LNF – OAR meeting, 16 April 2014

The Quest for Gravitational Waves a global strategy

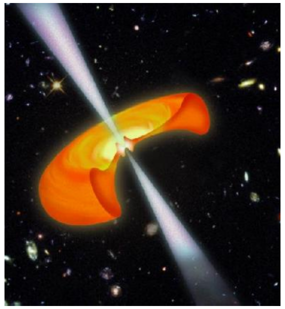
Eugenio Coccia
U. of Rome "Tor Vergata"
and INFN Gran Sasso Science Institute
Chair, Gravitational Wave International Committee

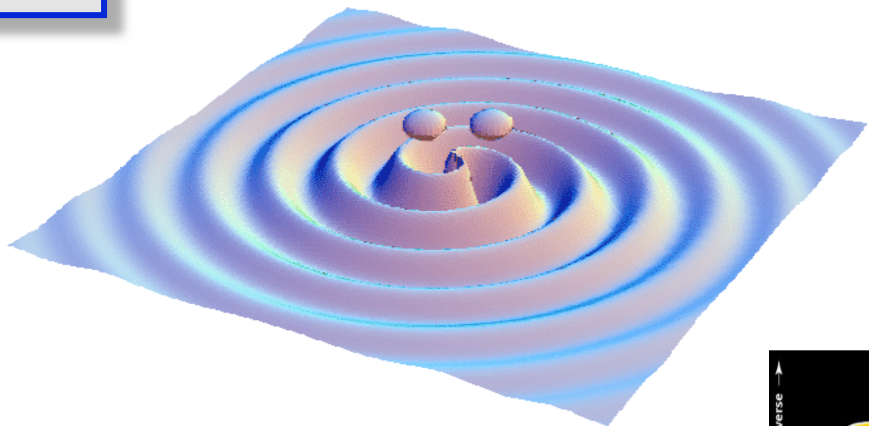
THE QUEST FOR GW: OBJECTIVES

FIRST DETECTION
test Einstein prediction

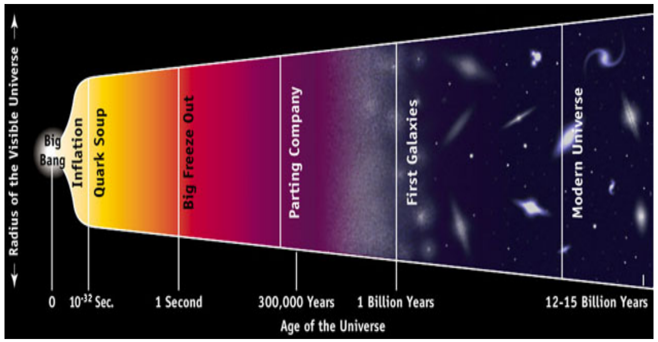
$$\mathbf{G} = \frac{8\pi G}{c^4}\mathbf{T}$$

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



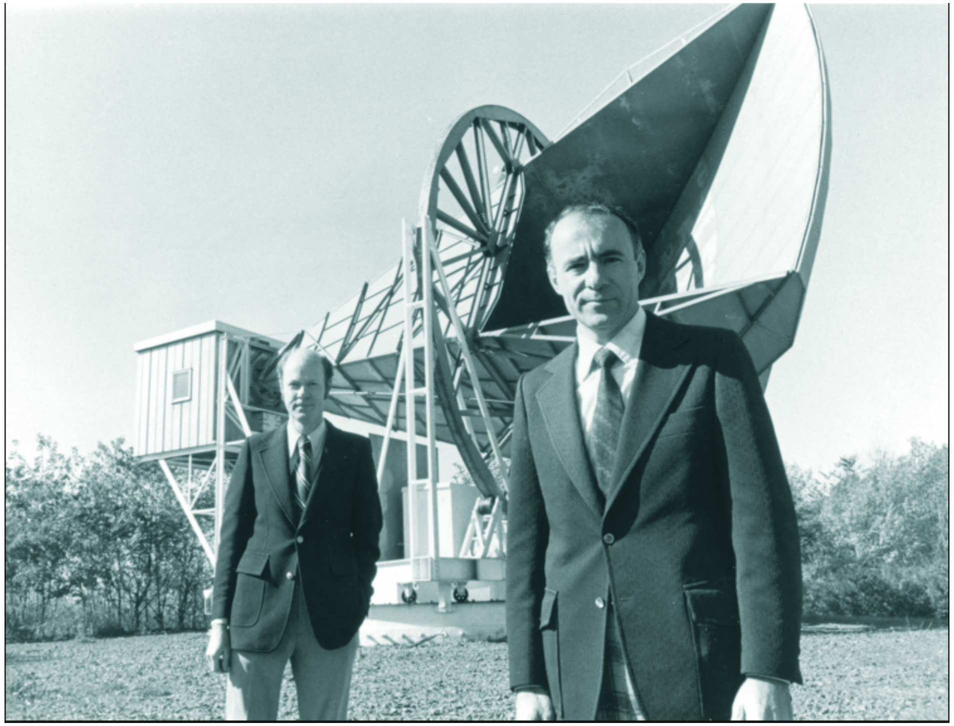


COSMOLOGY
the Planck time:
look as back in time as theorist can conceive



During the sixties Amaldi tried to push the Italian physicists in the direction of new researches in the birth phase:

Infrared Background radiation and Gravitational Waves (after Penzias & Wilson and Weber's experiments).



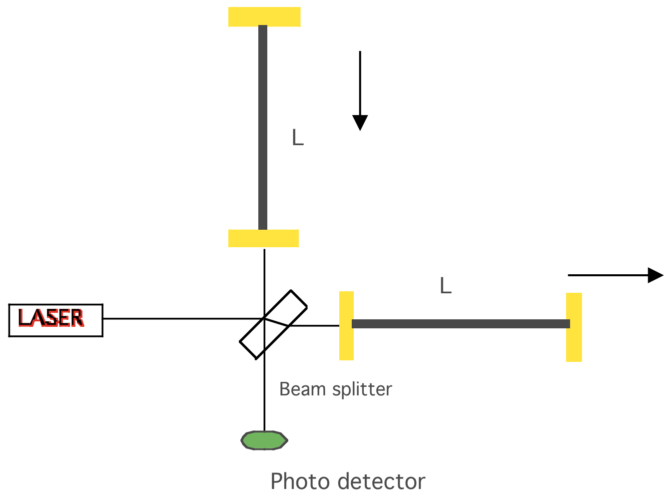
Guido Pizzella was Amaldi's assistant and wanted to change its activity from space research (he worked with Van Allen in USA) to a more fundamental field. His decision was: Gravitational Waves (Francesco Melchiorri later choose the infrared background).

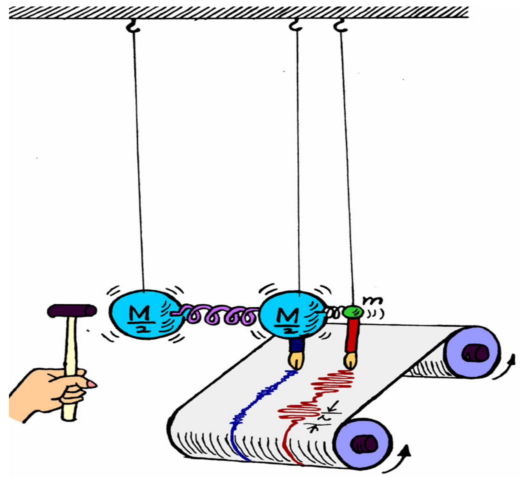
In the words of Guido:

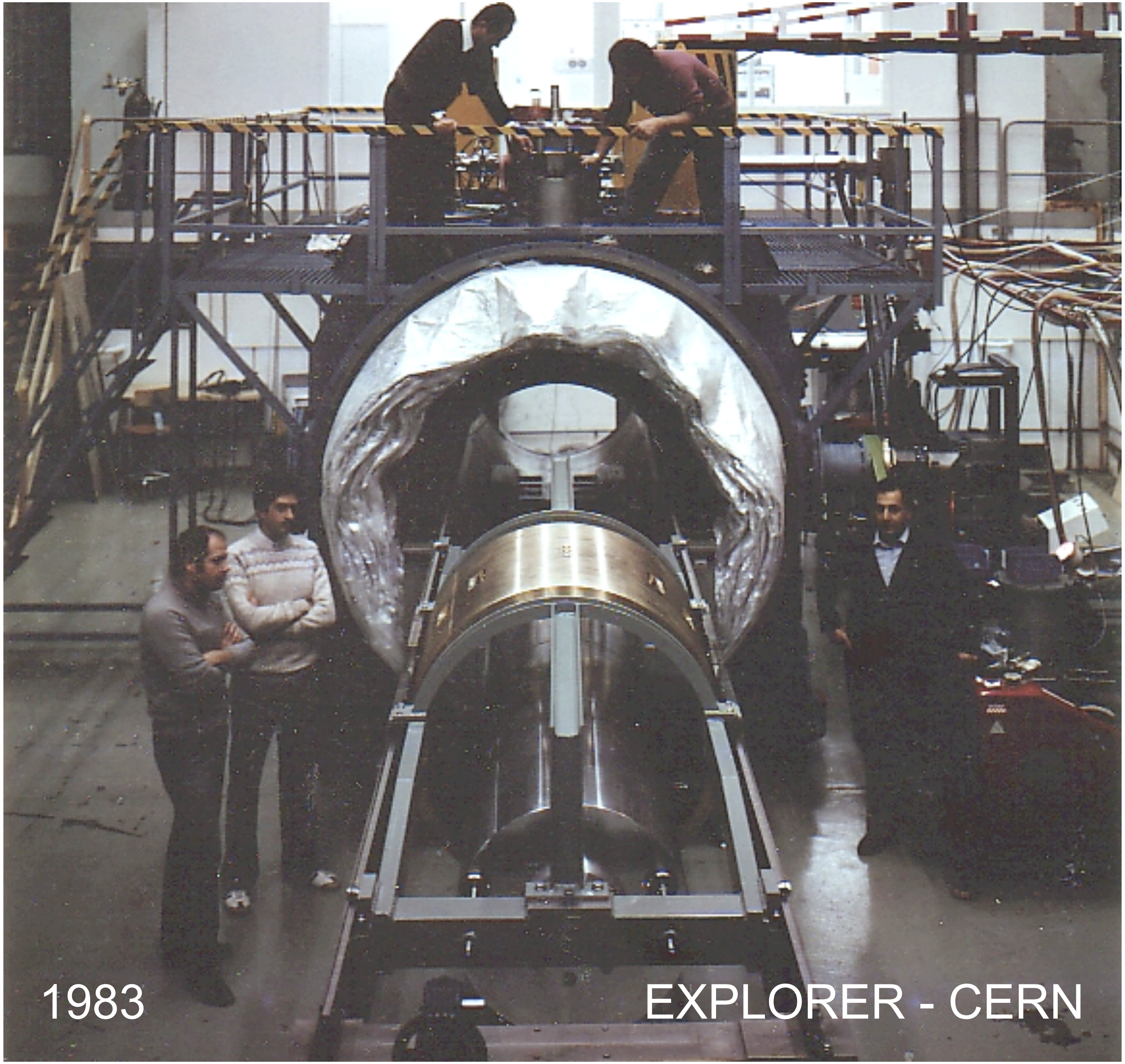
"On September 3rd 1970, I said to Amaldi: *Professor, I want to make an experiment for the search of gravitational waves*. His eyes lighted and immediately we agreed to proceed. He informed me that Massimo Cerdonio was thinking how to use the SQUID, he was studying for biologic studies, for the search of GW."

