Gravitational Wave detection:

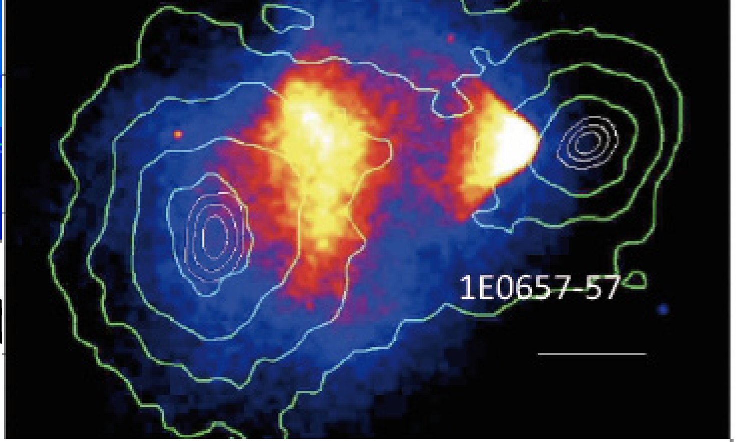
… from 1st generation interferometers to ET

Michele Punturo

INFN Perugia and EGO

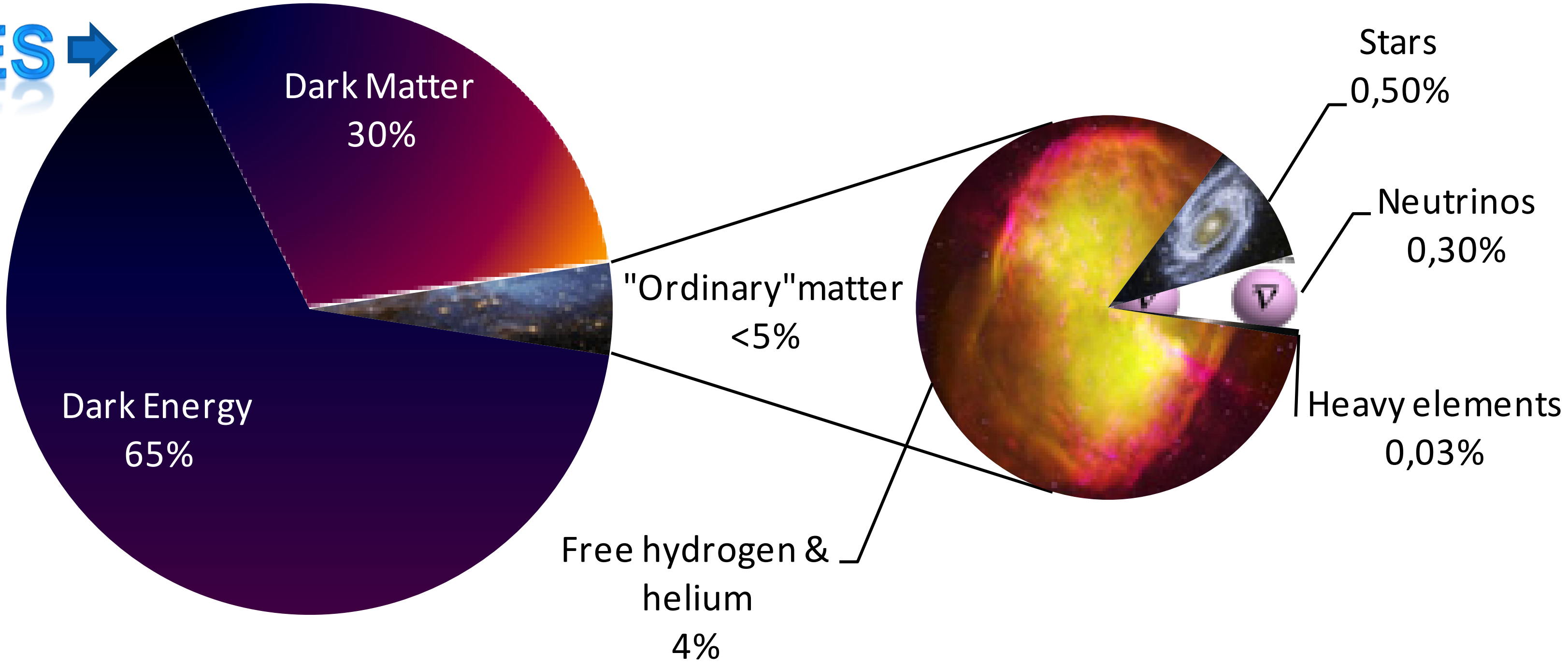
INFN-PG Workshop 2012

Gravitational kingdom



Universe composit

GRAVITATIONAL CLUES



Talk Outline

- Introduction to the Gravitational Wave (GW) search
- Gravitational wave interferometric detectors
  - Working principles
  - Current status
  - Advanced detectors
  - 3rd generation of gravitational wave observatories
    - The Einstein Telescope

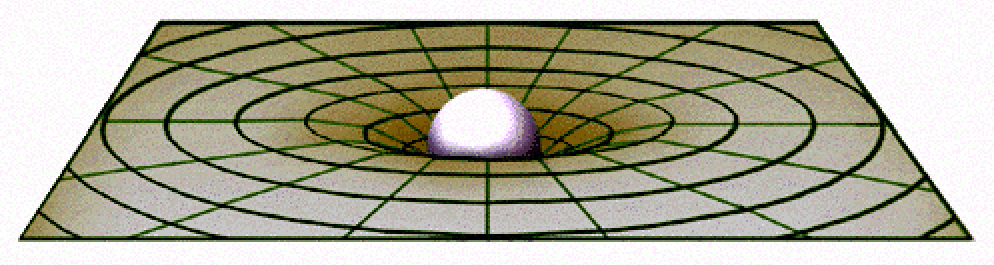
General Relativity and GW

- GW are predicted by the Einstein General Relativity (GR) theory
  - Formal treatment of the GW in GR is beyond the scope of this talk and only the aspects important for the GW detection will be considered

Einstein field equation links the source of the space-time deformation ($T_{\mu\nu}$ Energy-impulse tensor)

$$T_{\mu\nu} = -\frac{c^4}{8\pi G} G_{\mu\nu}$$

to the effect of the deformation ($G_{\mu\nu}$ the deformation tensor)



Far from the big masses Einstein field equation admits (linear approximation) wave solution (small perturbation of the background geometry)

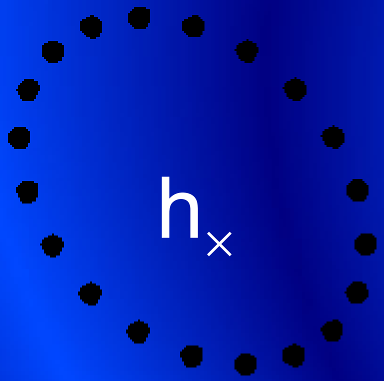
$$\mathbf{g} = \eta + \mathbf{h} \ \text{ with } |h_{\mu\nu}| << 1 \ \Rightarrow \ \left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) h_{\mu\nu} = 0$$

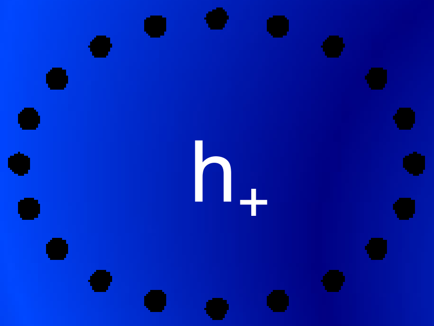
Gravitational Waves

- Gravitational waves are a perturbation of the space-time geometry
- They present two polarizations

$$\mathbf{h}(z,t) = e^{i(\omega t - kz)} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_{+} & h_{\times} & 0 \\ 0 & h_{\times} & -h_{+} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

- The effect of GWs on a mass distribution is the modulation of the reciprocal distance of the masses





Quantify the “deformation”

- The amplitude of the space-time deformation is:

$$h_{\mu\nu} = \frac{2G}{c^4} \cdot \frac{1}{r} \ddot{Q}_{\mu\nu}$$

Where $Q_{\mu\nu}$ is the quadrupolar moment of the GW source

and r is the distance between the detector and the GW source

- Let suppose to have a system of 2 coalescing neutron stars, located in the Virgo cluster (r~10Mpc):

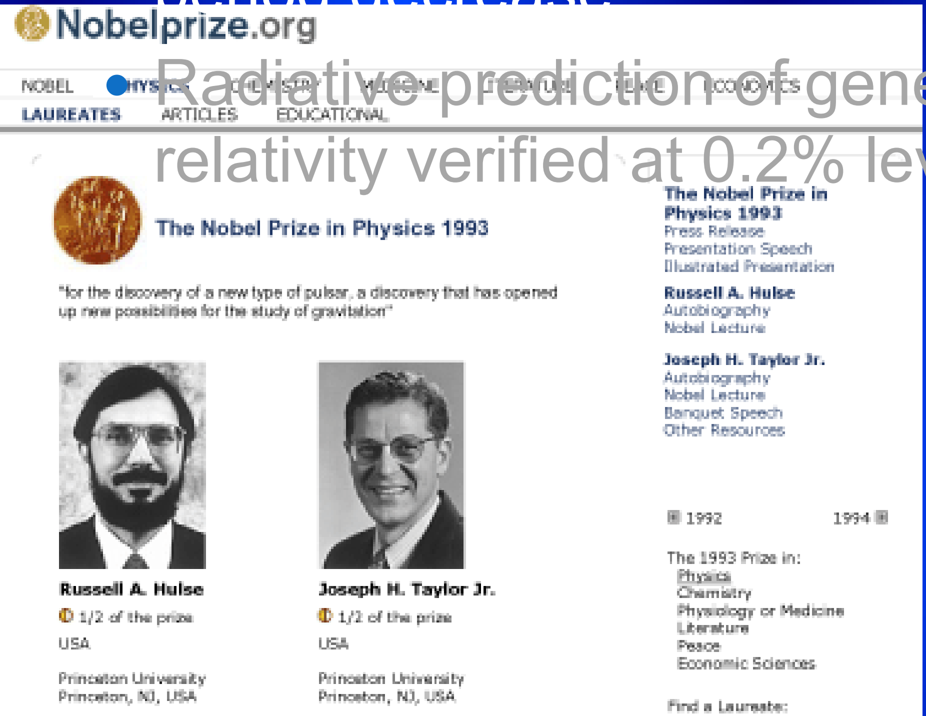
$$h \approx 10^{-21} - 10^{-22}$$

$$\left.\begin{array}{l} \delta L \approx \frac{h}{2} \cdot L_0 \\ L_0 \approx 10^3 m \end{array}\right\} \Rightarrow \boxed{\delta L \approx 10^{-18} - 10^{-19} m}$$

Extremely challenging for the detectors

But, GWs really exist?

- Neutron star binary system: PSR1913+16
  - 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 decrease
  - Radiative prediction of general relativity verified at 0.2% level



Nobelprize.org

The Nobel Prize in Physics 1993

"for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"

Russell A. Hulse
1/2 of the prize
USA
Princeton University
Princeton, NJ, USA
b. 1950

Joseph H. Taylor Jr.
1/2 of the prize
USA
Princeton University
Princeton, NJ, USA
b. 1941

The Nobel Prize in Physics 1993
Press Release
Presentation Speech
Illustrated Presentation

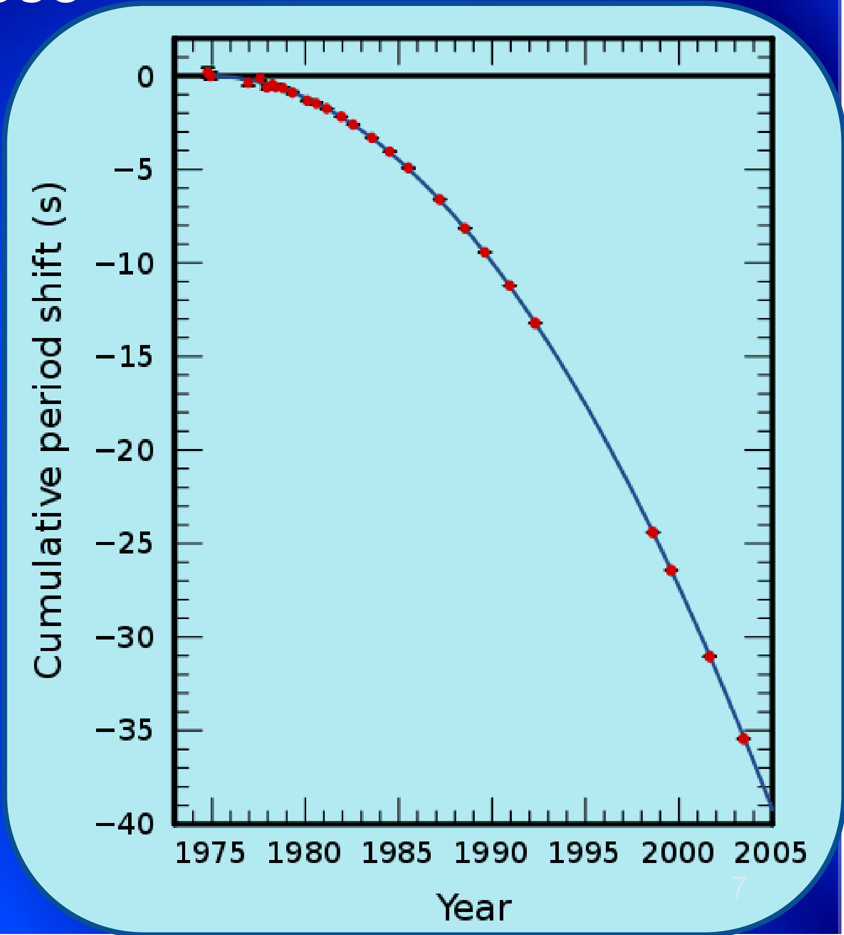
Russell A. Hulse
Autobiography
Nobel Lecture

Joseph H. Taylor Jr.
Autobiography
Nobel Lecture
Banquet Speech
Other Resources

1992 1994

The 1993 Prize in:
Physics
Chemistry
Physiology or Medicine
Literature
Peace
Economic Sciences

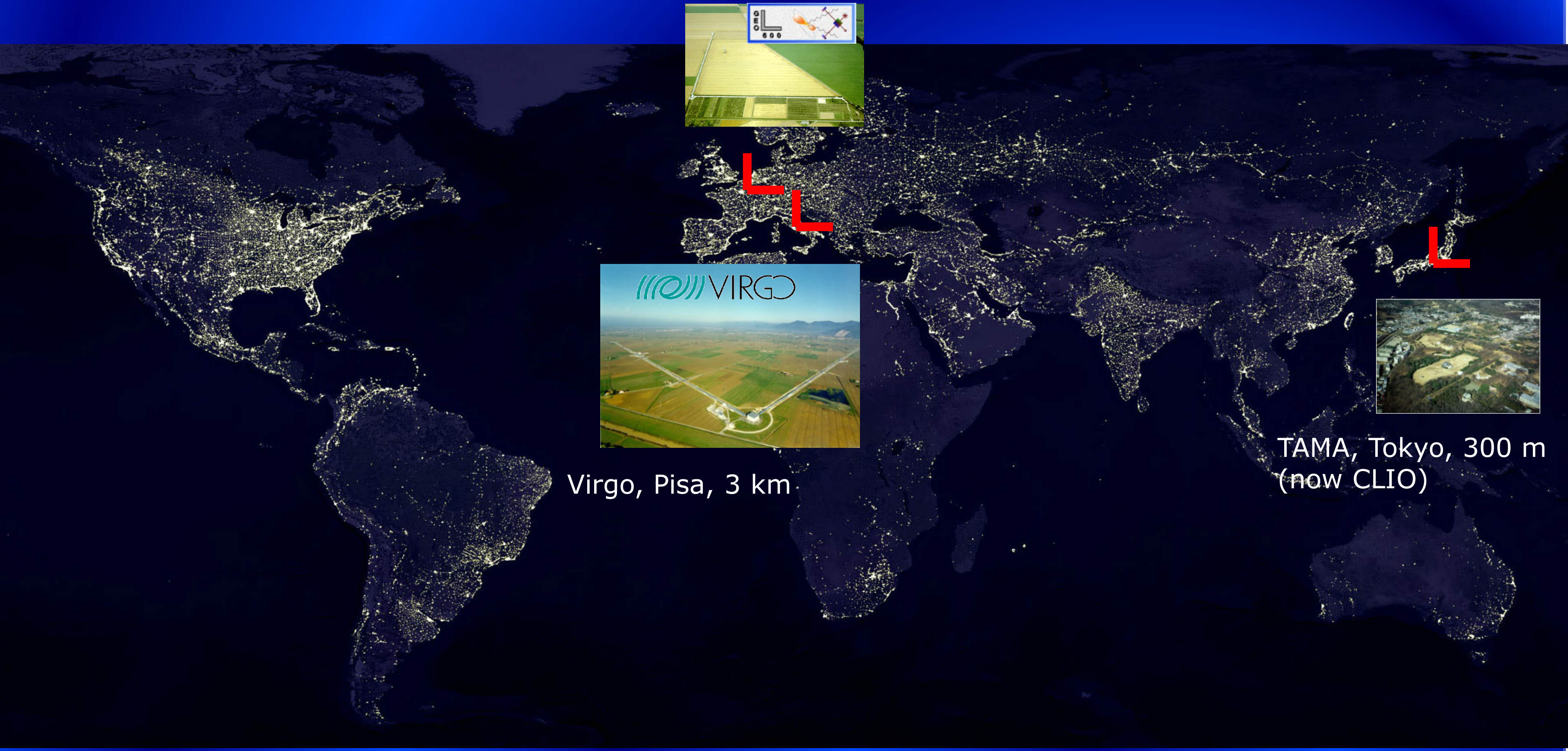
Find a Laureate:
Name



Nobel Prize 1993: Hulse and Taylor

GW interferometric initial detectors

- A network of detectors has been active in the World until few years ago



GEO, Hannover, 600 m

Virgo, Pisa, 3 km

TAMA, Tokyo, 300 m
(now CLIO)

VIRGO

- LAPP – Annecy
- NIKHEF – Amsterdam
- RMKI - Budapest
- INFN – Firenze-Urbino
- INFN – Genova
- INFN – LNF
- LMA – Lyon
- INFN – Napoli
- OCA – Nice
- LAL – Orsay
- APC – Paris
- LKB - Paris
- INFN – Padova-Trento
- INFN – Perugia
- INFN - Pisa
- INFN – Roma 1
- INFN – Roma 2
- POLGRAV - Warsaw

GEO600

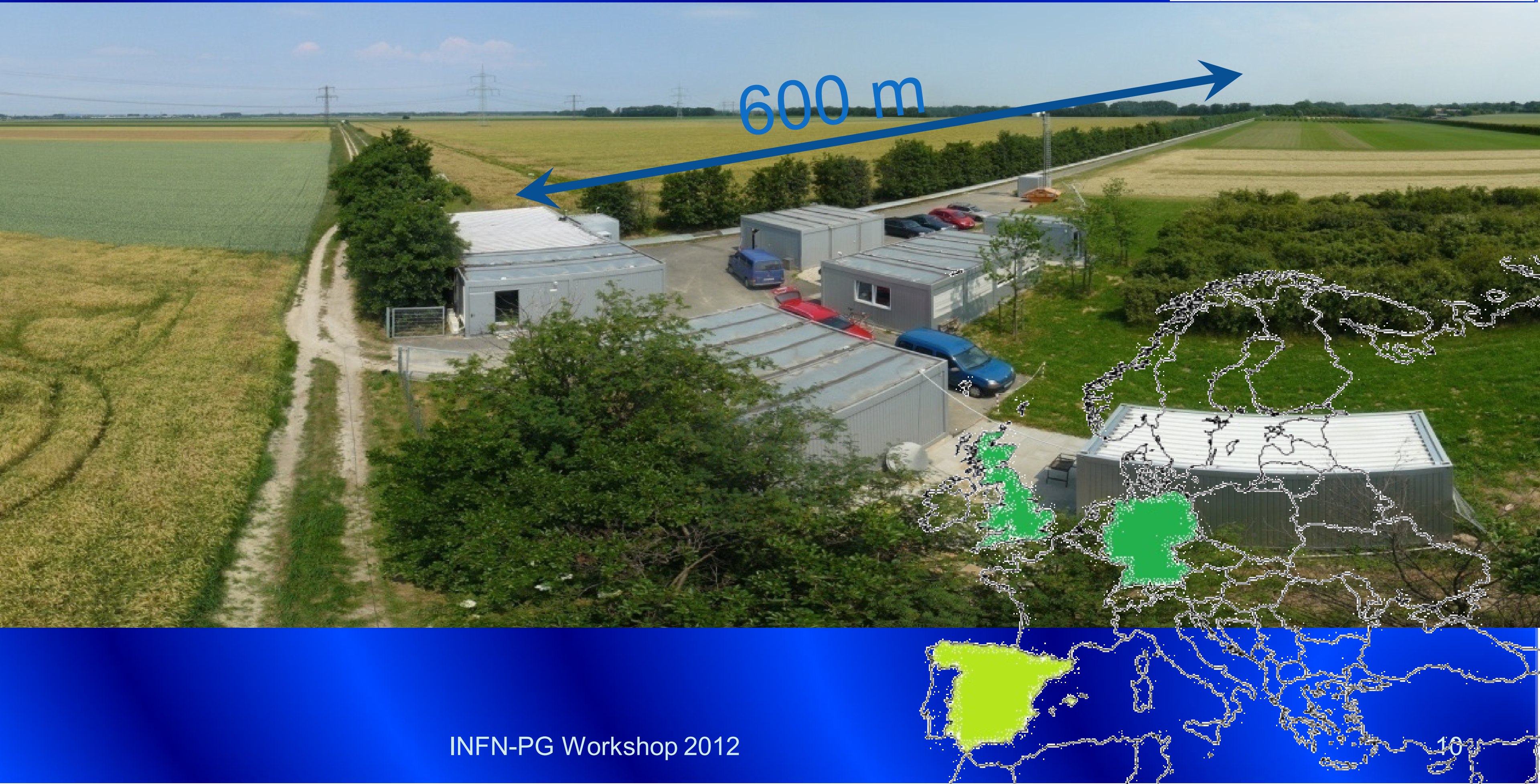
Leibniz Universität Hannover

CARDIFF UNIVERSITY

UNIVERSITY OF BIRMINGHAM

IGR

UIB Universitat de les Illes Balears



GW interferometric initial detectors

- A network of detectors has been active in the World until few years ago

LIGO Hanford, 4 km:
2 ITF on the same site!

