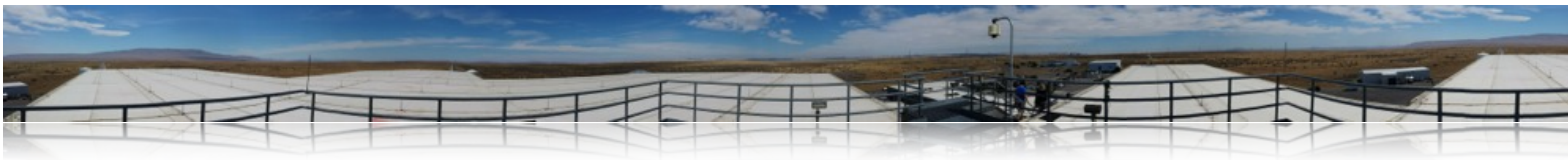
Second Generation Gravitational-Wave Observatories



Leonard E. Parker
Center for Gravitation
Cosmology and Astrophysics

UNIVERSITY of WISCONSIN
UWMILWAUKEE

Chris Pankow
(University of Wisconsin–Milwaukee)

for the **LIGO Scientific Collaboration**
and **Virgo Collaboration**

LSC

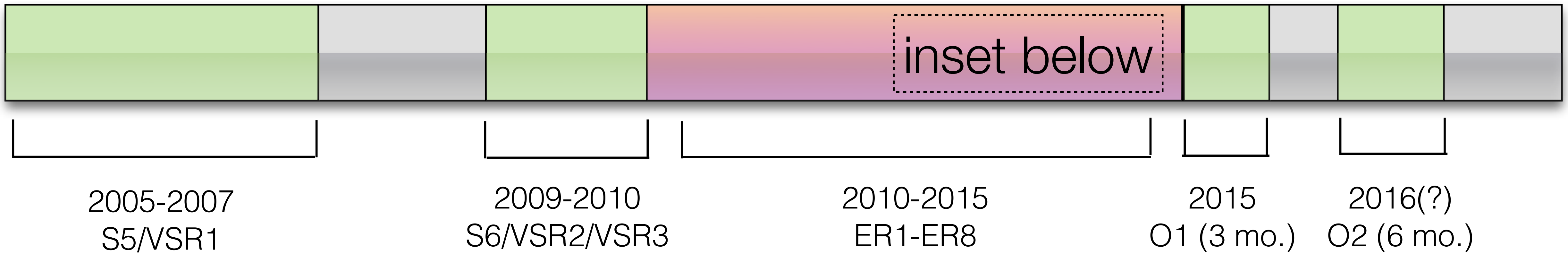
VIRGO

Rencontres du Vietnam
August 8th, 2014

LIGO G1400721 v3

Who We Are

- Collaboration of nearly 1000 scientists, engineers, and researchers with ~100 institutions on four continents developing and operating a combined four laser interferometer gravitational-wave detectors
- Original construction began in late 90s, increasing sensitivity through early 2000s — first generation ("initial") design sensitivity ($\Delta L/L \sim 10^{-23}$ @ 200 Hz) reached in 2005
- Initial LIGO detectors decommissioned in 2010, Virgo soon thereafter, upgrades aiming to incrementally approach a x10 increase in sensitive range as well as broader frequency sensitivity over the next three years
- About 8 combined years (~3 years of coincidence) worth of observational data
- Perform searches for gravitational waves from compact binaries, deformations of neutron stars, stochastic background, supernovas, GRBs, etc...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2010-2015
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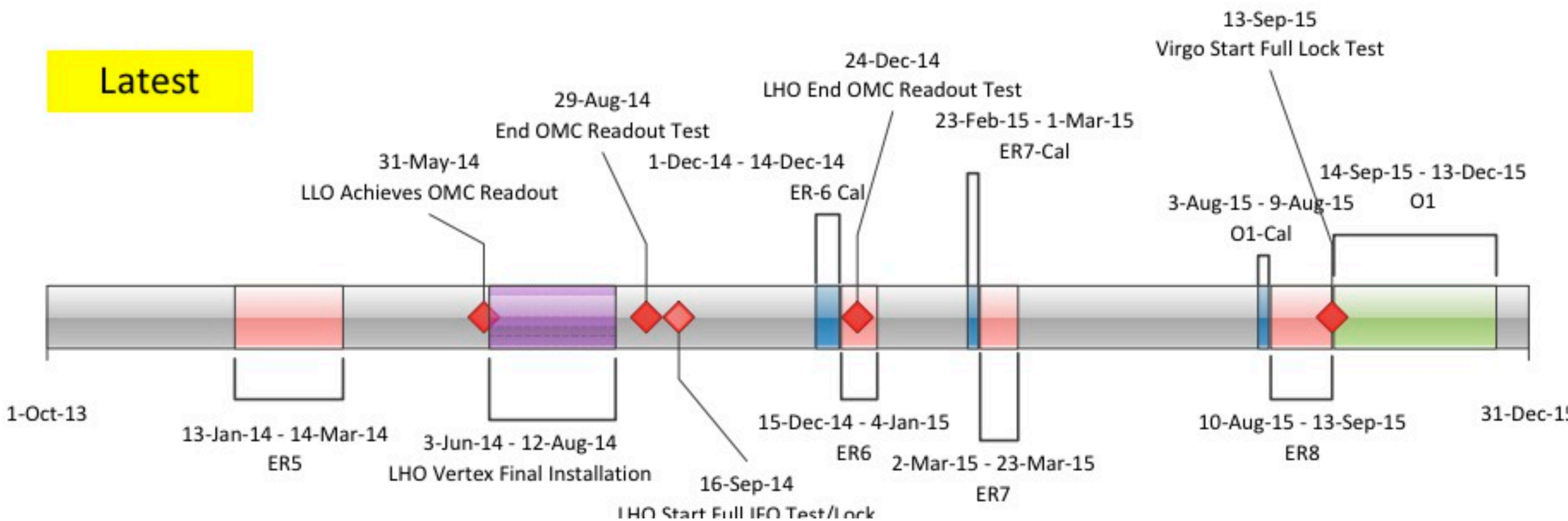
2015
O1 (3 mo.)
2016(?)
O2 (6 mo.)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ER8
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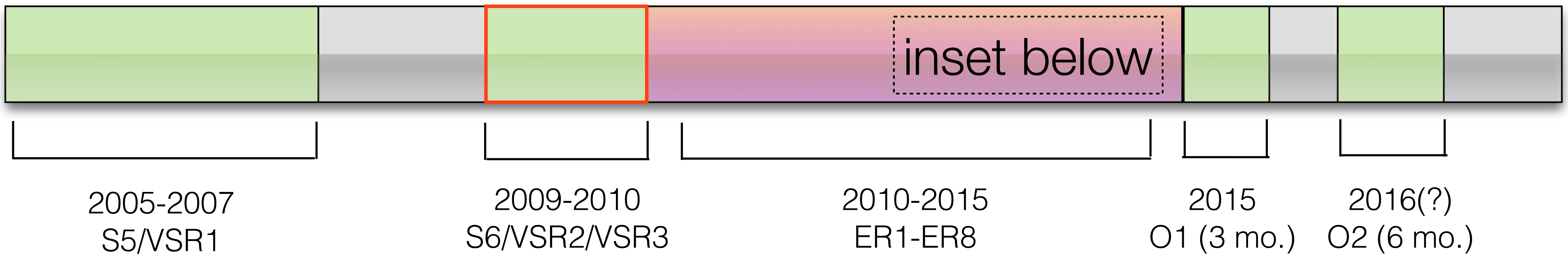

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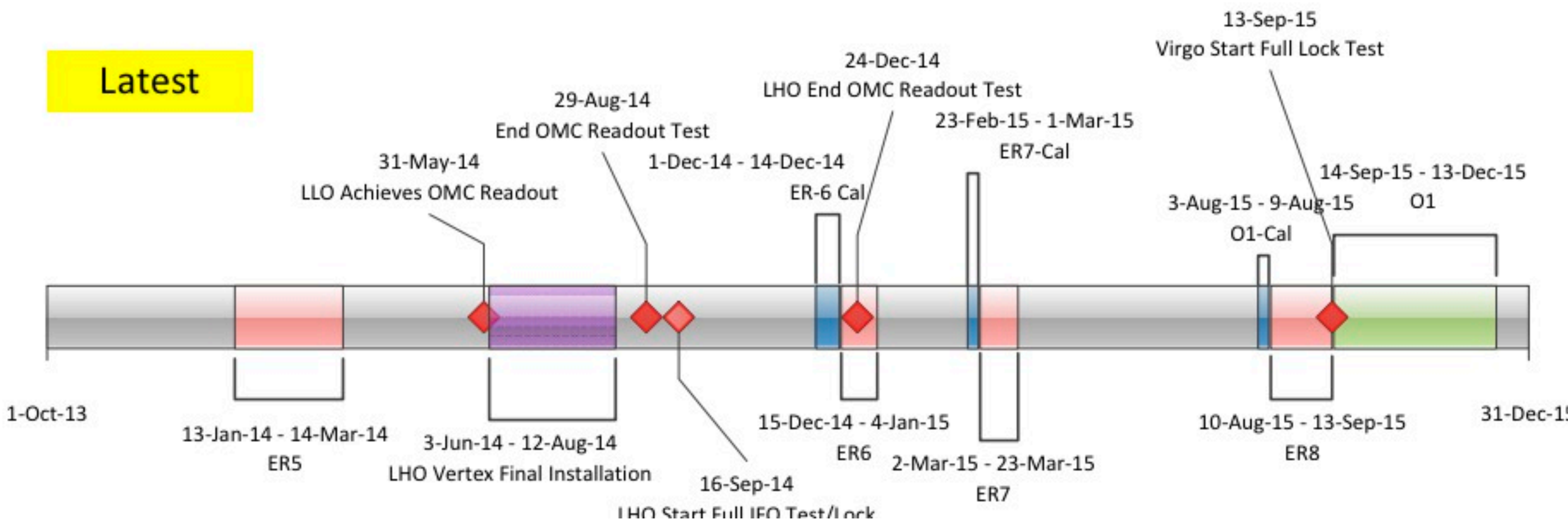

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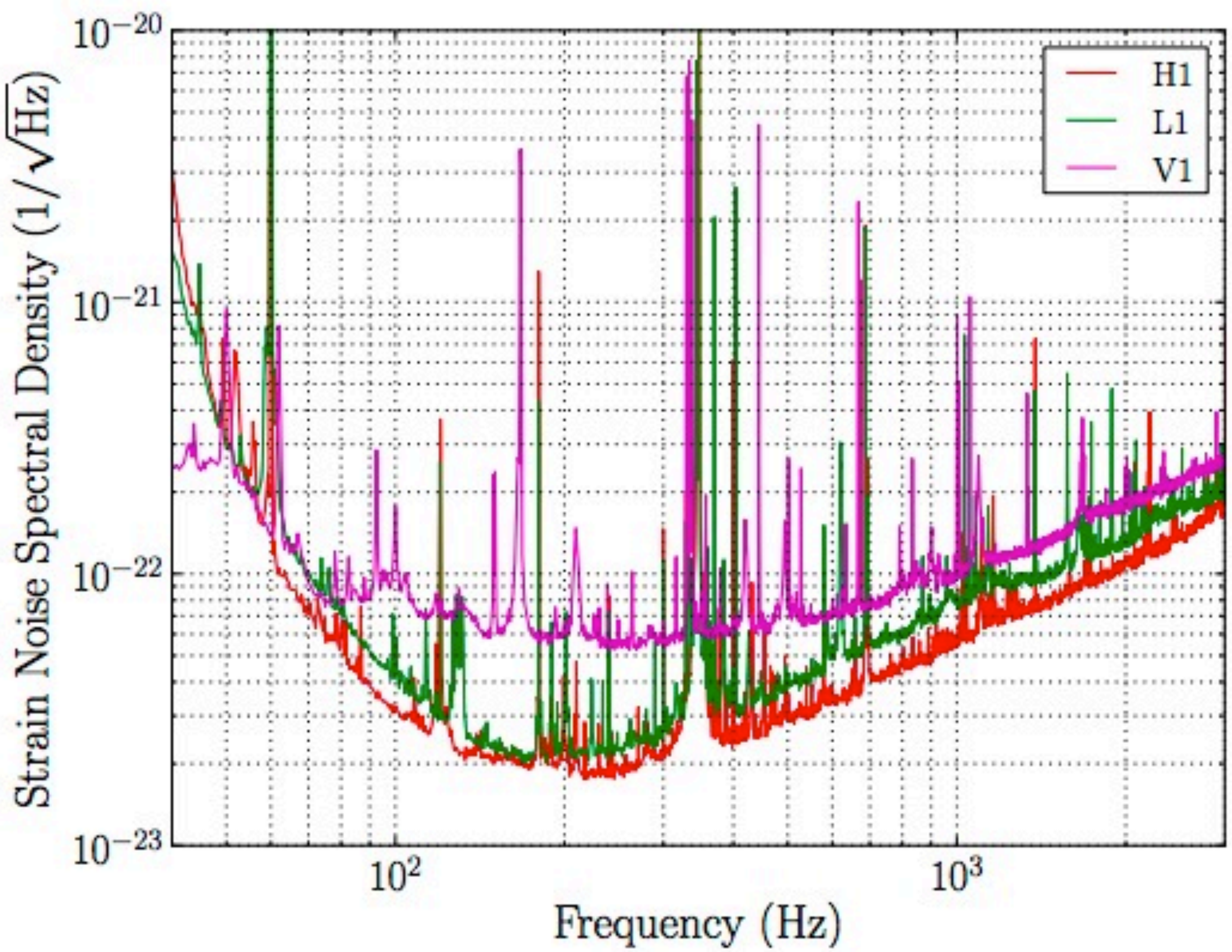
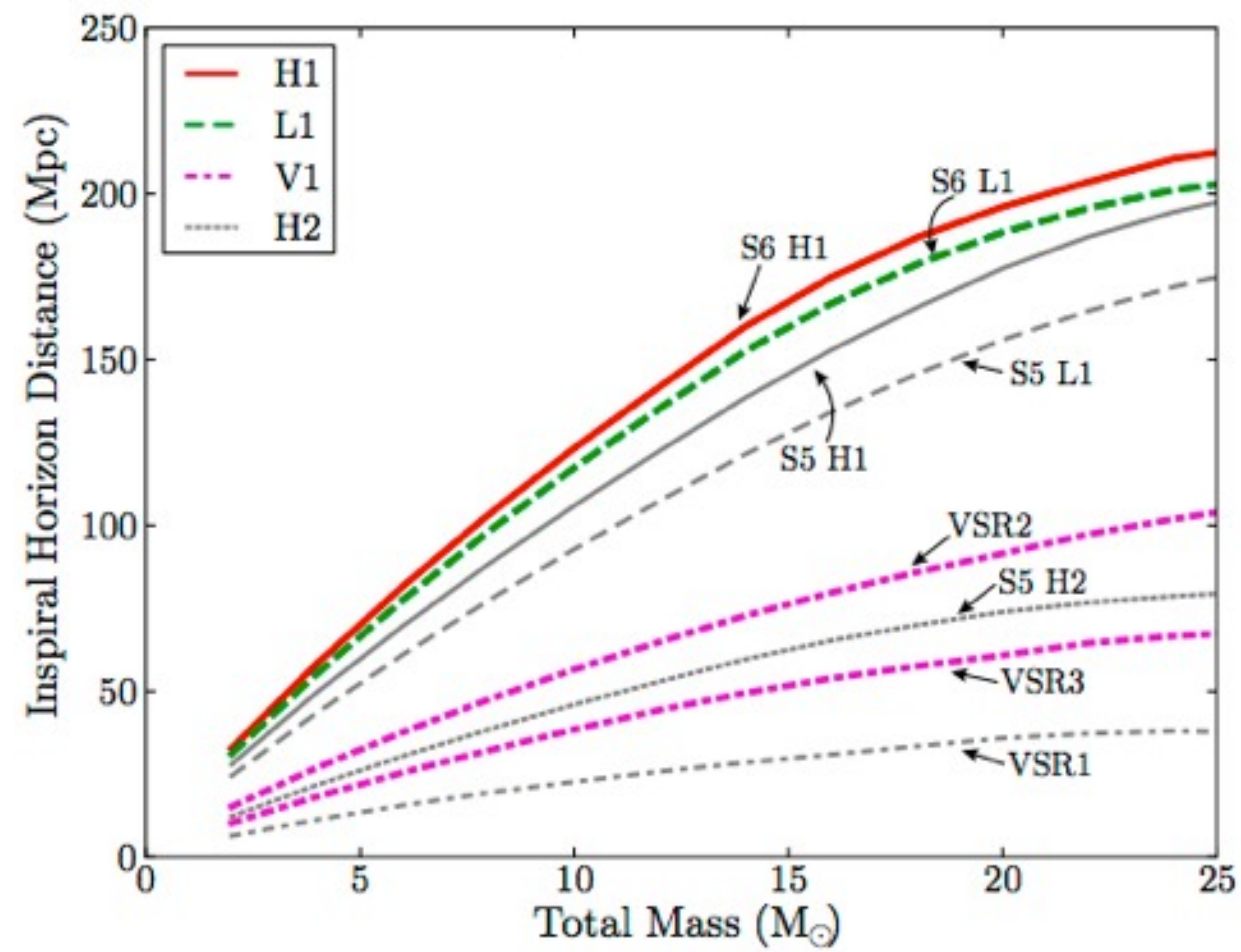
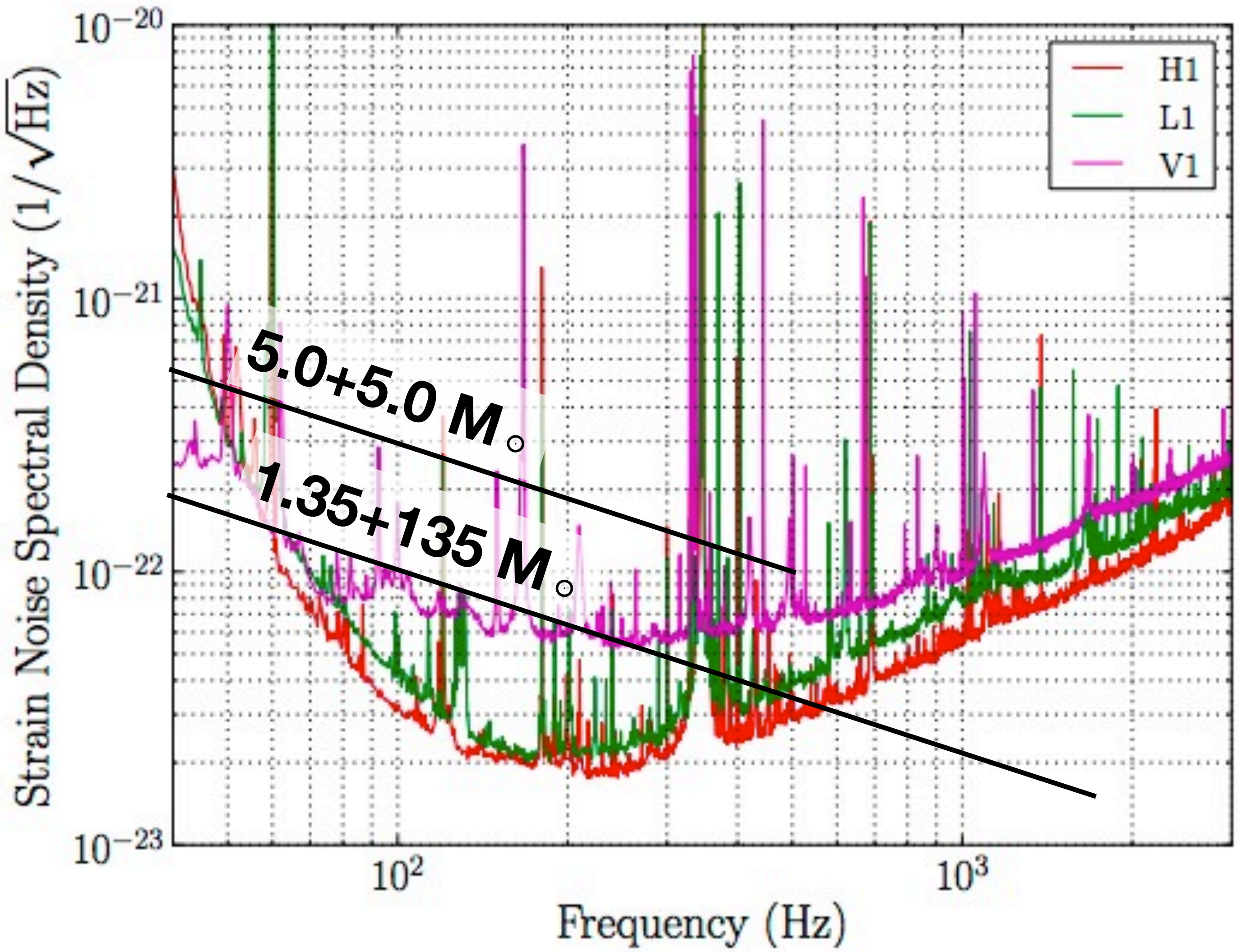
S6/VSR2/3 Sensitivity

