Results from the first science run of advanced GW detectors

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On Behalf of the LIGO Scientific Collaboration and the VIRGO Collaboration

51ST RENCONTRES DE MORIOND – ELECTROWEAK INTERACTIONS AND UNIFIED THEORIES

12TH -19TH MARCH 2016 - LA THUILE, ITALY

GWs in a nutshell

Gravitational waves are dynamic fluctuations in the fabric of space-time, propagating at the speed of light

Predicted by Einstein 100 years ago; first indirect confirmation by Hulse & Taylor (Nobel Prize in 1993)

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

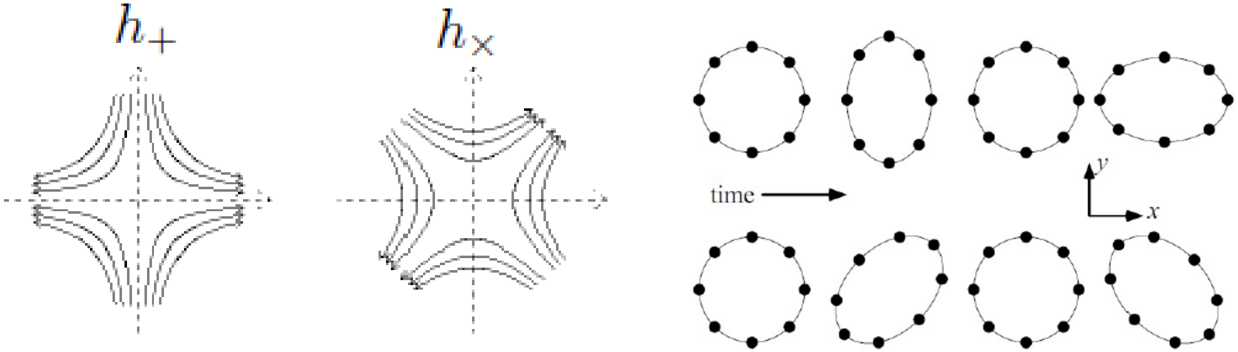
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

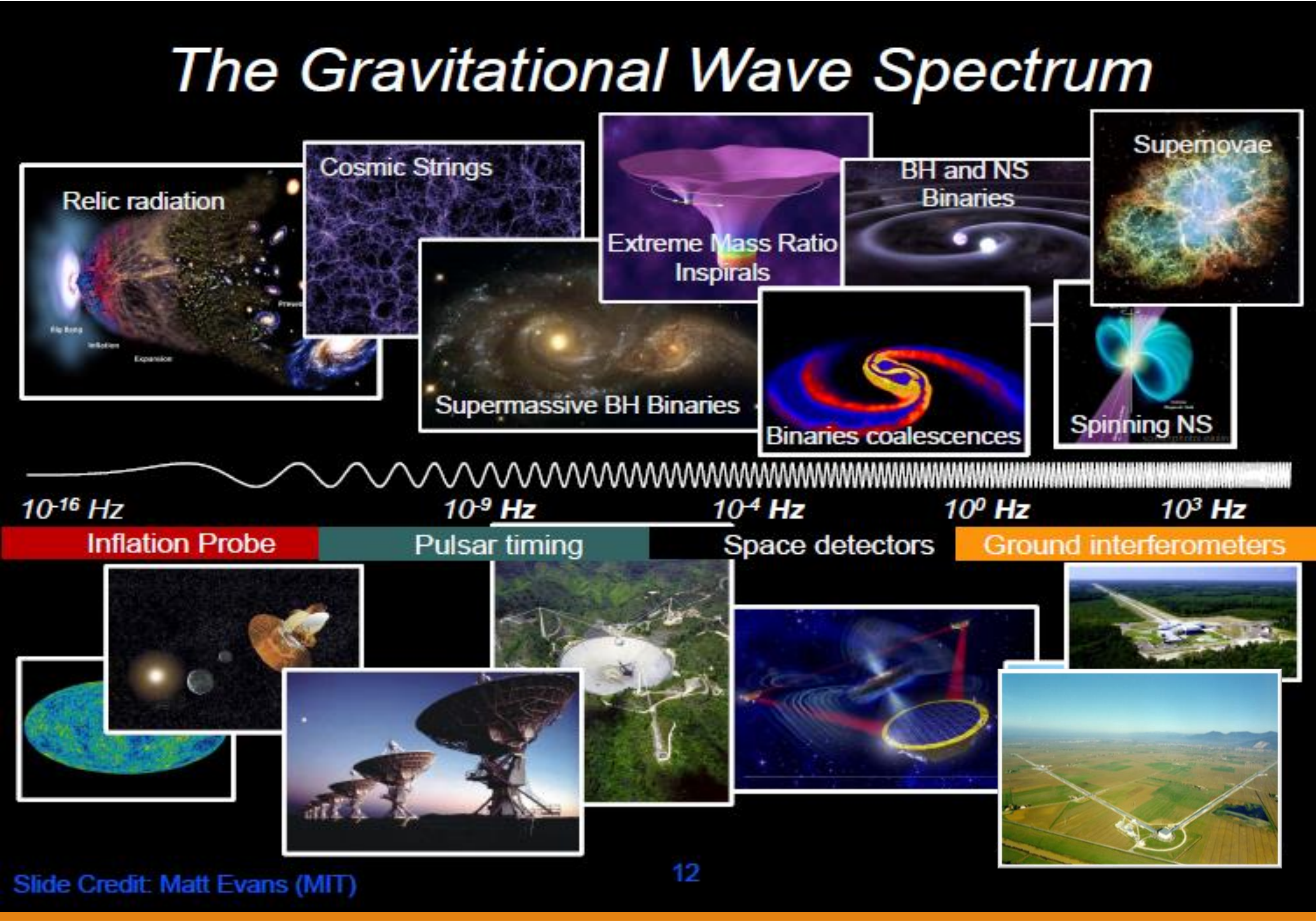
$$|h_{\mu\nu}| << 1 \qquad \left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) h_{\mu\nu} = 0$$

$$h_{\mu\nu} = h_+(t - z/c) + h_x(t - z/c)$$

Emitted from accelerating mass distributions (quadrupole mass moment – no dipole radiation)

GWs carry *direct* information about the relativistic motion of bulk matter





The Gravitational Wave Spectrum

Relic radiation

Cosmic Strings

Extreme Mass Ratio Inspirals

BH and NS Binaries

Supernovae

Supermassive BH Binaries

Binaries coalescences

Spinning NS

10^{-16} Hz

10^{-9} Hz

10^{-4} Hz

10^{0} Hz

10^{3} Hz

Inflation Probe

Pulsar timing

Space detectors

Ground interferometers

Slide Credit: Matt Evans (MIT)

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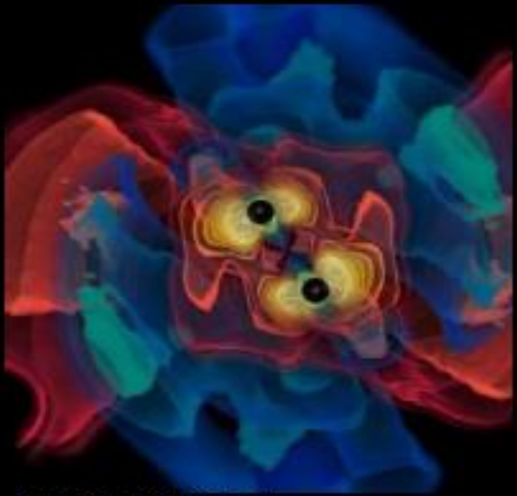
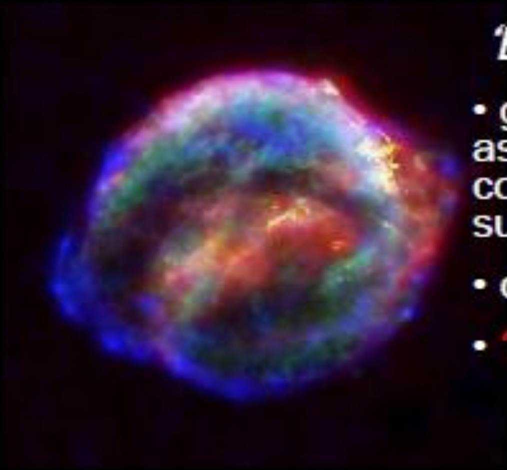
Astrophysical targets for ground-based detectors



Credit: AEI, CCT, LSU

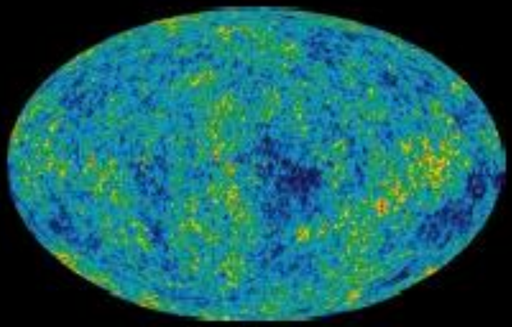
Coalescing Binary Systems

- Neutron stars, low mass black holes, and NS/BS systems



'Bursts'

- galactic asymmetric core collapse supernovae
- cosmic strings
- ???



