Introduction to gravitational wave physics, results and perspectives

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Seminar UT Dresden

June 2018

Announcements

- « The LIGO and Virgo collaborations were very proud to announce that, on September 14th 2015 at 9:50 AM, the two LIGO interferometric detectors recorded an event, called GW150914, that was identified as the passage of a gravitational wave produced by the coalescence of two black holes of respectively 29 and 36 times the mass of the sun, located at a distance of 1.3 billion light-years. »

- « LIGO and Virgo did it again… four times ! »

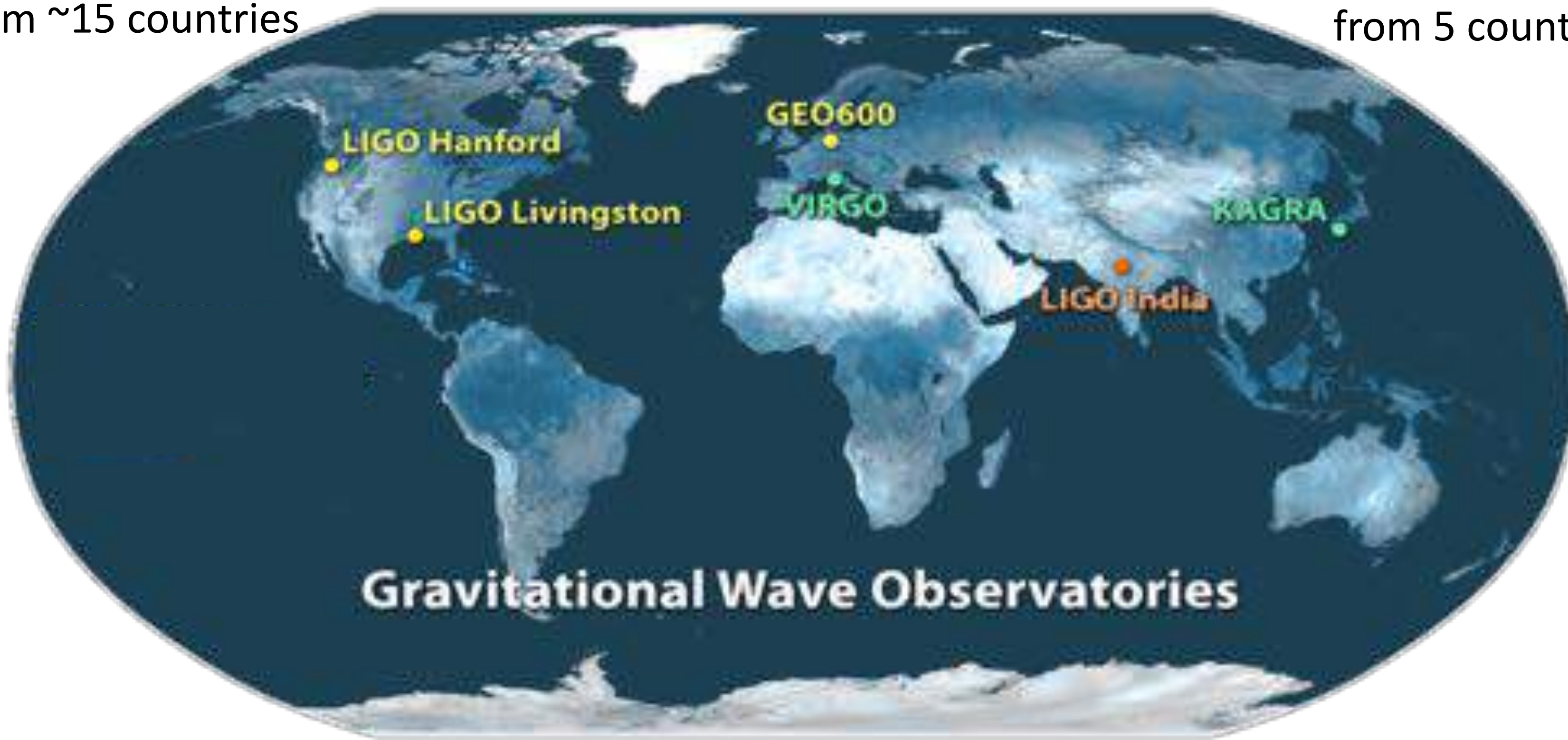
- « On August 17th 2017 at 12:41 PM, LIGO and Virgo collaborations announced the first detection of a binary neutron star merger, GW170817 »

Detections of gravitational waves

By the network of interferometric detectors
Advanced LIGO – Advanced Virgo

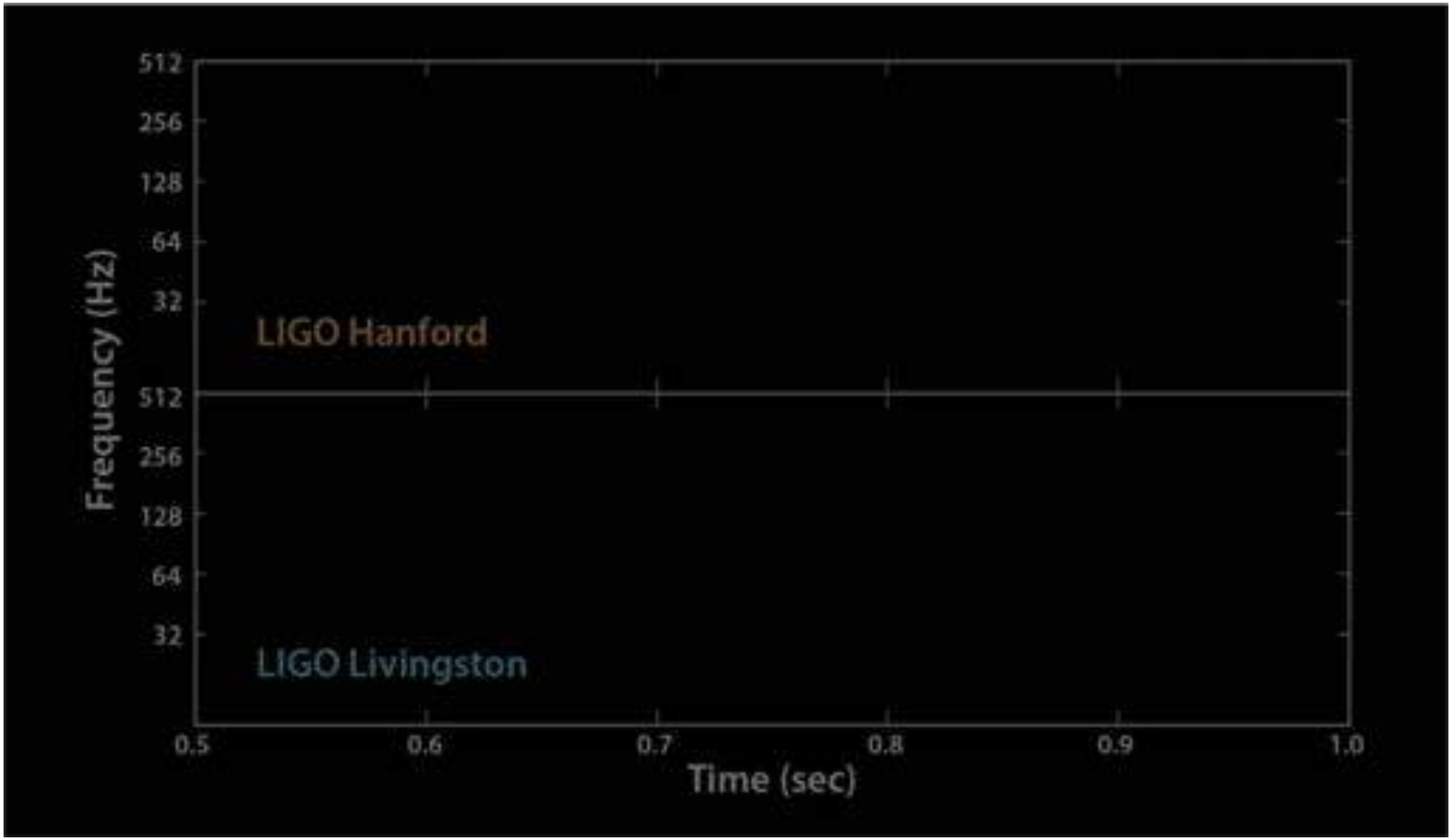
LSC : ~900 members
~80 institutions
from ~15 countries

Virgo : ~200 members
19 laboratories
from 5 countries

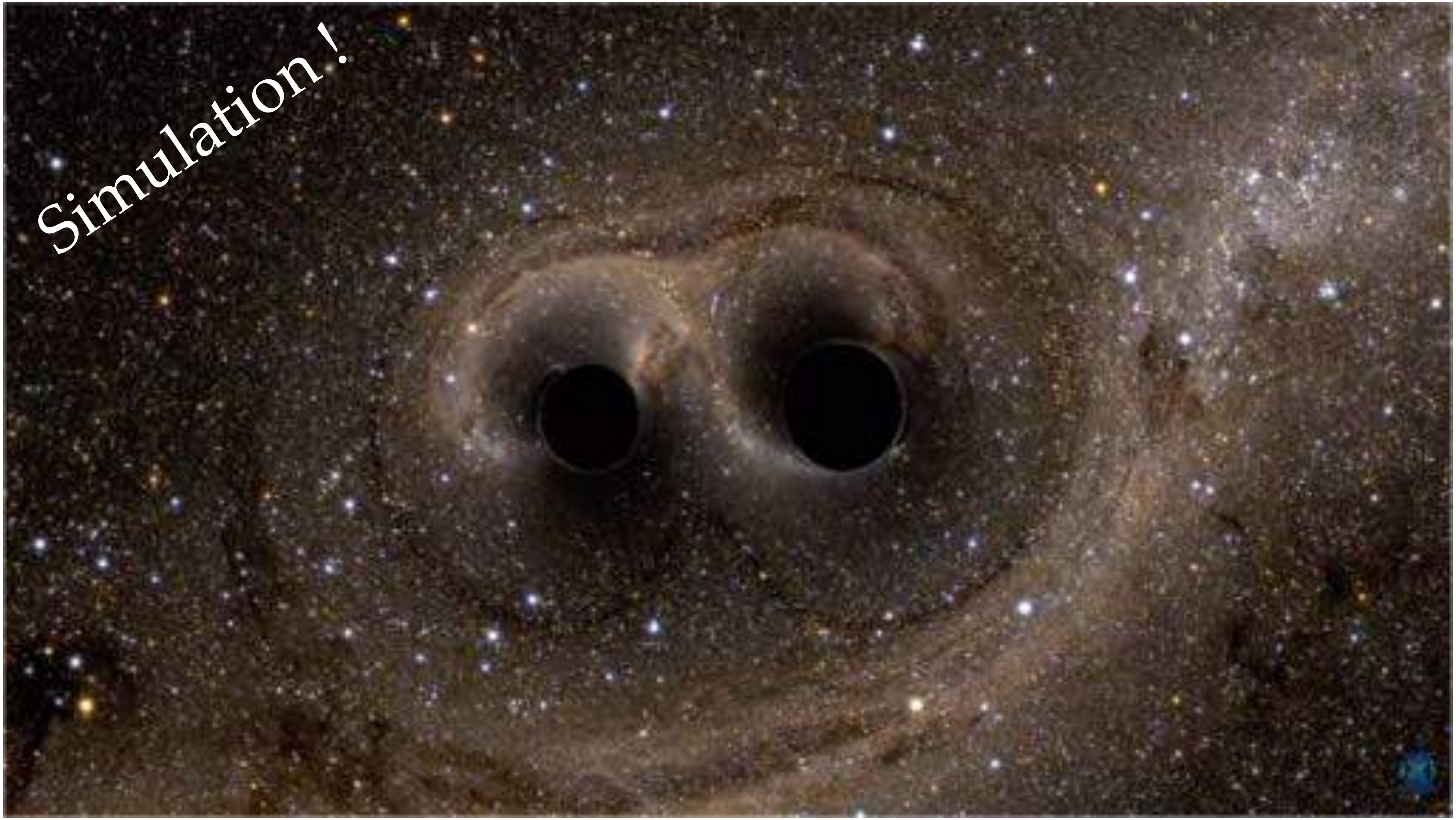


Since 2007, LVC = LIGO-Virgo Collaboration

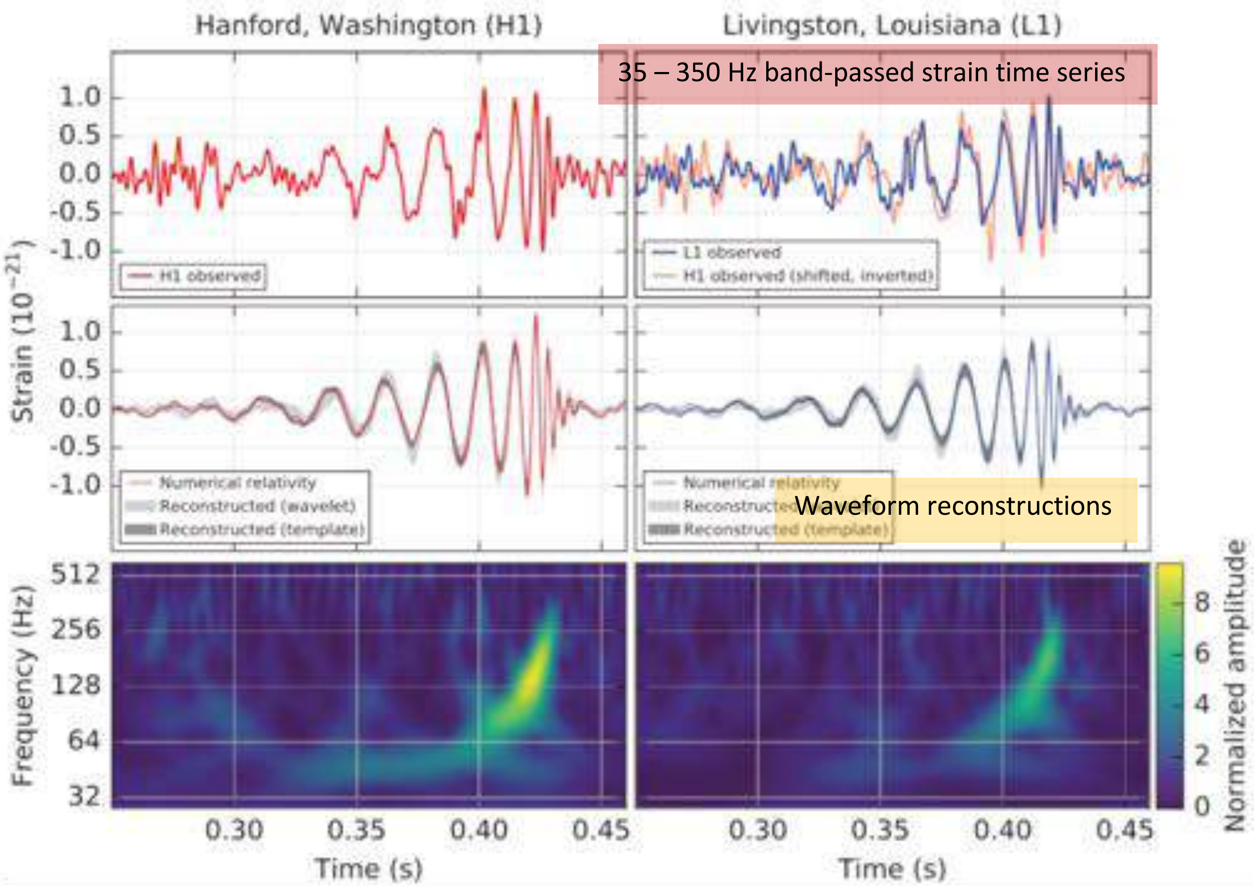
How does it « sound » ?



What does it look like ?



What does it look like in LIGO/Virgo ?



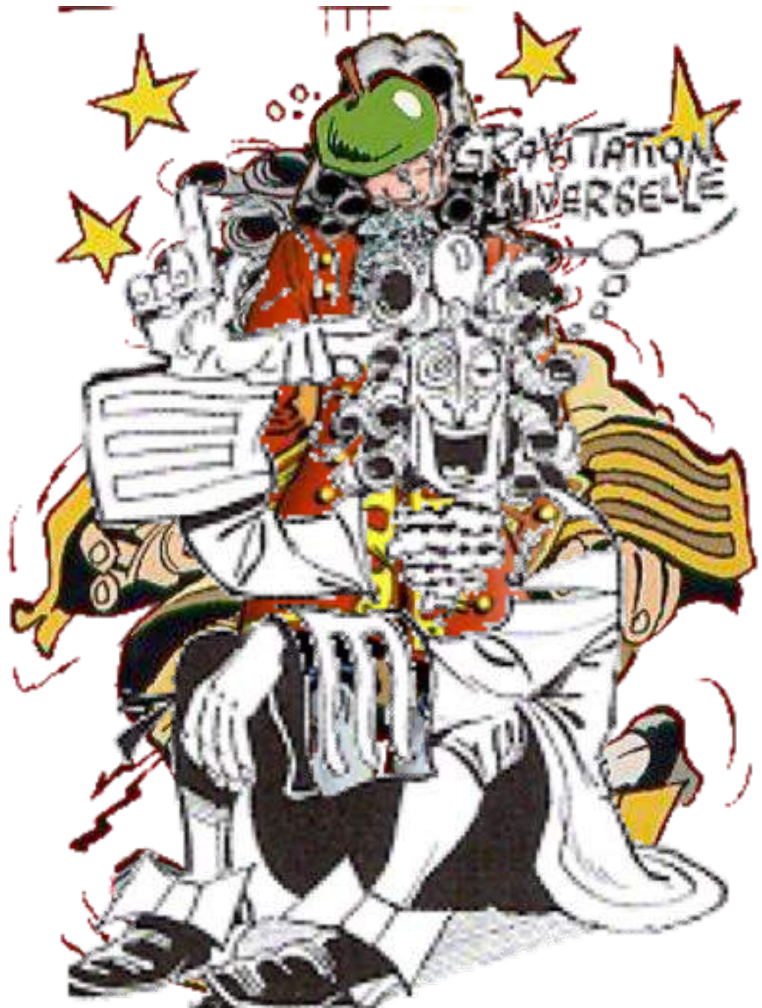
- Nickname : GW150914
  - Detected September 14, 2015 at 09:50:45 UTC
  - Masses : 29 and 36 solar masses
  - Distance : ~ 1.3 Glyr
  - Duration : 0.2 s

« The » first detection, gave the Nobel prize to Weiss, Barish and Thorne opened a new era of gravitational astronomy

How do gravitational waves come from General Relativity?

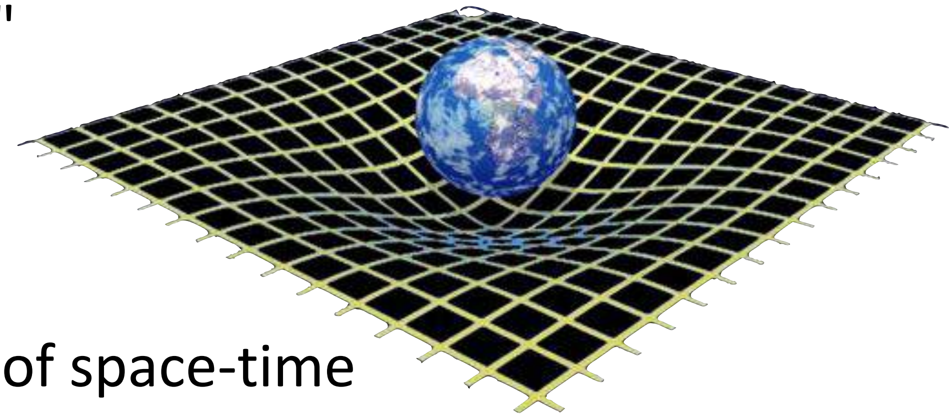
How does it work ?

- Main ingredient : gravity

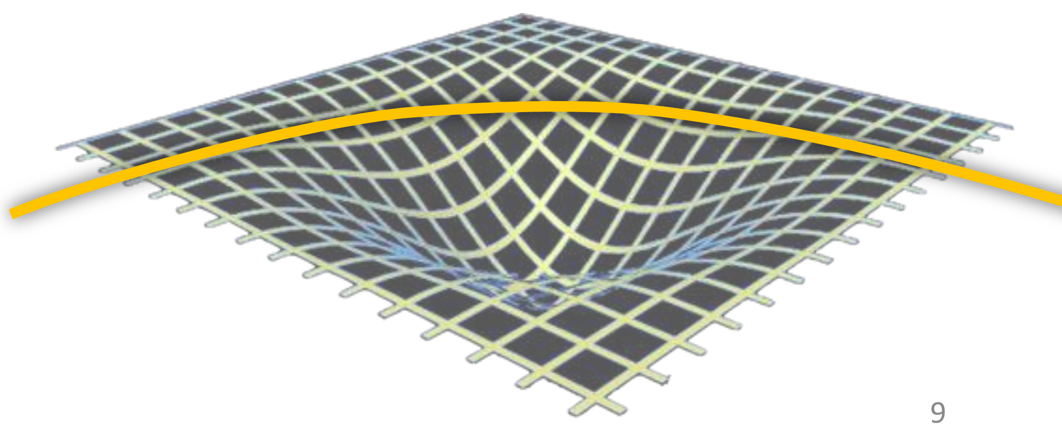


The work of gravity

- Theory of General Relativity (GR)
- Einstein 1915-1918 : geometric theory of gravitation
- A mass "bends" and "deforms" space-time



- The trajectory of a mass is influenced by the curvature of space-time



Towards the Einstein Field Equations

- Space time deformation and curvature represented by
  - $g_{\mu\nu}$ the metric tensor
  - or alternatively
  - $R_{\mu\nu}$ the Ricci tensor (depends only on $g_{\mu\nu}$ and derivatives)

- Energy-momentum (includes mass) represented by
  - $T_{\mu\nu}$ the energy-momentum tensor

- We speak about space-time
  - => time dependence included

The Einstein Field Equations

- What relation links deformation of space-time and energy-momentum ?
- Answer : the Einstein Field Equations (EFE)

$$\underbrace{\left(R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R\right)}_{\text{curvature term}} = 8\pi G \underbrace{\left(T_{\mu\nu}\right)}_{\text{energy-momentum term}}$$

with c = 1 ! would be $\frac{8\pi G}{c^4}$.

- Energy-momentum bends spacetime
  - being far from some energy density doesn't mean there is no bending !
- Spacetime tells mass (energy momentum) how to move
- These equations are non-linear

Gravitational waves

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

definierten Größen $\gamma_{\mu\nu}$, welche linearen orthogonalen Transformationen gegenüber Tensorcharakter besitzen, gegen 1 als kleine Größen behandelt werden können, deren Quadrate und Produkte gegen die ersten Potenzen vernachlässigt werden dürfen. Dabei ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} = 0$, je nachdem $\mu = \nu$ oder $\mu \neq \nu$.

