Advanced LIGO and Advanced Virgo O1 and O2 Results and Future Plans

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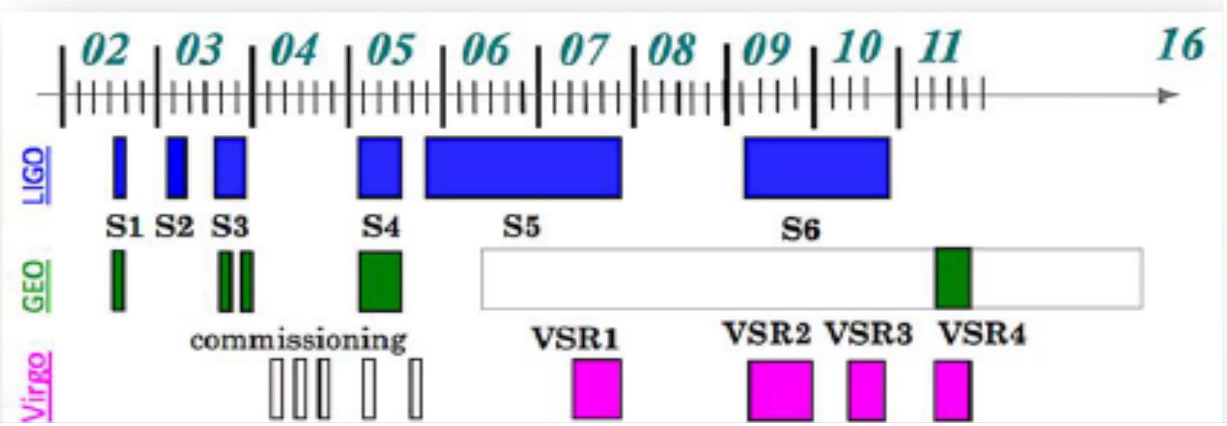
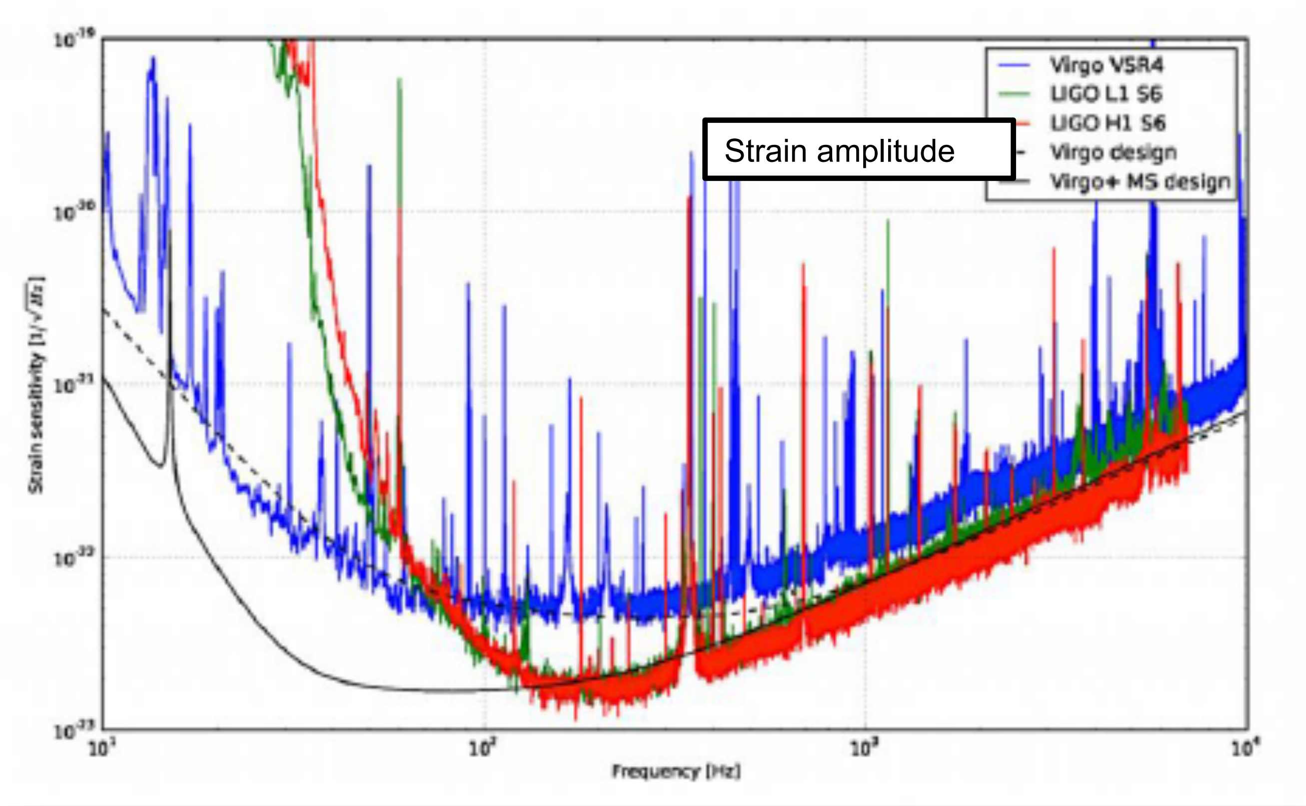
The Beginning: first generation

1st generation LIGO, Virgo and GEO600 operated for about one decade

- Demonstrated a reliable technology
  - duty cycle up to 80%, good stationarity of noise
  - good knowledge of limiting noise sources

- ***No detections*** (expected detection rate ~0.01 ev/yrs) but:
  - lots of science produced meanwhile!
  - clear path towards 2nd generation antennas





Strain amplitude

Beyond first generation, towards Advanced Detectors: noise reduction

Strain Spectral Amplitude (Hz)$^{-1/2}$

Seismic

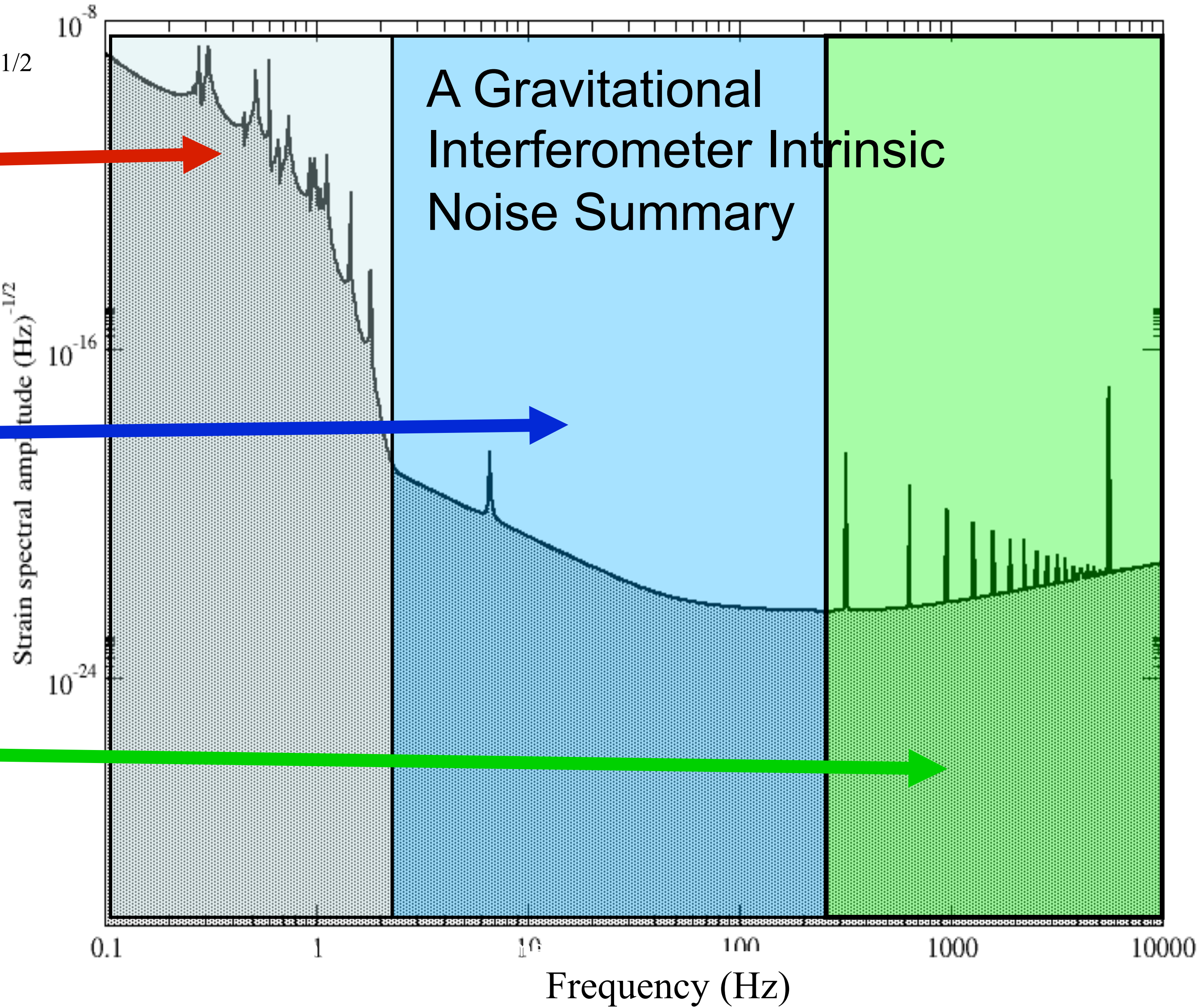
Passive and Active Attenuators

Thermal

Low dissipation materials for coatings, mirrors and suspensions

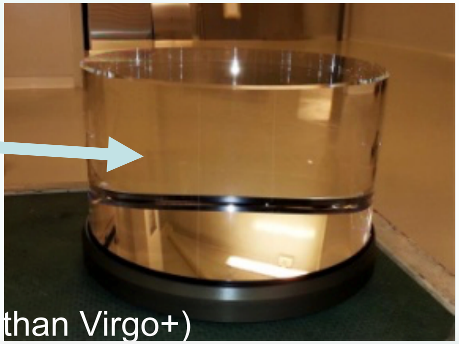
Shot

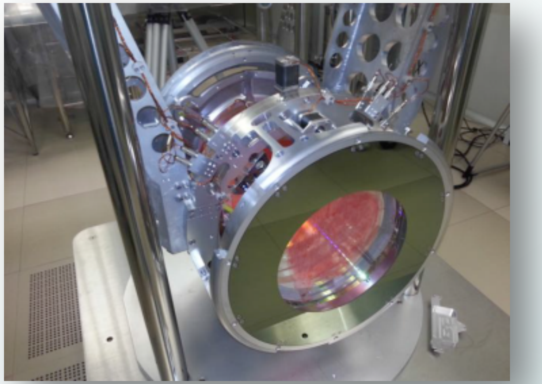
High Laser Power, Signal Recycling Techniques

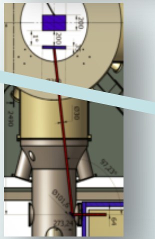


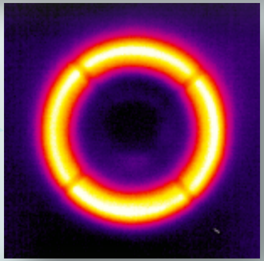
Towards Advanced Detectors: actions

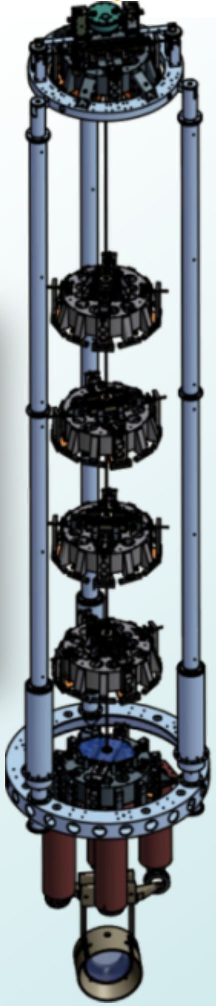
- **Reducing thermal noise:**
  - **Increased beam size @ input TM (2.5 x larger)**
  - **Larger Mirror Masses (2x larger, 42 kg instead of 21 kg)**
  - Improved mirrors' planarity (16 x better)
  - Improved coatings for lower losses (7 x better)
- **Reducing quantum noise:**
  - Increased finesse of arm cavities (9 x larger than iVirgo, 3 x larger than Virgo+)
  - High power laser (16 x more input power)
  - Heavier test masses (2 x heavier)
- **Seismic isolation:**
  - iVirgo superattenuators compatible with AdV specs
  - adapted for new payload (added mass and complexity)
  - new electronics
- **Thermal compensation** (100 x higher power on TM):
  - ring heaters
  - double axicon CO_2 actuators
  - CO_2 central heating
- **Better vacuum** (10^{-9} mbar instead of 10^{-7})
- **Stray light control**
  - Suspended external optical benches in vacuum
  - New set of baffles

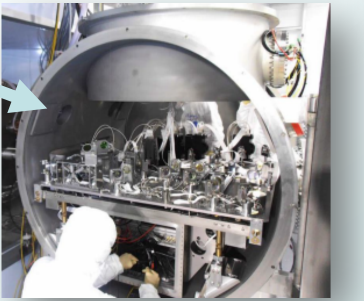




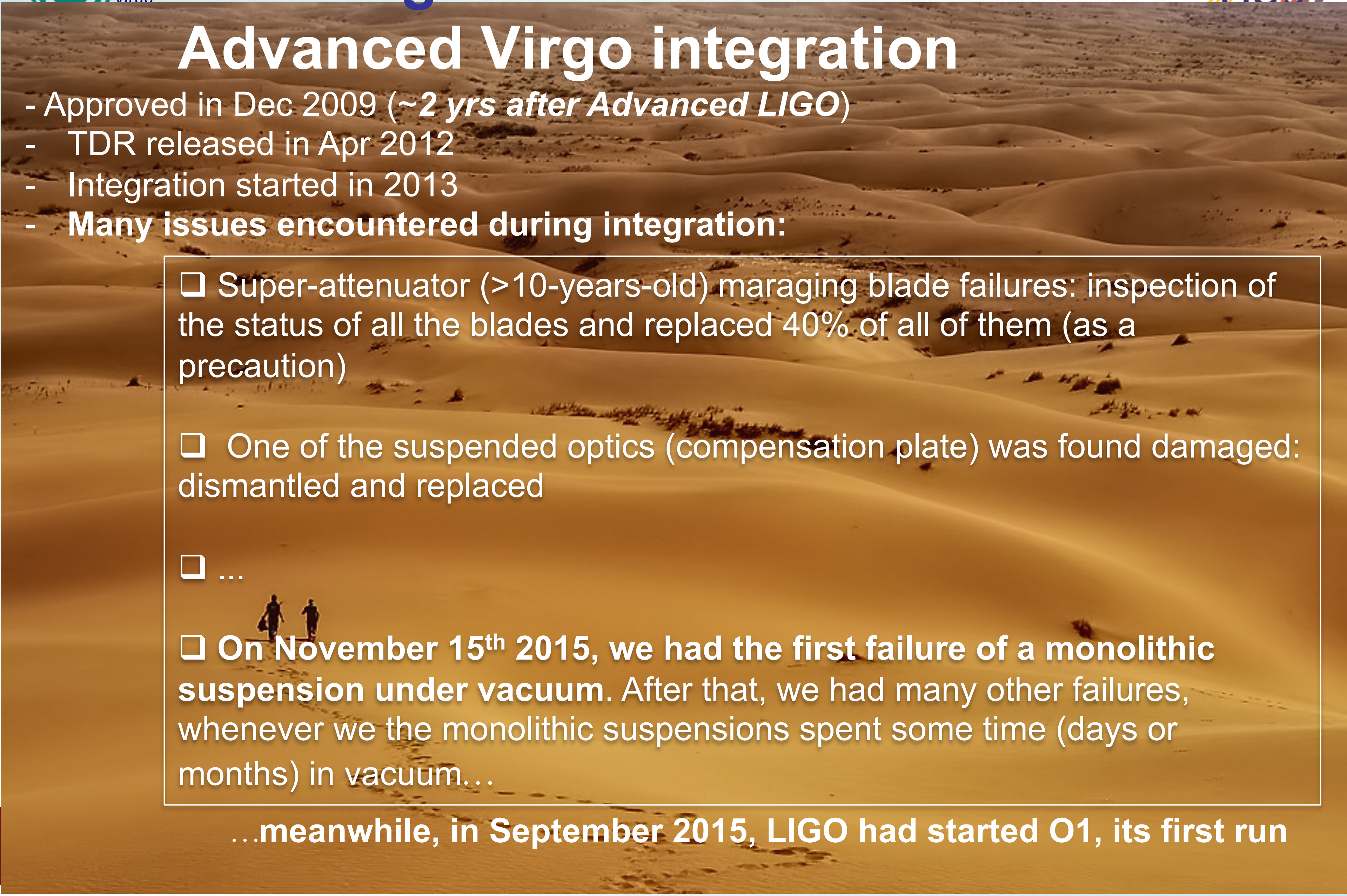








Crossing the desert: Advanced Virgo integration



- Approved in Dec 2009 (~***2 yrs after Advanced LIGO***)
- TDR released in Apr 2012
- Integration started in 2013
- **Many issues encountered during integration:**

☐ Super-attenuator (>10-years-old) maraging blade failures: inspection of the status of all the blades and replaced 40% of all of them (as a precaution)

☐ One of the suspended optics (compensation plate) was found damaged: dismantled and replaced

☐ ...

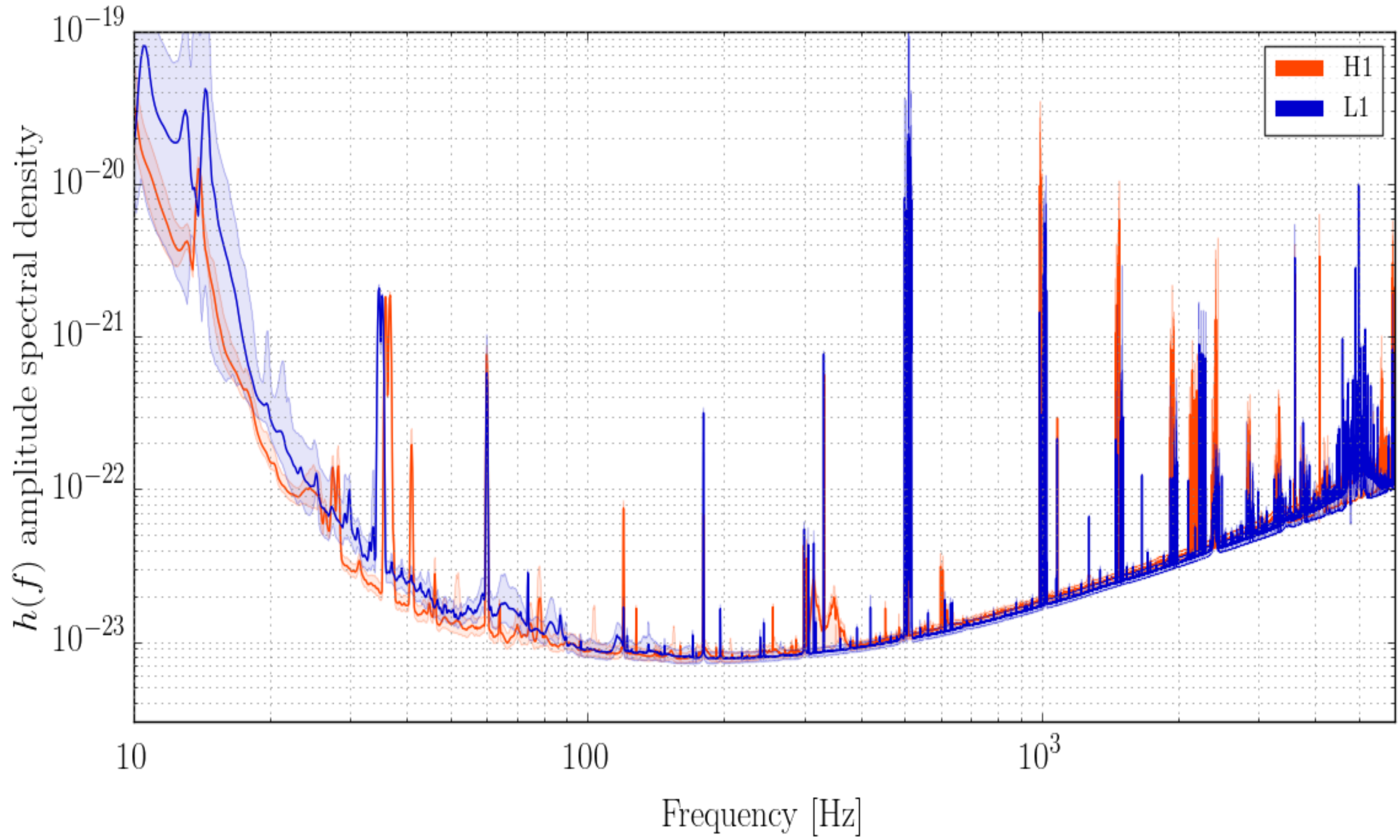
☐ **On November 15th 2015, we had the first failure of a monolithic suspension under vacuum**. After that, we had many other failures, whenever we the monolithic suspensions spent some time (days or months) in vacuum…

