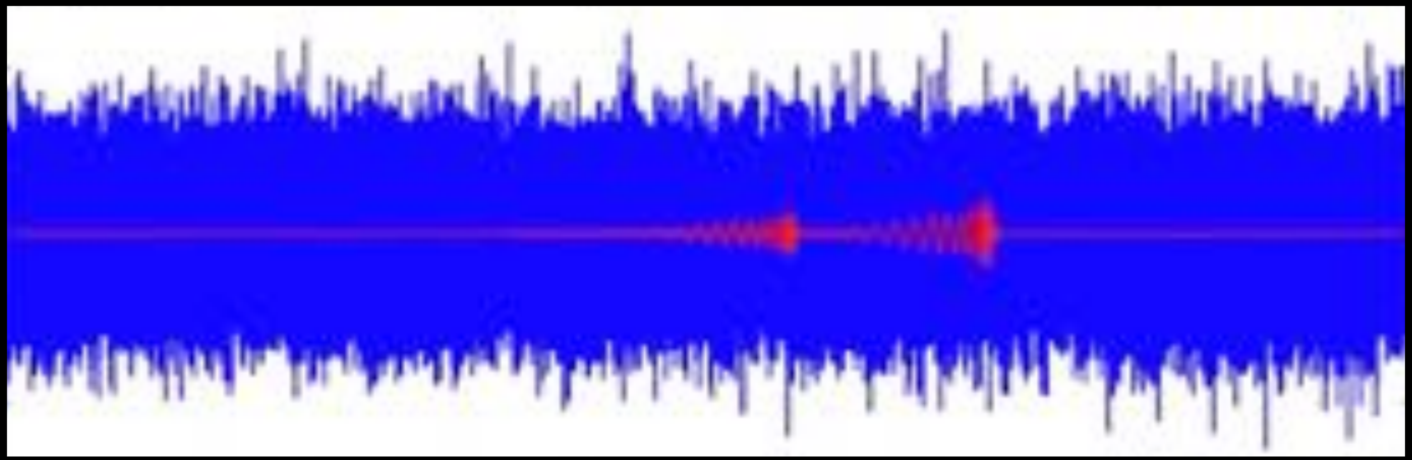
Matched filtering



Dr. Jess McIver

LSSTC DSFP

June 13, 2019

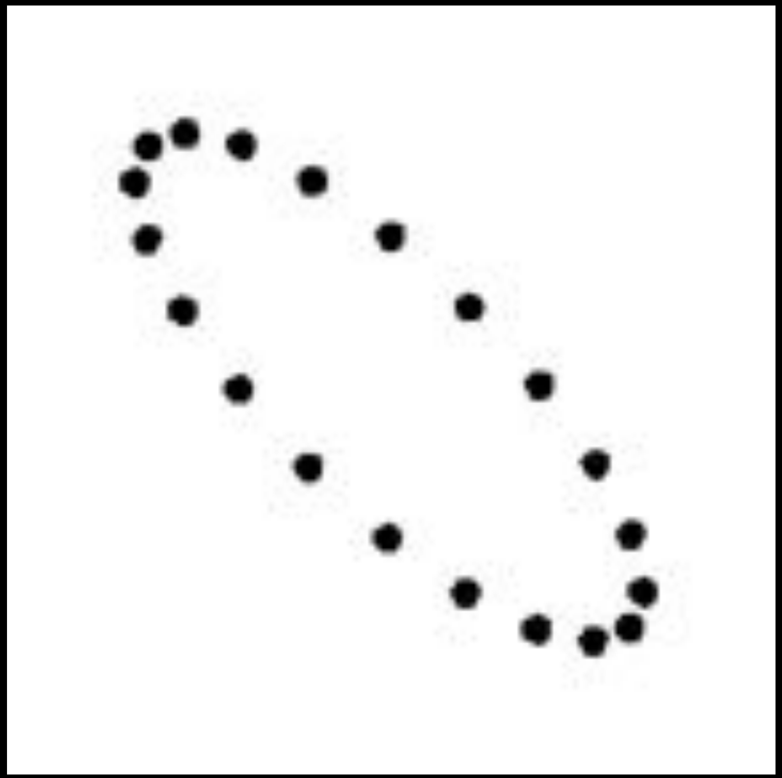
LIGO DCC G1901110

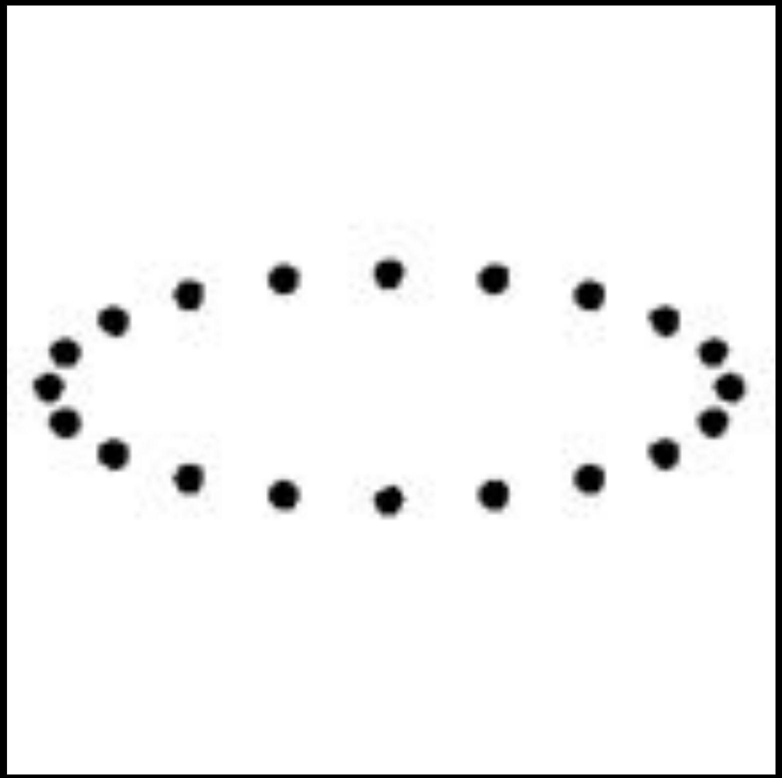
Caltech

LIGO

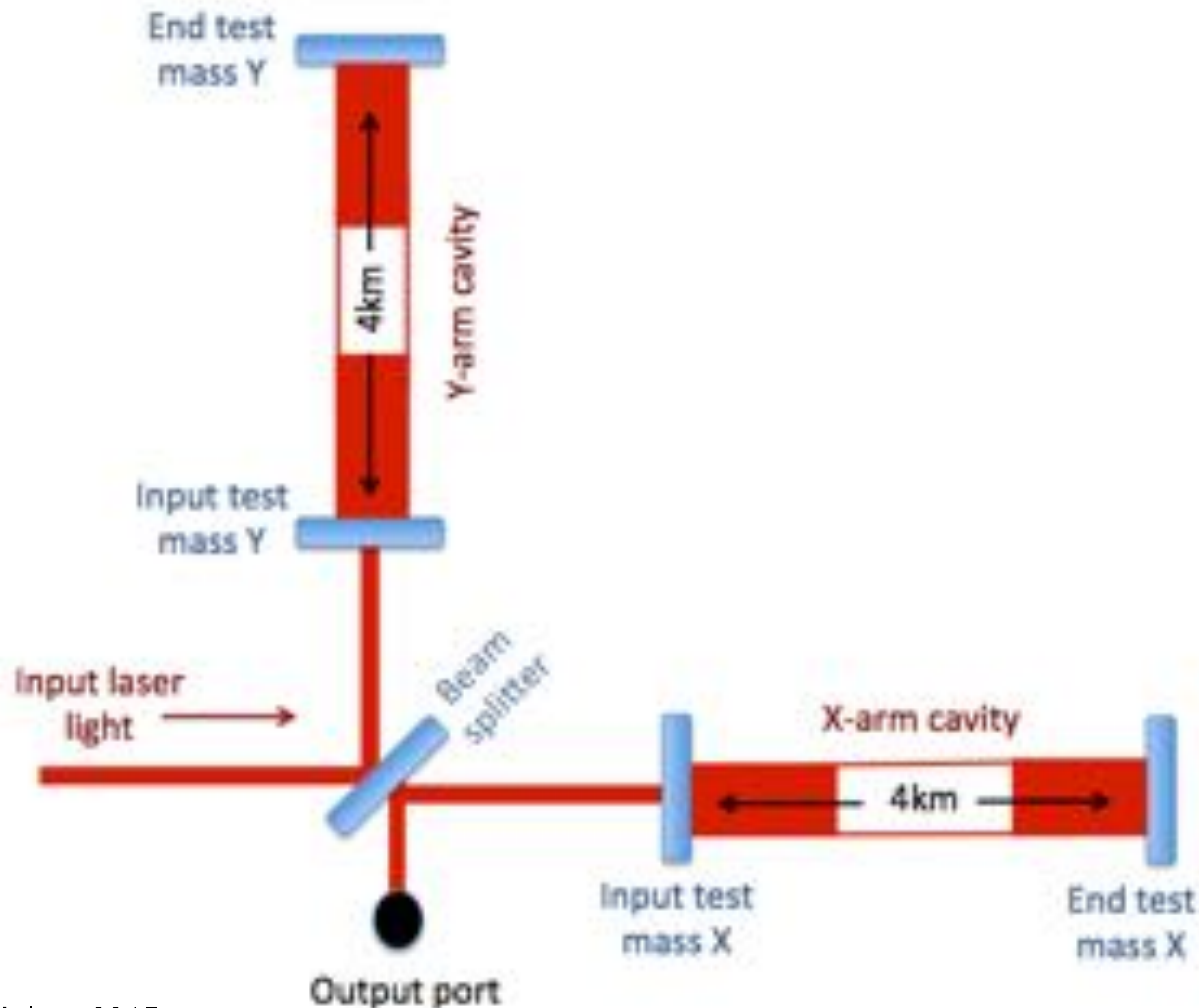
Gravitational wave propagation

Spacetime strain h(t) measured as $\frac{\Delta L}{L}$



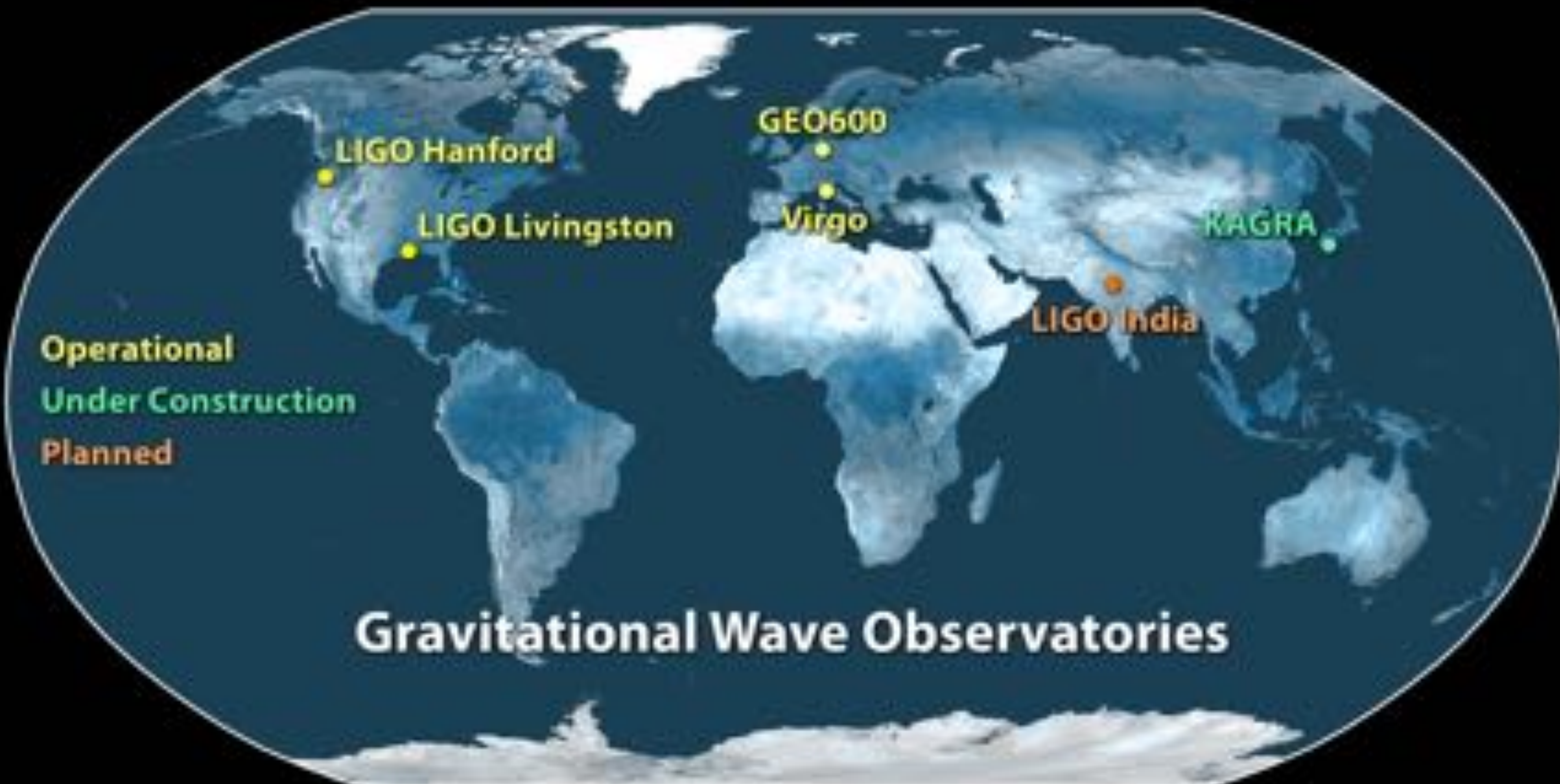


Observing GWs with interferometry



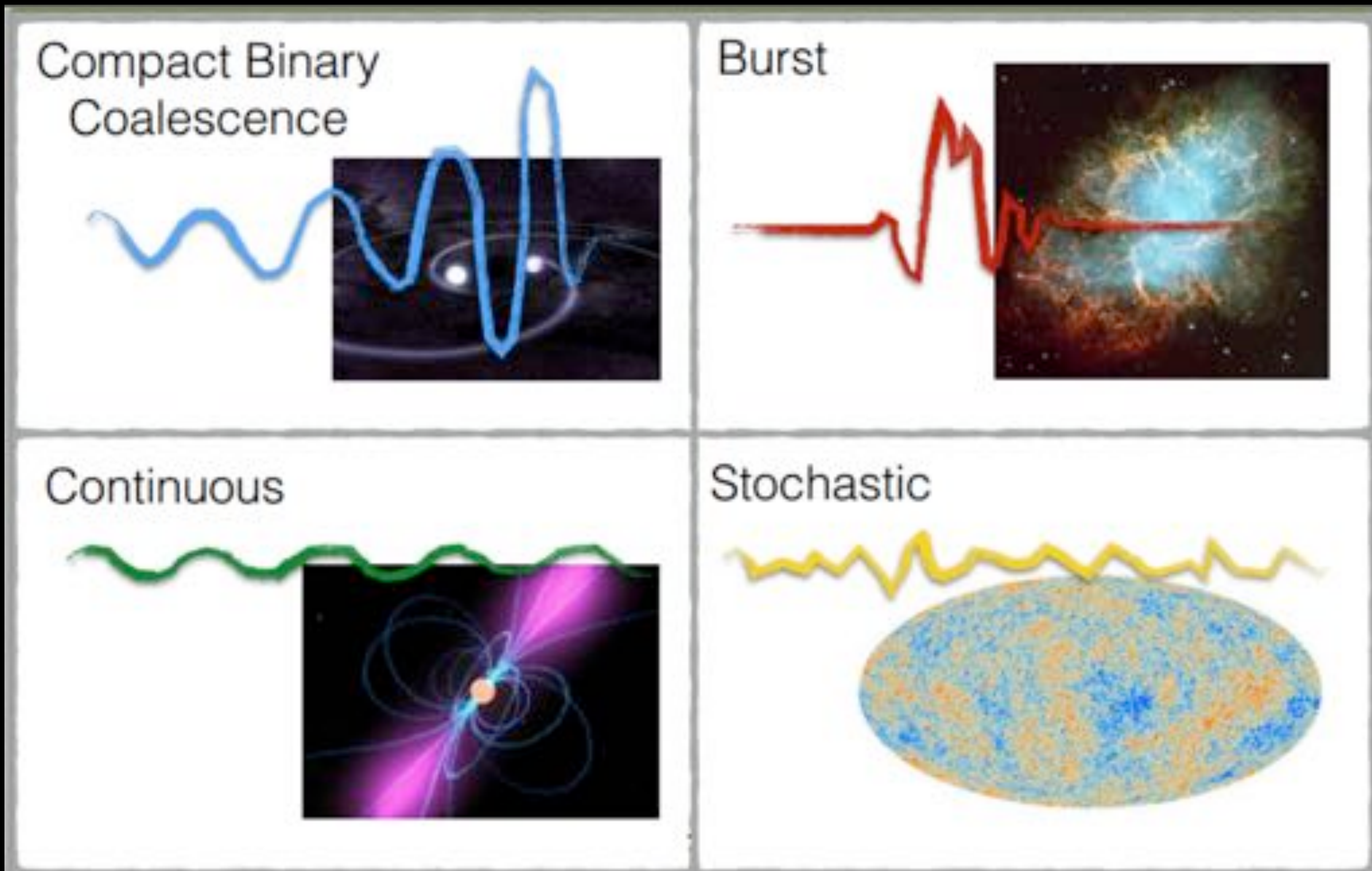
McIver 2015

The global network of current gen interferometers

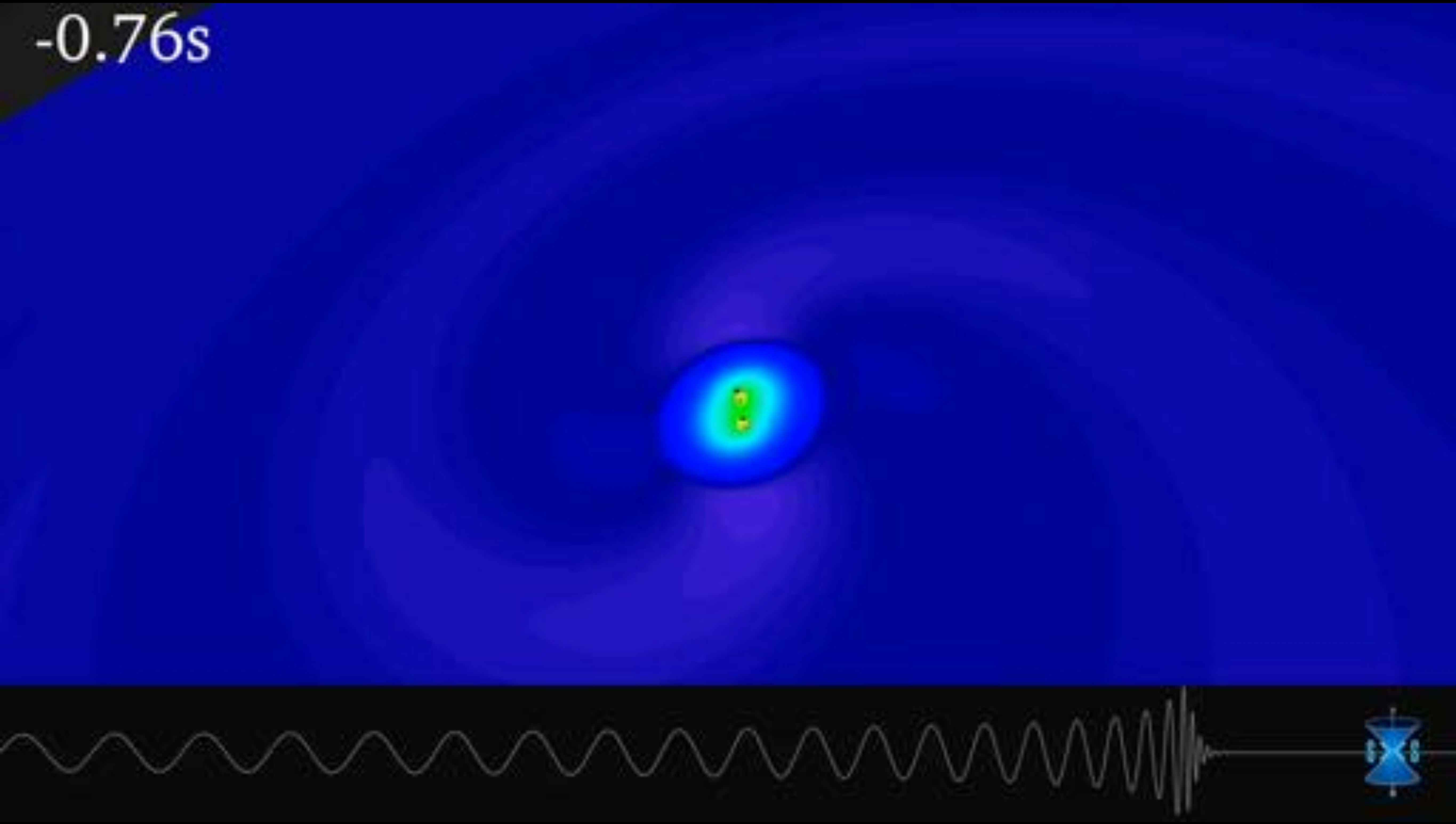


LIGO/Caltech

Gravitational wave searches

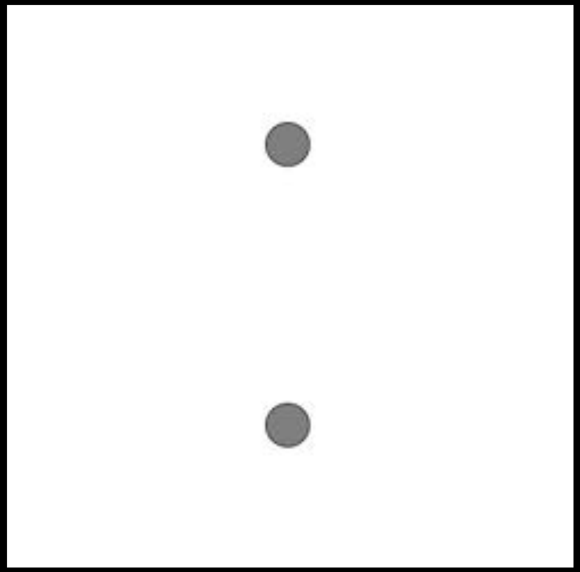


A binary black hole coalescence

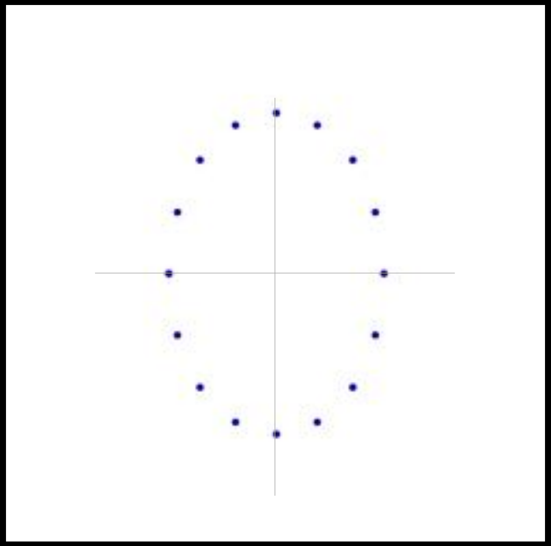


Compact binary sources

Massive objects orbit



Spacetime response above orbital plane



$$E_{orbit} = \frac{M_1 M_2}{M_\odot^2} \frac{3R_{S,\odot}}{2a} 10^{53} \text{ erg}$$

