Advanced Virgo: status and gravitational waves detection

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Minkowski vs general metric

$$ds^2 = \eta_{\mu\nu} dx^\mu dx^\nu$$

Space-time distance

$$\eta_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Flat space-time

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

$$g_{\mu\nu} = \begin{pmatrix} g_{00} & g_{01} & g_{02} & g_{03} \\ g_{10} & g_{11} & g_{12} & g_{13} \\ g_{20} & g_{21} & g_{22} & g_{23} \\ g_{30} & g_{31} & g_{32} & g_{33} \end{pmatrix}$$

Generic curved space-time

Gravitational waves

In weak field approximation, the effects of the gravity can be see as a perturbation:

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Minkowski

perturbation

Almost flat space-time

No matter

Transverse-Traceless Gauge

The Einstein equation takes the form of a standard WAVE EQUATION

$$\left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) h_{\mu\nu} = 0$$

Gravitational waves

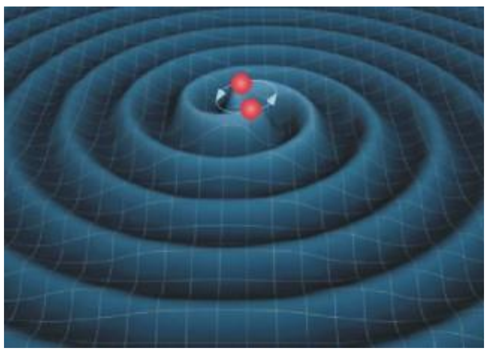
Solving the wave equation, the **perturbation** can be described by a wave with two polarization

$$h = a\,\hat{h}_+ + b\,\hat{h}_\times$$

$$\hat{h}_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & a & b & 0 \\ 0 & b & -a & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

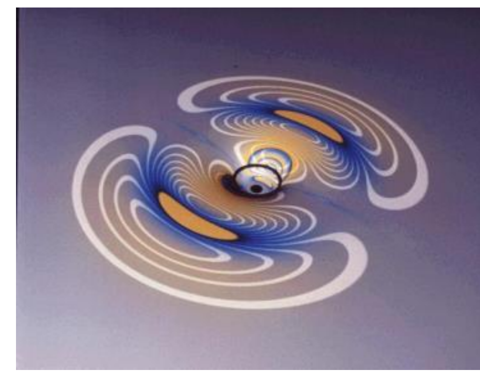
$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu \rightarrow \Delta s_{12} \propto \mathbf{Lh}$$

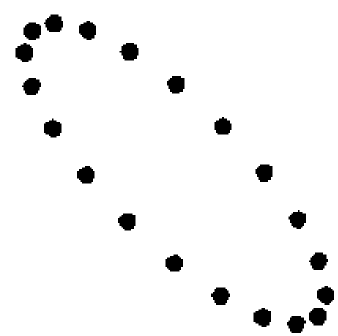
Variation of distance proportional to **L** and **h**



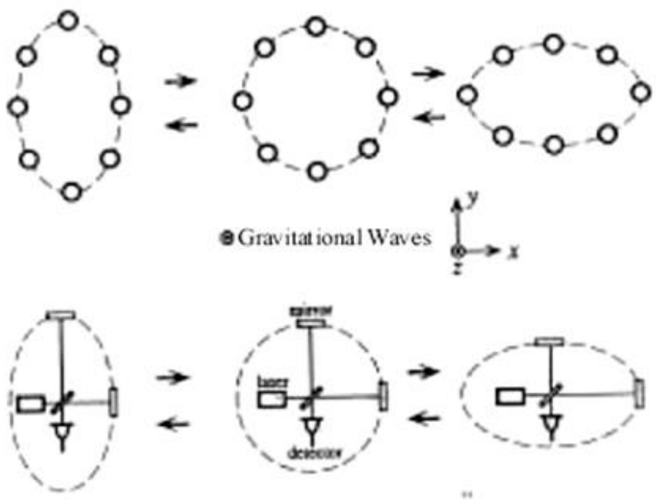
$$\hat{h}_+ = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\hat{h}_\times = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$



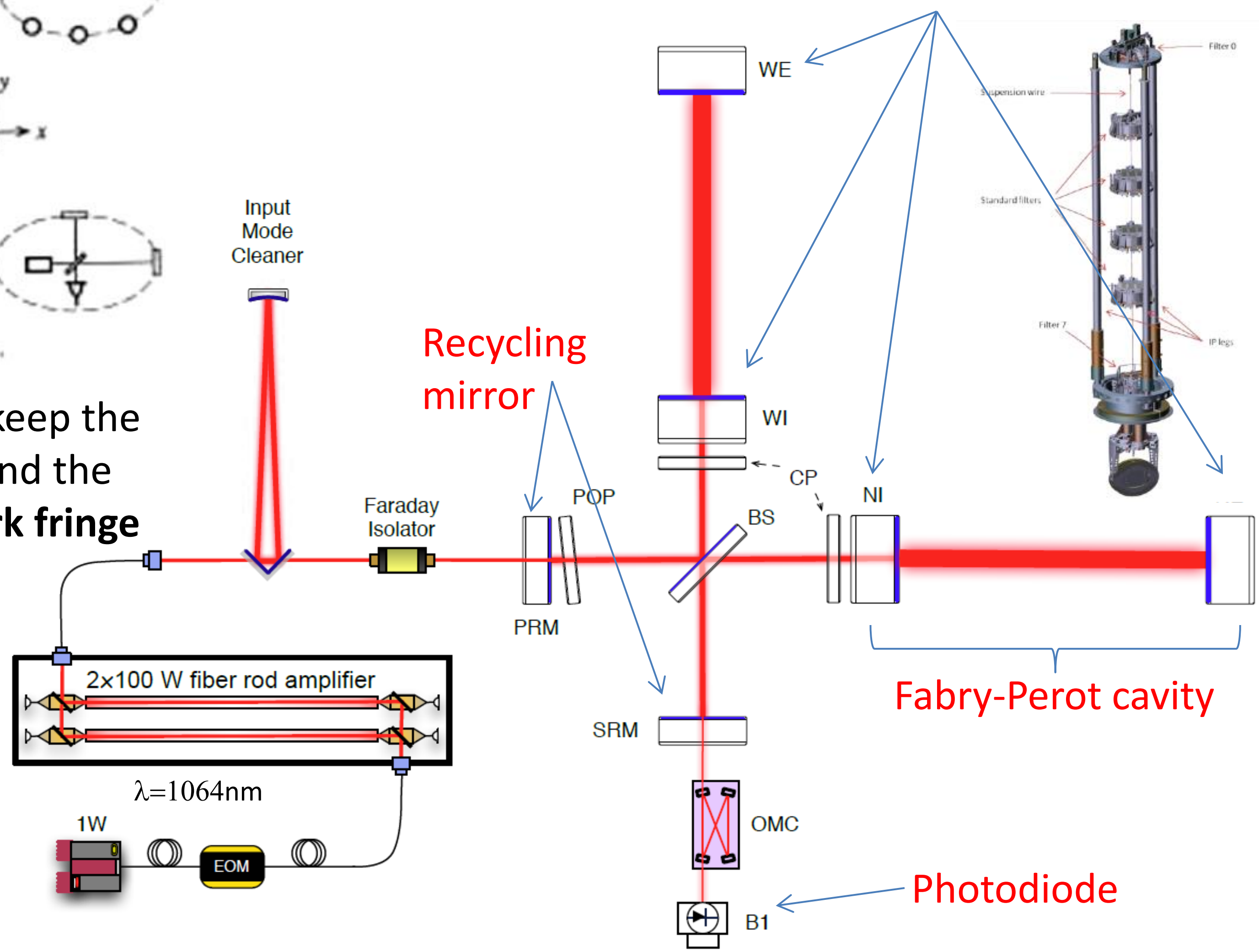


GW Detection principles

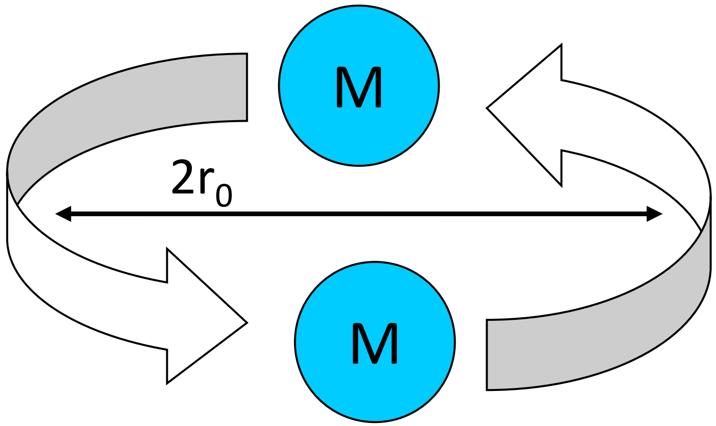


Variation of the distance (optical path) between free-falling masses → suspended mirrors

The control systems keep the cavity at resonance and the interferometer at **dark fringe**



Gravitational waves - numbers



$$M = 3\cdot 10^{30}\ \mathrm{kg} = 1.4\mathrm{M}_S$$
$$r_0 = 20\ \mathrm{km}$$
$$f_{\mathrm{orb}} = 400\ \mathrm{Hz}$$
$$D = 15\ \mathrm{Mpc} \approx 4.5\times 10^{23}\, m$$

VIRGO Cluster Distance

$$\begin{cases} h_{xx} = -h_{yy} = \dfrac{32\pi^2 G}{Dc^4} M r_0^2 f_{\mathrm{orb}} \cos 2(2\pi\ f_{\mathrm{orb}})t \\ h_{xy} = h_{yx} = -\dfrac{32\pi^2 G}{Dc^4} M r_0^2 f_{\mathrm{orb}} \sin 2(2\pi\ f_{\mathrm{orb}})t \end{cases}$$

$$h \equiv \left|h_{\mu\nu}\right| \approx \frac{r_{s1} r_{s2}}{r_0 D} \approx 10^{-21} \Rightarrow \Delta s \approx 10^{-18} m \sim \frac{\boldsymbol{R_{nucleus}}}{\boldsymbol{10^3}}$$

This is the big challenge

GW Detectors

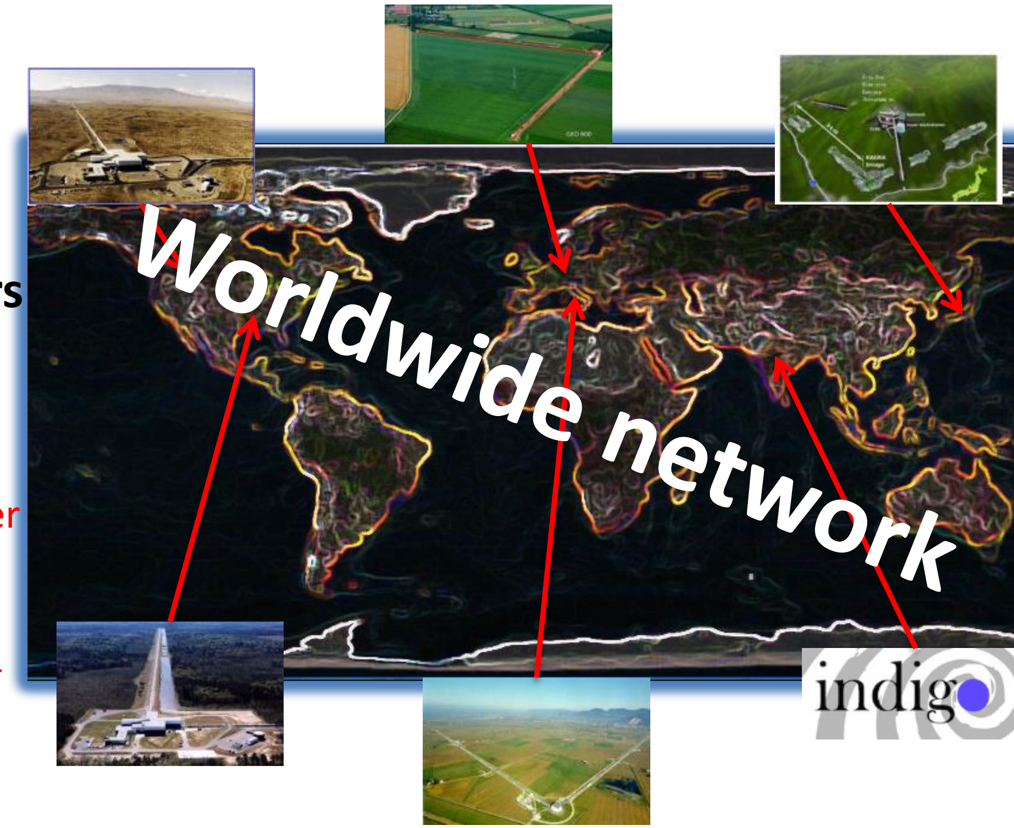
1st generation interferometric detectors

- Initial LIGO, Virgo, GEO600

  Virgo commissioning started in 2003

  1st science run in 2007

- Enhanced LIGO, Virgo+ (2008 - 2011)



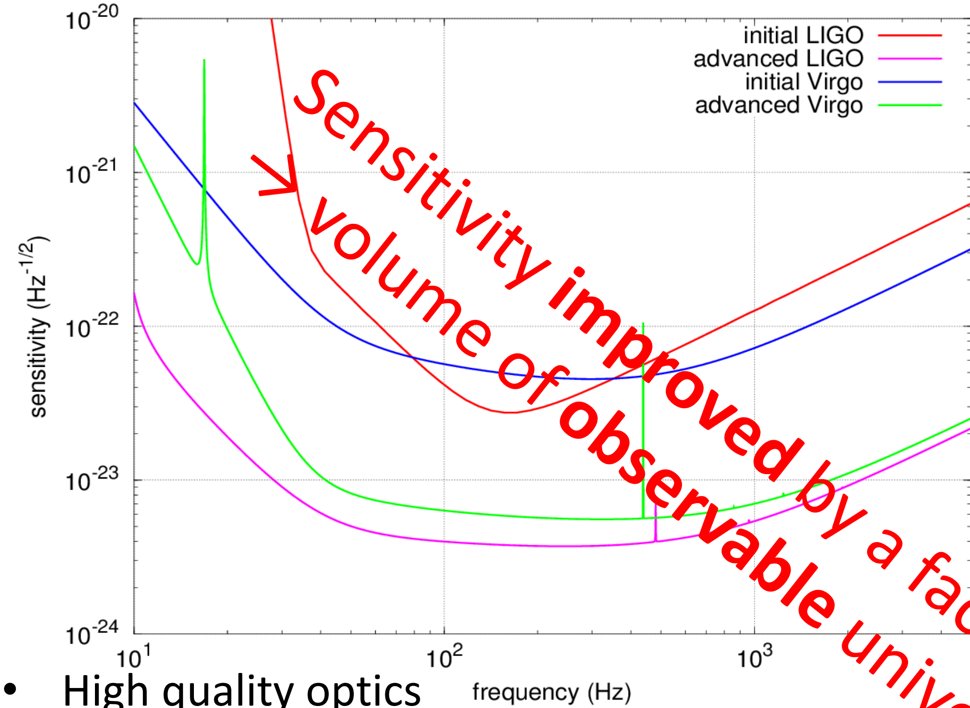
2nd generation interferometric detectors

- Advanced LIGO, Advanced Virgo, GEO-HF, KAGRA, LIGO-India
  - Construction: 2011-2015
  - Commissioning of full interferometer starts in 2015
  - First observation run in 2015 with intermediate configuration → 2016-2021: commissioning and observations runs → progressing towards nominal sensitivity

Beginning of routine observations + Worldwide Network

- GW astronomy

Advanced Virgo project



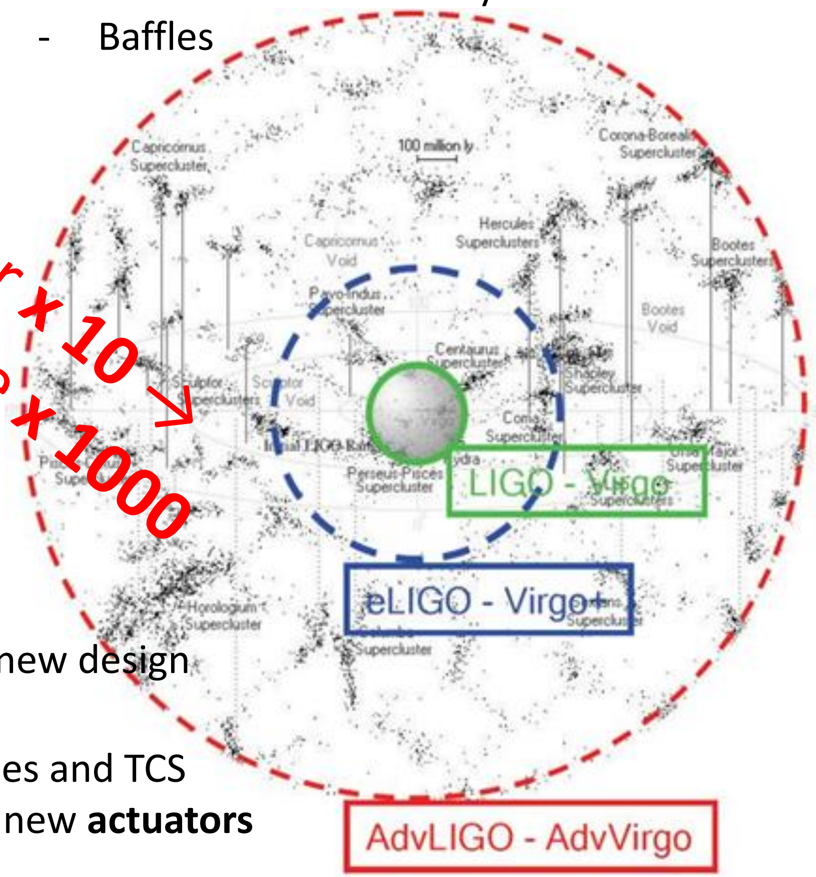
Improvements

- **Sensing devices** suspended and under vacuum
  - 2 stages SA
- **Signal recycling**: to tune the ITF
- **Larger beam**
  - Modification of UHV system
  - Baffles

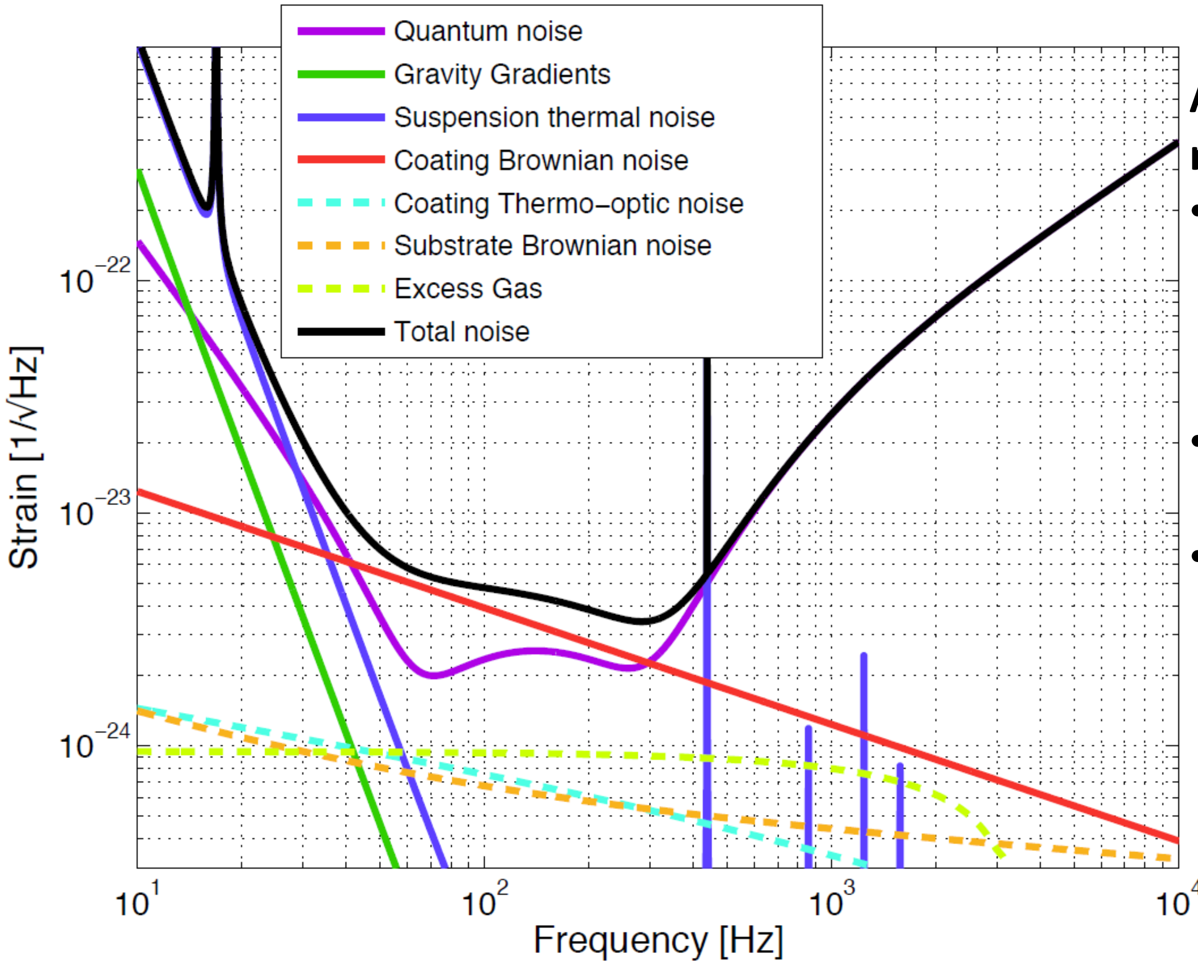
Sensitivity **improved** by a factor **x 10** →