…**meanwhile, in September 2015, LIGO had started O1, its first run**

O1 summary

September 12, 2015 - January 19, 2016

LIGO Sensitivity during O1

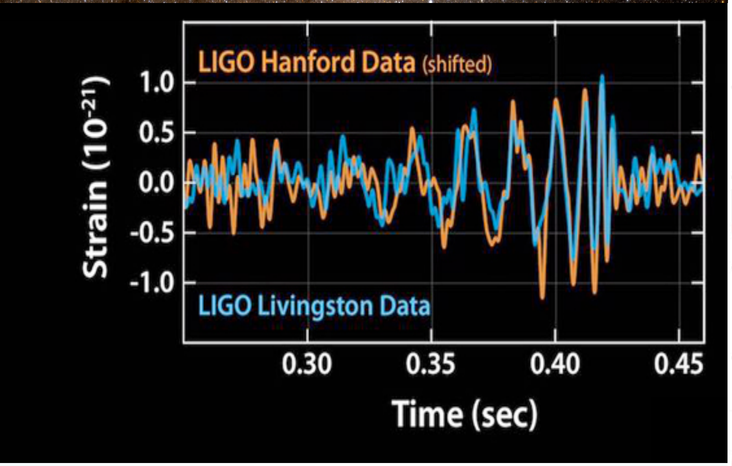


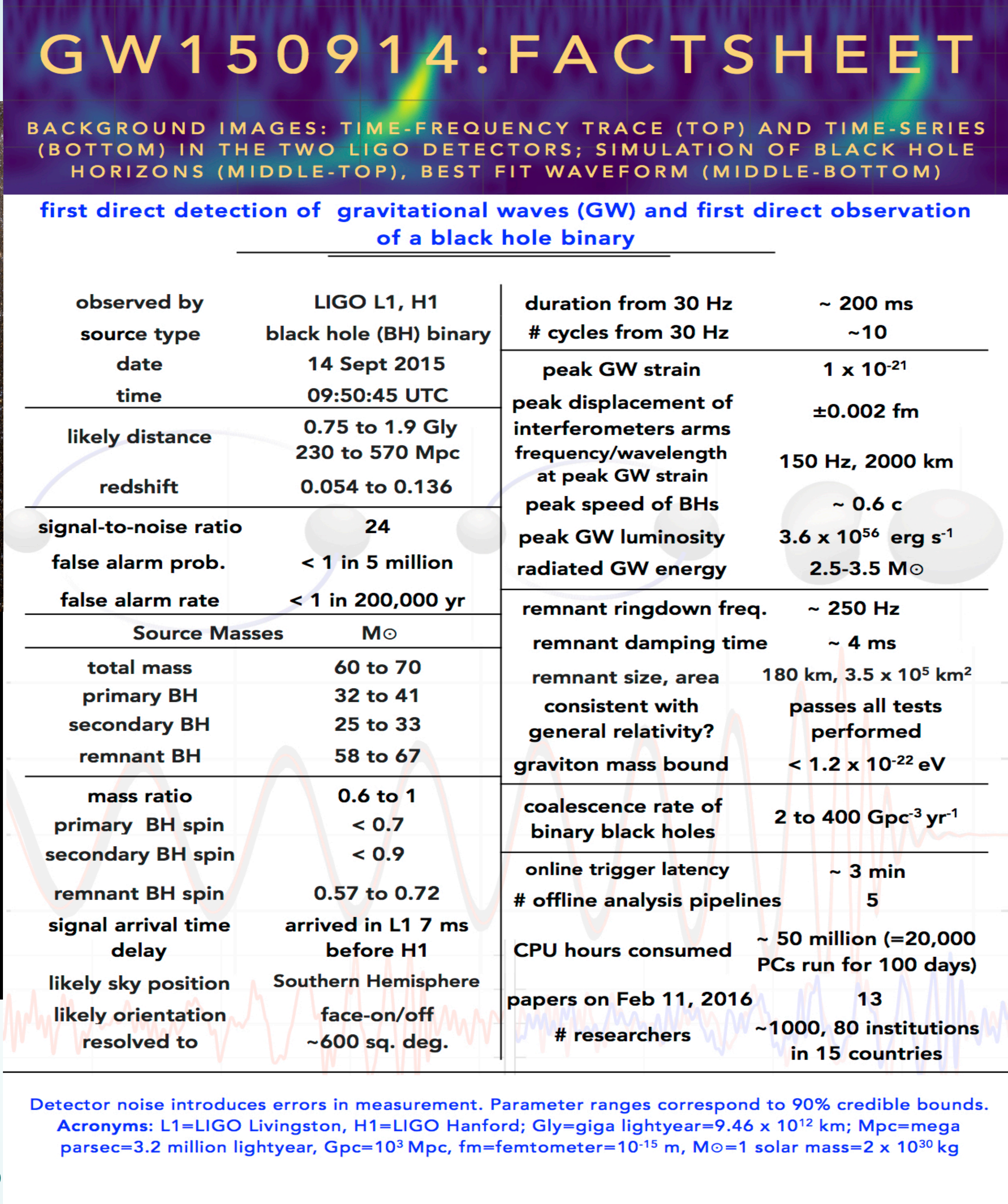
Hunting black–hole binary systems

Advanced Virgo

The first event

Schwarzschild radi
170 km - 210 km





GW150914:FACTSHEET

BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; SIMULATION OF BLACK HOLE HORIZONS (MIDDLE-TOP), BEST FIT WAVEFORM (MIDDLE-BOTTOM)

first direct detection of gravitational waves (GW) and first direct observation of a black hole binary

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr
Source Masses	$M_\odot$
total mass	60 to 70
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	58 to 67
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.57 to 0.72
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1 x 10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6 x 10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 $M_\odot$
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5 x 10^{5} km^{2}
consistent with general relativity?	passes all tests performed
graviton mass bound	< 1.2 x 10^{-22} eV
coalescence rate of binary black holes	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

Detector noise introduces errors in measurement. Parameter ranges correspond to 90% credible bounds.
Acronyms: L1=LIGO Livingston, H1=LIGO Hanford; Gly=giga lightyear=9.46 x 10^{12} km; Mpc=mega parsec=3.2 million lightyear, Gpc=10^{3} Mpc, fm=femtometer=10^{-15} m, $M_\odot$=1 solar mass=2 x 10^{30} kg

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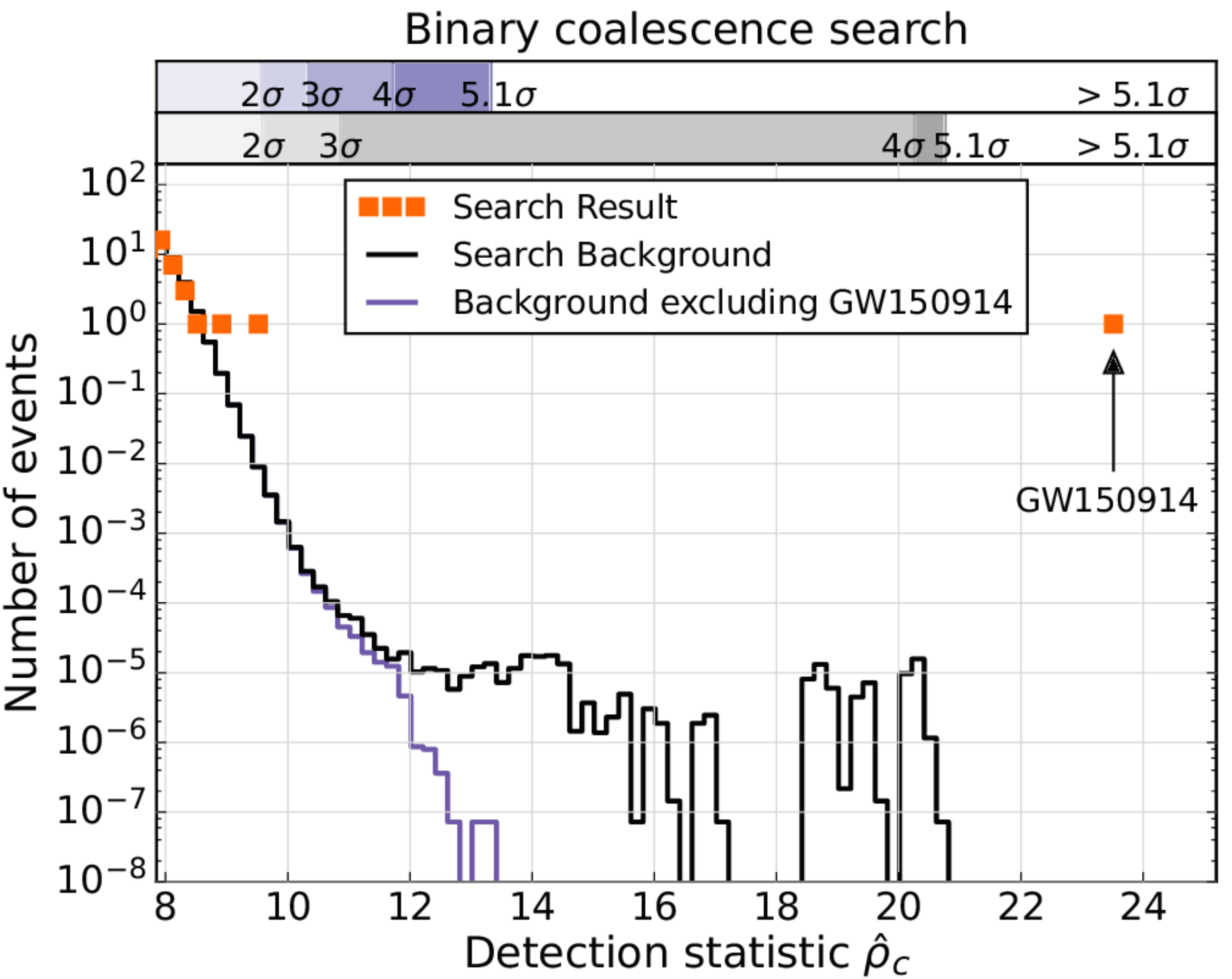
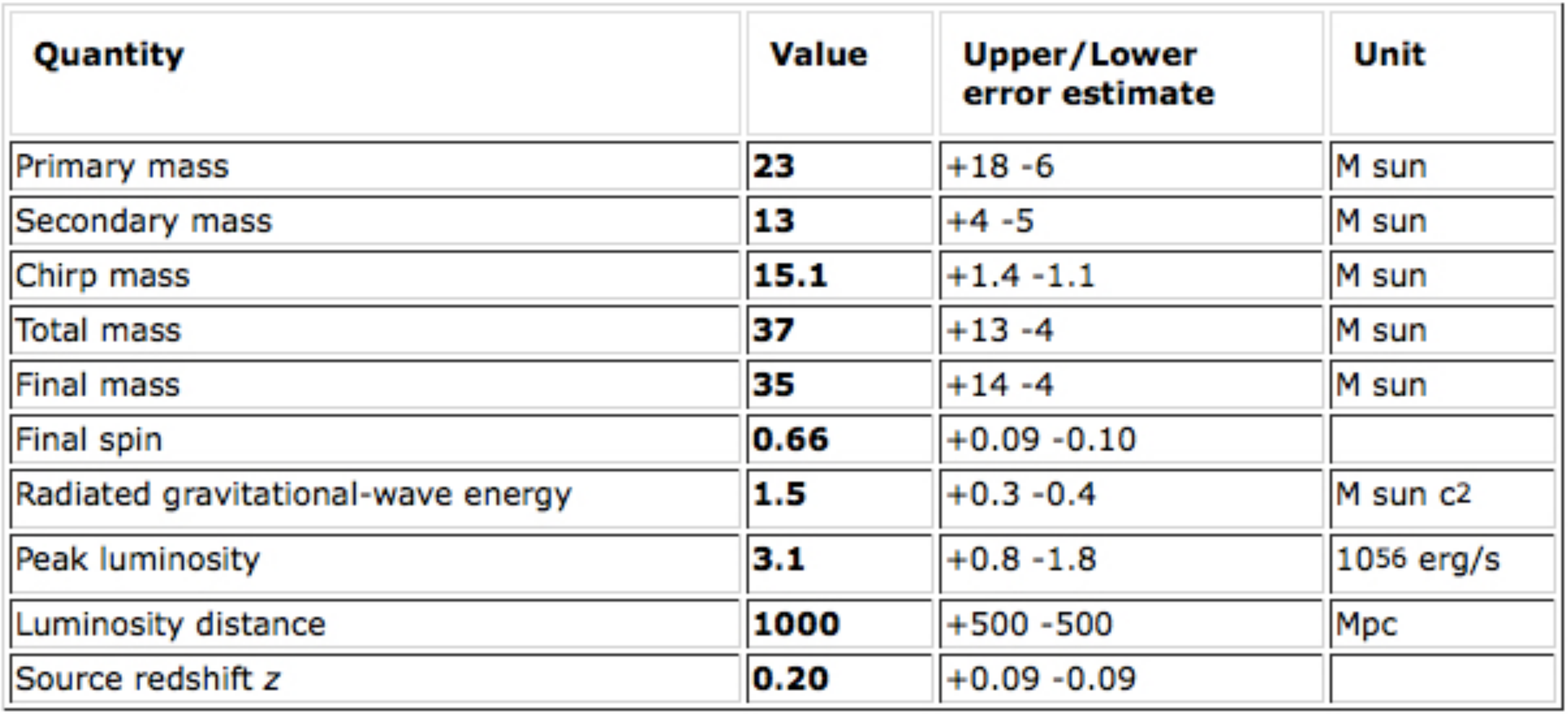

Binary coalescence search
2σ 3σ 4σ 5.1σ
> 5.1σ
2σ 3σ
4σ 5.1σ
> 5.1σ
Search Result
Search Background
Background excluding GW150914
GW150914
Number of events
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
8
10
12
14
16
18
20
22
24
Detection statistic $\hat{\rho}_c$

LVT151012

1.7 σ

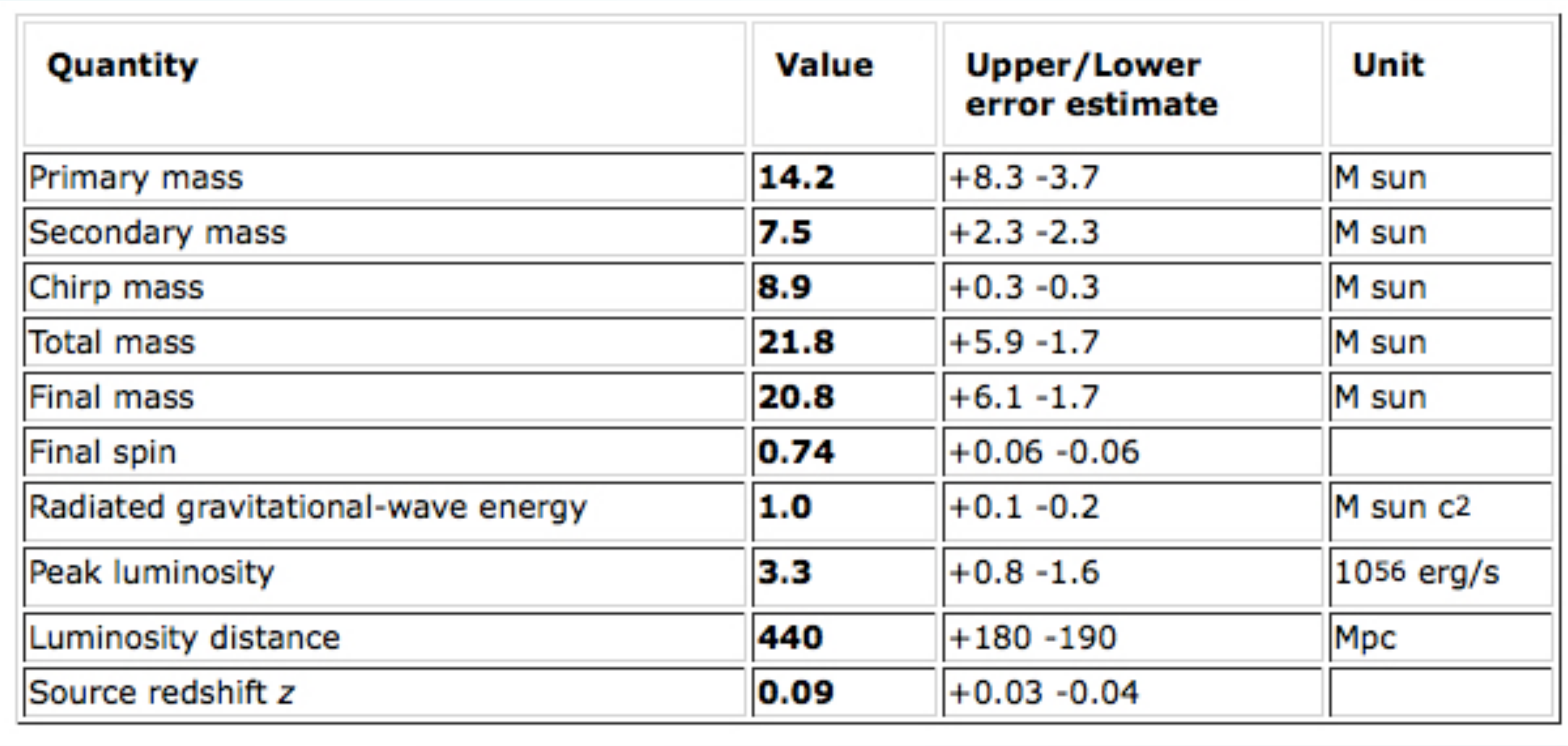
October 12, 2015 at 09:54:43.44 UTC.



Quantity	Value	Upper/Lower error estimate	Unit
Primary mass	**23**	+18 -6	M sun
Secondary mass	**13**	+4 -5	M sun
Chirp mass	**15.1**	+1.4 -1.1	M sun
Total mass	**37**	+13 -4	M sun
Final mass	**35**	+14 -4	M sun
Final spin	**0.66**	+0.09 -0.10	
Radiated gravitational-wave energy	**1.5**	+0.3 -0.4	M sun c2
Peak luminosity	**3.1**	+0.8 -1.8	1056 erg/s
Luminosity distance	**1000**	+500 -500	Mpc
Source redshift z	**0.20**	+0.09 -0.09	

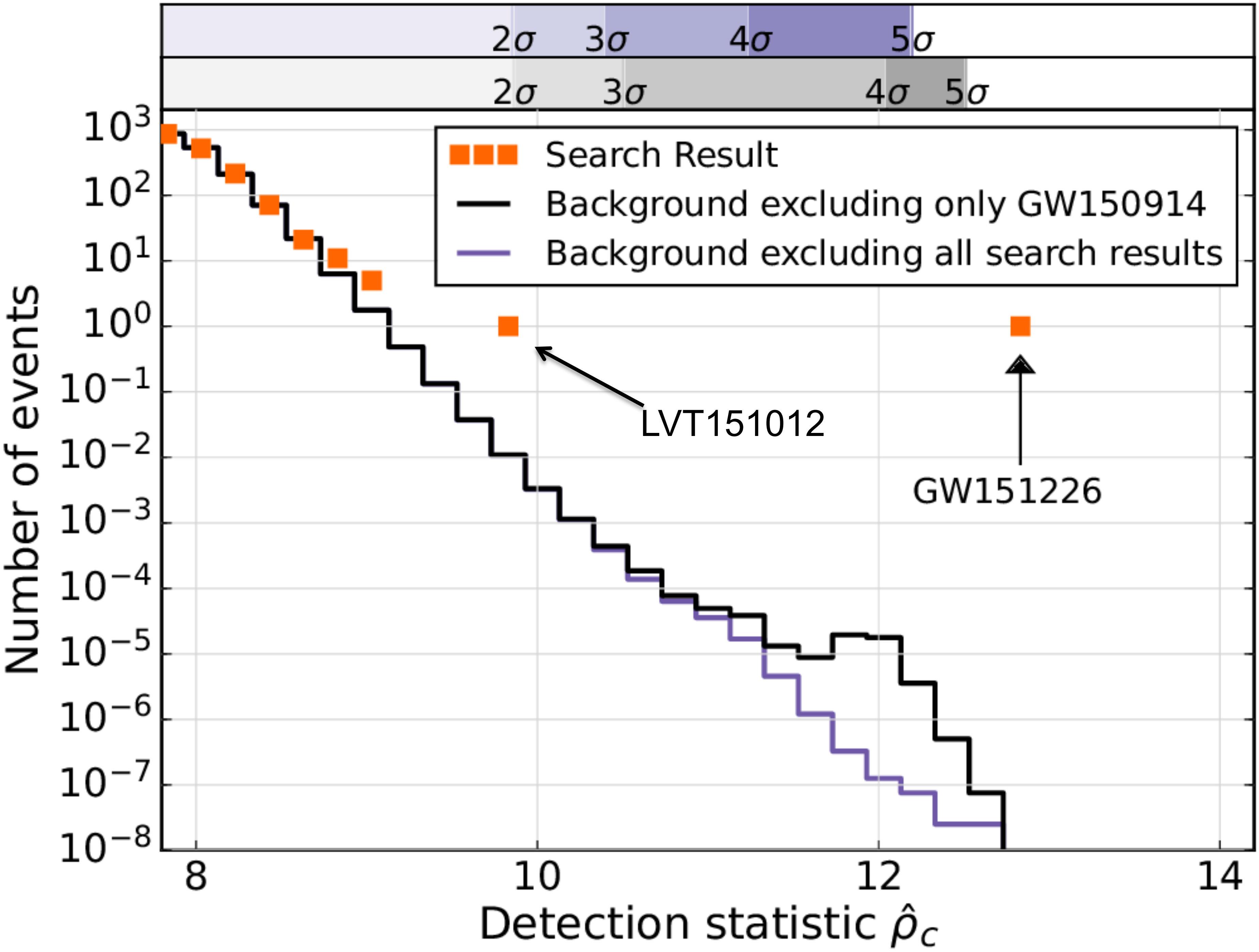
GW151226

5 σ



Quantity	Value	Upper/Lower error estimate	Unit
Primary mass	**14.2**	+8.3 -3.7	M sun
Secondary mass	**7.5**	+2.3 -2.3	M sun
Chirp mass	**8.9**	+0.3 -0.3	M sun
Total mass	**21.8**	+5.9 -1.7	M sun
Final mass	**20.8**	+6.1 -1.7	M sun
Final spin	**0.74**	+0.06 -0.06	
Radiated gravitational-wave energy	**1.0**	+0.1 -0.2	M sun c2
Peak luminosity	**3.3**	+0.8 -1.6	1056 erg/s
Luminosity distance	**440**	+180 -190	Mpc
Source redshift *z*	**0.09**	+0.03 -0.04	

PRL 116, 241103 (2016)


2σ
3σ
4σ
5σ
2σ
3σ
4σ
5σ
Search Result
Background excluding only GW150914
Background excluding all search results
LVT151012
GW151226
Number of events
10^3
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
Detection statistic $\hat{\rho}_c$

