Overview of Gravitational Wave Observations by LIGO and Virgo

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LIGO Scientific Collaboration and Virgo Collaboration

Vulcano Workshop 2016, May 23

Published Discoveries

- Detection of a propagating Gravitational Wave
- Direct observation of a stellar-mass Black Hole binary → merger
- The most luminous astrophysical event detected

plus

- ***test of General Relativity in strong field & highly relativistic regime***
- …

The Dawn of novel Explorations

- **Astronomy & Astrophysics with LIGO-Virgo**

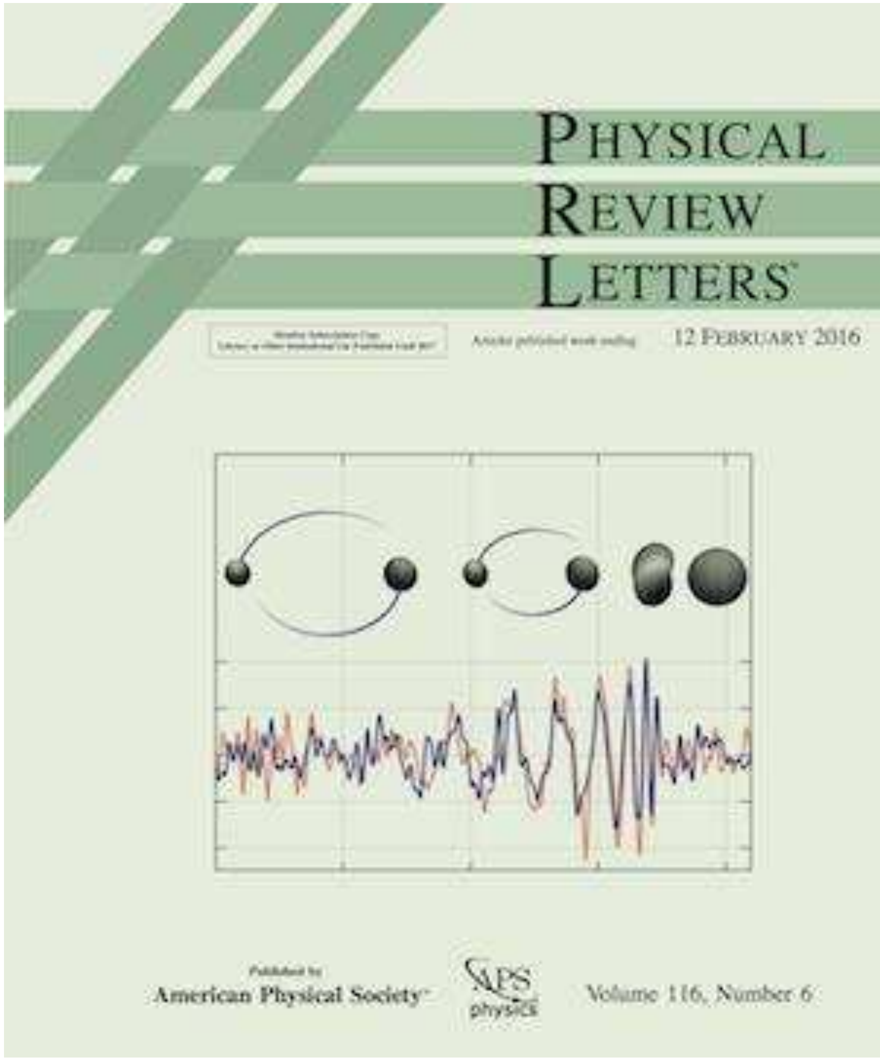
  → *talks by E.Coccia, M.Branchesi, M.Boer on Friday*
- **Fundamental Physics**

  → *talk by S.Capozziello this morning*

LIGO-Virgo Collaborations opened a new perception of space-time

Outline

- **first Observation Run by the Advanced LIGO detectors**
- **GW150914:**
  - ✓ ***detection***
  - ✓ ***interpretation***
  - ✓ ***tests of general relativity***
- **extending the network of GW detectors**
  - ○ **Advanced Virgo**
  - ○ **next GW surveys**
- **outlook**



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Gravitational Waves far away from sources

☐ gravitational waves carry curvature, energy, momentum, angular momentum

☐ weak-field linear approximation

- analogies with electromagnetic waves:

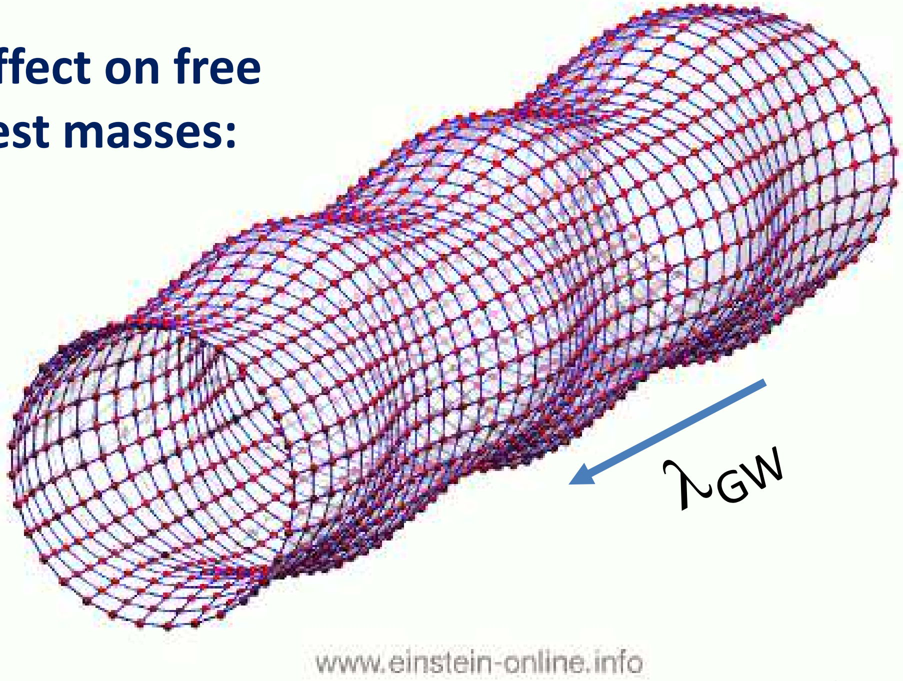
  light speed, transverse, 2 polarization components

- peculiarities of GWs:

  tidal deformations of extended bodies, no measurable local effect

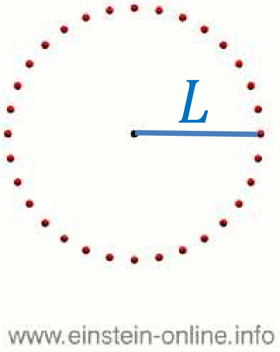
  polarization components rotated by $\frac{\pi}{4}$ *in the wavefront:* $h_+ \quad h_\times$

Effect on free test masses:



in wavefront plane:

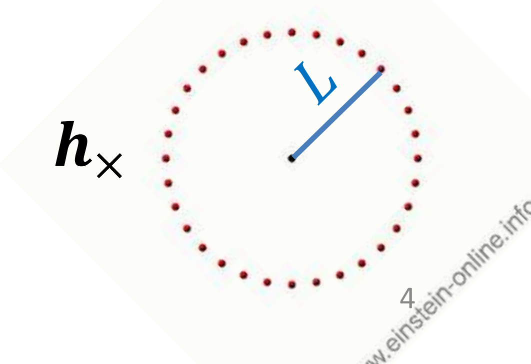
$\boldsymbol{h}_+$



GW amplitude is strain:

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

$\boldsymbol{h}_\times$



directional sensitivity of detectors

Each interferometer senses one of the two polarizations of GWs

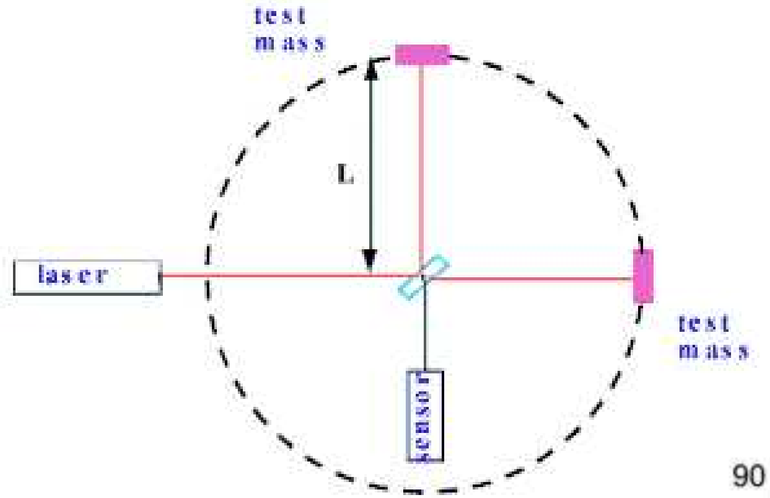
- measures one linear combination:

$$h = F_+ h_+ + F_\times h_\times$$

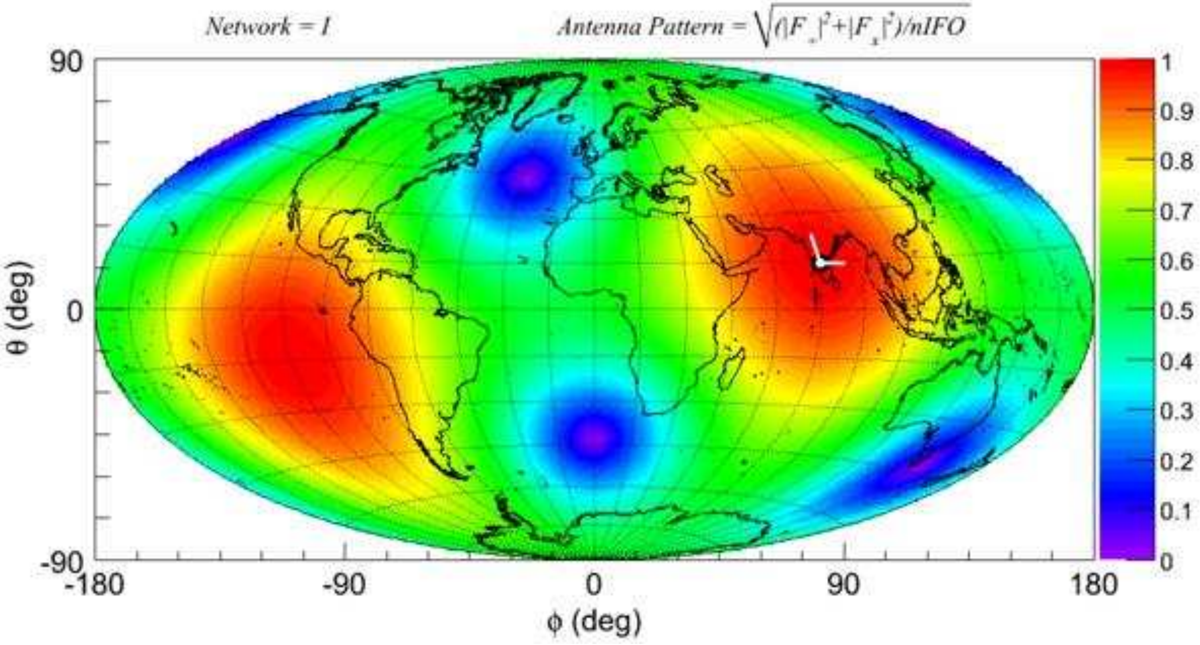
$$F_{+,\times}(\text{sky direction})$$

antenna patterns for + and x

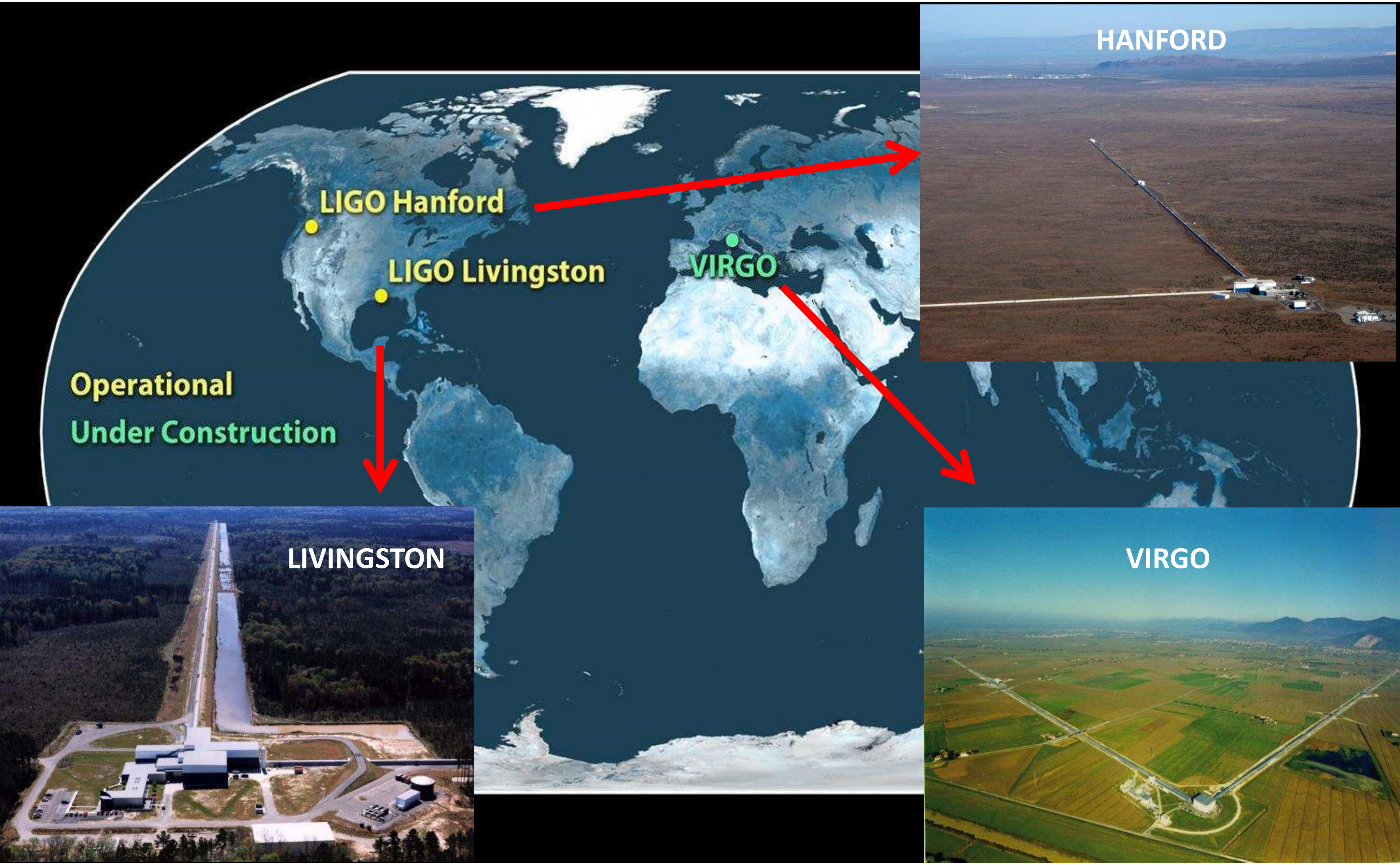
- misses the orthogonal combination of GW polarizations.



directional sensitivity to the optimal polarization component is broad:



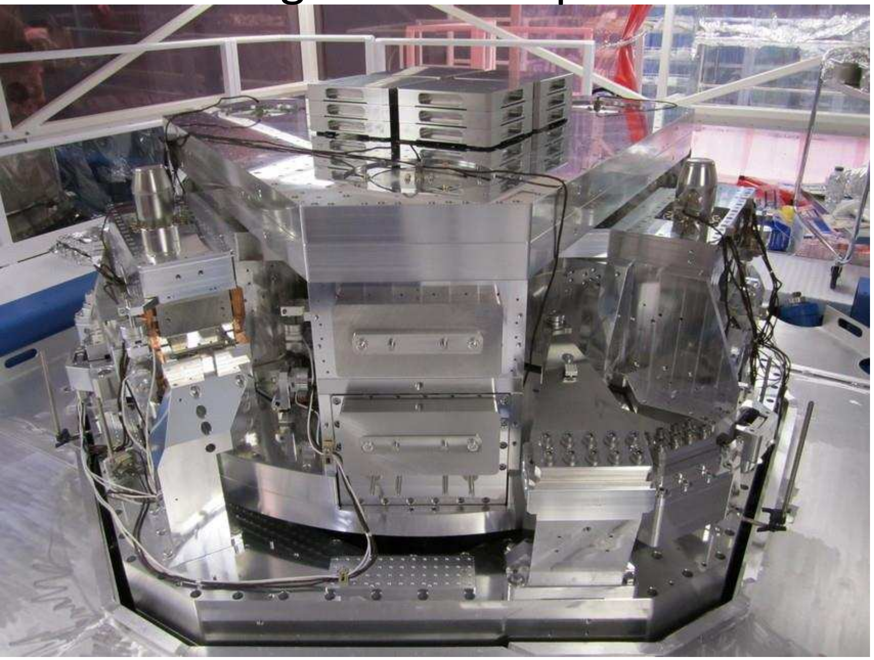
The LIGOs and Virgo long-arm detectors



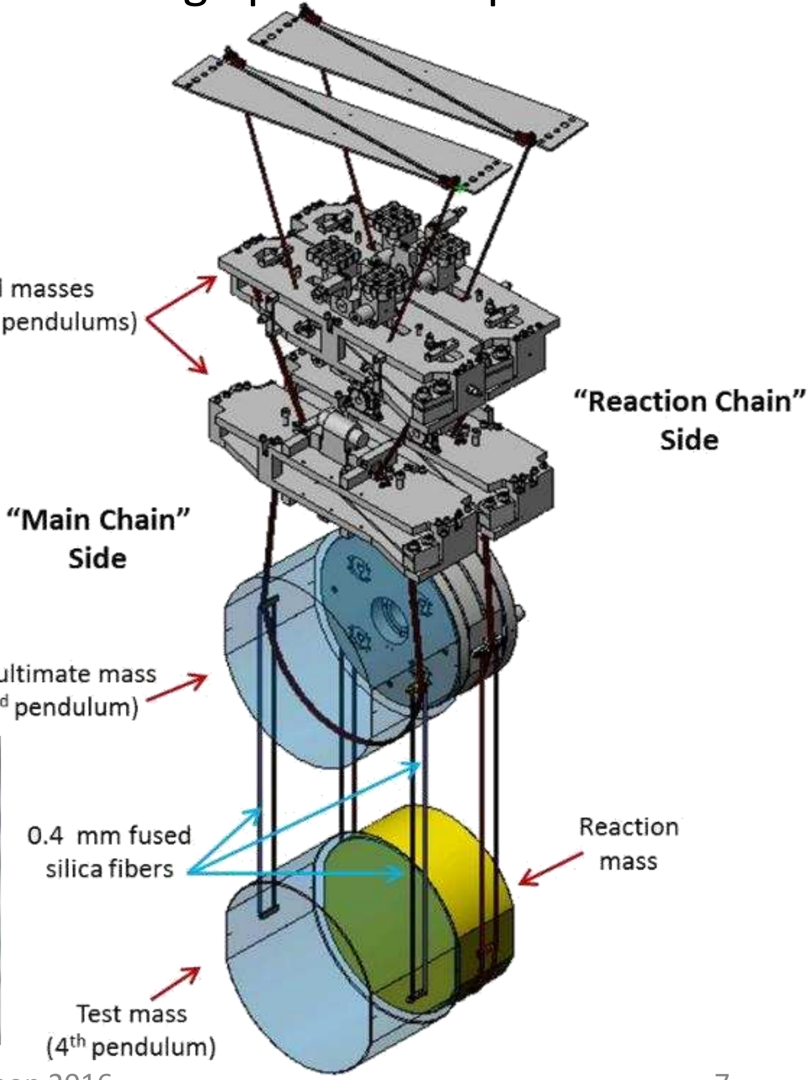
Advanced LIGO upgrades: suspensions

seismic noise reduction (>10^{10} above 10 Hz)

first stage active suspension

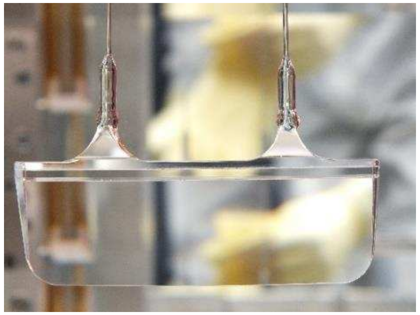


last stage passive suspension



Monolitic suspension

thermal noise reduction

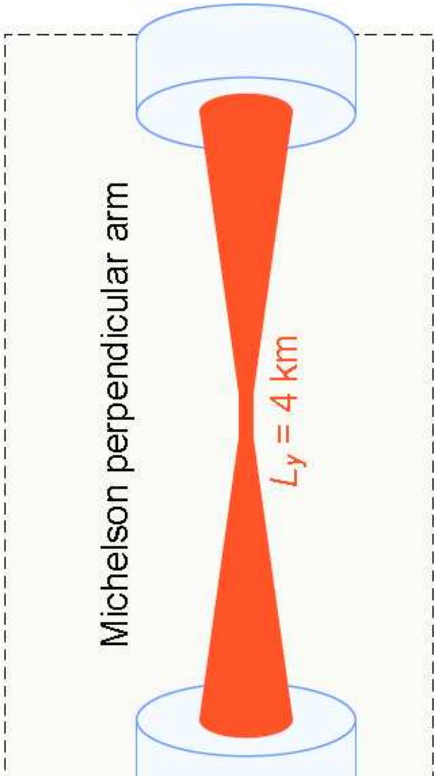


Advanced LIGO upgrades

Photon shot noise reduction

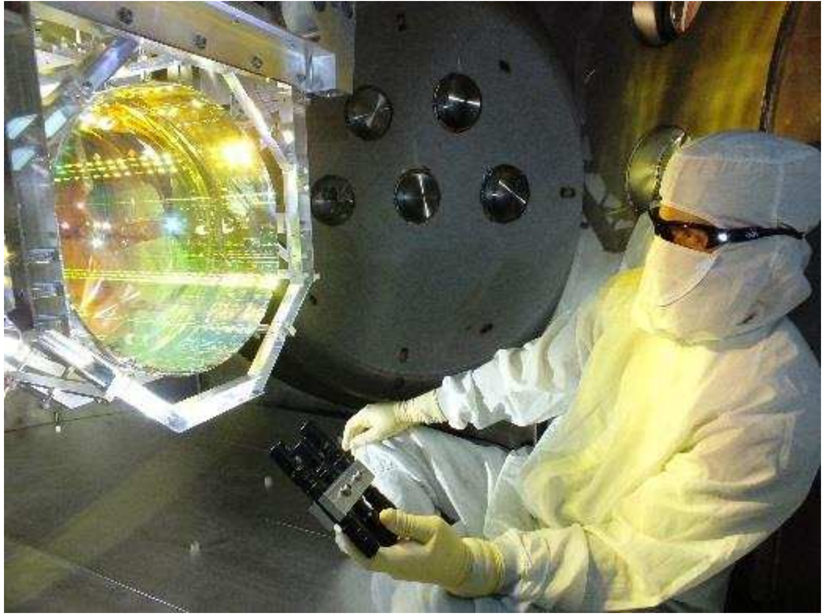
- 4 km optical resonators, optical gain 300
- 100 kW circulating laser power (design target is 750 kW)

