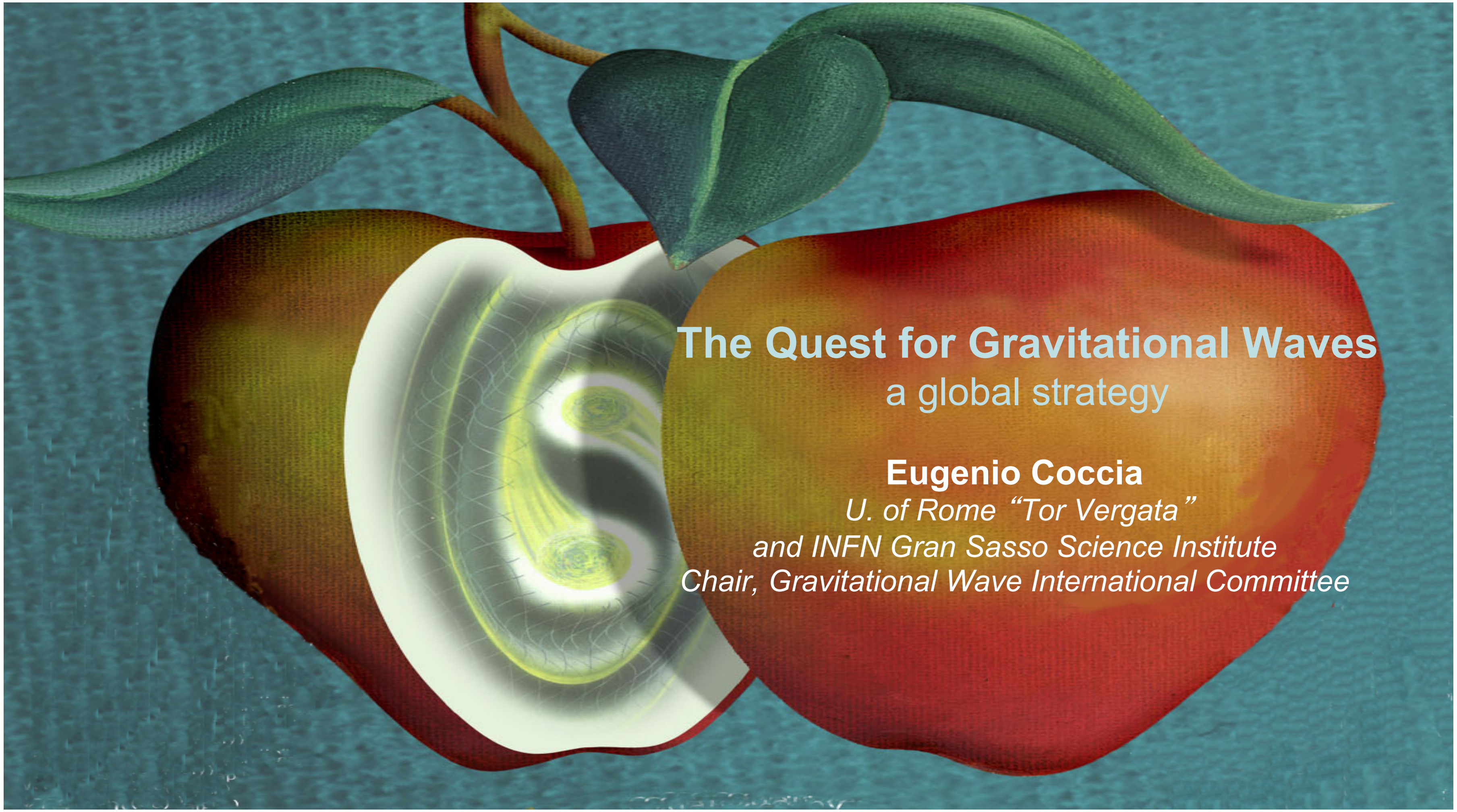
XV International Workshop on Neutrino Telescopes - Venice 15 March, 2013



The Quest for Gravitational Waves

a global strategy

Eugenio Coccia

U. of Rome "Tor Vergata"

and INFN Gran Sasso Science Institute

Chair, Gravitational Wave International Committee

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GSSI GRAN SASSO SCIENCE INSTITUTE
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The Gran Sasso Science Institute

It is an international PhD school and a center for advanced studies in physics, mathematics, computer science and social sciences.

Its purpose is to form high level human capital, integrating education and research in a lively interdisciplinary environment.

PRE-APPLICATION

Contents

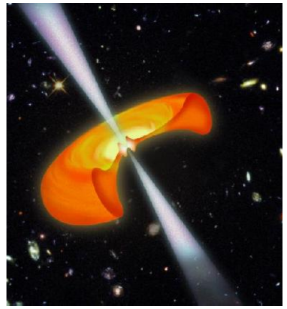
- GWs and detectors
- News from ground and for space
- The global strategy

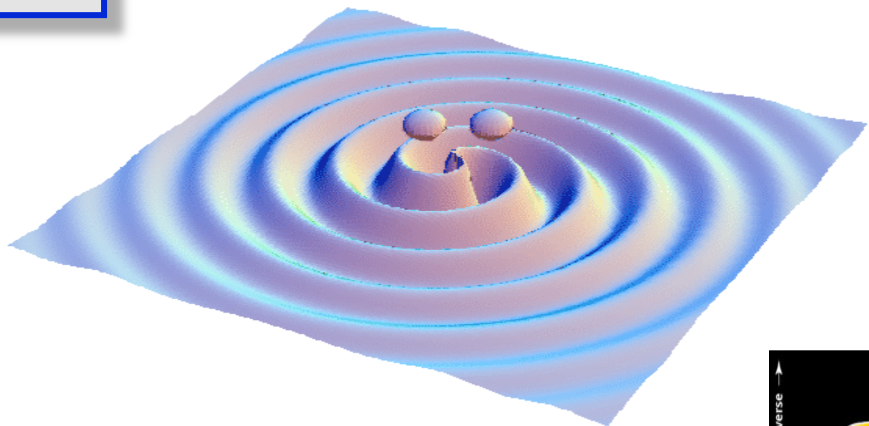
THE QUEST FOR GW: OBJECTIVES

FIRST DETECTION
test Einstein prediction

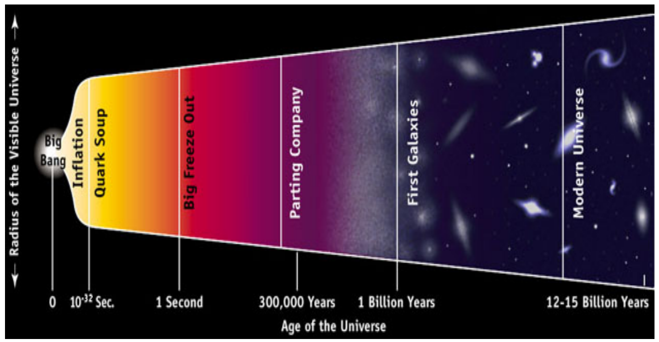
$$\mathbf{G} = \frac{8\pi G}{c^4}\mathbf{T}$$

ASTRONOMY & ASTROPHYSICS
look beyond the visible
understand BH, NS and supernovae
understand GRB





COSMOLOGY
the Planck time:
look as back in time as theorist can conceive



Gravitational waves are strain in space propagating with the speed of light

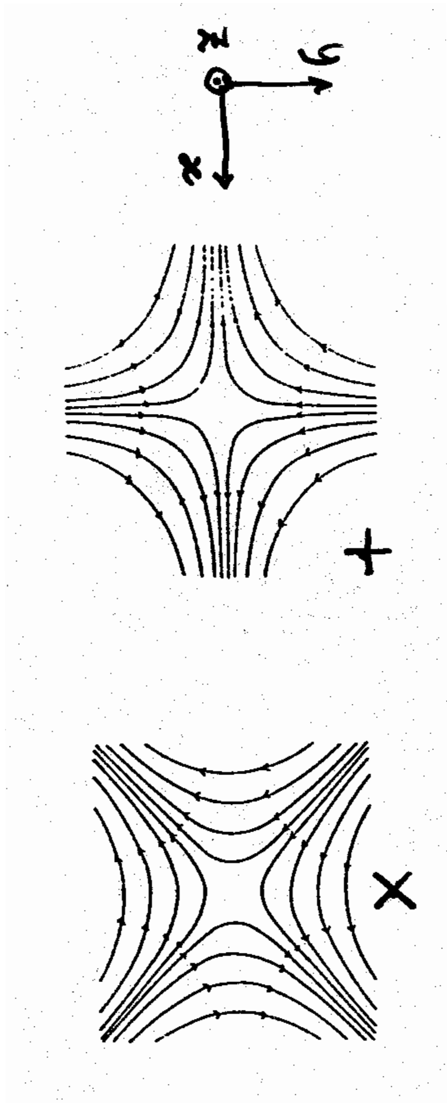
Main features

- **2 transversal polarization states**
- **Associated with massless, spin 2 particles (gravitons)**
- **Emitted by time-varying quadrupole mass moment**
  no dipole radiation because of conservation laws

$$-\frac{dE}{dt} = \frac{2G}{3c^3}\left(\ddot{d}\right)^2 + \frac{G}{45c^5}\left(\dddot{Q}\right)^2 + \dots$$

$$\dot{d} = \sum_i m_i \dot{x}_i \Rightarrow \ddot{d} \equiv 0 \qquad Q_{ij} = \int \rho x_i x_j d^3x$$

$$h_{ij}(t) = \frac{2G}{rc^4}\ddot{Q}_{ij}(t - r/c)$$



- No laboratory equivalent of Hertz experiments for production of GWs

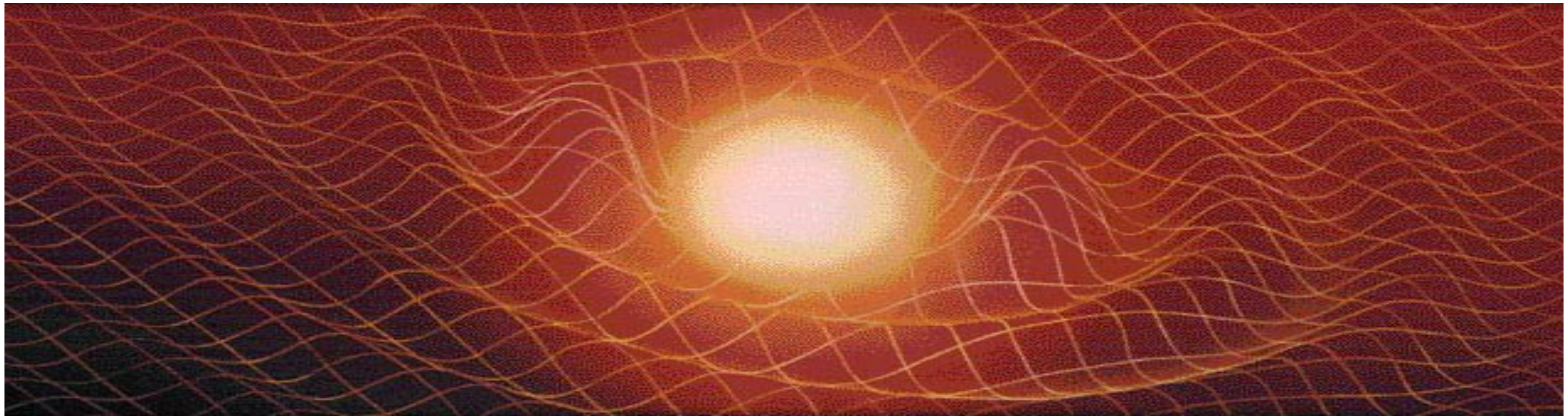
Luminosity due to a mass M and size R oscillating at frequency $\omega \sim v/R$:

$$L = \frac{2G}{5c^5}\left\langle \dddot{Q}^2 \right\rangle \approx \frac{GM^2v^6}{R^2c^5} \qquad Q \approx MR^2 \sin\omega t$$

M=1000 tons, steel rotor, f = 4 Hz ⟹ $L = 10^{-30}$ W
Einstein: " .. *a pratically vanishing value…*"

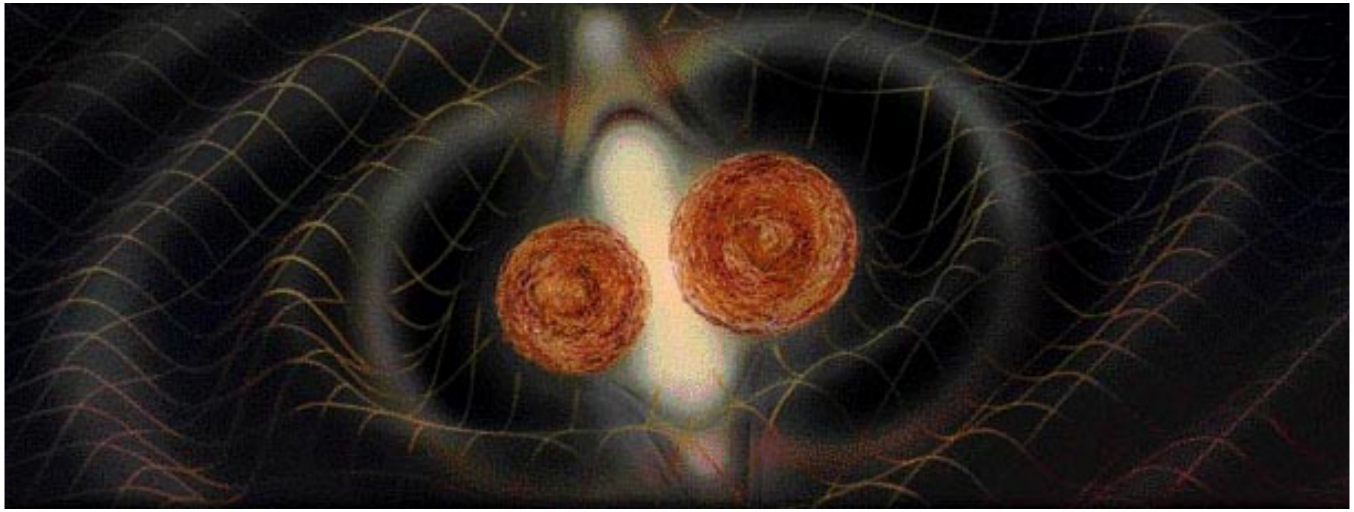
Collapse to neutron star 1.4 M_o ⟹ $L = 10^{52}$ W

$h \sim L^{1/2}d^{-1}$; source in the Galaxy $h \sim 10^{-18}$, in VIRGO cluster $h \sim 10^{-21}$
Fairbank: "*...a challenge for contemporary experimental physics..*"



Gravitational radiation is a tool for astronomical observations

GWs can reveal features of their sources that cannot be learnt by electromagnetic, cosmic rays or neutrino studies (Kip Thorne)