NASA/WMAP Science Team

Stochastic GWs

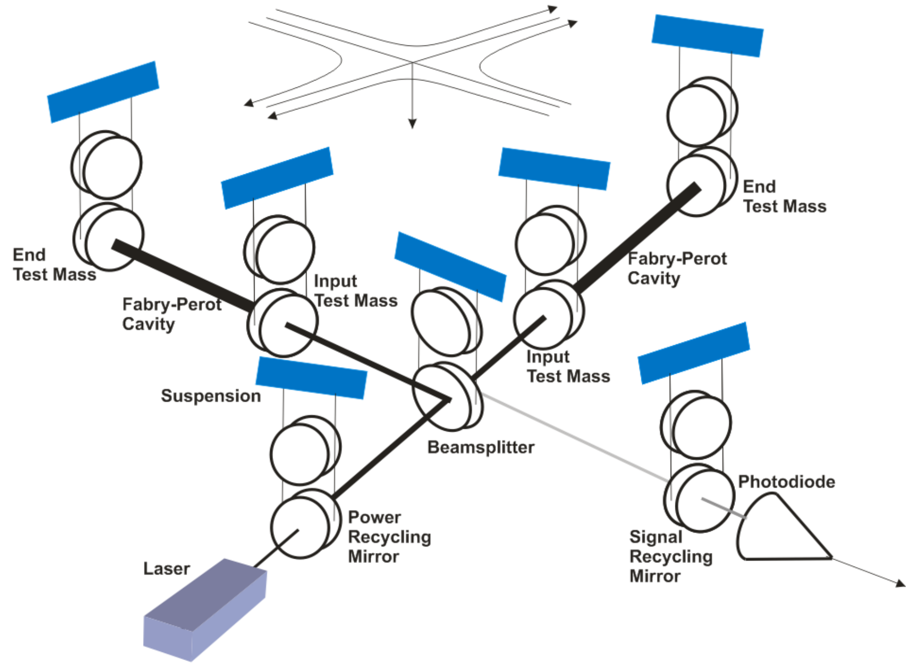
- Incoherent background from primordial GWs or an ensemble of unphased sources
- primordial GWs unlikely to detect, but can bound in the 10-10000 Hz range

Casey Reed, Penn State

Continuous Sources

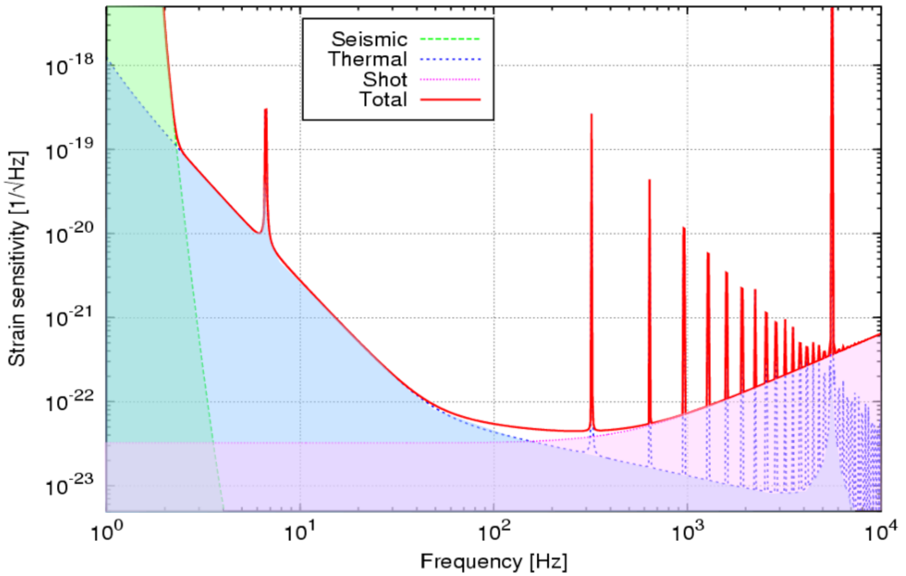
- Spinning neutron stars
- probe crustal deformations, 'EOS, quarki-ness'

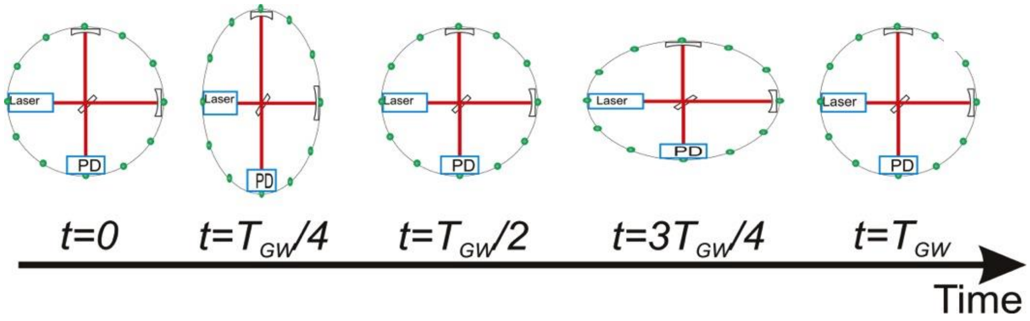
Detector’s working principle



Typically h ~ 10^{-21}

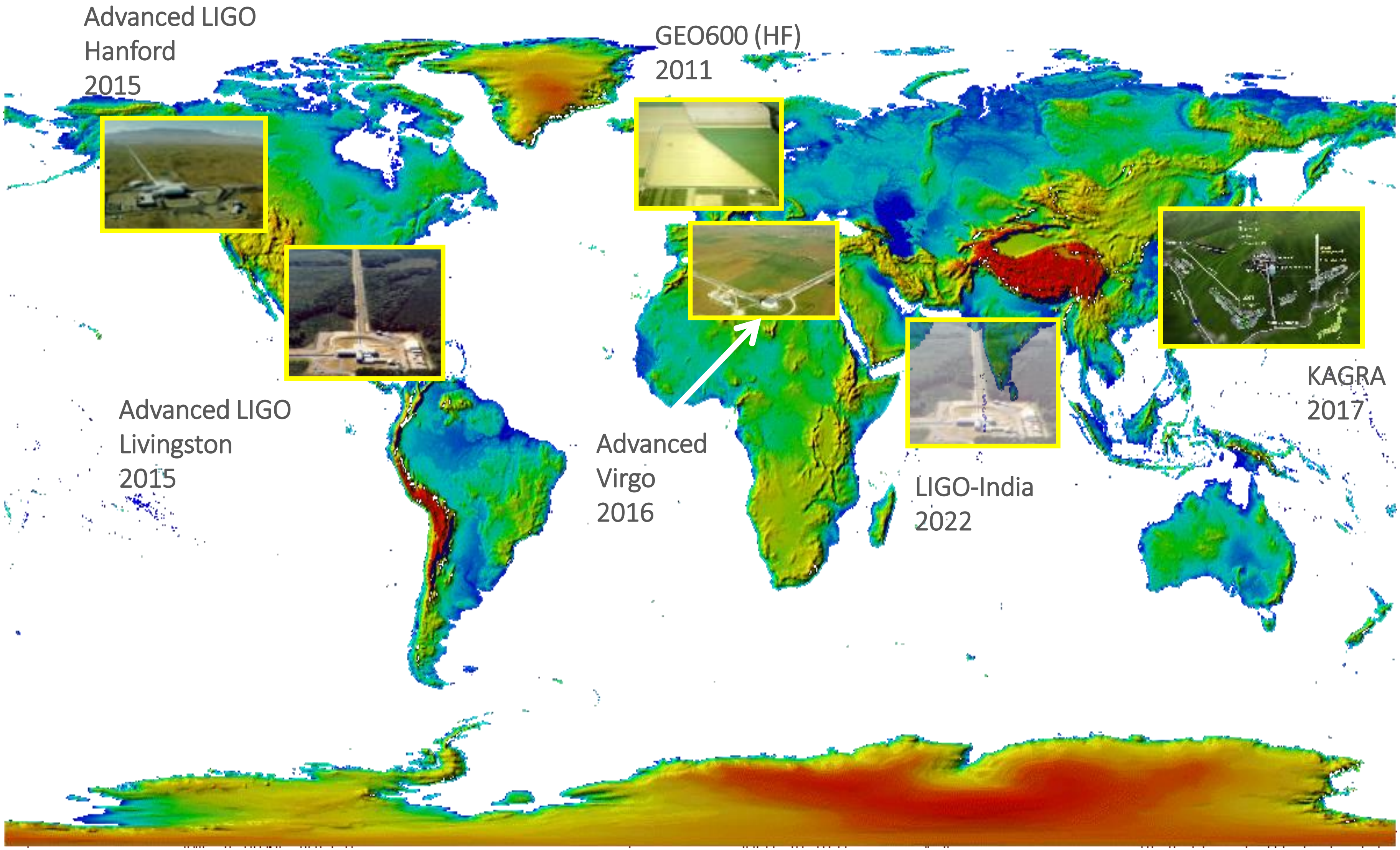
$\Delta L \sim h\,L \rightarrow$ if L ~ km $\rightarrow \Delta L \sim 10^{-18}$ m





Technical issues - alignment, electronics, acoustics, etc - may limit us before we reach these fundamental noise sources