Advanced Virgo

O1 summary of BBH Physics

Sharp cut due to the assumption $m^{source}_1 \geq m^{source}_2$

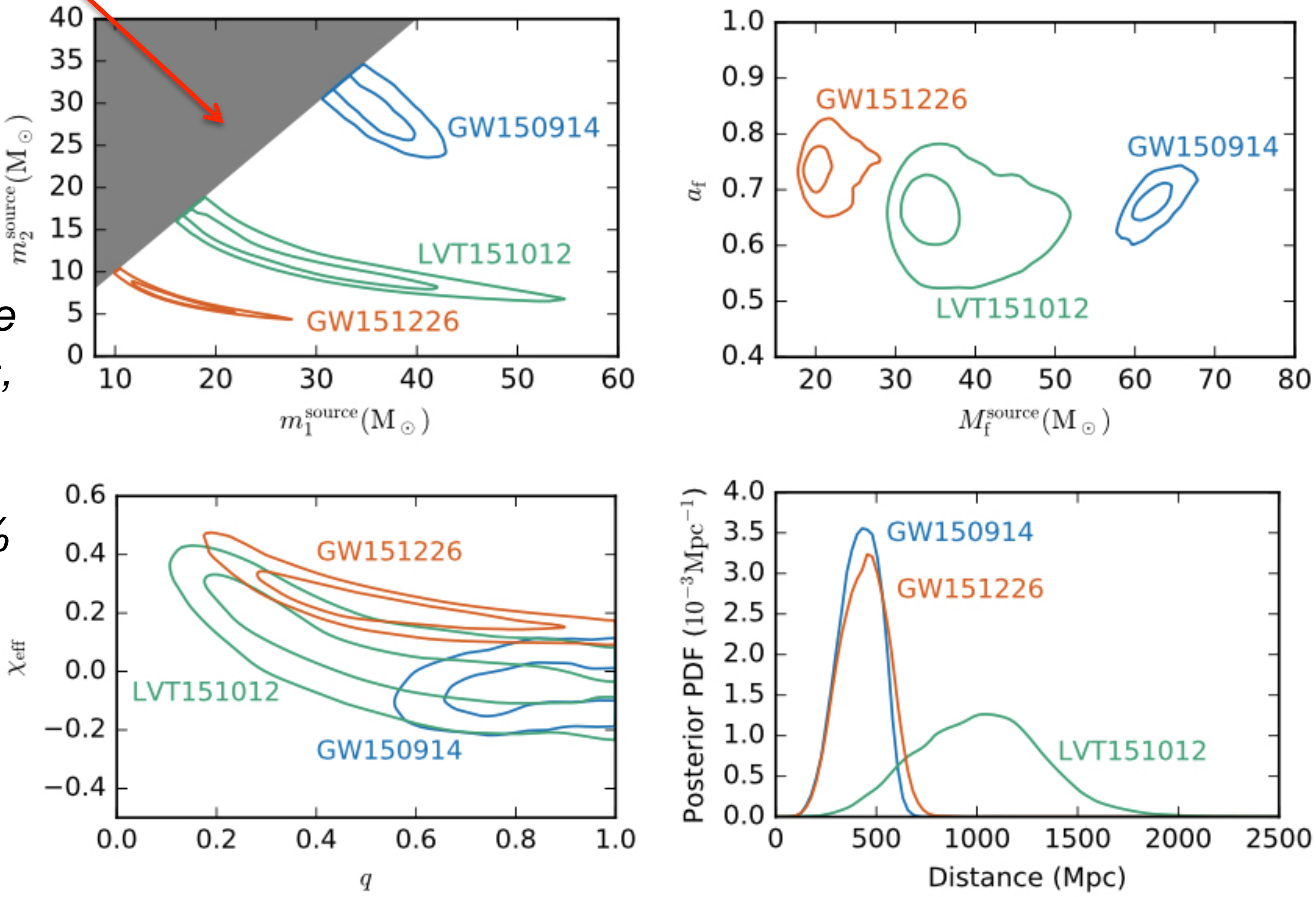
$$a_{1,2} = \frac{c}{G m_{1,2}^2} |S_{1,2}|,$$

a_f and m_f spin and mass of the final BH

$$\chi_{1,2} = \frac{c}{G m_{1,2}^2} S_{1,2} \cdot \hat{L}.$$

$$\chi_{\rm eff} = \frac{m_1 \chi_1 + m_2 \chi_2}{M}$$

Posterior probability densities of the masses, spins, and distance. Contour plots at 50 and 90% of confidence level



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CW signal search in O1

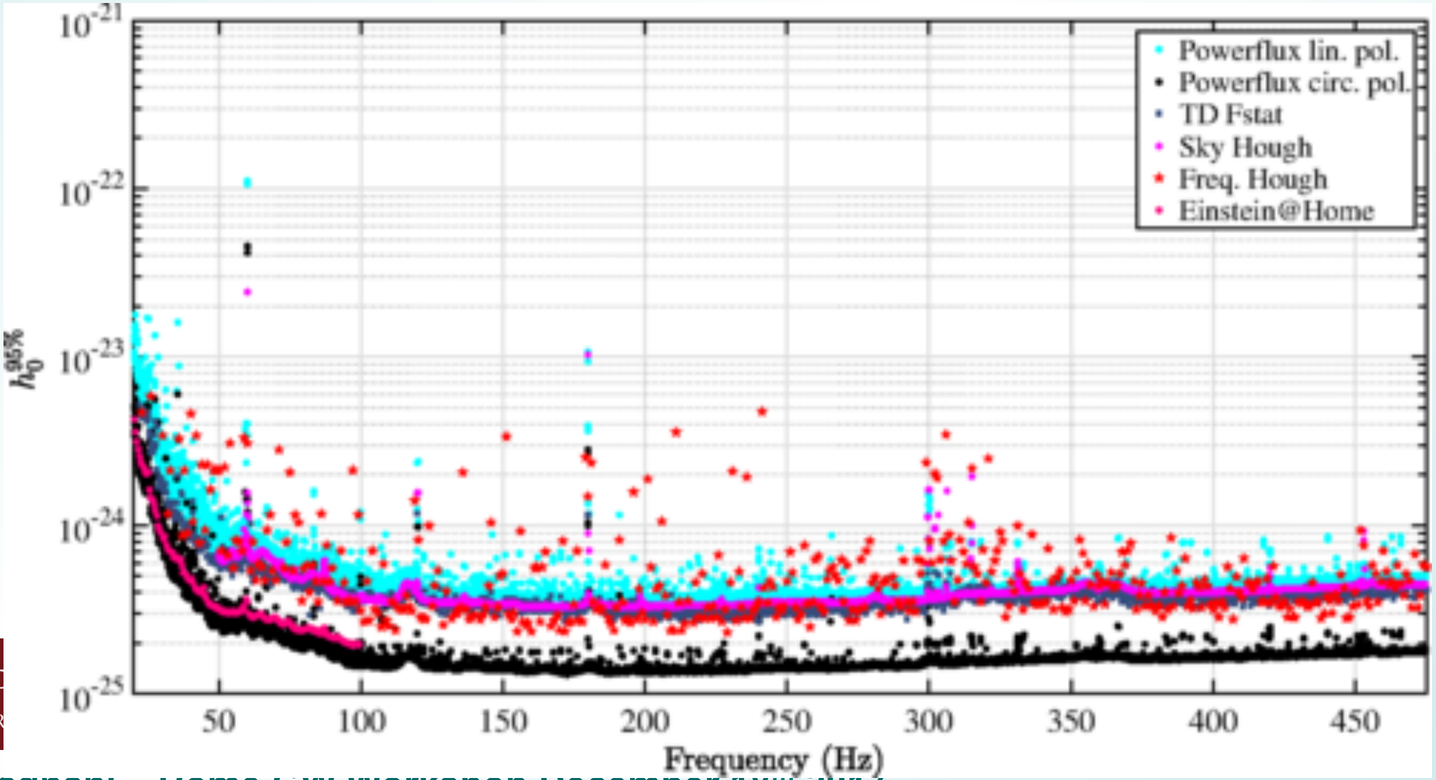
Abbott et al. Phys. Rev. D 96, 062002

All-sky search for periodic gravitational waves in the frequency band 20 - 475 Hz and with a frequency time derivative in the range of [− 1.0 + 0.1] ×10 $^{-8}$ Hz/s

Best upper limits:

Linear polarization @170 Hz ➔ $h_o \simeq 4\times10^{-25}$

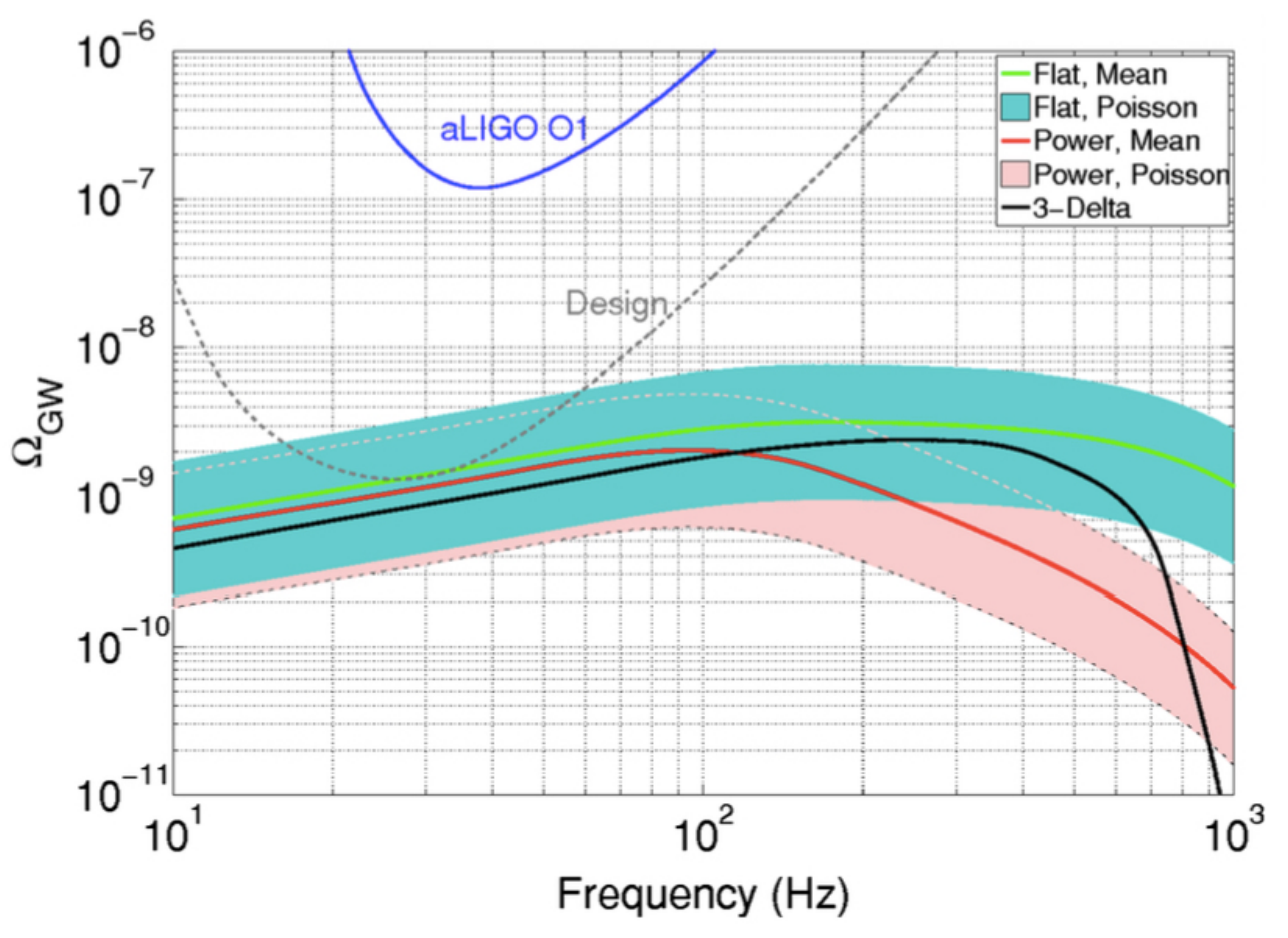
Circular polarization @170 Hz ➔ $h_o \simeq 1.5 \times 10^{-25}$



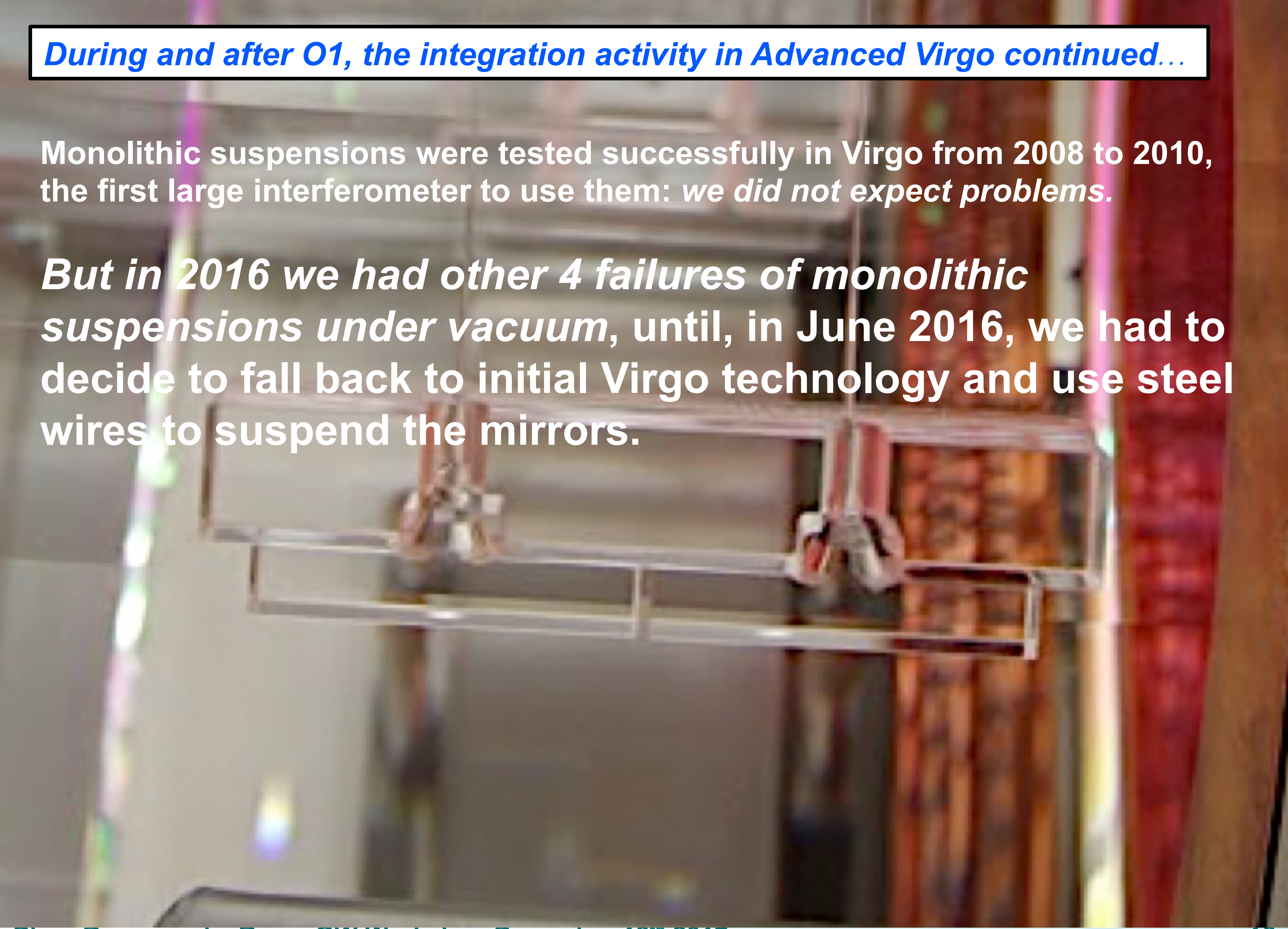
Upper limit of BHBH stochastic background

Potential spectra for a BBH background, using the flat-log, power-law, and three-delta mass distribution with the local rate inferred from the O1 detections

Upper Limits on the Stochastic Gravitational-Wave Background from Advanced LIGO's First Observing Run - LIGO Scientific and Virgo Collaborations (Abbott, Benjamin P. *et al.*) Phys.Rev.Lett. 118 (2017) no.12, 121101, Erratum: Phys.Rev.Lett. 119 (2017) no.2, 029901 arXiv:1612.02029 [gr-qc]



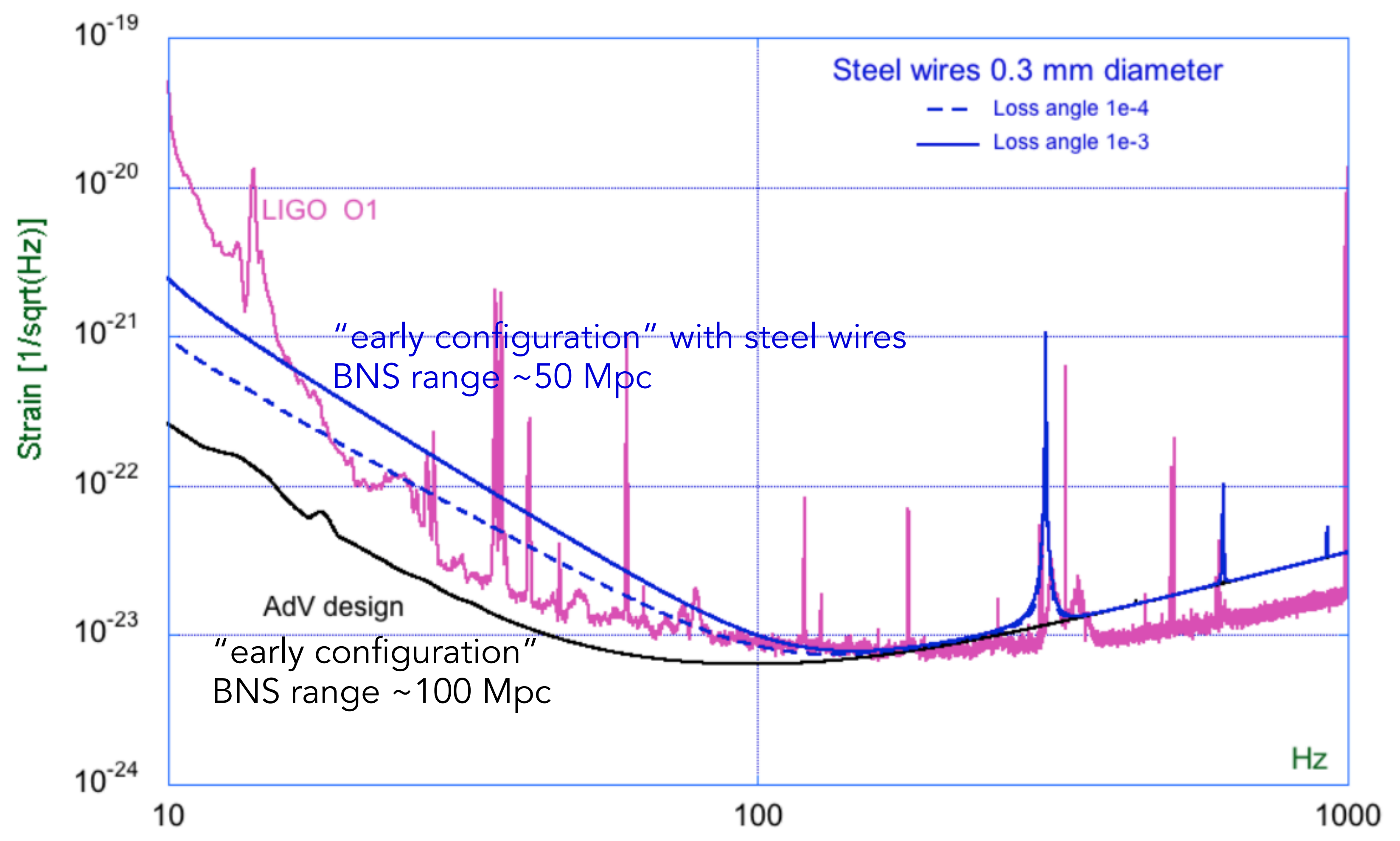
During and after O1, the integration activity in Advanced Virgo continued…



Monolithic suspensions were tested successfully in Virgo from 2008 to 2010, the first large interferometer to use them: *we did not expect problems.*

***But in 2016 we had other 4 failures of monolithic suspensions under vacuum*, until, in June 2016, we had to decide to fall back to initial Virgo technology and use steel wires to suspend the mirrors.**

During and after O1, the integration activity in Advanced Virgo continued



"early configuration" with steel wires
BNS range ~50 Mpc

"early configuration"
BNS range ~100 Mpc

In this way we could still the reach the sensitivity goal of the early phase of Advanced Virgo.

In parallel, we made an extensive and intense research to understand the cause:

Eventually, in november 2016, the culprit was found: ***dust particle generated by scroll pumps and blown towards the fibers during ventings of the vacuum chamber.***

Risk mitigation action plan implemented:

– upgrade of the vacuum system: scroll pumps replacement, modifications of the venting piping

– installation of “fiber guards”

After O2, test masses are now being suspended again with fused silica fibers.

