# Observing Gravitational Waves with Advanced LIGO

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LIGO-G1602189

# LIGO

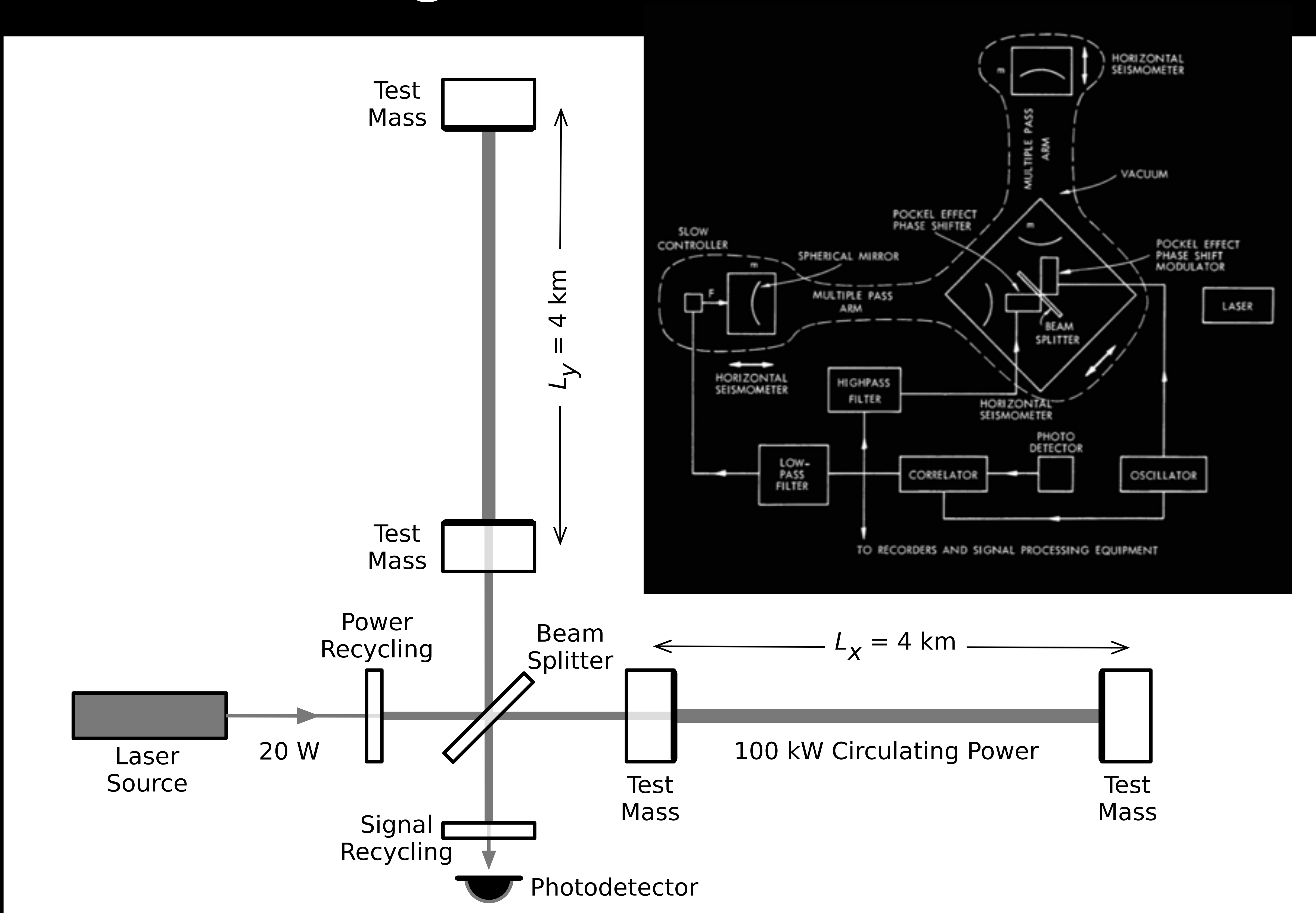
## Laser Interferometer Gravitational-wave Observatory

LIGO-Hanford

LIGO-Livingston

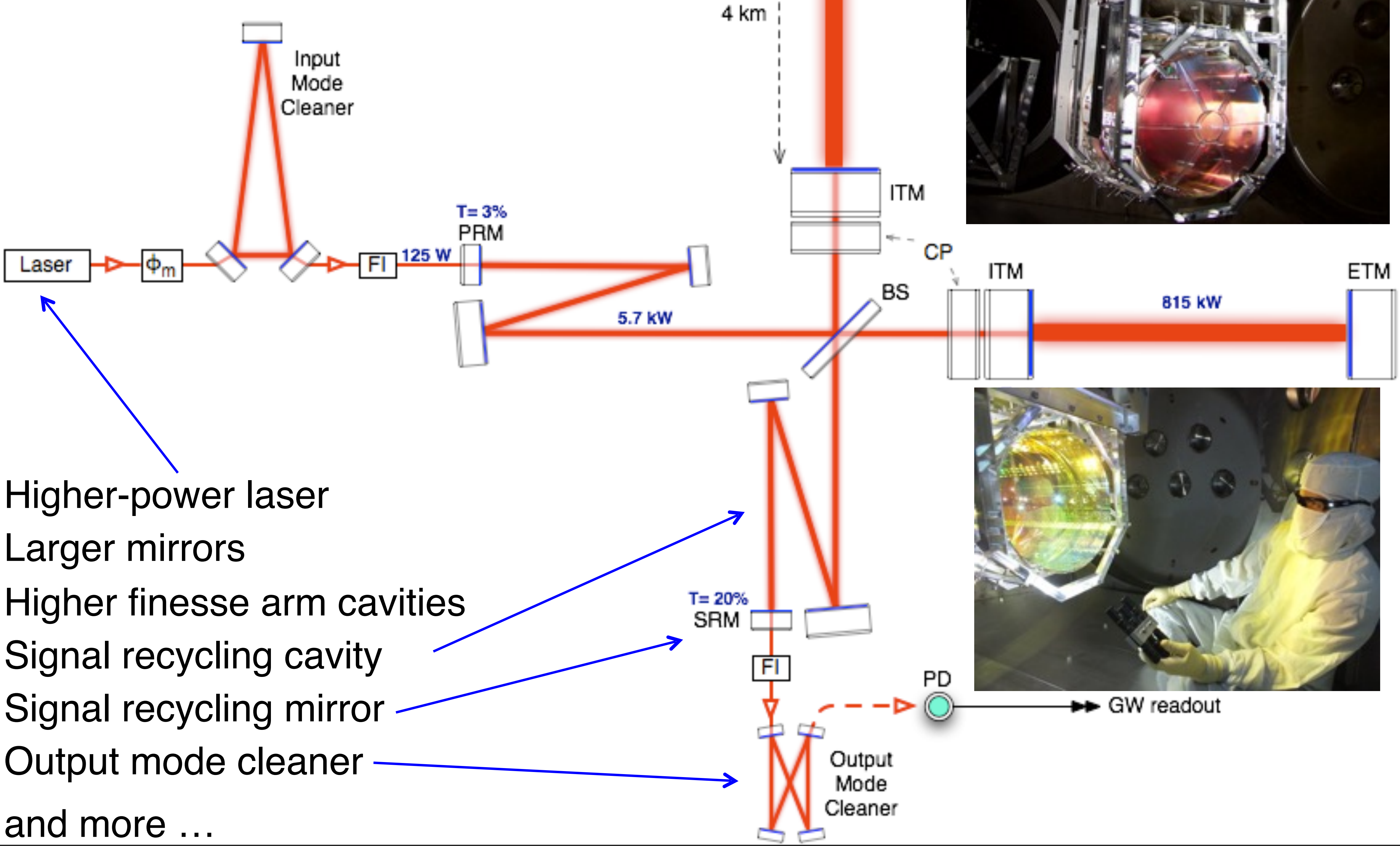

# The design

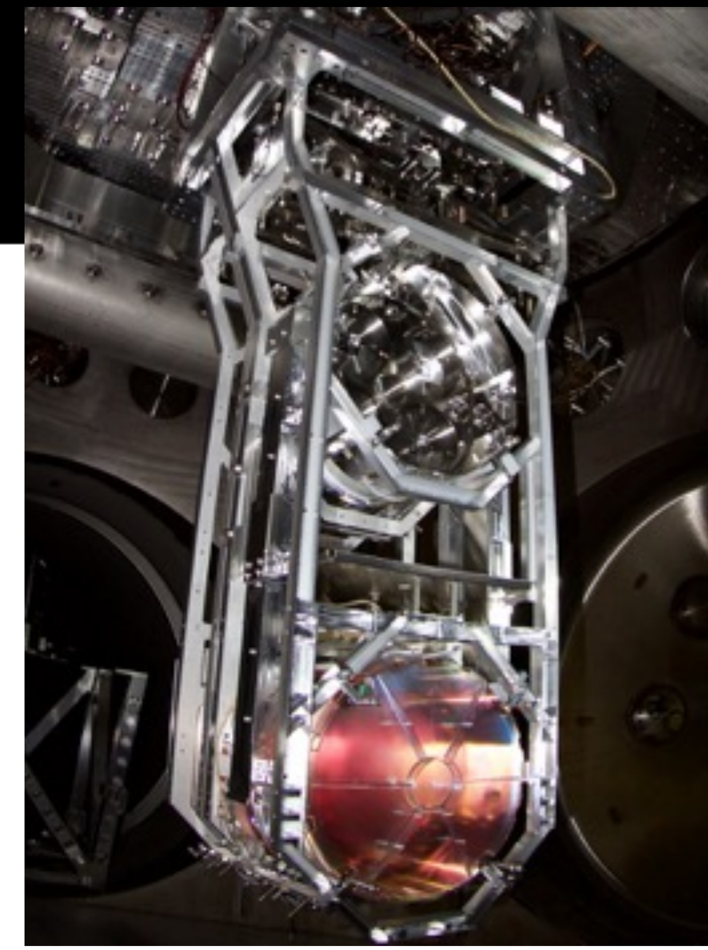
Weiss's 1972 design study
(Weiss, *Electromagnetically Coupled Broadband Gravitational Antenna*, 1972 **Tech. Rep. MIT**)



# Advanced LIGO

Comprehensive upgrade of Initial LIGO instrumentation in the same vacuum system

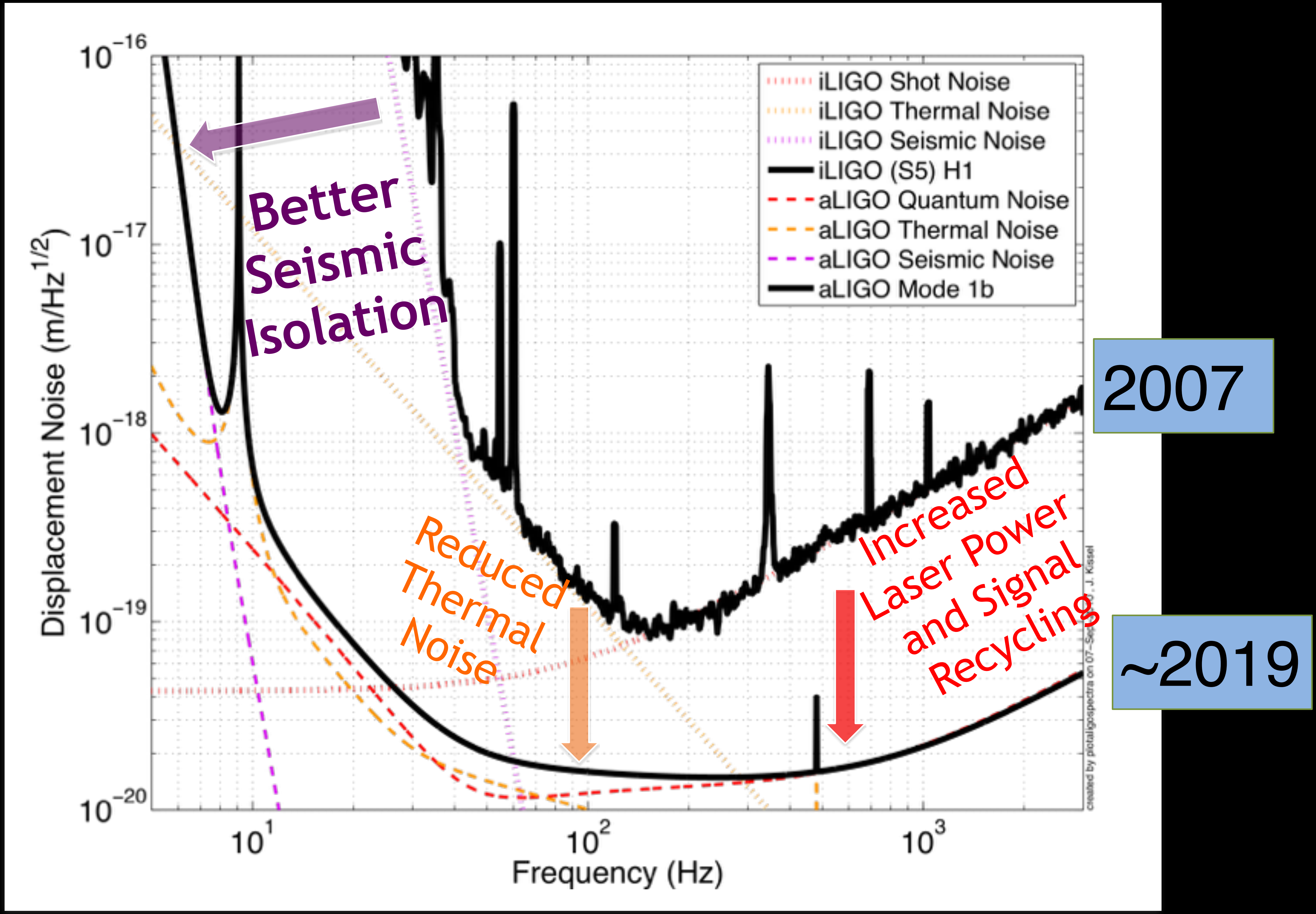


## Improvements

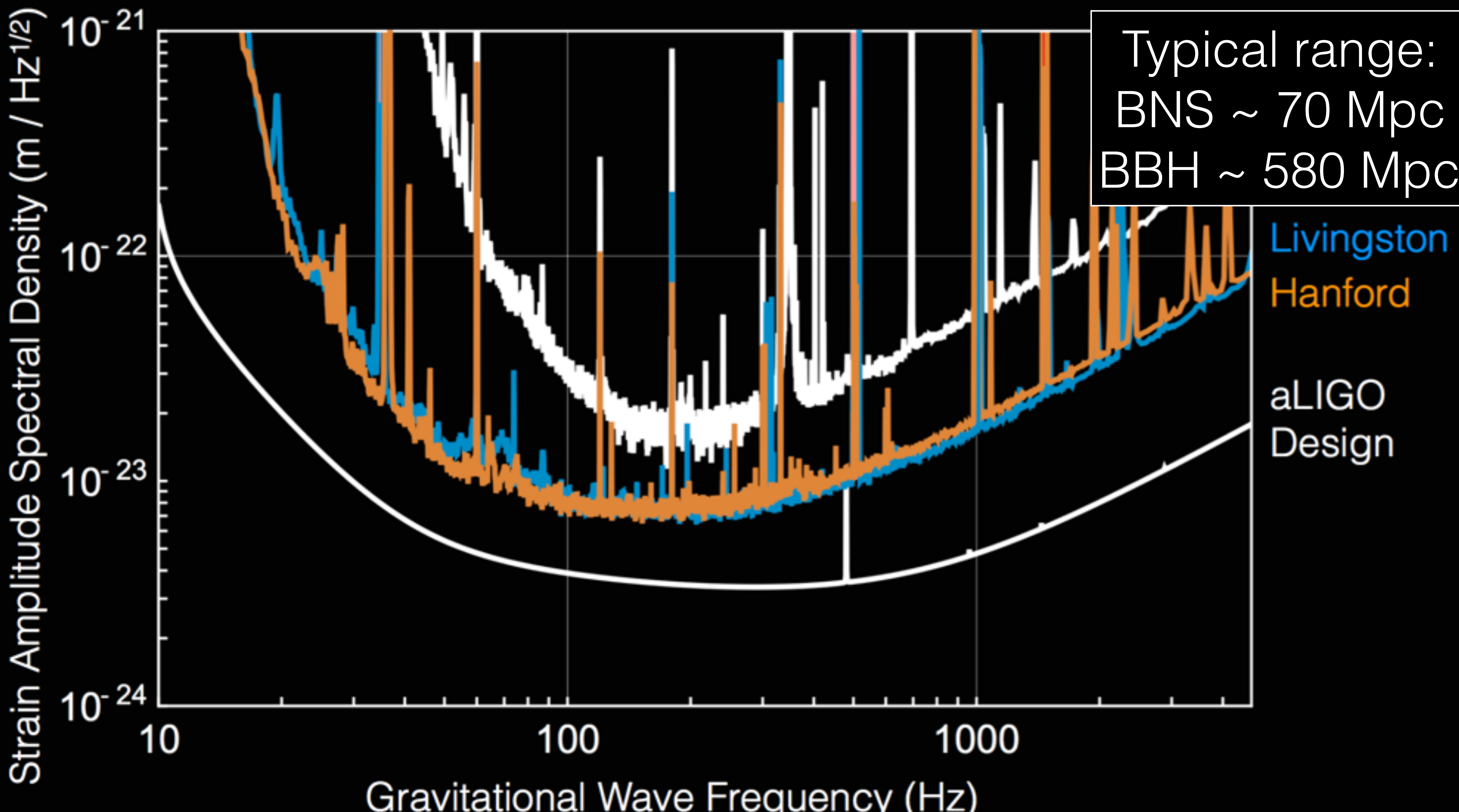
- Higher-power laser
- Larger mirrors
- Higher finesse arm cavities
- Signal recycling cavity
- Signal recycling mirror
- Output mode cleaner
- and more …

