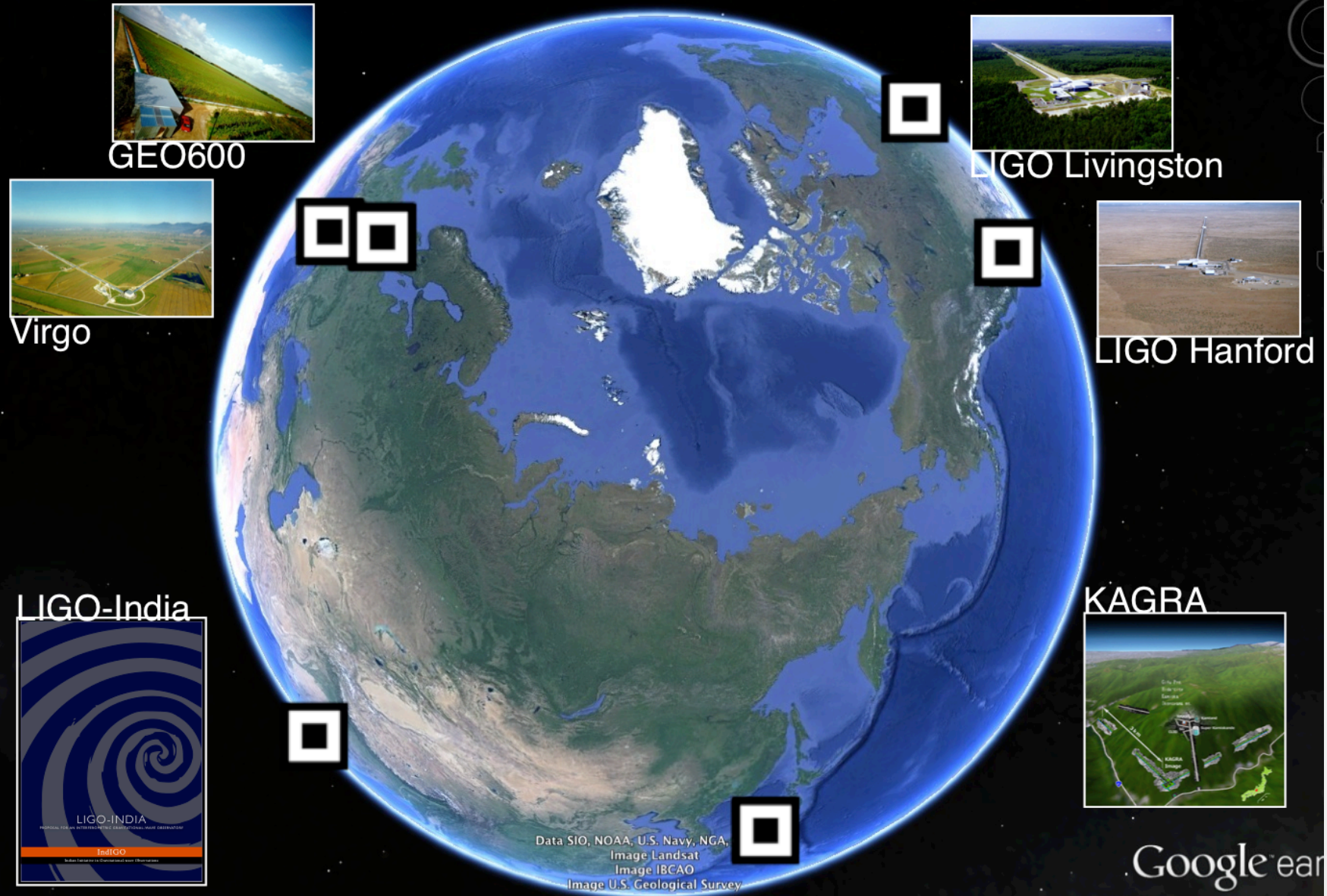


Listening to the gravitational wave universe with Advanced LIGO



Ik Siong Heng,
University of Glasgow,
on behalf of the LIGO Scientific Collaboration and Virgo

Gravitational wave detector network

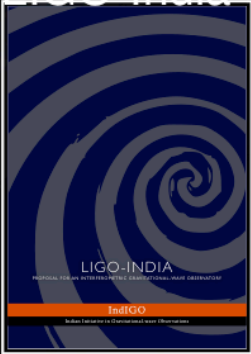


GEO600



Virgo

LIGO-India



LIGO Livingston



LIGO Hanford

KAGRA



Data SIO, NOAA, U.S. Navy, NGA,
Image Landsat
Image IBCAO
Image U.S. Geological Survey

Google Earth



LIGO Hanford Observatory

Hanford, WA

*LIGO Livingston
Observatory*

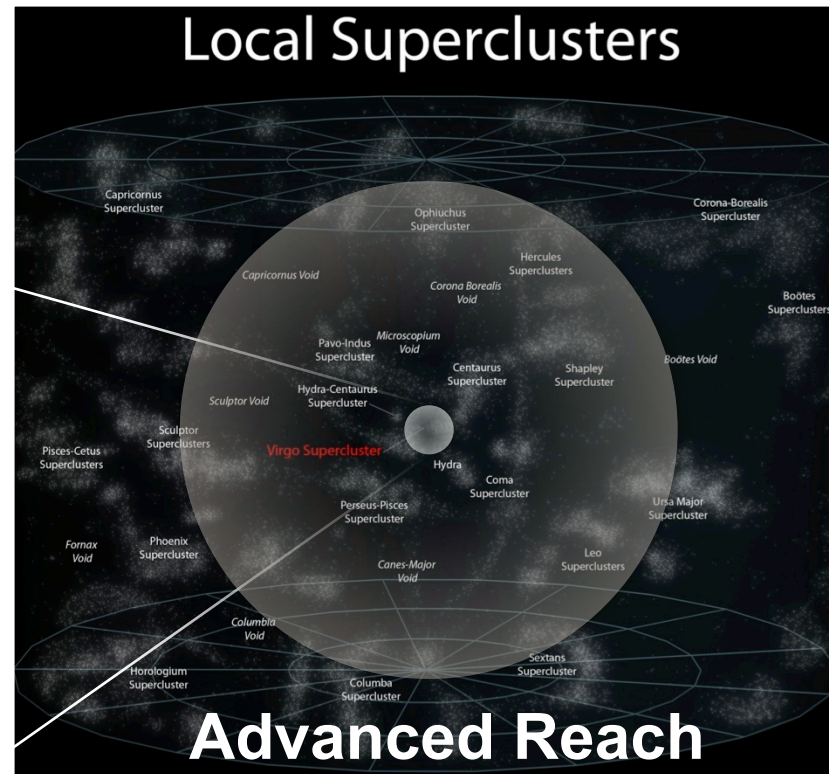


Advanced LIGO

- Advanced LIGO aims to improve sensitivity by a factor of 10 with respect to LIGO, leading to a factor of 1000 increase in search volume and, thus, expected event rate

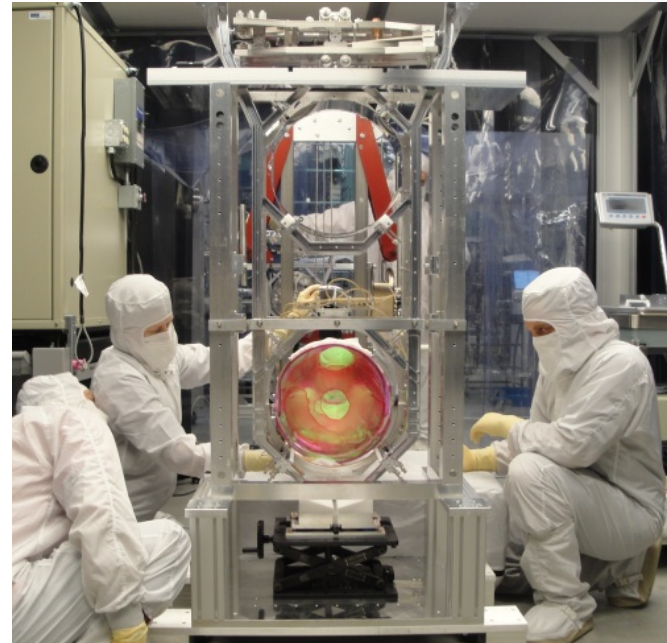
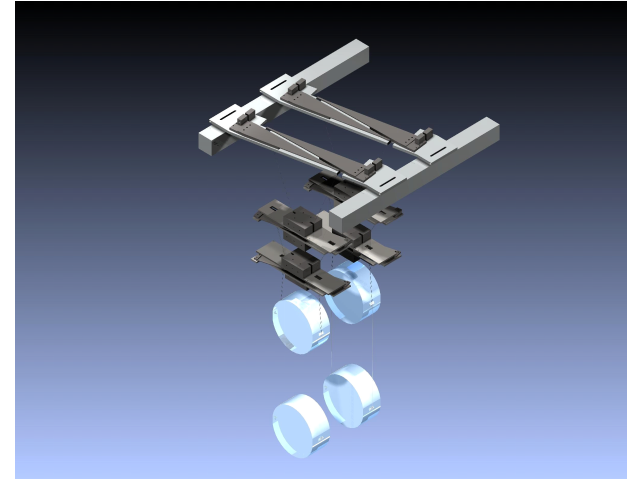


image credit: Matt Evans (MIT)



Upgrading to Advanced LIGO

- Lasers become more powerful:
use 200 W lasers
- Improvements to suspensions
 - test masses (previously 10 kg simple pendulums) become 40 kg monolithic suspensions in quadruple pendulums
 - improved optical systems
- Seismic isolation goes from passive to active