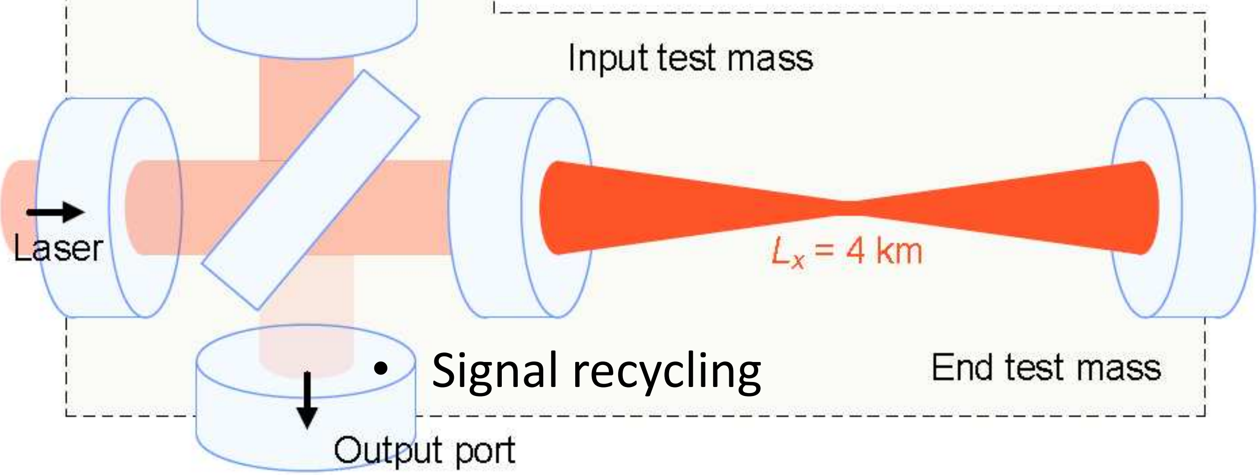
- 20 W input laser (up to 180 W available), 1 Hz line-width



Thermal & radiation pressure noise reduction

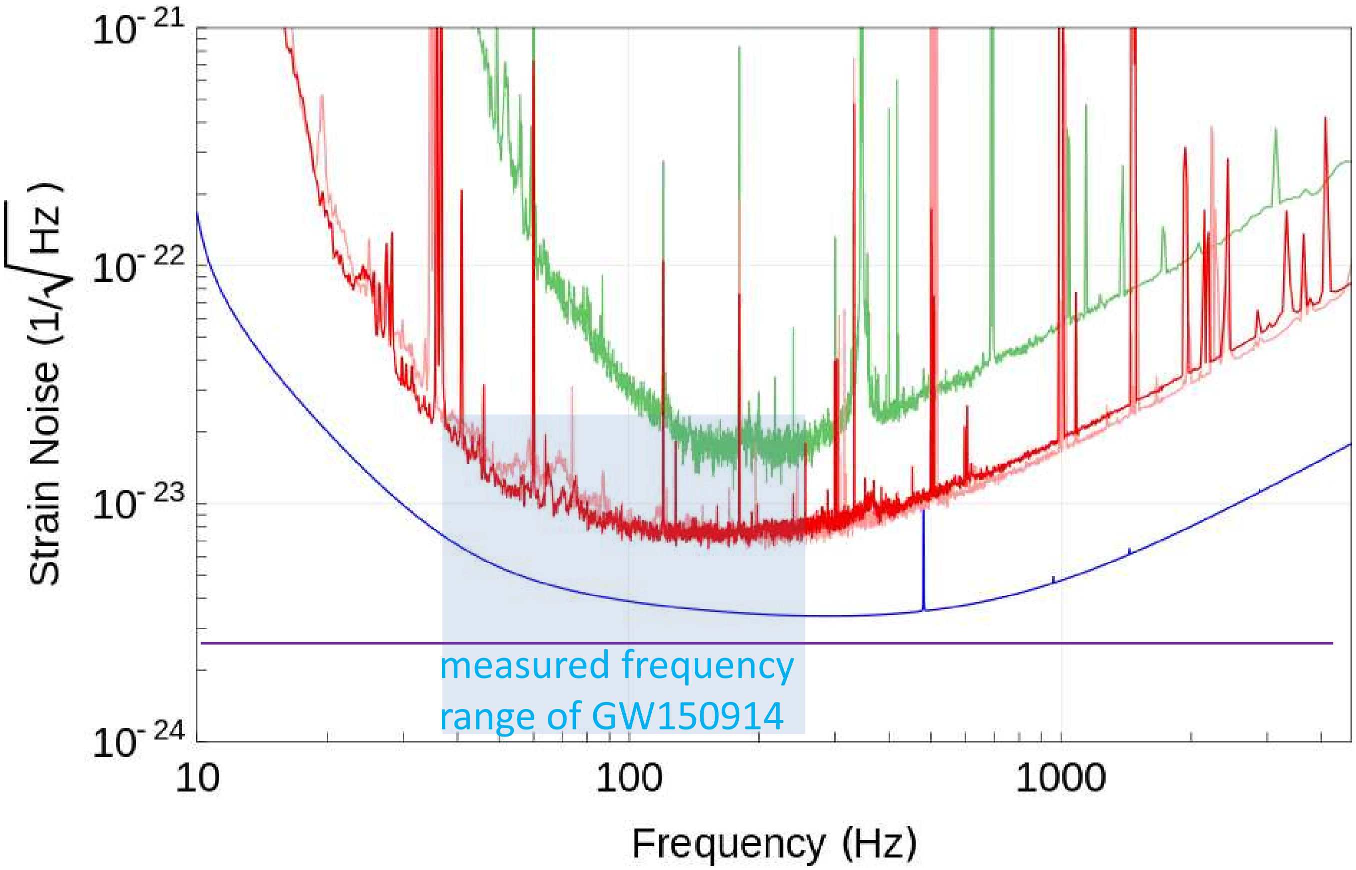
Larger mass mirrors, improved coatings





- Signal recycling

Spectral sensitivity of Advanced LIGO detectors



--LIGO S6 run (2010)

--Advanced LIGO O1 run (2015)

--Advanced LIGO design goal

-- $10^{-20} m/\sqrt{Hz}$ displacement noise (single arm)

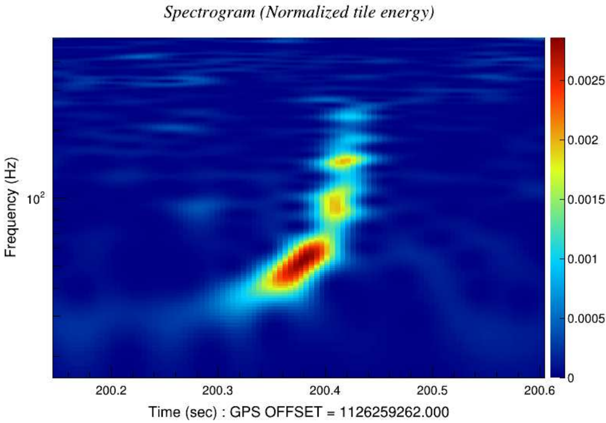
- ❑ observations 2015 vs 2010:

averaged observable volume of Universe : **~100x** gain for **BBH** like GW150914
~30x gain for **BNS** coalescence events

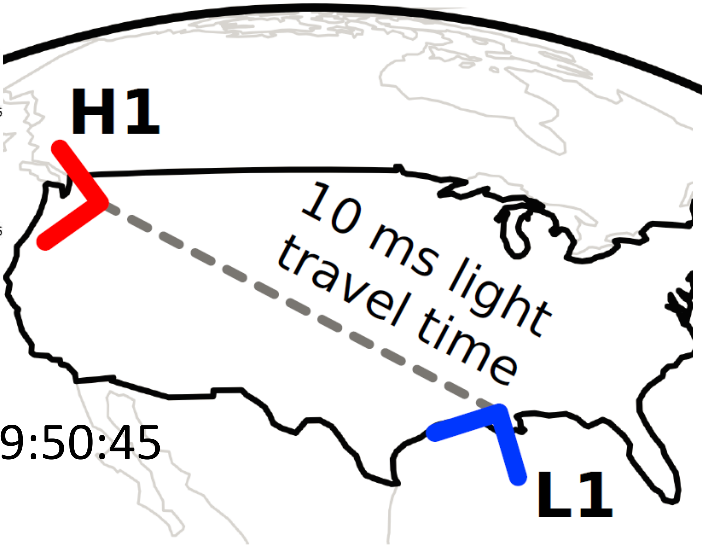
- ❑ **16day recent observation** exceed detection potential of all previous observations

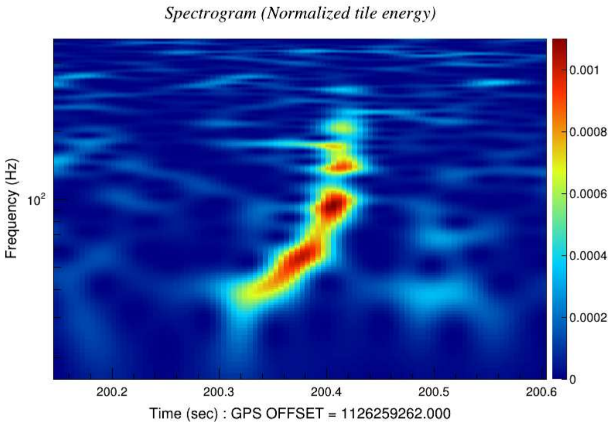
GW150914 chronology

- Last days of LIGO Engineering Run before planned Science Run



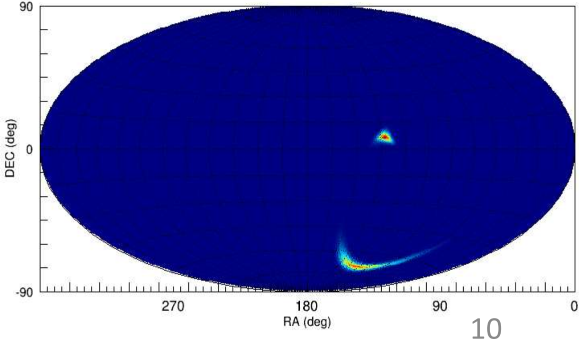
Delay time 7 ms





- Sept. 14, 2015 UTC: 09:50:45
- \+ 3 minutes:
  rapid alert from our low latency detection pipeline (coherent Wave Burst: Florida, Hannover, Padova-Trento)
- \+ 17 minutes:
  first sky map (cWB), 600 deg^2 @ 90% c.l.
- \+ 4 hours / next days:
  confirmations by other data analysis pipelines

sky localization map



GW150914 observation run

- ☐ **prompt switch from Engineering Run to Science Mode Operation**
  priority to stable operation of LIGO detectors
  start of cross checks: *detection check-list*

- ☐ next calendar day:
  alert sent via GCN circular to 62 partner astronomers (including INAF)
  target latency in science mode would have been < 1 hour

- ☐ week timescale:
  started **internal LIGO-Virgo procedure for validation of GW detection**
  end to end detection validation was previously tested in 2010 (blind injection challenge)

- ☐ decision to **continue observing in stable detector configuration** until **LIGO detectors integrate at least 15 days of joint observation time**

