The Universe remembers: gravitational-wave memory with LIGO

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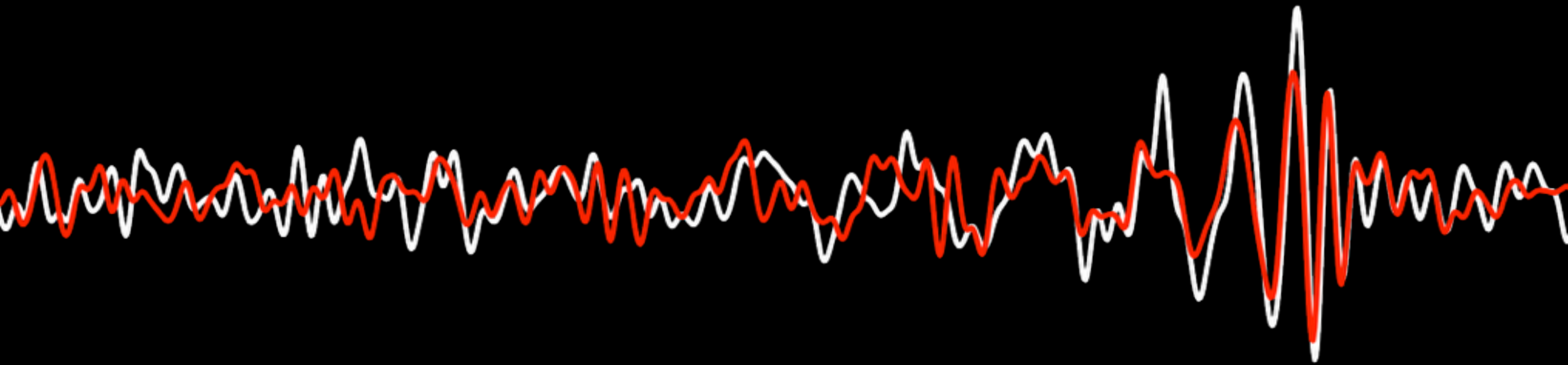
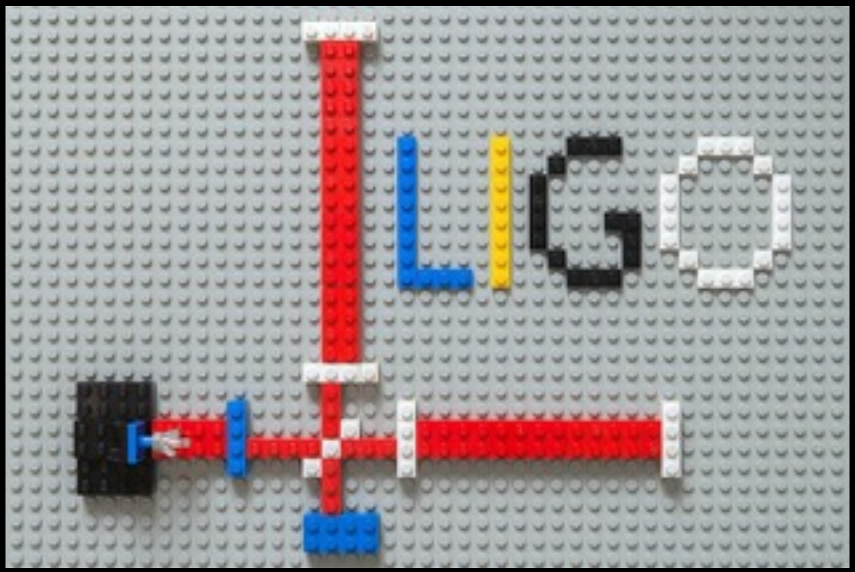
Jonathan Blackman, Yanbei Chen (CalTech)