# From iLIGO to aLIGO



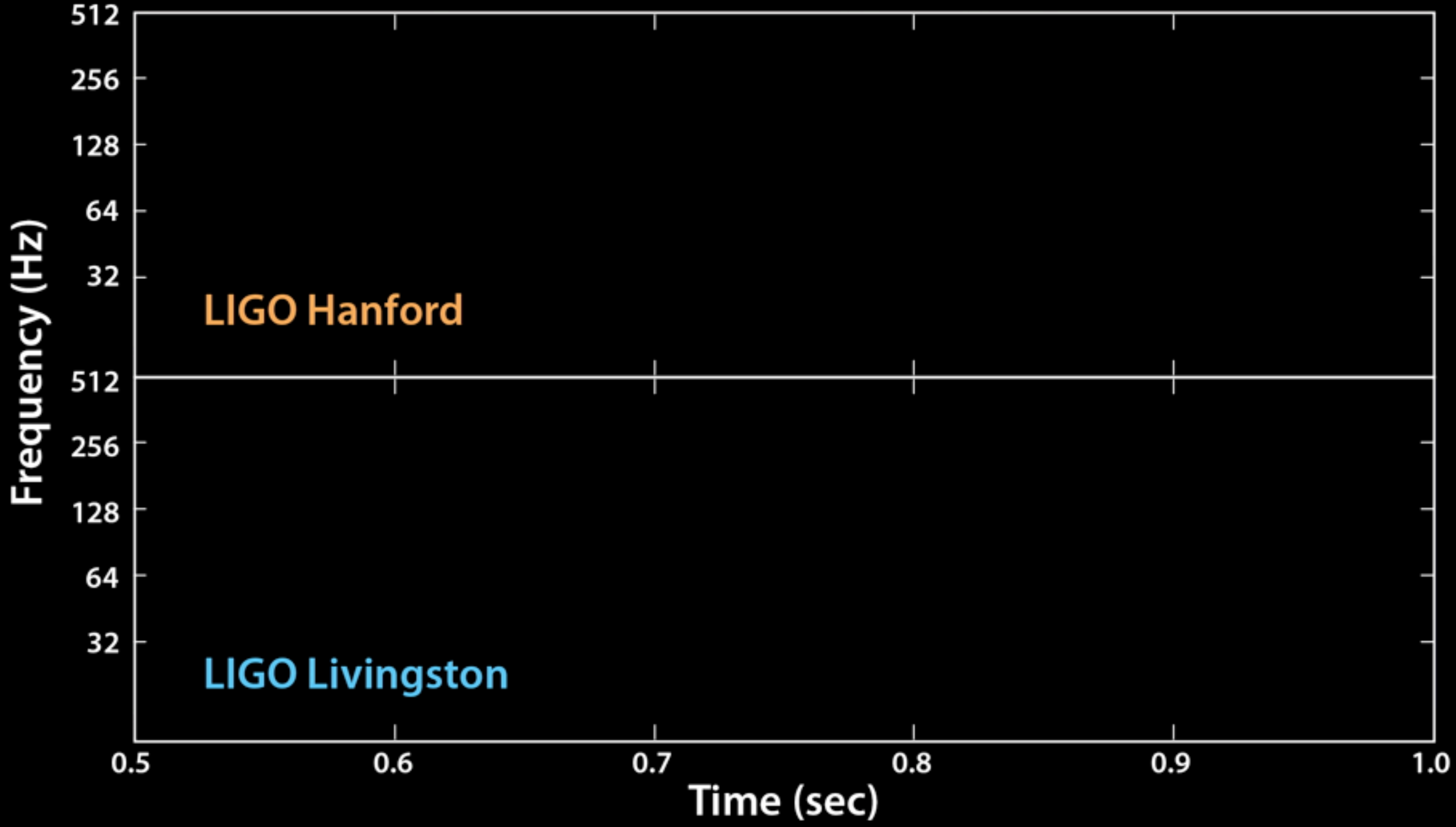

https://dcc.ligo.org/LIGO-P1000103/public

# Sensitivity: past, present and future

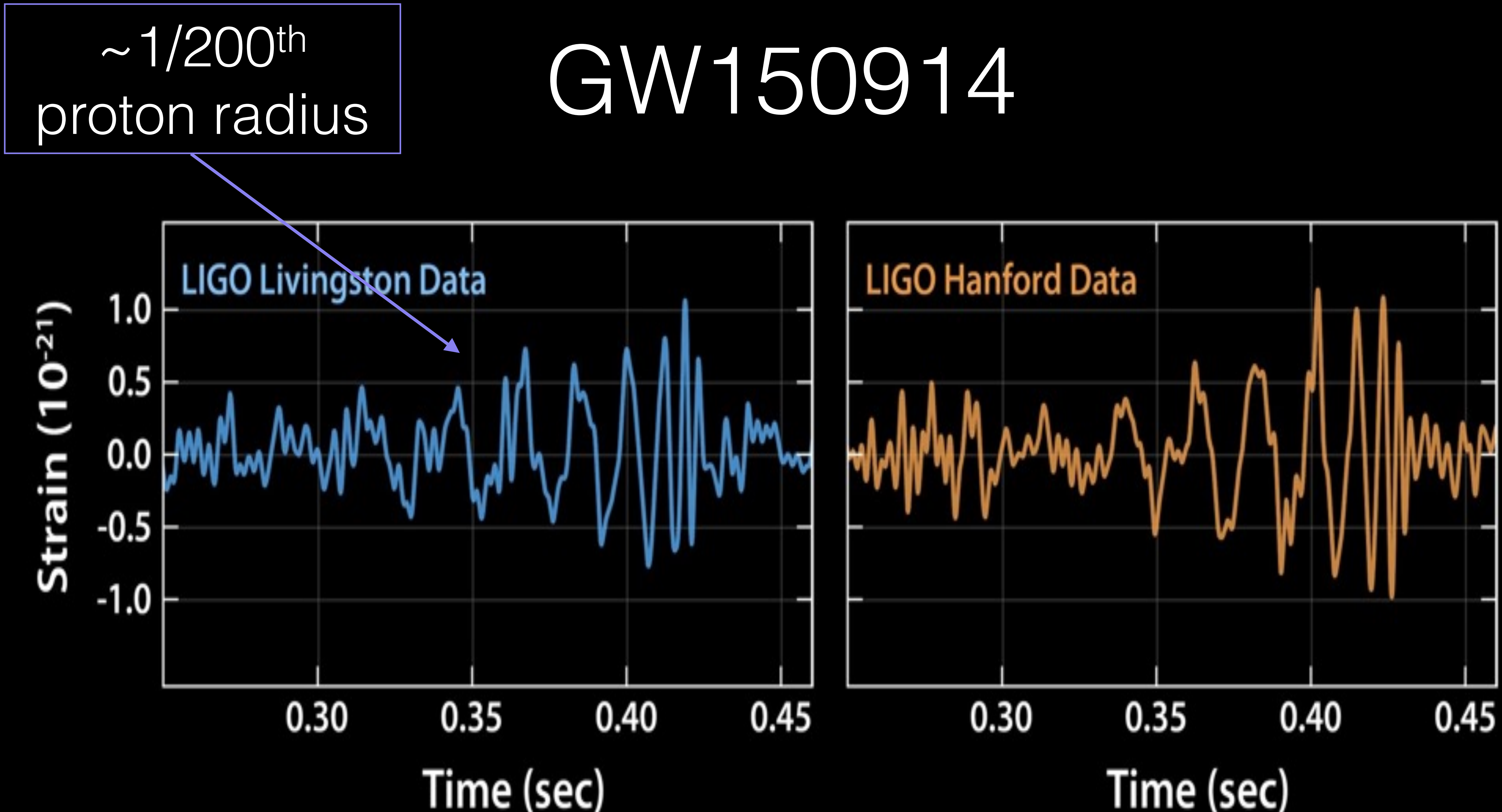



PRL 116, 131103 (2016)

# In the early hours of September 14th, 2015…



# GW150914

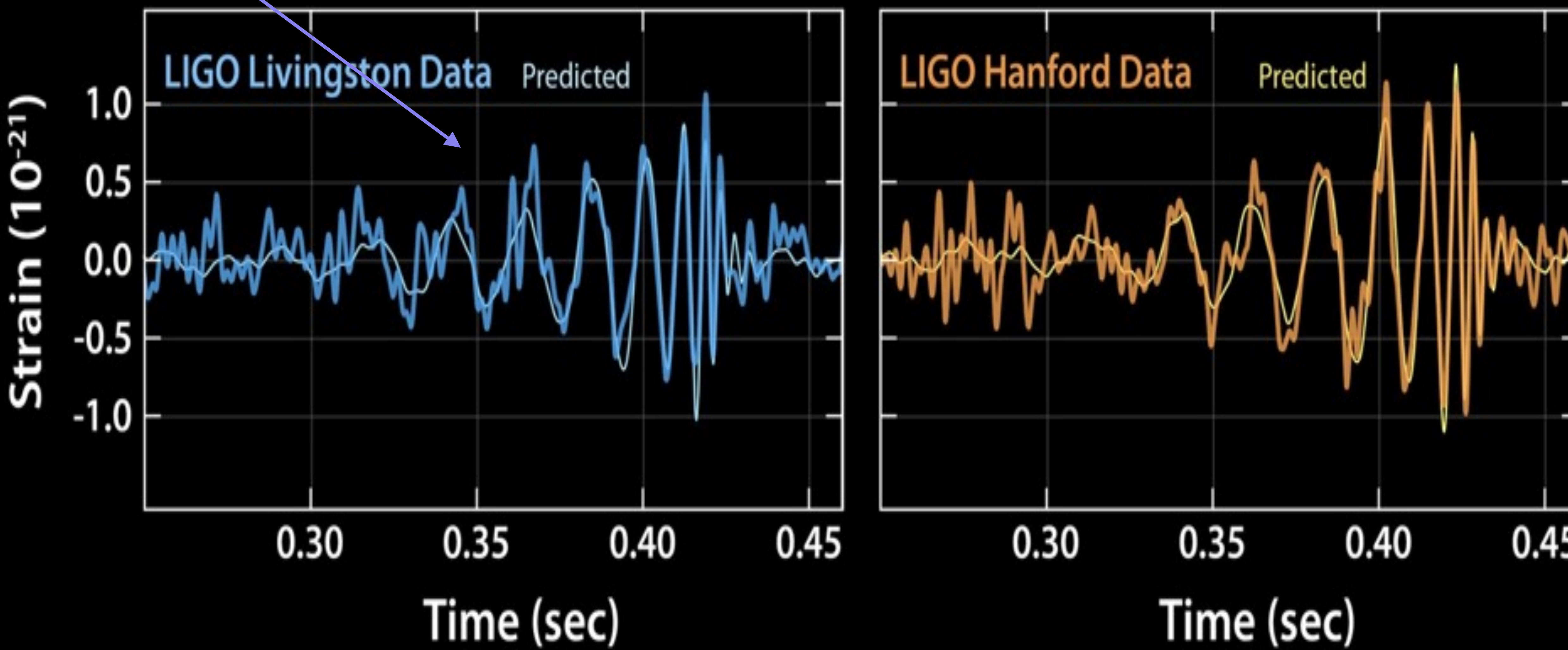



PRL 116, 061102 (2016)

- Observed on September 14th, 2015 at 09:40:45 UTC
- First observed in LIGO-Livingston then 7ms later at LIGO-Hanford
- Over 0.2 seconds the signal increases in frequency and amplitude over ~8 cycles from 35Hz to peak amplitude at 150 Hz

~1/200th proton radius

# GW150914




PRL 116, 061102 (2016)

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# The … ent…

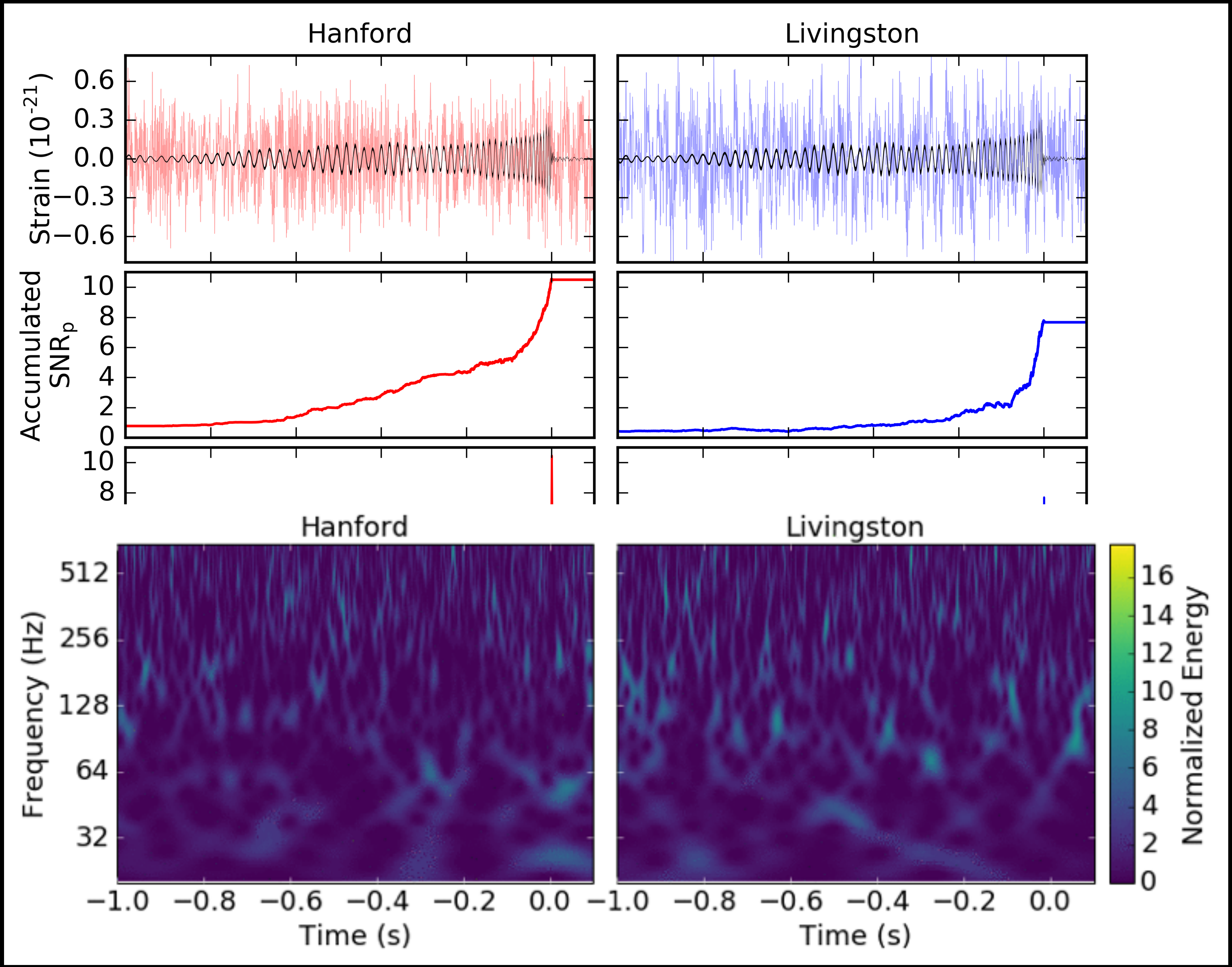



I. … tem PSR B1913+16

In 1916, the year … ient observations of

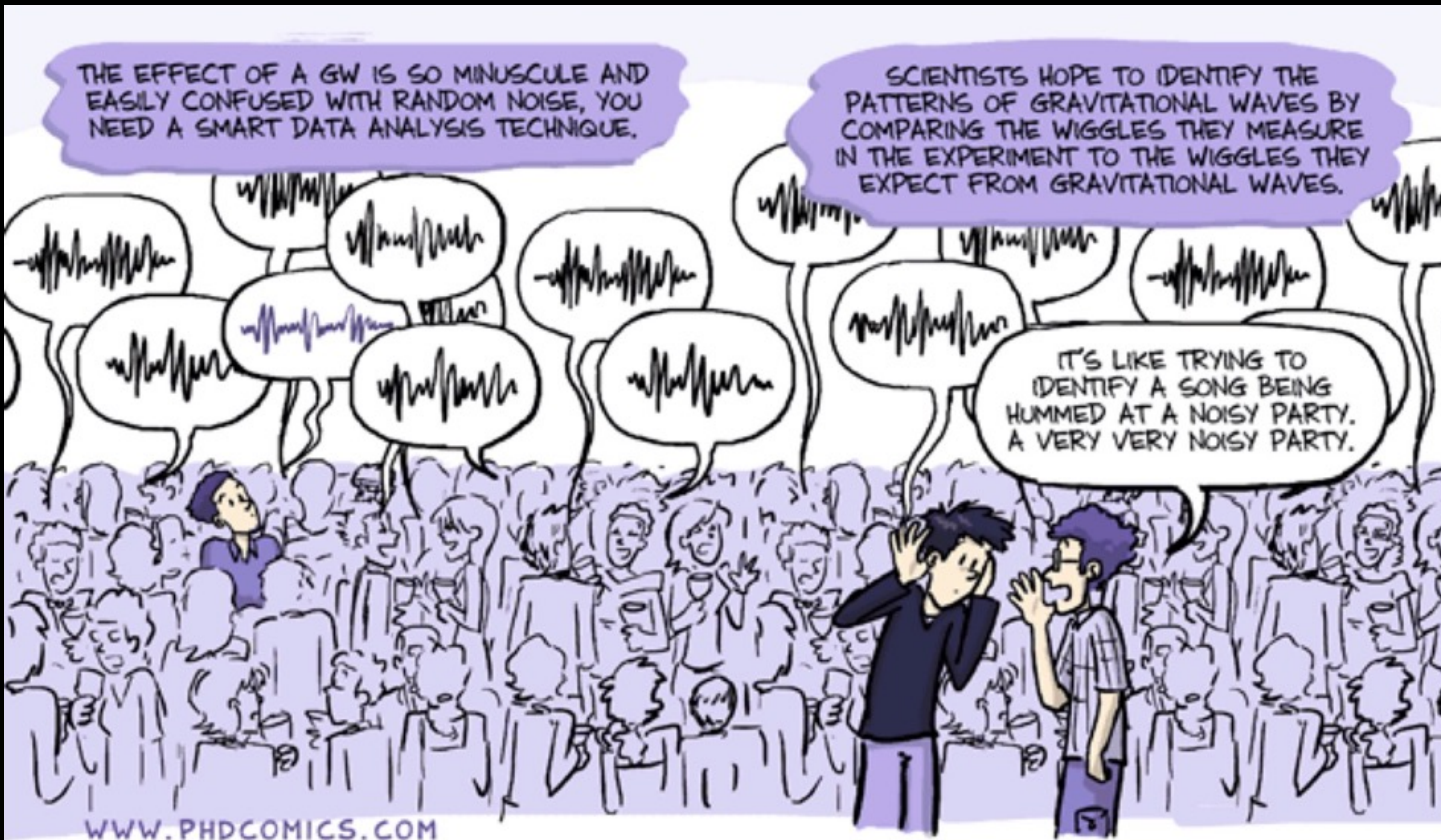
its energy loss by Taylor and Weisberg [21] demonstrated