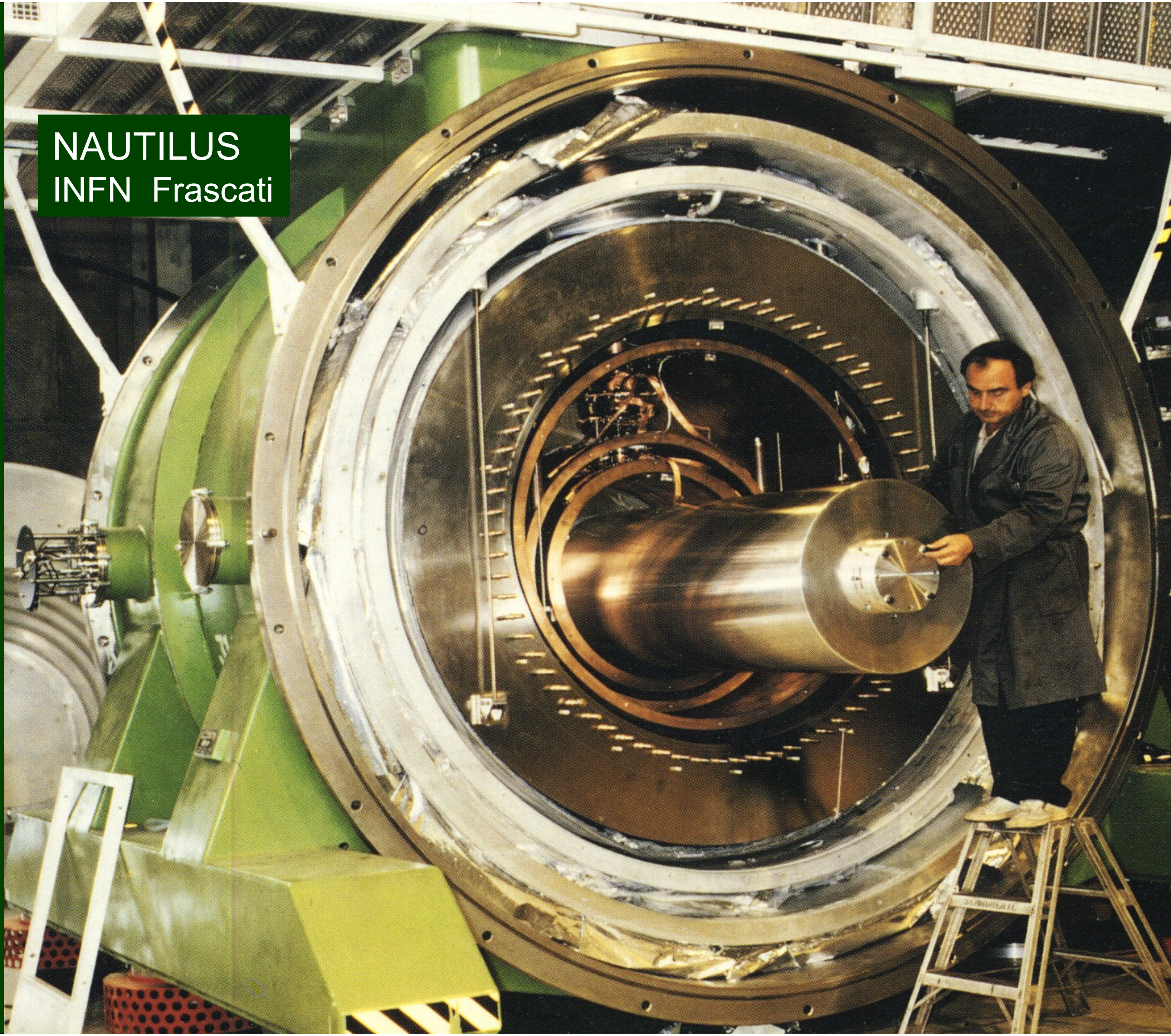
$$h = \frac{\Delta L}{L}$$

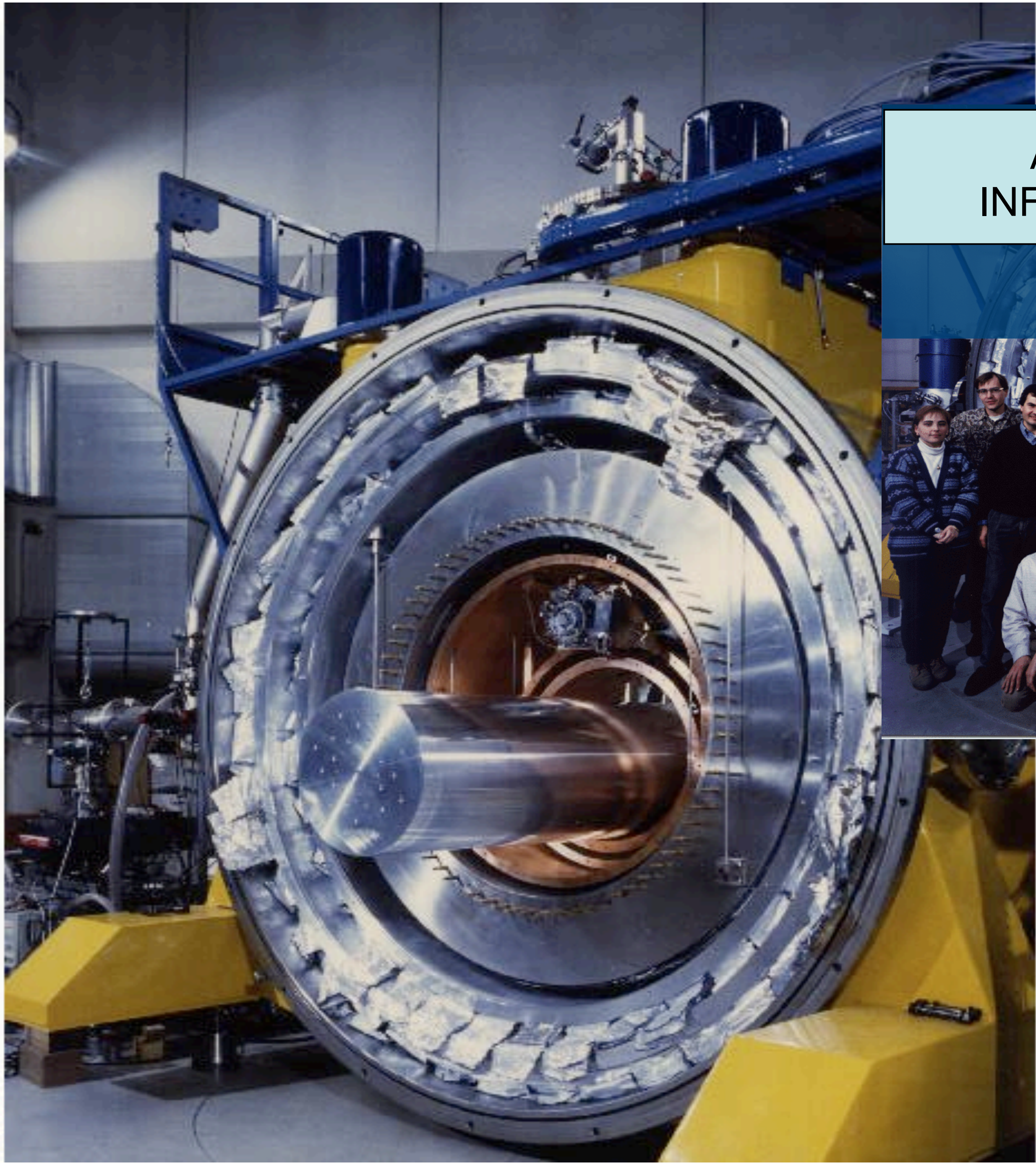
$$\ddot{x}(t) + \tau^{-1}\dot{x}(t) + \omega_0^2 x(t) = \frac{l}{2}\ddot{h}(t)$$






