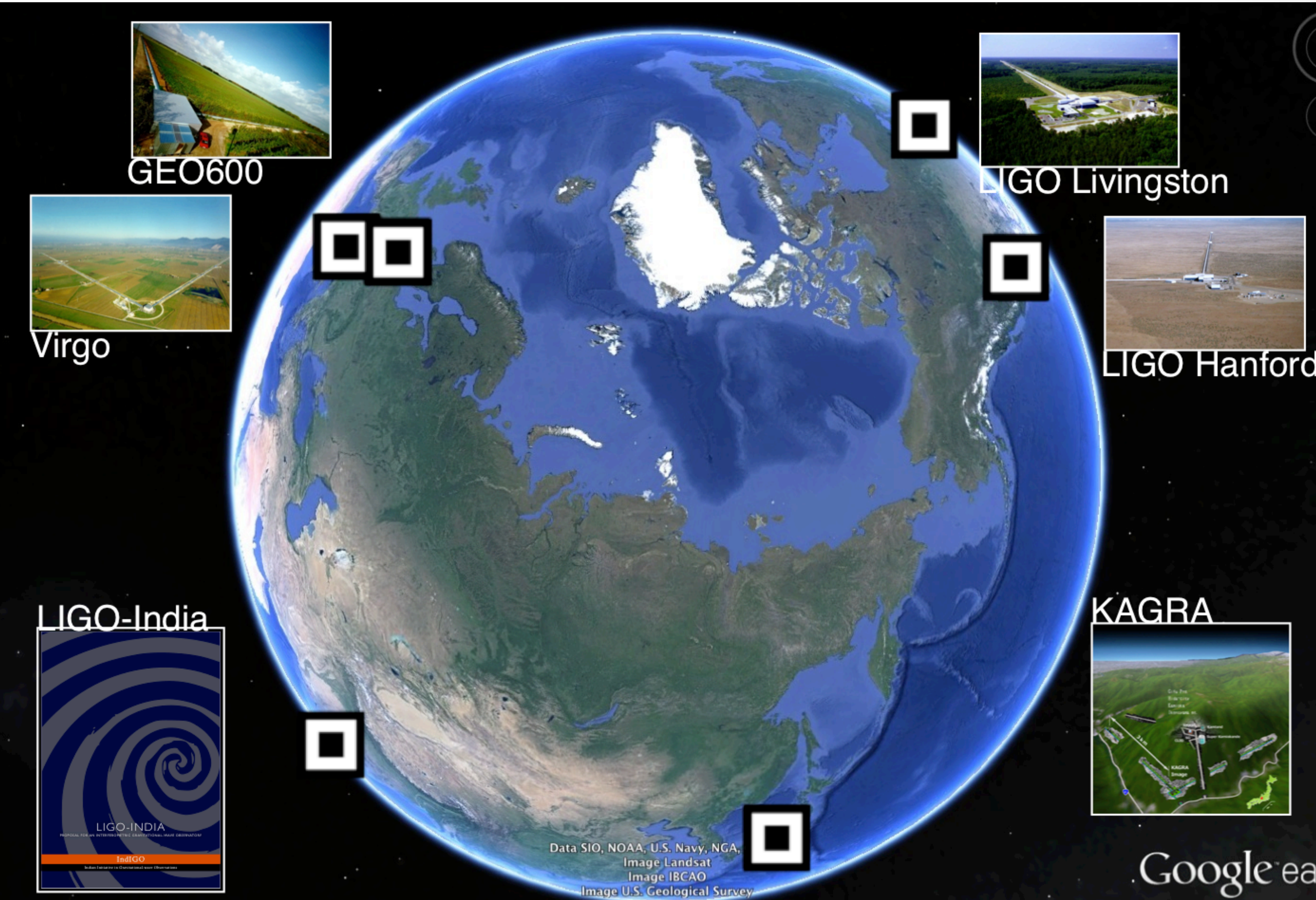
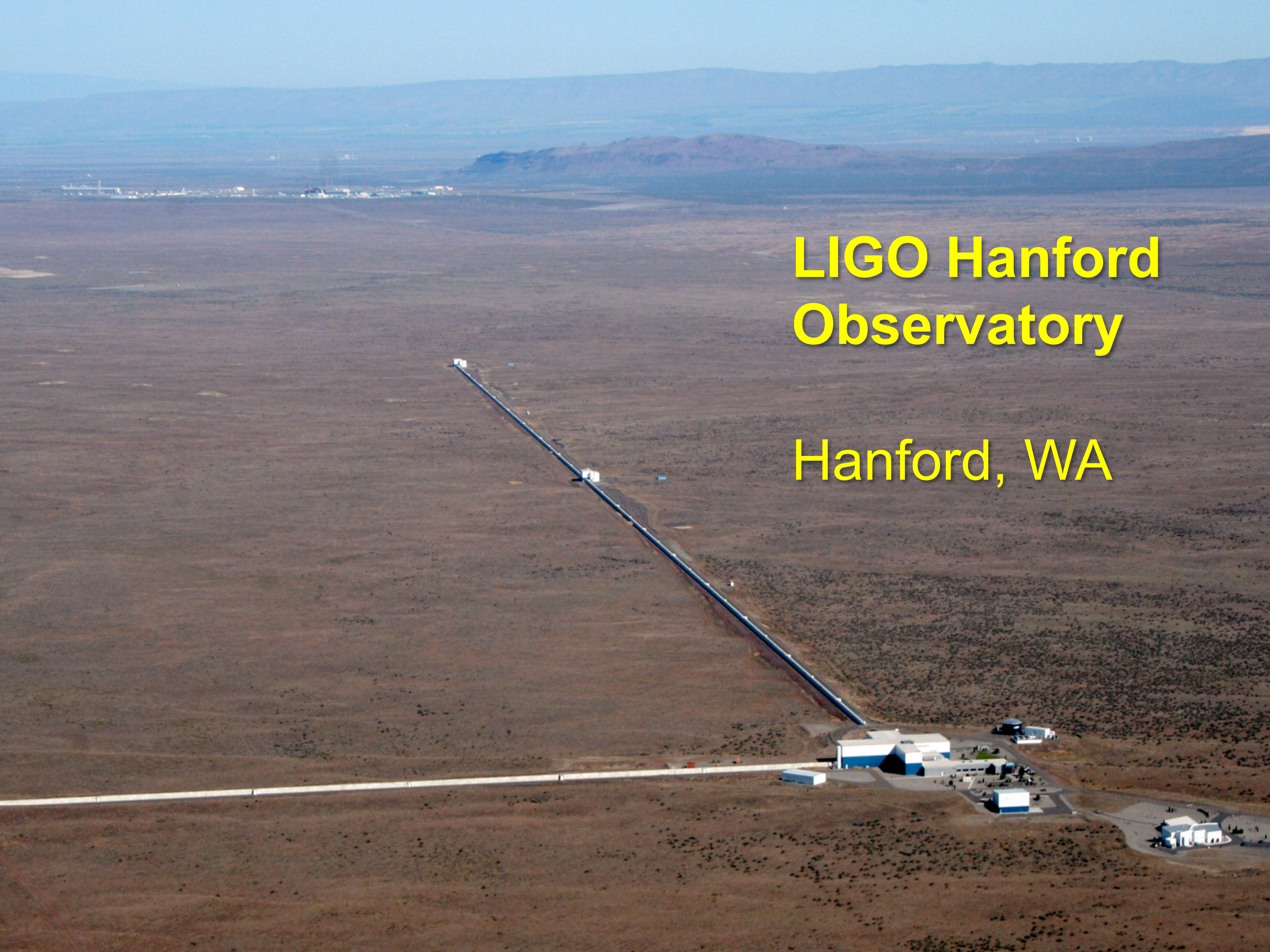
Listening to the gravitational wave universe with Advanced LIGO

