Introduction to the detection of gravitational waves

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Plan of the talk

1. GW research motivations
2. Sources
3. Principles of interferometric detection
4. What is Virgo
5. LIGO-Virgo joint observation
6. The discovery
7. The start of the GW astronomy

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Coupling constants

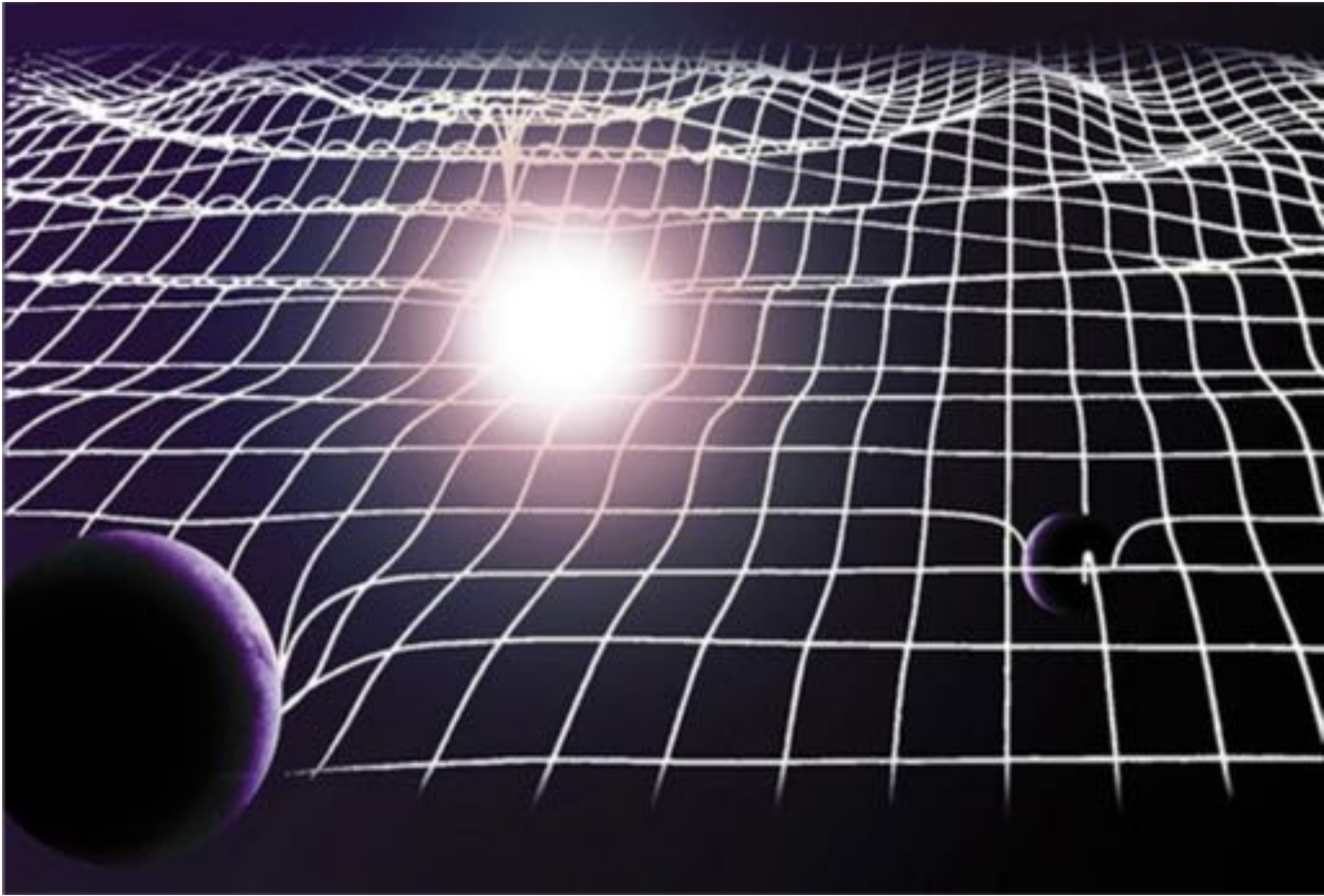
strong	*e.m.*	*weak*	*gravity*
0.1	1/137	10^{-5}	10^{-39}

GW emission: very energetic events but almost no interaction

- In SN collapse ν withstand 10^3 interactions before leaving the star, GW leave the core undisturbed
- Decoupling after Big Bang
  - GW $\sim 10^{-43}$ s ($T \sim 10^{19}$ GeV)
  - ν $\sim$ 1 s ($T \sim 1$ MeV)
  - e.m. $\sim 10^{12}$ s ($T \sim 0.2$ eV)

Ideal information carrier,
Universe transparent to GW all the way back to the Big Bang!!

The equations of general relativity



Einstein notations

- The indexes α,β,δ,ν,μ, correspond to the 4- dimensions of the space-time.
- Two equal indexes mean that a summation is implicitly assumed to be present in the formula
- Coordinates with superscript index are called contro-variant a^{α} , those with subscript index are co-variant a_{α}. ➔ $a_m = a^m$, $a_1 = -a^1$

$$a^{\alpha} b_{\alpha} = \sum_{\alpha=1,4} a^{\alpha} b_{\alpha}$$

The geometry of the space-time

- Minkowski geometry

$$ds^2 = \eta_{\alpha\beta}\, dx^\alpha dx^\beta$$

η is the diagonal matrix whose diagonal elements are $(-c, 1, 1, 1)$

- In general, in a curved space

$$ds^2 = g_{\alpha\beta} dx^\alpha dx^\beta$$

where g is the metric tensor, a 4×4 matrix whose elements are functions of the space coordinates

- A free particle follows a geodetic line of the space-time

- The properties of the space-time geometry are embedded in the Riemann tensor, which depends on the second derivates of the metric tensor g

Crucial quantities

$$R^i_{klm} = \frac{\partial \Gamma^i_{km}}{\partial x^l} - \frac{\partial \Gamma^i_{kl}}{\partial x^m} + \Gamma^i_{nl}\Gamma^n_{km} - \Gamma^i_{nm}\Gamma^n_{kl}$$

Riemann Tensor

$$\Gamma^i_{kl} = \frac{1}{2} g^{im}\left(\frac{\partial g_{mk}}{\partial x^l} + \frac{\partial g_{ml}}{\partial x^k} - \frac{\partial g_{kl}}{\partial x^m}\right)$$

Christoffel symbols

$$g^k_i R^i_{k\mu\nu} = R_{\mu\nu}$$

Ricci Tensor

$$R = g^{\mu\nu} R_{\mu\nu}$$

Ricci scalar

$$T_{\mu\nu}$$

Stress-energy tensor, connected to the system mass-energy distribution.

VIRGO

From Einstein to wave equation

Einstein equations

$$R_{ij} - \frac{1}{2} g_{ij} R^{\lambda}{}_{\lambda} = -\frac{8\pi G}{c^4} T_{ij}$$

$$R^{k}{}_{ijm}(\Gamma^{k}{}_{ij}, \frac{\partial \Gamma^{k}{}_{ij}}{\partial x^{m}})$$

$$\Gamma^{k}{}_{ij}(g_{ij}, \frac{\partial g_{ik}}{\partial x_{m}})$$

In general no analytical solution…

Weak filed hypothesis g_{ik} » $\eta_{ik} + h_{ik}$ $|h_{ik}|$ « 1

At the first order in h and assuming the harmonic gauge $\frac{\partial h^{\alpha}_{\beta}}{\partial x_{\beta}}$

The wave equation

$$(\partial^2/\partial x^\lambda \partial x_\lambda)\, h_{\mu\nu} - (\partial^2/\partial x^\lambda \partial x^\mu)\, h^\lambda{}_\nu - (\partial^2/\partial x^\lambda \partial x^\nu)\, h^\lambda{}_\mu + (\partial^2/\partial x^\mu \partial x^\nu)\, h^\lambda{}_\lambda = -(16\pi G/c^4) T'_{\mu\nu}$$

$$\Box h_{ij} = -\frac{16\pi G}{c^4} T_{ij} - \frac{1}{2}\eta_{ij} T^\lambda{}_\lambda$$

$$h_{ij} = -\frac{4\pi}{c^4} \int \frac{\left[T_{ij} - \frac{1}{2}\eta_{ij} T^\lambda{}_\lambda \right]_{t-r/c}}{\vec{x} - \vec{x}'} d^3 \vec{x}'$$

In the free space $\longrightarrow$ $\Box h_{ij} = 0$

The plane wave

$$\Box h_{ij} = -\frac{16\pi G}{c^4}\left(T_{ij} - \frac{1}{2}\eta_{ij}T^{\lambda}{}_{\lambda}\right) \longrightarrow h_{ij} = -\frac{4\pi}{c^4}\int \frac{\left[T_{ij} - \frac{1}{2}\eta_{ij}T^{\lambda}{}_{\lambda}\right]_{t-r/c}}{\vec{x} - \vec{x}'} d^3\vec{x}'$$

In the free space $\longrightarrow$ $\Box h_{ij} = 0$

$\downarrow$

$$h_{ij} = \varepsilon_{ij} e^{ik_\lambda x^\lambda} + \varepsilon_{ij}{}^{*} e^{-ik_\lambda x^\lambda}$$

(Dispersion equation)

$$k_\lambda k^\lambda = 0$$

$$k_i \mathring{a}^i{}_j = \frac{1}{2} k_j \mathring{a}^i{}_i$$

Gauge TT $\longrightarrow$ 4 of the 6 independent components of the tensor ε αρε ζερο

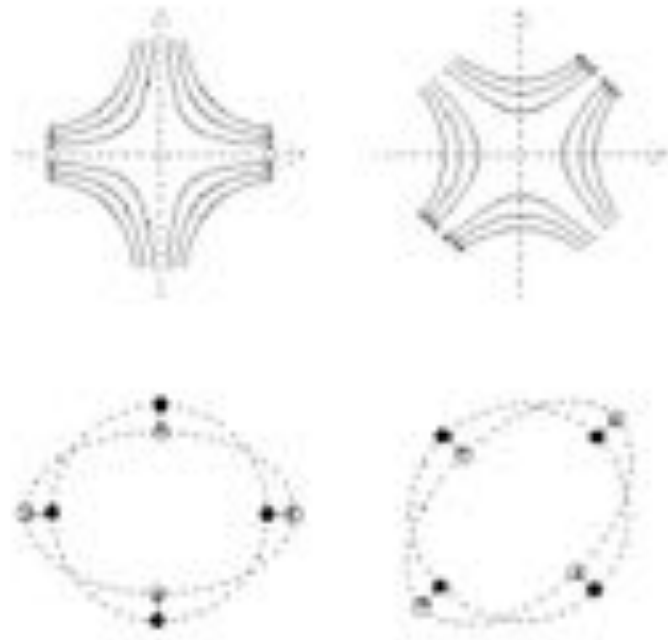
2 independent components ➔ 2 polarizations

Assuming a propagation along z $\longrightarrow$

$$\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_{xx} & h_{xy} & 0 \\ 0 & h_{yx} & h_{yy} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_X & 0 \\ 0 & h_X & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

The effect of a gravitation wave on test particles

$$\delta\xi^{\alpha} = \frac{1}{2} h^{TT}_{\alpha\beta} \xi_{\beta}$$



Polarization plus
+

Polarization cross
X

The GW emission

$$h_{ij} = -\frac{4\pi}{c^4}\int \frac{\left[T_{ij} - \frac{1}{2}\eta_{ij}T^{\lambda}{}_{\lambda}\right]_{t-r/c}}{\vec{x}-\vec{x}'} d^3\vec{x}' \longrightarrow$$ Multipole expansion (r_{source}/λ)

$$\vec{d} = \int \rho(\vec{x}) d^3\vec{x} \longrightarrow \ddot{\vec{d}} = 0$$ Momentum conservation

$$\vec{\mu} = \int \rho(\vec{x})\vec{x}\times v(\vec{x}) d^3\vec{x} \longrightarrow \dot{\vec{\mu}} = 0$$ Angular momentum conservation

$$\ddot{I}_{jk} = \int \left(x_{\mu}x_{\nu} - \frac{1}{3}\delta_{\mu\iota}r^2 \right) \rho(\vec{x}) d\vec{x}$$ First term contributing to the emission

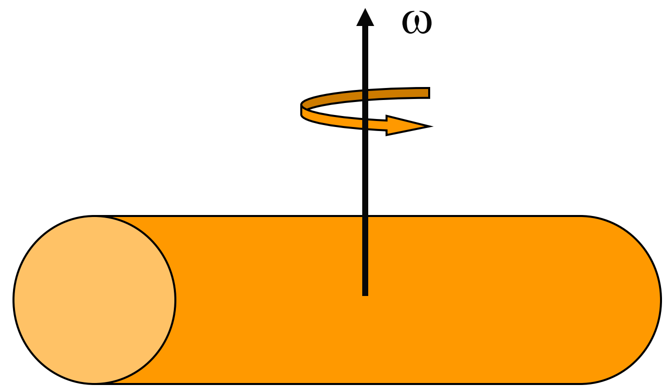
$$L = \frac{1}{5}\frac{G}{c^5}\left[\dddot{I}_{jk}(t - r/c)\right]^{TT}$$ Source Luminosity

Order of magnitude I

$$L = \frac{1}{5}\frac{G}{c^5}\left[\dddot{I}_{jk}(t - r/c)\right]^{TT}$$

$$L \approx \frac{G}{c^5} M^2 L^4 \omega^6$$

(3.6 x 10^{-52} W)$^{-1}$



M = 1000 tons

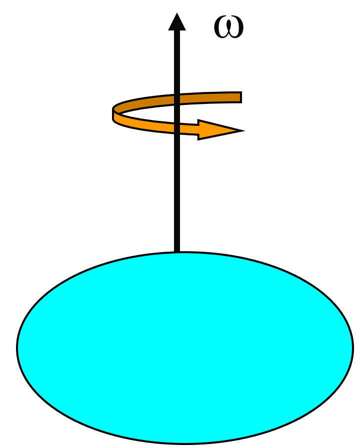
L = 100 m

ω = 10 rad / s

Luminosity ~ 10^{-26} W !!!

Order of magnitude II

$$L = \frac{1}{5}\frac{G}{c^5}\left[\dddot{I}_{jk}(t - r/c)\right]^{TT}$$



Compact stellar Object

$$L \approx \frac{G}{c^5} M^2 L^4 \omega^6$$

$$r_S \approx \frac{2GM}{c^2} \rightarrow M \approx \frac{c^2 r_S}{2G} \approx \frac{c^2 r_S}{G}$$

$$v = r\omega \rightarrow \omega \approx v/r \rightarrow \omega \approx \beta(c/r)$$

$3\ 10^{-2}$ $3\ 10^{-2}$

Pre-coalescinig Neutron Stars

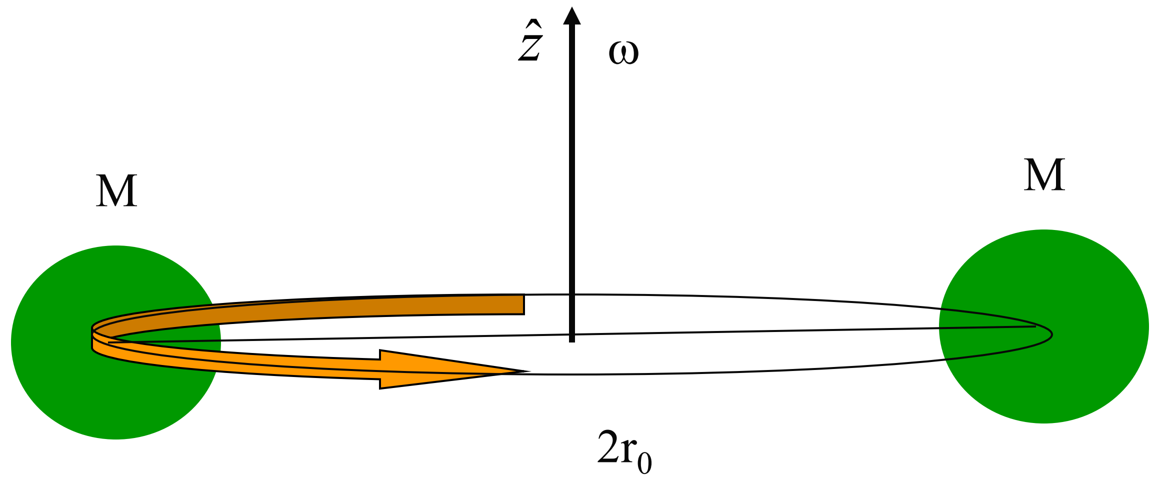
$$L \approx \frac{G}{c^5} M^2 L^4 \omega^6 \approx \frac{G}{c^5} \cdot \frac{c^4 r_s^2}{G^2} \cdot r^4 \cdot \frac{\beta^6 c^6}{r^6} \approx \frac{c^5}{G}\left(\frac{r_s}{r}\right)^2 \beta^6$$

Luminosity 10^{43} W → 10^{17} Sun luminosity

Binary system

$$h_{jk} = \frac{2}{r}\frac{G}{c^4}\left[\ddot{I}_{jk}(t-r/c)\right]^{TT}$$

$$\ddot{I}_{jk} = \int\left(x_\mu x_\nu - \frac{1}{3}\delta_{\mu\iota} r^2\right)\rho(\vec{x})d\vec{x}$$



$$I_{xx} = 2Mr_0^{\ 2}\left(\cos^2 2\pi f_{orb}t - \frac{1}{3}\right)$$

$$I_{yy} = 2Mr_0^{\ 2}\left(\sin^2 2\pi f_{orb}t - \frac{1}{3}\right)$$

2 times the rotation frequency

$$I_{xy} = I_{yx} = 2Mr_0^{\ 2}\cos 2\pi f_{orb}t \sin 2\pi f_{orb}t$$

$$I_{zz} = -\frac{1}{3}Mr_0^{\ 2}$$

$$h_{xx} = -h_{yy} = \frac{32\pi^2 G}{Rc^4}Mr_0^{\ 2} f_{orb}^{\ \ 2}\cos 2(2\pi f_{orb})t$$

$$h_{xy} = -h_{yx} = \frac{-32\pi^2 G}{Rc^4}Mr_0^{\ 2} f_{orb}^{\ \ 2}\sin 2(2\pi f_{orb})t$$

Target GW amplitude

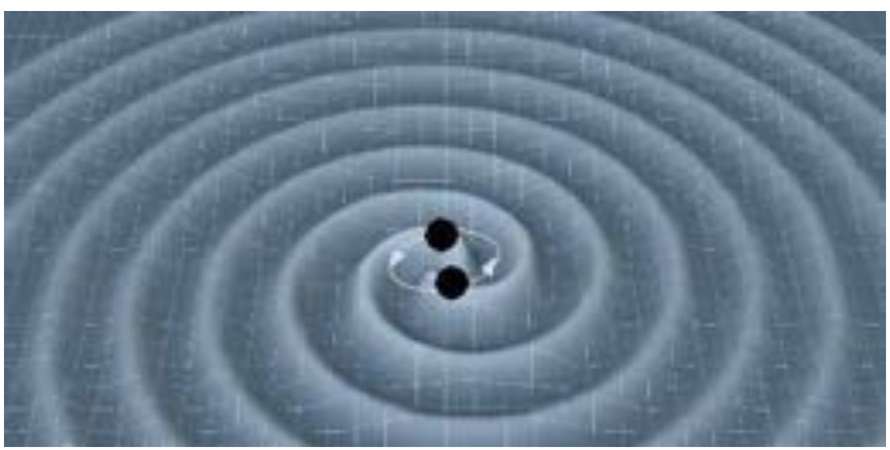
- Luminosity: $$P = \frac{G}{5c^5} < \dddot{Q}^{ij} \dddot{Q}_{ij} > \approx \varepsilon \cdot \frac{c^5}{G} \left(\frac{R_S}{R} \right)^2 \left(\frac{v}{c} \right)^6$$

10^{59} erg/s

<u>Compactness *C*</u>
1 for BH
0.3 for NS
10^{-4} for WD

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

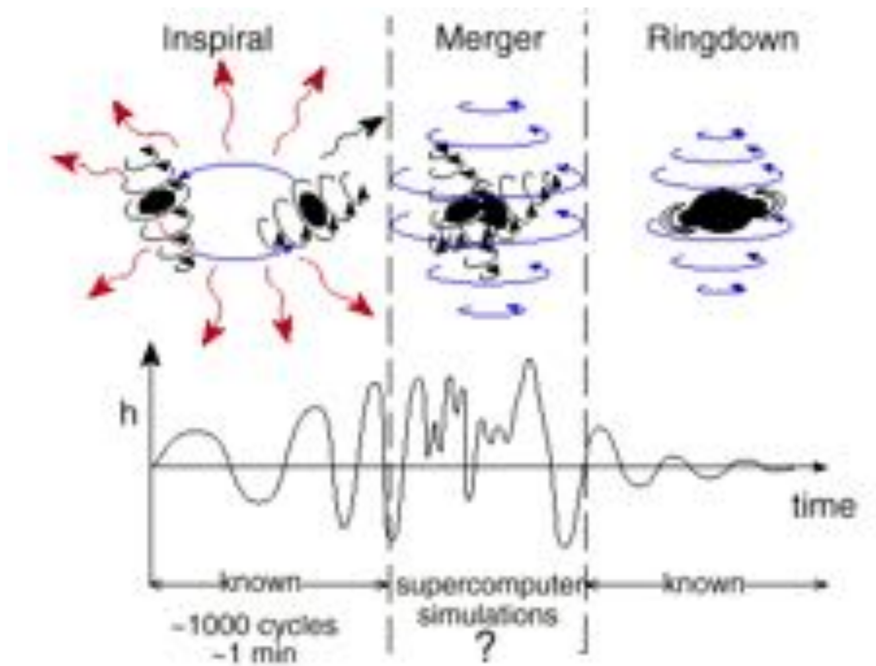
Efficient sources of GW must be "compact" and "fast"
GW detectors are sensitive to aplitude $h : 1/r$ attenuation!

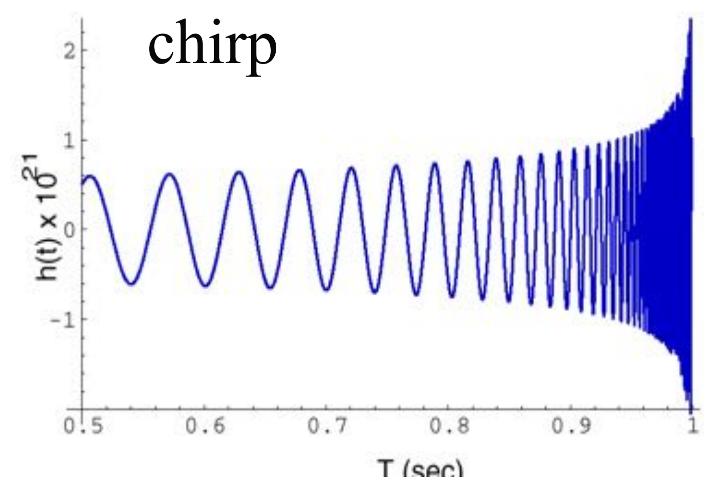


Target amplitude:
coalescing NS/NS in the Virgo cluster
(r ~10 Mpc)

$h \sim 10^{-21}$

Coalescent binaries





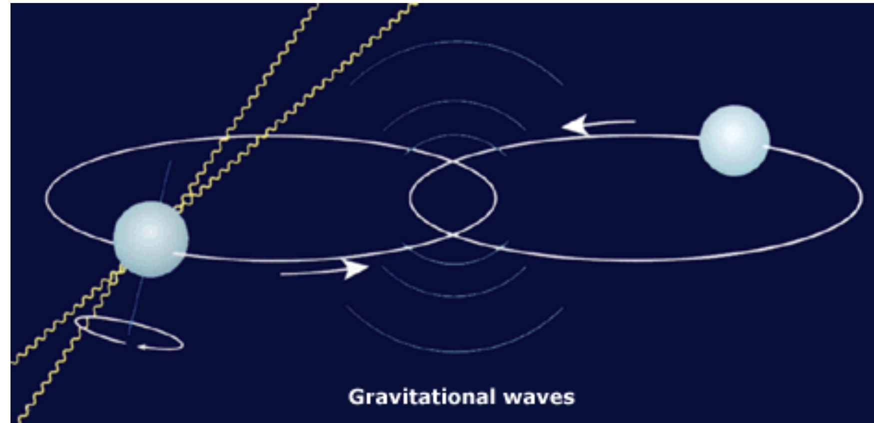
$$h_{jk} = \frac{2}{r}\frac{G}{c^4}\left[\ddot{I}_{jk}(t - r/c)\right]^{TT}$$

$$\tau = \frac{f}{\dot{f}} = 7.8\left(\frac{100Hz}{f}\right)^{8/3}\left(\frac{M_\Theta}{M}\right)^{2/3}\left(\frac{M_\Theta}{\mu}\right)^{2/3}$$

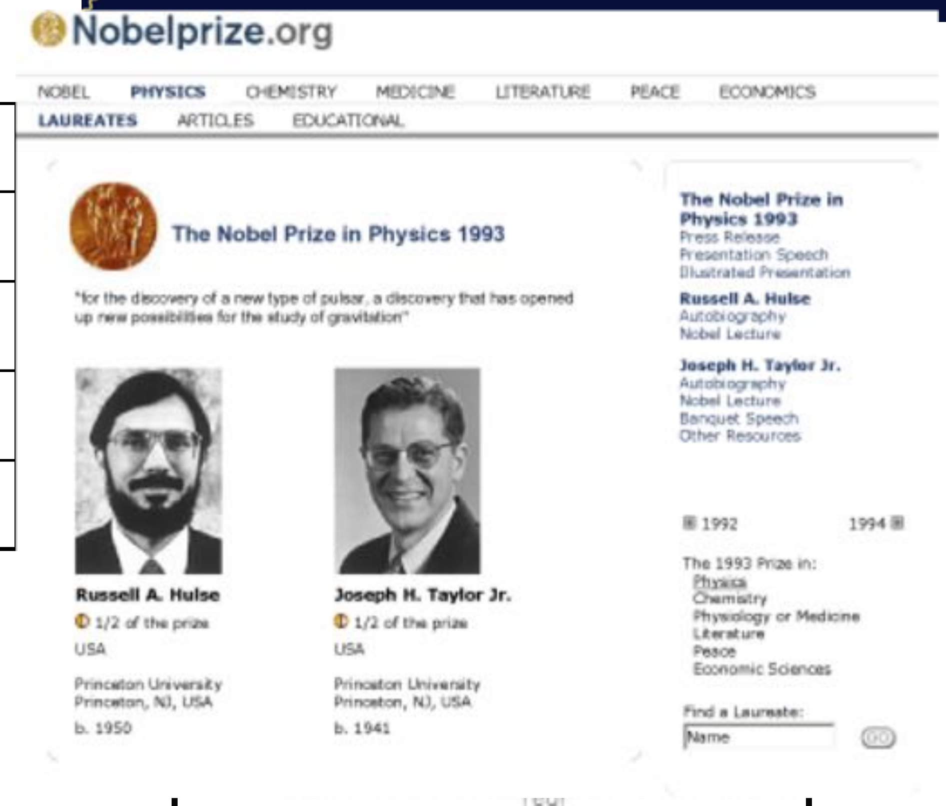
← Tempo di Permanenza cresce fortemente alle basse frequenze

Indirect proof of GW existence

- Pulsar bound to a “dark companion”, 7 kpc away.
- 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



P (s)	**27906.9807807(9)**
dP/dt	**$-2.425(10)\cdot 10^{-12}$**
dω/dt (°/yr)	**4.226628(18)**
M_p	**$1.442 \pm 0.003\ M_{\odot}$**
M_c	**$1.386 \pm 0.003\ M_{\odot}$**



Nobel Prize 1993: Hulse and Taylor

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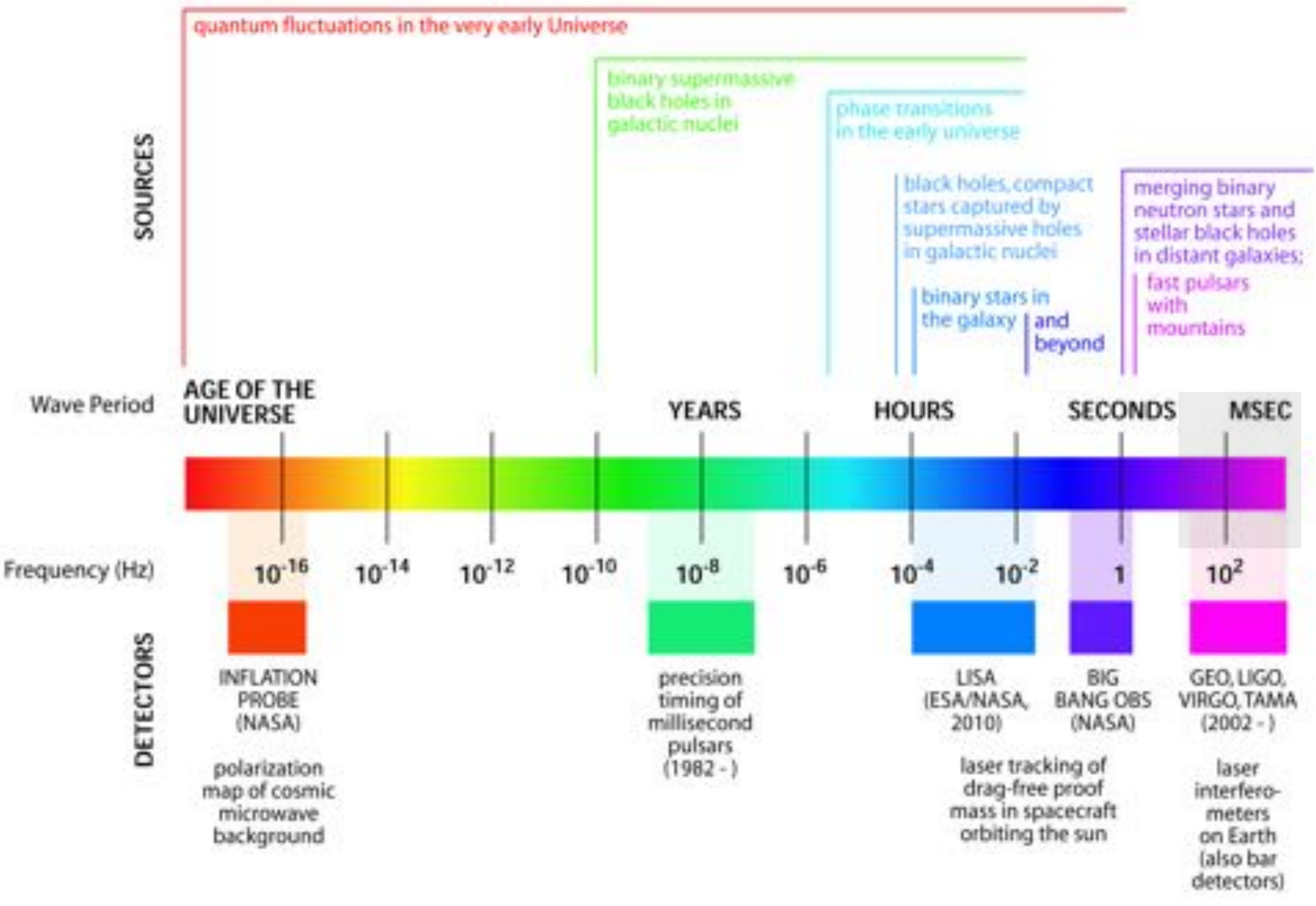
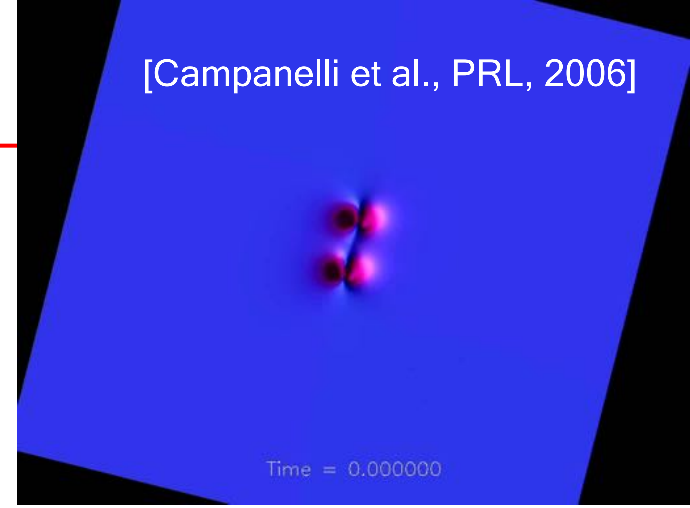
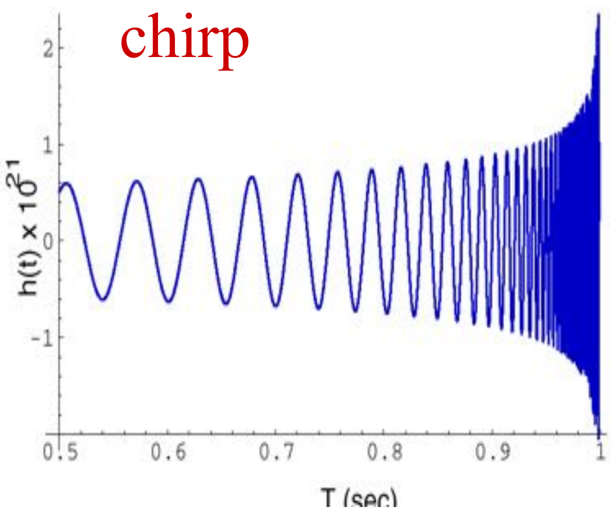
THE GRAVITATIONAL WAVE SPECTRUM