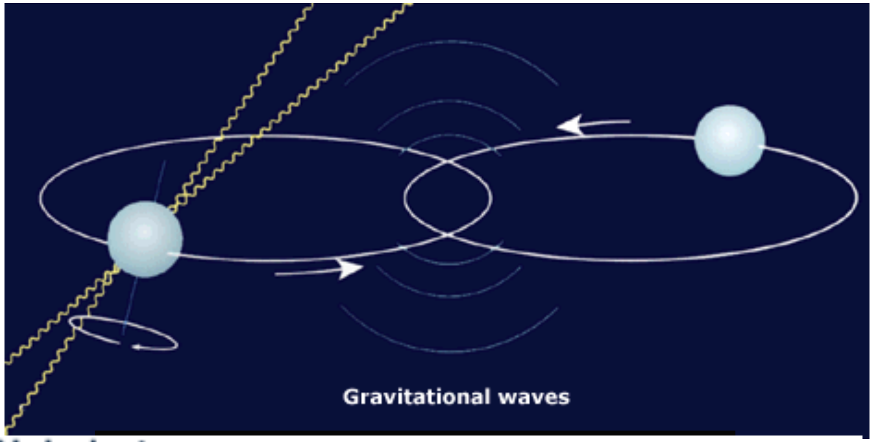


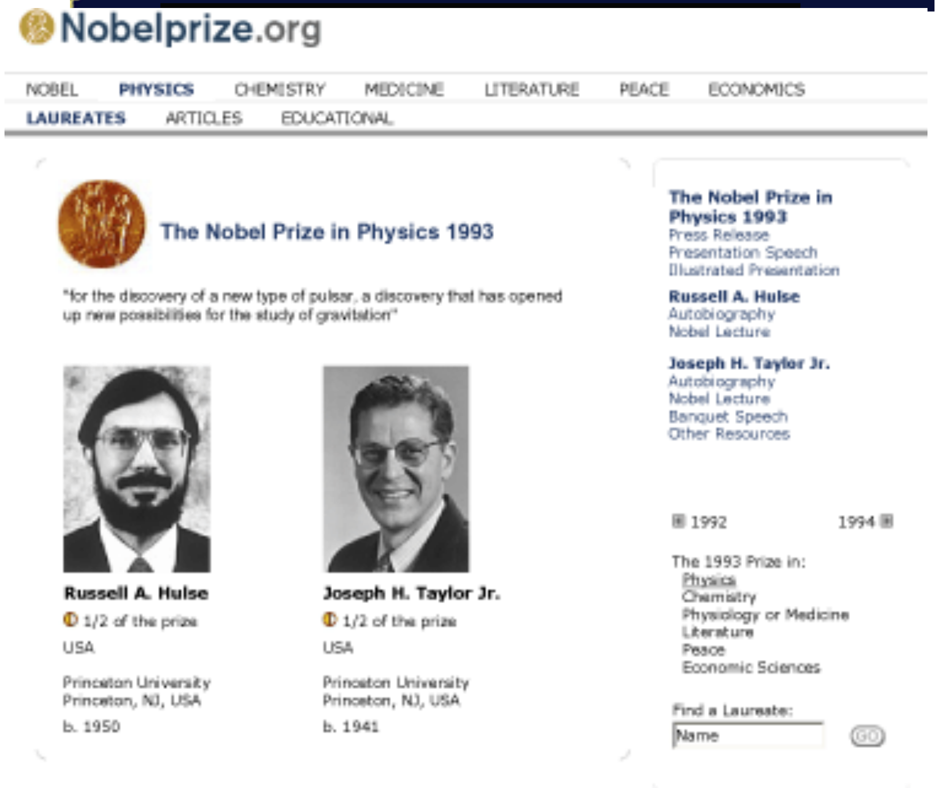
- GWs are emitted by coherent acceleration of large portion of matter

- GWs cannot be shielded and arrive to the detector in pristine condition

PSR1913+16: GWs do exist

- Pulsar bound to a “dark companion”, 7 kpc from Earth.
- Relativistic clock: $v_{max}/c \sim 10^{-3}$
- GR predicts such a system to loose energy via GW emission: orbital period decreases
- Radiative prediction of general relativity verified at 0.2% level

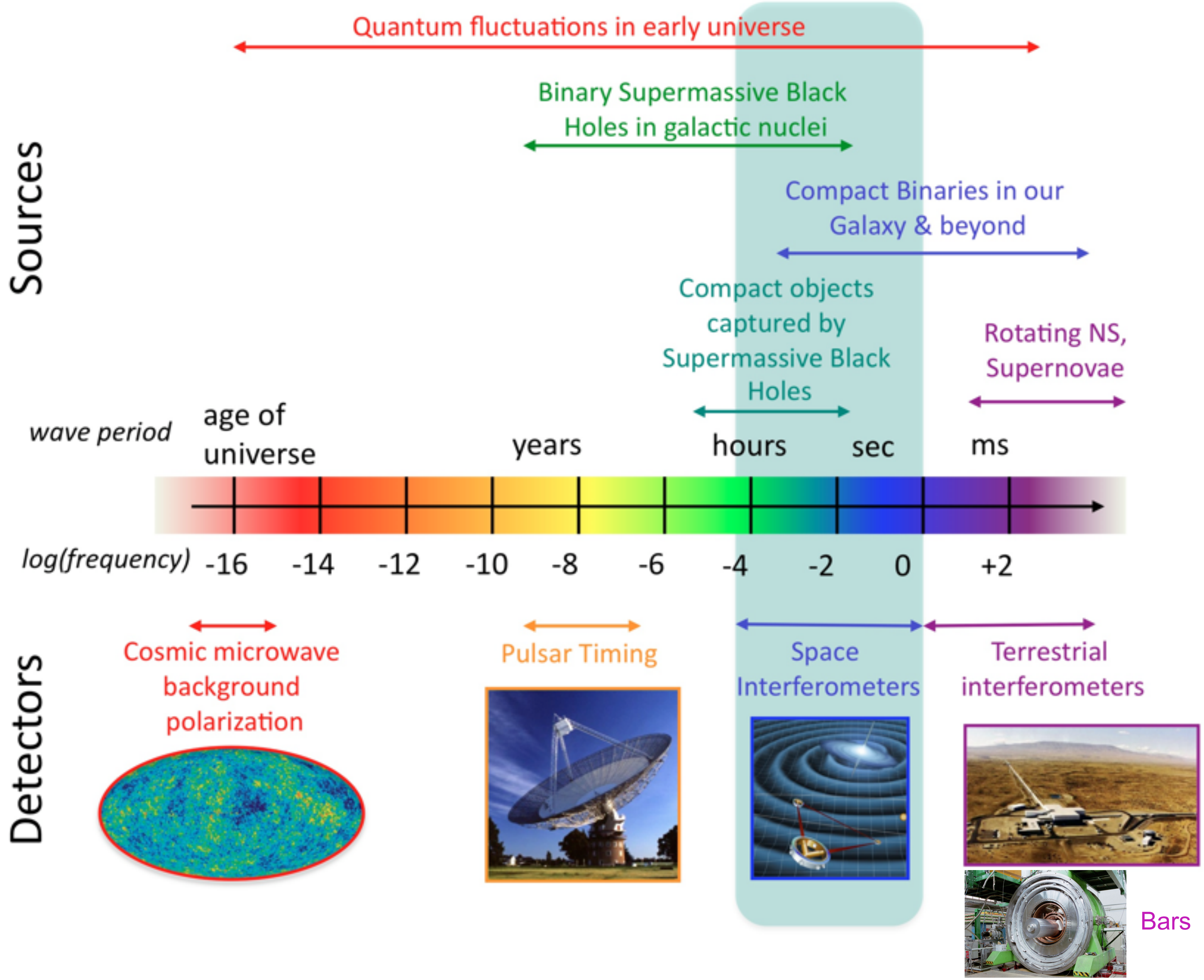


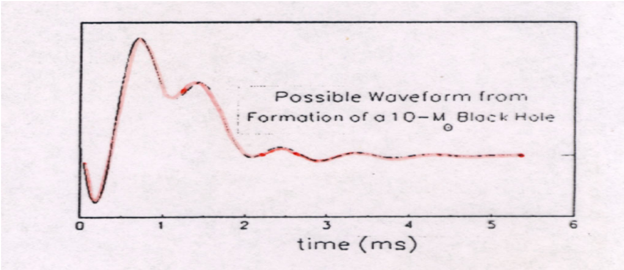


$P\ (s)$	**27906.9807807(9)**
dP/dt	**-2.425(10)·10^{-12}**
$d\omega/dt\ (^{o}/yr)$	**4.226628(18)**
M_p	**1.442 ± 0.003 $M_{\odot}$**
M_c	**1.386 ± 0.003 $M_{\odot}$**

Nobel Prize 1993: Hulse and Taylor

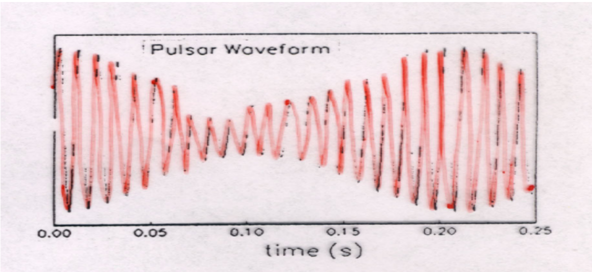
The Gravitational Wave Spectrum





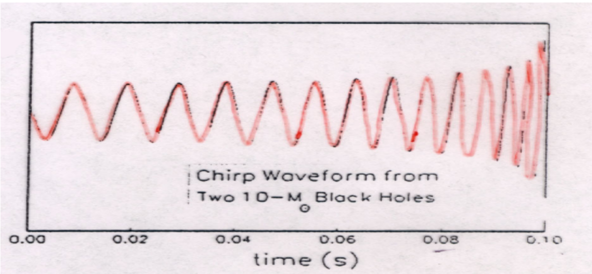
SUPERNOVAE.
If the collapse core is non-symmetrical, the event can give off considerable radiation in a millisecond timescale.

Information
Inner detailed dynamics of supernova
See NS and BH being formed
Nuclear physics at high density



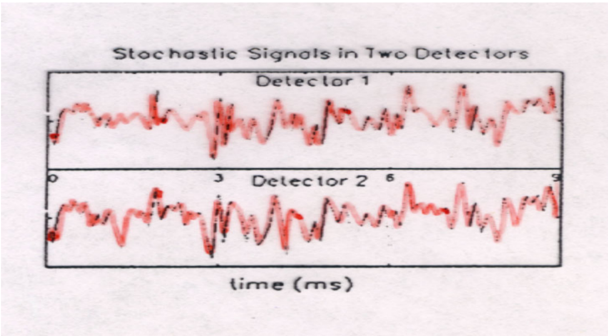
SPINNING NEUTRON STARS.
Pulsars are rapidly spinning neutron stars. If they have an irregular shape, they give off a signal at constant frequency (prec./Dpl.)

Information
Neutron star locations near the Earth
Neutron star Physics
Pulsar evolution



COALESCING BINARIES.
Two compact objects (NS or BH) spiraling together from a binary orbit give a chirp signal, whose shape identifies the masses and the distance

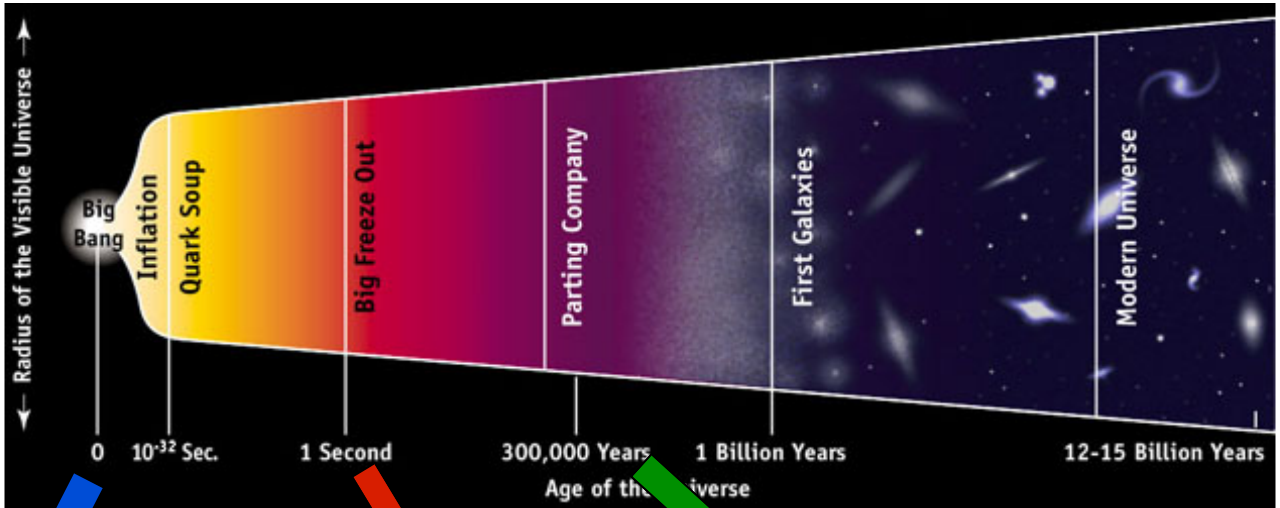
Information
Masses of the objects
BH identification
Distance to the system
Hubble constant
Test of strong-field general relativity



STOCHASTIC BACKGROUND.
Random background, relic of the early universe and depending on unknown particle physics. It will look like noise in any one detector, but two detectors will be correlated.

