All sky search for long duration gravitational-wave transients

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PHENIICS Fest – 31 May 2017

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Outline

Let's come back 1.3 billion years ago.
- Binary black hole waltz
- Effect of gravitational vibration through the Earth
- Interferometric detector, ears of gravitational wave astronomy

Long duration GW transients
- What is a « long duration» GW transient ?
- Long GW transient sources

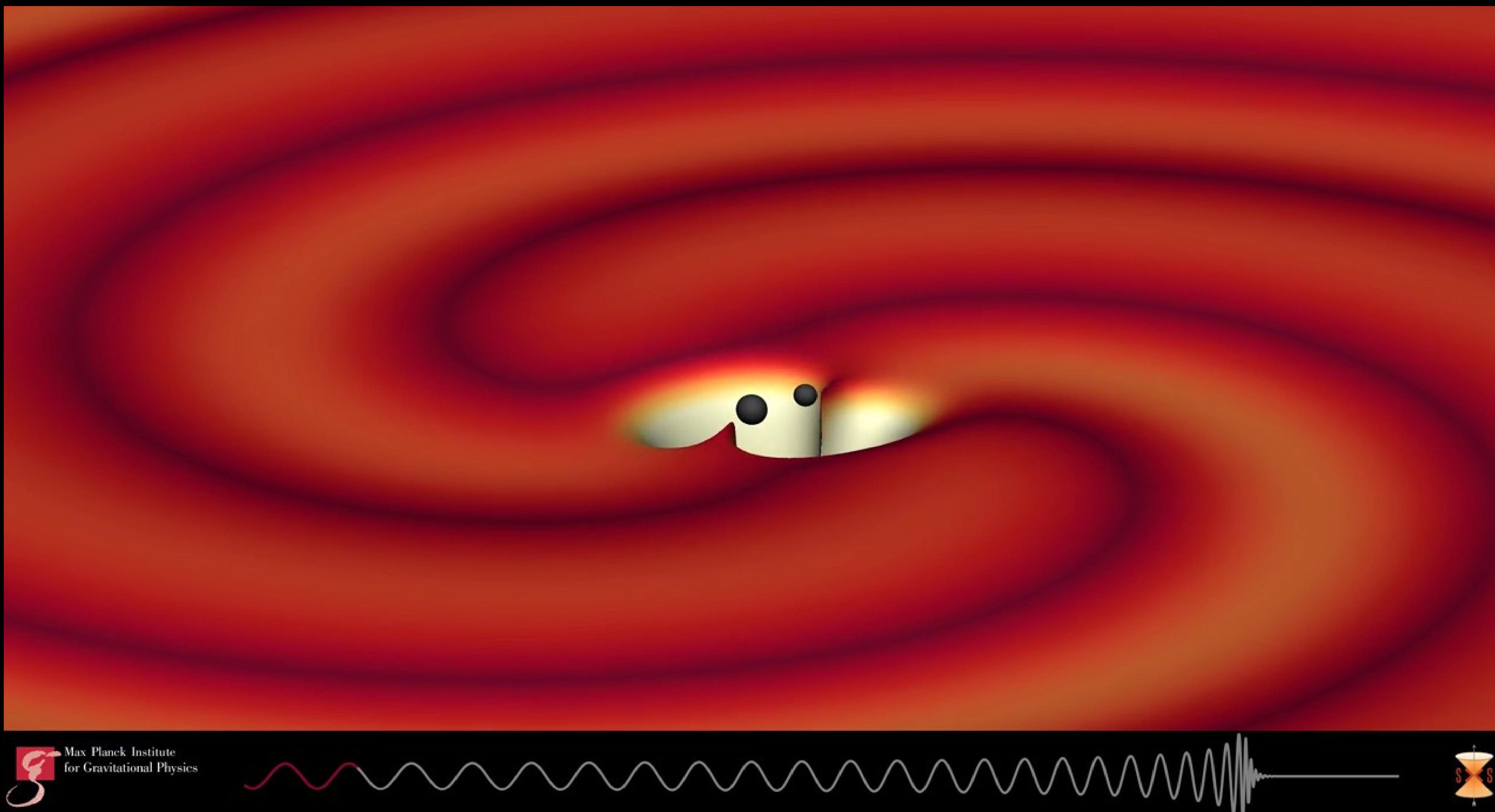
Initial LIGO detectors, S5/S6 data search results

Advanced LIGO detectors, O1 data search overview

Conclusion and perspectives

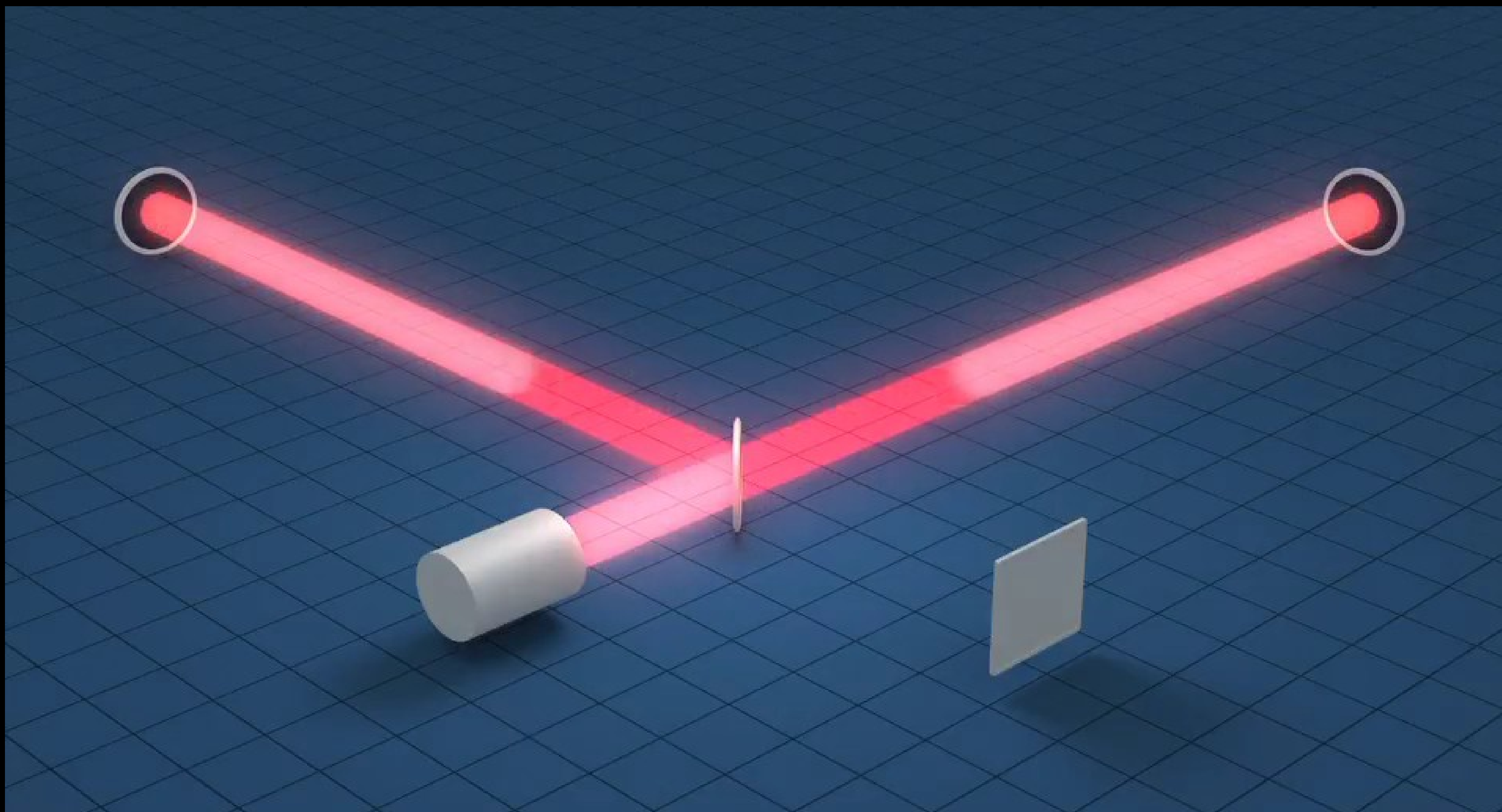
GW150916

GW generation



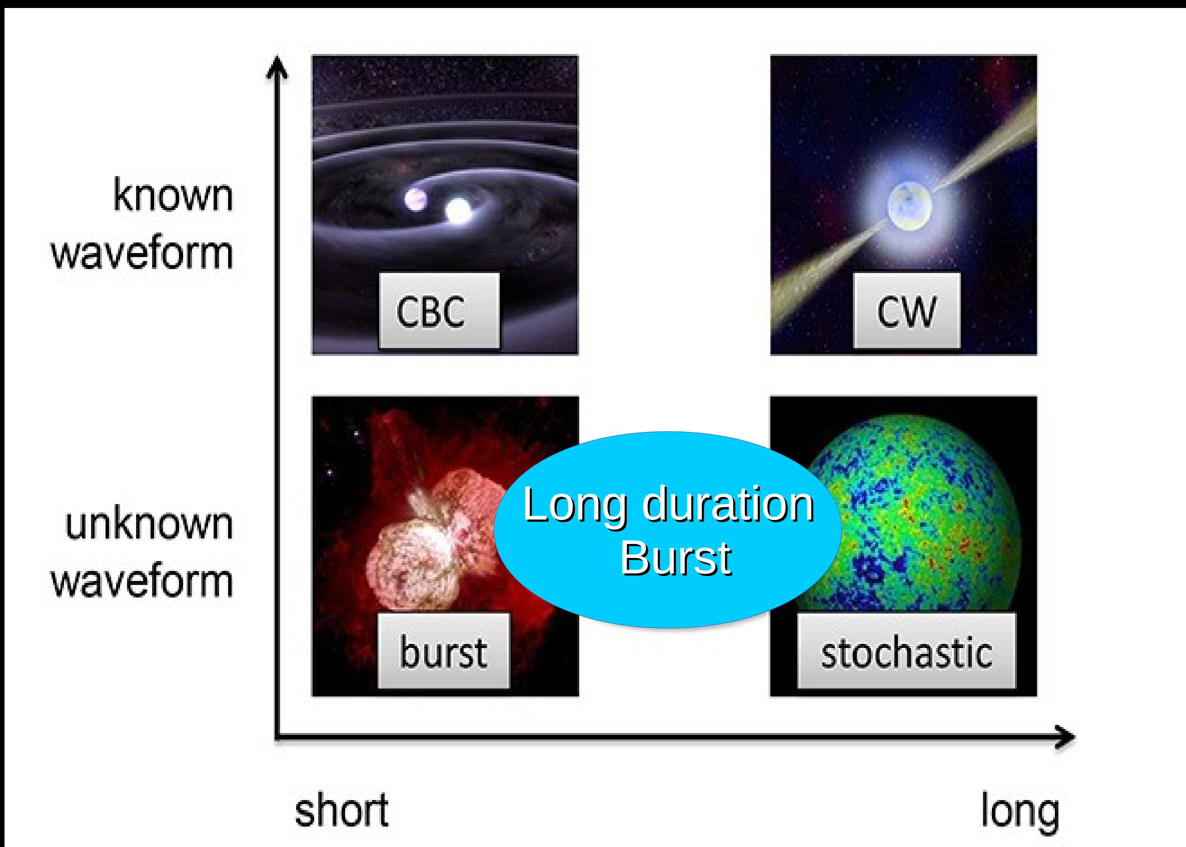
GW effect on the earth

Interferometric detectors



See Angelique's poster for more information about interferometric detectors and upgrades

Long duration GW burst



Unmodeled search for long duration gravitational waves (>10s)

Promising search

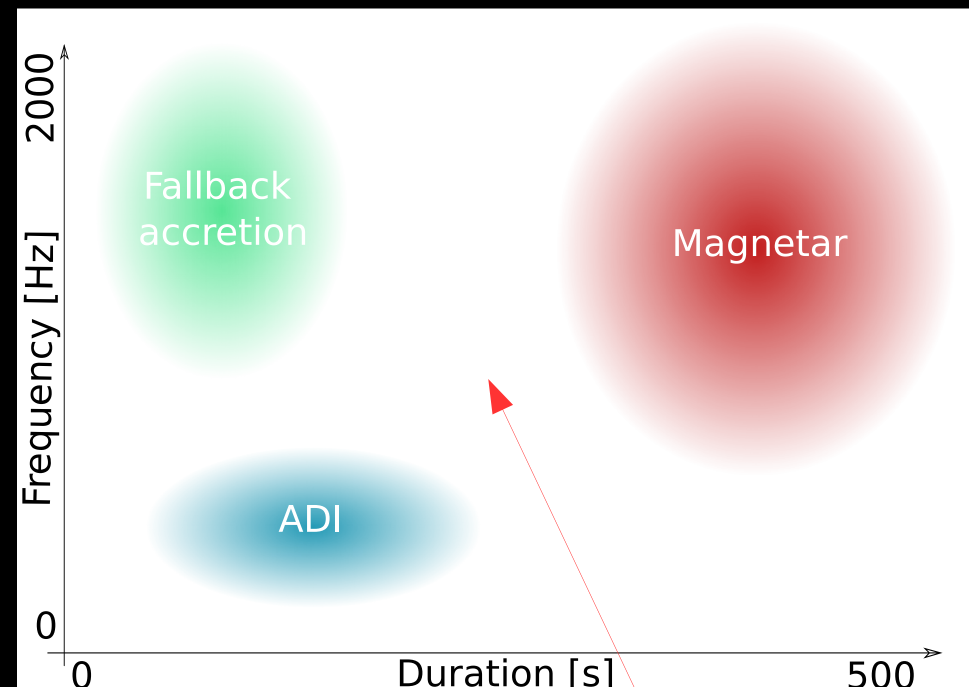
- Search for promising sources in part of the parameters space, unexplored so far
- Bridging burst/stochastic/continuous waves parameters space.