→ volume of **observable** universe **x 1000**

- High quality optics
  - Heavier **mirrors** (x2 -> 42kg)
  - High quality surface (0,2 nm rms)
  - Optimized **coating** with lower absorption
  - **HP laser**
  - Larger **Finesse** (x3 -> F~450)
  - **Thermal compensation**
  - **Monolithic suspension**: new clamping system and new design
- Mechanics
  - **New payload** adapted for the heavier mirrors, baffles and TCS
  - Changing in the control strategies: new **sensor** and new **actuators**
  - Optimized SA for heavier payload



Sensitivity curve expected for AdVirgo



AdVirgo main fundamental noises:

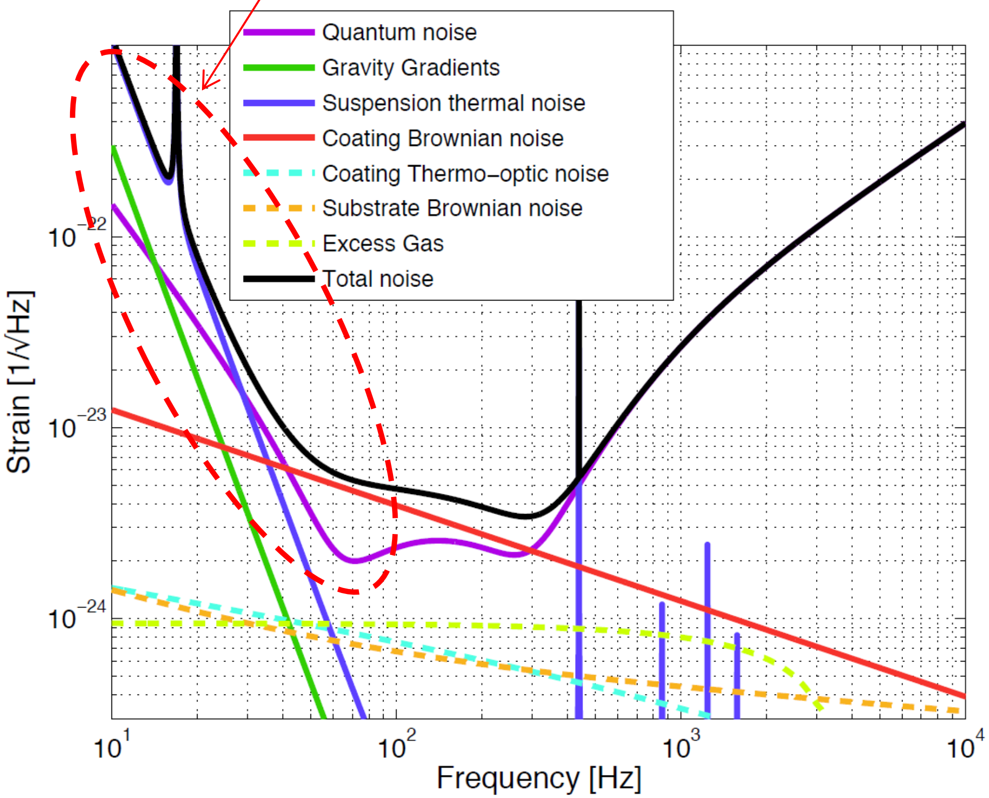
- Quantum noise
  - Shot noise: f > 300 Hz
  - Radiation pressure noise: f = 20 - 40 Hz
- Thermal noise (mostly mirrors coating): f = 40 - 300 Hz
- Seismic noise and gravity gradients: f < 20 Hz

Quantum noise

- **Radiation** pressure: Low freq. range ~ $\sqrt{P_{laser}}$
- **Shot** noise: High freq. range ~ $\sqrt{\frac{1}{P_{laser}}}$

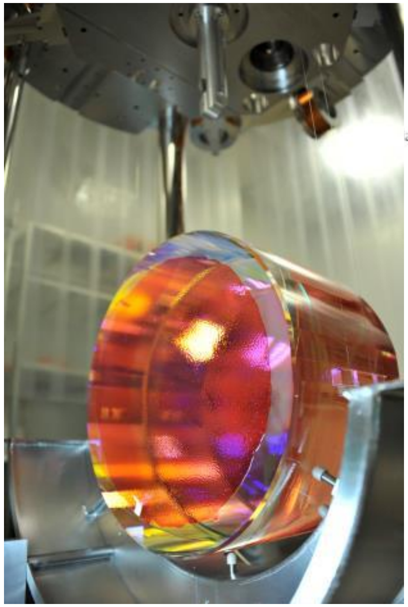
1 - Low frequency range

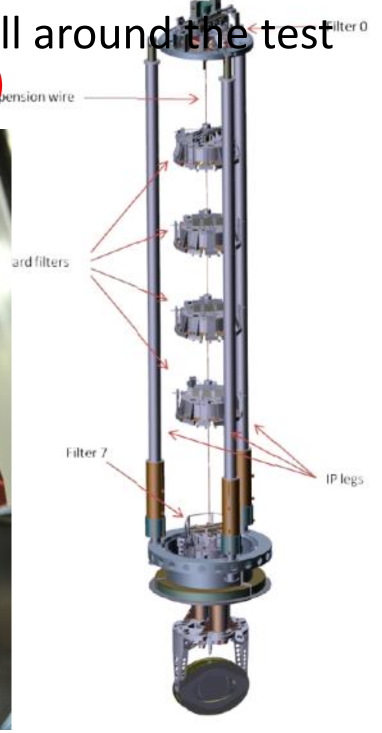
Limited by quantum noise, suspension thermal noise, newtonian noise



Improvements:

- **Suspension thermal noise** could be reduced by further suspension optimization (upper and lower susp.)
- **Quantum noise** could be reduced by frequency dependent squeezing *(see Luca Natticchioni presentation)*
- **Newtonian noise** could be computed and subtracted by realizing a network of many seismometer all around the test masses *(under study)*





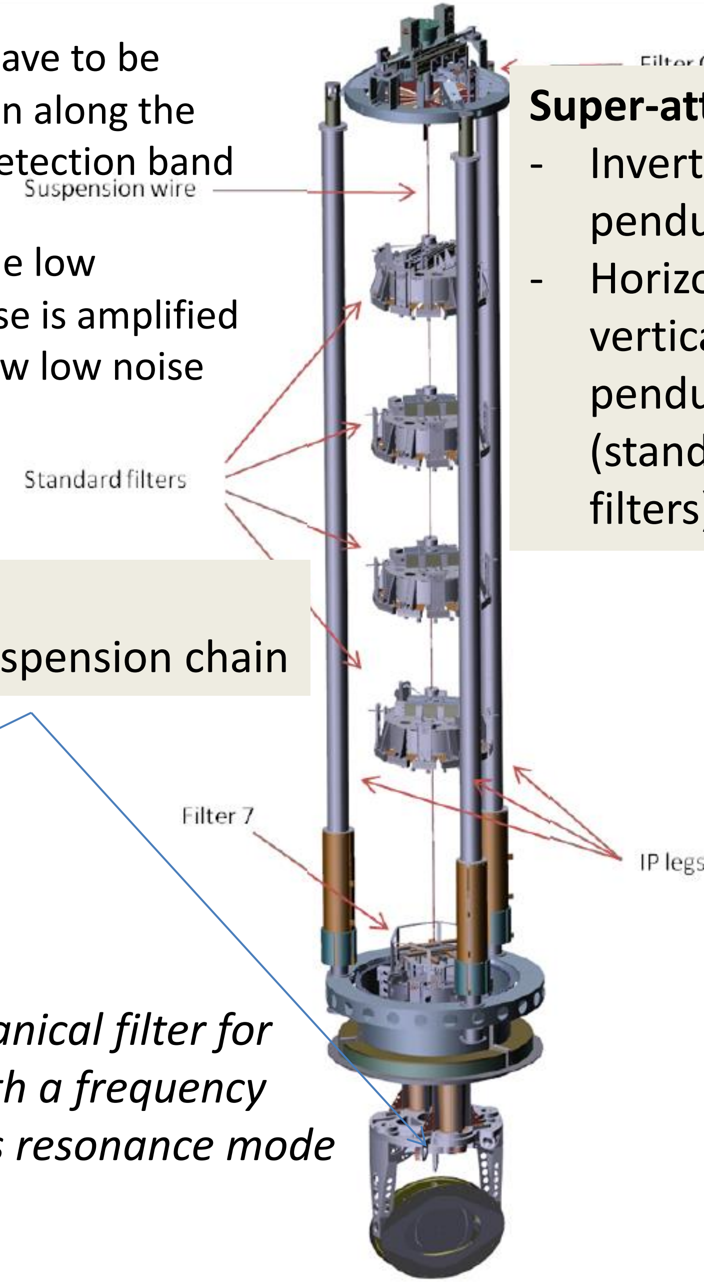
Seismic isolator - Suspension chain

Passive attenuation : the ground seismic vibrations have to be attenuated in order to reduce the residual mirror motion along the beam well below the interferometer sensitivity in the detection band

Active mode damping : the large mirror motion in the low frequency range below a few Hz, where the seismic noise is amplified by the filter chain resonances, has to be damped to allow low noise hierarchical control of the payload

Mirror Payload
Last stage of suspension chain

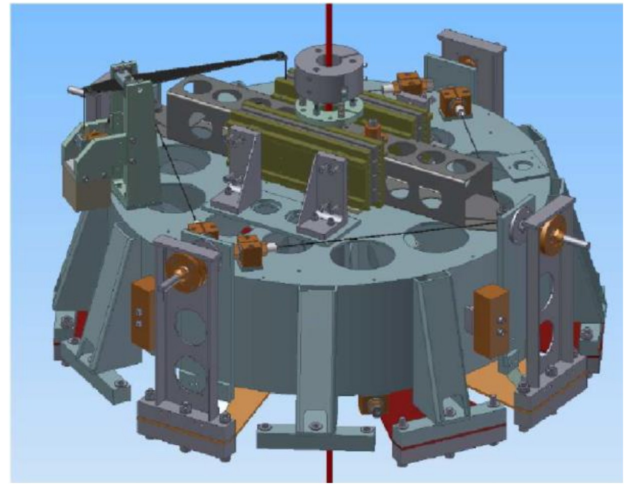
Pendulum
Natural mechanical filter for the signals with a frequency higher than its resonance mode

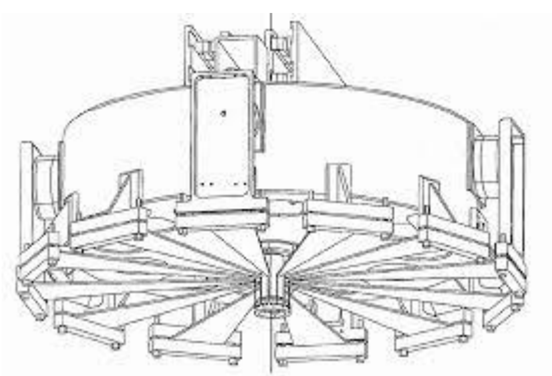


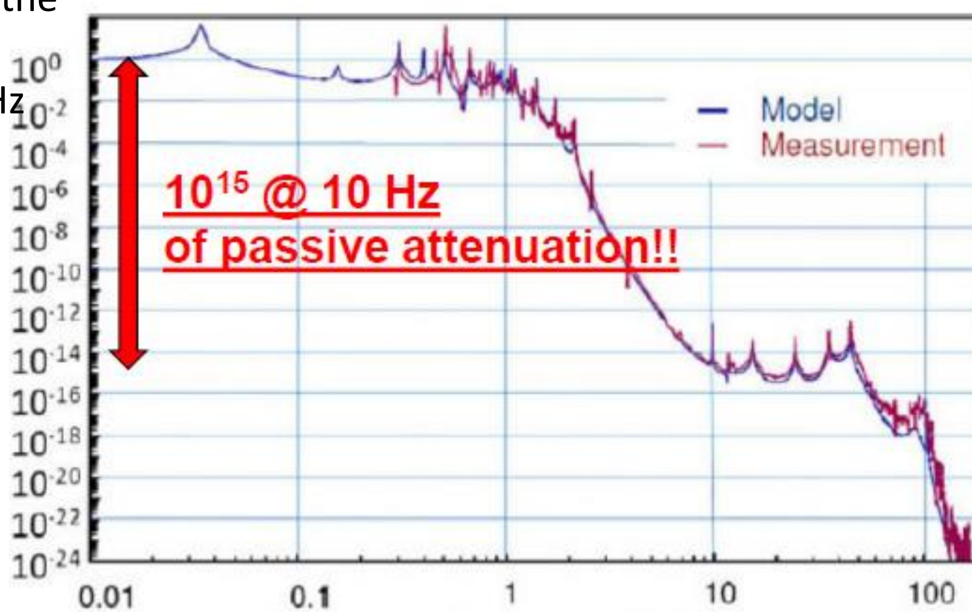
Super-attenuator
- Inverted pendulum
- Horizontal and vertical pendulums (standard filters)

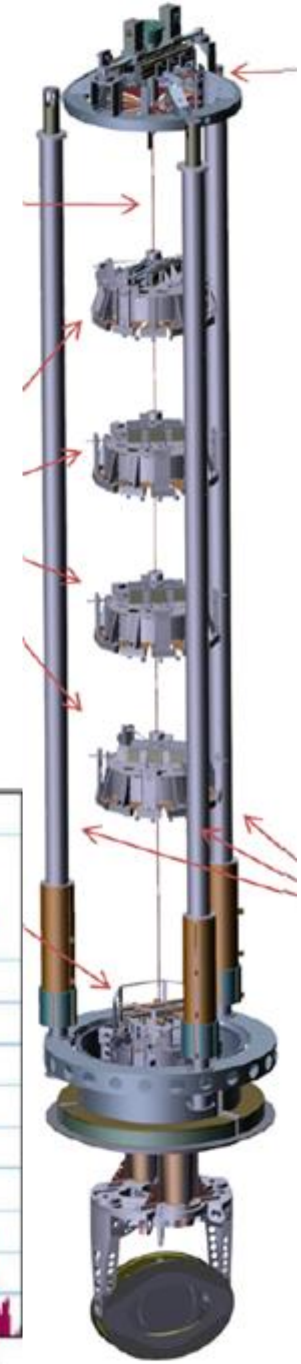
SA - Passive attenuation

- **1 Inverted Pendulum**
  - Monolithic legs
  - Flexible joints
  - Resonance mode f_0 ~40mHz
- **5 horizontal stages**
  - Standard steel filters (~ 110kg)
  - Resonance mode f_0 ~2Hz
  - Reduction factor $f_0^{2*(n\text{-stages})}$
- **5 vertical stages**
  - Pre-stressed curved blades
  - Magnetic anti-springs on the central cross-bar
  - Resonance mode f_0 ~0.4Hz









SA – Mode damping

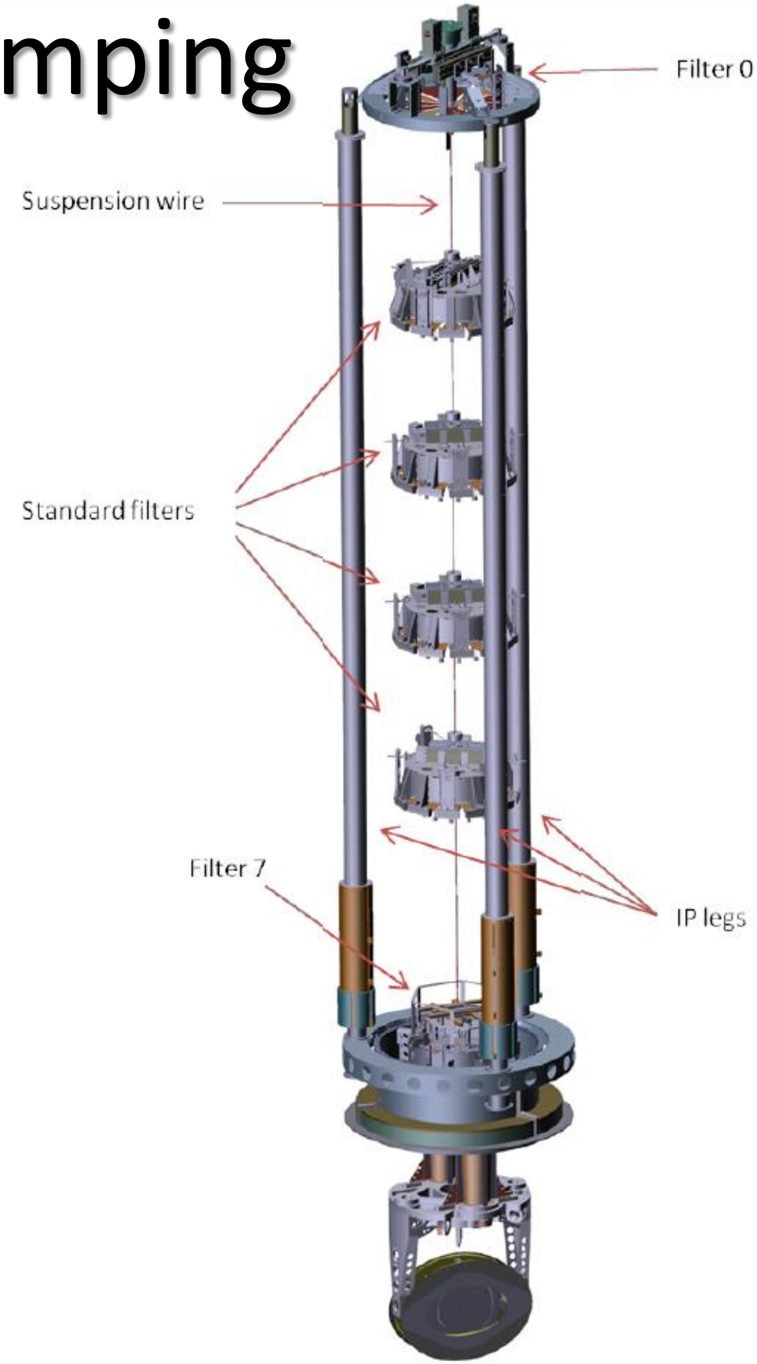
- **18 LVDTs** of 3 different types
  - 9 Vertical LVDTs (F0 –F7 Crossbar, Bottom Ring)
  - 3 F0 Horizontal LVDT
  - 6 F7 LVDTs

- **5 Accelerometers** of 2 different types :
  - 3 Horizontal Accs
  - 2 Vertical Accs

- **23 Coils** of 4 different types
  - 5 F0 Coils
  - 6 F7 Coils
  - 8 Marionette coils
  - 4 Mirror coils

- **3 Piezos** on bottom ring (**New in AdV**)

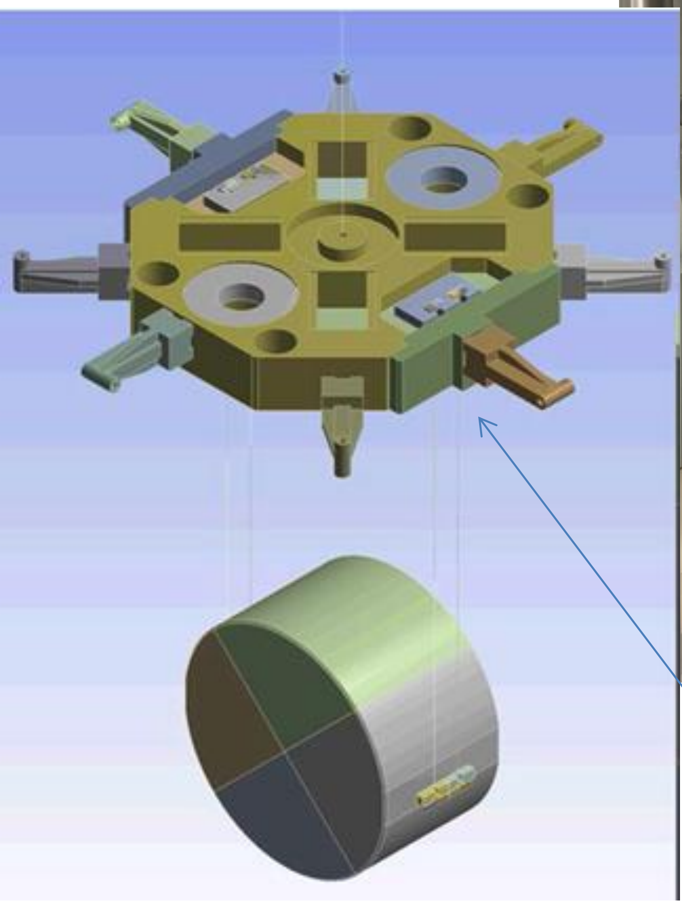
- **21 Motors**
  - 1 Top screw F0 vertical motor
  - 3 F0 trolley motors
  - 6 Fishing rod motors
  - 2 Marionette motors
  - 4 F7 motors
  - 5 Accelerometer motors