Advanced LIGO design sensitivity

Fundamental Noises:

I. *Displacement noise*

→ $\Delta L(f)$

- Seismic noise
- Radiation Pressure
- Thermal noise

- Suspensions
- Optics

• Sensing Noise

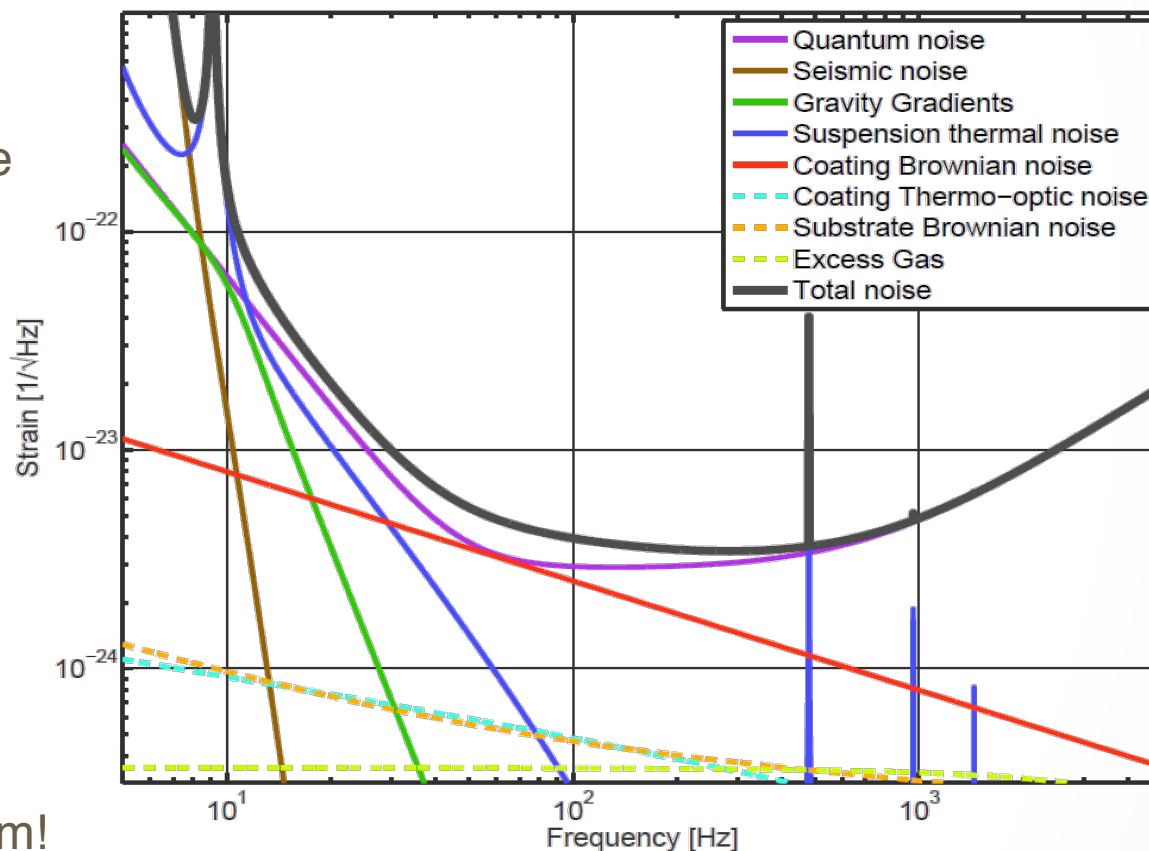
→ $\Delta t_{\text{photon}}(f)$

- Shot Noise
- Residual Gas

Technical Noises:

- Loads of them!

Advanced LIGO Design Noise Budget

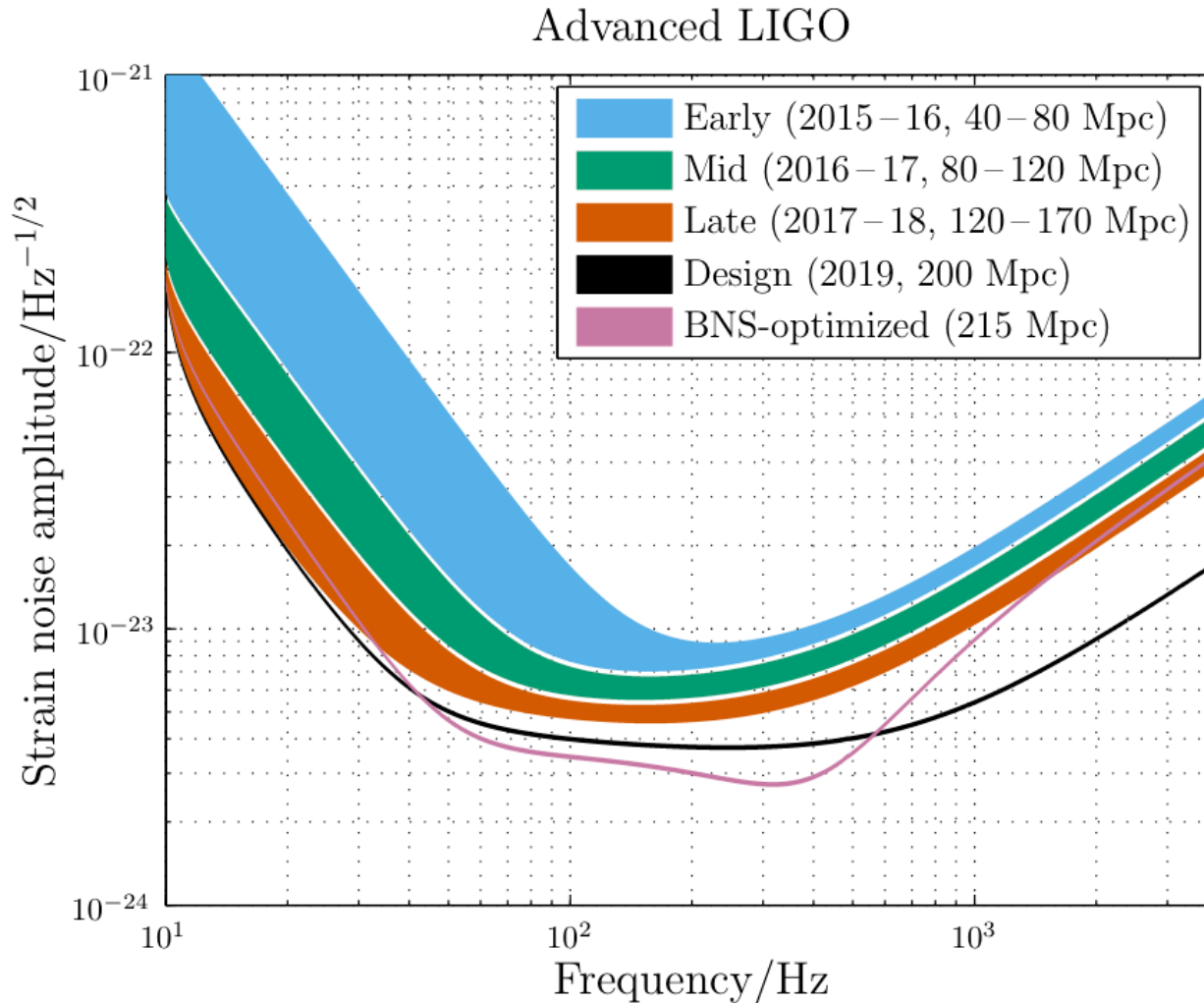


Towards design sensitivity

		O1	O2	O3		
Epoch		2015–2016	2016–2017	2017–2018	2019+	2022+ (India)
Estimated run duration		4 months	6 months	9 months	(per year)	(per year)
Burst range/Mpc	LIGO	40–60	60–75	75–90	105	105
	Virgo	—	20–40	40–50	40–80	80
BNS range/Mpc	LIGO	40–80	80–120	120–170	200	200
	Virgo	—	20–60	60–85	65–115	130
Estimated BNS detections		0.0005–4	0.006–20	0.04–100	0.2–200	0.4–400
90% CR	% within median/deg ²	5 deg ²	< 1	2	> 1–2	> 3–8
		20 deg ²	< 1	14	> 10	> 8–30
			480	230	—	—