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

Gravitational wave detector network

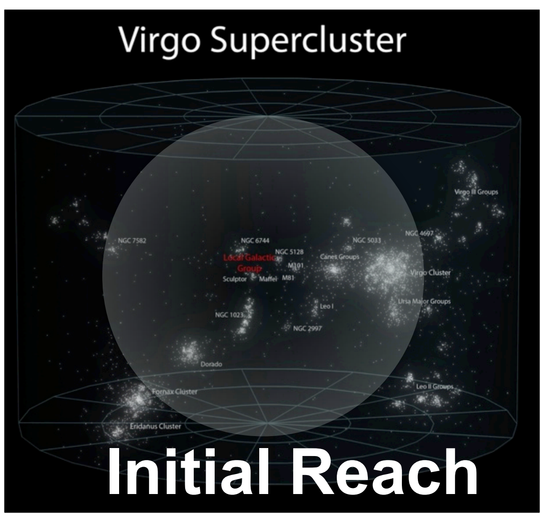



LIGO Hanford
Observatory
Hanford, WA


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



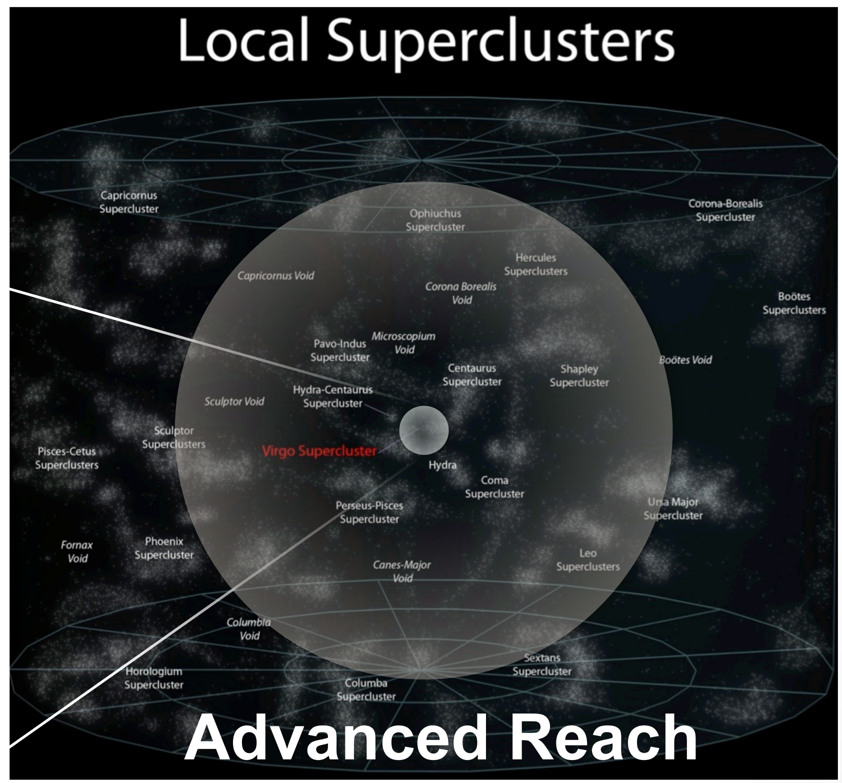
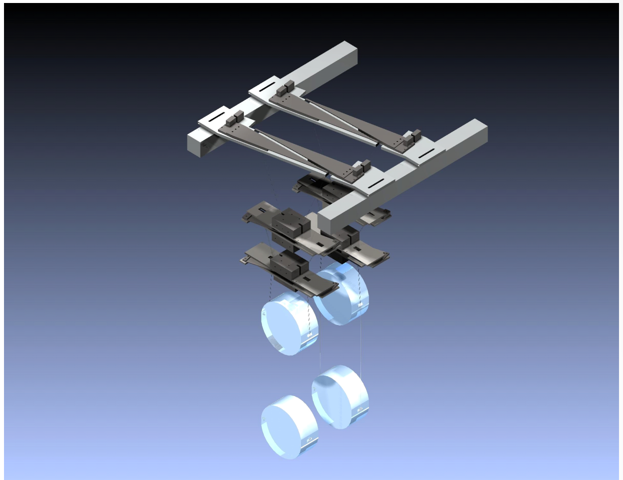


image credit: Matt Evans (MIT)

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

→ ΔL(f)

- Seismic noise
- Radiation Pressure
- Thermal noise
  - Suspensions
  - Optics
- Sensing Noise

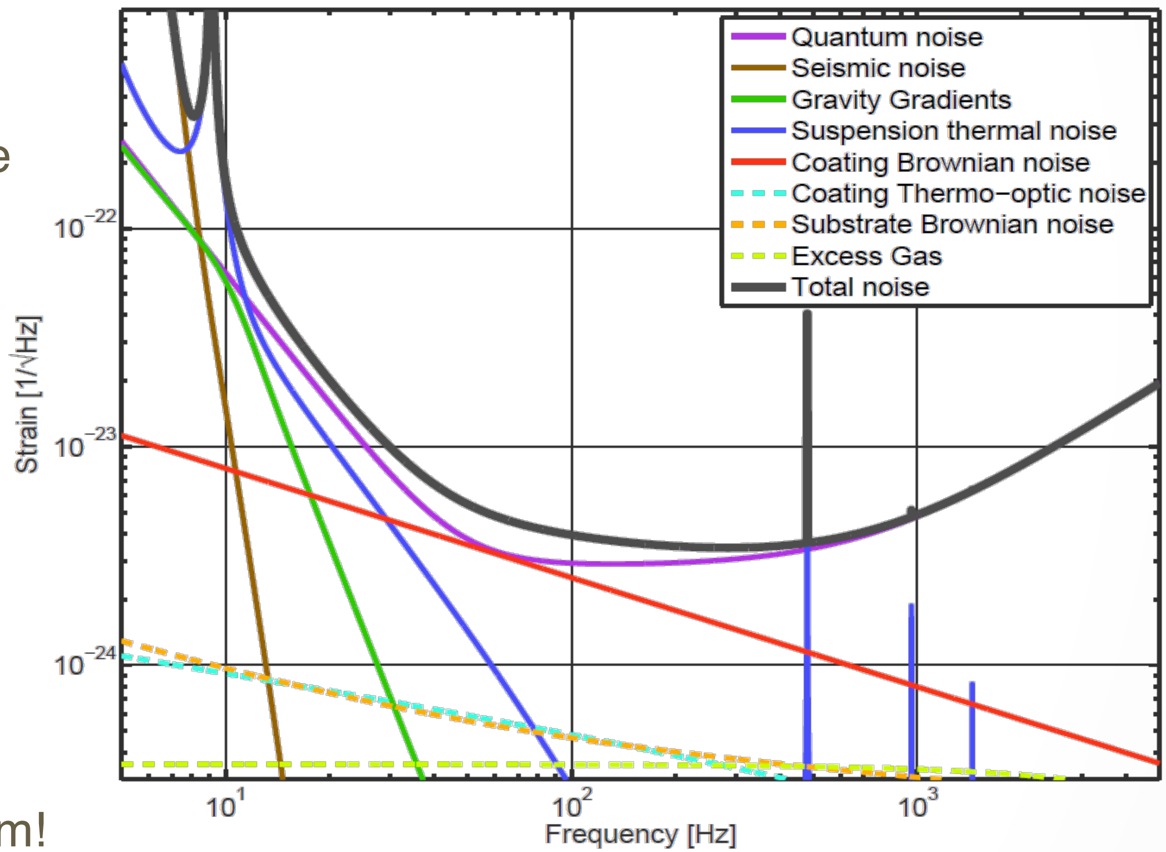
→ $\Delta t_{photon}(f)$

  - Shot Noise
  - Residual Gas

Technical Noises:

  - Loads of them!

Advanced LIGO Design Noise Budget

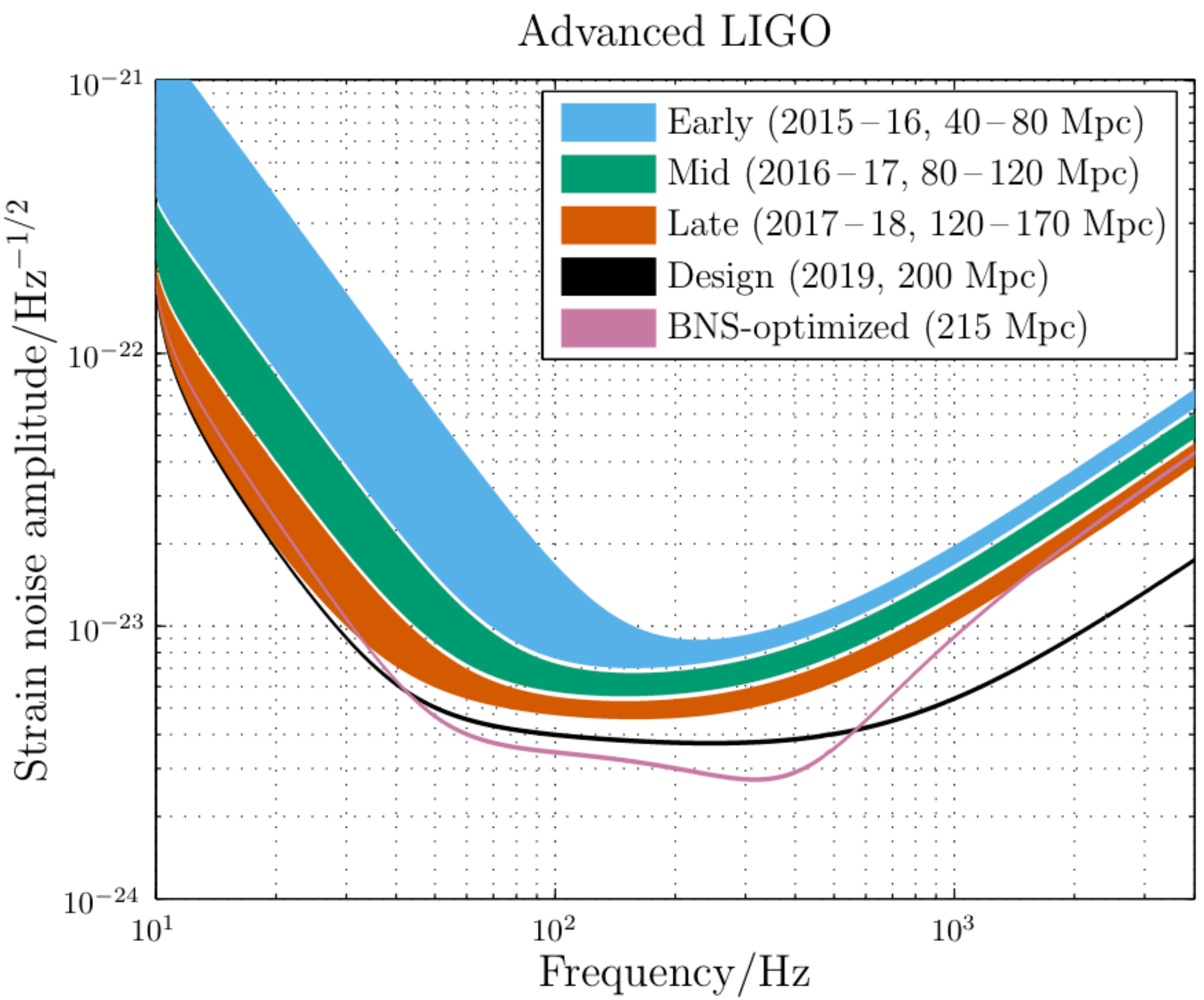


Towards design sensitivity

			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	5 deg^2	< 1	2	> *1 – 2*	> *3 – 8*	> *20*
		20 deg^2	< 1	14	> *10*	> *8 – 30*	> *50*
	median/deg^2		480	230	—	—	—

