power laser (35 W)
from GEO600/LZH
+ new read-out scheme
→ factor ~ 3 in sensitivity
(since July 2009)

joint LIGO/GEO project

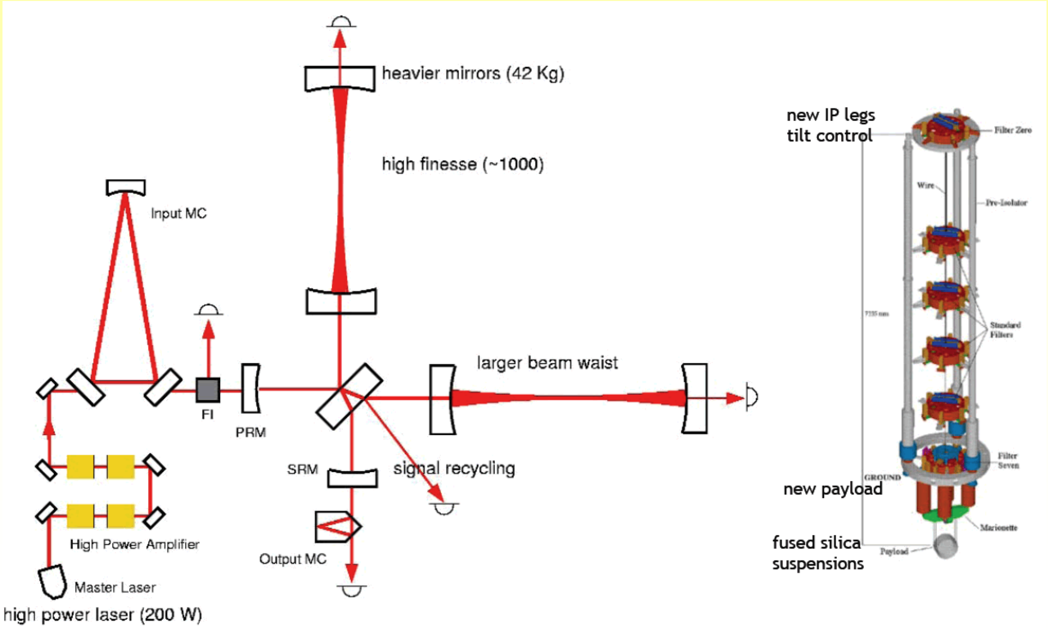


Advanced LIGO
new anti-seismic system, new optics
monolithic suspensions + high-power laser
(180 W) + signal recycling from GEO
→ another factor of ~ 5 in sensitivity,
(about 2015)

→ increase in volume and rate by ~ 1000

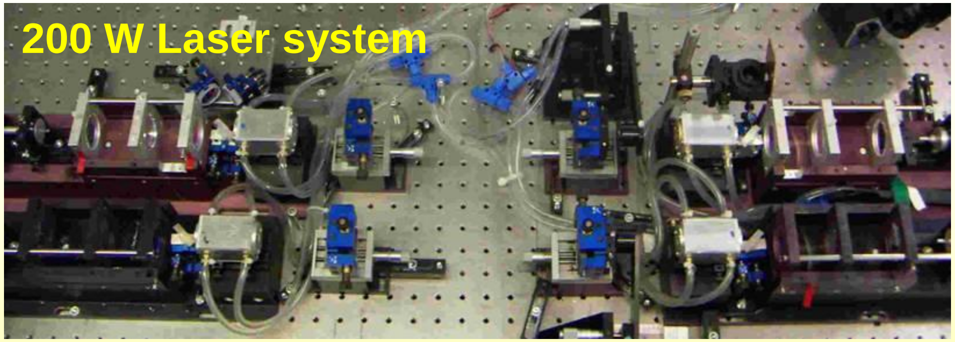
Future of Virgo

Virgo+
new laser amplifier ($Nd:YVO_4$)
+ monolithic suspension
→ factor 2 in sensitivity
(about 2010)



joint Virgo/GEO project

Advanced Virgo
signal recycling
+ heavier mirrors
+ high power laser (200 W)
→ another factor of ~ 5 in sensitivity
(about 2014)