Using stochastic background search techniques (cross-correlation)

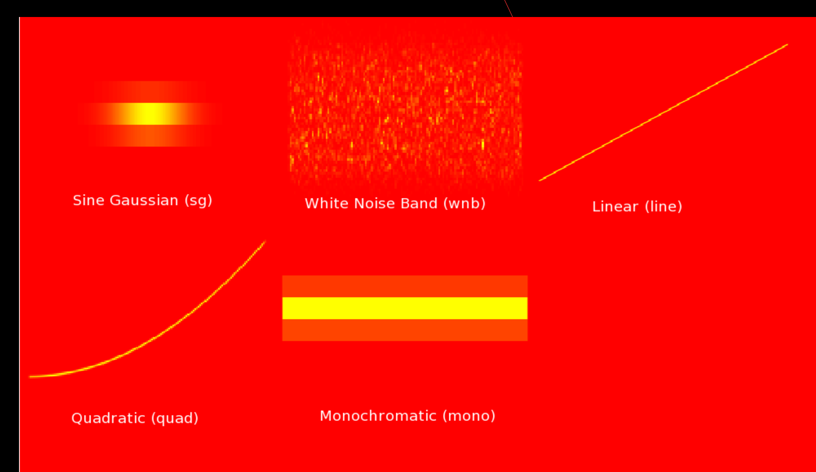
- Large parameter space
- Model-independent search
- All-sky/all-time search

Sources

- Many potential sources, but rough modelling
- Waveforms models:
  - van Putten accretion disk instabilities and fragmentation (ADI) [1]
  - Rotational instabilities in proto-neutron star (PNS) remnants [2]
  - Proto-neutron star convection [3]
  - Fallback accretion on neutron stars [4]
  - Instabilities in central magnetars [5]
  - Neutron star r-modes
  - ...



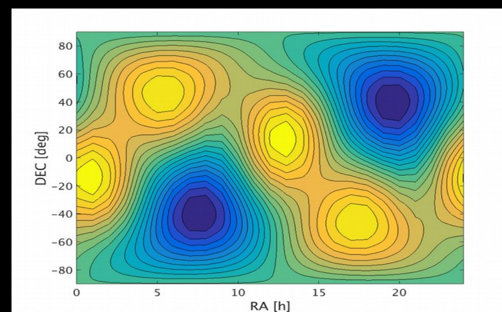
Use of adhoc waveforms to completely span the parameters space.



[1] van Putten, PRL 87, 091101 (2001)
[2] Ott et al, Astrophys. J. 625, L119 (2005)
[3] Kotake et al, Astrophys. J. 697, L133 (2009)
[4] Piro and Thrane, Astrophys. J. 761, 63 (2012)
[5] Corsi and Meszaros, Astrophys. J. 702, 1171 (2011)

STAMP-AS pipeline

All sky search



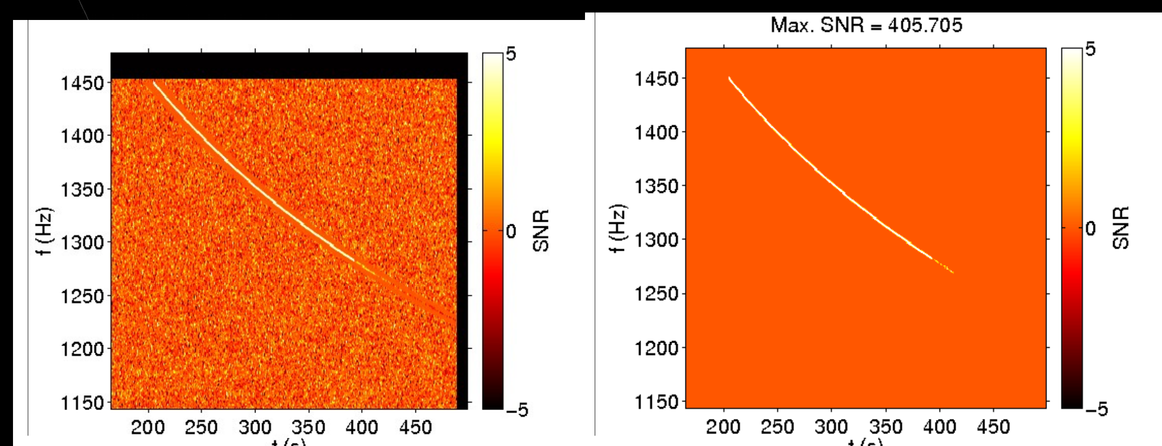
No signal assumption

Parameter space
Frequency range: 40-1000Hz
Time window : 500 s

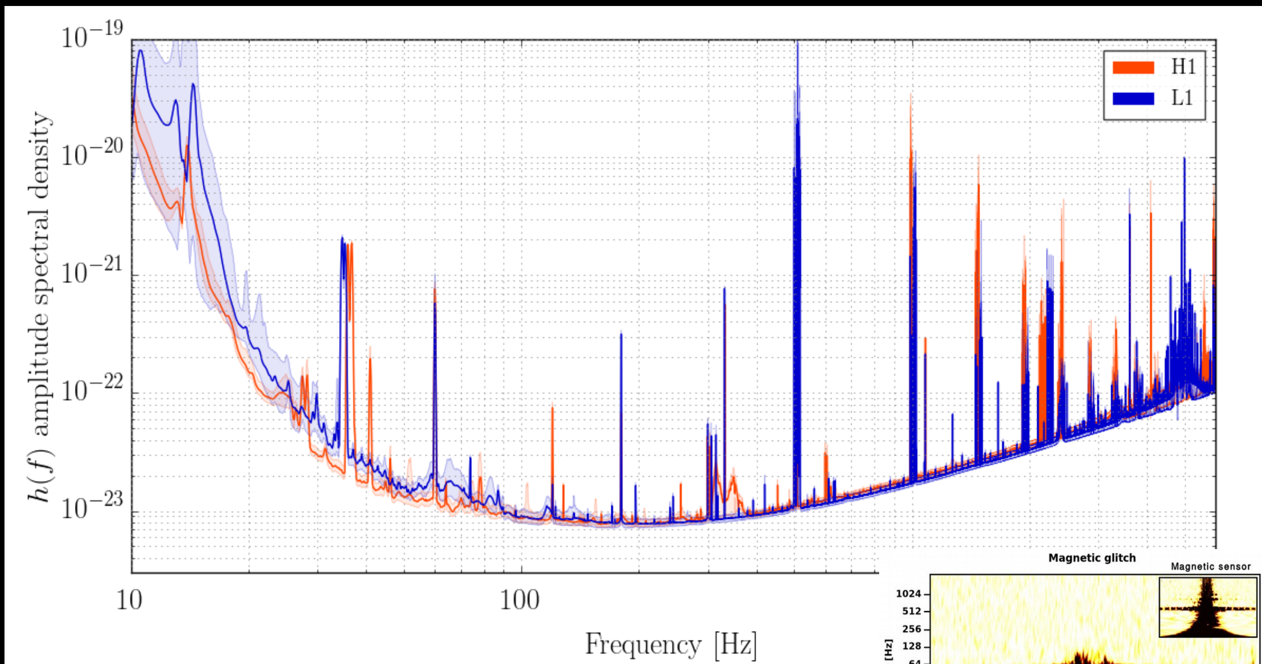
Detector 1

Cross-correlation → Coherent FTmap → Clustering → Triggers

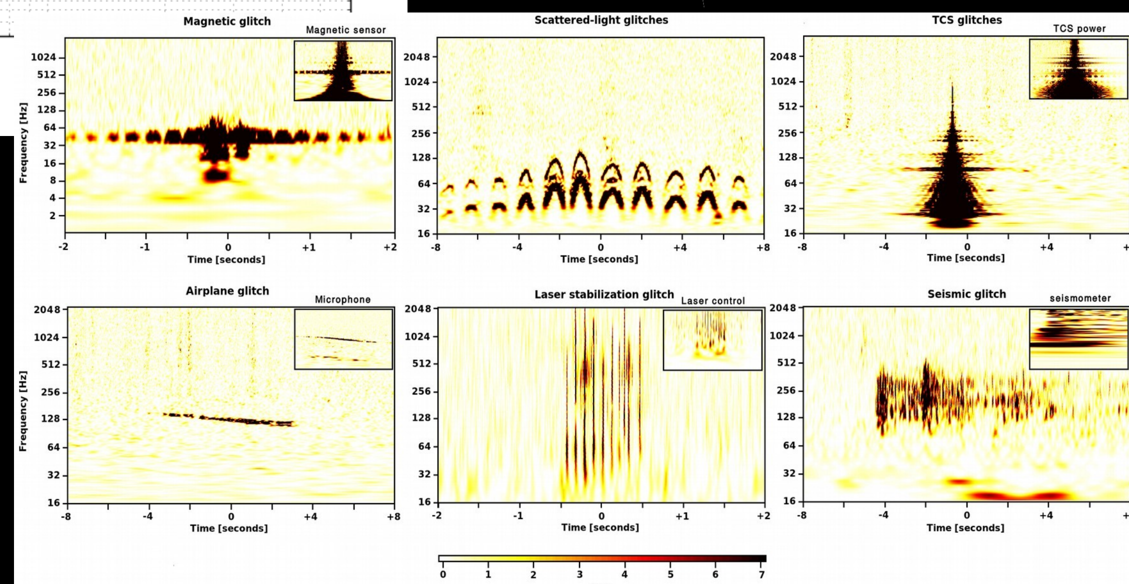
Detector 2



Noise (spectral & glitch)



Transient noise

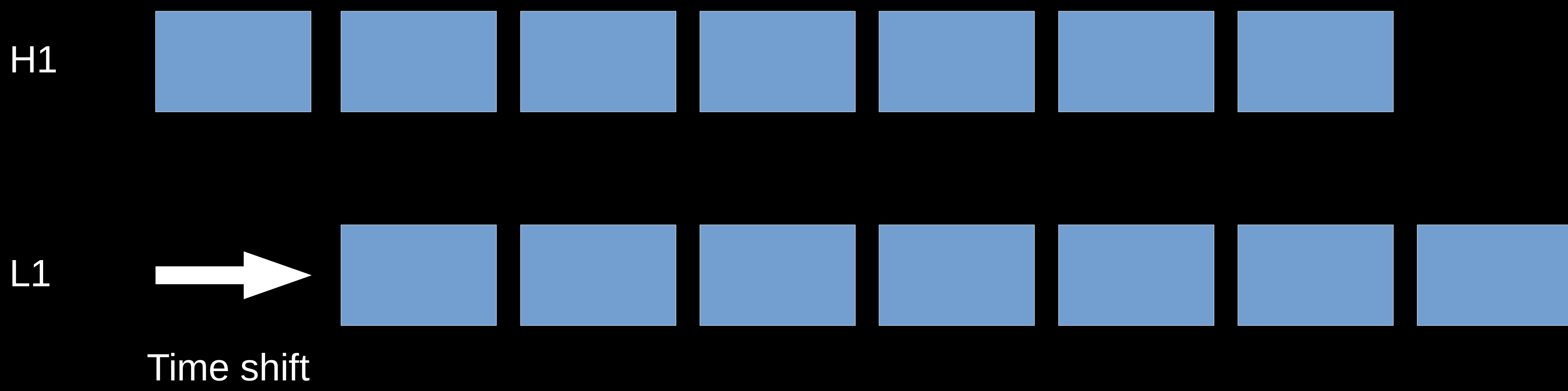


Spectral noise

The data are not Gaussian →
We cannot estimate the background
using Monte Carlo methods