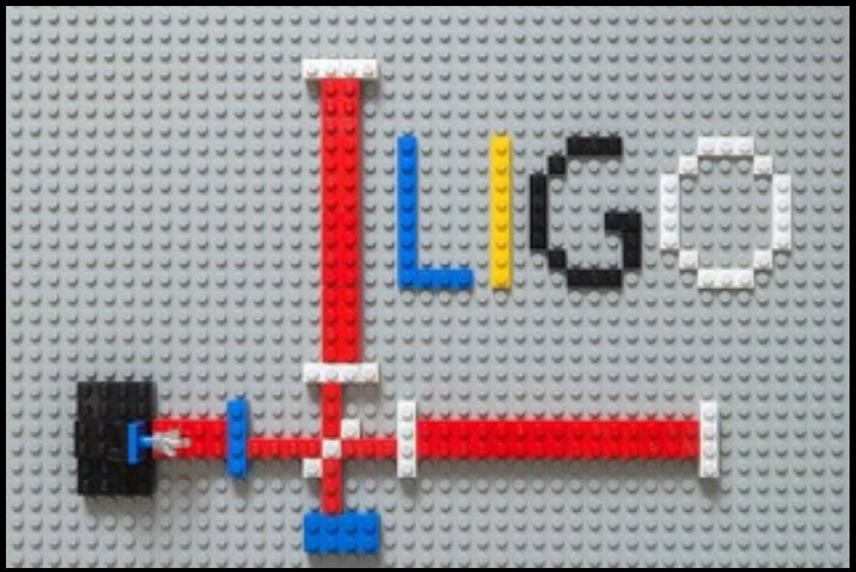
LSC LIGO Scientific Collaboration

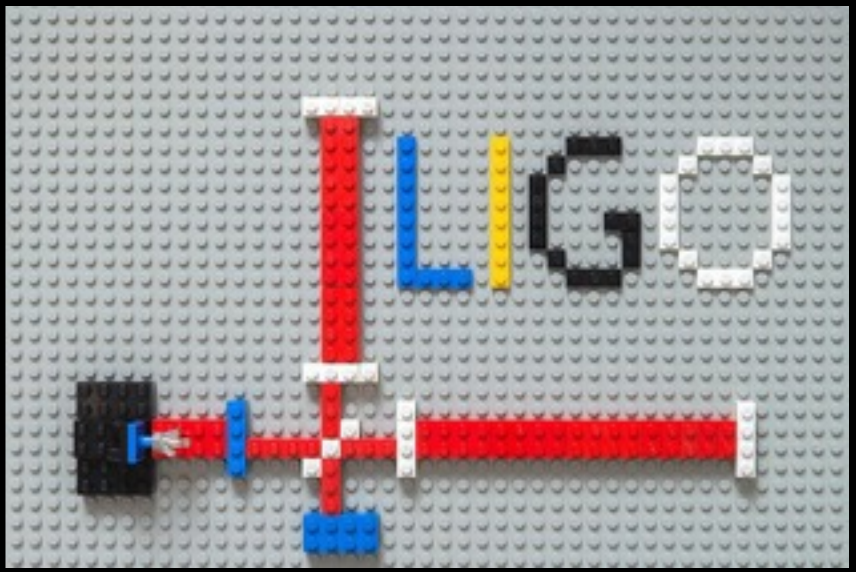
MONASH University

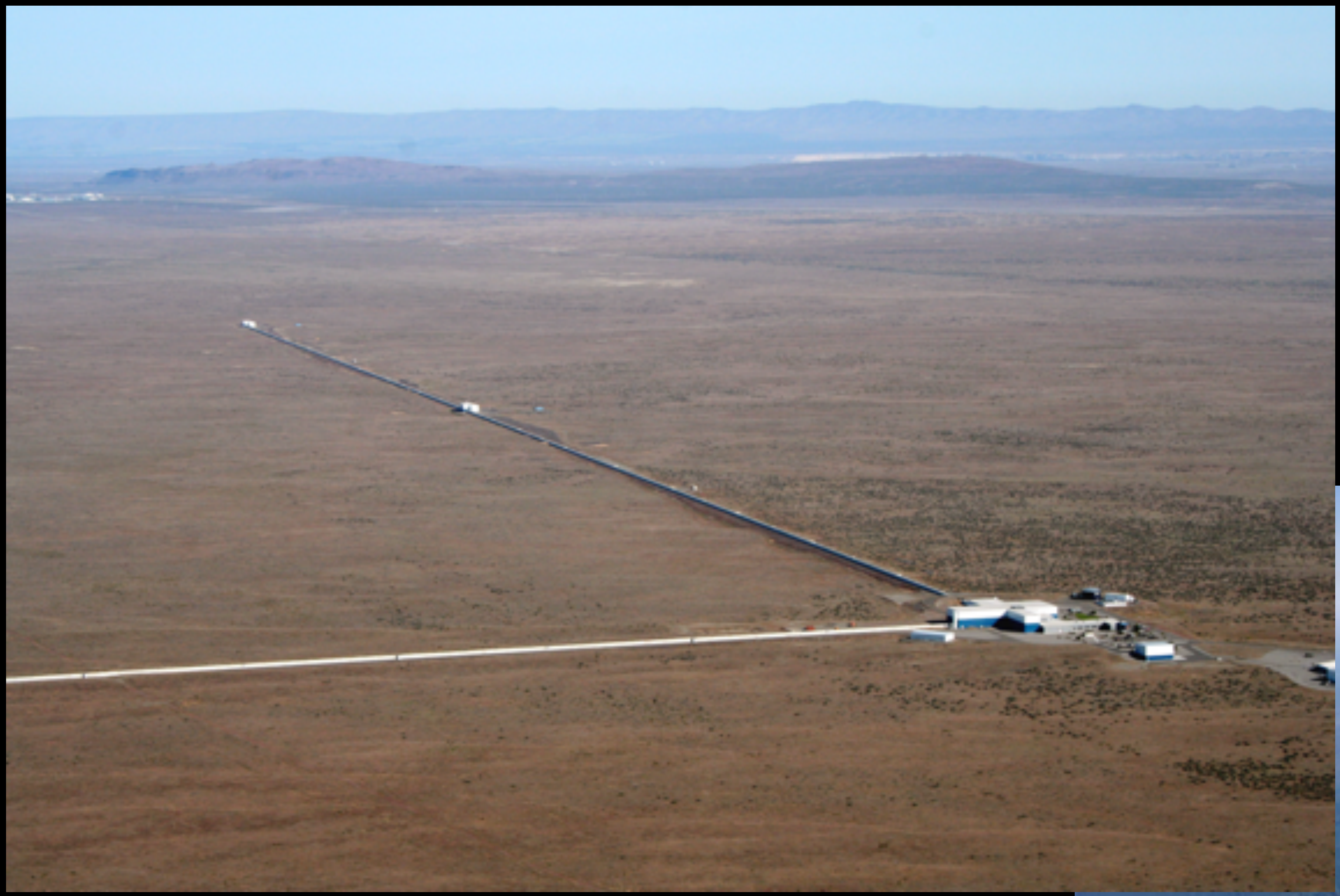
14th September 2015 - GW150914





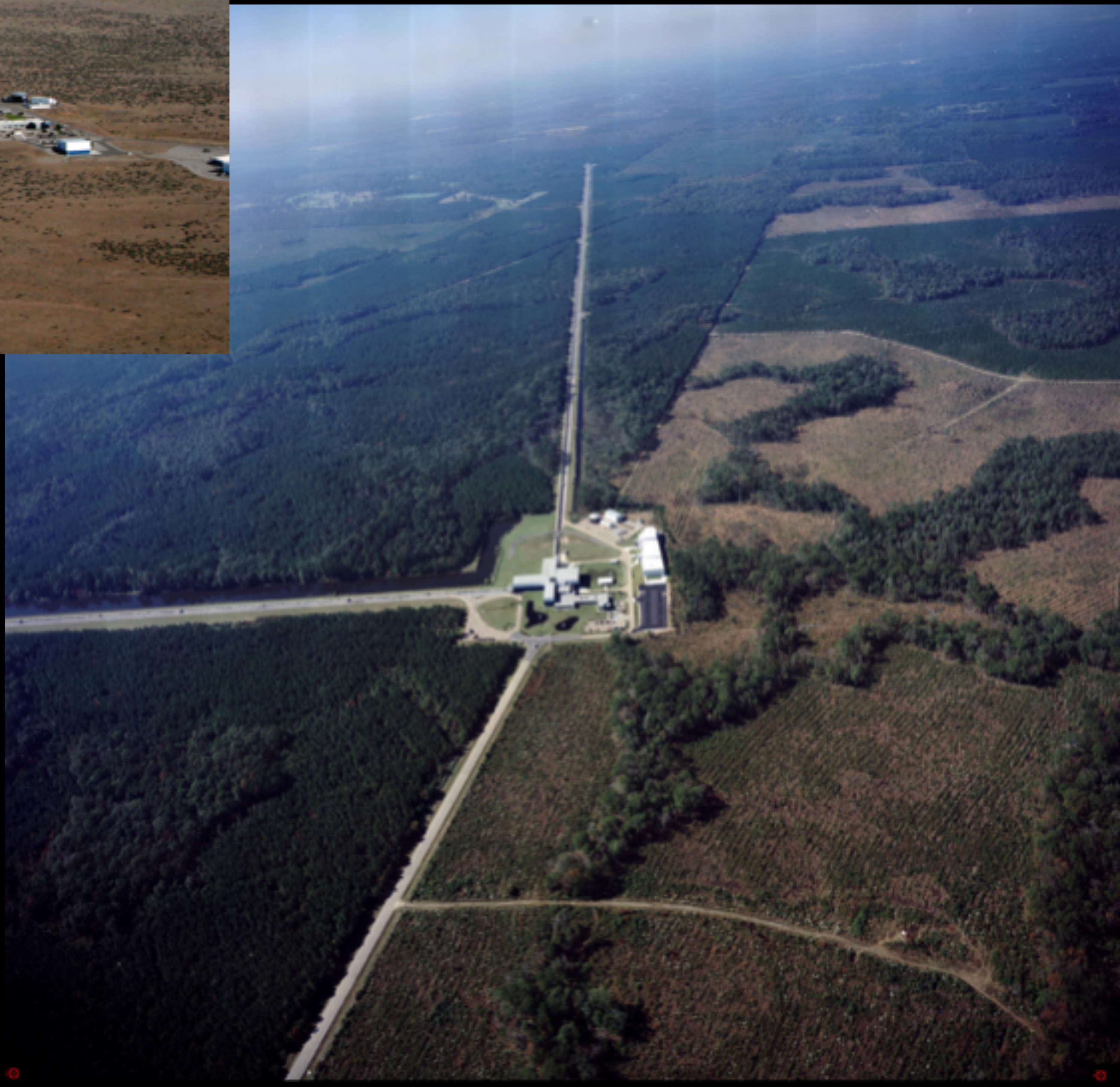


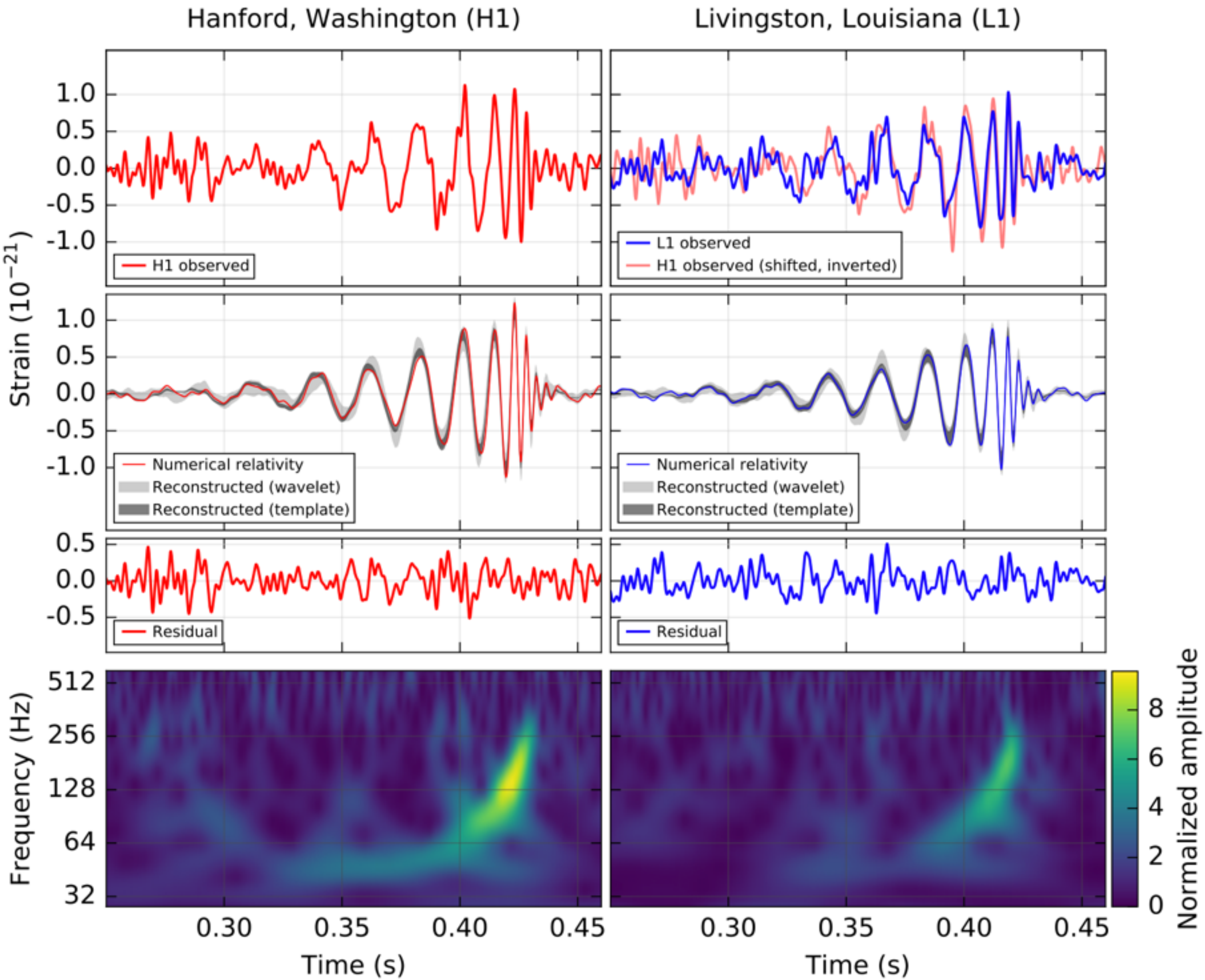




LIGO Hanford

LIGO Livingston



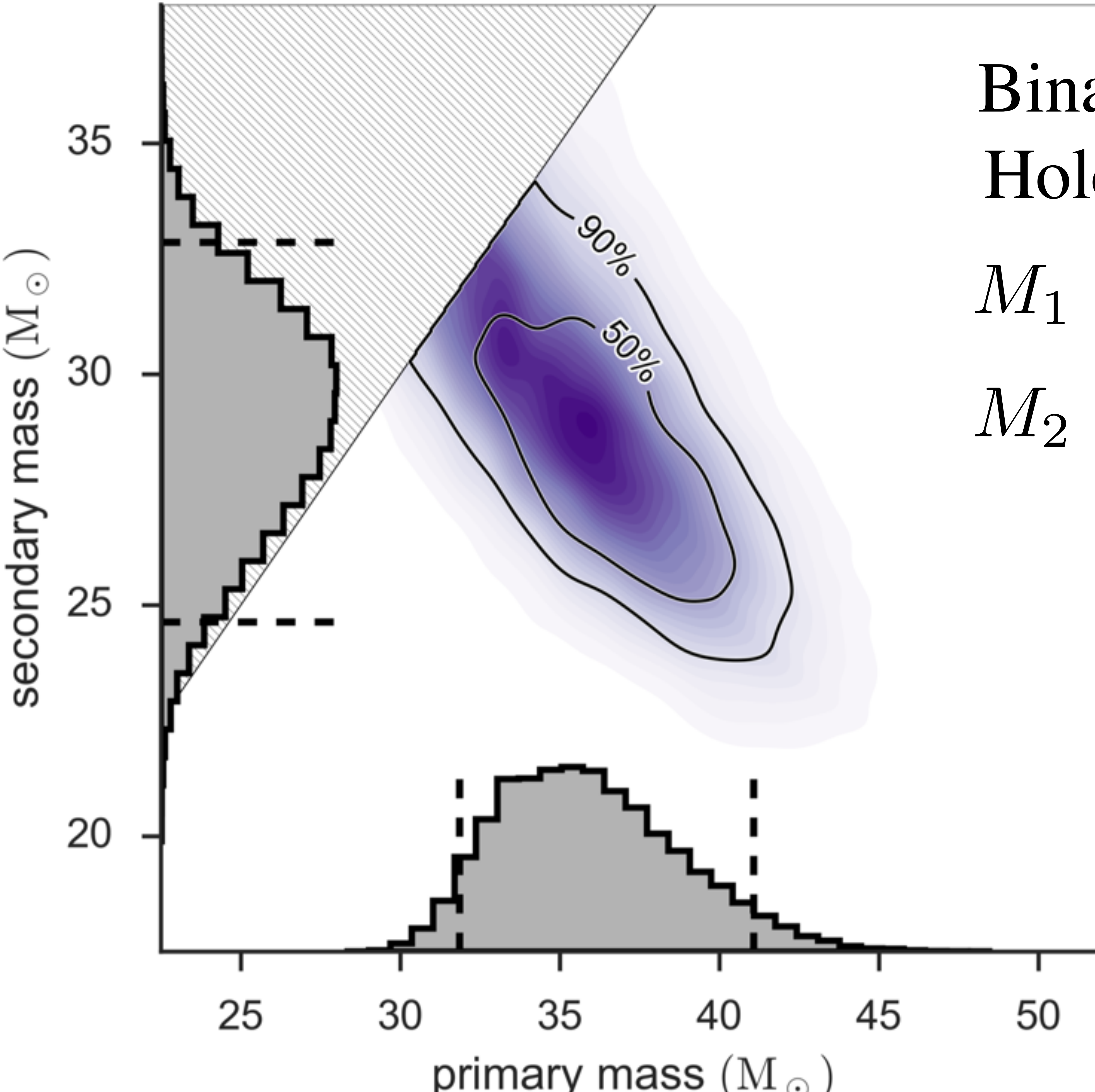


Abbott et al. (2016) - GW150914

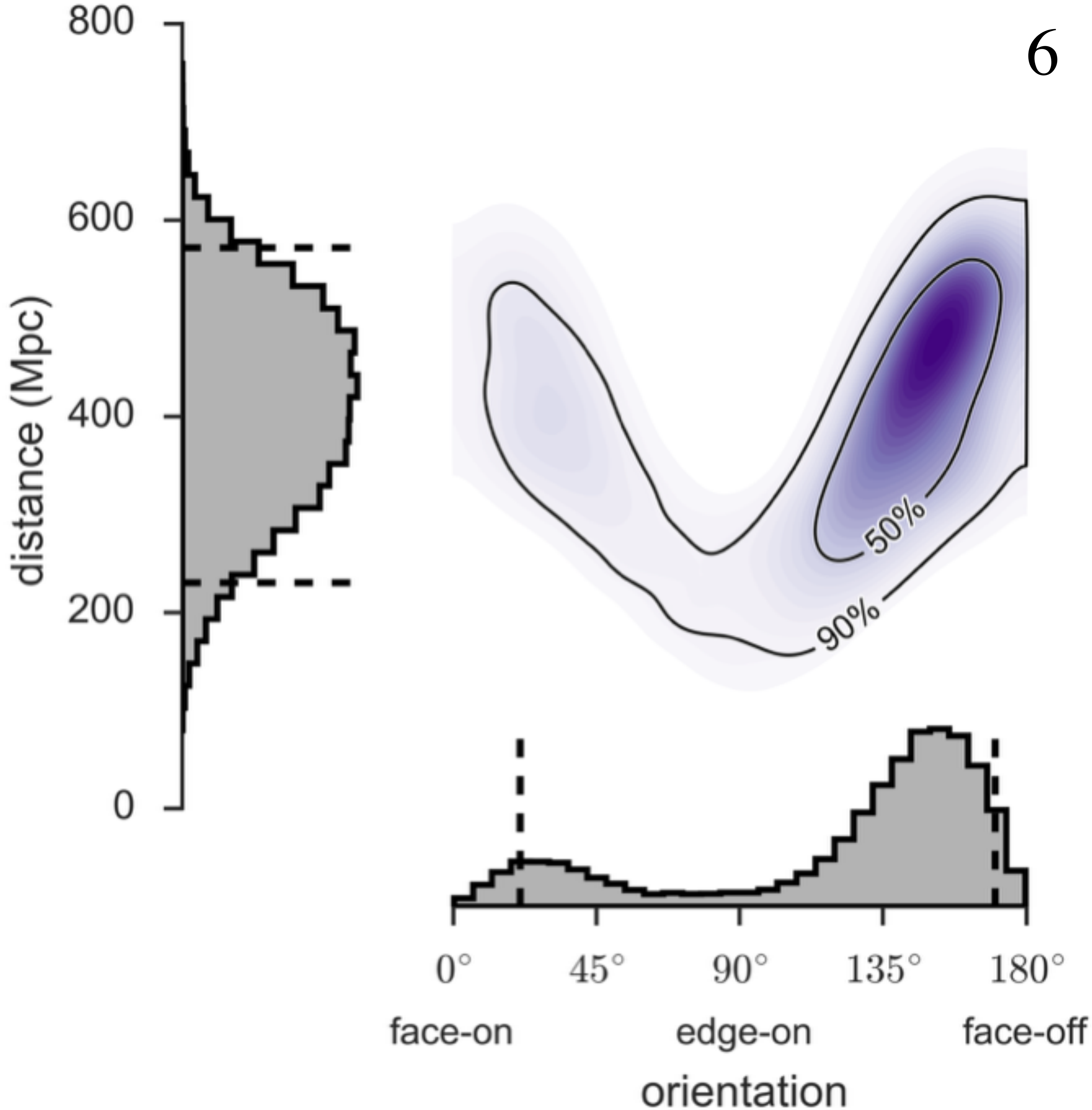
Binary Black Hole Merger

$M_1 \approx 36\, M_\odot$

$M_2 \approx 29\, M_\odot$



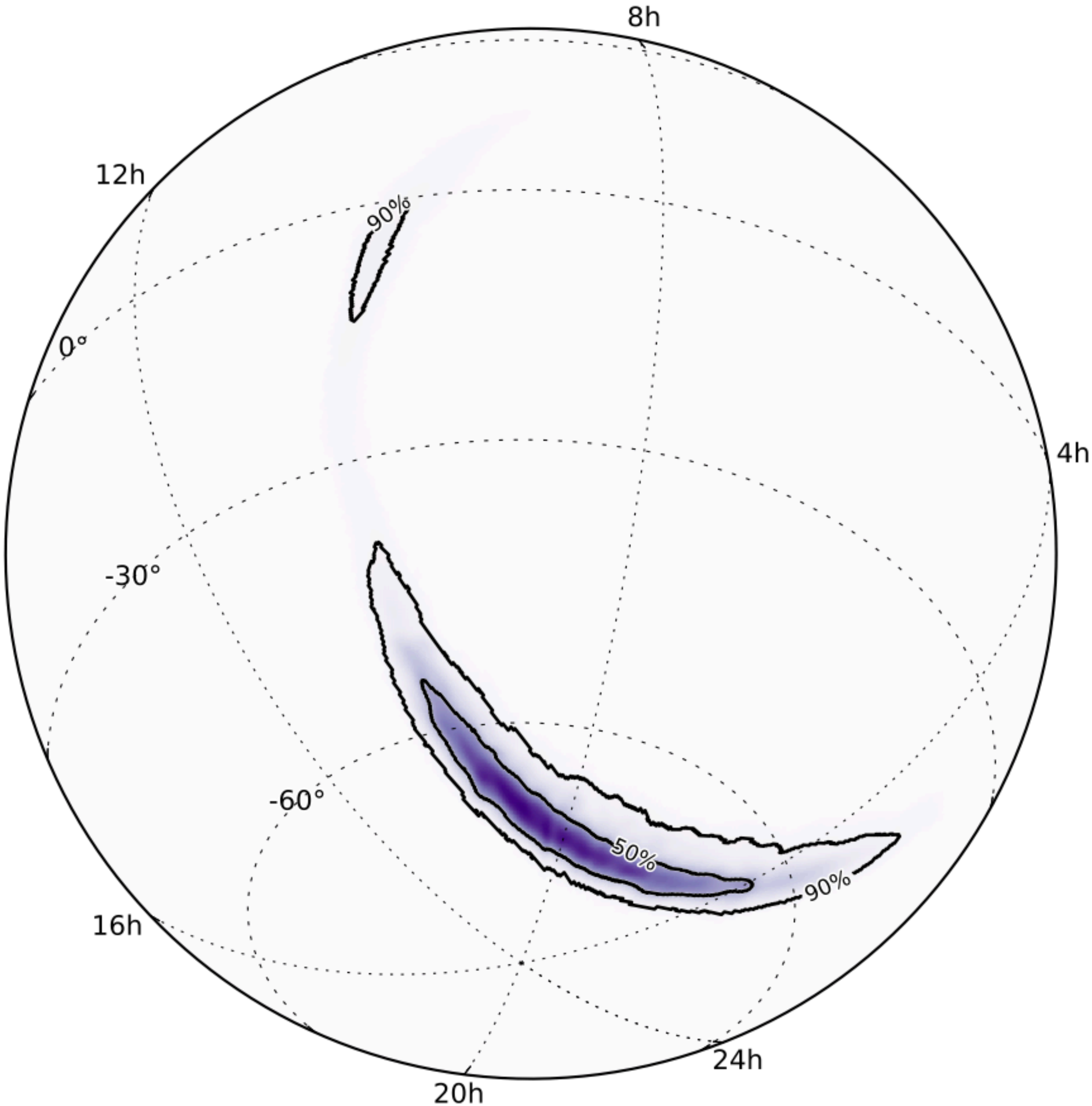