GW detectors network



Advanced LIGO
Hanford
2015

GEO600 (HF)
2011

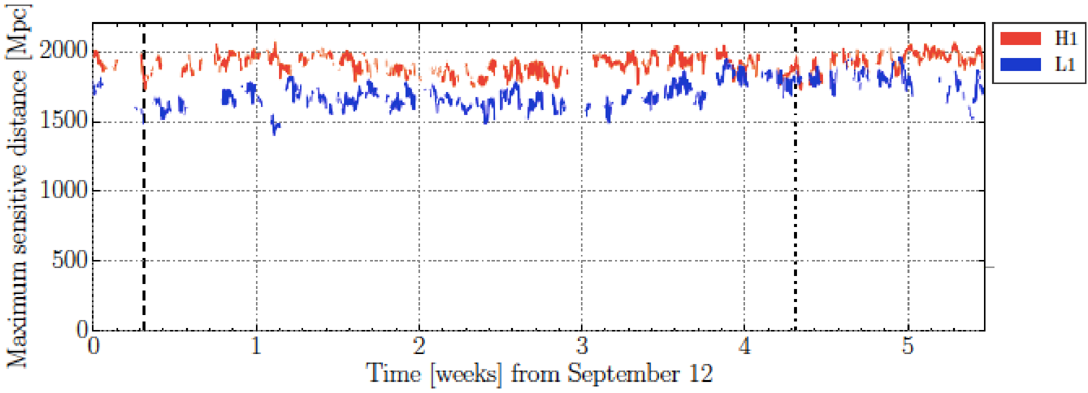
Advanced LIGO
Livingston
2015

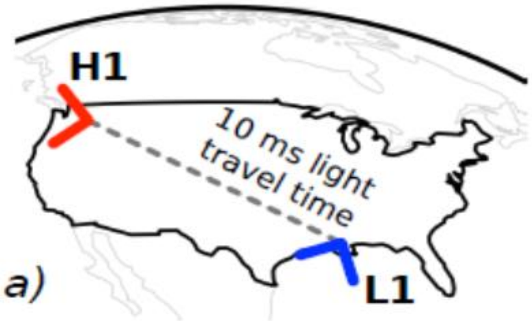
Advanced
Virgo
2016

LIGO-India
2022

KAGRA
2017

O1 aLIGO science run



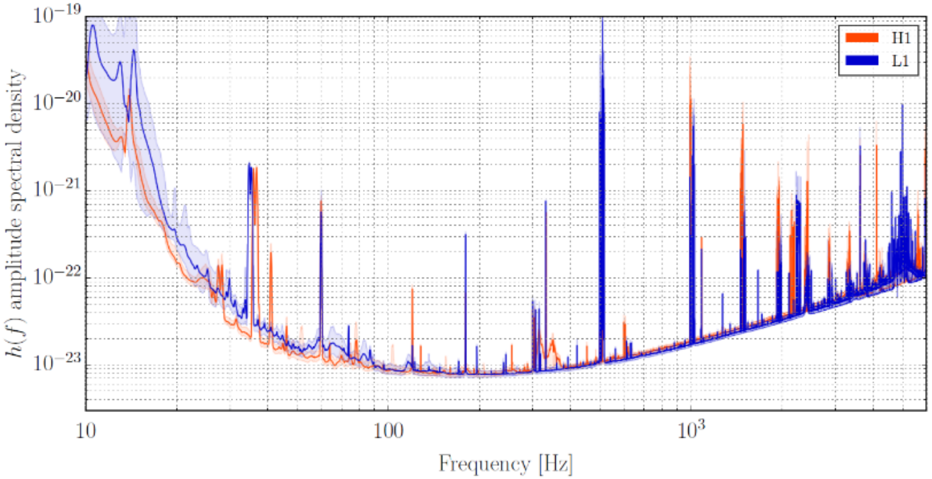


Hanford and Livingstone running with similar sensitivities:

- $10^{-23}/\sqrt{\text{Hz}}$ @ 100 Hz
- Improvement by 3-4 times wrt LIGO between 100-300 Hz

Analyzed data period from Sept 12th to Oct 20th

- Coincidence duty cycle ~ 48%
- 16 days of coincidence time



O1: from Sept 2015 to Jan 2016

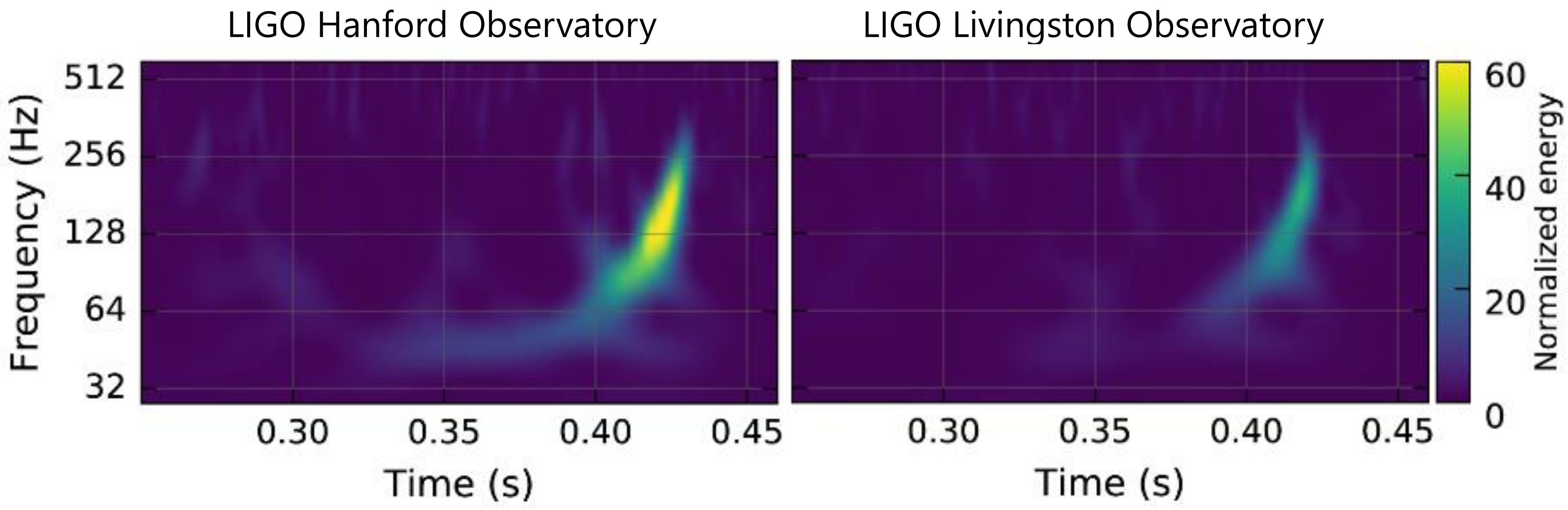
- ER8 before the science run, interferometer configuration frozen since Sept 12th

The Event: GW150914

On September 14, 2015 at 09:50:45 UTC the LIGO Hanford, WA, and Livingston, LA, observatories detected a coincident signal.

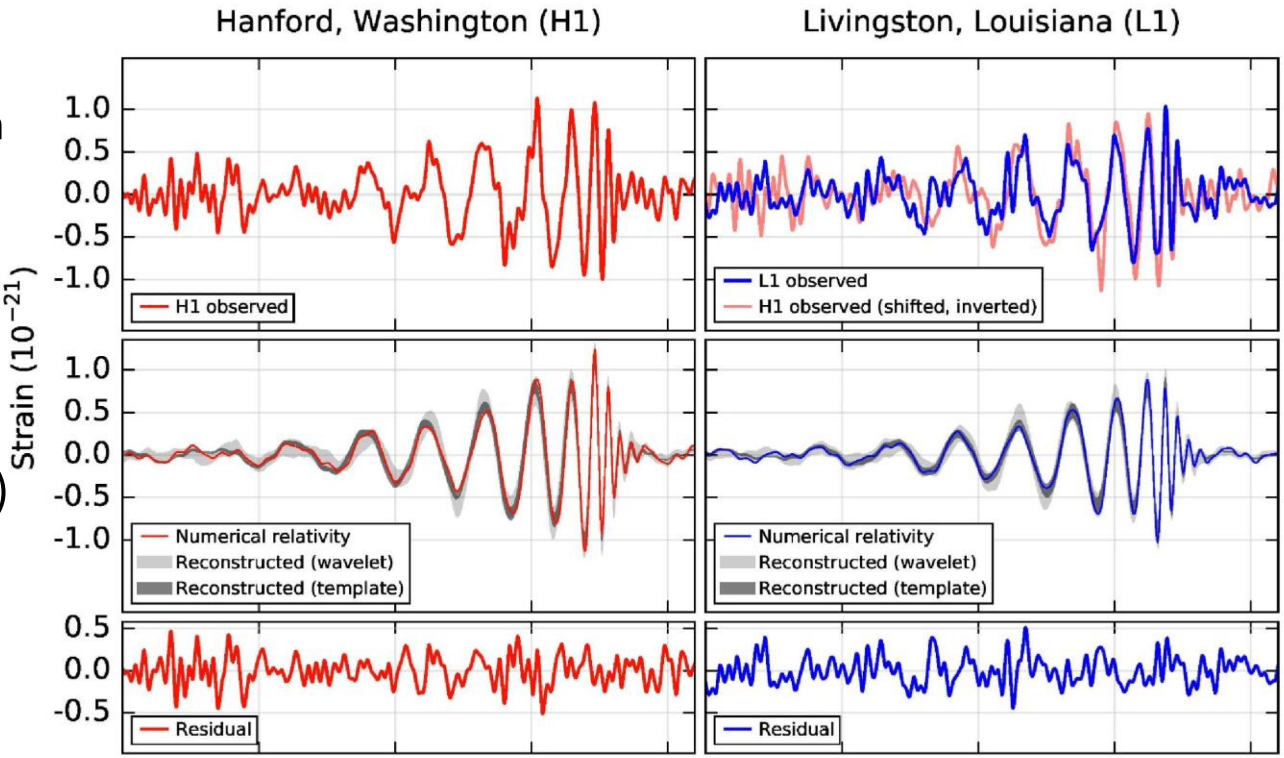
The event was flagged as **GW150914**

Exhaustive investigations of instrumental and environmental disturbances were performed, giving no evidence that GW150914 is an instrumental artifact