December 13th 2017

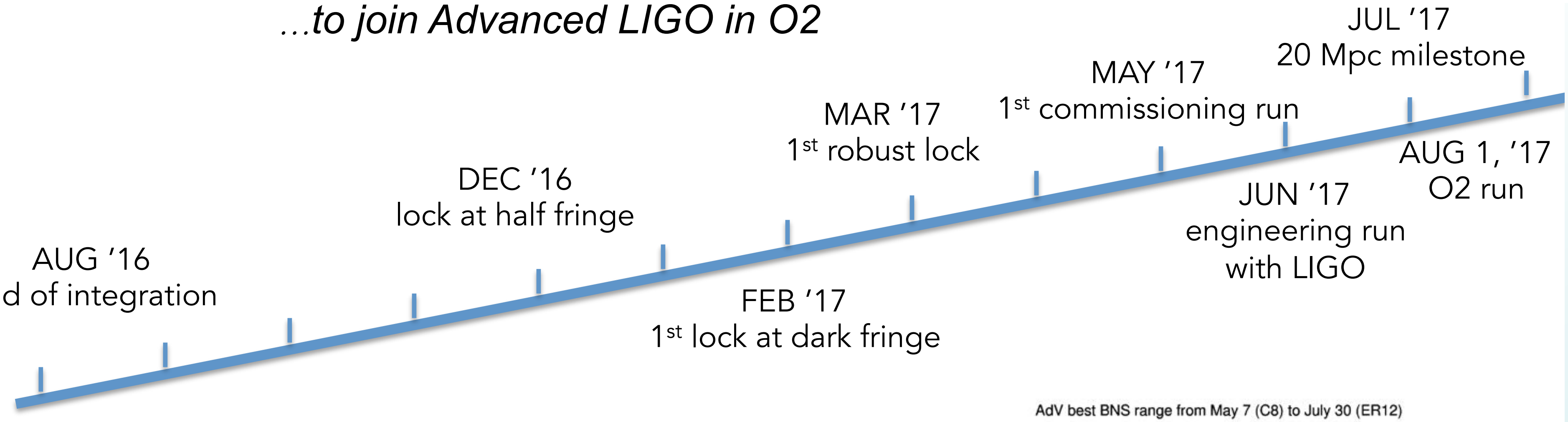
N.END. reassembled with monolithic suspension

FOTO PERCI

In August 2016 the Advanced Virgo was completed and we started…

The Commissioning Rush

…to join Advanced LIGO in O2



AUG '16
end of integration

DEC '16
lock at half fringe

FEB '17
1st lock at dark fringe

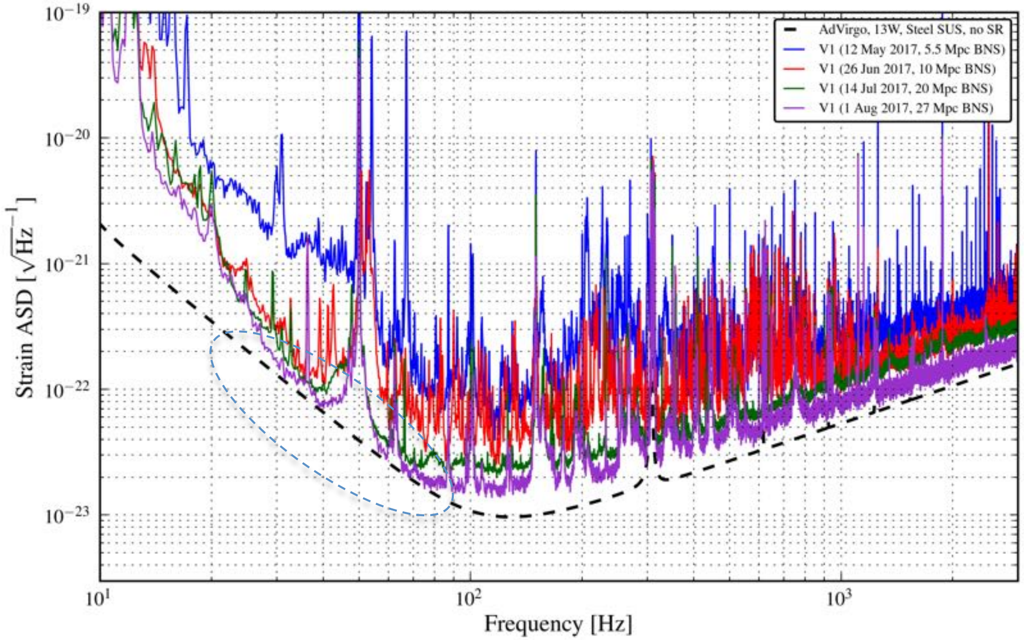
MAR '17
1st robust lock

MAY '17
1st commissioning run

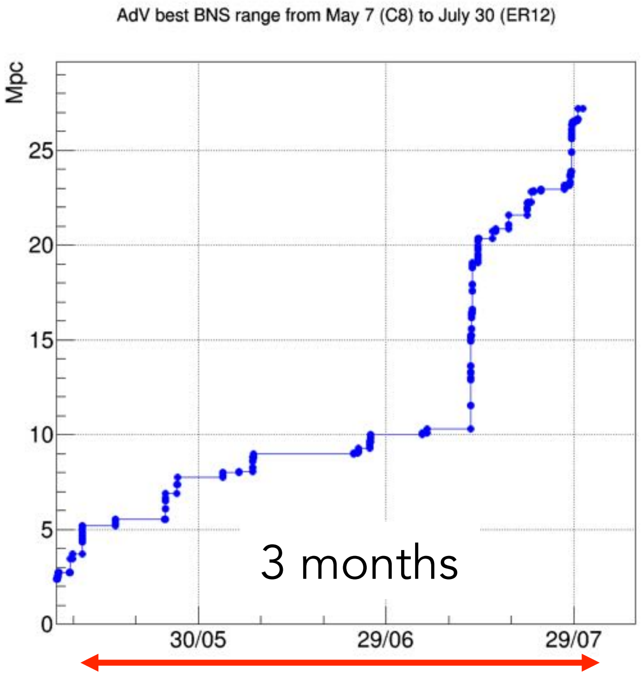
JUN '17
engineering run
with LIGO

JUL '17
20 Mpc milestone

AUG 1, '17
O2 run



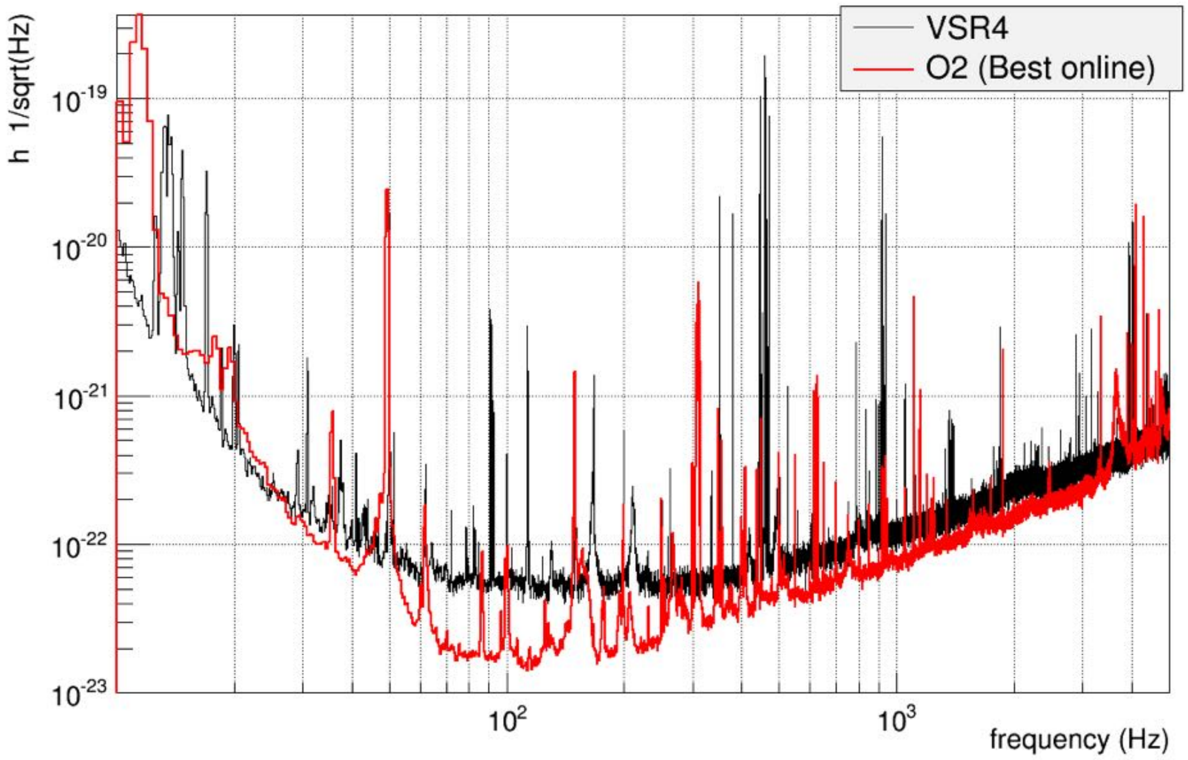
IFN Pis



3 months

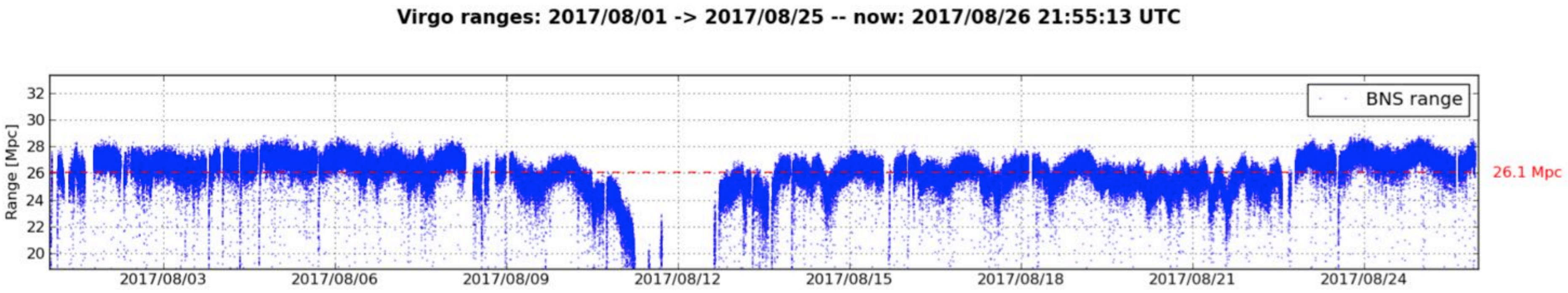
On August 1st 2017 Advanced Virgo joined Advanced LIGO in O2.

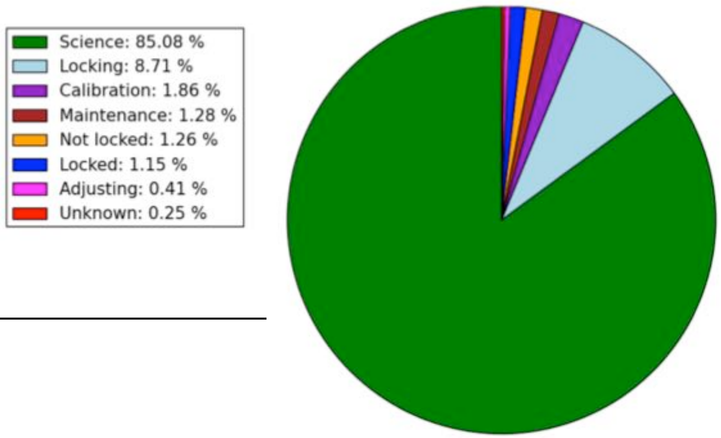
O2 had started in November 2016, and was due to end on August 25th 2017.



- VIRGO+ (2011): BNS range of 12 Mpc
- AdV (O2): 28 Mpc, ~12x larger volume of universe reached
  - now further improved: >30 Mpc

Advanced Virgo in O2





DUTY CYCLE: 85% (!!)

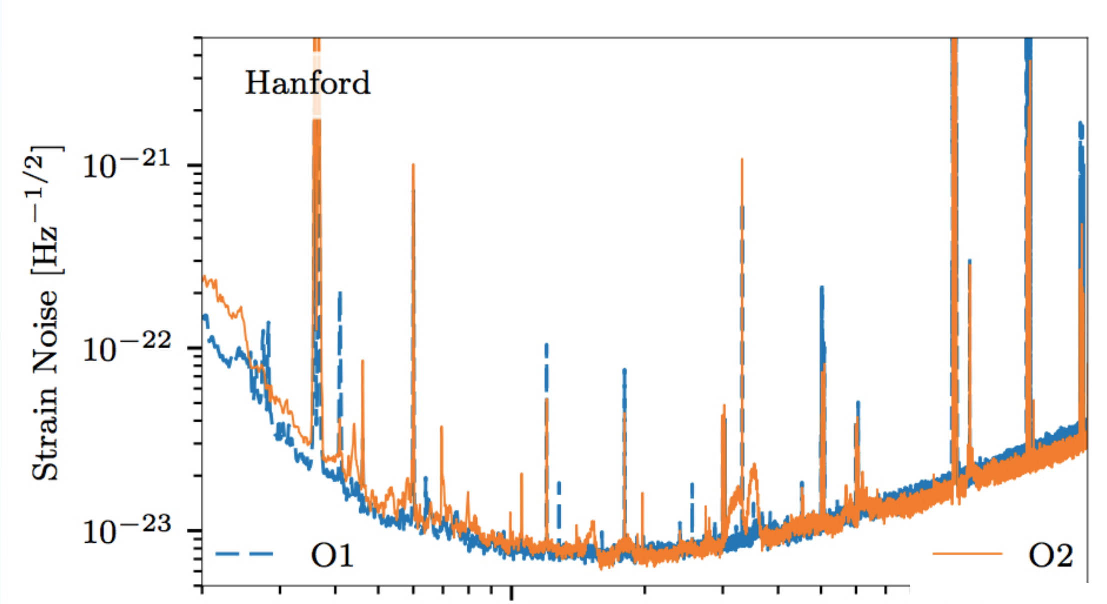
LONGEST LOCK STRETCH: 69 hours

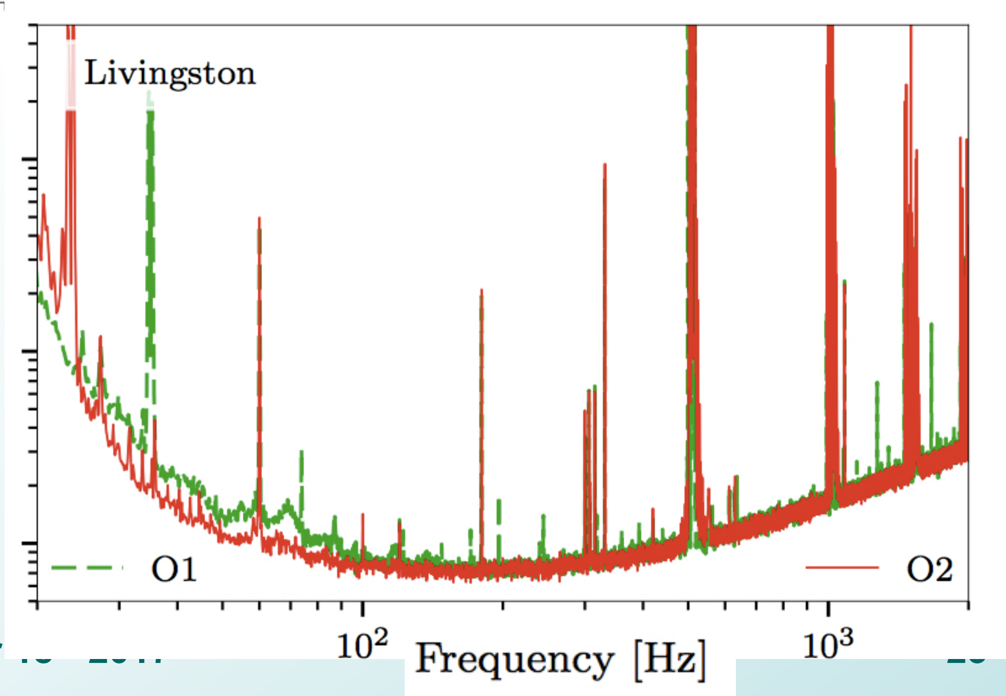
HIGHEST BNS RANGE: 28.2 Mpc

AVERAGE RANGE: BNS 26 - BBH_{10} 134 - BBH_{30} 314 Mpc

O2 summary
November 30, 2016
August 25, 2017
(with Christmas break)

LIGO Sensitivity during O2

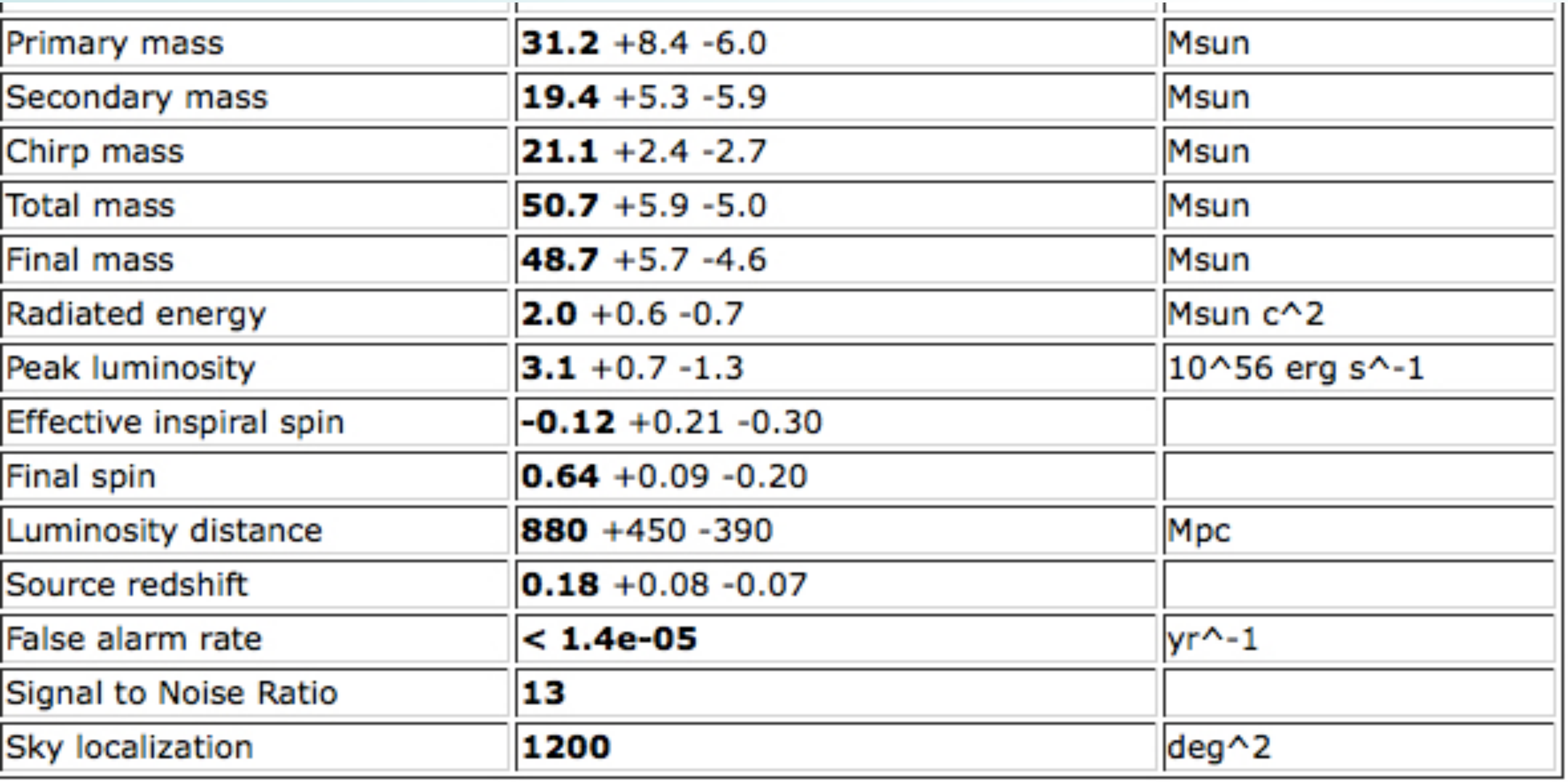




GW170104

Again a BBH

January 04 2017, 10:11:58.6 UTC



Primary mass	**31.2** +8.4 -6.0	Msun
Secondary mass	**19.4** +5.3 -5.9	Msun
Chirp mass	**21.1** +2.4 -2.7	Msun
Total mass	**50.7** +5.9 -5.0	Msun
Final mass	**48.7** +5.7 -4.6	Msun
Radiated energy	**2.0** +0.6 -0.7	Msun c^2
Peak luminosity	**3.1** +0.7 -1.3	10^56 erg s^-1
Effective inspiral spin	**-0.12** +0.21 -0.30	
Final spin	**0.64** +0.09 -0.20	
Luminosity distance	**880** +450 -390	Mpc
Source redshift	**0.18** +0.08 -0.07	
False alarm rate	**< 1.4e-05**	yr^-1
Signal to Noise Ratio	**13**	
Sky localization	**1200**	deg^2

Network signal-to-noise ratio of 13 and a false-alarm-rate of once per 7 x 10^4 years

Advanced Virgo

GW170608

The last found BBH

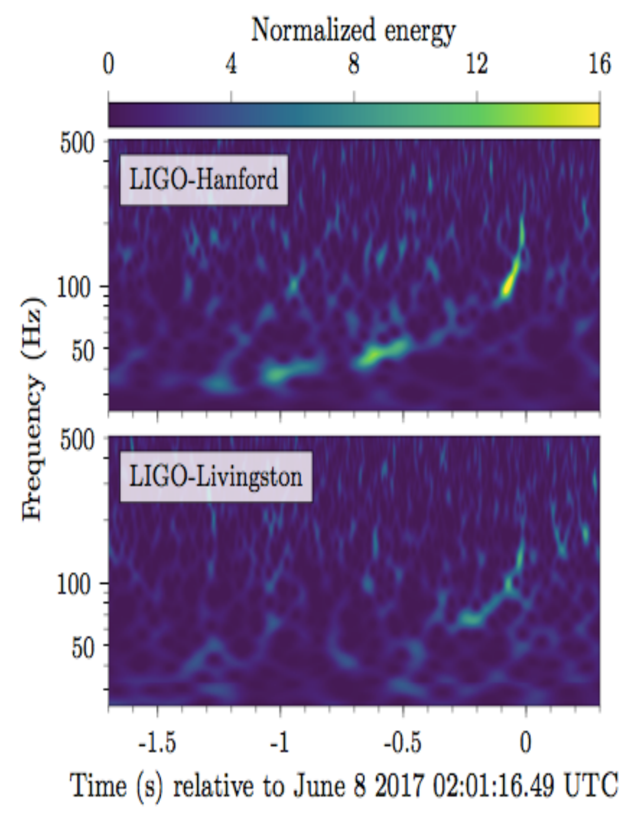
LIGO VIRGO

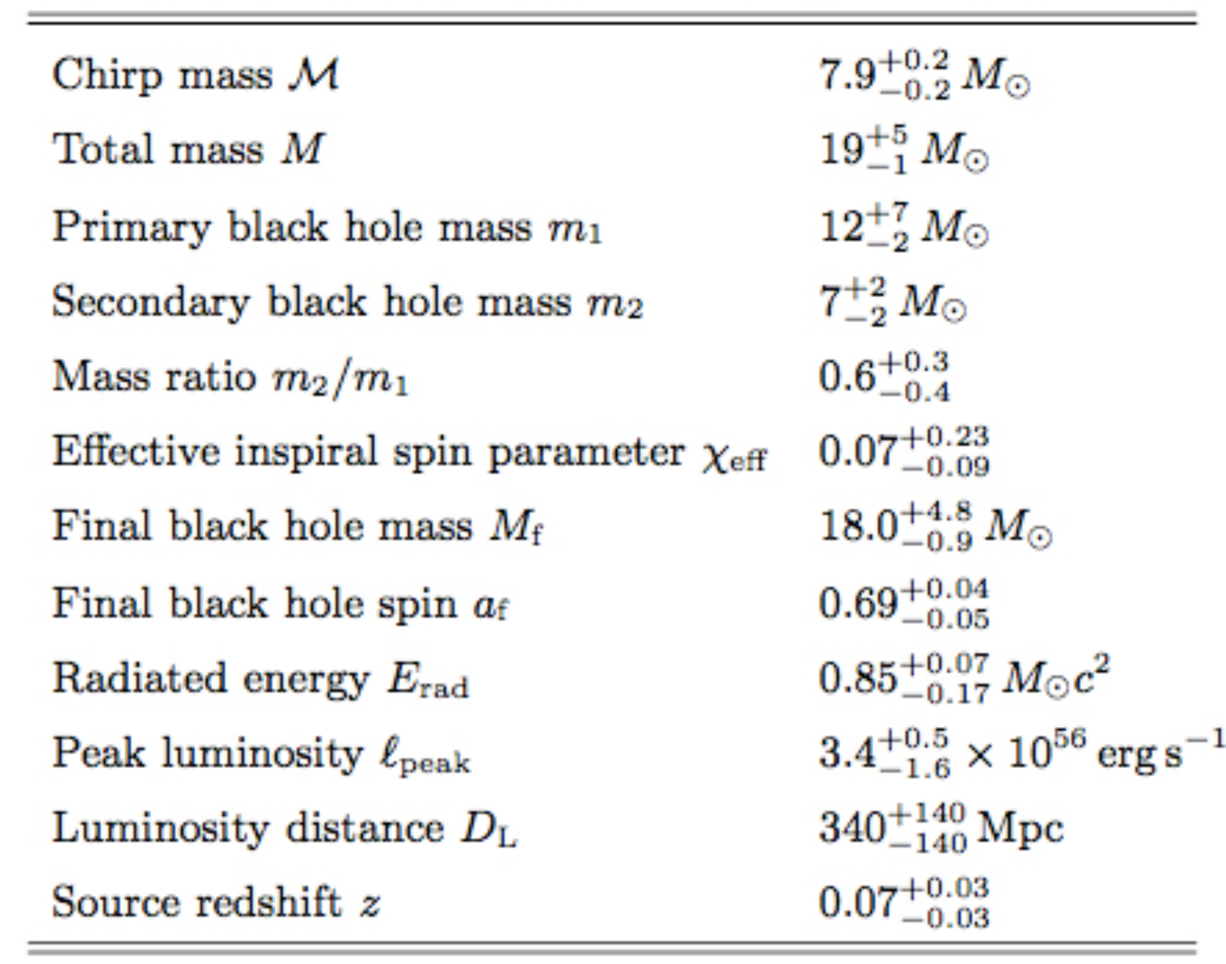
Abbott et al.