Abbott et al. (2016) - GW150914



$D \approx 410\,\mathrm{Mpc}$

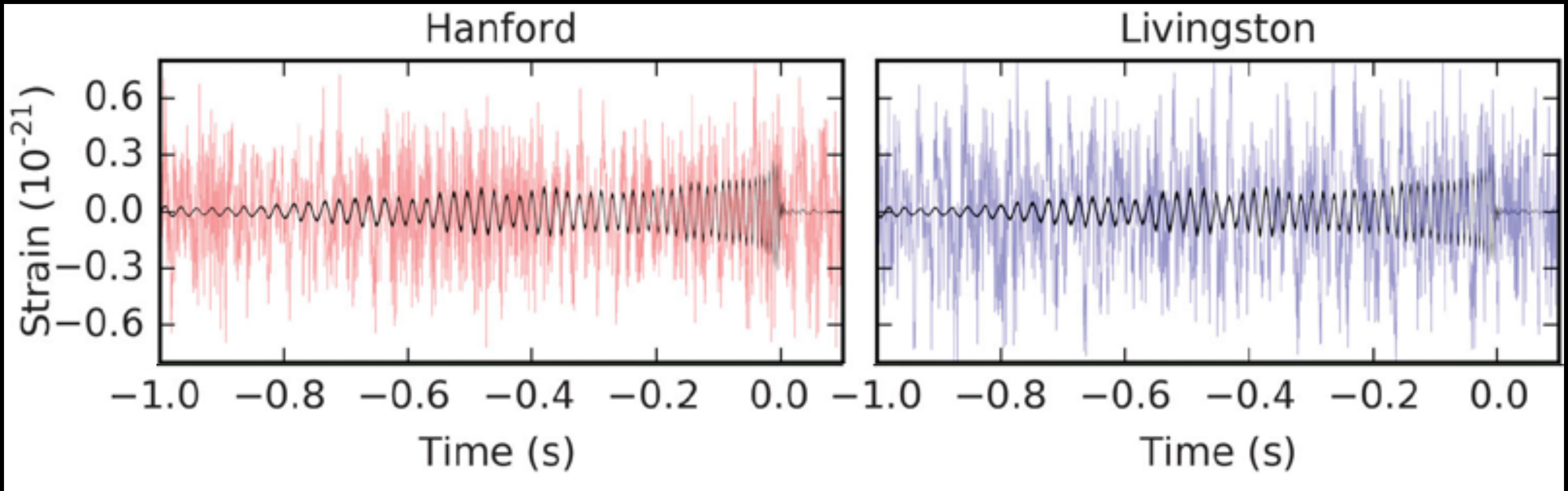
Abbott et al. (2016) - GW150914

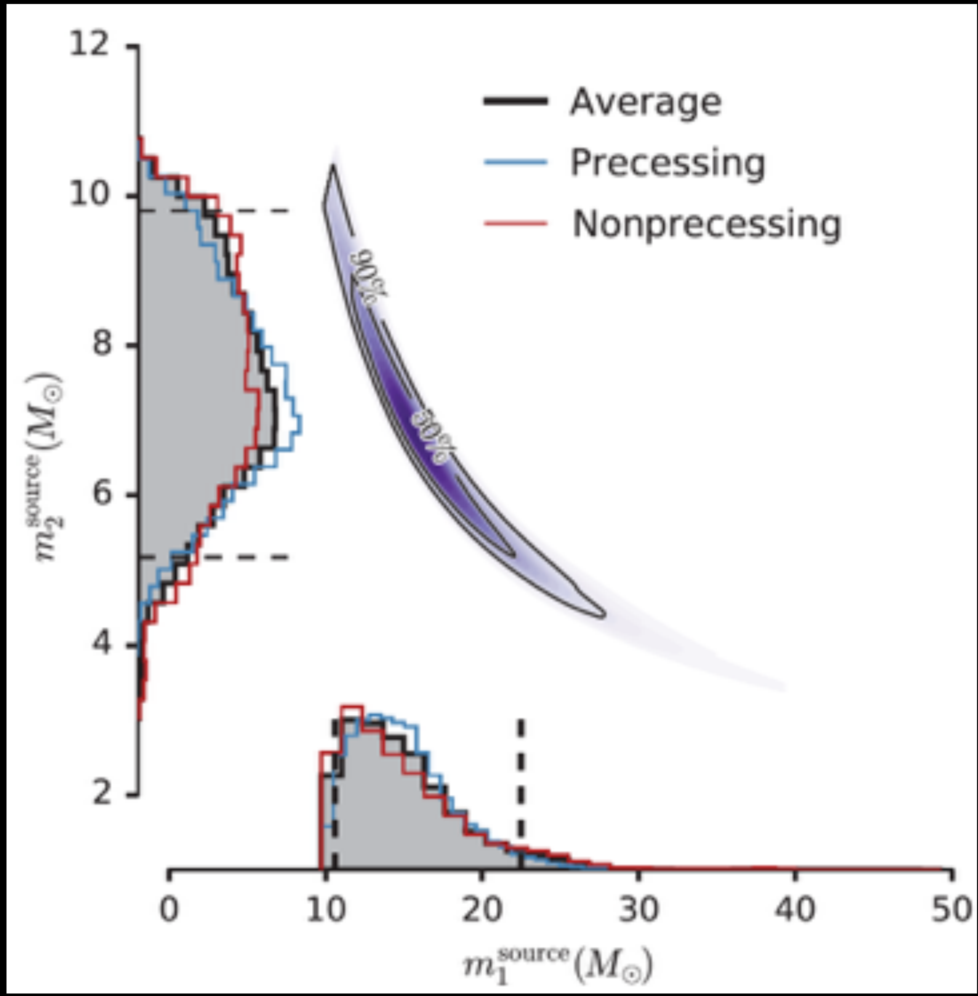
Sky location unknown



Abbott et al. (2016) - GW150914

26th December 2015 - GW151226

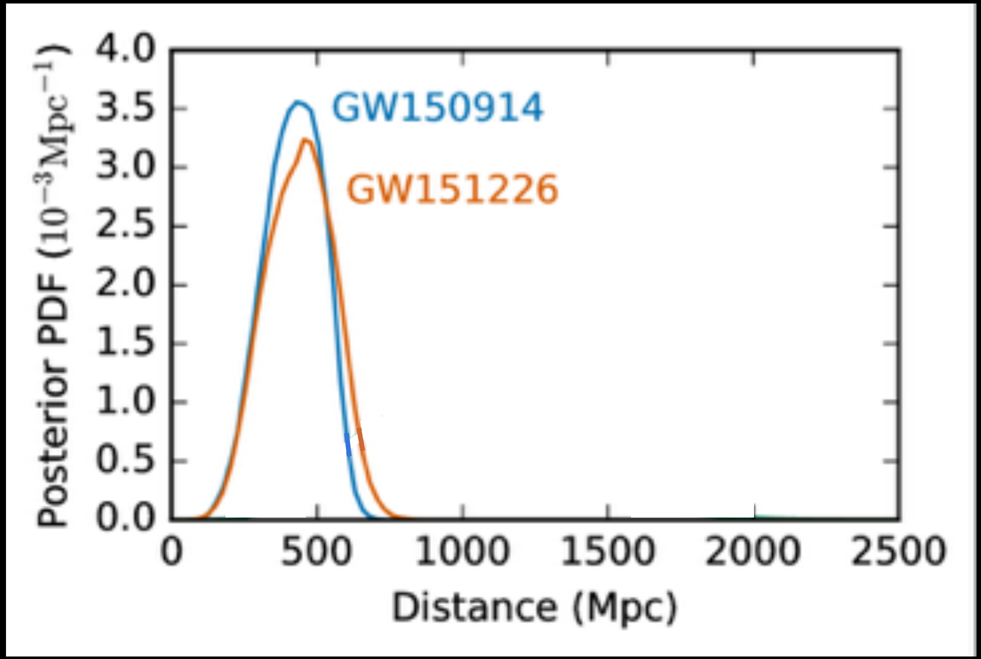




$M_1 \approx 14\, M_\odot$

$M_2 \approx 8\, M_\odot$

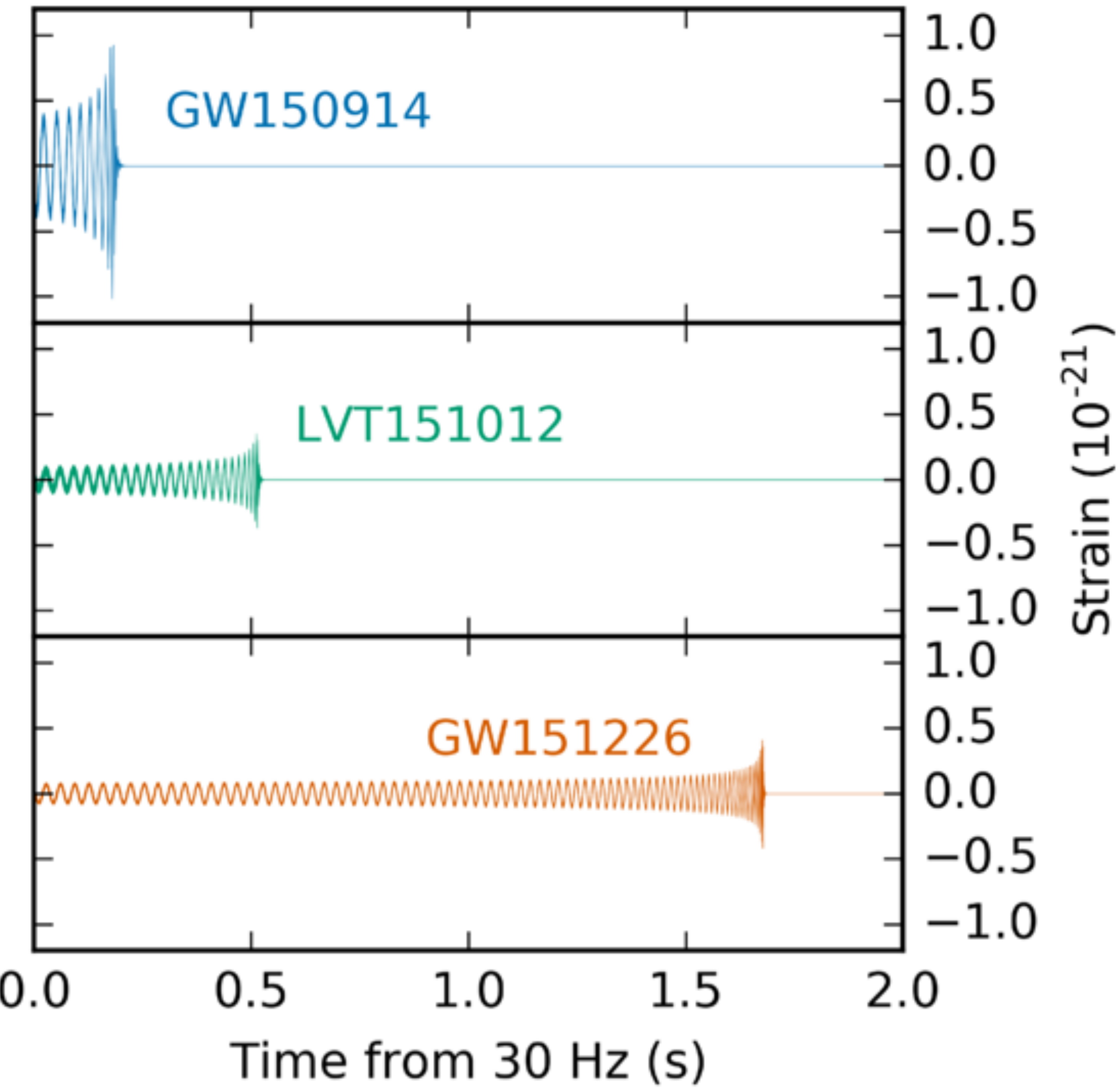
$D \approx\ 400\,\mathrm{Mpc}$

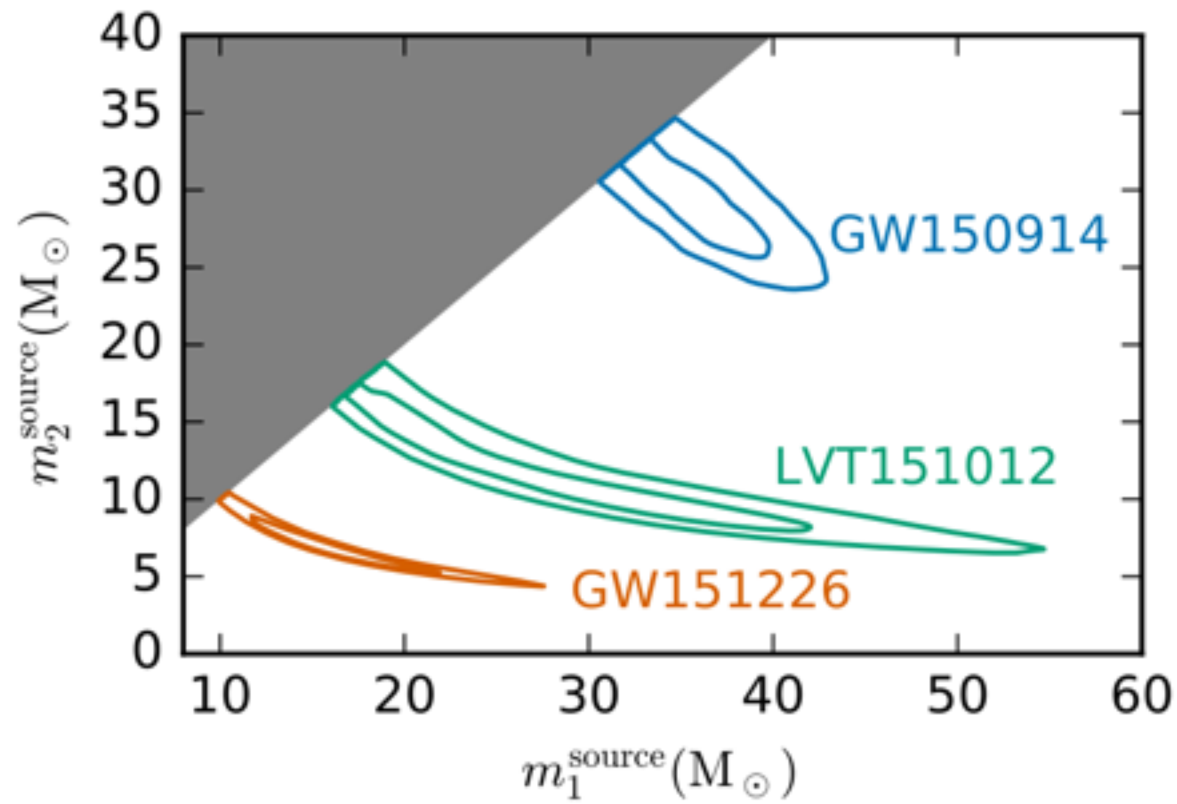


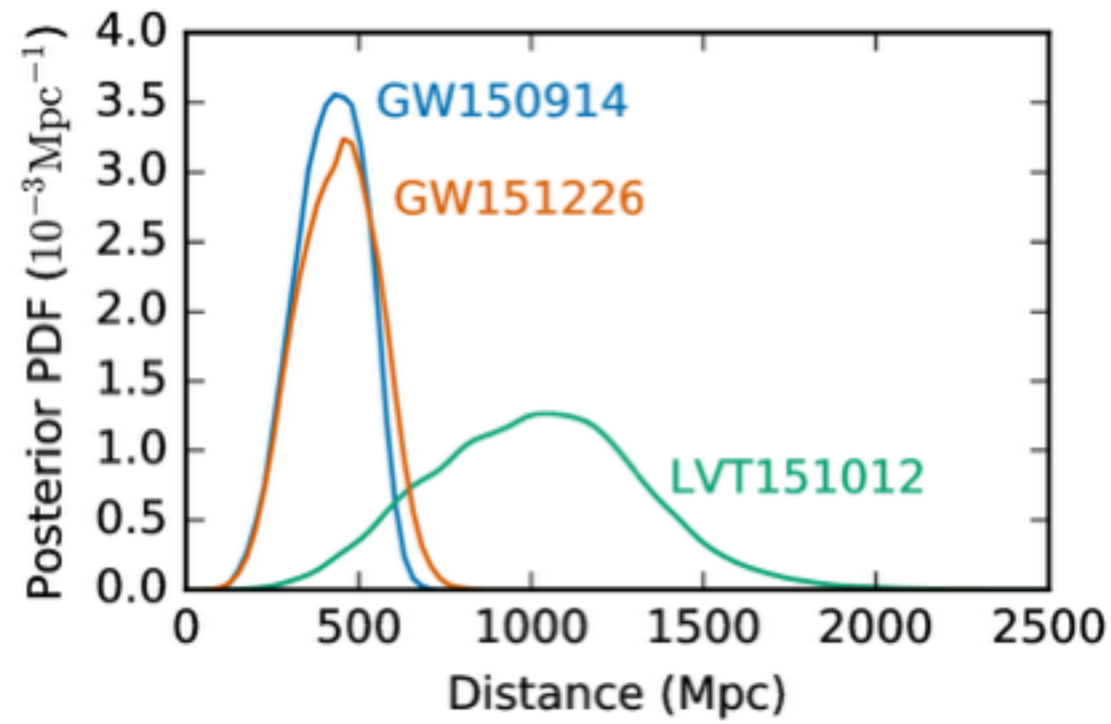
Abbott et al. (2016) - GW151226

2.5 measurements!