GW150914: the signal

- Top row left – Hanford
- Top row right – Livingston
- Time difference ~ 6.9 ms with Livingston first
- Second row – calculated GW strain using Numerical Relativity** (EOBNR and IMRPhenom) and reconstructed waveforms (shaded)
- Third Row – residuals



** Talk by A. Nagar, right after this

GW150914: the source analysis

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3}\dot{f}\right]^{3/5}$$

$$\mathcal{M} \simeq 30 M_\odot$$

$$M = m_1 + m_2 \text{ is } \gtrsim 70 M_\odot$$

NS-NS binary excluded

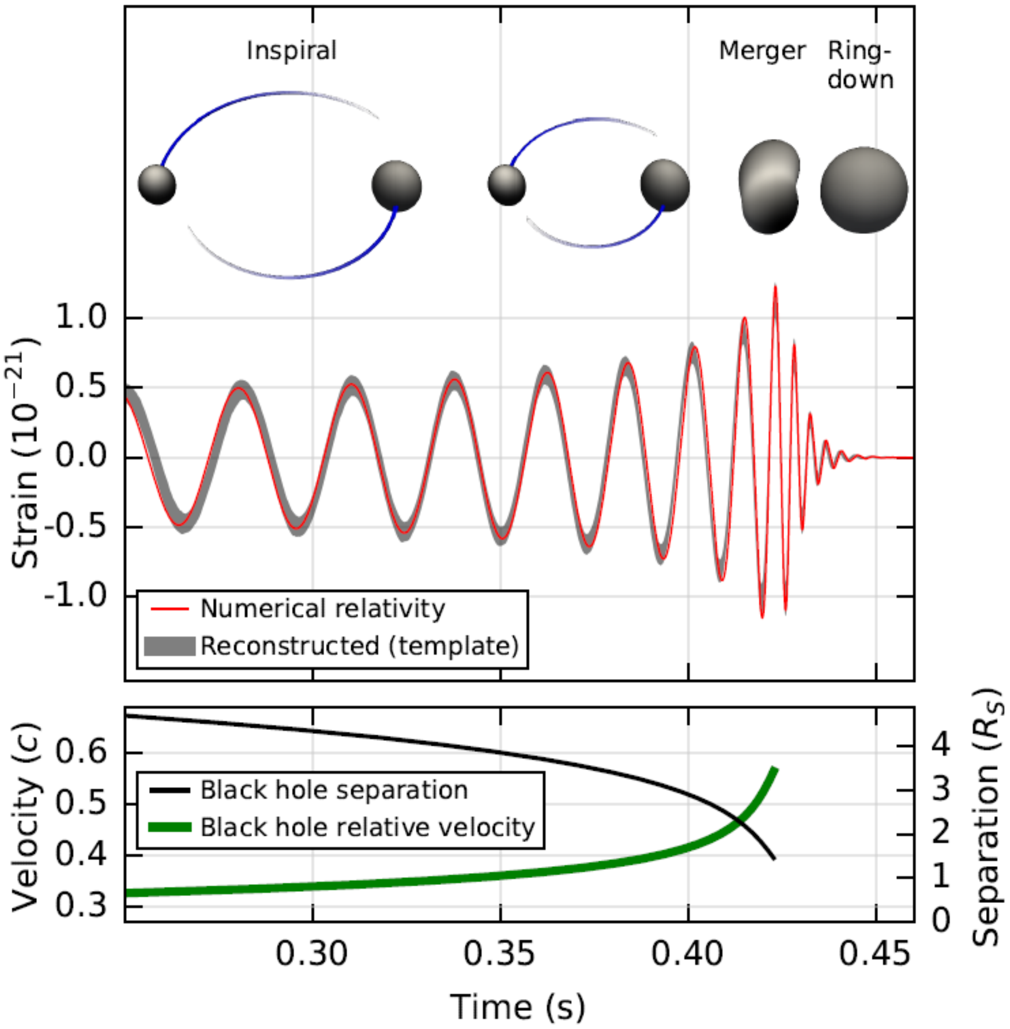
Binary system BH-NS?
If so, M_{BH} very large (~3000 $M_\odot$) ⇒
Coalescence happens at lower frequencies
NS-BH binary excluded

Binary system BH-BH, similar masses;

$$f_{\max} = 150\text{ Hz} \Rightarrow \omega_{Kepl} = 2\pi \cdot f_{\max}/2 = 2\pi \cdot 75\text{ Hz}$$

$$R = \left[\frac{GM}{\omega_{Kepl}^2}\right]^{\frac{1}{3}} \approx 350\text{ km} \quad R_{Schwarz} = \frac{2GM}{c^2} \approx 210\text{ km}$$

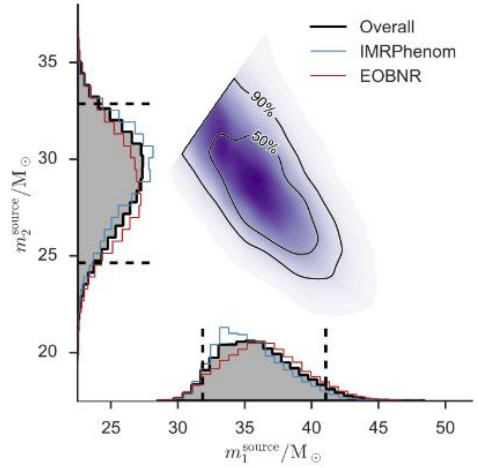
2 BHs (~ 30 $M_\odot$ each) colliding at *c*/2



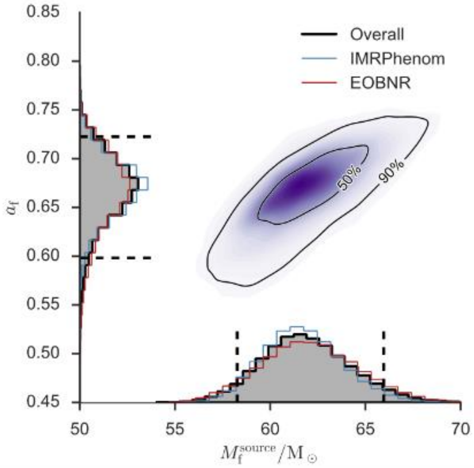
Estimated source parameters

Median values with 90% credible intervals, including statistical errors from averaging the results of different waveform models. Masses are given in the source frame: to convert in the detector frame multiply by (1+z). The source redshift assumes standard cosmology: $D_L \rightarrow z$ assuming ΛCDM with $H_0 = 67.9$ km s^{-1} Mpc^{-1} and $\Omega_m = 0.306$

Total energy radiated in gravitational waves is $3.0 \pm 0.5\, M_\odot c^2$. The system reached a peak luminosity ~3.6×10^{56} erg, and the spin of the final black hole < 0.7



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

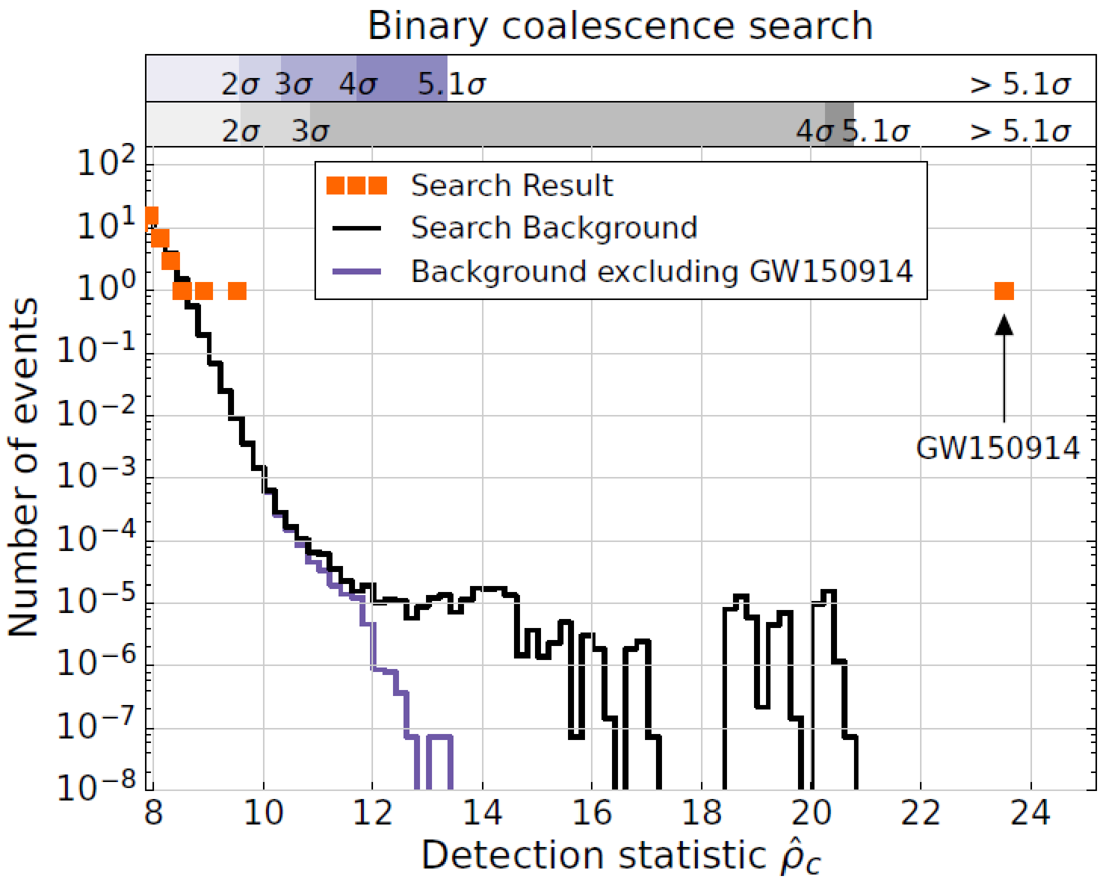


Assessing the statistical significance

- 16 days of coincidence observation (Sept. 12th to Oct. 20th 2015).
- Targets searches for Compact Binary Coalescence (NS-NS, NS-BH, BH-BH)
    - Search for individual masses from 1 to 99 solar masses; total mass < 100 solar masses and dimensionless spin < 0.99
    - Model system with combination of Post-Newtonian, black hole perturbation theory and numerical relativity
    - ~250.000 wave forms used to cover the parameter space
    - Calculate matched filter SNR $\rho(t)$ as function of time for each template and identify maxima and calculate χ^2 to test consistency with matched template
- Produce lists of candidate events for each detector
- Search for coincidences within 15 msec (10 msec travel time + 5 msec, uncertainty in arrival time of weak signals), coming from the same template.
- Coincident events ranked by the quadrature sum ρ_c of the SNRs of each detector
- Background estimation:
    - Time shift one list wrt the other → all coincidences are now only due to chance
    - Repeat 10^7 times (equivalent to observing for 608.000 years)
    - Count number of times that each ρ_c has been found by chance (low SNRs have a higher probability to occur by chance)

