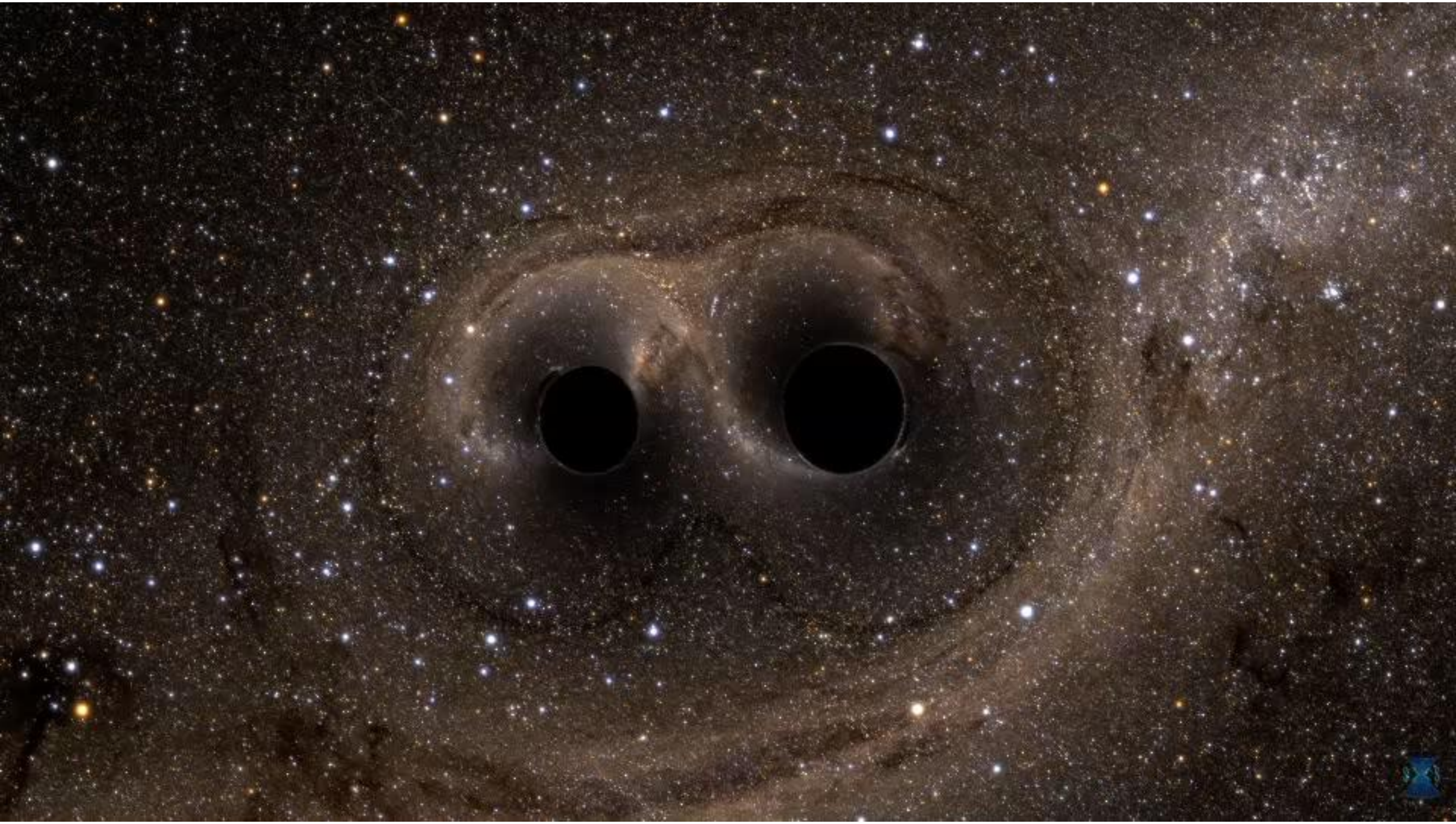
Detection of Gravitational Waves

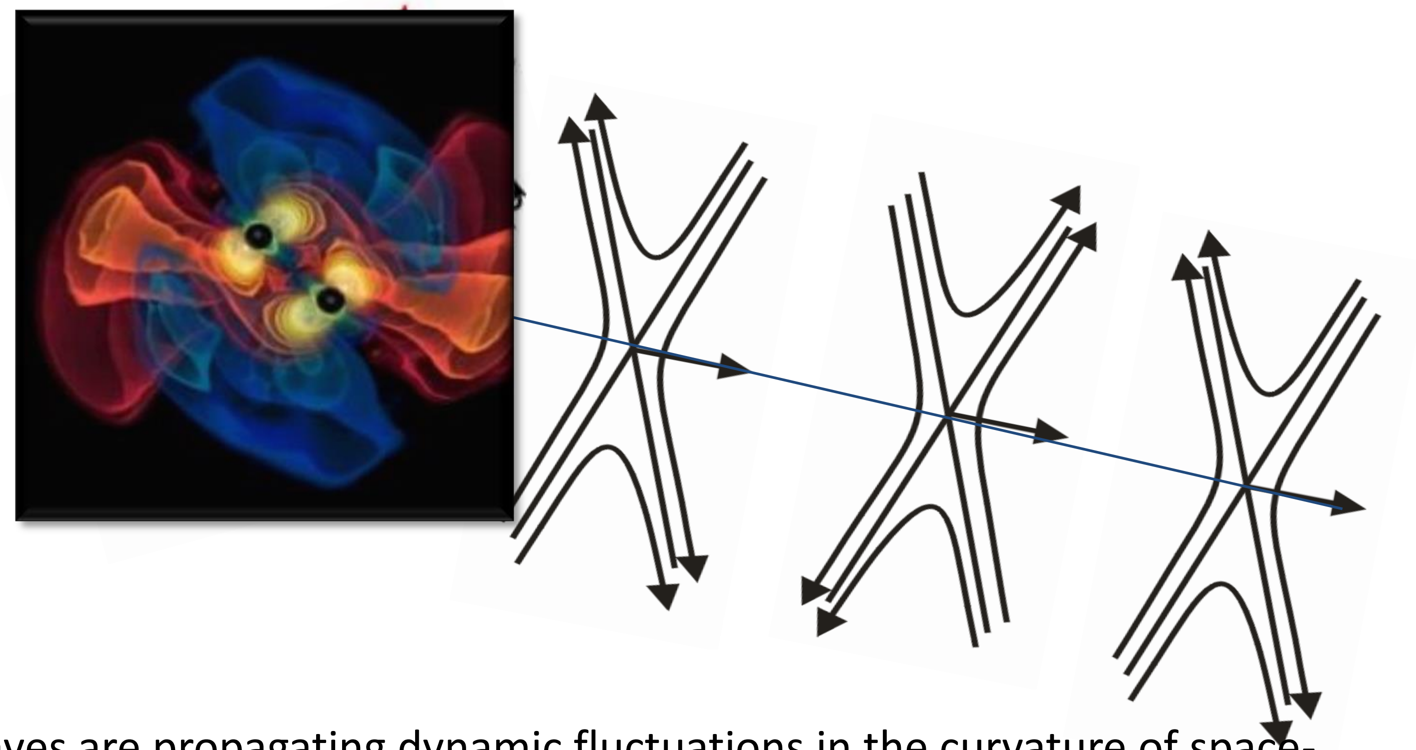
Enrico Calloni

on behalf of the Virgo Naples group and

on behalf of the LIGO Scientific and VIRGO collaborations



Introduction to Gravitational Waves



Gravitational waves are propagating dynamic fluctuations in the curvature of space-time (‘ripples’ in space-time)

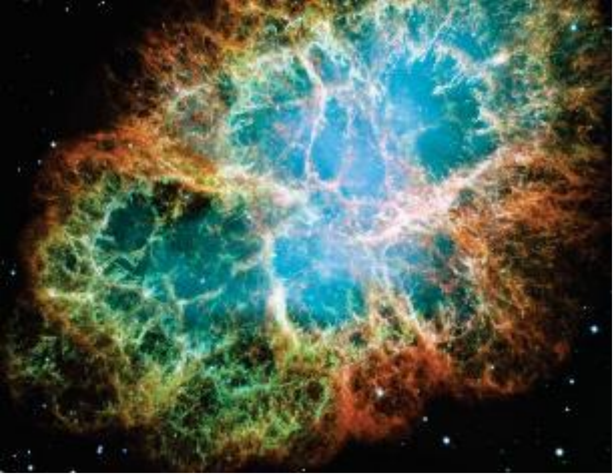
Predicted by Einstein 100 years ago; confirmation by Hulse/Taylor/Weisberg

Emitted from accelerating mass distributions

Sourced by the time-dependence of the quadrupole mass moment

Practically, need massive objects at speeds approaching the speed of light

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

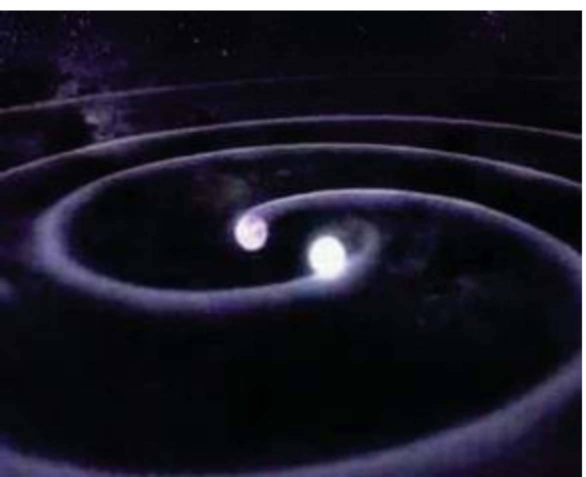


Supernovae

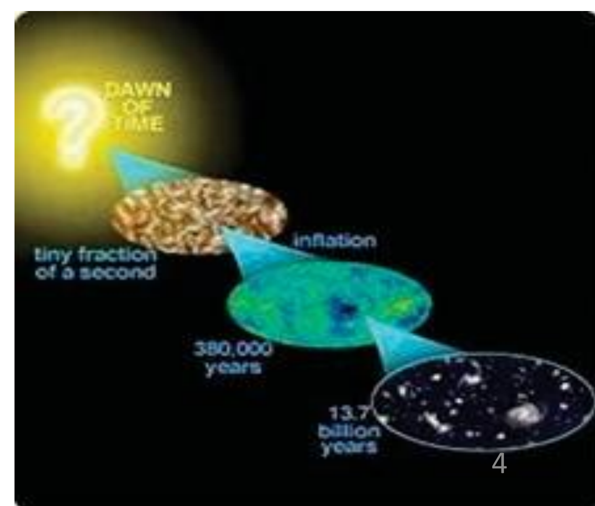
Rotating neutron stars

Hunting the GW signals

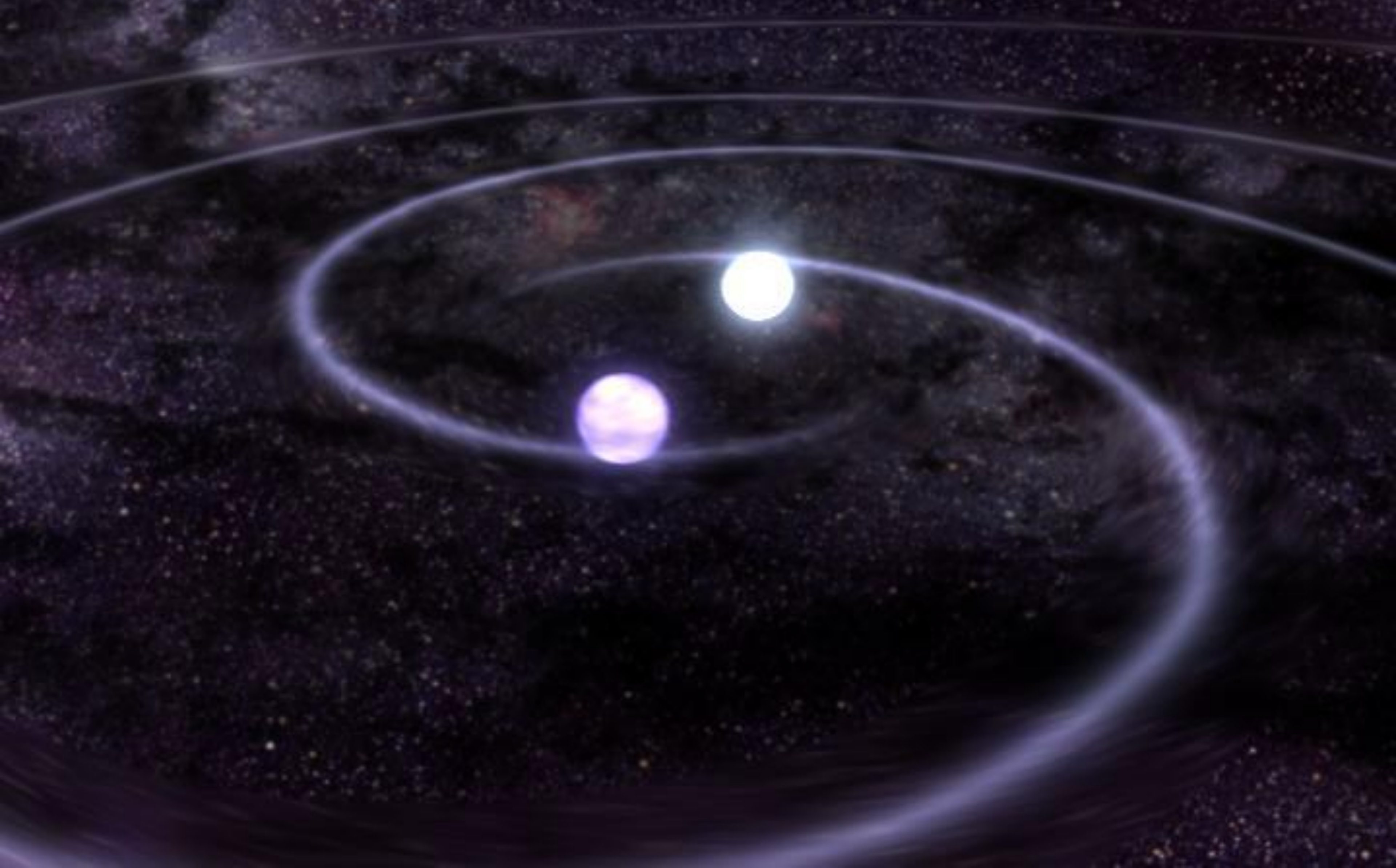
Coalescent Binary Sytem

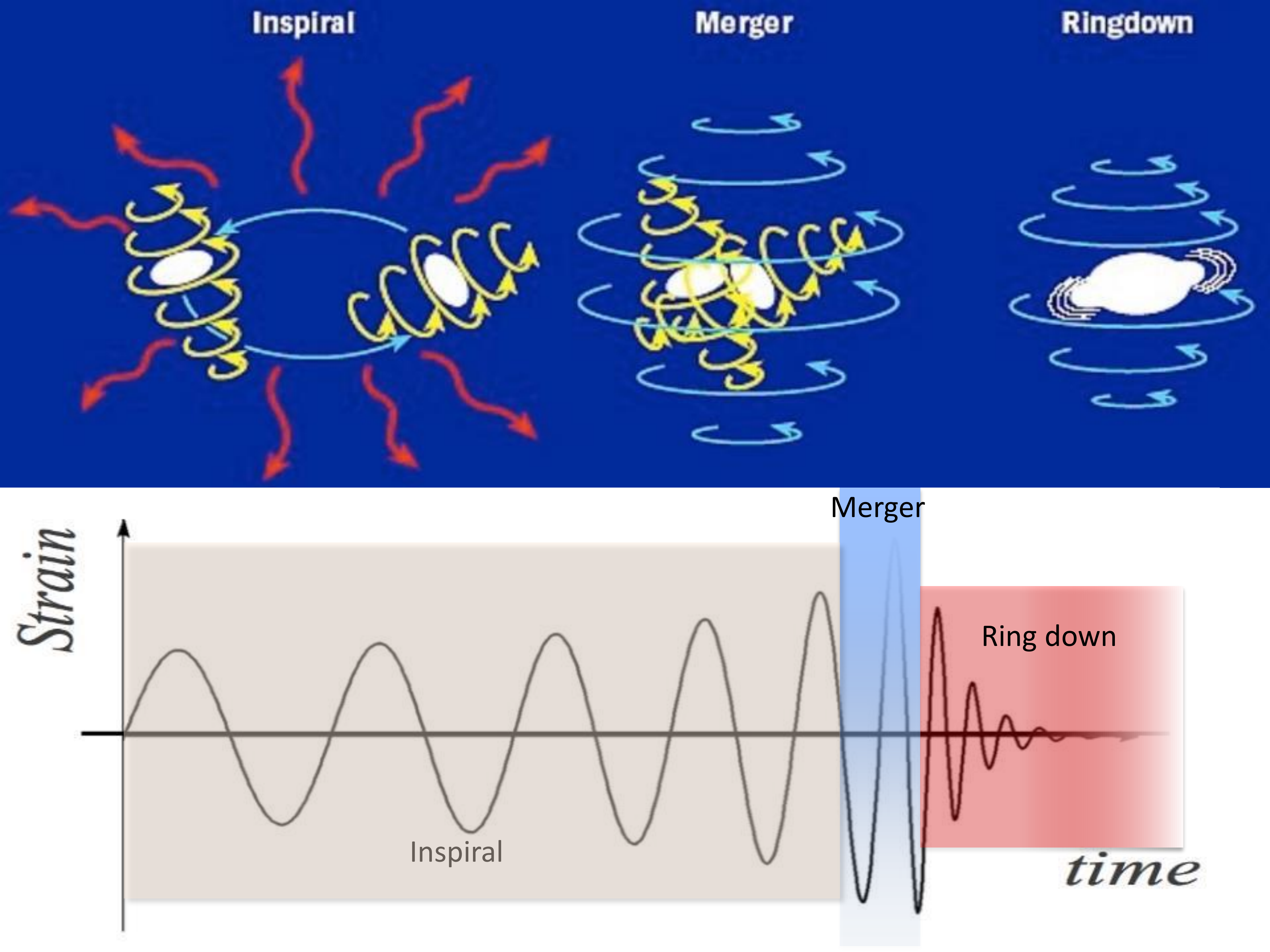


GW stochastic background



A Golden GW Signal





Inspiral
Merger
Ringdown
Strain
Merger
Ring down
Inspiral
time

Emission during the inspiral phase

$$h_+(t) = A_{\rm GW}(t)\left(1+\cos^2\iota\right)\cos\phi_{\rm GW}(t)$$
$$h_\times(t) = -2A_{\rm GW}(t)\cos\iota\sin\phi_{\rm GW}(t)$$

ι ➔ *the inclination angle between the direction of the detector as seen from the binary's center-of-mass, and the normal to the orbital plane*

During the inspiral, if the phase ϕ_{GW} is computed using PN expansion, at the leading order the phase evolution depends on the chirp mass

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

*Addition parameters (q= [m_1 / m_2] and **L**) , enter at the following orders*

When the two compact objects are closer , PN fails and NR is used

Source parameter extraction - I

- From the inspiral, we measure the chirp mass $\mathcal{M}$ with good accuracy

- During the inspiral, the in-plane components of the spins cause the binary's orbital plane to precess around the the total angular momentum of the binary.

- <u>Depending on the orientation of the binary</u>, precession effects can produce an amplitude and phase modulation of the signal at the detector

Source parameter extraction - II

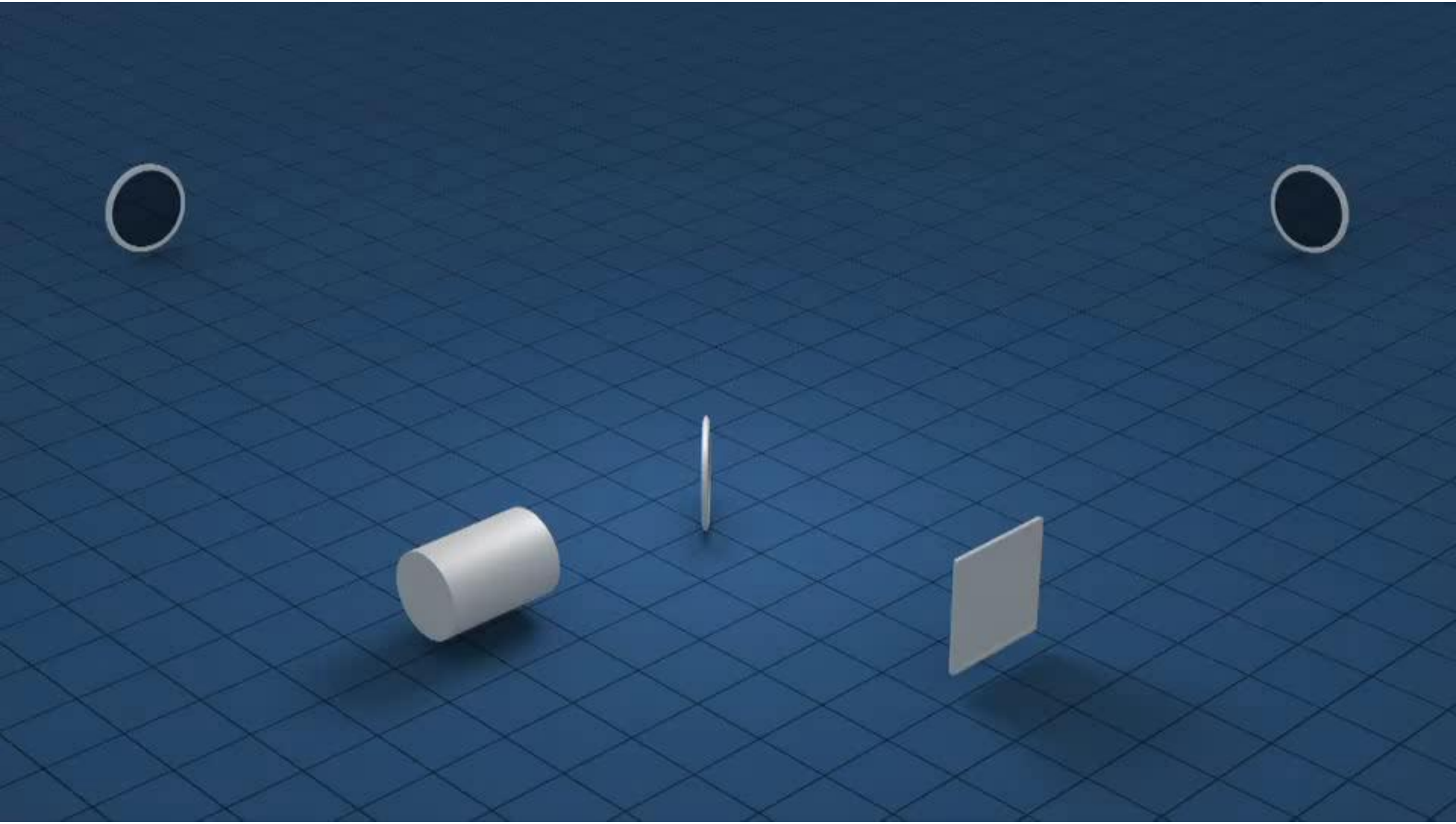
- $r > 10\ G\ M_{tot}/c^2$ ➔ Inspiral phase, PN expansion
  - Chirp mass measurement