# GW151226




PRL 116, 241103 (2016)

# Making a detection

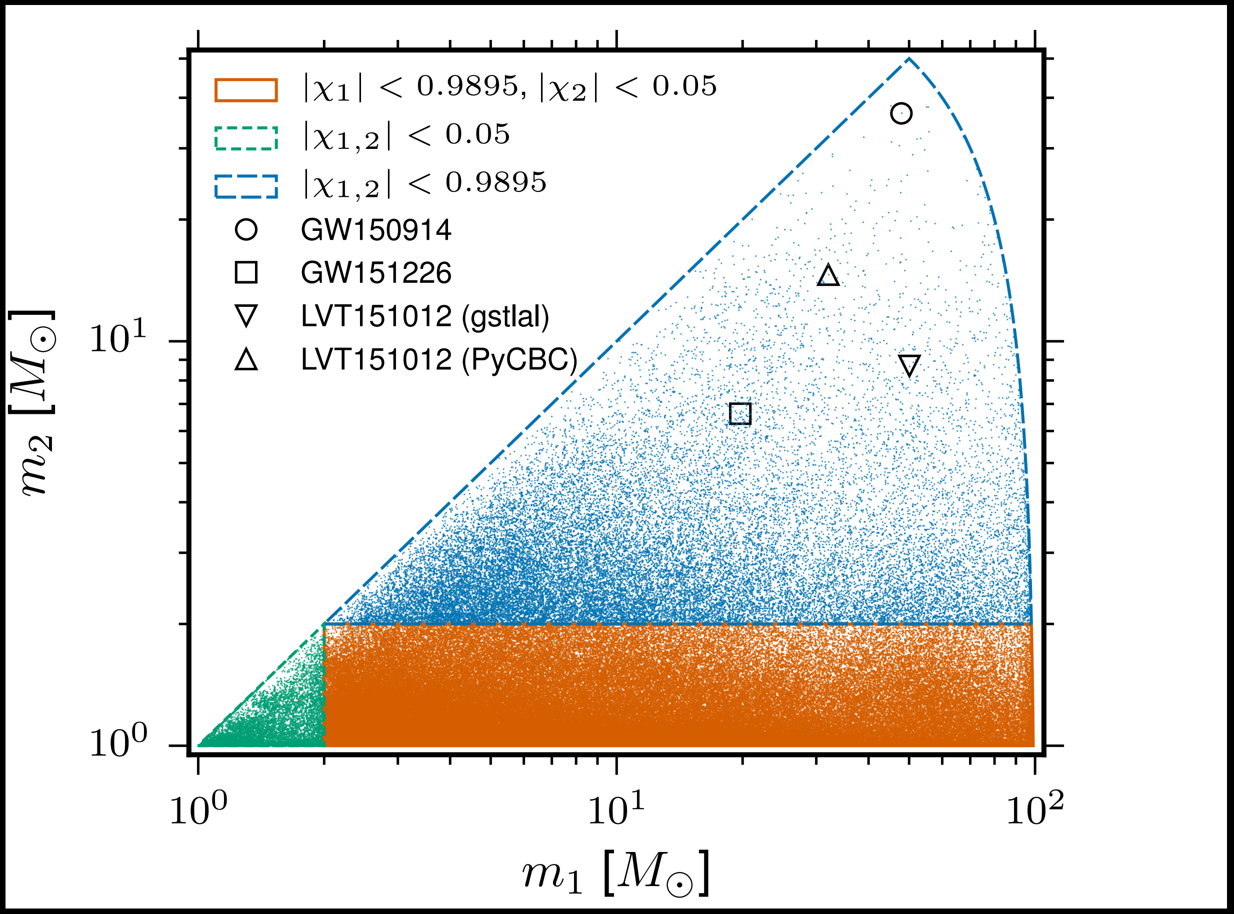


# Template space

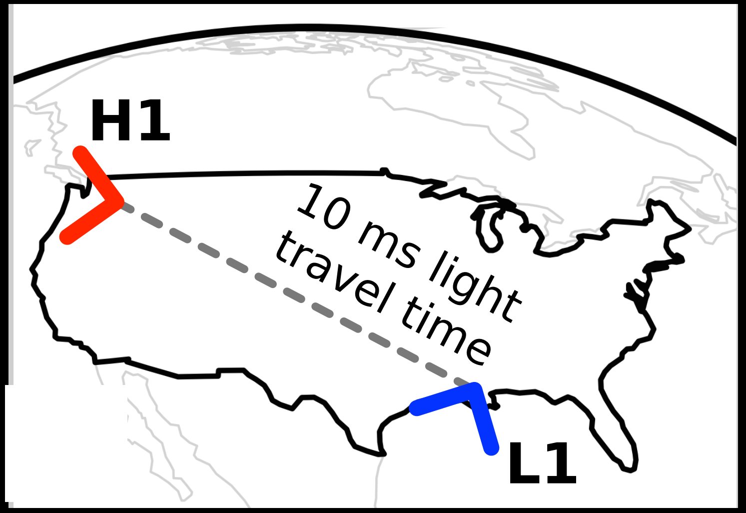
- To detect signals from compact-object binaries, we construct a bank of template waveforms and matched-filter the data

$$\rho = \frac{\langle s|h\rangle}{\sqrt{\langle h|h\rangle}}$$

$$\langle a|b\rangle = 4\mathrm{Re}\int_{f_{\mathrm{low}}}^{f_{\mathrm{high}}} \frac{\tilde{a}(f)\tilde{b}(f)}{S_n(f)}\,df$$




- An event must match the same waveform template in both detectors within the light travel time between sites

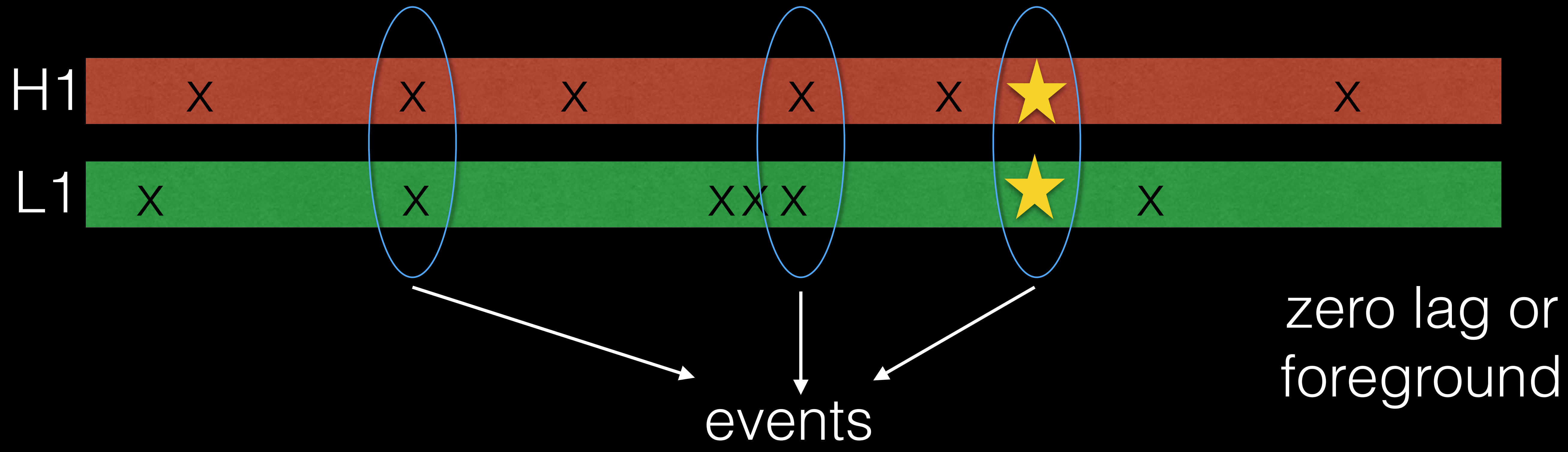



10 ms + 5 ms for uncertainly in arrival time of weak signals

- Events are assigned a detection-statistic value that ranks their likelihood of being a gravitational wave signal

# Calculating Significance

- Determined by rate at which detector noise produces an event with a detection statistic value equal to or higher than the candidate event
- Background set of data is created from coincident data from multiple detectors
- Slide the timestamps of one detector's data by many multiples of 0.1s and computing a new set of coincident events




Usman et al., arXiv: 1508.02357 (2015)

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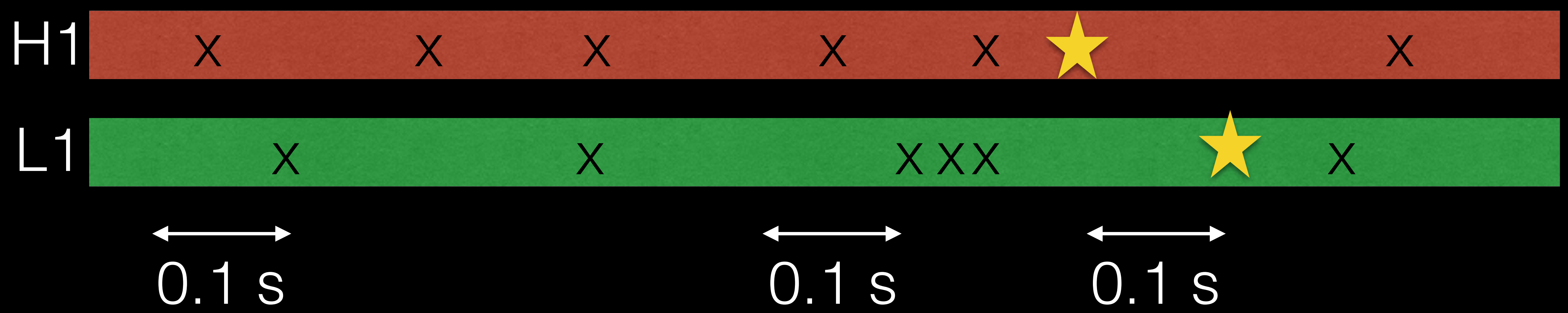


Time shifted data

Usman et al., arXiv: 1508.02357 (2015)

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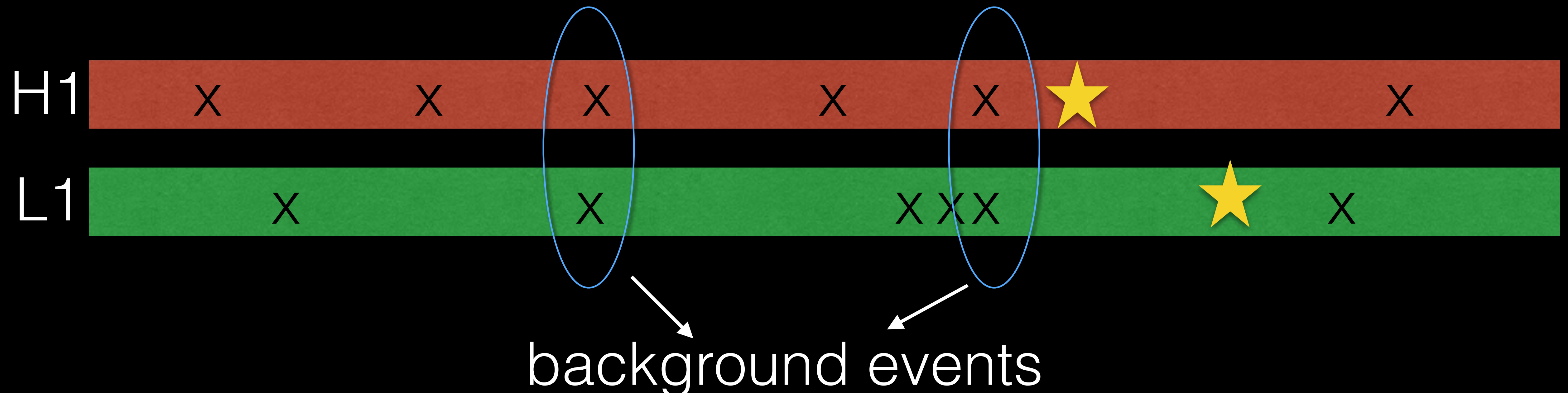
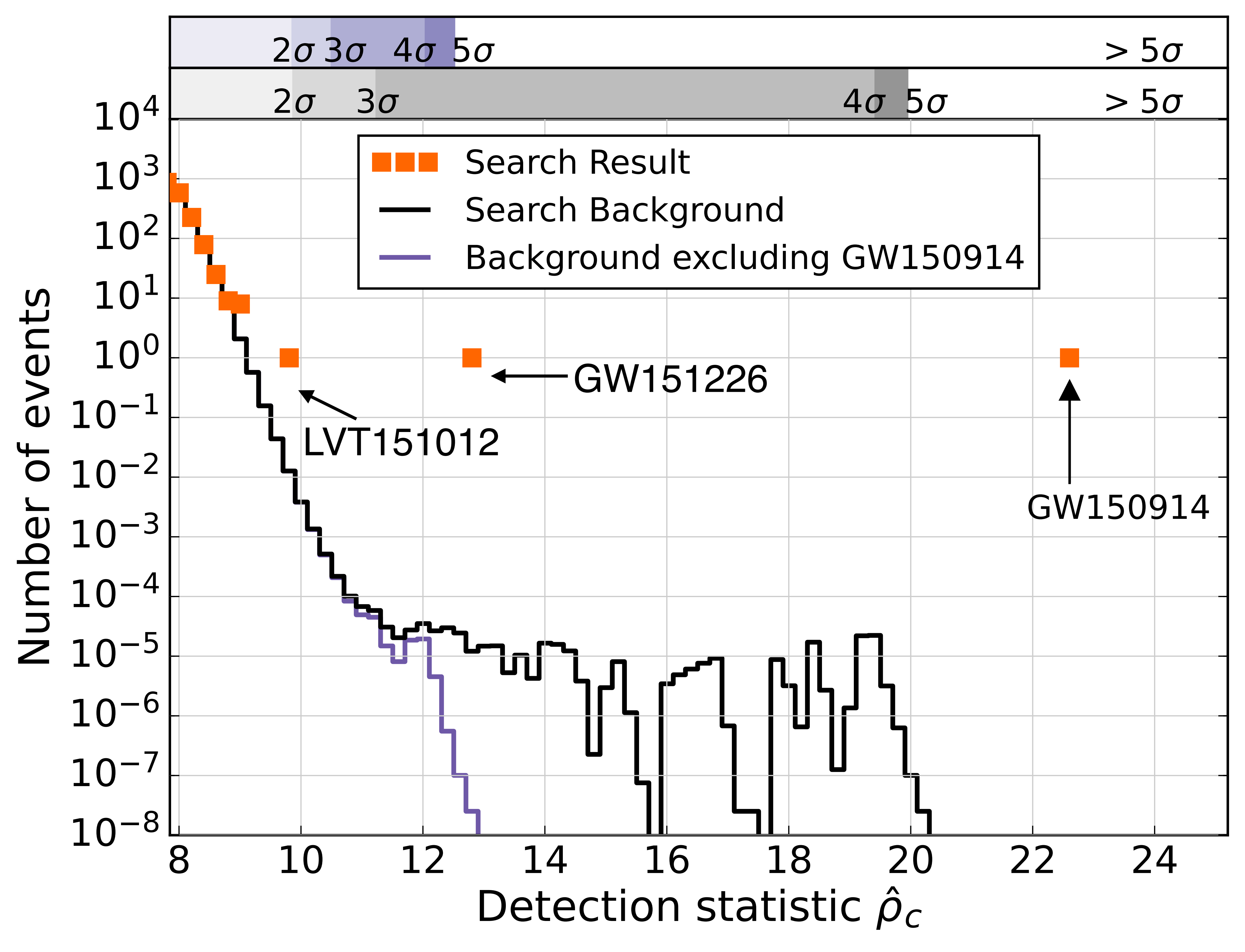



