LIGO/Virgo results from the first run of the Advanced gravitational waves detectors

Gianluca Gemme - *INFN Genova*

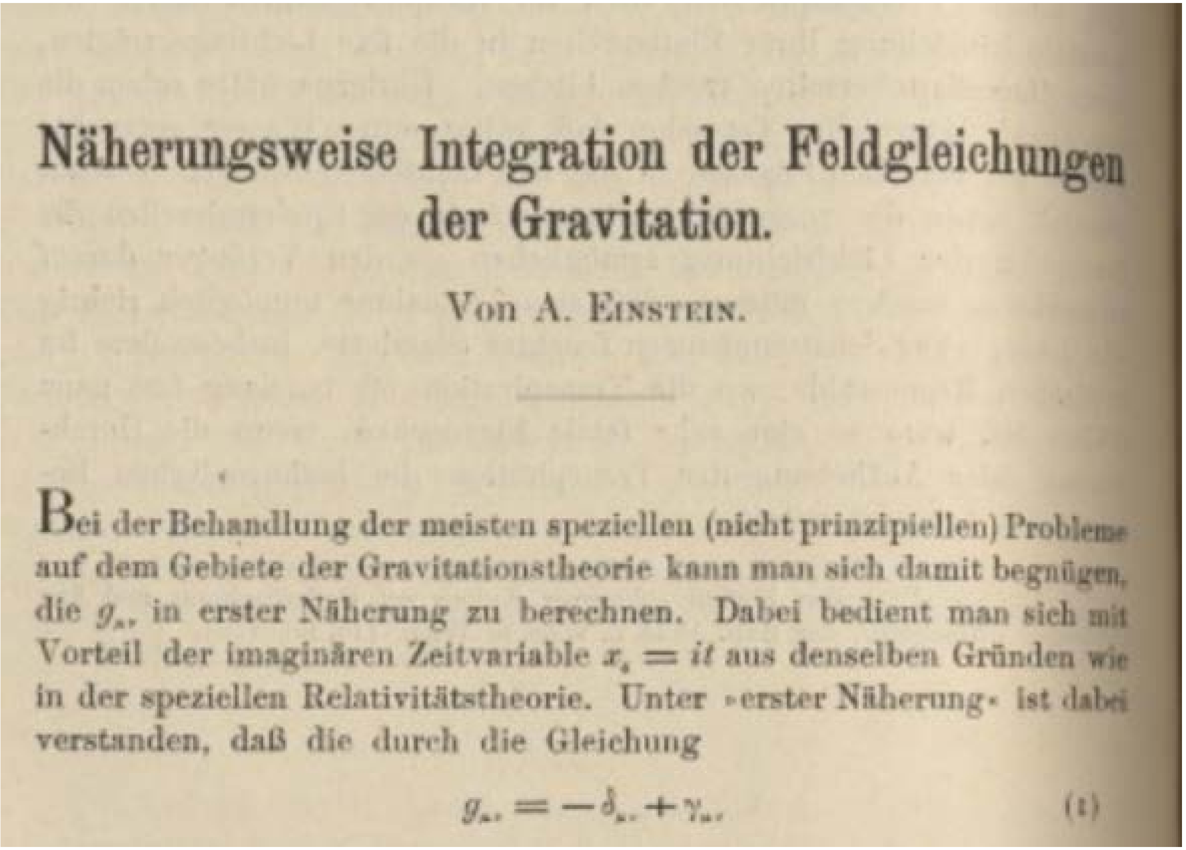
on behalf of the LIGO Scientific Collaboration and the Virgo Collaboration

LIGO Livingston Observatory
Louisiana, USA

Virgo, Cascina, Italy

LIGO Hanford Observatory
Washington, USA

1916

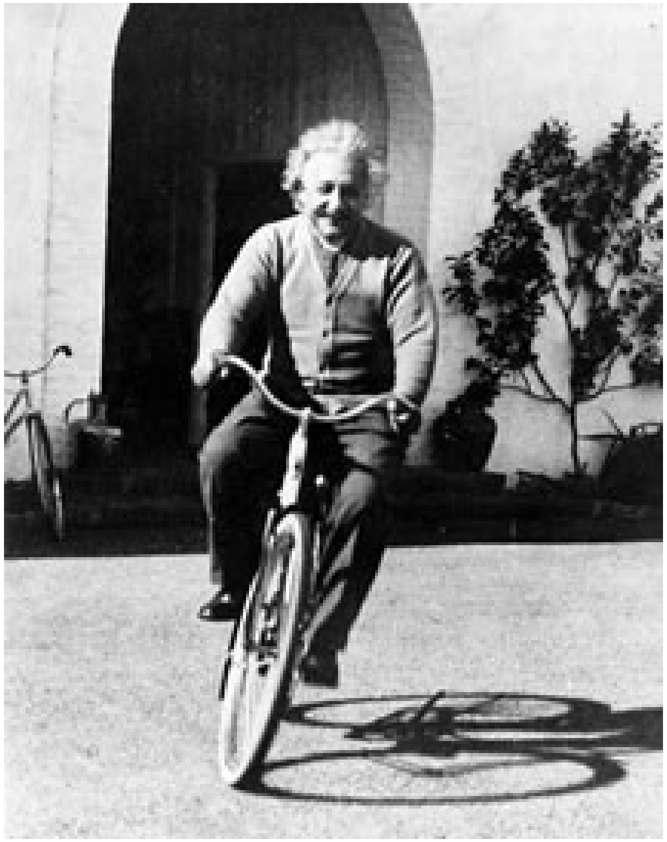


Näherungsweise Integration der Feldgleichungen der Gravitation.

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

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

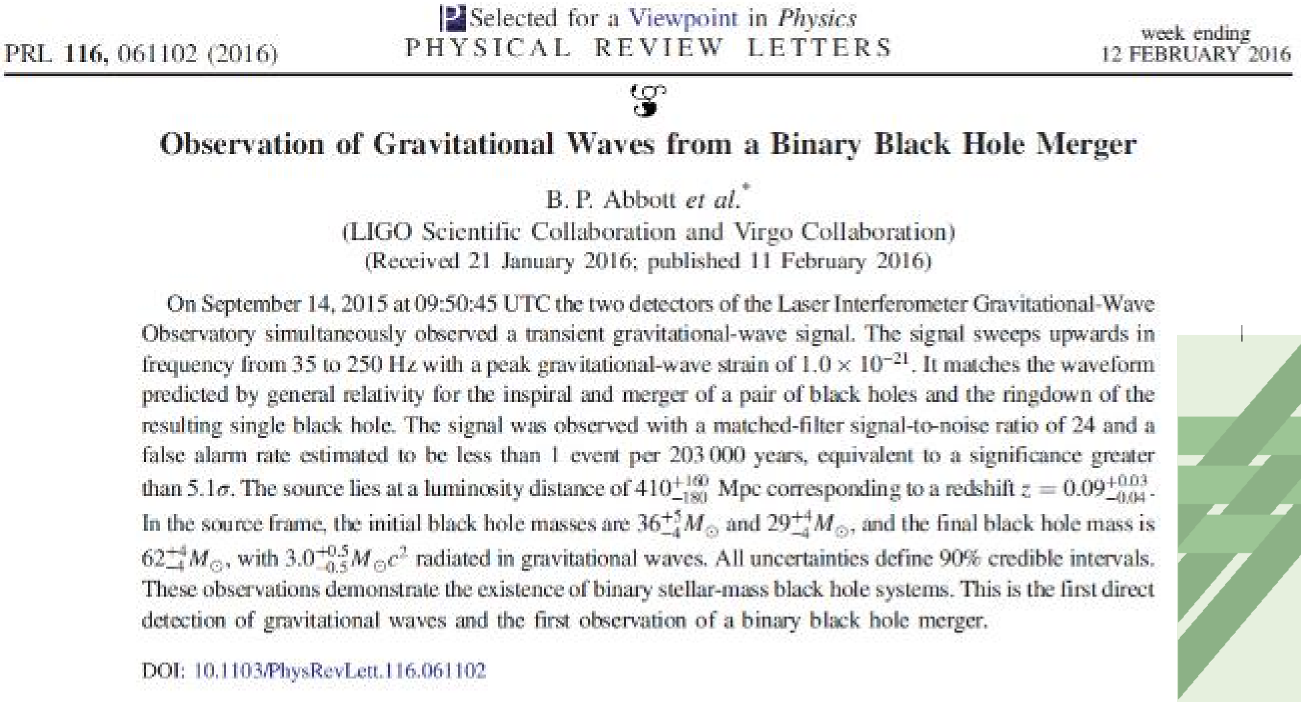


Albert Einstein

Näherungsweise Integration der Feldgleichungen der Gravitation, Berlin 22.6.1916

Approximate integration of the field equations of gravitation

2016



PRL **116,** 061102 (2016)

Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS

week ending
12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

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

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_{\odot}$ and $29^{+4}_{-4} M_{\odot}$, and the final black hole mass is $62^{+4}_{-4} M_{\odot}$, with $3.0^{+0.5}_{-0.5} M_{\odot} c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

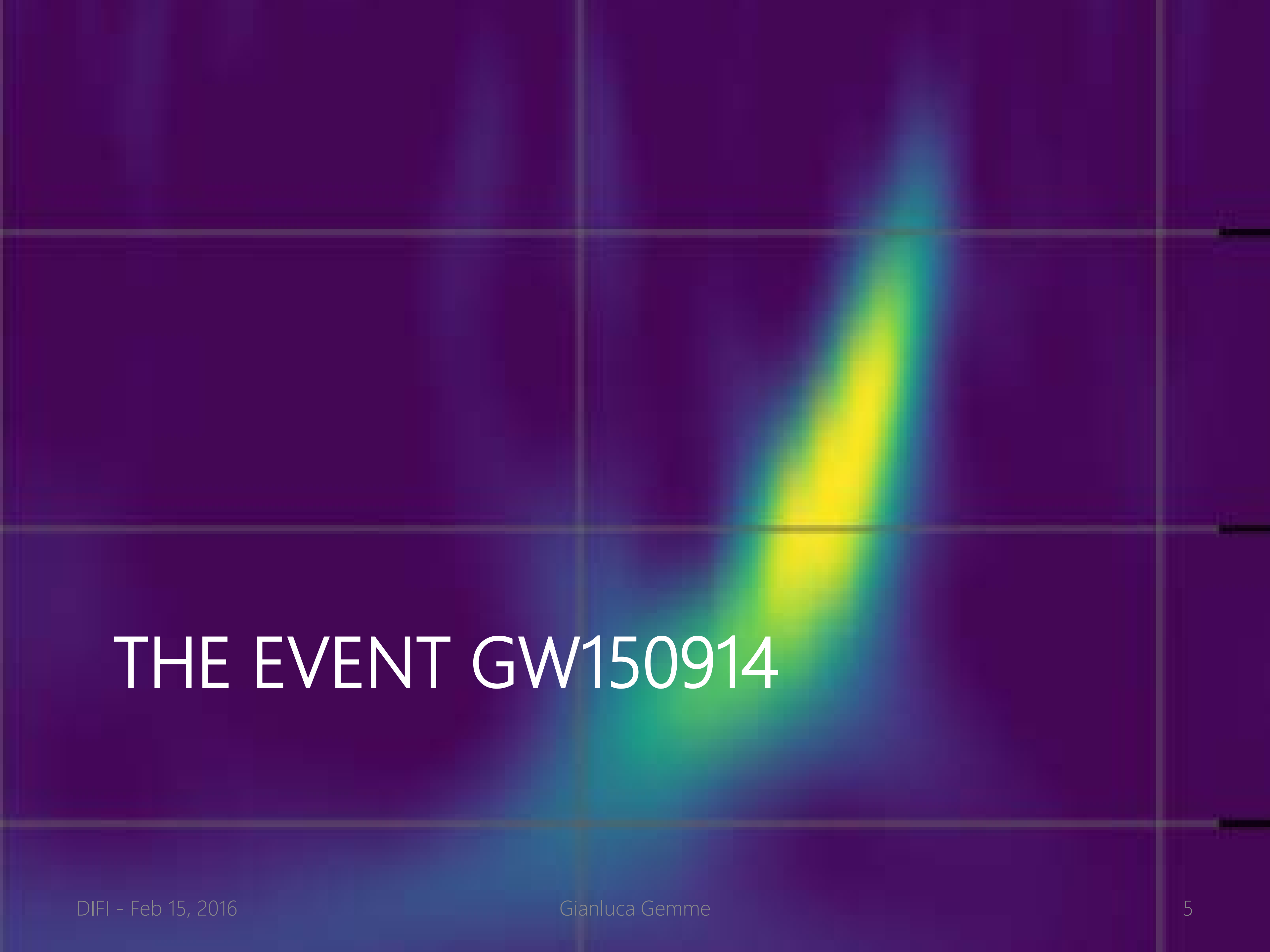
DOI: 10.1103/PhysRevLett.116.061102

229,000 paper downloads from APS in the first 24 hours

Phys. Rev. Lett. 116, 061102 (2016)

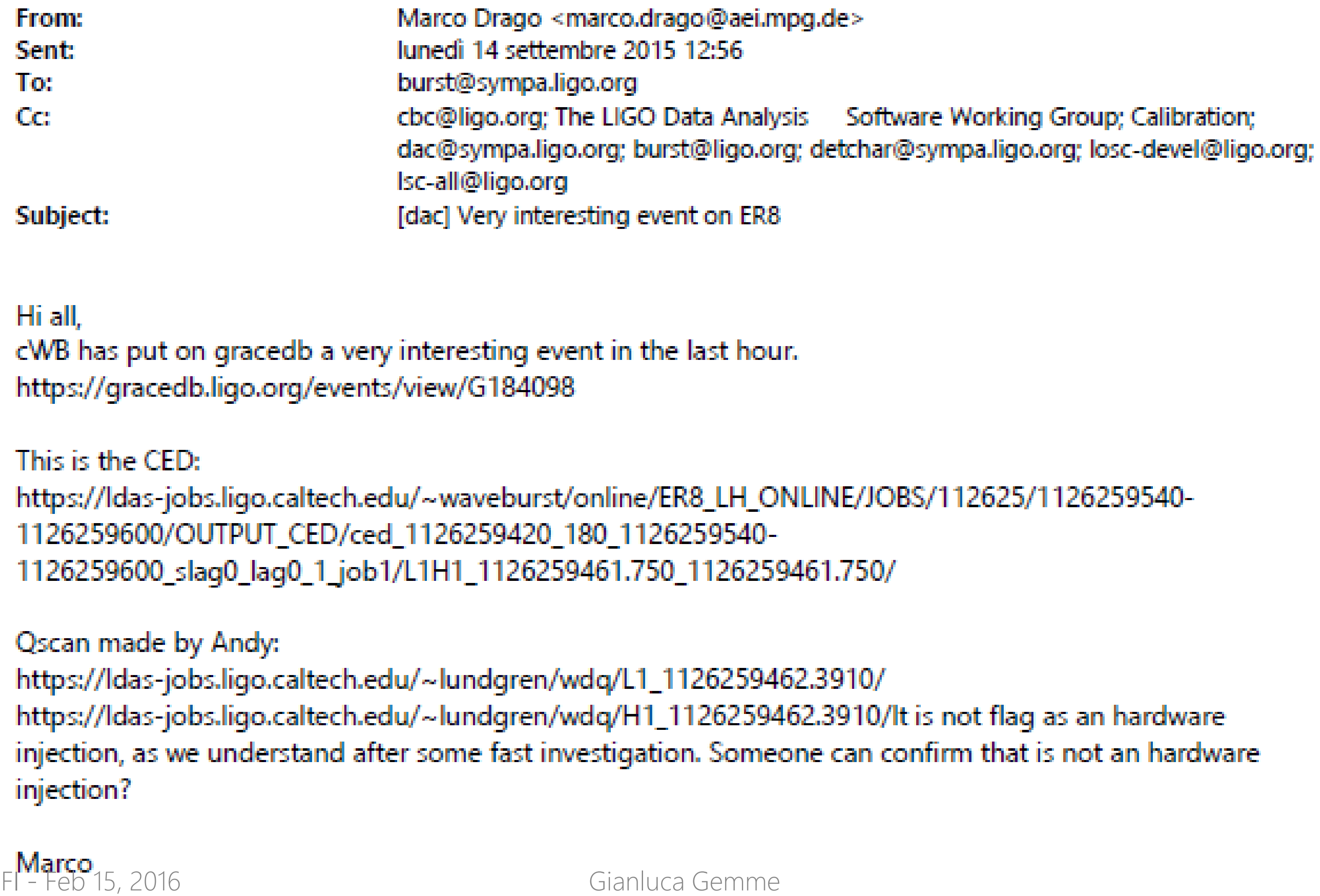
GW150914 papers

- Detection Paper
  [Phys. Rev. Lett. 116, 061102 (2016)]
  arXiv:1602.03837
- Astrophysics implications
  ApJL, 818, L22, 2016
  arXiv:1602.03846
- Test of GR
  arXiv:1602.03841
- Rates
  arXiv:1602.03842
- Stochastic Background
  arXiv:1602.03847
- EM follow-up
  in preparation
- High Energy Neutrinos
  in preparation
- CBC searches
  arXiv:1602.03839
- Unmodeled searches
  arXiv:1602.03843
- Parameter Estimation
  arXiv:1602.03840
- Instrument
  arXiv:1602.03838
- DetChar
  arXiv:1602.03844
- Calibration
  arXiv:1602.03845
- Public data release
  https://losc.ligo.org/events/GW150914