Wir werden zeigen, daß diese $\gamma_{\mu\nu}$ in analoger Weise berechnet werden können wie die retardierten Potentiale der Elektrodynamik. Daraus folgt dann zunächst, daß sich die Gravitationsfelder mit Lichtgeschwindigkeit ausbreiten. Wir werden im Anschluß an diese allgemeine Lösung die Gravitationswellen und deren Entstehungsweise untersuchen. Es hat sich gezeigt, daß die von mir vorgeschlagene Wahl des Bezugssystems gemäß der Bedingung $g = |g_{\mu\nu}| = -1$ für

Gravitational waves

- Flat space-time = Minkowski metric
  - Add a perturbation $h_{\mu\nu}$ to the metric of a flat space
  - Linearize Einstein Field Equations
  - Choose a coordinate system ("Transverse Traceless" (T T) gauge)
- Obtain a wave equation

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

(in vacuum, no $T_{\mu\nu}$)

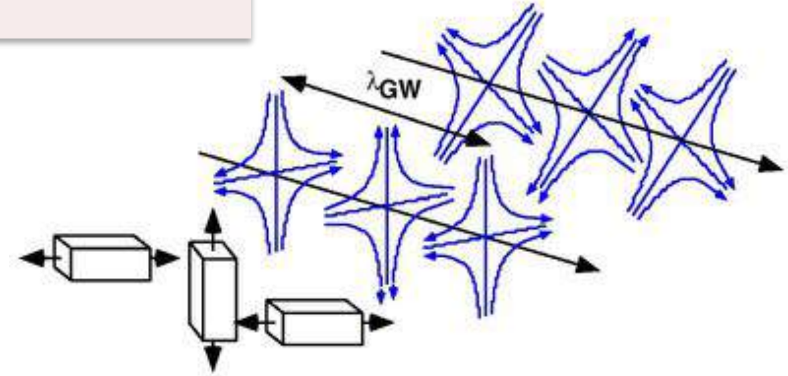
- Solution (in vacuum) :

$$h_{\mu\nu} = A_{\mu\nu} \cdot e^{-i(\vec{k}\cdot\vec{x}-\omega\cdot t)}$$

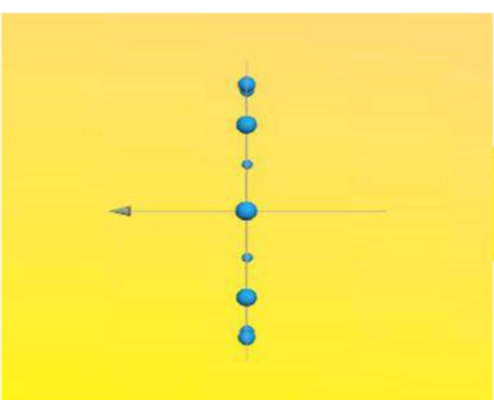
Gravitational waves

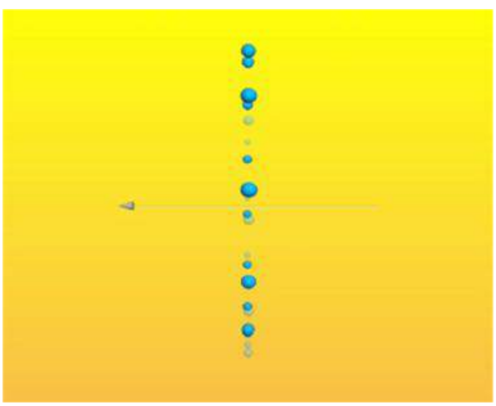
$$h_{\mu\nu} = A_{\mu\nu} \cdot e^{-i(\vec{k}\cdot\vec{x}-\omega\cdot t)}$$

- In vacuum
  - Plane wave
  - Speed = c (speed of light)
- 2 polarizations
  - Rotated by 45° one vs the other



- Effect on a set of (free) “test” masses



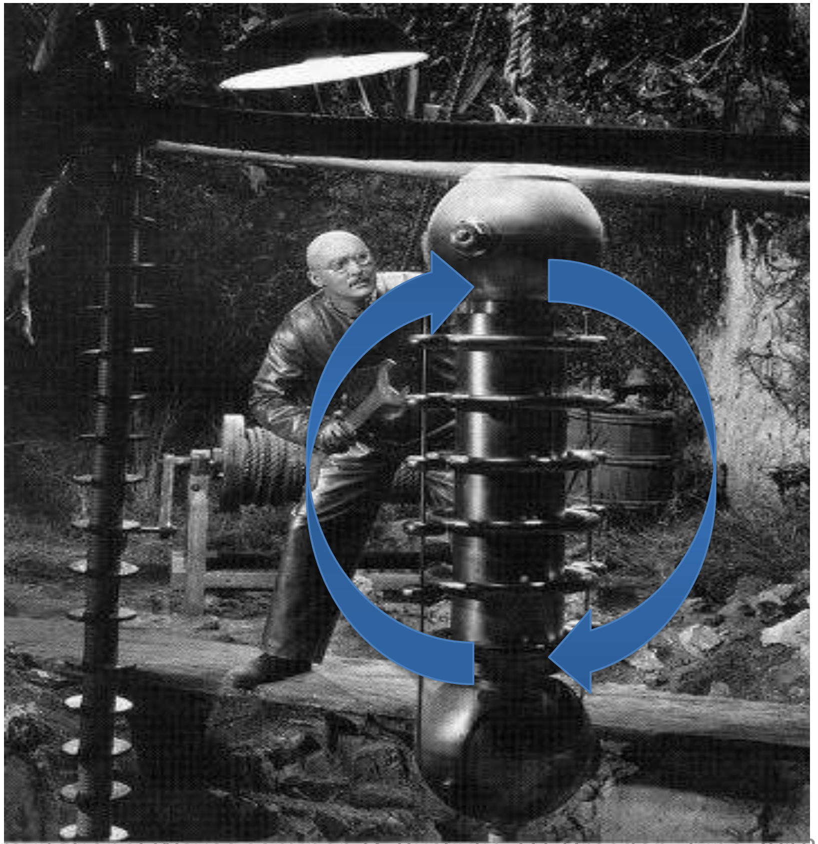


$$h_{\mu\nu} = h_+(t - z/c) + h_x(t - z/c)$$

Gravitational waves

- Production :

  - Distribution of masses : acceleration of quadrupolar moment



$$h \approx 32\pi^2 \cdot \frac{G}{c^4} \cdot \frac{1}{r} \cdot M \cdot R^2 \cdot f_{orb}^2$$

- Examples
  - M = 1000 kg, R = 1 m, f = 1 kHz, r = 300 m

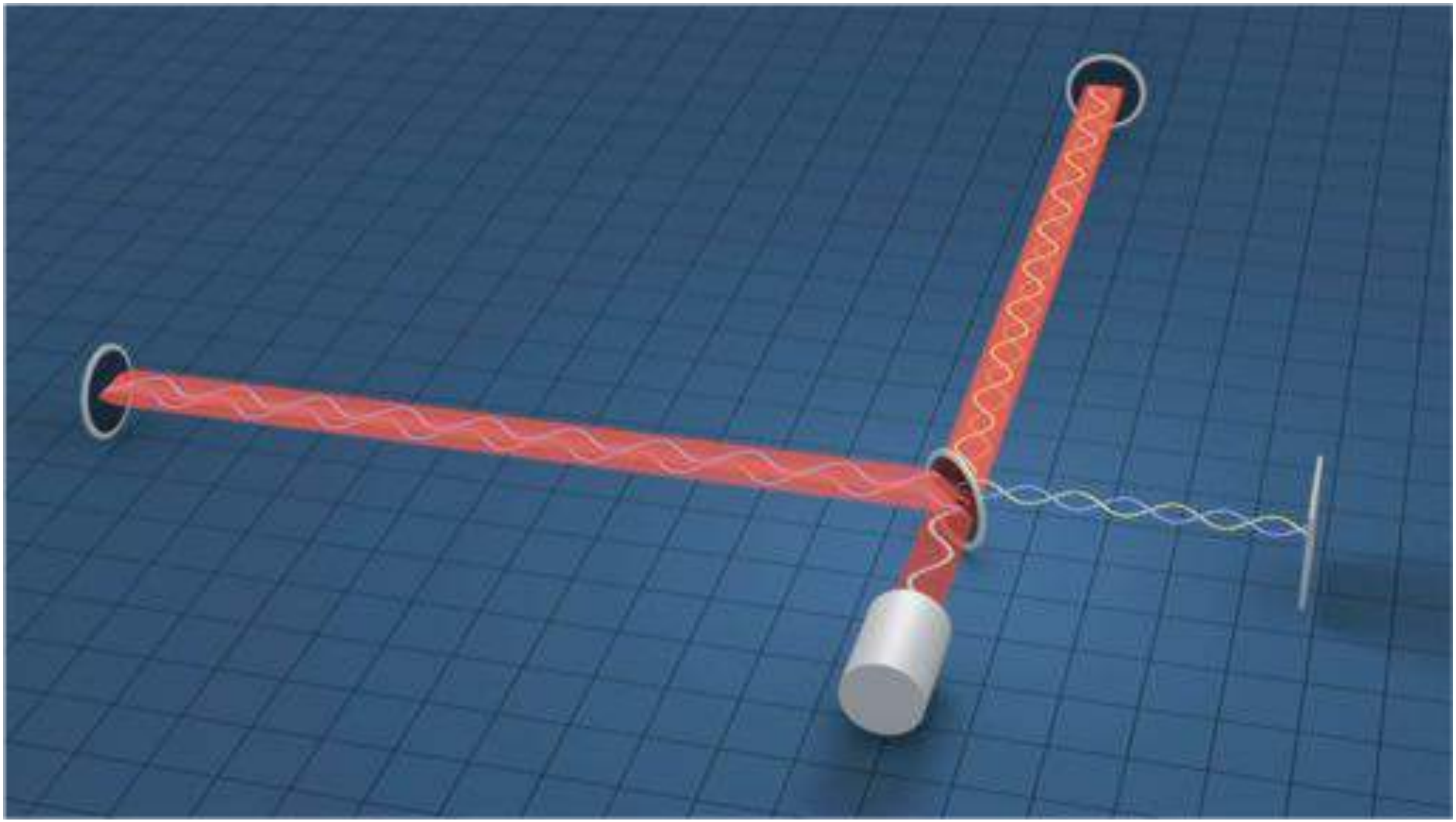
    $h \sim 10^{-35}$

  - $M = 1.4\ M_{\odot}$, R = 20 km, f = 400 Hz, $r = 10^{23}$ m (15 Mpc = 48,9 Mlyr)

    $h \sim 10^{-21}$

How do we detect gravitational waves?

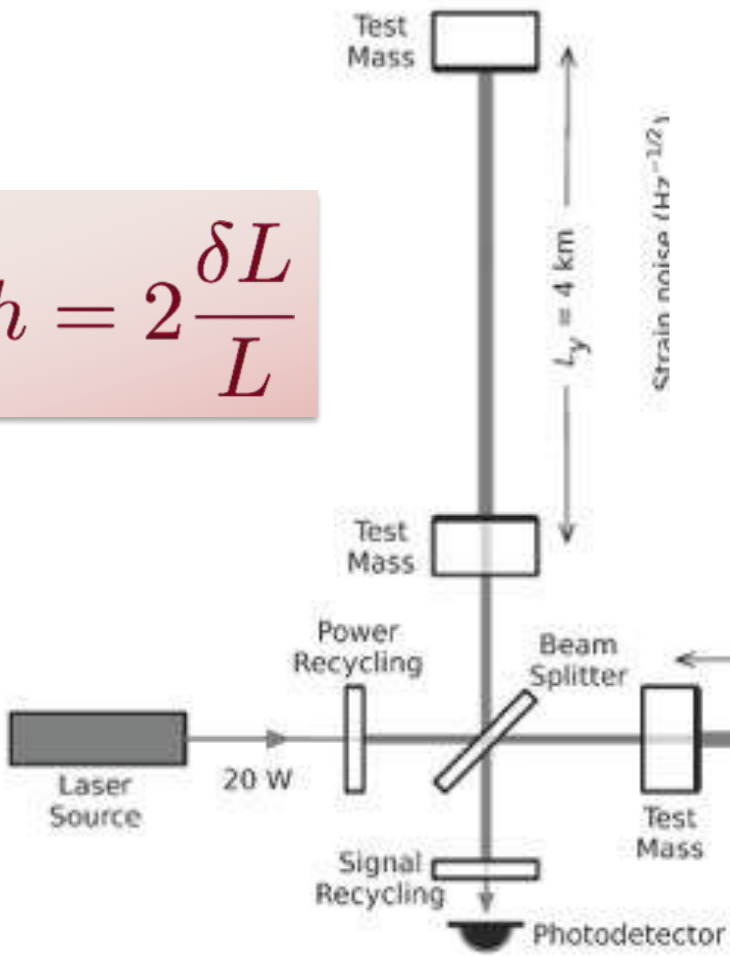
Michelson interferometer : a gravitational waves "sensor"



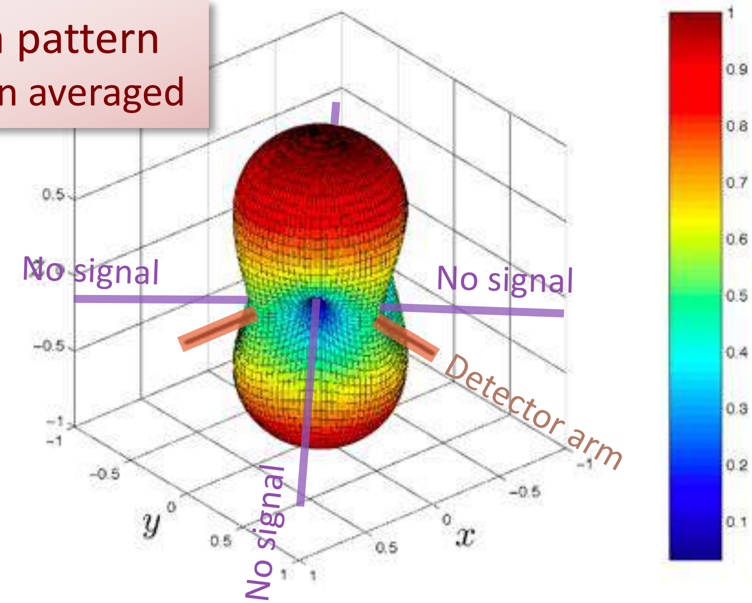
LIGO and Virgo Collaborations

Michelson interferometer : a gravitational waves "sensor"

$$h = 2\frac{\delta L}{L}$$

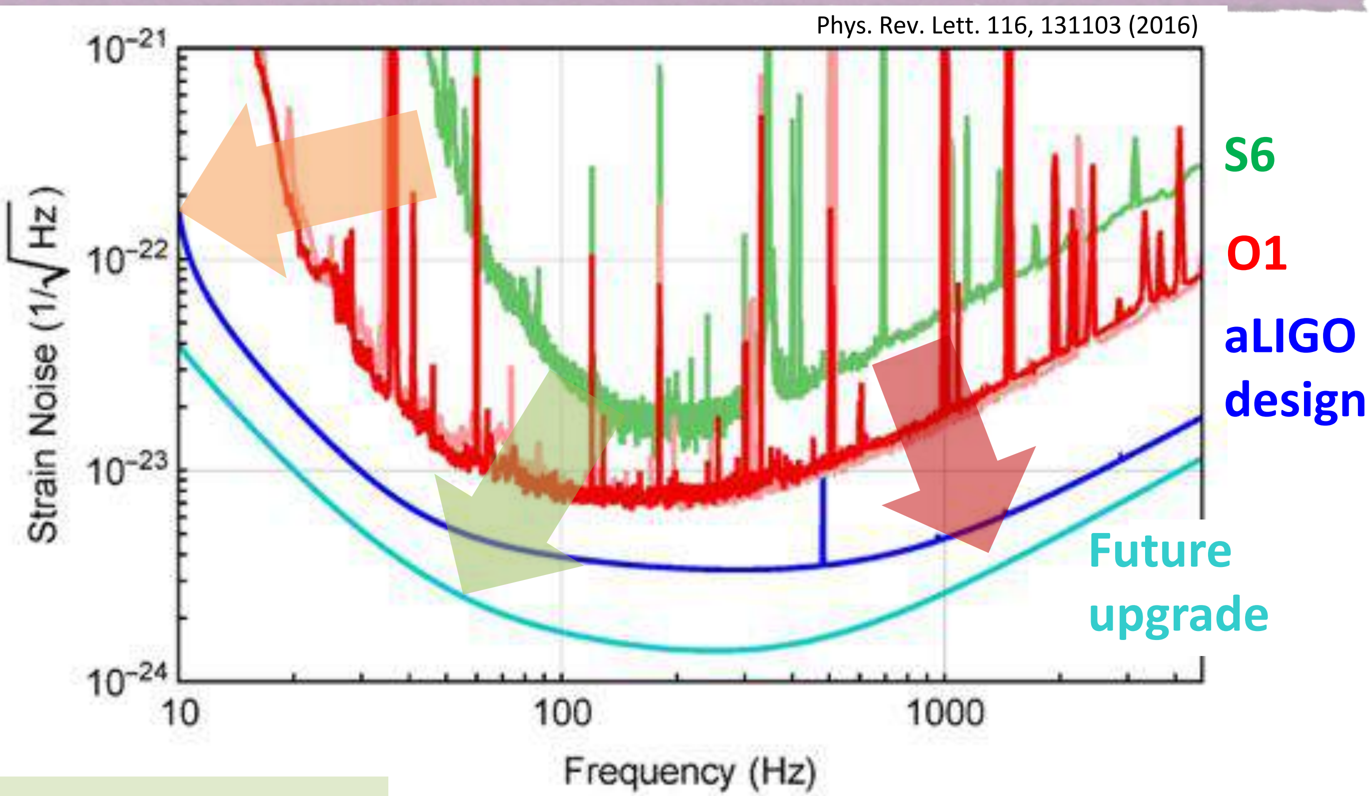


Antenna pattern
Polarization averaged



$$h \approx 10^{-21} \quad \Rightarrow \quad \delta L \approx 10^{-18}\ \text{m}$$

Noises / sensitivity

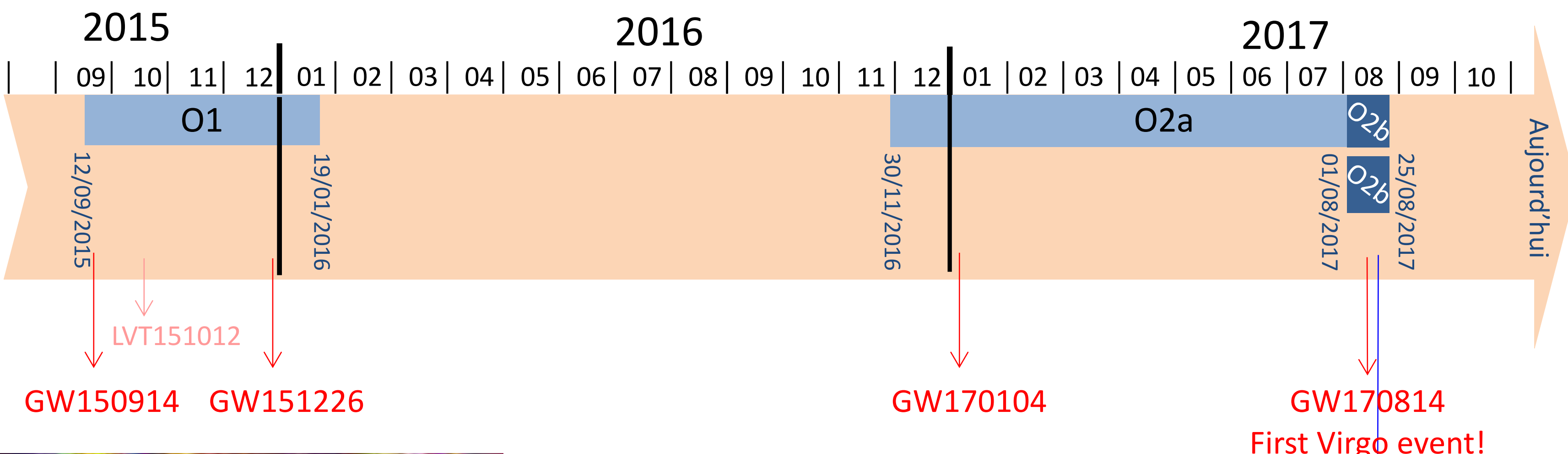


Seismic noise
Very good seismic isolation

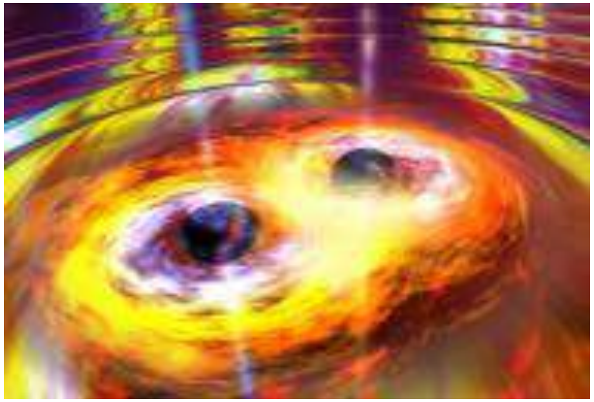
Thermal noise
Monolithic suspensions
Very good mirror coatings
Large beam size

Quantum noise
High laser power
Thermal compensation
Signal recycling
DC detection

The LIGO/Virgo O1 and O2 runs



GW170817
+ multi-messenger detections!