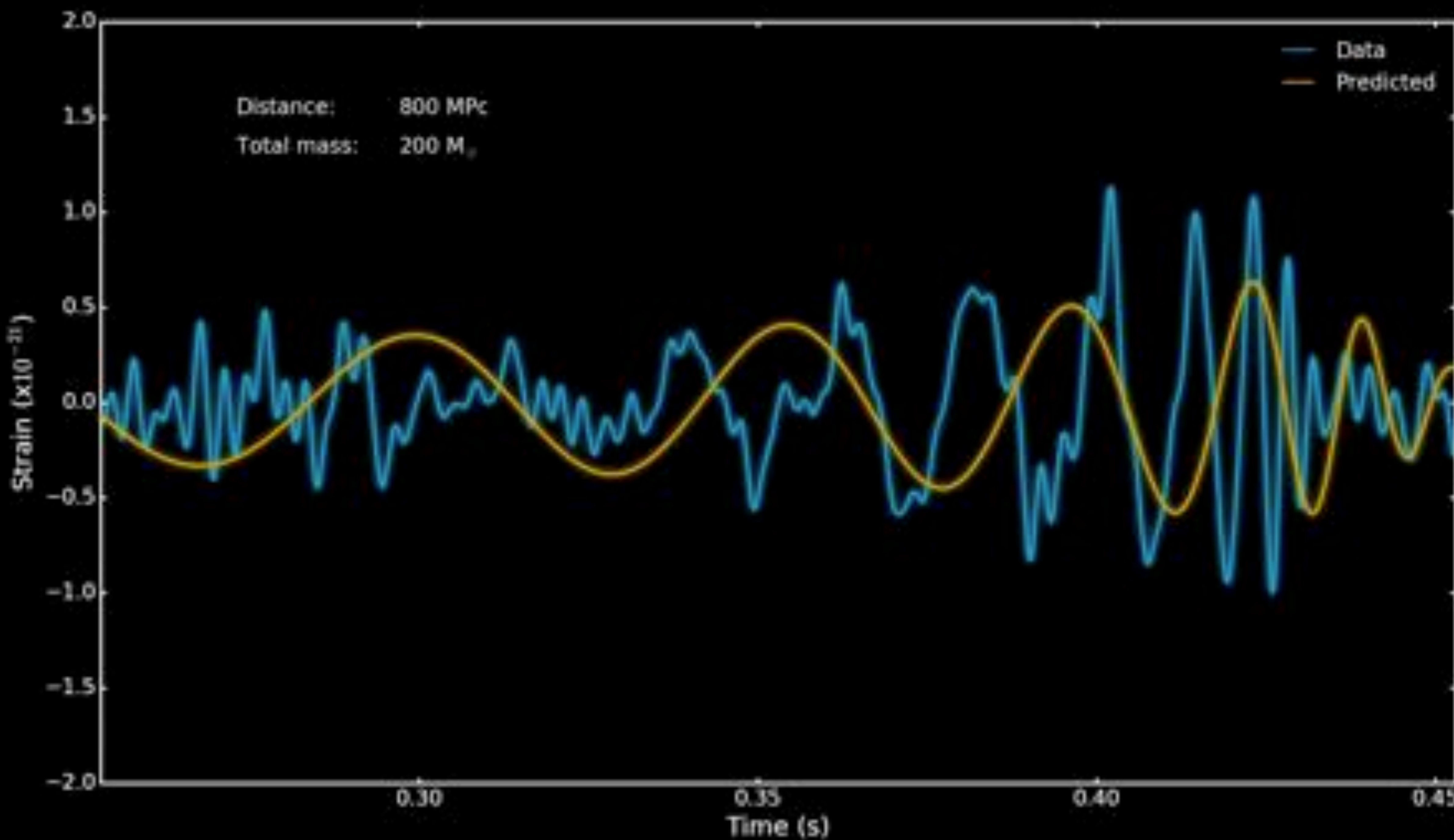
$$f = \left(\frac{M_1 + M_2}{M_\odot}\right)^{1/2} \left(\frac{3R_{S,\odot}}{a}\right)^{3/2} 3 \text{ kHz}$$

$$L_{GW} = \frac{M_1^2 M_2^2 (M_1 + M_2)}{M_\odot^5} \left(\frac{3R_{S,\odot}}{a}\right)^5 10^{56} \text{erg/s}$$

$$h = \frac{M_1 M_2}{M_\odot^2} \frac{3R_{S,\odot}}{a} \frac{100 \text{ Mpc}}{d_L} 10^{-22}$$

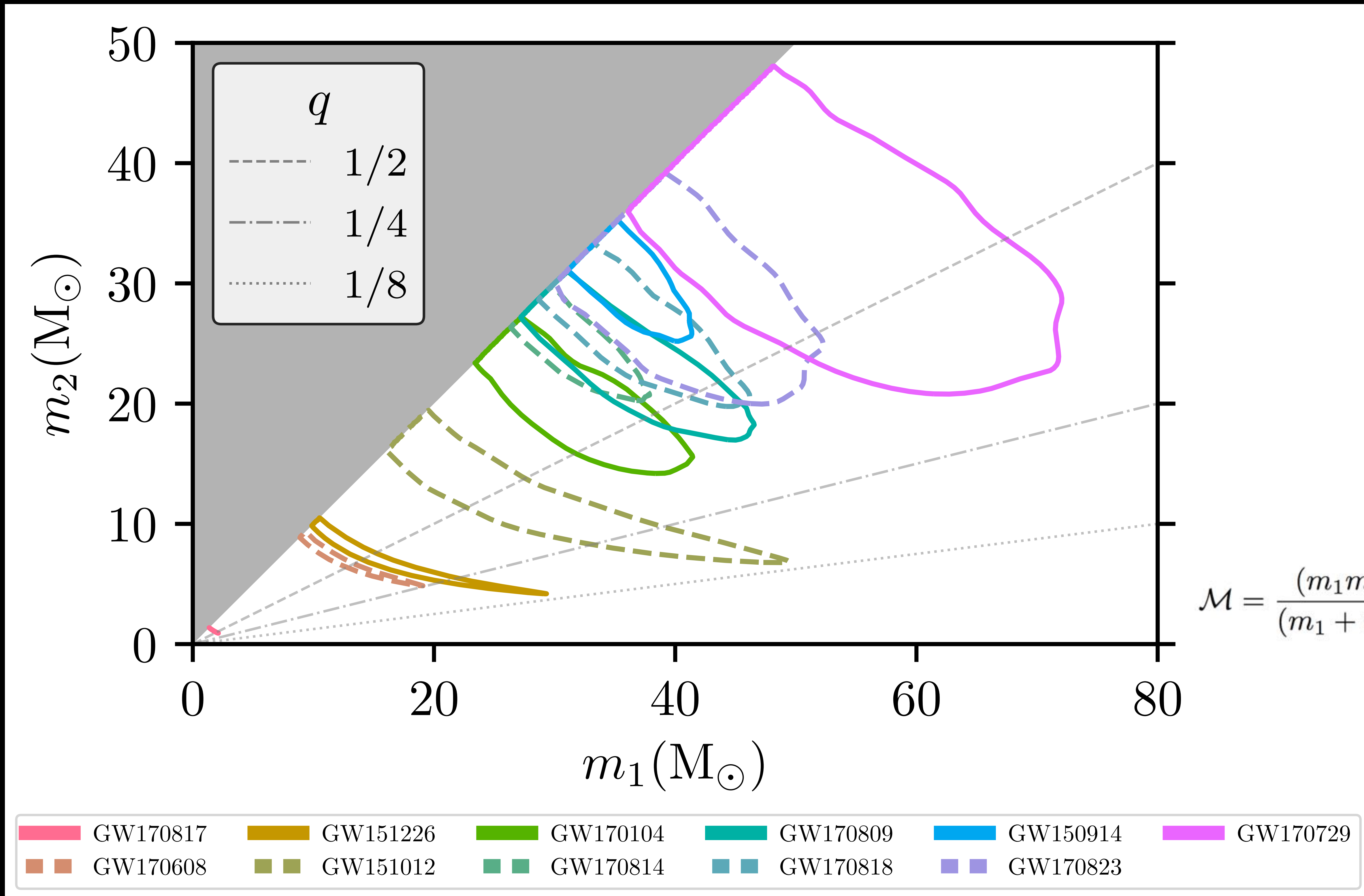
Slide adapted from J. Read

Inferring mass and distance



Credit: LIGO/Cardiff University/C.North/M.Hannam

A Bayesian inference

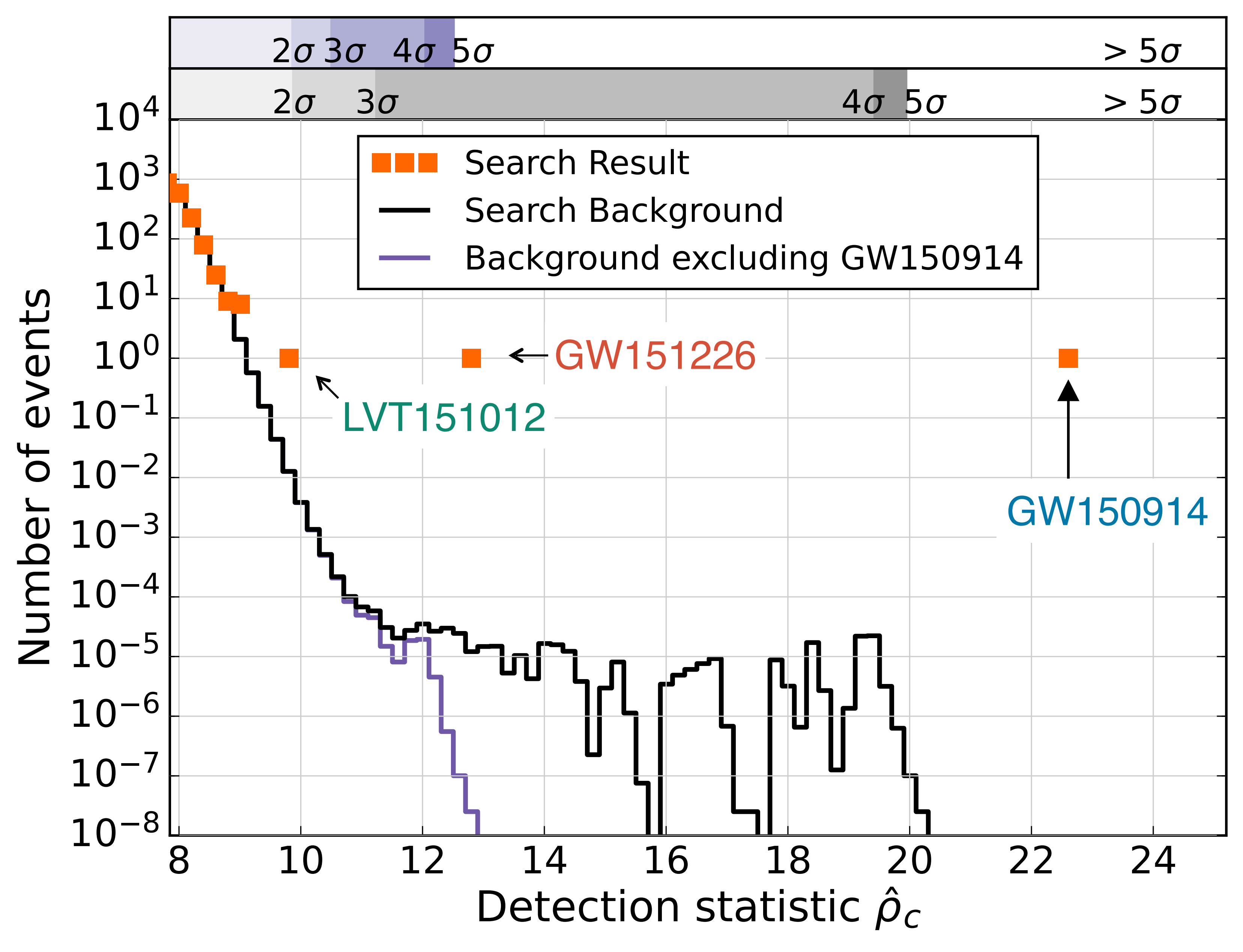


$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

B.P. Abbott et al. arXiv 1811.12907 (2018)

How do we identify signals? How significant are they?

Goal: understand this plot!



B. P. Abbott et al. Phys. Rev. X (2016)

Searching for signals with matched filtering

Slide adapted from S. Caudill

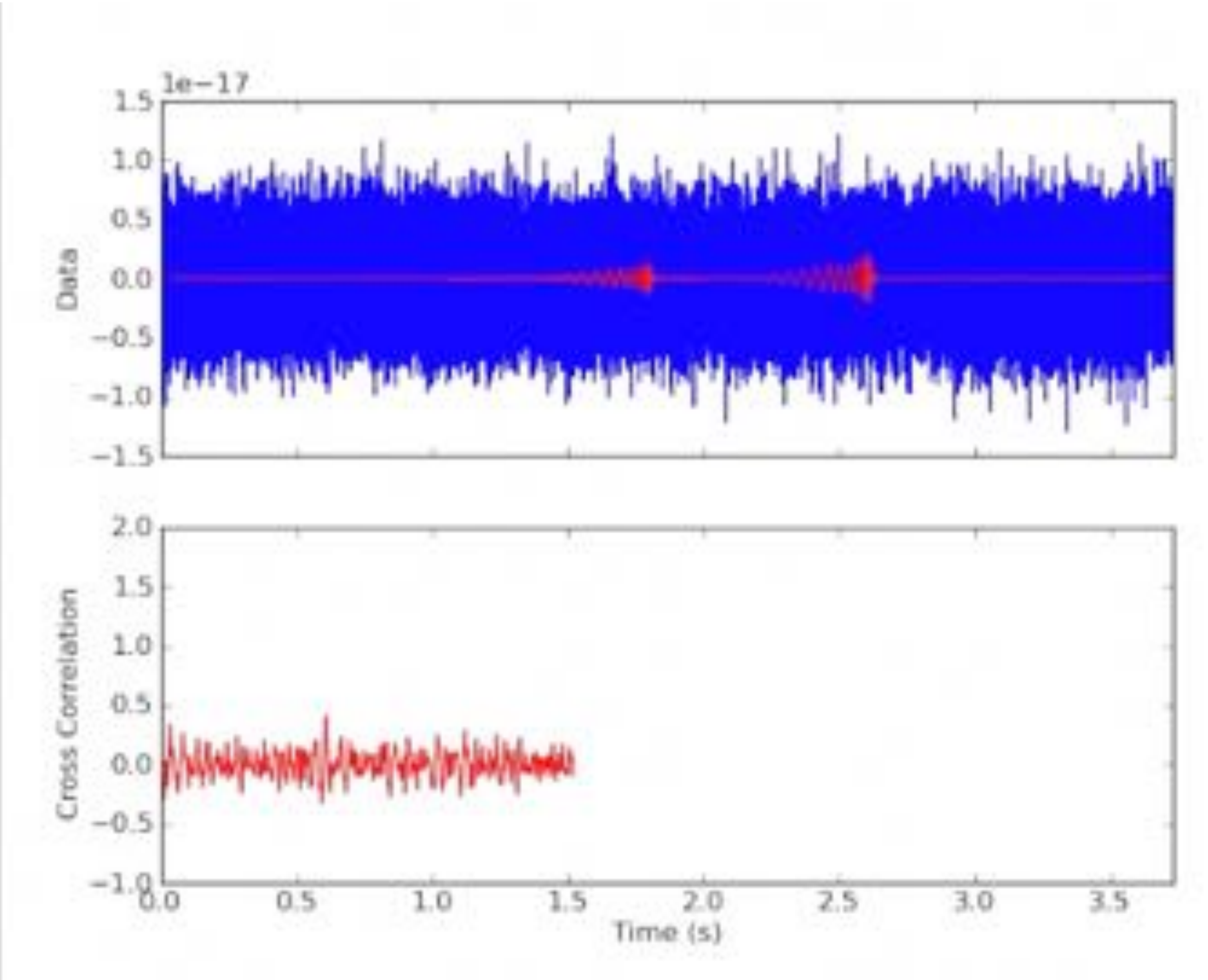
$$\rho^2(t) = \left[\langle s|h_c\rangle^2(t) + \langle s|h_s\rangle^2(t) \right]$$

Searching for signals with matched filtering

Slide adapted from S. Caudill

$$\rho^2(t) = \left[\langle s|h_c\rangle^2(t) + \langle s|h_s\rangle^2(t)\right]$$

Matched filter signal-to-noise ratio



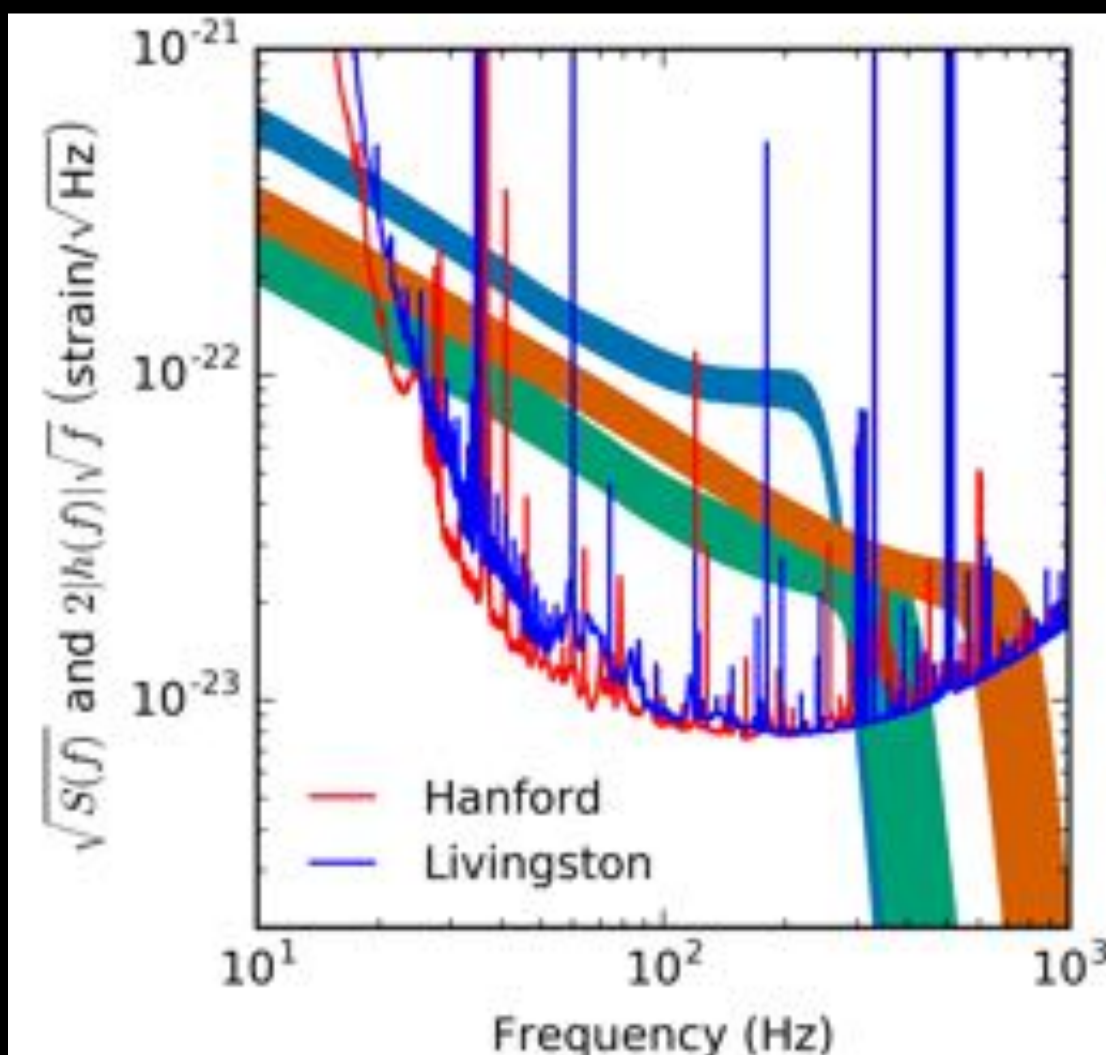
B. P. Abbott et al. Phys. Rev. X (2016)

