Long baseline interferometers for gravitational wave astronomy

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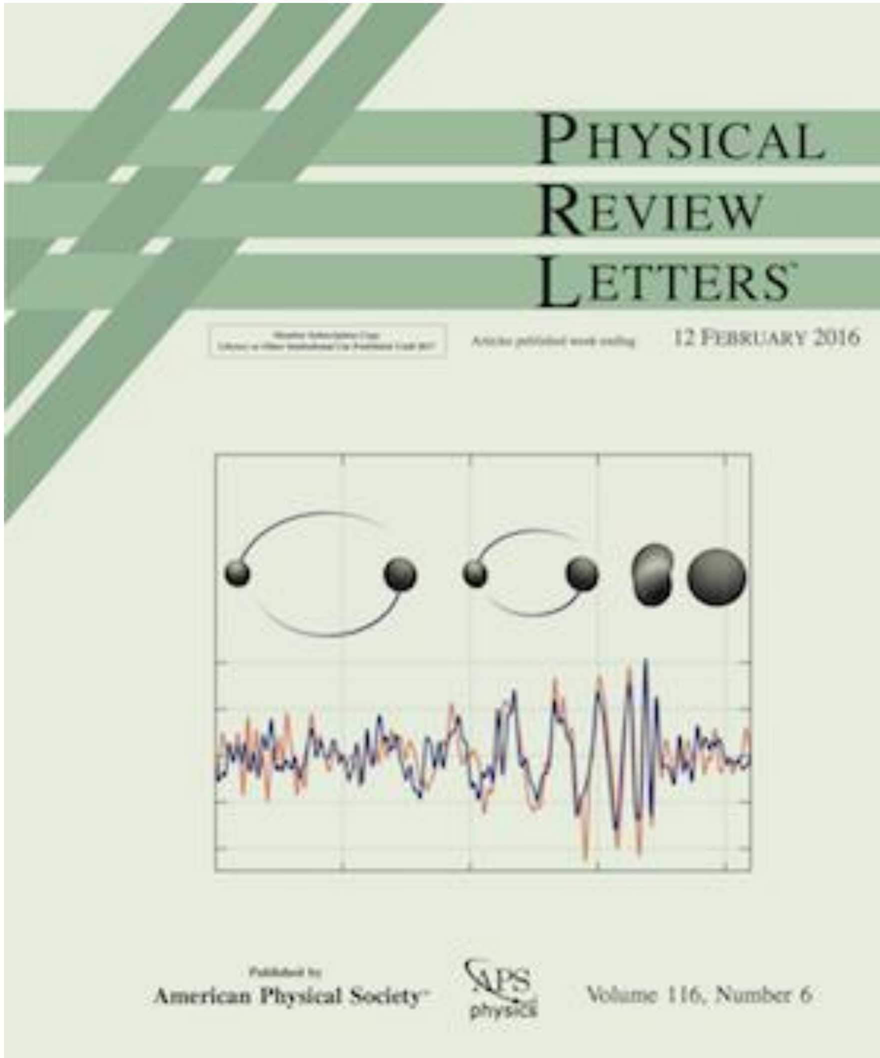
Outline

- Update on gravitational wave results from the first advanced LIGO observation run
- Sensitivity of a gravitational wave interferometers
- State-of-the-art noise performances of detectors
- outlook



PHYSICAL
REVIEW
LETTERS

Articles published week ending 12 FEBRUARY 2016

Published by
American Physical Society

APS physics

Volume 116, Number 6

Published Discoveries

- **Detection of propagating Gravitational Waves**
- **Direct observations of a stellar-mass Black Hole binary → merger**
- **The most luminous astrophysical events detected**

plus

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

The Dawn of novel Explorations

- **Astronomy & Astrophysics …** *distance scale, BH & NS formation, GRBs…*
- **Fundamental Physics**

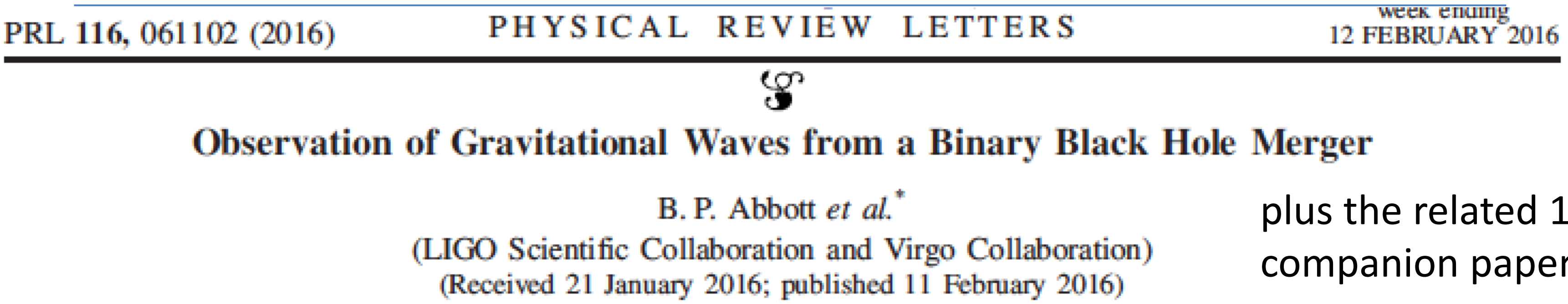
→ *space-time and extended theories of gravity*

→ *event horizons of Black Holes*

→ *equations of state of Neutron Stars*

Papers

https://www.ligo.caltech.edu/s
http://www.virgo-gw.eu/

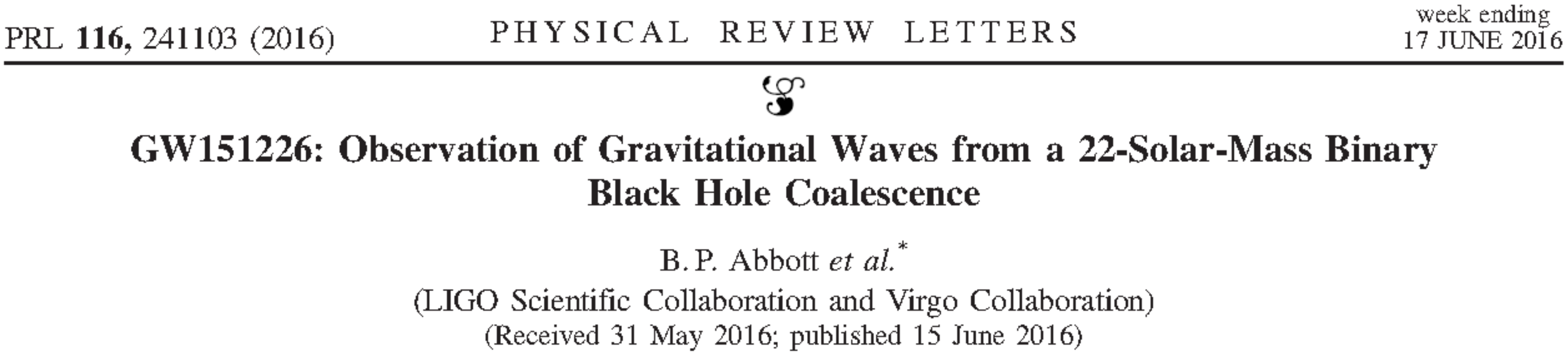


PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

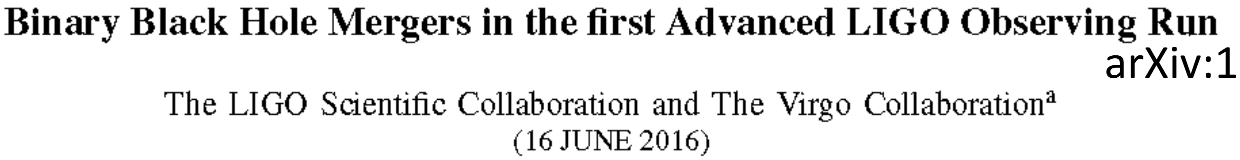
plus the related 12 companion papers



PRL **116,** 241103 (2016) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2016

GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 31 May 2016; published 15 June 2016)



Binary Black Hole Mergers in the first Advanced LIGO Observing Run

arXiv:1606.04856

The LIGO Scientific Collaboration and The Virgo Collaboration[a]
(16 JUNE 2016)

DATA are released to public: ***LIGO Open Science Center*** **https://losc.ligo.org**

Gravitational Waves far away from sources

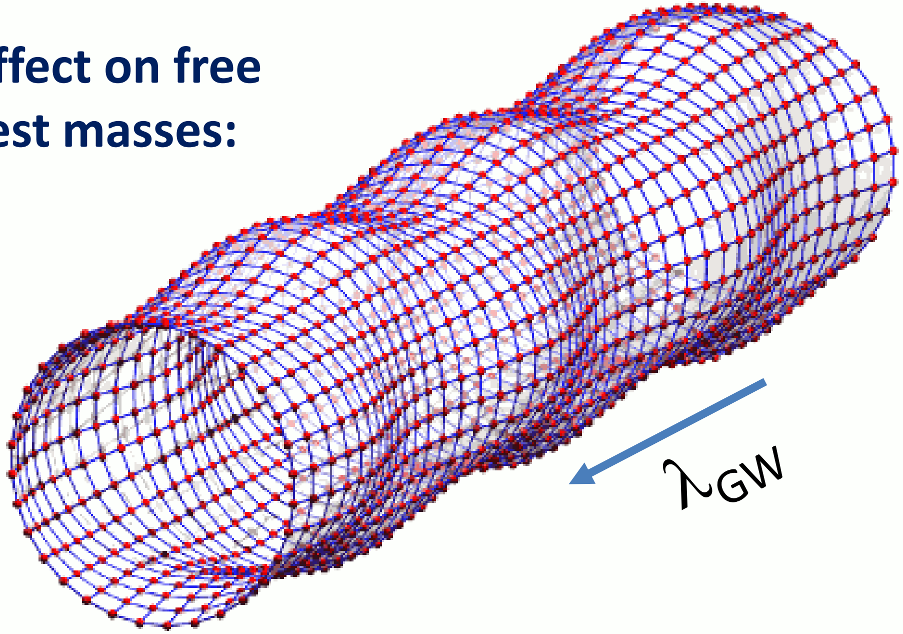
- gravitational waves carry curvature, energy, momentum, angular momentum
- weak-field linear approximation in General Relativity
  - analogies with electromagnetic waves:

    light speed, massless, 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:



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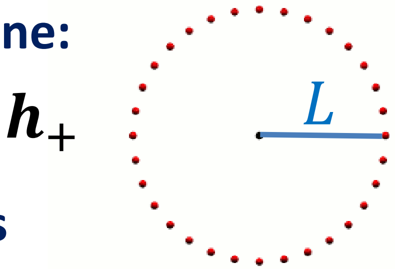
in wavefront plane:



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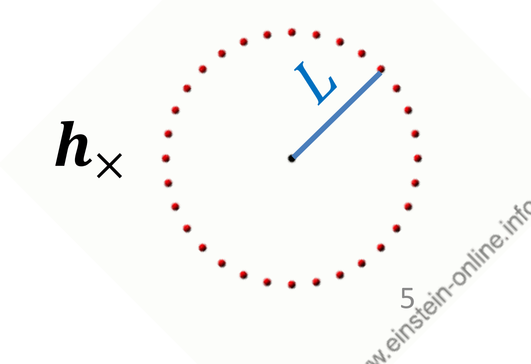
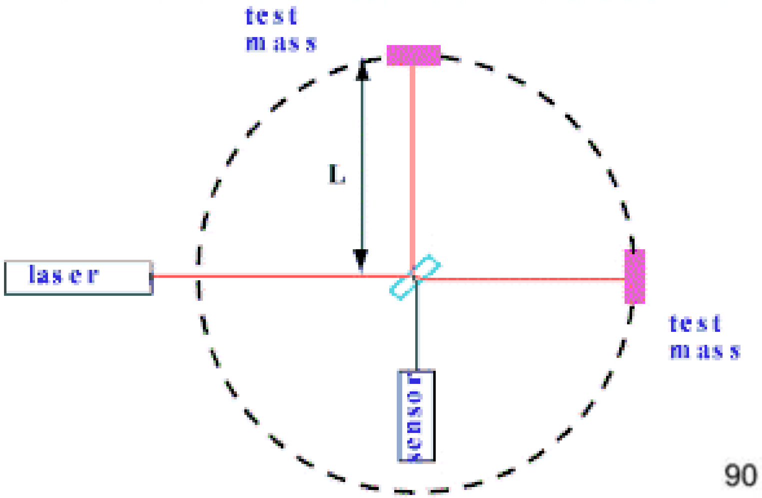
GW amplitude is strain:

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



directional sensitivity of detectors

Each interferometer senses one of the two polarizations of GWs



- measures one linear combination:

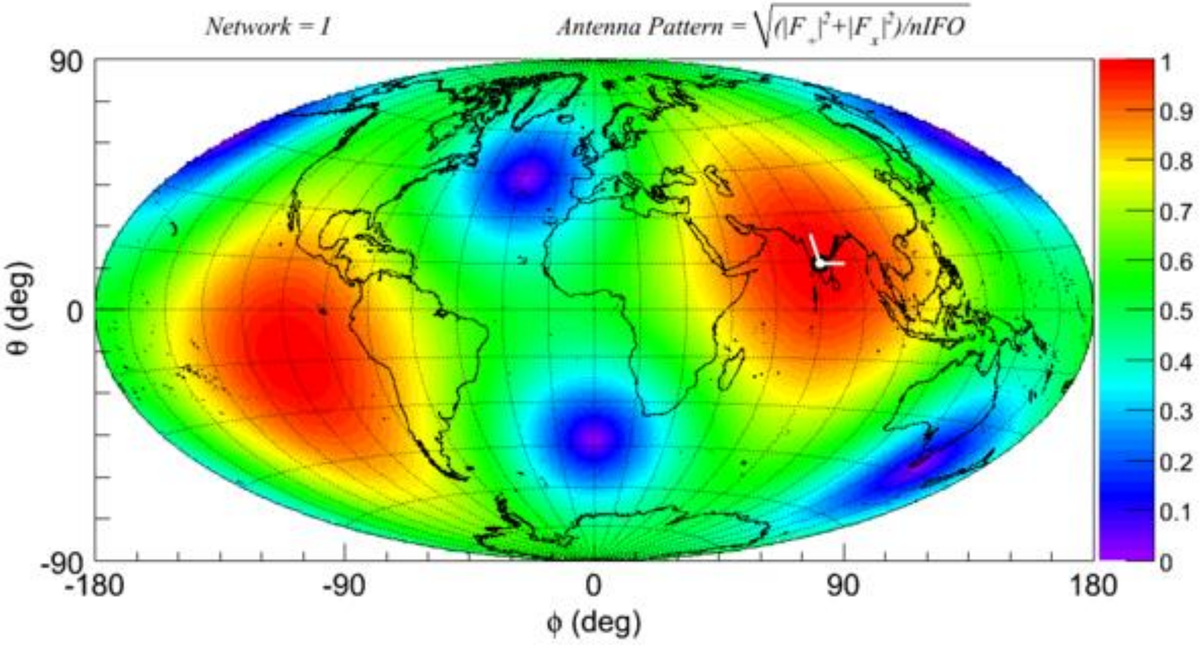
$$h = F_+ h_+ + F_\times h_\times$$

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

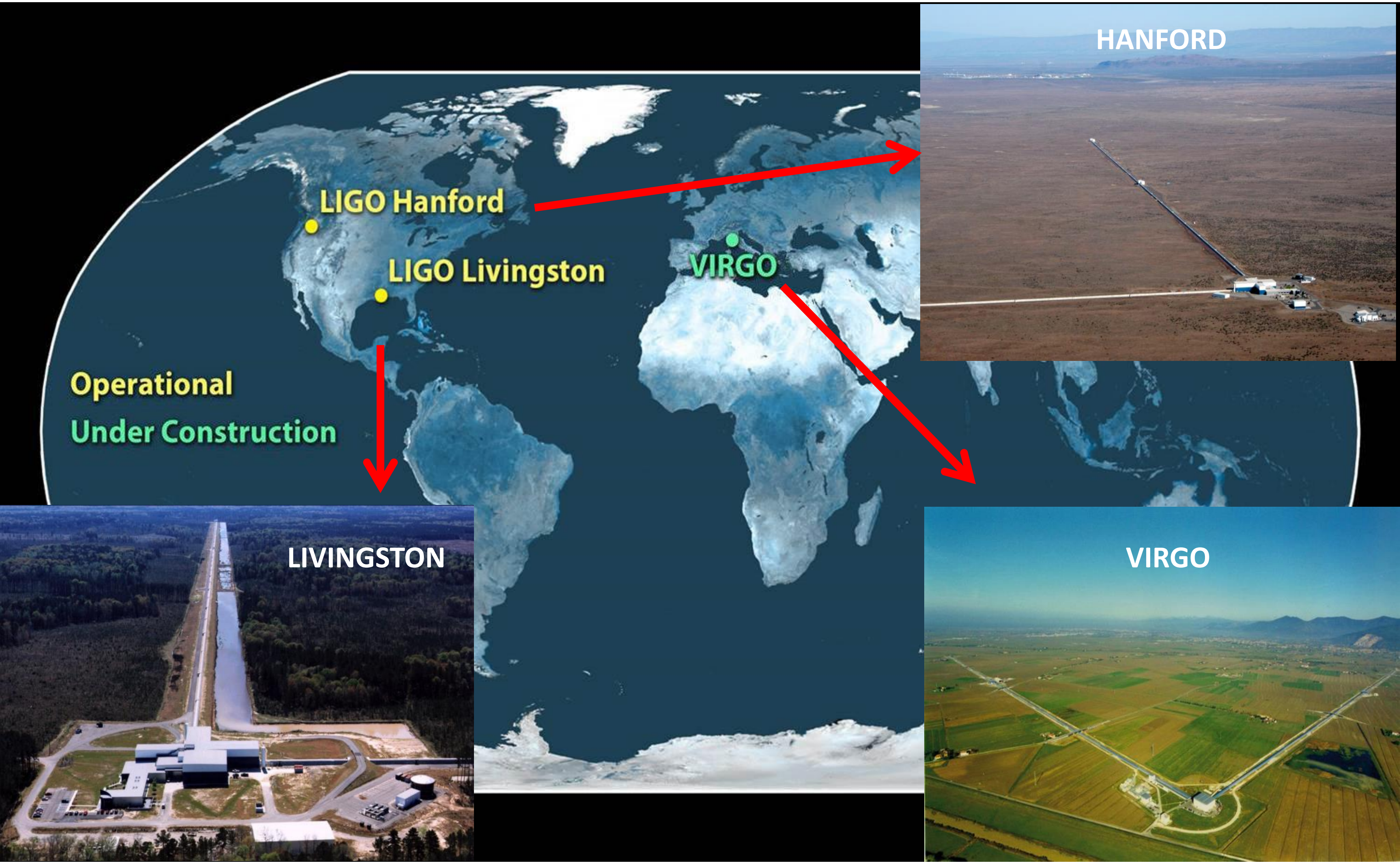
antenna patterns for + and x

- misses the orthogonal combination of GW polarizations.

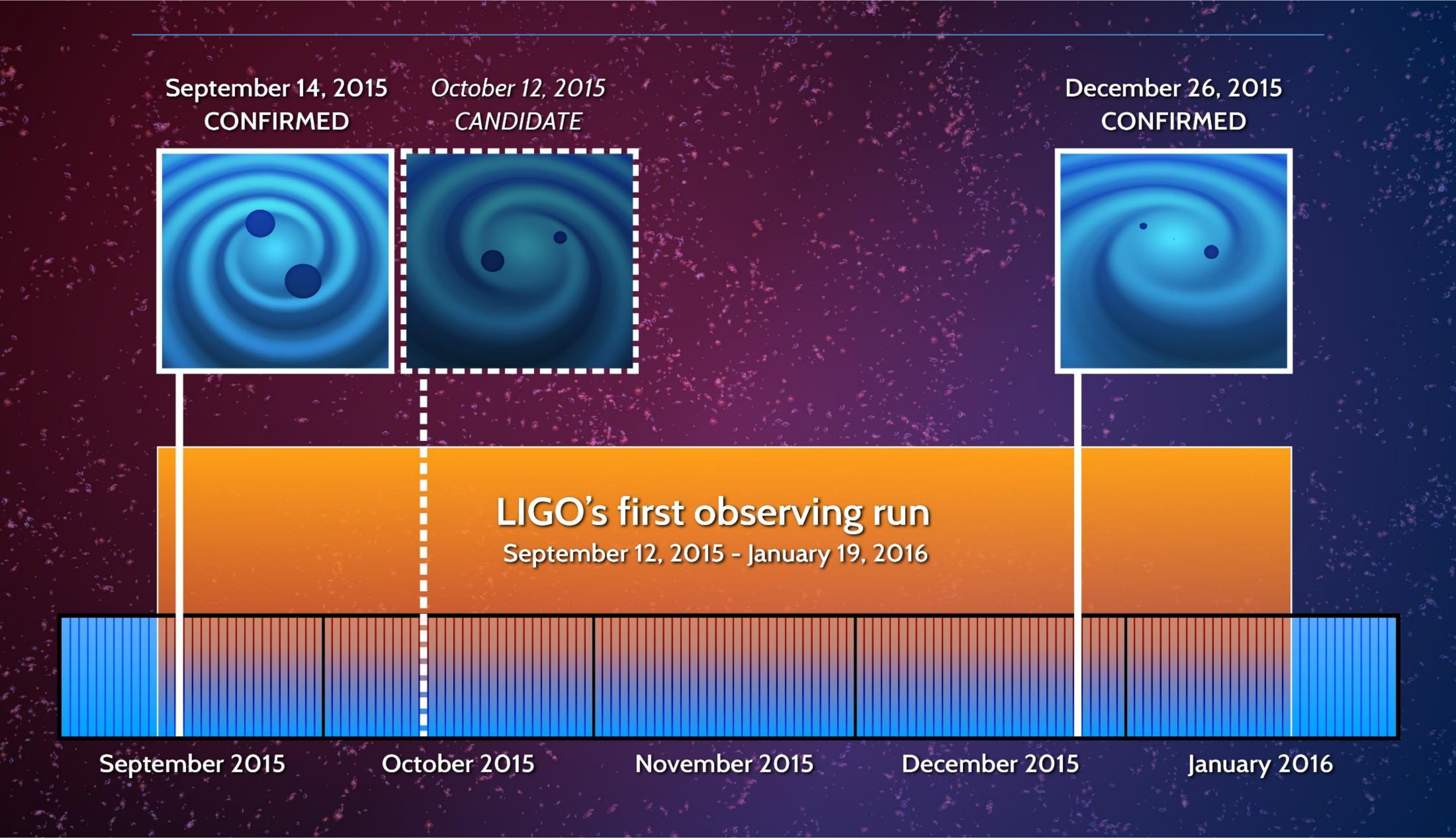
directional sensitivity to the optimal polarization component is broad:



The LIGOs and Virgo long-arm detectors

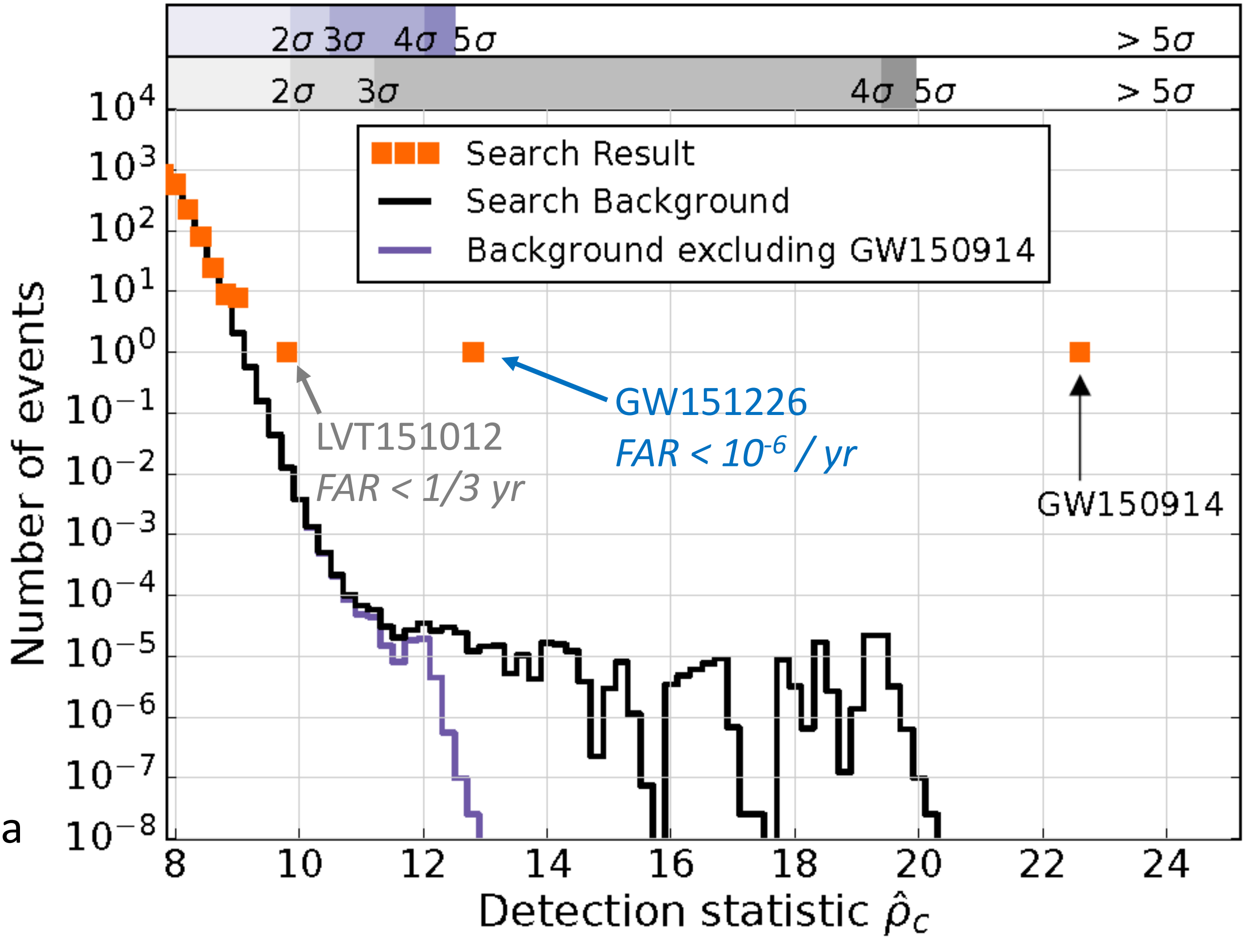


Binary Black Hole coalescences in O1



48.6*d* of coincident time with science quality data

statistical confidence of O1 BBH results



LVT151012
FAR < 1/3 yr

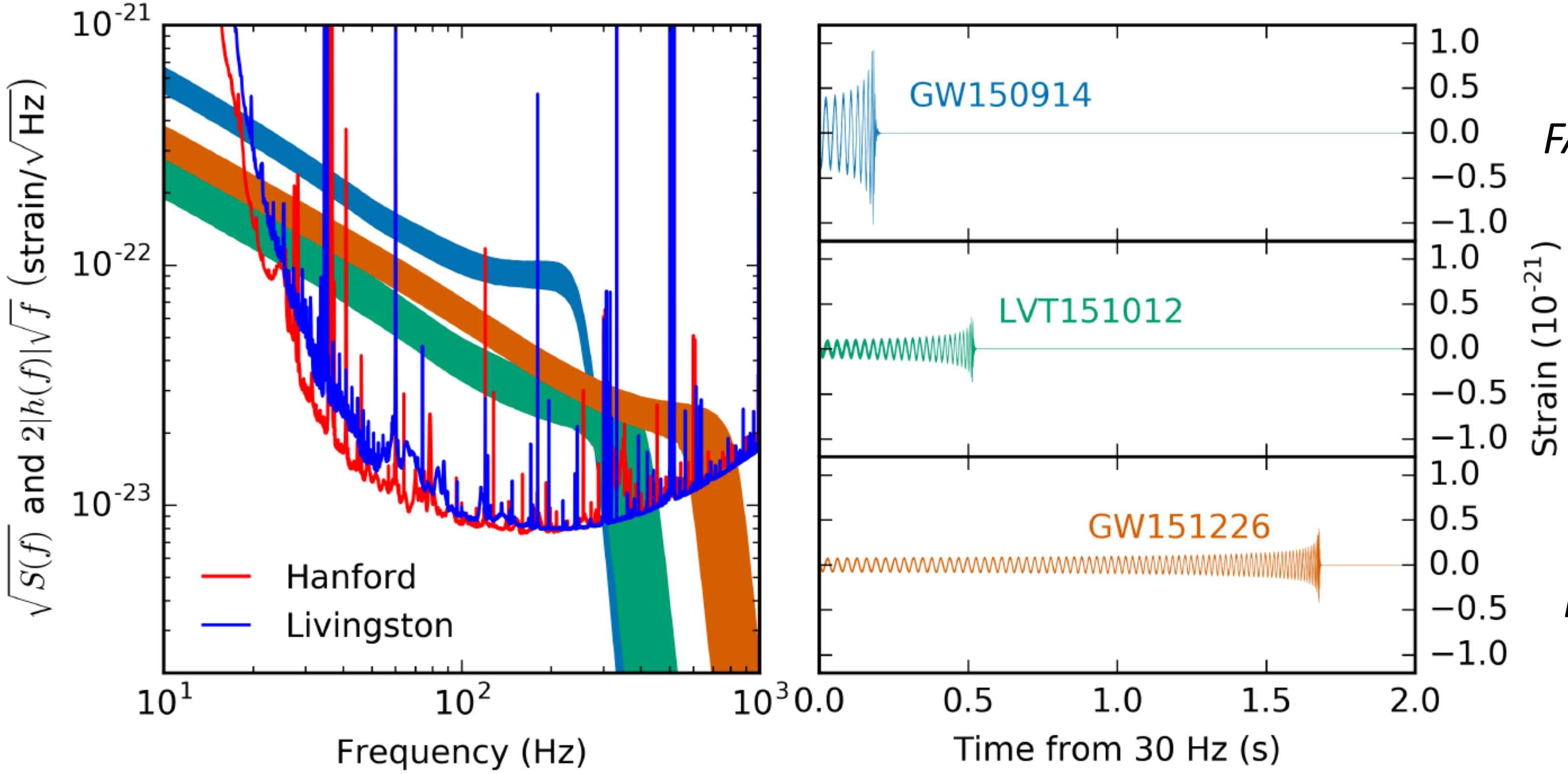
GW151226
FAR < 10^{-6} / yr

False Alarm Rate < 10^{-6} / yr

46.1*d* of analyzed coincident data

LVT151012: astrophysical origin is more likely than noise artifact
insufficient confidence to claim a detection

Binary Black Hole coalescences in O1



SNR≈ 24
FAR < 10^{-6} / yr

SNR≈ 10
FAR < 1/3 yr

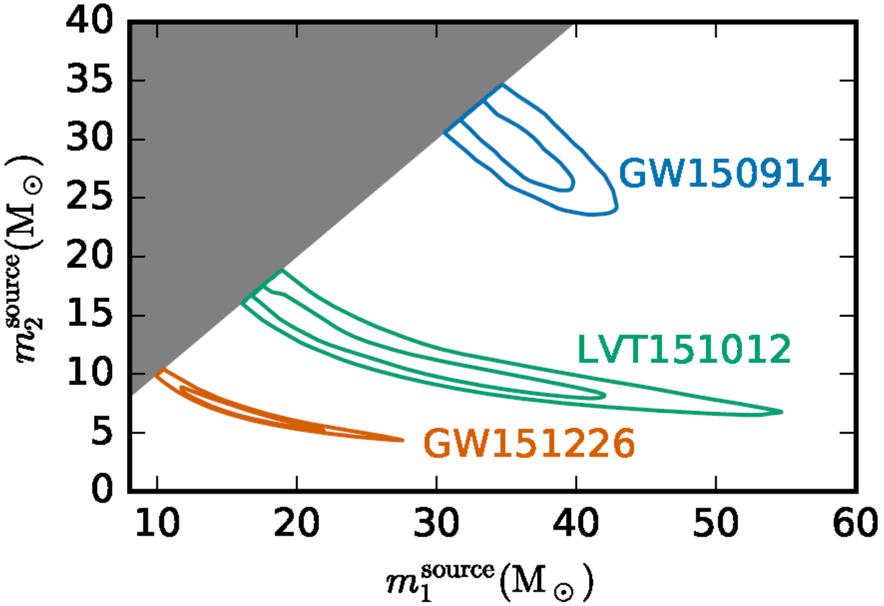
SNR≈ 13
FAR < 10^{-6} / yr

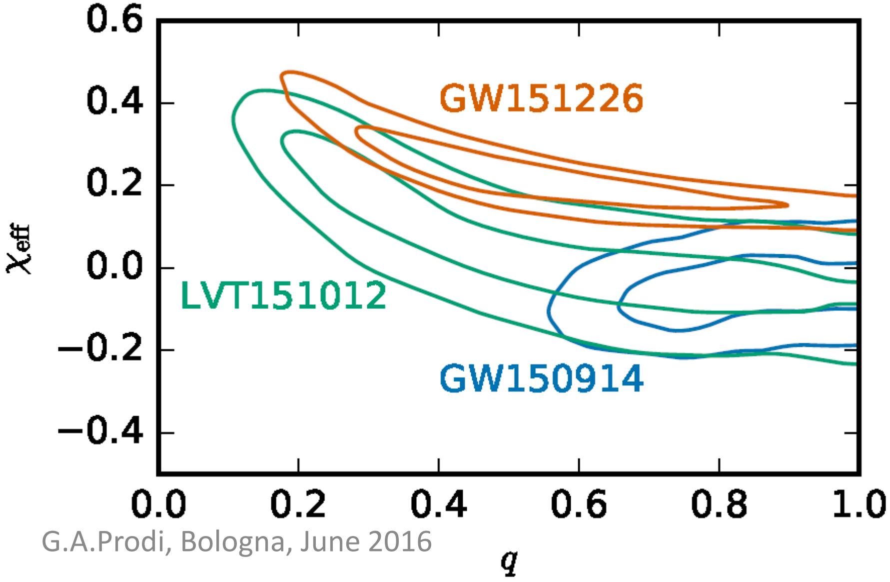
$$SNR^2 = \int_0^\infty \frac{\left(2\sqrt{f}\,\tilde{h}(f)\right)^2}{S(f)}\,\mathrm{d}ln(f)$$

inspiral – merger – ringdown phases

Black Holes are the simplest compact GR objects
⇒ Unprecedented study of 2 body motion in strong field & highly relativistic regime

Binary Black Holes





Inspiral waveform dominated by

Chirp mass $= \dfrac{(m_1 m_2)^{3/5}}{M^{1/5}}$

~ constant chirp mass

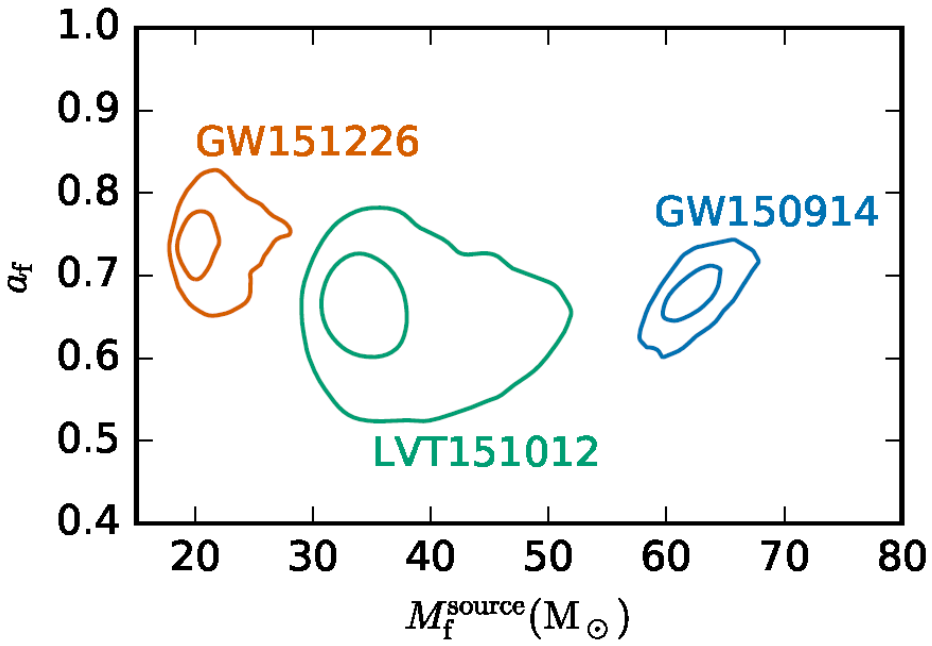
Other most relevant parameters are:

- ***mass ratio*** $q = \dfrac{m_2}{m_1}$ where $m_2 < m_1$
- ***effective spin*** $\chi_{eff} = \dfrac{m_1\chi_1 + m_2\chi_2}{M}$ weighted spin along orbital angular momentum

which give partially degenerate effects.