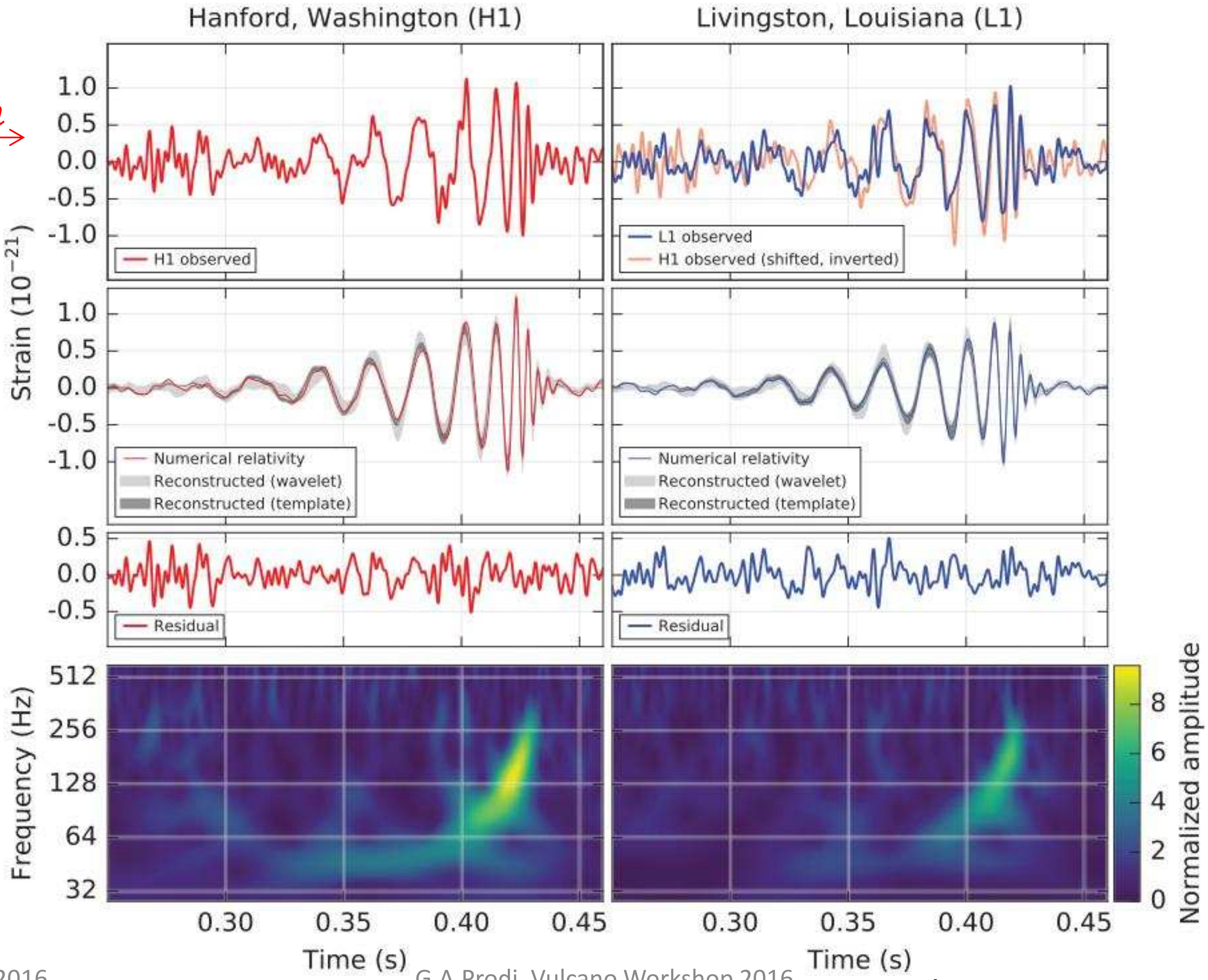
Sept. 12th – Oct. 20th

Resulting joint observation time 17 days

Duty cycle: H1 70%, L1 55%, joint time 50%

GW150914

$10^{-18}\,m \longrightarrow$



Phys. Rev. Lett. **116**, 061102

GW150914 confidence level

- ☐ **ruled out environmental influences and non-Gaussian instrument noise** at either LIGO detector for GW150914 [*arXiv: 1602.03844,* CQG *in press*]

- ☐ **two independent data analysis methods** used to estimate the confidence:

- ✓ **Search for GW transients of general waveforms**,
  coherent responses in distant detectors using minimal assumptions,
  the more general discovery tools

- ✓ **Search for GW transients from compact binary coalescences**
  matched filtering methods

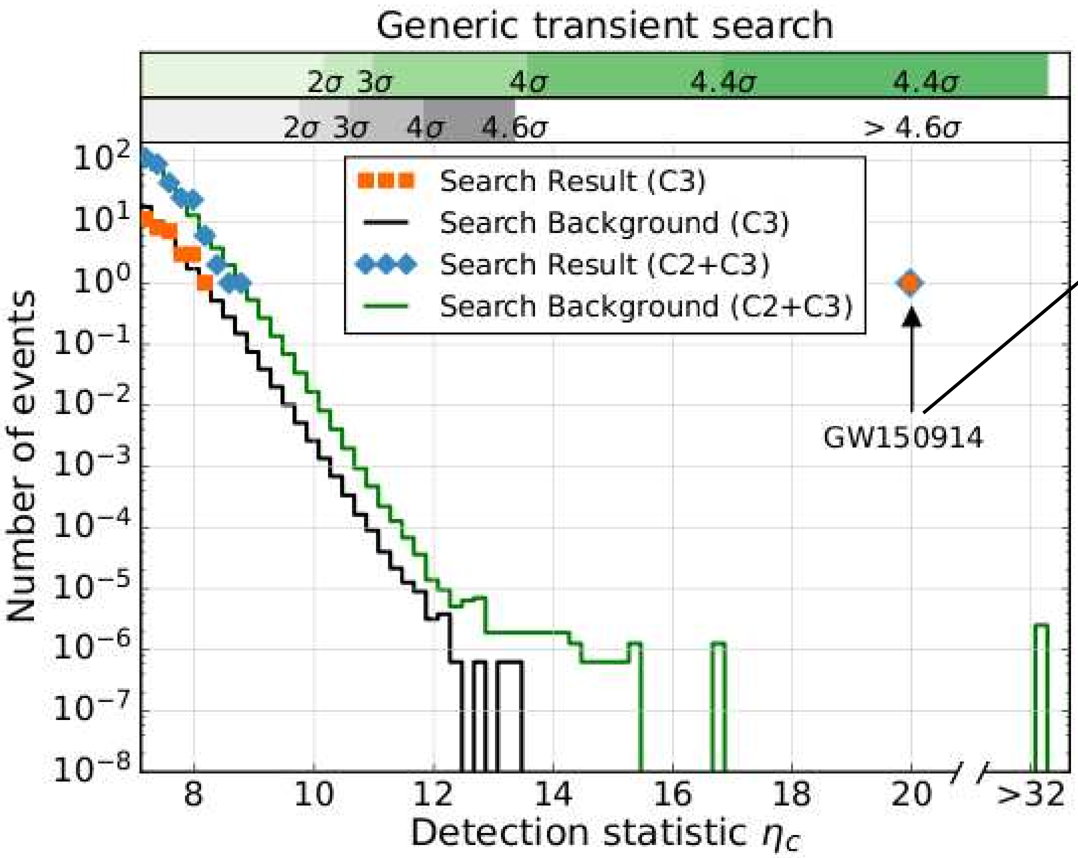
Estimated **False Alarm Rate** of GW150914:

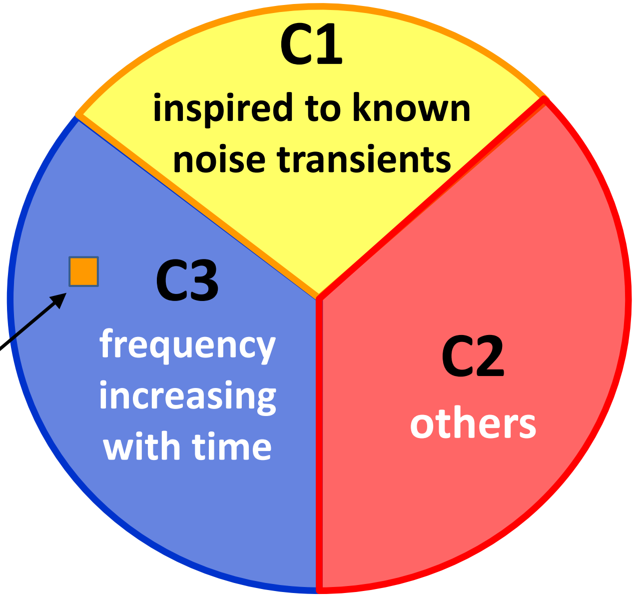
- **< 1 / 22500 years** in wider context of generic transient signals
- **< 1 / 203000 years** within compact binary coalescence signals

GW150914 confidence, general transient signals

Coherent WaveBurst pipeline has been the reference for generic transients:

- **Search parameter space divided into 3 classes** of different signal morphologies
- **GW150914** is the strongest event of the search
- **67400 years** of equivalent off-source data





C1

inspired to known noise transients

C3

frequency increasing with time

C2

others

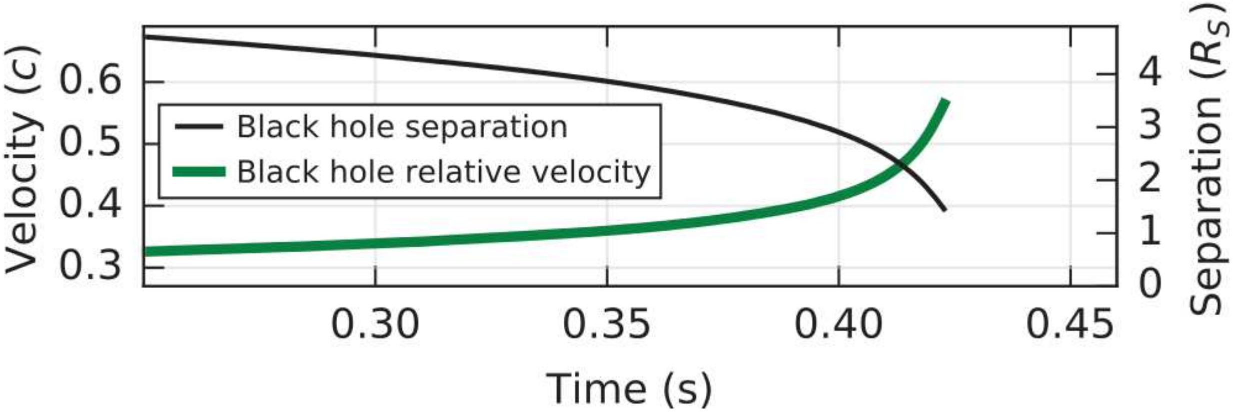
trial factor =3

transient noise events as strong as or stronger than GW150914 have

- **rate < 1 in 22500 years**
- **false alarm probability < $2 \cdot 10^{-6}$** during the analyzed time

GW150914: inspiral

- time-frequency evolution is typical of the inspiral-merger-ringdown of a compact binary coalescence
- f and $\dot{f}$ in inspiral cycles measure the chirp mass $M_{chirp} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} \approx 30\ M_\odot$ and $M = m_1 + m_2 \gtrsim 70\ M_\odot$



$$R_S = \frac{2GM}{c^2} \cong 210\ km$$

Lower limit to the sum of Schwarzschild radii of progenitors

Newtonian approximations for:

- **orbital separation** $R \approx \left(\frac{GM}{4\pi^2 f^2}\right)^{1/3} \approx 350 km$ at end of inspiral (orbital frequency ≈75 *Hz*)
- **orbital speed** up to 0.5 *c*

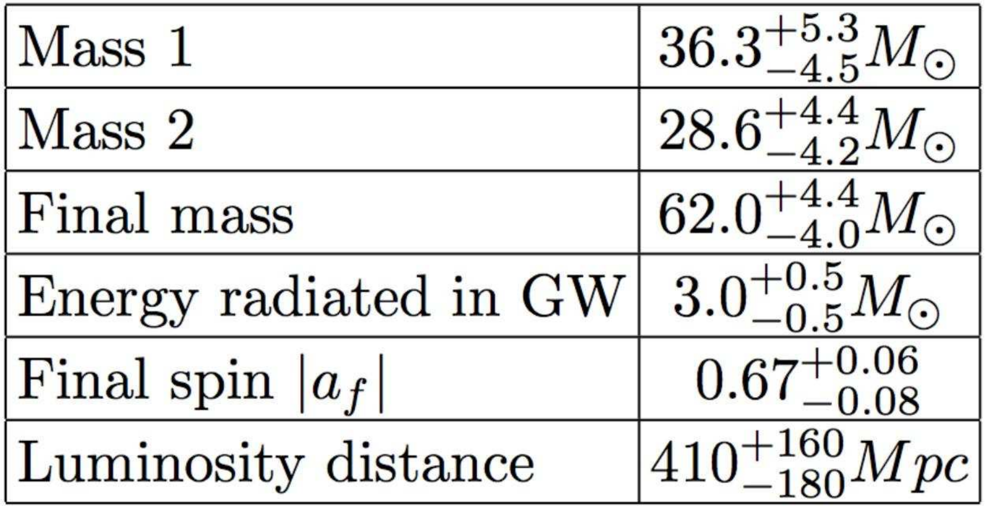
Black Holes progenitors are the only known compact objects that can orbit up to frequency ≈ *75Hz* before collision

Phys. Rev. Lett. **116**, 061102

GW150914 parameters [arXiv:1602.03840]

- **Parameter Estimation** is achieved by Bayesian model selection over a template bank of analytical waveforms calibrated against numerical relativity simulations of the merger

Monte Carlo methods on 17 Parameters: 2 masses, 2x3 spin, distance, 2 sky coordinates, 4 orbital parameters, time and phase of coalescence.