1983
EXPLORER - CERN

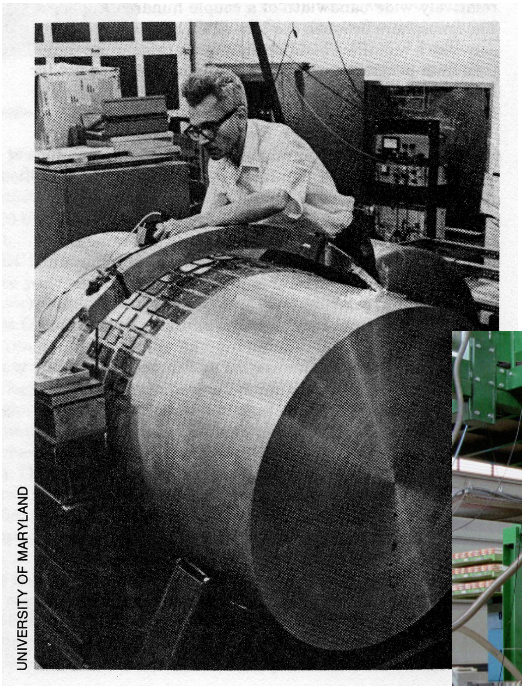

NAUTILUS
INFN Frascati



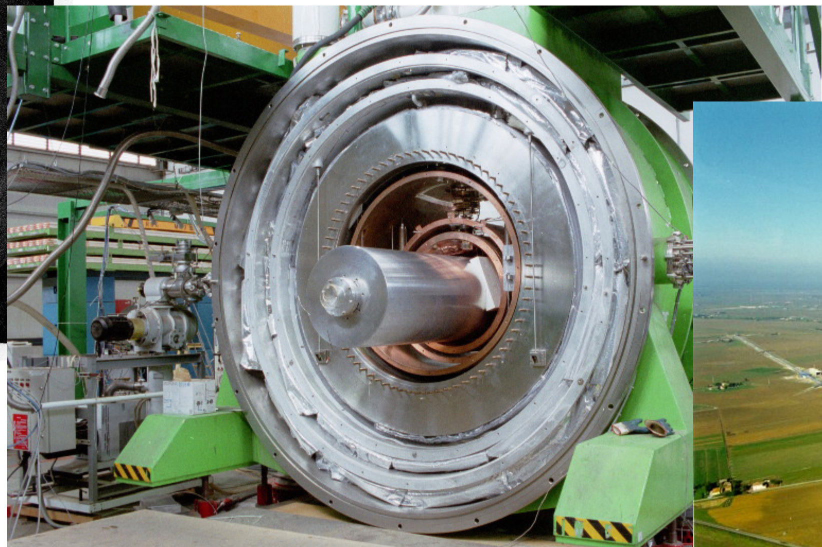

AURIGA
INFN Legnaro

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

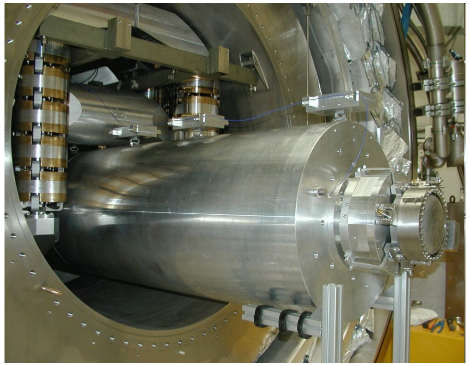


90’ : Cryogenic Bars

2005 - : Large Interferometers

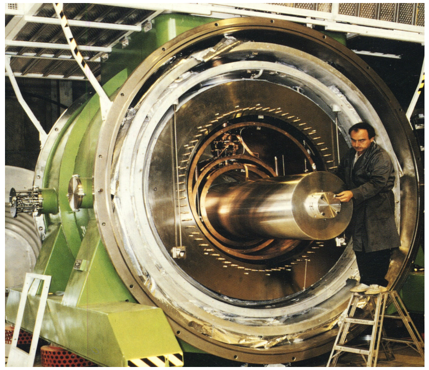
1997: GWIC was formed

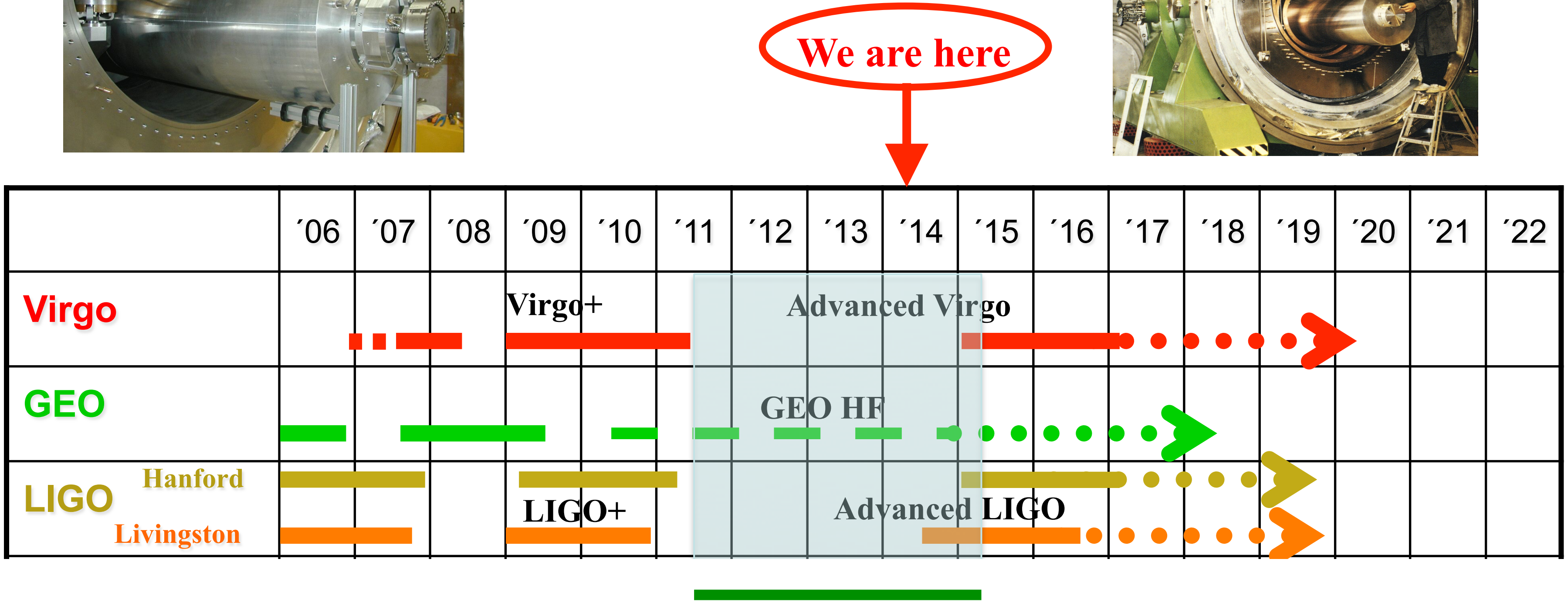
AURIGA - LNL



AUNA

NAUTILUS - LNF





Window of opportunity
for AURIGA and NAUTILUS

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.

Adalberto Giazotto

Alain Brillet

GWIC
Gravitational Wave International Committee

https://gwic.ligo.org/

- Home
- News
- GWIC Roadmap
- Thesis Prizes
- Statements
- Conferences
- GWIC meetings
- Reports to IUPAP
- Simulation Programs
- GWIC By-laws
- Members
- Related Links

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.

More about GWIC:

GWIC - Ten Years on (PDF) reprinted from Matters of Gravity (Fall 2007),
the newsletter of the Topical Group on Gravitation of the American Physical Society.

- GWIC is now an IUPAP Working group (WG11)
- Progresses towards LIGO-India
- GWIC thesis Prize named after Stefano Braccini
- EC elected GWIC Chair for another two-years mandate

Member Projects and Representatives

Chair

- Eugenio Coccia, University of Rome "Tor Vergata" (GWIC, 2000--, Chair 2011--)

ACIGA

- Peter Veitch, University of Adelaide, 2013--

AURIGA

- Massimo Cerdonio, University of Padua and INFN, 1997--

Einstein Telescope

- Michele Punturo, INFN-Perugia, 2009--

European Pulsar Timing Array (EPTA)

- Michael Kramer, Jodrell Bank Centre for Astrophysics (University of Manchester), 2009--

GEO 600

- Karsten Danzmann, Albert-Einstein-Institut fur Gravitationsphysik and University of Hannover, 1
- Sheila Rowan, University of Glasgow, 2009--

IndIGO

- Bala Iyer, Raman Research Institute, 2011--

KAGRA (formerly LCGT)

- Yoshio Saito, KEK, 2013--
- Takaaki Kajita, Institute for Cosmic Ray Research, University of Tokyo, 2011--

LIGO, including the LSC

- Dave Reitze, California Institute of Technology and University of Florida, 2007--
- Gabriela Gonzalez, Louisiana State University, 2011--

LISA Community

- Neil Cornish, Montana State University, 2012--
- Bernard Schutz, Albert-Einstein-Institut fur Gravitationphysik, 2001--
- Robin Stebbins, Goddard Space Flight Center, 2001--
- Stefano Vitale, University of Trento, 2001--

NANOGrav

- Frederick Jenet, University of Texas, Brownsville, 2013--

NAUTILUS

- Eugenio Coccia, University of Rome "Tor Vergata", 2000--

Parkes Pulsar Timing Array (PPTA)

- George Hobbs, Australia Telescope National Facility (ATNF), 2013--

Spherical Acoustic Detectors

- Odylio D. Aguiar, Instituto Nacional de Pesquisas Espaciais, Brazil, 2011--

Virgo

- Francesco Fidecaro, University of Pisa, 2007--
- Jean-Yves Vinet, Observatoire de la Côte d'Azur, 2011--

Theory Community

- Clifford Will, University of Florida, 2000--

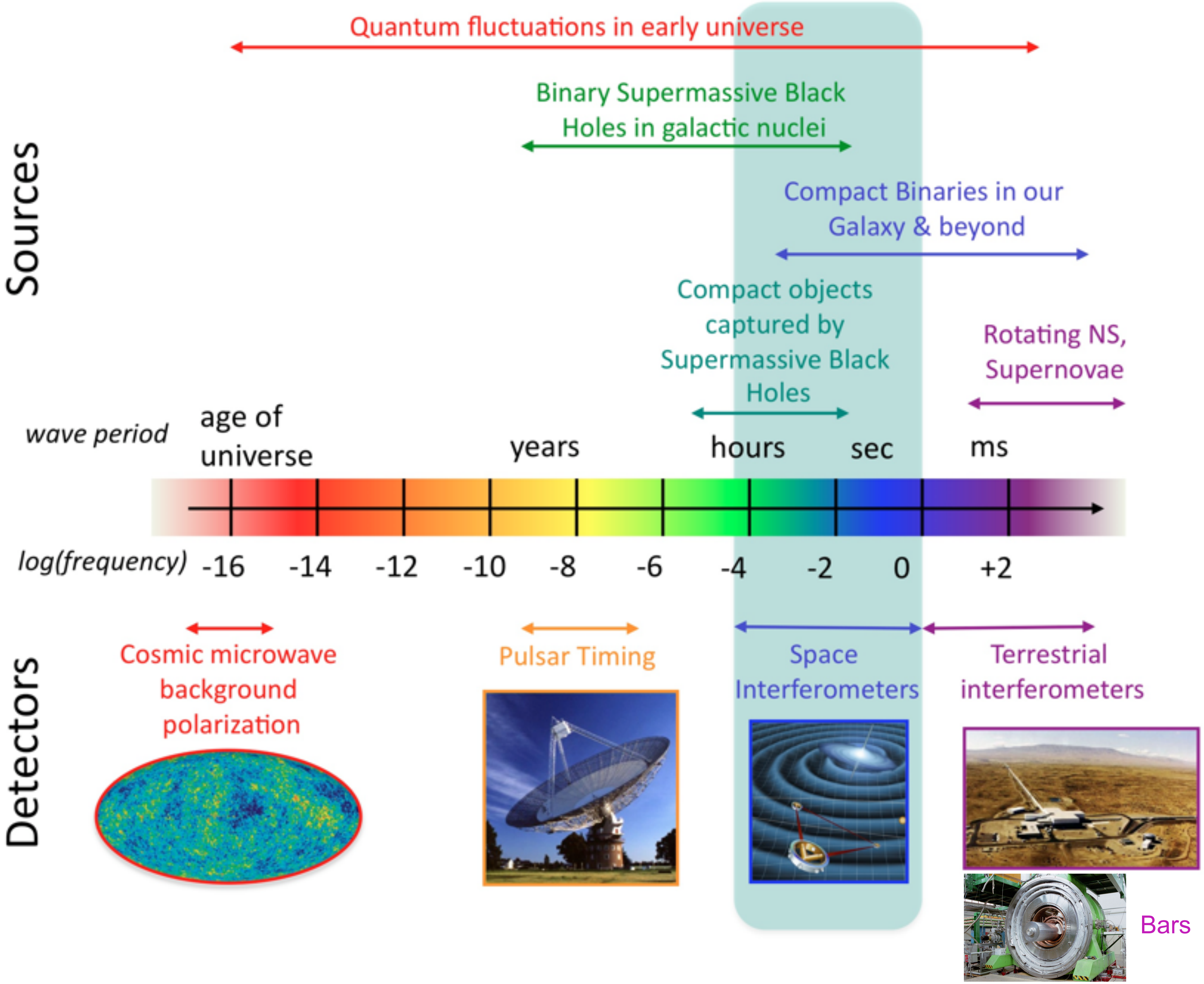
IUPAP Affiliate Commission AC2 (International Commission on General Relativity and Gravitation)

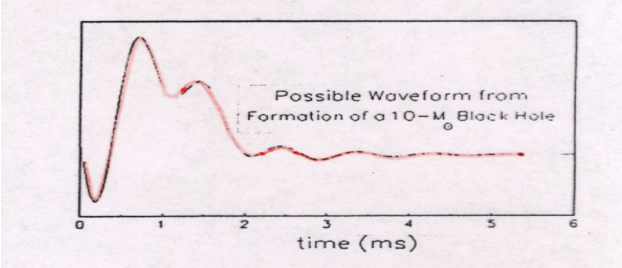
- Beverly Berger, 2013--

Executive Secretary

- Stan Whitcomb, California Institute of Technology, 2007--

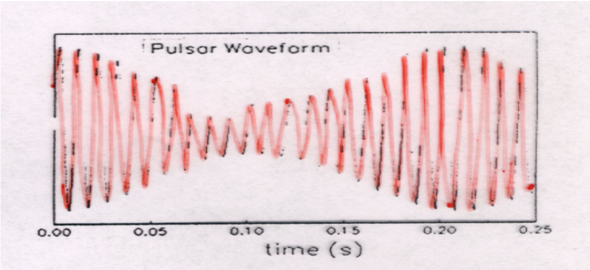
The Gravitational Wave Spectrum





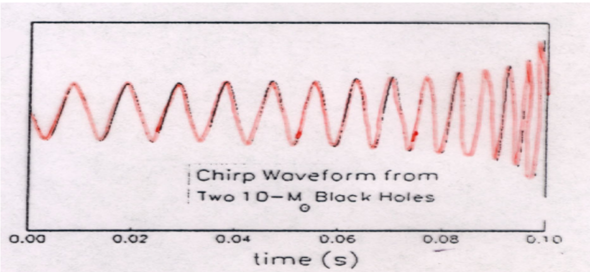
SUPERNOVAE.
If the collapse core is non-symmetrical, the event can give off considerable radiation in a millisecond timescale.