Future of GEO600

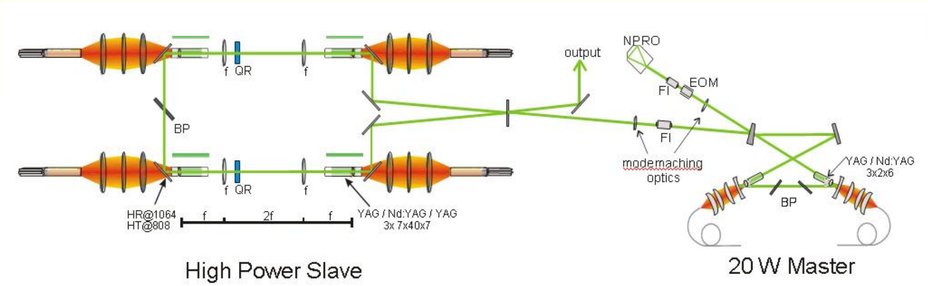
GEO-HF

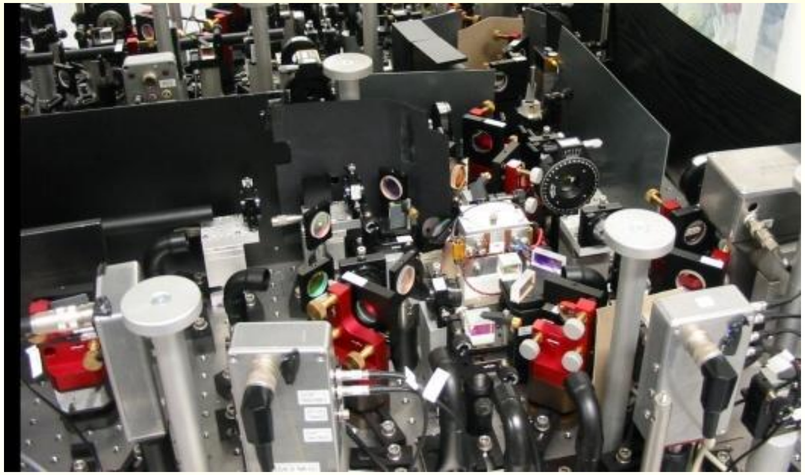
high-frequency extension up to 5 kHz

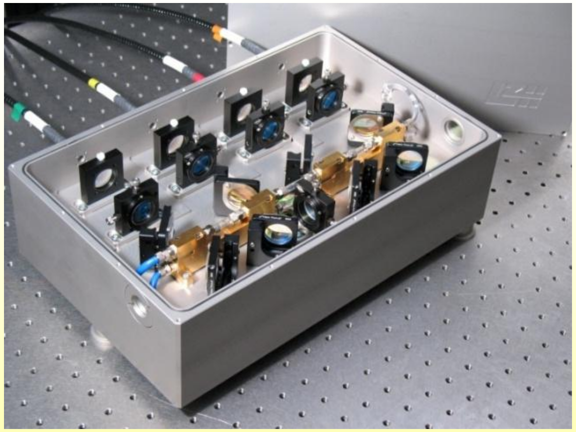
high-power laser + squeezed light + new mirrors

→ another factor of ~ 8 in sensitivity

(about 2011)