THE EVENT GW150914

September 14, 2015 – 12:56 CET



From: Marco Drago <marco.drago@aei.mpg.de>
Sent: lunedì 14 settembre 2015 12:56
To: burst@sympa.ligo.org
Cc: cbc@ligo.org; The LIGO Data Analysis Software Working Group; Calibration; dac@sympa.ligo.org; burst@ligo.org; detchar@sympa.ligo.org; losc-devel@ligo.org; lsc-all@ligo.org
Subject: [dac] Very interesting event on ER8

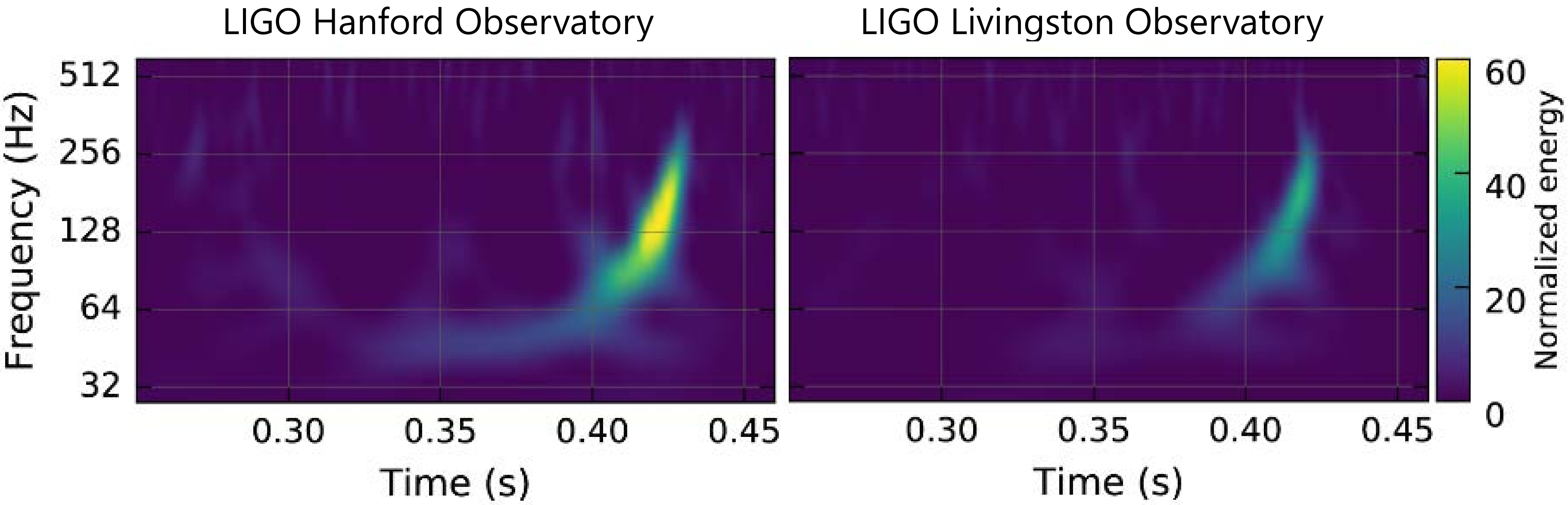
Hi all,
cWB has put on gracedb a very interesting event in the last hour.
https://gracedb.ligo.org/events/view/G184098

This is the CED:
https://ldas-jobs.ligo.caltech.edu/~waveburst/online/ER8_LH_ONLINE/JOBS/112625/1126259540-1126259600/OUTPUT_CED/ced_1126259420_180_1126259540-1126259600_slag0_lag0_1_job1/L1H1_1126259461.750_1126259461.750/

Qscan made by Andy:
https://ldas-jobs.ligo.caltech.edu/~lundgren/wdq/L1_1126259462.3910/
https://ldas-jobs.ligo.caltech.edu/~lundgren/wdq/H1_1126259462.3910/It is not flag as an hardware injection, as we understand after some fast investigation. Someone can confirm that is not an hardware injection?

Marco

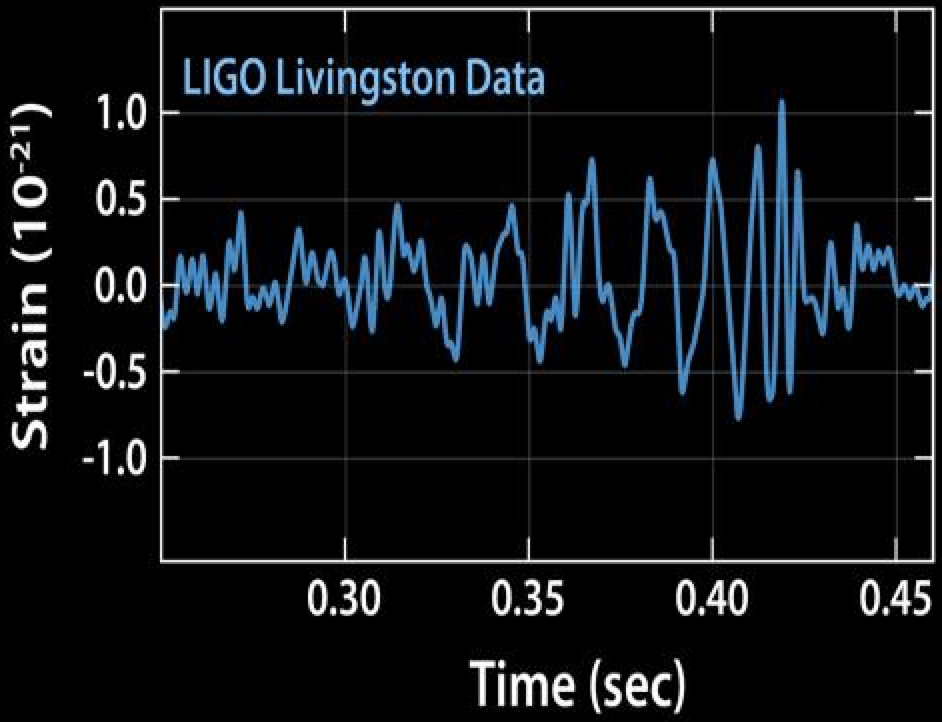
September 14, 2015 – 11:50:45 CET

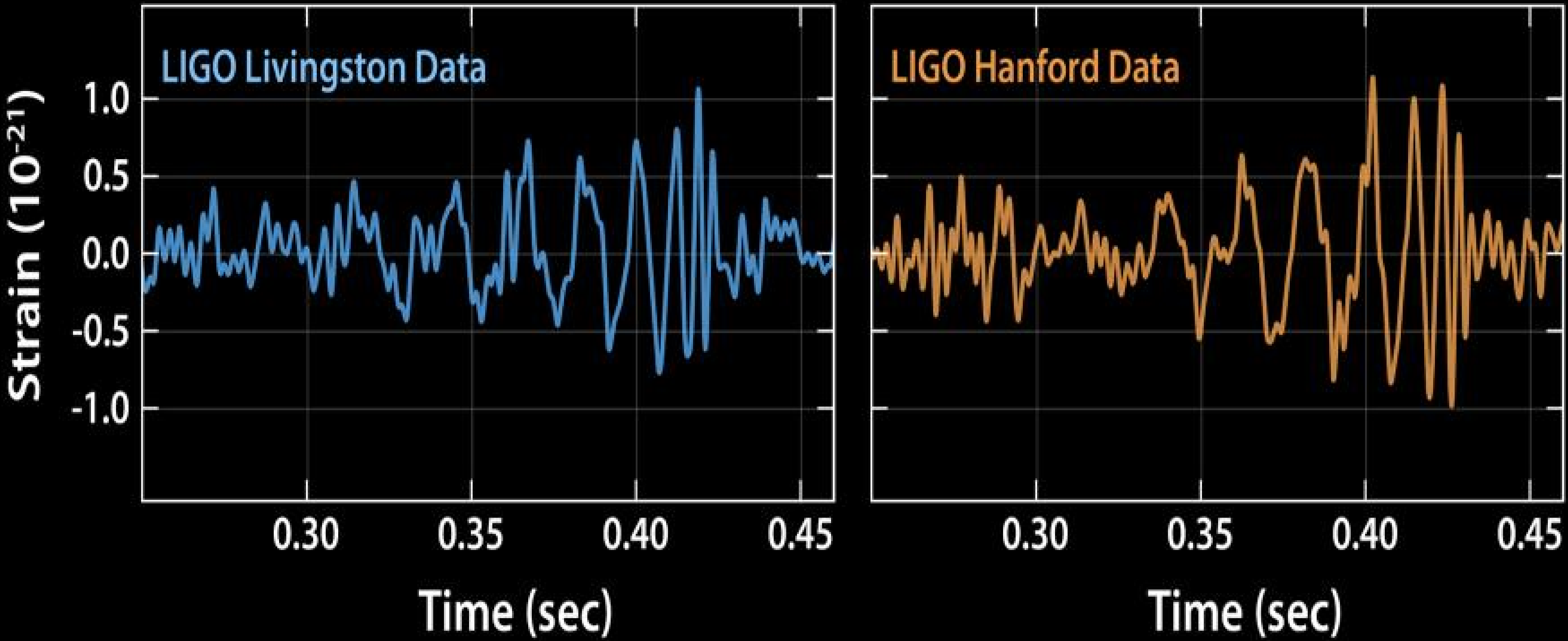

LIGO Hanford Observatory

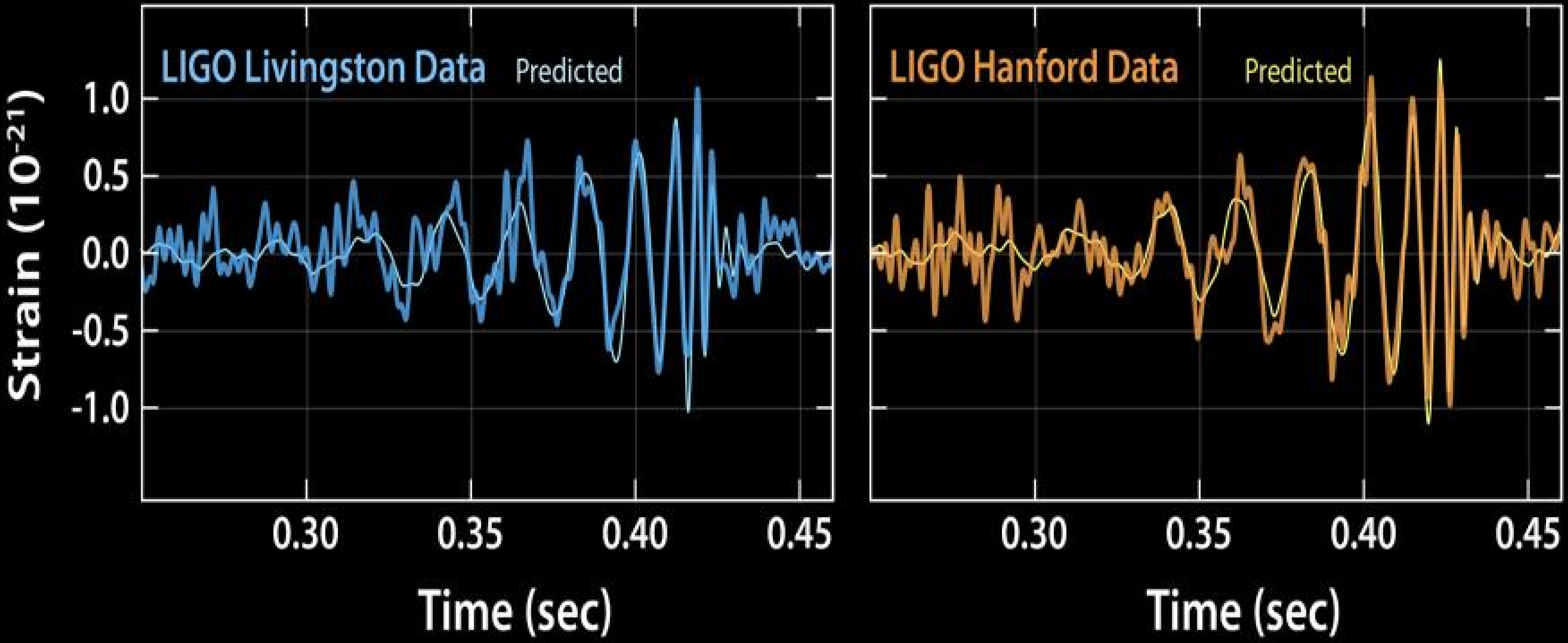
LIGO Livingston Observatory

Initial detection made by a low latency searches for generic GW transients: **Coherent WaveBurst**

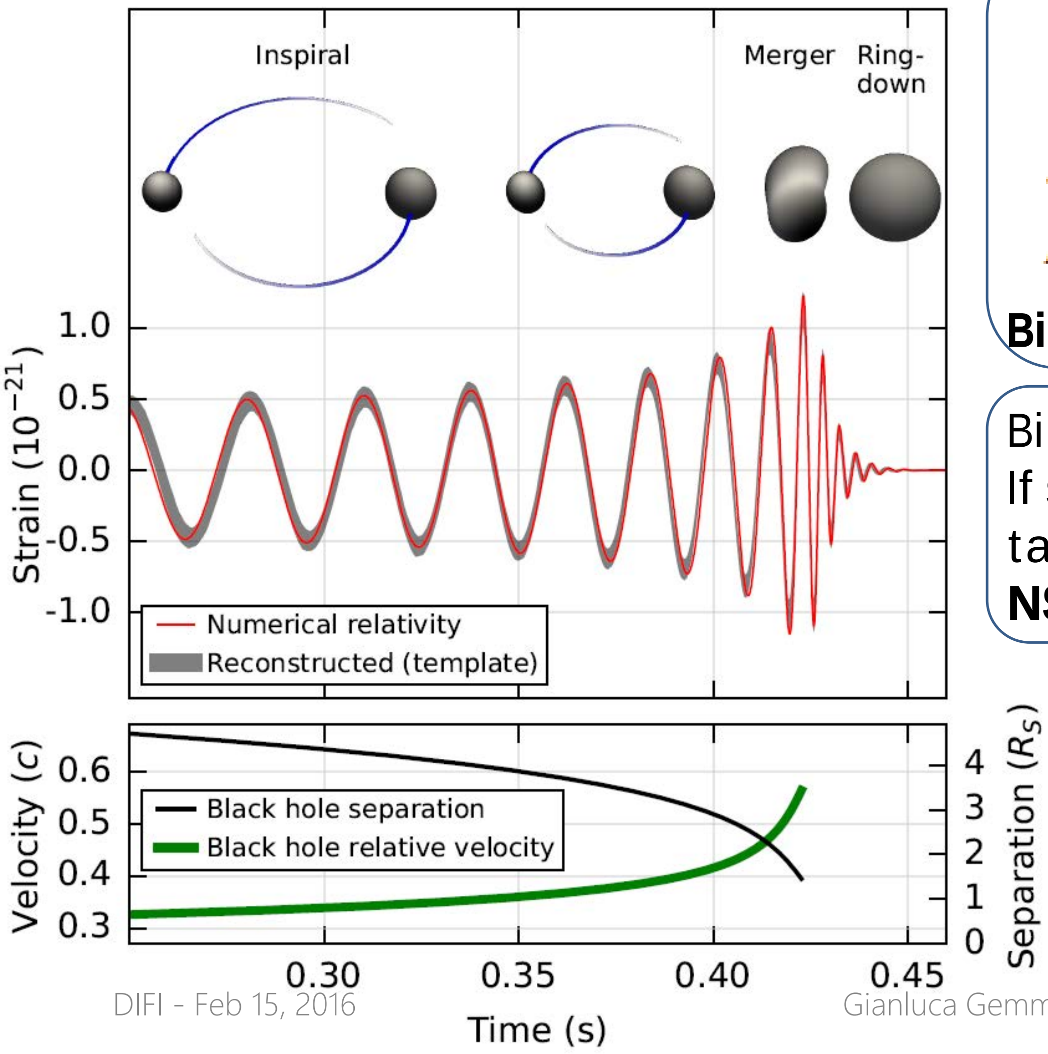
Reported within 3 minutes after data acquisition


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


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)
0.30
0.35
0.40
0.45
Time (sec)

Why black holes?