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



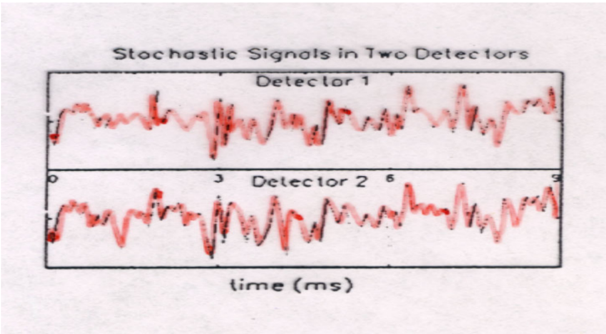
SPINNING NEUTRON STARS.
Pulsars are rapidly spinning neutron stars. If they have an irregular shape, they give off a signal at constant frequency (prec./Dpl.)

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

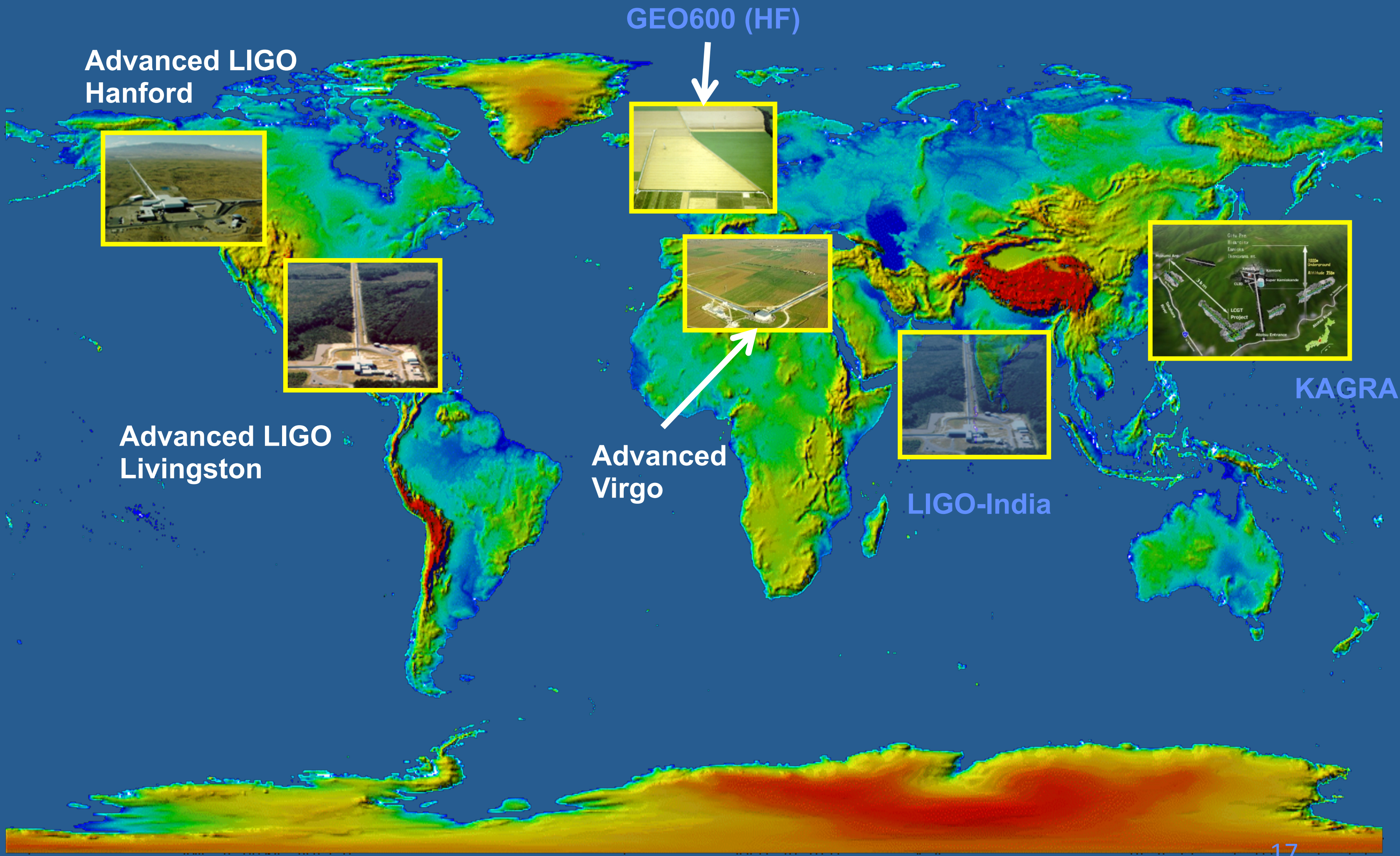
Information
Masses of the objects
BH identification
Distance to the system
Hubble constant
Test of strong-field general relativity



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

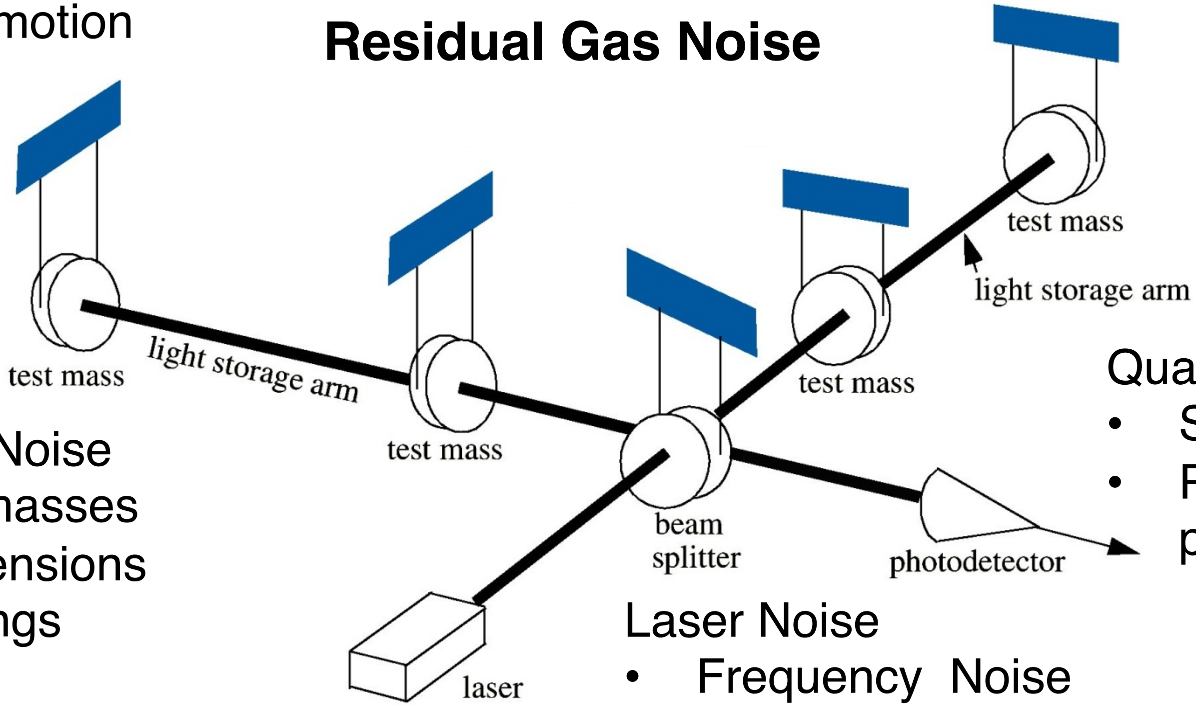
The Advanced GW Detector Network



Limits to Sensitivity

Vibrational Noise
- Ground motion
- Acoustic

Residual Gas Noise

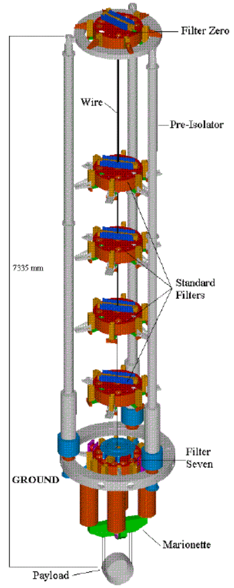


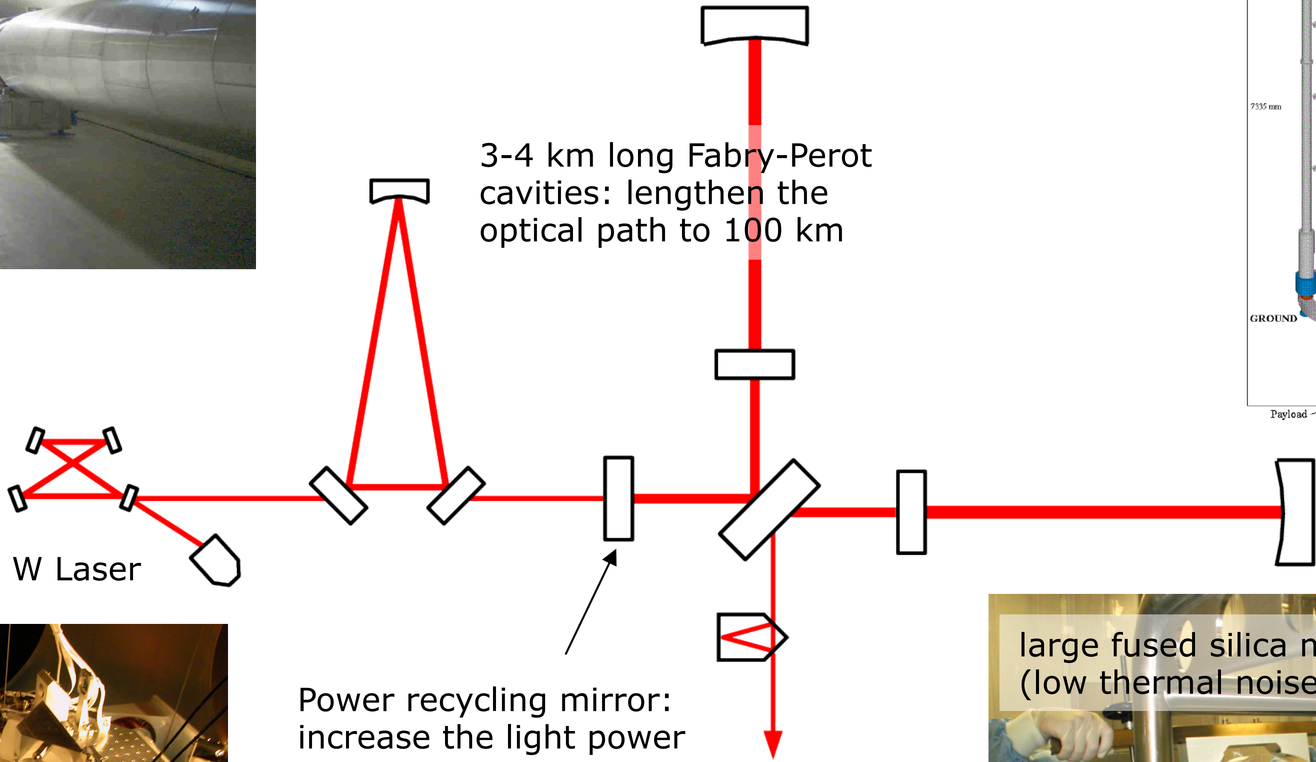
Thermal Noise
- Test masses
- Suspensions
- Coatings

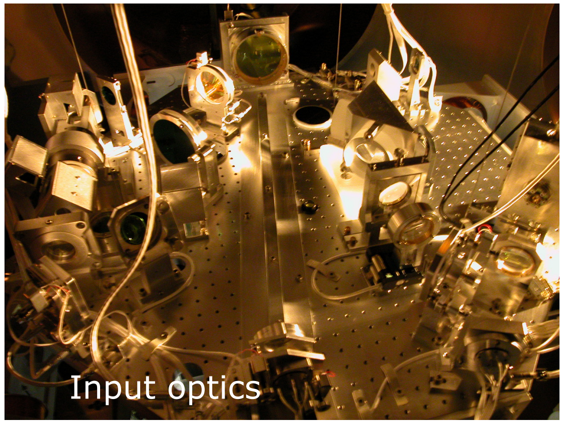
Quantum Noise
- Shot Noise
- Radiation pressure Noise