- $r < 10\ G\ M_{tot}/c^2$ ➔ Merger and ringdown, NR wave description
  - Measurement of the final BH mass and Spin
  - Amount of energy emitted similar to the entire inspiral phase

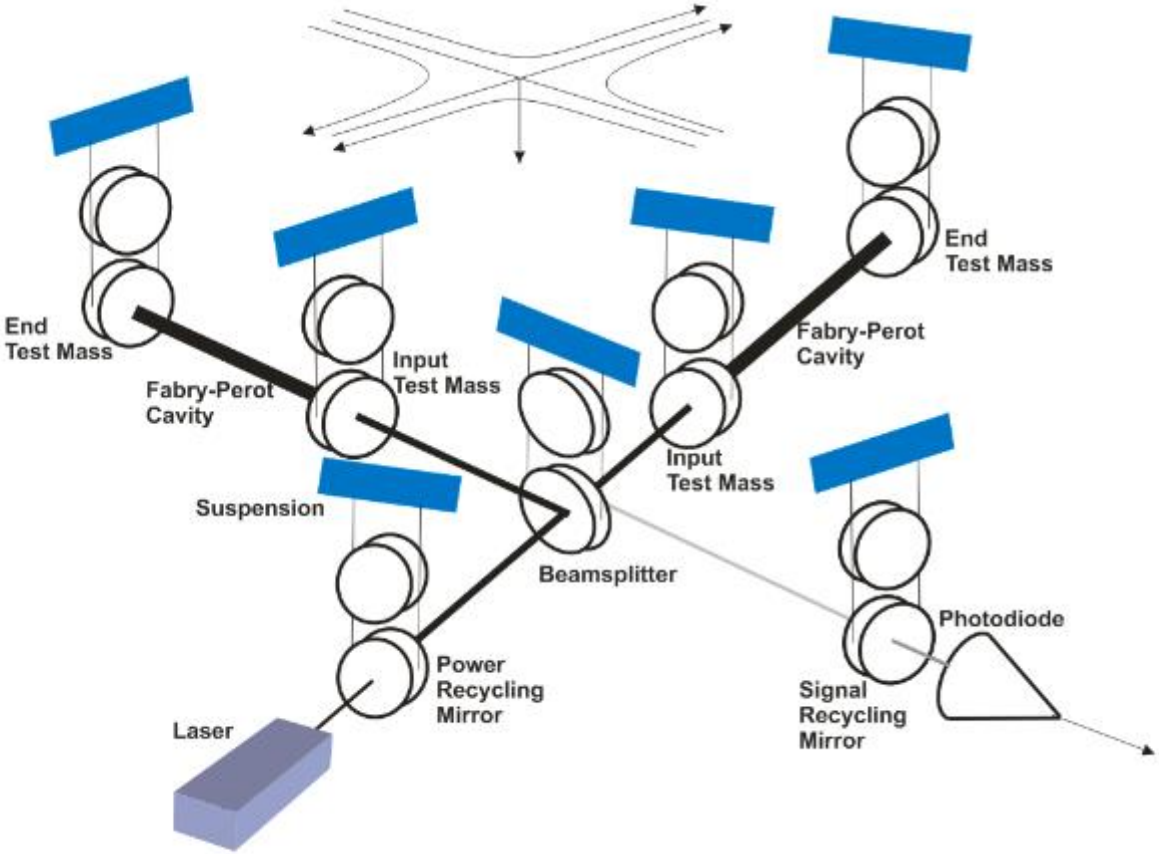
Cosmological corrections

- If the source is at a cosmological distance with redshift z, then
  - *distance* ➔ luminosity distance D_L ,
  - *Frequency* is the ***observed*** one , *f*, *redshifted by (1+z) to the respect of the source frequency*,
  - Each mass m ➔ $(1+z)\,m$.

The detector

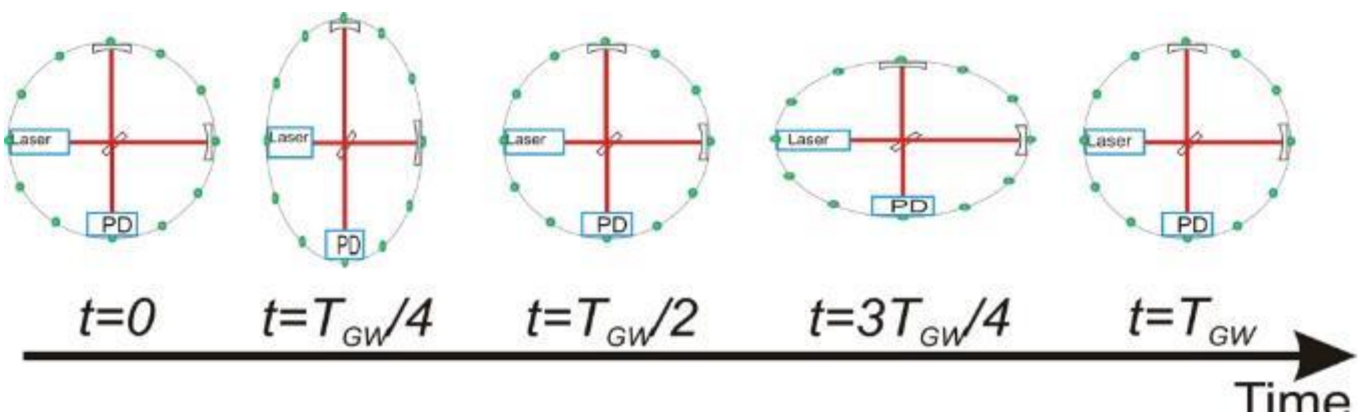


The detection principle

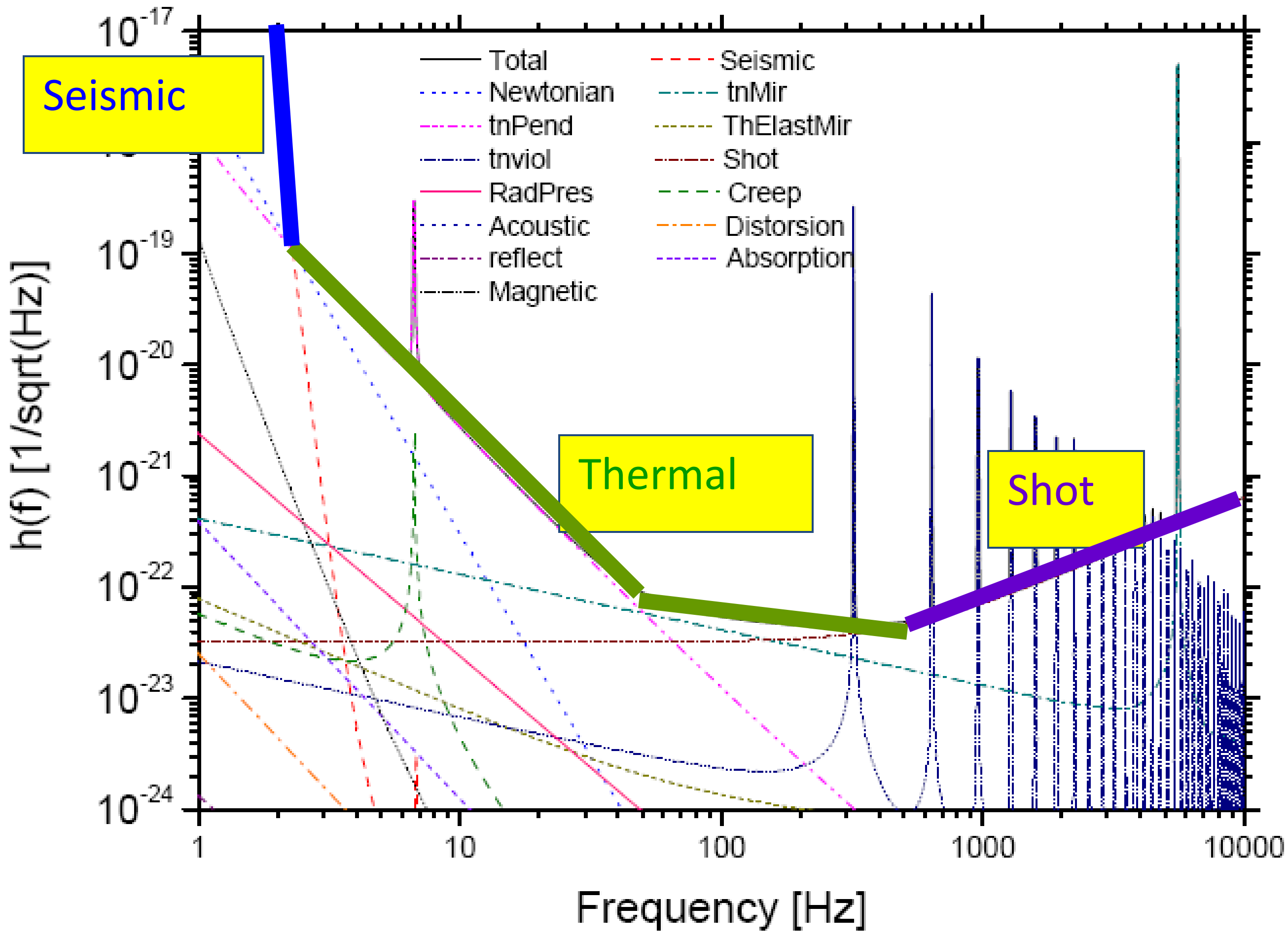


$$h = \frac{DL}{L} \sim 10^{-22}$$

$$i_{pd}(t) = \frac{DL}{L}(t)$$



A typical sensitivity curve



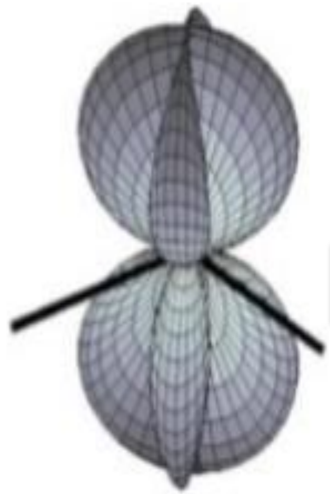
Location in the sky

- GW laser interferometers are not pointing telescopes,

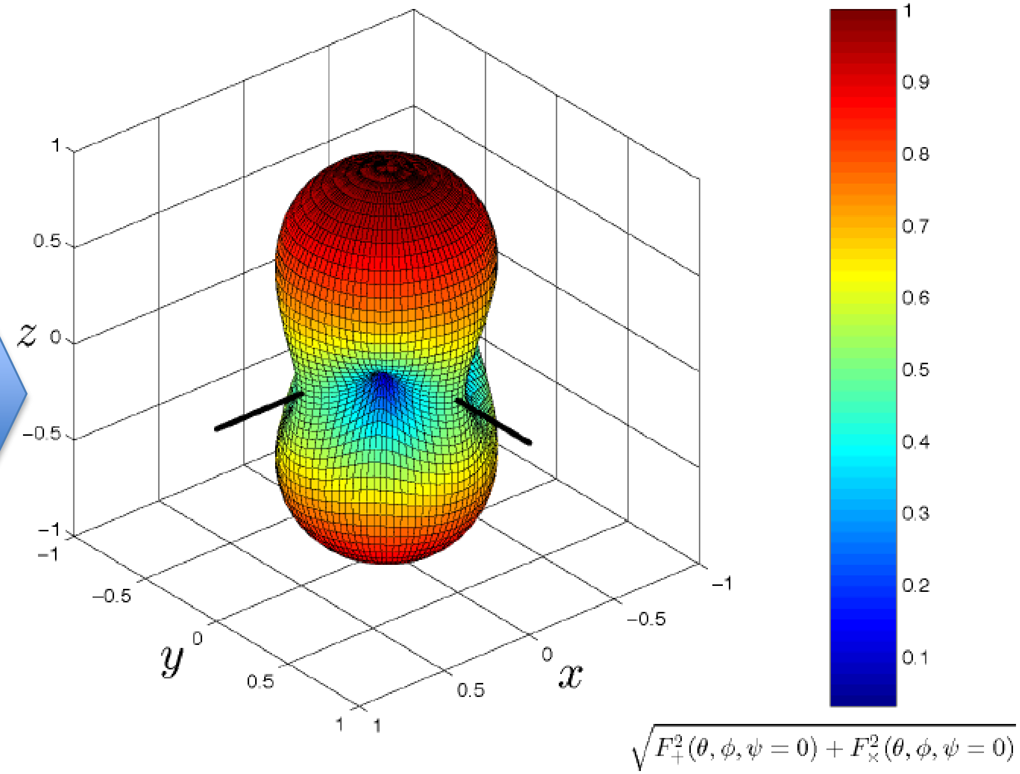
- Sky location can be reconstructed through the time of arrival of GW radiation at the different detector sites, as well as the relative amplitude and phase of the GWs in different detectors.

Antenna pattern

F_+



F_x



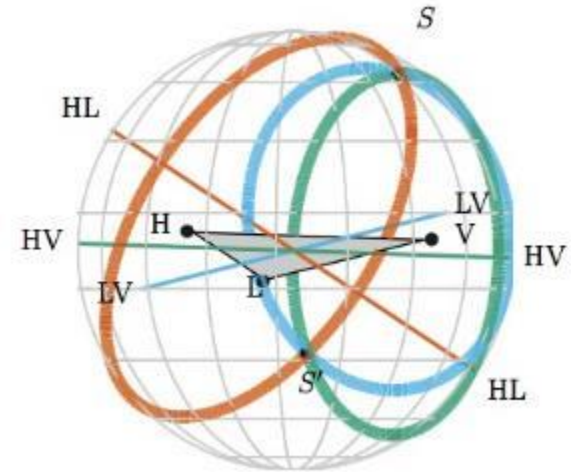
$$S = F_+(\alpha, \delta, \psi)\, h_+ + F_-(\alpha, \delta, \psi)\, h_-$$

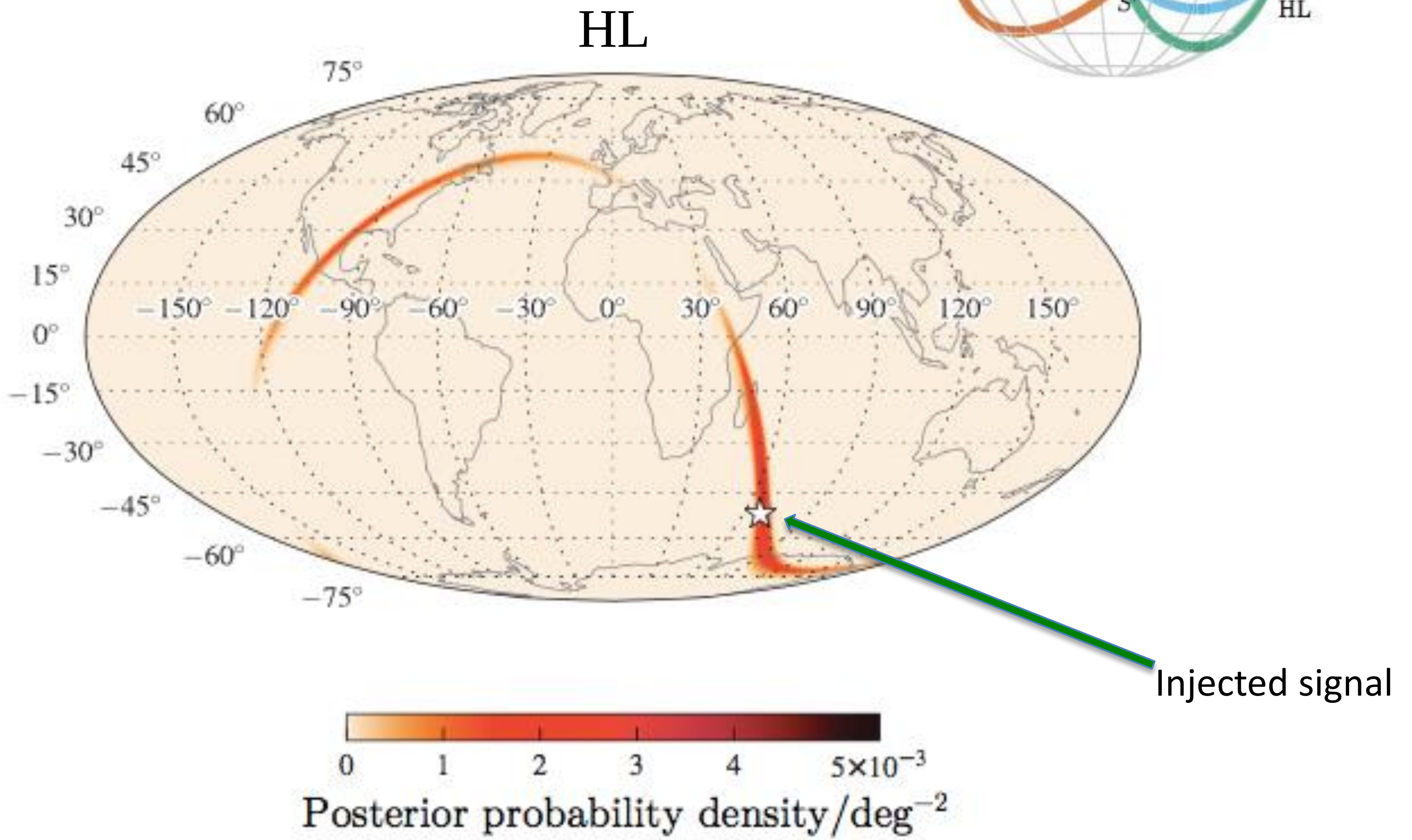
Sky position and polarization angle

- The radiation emitted in a CBC along the orbital axis ➔ circularly polarized
- The radiation emitted in a CBC on the equatorial plane ➔ linearly polarized

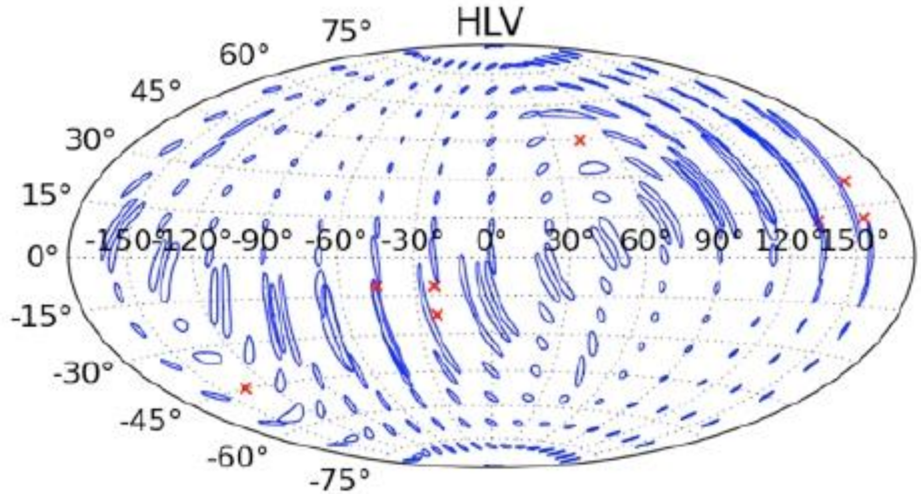
- Observing with more than one detector we can infer both the location in the sky and the degree of elliptical polarization

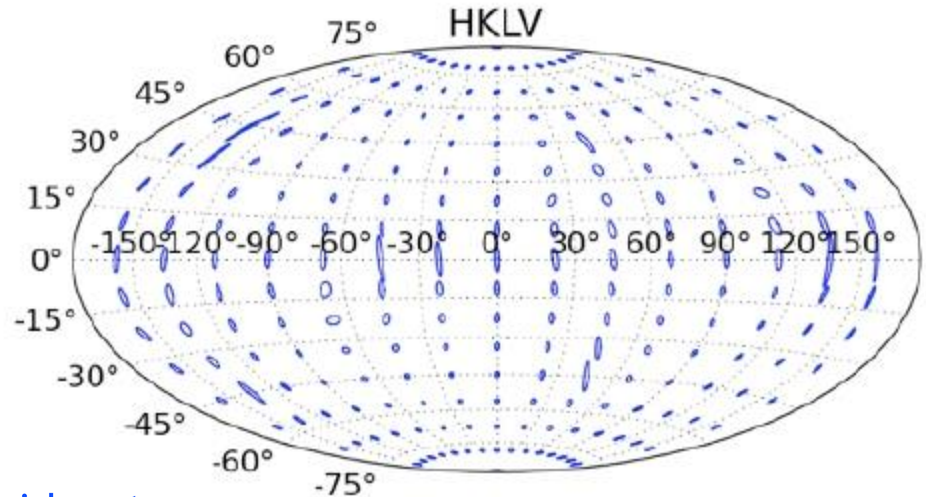
Transient Source Localization: 2 detectors



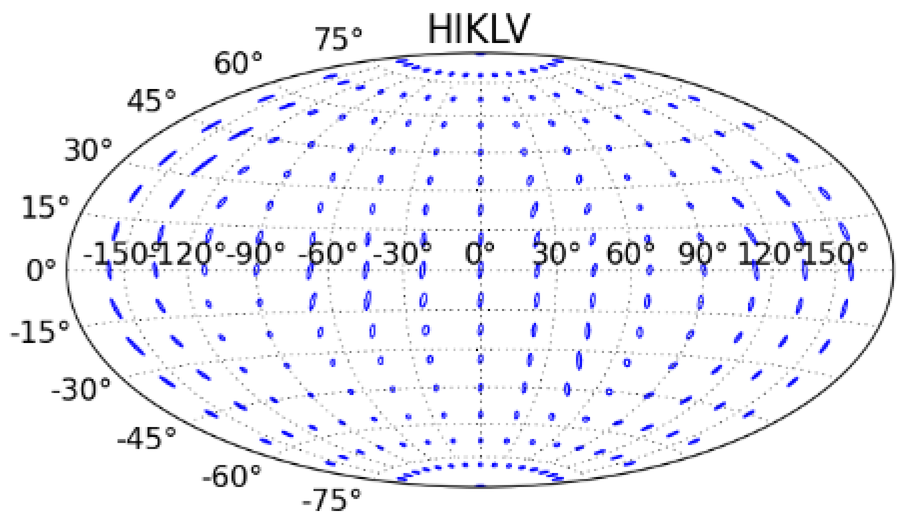


Transient Source Localization:
3 , 4 , 5 detectors





Credit: S. Fairhurst



The 2007 GW network

H1- Hanford – Washington state

Virgo – Cascina (Pisa) – EGO site

GEO600 – Hannover - Germany

L1- Livingston – Louisiana state

A bit of history

- *The **LIGO** project was approved in **1992** and inaugurated in **1999**. Built at a cost of almost $3x10^8$ \$, LIGO was the largest single enterprise ever undertaken by the foundation. It started the operation in 2002.*
- **VIRGO** was formally proposed in 1989 and approved in 1993. The construction was divided in two step: it started in 1996 and then completed in 2003. The first science run is date 2007. The total investment done by CNRS and INFN was almost 8×10^7 \$.
- ***GEO600** was proposed in 1994. Since September 1995 this British-German GW detector was under construction. The first science run was performed in 2002. In 2013 Squeezing light was used over one complete year!*
- First attempt to exchange data and mix the data analysis groups started in 2004. The formal **MoU of data sharing and common analysis** among **GEO-LIGO-VIRGO** was signed in **2007**.