Information
Confirmation of Big Bang, and inflation
Unique probe to the Planck epoch
Existence of cosmic strings

Relic Stochastic Background



Relic gravitons

Relic neutrinos

CMBR

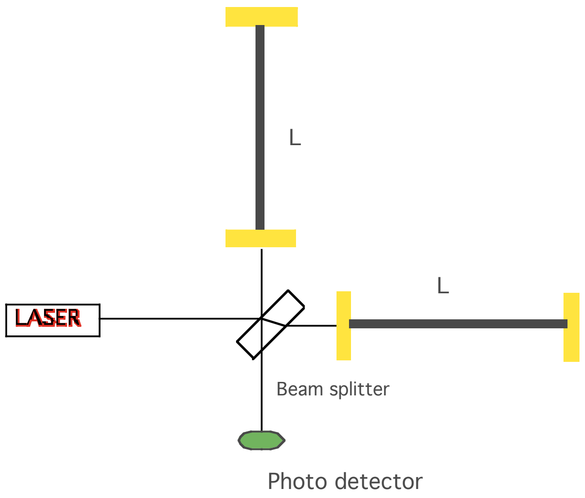
- Imprinting of the early expansion of the universe
- Correlation of at least two detectors needed

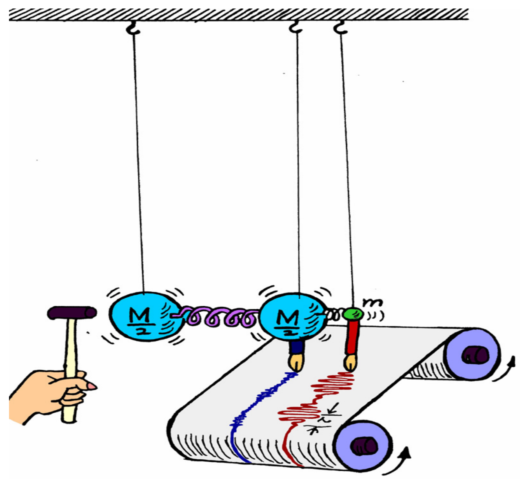
Every newly opened astronomical window has found unexpected results

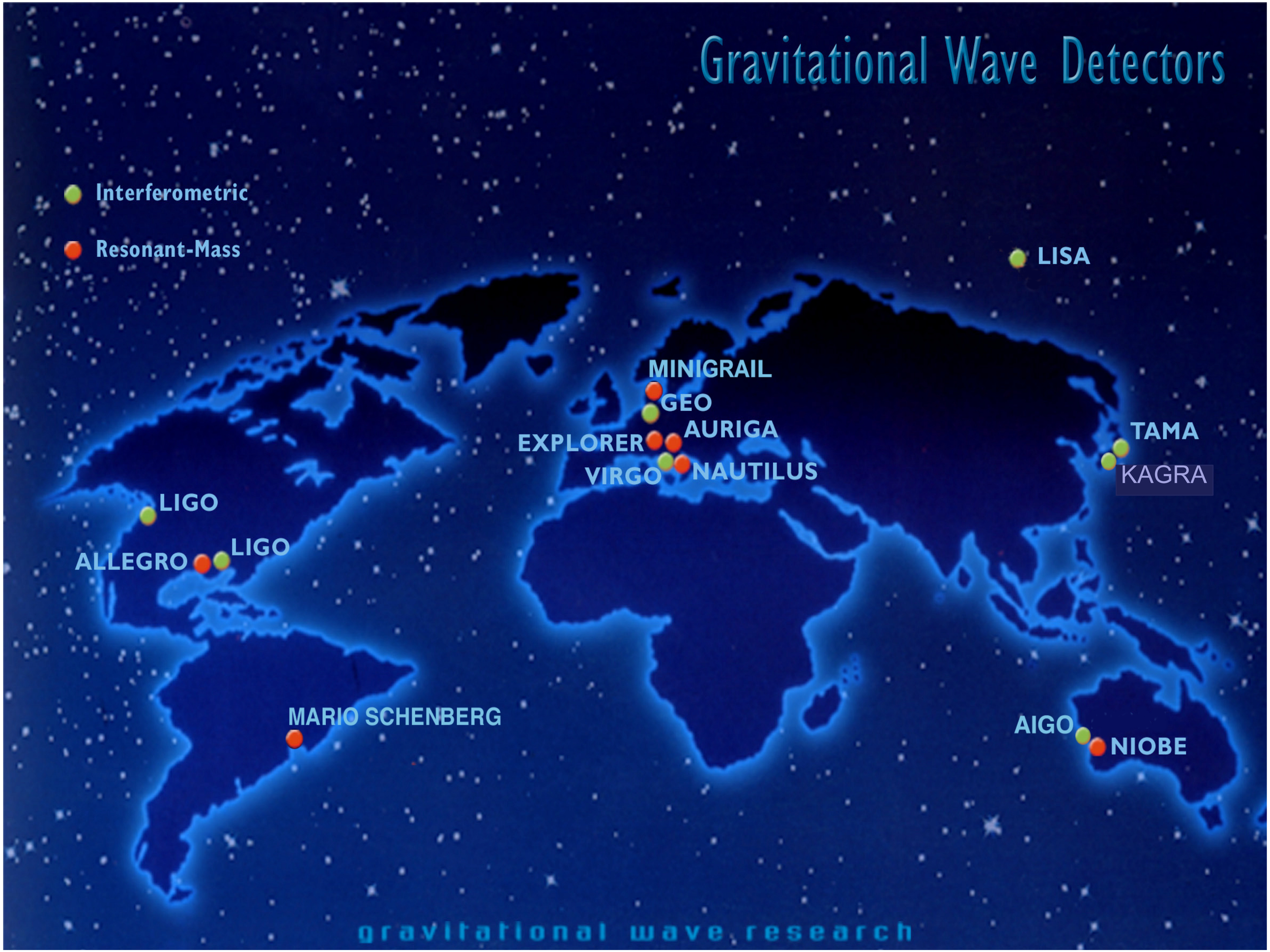
Window	Opened	1st Surprise	Year
Optical	1609 Galilei	Jupiter's moons	1610
Cosmic Rays	1912	Muon	1930s
Radio	1930s	Giant Radio Galaxies CMB Pulsars	1950s 1964 1967
X - ray	1948	Sco X-1 X-ray binaries	1962 1969 Uhuru
γ - ray	1961 Explorer 11	GRBs	Late 1960s+ Vela

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

$$\ddot{x}(t) + \tau^{-1}\dot{x}(t) + \omega_0^2 x(t) = \frac{1}{2}\ddot{h}(t)$$



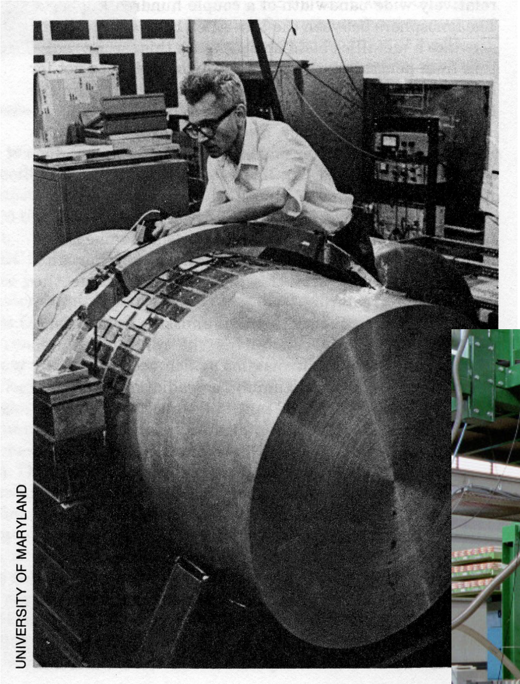




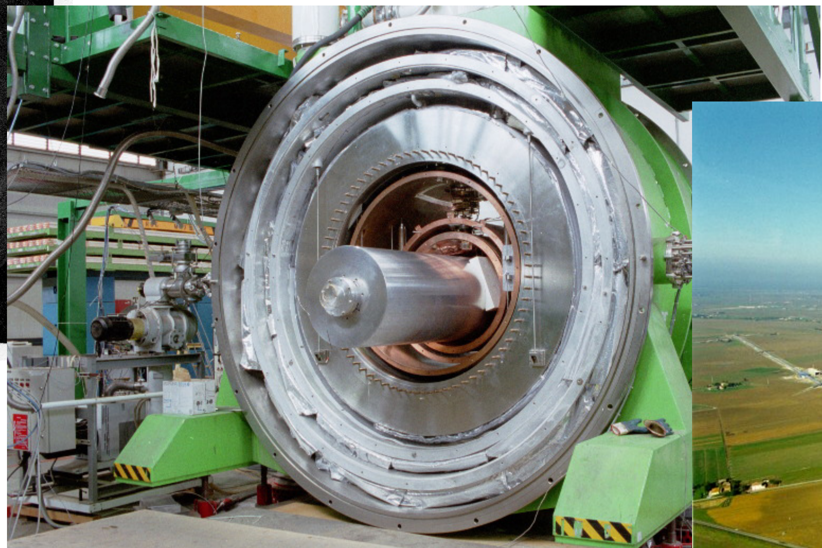
Gravitational Wave Detectors
Interferometric
Resonant-Mass
LISA
MINIGRAIL
GEO
AURIGA
EXPLORER
VIRGO
NAUTILUS
TAMA
KAGRA
LIGO
ALLEGRO
LIGO
MARIO SCHENBERG
AIGO
NIOBE
gravitational wave research

Some perspective: 40 years of attempts at detection:

Since the pioneering work of Joseph Weber in the ‘70, the search for Gravitational Waves has never stopped, with an increasing effort of manpower and ingenuity:



70’ : Joe Weber pioneering work



90’ : Cryogenic Bars

2005 - : Large Interferometers

1997: GWIC was formed

http://gwic.ligo.org

GWIC

Gravitational Wave International Committee

Home

News

GWIC Roadmap

Thesis Prize

Statements

Conferences

GWIC meetings

Reports to PaNAGIC

GWIC By-laws

The Gravitational Wave International Committee:

GWIC, the Gravitational Wave International Committee, was formed in 1997 to facilitate international collaboration and cooperation in the construction, operation and use of the major gravitational wave detection facilities world-wide. It is associated with the International Union of Pure and Applied Physics as its Working Group WG.11. Through this association, GWIC is connected with the International Society on General Relativity and Gravitation (IUPAP's Affiliated Commission AC.2), its Commission C19 (Astrophysics), and another Working Group, the AstroParticle Physics International Committee (APPIC).

GWIC's Goals:

- Promote international cooperation in all phases of construction and scientific exploitation of gravitational-wave detectors;
- Coordinate and support long-range planning for new instrument proposals, or proposals for instrument upgrades;
- Promote the development of gravitational-wave detection as an astronomical tool, exploiting especially the potential for multi-messenger astrophysics;
- Organize regular, world-inclusive meetings and workshops for the study of problems related to the development and exploitation of new or enhanced gravitational-wave detectors, and foster research and development of new technology;
- Represent the gravitational-wave detection community internationally, acting as its advocate;
- Provide a forum for project leaders to regularly meet, discuss, and jointly plan the operations and direction of their detectors and experimental gravitational-wave physics generally.

The phase change and the future

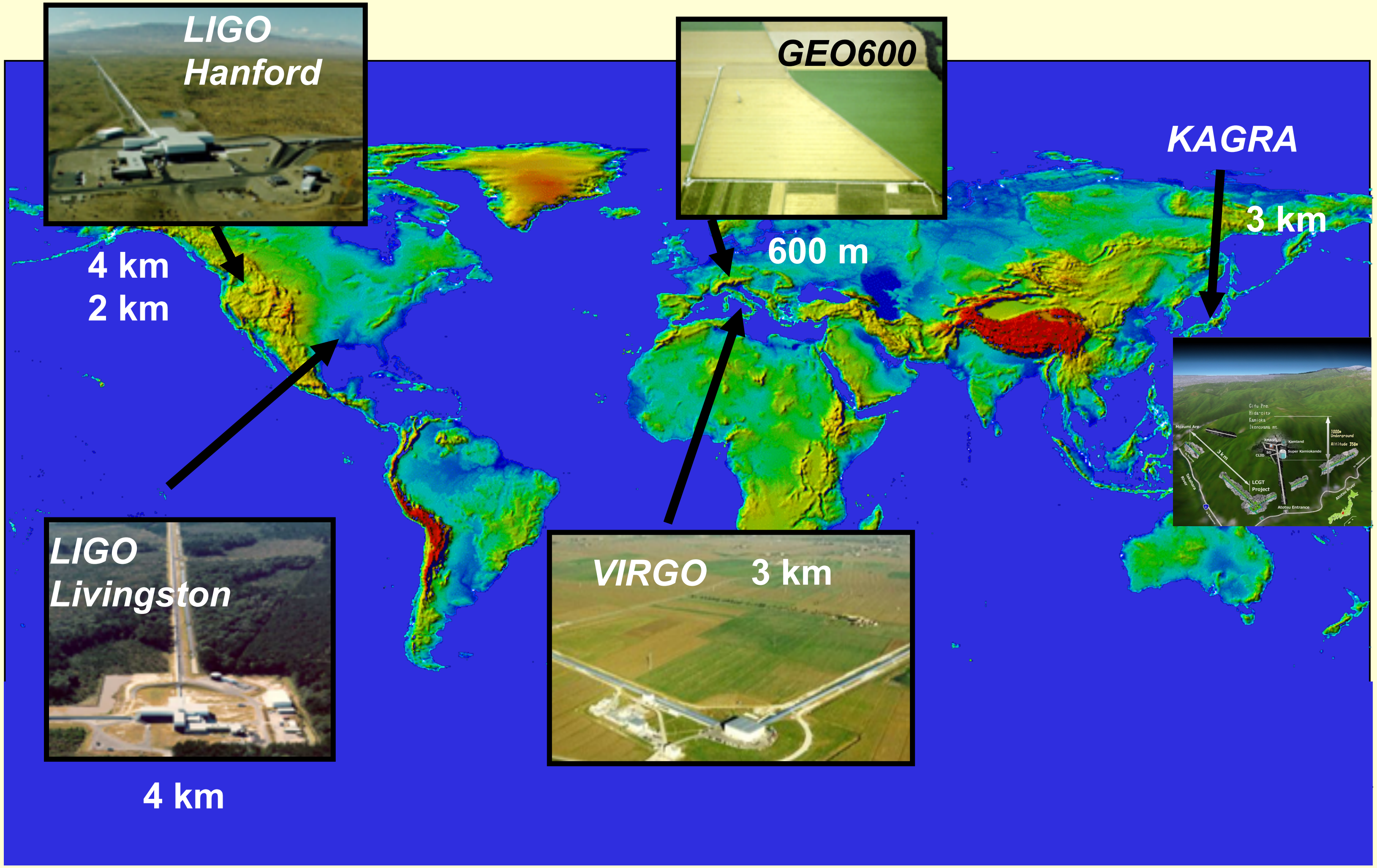
1960 – 2005 view
Given the uncharted territory that gravitational-wave detectors are probing, *unexpected* sources may actually provide the first detection.

2005 on view
Only new high sensitivity detectors can provide the first detection and open the GW astronomy

The contribution of Resonant Bars has been essential in establishing the field, giving interesting results and putting some important upper limits on the gravitational landscape around us, but now the hope for guaranteed detection is in the Network of long arm interferometers.