GW151226 shows $\chi_{eff} > 0$
i.e. at least one component with spin

Black Holes remnants



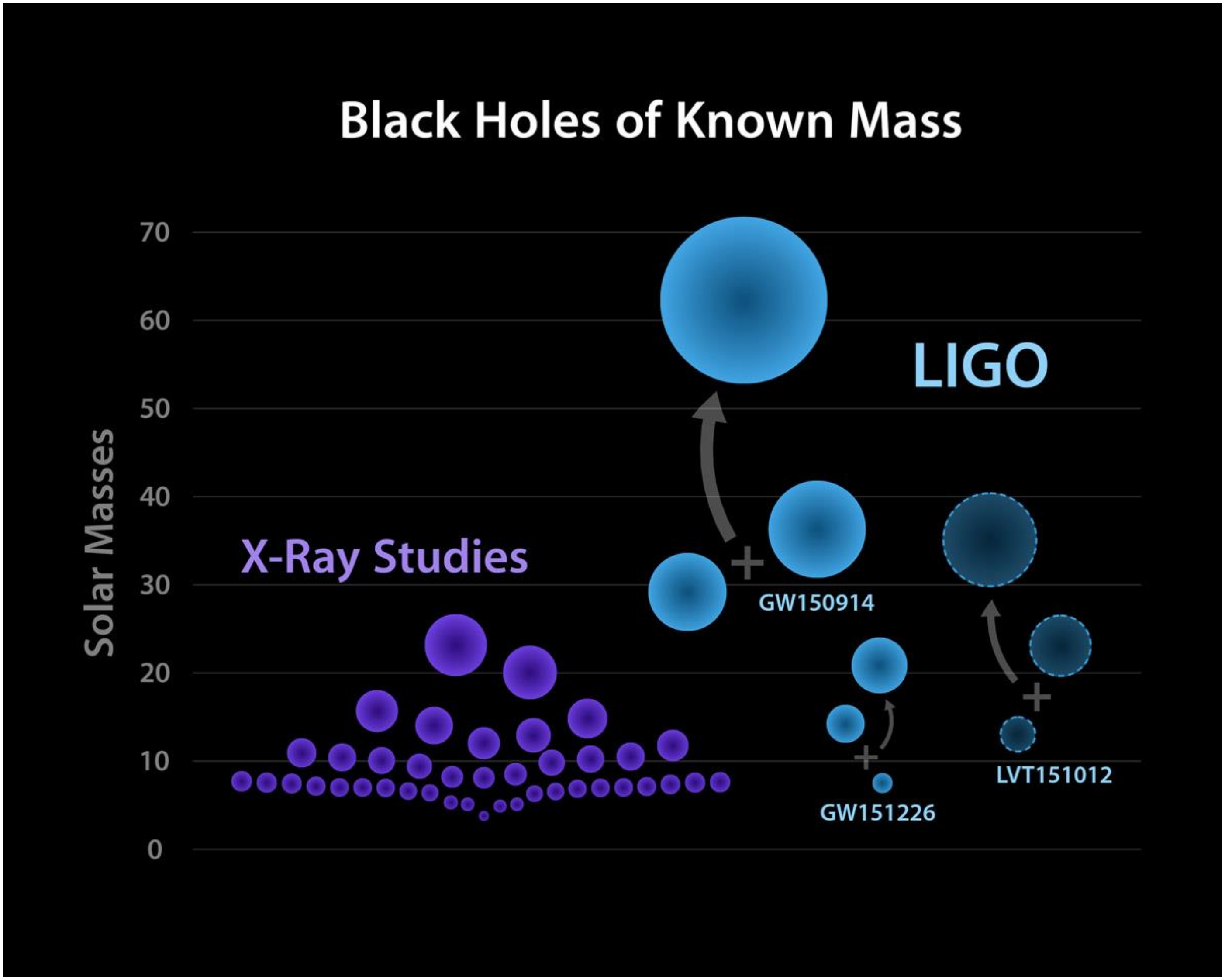
Merger and ringdown allow to estimate the remnant mass and spin

Remnant dimensionless spin $a_f = \frac{c}{Gm^2}|S| \sim 0.7$ as expected for mergers of similar mass BHs

Radiated Energies: $\mathbf{1 M_\odot c^2}$ $\mathbf{1.5 M_\odot c^2}$ $\mathbf{3 M_\odot c^2}$

Peak luminosities: $\mathbf{3.1 - 3.6\ 10^{56}\ erg/s}$

Mass distribution of Black Holes



luminosity distance

Gravitational Wave amplitude $A(t) \propto {}^{1}/_{D}$

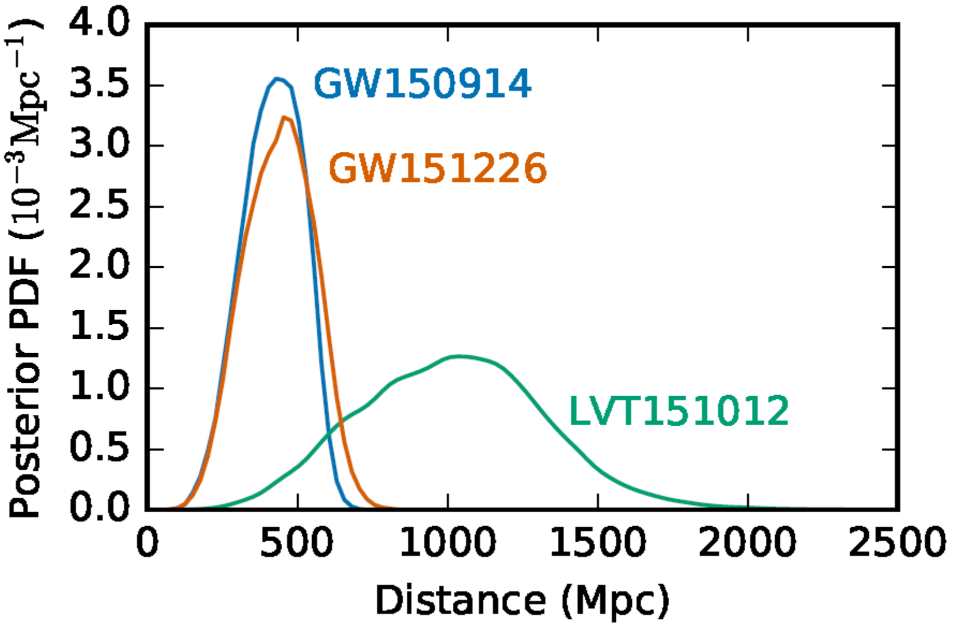
BBH coalescences are well modeled "candles" :

$$h_+(t) = A(t)\left(1 + cos^2(i)\right)\cos\left(\phi(t)\right)$$

$$h_x(t) = -2A(t)\cos(i)\sin\left(\phi(t)\right)$$

...but: LIGOs senses only one linear combination of the polarizations

$\Rightarrow$ degeneracy with inclination angle i



No redshift measurement is possible by GWs alone:

$$f_{earth} = \frac{f_{source}}{(1+z)}$$

is mimicked by

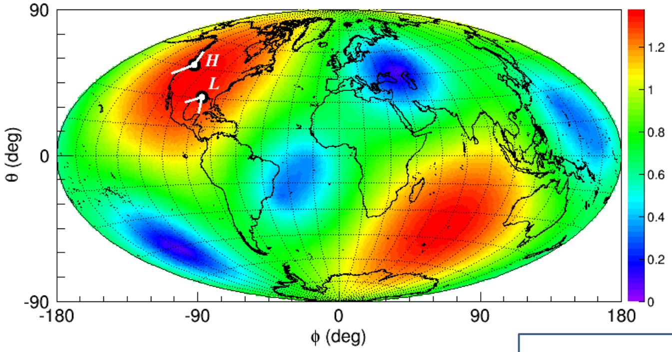
$$M_{earth} = (1+z)M_{source}$$

Benefits of a 3 detectors network

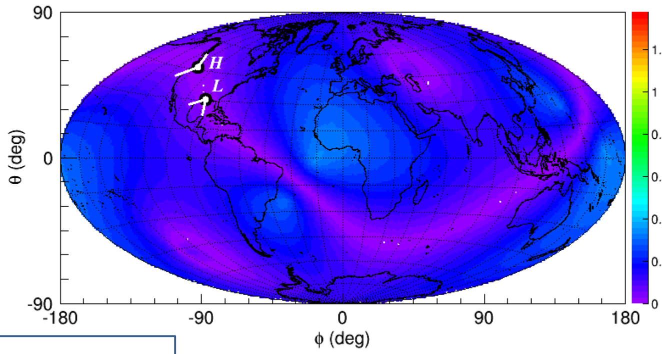
- **Detection confidence** is greatly improved: lower background and higher SNR
- Better **coverage of sky and GW polarizations**: better waveform reconstruction

LIGO H1+LIGO L1

$|\vec{F}_+|$

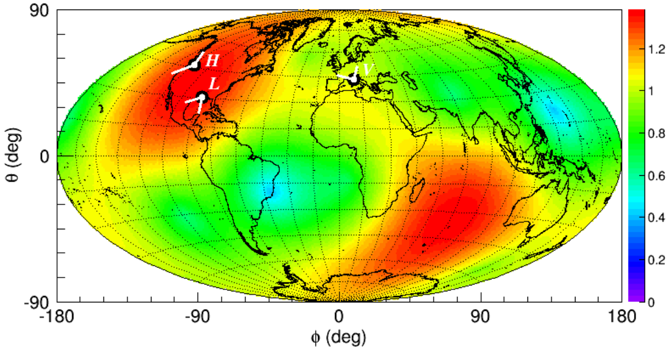


$|\vec{F}_\times|$

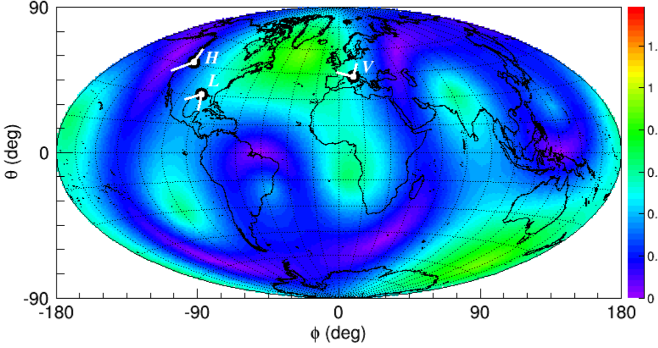


LIGO H1+LIGO L1**+ Virgo**

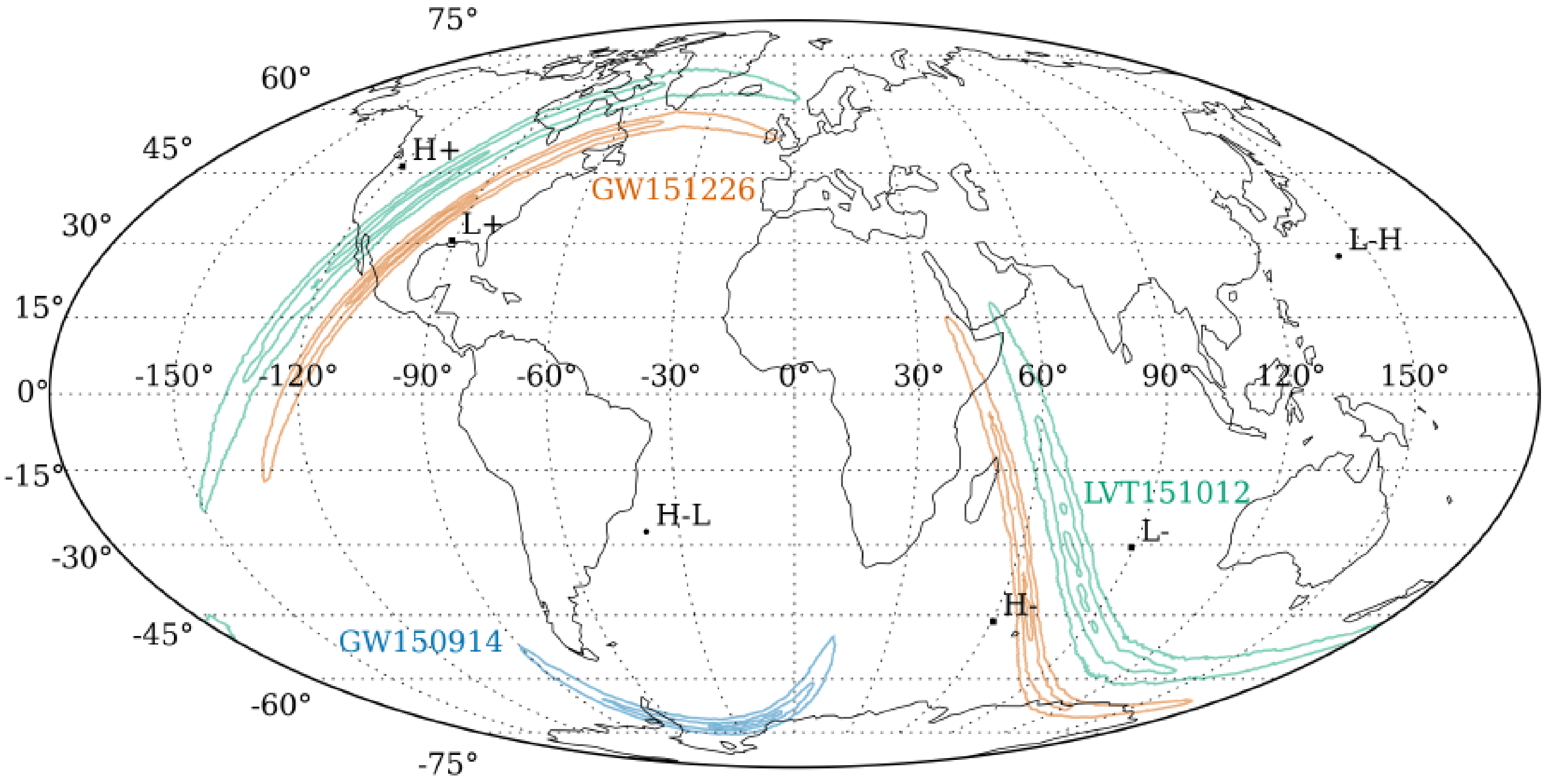
$|\vec{F}_+|$



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



source localization

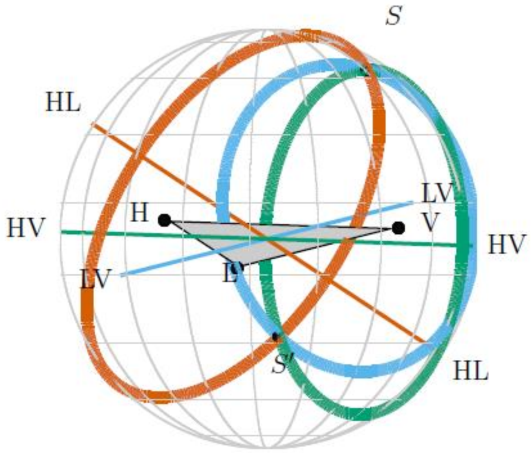


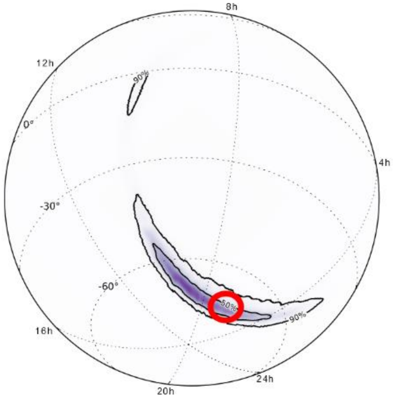
90% sky error regions are very wide and broken annuli:
GW150914: 250 deg^2 , GW151226: 850 deg^2 , LVT151012: 1600 deg^2

Benefits of a 3 detectors network

- **sky localization** greatly improved

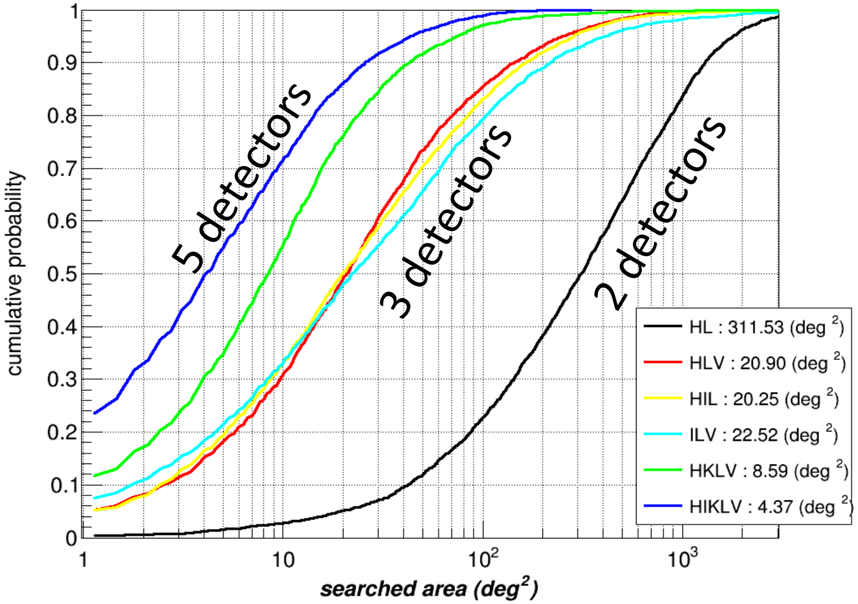
Example based on GW150914





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

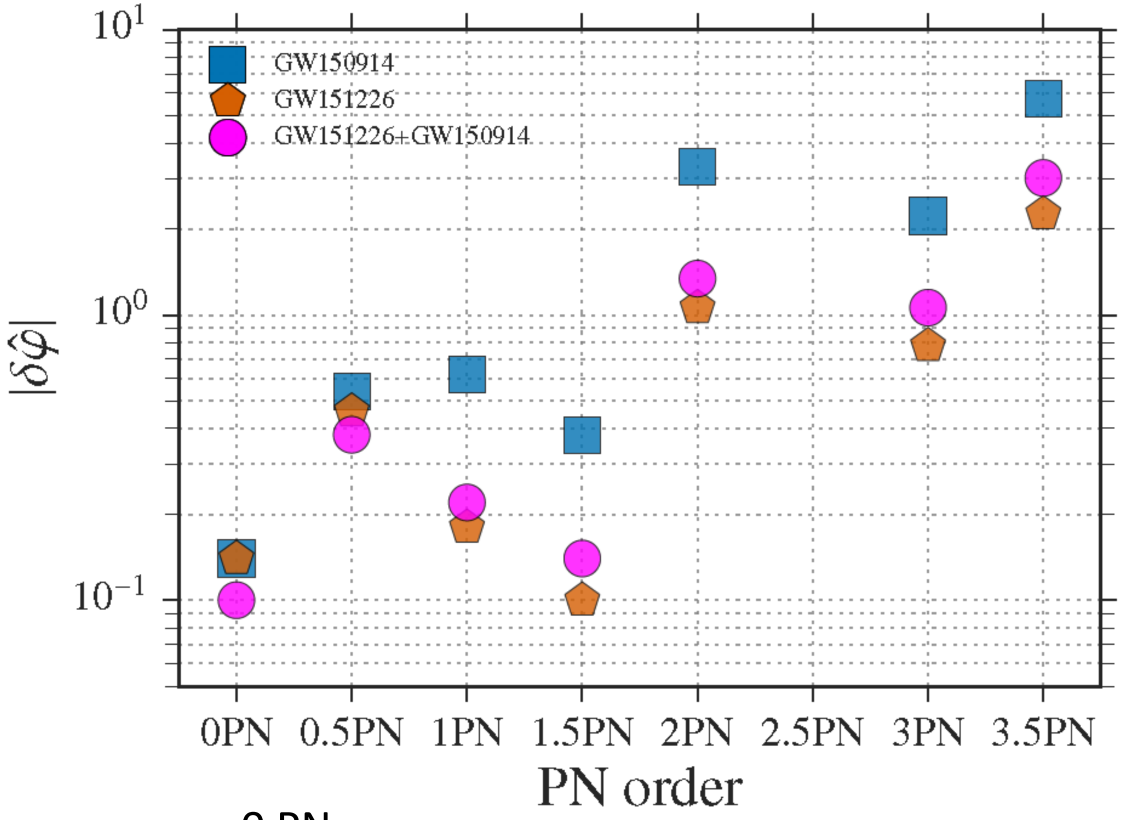
Testing GR beyond quadrupolar formula [arXiv:1602.03841]

First test of GR in strong field and highly relativistic speed
by checking the phase evolution of the inspiral signals of GW150914, GW151226

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

where $(1+\delta\varphi)$ describes possible deviations from GR prediction per each Post Newtonian order to the quadrupolar emission formula (considering one PN at a time)

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



0 PN
Quadrupolar
formula

10 years of double pulsar
J0737-3039
$v/c \sim 2\ 10^{-3}$, $GM/rc^2 \sim 5\ 10^{-6}$

Bounds for dispersion relation of GWs [arXiv:1602.03841]

- **Assuming a phenomenological dispersion relation**

m_g rest-mass
E energy
p momentum

graviton

$$E^2 = p^2c^2 + m_g^2c^4$$

$\Rightarrow$ frequency dependent graviton speed

$$v^2 = c^2\left(1 - \left(\frac{hc}{\lambda_g E}\right)^2\right)$$

$$\lambda_g \equiv \frac{h}{m_g c}$$ Compton wavelength

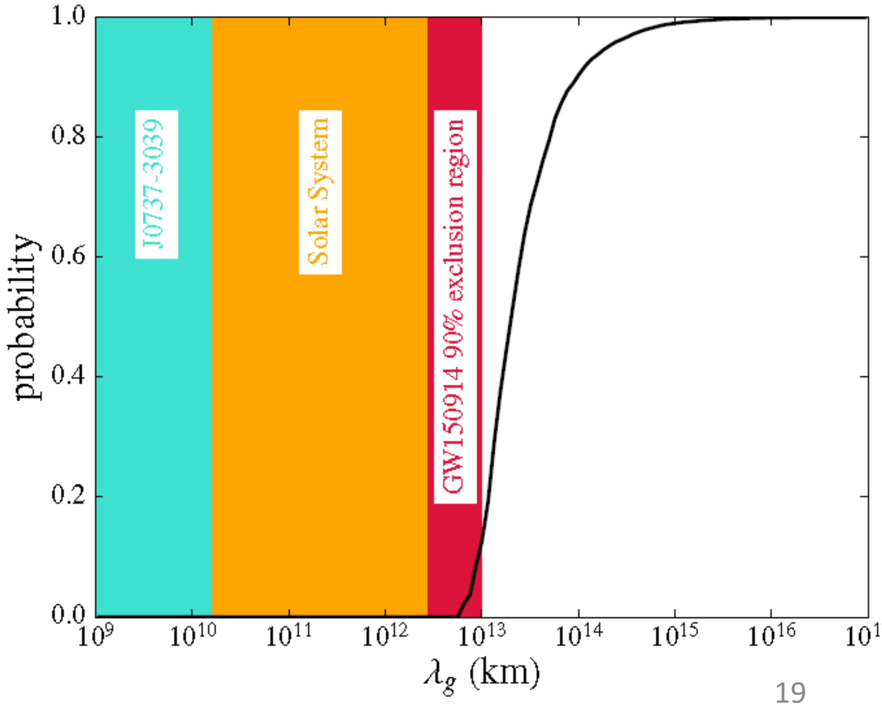
$\Rightarrow$ 1 PN effect on GW phase evolution, $\propto$ Distance

90% bound from GW150914 is the best direct bound:

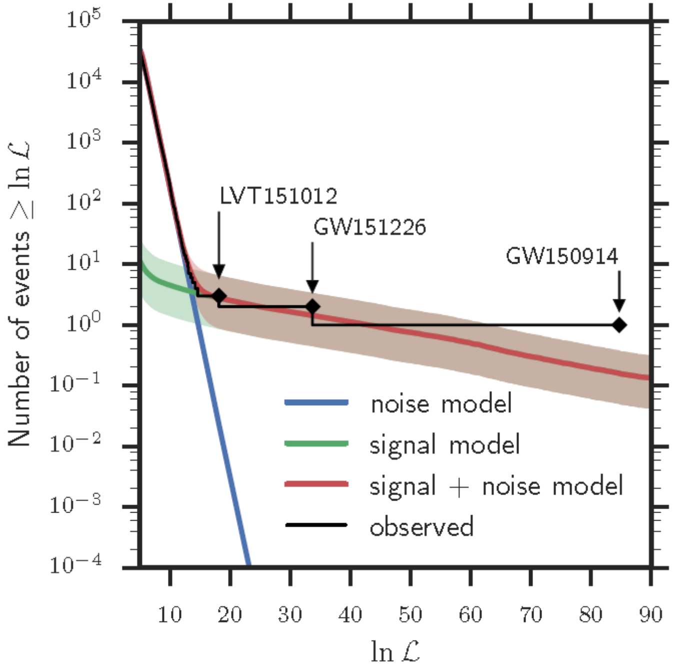
$$\lambda_g > 1.6\ 10^{13}\ km$$

$$m_g < 1.2\ 10^{-22}\ eV/c^2$$

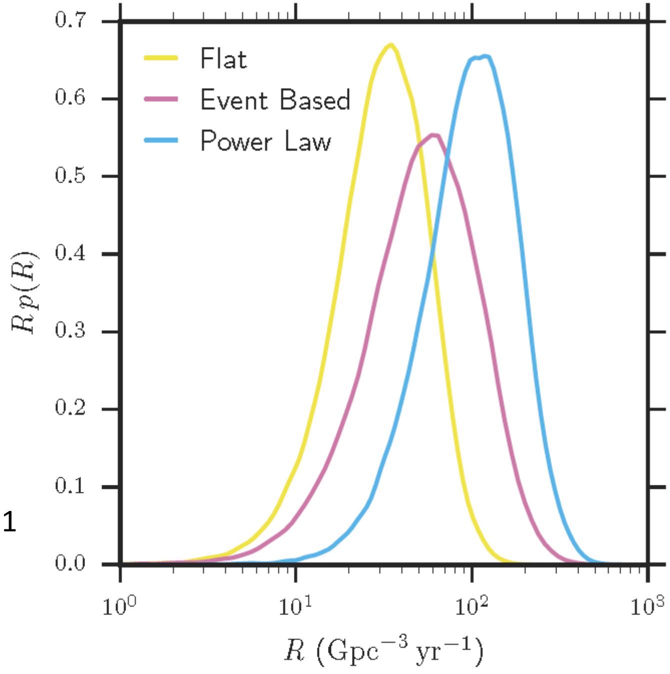
All other more stringent bounds to date are models/assumptions dependent (e.g. weak gravitational lensing relies on dark matter distribution …)



rate of Binary Black Hole mergers

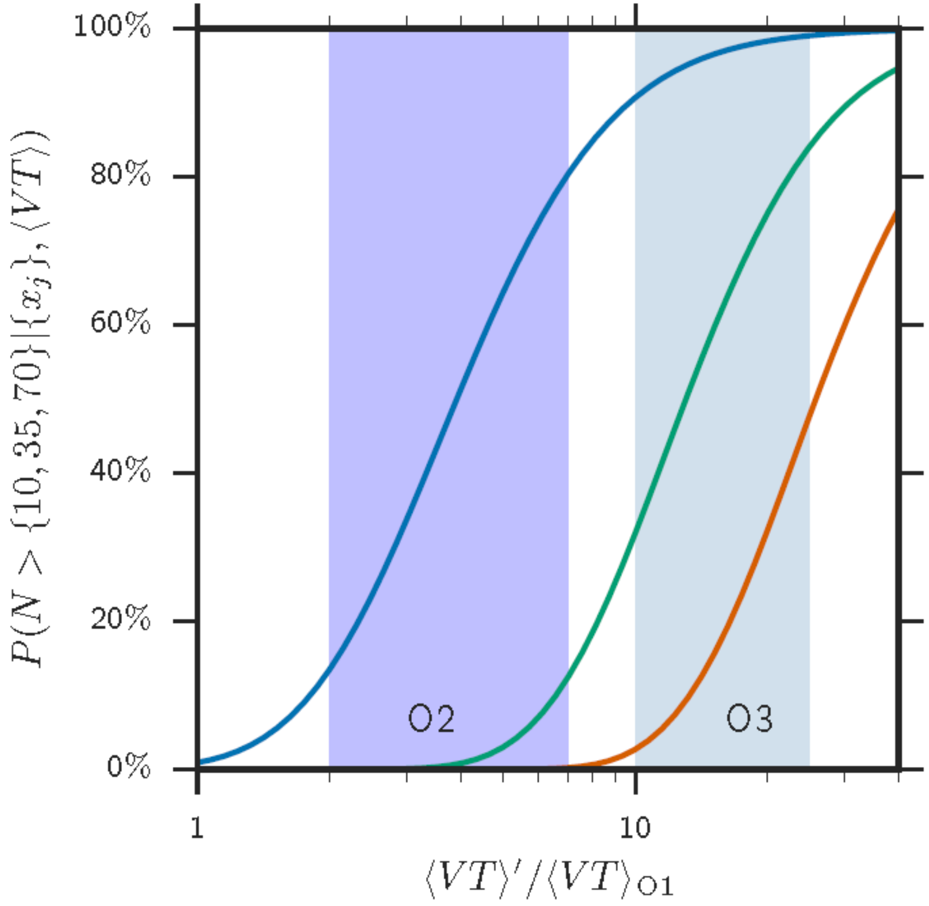


Modeling the observed distribution as sum of contributions of terrestrial origin + astrophysical origin (with different formation models)