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

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

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

Binary neutron stars excluded

Binary made by one BH and one NS?
If so, M_{BH} very large ⇒Coalescence takes place at lower frequencies
NS-BH binary excluded

$$\omega_{\mathrm{Kepler-max}} = 2\pi f_{\mathrm{GW-max}}/2 = 2\pi \times 75\ \mathrm{Hz}.$$

$$R = \left[\frac{GM}{\omega^2_{\mathrm{Kepler-max}}}\right]^{1/3} \sim 350\ \mathrm{km}.$$

$$r_{\mathrm{Schwarz}}(M) = \frac{2GM}{c^2}$$ ~ **210 km**

Measuring the parameters

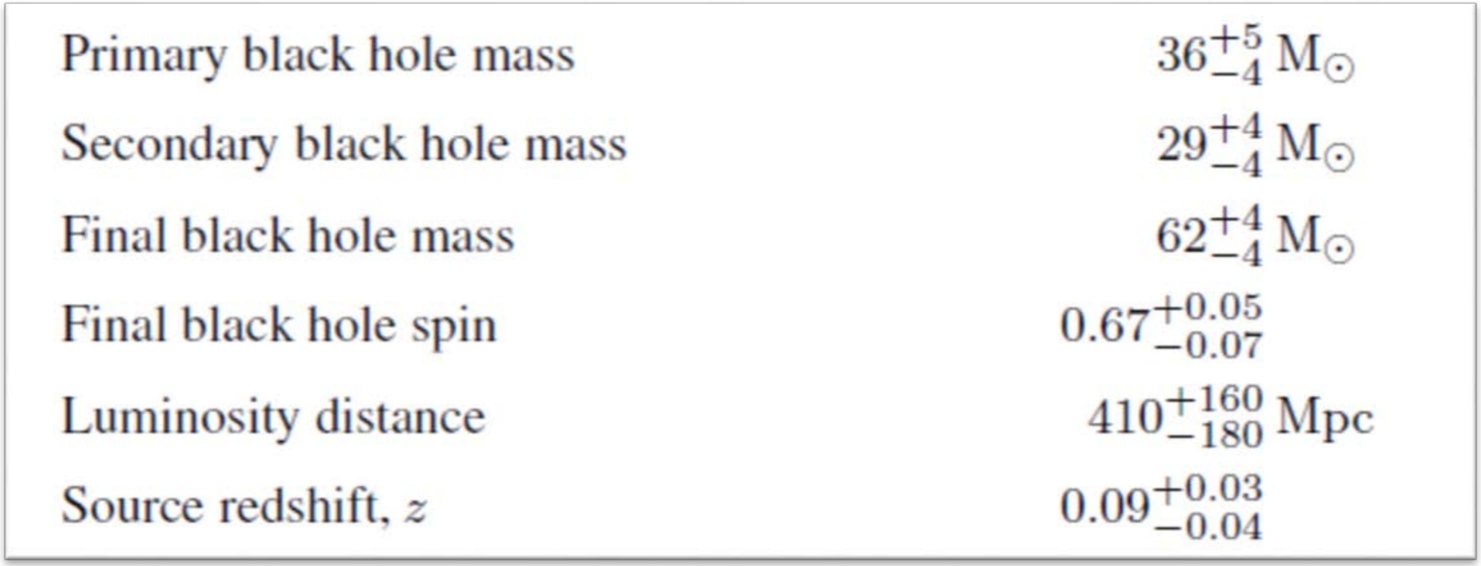
- Orbits decay due to emission of gravitational waves
  - **Leading order** determined by "chirp mass"

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

  - Next orders allow for measurement of mass ratio and spins
  - We directly measure the red-shifted masses (1+z)m
  - Amplitude inversely proportional to luminosity distance
- Orbital precession occurs when spins are misaligned with orbital angular momentum – no evidence for precession
- Sky location, and binary orientation information extracted from time-delays and differences in observed amplitude and phase in the detectors

Source Parameters for GW150914

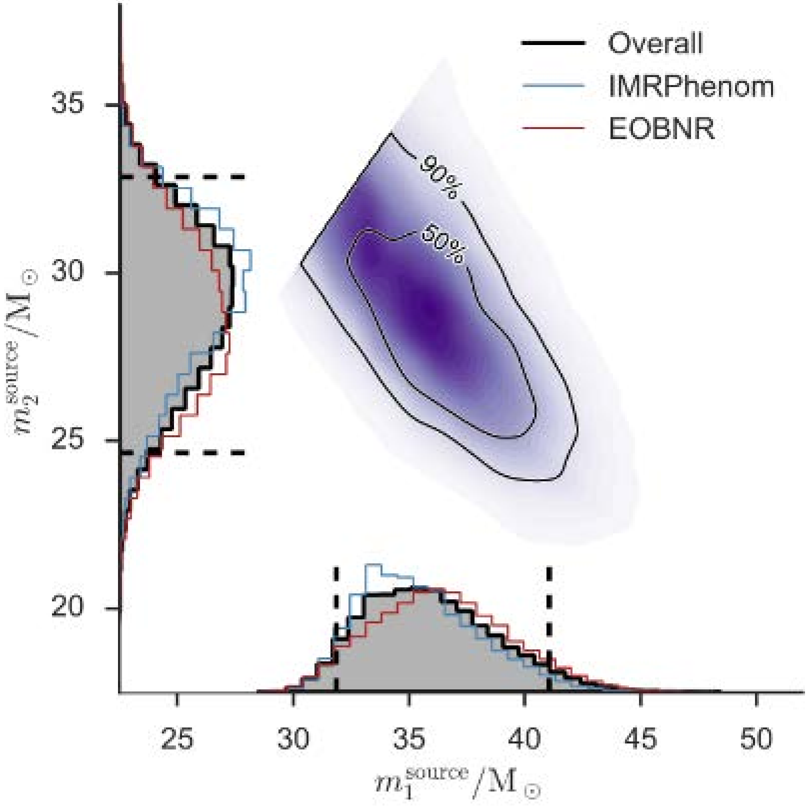
- Use numerical simulations fits of black hole merger to determine parameters, we determine total energy radiated in gravitational waves is 3.0±0.5 $M_o\, c^2$
- The system reached a peak ~3.6 x10^{56} ergs, and the spin of the final black hole < 0.7 (not maximal spin)



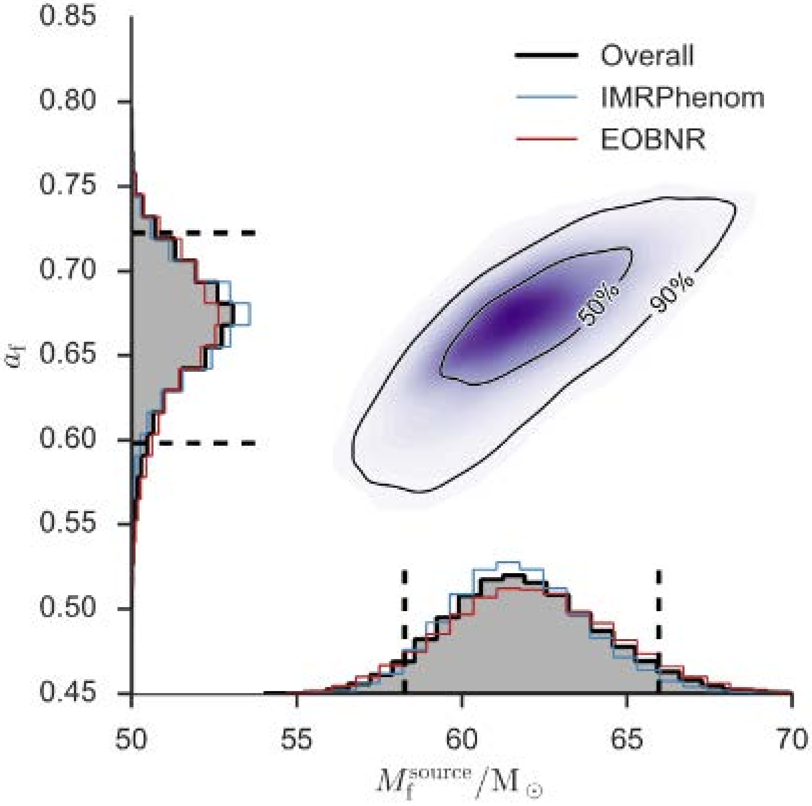
Primary black hole mass	$36^{+5}_{-4}\ \mathrm{M}_\odot$
Secondary black hole mass	$29^{+4}_{-4}\ \mathrm{M}_\odot$
Final black hole mass	$62^{+4}_{-4}\ \mathrm{M}_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	$410^{+160}_{-180}\ \mathrm{Mpc}$
Source redshift, z	$0.09^{+0.03}_{-0.04}$