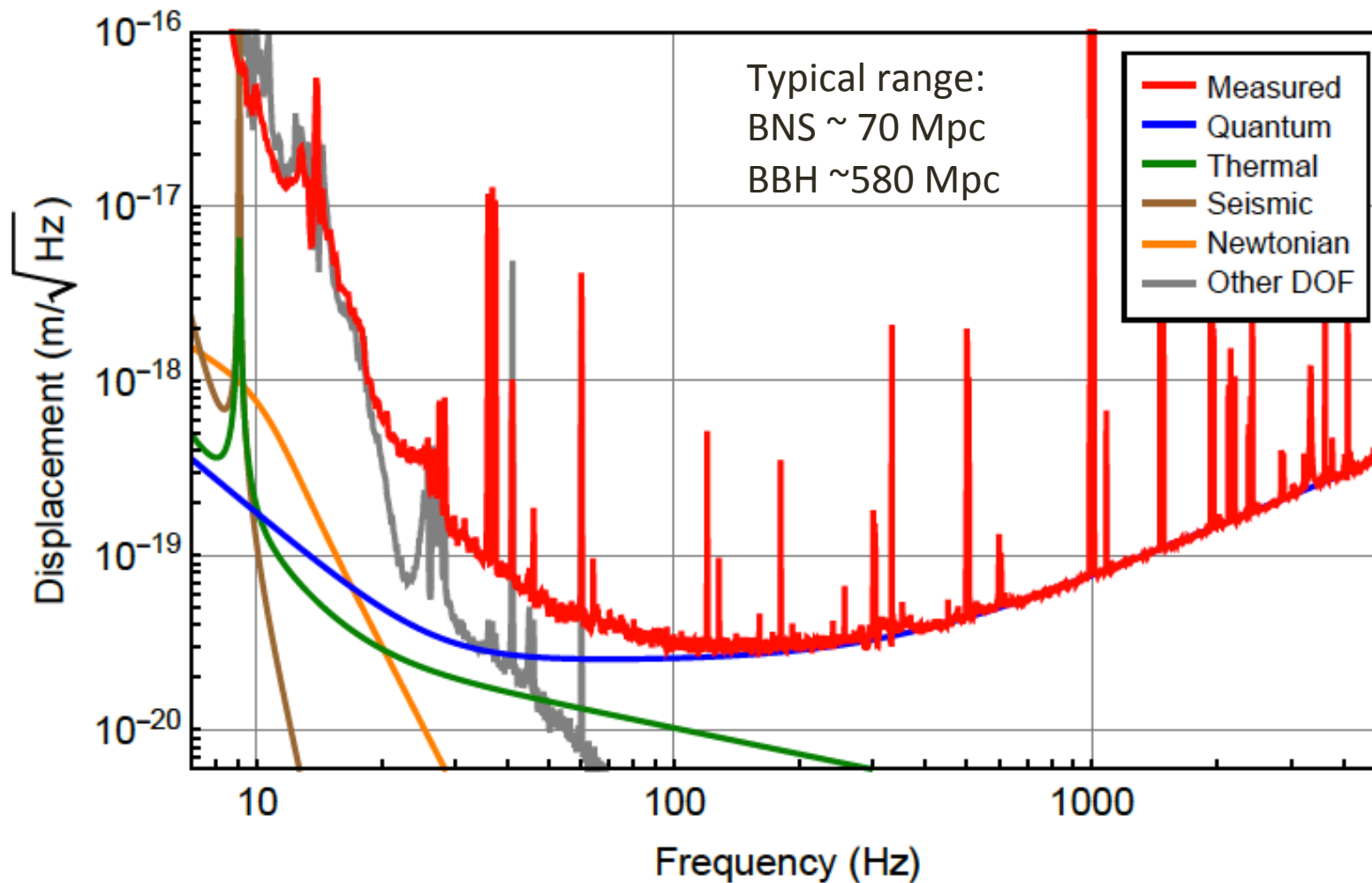
[arXiv:1304.0670](https://arxiv.org/abs/1304.0670)

Towards design sensitivity



[arXiv:1304.0670](https://arxiv.org/abs/1304.0670)

Observing run 1 (O1)



Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, Phys. Rev. Lett. 116, 131103 (2016).

Observing run 1 (01)

- Observing run 1 is the first science data taking run of Advanced LIGO
 - Sept 12, 2015 to Jan 19, 2016
 - Coincident observing time of ~51 days
- Sensitivity improvement of ~5 over initial LIGO
- Detected 2 gravitational wave signals from binary black hole coalescence and merger
 - plus one candidate event
- Detection papers:
 - GW150914: *PRL* **116**, 061102 (2016)
 - GW151226: *PRL* **116**, 241103 (2016)
- Also performed searches for gravitational waves from unmodelled transients, rapidly rotating neutron stars, a stochastic gravitational wave background and more

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LSC LIGO Scientific Collaboration **VIRGO**

Detections News About LIGO science Educational resources Multimedia For researchers

Introduction Advanced LIGO Frequently Asked Questions Popular Articles Science Summaries

OBSERVATION OF GRAVITATIONAL WAVES FROM A BINARY BLACK HOLE MERGER

Read this summary [in PDF format] in [Chinese](#) | [French](#) | [German](#) | [Japanese](#) | [Spanish](#)

FIGURES FROM THE PUBLICATION

For more information on how these figures were generated and their meaning, see the main publication at [Physical Review Letters](#).

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GW151226: OBSERVATION OF GRAVITATIONAL WAVES FROM A 22 SOLAR-MASS BINARY BLACK HOLE

[PDF version](#)

Read this summary [in PDF format] in [French](#) | [German](#) | [Spanish](#)

A few months after the first detection of gravitational waves from the big Laser Interferometer Gravitational-Wave Observatory (LIGO) has made waves from the collision and merger of a pair of black holes. This signal was detected by the LIGO detectors on 26 December 2015 at 03:38:53 UTC.

The signal, which came from a distance of around 1.4 billion light-years away, was produced when two extremely dense objects merge. Binary system gravitational waves for which the LIGO detectors are searching. Gravitational waves carry energy away from such a binary system, causing the two objects to spiral in and closer together. This inspiral brings the objects closer and closer together as they stretch and squash space-time as they spiral in and closer together.

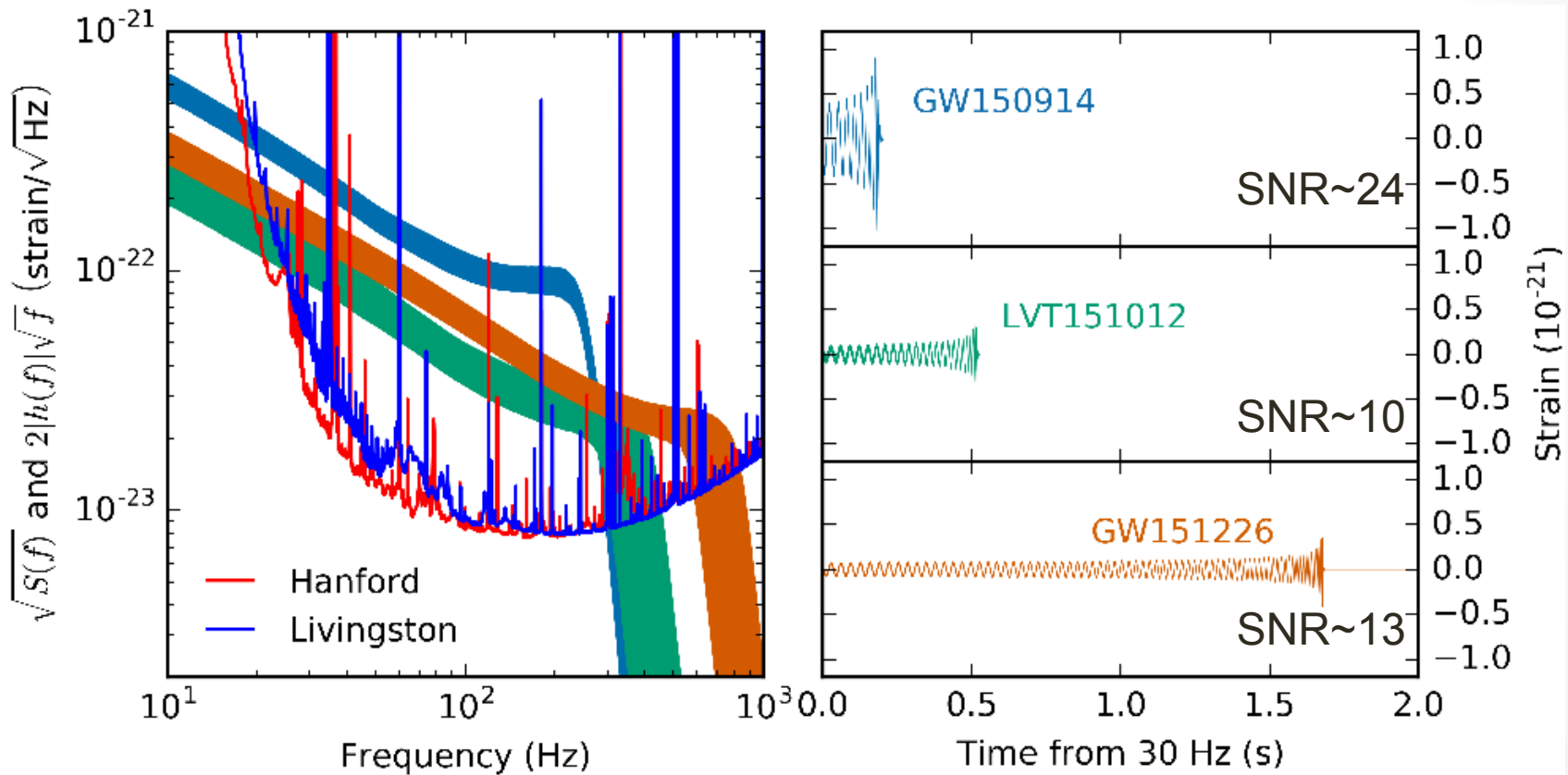
Hanford Livingston

Frequency (Hz)

Time (s)