Rates range at 90% confidence: 9-240 Gpc^{-3} yr^{-1}

rate of Binary Black Hole mergers

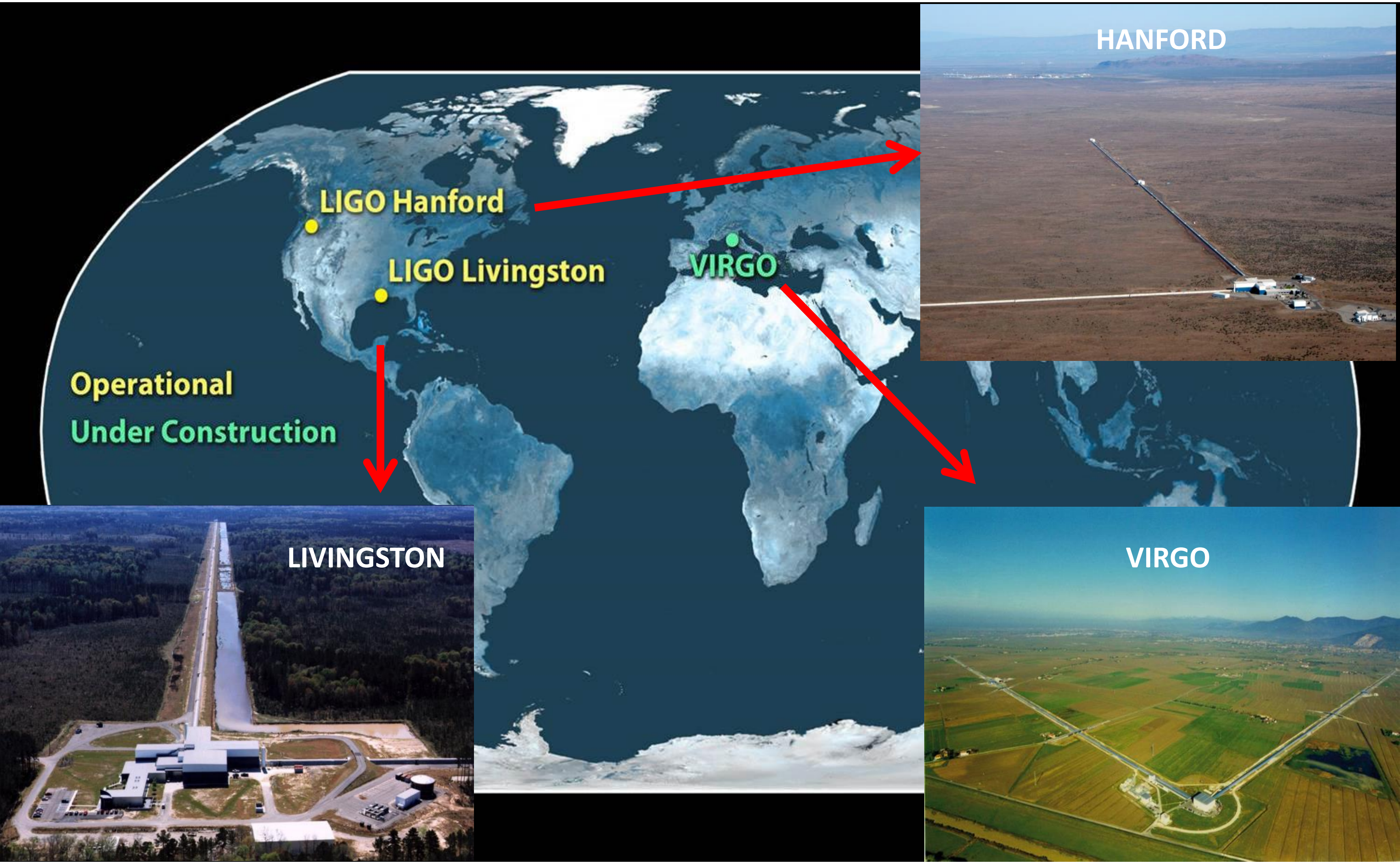


P(N>10)
P(N>35)
P(N>70)

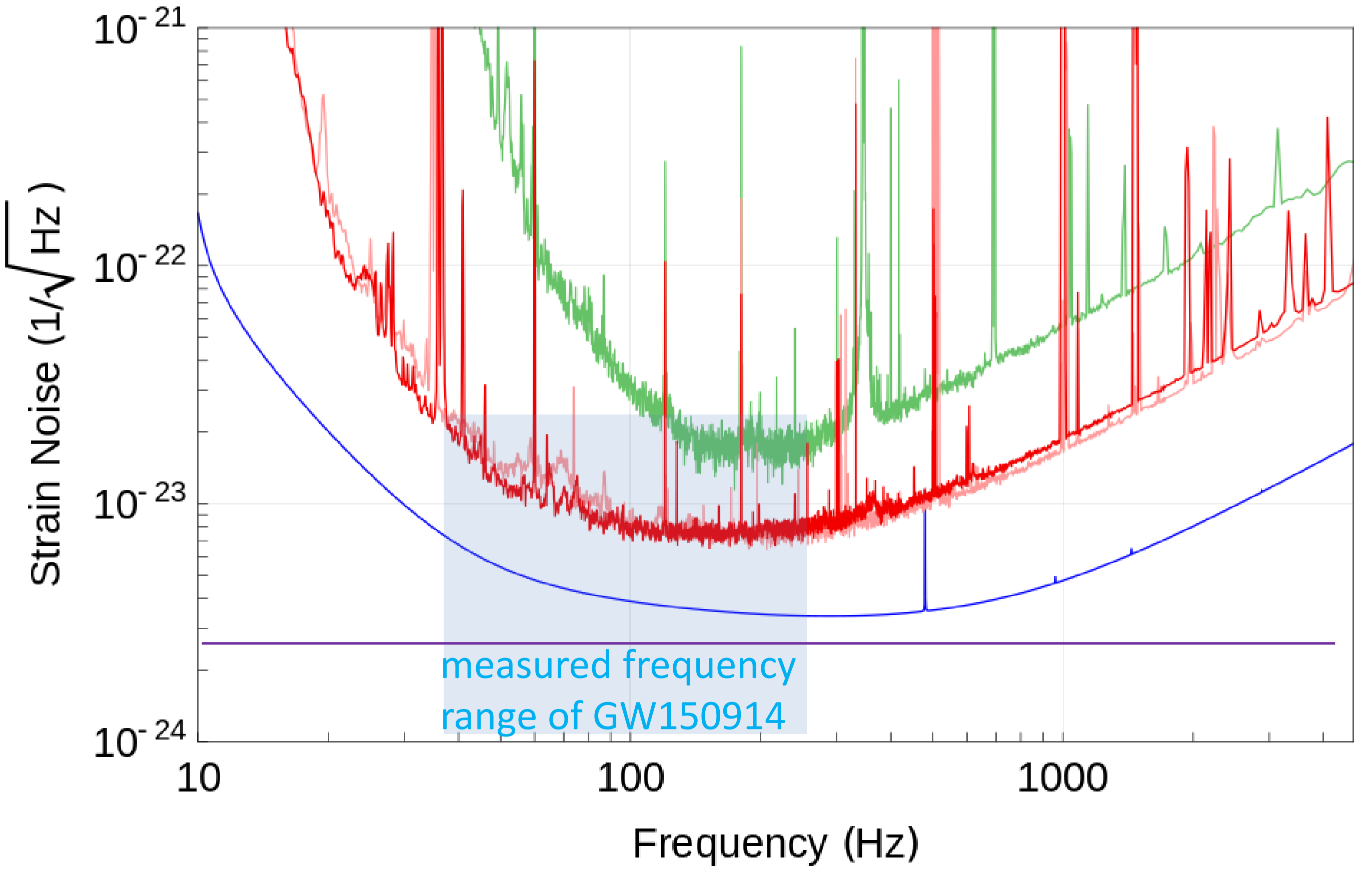
Probability of N detections as a function of surveyed time-volume normalized to LIGO O1 observation

Standing questions:
Dynamical formation or isolated binary evolution ?
Recent formation and prompt merger or early universe formation and long lived binaries ?
No-hair theorem ? Second law of BH dynamics ? Extension to General Relativity ?

The LIGOs and Virgo long-arm detectors



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

- ☐ **first 16days of 2015 joint observation** exceed detection potential of all previous observations

Michelson Interferometers

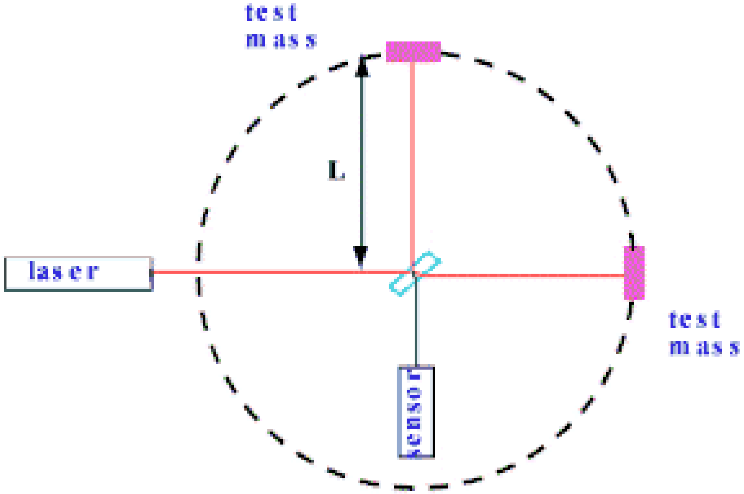
Measuring distance changes by light beams.

Differential changes ΔL of arms

$\Rightarrow$ optical phase difference $\Delta\phi$ at the antisymmetric port

$\Rightarrow$ light power variations at sensor.

$$\frac{P_{out}}{P_{in}} = \sin^2\left(\frac{2\pi\left(L_x - L_y\right)}{\lambda_L}\right)$$



- 2 almost **balanced-length arms** allow common mode rejection of many technical noises.
- Operation close to **dark fringe** ($P_{out} \sim 0$) allows a «null measurement», i.e. more favorable $\Delta P_{out}/P_{out}$
- Want **high P_{in}** : signal scales with circulating power

Michelson Interferometers and GWs

effect of an harmonic gravitational wave with $f_{GW}\lambda_{GW}$=c

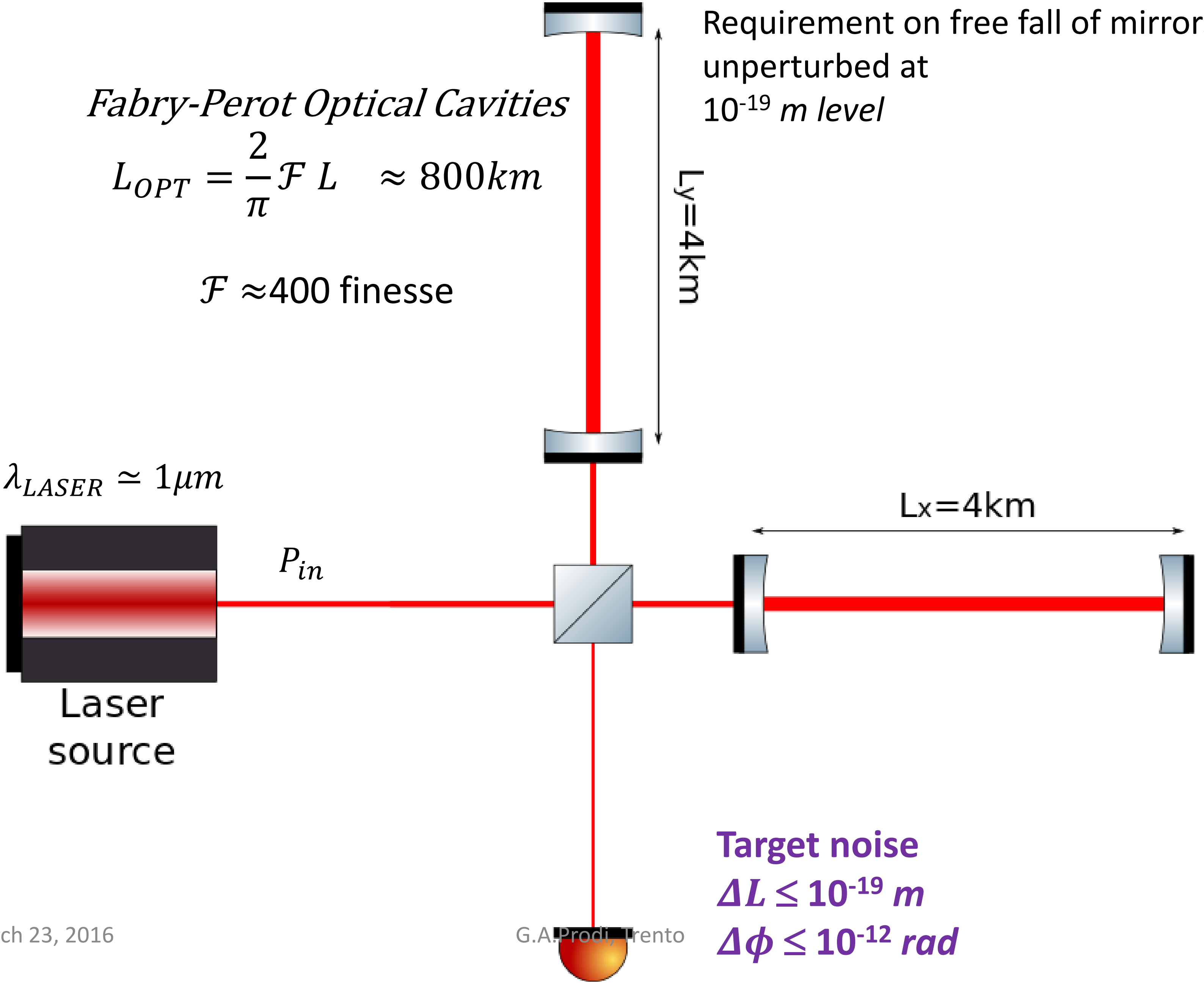
$$\frac{P_{out}}{P_{in}} = \sin^2\left(\frac{2\pi\left(L_x - L_y\right)}{\lambda_L} + 2h_0 \boxed{\frac{2\pi}{\lambda_L} L \operatorname{sinc}\left(\frac{2\pi}{\lambda_{GW}} L\right)} \cos\left(2\pi f_{GW} t - \frac{2\pi L}{\lambda_{GW}}\right)\right)$$

maximum response for $L = \frac{\lambda_{GW}}{4} \Leftrightarrow L = 750km\left(\frac{100Hz}{f_{GW}}\right)$

optimal arm length

- Increase light storage time in each arm by **optical resonant cavities**

Optical layout



Requirement on free fall of mirrors:
unperturbed at
10^{-19} *m level*

Fabry-Perot Optical Cavities

$$L_{OPT} = \frac{2}{\pi}\mathcal{F}\,L \quad \approx 800km$$

$\mathcal{F}$ ≈400 finesse

$\lambda_{LASER} \simeq 1\mu m$

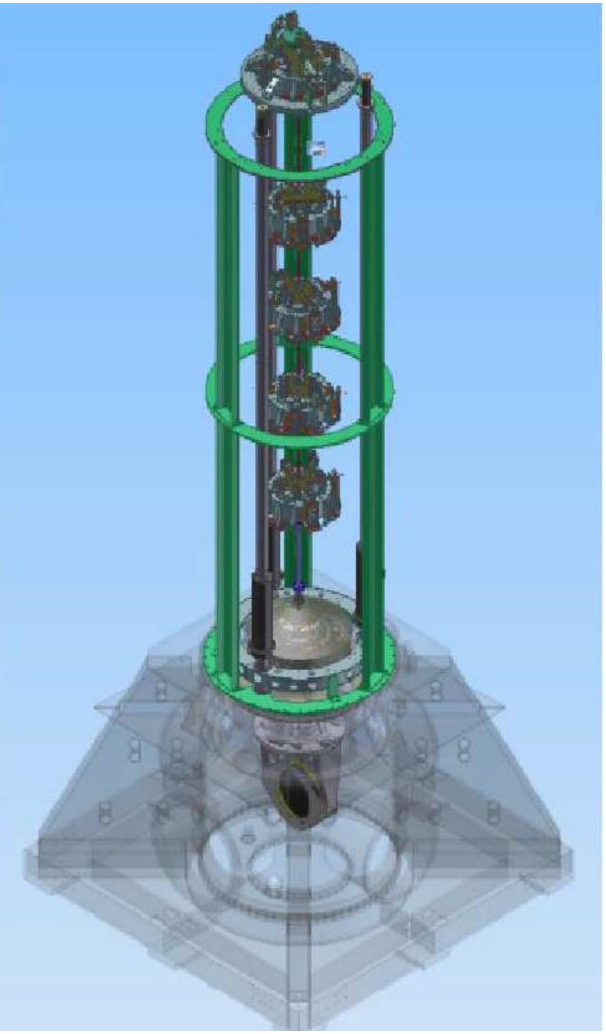
Target noise

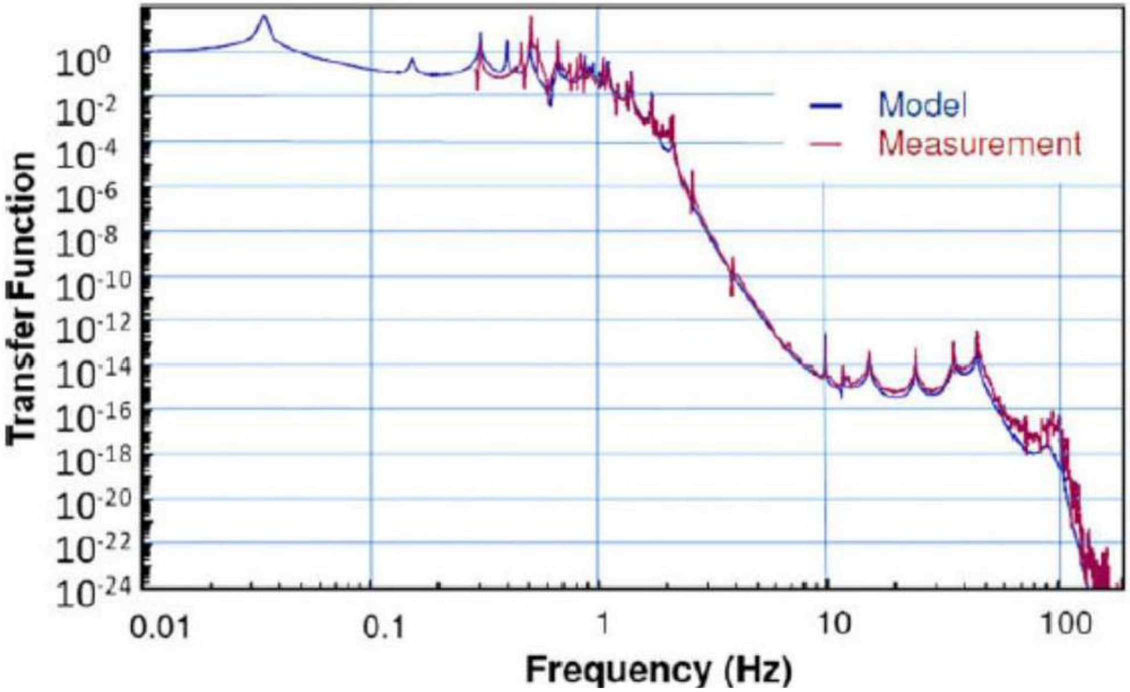
$\Delta L \leq 10^{-19}\ m$

$\Delta\phi \leq 10^{-12}\ rad$

Mirrors' free fall

Multi-stage mechanical filters for the mirror's 6 DoF (Super-Attenuator Towers) ensure **> 10^{12} attenuation above 10Hz**

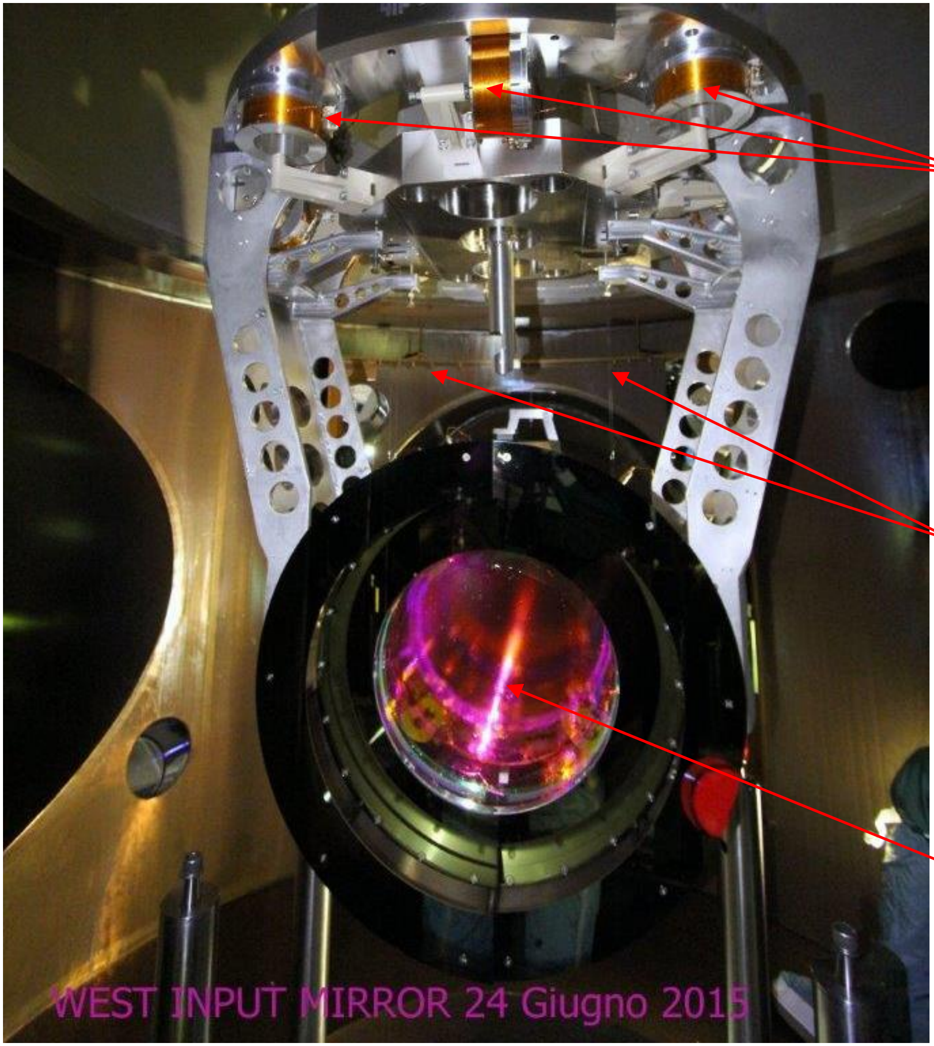




- **Seismic noise** in normal conditions is suppressed
- Hierarchical **controls and actuators** have to ensure $x_{RMS} \sim 10^{-13} m$ and $\theta_{RMS} \sim 10^{-9} rad$ in order to lock the interferometer

innermost suspension stage

Advanced Virgo Mirror suspended



actuators

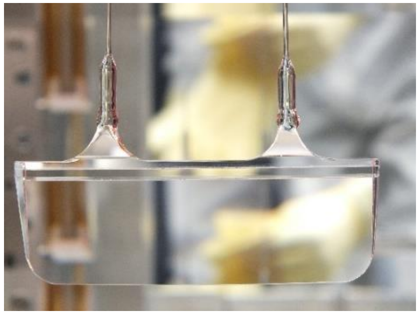
fused silica fibers

mirror

Displacement thermal noise (Brownian noise) is set by mechanical dissipations through the fluctuation-dissipation theorem.

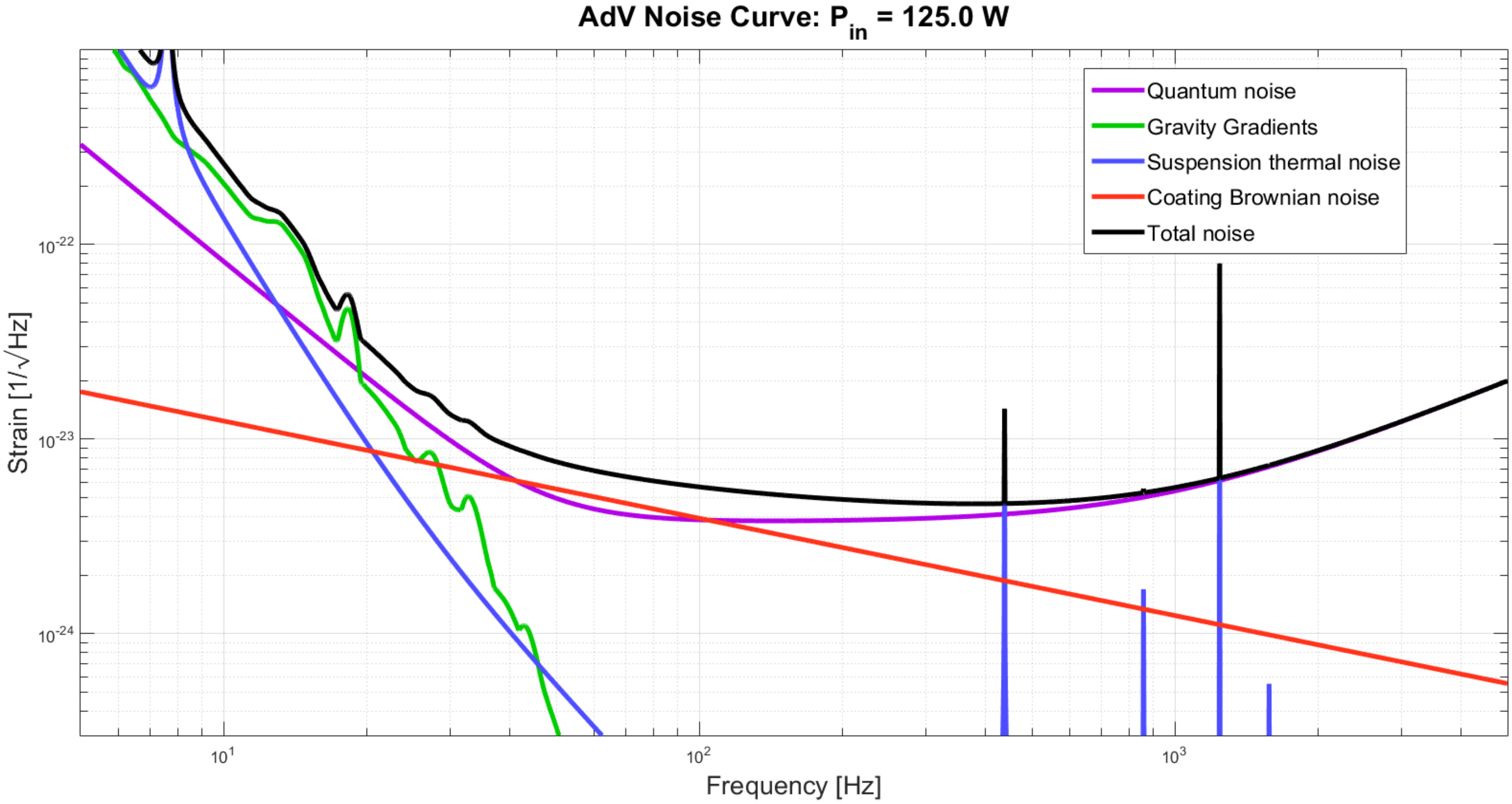
inner stages of suspensions must have very low mechanical dissipations,
i.e. loss angles $\leq 10^{-7}$ rad

“monolithic” suspensions

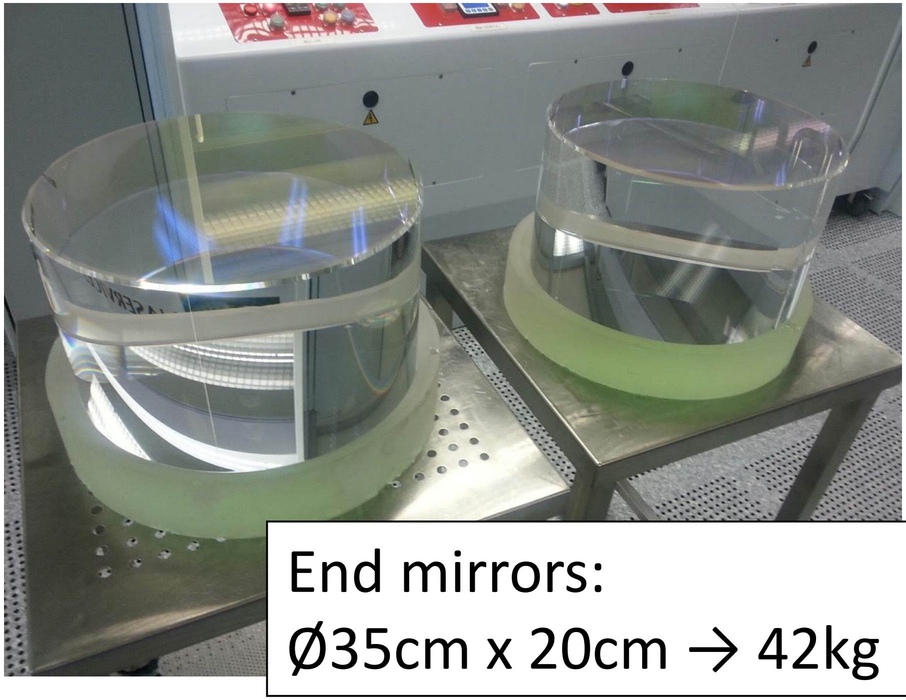


sample noise performances

- Not possible to shield **gravity gradients.** This Newtonian noise is a fundamental limit for the lower frequency end of ground based detectors.