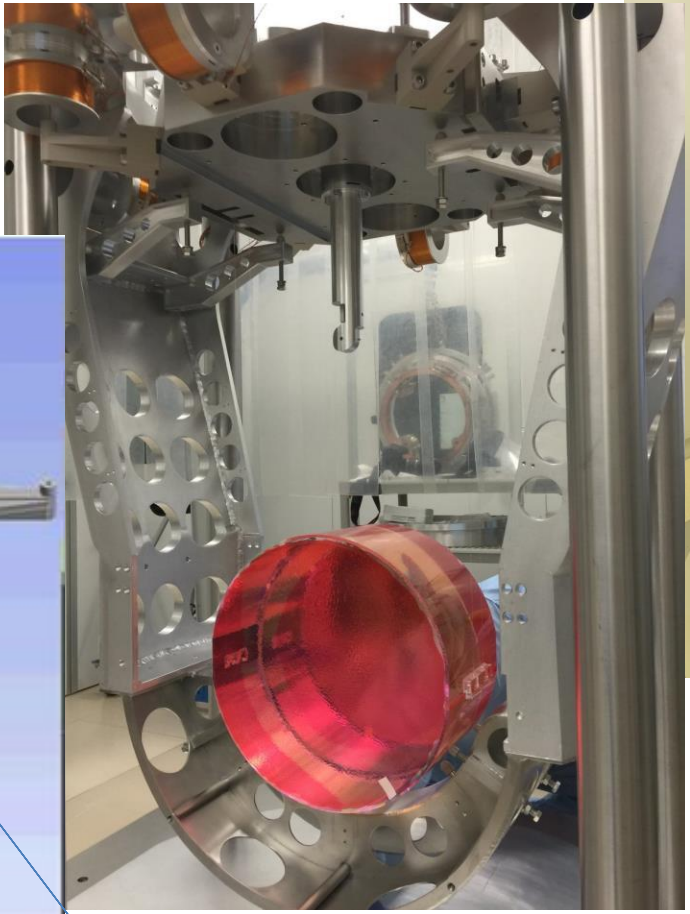


Mirror payload

Why monolithic suspension? → **Fluctuation-Dissipation theorem**

- $Q_{FS} \sim 10^7 - 10^8$
- $Q_{Steel} \sim 10^3 - 10^4$





Marionetta (*puppet*)

Breaking strength

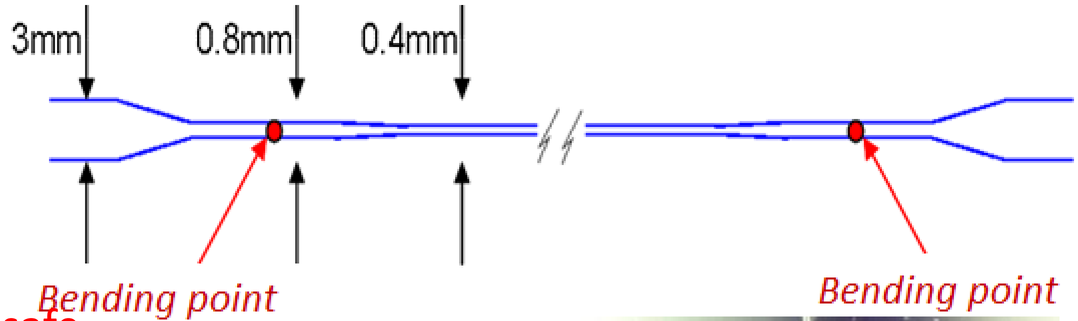
- FS ~ 4GPa
- Steel ~ 2GPa

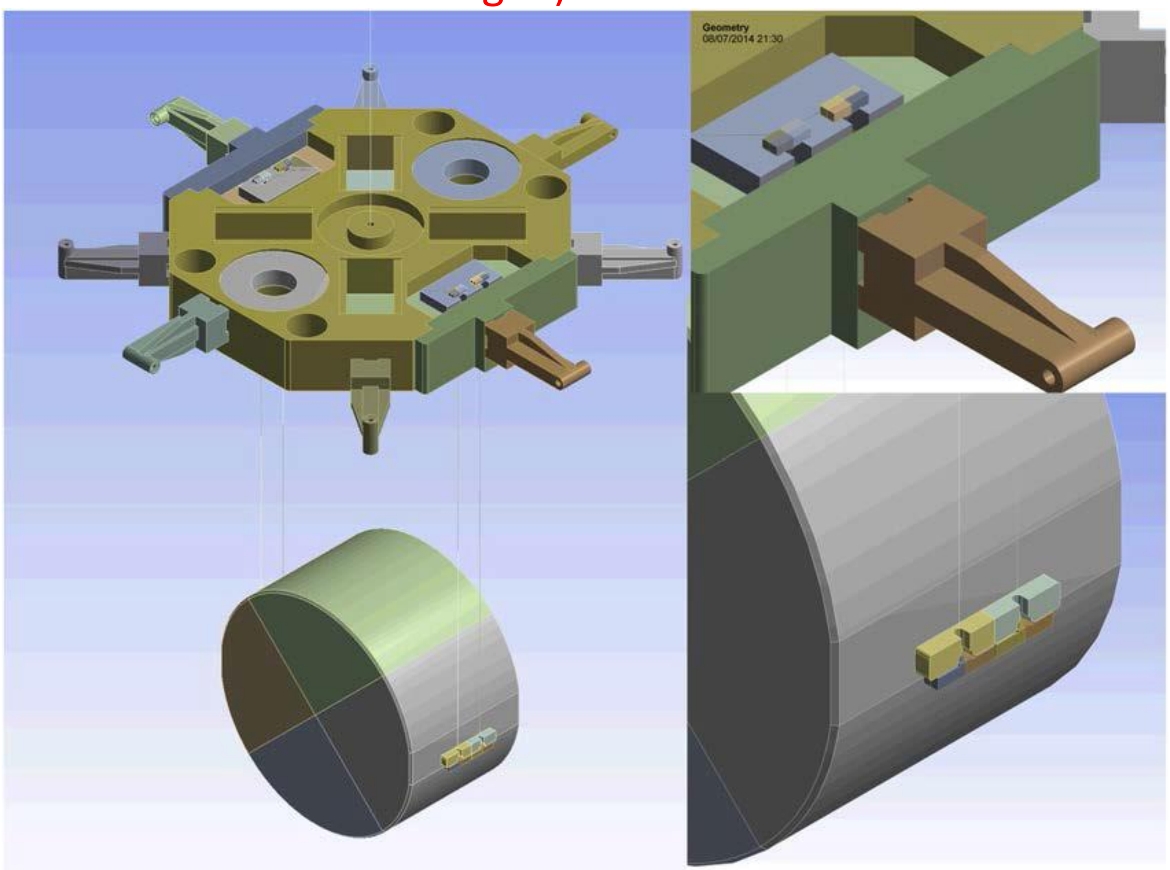
Monolithic Suspension

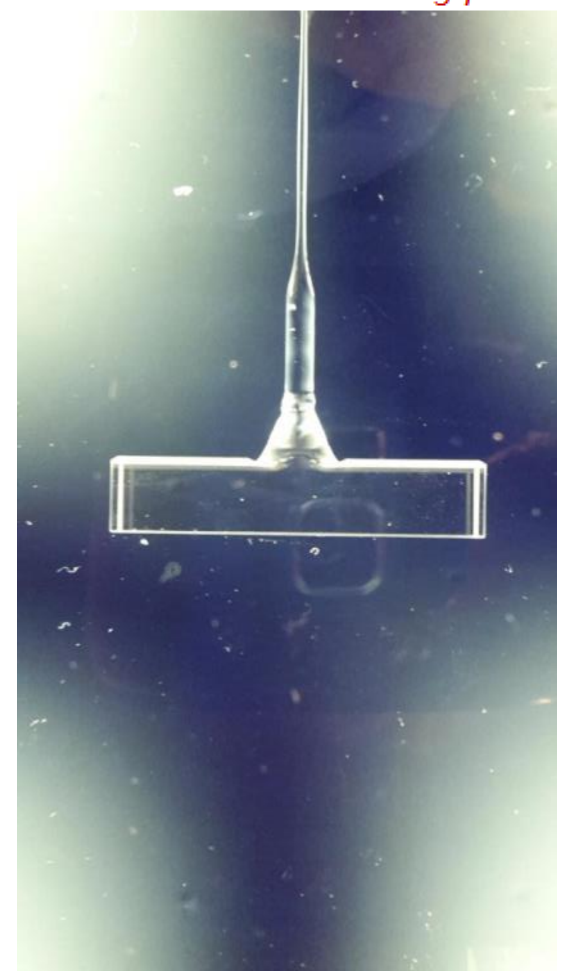
Fiber Shape

Dumb-bell shaped fiber (aLIGO)

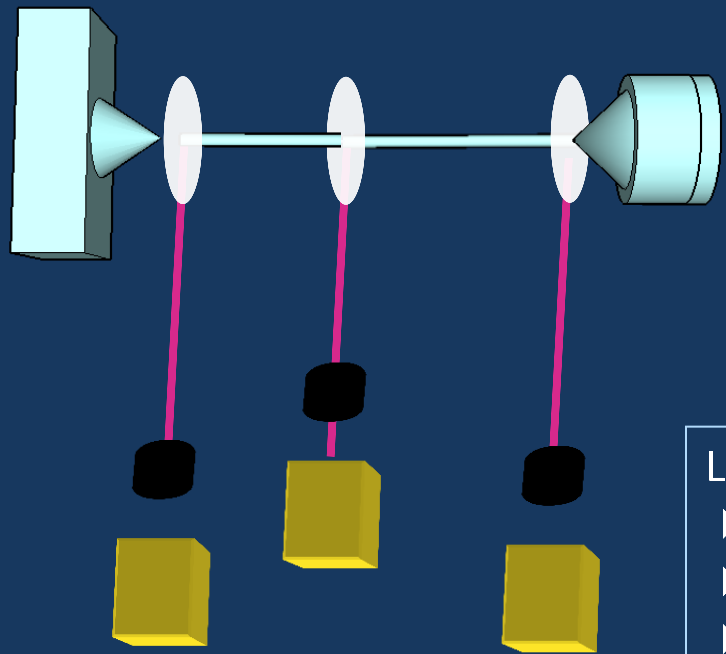
- fiber diameter 0.4mm
- bouncing mode < 10Hz
- violins modes > 400Hz
- working load ~780MPa (reasonably safe, about the same of Virgo+)







Fibers production



Laser pulling of 1.5 mm thick silica bars:

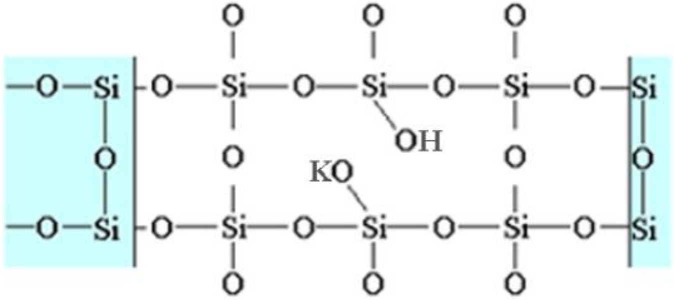
- Welding
- Annealing
- Controlled pulling

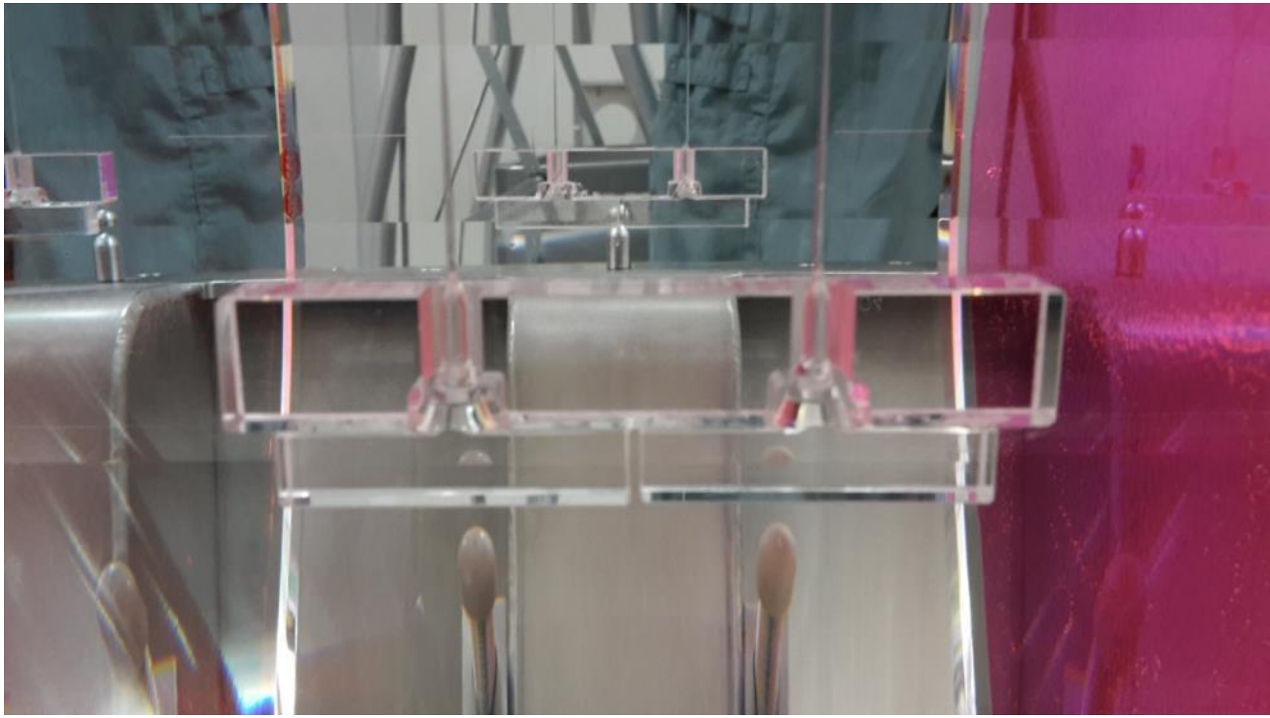
200 W CO_2 laser

MS – Gluing procedure

Silicate bonding technique

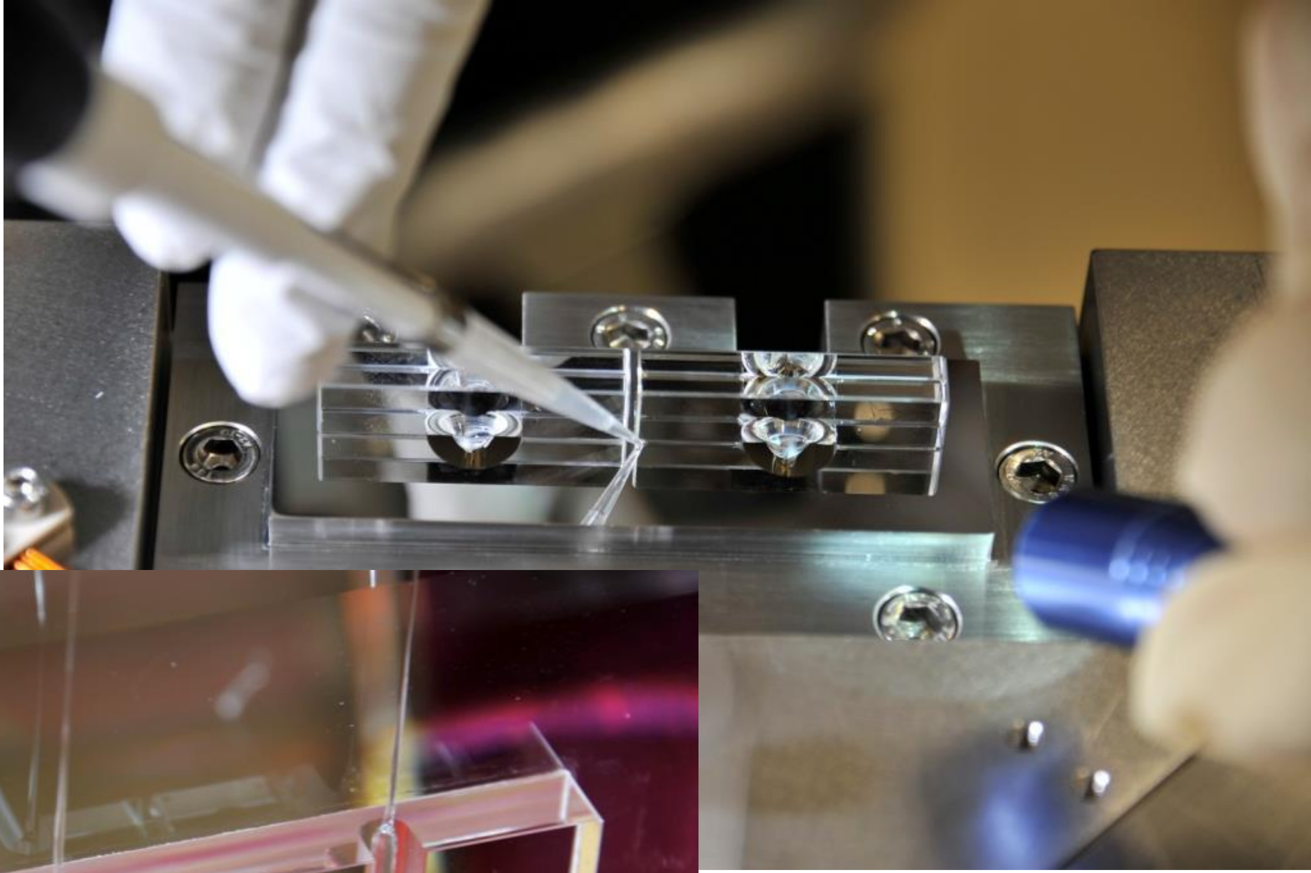
- very clean (piranha solution) and flat surface ($\lambda/10$)
- solution of pure water and KOH





Advanced Virgo

Upper clamp: the upper clamp system is formed by a steel plate with a $\lambda/10$ quality surface. The silica-steel parts are glued by the silicate bonding technique. For this kind of gluing, we measured a minimum breaking strength of 5MPa.



Lower Clamp: the anchors are glued to the ear by the silicate bonding technique.

Crash test

Status

- **Super-attenautors:**
  - old blades replaced
  - all the tower are tuned
  - old electronics replaced and in commissioning phase
  - new sensors on the bottom ring under test
  - tilt-meter under development

- **Mirrors monolithic suspension:**
  - 4 payload mounted in 2015
    - NE payload fully operated
    - NI, WI, WE payloads failed after few months: reasons under study →
      → 3 monolithic suspensions were replaced with more traditional steel suspensions in order to proceed with the commissioning operations

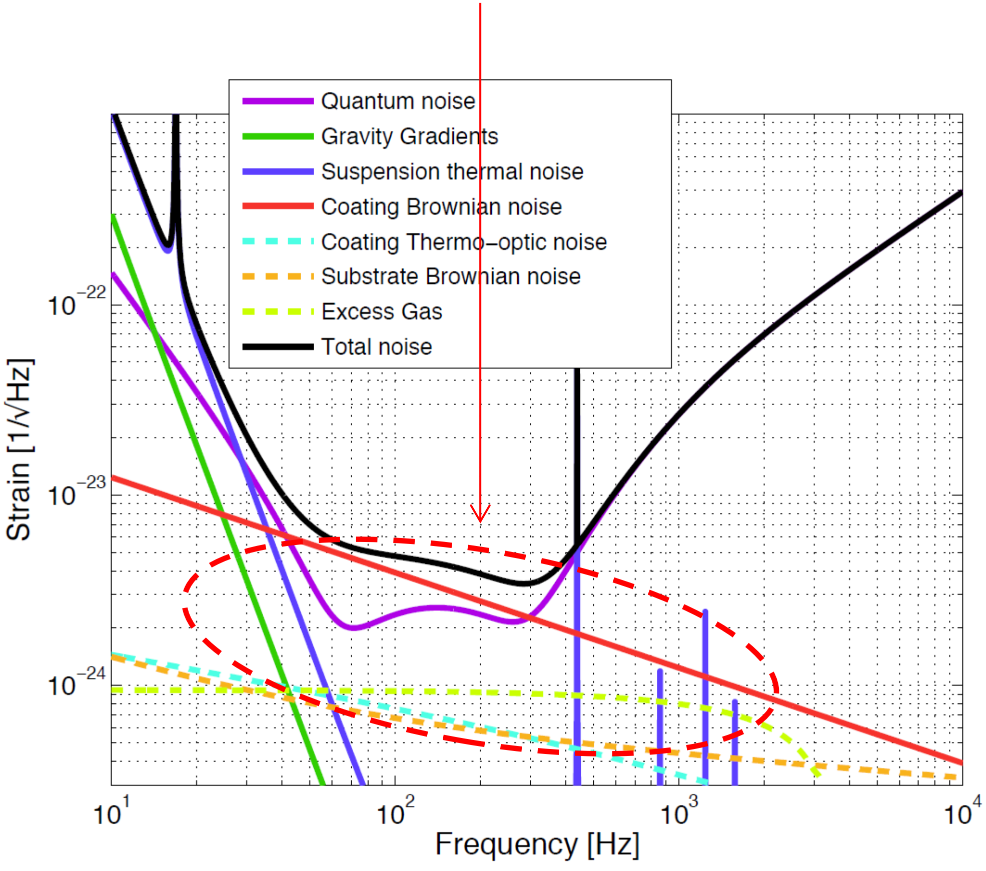
Expected range with steel suspensions:

BNS Inspiral Range(4 steel) 3.00e-04 mm, phi= 1.00e-04: , 60.31 Mpc
BNS Inspiral Range(4 steel) 3.00e-04 mm, phi= 1.00e-03: , 51.37 Mpc