GWIC
Gravitational Wave International Committee

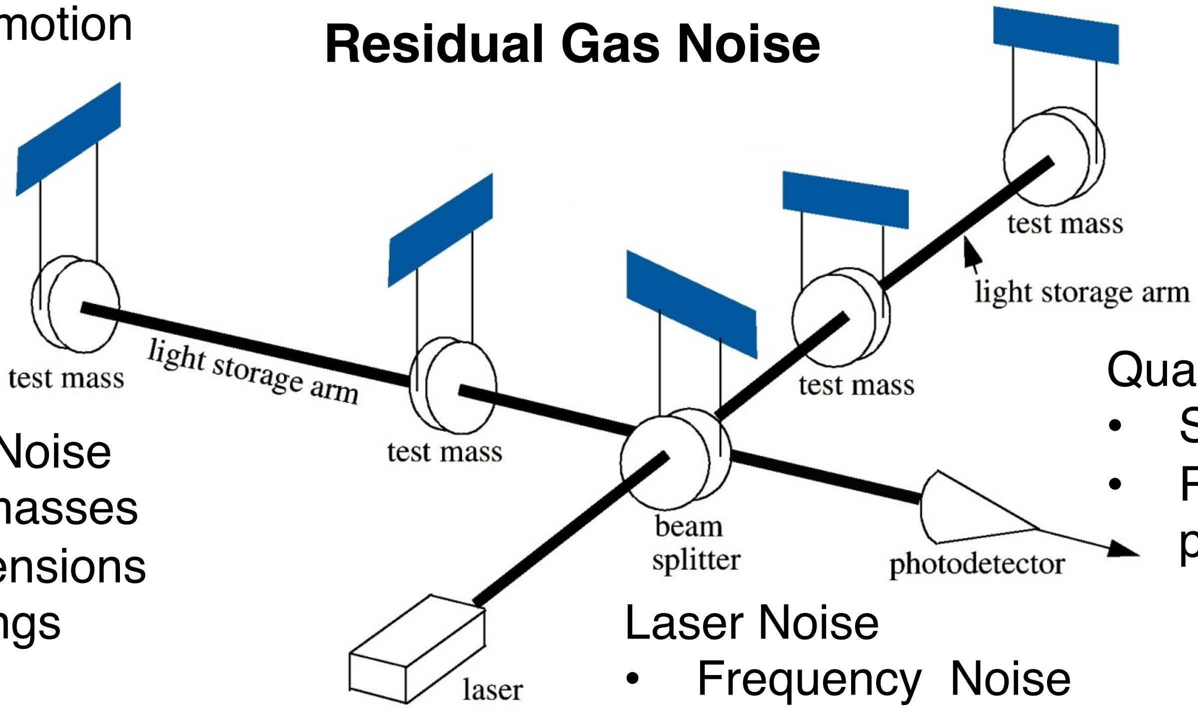
Worldwide network of Interferometers



Limits to Sensitivity

Vibrational Noise
- Ground motion
- Acoustic

Residual Gas Noise



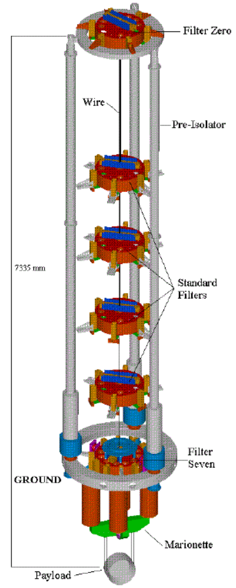
Thermal Noise
- Test masses
- Suspensions
- Coatings

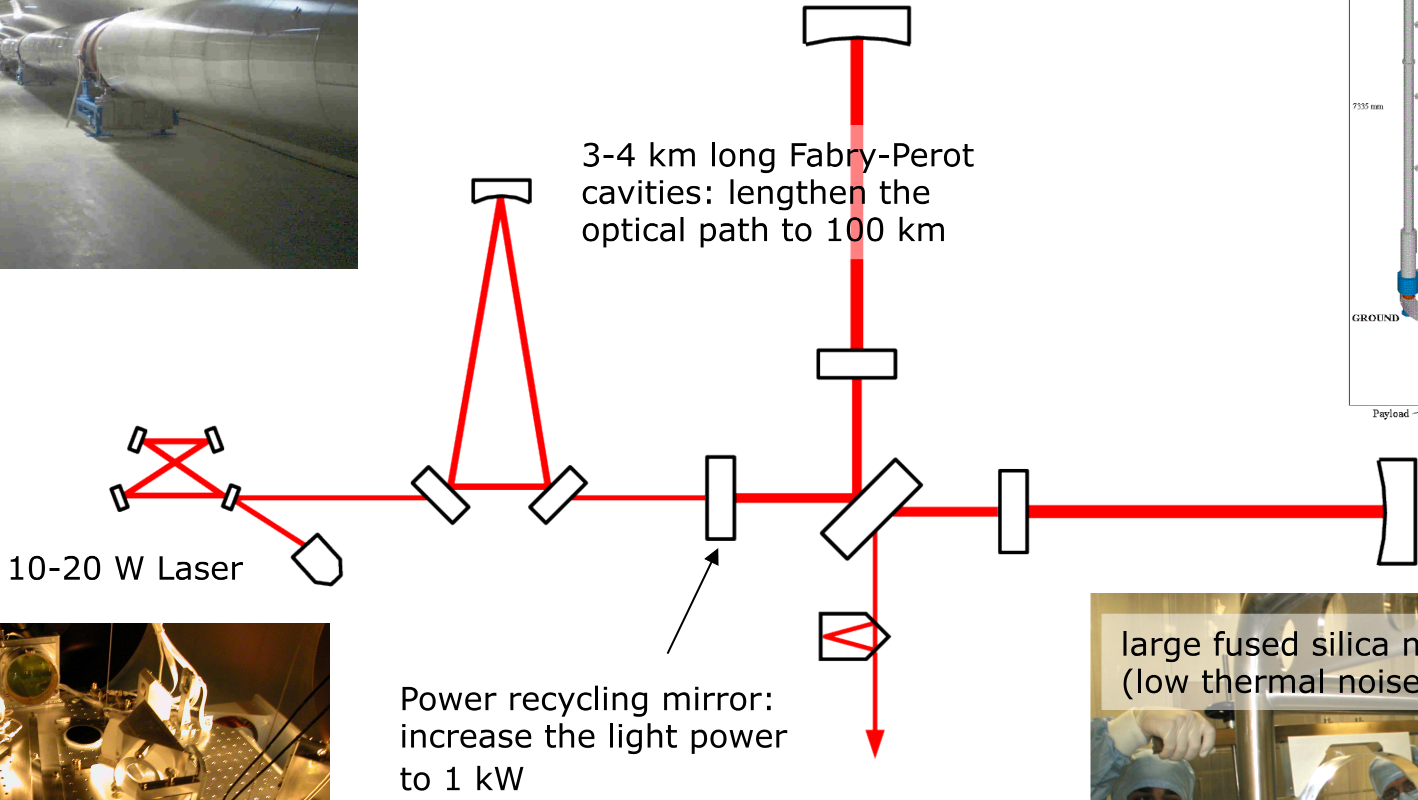
Quantum Noise
- Shot Noise
- Radiation pressure Noise

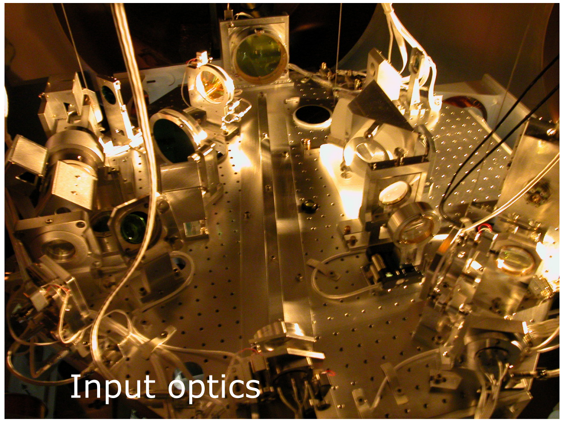
Laser Noise
- Frequency Noise
- Intensity Noise