Mass 1	$36.3^{+5.3}_{-4.5} M_\odot$
Mass 2	$28.6^{+4.4}_{-4.2} M_\odot$
Final mass	$62.0^{+4.4}_{-4.0} M_\odot$
Energy radiated in GW	$3.0^{+0.5}_{-0.5} M_\odot$
Final spin $\lvert a_f \rvert$	$0.67^{+0.06}_{-0.08}$
Luminosity distance	$410^{+160}_{-180} Mpc$

higher mass values than expected

$$\gtrsim 30 M_\odot$$

$3M_\odot$ unbalance:

very high GW luminosity

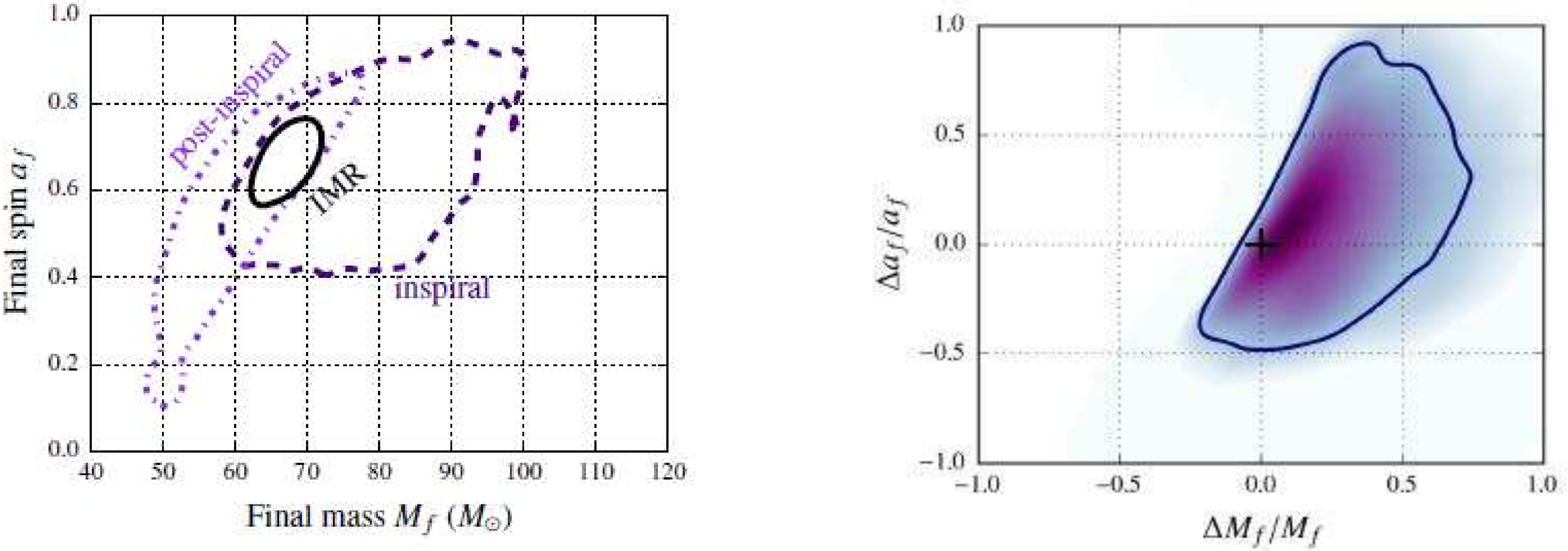
$$L_{peak} \approx 3.6 \cdot 10^{49} W$$

most energetic astrophysical event observed

high uncertainty: degeneracy between distance and inclination angle to the source, since the LIGOs are sensitive to only one polarization of the GW

Consistency with GR Black Hole solution [arXiv:1602.03841]

- ☐ Leftover residuals of GW150914 are not statistically distinguishable from instrumental noise
- ☐ Mass and spin of the remnant BH are predicted using separately inspiral phase and post inspiral phase. No evidence of inconsistency with the inspiral-merger-ringdown analysis.



- Test of GR consistency of the measured quasi normal mode observation (3-5ms after merger)

$$f_{220}^{QNM} = 251^{+8}_{-8}\,\mathrm{Hz} \qquad \tau_{220}^{QNM} = 4.0^{+0.3}_{-0.3}$$

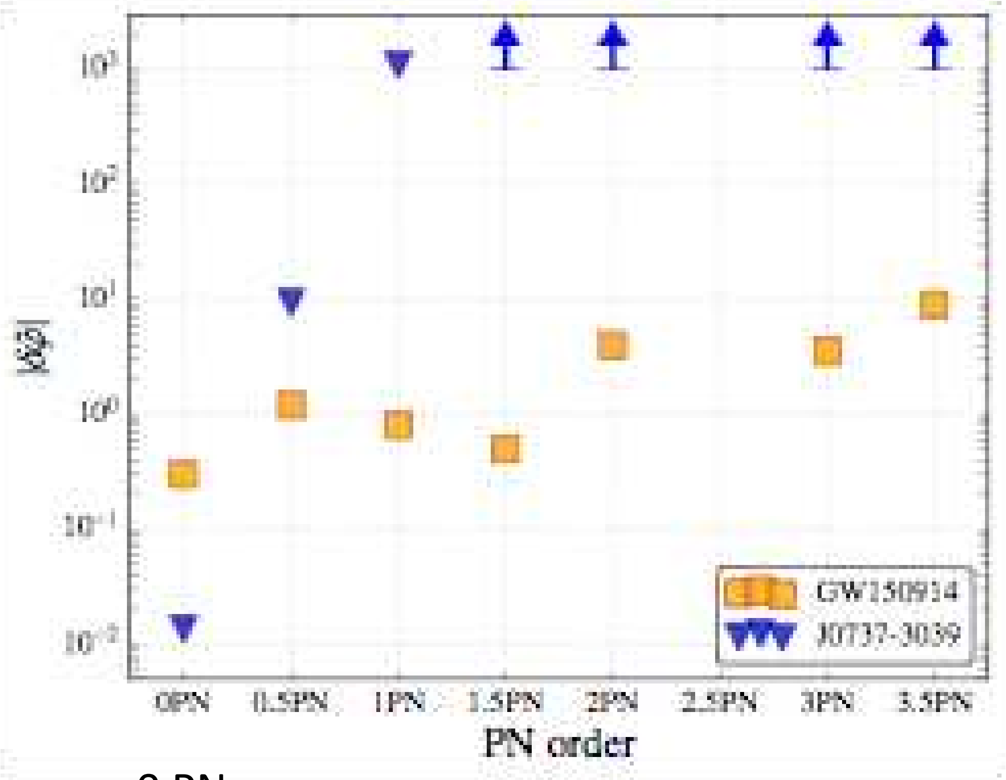
Testing GR beyond quadrupolar formula [arXiv:1602.03841]

First test of GR in strong field and highly relativistic speed
by checking the phase evolution of the inspiral signal of GW150914

90% upper limits on $|\delta\varphi|$

where $(1+\delta\varphi)$ describe the possible deviations from GR prediction per each Post Newtonian correction to the quadrupolar formula

New upper limits have been set for all PN orders up to 3.5 except for 2.5 PN, unmeasurable with inspiral signal (degenerate with inspiral phase evolution)



0 PN
Quadrupolar
formula

Astrophysical implications [arXiv:1602.03840]

☐ **Formation of single Black Hole by stellar evolution**

Previous to GW150914: X-Ray Binaries show candidate BH with mass peaked in $5 - 10\ M_{\odot}$ and none above $25\ M_{\odot}$

GW150914: both BHs are $\gtrsim 25\ M_{\odot}$

Favours weak stellar winds and low metallicity star progenitors

☐ **First binary Black Hole evidence**

☐ **Binary BHs are formed close** enough to merge within the Universe lifetime

mainly 2 possibilities for BBH formation *not discriminated by GW150914*

As evolution of isolated binary systems

Expected aligned spins with orbital angular momentum

As result of dynamical interaction in dense stellar environments

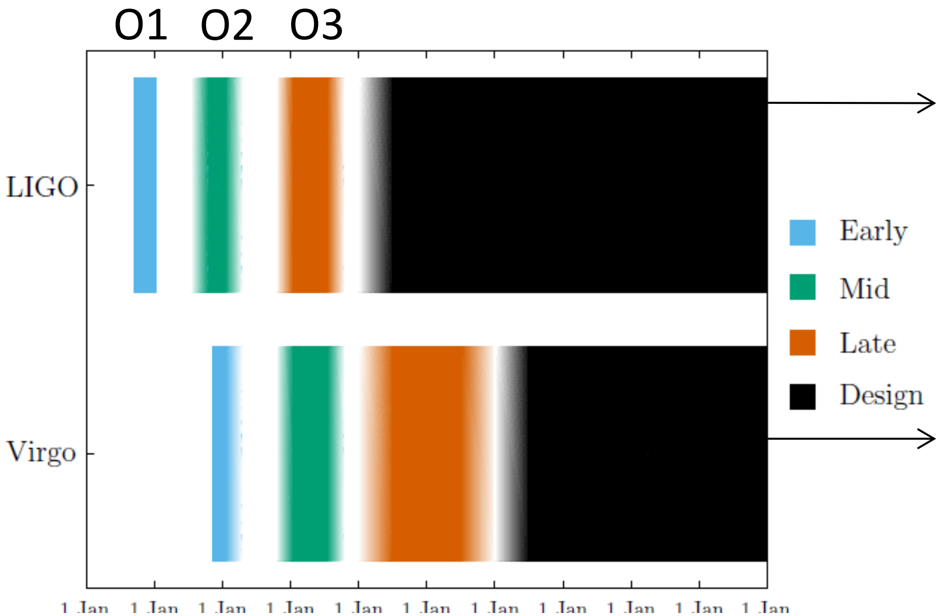
Expected non correlated spins of BH pairs: misalignment is likely

☐ **Rate of BBH mergers in local Universe**: $4 - 200\ GPc^{-3}y^{-1}$

Excludes the lowest rate models previously expected [arXiv:1602.03842]

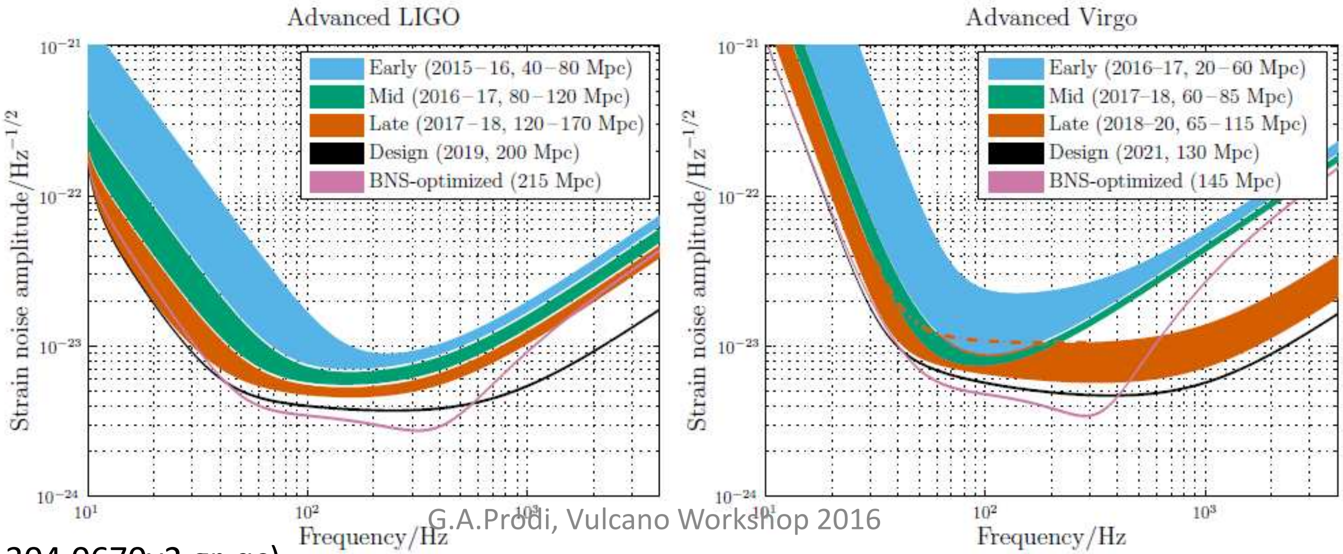
Mid term plans for LIGO-Virgo surveys

Performances upgraded in steps, interleaved by scientific observation runs:



Design sensitivity:

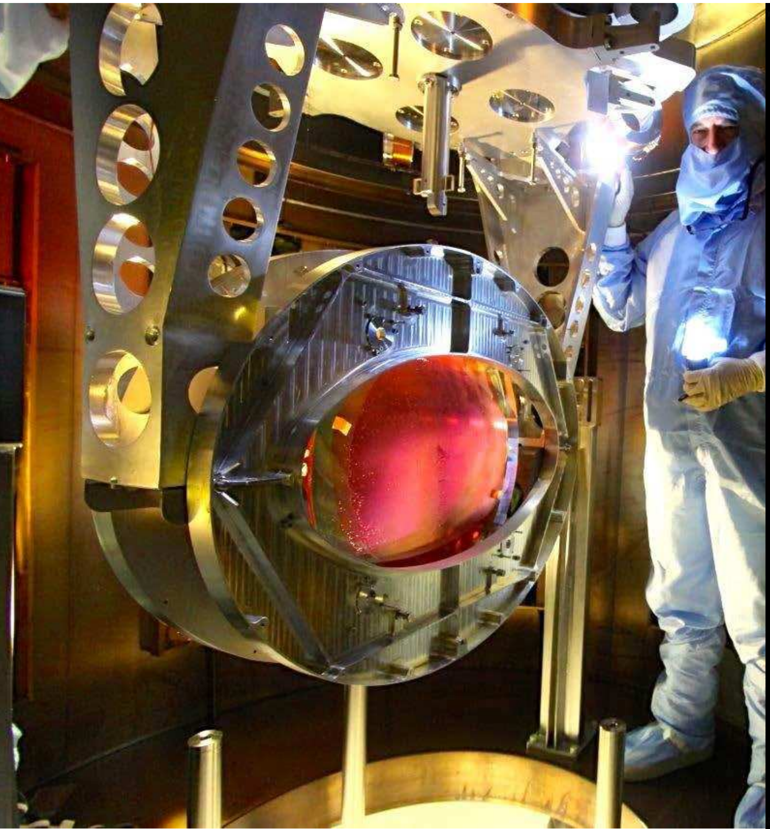
- 1000x gain in surveyed volume of the Universe
- estimated BNS detection rate: 0.2-200 per year
- sky position error ~5 deg^2

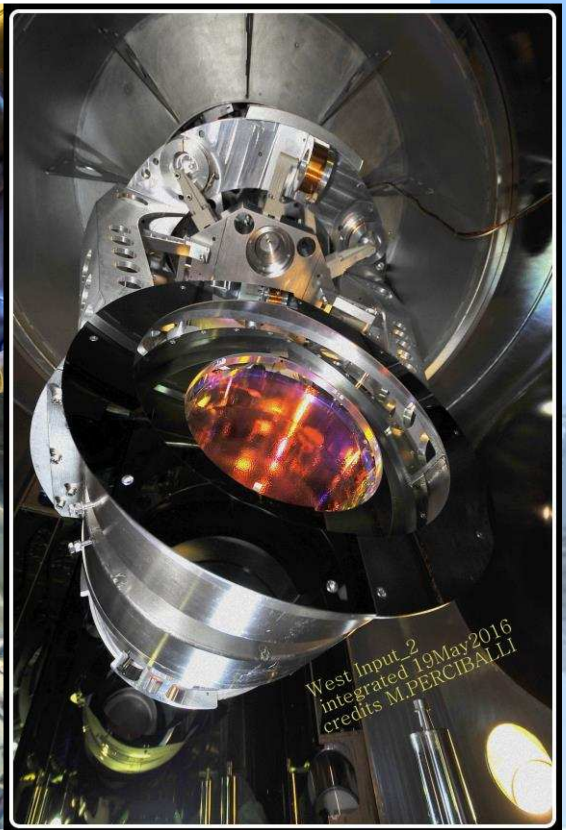


Details in (arXiv: 1304.0670v2 gr-qc)

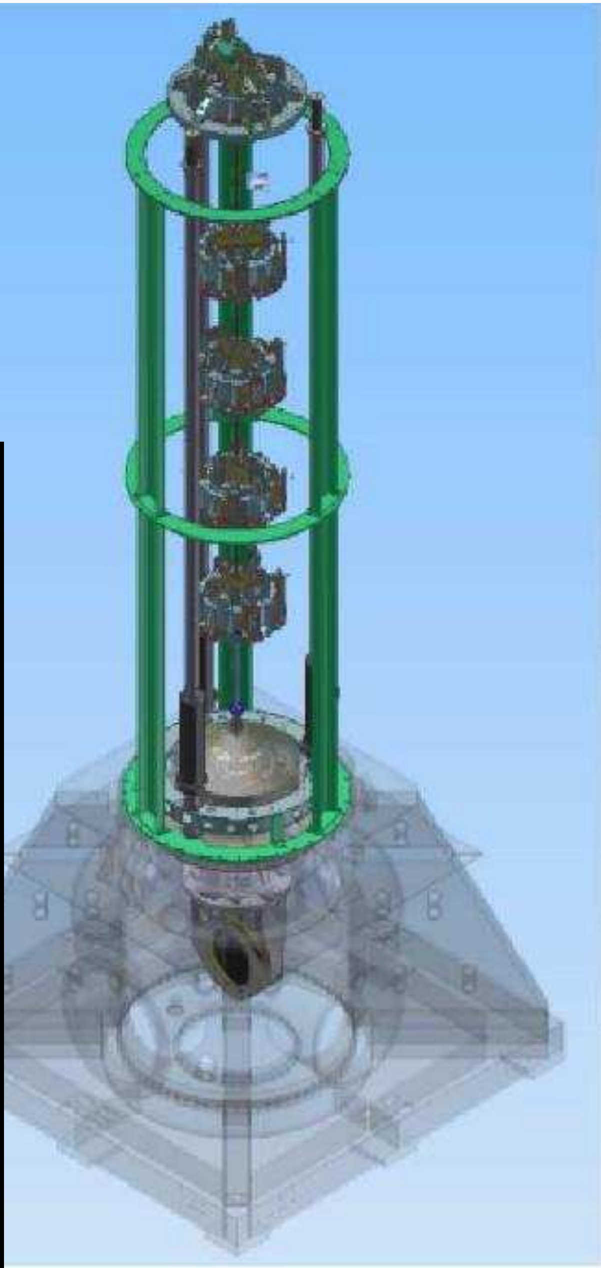
Advanced Virgo

- one 3 km-long cavity is under test
- completing integration of the last 2 mirrors
- commissioning of full interferometer from July
- aiming to join O2 by end of 2016, as soon as the sensitivity gets interesting ("early" phase)





West Input_2
integrated 19May2016
credits M.PERCIBALLI

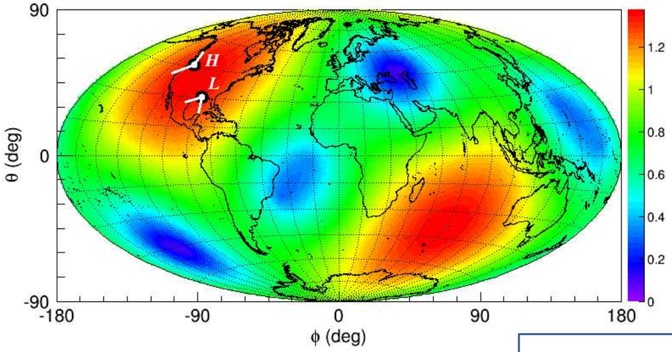


Benefits of a 3 detectors network

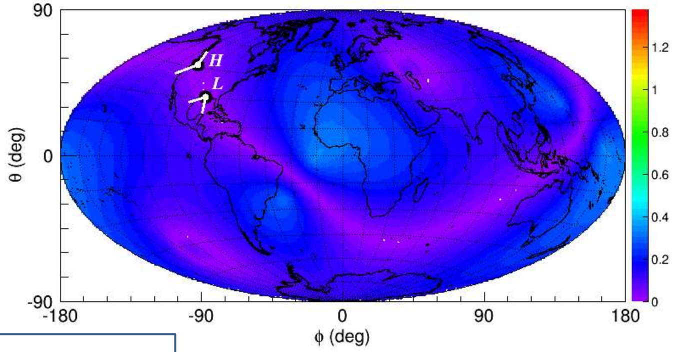
- **Detection confidence** is greatly improved: lower background and higher SNR
- Better **coverage of sky and GW polarizations**: better waveform reconstruction