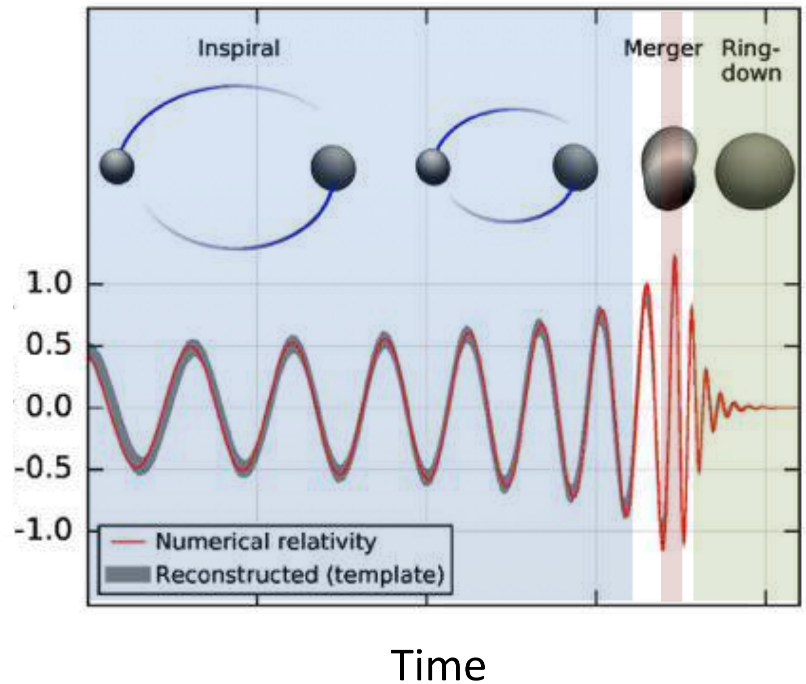
O2 duty cycles :
- LIGO H1: ~60%
- LIGO L1: ~60%
- Virgo V1: ~80% (O2b)

Extracting the signal of a binary compact object merger

Searching for the coalescence of a binary system of compact objects

- Target: Signals from the coalescence of a binary system of compact objects
  - Neutron stars (BNS), Neutron Star + Black Hole (NS-BH), Binary Black Hole (BBH)
- Phases of the coalescence:
  - *Inspiral*
    - Masses m_1 and m_2 orbit around each other
    - Emitting GW
      - Frequency ↗ , amplitude ↗
    - Waveform characterized by « chirp mass »

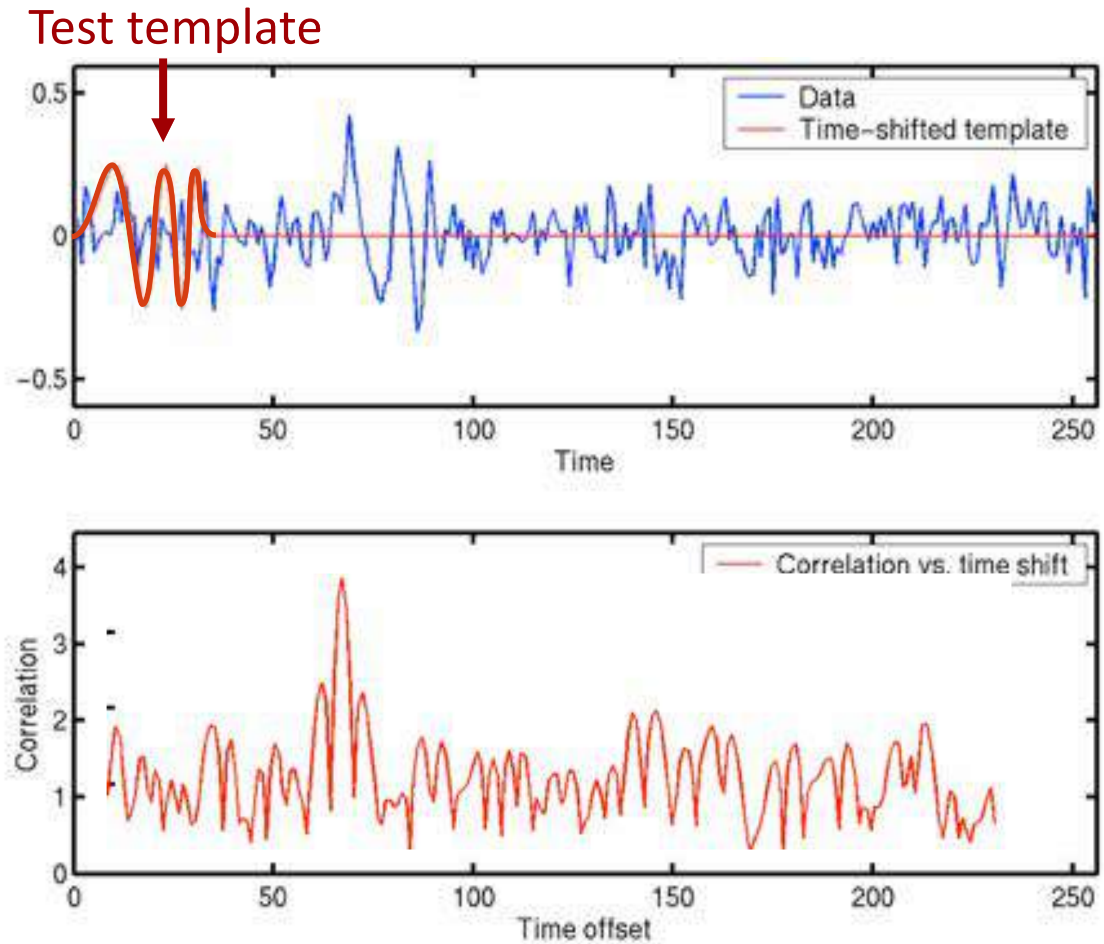
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3}\dot{f}\right]^{3/5}$$



  - *Merger* : numerical relativity computation
  - *Ringdown* : decompose in quasi-normal modes

Searching for the coalescence of a binary system of compact objects

- Modelled search : analysis principle
  - Production of a bank of templates (theoretical waveforms)
  - Matched filtering = weighted cross correlation signal/template



Searching for the coalescence of a binary system of compact objects

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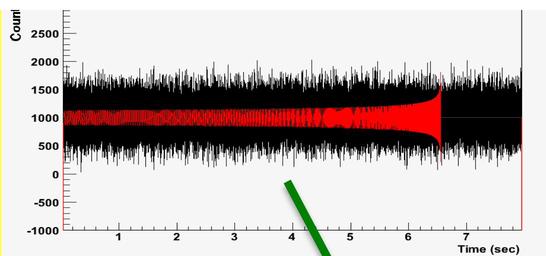
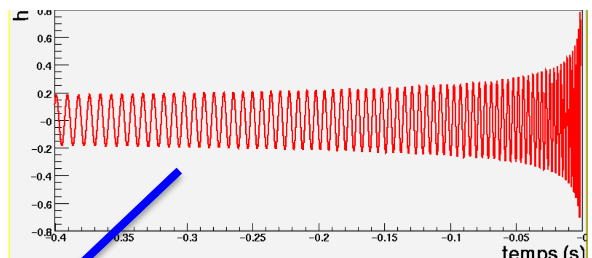
Signal embedded in the noise



$\otimes$

Template



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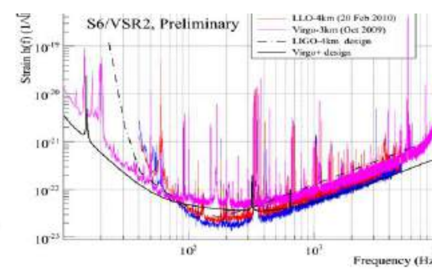
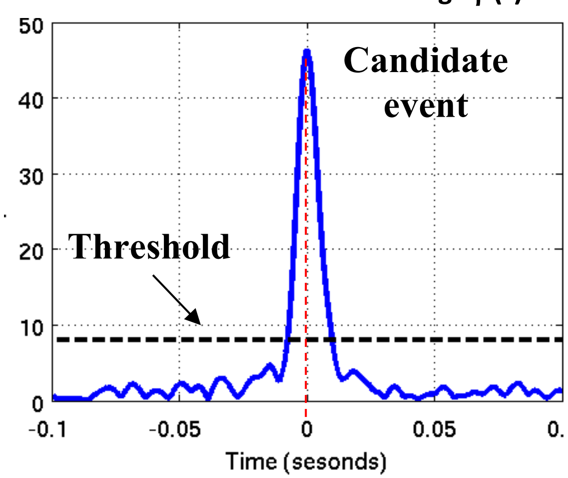
Detectors noise spectral density



$$\langle \tilde{a}, \widetilde{T} \rangle = 2 \left[\int_0^\infty \frac{\tilde{a}(f).\widetilde{T}^*(f)}{S_n(f)} \mathrm{d}f + \mathrm{c.c.} \right]$$

Result of the matched filtering : ρ(t)



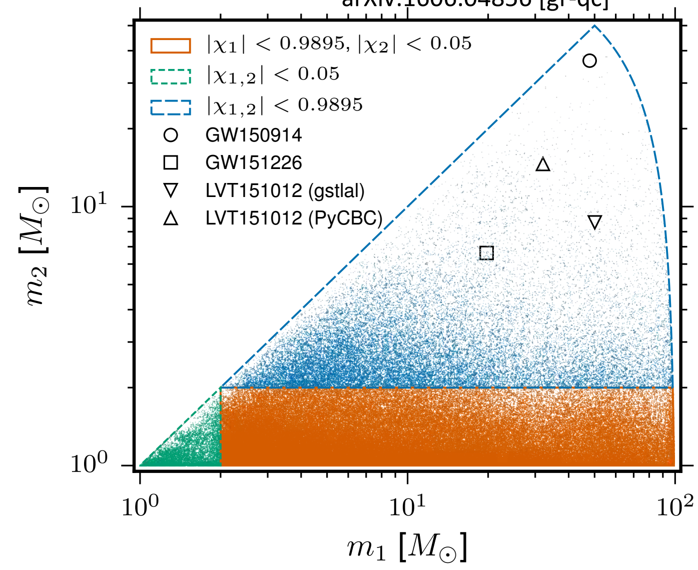
- Very sensitive to phase evolution

Searching for the coalescence of a binary system of compact objects

- **Intrinsic parameters**
  - masses, spins (aligned) drive
    - the system dynamics
    - the waveform evolution
  - 4-D parameter space scanned with ~250,000 - 10^6 templates

m_1, m_2, s_1, s_2

arXiv:1606.04856 [gr-qc]



Phys. Rev. D 93, 122003 (2016)

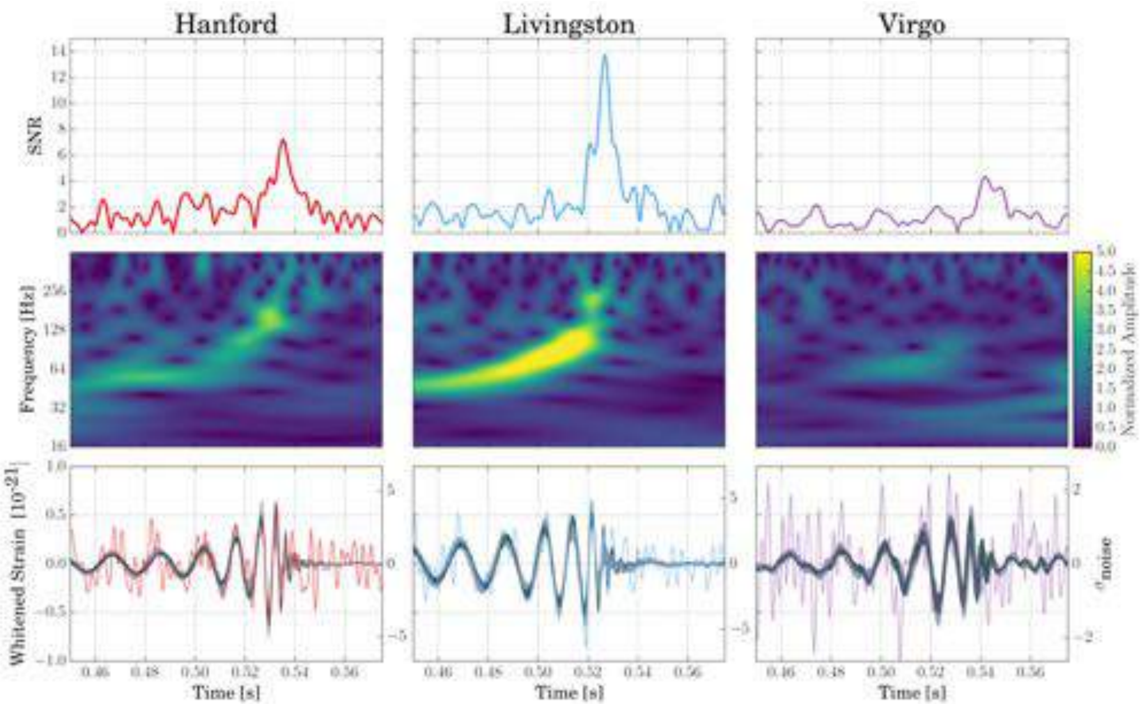
- **Extrinsic parameters**
  - Position in the sky, orientation of the binary, initial phase,… impact
    - Arrival time of the signal
    - Global amplitude and phase
  - Maximized over

$\iota, \Psi, \phi_0, t_0, \ldots$

Binary black holes detected and their physics

GW170814 : the first Virgo event !

- Détected on August 14, 2017 at 10:30:53 UTC
- Rapport signal sur bruit combiné (SNR) = 18
- False alarm rate f < 1 in 27000 years

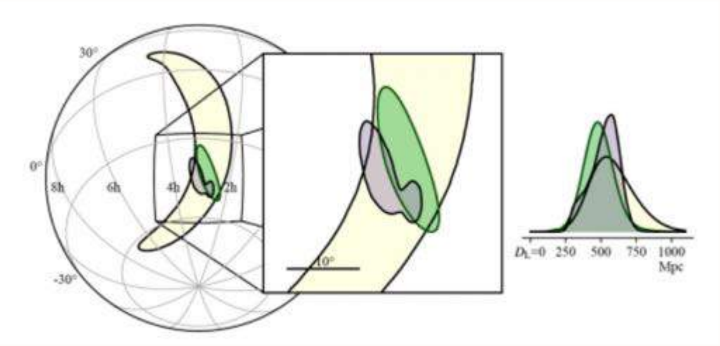


Primary black hole mass m_1	$30.5^{+5.7}_{-3.0}\,M_\odot$
Secondary black hole mass m_2	$25.3^{+2.8}_{-4.2}\,M_\odot$
Chirp mass $\mathcal{M}$	$24.1^{+1.4}_{-1.1}\,M_\odot$
Total mass M	$55.9^{+3.4}_{-2.7}\,M_\odot$
Final black hole mass M_f	$53.2^{+3.2}_{-2.5}\,M_\odot$
Radiated energy E_{rad}	$2.7^{+0.4}_{-0.3}\,M_\odot c^2$
Peak luminosity ℓ_{peak}	$3.7^{+0.5}_{-0.5} \times 10^{56}$ erg s^{-1}
Effective inspiral spin parameter χ_{eff}	$0.06^{+0.12}_{-0.12}$
Final black hole spin a_f	$0.70^{+0.07}_{-0.05}$
Luminosity distance D_L	540^{+130}_{-210} Mpc
Source redshift z	$0.11^{+0.03}_{-0.04}$

-> the merger of a system of binary black holes
similar to the first ever detected event GW150914

It is better with Virgo !

Better source localization



With the two LIGO alone: 700 deg^2

↓

Including Virgo: 80 deg^2

2D localization

→ area on the sky reduced by a factor ~10

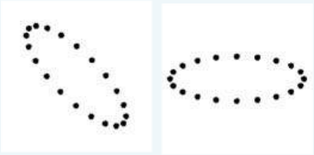
Localisation 3D

→ Volume in the sky reduced by a factor ~20

First tests of the polarisation of the GW

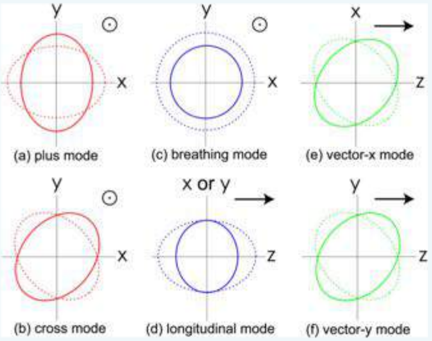
General Relativity

→ 2 polarisation modes



General metric theories of gravity

→ 6 authorized modes



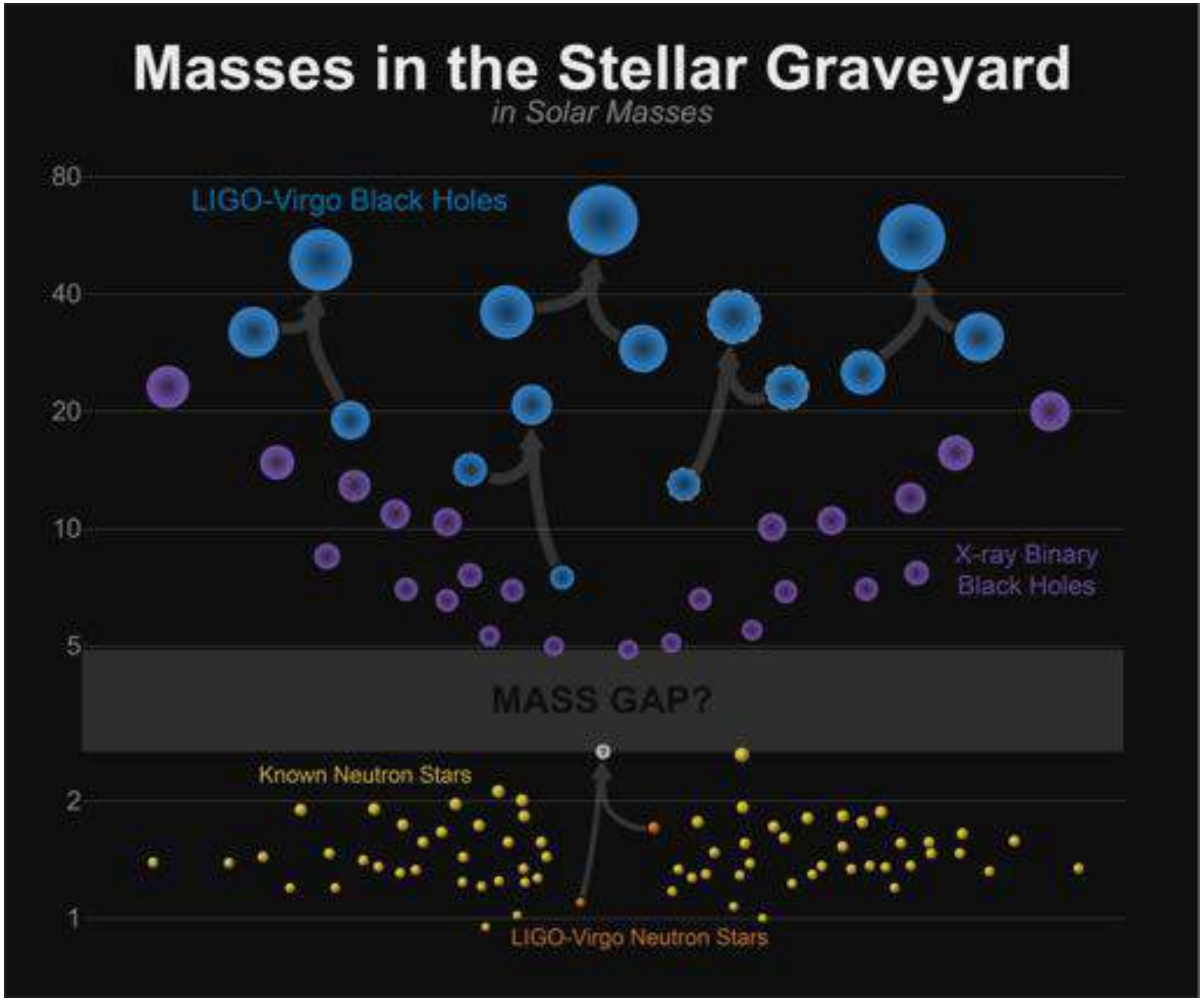
New tests with GW170814

An interferometer is sensitive to the GW projection on the « + » mode local to the détector.

Study of the GW polarization modes with several detectors with different orientations

→ « pure » + and x modes favored w.r.t. pure scalar/vector polarizations (polarization mixtures not tested yet)

Binary compact objects masses



Binary black holes

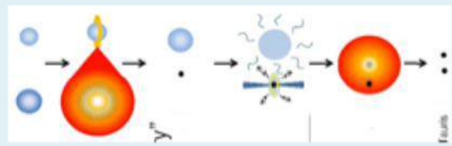
Binary neutron stars

Binary BH coalescence physics

Astrophysics implications

Formation of the binary BH

Evolution of binary stars (disfavored ?)

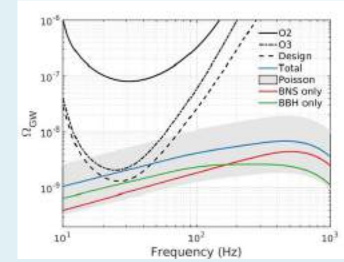


Isolated BH capture

Determination of the distribution and coalescence rate of the binary BH population

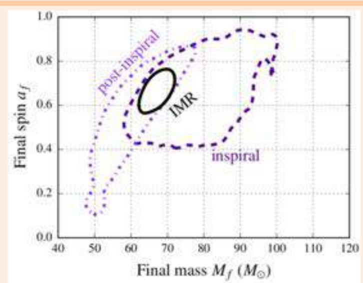
$$R = 12 - 213 \quad \mathrm{Gpc}^{-3}.\mathrm{yr}^{-1}$$

Estimate of the coalescing binary BH stochastic background of GW

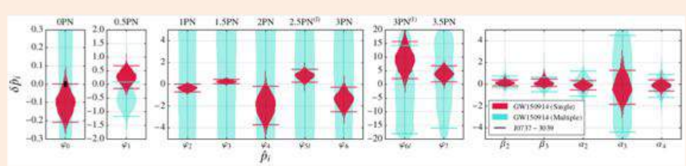


Tests of GR

Check the consistency of the parts of the waveform (inspiral, merger, ringdown).

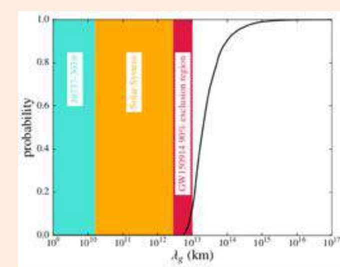


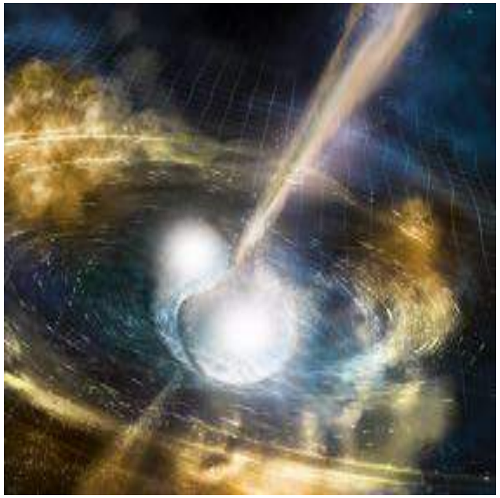
Search for deviation to GR in the waveform.



Upper limits of the graviton mass, test of Lorentz invariance violation.