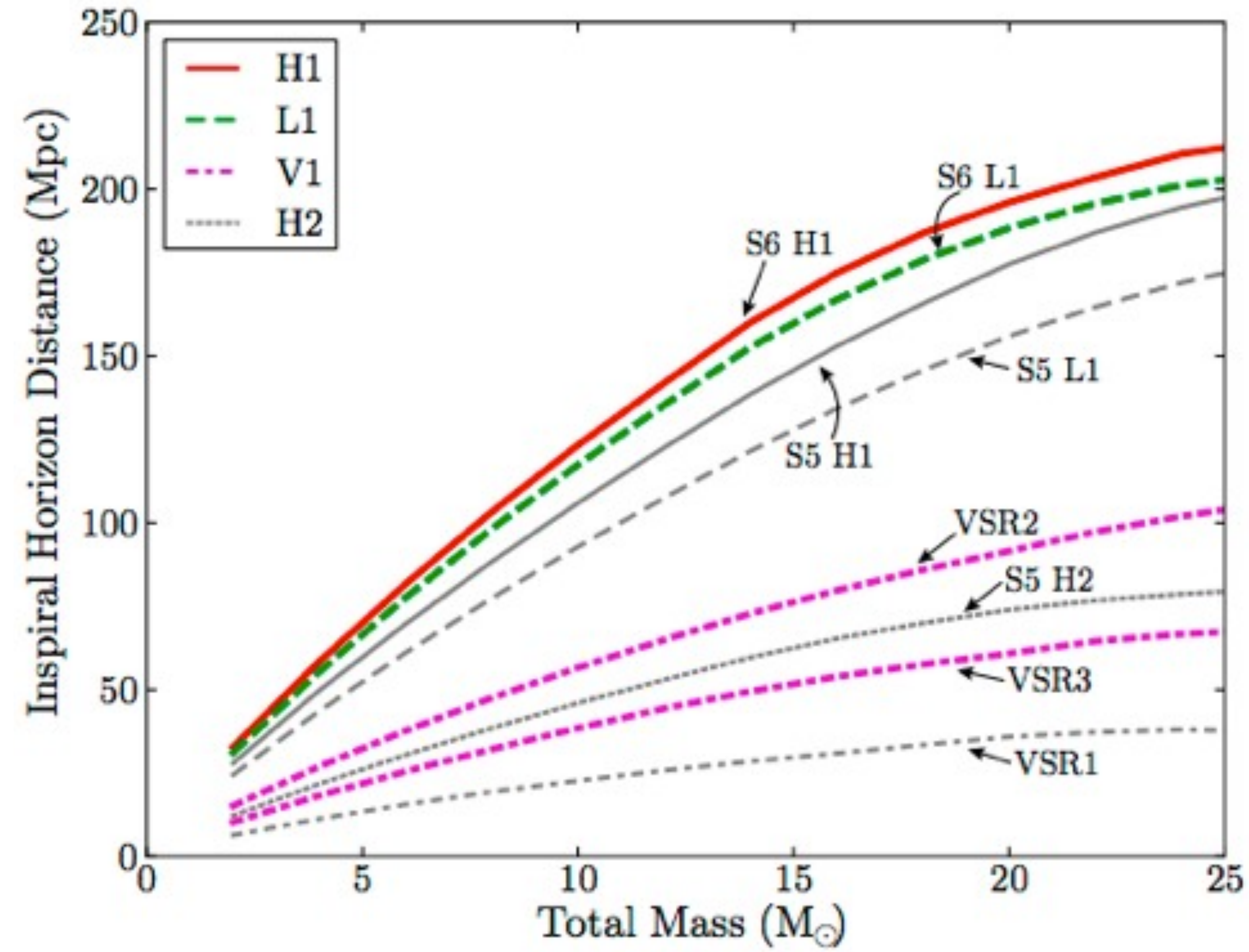




Horizon Distance: Distance to optimally oriented SNR 8 binary coalescence

S6/VSR2/3 Sensitivity





Horizon Distance: Distance to optimally oriented SNR 8 binary coalescence

LSC VIRGO

S6/VSR2/VSR3 Review

source (non-spinning)	current upper limit	predicted rate
neutron star binaries (1.35 + 1.35 $M_\odot$)	1.3×10^{-4} Mpc^{-3} yr^{-1}	10^{-6} Mpc^{-3} yr^{-1}
stellar mass BH binaries (5 + 5 $M_\odot$)	6.4×10^{-6} Mpc^{-3} yr^{-1}	5×10^{-9} Mpc^{-3} yr^{-1}
mixed binaries (1.35 + 5 $M_\odot$)	3.1×10^{-5} Mpc^{-3} yr^{-1}	3×10^{-8} Mpc^{-3} yr^{-1}
"high stellar mass" BH binaries (50 + 50 $M_\odot$)	7×10^{-8} Mpc^{-3} yr^{-1}	—
intermediate mass BH binaries (center of 88 + 88 $M_\odot$)	1.2×10^{-7} Mpc^{-3} yr^{-1}	3×10^{-10} Mpc^{-3} yr^{-1}
ringdowns (BH merger, q=1:4, M_T=125 $M_\odot$)	1.1×10^{-7} Mpc^{-3} yr^{-1}	3×10^{-10} Mpc^{-3} yr^{-1}
generic short-duration transient (BH merger, supernova, etc...)	1.3 yr^{-1}	—

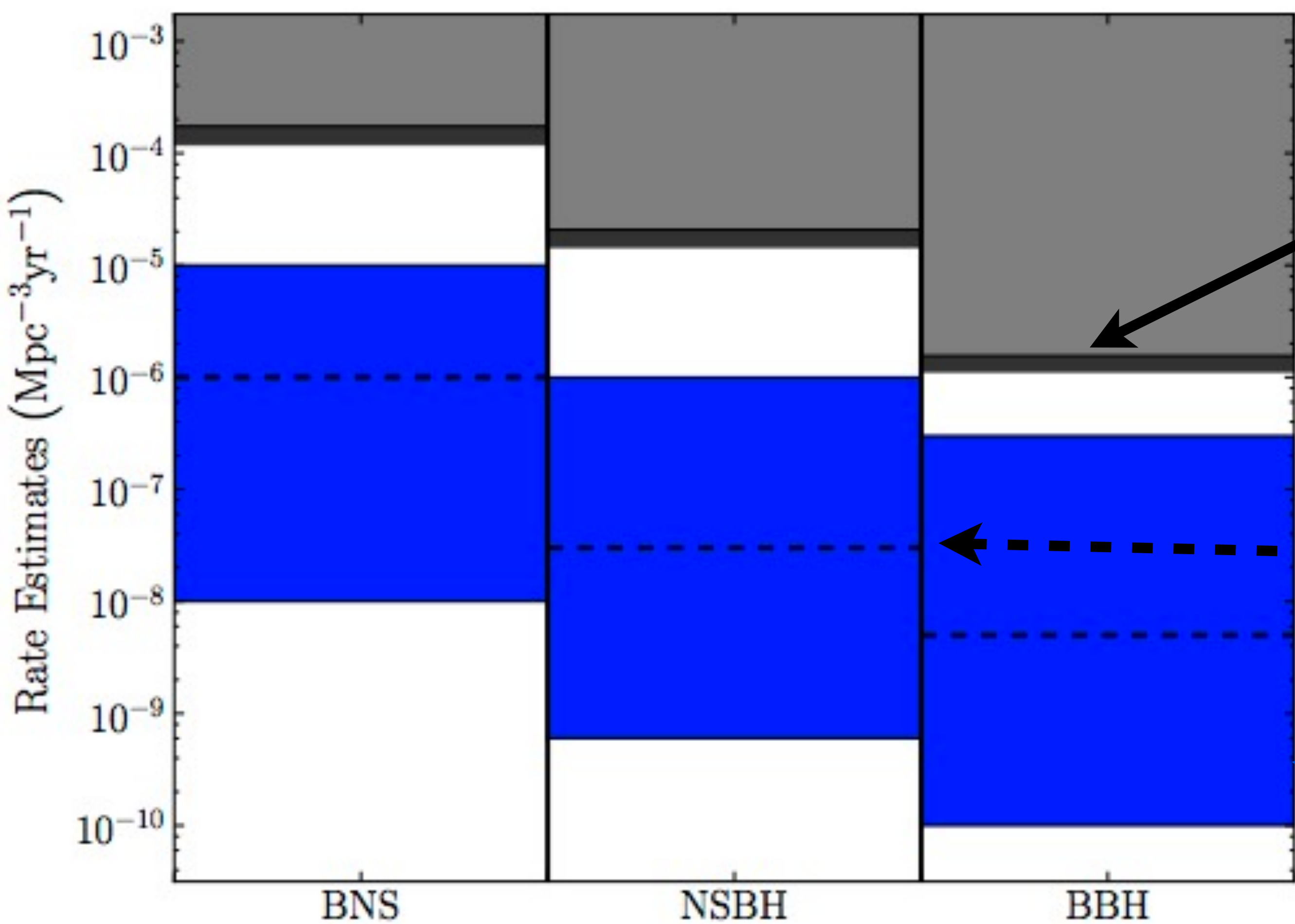
Phys. Rev. D 85 082002
Phys. Rev. D 87 022002

Phys. Rev. D 89 122003
Phys. Rev. D 89 102006

Phys. Rev. D 85 122007

Compact Binary Upper Limits

- Still a few orders of magnitude away from expected astrophysical rates

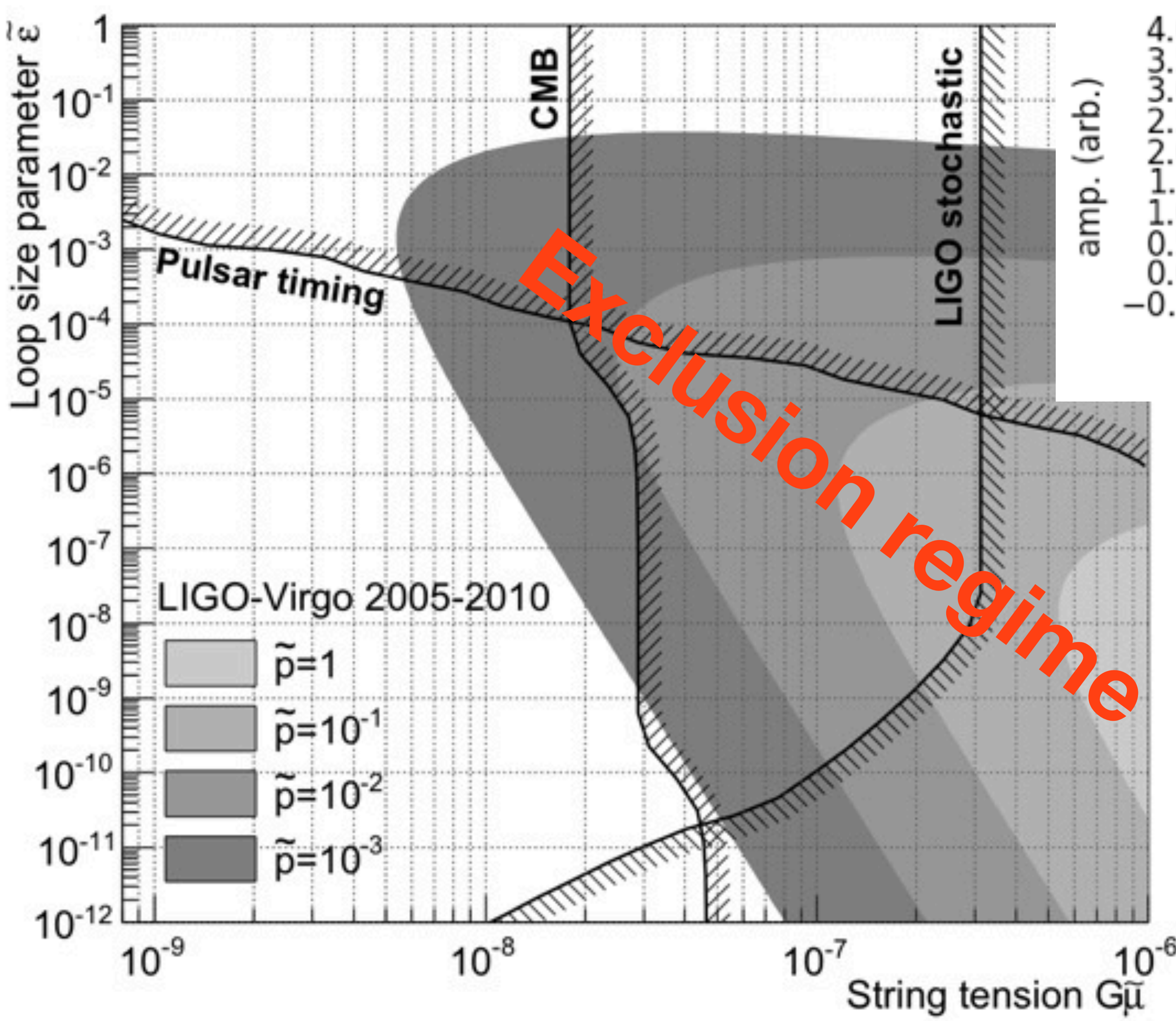


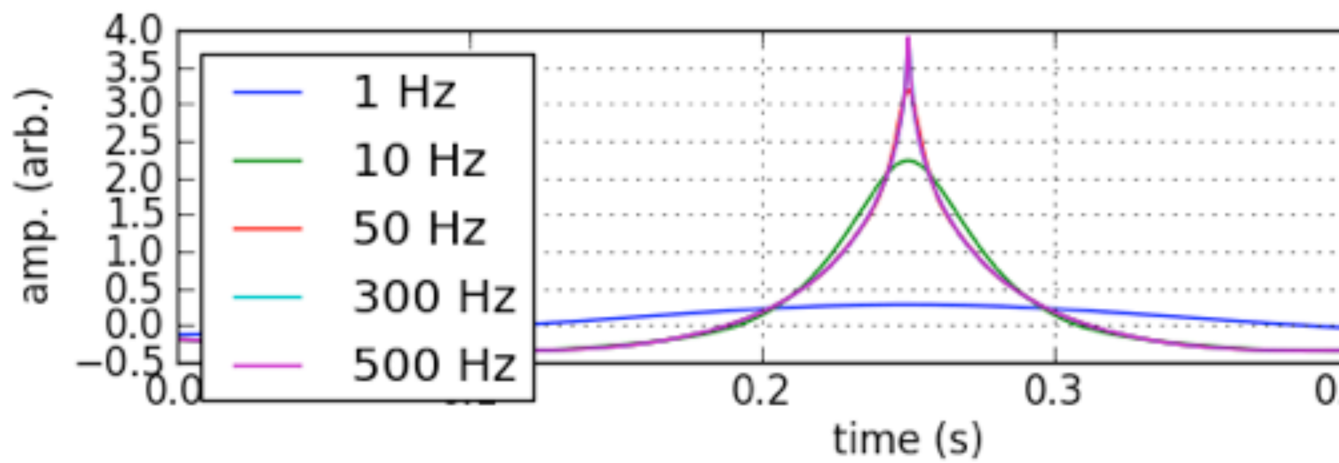
Current LIGO-Virgo established upper limits

Expected Event Rate with "Error Bars"

Cosmic Strings

- Formed via phase transitions in the early universe giving rise to topological defects; string theory also provides creation mechanisms (superstrings)



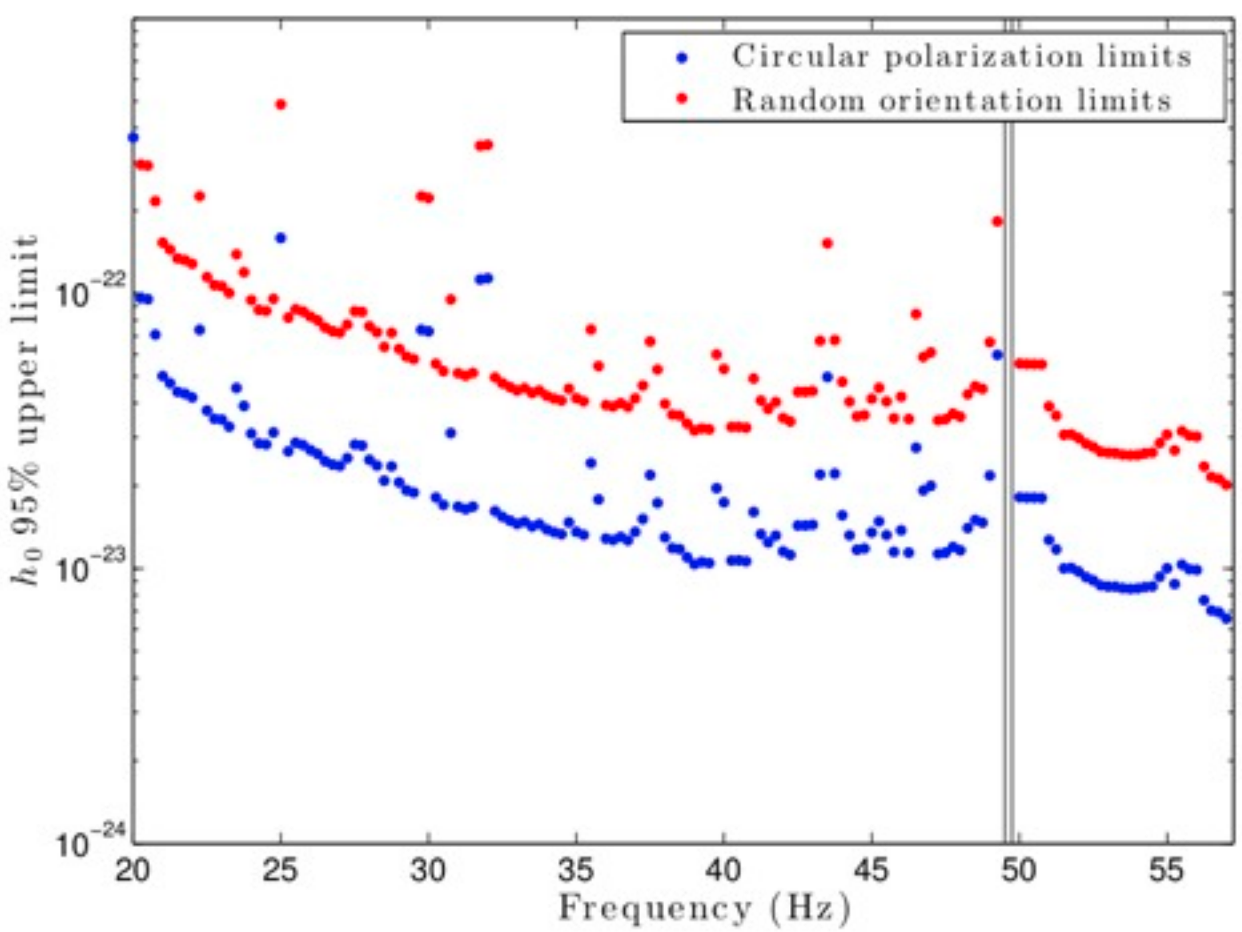


- Vastly improved upper limits (factor of 3 over earlier limits) on "tension" (Gμ) vs. "loop size" (ε) vs. "reconnection probability" (p) via matched-filtering search including S5/VSR1 and S6/VSR2/VSR3 data