Masses and spin

Component masses

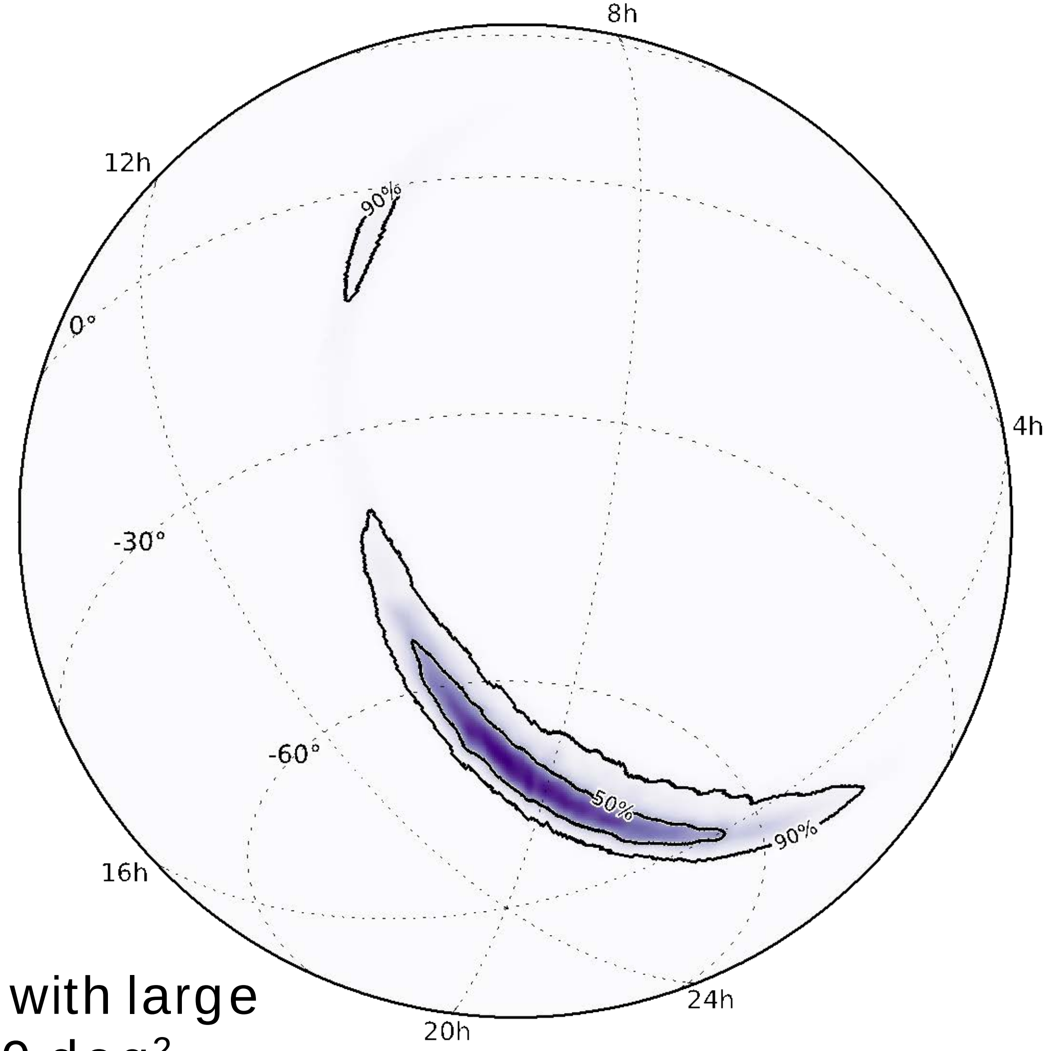


Final black hole mass and spin

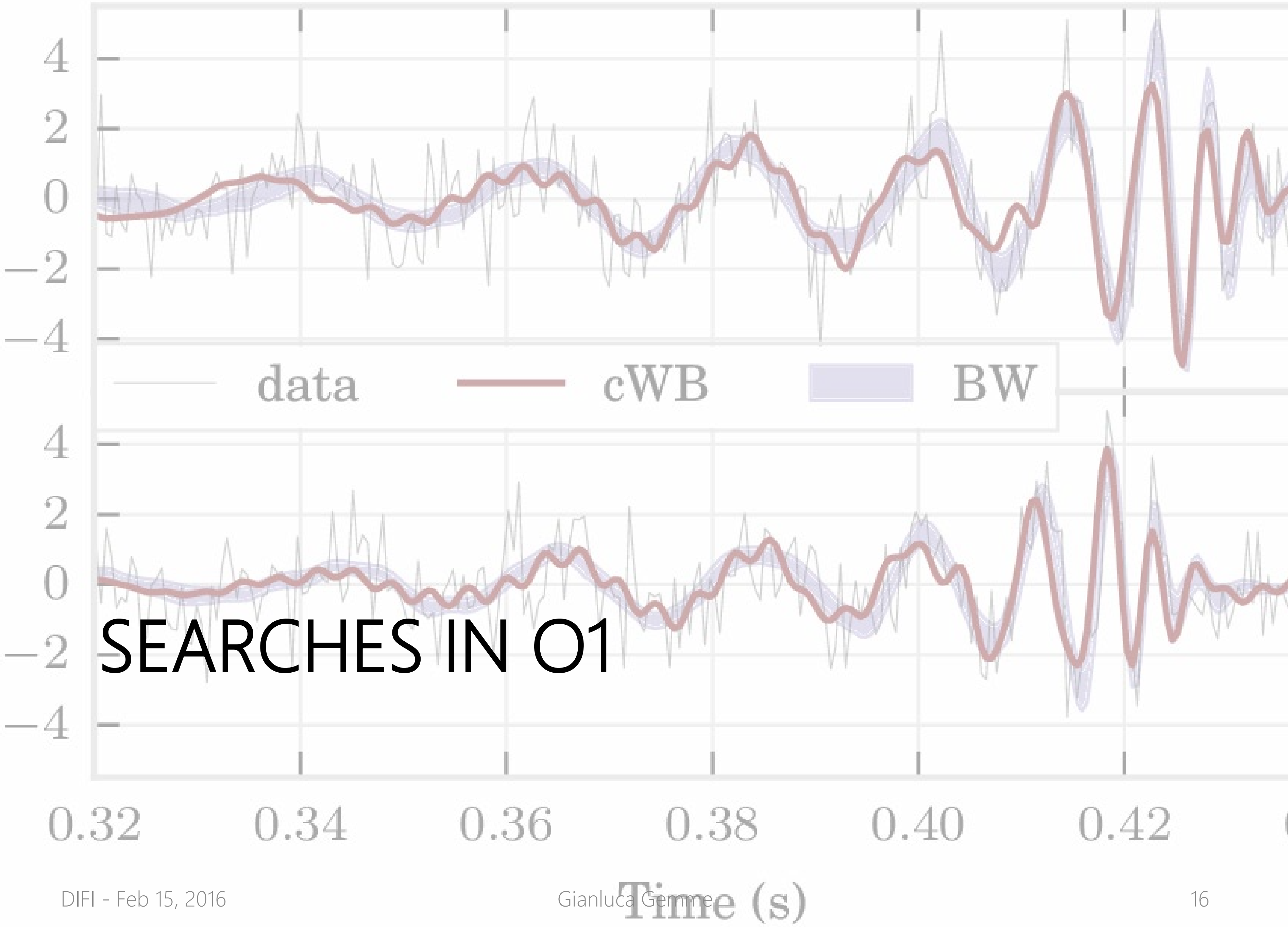


arXiv:1602.03840

Sky location



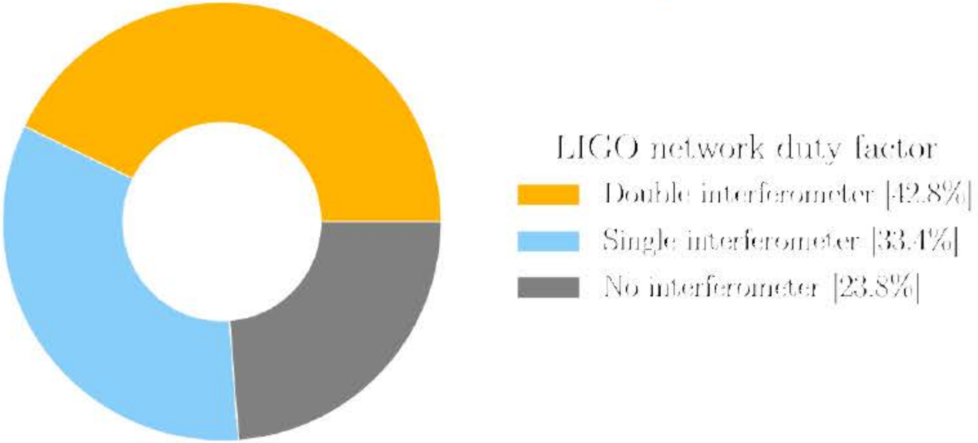
Source location with large uncertainty ~ 600 deg^2

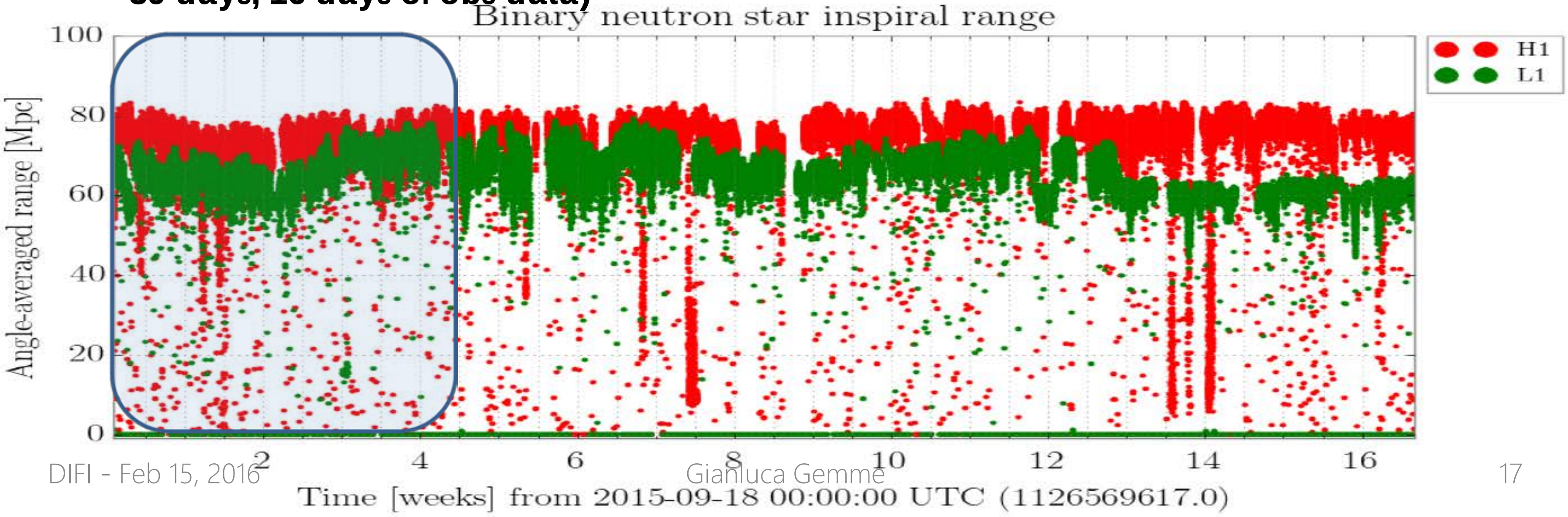


SEARCHES IN O1

O1 in a nutshell

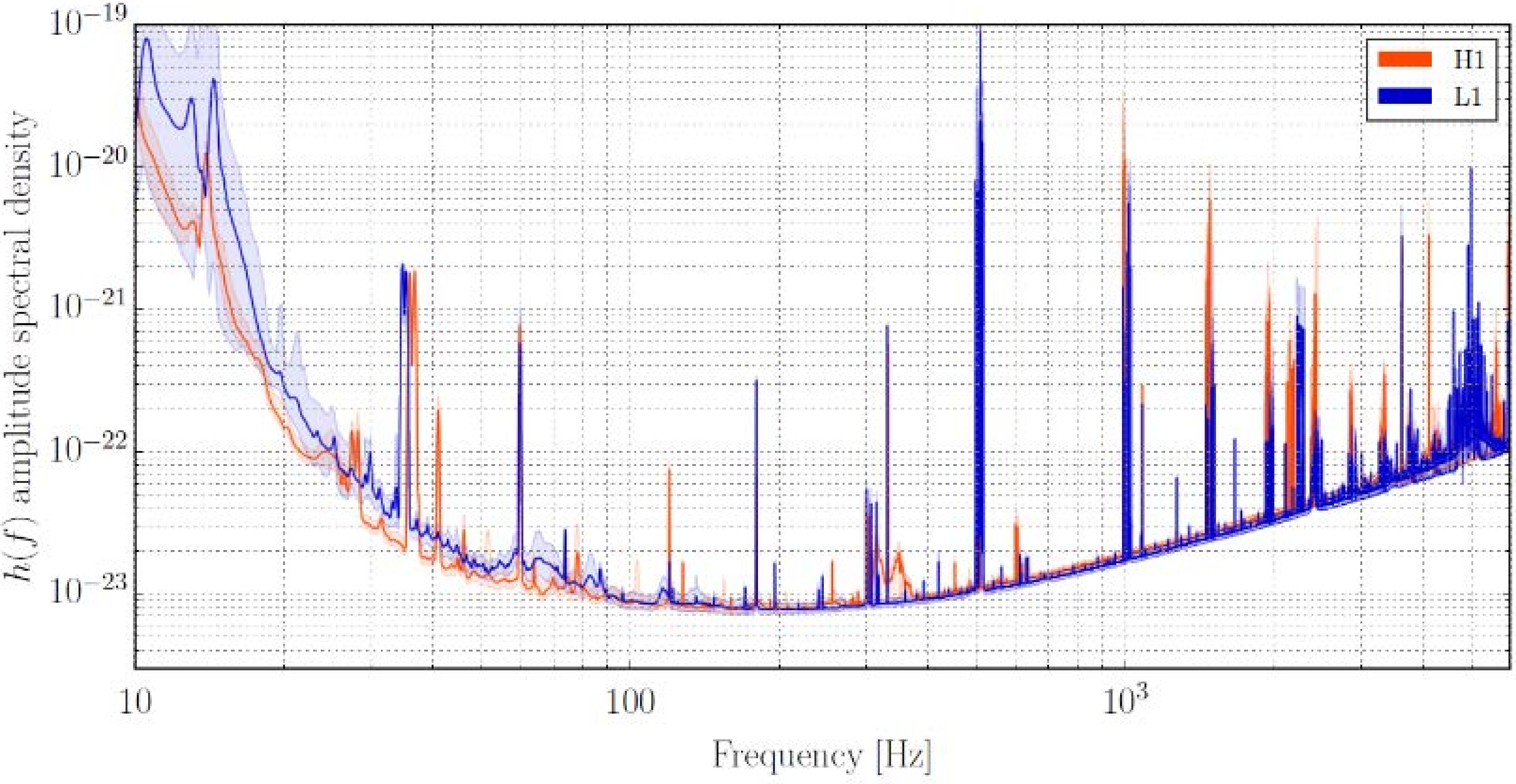
- Official dates : 18th of September 2015 to 12th of January 2016
- Dates with very good confidence : from the 12th of September to the 15th of January 2016
- H1 livetime : 62.6 %
- L1 livetime : 55.3 %





time analyzed to determine the significance of GW150914 (Sept 12 - Oct 20, 2015, 39 days, 16 days of obs data)

O1 sensitivity

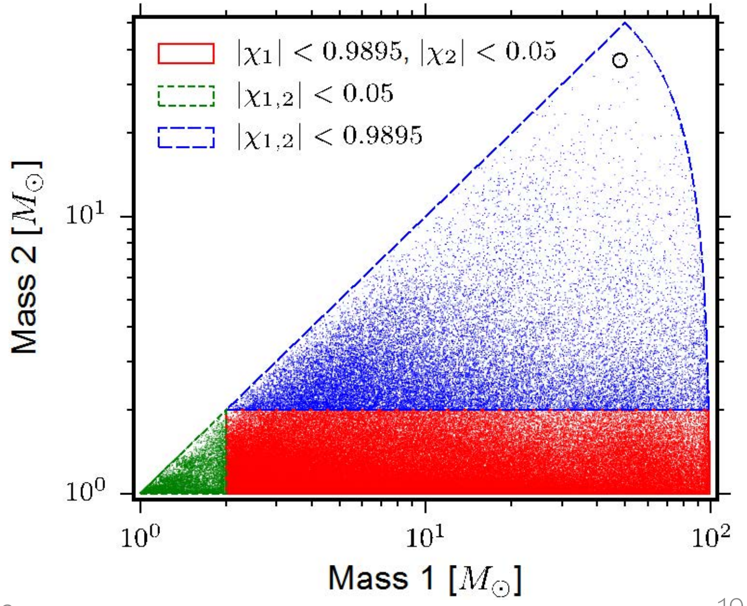


average measured strain-equivalent noise, of the Advanced LIGO detectors during the time analyzed to determine the significance of GW150914 (Sept 12 - Oct 20, 2015)

Transient Event Searches

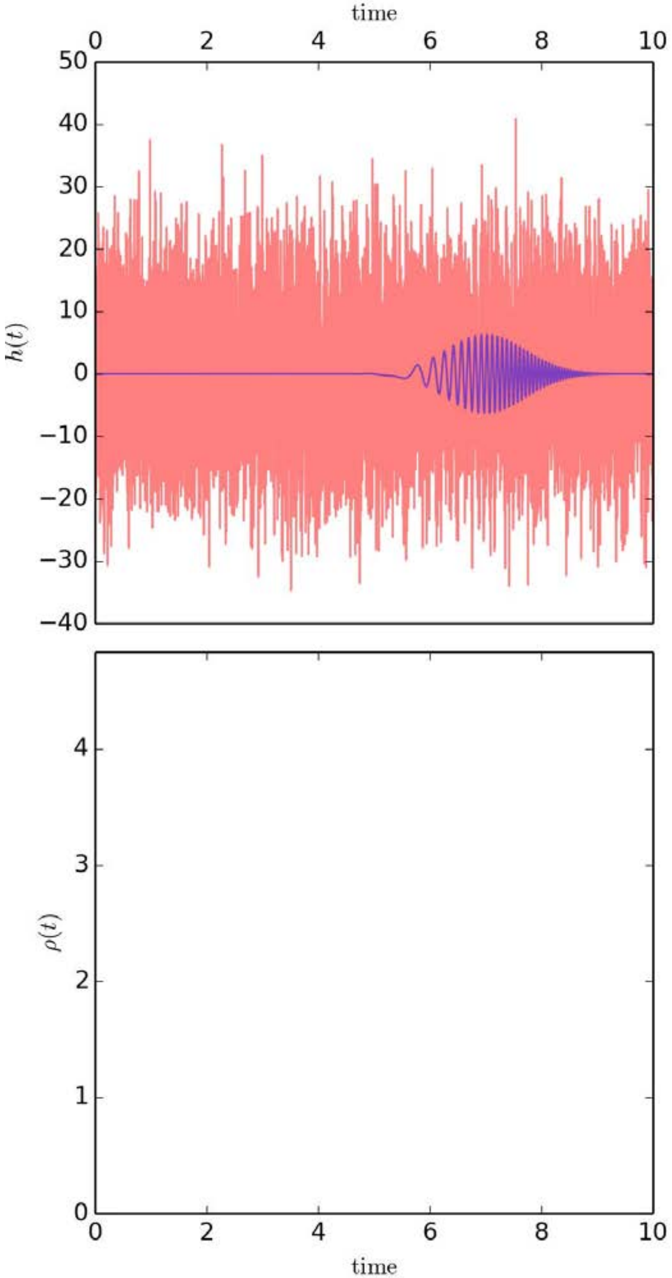
Binary Coalescence search

- Targets searches for GW emission from binary sources
- Component masses 1 to 99 solar masses;
  total mass, up to 100 solar masses
  dimensionless spin < 0.99
- ~250,000 wave forms, calculated using analytical and numerical methods, are used to cover the parameter space