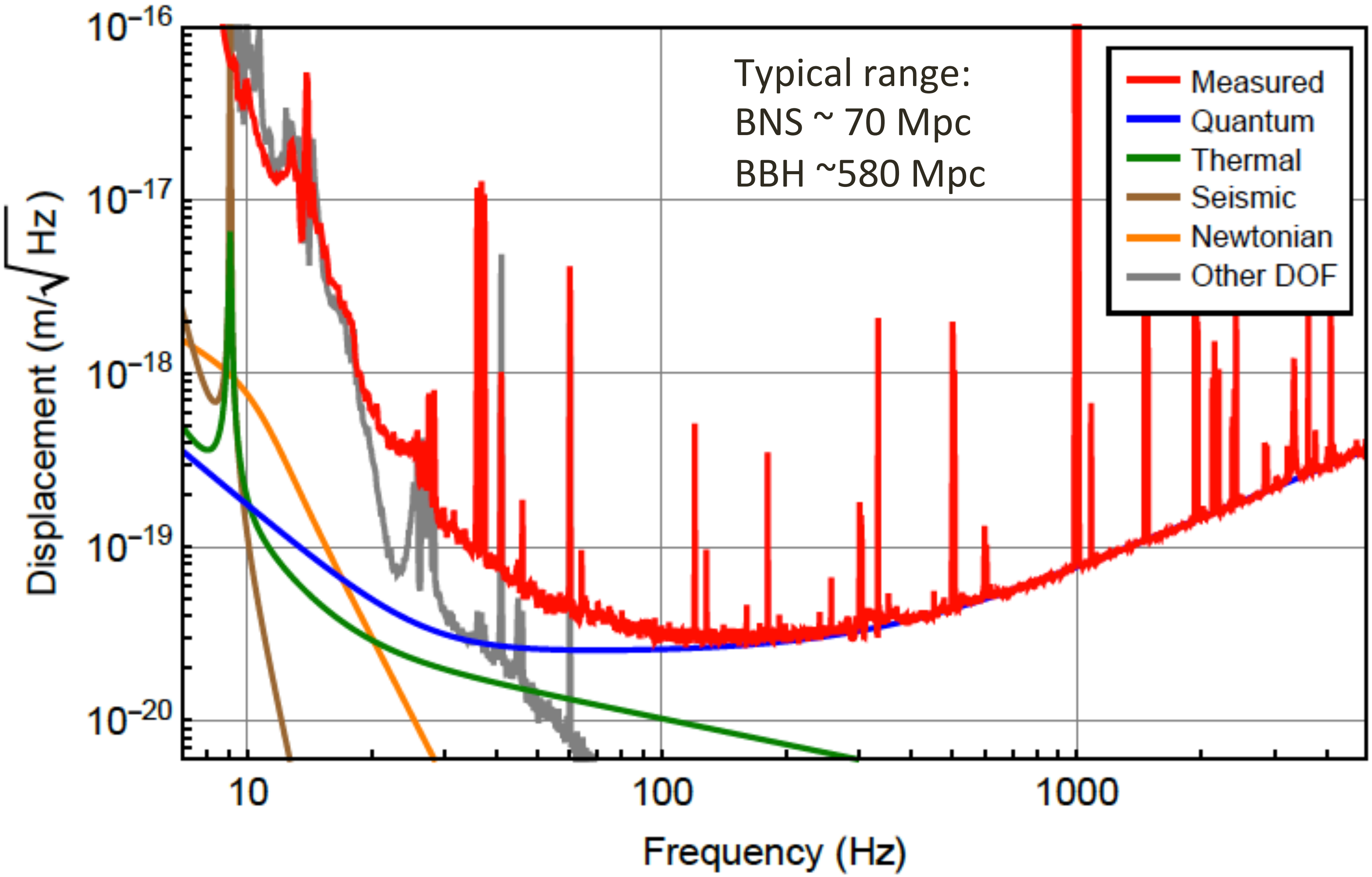
arXiv:1304.0670

Towards design sensitivity



arXiv:1304.0670

Observing run 1 (O1)



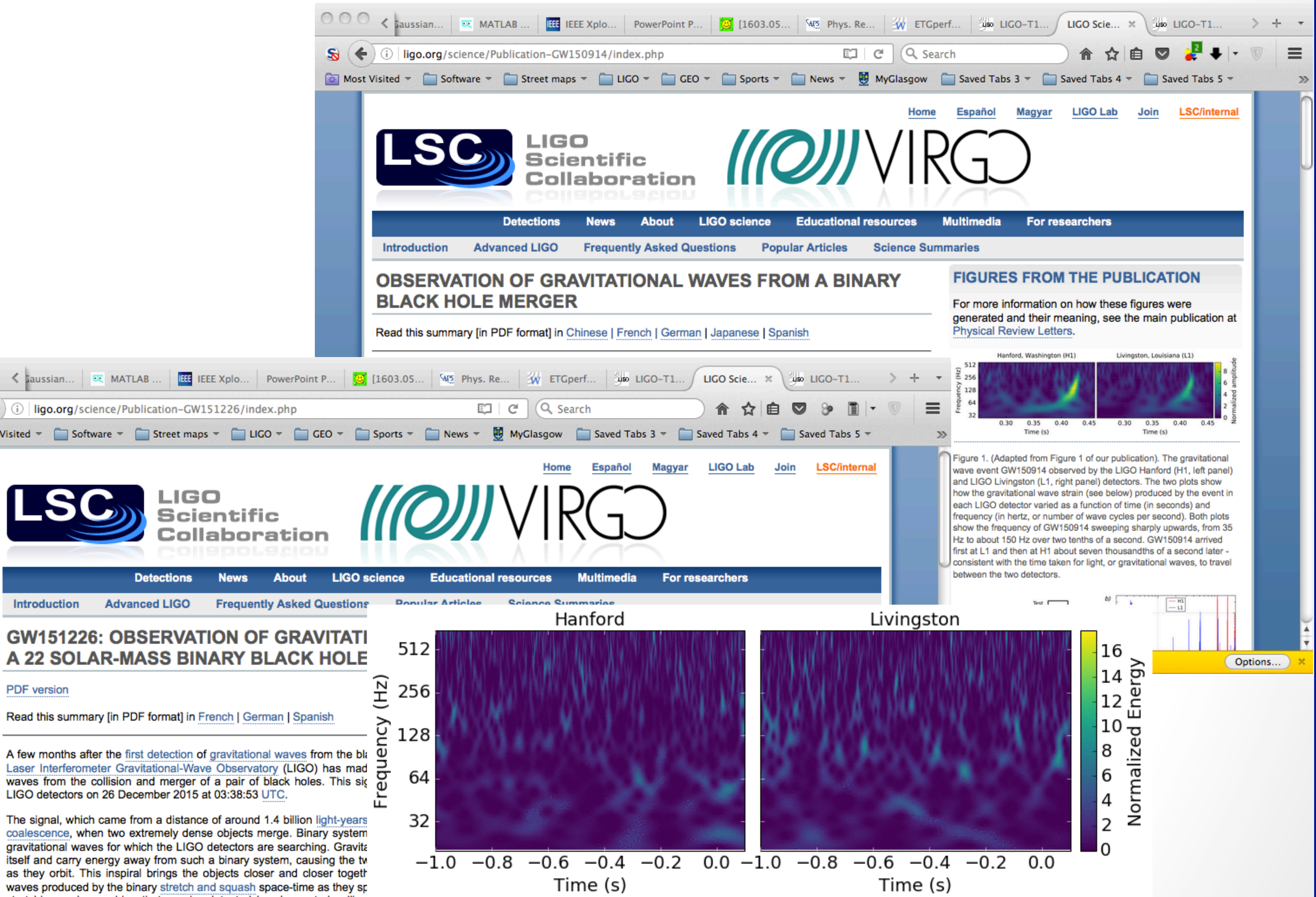
Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, Phys. Rev. Lett. 116, 131103 (2016).

Observing run 1 (O1)