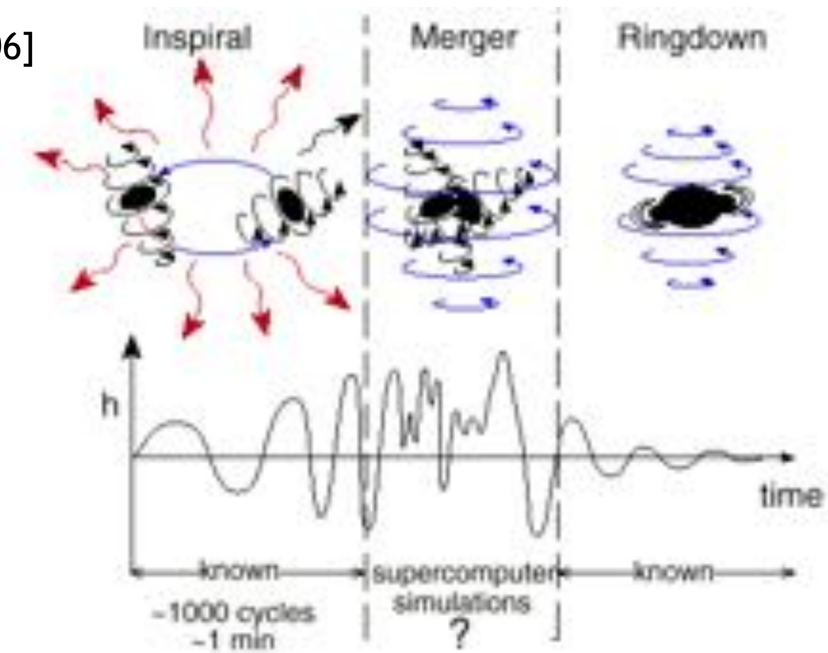


CBC

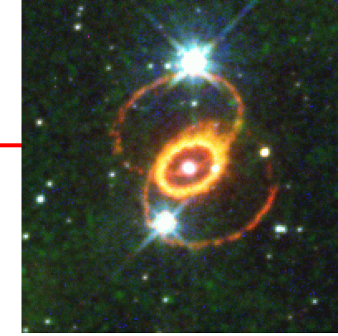
- Compact stars (NS/NS, NS/BH, BH/BH)
- Inspiral signal accurately predictable
  - Newtonian dynamics
  - Post-Newtonian corrections (3PN, $(v/c)^{11/2}$) [L.Blanchet et al., 1996]
- Recent big progress in merger 3D simulation [Baker et al 2006, Praetorious 2006]



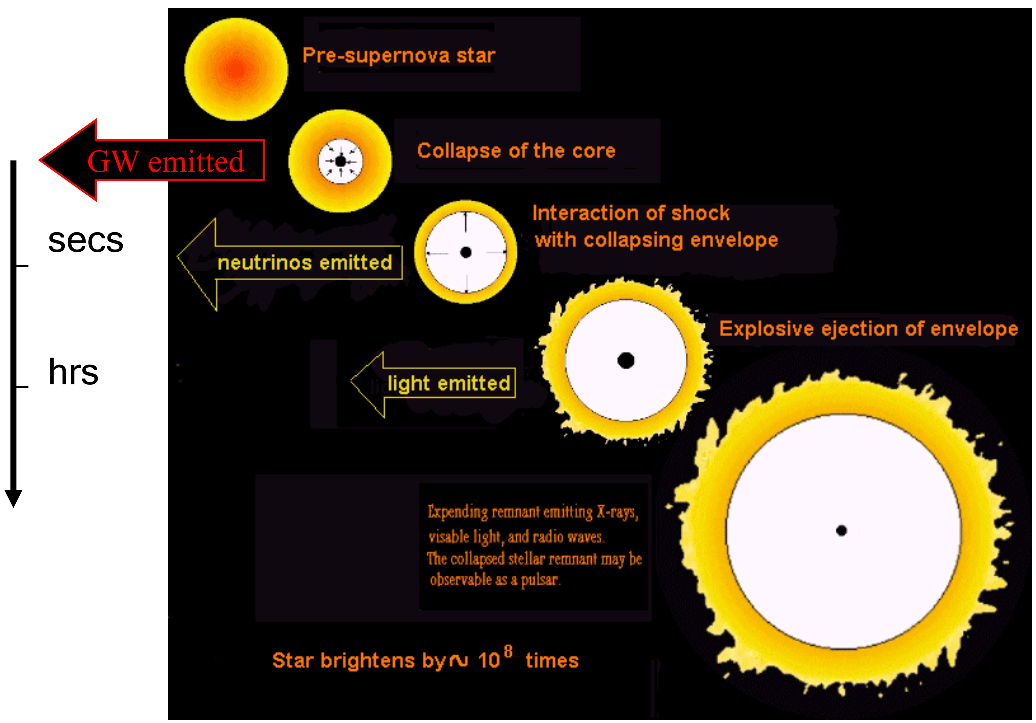


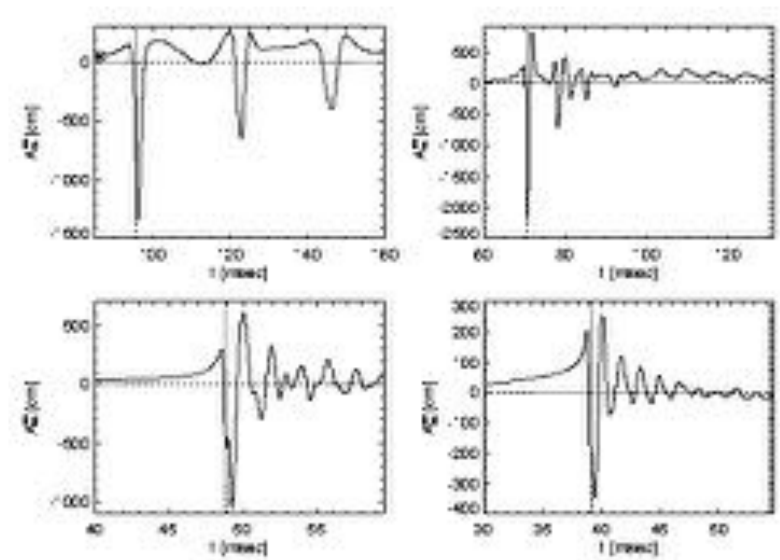


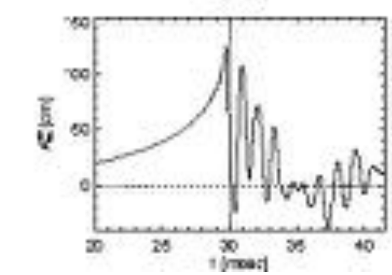
Supernovae



- Collapse dynamics and waveform badly predictable
- Estimated rate: several /yr in the VIRGO cluster, but the efficiency of GW emission is strongly model dependent
- Simulations suggest $E_{GW} \sim 10^{-6}\ M_{\odot}c^2$, but NS kick velocities suggest possible strong asymmetries



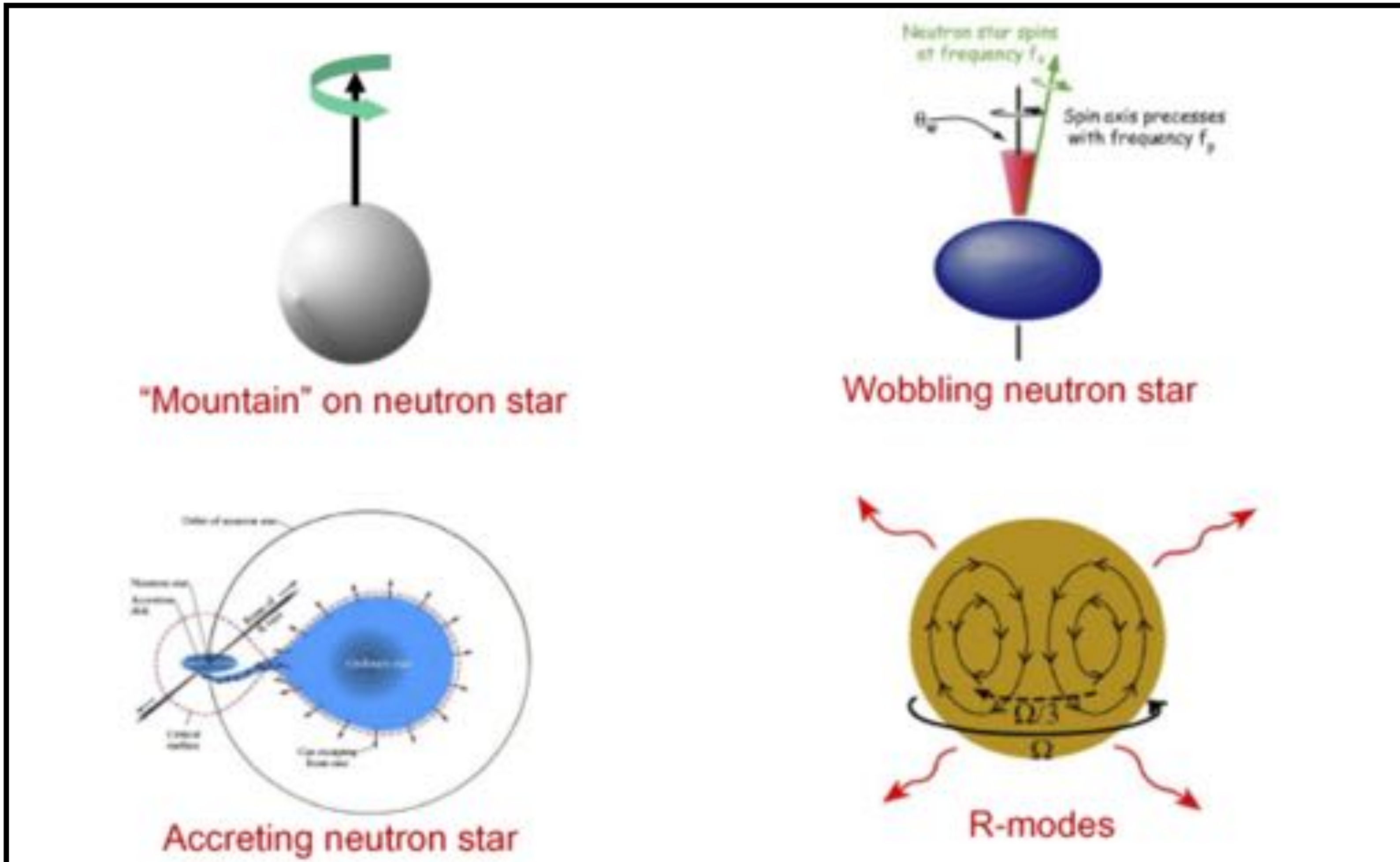




Γ_r	ρ_c [g/cm³]	E_{GW} [$M_{\odot}c^2$]
1.325	1.73e+14	8.78e-09
1.320	2.79e+14	5.31e-08
1.310	3.36e+14	2.79e-08
1.300	3.72e+14	4.31e-09
1.280	4.23e+14	4.26e-10

[Zwerger, Muller]

More on neutron stars

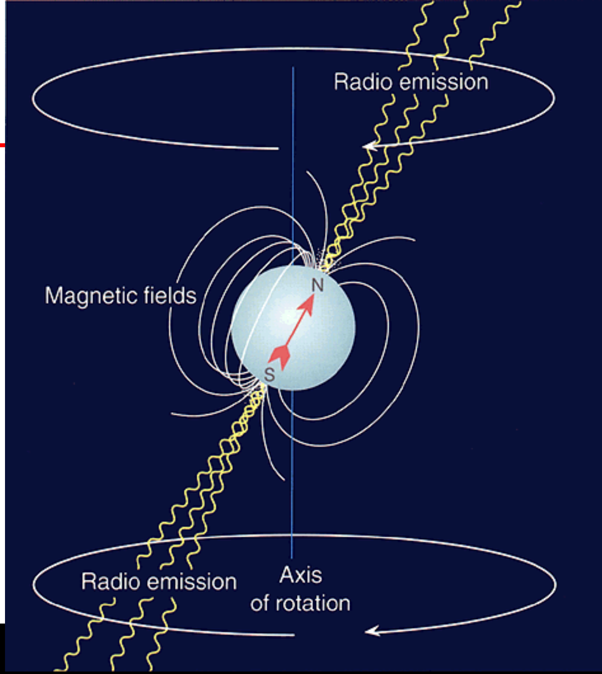


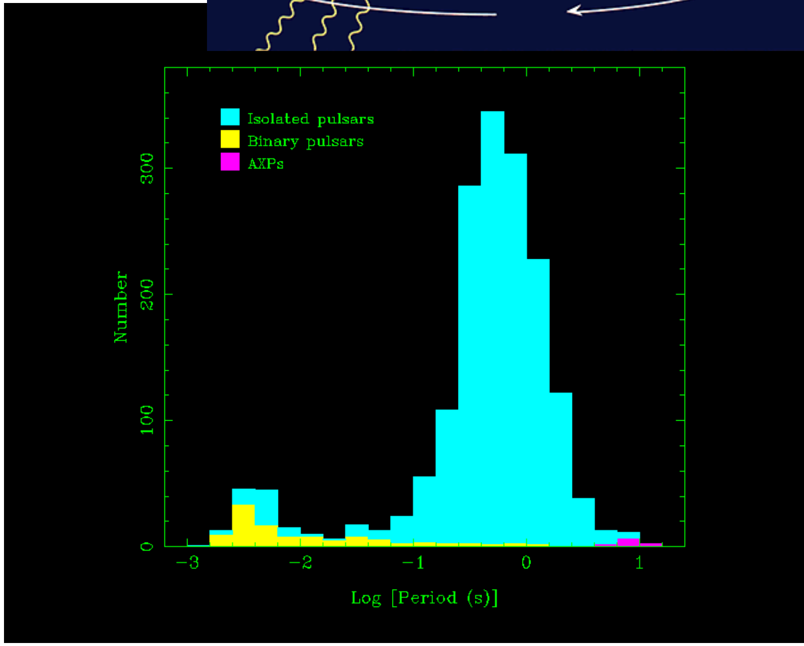
Spinning NS

- Non-axisymmetric rotating NS emit periodic GW at $f=2f_{spin}$ but…weak

$$h \approx 3\cdot 10^{-27}\left(\frac{10\,\mathrm{kpc}}{r}\right)\left(\frac{I}{10^{45}\ \mathrm{g/cm^2}}\right)\left(\frac{f}{200\ \mathrm{Hz}}\right)^2\left(\frac{\varepsilon}{10^{-6}}\right)$$

- SNR can be increased by integrating the signal for long time (months) but…need Doppler correction of Earth motion: $\Delta f/f$ ⍰ 10^{-4}
- 10^9 NS in the galaxy, 1740 known but…blind search limited by computing power

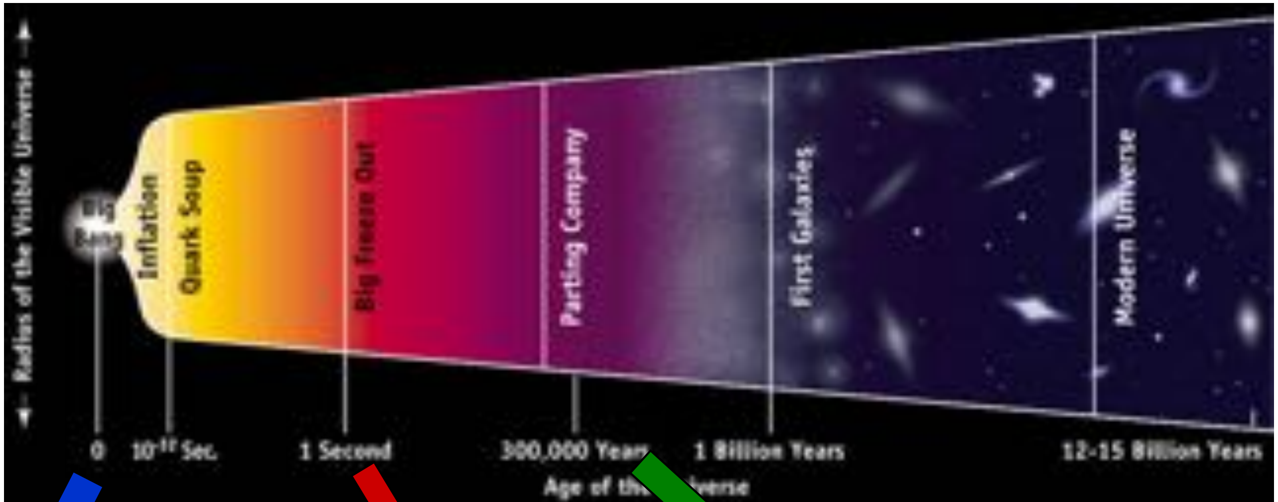




Data from ATNF Pulsar Catalogue

(www.atnf.csiro.au/research/pulsar/psrcat)

Relic Stochastic Background



Relic gravitons

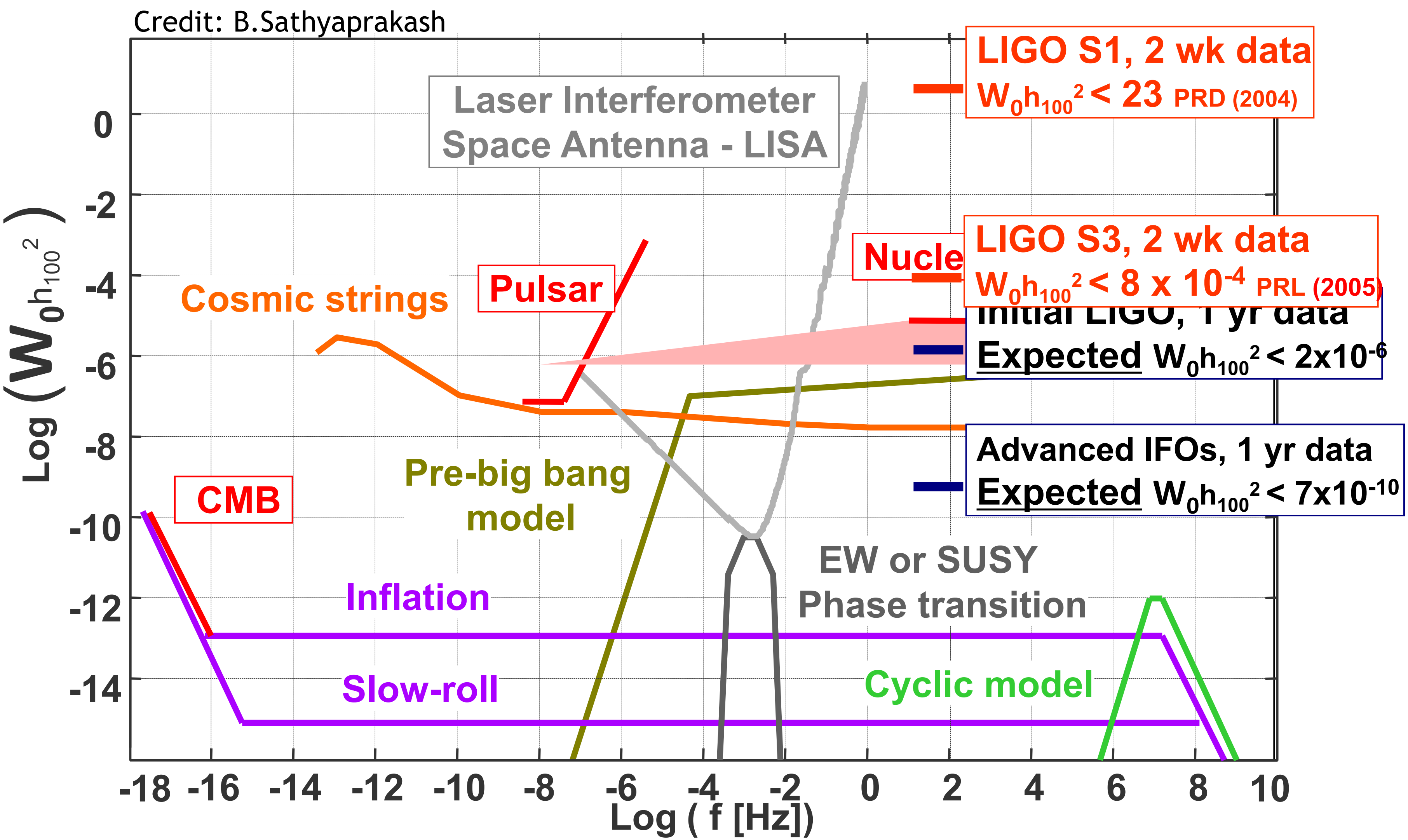
Relic neutrinos

CMBR

- Imprinting of the early expansion of the universe
- Correlation of two interferometers needed for detection

Background from standard inflation too weak.

Hope from string models [Buonanno et al. 1997]



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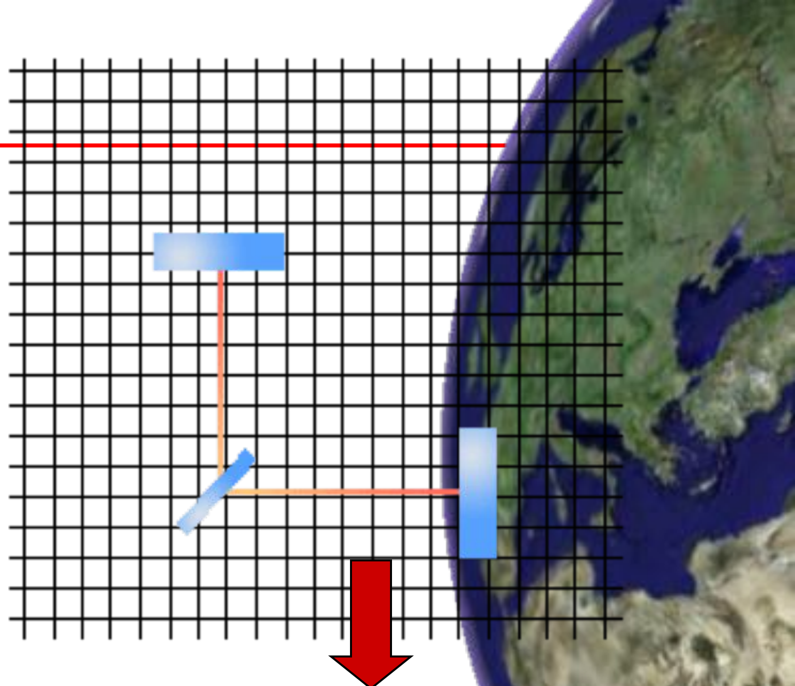
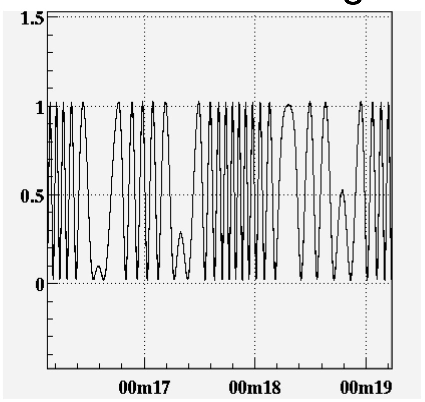
VIRGO

Detection

GW induce space-time deformation

Measure space-time Strain using light





$$\Delta L \approx \frac{1}{2} hL$$

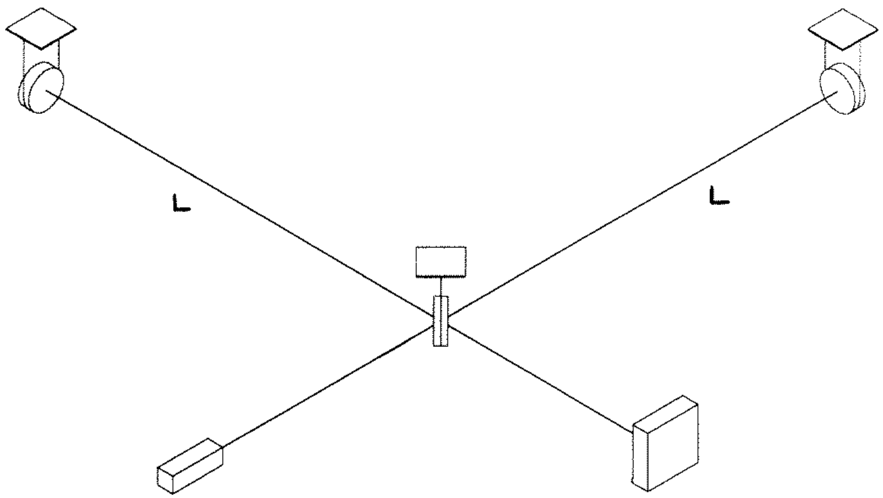
Target h ~ 10^{-21}
(NS/NS @Virgo Cluster)

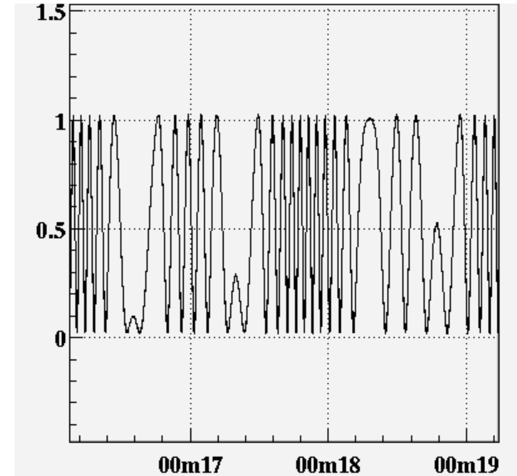
Feasible L ~ 10^{3} m

Need to measure: $\Delta L \sim 10^{-18}$ m

Great challenge for experimentalists!

A simple detector





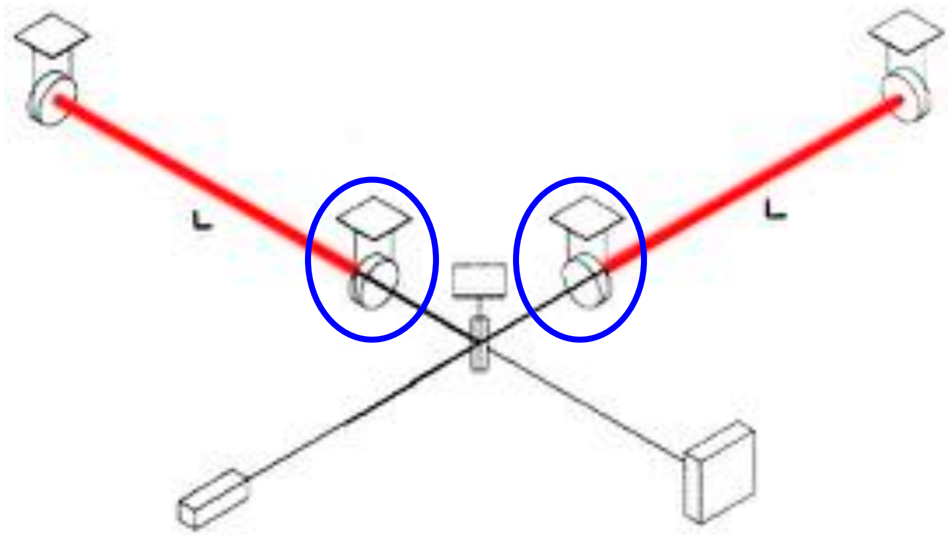
$$P_{out} = P_{in} \cos^2(\phi_0 + \phi_{gw})$$

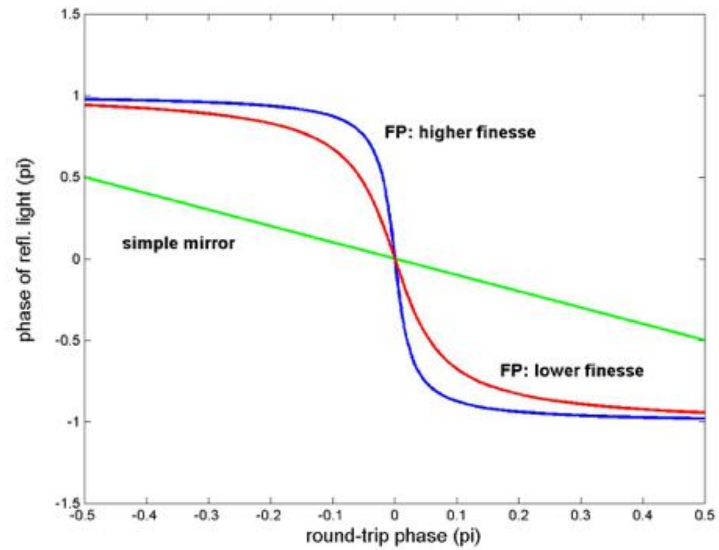
$$\phi_{gw} = \frac{4\pi}{\lambda} L \cdot h$$

P_{out} depends also on P_{in} , λ, L.

ITF sensitive to power and frequency fluctuations, displacement noises, …

Increasing the optical path





Effective length: $$L' = L \cdot \frac{2F}{\pi}$$

- **Fabry-Perot cavities:** amplify the length-to-phase transduction
- **Higher finesse** =➔ higher $d\phi/dL$
- *Drawback: works only at resonance*

Optical Readout Noise

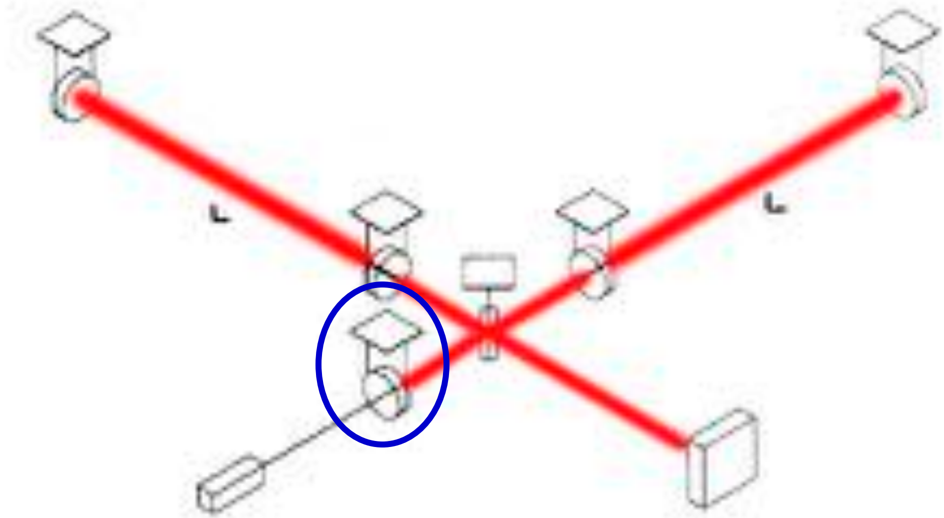
- Power fluctuations limit the phase sensitivity. Ultimate power fluctuations associated to the quantum nature of light
- Shot noise (assuming P,λ stable): $$\tilde{\phi}_{shot} = \sqrt{\frac{2\hbar\omega}{P}} \Rightarrow \tilde{h}_{shot} = \frac{1}{L}\sqrt{\frac{\hbar c\lambda}{\pi \cdot P}}$$
- L = 100 km, P = 1 kW ⇒ $$\tilde{h}_{shot} \approx 3\cdot 10^{-23} \ /\sqrt{\text{Hz}}$$ $$h_{shot} \approx 10^{-21}$$

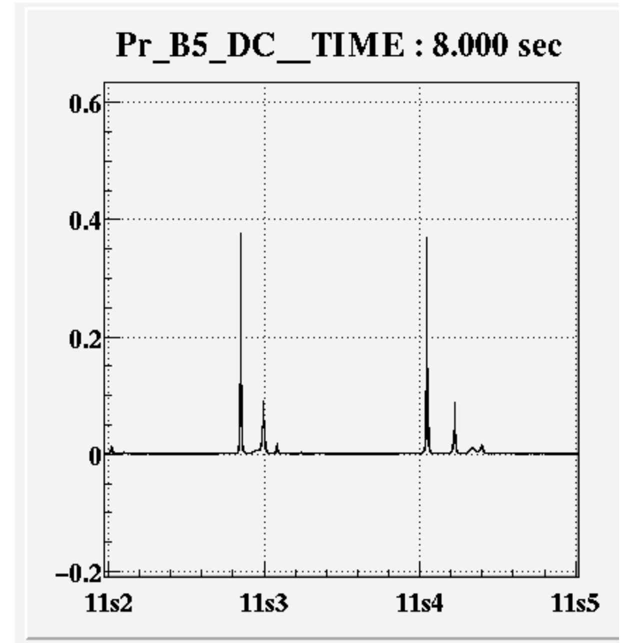
Lengthen the detector to 100 km.

Increase the light power more than 1 kW.

HOW?

kWatts power injected!