GW170608: OBSERVATION OF A 19-SOLAR-MASS BINARY BLACK HOLE COALESCENCE

arXiv:1711.05578 sub.to APJ

June 8, 2017 at 02:01:16.49 UTC





Chirp mass $\mathcal{M}$	$7.9^{+0.2}_{-0.2}\,M_\odot$
Total mass M	$19^{+5}_{-1}\,M_\odot$
Primary black hole mass m_1	$12^{+7}_{-2}\,M_\odot$
Secondary black hole mass m_2	$7^{+2}_{-2}\,M_\odot$
Mass ratio m_2/m_1	$0.6^{+0.3}_{-0.4}$
Effective inspiral spin parameter χ_{eff}	$0.07^{+0.23}_{-0.09}$
Final black hole mass M_{f}	$18.0^{+4.8}_{-0.9}\,M_\odot$
Final black hole spin a_{f}	$0.69^{+0.04}_{-0.05}$
Radiated energy E_{rad}	$0.85^{+0.07}_{-0.17}\,M_\odot c^2$
Peak luminosity ℓ_{peak}	$3.4^{+0.5}_{-1.6} \times 10^{56}\,\mathrm{erg\,s^{-1}}$
Luminosity distance D_{L}	$340^{+140}_{-140}\,\mathrm{Mpc}$
Source redshift z	$0.07^{+0.03}_{-0.03}$

Network signal-to-noise ratio of 13

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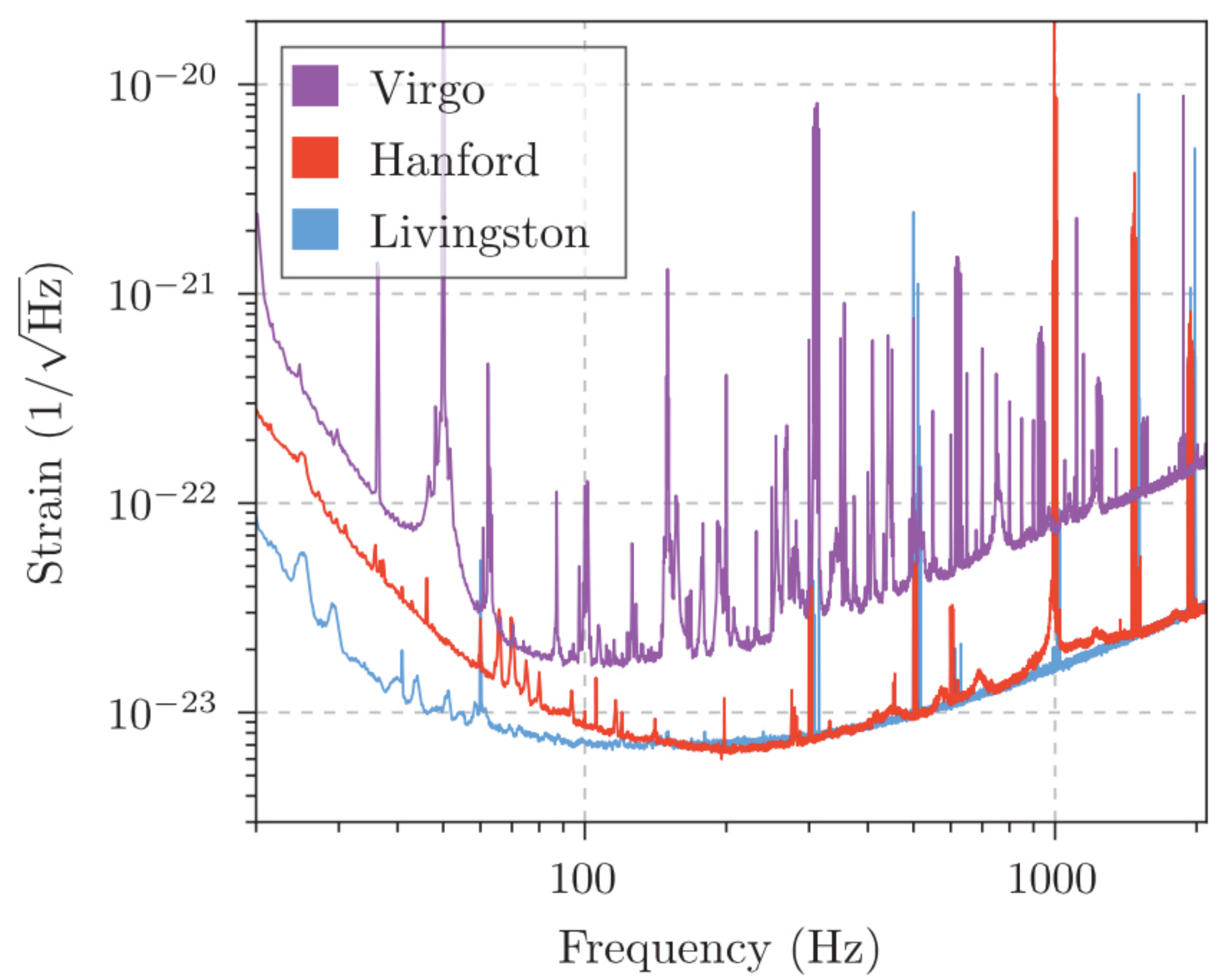
BH-BH coalescent Rate of 12–213 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ confirmed

August 1st, 2017

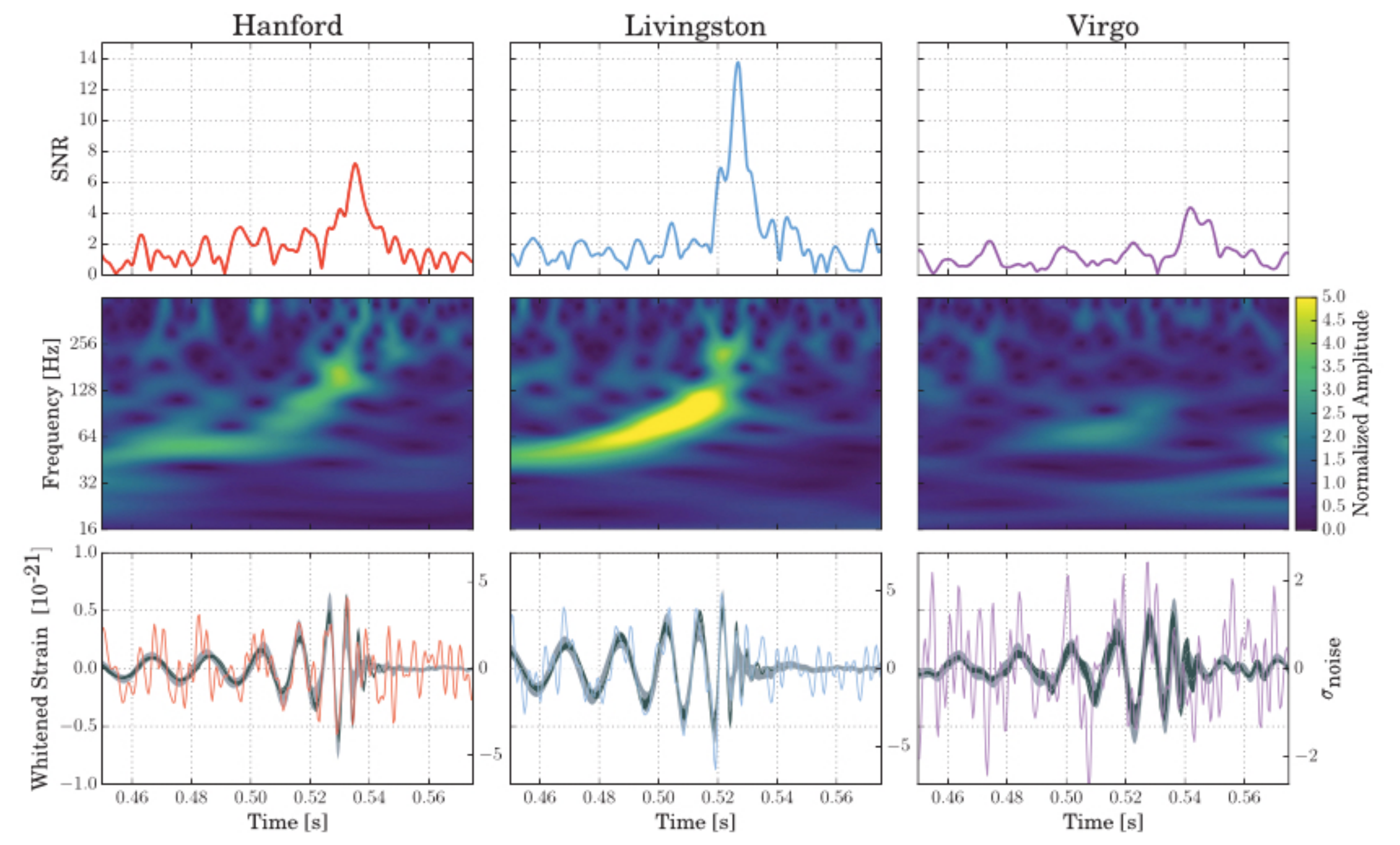
Space

The network is completed

Triple sensitivity



August 14th 2017



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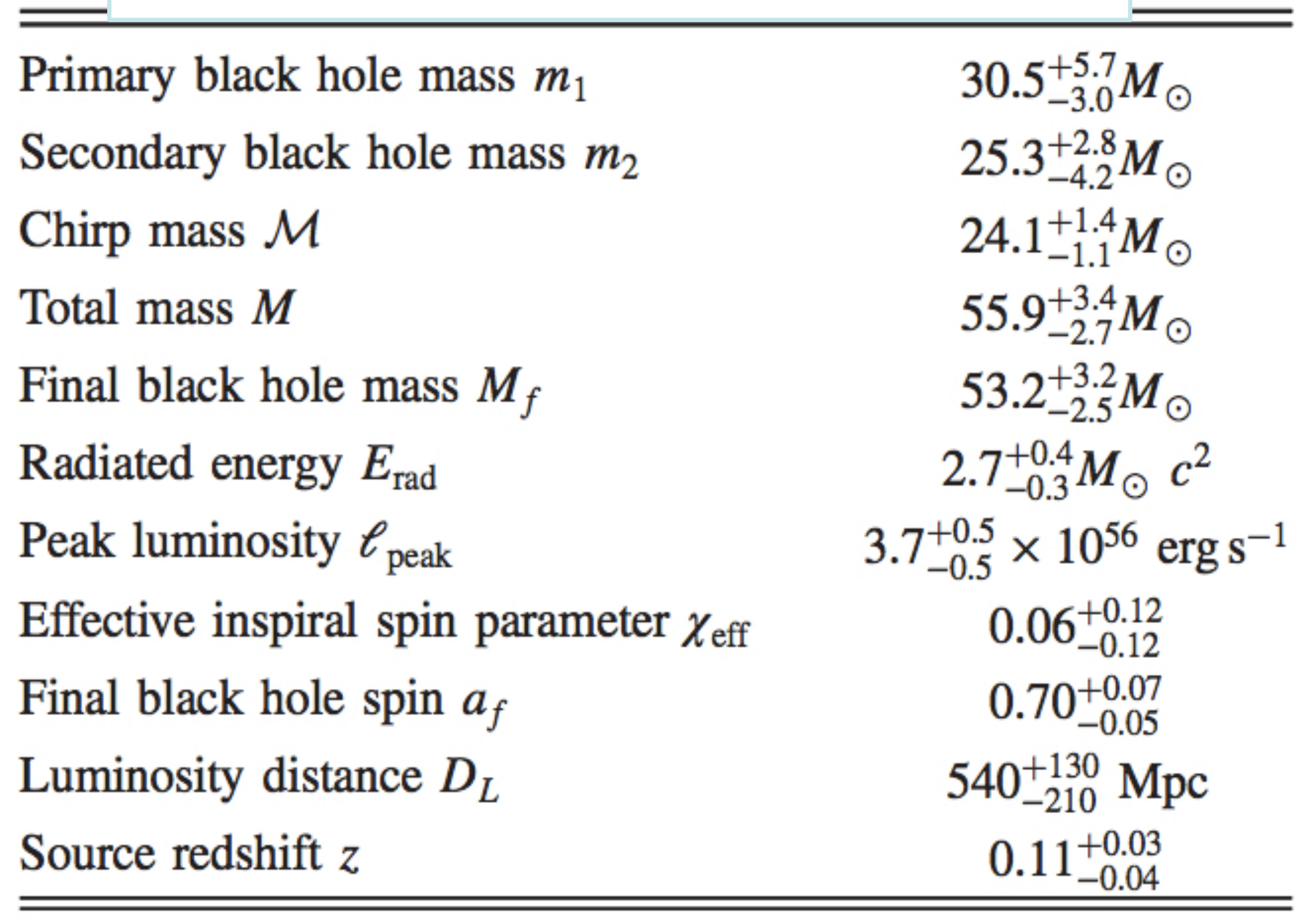
GW170814 : A three-detector observation of gravitational waves from a binary black hole coalescence, available from doi:10.1103/PhysRevLett.119.141101.

GW170814: fact sheet

False-alarm rate of $\lesssim$1 in 27 000 years
3-detector network matched-filter SNR=18



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 $E_{\rm rad}$	$2.7^{+0.4}_{-0.3} M_\odot\, c^2$
Peak luminosity $\ell_{\rm peak}$	$3.7^{+0.5}_{-0.5} \times 10^{56}\ {\rm erg\, s^{-1}}$
Effective inspiral spin parameter $\chi_{\rm eff}$	$0.06^{+0.12}_{-0.12}$
Final black hole spin a_f	$0.70^{+0.07}_{-0.05}$
Luminosity distance D_L	540^{+130}_{-210} Mpc
Source redshift z	$0.11^{+0.03}_{-0.04}$

GRAVITATIONAL-WAVE POLARIZATIONS

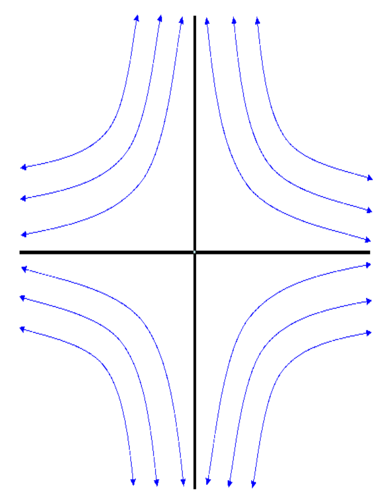
GR predicts that metric perturbations has 2 tensor degrees of freedom ➔ Spin 2

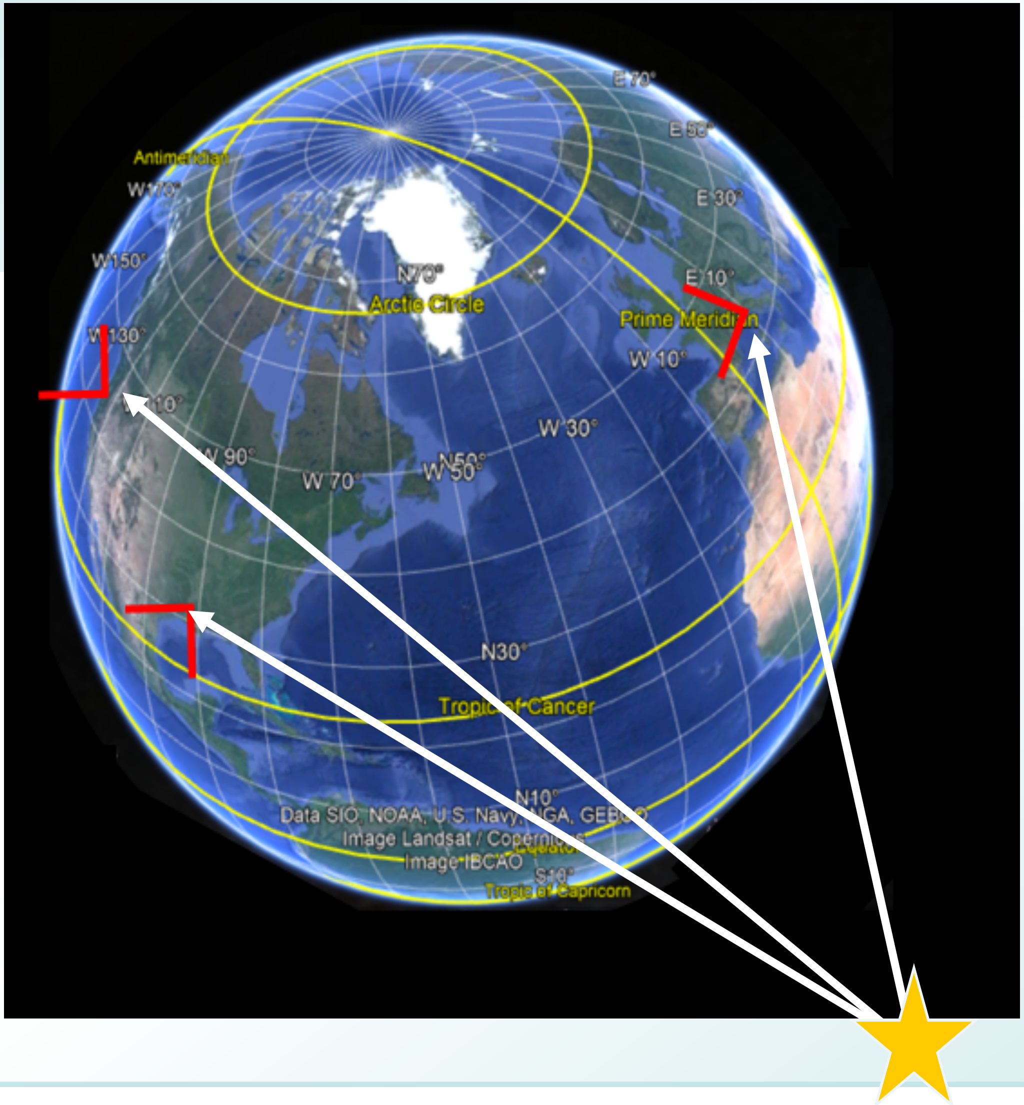
This is a subset of 6 independent modes predicted by the generic metric theories of gravity ➔ Spin 0 , Spin 1 , Spin 2

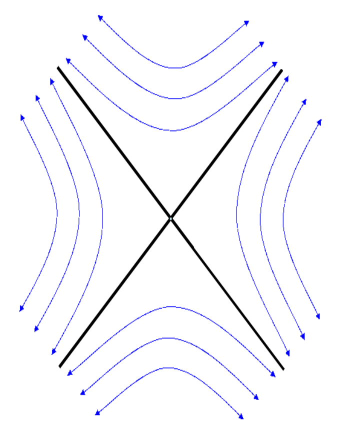
Spin2 ➔ evidence from measurements of the rate of orbital decay of binary pulsars

The 3 detector operation ➔ probe of the GW polarizations

by studying the wave geometry directly through the projection of the metric perturbation onto the network of the 3 detecors not aligned.