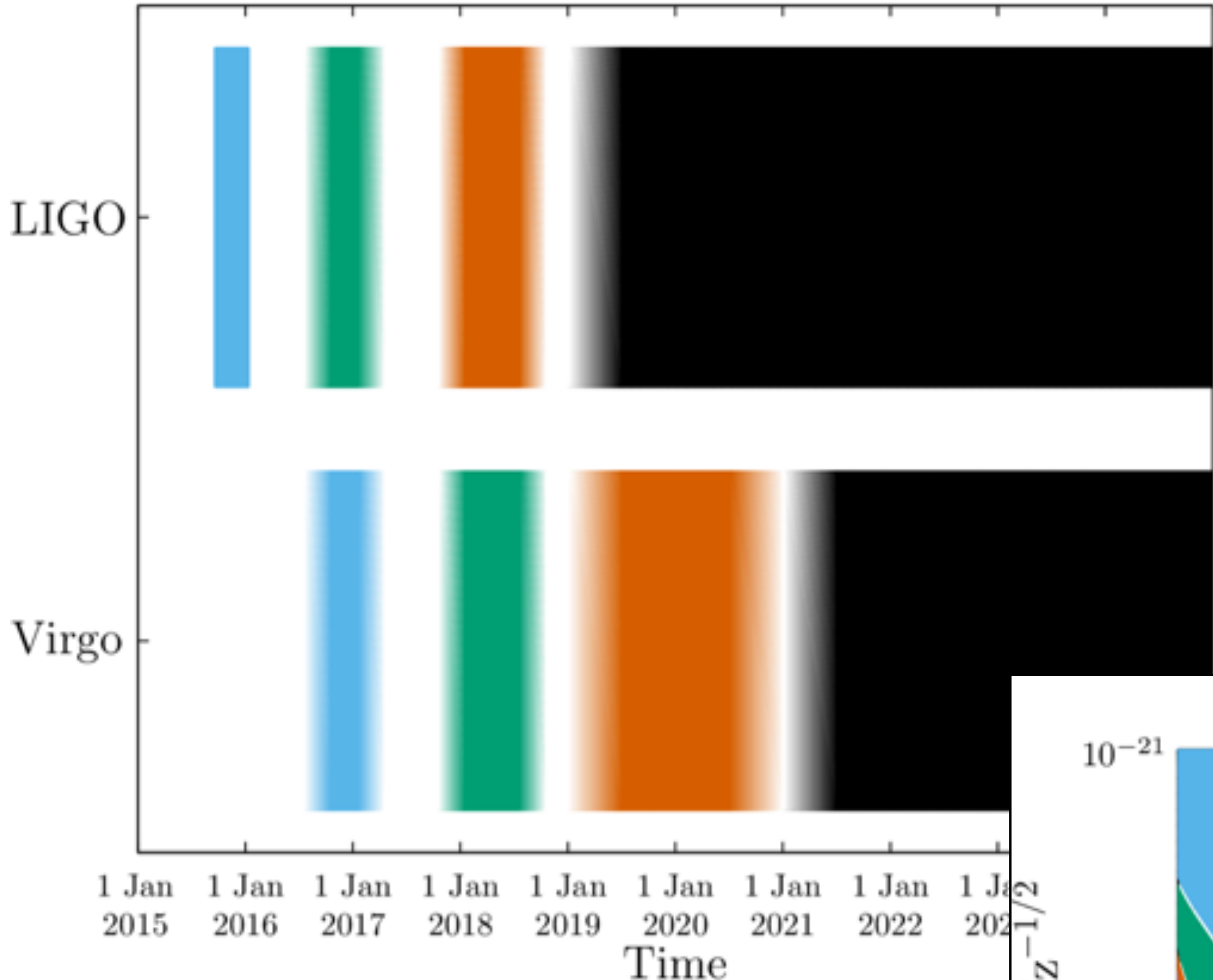
September 2015 — February 2016

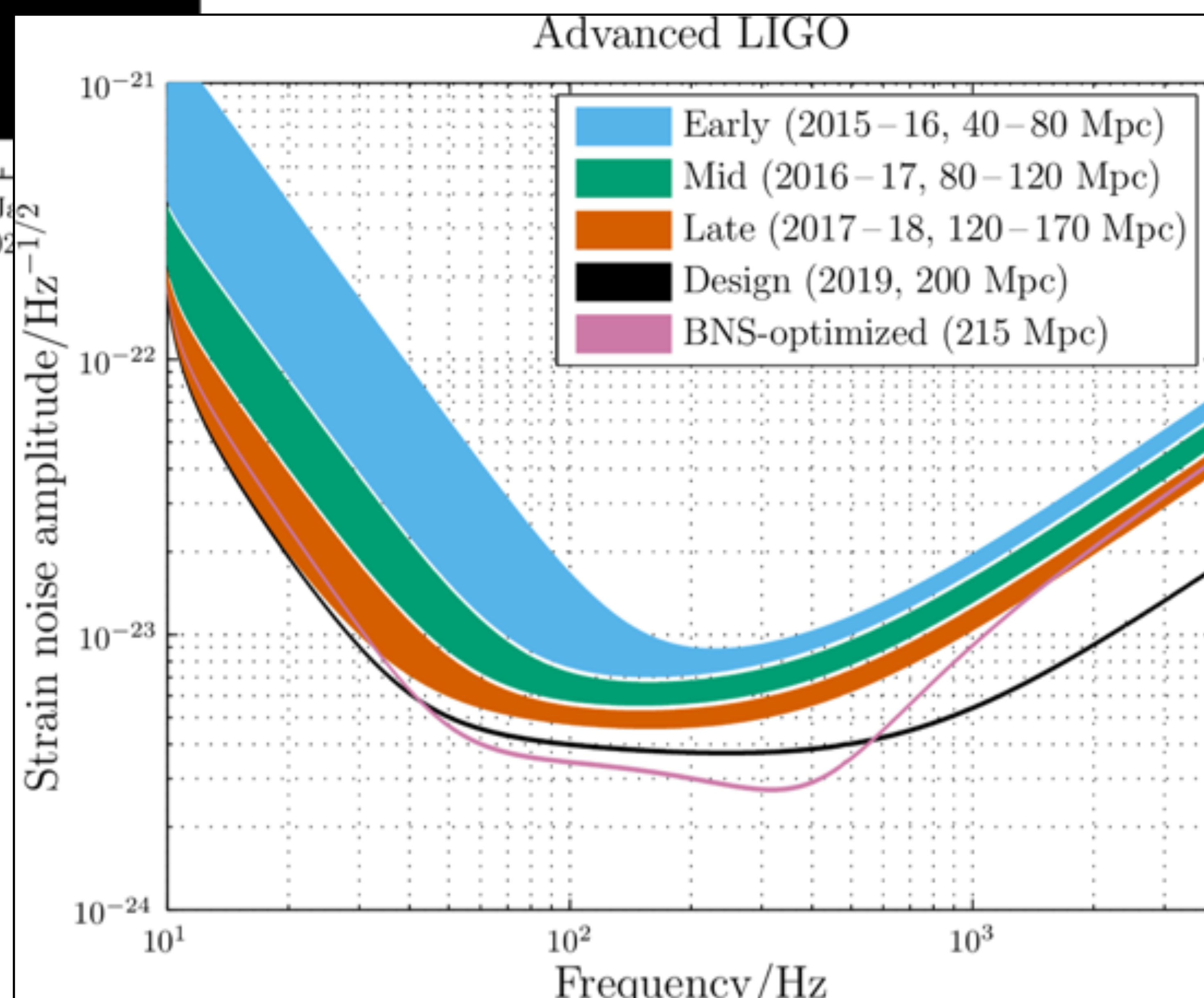






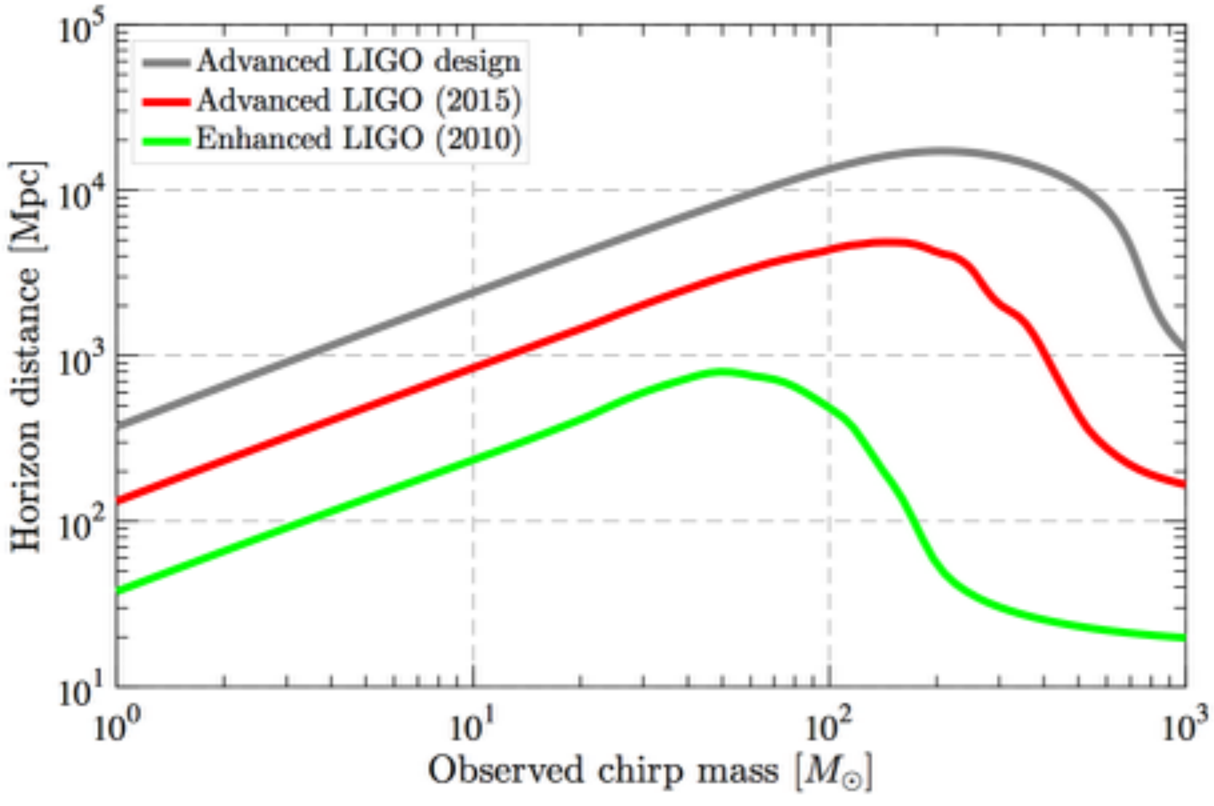
Abbott et al. (2016) - O1 BBH

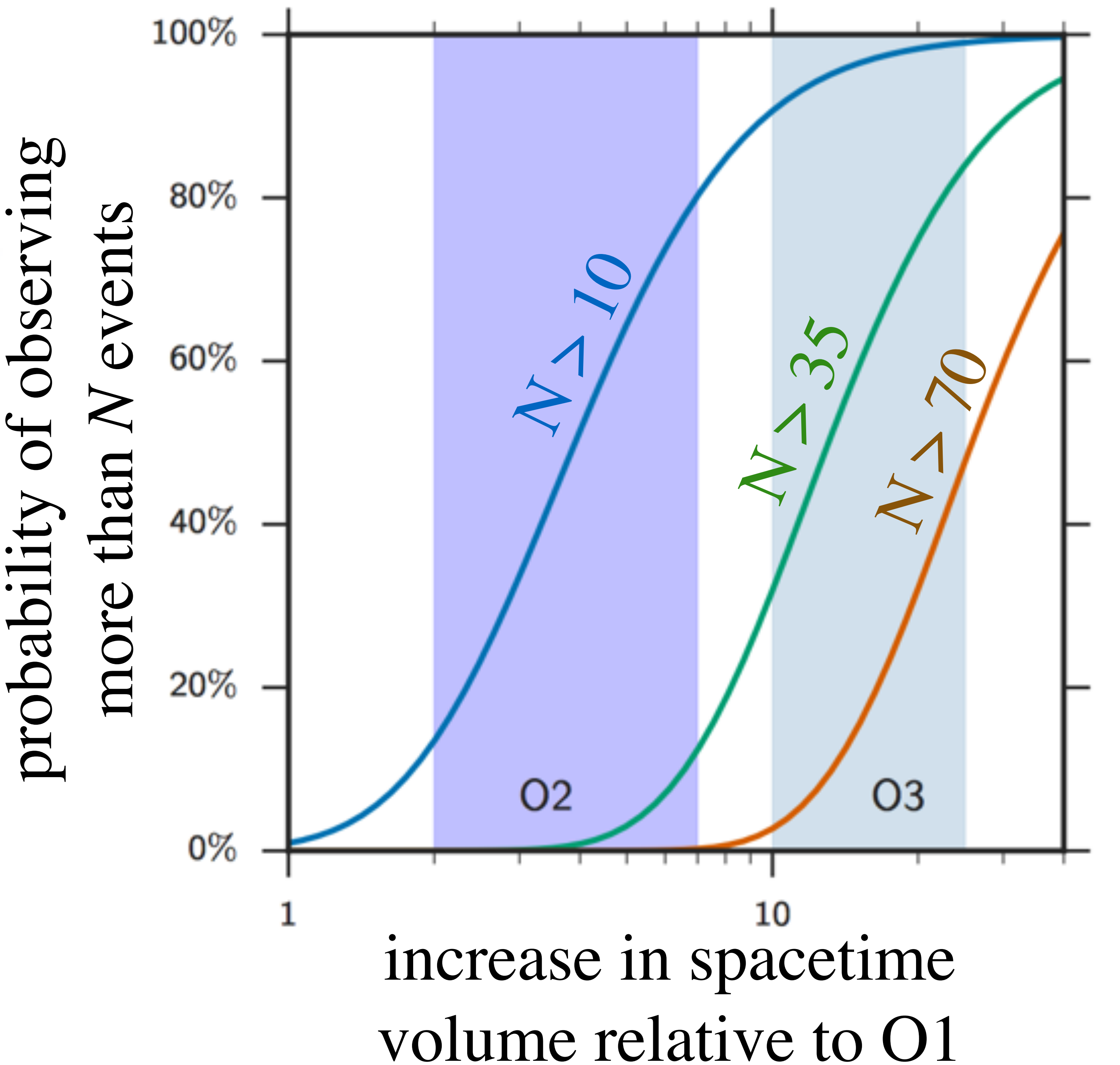




Abbott et al. (2016) - Living Rev. Relativity

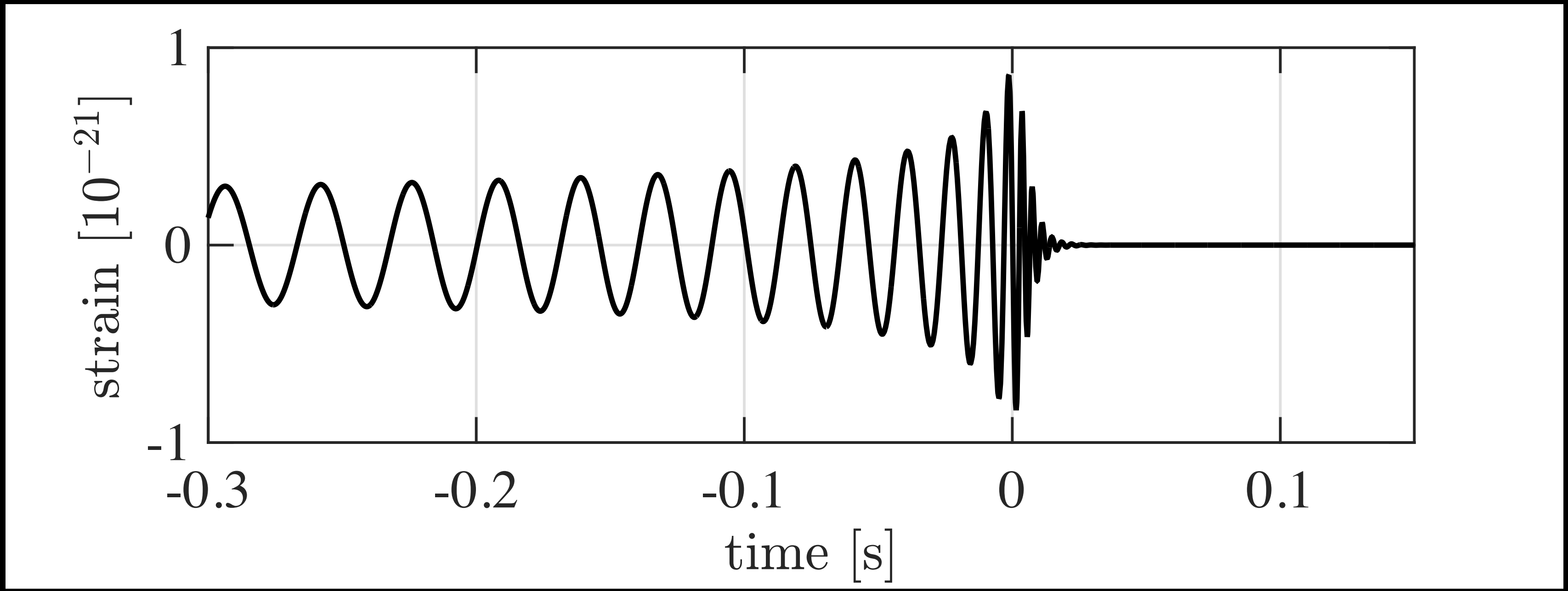
Expected Detection Rates

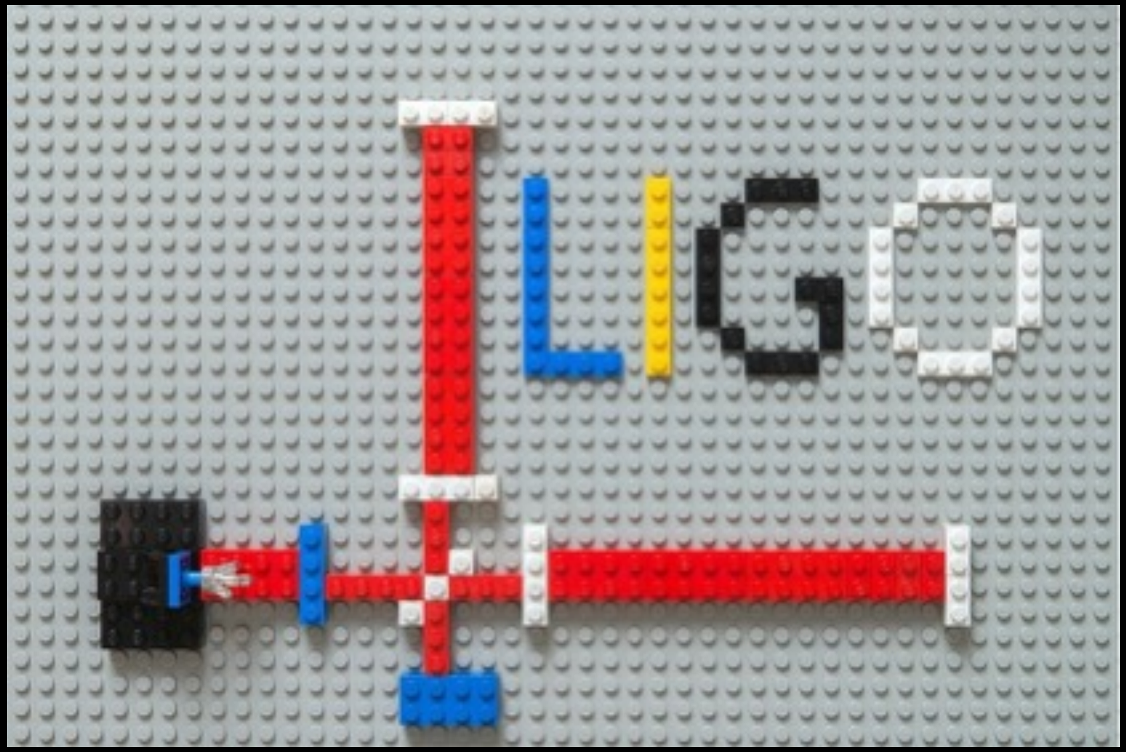


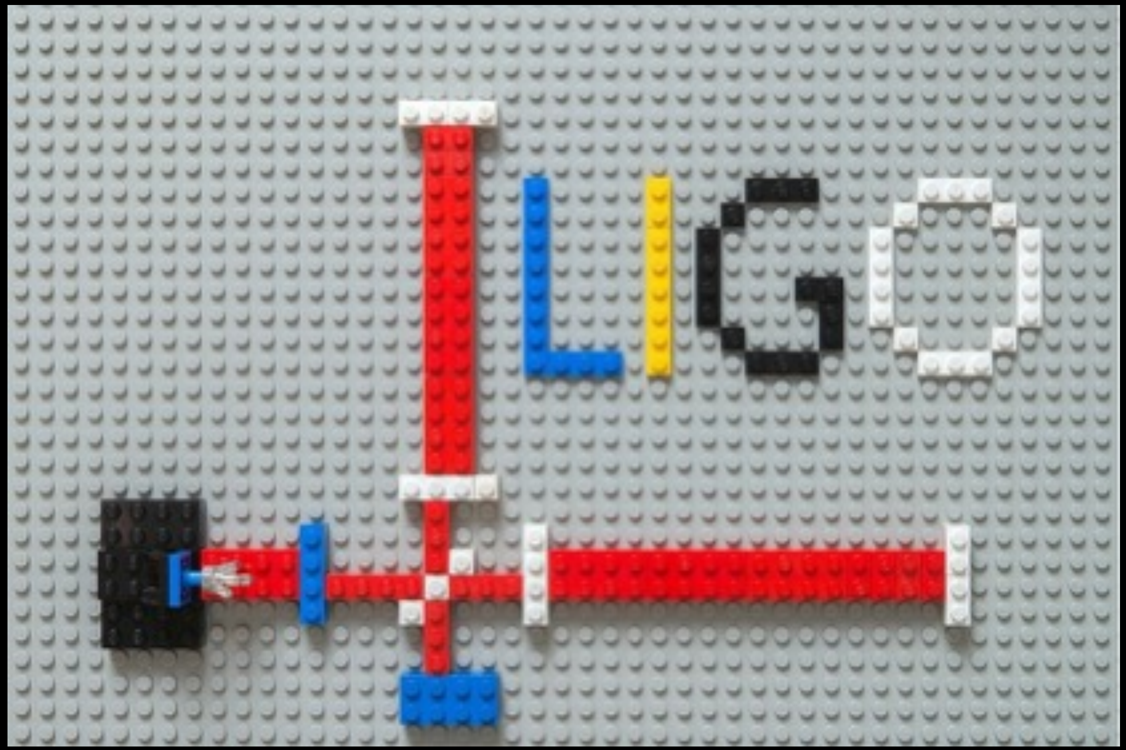


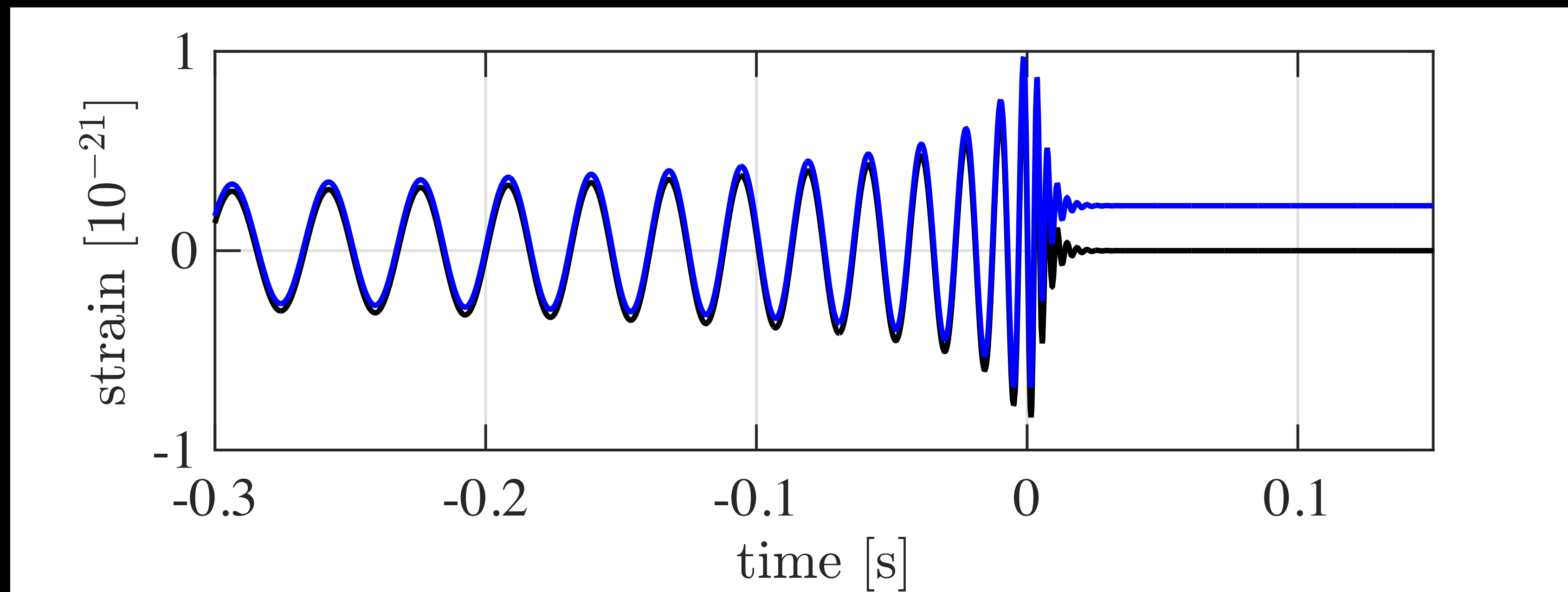
Abbott et al. (2016) - O1 BBH

What can we learn from the inevitable ***ensemble*** of events, that cannot be learnt from individual events?