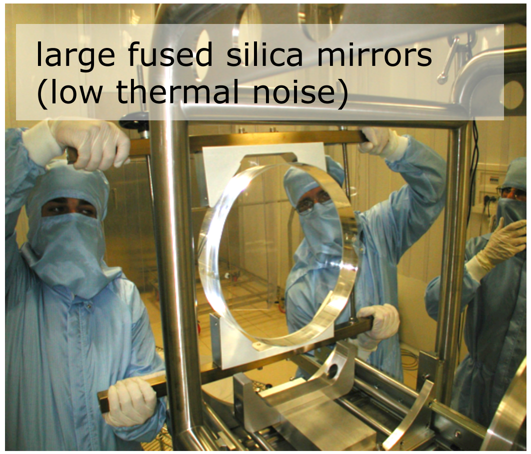
Laser Noise
- Frequency Noise
- Intensity Noise

A real detector scheme



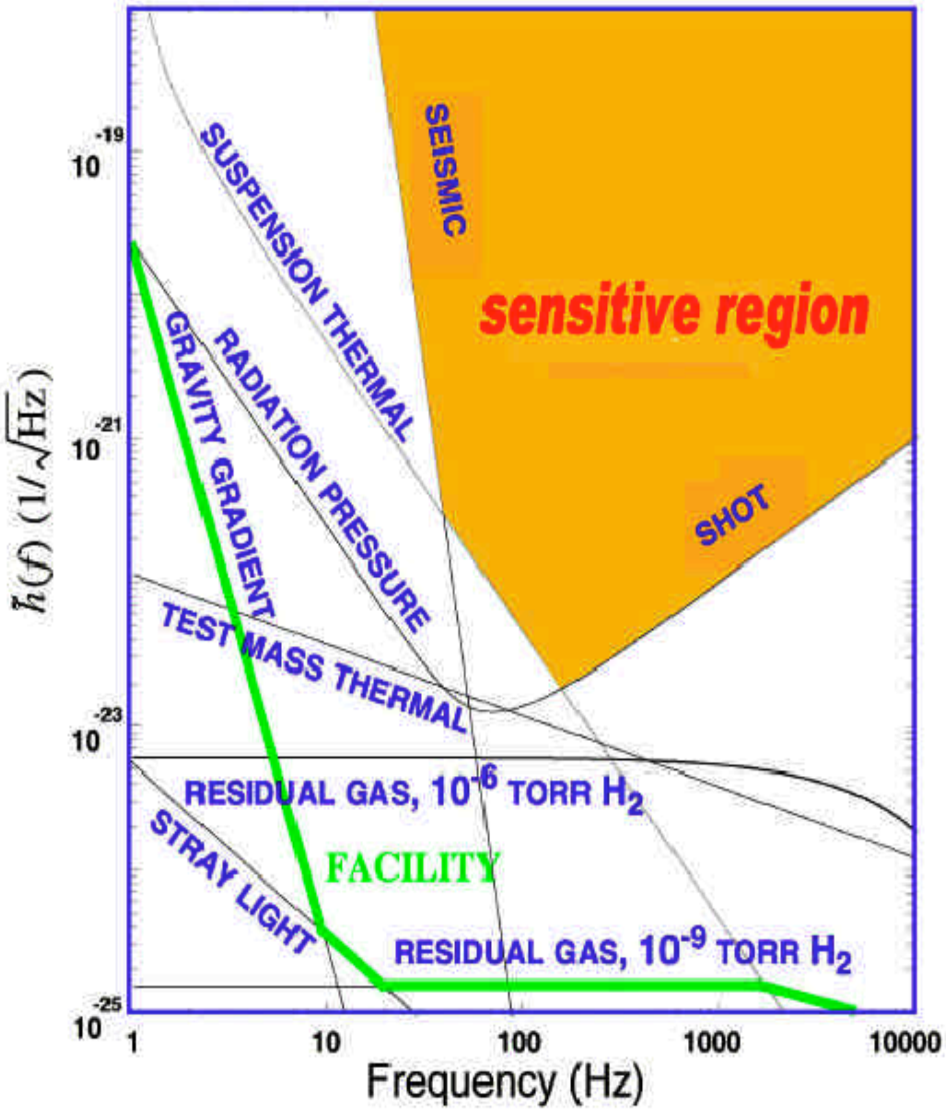


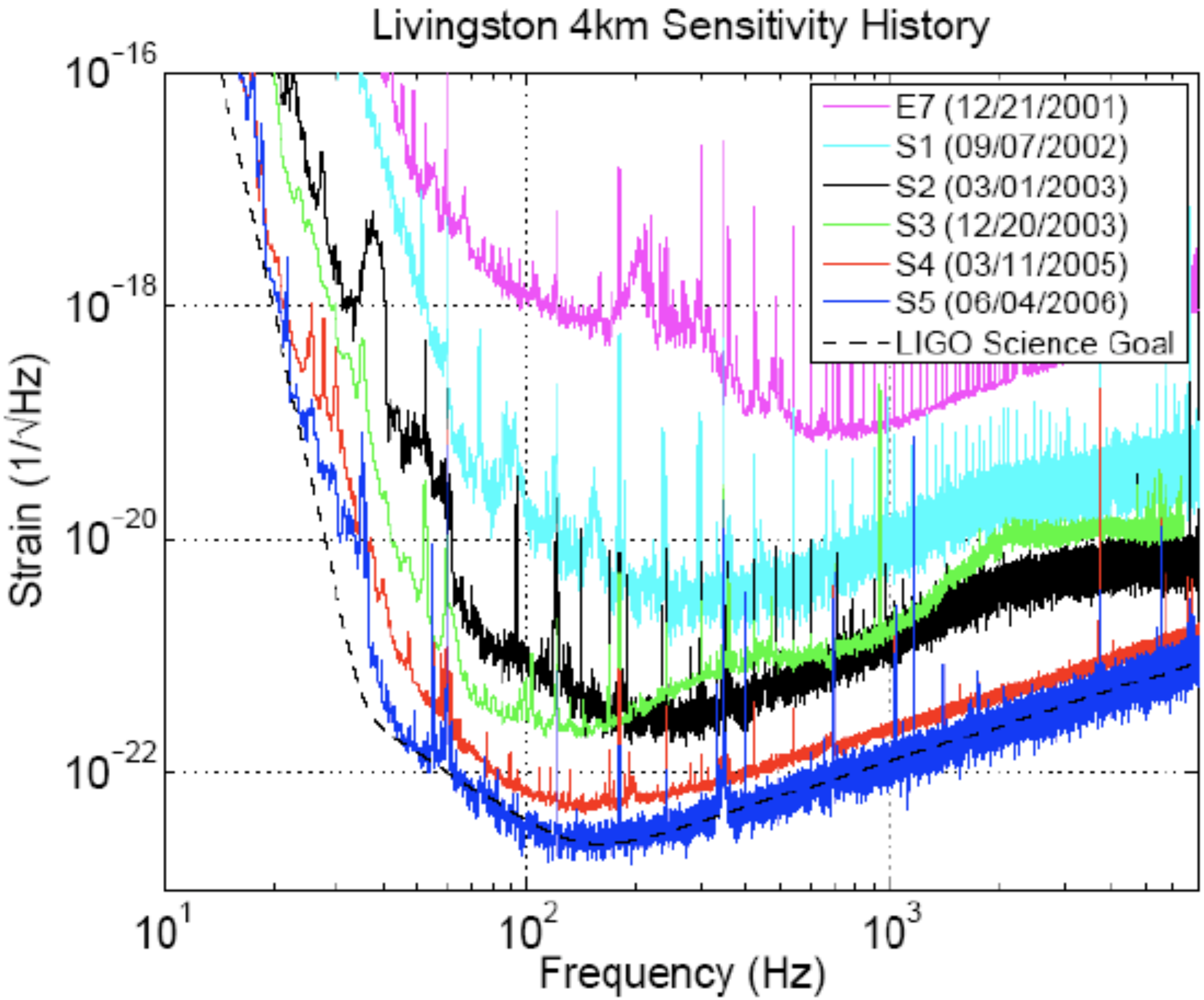




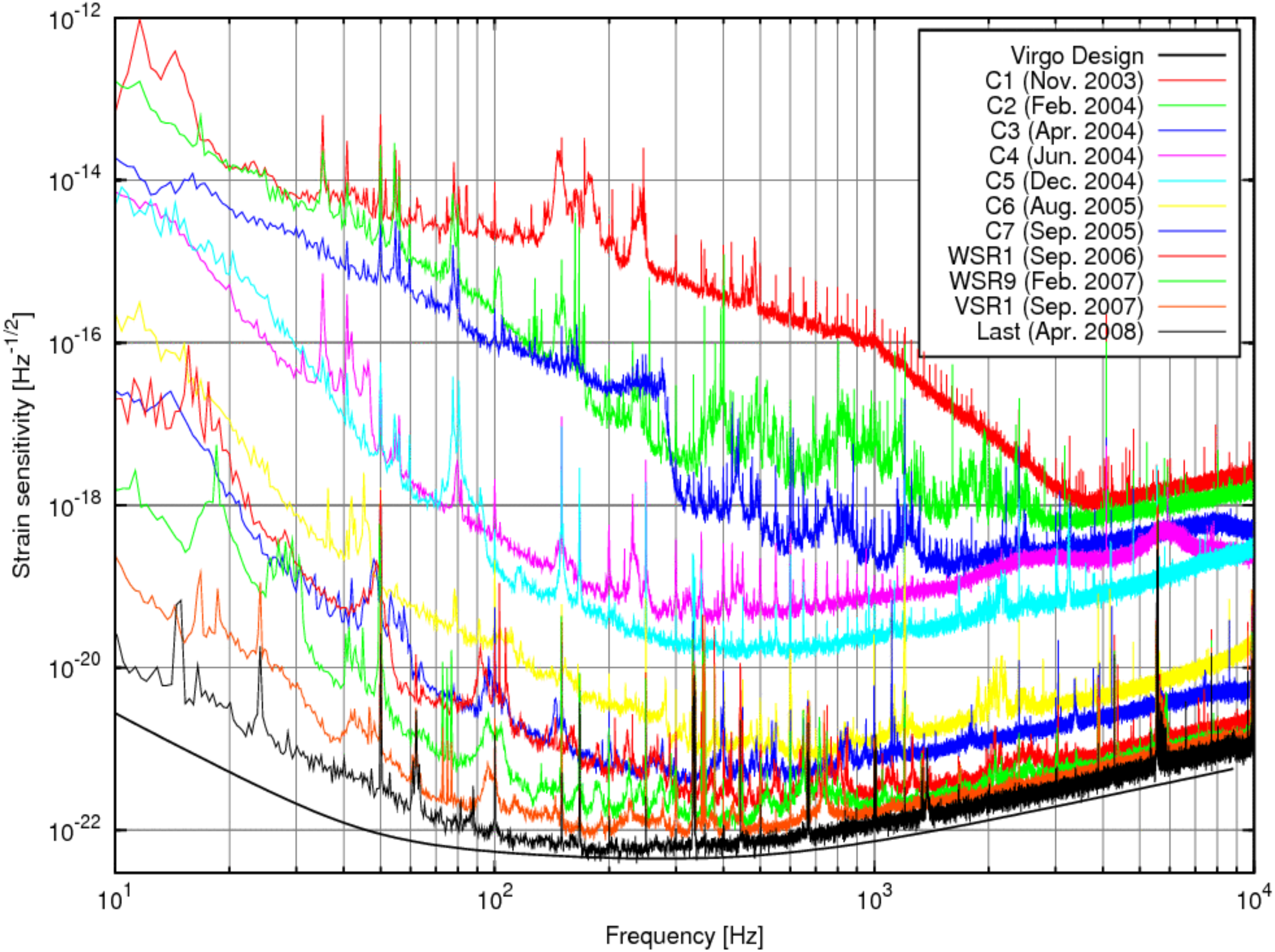
- Interferometry is limited by three fundamental noise sources
  - **seismic noise** at the lowest frequencies
  - **thermal noise** at intermediate frequencies
  - **shot noise** at high frequencies