Normalized Energy

Binary black hole observations in O1

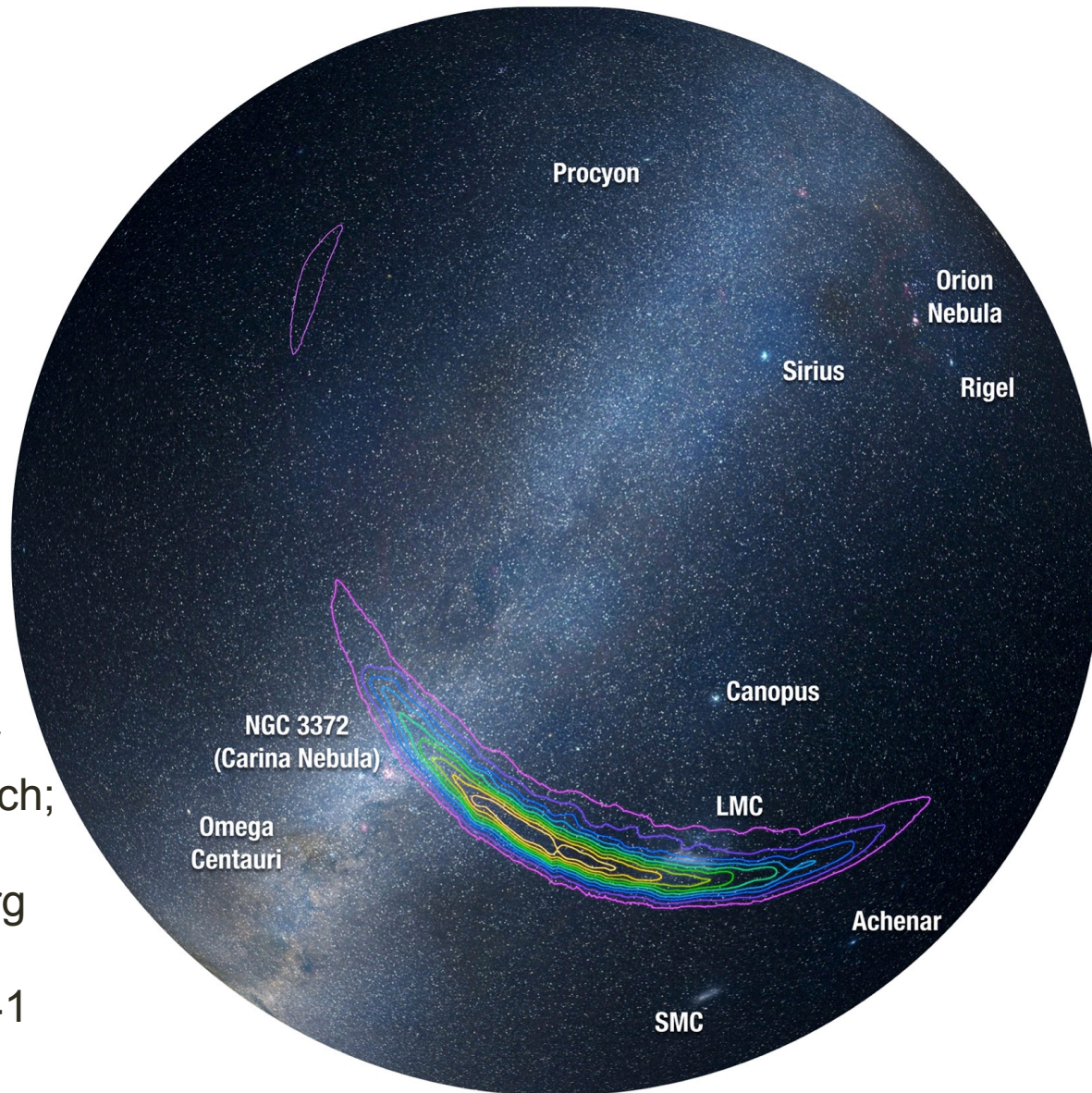


arXiv:1606.04856

Event	GW150914	GW151226	LVT151012
Primary mass $m_1^{\text{source}} / M_{\odot}$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\text{source}} / M_{\odot}$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathcal{M}^{\text{source}} / M_{\odot}$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\text{source}} / M_{\odot}$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
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 $\Delta\Omega / \text{deg}^2$	230	850	1600

modified version of table in arXiv:1606.04856

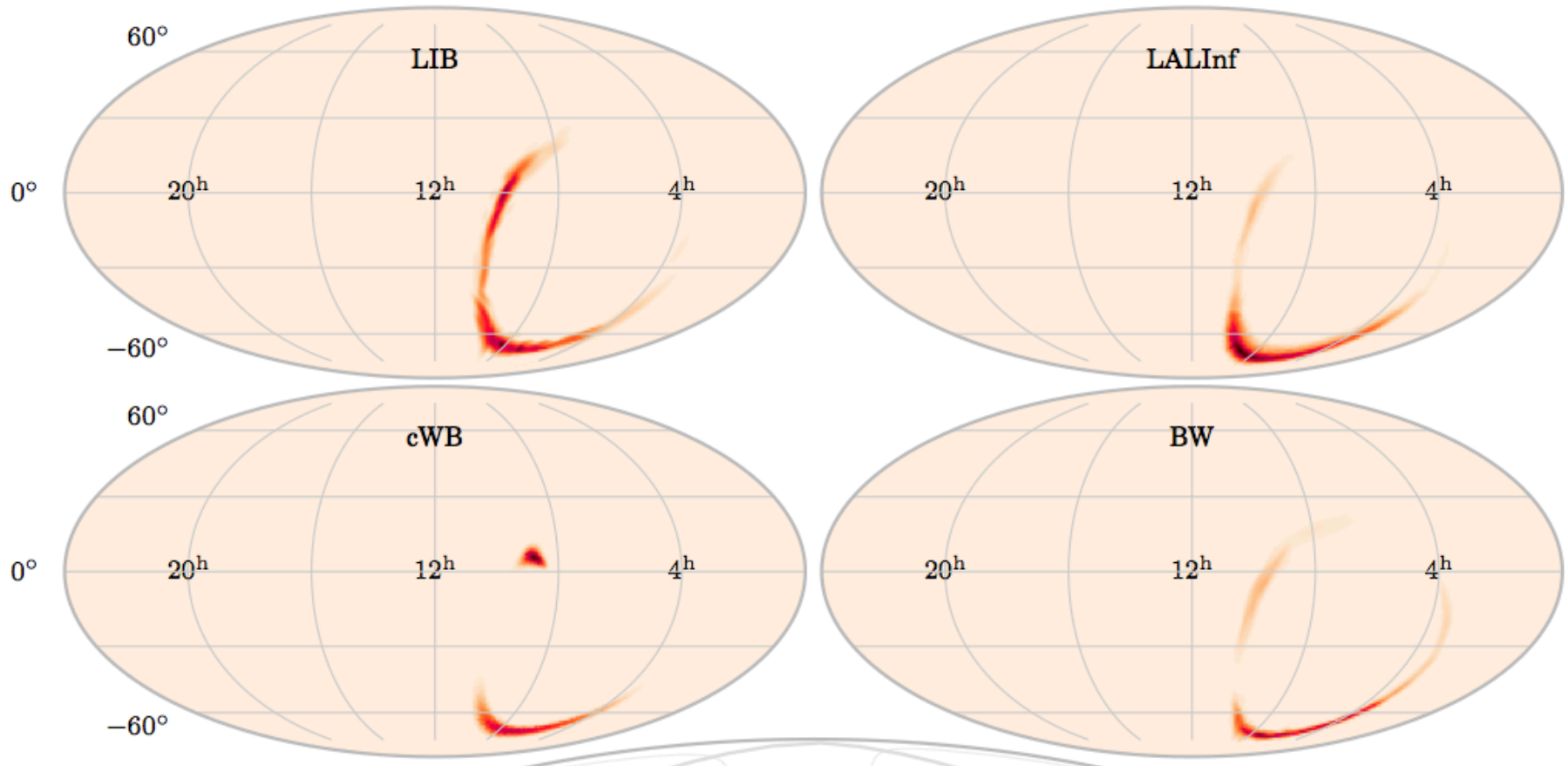
GW150914: sky location estimate



Credit: Shane Larson, Northwestern University; Roy Williams, Caltech; Thomas Boch, CDS Strasbourg