Time shifted data

Usman et al., arXiv: 1508.02357 (2015)

# Results from the first observing run
# (12th Sept 2015 - 19th Jan 2016)




Abbott et al., Phys. Rev. X 6, 041015 (2016)

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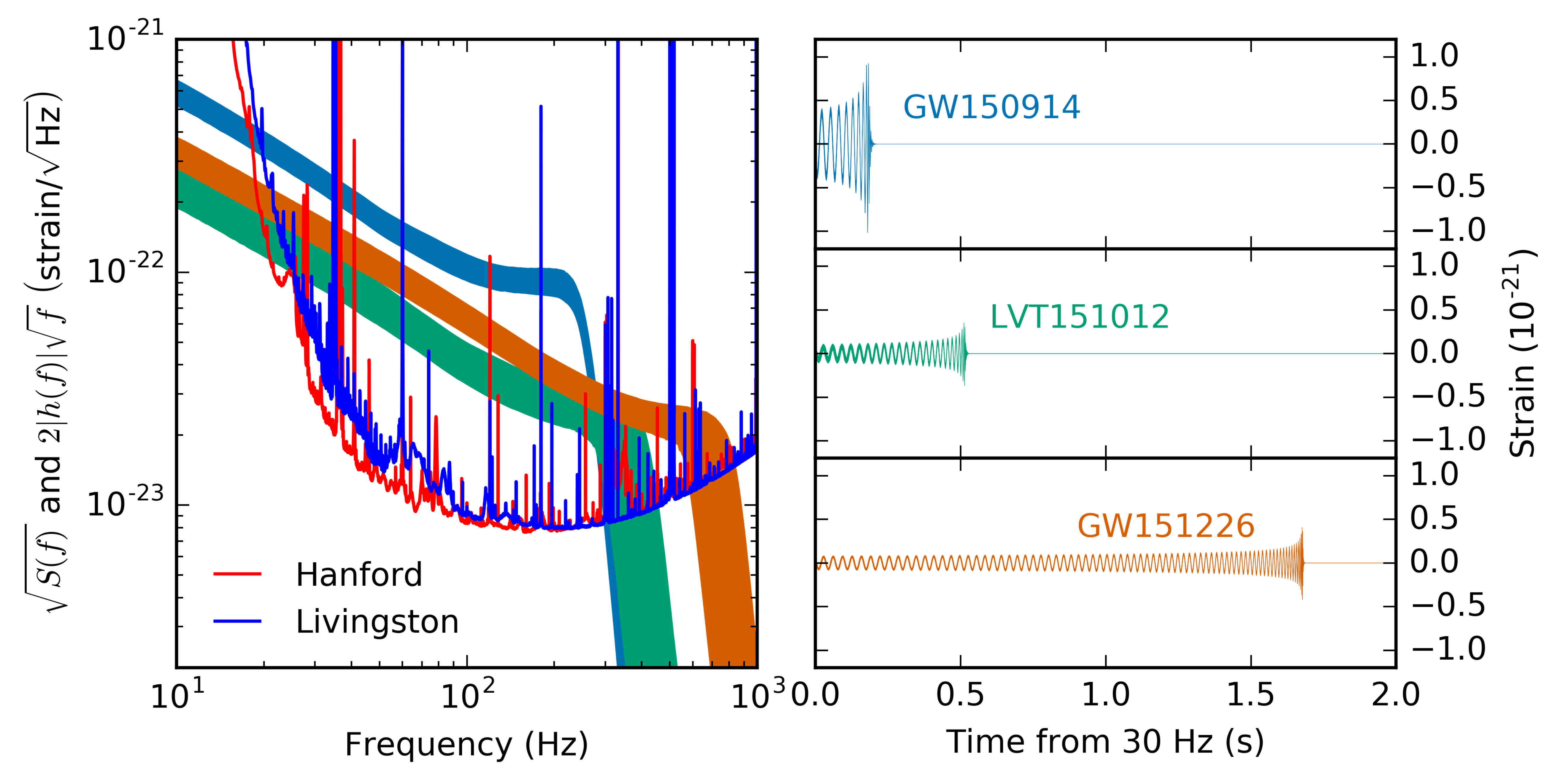
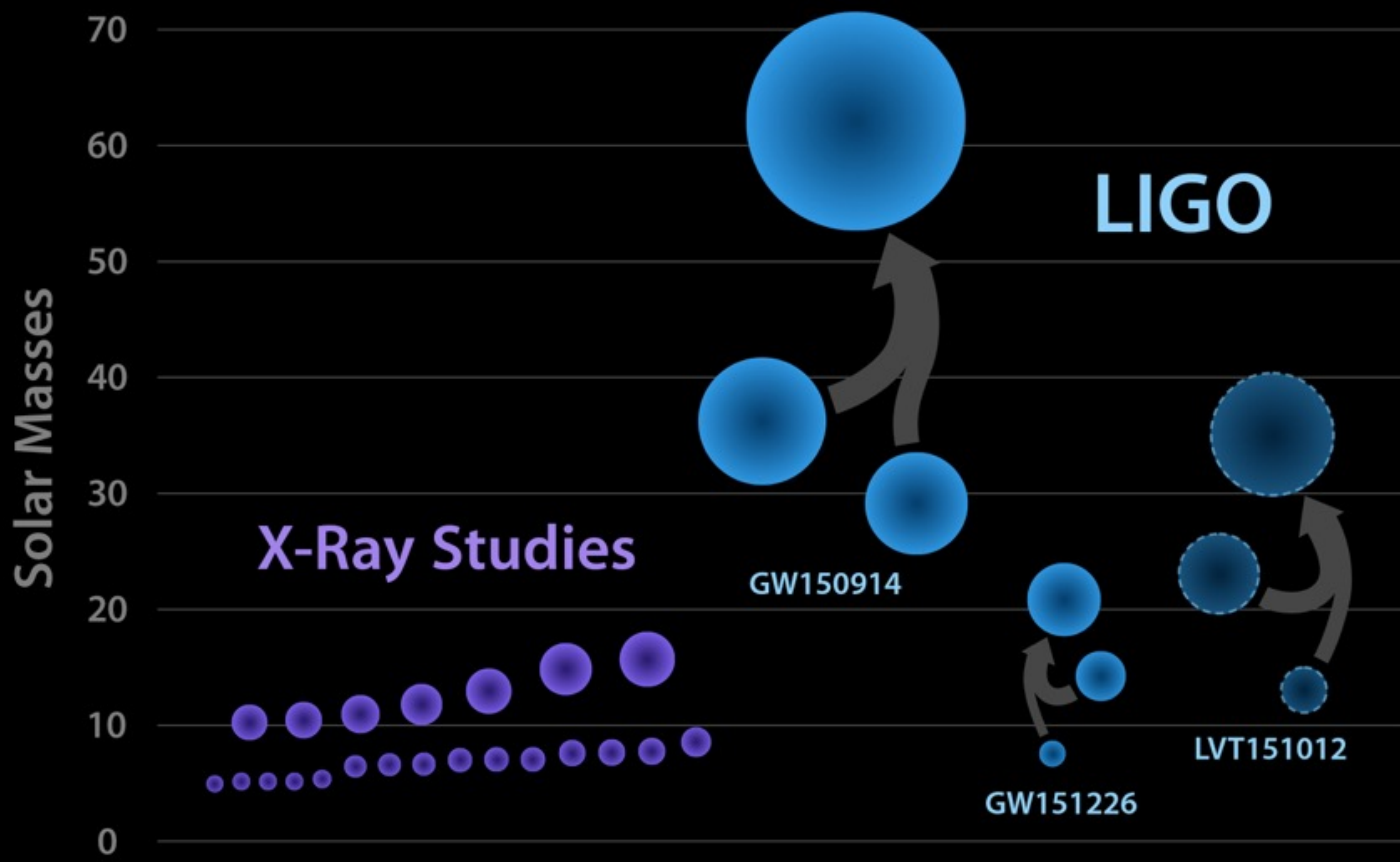



Abbott et al., Phys. Rev. X 6, 041015 (2016)

# Black Holes of Known Mass



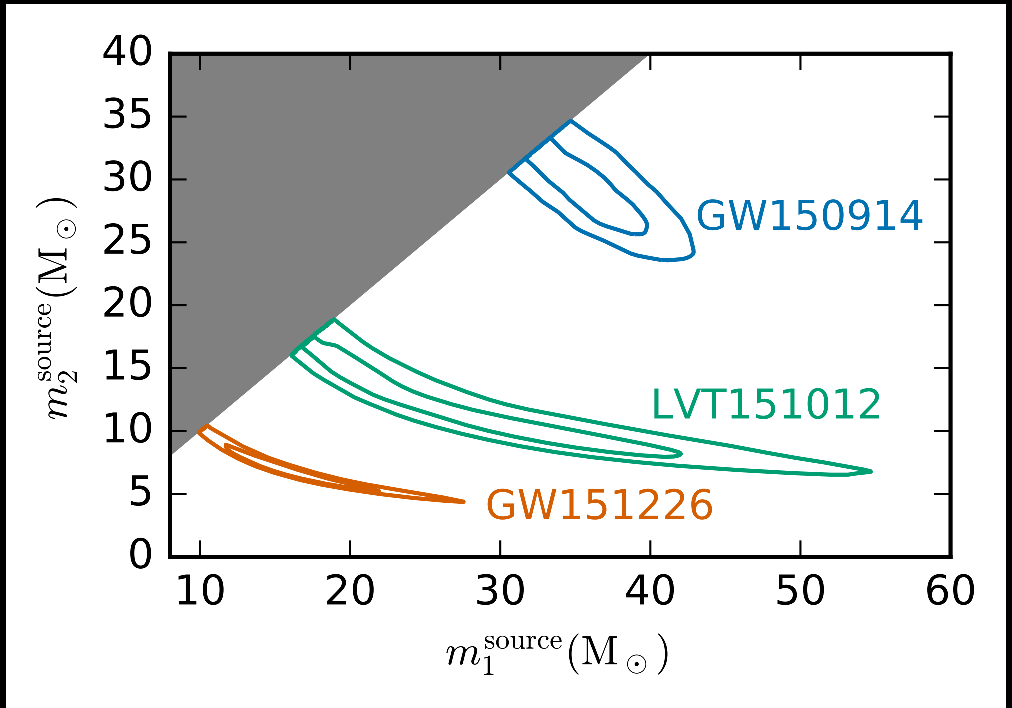

c

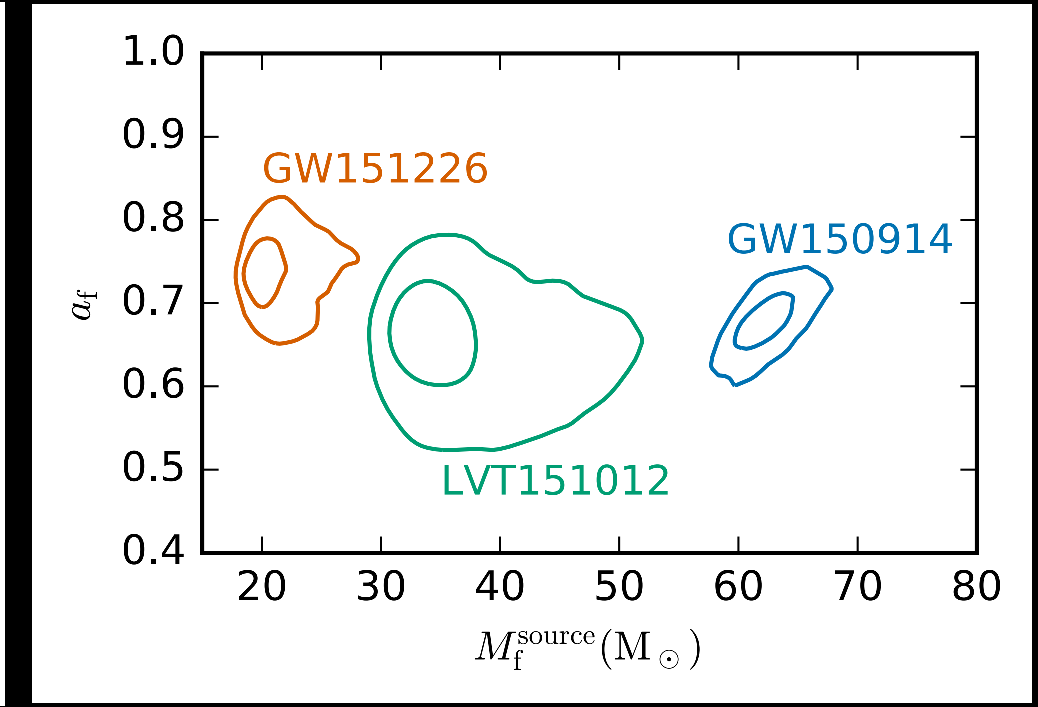
t

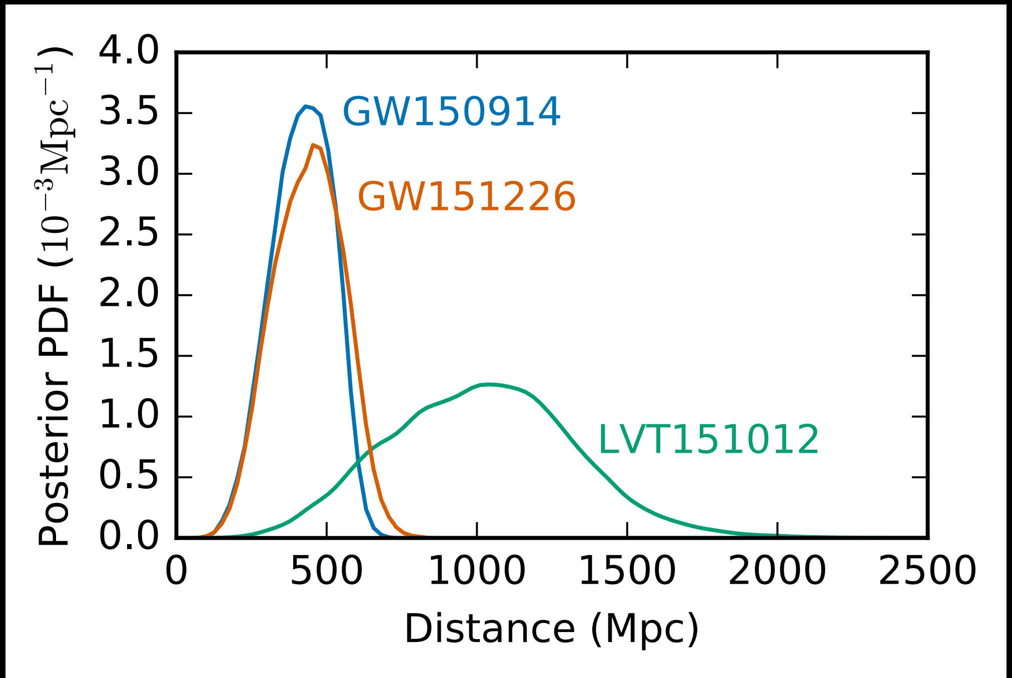
Abb

# Parameters of the BBH systems

Posterior probability densities of the masses, spins and distance to the three events




All 3 remnant black holes have spins ~0.7 as expected for the merger of similar mass black holes in a binary

Abbott et al., Phys. Rev. X 6, 041015 (2016)

