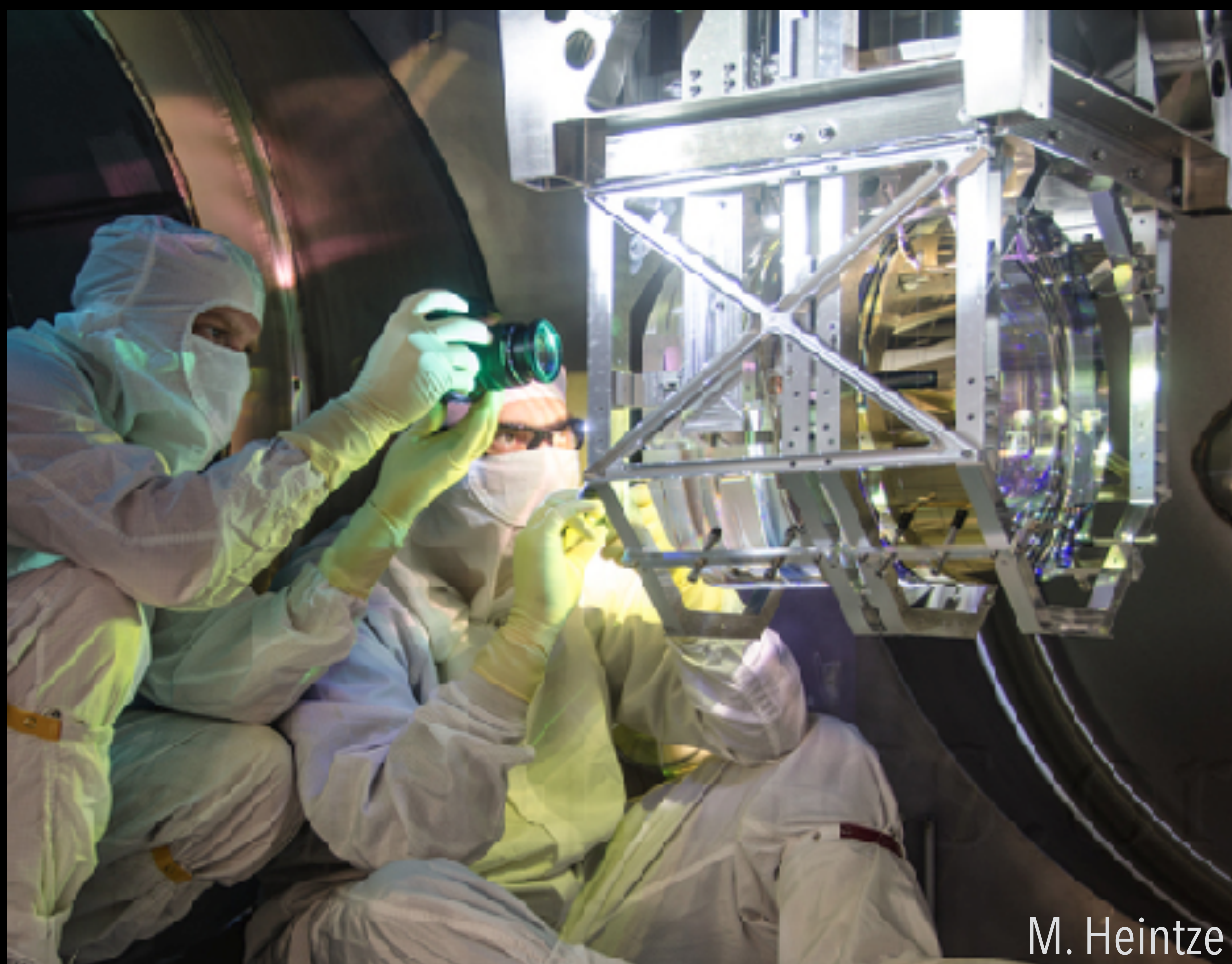
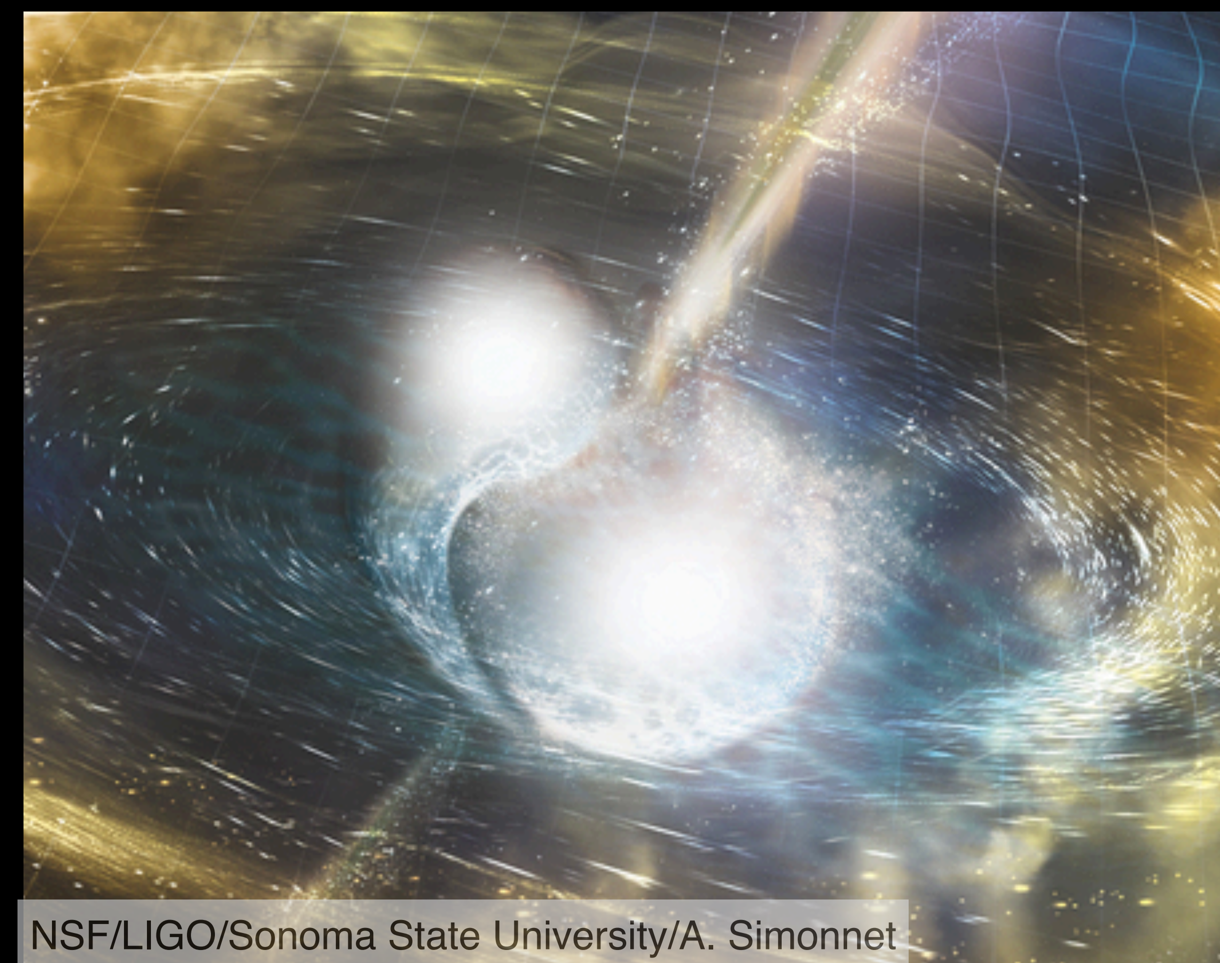
Gravitational wave astronomy

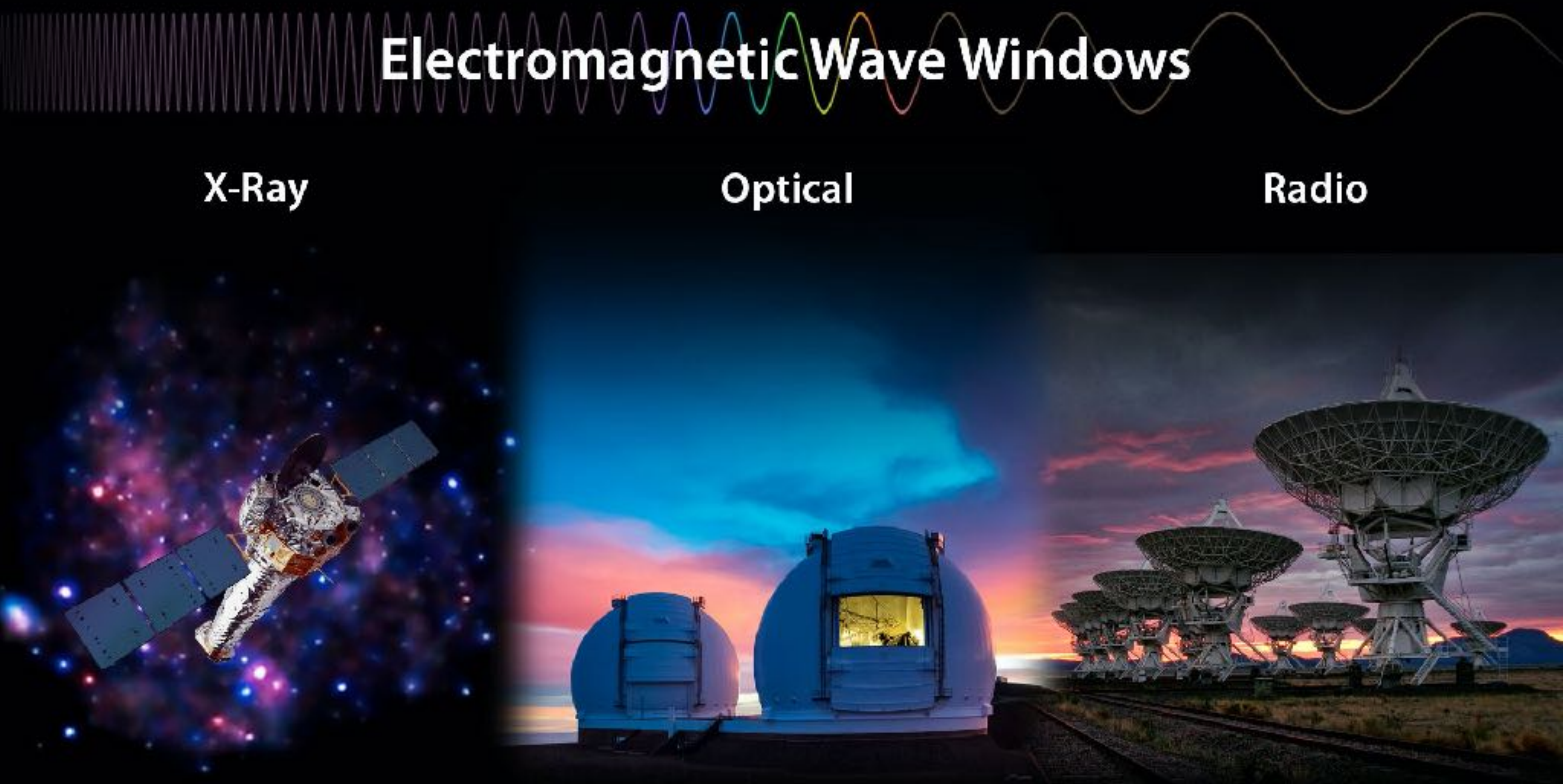

M. Heintze


NSF/LIGO/Sonoma State University/A. Simonnet

Jess McIver
GWANW student workshop
June 28, 2021

LIGO DCC G2101355

Astronomy with light

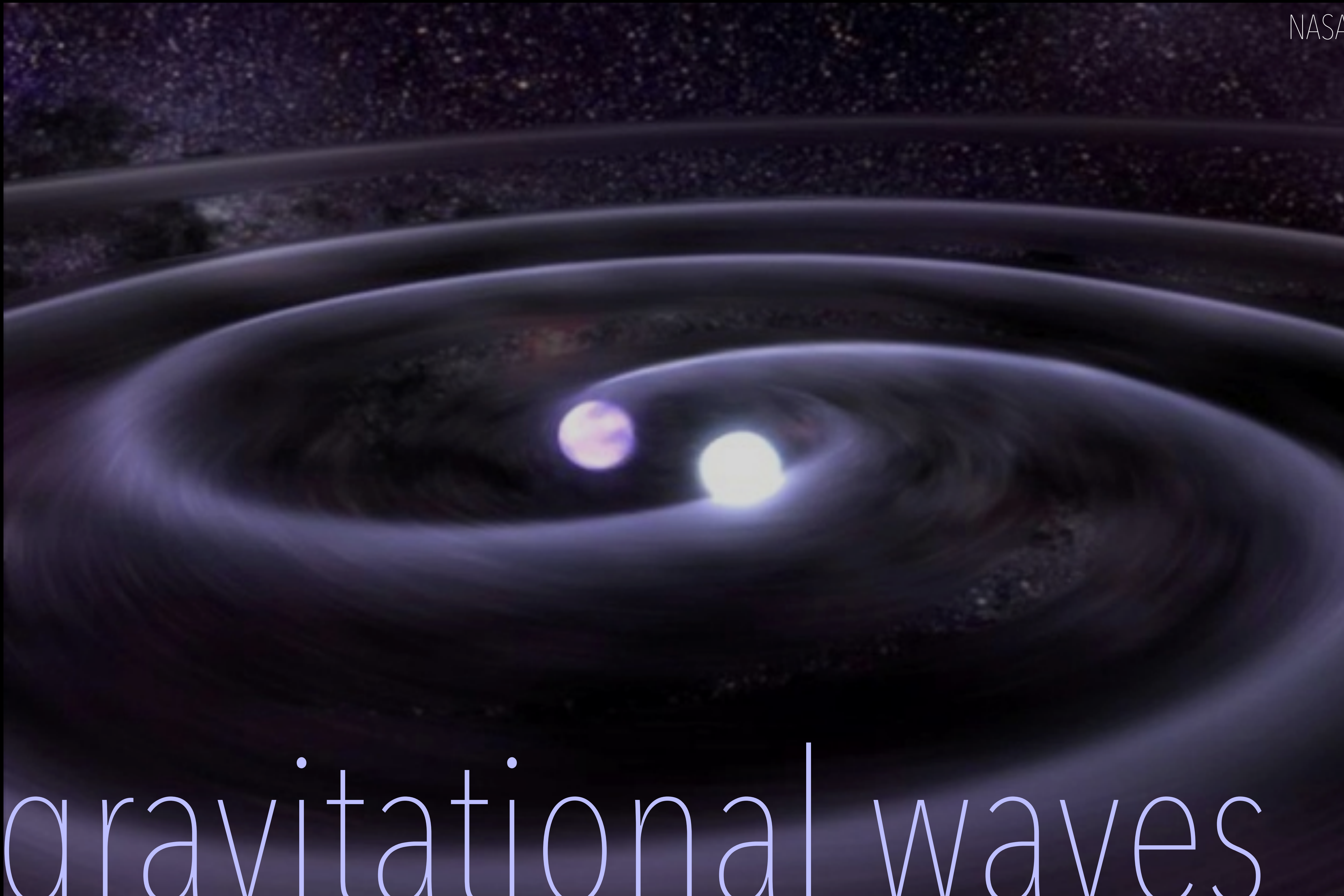


L. Nuttall

Gravitational Wave Periods

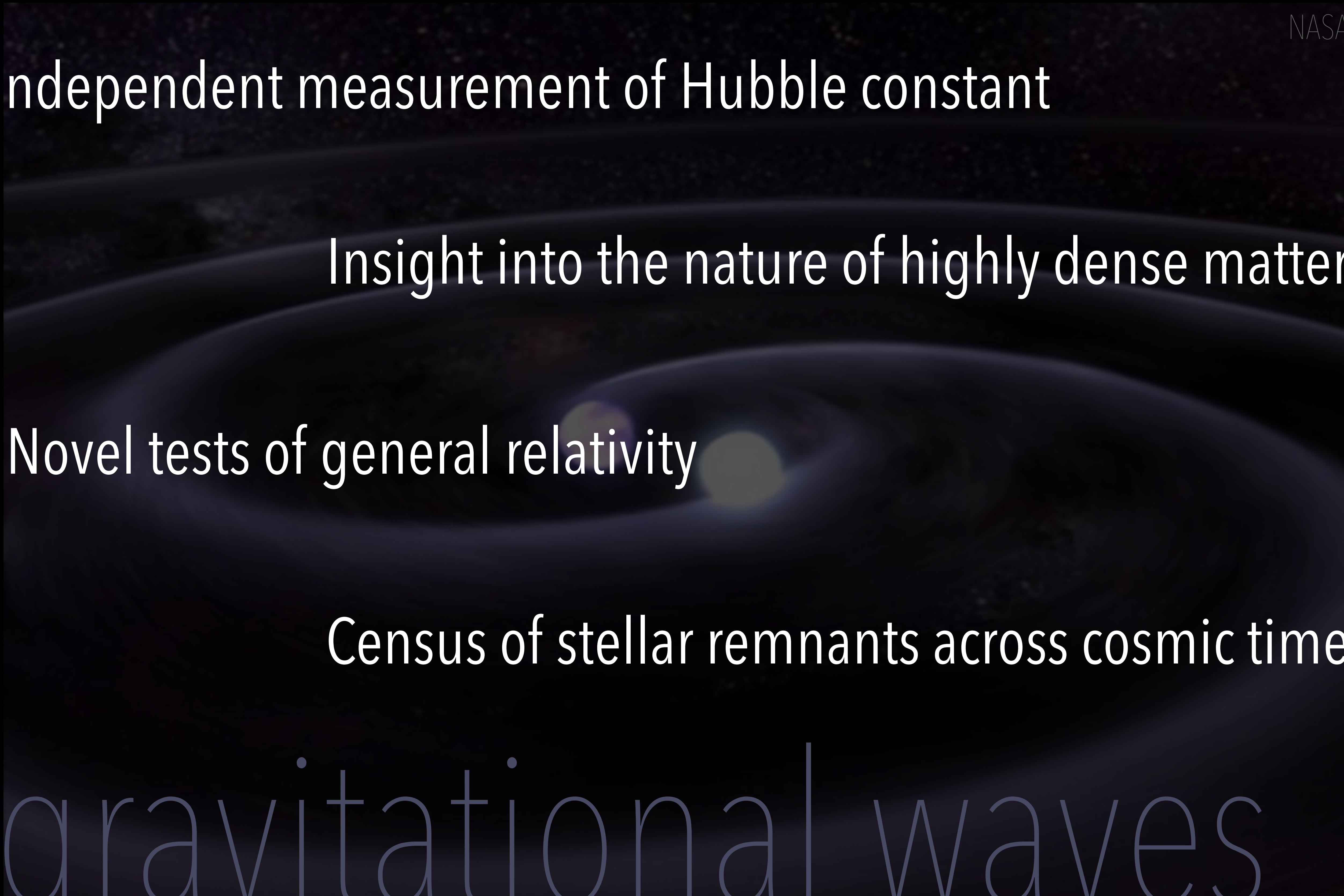
Milliseconds	Minutes to Hours	Years to Decades	Billions of Years

LIGO/Virgo	LISA	Pulsar timing	CMB polarization



gravitational waves

a new view of the universe



Independent measurement of Hubble constant

Insight into the nature of highly dense matter

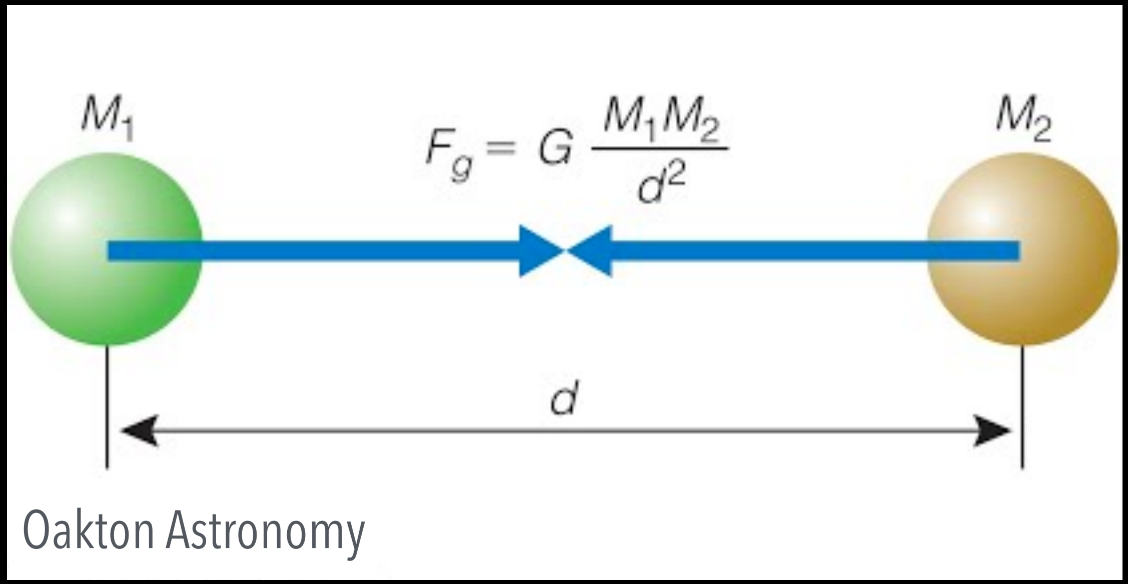
Novel tests of general relativity

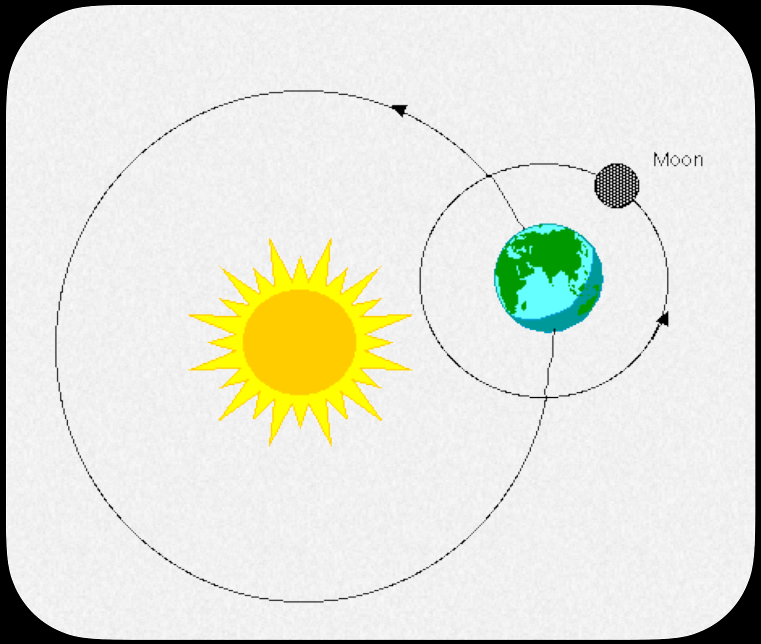
Census of stellar remnants across cosmic time