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

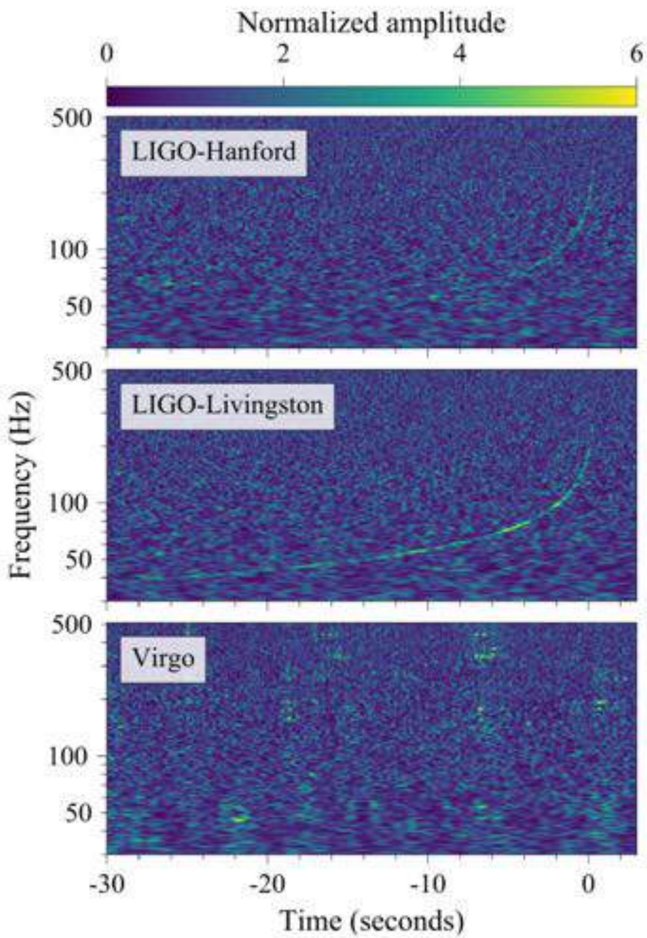




First multi-messenger detection of a coalescence of neutron stars : GW170817

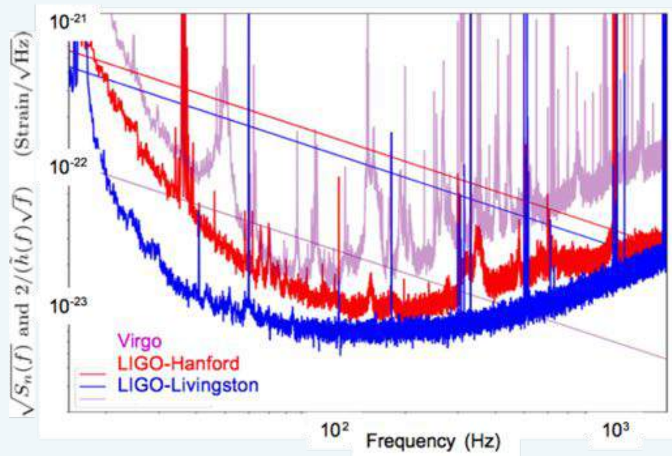
Coalescence in the LIGO-Virgo data

- Detected on August 17, 2017 at 12:41:04.4 UTC
- Combined signal over noise ratio (SNR) = 32.4
- False alarm rate f < 1 over 80000 ans

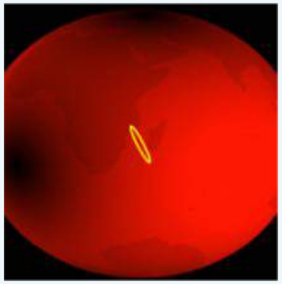


Abbott et al., PRL, 119, 161101 (2017)

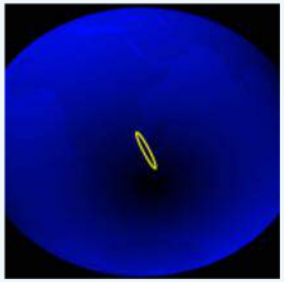
- Weak signal in Virgo
  - Lower sensitivity + unfavorable orientation
  - Virgo does not participate to the detection
  - But significant effect on parameter estimation
  - Especially localisation



Antenna pattern projection on Earth
(darker = less sensitive)

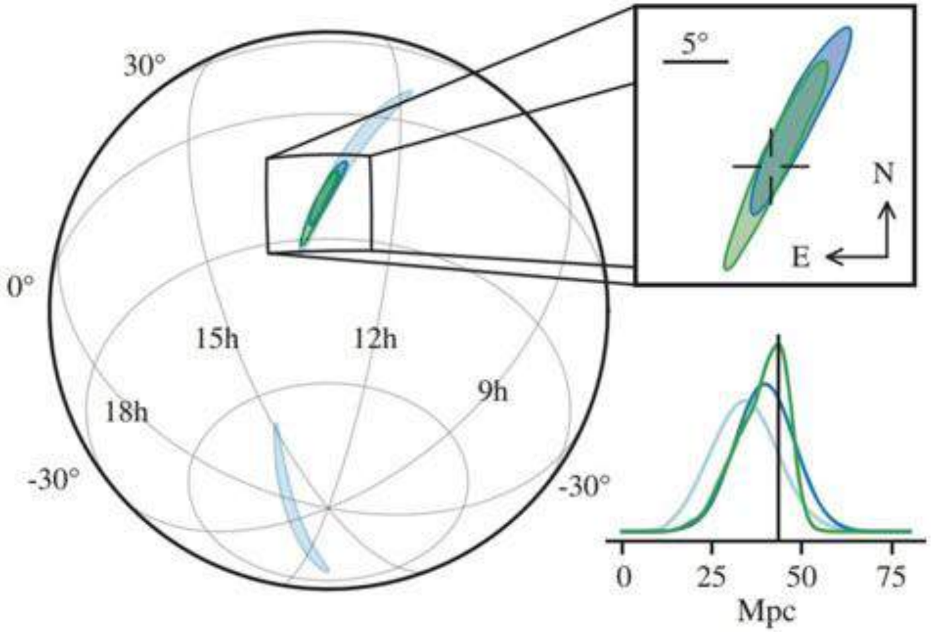


LIGO (Livingston)



Virgo

Localisation of the source GW170817



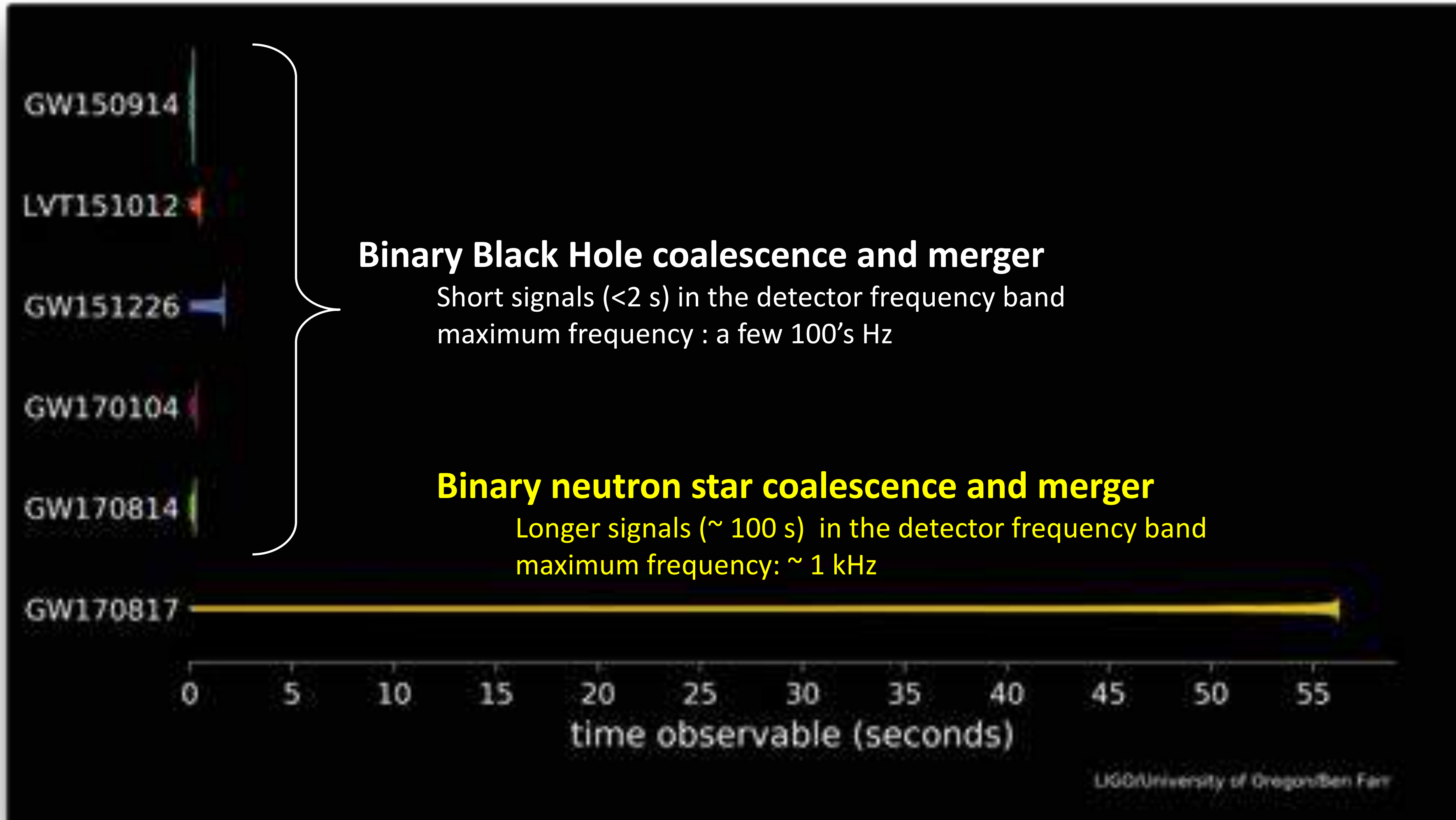
- Sky location:
  - rapid loc. with HL: 190 deg^2
  - rapid loc. with HLV: 31 deg^2 - final loc. with HLV: 28 deg^2

- Luminosity distance: 40 Mpc
  (~120 millions of light-years)

→ 3D position: 380 Mpc^3

- The source gives the closest and most precisely localized GW signal up to now
- Trigger electromagnetic and neutrino followup observations
- ➔ Identification of NGC4993 as the host galaxy

Detected signals length comparison



Shape of the signal -> information on the source type and parameters

Intrinsic parameters

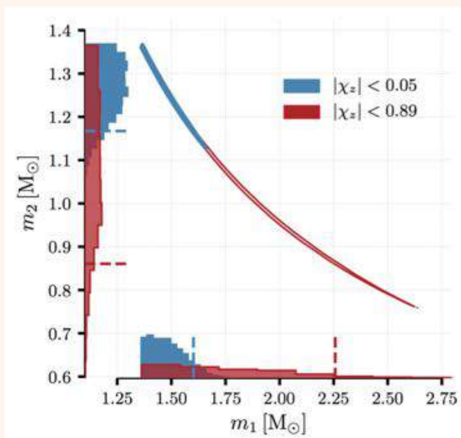
Abbott et al., PRL, 119, 161101 (2017)

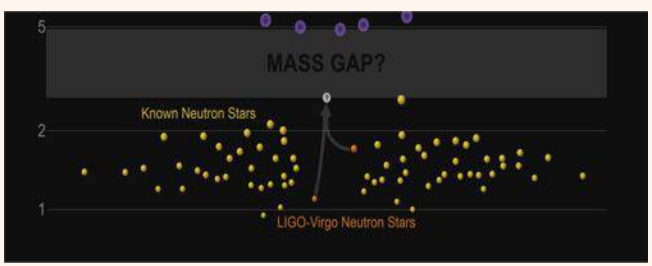
	low-spin ($\|\chi\| < 0.05$)	high-spin ($\|\chi\| < 0.89$)
$M_{chirp}(M_\odot)$	$1.188^{+0.004}_{-0.002}$	
$m_1\ (M_\odot)$	1.36–1.60	1.36 – 2.26
$m_2\ (M_\odot)$	1.17–1.36	0.86 – 1.36
$m_{tot}\ (M_\odot)$	$2.74^{+0.04}_{-0.01}$	$2.82^{+0.47}_{-0.09}$

Objects masses

Degeneracy between mass ratio and aligned spin components

→ Masses < 2.3 $M_\odot$

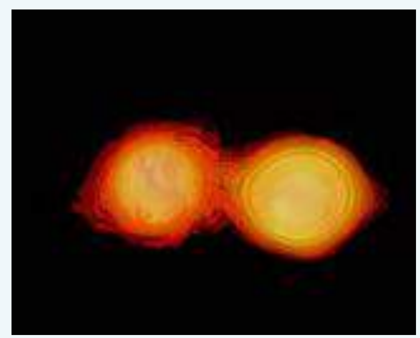




Masses consistent with neutron stars

Equation of state of neutron stars

Tidal field of the companion ➡ Deformation of the neutron star ➡ Imprint on the shape of the gravitational wave, from f>600 Hz (parameter Λ)



Collision happens earlier than w/o tidal effect
Modified final spin

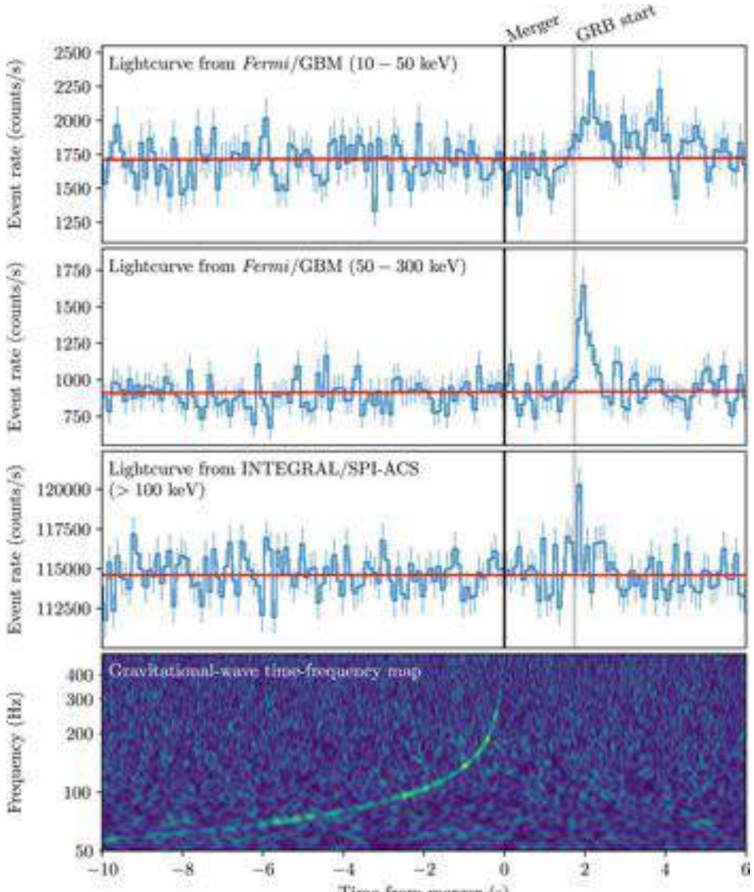
→ disfavour equations of state of neutron stars that predict less compact stars:
radius < 15 km

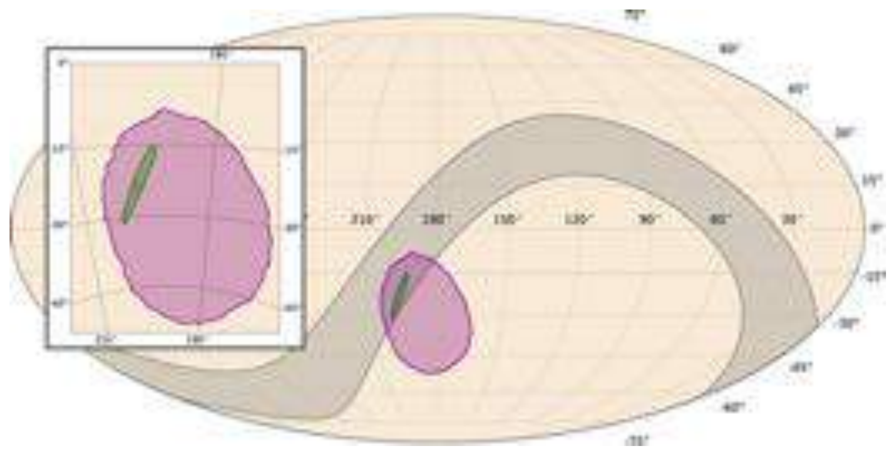
Association with a Gamma Ray Burst

- GRB170817A detected by Fermi and INTEGRAL
  - Gamma emission ~ 1.7 s after the merger
  - 3 times more likely to be a short GRB than a long GRB

GRB sky localisation (90% CL)

Fermi-GBM (1100 deg^2)
Fermi and INTEGRAL (deg^2)
LIGO-Virgo (28 deg^2)



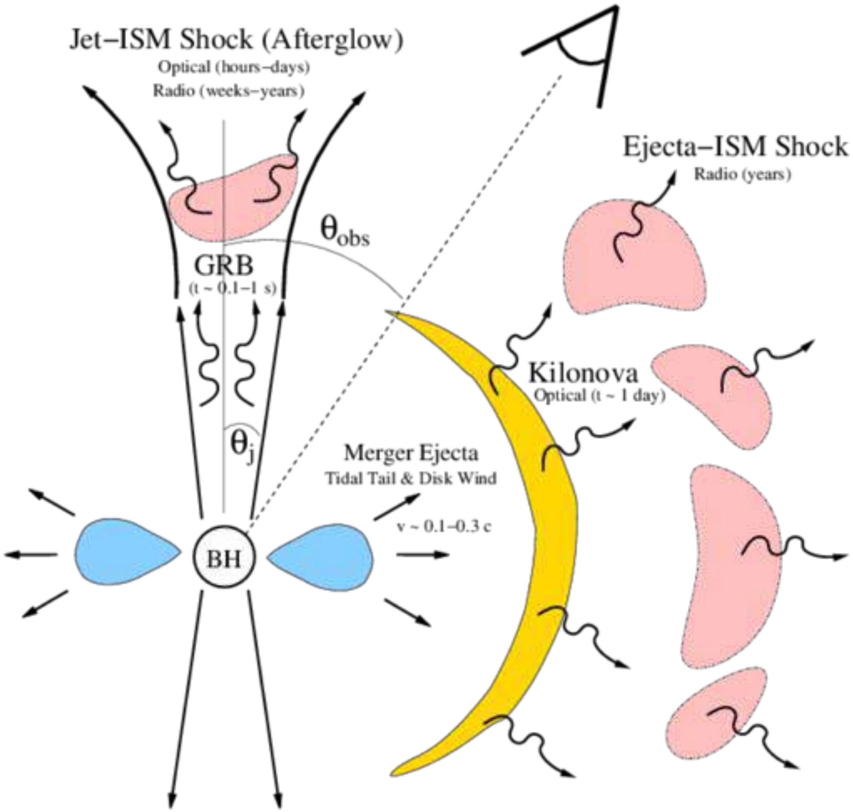


Random time and localisation association probability : 5.0 x 10^{-8}

-> association validated at 5.3 σ

First direct evidence that binary neutron star mergers are progenitors of (at least some) short gamma-ray bursts!

Electromagnetic counterpart



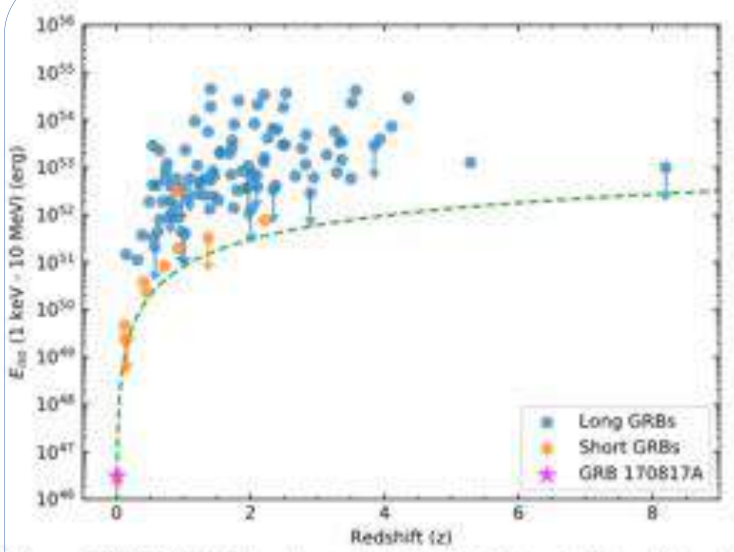
- Short Gamma Ray Burst (sGRB) :
  - Jet
    - Prompt γ-ray emission
    - A few seconds after the merger
    - Duration < 2 s
    - Beamed
  - Interaction of the jet with the interstellar medium
    - Afterglow emission
    - Few days after the merger
    - Evolves from X-rays -> radio
- Kilonova
  - Conversion of hot ejected matter into r-processed elements, disintegration and thermal emission
    - Black body emission + broad structures
    - Few hours/days after the merger
    - Visible in UV / optical / IR
    - Rapid spectral evolution

New insight into gamma-ray bursts

GW170817 waveform → loose limit on BNS viewing angle, but degeneracy with source distance

- Θ < 56°   from GW data alone
- Θ < 36°   using the known distance to the host galaxy NGC 4993

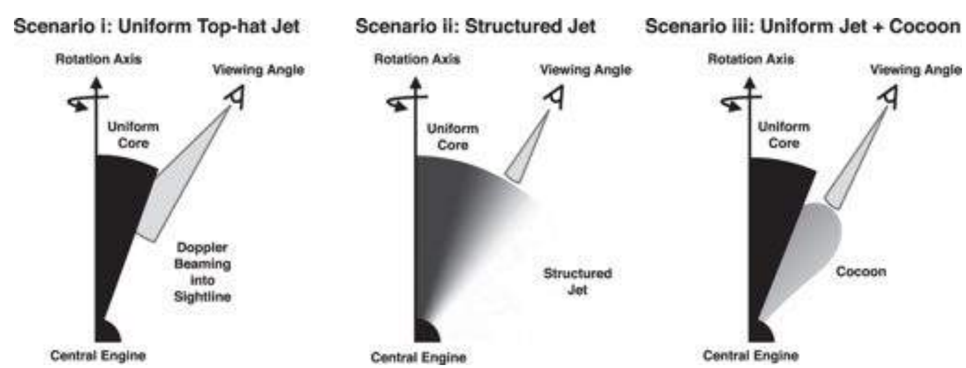
→ compatible with jet pointing towards Earth



GRB170817A:

- the **closest** short GRB with know distance (z~0.008)
  (previous closest, GRB061201: z ~0;11)
- 10^2 to 10^6 times **less energetic** than other bursts

→ implications/questions on the structure of the jet



Prediction of detection rates

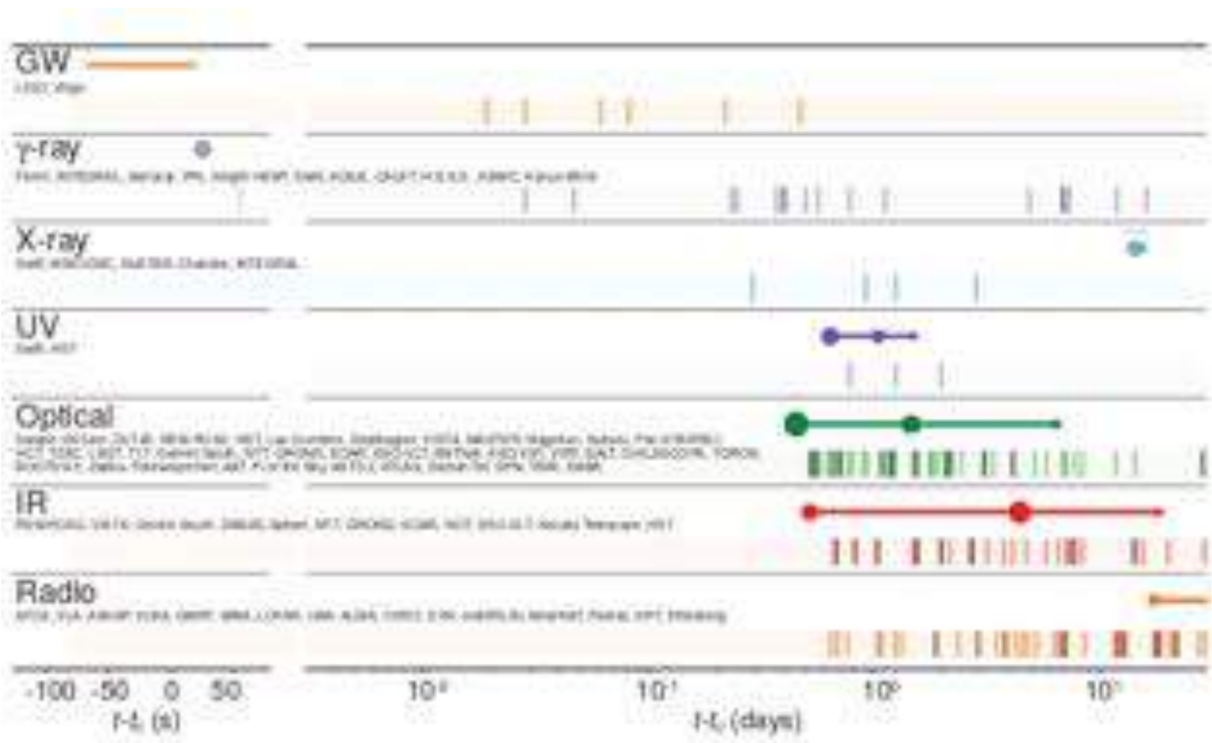
- higher rate than previously expected for sGRB to be seen in gamma-rays
- 1-50 BNS mergers expected in LIGO-Virgo during run O3 (wrt previously estimated 0.04-100)