LIGO-D1600041

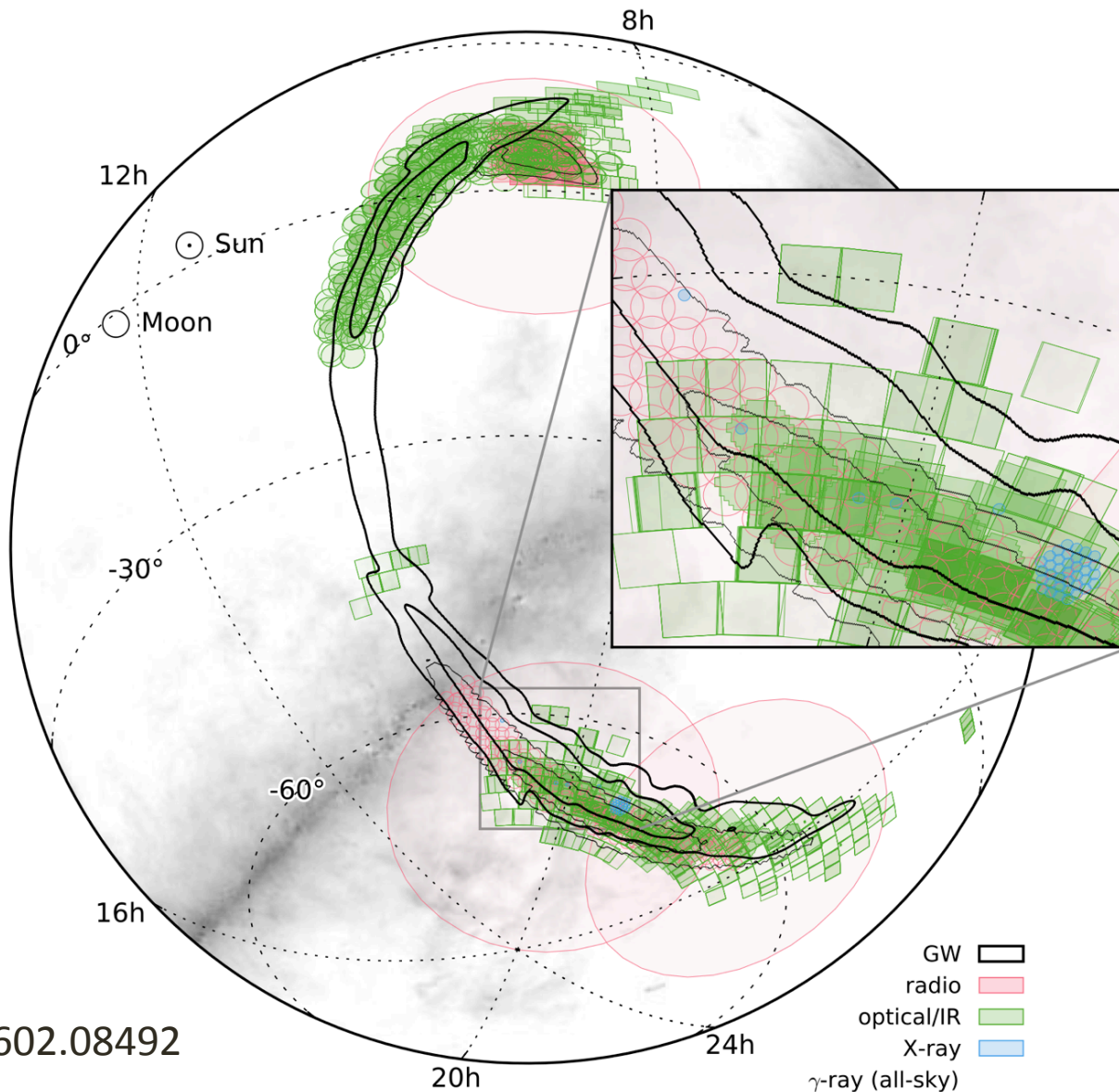
GW150914: Rapid source sky localisation



- cWB, LIB, BW: burst analyses
- LALInf: sky location estimate assuming full waveform model