Searching for signals with matched filtering

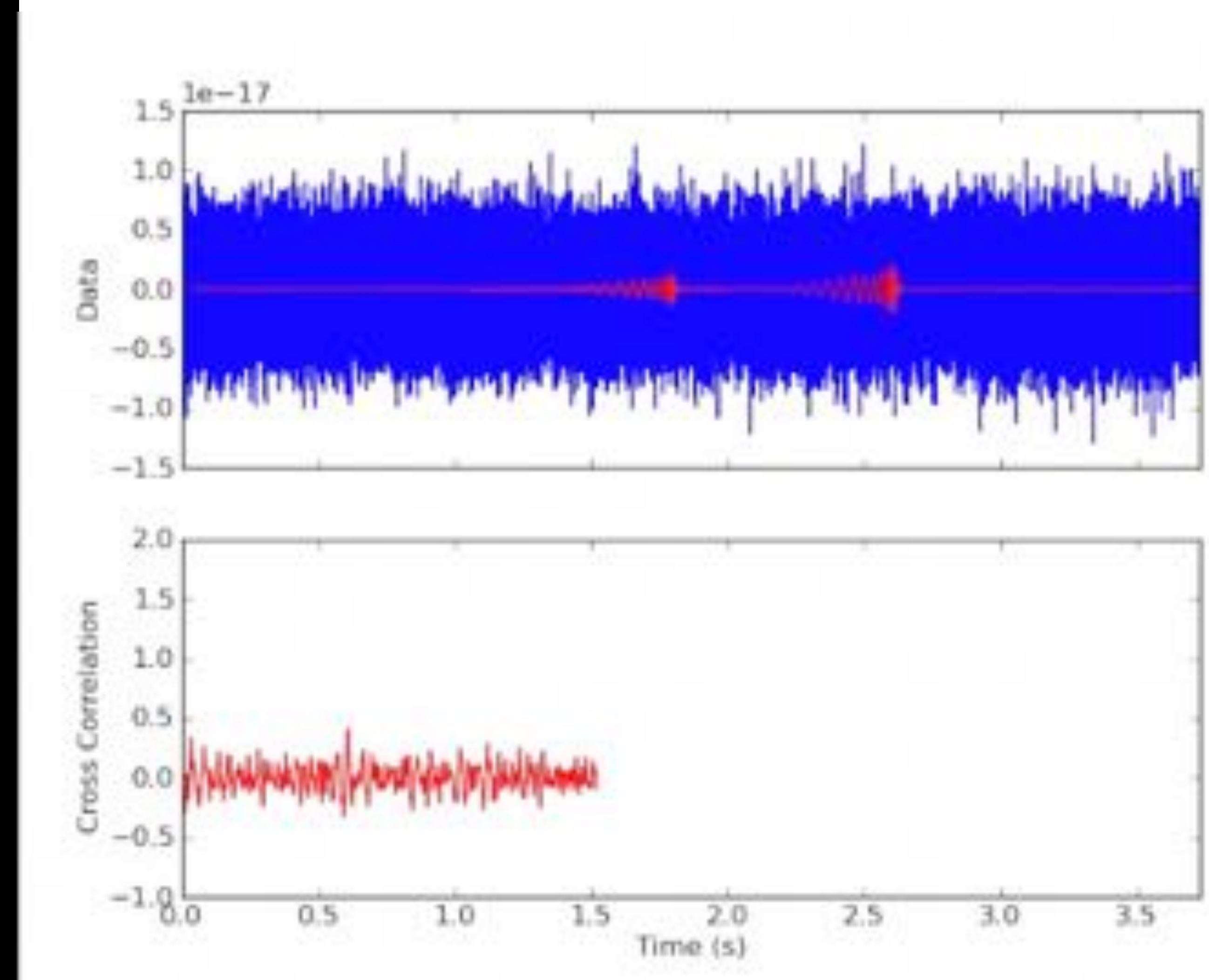
Slide adapted from S. Caudill

$$\rho^2(t) = \left[\langle s|h_c\rangle^2(t) + \langle s|h_s\rangle^2(t)\right]$$

$$\langle s|h\rangle = 4\mathrm{Re}\int_0^\infty \frac{\tilde{s}(f)\tilde{h}^*(f)}{S_n(f)} e^{2\pi i f t} df$$



Matched filter signal-to-noise ratio



B. P. Abbott et al. Phys. Rev. X (2016)

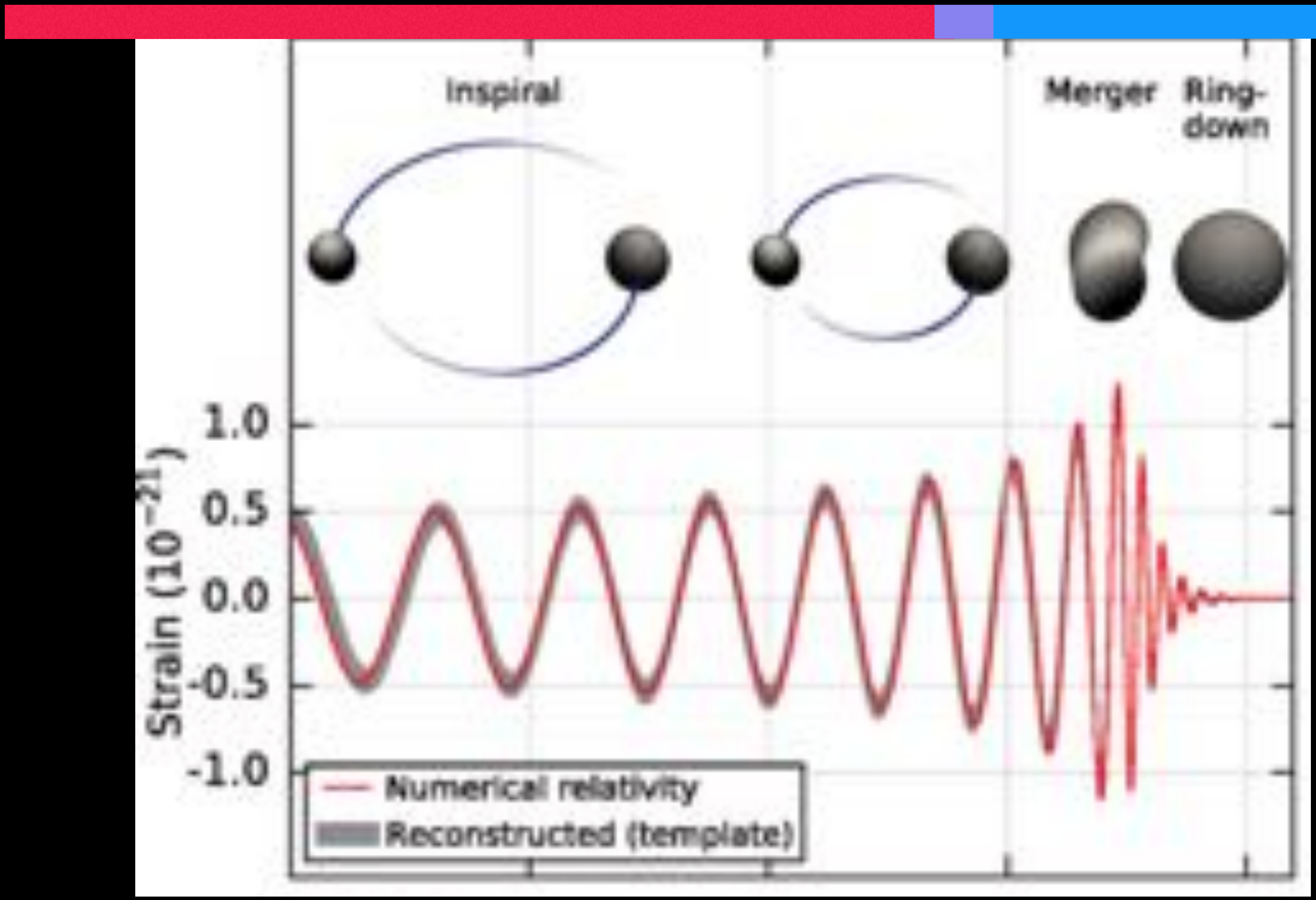
Constructing templates

Post-Newtonian point approximations

Valid for v << c

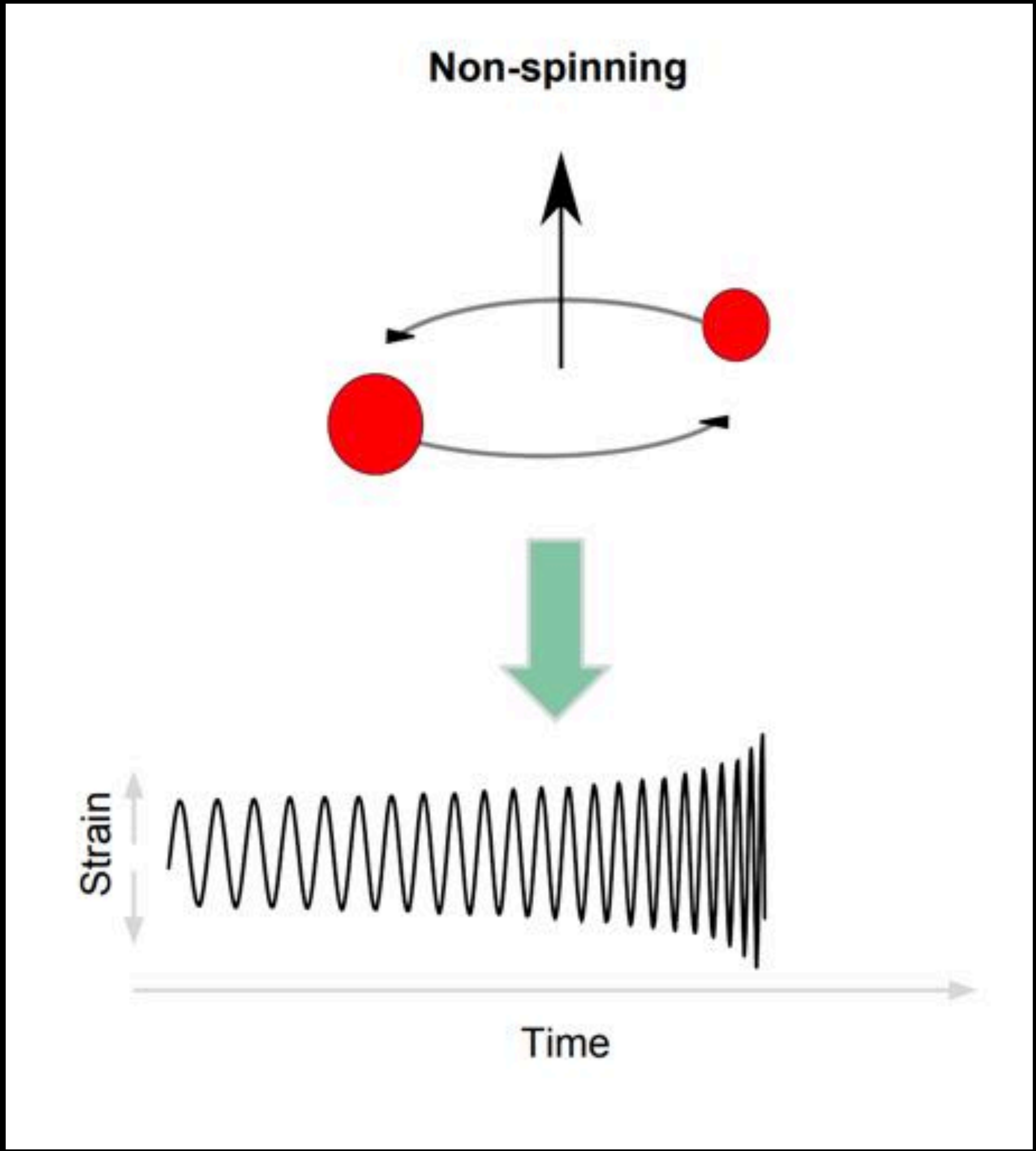
Numerical Relativity

Valid everywhere - very very expensive to generate



B.P. Abbott et al, PRL 2016

Constructing templates: spin



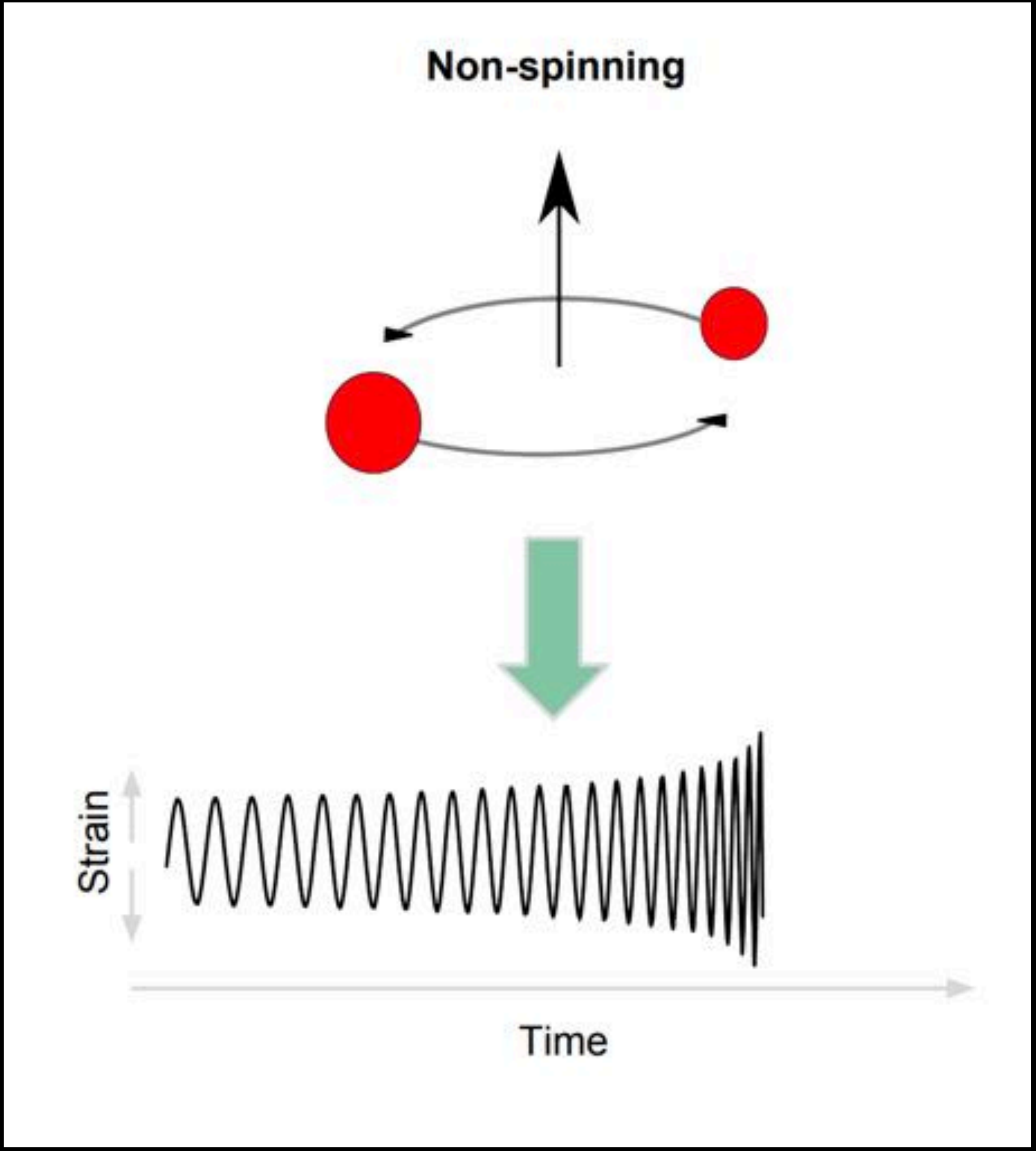
Images by Alex Nitz

Constructing templates: spin

Breakout question

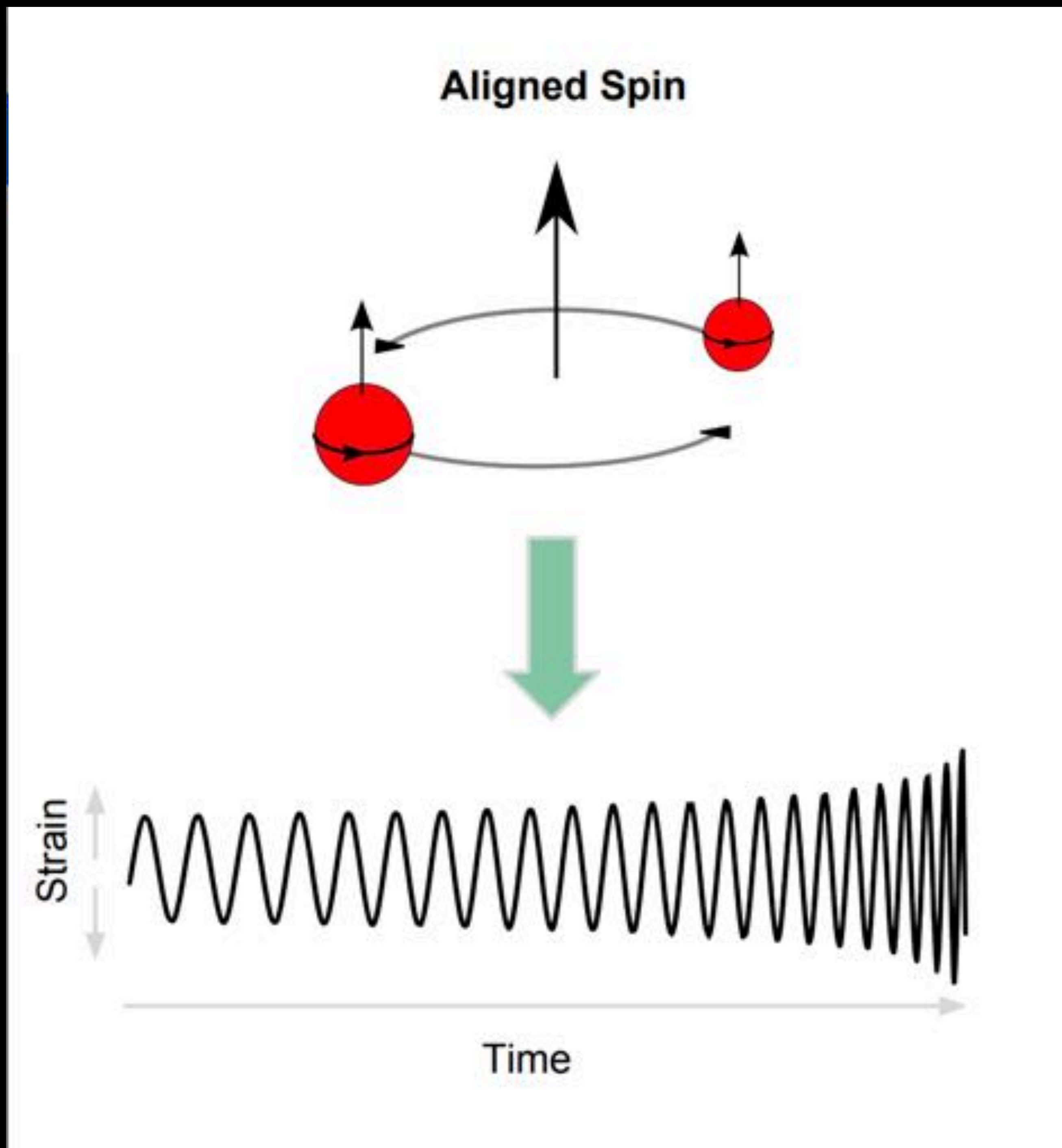
If the component objects have spin aligned with the orbital angular momentum, will that make the signal template:

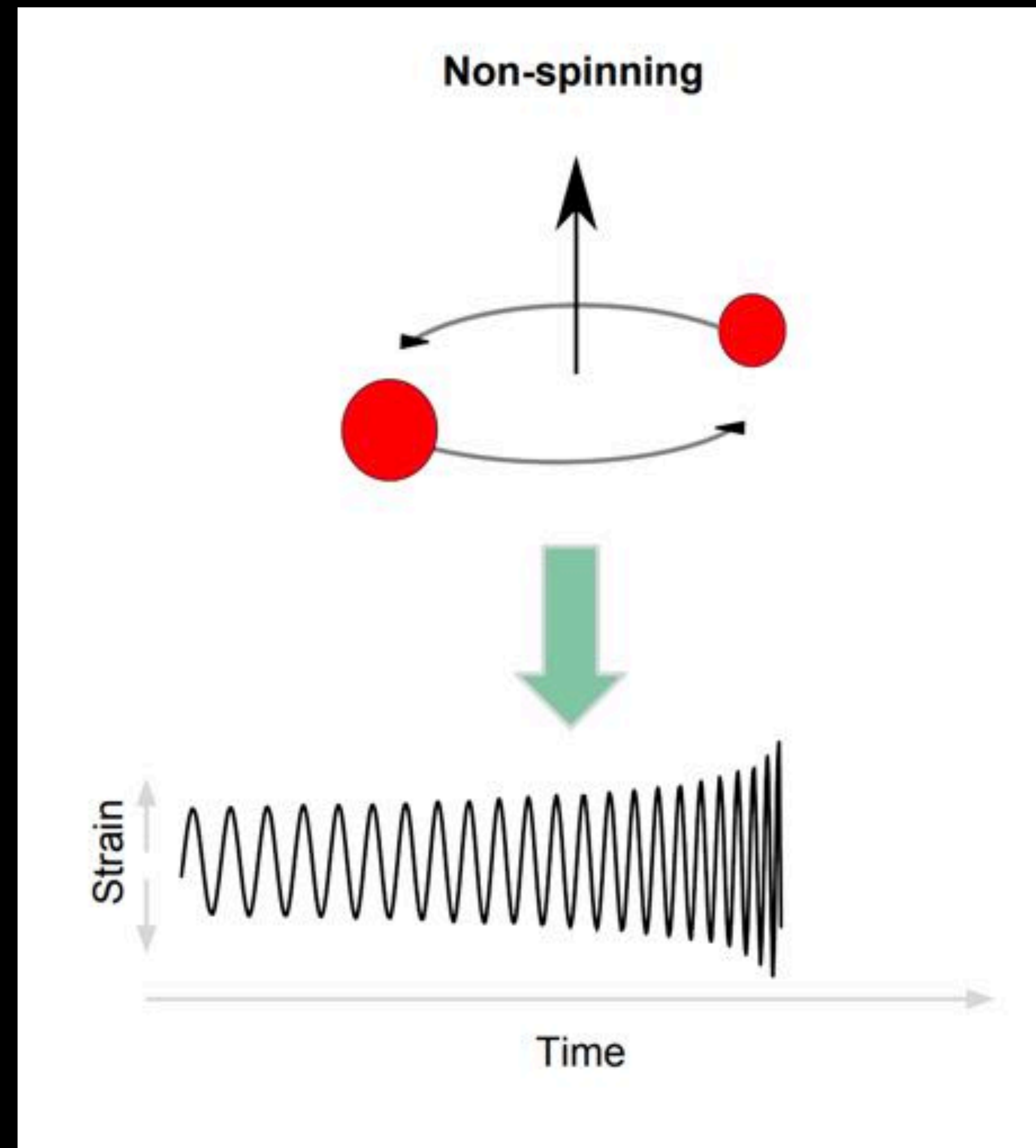
1. Longer
2. Shorter
3. The same



Images by Alex Nitz

Constructing templates: spin

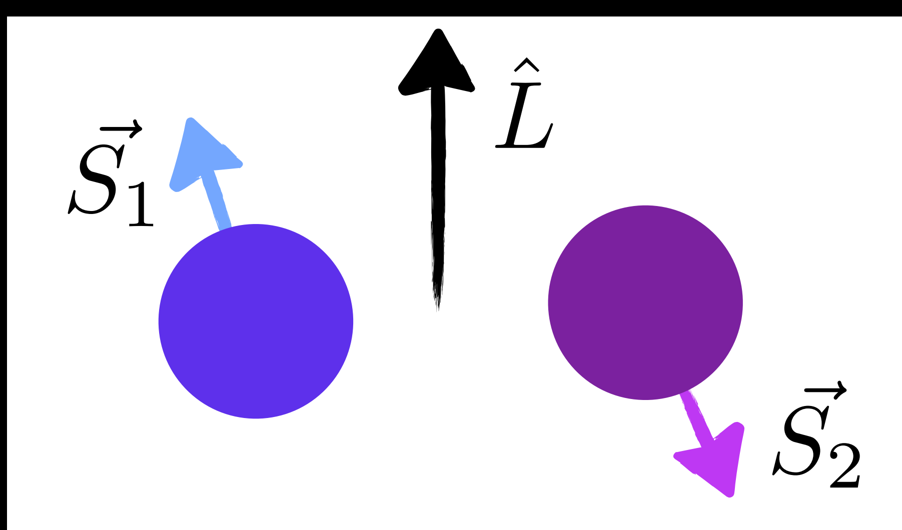


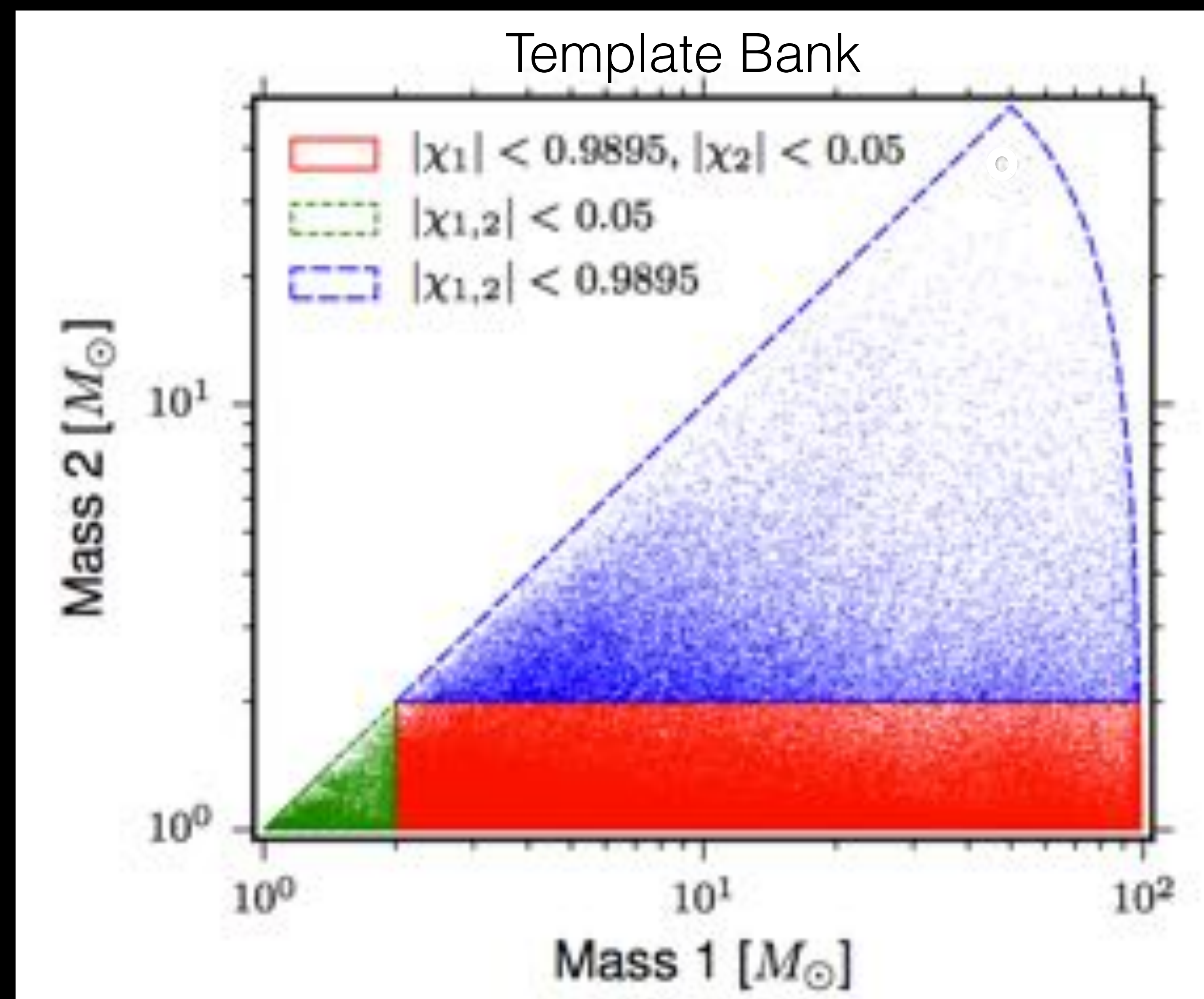


Images by Alex Nitz

Building a template bank

$$\chi_{1,2} \propto \vec{S_{1,2}} \cdot \hat{L}$$



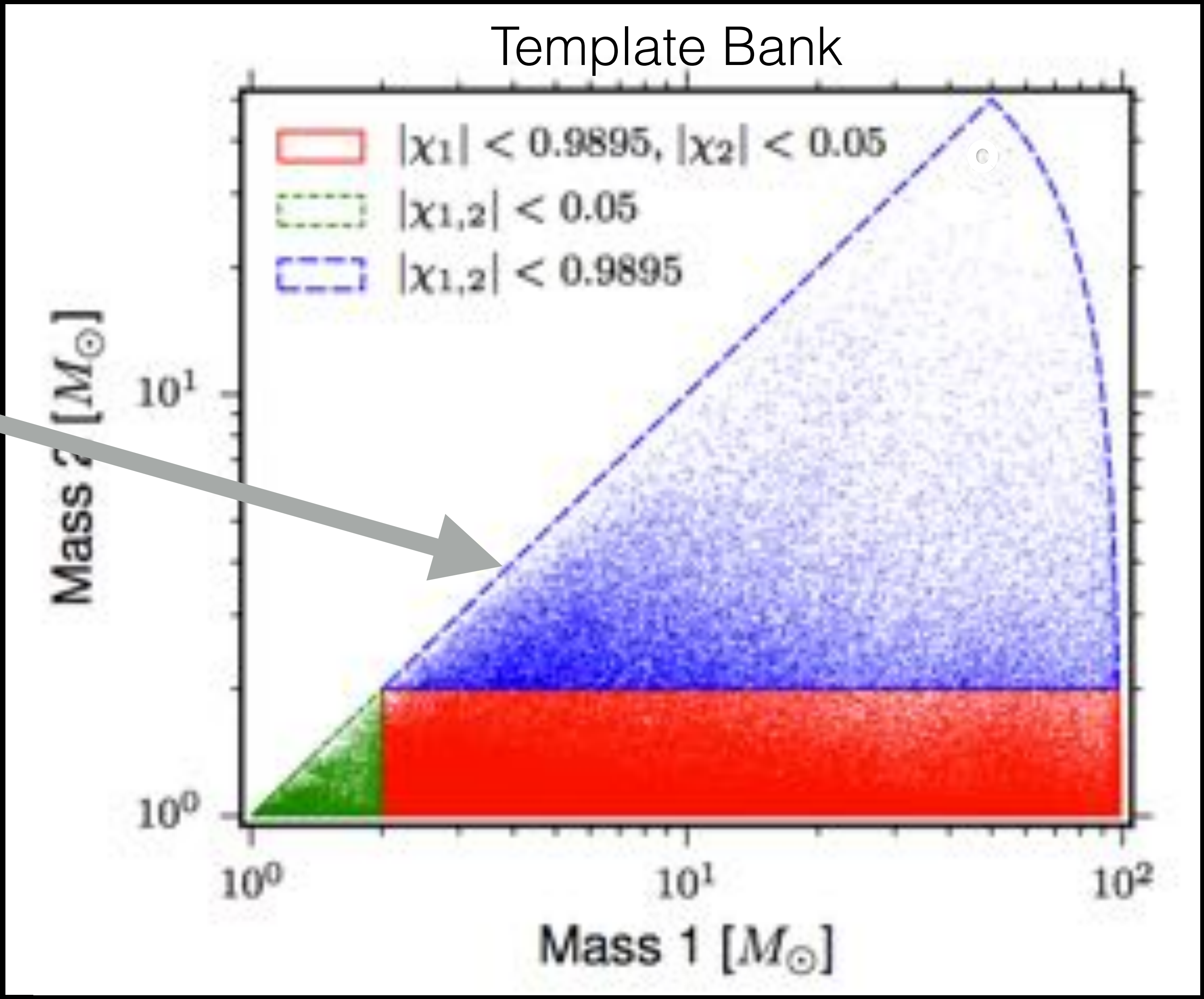


B. P. Abbott et al. Phys. Rev. X (2016)

Building a template bank

Breakout question

What defines the separation between each template?

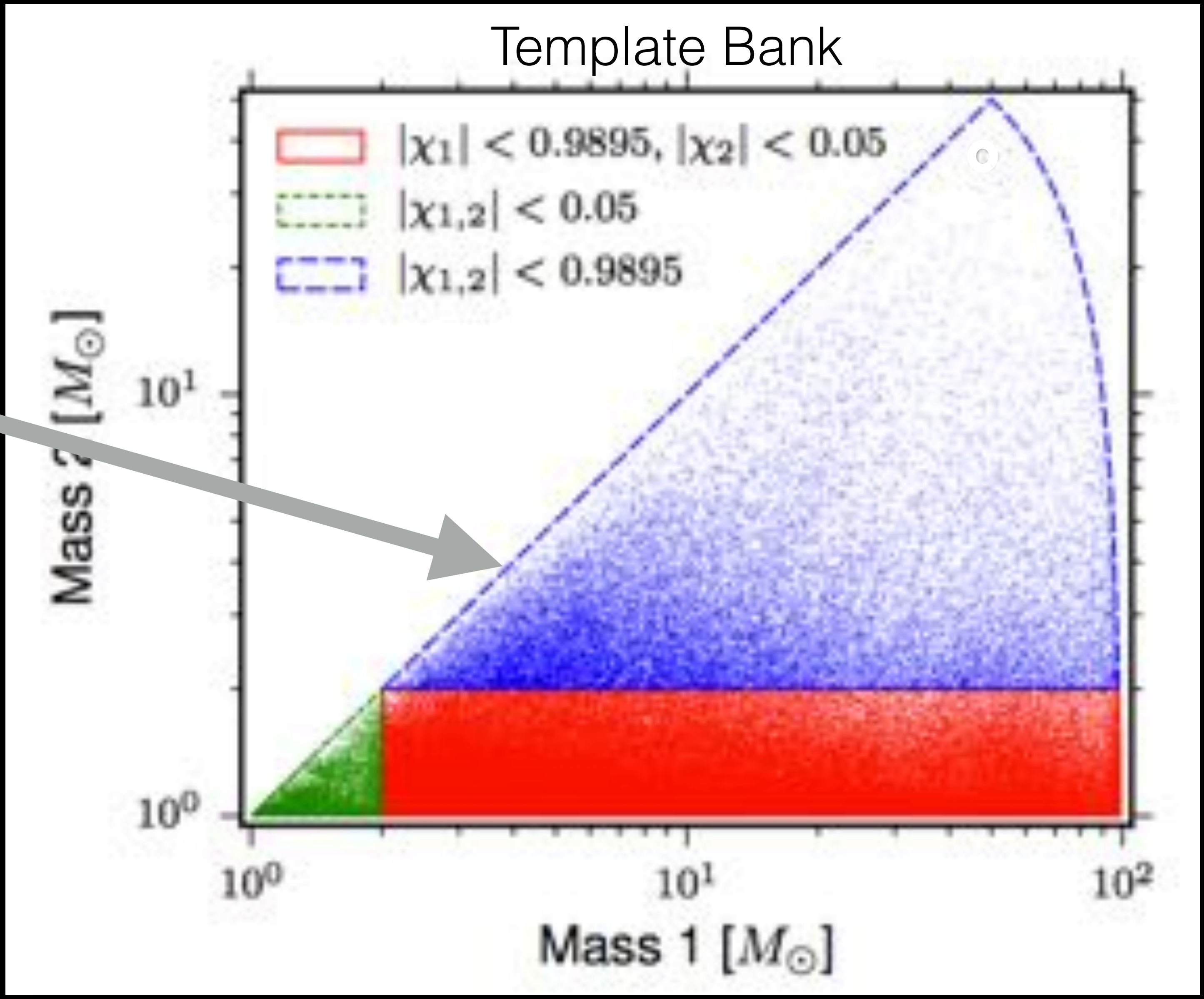


B. P. Abbott et al. Phys. Rev. X (2016)

Building a template bank

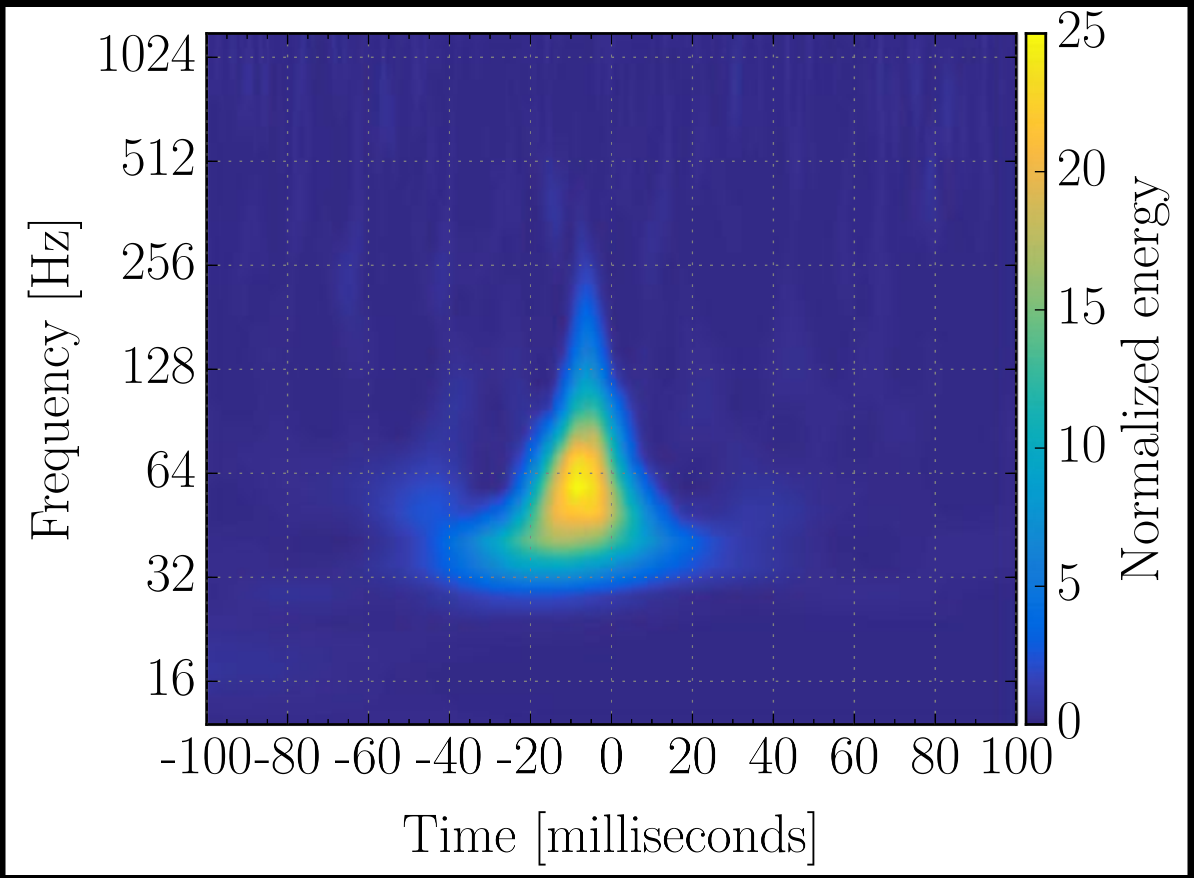
What defines the separation between each template?