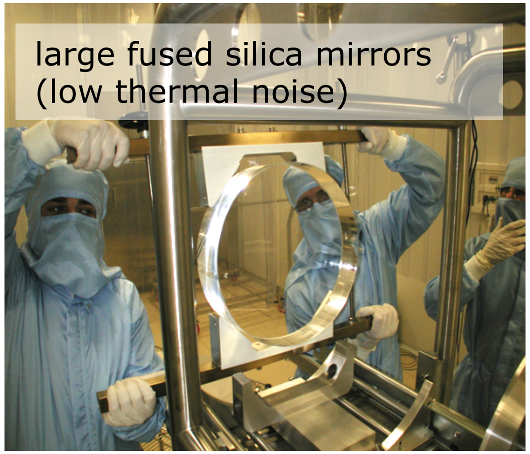
A real detector scheme

Isolation from ground vibrations



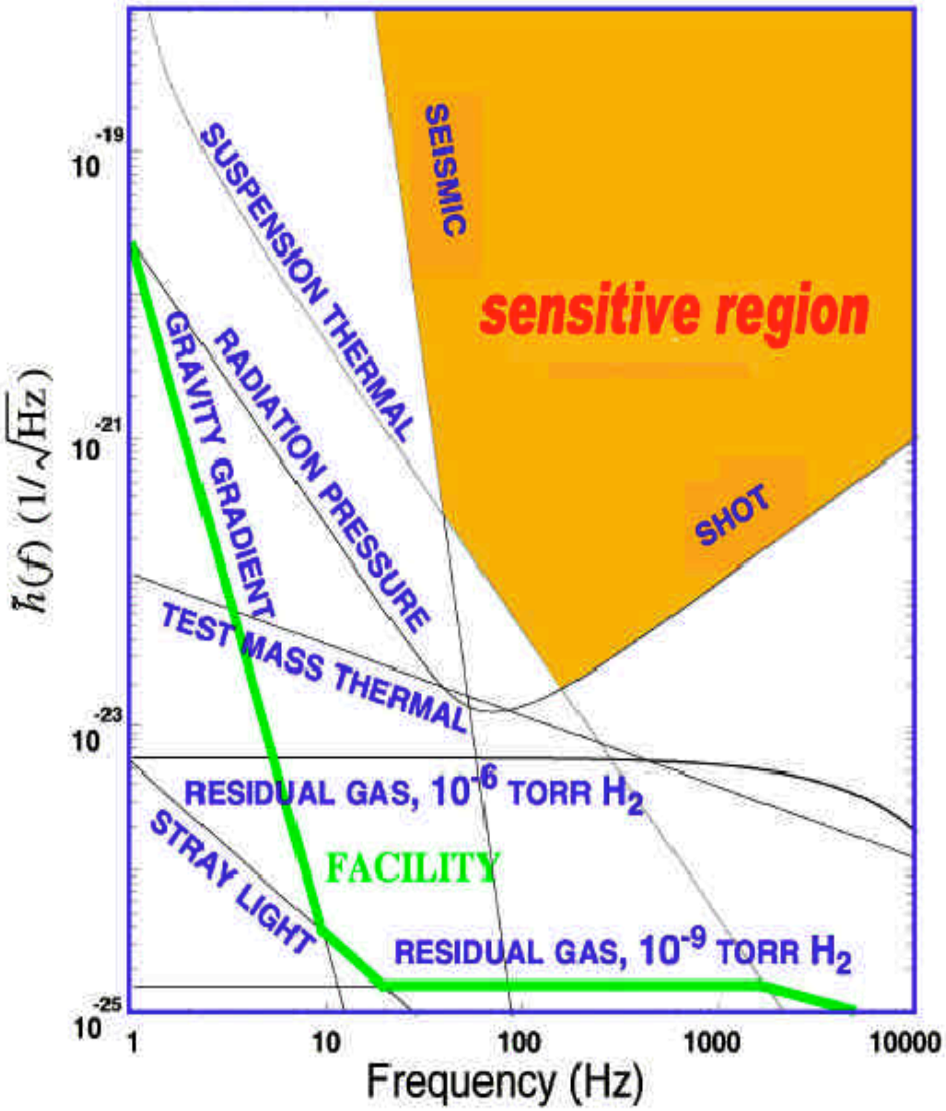


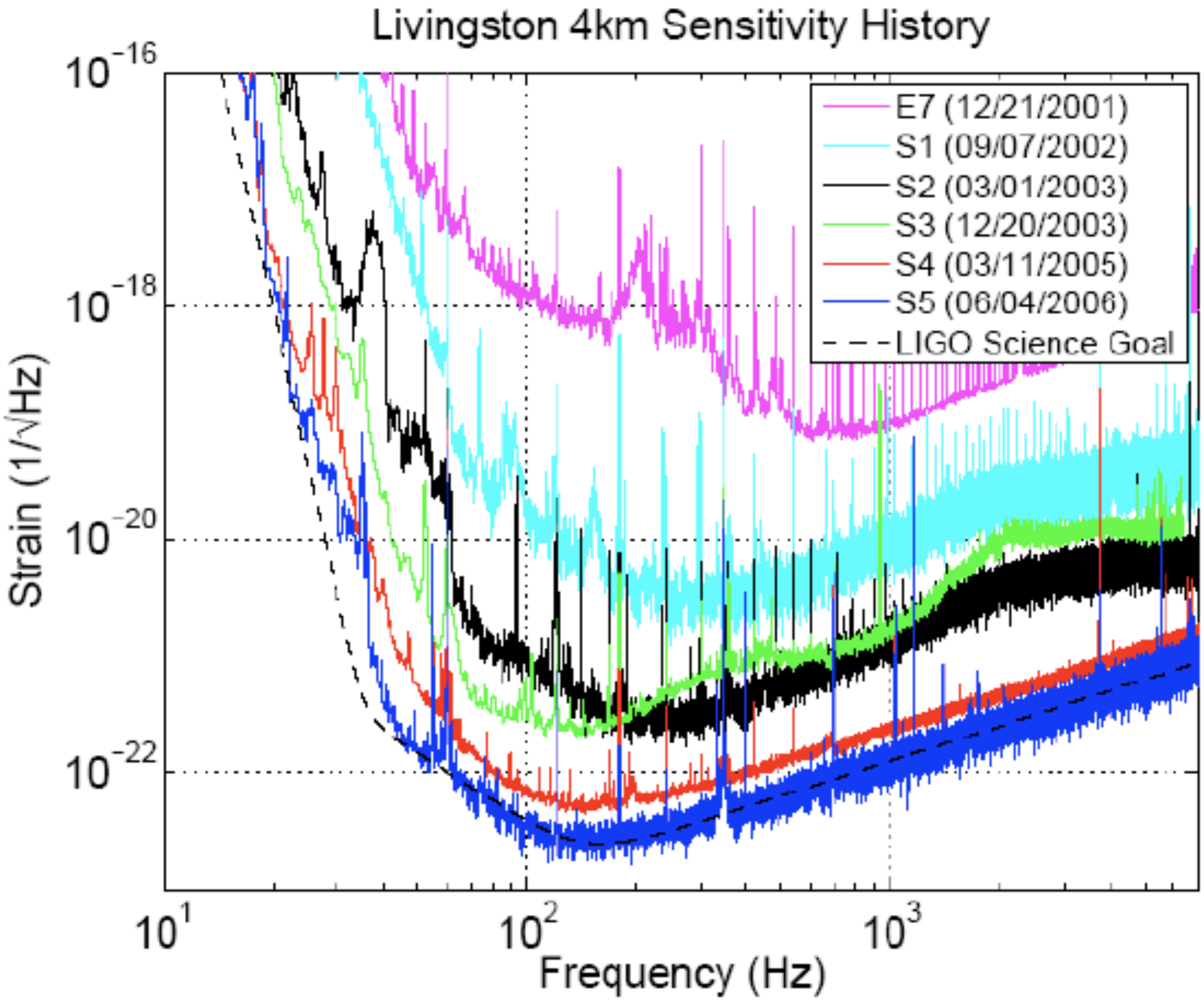




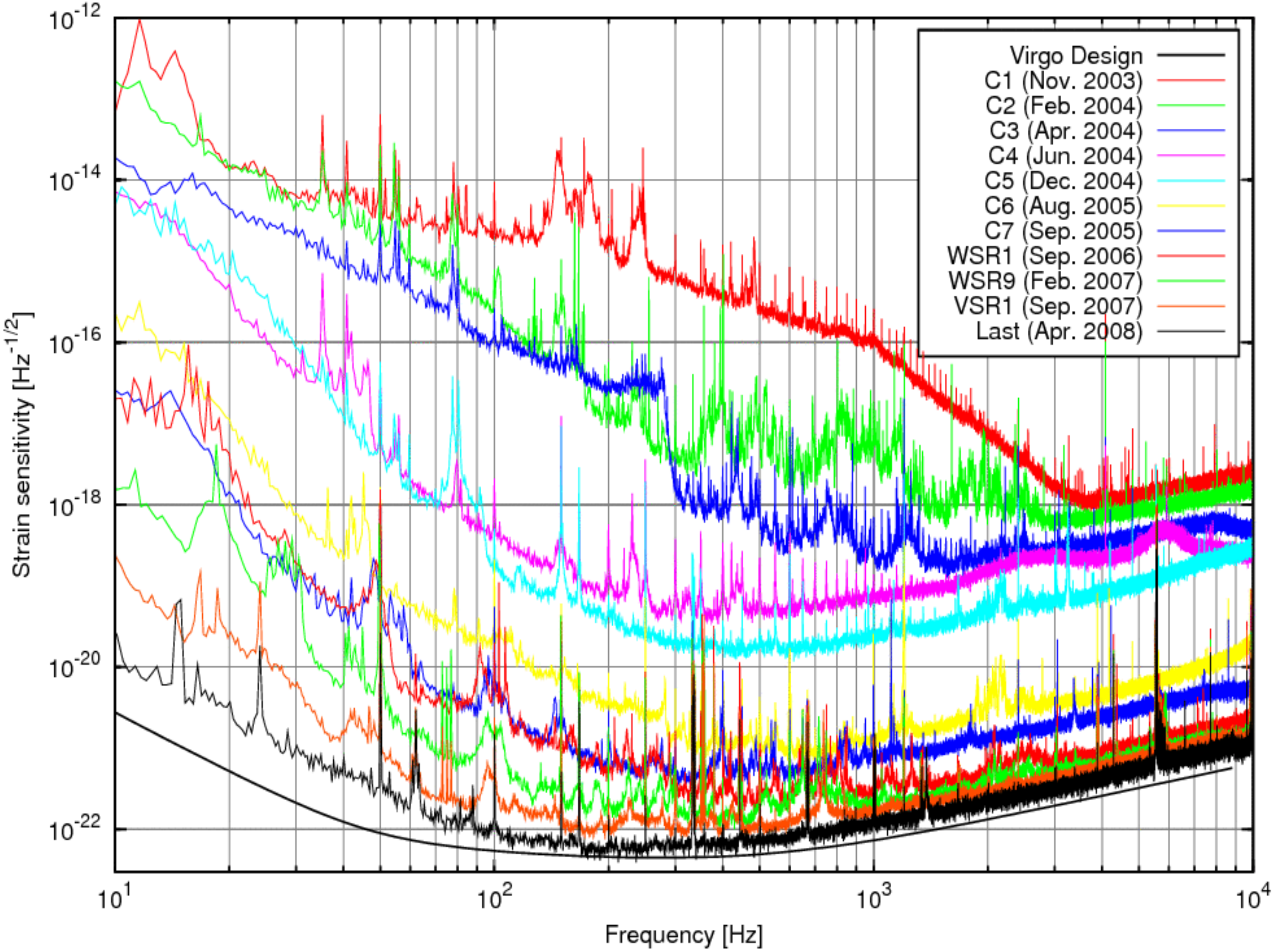
- Interferometry is limited by three fundamental noise sources
  - seismic noise at the lowest frequencies
  - thermal noise at intermediate frequencies
  - shot noise at high frequencies

- Many other noise sources lurk underneath and must be controlled as the instrument is improved





Livingston 4km Sensitivity History
E7 (12/21/2001)
S1 (09/07/2002)
S2 (03/01/2003)
S3 (12/20/2003)
S4 (03/11/2005)
S5 (06/04/2006)
LIGO Science Goal
Strain (1/√Hz)
Frequency (Hz)



Virgo Design
C1 (Nov. 2003)
C2 (Feb. 2004)
C3 (Apr. 2004)
C4 (Jun. 2004)
C5 (Dec. 2004)
C6 (Aug. 2005)
C7 (Sep. 2005)
WSR1 (Sep. 2006)
WSR9 (Feb. 2007)
VSR1 (Sep. 2007)
Last (Apr. 2008)
Strain sensitivity [Hz^-1/2]
Frequency [Hz]
10^-12
10^-14
10^-16
10^-18
10^-20
10^-22
10^1
10^2
10^3
10^4

Results from Initial Detectors: Some highlights from LIGO and Virgo

Several ~year long science data runs by LIGO and Virgo

Since 2007 all data analyzed jointly

- Limits on GW emission from known msec pulsars
  - Crab pulsar emitting less than 2% of available spin-down energy in gravitational waves
- Limits on compact binary (NS-NS, NS-BH, BH-BH) coalescence rates in our local neighborhood (~20 Mpc)
- Limits on stochastic background in 100 Hz range
  - Limit beats the limit derived from Big Bang nucleosynthesis

LIGO-VIRGO recent papers

All sky search for periodic gravitational waves in the full LIGO S5 science data.
Published in Phys.Rev. D85 022001, 2012.

Directional limits on persistent gravitational waves using LIGO S5 science data.
Phys. Rev. Lett. 107:271102, 2011.

Beating the spin-down limit on gravitational wave emission from the Vela pulsar.
Astrophys. J. 737, 93, 2011

Search for Gravitational Wave Bursts from Six Magnetars.
Astrophys. J. 734, L35, 2011.

Search for gravitational waves from binary black hole inspiral, merger and ringdown.
Phys. Rev. D83:122005, 2011.

Search for GW inspiral signals associated with Gamma-Ray bursts during LIGO's fifth and Virgo's first science run.
Astrophys. J. 715:1453-1461, 2010.

Searches for gravitational waves from known pulsars with S5 LIGO data.
Astrophys. J. 713:671-685, 2010.

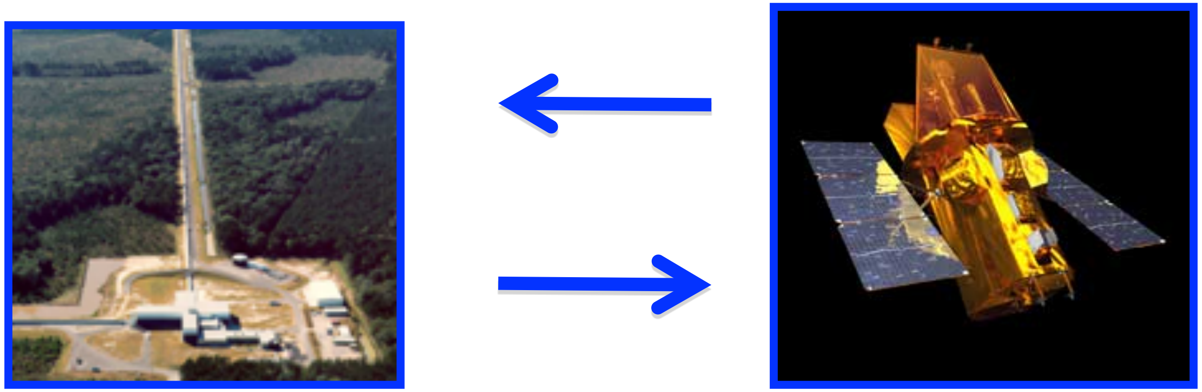
Search for GW bursts associated with Gamma-Ray bursts using data from LIGO Science Run 5 and Virgo Science Run 1.
The LIGO and the Virgo Collaborations
Astrophys. J. 715:1438-1452, 2010.

All-sky search for gravitational-wave bursts in the first joint LIGO-GEO-Virgo run.
Phys. Rev. D81, 102001, 2010

Search for Gravitational Waves from Compact Binary Coalescence in LIGO and Virgo Data from S5 and VSR1.
Phys. Rev. D82, 102001, 2010

An upper limit on the stochastic GW background of cosmological origin
Nature 460, 08278, 2009

Multimessenger Astronomy with Gravitational Waves



- Offline searches in which external electromagnetic triggers are used to dig into GW data
  GRBs from Fermi, Swift and other contributors to GCN network
- Search for Coincidence with Neutrinos
- Low-latency electromagnetic follow-up of GW triggers

A First Search for coincident Gravitational Waves and High Energy Neutrinos using LIGO, Virgo and ANTARES data from 2007

LIGO Scientific and Virgo Collaborations (S. Adrian-Martinez *et al.*). May 2012. 35 pp.

LIGO-P1200006
e-Print: arXiv:1205.3018 [astro-ph.HE] | PDF

ABSTRACT

We present the results of the first search for gravitational wave bursts associated with high energy neutrinos. Together, these messengers could reveal new, hidden sources that are not observed by conventional photon astronomy, particularly at high energy. Our search uses neutrinos detected by the underwater neutrino telescope ANTARES in its 5 line configuration during the period January - September 2007, which coincided with the fifth and first science runs of LIGO and Virgo, respectively. The LIGO-Virgo data were analysed for candidate gravitational-wave signals coincident in time and direction with the neutrino events. No significant coincident events were observed. We place limits on the density of joint high energy neutrino - gravitational wave emission events in the local universe, and compare them with densities of merger and core-collapse events.

Subject headings: gravitational waves — high energy neutrinos

Phys.Rev.Lett. 103 (2009) 031102

Neutrinos from Supernovae as a Trigger for Gravitational Wave Search

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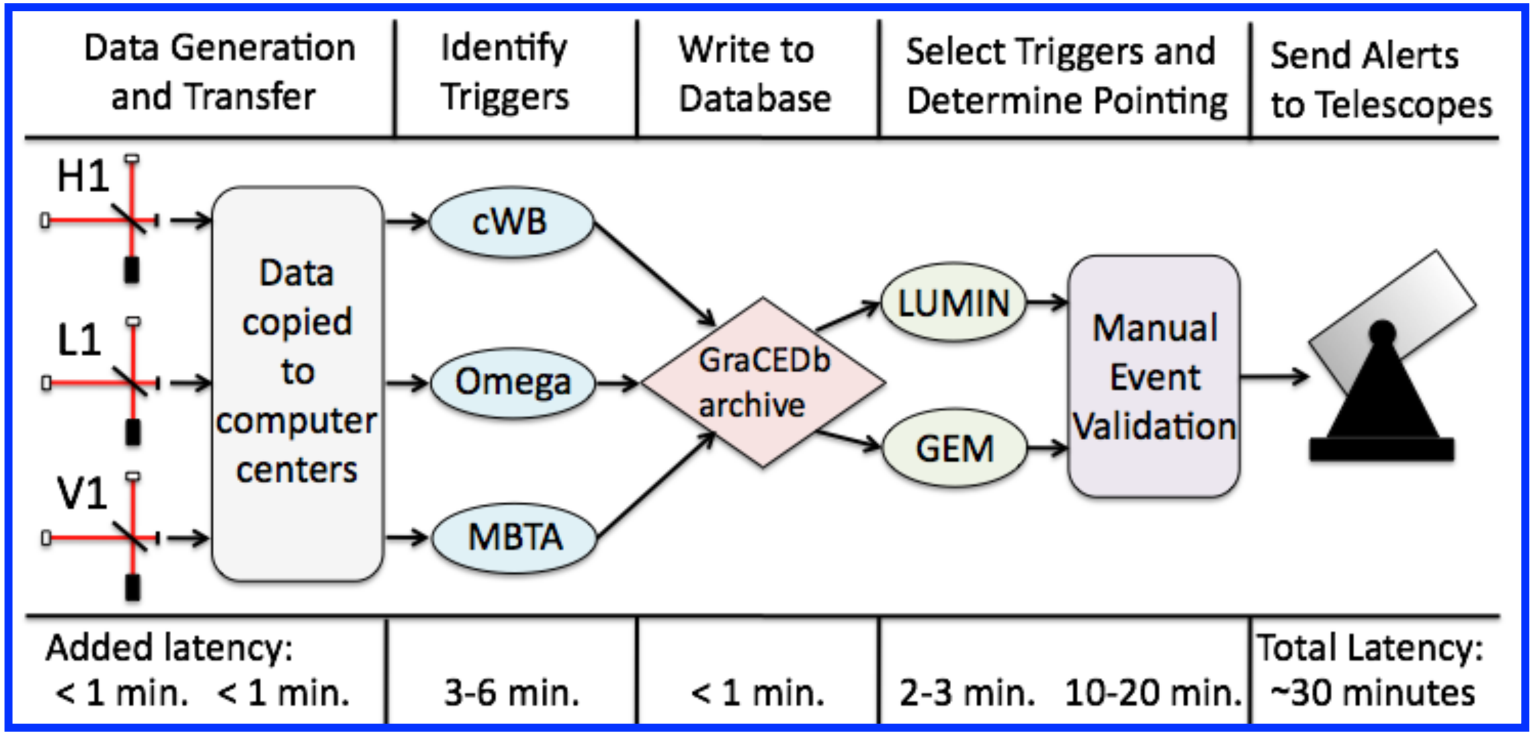
[2] *University of L'Aquila, Coppito (AQ), Italy*
[3] *University of Rome "Tor Vergata", Rome, Italy*
[4] *Istituto di Fisica dello Spazio Interplanetario (INAF), I-10133 Torino, Italy*
[5] *INFN, I-10125 Torino, Italy*

Exploiting an improved analysis of the $\bar{\nu}_e$ signal from the explosion of a galactic core collapse supernova, we show that it is possible to identify within about ten milliseconds the time of the bounce, which is strongly correlated to the time of the maximum amplitude of the gravitational signal. This allows to precisely identify the gravitational wave burst timing.