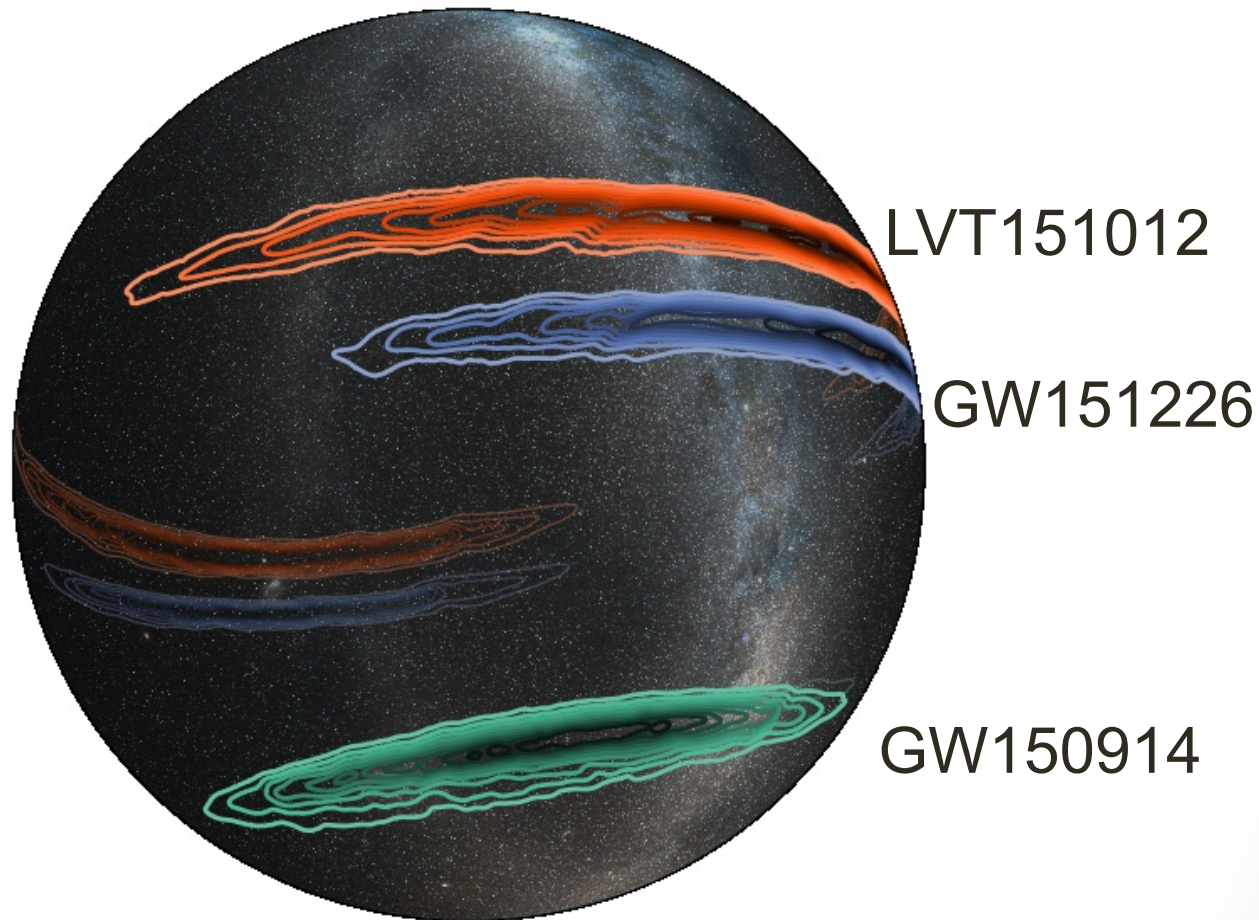
<http://arxiv.org/abs/1602.03843>

GW150914: search for counterparts



arXiv:1602.08492

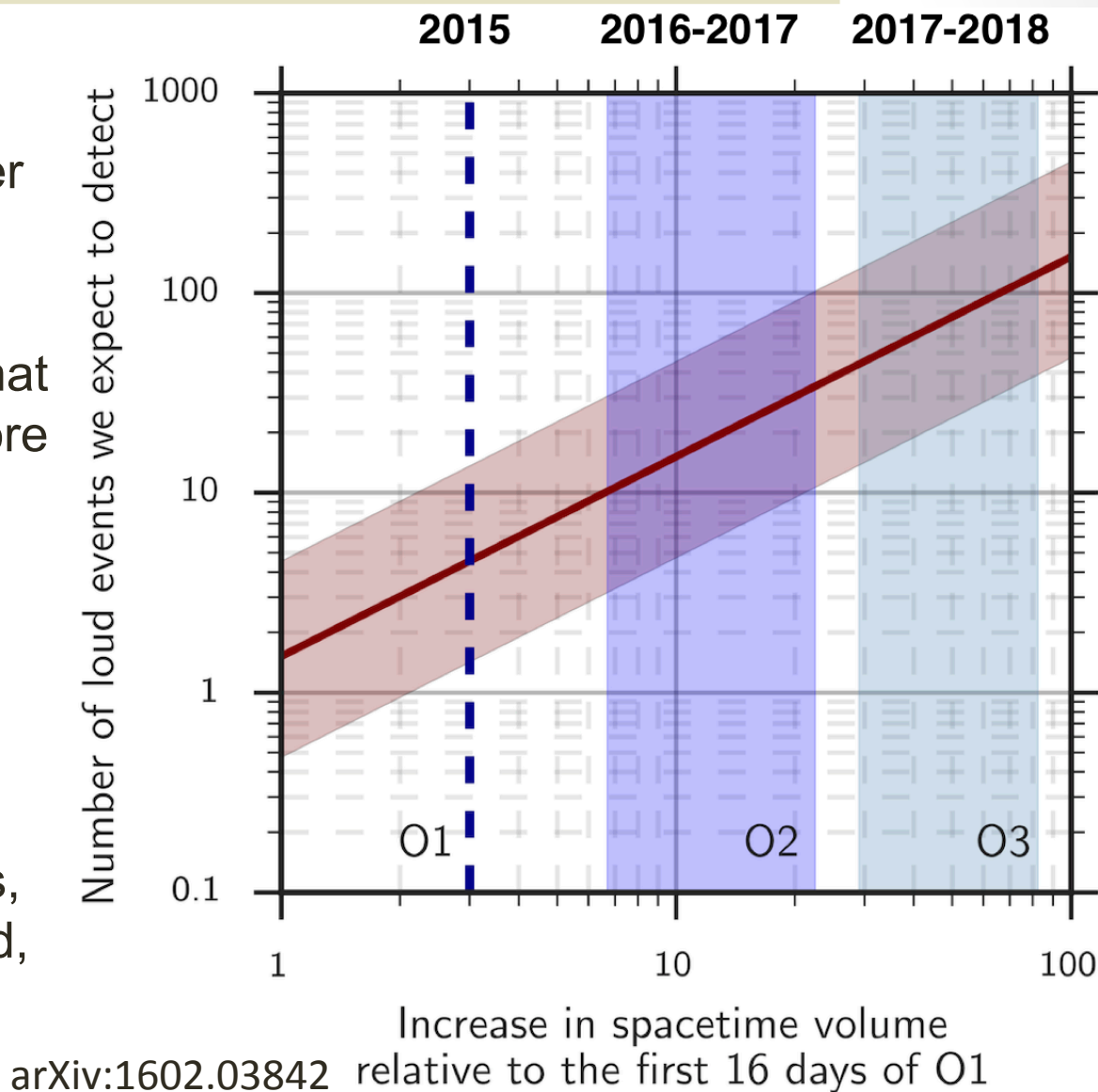
Sky location estimates



Credit: LIGO/Leo Singer (Milky Way image: Axel Mellinger) LIGO-G1601316

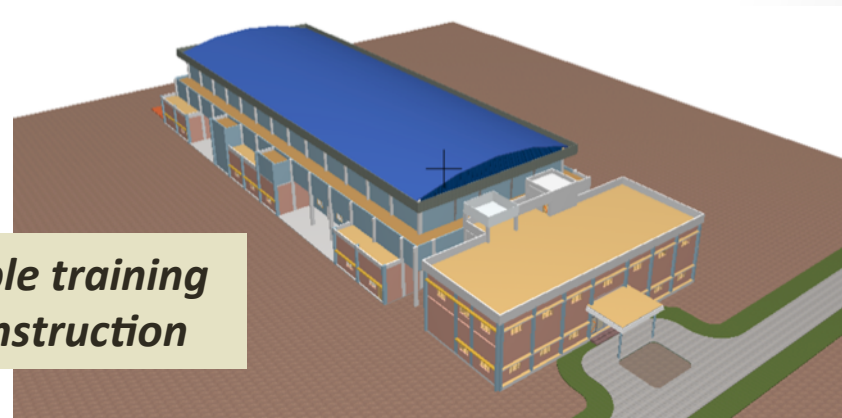
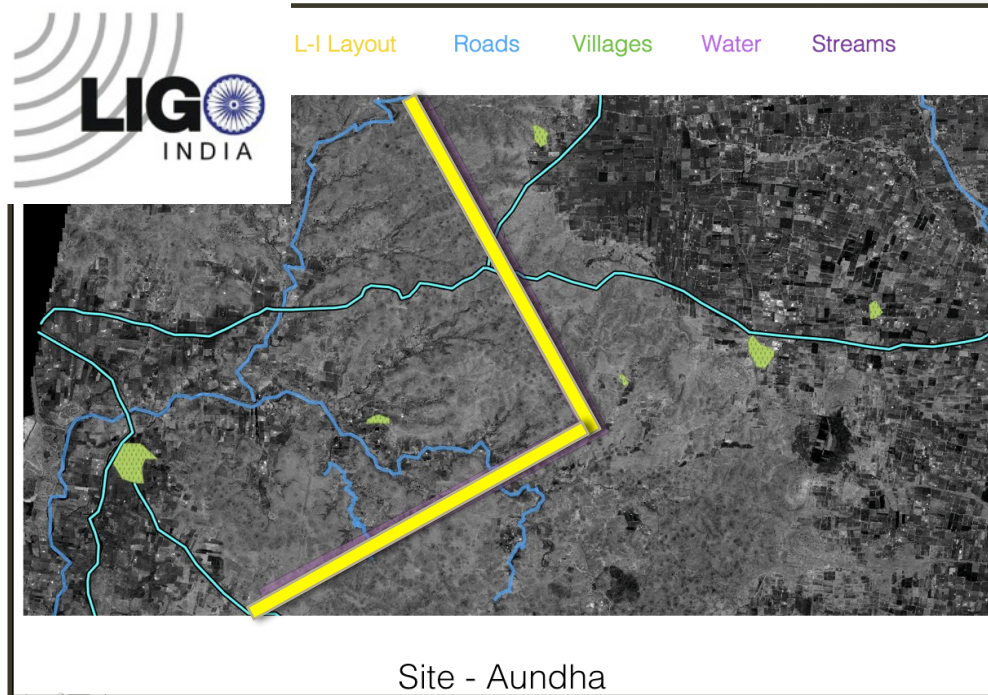
Prospects for next runs

- The next Observing Runs target improved sensitivities and longer runs
- It is extremely likely that there will be many more binary black hole detections
- Also be searching for signals from binary neutron stars, unmodelled transients, stochastic background, rotating neutron stars, cosmic strings....



LIGO India

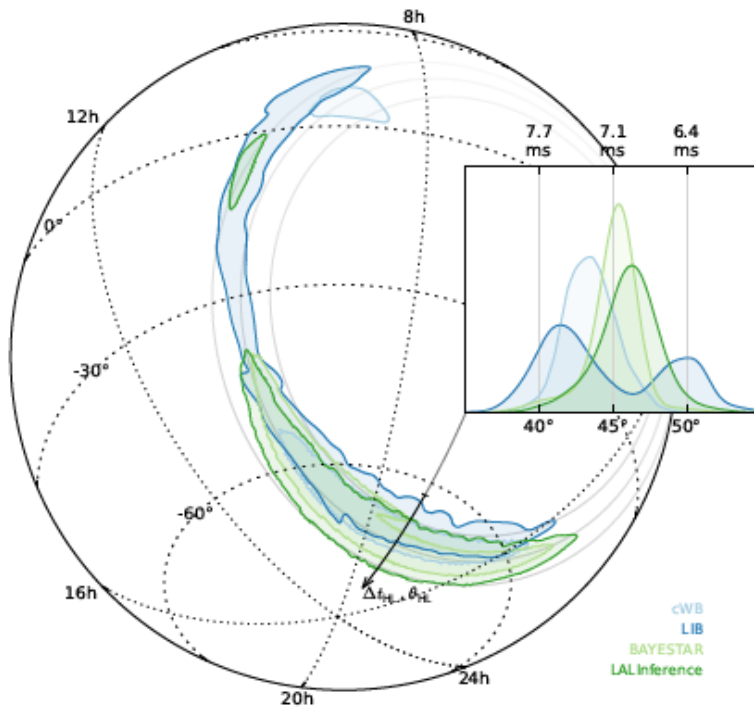
- LIGO-India is an Advanced LIGO detector in India
- It has been approved by the Indian government
- Undergoing site selection process



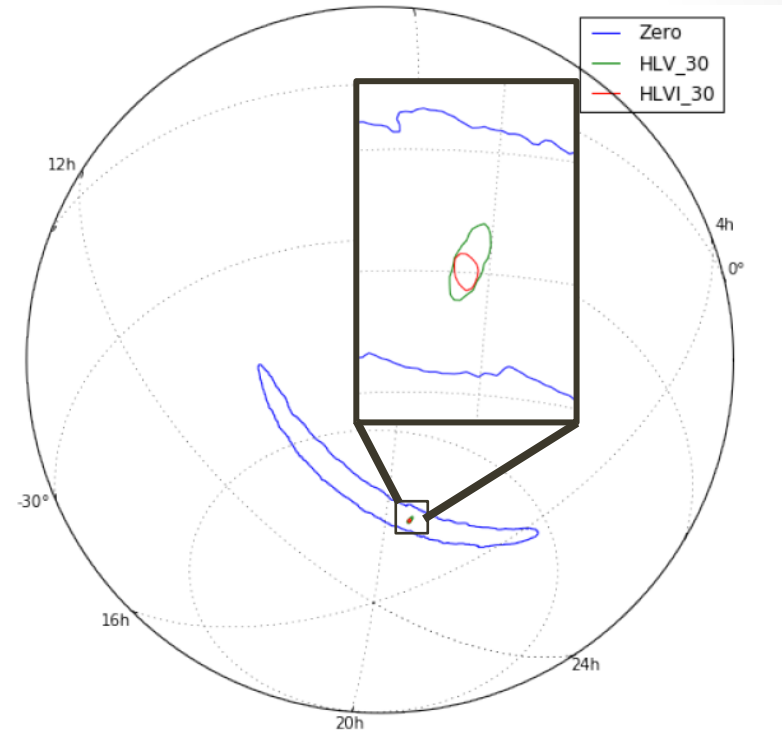
Off-site facility to enable training prior to LIGO-India construction