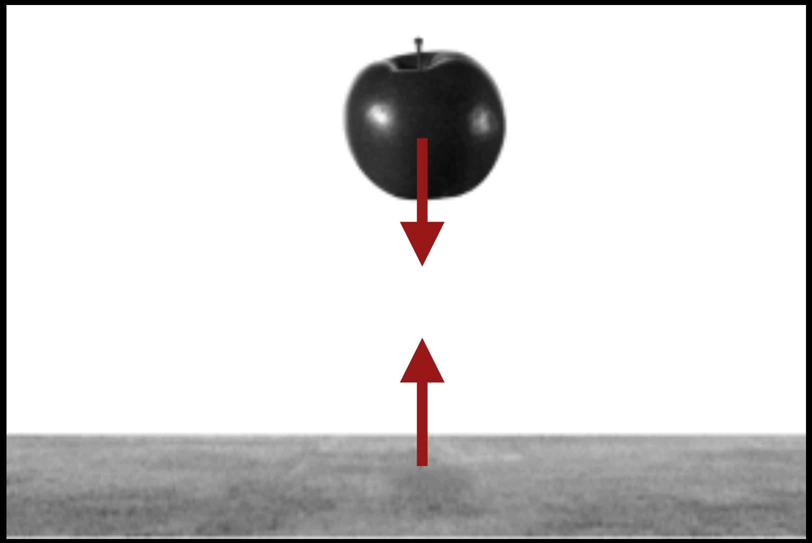
gravitational waves

a new view of the universe

Newton's Gravity



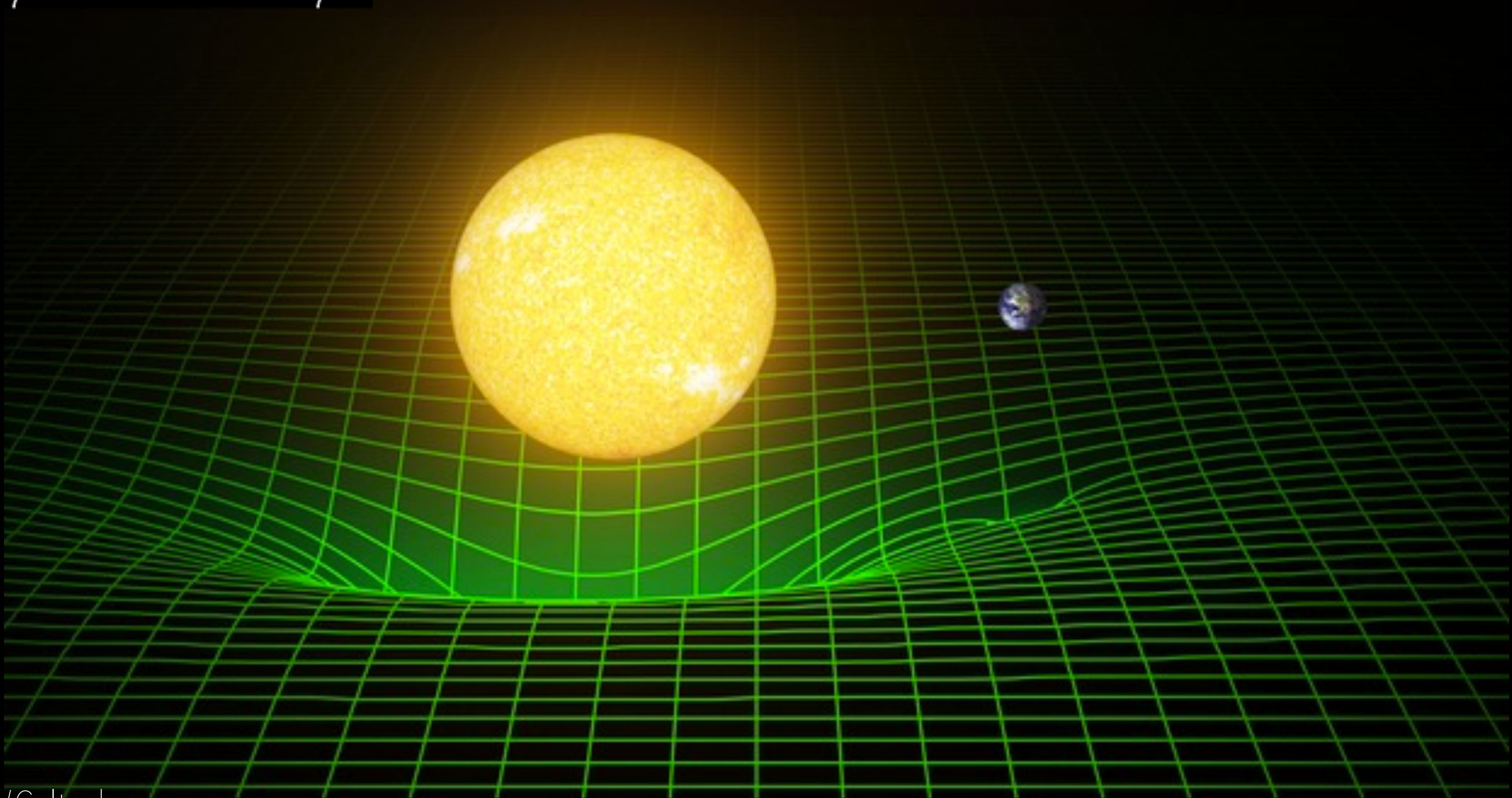




Einstein's Gravity: General Relativity

Matter tells spacetime how to curve
Spacetime tells matter how to move
- John Wheeler

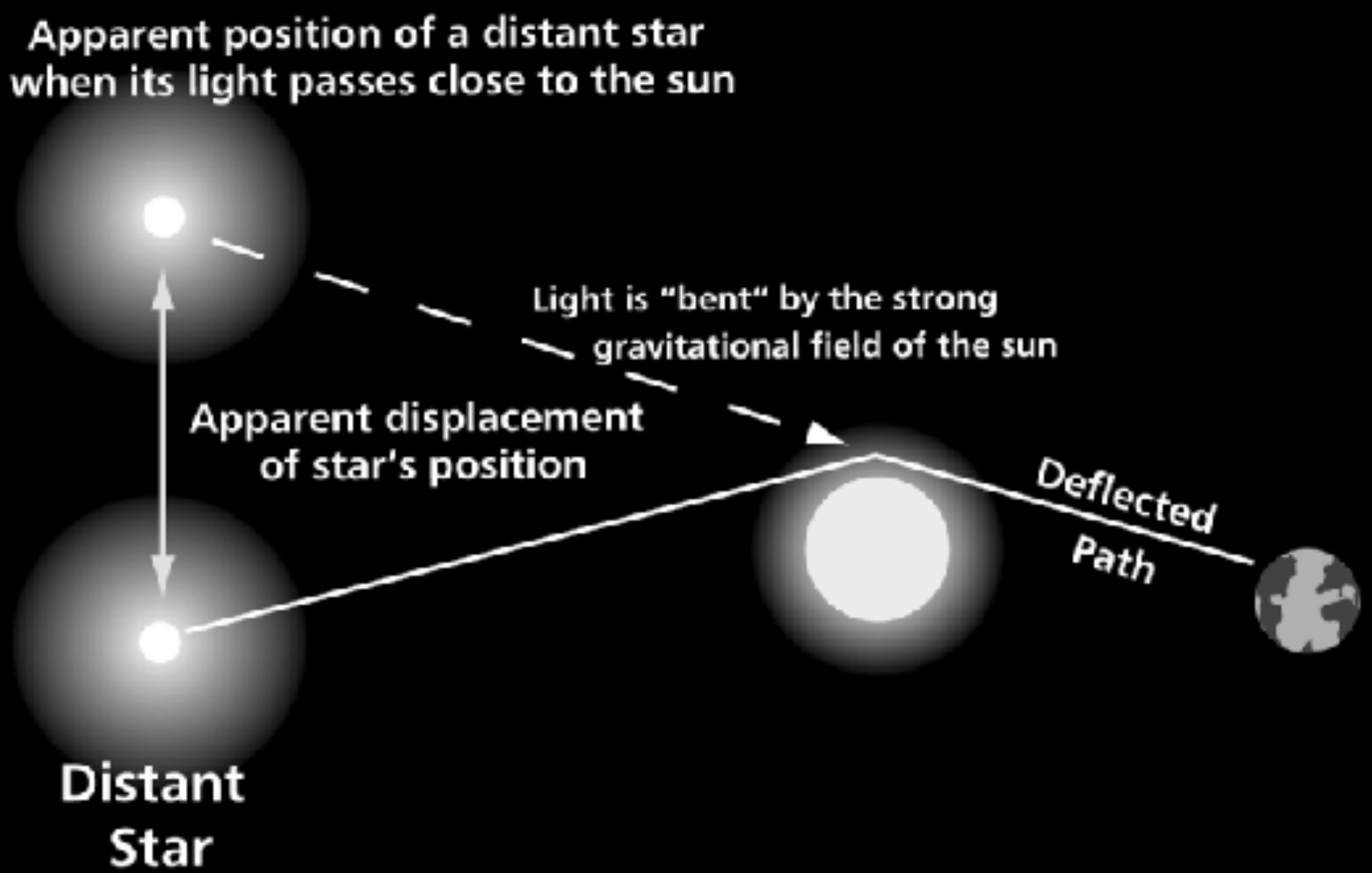
$$G_{\mu\nu} = 8\pi \; T_{\mu\nu}$$



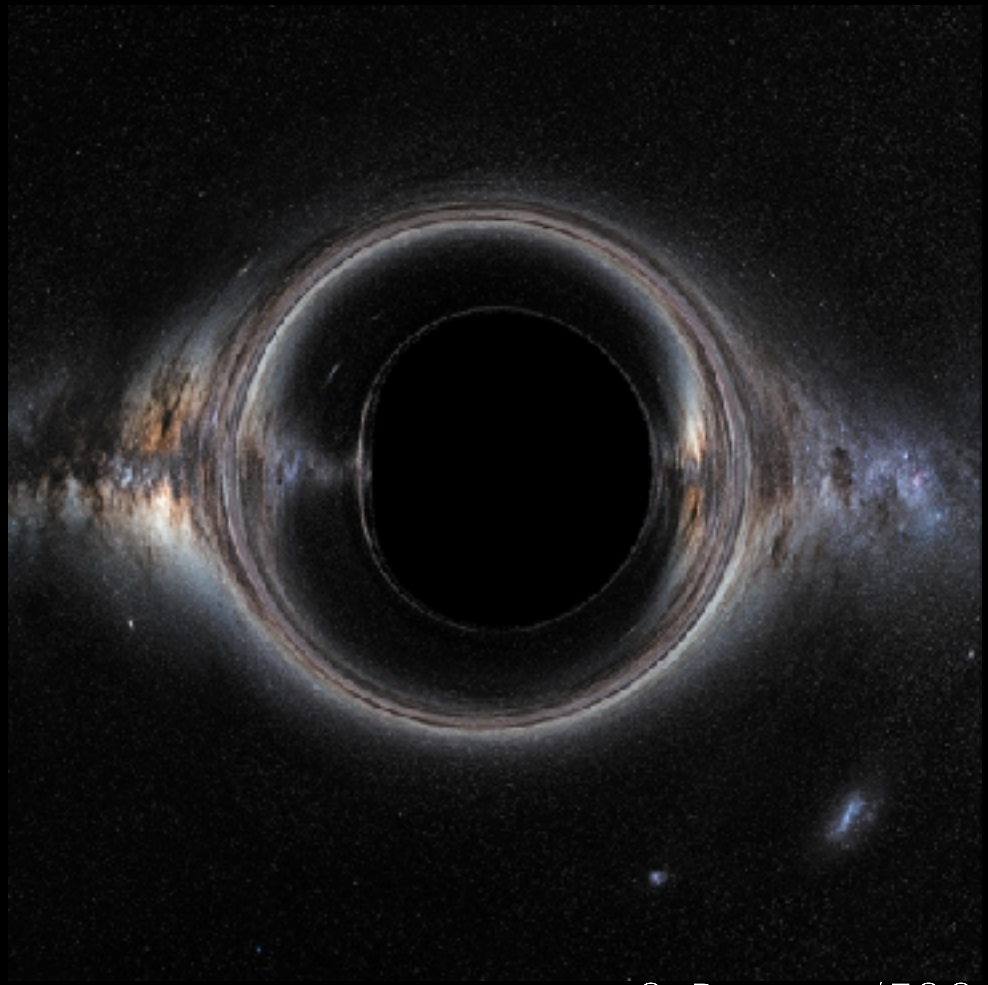
LIGO/Caltech

Some of Einstein's predictions

Gravity bends light



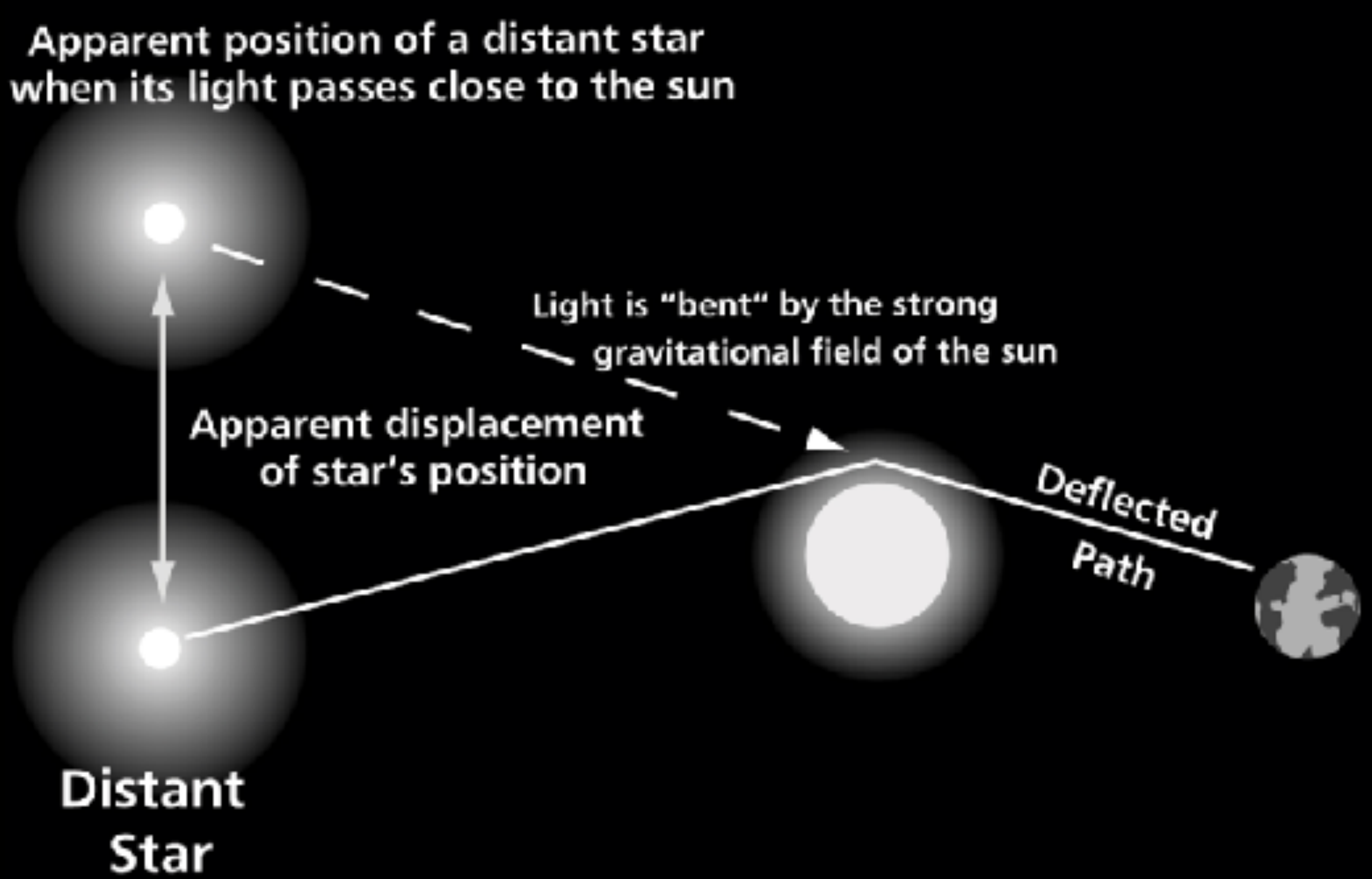
Black holes



S. Brunier /ESO

Some of Einstein's predictions

Gravity bends light



Black holes


The New York Times.

LIGHTS ALL ASKEW IN THE HEAVENS

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

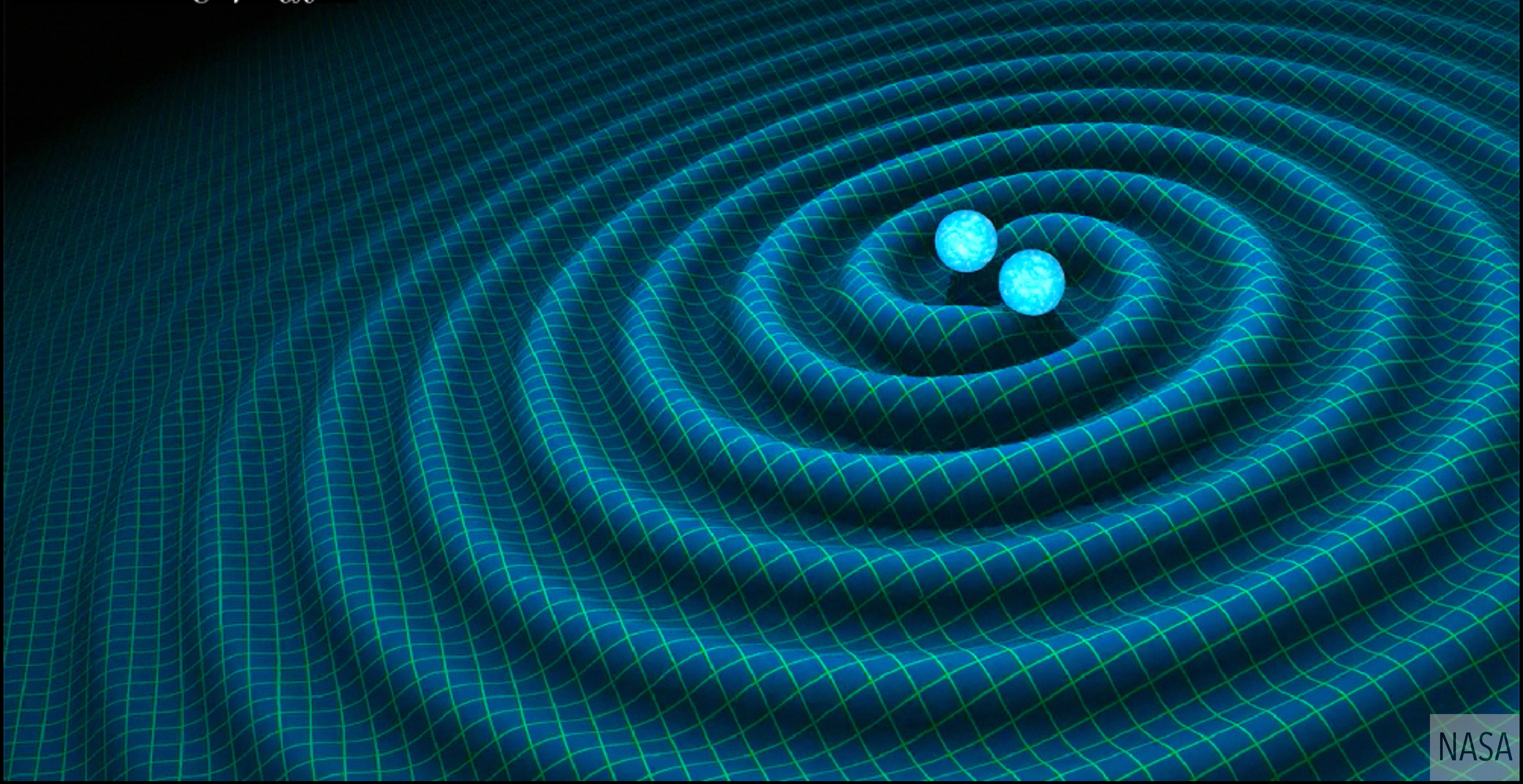
S. Brunier /ESO

Measured by Eddington in 1919 during a total solar eclipse!