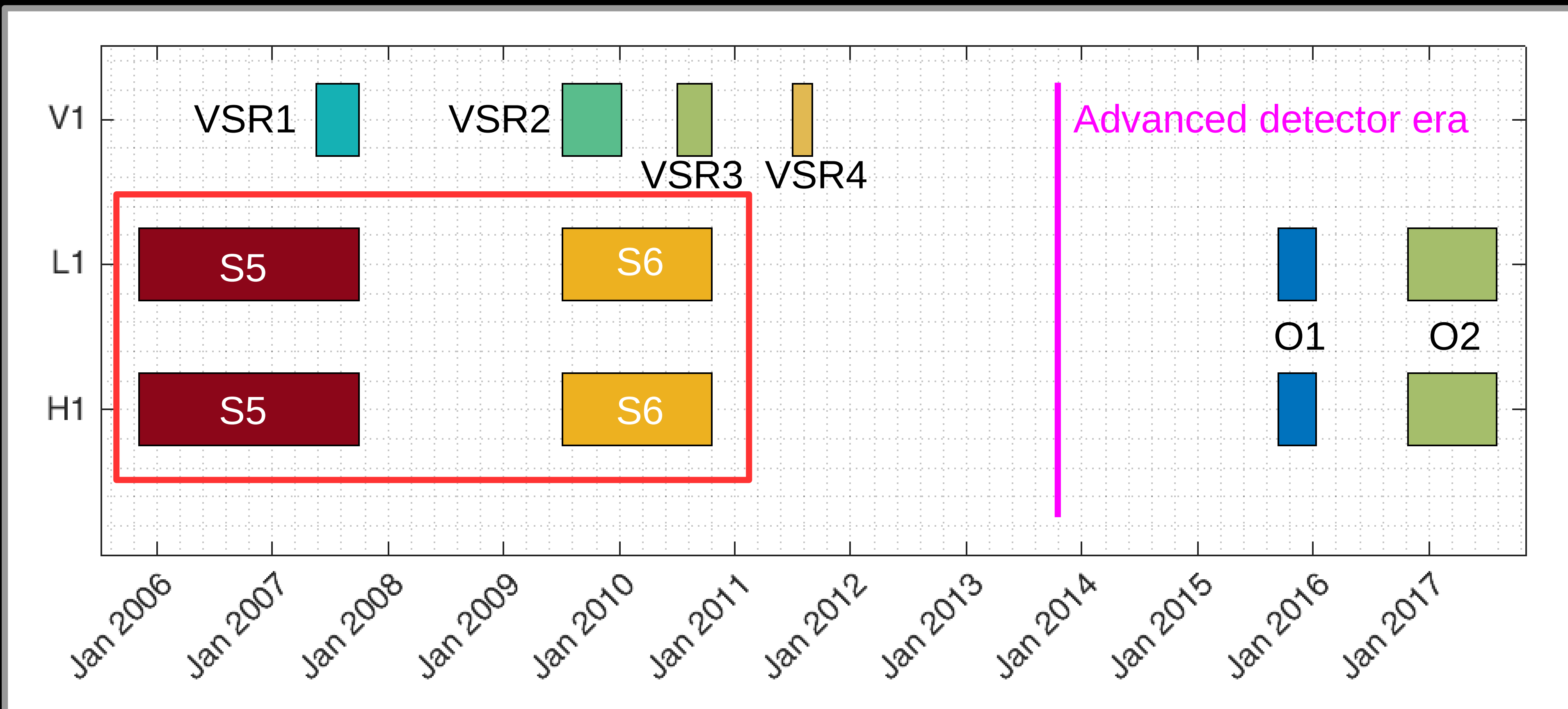
Time slide methods

Insert a time shift betweeen the two detectors data stream.

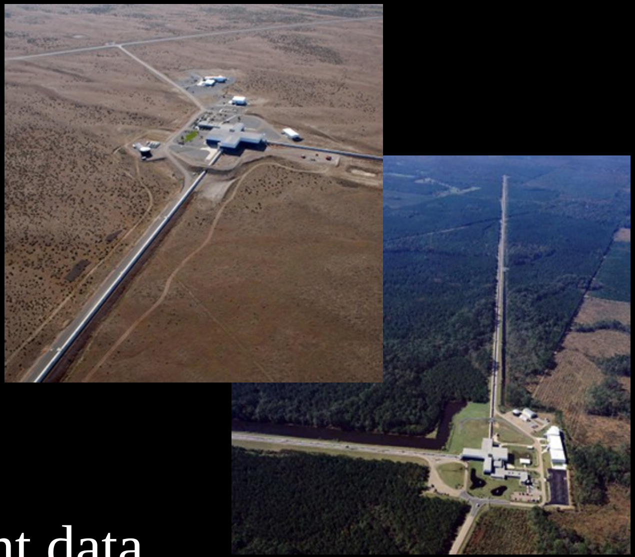


Every coincident event is not astrophysical => this is a false alarm
We can estimate the background of the search considering the distribution of false alarms

S5/S6 results



S5/S6 search



S5/S6 scientific run :

- Two detectors **H1** (Hanford) **L1** (Livingston)
- **S5 run** : *Nov 5, 2005 - Sep 30 2007*
    - 283 days of coincident data
- **S6 run** : *Jul 7, 2009 - Oct 20 2010*
    - 133 days of coincident data
- **Combining S5/S6** : more than 1 year of coincident data

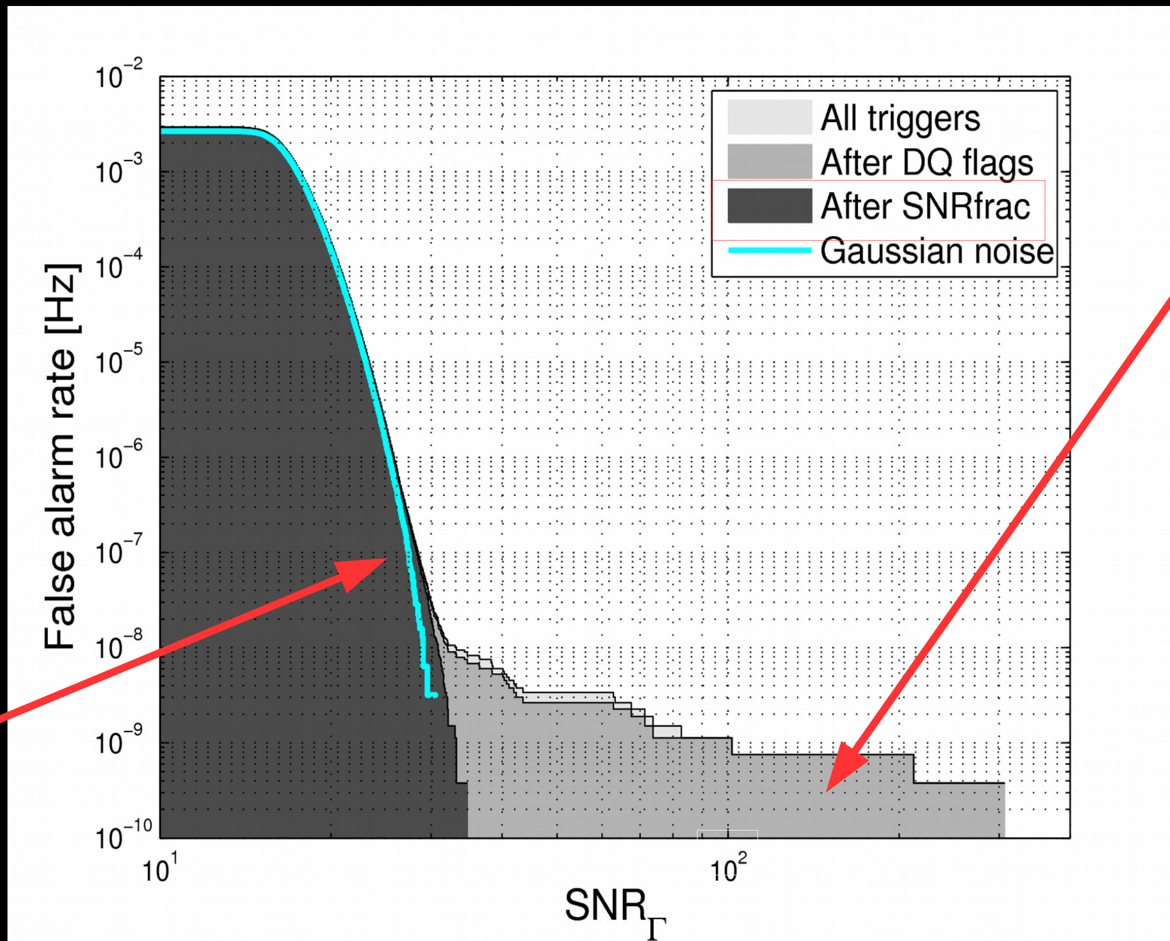
- First search for long-duration transients with LIGO data.
- S5/S6 data search published - Phys. Rev. D 93, 042005 (2016)

Analysis :

- Background studies.
- Results from the full S5/S6 run.
- Search efficiency estimated using physical (ADI) and ad-hoc waveforms (15 waveforms total).

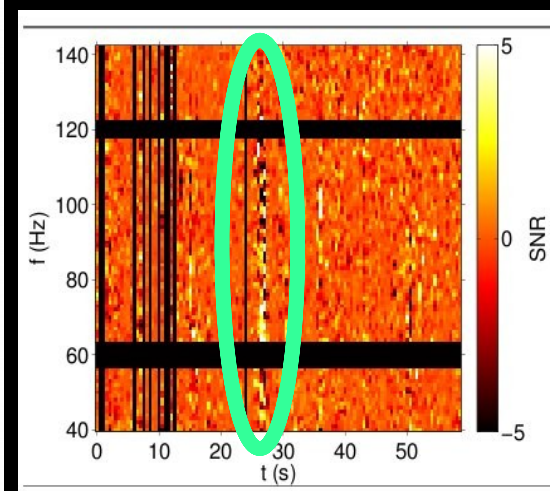
S5/S6 background

Phys. Rev. D 93, 042005 (2016)



Final distribution close to Gaussian noise expectation

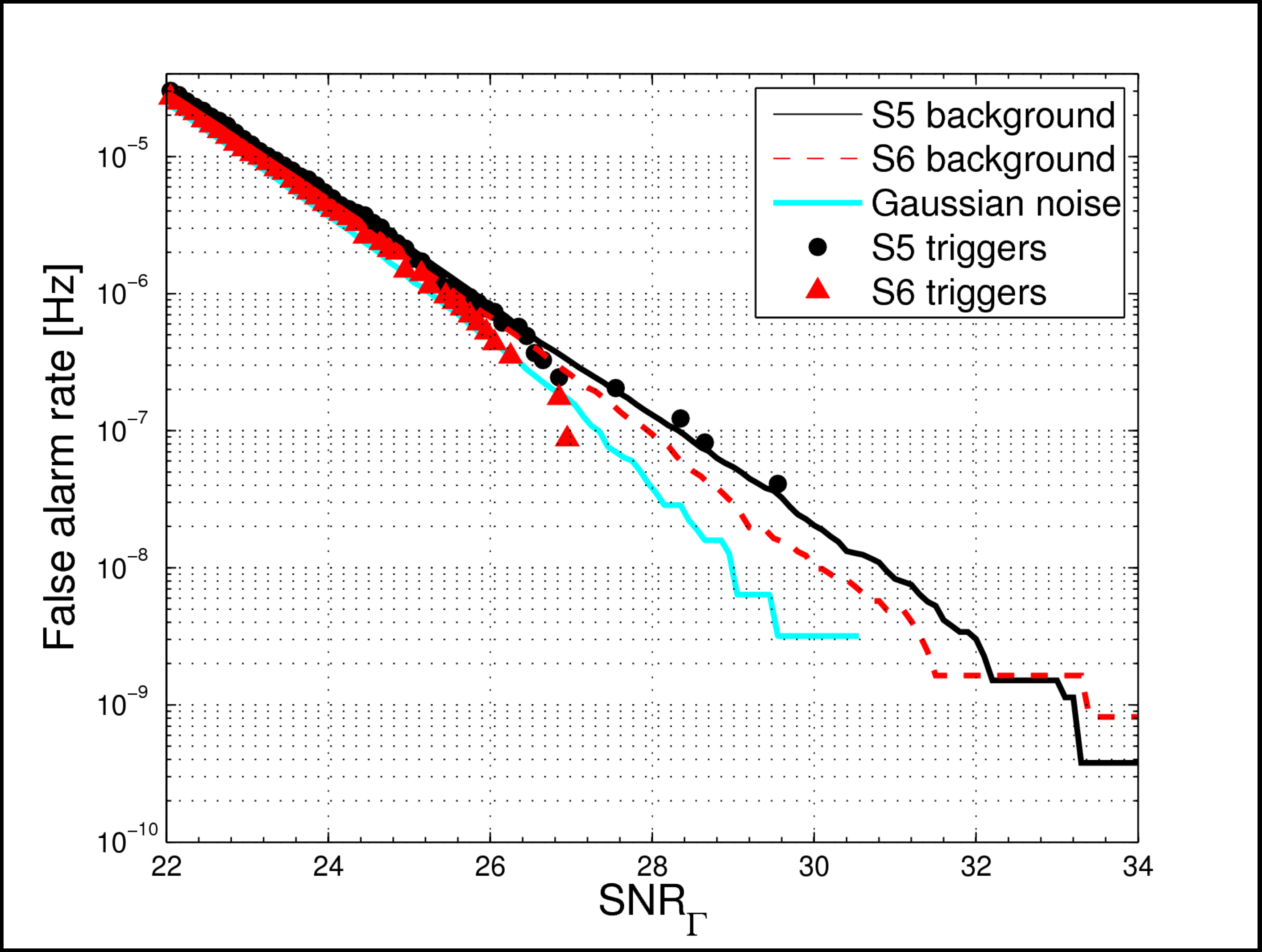
Some outliers due to instrumental noise → suppressed by vetoes