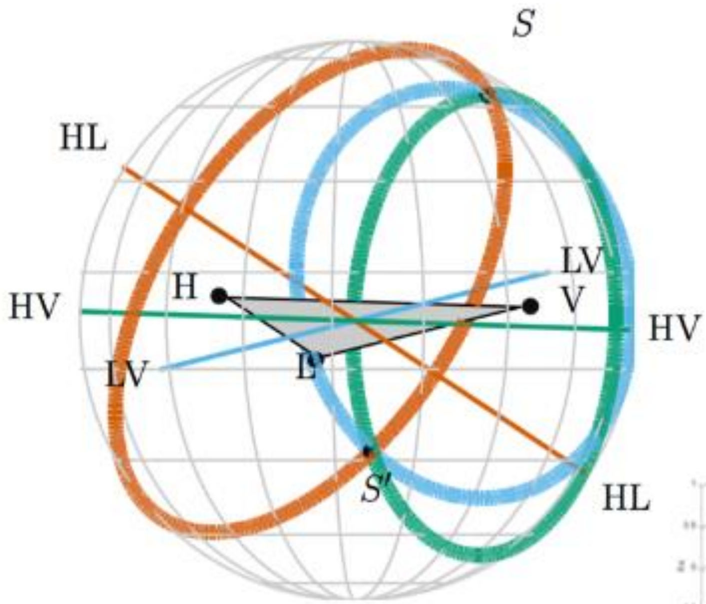
Assessing the statistical significance

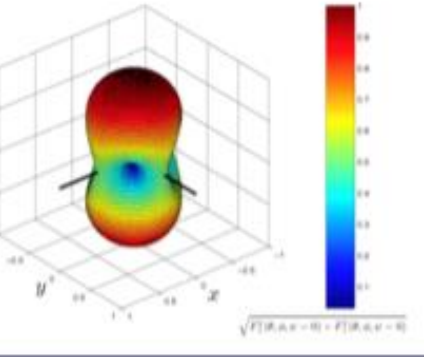
- number of candidate events (orange markers)
- number of background events (black and purple lines)
- significance of an event in Gaussian standard deviations based on the corresponding noise background

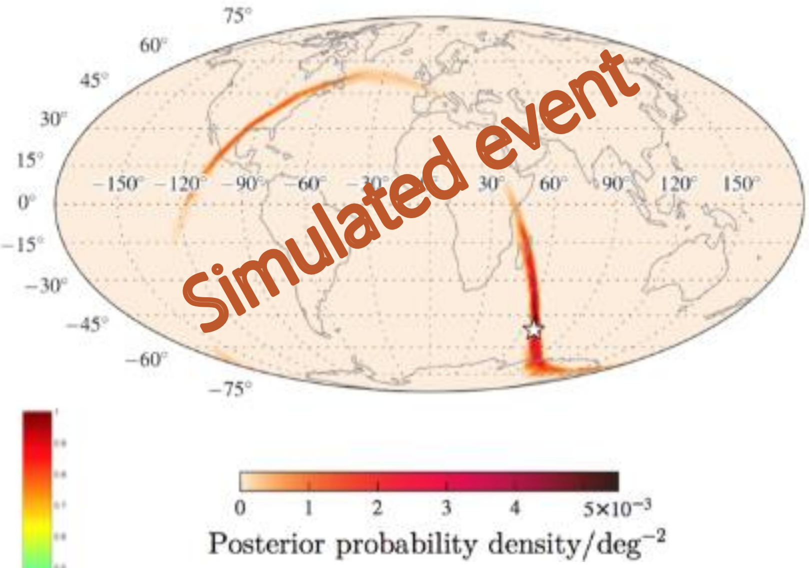


- False alarm rate < 1 per 203.000 years,
- Poissonian false alarm probability < 2 x 10^{-7}
- Significance > 5.1 σ

Sky localization



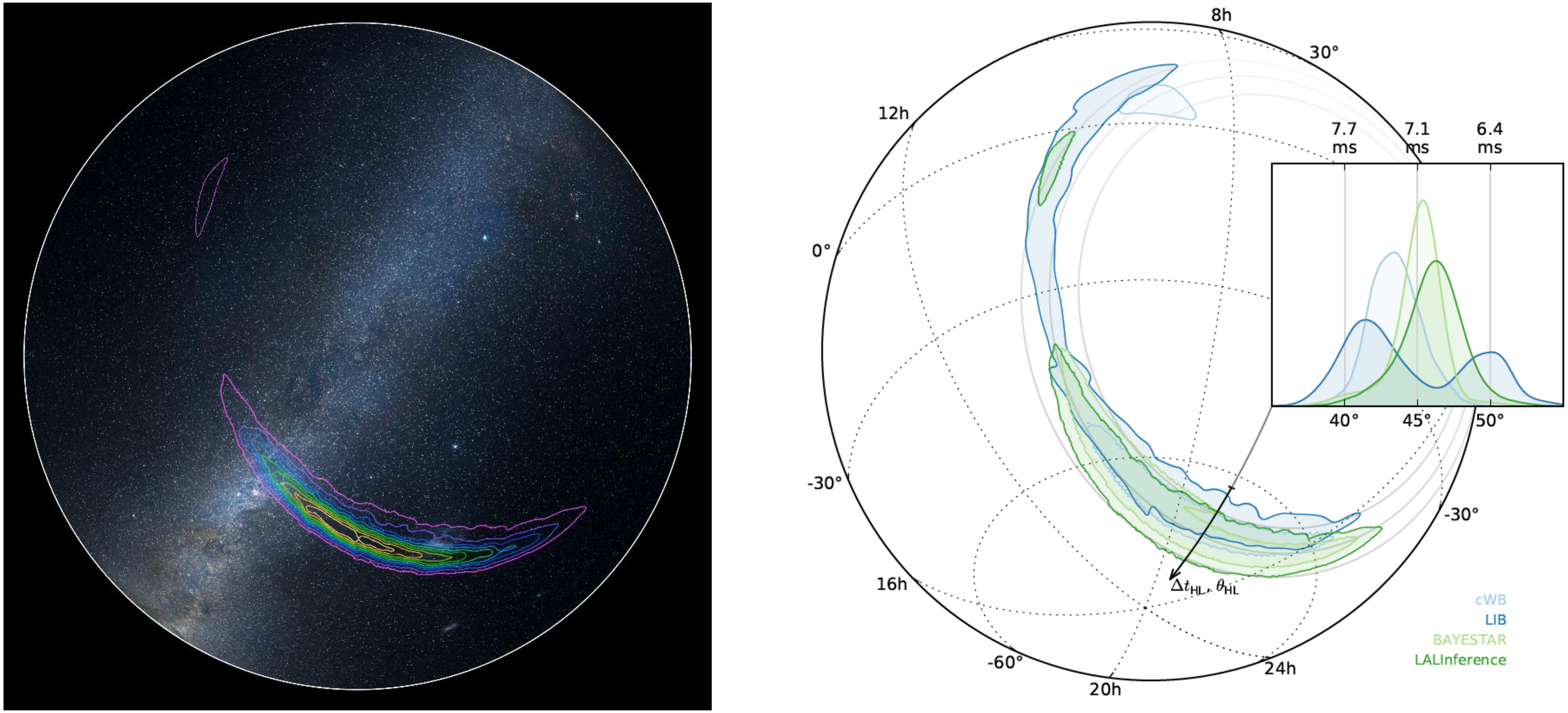




Sky location reconstructed through the time of arrival of GW radiation at the different detector sites, as well as the relative amplitude and phase of the GWs in different detectors.