1
0
-1
strain $[10^{-21}]$
-0.3
-0.2
-0.1
0
0.1
time [s]


LIGO


LIGO


1
0
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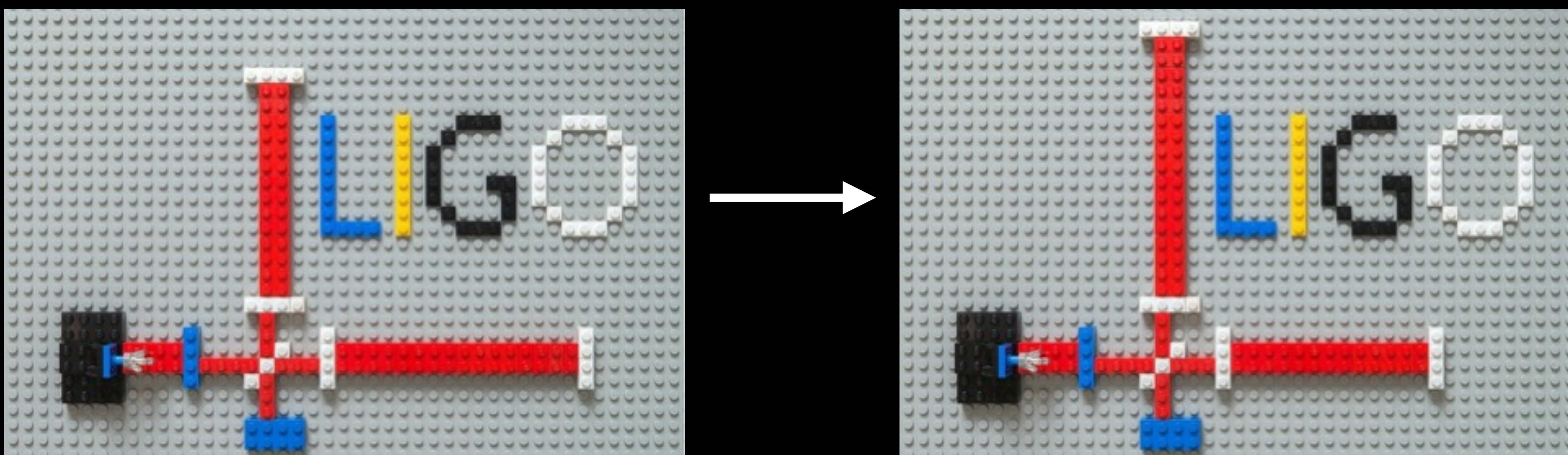
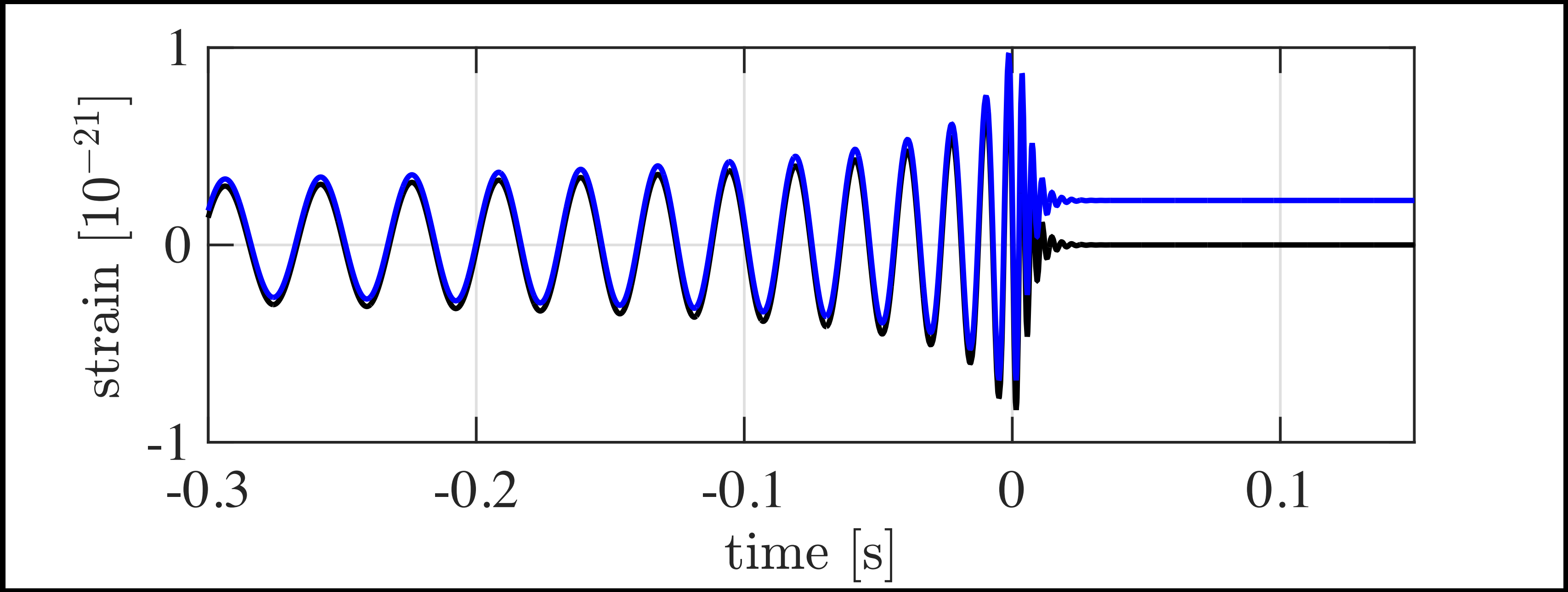
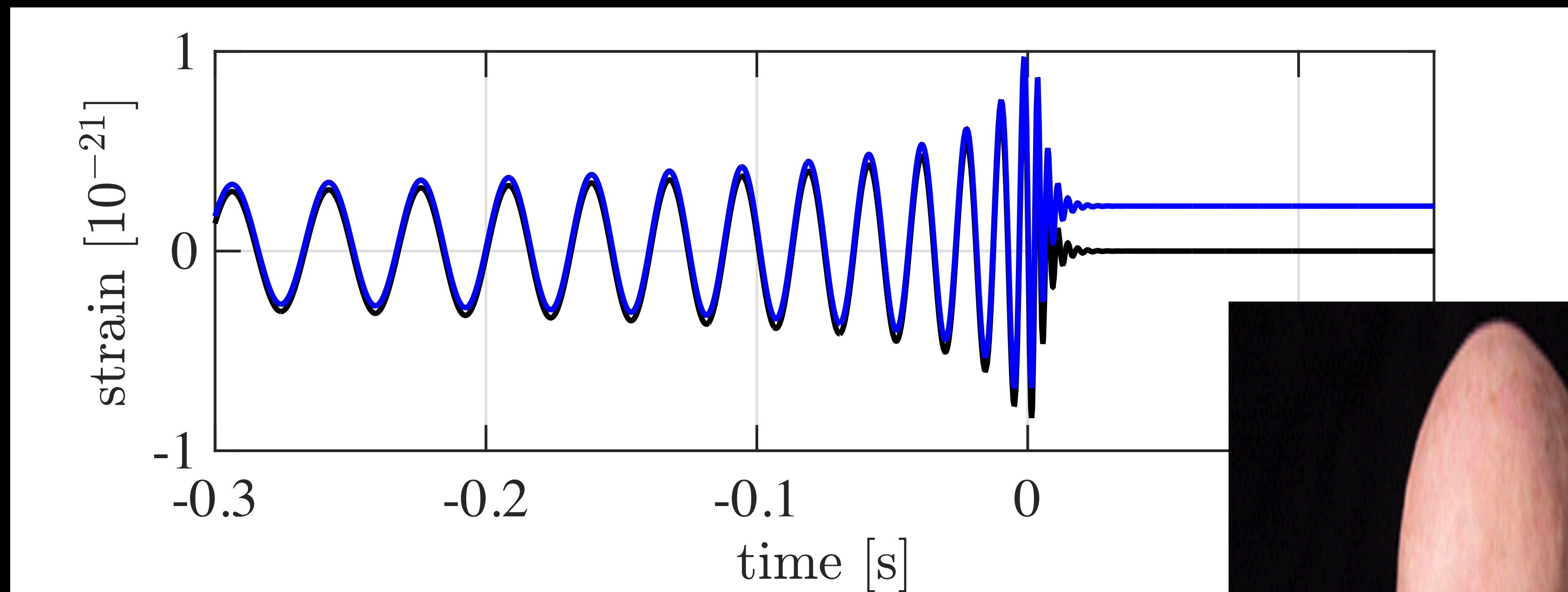
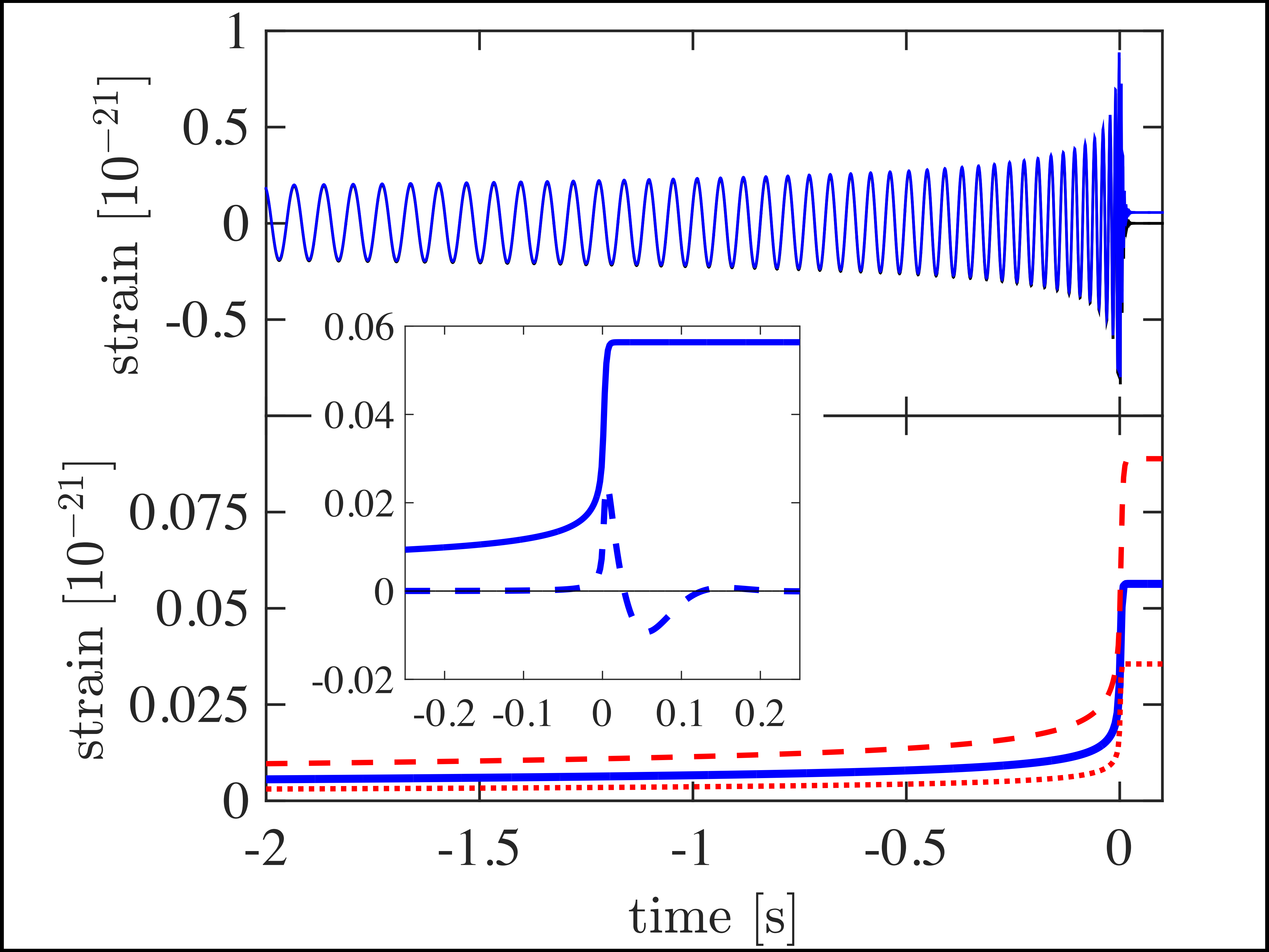
0
0.1
time [s]


LIGO
LIGO


strain [10^{-21}]
1
0
-1
-0.3
-0.2
-0.1
0
0.1
time [s]


1
0
-1
strain [10−21]
-0.3
-0.2
-0.1
0
time [s]

How the detector responds

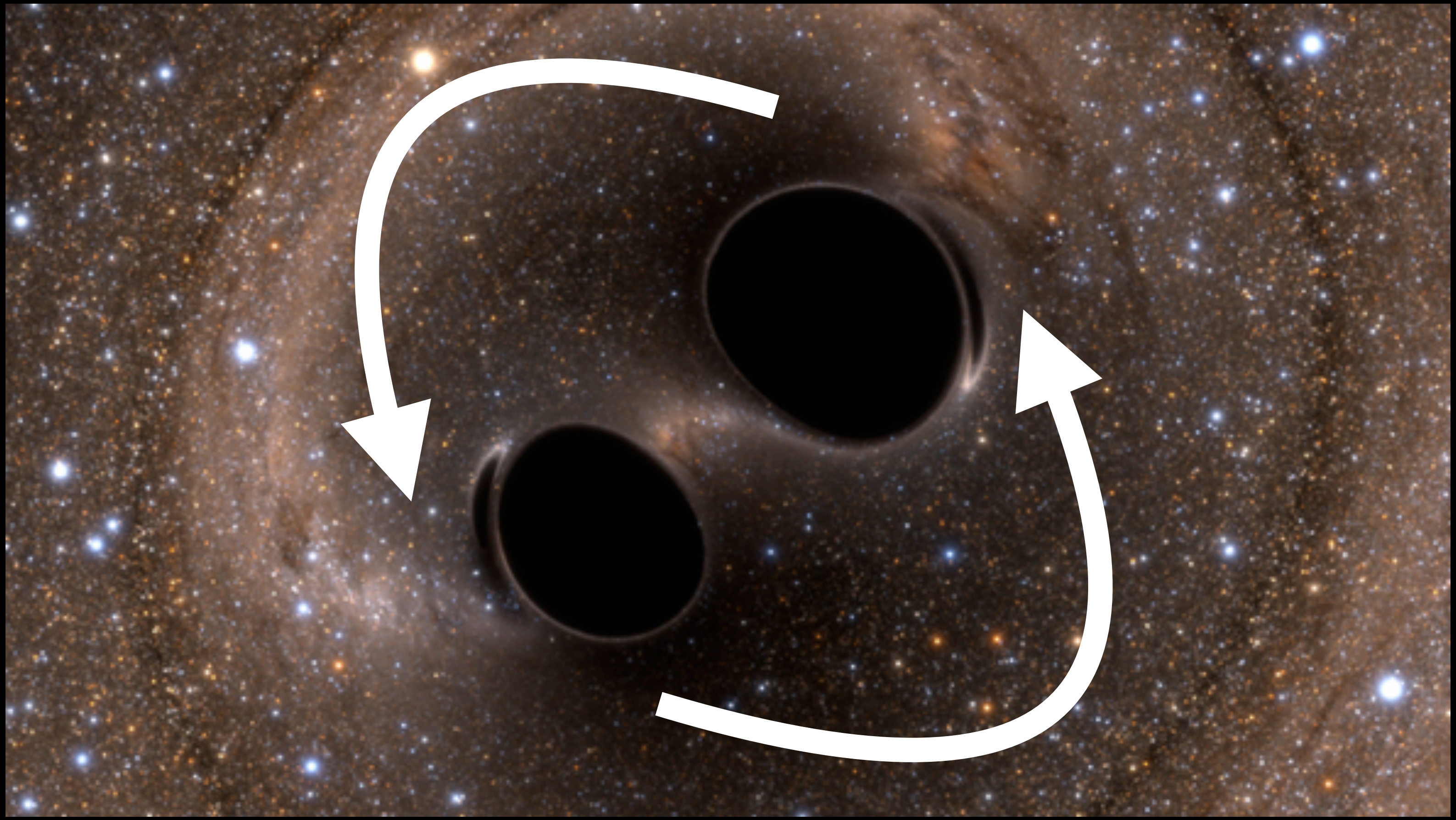


Lasky et al. (2016)

What is memory?

$$h \propto \frac{\ddot{Q}}{d}$$

- non-zero from inspiral of point masses



e.g., Braginsky & Thorne (1987), Christodoulou (1991), Thorne (1992)

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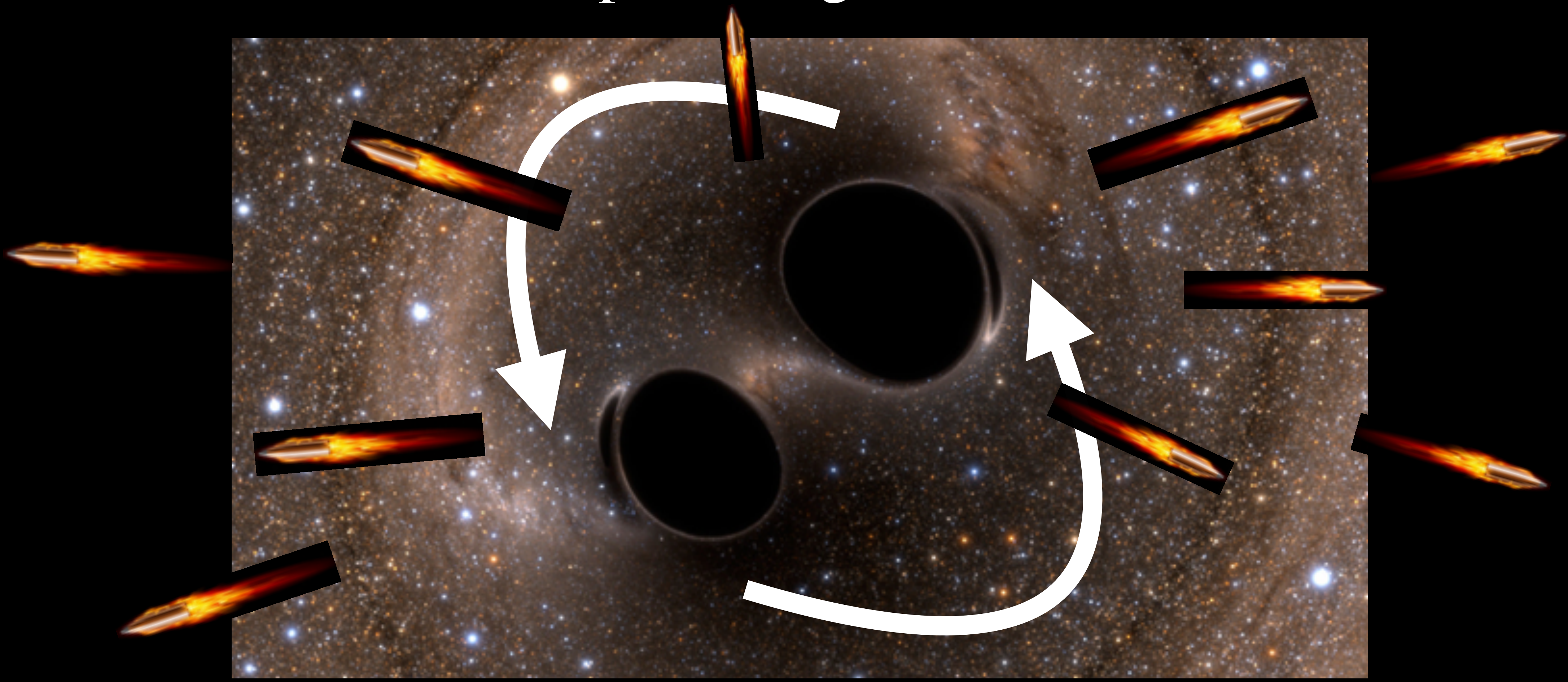
- also from anisotropic distribution of projectiles (**gravitons**) leaving source
  - alternatively, think of gravitational waves providing extra source term