With its orientation, Virgo allows to access the second polarization in addition to the polarization accessible with the LIGO detectors

Preliminary Bayesian analysis on polarization

Coherent Bayesian analysis done comparing

antenna response functions with tensor polarization

- response for scalar polarizations
- response for vector polarization

Bayes' factor of the purely tensor polarization

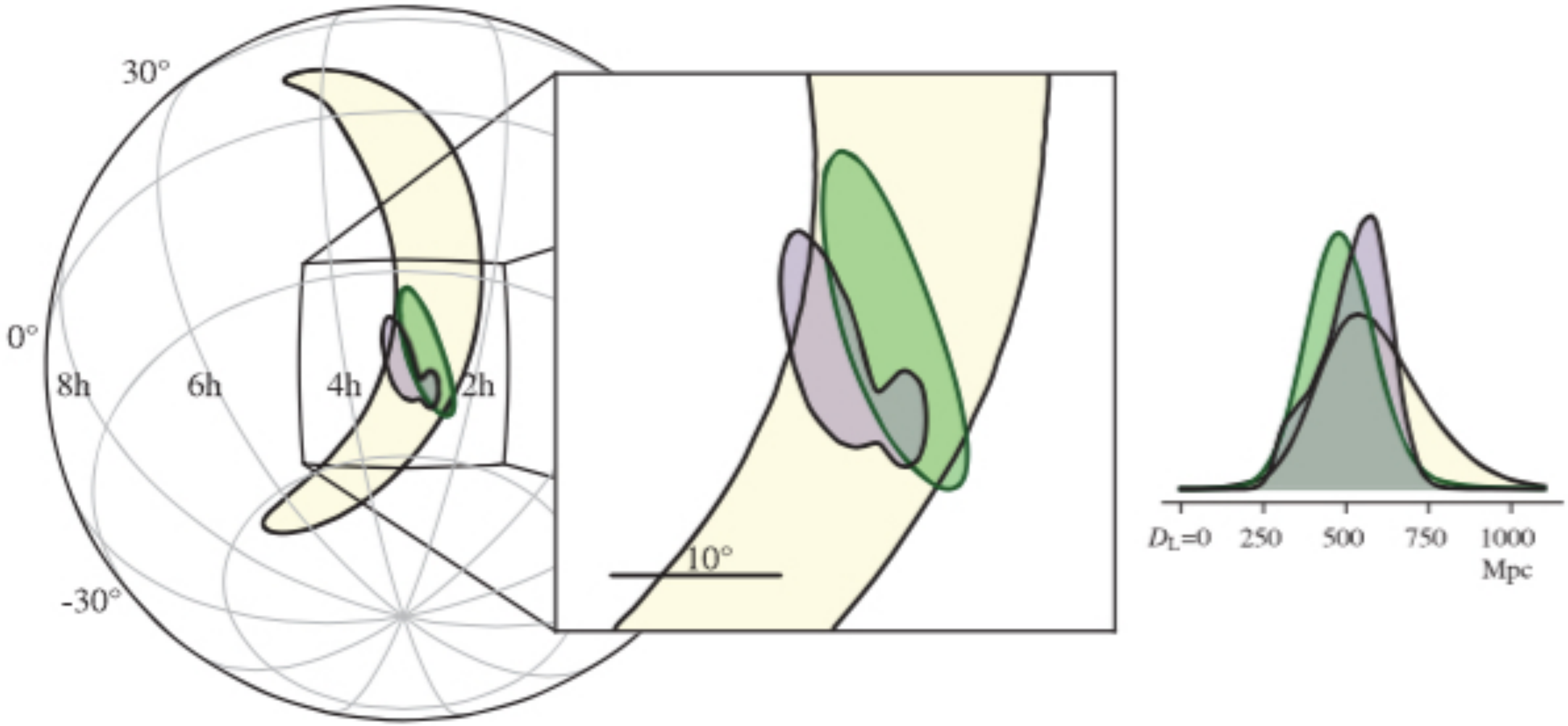
***200** against purely vector*

***1000** against purely scalar*

Preliminary study

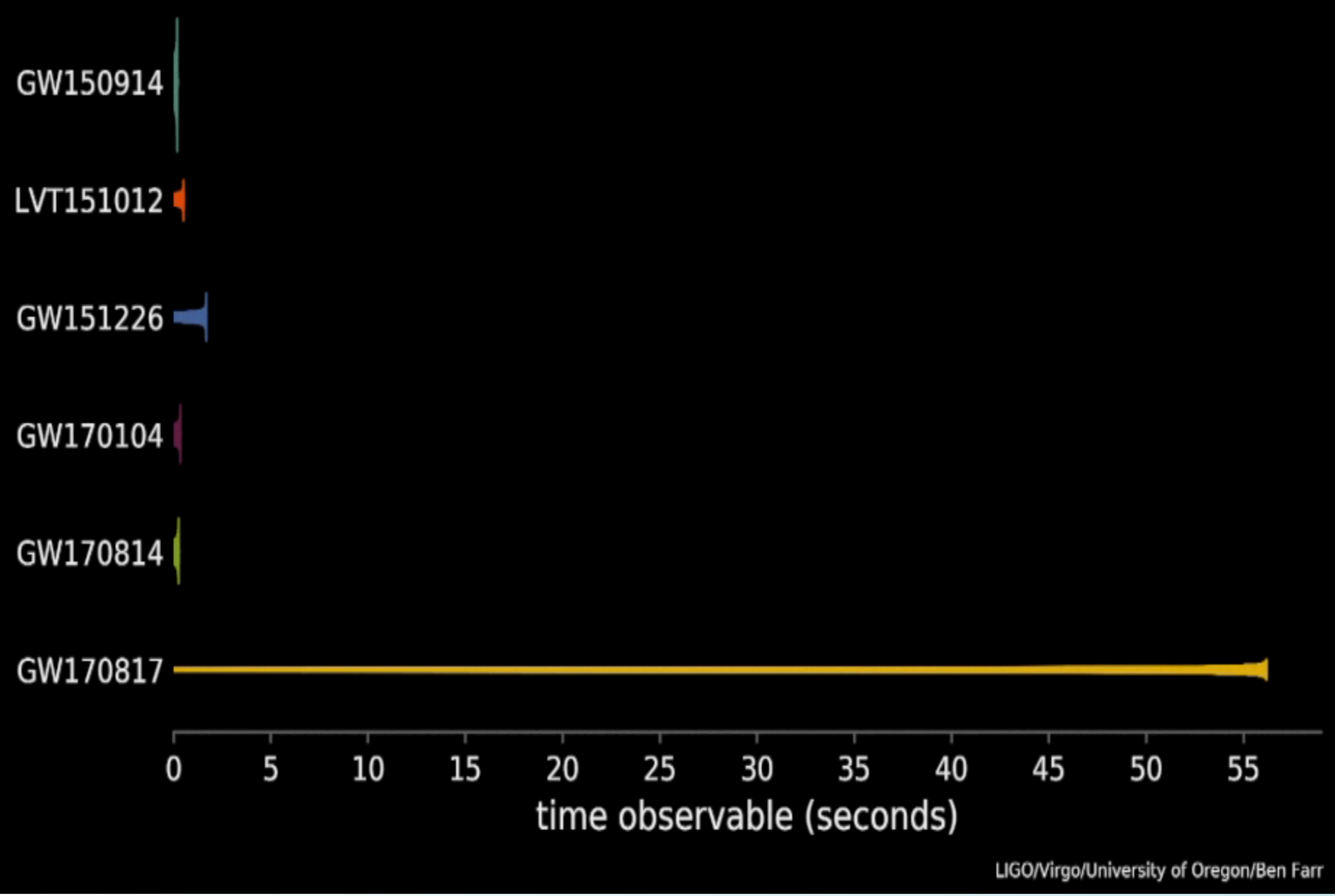
Sky Localization

90% credible region ➔ 1160 deg2 using only the two LIGO detectors
➔ 60 deg2 using all three detectors



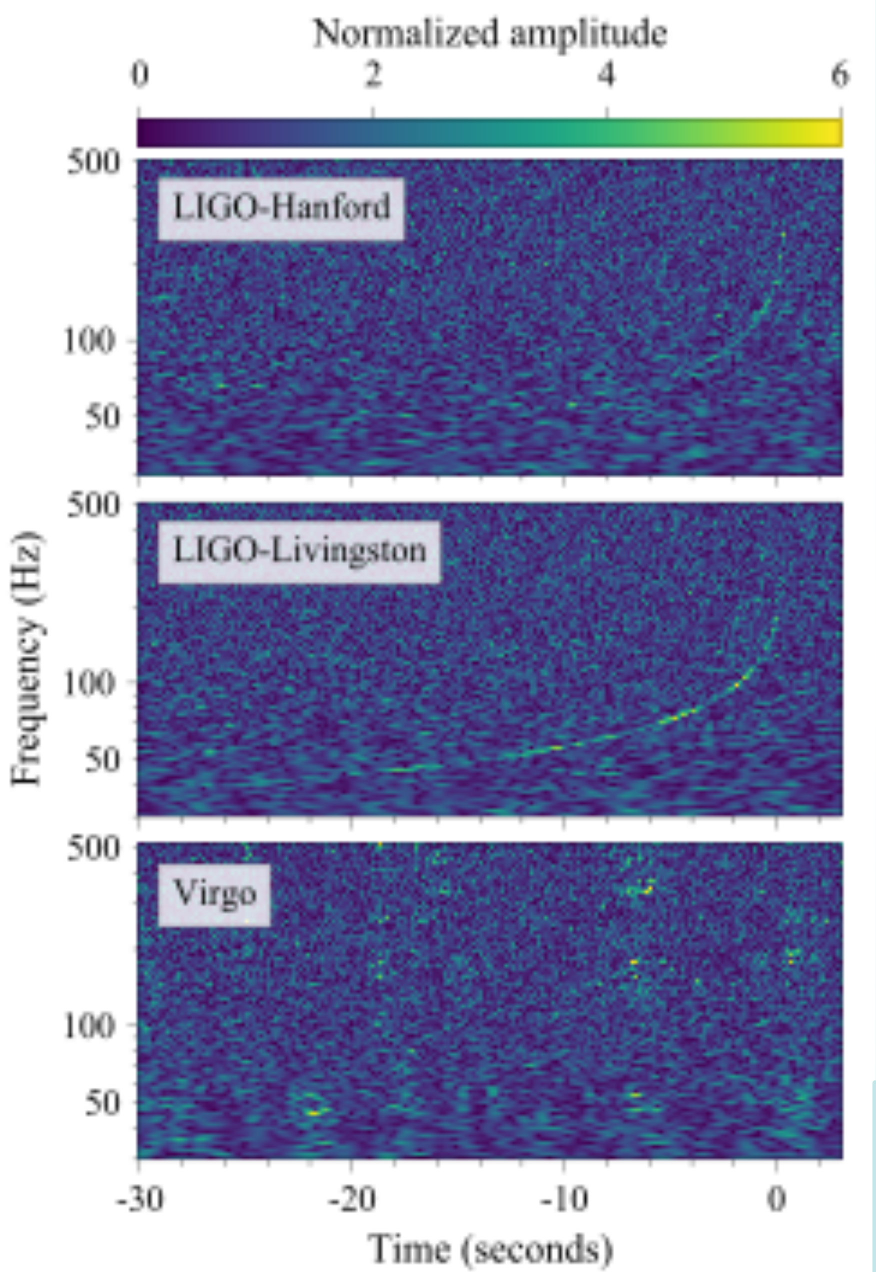
Localization of GW170814. The rapid localization using data from the two LIGO sites is shown in yellow, with the inclusion of data from Virgo shown in green. The full Bayesian localization is shown in purple. The contours represent the 90% credible regions. The left panel is an orthographic projection and the inset in the center is a gnomonic projection; both are in equatorial coordinates. The inset on the right shows the posterior probability distribution for the luminosity distance, marginalized over the whole sky.

August 17th 2017



LIGO/Virgo/University of Oregon/Ben Farr

GW170817



LIGO and the Virgo detectors were operational at the time of the binary neutron star inspiral **12:41:04.4 UTC**

GW170817 swept through the detectors' sensitive band in **~100s**.

f_{start} ~ 24Hz.

Loudest (network SNR of **32.4**), closest and best localized signal signal ever observed by LIGO and Virgo

Sky position localization for GW170814 is within an area of **~ 30 deg^2**

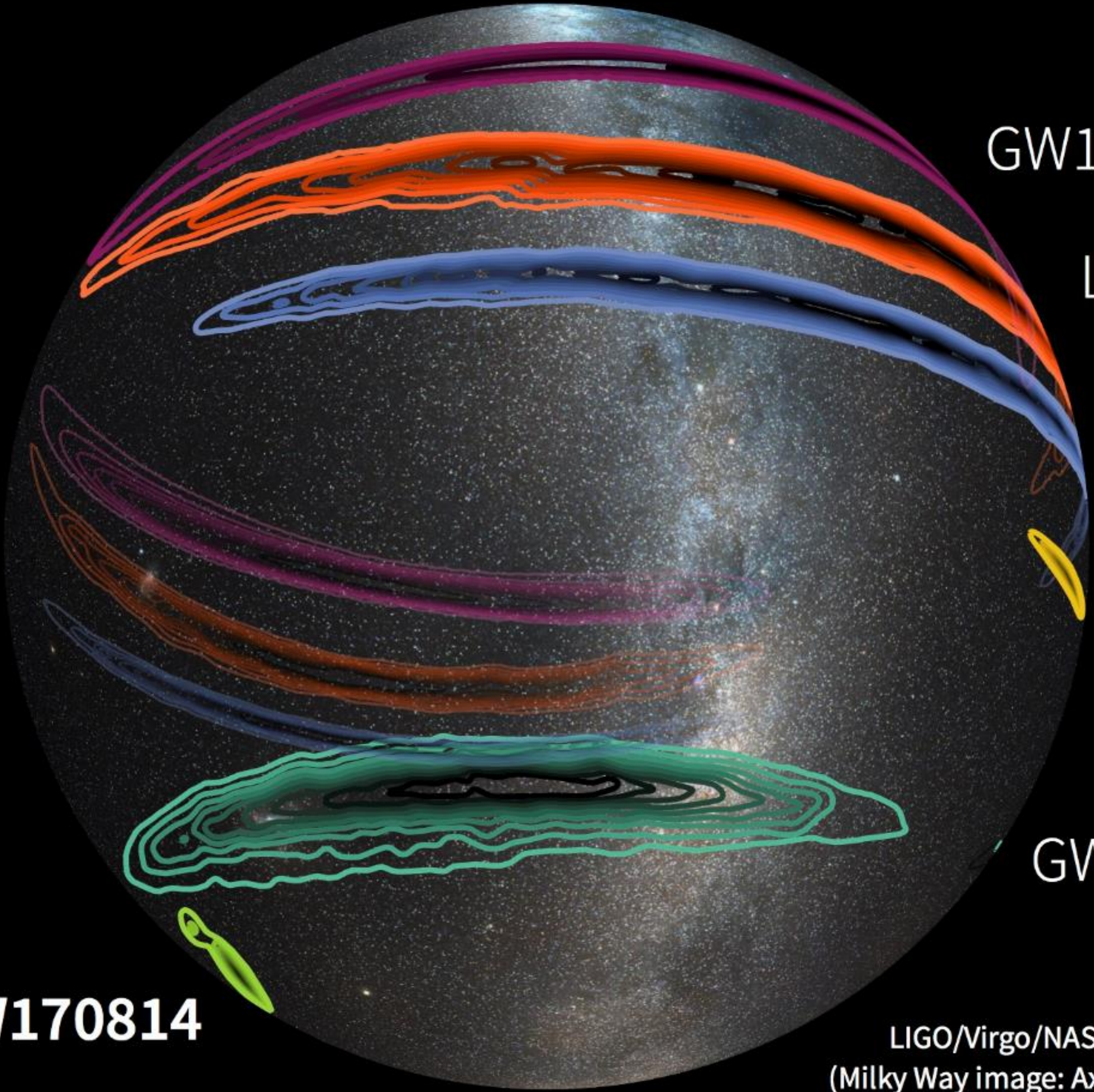
Radiated energy > **$0.025\ M_o\ c^2$**

observed by	H, L, V
source type	binary neutron star (NS)
date	17 August 2017
time of merger	12:41:04 UTC
signal-to-noise ratio	32.4
false alarm rate	< 1 in 80 000 years
distance	85 to 160 million light-years
total mass	2.73 to 3.29 $M_\odot$
primary NS mass	1.36 to 2.26 $M_\odot$
secondary NS mass	0.86 to 1.36 $M_\odot$
mass ratio	0.4 to 1.0
radiated GW energy	$> 0.025\ M_\odot c^2$
radii of NSs	likely ≲ 15 km
effective spin parameter	-0.01 to 0.17
effective precession spin parameter	unconstrained
GW speed deviation from speed of light	< few parts in 10^{15}

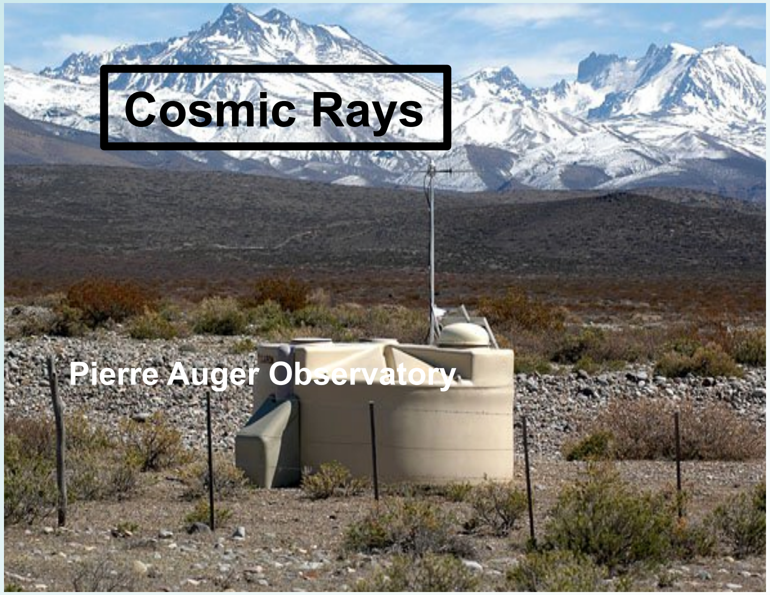
inferred duration from 30 Hz to 2048 Hz**	~ 60 s
inferred # of GW cycles from 30 Hz to 2048 Hz**	~ 3000
initial astronomer alert latency*	27 min
HLV sky map alert latency*	5 hrs 14 min
HLV sky area†	28 deg^2
# of EM observatories that followed the trigger	~ 70
also observed in	gamma-ray, X-ray, ultraviolet, optical, infrared, radio
host galaxy	NGC 4993
source RA, Dec	$13^h09^m48^s$, -23°22'53"
sky location	in Hydra constellation
viewing angle (without and with host galaxy identification)	≤ 56° and ≤ 28°
Hubble constant inferred from host galaxy identification	62 to 107 $\text{km s}^{-1}\ \text{Mpc}^{-1}$

The inferred local coalescence rate density of BNS systems is

$$R = 1540^{+3200}_{-1220}\ \text{Gpc}^{-3}\,\text{yr}^{-1}$$



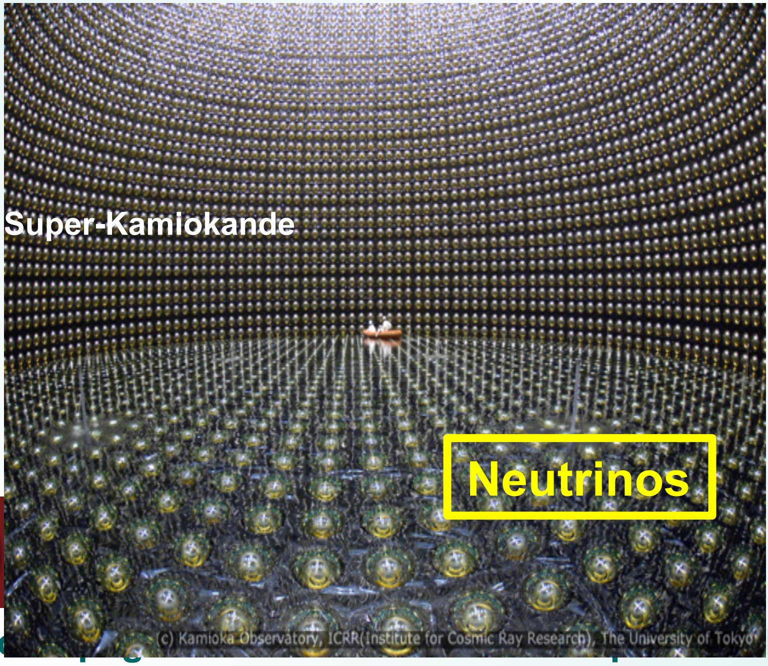
LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)



Cosmic Rays

Pierre Auger Observatory

Photons



Super-Kamiokande

Neutrinos

(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

Hubble constant: $v_H = H_0 D$

“A Gravitational-Wave Standard Siren Measurement of the Hubble Constant”, Nature [https://doi.org/10.1038/nature24471]

- CBC signals are “**standard sirens**”:

$$h_+(t) = \frac{1+\cos^2\iota}{2}\frac{G\mathcal{M}}{c^2 D}\left(\frac{5G\mathcal{M}}{c^3}\right)^{1/4}\cos\left(\int 2\pi f dt\right)$$

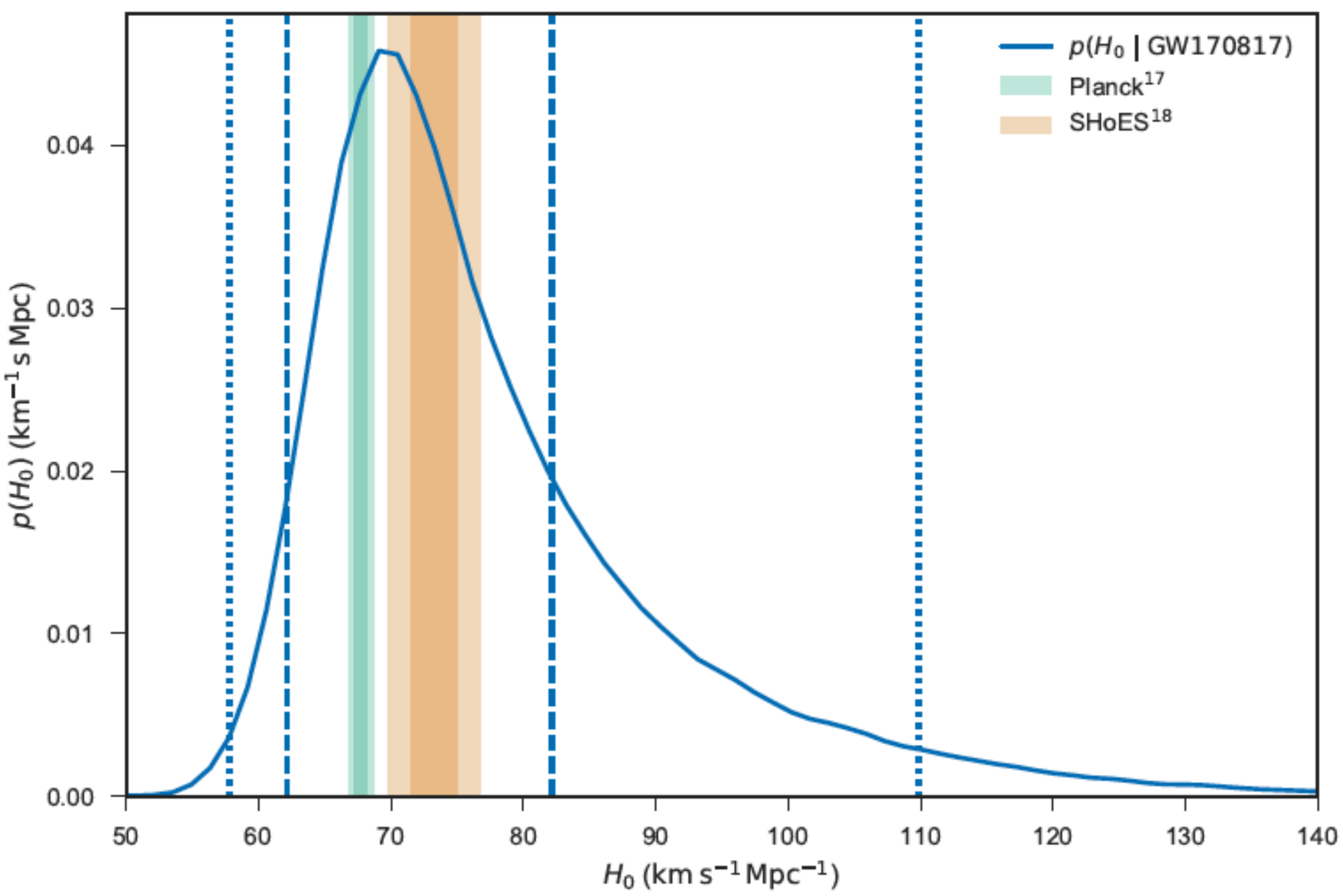
$$h_\times(t) = \cos\iota\frac{G\mathcal{M}}{c^2 D}\left(\frac{5G\mathcal{M}}{c^3}\right)^{1/4}\text{sin}\left(\int 2\pi f dt\right)$$

$\mathcal{M} = \mu^{3/5} M^{2/5}$: measured from the “chirp”

- From GW data compute the joint posterior distribution of cos(i) and D. At least a 3-detector network is needed.
- Estimate the local “Hubble flow” using association with NGC 4993 and correcting for the local peculiar motions (~10%)