Example of instumental noise

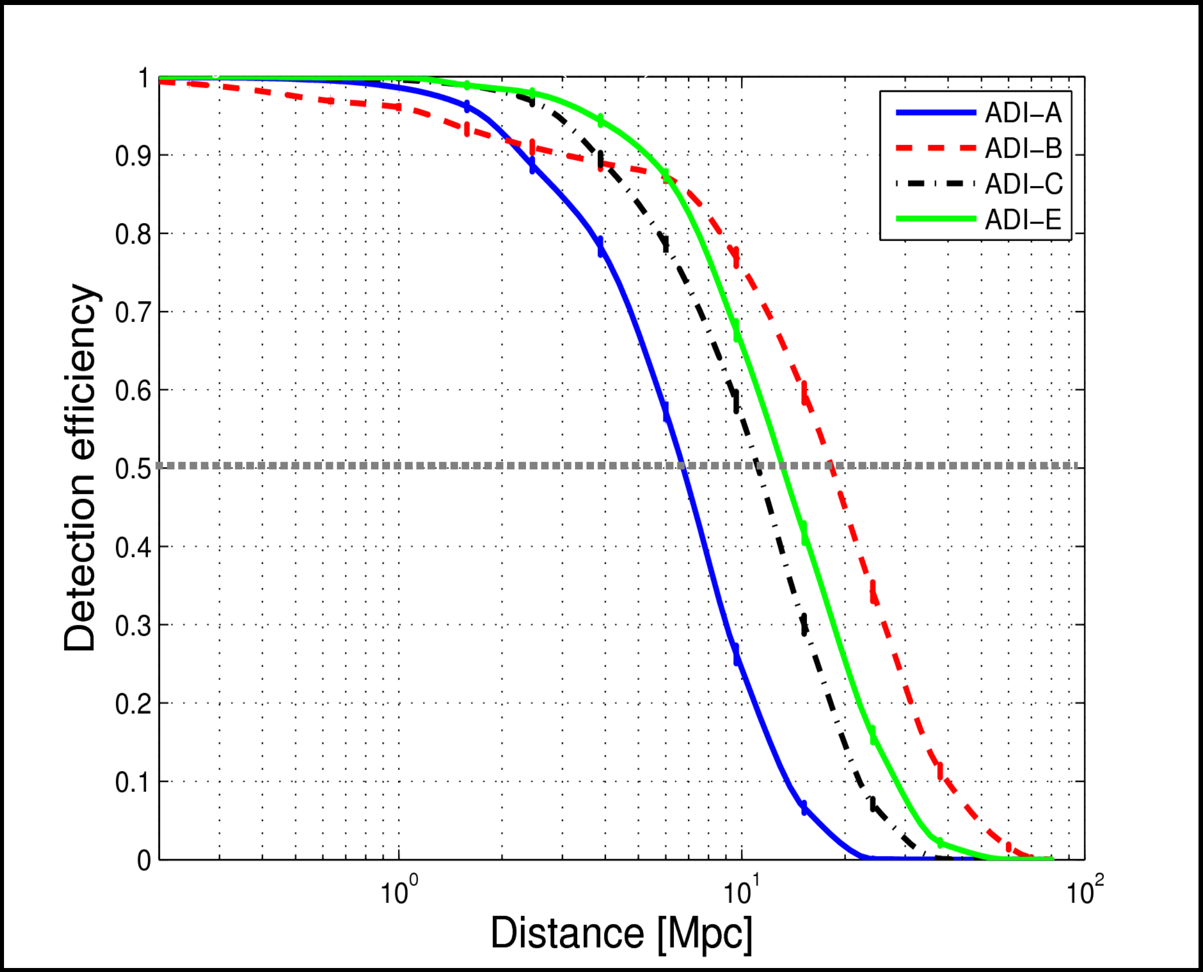
S5/S6 results

Phys. Rev. D 93, 042005 (2016)



- No signifiant GW candidate.
- search results are consistent with expectations for noise

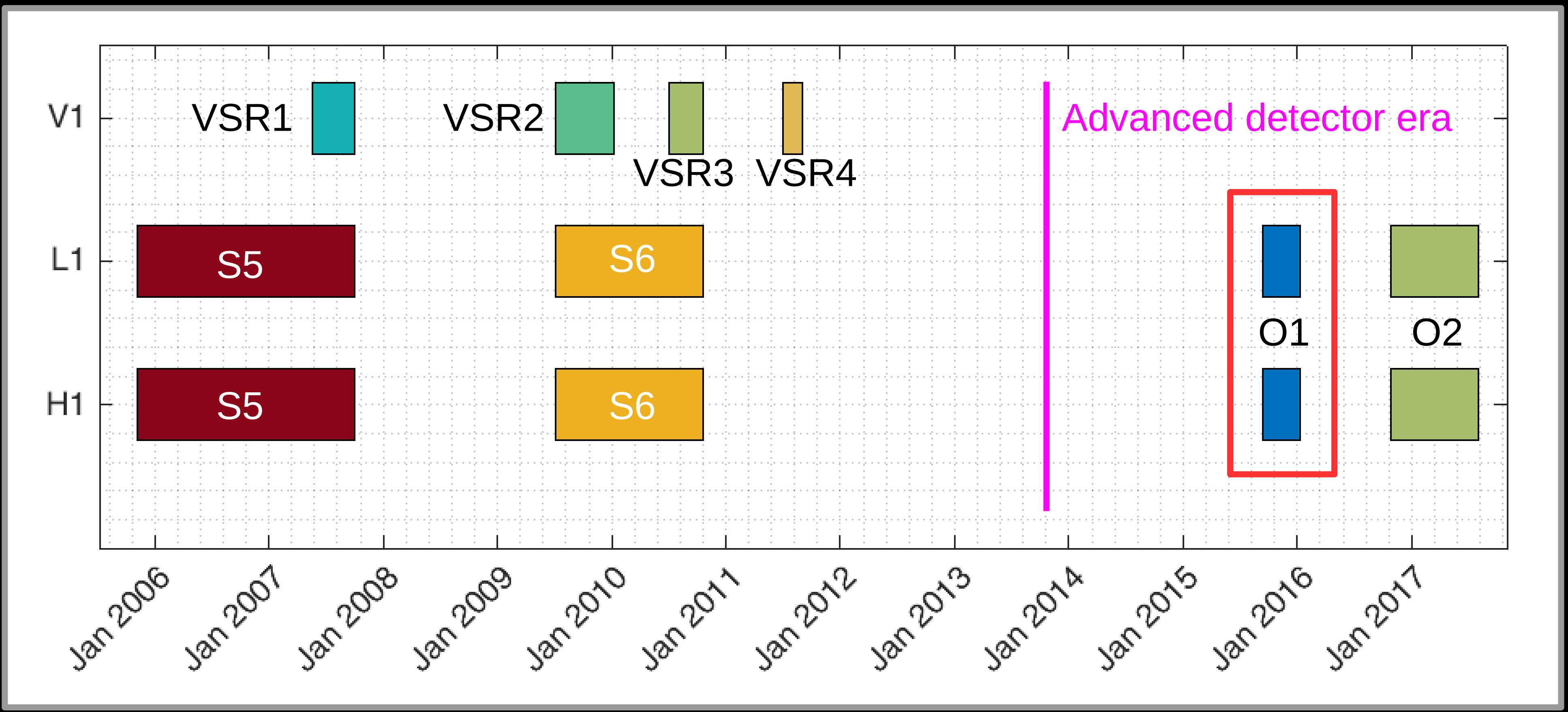
S5/S6 sensitivity



name	Fmin [Hz]	Fmax [Hz]	Duration [s]	Distance @ 50 % [Mpc]
Adi A	135	166	39	5.4
Adi B	110	209	9.4	16.3
Adi C	130	250	236	8.9
Adi D	111	234	76	11.5

~ 10 – 20 Mpc → sensitive to the local univers.

O1 results



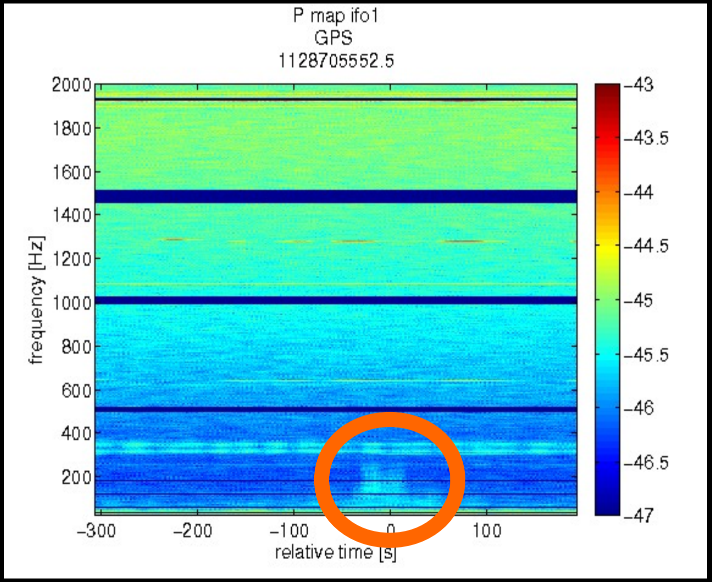
V1
L1
H1
VSR1
VSR2
VSR3
VSR4
Advanced detector era
S5
S5
S6
S6
O1
O2
Jan 2006
Jan 2007
Jan 2008
Jan 2009
Jan 2010
Jan 2011
Jan 2012
Jan 2013
Jan 2014
Jan 2015
Jan 2016
Jan 2017

O1 search

New detectors
- Advanced LIGO is a complete new detector.
- New instrumental noise sources.
- Expect factor 3 on the search sensitivity.

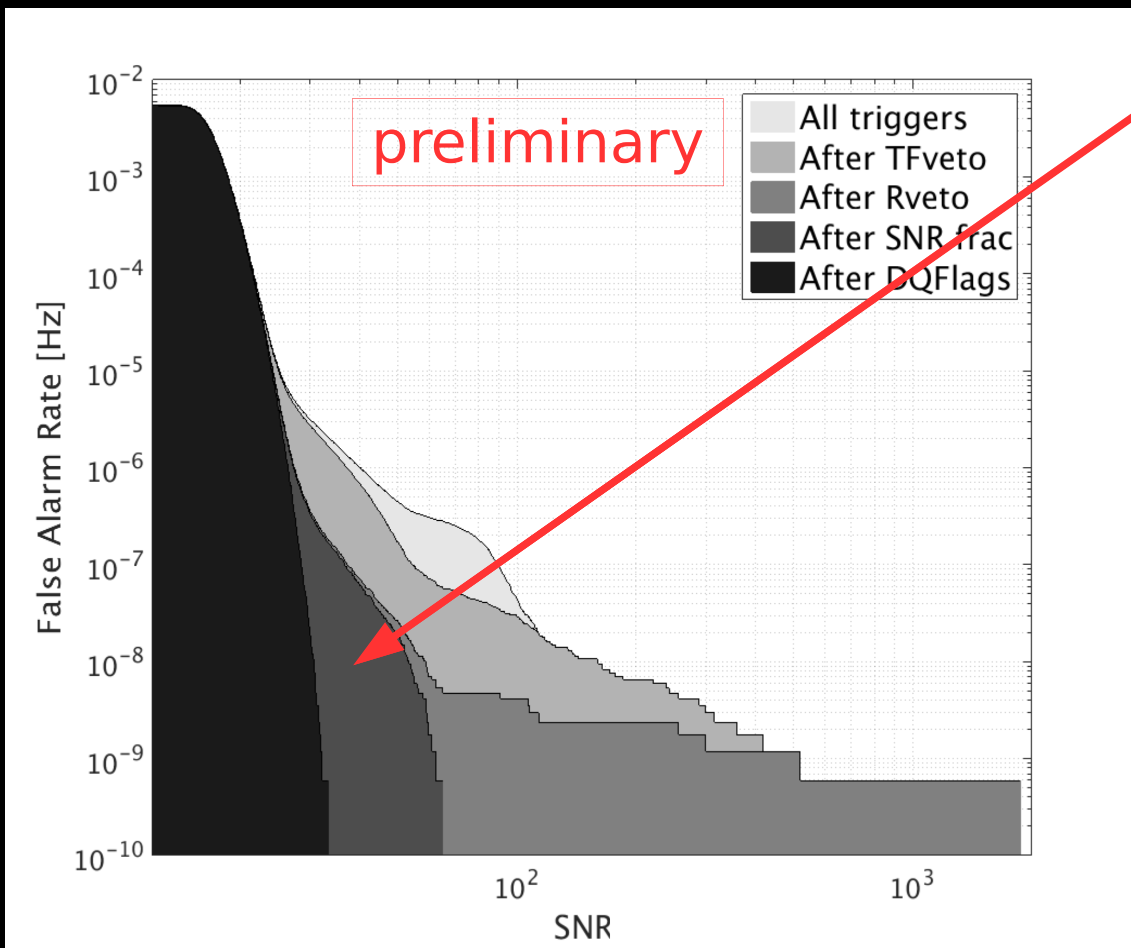
O1 :
- 2 detectors H1 & L1
- *From Sep 12, 2015 to Jan 12, 2016* – 48 days of coincident data.