→ 0.1 to 1.4 joint detections for GW and Fermi sGRB during run O3 (end 2018-2019)

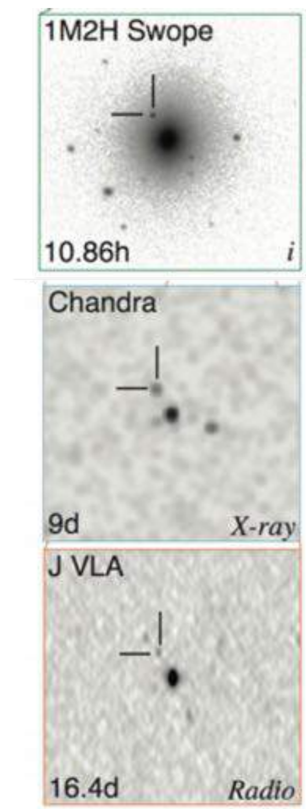
Abbot at al., ApJ, 848, 13 (2017)

Electromagnetic followup

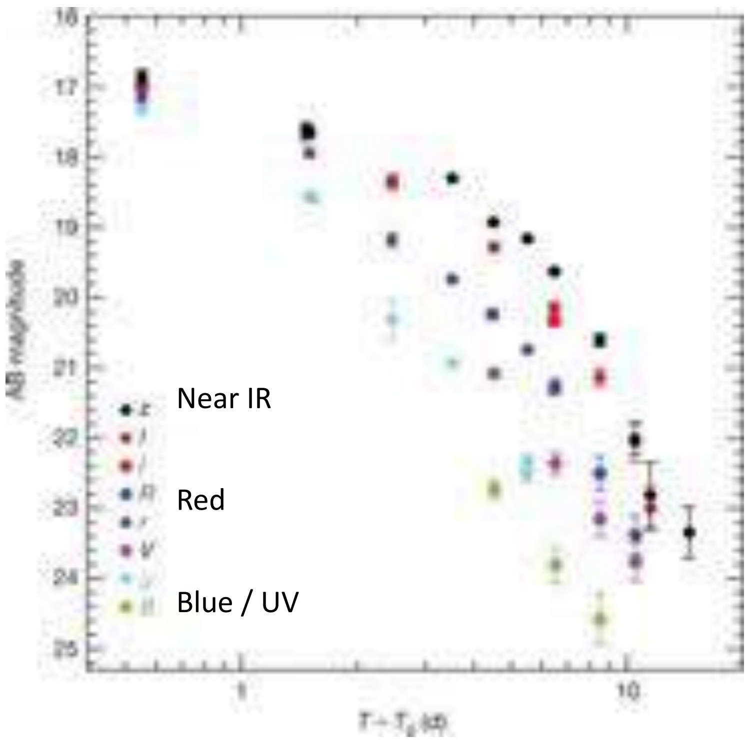
T0	T0 + 1.7 s	T0 + 5 h	T0 + 11 h	T0 + 11 h	T0 + 9 d	T0 + 16 d
GW detection	GRRB detection	GW localization	Optical counterpart	Host galaxy NGC4993	X counterpart	Radio counterpart



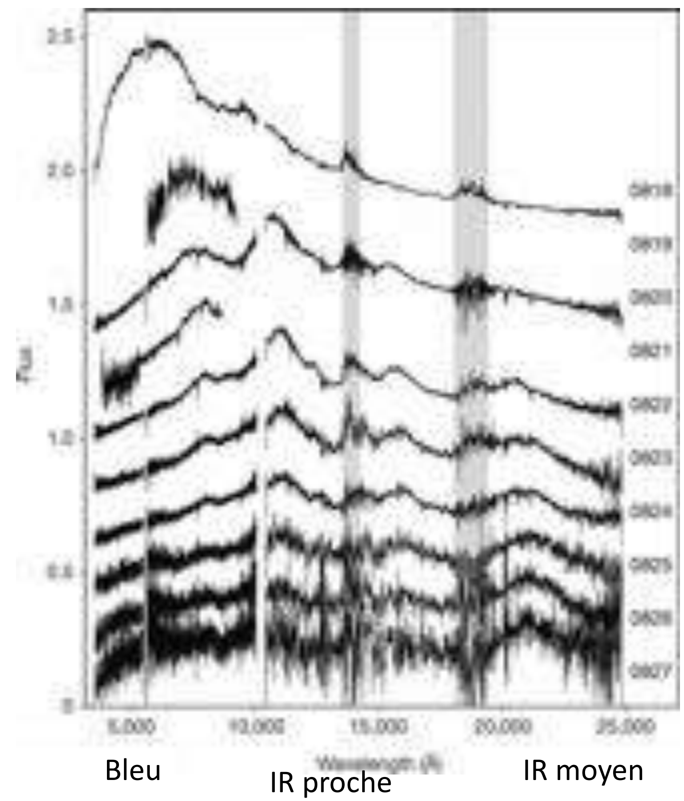
Host galaxy at 40 Mpc (130 Mlyr)



Evolution of the optical transient



Light curves

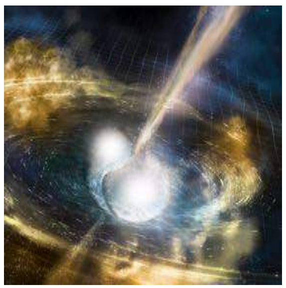


Spectrum evolution

- Good agreement with « kilonova » models (= « macronova »)
- First spectral identification of a kilonova
- Probably the main source of heavy elements in the universe

GW/GRB association : GW speed

Emission during the merger
-> GW and γ rays



Assumption : γ rays emitted
btw 0 and 10 s after the GW

Propagation
On at least 26 Mpc

GW

γ rays

Detection

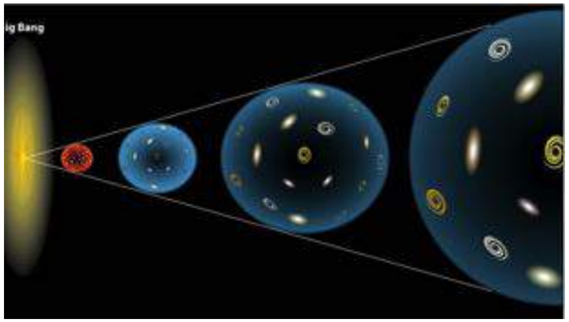
γ Rays detected
1.75 ± 0.05 s after GW
from the merger

Difference between speed of gravity and speed of light

$$[-3 \times 10^{-15}; +7 \times 10^{-16}] \times c$$

Hubble constant measurement

H_0 = expansion rate of the universe today



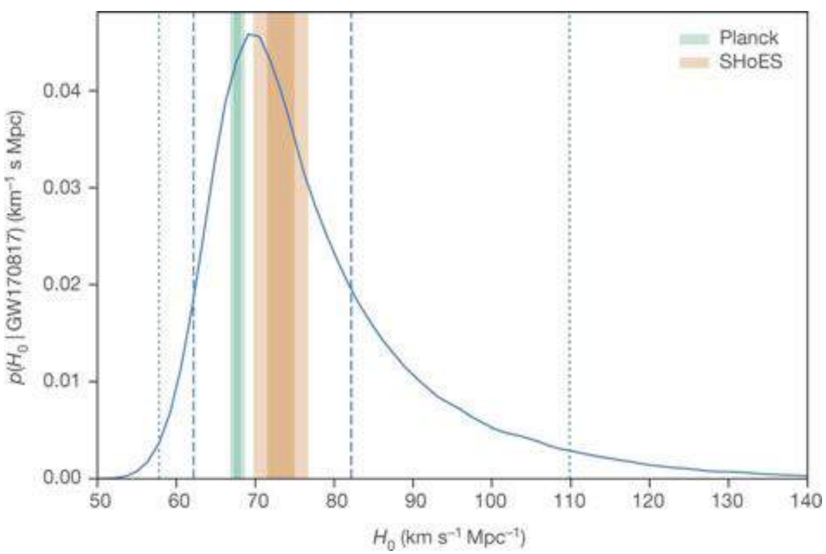
GW170817 may be used as a standard "siren"

$$D_{luminosity} = H_0 \times v_r$$

Direct estimation with the GW signal: $(43.8^{+2.9}_{-6.9}\,\mathrm{Mpc})$

Given by the redshift of the host galaxy $(3017 \pm 166\,\mathrm{km/s})$

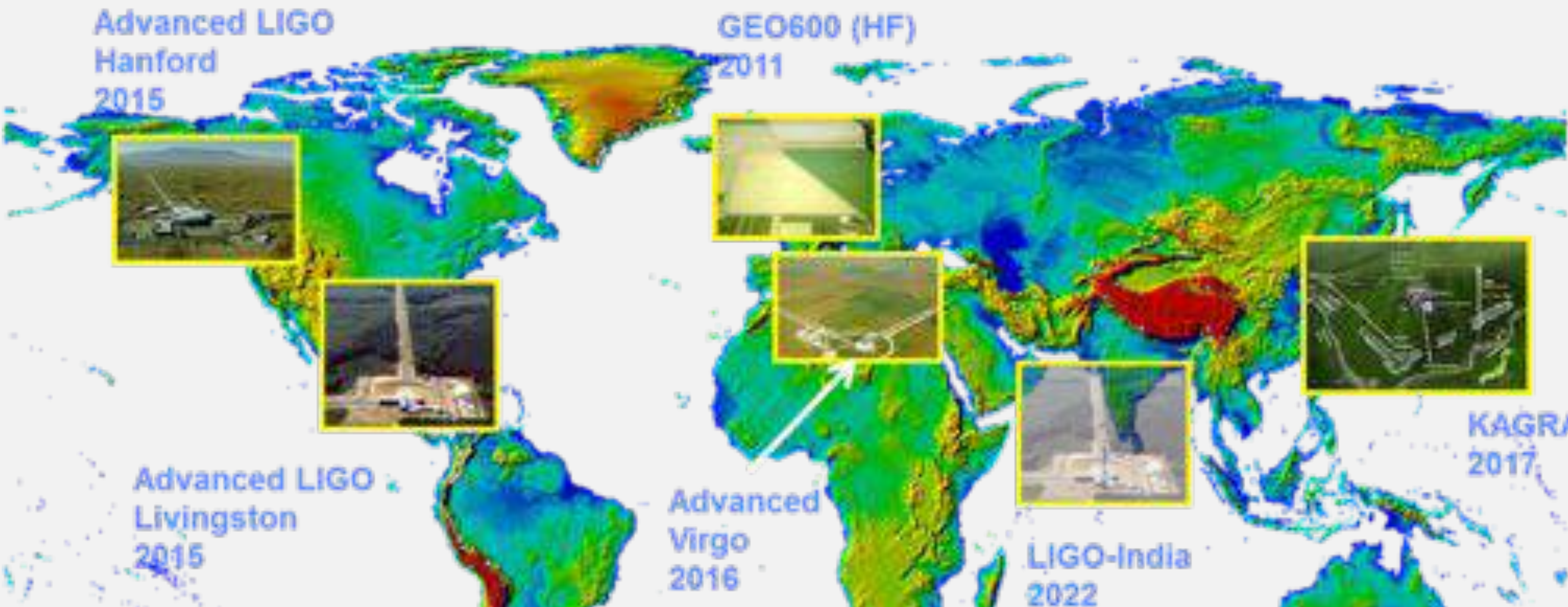
$\rightarrow$ $H_0 = 70^{+12}_{-8}\ \mathrm{km/s\ Mpc^{-1}}$



Independent measurement of H_0
→ may help to resolve the current « tension »

Present and future

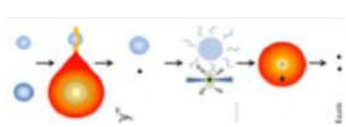
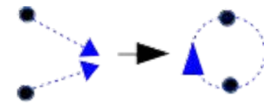
A glimpse at the future



Epoch			2015 – 2016	2016 – 2017	2018 – 2019	2020+	2024+
Planned run duration			4 months	9 months	12 months	(per year)	(per year)
Expected burst range/Mpc		LIGO	40 – 60	60 – 75	75 – 90	105	105
		Virgo	—	20 – 40	40 – 50	40 – 70	80
		KAGRA	—	—	—	—	100
Expected BNS range/Mpc		LIGO	40 – 80	80 – 120	120 – 170	190	190
		Virgo	—	20 – 65	65 – 85	65 – 115	125
		KAGRA	—	—	—	—	140
Achieved BNS range/Mpc		LIGO	60 – 80	*60 – 100*	—	—	—
		Virgo	—	*25 – 30*	—	—	—
		KAGRA	—	—	—	—	—
Estimated BNS detections			0.002 – 2	0.007 – 30	0.04 – 100	0.1 – 200	0.4 – 400
Actual BNS detections			0	—	—	—	—
90% CR	% within	5 deg^2	< 1	1 – 5	1 – 4	3 – 7	23 – 30
		20 deg^2	< 1	7 – 14	12 – 21	14 – 22	65 – 73
	median/deg^2		460 – 530	230 – 320	120 – 180	110 – 180	9 – 12
Searched area	% within	5 deg^2	4 – 6	15 – 21	20 – 26	23 – 29	62 – 67
		20 deg^2	14 – 17	33 – 41	42 – 50	44 – 52	87 – 90

Non exhaustive list of current and future studies

- Astrophysics implications
  - Binary black hole / neutron star formation

  - GRB origin/physics, jet beaming
  - Kilonovae modeling
  - Equation Of State (EOS) of the neutron stars
  - Neutron star resulting from the merger : long or short lived ?
  - BNS population distribution inference and coalescence rate

$$R = 1540^{+3200}_{-1220} \quad \mathrm{Gpc}^{-3}.\mathrm{yr}^{-1}$$

$$(R < 12600\,\mathrm{Gpc}^{-3}.\mathrm{yr}^{-1} \quad \text{from} \quad 01)$$

  - Estimate of the BNS coalescence GW stochastic background (confusion noise)
    - Detection in the coming years

- GR tests
  - Limits on the speed of GW (w.r.t *c*)
  - Search for devations to GR in the waveform
  - GW polarization studies
  - New limits on violation of the Lorentz invariance
  - New test of the equivalence principle

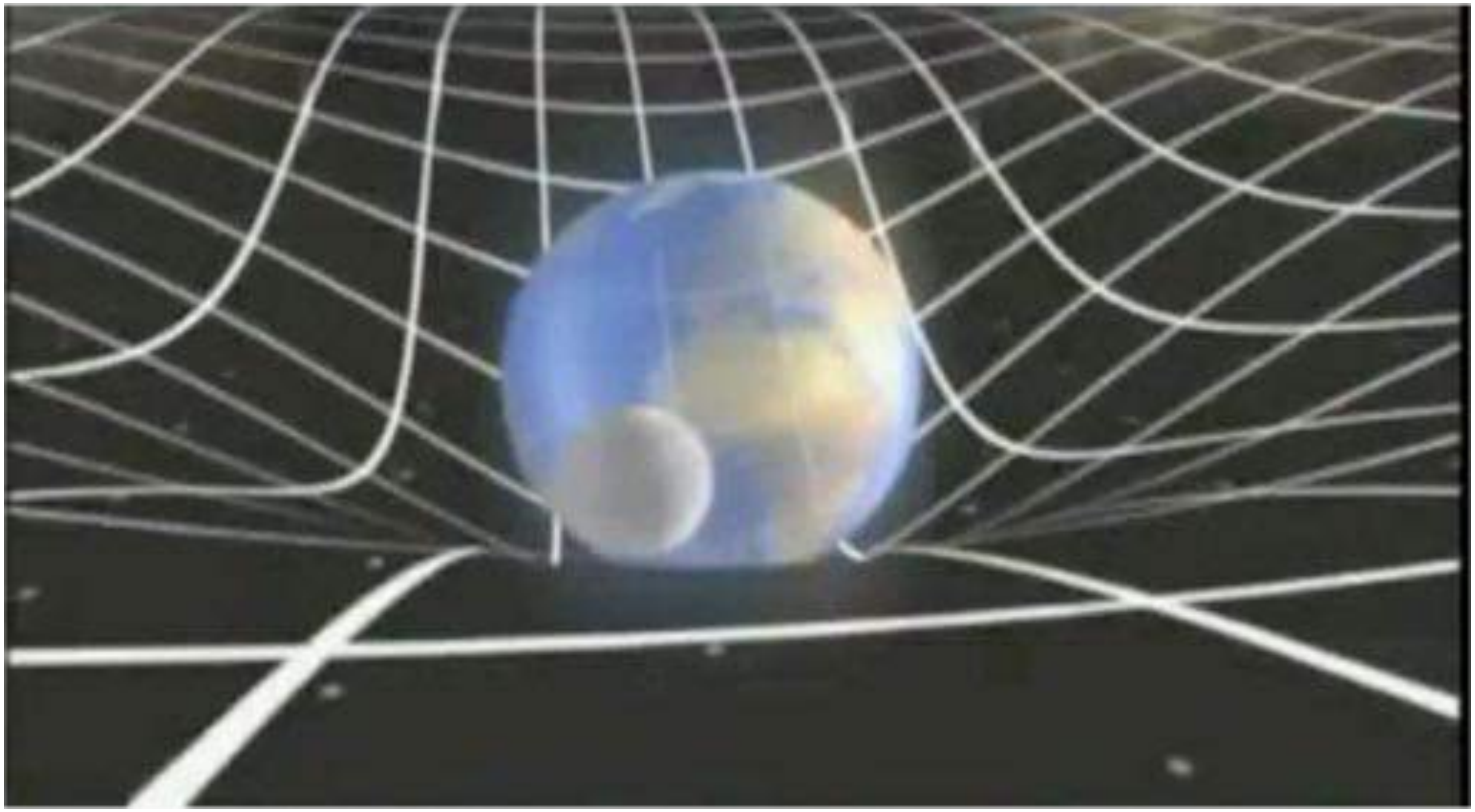
- Cosmology
  - Independent measurement of the Hubble constant

Conclusion

- "Premières"…
  - First observation of the coalescence of a black hole
  - First tests of the polarization of a GW
  - First confirmed association between a BNS coalescence and a short GRB
  - First photometric observation of a kilonova
  - First measure of the Hubble constant with GW
- For the future, we hope / wait for
  - Detection of a neutron star – black hole coalescence
  - Detection of the stochastic bckgd of GW produced by BNS and BBH in the universe
  - Detection of a GW produced by a supernova
  - More multi-messenger detections
- And there is more work on continuous GW (pulsars) and non modeled transients
- And we prepare LIGO and Virgo for the O3 run at the beginning of 2019
  - (upgrade/commissioning)

- Spares

The work of gravity

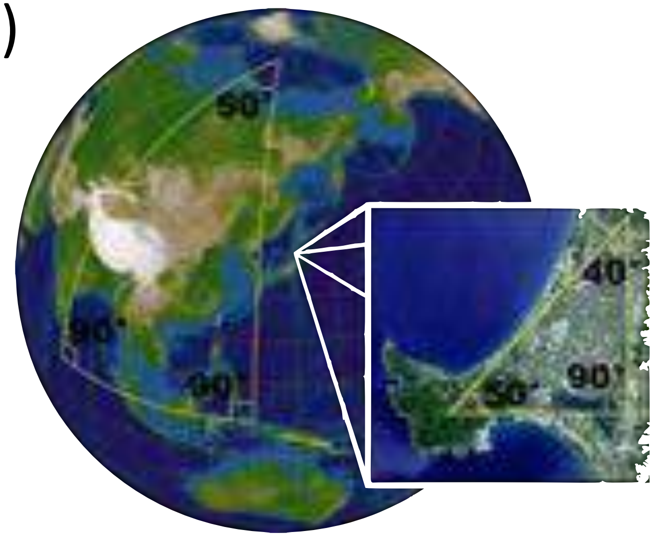


- But this is only a picture !
- Space-time is not an elastic surface in 2 dimensions !
- Very difficult to represent in 3 (rather 4) dimensions

« Curved » space-time

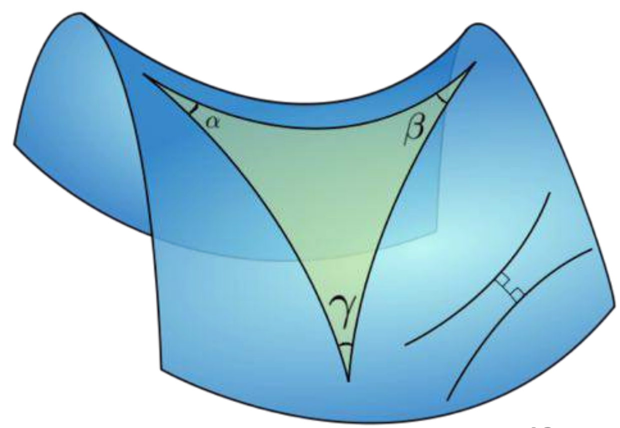
- What is a curved space ? (= "manifold")
  - examples : sphere, saddle
- Can we measure curvature ?
  - we cannot see our space from "outside"
  - but we can measure angles
  - the sum of the angles of a triangle is not always equal to π !
- positive curvature

$$\sum \text{angles} = \alpha + \beta + \gamma > \pi$$



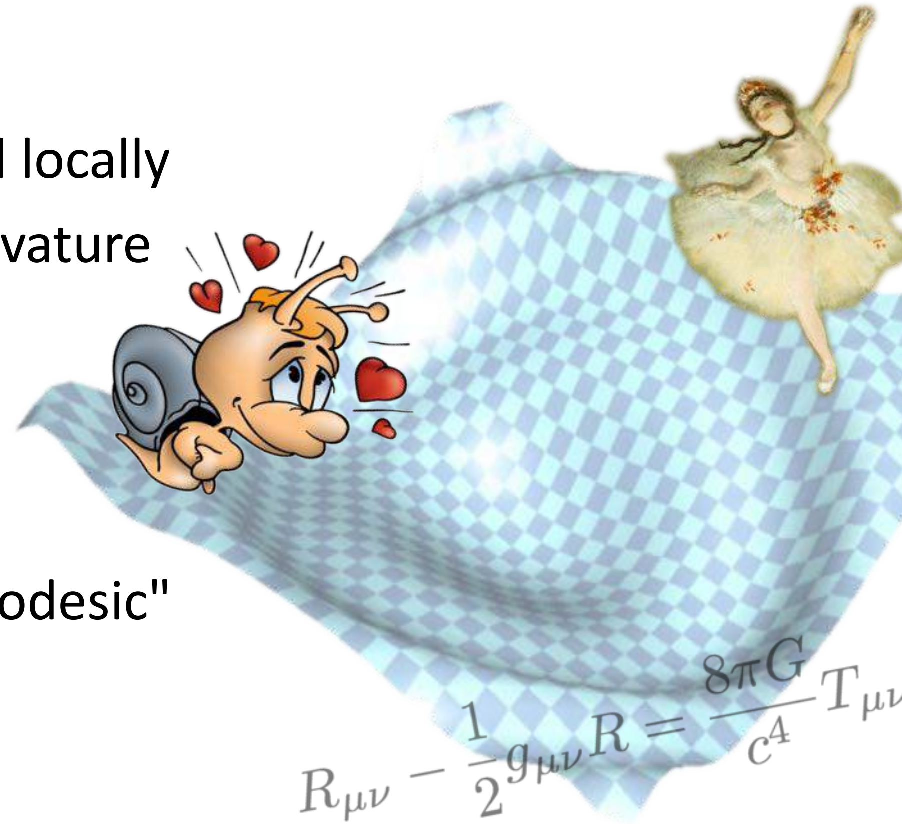
- negative curvature

$$\sum \text{angles} = \alpha + \beta + \gamma < \pi$$



Curvature of space-time

- Newton : space is Euclidian (flat) and time is universal
  - flat space-time !
- General Relativity
  - space is curved and time is defined locally
  - one cannot go "out" to see the curvature
    - "intrinsically" curved space
    - intrinsic curvature
  - go straight (free fall) = follow a "geodesic"
  - note that the time is also curved !
  - as a first approximation, finds
    the results (trajectories) of newtonian mechanics