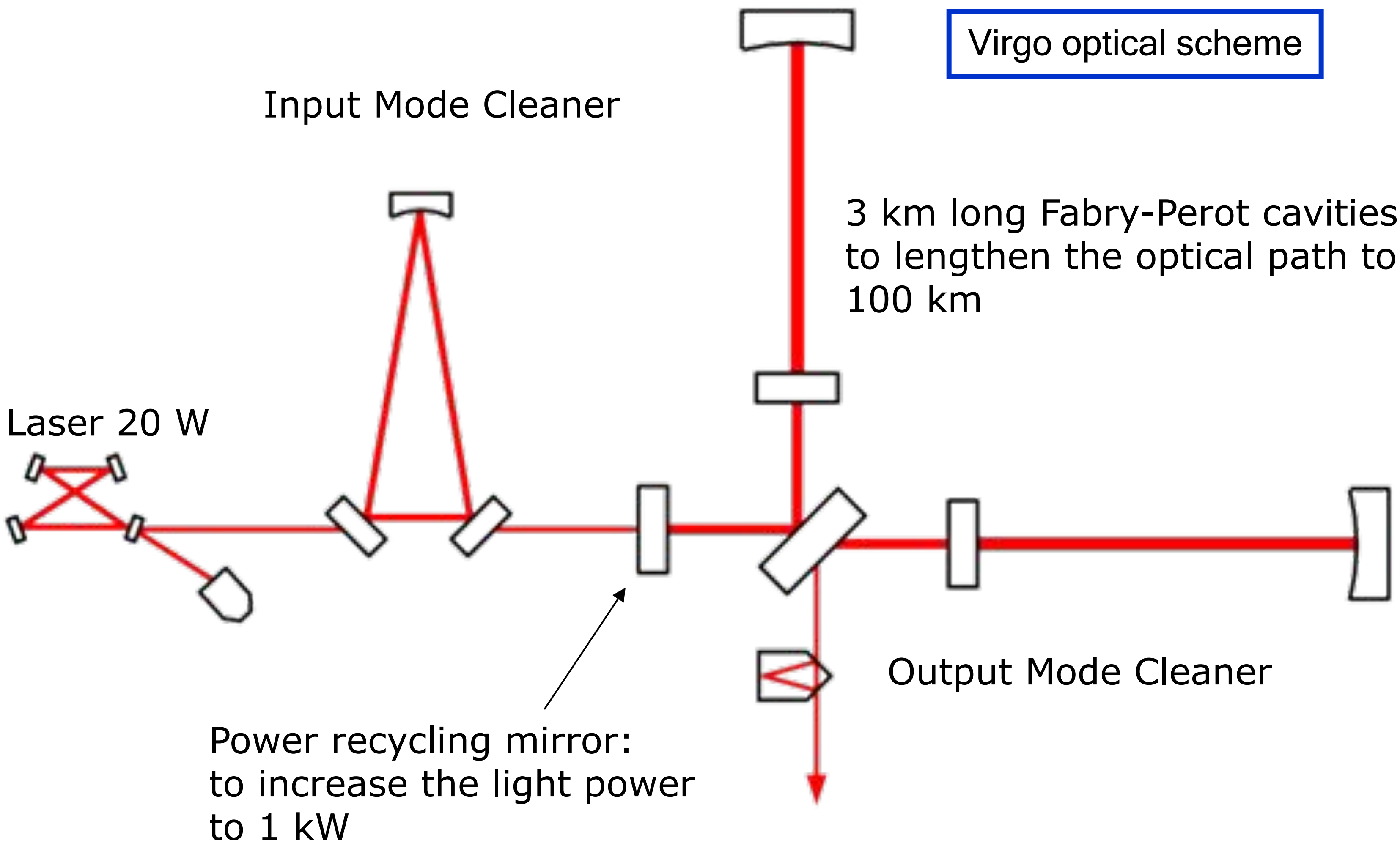




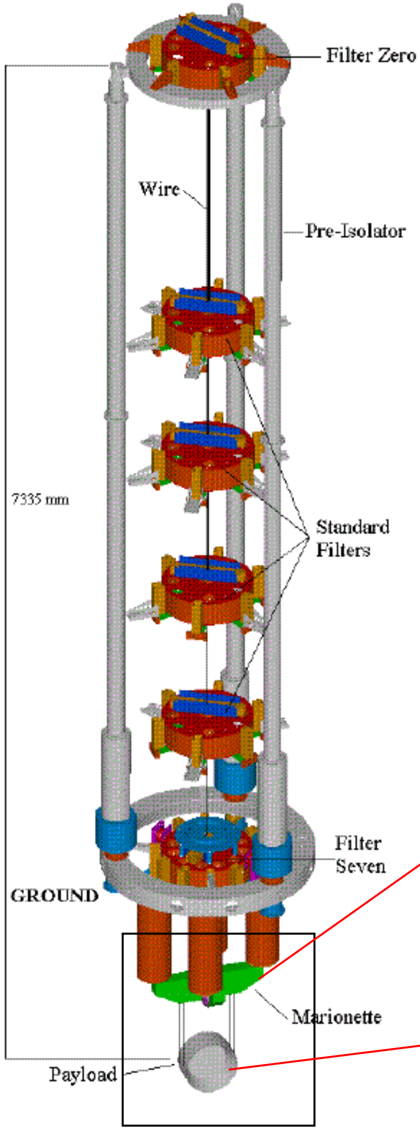
Interferometer Ecology: recycle the wasted light!

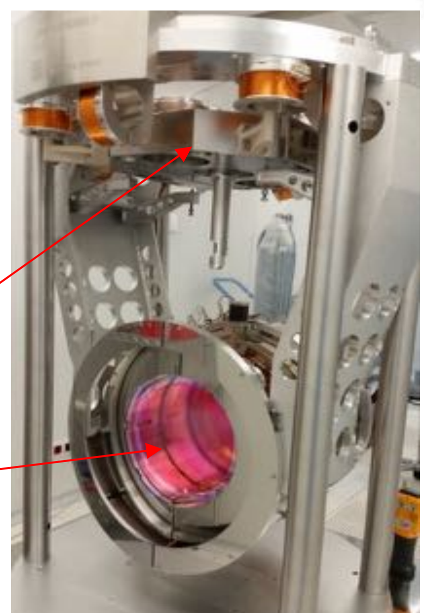
- P_{eff}= *Recycling factor* $\cdot P_{in}$ ➔ 50 x 20 W = 1 kW
- Shot noise reduced by a factor ~ 7
- One more cavity to be controlled !

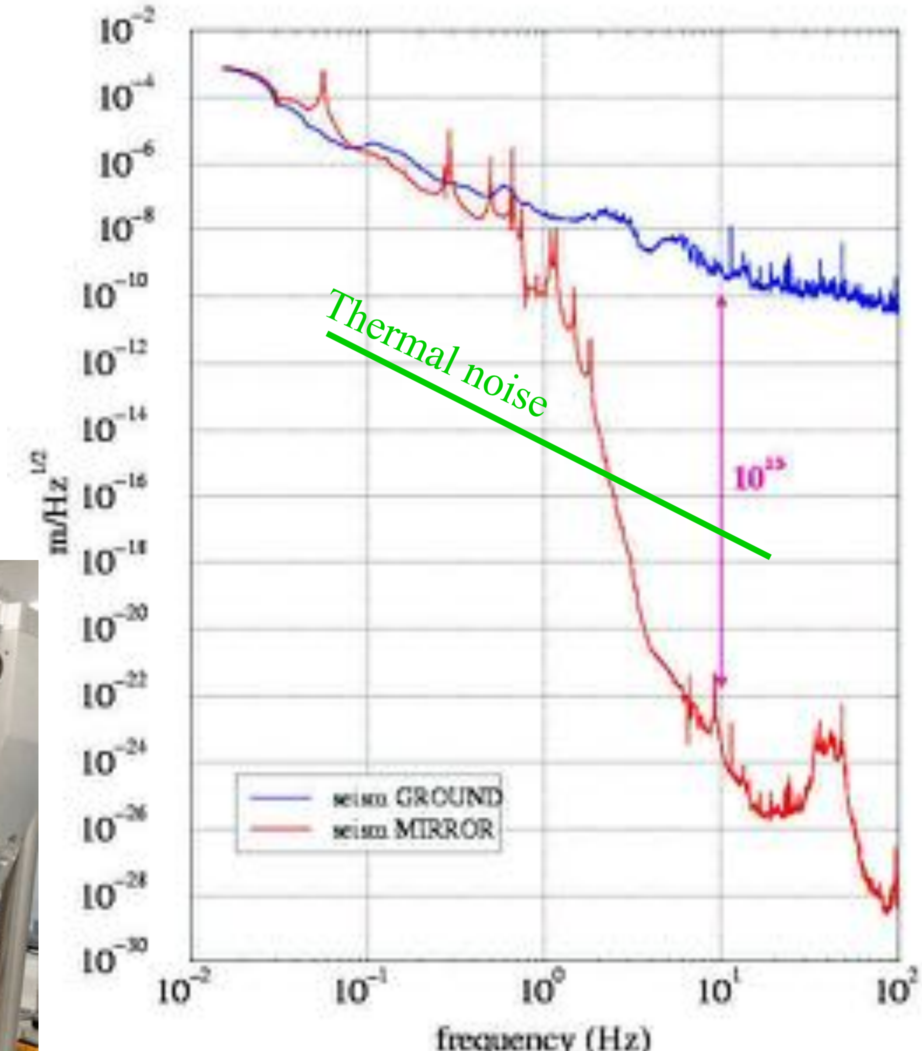
A real detector scheme



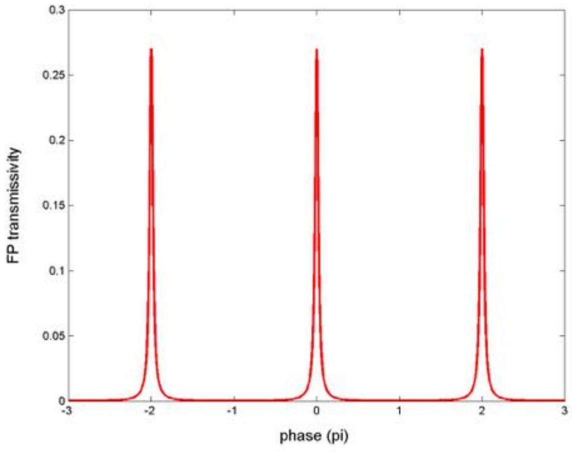
Free falling test masses

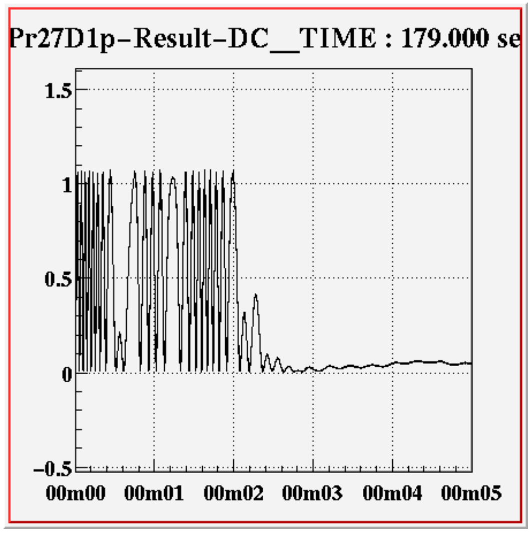






ITF Operation Conditions



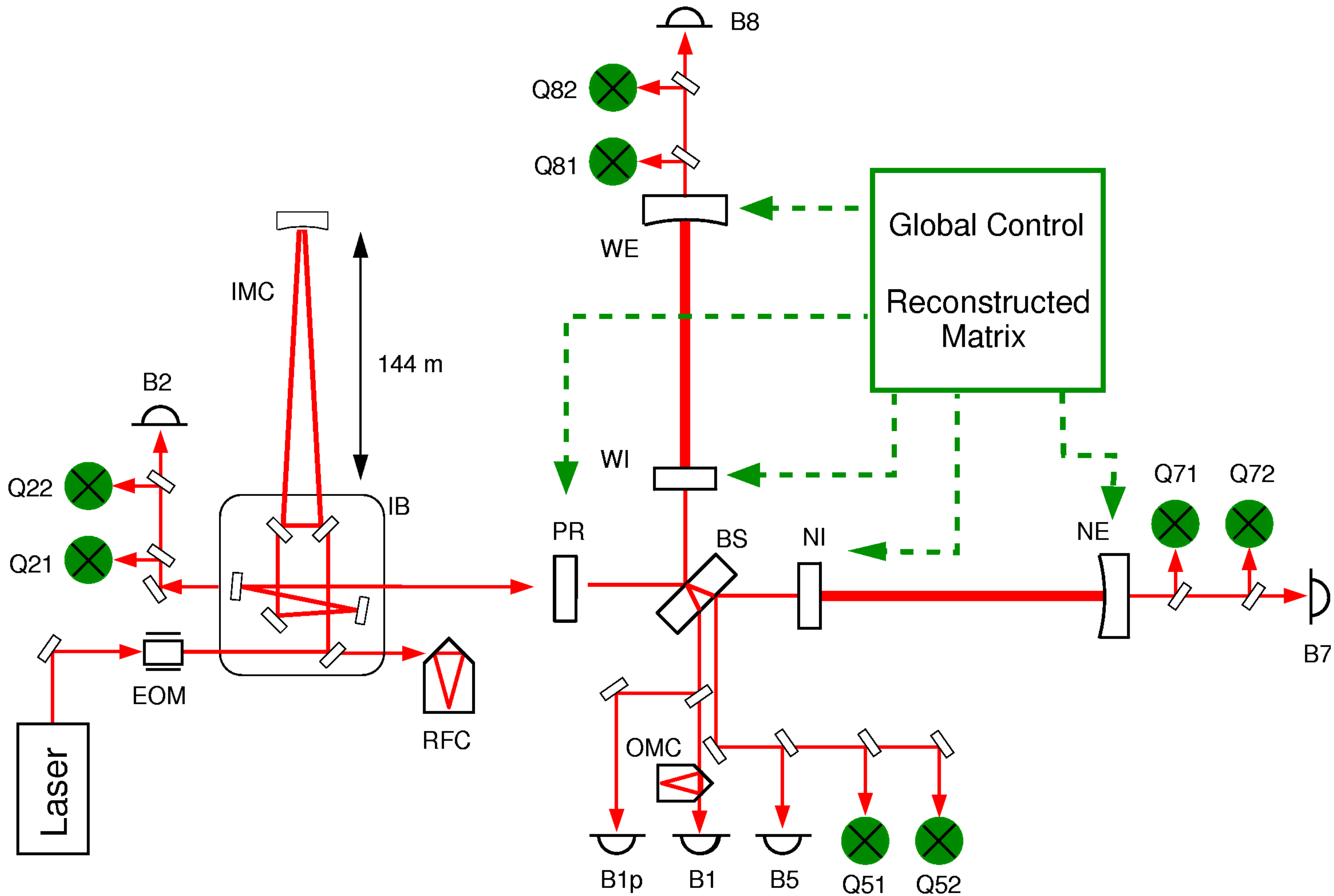


- Keep the FP cavities in resonance
  - Maximize the phase response
- Keep the PR cavity in resonance
  - Minimize the shot noise
- Keep the output on the “dark fringe”
  - Reduce the dependence on power fluctuations

L O C K I N G

Keep the armlength constant within
10^{-12} m !
ACTIVE CONTROLS NEEDED!

Interferometer control



Plan of the talk

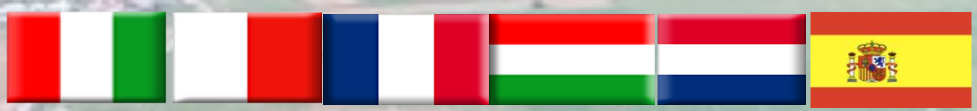
1. GW research motivations
2. Sources
3. Principles of interferometric detection
4. ***What is Virgo***
5. LIGO-Virgo joint observation
6. The discovery
7. The start of the GW astronomy

VIRGO

SAN GIULIANO TERME
PISA
Calci
Buti
Cascine
Montemagno
Caprona
Bientina
Vicopisano
Calcinaia
Fornacette
CASCINA
PONTEDERA
TENUTA DI
COLTANO
Palazzi
Ponsacco
Collesalvetti
INFN
VIRGO

THE VIRGO COLLABORATION:
6 European countries
22 labs

- Participated by scientists from Italy and France (former founders of Virgo), The Netherlands, Poland, Hungary and Spain



APC Paris
ARTEMIS Nice
EGO Cascina
INFN Firenze-Urbino
INFN Genova
INFN Napoli
INFN Perugia
INFN Pisa
INFN Roma La Sapienza
INFN Roma Tor Vergata
INFN Trento-Padova
LAL Orsay – ESPCI Paris
LAPP Annecy
LKB Paris
LMA Lyon
NIKHEF Amsterdam
POLGRAW(Poland)
RADBOUD Uni. Nijmegen
RMKI Budapest
Valencia university
INFN Salerno
INFN Milano Bicocca/parma

What is EGO

- EGO ➔ European Gravitational Observatory

- CNRS for France and INFN for Italy have created the "*private italian*" consortium EGO, which has to manage the site and ensure the long term scientific exploitation of the Virgo detector

- The governing body of EGO is the ***Council*** composed of six members nominated by the funding institutions (+ NIKHEF observers). The Council appoints the Director: Stavros Katsanevas

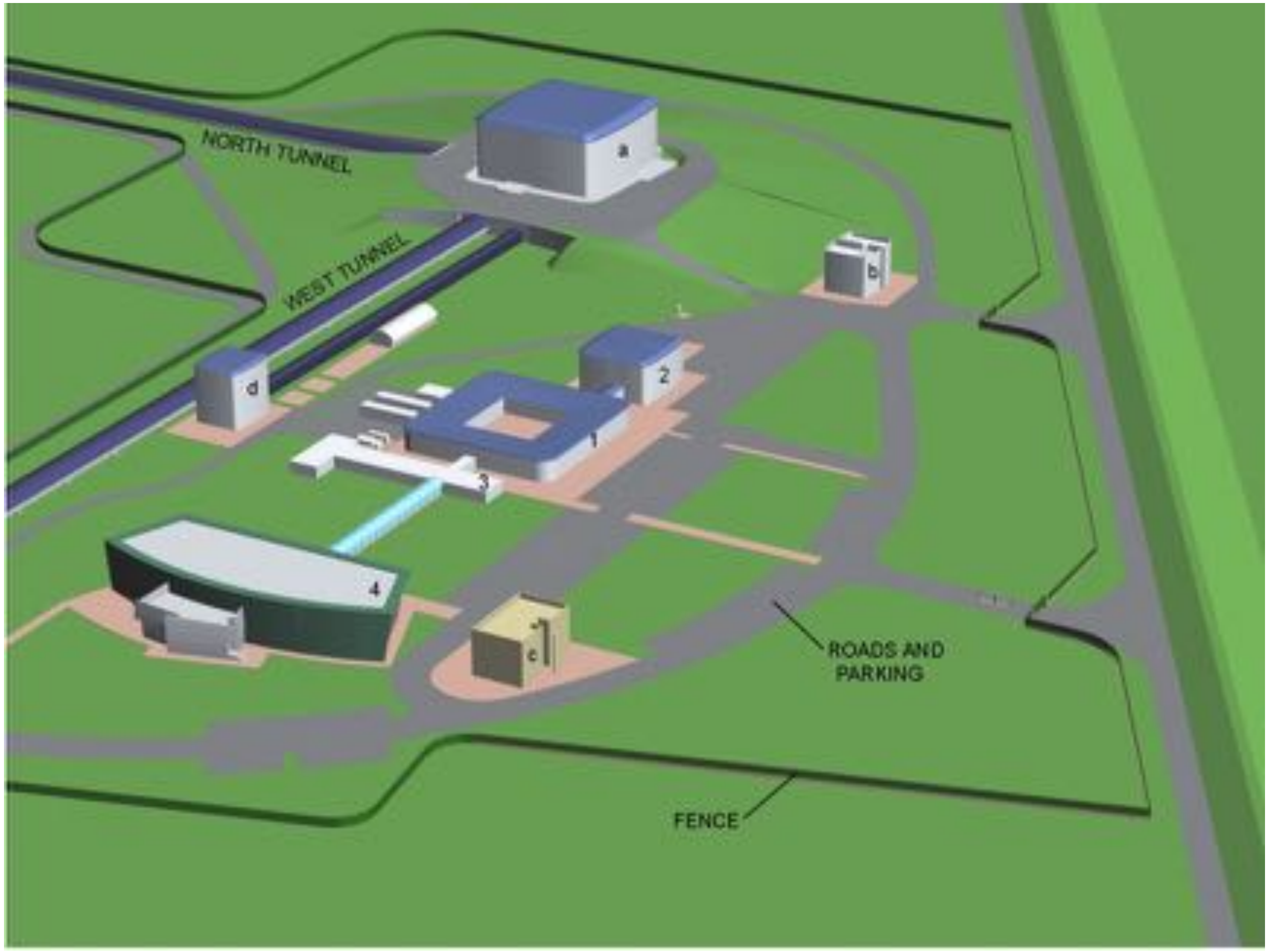
- The Scientific and Technical Advisory Committee (***STAC***), composed of up to *10 international scientific personalities*, advises the Council on the activity of EGO and the progress of Virgo

A dedicated infrastructure

The general requirements :

- infrastructure capable of a 30 year life-time;
- the interferometer located on a flat, controlled area, as far away as possible from mechanical vibration sources (such as roads, trains, industries);
- perturbation to the geological, biological and economical equilibrium of the surrounding region kept to a minumum;
- the foundations of the buildings have to guarantee that the mirror suspension points will not move more than 1 mm per day;
- In 30 years the foundations of the tunnel have to guarantee that the centre of any cross-section of the vacuum tube remains within a straight cylinder of 50 mm radius;

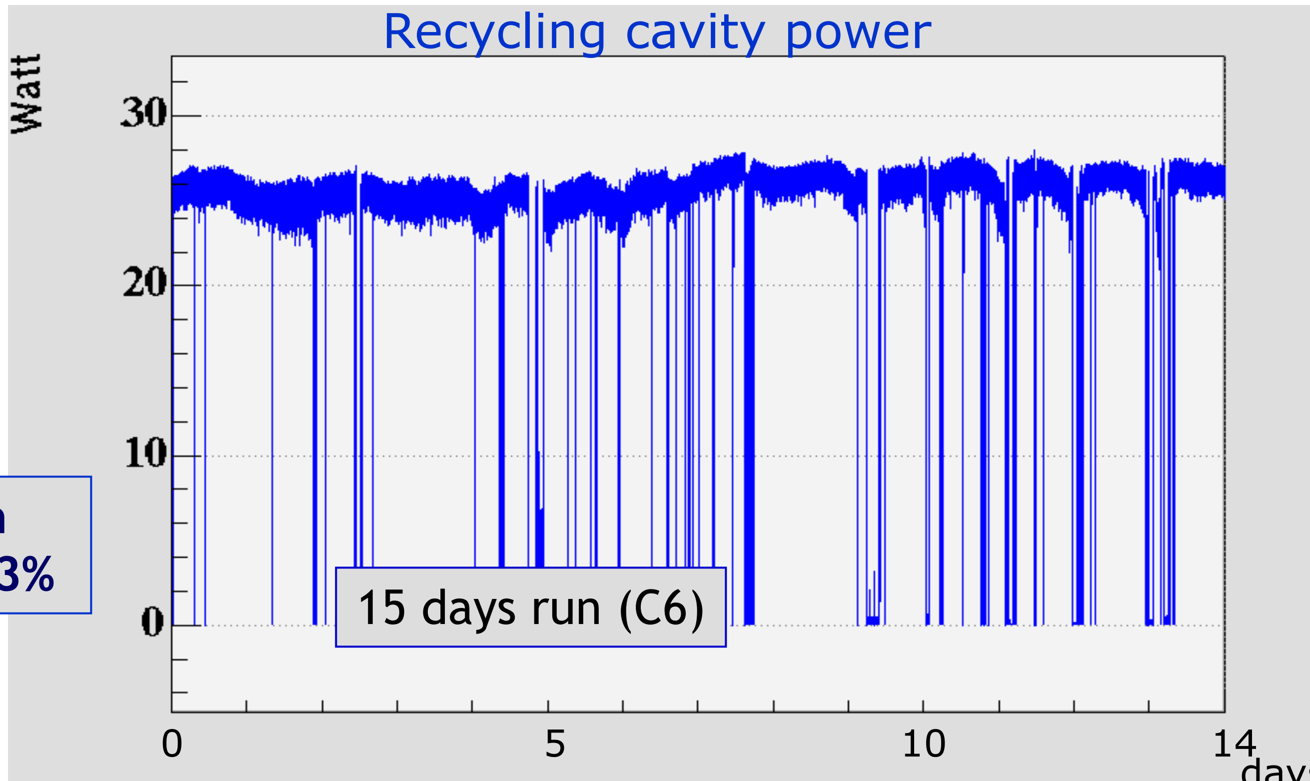
The Virgo Infrastructure



a- Central Building, b- old Technical Building, c- new Technical Building, d- Mode Cleaner Building, 1- Office Building, 2- Control Building, 3- Office Trailers, 4- Main Building.

Virgo stability

A good duty cycle is crucial:
Virgo performs very well thanks to its sophisticated vibration isolator

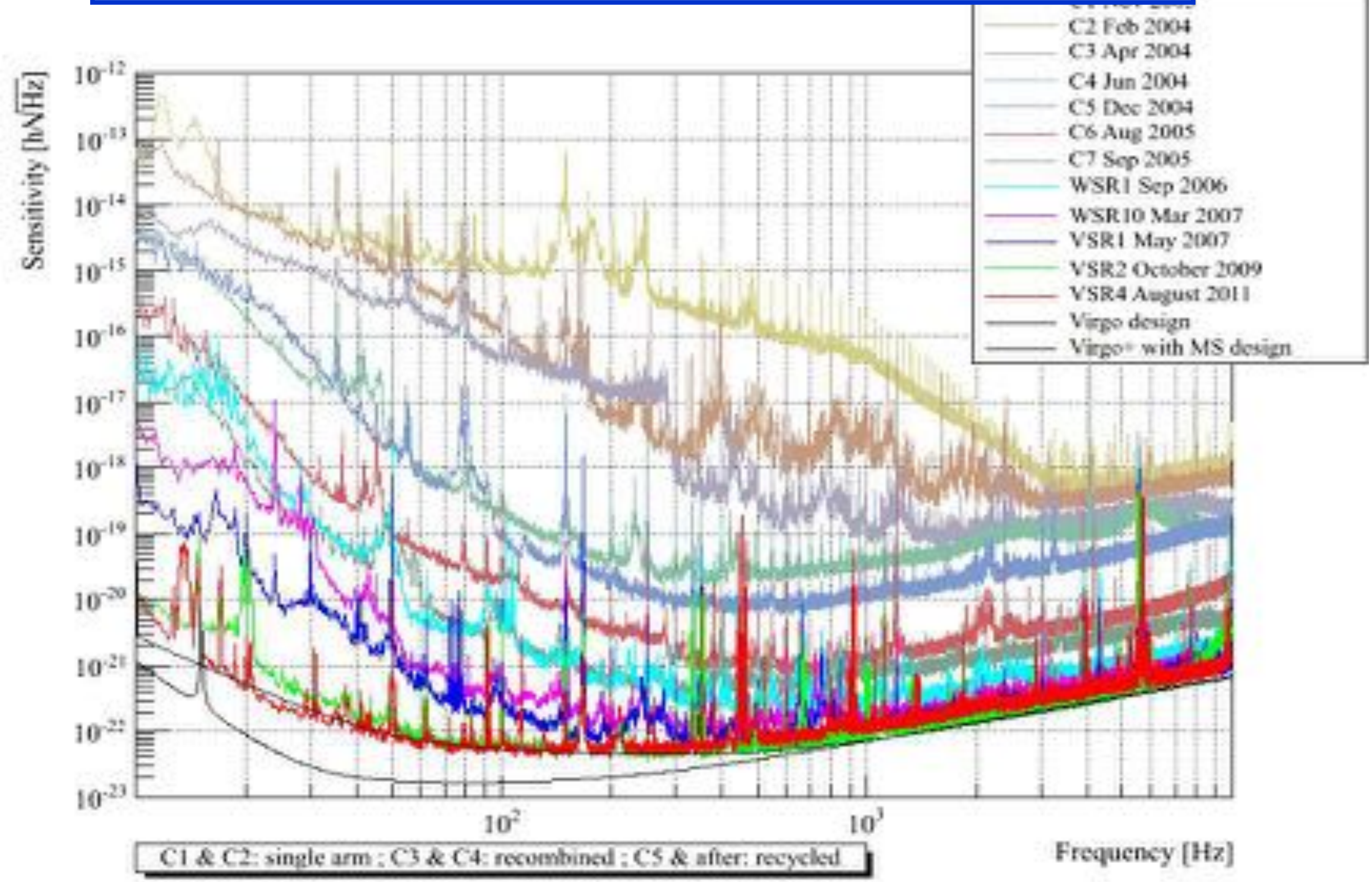


Duration: **336 h**
Duty cycle: **89.3%**

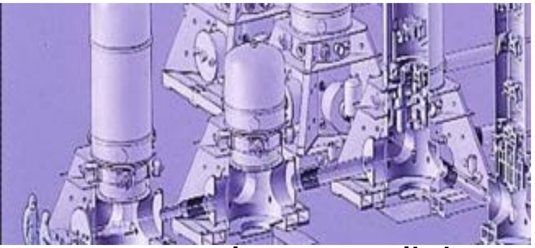
Longest lock stretch: **40 hours**

VIRGO sensitivity progress

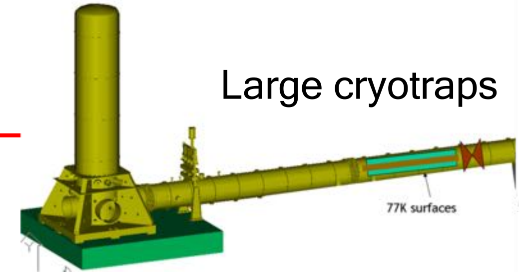
Virgo commissioning started in 2003 and achieved the design sensitivity



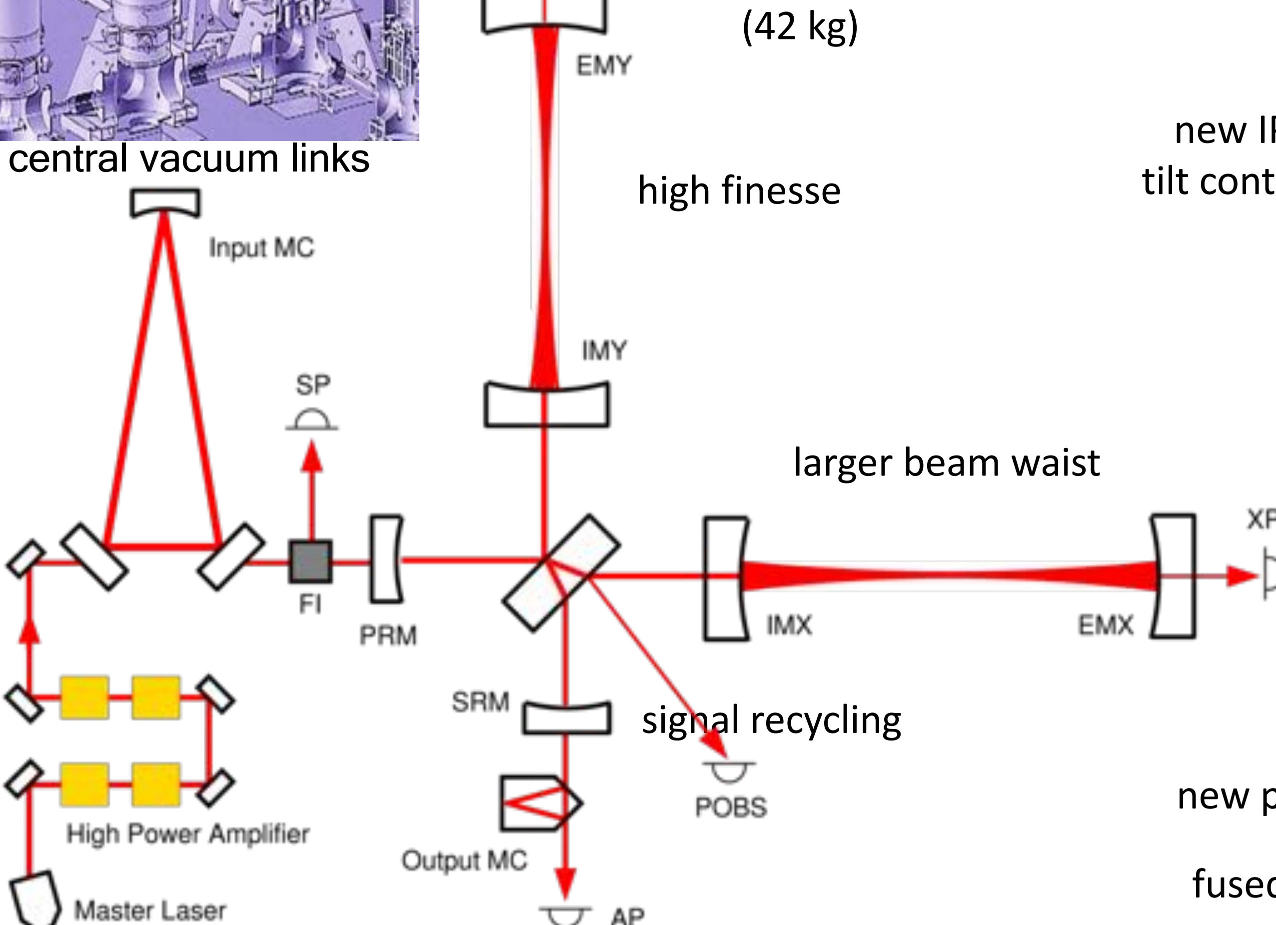
Ad Virgo in a nutshell



Larger central vacuum links



Large cryotraps



heavier mirrors
(42 kg)

high finesse

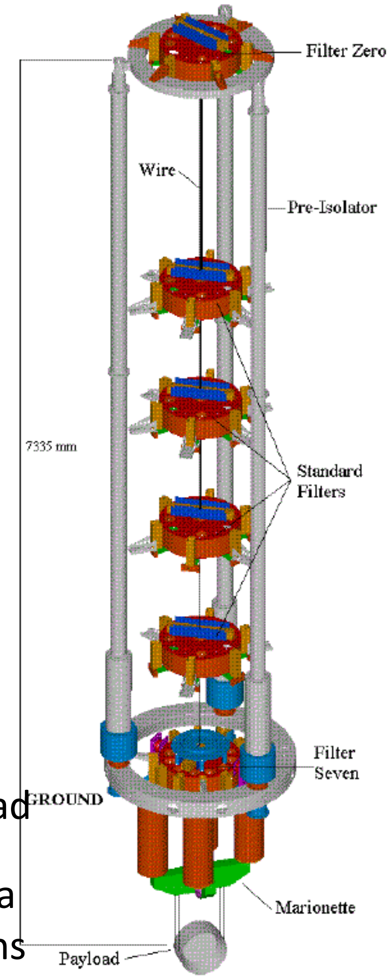
new IP
tilt control

larger beam waist

signal recycling

high power SSL
(200 W)