GEO, Hannover, 600 m

Virgo, Cascina, 3 km

LIGO Livingston, 4 km

TAMA, Tokyo, 300 m
(now CLIO)

LIGO Scientific Collaboration

LIGO

LSC


GEO600, Hannover, Germany


LIGO – Hanford, WA


LIGO – Livingston, LA

Massachusetts Institute of Technology

California Institute of Technology

Leland Stanford Junior University

PENNSTATE

University of Glasgow

GEO 600

University of Washington

ACIGA

Southern University

Università degli Studi del Sannio

University of Rochester

University of Wisconsin Milwaukee

ANU The Australian National University

University of Maryland

UTB TSC

The University of Western Australia

Trinity University

Loyola University New Orleans

University of Massachusetts Amherst

Andrews University

The University of Texas at Austin

UIB Universitat de les Illes Balears

Northwestern University

Syracuse University

NASA Goddard Space Flight Center

R·I·T

Moscow State University

The University of Adelaide Australia

Cardiff University

Montana State University

Michigan

San José State University

Washington State University

University of Southampton

Tsinghua University

NAOJ

LSU

Embry-Riddle Aeronautical University

The University of Mississippi

Carleton College

California State University Fullerton

University of Minnesota

UF University of Florida

Science & Technology Facilities Council Rutherford Appleton Laboratory

Universität Hannover

University of Strathclyde

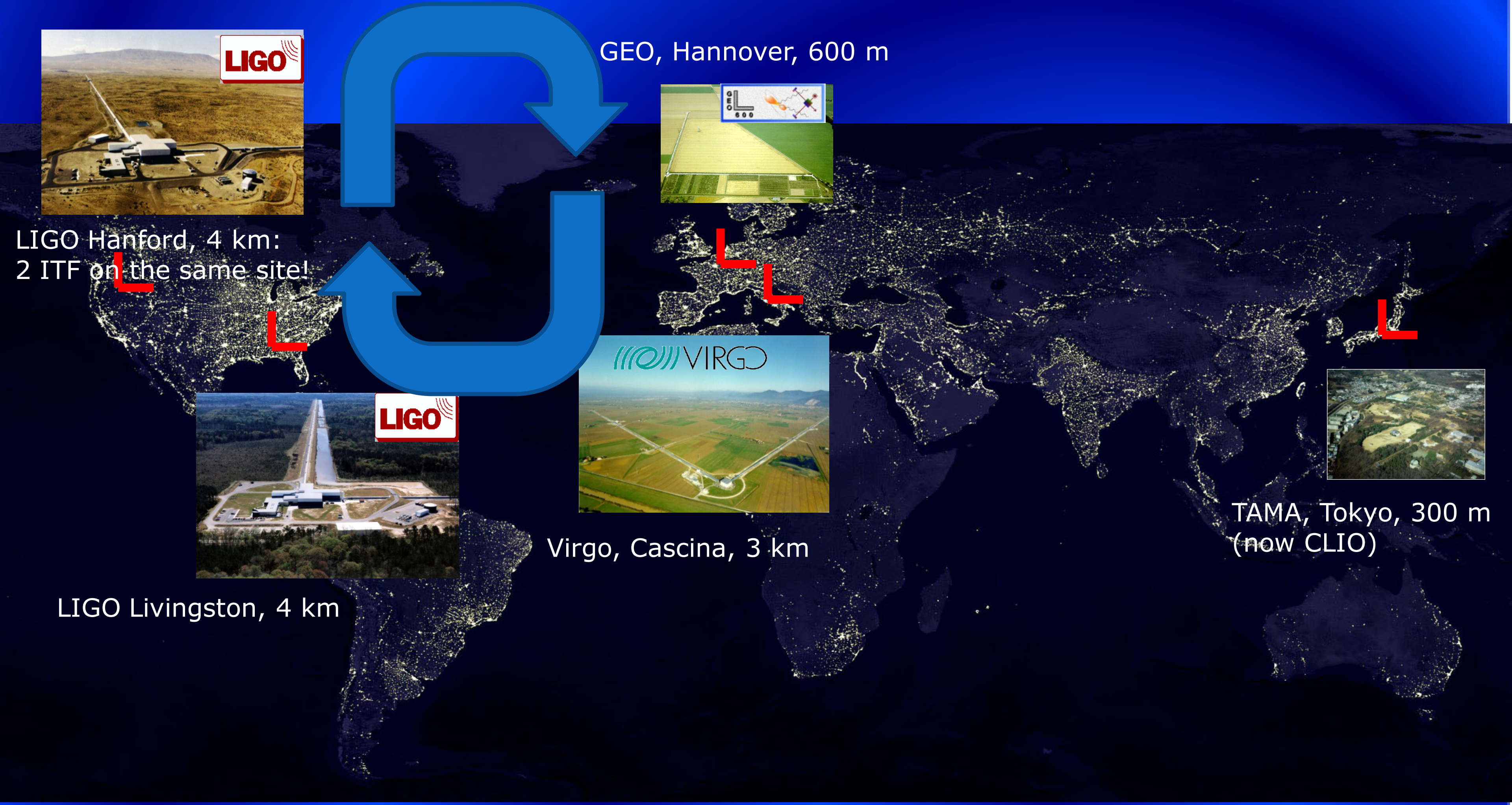
Southern University Agricultural & Mechanical College

Hobart and William Smith Colleges

Charles Sturt University

GW interferometric initial detectors

- A network of detectors has been active in the World until few years ago



LIGO Hanford, 4 km:
2 ITF on the same site!

GEO, Hannover, 600 m

LIGO Livingston, 4 km

Virgo, Cascina, 3 km

TAMA, Tokyo, 300 m
(now CLIO)

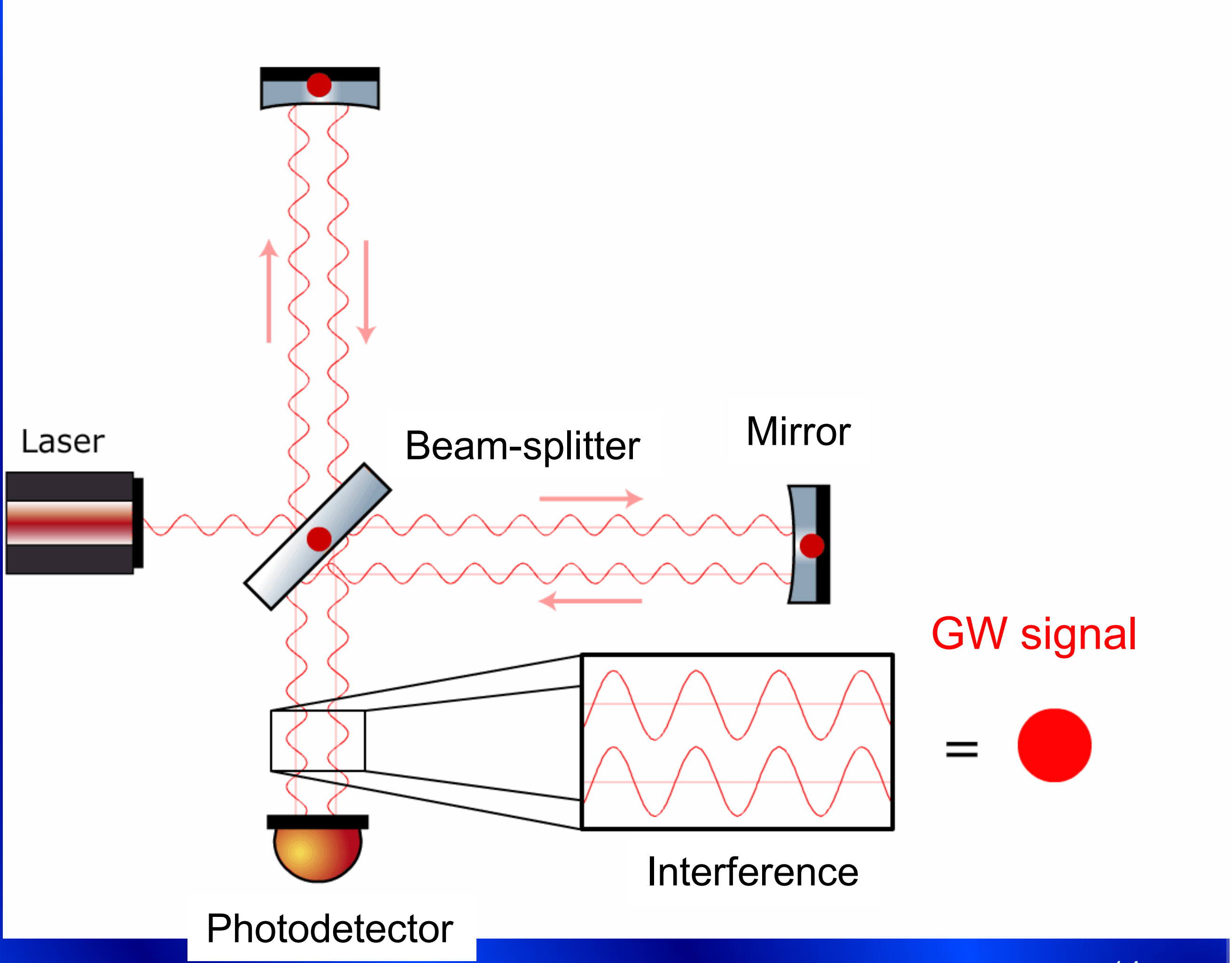
Working principle

- The quadrupolar nature of the GW makes the Michelson interferometer a “natural” GW detector

$$\delta L \approx \frac{h}{2} \cdot L_0$$

$10^2 \leq L_0 \leq 10^4$ m in terrestrial detectors

$$\phi_{GW} = \frac{4\pi}{\lambda} L_0 \cdot h$$

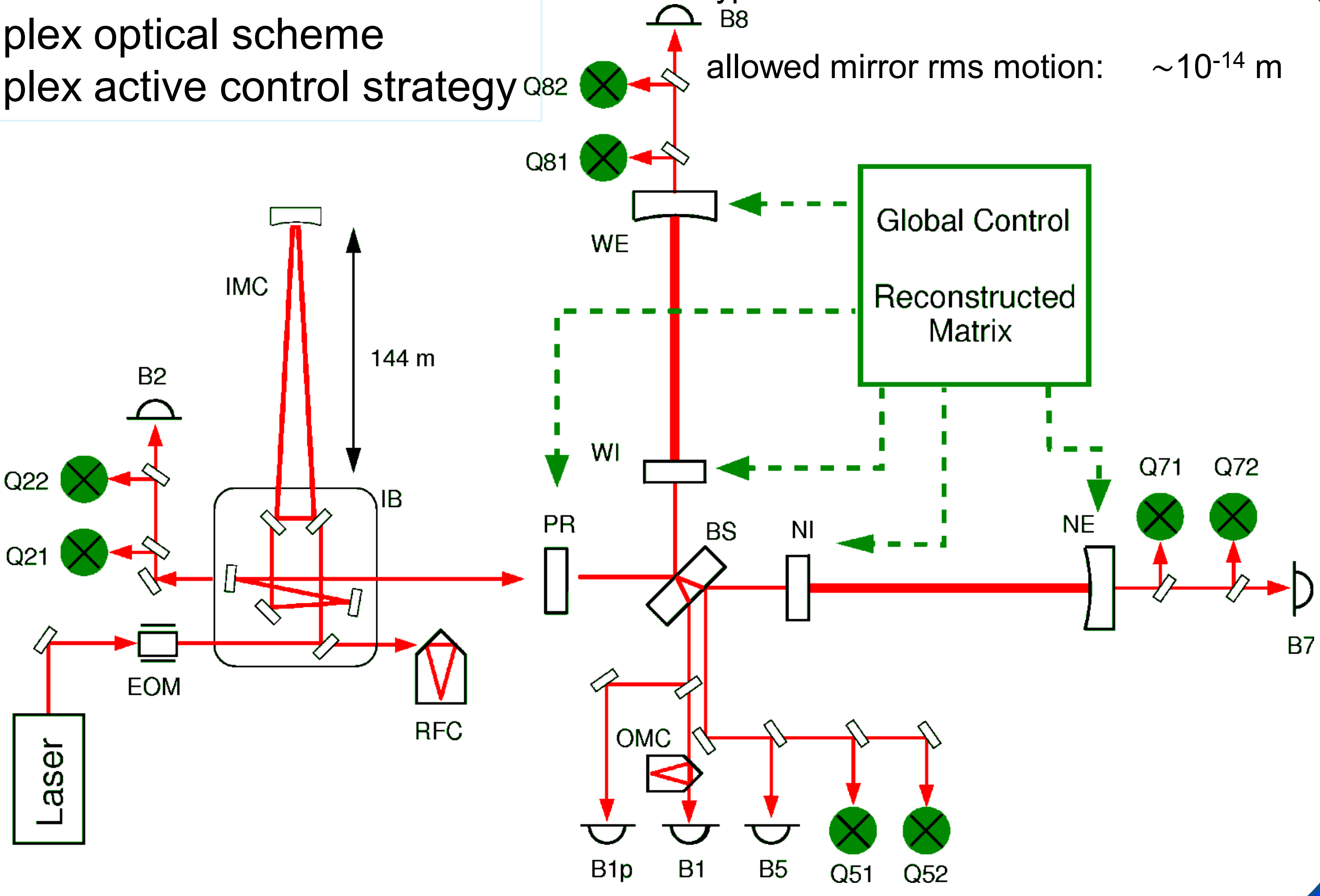


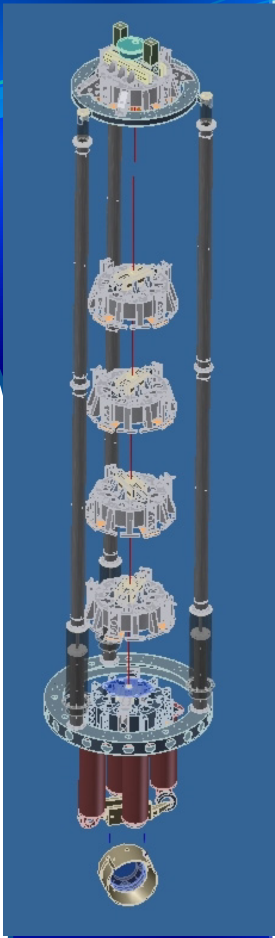
Real life: complex machine

Complex optical scheme
Complex active control strategy

typical earth crust tidal strain: ~10^{-4} m

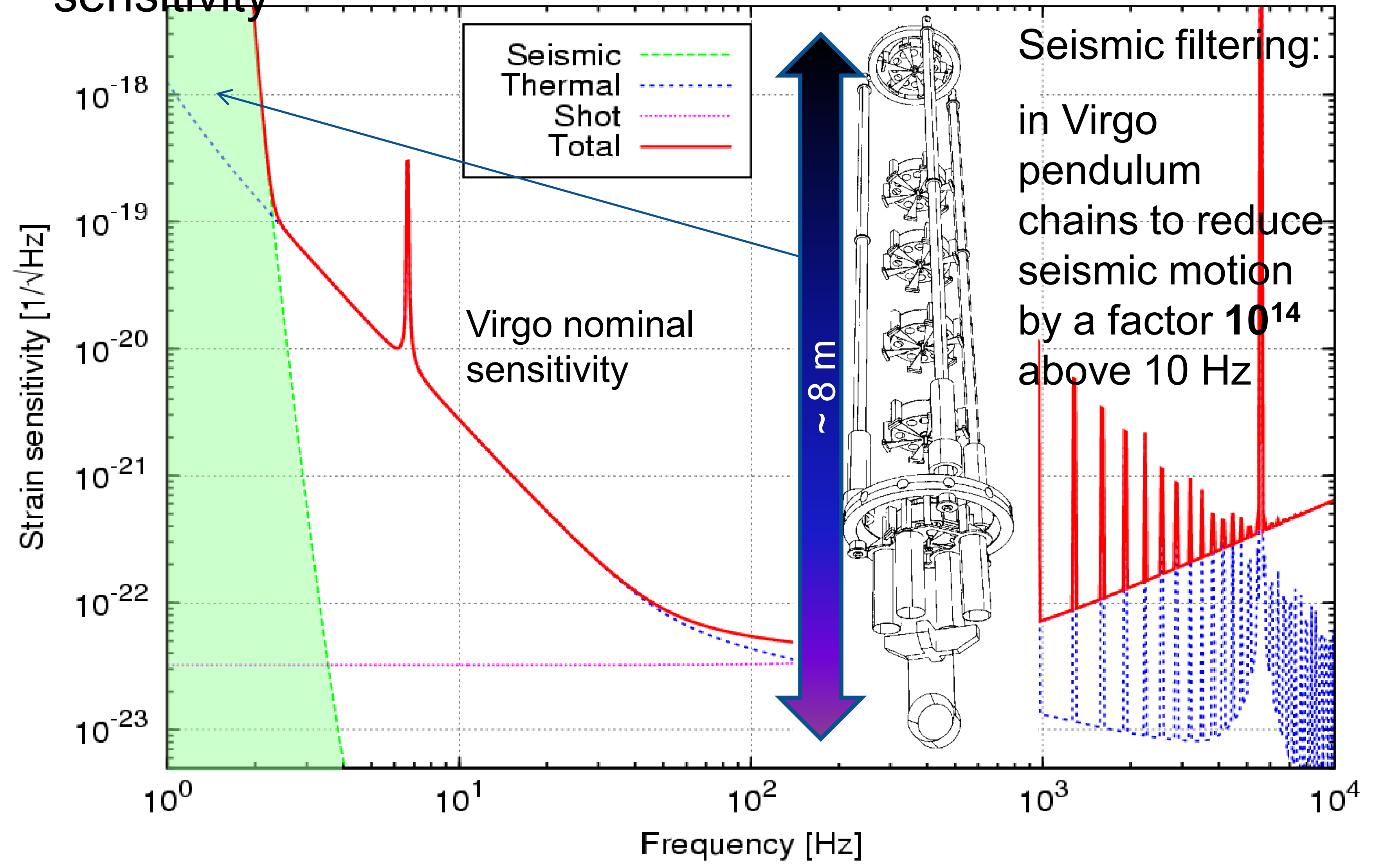
allowed mirror rms motion: ~10^{-14} m





Detector sensitivity

- The faint space-time deformation measurement must compete with a series of noise sources that are spoiling the detector sensitivity