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

The metric

- In space-time, measure
  - the distance between two points
  - the angle between two vectors
- Measure of the distance between two infinitesimally close events in spacetime
- Need a "metric", start from the "line element" seen in special relativity :

$$ds^2 = -dt^2 + dx^2 + dy^2 + dz^2$$

with c = 1

- Which can be written $ds^2 = \eta_{\alpha\beta} dx^\alpha dx^\beta$

$$\eta_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad \text{and} \quad dx^0 = dt, \quad dx^1 = dx, \quad dx^2 = dy, \quad dx^3 = dz$$

- $\eta_{\mu\nu}$ is the metric of a flat spacetime,
  - Minkowski spacetime, used in special relativity

The metric

- But the space is not flat !
- The metric can be general : $g_{\mu\nu}$

- It contains all information about spacetime curvature
  - It is a « rank 2 tensor »

- The curvature is also defined by another tensor, which depends on $g_{\mu\nu}$
  - the Ricci tensor $R_{\mu\nu}$

- **But what generates the curvature of spacetime ?**

O1 run

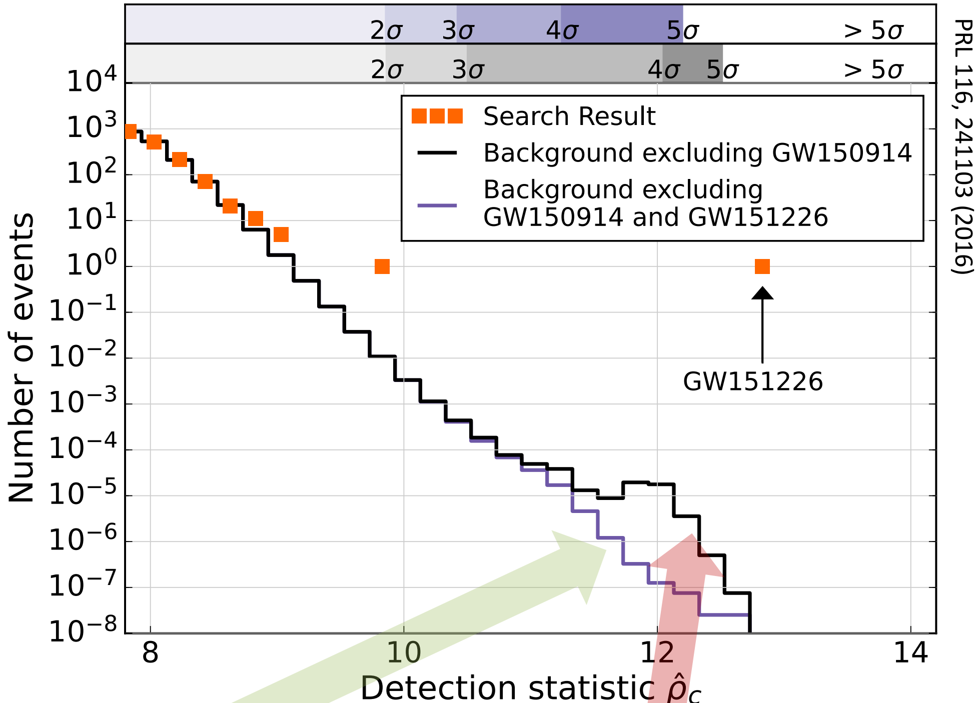
- September 12, 2015 – January 12, 2016
  - Preceded by engineering run ER8 – from Aug 17
  - Stable data taking from Sep 12
  - O1 scheduled to start on Sep 18
    - When fully ready with calibration / hardware injections / EM follow-up alerts / computing
  - 51.5 days of coincident data
    - H1 = LIGO Hanford, L1 = LIGO Livingston

CBC BBH search result : GW151226

- GW151226 is the second loudest event in the search, $\hat{\rho}_c = 12.8$

  - Remove all triggers associated with GW150914 (confidently identified as GW) from background calculation

  - Significance $> 5.3\sigma$



Background excluding contribution from GW150914 and GW151226 (gauge significance of other triggers)

Coincidences between single detector triggers from GW151226 and noise in other detector (excluding GW150914 triggers)

CBC BBH search result : LVT151210

- Third most significant event in the search,

  $\hat{\rho}_c$ = 9.7

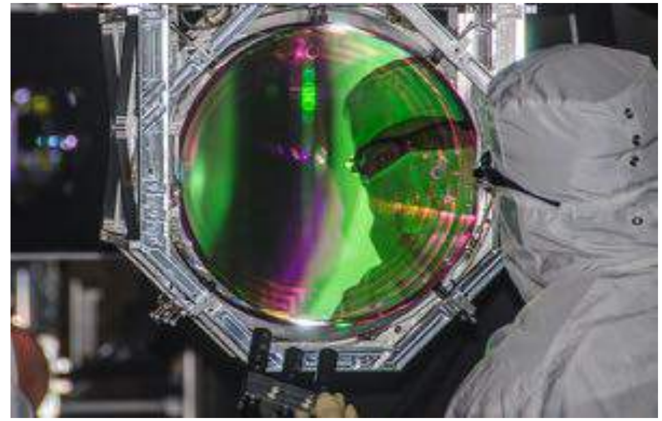
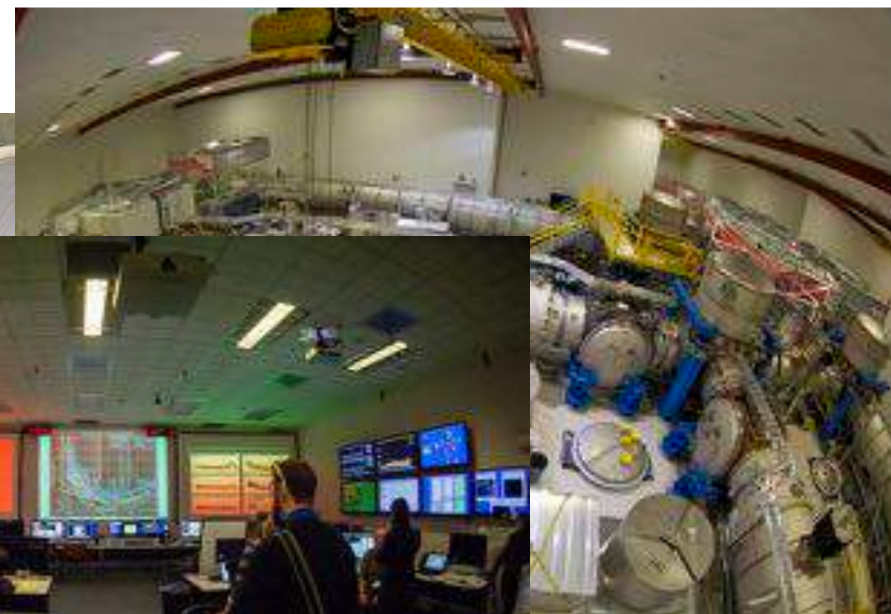
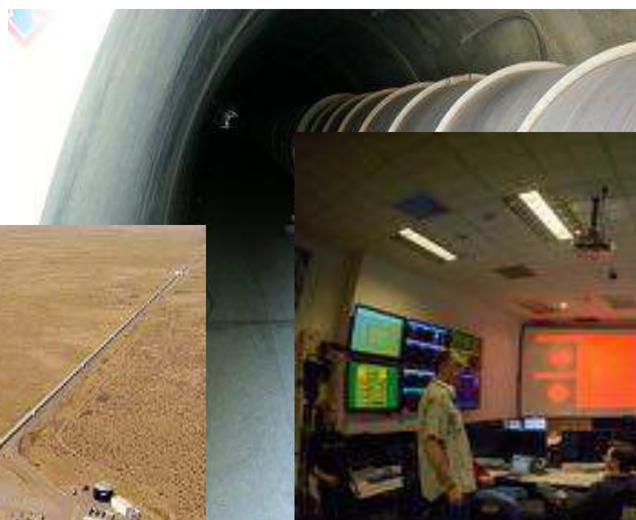
  - Significance $2\,\sigma$ in one of the analyzes

  - No instrumental/environmental artefact

  - Parameter estimation results consistent with astrophysical BBH source

What does Virgo look like ?

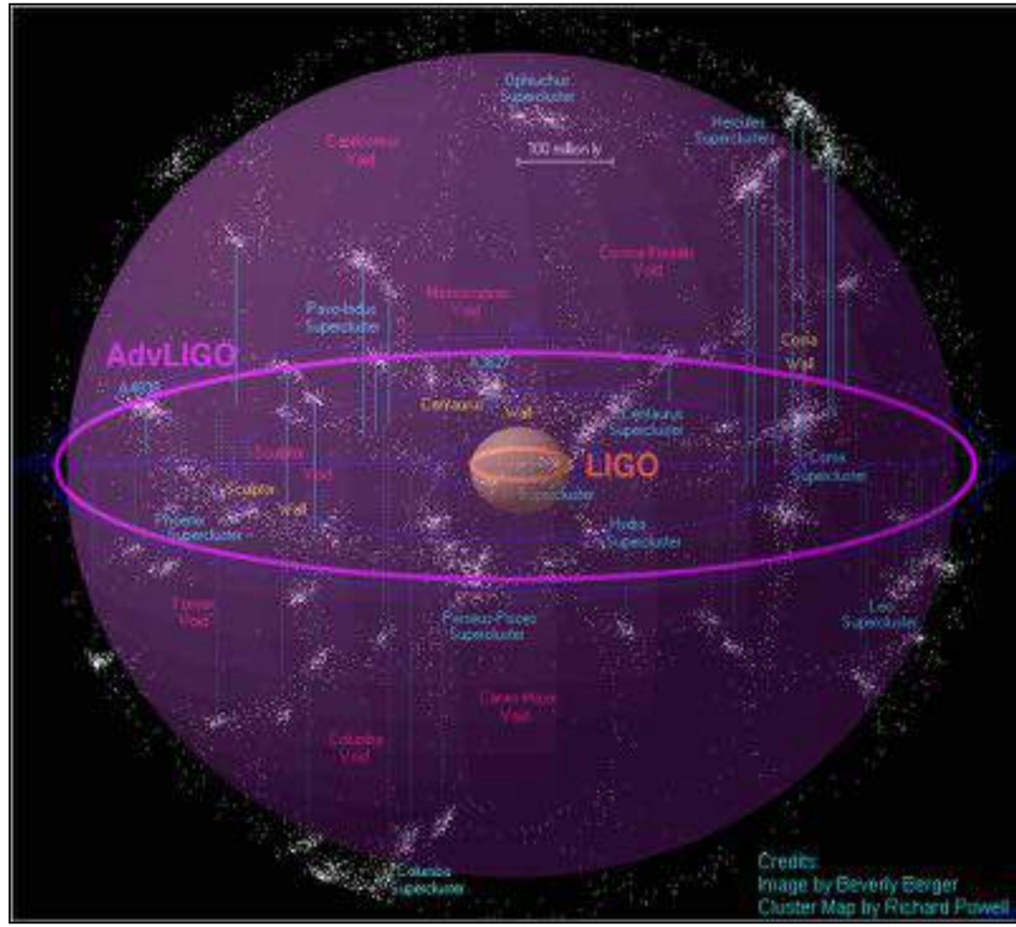
What does LIGO look like ?

- Horizon = distance at which a reference compact body coalescence gives a SNR (Signal over Noise Ratio) of 8 in the detectors

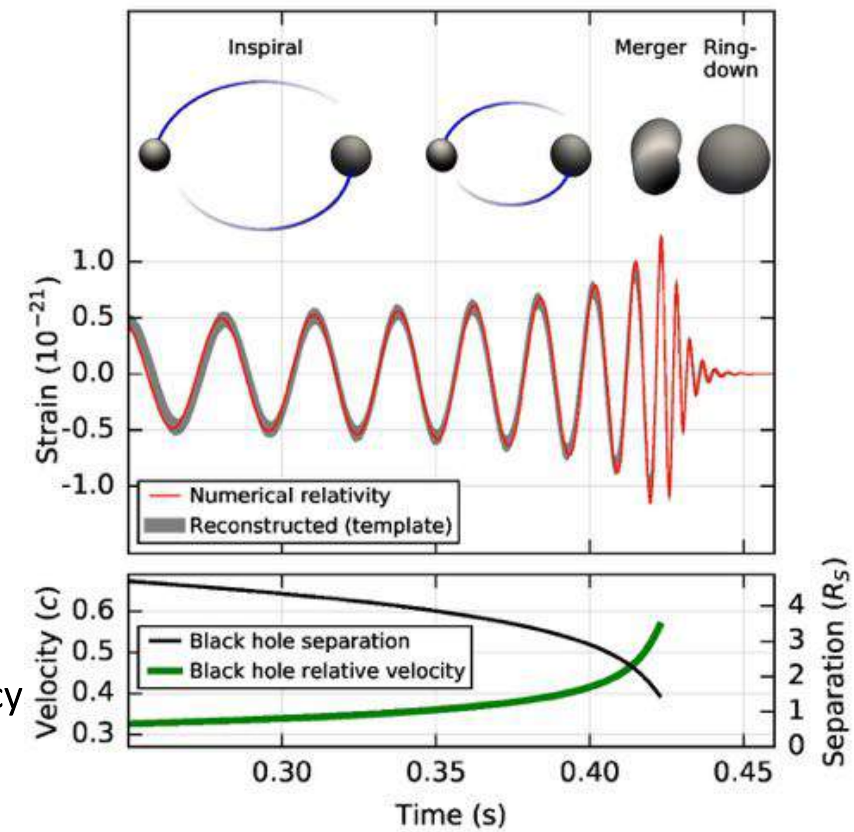
- Picture : reference = 2 x 1.4 $M_\odot$ neutron star coalescence, average orientation

- Sensitivity x 10 $\Leftrightarrow$ Sensitive volume x 10^3



Black holes coalescences ? Yes !

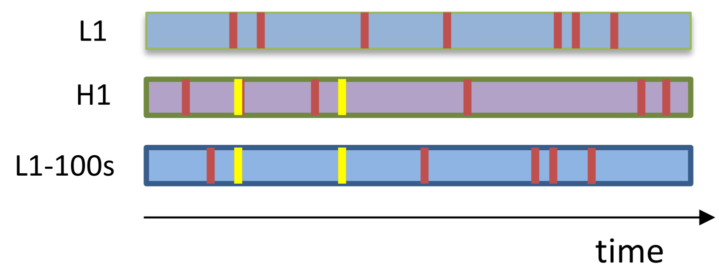
- Example of GW150914
- Over 0.2 s, frequency and amplitude increase from 35 Hz to f_{peak} = 150 Hz (~ 8 cycles)
  - Reminder : the "chirp mass" characterizes the inspiral phase
  - Finds $\mathcal{M} \simeq 30 M_\odot$,
    $$M = m_1 + m_2 \gtrsim 70 M_\odot$$
  - Keplerian separation gets close to Schwarzschild radius
    $$R_S = 2GM/c^2 \gtrsim 210 \text{ km}$$
  - Very close and compact objects
    - BNS too light, NSBH merge at lower frequency



- Decay of waveform after peak
  - consistent with damped oscillations of BH (relaxing to final stationary Kerr configuration)
  - SNR too low to claim observation of quasi normal modes

False alarm rate

- False alarm rate
  - Measured from background estimated on data
  - Time shifts by N x 0.1 s between H1 and L1



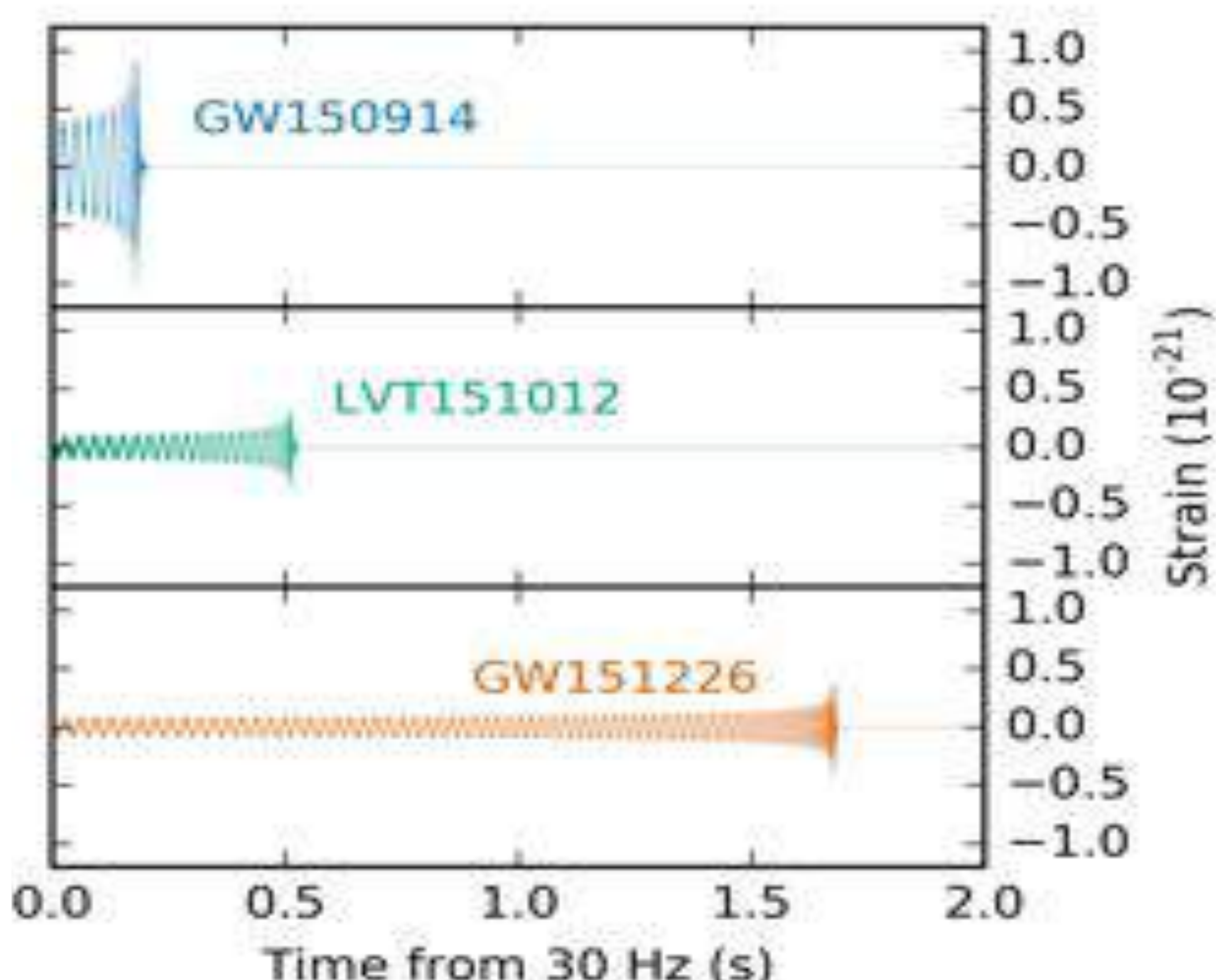
  - Case of GW150914, first analysis for February annoucement
    - N_{max} = 10^7 shifts, T_{bkgd} = 200,000 yrs
    - GW150914 louder than all background ➔ lower limit on significance

- Importance of vetoing environmental transient disturbances.
  - Monitoring by array of sensors
  - ~10^5 channels for each detector

Seismometers, accelerometers, microphones, magnetometers, radio receivers, weather sensors, AC-power line monitors, cosmic ray detector

Matching waveform examples

- From 30 Hz
  - Start of the sensitive band of detectors



Parameter Estimation

- Intrinsic parameters (8)
  - Masses (2) + Spins (6)
- Extrinsic parameters (9)
  - Location : luminosity distance, right ascension, declination (3)
  - Orientation: inclination, polarization (2)
  - Time and phase of coalescence (2)
  - Eccentricity (2)

- PE (parameter estimation) based on coherent analysis across detector network
  - Bayesian framework: Computes likelihood of data given parameter
  - Based on match between data and predicted waveform
  - Explores full multidimensional parameter space with fine stochastic sampling

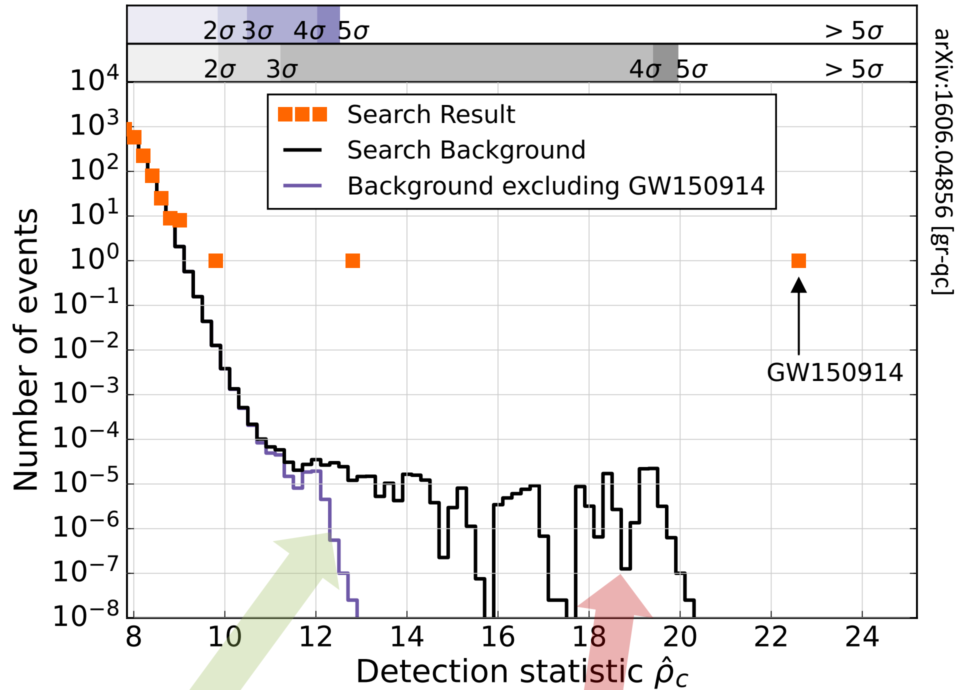
- PE relies on accurate waveform models
  - Crucial progress over past decade to model all phases of BBH coalescence: Inspiral, Merger, Ringdown (IMR)
  - Waveform models combine perturbative theory and numerical relativity
    - EOBNR: Aligned spins (11 parameters)
    - IMRPhenom: Aligned spins + one effective precession spin parameter (12 parameters)
  - Still missing: eccentricity, higher order gravitational modes, full spin generality