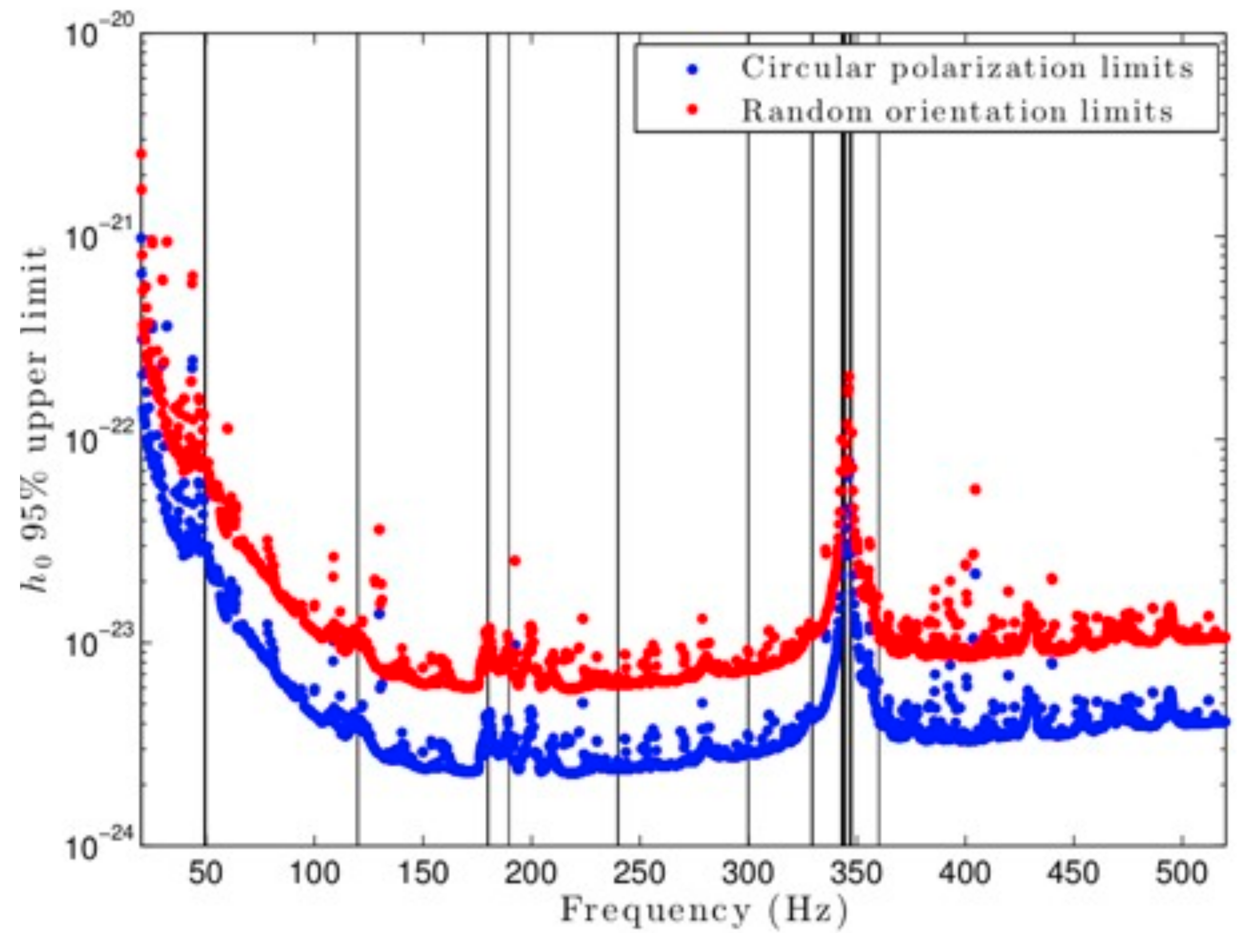
Phys. Rev. Lett. 112 131101

Search for Continuous GW from Binaries

- First of its kind undirected all-sky search for continuous (sine-wave) signals from neutron stars in binaries — also searched for signal from well constrained low mass X-ray binary source Scorpius X-1



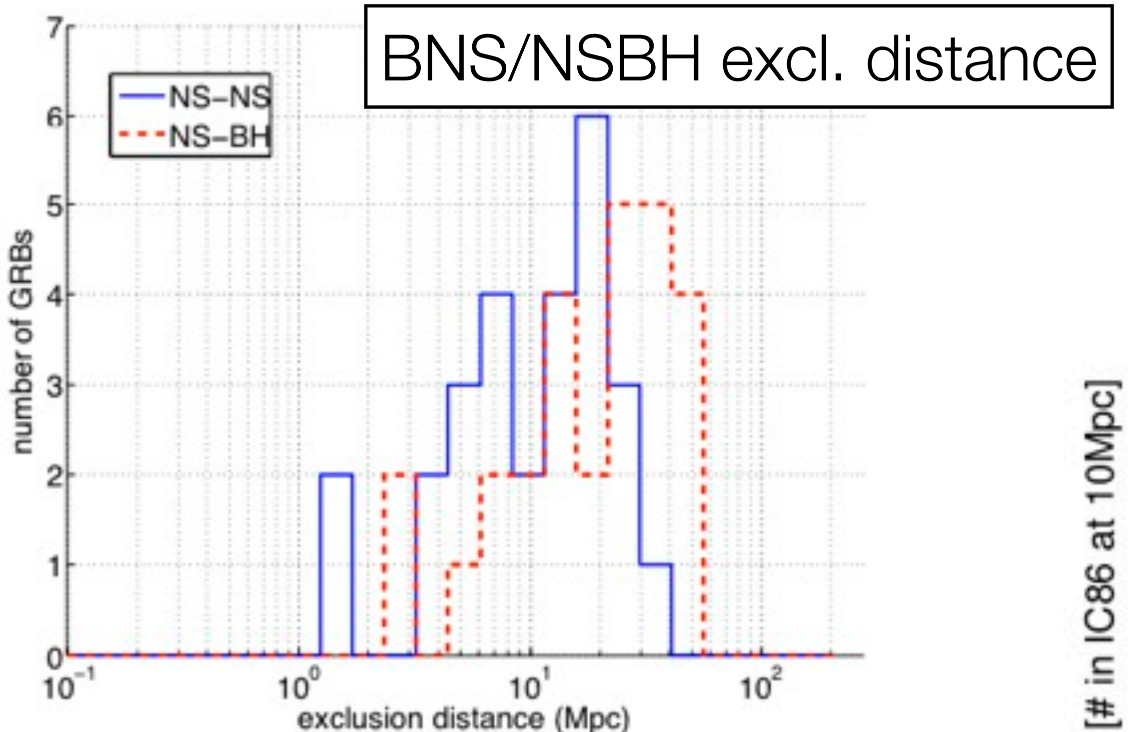
Scorpius X-1

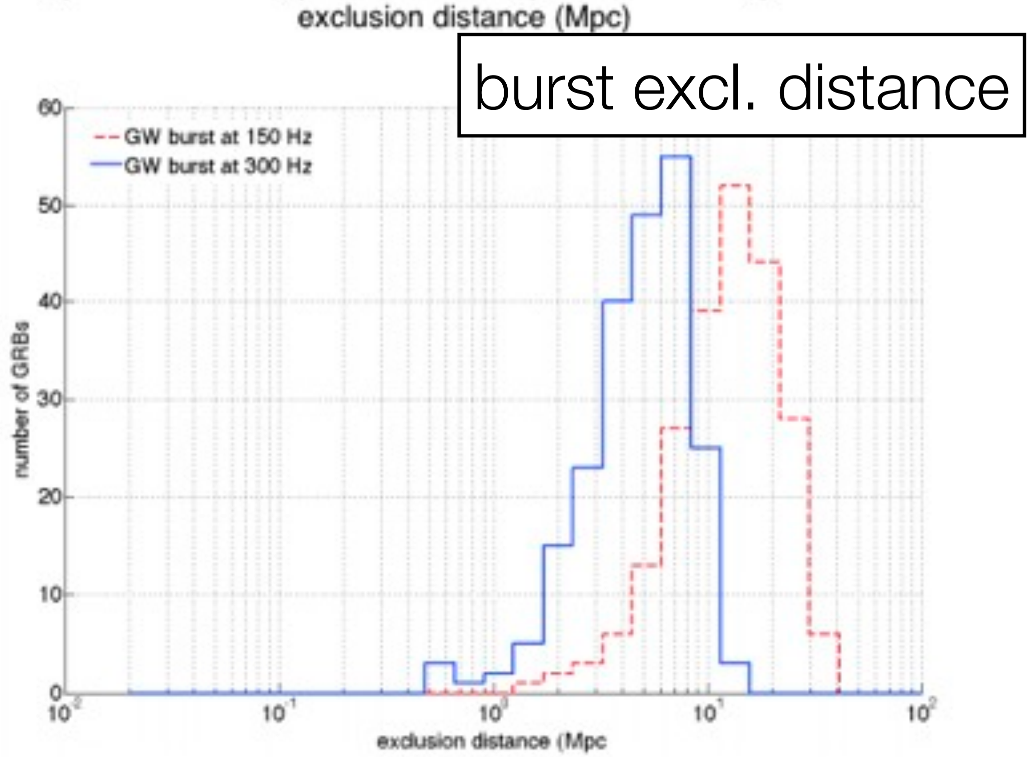


All-sky

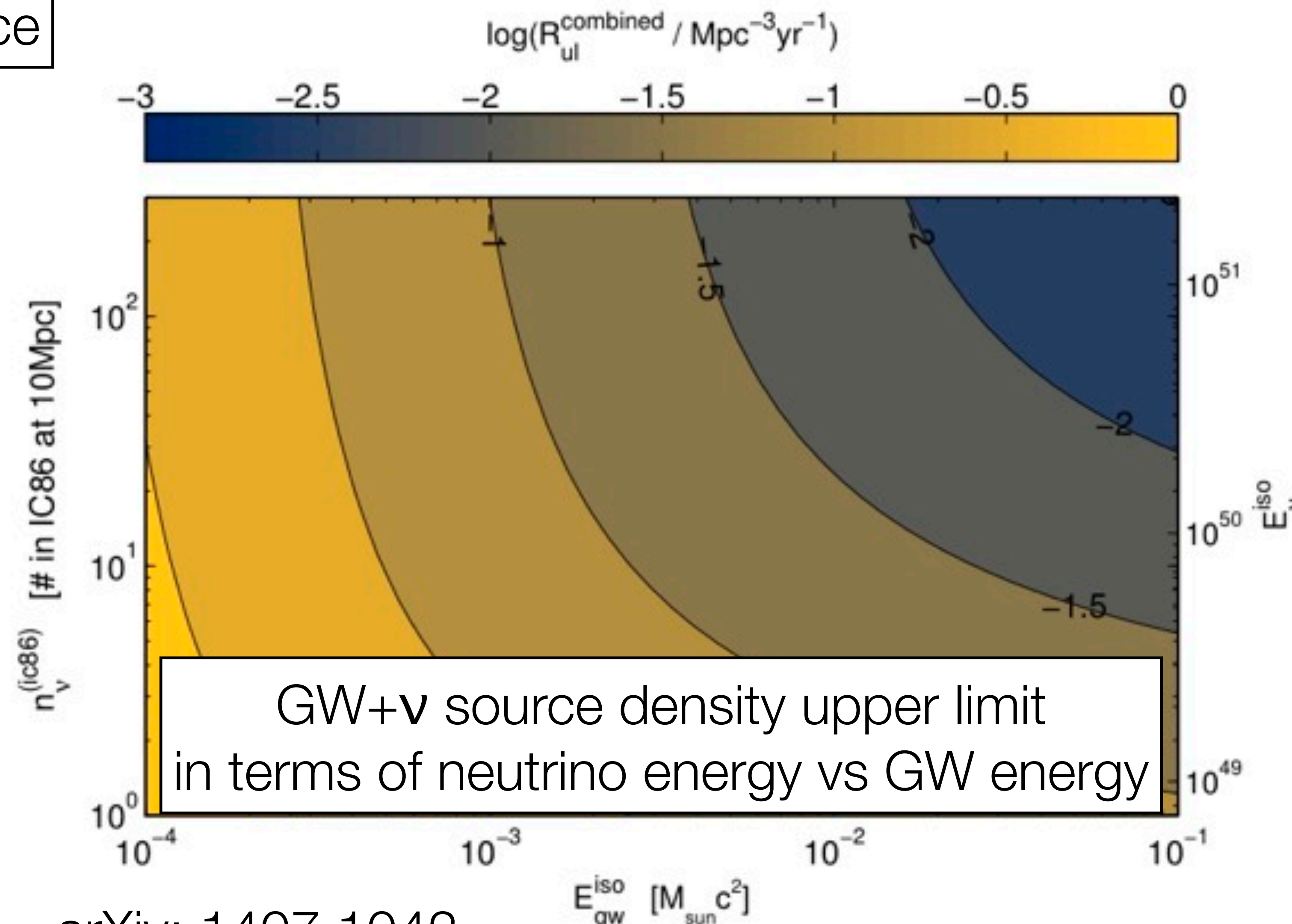
arXiv: 1405.7904

Multi-Messenger Astronomy: GRB / HEN



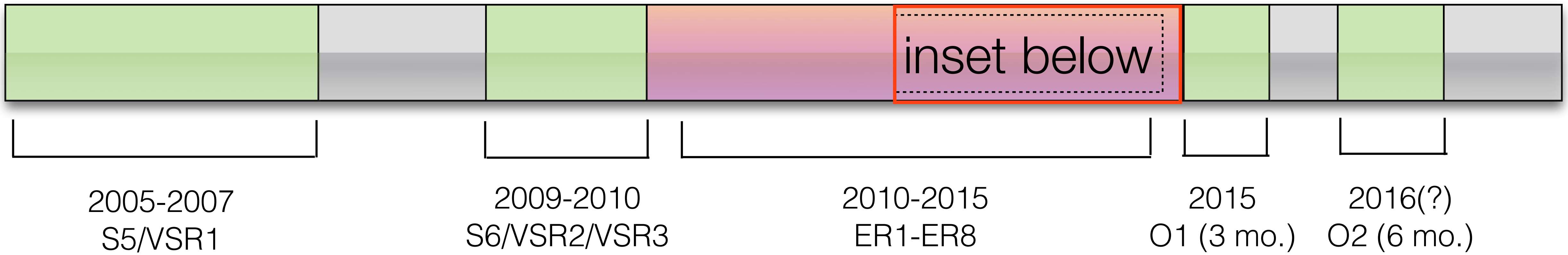


Phys. Rev. Lett. 113 011102



arXiv: 1407.1042

Search	FAR $[\mathrm{yr}^{-1}]$	$h_{\mathrm{rss}}^{50\%}$ $[\mathrm{Hz}^{-1/2}]$	Dist. [Mpc]
GW-only	0.1	9×10^{-22}	5
GW-only	0.01	1.7×10^{-21}	3
GW+neutrino	0.1	5×10^{-22}	9
GW+neutrino	0.01	6×10^{-22}	8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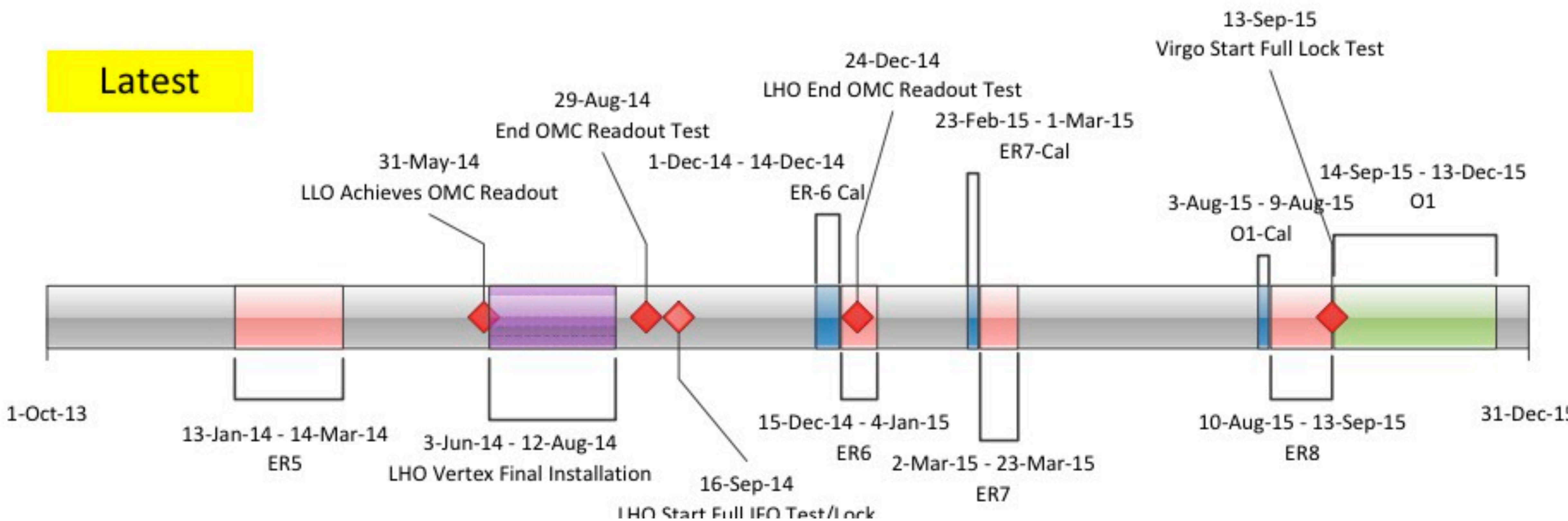
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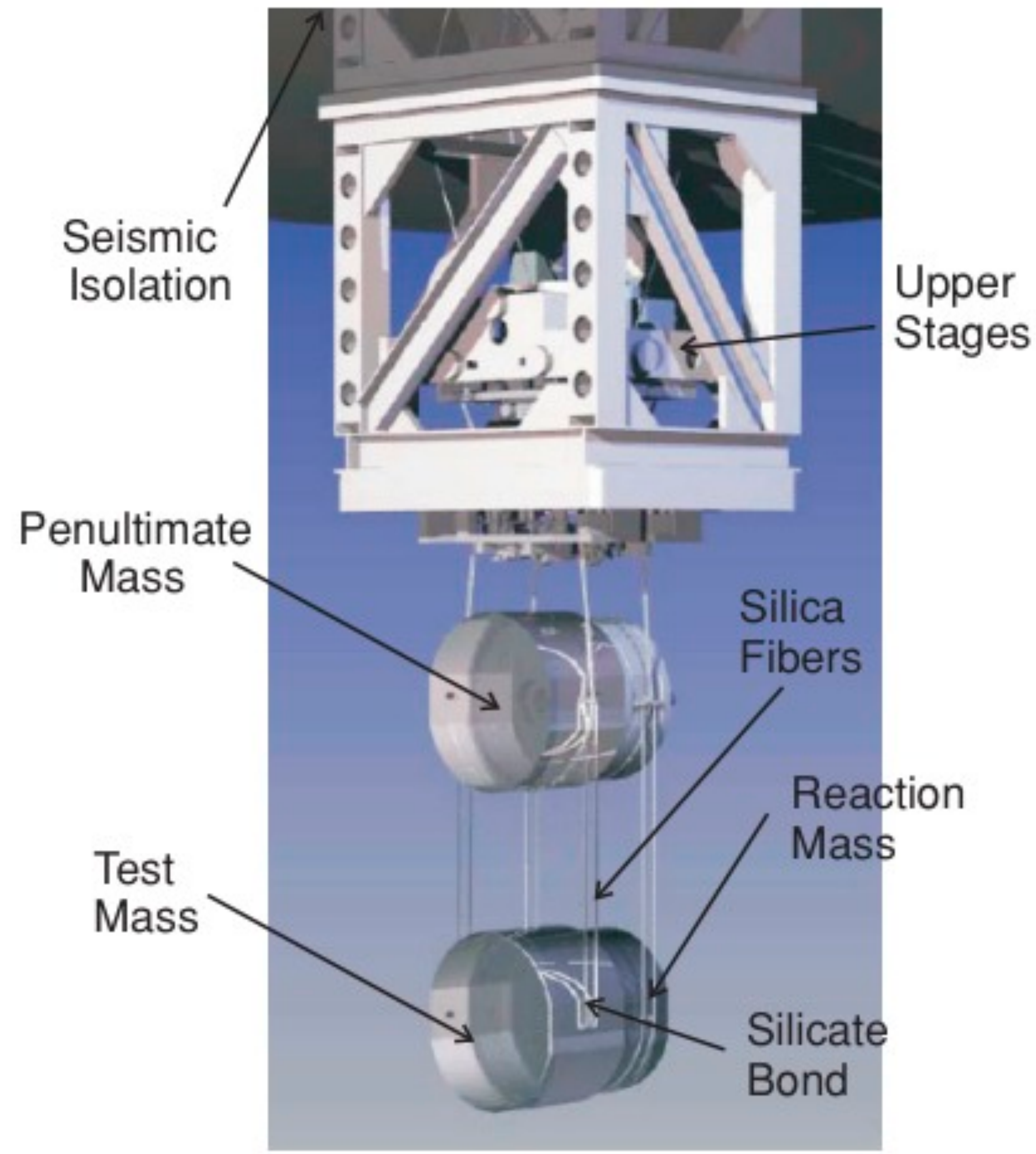
G1301309-v9