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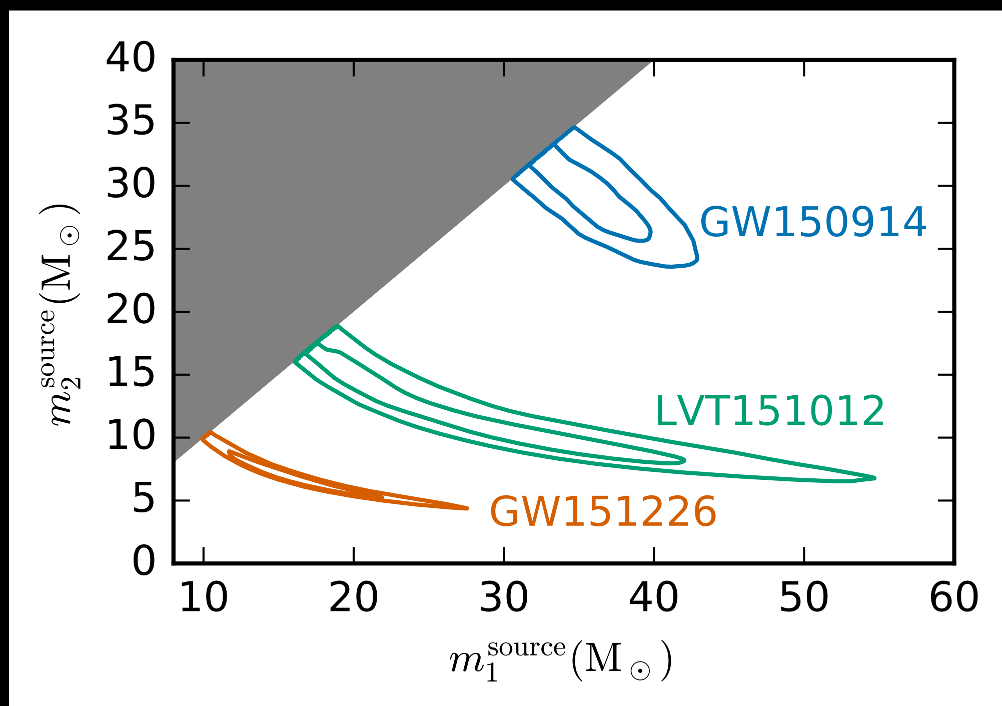
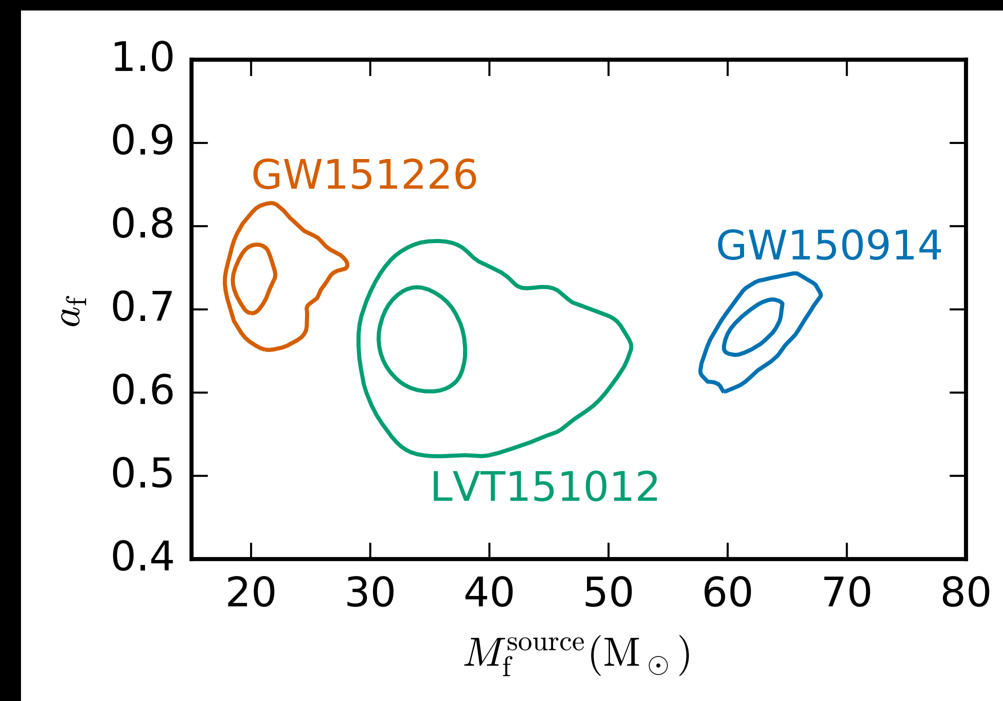
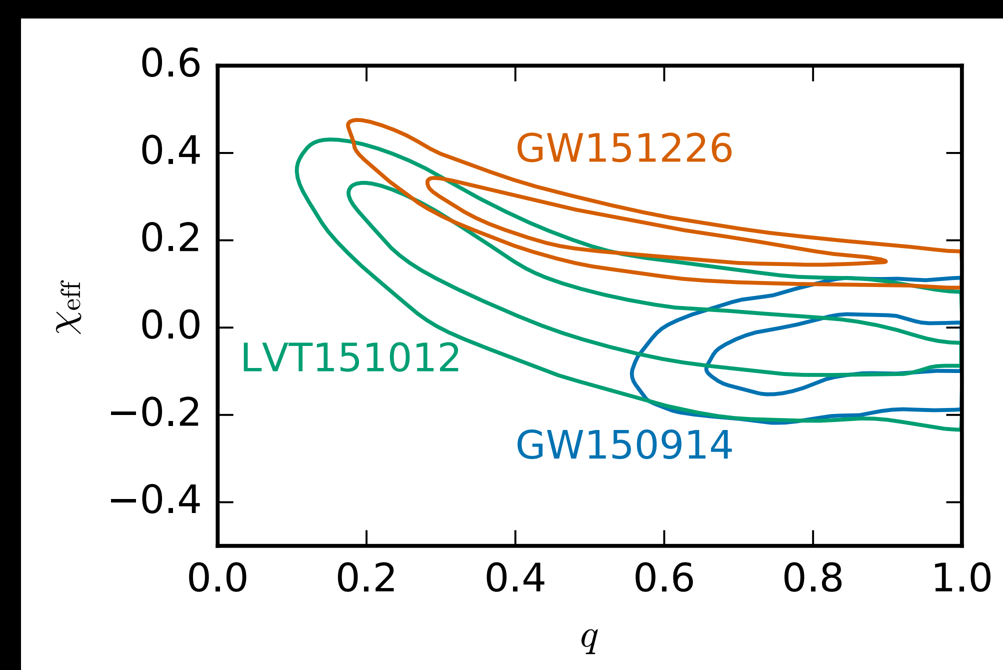



- For GW151226 at least one black hole has spin magnitude > 0.2
- Large spins parallel to angular momentum are disfavoured

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

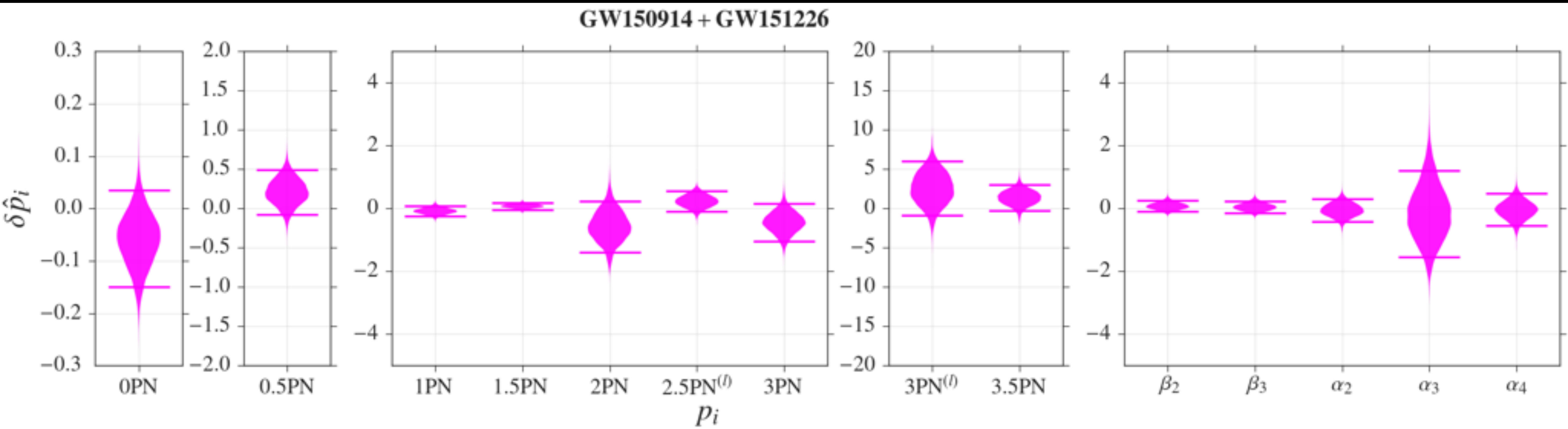
$$\chi_{1,2} = \frac{c}{G m_{1,2}^2}\, \vec{S}_{1,2} \cdot \hat{L}$$




Abbott et al., Phys. Rev. X 6, 041015 (2016)

# Tests of General Relativity

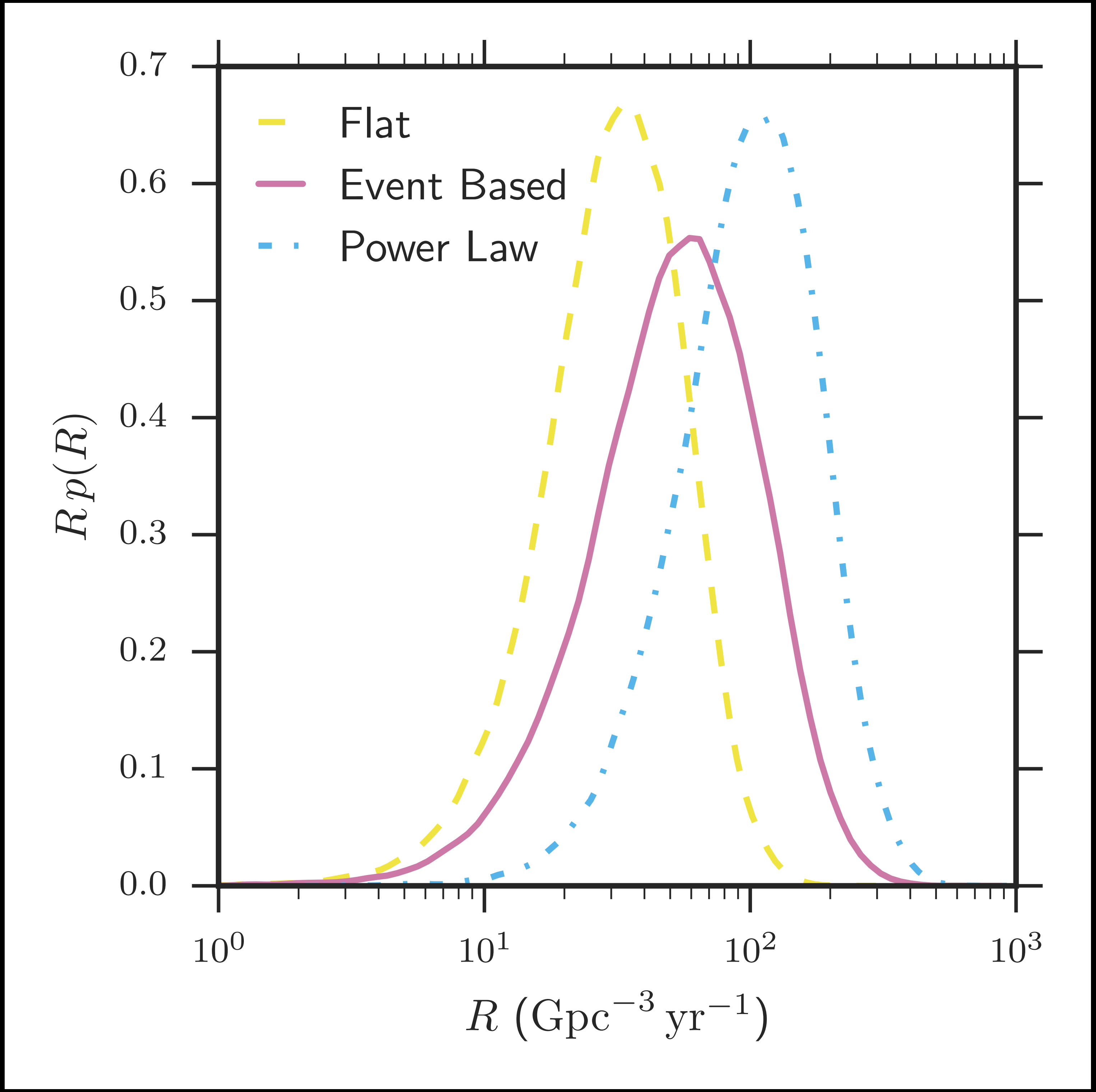
- Allowing deviations in post-Newtonian waveform model
- Parameter deviations are reasonably consistent with zero




- GW150914 - merger-ringdown regime occurred at best instrument sensitivity. Only several cycles in LIGO sensitivity band.
- GW151226 - many cycles in sensitivity band. Signal provides opportunity to probe PN inspiral

Abbott et al., Phys. Rev. X 6, 041015 (2016)

# Rate of BBH mergers

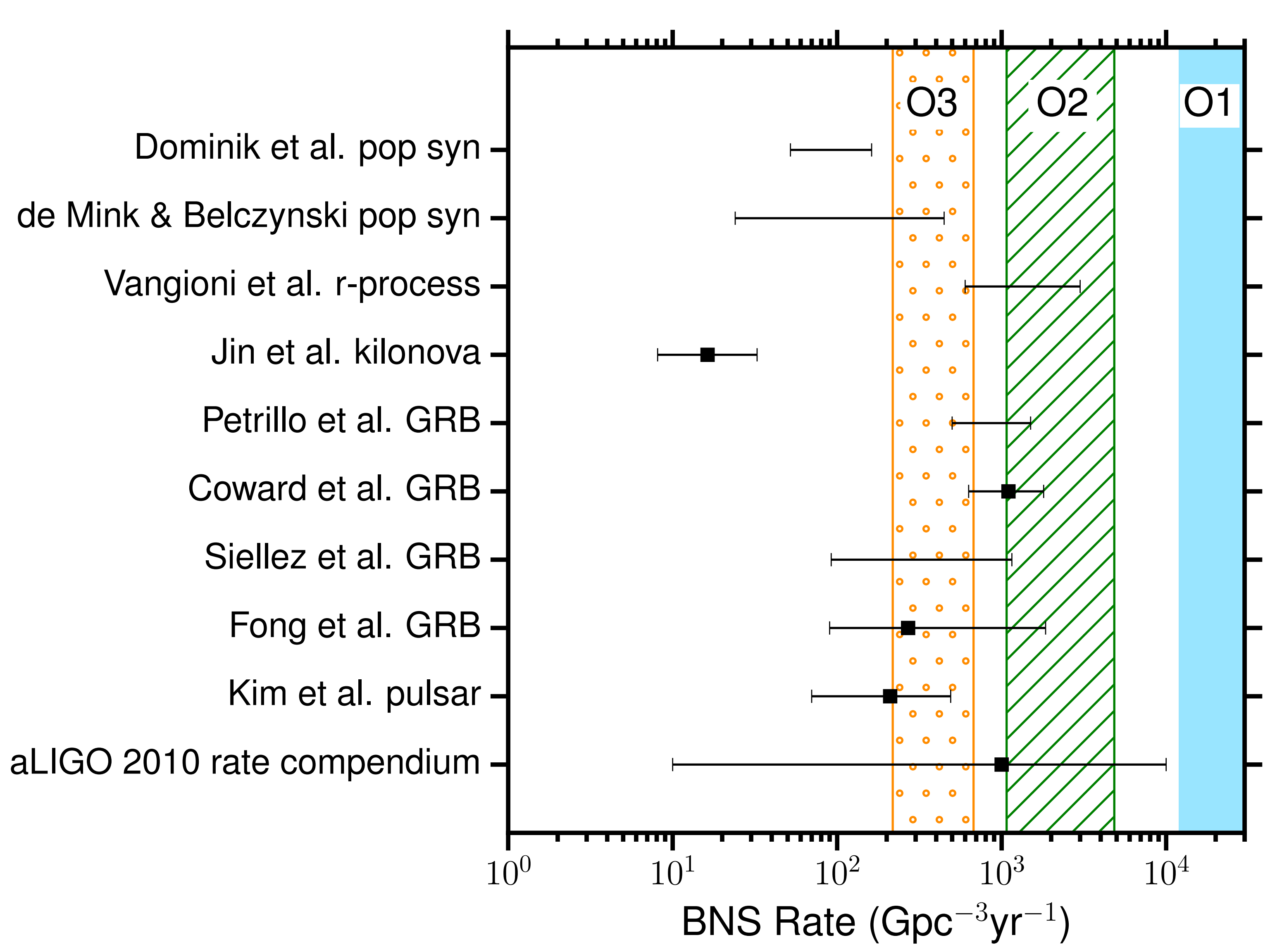



- Knowledge about BBH merger rates depend on the mass distribution - which we don't know very well yet!
- Assume a few different mass distributions
- Infer the BBH merger rate is in the range 9-240 Gpc$^{-3}$yr$^{-1}$

Abbott et al. arXiv: 1606.04856 (2016)

# Searching for BNS and NS-BH systems

During O1 we looking for gravitational waves from binary neutron star (BNS) and neutron star - black hole (NS-BH) systems




- O1 90% upper limit BNS rate compared to other published rates
- Constrain the merger rate of BNS systems with component masses of 1.35±0.13 $M_\odot$ to be less than 12,600 $Gpc^{-3}$ $yr^{-1}$

Abbott et al., arXiv: 1607.07456 (2016)