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

- Masses
- Spins
  - Weakly constrained
- Radiated energy
- Peak luminosity

CBC BBH search result : GW150914

- Statistic
  - $\hat{\rho} = \rho / \{[1 + (\chi_r^2)^3]/2\}^{1/6}$
  - $\hat{\rho}_c = \sqrt{\hat{\rho}_{H1}^2 + \hat{\rho}_{L1}^2}$
- Significance
  - GW150914 is the loudest event in the search, $\hat{\rho}_c$ = 22.7
  - Individual triggers in L1 and H1 (forming GW150914): highest $\hat{\rho}$ in each detector
  - Significance $> 5.3\sigma$

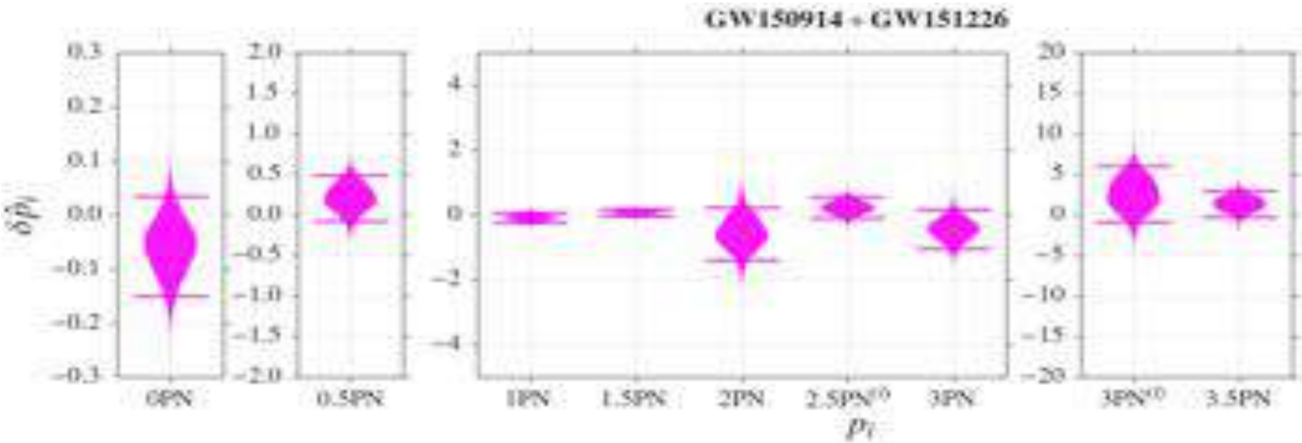


Background excluding contribution from GW150914 (gauge significance of other triggers)

Coincidences between single detector triggers from GW150914 and noise in other detector

Testing GR with GW150914 (II)

- No evidence for deviation from GR in waveform



arXiv:1606.04856 [gr-qc]

- No evidence for dispersion in signal propagation
  - Bounds :

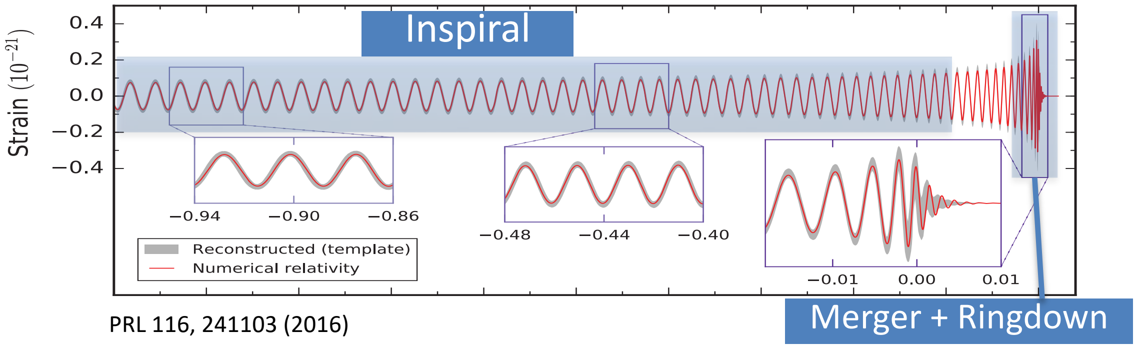
$$\lambda_g > 10^{13}\ \mathrm{km}$$

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

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

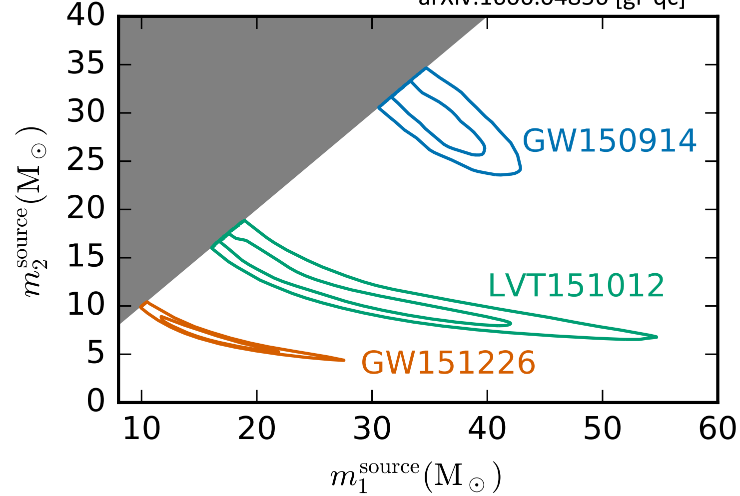
  - More constraining than bounds from
    - Solar System observations
    - binary pulsar observations
  - Less constraining than model dependent bounds from
    - large scale dynamics of galactic clusters
    - weak gravitational lensing observations

Intrinsic Parameters



PRL 116, 241103 (2016)

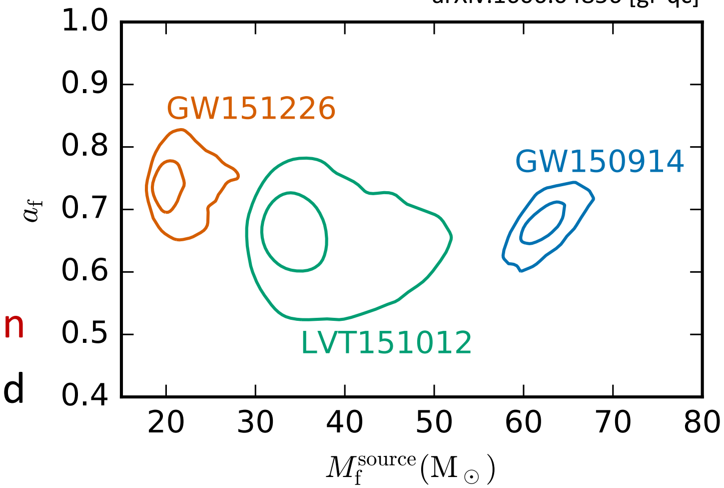
arXiv:1606.04856 [gr-qc]



- Encoded in GW signal :
  - ***Inspiral***
    - chirp mass, mass ratio, spin components
    - Additional spin effect
      - If not // orbital angular momentum: orbital plane precession

        ➔ Amplitude and phase modulation
  - ***Merger and ringdown***
    - Primarily governed by final black hole mass and spin
    - Masses and spins of binary fully determine mass and spin of final black hole in general relativity

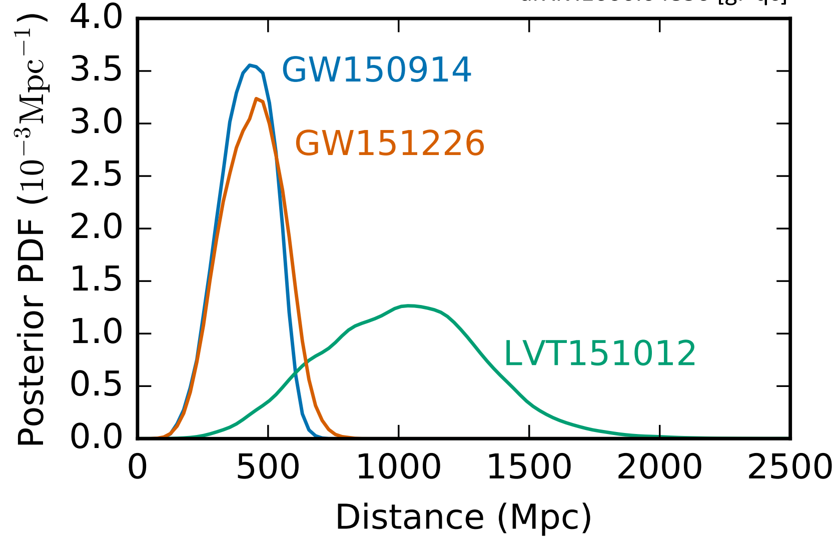
arXiv:1606.04856 [gr-qc]

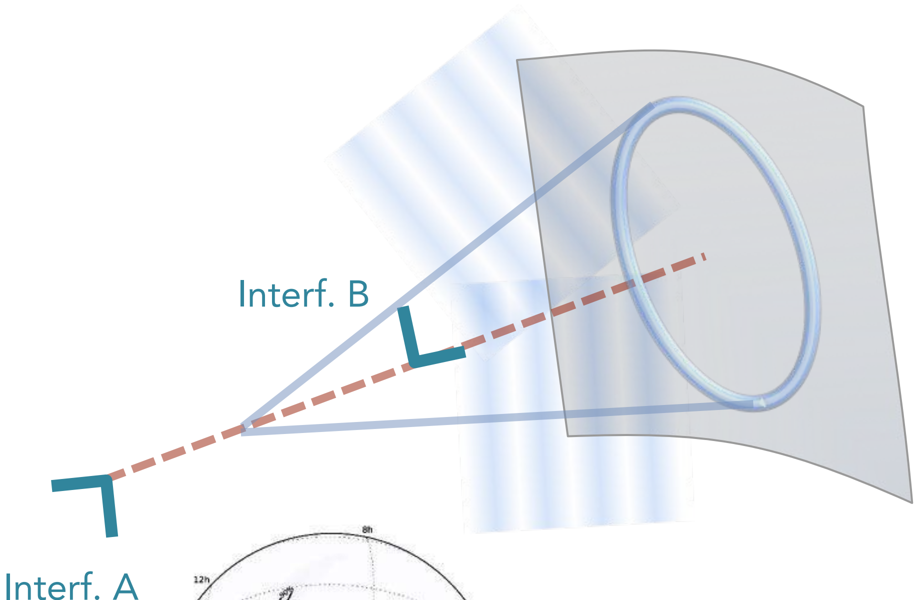


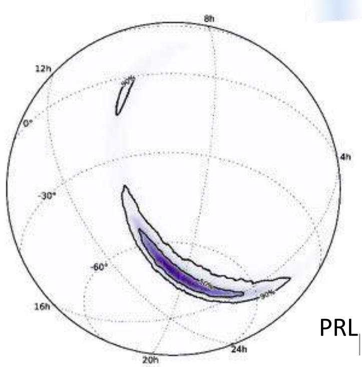
Extrinsic Parameters

- Amplitude depends on masses, distance, and geometrical factors
  - Distance – inclination degeneracy

arXiv:1606.04856 [gr-qc]







PRL 116, 241102 (2016)

- Source location on the sky
  - inferred primarily from
    - time of flight $6.9^{+0.5}_{-0.4}$ ms for GW150914
    - amplitude and phase consistency
  - Limited accuracy with two detector network
  - 2-D 90% credible region 230 deg^2 (GW150914)
  - 3-D uncertainty volume contains ~10^5 Milky Way equivalent galaxies

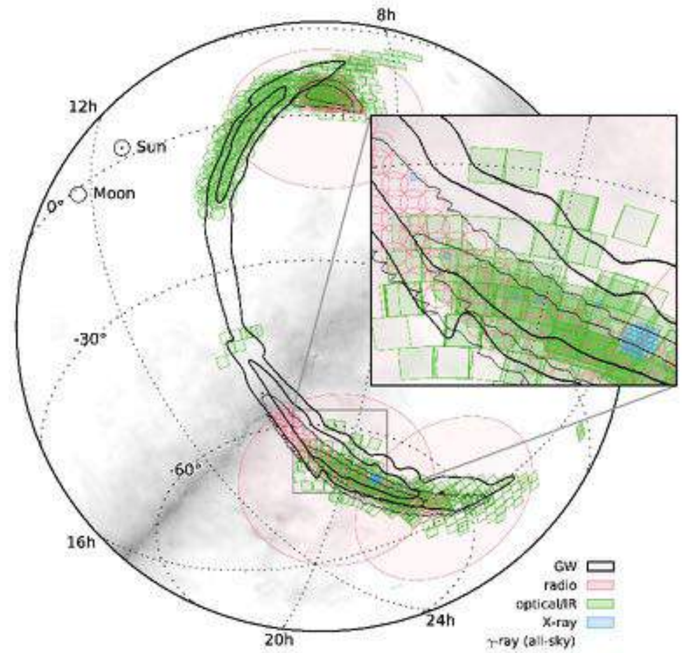
Multi-messenger astronomy

- LVC called for EM observers to join a follow-up program
  - LIGO and Virgo promptly share interesting triggers
  - 70 MoUs, 160 instruments covering full spectrum
    - (from radio to very high energy gamma-rays)

- 25 teams reported follow-up observation of GW150914

- We analyzed thoroughly data around the times of interesting Gamma Ray Bursts
  -> no signal (up to now)

- This is the birth of multi-messenger astronomy with GW !
  (even if we didn't see anything in coincidence)



ApJ Letters, 826:L13, 2016 July 20

Testing GR

- Most relativistic binary pulsar known today
  - J0737-3039, orbital velocity $v/c \sim 2 \times 10^{-3}$
- GW150914
  - Strong field, non linear, high velocity regime $v/c \sim 0.5$

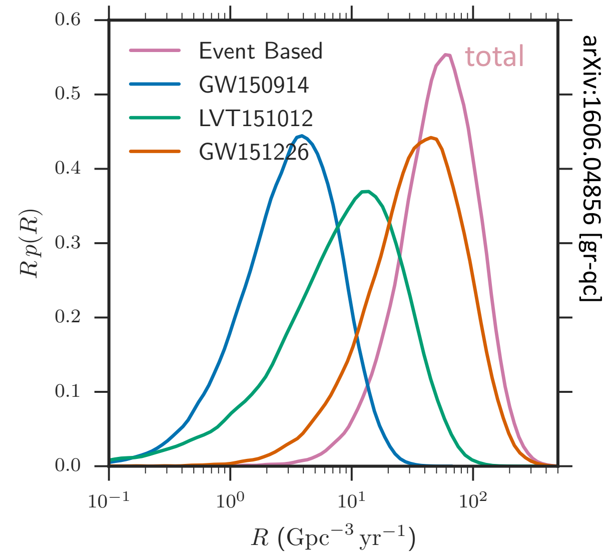
- "Loud" SNR -> coarse tests
  - Waveform internal consistency check
  - No evidence for deviation from General Relativity in waveform
  - Bound on Compton wavelength (graviton mass)
    - No evidence for dispersion in signal propagation

$$\left(\frac{v}{c}\right)^2 = 1 - \left(\frac{hc}{\lambda_g E}\right)^2 \qquad \lambda_g > 10^{13}\ \mathrm{km} \qquad m_g \leq 1.2 \times 10^{-22}\ \mathrm{eV/c^2}$$

- More contraining than bounds from the solar system
- Less constraining than model dependent bounds from large scale dynamics of galactic clusters

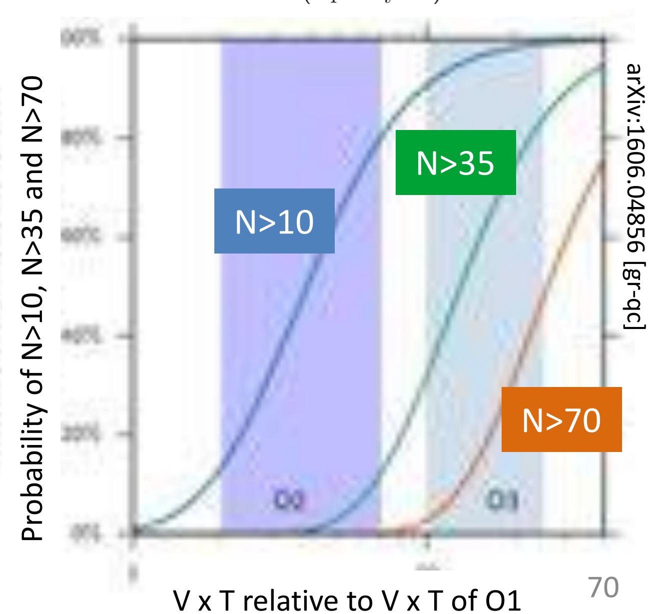
Rate of BBH mergers

- Astrophysical rate inference
  - Counting signals in experiment
  - Estimating sensitivity to population of sources
    - Depends on mass distribution (hardly known)



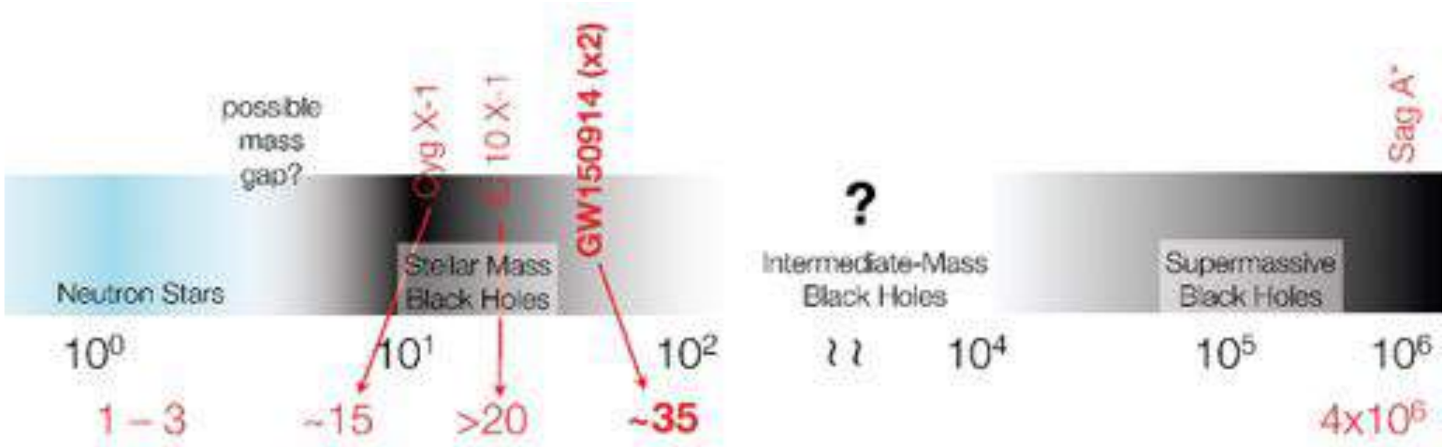
- Low statistics and variety of assumptions -> broad rate range
  - R ~ 9 – 240 Gpc^{-3} yr^{-1}
  - Previsously : R ~ 0.1 – 300 Gpc^{-3} yr^{-1} (electromagnetic observations and population modeling)

- Project expected number of highly significant events as a function of surveyed time x volume



Astrophysics implications

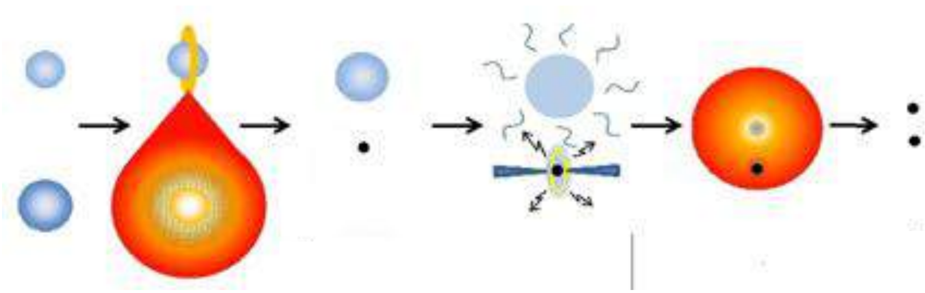
- Relatively massive black holes (> 25 $M_\odot$) exist in nature

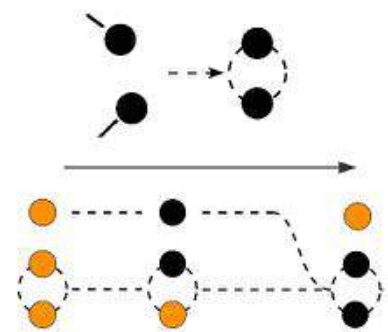


- Massive progenitor stars
  => low mass loss during its life
  => weak stellar wind
- Metallicity = proportion of elements heavier than He
  - High metallicity => strong stellar wind
- => formation of progenitors
  in a low metallicity environment

Astrophysics implications

- Binary black holes form in nature
  - Formation :
    - Isolated binaries
    - Dynamical capture (dense stellar regions)
  - Detected events do not allow to identify formation channel
    - Future : information on the spins can help

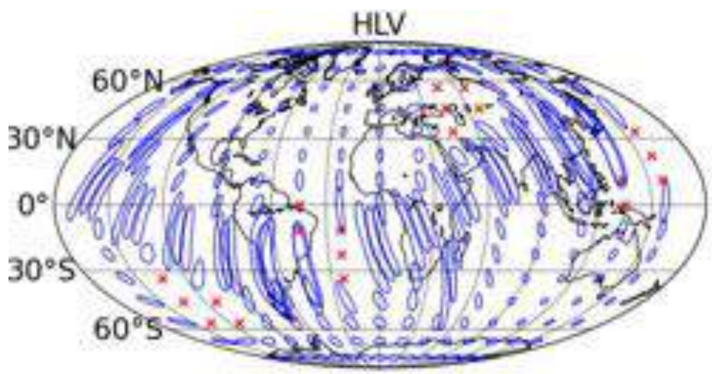




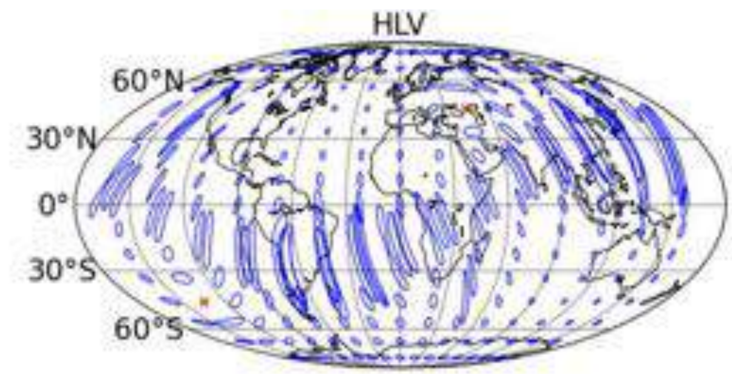
- Binary Black Holes merge within age of Universe at detectable rate
  - Inferred rate consistent with higher end of rate predictions (> 1 $Gpc^{-3}\ yr^{-1}$)