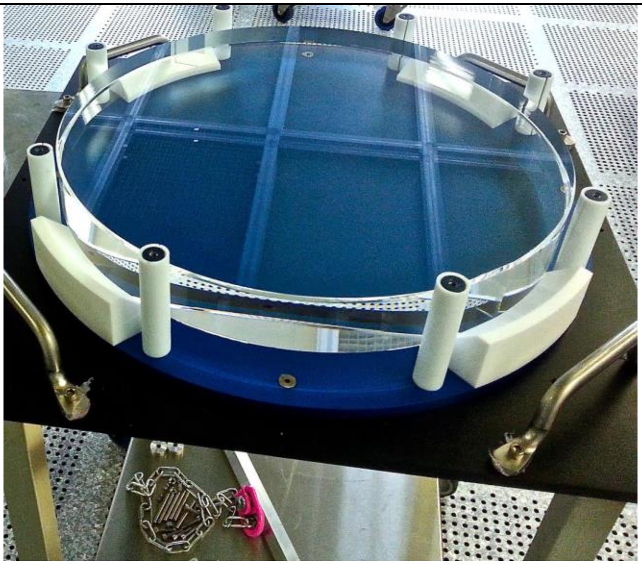


mirrors' reference surface



End mirrors:
Ø35cm x 20cm → 42kg

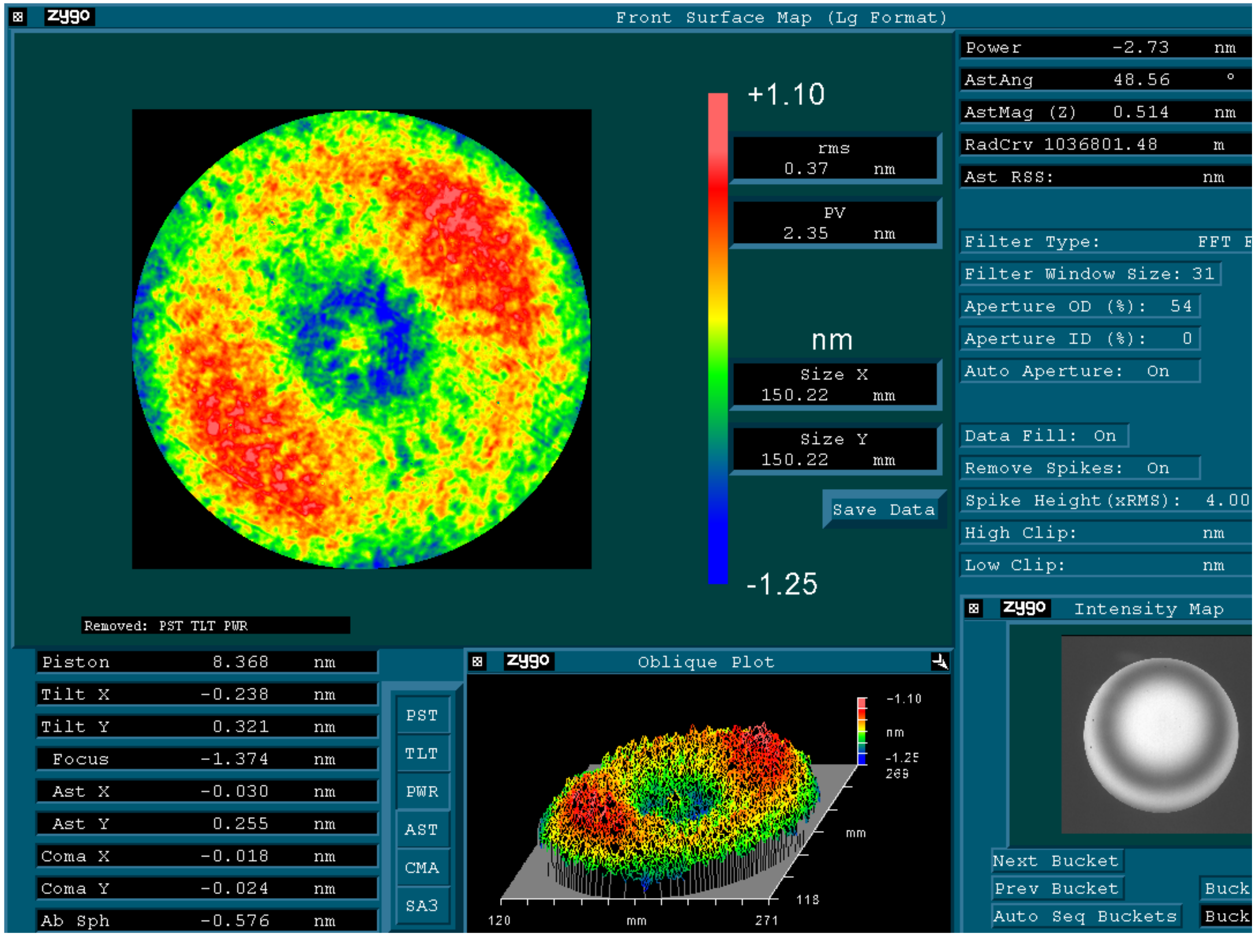
Beam splitter:
Ø55cm x 6.5cm → 34kg



Very large area as reference surface to average out noise contribution which are uncorrelated over short scale.

mirrors’ reference surface

Ultra high reflectivity optical coating: multilayer of SiO2 and Tantalum Oxide doped Ti



rms 0.37 nm

PV 2.35 nm

Size X 150.22 mm

Size Y 150.22 mm

Removed: PST TLT PWR

Power -2.73 nm

AstAng 48.56 °

AstMag (Z) 0.514 nm

RadCrv 1036801.48 m

Ast RSS: nm

Filter Type: FFT F

Filter Window Size: 31

Aperture OD (%): 54

Aperture ID (%): 0

Auto Aperture: On

Data Fill: On

Remove Spikes: On

Spike Height (xRMS): 4.00

High Clip: nm

Low Clip: nm

Piston 8.368 nm

Tilt X -0.238 nm

Tilt Y 0.321 nm

Focus -1.374 nm

Ast X -0.030 nm

Ast Y 0.255 nm

Coma X -0.018 nm

Coma Y -0.024 nm

Ab Sph -0.576 nm

radius of curvature ≈1.5 *km*
roughness <0.4 *nm*
diffusion losses <0.3 *ppm*

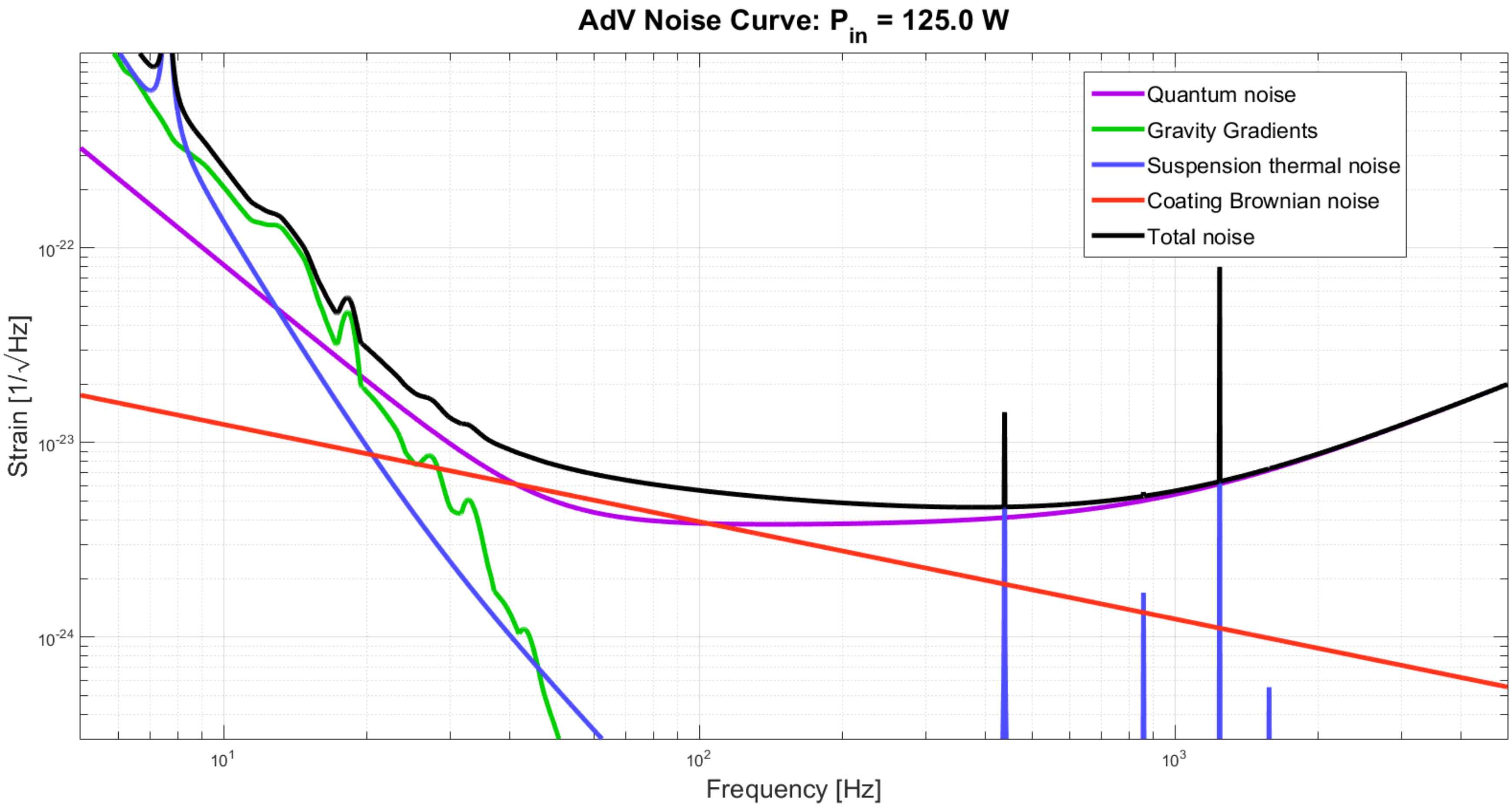
coating thickness ≈ 1 *um*

Brownian noise of coating is the dominating thermal noise, since coating loss angles are $\approx \; 10^{-4}$ *rad*

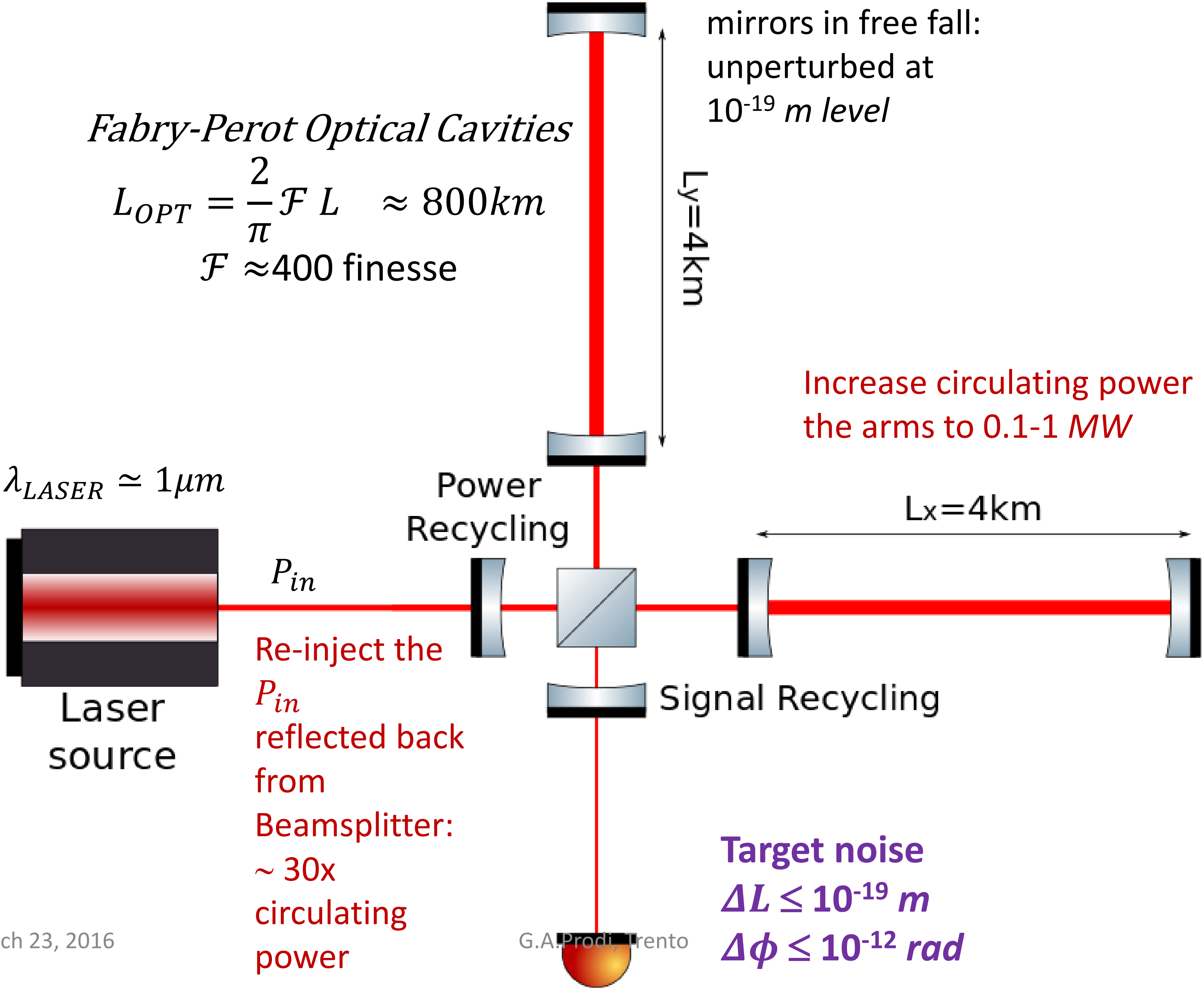
Need to probe the widest area possible with the light wavefront, so to smooth out the contribution of this thermal noise.

sample noise performances

coating thermal noise



Optical layout



mirrors in free fall: unperturbed at 10^{-19} *m level*

Fabry-Perot Optical Cavities

$$L_{OPT} = \frac{2}{\pi}\mathcal{F}\,L \quad \approx 800km$$

$\mathcal{F}$ ≈400 finesse

Increase circulating power in the arms to 0.1-1 *MW*

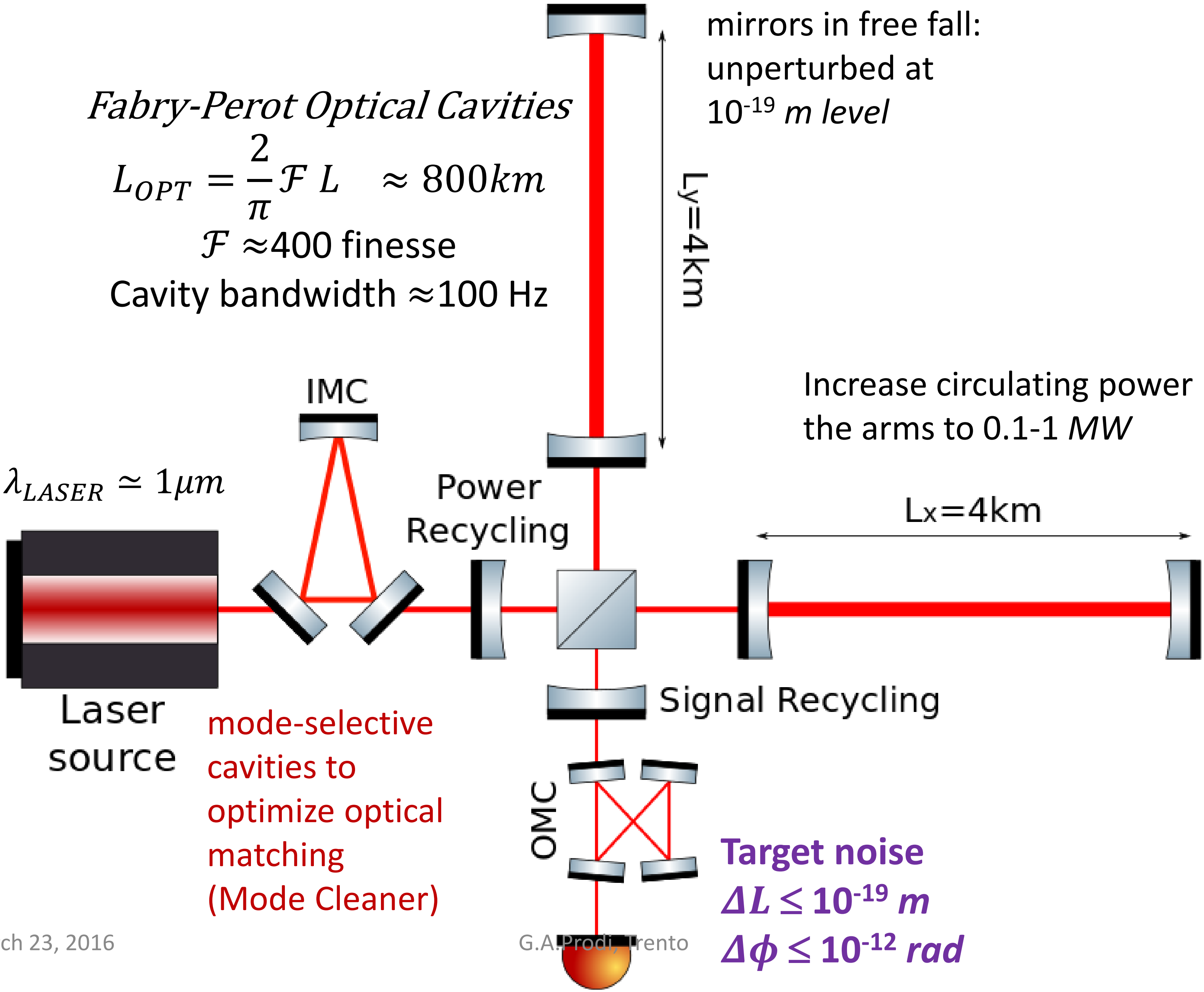
Re-inject the P_{in} reflected back from Beamsplitter: ~ 30x circulating power

Target noise

$\boldsymbol{\Delta L \leq 10^{-19}\ m}$

$\boldsymbol{\Delta \phi \leq 10^{-12}\ rad}$

Optical layout



Fabry-Perot Optical Cavities

$$L_{OPT} = \frac{2}{\pi}\mathcal{F}\,L \quad \approx 800km$$

$\mathcal{F}$ ≈400 finesse

Cavity bandwidth ≈100 Hz

mirrors in free fall: unperturbed at 10^{-19} *m level*

Increase circulating power in the arms to 0.1-1 *MW*

$\lambda_{LASER} \simeq 1\mu m$

mode-selective cavities to optimize optical matching (Mode Cleaner)

Target noise

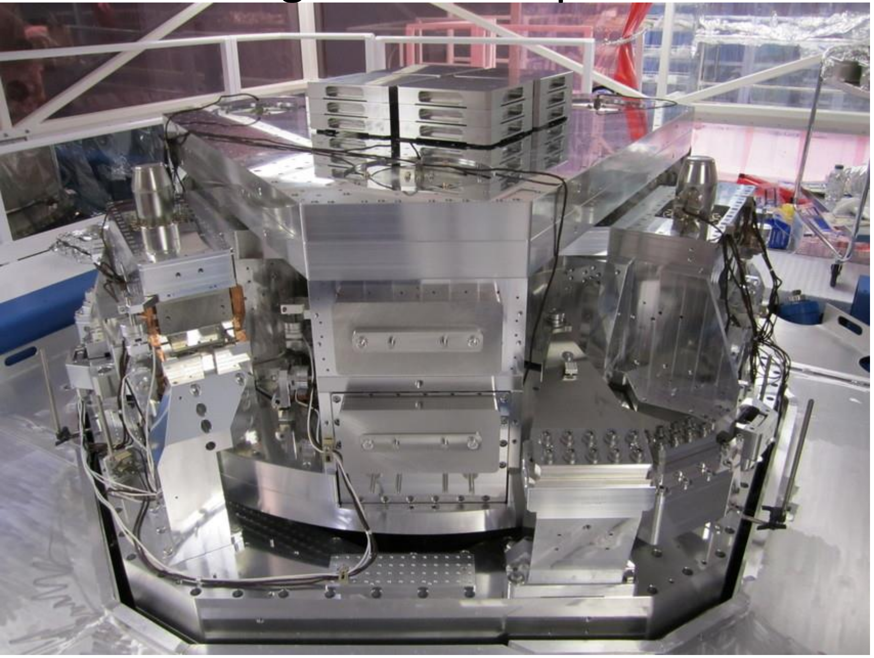
$\Delta L \leq 10^{-19}$ m

$\Delta\phi \leq 10^{-12}$ rad

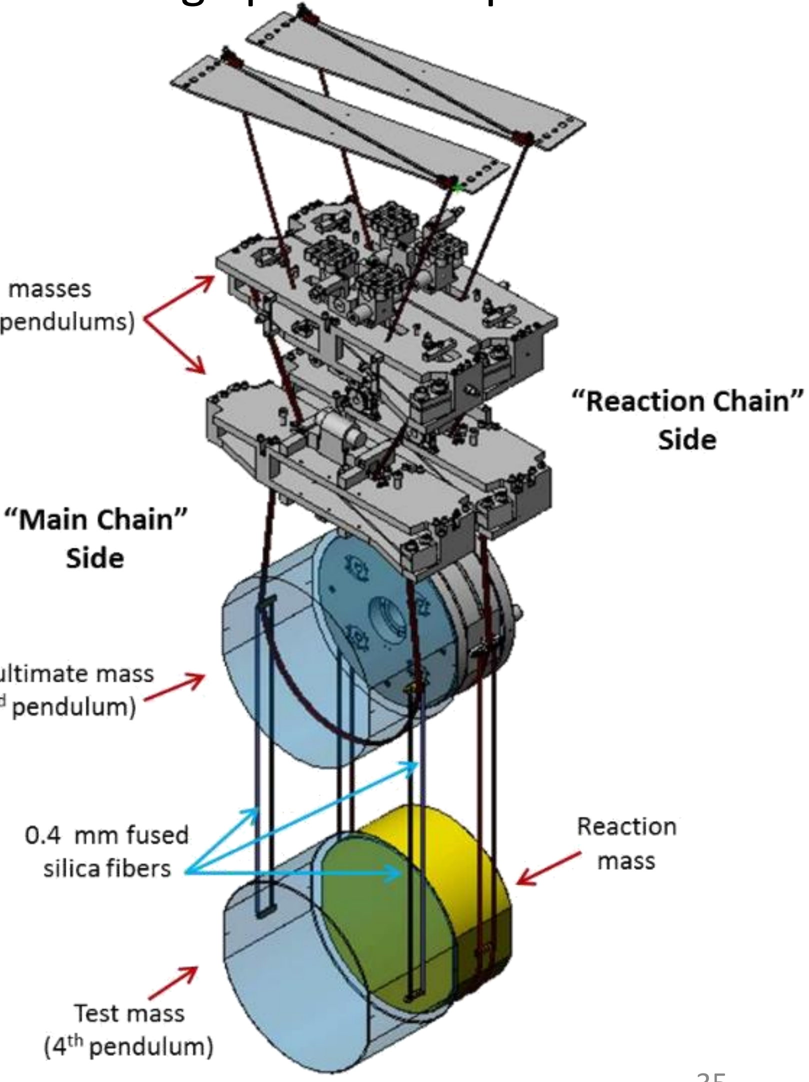
Advanced LIGO upgrades: suspensions

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

first stage active suspension

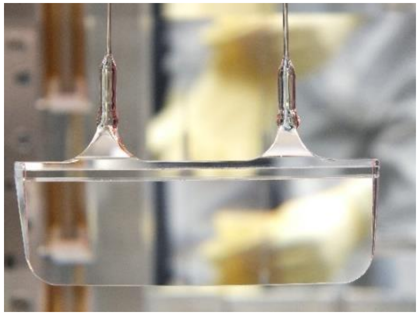


last stage passive suspension



Monolitic suspension

thermal noise reduction



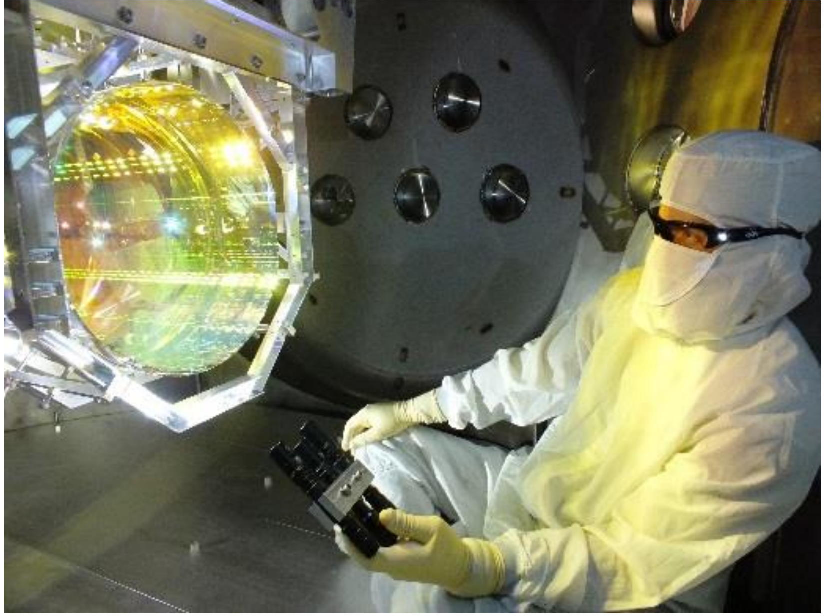
Advanced LIGO upgrades

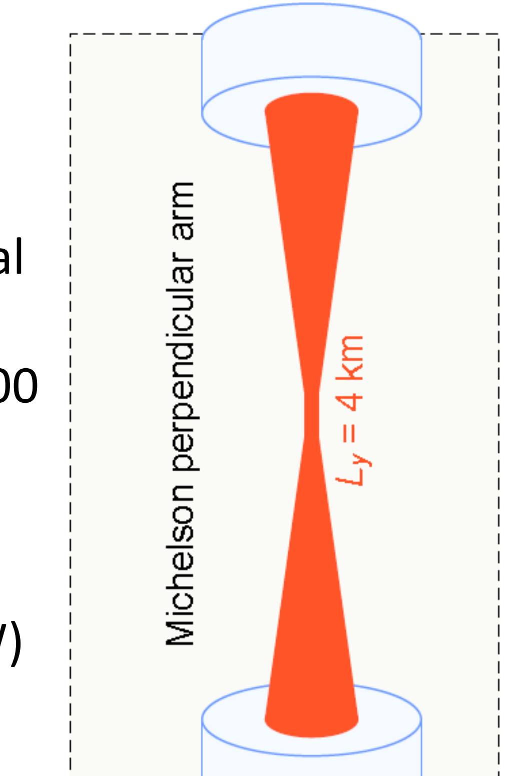
Photon shot noise reduction

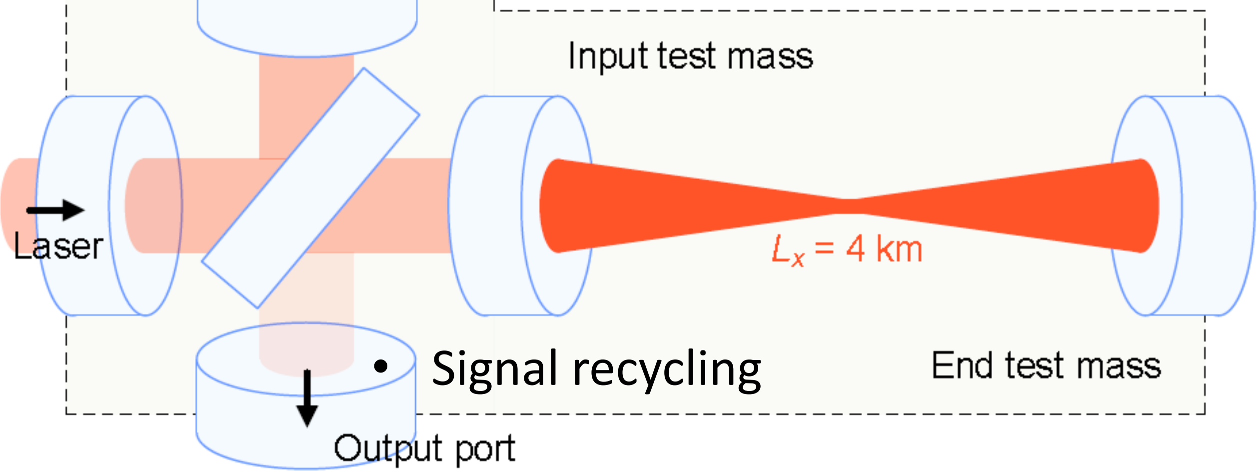
- 4 *km* long optical resonators, optical gain ≈ 300
- 100 kW circulating laser power (design target is 750 kW)

Thermal & radiation pressure noise reduction

Larger mass mirrors, improved coatings



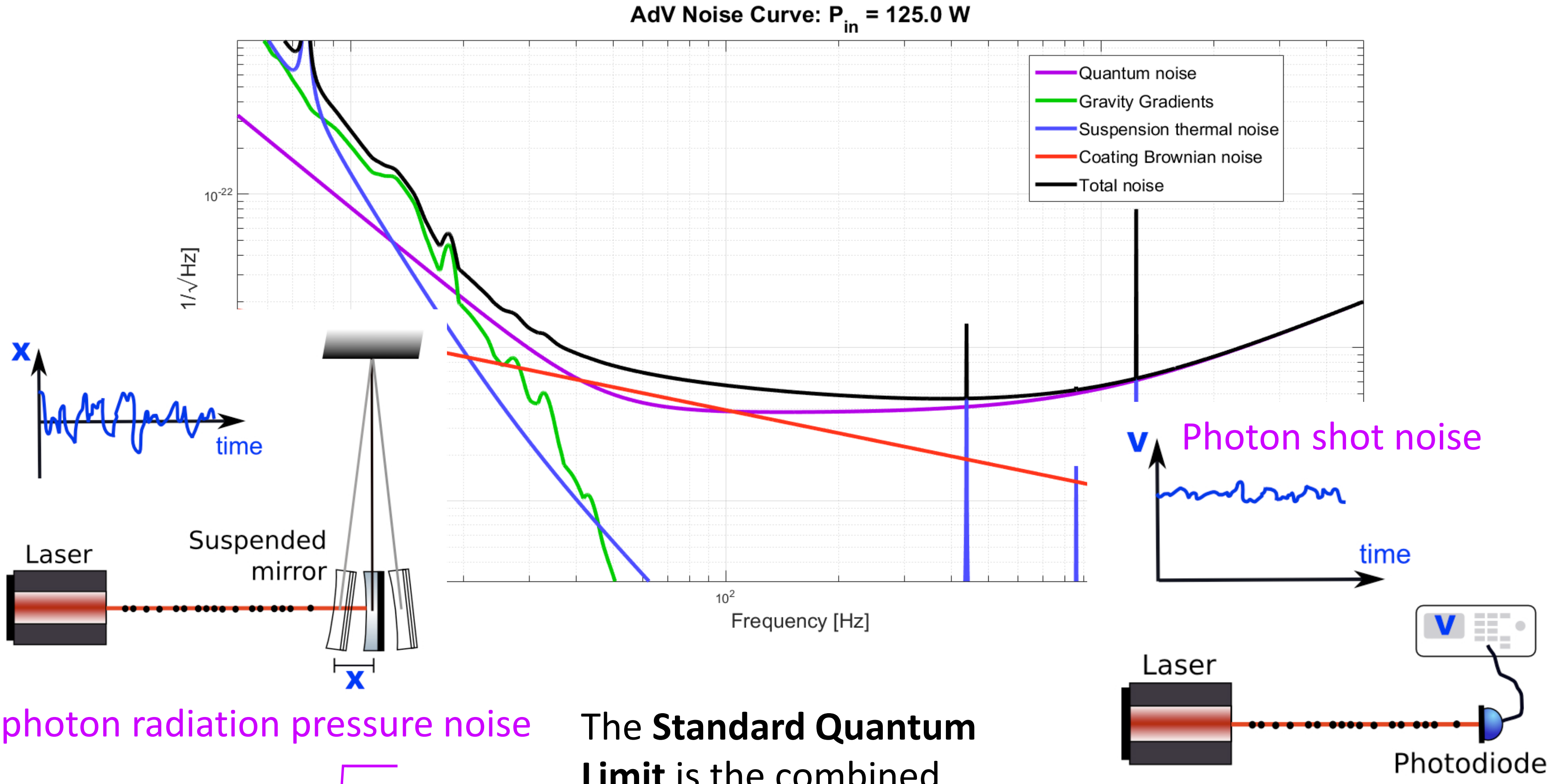




- 20 W input laser (up to 180 W available), 1 Hz line-width
- Signal recycling

quantum noises

photons in a laser beam are a Poisson point process.



photon radiation pressure noise

$$\Delta L(f) \propto \frac{1}{mf^2}\sqrt{\frac{h\boldsymbol{P}}{\lambda c}}$$

The **Standard Quantum Limit** is the combined result of **shot noise + radiation pressure noise**

Photon shot noise

$$\Delta L(f) \propto \frac{\lambda}{2\pi}\sqrt{\frac{h\nu}{\boldsymbol{P}}}$$

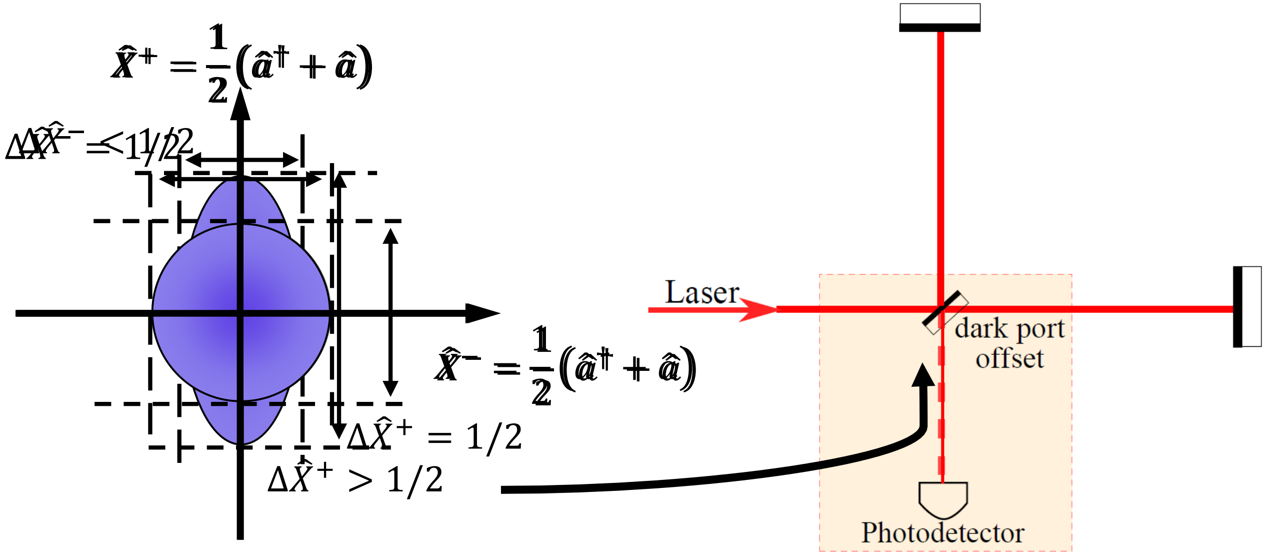
Squeezed Light Sensitivity Enhancement

Once operated on the dark fringe

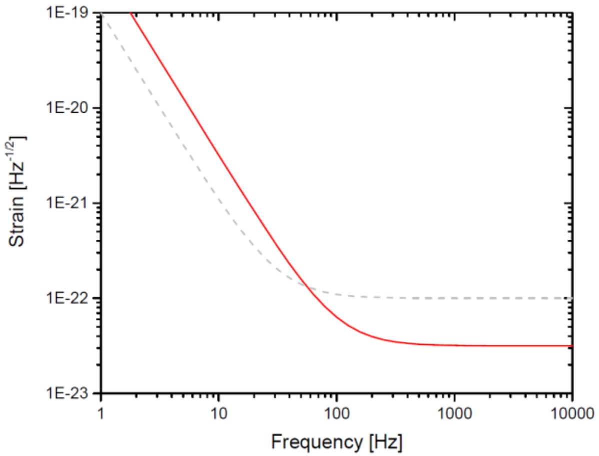
Let's change the vacuum state

GW interferometers are the largest (and most expensive) homodyne detectors for a coherent vacuum state.