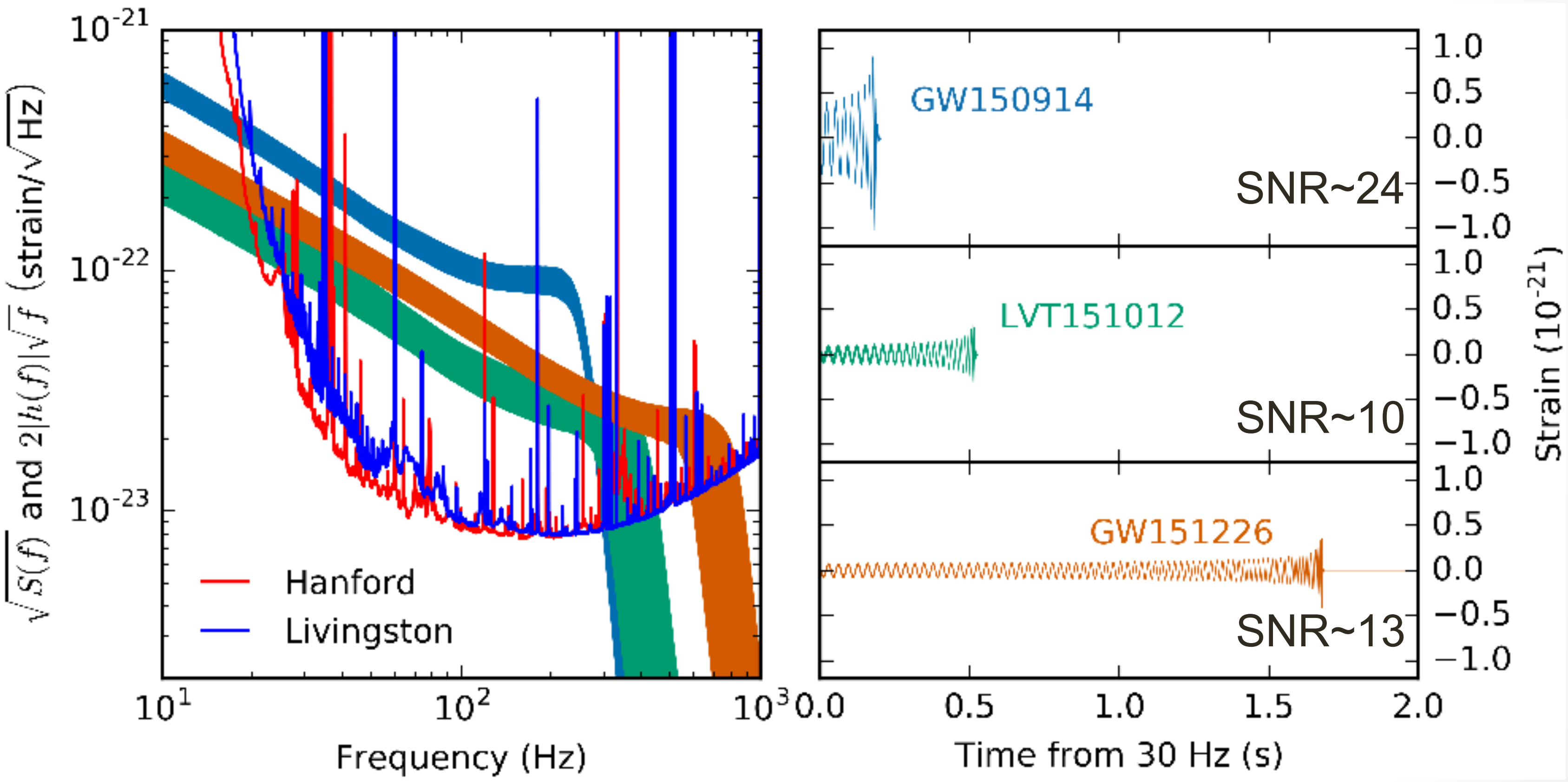
- Observing run 1 is the first science data taking run of Advanced LIGO
  - Sept 12, 2015 to Jan 19, 2016
  - Coincident observing time of ~51 days
- Sensitivity improvement of ~5 over initial LIGO
- Detected 2 gravitational wave signals from binary black hole coalescence and merger
  - plus one candidate 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

Science summaries

http://www.ligo.org/science/outreach.php



Binary black hole observations in O1

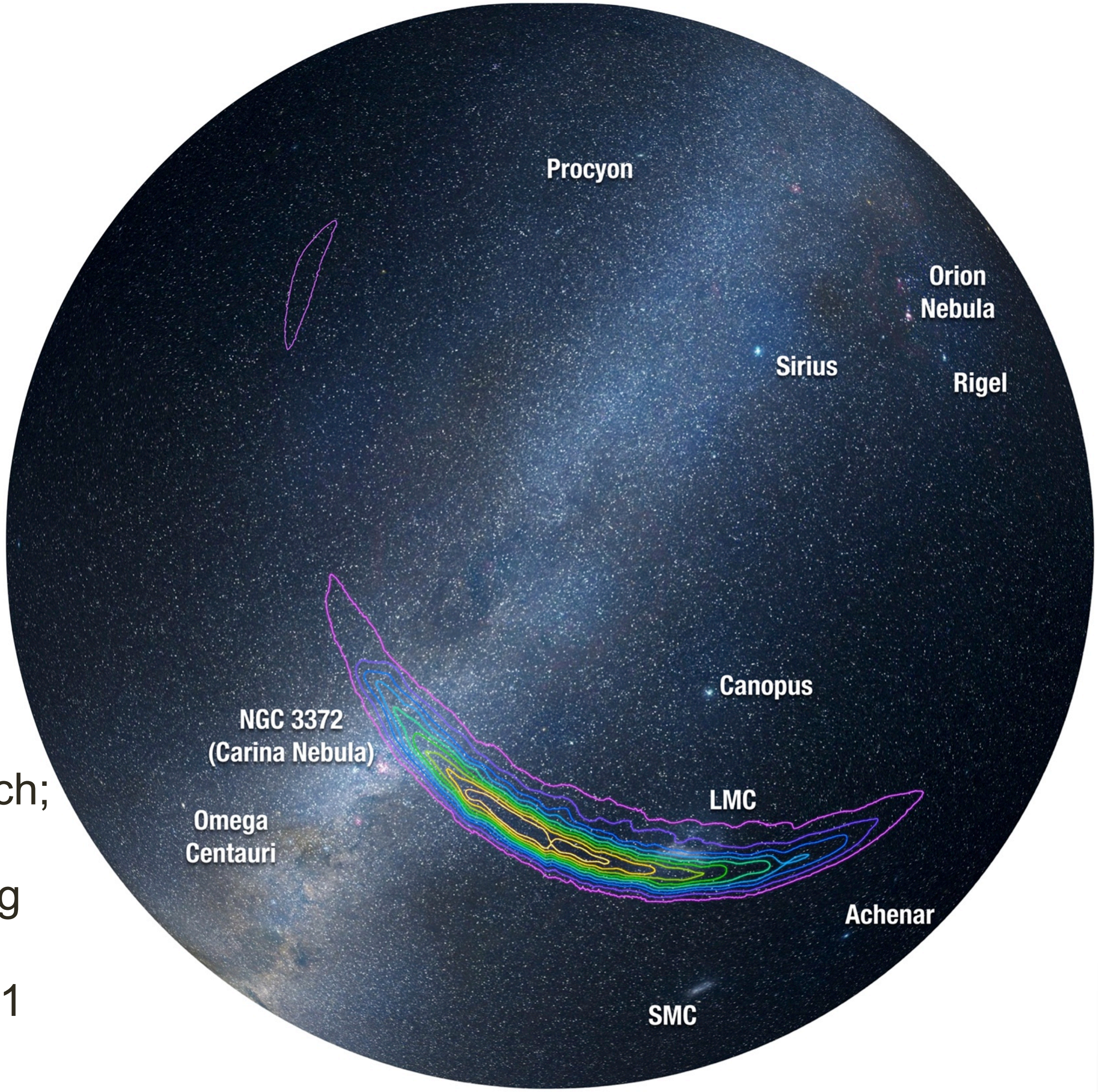


arXiv:1606.04856

Event	GW150914	GW151226	LVT151012
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 $\mathscr{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
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}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	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