Gravitational waves

Ripples in the fabric of spacetime
generated by the acceleration of matter

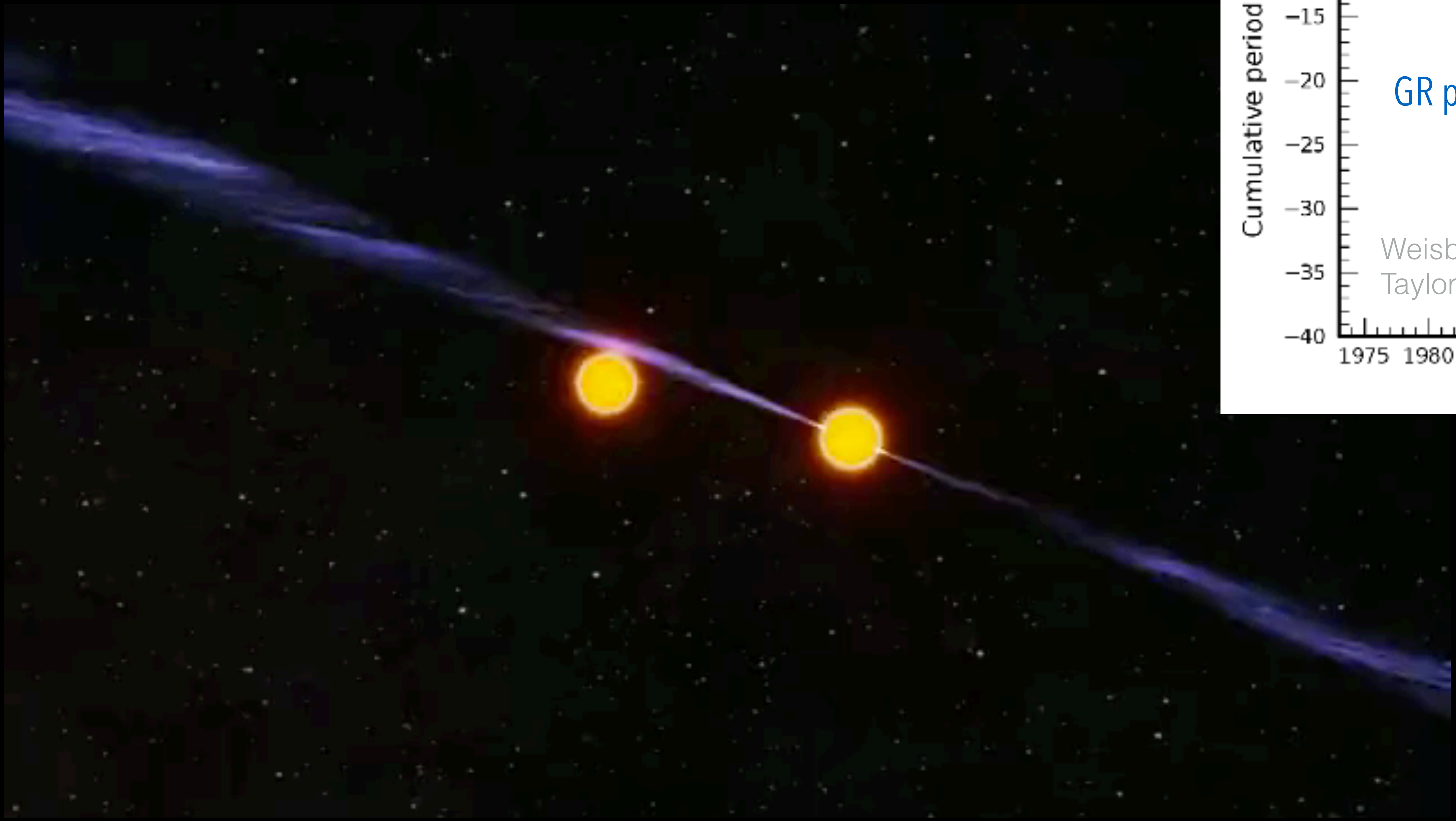
$$h_{ij}(t) \propto \frac{G}{c^4 r}\frac{d^2 I_{ij}}{dt^2}$$

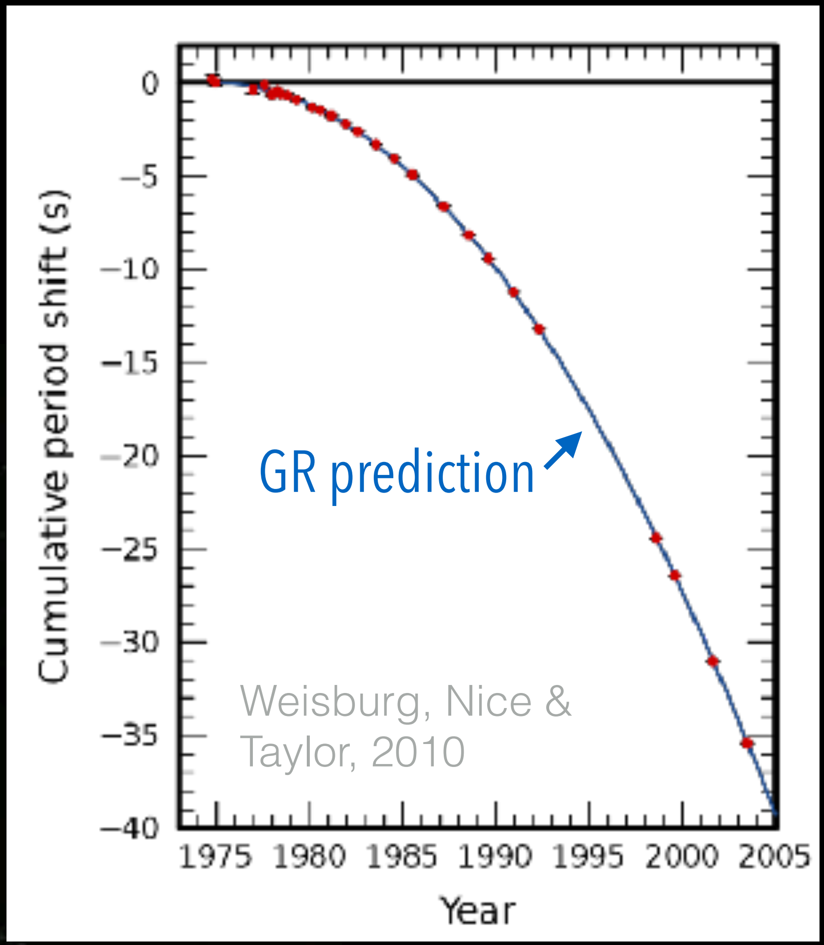


Indirect evidence of gravitational waves

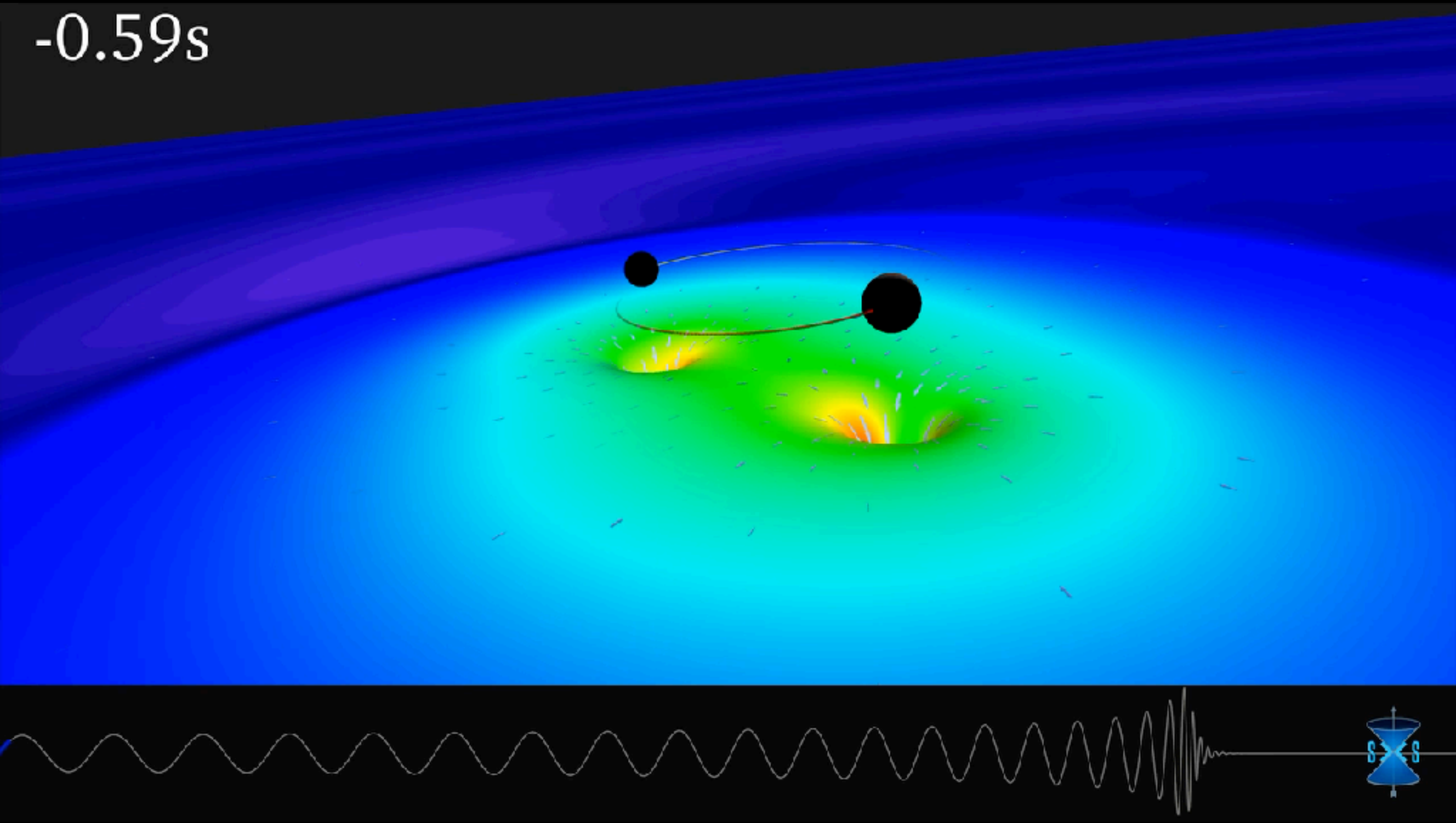
Hulse-Taylor Binary Pulsar

Won the Nobel Prize in Physics in 1993!





A binary black hole coalescence

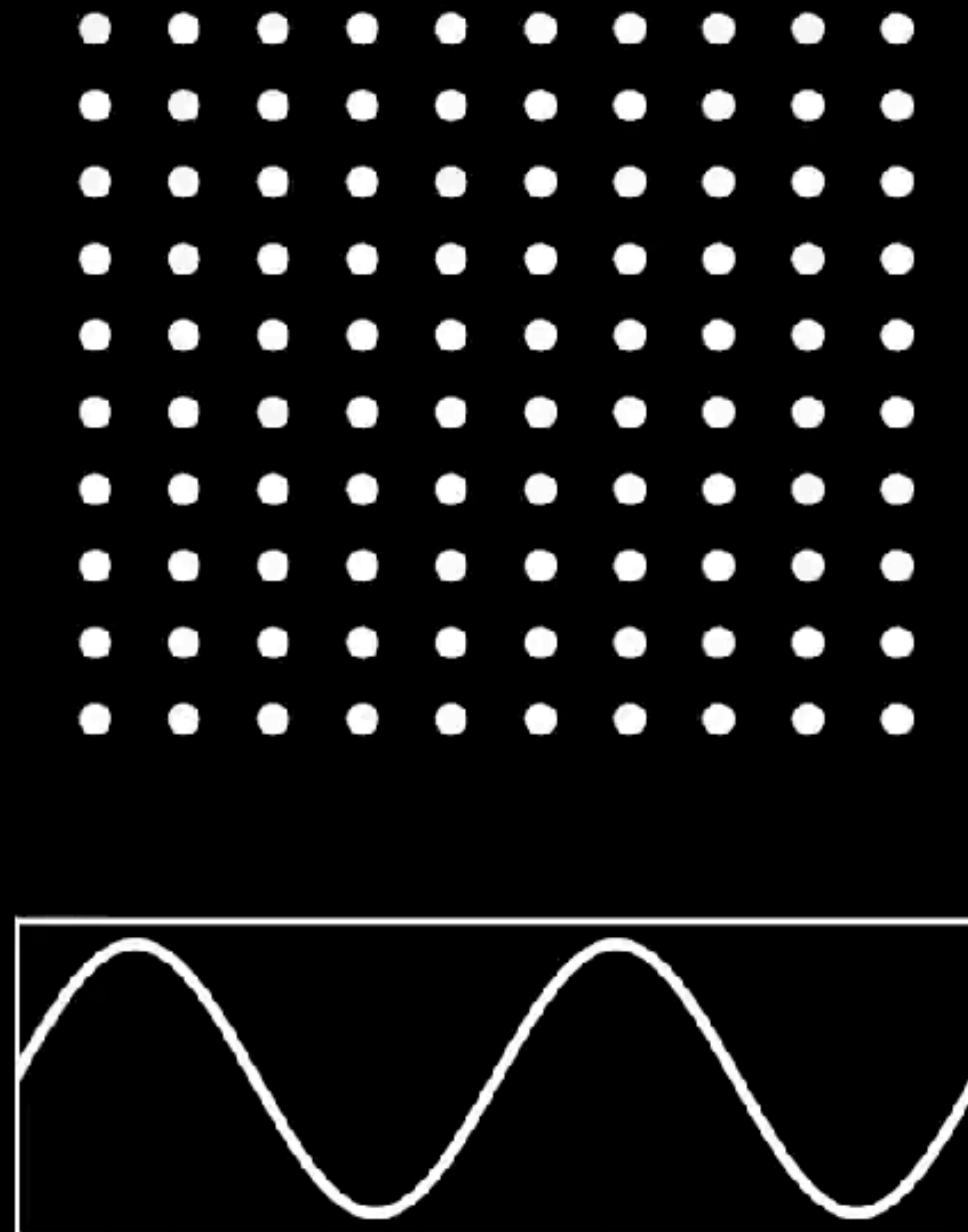


SXS

Gravitational wave strain

Induced spacetime strain h(t)

$$h_{ij}(t) \propto \frac{G}{c^4 r}\frac{d^2 I_{ij}}{dt^2}$$

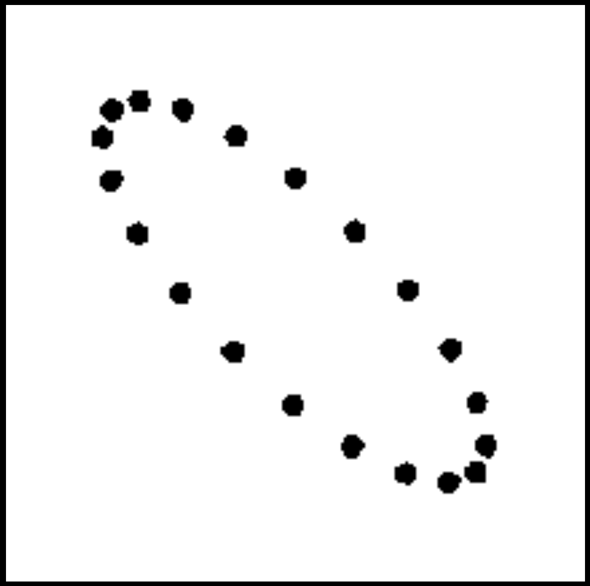


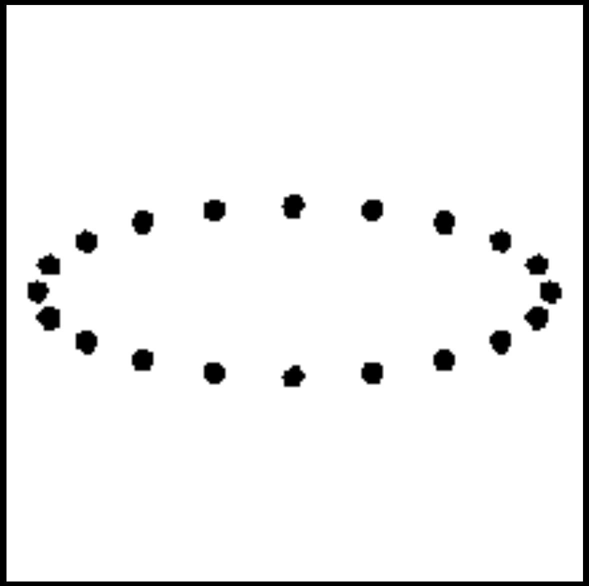
Measured spacetime strain h(t)