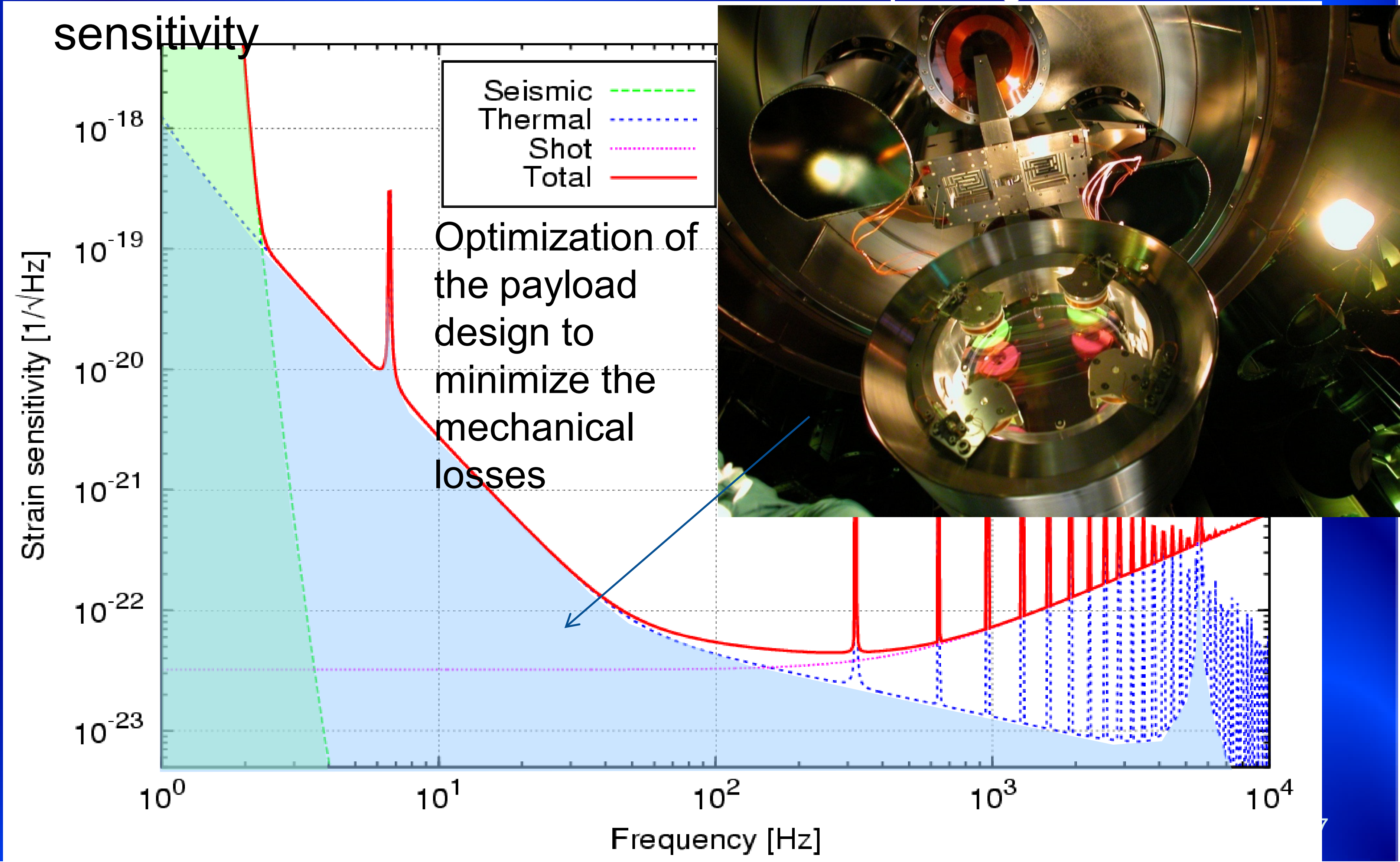
Virgo nominal sensitivity

Seismic filtering:

in Virgo pendulum chains to reduce seismic motion by a factor **10^{14}** above 10 Hz

Detector sensitivity

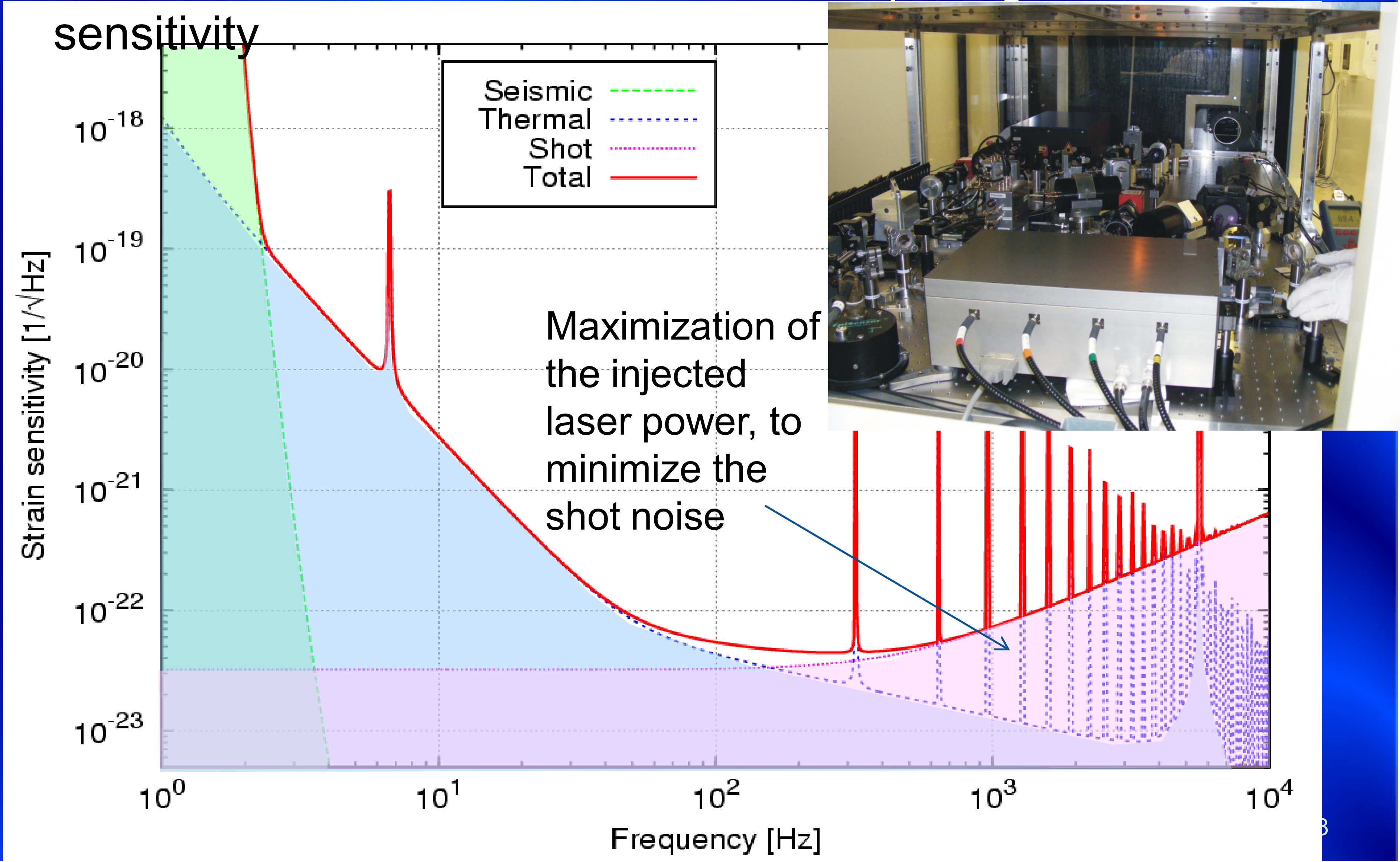
- The faint space-time deformation measurement must compete with a series of noise sources that are spoiling the detector sensitivity



Optimization of the payload design to minimize the mechanical losses

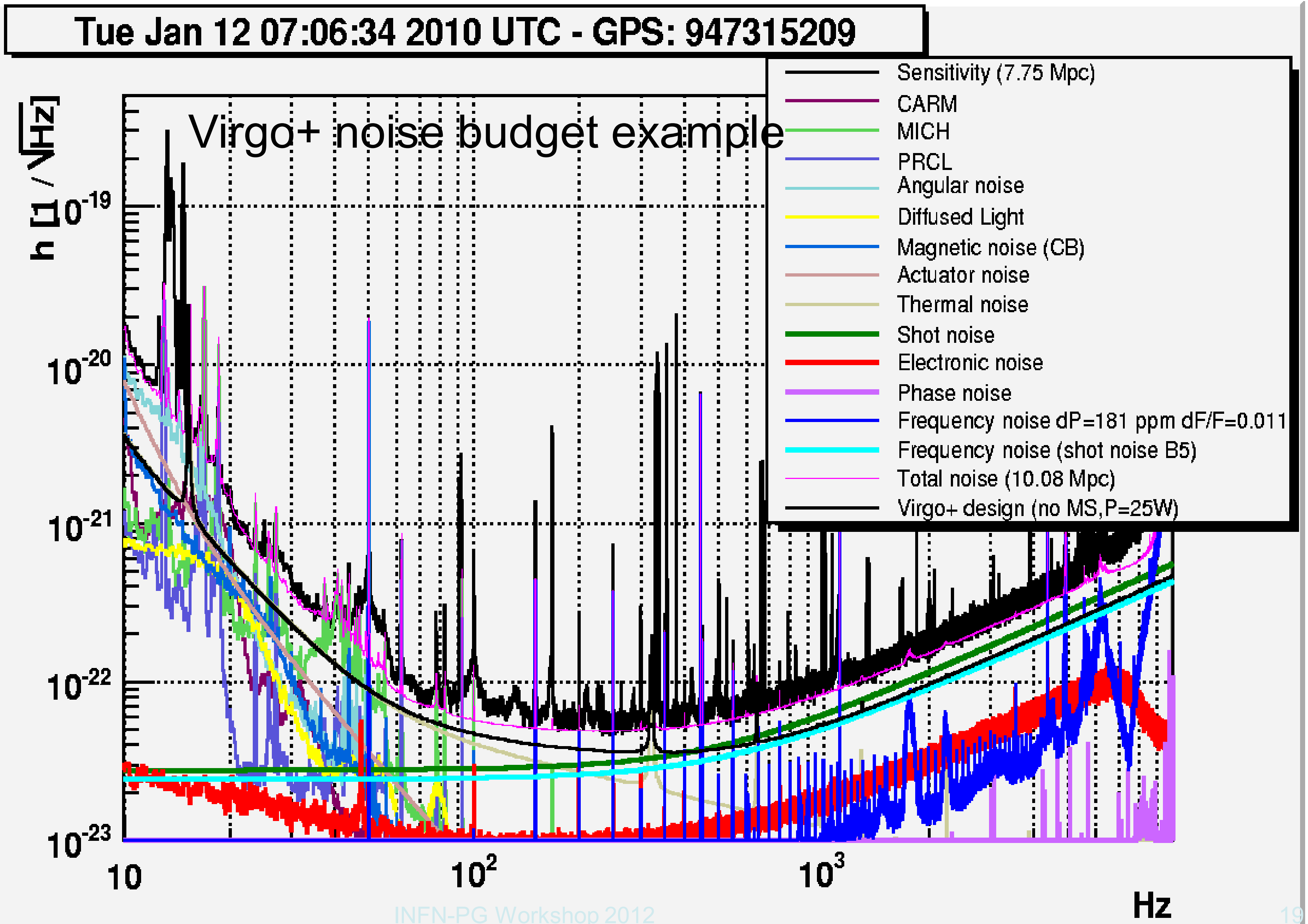
Detector sensitivity

- The faint space-time deformation measurement must compete with a series of noise sources that are spoiling the detector sensitivity



Maximization of the injected laser power, to minimize the shot noise

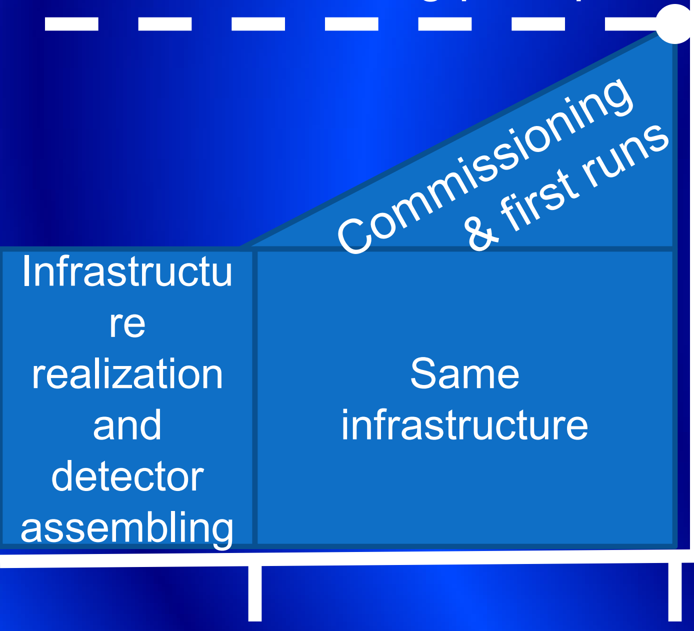
Noise budget: real life



Virgo+ noise budget example

GW interferometer past evolution

- Evolution of the GW detectors (Virgo example):



Proof of the working principle

Commissioning & first runs

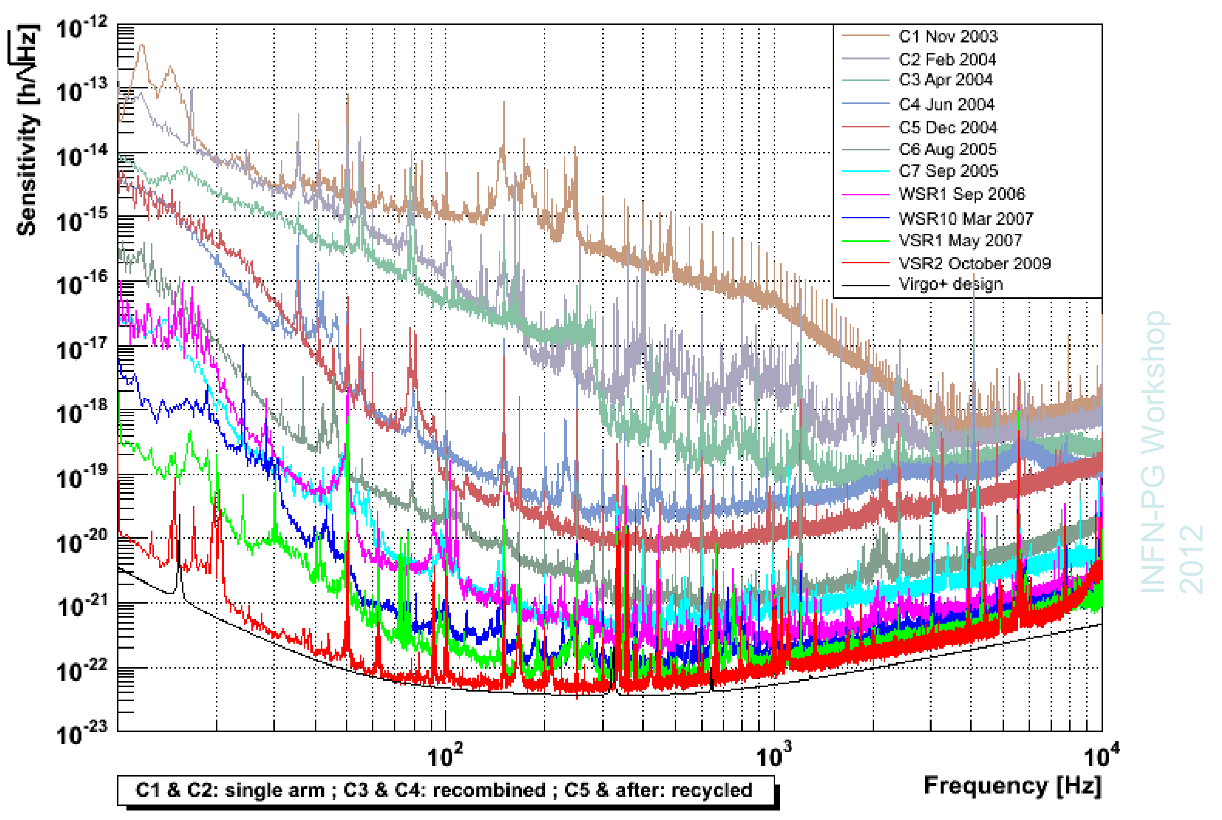
Infrastructure realization and detector assembling

Same infrastructure

2003

2008

year



GW interferometer past evolution

- Evolution of the GW

The Astrophysical Journal, 713:671–685, 2010 April 10 doi:10.1088/0004-637X/713/1/671

SEARCHES FOR GRAVITATIONAL WAVES FROM KNOWN PULSARS WITH SCIENCE RUN 5 LIGO DATA

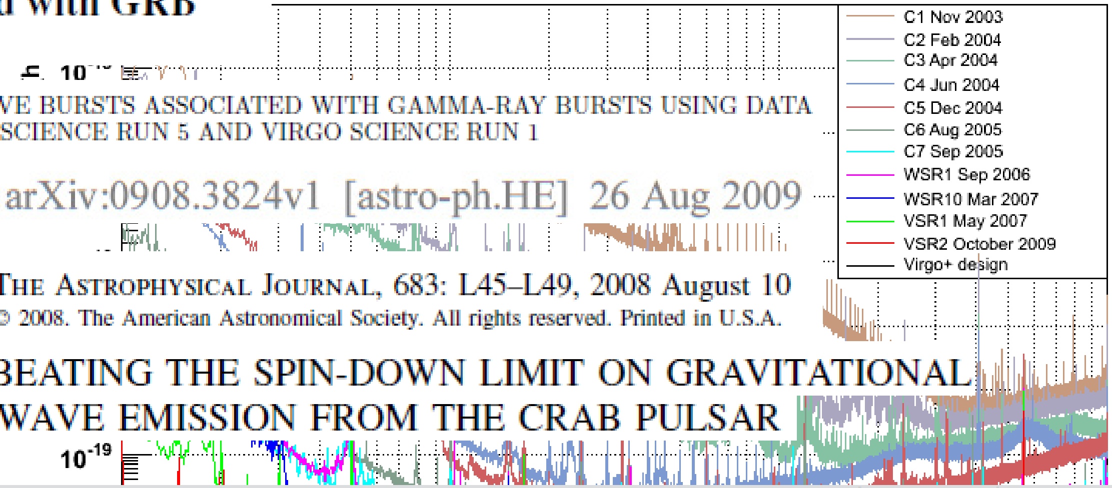
IOP Publishing Classical and Quantum Gravity

Class. Quantum Grav. 25 (2008) 225001 (20pp) doi:10.1088/0264-9381/25/22/225001

Search for gravitational waves associated with GRB 050915a using the Virgo detector

SEARCH FOR GRAVITATIONAL-WAVE BURSTS ASSOCIATED WITH GAMMA-RAY BURSTS USING DATA FROM LIGO SCIENCE RUN 5 AND VIRGO SCIENCE RUN 1

arXiv:0908.3824v1 [astro-ph.HE] 26 Aug 2009



The Astrophysical Journal, 683: L45–L49, 2008 August 10

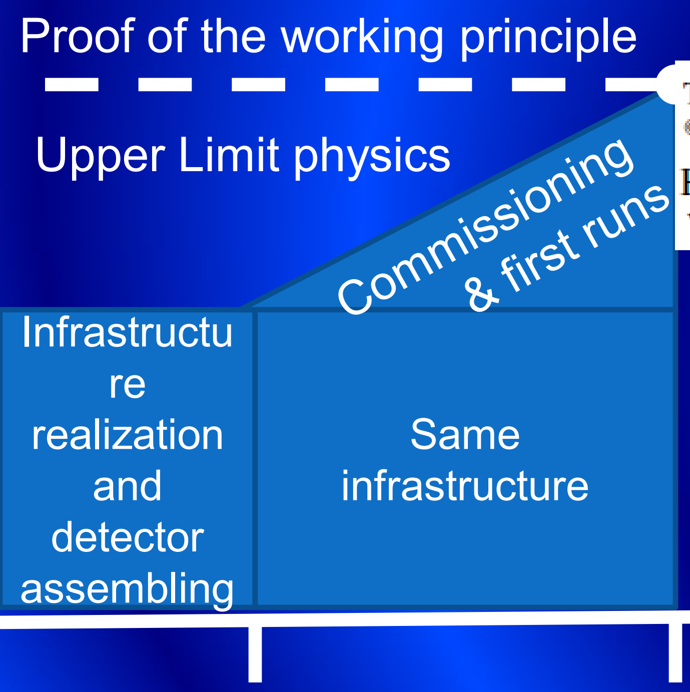
BEATING THE SPIN-DOWN LIMIT ON GRAVITATIONAL WAVE EMISSION FROM THE CRAB PULSAR

nature Vol 460 | 20 August 2009 | doi:10.1038/nature08278

LETTERS

An upper limit on the stochastic gravitational-wave background of cosmological origin