BBH Inspiral Range(4 steel) 3.00e-04 mm, phi= 1.00e-04: , 313.22 Mpc
BBH Inspiral Range(4 steel) 3.00e-04 mm, phi= 1.00e-03: , 199.15 Mpc

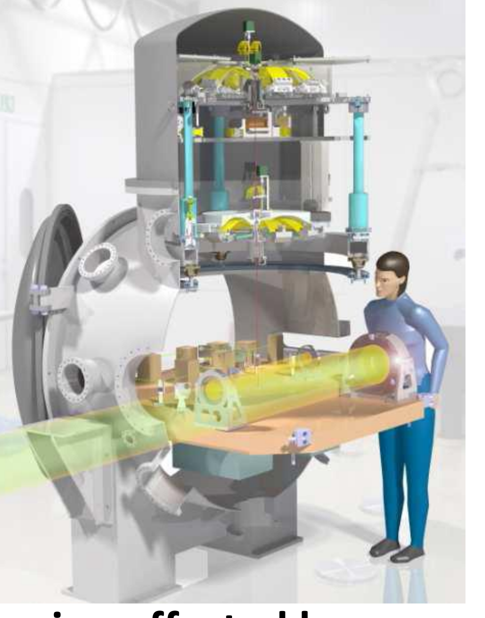
2- Medium frequency range

Limited by coating thermal noise



Improvements:

- Mirror **coatings** engineered for low losses
- Optical configuration: **larger beam** spot



Frequency region affected by environmental noise coupling → improved with:

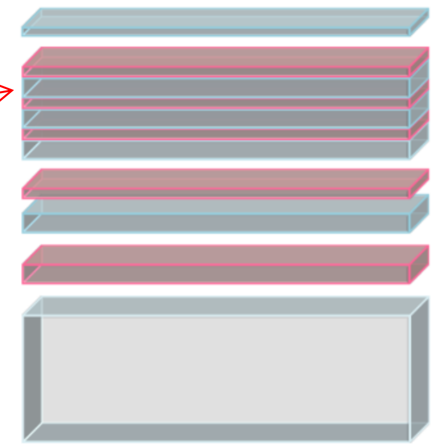
- Photodiodes on suspended benches under vacuum
- Baffles to shield mirrors, pipes, vacuum chambers exposed to scattered light

Mirror Thermal Noise

Reduce the coating losses find **new “recipe”** to reduce mechanical losses while preserving optical quality R&D in progress in several labs, would benefit of a **coordinated approach**

Optimized coating → a new paradigm: doped coating, not a quarter wave coating

Alternating layers of Silica and titania doped tantala

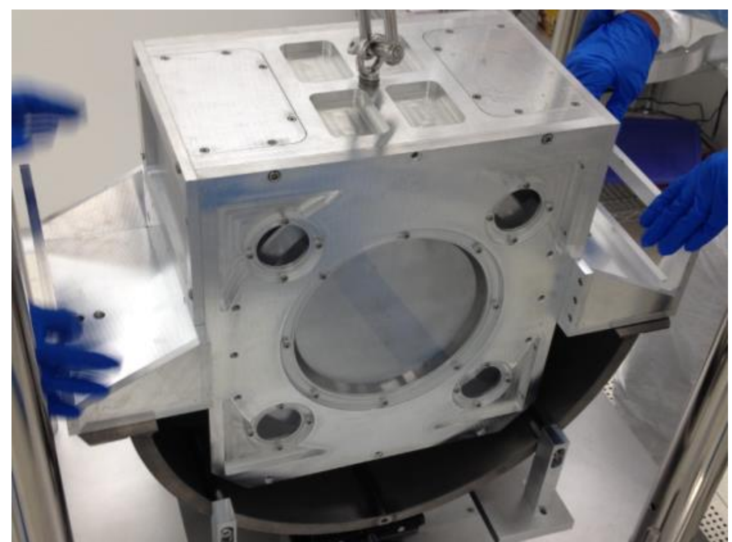


Mirror box

- Handling and traveling box
- Centering system: gluing and mounting procedure
- Protection

Heavier substrates

- New substrates:
  - Diameter = 35cm
  - Weight = 42kg (x2 Virgo+)
- Suprasil 3001 / 312
- High quality surface
  - Surface roughness: rms<0.1 nm;
  - Flatness peak-to-valley<λ/20;
  - Scratch/dig better than 20/10;



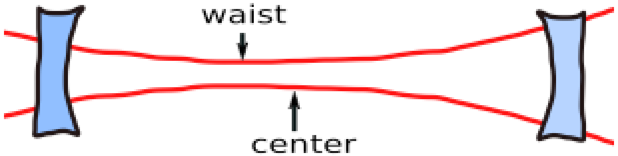
Larger beam

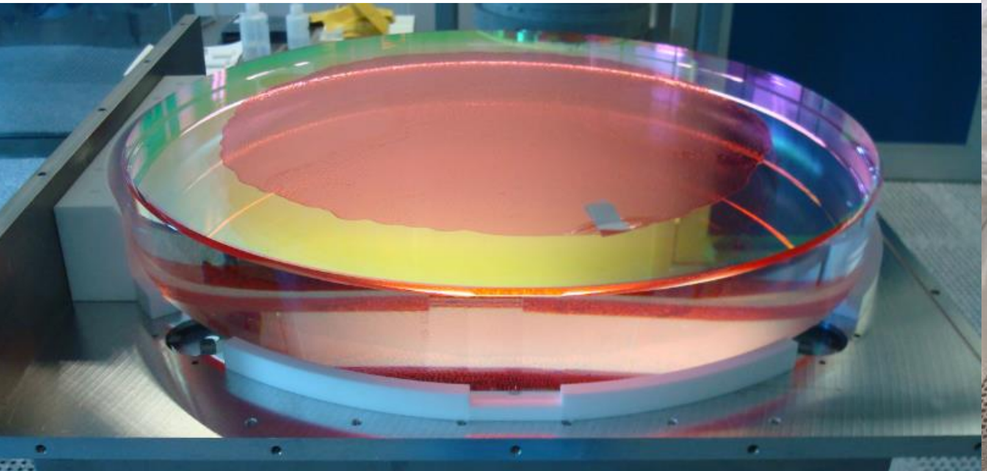
Use larger beams needs of larger mirrors → AdVirgo has suspended the largest mirror ever in GW field (beam splitter, 55 cm diameter) need improvement of:

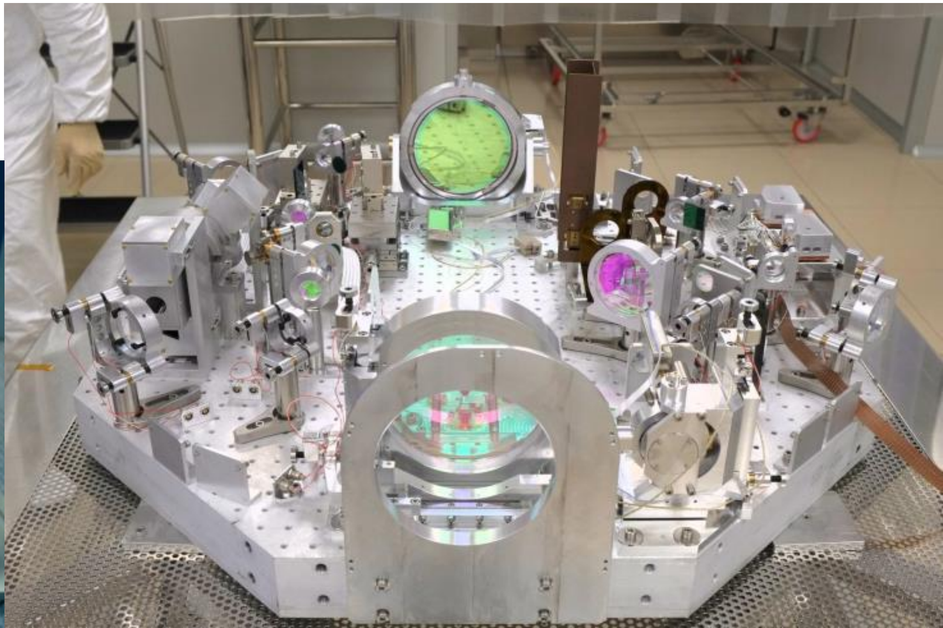
- **uniformity of coating** deposition over a large area
- proper **management of aberrations**
  - optics quality
  - thermal compensation system (**TCS**)
  - degeneracy of the sidebands very sensitive to thermal effects, substrate defects
- re-design of input & output benches and telescopes to fit the **waist position** and to separate the main beam from the **auxiliary beams**
- new vacuum links

$$S_{TNcoat}(f) = \frac{4k_BT}{\pi^2 f Y}\frac{d}{R^2}\left(\frac{Y'}{Y}\phi_{\parallel} + \frac{Y}{Y'}\phi_{\perp}\right)$$

Beam radius on mirror







Status

- **Mirror Thermal Noise**
  - all the **mirrors** were produced and installed
  - substrates, surface and coatings quality in the **specifications or even better**

- **Larger beam**
  - **Beam Splitter** installed
  - **telescope**, **injection system** and **detection system** installed: in commissioning phase for the fine tuning
  - optimization of the **waist position** (different coating TN on the input and end mirrors): done

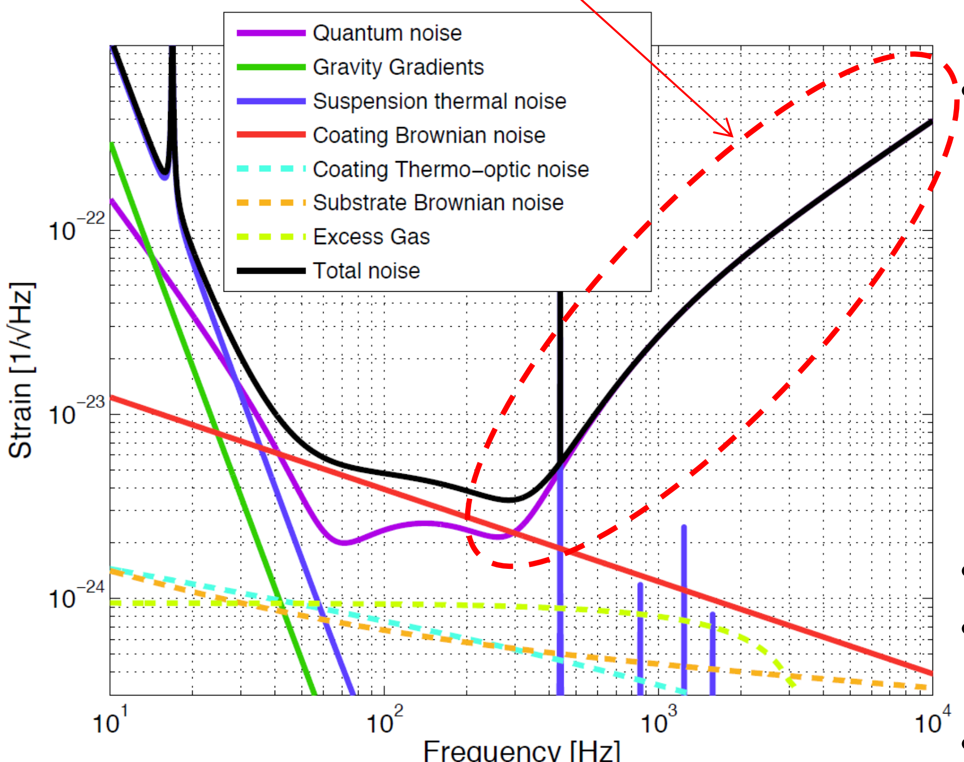
- **Suspended benches**
  - mini-tower ready
  - optics installed and in commissioning phase: fine tuning needs a better beam from the cavities

- **Baffles**
  - Produced and installed

3 - High frequency range

- In principle could be improved by further increasing the laser power → this is very challenging for the parametric instabilities and for the management of thermal aberrations

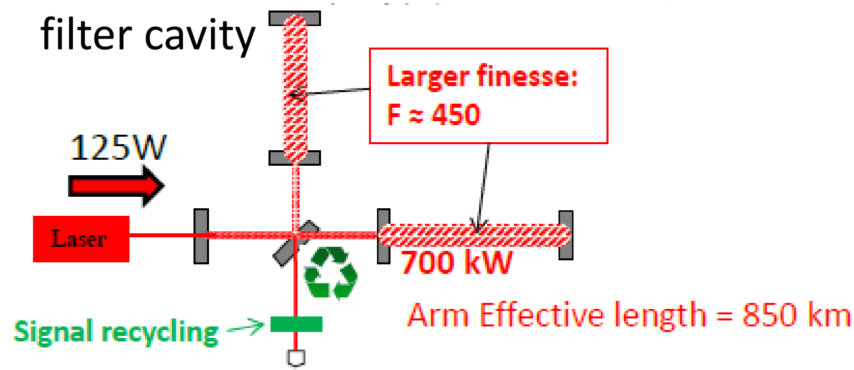
Limited by quantum noise



Larger power requires:

- New laser amplifiers
- Heavier, low absorption optics (substrates, coatings)
- Smart systems to correct for thermal aberrations (TCS)

- Standard squeezing reduces the HF noise while enhancing the LF noise
- Frequency dependent squeezing improves the noise in the whole band: requires a filter cavity

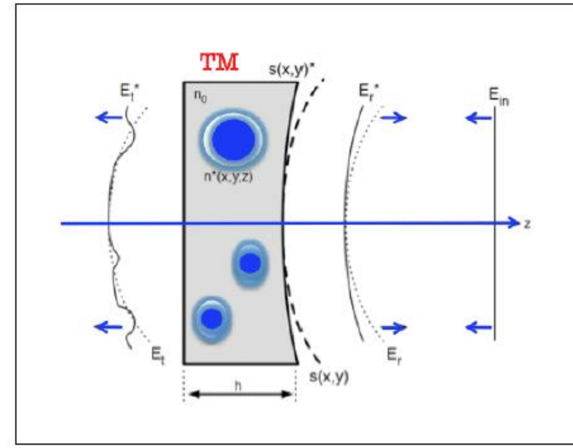


- **Higher laser power**: 125 W injected
- **Higher finesse** of the arm cavities → 700 kW in the arm cavities (x3 Virgo+)
- Optical configuration: **signal recycling**
  - sidebands high order modes are nearly resonant
  - Degeneracy of the sidebands very sensitive to thermal effects, substrate defects
- **DC detection**

Thermal compensation system

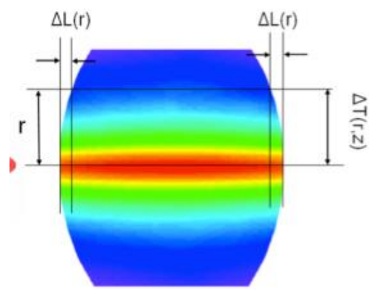
Sources

- imperfections in the production of the material used for the mirrors (cold defects);
- absorption of optical power in the coatings and substrates of the optics (dynamic effects).

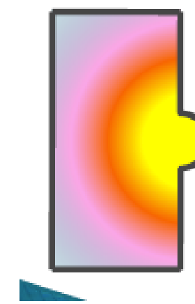


Thermal effects

- Thermal lensing

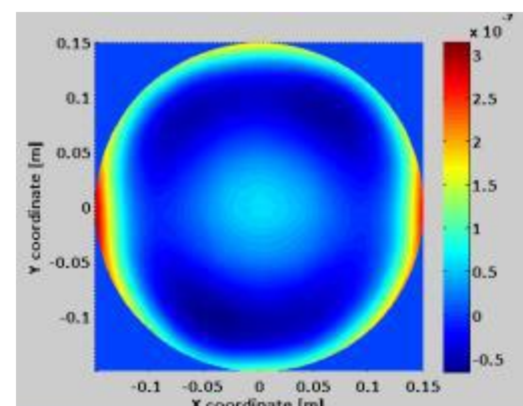


- Thermoelastic effect



Consequences

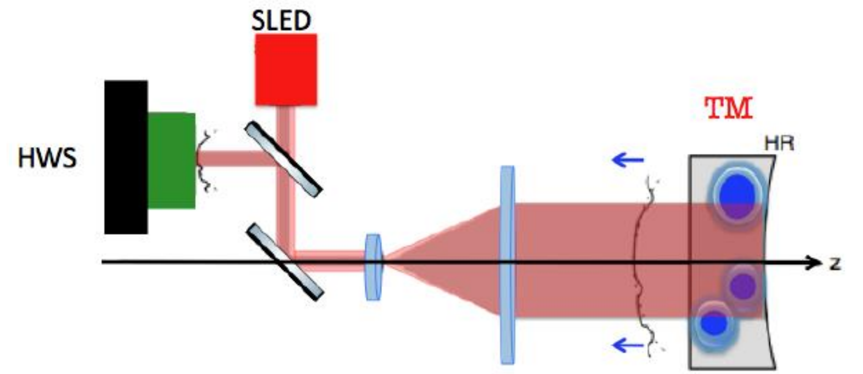
- Scatter light to Higher Order Modes (HOM):
- Error signals power to control the cavities decreases;
- Fabry-Pérot Cavity power decreases ->loss of sensitivity;
- Worsen interference at Beam Splitter -> junk light at the dark port.



Thermal compensation system

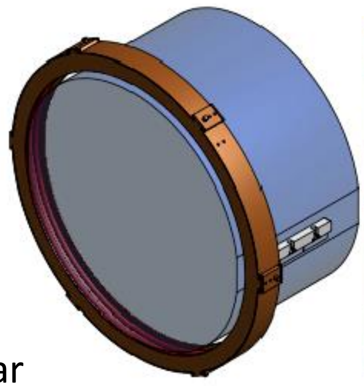
Sensors

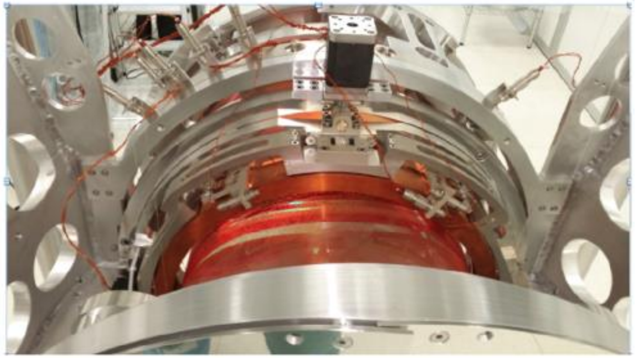
- **Hartmann Sensor**: change of a 'live' wave front relative to a reference wave front through an incoherent probe beam [fiber coupled super-luminescent diode (SLED)]
- **Phase Camera**



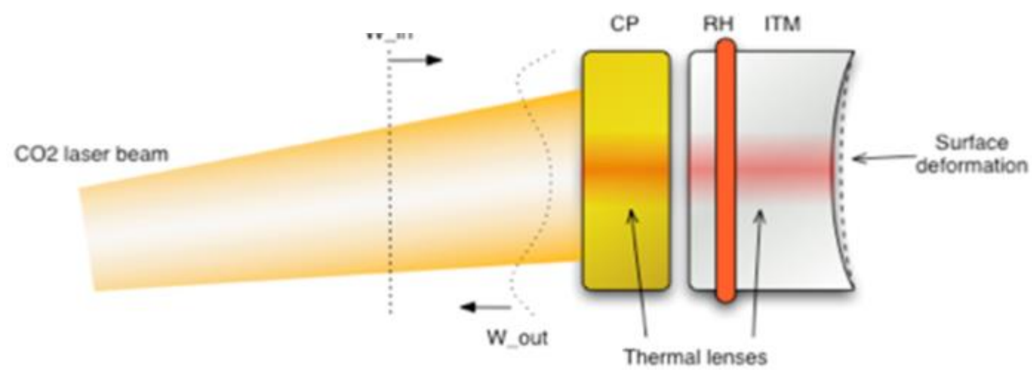
Actuators

- **Ring Heater (RH):** corrects errors in the radius of **curvature** of mirrors due to the absorption of the laser power and manufacturing accuracy (Silica rings with NiCr wires as conductors , copper shield to increase the efficiency)





- **Double axicon system (DAS)**: two CO_2 annular beams incident on **auxiliary optic** called compensation plate (CP) to correct the **axial-symmetric** terms of thermal lensing
- **Scanning system**: a modulated CO_2 beam scanning the CP surface to correct the **non-symmetric** terms of thermal lensing (point defects)



Intermediate configuration - Signal recycling cavity-

- **No signal recycling:** reduce locking complexity
- **Use Virgo+ laser** up to 60W
- **Low power:** reduce risks with thermal effects and high power laser

Target BNS inspiral range: >100 Mpc

Configuration upgrade schedule to be discussed with the partners

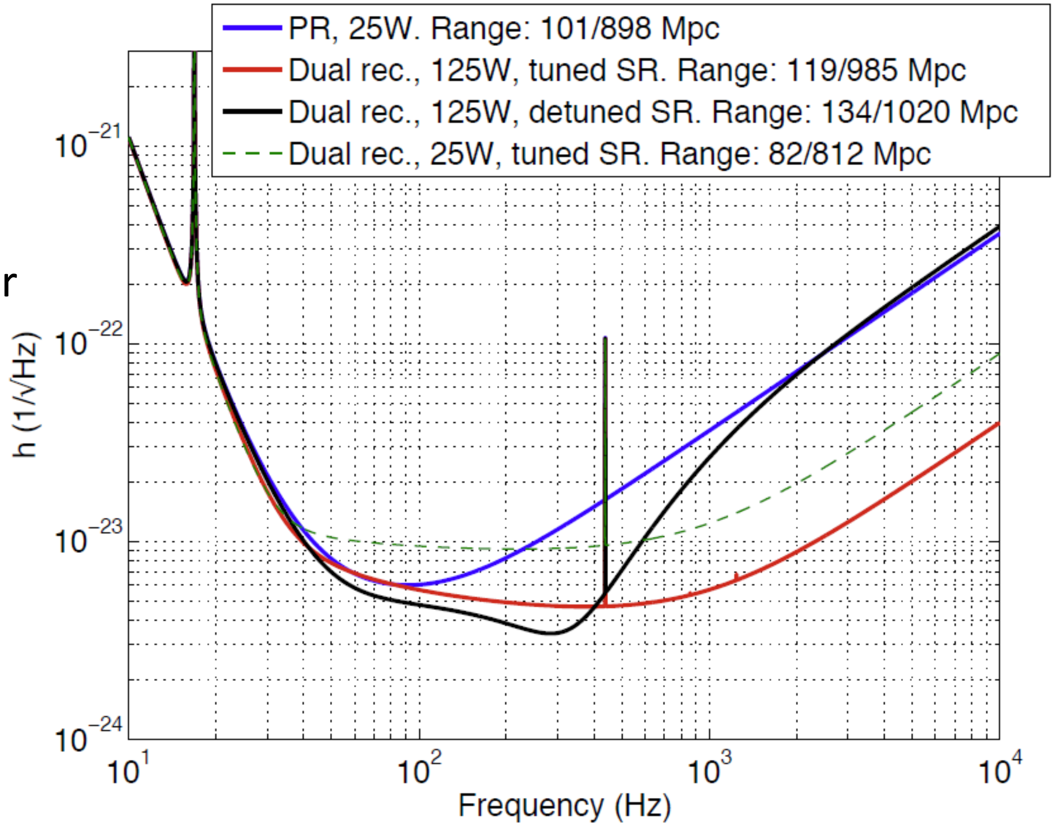


Figure 1.3: Scenario for the evolution of the AdV sensitivity: early operation (blue), 25 W input power, no SR; late operation, wideband tuning (red), 125 W input power, tuned SR; late operation, optimized for BNS (black), 125 W input power, detuned SR (0.35 rad). In the legend, the inspiral ranges for BNS and BBH (each BH of 30 $M_\odot$) in Mpc are reported. Dual recycling curves are obtained without changing the SR mirror.