arXiv:1602.03839

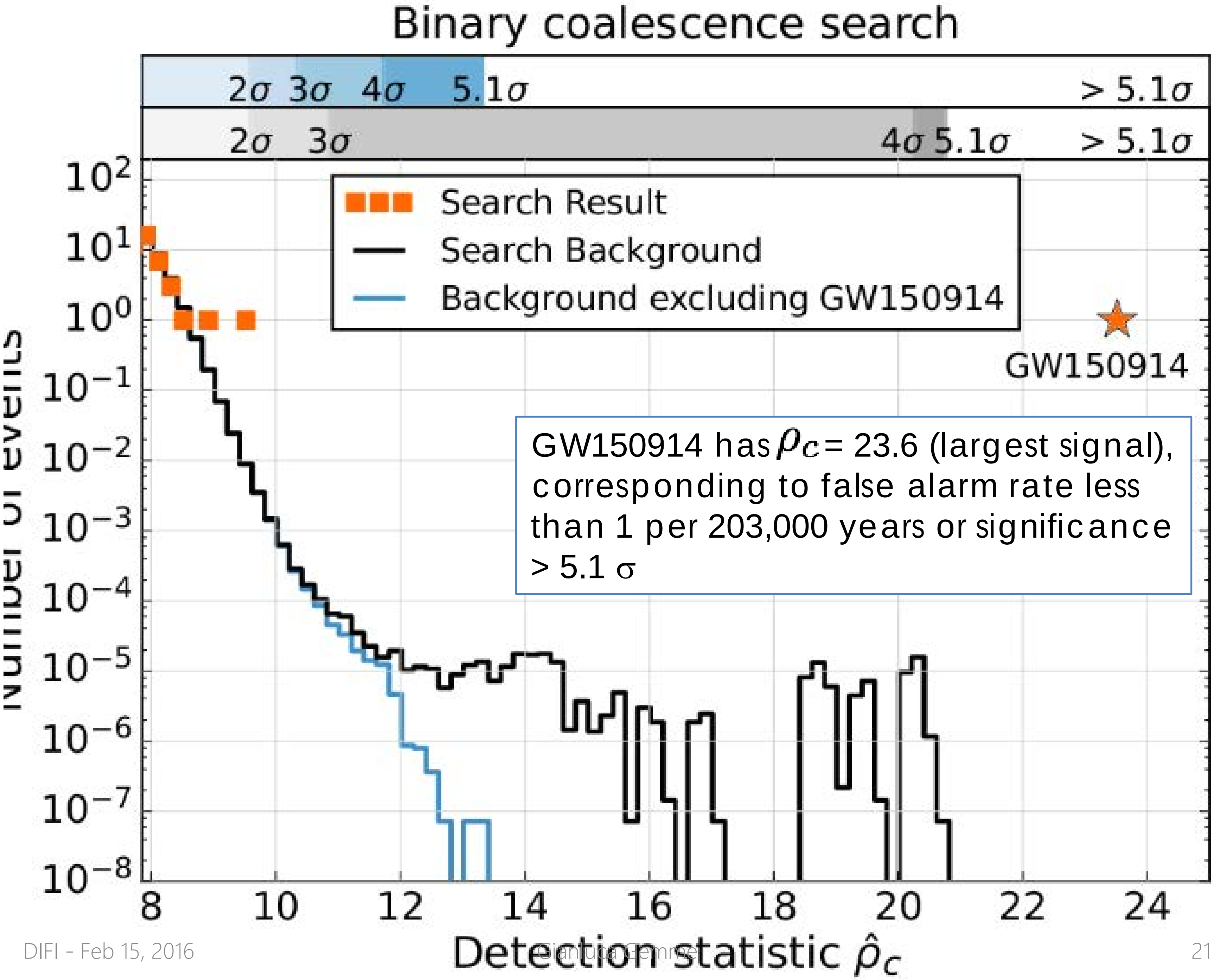
Matched filtering



- Calculate matched filter signal/noise as function of time ρ(t) and identify maxima and calculate χ^2 to test consistency with matched template, then apply detector coincidence within 15 msec

- Calculate quadrature sum ρ_c of the signal to noise of each detector

- Background: Time shift and recalculate 10^7 times equivalent to 608,000 years



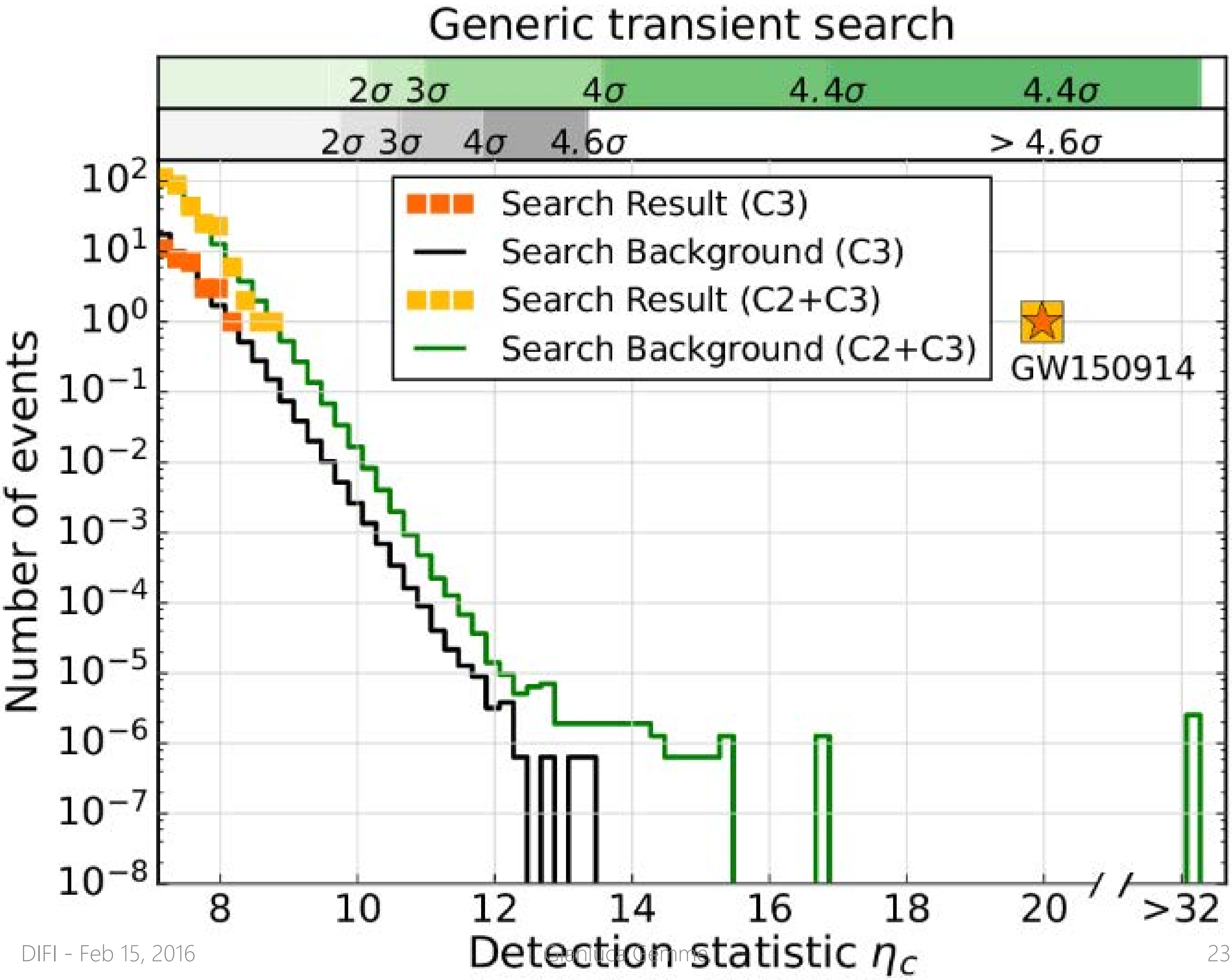
GW150914 has $\rho_c = 23.6$ (largest signal), corresponding to false alarm rate less than 1 per 203,000 years or significance > 5.1 σ

Transient Event Searches

Generic Transient Search

- No specific waveform model: identifies coincident excess power in time-frequency representations (f < 1 kHz and t < few seconds)
- Reconstruct waveform 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 by cross correlating the two reconstructed waveforms and E_n is residual noise energy
- Restricting to events with f increasing with time, GW150914 is the strongest event in the search with $\eta_c = 20$
- Yields false alarm rate < 1 per 22,500 years
- Probability of background event during data run $< 2\ 10^{-6}$ or $> 4.6\ \sigma$

arXiv:1602.03843


Generic transient search
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
Number of events
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
8
10
12
14
16
18
20
>32
Detection statistic η_c

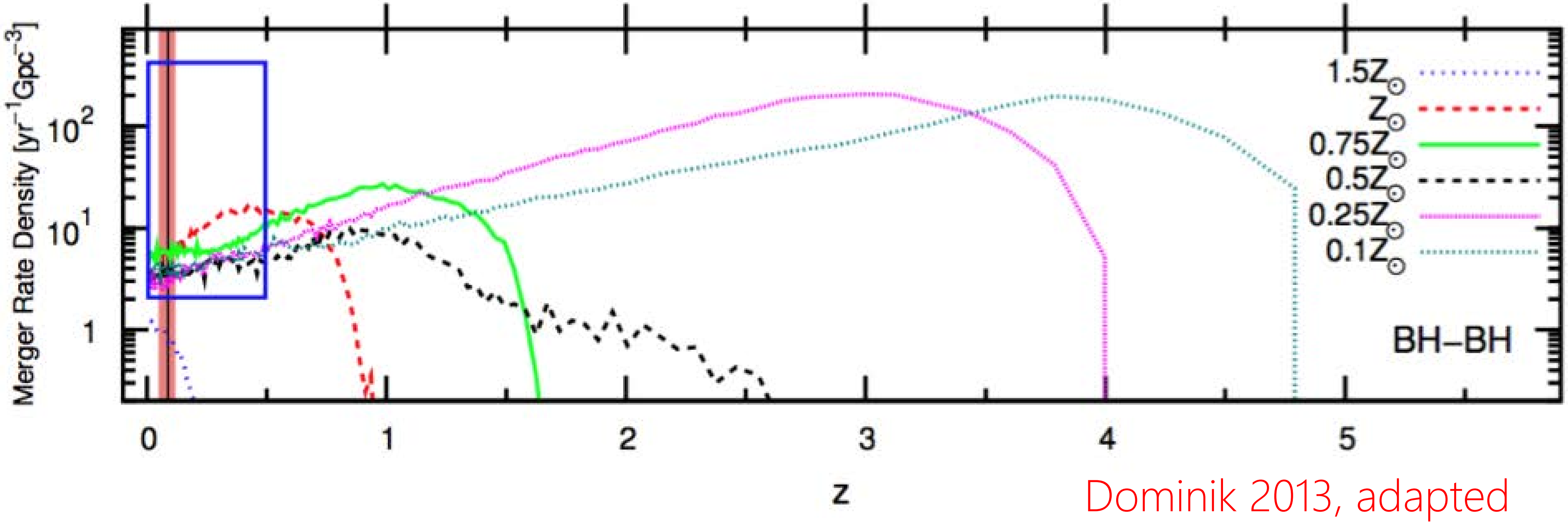
IMPLICATIONS OF GW150914

Astrophysics implications
Key facts

- Binary black holes do exist!
  - **Form** and **merge** in time scales accessible to us
  - Predictions previously encompassed $[0 - 10^3]$ / Gpc^3 / yr
  - Now we exclude lowest end: **rate > 1 Gpc^3 / yr**
- Masses ($M > 20\ M_\odot$) large compared with *known* stellar mass BHs
- Progenitors are
  - Likely **heavy**, $M > 60\ M_\odot$
  - Likely with a **low metallicity**, $Z < 0.25\ Z_\odot$
- Measured redshift $z \sim 0.1$
- **Low metallicity models can produce low-*z* mergers at rates consistent with our observation**

ApJL, 818, L22, 2016

A bright future?



Dominik 2013, adapted

- GW150914 BBH could have been born either
  - **Recently**, with a short merger time
  - **Earlier**, with a long merger time
  - We cannot distinguish with a single observation
- Depending on models, at higher redshifts the rate increases!
  - Potential for a *very* bright aLIGO, AdV future!

Testing GR

- Most relativistic binary know today : J0737-3039
  - Orbital velocity $v/c \sim 2 \times 10^{-3}$

- GW150914 : Higly disturbed black holes
  - Non linear dynamics
- Access to the properties of space-time
  - Strong field, high velocity regime testable for the first time

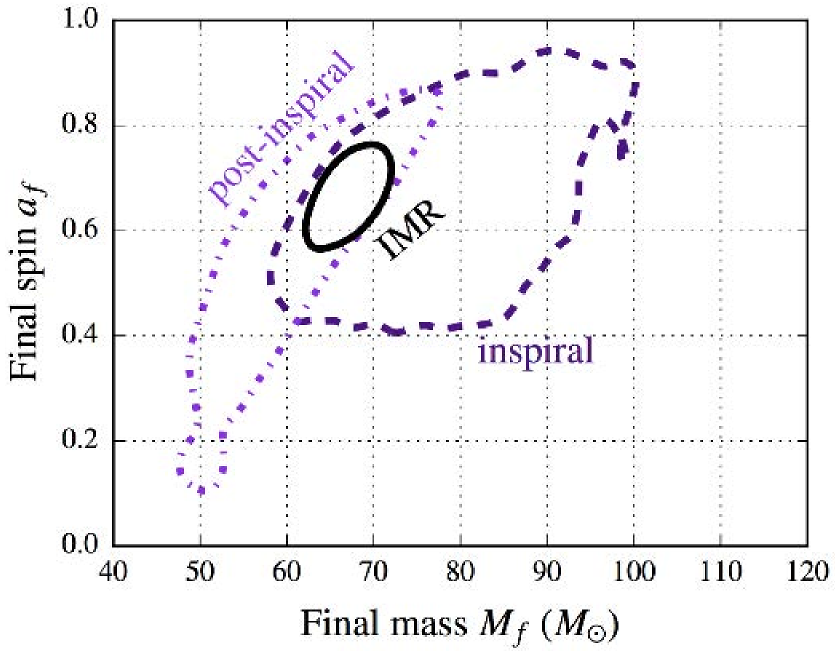
$$v/c \sim 0.6$$

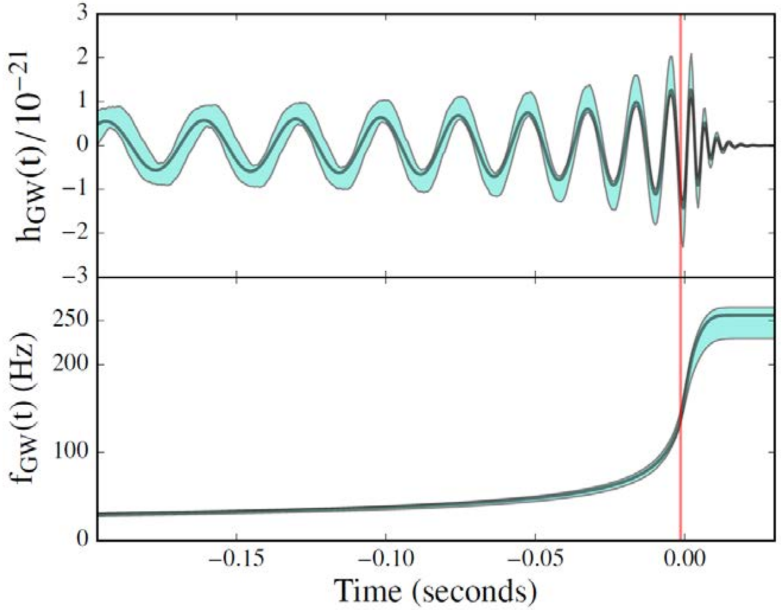
- Tests :
  - Waveform internal consistency check
  - Deviation of PN coefficients from General Relativity
  - Bound on graviton mass

- All tests are consistent with predictions of General Relativity

arXiv:1602.03841

Waveform internal consistency





1. Predict final black hole mass and spin from the inspiral signal
2. Predict final black hole mass and spin from the ring-down phase
3. Compare to check consistency of GR in different regimes

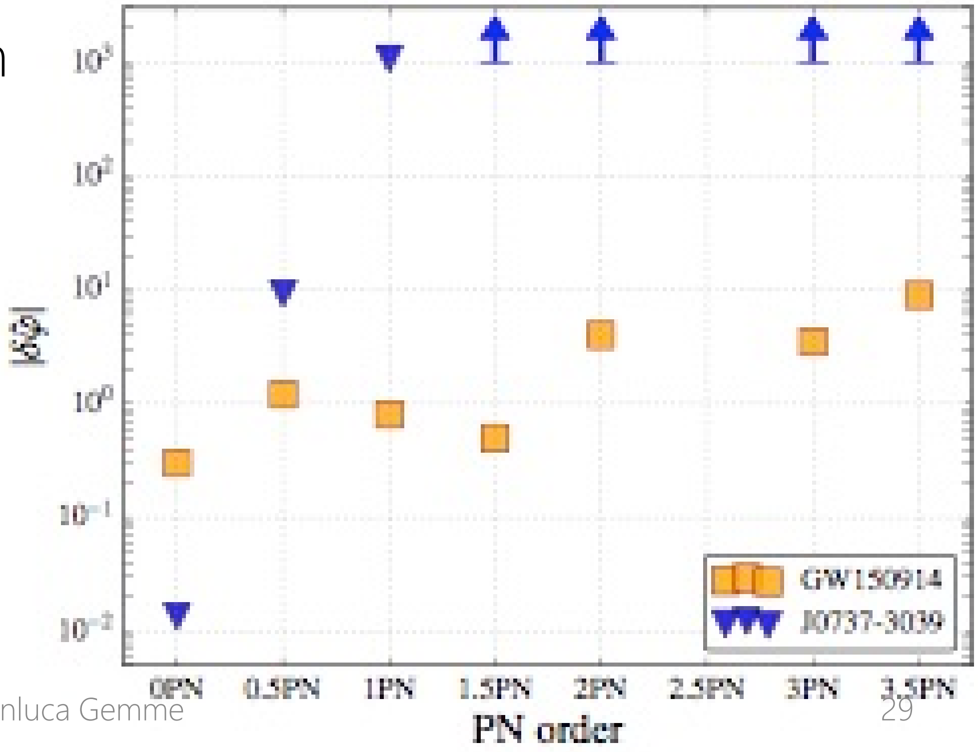
arXiv:1602.03841

Deviation of PN coefficients from GR

- Post Newtonian formalism
- Phase of the inspiral waveform -> power series in $f^{1/3}$
- Nominal value predicted by GR
- Allow variation of the coefficients

  -> Is the resulting waveform consistent with data ?