GW Science From First Generation

The Astrophysical Journal, 715:1438–1452, 2010 June 1 doi:10.1088/0004-637X/715/2/1438

SEARCH FOR GRAVITATIONAL-WAVE BURSTS ASSOCIATED WITH GAMMA-RAY BURSTS USING DATA FROM LIGO SCIENCE RUN 5 AND VIRGO SCIENCE RUN 1

PHYSICAL REVIEW D **82**, 102001 (2010)

Search for gravitational waves from compact binary coalescence in LIGO and Virgo data from S5 and VSR1

PHYSICAL REVIEW D **81**, 102001 (2010)

All-sky search for gravitational-wave bursts in the first joint LIGO-GEO-Virgo run

The Astrophysical Journal, 715:1453–1461, 2010 June 1 doi:10.1088/0004-637X/715/2/1453

SEARCH FOR GRAVITATIONAL-WAVE INSPIRAL SIGNALS ASSOCIATED WITH SHORT GAMMA-RAY BURSTS DURING LIGO'S FIFTH AND VIRGO'S FIRST SCIENCE RUN

nature

LETTERS

Beating the spin-down limit on gravitational wave emission from the Vela pulsar

arXiv:1104.2712v2 [astro-ph.HE] 15 Apr 2011

An upper limit on the stochastic gravitational-wave background of cosmological origin

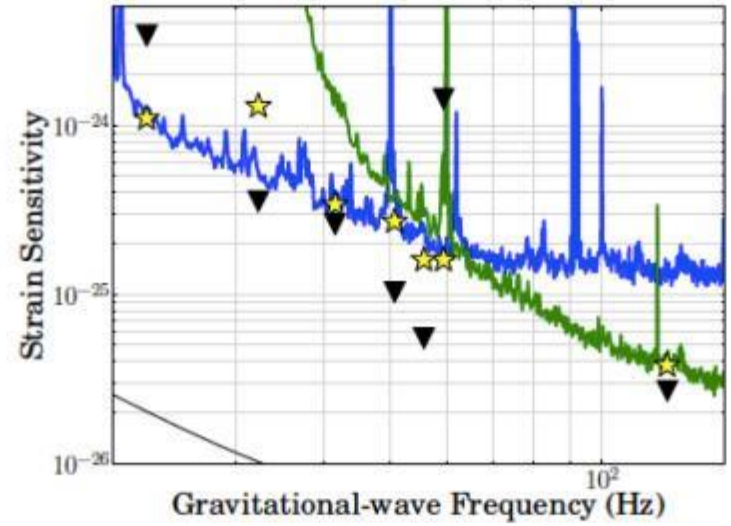
The LIGO Scientific Collaboration* & The Virgo Collaboration*

CW and stochastic signal searches

- **For Crab and Vela pulsars we are below the "spin-down limit"**: constrain the fraction of spin-down energy due to GW J0534+2200

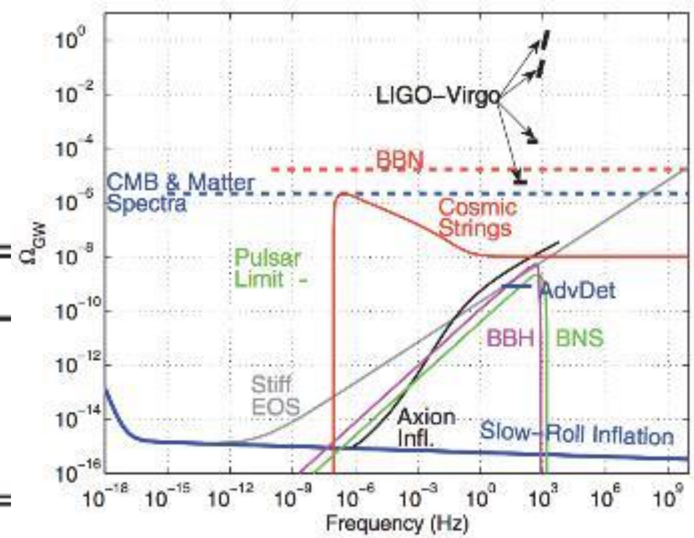
  [Aasi et al. ApJ 2014]

Pulsar	$h_{95\%}$	ε
J0534+2200	$1.8(1.6)\times10^{-25}$	$9.7(8.6)\times10^{-5}$
J0835-4510	$1.1(1.0)\times10^{-24}$	$6.0(5.5)\times10^{-4}$



- Upper Limits on the Stochastic Gravitational-Wave Background [PRL 113, 231101 (2014)]

Frequency (Hz)	f_{ref} (Hz)	α	Ω_α
41.5–169.25	...	0	$(-1.8 \pm 4.3) \times 10^{-6}$
170–600	...	0	$(9.6 \pm 4.3) \times 10^{-5}$
600–1000	900	3	0.026 ± 0.052
1000–1726	1300	3	-0.077 ± 0.53

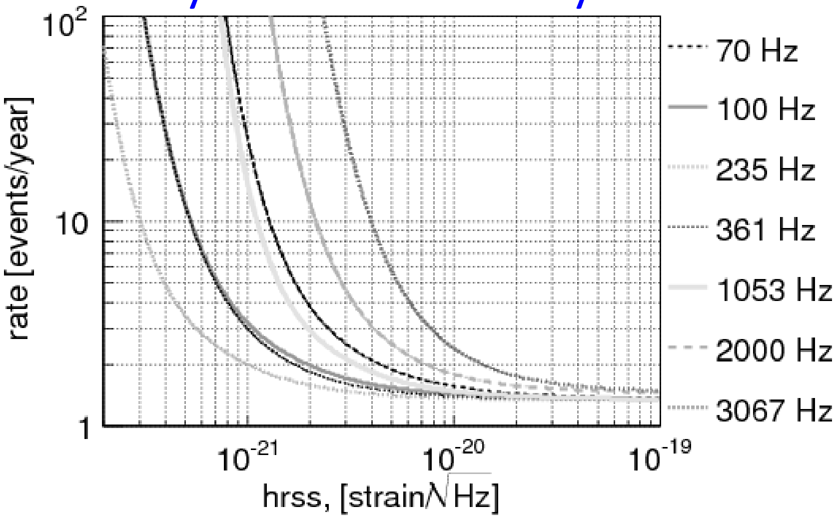


All-Sky Burst Search

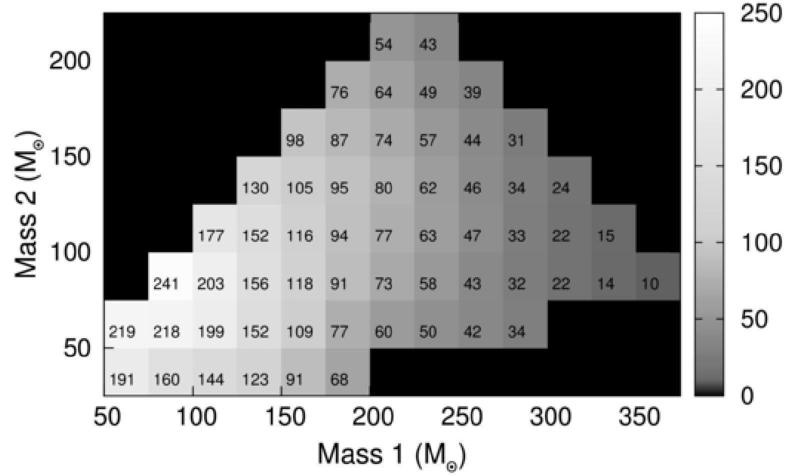
Phys. Rev. D 85, 122007 (2012)

➢ All-sky, all-times search for signals which do not assume specific morphology (GW ‘bursts’) is least constrained transient search – open to many source models and unexpected signals

All-sky search Sensitivity



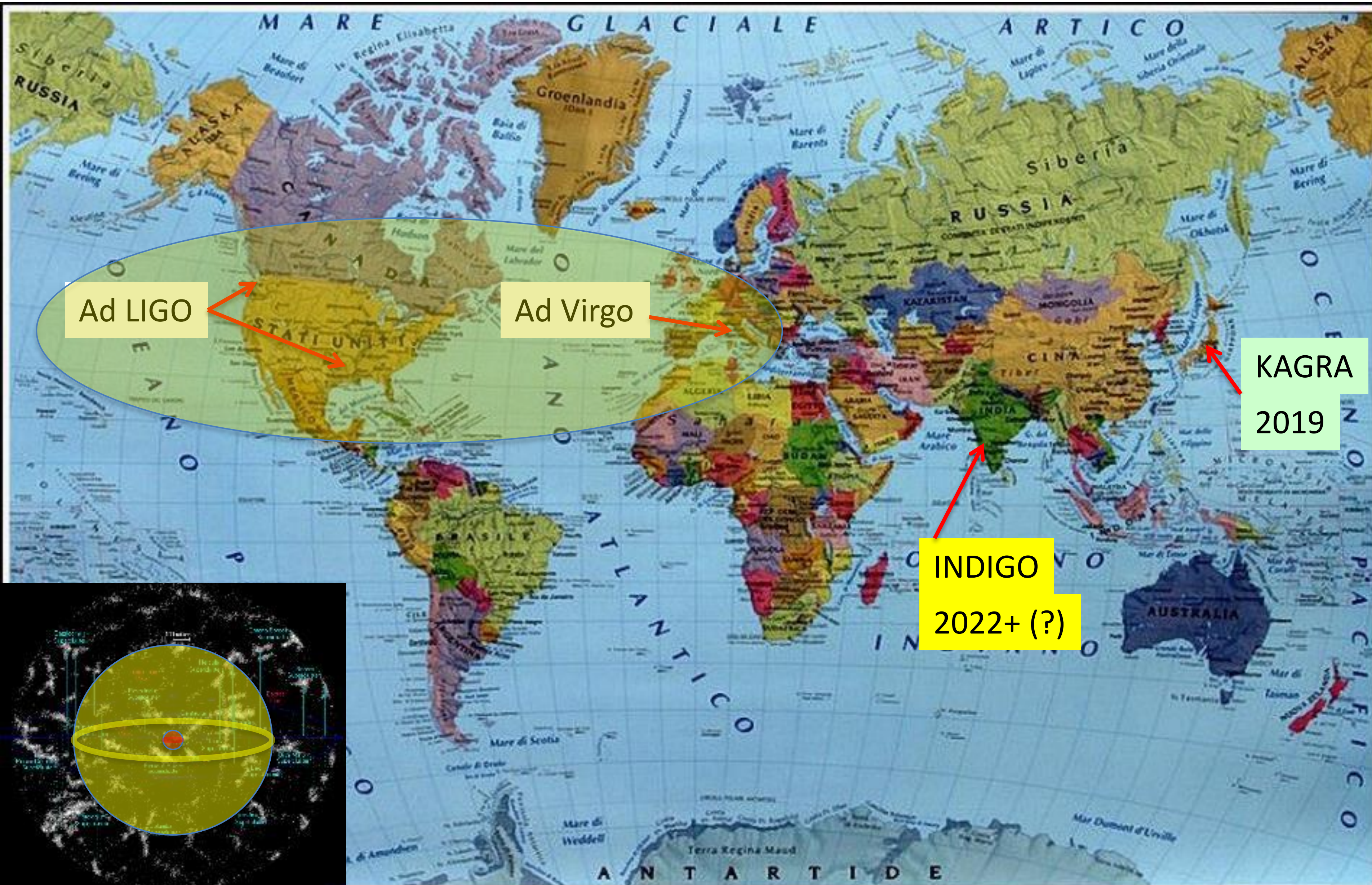
IMBH Sensitivity Range in Mpc



➢ Intermediate Mass Black Hole search uses same algorithm to target black hole binaries at larger masses than CBC searches

Phys. Rev. D 85, 102004 (2012) 23

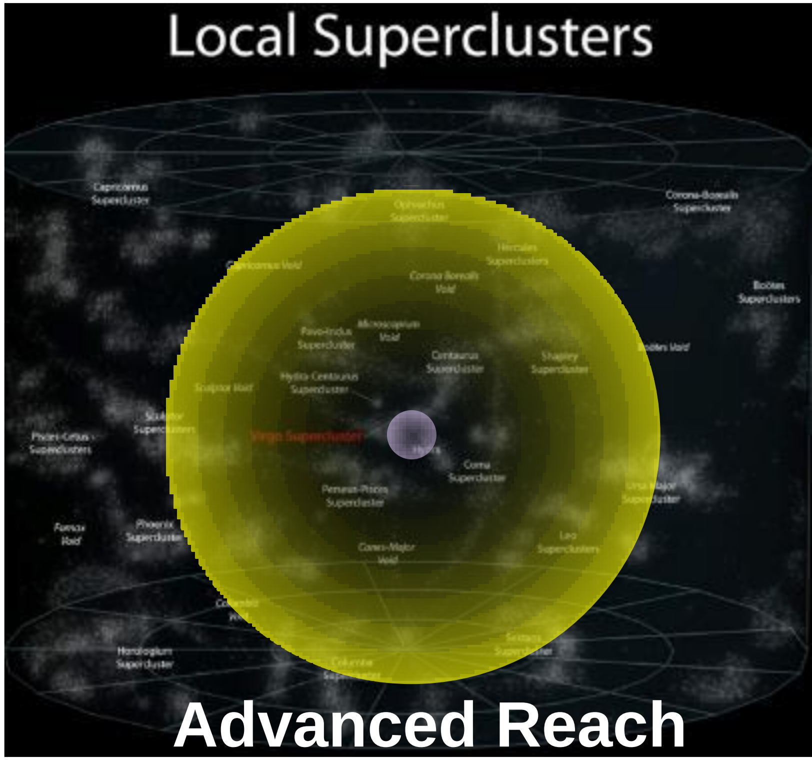
The GW network of the Advanced detectors



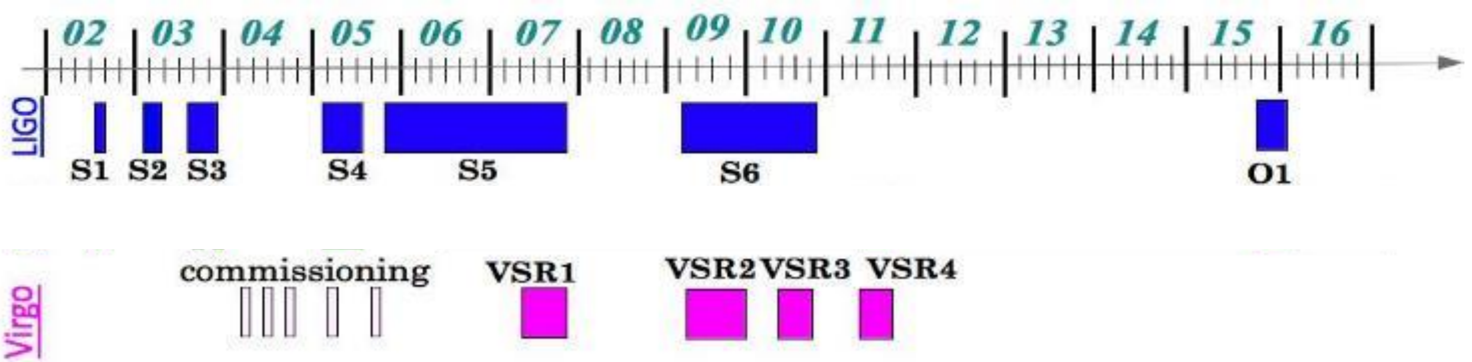
Advanced detectors

- Upgrade of the LIGO
- LIGO cost: $205M (NSF) and $16M in hardware from partners in Germany, UK, and Australia
- aLIGO approved in 2008, inauguration May 2015
- First observing run O1 from mid-September 2015 to mid-January 2016.

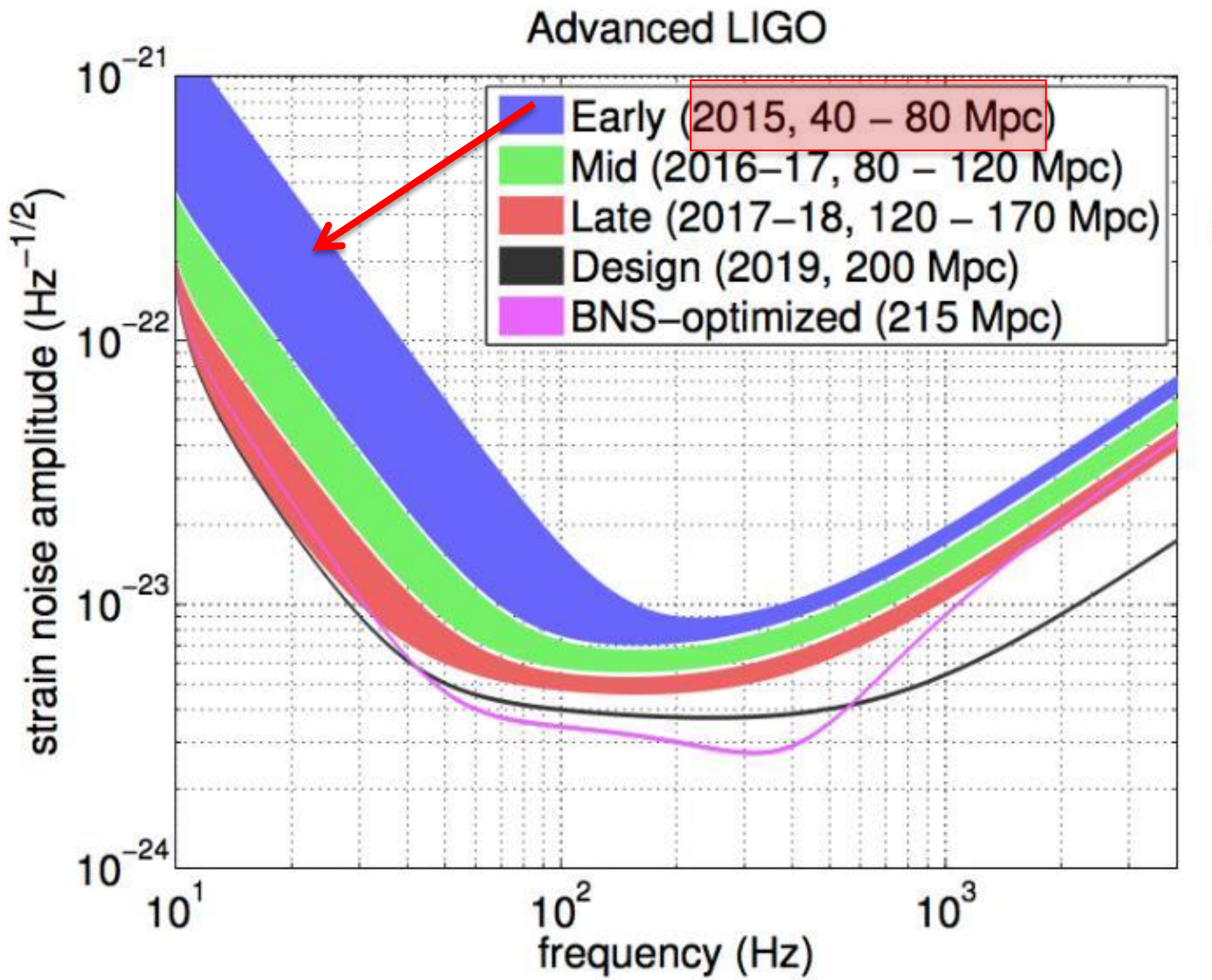
- Upgrade of Virgo
- aVirgo cost: 23 M from CNRS,INFN and NIKHEF
- aVirgo approved in 2011 and project started in 2012
- Installation to be completed in the first half of 2016



Ultimately 10x more sensitive
→1000x more volume probed

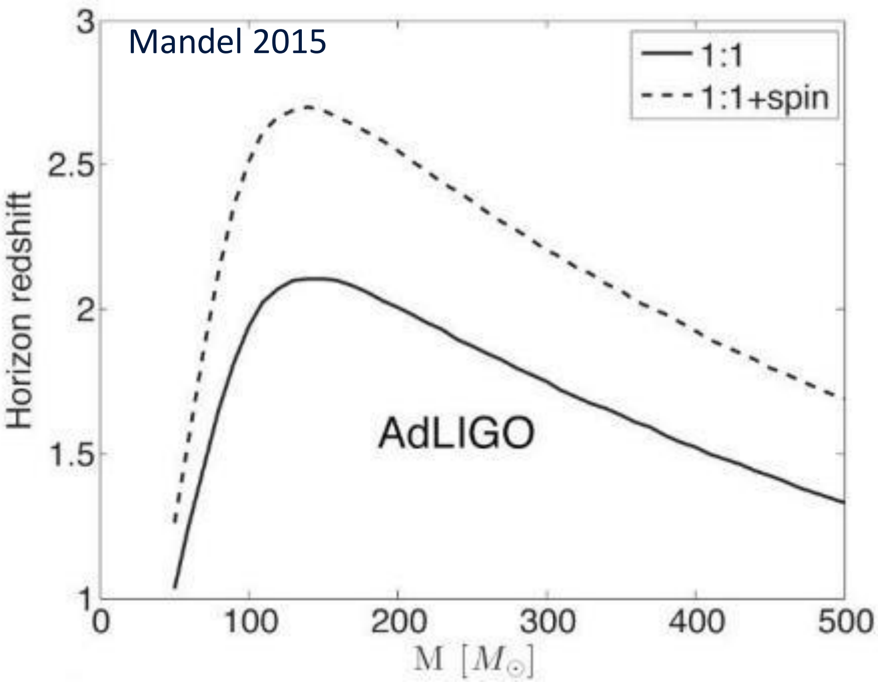


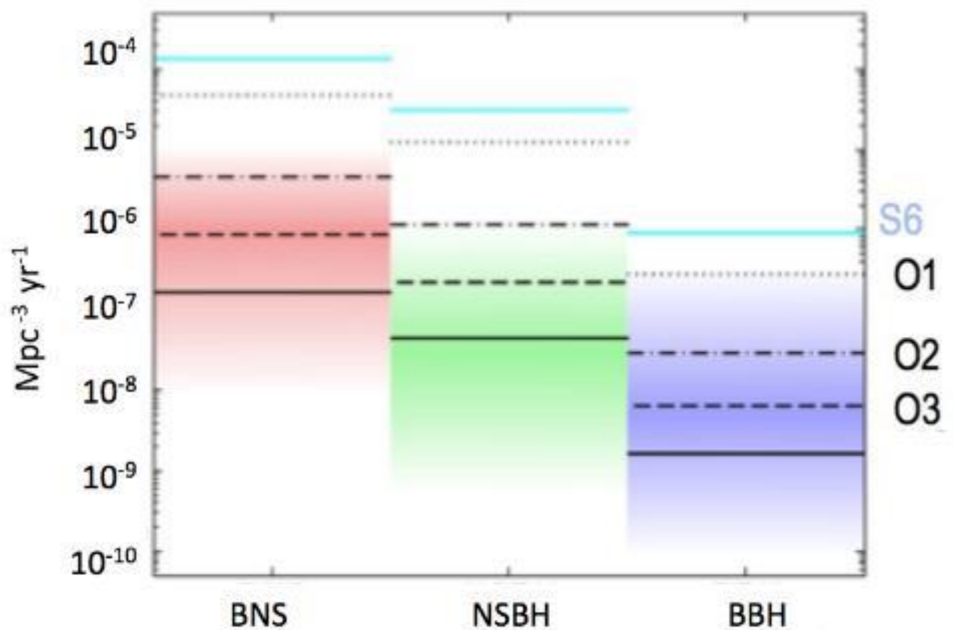
First sensitivity target achieved already !