Low Latency EM Follow-Up Program



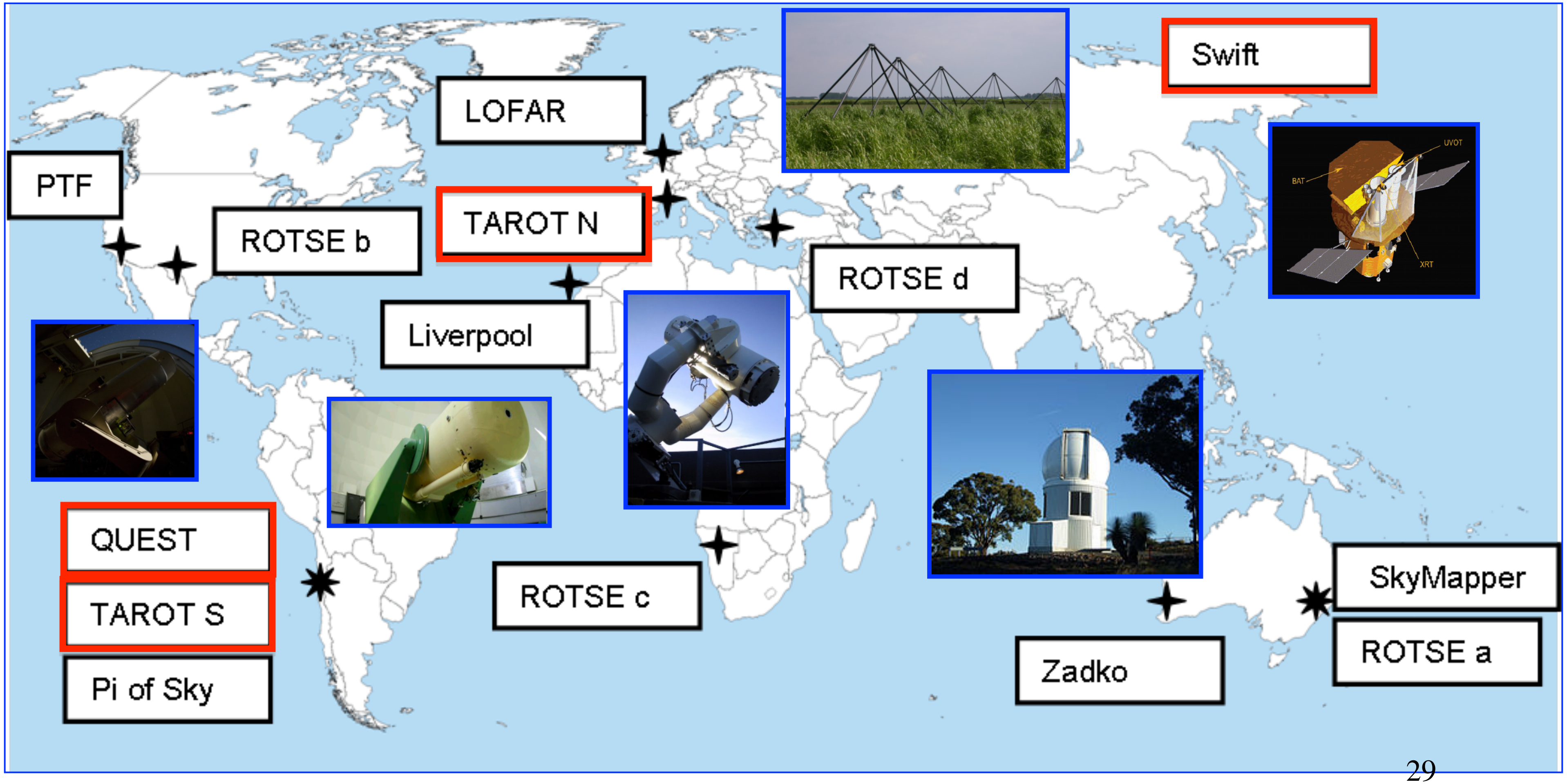
- Subthreshold candidate GW events sent to partner ~meter class telescopes network
- Target alert rate of 1 per week
- Ran during parts of most recent science runs Dec 2009-Jan 2010 and Sep to Oct 2010
- Images obtained for 8 different events

Astronomy & Astrophysics 539 (2012)A124

Astronomy & Astrophysics 541 (2012)A155

Telescope Network

Used in winter and autumn run (red box)   autumn run only (black box)

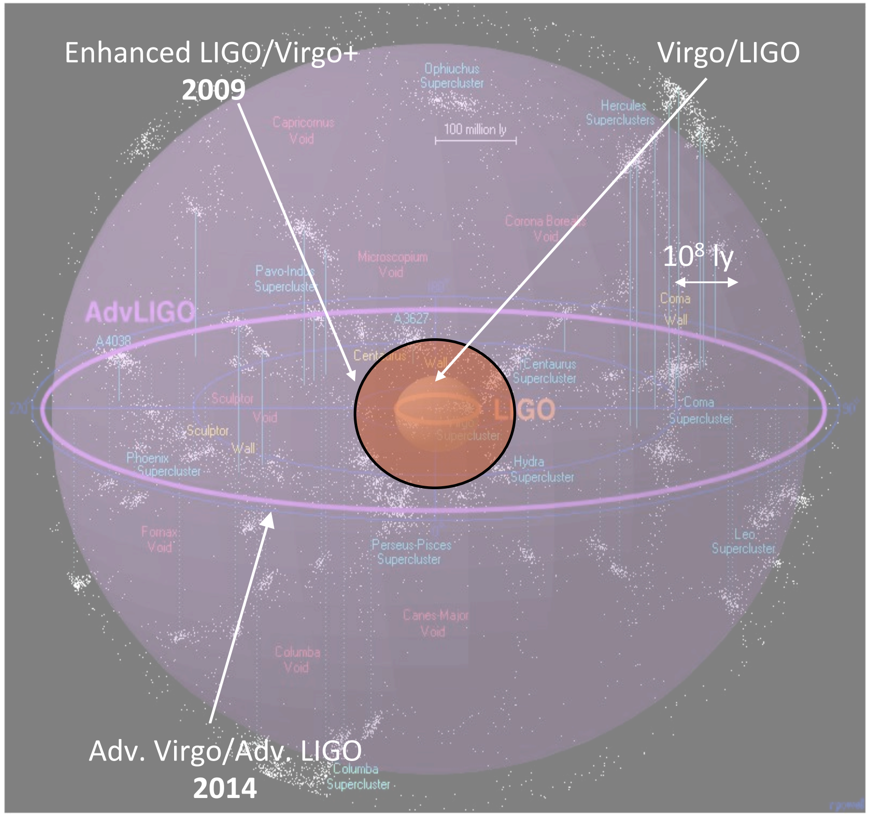


2nd GENERATION: DISCOVERY AND ASTRONOMY

2nd generation detectors:
Advanced Virgo, Advanced LIGO

GOAL:
sensitivity 10x better →
look 10x further →
Detection rate 1000x larger

NS-NS detectable as far as 300 Mpc
BH-BH detectable at cosmological distances
10s to 100s of events/year expected!

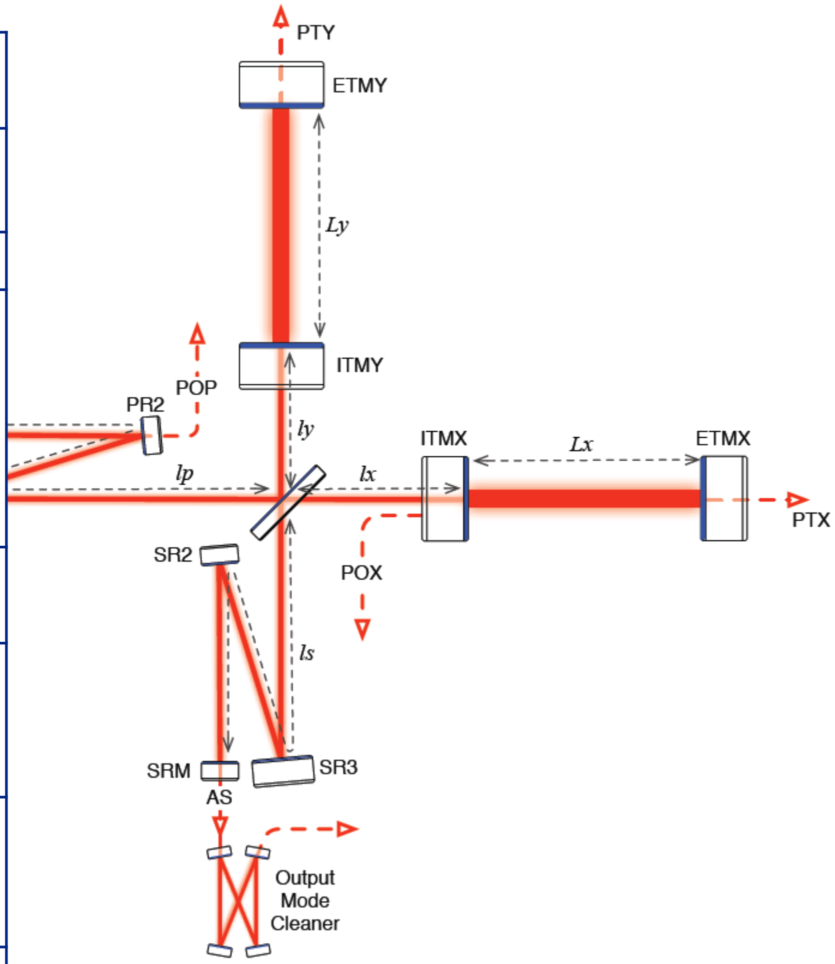


Credit: R.Powell, B.Berger

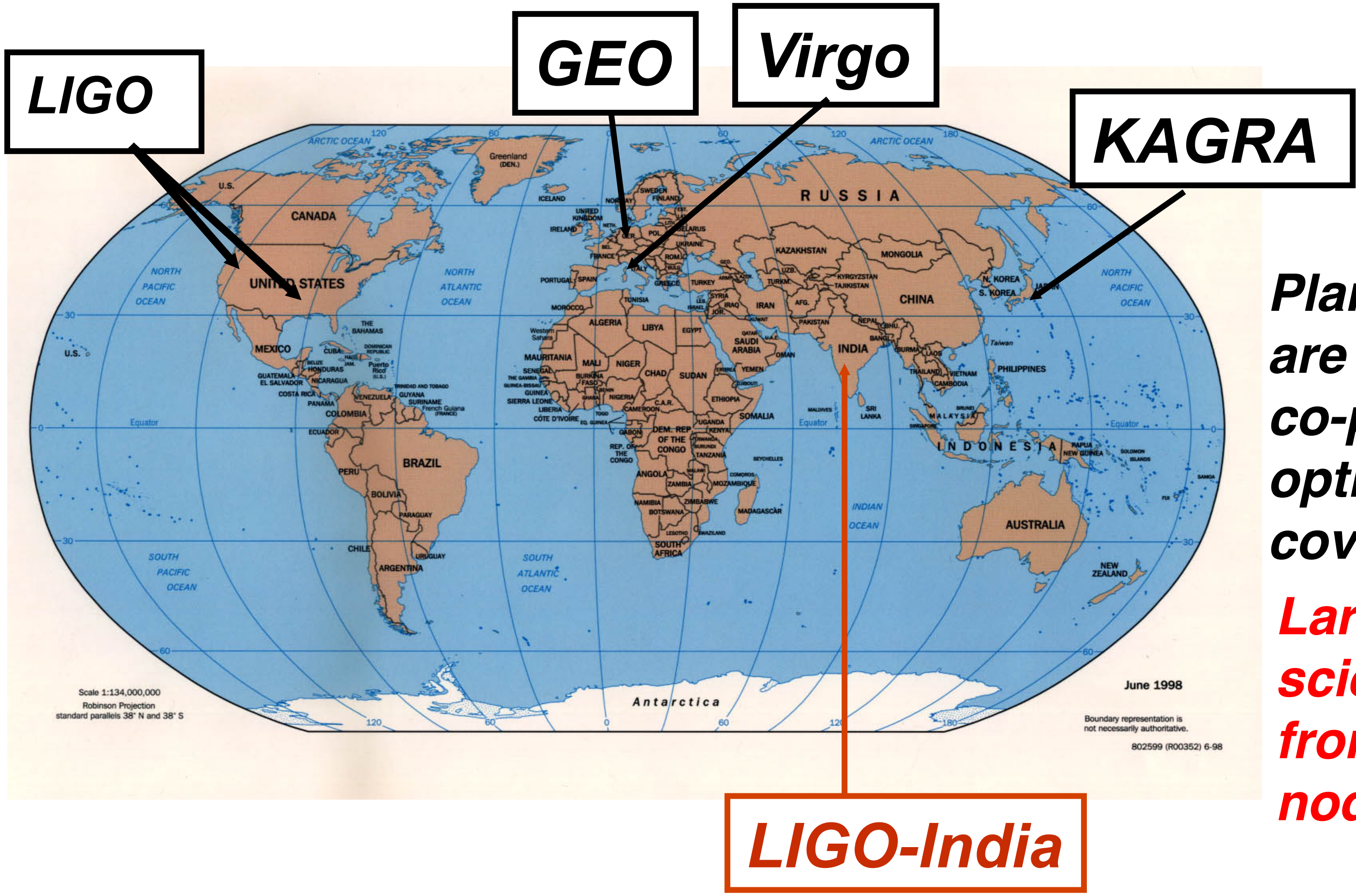
Advanced LIGO/virgo overview

What is Advanced?