The LIGO Scientific Collaboration* & The Virgo Collaboration*


Proof of the working principle

Upper Limit physics

Commissioning & first runs

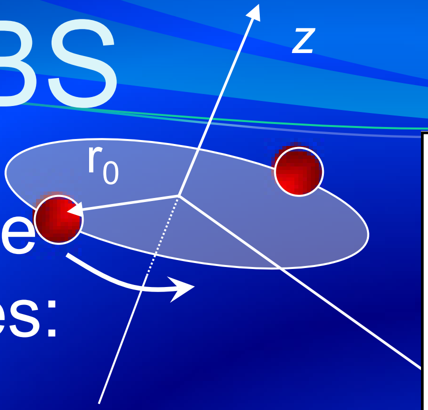
Infrastructure realization and detector assembling

Same infrastructure

2003

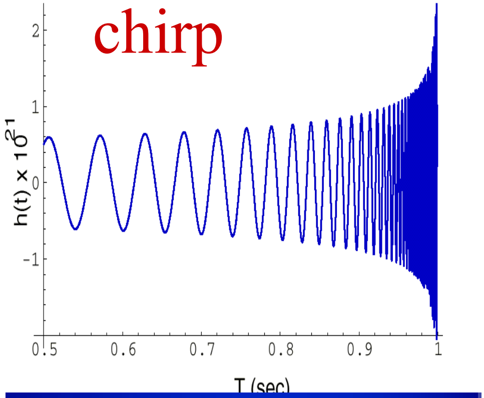
2008

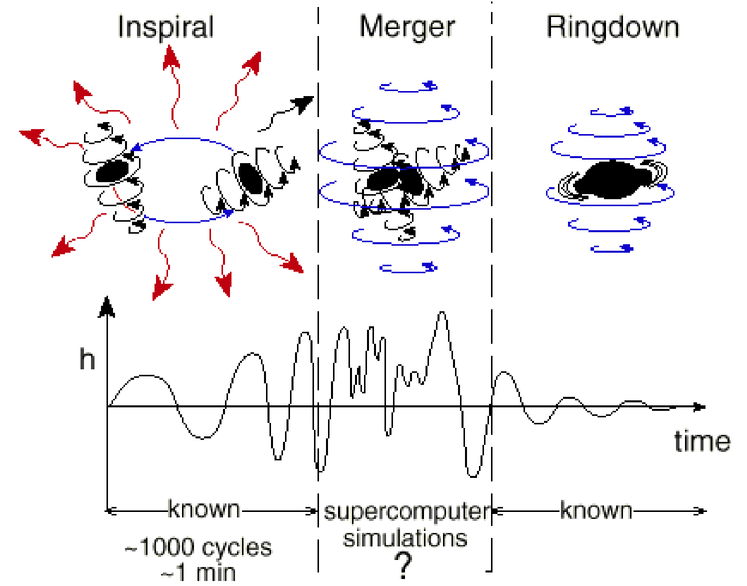
GW sources: BS



BH-BH

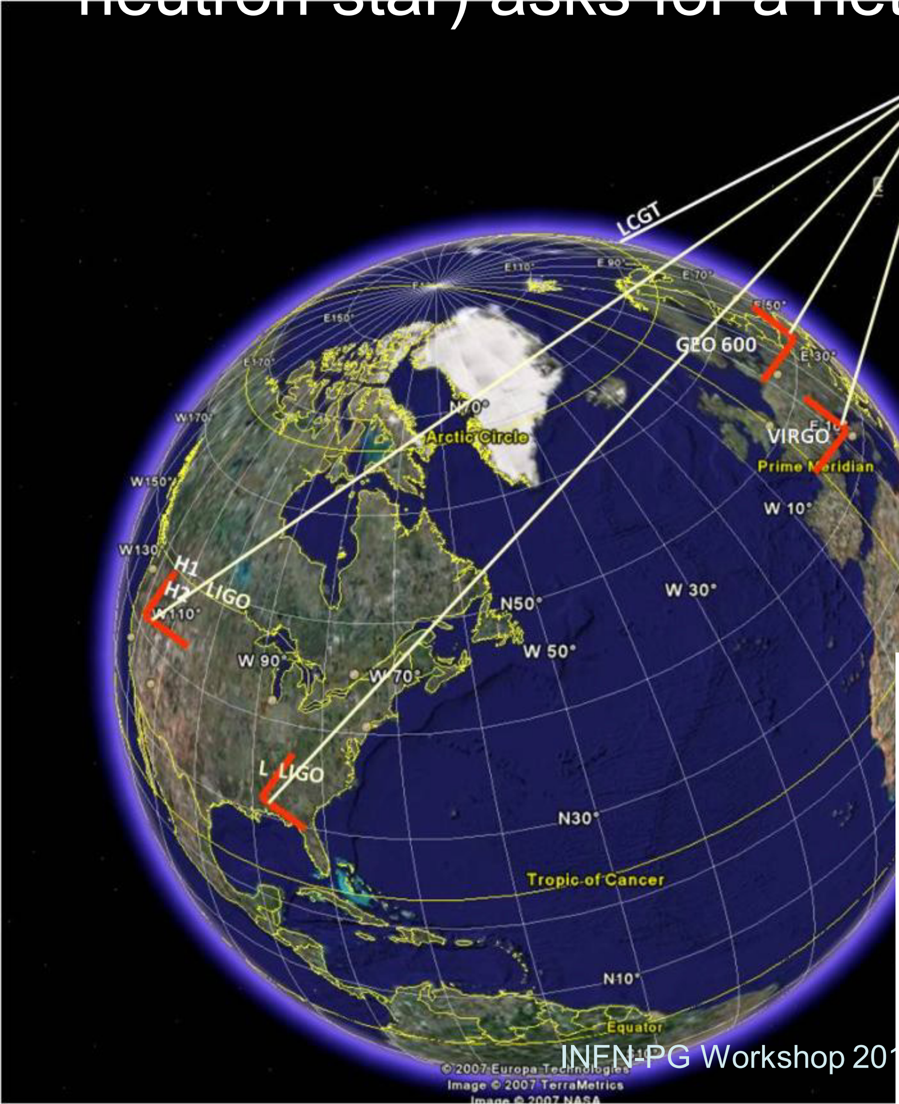
- Binary systems of massive and compact stellar bodies:
  - NS-NS, NS-BH, BH-BH
- Source of crucial interest:
  - We are able to model (roughly) the signal using the (post) Newtonian physics



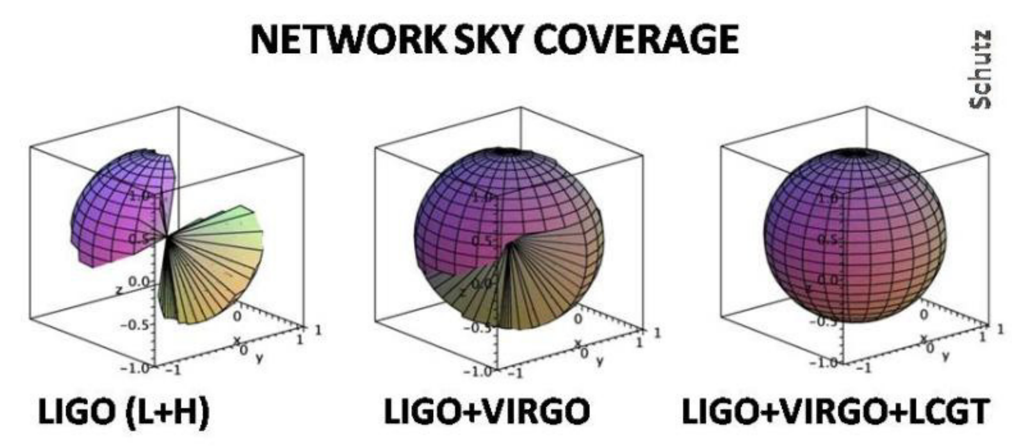


Network of GW detectors

- The search for GW signal emitted by a binary system (of neutron star) asks for a network of (distant) detectors

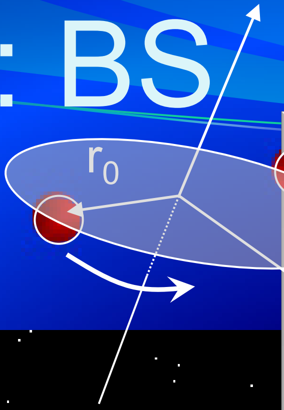


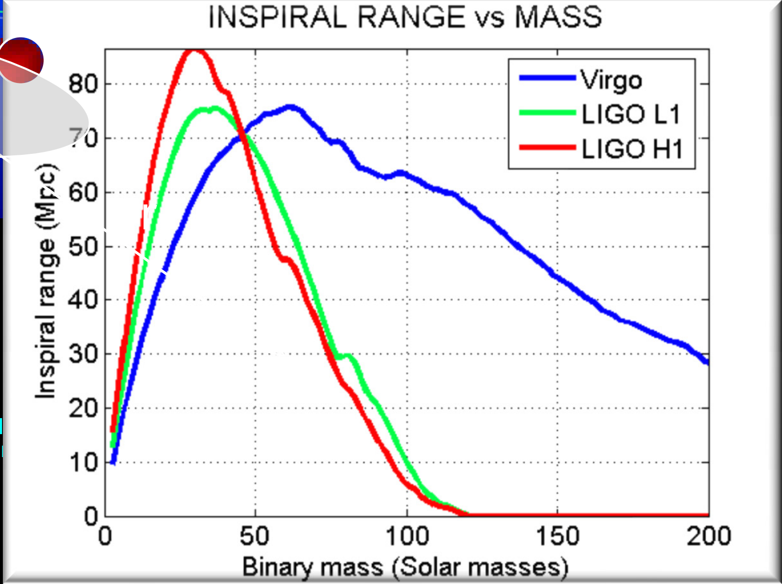
- Event reconstruction
  - Source location in the sky
  - Reconstruction of polarization components
  - Reconstruction of amplitude at source and determination of source distance (BNS)
- Detection probability increase
- Detection confidence increase
- Larger uptime
- Better sky coverage



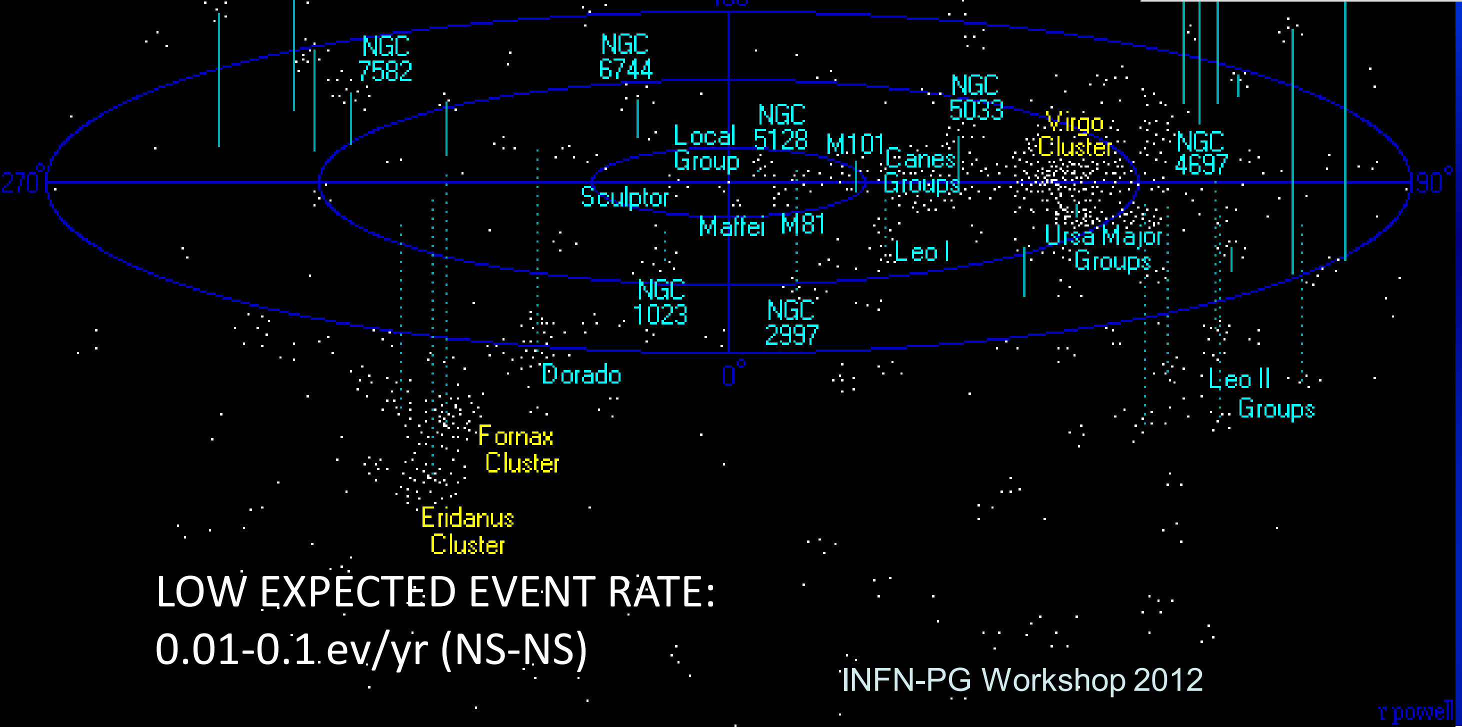
GW sources: BS

- Binary systems of massive and compact stellar bodies:
  - NS-NS, NS-BH, BH-BH





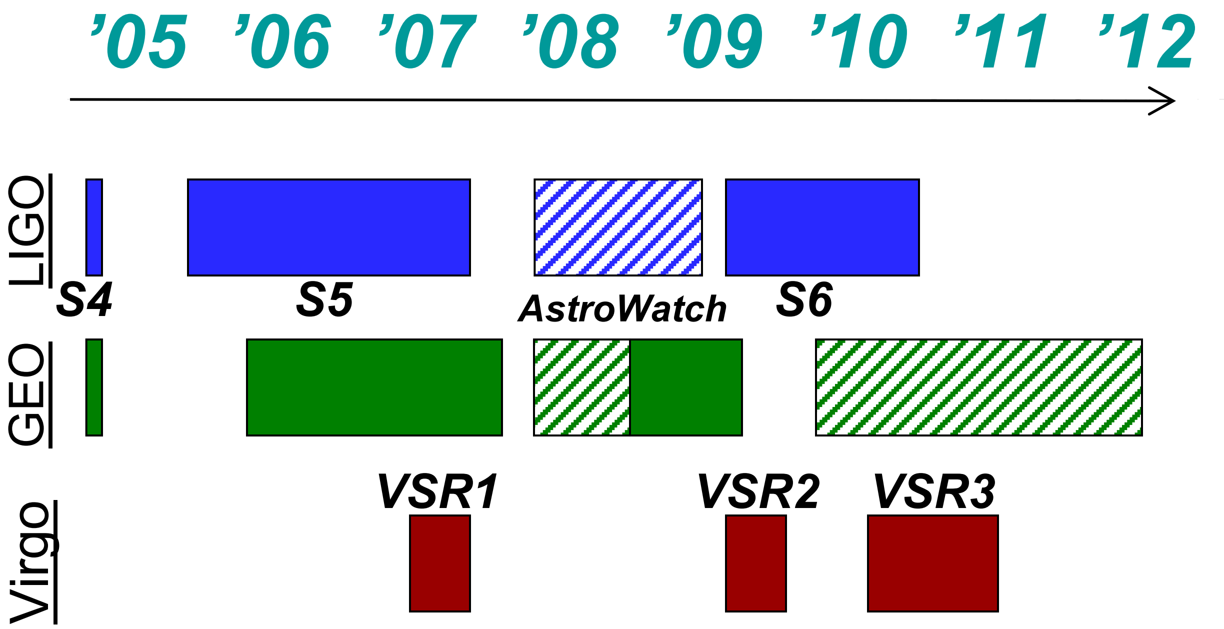
1ST GENERATION INTERFEROMETERS COULD DETECT A NS-NS COALESCENCE AS FAR AS VIRGO CLUSTER (15 MPc)

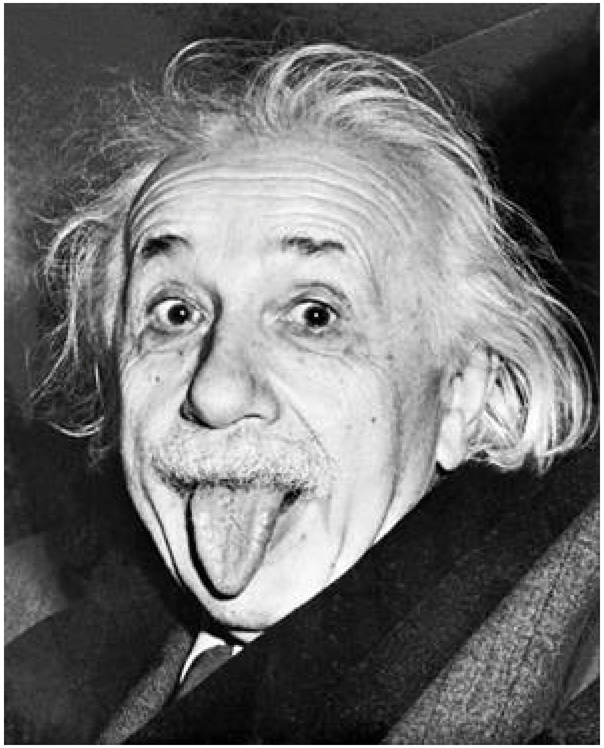


LOW EXPECTED EVENT RATE:
0.01-0.1 ev/yr (NS-NS)

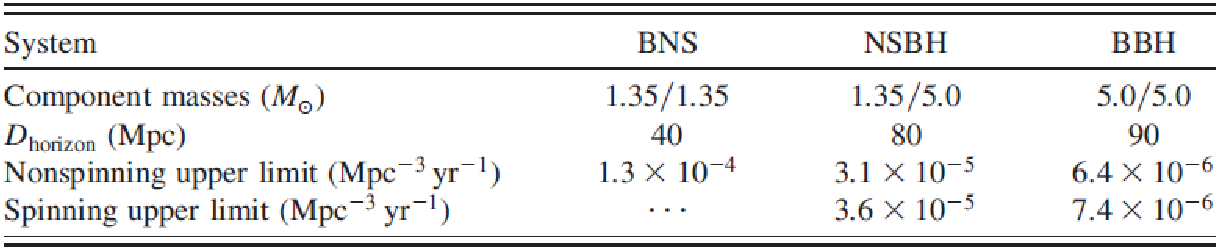
Scientific runs

- A series of runs have been performed by the GW network
- As expected, no BS detection so far!