Compact Coalescing Binaries

Detection perspectives with advanced detectors Phys. Rev D85 (2012) 082002





Epoch		2015	2016–2017	2017–2018	2019+	2022+ (India)
Estimated run duration		3 months	6 months	9 months	(per year)	(per year)
BNS range/Mpc	LIGO	40–80	80–120	120–170	200	200
	Virgo	–	20–60	60–85	65–130	130
BNS detections		0.0004–3	0.006–20	0.04–100	0.2–200	0.4–400

Probe beyond local universe
100 $M_\odot$ + 100 $M_\odot$ BBH visible out to ~16 Gpc at design sensitivity (~5 Gpc in O1), even further if the source is spinning

LIGO upgrade concluded

The Advanced LIGO dedication ceremony was held at Hanford on May 19, 2015

H1- Hanford – Washington state

VIRGO will end the upgrade in 2016

L1- Livingston – Louisiana state

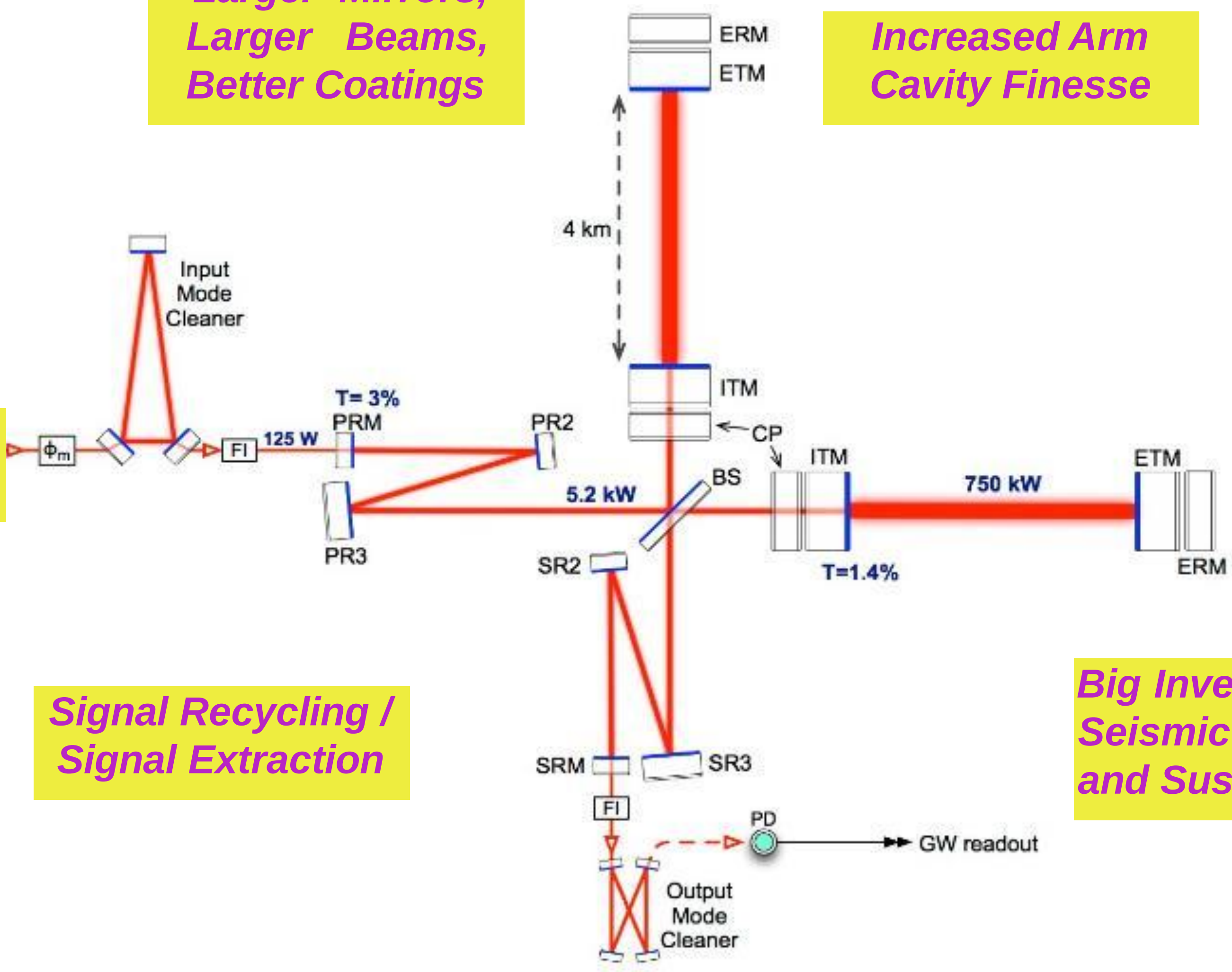
Hardware highlights

From the first generation to the second one

Larger Mirrors, Larger Beams, Better Coatings

Increased Arm Cavity Finesse

Increased Laser Power

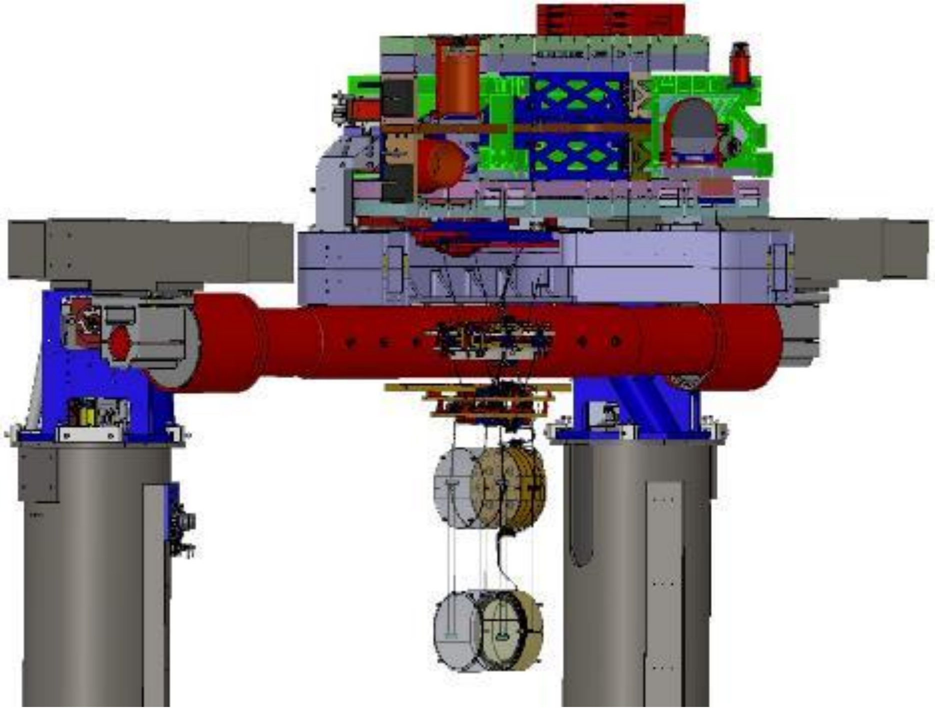


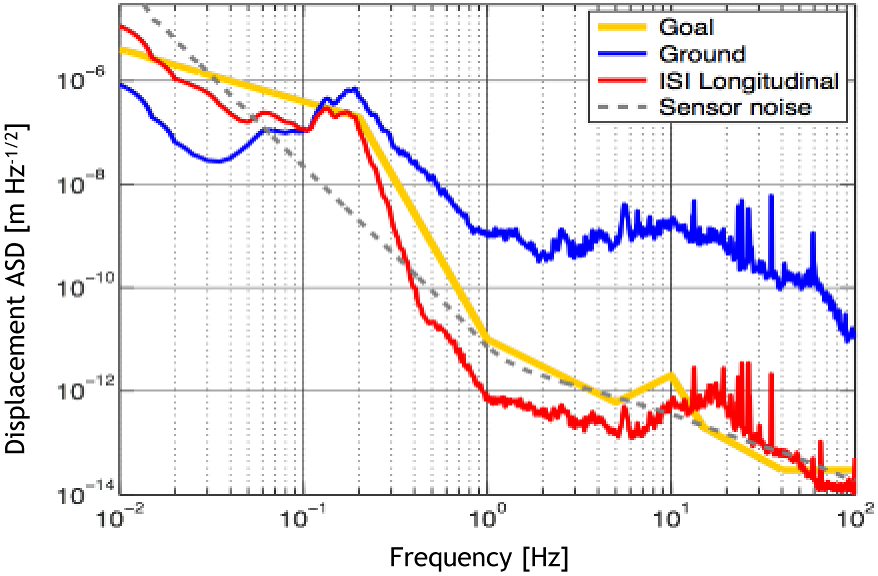
Signal Recycling / Signal Extraction

Big Investment in Seismic Isolation and Suspensions

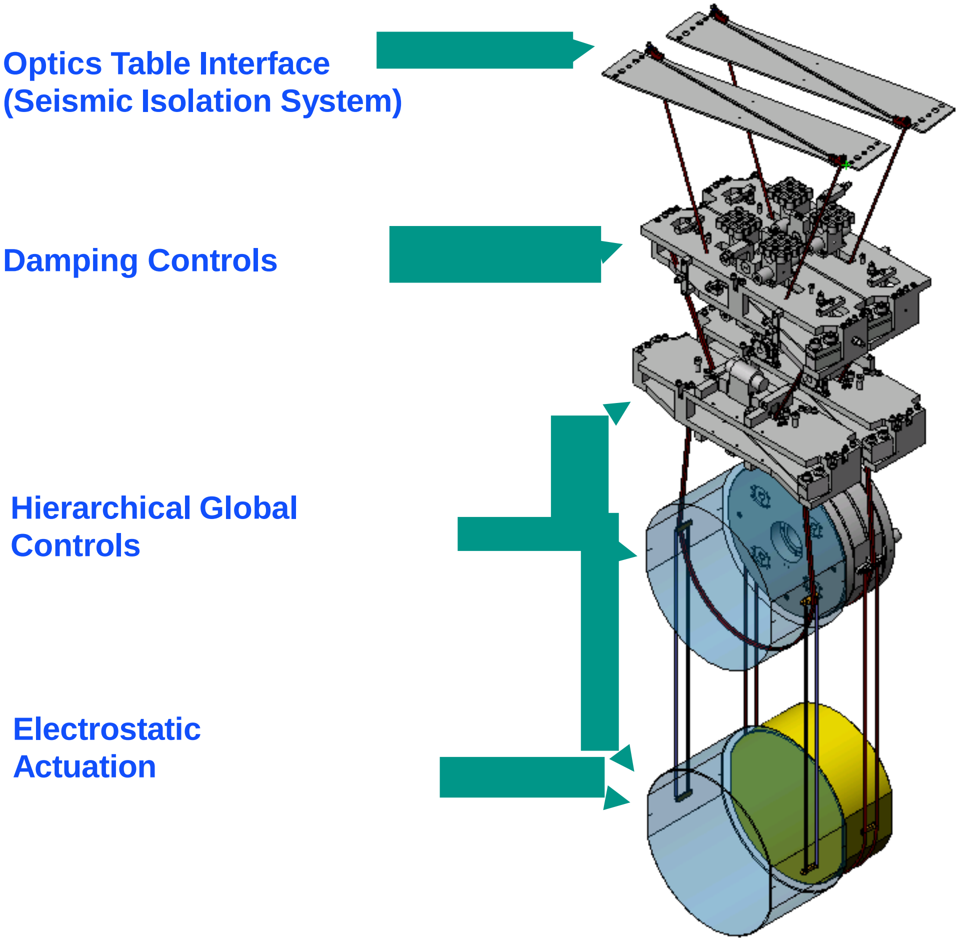
Active Seismic Isolation for in-vacuum Optical Tables

Credits to D. Hoak





Four-stage monolithic suspensions larger mirrors



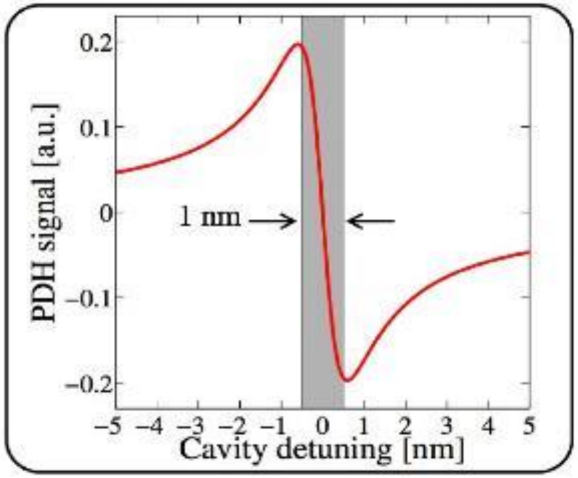
Credits to D. Hoak

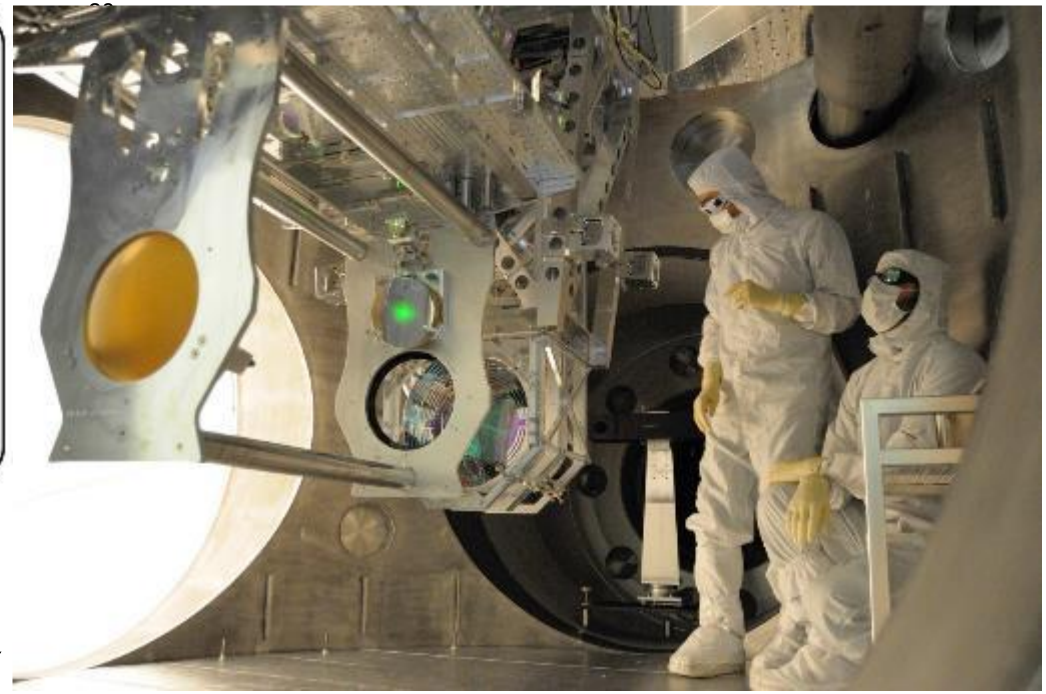
10x more laser power —> Reduced shot noise

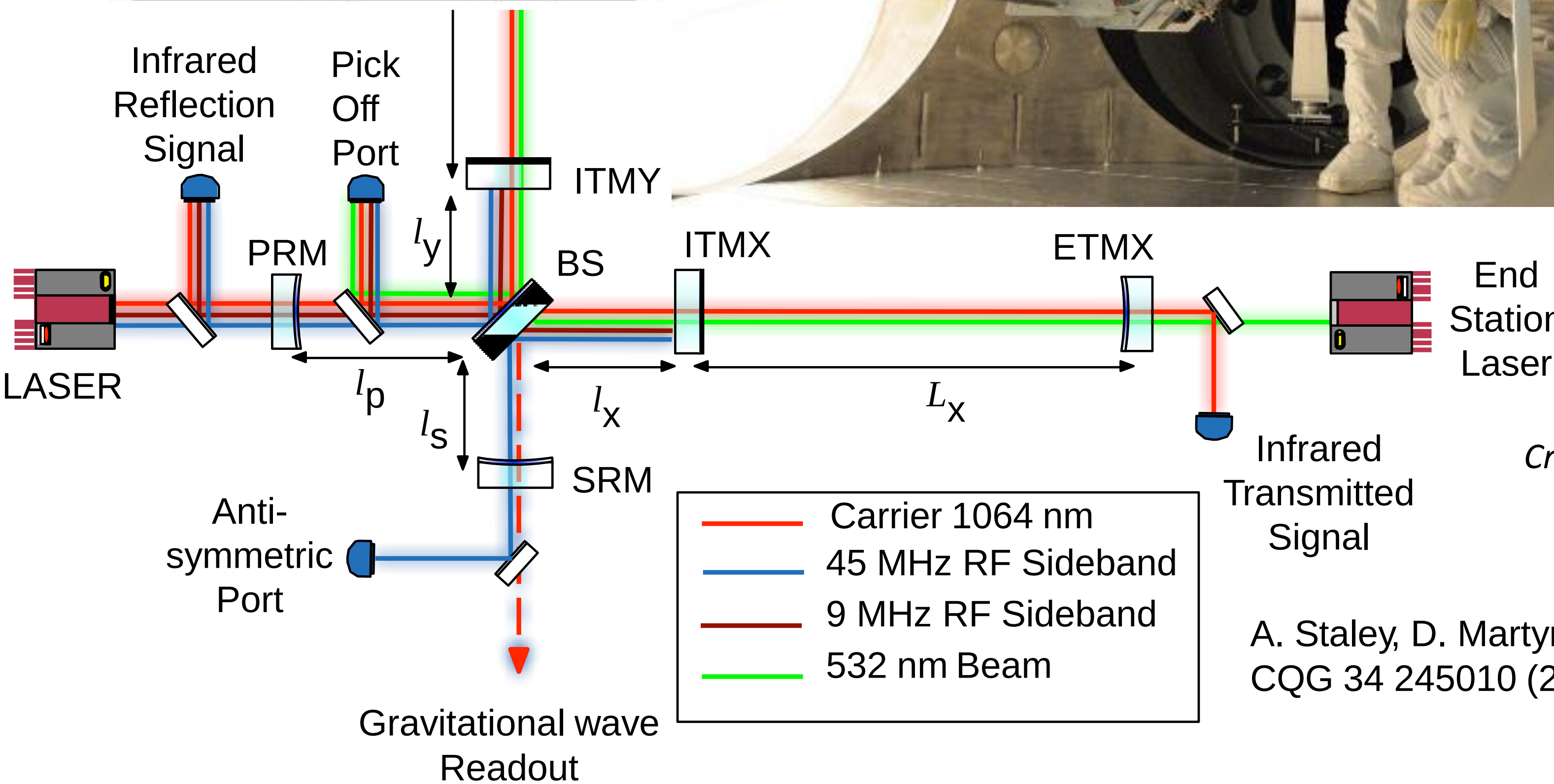
Larger test masses —> Larger beam size —> Coating thermal noise coupling is reduced
—> Less sensitive to radiation pressure noise from increased power