squeezed vacuum state



increased sensitivity to GWs in high freq. band



reduces shot noise at the cost of increasing radiation pressure

Demonstrated on GEO and LIGO detectors

LETTERS

nature physics

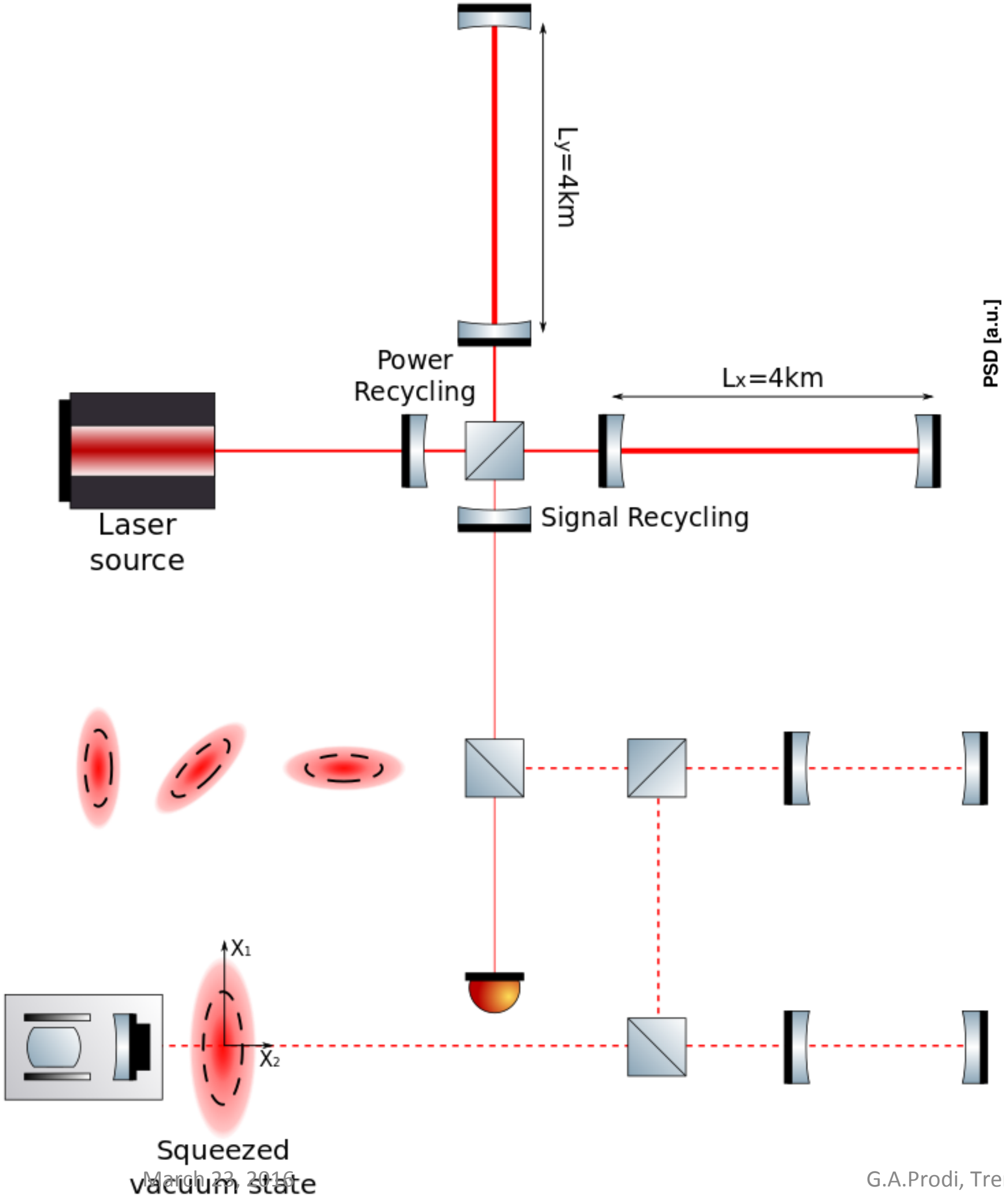
A gravitational wave observatory operating beyond the quantum shot-noise limit

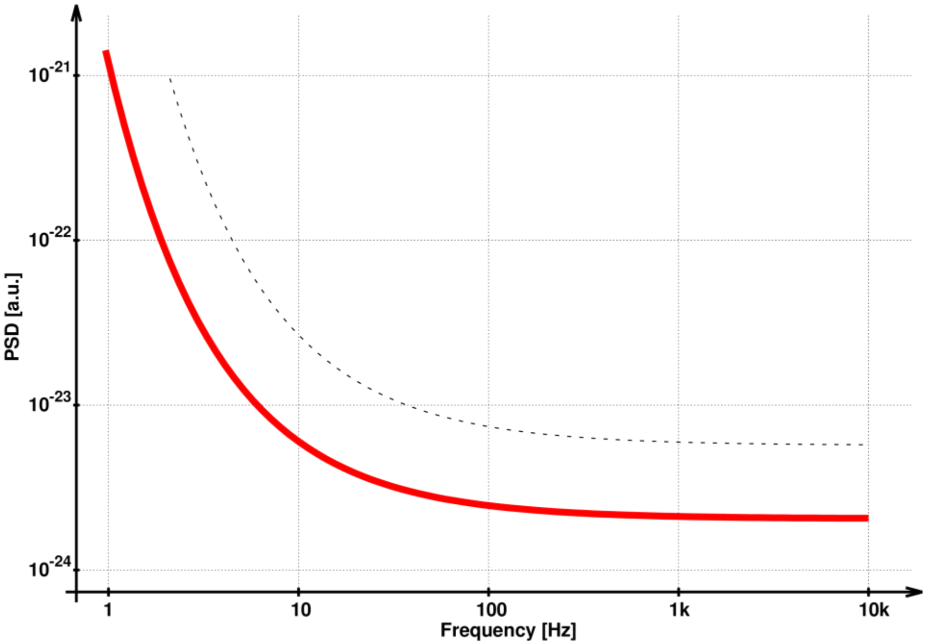
nature photonics

LETTERS

Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light

Frequency dependent squeezing

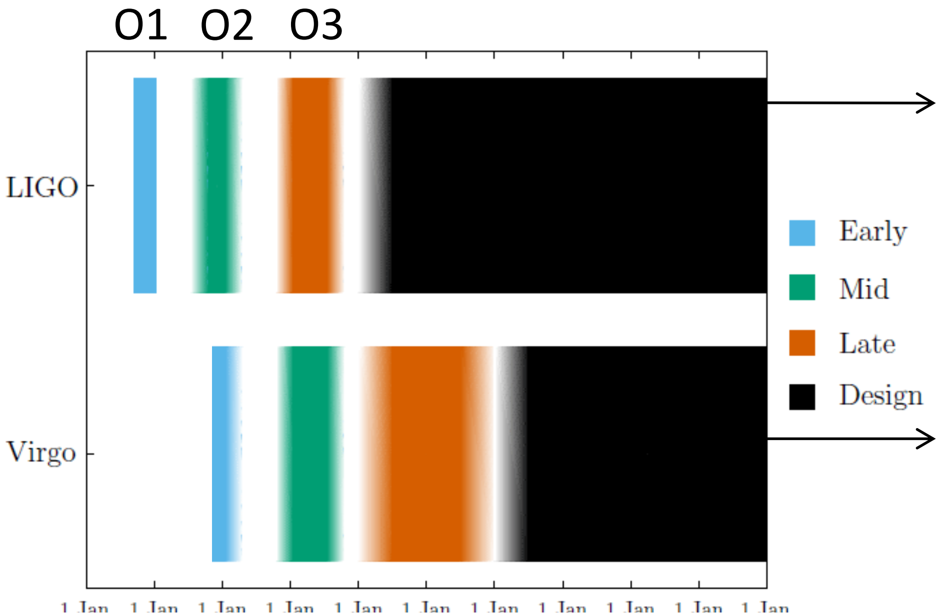




Beyond standard quantum limit

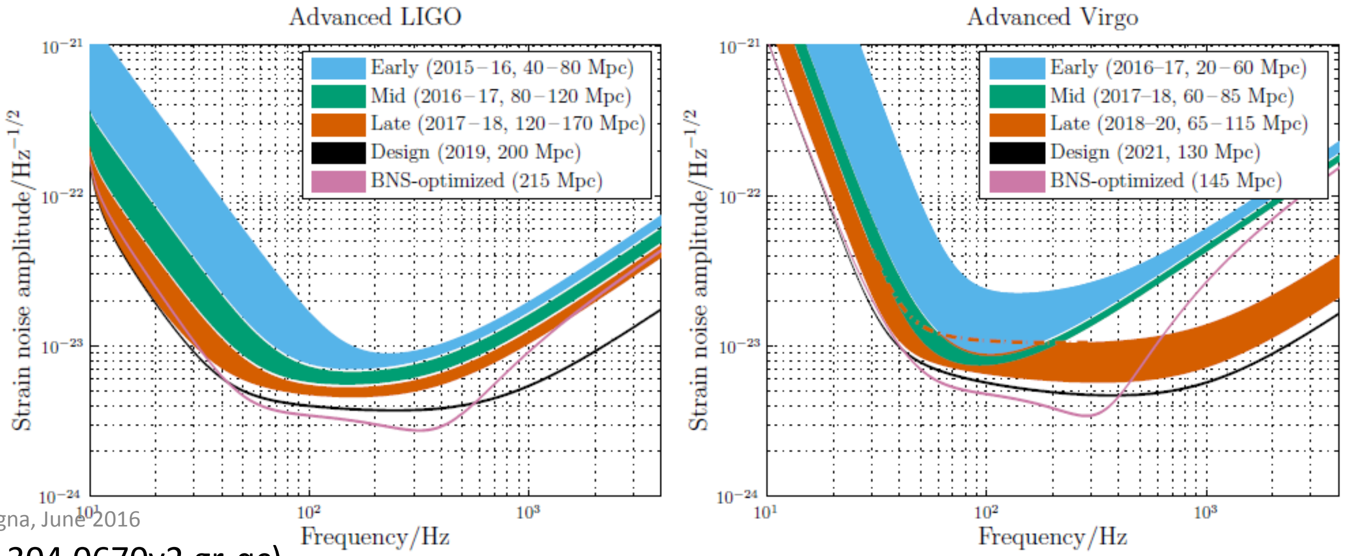
Mid term plans for LIGO-Virgo surveys

Performances upgraded in steps, interleaved by scientific observation runs:



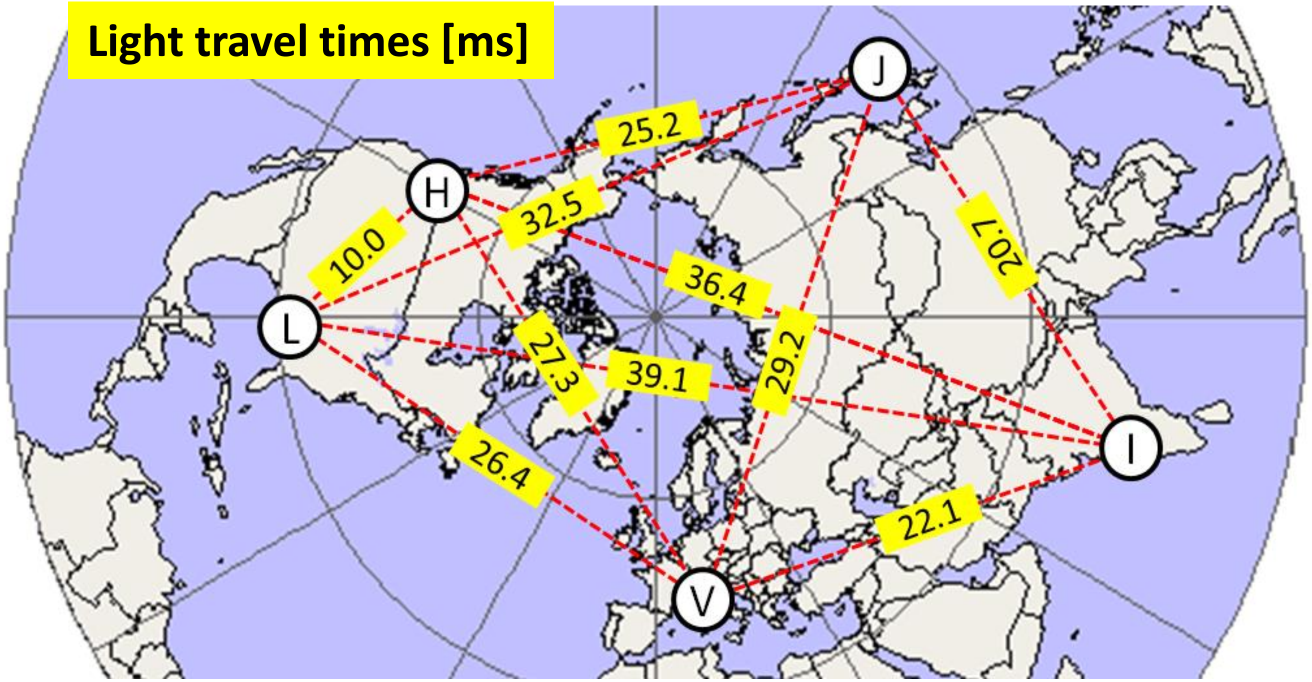
Design sensitivity:

- 1000x gain in surveyed volume of the Universe
- **estimated BNS detection rate: 0.4-400/year**
- sky position error ~5 deg^2



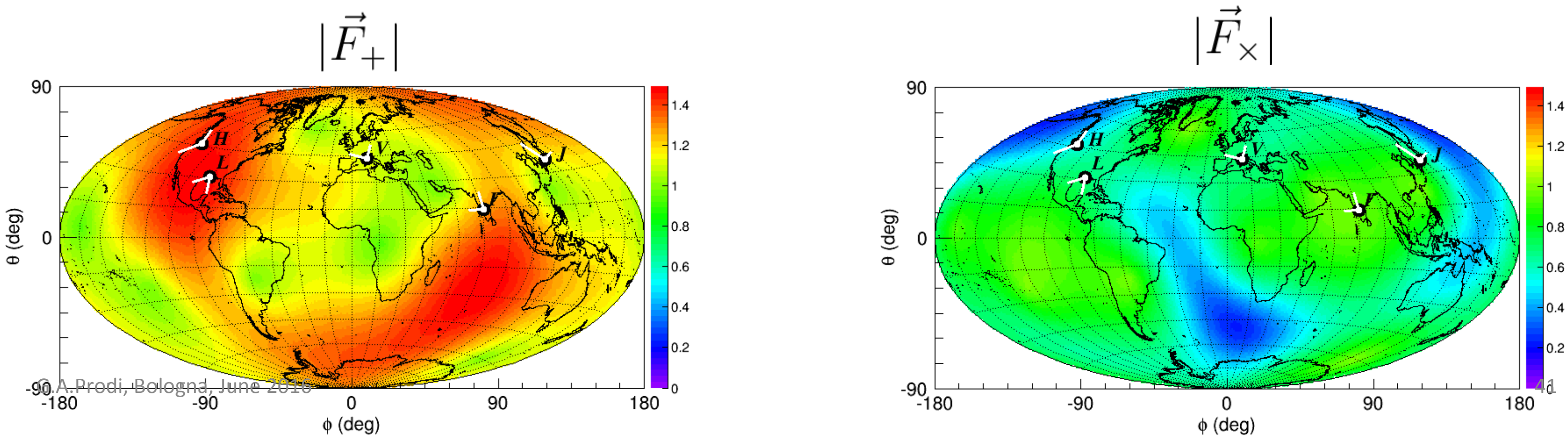
Details in (arXiv: 1304.0670v2 gr-qc)

2019+ scenario



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

Sky coverage of the whole observatory



final remarks

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

  Final results for Binary Black Hole Mergers have been released

  more searches are being pursued, e.g. more massive BBH, transients of generic waveform, triggered searches, multimessenger searches, ...

- ➢ Advanced Virgo will start commissioning of full interferometer in July.
- ➢ the upcoming network will cover both GW polarizations for half of the sky.
- ➢ Advanced interferometers will improve sensitivity by a factor 3 in a 3-5 years time-scale.
- ➢ Binary BH detections will become routine; improving reconstruction of BH characteristics for fundamental physics and for astrophysics.
- ➢ Looking for other sources: NS emissions, ...
- ➢ 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

Equazioni di campo

- Gravitazione Newtoniana: spazio e tempo sono assoluti e infinitamente rigidi
- Relatività Generale : spazio-tempo è dinamico

$$\underbrace{R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu}}_{deformazione\ dello\ spazio-tempo} = \frac{8\pi G}{\underbrace{c^4}_{2.1 \cdot 10^{-43} \frac{1}{N}}}\ \left. T_{\mu\nu} \right\} \begin{array}{l} sorgente\ del\ campo: \\ tensore\ energia \\ -\ impulso \end{array}$$

$$\frac{c^4}{8\pi G} \approx 5 \cdot 10^{42}\ N \approx \frac{10^{42} N}{grado\ di\ liberta'}$$

- Lontanamente somigliante all’equazione dell’elasticità

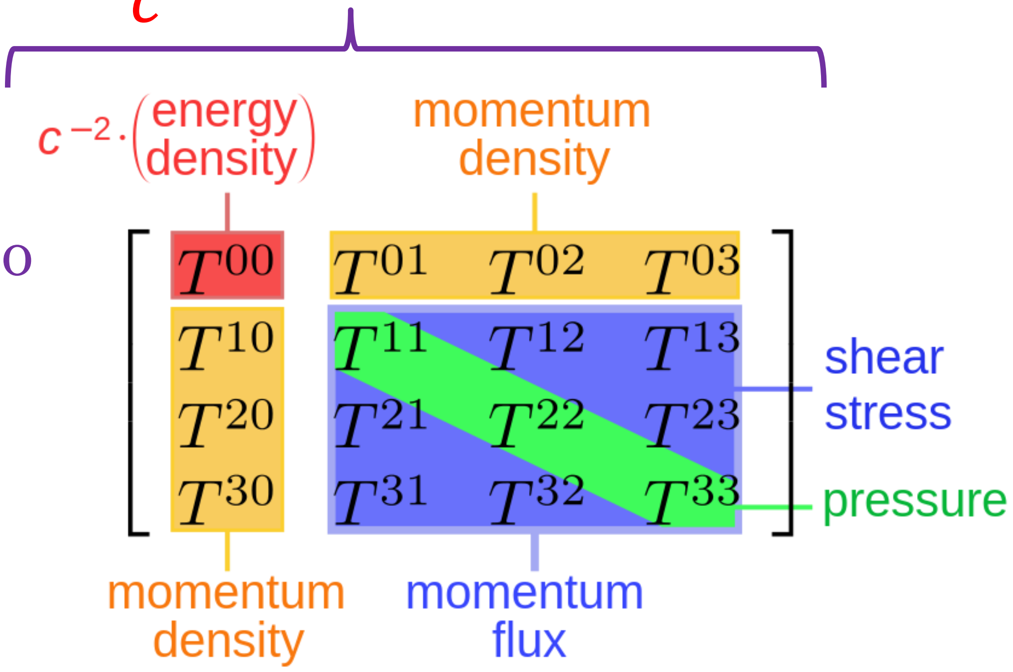
$$strain = \frac{1}{rigidita'}\ stress$$

Equazioni di campo

- Equazione di campo tensoriale, 10 equazioni di cui 6 indipendenti

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = \frac{8\pi G}{c^4}\, T_{\mu\nu}$$

Tensore energia-impulso:



$$\begin{bmatrix} T^{00} & T^{01} & T^{02} & T^{03} \\ T^{10} & T^{11} & T^{12} & T^{13} \\ T^{20} & T^{21} & T^{22} & T^{23} \\ T^{30} & T^{31} & T^{32} & T^{33} \end{bmatrix}$$

deve includere il contributo dovuto al campo gravitazionale stesso

Equazioni NON lineari

Consistency with GR Black Hole solution [arXiv:1602.03841]

❑ Parametrized **waveform models** calibrated to Numerical Relativity simulations. Two methods:

- EOBNR: Effective One Body analytical solutions calibrated to Numerical Relativity simulations for the highest order Post Newtonian terms
- IMRPhenom: phenomenological waveforms from hybridization of EOB (inspiral) with NR (merger, ringdown)

Systematic uncertainties << statistical uncertanties at SNR ~ 25

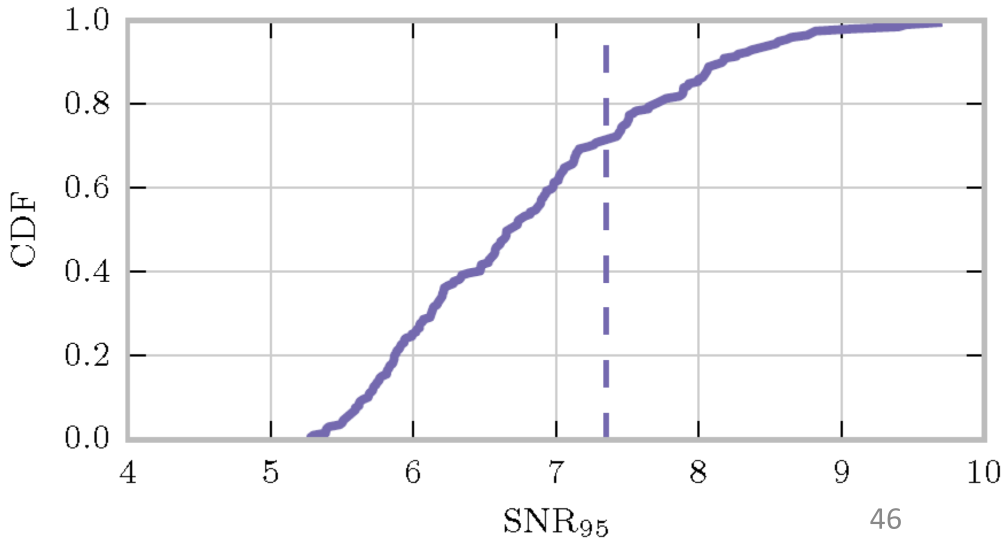
❑ Testing for deviations from GR waveform not degenerate with changes of parameters of the binary.

Leftover residuals of GW150914 by subtracting contributions of the best waveform are not statistically distinguishable from instrumental noise.

95% credible upper bound on network coherent SNR in the residuals is ~ 7.3:

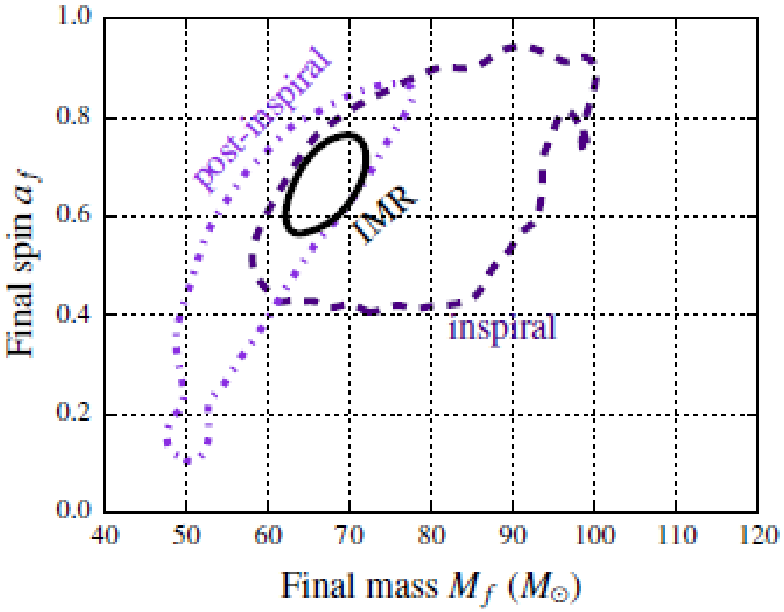
⇒ Fitting Factor of best waveform model to the data > 96%

⇒ < 4% deviations from GR in terms of noise-weighted correlation



Consistency with GR Black Hole solution [arXiv:1602.03841]

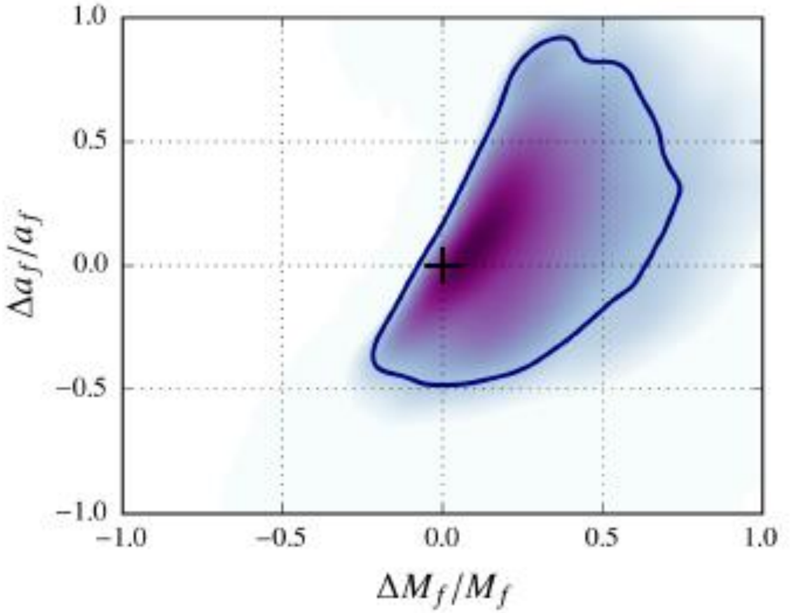
- **Mass** and **spin** of the remnant BH are predicted using separately inspiral phase and post-inspiral phase. Similar to a goodness of fit test.



- 90% credible regions of Inspiral and post-inspiral joint posterior estimates show an overlap.
- sanity check: estimates from entire waveform IMR lies in overlap region

No evidence of inconsistencies.

Fractional difference between inspiral and post-ispiral estimates



- 90% contour

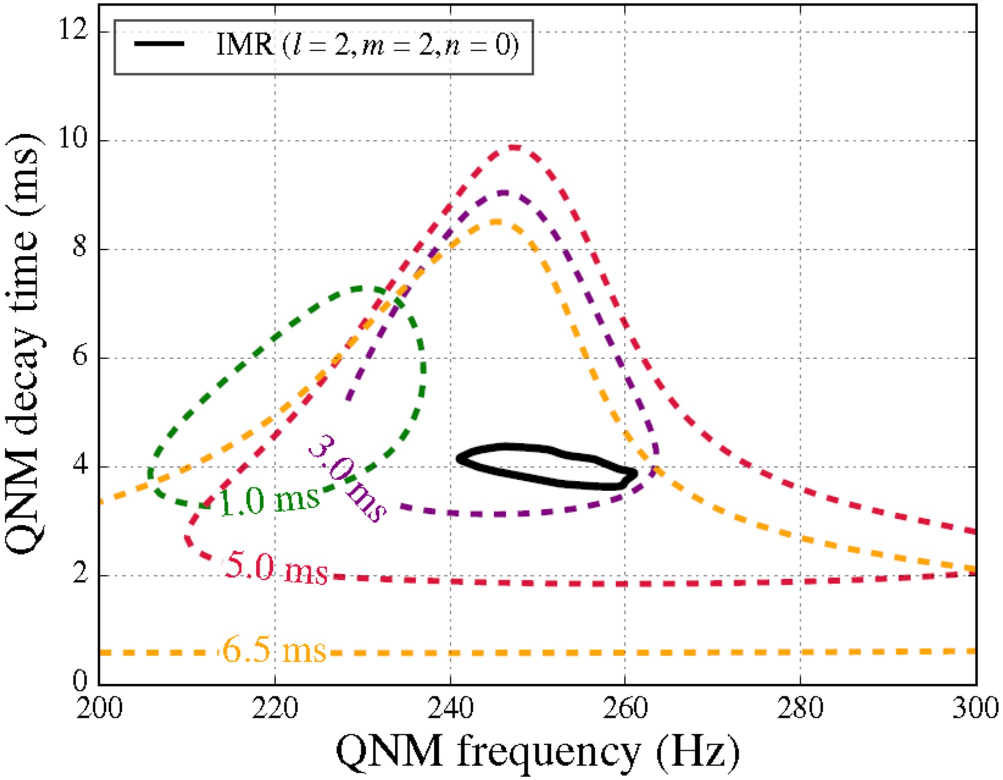
Consistency with GR Black Hole solution [arXiv:1602.03841]

- **Least damped Quasi Normal Mode** of remnant BH: fundamental quadrupolar 2,2,0

NR with GW150914 parameters gives frequency and damping time:

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

this mode should dominate
ring-down phase ~ 3 *ms* ~ 10 *M*
after merger time

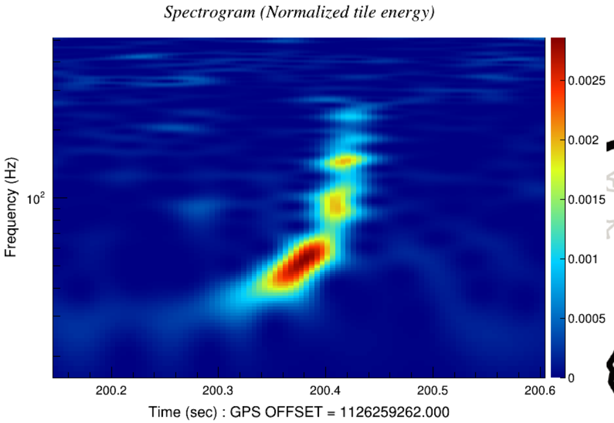


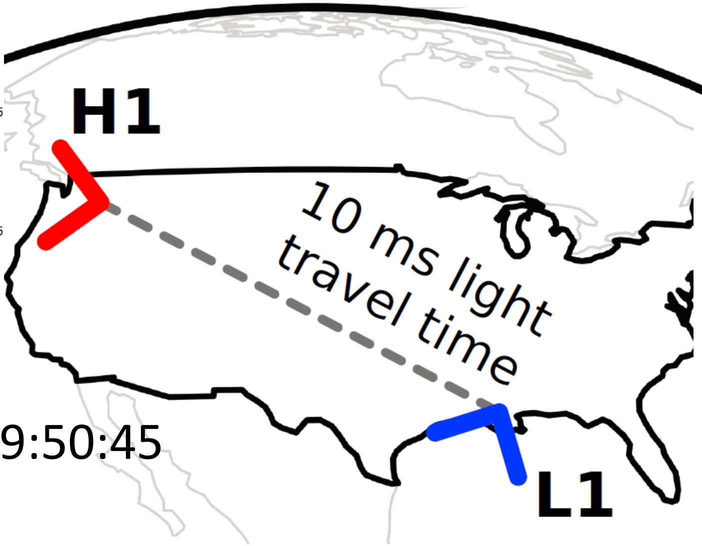
90% credible regions of parameters of a fit to damped sinusoid starting after 1 ms, 3 ms, , 5 ms from merger
⇒ weak direct evidence for this QNM in GW150914