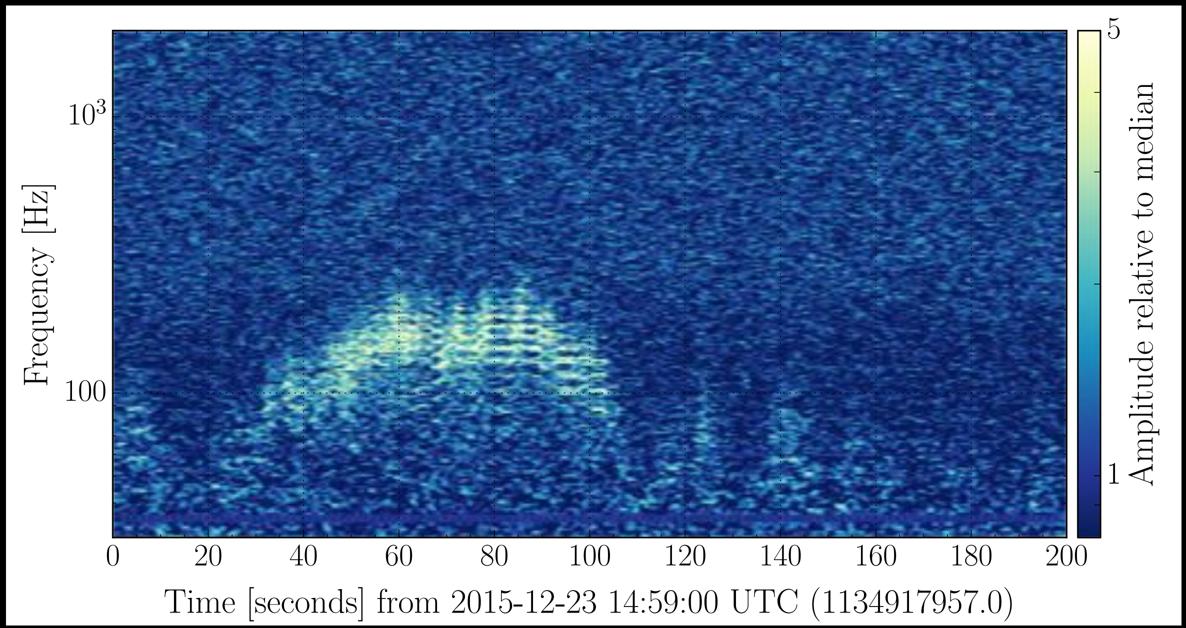
Maximum allowed mismatch between one template and the next



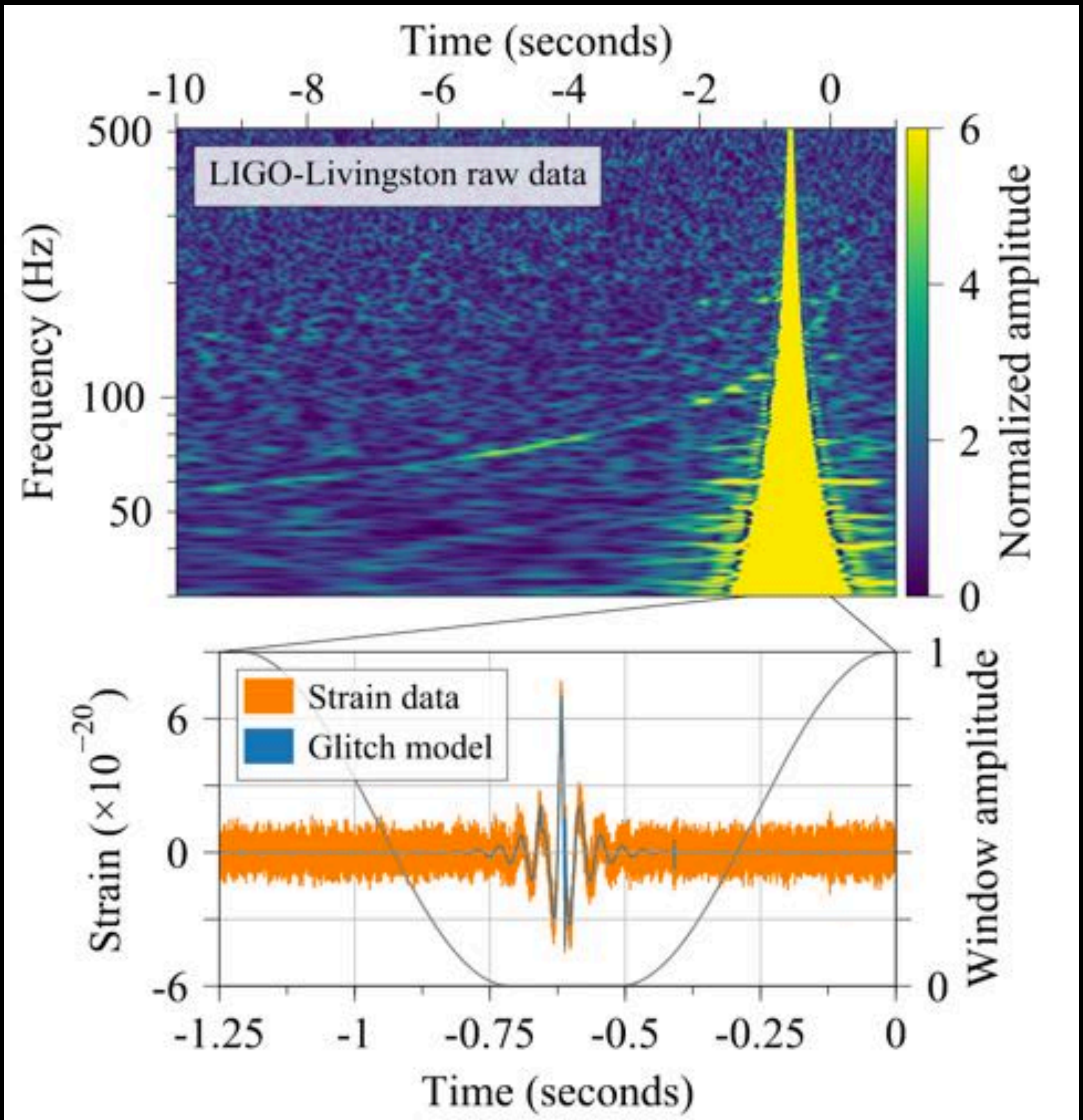
B. P. Abbott et al. Phys. Rev. X (2016)

Challenge:
LIGO data is non-stationary/non-Gaussian!



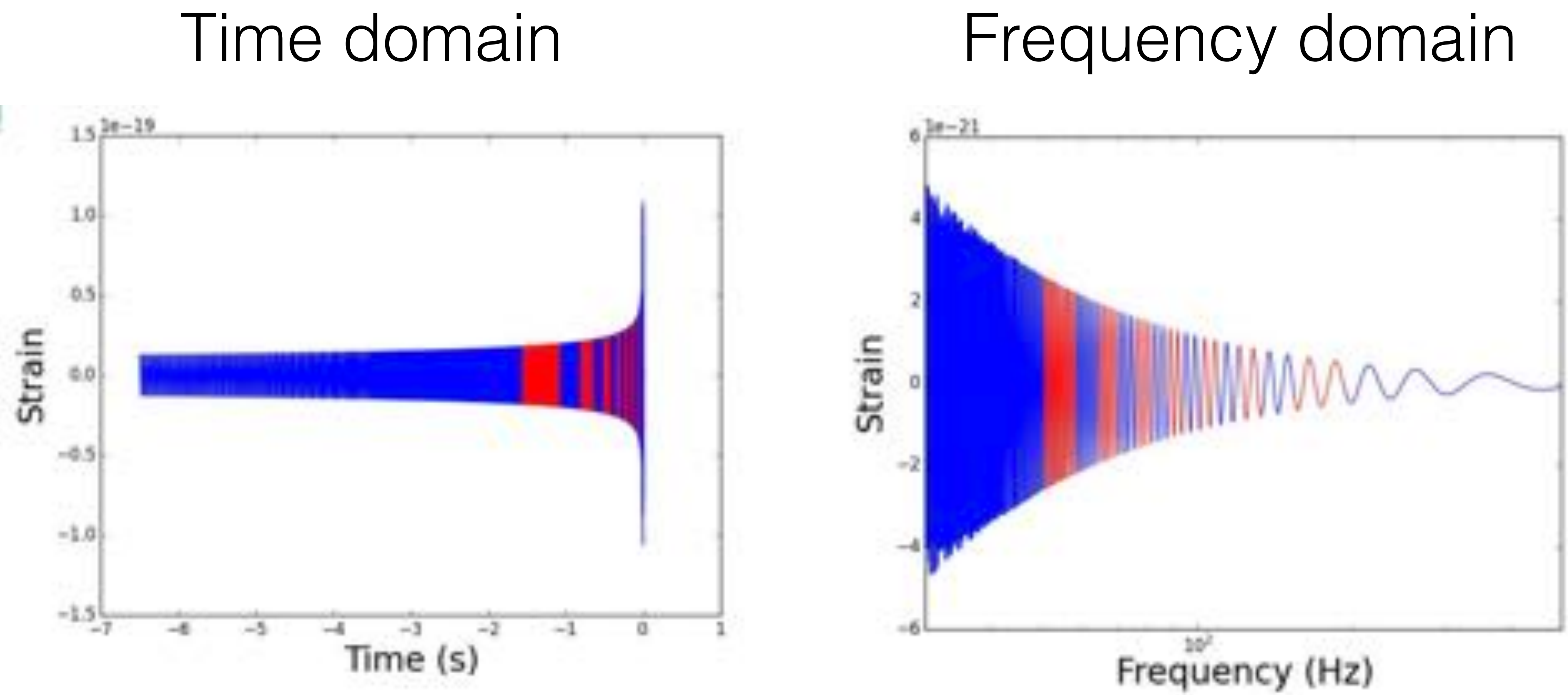


B.P Abbott et al. CQG (2018)



B.P. Abbott et al PRL. (2017)

The Chi-squared test



Divide the template into frequency bands of equal expected power

$$\chi^2 \propto \sum (\rho_l - \rho/N_{bins})^2$$

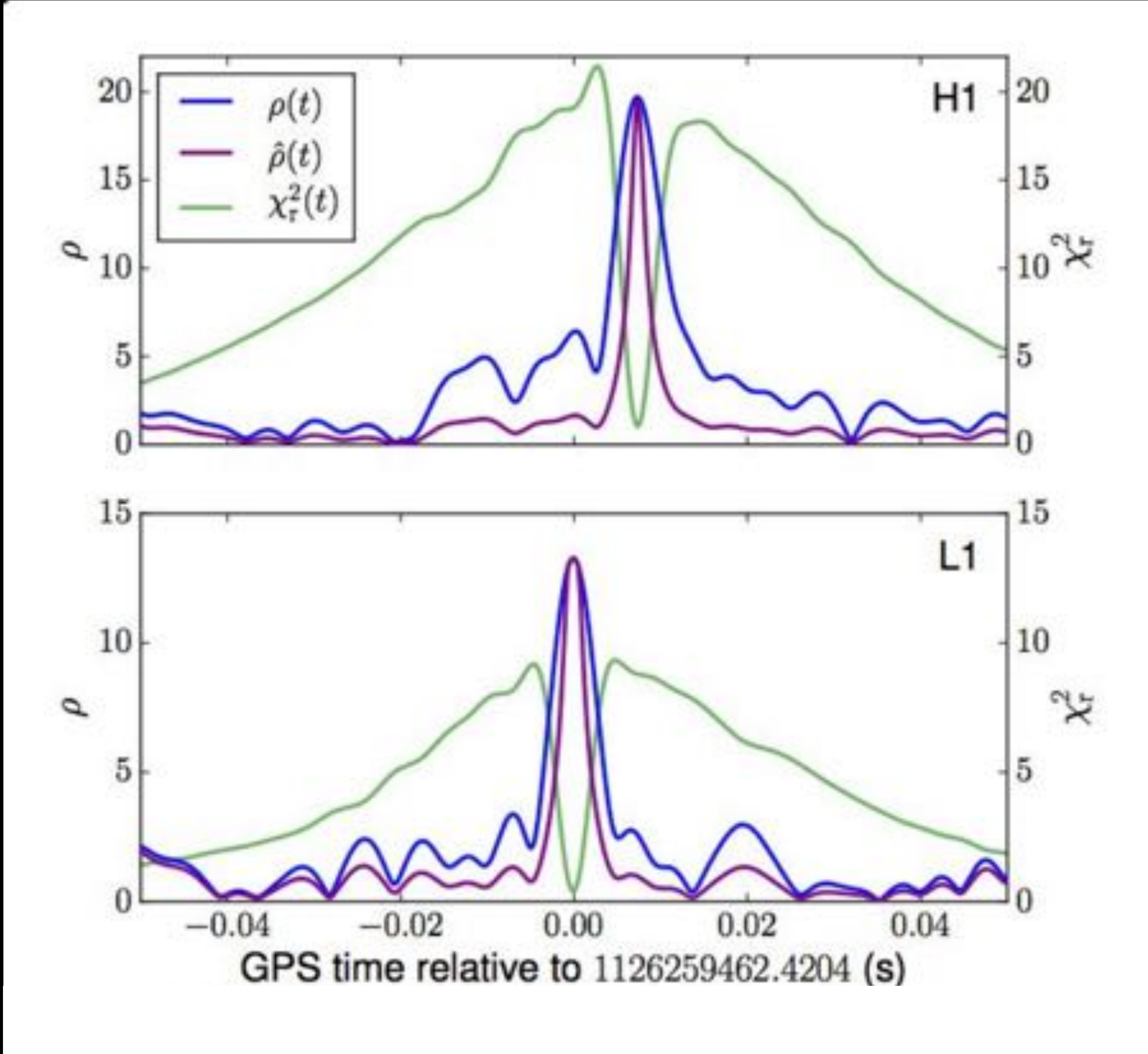
Adapted from slide by Alex Nitz

Chi-squared re-weighting

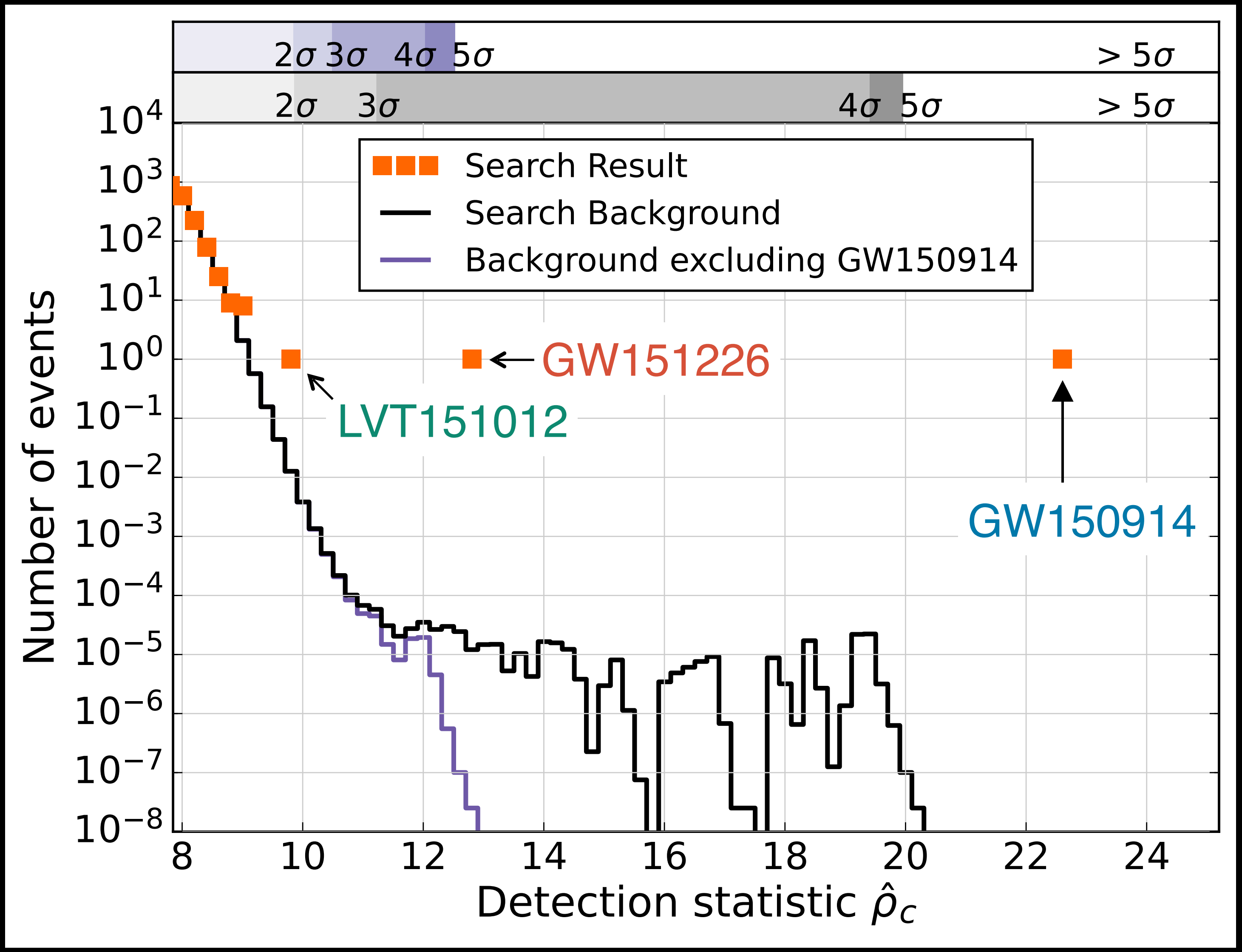
Redefine SNR to downweight the SNR of triggers with high Chi-squared

$$\hat{\rho} = \begin{cases} \rho \Big/ [(1 + (\chi_r^2)^3)/2]^{\frac{1}{6}}, & \text{if } \chi_r^2 > 1, \\ \rho, & \text{if } \chi_r^2 \leq 1. \end{cases}$$

GW150914: an example



Calculating event significance



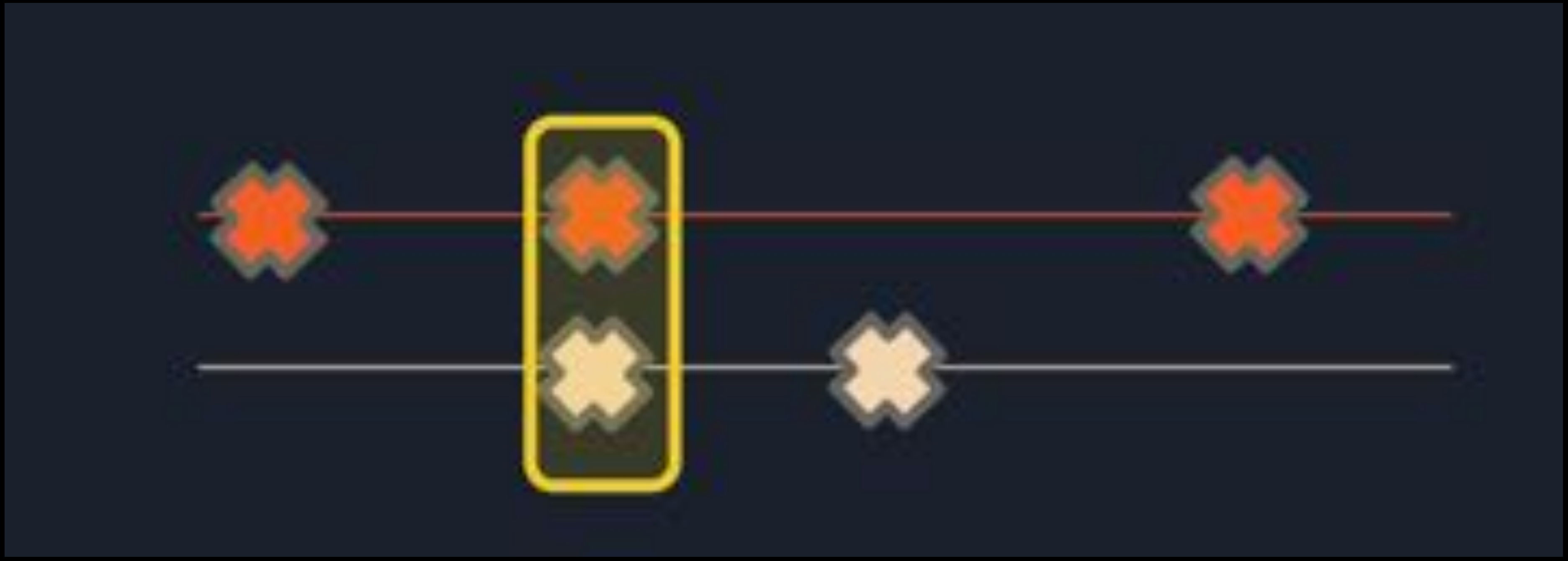
B. P. Abbott et al. Phys. Rev. X (2016)

Calculating the foreground

Look for trigger coincidence within gravitational wave travel time between triggers

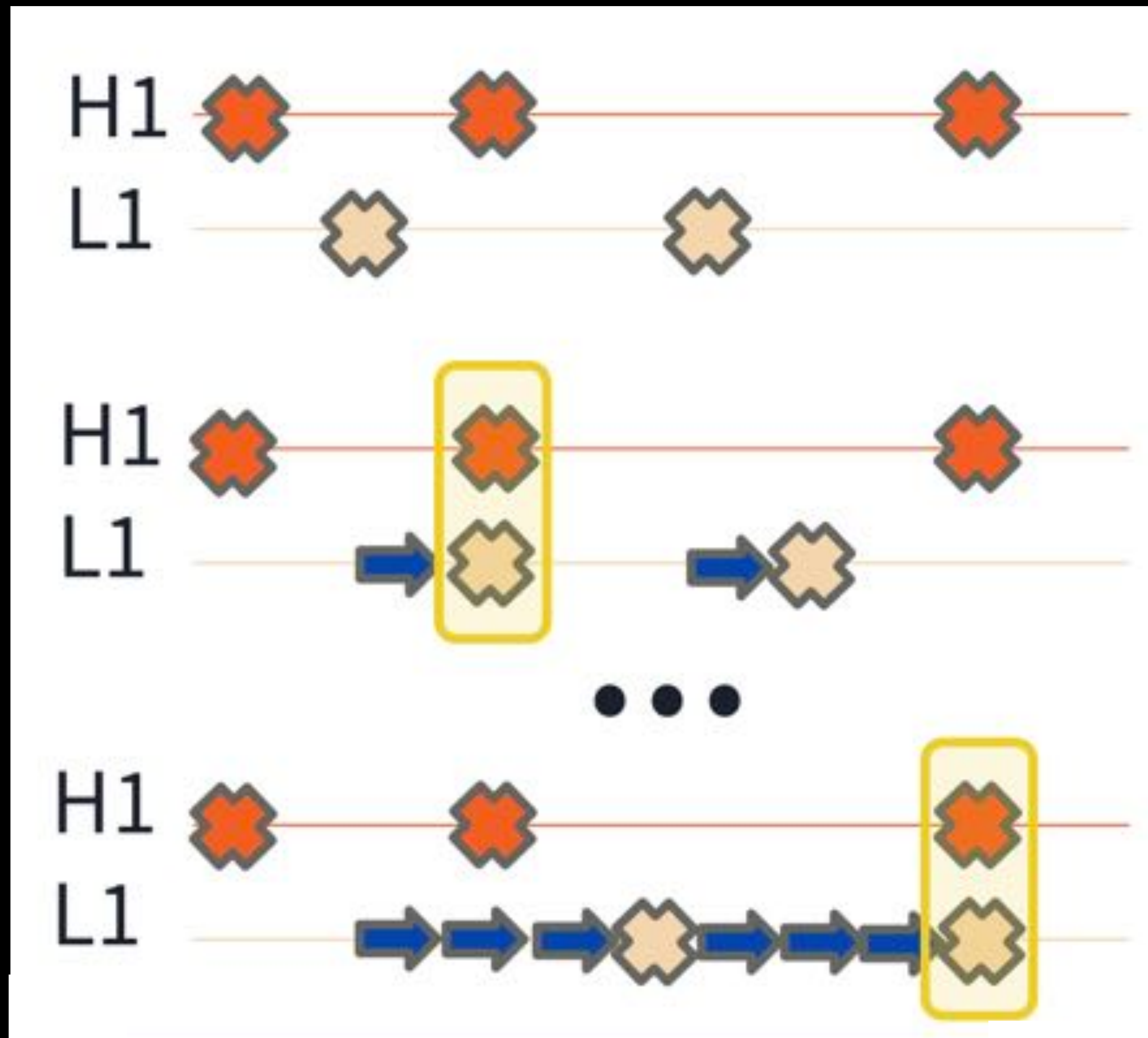
Network SNR is quadrature sum of single detector SNRs