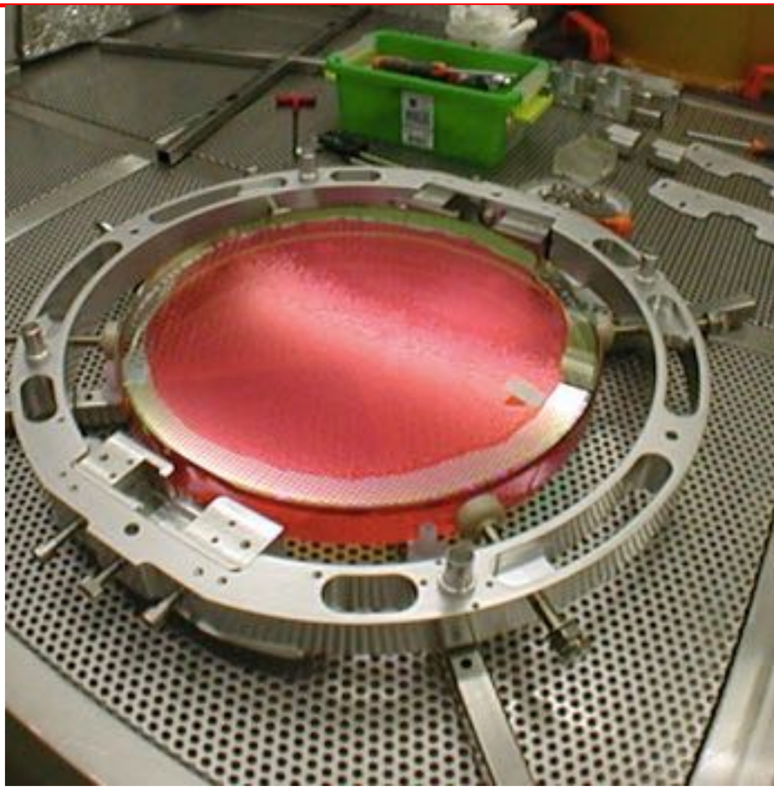
DC detection



new payload

fused silica
suspensions

The adV mirrors



Substrate: SiO_2

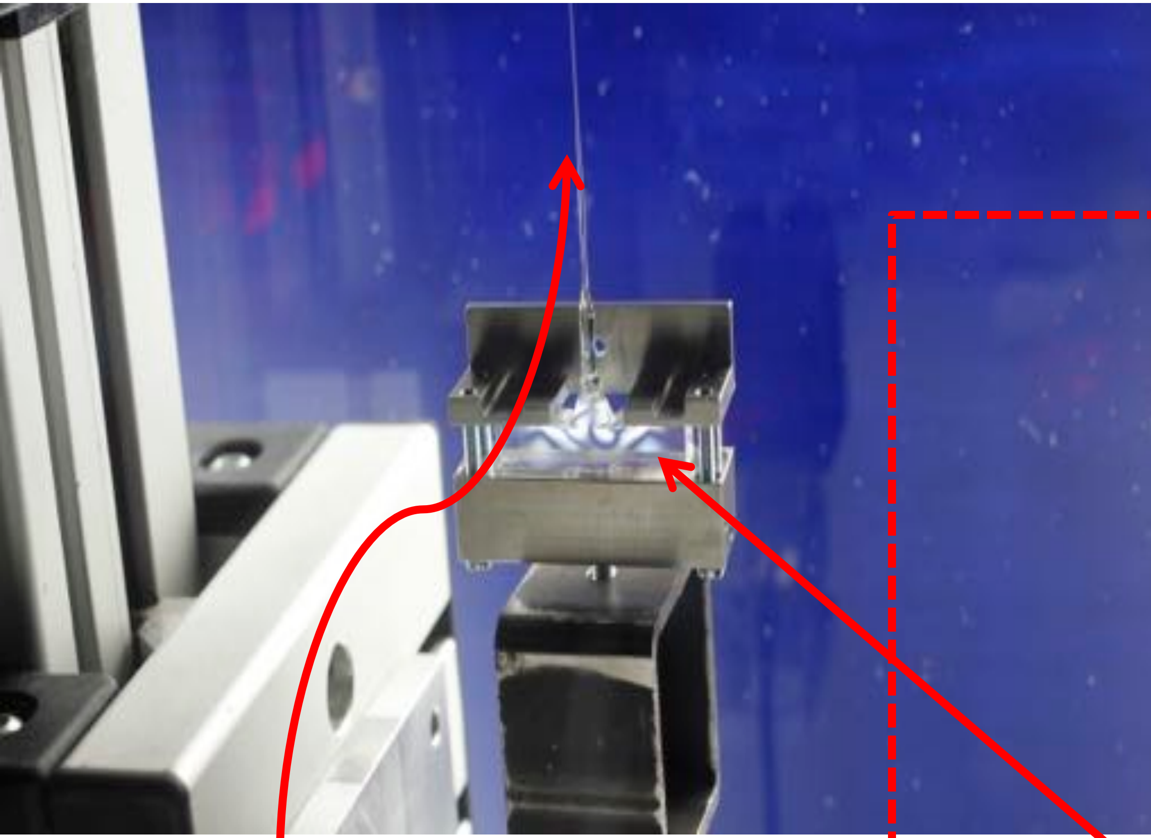
Mirror: 42 kg, 35 cm diameter, 20 cm thick

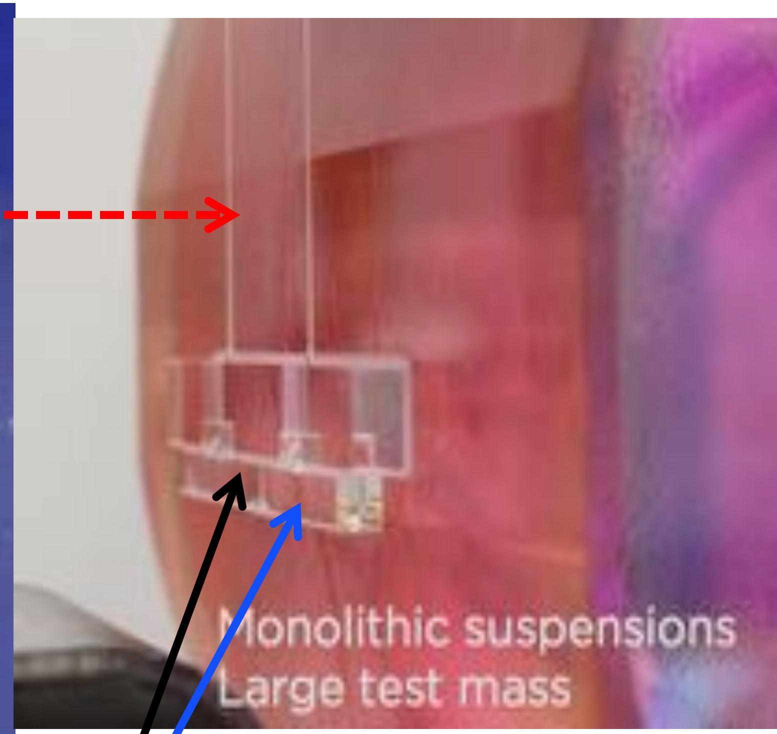
Beam Splitter: 50 cm diameter, 10 cm thick

Homogenity < 5 x 10^{-7}

Surface uniformity< 1 10^{-9} m

The mirror suspension





Four fibers of SiO_2:
0,4 mm diameter
70 cm length

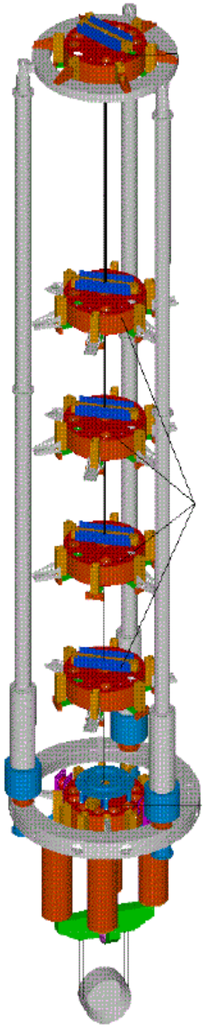
Anchors attached to the ears, bonded to the mirror via *Silica bonding*

suspended to a Superattenuator

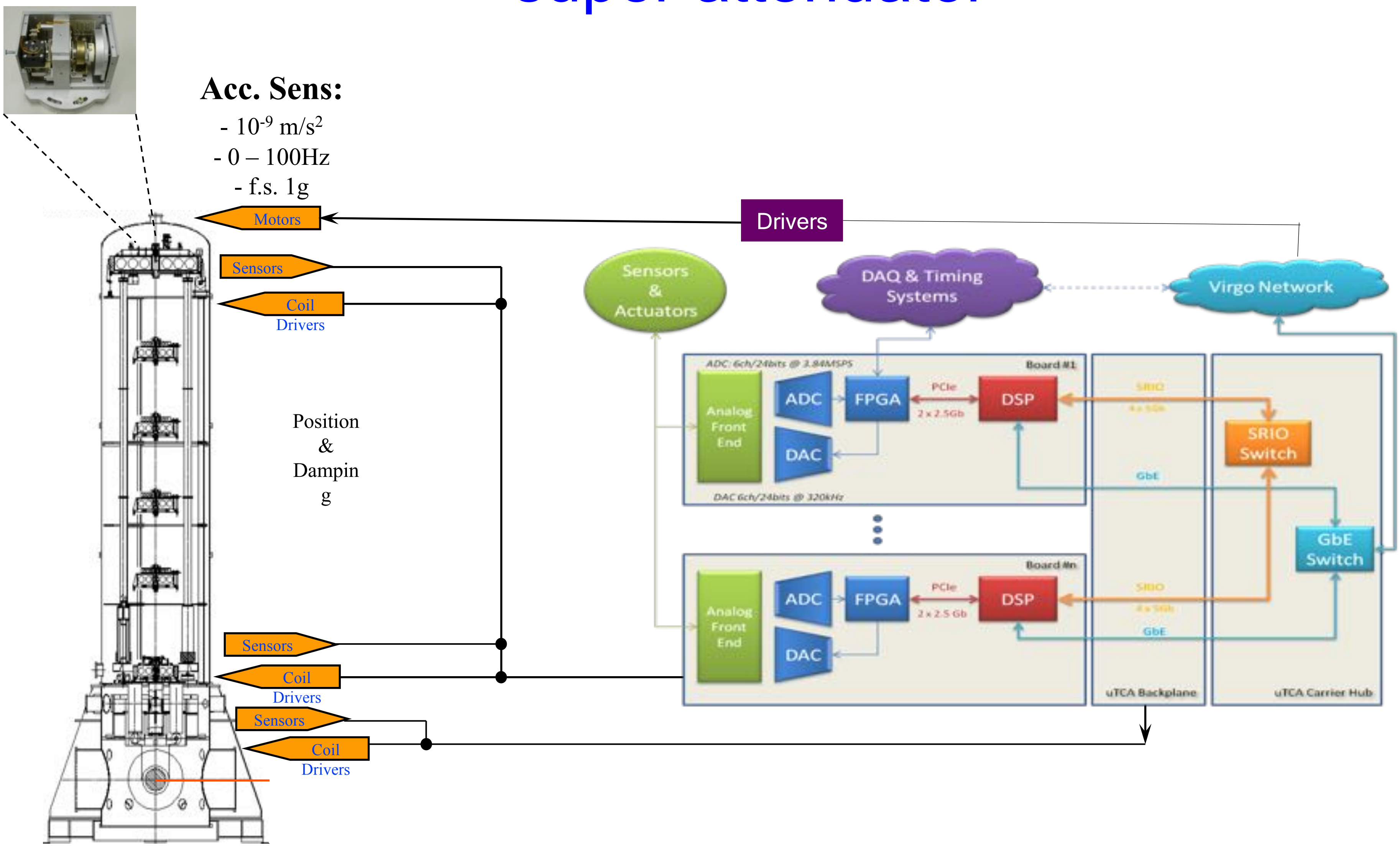
VIRGO

The vacuum to reduce the diffusion of the light

Seismic noise attenuation



Electronic control of the super attenuator



Superattenuator

Plan of the Talk

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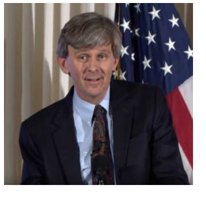
VIRGO

What is LIGO

- LIGO is a project supported by the National Science Foundation (NSF) in USA
- NSF signed the LIGO contract with the California Institute of Technology (CalTech)
- A sub-contract was signed with the Massachusetts Institute of Technology (MIT)
- The contract budget includes Investment and Salary. The target is the construction, the maintenence and the exploitation of two LIGO Interferometers - originally 3 Interferometers: 2 in Hanford (Washington state), 1 in Livingstone (Louisiana)
- Hierarchy ;
  - Director (CalTech): David Reitze
  - Deputy director (CalTech): Albert Lazzarini



What is LSC

- LSC ➔ LIGO Scientific Collaboration
- LIGO Scientific Collaboration is a group of worldwide scientists who have joined together in the search for gravitational waves exploiting the data of the LIGO and GEO600 data (GEO600 is a detector in Hannover, Germany)
- Founded in 1997 under the initiative of the former LIGO director Barry Barish: total members 1008 distributed in 15 different nations
- *Governed by*: The Collaboration Council (more than 100 representatives of the different groups)
- *Spokesperson*: Dr. David Shoemaker, M.I.T.

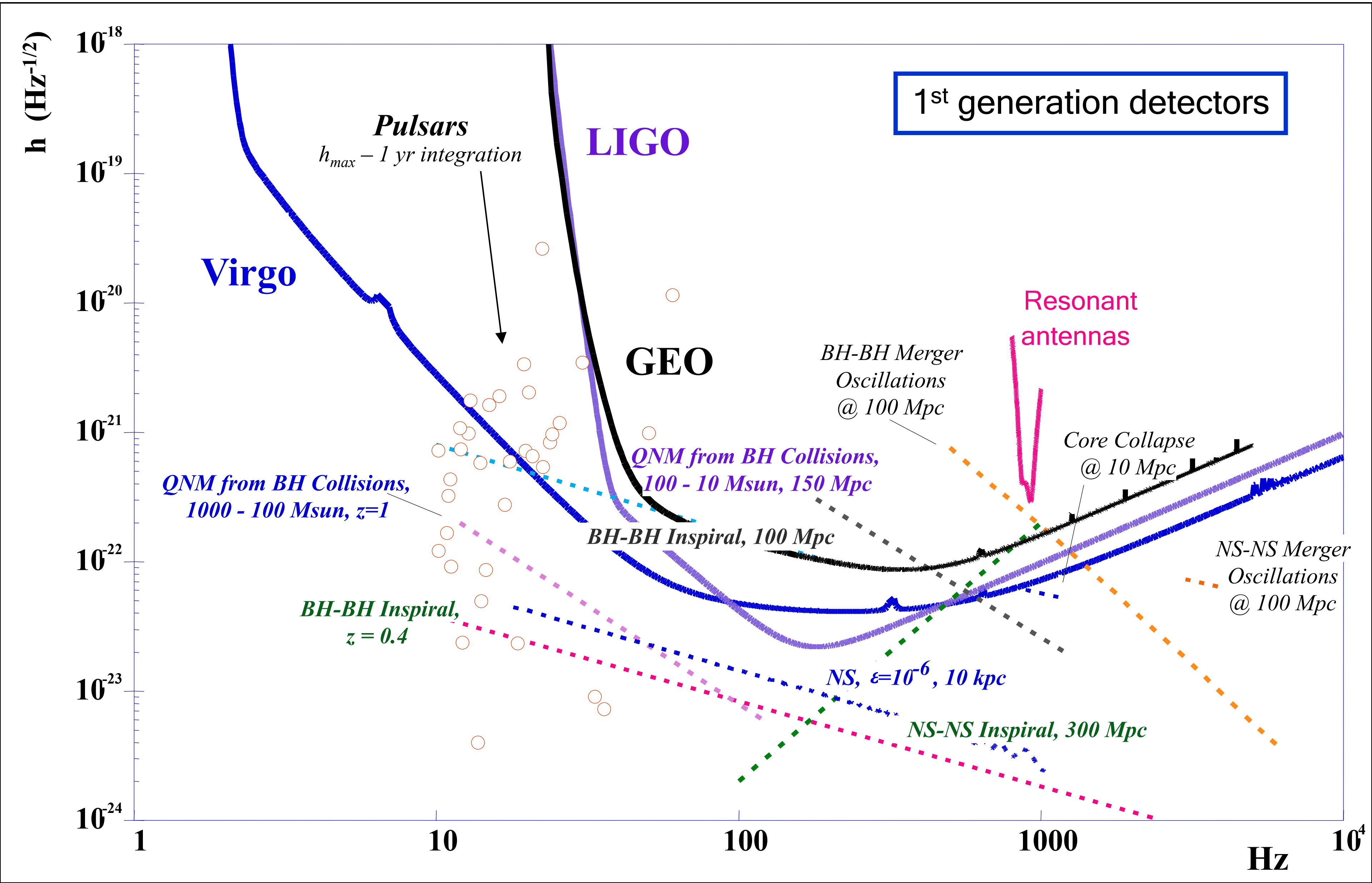
- *Assistant Spokesperson*: Prof. Laura Cadonati, Georgia Tech university (Atlanta-Georgia)

The LIGO Observatories

Credit: P.Shawan

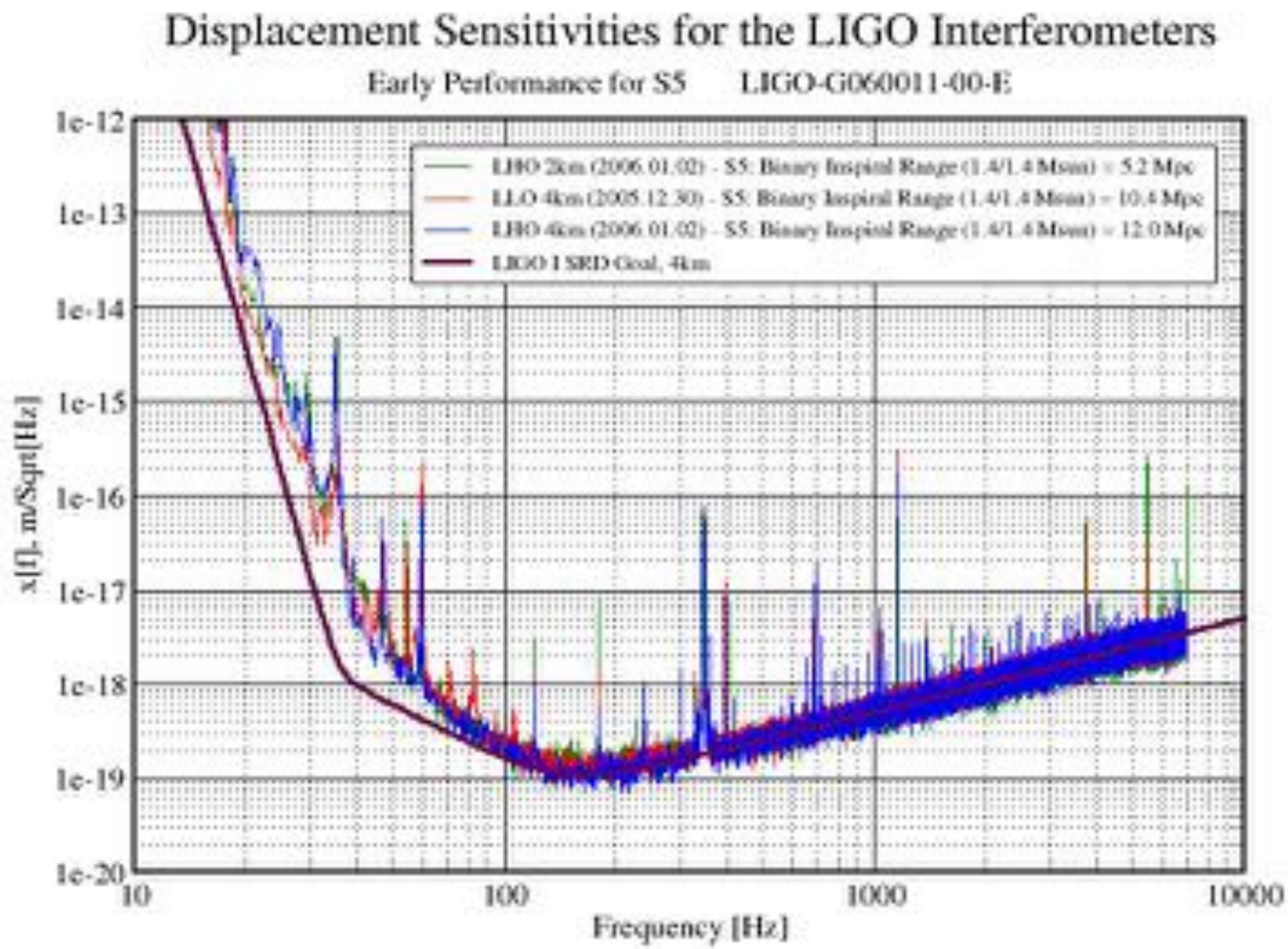
- Adapted from “The Blue Marble: Land Surface, Ocean Color and Sea Ice” at visibleearth.nasa.gov
- NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group Additional data: USGS EROS Data Center (topography); USGS Terrestrial Remote Sensing Flagstaff Field Center (Antarctica); Defense Meteorological Satellite Program (city lights).

Sensitivity curves



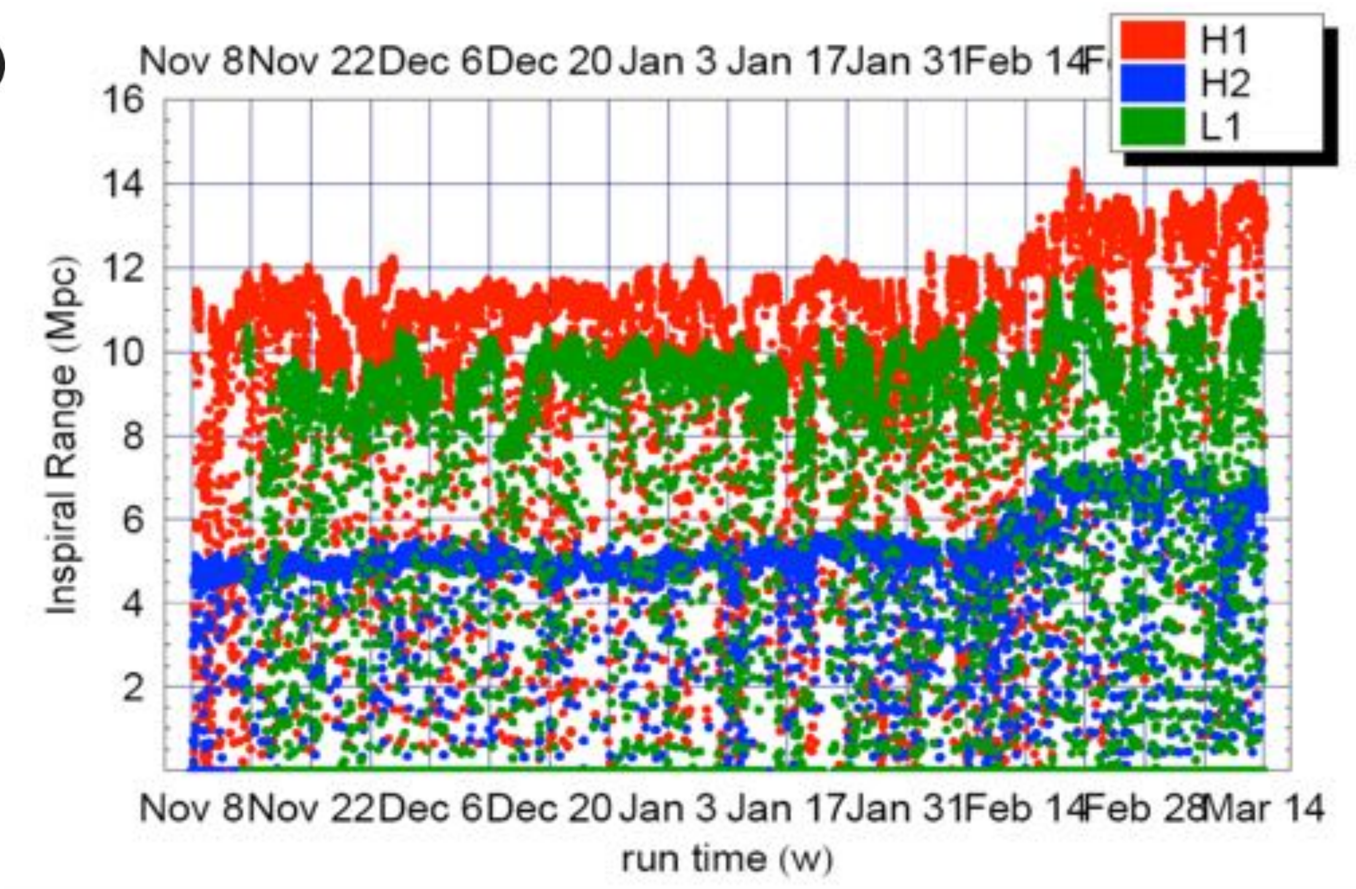
LIGO

Commissioning started in 1999.
Design sensitivity achieved.
Detector technology demonstated



LIGO Scientific Collaboration

LIGO observation range (averaged) for NS/NS inspiral:
14 Mpc



LIGO Scientific Collaboration

The “single machine”

MOU to be signed between LIGO Scientific Collaboration and Virgo:

- Full exchange of data, joint analysis
- Coordinate science runs, commissioning and shutdowns
- Joint publications

The LIGO - VIRGO MoU

- In 2004 LIGO and Virgo started a first exercise to test the data exchange and compare the software performance developed in the two collaborations.

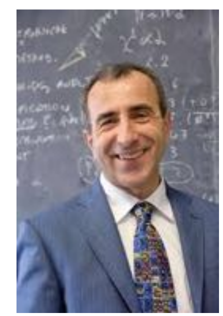
- In 2007 a formal Memorandum of Understanding (MoU) between the two collaborations was signed: “”*We intend to carry out the search for gravitational waves in a spirit of teamwork, not competition. “”*

- *“”The terms governing work on data analysis are exclusive; that is, the parties agree that all of the data analysis work that they do will be carried out under the framework of this agreement…omissis…, all subsequent observational data will be open to both collaborations, to be used in the framework of Joint Data Analysis Groups on all gravitational wave analysis topics. All gravitational wave data analysis will be carried out under the umbrella of this agreement between LIGO and VIRGO; there will be no LSC-only or Virgo-only gravitational wave data analyses while this agreement remains in force. “”*

Data Analysis Organization

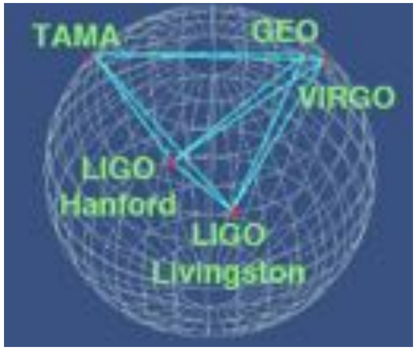
- Data Analysis Council (DAC) , co-chaired by LSC and Virgo
  - Peter Swan for LSC – professor at university of Maryland

  - Giovanni Prodi for Virgo, professor at the university of Trento & INFN TPFA



- Joint groups of data analysis, co-chaired by LSC and Virgo
  - Burst , CBC, CW, SB and DetChar

The benefits of a network

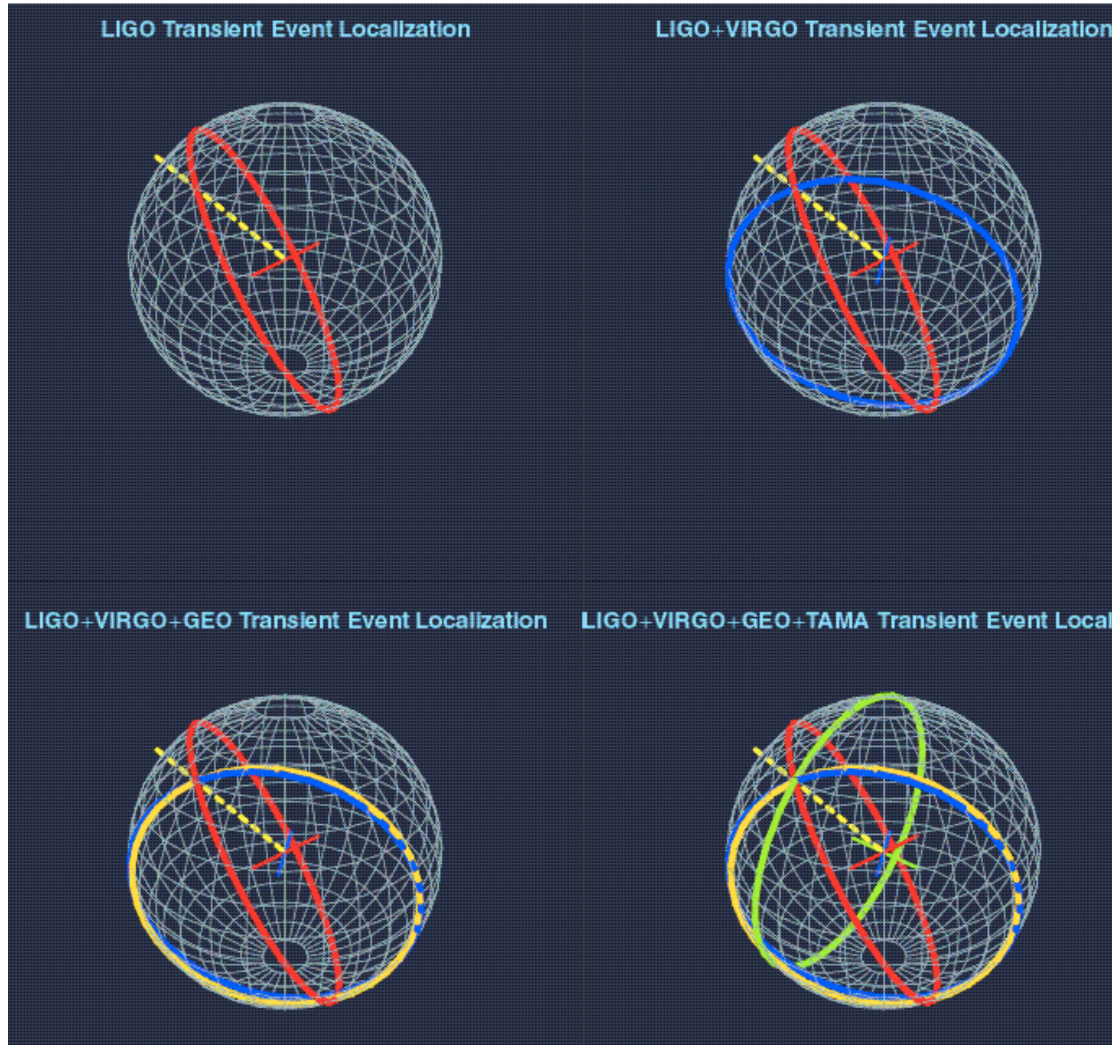


False alarm rejection requires coincidence

Triangulation allows to **pinpoint the source**

The network allows to deconvolve detector response and signal waveform → **measure signal parameters**

Longer **observation time**, better **sky coverage**

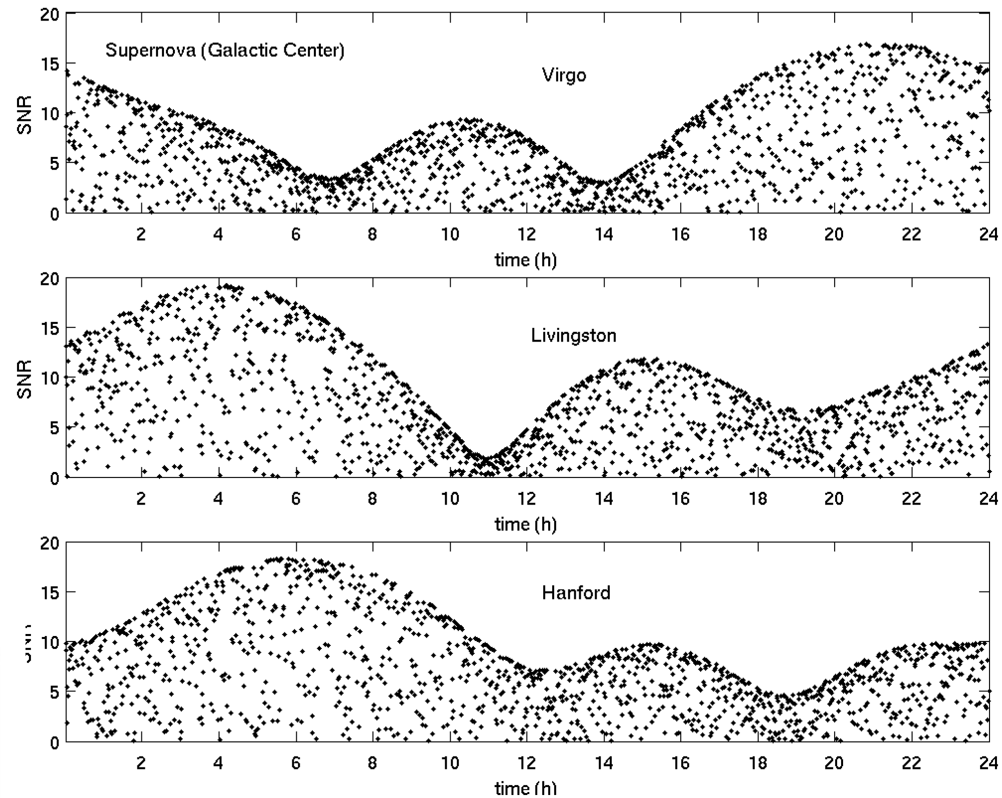


Bursts and sky coverage

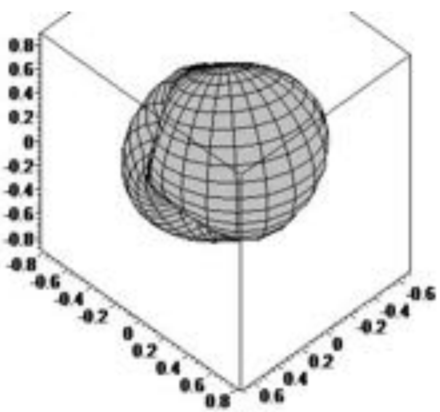
SIMULATION: *burst events at the galactic center*

LIGO-Virgo contact group

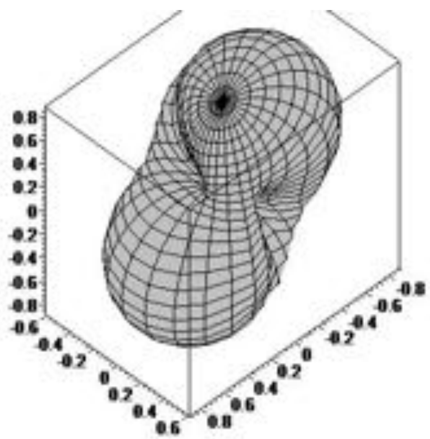
- Detector angular response not isotropic
- Sensitivity changes with the detector orientation
- The network improves the sky coverage