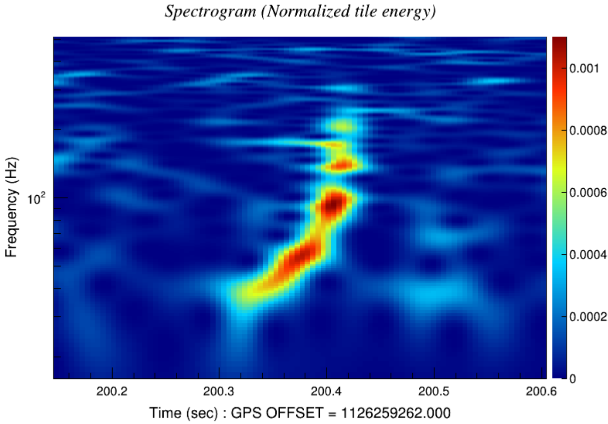
Need to directly measure at least 2 QNMs to test no-hair theorem and 2nd law of BH dynamics

GW150914 chronology

- ☐ Last days of LIGO Engineering Run before planned Science Run



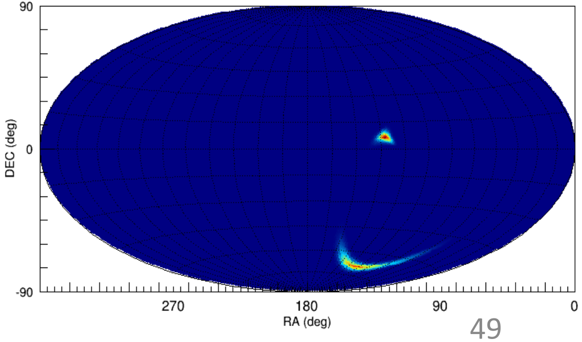




Delay time 7 ms

- ☐ 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)

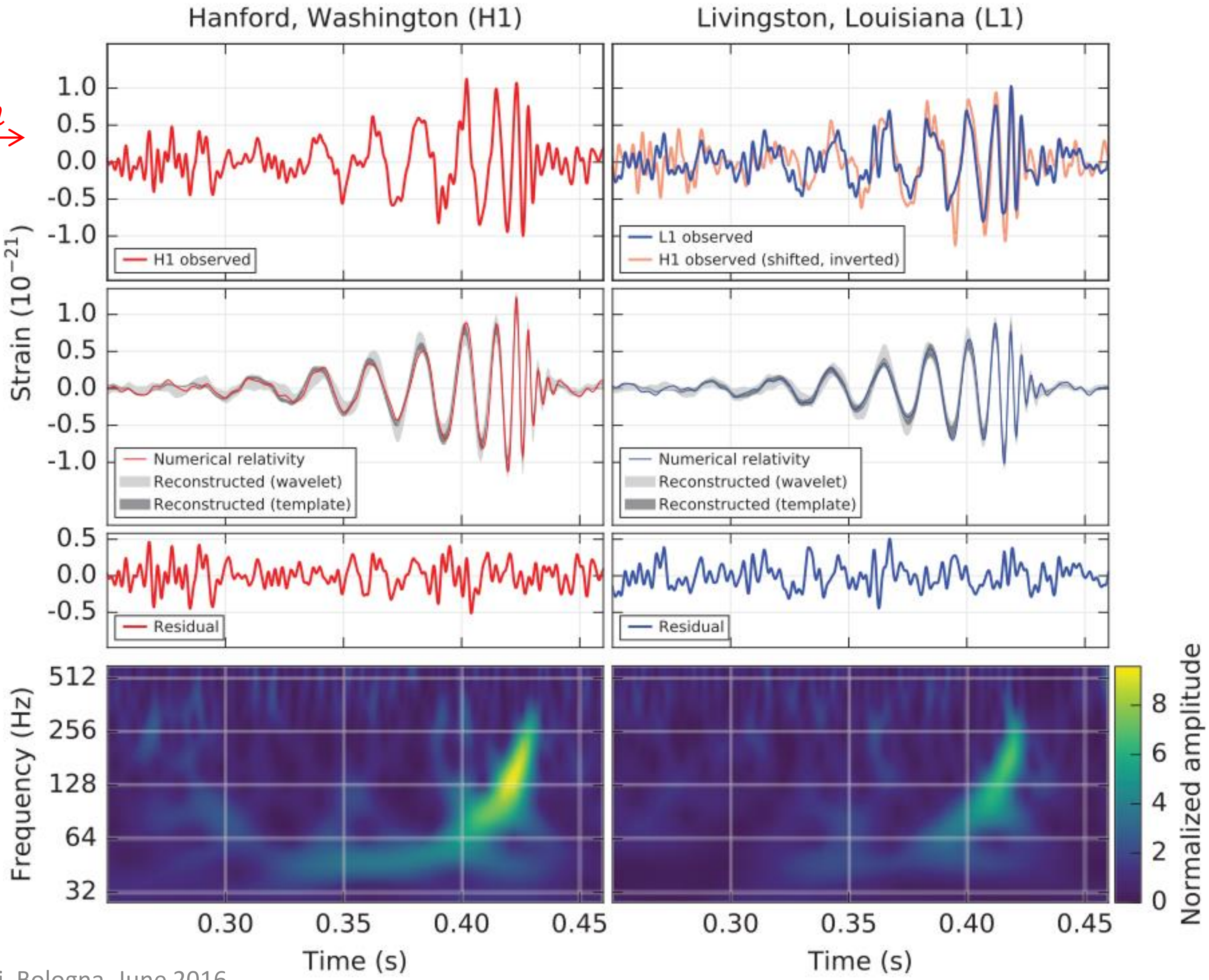
- ☐ decision to **continue observing in stable detector configuration** until **LIGO detectors integrate at least 15 days of joint observation time**

Sept. 12th – Oct. 20th

Resulting joint observation time **17 days**

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

GW150914



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

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

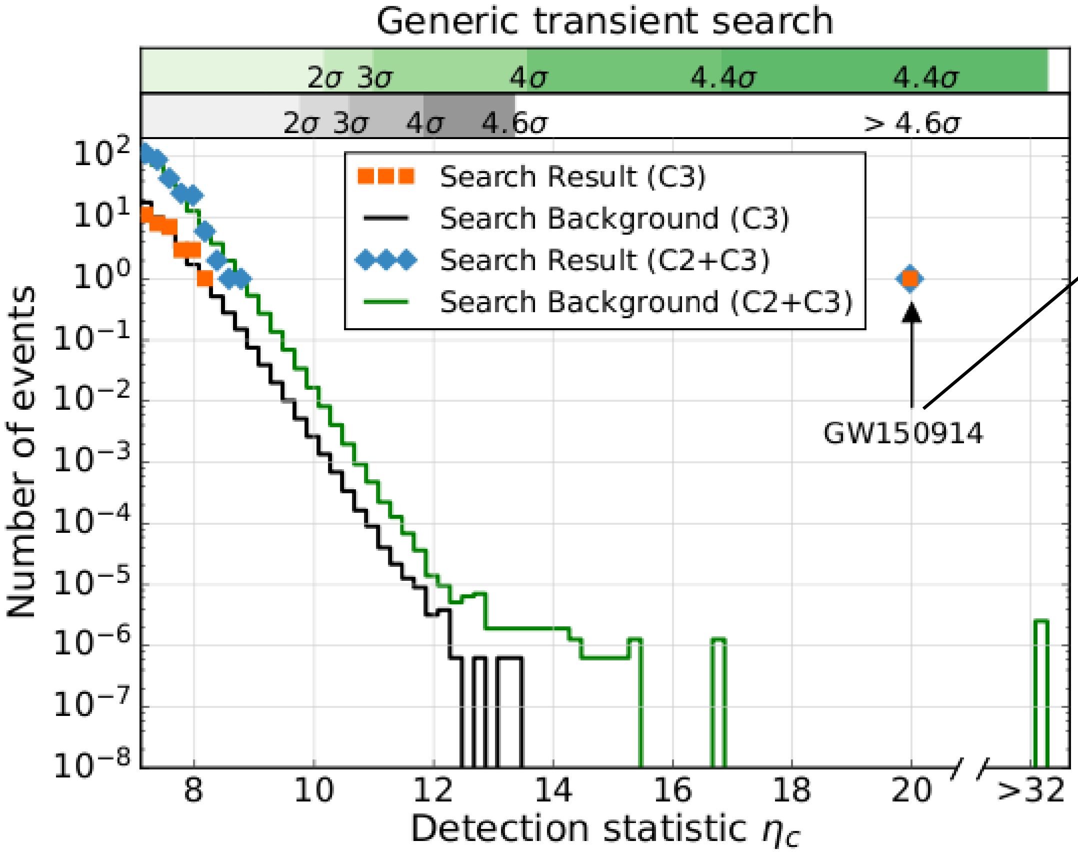
Estimated **False Alarm Rate** of GW150914:

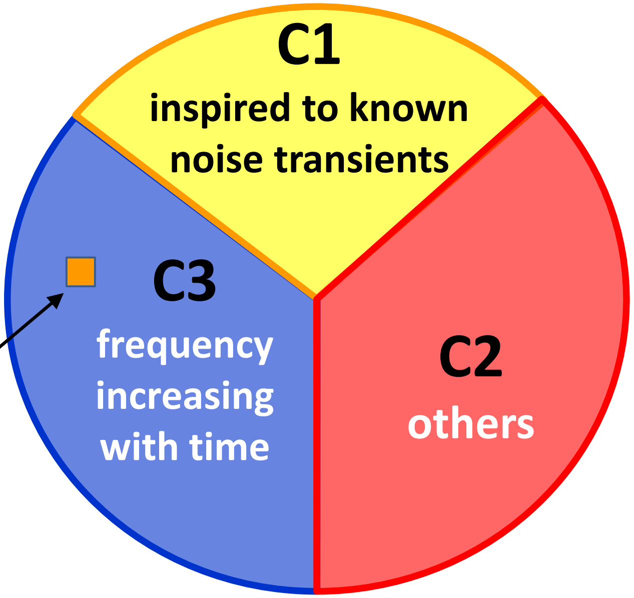
- **< 1 / 22500 years** in wider context of generic transient signals
- **< 1 / 203000 years** within compact binary coalescence signals

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

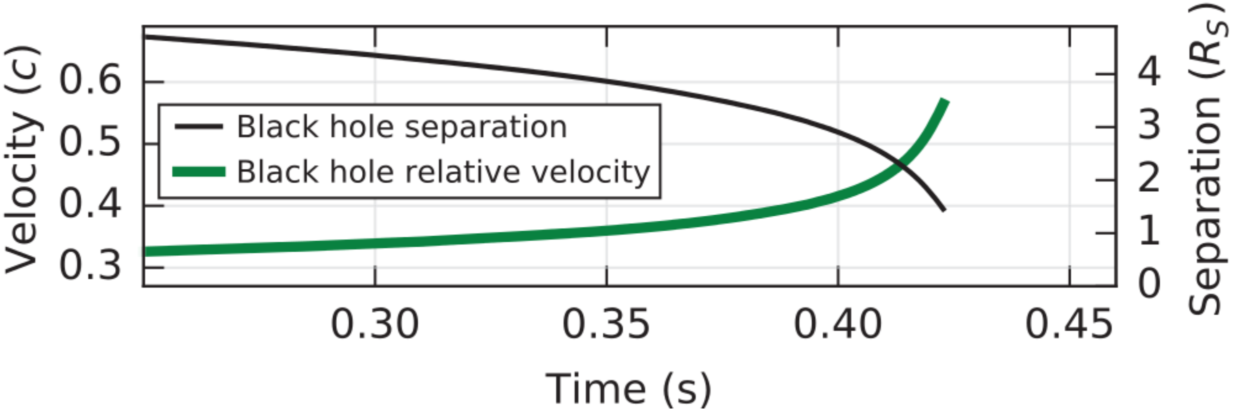
transient noise events as strong as or stronger than GW150914 have

- **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 lower limits total mass $M = m_1 + m_2 \gtrsim 70\ M_\odot$



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

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:** > 0.3 *c*, up to more than 0.5 *c*

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

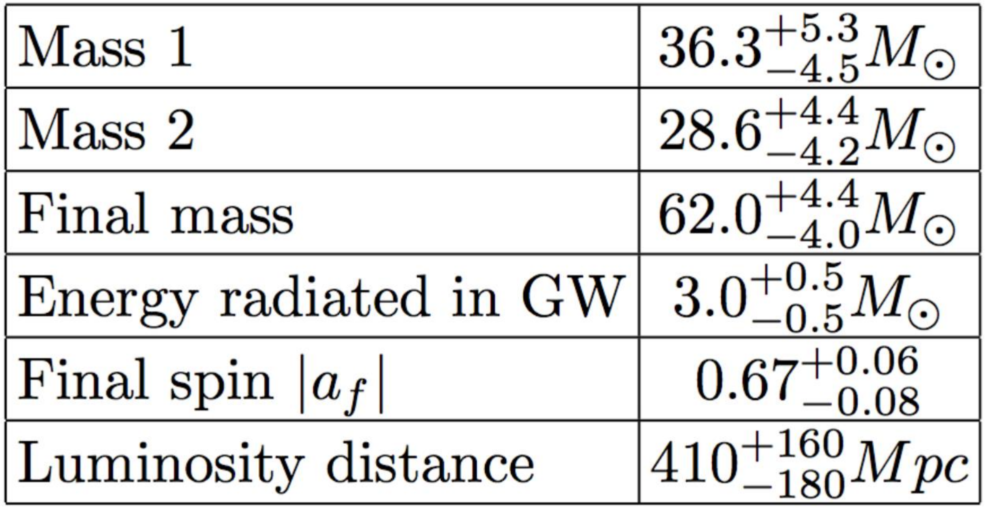
Phys. Rev. Lett. **116**, 061102

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

17 dimensions parameter space: 2 masses, 2x3 spin, distance, 2 sky coordinates, 4 orbital parameters, time and phase of coalescence.

15 parameters investigated (assumption of circular orbits0



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 $\|a_f\|$	$0.67^{+0.06}_{-0.08}$
Luminosity distance	$410^{+160}_{-180} Mpc$

higher mass values than expected

$\gtrsim 30 M_\odot$

$3 M_\odot$ unbalance:

very high GW luminosity

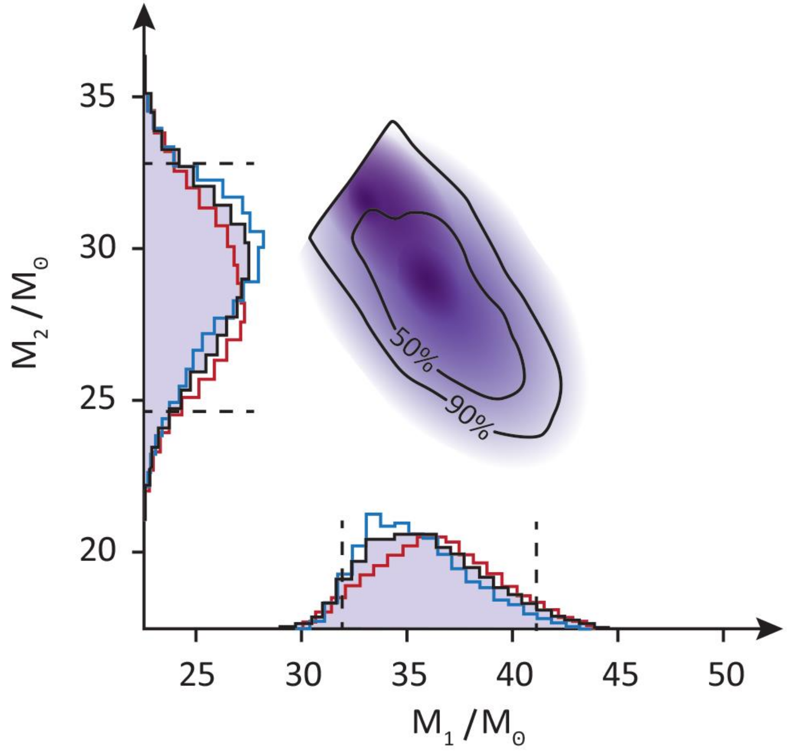
$$L_{peak} \approx 3.6 \cdot 10^{49} W$$

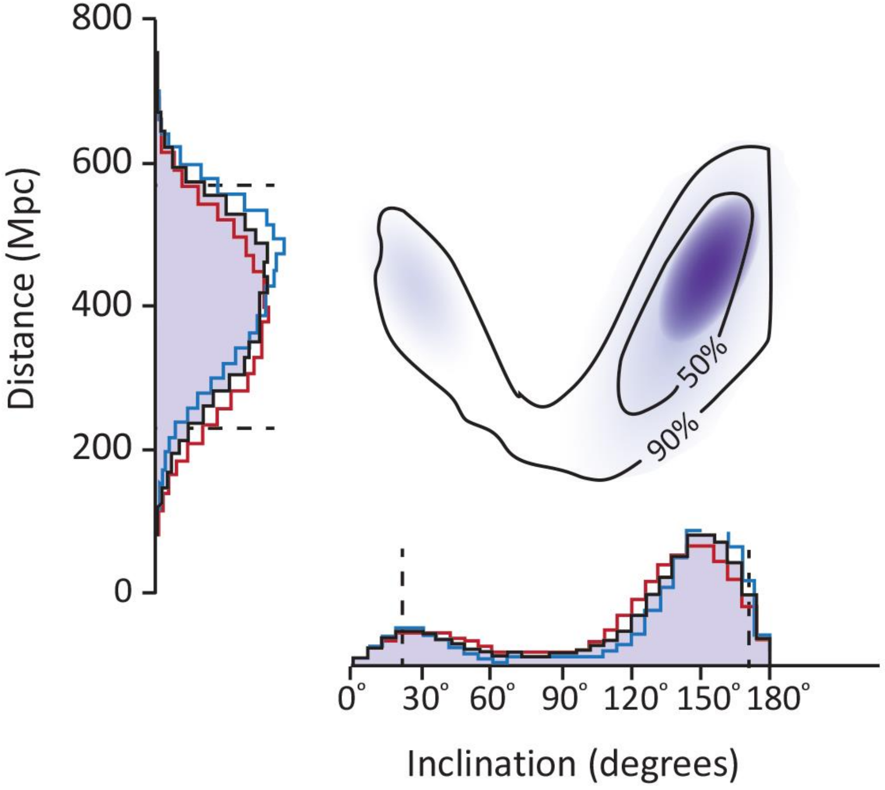
most energetic astrophysical event observed

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

GW150914 parameters [arXiv:1602.03840]

☐ no cosmological red shift measurement is possible from GWs alone, since a frequency rescaling is indistinguishable from a mass rescaling

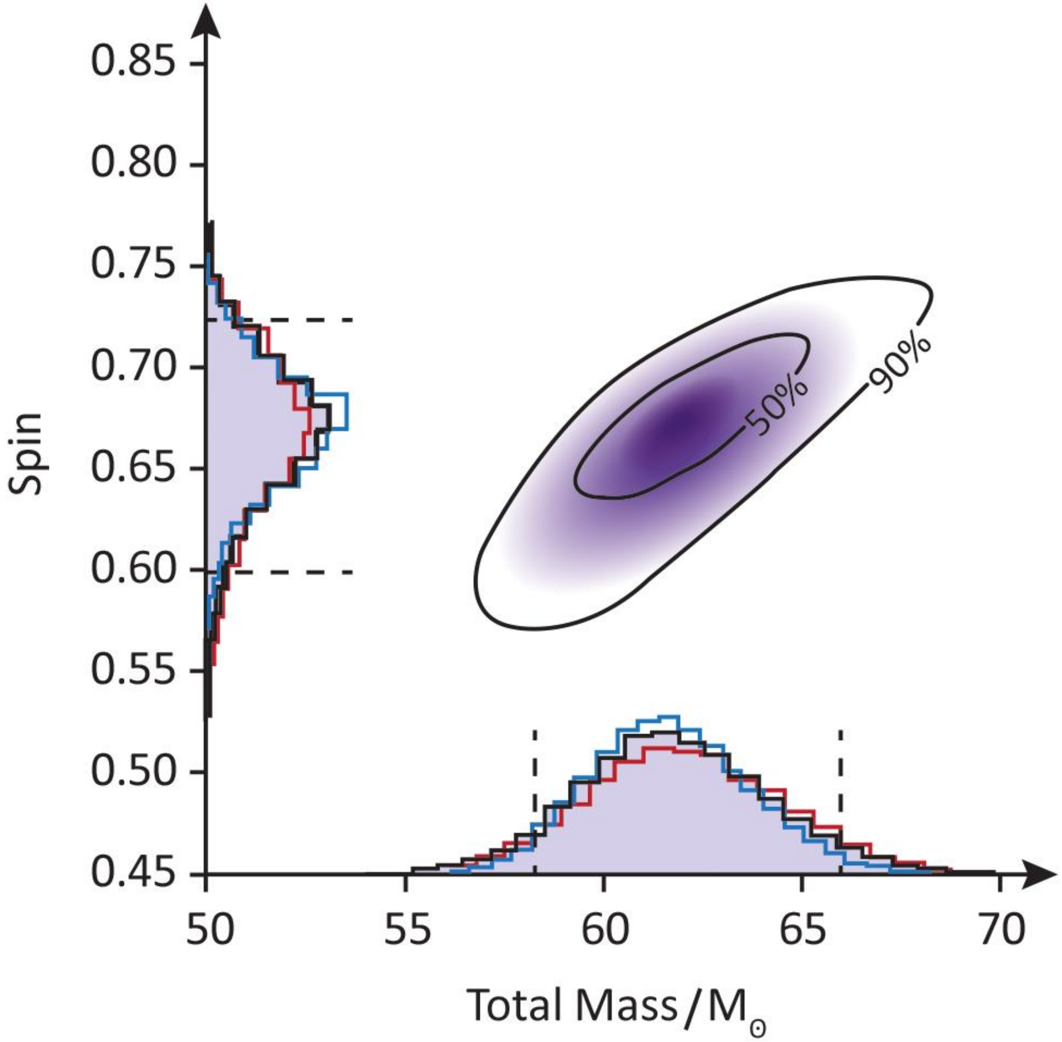




GW150914 parameters [arXiv:1602.03840]

Remnant BH mass and spin

Embedded intrinsically in waveform model (fitting to Waveform calibrated to Numerical Relativity)



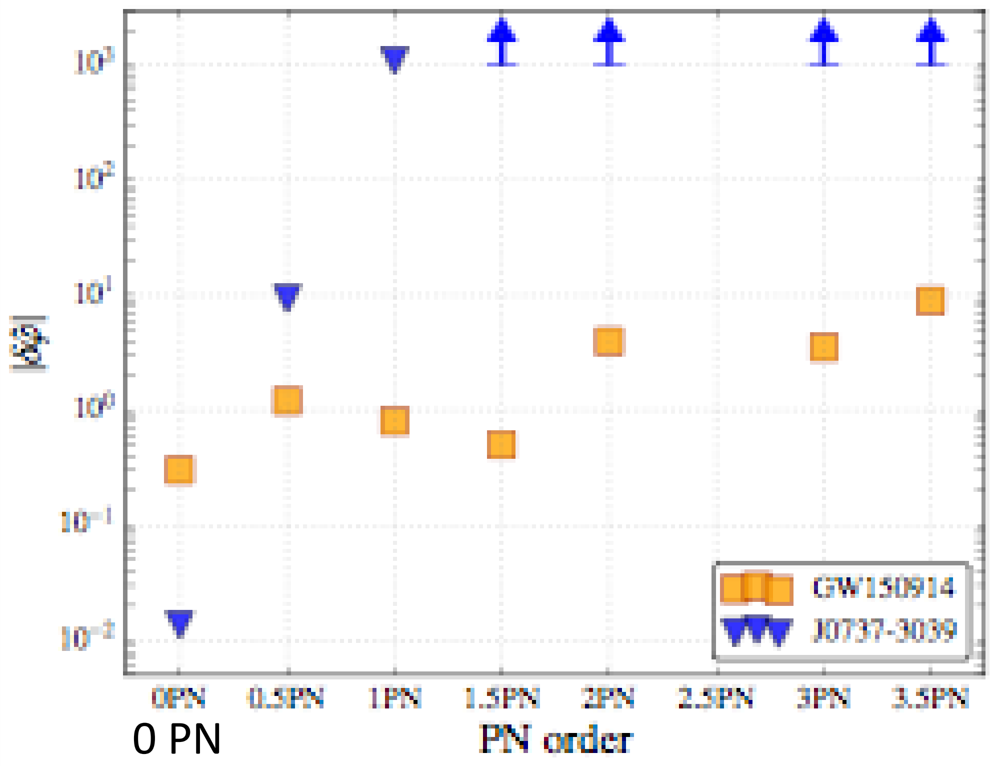
Testing GR beyond quadrupolar formula [arXiv:1602.03841]

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 $(1 + \delta\varphi)$ describes possible deviations from GR prediction per each Post Newtonian order to the quadrupolar emission formula (considering one PN at a time)

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



0 PN
Quadrupolar
formula

10 years of double pulsar
J0737-3039
$v/c \sim 2\ 10^{-3}$, $GM/rc^2 \sim 5\ 10^{-6}$

Improvements expected from lower mass BBH detections (longer duration inspiral in bandwidth)

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

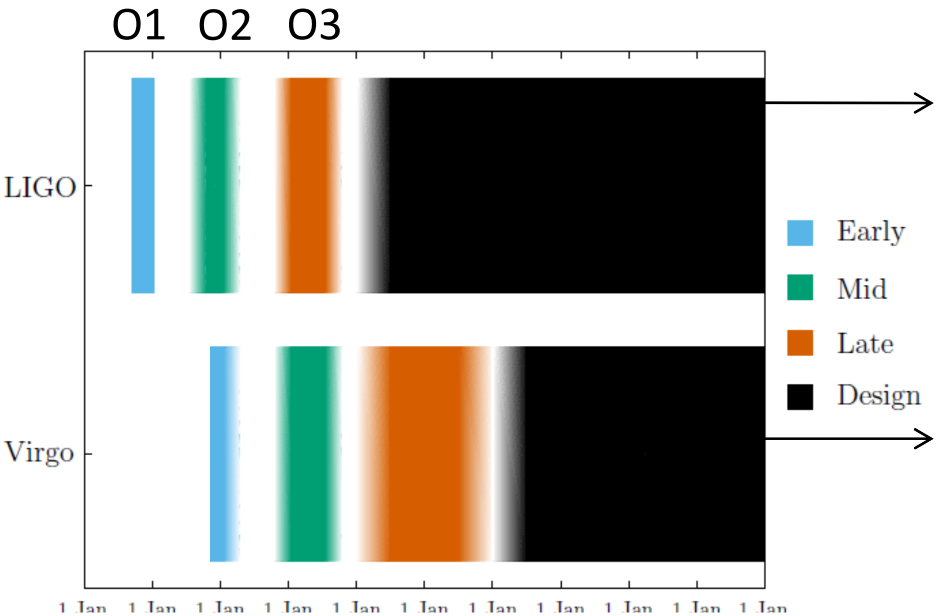
Expected non correlated spins of BH pairs: misalignment is likely

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

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

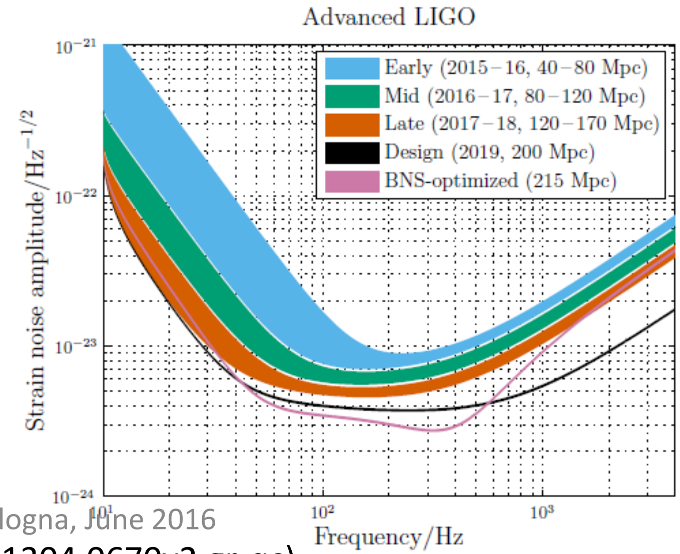
Mid term plans for LIGO-Virgo surveys

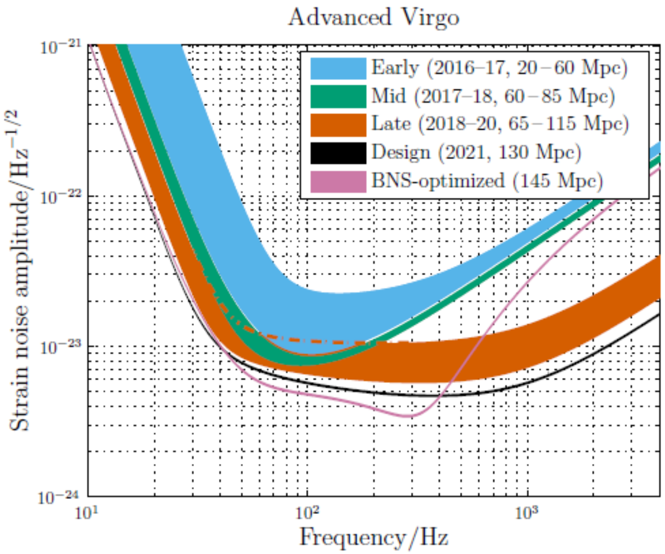
Performances upgraded in steps, interleaved by scientific observation runs:



Design sensitivity:

- 1000x gain in surveyed volume of the Universe
- **estimated BNS detection rate: 0.4-400/year**
- sky position error ~5 deg^2

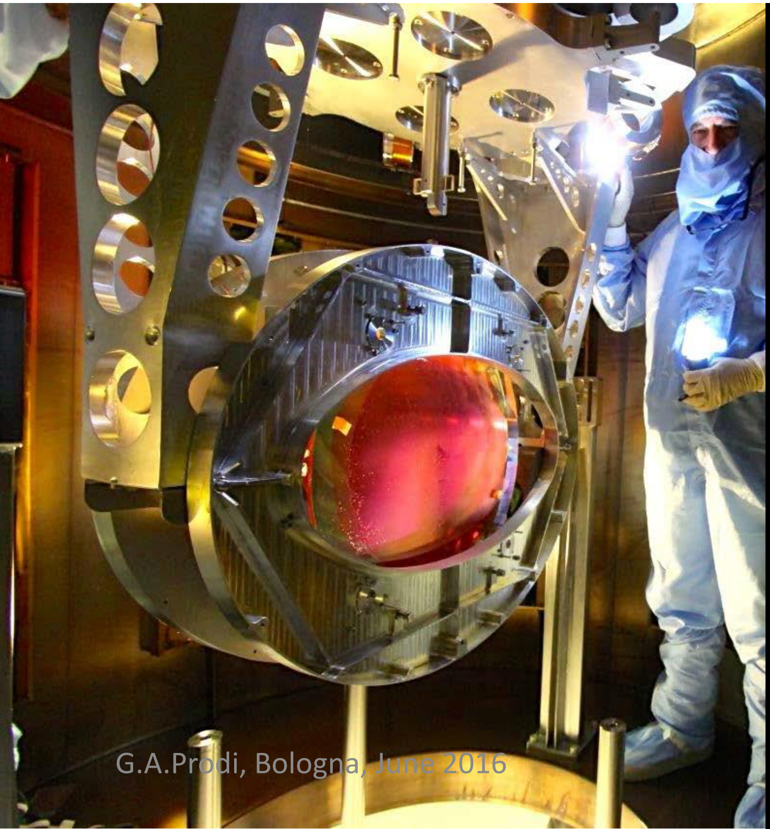


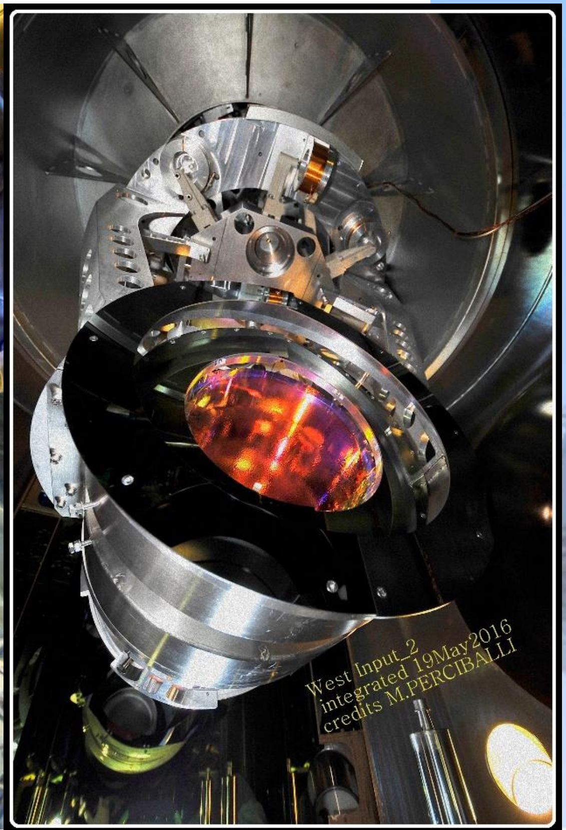


Details in (arXiv: 1304.0670v2 gr-qc)