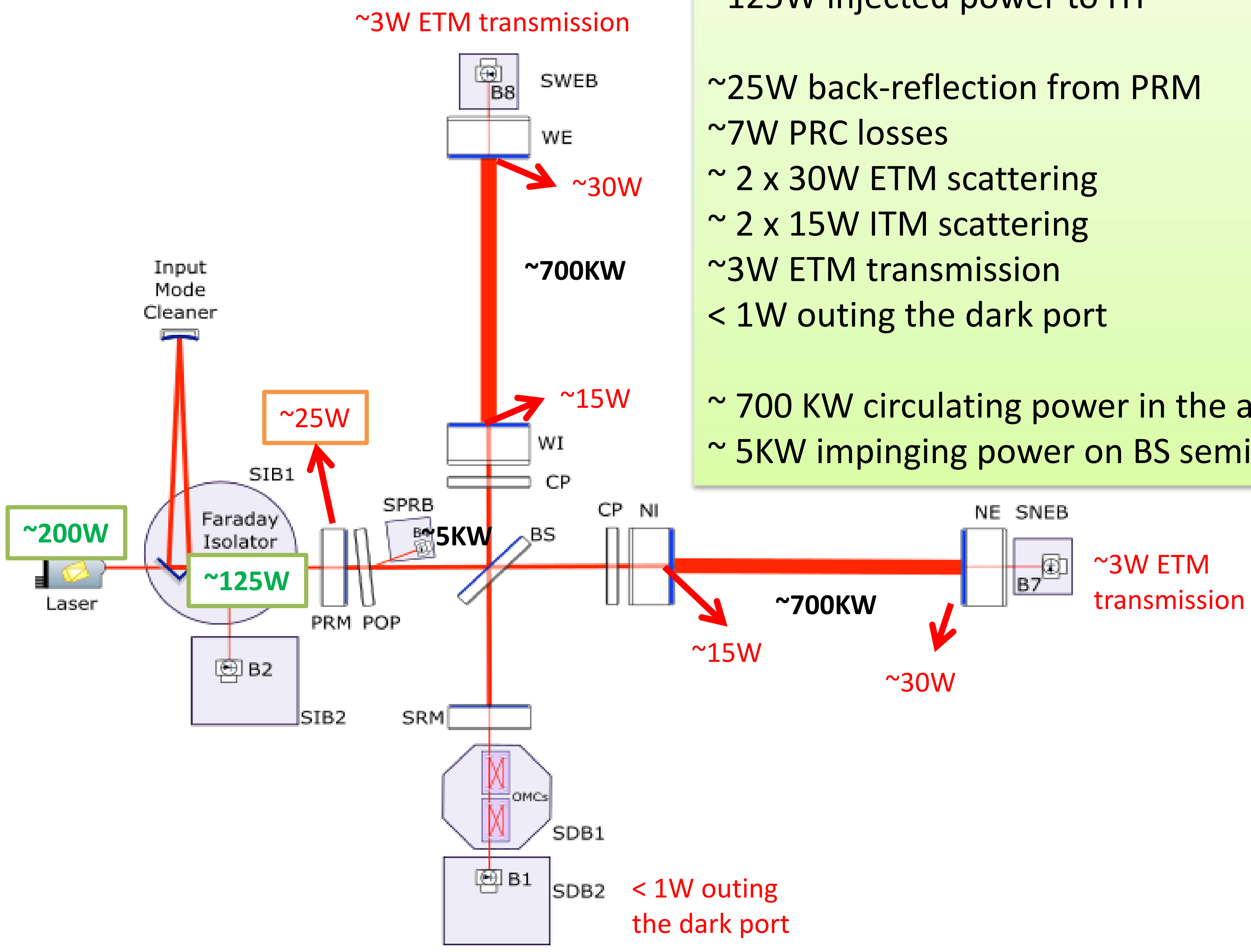
Status

- **Thermal Compensation System**
  - **Compensation Plates** and **ring heater**: installed and in commissioning phase
  - **CO_2** laser benches: installed and pre-commissioning phase
  - **Hartmann sensors**: 1 sensor installed on the injection system and 5 ready to be installed
  - **Phase camera**: to be installed

- **Laser**
  - **60W laser**: ready
  - 125W laser: under development

- **Signal recycling**
  - **SR Mirror**: installed and in commissioning phase also if we are not using it now

Final optical scheme



Power budget:

~200W Input laser
~125W injected power to ITF

~25W back-reflection from PRM
~7W PRC losses
~ 2 x 30W ETM scattering
~ 2 x 15W ITM scattering
~3W ETM transmission
< 1W outing the dark port

~ 700 KW circulating power in the arm cavity
~ 5KW impinging power on BS semi-reflecting side

The network since 2007

MOU signed between LIGO Scientific Collaboration and Virgo:

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

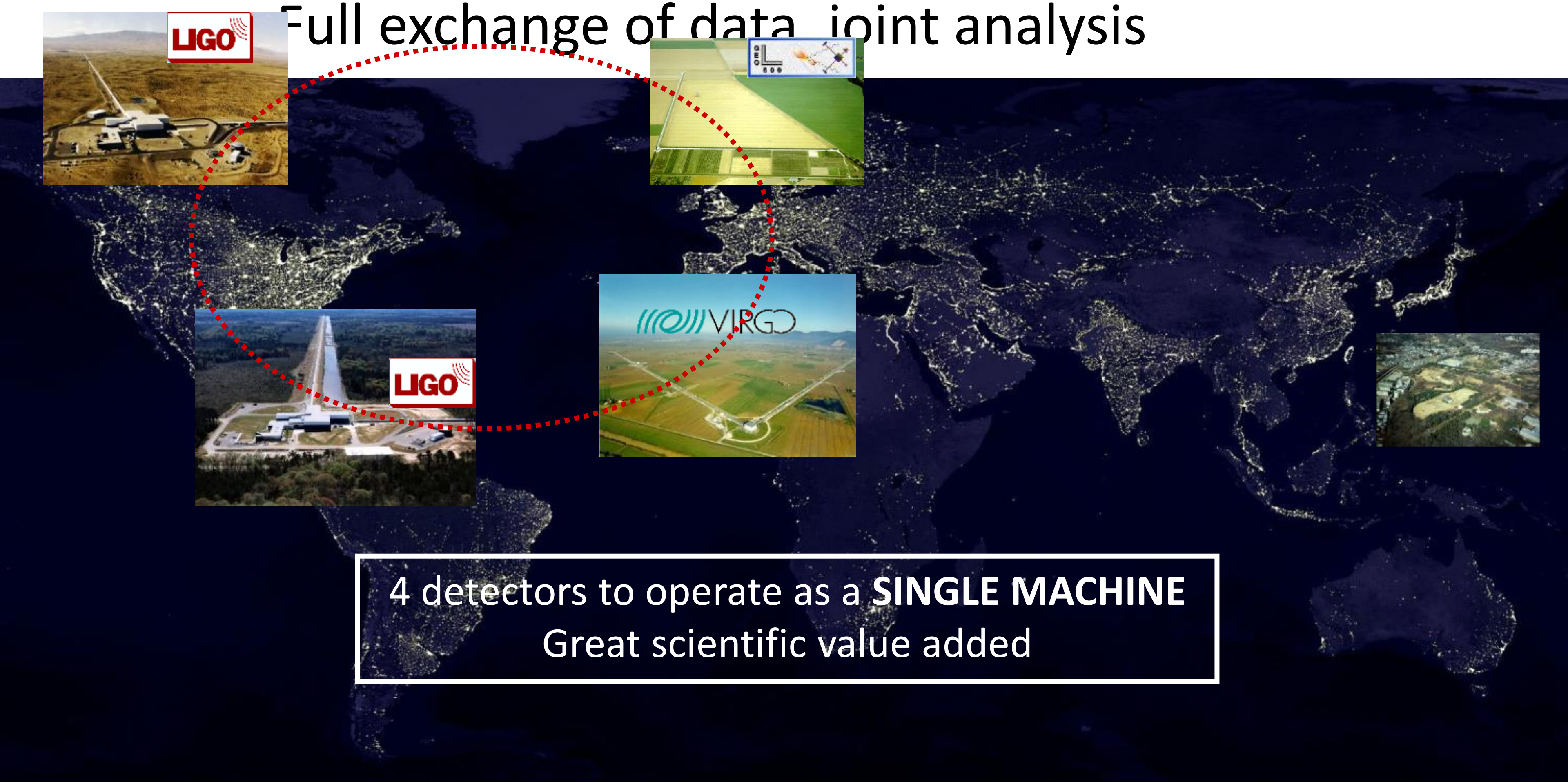
Sky location improvement

- 2 IFO →~400 sq deg
- 3 IFO →~100 sp deg
- 4 IFO →~ 10 sq deg

The network since 2007

MOU signed between LIGO Scientific Collaboration and Virgo:

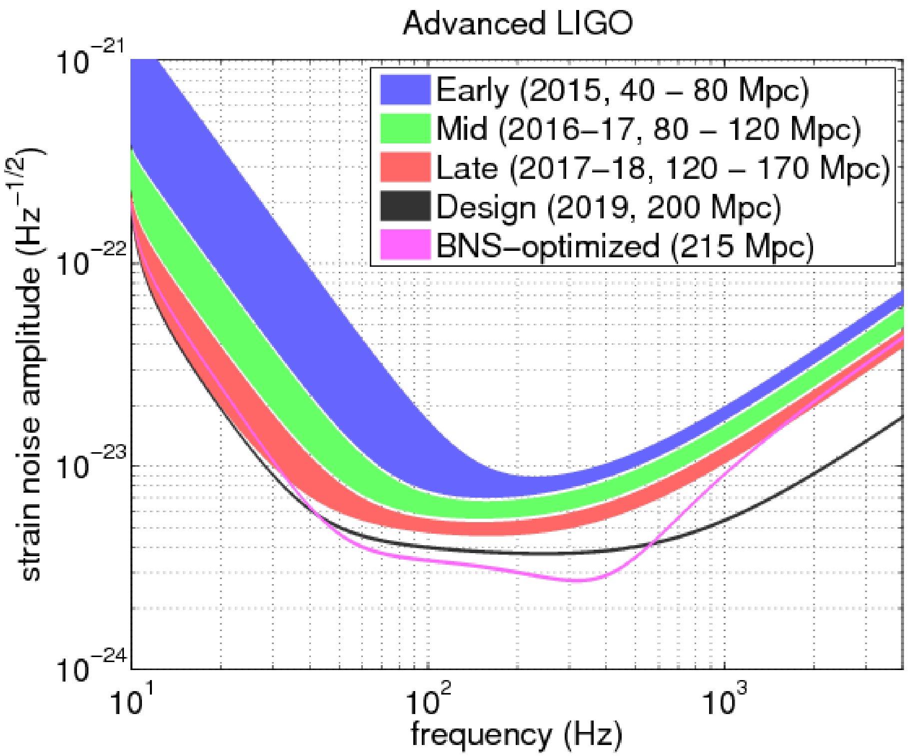
- Full exchange of data, joint analysis

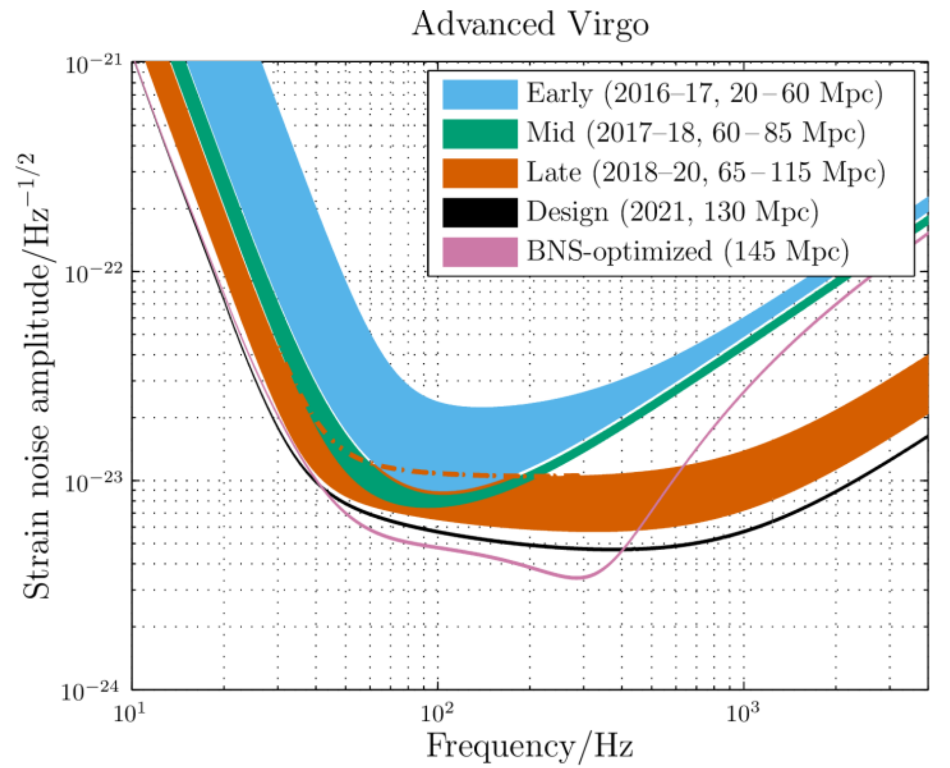


4 detectors to operate as a **SINGLE MACHINE**
Great scientific value added

Next future - Observing scenario

Main goal: join aLIGO for **early science runs** → Advanced Virgo was funded ~2 years after aLIGO
Start in 2015 with a **intermediate configuration**, similar to Virgo+ to reduce commissioning time





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

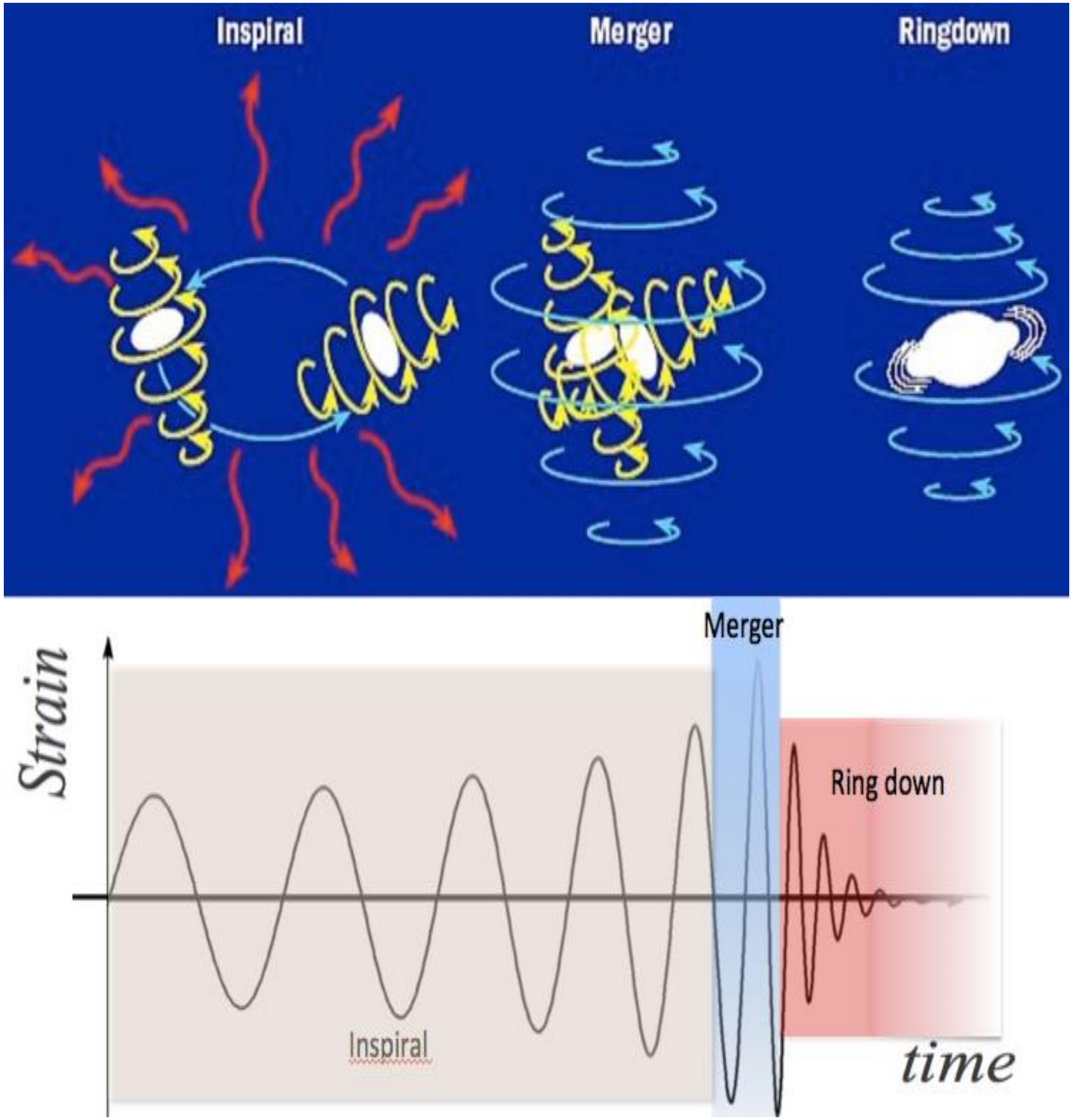
AdLigo first run

The first observing run of LIGO in the advanced configuration took place from September 12, 2015 to January 19, 2016

Total coincident time: 51.5 days

The data quality checks reduce the hunting time to: 48.6 days

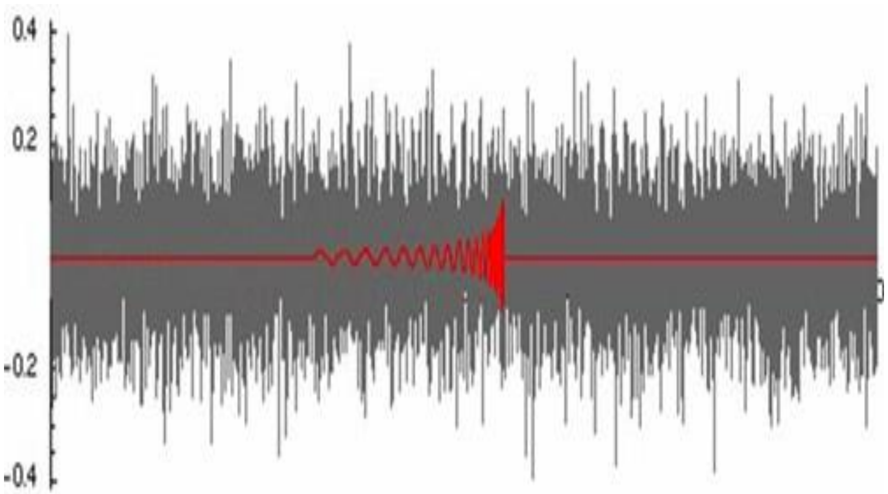
Black holes search

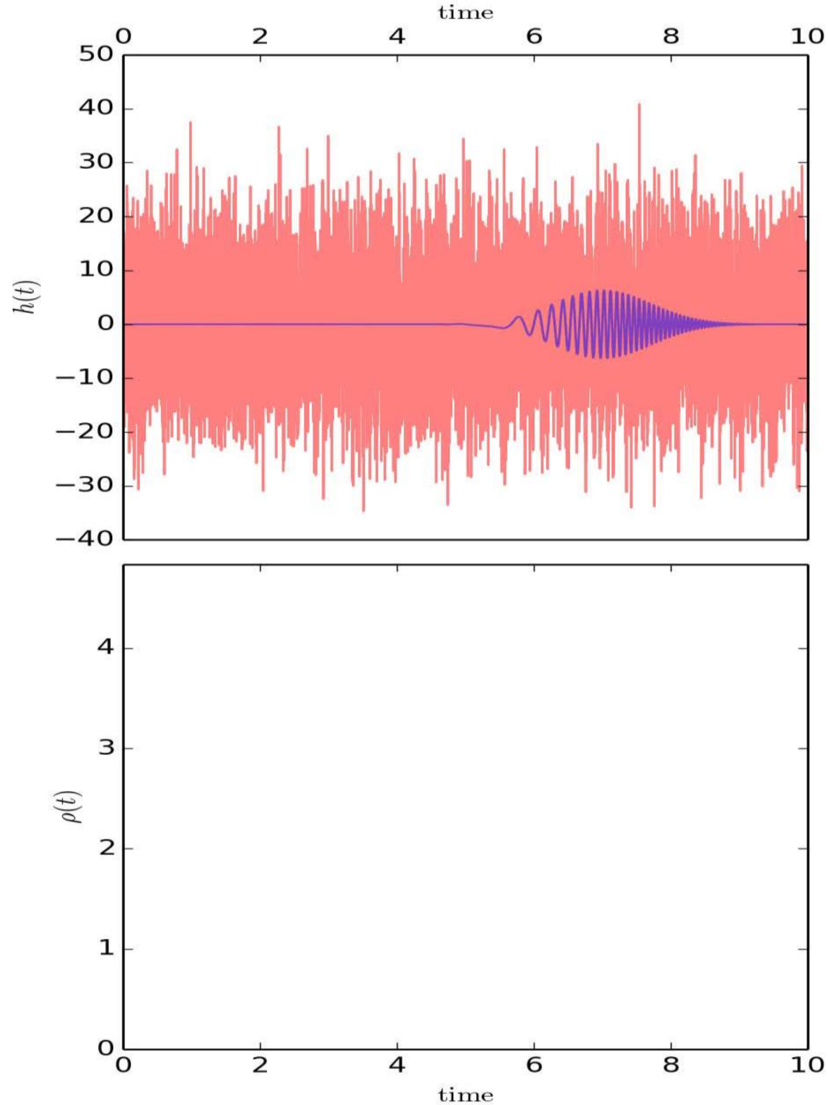


The search for black hole signals is performed over a range of frequencies from 30 Hz to several kHz.