Two interferometers (HL) can only determine an **annulus** in the sky

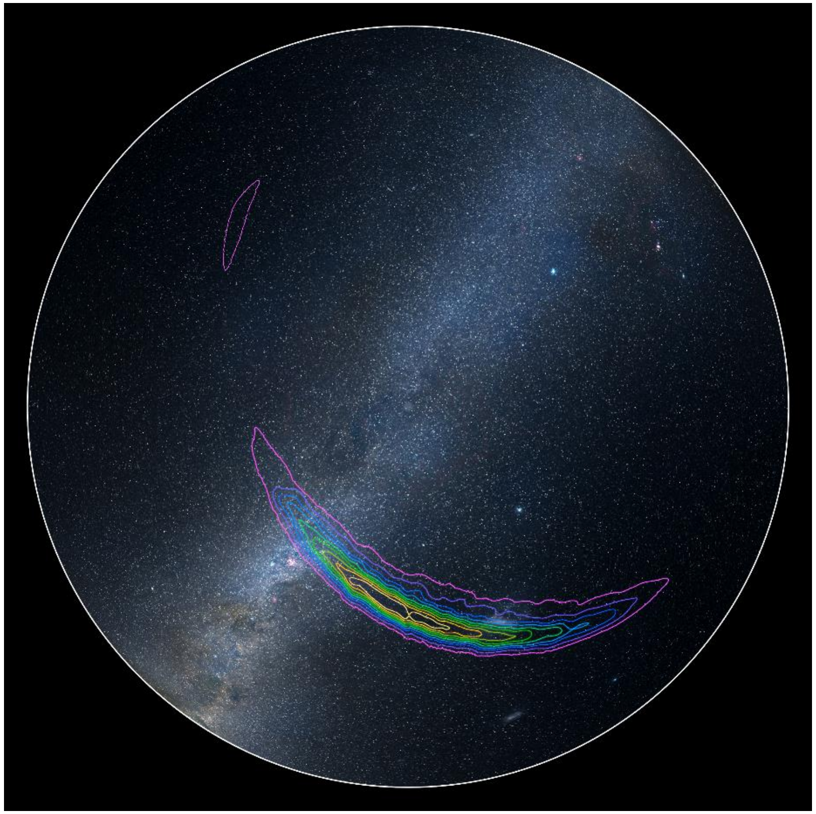
Sky localization

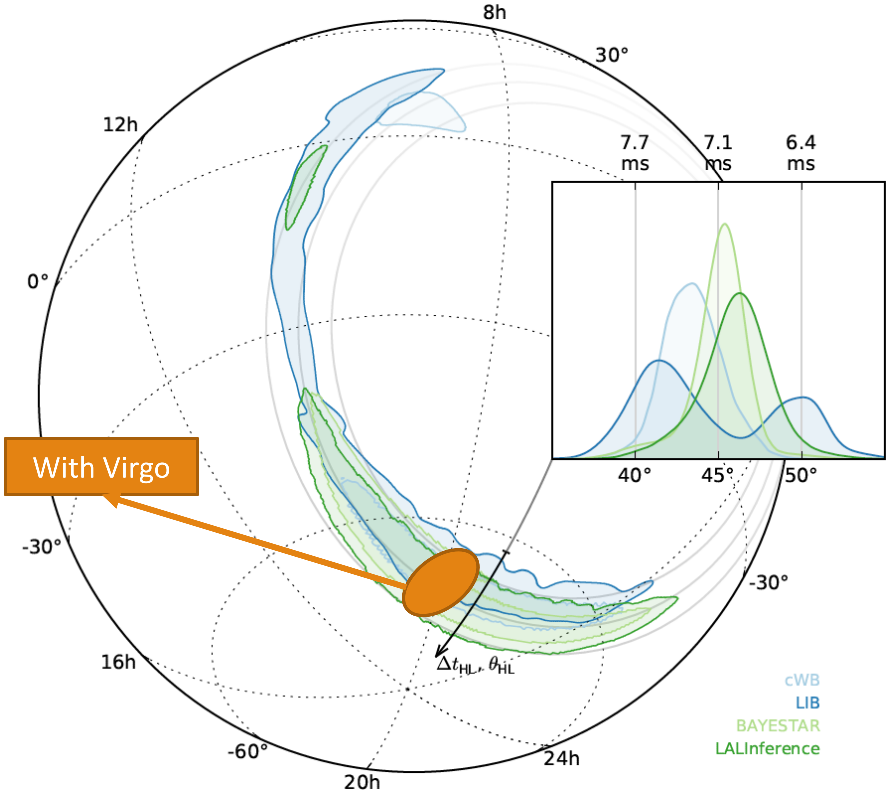


Comparison of different GW sky maps, showing the 90% credible level contours for each algorithm. The inset shows the distribution of the polar angle θ_{HL} (equivalently, the arrival time difference Δt_{HL}).

GW150914 has been localized in an area of 590 deg^2 in the southern emisphere

Sky localization





With Virgo

Comparison of different GW sky maps, showing the 90% credible level contours for each algorithm. The inset shows the distribution of the polar angle θ_{HL} (equivalently, the arrival time difference Δt_{HL}).

GW150914 has been localized in an area of 590 deg^2 in the southern emisphere

With Virgo, the sky localization area would have been much better

Astrophysical implications

Existence of binary black holes systems proved

- **Form** and **merge** within the Hubble time
- Previous predicted rates ranged $[0 - 10^3]$ / Gpc^3 / yr
- Lowest end excluded: **rate > 1 / Gpc^3 / yr**

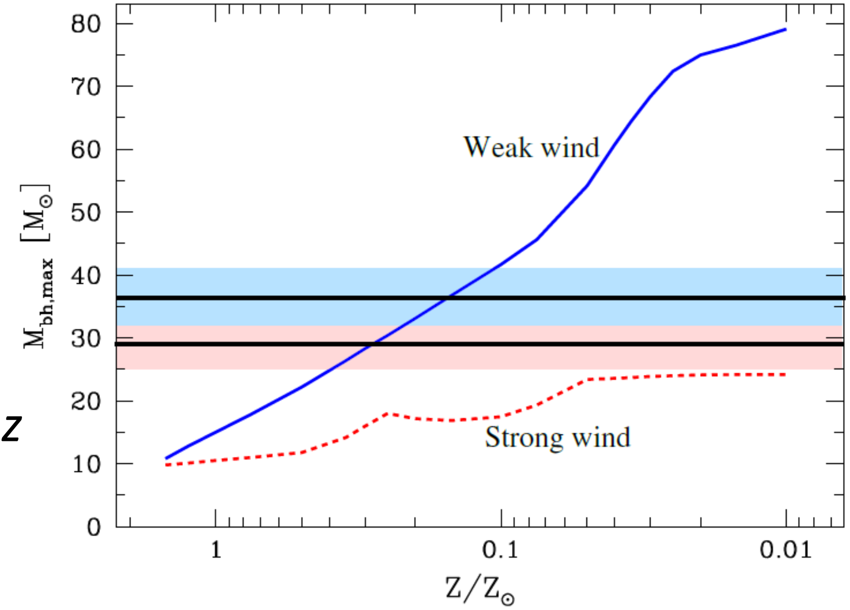
Component masses ($M > 20\, M_\odot$) large compared with *known* stellar mass BHs

Stellar progenitors are

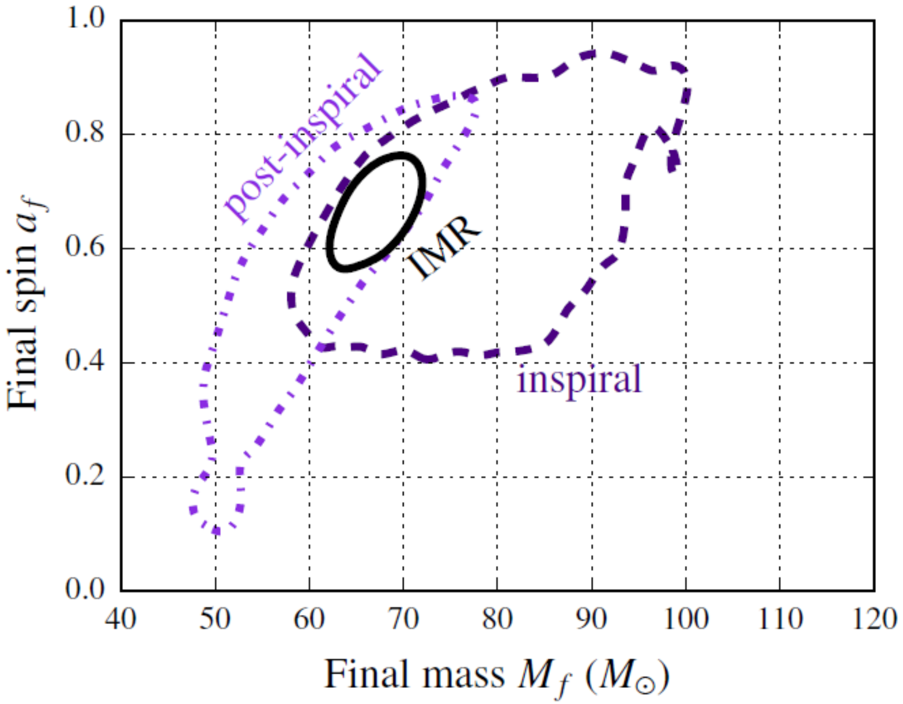
- Likely **heavy**, $M > 60\, M_\odot$
- Likely with a **low metallicity**, $Z < 0.25\, Z_\odot$
- Require **weak** solar wind

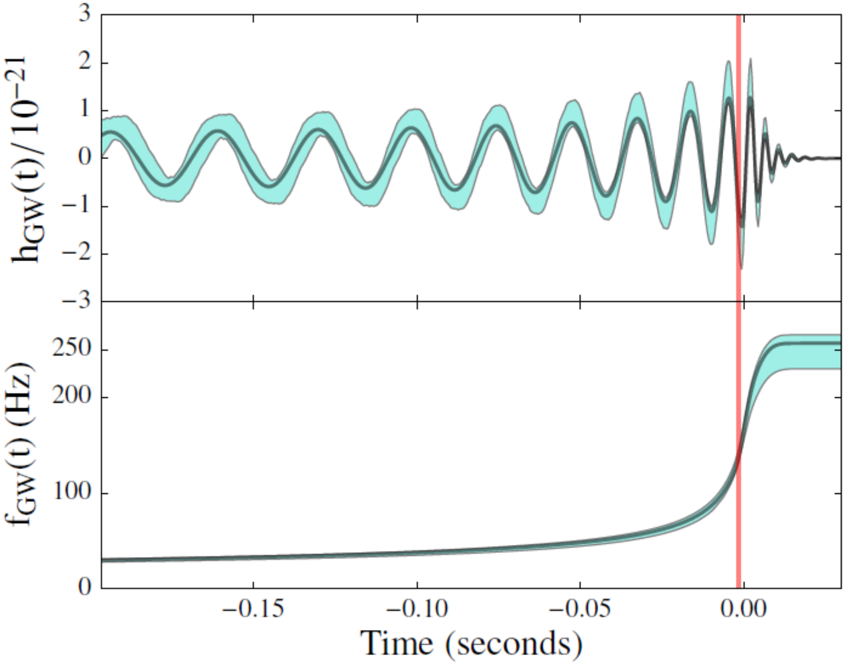
Measured redshift $z \sim 0.1$

Low metallicity models can produce low-*z* mergers at rates consistent with our observation



Testing GR: Waveform consistency





Prediction of final black hole mass and spin

90% credible regions for the waveform and GW frequency of GW150914 versus time. The solid lines in each panel indicate the most probable waveform from GW150914 and its GW frequency.