LIGO Hanford



Virgo

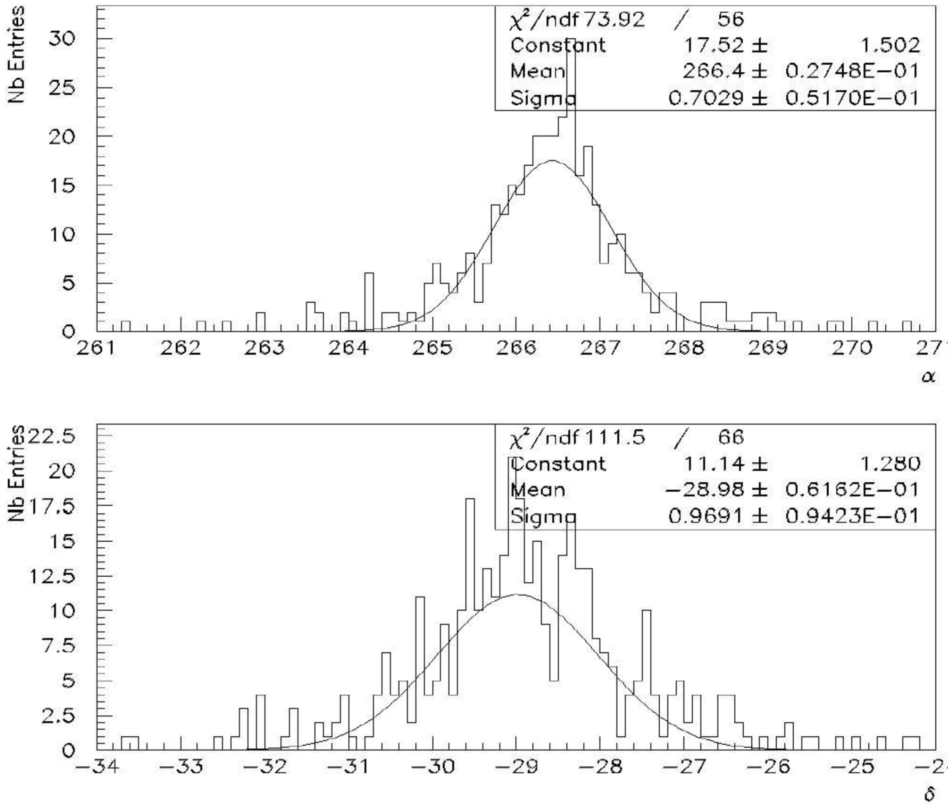


Bursts and sky coverage

SIMULATION: *burst events at the galactic center*

LIGO-Virgo contact group

- Triple coincidence allows to locate events in the sky
- Right ascension and declination can be measured with an accuracy of ~1° (SNR=10)



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LIGO upgrade

concluded

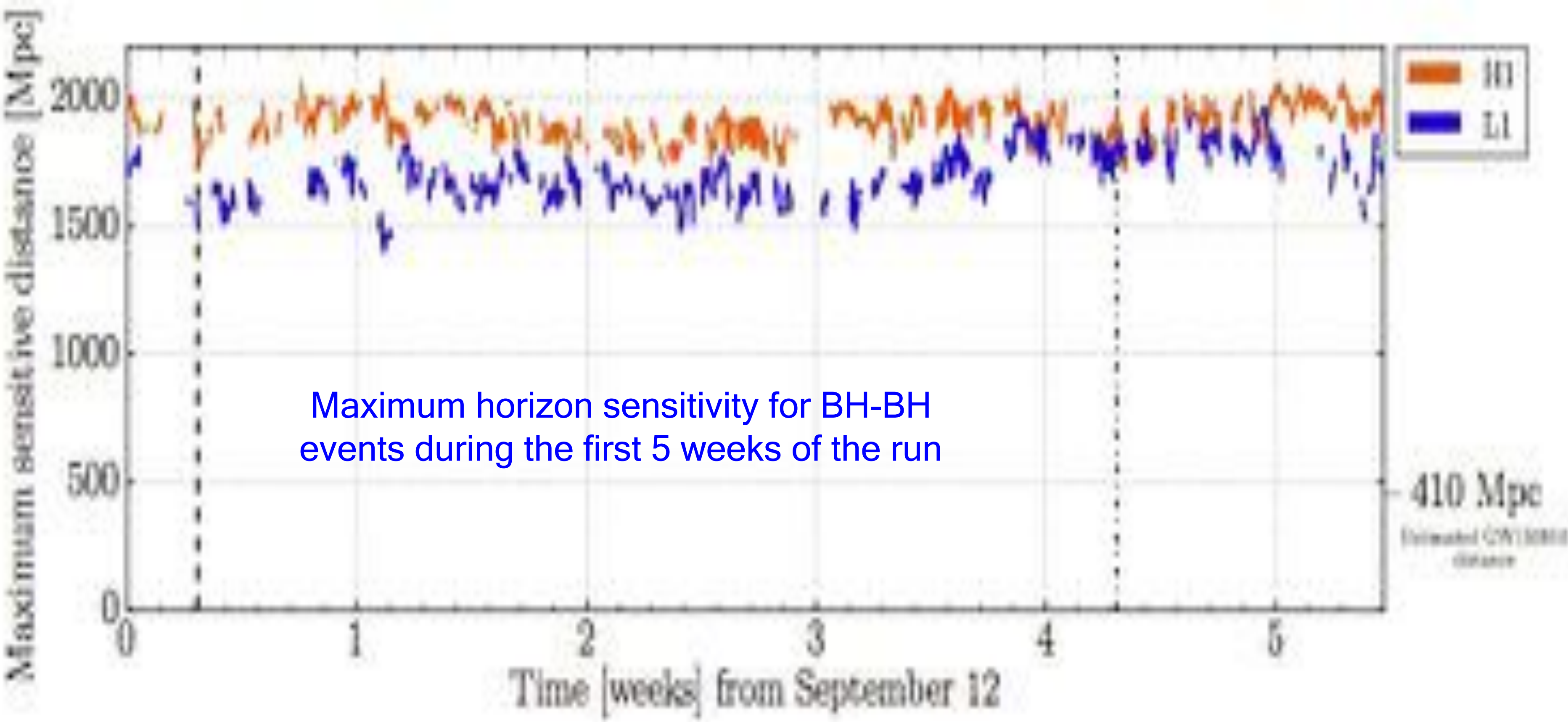
The Advanced LIGO dedication ceremony was held at Hanford on May 19, 2015

H1- Hanford – Washington state

VIRGO will end the upgrade in 2016

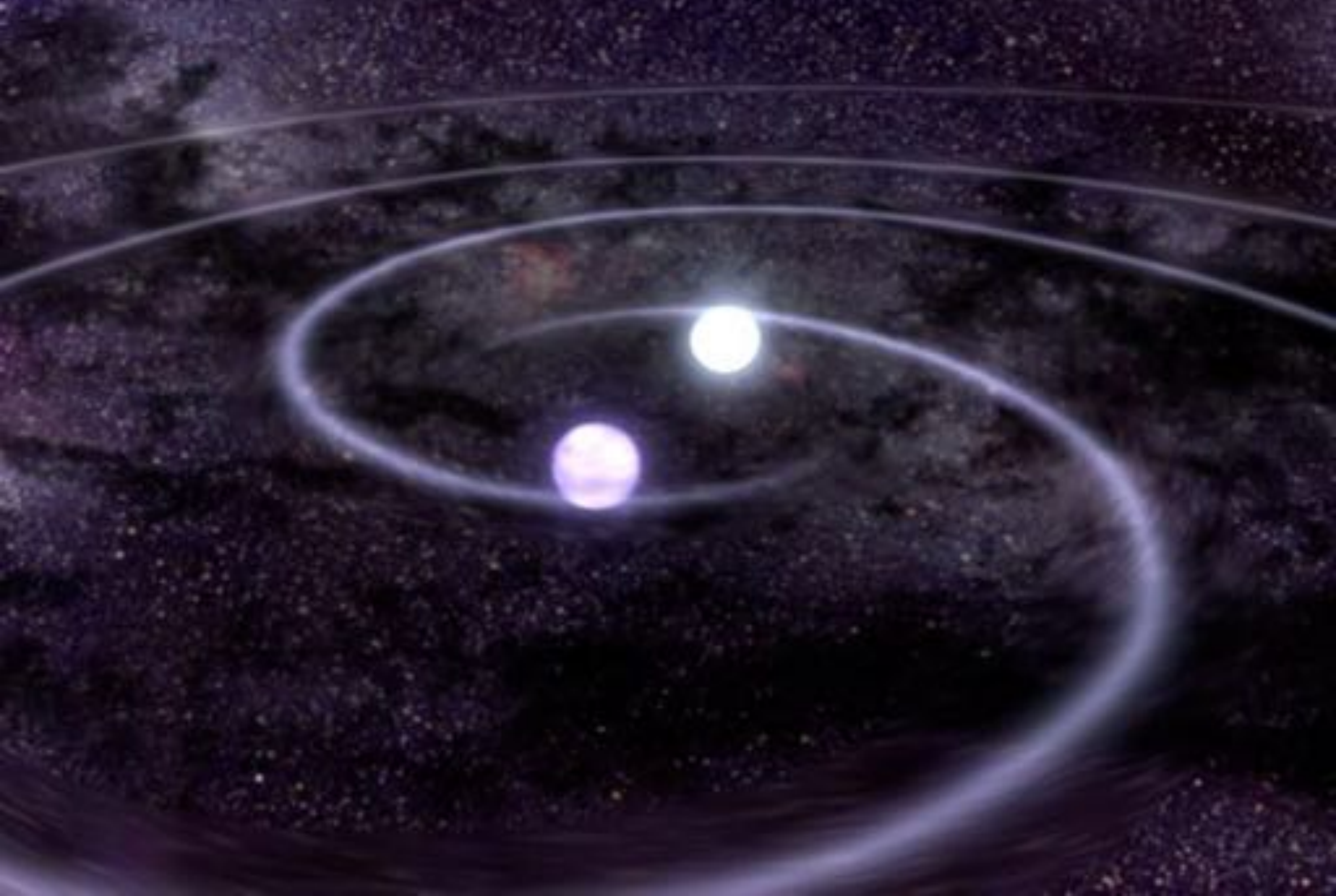
L1- Livingston – Louisiana state

The first month of the run

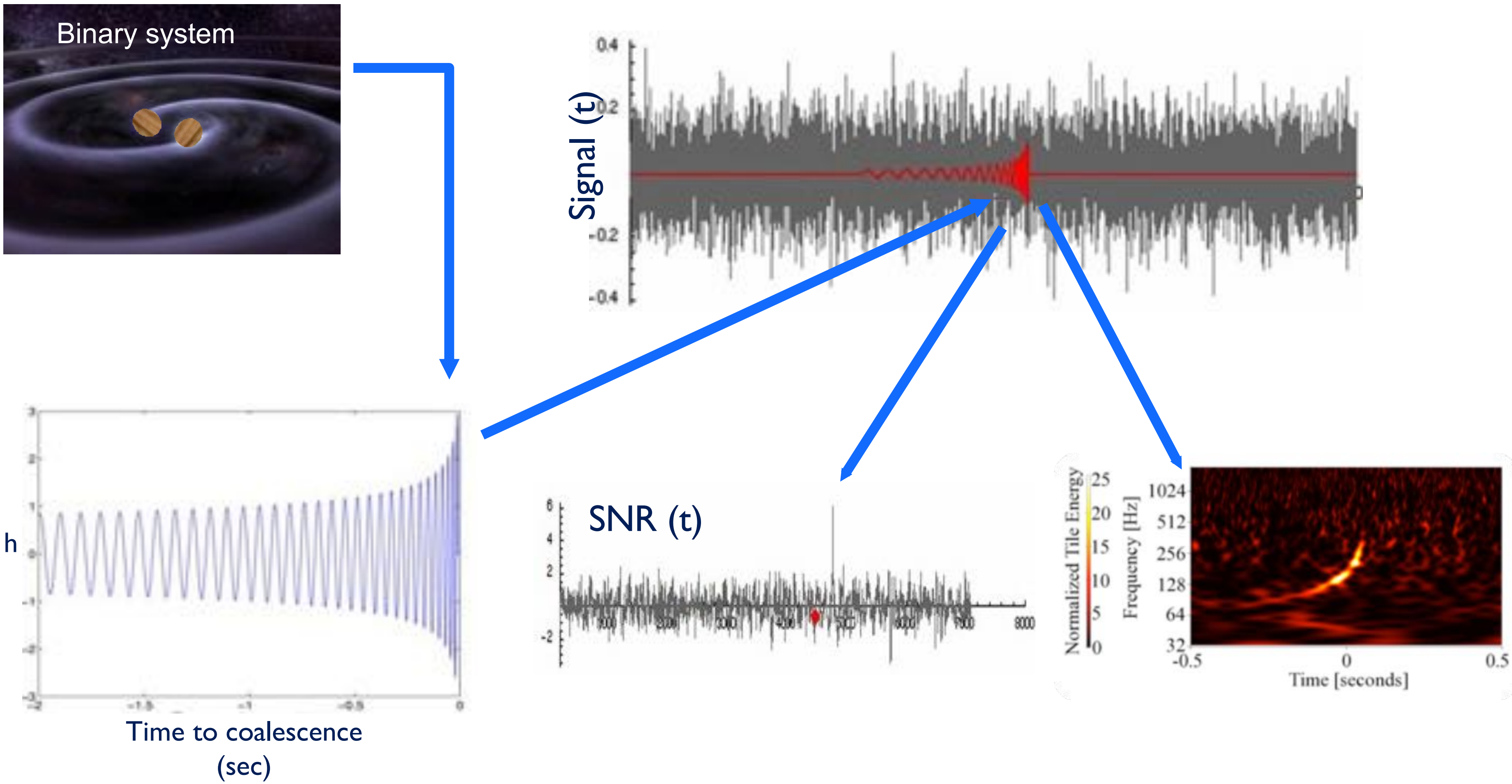


- Interferometers locked in their nominal data-taking configurations
  - ➢ The performance of the instruments **exceeded** the median expected, and almost met the upper range expected in the 2015 (O1) observation run

The Golden Signal



How the signal might look like



cWB: minimal assumption algorithm for searching transients

- Require coherent signals in multiple detectors, using direction-dependent antenna response
- Look for excess power in time-frequency space using wavelet decomposition

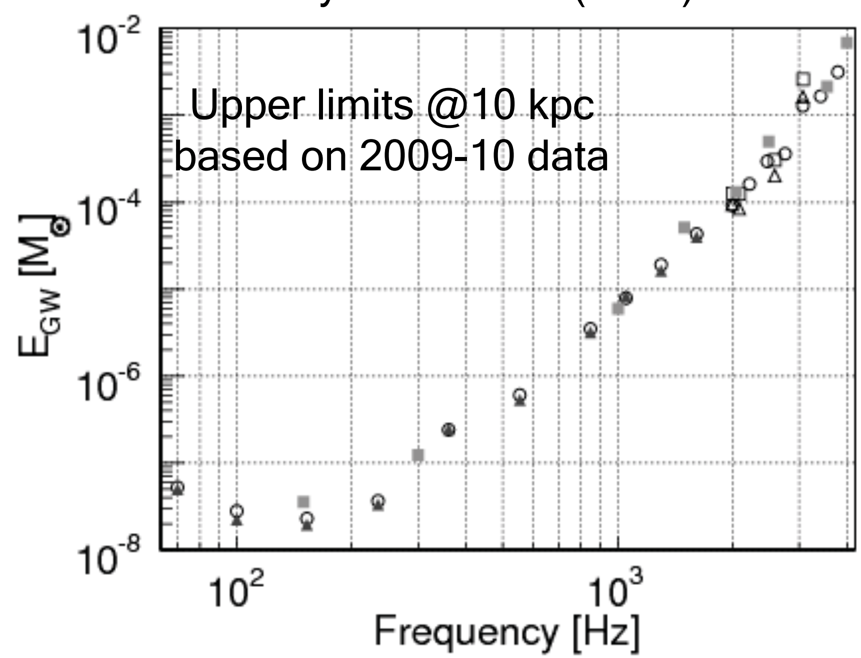
The event are ranked using a variable quoting the SNR of the coherent signal in the network

$$\eta_c = \sqrt{\frac{2E_c}{(1 + E_n/E_c)}}$$

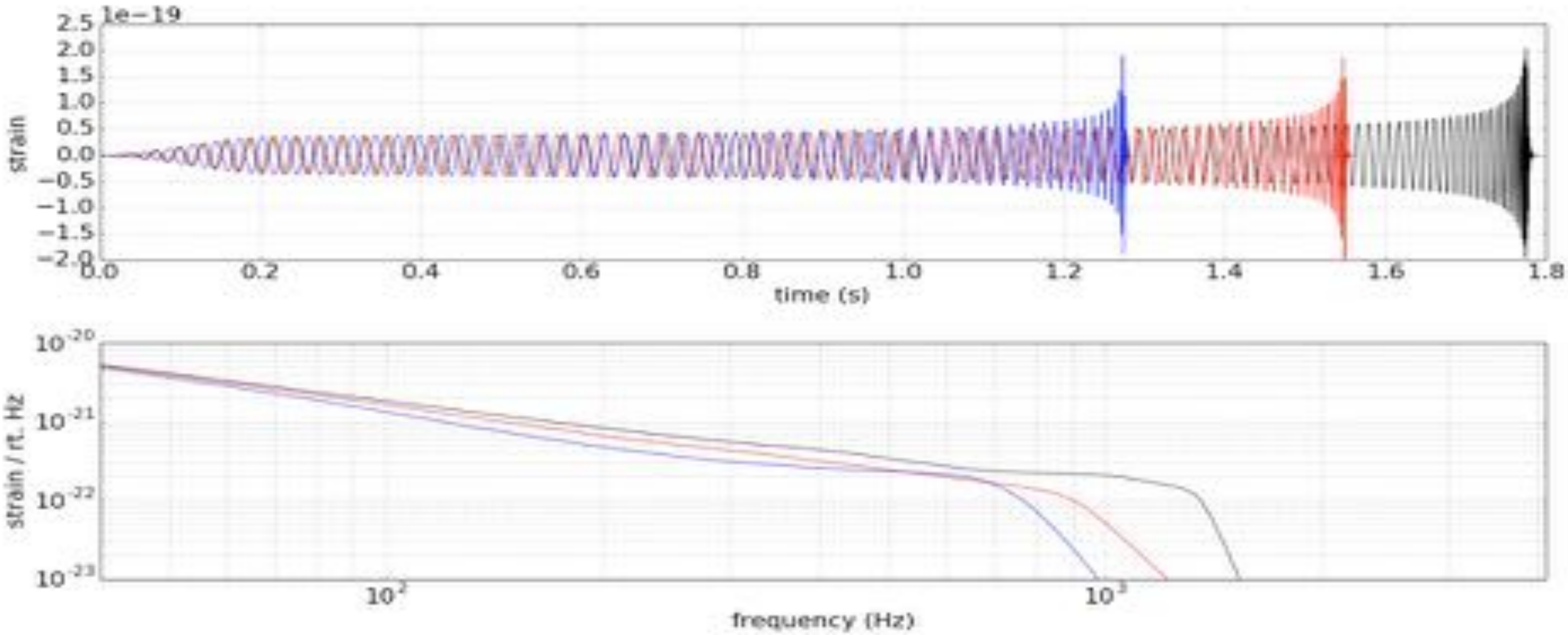
E_c ➔ Normalized coherent energy between the two detectors

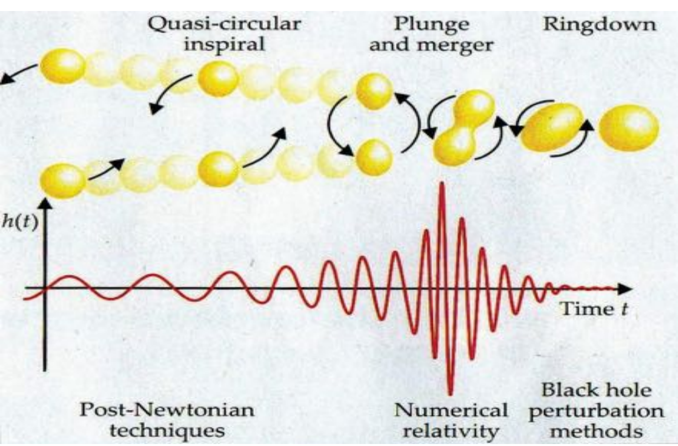
E_n ➔ normalized noise energy derived by subtracting the reconstructed signal from the data

Phys. Rev D 85 (2012) 122007



Compact Binary Coalescence: Waveforms



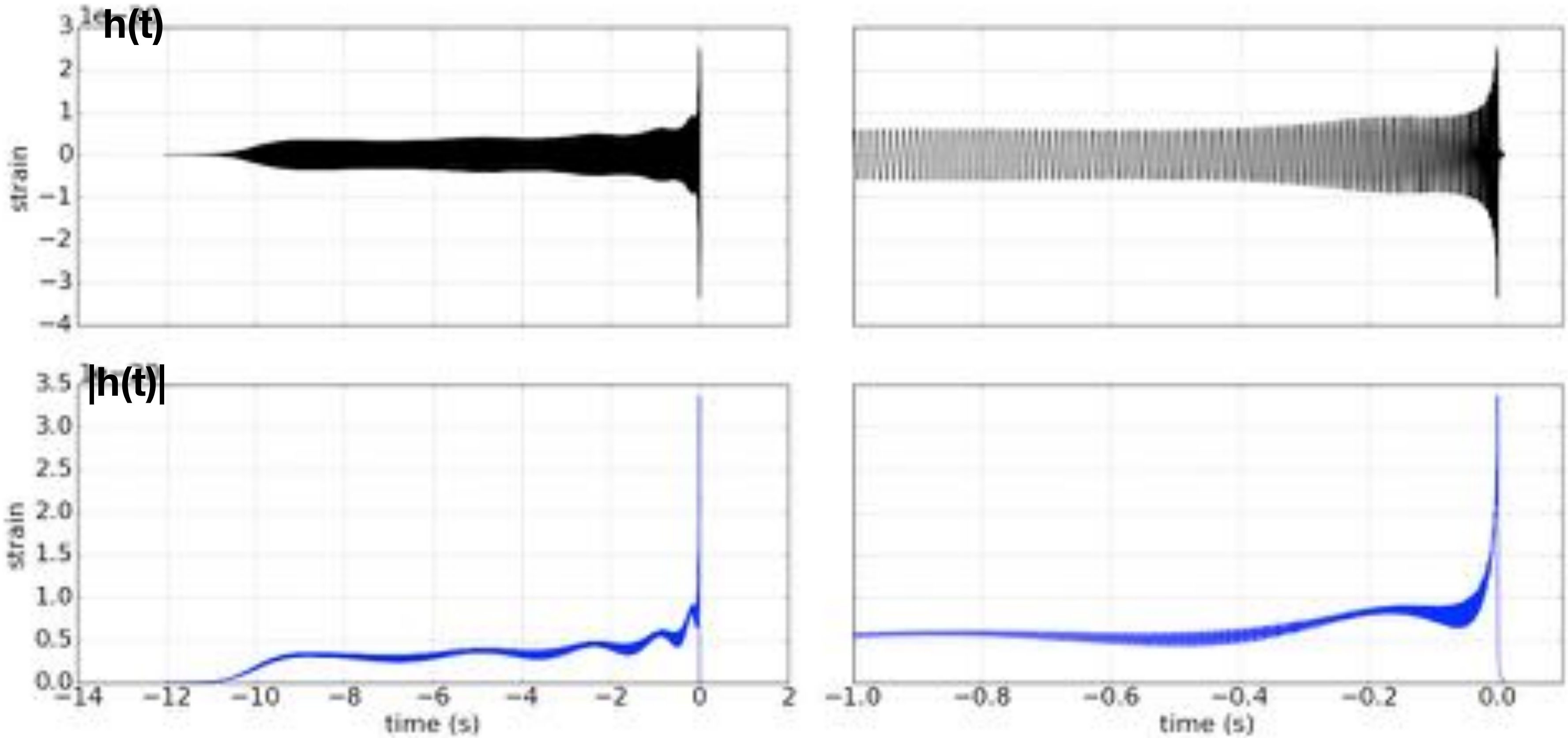


$m_1 = m_2 = 10\ M_\odot$

$_z = s_{2,z} = 0.99$ $s_{1,z} = 0.99,\ s_{2,z} = -0.99$

$s_{1,z} = s_{2,z} = -0.99$

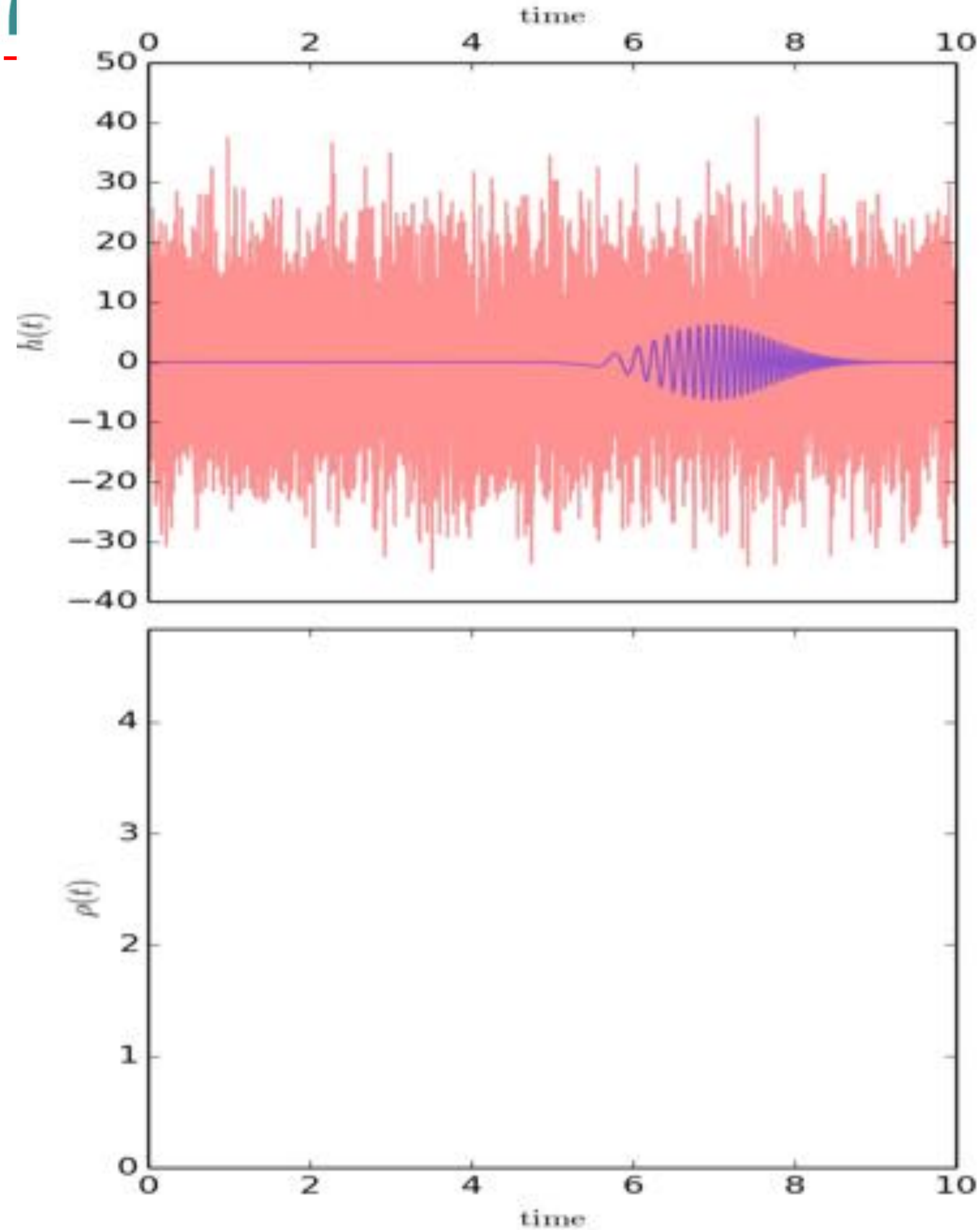
Compact Binary Coalescence



Effects of Precession $m_1 = 5$ $m_2 = 1.4$

$s_{1,x} = s_{1,y} = 0.5$

modulation envelope

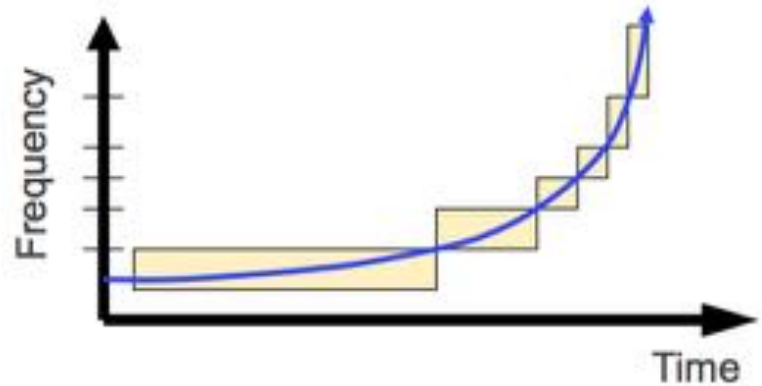


Assuming that the signal is CBC like: the matched filter search is the optimum linear approach for the detection

Waveform consistency: χ^2 test

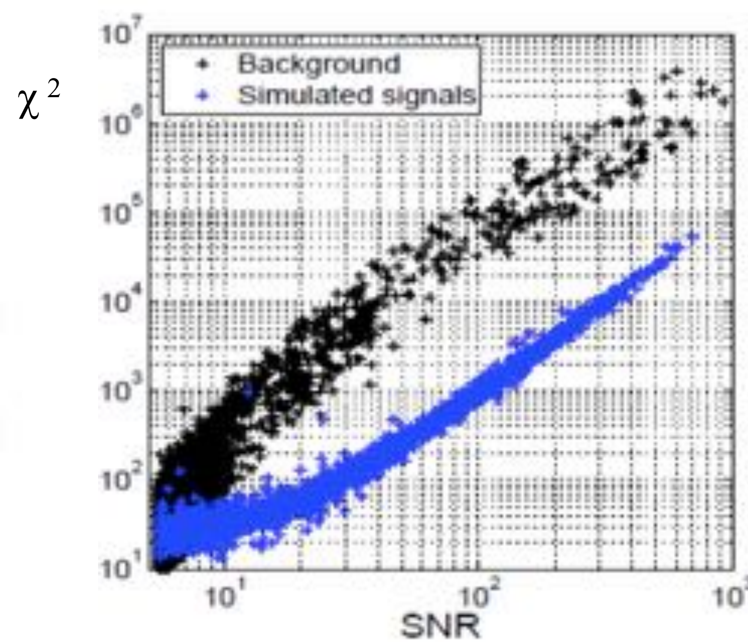
- Divide the "selected" template into p parts
- The frequency intervals are chosen so that for a true signal, the SNR is uniformly shared among the frequency bands
- For a stationary and Gaussian noise has an expectation value:

$$\chi^2(t) = p \sum_{j=1}^{p} |\rho_j - \frac{\rho}{p}|^2$$

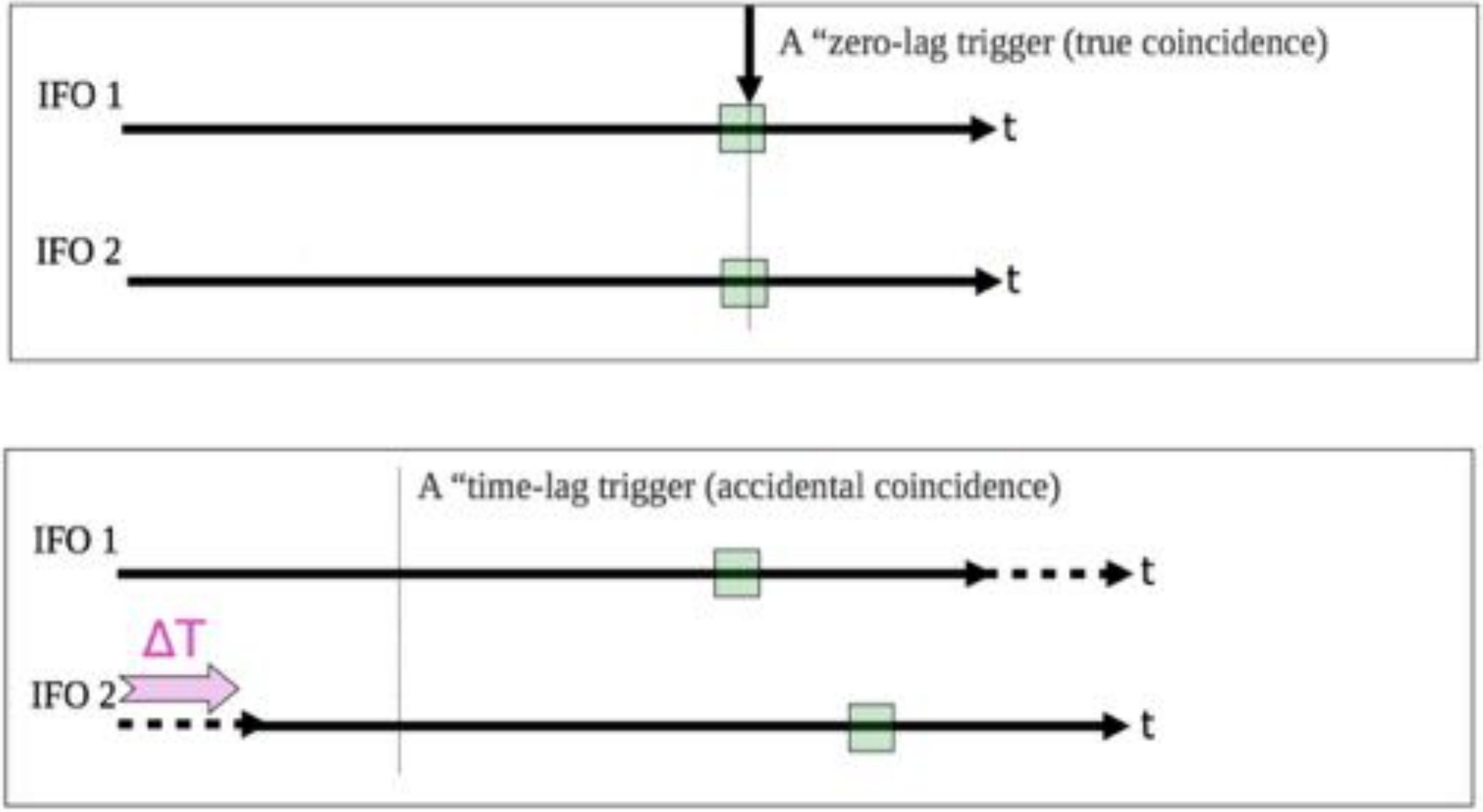


- In practise χ^2 values are larger than expected for large SNR (discrete template banks effect) → cut in (SNR, χ^2) plane
- Weighted SNR

$$\rho_{\rm new} = \begin{cases} \rho, & \chi^2 \leq n_{\rm dof} \\ \dfrac{\rho}{\left[\left(1 + \frac{\chi^2}{n_{dof}}^{4/3}\right)/2\right]^{1/4}}, & \chi^2 > n_{\rm dof} \end{cases}$$