But, upper limit physics explored!
(PRD 85, 082002 – 2012, Nature 460, 990-994 . 2009)



System	BNS	NSBH	BBH
Component masses ($M_\odot$)	1.35/1.35	1.35/5.0	5.0/5.0
D_{horizon} (Mpc)	40	80	90
Nonspinning upper limit ($\text{Mpc}^{-3}\,\text{yr}^{-1}$)	1.3×10^{-4}	3.1×10^{-5}	6.4×10^{-6}
Spinning upper limit ($\text{Mpc}^{-3}\,\text{yr}^{-1}$)	···	3.6×10^{-5}	7.4×10^{-6}

GW source: Isolated NS

- Not-axisymmetric rotating neutron stars (pulsars) are expected to emit GW at frequency double of the spinning one

$$h \approx \frac{G}{rc^4} \varepsilon \cdot I_{zz} \cdot \Omega^2$$

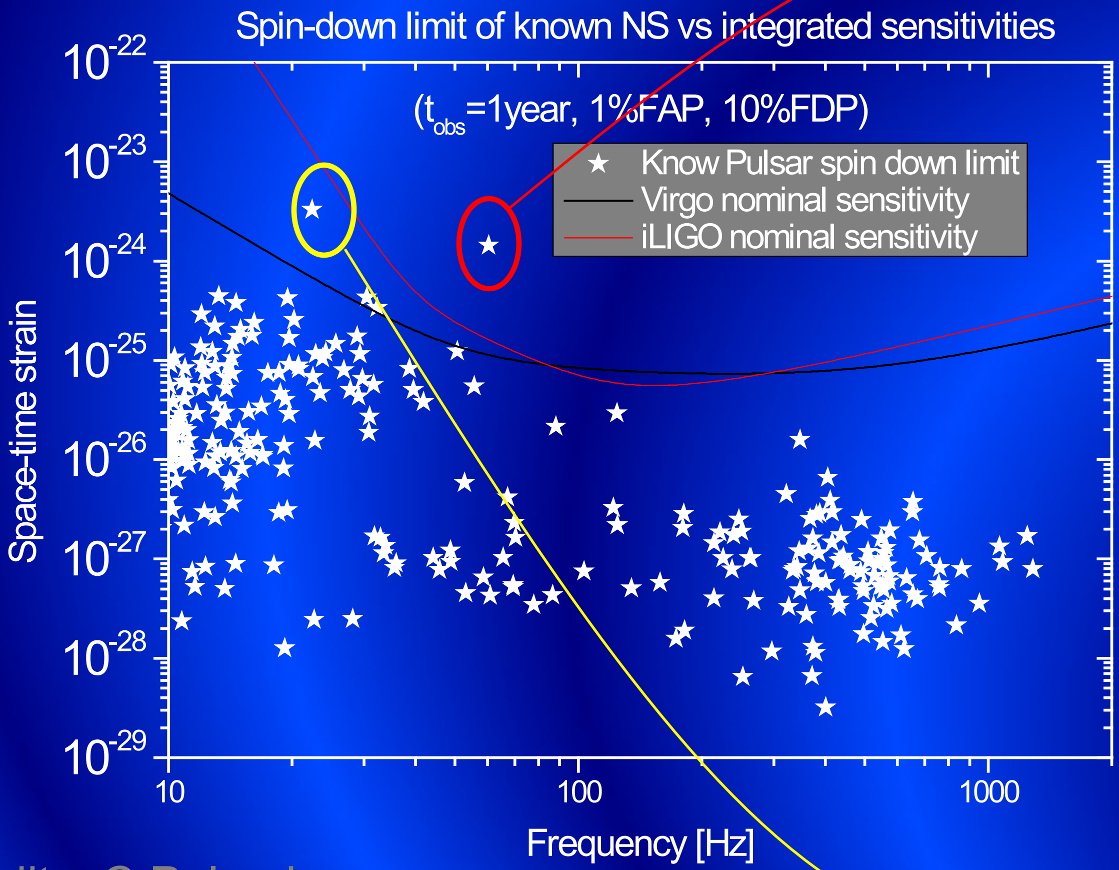
$$I_{zz} \approx 10^{38}\, kg \cdot m^2$$

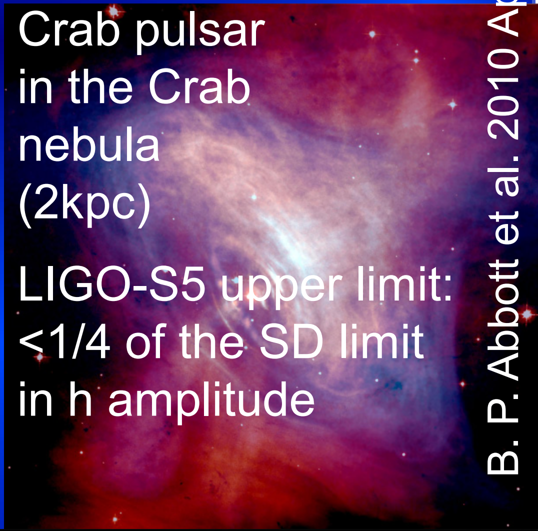
$$\varepsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}$$

- The periodicity of the signal allows to increase the SNR integrating for a long time
  - But Doppler effect correction needed because of the Earth motion determines a computational obstacle to a full blind search
- Detection of GW from a NS gives info on the internal structure of the star (ε limit is related to the superfluid/strange matter nature of the star, to the magnetic field, …)

GW sources: isolated NS

- Isolated NS are a possible source of GW if they have a non-null quadrupolar moment (ellipticity)

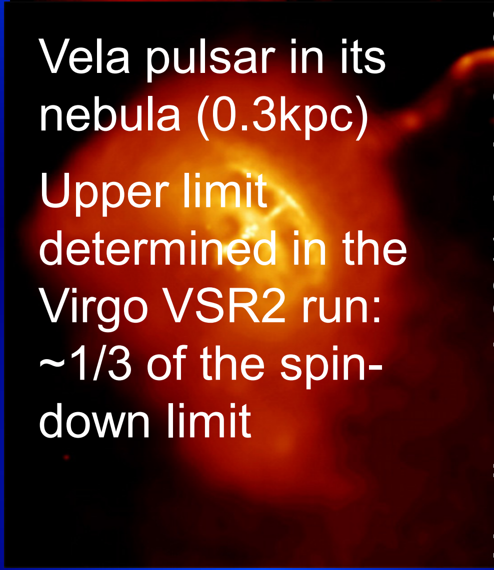




Crab pulsar in the Crab nebula (2kpc)

LIGO-S5 upper limit: <1/4 of the SD limit in h amplitude

B. P. Abbott et al. 2010 ApJ 713 671



Vela pulsar in its nebula (0.3kpc)

Upper limit determined in the Virgo VSR2 run: ~1/3 of the spin-down limit

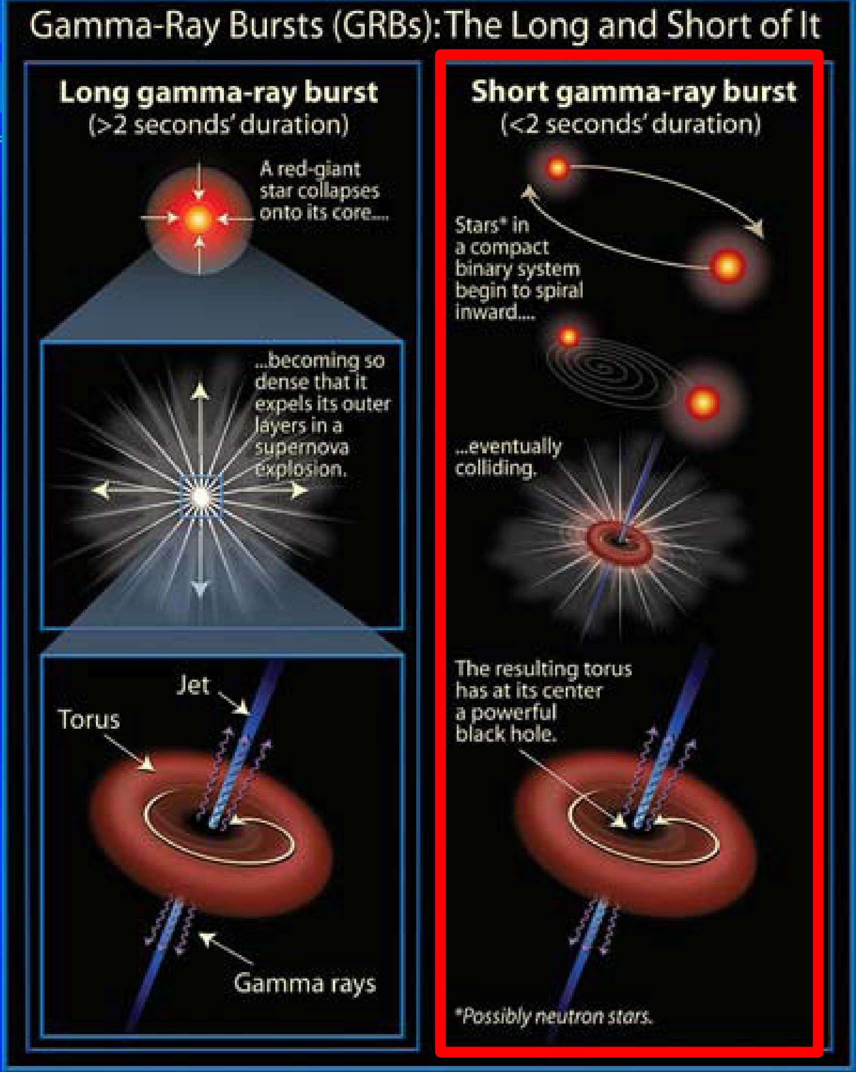
J. Abadie *et al.* 2011 *ApJ* **737** 93

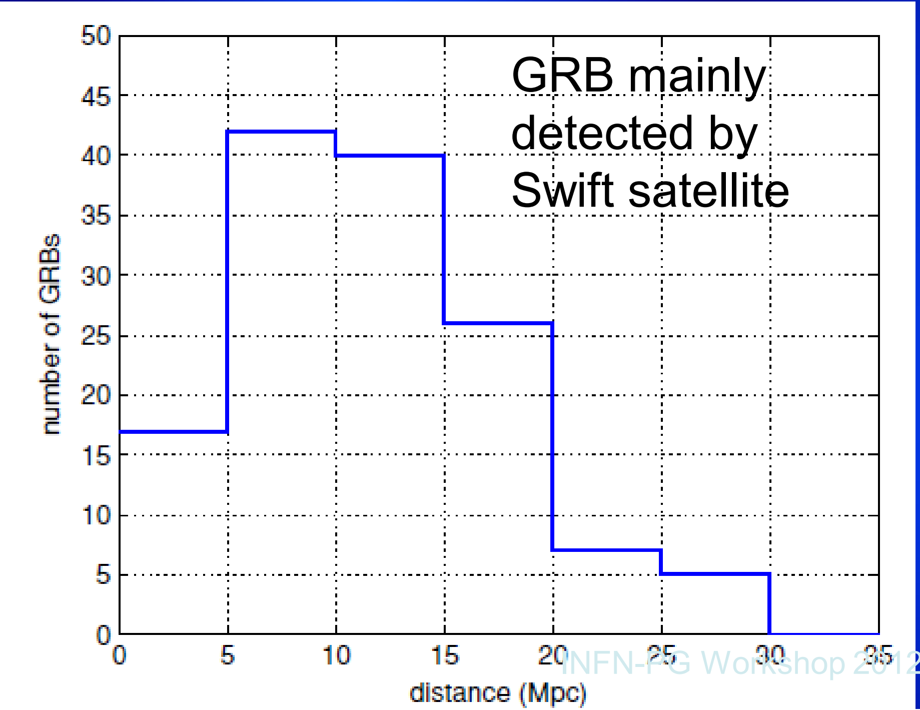
Credits: C.Palomba

GW sources: GRB

- Gamma ray bursts are subdivided in 2 classes:
  - Long (>2s duration): SNe generation mechanism
  - Short (<2s): BNS coalescence mechanism → GW

B.P. Abbot (LSC and Virgo coll), Astr. Jour. 715 (2010), 1438



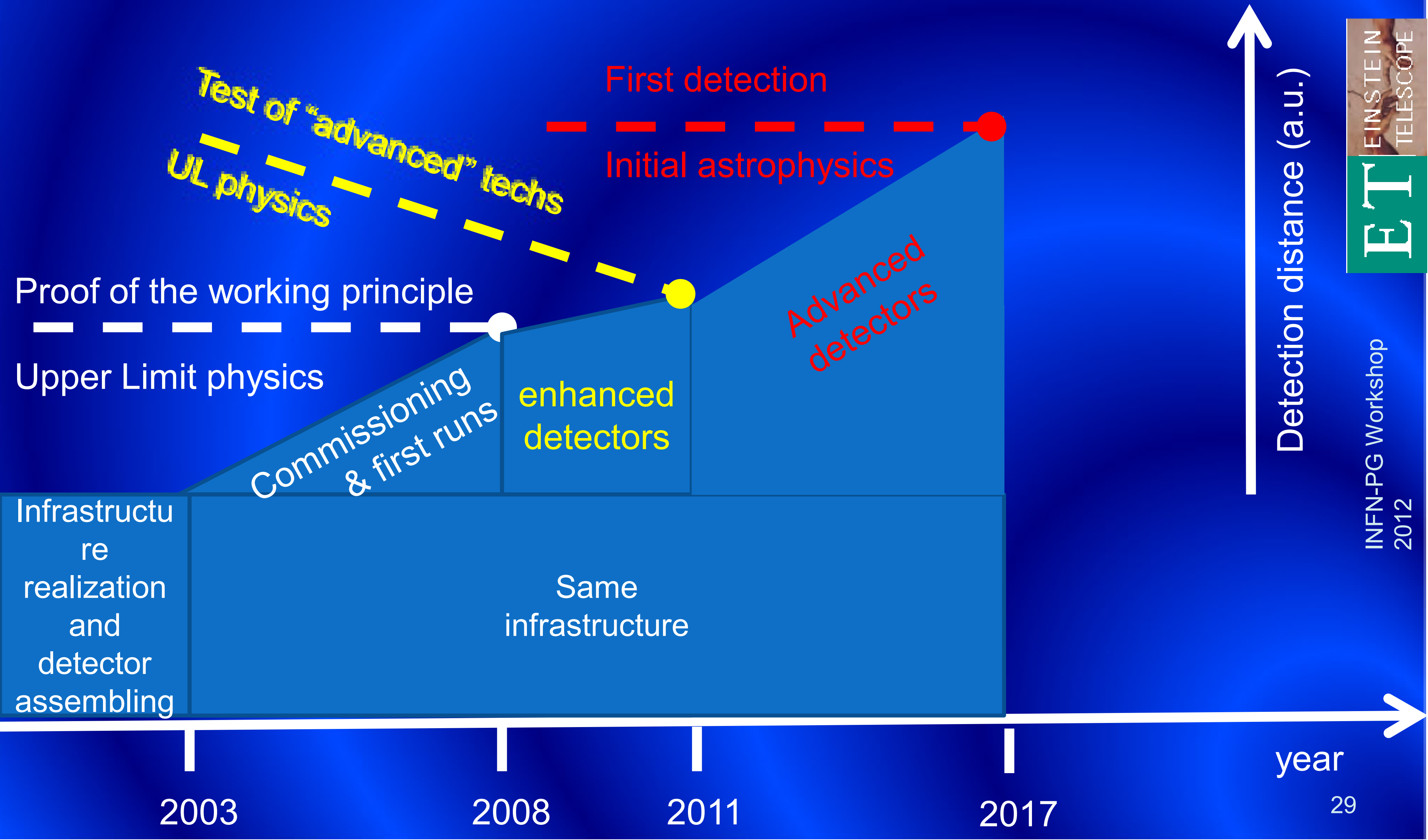


GRB mainly detected by Swift satellite

- A series (137) of GRB occurred during the LIGO-S5/Virgo-VSR1 run
- No detection occurred, but lower limit for the distance of each GRB event

GW interferometer present evolution

- Evolution of the GW detectors (Virgo example):



First detection

Initial astrophysics

Test of "advanced" techs

UL physics

Proof of the working principle

Upper Limit physics

Commissioning & first runs

enhanced detectors

Advanced detectors

Infrastructure realization and detector assembling

Same infrastructure

Detection distance (a.u.)

year

2003

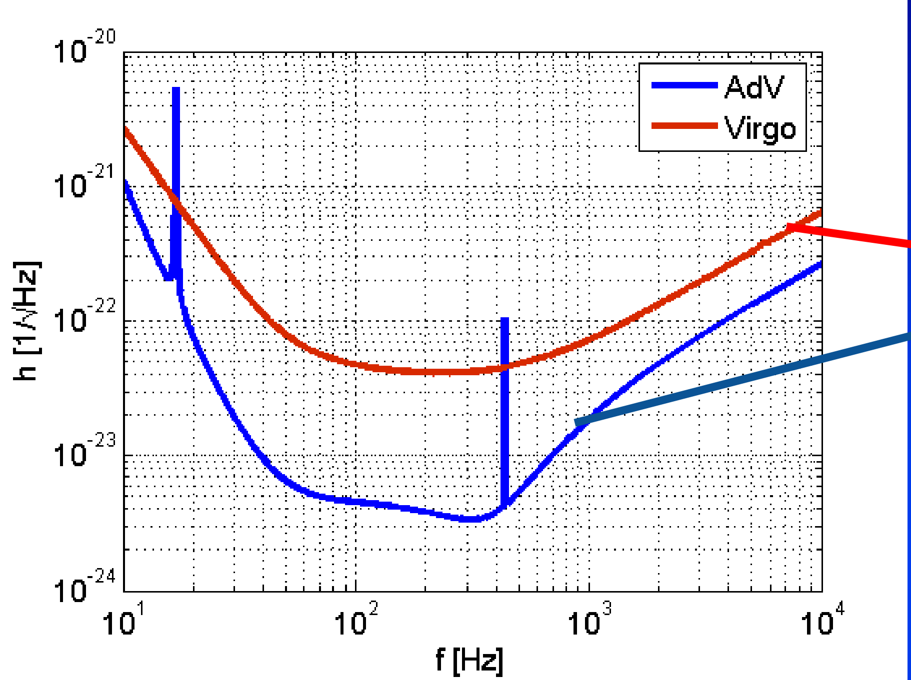
2008

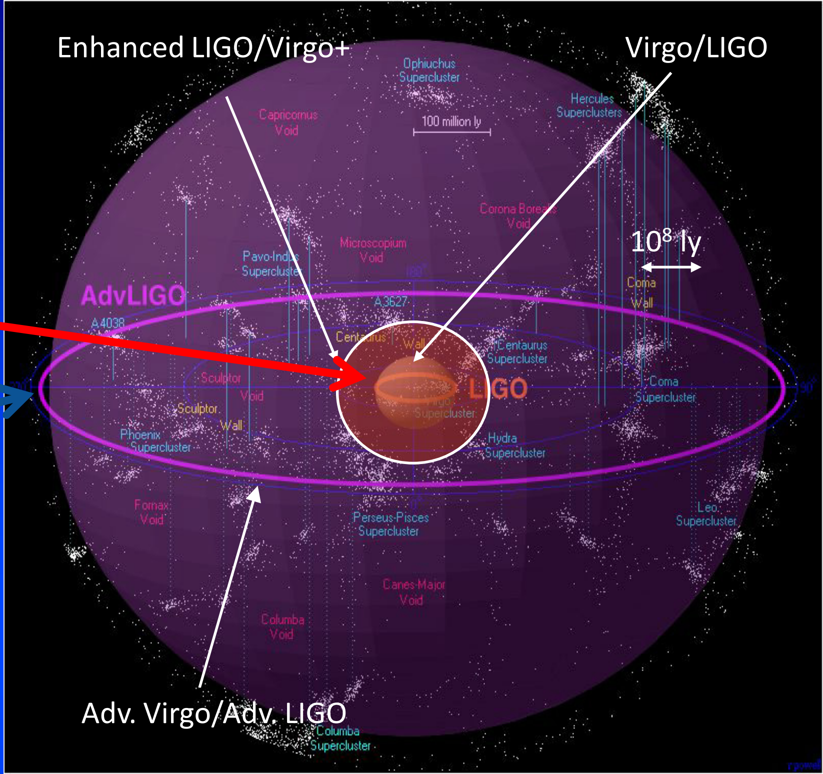
2011

2017

Advanced detectors

- The upgrade to the advanced phase (2^{nd} generation) is just started. The detectors should be back in commissioning in 2014
- Advanced are promising roughly a factor 10 in sensitivity improvement:



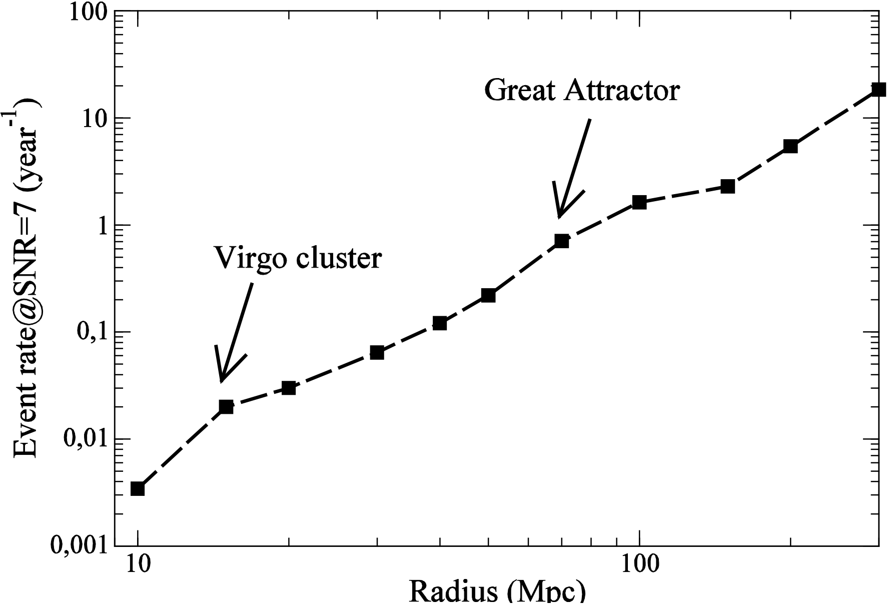


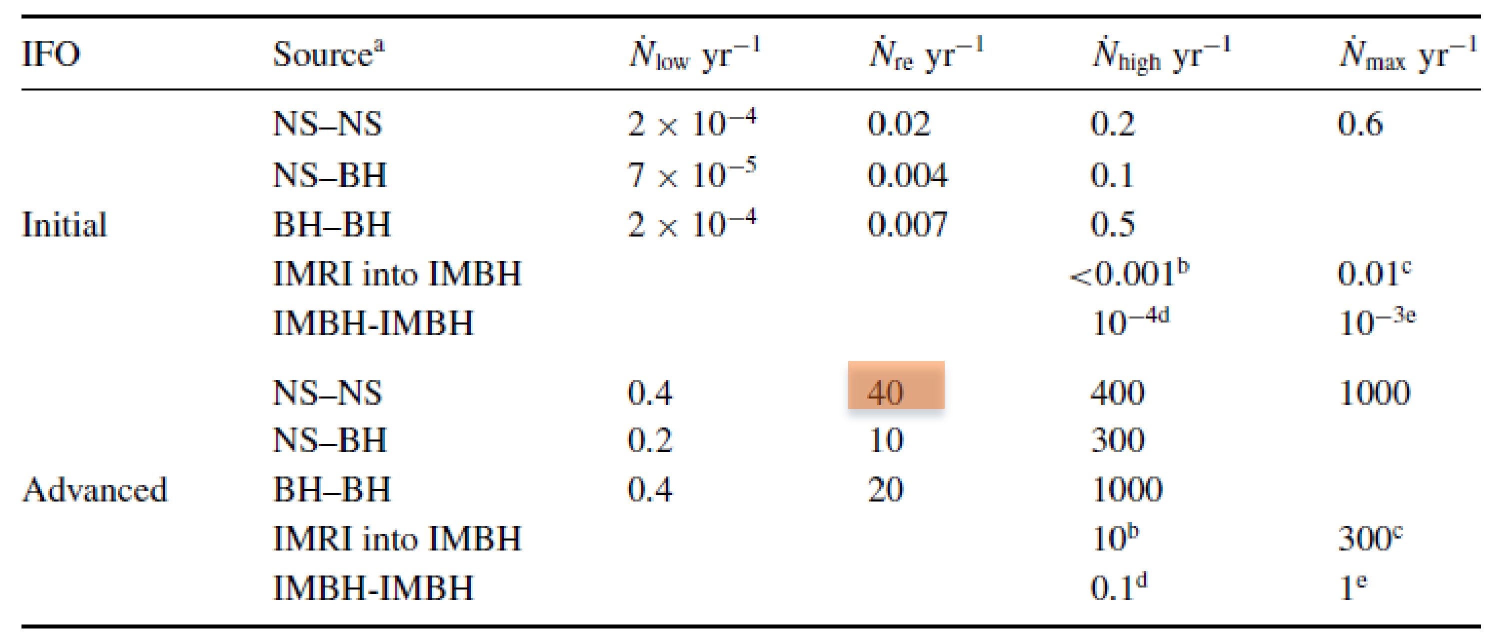
Credit: R.Powell, B.Berger

- This allows a detection distance for coalescing BNS of about 130-200Mpc

Advanced detectors: BNS detection rates

- The detection rate follows the sight distance with a roughly cubic law:
  - A BNS detection rate of few tens per year with a limited SNR: detection is assured



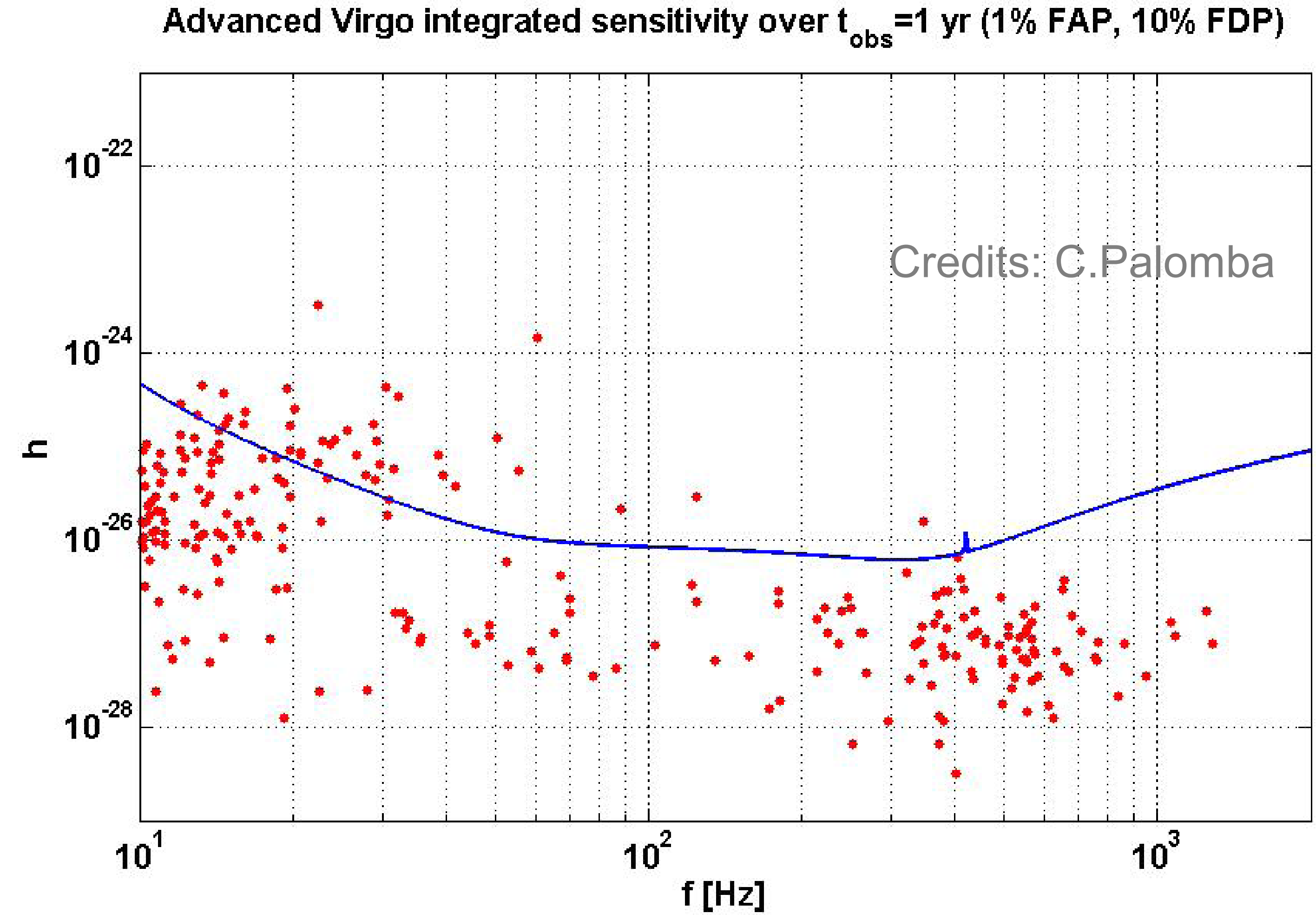


IFO	Source^{a}	$\dot{N}_{\mathrm{low}}$ yr^{-1}	$\dot{N}_{\mathrm{re}}$ yr^{-1}	$\dot{N}_{\mathrm{high}}$ yr^{-1}	$\dot{N}_{\mathrm{max}}$ yr^{-1}
Initial	NS–NS	2×10^{-4}	0.02	0.2	0.6
	NS–BH	7×10^{-5}	0.004	0.1	
	BH–BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			$<0.001^{b}$	0.01^{c}
	IMBH-IMBH			10^{-4d}	10^{-3e}
Advanced	NS–NS	0.4	40	400	1000
	NS–BH	0.2	10	300	
	BH–BH	0.4	20	1000	
	IMRI into IMBH			10^{b}	300^{c}
	IMBH-IMBH			0.1^{d}	1^{e}

Abadie et al. (LSC & Virgo), arXiv:1003.2480; CQG 27, 173001 (2010)

Advanced detectors: pulsars

- Better sensitivities, especially at low frequency, will allow to beat the spin-down limit for many pulsars



Credits: C.Palomba

New players !

- KAGRA
  - A 2.5 generation detector, under construction in Japan, implementing new (3G) underground and cryogenic technologies in a 3km long site in Kamioka (2018)

140M€ investment

New players !

- KAGRA
  - A 2.5 generation detector, under construction in Japan, implementing new (3G) underground and cryogenic technologies in a 3km long site in Kamioka (2018)
- LIGO-India
  - The move of aLIGO-H2 to India to improve pointing capabilities of the GW detector network (2018-2020) is almost decided
- AIGO
  - Attempt to build a GW interferometer in Australia

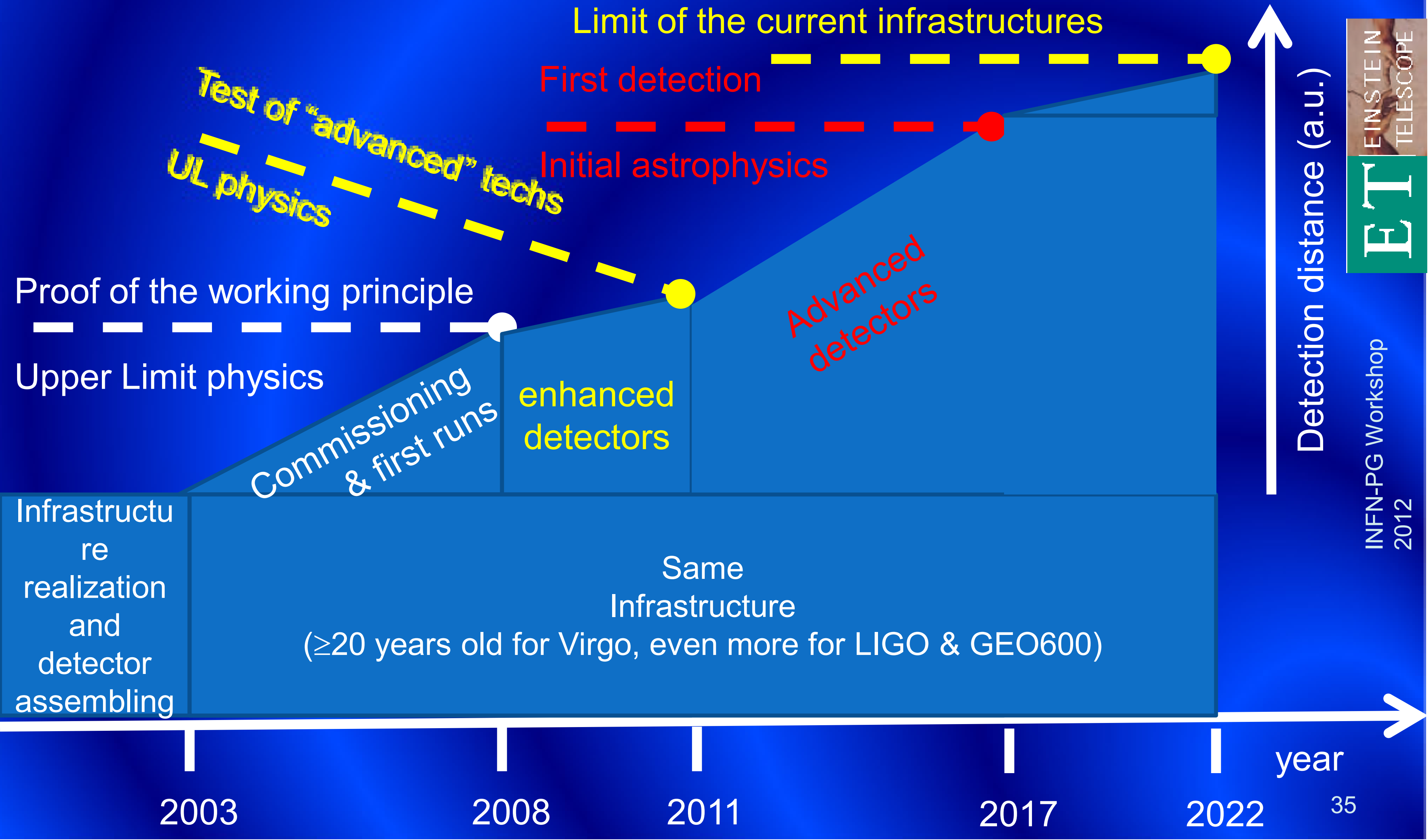
3rd generation?

Precision Astrophysics

Cosmology

?

- Evolution of the GW detectors (Virgo example):



Limit of the current infrastructures

First detection

Initial astrophysics

Test of “advanced” techs

UL physics

Proof of the working principle

Upper Limit physics

Commissioning & first runs

enhanced detectors

Advanced detectors

Infrastructure realization and detector assembling

Same Infrastructure (≥20 years old for Virgo, even more for LIGO & GEO600)

Detection distance (a.u.)

year

2003

2008

2011

2017

2022

ET EINSTEIN TELESCOPE

INFN-PG Workshop 2012

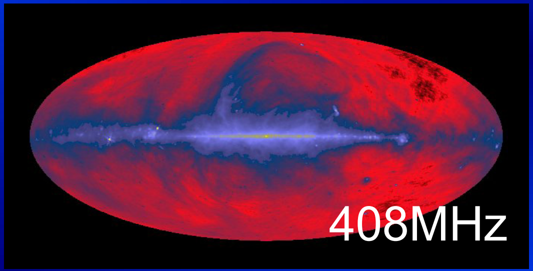
GW Astronomy?

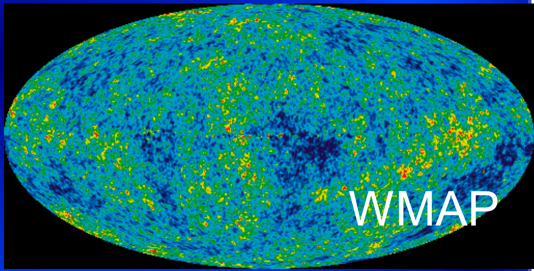
- Is our target the precision Astronomy with GW detectors?
  - Let learn from who is doing astronomy now:

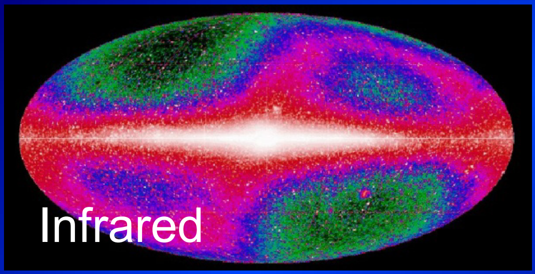
“Electro-magnetic” Telescopes

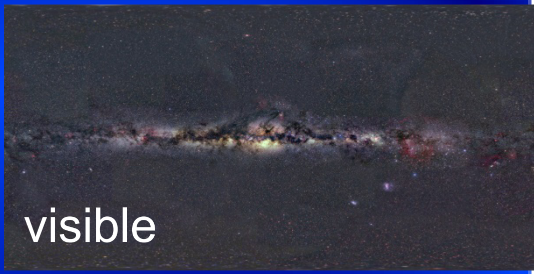
E.M. Astronomy

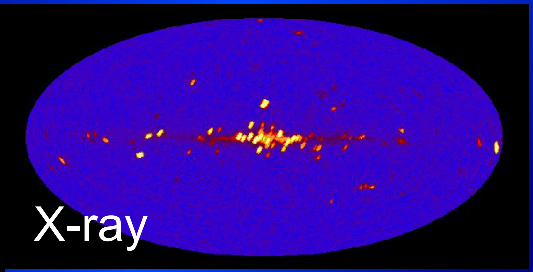
- Current e.m. telescopes are mapping almost the entire Universe
- Keywords:
  - Map it in all the accessible wavelengths
  - See as far as possible
    - Galaxy UDFy-38135539 in Ultra Deep Field image (Hubble Telescope) ~ 13.1 Gly

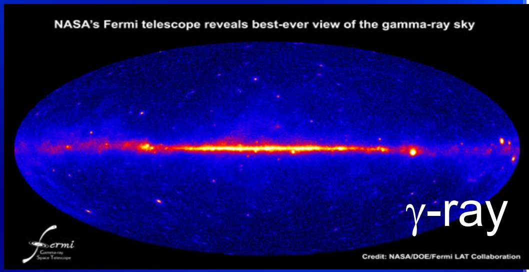


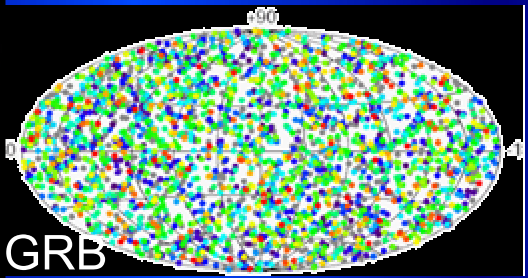








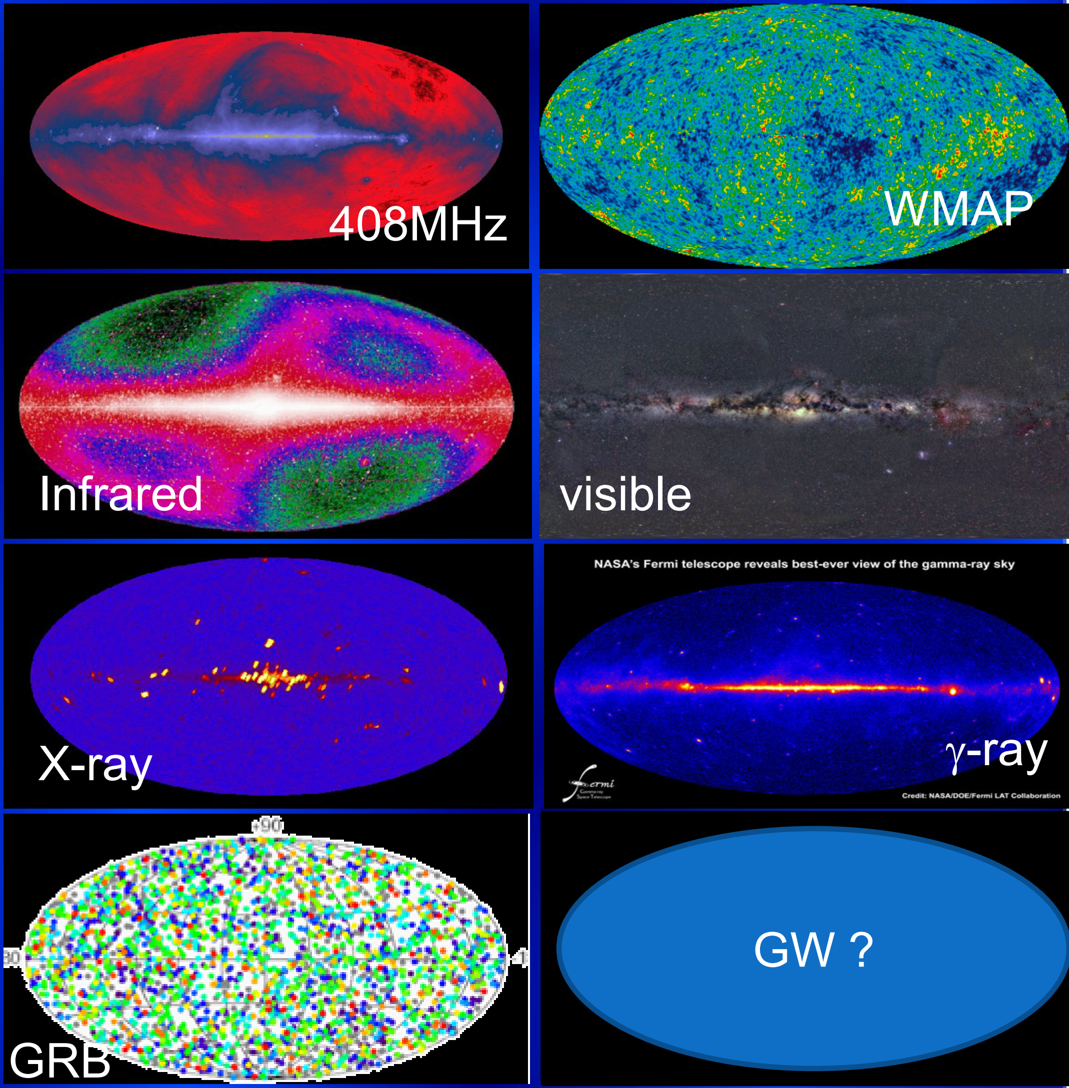




M. Trenti, Nature 467, 924–925 (21 October 2010)

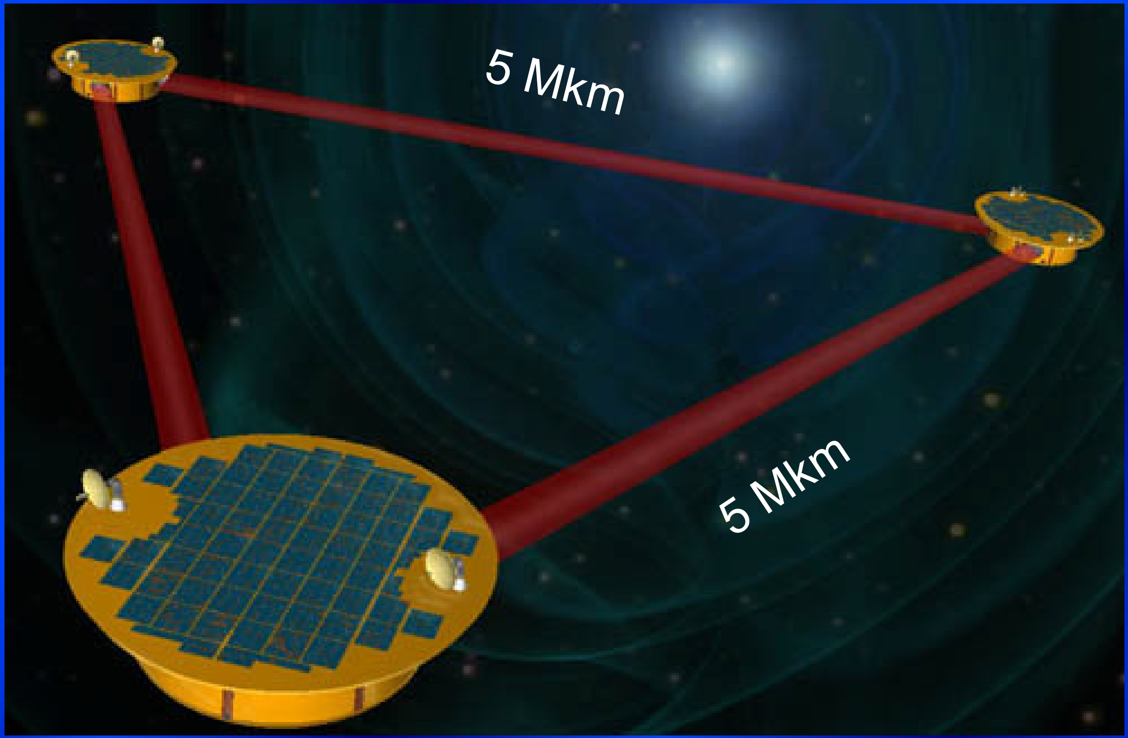
GW Astronomy ?