- 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)
10^-16
10^-18
10^-20
10^-22
10^1
10^2
10^3



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 ms 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

Constraints on cosmic (super)strings from the LIGO-Virgo gravitational-wave detectors
e-Print: **arXiv:1310.2384** **[gr-qc] |**

First Searches for Optical Counterparts to Gravitational-wave Candidate Events
e-Print: **arXiv:1310.2314**

A directed search for continuous Gravitational Waves from the Galactic Center
e-Print: **arXiv:1309.6221** **[gr-qc] |**

A search for long-lived gravitational-wave transients coincident with long gamma-ray bursts
e-Print: **arXiv:1309.6160** **[astro-ph.HE]**

Gravitational waves from known pulsars: results from the initial detector era
e-Print: **arXiv:1309.4027** **[astro-ph.HE]**

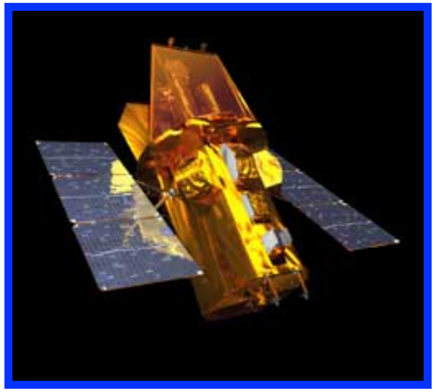
Prospects for Localization of GW Transients by the Advanced LIGO and Advanced Virgo Observatories
e-Print: **arXiv:1304.0670** **[gr-qc]**

Parameter estimation for compact binary coalescence signals with the first generation GW detector network
LIGO and Virgo Collaborations (J. Aasi (Caltech) *et al.*). Apr 5, 2013. 23 pp.
Phys.Rev. D88 (2013) 062001

Search for GW from Binary Black Hole Inspiral, Merger and Ringdown in LIGO-Virgo Data from 2009-2010
Phys.Rev. D87 (2013) 022002

Einstein@Home all-sky search for periodic gravitational waves in LIGO S5 data
Phys.Rev. D87 (2013) 4, 042001

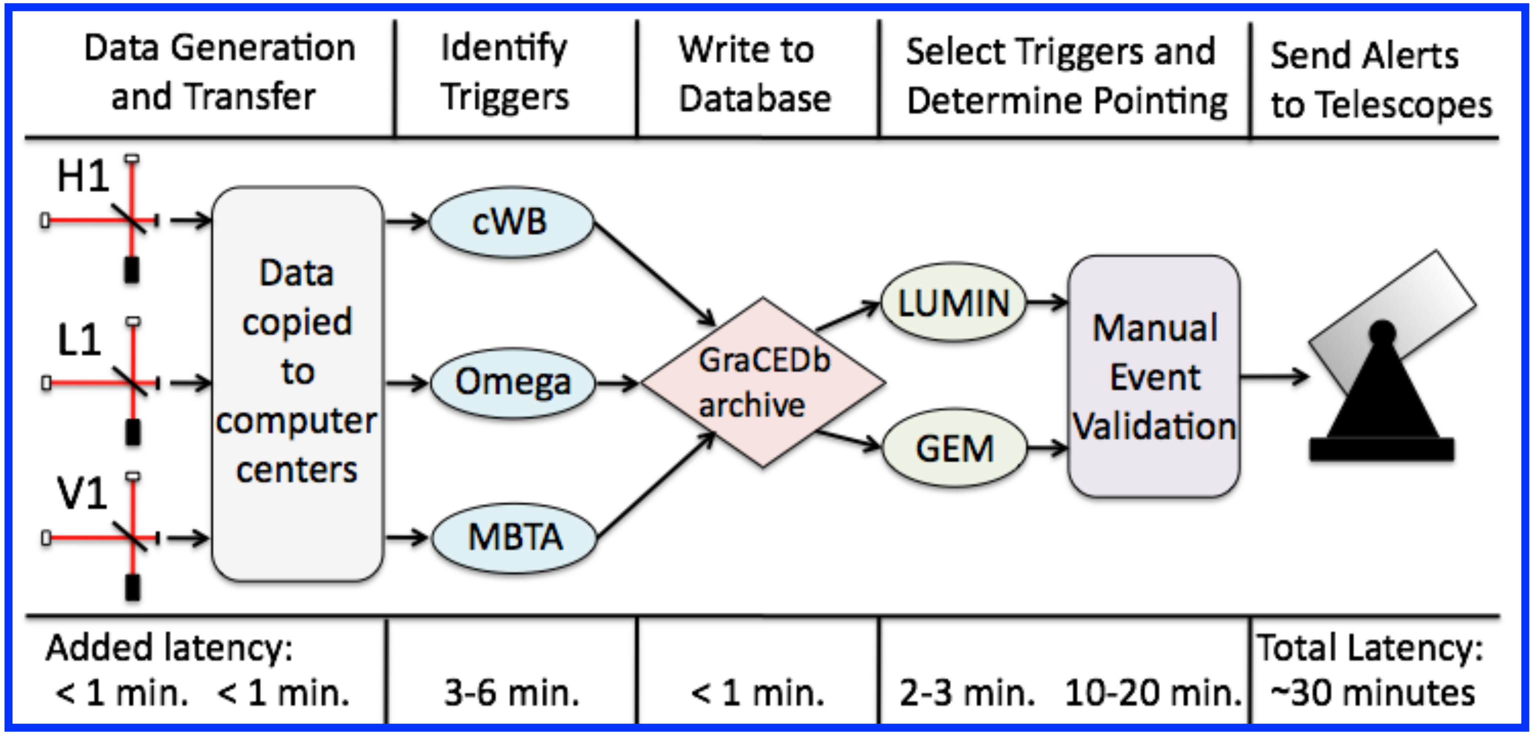
Multimessenger Astronomy with Gravitational Waves



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

LSC VIRGO

Low Latency EM Follow-Up Program



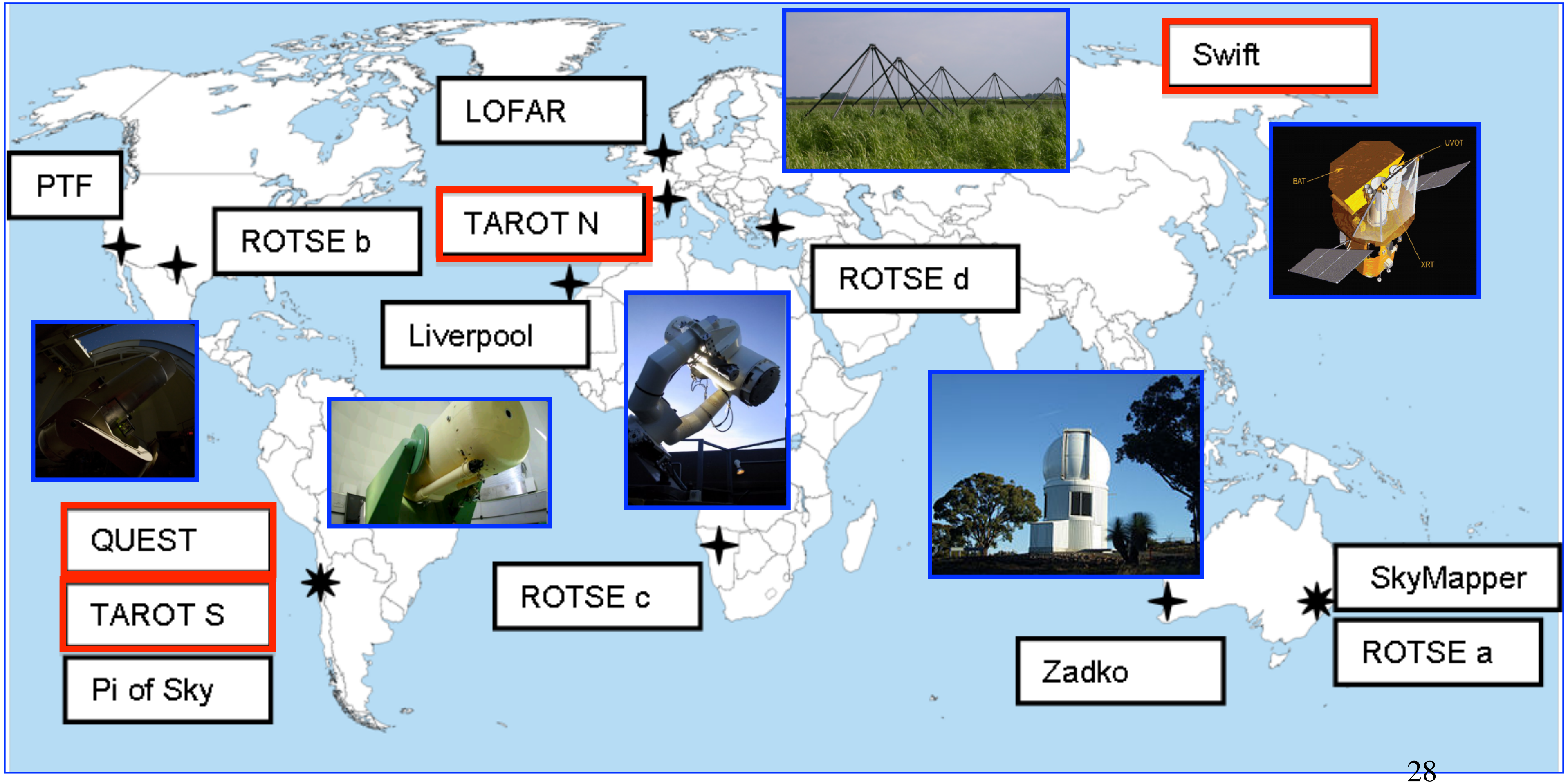
- Subthreshold candidate GW events sent to partner ~meter class telescopes network
- Target alert rate of 1 per week
- Ran during parts of most recent science runs Dec 2009-Jan 2010 and Sep to Oct 2010
- Images obtained for 8 different events

Astronomy & Astrophysics 539 (2012)A124

Astronomy & Astrophysics 541 (2012)A155

Telescope Network

Used in winter and autumn run   autumn run only



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

Det

Neutrinos from Supernovae as a Trigger for Gravitational Wave Search

G. Pagliaroli,[1,2] F. Vissani,[1] E. Coccia,[1,3] and W. Fulgione[4,5]
[1] *INFN, Laboratori Nazionali del Gran Sasso, Assergi (AQ), Italy*
[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.