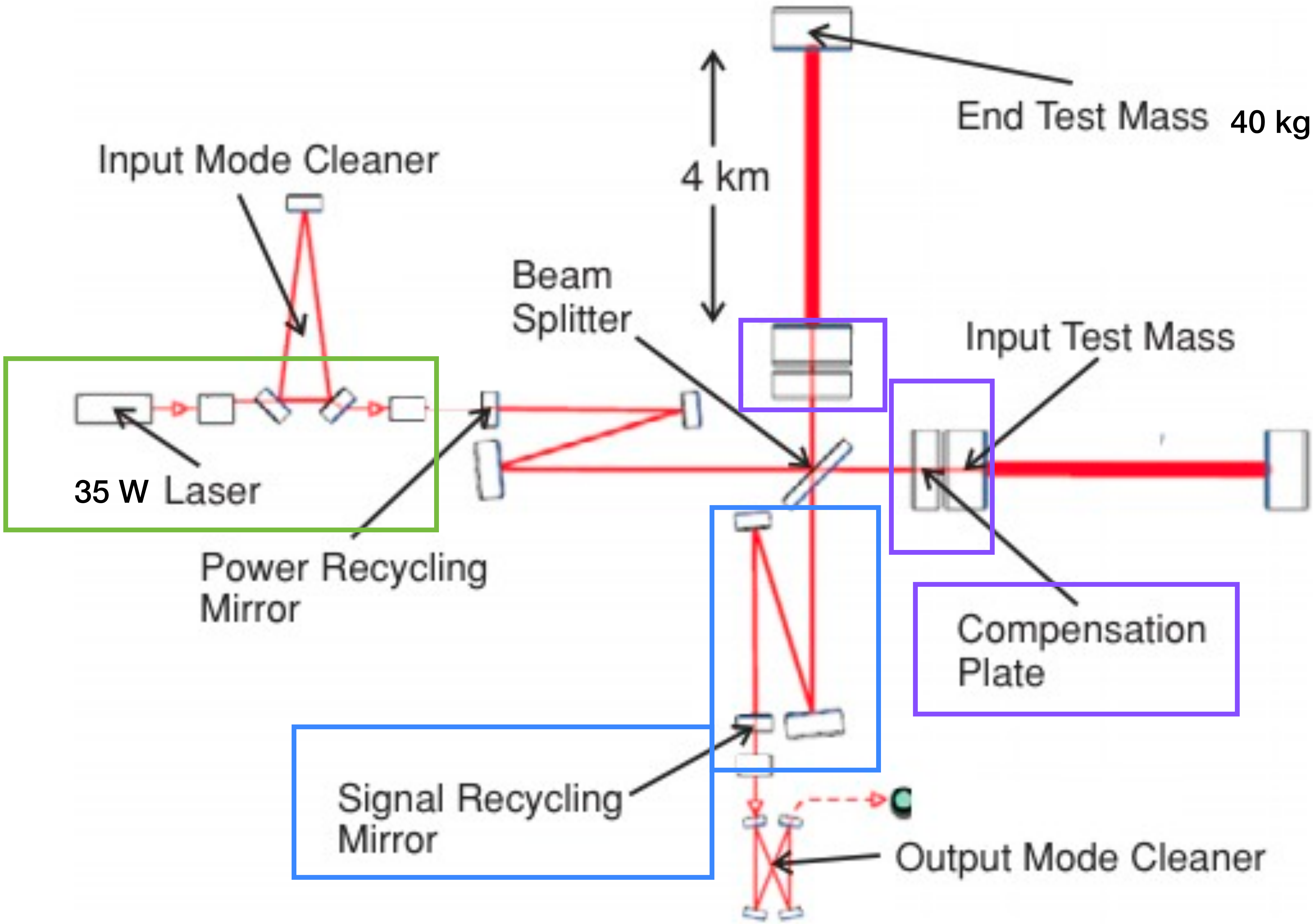
The Path to Advanced GW Interferometry

- Improvements planned since 2010 runs:
  - Seismic isolation: passive → three and four stage passive isolation (benefits below ~50 Hz and lower accessible bandwidth down to 10 Hz) active hydraulic isolation stage
  - Signal recycling mirror → increased power circulating in the arms (reduce shot noise above ~200 Hz)
  - Increasing input laser power (~10 → 180 W) to reduce shot noise at high frequencies (Current is 35 W as demonstrated in S6 and now permanently on)
  - Thermal compensation of optical astigmatism at high laser power



Harry, et al. *CQG 27 (201)) 084006*

2015 Era Upgrades



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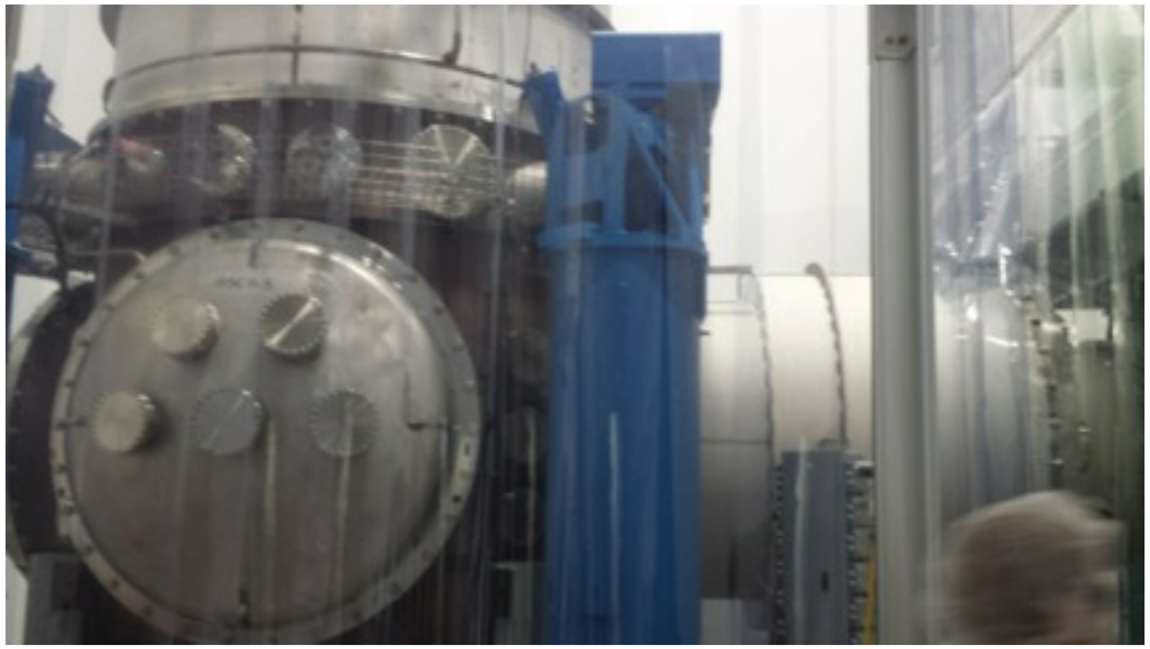
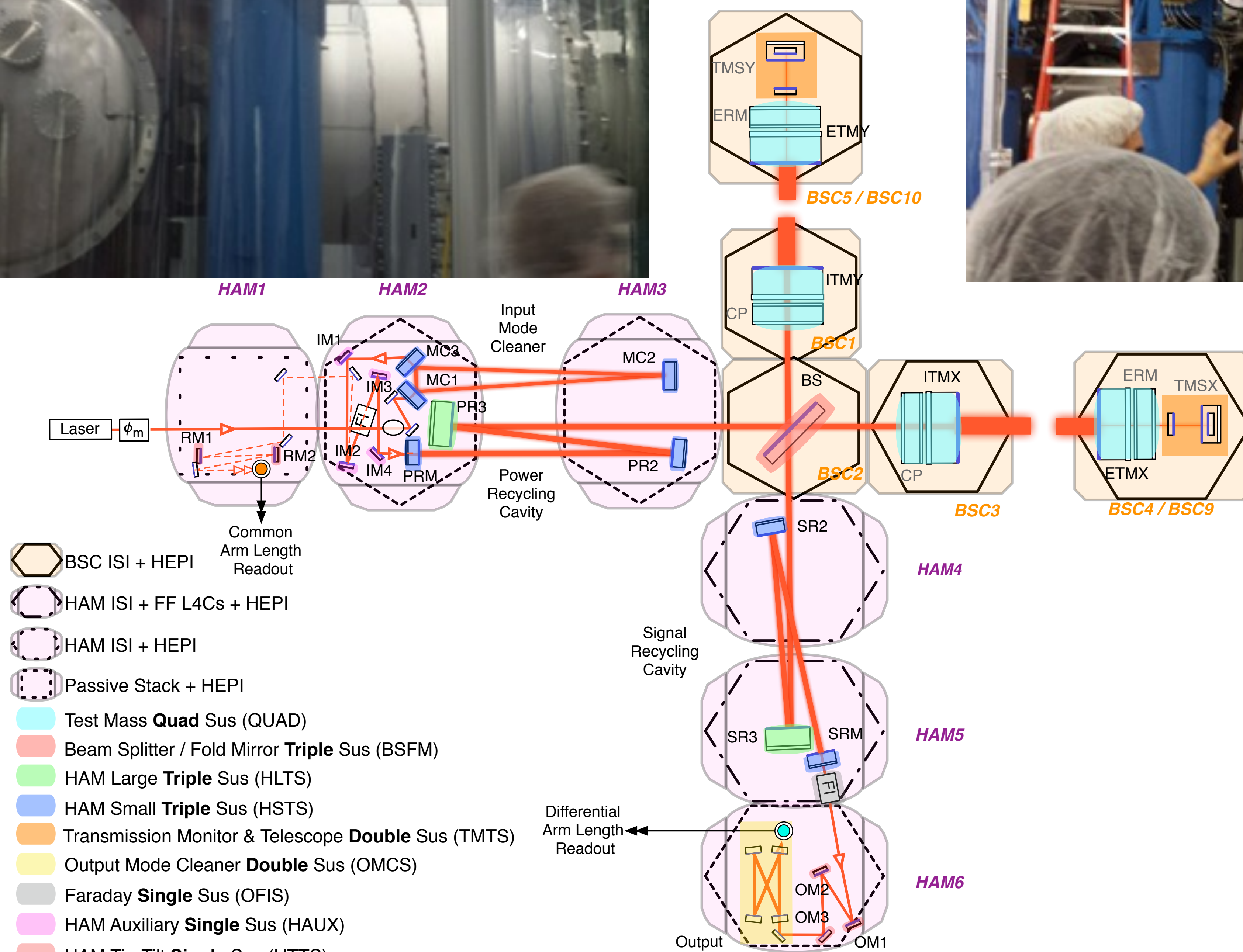


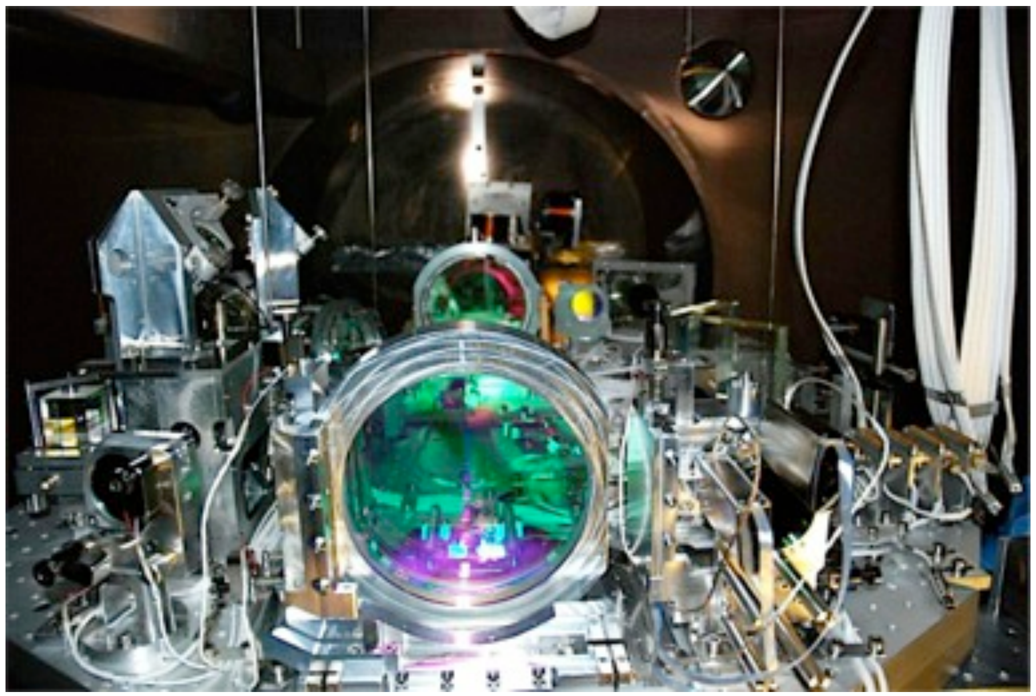


Towards the Future

- Other planned improvements:
  - One more order of magnitude in laser power (35 → 180 W)
    - Push down the sensitivity curves towards the shallow 2018 design curve
  - “Tune” the signal recycling mirror: allow for better sensitivity at specific frequencies (e.g. a factor of a few for some periodic signals)
  - Light “squeezing”: Overtake fundamental quantum noise limit at high frequencies

Harry, et al. *CQG 27 (201)) 084006*

Advanced Virgo

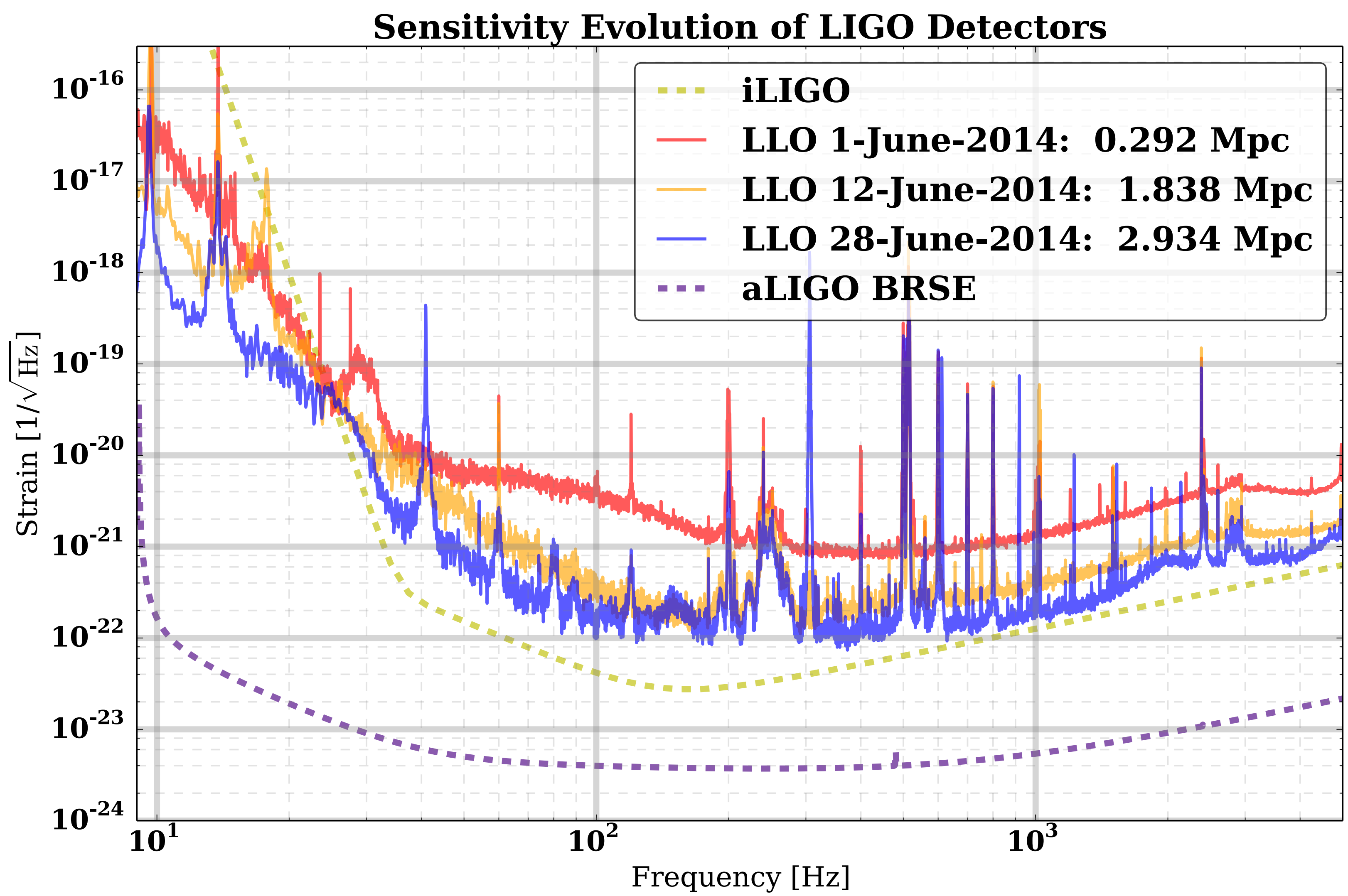


- First major milestone completed on time: locked the input mode cleaner (first stages of input optics before the beam splitter)
- Intense installation work happening on site, installing suspension, additional vacuum chambers, preparing optical payloads, etc...:
  - Early 2015: all optics installed near beamsplitter, start of inner interferometer commissioning
  - Summer 2015: End mirrors installed, test one arm of the instrument
  - Fall 2015: Full interferometer locking and commissioning
  - 2016: First science data and joint run with LIGO interferometers

Interferometer Locking and Acceptance

- The Livingston, Louisiana interferometer has achieved several stable locks, one of which was 2+ hrs: this is the ***acceptance*** goal for the advanced LIGO interferometers — major milestone!