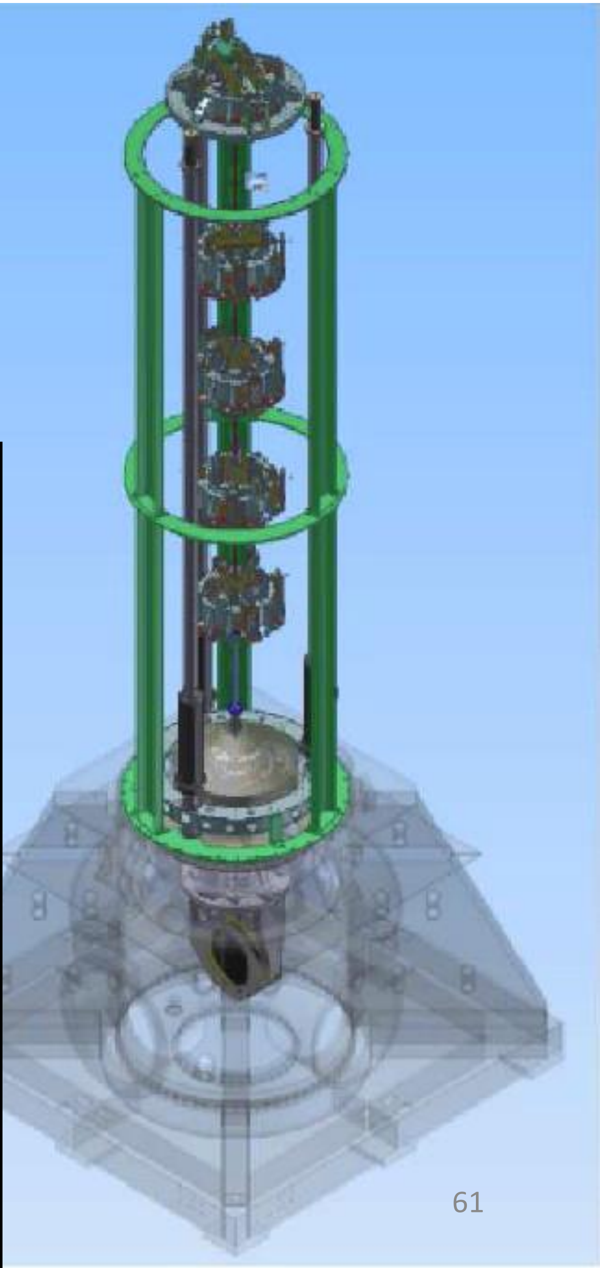
Advanced Virgo

- ☐ one 3 km-long cavity is locked and 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

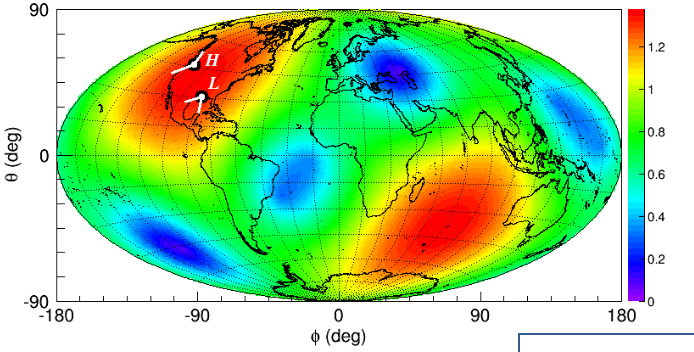


Benefits of a 3 detectors network

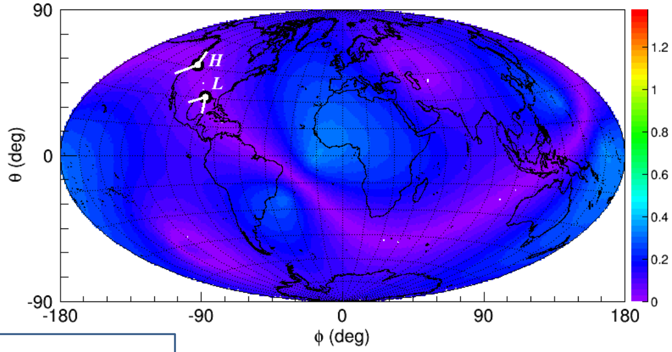
- **Detection confidence** is greatly improved: lower background and higher SNR
- Better **coverage of sky and GW polarizations**: better waveform reconstruction

LIGO H1+LIGO L1

$|\vec{F}_+|$

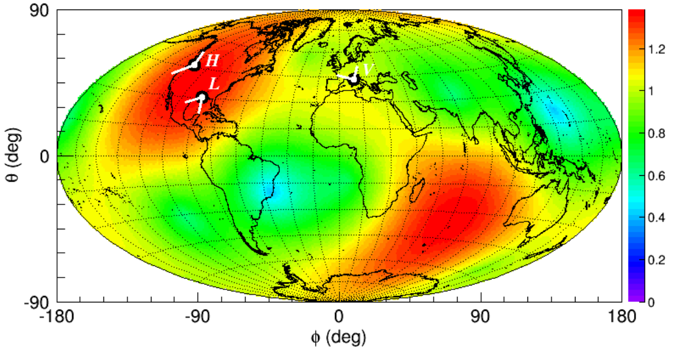


$|\vec{F}_\times|$

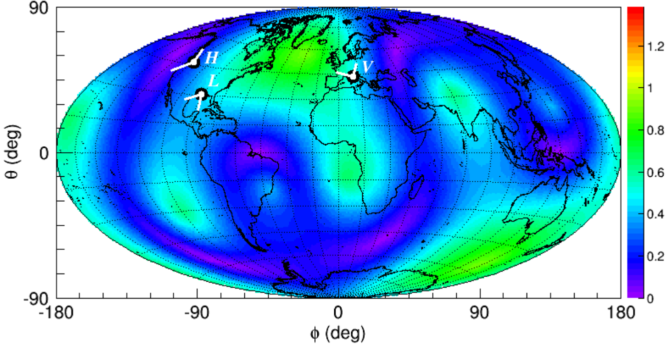


LIGO H1+LIGO L1**+ Virgo**

$|\vec{F}_+|$



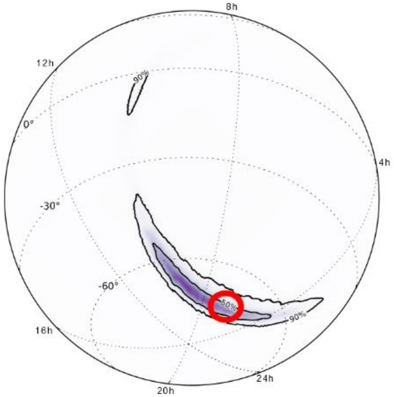
$|\vec{F}_\times|$



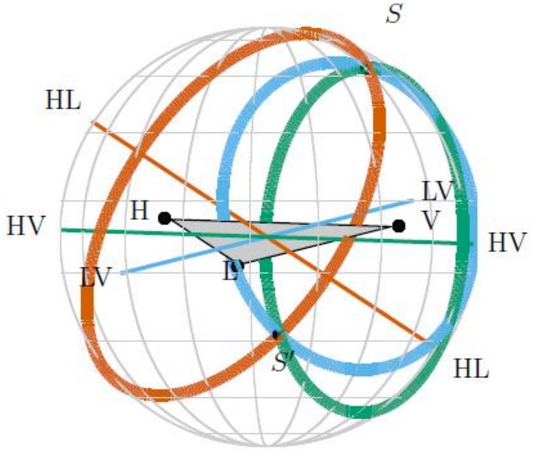
Benefits of a 3 detectors network

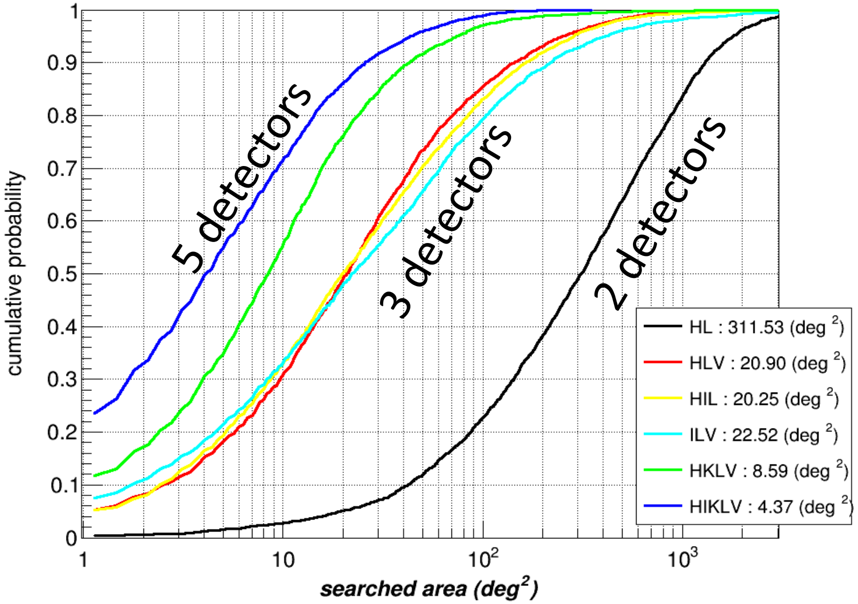
- **sky localization** greatly improved

Example based on GW150914



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

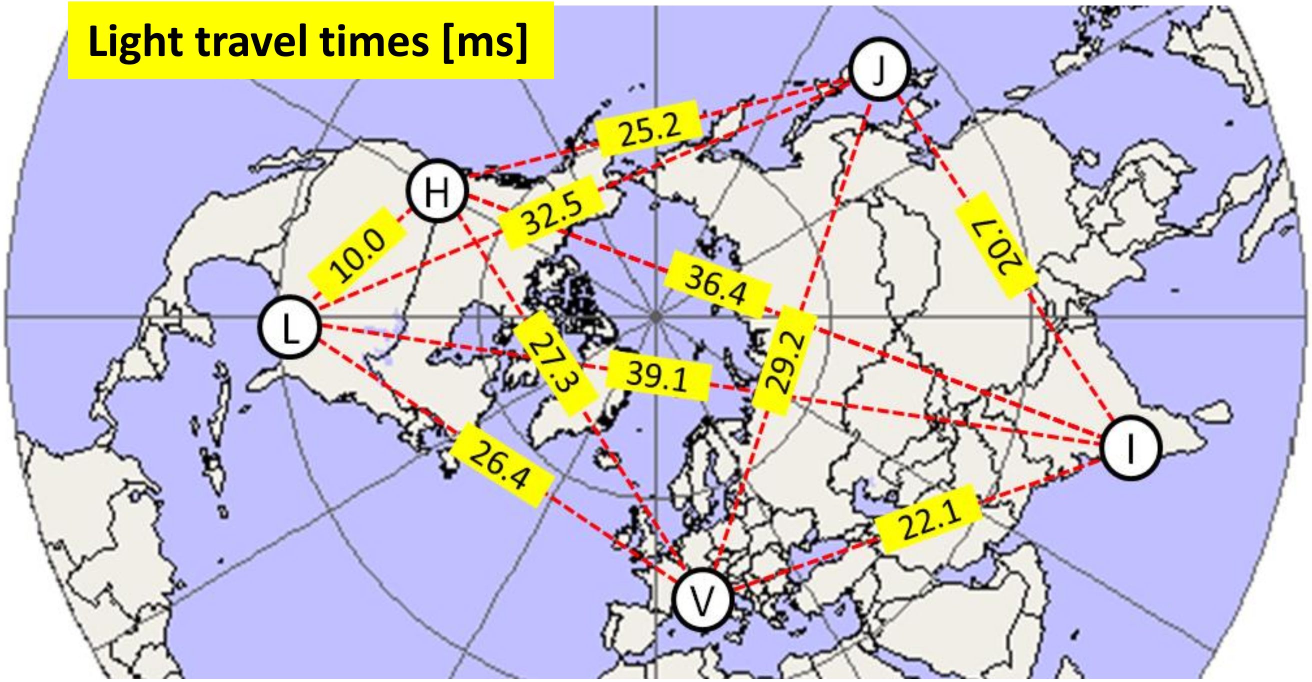




triangulation helps,
in addition we use consistency in amplitude sensitivities

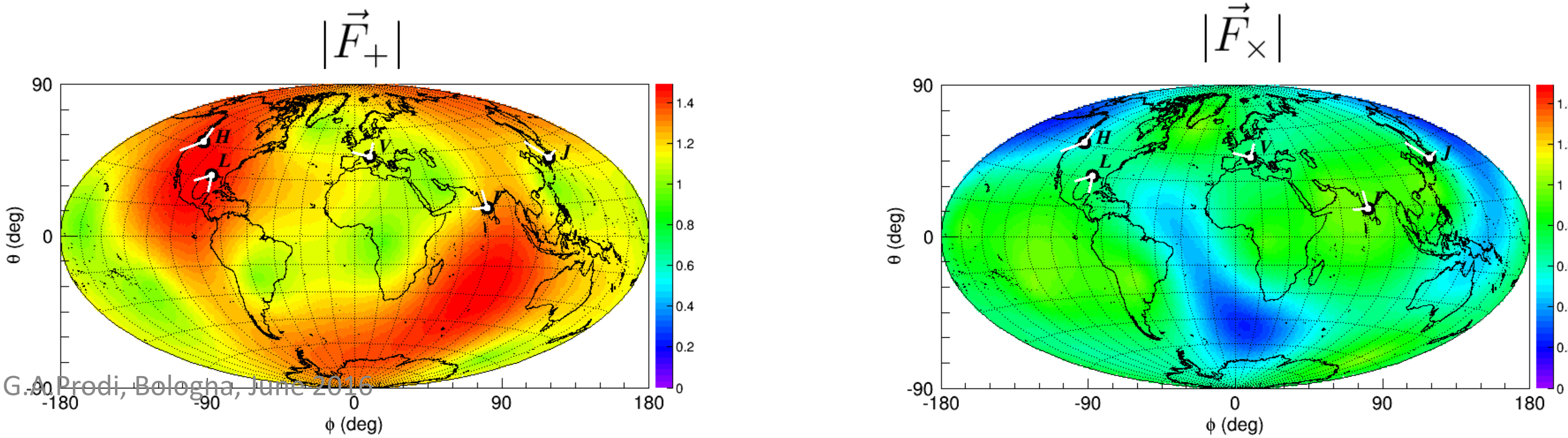
- increase of the **time coverage of the survey** by detector pairs

2019+ scenario



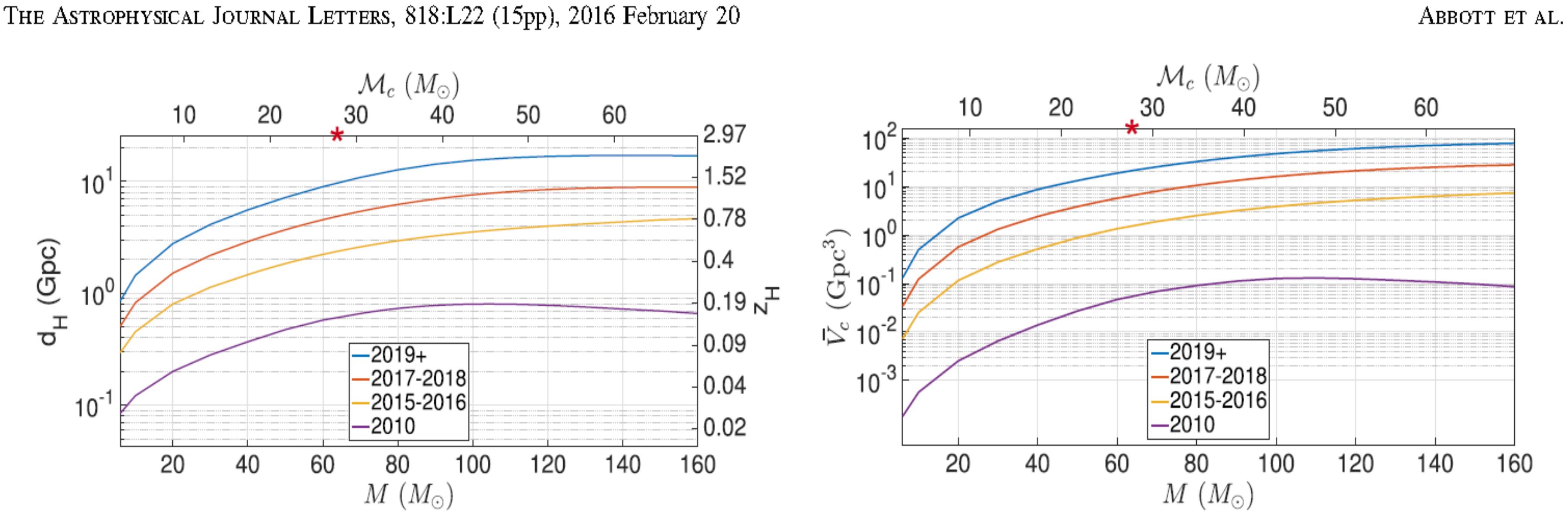
Two more interferometers will join LIGO and Virgo: KAGRA (Japan, 2019) and LIGO India (approved on February 2016)

Sky coverage of the whole observatory



observable volume of universe

Average Horizon distance and commoving volume for equal mass Binary BH mergers in planned LIGO-Virgo observations



The Astrophysical Journal Letters, 818:L22 (15pp), 2016 February 20 Abbott et al.

from stellar mass BH to NS coalescences

☐ **BHs are the simplest GR objects**

parametrized and accurate **template banks** has been calibrated against many Numerical Relativity simulations.

- ✓ matched filtering techniques for detection and parameter estimation
- ✓ inspiral phase provide best tests of GR
- ○ **ring-down of remnant is best footprint of event horizon**

☐ **detectors have top spectral performances at merger frequencies of stellar mass BH binary**

best Signal-to-Noise Ratio

☐ **NSs include a lot more physics**

templates describe **inspiral** phase

- ✓ matched filter for detection of inspiral

merger waveform catalogs by Numerical Relativity simulations explore the parameters space.

- ○ measurement of merger waveforms need to be more general
- ○ late inspiral orbits are affected by NS tidal deformations
- ○ **merger and post-merger are best footprints of NS Equations of State**

☐ **detectors have worse spectral performance at merger and post merger of NS coalescences**

disfavours measurement of merger and post-merger characteristics

final remarks

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

  Final results for Binary Black Hole Mergers have been released

  more searches are being pursued, e.g. more massive BBH, transients of generic waveform, triggered searches, multimessenger searches, ...
- ➢ Advanced Virgo will start commissioning of full interferometer in July.
- ➢ the upcoming network will cover both GW polarizations for half of the sky.
- ➢ Advanced interferometers will improve sensitivity by a factor 3 in a 3-5 years time-scale.
- ➢ Binary BH detections will become routine; improving reconstruction of BH characteristics for fundamental physics and for astrophysics.
- ➢ Looking for other sources: NS emissions, ...
- ➢ 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

Inspiral of NS-NS or NS-BH binaries

☐ **NS Equation of State affects inspiral phase through tidal interactions**

ongoing development of robust theoretical models in the Effective One Body formalism, including:

- adiabatic NS tides (i.e. hydrostatic), multipoles corrections

  see e.g. Bernuzzi et al., PRL 114, 161103 (2015)
- dynamical NS tides (i.e. normal mode dynamics), fundamental quadrupole contribution

  Hinderer et al., PRL 116, 181101 (2016)

Main parameters are NS **tidal deformability constants** (Love numbers) and **eigenfrequency of fundamental quadrupolar mode**.

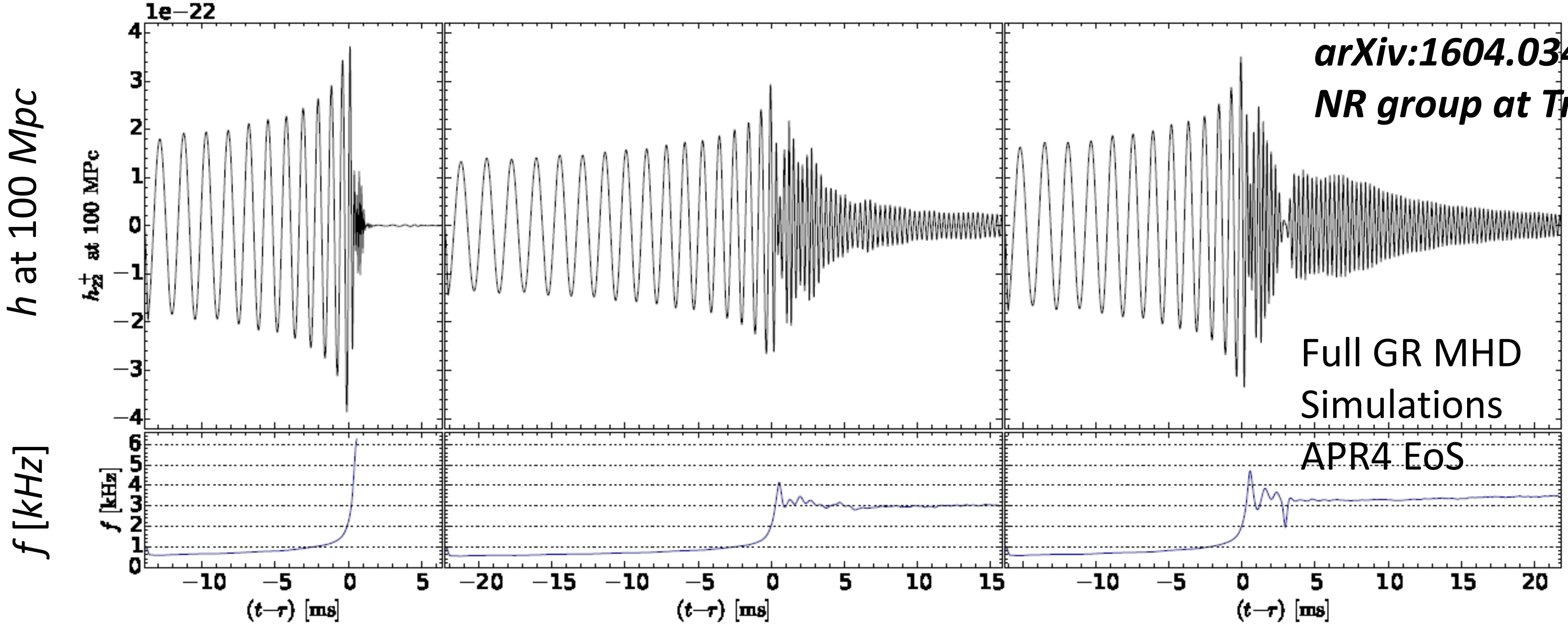
- testing models against **Numerical Relativity simulations**.

Next steps:

○ construction of template banks for parameter estimation of NS-BH and NS-NS inspirals

○ check performances as parameter estimation method

merger and post-merger of NS-NS



arXiv:1604.03445
NR group at Trento

Full GR MHD Simulations
APR4 EoS

Prompt collapse to BH

1.43+1.43 $M_\odot$

no detectable post-merger by LIGO-Virgo

Supramassive NS remnants

richest messengers of NS properties

1.22+1.22 $M_\odot$

1.29+1.42 $M_\odot$

Signal-to-Noise Ratio of post-merger in LIGO-Virgo is a small fraction of the total (< 10%)

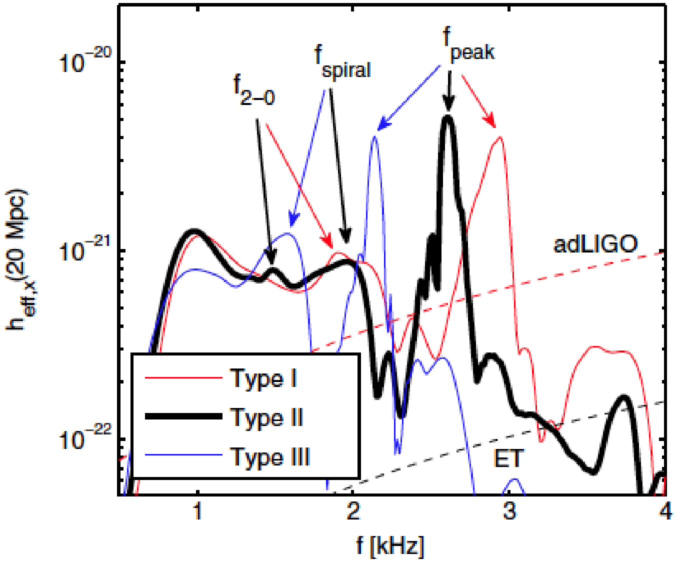
post-merger signals from NS remnants

- **Large variability of time-frequency features**
- **Frequencies of main spectral features correlate with NS properties**

quadrupolar tidal deformability, compactnes
and mass ratios of progenitors

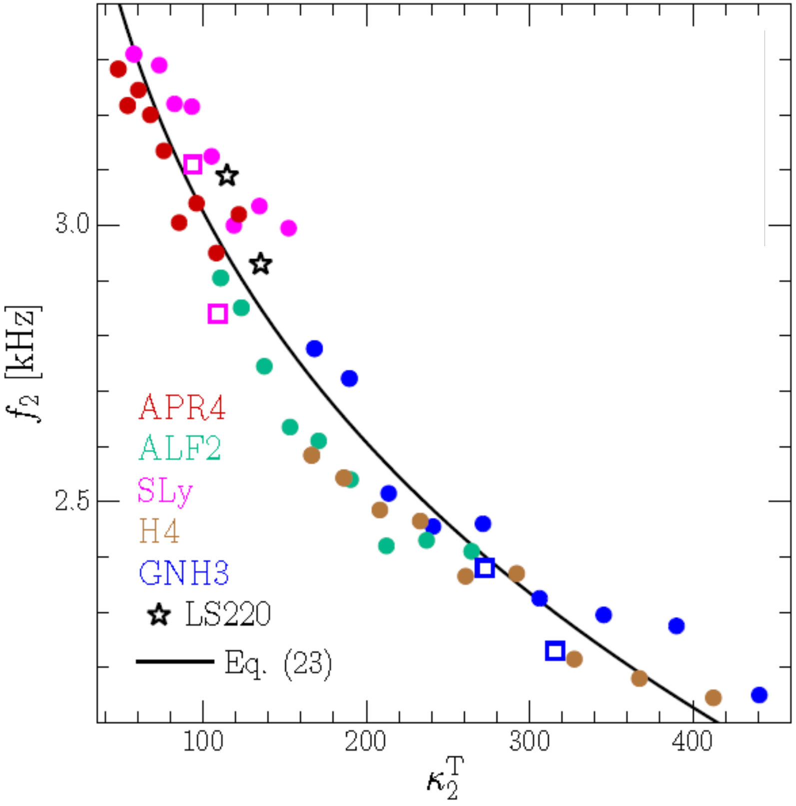
Warning: interpretation/understanding of NR simulations is still not “universally” shared

Bauswein & Stergioulas
PHYSICAL REVIEW D 91, 124056 (2015)



type I: *higher mass, softer EoS*
type II: *intermediate*
type III: *lower mass, stiffer EoS*

Rezzolla & Takami arXiv:1604.00246

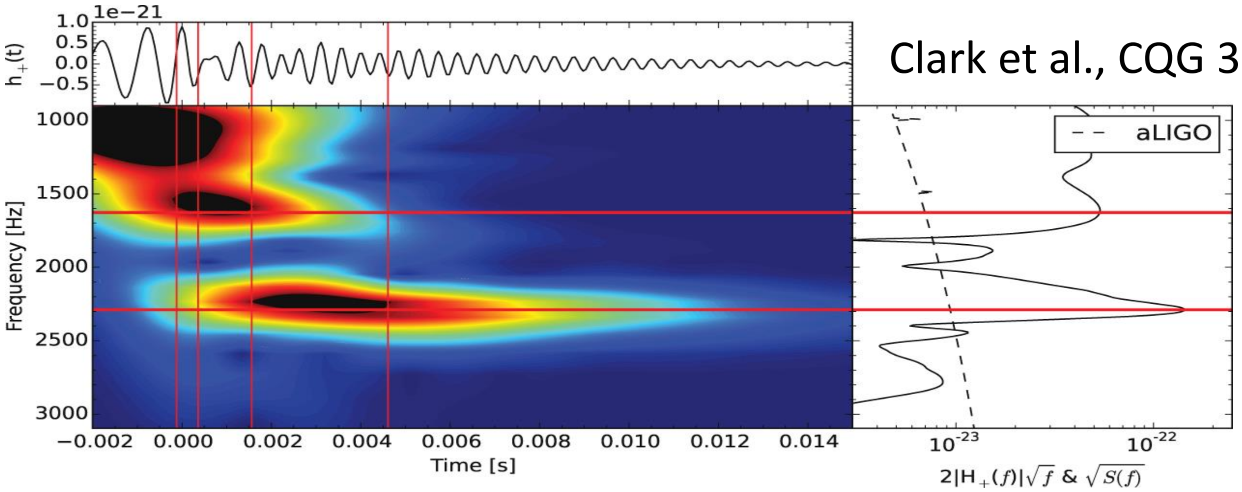


Tidal deformability

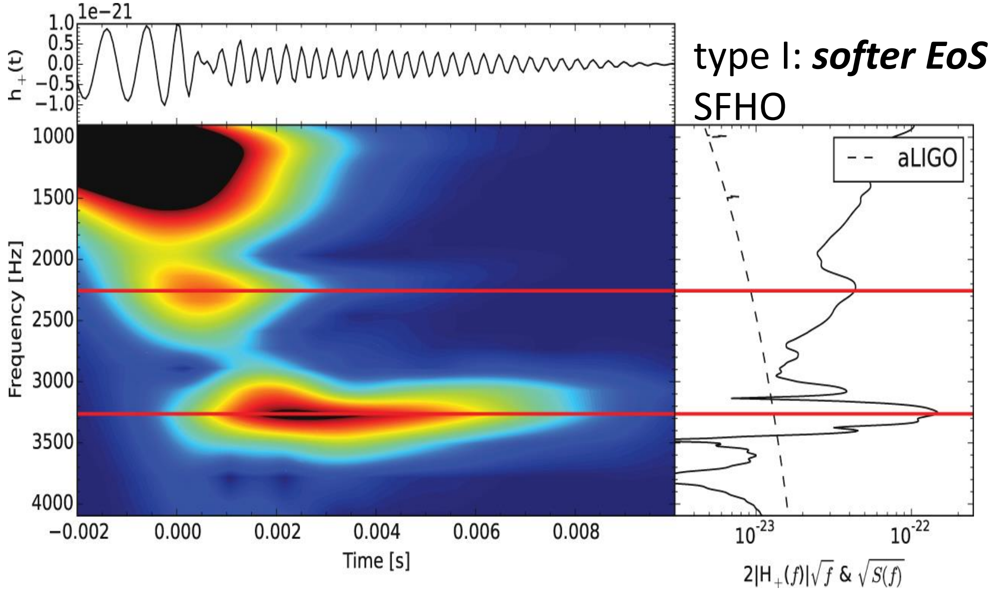
also PRD 91, 064001 (2015)

post-merger signals from NS remnants

Clark et al., CQG 33 (2016) 085003



type III: ***stiffer EoS***
TM1



type I: ***softer EoS***
SFHO

Detectability of post-merger

zero order estimate

	Horizon	Rate
Adv LIGO	30 Mpc	1/century
LIGO A+	80 Mpc	13/century
LIGO V	140 Mpc	41/century

see also Clark et al, PRD 90, 062004 (2014)

work in progress at Padova-Trento

- Virgo data analysis group: improve capabilities of waveform reconstruction by the reference pipeline LIGO-Virgo to detect generic transient signals

- Numerical Relativity group (PI *Giacomazzo*) Full GR MagnetoHydroDynamic simulation to deepen understanding of NS sources and extend exploration of emitted gravitational waves

improving methods to detect merger and post-merger features and to infer NS properties

hierarchical analysis scheme:

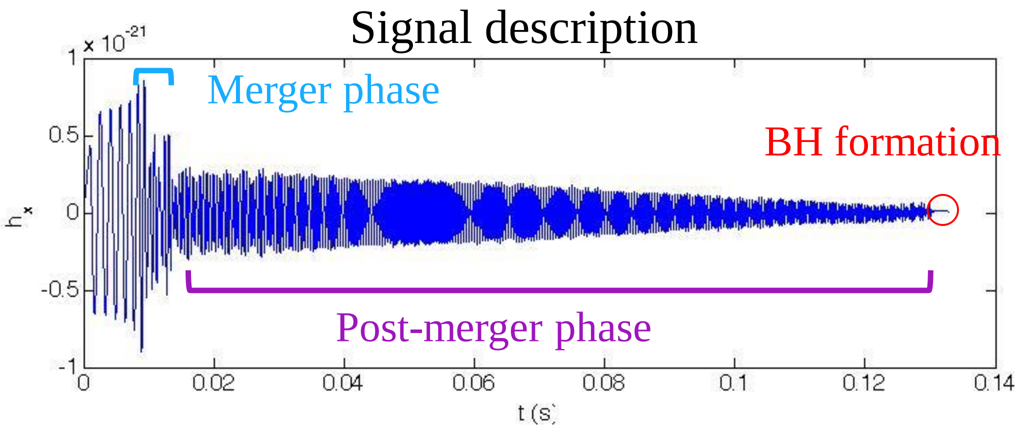
1. discrimination with controlled false alarm probability of

NS post-merger candidates **versus** **null hypothesis**
e.g. prompt collapse to BH

2. follow-up estimation of waveform parameters related to EoS

nothing detectable in LIGO-Virgo band

waveform reconstruction

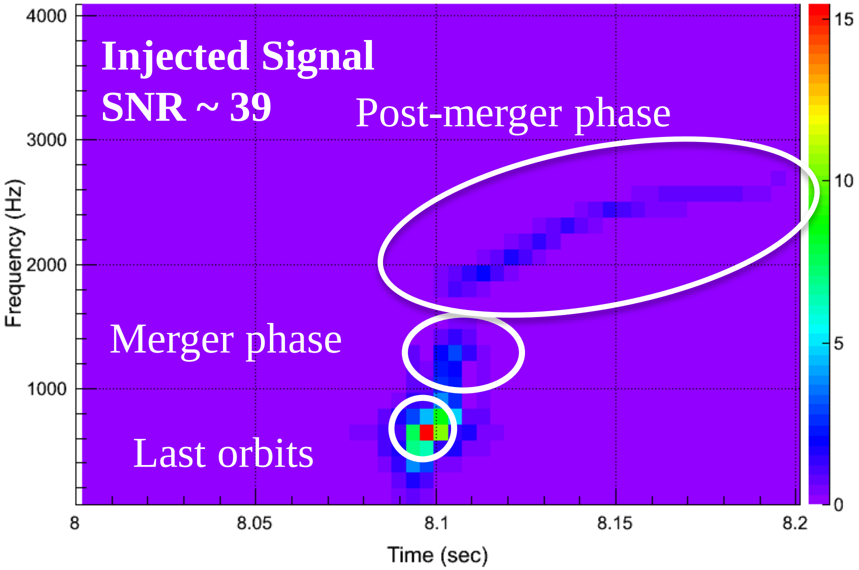


Numerical Relativity waveform courtesy of L. Baiotti and B. Giacomazzo.