Testing GR: Bound on graviton mass

If graviton is massive, then its speed is less than *c*

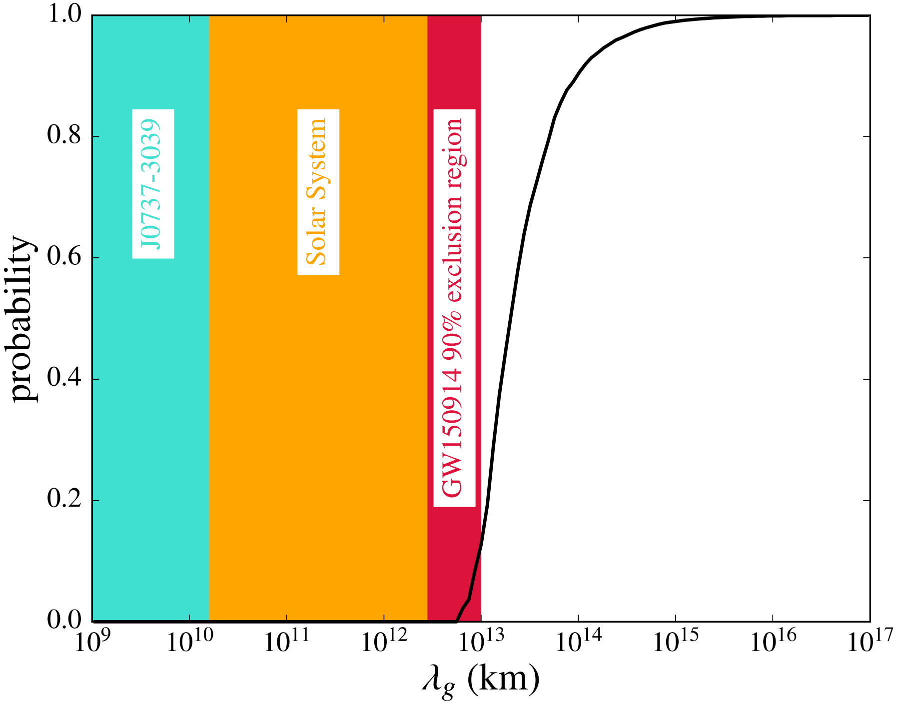
→ GWs would obey a modified dispersion relation

GW150914: $\lambda_g > 10^{13}$ km with 90% CL

or

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

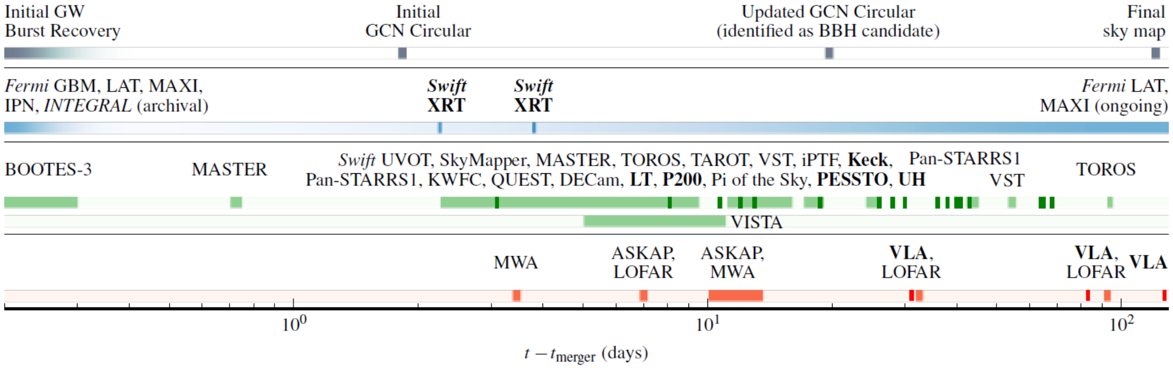
- GW150914 is the most relativistic known system (v/*c* ~ 0.6)
- limit better than that set by Solar System observations
- thousand time better of the binary pulsar bounds (v/*c* ~ 2 x 10^{-3})
- worse than bounds from dynamics of galaxy clusters and weak lensing observations (model-dependent bounds)

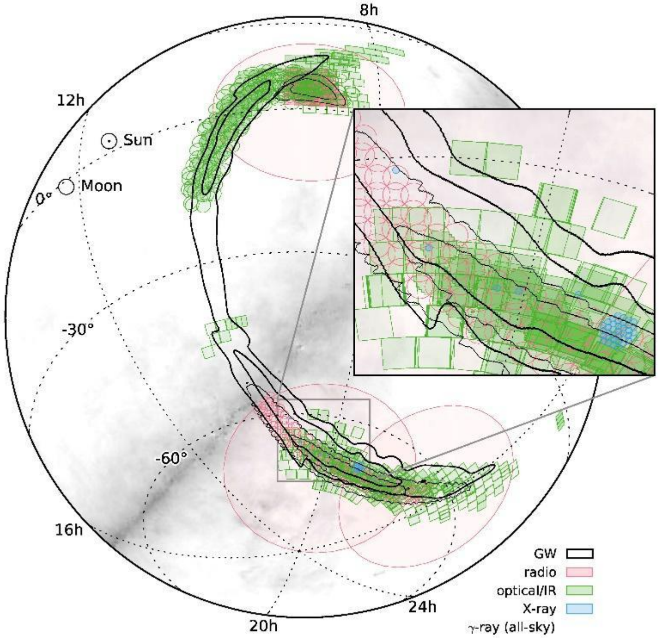


EM follow-up

LVC called for EM observers to join a follow-up program

- LIGO and Virgo share promptly interesting triggers, also providing limited information on direction
- > 70 MoUs, 160 instruments covering full spectrum from radio to very high energy gamma-rays





Big participation to GW150914 observation:

- 25 groups carried out observations
- No EM counterpart detected (as expected)

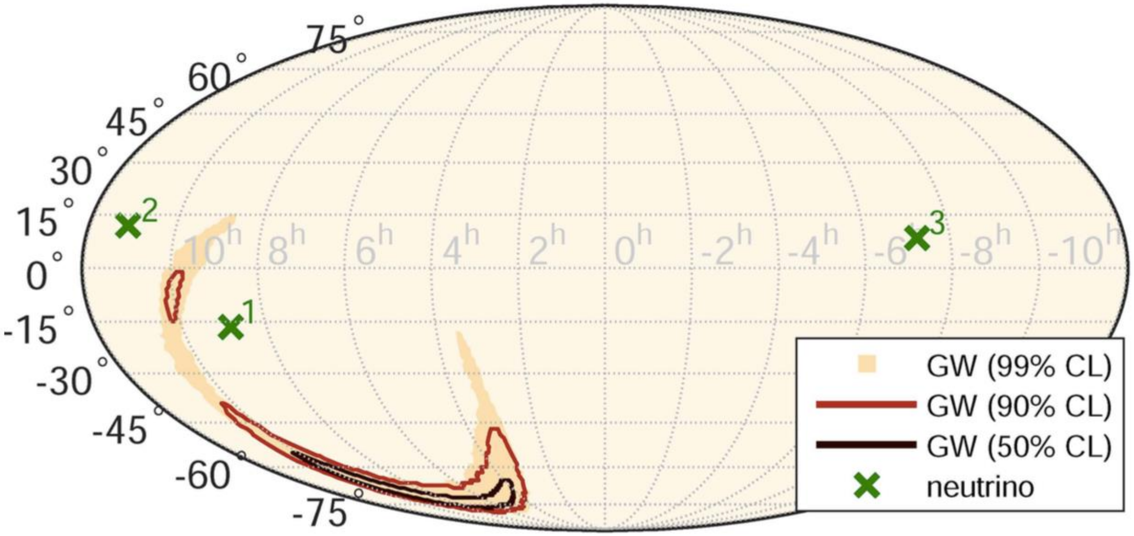
Follow-up with high energy neutrinos

Search for coincident high energy neutrino candidates in IceCube and ANTARES data

- HEν expected in (unlikely) scenario of BH + accretion disk system
- Search window ± 500 s