- Hanford is very close to closing out installation and locking is expected to occur rapidly after this



https://www.advancedligo.mit.edu/adligo_news.html

Horizon Distance: Distance to optimally oriented SNR 8 1.35+1.35 binary coalescence

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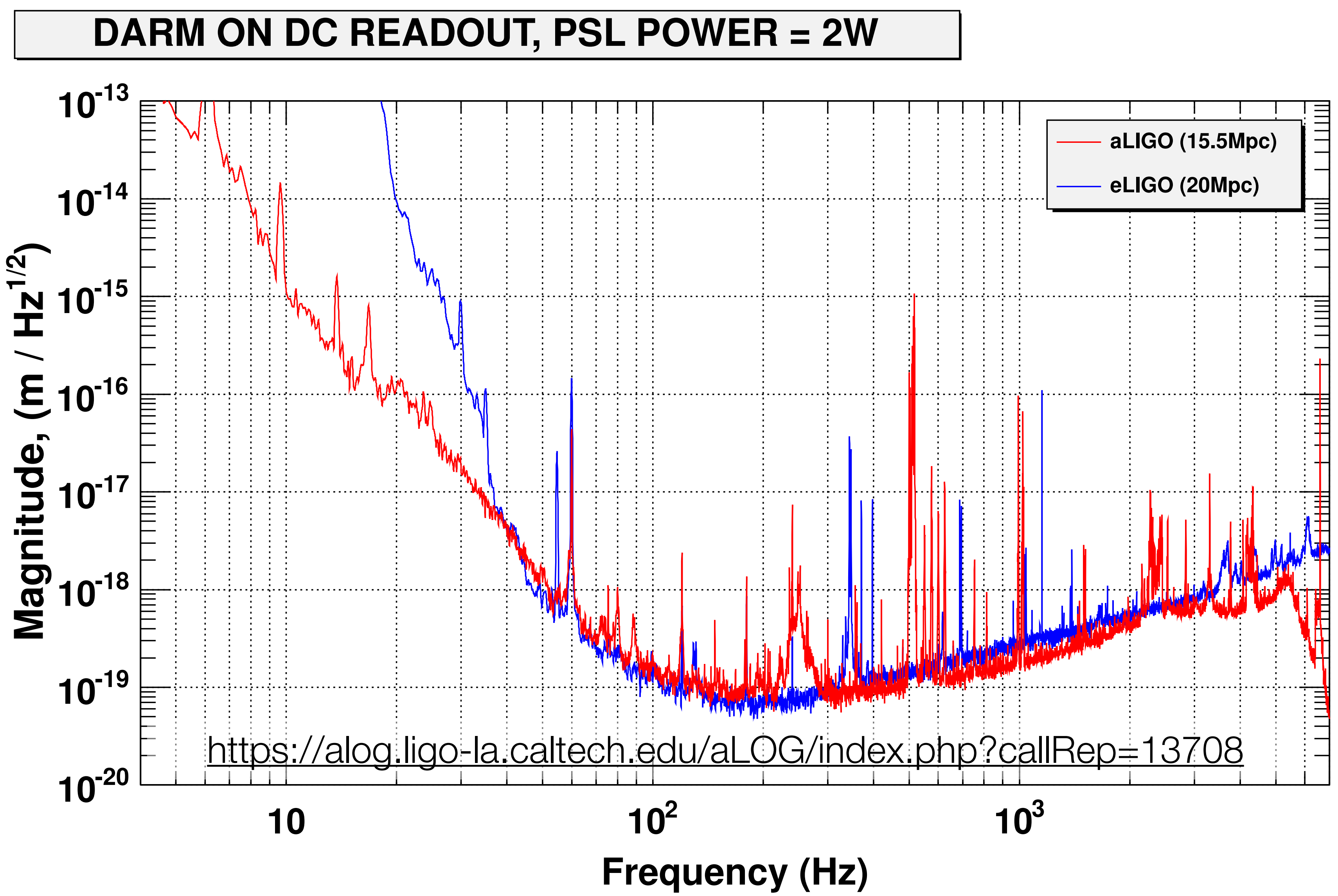

Livingston detector displacement spectra
eLIGO circa. 2010 (*horizon 20 Mpc*)
aLIGO July 23rd, 2014 (*horizon 15 Mpc*)

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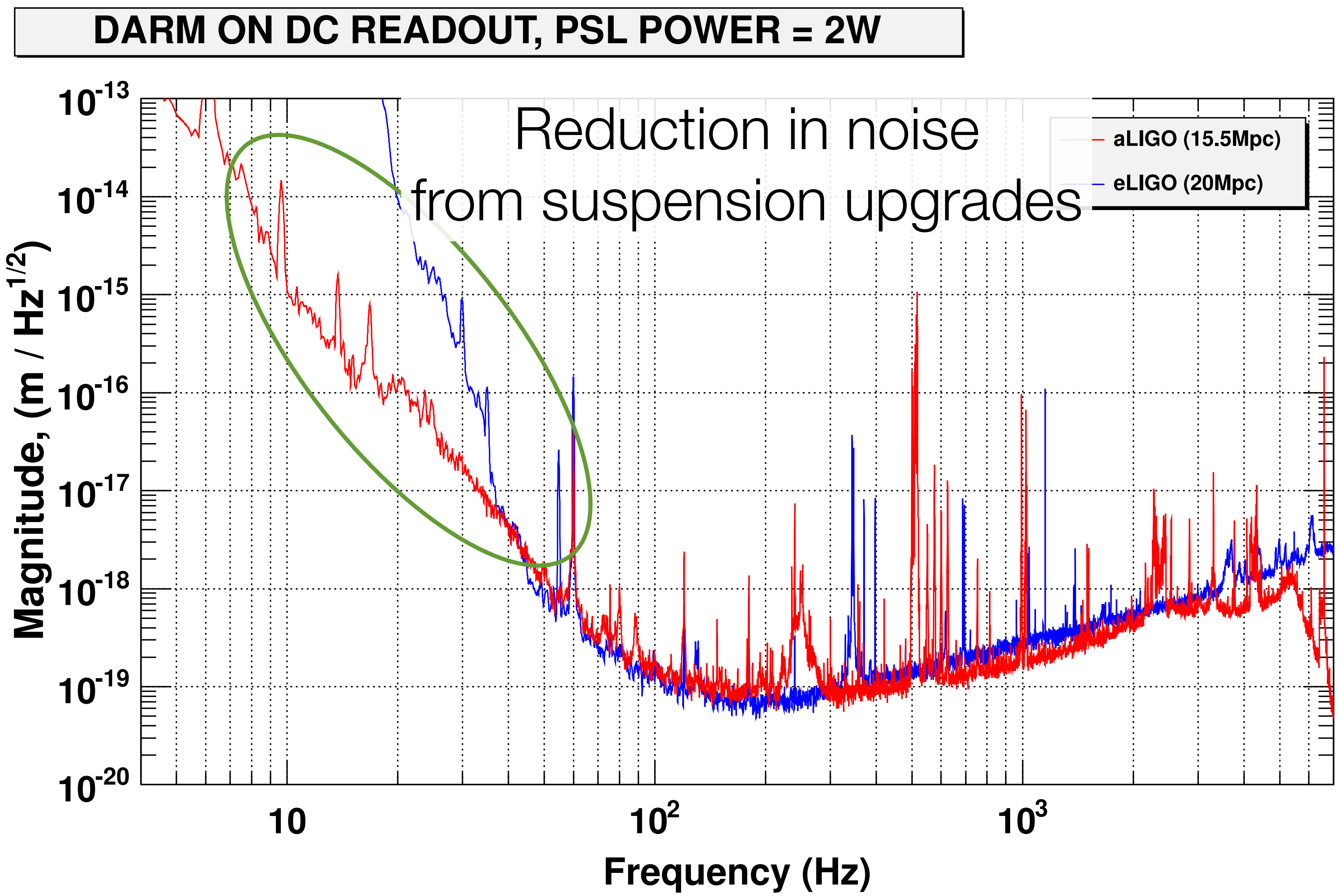

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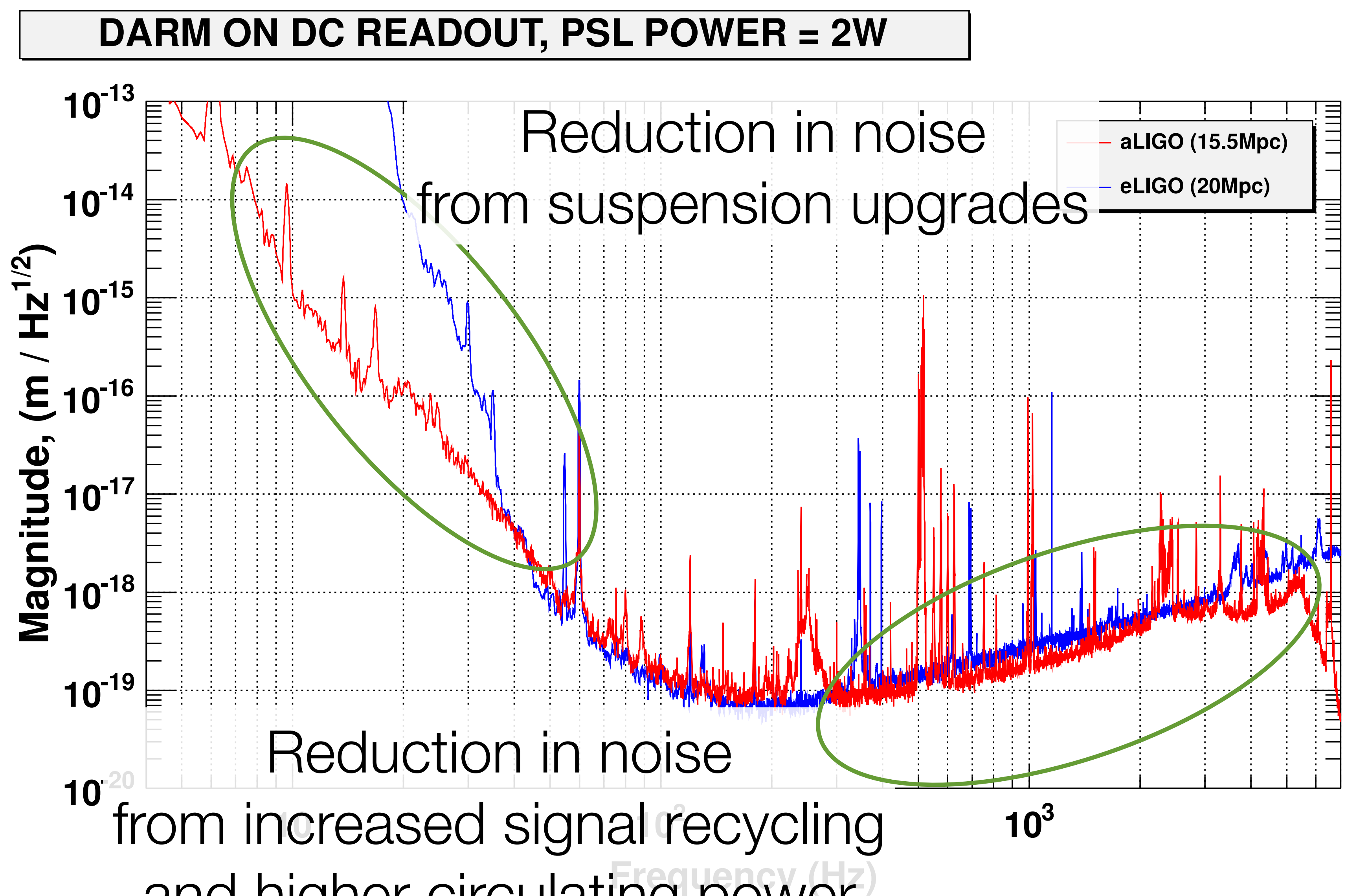

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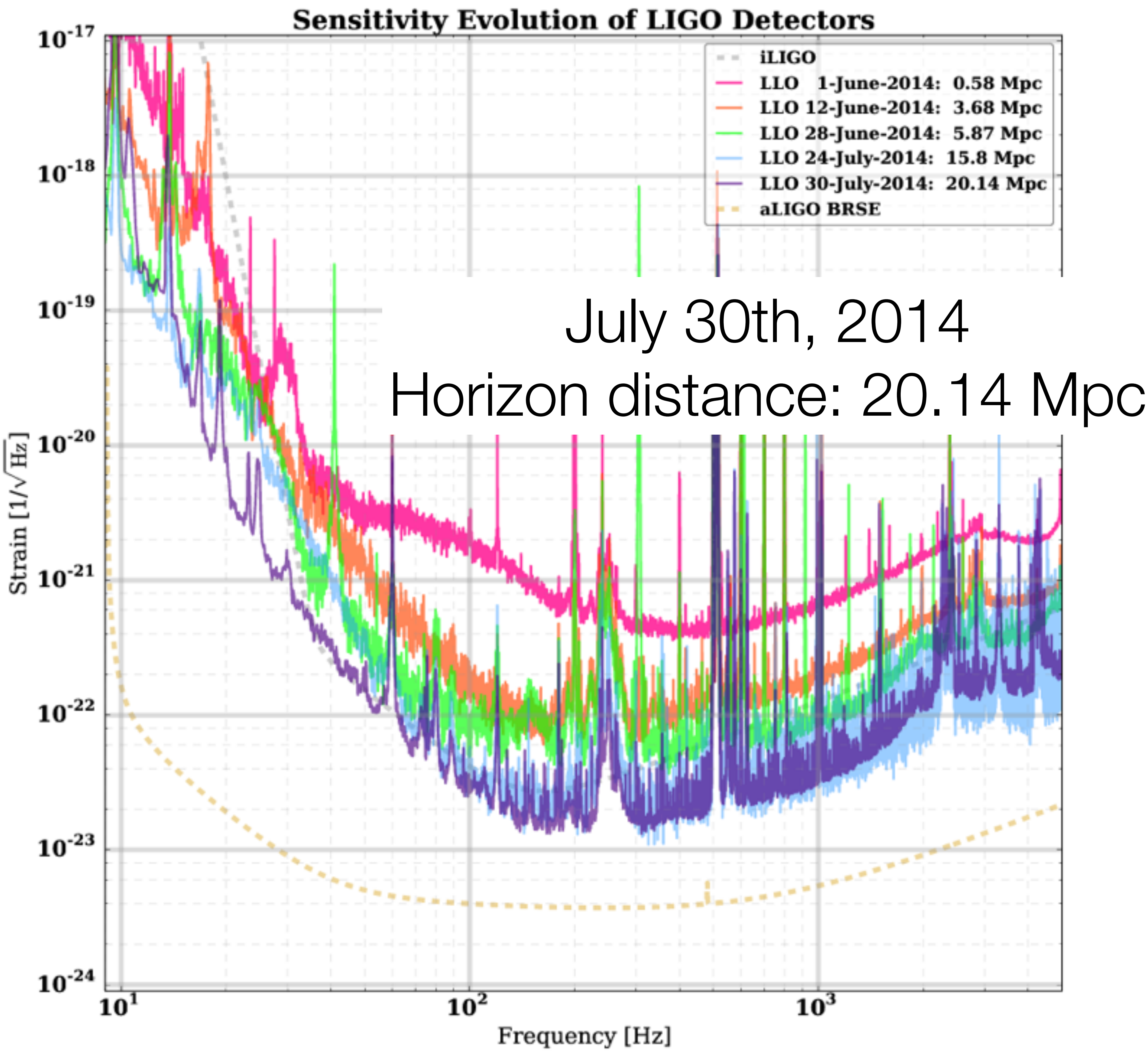

Sensitivity Evolution of LIGO Detectors
iLIGO
LLO 1-June-2014: 0.58 Mpc
LLO 12-June-2014: 3.68 Mpc
LLO 28-June-2014: 5.87 Mpc
LLO 24-July-2014: 15.8 Mpc
LLO 30-July-2014: 20.14 Mpc
aLIGO BRSE
Strain [1/√Hz]
Frequency [Hz]
July 30th, 2014
Horizon distance: 20.14 Mpc

LSC VIRGO

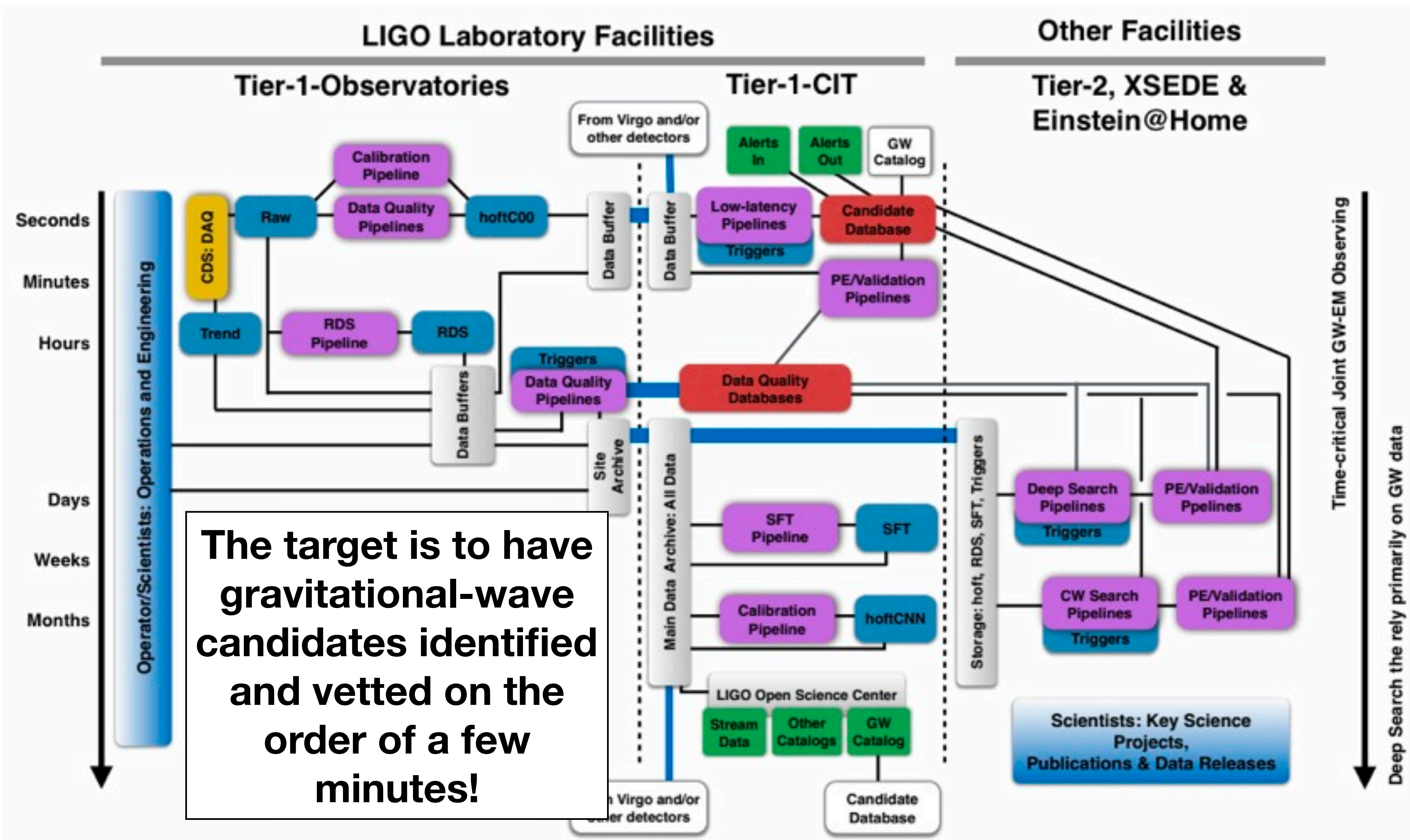
Engineering/Commissioning Runs

- End-to-end practice from data acquisition to candidate follow up and external communication including **low latency trigger analysis and dissemination**