$$\rho_c = \sqrt{\rho_H^2 + \rho_L^2}$$



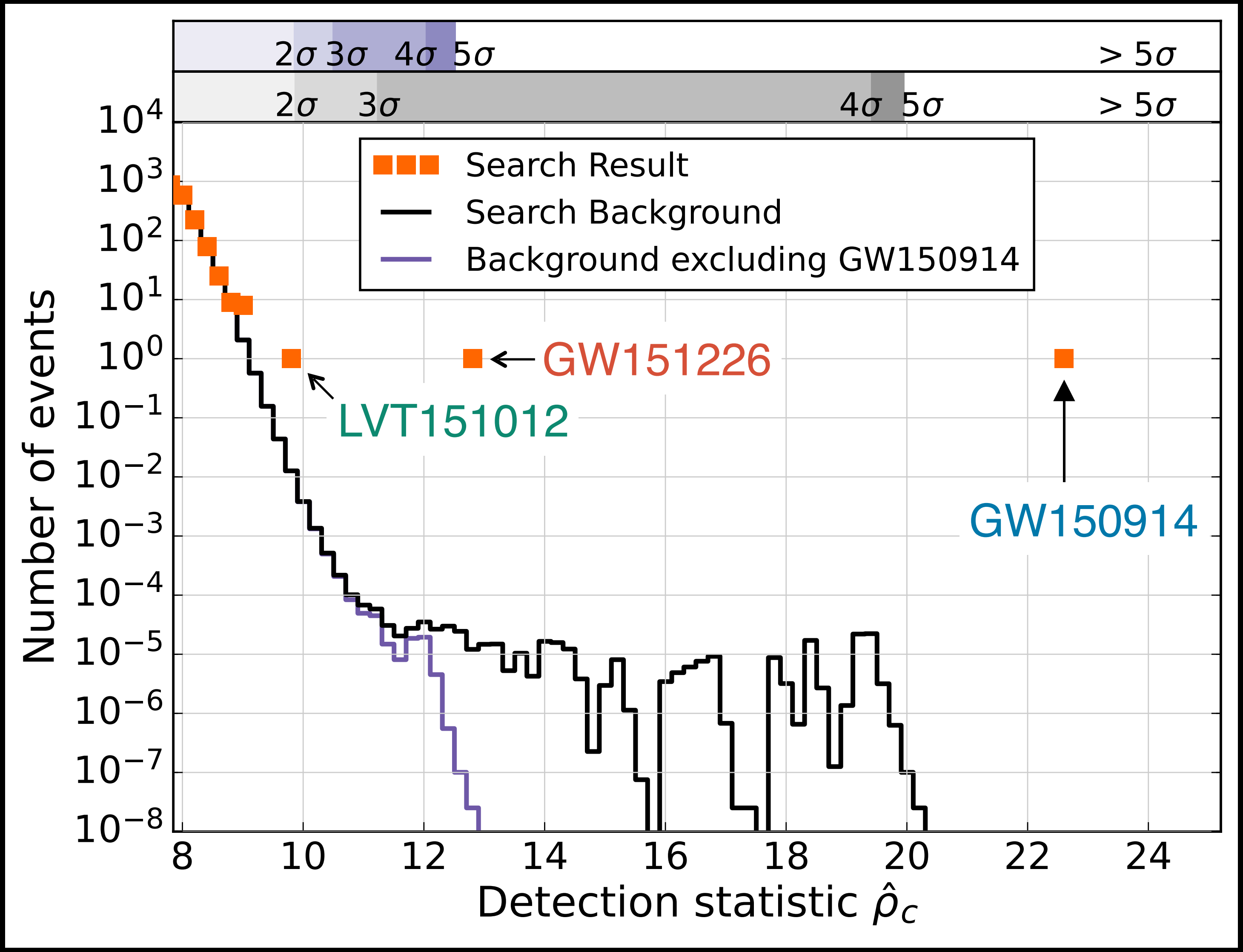
Graphic by Alex Nitz

Calculating the noise background



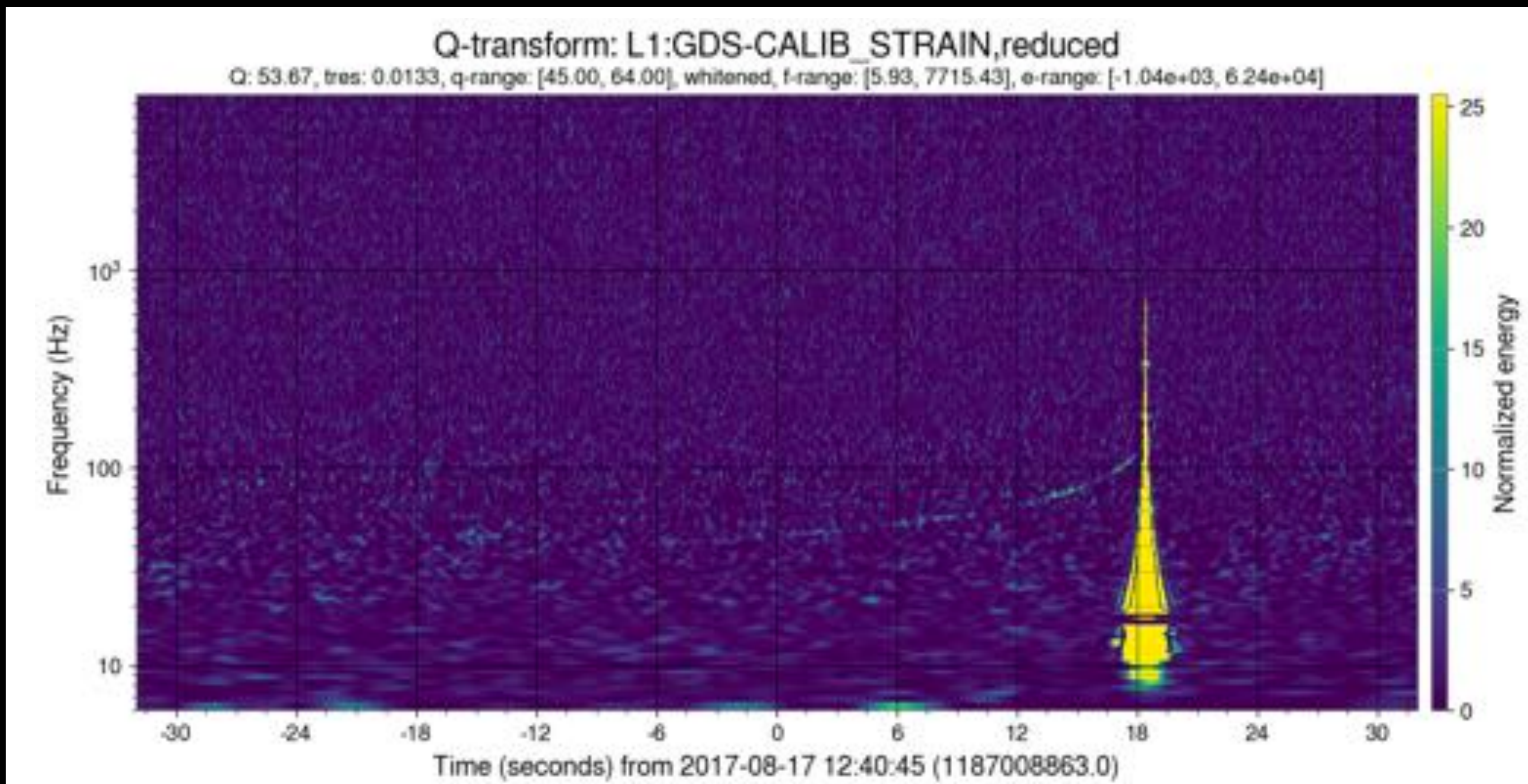
Graphic by Alex Nitz

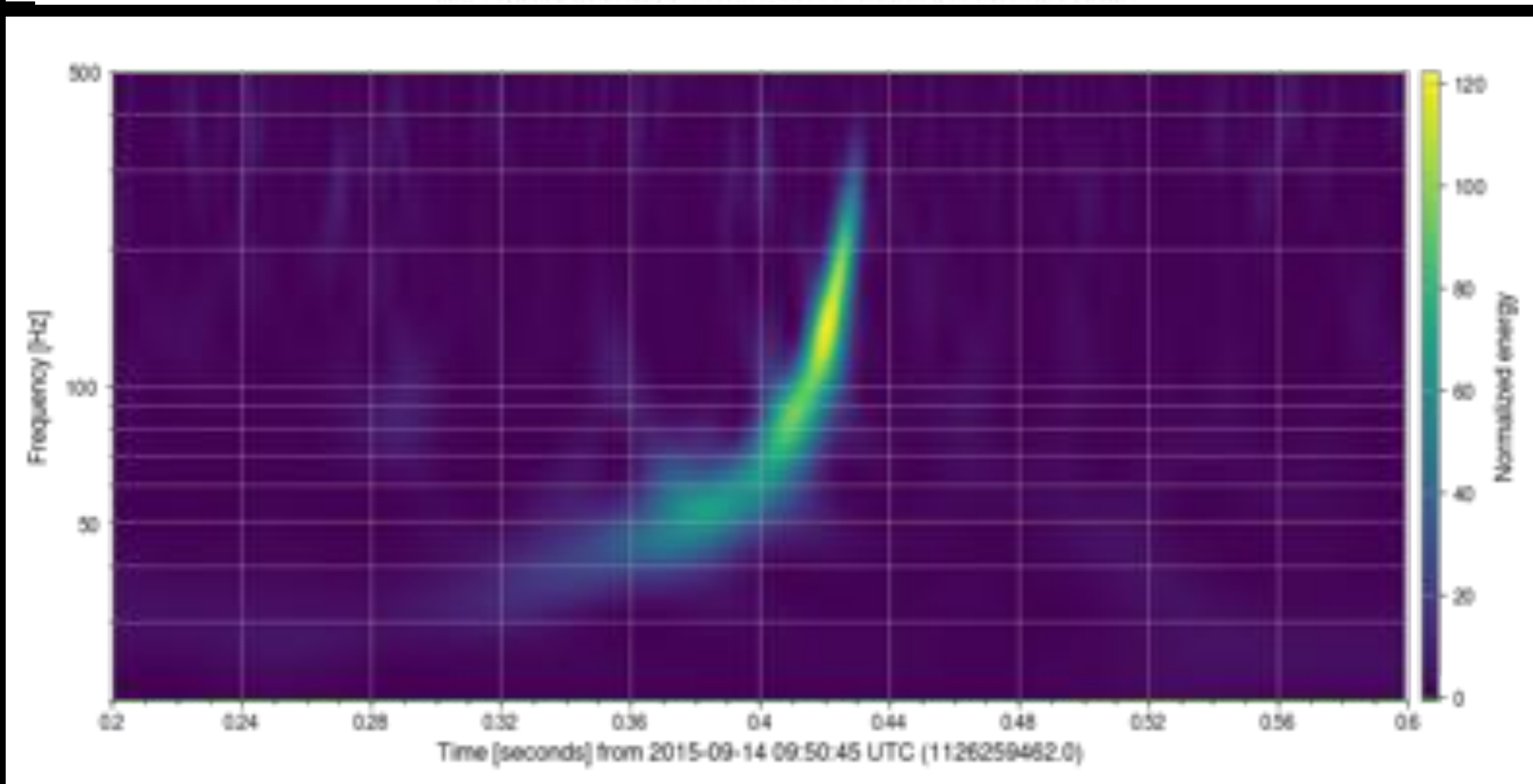
Calculating the noise background



B. P. Abbott et al. Phys. Rev. X (2016)

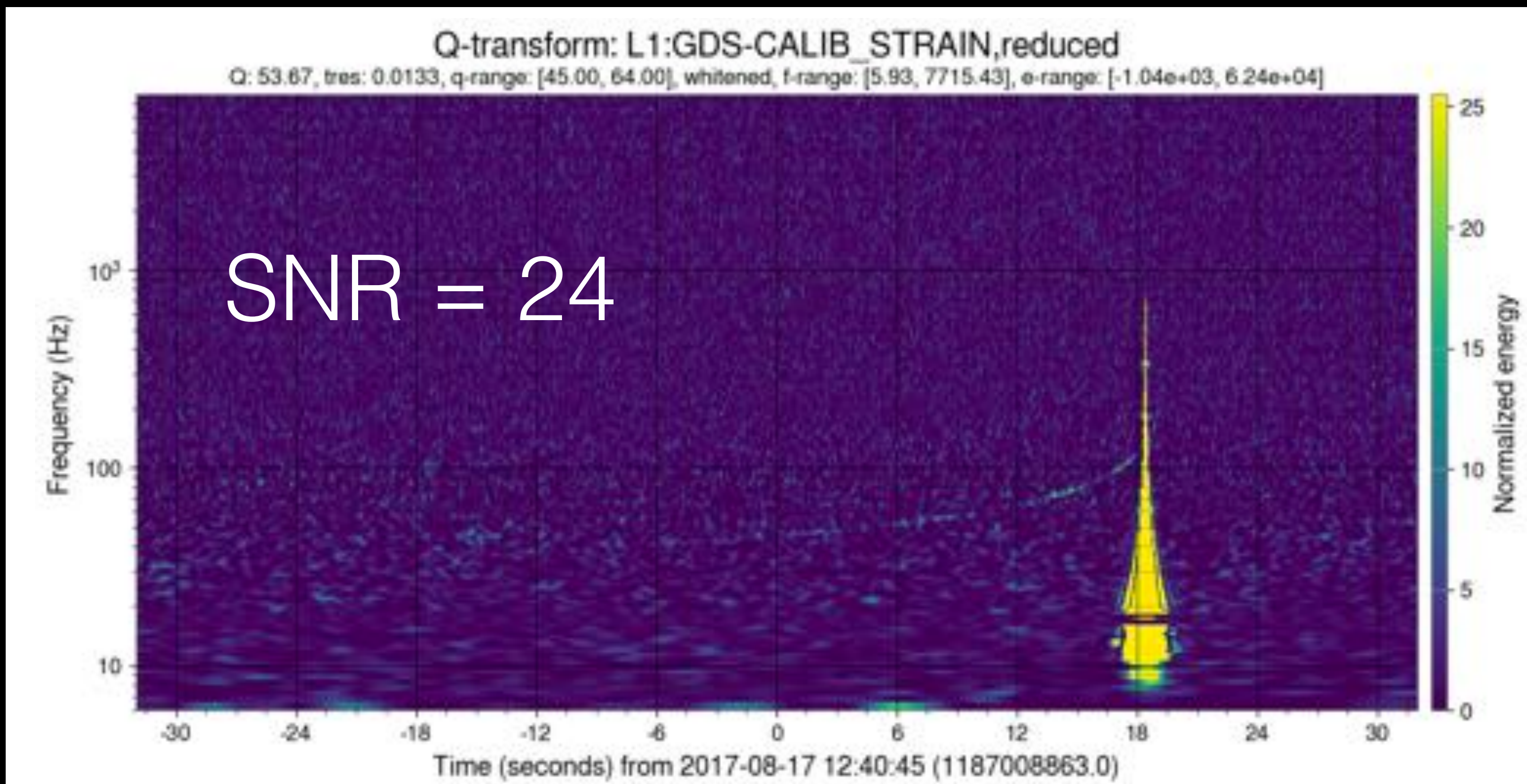
Breakout question

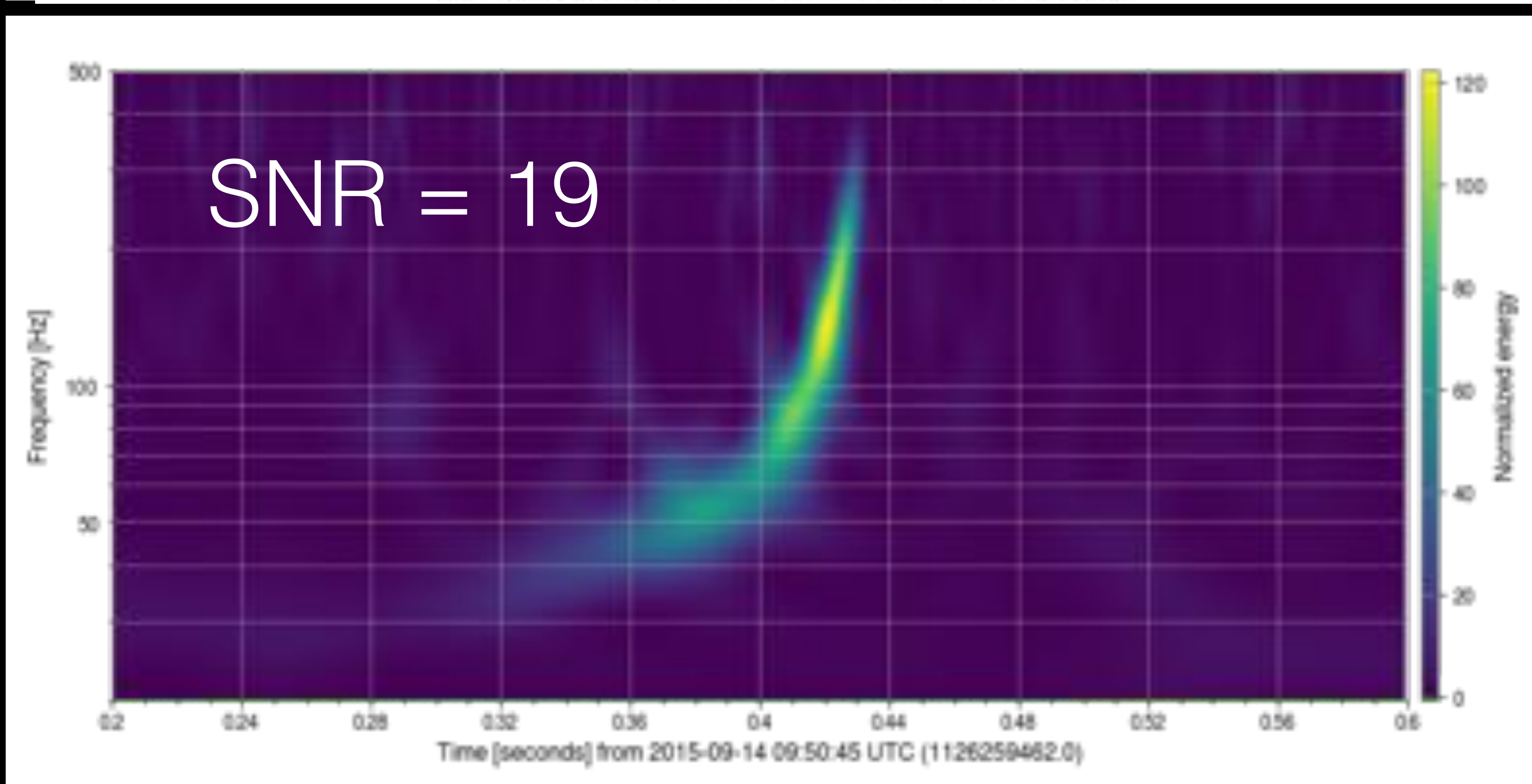




Which of these signals has a higher (single detector) matched filter SNR?

Breakout question



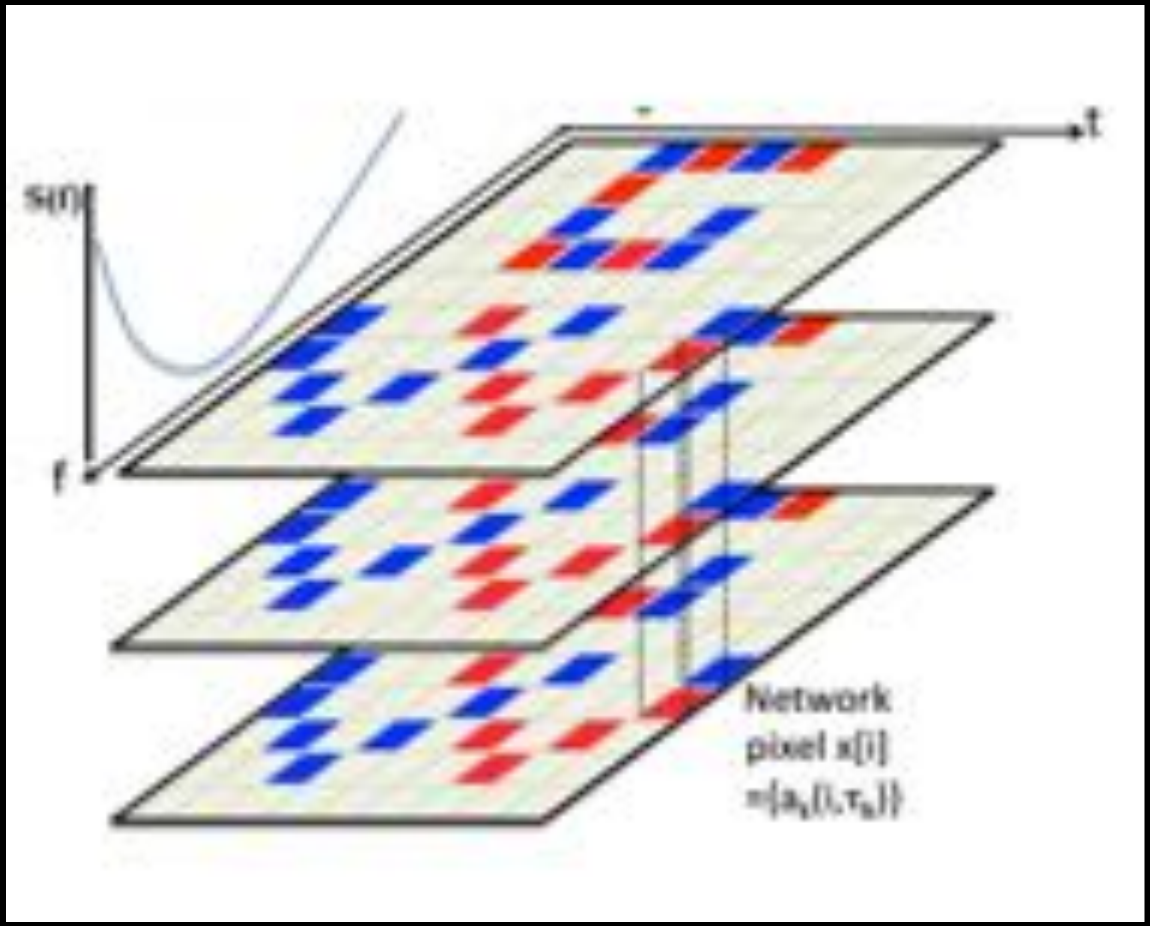


Which of these signals has a higher (single detector) matched filter SNR?