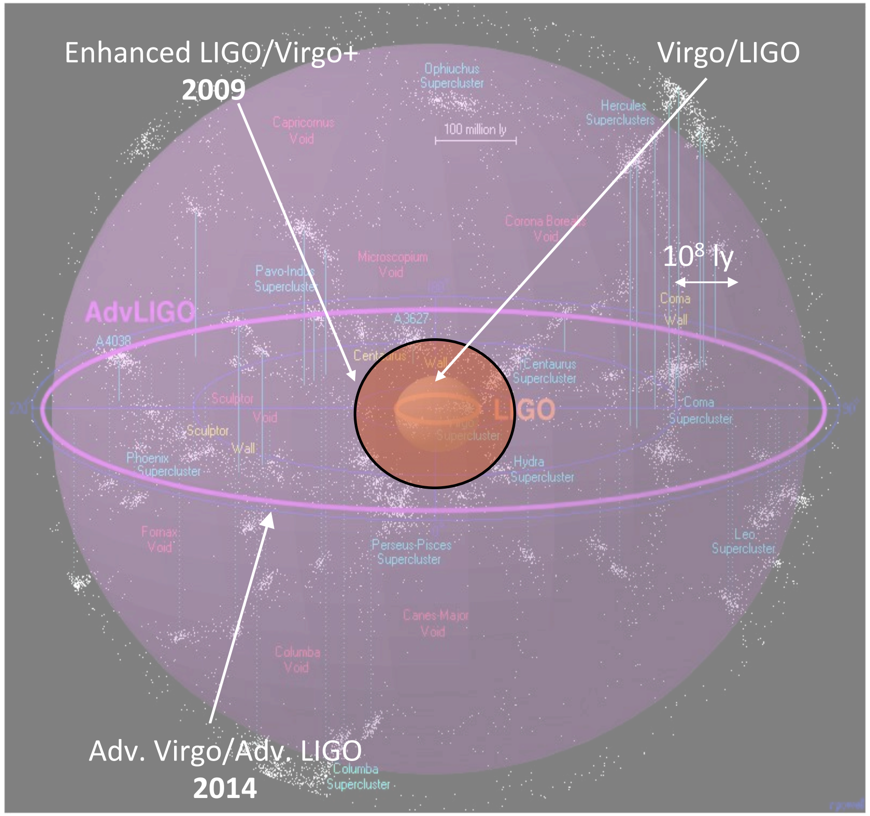
2nd GENERATION:
DISCOVERY AND ASTRONOMY

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!

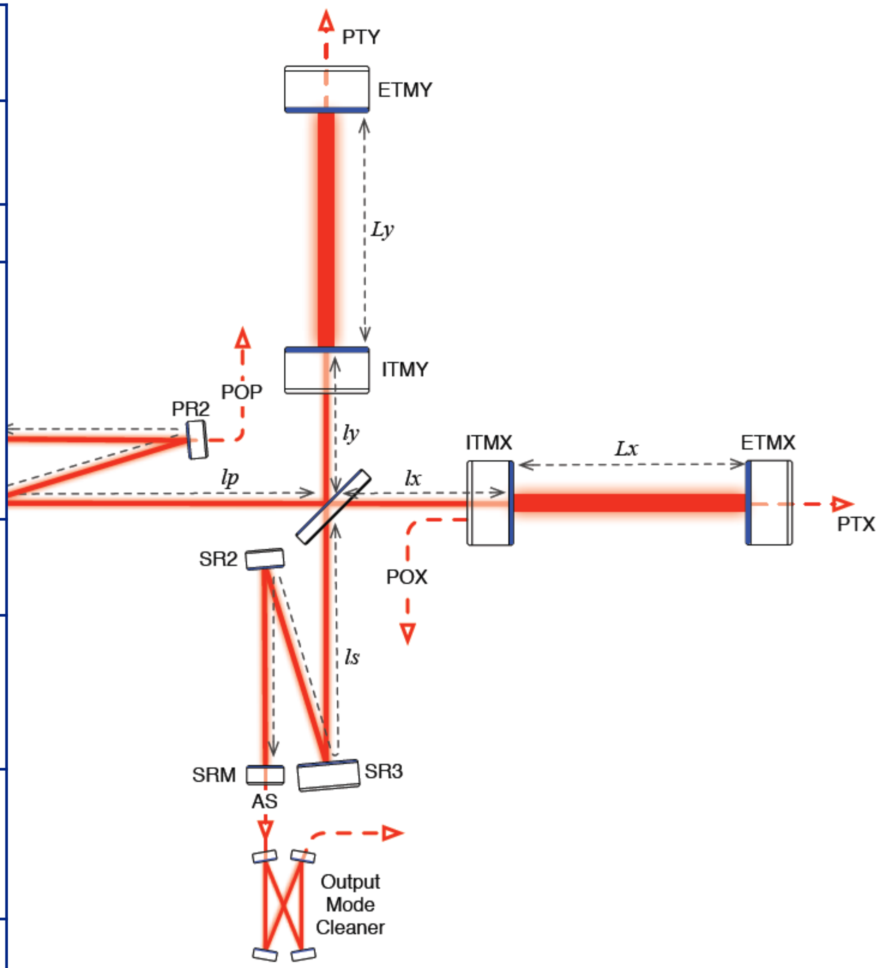


Credit: R.Powell, B.Berger

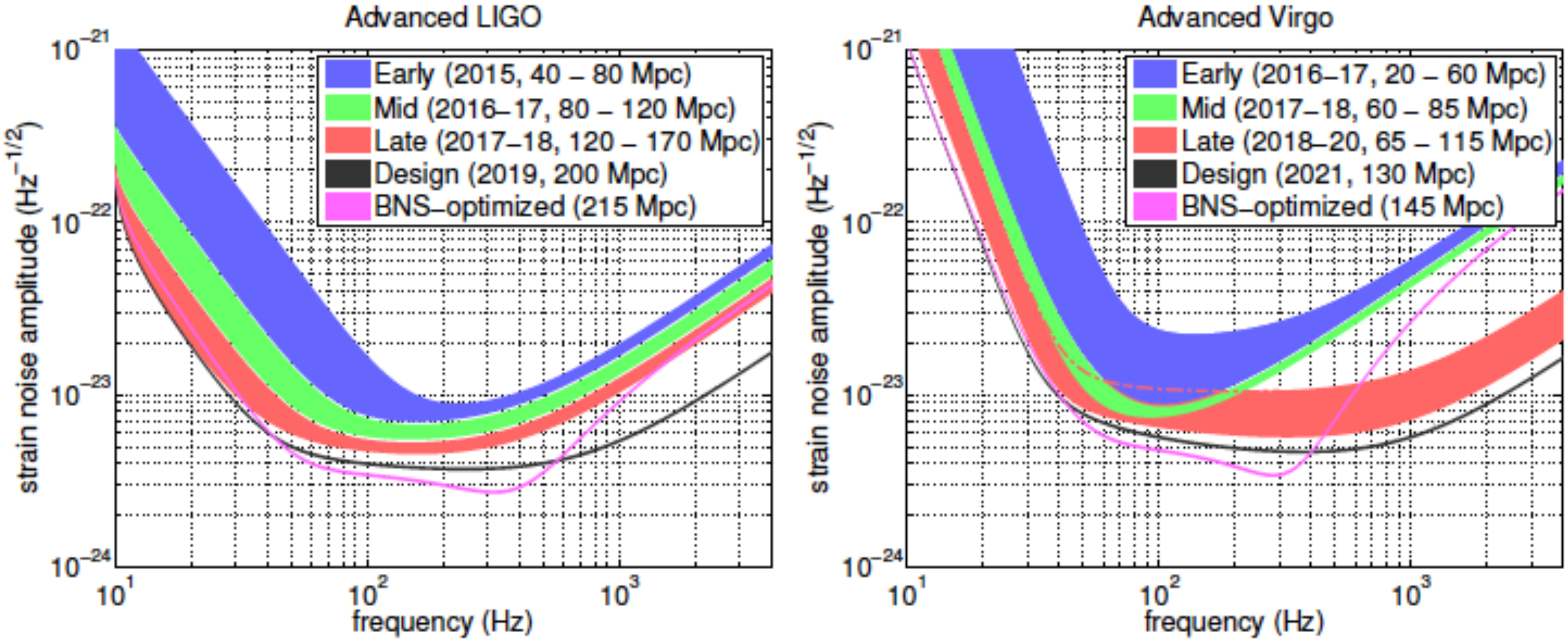
Advanced LIGO/Virgo overview

What is Advanced?

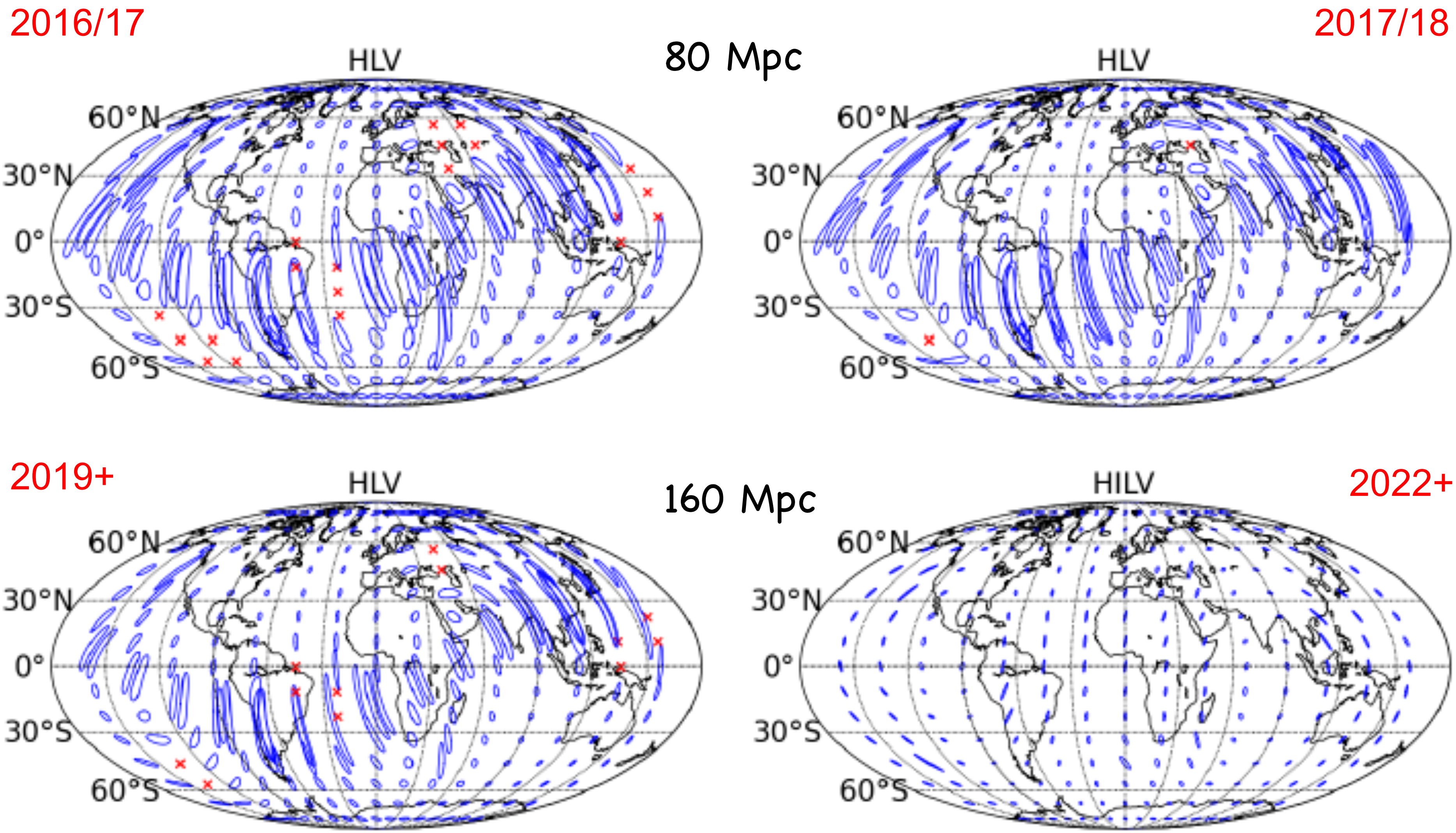
Parameter	Initial LIGO/Virgo	Advanced LIGO/ Virgo
Input Laser Power	10 W (10 kW arm)	180 W (>700 kW arm)
Mirror Mass	10 kg/20kg	40 kg
Interferometer Topology	Power-recycled Fabry-Perot arm cavity Michelson	Dual-recycled Fabry-Perot arm cavity Michelson (LIGO stable recycling cavities)
GW Readout Method	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