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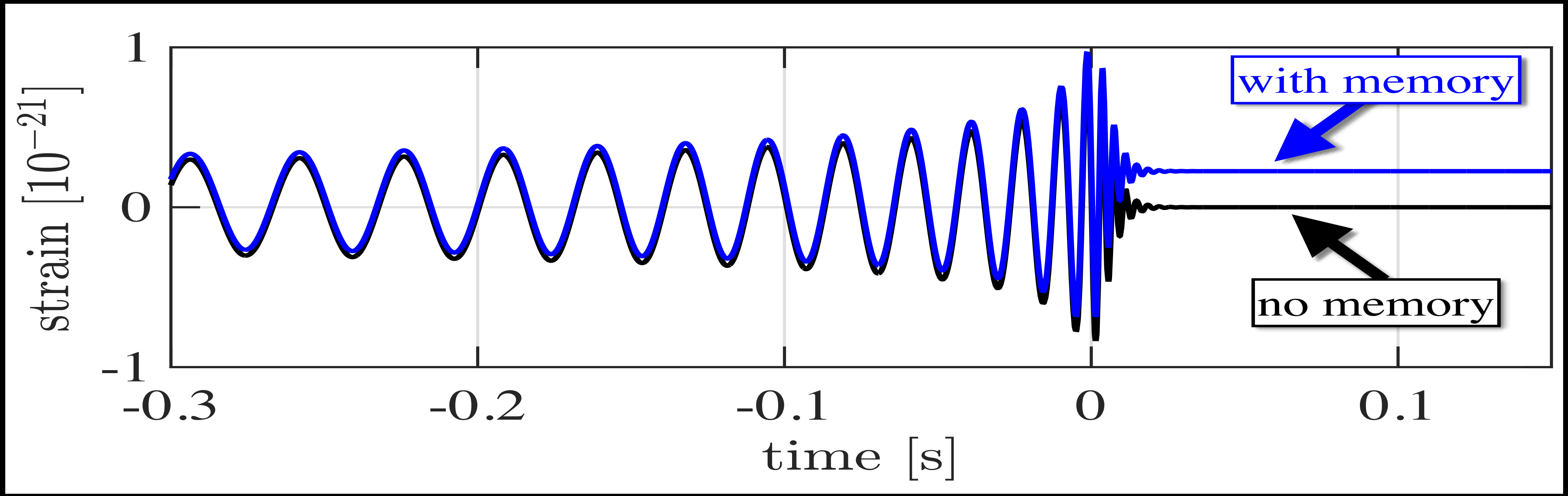
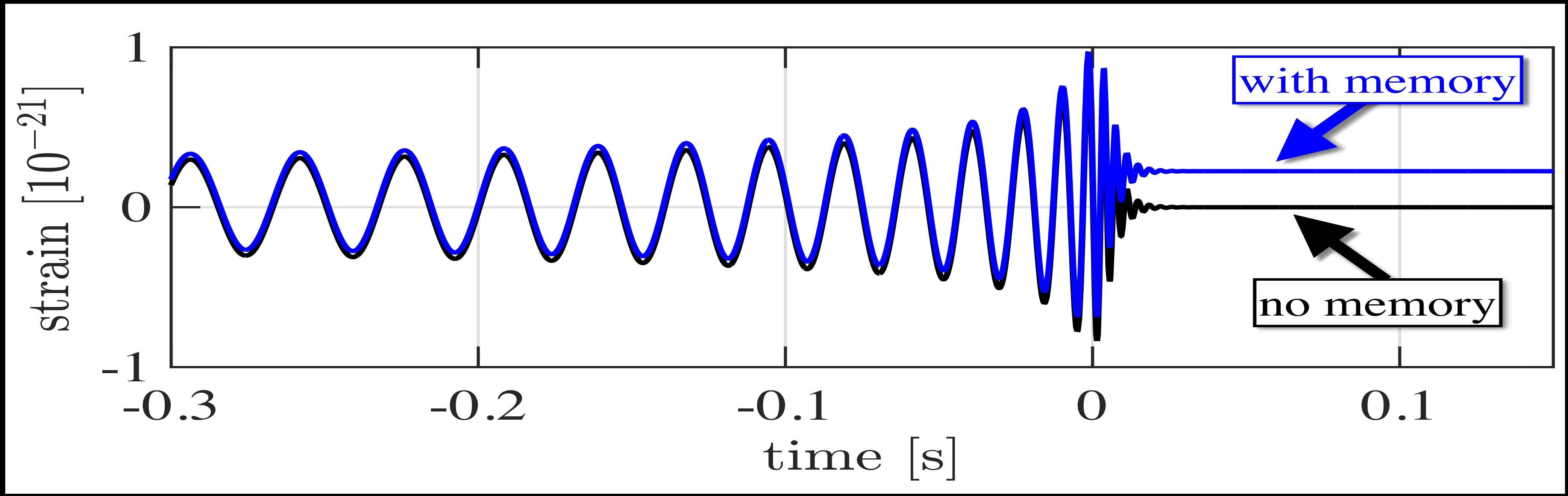
Non-oscillatory contribution to GW signal:
Permanent displacement of spacetime



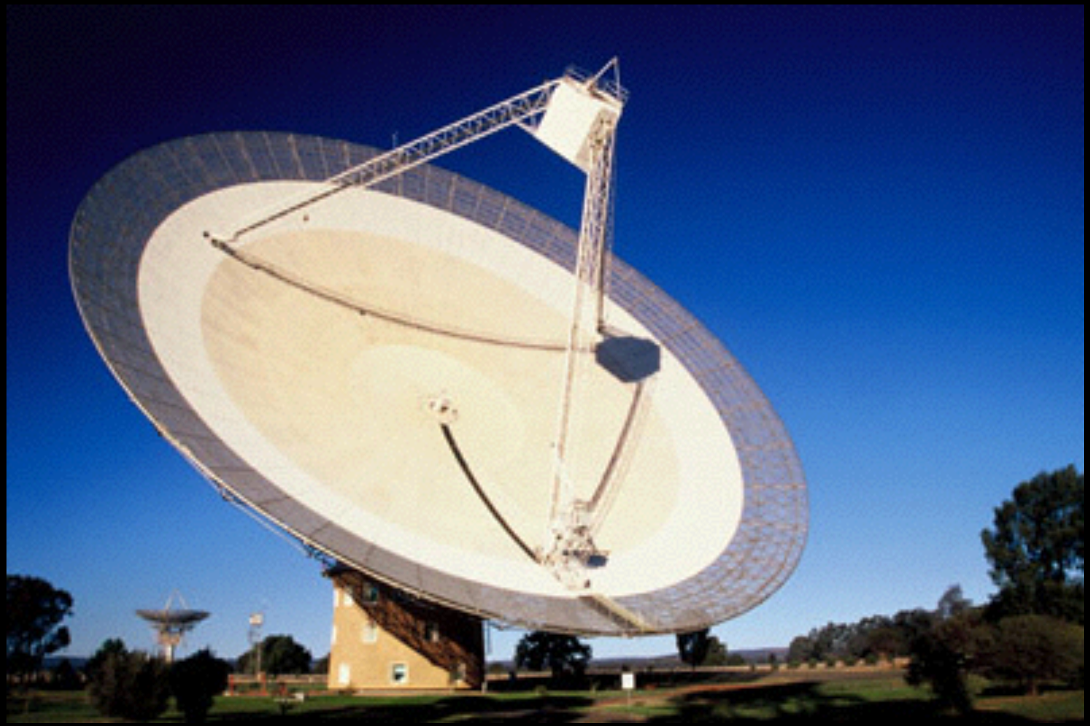
how BIG is the effect?

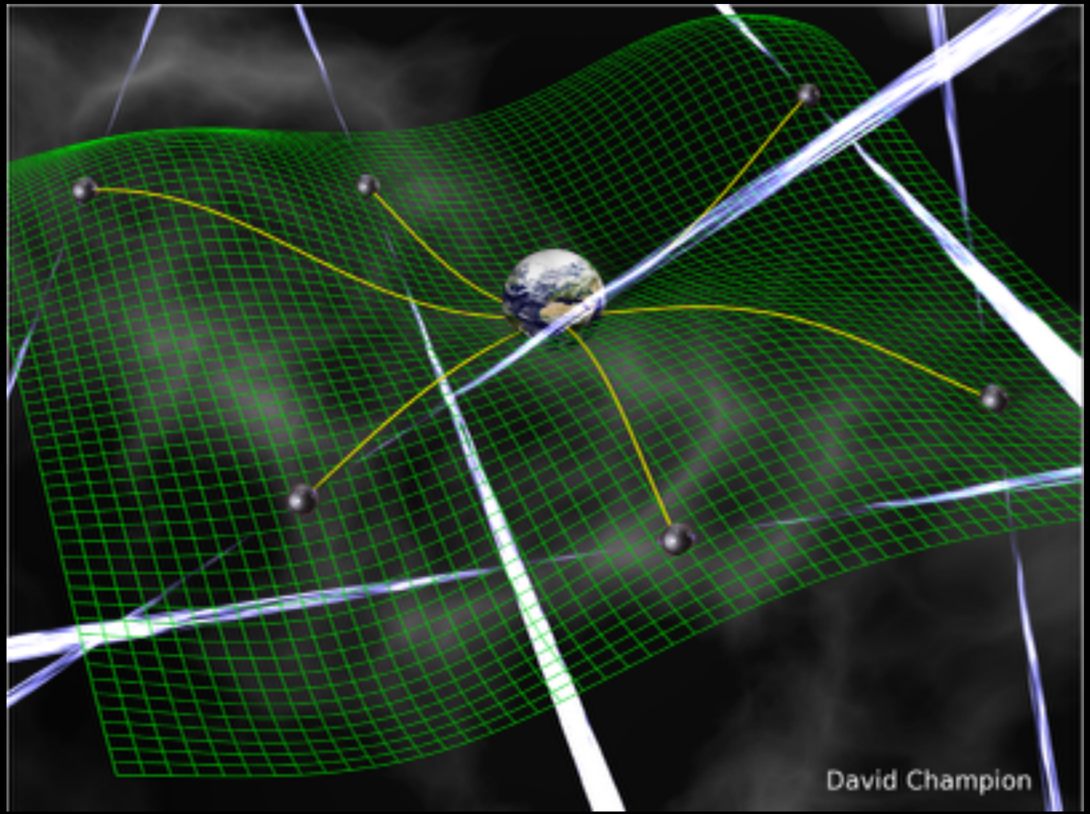
$$\text{GW150914:} \quad \frac{\text{oscillatory strain}}{\text{memory strain}} \approx \frac{1}{20}$$



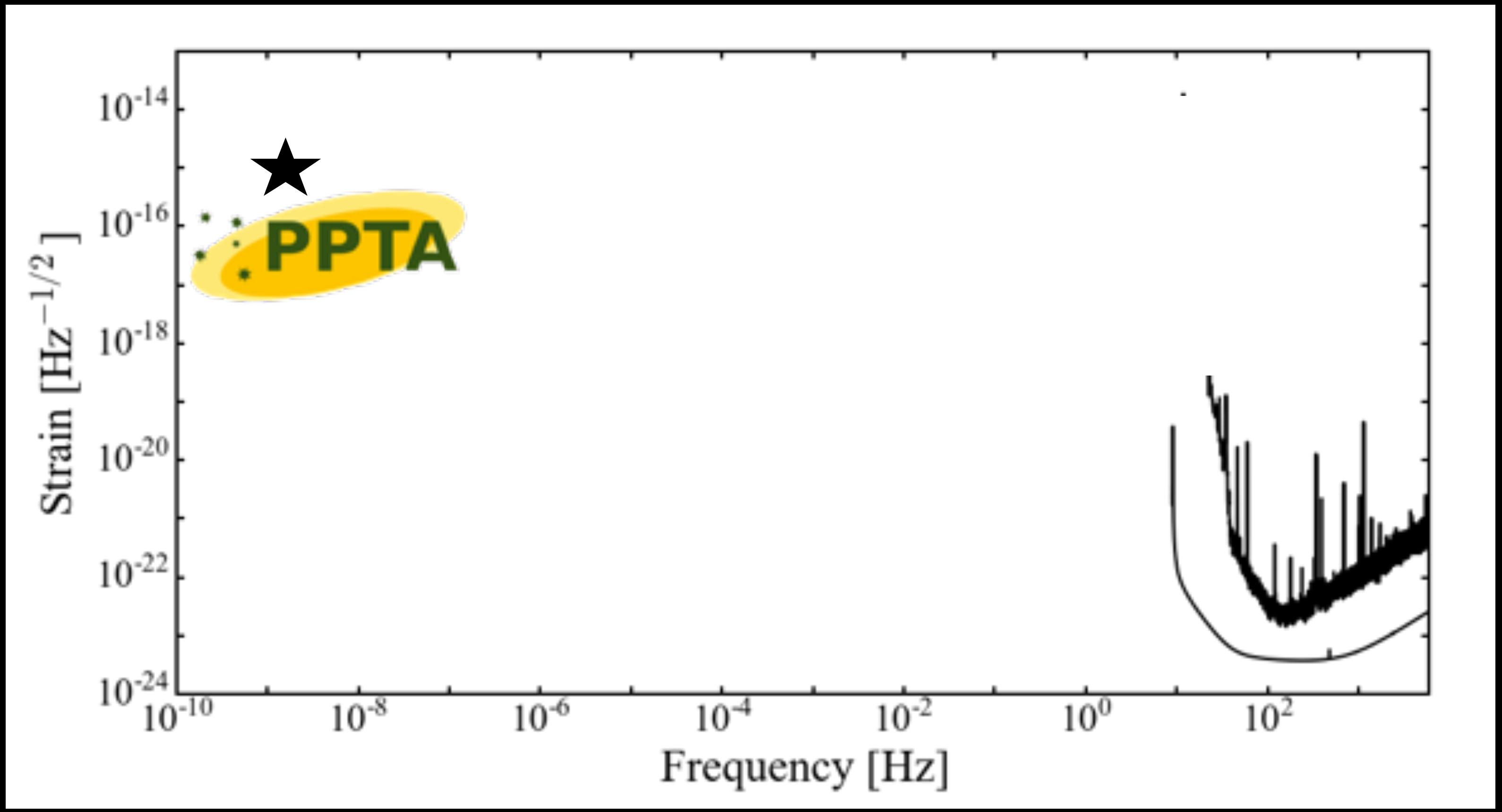
Lasky et al. (2016)

Previous efforts: Pulsar Timing Arrays





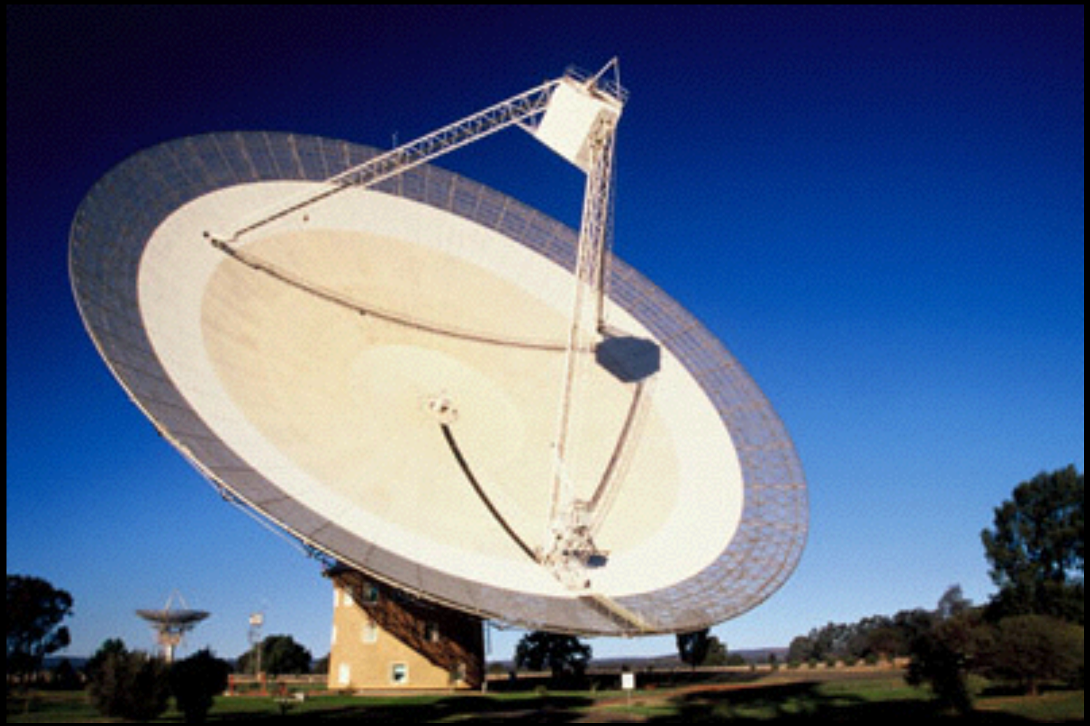
- PTAs search for nHz gravitational waves