$$\frac{\Delta L}{L}$$

Movie: Carl Rodriguez

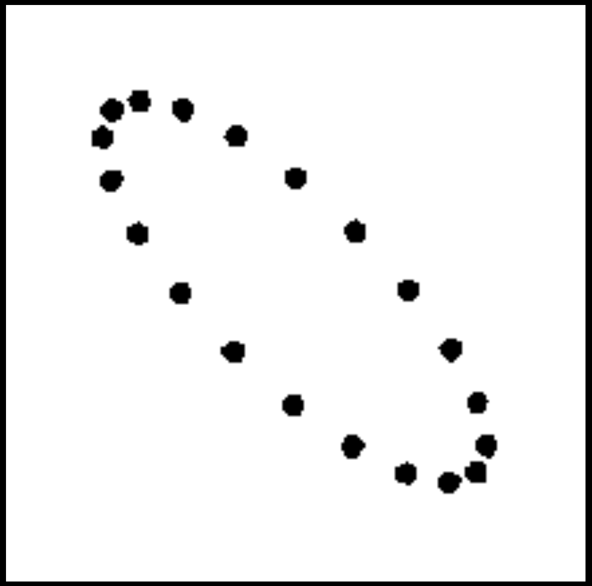
Gravitational wave propagation

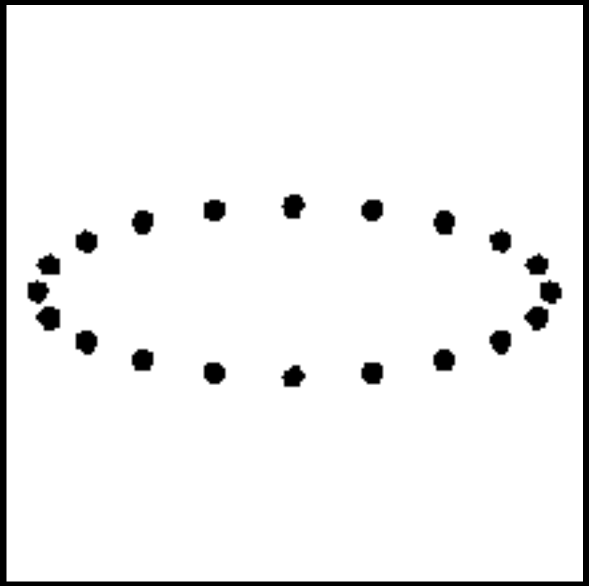


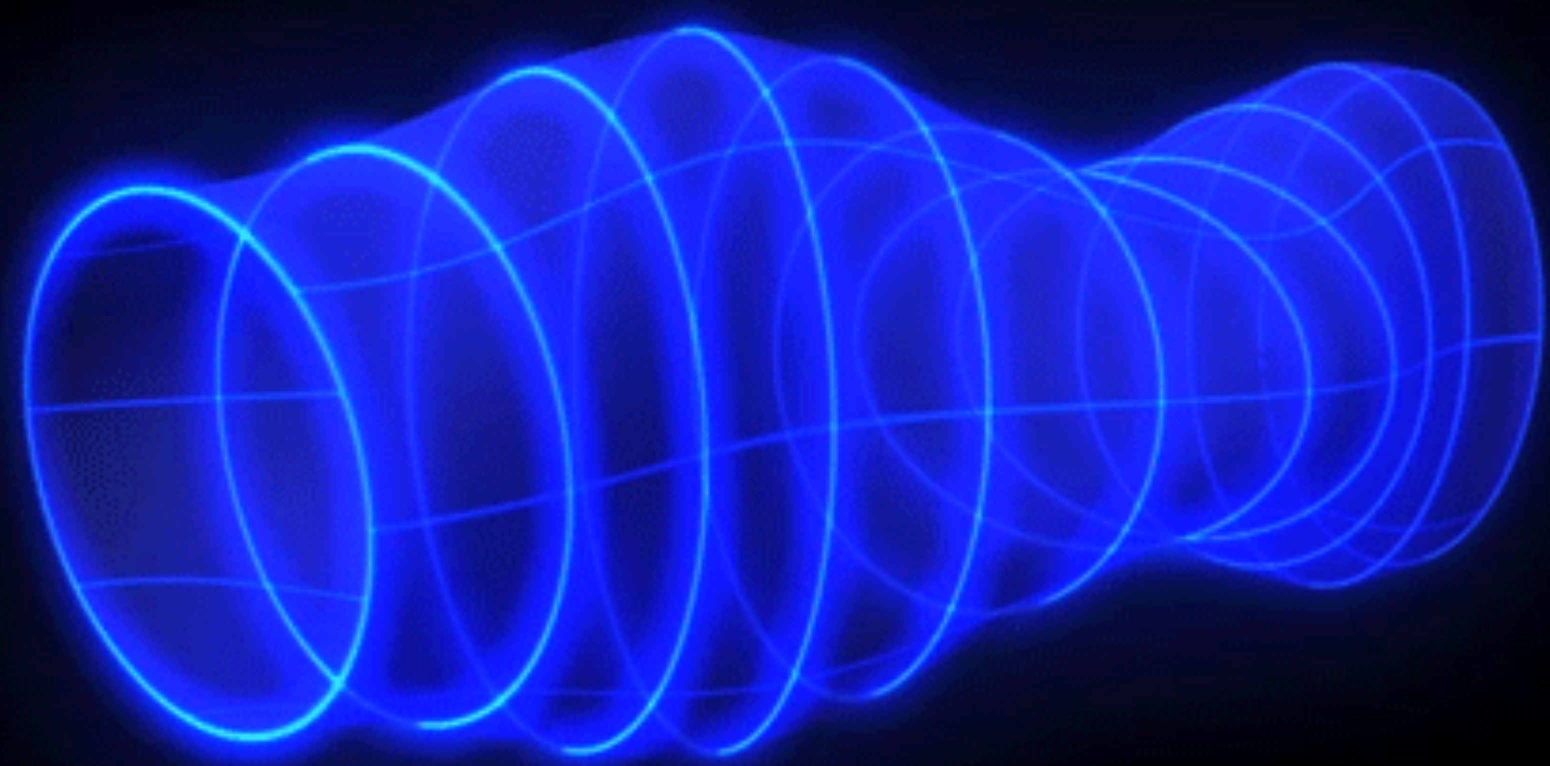


ESA

Gravitational wave propagation

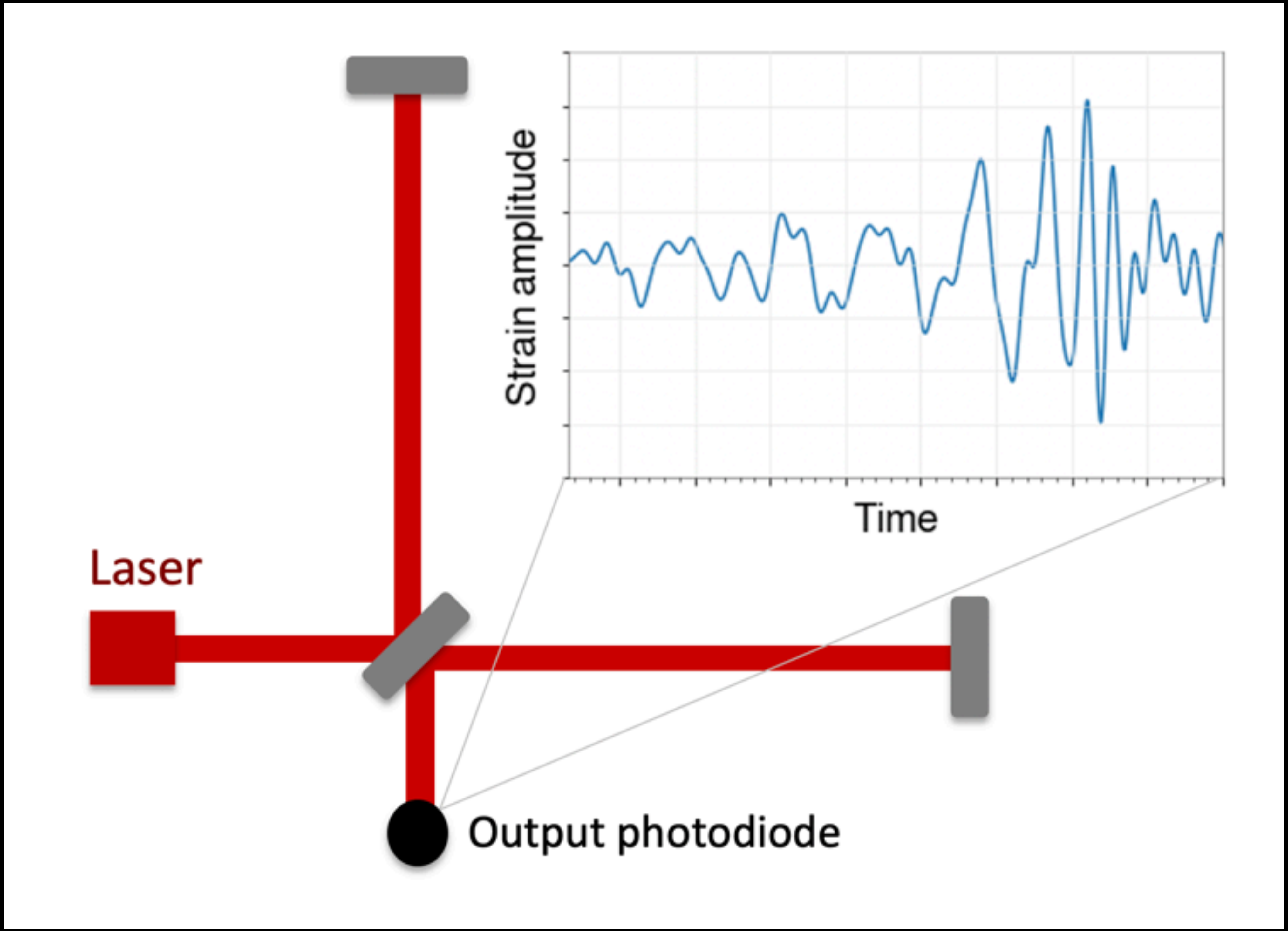






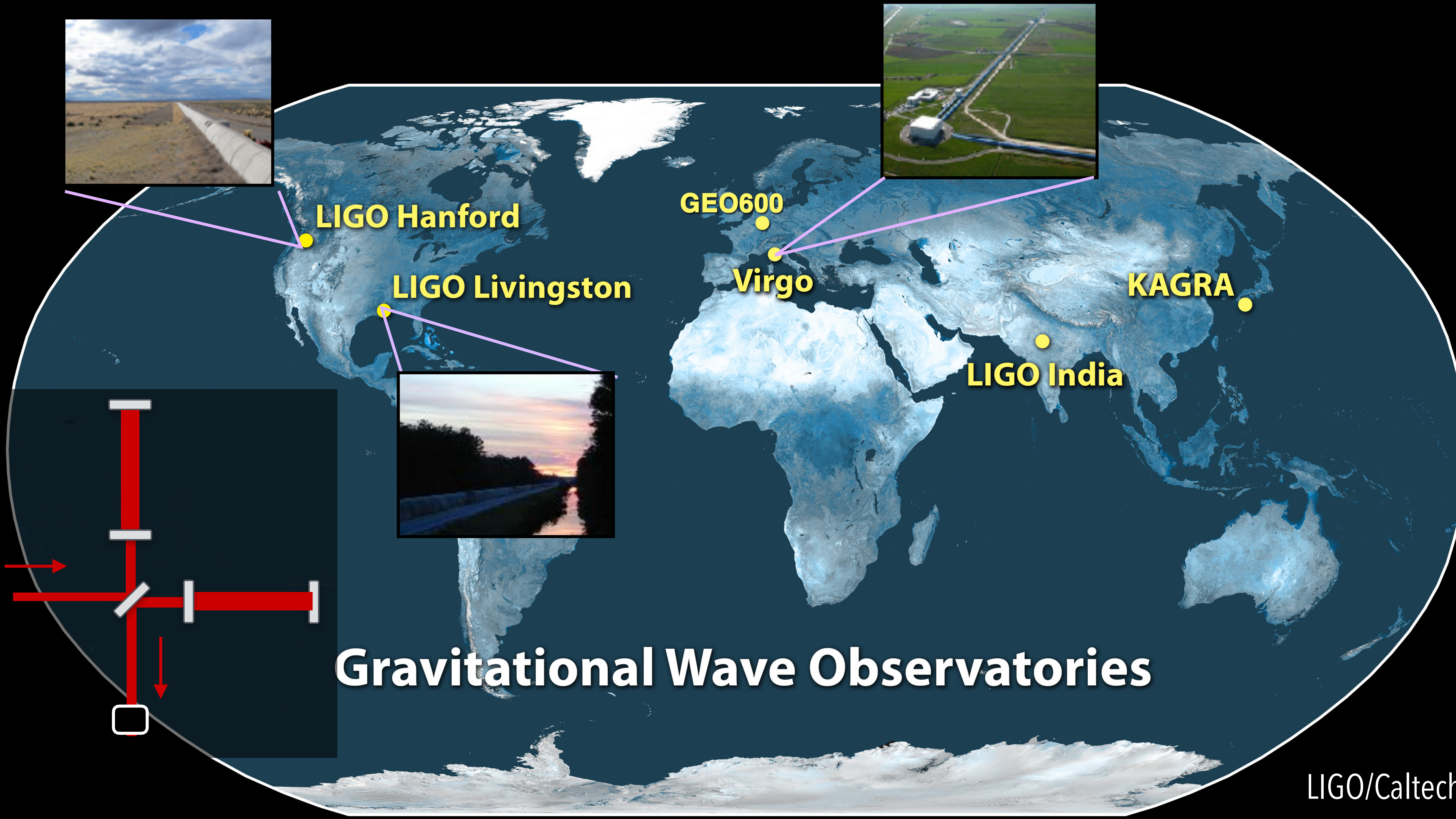
ESA

Observing GWs with interferometry



LIGO DCC P1500072

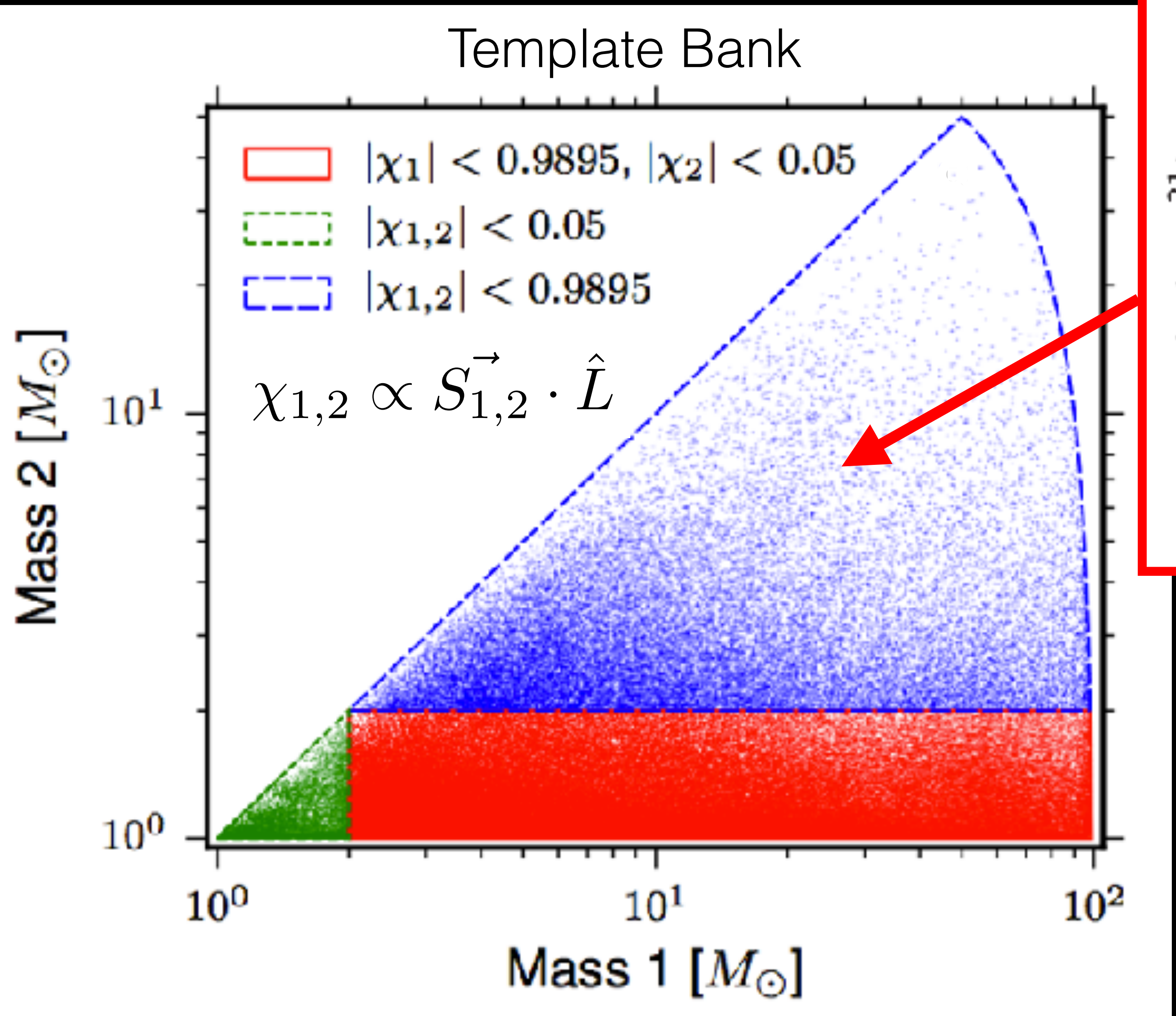
Detector network in O3

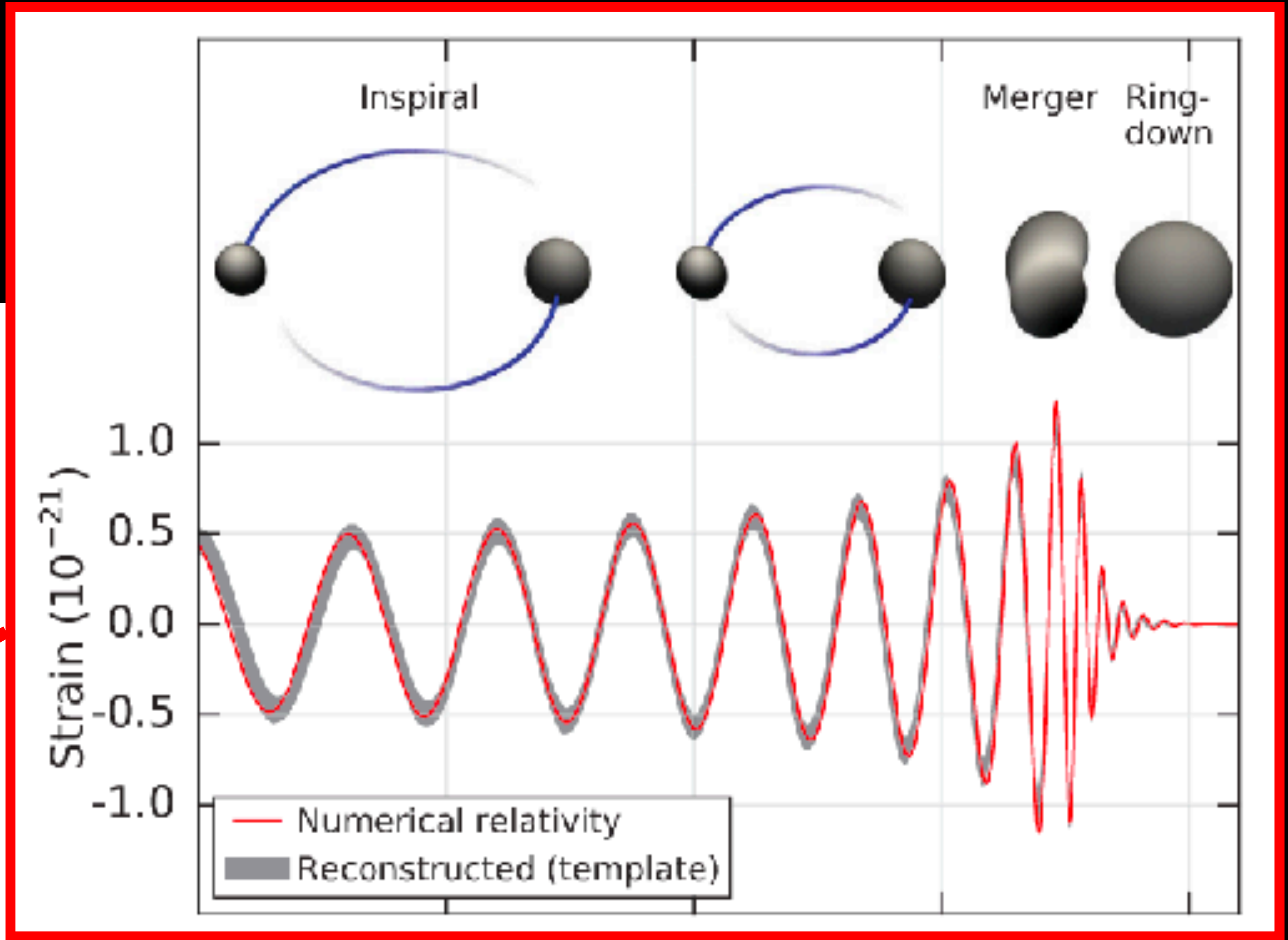


LIGO/Caltech

Searching for signals with matched filtering

Slide adapted from S. Caudill and M. Cabero Mueller





B.P Abbott et al., Phys. Rev. Lett. 116, 061102 (2016)

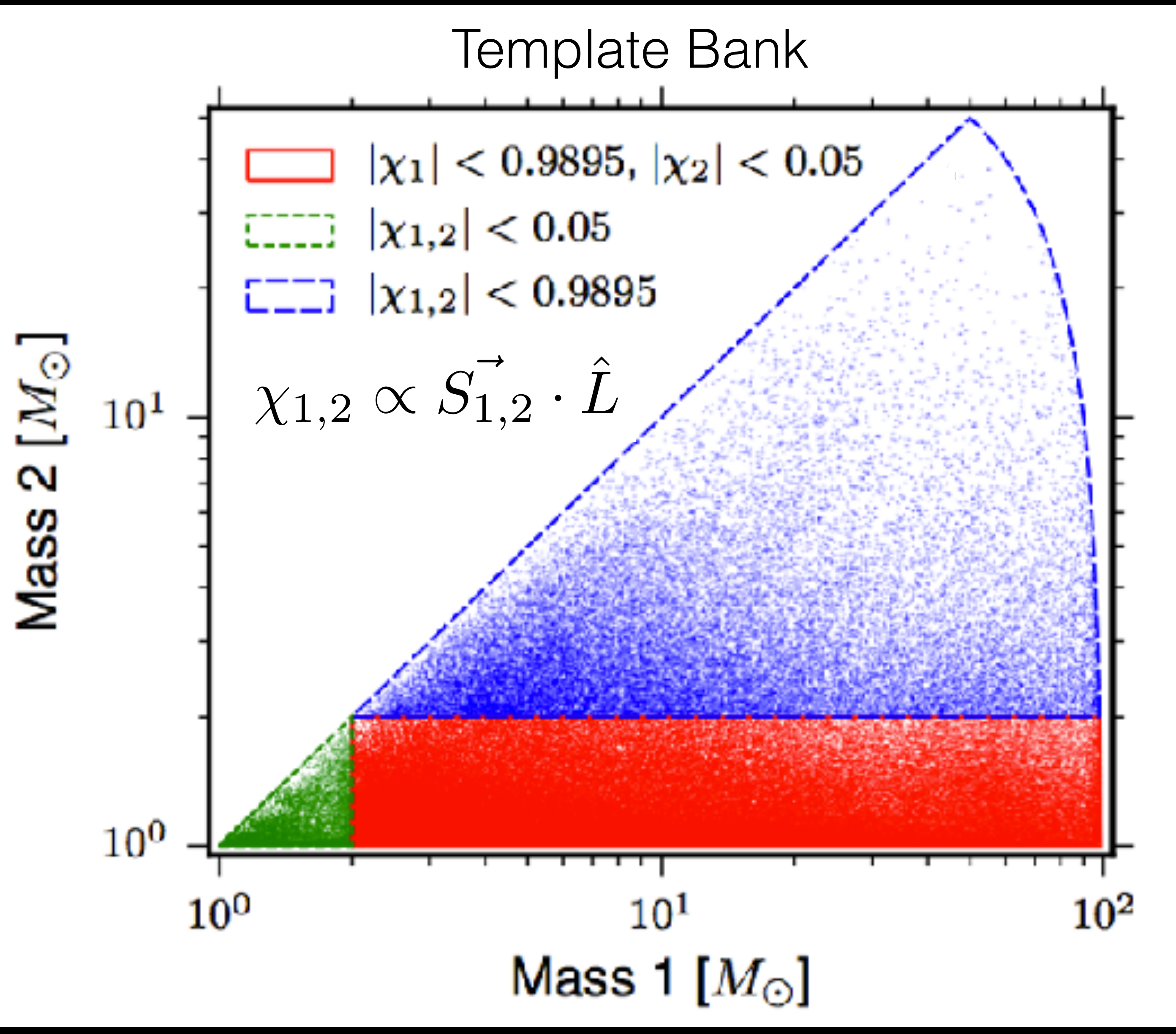
B. P. Abbott et al. Phys. Rev. X (2016)