modified version of table in arXiv:1606.04856

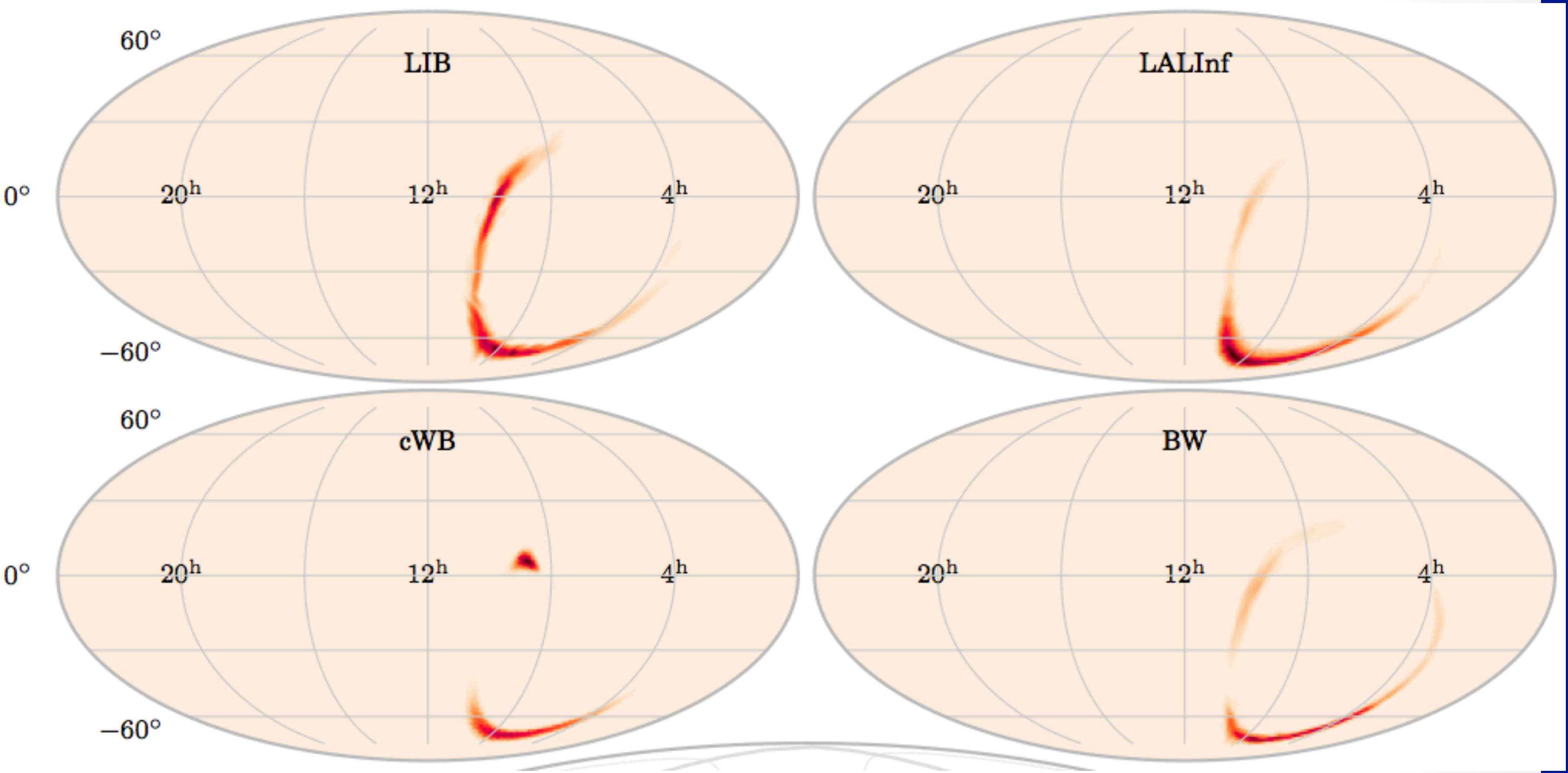
GW150914: sky location estimate



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

LIGO-D1600041

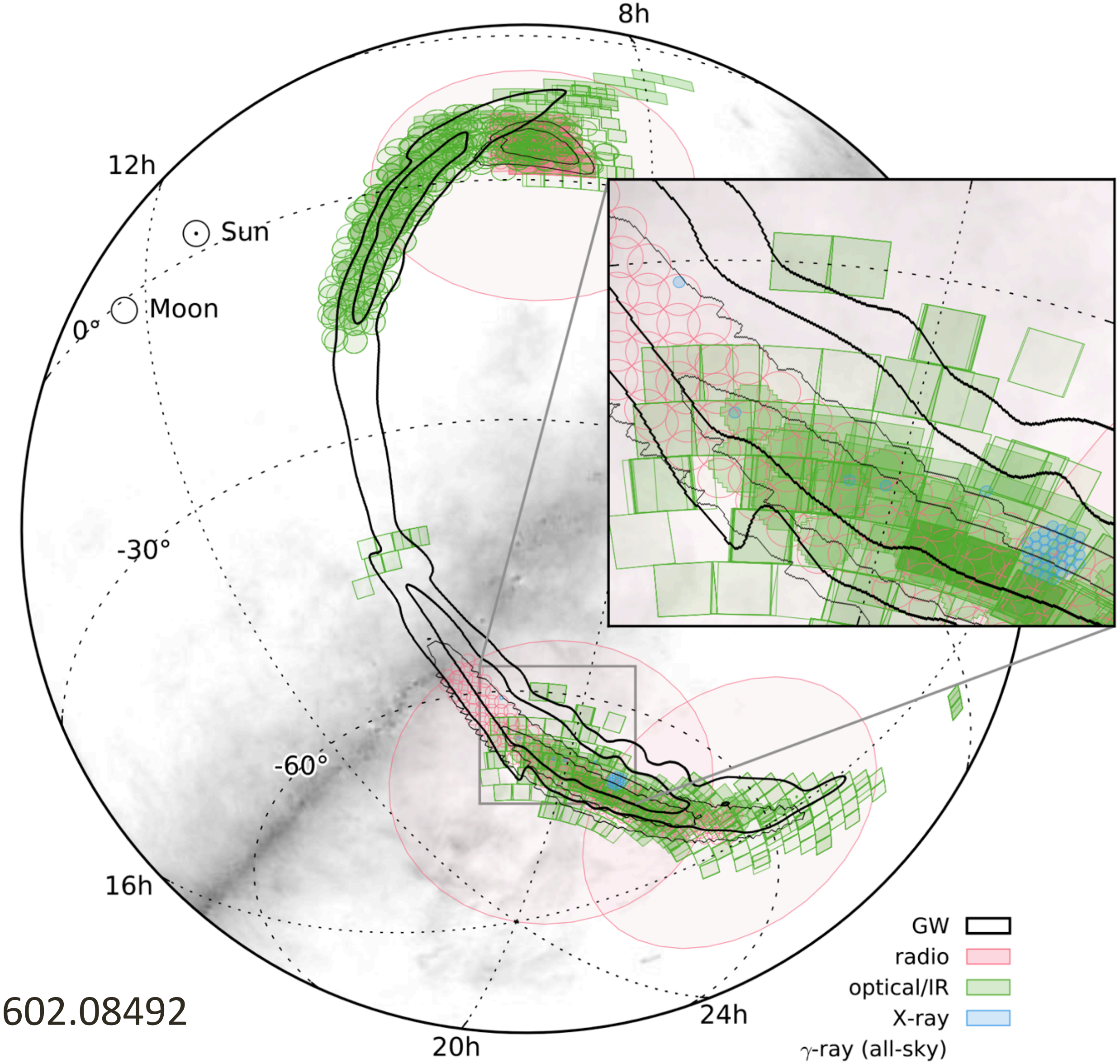
GW150914: Rapid source sky localisation



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

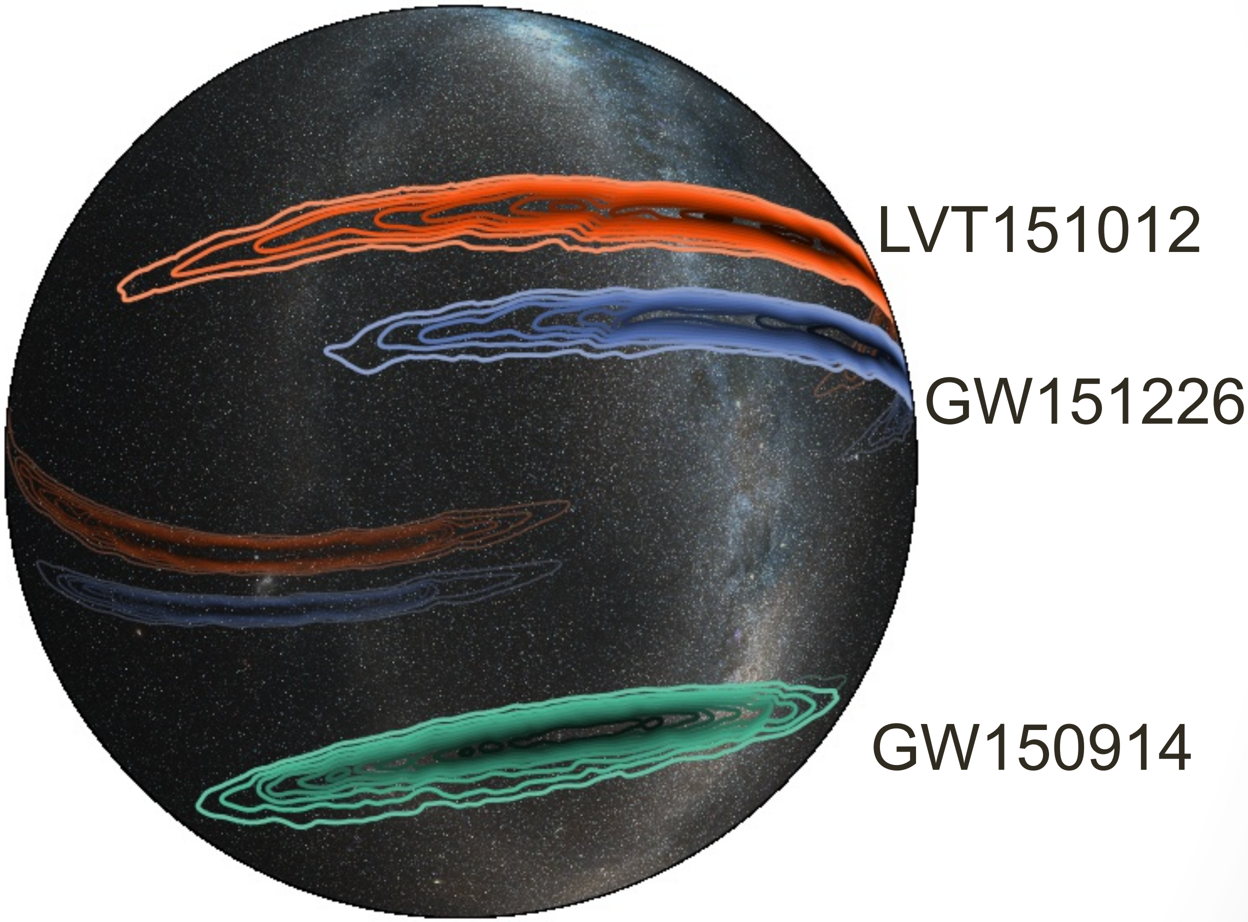
http://arxiv.org/abs/1602.03843

GW150914: search for counterparts



arXiv:1602.08492

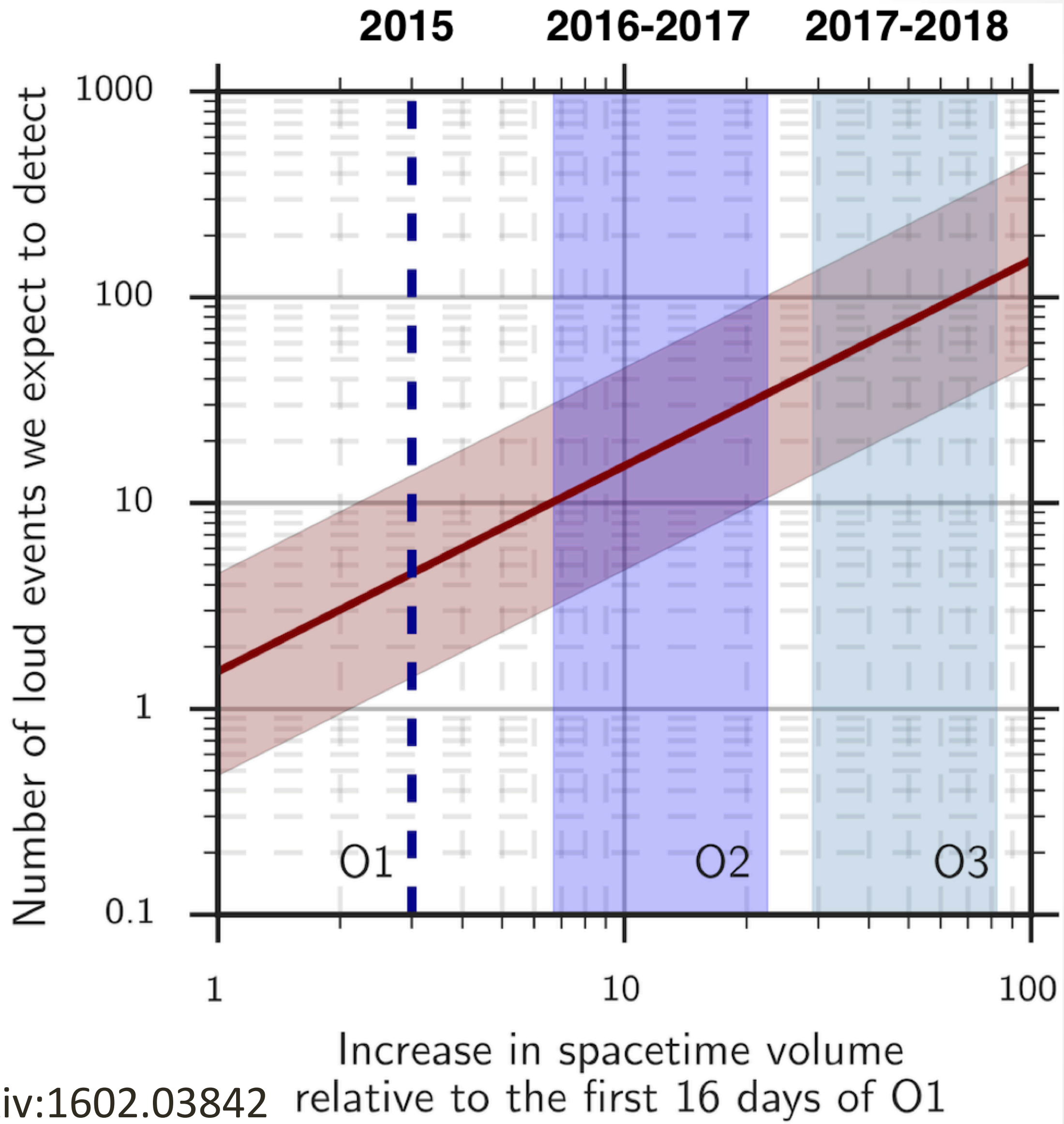
Sky location estimates



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

Prospects for next runs