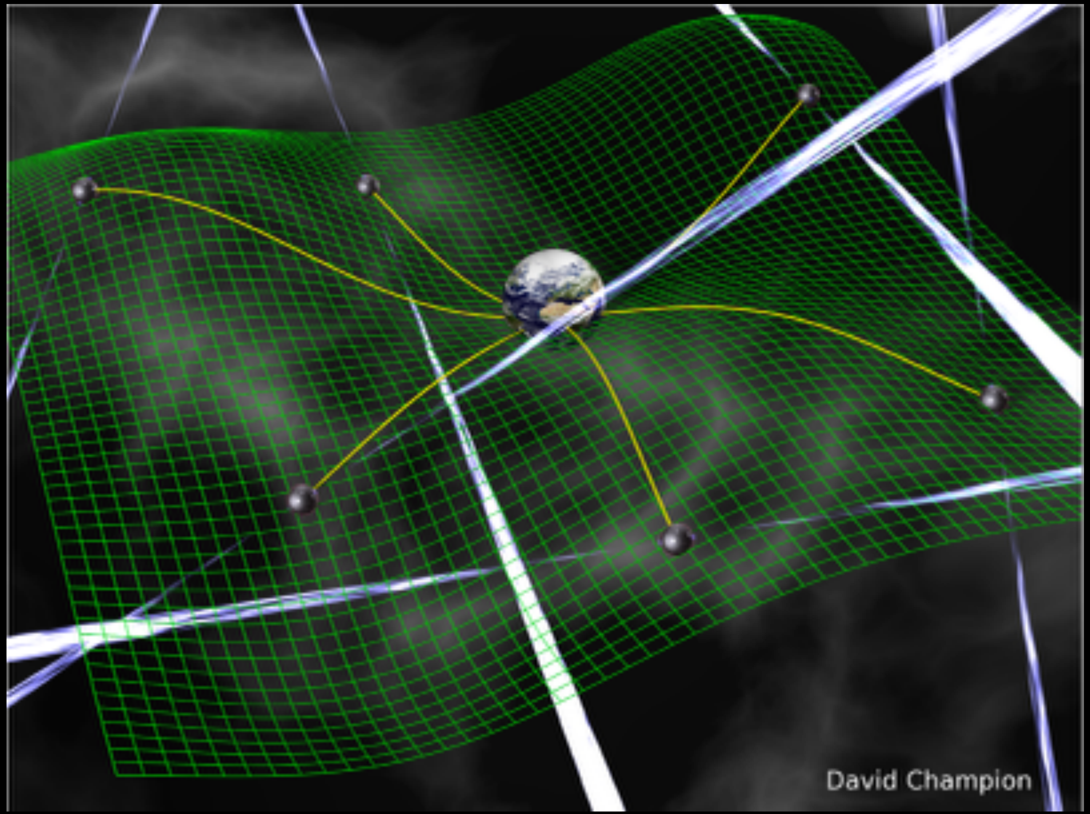


<u>Oscillatory GWs from binary black holes</u>

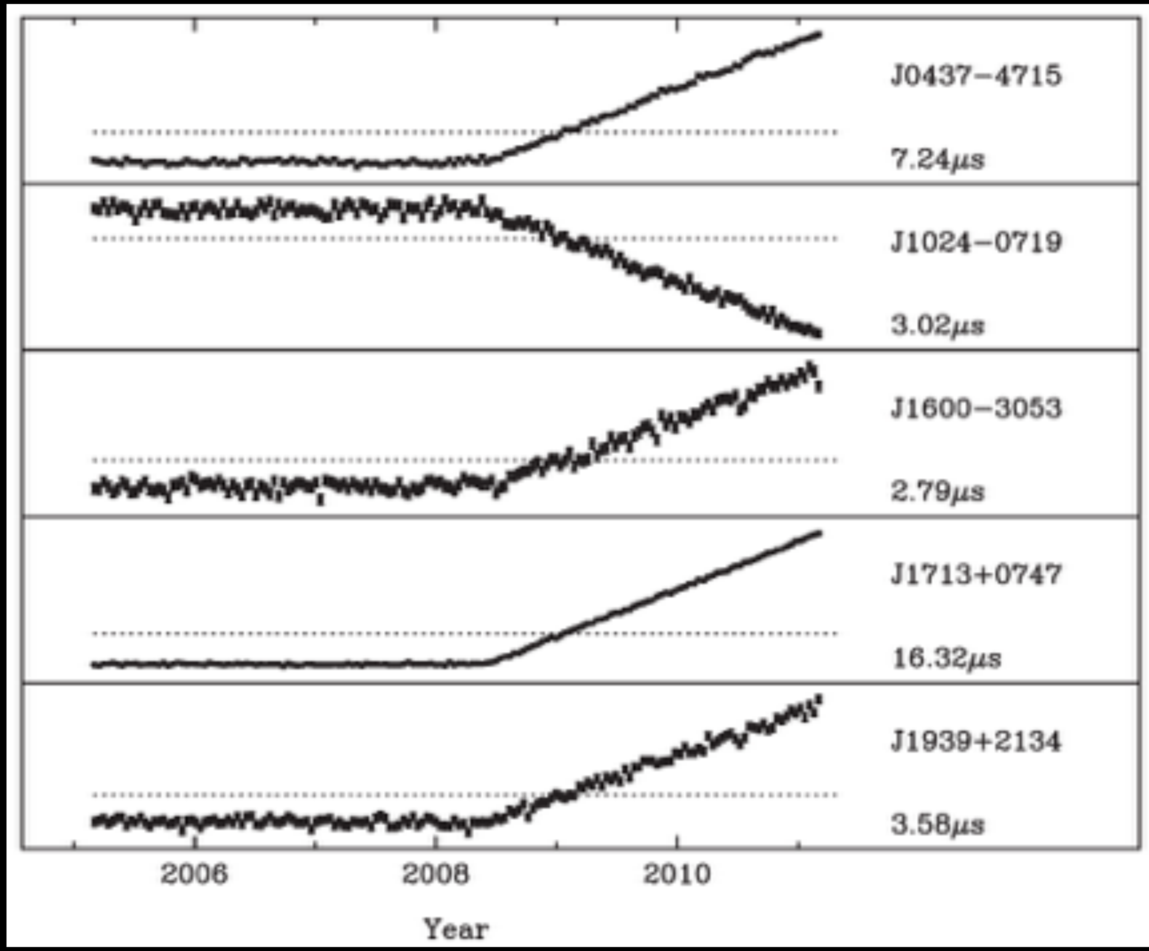
Best limit from Parkes (Shannon et al., 2015):
Non-detections impact models of galaxy formation

Previous efforts: Pulsar Timing Arrays





- PTAs search for nHz gravitational waves
- Sensitive to memory from supermassive black hole mergers (no detections)
- Predicted event rates are low



Wang et al. (2015)

Detecting memory from an **ensemble** of events with LIGO

- Any given signal is too weak to detect
- Proposal: **measure the sum of many signals**

- We know the arrival time of each signal
  - subtract oscillatory component
  - search for memory

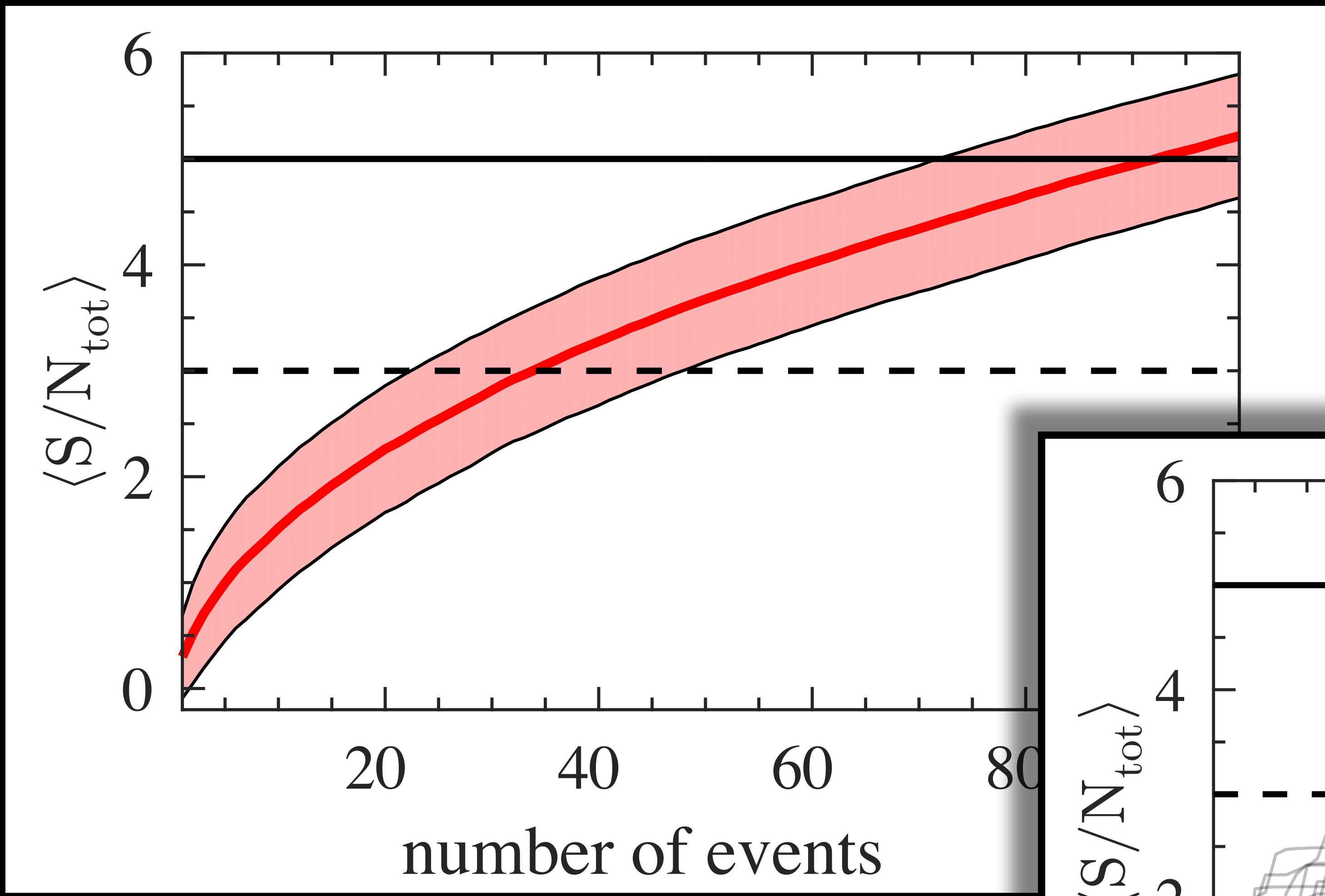
- Design statistics for adding signal

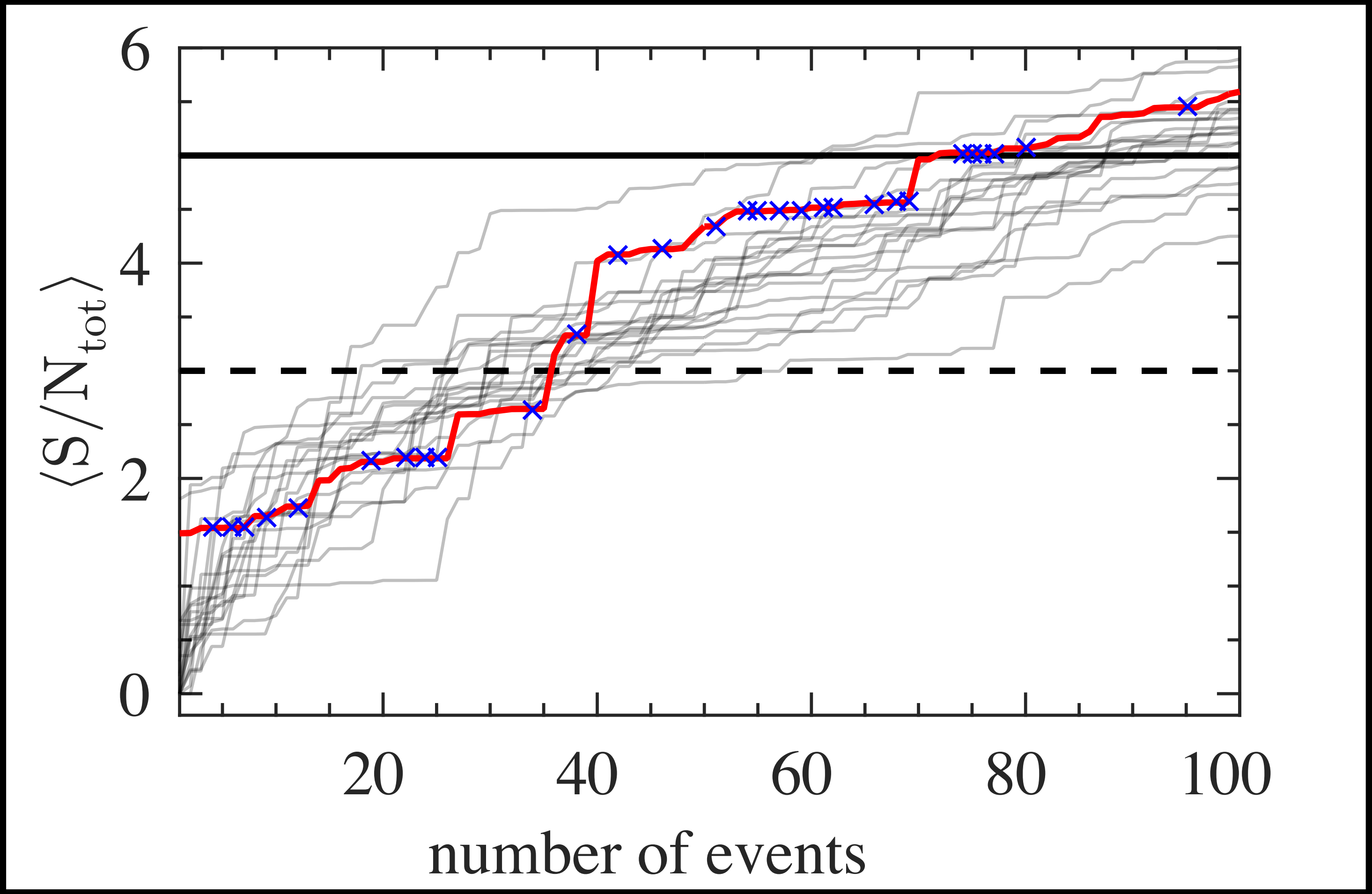
Lasky et al. (2016)

For the frequentists…

optimal matched filter

$$S/N_{\rm tot} = \left(\sum_{i=1}^{N} \sum_{j=1}^{N_{\rm IFO}} S/N_{i,j}^2 \right)^{1/2}$$





Advanced LIGO:
~ **35** 'loudish'
black hole observations

Lasky et al. (2016)

Measurement Subtleties

- Oscillatory (h_{22}) waveform component invariant under

$$\psi \rightarrow \psi + \pi/2 \qquad \phi_c \rightarrow \phi_c + \pi/2$$

$$h_{22}(\psi,\, \phi_c) = h_{22}(\psi + \pi/2,\, \phi_c + \pi/2)$$

Lasky et al. (2016)

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$$h_{22}(\psi,\, \phi_c) = h_{22}(\psi + \pi/2,\, \phi_c + \pi/2)$$

- but, memory component incurs a minus sign

$$h_{22}^{\mathrm{mem}}(\psi,\, \phi_c) = -h_{22}^{\mathrm{mem}}(\psi + \pi/2,\, \phi_c + \pi/2)$$

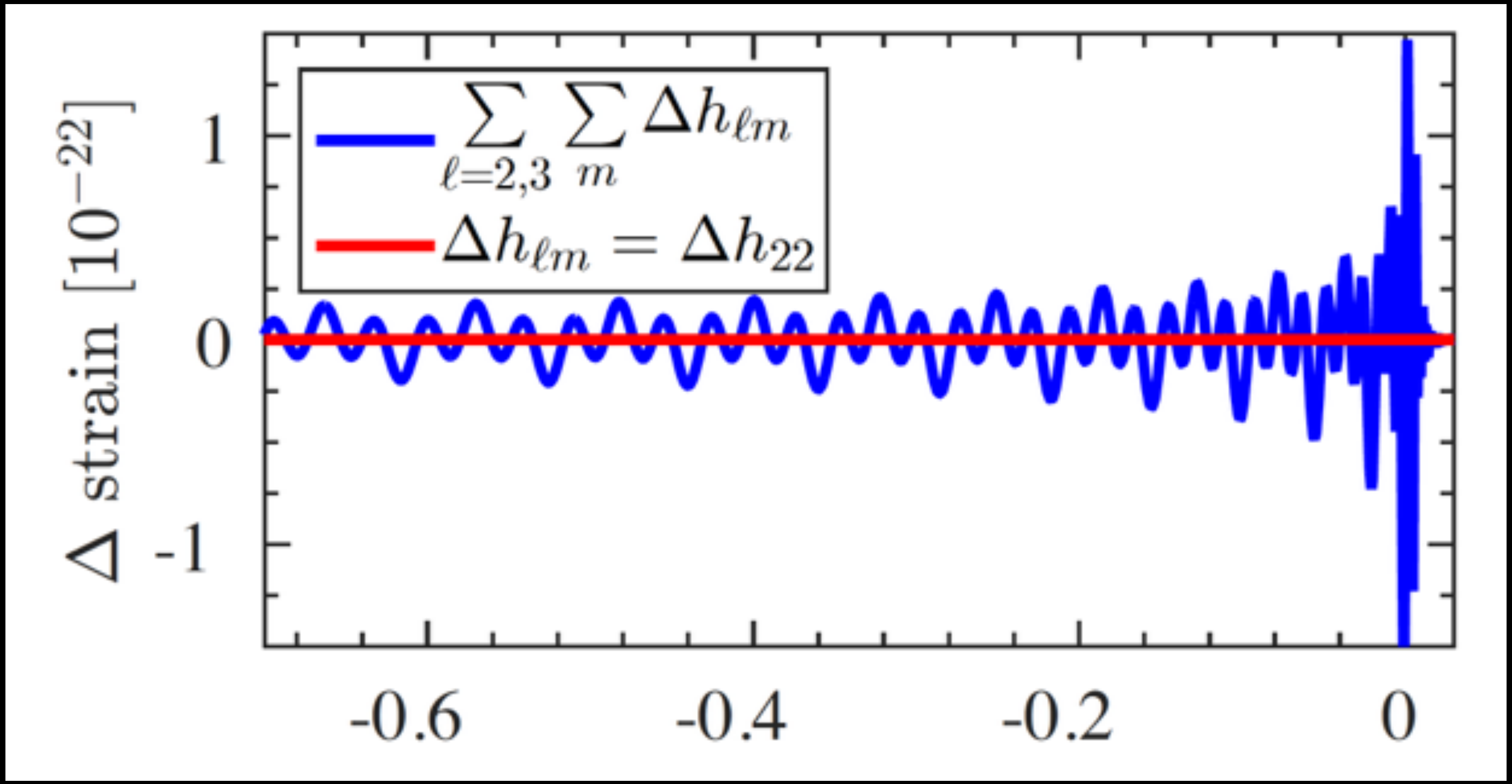
Lasky et al. (2016)

- Solution: higher order modes

$$\Delta h_{\ell m} \propto h_{\ell m}(\psi, \phi_c) - h_{\ell m}(\psi + \pi/2,\, \phi_c + \pi/2)$$