“Un-modelled” burst searches

cWB - an all-sky coherent burst search

- Projects the data onto a Meyer wavelet basis.
- Extracts significant events using a coherent likelihood statistic maximized over all potential sky positions.



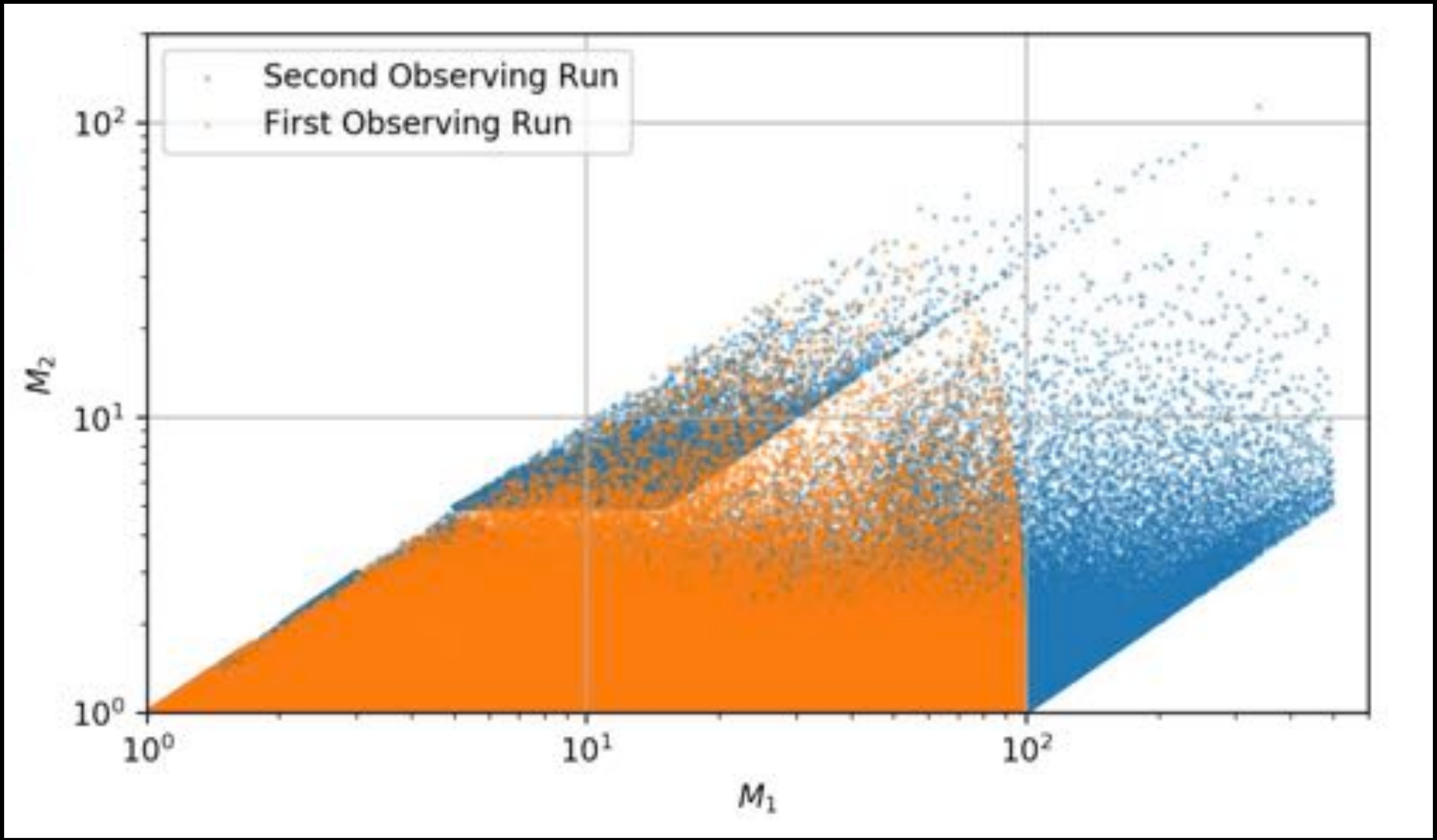
GWTC-1: confident detections

#UpToEleven
Four new binary black hole mergers!
GW151012 designated a GW event!

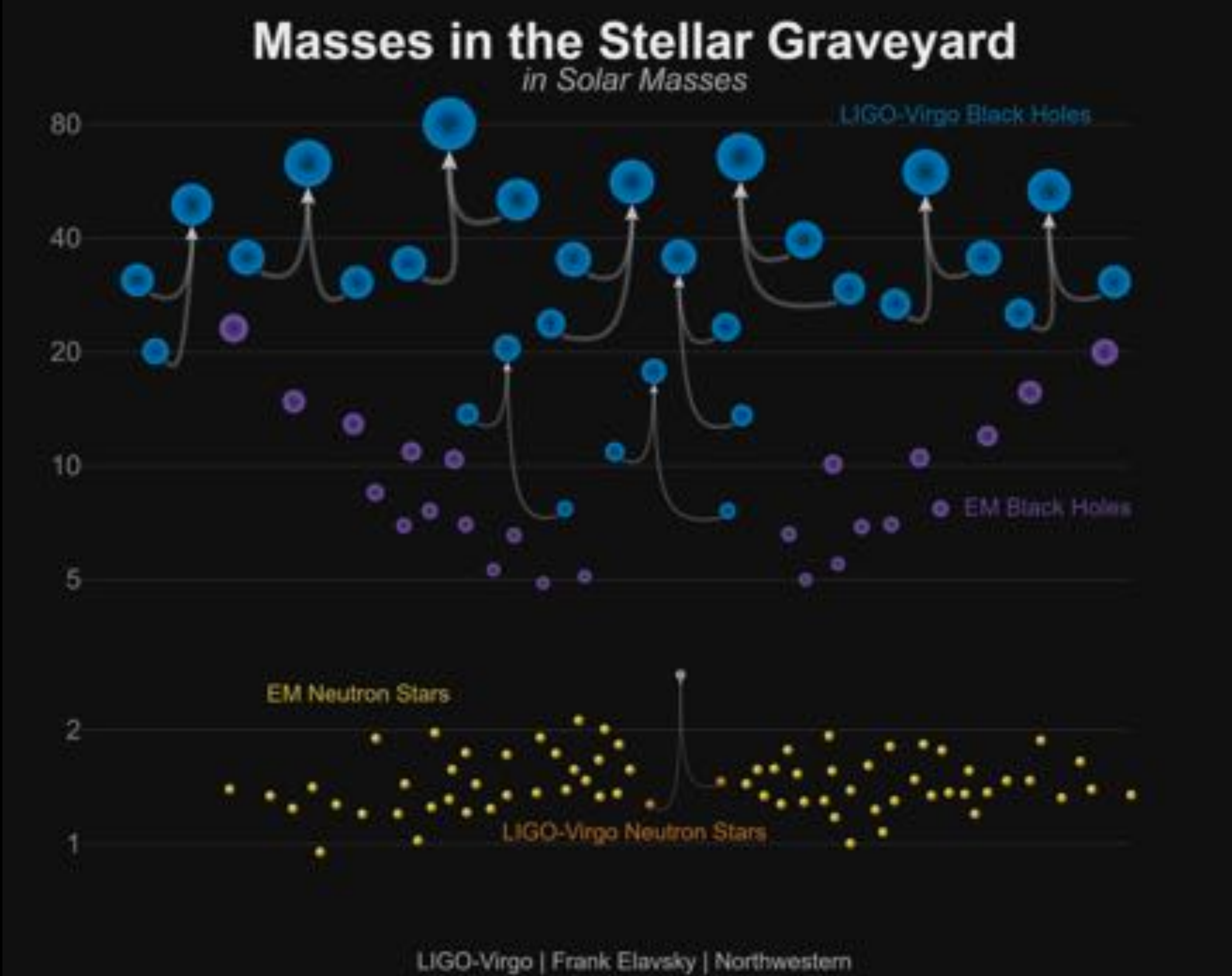
Event		UTC Time	FAR [y^{-1}] PyCBC	GstLAL	cWB	Network SNR PyCBC	GstLAL	cWB
GW150914		09:50:45.4	$< 1.53 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	$< 1.63 \times 10^{-4}$	23.6	24.4	25.2
GW151012		09:54:43.4	0.17	7.92×10^{-3}	–	9.5	10.0	–
GW151226		03:38:53.6	$< 1.69 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	0.02	13.1	13.1	11.9
GW170104		10:11:58.6	$< 1.37 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	2.91×10^{-4}	13.0	13.0	13.0
GW170608		02:01:16.5	$< 3.09 \times 10^{-4}$	$< 1.00 \times 10^{-7}$	1.44×10^{-4}	15.4	14.9	14.1
GW170729	V	18:56:29.3	1.36	0.18	0.02	9.8	10.8	10.2
GW170809	V	08:28:21.8	1.45×10^{-4}	$< 1.00 \times 10^{-7}$	–	12.2	12.4	–
GW170814	V	10:30:43.5	$< 1.25 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	$< 2.08 \times 10^{-4}$	16.3	15.9	17.2
GW170817	V(G)	12:41:04.4	$< 1.25 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	–	30.9	33.0	–
GW170818	V	02:25:09.1	–	4.20×10^{-5}	–	–	11.3	–
GW170823		13:13:58.5	$< 3.29 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	2.14×10^{-3}	11.1	11.5	10.8

B.P. Abbott et al. arXiv 1811.12907 (2018)

GWTC-1: template bank additions



Plot by Alex Nitz


Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern

GW candidates in O3 thus far

16 alerts issued since April 1st.
14 un-retracted events in 8.5 weeks!

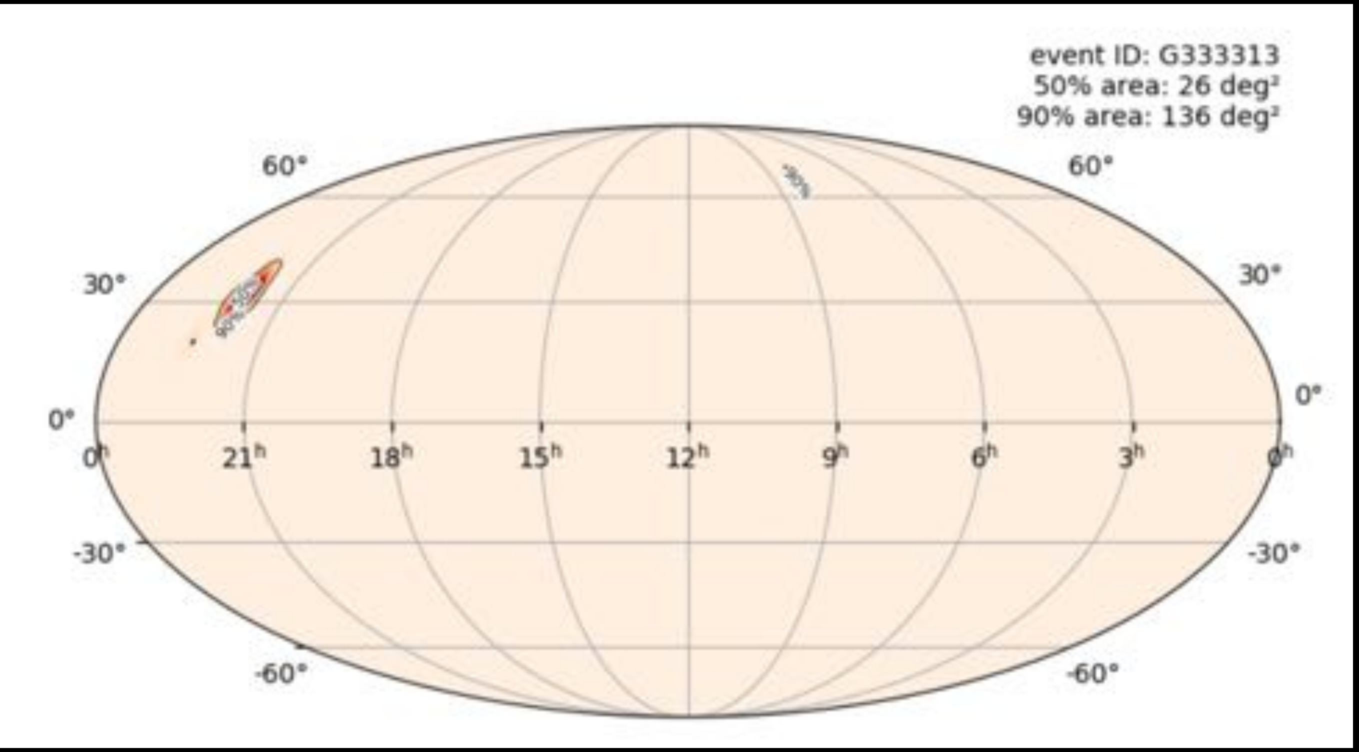
UID	Labels	FAR
S190602aq	PE_READY ADVOK SKYMAP_READY	1.90052750535e-09
S190521r	PE_READY ADVOK SKYMAP_READY	3.16754584224e-10
S190521g	PE_READY ADVOK SKYMAP_READY	3.80105501069e-09
S190519bj	PE_READY ADVOK SKYMAP_READY	5.70158251604e-09
S190517h	PE_READY ADVOK SKYMAP_READY	2.37290998502e-09
S190513bm	ADVOK SKYMAP_READY EMBRIGHT_F	3.73400311637e-13
S190512at	PE_READY ADVOK SKYMAP_READY	1.90052750535e-09
S190510g	ADVOK SKYMAP_READY EMBRIGHT_F	8.8335691573e-09
S190503bf	ADVOK SKYMAP_READY EMBRIGHT_F	1.63611159504e-09
S190426c	PE_READY ADVOK SKYMAP_READY	1.94694181763e-08
S190425z	ADVOK SKYMAP_READY EMBRIGHT_F	4.53764787126e-13
S190421ar	PE_READY ADVOK SKYMAP_READY	1.48874654585e-08
S190412m	PE_READY ADVOK SKYMAP_READY	1.68289586112e-27
S190408an	PE_READY ADVOK SKYMAP_READY	2.81096164616e-18

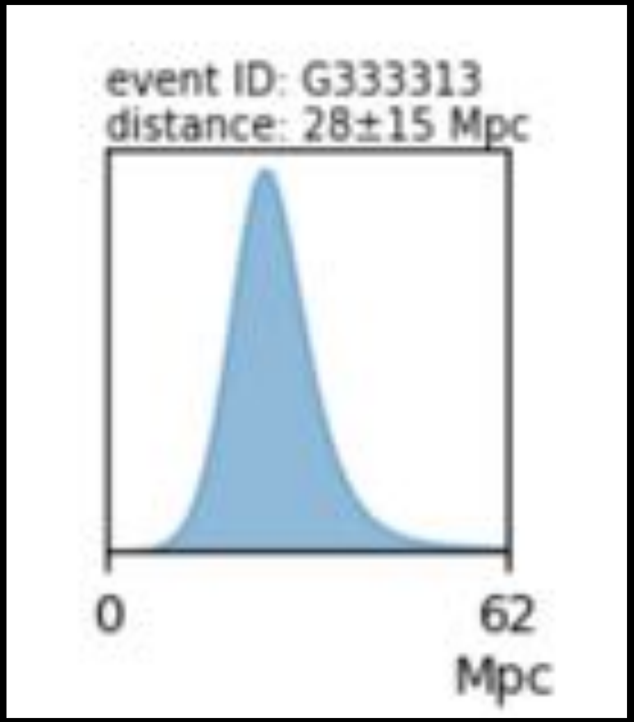
- 11 likely BBHs
- 2 BNSs (one likely, one 58% terrestrial)
- 1 potential NSBH candidate
- (BNS (49%), MassGap (24%), NSBH (13%), Terrestrial (14%))

Challenge: S190518bb case study

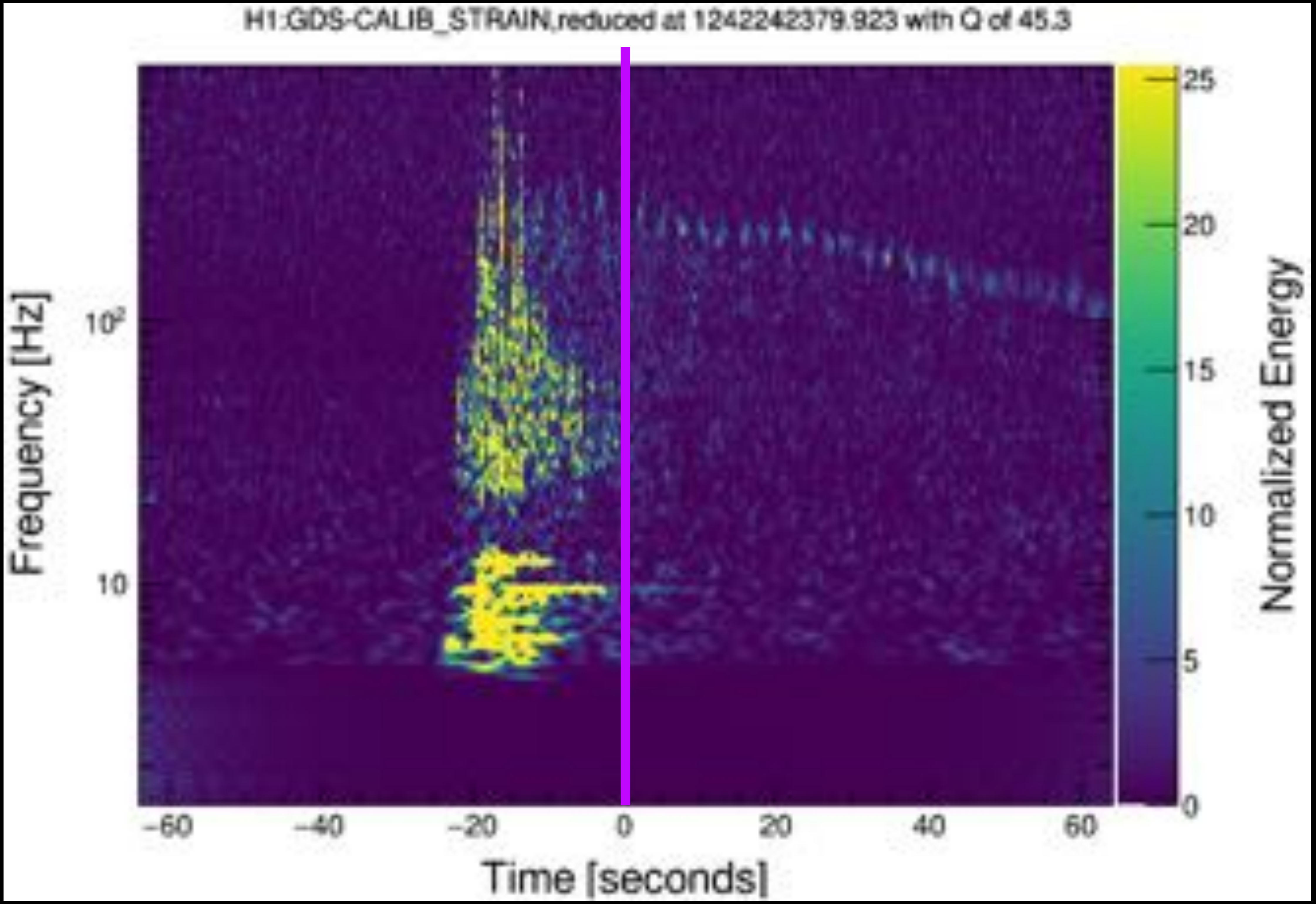
Automatic Preliminary Notice sent ~6 minutes after the event:

FAR: 1.004e-08 [Hz] (one per ~3 years)
PROB_NS: 1.00 [range is 0.0-1.0]
PROB_REMNANT: 1.00 [range is 0.0-1.0]
PROB_BNS: 0.75 [range is 0.0-1.0]
PROB_TERRES: 0.24 [range is 0.0-1.0]