- Enlarge as much as possible the frequency range of GW detectors
  - Pulsar Timing Arrays
    - 10^{-9}-10^{-6} Hz
  - Space based detectors (LISA/NGO, DECIGO)
    - 10^{-5}-10^{-1} Hz
  - Ground based detectors
    - 1-10^{4}Hz
- Improve as much as possible the sensitivity to increase the detection volume (rate) and the observation SNR



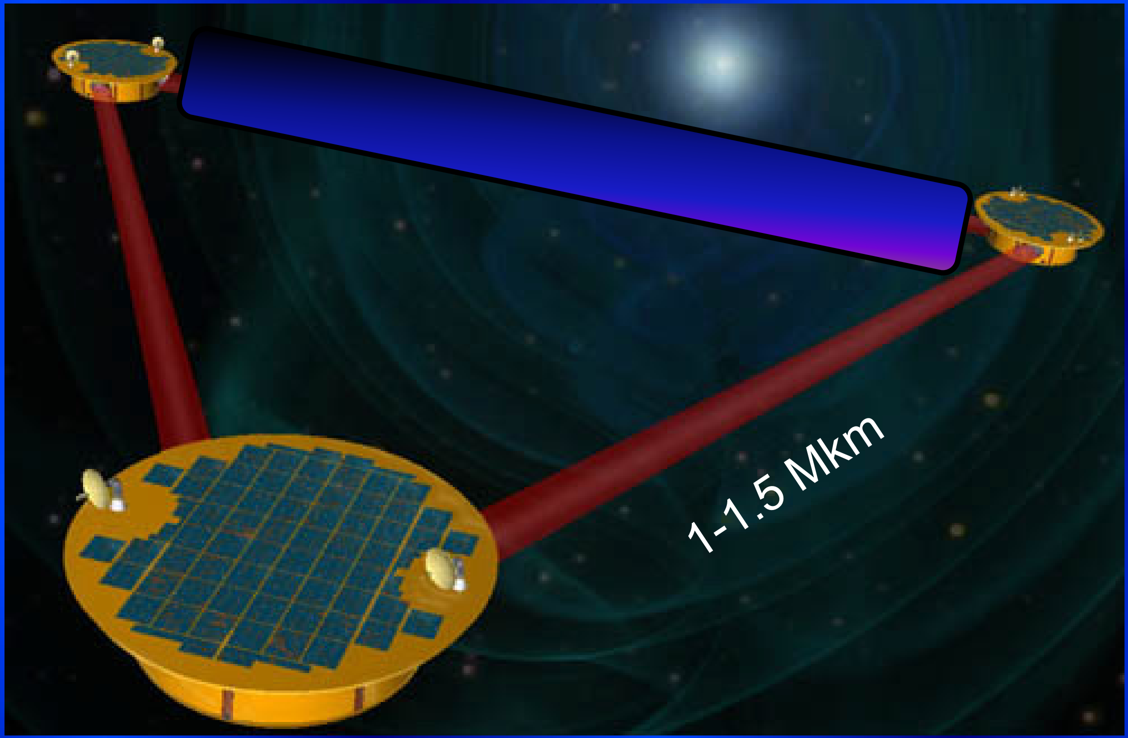
LISA

- Space based gravitational wave detector
- ESA-NASA project
- Focused in the very low frequencies: $10^{-5} – 10^{-2}$ Hz



eLISA/NGO

- Space based gravitational wave detector
- ESA-~~NASA~~ project
- Focused in the ~~very~~ low frequencies: 10^{-3} – 10^{-1} Hz



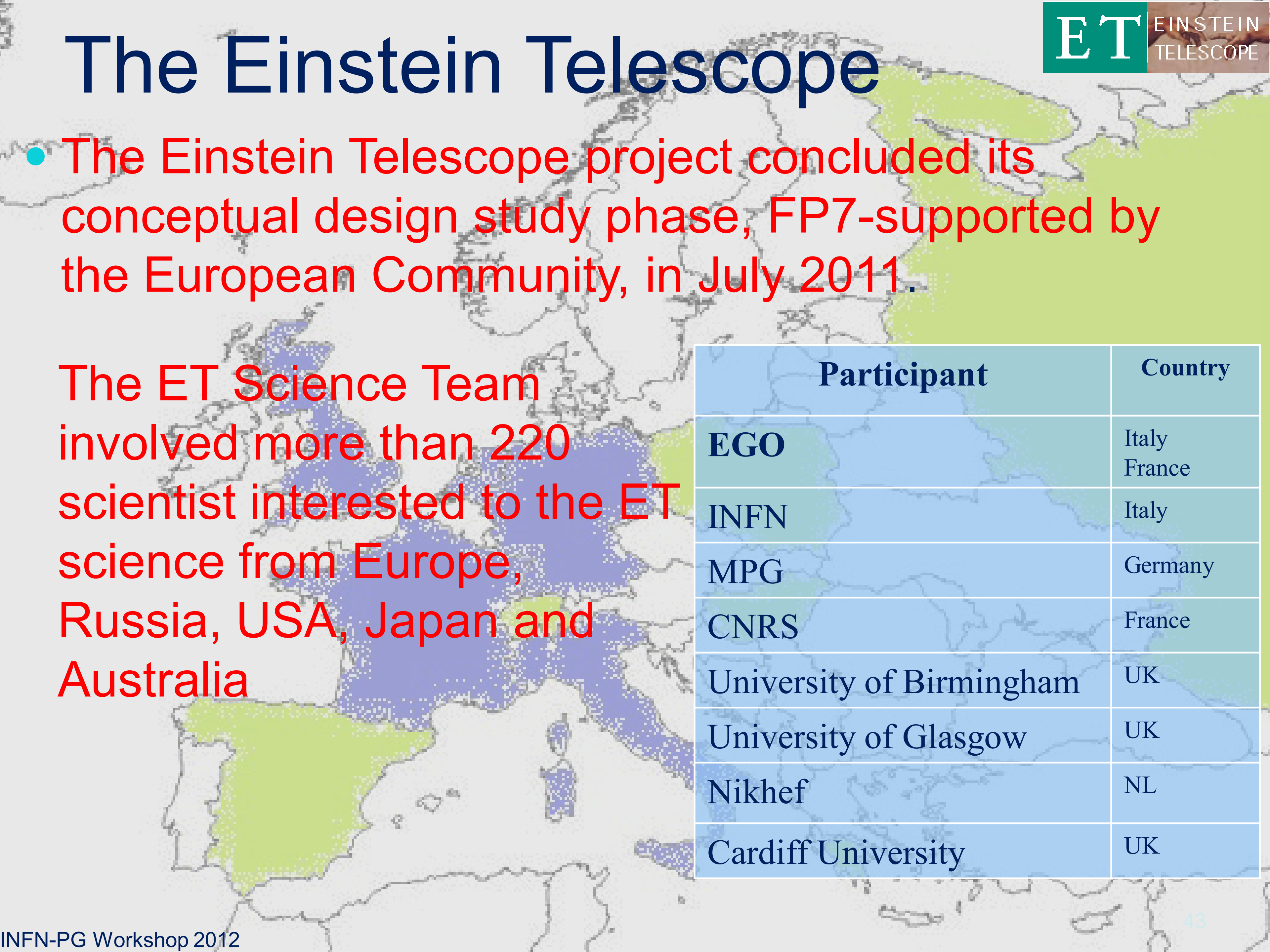
Beyond Advanced Detectors

- Let suppose to gain a factor 10 wrt the Advanced detectors: What could we do?
- Astrophysics:
  - Measure in great detail the physical parameters of the stellar bodies composing the binary systems
    - NS-NS, NS-BH, BH-BH
    - Constrain the Equation of State of NS through the measurement
      - of the merging phase of BNS
      - of the NS stellar modes
      - of the gravitational continuous wave emitted by a pulsar NS
  - Contribute to solve the GRB enigma
- Relativity
  - Compare the numerical relativity model describing the coalescence of intermediate mass black holes
  - Test General Relativity against other gravitation theories
- Cosmology
  - Measure few cosmological parameters using the GW signal from BNS emitting also an e.m. signal (like GRB)
  - Probe the first instant of the universe and its evolution through the measurement of the GW stochastic background
- Astro-particle:
  - Contribute to the measure the neutrino mass
  - Constrain the graviton mass measurement

Scientific Potential of Einstein Telescope
B.S.Sathyaprakash et al., CQG 29 (2012), 124013 ,
arXiv:1108.1423v2 [gr-qc]

3G

The Einstein Telescope



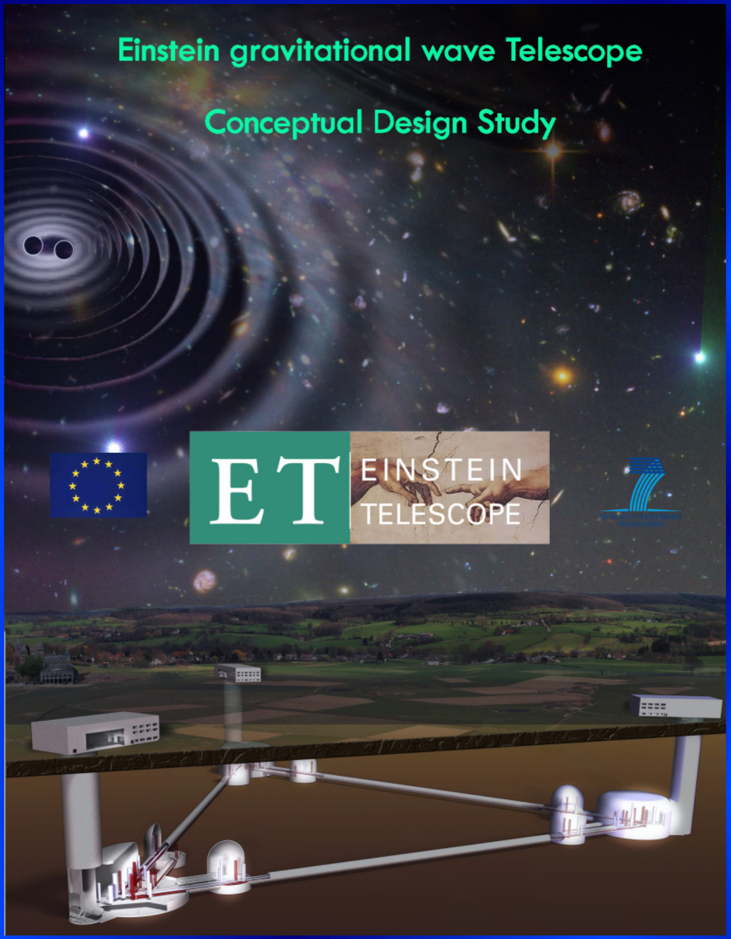
- The Einstein Telescope project concluded its conceptual design study phase, FP7-supported by the European Community, in July 2011.

The ET Science Team involved more than 220 scientist interested to the ET science from Europe, Russia, USA, Japan and Australia

Participant	Country
EGO	Italy France
INFN	Italy
MPG	Germany
CNRS	France
University of Birmingham	UK
University of Glasgow	UK
Nikhef	NL
Cardiff University	UK

Conceptual Design Document

- ET conceptual design document released:
  - https://tds.ego-gw.it/ql/?c=7954
- ~400 pages describing the main characteristics of the observatory
- The main conclusion is the demonstration of the need of a **new research infrastructure**, allowing the prosecution of the GW **observation** for decades.



Einstein gravitational wave Telescope

Conceptual Design Study

ET EINSTEIN TELESCOPE

ET: a 3rd generation GW observatory

- ET will be an underground & cryogenic set of detectors
- The Japanese KAGRA, under construction, is pioneering the technology

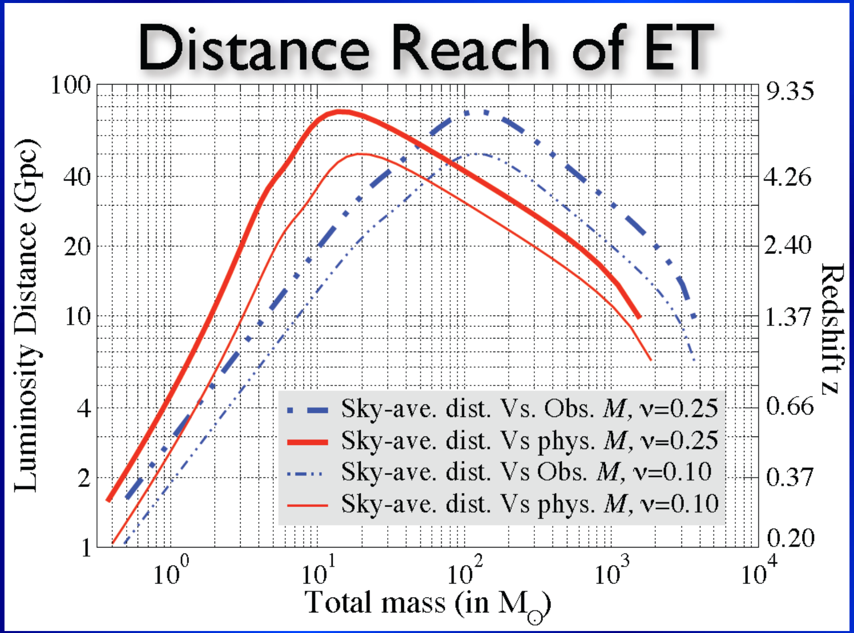
KAGRA

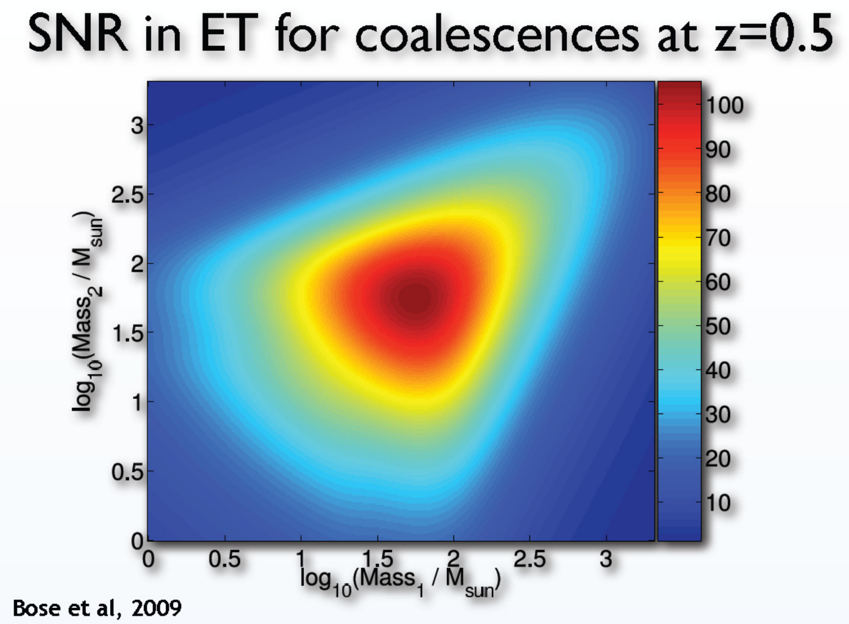
SEVENTH FRAMEWORK PROGRAMME

ELiTES

ET EINSTEIN TELESCOPE

Binary System of massive stars


Distance Reach of ET


SNR in ET for coalescences at z=0.5

Bose et al, 2009

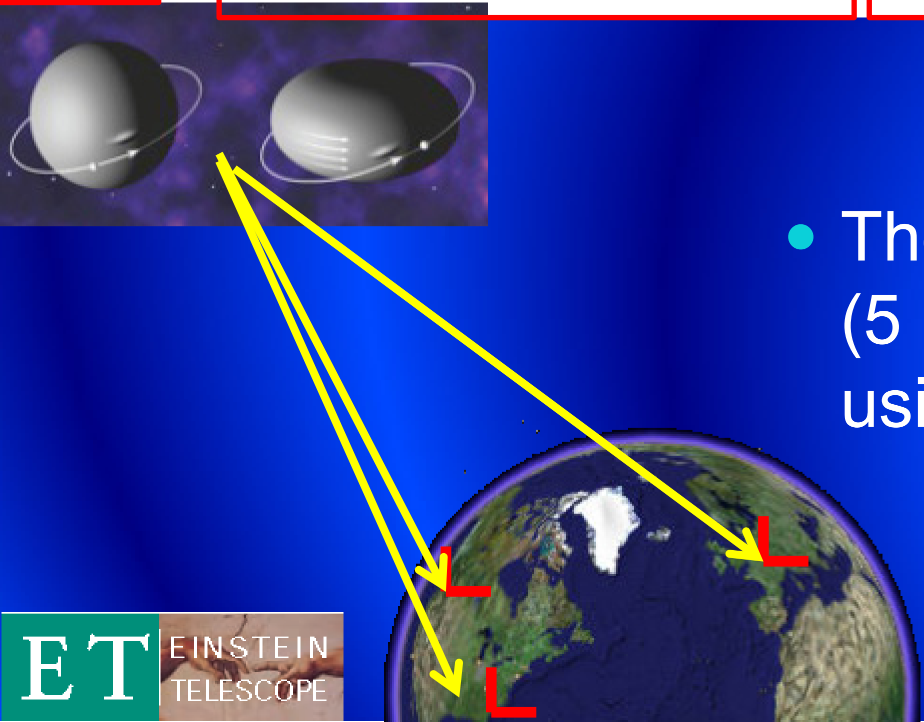
- The new possibilities (for BS) of a 3rd generation GW observatory emerge from these two plots:
  - Cosmological detection distance
  - Frequent high SNR events

Cosmological detection distance

- BNS are considered “standard sirens” (Schutz 1986) because, the amplitude depends only on the Chirp Mass and Luminosity distance D_L

$$\boxed{A(t)} = \boxed{\left[M_c\left(m_1, m_2\right)\right]^{\frac{5}{3}}\left[\omega(t)\right]^{\frac{2}{3}}}\,\boxed{\frac{F(\theta, \phi, \psi, i)}{D_L}}$$