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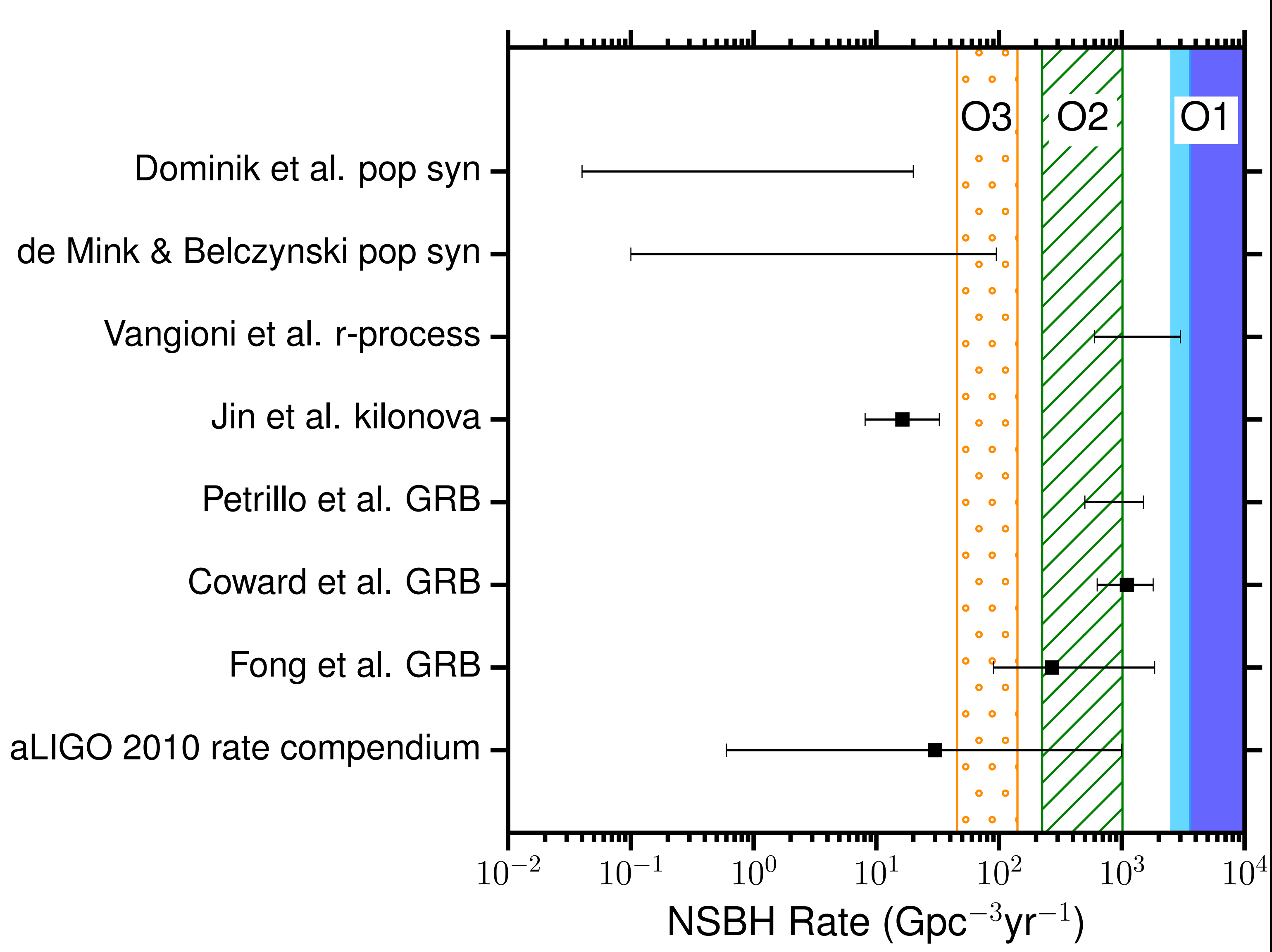



- O1 90% upper limit NS-BH rate compared to other published rates
- Dark blue assumes 1.4-5 $M_\odot$ and light blue 1.4-10 $M_\odot$
- Constrain the merger rate of NS-BH systems with BH at least 5 $M_\odot$ to be less than 3,600 $Gpc^{-3}$ $yr^{-1}$ (assuming isotropic distribution of component spins)
- O2 and O3 BNS ranges are assumed to be 1-1.9 and 1.9-2.7 times larger than O1

Abbott et al., arXiv: 1607.07456 (2016)

# Future Network

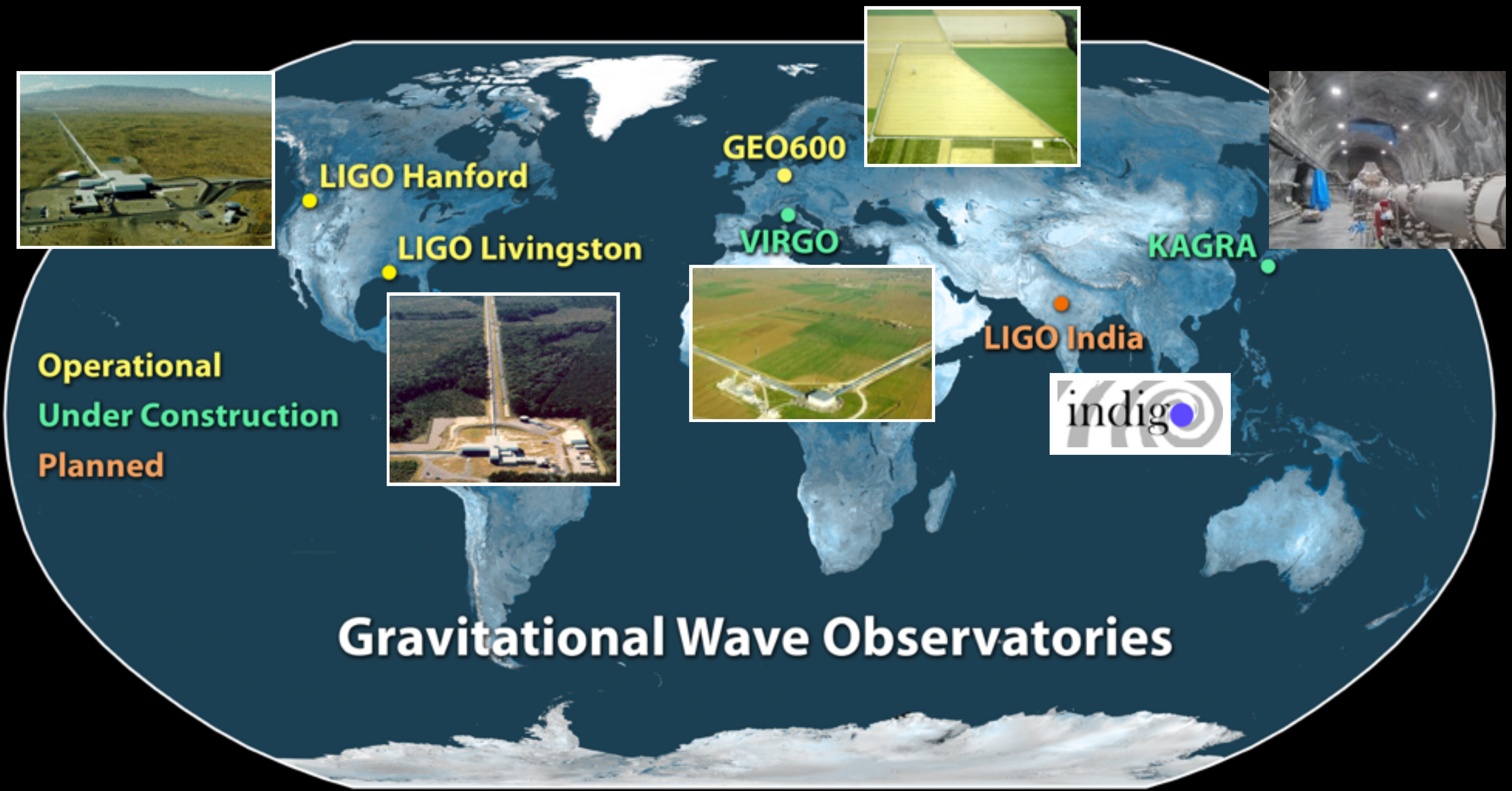
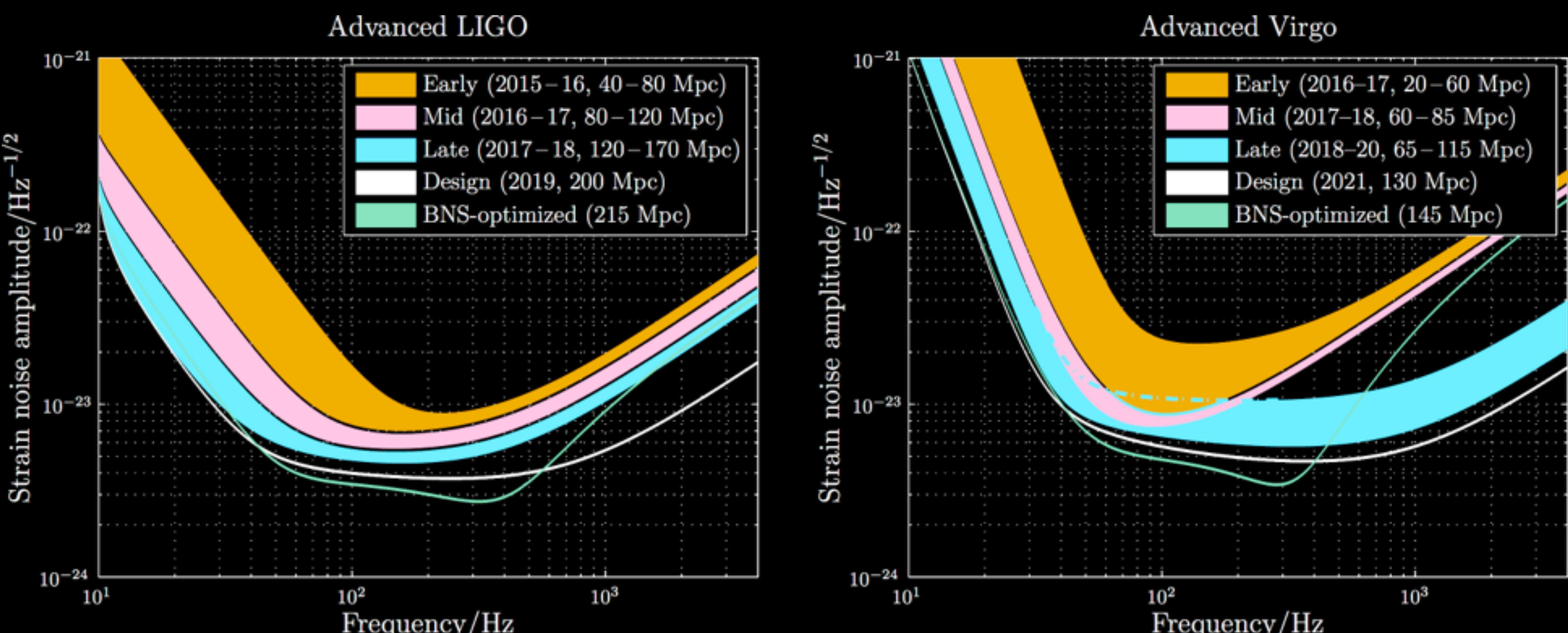



Image Credit: Caltech/MIT/LIGO Lab

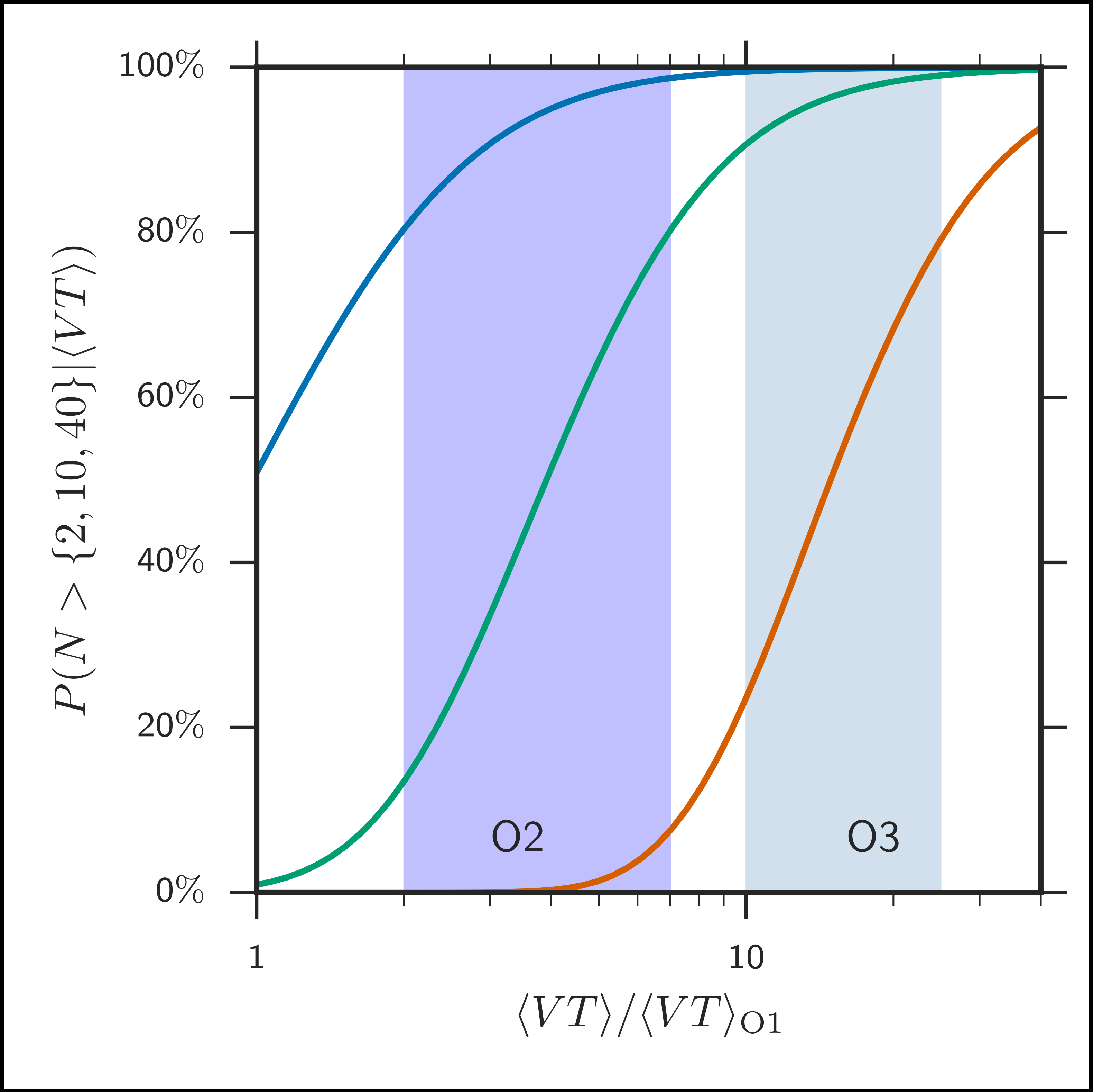
# Future Sensitivity

Advanced LIGO's sensitivity was at the upper end of that predicted for the first observing run




Abbott et al. Living Reviews in Relativity **19**, 1 (2016)

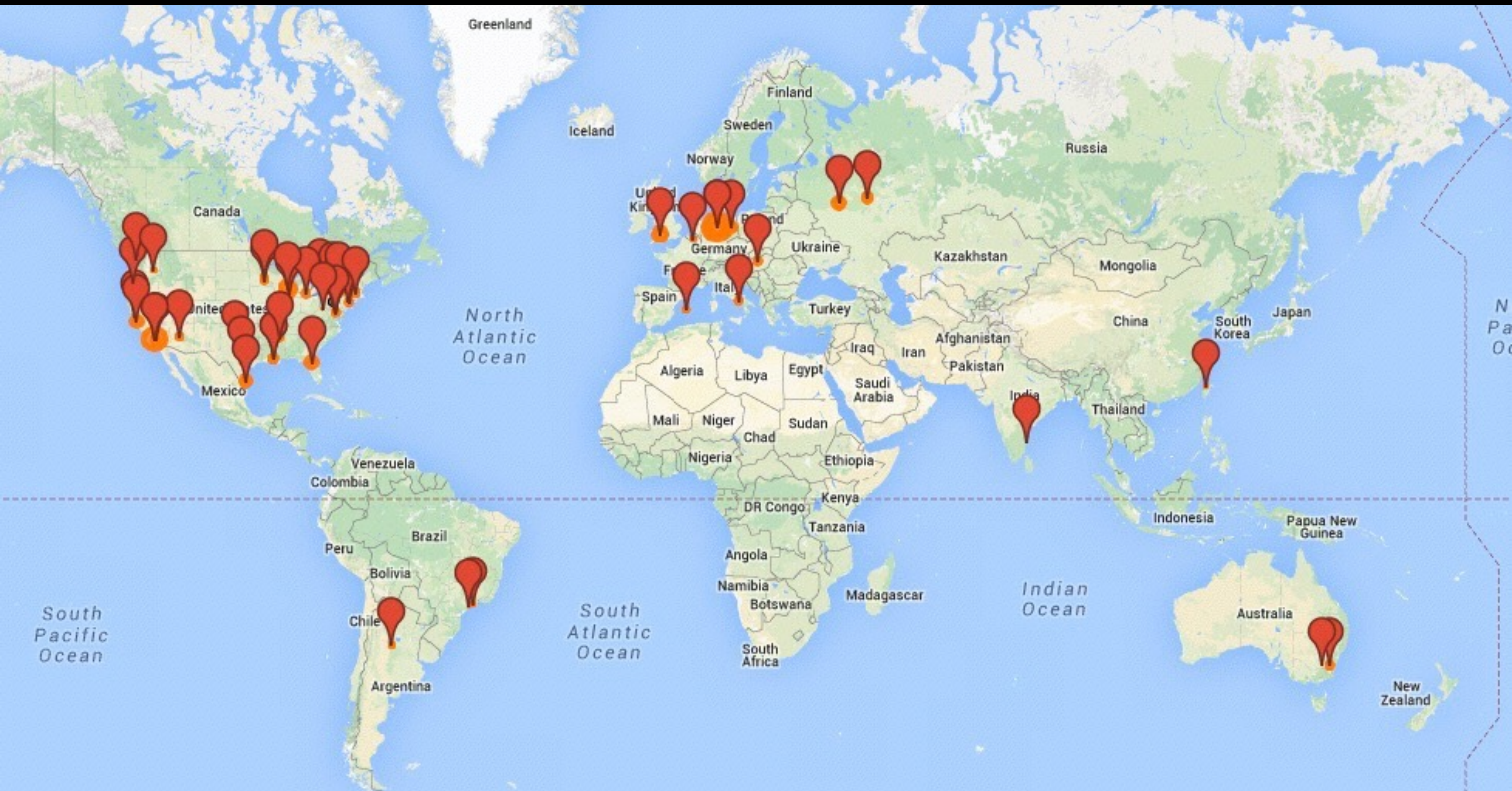
# Future Rates of BBH Mergers




- The second observing run is starting in ~month
- Plan is to run until christmas followed by a break for the holidays
- Continue running until early spring when Virgo will join

Abbott et al. arXiv: 1606.04856 (2016)