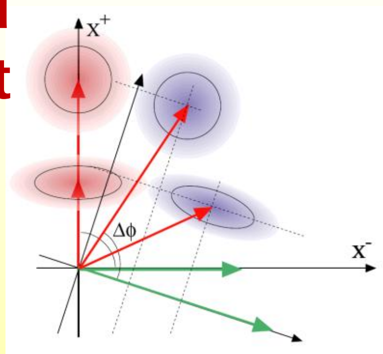


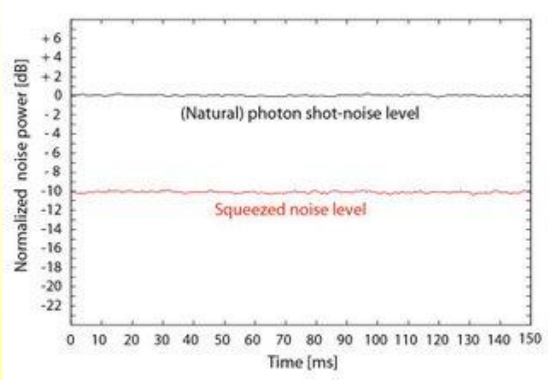




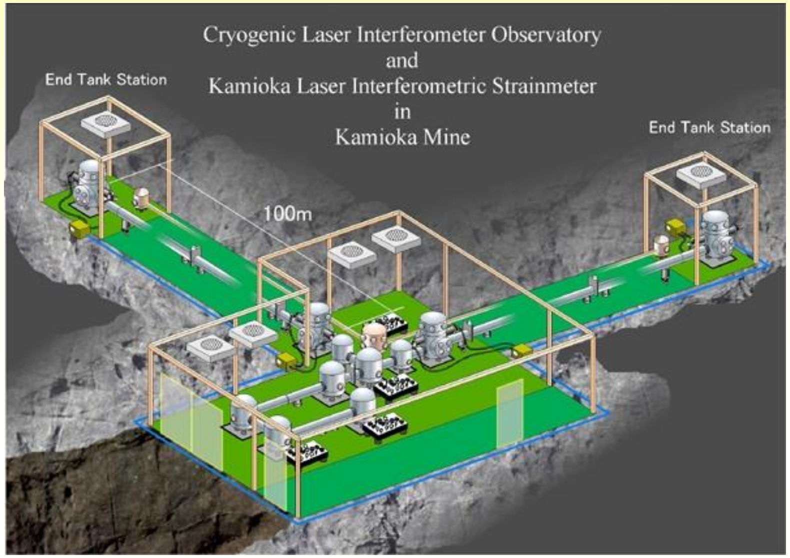
35 W laser

squeezed light

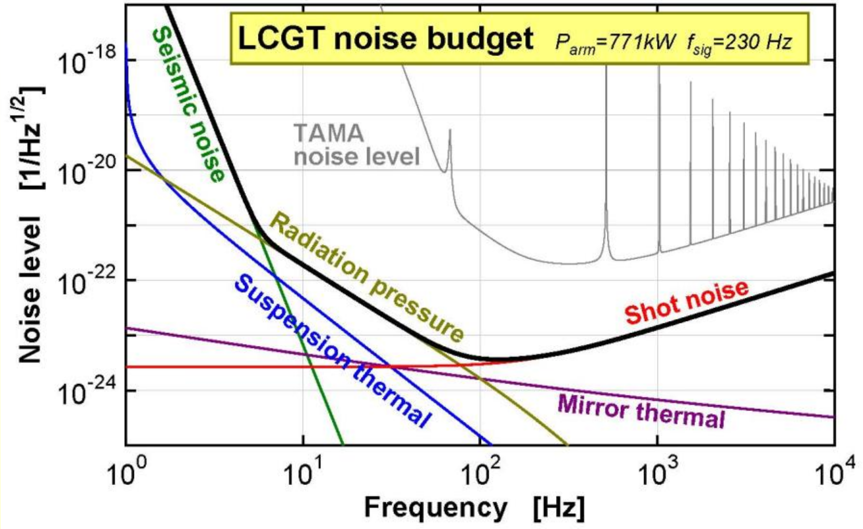




CLIO & LCGT

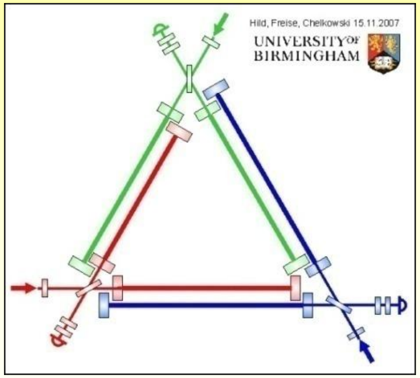


Large-scale Cryogenic Gravitational-wave Telescope
a TAMA-like 3 km interferometer with signal recycling + cooled to cryogenic temperatures + 2 parallel interferometers in the same vacuum system
(about ??)