Arm Length Stabilization

LIGO-G1300524





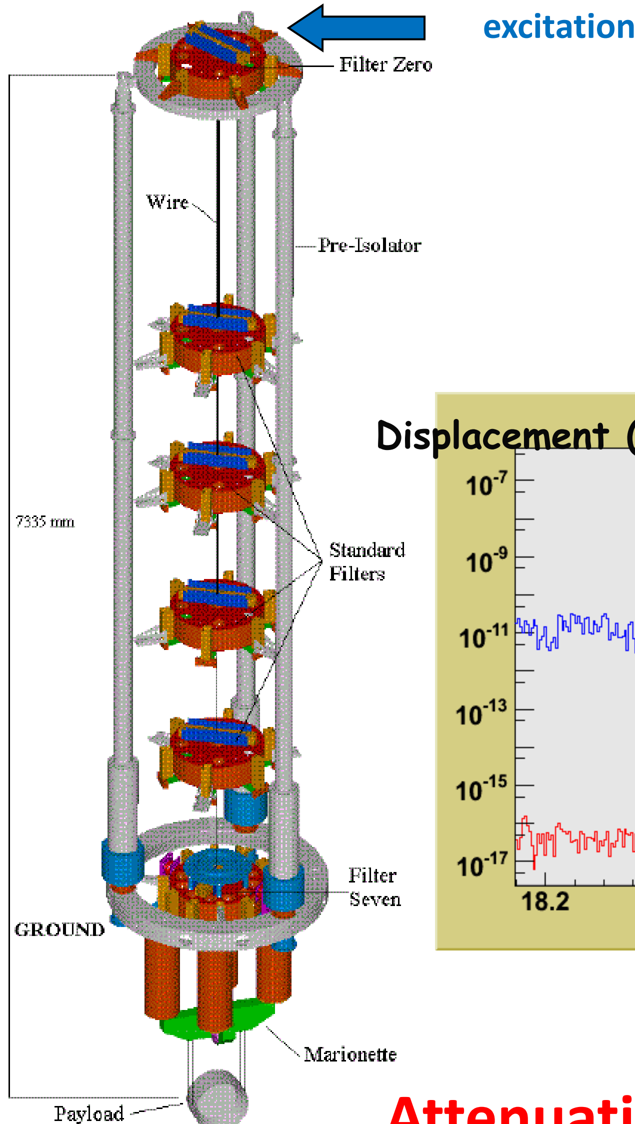


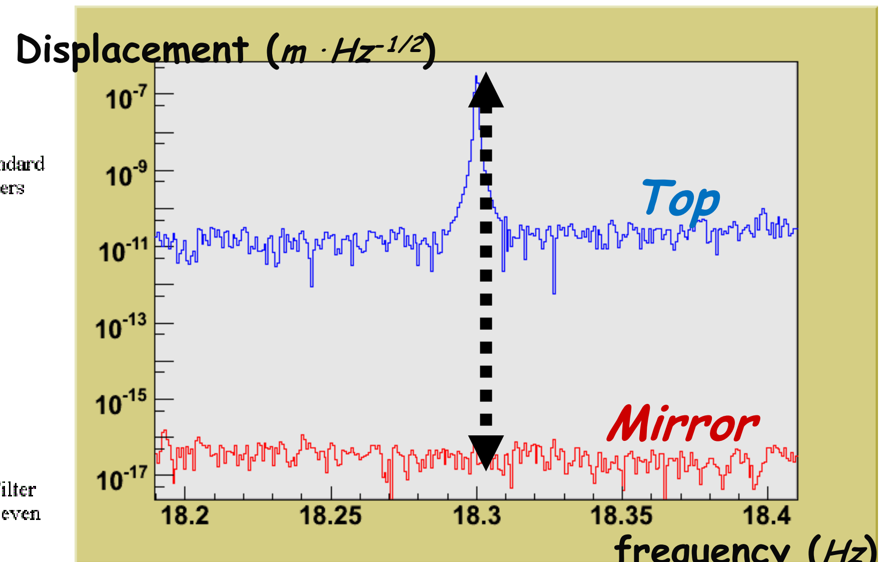
Credits to D. Hoak

A. Staley, D. Martynov et al., CQG 34 245010 (2015)

Virgo pioneered the low frequency strategy

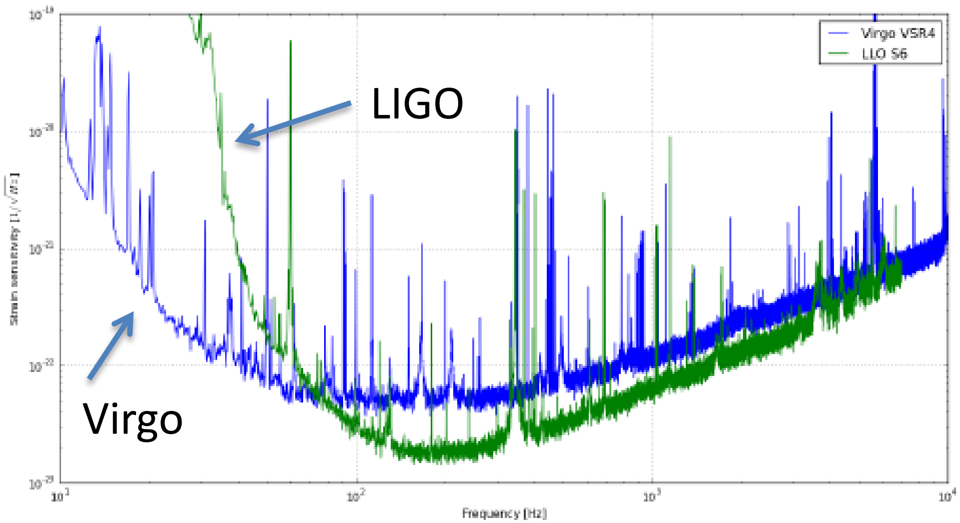
Super Attenuator Chain

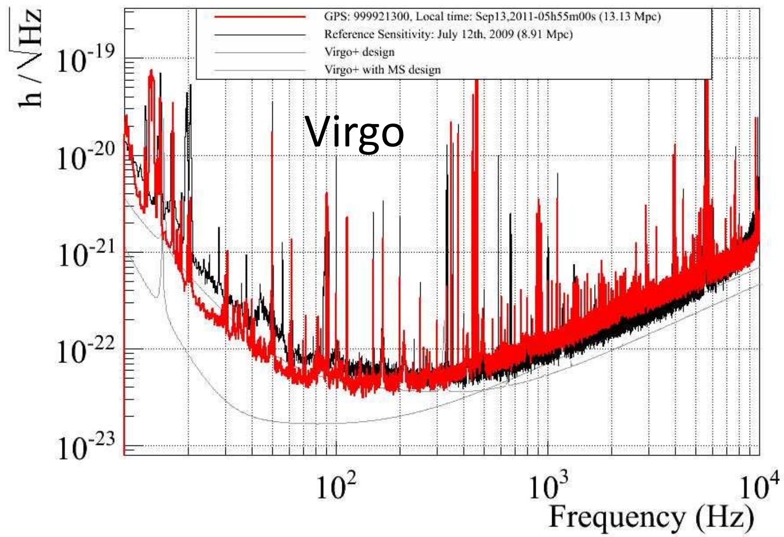




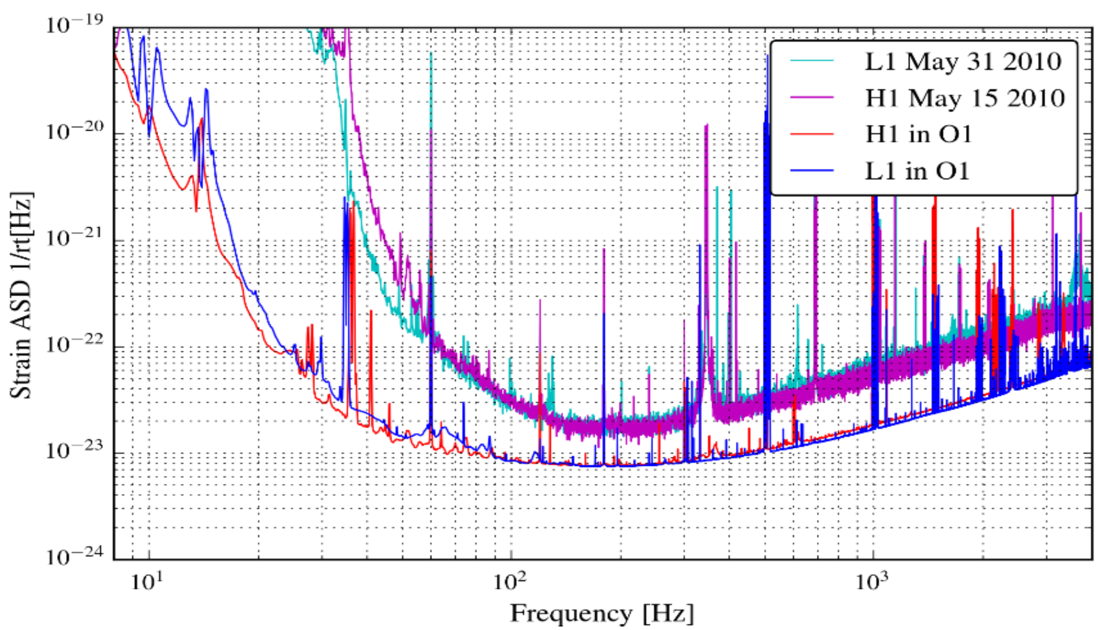
Attenuation factor > 10^{10}

LIGO and Virgo in the past



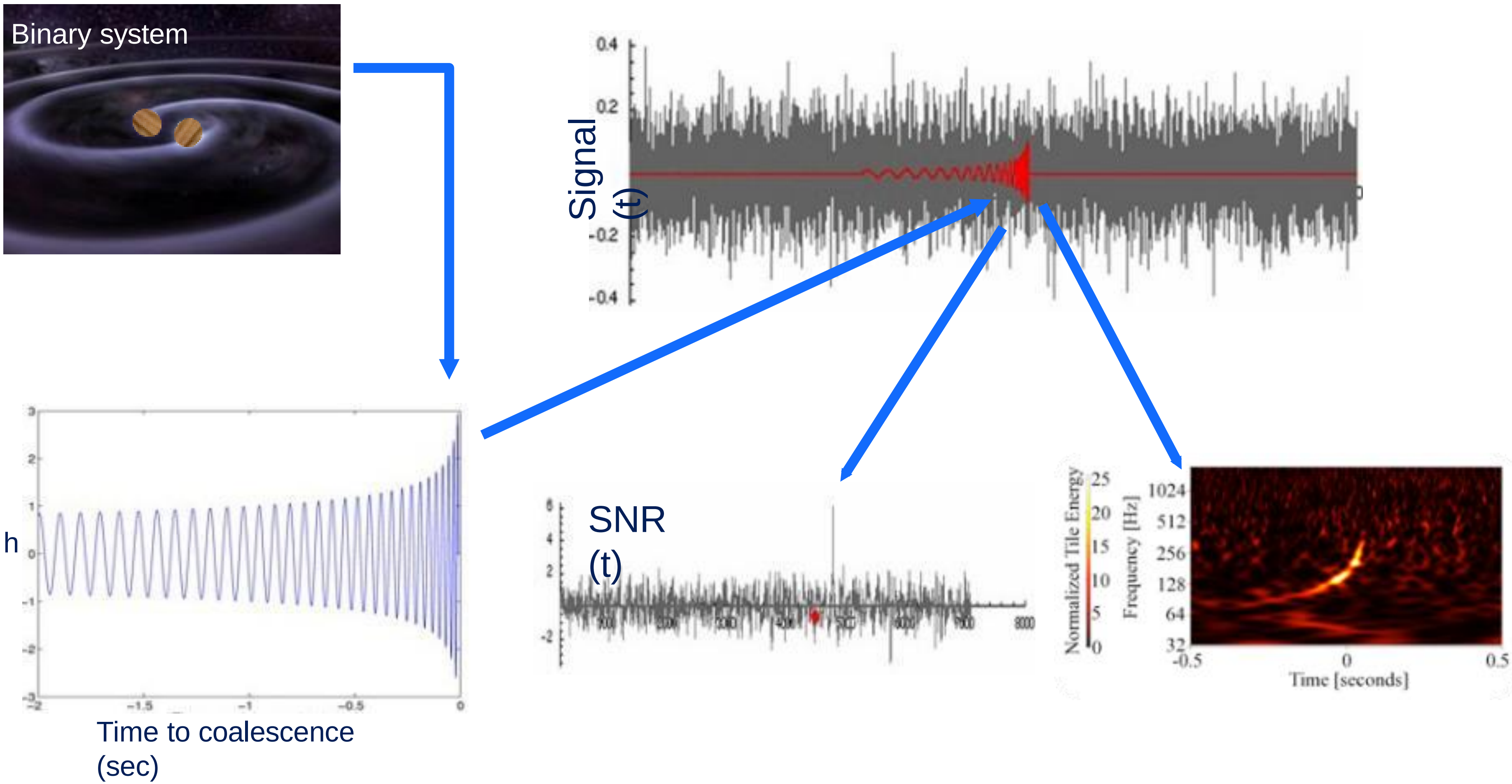


From LIGO to aLIGO: Sensitivity improvements



Data Analysis:
Extracting the signal from the noise

How the signal might look like



Coherent Wave Burst (cWB) algorithm: minimal assumption for searching transients

- Require coherent signals in multiple detectors, using direction-dependent antenna response

- Look for excess power in time-frequency space using wavelet decomposition

The event are ranked using a variable quoting
the SNR of the coherent signal in the network

$$E_c = \sum_{i \in C} \sum_{n \neq m} w_n[i] P_{nm}[i] w_m[i]$$

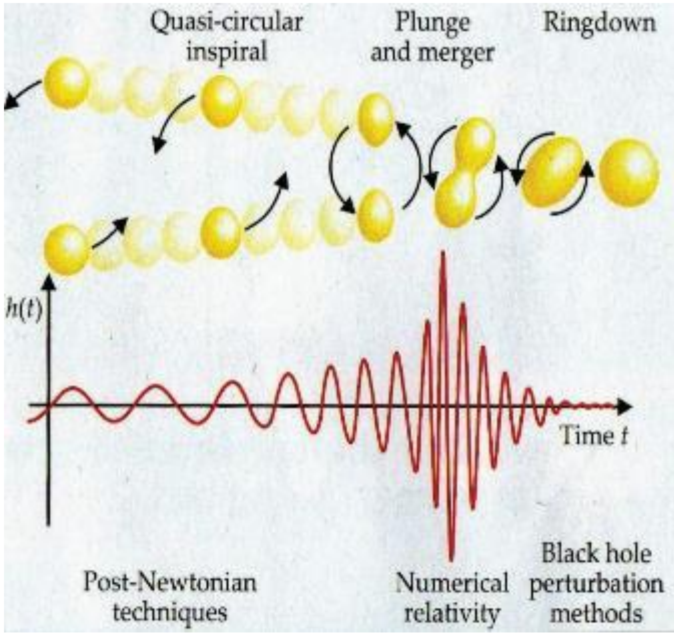
$$\eta_c = \sqrt{\frac{2E_c}{(1 + E_n/E_c)}}$$

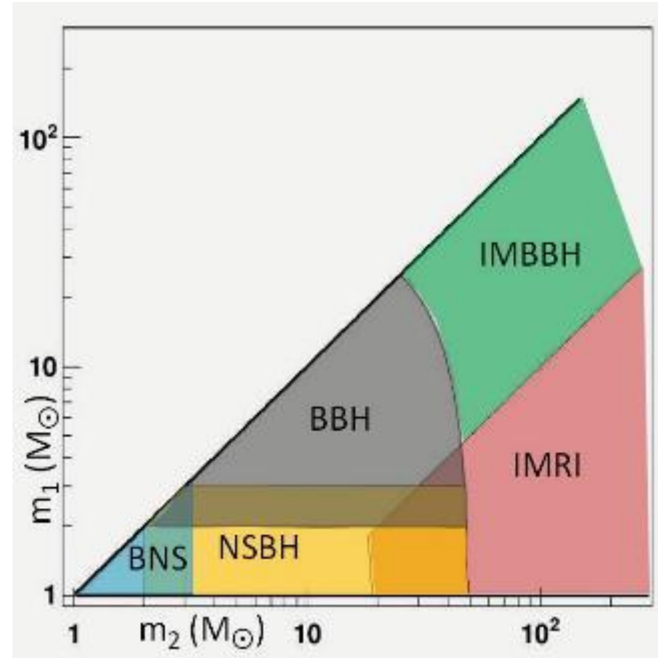
E_c → Normalized coherent energy between the two detectors

E_n → normalized noise energy derived by subtracting the reconstructed signal from the data

Particularly useful also for low-latency transient search → trigger
Multimessenger follow up:
event reported 3 minutes after the data were collected

Matched filter for CBC search

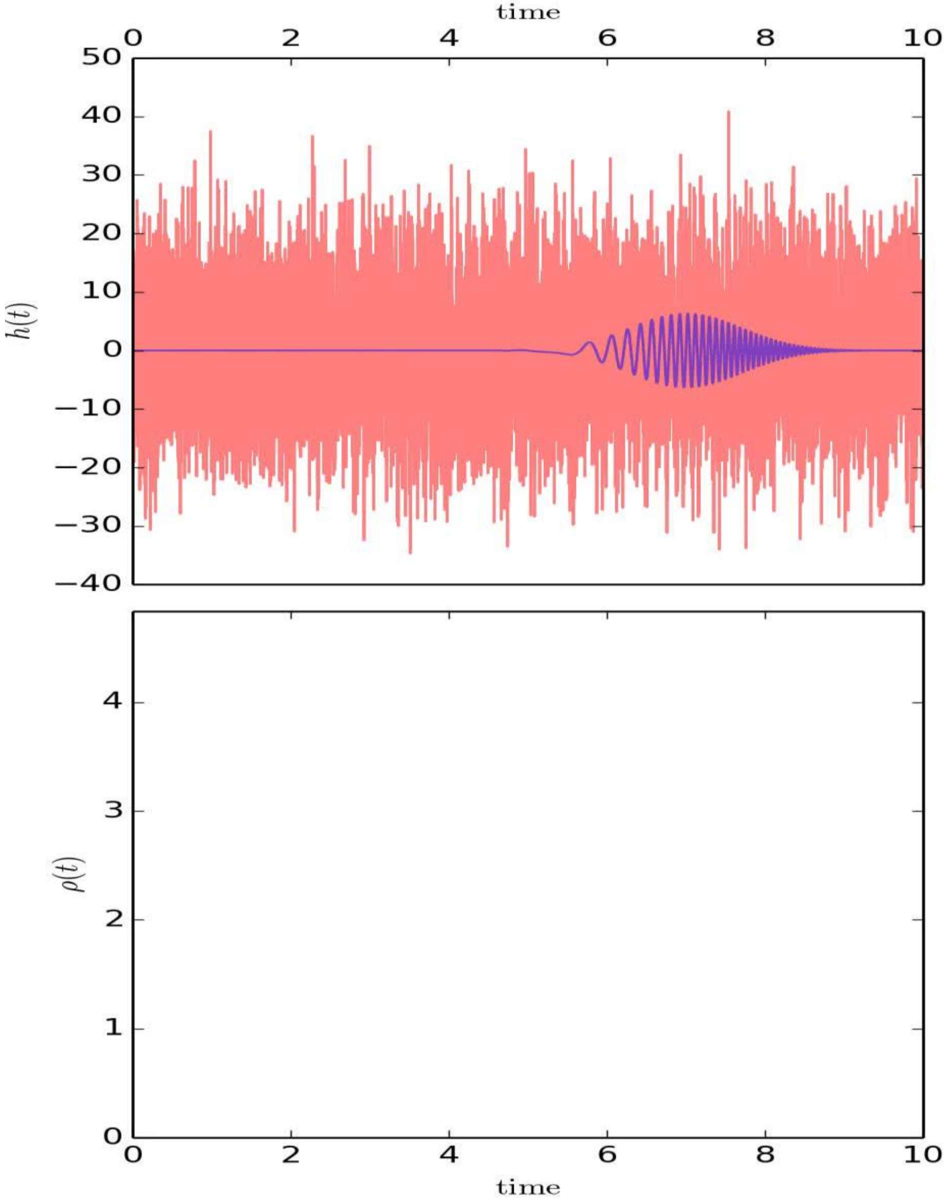




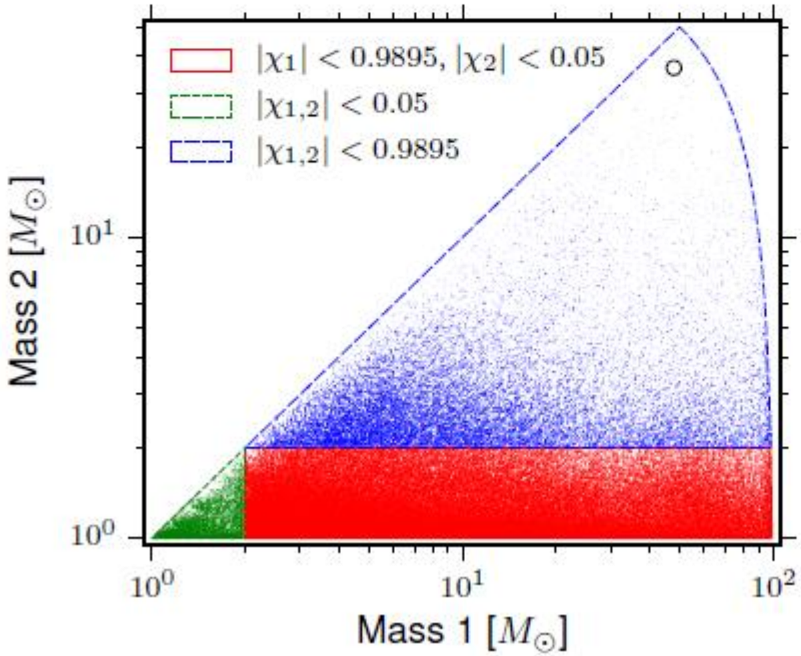
Search use waveform predictions to perform matched filtering

- EOBNR ➔ The effective-one-body (EOB) formalism combines perturbative results from the weak-field PN approximation with strong-field effects from the test-particle limit.

- IMR-Phenomen ➔ It is based on extending frequency-domain PN expressions and hybridizing PN and EOB with NR waveforms.

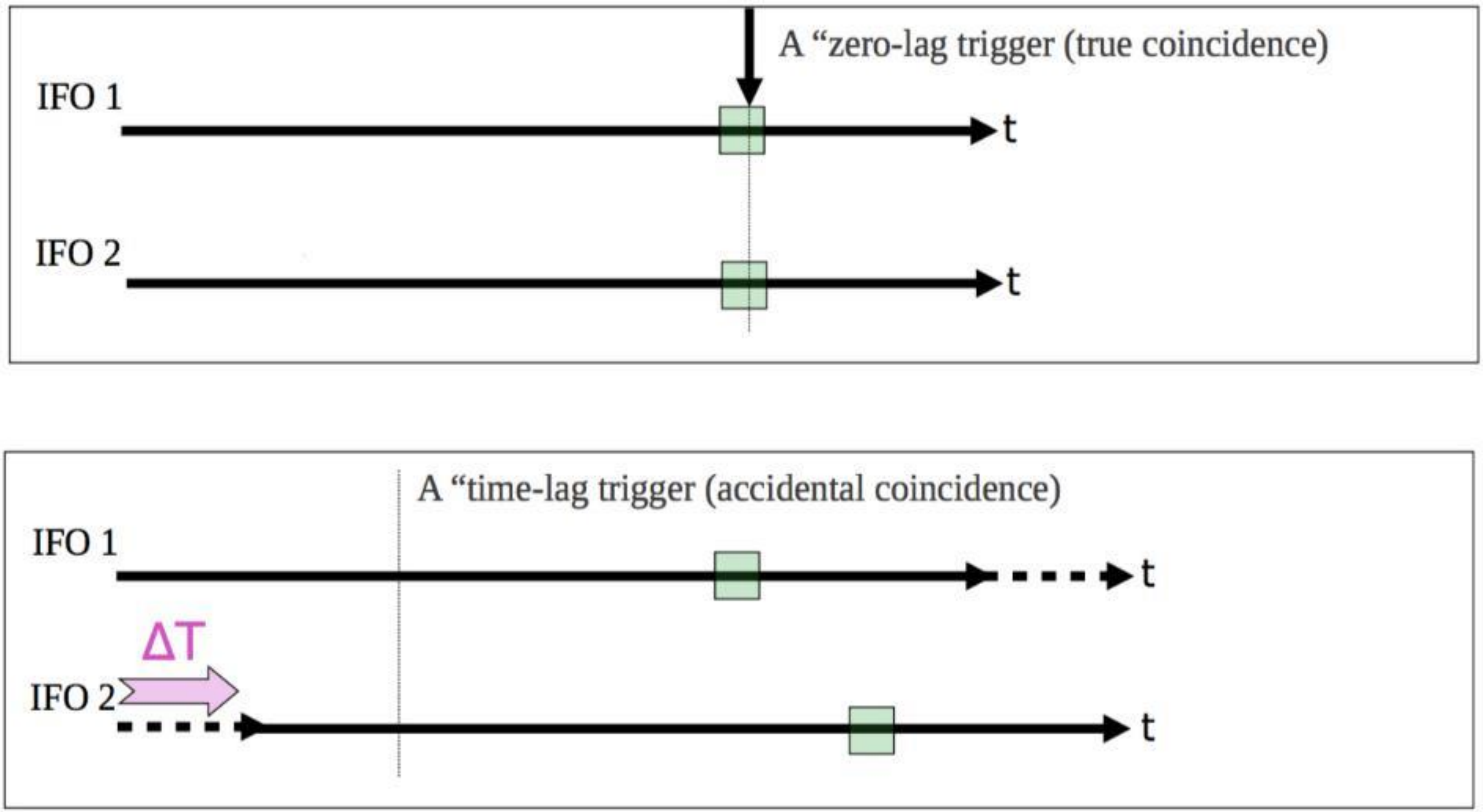


Matched filter search



250.000 Templates to loose less than 3% on SNR

Background estimation



The first run of the advanced detectors

Hanford (H1) and Livingston (L1) in action

The detector was in a rather stable conditions from the beginning of September 2015 and took data until January 2016

Here we present just the analysis of the data taken

in the period from September 12 to October 20, 2015

16 days of coincident data taking !!