Pipeline
- Parameter space extended :
  [40-1000] Hz -> [24-2000] Hz
- 3 additional pipelines.
- New physical waveforms added (magnetar & fallback accretion).



Example of a noise event seen in O1 data

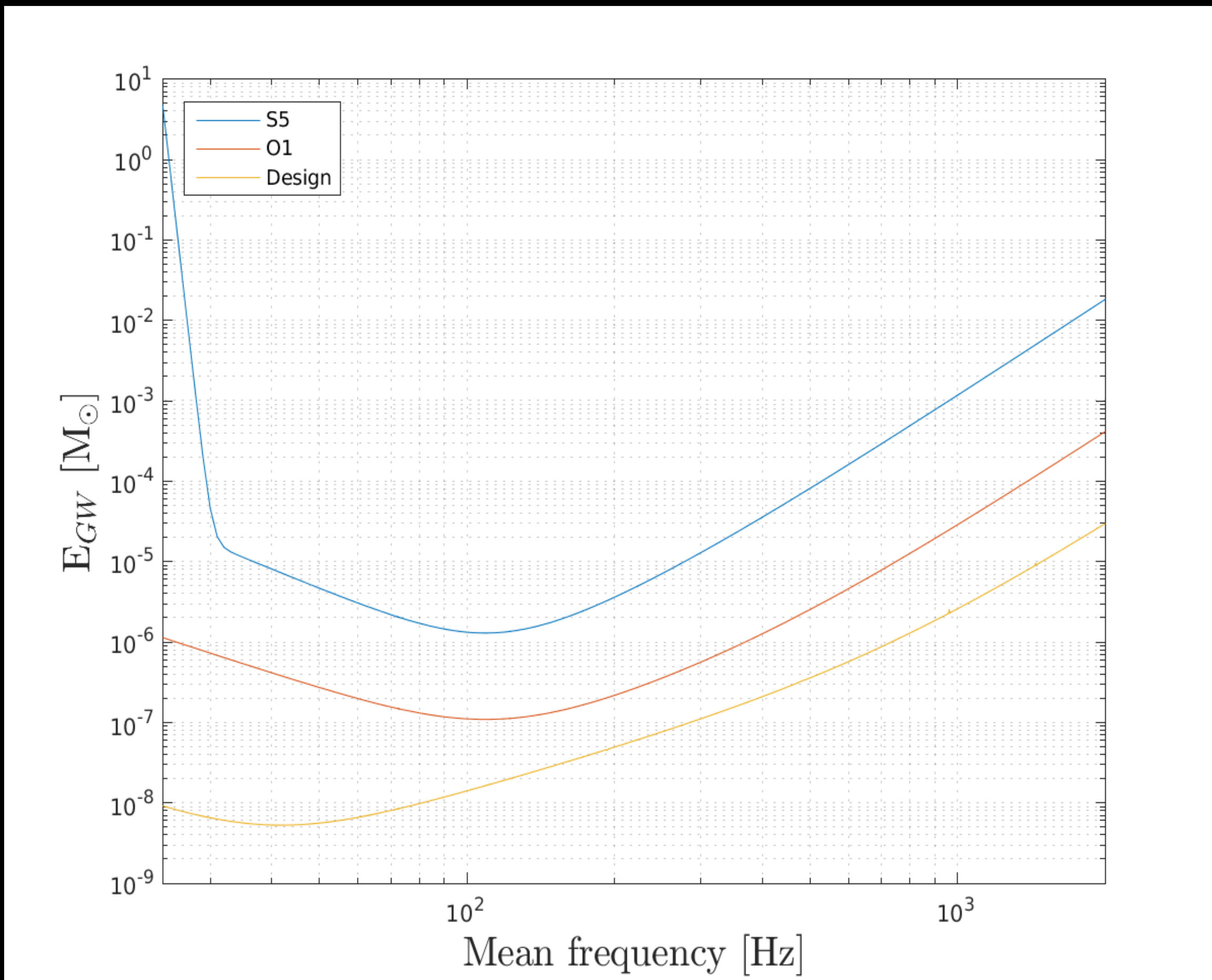
O1 preliminary analysis



- Data noisier than S5/S6 ...
- But expected background distribution close to a Gaussian distribution after all selection steps applied.

Analysis complete.
Improvement : Factor ~3 wrt S5/S6 search sensitivity.
Example : ADI sensitivity distance ~30-60 Mpc

O1 predicted sensitivity



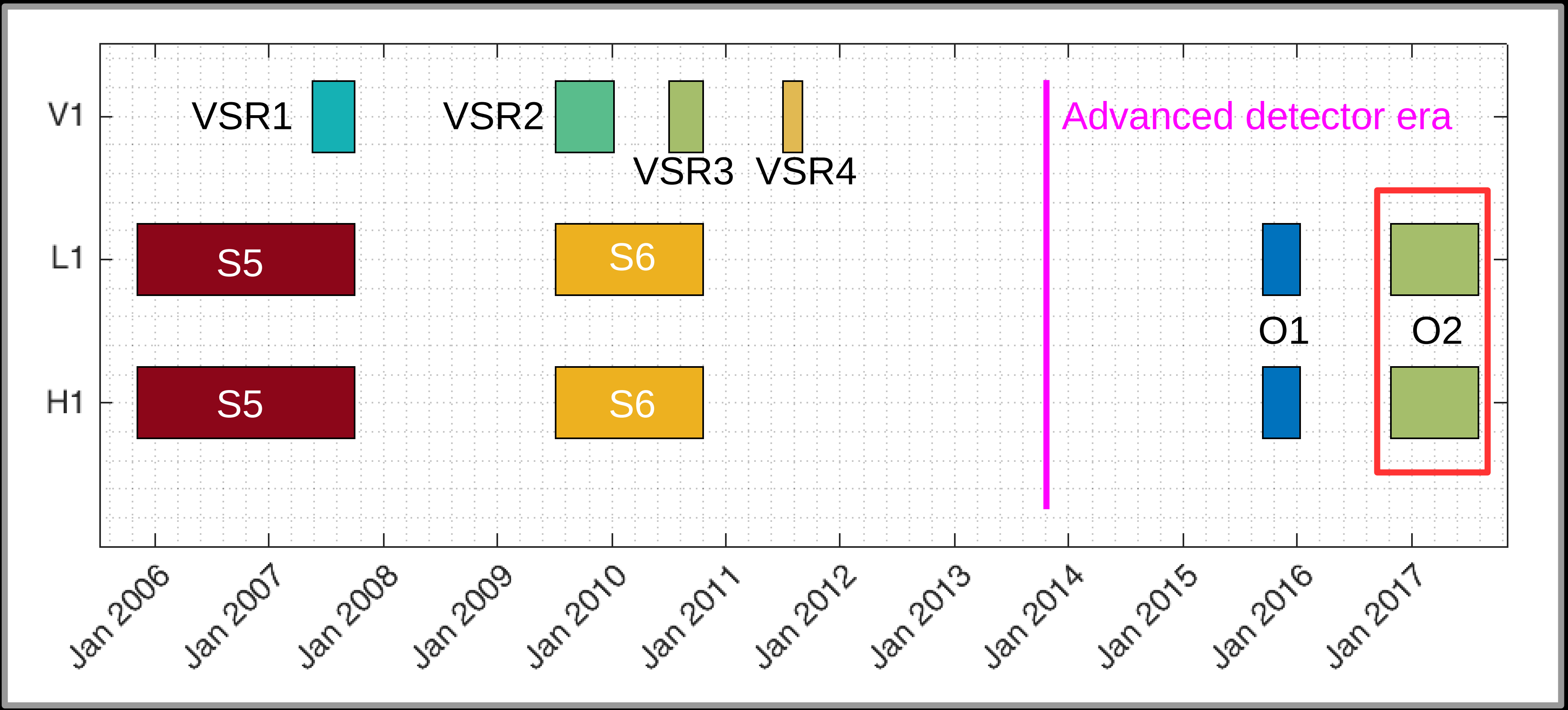
O1 and "design" sensitivity extrapolated using S5/S6 results

Energy computed for a source at 10kpc for an efficiency of 50% :

$$E_{\rm GW} = \frac{c^3 r^2}{4G} \int_{-\inf}^{\inf} \langle \dot{h}_+^2 + \dot{h}_\times^2 \rangle dt,$$

Sensitivity improvement ~ factor 3 wrt S5/S6 run.

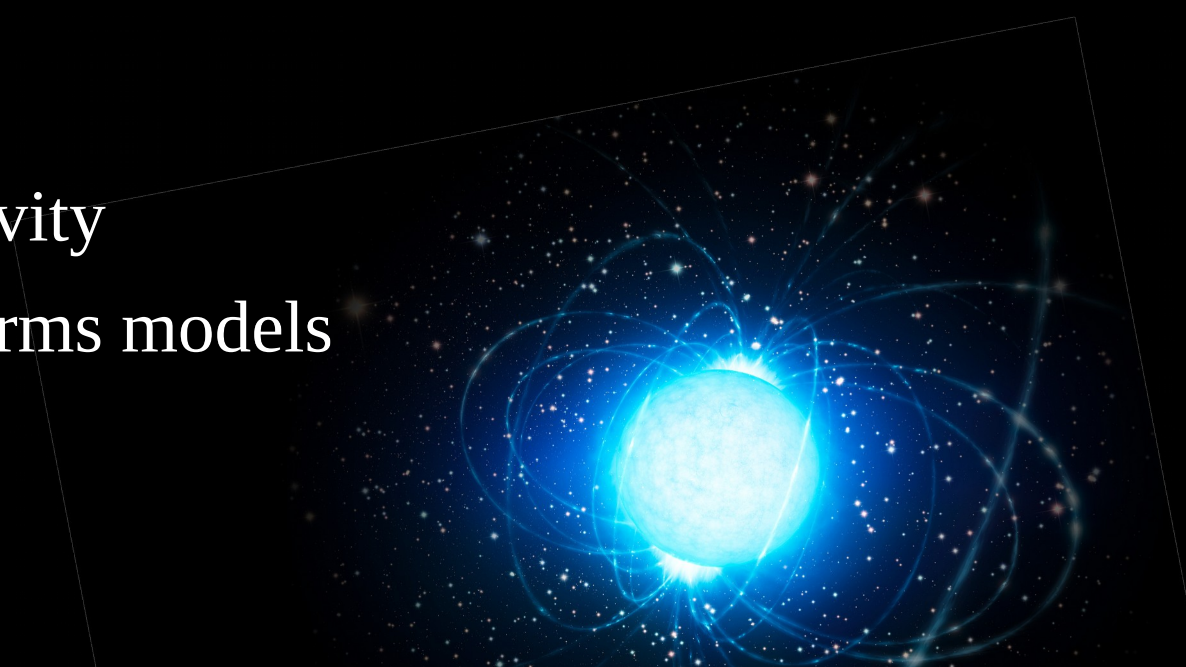
O2 search


V1
L1
H1
VSR1
VSR2
VSR3
VSR4
Advanced detector era
S5
S5
S6
S6
O1
O2
Jan 2006
Jan 2007
Jan 2008
Jan 2009
Jan 2010
Jan 2011
Jan 2012
Jan 2013
Jan 2014
Jan 2015
Jan 2016
Jan 2017