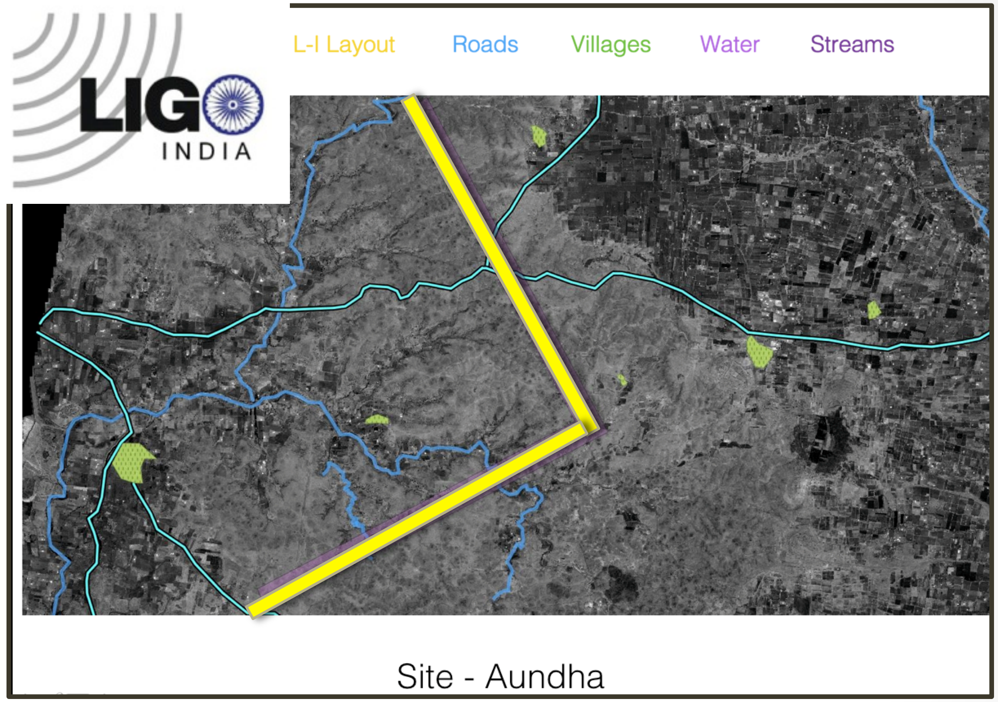
- The next Observing Runs target improved sensitivities and longer runs
- It is extremely likely that there will be many more binary black hole detections
- Also be searching for signals from binary neutron stars, unmodelled transients, stochastic background, rotating neutron stars, cosmic strings....

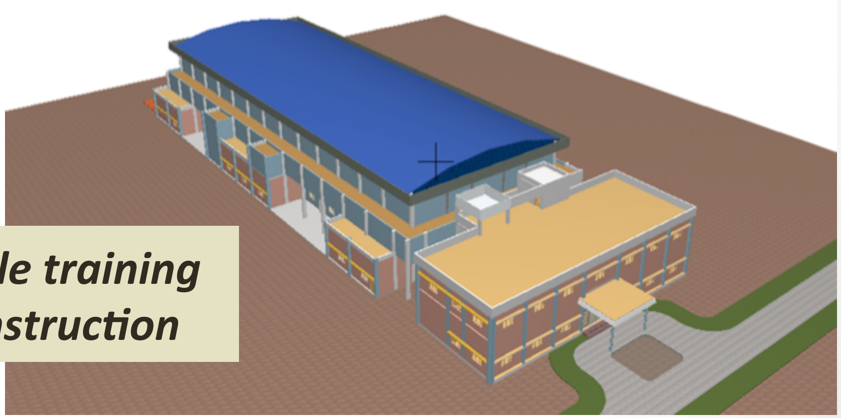


arXiv:1602.03842

LIGO India

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

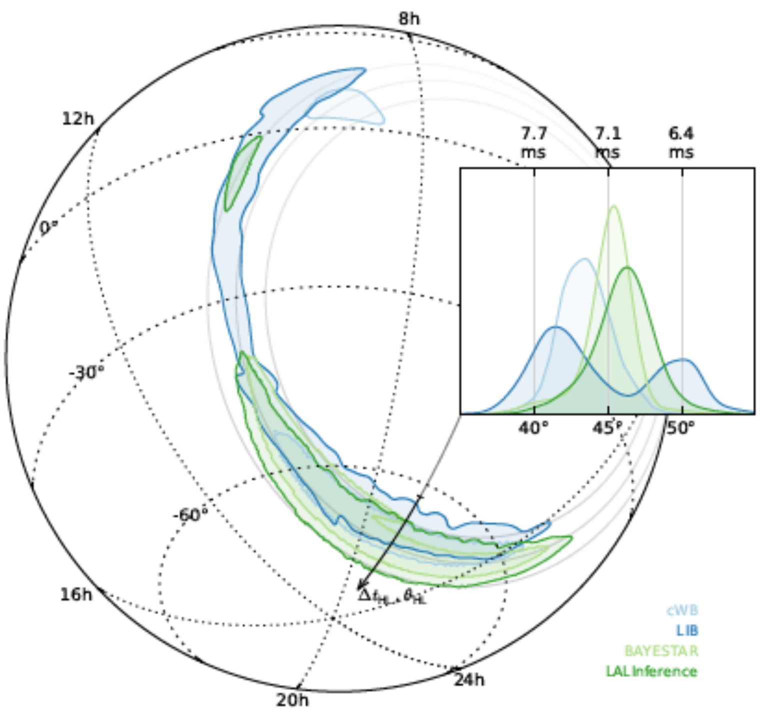




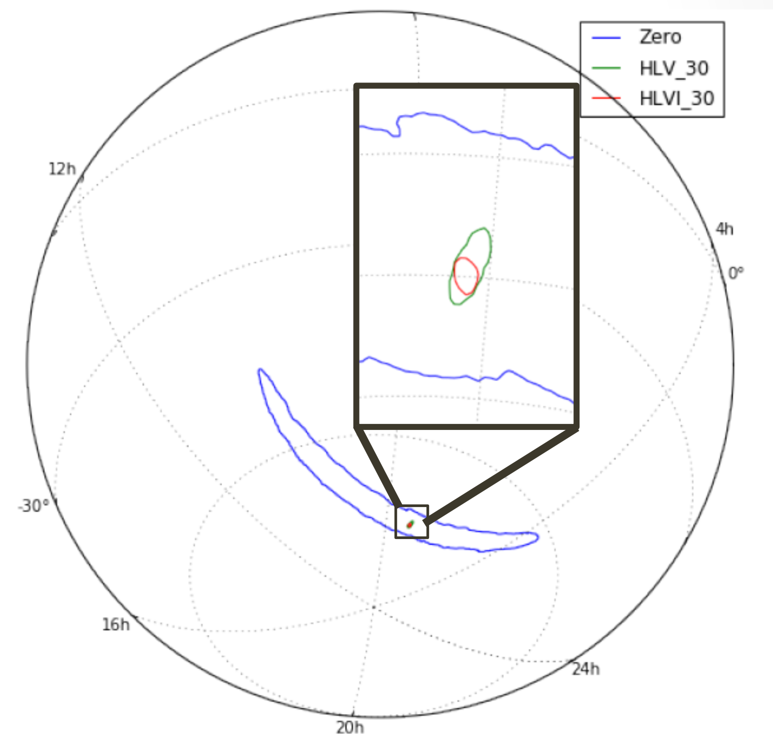
Off-site facility to enable training prior to LIGO-India construction