# LIGO Scientific Collaboration and Virgo Collaboration




www.ligo.org

1000+ members, 90 institutions, 16 countries

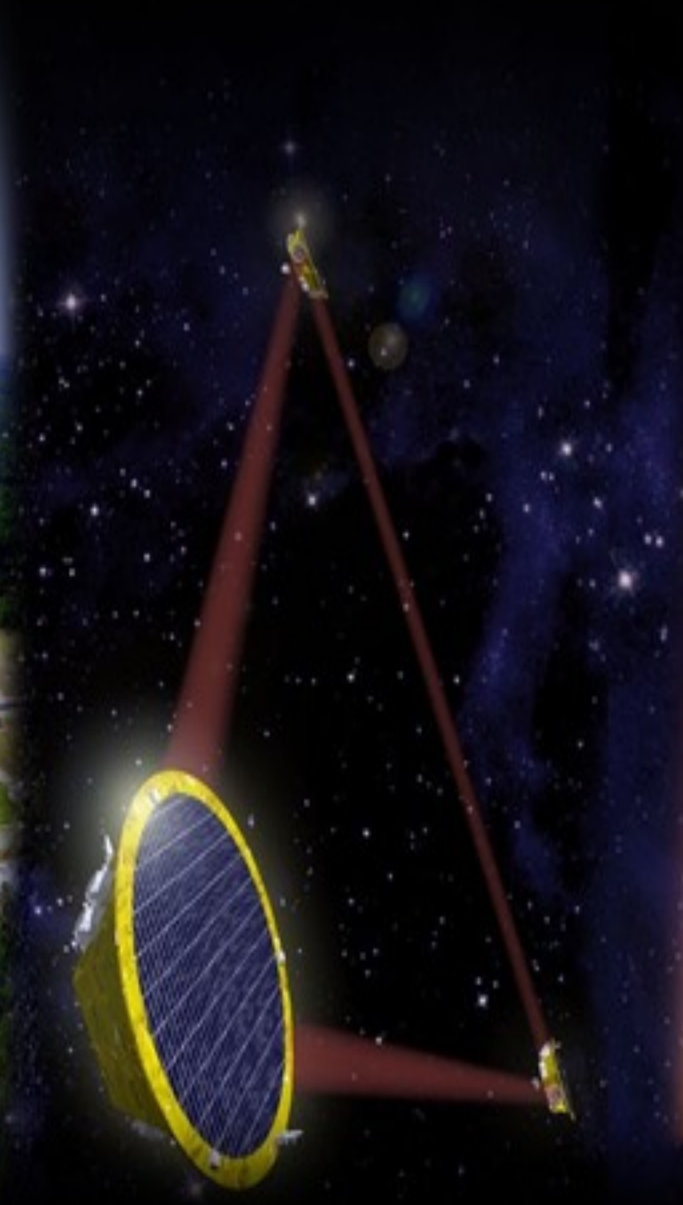
Slide: Gabriela González

# Extra Slides

# Gravitational Wave Periods

Milliseconds

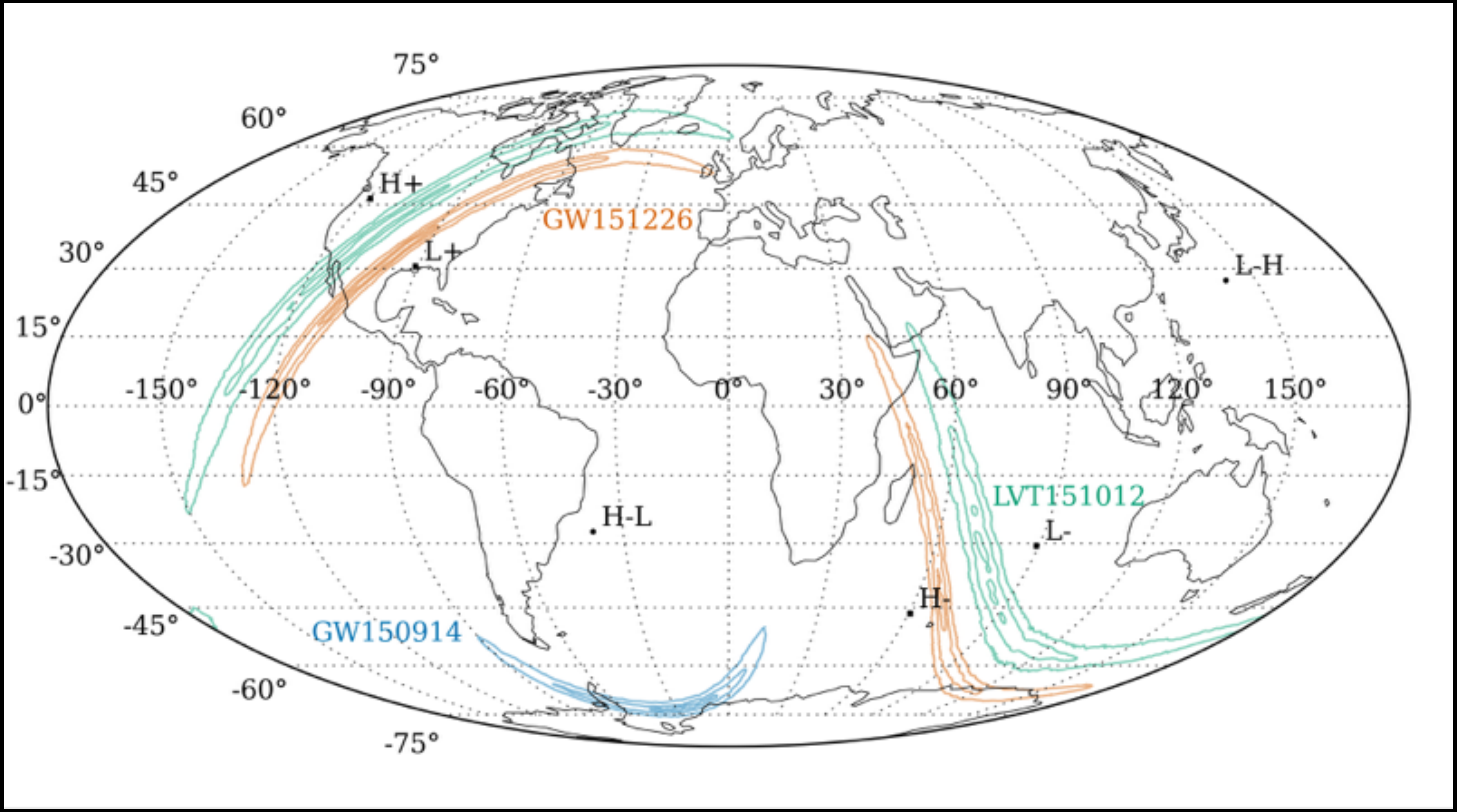
Minutes
to Hours



Years
to Decades

Billions
of Years

# Localisation

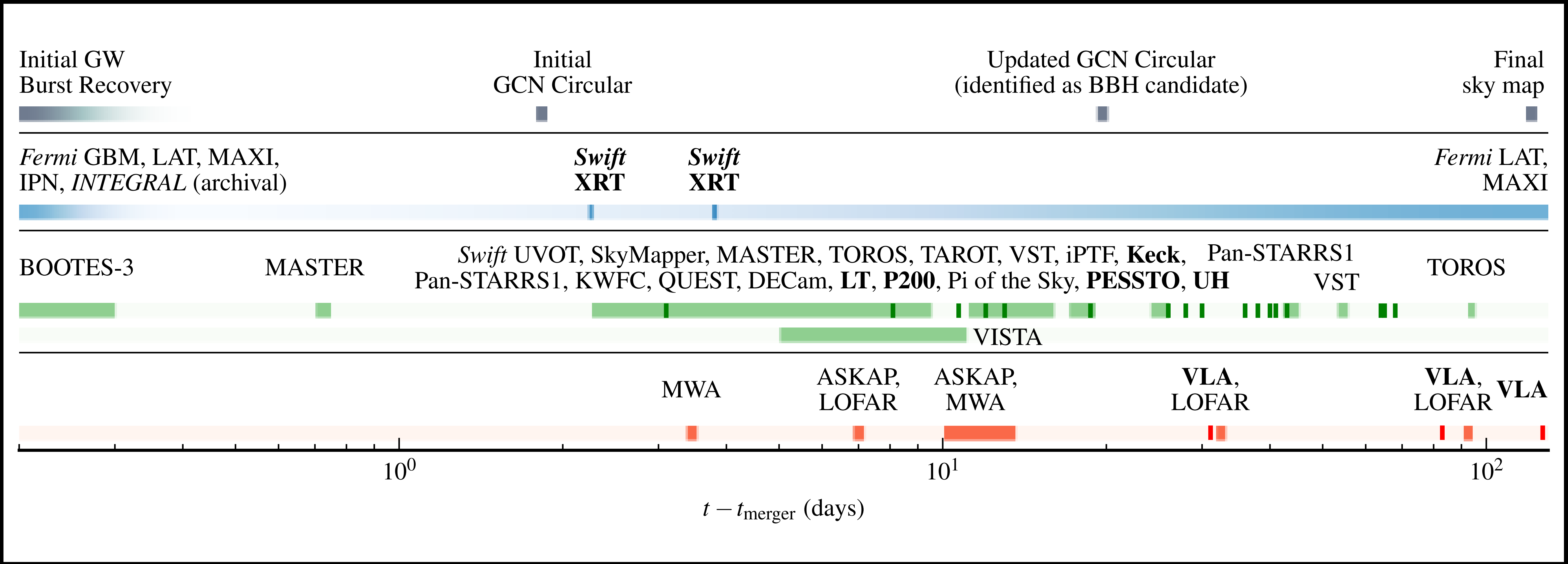



Sky localization depends on:
- the location and orientation of the detectors
- time delay between signal arrival at spatially separated sites



Abbott et al., Phys. Rev. X 6, 041015 (2016)

# Electromagnetic Follow-Up




Timeline of observations of GW150914, separated by band and relative to the time of the gravitational wave event

Abbott et al. ApJ 826, Number 1 (2016)

# The first observing run (O1)

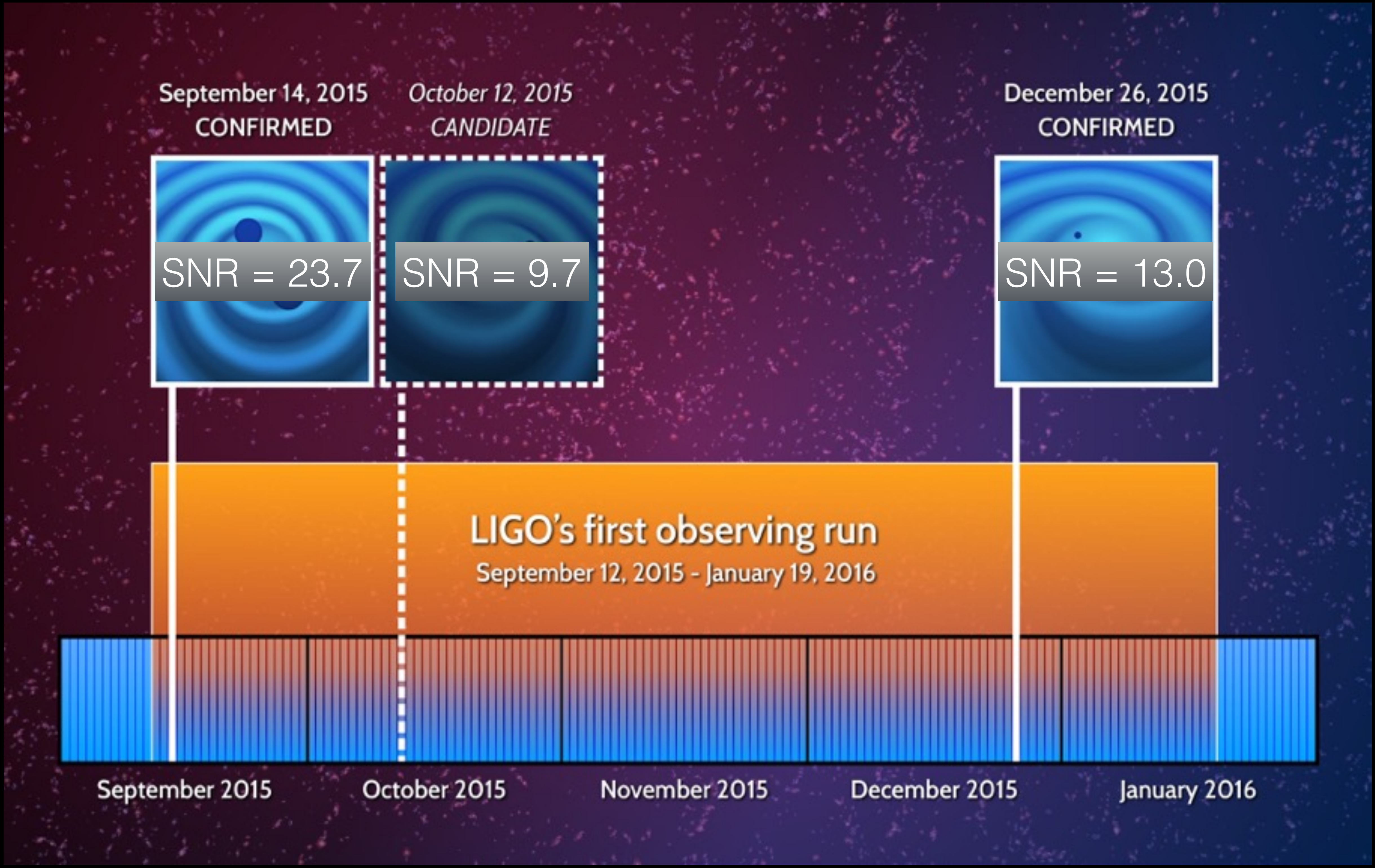
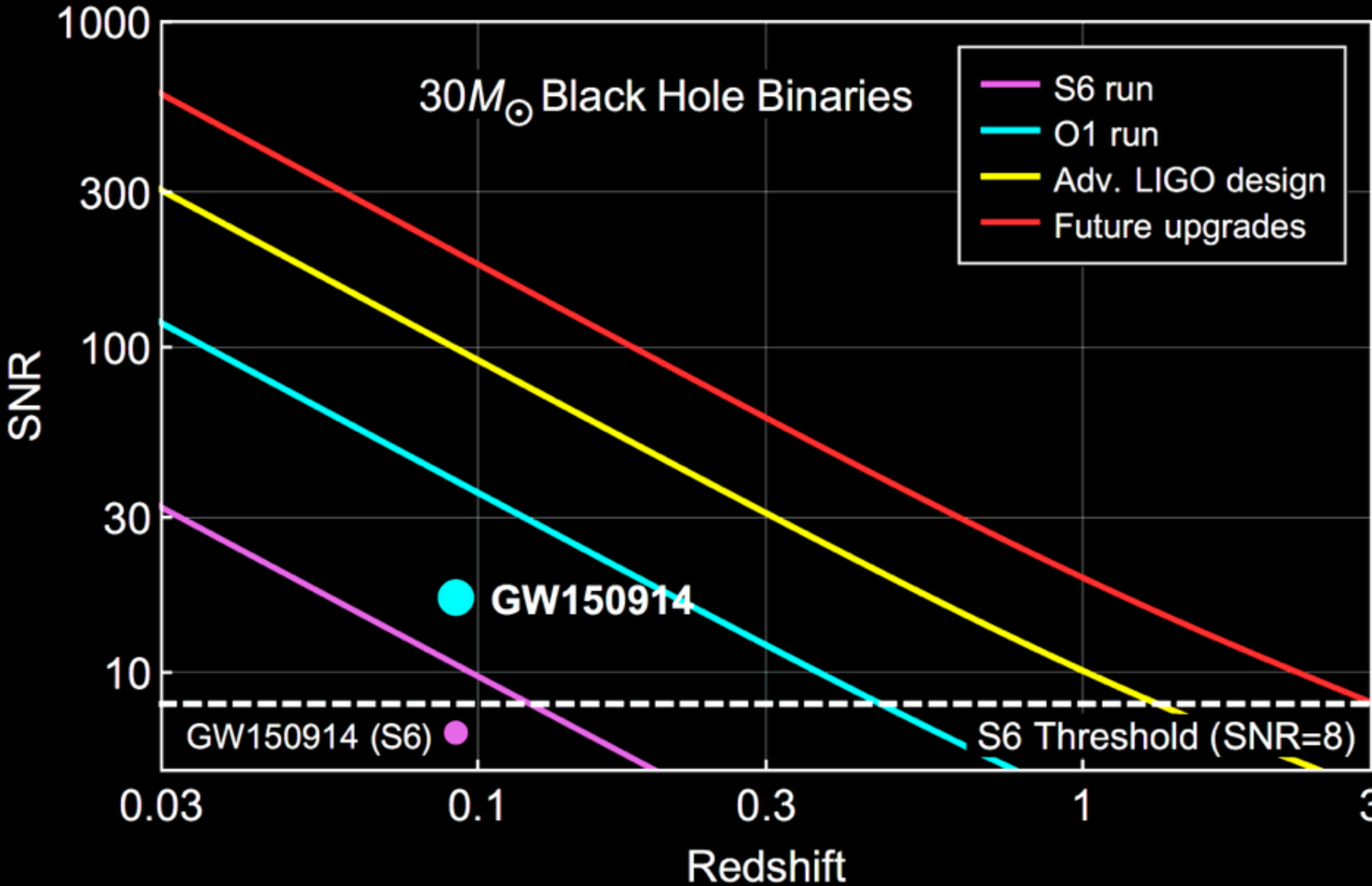
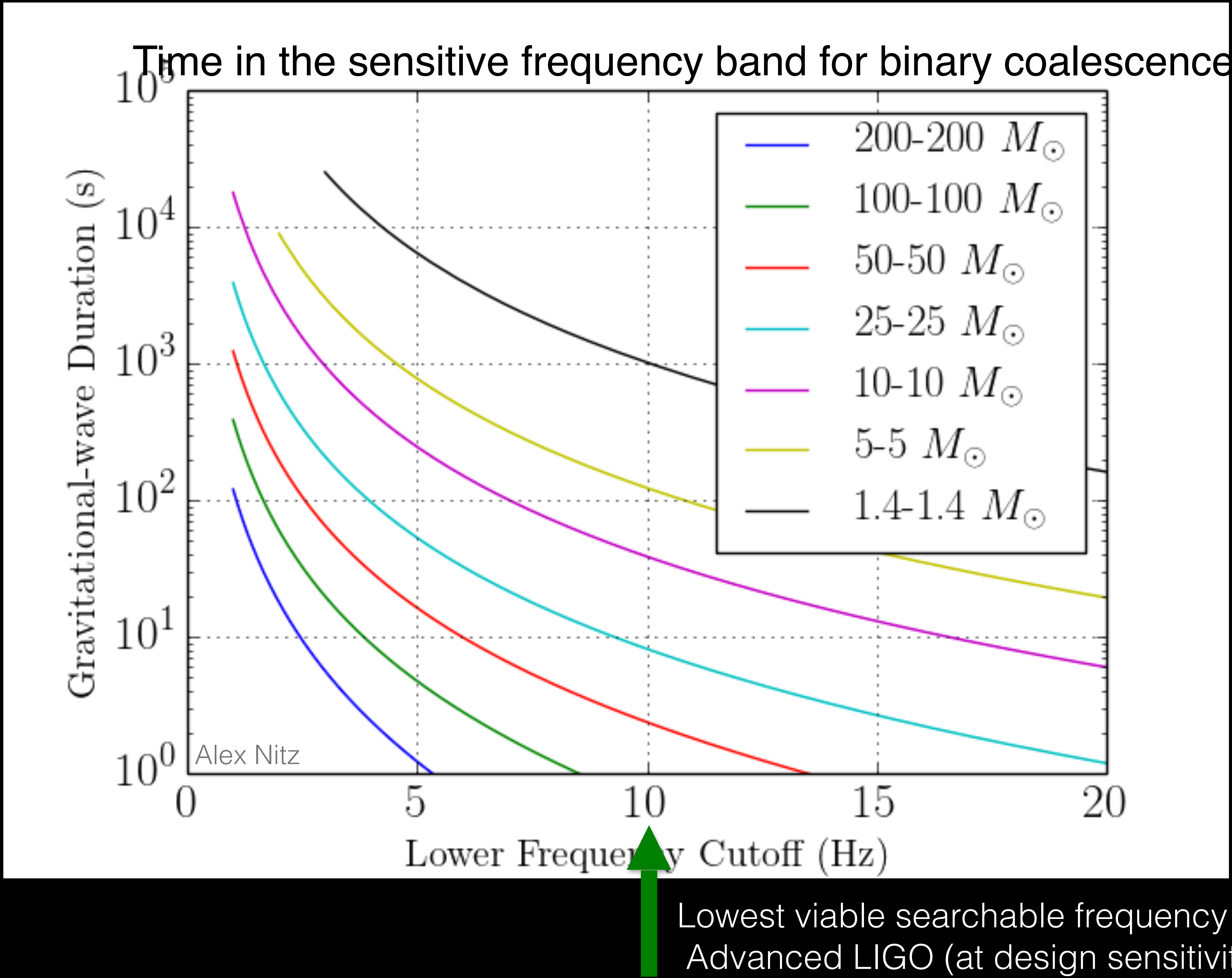