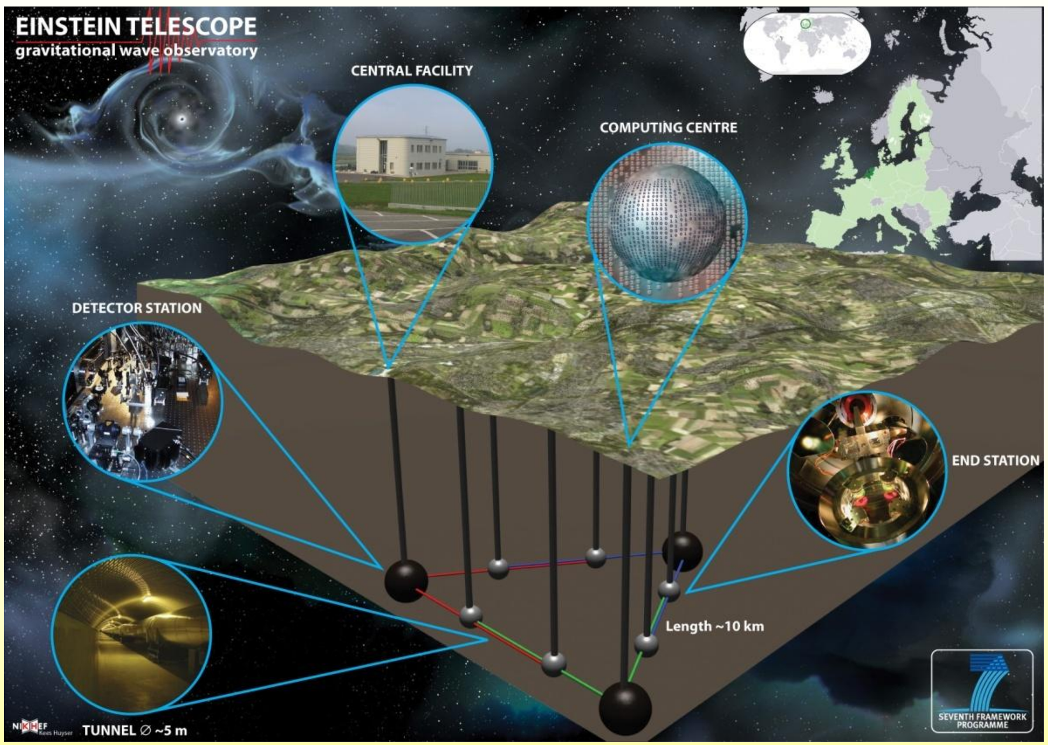


Cryogenic Laser Interferometer Observatory, **a 100 m interferometer has been built in the Kamioka mine to demonstrate cryogenic technology and the benefits of an underground location**