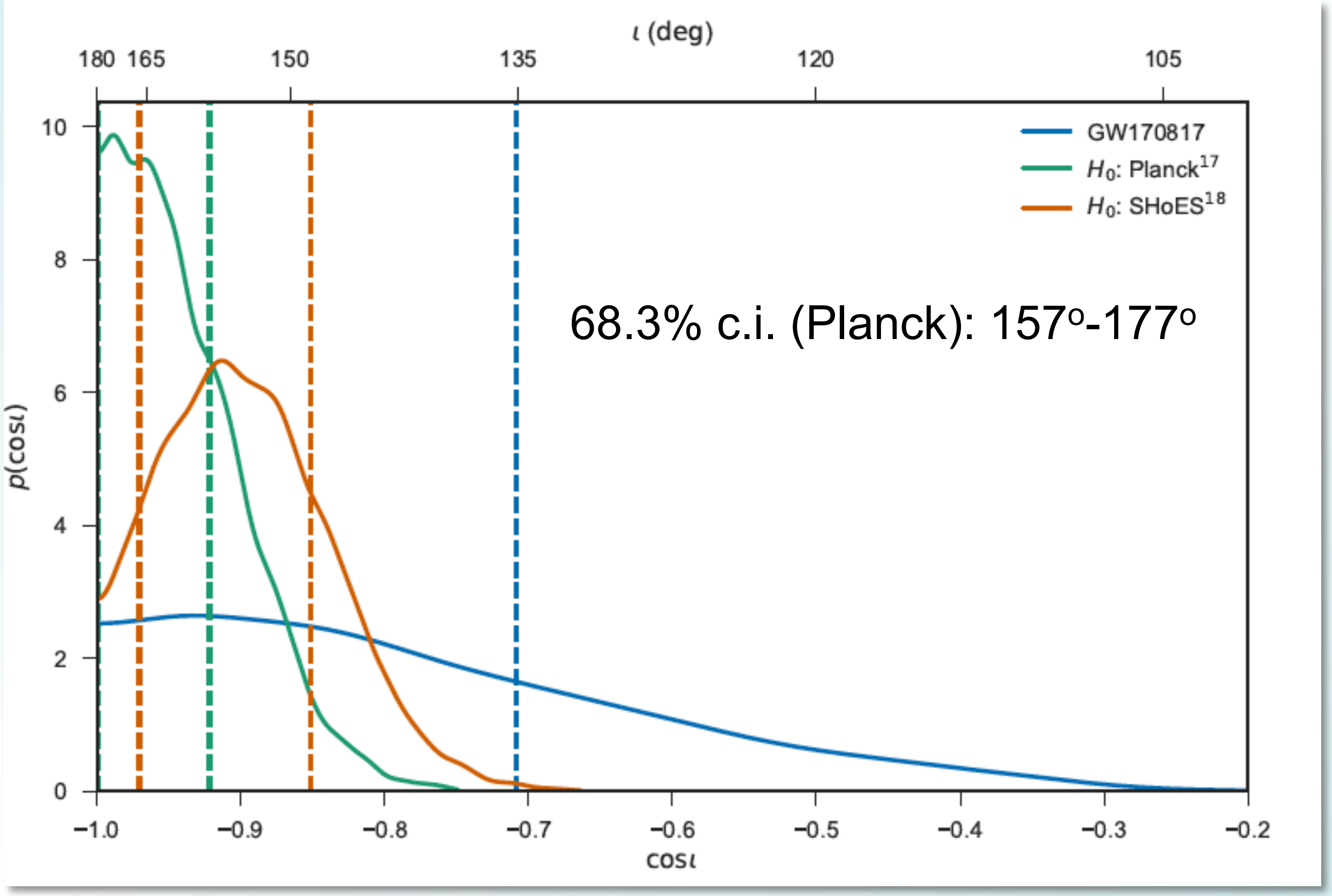
=> Obtain an estimation of H_0 independent on any “cosmic ladder”

$$H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$



- Compatible with both Planck and SHoES results
- Combining analysis of future CBC signals will improve H_0 estimation to %-level precision

- On the other hand, by using EM estimations of H_0 a measure of the binary system inclination angle can be obtained



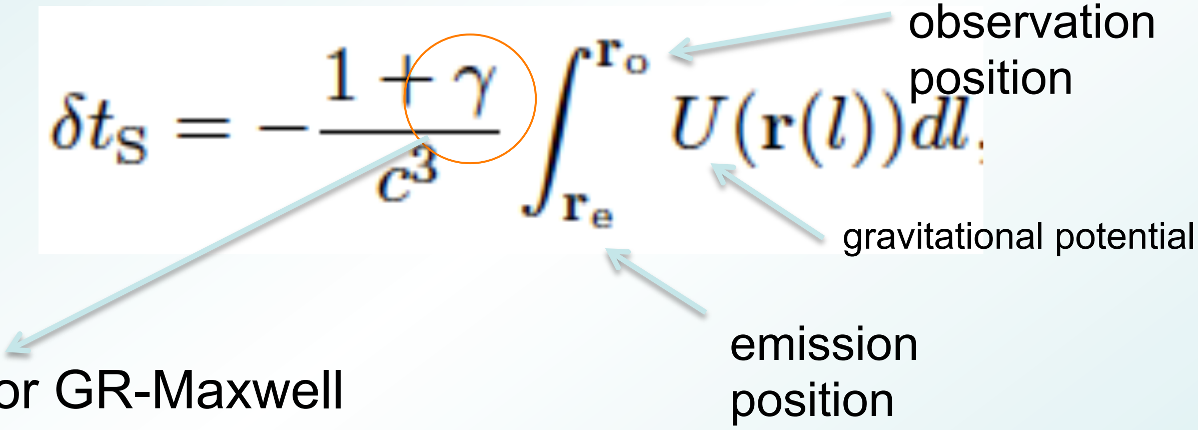
68.3% c.i. (Planck): 157°-177°

- Impact on GRB modeling (energetics, beaming,…)

Fundamental physics of gravity

“Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB170817A”, Astrophys. J. Lett. [https://doi.org/10.3847/2041-8213/aa920c]

- ✓ Einstein Equivalence Principle: use the Shapiro delay to test if GW and EM waves are affected by the background gravitational potential in the same way



$$\delta t_S = -\frac{1+\gamma}{c^3}\int_{\mathbf{r}_e}^{\mathbf{r}_o} U(\mathbf{r}(l))\,dl,$$

observation position

gravitational potential

emission position

$\gamma_{GW} = \gamma_{EM} = 1$ for GR-Maxwell Theory

$$-1.2 \times 10^{-6} \le \gamma_{GW} - \gamma_{EM} \le 2.6 \times 10^{-7}$$

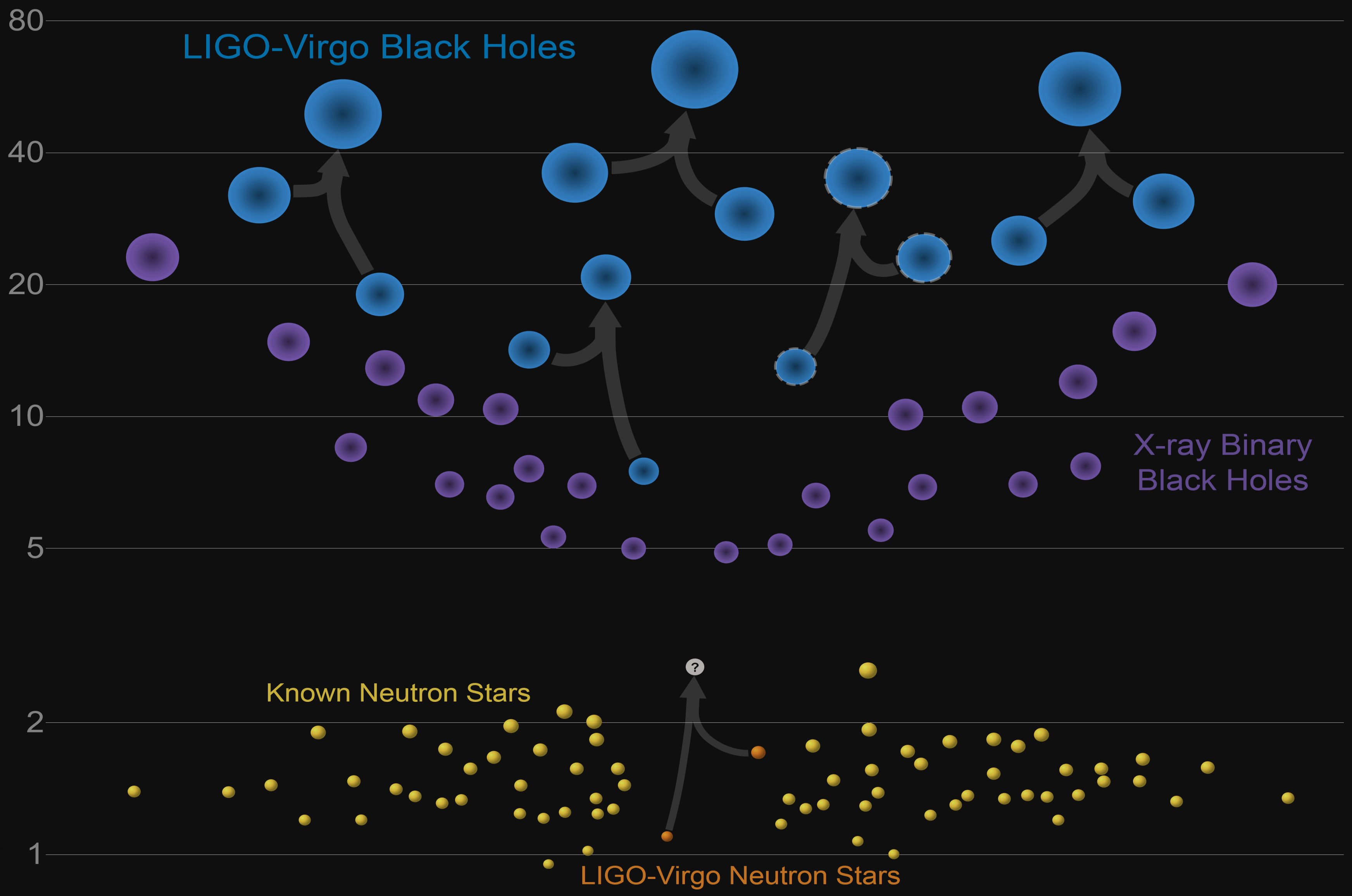
- ✓ **Upper limit on the difference between graviton and photon velocity**

$$-3 \times 10^{-15} \le (v - c_{em})/c_{em} \le 7 \times 10^{-16}$$

(lower bound assuming the EM signal was emitted 10 s after the GW signal)

Masses in the Stellar Graveyard

in Solar Masses



Credit: Robert Hurt/Aurore Simmonet/Frank Elavsky

What Next?

Short term Plan

Fall 2018 ====➔ start of O3 with 3 detectors in operation

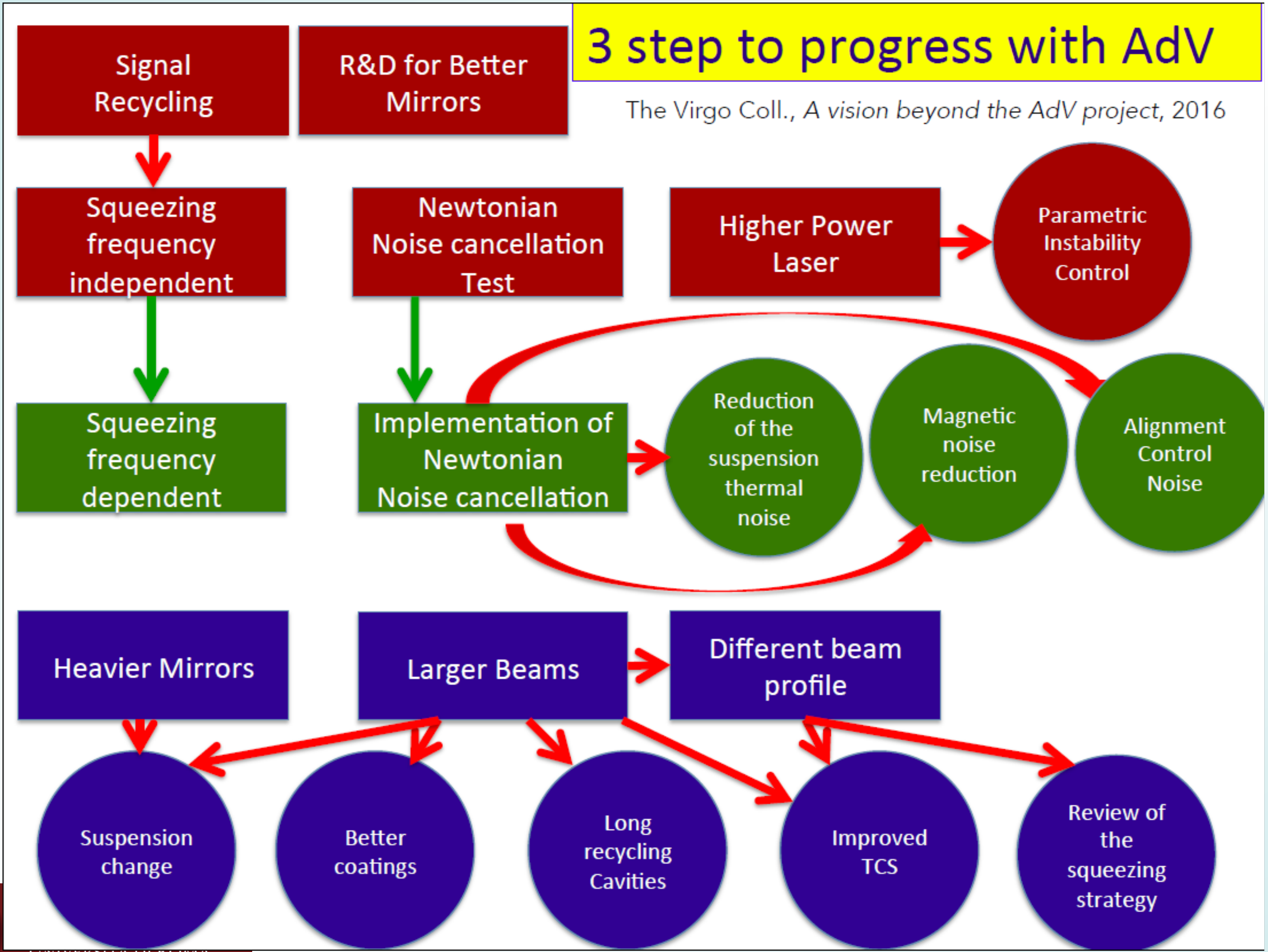
Main improvements

LIGO
- mirror cleaning
- increased light power
- squeezed light in one interferometer
- vacuum leak repaired

Virgo
- vacuum cleaning
- mirror cleaning
- monolithic suspension
- electronics improvement
- new powerful laser
- frequency independent squeezing
- sensor deployment to test the Newtonian noise cancellation

Data taking duration ~ 1/(1.5?) year

Beyond Advanced Virgo

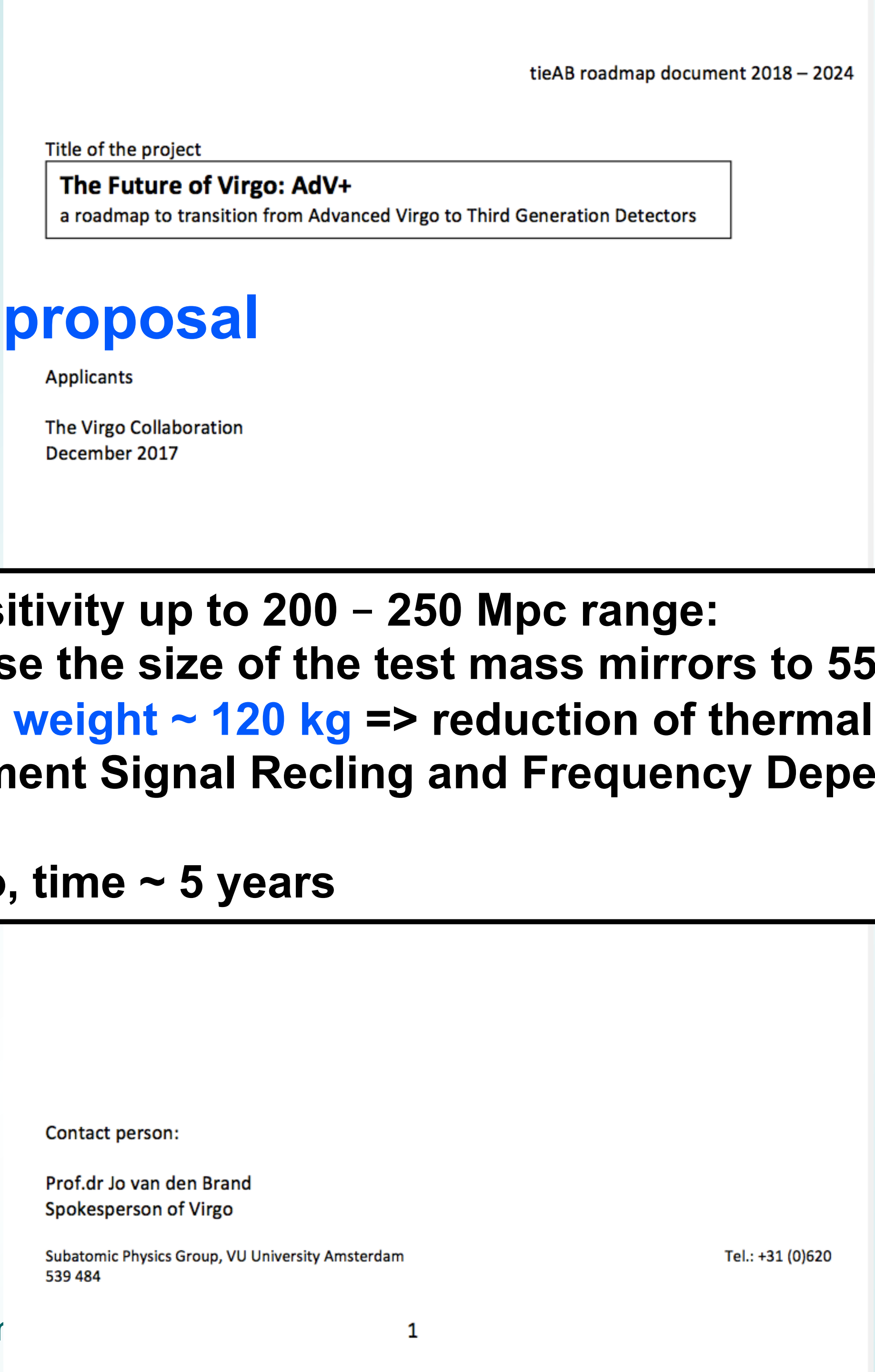


3 step to progress with AdV

The Virgo Coll., *A vision beyond the AdV project*, 2016

Signal Recycling
R&D for Better Mirrors
Squeezing frequency independent
Newtonian Noise cancellation Test
Higher Power Laser
Parametric Instability Control
Squeezing frequency dependent
Implementation of Newtonian Noise cancellation
Reduction of the suspension thermal noise
Magnetic noise reduction
Alignment Control Noise
Heavier Mirrors
Larger Beams
Different beam profile
Suspension change
Better coatings
Long recycling Cavities
Improved TCS
Review of the squeezing strategy

The AdV+ proposal



tieAB roadmap document 2018 – 2024

Title of the project

The Future of Virgo: AdV+
a roadmap to transition from Advanced Virgo to Third Generation Detectors

Applicants

The Virgo Collaboration
December 2017

Contact person:

Prof.dr Jo van den Brand
Spokesperson of Virgo

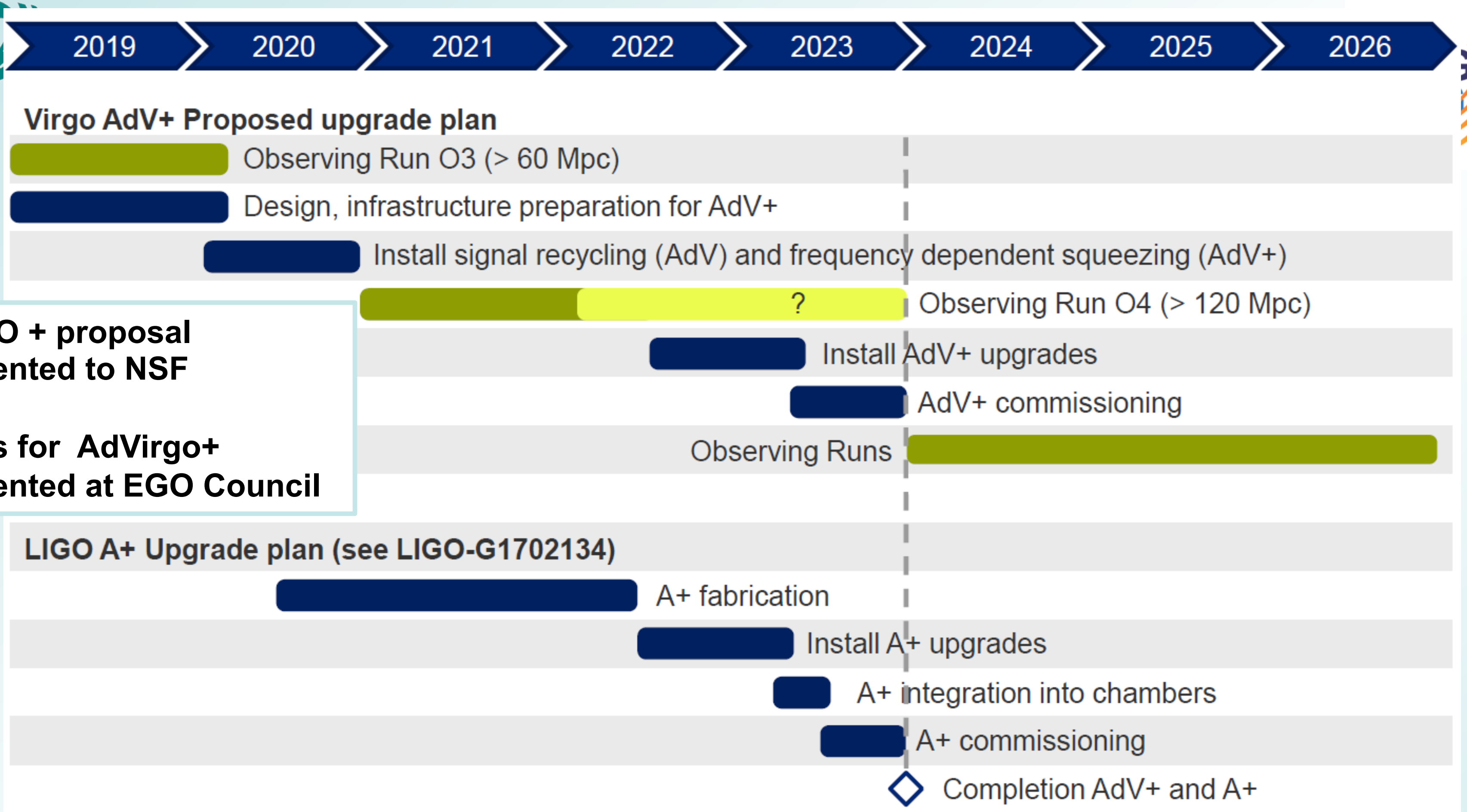
Subatomic Physics Group, VU University Amsterdam
Tel.: +31 (0)620 539 484

1

Increase of sensitivity up to 200 – 250 Mpc range:

- **Increase the size of the test mass mirrors to 550 mm ø, 400 mm thicknes**
  weight ~ 120 kg => reduction of thermal noise.
- **Implement Signal Recling and Frequency Dependent Squeezing**

Cost ~ 25 MEuro, time ~ 5 years



2019 2020 2021 2022 2023 2024 2025 2026

Virgo AdV+ Proposed upgrade plan

Observing Run O3 (> 60 Mpc)

Design, infrastructure preparation for AdV+

Install signal recycling (AdV) and frequency dependent squeezing (AdV+)

? Observing Run O4 (> 120 Mpc)

Install AdV+ upgrades

AdV+ commissioning

Observing Runs

LIGO A+ Upgrade plan (see LIGO-G1702134)

A+ fabrication

Install A+ upgrades

A+ integration into chambers

A+ commissioning

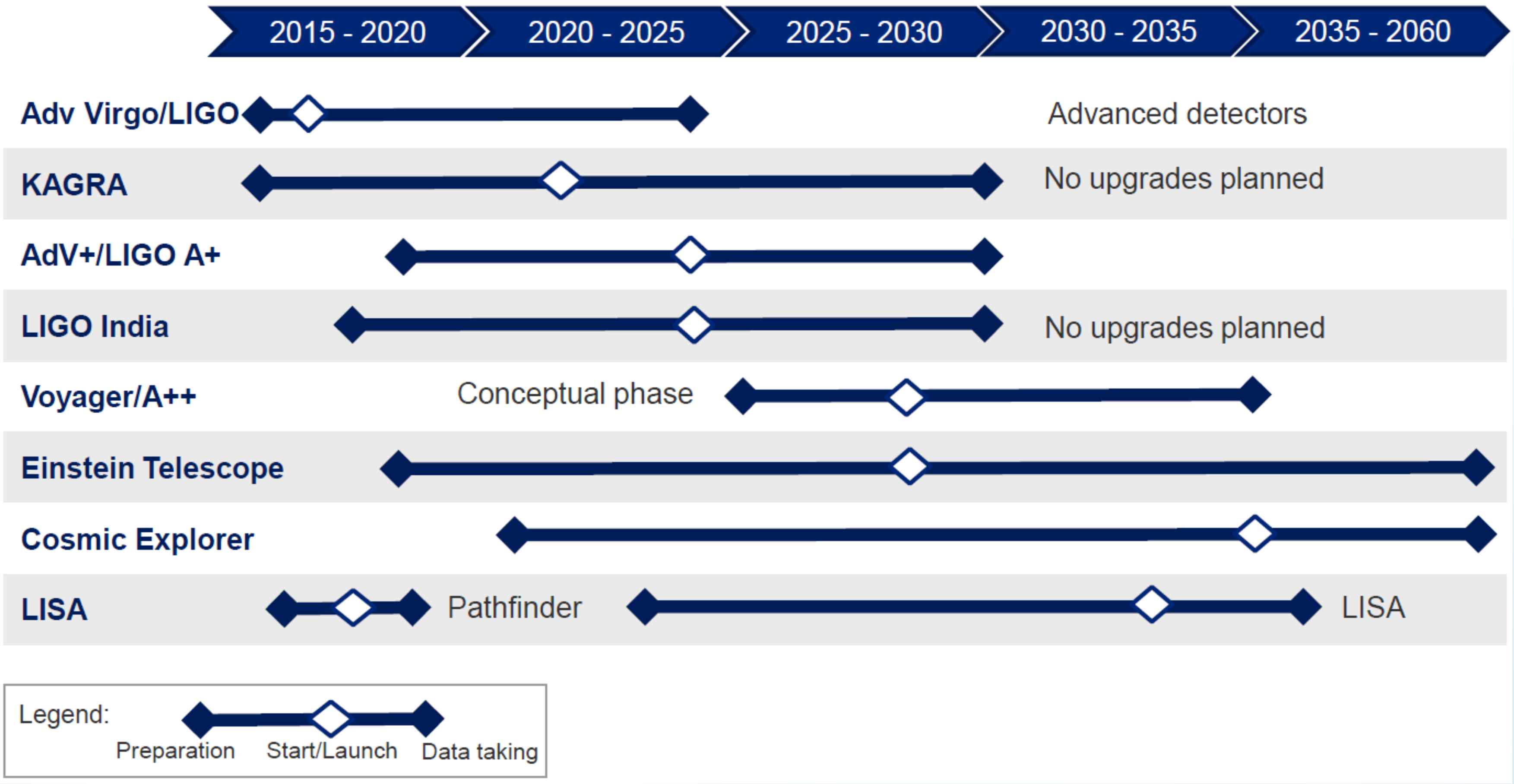
Completion AdV+ and A+

aLIGO + proposal presented to NSF

Plans for AdVirgo+ presented at EGO Council

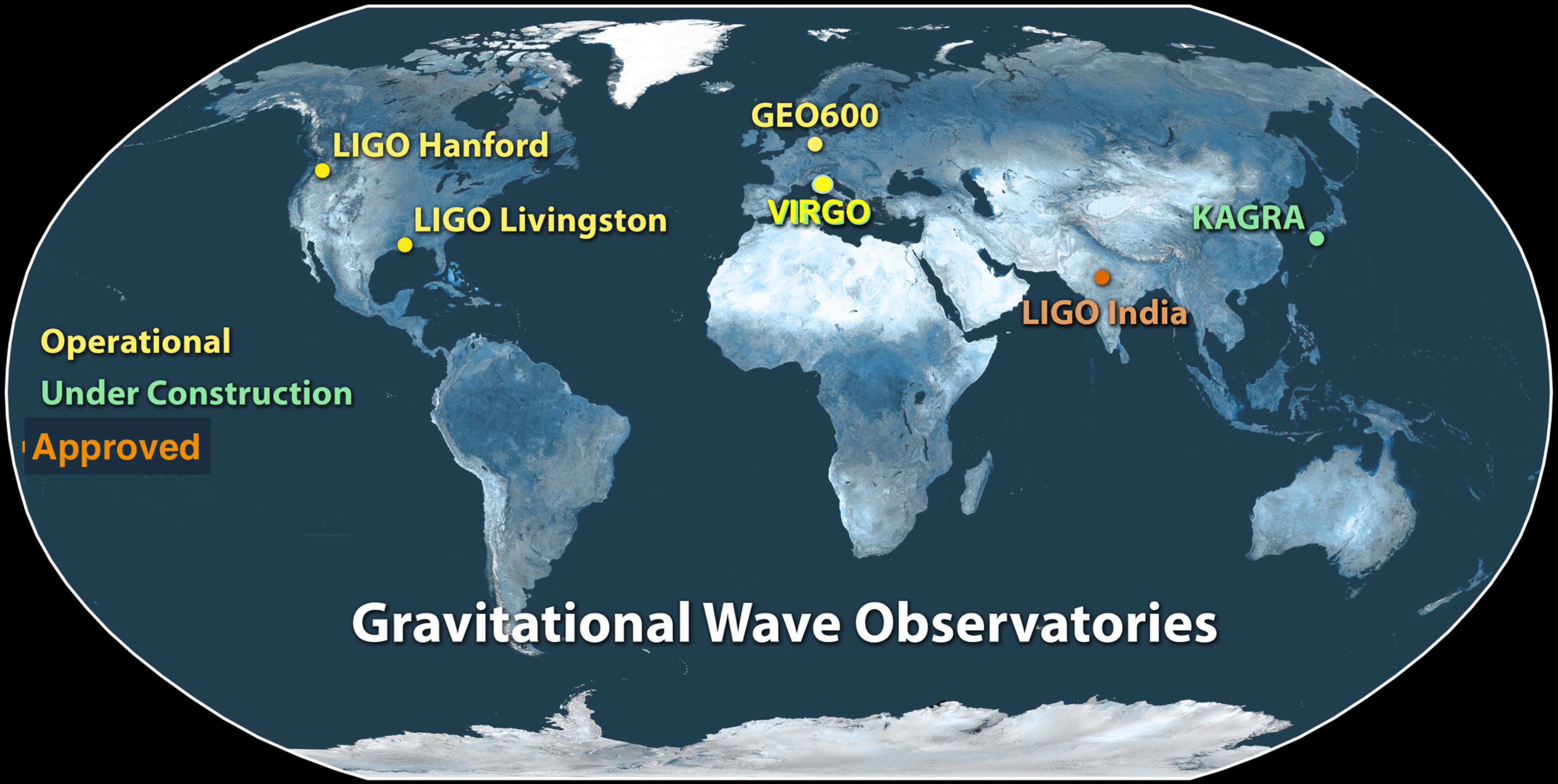
Timeline of AdV+ upgrade project. *Observing runs are indicated in green, while AdV+ activities are shown in blue. Note that AdV+ is as much as possible synchronous with the LIGO A+ upgrade. Both projects aim to complete their work at the beginning of 2024. Note that at this moment the completion of the O4 science run has not been defined.*

Evolution of GW Detectors



Advanced LIGO started operation in September 2015, together with GEO-HF. Advanced Virgo joined in 2017. Upgrade plans A+ and AdV+ are planned for LIGO and Virgo, respectively. KAGRA is under construction in Japan and will join the network in 2020. LIGO India is expected to join in 2024. Einstein Telescope could be operational as early as 2028. Cosmic Explorer is a third generation interferometer now under study in the USA. LISA is a space-based interferometer with a launch data in 2034 that is expected to run in parallel with ET and Cosmic Explorer.

Network of the second generation of detectors

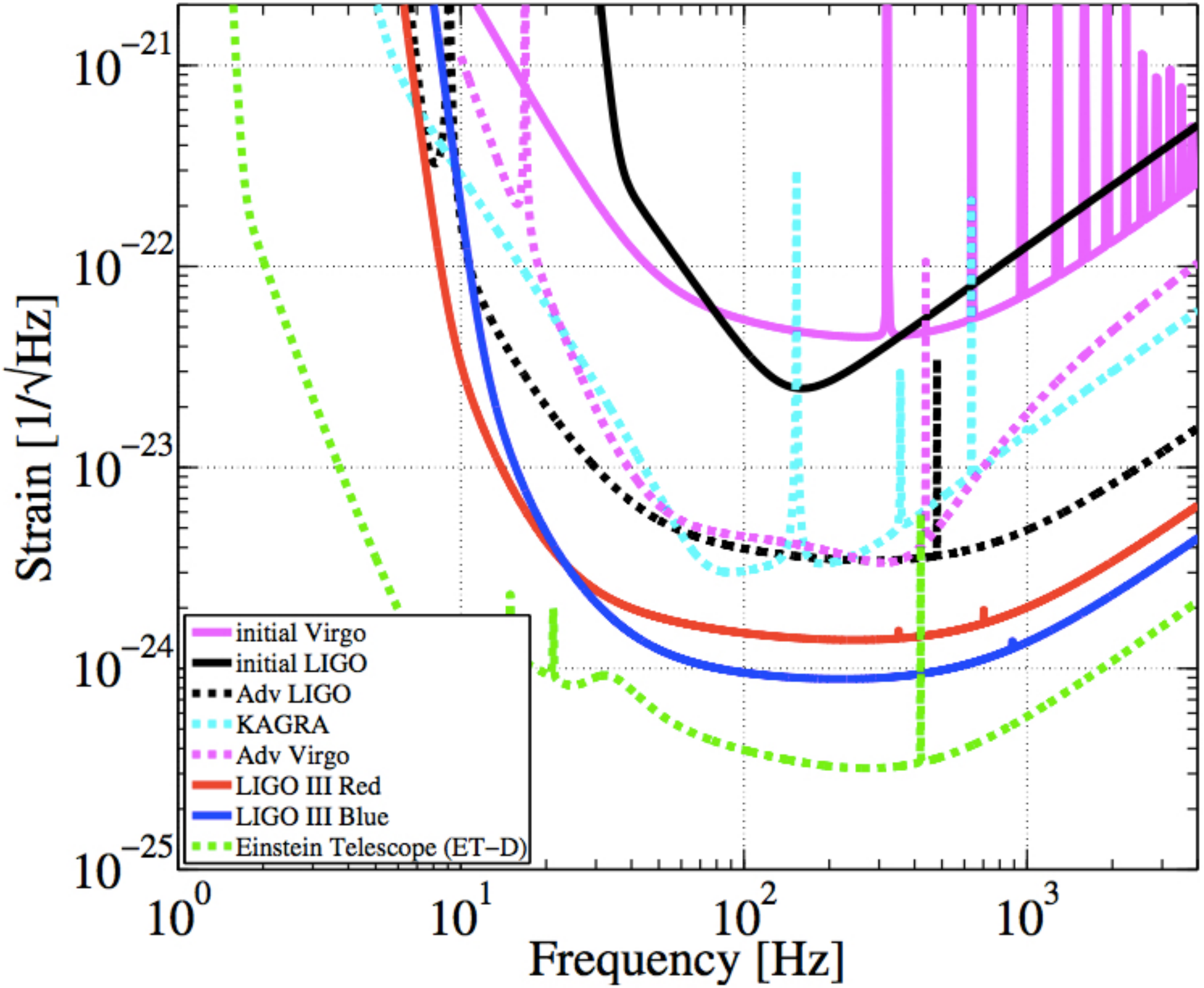


An attempt to foretell the future

LIGO-T1200099–v6
Technical Note

Astrophysical Motivations for Third Generation Interferometers

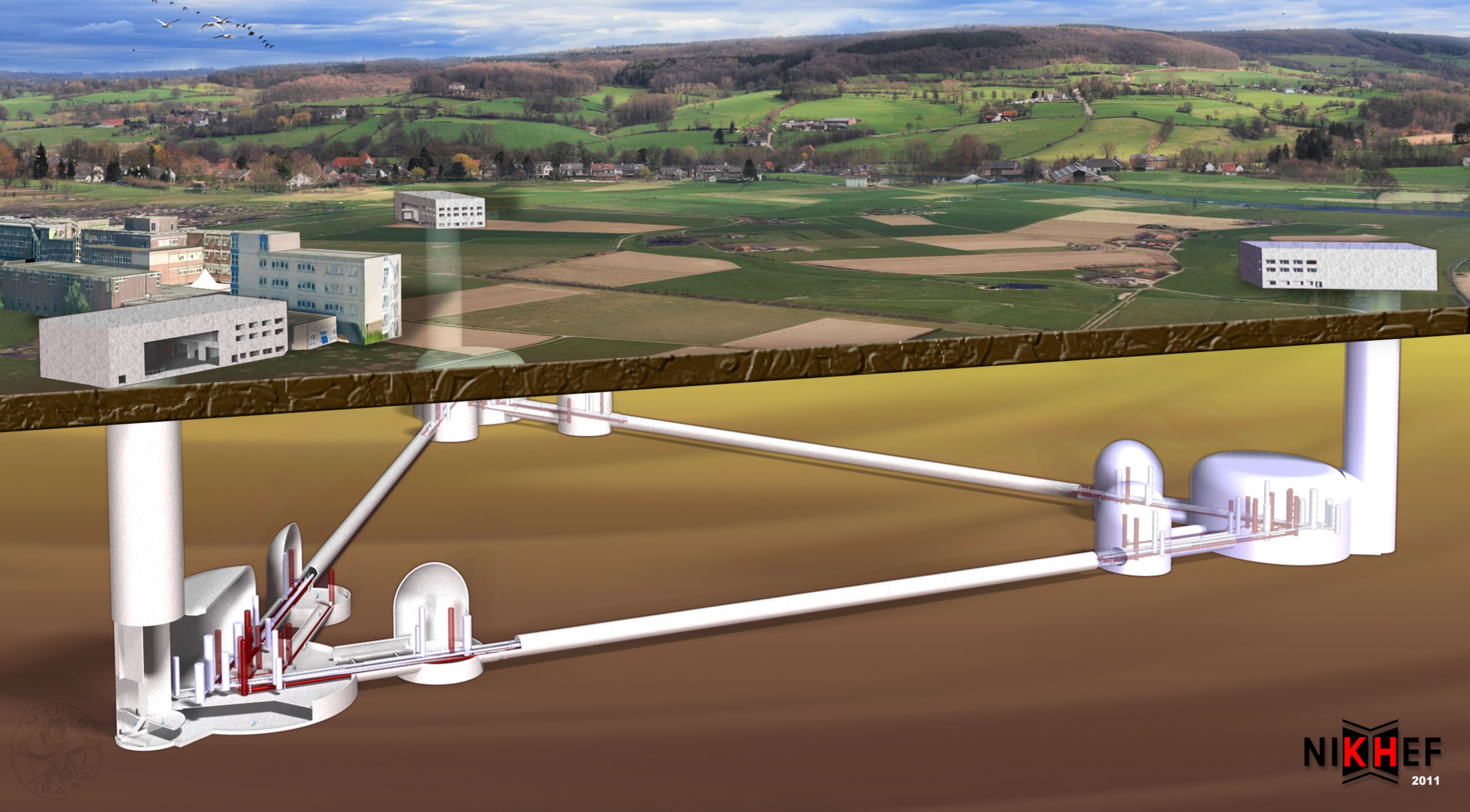
R. X Adhikari, Y. Chen, P. Ajith, J. Clark, V. Dergachev, N. Fotopoulos, S. E. Gossan, I. Mandel, M. Okounkova, V. Raymond, J. Read, J. G. Rollins



Einstein Telescope

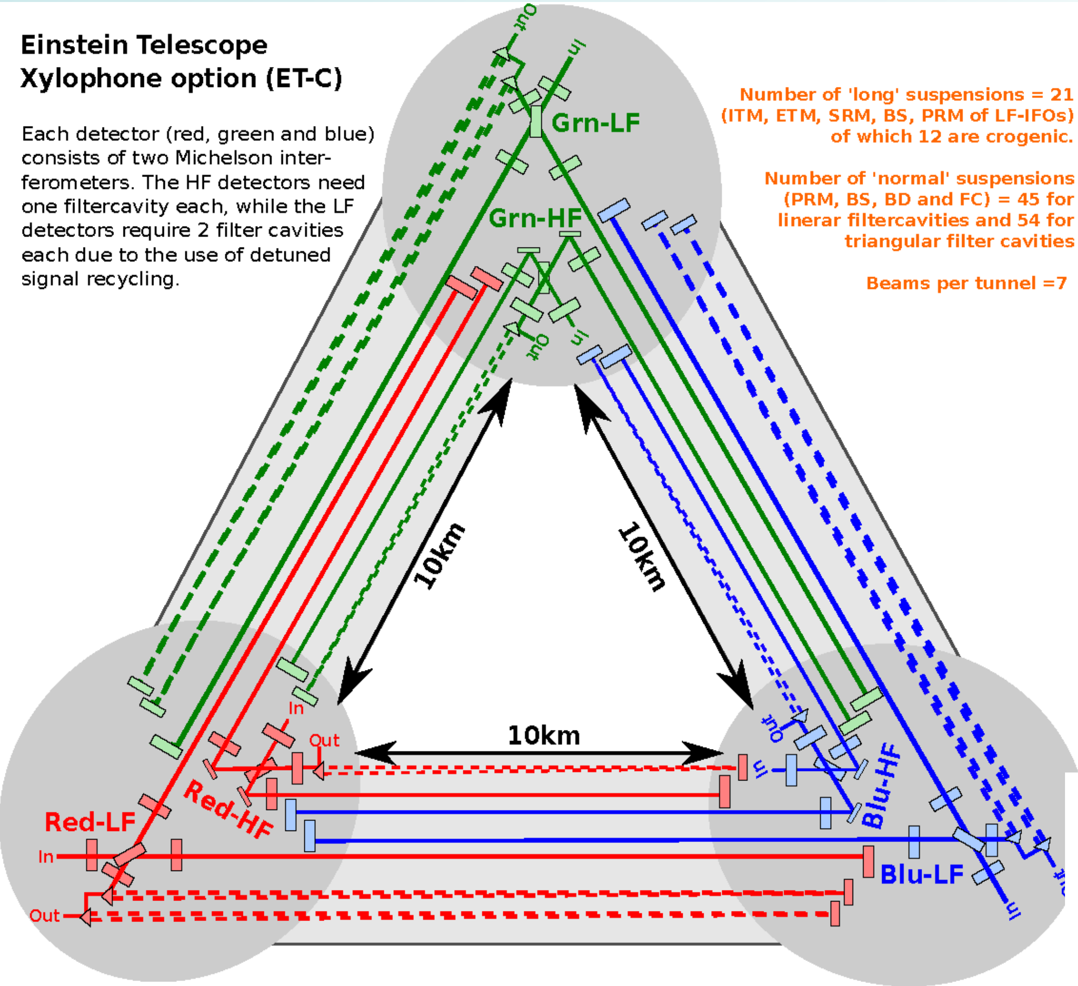
The next gravitational wave observatory

Project study started ~2010, with good progress



NIKHEF 2011

The ET infrastructure in Sardinia



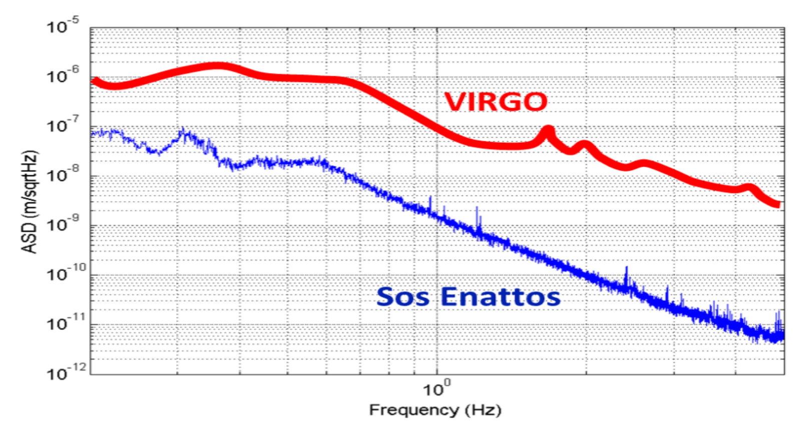
Einstein Telescope Xylophone option (ET-C)

Each detector (red, green and blue) consists of two Michelson interferometers. The HF detectors need one filtercavity each, while the LF detectors require 2 filter cavities each due to the use of detuned signal recycling.

Number of 'long' suspensions = 21 (ITM, ETM, SRM, BS, PRM of LF-IFOs) of which 12 are crogenic.

Number of 'normal' suspensions (PRM, BS, BD and FC) = 45 for linear filtercavities and 54 for triangular filter cavities

Beams per tunnel =7



Concluding Remarks

VIRGO is a *key player* in the starting era of the multi-messenger observation of the universe: a lot of science will come out of that.

☐ **The sensitivity of the detectors will keep growing and the science outcome will get richer and richer**

☐ **VIRGO (and its community) <u>must remain</u> a key player in the field**

- **fill the sensitivity gap with LIGO**
- **prepare the detector upgrades**
- **prepare for a new 3G detector**

☐ **A bright future for the GW field and the multi-messenger astronomy (i.e. astrophysics/cosmology/fundamental physics)**

End…

…of the beginning