Future Localization Prospects

Face-on BNS
@ 80 Mpc

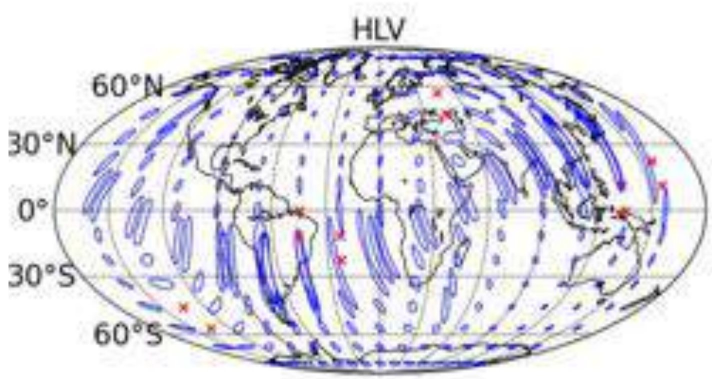


2016-17

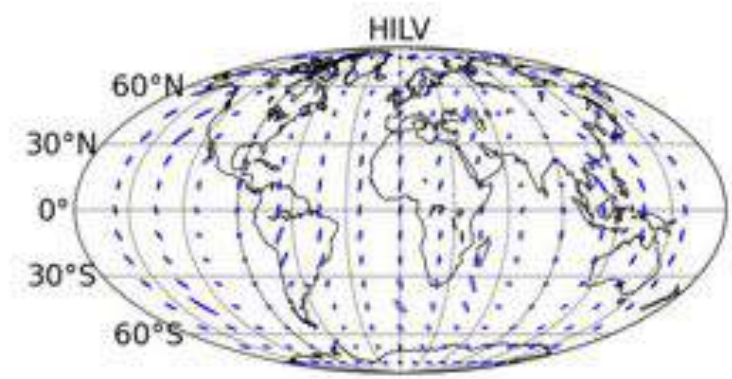


2017-18

Face-on BNS
@ 160 Mpc



2019+



2022+

HLV = Hanford-Livingston-Virgo

HILV = Hanford-LIGO India-Livingston-Virgo

From one generation to the next (II)

Terrestrial detectors

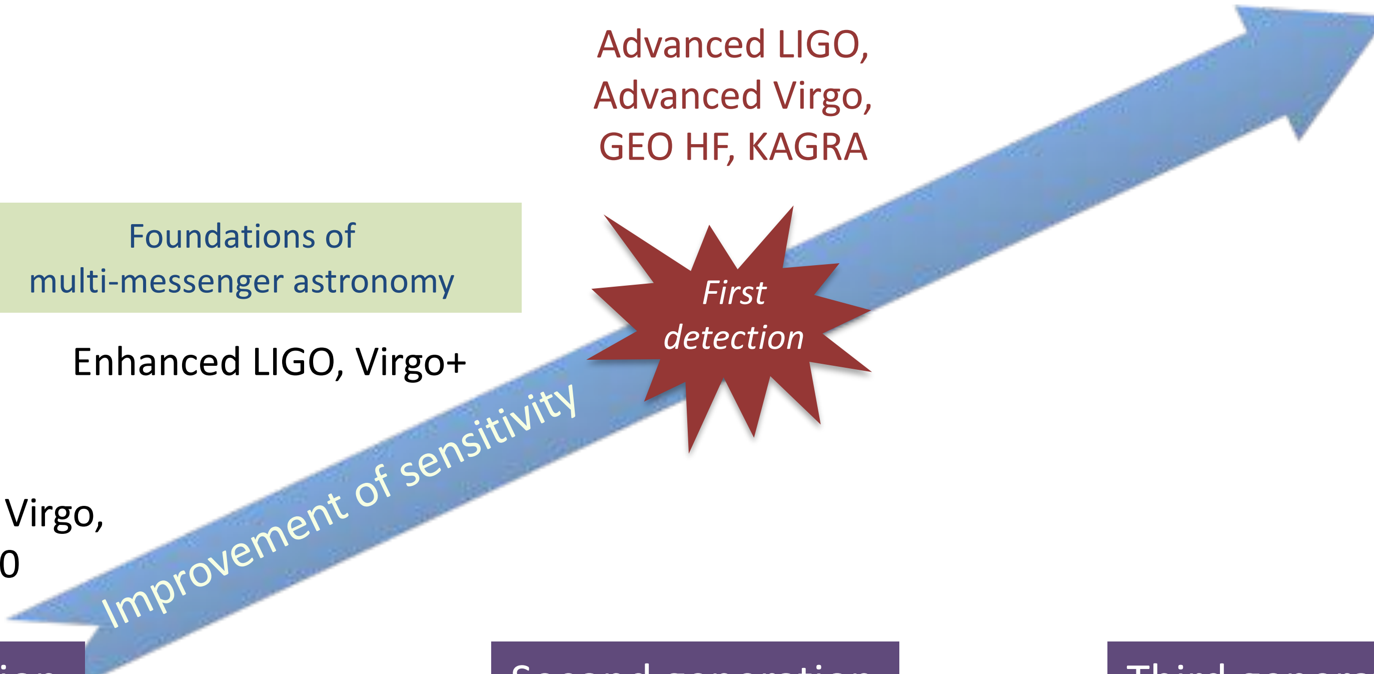
Einstein Telescope (ET)

Advanced LIGO,
Advanced Virgo,
GEO HF, KAGRA

Foundations of
multi-messenger astronomy

Enhanced LIGO, Virgo+

Initial LIGO, Virgo,
GEO600



First generation

Data taking
Rates upper limits
Building the network

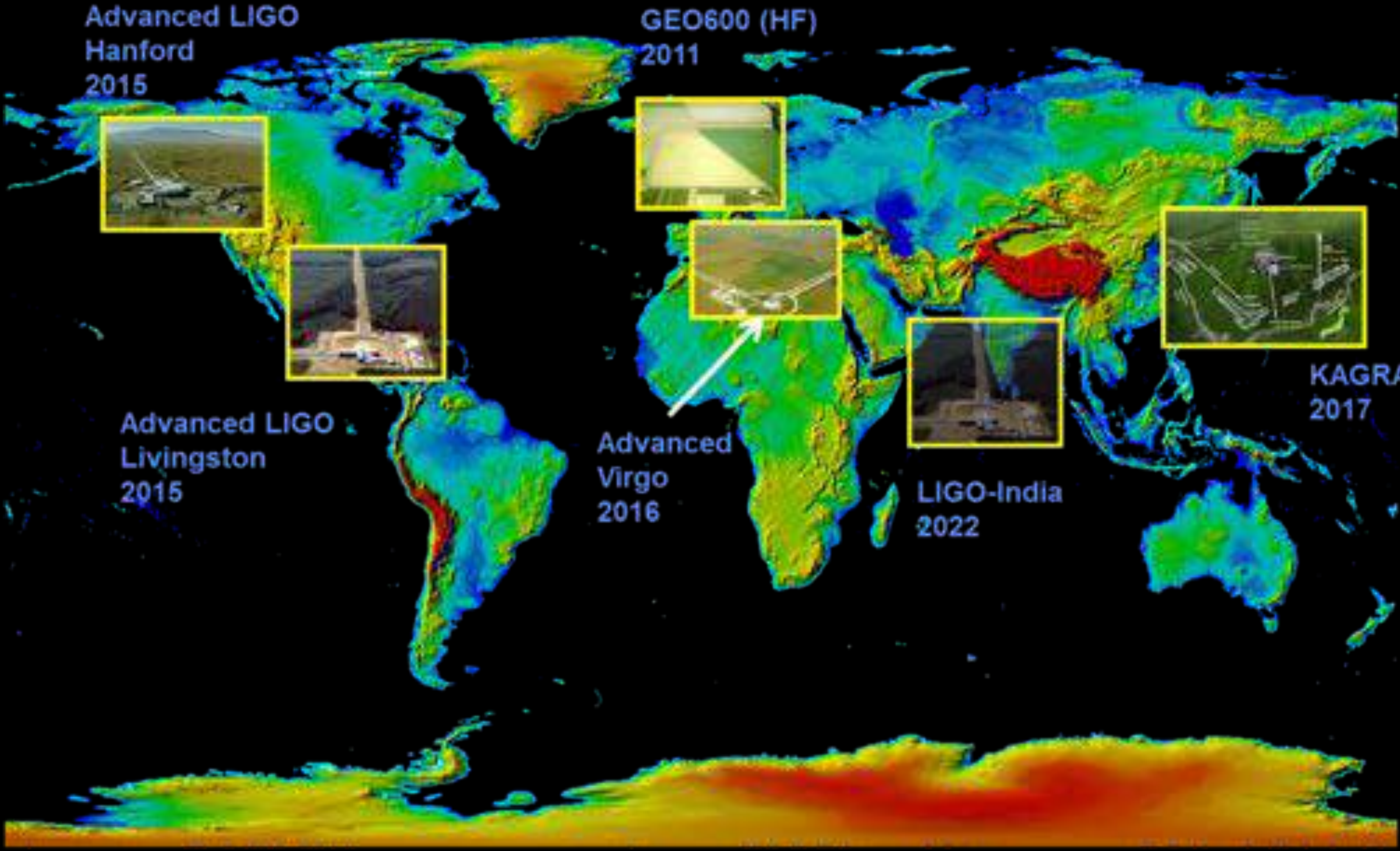
Second generation

Towards routine observations,
GW astronomy

Third generation

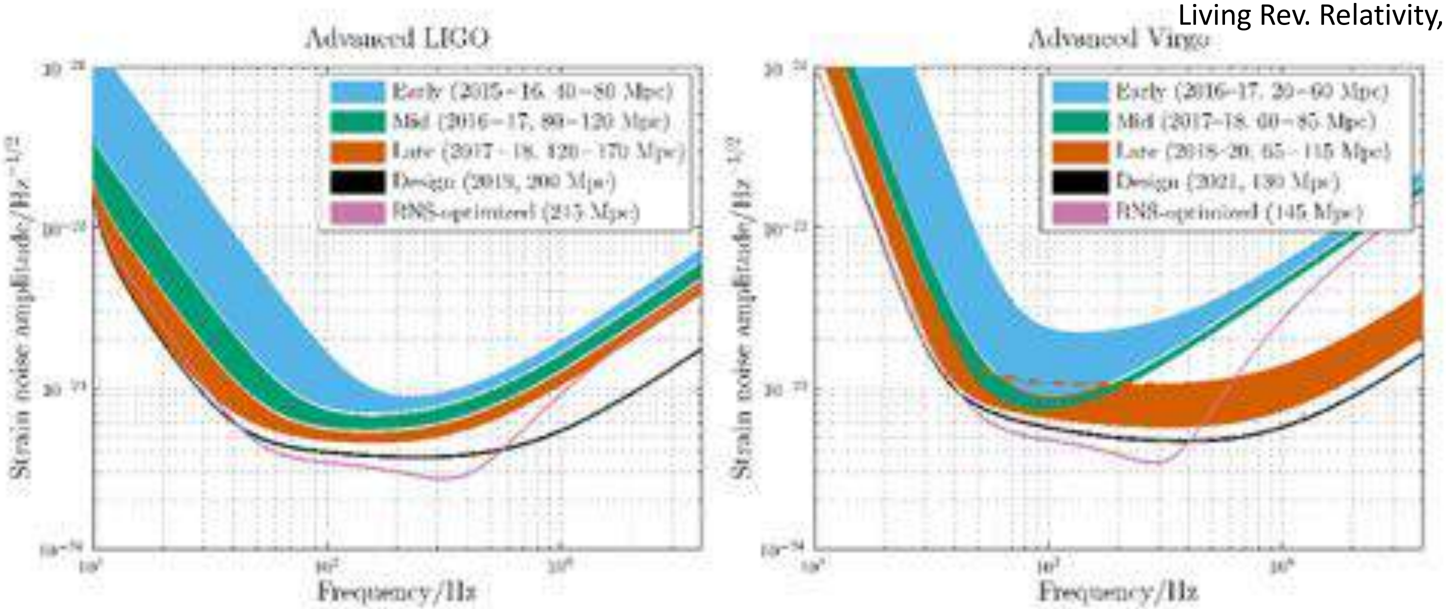
In-depth observation of
the universe with GW

2nd Generation Network



Plan and sensitivity evolution

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

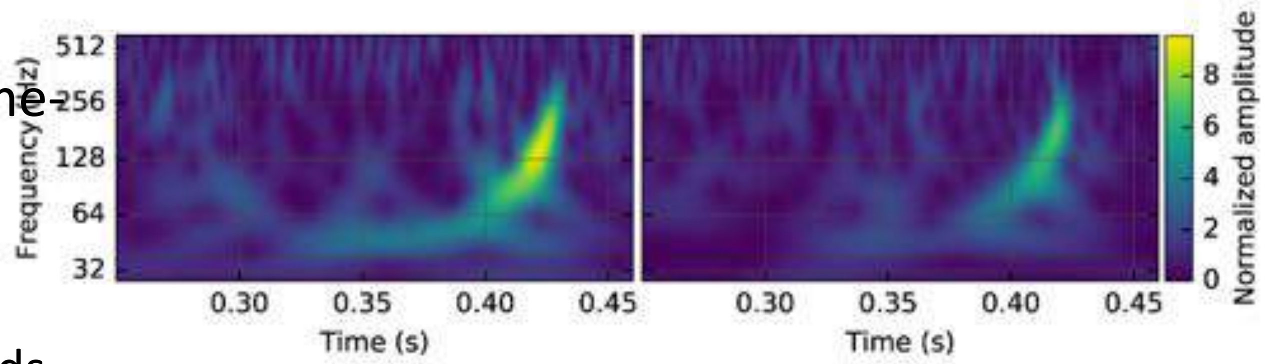


Epoch			2015 – 2016	2016 – 2017	2017 – 2018	2019+	2022+ (India)
Estimated run duration			4 months	6 months	9 months	(per year)	(per year)
Burst range/Mpc		LIGO	40 – 60	60 – 75	75 – 90	105	105
		Virgo	—	20 – 40	40 – 50	40 – 80	80
BNS range/Mpc		LIGO	40 – 80	80 – 120	120 – 170	200	200
		Virgo	—	20 – 60	60 – 85	65 – 115	130
Estimated BNS detections			0.0005 – 4	0.006 – 20	0.04 – 100	0.2 – 200	0.4 – 400
90% CR	% within	5 deg^2	< 1	2	> *1 – 2*	> *3 – 8*	> *20*
		20 deg^2	< 1	14	> *10*	> *8 – 30*	> *50*
	median/deg^2		480	230	—	—	—
searched area	% within	5 deg^2	6	20	—	—	—
		20 deg^2	16	44	—	—	—
	median/deg^2		88	29	—	—	—

Generic Transient Search

- Operates without a specific search model

- Identifies coincident excess power in time-frequency representations of h(t)
  - Frequency < 1 kHz
  - Duration < a few seconds



- Reconstructs signal waveforms consistent with common GW signal in both detectors using multi-detector maximum likelihood method

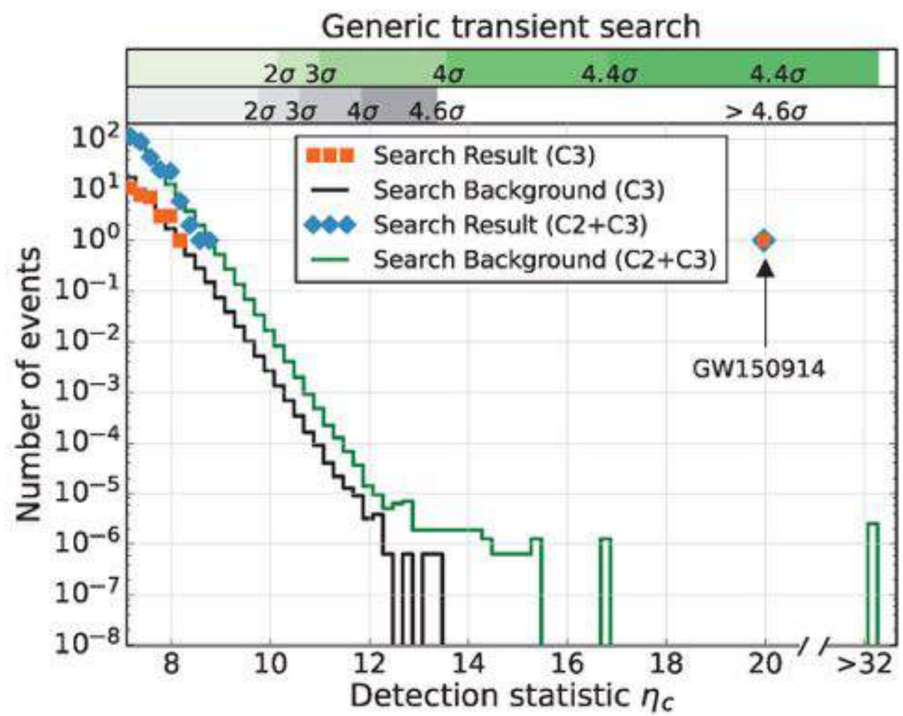
- Detection statistic
  - $$\eta_c = \sqrt{\frac{2E_c}{(1 + E_n/E_c)}}$$

E_c: dimensionless coherent signal energy obtained by cross-correlating the two reconstructed waveforms
E_n: dimensionless residual noise energy after reconstructed signal is subtracted from data

- Signals divided into 3 search classes based on their time-frequency morphology
  - C3 : Events with frequency increasing with time – CBC like

Generic Transient Search Result

- GW150914 loudest event in C3 search class, $\eta_c = 20$
- Significance also measured from time slides
  - T_{bckd} = 67,400 yr , trial factors
  - FAR < 1 per 22,500 yr
  - FAP < 2 10^{-6} ➔ > 4.6 σ

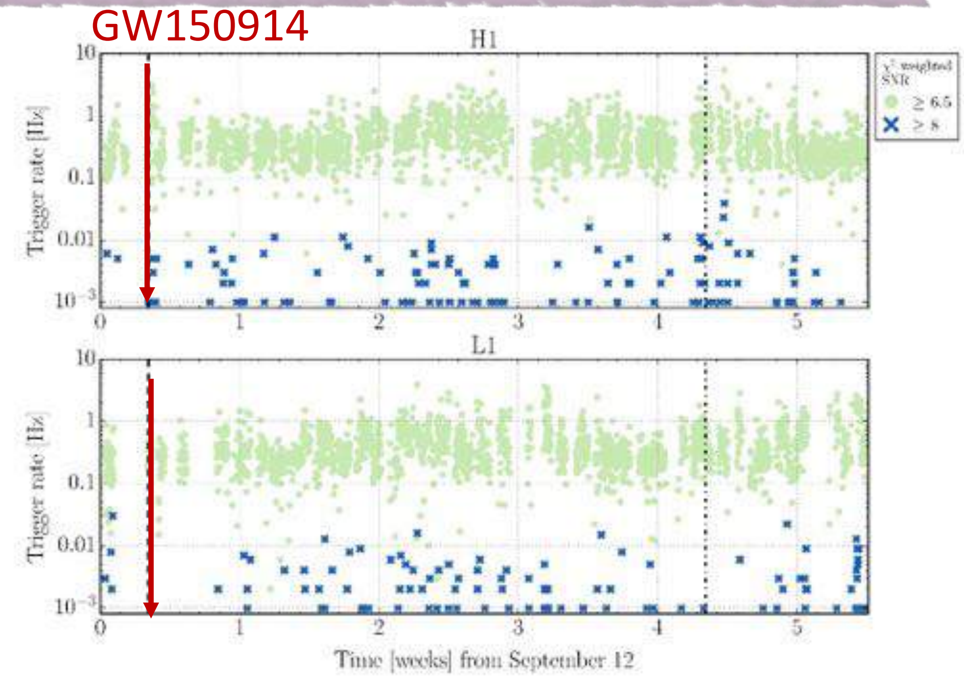


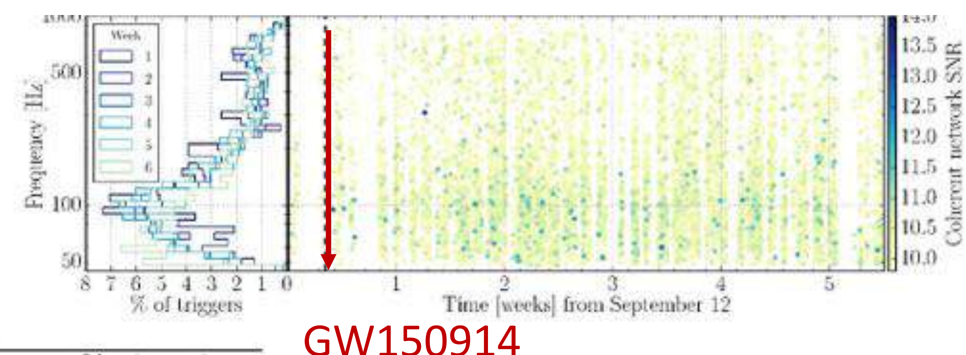
Data quality

- On analyzed period
  - Clean data set
  - Homogeneous background

- Data quality vetoes
  - Identify periods with intrumental or environmental problems
  - Veto those periods

  - GW150914 >> every background event even without DQ vetoes

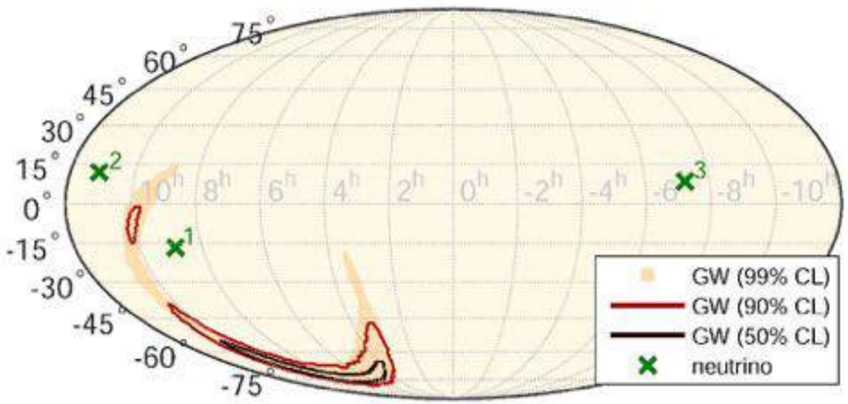




Hanford			Livingston		
DQ veto category	Total deadtime (s)	% of total coincident time	DQ veto category	Total deadtime (s)	% of total coincident time
1	73446	4.62%	1	1066	0.07%
2	5522	0.35%	2	87	0.01%

High-Energy Neutrino Follow-up

- Search for coincident high energy neutrino candidates in IceCube and ANTARES data
  - HEN ν 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
  - 0 ν candidate in ANTARES
  - Consistent with expected atmospheric background
  - No ν candidate directionally coincident with GW150914

- Derive ν fluence upper limit (direction dependent)
- Derive constraint on total energy emitted in ν by the source
  - $$E^{ul}_{\nu,tot} \sim 10^{52}\text{–}10^{54} \left(\frac{D_{gw}}{410\,\mathrm{Mpc}}\right)^2 \mathrm{erg}$$

Expected BBH Stochastic Background

- GW150914 suggests population of BBH with relatively high mass
- Stochastic GW background from BBH could be higher than expected
  - Incoherent superposition of all merging binaries in Universe
  - Dominated by inspiral phase
- Estimated energy density

$$\Omega_{\rm GW}(f = 25\,{\rm Hz}) = 1.1^{+2.7}_{-0.9} \times 10^{-9}$$

- Statistical uncertainty due to poorly constrained merger rate currently dominates model uncertainties
- Background potentially detectable by Advanced LIGO / Advanced Virgo at projected final sensitivity

$$\Omega_{\rm GW}(f) = \frac{f}{\rho_c}\frac{d\rho_{\rm GW}}{df}$$