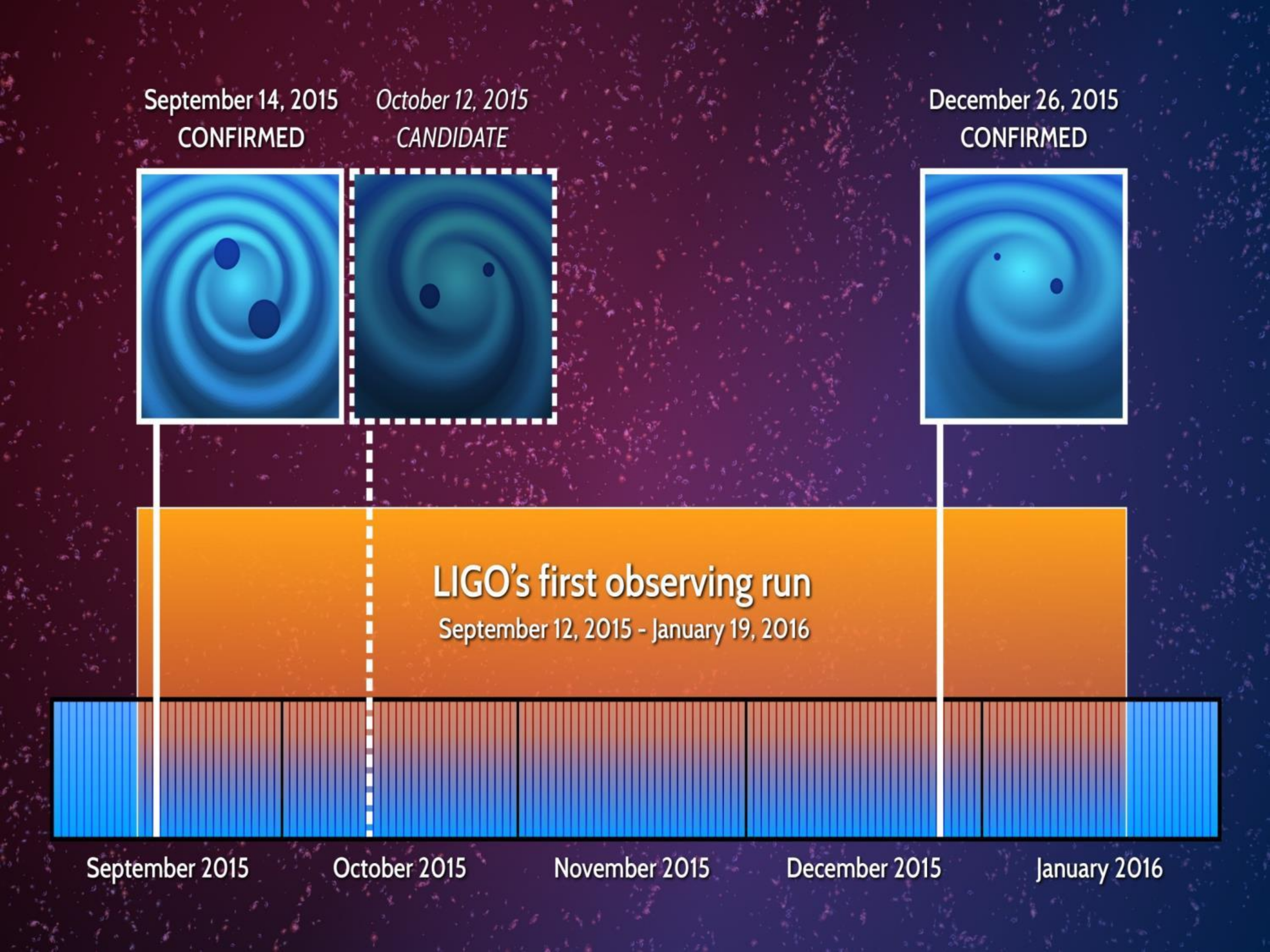
These are the typical frequencies of the gravitational waves emitted during the late inspiral, merger and ringdown of stellar mass black hole binaries.

Matched filter method





The *matched filter*, is obtained by correlating the hypothetical signal with the interferometer output signal to infer the presence of the gravitational wave signal hidden in the data.


September 14, 2015
CONFIRMED
October 12, 2015
CANDIDATE
December 26, 2015
CONFIRMED
LIGO's first observing run
September 12, 2015 - January 19, 2016
September 2015
October 2015
November 2015
December 2015
January 2016

GW events

The search identified two events regarding two black holes mergers and one candidate event:

GW150914 ➔ Signal/Noise =24

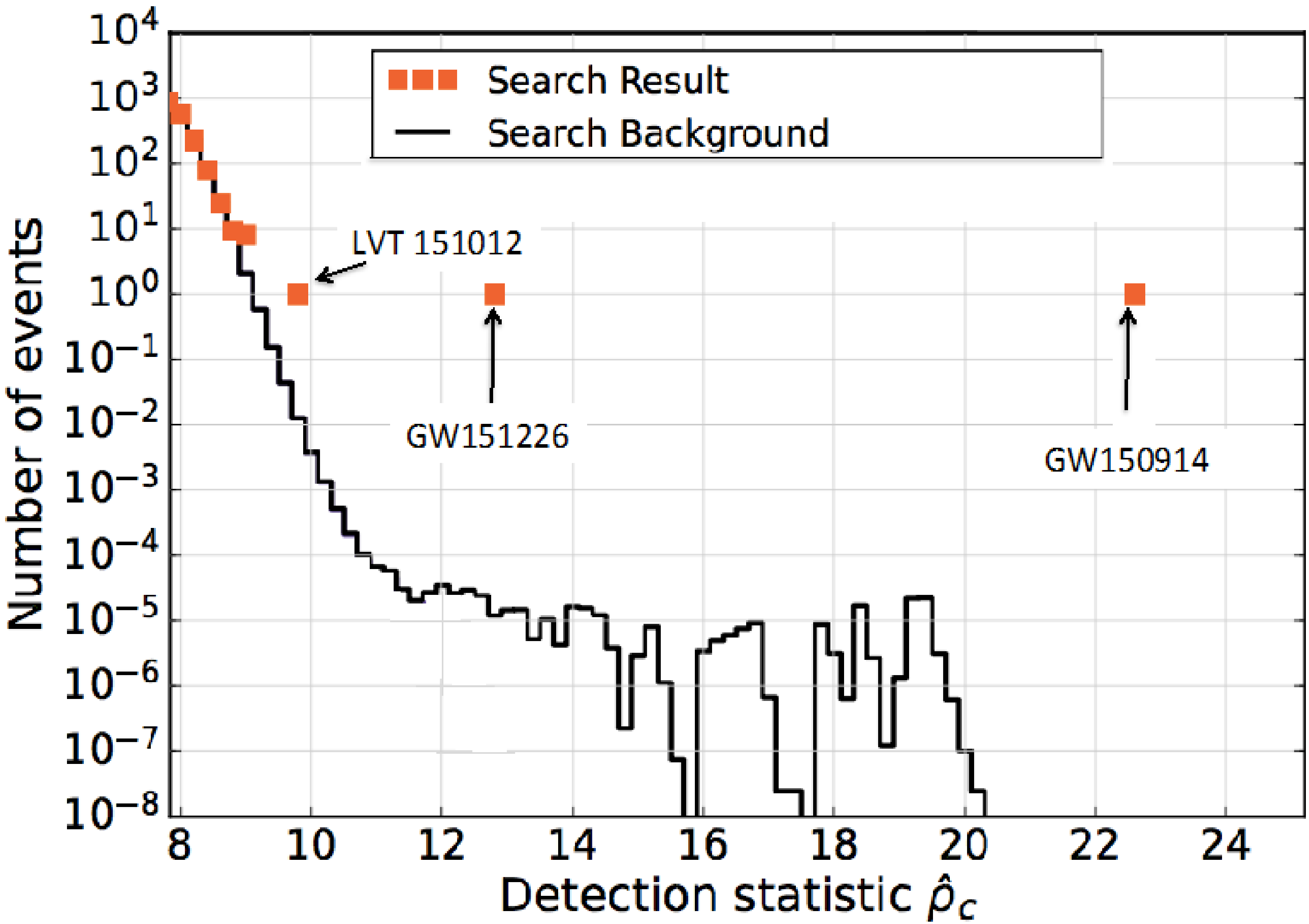
GW151226 ➔ Signal/Noise = 13

+

LVT151012 ➔Signal/Noise *=9.7*

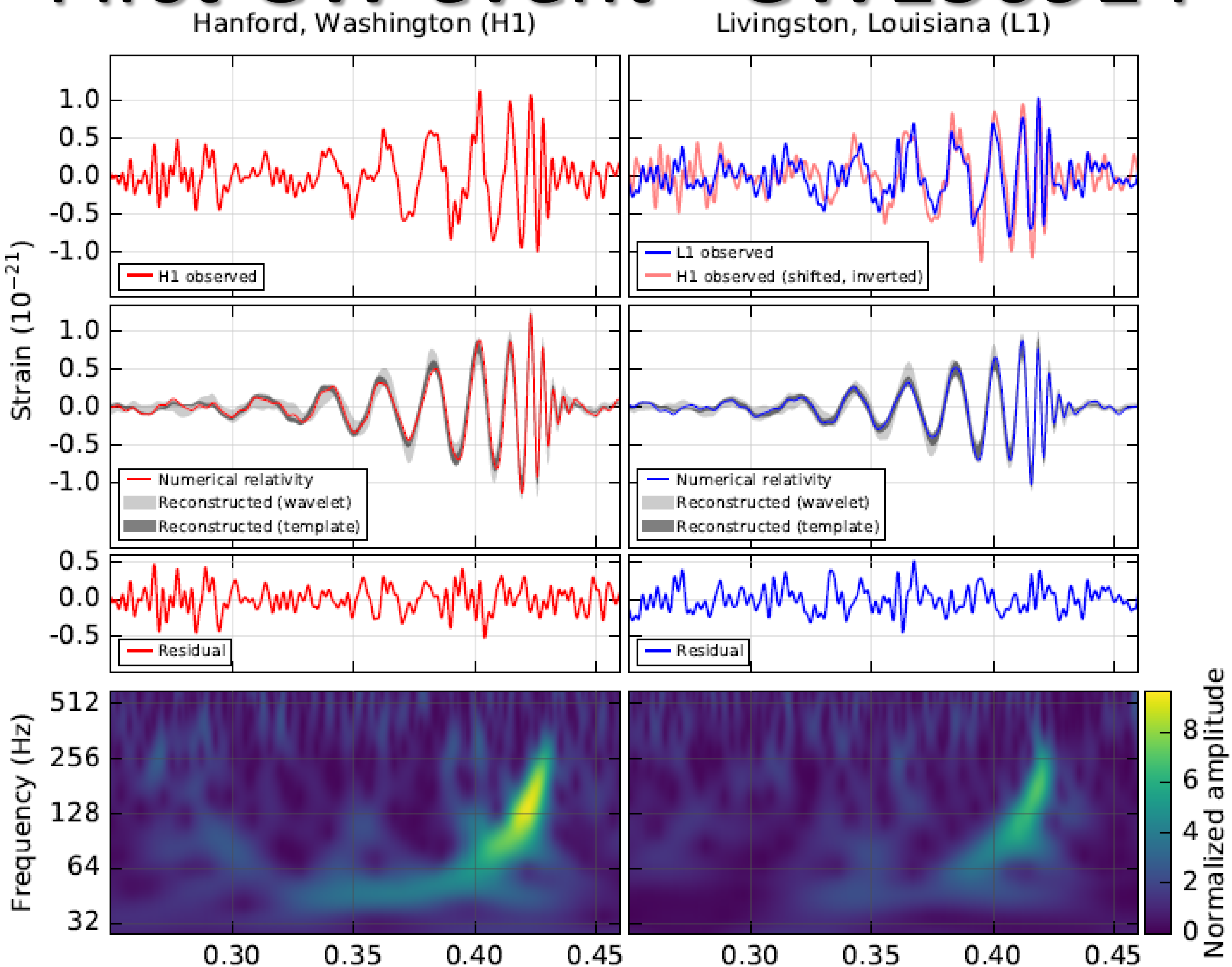
While we are not so confident to tag this as a detection, it is more likely to be a gravitational wave signal than not

Detection statistics



Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate FAR/yr^{-1}	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\,\sigma$	$> 5.3\,\sigma$	1.7σ
Primary mass $m_1^{\text{source}}/\text{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\text{source}}/\text{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathscr{M}^{\text{source}}/\text{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\text{source}}/\text{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\text{f}}^{\text{source}}/\text{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_{f}	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\text{rad}}/(\text{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\text{peak}}/(\text{erg}\,\text{s}^{-1})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance D_{L}/Mpc	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\text{deg}^2$	230	850	1600

First GW event - GW150914

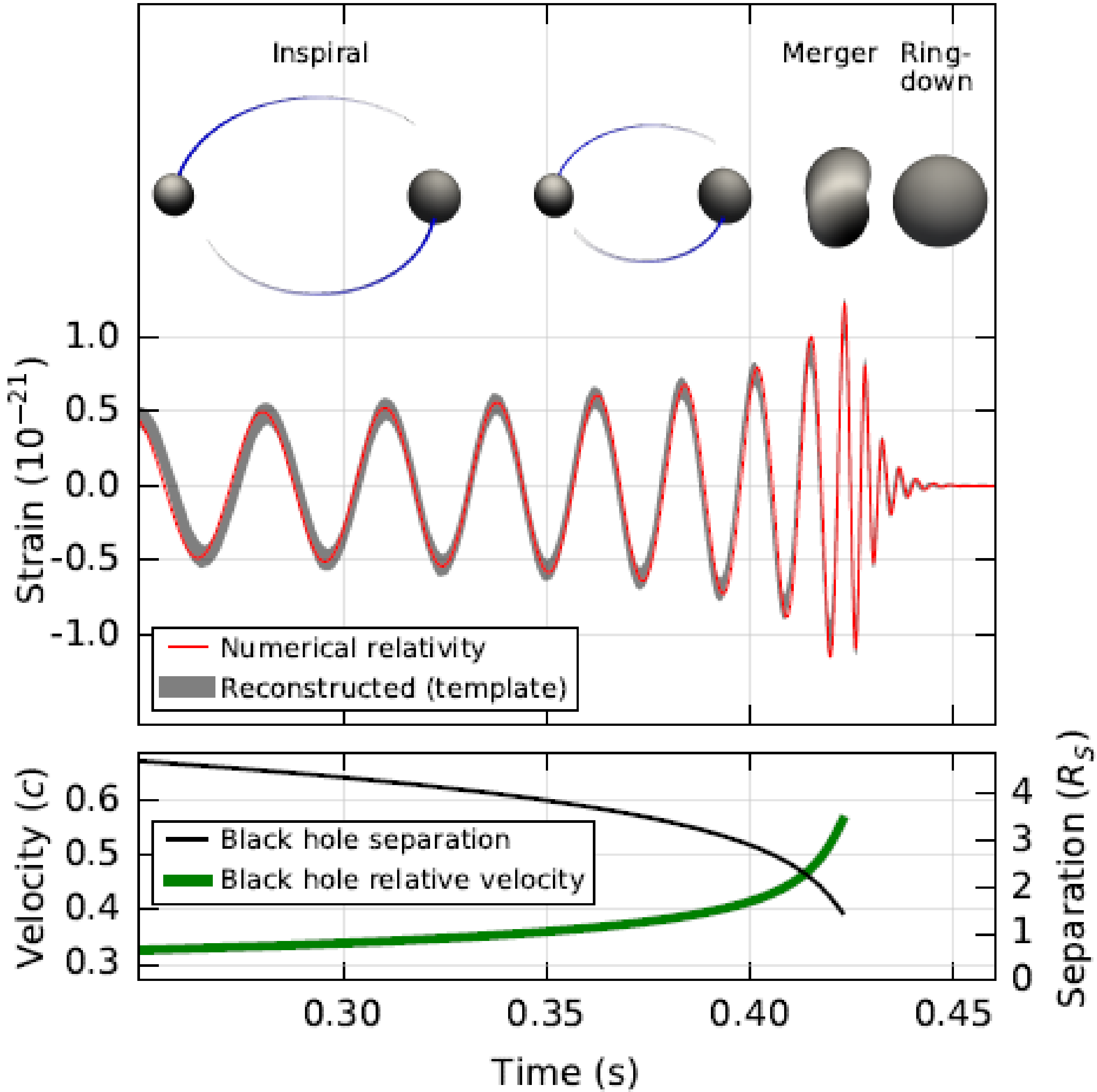


$M_{BH1} = 36\ M_{sol}$ $M_{FBH} = 62\ M_{sol}$ $D_{BH\text{-}BH\ (before\ merger)} = 250$ km

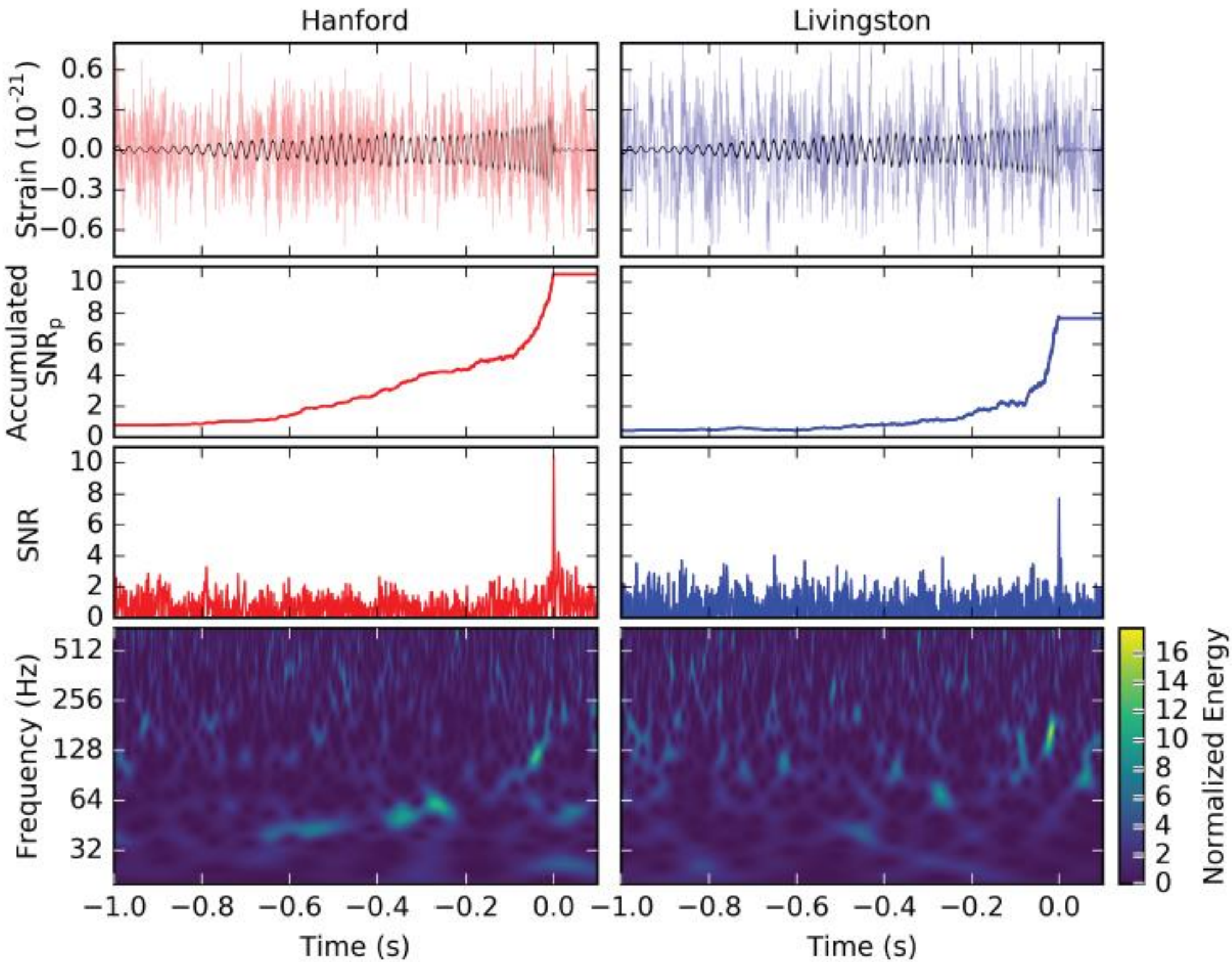
$M_{BH2} = 29\ M_{sol}$ $E_{gw} = 3\ M_{sol}$ Distance = 410 Mpc