- No evidence
  for violations of GR



arXiv:1602.03841

Upper bound on the graviton mass

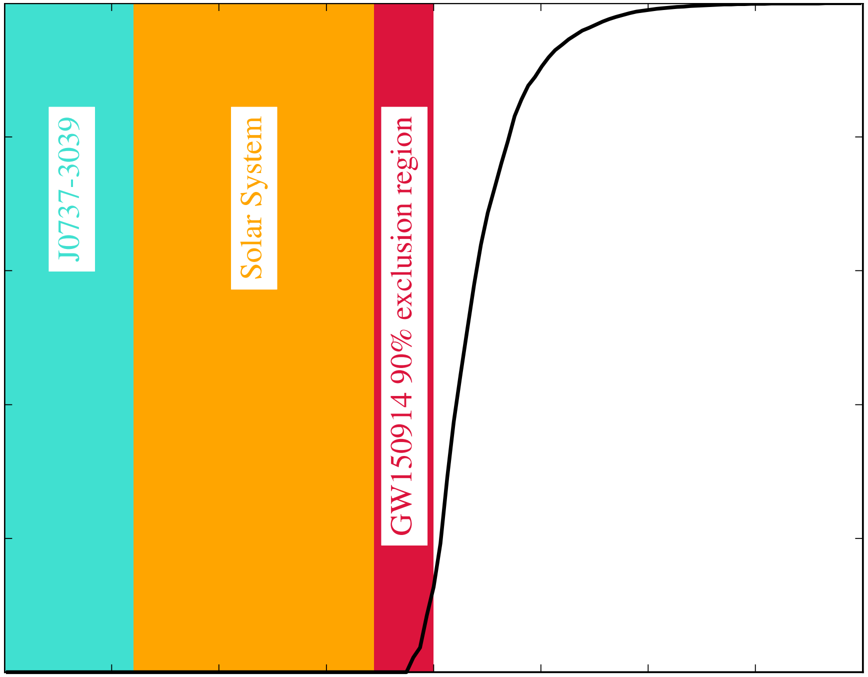
- If $c_{GW} < c$

⇔ gravitational waves have a modified dispersion relation

- Findings : at 90 % confidence, $\lambda_g > 10^{13}\ \mathrm{km}$

or equivalently

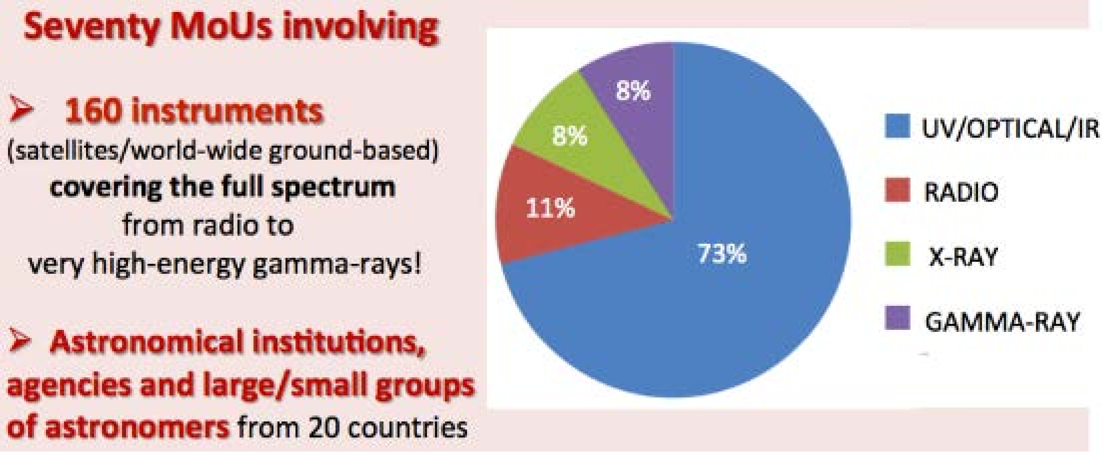
$m_g < 1.2 \times 10^{-22}\ \mathrm{eV/c^2}$



[arXiv:1602.03841](https://arxiv.org/abs/1602.03841)

EM follow-up key facts

- LVC called for EM observers to join a follow-up program
  - LIGO and Virgo share *promptly* with astronomers interesting triggers; up to a few at current sensitivity
  - Provide limited directional information, promptly estimated

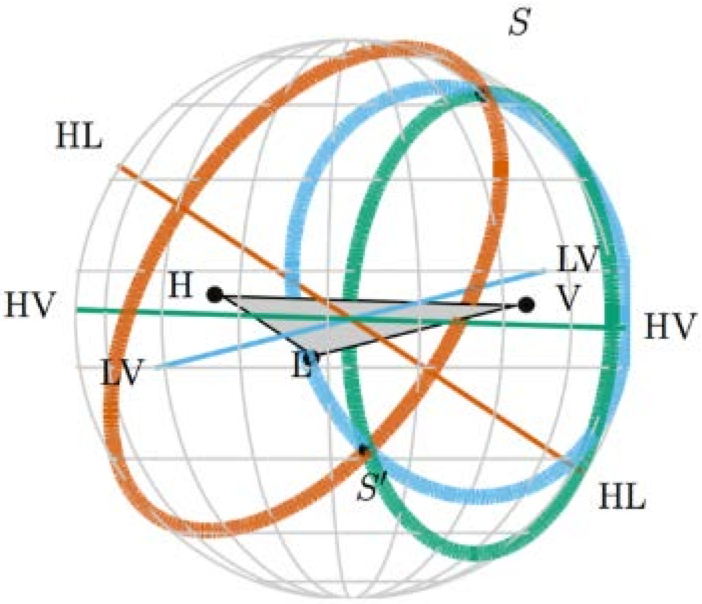


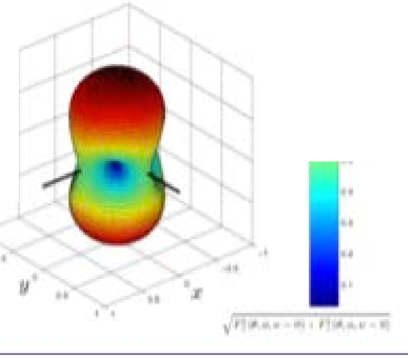
Seventy MoUs involving

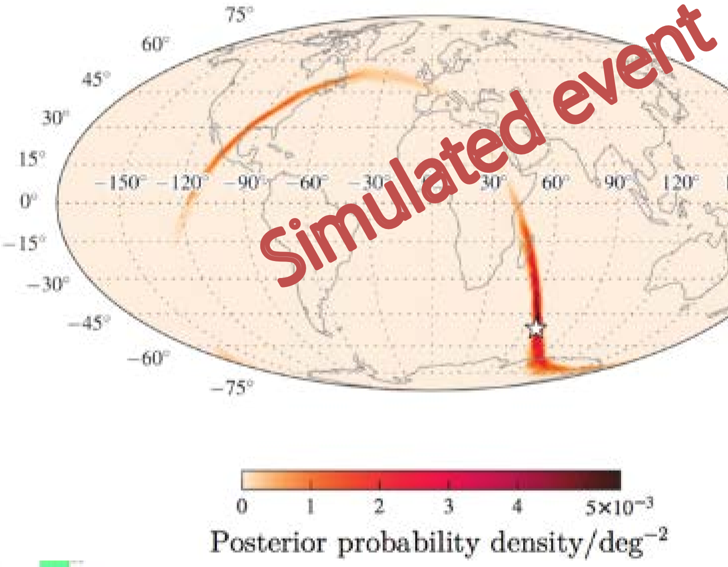
- ➢ **160 instruments** (satellites/world-wide ground-based) **covering the full spectrum** from radio to very high-energy gamma-rays!
- ➢ **Astronomical institutions, agencies and large/small groups of astronomers** from 20 countries

- Big participation to GW150914 observation:
  - 24 groups carried out observations
  - Challenging! Source location with large uncertainty ~ 600 deg^2

Why is our error box so large?





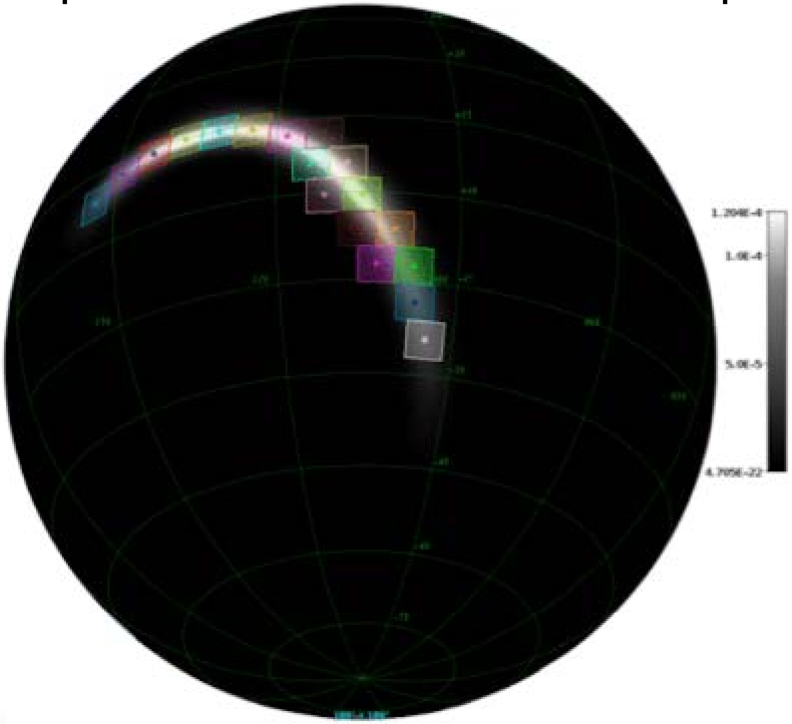


- Two interferometers (HL), each with poor directionality, determine by time delay an **annulus** in the sky
- Folding in also amplitude information, we can do a bit better (*in the RHS, a **simulation** with a BNS event*)

How do we cope? With telescope time..

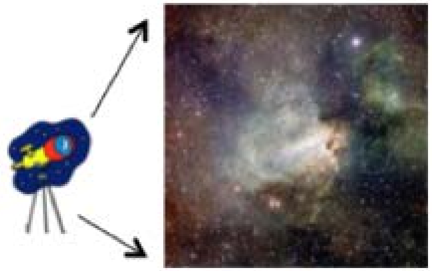
```
Python 2.7.6 (default, Jun 22 2015, 17:58:13)
[GCC 4.8.2] on linux2
Type "copyright", "credits" or "license()" for more information.
>>> import GWsky
>>> GWsky.main()
 Load a probability skymap
 : bayestar.fits(11).gz
////////////////////////////////////
 Provide the probability value (< 1) to define the confidence region;
(e.g. 1 for all the sky, 0.5 to manage only the 50% confidence region)
 : 0.90
The area confined in 90.0% of probability is 805.83 deg^2.

 The table that contained those pixels is displayed in Aladin plane
 < contour_ipix.out >
////////////////////////////////////
 Insert the size of your Field of View (FoV);
 x[deg], y[deg] : 
```



- A *sky map* produced by LIGO and Virgo is tiled with multiple observations, searching for transients
- Looking for fading objects, repeat observations after days