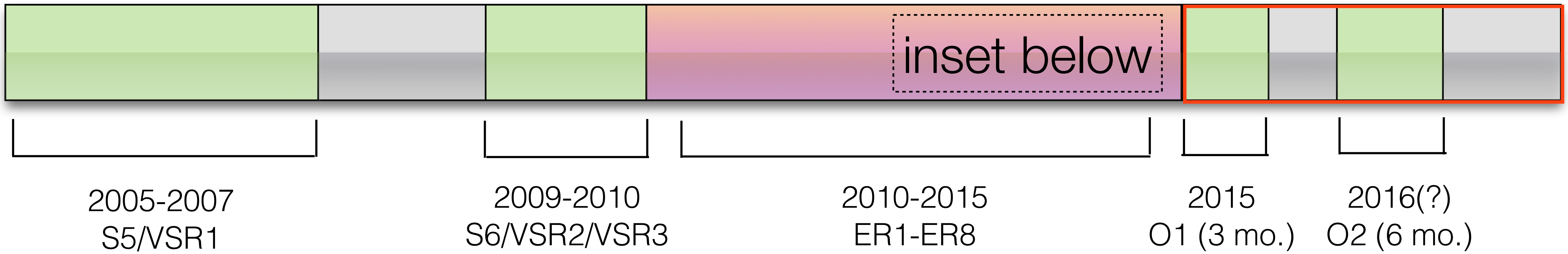
IFO data acquisition

“online” data analysis and follow up

“deep” GW searches and parameter estimation



The target is to have gravitational-wave candidates identified and vetted on the order of a few minutes!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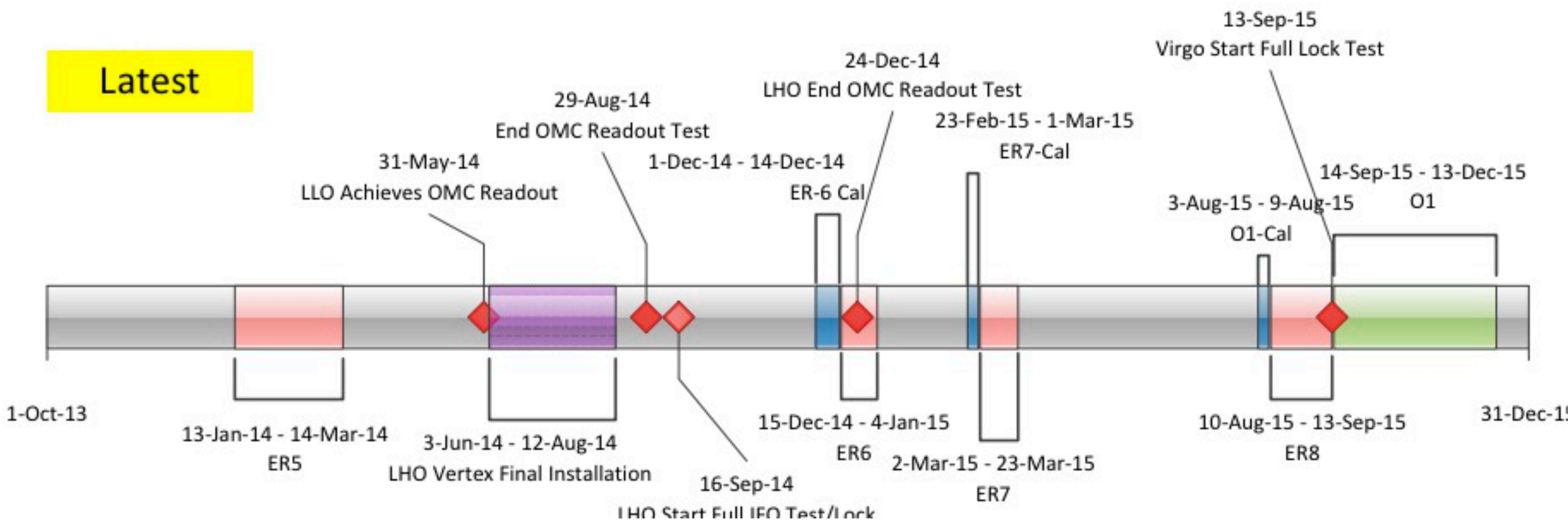
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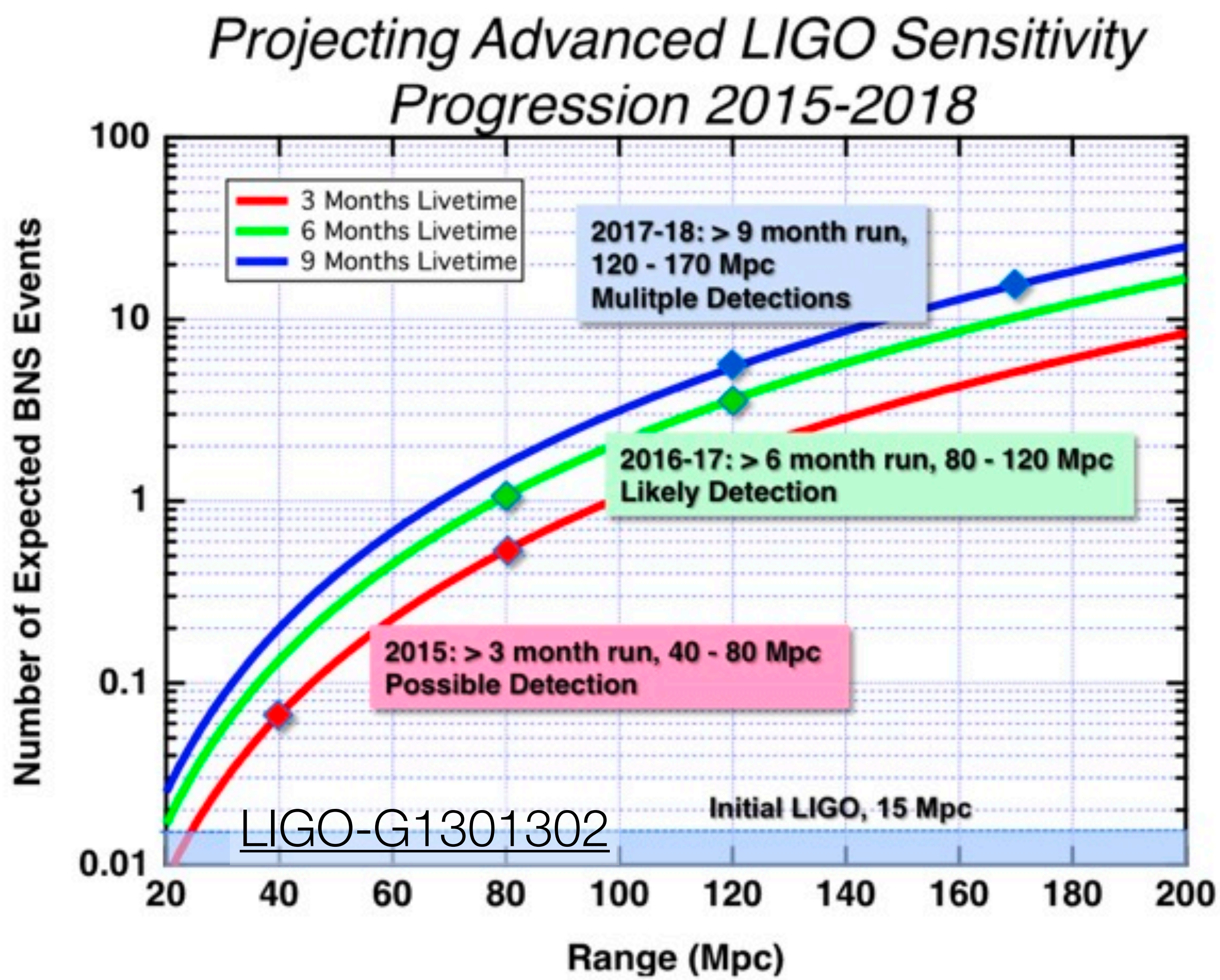
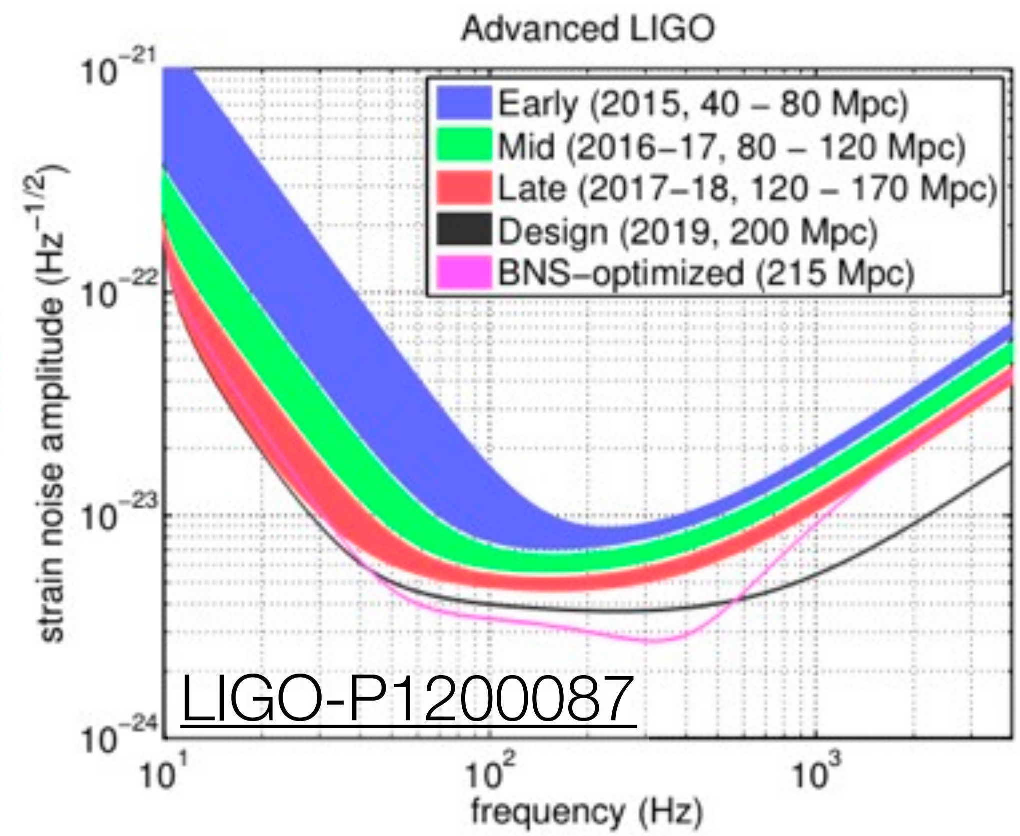
Ground-Based Interferometer Networks (2015)

"Mollweide projection SW" by Strebe - Own work. Licensed under Creative Commons Attribution-Share Alike 3.0 via Wikimedia Commons - https://commons.wikimedia.org/wiki/File:Mollweide_projection_SW.jpg#mediaviewer/File:Mollweide_projection_SW.jpg

The Next Three Years

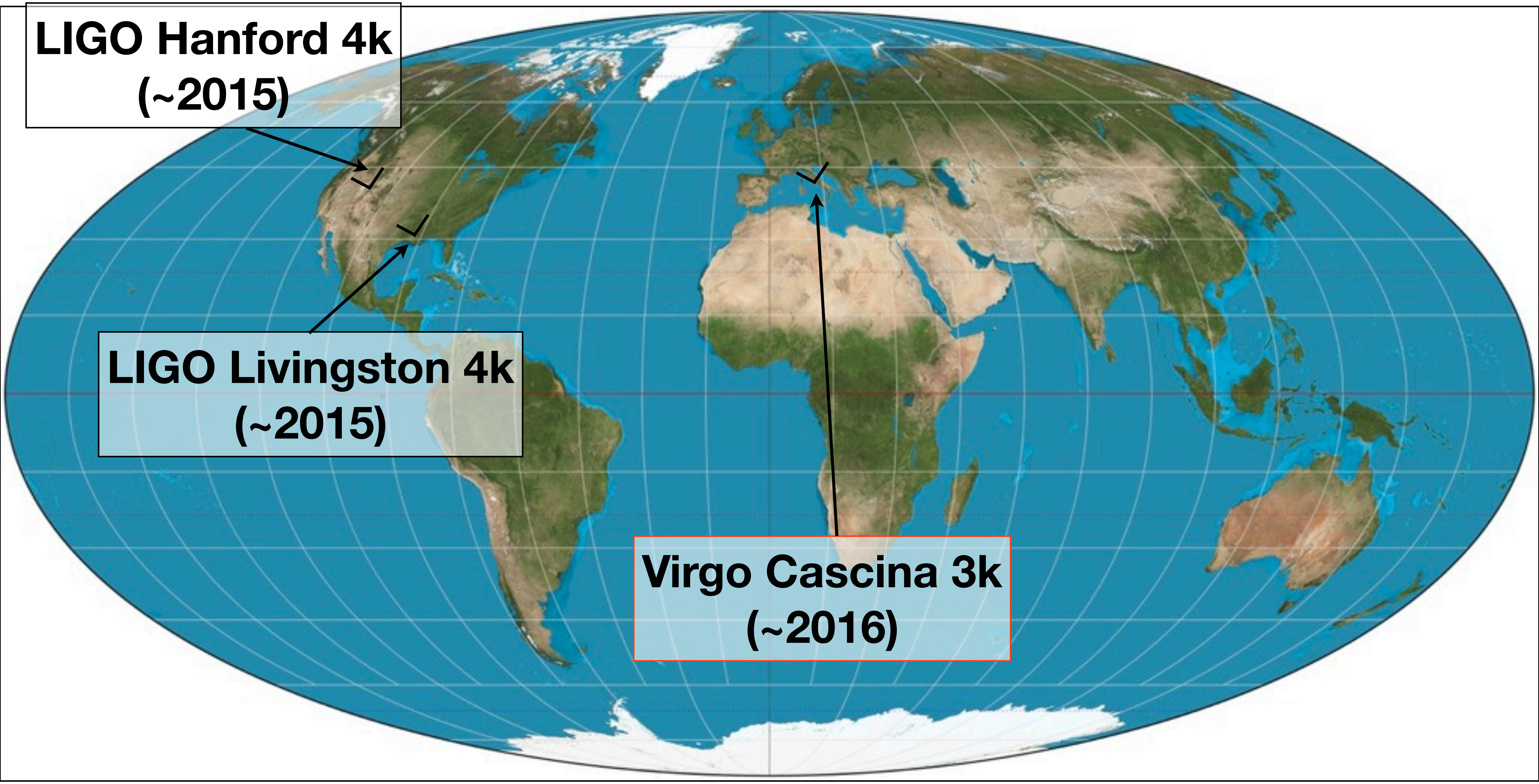




As sensitivity increases, so does the length of the observation run: Optimize volume searched

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–

Ground-Based Interferometer Networks (2016)



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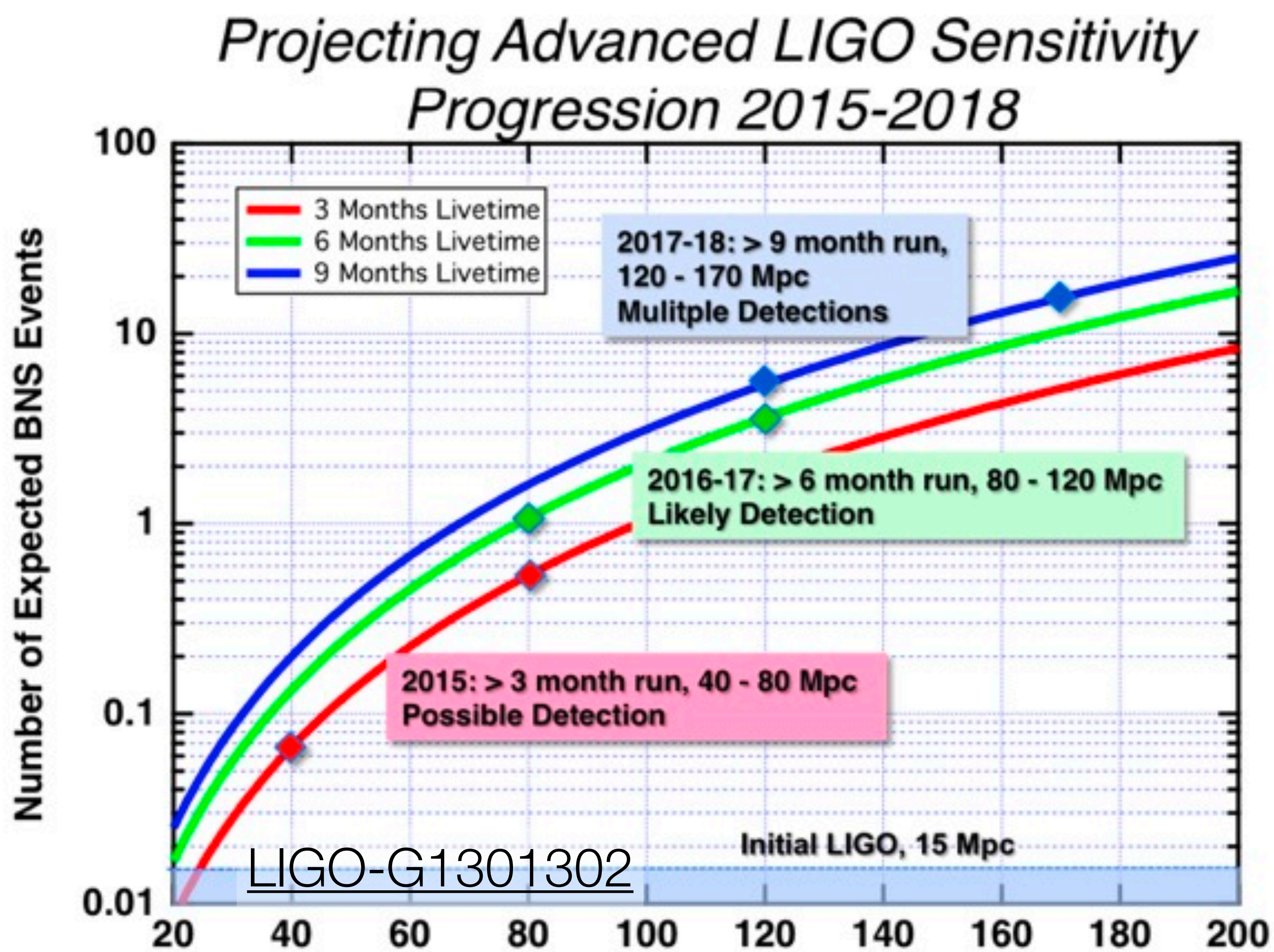
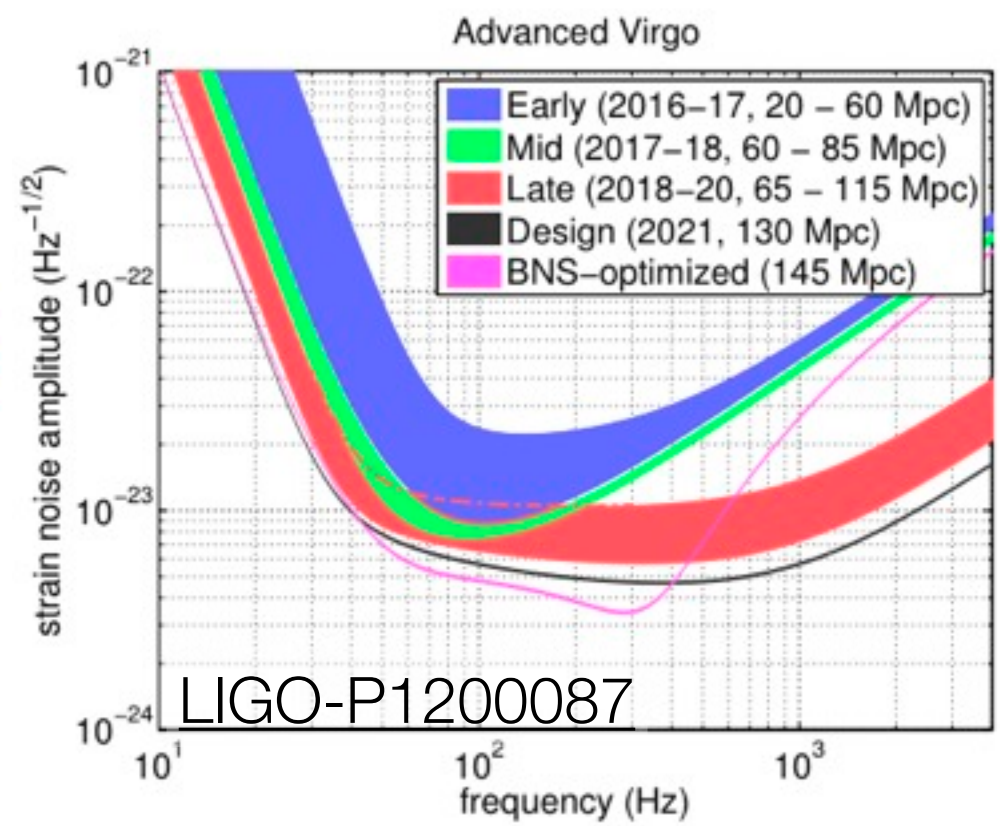
The Next Three Years