ET



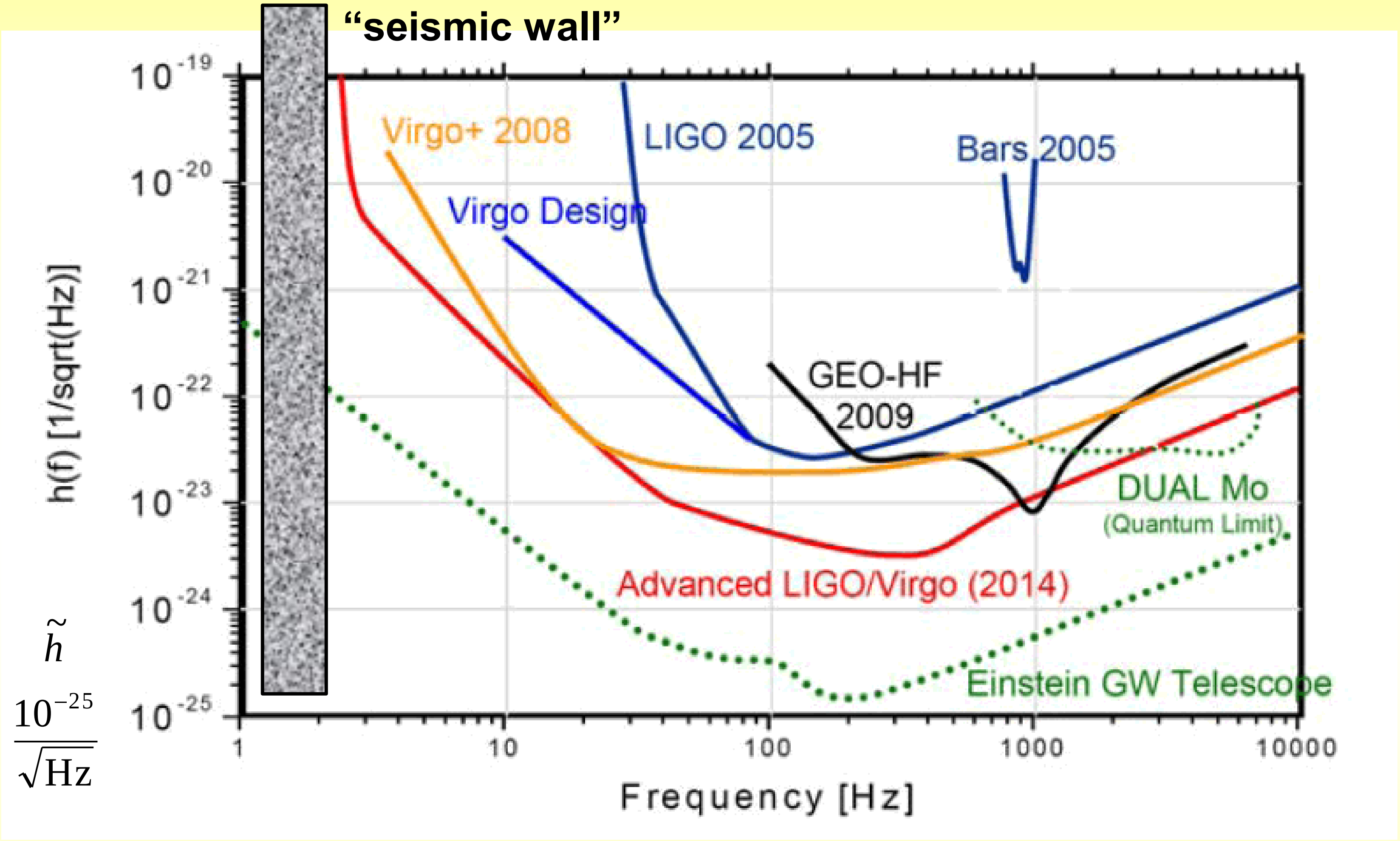
Einstein Gravitational-Wave Telescope
Underground location + cryogenic cooling
+ quantum non-demolition techniques:
10 x sensitivity of AdvLIGO & Virgo+
(about 2025)



Triangular shape ?
30 km overall beam-tube length ?

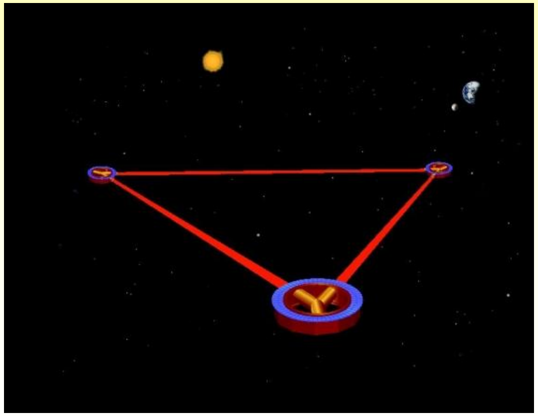
Design study funded by the
European Commission
2009 - 2011

Ground-Based GW Detectors



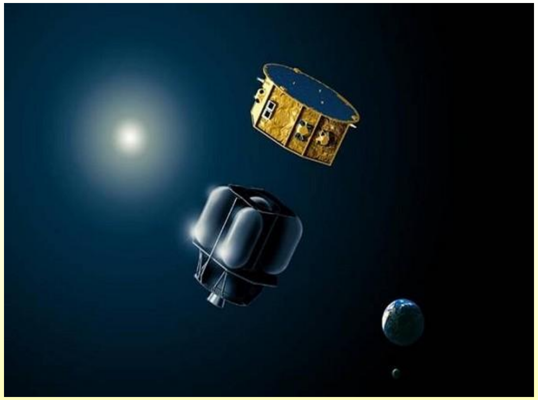
Comparison of actual and future ground-based GW detectors

LISA



Laser Interferometer Space Antenna
arm length: 5 Million km
opens the mHz band: 10^{-4} Hz … 1 Hz
with a sensitivity of 10^{-24}
joint project of ESA & NASA
(about 2022)