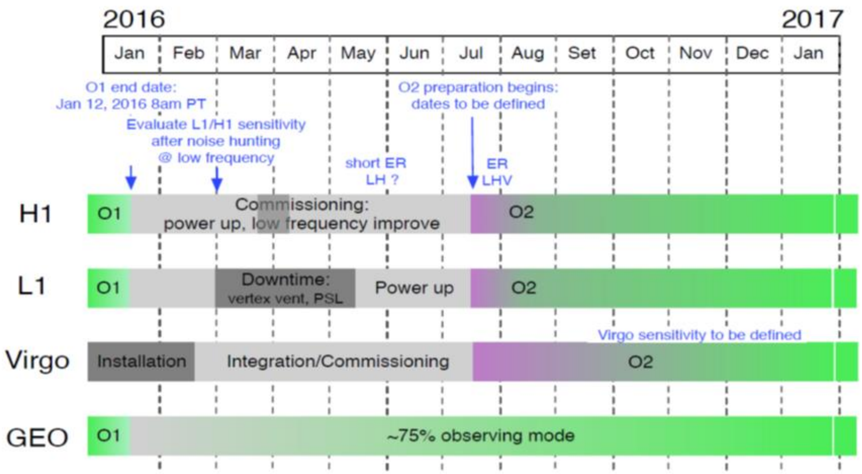
No ν candidate in both temporal and spatial coincidence

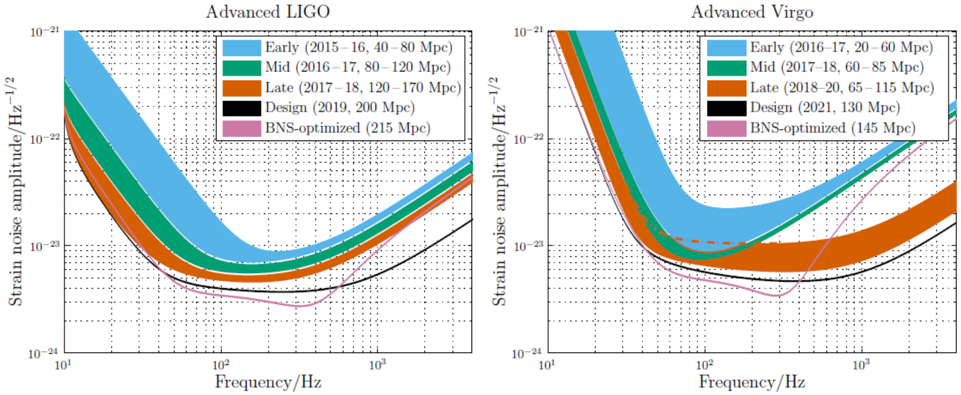
- 3 ν candidates in IceCube and 0 ν candidate in ANTARES
  - Consistent with expected atmospheric background
- None of ν candidates directionally coincident with GW150914



LIGO/Virgo next science run: O2

LIGO and Virgo are now off-line for commissioning/integration



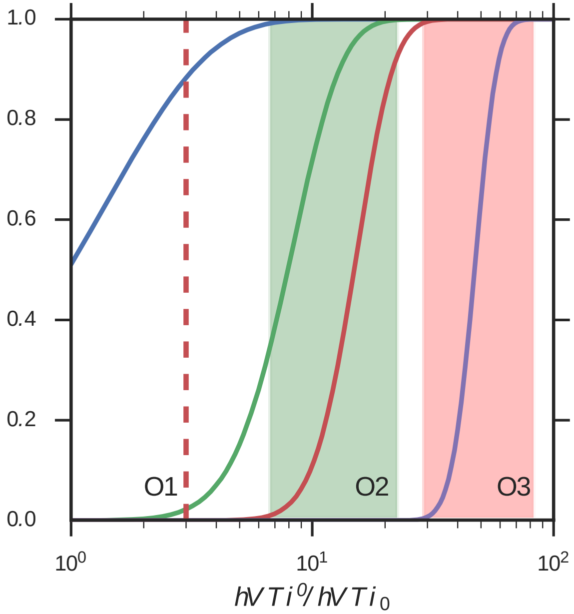


Probability of observing

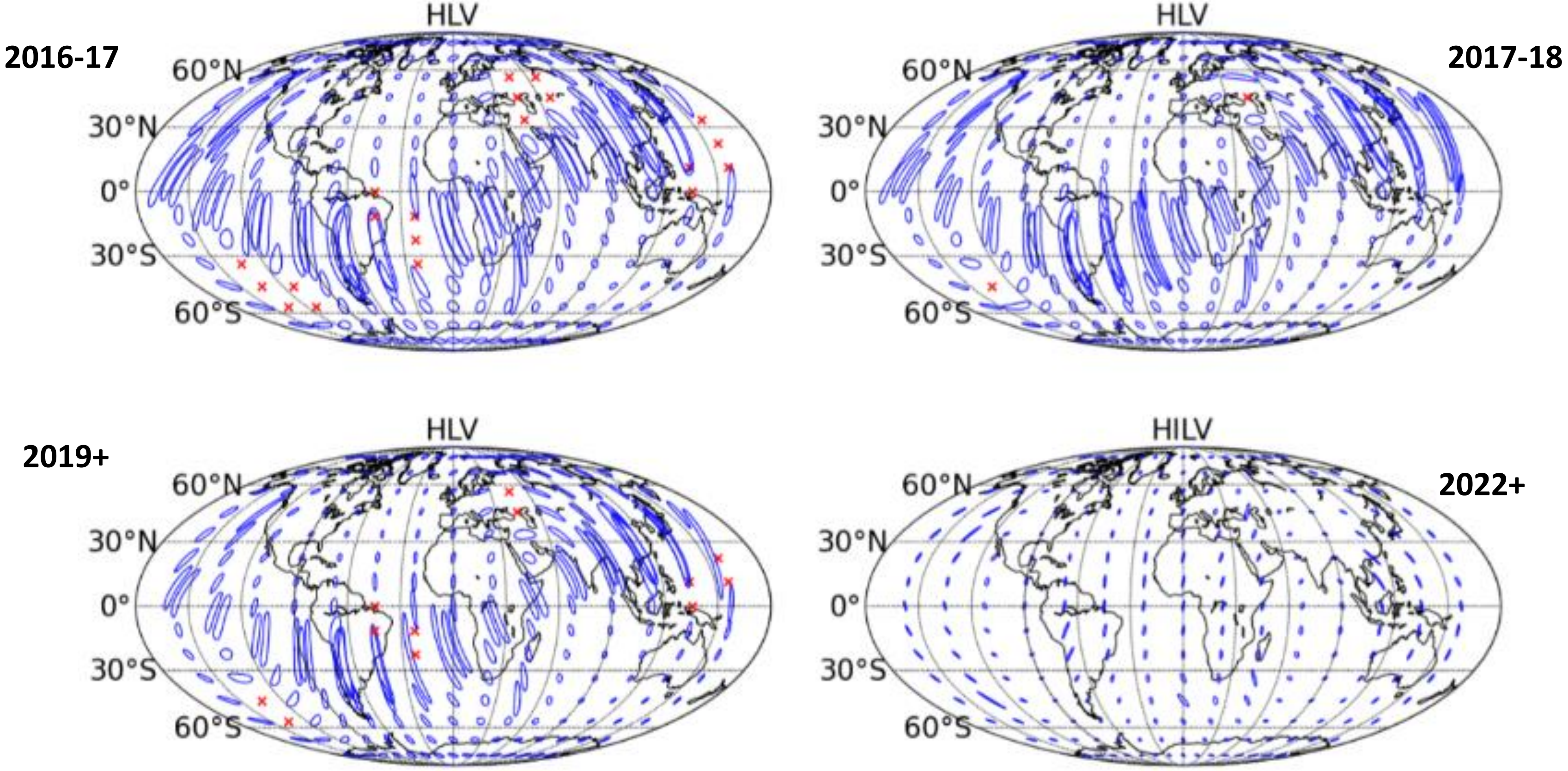
- N > 0 (blue)
- N > 5 (green)
- N > 10 (red)
- N > 35 (purple)

highly significant events, (FARs <1/century)

as a function of surveyed time-volume.



Sky localization perspectives



2016-17

2017-18

2019+

2022+

With Virgo, no more annulus

As sensitivity improves, so does the localization

With LIGO-Virgo network at design sensitivity, GW150914 could have been localized to less than 20 deg^2

Conclusions

We observed gravitational waves from the merger of two stellar mass black holes: a clear and loud signal.

The detected waveforms match the prediction of general relativity for the inspiral and merger of a binary black hole system and the ringdown of the resulting black hole.

This observation is the **first direct detection** of gravitational waves and the **first observation** of a binary black hole merger.

Only a fraction of O1 analyzed, more data is being analyzed.

This discovery opens up two new paths:

- Testing gravitation in uncharted territory;
- Gravitational wave astronomy.

Enriched network in 2016 with Advanced Virgo

GW150914 Companion papers

Detection Paper
Phys. Rev. Lett. 116, 061102 (2016)
arXiv:1602.03837

Observing scenario
Living Rev. Relativity 19, 1 (2016)

Astrophysics implications
ApJL, 818, L22, 2016
arXiv:1602.03846

Test of GR
arXiv:1602.03841

Rates
arXiv:1602.03842

Stochastic Background
arXiv:1602.03847

EM follow-up and HEν
arXiv:1602.05411
arXiv:1602.08492

CBC searches
arXiv:1602.03839

Unmodeled searches
arXiv:1602.03843

Parameter Estimation
arXiv:1602.03840

Instrument
arXiv:1602.03838

DetChar
arXiv:1602.03844

Calibration
arXiv:1602.03845

Public data release
https://losc.ligo.org/events/GW150914