O2 search

- Analysis on going
  - Low latency analysis (week by week)
  - Background estimated
  - Understanding new noises families

- To be done
  - Estimated sensitivity
  - Add new waveforms models



Conclusion & perspective

Summary

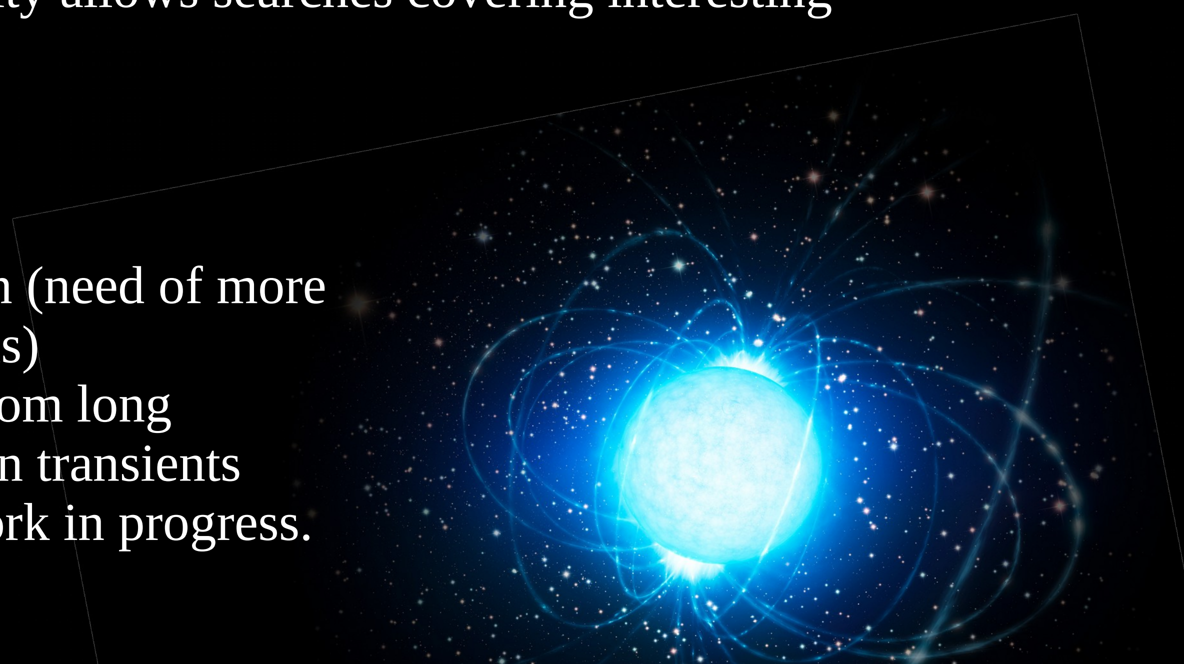
- Long duration GW transients : recent search in the Virgo-LIGO Scientific Collaboration
- Difficulties : rather large parameter space & no signal waveform assumptions
- We have developed many selection cuts that significantly reduce the background outliers

Promising search

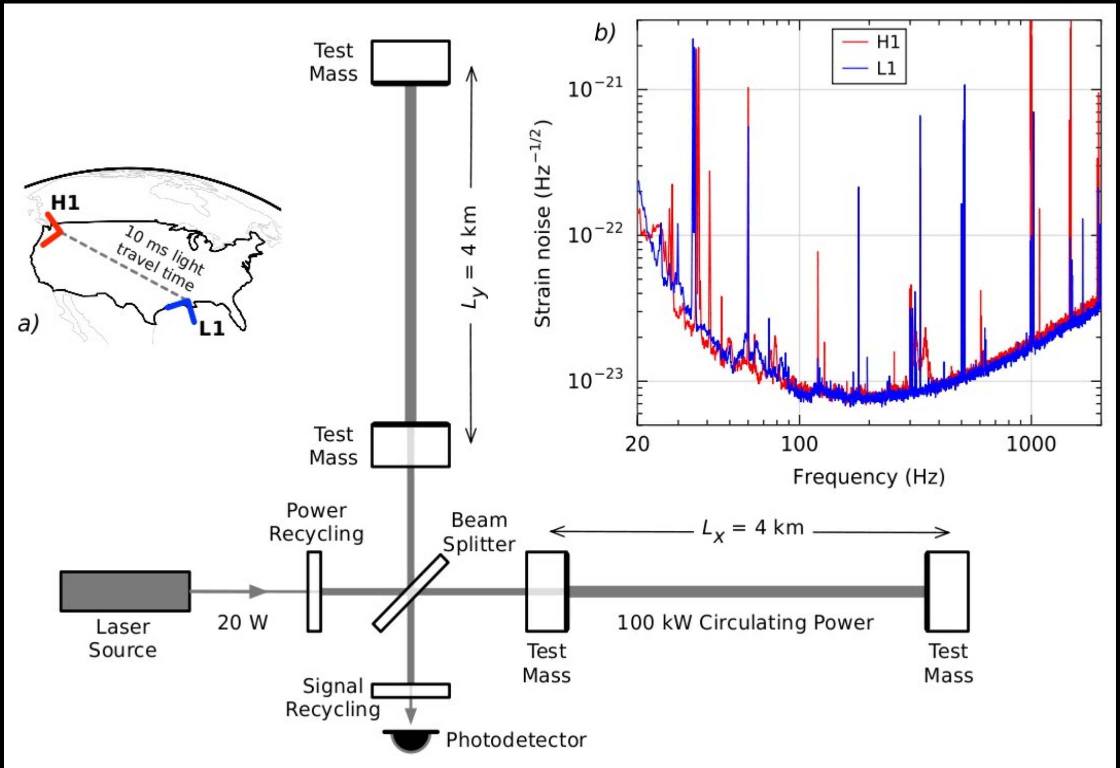
- Bridging burst/stochastic/continuous waves parameter space
- Advanced detectors' sensitivity allows searches covering interesting
- astrophysical distances

Perspectives

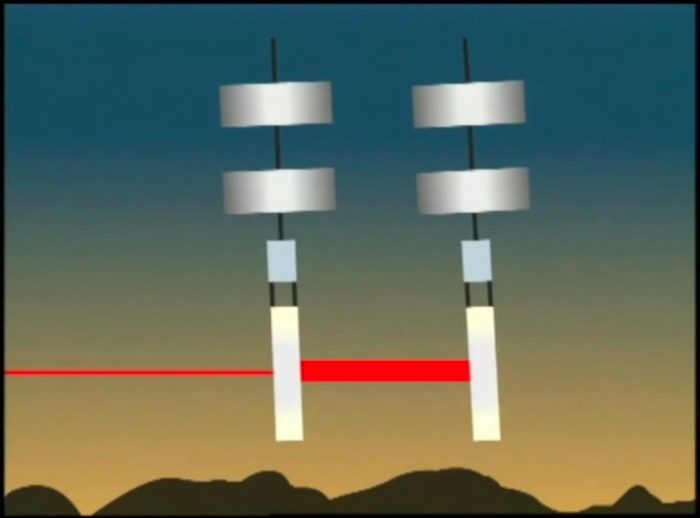
- Source parameters estimation (need of more
- accurate astrophysical models)
- Increase parameter space : from long
- duration to very long duration transients
- (1 day $\rightarrow$ several weeks) work in progress.

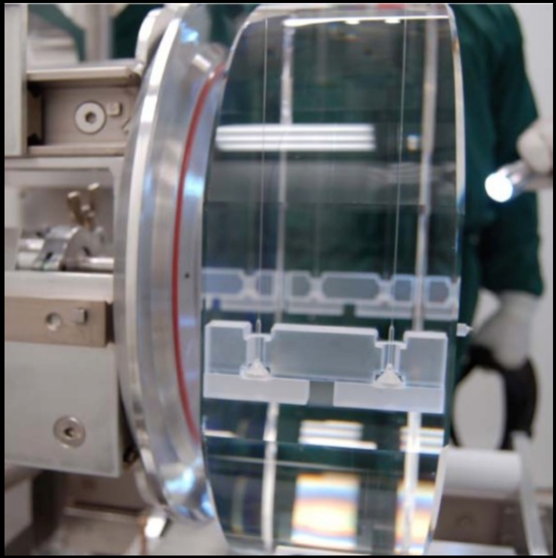


Detector

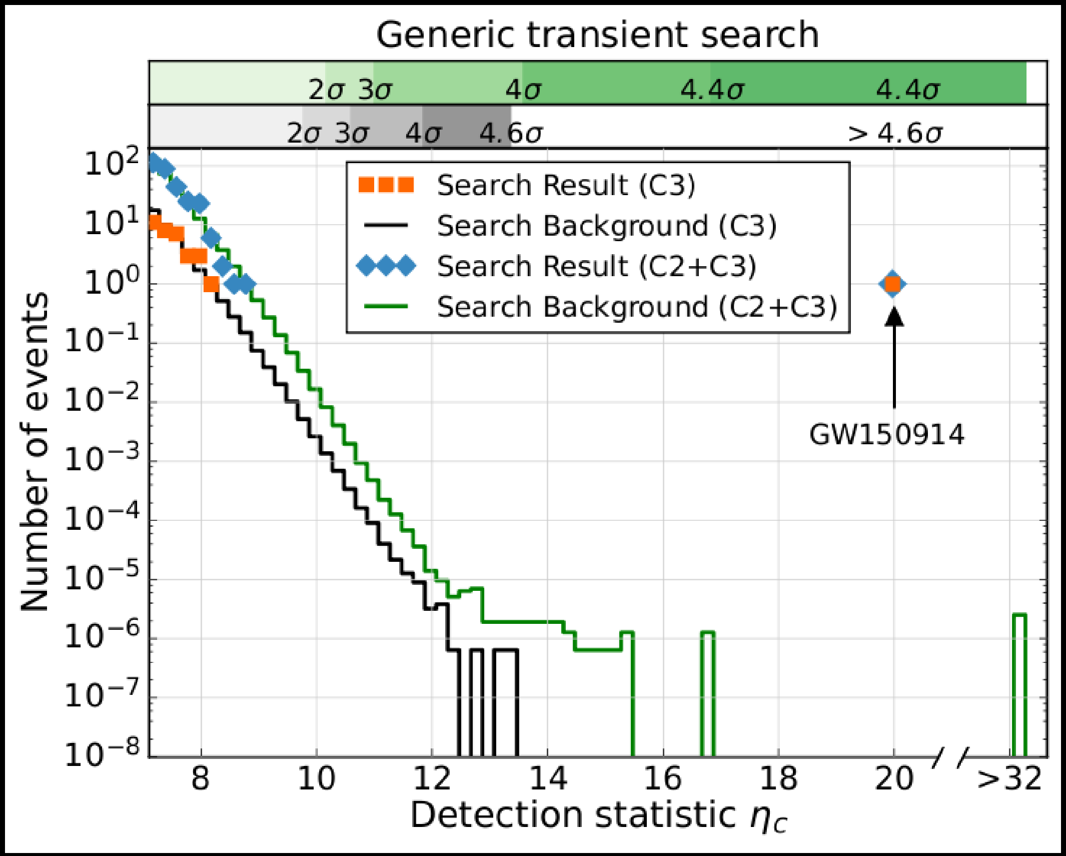


a)
H1
L1
10 ms light travel time
Test Mass
Test Mass
L_y = 4 km
Power Recycling
Beam Splitter
L_x = 4 km
Laser Source
20 W
100 kW Circulating Power
Test Mass
Test Mass
Signal Recycling
Photodetector
b)
H1
L1
Strain noise ($Hz^{-1/2}$)
10^{-21}
10^{-22}
10^{-23}
20
100
1000
Frequency (Hz)