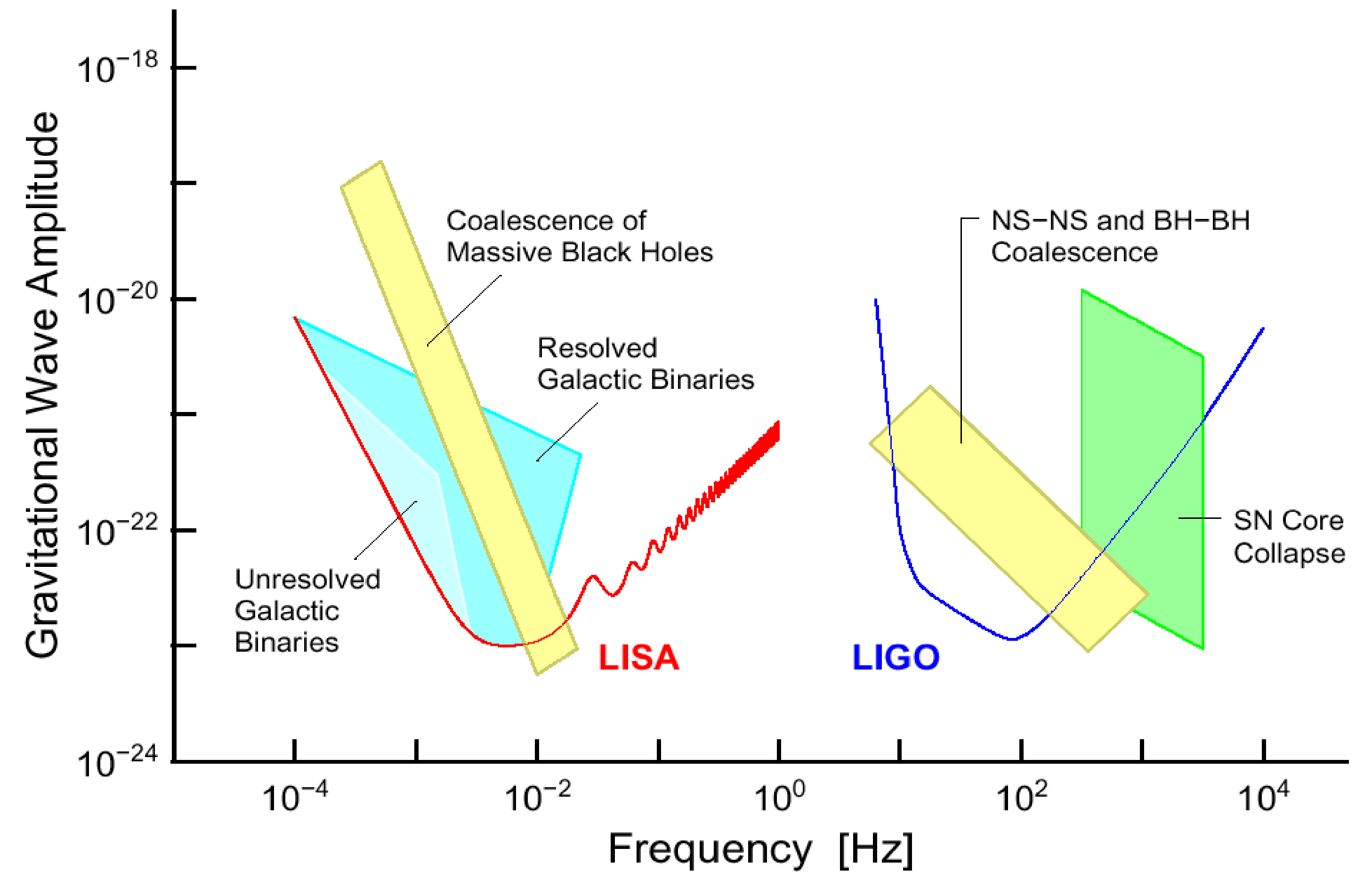
Flagship project of NASA's "Beyond Einstein" programme



LISA Pathfinder
a technology demonstration mission for LISA consisting of two LISA-like test masses in a single satellite
@ Lissajous orbit around L1
(April 2012)