16 days of data produced by 2 interferometers:

Monitor of environmental disturbances and interferometer's operating point control

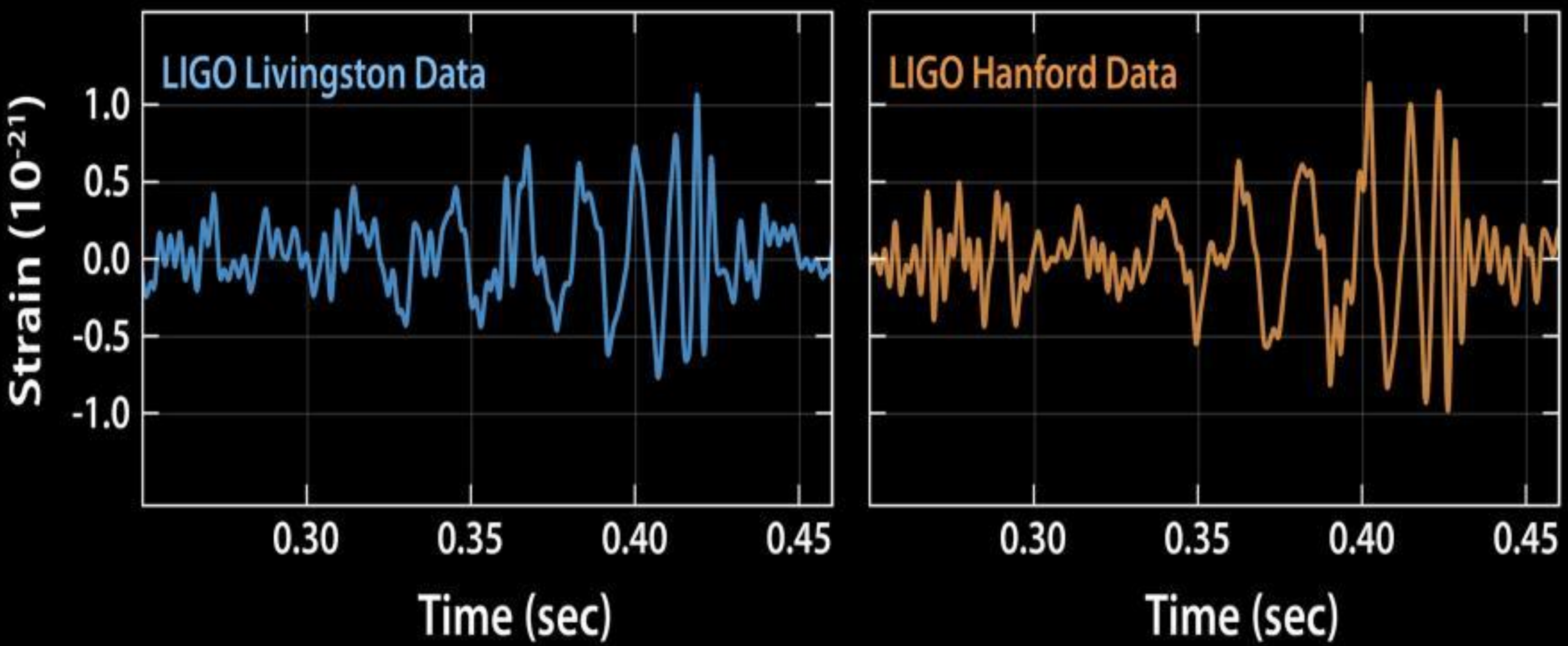
- Each observatory site is equipped with an array of sensors:
  - seismometers, accelerometers, microphones,
  - magnetometers, radio receivers, weather sensors,
  - AC-power line monitors,
  - a cosmic-ray detector
- 10^5 channels record the interferometer's operating point
- Data collection is synchronized to GPS time to better than 10 μs.
  - Timing accuracy verified with an atomic clock and a secondary GPS receiver at each observatory site.

The event

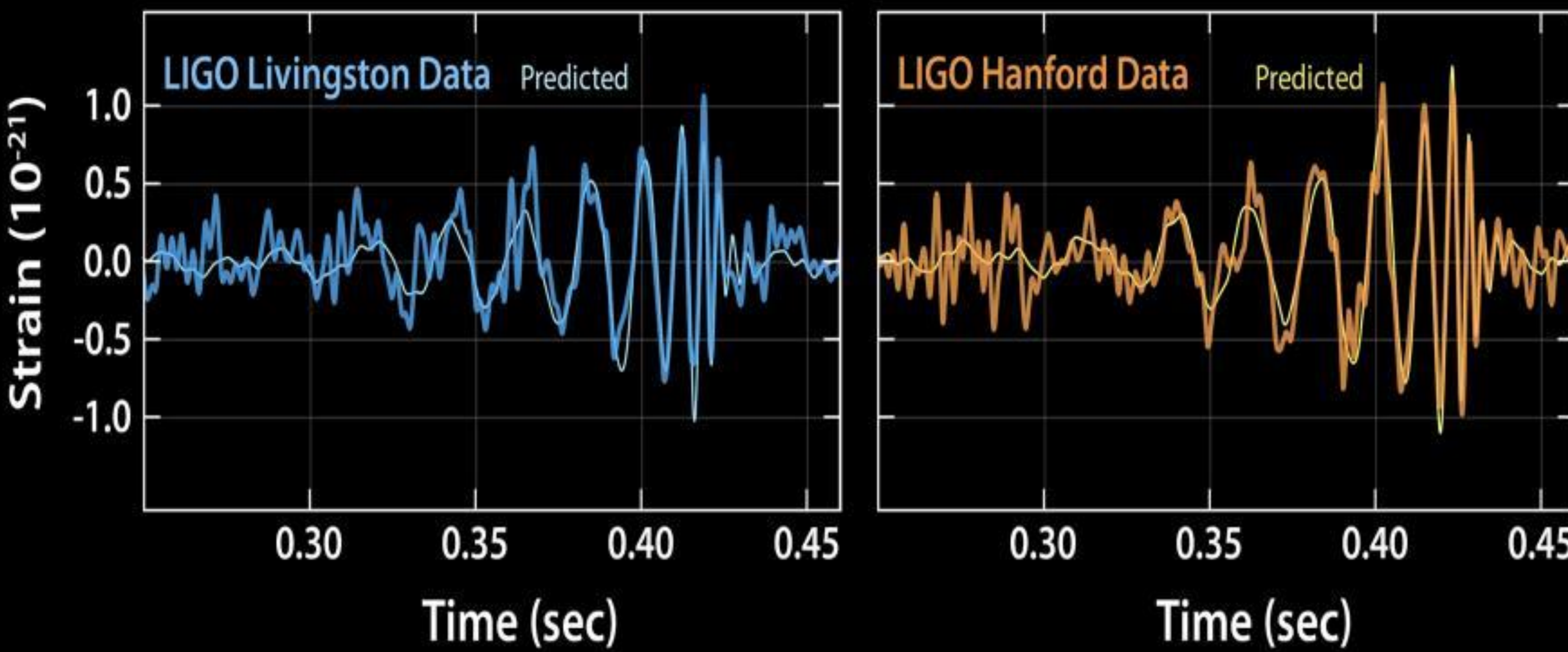
- ***On September 14, 2015 at 09:50:45 UTC*** *the LIGO Hanford, WA, and Livingston, LA, observatories detected a coincident signal*.

- The event was flagged as GW150914

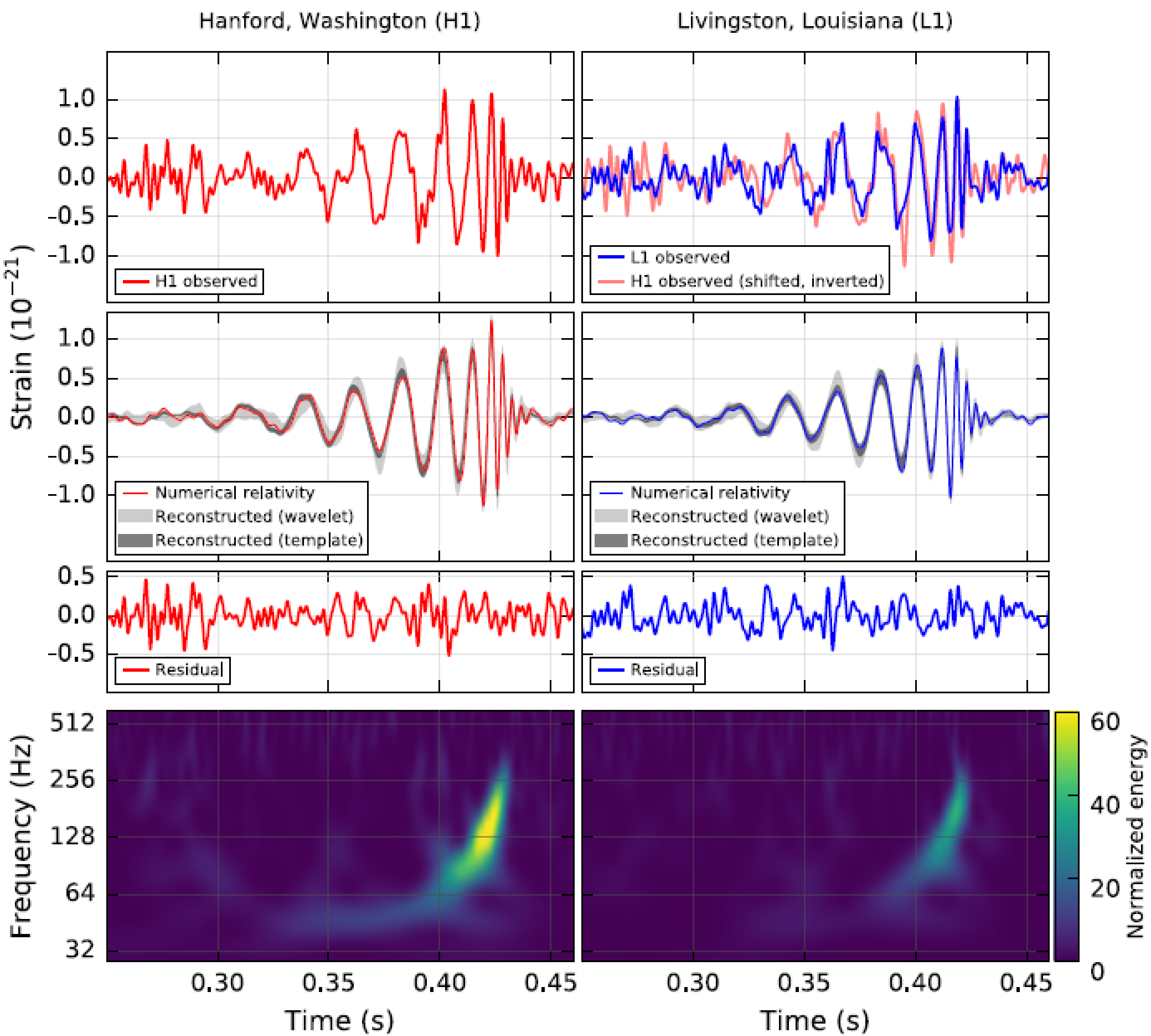
- Exhaustive investigations of instrumental and environmental disturbances were performed, giving ***no evidence*** that GW150914 is an instrumental artifact



LIGO Livingston Data
LIGO Hanford Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
Time (sec)



LIGO Livingston Data
Predicted
LIGO Hanford Data
Predicted
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
Time (sec)

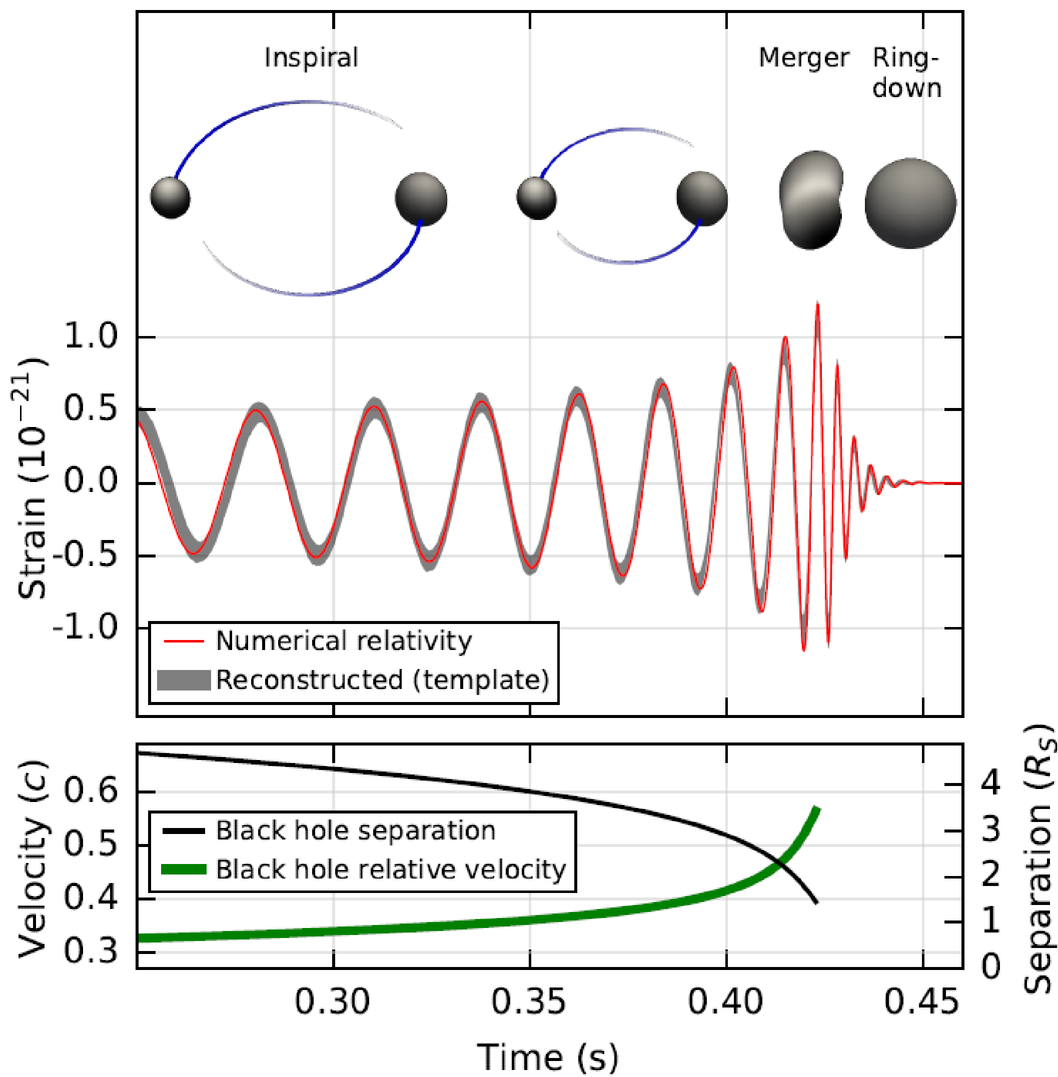


Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
Normalized energy
Time (s)

Estimated GW Strain Amplitude: GW150914

Full bandwidth waveforms without filtering. Numerical relativity models of black hole horizons during coalescence

Effective black hole separation in units of Schwarzschild radius ($R_s=2GM/c^2$); and effective relative velocities given by post-Newtonian parameter $v/c = (GM\pi f/c^3)^{1/3}$



Assessing the statistical significance of the event

Generic transient search: minimum bias

cWB version online: event detected with 3 minutes of latency

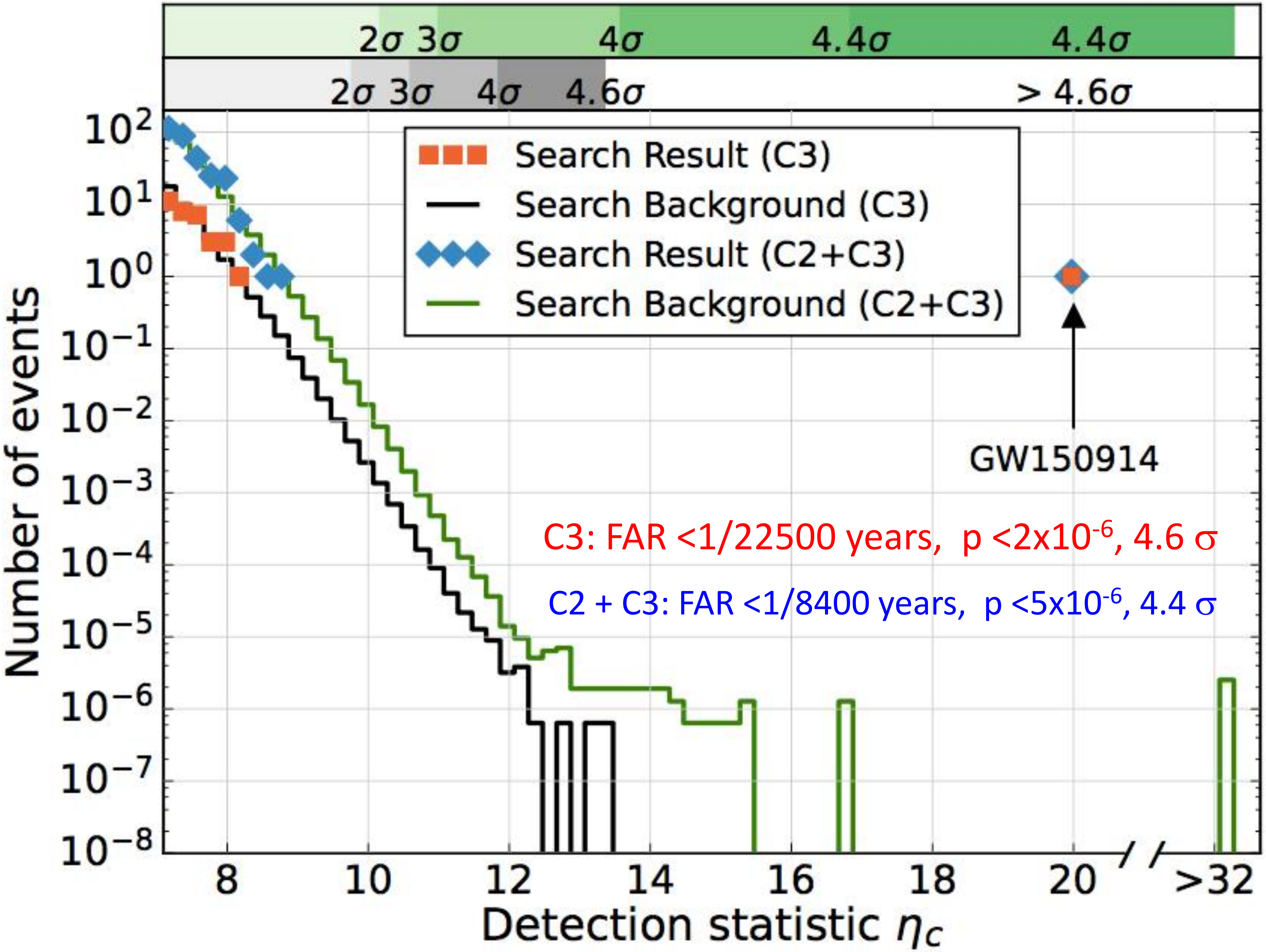
cWB version off-line: data reanalyzed to assess the statistical significance

Events classified in 3 different classes (→ trial factor):

- C1 class → events with time-frequency morphology of known populations of noise transients: excluded;
- C3 class → events with frequency that increases with time;
- C2 class → all remaining events.

Background evaluation → Based on the time shift method:

Number of shift produced an equivalent to 67400 years

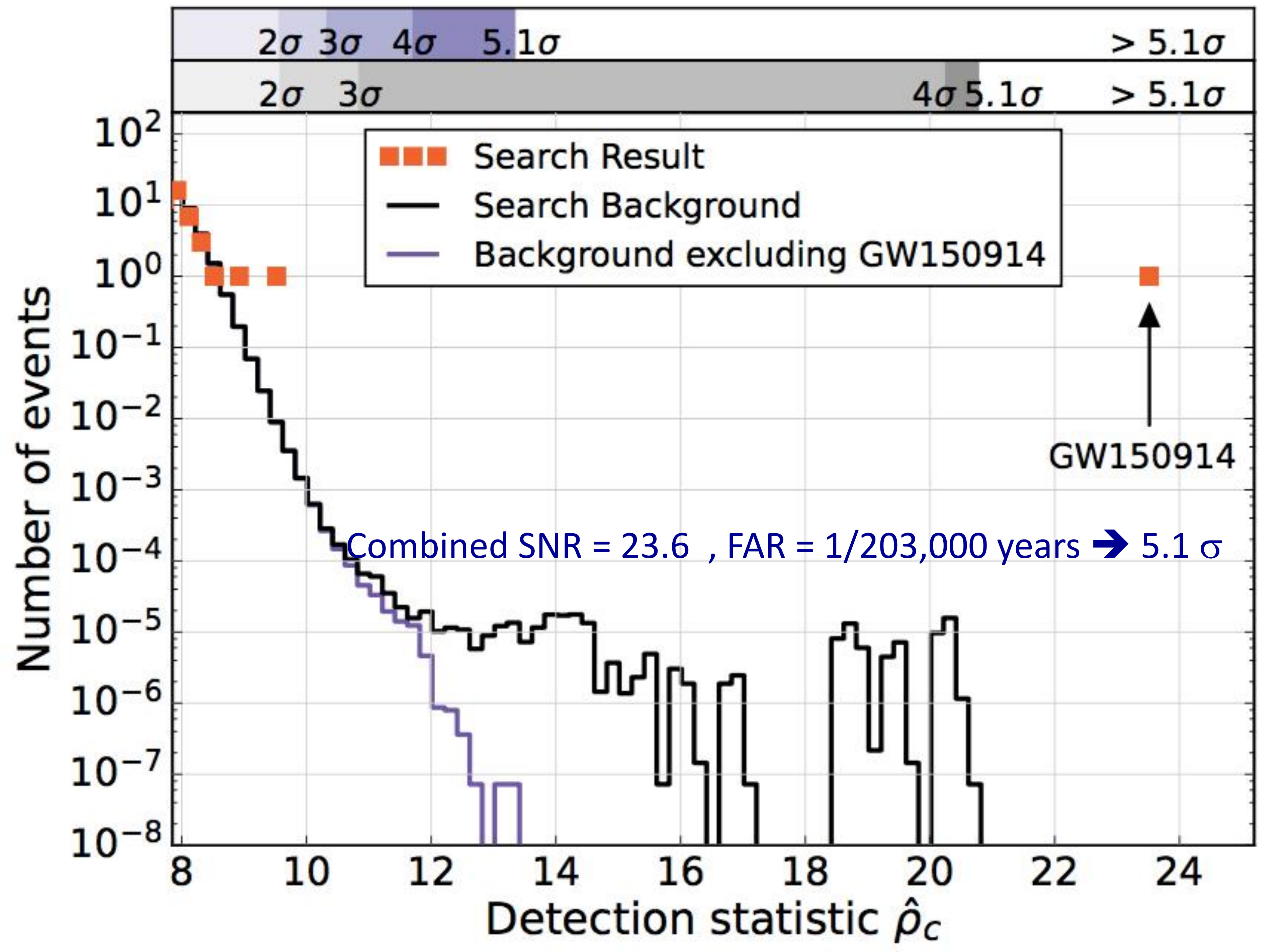


2σ 3σ
4σ
4.4σ
4.4σ
2σ 3σ
4σ
4.6σ
> 4.6σ
Search Result (C3)
Search Background (C3)
Search Result (C2+C3)
Search Background (C2+C3)
GW150914
C3: FAR <1/22500 years, p <2x10-6, 4.6 σ
C2 + C3: FAR <1/8400 years, p <5x10-6, 4.4 σ
Number of events
Detection statistic ηc
8
10
12
14
16
18
20
>32