Background estimation



One Month of Observation

- The analysis covered the period from September 12th to October 20th

- 16 days of coincidence data (both Hanford and Livingston locked)

Potential horizon for different kind of CCB signals

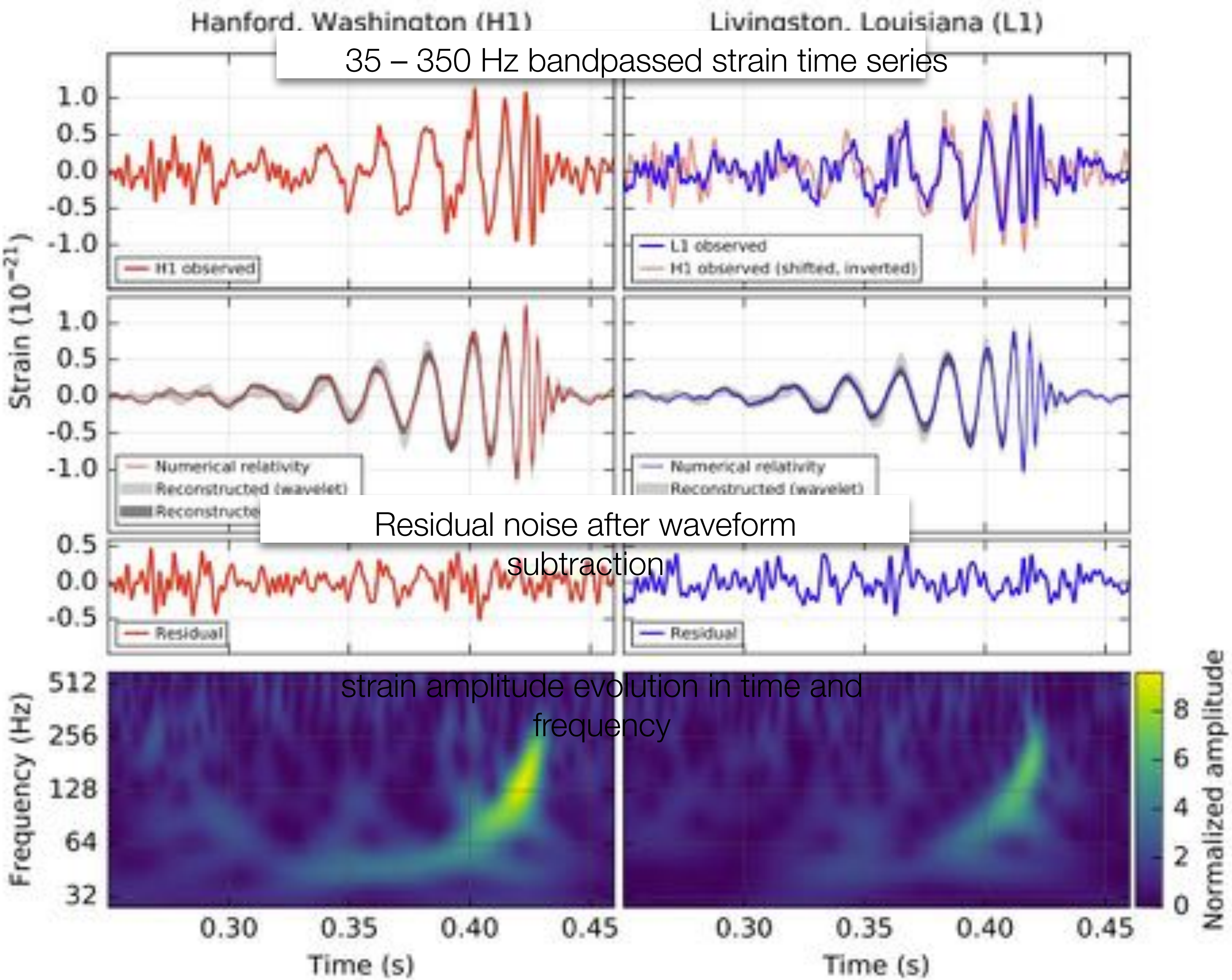
- 1.4 $M_\odot$ + 1.4 $M_\odot$ ➔ horizon: 130 Mpc
- 1.4 $M_\odot$ + 5 $M_\odot$ ➔ horizon: 200 Mpc
- 20 $M_\odot$ + 20 $M_\odot$ ➔ horizon: ~1 Gpc

Signal-to-Noise ratio (SNR)

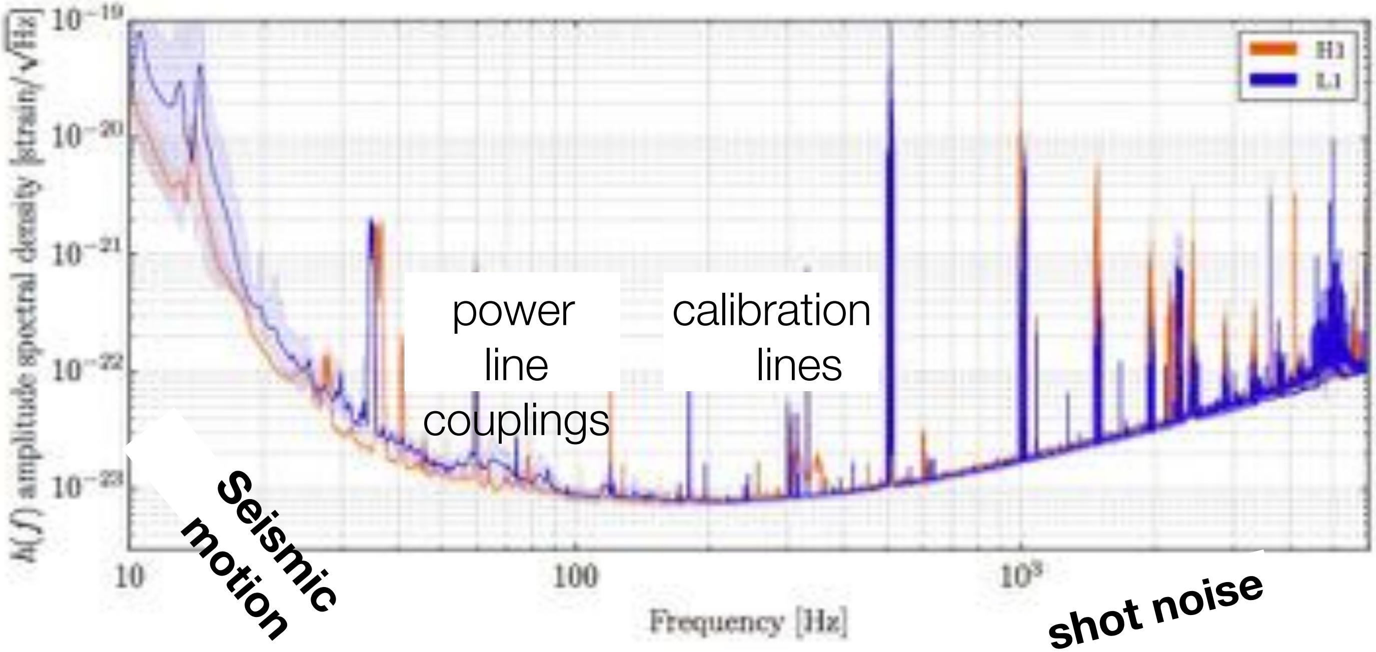
$$\rho = 4 \int_0^\infty \frac{\tilde{h}(f)\tilde{d}(f)^*}{S(f)} df$$

Horizon distance (luminosity)

$$d_h = \frac{4}{\bar{\rho}} \int_0^\infty \frac{\tilde{h}_{1\ \mathrm{Mpc}}(f)\tilde{d}(f)^*}{S(f)} df$$


Hanford, Washington (H1)
Livingston, Louisiana (L1)
35 – 350 Hz bandpassed strain time series
H1 observed
L1 observed
H1 observed (shifted, inverted)
Strain (10^{-21})
Numerical relativity
Reconstructed (wavelet)
Residual noise after waveform subtraction
Residual
strain amplitude evolution in time and frequency
Frequency (Hz)
Normalized amplitude
Time (s)

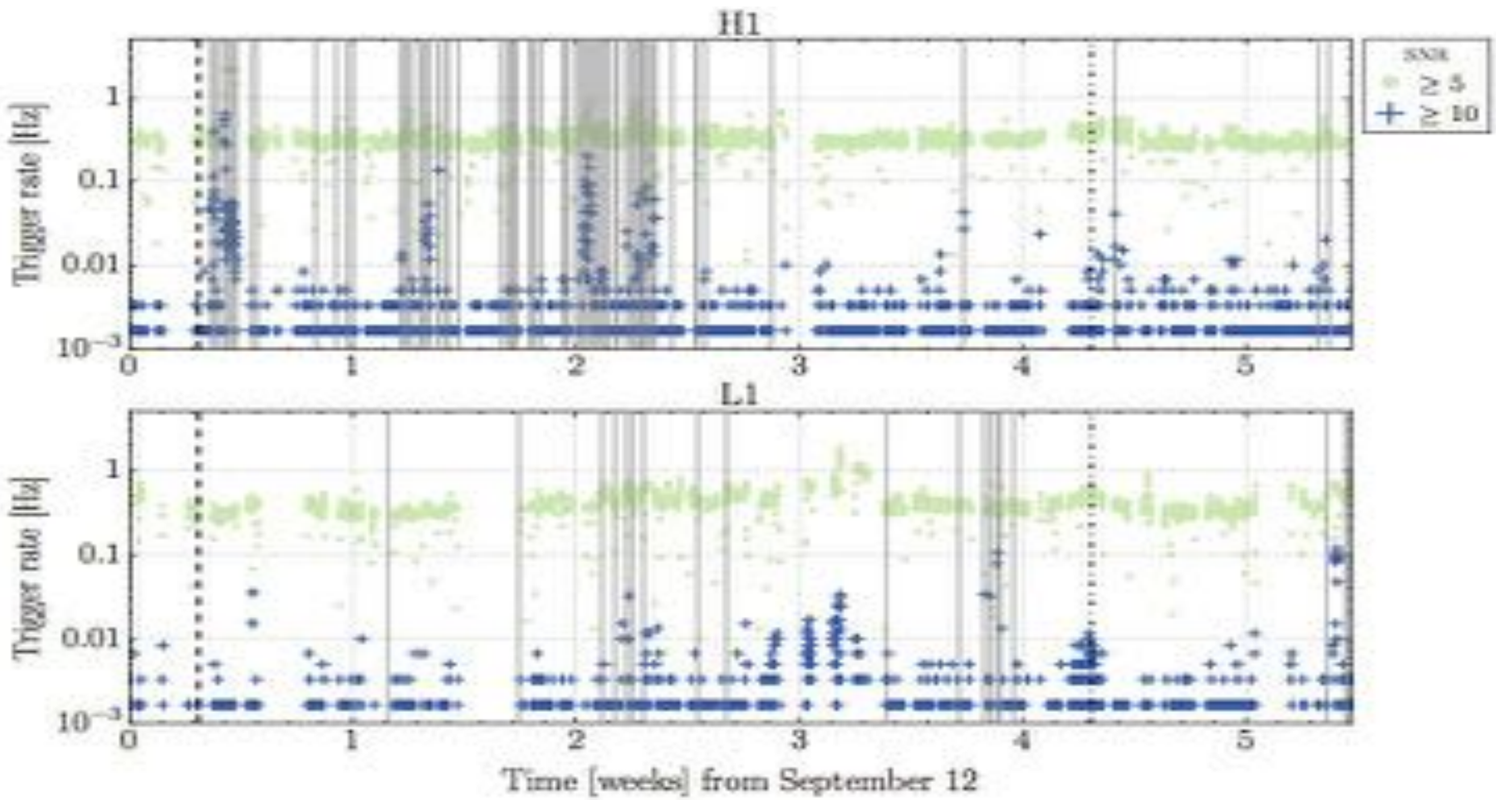
Sanity Checks



- Thousands of DAQ channels to acquire **electric, magnetic, and seismic** measurements from both instruments in addition to the cahnnels devoted to monitor nd control the status of the interferometers
- Spectral correlations as well as statistical correlations computed between transients in the channel and the GW strain channel

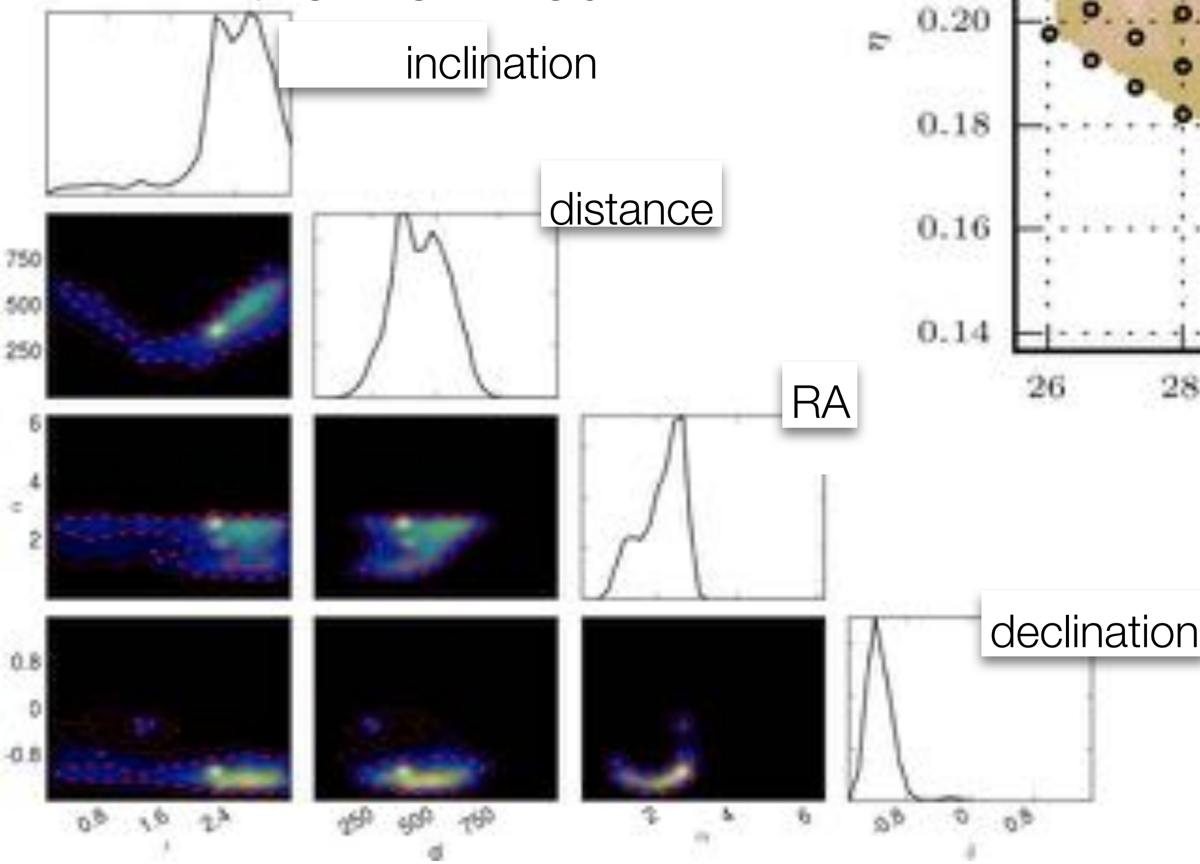
Data Quality and Sanity Checks

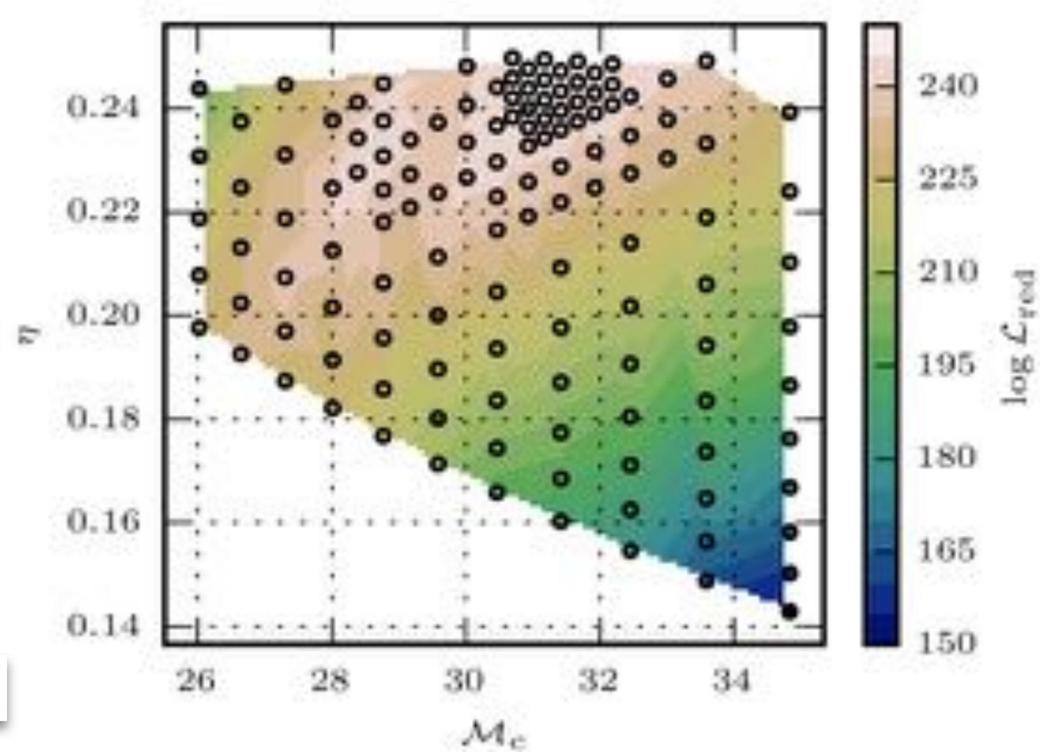
- **Candidates are vetoed if a correlation is detected**
- Data near GW150914 is **very clean**, no *a priori* or *a posteriori* vetoes would have indicated non- astrophysical origin



Rapid Parameter Estimation

Mass estimates and source orientation in less than an hour

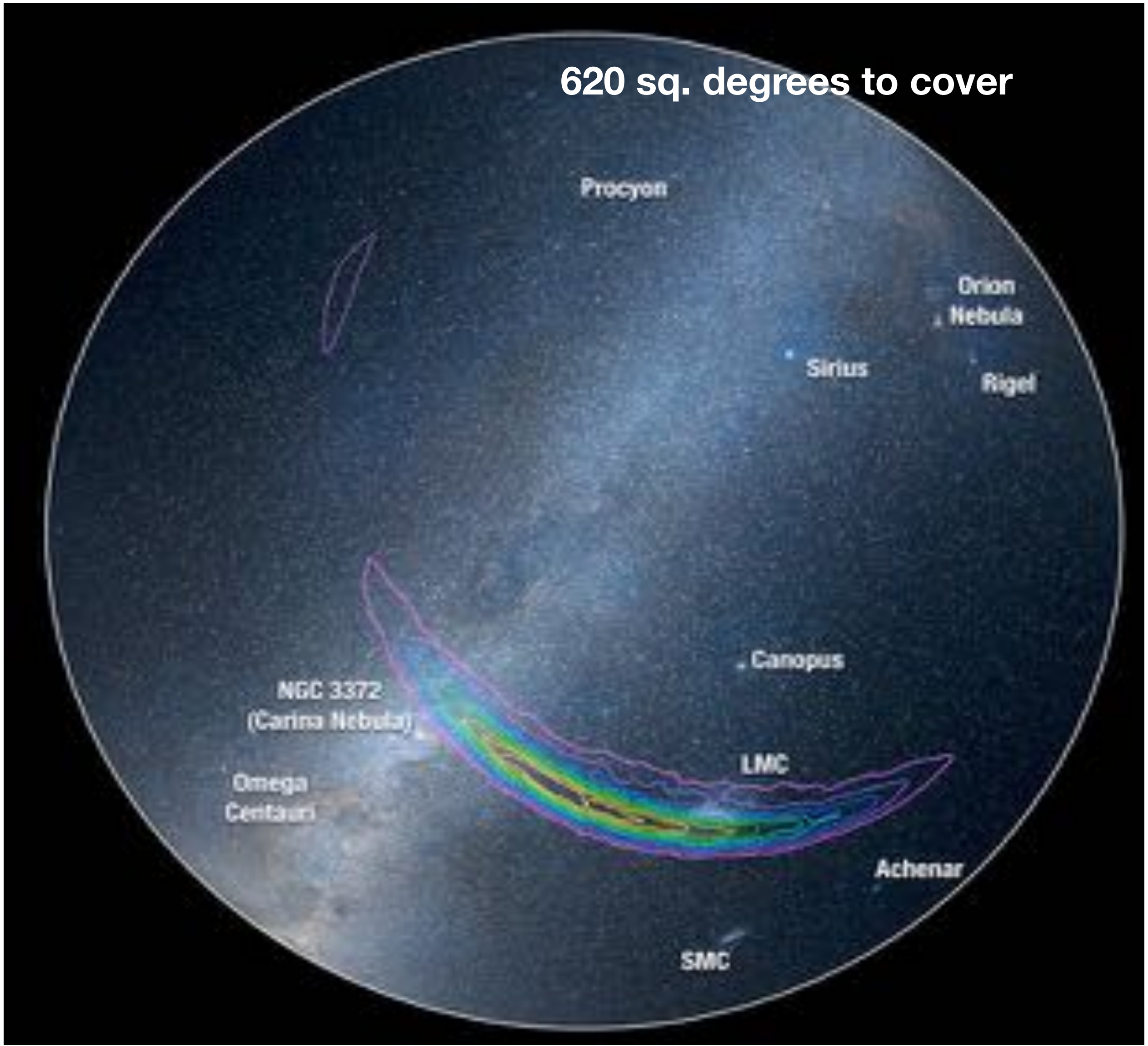




GW Source: Sky Position-Posterior Probability

Sky areas broadly consistent with simply triangulation, and mostly cross-consistent

Triangulation ring consistent with time delay of about ~7ms



Minimum Bias Search

cWB version online: event detected with 2 minutes of latency

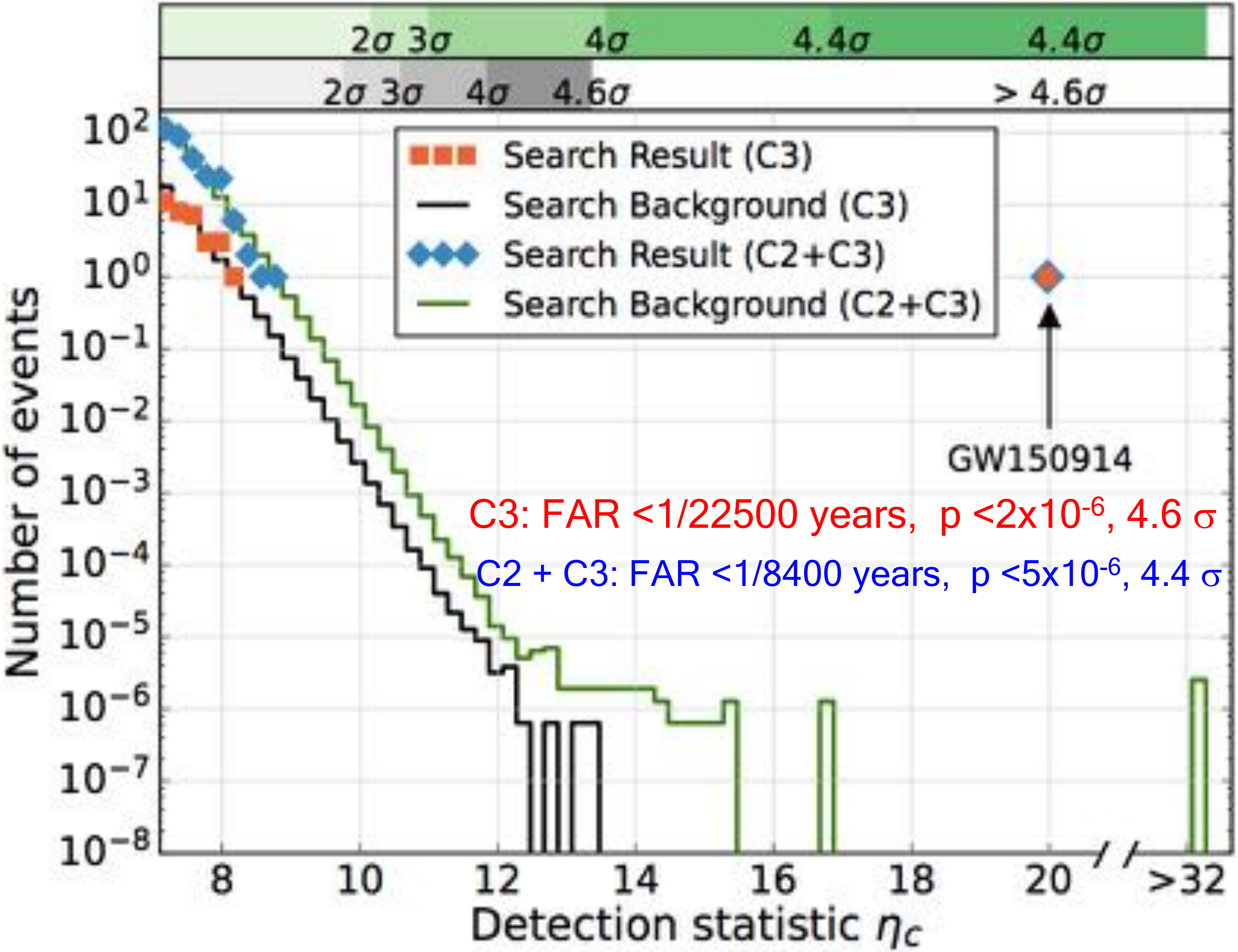
cWB version off-line: data reanalyzed to assess the statistical significance

Events classified in 3 different classes (➔ trial factor):

- C1 class ➔ events with time-frequency morphology of known populations of noise transients: excluded;
- C3 class ➔ events with frequency that increases with time;
- C2 class ➔ all remaining events.

Background evaluation ➔ Based on the time shift method:

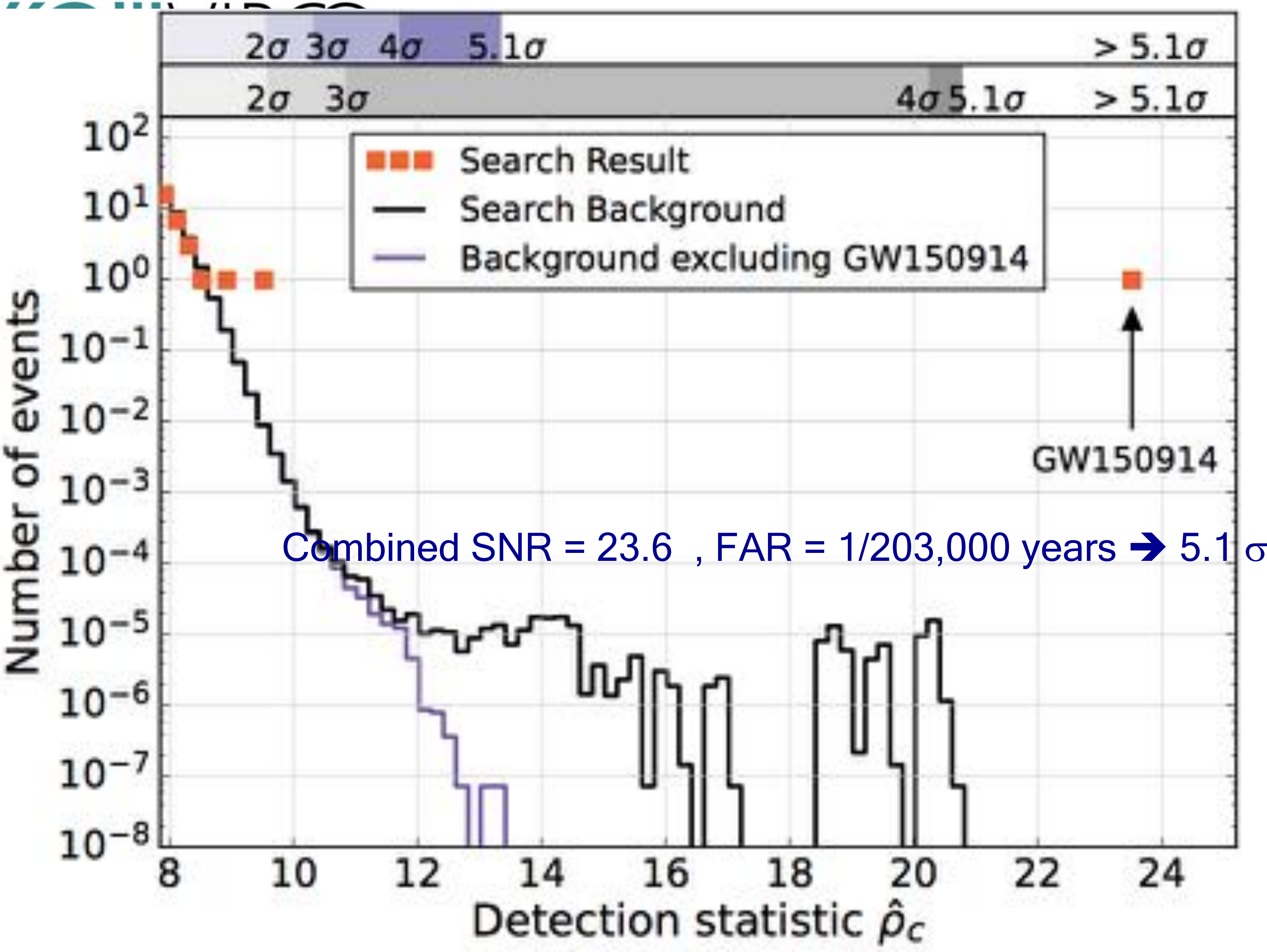
Number of shift produced an equivalent to 67400 years



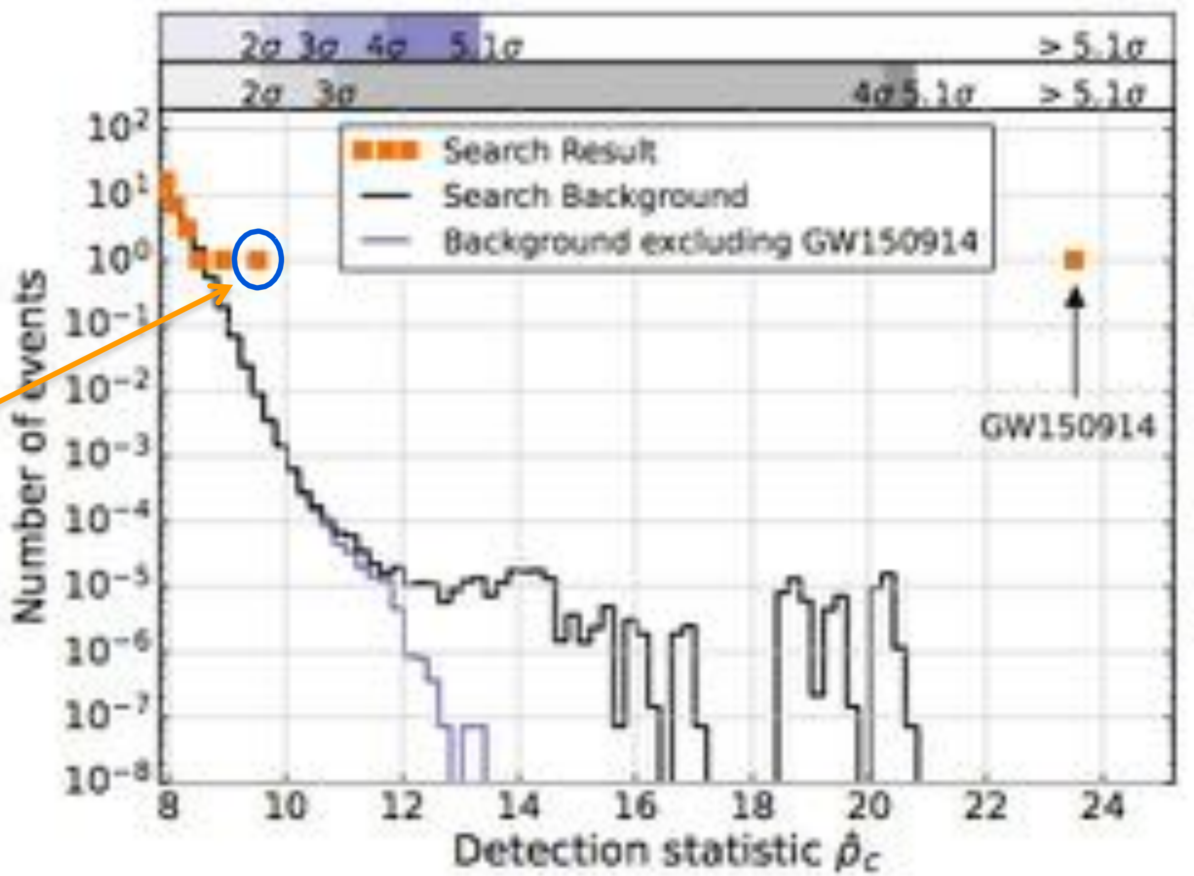
2σ 3σ 4σ 4.4σ 4.4σ
2σ 3σ 4σ 4.6σ > 4.6σ
Search Result (C3)
Search Background (C3)
Search Result (C2+C3)
Search Background (C2+C3)
GW150914
C3: FAR <1/22500 years, p <2x10^-6, 4.6 σ
C2 + C3: FAR <1/8400 years, p <5x10^-6, 4.4 σ
Number of events
Detection statistic ηc
10^2 10^1 10^0 10^-1 10^-2 10^-3 10^-4 10^-5 10^-6 10^-7 10^-8
8 10 12 14 16 18 20 >32

Binary Coalescence search

- 2.5 x 10^5 waveforms (mass range 1- 99 $M_\odot$)
  - EOBNR ➔ The effective-one-body (EOB) formalism combines perturbative results from the weak-field PN approximation with strong-field effects from the test-particle limit.
  - IMR-Phenomen ➔ It is based on extending frequency-domain PN expressions and hybridizing PN and EOB with NR waveforms.
- SNR of the Matched filter computed as function of time $\rho(t)$ and identify maxima and calculate χ^2 to test consistency with the matched template, then apply detector coincidence within 15 ms
- Calculate quadrature sum $\rho_C^2(t) = \rho_H^2(t) + \rho_L^2(t)$ of the SNR of each detector
- Background computed by shifting 10^7 times equivalent to 608,000 years


2σ 3σ 4σ 5.1σ
> 5.1σ
2σ 3σ
4σ 5.1σ
> 5.1σ
Search Result
Search Background
Background excluding GW150914
GW150914
Combined SNR = 23.6 , FAR = 1/203,000 years ➔ 5.1 σ
Number of events
Detection statistic $\hat{\rho}_c$
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
8
10
12
14
16
18
20
22
24

The LVT 151012 case



Event less significant!