$\Delta h_{\ell m} = 0$ degeneracy not broken :-(

$\Delta h_{\ell m} \neq 0$ sign of memory known :-)



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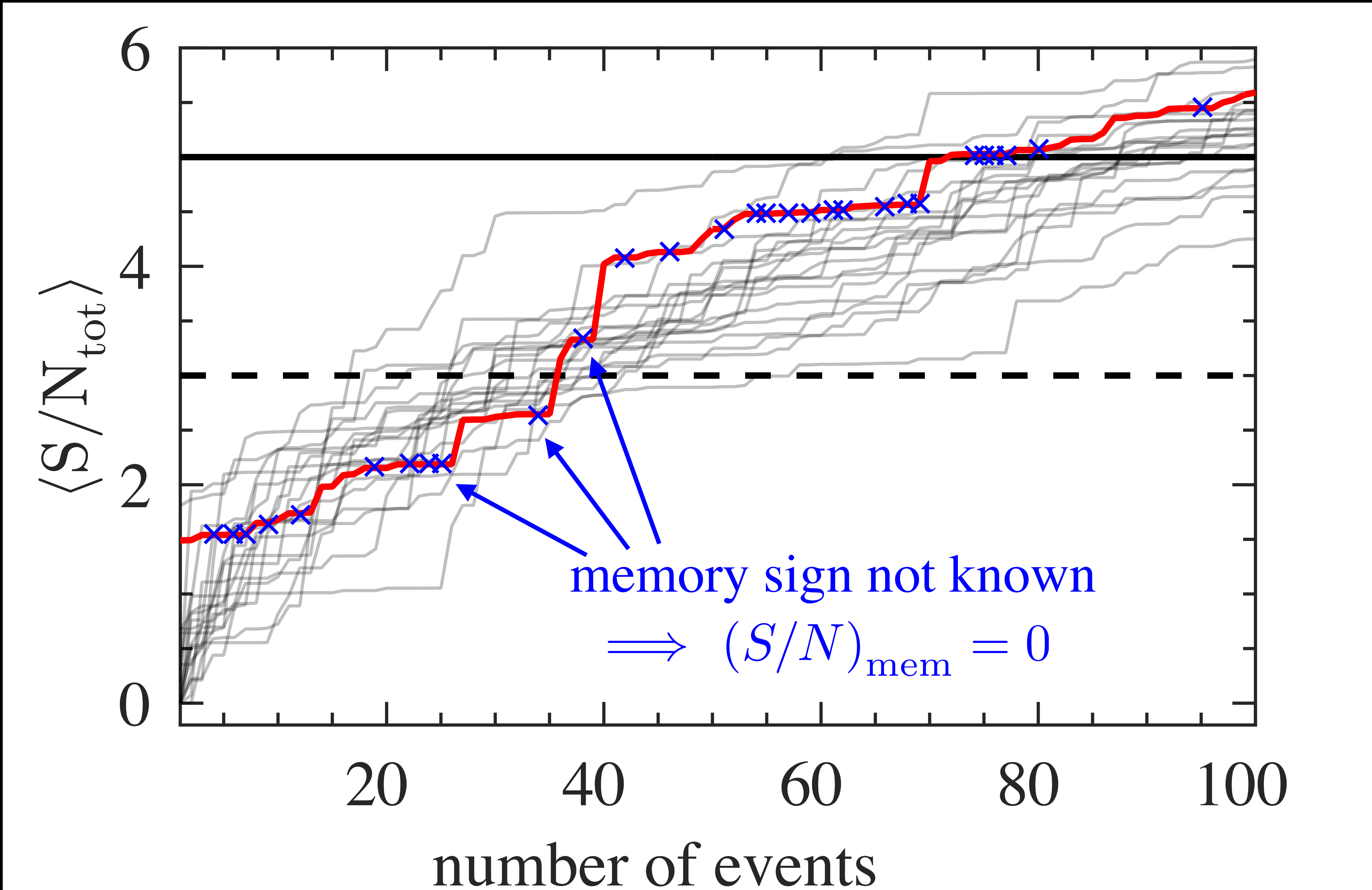
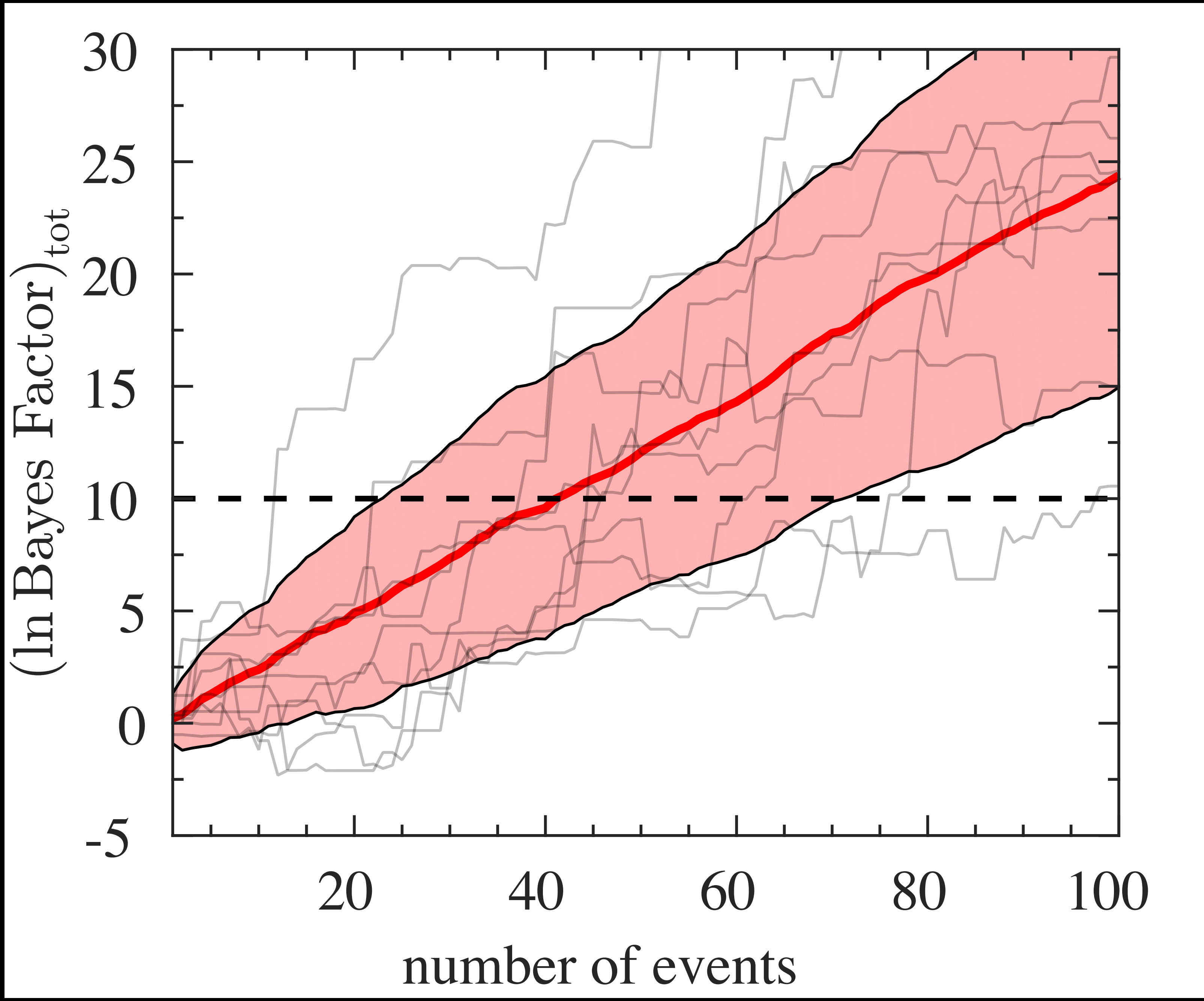


Lasky et al. (2016)

The Bayesian approach…



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Lasky et al. (2016)

Other ways to detect memory in LIGO: Orphan Memory

- Can we detect memory without detecting the oscillatory part of the waveform?

McNeill, Thrane, Lasky & Levin (in prep)

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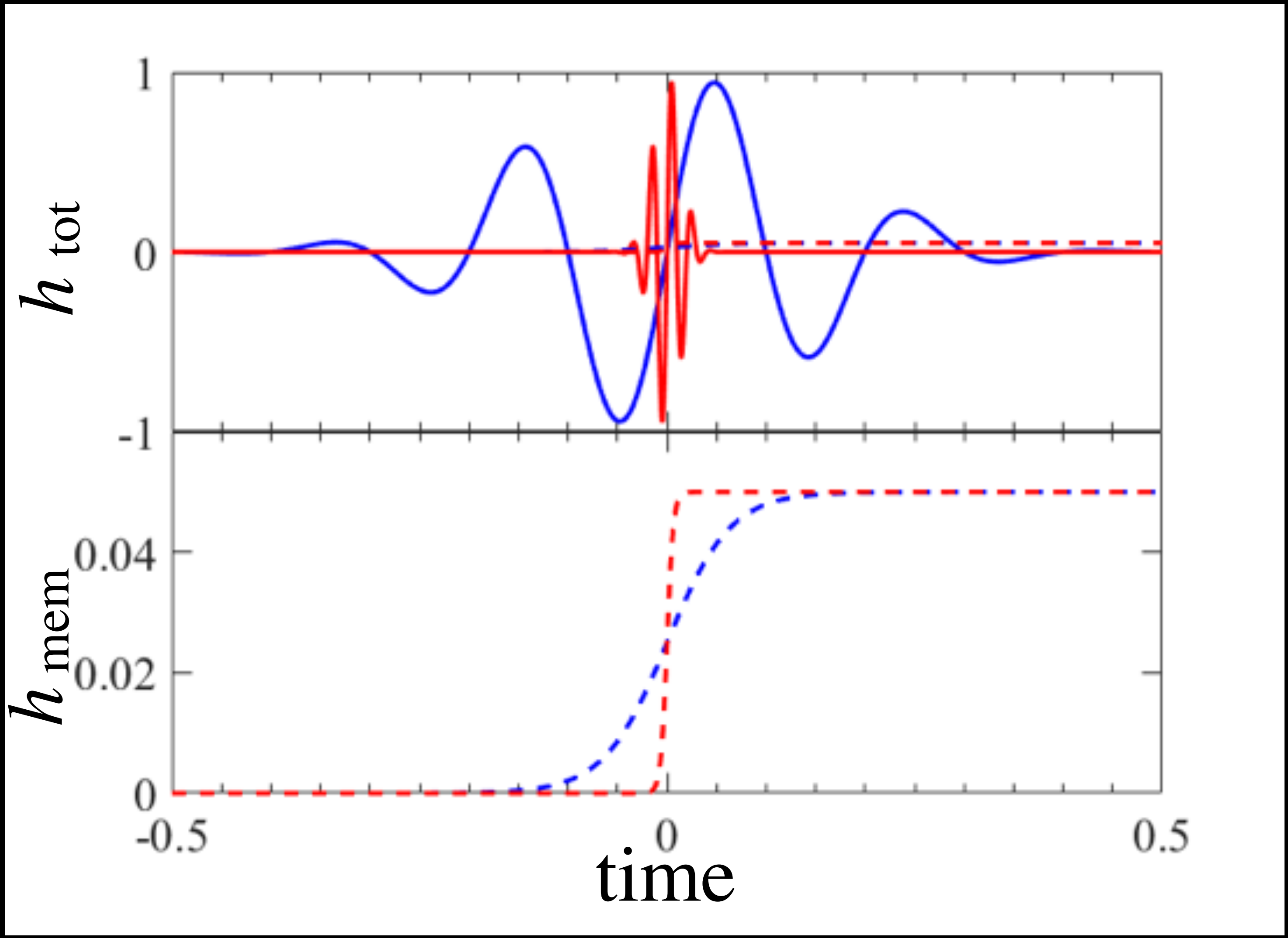
- Yes:
  - high-frequency burst signals
  - memory is step-function

$$\implies h_{\mathrm{mem}}(f) \propto f^{-1}$$



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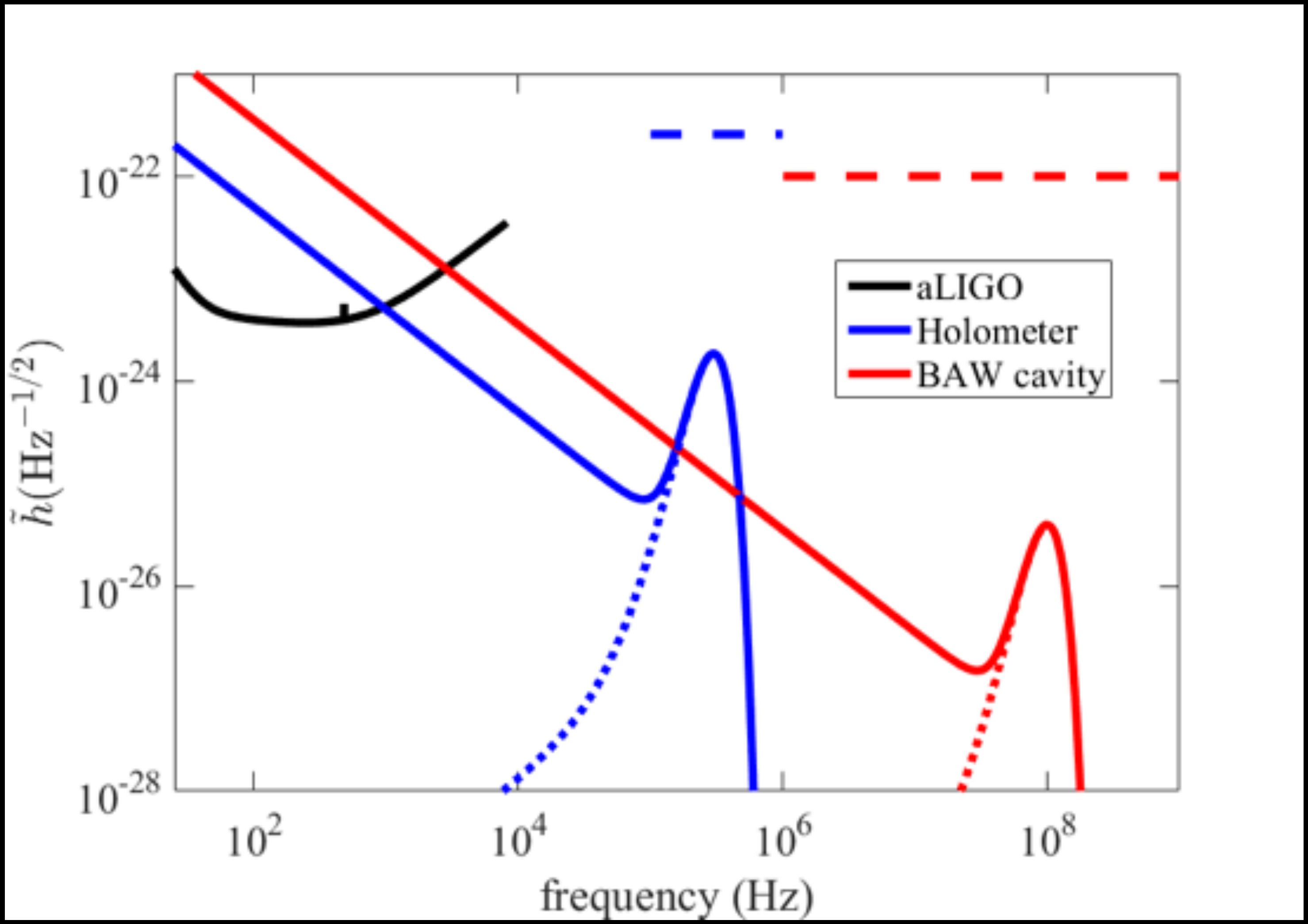
- Extends LIGO's bandwidth by orders of magnitude!



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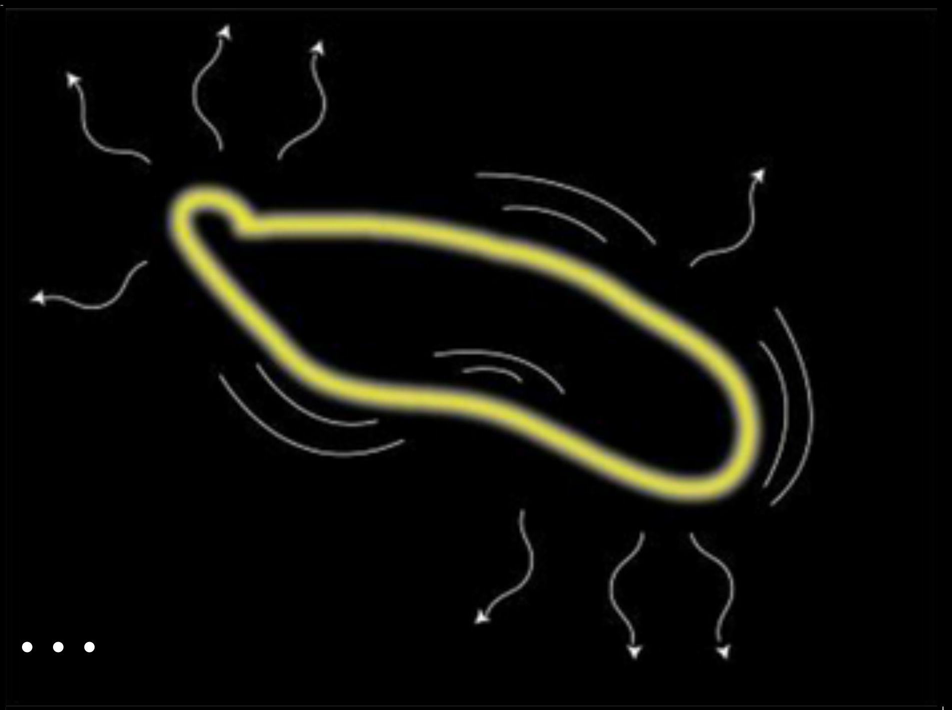

- High frequency sources?
  - Cosmic strings
  - stellar oscillation modes
  - plasma instabilities in e.g., SNe, GRBs, …
  - Brane-world black hole modes
  - dark matter collapse in stars

(for review, see Cruise 2012)

McNeill, Thrane, Lasky & Levin (in prep)

Conclusions

- gravitational-wave memory:
  - permanent deformation of spacetime!!

- Advanced LIGO:
  - ~ 35 ‘loudish’ binary black hole mergers
  - ***ensemble*** observations allow us to learn physics more than the sum of the parts