.. and smart algorithms

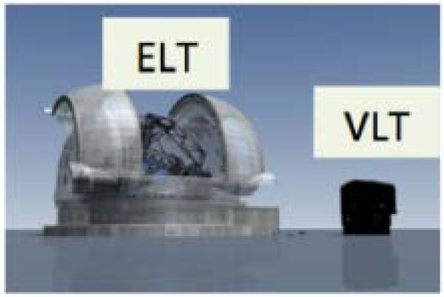


Wide-field telescope
FOV >1 sq.degree

⬇

"Fast" and "smart" software to select a sample of candidate counterparts

⬇

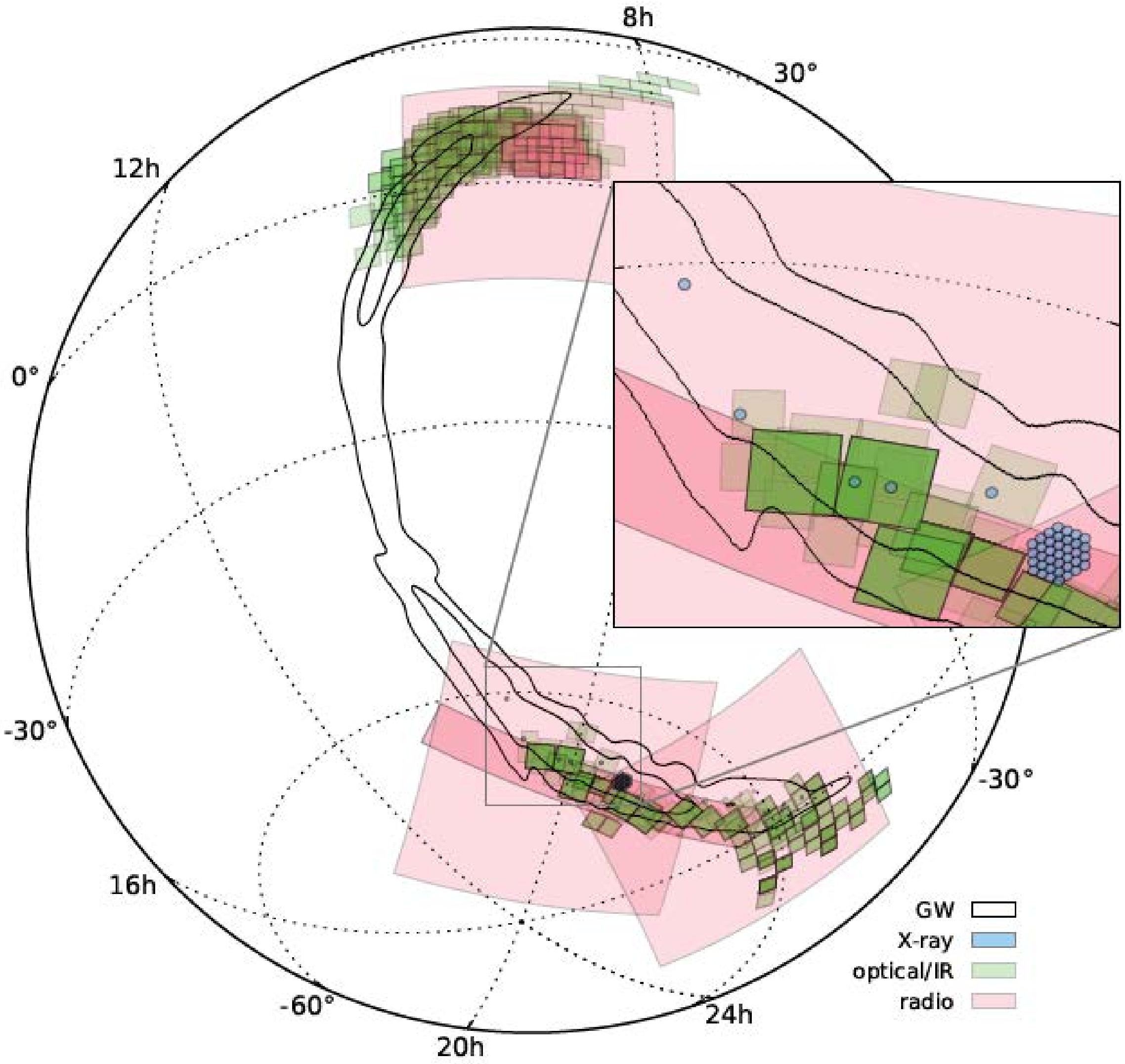


Larger telescope to **characterize** the candidate nature

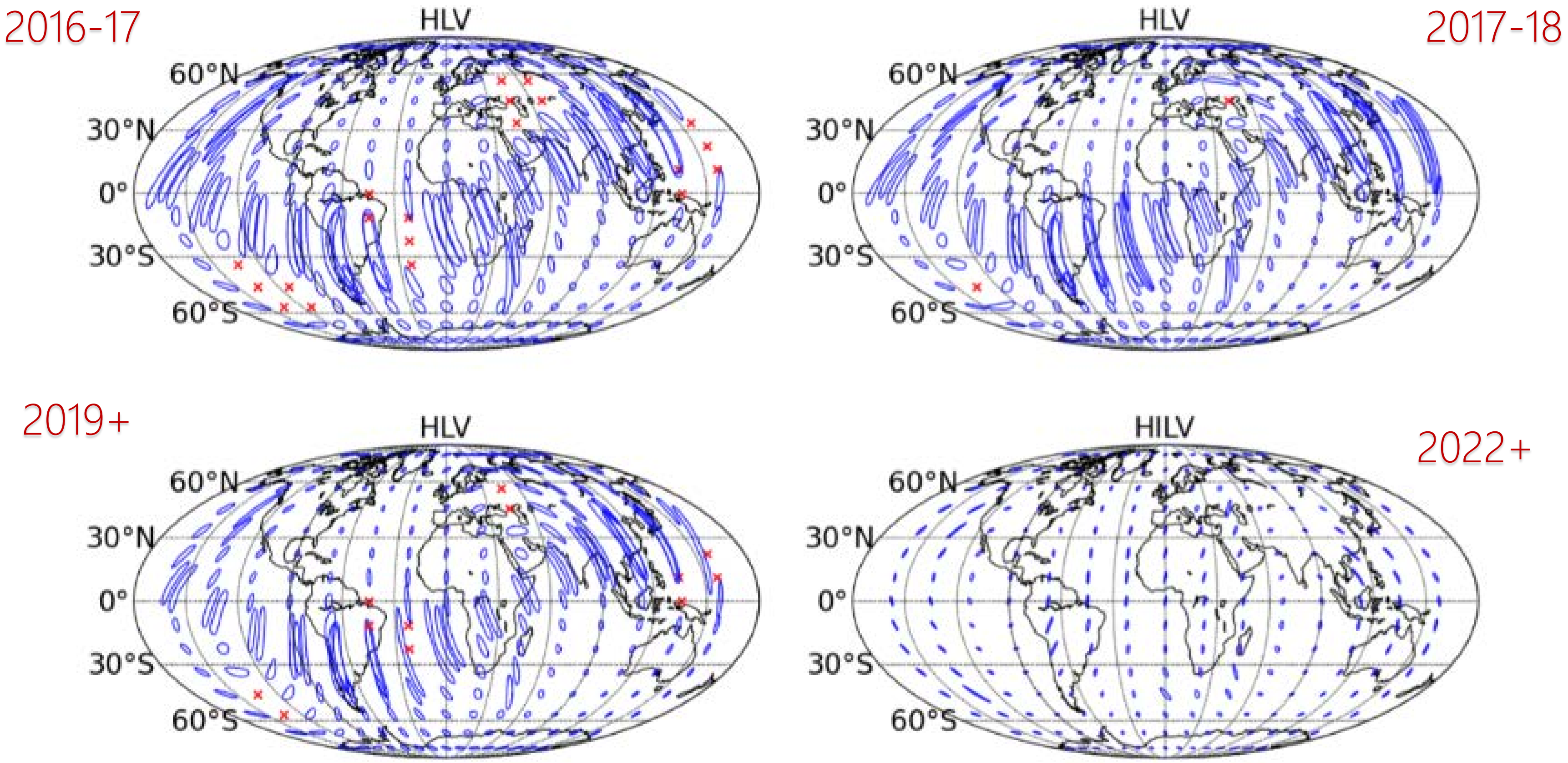
⬇

The EM Counterpart!

Aasi et al. 2014, ApJS, 211


8h
30°
12h
0°
-30°
-30°
16h
-60°
20h
24h
GW
X-ray
optical/IR
radio

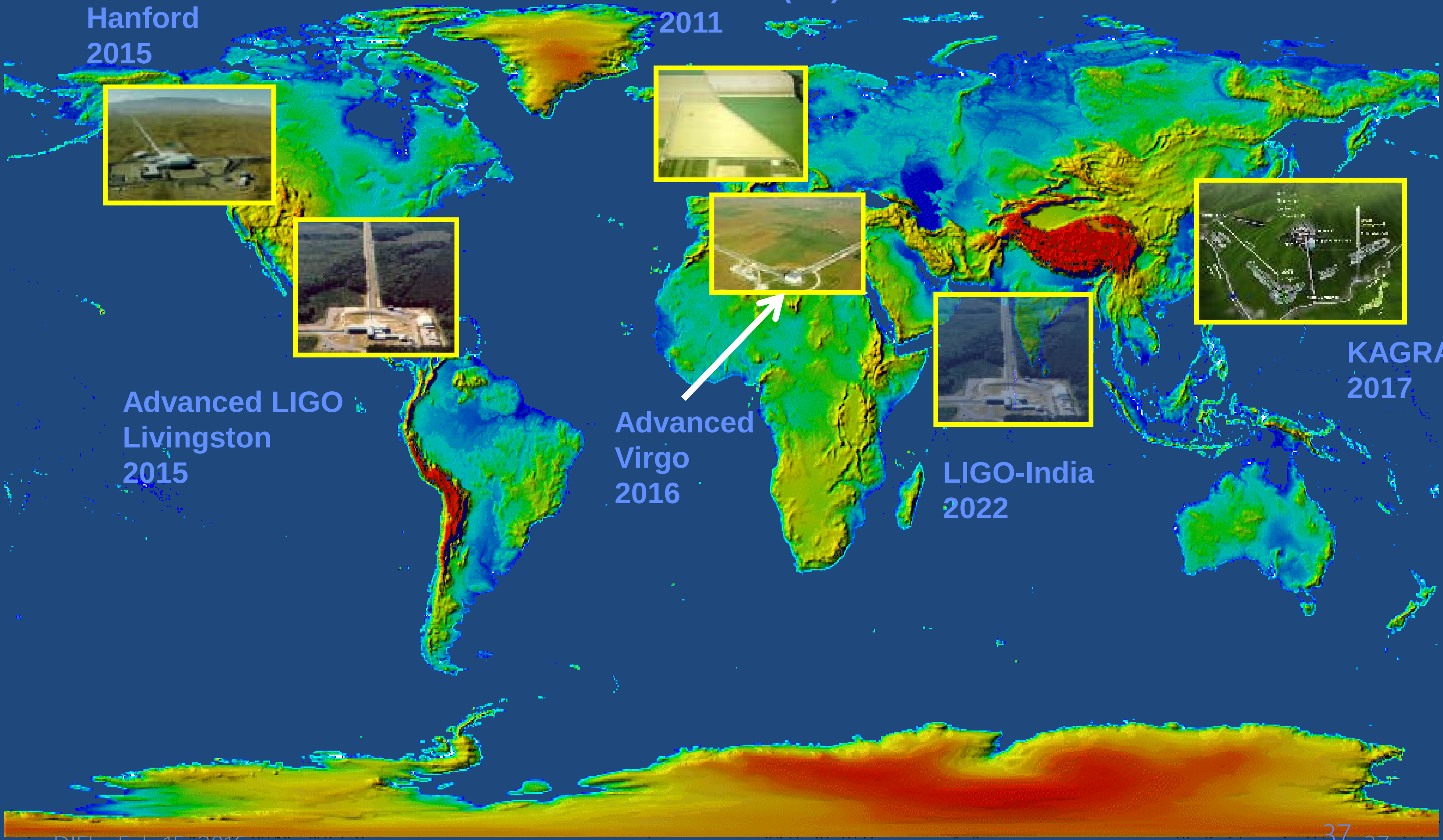
In the future, we’ll be more precise



- Adding Virgo will break the annulus
- As sensitivity progresses, so does the localization
- In the design LIGO-Virgo network, GW150914 could have been localized to less than 20 deg^2

The advanced GW detector network:

2015-2025



Advanced LIGO
Hanford
2015

GEO600 (HF)
2011

Advanced LIGO
Livingston
2015

Advanced
Virgo
2016

LIGO-India
2022

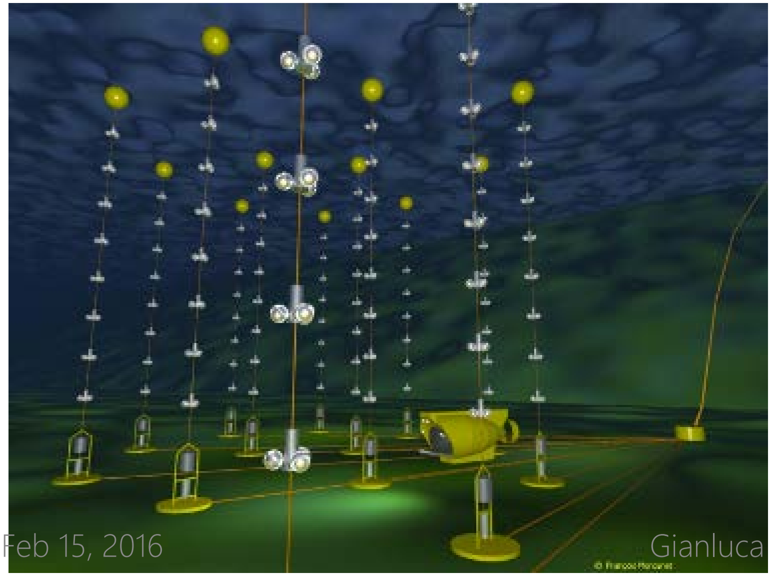
KAGRA
2017

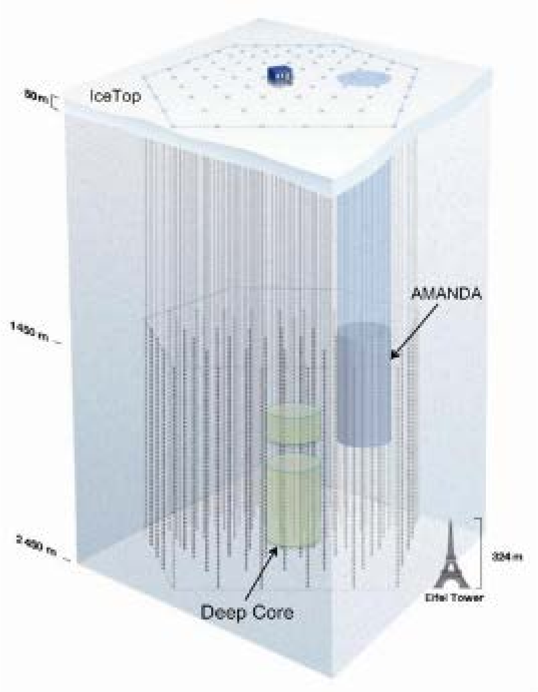
Any neutrino background ?

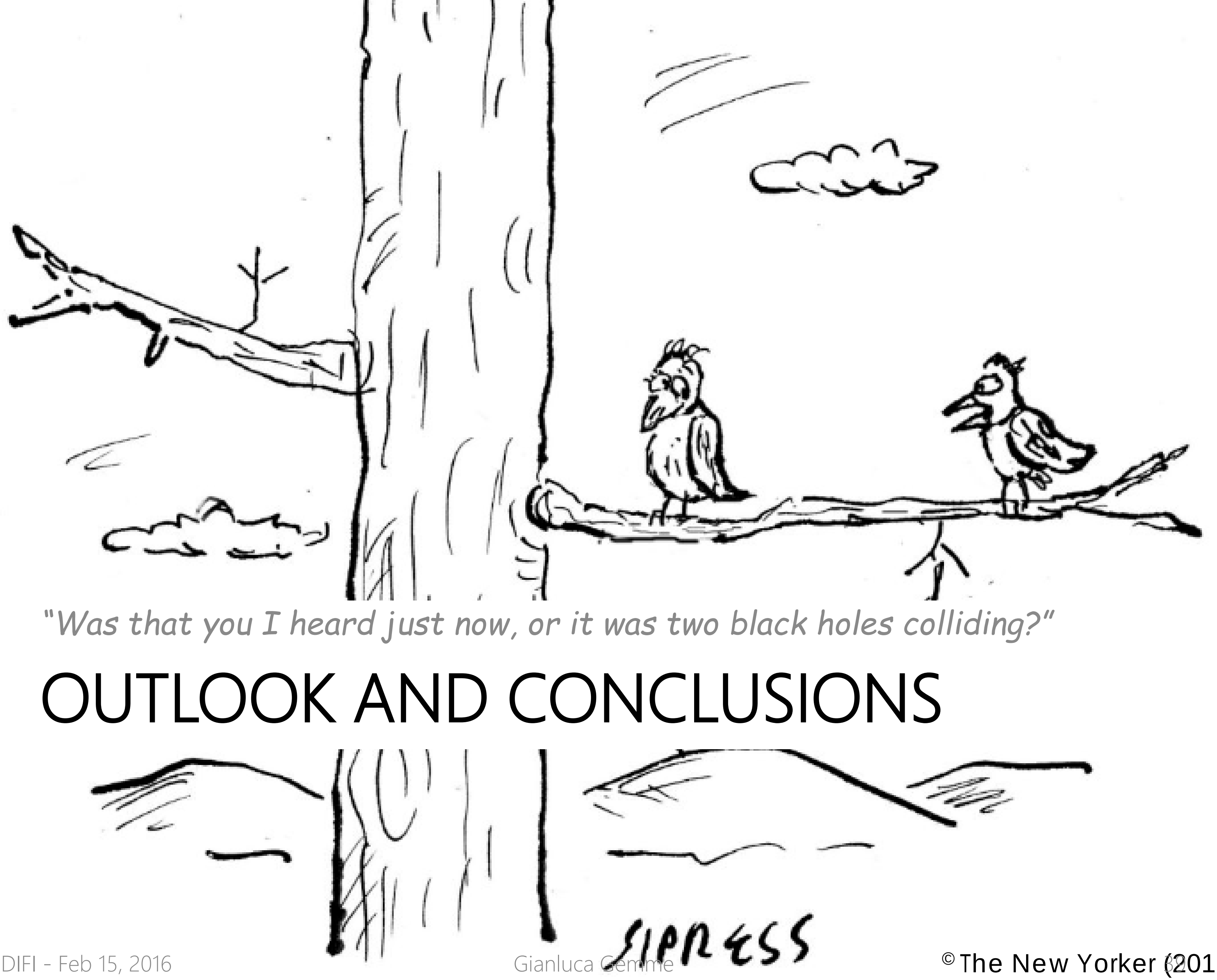
- IceCube, Antares are looking for coincident ν
- Search a 500s window of the GW event: already used in the past, safe even with a light neutrino, for high-energy ν

$$\Delta t_{prop} = 200s \left(\frac{d}{400Mpc}\right)\left(\frac{m_\nu}{1eV}\right)\left(\frac{10MeV}{E_\nu}\right)^2$$