Image Credit: LIGO




Abbott et al. Phys. Rev. Lett. **116**, 131103 (2016)

# What does better low frequency sensitivity buy us?

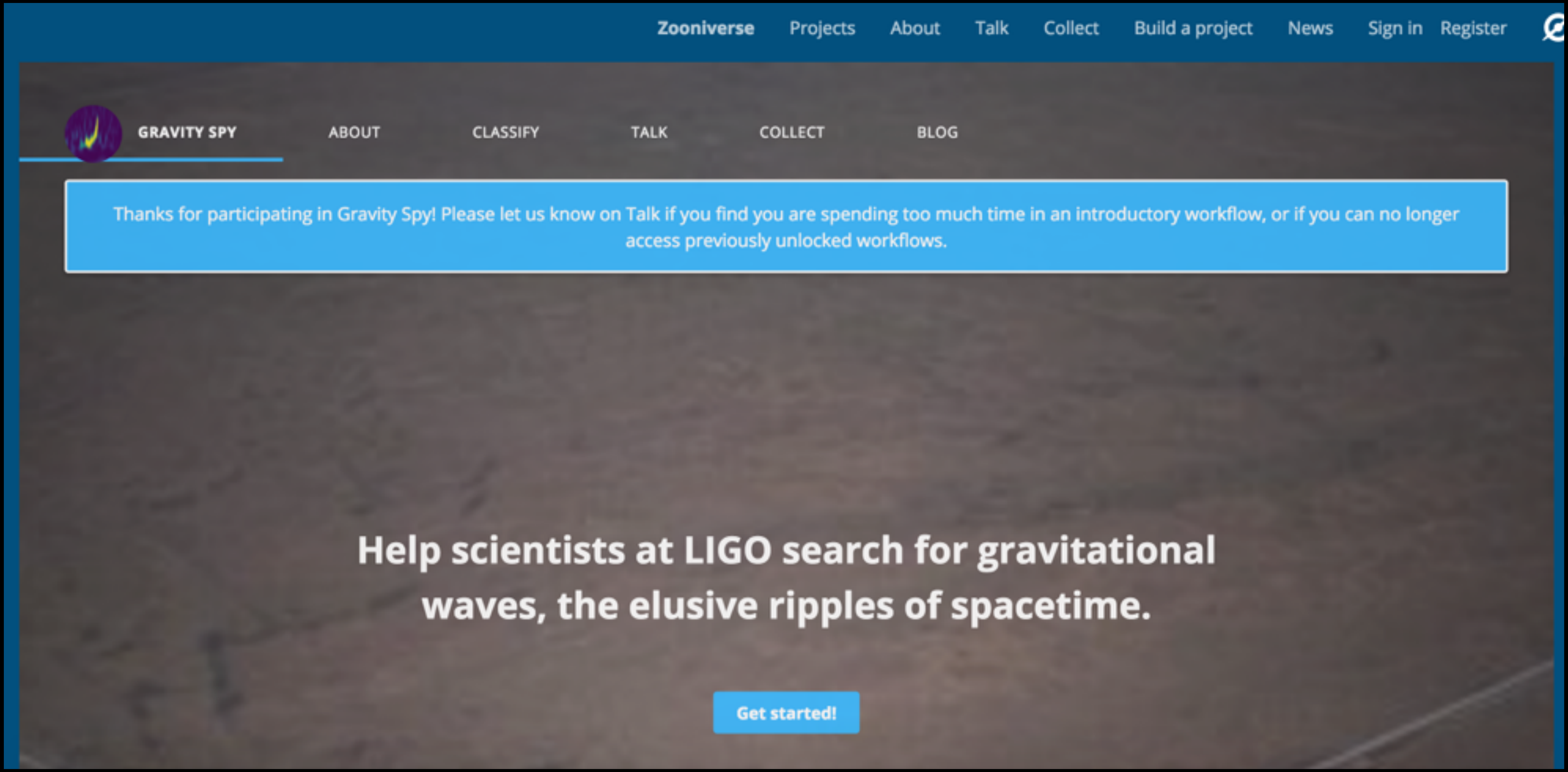



Lowest viable searchable frequency for Advanced LIGO (at design sensitivity)

# GravitySpy

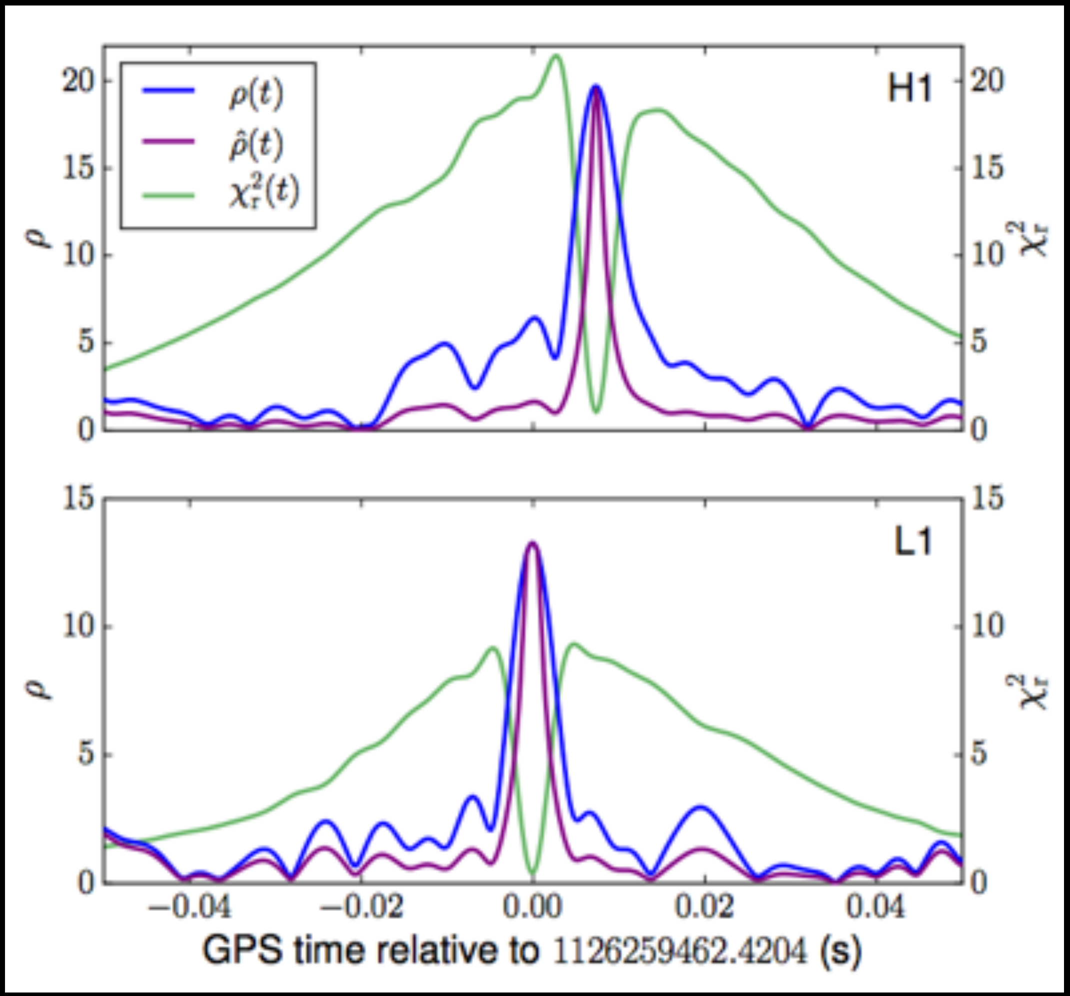
https://www.zooniverse.org/projects/zooniverse/gravity-spy/

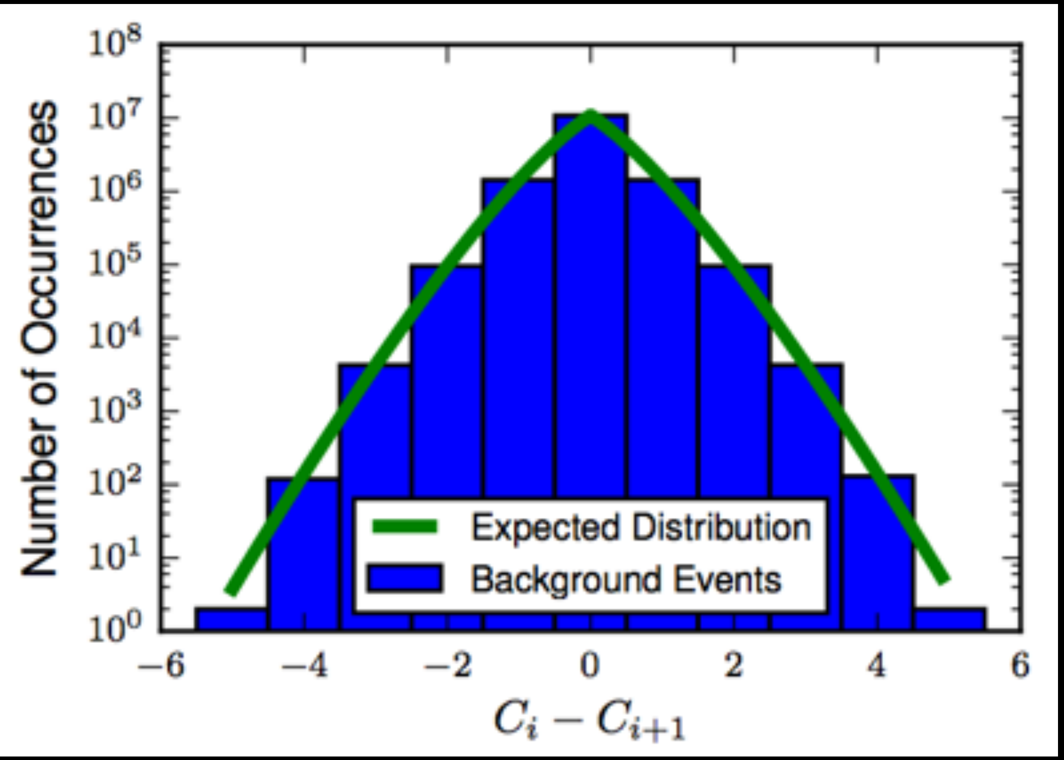
Help us classify glitches!



# LIGO Magazine


# Independence of time shifts




- Different time-shifted analyses give independent realizations of a counting experiment for noise background events.
- It's not the length of the template (which can be < 0.1s) that matters, but rather the autocorrelation function (the width of the peak in the SNR - 1ms)
- The number of background events having $\rho_c > 9$ between consecutive time shifts, where $C_i$ denotes the number of events in the ith time shift
- 0.1 s time shifts are independent trials of a Poisson process, even with non-Gaussian transients in the data

# How do we know this was an astrophysical source and not something the detectors made up?

We performed every check we could think of…

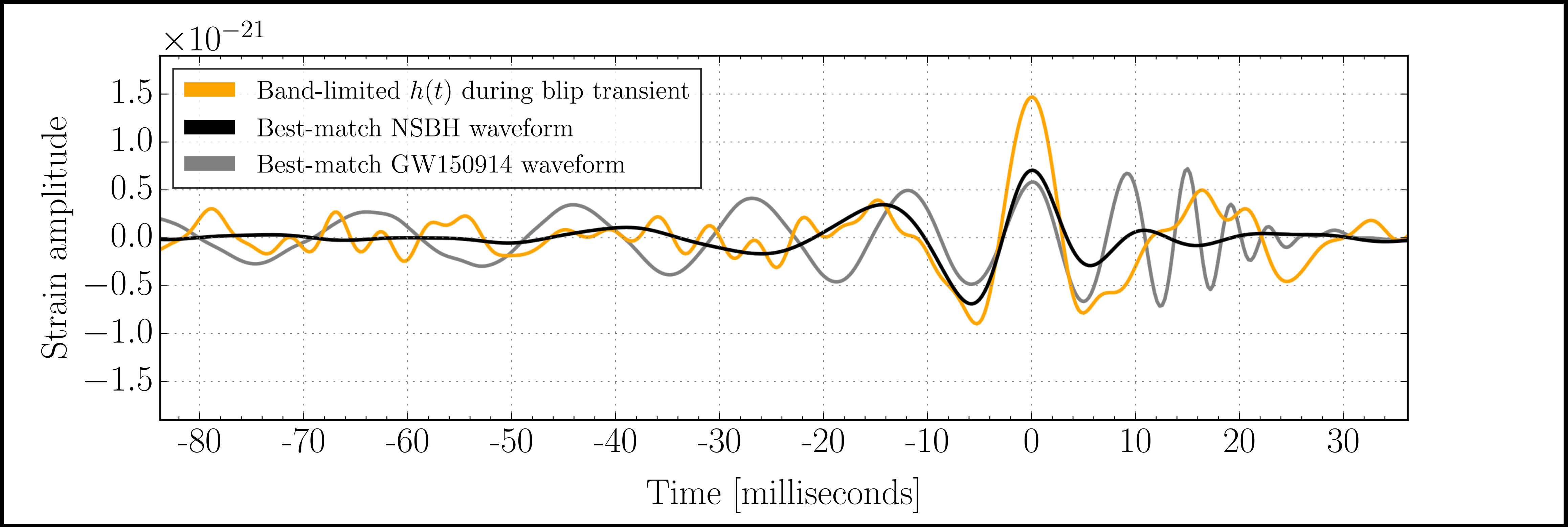
- Checked for correlated (solar weather, lightning

**Cannot find any instrumental cause - this signal can only be produced from two black holes colliding**

conditions

- Checked the whereabouts of every person on site (physically and remotely connected)
- Checked for ‘injections’
- Tracked the signal throughout the interferometer

# Blip Glitch




A blip transient in LIGO-Livingston strain data that produced a significant background trigger in the CBC analysis in orange, and the best-match template waveform (amplitude-scaled for comparison) in black, which exhibits a few more low-SNR cycles but otherwise quite similar morphology