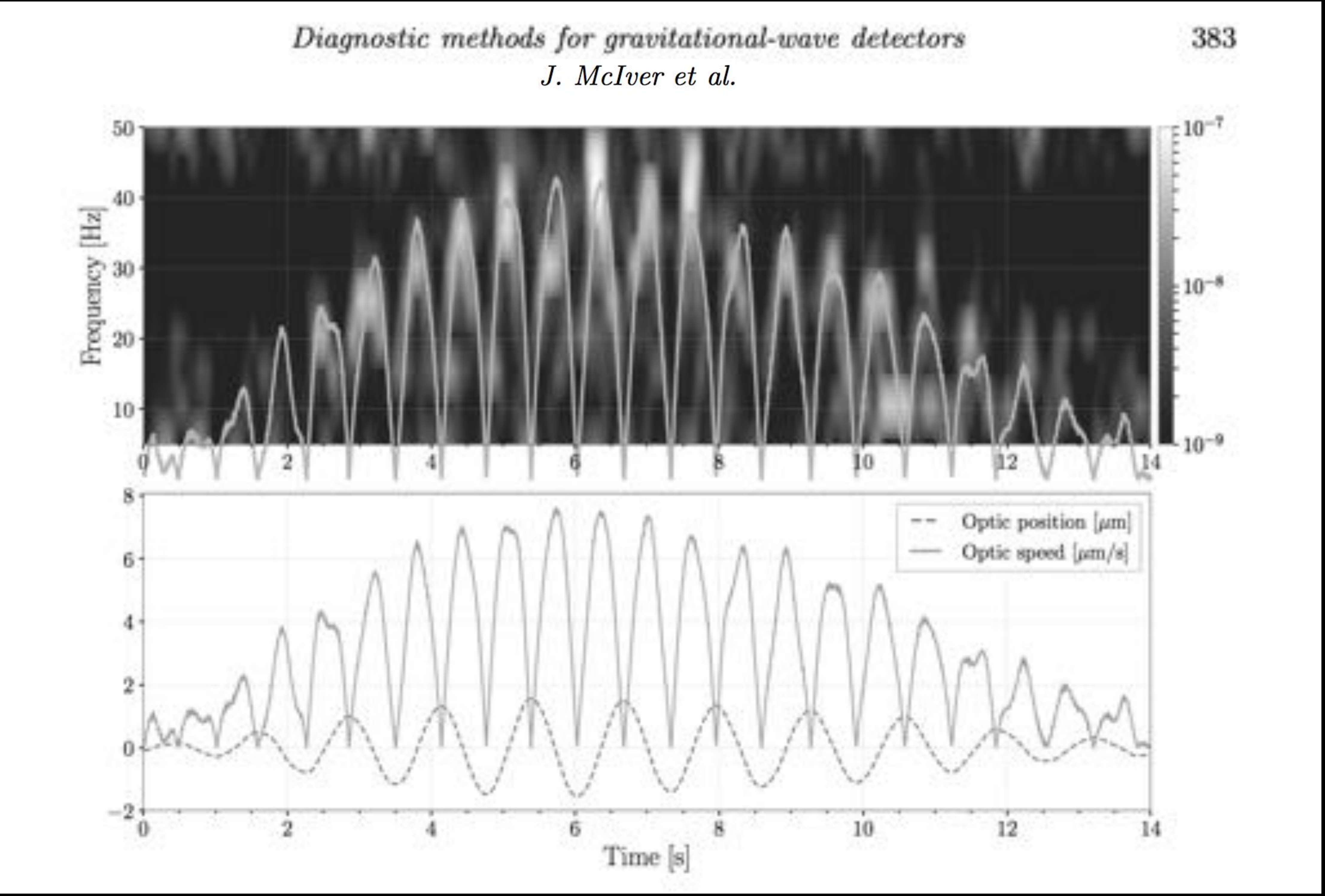


Challenge: S190518bb case study



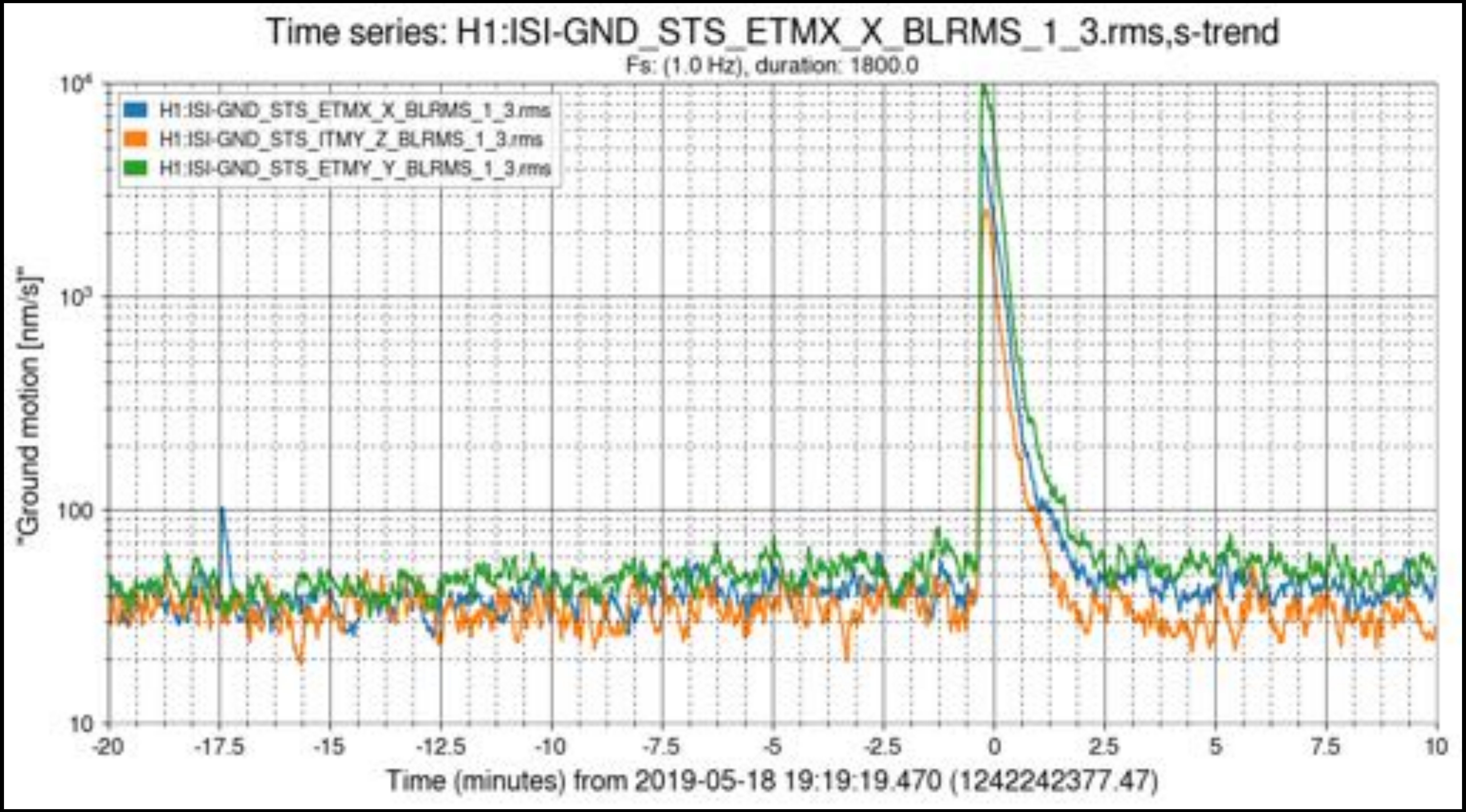
LIGO DCC G1900994

Light scattering



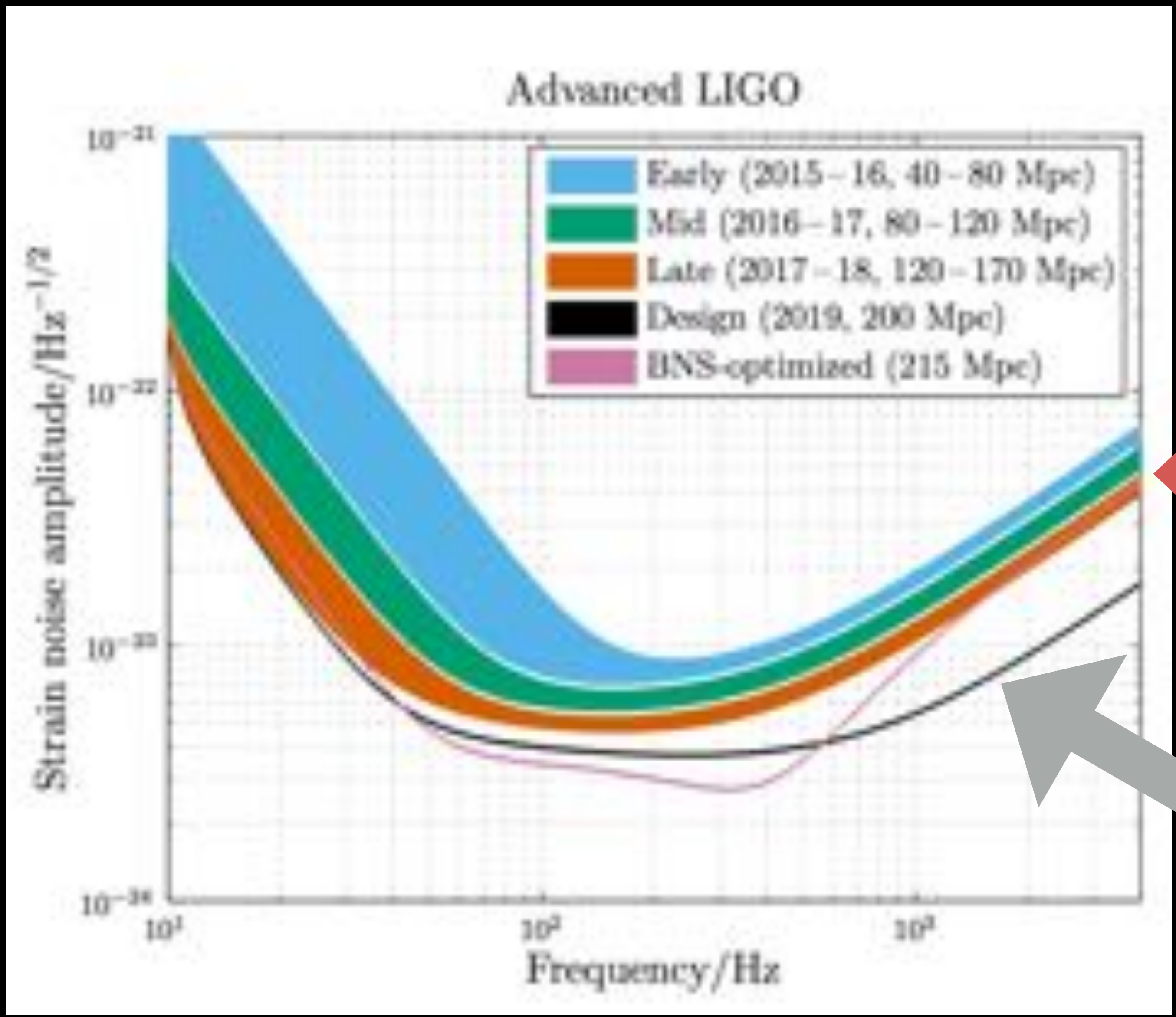
Advanced Interferometric Gravitational-Wave Detectors (Edited by Saulson, Grote, Reitze) 2019

Challenge: S190518bb case study



LIGO DCC G1900994

Roadmap to LIGO design sensitivity



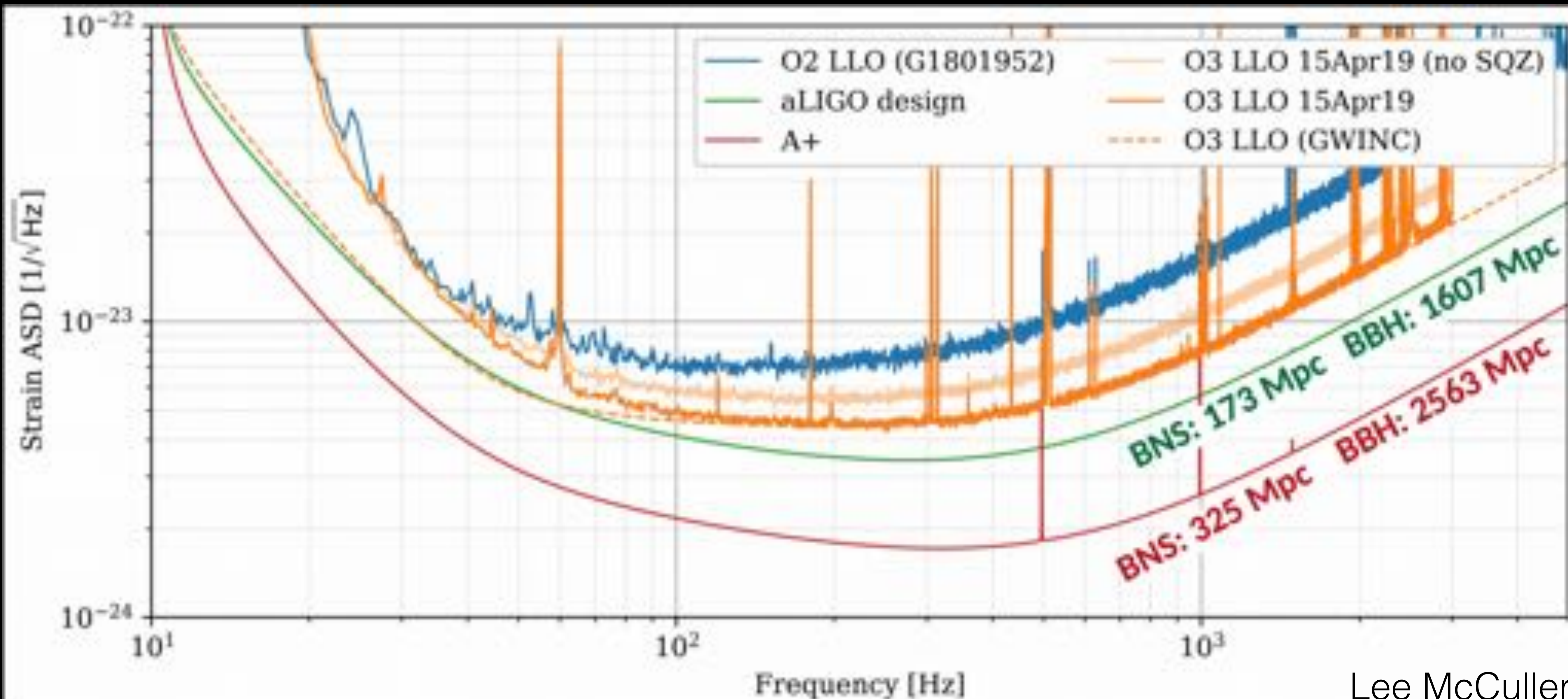
Expectation for the third LIGO observing run (O3)
1 signal/week!

Up to **1 signal/day** at design sensitivity!

arXiv 1304.0670

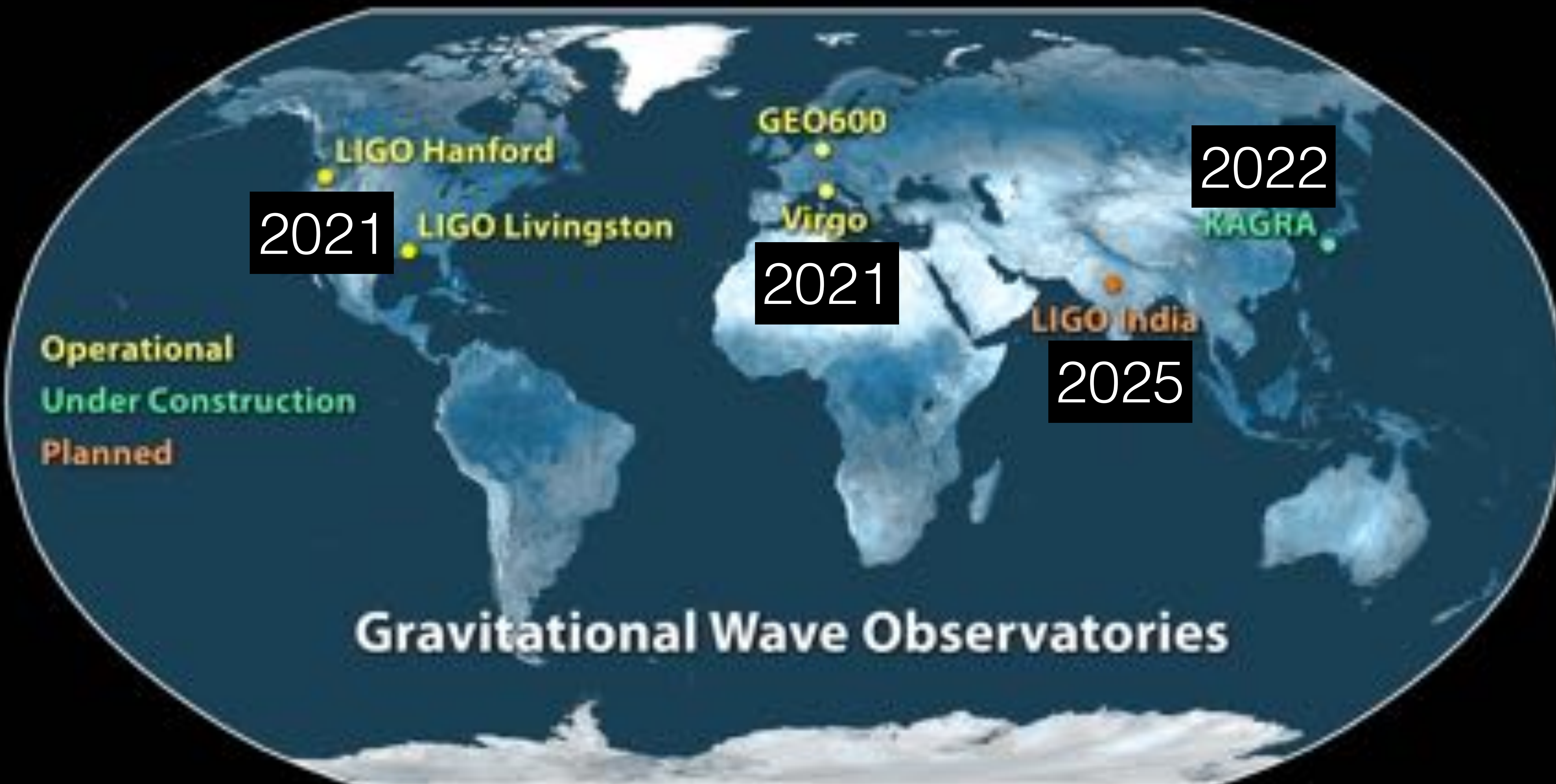
A+ by the mid 2020s

- Frequency-dependent light squeezing
- 300m filter cavity
- Improved coatings
- Bigger beam splitter, improved suspensions



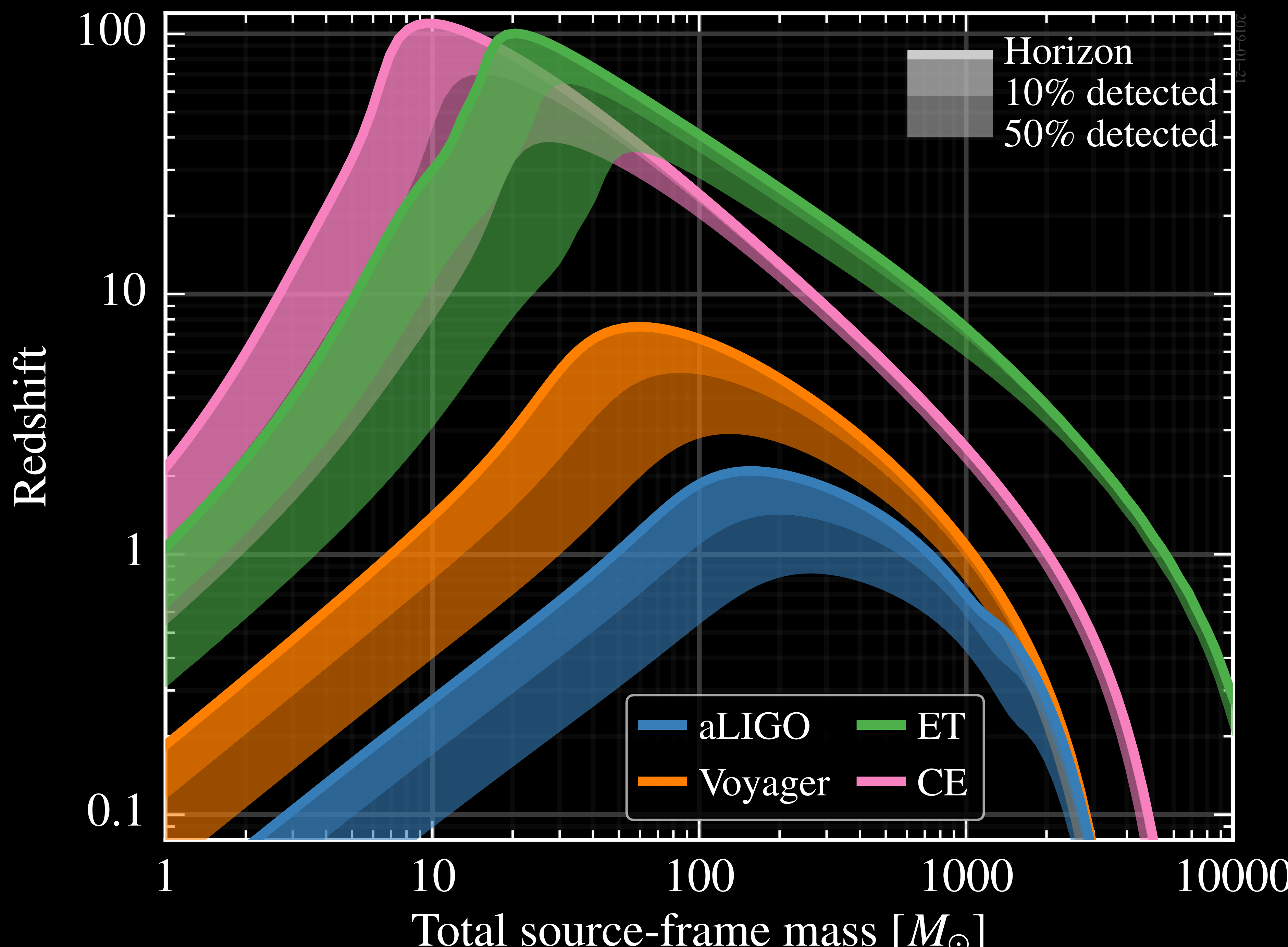
Lee McCuller

The global network of current gen interferometers



LIGO/Caltech

Next generation detectors



Evan Hall et al 2019

Cosmic reach of next generation detectors