Binary Coalescence search

Search for GW emission by binary system: total mass range 1- 99 $M_{\odot}$

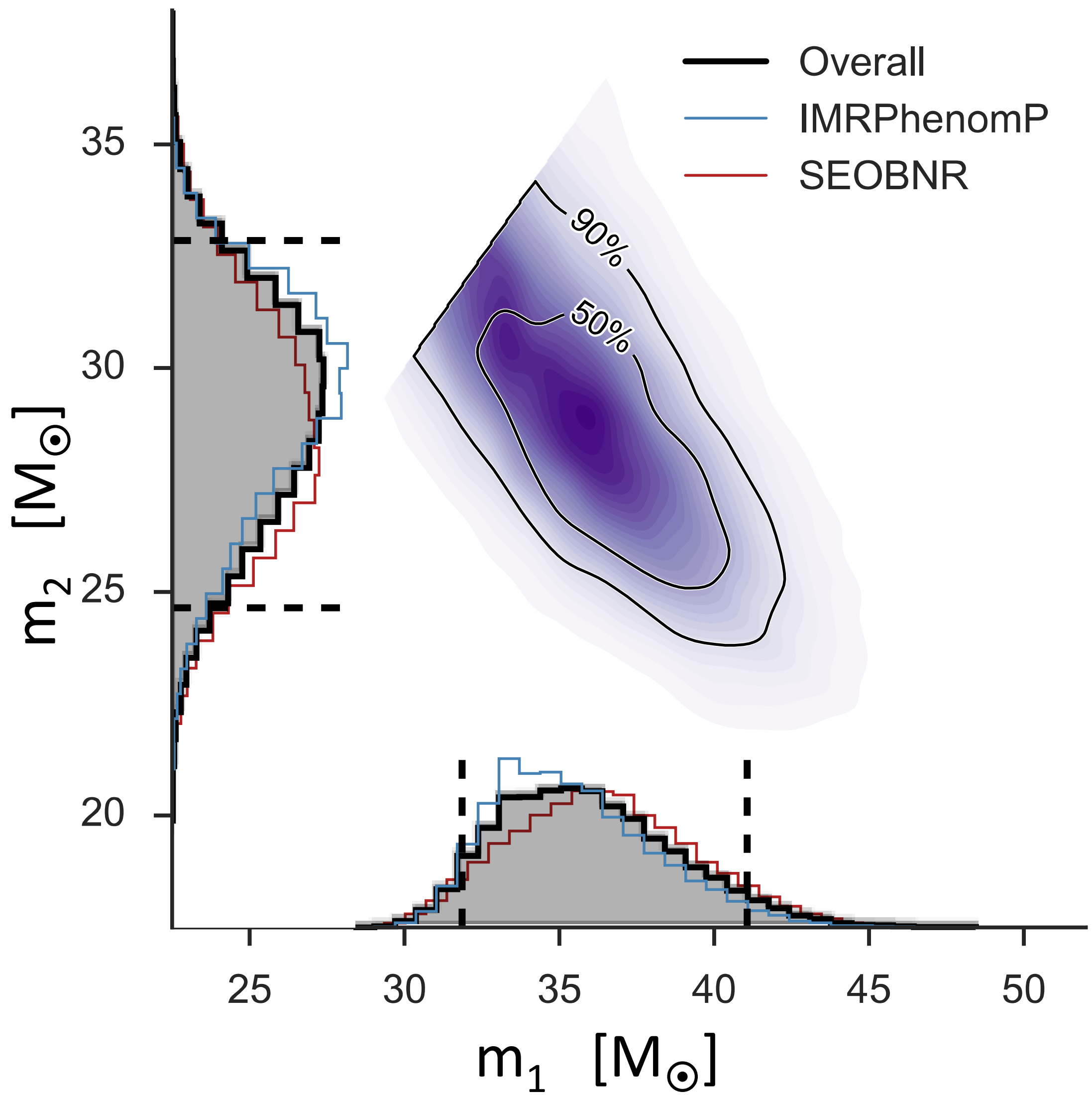
- $> 4\ M_{\odot}$ Model based on PN, BH perturbation theory and NR
- $\sim 2.5 \times 10^5$ wave forms used to cover the parameter space
- SNR of the Matched filter computed as function of time $\rho(t)$ and identify maxima and calculate χ^2 to test consistency with the matched template, then apply detector coincidence within 15 ms
- Background computed by shifting 10^7 times equivalent to 680.000 years
- Combined SNR = 23.6 , FAR = 1/203,000 years ➔ 5.1 σ



2σ 3σ 4σ 5.1σ
> 5.1σ
2σ 3σ
4σ 5.1σ
> 5.1σ
Search Result
Search Background
Background excluding GW150914
GW150914
Combined SNR = 23.6 , FAR = 1/203,000 years → 5.1 σ
Number of events
Detection statistic $\hat{\rho}_c$

The Parameter Estimation

Parameter Estimation: probability density functions (PDFs) of masses at the source frame



Source parameters for GW150914

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

Estimated source parameters from GW150914. We report median values with 90% credible intervals that include 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 Ω_m =0.306

Energy emitted and Angular momentum

- Energy emitted in GW $\quad 3^{+0.5}_{-0.5}\ M_\odot c^2$
- GW luminosity peak $\quad 3.6^{+0.5}_{-0.4} \times 10^{56}$ erg/s

  $200^{+30}_{-20}\ M_\odot c^2/s$

Values consistent with the GR predictions

2%-3% of Newtonian energy in the inspirable phase ending at ($r \approx 5GM/c^2$)

+ Num. Rel. prediction for the final phase 2%-3%

$$\mathcal{F} \sim \frac{c^3|\dot{h}|^2}{32\pi G} \sim 10^{-2}\ \mathrm{W\ m^{-2}}$$

$\boxed{D_L \approx 410\ Mpc}$

- Angular momentum

  in the final phase of the inspiral, the total angular moment **L** dominated by the orbital one

  Spin of the final BH $\quad \mathbf{S} = \mathbf{L} - \mathbf{L}_{\text{emit. GW}}$

	EOBNR	IMRPhenom	Overall
Detector-frame total mass $M/\mathrm{M}_\odot$	$70.3^{+5.3}_{-4.8}$	$70.7^{+3.8}_{-4.0}$	$70.5^{+4.6\pm0.9}_{-4.5\pm1.0}$
Detector-frame chirp mass $\mathcal{M}/\mathrm{M}_\odot$	$30.2^{+2.5}_{-1.9}$	$30.5^{+1.7}_{-1.8}$	$30.3^{+2.1\pm0.4}_{-1.9\pm0.4}$
Detector-frame primary mass $m_1/\mathrm{M}_\odot$	$39.4^{+5.5}_{-4.9}$	$38.3^{+5.5}_{-3.5}$	$38.8^{+5.6\pm0.9}_{-4.1\pm0.3}$
Detector-frame secondary mass $m_2/\mathrm{M}_\odot$	$30.9^{+4.8}_{-4.4}$	$32.2^{+3.6}_{-5.0}$	$31.6^{+4.2\pm0.1}_{-4.9\pm0.6}$
Detector-frame final mass $M_\mathrm{f}/\mathrm{M}_\odot$	$67.1^{+4.6}_{-4.4}$	$67.4^{+3.4}_{-3.6}$	$67.3^{+4.1\pm0.8}_{-4.0\pm0.9}$
Source-frame total mass $M^\mathrm{source}/\mathrm{M}_\odot$	$65.0^{+5.0}_{-4.4}$	$64.6^{+4.1}_{-3.5}$	$64.8^{+4.6\pm1.0}_{-3.9\pm0.5}$
Source-frame chirp mass $\mathcal{M}^\mathrm{source}/\mathrm{M}_\odot$	$27.9^{+2.3}_{-1.8}$	$27.9^{+1.8}_{-1.6}$	$27.9^{+2.1\pm0.4}_{-1.7\pm0.2}$
Source-frame primary mass $m_1^\mathrm{source}/\mathrm{M}_\odot$	$36.3^{+5.3}_{-4.5}$	$35.1^{+5.2}_{-3.3}$	$35.7^{+5.4\pm1.1}_{-3.8\pm0.0}$
Source-frame secondary mass $m_2^\mathrm{source}/\mathrm{M}_\odot$	$28.6^{+4.4}_{-4.2}$	$29.5^{+3.3}_{-4.5}$	$29.1^{+3.8\pm0.2}_{-4.4\pm0.5}$
Source-fame final mass $M_\mathrm{f}^\mathrm{source}/\mathrm{M}_\odot$	$62.0^{+4.4}_{-4.0}$	$61.6^{+3.7}_{-3.1}$	$61.8^{+4.2\pm0.9}_{-3.5\pm0.4}$
Mass ratio q	$0.79^{+0.18}_{-0.19}$	$0.84^{+0.14}_{-0.21}$	$0.82^{+0.16\pm0.01}_{-0.21\pm0.03}$
Effective inspiral spin parameter χ_eff	$-0.09^{+0.19}_{-0.17}$	$-0.03^{+0.14}_{-0.15}$	$-0.06^{+0.17\pm0.01}_{-0.18\pm0.07}$
Dimensionless primary spin magnitude a_1	$0.32^{+0.45}_{-0.28}$	$0.31^{+0.51}_{-0.27}$	$0.31^{+0.48\pm0.04}_{-0.28\pm0.01}$
Dimensionless secondary spin magnitude a_2	$0.57^{+0.40}_{-0.51}$	$0.39^{+0.50}_{-0.34}$	$0.46^{+0.48\pm0.07}_{-0.42\pm0.01}$
Final spin a_f	$0.67^{+0.06}_{-0.08}$	$0.67^{+0.05}_{-0.05}$	$0.67^{+0.05\pm0.00}_{-0.07\pm0.03}$
Luminosity distance $D_\mathrm{L}/\mathrm{Mpc}$	390^{+170}_{-180}	440^{+140}_{-180}	$410^{+160\pm20}_{-180\pm40}$
Source redshift z	$0.083^{+0.033}_{-0.036}$	$0.093^{+0.028}_{-0.036}$	$0.088^{+0.031\pm0.004}_{-0.038\pm0.009}$
Upper bound on primary spin magnitude a_1	0.65	0.71	0.69 ± 0.05
Upper bound on secondary spin magnitude a_2	0.93	0.81	0.88 ± 0.10
Lower bound on mass ratio q	0.64	0.67	0.65 ± 0.03
Log Bayes factor $\ln \mathcal{B}_{\mathrm{s/n}}$	288.7 ± 0.2	290.1 ± 0.2	—

Few Companion Results

Astrophysical implications (accepted on ApJL)

- GW150914 demonstrates the existence of stellar-mass black holes of $M > 25M_\odot$,
  - binary black holes can form in nature and merge within a Hubble time

- Binary black holes have been predicted to form both in isolated binaries and in dense environments by dynamical interactions .

- Formation of such massive black holes from stellar evolution
  - weak massive-star winds, and stellar environments with metallicity lower than 1/2 the solar value

Event rates evaluation → 2–400 $Gpc^{-3}\,yr^{-1}$

- Considering only GW150914 event and assuming that the BBH merger rate is constant in the comoving frame, we infer a 90% credible range of 2–53 $Gpc^{-3}\,yr^{-1}$ (in the comoving frame)

- Incorporating all triggers that pass the search threshold (independent of their astrophysical origin) and several other models, we obtain rate estimates ranging from 6–400 $Gpc^{-3}\,yr^{-1}$

Stochastic back. of astrophysical origin

- Superposition of unresolved GW emission of binary black hole sources at larger distances.
- Prediction Ω_{GW} (~ f = 25 Hz) $1.1^{+2.7}_{-0.9} \times 10^{-9}$ with 90% confidence.
- Potentially measurable by the Advanced LIGO/at their projected final sensitivity

Testing General Relativity

- The phase of the gravitational waveform during the inspiral can be ex- pressed as a power-series in $f^{1/3}$.
- The coefficients of this expansion can be computed in general relativity

  -GR test : allow the coefficients to deviate from the nominal GR value

Compton Wave-length of the Graviton

C. M. Will, Phys. Rev. D 57, 2061 (1998).

- We assume a modified dispersion relation for gravitational waves

$$(v_g /c)^2 = 1 - \{\boldsymbol{h}\, c /(\lambda_g E)\}^2$$

- In the massive graviton theory an extra phase term is added to the CBC evolution (formally a 1PN order term) [C.Will PRD, 57, 2061 (1998)]

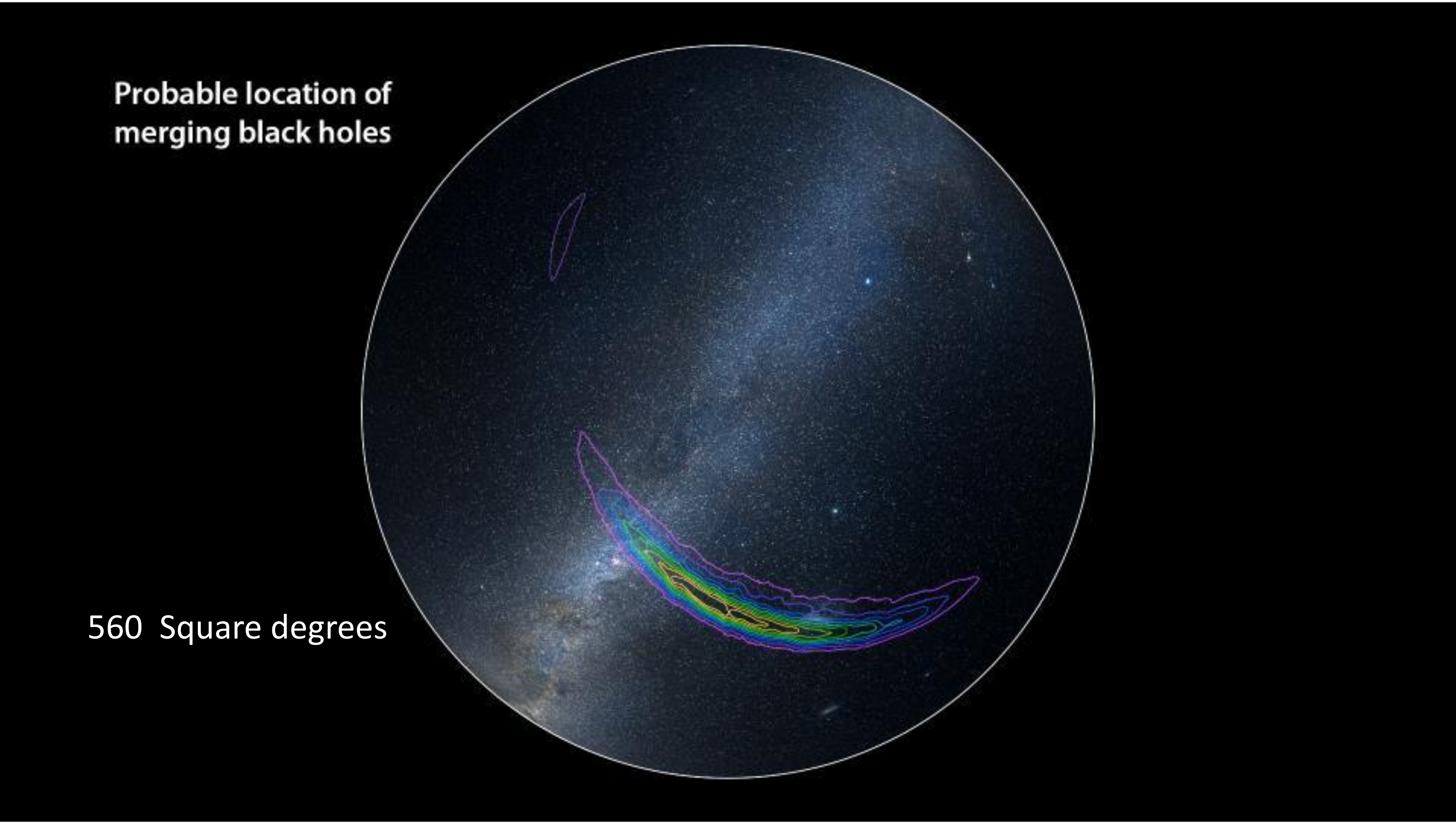
$$\phi_{MG}(f) = -(\pi D c) / [\lambda_g{}^2 (1 + z) f]$$

- Our constrain on the 1PN terms permit to derive a down limit for the Compton wavelength of the graviton

$$\lambda_g = \boldsymbol{h} / (m_g c) > 10^{13} \text{ km}$$

- It corresponds to a limit $m_g < 1.2 \times 10^{-22}$ eV/c^2.
  - limit better than that set by Solar System observations
  - thousand time better of the binary pulsar bounds
  - worse than bounds from dynamics of galaxy clusters and weak lensing observations (model- dependent bounds)

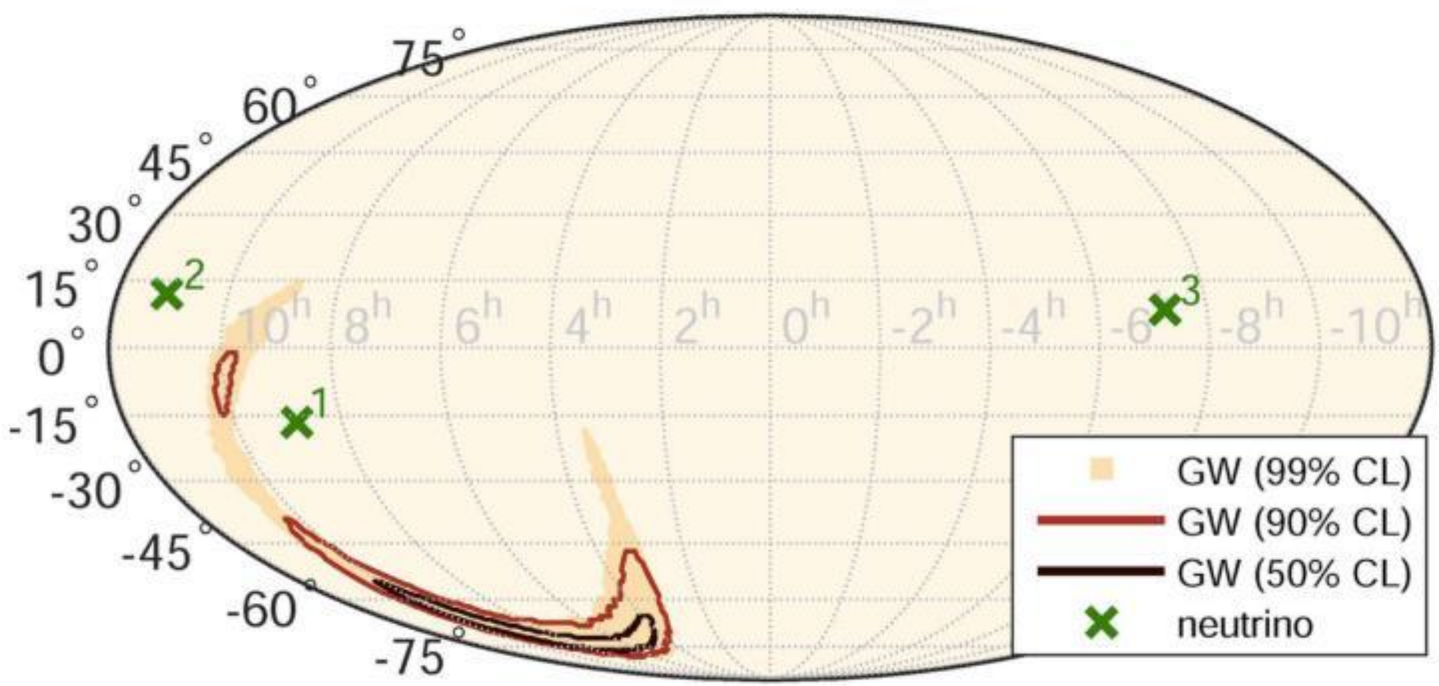
The e.m. and ν follow up



560 Square degrees

GW – HEN Coincidence search

- Search for coincident neutrino candidates to GW150914 within the data recorded by the IceCube and Antares neutrino detectors.
  - Time coincidence window ±500 s
- Number of neutrino candidates detected by IceCube and Antares were 3 and 0, respectively
- None of the neutrino candidates were directionally coincident with GW150914.