Improved sky localisation

GW150914: LIGO only

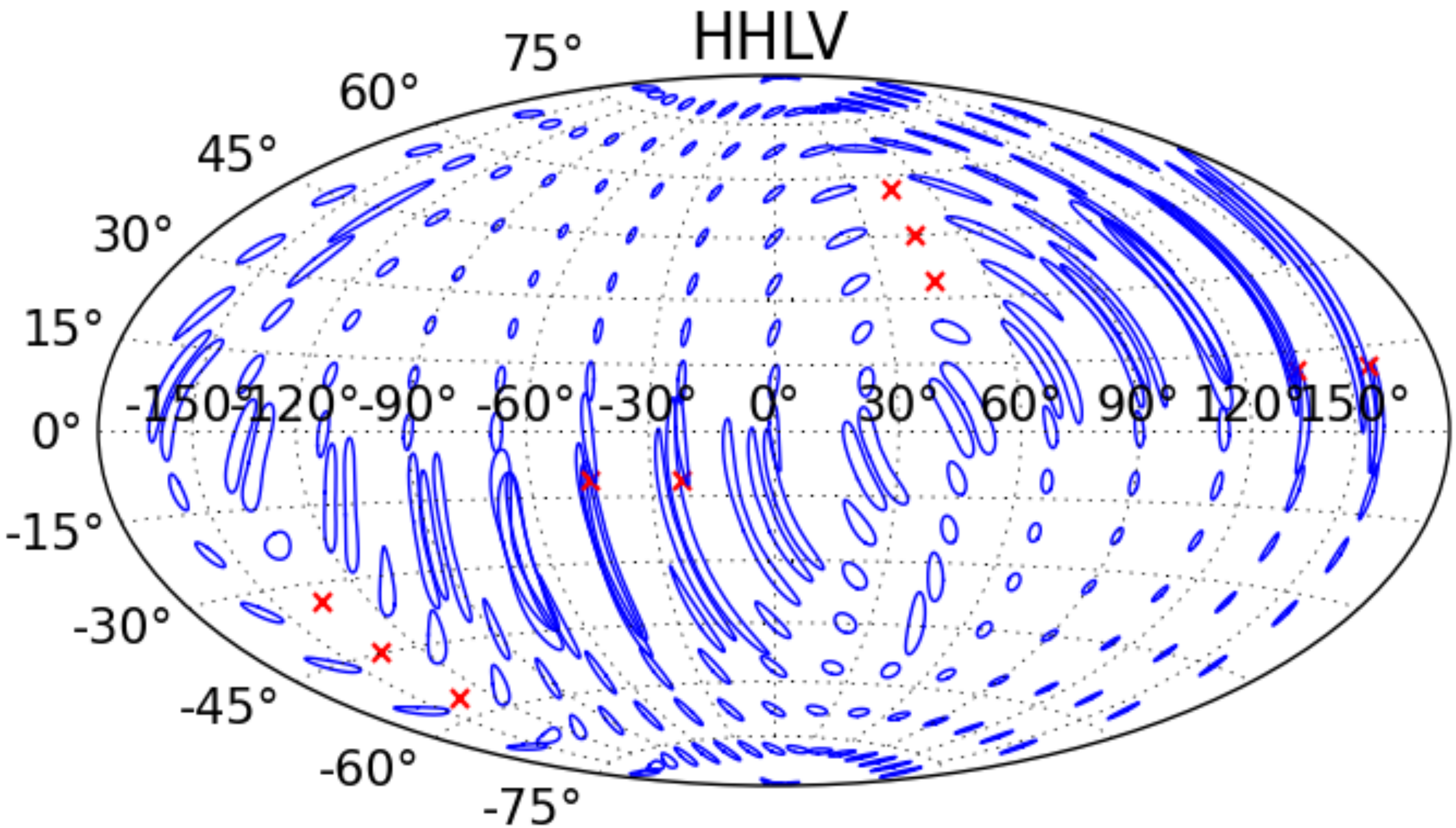


GW150914: LIGO → LV → LVI
(Preliminary)



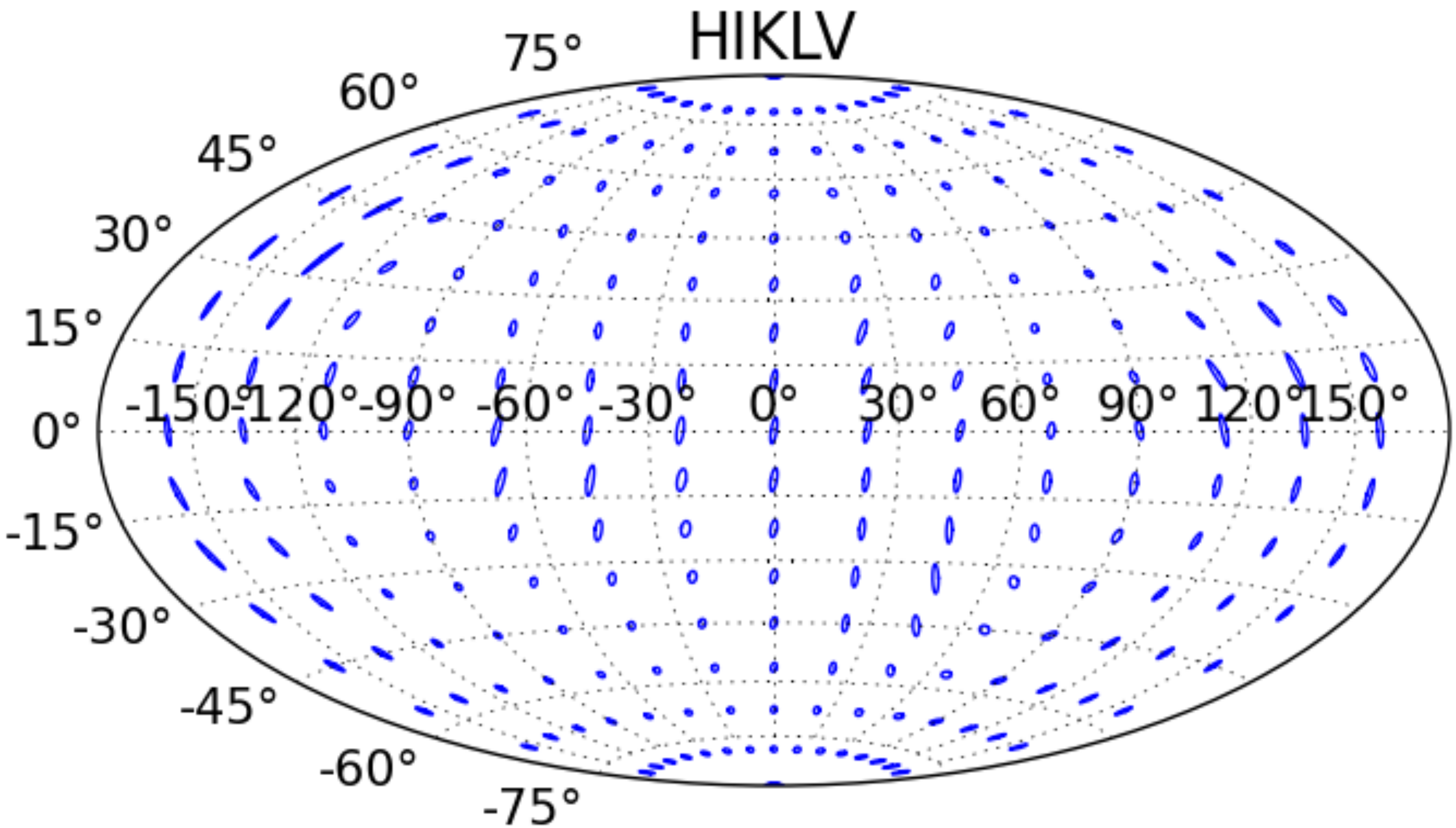
375° → 9.3° → 7.8°
(99% confidence level)

Sky localisation with 3 detector sites



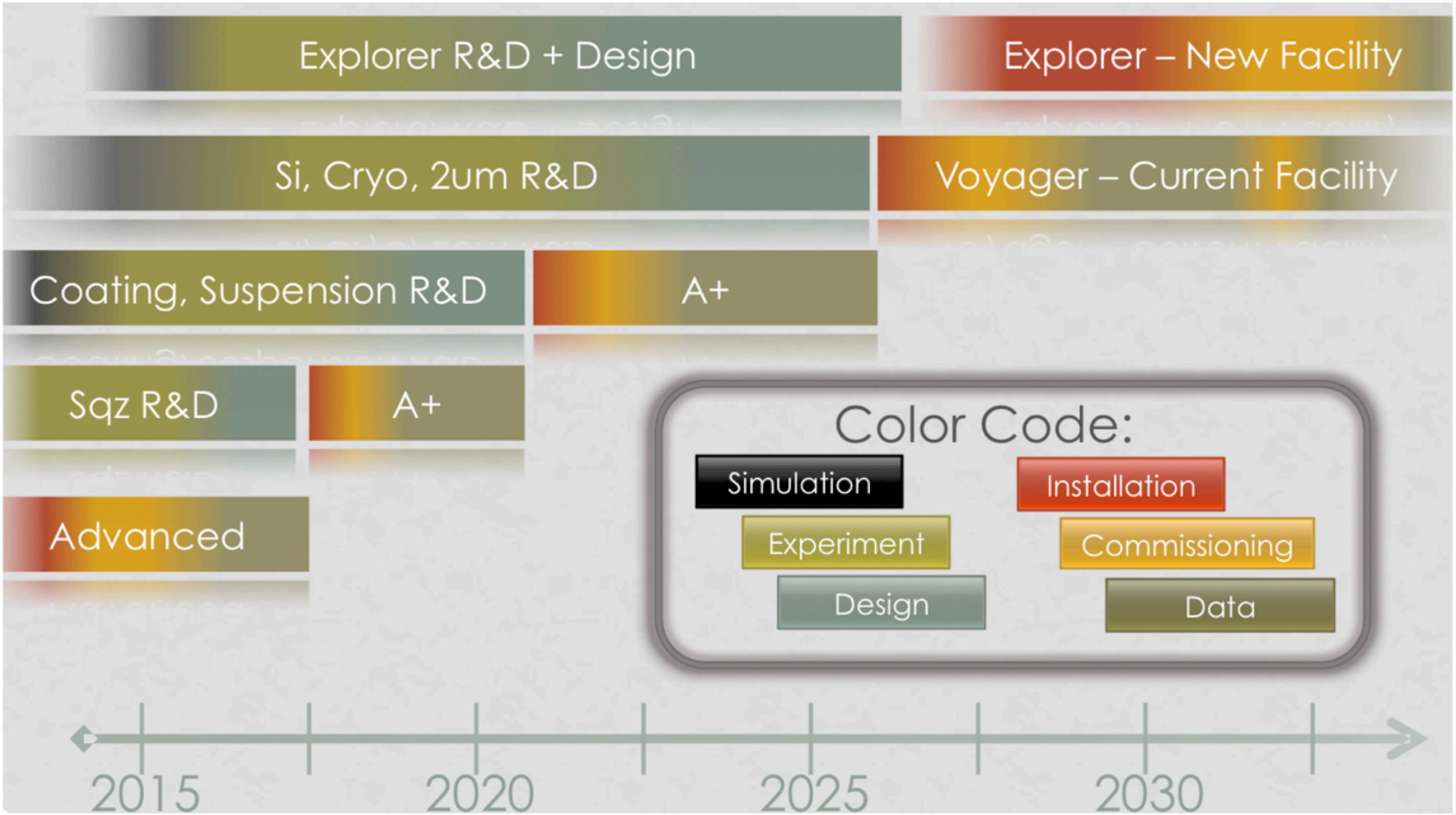
S. Fairhurst, “*Improved source localization with LIGO India*”, arXiv:1205.6611v1