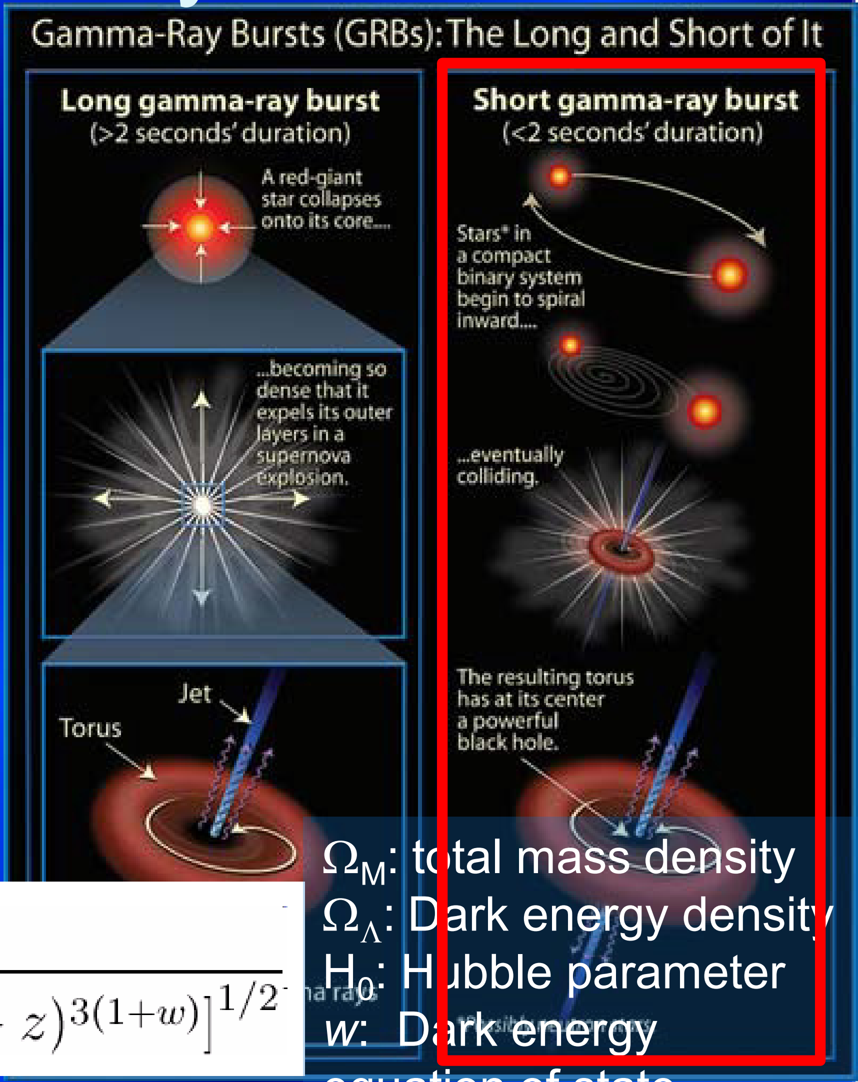
- The masses are determined by detecting the frequency sweep through matched filtering



- The sky localization of the source (5 parameters) is determined by using 3 detectors

Multi-messenger Astronomy: GW+GRB

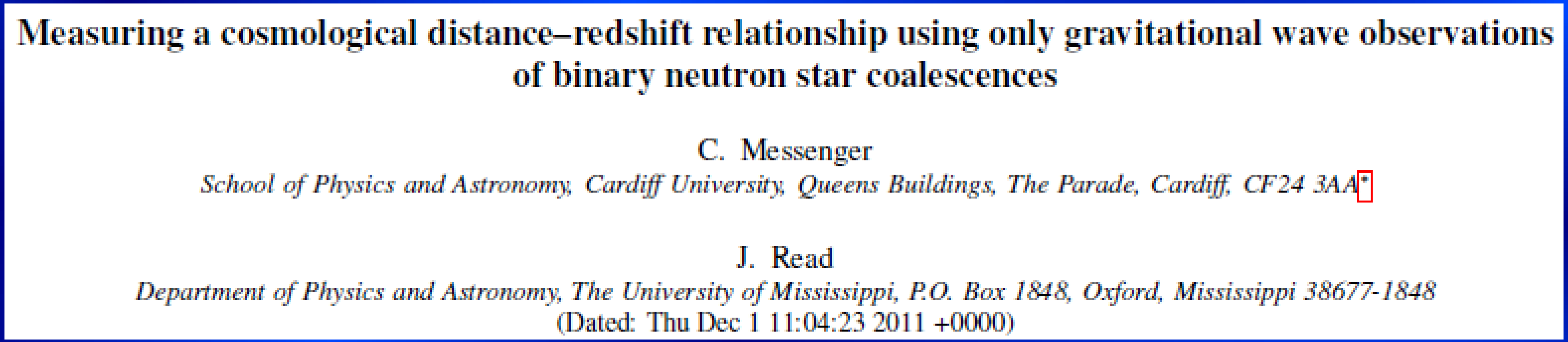
- The red-shift ambiguity “requires” an E.M. counterpart (GRB) to identify the hosting galaxy and then the red-shift *z*.
- Knowing D_L and *z* it is possible to probe the adopted cosmological model:



$$D_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz}{\left[\Omega_M (1+z)^3 + \Omega_\Lambda (1+z)^{3(1+w)}\right]^{1/2}}$$

Ω_M: total mass density
Ω_Λ: Dark energy density
H_0: Hubble parameter
w: Dark energy equation of state parameter

Cosmology with ET



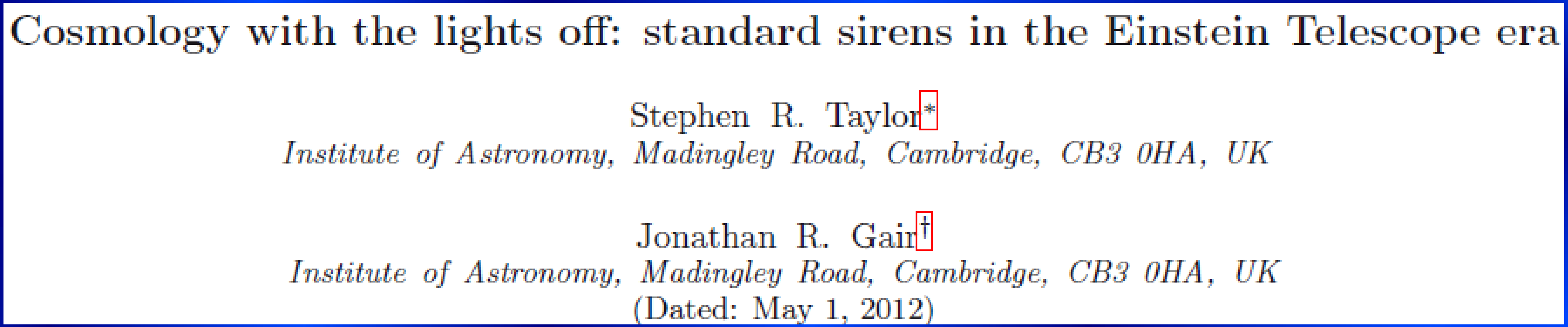
Measuring a cosmological distance–redshift relationship using only gravitational wave observations of binary neutron star coalescences

C. Messenger
School of Physics and Astronomy, Cardiff University, Queens Buildings, The Parade, Cardiff, CF24 3AA[*]

J. Read
Department of Physics and Astronomy, The University of Mississippi, P.O. Box 1848, Oxford, Mississippi 38677-1848

(Dated: Thu Dec 1 11:04:23 2011 +0000)

- BNS aren't point particles! In the last phase of the coalescence the tidal deformation plays a role in the phase of the emitted wave and, if the EOS of the NS is known, it is possible to compute the physical masses: the degeneracy is broken!



Cosmology with the lights off: standard sirens in the Einstein Telescope era

Stephen R. Taylor[*]
Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, UK

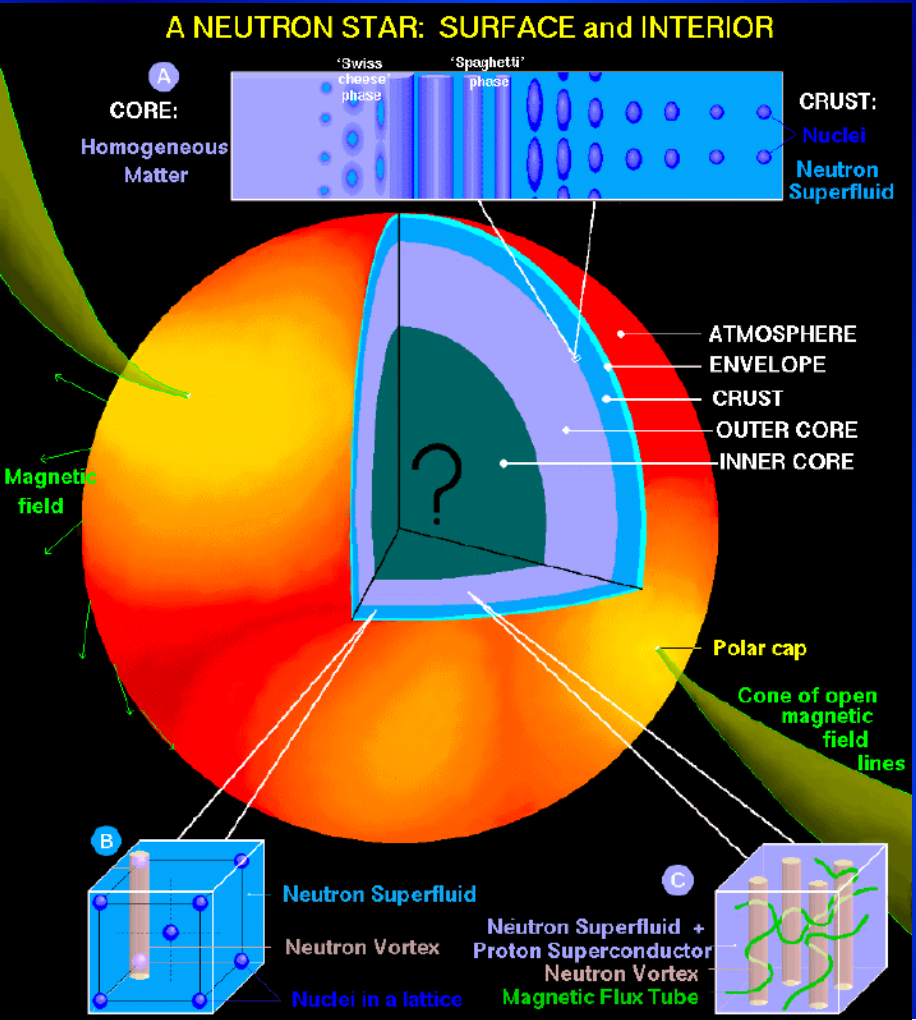
Jonathan R. Gair[†]
Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, UK

(Dated: May 1, 2012)

- The mass distribution of NS is quite narrow → the incertitude on the physical mass is small knowing the reconstructed mass

Neutron Stars (NS)

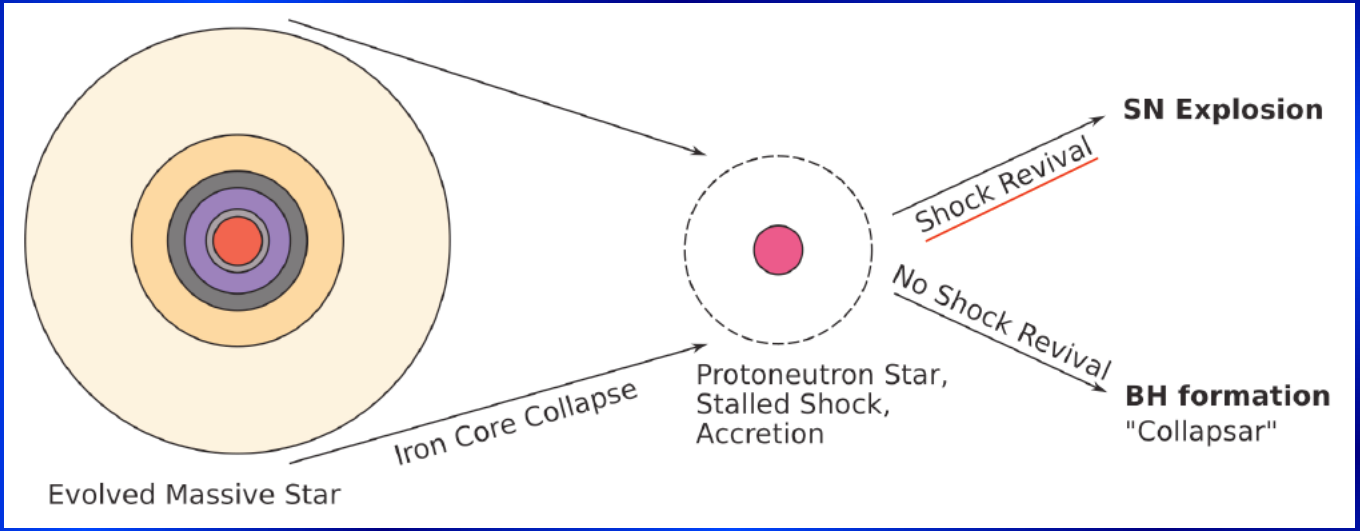
- The EOS of the NS matter is still unknown
  - Why it pulses? It is a neutron or a “strange” matter star?



- What is the role of the Magnetic field in a NS?
- GW could investigate the NS EOS detecting the signal produced in different processes:
  - Coalescence of binaries
    - Full NR simulation of the plunge and merger phase
  - Asteroseismology
    - Detecting the internal modes of the NS
  - Continuous Wave (CW) emission of isolated NS

Supernova Explosions

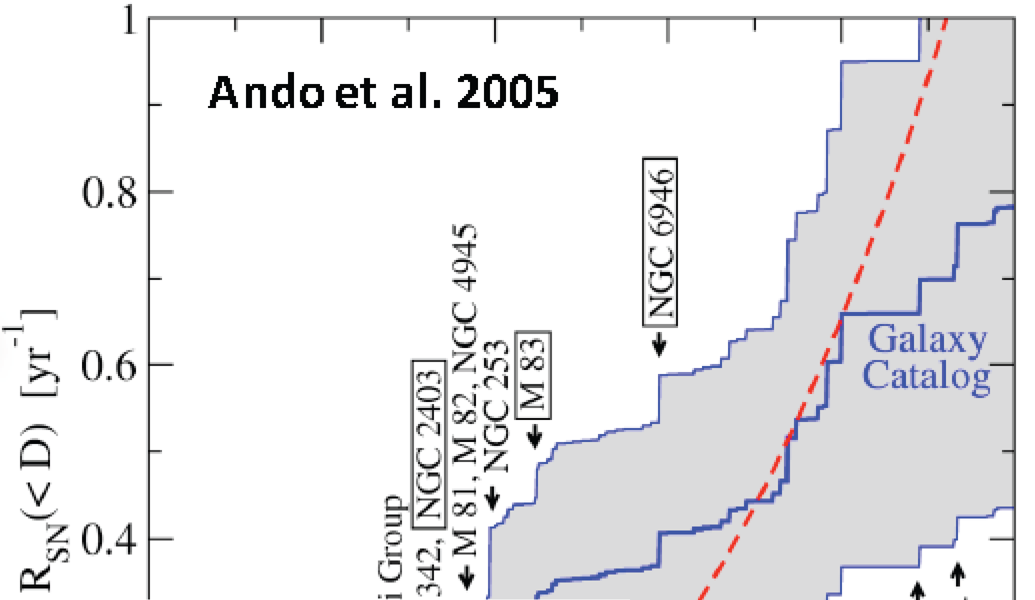
- Mechanism of the core-collapse SNe still unclear
  - Shock Revival mechanism(s) after the core bounce TBC

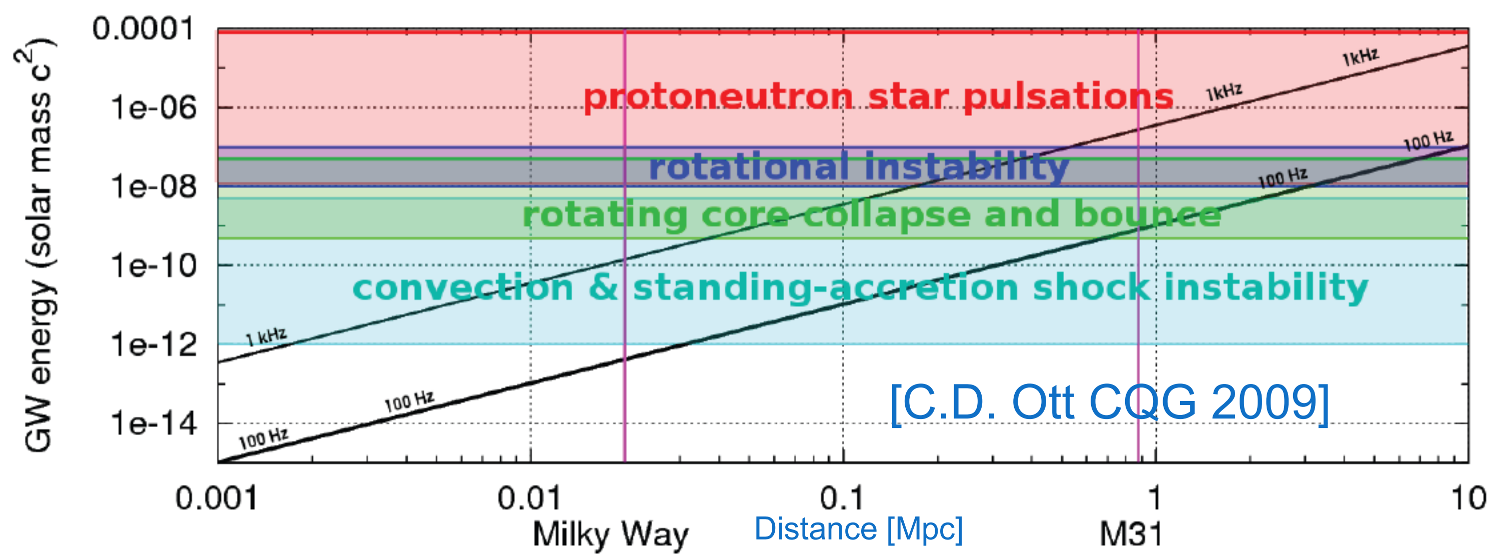


- GWs generated by a SNe should bring information from the inner massive part of the process and could constrains on the core-collapse mechanisms

SNe rates with ET

- Expected rate for SNe is about 1 evt / 20 years in the detection range of initial to advanced detectors
  - Our galaxy & local group
- To have a decent (0.5 evt/year) event rate about 5 Mpc must be reached
- ET nominal sensitivity can promise this target



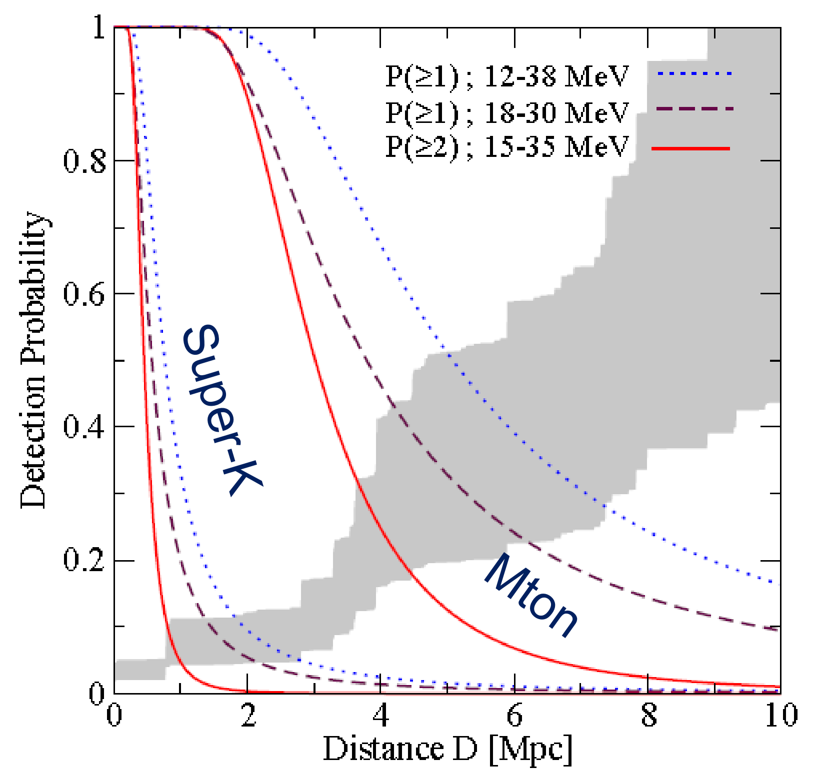


[C.D. Ott CQG 2009]

Neutrinos from SNe

- SNe detection with a GW detector could bring additional info:
  - The 99% of the 10^{53} erg emitted in the SNe are transported by neutrinos
  - If a “simultaneous” detection of neutrinos and GW occurs the mass of the neutrino could be constrained at 1eV level (Arnaud 2002)
- But looking at the detection range of existing neutrino detectors (<Local group limited) is discouraging
- Some promising evaluation has been made (Ando 2005) for the next generation of Megaton-scale detectors

Ando 2005



Conclusions

- GW detection is expected within ~5 years
  - Or something wrong is in GR
- The research field is still growing (new actors)
- GW astronomy will be consolidated gaining anther factor 10 in sensitivity wrt advanced detectors:
  - 3G (Einstein Telescope)

END