$v_{BH\ (before\ merger)} = c/2$

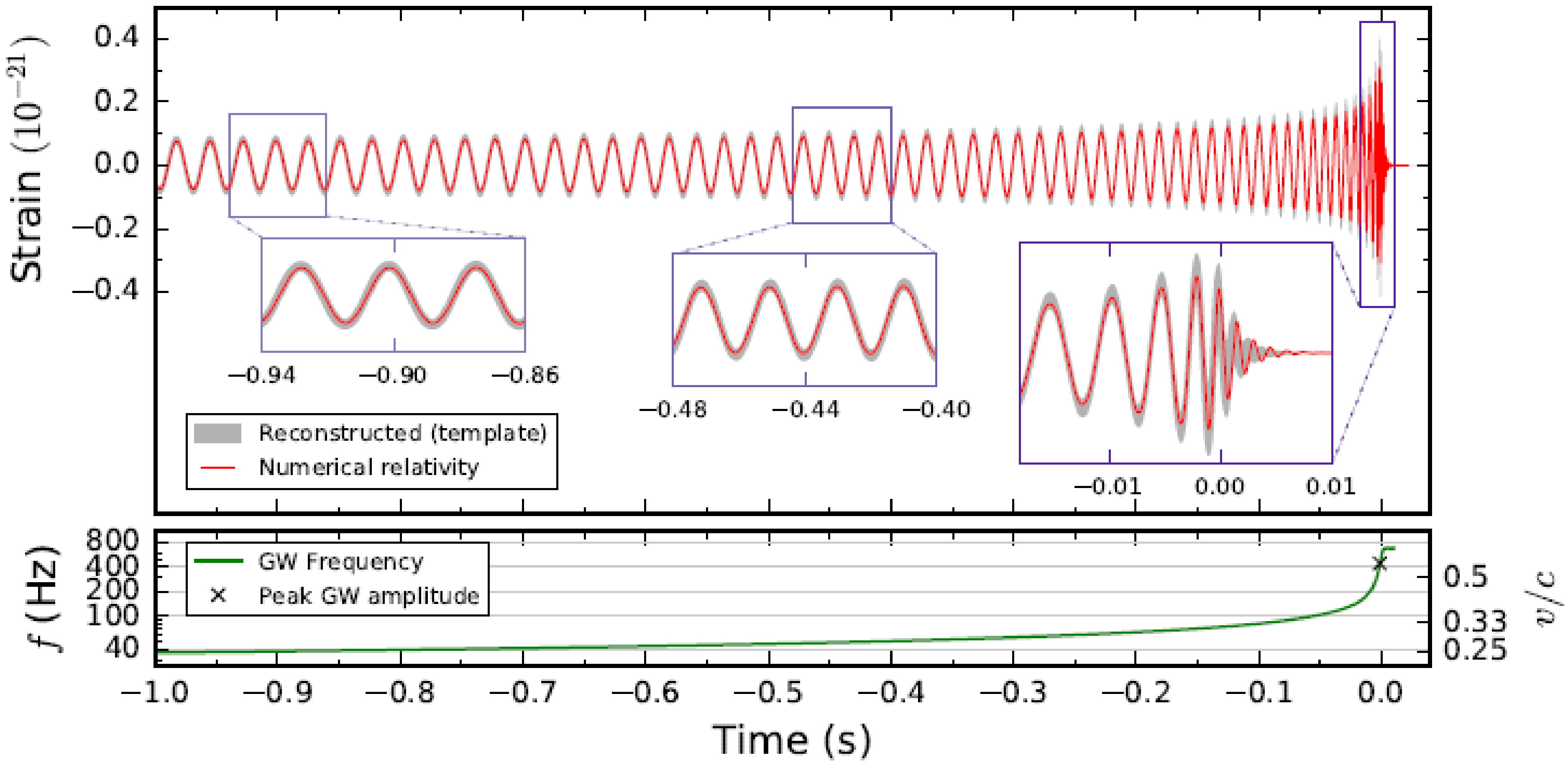
First GW event - GW150914



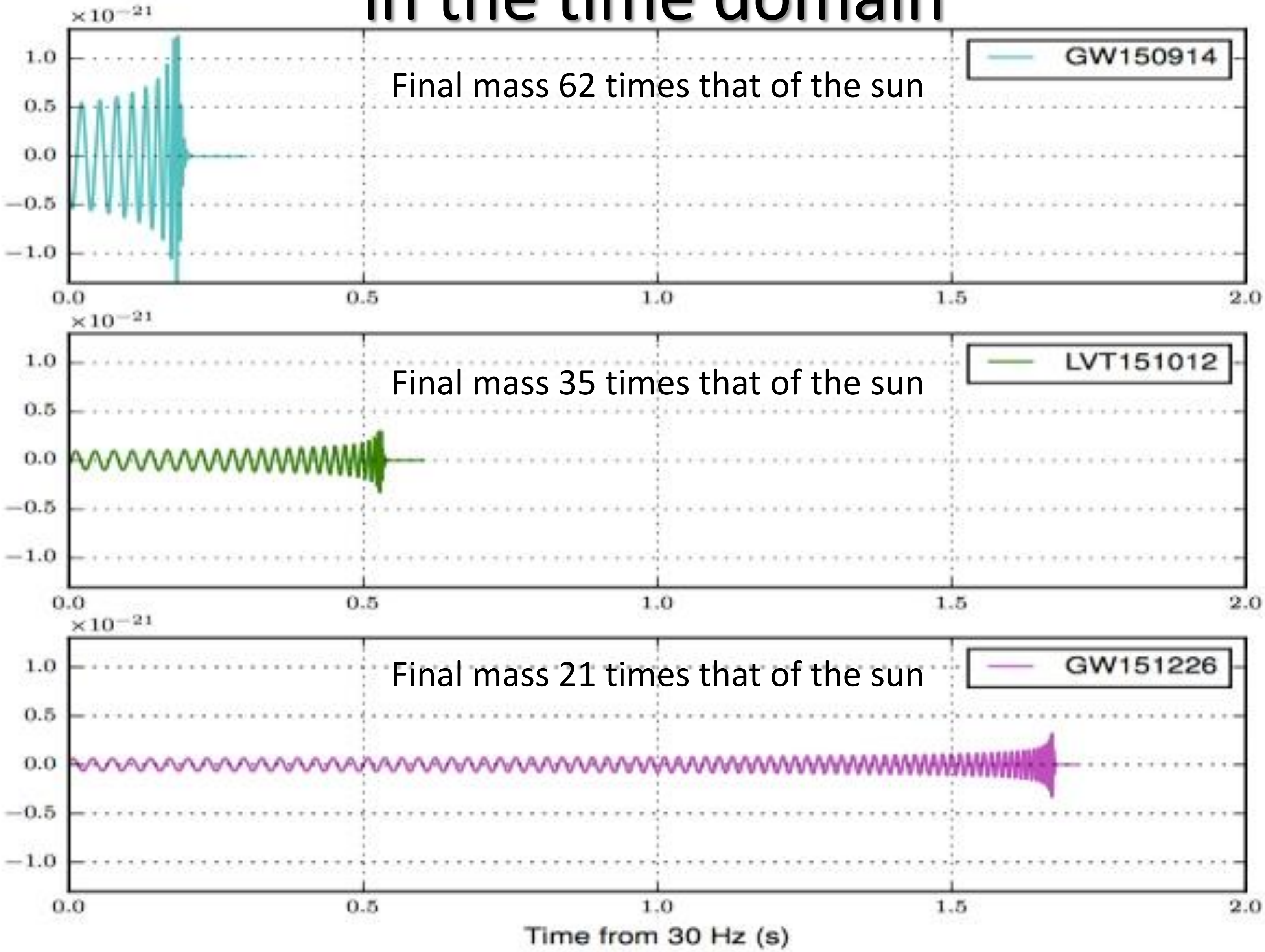
Second GW event - GW151226



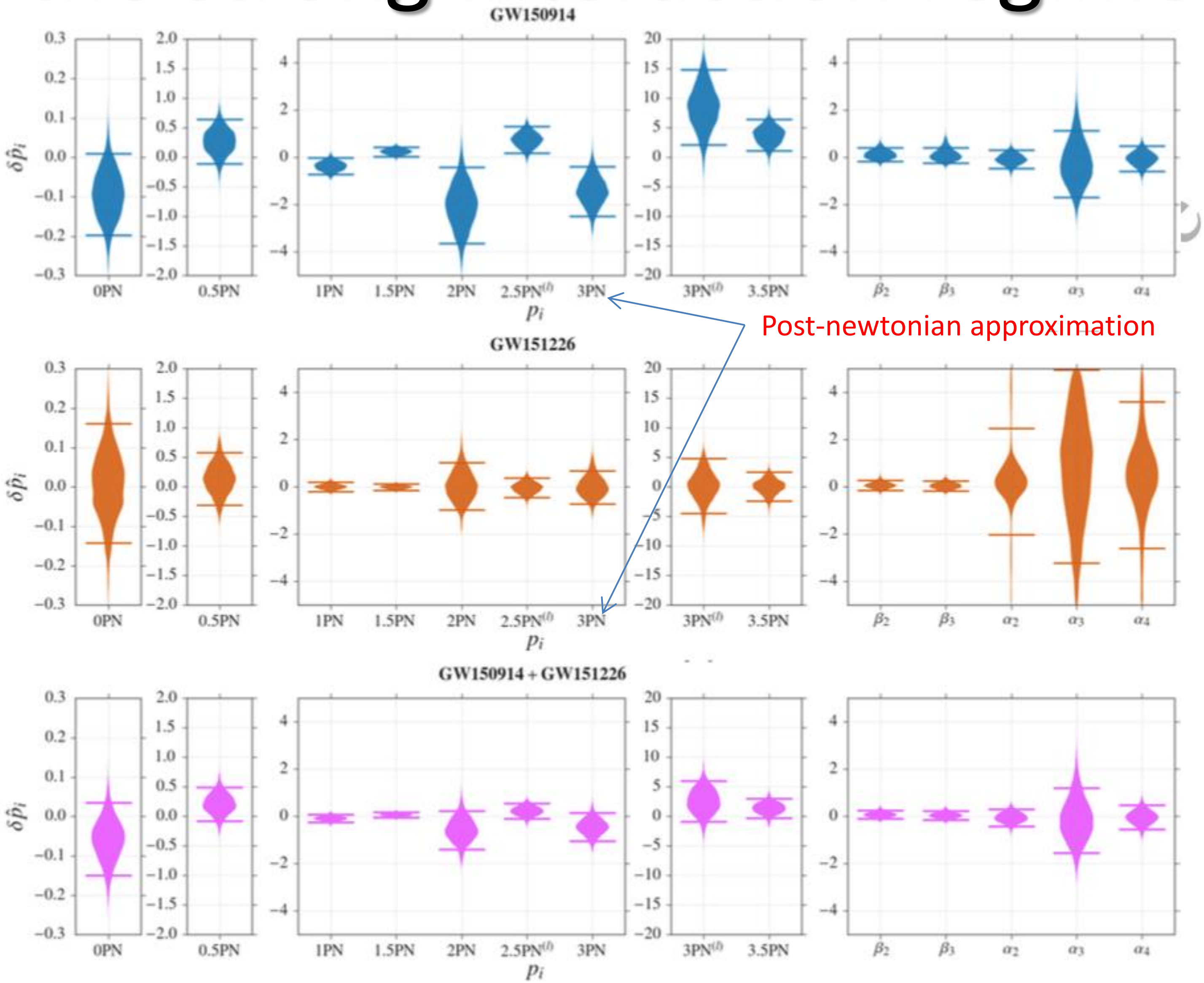
Second GW event - GW151226



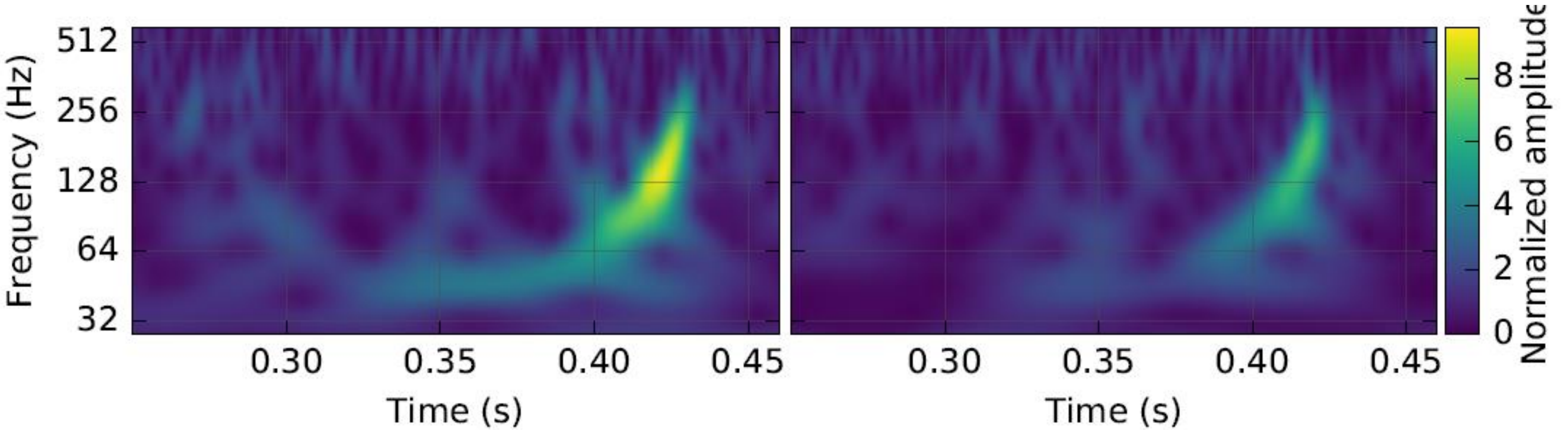
Comparison of the three signals in the time domain



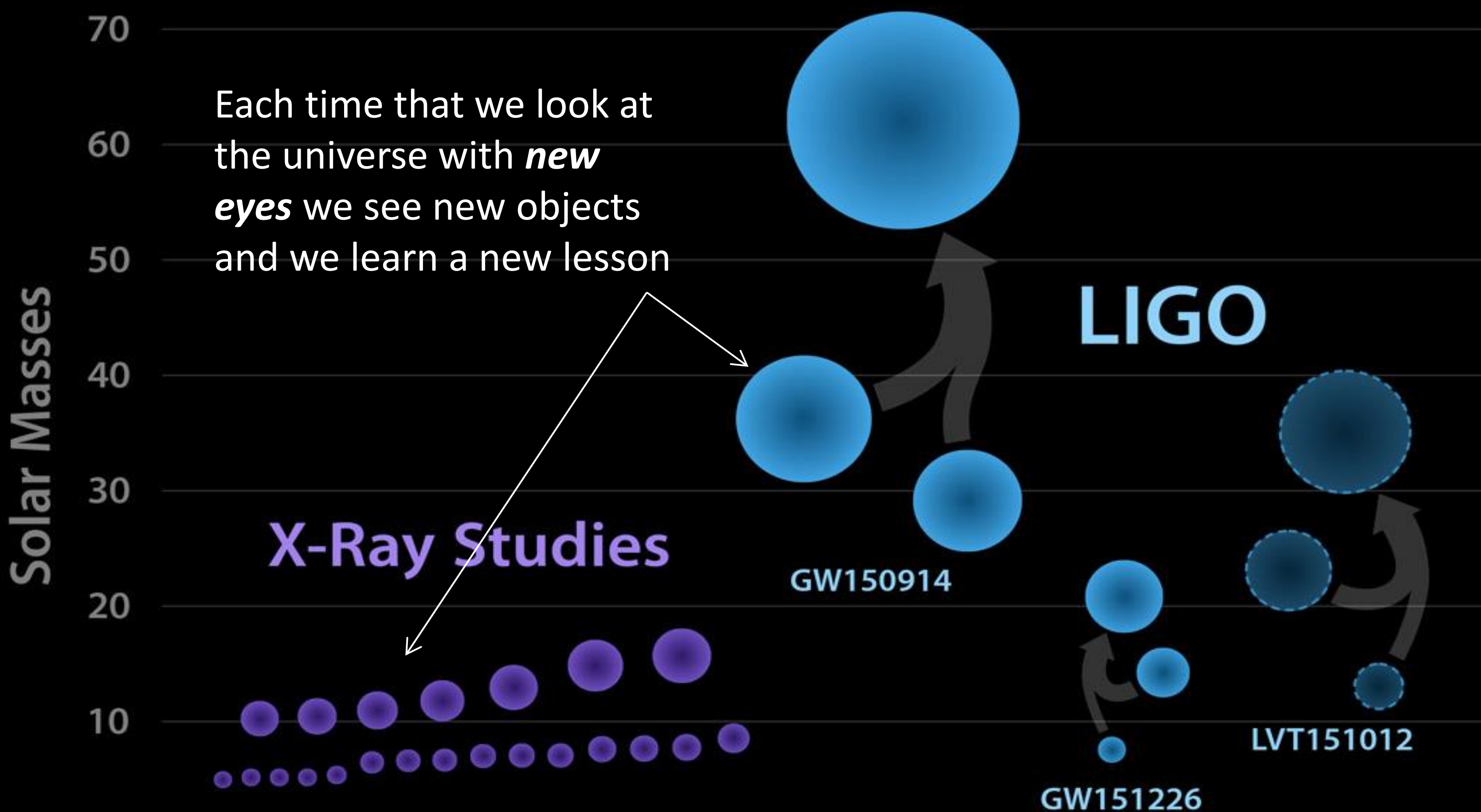
General Relativity tests in the strong interaction regime