- *Full offline deep search revealed a second event on October 12, 2015: false alarm probability of ~2%*
- Iif it is interpreted as a candidate of astrophysical origin, still very likely a binary black hole coalescence

Parameter Estimation

Primary black hole mass	$36^{+5}_{-4}\ M_\odot$
Secondary black hole mass	$29^{+4}_{-4}\ M_\odot$
Final black hole mass	$62^{+4}_{-4}\ M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift, z	$0.09^{+0.03}_{-0.04}$

One of the most energetic astronomical event ever observed:

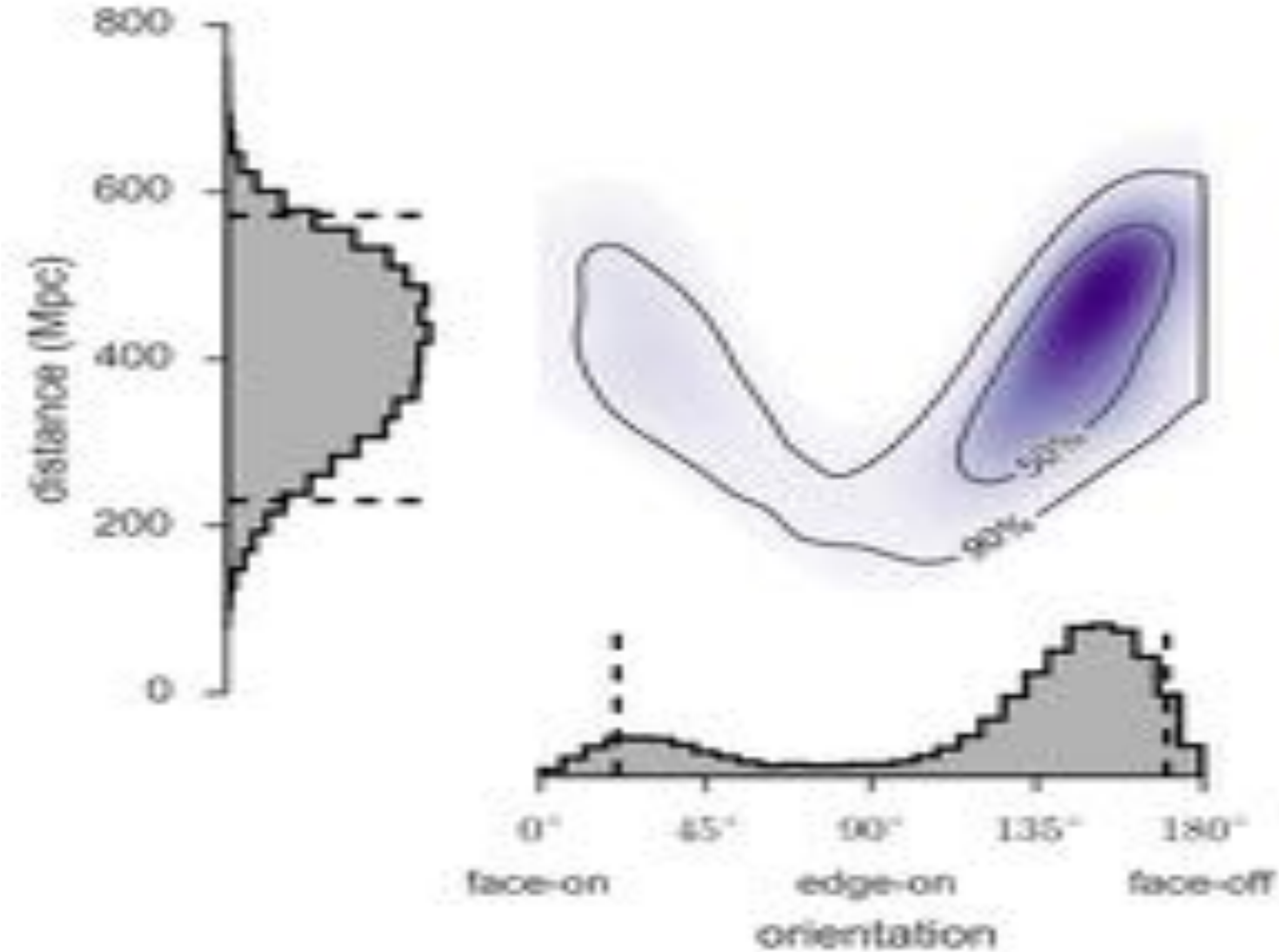
Power emitted ~ **200 $M_\odot$ /s**

Energy emitted ~**10^{49} J ➔ 3 $M_\odot c^2$**

50 times brighter of the entire visible universe

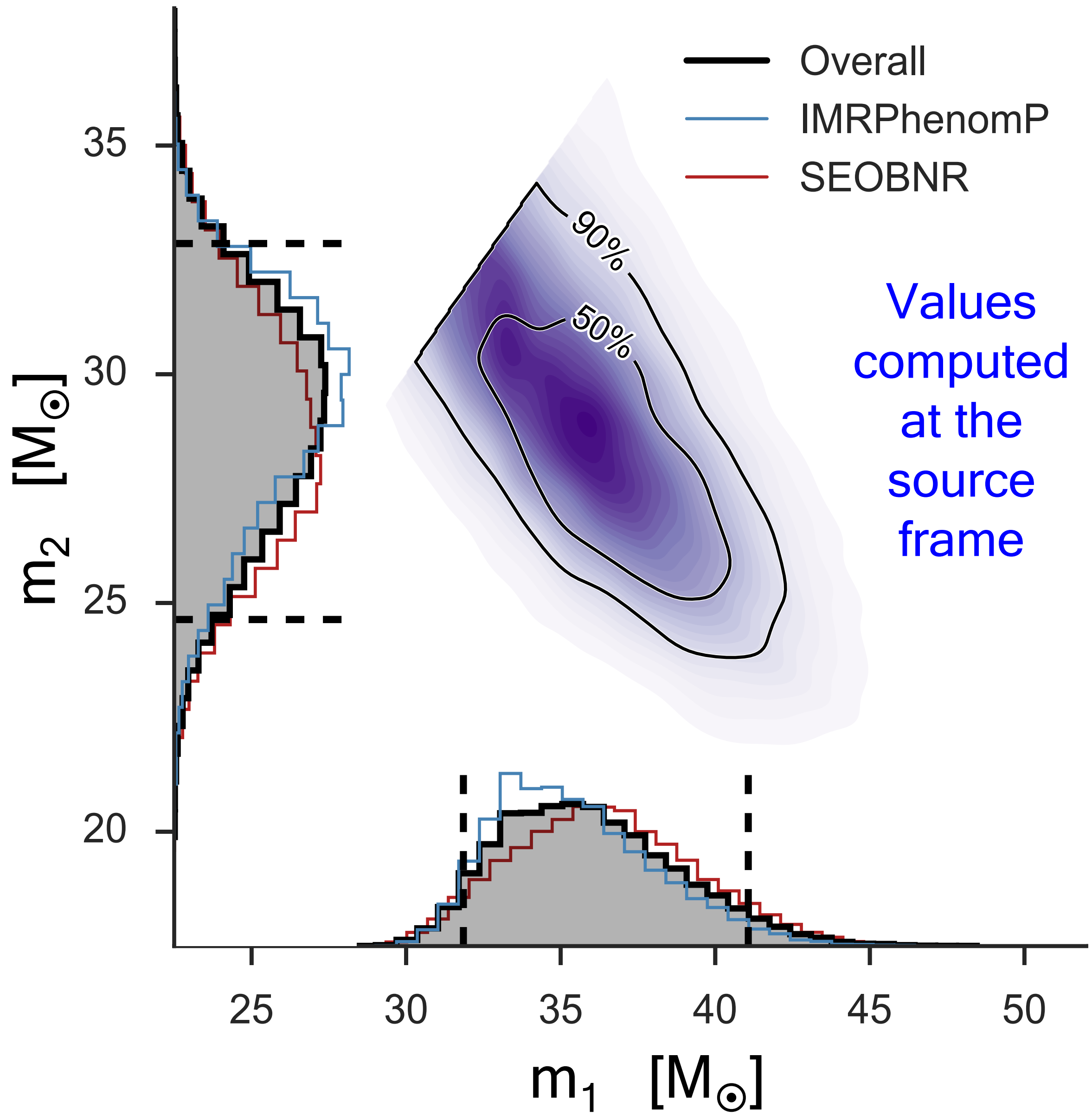
Distance and Orientation

Typical distance / inclination degeneracy could be broken by spin effects, now favouring a “face on” orientation



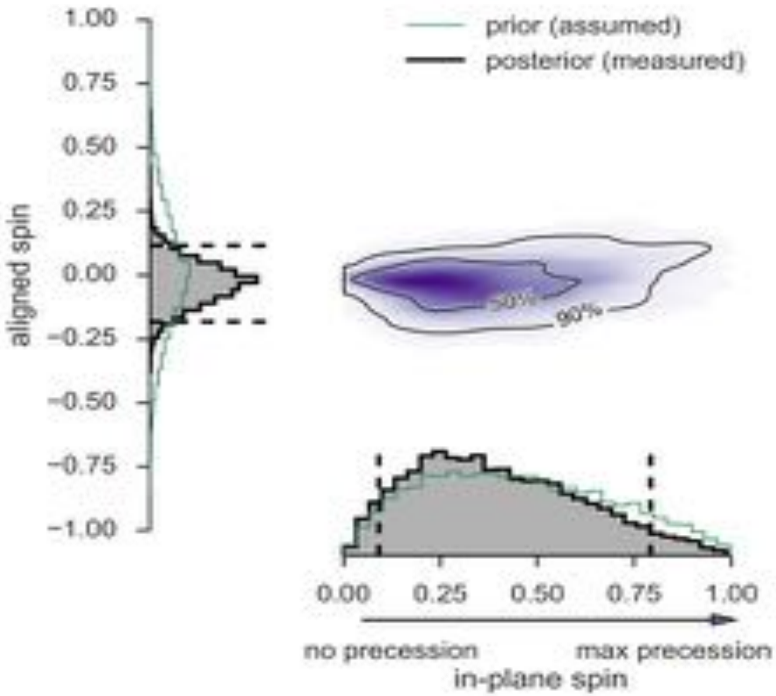
Black Hole Masses

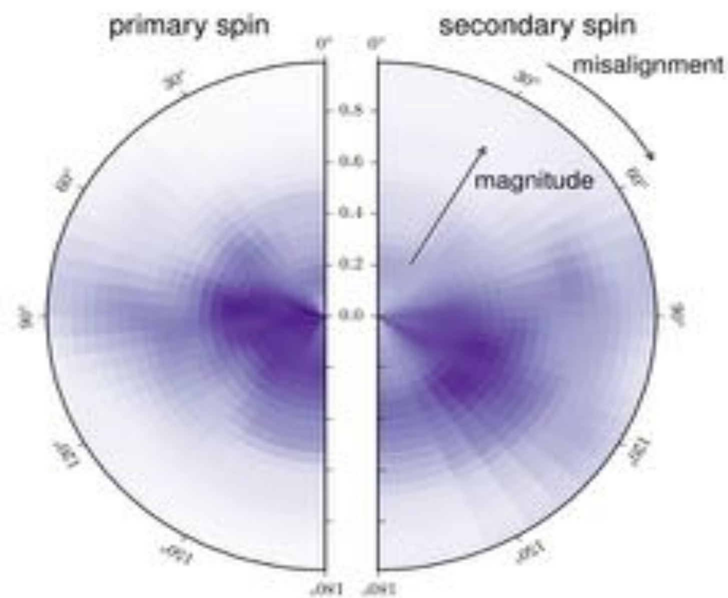
- Degeneracies in waveform morphology arise along equal chirp mass lines in m_1/ m_2 space
- Since M_c (or total mass) is the better measured quantity m_1/m_2 is anticorrelated
- Detected masses are redshifted, lower frequency (detector frame masses are ~39 + 32 $M_\odot$)



Values computed at the source frame

Source Spin Parameters





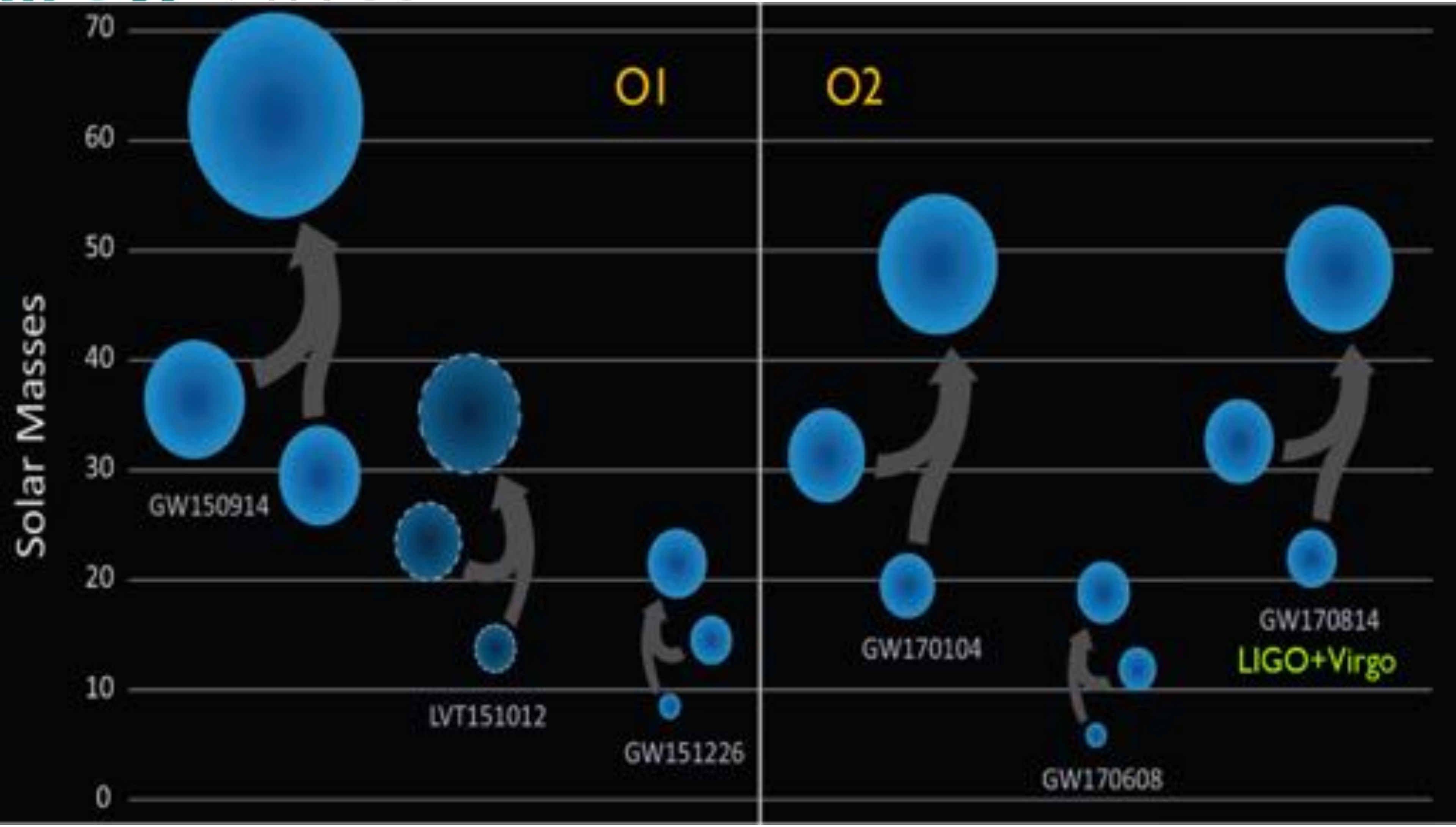
Aligned spin measures components of $S_{1,2}$ along the orbital angular momentum

Components of $S_{1,2}$ spin in the plane of the instantaneous orbit

Spin nearly aligned , but not really able to measure the precessional component

Caveat: If *L* aligned with line of sight ("face on"), precession is mostly unobservable

BBH detected by LIGO & VIRGO



Analysis of O2 not completed yet !

In particular, Virgo data cleaning still on the way!

Astrophysical Implications

- Stellar mass binary black hole systems exist!
- Stellar mass binary black hole systems can merge in less than a Hubble time.
- ***First observation of 'heavy' stellar mass (> 25 $M_\odot$) black holes***
- Heavy mass BBH system most likely formed in a low-metallicity environment: < ½-¼ $Z_\odot$

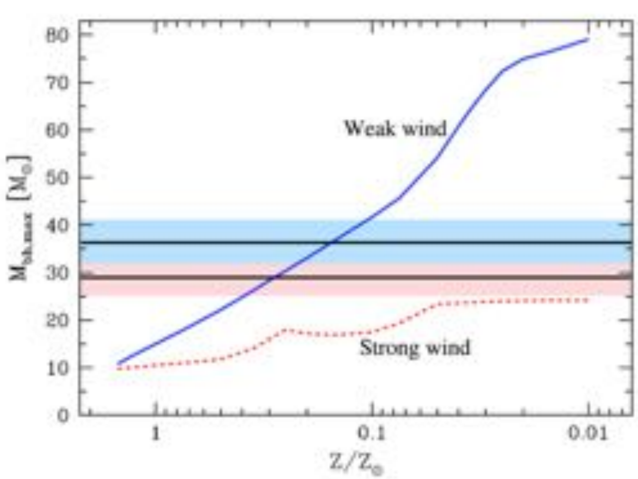
What to expect in the future:

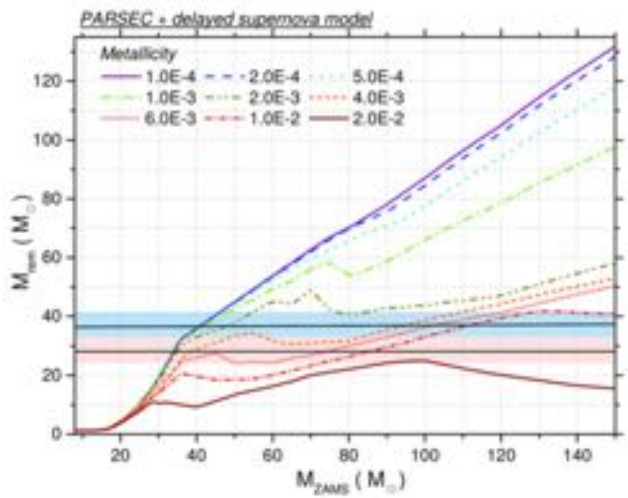
- Determination of mass and spin spectrum of black holes
  - Confirm or rule out dark matter scenarios??
- **Determine preferred formation channels: isolated binary evolution vs dynamical capture in dense stellar environments**

Dependence of maximum BH mass on metallicity for the old (strong) and new (weak) massive star winds

Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, "Astrophysical Implications of the Binary Black-Hole Merger GW150914", ApJL, 818, L22, 2016 ;"The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914", arXiv:1602.03842

compact-remnant mass





Zero-age main-sequence progenitor mass

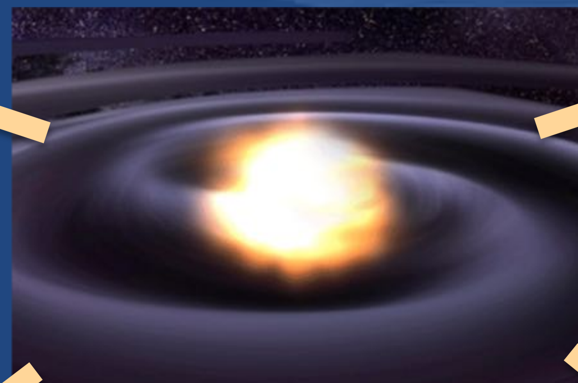
VIRGO

Plan of the talk

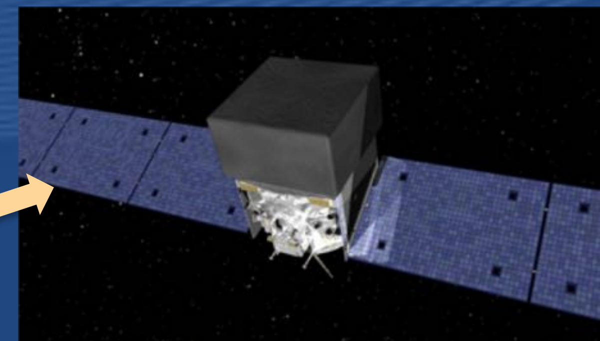
1. GW research motivations
2. Sources
3. Principles of interferometric detection
4. What is Virgo
5. LIGO-Virgo joint observation
6. The discovery
7. ***The start of the GW astronomy***

Multi-messenger Astronomy with Gravitational Waves

Binary Neutron Star Merger



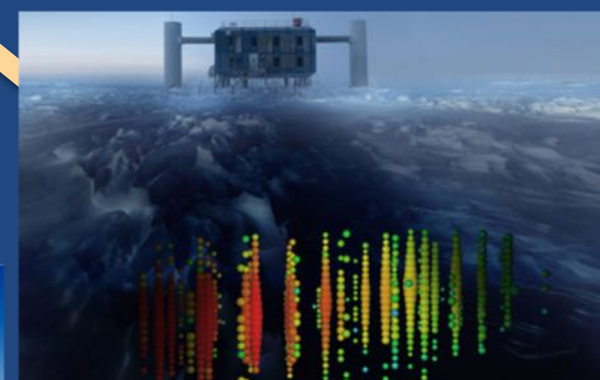
Gravitational Waves



X-rays/Gamma-rays

Visible/Infrared Light

Radio Waves

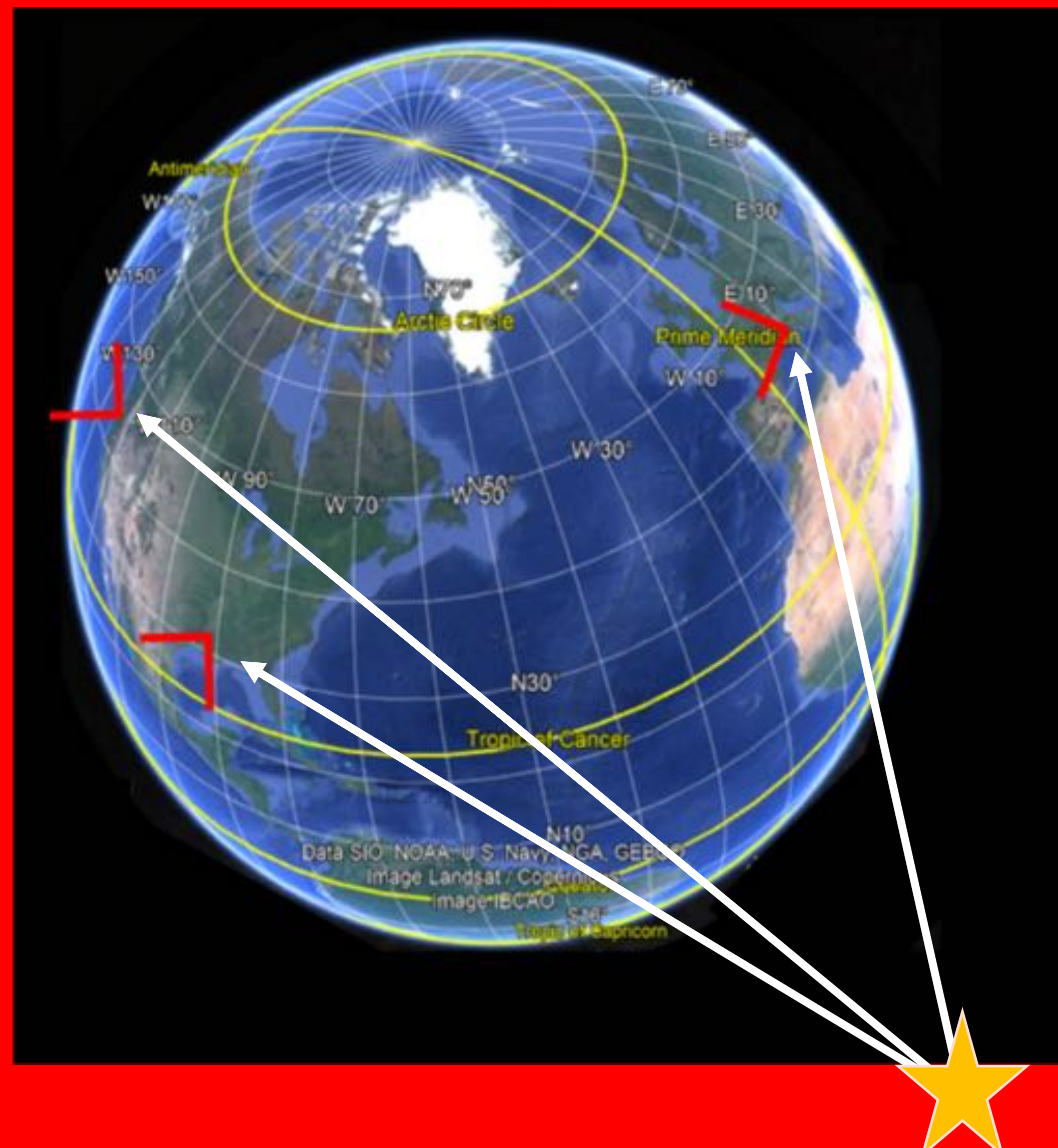


Neutrinos

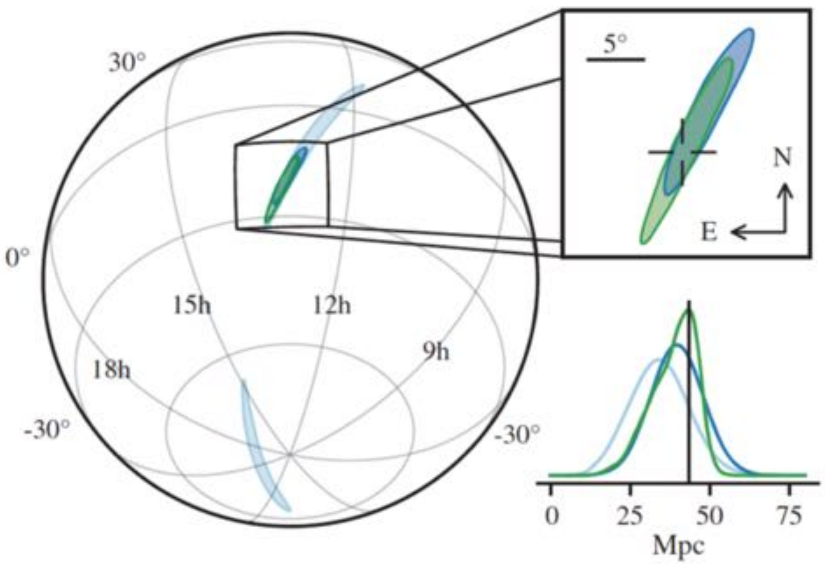

Virgo, Cascina, Italy


LIGO, Livingston, LA

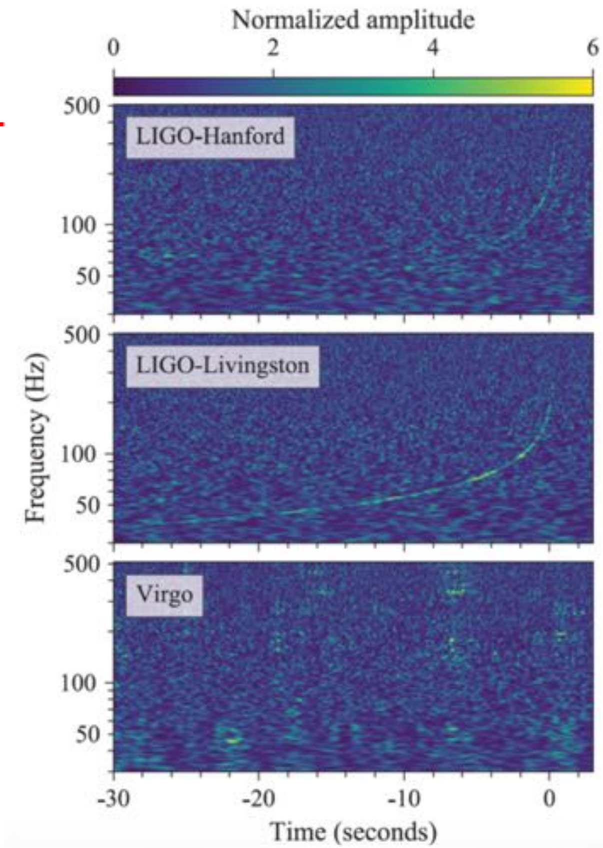

LIGO, Hanford, WA


Arctic Circle
Prime Meridian
Tropic of Cancer
W 30°
W 70°
E 30°
N30°

GW170817: Detected a Binary Neutron Star Merger



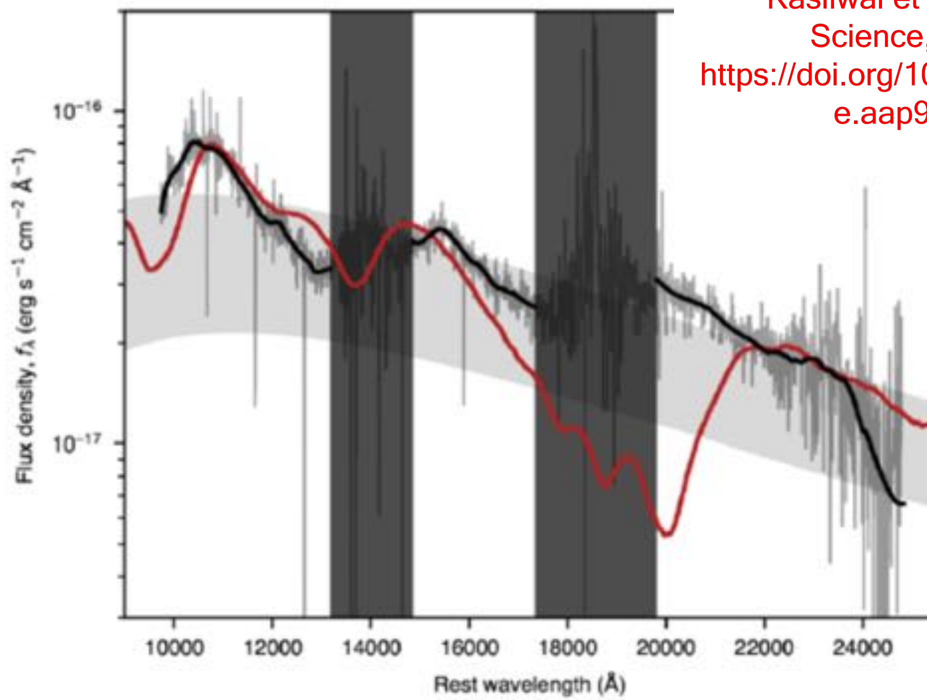
Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral" Phys. Rev. Lett. 161101 (2017)



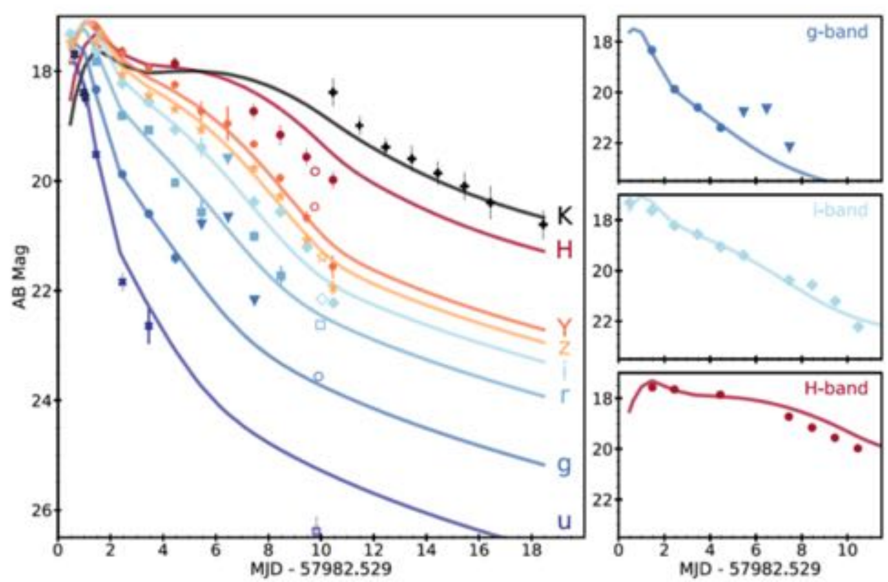
	Low-spin priors ($\|\chi\| \leq 0.05$)	High-spin priors ($\|\chi\| \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance D_L	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