Sky localisation with 5 detector sites



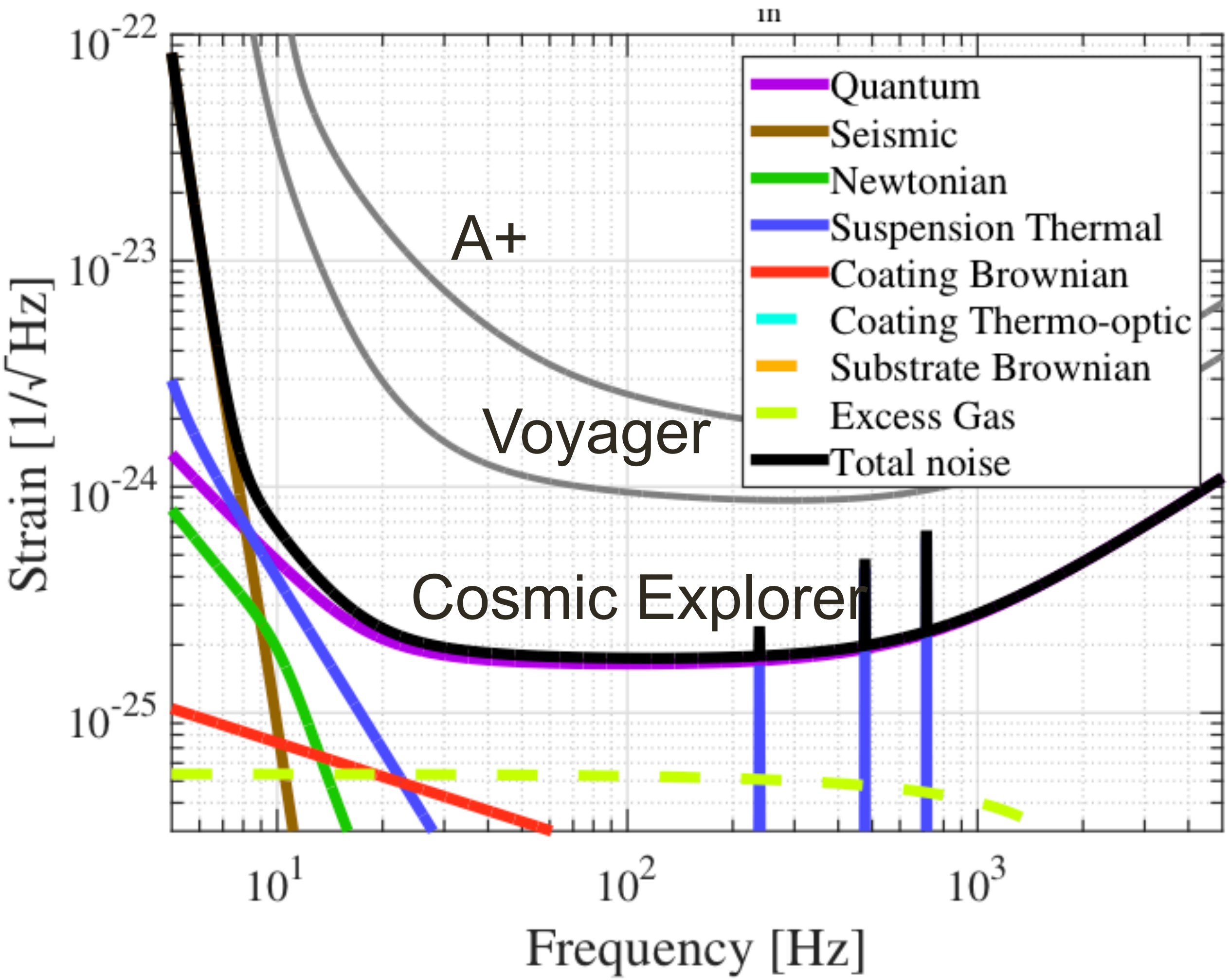
S. Fairhurst, "*Improved source localization with LIGO India*", arXiv:1205.6611v1

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~13

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

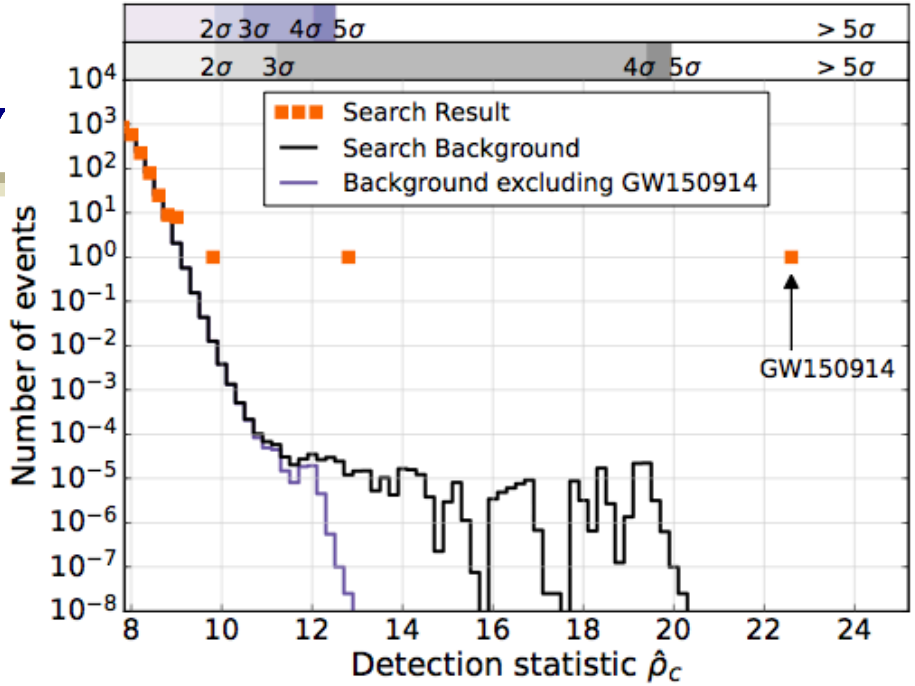
Science questions to be answered

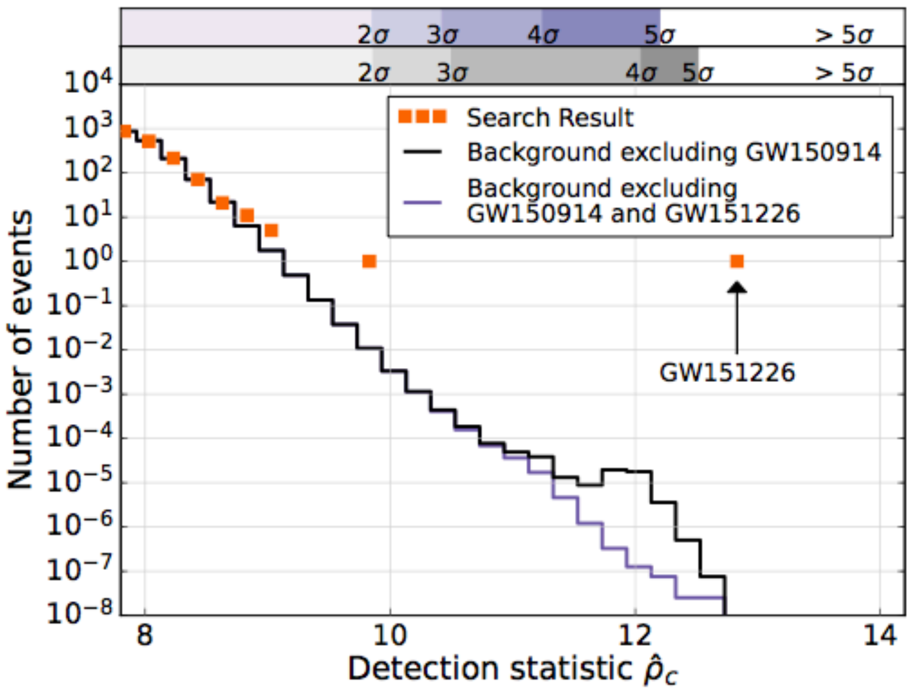
- Fundamental Physics
  - Is the nature of gravitational radiation as predicted by Einstein?
  - Are nature's black holes the black holes of general relativity?
  - What is the equation of state of ultra dense matter in neutron stars?
- Astrophysics
  - What is the central engine behind gamma-ray bursts?
  - 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

Binary … ns in O1





EM partners