Parameter	Initial LIGO/Virgo	Advanced LIGO/ Virgo
Input Laser Power	10 W (10 kW arm)	180 W (>700 kW arm)
Mirror Mass	10 kg/20kg	40 kg
Interferometer Topology	Power-recycled Fabry-Perot arm cavity Michelson	Dual-recycled Fabry-Perot arm cavity Michelson (LIGO stable recycling cavities)
GW Readout Method	RF heterodyne	DC homodyne
Optimal Strain Sensitivity	3 x 10-23 / rHz 6 x 10-23 / rHz	Tunable, better than 5 x 10-24 / rHz in broadband
Seismic Isolation Performance	flow ~ 50 Hz flow ~ 10 Hz	flow ~ 12 Hz flow ~ 10 Hz
Mirror Suspensions	Single Pendulum/ Hepta Pendulum	Quadruple Pendulum/ Hepta Pendulum



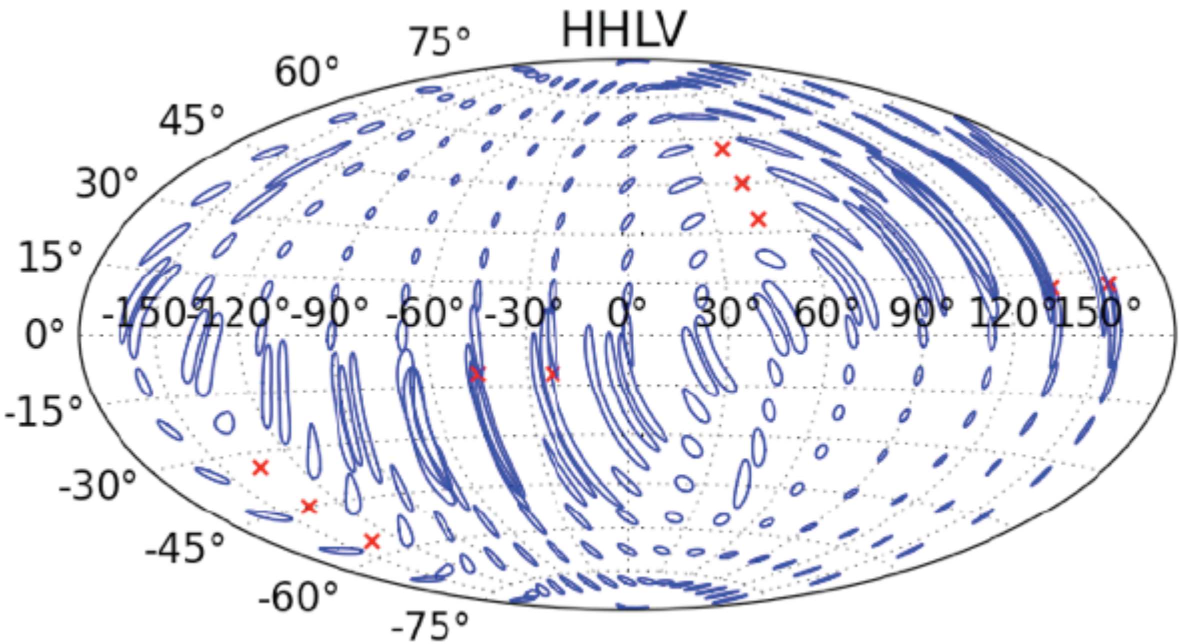
Completing the Global Network



Planned detectors are very close to co-planar—not optimal for all-sky coverage

Large increase to science capability from a southern node in the network

Localization capability: LIGO-Virgo only

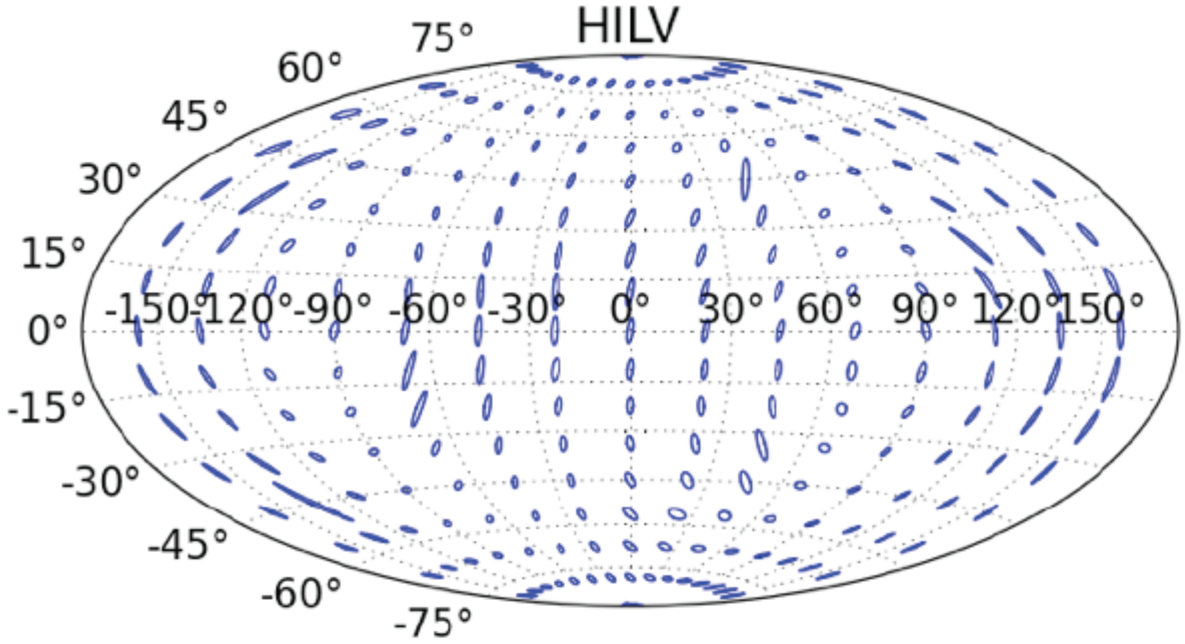


Fairhurst 2011

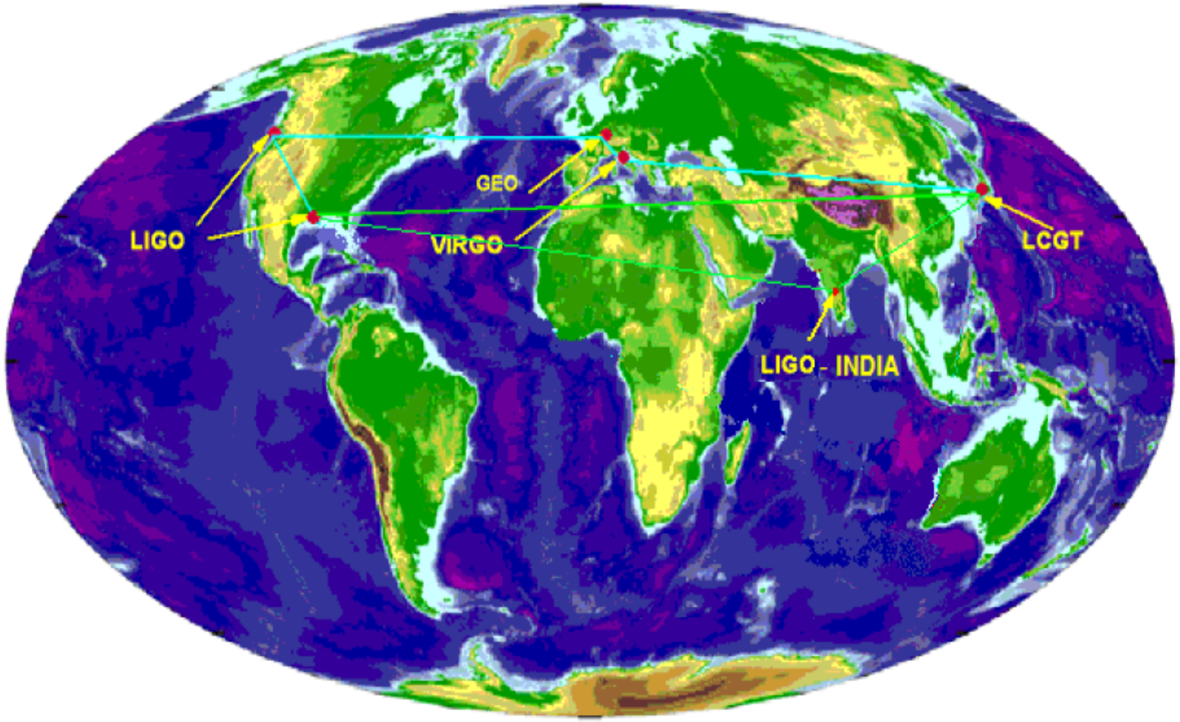
Red crosses denote regions where the network has blind spots

10

Localization capability: LIGO-Virgo plus LIGO-India

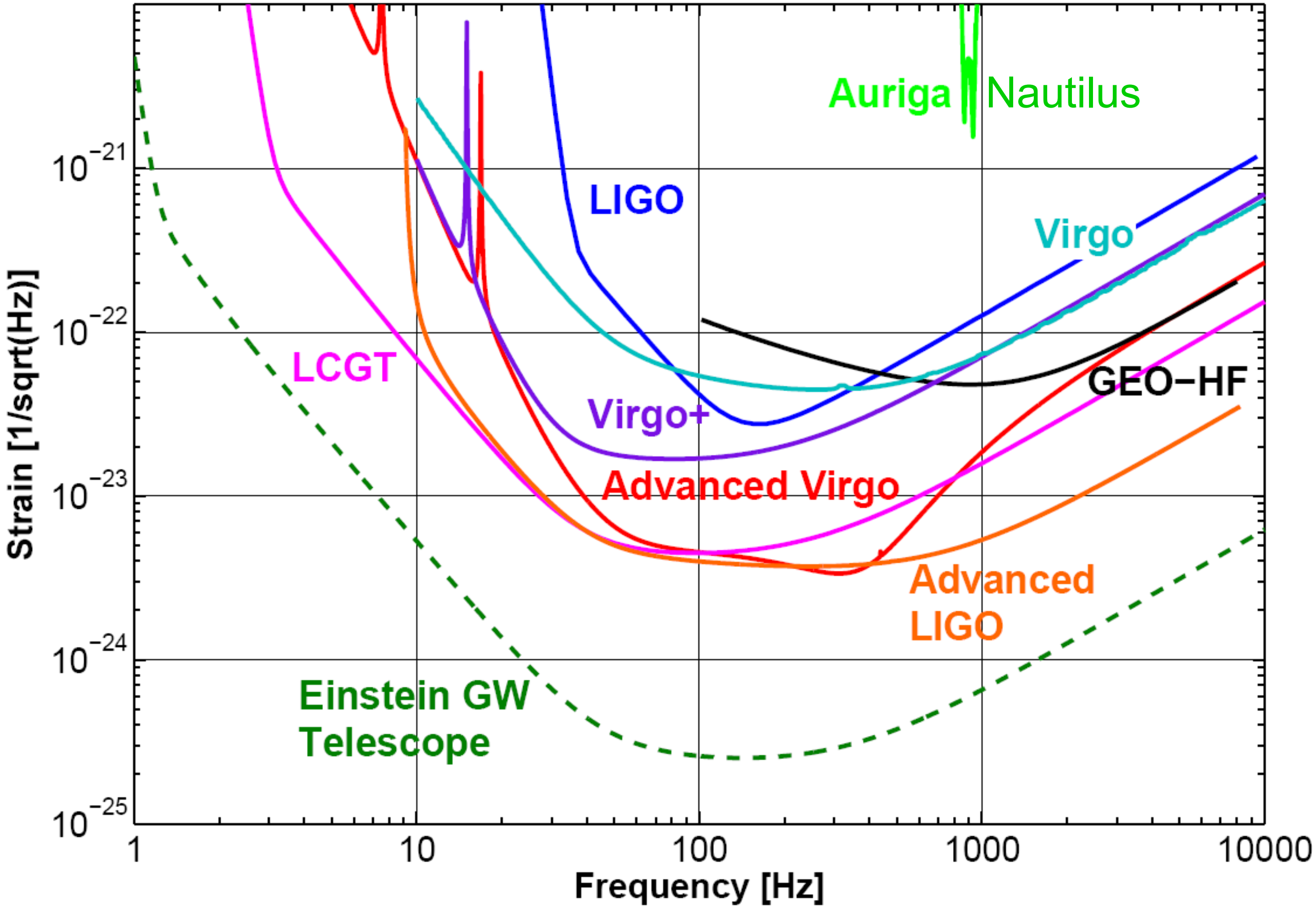


Fairhurst 2011

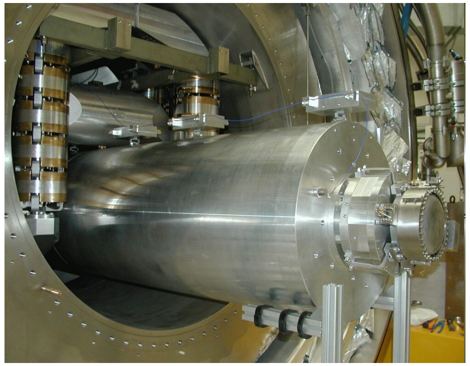


- We are on the threshold of a new era of gravitational wave astrophysics
- First generation detectors have broken new ground in optical sensitivity
  - Initial detectors have proven technique
- Second generation detectors are starting installation
  - Will expand the “Science” (astrophysics) by factor of 1000
- In the next decade, emphasis will be on the *NETWORK*