Kilonovae

- Electromagnetic follow-up of GW170817 provides strong evidence for kilonova model
  - kilonova - isotropic thermal emission produced by radioactive decay of rapid neutron capture ('r-process') elements synthesized in the merger ejecta
- Spectra taken over 2 week perio across all electromagnetic bands consistent with kilonova models
  - "Blue" early emission dominated by Fe-group and light r-process formation; later "red" emission dominated by heavy element (lanthanide) formation
- Recent radio data prefers 'cocoon' model to classical short hard GRB production



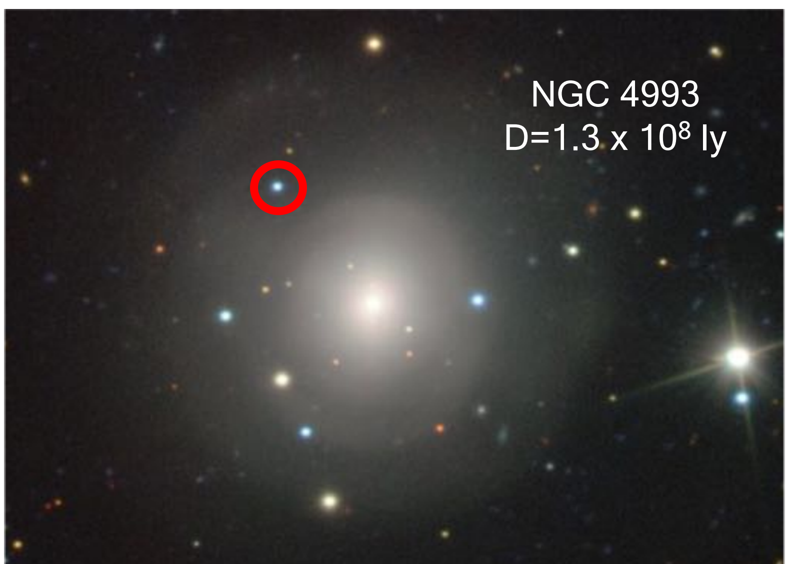
Kasliwal et al. 2017, Science, DOI: https://doi.org/10.1126/science.aap9455



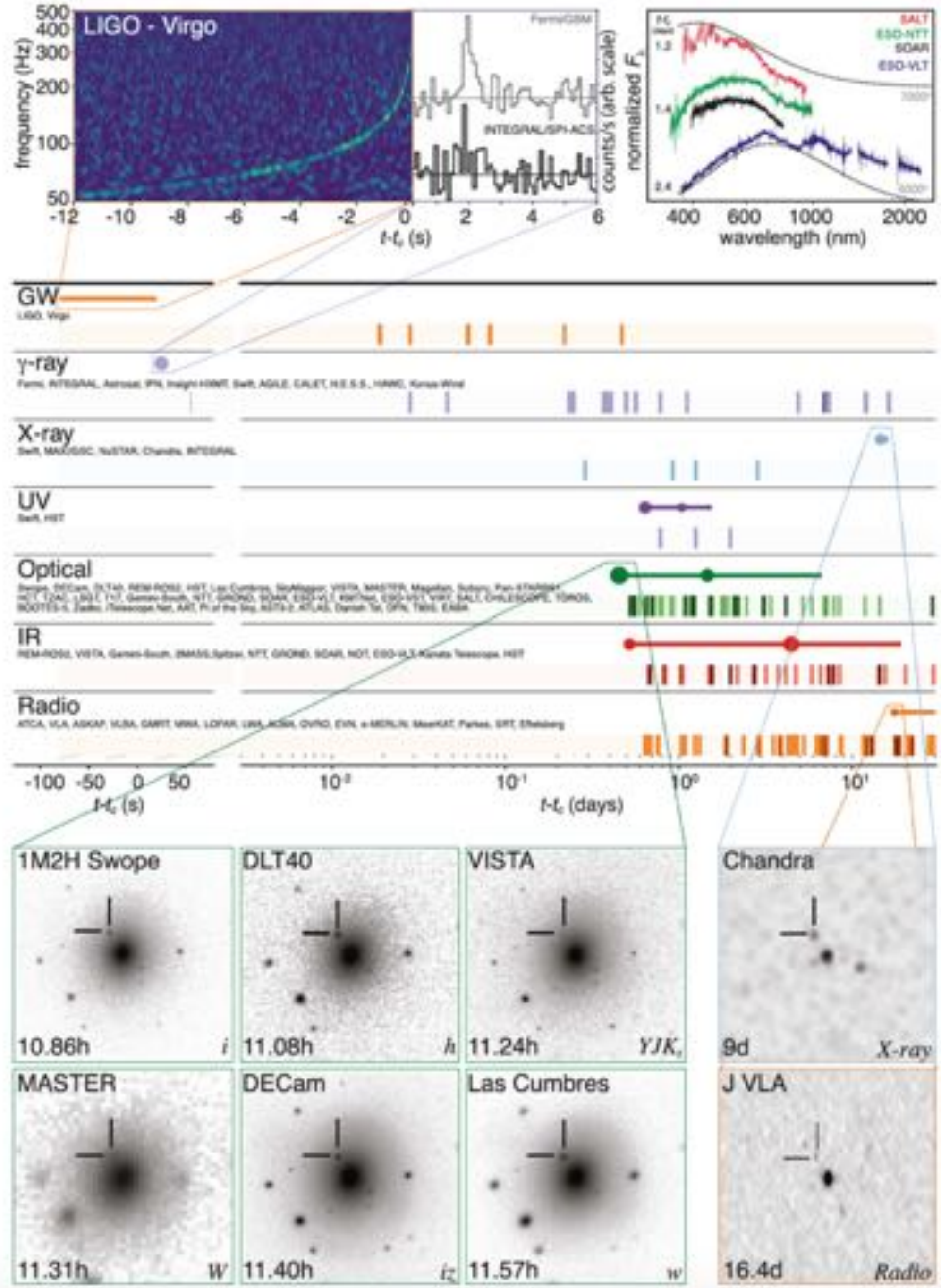
Cowperthwaite, et al. 2017, Ap. J. Lett. DOI: https://doi.org/10.3847/2041-8213/aa8fc7

Observations Across the Electromagnetic Spectrum!

Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, “Multi-messenger Observations of a Binary Neutron Star Merger” Astrophys. J. Lett., 848:L12, (2017)



Credit: European Southern Observatory
Very Large Telescope

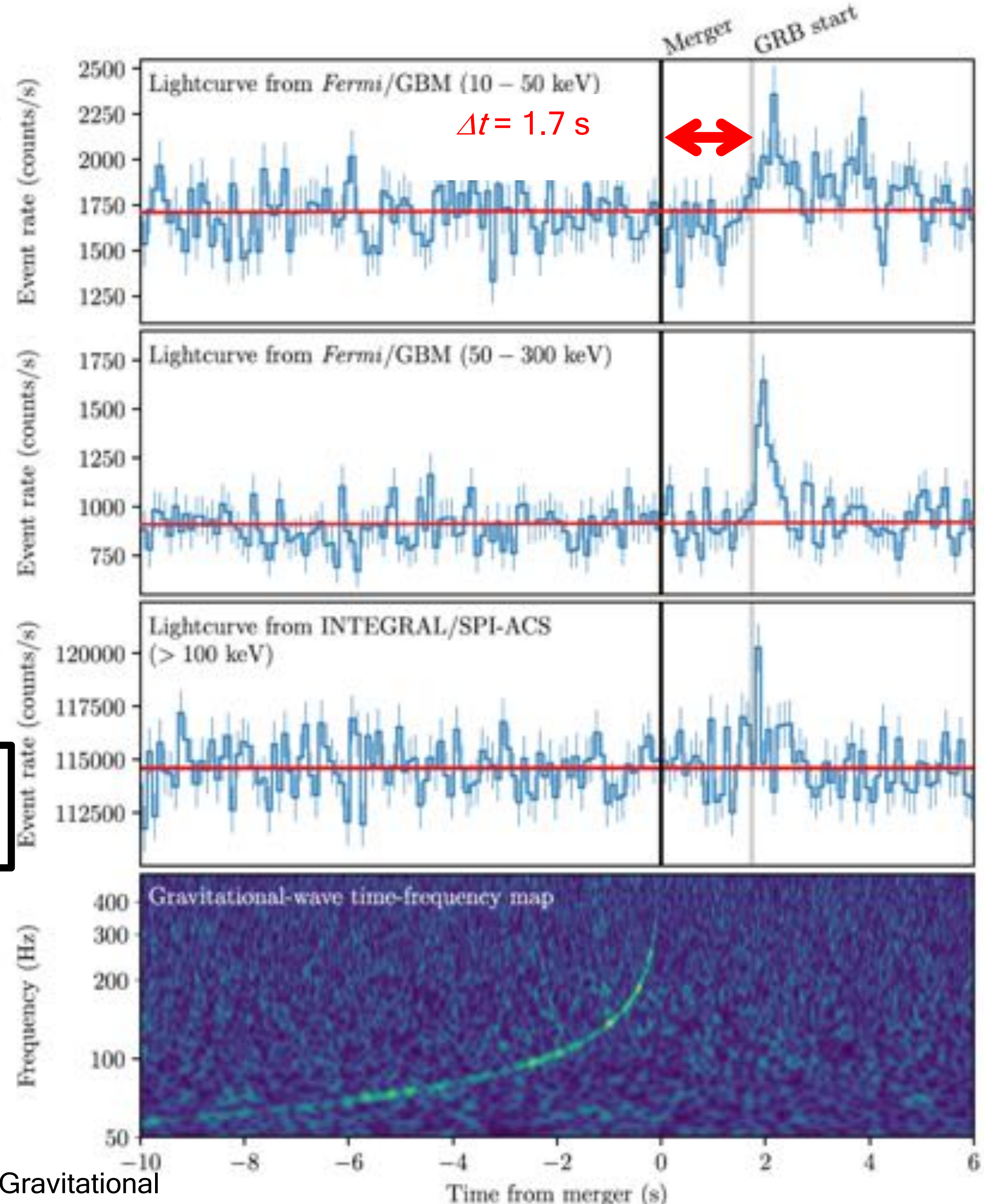


Are Gravitons Massless?

- GW170817 provides a stringent test of the speed of gravitational wave $\frac{v_{GW} - c}{c} \approx \frac{c\Delta t}{D}$
- Δt =1.74 +/- 0.05 s
- $D \approx$ 26 Mpc
  - Conservative limit – use 90% confidence level lower limit on GW source from parameter estimation

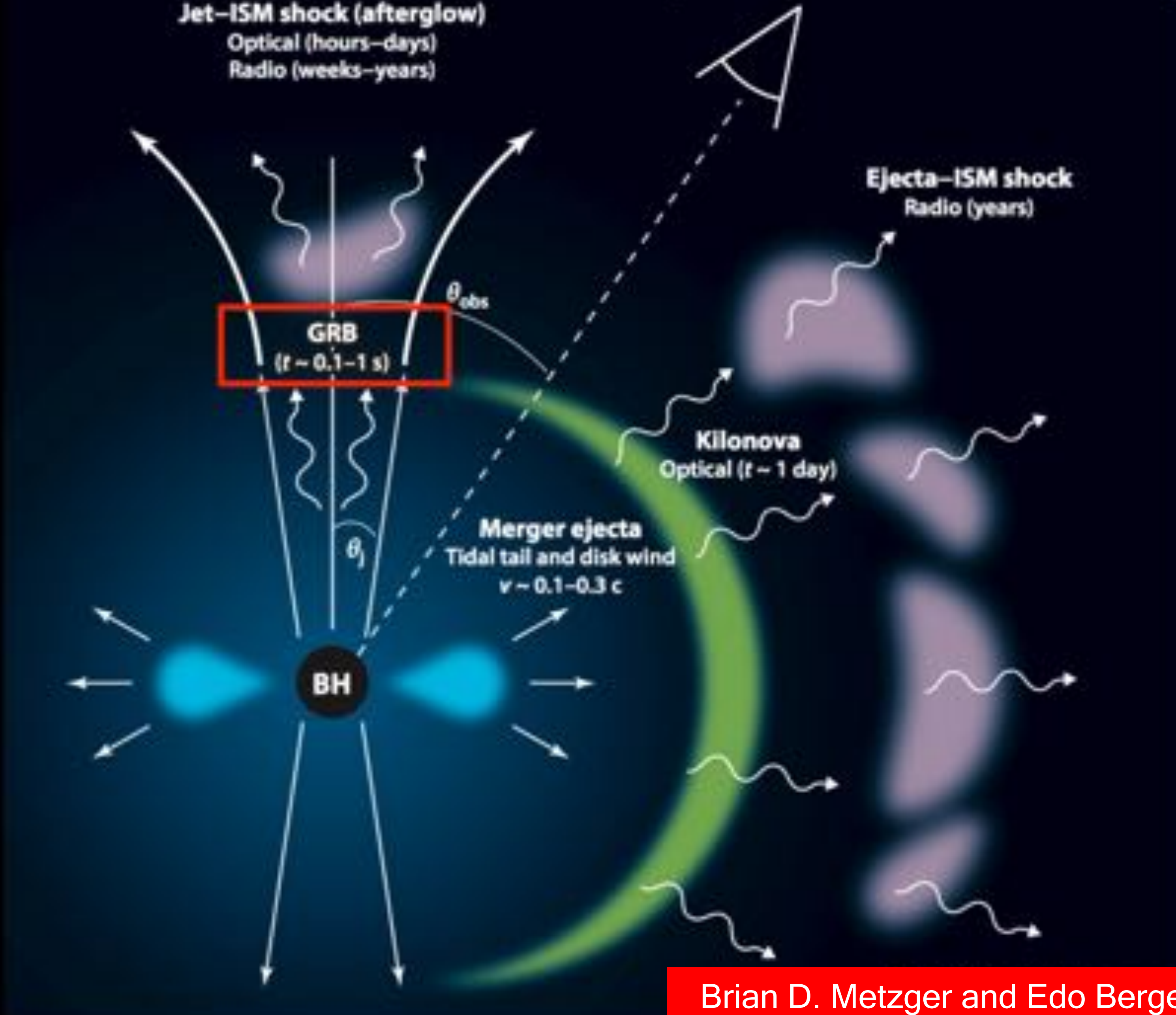
$$-3 \times 10^{-16} \leq \frac{v_{GW} - c}{c} \leq +7 \times 10^{-16}$$

- GW170814 also puts limits on violations of Lorentz Invariance and Equivalence Principle



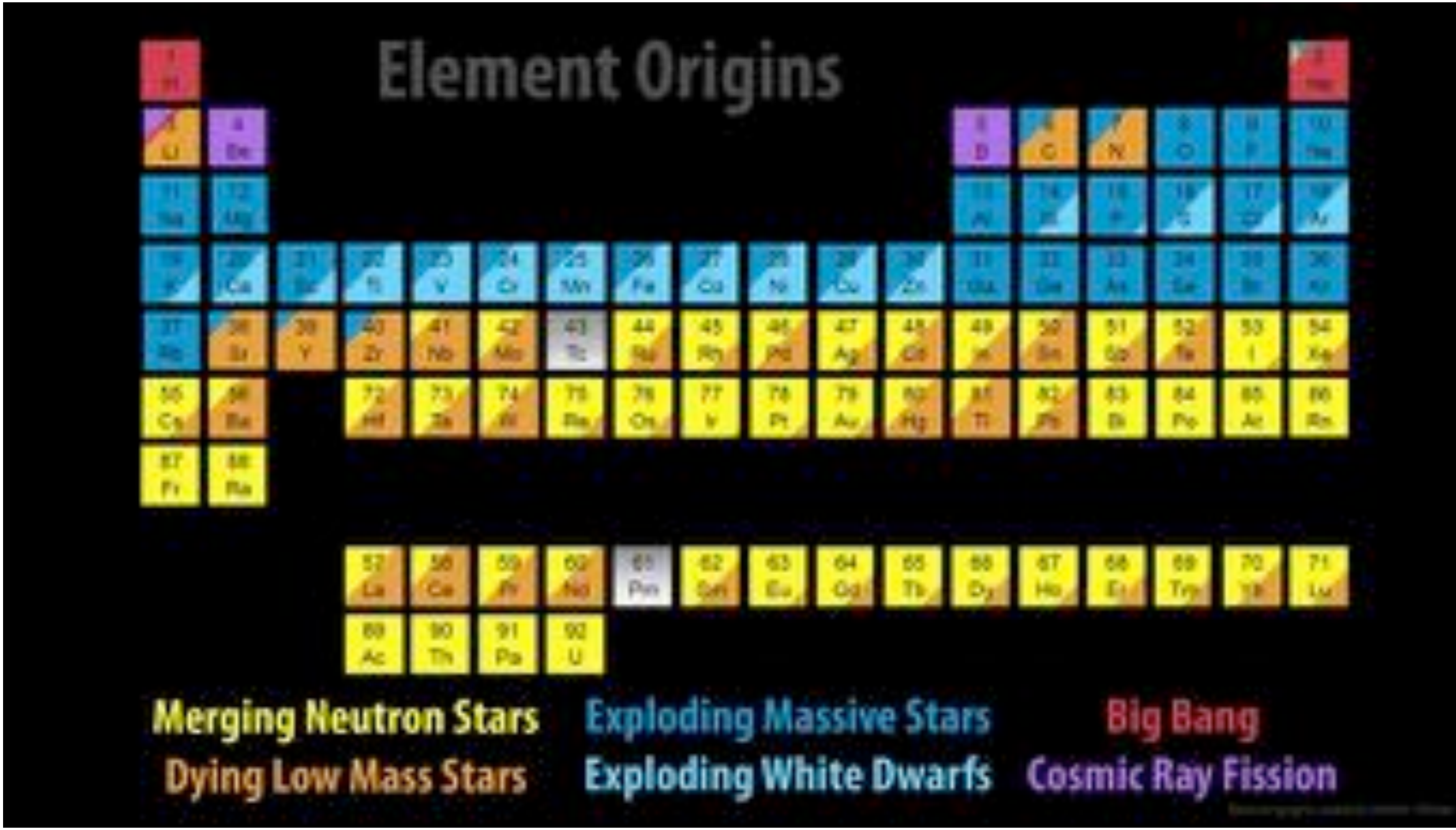
LIGO Scientific Collaboration and Virgo Collaboration, Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A" Astrophys. J. Lett., 848:L13, (2017)

Electromagnetic Counterparts of NS Mergers



Brian D. Metzger and Edo Berger, 2012

VIRGO

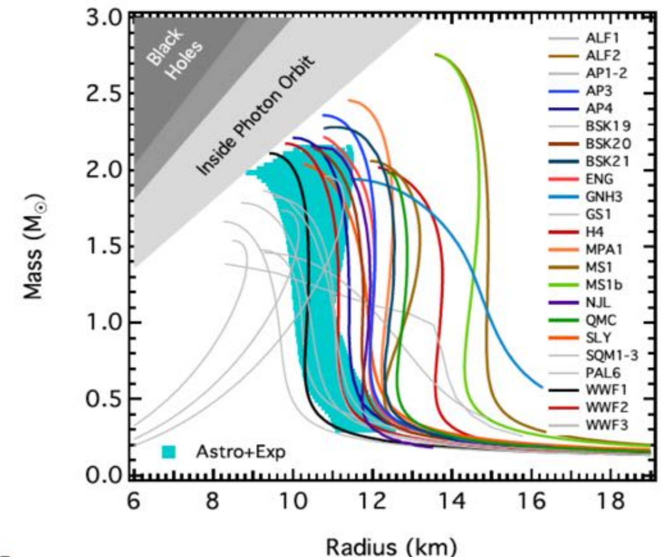


Element Origins
Merging Neutron Stars
Exploding Massive Stars
Big Bang
Dying Low Mass Stars
Exploding White Dwarfs
Cosmic Ray Fission

VIRGO

Constraining on NES

Ozel and Friere (2016)

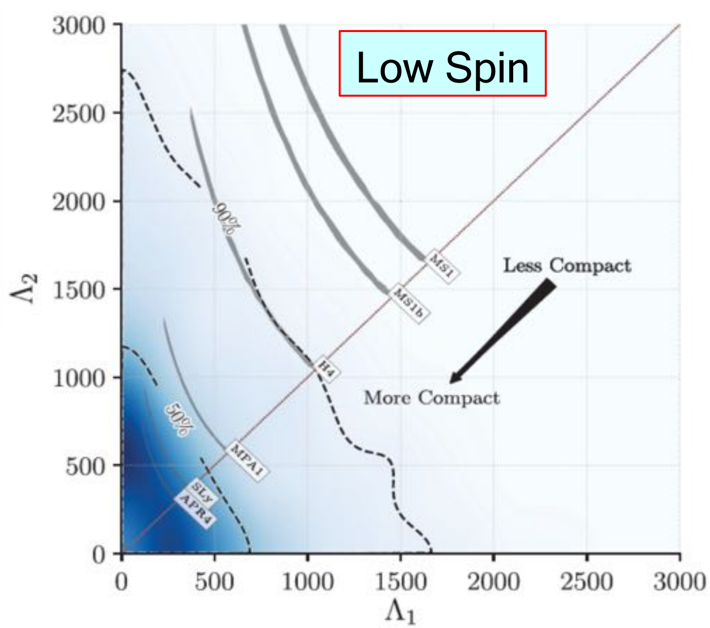


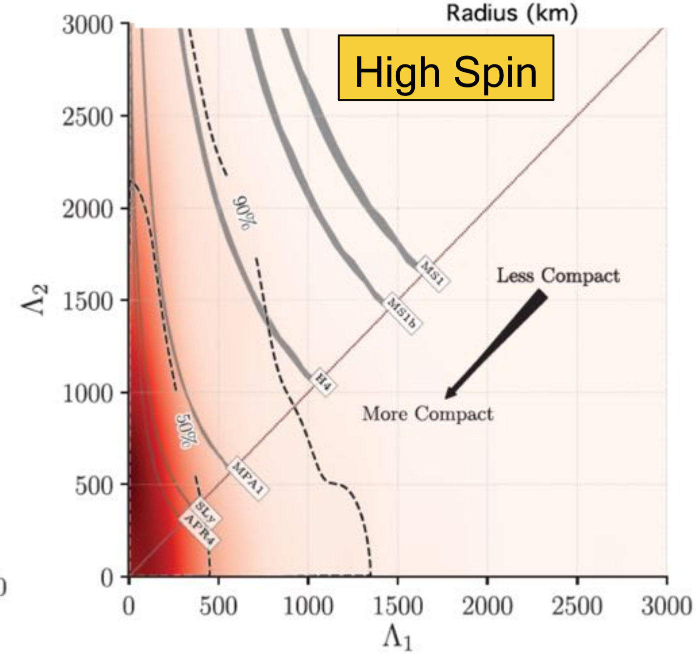
- Gravitational waveforms contain information about NS tidal deformations → allows us to constrain NS equations of state (EOS)
- Tidal deformability parameter:

$$\Lambda = \frac{2}{3} k_2 \left(\frac{R}{M} \right)^5$$

- GW170817 data consistent with softer EOS → more compa

Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, “GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral” Phys. Rev. Lett. 161101 (2017)





VIRGO

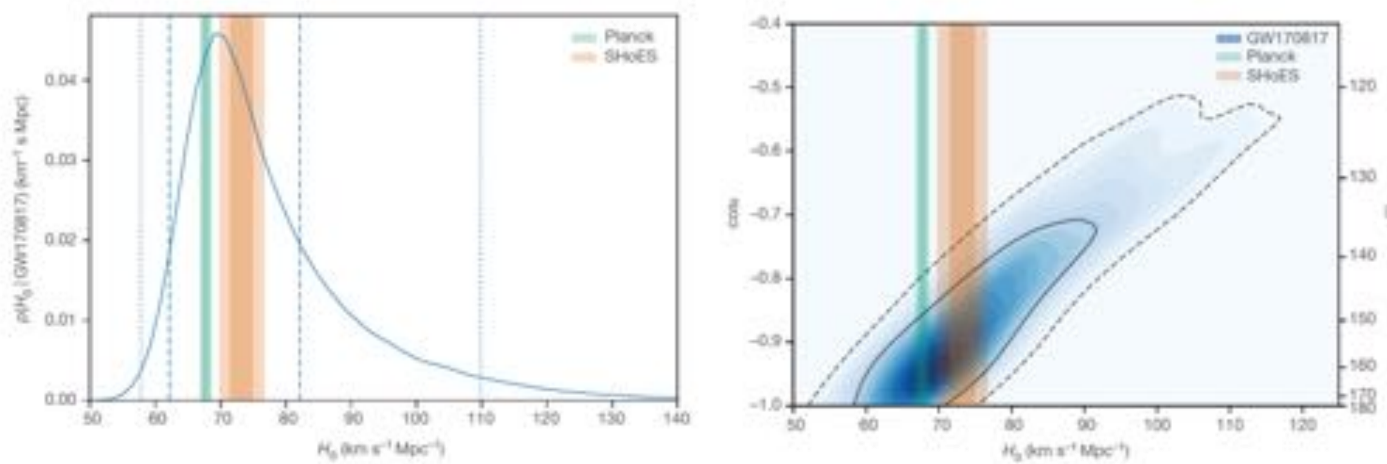
A gravitational-wave standard siren: measurement of the Hubble constant

- Gravitational waves are 'standard sirens', providing absolute measure of luminosity distance d_L
- can be used to determine H_0 directly if red shift is known:

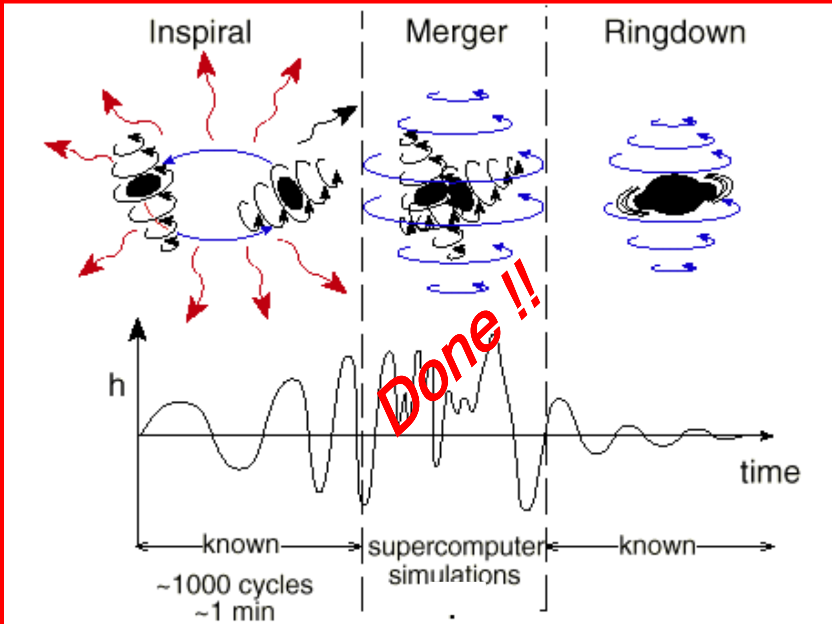
$$c\,z = H_0\,d_L$$

- … without the need for a cosmic distance ladder!

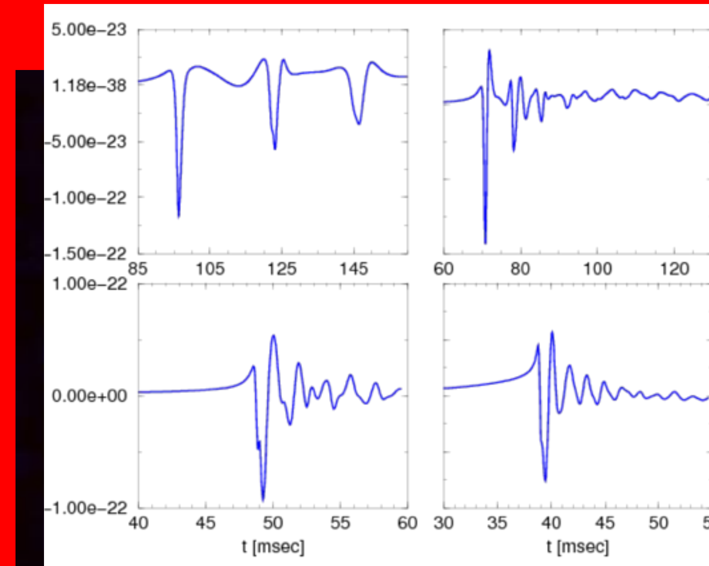
$H_0 = 70\ (+12,\ -\ 8)$ km/s/Mpc



Abbott, et al., LIGO-Virgo Collaboration, 1M2H, DeCAM GW-EM & DES, DLT40, Las Cumbres Observatory, VINRO UGE, MASTER Collaborations, A gravitational-wave standard siren measurement of the Hubble constant", *Nature* 551, 85-88 (2017).



Credit: AEI, CCT, LSU



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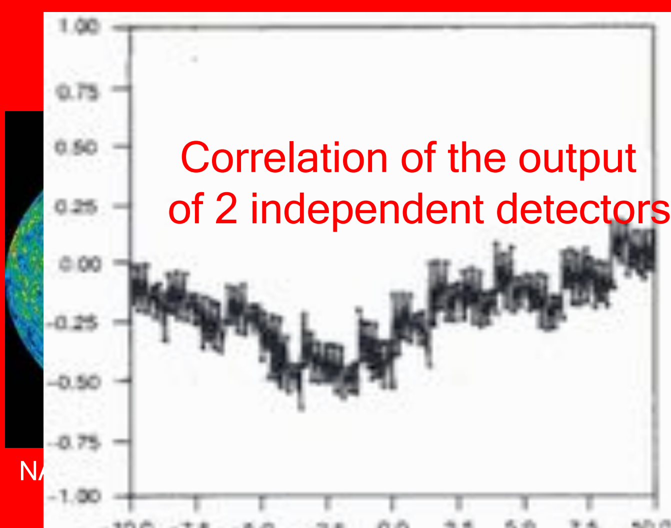
Science target



NA

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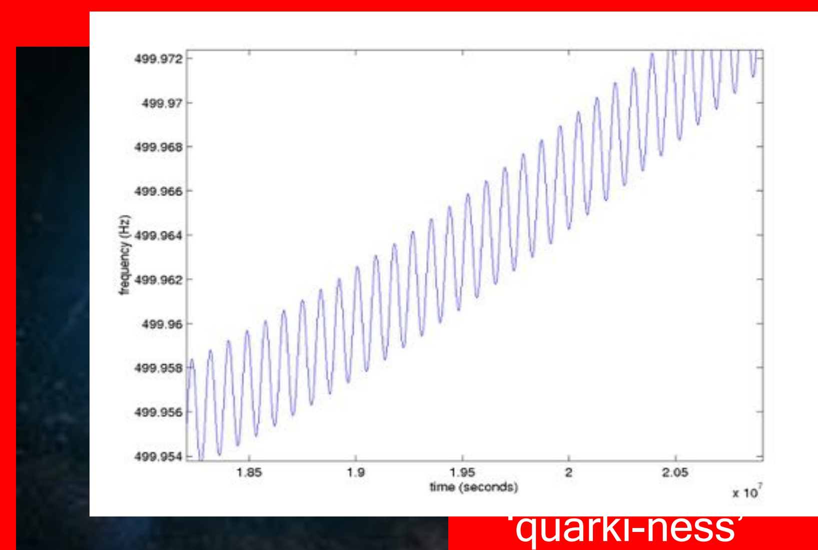


'quarki-ness'

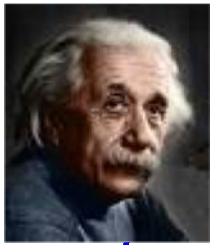
Casey Reed, Penn State

Conclusion

LSC and Virgo collaborations opened a new window on the universe

GW will probe the status of the matter in the extreme condition

Deviation from the prediction of the classical physics can be the clue of a super unification phenomenon



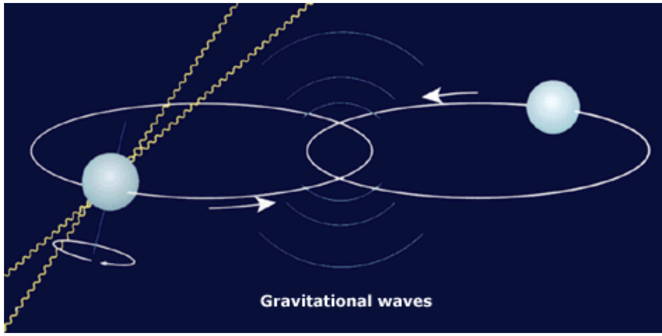
GW will help to go beyond Einstein

Science goes step by step and every man depends on the work of his predecessors. When you hear of a sudden unexpected discovery—a bolt from the blue—you can always be sure that it has grown up by the influence of one man or another, and it is the mutual influence which makes the enormous possibility of scientific advance. --— Sir Ernest Rutherford

Extra Slides

How Many Events?

COALESCING COMPACT BINARIES



- Waveform accurately predicted: VIRGO/LIGO can detect a NS/NS event as far as **30 Mpc**
- Uncertain event rates. Calculated by:
  - statistical analysis (observed binary systems)
  - theoretical investigations (population synthesis, evolution models)

	NS/NS	NS/BH	BH/BH
Milky Way event rate	10^{-5} - 10^{-3} yr^{-1}	10^{-6} - 10^{-4} yr^{-1}	0 - 10^{-4} yr^{-1}
Detector range	20 Mpc	40 Mpc	100 Mpc
Detection rate	10^{-3} - few yr $^{-1}$		

[Burgay et al., 2003 - Nutzman et al., 2004]

System Parameterization

At a given reference time t_c / assume zero eccentricity

Extrinsic

Intrinsic