Plausible scenario
for the operation of the LIGO-Virgo network over the next decade

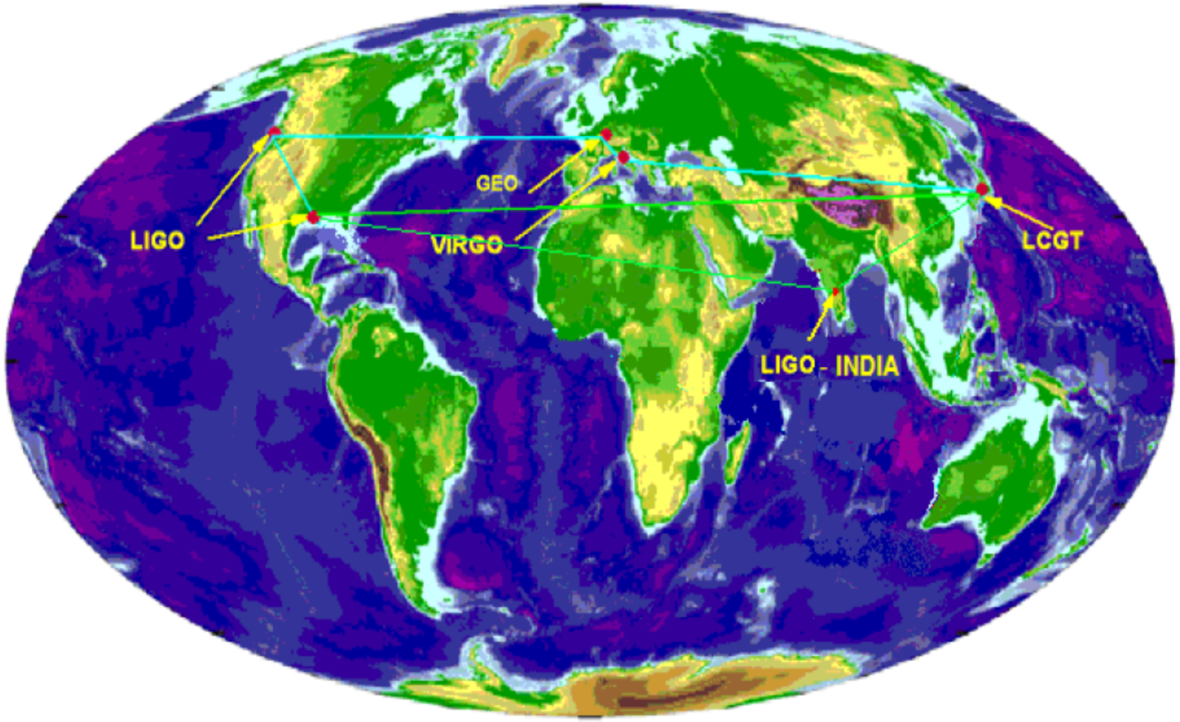


Epoch	Estimated Run Duration	$E_{\mathrm{GW}} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48



Localization expected for a BNS system

The ellipses show 90% confidence localization areas, and the red crosses show regions of the sky where the signal would not be condently detected.

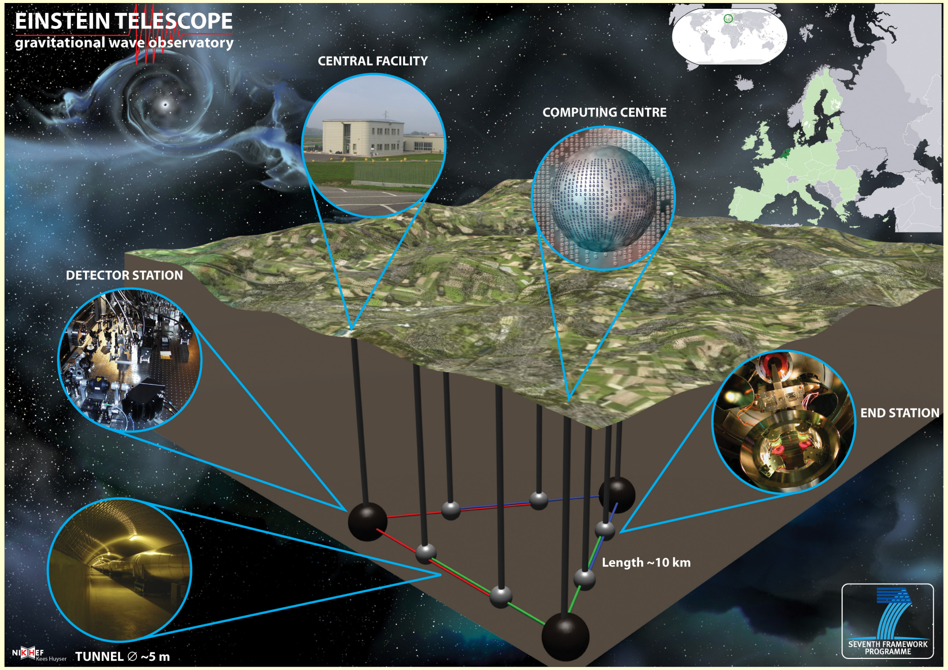


- We are on the threshold of a new era of gravitational wave astrophysics
- First generation detectors have broken new ground in optical sensitivity
  - Initial detectors have proven technique
- Second generation detectors are starting installation
  - Will expand the “Science” (astrophysics) by factor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

8 Recommendations to GWIC to guide the development of the field

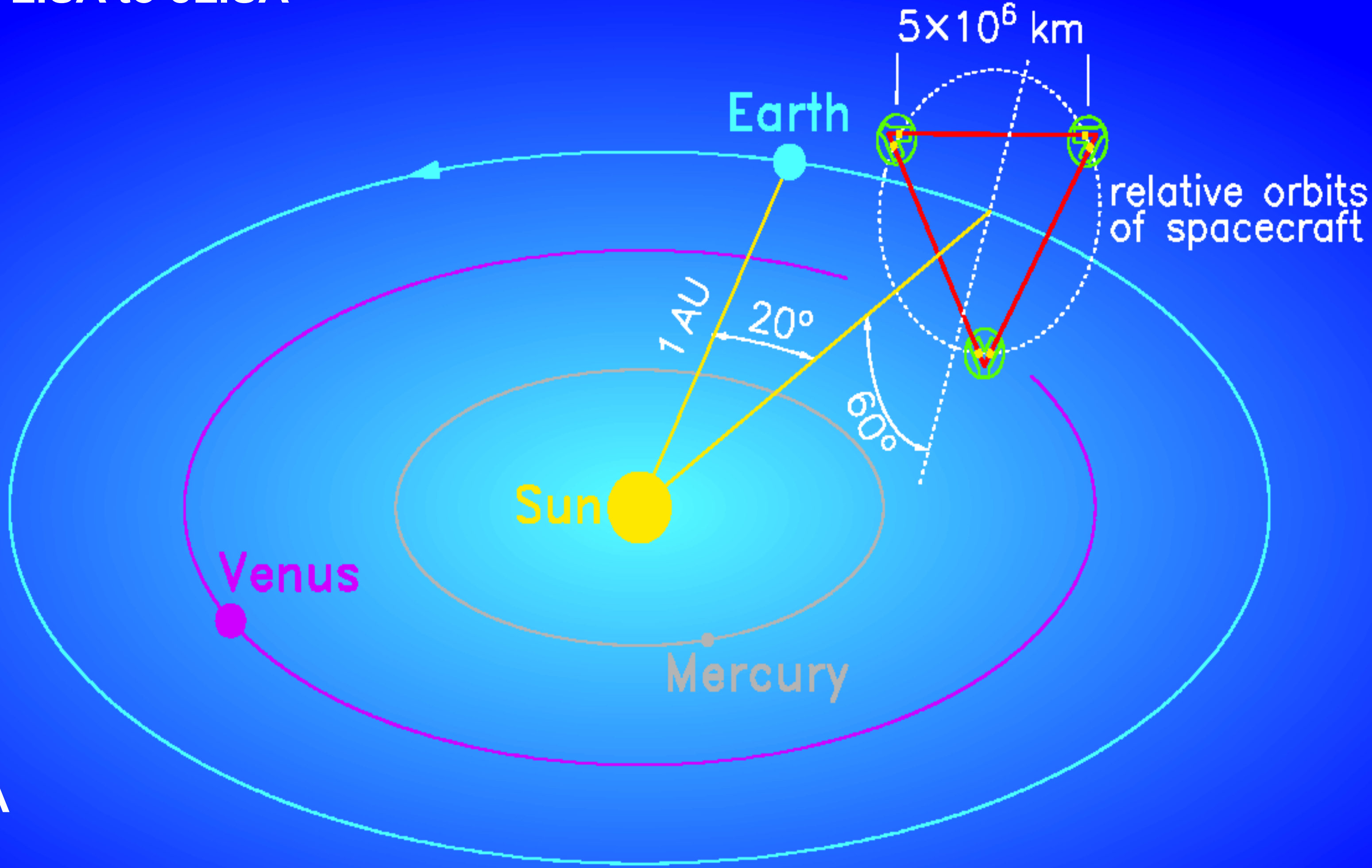
8.5 Toward a third-generation global network

"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.

From LISA to eLISA



eLISA

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

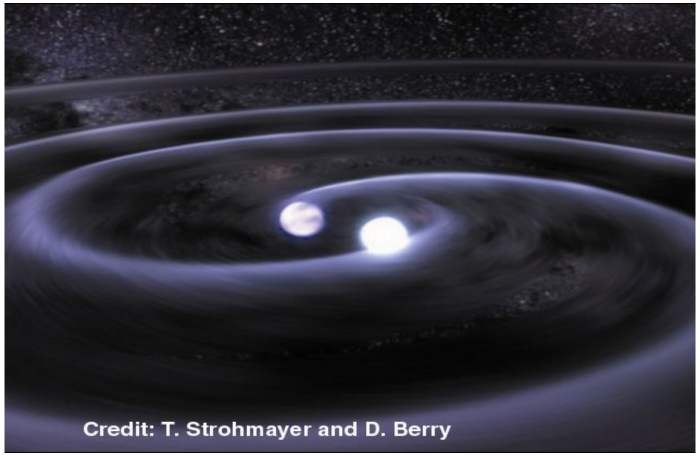
2030

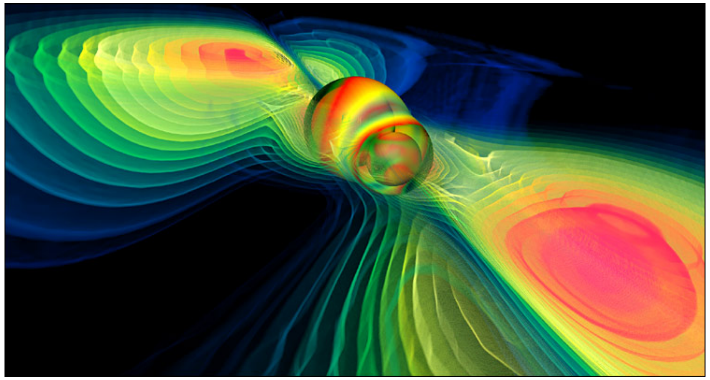
THE GLOBAL PLAN

- Advanced Detectors (LIGO, VIRGO +) will initiate gravitational wave astronomy through the detection of the most luminous sources - compact binary mergers.

- Third Generation Detectors (ET and others) will expand detection horizons and provide new tools for extending knowledge of fundamental physics, cosmology and relativistic astrophysics.

- Observation of low frequency gravitational wave with LISA/NGO will probe the role of super-massive black holes in galaxy formation and evolution





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