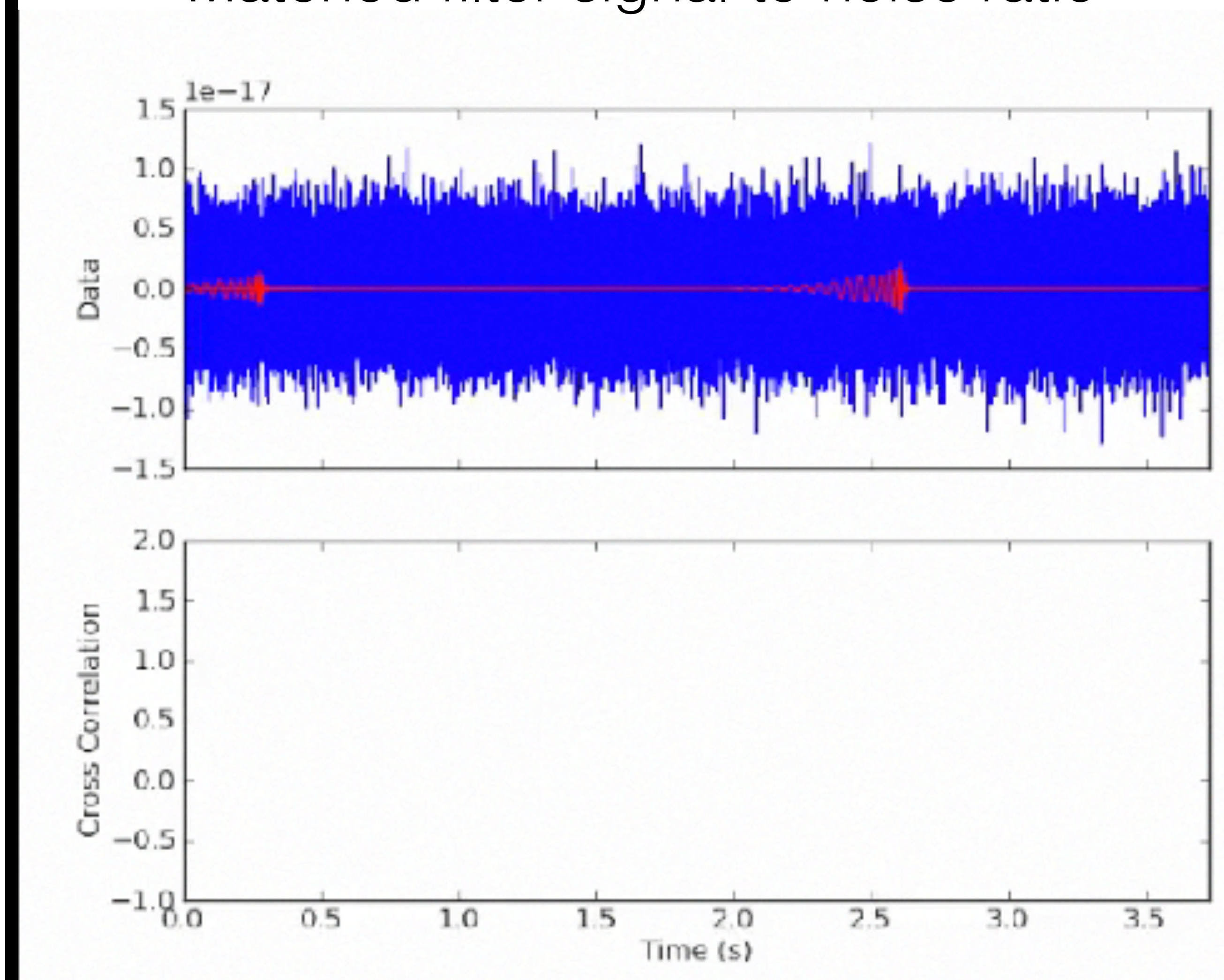
Searching for signals with matched filtering

Slide adapted from S. Caudill

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

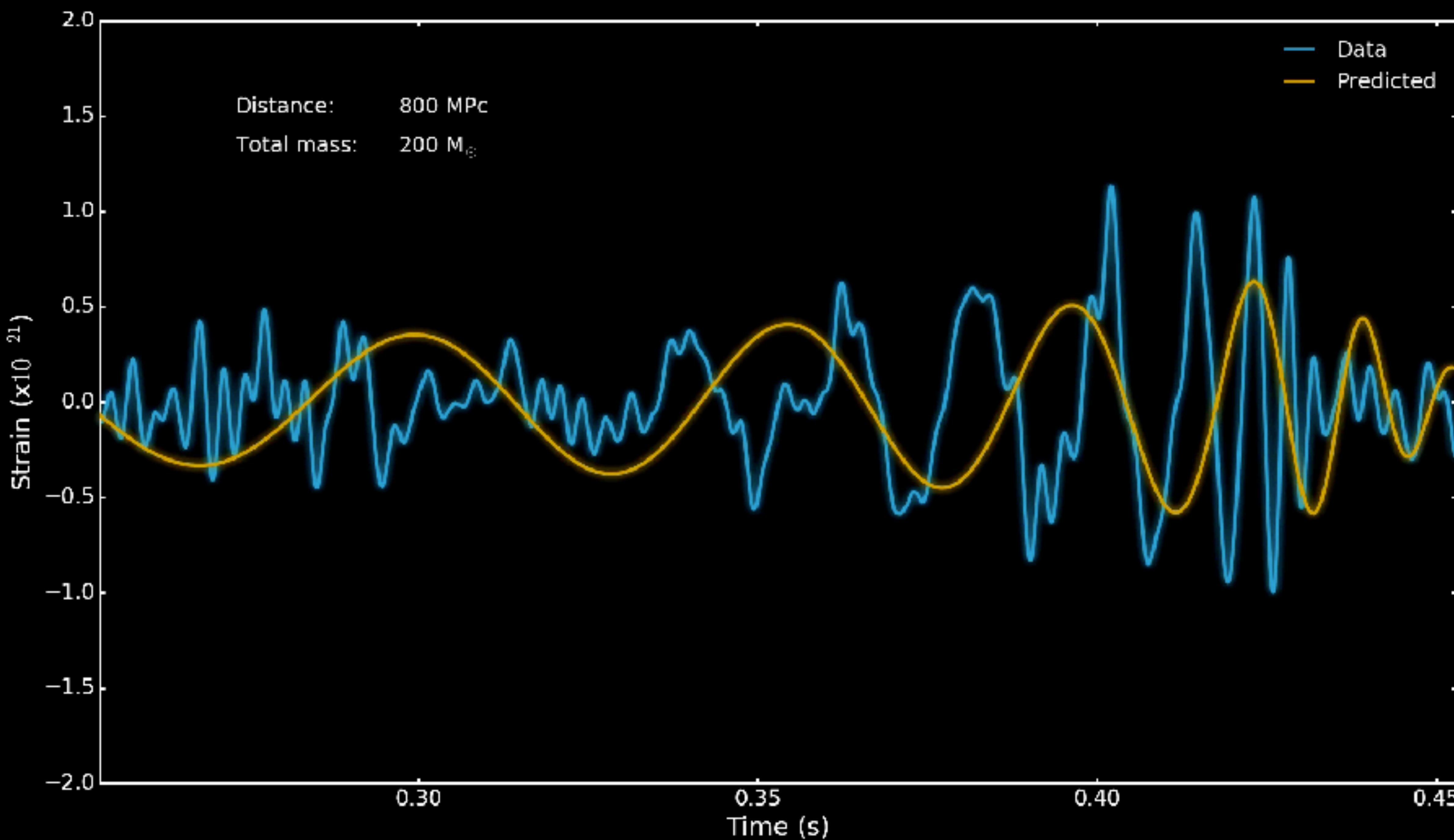
$$\langle s|h \rangle = 4\mathrm{Re} \int_0^\infty \frac{\tilde{s}(f)\tilde{h}^*(f)}{S_n(f)} e^{2\pi i f t} df$$





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

Inferring mass and distance



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

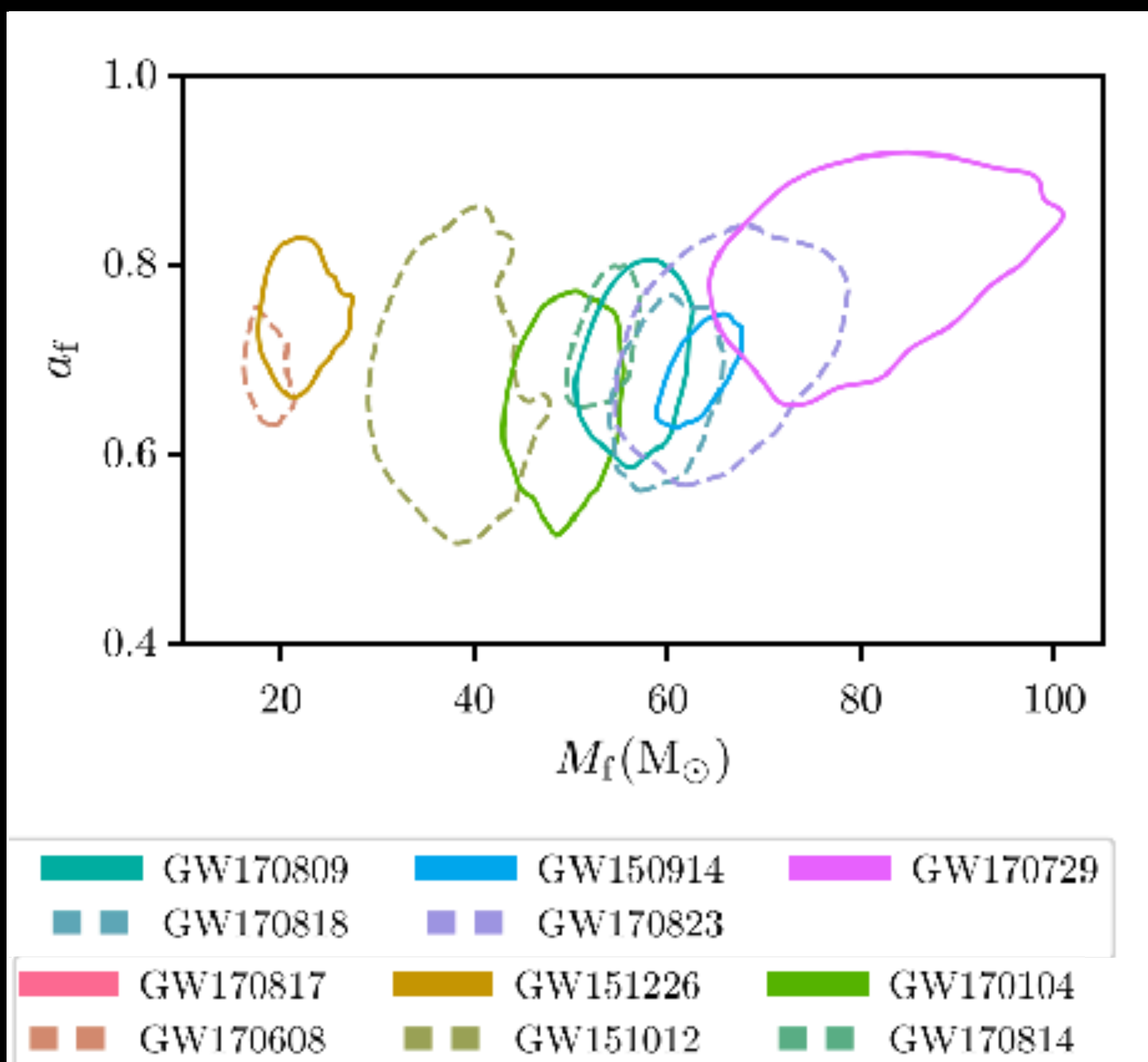
Bayesian inference of source properties

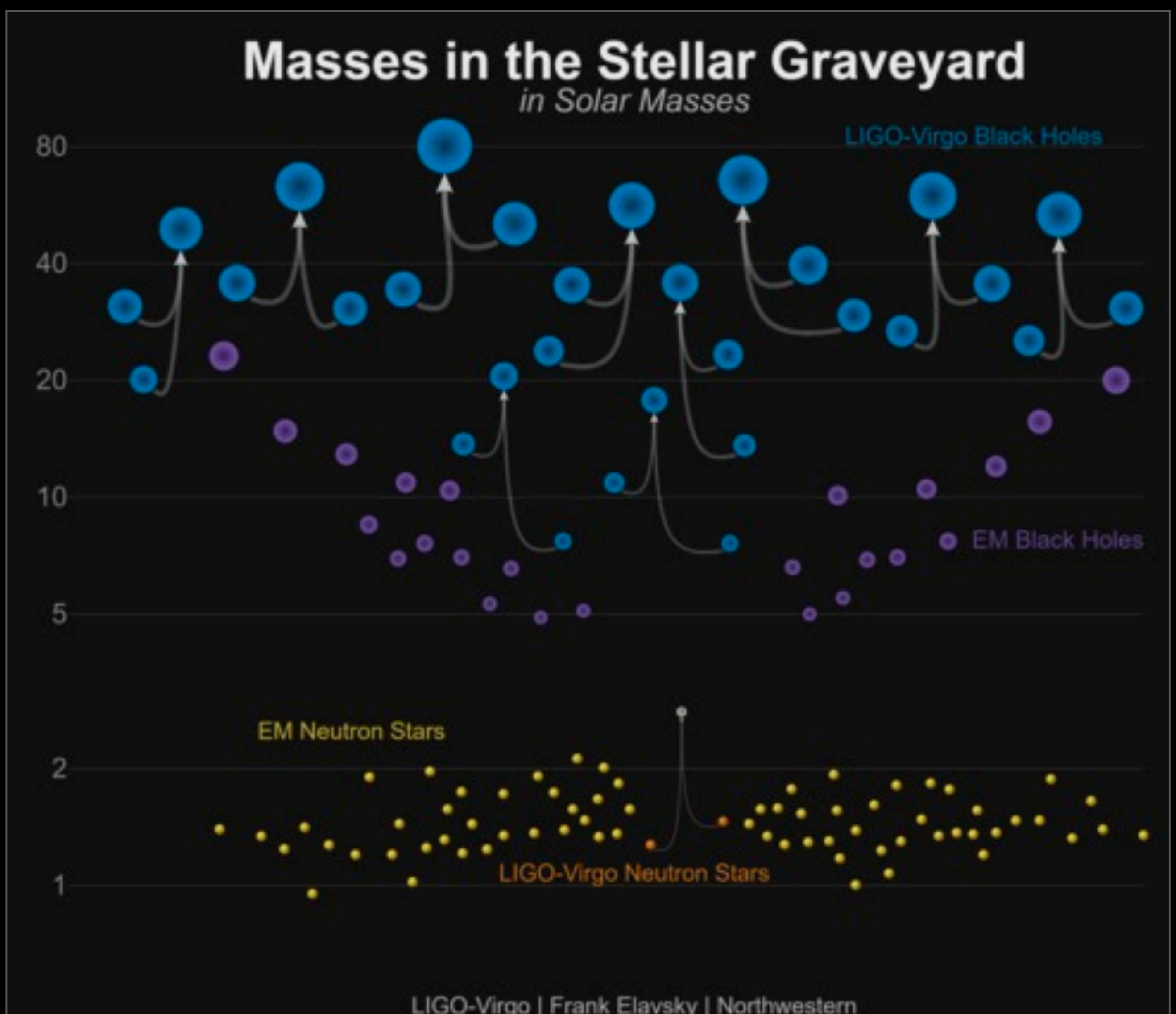
$$\boldsymbol{d} = \boldsymbol{h} + \boldsymbol{n}.$$

← Data model d = signal (through lens of detector network) h + detector noise n

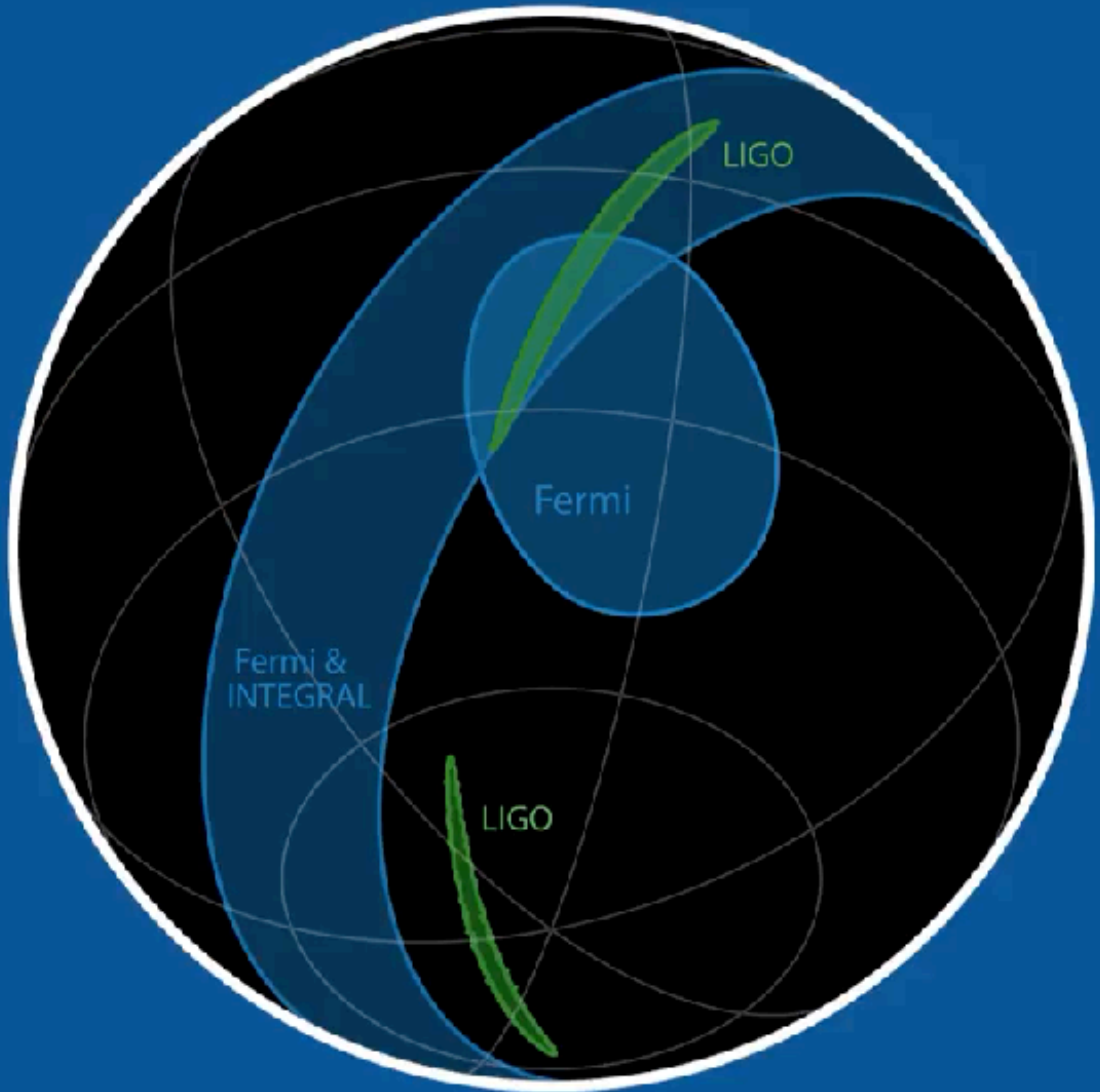
$$p(\boldsymbol{d}|H_N, S_n(f)) = \exp \sum_i \left[-\frac{2|\tilde{d}_i|^2}{TS_n(f_i)} - \frac{1}{2}\log(\pi T S_n(f_i)/2) \right]$$