LIGO H1+LIGO L1

$|\vec{F}_+|$

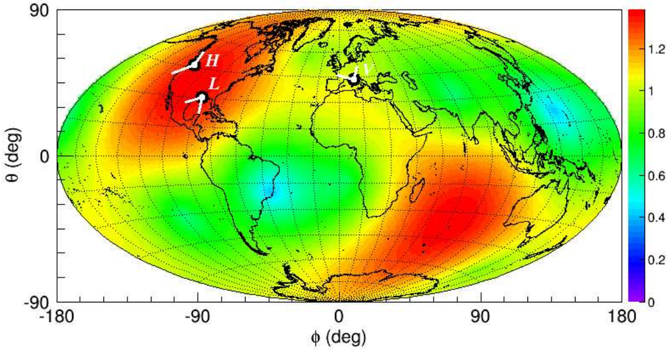


$|\vec{F}_\times|$

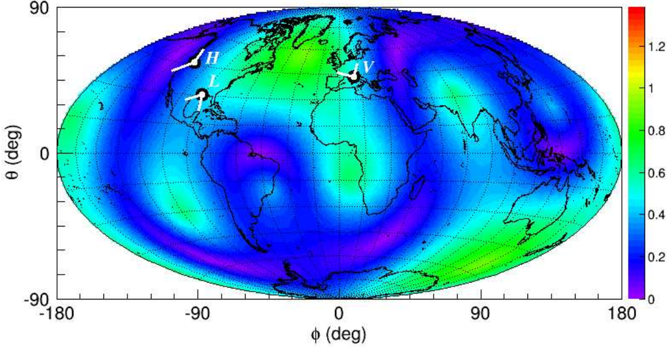


LIGO H1+LIGO L1**+ Virgo**

$|\vec{F}_+|$



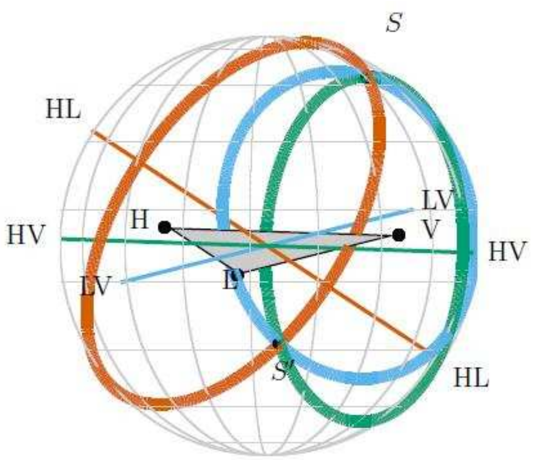
$|\vec{F}_\times|$

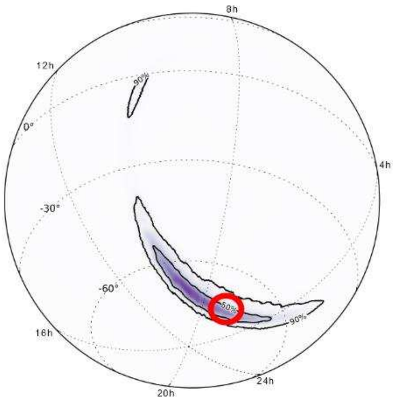


Benefits of a 3 detector network

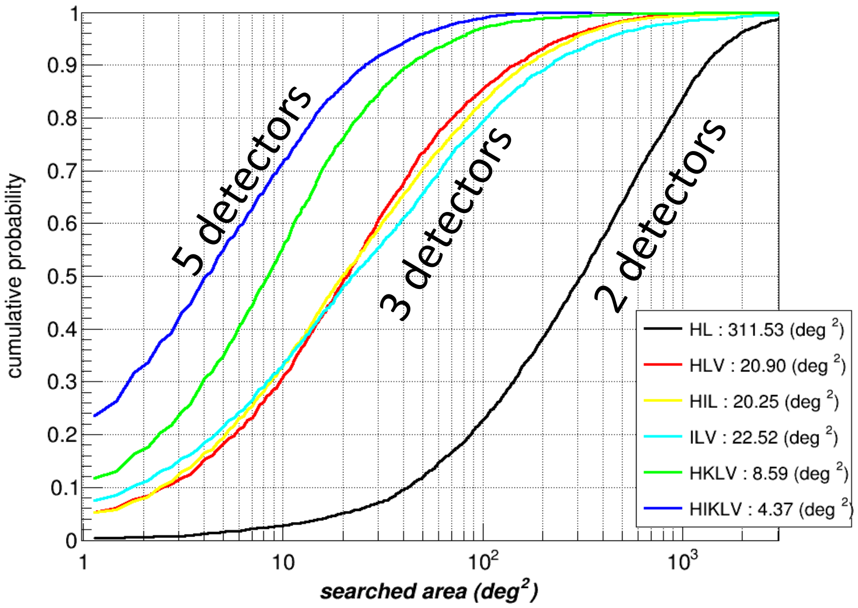
- **sky localization** greatly improved

Example based on GW150914





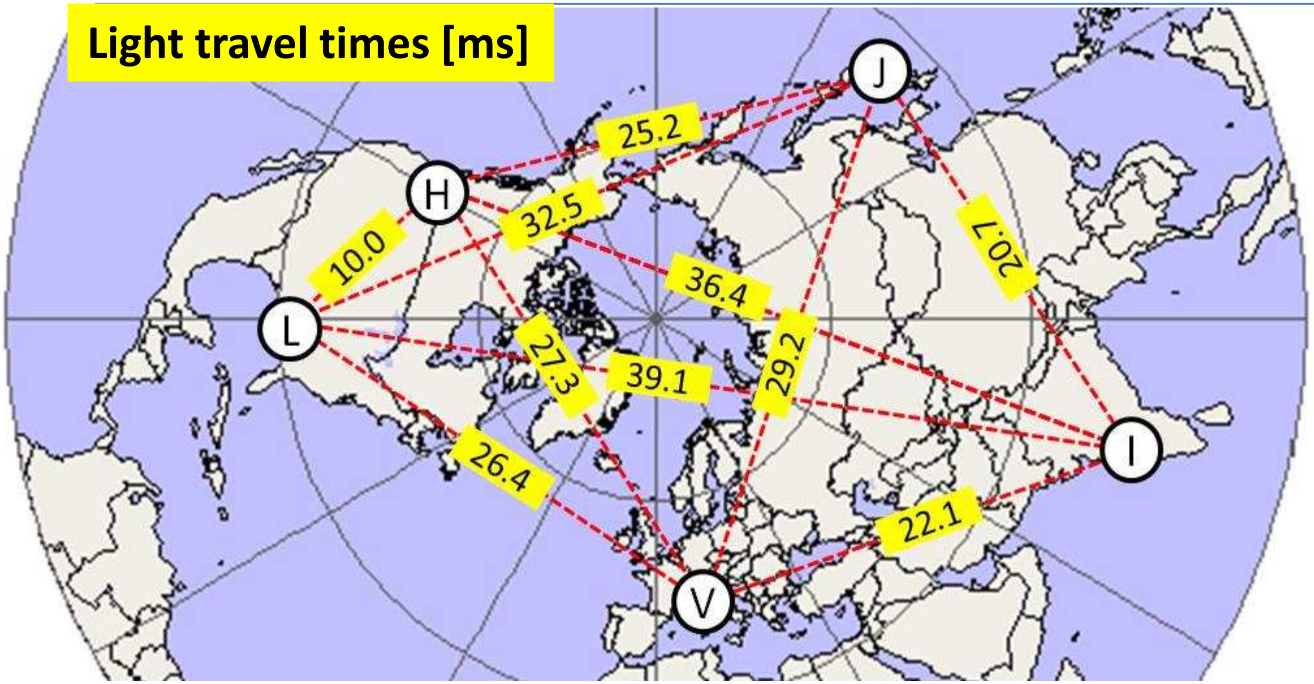
L1H1: 600 deg^2
L1H1V1: ≈20 deg^2
Expected reduction by a factor ~30 in 90% probability area



triangulation helps,
in addition we use consistency in amplitude sensitivities

- increase of the **time coverage of the survey** by detector pairs

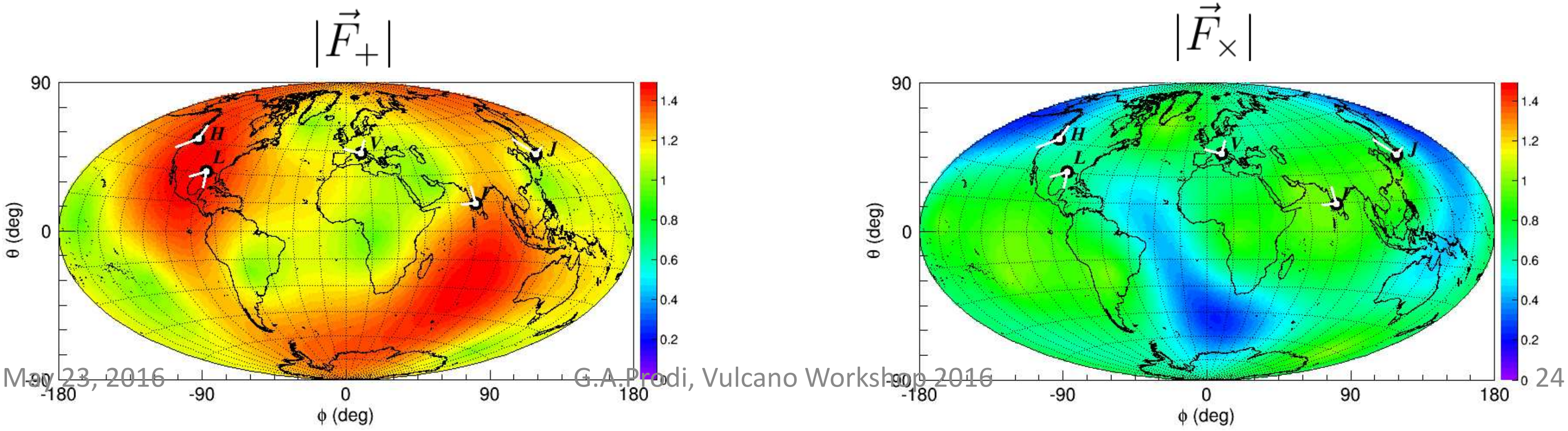
2019+ scenario



Light travel times [ms]

Two more interferometers will join LIGO and Virgo: KAGRA (Japan, 2019) and LIGO India (approved on February 2016)

Sky coverage of the whole observatory



$|\vec{F}_{+}|$ $|\vec{F}_{\times}|$

outlook

- Advanced LIGOs first observation campaign has been completed, Sept. 12-2015 – Jan. 19 2016

Expect to see the complete results very soon !

- Advanced Virgo will start very soon commissioning of full interferometer.
- The upcoming network will cover both GW polarizations.
- Advanced interferometers will improve sensitivity by a factor 3 in a 3-5 years time-scale.
- Current technologies and facilities could allow a further improvement in sensitivity by a factor 2
- New facilities and significant technology development will be required for additional improvements

Sources of Gravitational Waves

- **mass-Dipole Moment**, [M R], is proportional to the position of the Center of Mass of the system:

  forbidden dipolar emission of GWs from isolated systems

- leading order emission is **mass-Quadrupole Moment $\boldsymbol{Q_{\mu\nu}}$** , [M R^2] :

  GW Luminosity is driven by $\dddot{Q}_{\mu\nu} \neq 0$

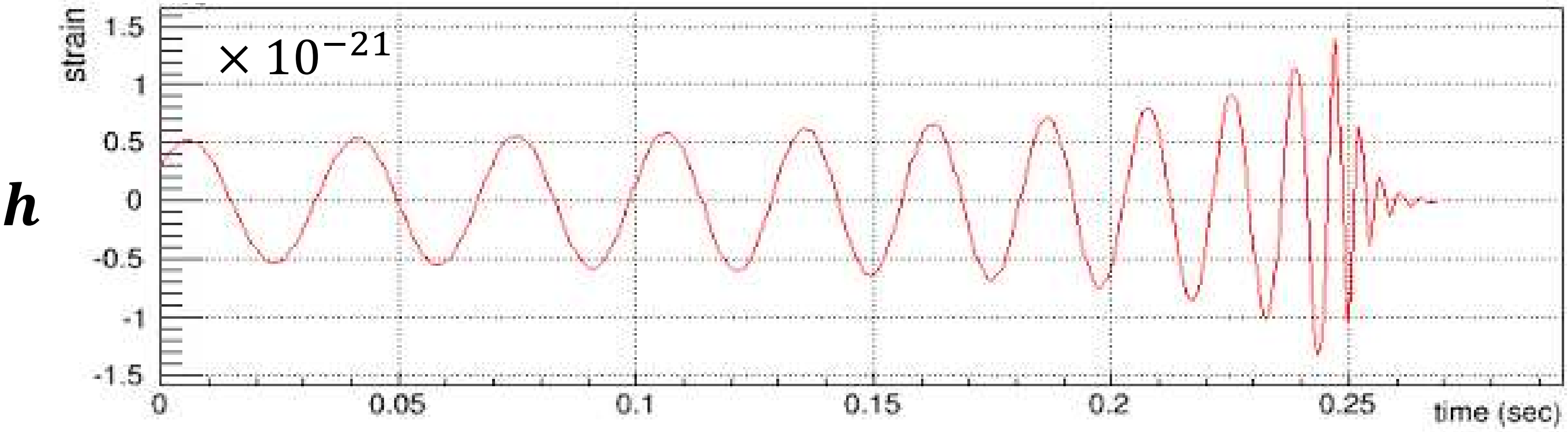
$$P \approx \frac{G}{5c^5}\dddot{Q}_{\mu\nu}\dddot{Q}^{\mu\nu} \sim \boxed{10^{39} W \left(\frac{f}{Hz}\right)^2 \left(\frac{M}{M_\odot}\right)^2 \left(\frac{v}{c}\right)^4 \quad \text{dimensional argument}}$$

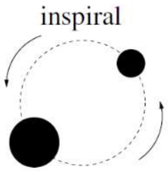
- most promising sources: binary compact systems of Neutron Stars and Black Holes at relativistic speed

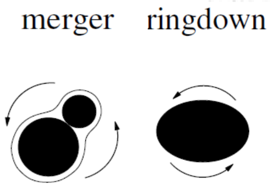
- generating detectable GWs as in Hertz-like experiment is not feasible

GWs from compact binary coalescences

- ❑ Coalescences of Binary Black Holes as GW150914 give the simplest signal in GR







Inspiral phase: GW emission described by quadrupole formula. Analytical solution available.

GW standard candle.

Last inspiraling cycles enter the bandwidth of earth-based detectors.

Merger: only numerical solution available.