Improved sky localisation

GW150914: LIGO only

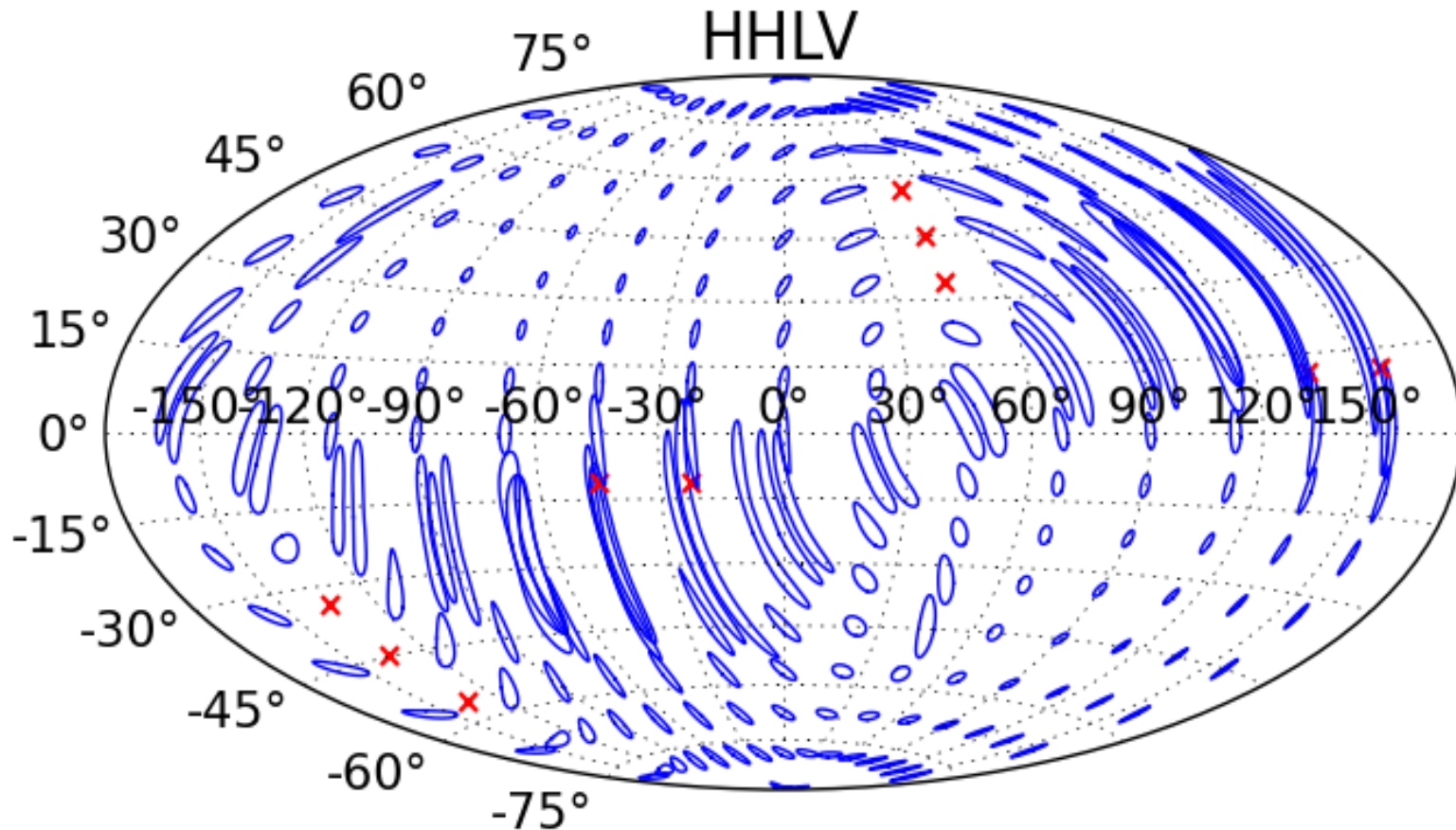


GW150914: LIGO → LV → LVI
(Preliminary)



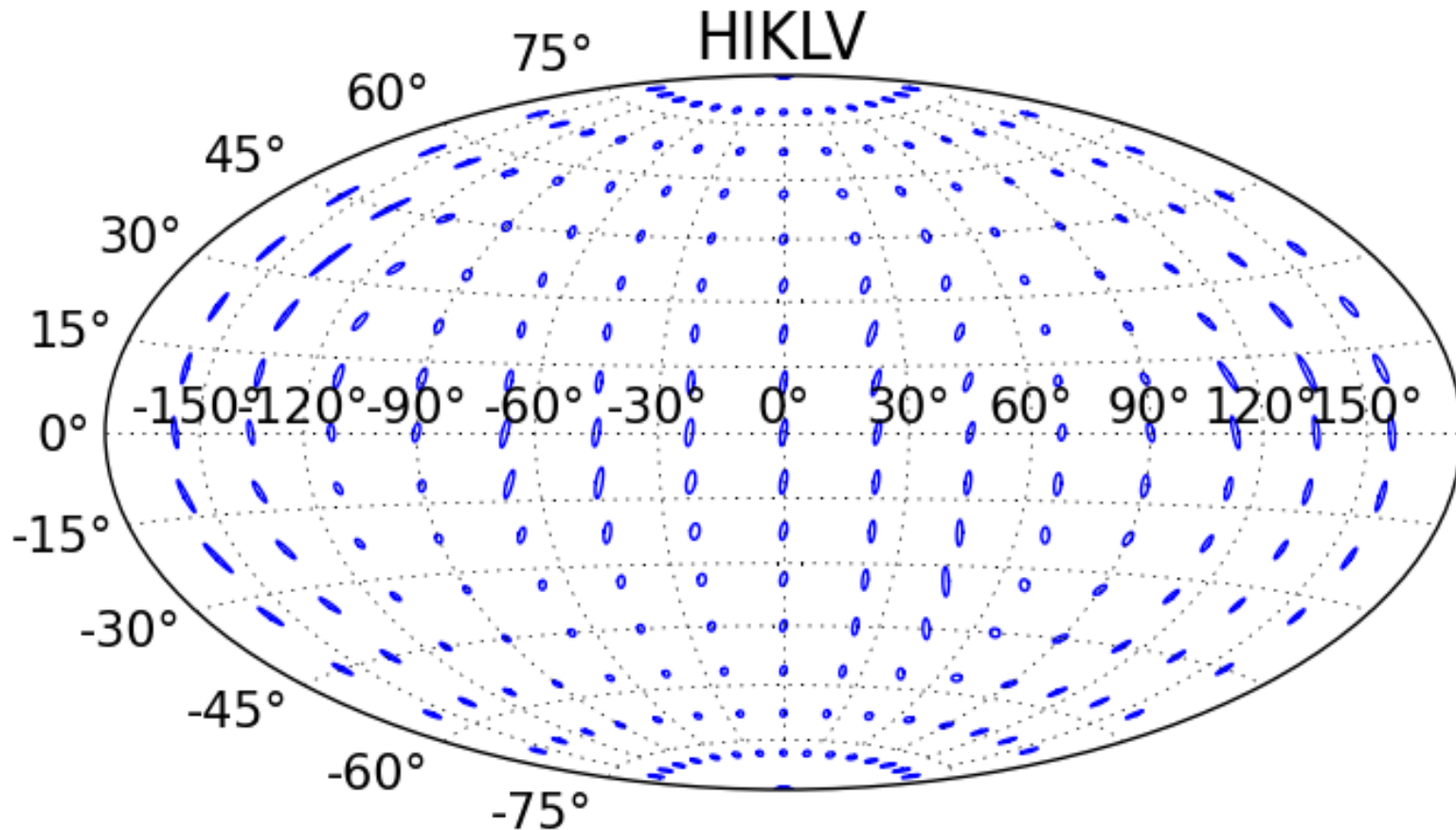
$375^\circ \rightarrow 9.3^\circ \rightarrow 7.8^\circ$
(99% confidence level)

Sky localisation with 3 detector sites



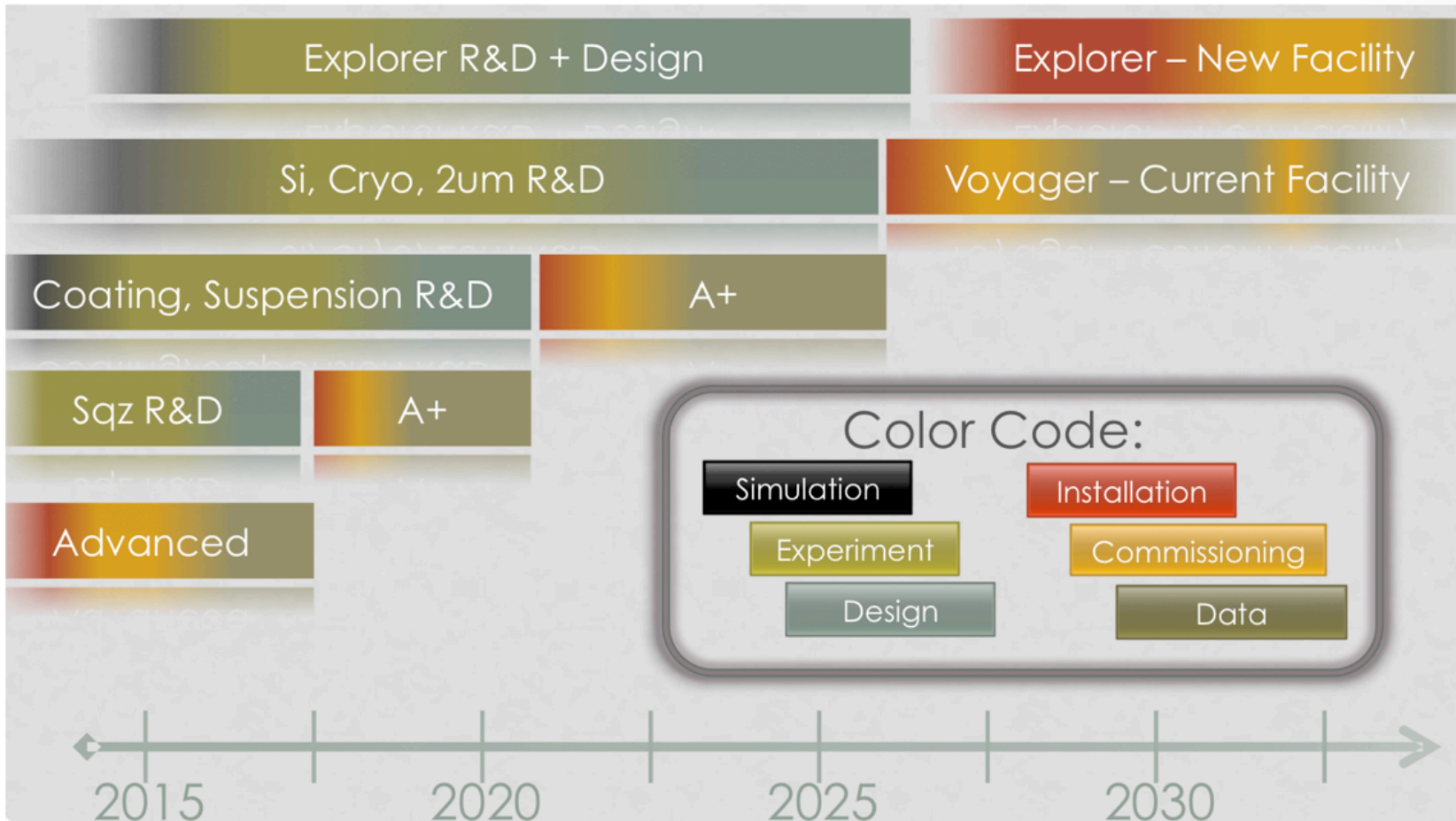
S. Fairhurst, "Improved source localization with LIGO India", [arXiv:1205.6611v1](https://arxiv.org/abs/1205.6611v1)