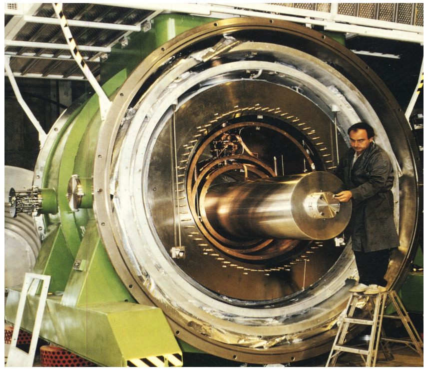
Summary of sensitivities



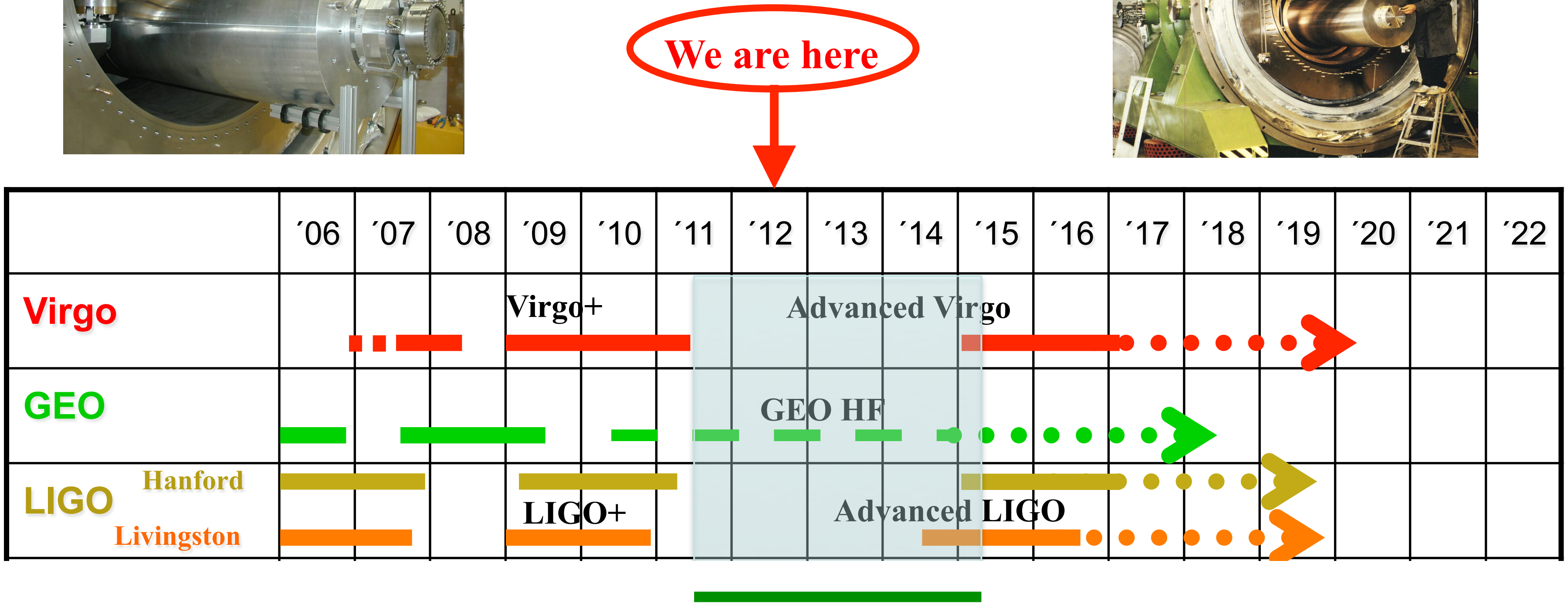
AURIGA - LNL



NAUTILUS - LNF



AUNA



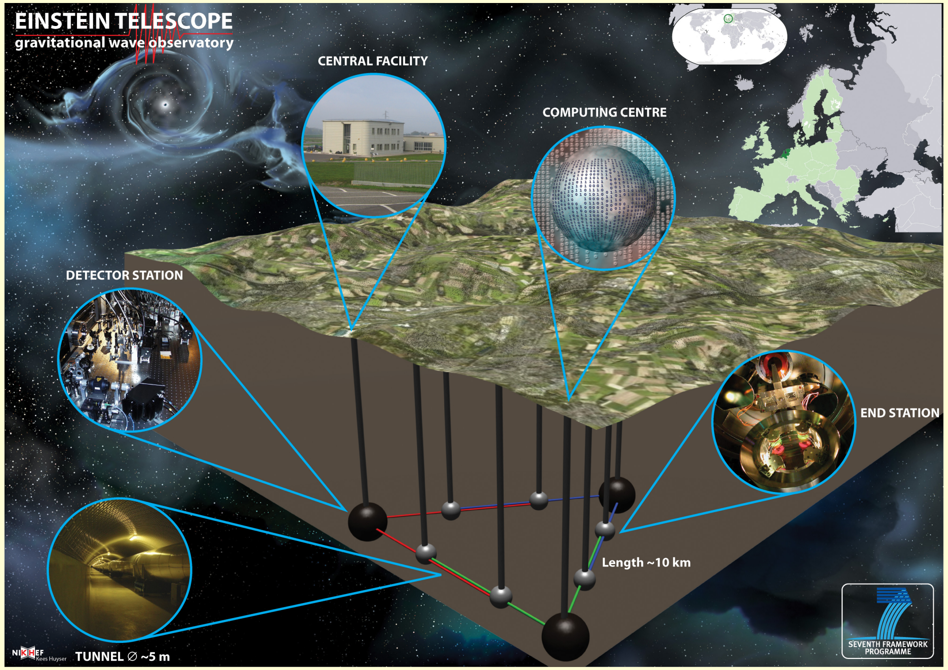
Window of opportunity for AURIGA and NAUTILUS

GWIC
Gravitational Wave International Committee

8 Recommendations to GWIC to guide the development of the field

8.5 Toward a third-generation global network

"Background— The scientific focus of a third-generation global network will be gravitational wave astronomy and astrophysics as well as cutting edge aspects of basic physics. Third-generation underground facilities are aimed at having excellent sensitivity from ~1 Hz to ~10^4 Hz. As such, they will greatly expand the new frontier of gravitational wave astronomy and astrophysics.

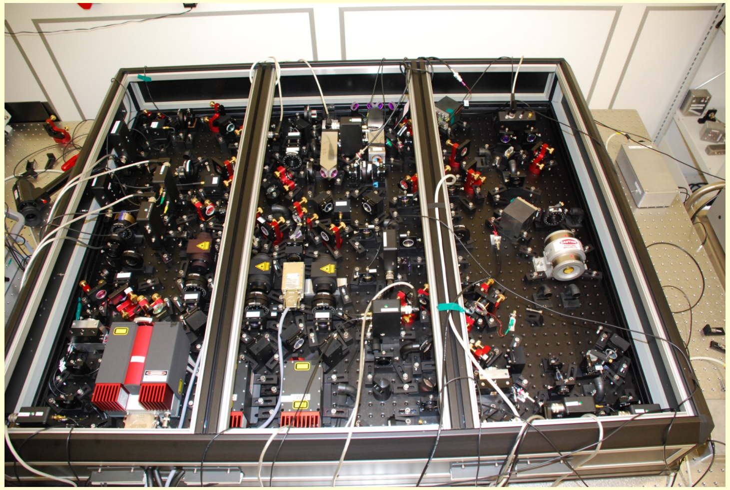


In Europe, a three year-long design study for a third-generation gravitational wave facility, the Einstein Telescope (ET), has recently begun with funding from the European Union.

8 Recommendations to GWIC to guide the development of the field

8.6 Development of key technologies for third generation ground-based instruments

- ***Cryogenics***
- ***Ultra Low loss Mirror Coatings***
- ***Non classical optical techniques***
- ***Newtonian Noise reduction***

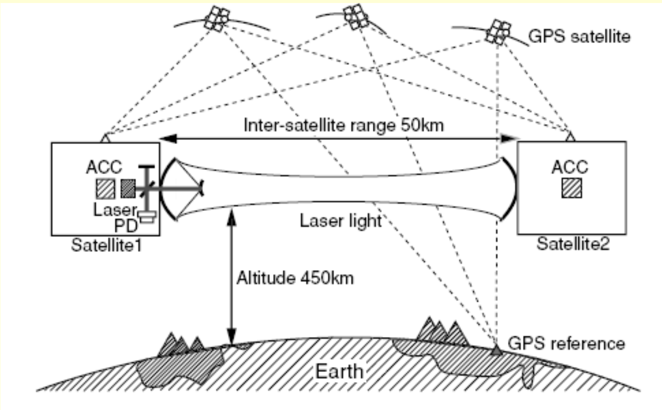


Recommendation—We recommend that GWIC sponsor a series of workshops, each focused on the status and development of a particular critical technology for gravitational wave instruments. Topics in such a series could include cryogenic techniques, coating development for reduced thermal noise, "Newtonian noise," techniques for quantum noise reduction, and overall network configuration. These workshops will help promote exchange of ideas, provide visibility and encouragement to new efforts in critical areas of technology development, and help bring to bear the combined resources of the community on these problems.

GWIC
Gravitational Wave International Committee

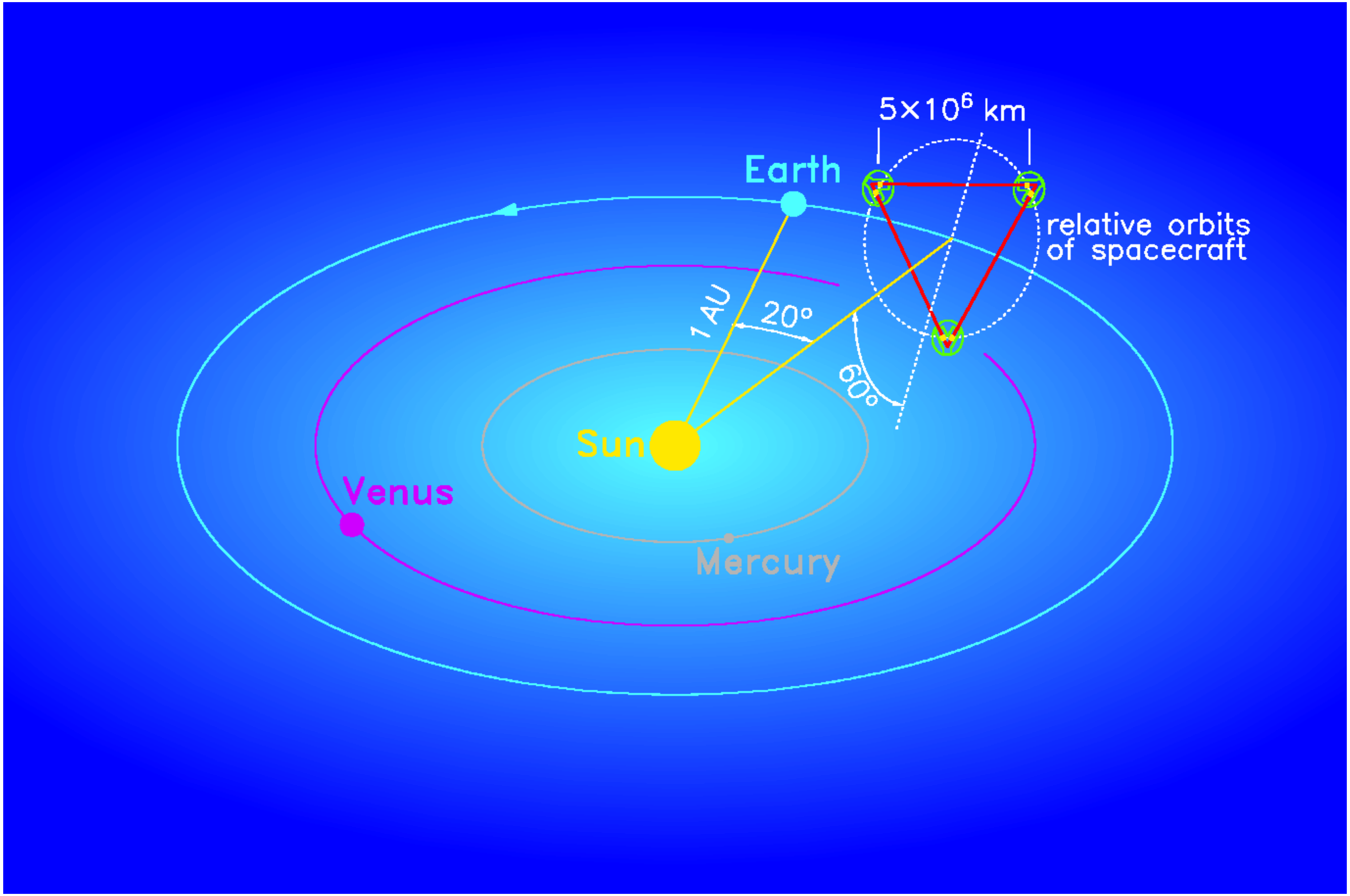
Impact of gravitational wave science on other fields

- The science of measurement
- Optics
- Space science and technology
- Geodesy and geophysics
- Material science and technology
- Cryogenics and cryogenic electronics
- Computing
- Methods in theoretical physics



Going into Space

- Astronomy has made huge advances using space-based instrumentation.
    - Motivation: get away from Earth-based obscuration
- In GWs, the Earth also provides an obscuring foreground at $f < 1$ Hz, due to fluctuations in Newtonian gravity.
    - Observations in the mHz region must be done in space.
- Since 1995, ESA has been developing LISA. NASA joined in 1998 but withdrew this year.



5×10⁶ km
Earth
relative orbits
of spacecraft
1 AU
20°
60°
Sun
Venus
Mercury

LISA becomes eLISA/NGO

- LISA was an equal-shares mission of ESA and NASA.
  - Rated second-highest priority for large space mission by US Decadal Survey 2010.
  - In competition in Europe for first L-launch with X-ray mission (IXO) and mission to Jupiter's moons (Laplace).
- In March this year, NASA dropped out because of financial problems due t James Webb Space Telescope.
- ESA asked all 3 competitors to re-design for Europe-only or Europe-led mission.

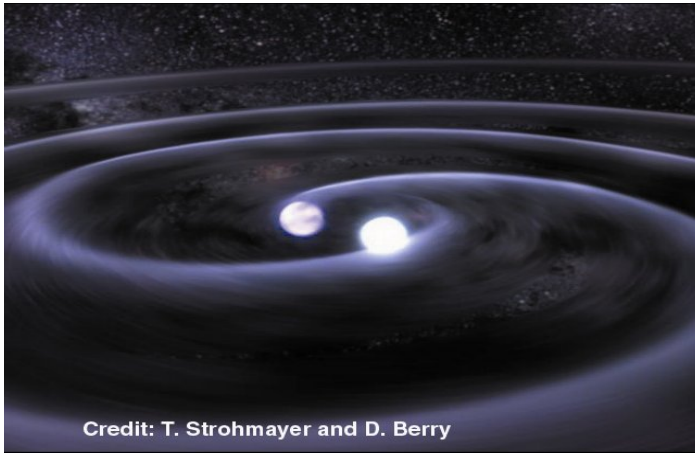
- Savings mainly in weight, launch cost.
- Two active arms, not three;
- Smaller arms (1Gm, not 5Gm);
- Re-use LISA Pathfinder hardware;

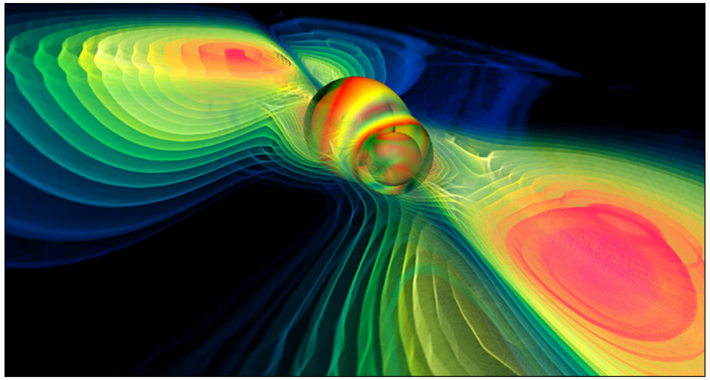
Science with Pulsar Timing

- The very low frequency nHz band can be explored by correlating arrival-time residuals of very stable millisecond radio pulsars.
  - Currently 3 collaborations: PPTA (Australia), NANOgrav (USA), EPTA (Europe).
- Band likely dominated by stochastic foreground from SMBH binaries. Observations now underway may reach this sensitivity in the period 2015-2020.
- Not unlikely that nearest SMBH binaries in the band can be picked out from the background.
- With periods of years, observations will only ever register a few cycles, so information content will be limited.

THE GLOBAL PLAN

- Advanced Detectors (LIGO, VIRGO +) will initiate gravitational wave astronomy through the detection of the most luminous sources - compact binary mergers.
- Observation of low frequency gravitational wave with LISA/NGO will probe the role of super-massive black holes in galaxy formation and evolution
- Third Generation Detectors (ET and others) will expand detection horizons and provide new tools for extending knowledge of fundamental physics, cosmology and relativistic astrophysics.





- Important Timescales