- Analysis is under way



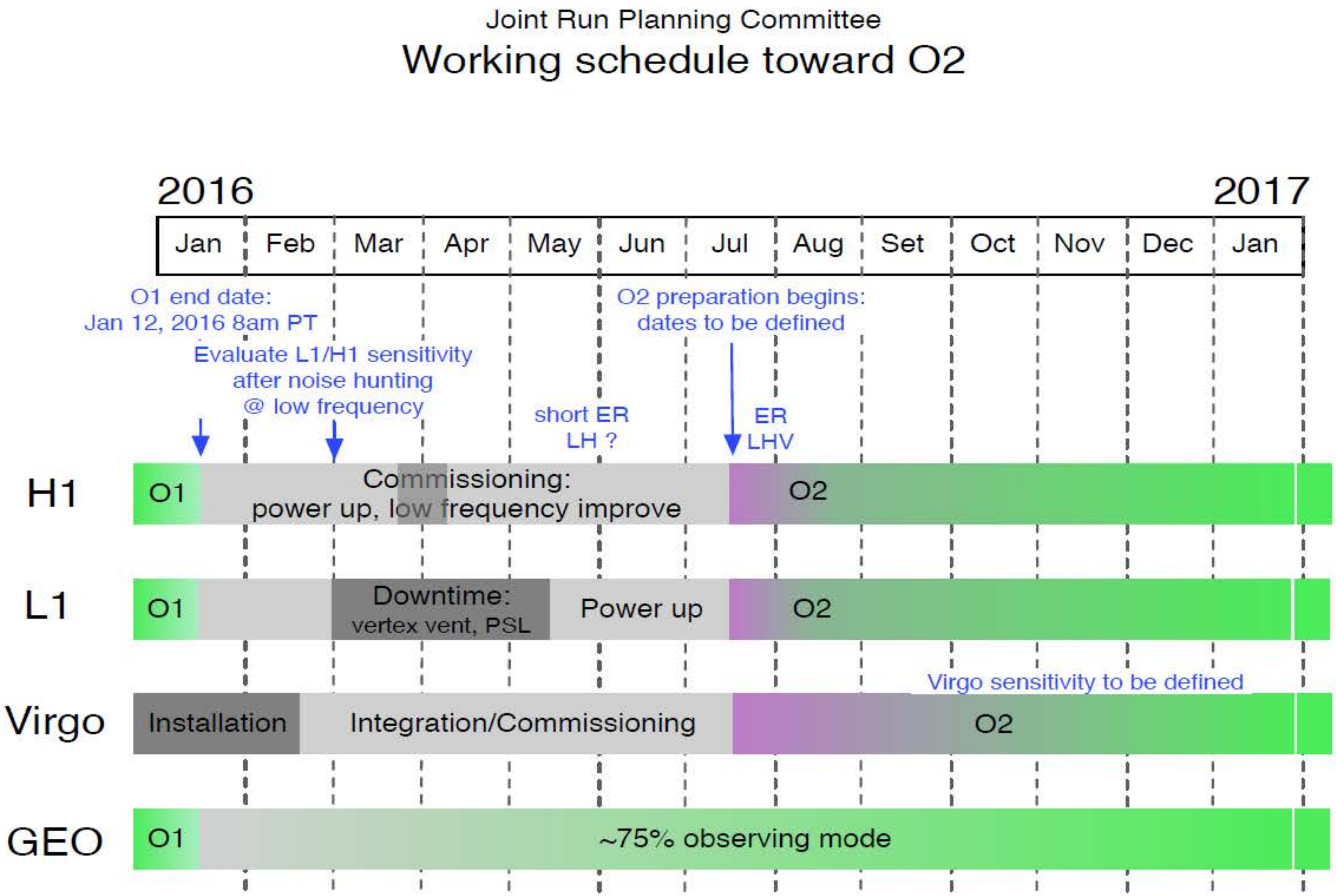




"Was that you I heard just now, or it was two black holes colliding?"

OUTLOOK AND CONCLUSIONS

Towards O2



Joint Run Planning Committee

Working schedule toward O2

BBH rates

- GW150914 observation → interesting rate of BBH events
  - Range within 2 – 400 / Gpc^3 / yr
  - High mass binary→ loud signal → visible far away
- At high redshifts, could be many more sub-threshold
  - Not detectable as individual signals
  - Potentially detectable as a correlated noise among detectors
- Predictions *in principle* model dependent
  - Depend on **Star Formation Rate**
  - Depend on **delay between formation and merger**, in turn depending on initial eccentricity, spin ….
  - We've got just one observation, hard to constrain models

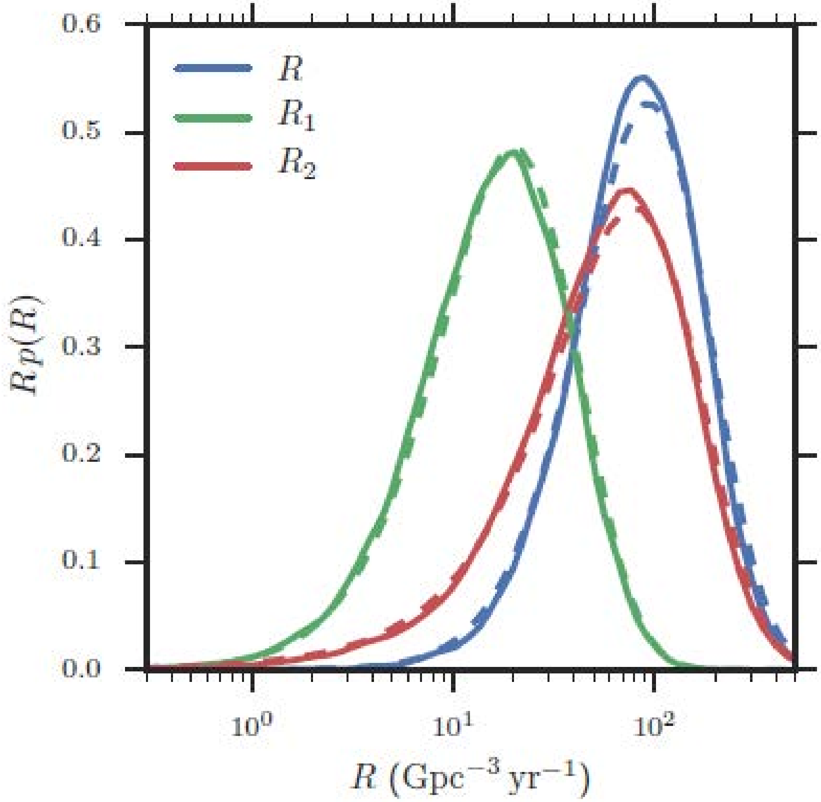
Rate estimates

- With only one event, can't measure rates accurately
- Estimates also depend upon astrophysical assumptions

- Rate: 4 - 53 Gpc^{-3}yr^{-1}
- Consistent with former predictions: 0.1 -300 Gpc^{-3}yr^{-1} (Abadie et al. 2010 arXiv:1003.2480)

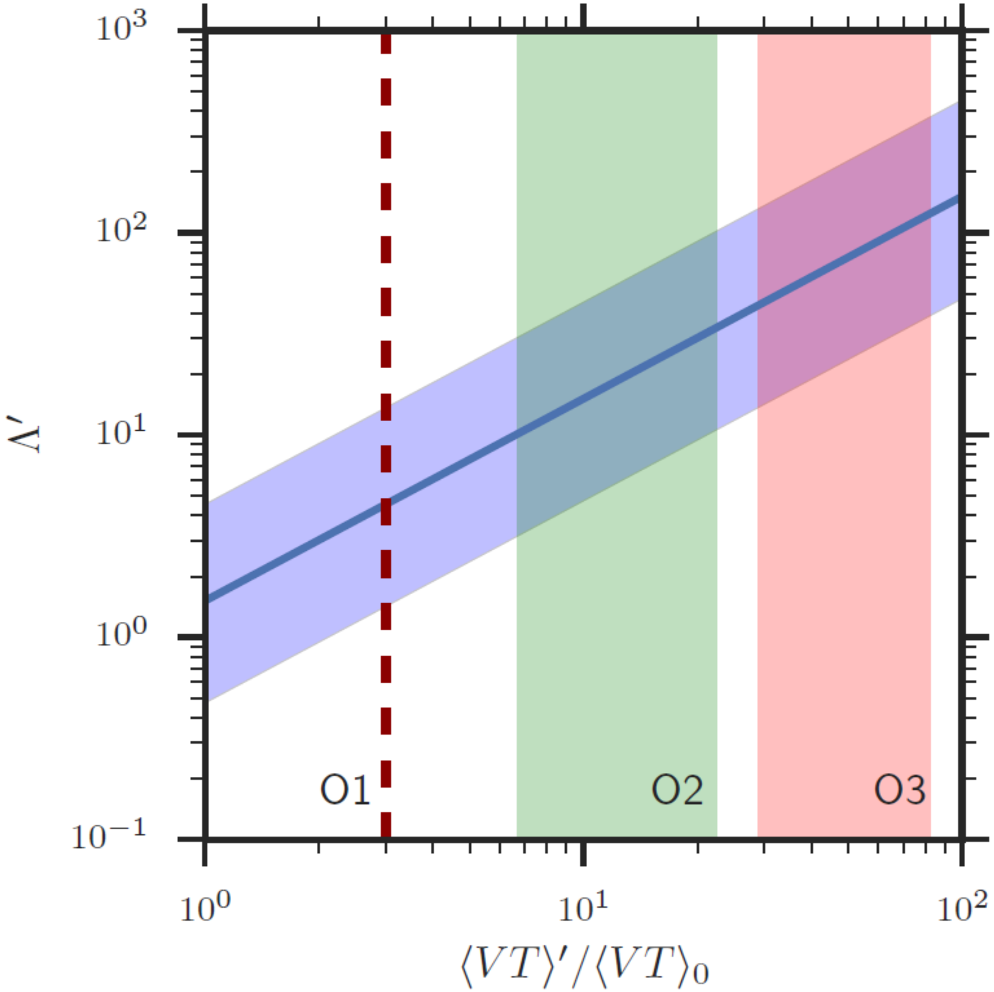
- Including LVT151012
  6 – 400 Gpc^{-3}yr^{-1}

- Overall 4 – 600 Gpc^{-3}yr^{-1}



arXiv:1602.03842

How many BBH merger in future data?



arXiv:1602.03842

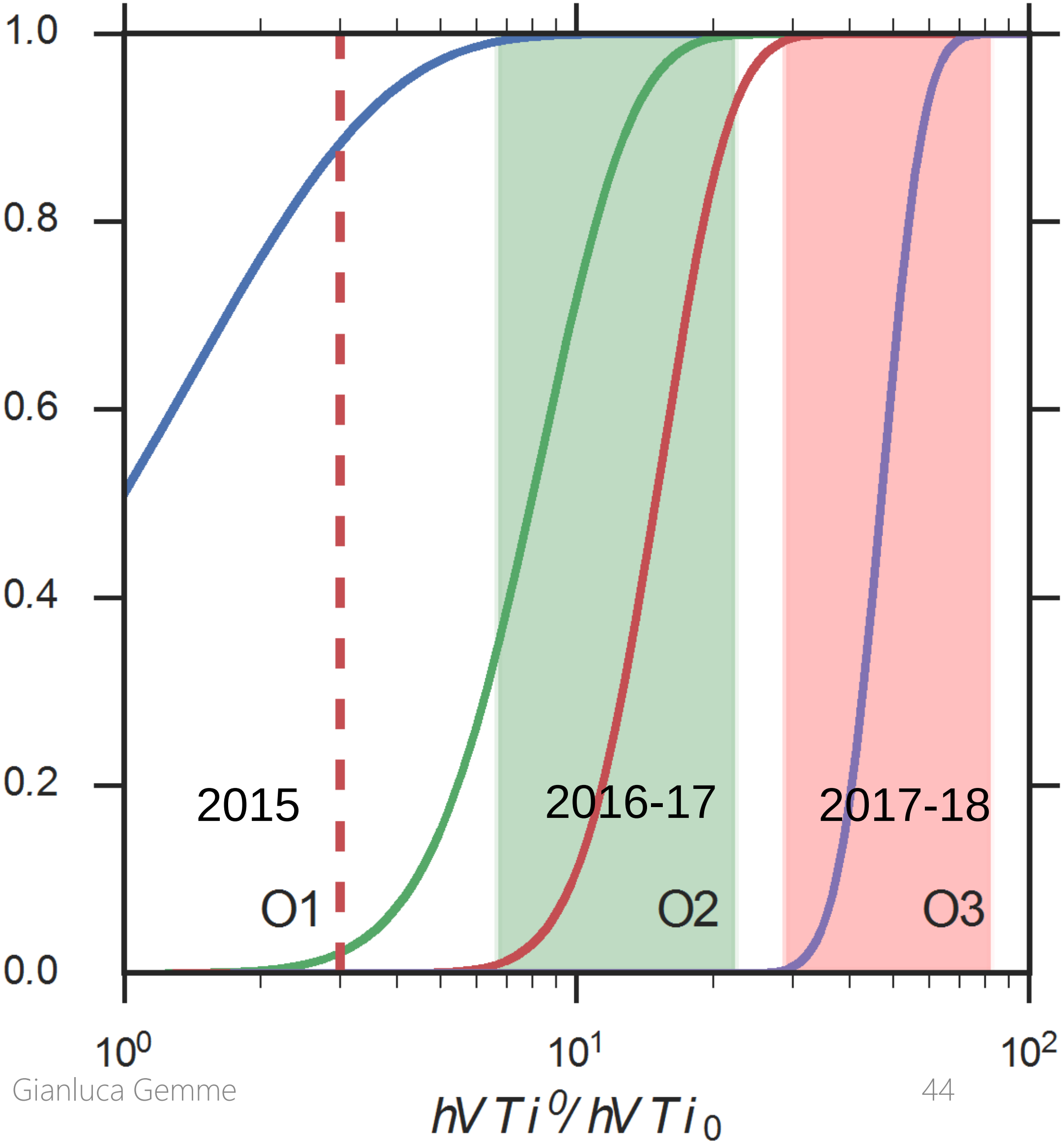
Expectations for future runs

Probability of observing

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

highly significant events, (FARs <1/century)

as a function of surveyed time-volume.



arXiv:1602.03842

Conclusions

- We observed gravitational waves from the merger of two stellar mass black holes
- The detected waveforms match the prediction of general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting black hole
- This observation is the first direct detection of gravitational waves and the first observation of a binary black hole merger