← Likelihood: expect the residual of d-h to be consistent with Gaussian noise

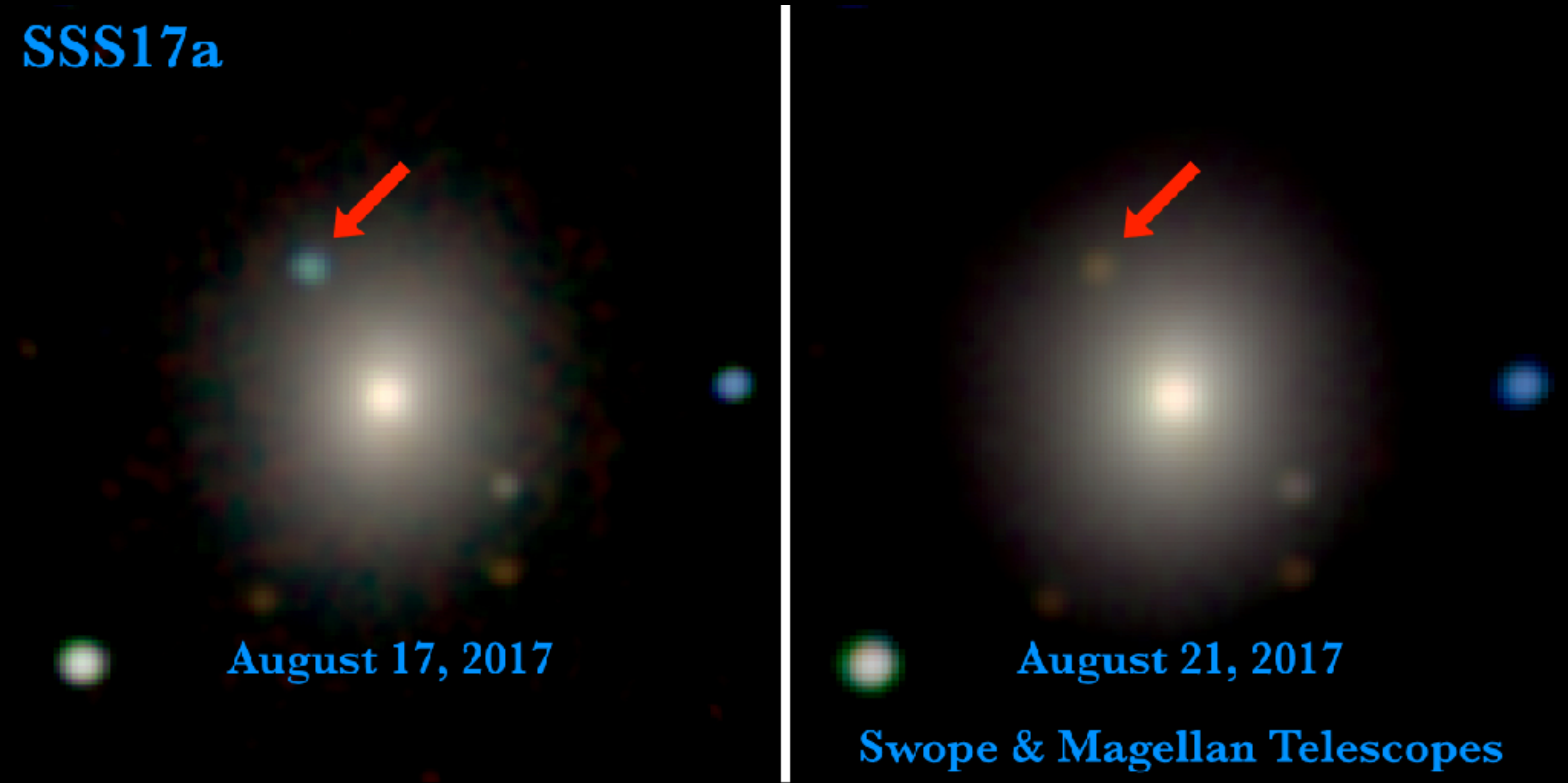




Sky localization with GWs



Discovery of an optical counterpart

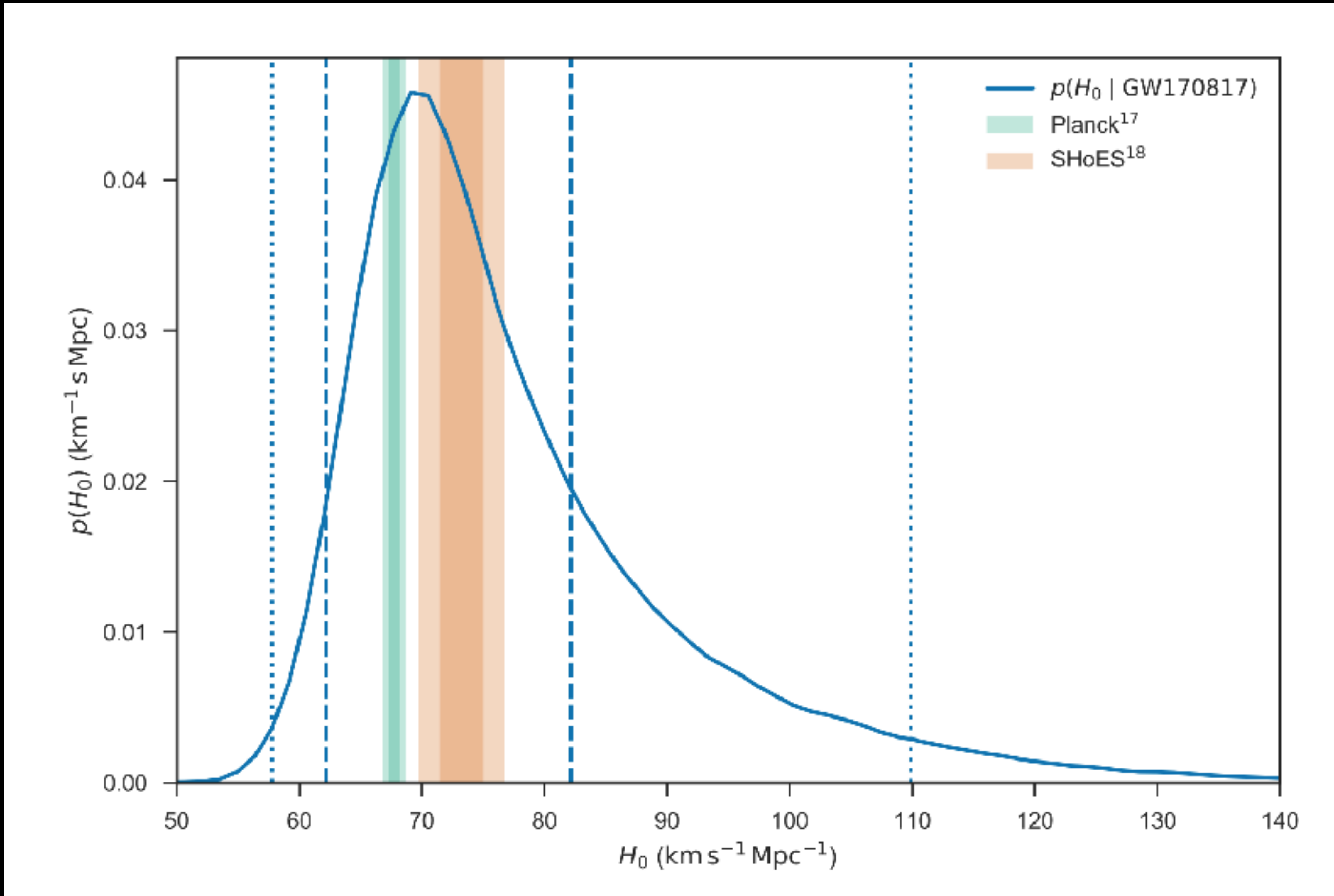


D. Coulter et al. 2017 arXiv 1710.05452
Image: 1M2H/UC Santa Cruz and Carnegie Observatories/Ryan Foley

The first multi-messenger discovery with GWs

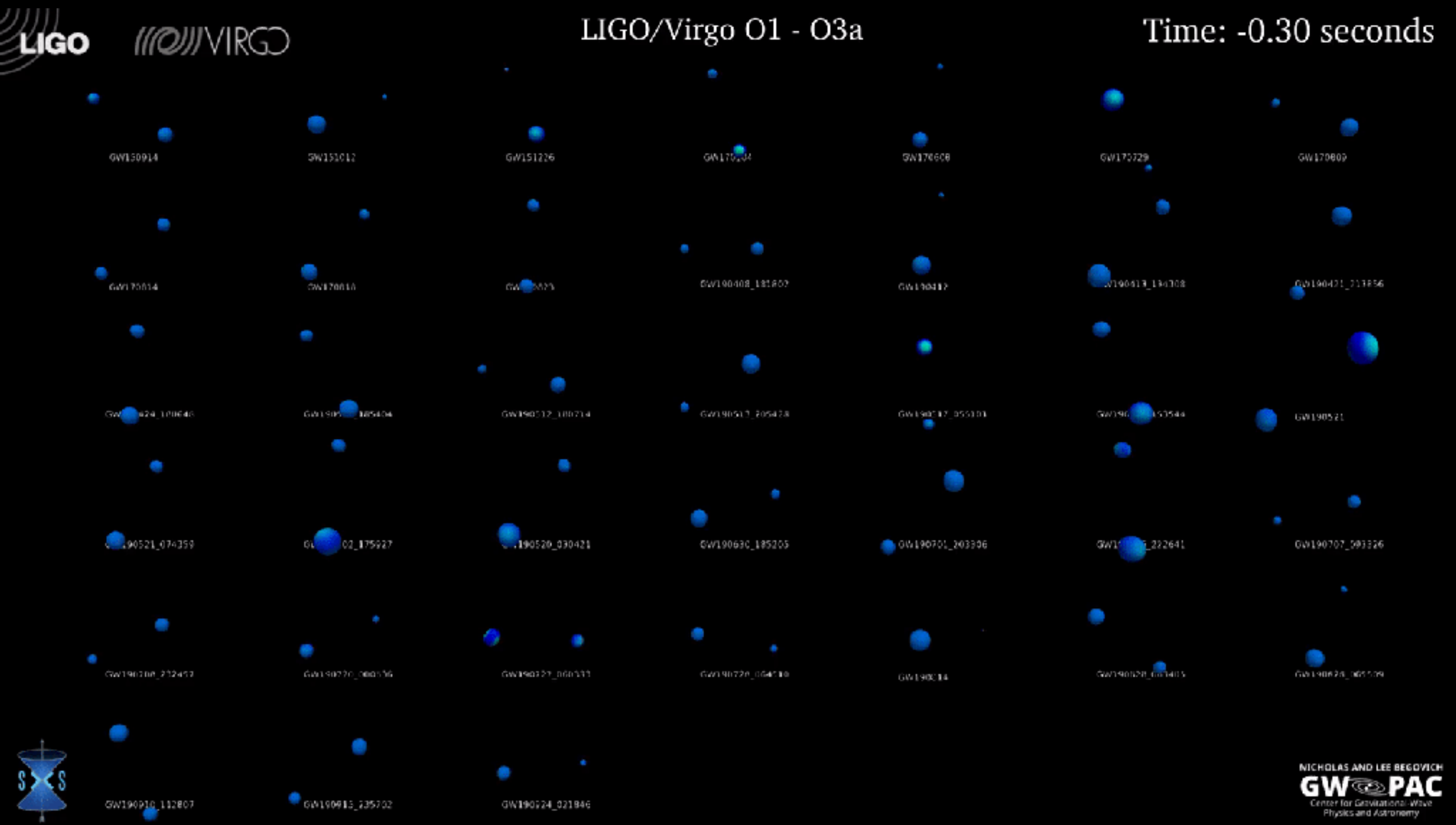
NASA/Goddard Space Flight Center/CI Lab

Cosmology with GWs



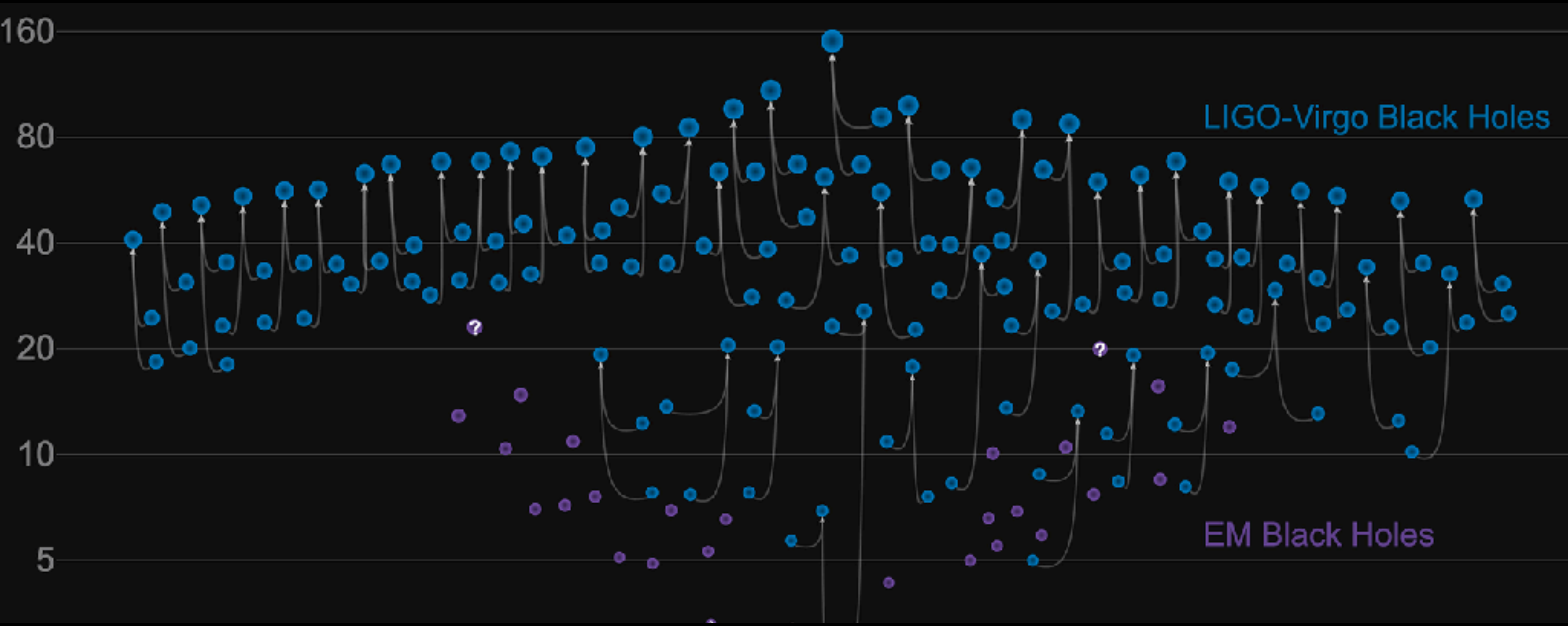
B.P. Abbott et al. Nature (2017)

The GW Orrery: what we've observed



BH masses from the first half of O3

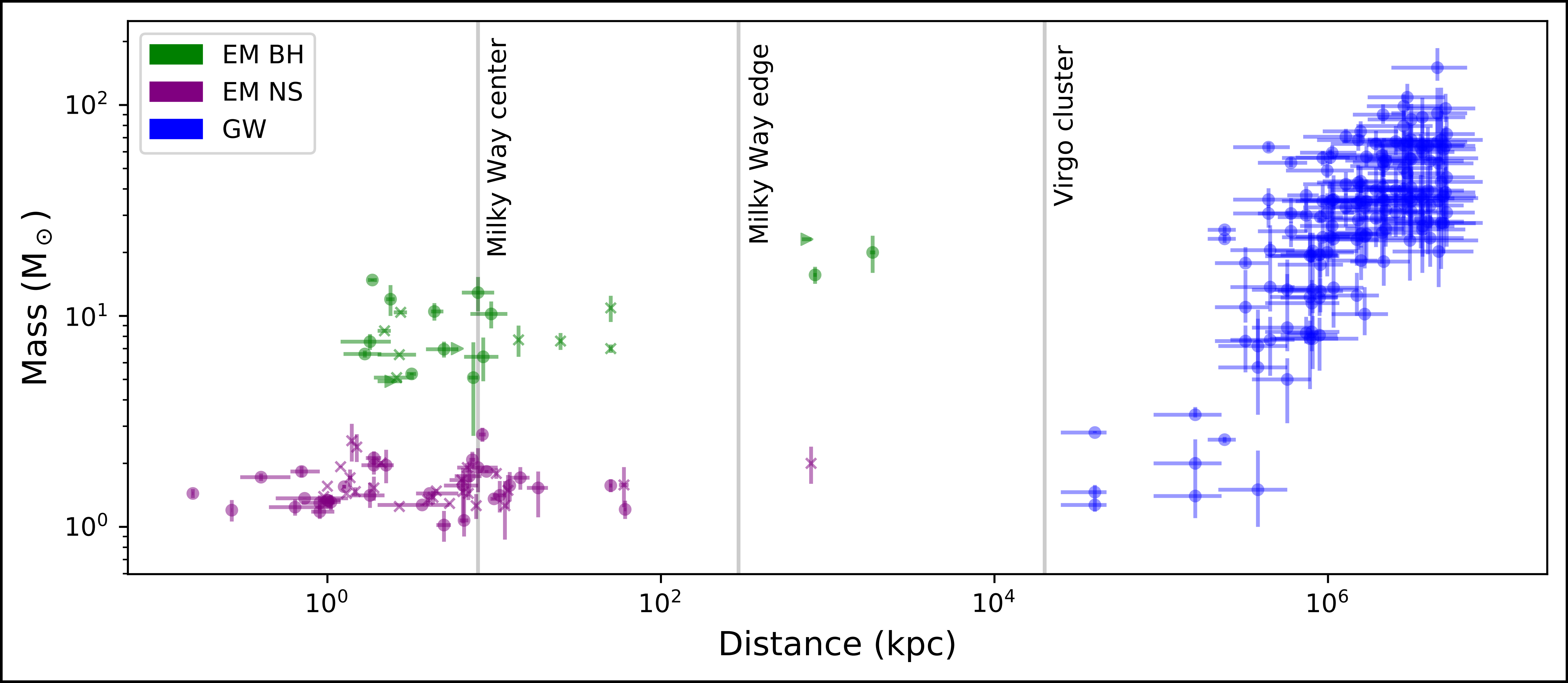
April 2019 - March 2020: Advanced LIGO and Advanced Virgo's third observing run (O3)



GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

GWs and the 'stellar graveyard'

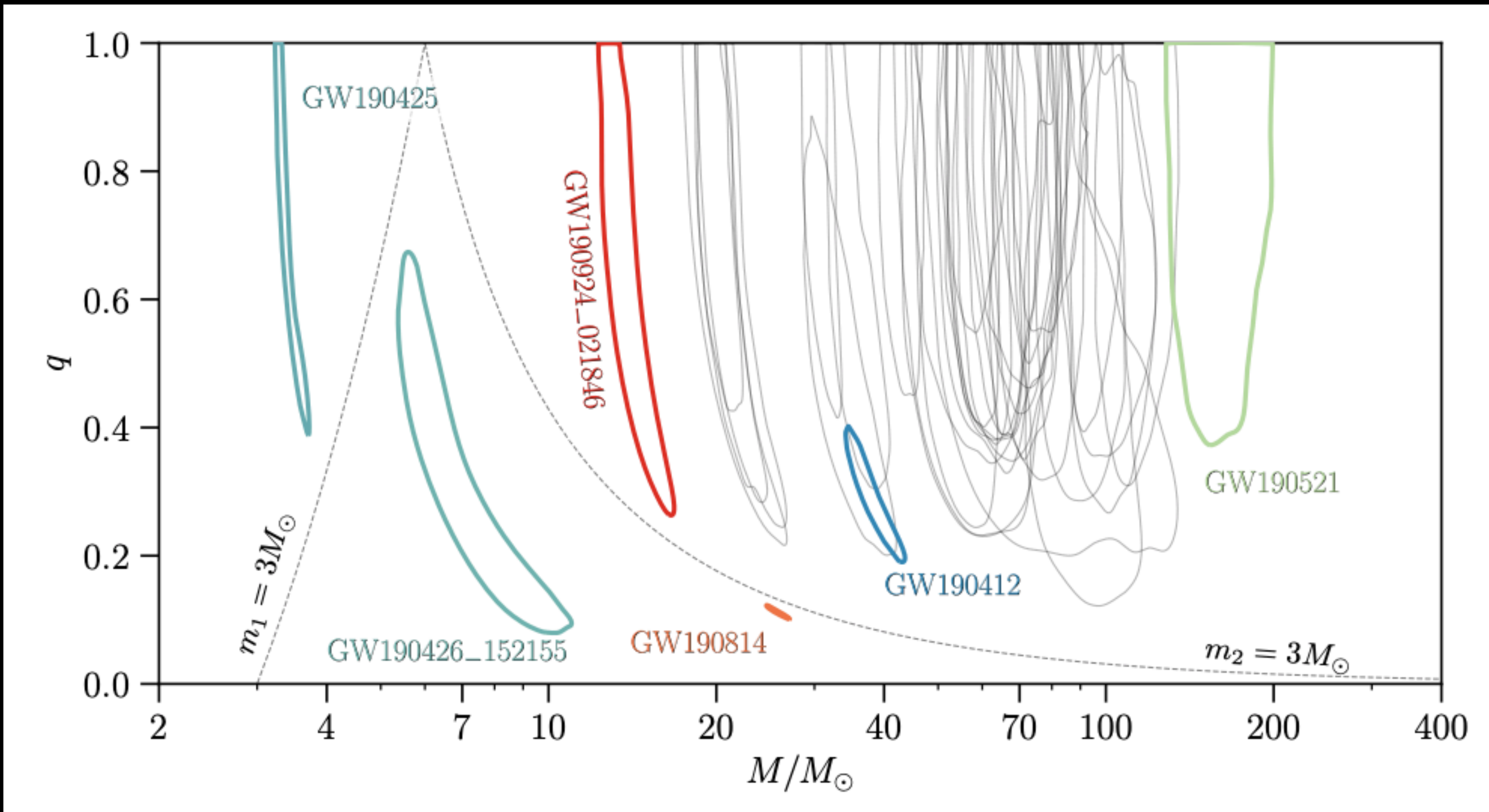
Known compact object masses vs. estimated distance



McIver and Shoemaker, in prep.