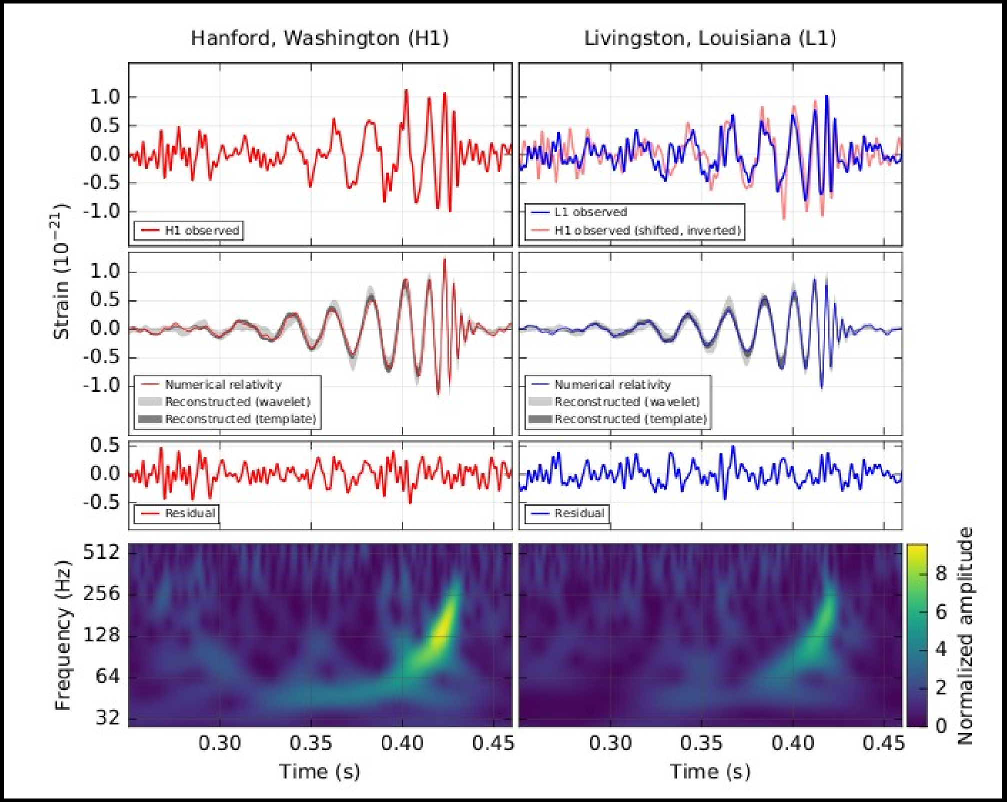




GW 150914

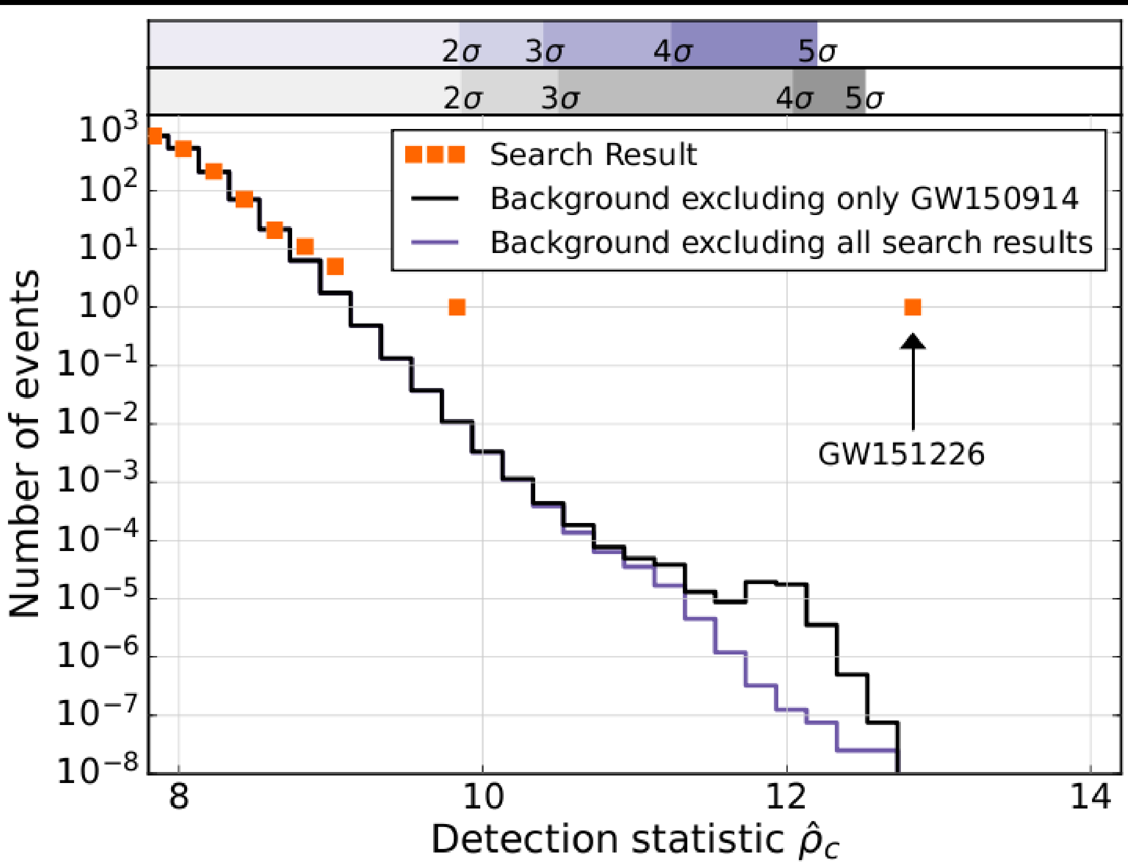


Generic transient search
2σ 3σ 4σ 4.4σ 4.4σ
2σ 3σ 4σ 4.6σ > 4.6σ
Search Result (C3)
Search Background (C3)
Search Result (C2+C3)
Search Background (C2+C3)
GW150914
Number of events
Detection statistic ηc

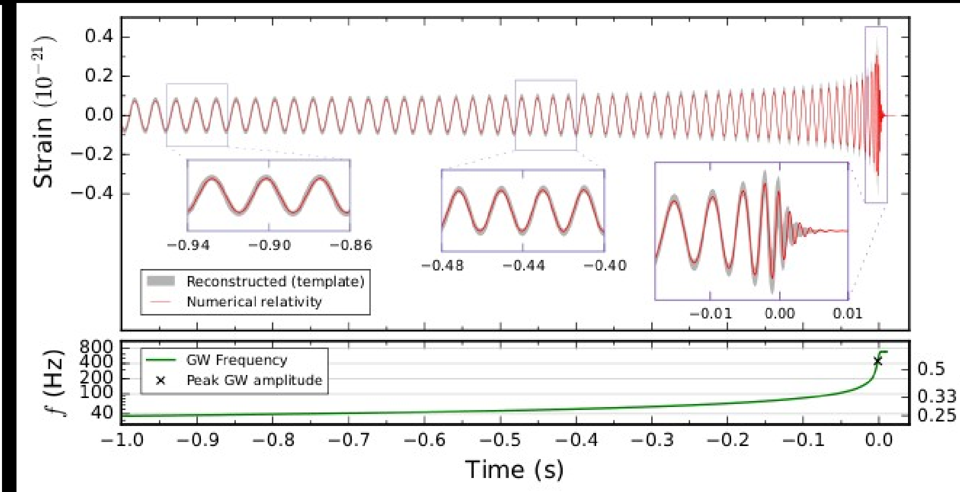


Hanford, Washington (H1)
Livingston, Louisiana (L1)
H1 observed
L1 observed
H1 observed (shifted, inverted)
Strain (10⁻²¹)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
Normalized amplitude
Time (s)

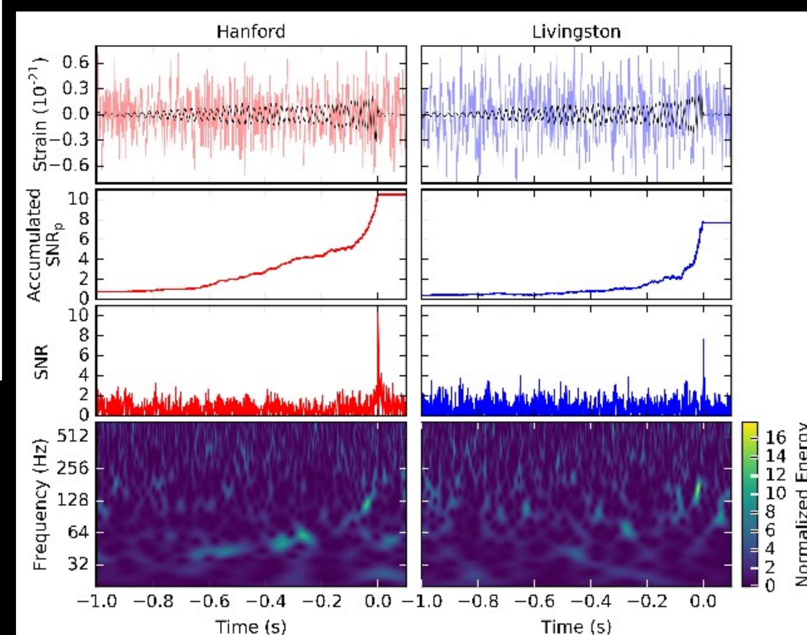
GW 151226



2σ 3σ 4σ 5σ
2σ 3σ 4σ 5σ
Search Result
Background excluding only GW150914
Background excluding all search results
GW151226
Number of events
Detection statistic $\hat{\rho}_c$

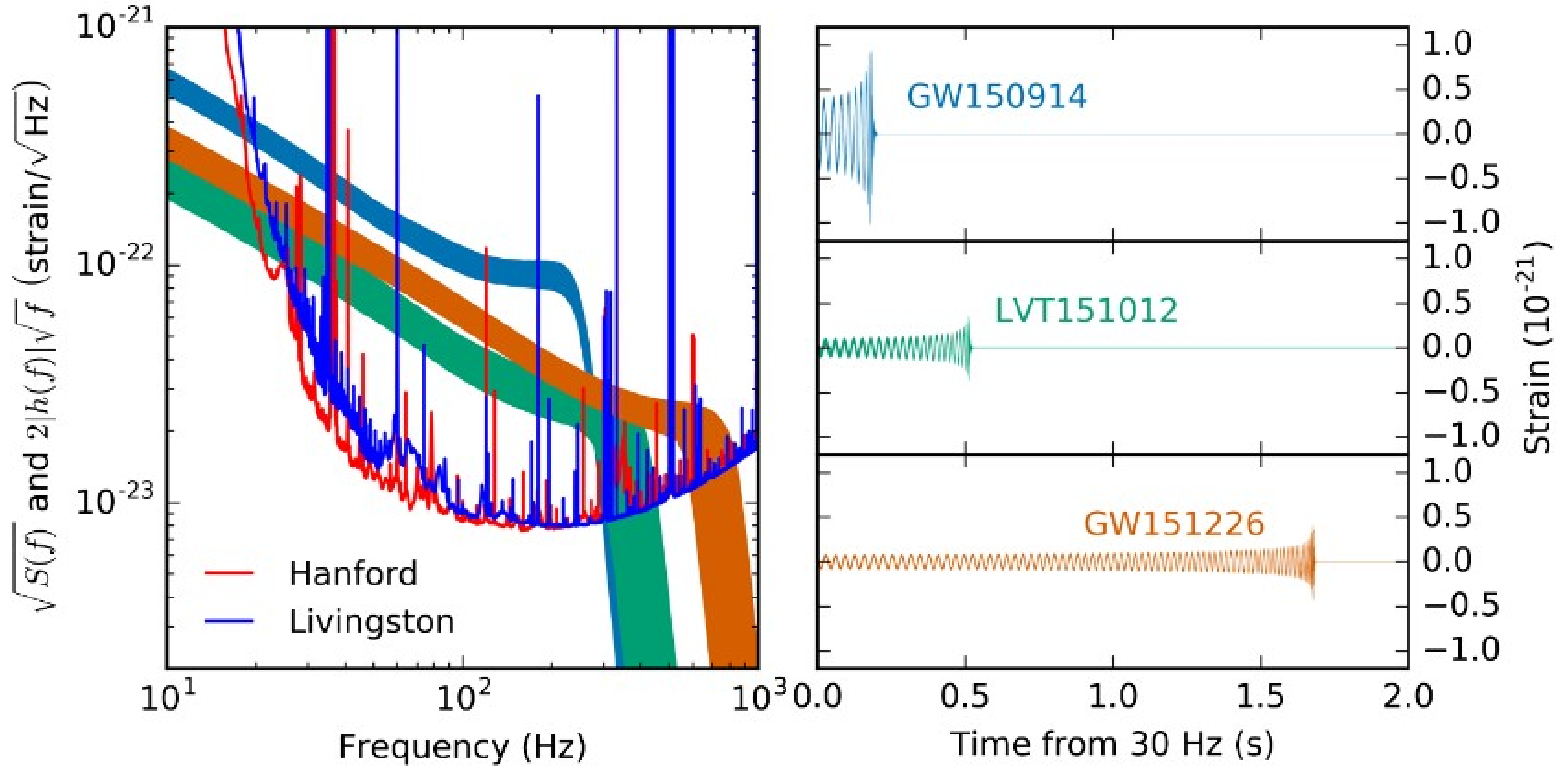


Strain (10^{-21})
Reconstructed (template)
Numerical relativity
GW Frequency
Peak GW amplitude
f (Hz)
Time (s)



Hanford
Livingston
Strain (10^{-21})
Accumulated SNR
SNR
Frequency (Hz)
Normalized Energy
Time (s)
Time (s)