Sky localisation with 5 detector sites



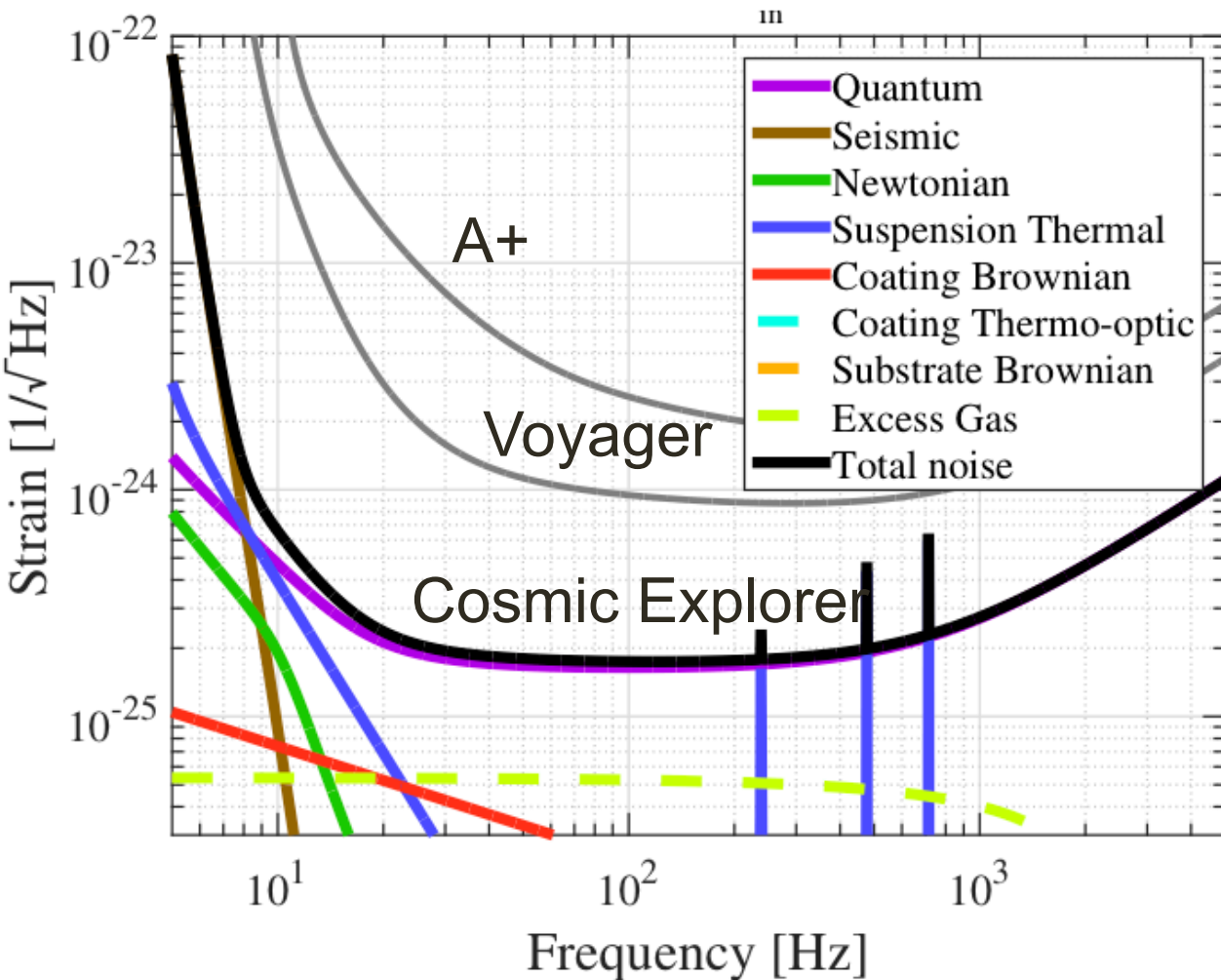
S. Fairhurst, "Improved source localization with LIGO India", [arXiv:1205.6611v1](https://arxiv.org/abs/1205.6611v1)

Beyond Advanced LIGO



Instrument Science white paper: <https://dcc.ligo.org/LIGO-T1500290>

A+, Voyager and Cosmic Explorer



- A+: upgrade to Advanced LIGO to have BNS range of 340 Mpc
- Voyager: further upgrade to increase BNS range to 1 Gpc
- Cosmic Explorer: new facility with BNS range of $z \sim 13$

<https://dcc.ligo.org/LIGO-T1500290>

Science questions to be answered

- **Fundamental Physics**

- Is the nature of gravitational radiation as predicted by Einstein?
- Are nature's black holes the black holes of general relativity?
- What is the equation of state of ultra dense matter in neutron stars?

- **Astrophysics**

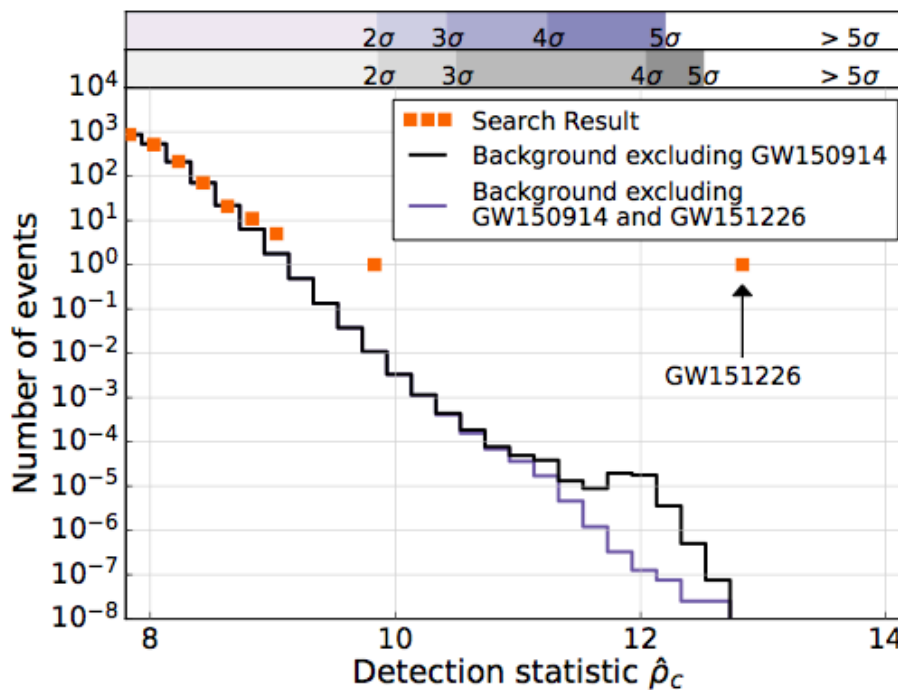
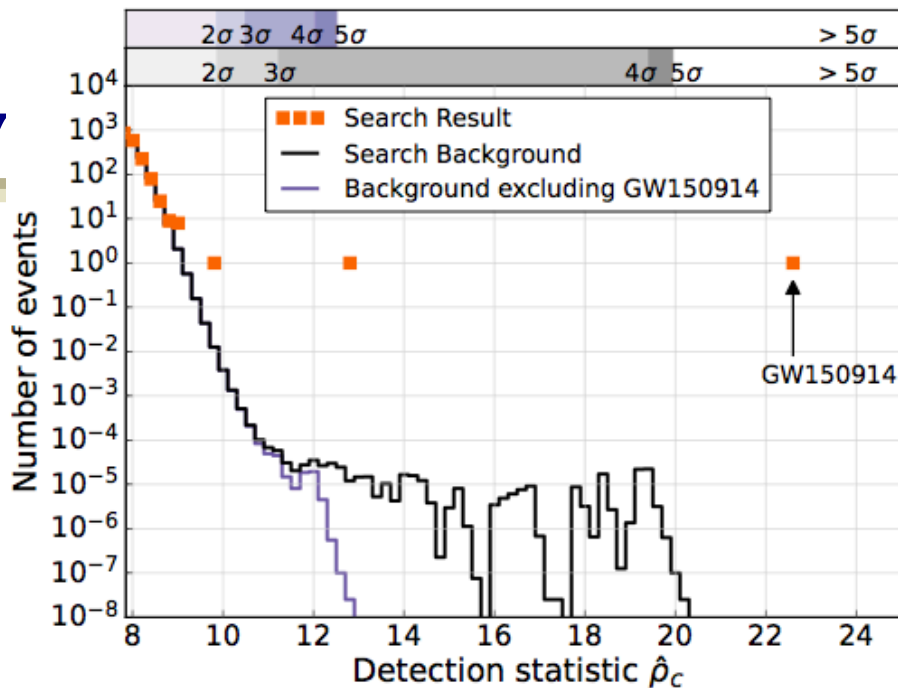
- What is the central engine behind gamma-ray bursts?
- What happens when a massive star collapses?
- How abundant are stellar mass black holes?
- How massive can neutron stars be?

- **Cosmology**

- What is the history of the accelerating expansion of the Universe?

.....and more!

Extra slides



EM partners