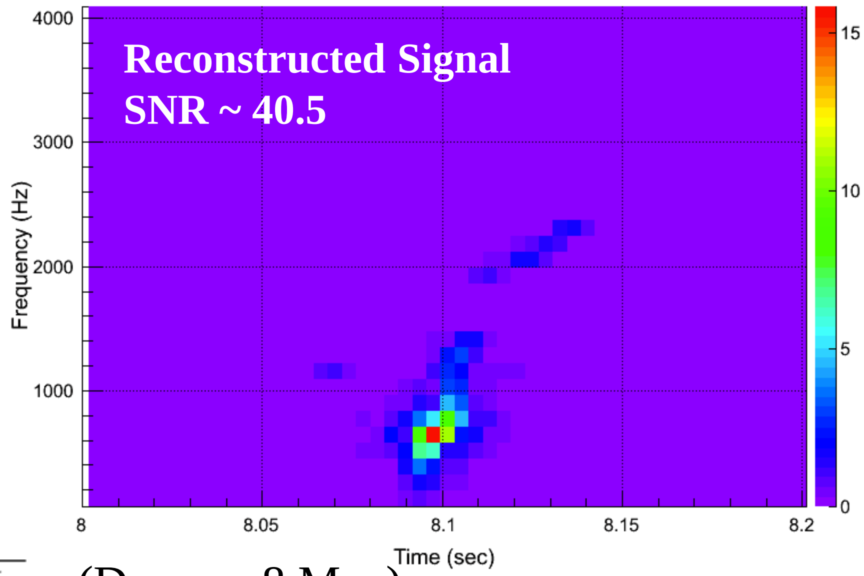
Binary NS-NS system: ~2.6 $M_\odot$

It produces a NS that survives for 0.1 s before collapse to BH.

L1-Injected Signal Time Frequency Map, dt~3.09 ms, df~128 Hz



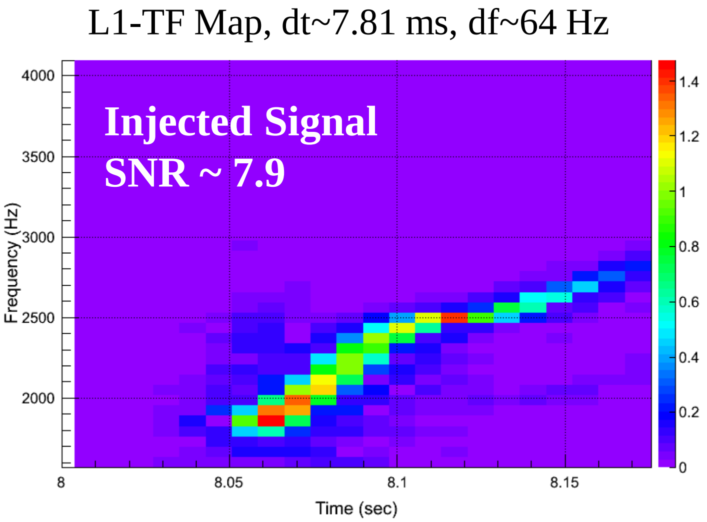
L1-Reconstructed Signal Time Frequency Map, dt~3.09 ms, df~128 Hz

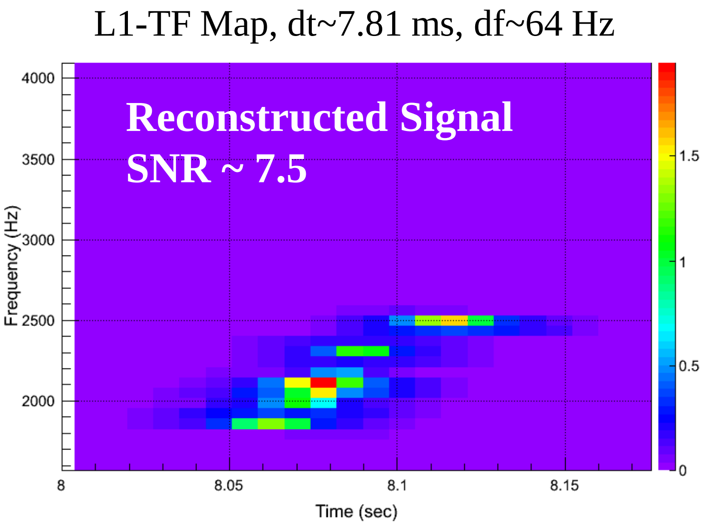


Total Network SNR~ 72, hrss~6x10^{-22} $1/\sqrt{Hz}$ (D_{source} ~ 8 Mpc)

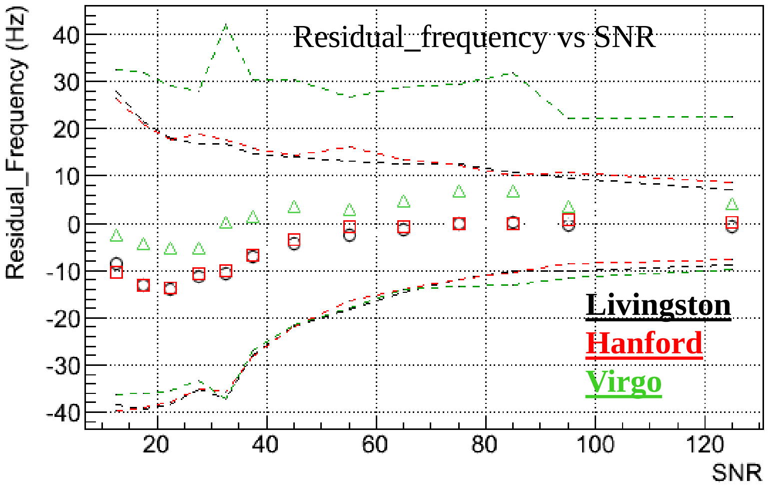
post-merger phase

PRELIMINARY RESULTS





Same sample event
Whitened data



- Studying the feature of the TF map in the post merger time frequency range (1600-4096 Hz) .

- Monte Carlo study: software signal injections in Gaussian noise in the distance range 1-20 Mpc to measure the accuracy of post-merger reconstruction.

final remarks

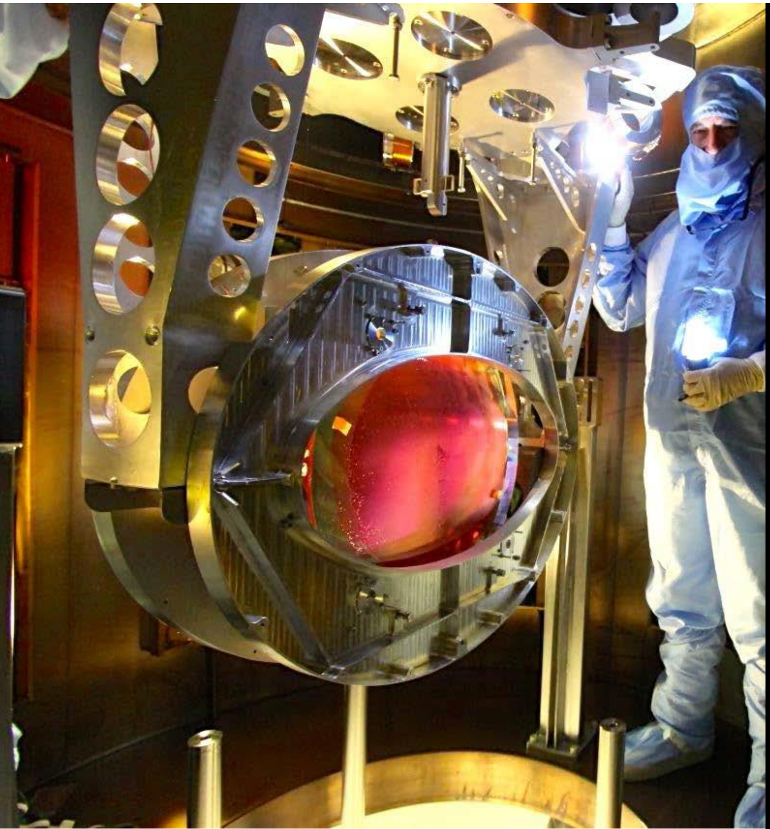
- ✓ Advanced LIGOs first observation campaign has been completed, Sept. 12-2015 – Jan. 19 2016

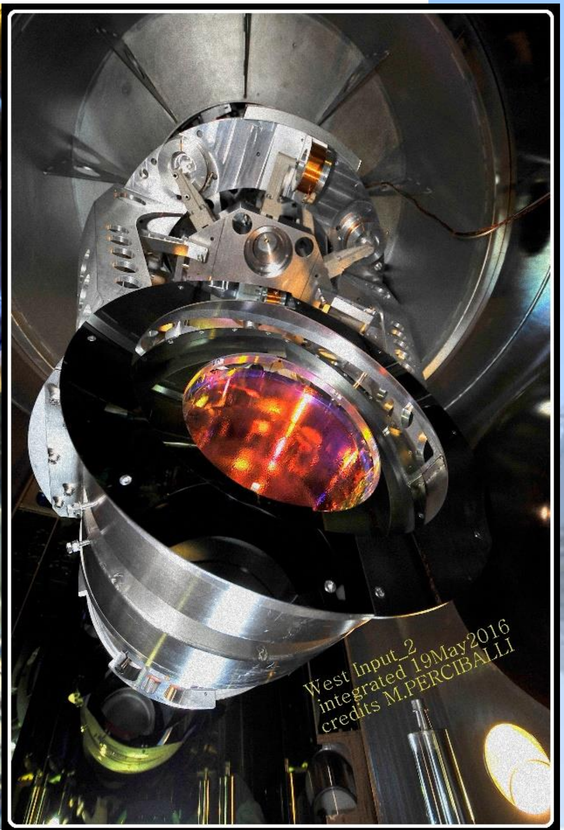
Expect to see the complete results very soon !

- Advanced Virgo will start commissioning of full interferometer in July.
- the upcoming network will cover both GW polarizations for half of the sky.
- 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
- Binary NS will likely be detected in the next few years, but limited to the inspiral part
- Matter effects in NS are much harder to be measured, first estimates give small rates, subject to large uncertainties. More developments and checks must still be pursued to establish expectations.

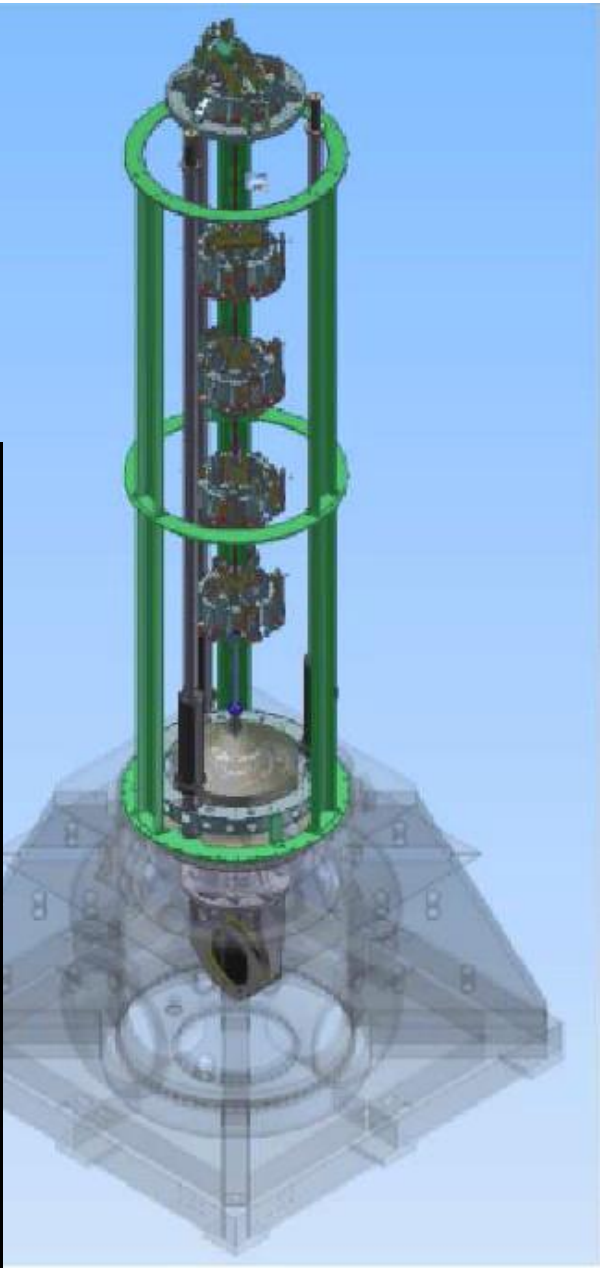
Advanced Virgo

- 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)

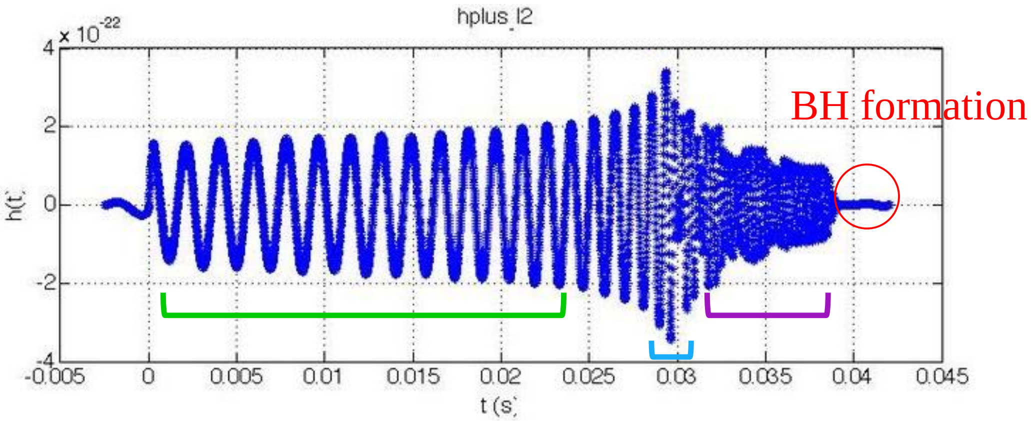




West Input_2
integrated 19May2016
credits M.PERCIBALLI



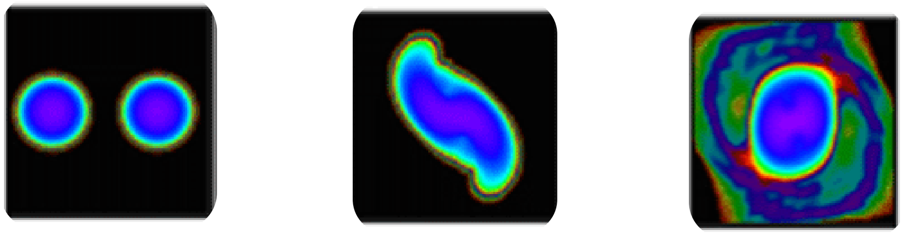
numerical relativity of binary neutron stars

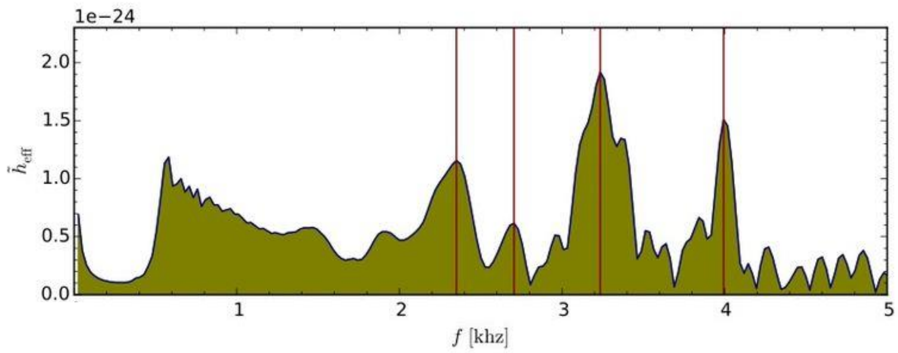


Inspiral phase

Merger phase

Post-merger phase





The coalescence of NS binary systems brings much physical properties.

⇩

EoS and astrophysical parameter (e. i. mass) leave their prints in merger and post-merger phase.

We are analyzing a catalog which collects BNS waveforms simulated by *Trento* and *GeorgiaTech Numerical Relativity groups*.

generic transient signal 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 parameter space (2 polarizations)

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

these methods can recover the entire Signal-to-Noise Ratio of the signal, but their background is polluted by non Gaussian outliers and need more effort to demonstrate highest significance wrt matched filtering techniques

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] :

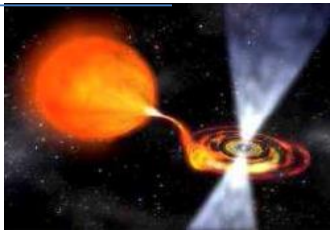
  GW Luminosity is driven by $\dddot{Q}_{\mu\nu} \neq 0$

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

- 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

continuos wave signals



- The expected gravitational radiation amplitude depends on frequency ν, distance r, moment of inertia I, ellipticity ε

Taking non zero ellipticity $\boxed{\epsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}}$

$$\boxed{h_0 = 10^{-26} \frac{\epsilon}{10^{-6}} \left(\frac{\nu}{100\ Hz} \right)^2 \left(\frac{10\ kpc}{r} \right) \left(\frac{I_{zz}}{10^{38}\ kg\ m^2} \right)}$$

- The signal emitted by a spinnign NS is nearly monocromatic, with a frequency slowly varying in time.

two polarization amplitudes ⇨

$$\boxed{\begin{aligned} h_+ &= h_0 \frac{1+\cos^2 i}{2} \cos(2\omega_{rot} t) \\ h_\times &= h_0 \cos i \sin(2\omega_{rot} t) \end{aligned}}$$

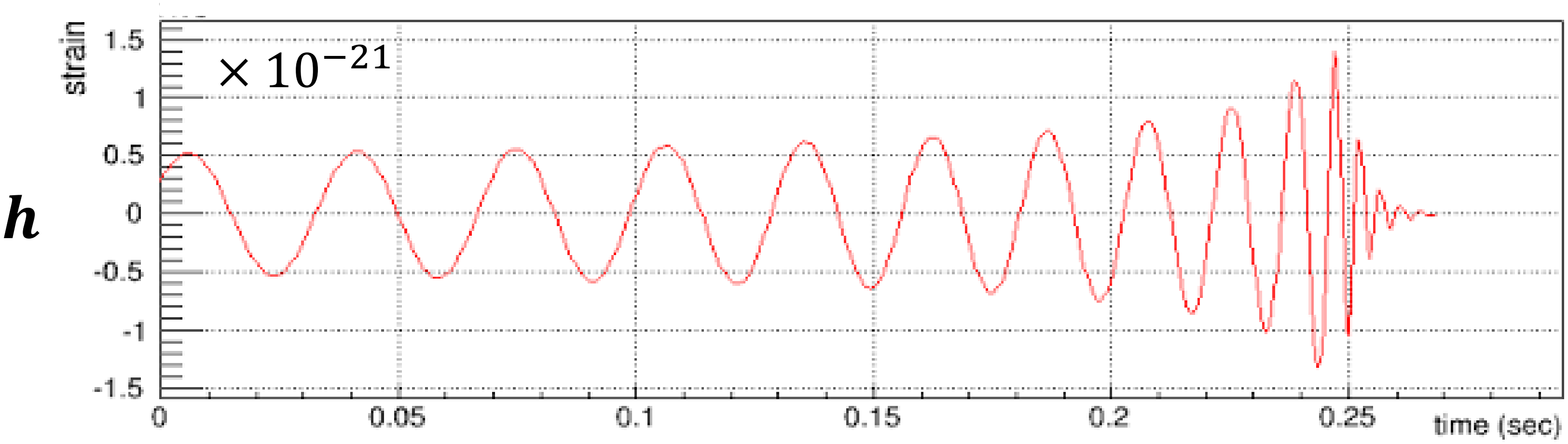
i inclination angle between rotation axis and line of sight

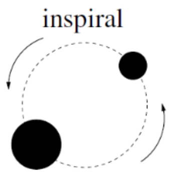
- The spinning NS emits GWs as twice its rotational frequency

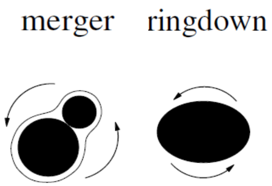
$$\boxed{\nu_{GW} = 2\ \nu_{rot}}$$

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.

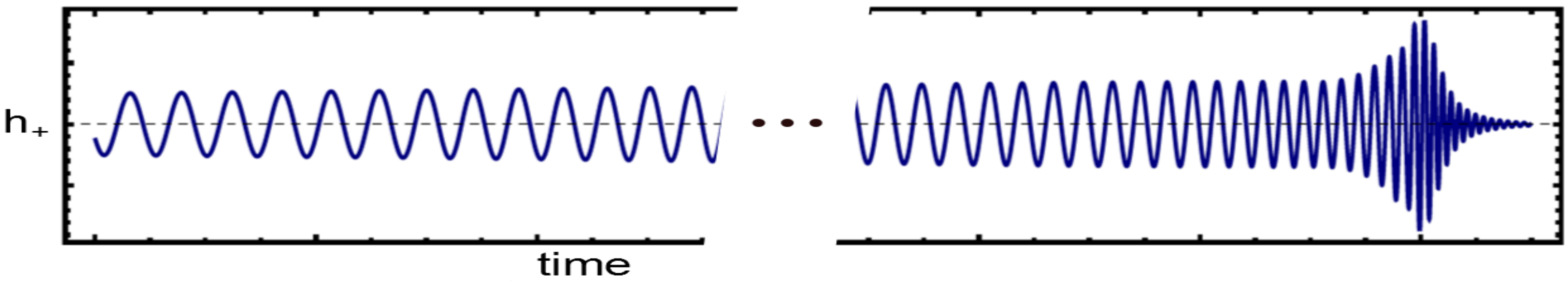
Ringdown: perturbative and numerical solutions

general relativity in strong field
highly non-linear regime

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

PSR1916+13 versus GW150914

Waveform



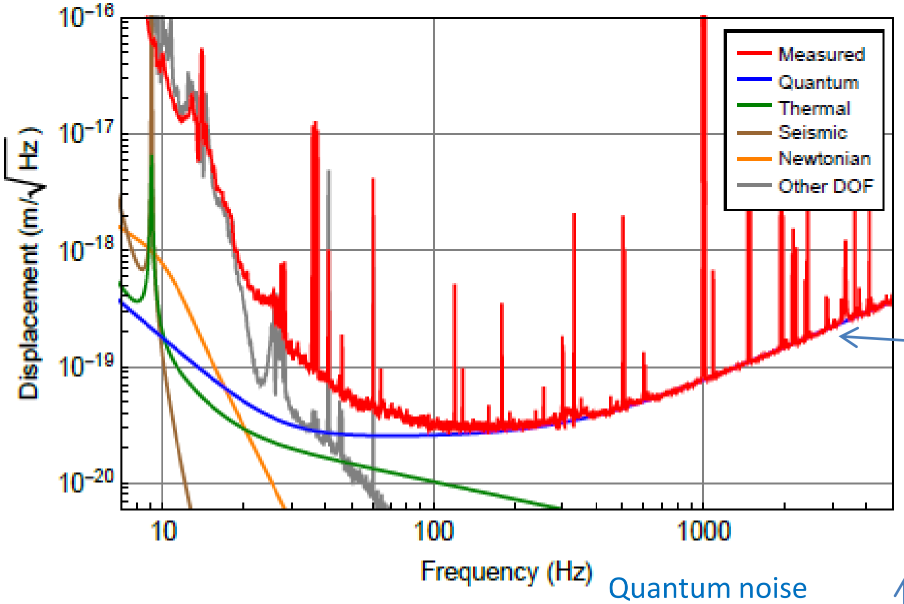
Hulse-Taylor: 30 years of observation time

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}
$7 \times 10^{-5}\,\mathrm{Hz}$	**GW frequency**	$30 - 300\,\mathrm{Hz}$
3×10^{8} years	**time to merge**	*merged*
$6 \times 10^{30}\,\mathrm{erg\,s^{-1}}$	**peak luminosity**	$3 \times 10^{56}\,\mathrm{erg\,s^{-1}}$
$6.4\,\mathrm{pc}$	**distance**	$410\,\mathrm{Mpc}$
$10^{6}\,\mathrm{km}$	**orbit dimension**	*merged*
$\sim 10^{-3}$	**v/c**	~ 0.5
$\sim 10^{-4}$	GM/rc^2	~ 1

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

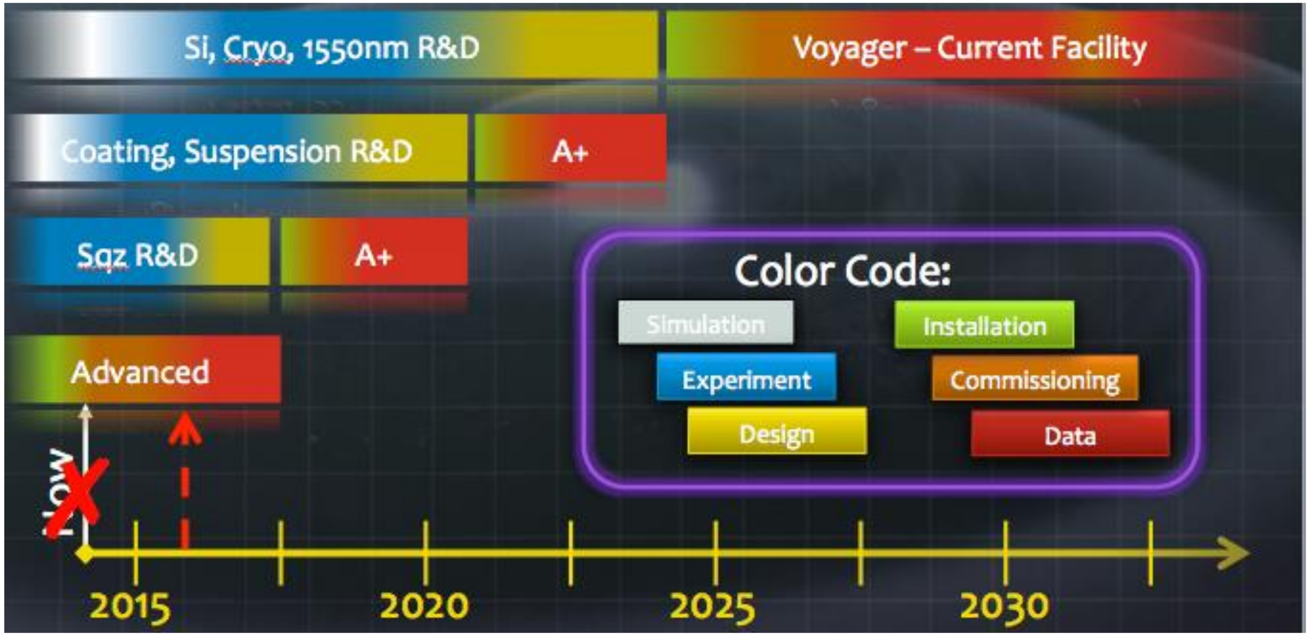
Next steps increase the detector input power up to 200 W (125 W for Virgo).
This means 500 kW of in cavity power.

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

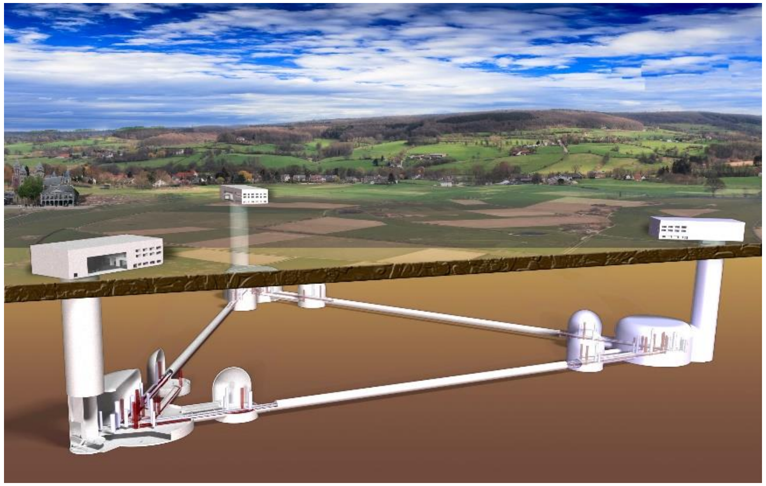


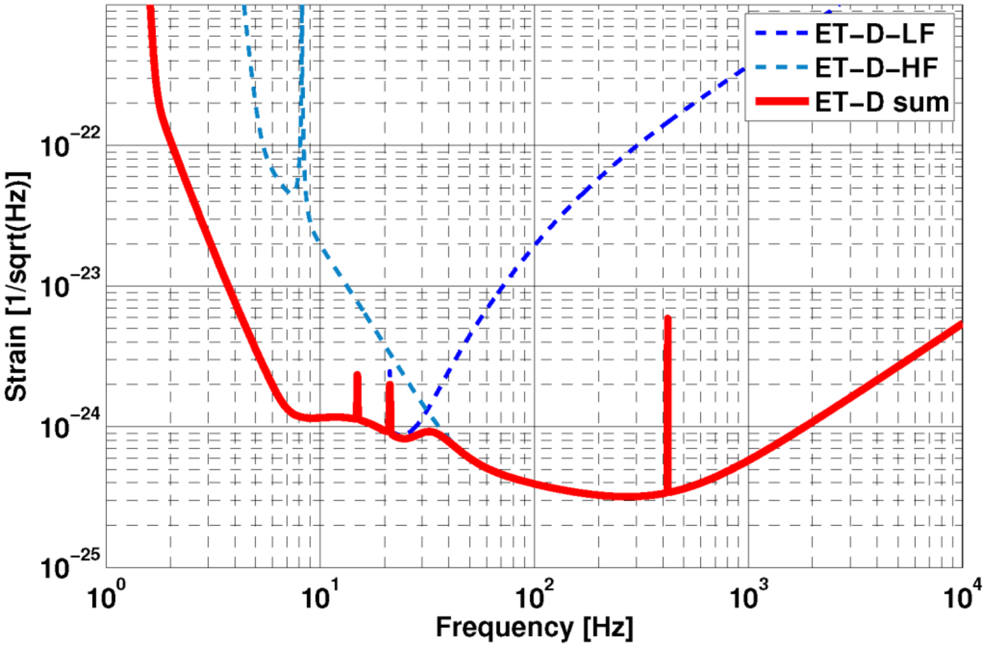
from LSC Whitepaper 2015

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