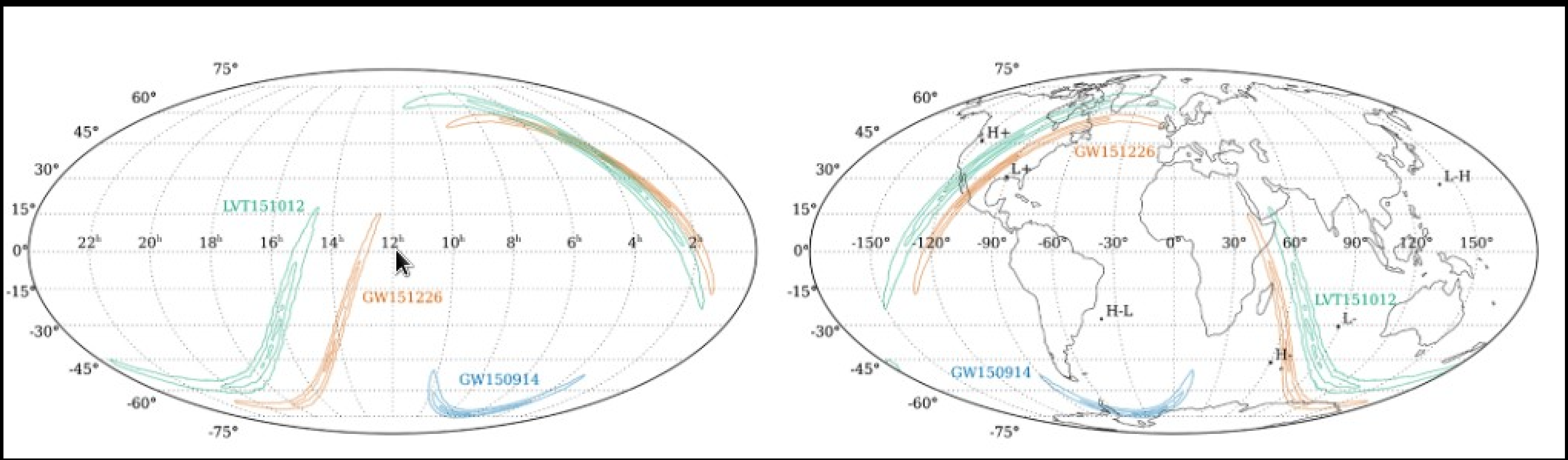
GW combinason

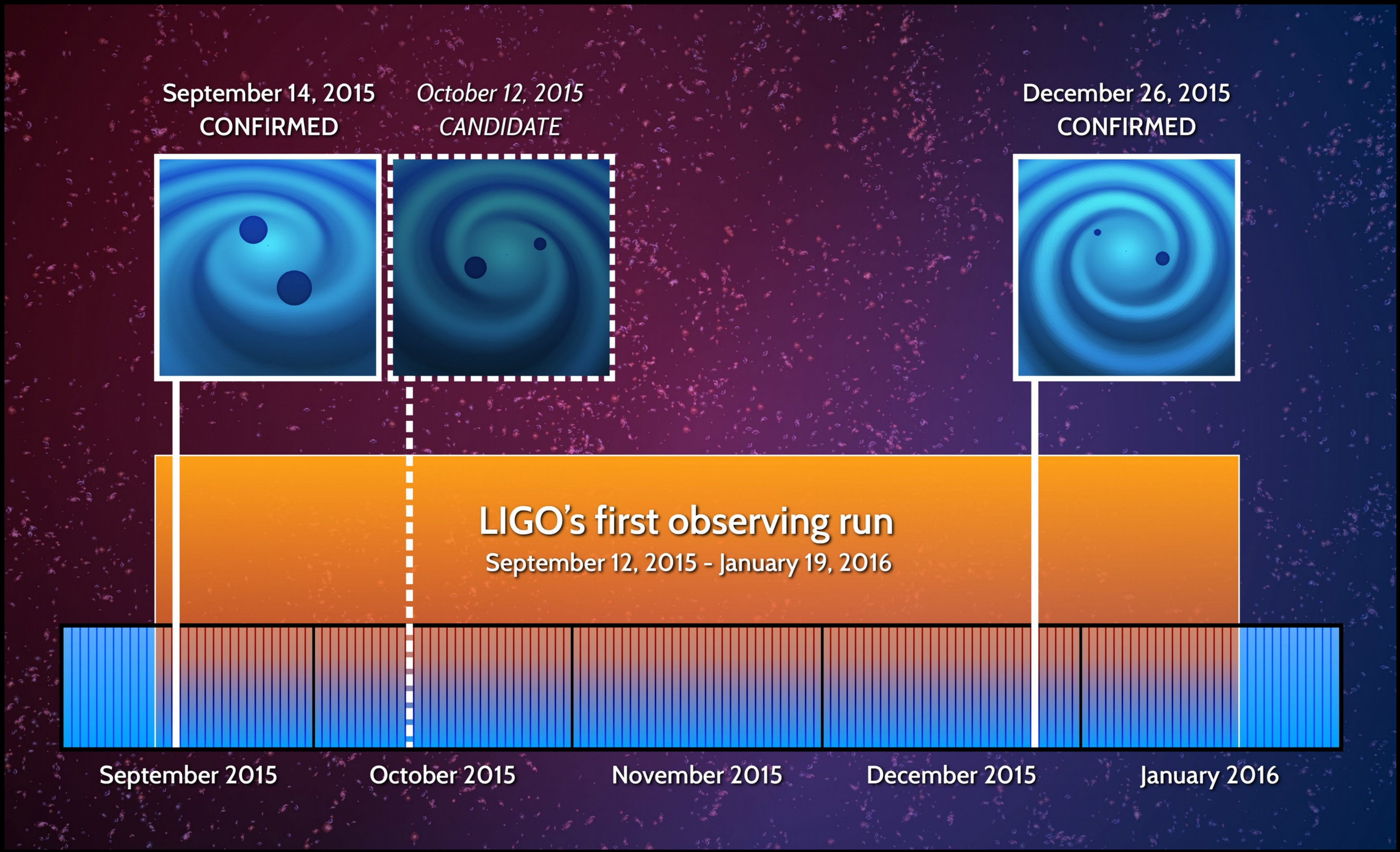


Parameters Estimation

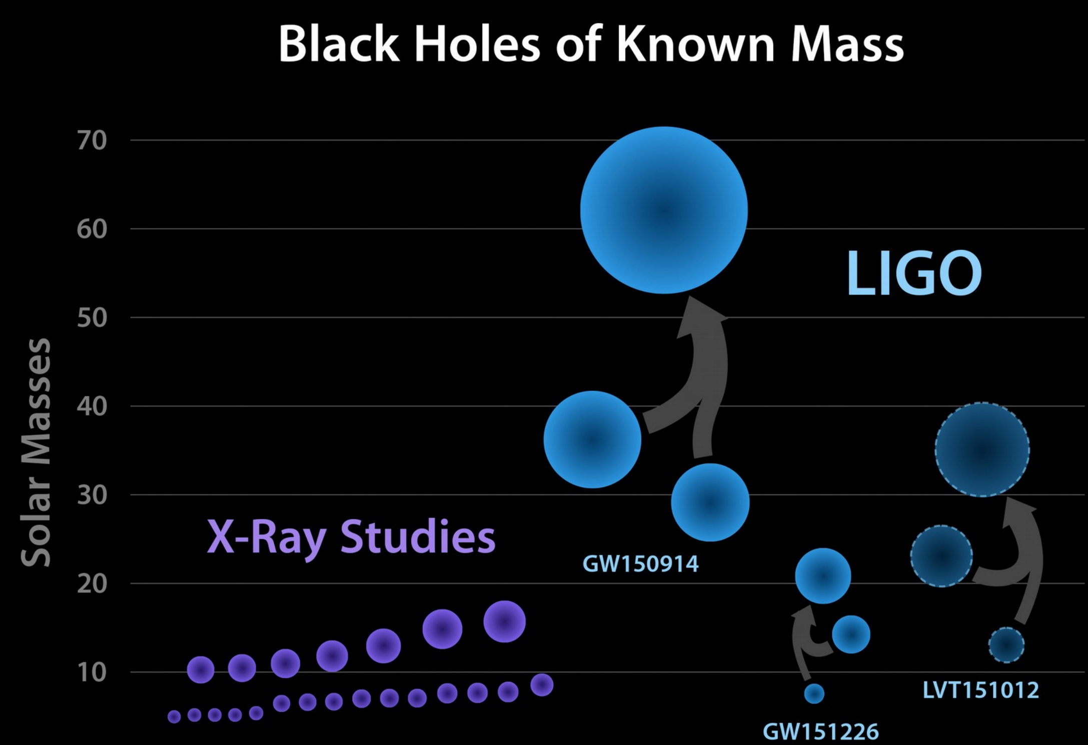
Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate FAR/yr^{-1}	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\sigma$	$> 5.3\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$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

Localization

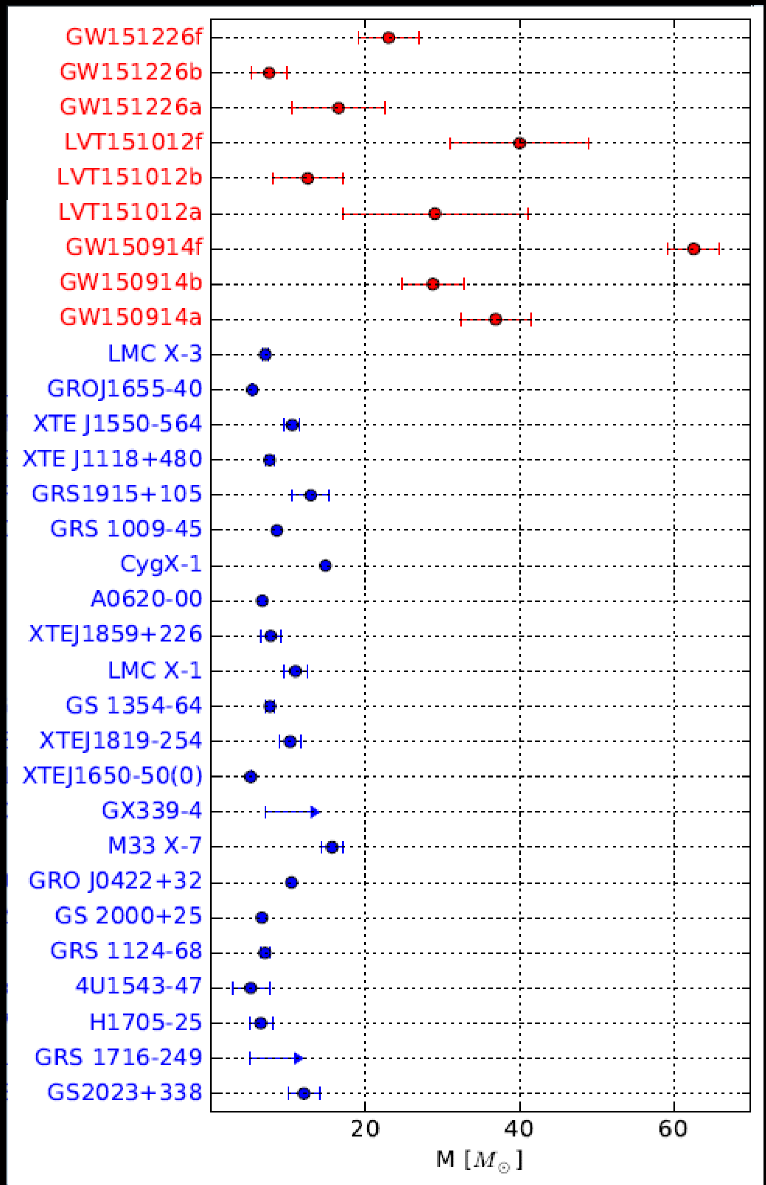



September 14, 2015
CONFIRMED
October 12, 2015
CANDIDATE
December 26, 2015
CONFIRMED
LIGO's first observing run
September 12, 2015 - January 19, 2016
September 2015
October 2015
November 2015
December 2015
January 2016

LIGO VIRGO



Black Holes of Known Mass
Solar Masses
70
60
50
40
30
20
10
0
LIGO
X-Ray Studies
GW150914
GW151226
LVT151012



GW151226f
GW151226b
GW151226a
LVT151012f
LVT151012b
LVT151012a
GW150914f
GW150914b
GW150914a
LMC X-3
GROJ1655-40
XTE J1550-564
XTE J1118+480
GRS1915+105
GRS 1009-45
CygX-1
A0620-00
XTEJ1859+226
LMC X-1
GS 1354-64
XTEJ1819-254
XTEJ1650-50(0)
GX339-4
M33 X-7
GRO J0422+32
GS 2000+25
GRS 1124-68
4U1543-47
H1705-25
GRS 1716-249
GS2023+338
20
40
60
M [$M_\odot$]