The first sound of GW



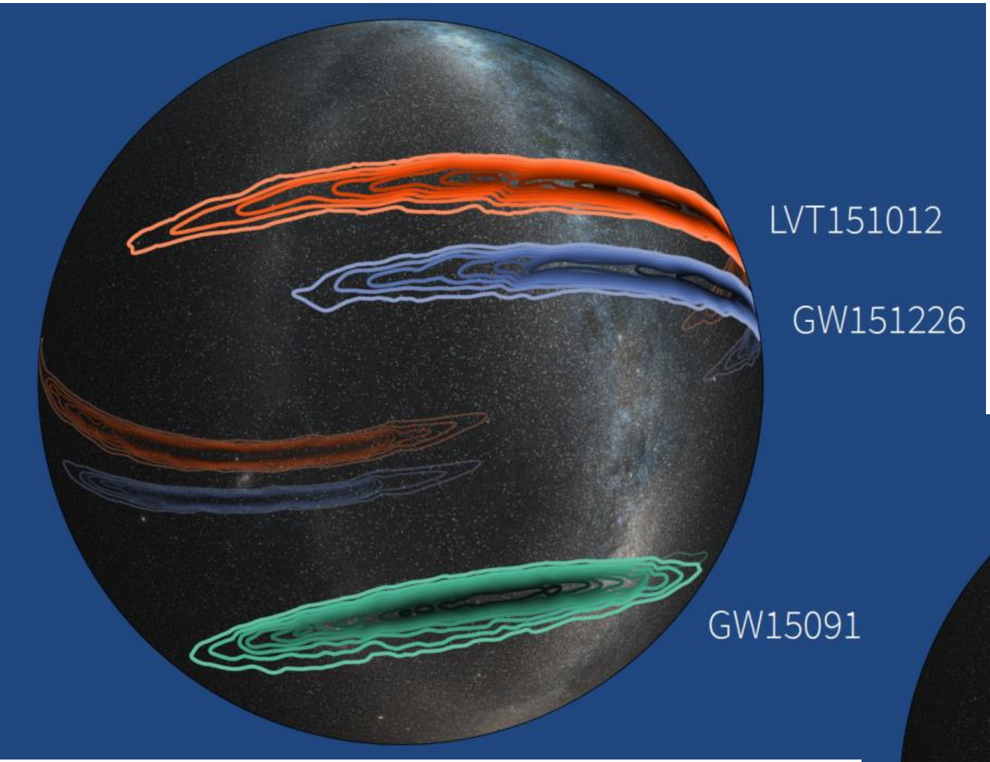
Black Holes of Known Mass



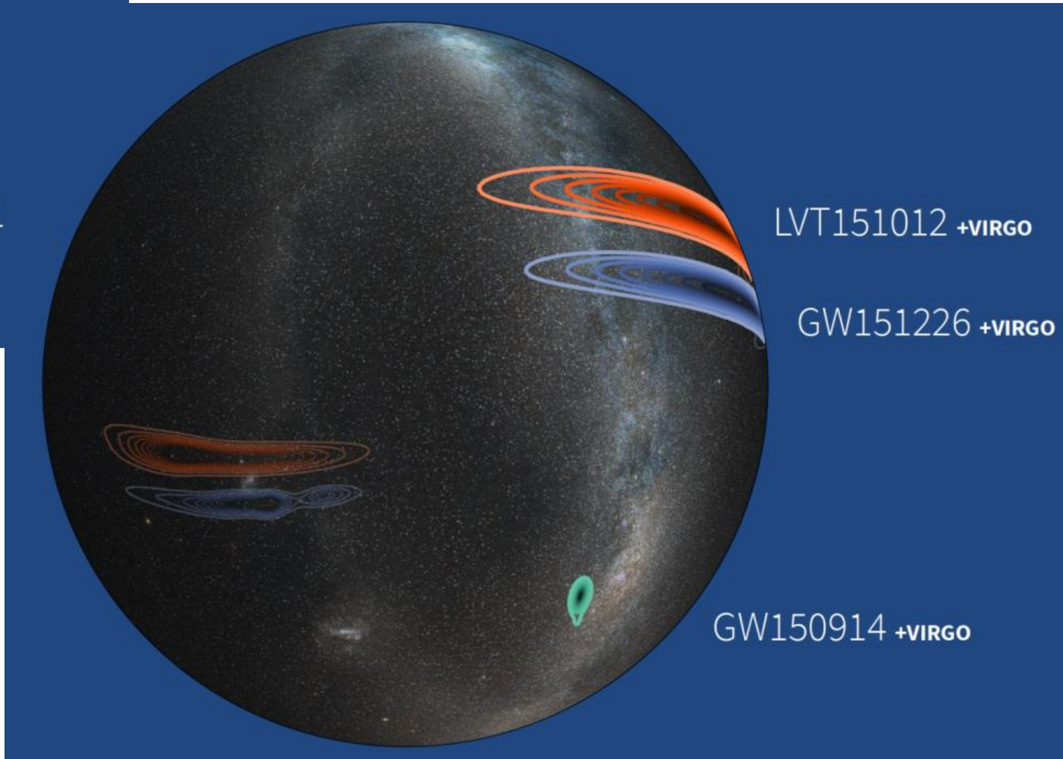
GW Network

Sky Locations of O1 Events without and with Virgo

Without Virgo



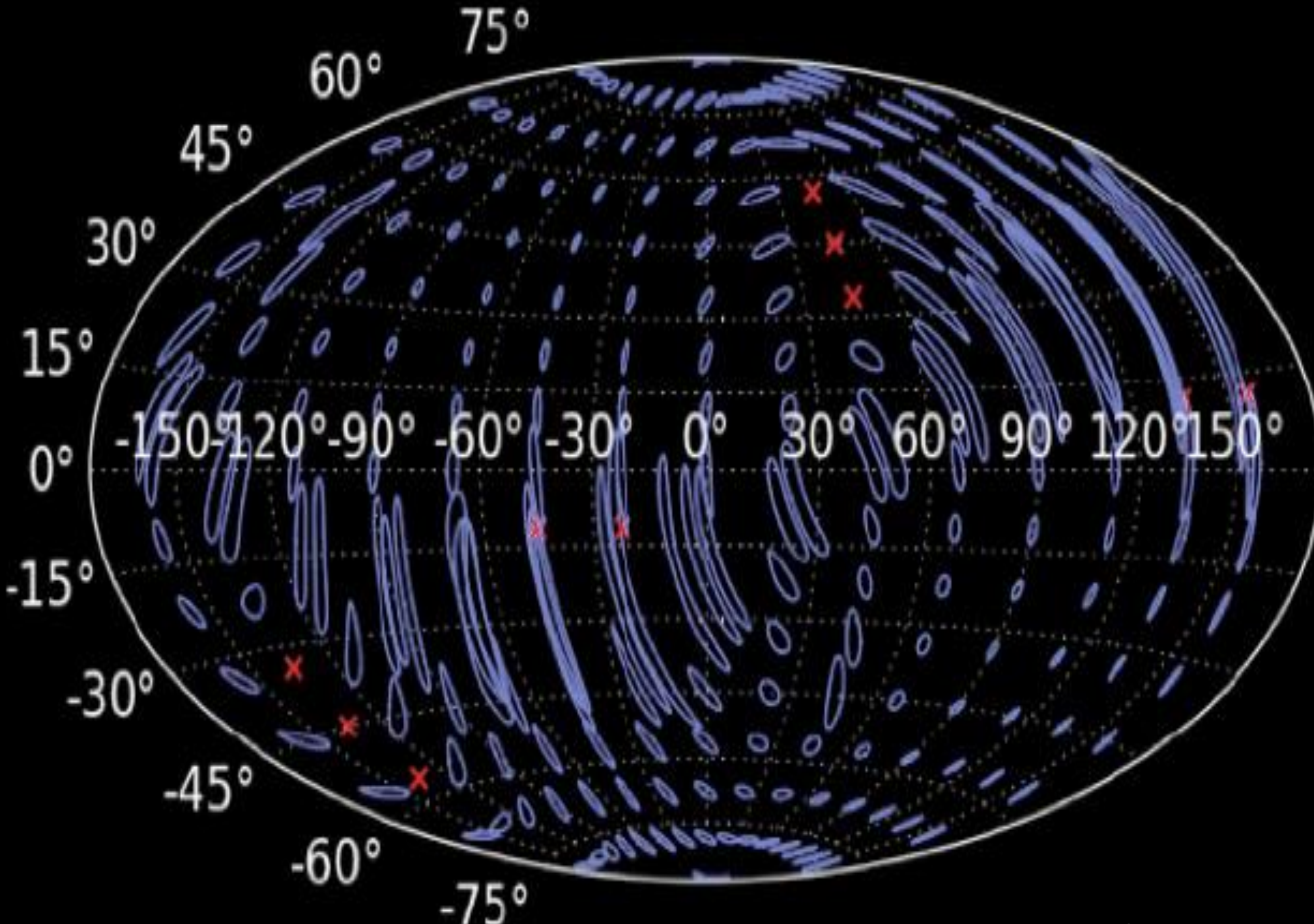
With Virgo



Sky location improvement

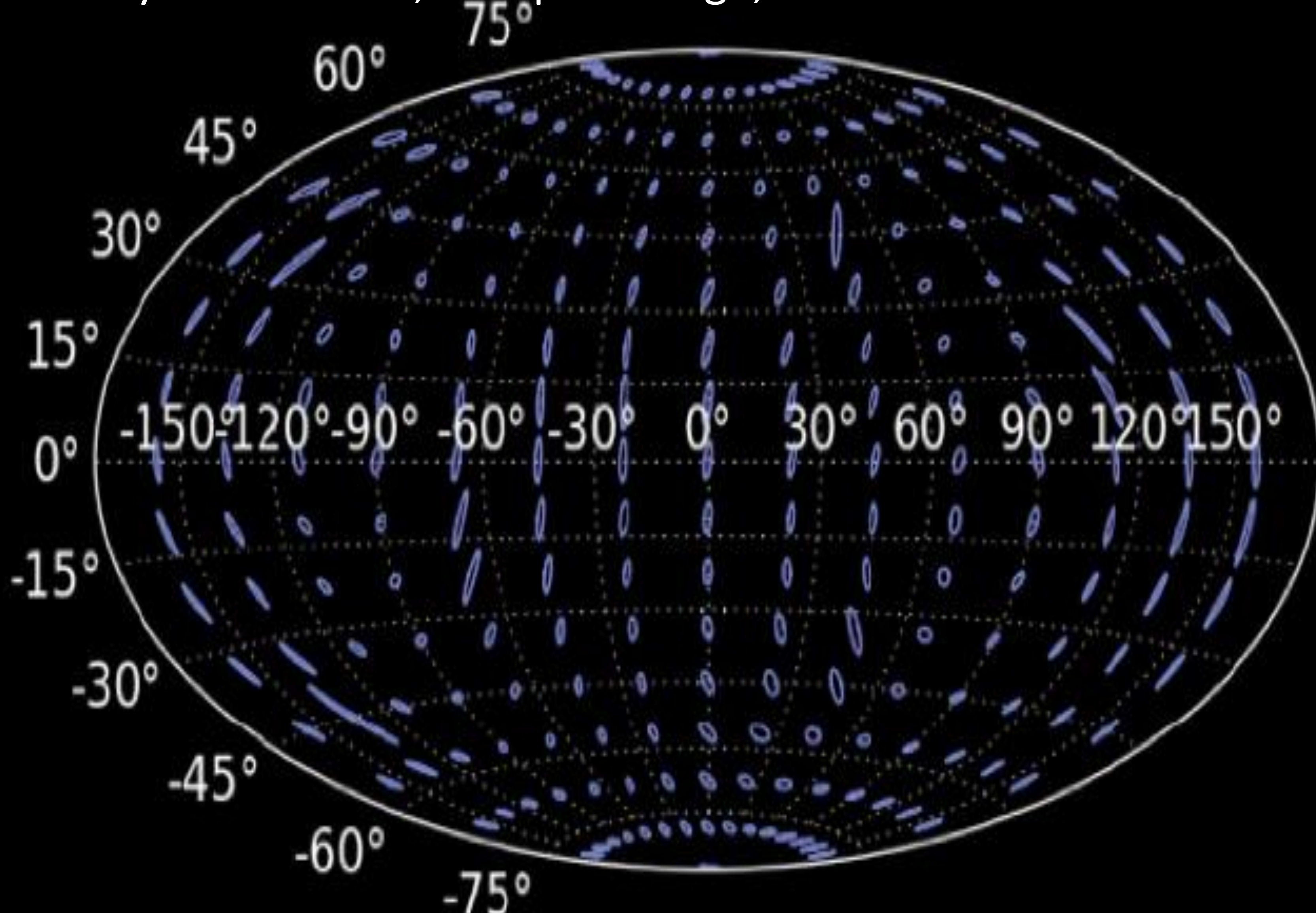
2 IFO →~400 sq deg
3 IFO →~100 sp deg
4 IFO →~ 10 sq deg

Simulation of Localization of a Gravitational Wave Event by the US LIGO and European Virgo Detectors



x: signal not confidently detected

Simulation of Localization of a Gravitational Wave Event by the US LIGO, European Virgo, and LIGO-India Detectors



Extending the Network

- aLIGO started observations in fall 2015. Advanced Virgo will join in 2016
- a large number of **astroparticle/astronomy projects** is signing **MoU** for the electro-magnetic follow up of GW candidate events

	eROSITA	Gamma/eROSITA			sci	
4	GW LSC group	George Washington University LSC group	Alessandra	Corsi	PI	
5	INAF	Project of Istituto Nazionale di Astrofisica	Giampaolo	Vettolani	Sci	
6	ARI LJMU	Astrophysics Research Institute, Liverpool John Moores University	Iain	Steele	Liv Tel Dir	
7	H.E.S.S.	H.E.S.S. collaboration	Christian	Stegmann	Sp	
8	Berger Time-Domain Research Group at Harvard	Berger Time-Domain Research Group at Harvard	Edo	Berger	PI	
9	Fermi	Fermi Gamma-ray Space Telescope	Julie	McEnery?	Pro	
10	USO/LVC Follow-Up	UBC Southern Observatory Follow-Up of Gravitational-Wave Candidates	Jeremy	Heyl	Tea	
11	AAO GW	Australian Astronomical	Warrick	Couch	Director	direc

LSC LIGO Scientific Collaboration VIRGO

news magazine Advanced LIGO science students/teachers/public multimedia partners about

Introduction Popular Articles LSC Scientific Publications Science Summaries Data Releases GW-EM Alerts

IDENTIFICATION AND FOLLOW UP OF ELECTROMAGNETIC COUNTERPARTS OF GRAVITATIONAL WAVE CANDIDATE EVENTS

The LIGO Scientific Collaboration (LSC) and the Virgo Collaboration currently plan to start taking data in 2015, and we expect the sensitivity of the network to improve over time. Gravitational-wave transient candidates will be identified promptly upon acquisition of the data; we aim for distributing information with an initial latency of a few tens of minutes initially, possibly improving later. The LSC and the Virgo Collaboration (LVC) wish to enable multi-messenger observations of astrophysical events by GW detectors along with a wide range of telescopes and instruments of mainstream astronomy.

In 2012, the LVC approved a statement (LSC, Virgo) that broadly outlines LVC policy on releasing GW triggers (partially-validated event candidates). Initially, triggers will be shared promptly only with astronomy partners who have signed an Memorandum of Understanding (MoU) with LVC involving an agreement on deliverables, publication policies, confidentiality, and reporting. After four GW events have been published, further event candidates with high confidence will be shared immediately with the entire astronomy community (and the public), while lower-significance candidates will continue to be shared promptly only with partners who have signed a MoU.

Through June to October 2013, we organized rounds of consultations with groups of astronomers that have expressed interest in the GW-EM follow-up program. Thanks to these consultations, we could define the framework and guiding rules for this program that are collected into a standard MoU template.

Devour thy Neighbor: An artist's illustration of two neutron stars close to merger look misshapen, becoming more oblong the closer they get to one another. A black hole is then formed and gamma rays shoot out as a GRB. (Credit: NASA/Swift)

OPEN CALL FOR PARTICIPATION TO GW-EM FOLLOW-UP PROGRAM, DUE FEB 16 2014.

On Dec 16 2013, we issued a call for proposals to sign standard MoU with the LVC. This call is open to all professional astronomers with demonstrated experience, and require that a partner bring some useful observing resource(s), not just astronomy expertise, to participate. GW triggers will be sent to groups that are in position to make observations in the course of next science runs circa 2015-2017 (arXiv:1304.0670, LIGO-P1200087, VIR-0288A-12). Our intent is to accept and sign MoUs with all qualified applicants. We expect to issue this call yearly in spring.

If you are interested in signing this agreement with LSC and Virgo, please read this document that provides important details of the GW-EM follow-up program, fill the application form in LIGO-F1300021, and email it to emf@ligo.org. **Also**, please fill the information fields below (including the filename of the file you emailed to us) and submit it before Feb 16, 2014.

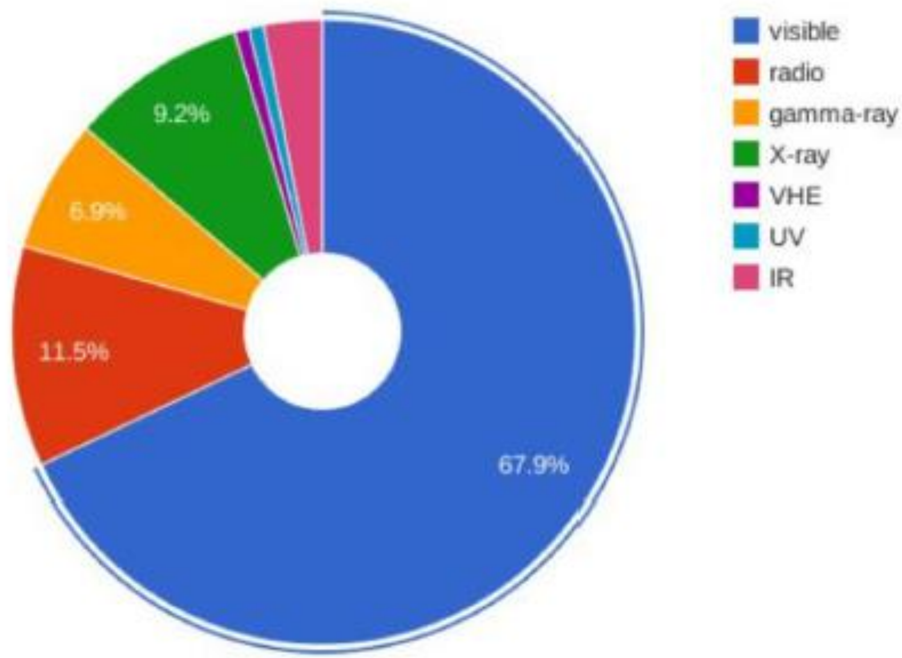
Extending the Network

LVC/partner astronomers MoU STATUS

66 applications

↓

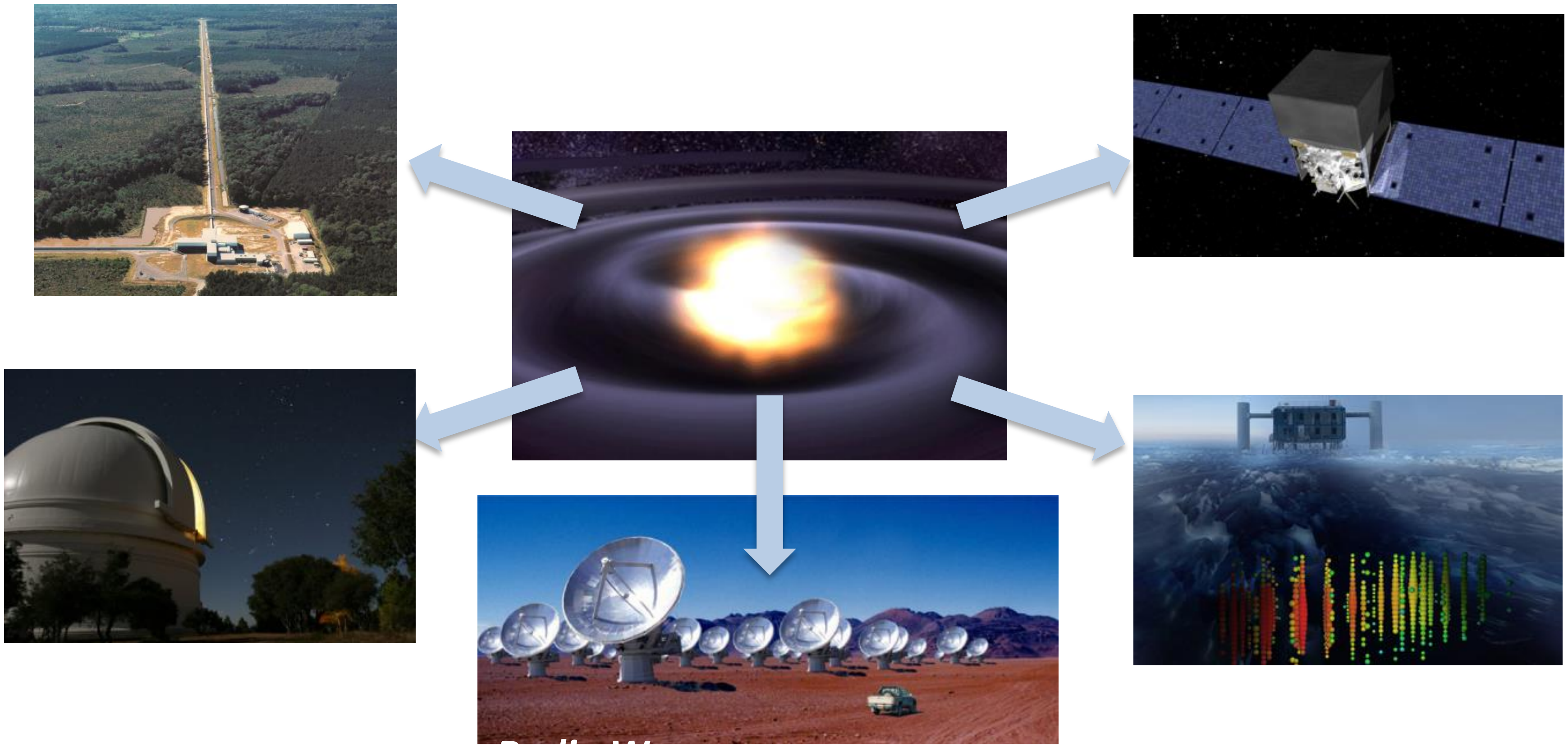
63 eligible to sign an MoU



60 % MoUs already signed!

Credit: M Branchesi

Multi-Messenger Astronomy: Gravitational Wave + Electromagnetic +Neutrinos



Conclusion

AdVirgo Status

- AdVirgo construction: 2011-2016
- Commissioning of full interferometer starts in 2016
- First observation run in 2016 with an **intermediate configuration** in order to reach AdLigo for O2 (begin of 2017)
  - No signal recycling (reduce locking complexity)
  - Use Virgo+ laser up to 60W (low power (reduce risks with thermal effects and high power laser)
  - Mirrors steel suspensions: to be improved with the monolithic suspension as soon as possible
- 2016-2021: commissioning and observations runs → progressing towards nominal sensitivity

GW events

- During the first observing run, we have observed **gravitational waves** from the coalescence of two stellar-mass BBHs:
  - GW150914
  - GW151226

  and the third candidate
  - LVT151012 also likely to be a BBH system

Next future: networks

- We are confident that in the next future science runs will observe many more events, hopefully with EM-neutrinos conterpart: **multi-messanger astronomy**