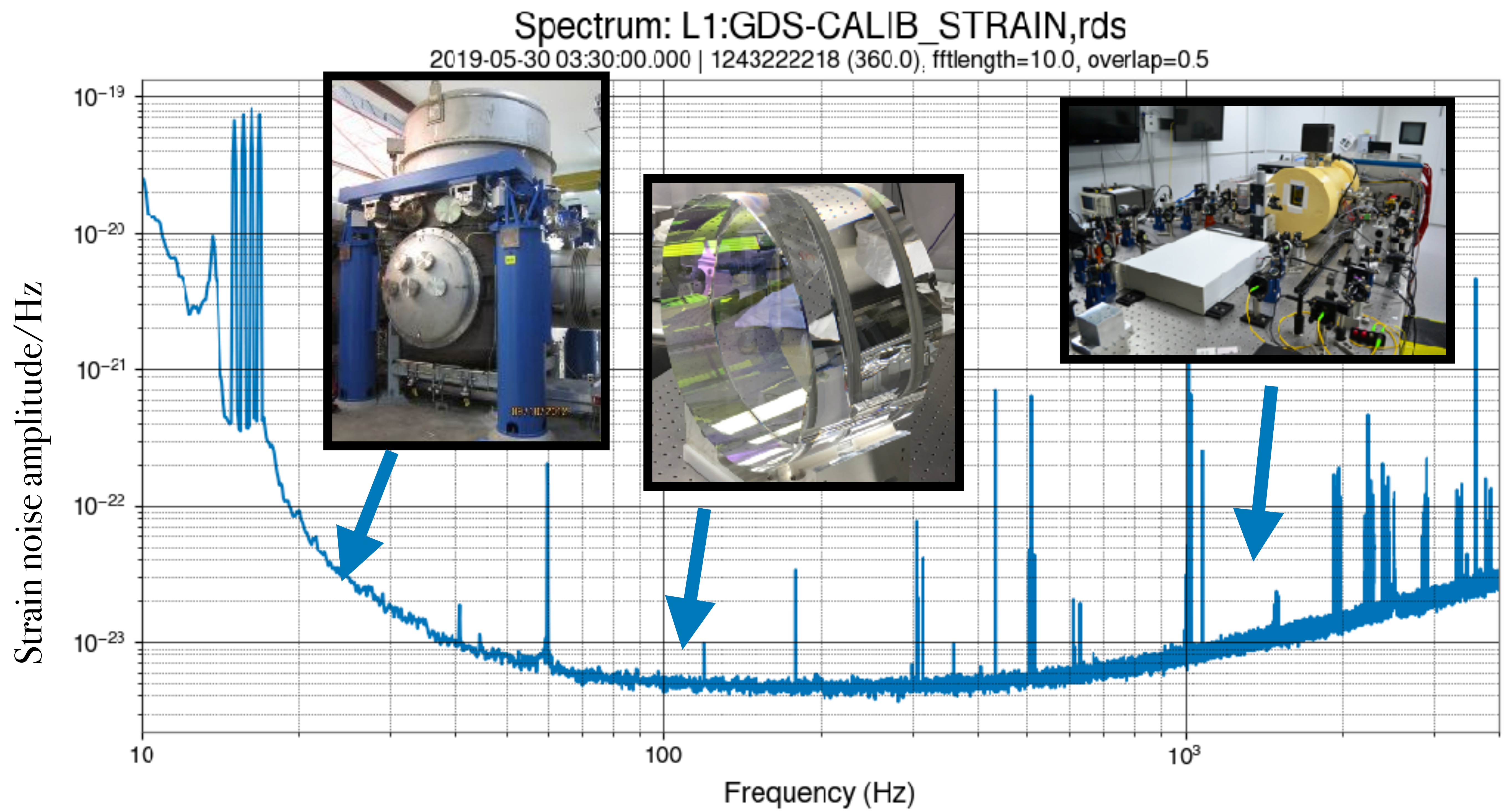
GWTC-2: estimating source properties

Results from LIGO-Virgo O3a: April-October 2019



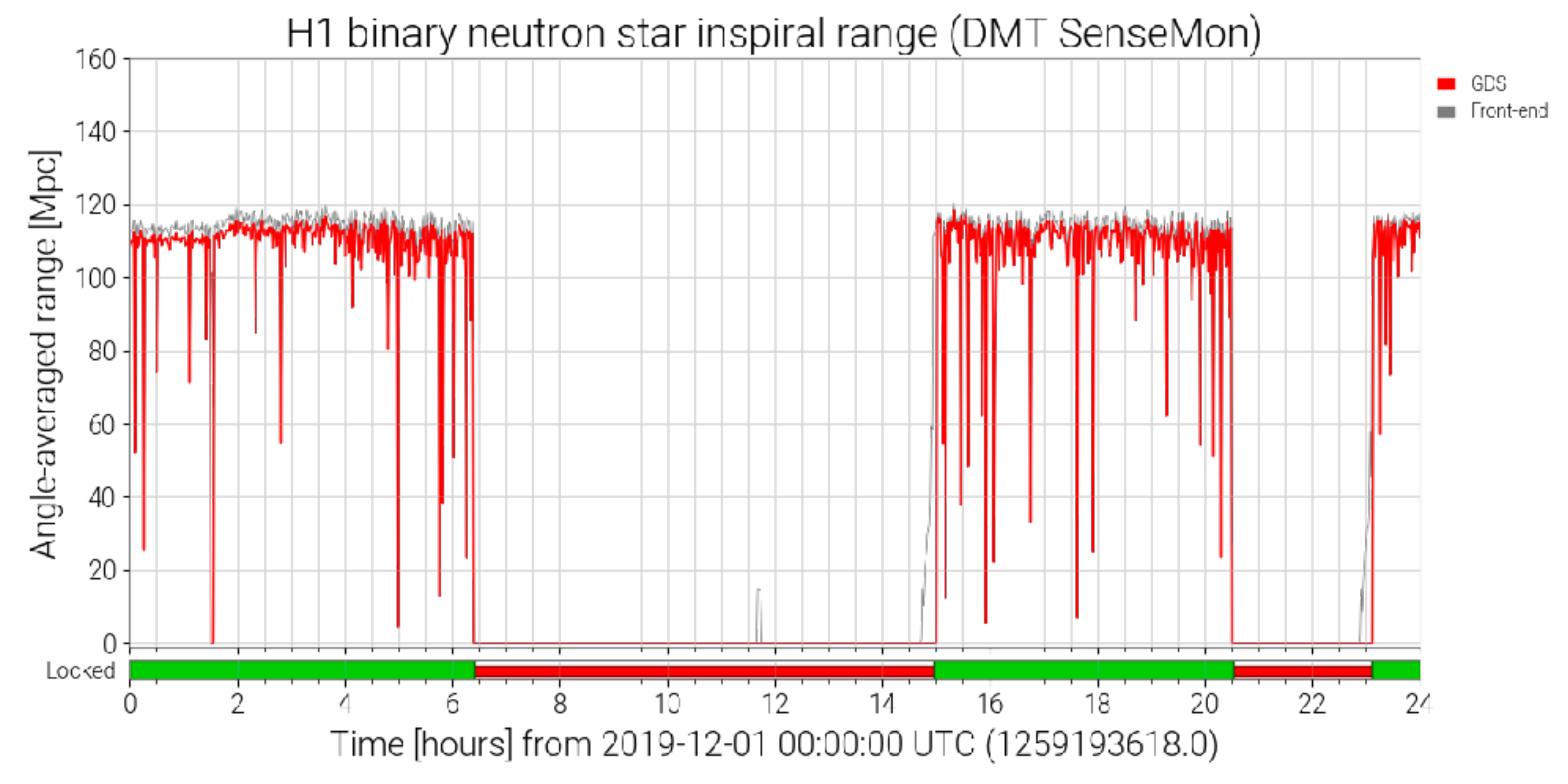
R Abbott et al. arXiv 2010.14527 (2020)

Advanced LIGO noise



Made with ligoDV web: https://ldvw.ligo.caltech.edu/ldvw/view

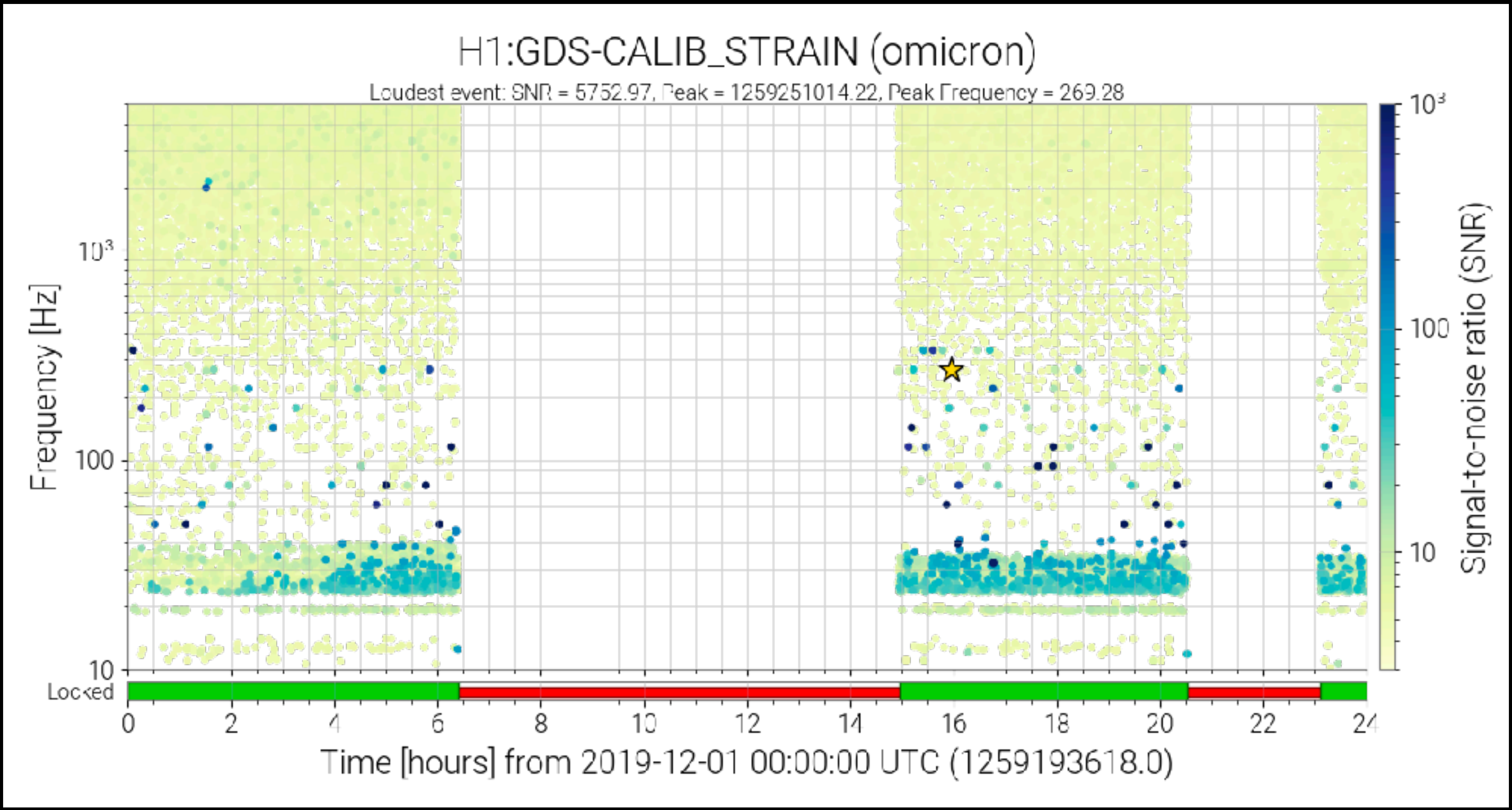
GW detector sensitivity



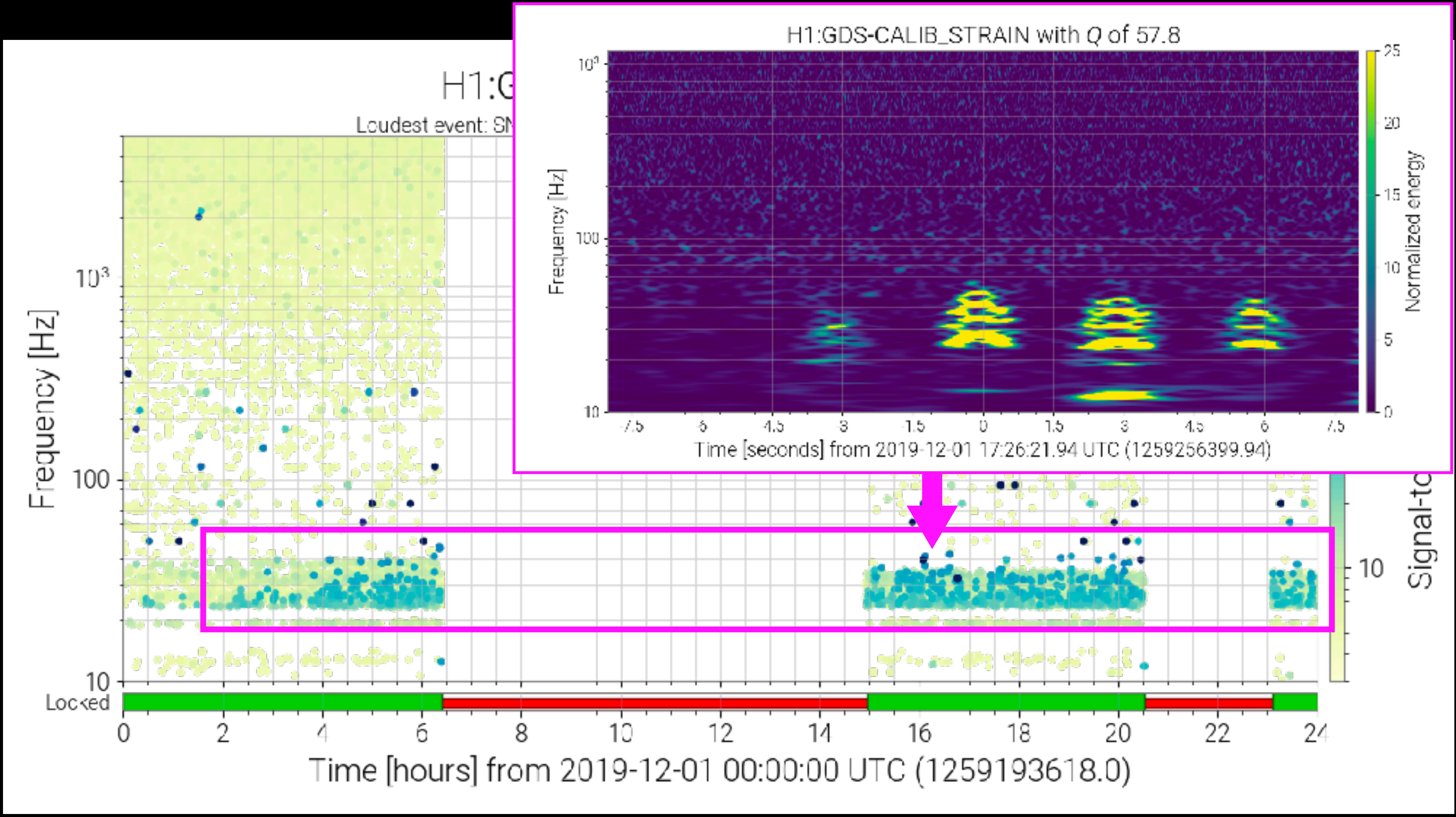
BNS inspiral range = given the PSD of the (average) noise, the distance at which we'd detect a 1.4-1.4 M_sol BNS with an SNR of 8, averaged over orientation and sky position angles

The LIGO summary pages

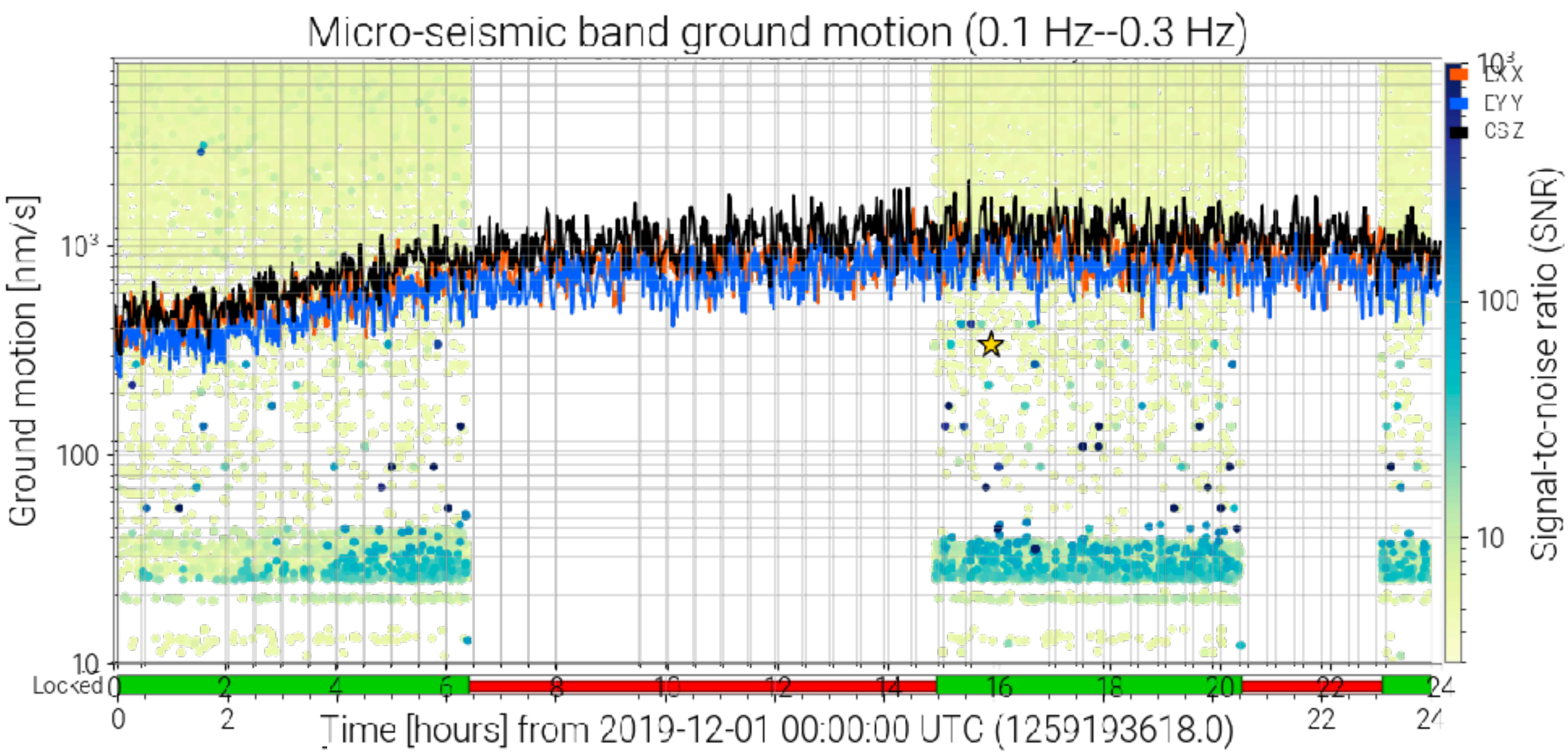
GW detector data: non-stationarity



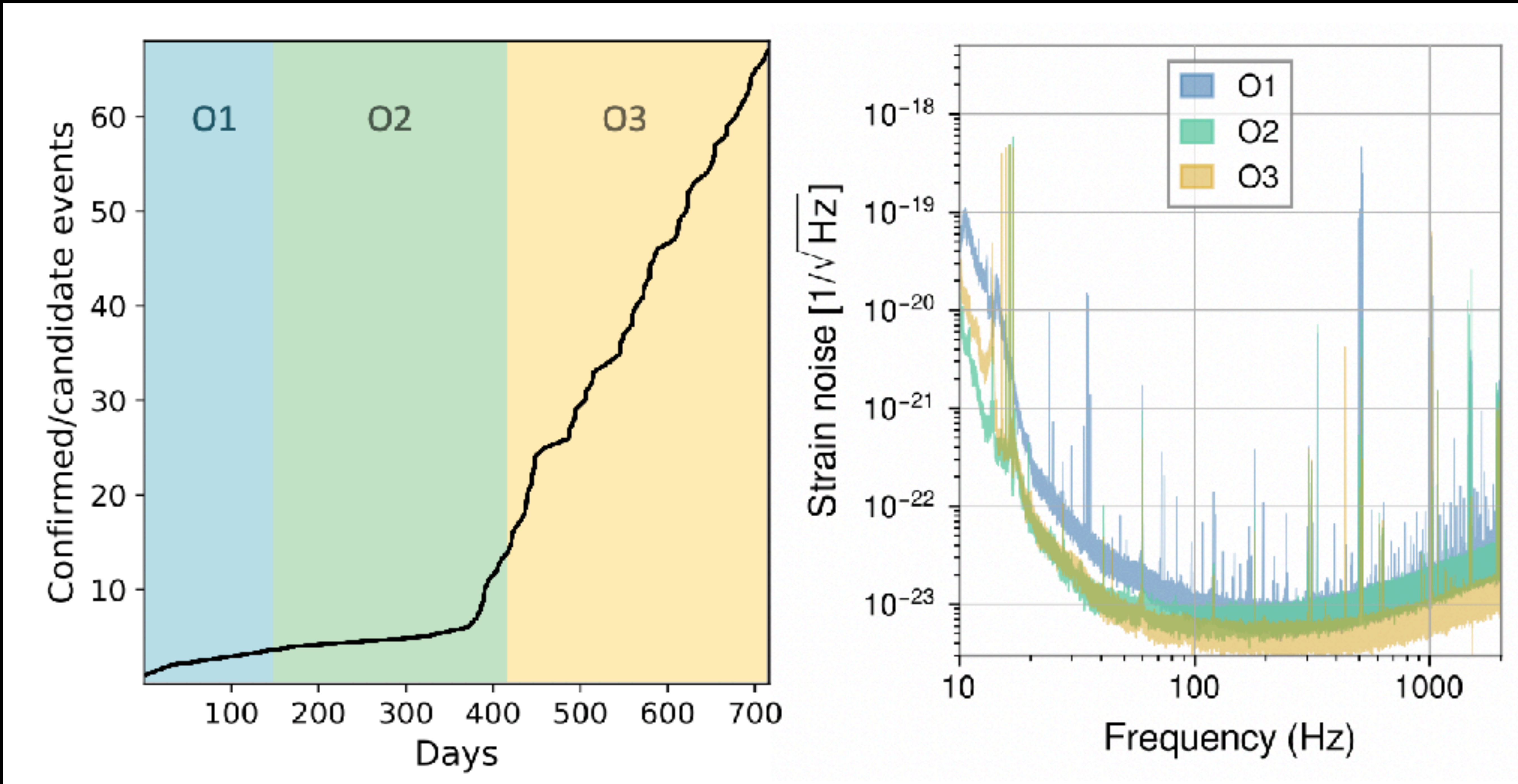
GW detector data: non-stationarity



Key question: what drives non-stationarity?