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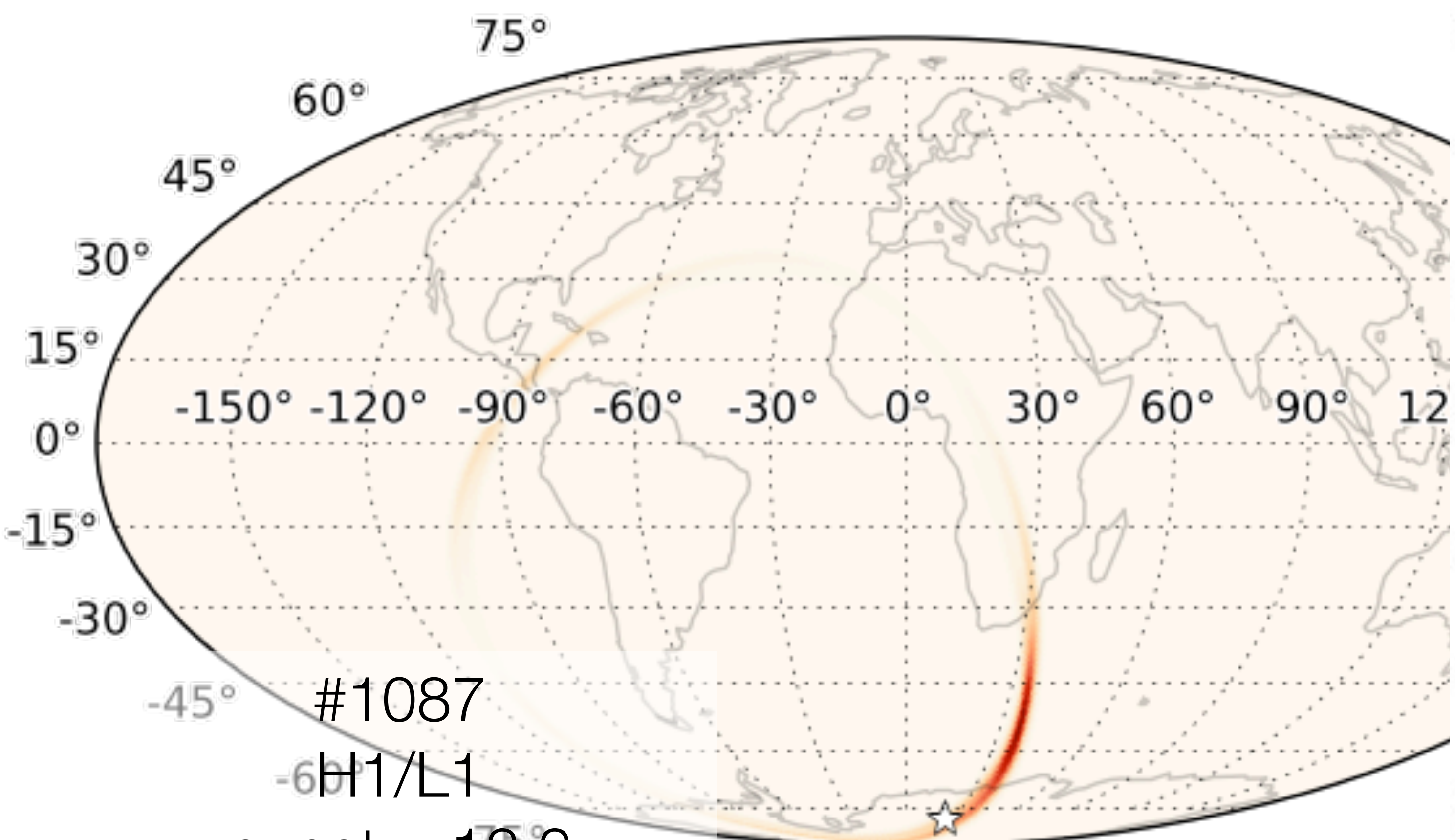
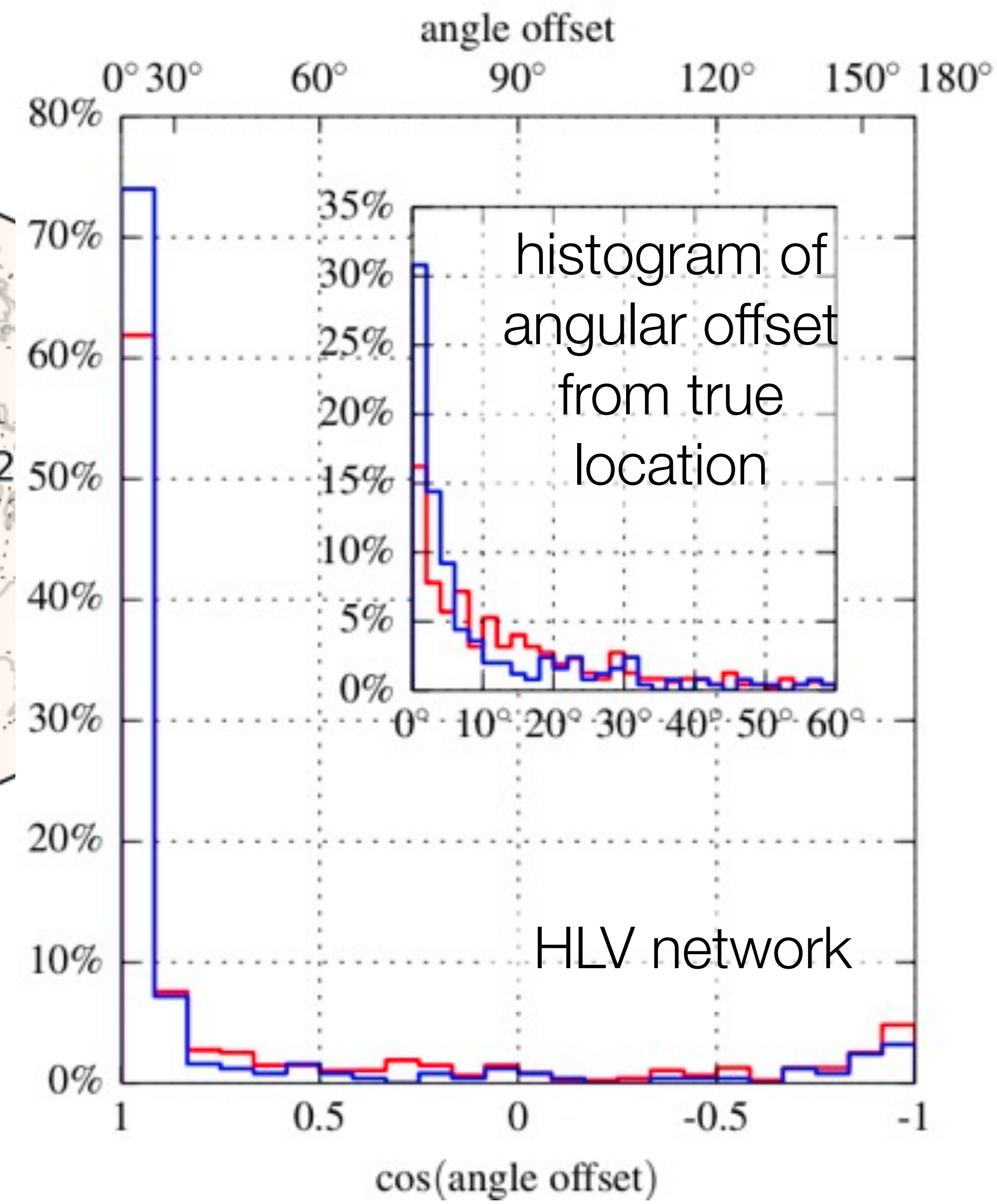
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12

2nd Gen. Multi-messenger Astronomy

- "The First Two Years of Electromagnetic Follow-Up with Advanced LIGO and Virgo"(Singer, et al., 2014)

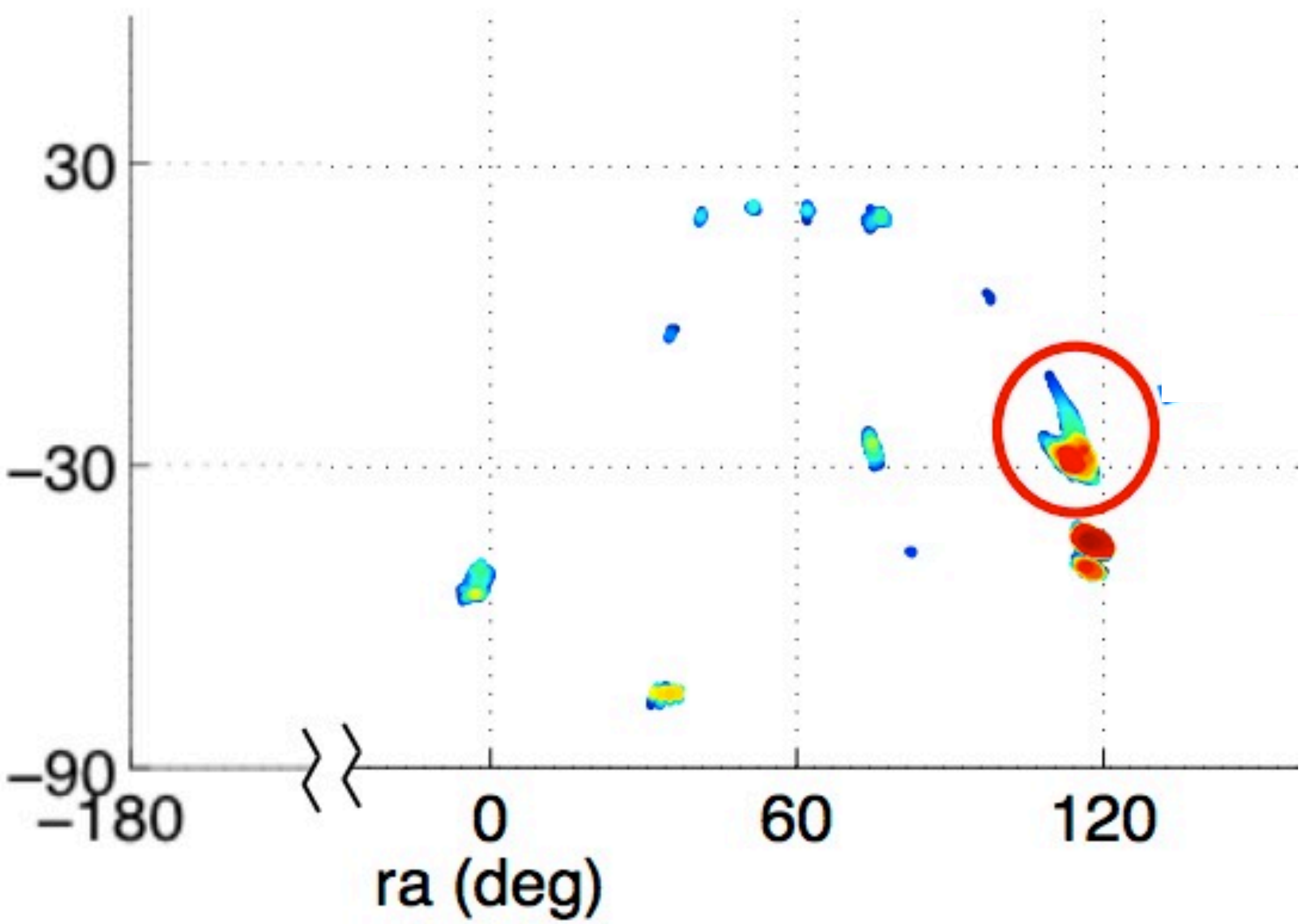


#1087
H1/L1
p_net = 13.2
50% = 220 sq. deg.
90% = 1000 sq. deg.
searched = 180 sq. seg.



http://www.ligo.org/science/first2years/

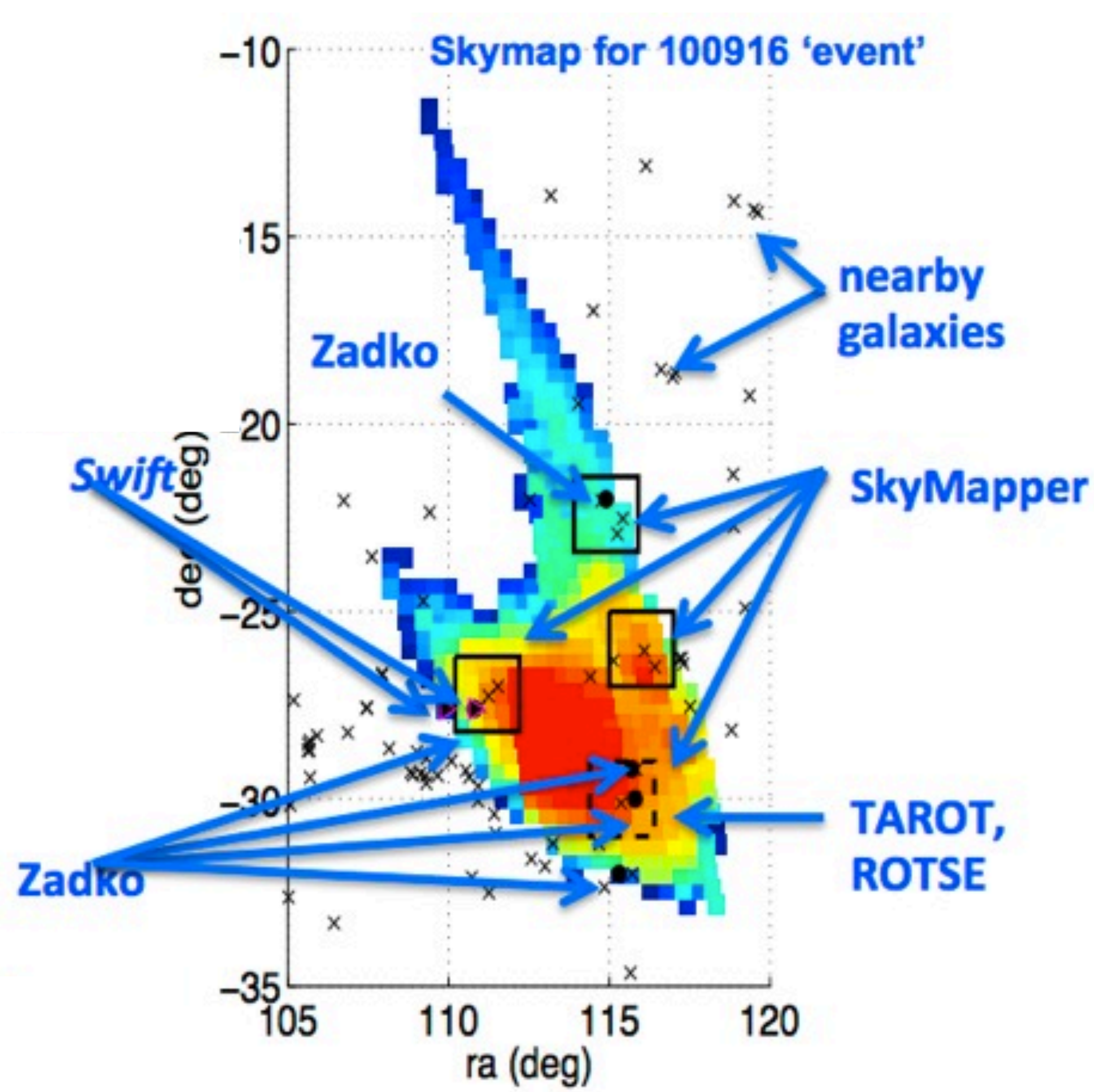
Follow-Up Prototyping



Ap. J. S. 211 7

- During the previous run, a pathfinder program was initiated between the LIGO and Virgo collaborations and electromagnetic observatories
- Challenge: weak SNR events generally have non-zero probability of origin location over hundreds square degrees along with likely disconnected regions on the sky

Follow-Up Prototyping



Ap. J. S. 211 7

- During the previous run, a pathfinder program was initiated between the LIGO and Virgo collaborations and electromagnetic observatories
- Challenge: weak SNR events generally have non-zero probability of origin location over hundreds square degrees along with likely disconnected regions on the sky
- Skymaps of source location probability were combined with a galaxy catalog and shared with partners who tiled the highest regions of probability

2nd Gen. Multi-messenger Astronomy

- Early follow up will require rapid and extensive parameter estimation (from GW astronomers; see talk from Vivien Raymond next!) and wide-field and/or high cadence observing facilities:

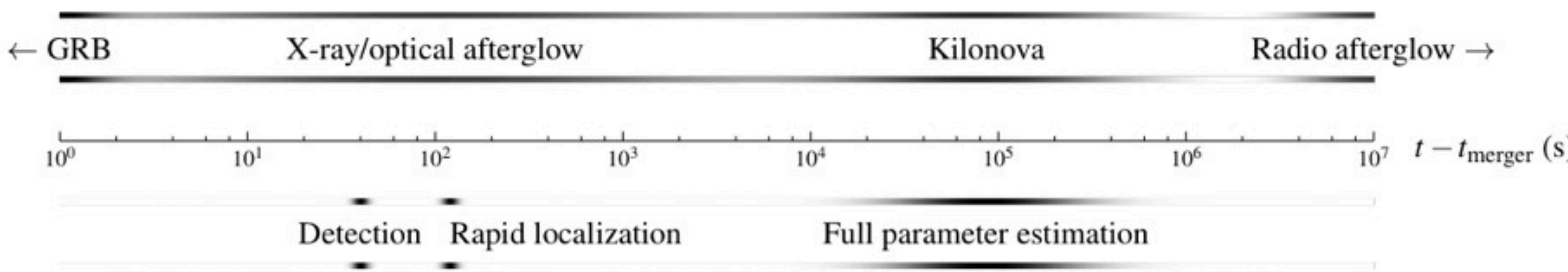


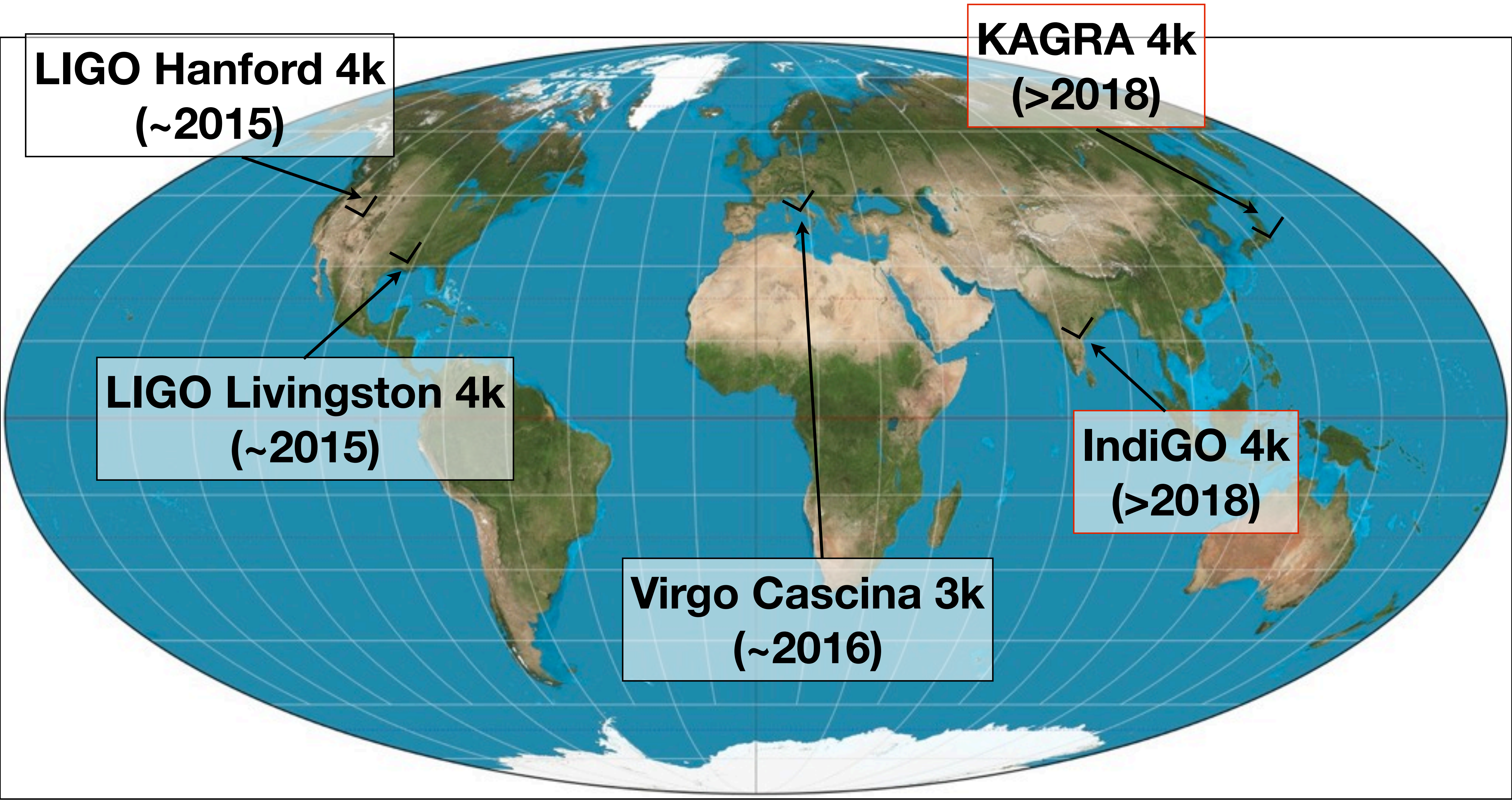
Figure 2. Rough timeline of compact binary merger electromagnetic emissions in relation to the timescale of the Advanced LIGO/Virgo analysis described in this paper. The time axis measures seconds after the merger.

- MoUs signed with ~40 partner telescopes/electromagnetic facilities

- Planned: GCNs, VOEvents, two-way information transfer with partners, system will be practiced and in place for the next observational run

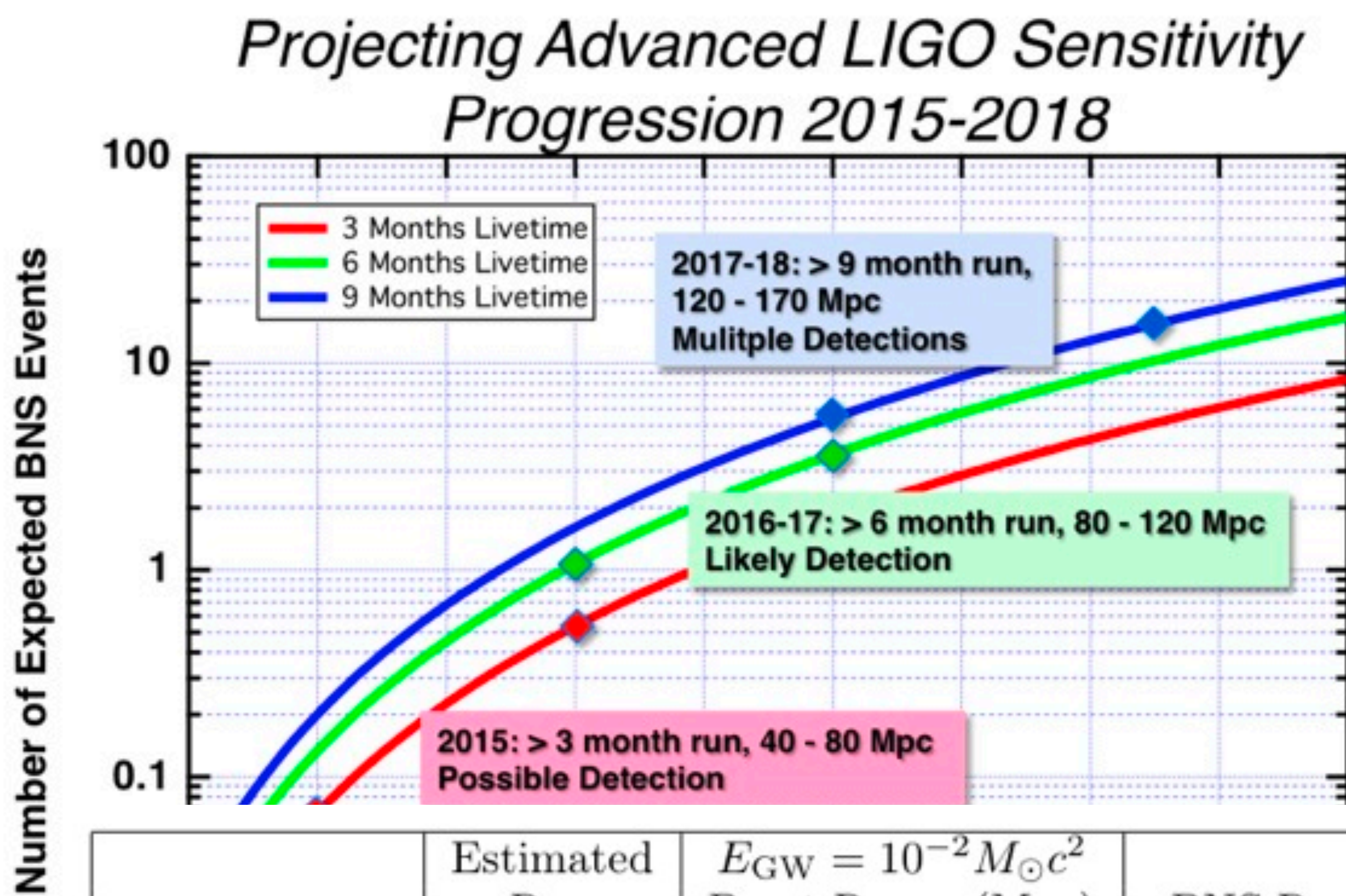
http://www.ligo.org/science/first2years/

Ground-Based Interferometer Networks (2018+)

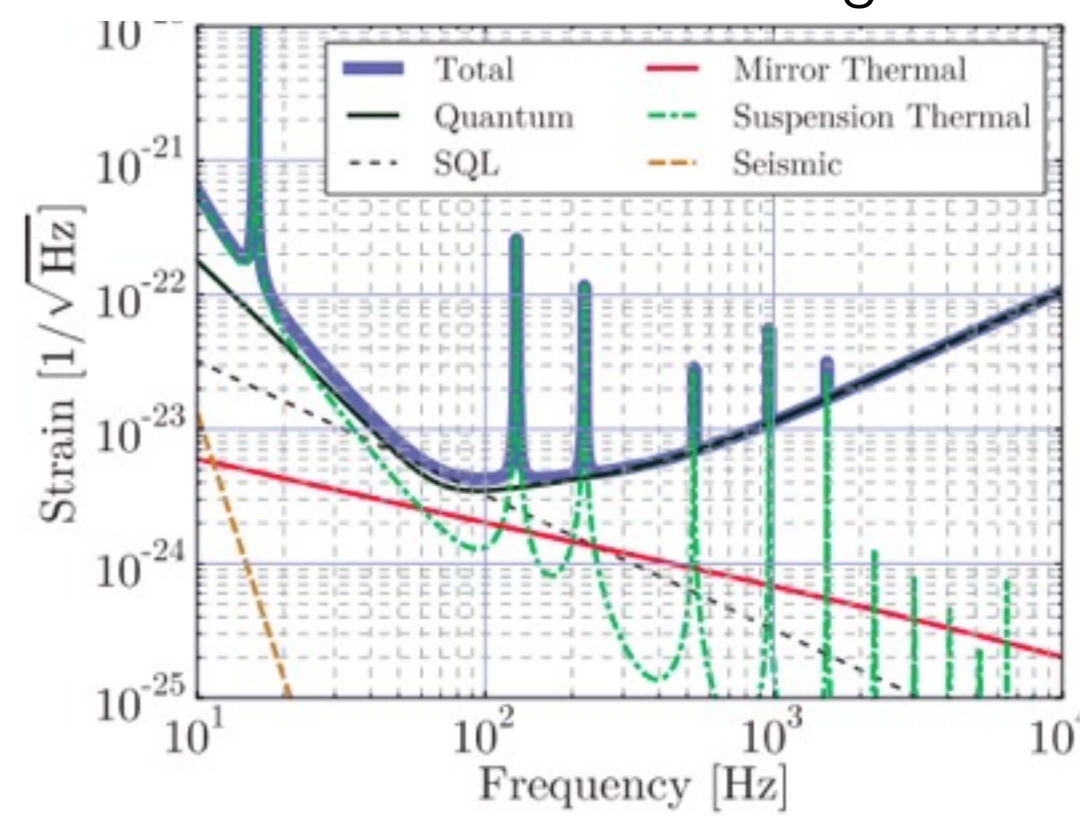


"Mollweide projection SW" by Strebe - Own work. Licensed under Creative Commons Attribution-Share Alike 3.0 via Wikimedia Commons - https://commons.wikimedia.org/wiki/File:Mollweide_projection_SW.jpg#mediaviewer/File:Mollweide_projection_SW.jpg

The Next Five Years



KAGRA broadband configuration



Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 $\deg^2$	20 $\deg^2$
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

LIGO-G1301302

Phys. Rev. D 88 043007

Concluding Remarks

- LIGO-Virgo instrument progress is accelerating!
  - One instrument functioning beyond previous sensitivity limits
  - Next observing run planned for next year!
- Multi-messenger astronomy with gravitational waves will be a challenging but rewarding prospect: Gravitational-wave astronomy looks to partner observations with electromagnetic and particle observatories; joint observations to explore questions in current astrophysics as well as open new avenues
- **Given current understanding/uncertainty of standard candle sources (like binary neutron stars) a detection(s) is ≤ 3 years away**

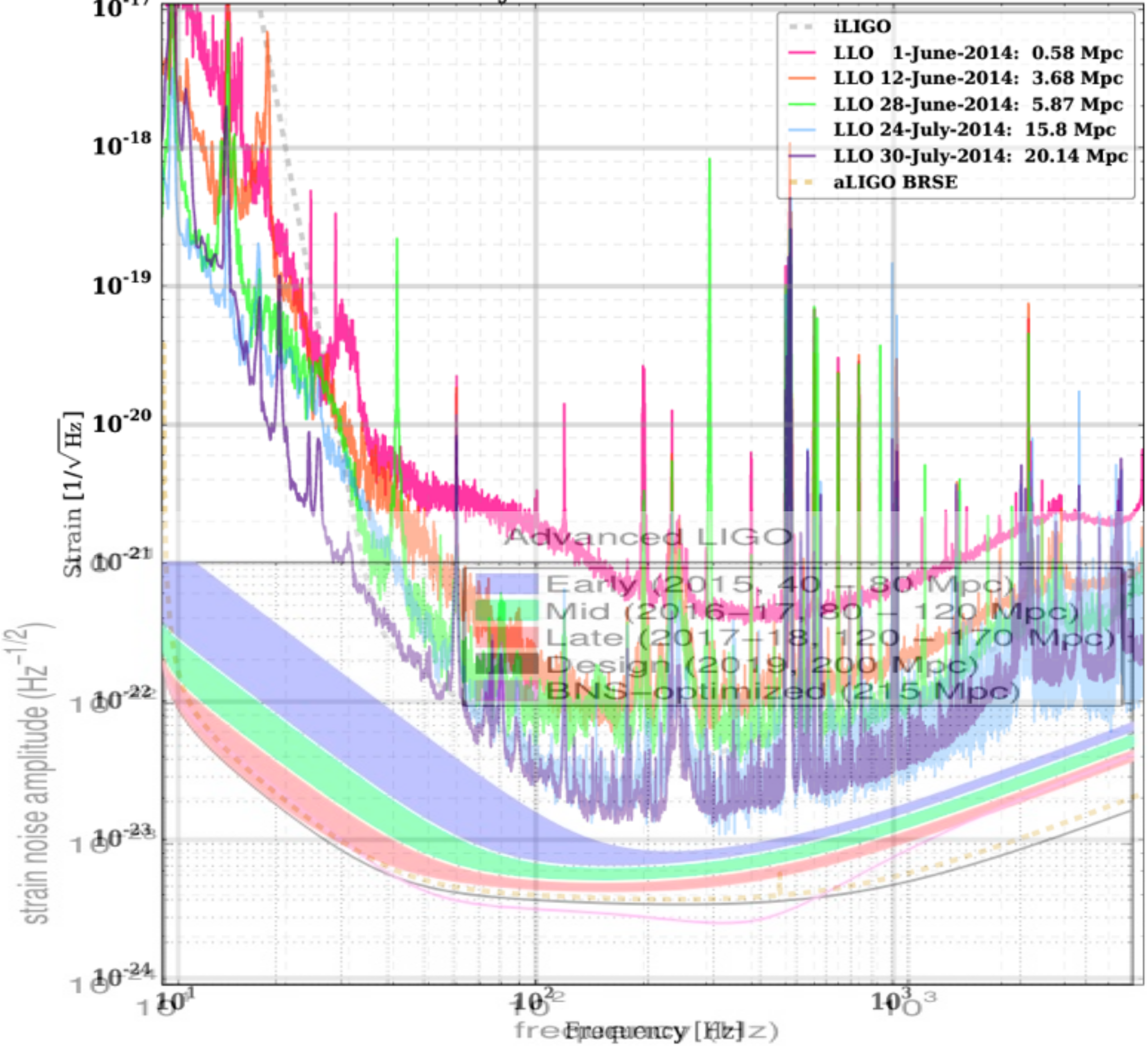
Just In Case

LSC VIRGO

2018 Preview

source	current upper limit	2nd gen rate	predicted rate
neutron star binaries (1.35 + 1.35 $M_\odot$)	1.3×10^{-4} Mpc^{-3} yr^{-1}	1.3×10^{-7} Mpc^{-3} yr^{-1}	$<$ 10^{-6} Mpc^{-3} yr^{-1}
stellar mass BH binaries (5 + 5 $M_\odot$)	6.4×10^{-6} Mpc^{-3} yr^{-1}	6.4×10^{-9} Mpc^{-3} yr^{-1}	$=$ 5×10^{-9} Mpc^{-3} yr^{-1}
mixed binaries (1.35 + 5 $M_\odot$)	3.1×10^{-5} Mpc^{-3} yr^{-1}	3.1×10^{-8} Mpc^{-3} yr^{-1}	$=$ 3×10^{-8} Mpc^{-3} yr^{-1}
"high stellar mass" BH binaries (50 + 50 $M_\odot$)	7×10^{-8} Mpc^{-3} yr^{-1}	7×10^{-11} Mpc^{-3} yr^{-1}	—
intermediate mass BH binaries (center of 88 + 88 $M_\odot$)	1.2×10^{-7} Mpc^{-3} yr^{-1}	1.2×10^{-10} Mpc^{-3} yr^{-1}	$<$ 3×10^{-10} Mpc^{-3} yr^{-1}
ringdowns (BH merger, q=1:4, M_T=125 $M_\odot$)	1.1×10^{-7} Mpc^{-3} yr^{-1}	1.1×10^{-10} Mpc^{-3} yr^{-1}	$<$ 3×10^{-10} Mpc^{-3} yr^{-1}
generic short-duration transient (BH merger, supernova, etc...)	1.3 yr^{-1}	1.3 yr^{-1}	—

Does Not Include Improvements to Detector Bandwidth


iLIGO
LLO 1-June-2014: 0.58 Mpc
LLO 12-June-2014: 3.68 Mpc
LLO 28-June-2014: 5.87 Mpc
LLO 24-July-2014: 15.8 Mpc
LLO 30-July-2014: 20.14 Mpc
aLIGO BRSE
Advanced LIGO
Early (2015, 40 – 80 Mpc)
Mid (2016–17, 80 – 120 Mpc)
Late (2017–18, 120 – 170 Mpc)
Design (2019, 200 Mpc)
BNS-optimized (215 Mpc)
Strain [1/√Hz]
strain noise amplitude (Hz$^{-1/2}$)
Frequency [Hz]
frequency (Hz)
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}