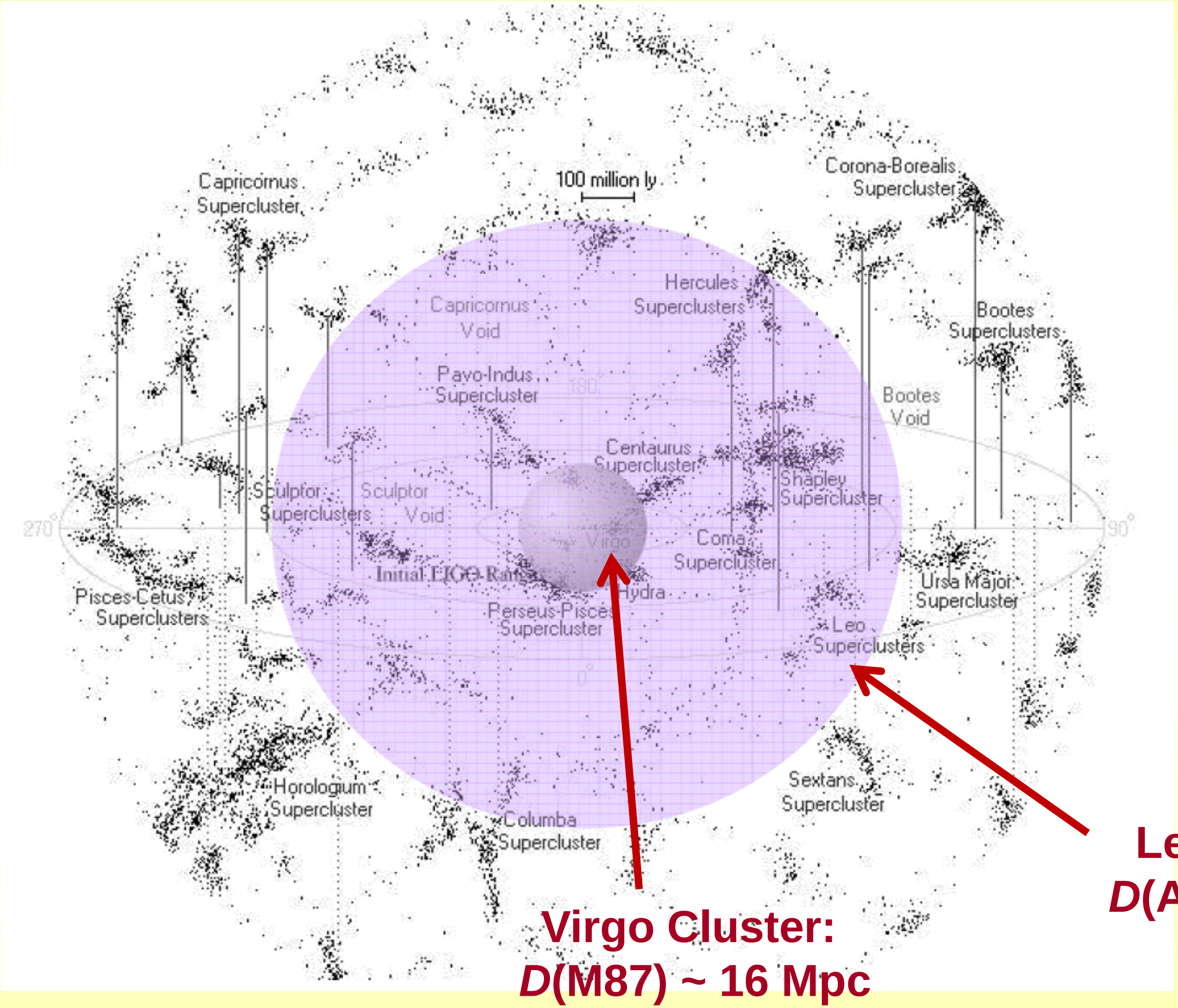
LISA Sensitivity

h



Earth-bound and space-bound detectors complement each other

The Realm of GW Astronomy



Virgo Cluster:
***D*(M87) ~ 16 Mpc**

Leo Supercluster
***D*(A1185) ~ 150 Mpc**

Range for NS-NS binaries:
LIGO ~ 20 Mpc
AdvLIGO ~ 200 Mpc

Regular detection of GW signals

LISA: supermassive BH-BH (10^5 – 10^8 $M_\odot$) mergers everywhere in the Universe