Ringdown: perturbative and numerical solutions

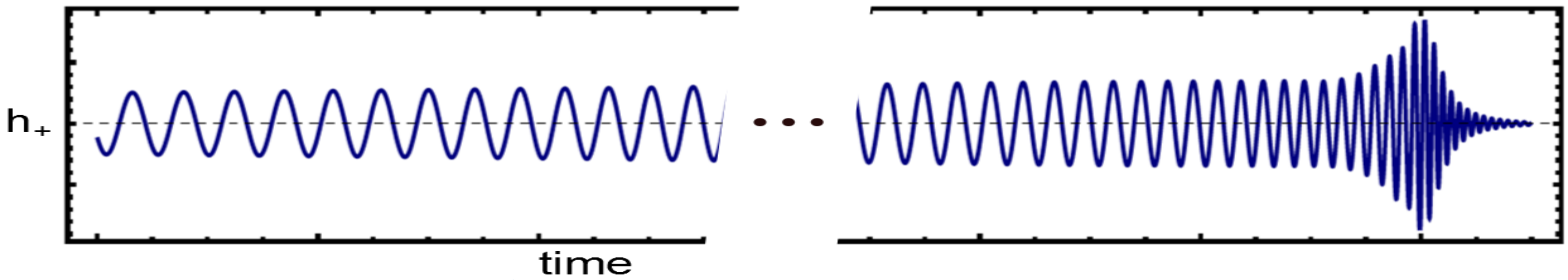
general relativity in strong field

highly non-linear regime

NS would bring more physics (Equation of State, ...)

PSR1916+13 versus GW150914

Waveform



Hulse-Taylor: 30 years of observation time

GW150914: 0.2 s

PSR1916+13	**observations**	**GW150914**
NS-NS	**compact object**	BH-BH
$M_1 = 1.44\,\mathrm{M}_\odot, M_2 = 1.3\,\mathrm{M}_\odot$	**mass**	$M_1 = 36\,\mathrm{M}_\odot, M_2 = 29\,\mathrm{M}_\odot$
4×10^{-23}	**GW at Earth**	2×10^{-21}
7×10^{-5} Hz	**GW frequency**	$30 - 300$ Hz
3×10^{8} years	**time to merge**	*merged*
$6 \times 10^{30}\,\mathrm{erg\,s^{-1}}$	**peak luminosity**	$3 \times 10^{56}\,\mathrm{erg\,s^{-1}}$
6.4 pc	**distance**	410 Mpc
10^6 km	**orbit dimension**	*merged*
$\sim 10^{-3}$	**v/c**	~ 0.5
$\sim 10^{-4}$	GM/rc^2	~ 1

generic transient searches

Robust search strategy: **coherent network data analysis** is mandatory to separate

coherent energy in different detectors (consistent with a GW excitation)

incoherent energy (estimate of independent noises of detectors)

GW plane

Null space

e.g. a likelihood Λ maximization of signal model vs noise model

gives

max{ ln(Λ) } = *coherent energy* + *incoherent energy*

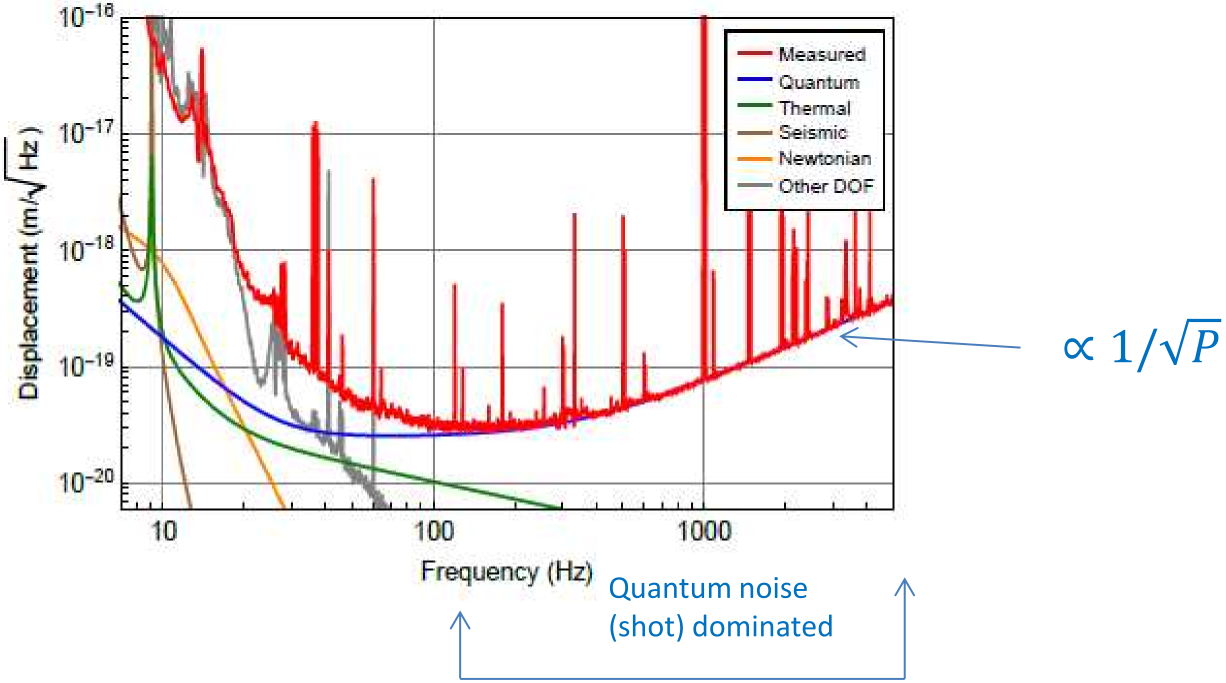
cross detectors terms

single detector terms

In general burst methods recover the entire energy (Signal to Noise Ratio) of the signal, but their background is polluted by non Gaussian outliers and need more effort to achieve highest significance

Quantum noise in detectors

High power operation is one of the most critical issues of the Advanced detectors



$\propto 1/\sqrt{P}$

Quantum noise (shot) dominated

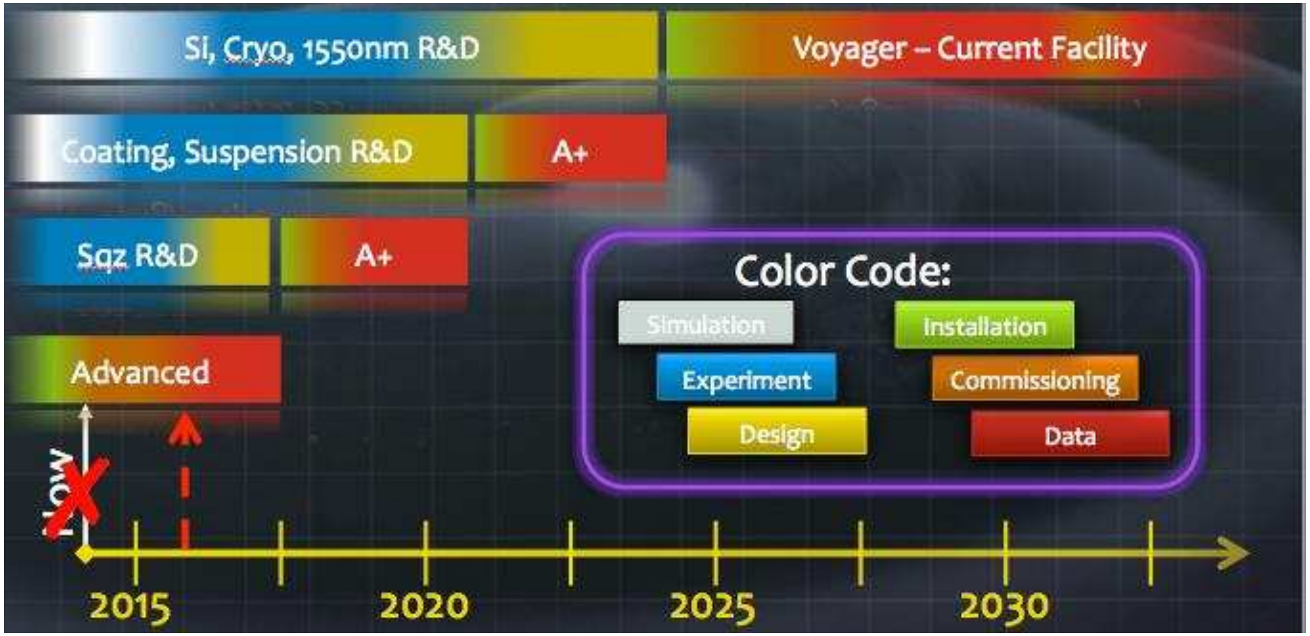
Next steps increase the detector input power up to 200 W (125 W for Virgo).
This means 500 kW of in cavity power.

Problems could arrise from photo-thermal effects (thermal lensing and nonequilibrium thermal noise) and dynamical instabilities

Is there an alterative to the high power?

Outlook 2020's

- ☐ Frequency dependent squeezing
  whole band 2x gain in sensitivity, 8x in visible volume
- ☐ Incremental upgrades of current Michelson infrastructures
  - larger & more massive optics (LIGO A+)
    additional 2x gain in sensitivity
  - add cryogenics (LIGO Voyager)
    additional 2x gain in sensitivity

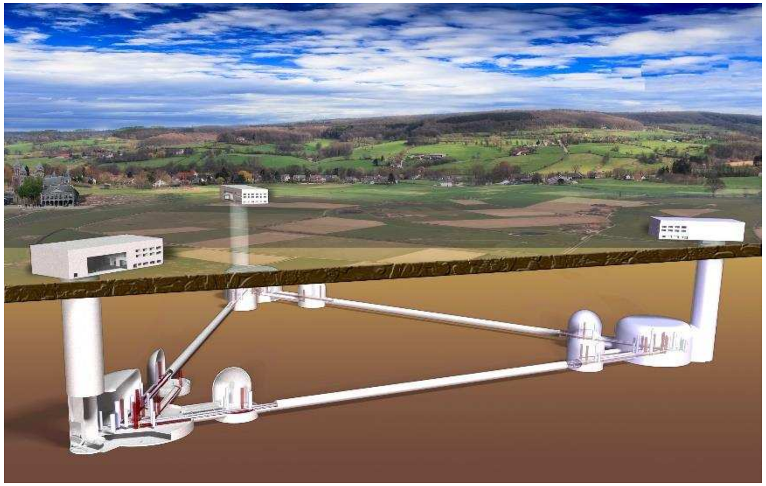


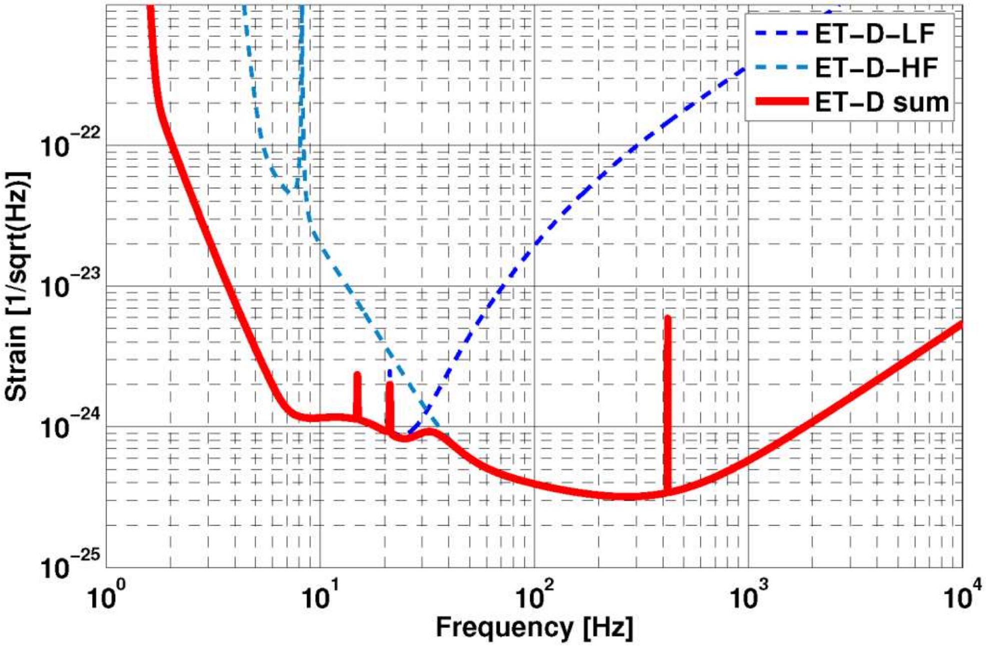
from LSC Whitepaper 2015

Outlook 2030's

Underground infrastructures for ≥ 10*km* arms:
Einstein Telescope, Cosmic Explorer

extend the sensitivity band to larger mass BHs at low frequency and to NS at high frequency





Gravitational Wave Detectors and Sources