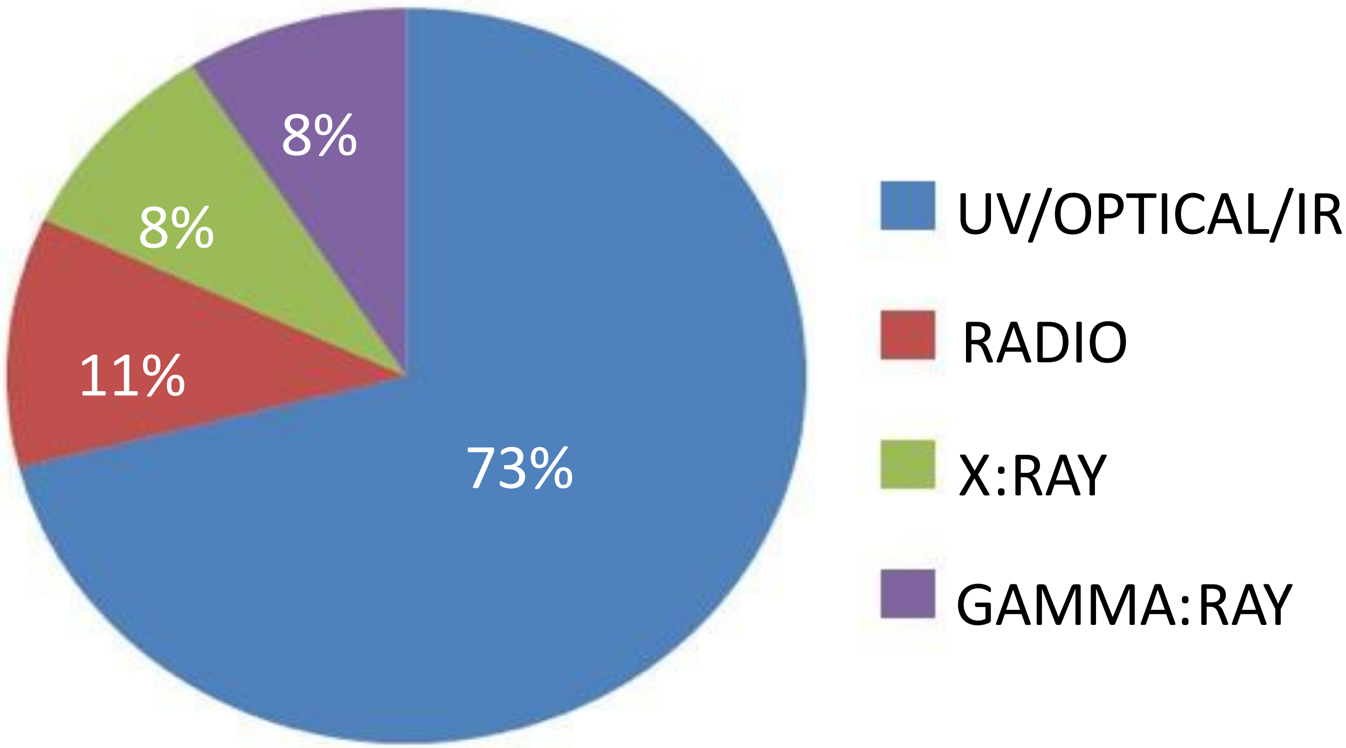


E.M.-messenger searches

About 74 MoUs: 19 countries, 150 instruments, covering the full spectrum from radio to very high-energy gamma rays

62 groups ready to observe at the time of the O1 start-up

20 group observed the sky once the trigger has been released

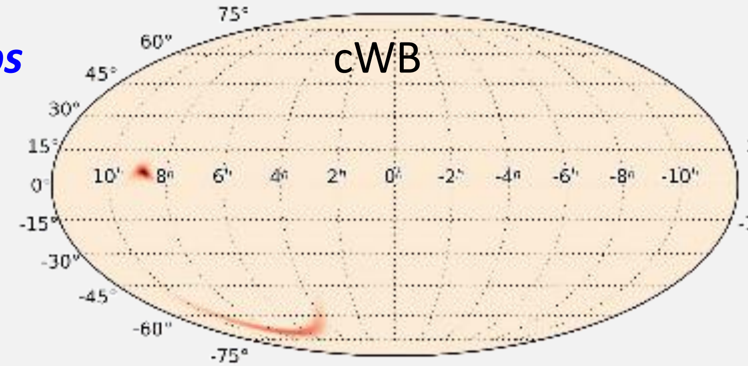


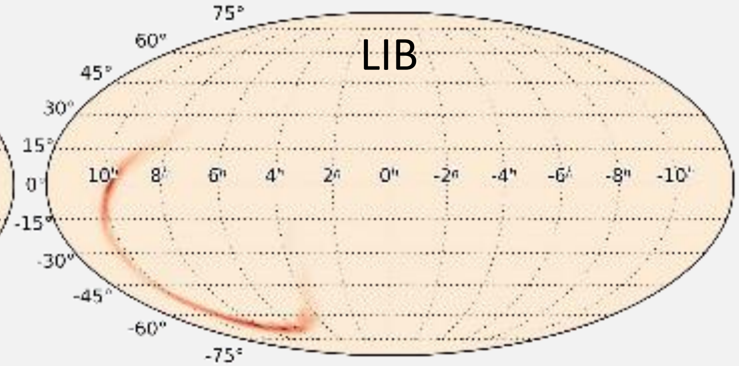
An article is in preparation: we summarize the em follow up effort

The Event – What LVC sent to the astronomers

- **16 Sept 05:39 *UTC*** *notification about the trigger identified by the online Burst analysis during ER8 (GCN 18330)*

Burst sky maps



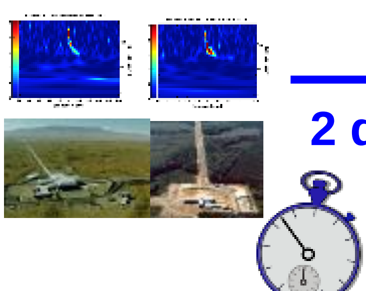


Event time *2015-09-14 09:50:45 UTC* ***FAR*** *1.178e-08 Hz 1/2.7 yr*

The 50% credible region spans about 200 deg^2 and the 90% region about 750 deg^2

- **03 Oct 2015** *update → waveform reconstruction appears consistent with expectations for a* ***binary black hole coalescence*** *(GCN 18388)*

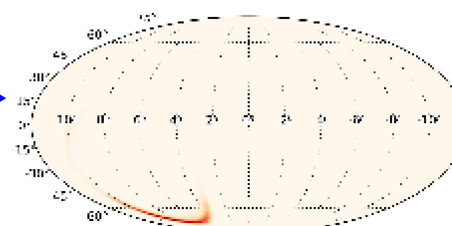
- **12 Jan 2016** *update* → offline calibration and re-analysis ***FAR < 1/100 yr*** *(GCN 18851)*
- **13 Jan** *update* → **Refined localizations** from CBC parameter estimation *(GCN 18858)*



2 days

19 days

4 months



LALinference

A glance to What’s Next

February 17.th 2016
Indian Government approval of Ligo-India Proposal

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पत्र सूचना कार्यालय, भारत सरकार

21-February 2016

Press Information Bureau, Government of India

A- A+

All Ministries

English Release 21-February 2016

Date 21 Month February Year 2016

President's Secretariat

2. Prime Minister of Nepal Calls on President
3. President's Greetings on the eve of Birthday of Guru Ravidasji
4. President of India's Message on the eve of Independence Day of St. Lucia

Prime Minister's Office

6. PM inaugurates Centenary Celebrations of Gaudiya Mission and Math
7. Excerpts of PM's Address at the launch of Shyama Prasad Mukherji Rurban Mission
8. Text of PM's speech at the Foundation Stone laying ceremony of Pradhan Mantri Awas Yojana in Chhattisgarh
9. PM launches National Rurban Mission
10. PM in Naya Raipur

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Cabinet | 17-February, 2016 14:55 IST

Cabinet grants 'in-principle' approval to the LIGO-India mega science proposal

The Union Cabinet chaired by the Prime Minister Shri Narendra Modi has given its 'in principle' approval to the LIGO-India mega science proposal for research on gravitational waves. The proposal, known as LIGO-India project (Laser Interferometer Gravitational-wave Observatory in India) is piloted by Department of Atomic Energy and Department of Science and Technology (DST). The approval coincides with the historic detection of gravitational waves a few days ago that opened up of a new window on the universe to unravel some of its greatest mysteries.

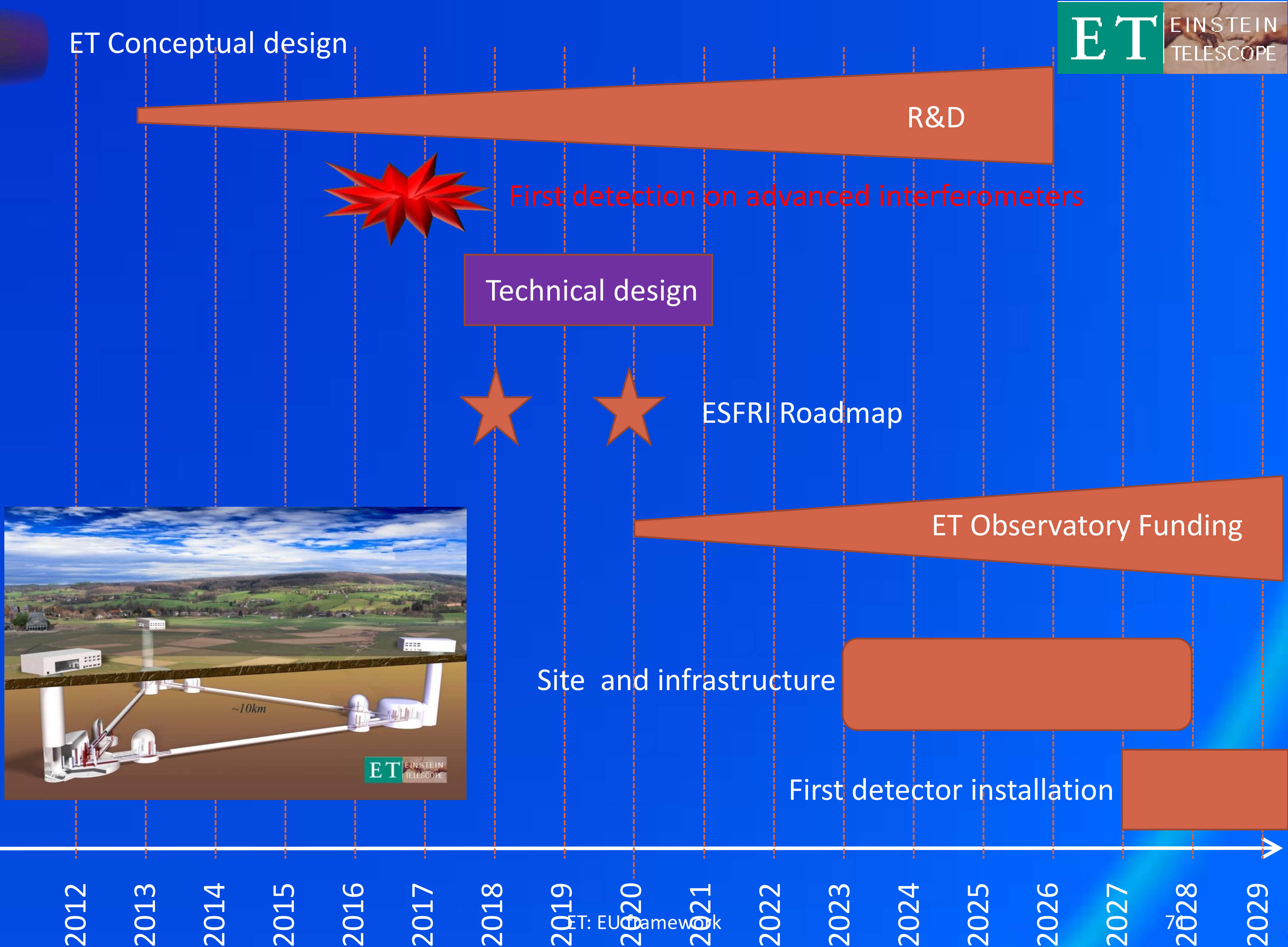
The LIGO-India project will establish a state-of-the-art gravitational wave observatory in India in collaboration with the LIGO Laboratory in the U.S. run by Caltech and MIT.

The project will bring unprecedented opportunities for scientists and engineers to dig deeper into the realm of gravitational wave and take global leadership in this new astronomical frontier.

LIGO-India will also bring considerable opportunities in cutting edge technology for the Indian industry which will be engaged in the construction of eight kilometre long beam tube at ultra-high vacuum on a levelled terrain.

The project will motivate Indian students and young scientists to explore newer frontiers of knowledge, and will add further impetus to scientific research in the country.

***


ET Conceptual design
R&D
First detection on advanced interferometers
Technical design
ESFRI Roadmap
ET Observatory Funding
Site and infrastructure
First detector installation
~10km
2012
2013
2014
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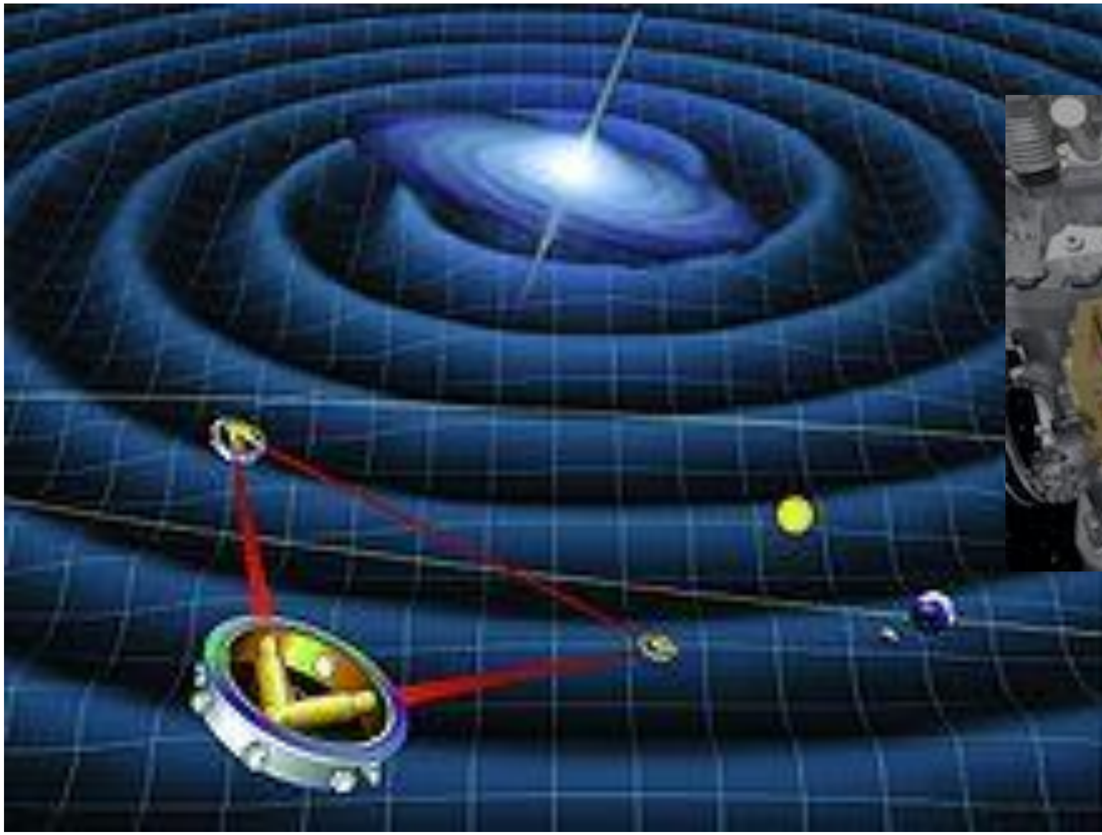
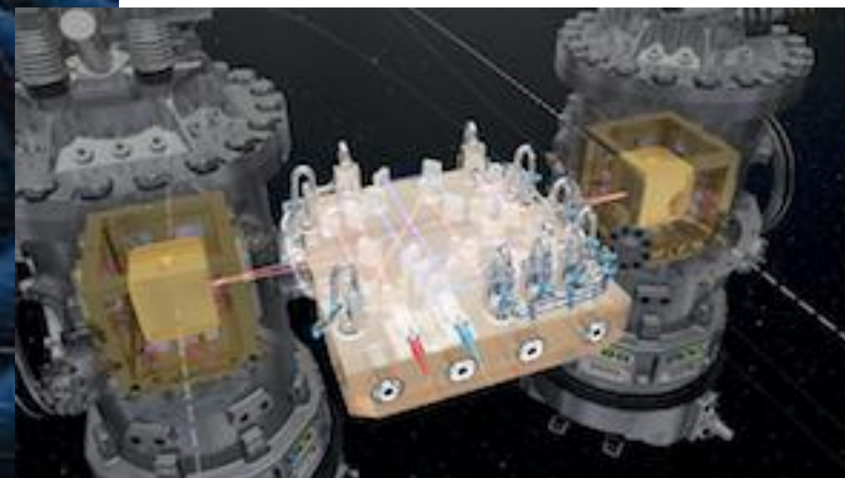
The detection of gravitationalwaves strongly enforces the proposal for future space-based detectors like LISA



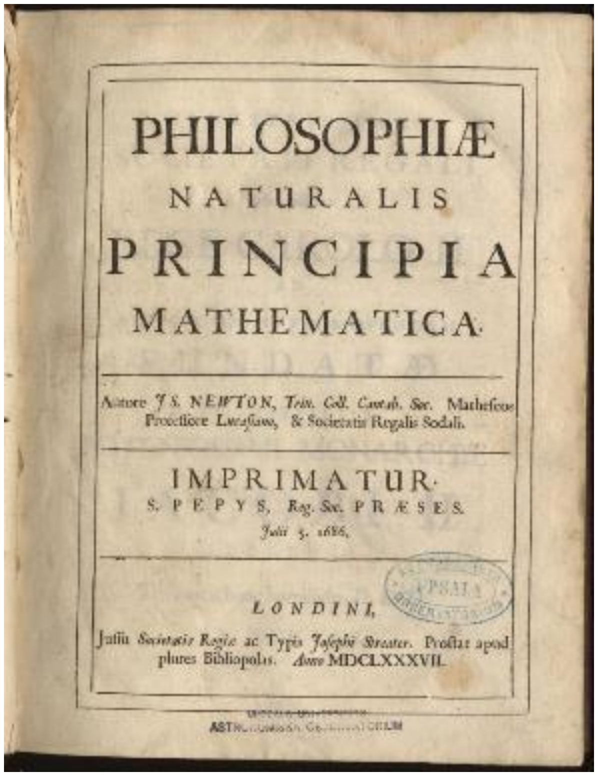
Artistic view of Lisa Detector



Lisa Pathfinder mirrors floating

Conclusions

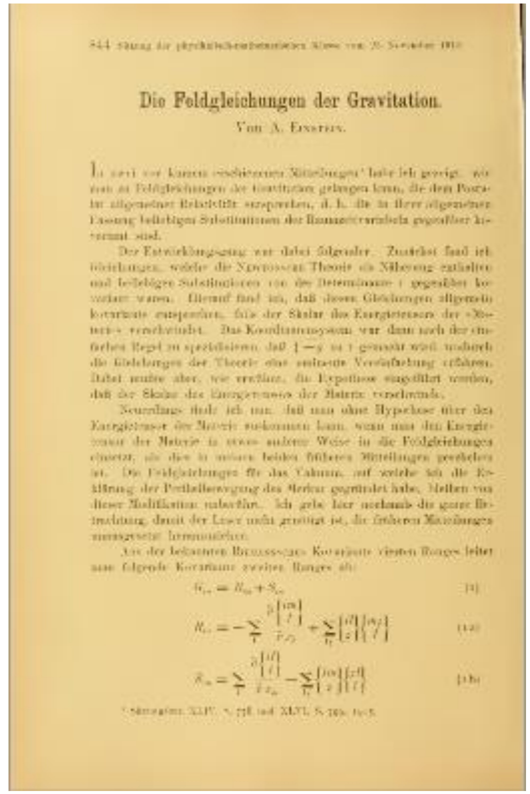
Conclusion

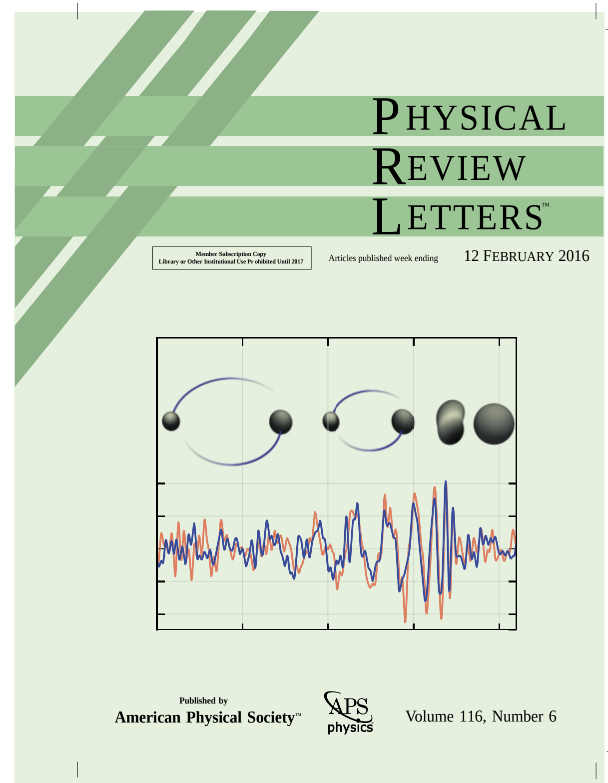

PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore J S. NEWTON, Trin. Coll. Cantab. Soc. Matheseos Professore Lucasiano, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, Reg. Soc. PRÆSES.
Julii 5. 1686.

LONDINI,
Jussu Societatis Regiæ ac Typis Josephi Streater. Prostat apud plures Bibliopolas. Anno MDCLXXXVII.

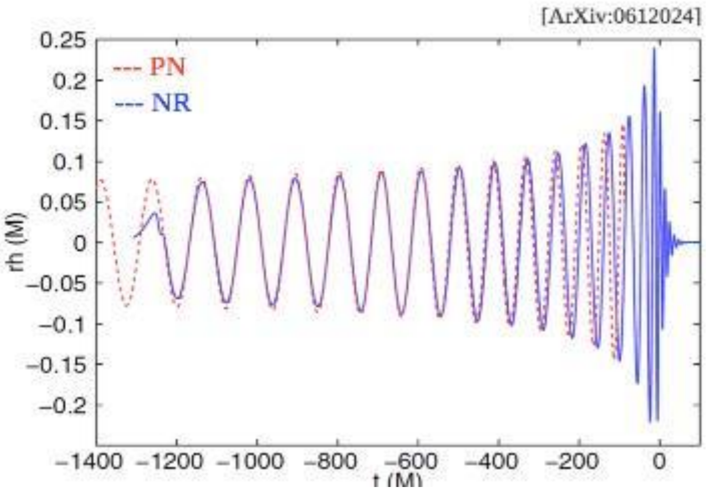

Die Feldgleichungen der Gravitation.
Von A. Einstein.

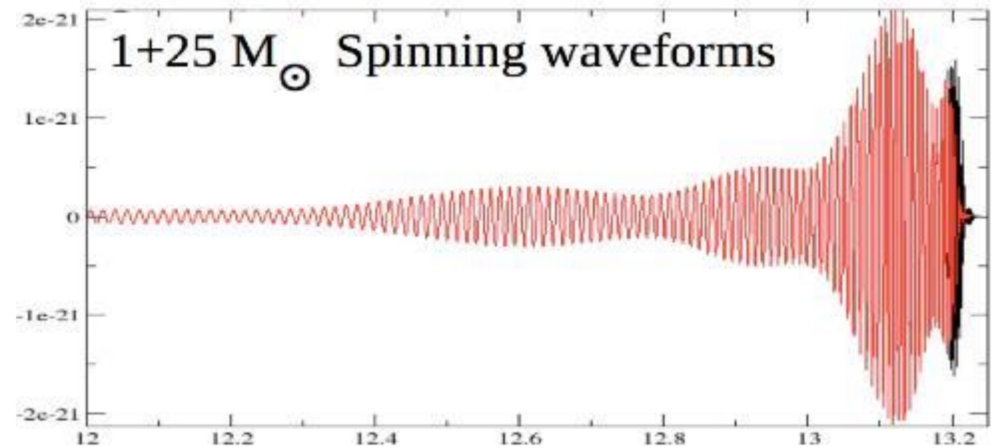


We detected Gravitational Waves
and really opened a new way
of observing the universe

Extra slides

Waveform zoology





	Approximations	Spins
Low mass $(M_{tot} < 12M_\odot)$	BNS case SNR dominated by the inspiral phase. Waveforms accurate until PN approx. breaks	For initial detectors: spin could be neglected. Advanced LIGO/Virgo: spin 0.015 - 0.1 → 3%-25% mismatch. Aligned spins is still OK?
High mass $(M_{tot} > 12M_\odot)$	For masses higher than 50 Msun, merger and ring-down contribute dominantly → need full waveform inspiral + merger + ring-down (IMR) Use of NR waveforms for merger.	BH spins is likely maximal Spin precession effects can be large. Spins cannot be neglected for Advanced LIGO/Virgo

Waveform template

- Model complete (include also spin-orbit (1.5 PN) and spin-spin (2PN) effects
- Waveforms stop at ISCO.

$$h(f) = Cf^{-7/6}e^{-i\Psi(f)}$$

$$\begin{aligned}
\Psi(f;M,\eta) \;=\;& 2\pi f t_C - 2\phi_C - \pi/4 \\
+\;& \pi\left[\frac{38\,645}{756} - \frac{65}{9}\eta\right]\left[1 + 3\ln\left(\frac{v}{v_0}\right)\right] + \left\{\frac{11\,583\,231\,236\,531}{4\,694\,215\,680} - \frac{640}{3}\pi^2 - \frac{6\,848}{21}(\gamma + \ln(4\,v))\right. \\
+\;& \left.\left(-\frac{15\,335\,597\,827}{3\,048\,192} + \frac{2\,255}{12}\pi^2\right)\eta + \frac{76\,055}{1\,728}\eta^2 - \frac{127\,825}{1\,296}\eta^3\right\}v^6 \\
+\;& \pi\left[\frac{77\,096\,675}{254\,016} + \frac{378\,515}{1\,512}\eta - \frac{74\,045}{756}\eta^2\right]v^7\Big\},
\end{aligned}$$

$$v = (\pi M f)^{1/3}$$