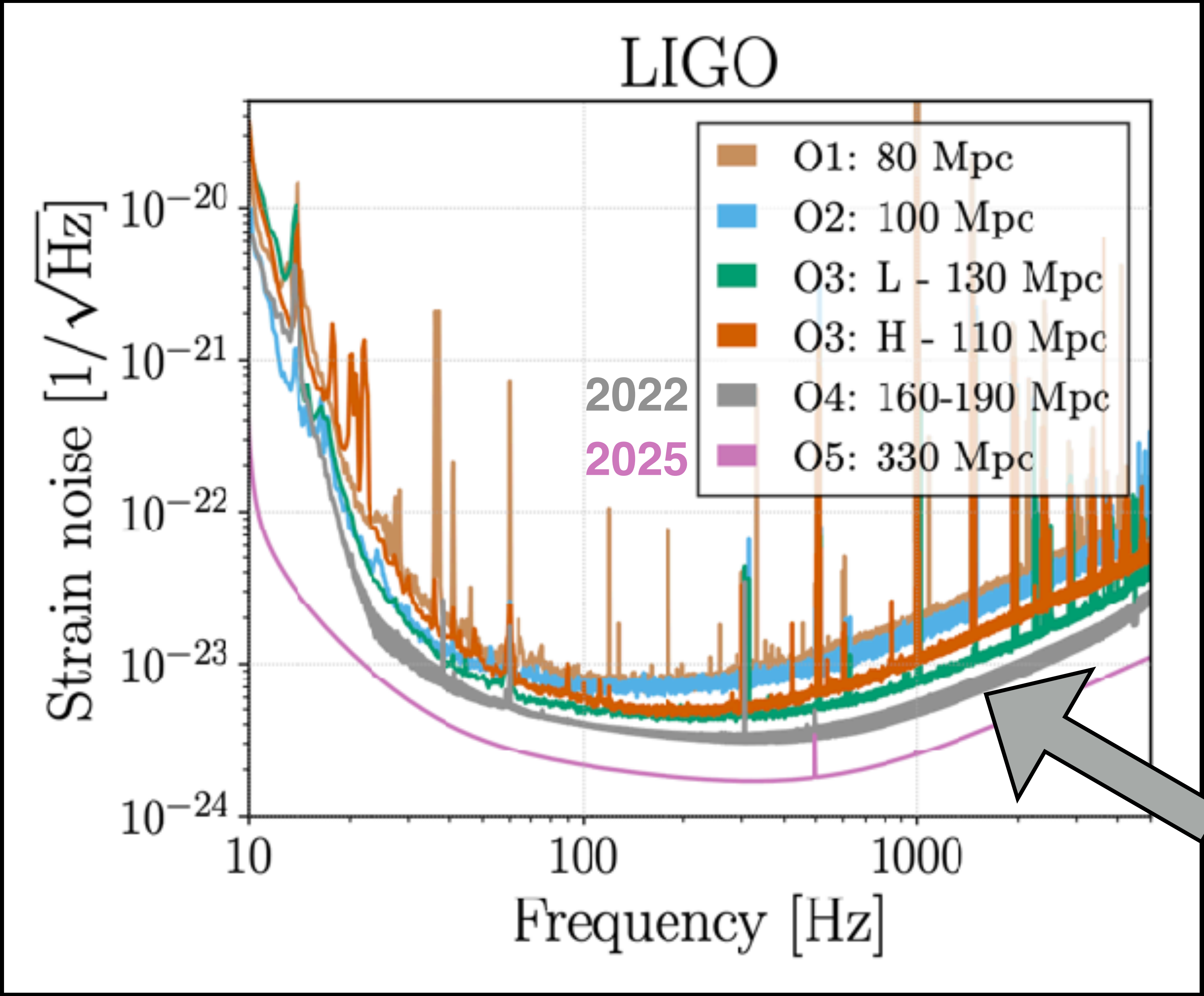


LIGO-Virgo candidate events over time



McIver and Shoemaker, in prep.

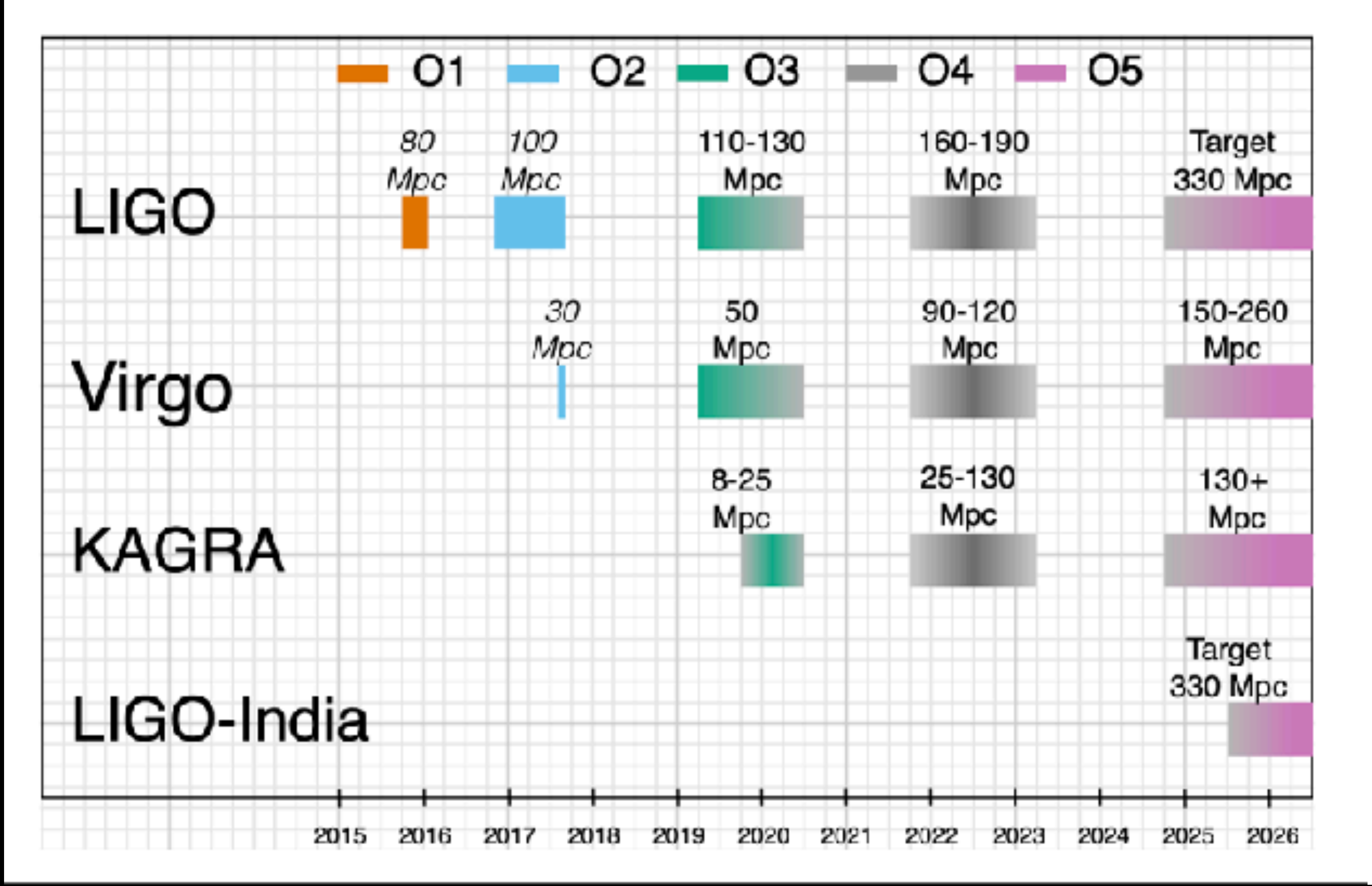
Roadmap to aLIGO design and A+

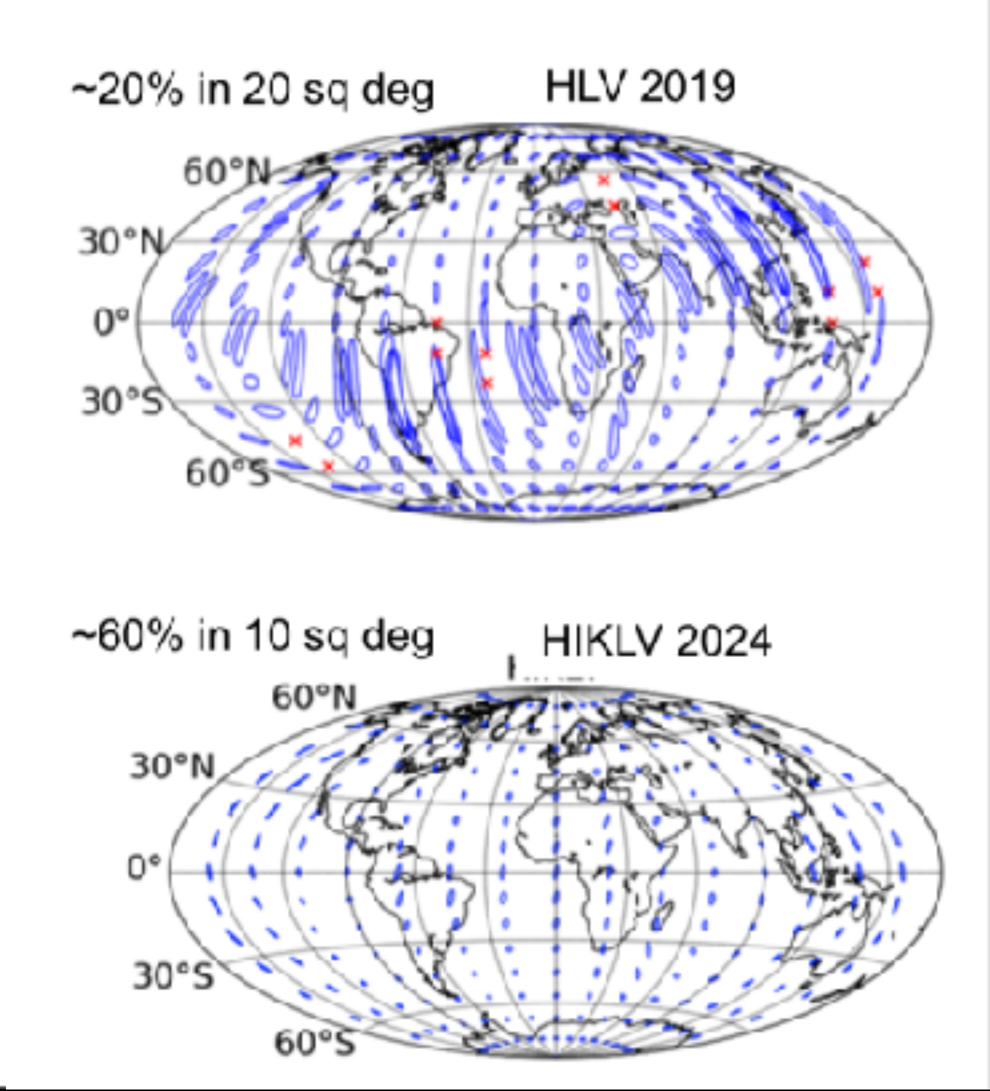


arXiv 1304.0670

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

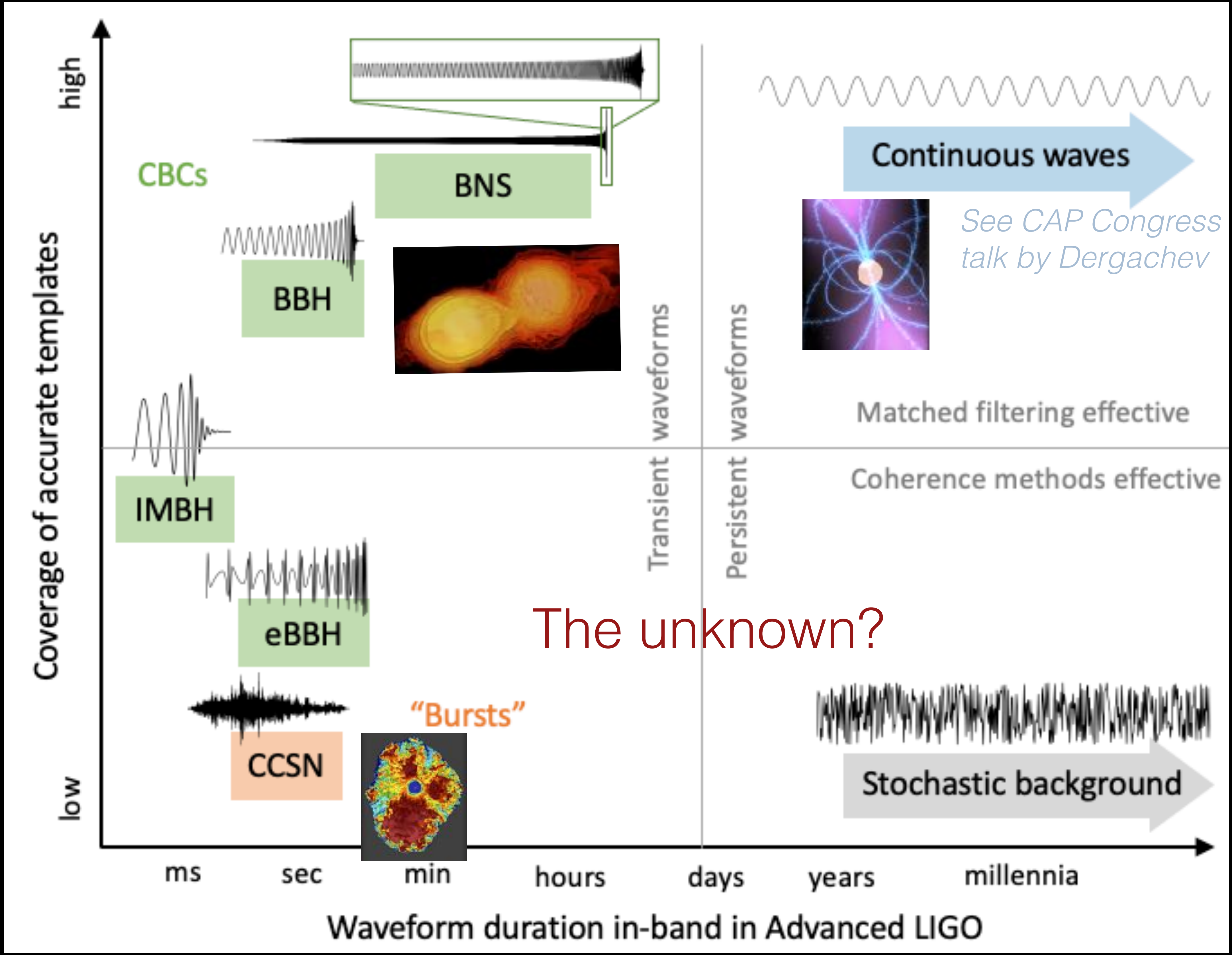
Reaching design sensitivity





arXiv 1304.0670

What else might we detect with current detectors?

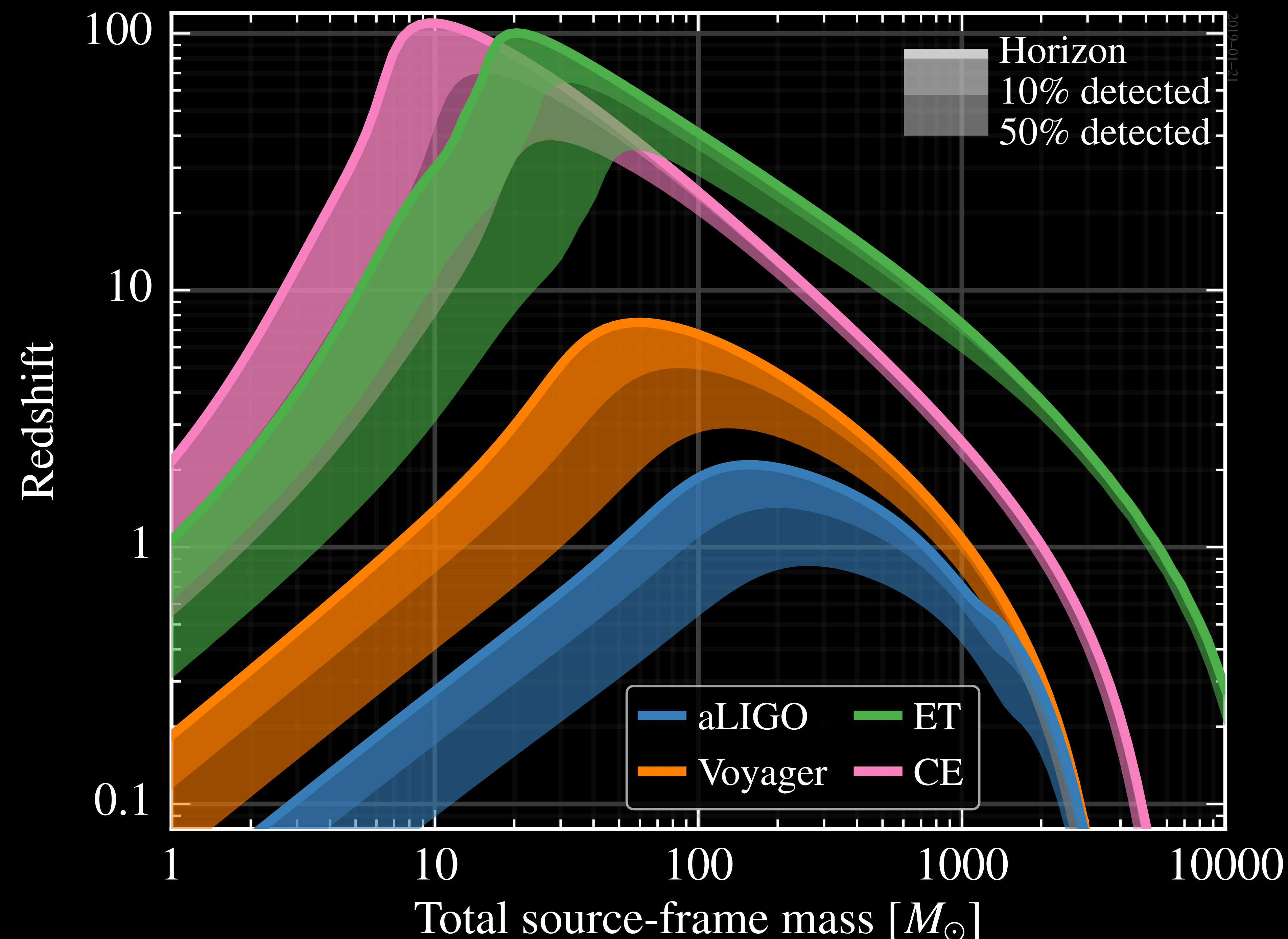


McIver and Shoemaker, CP 2021

LSC

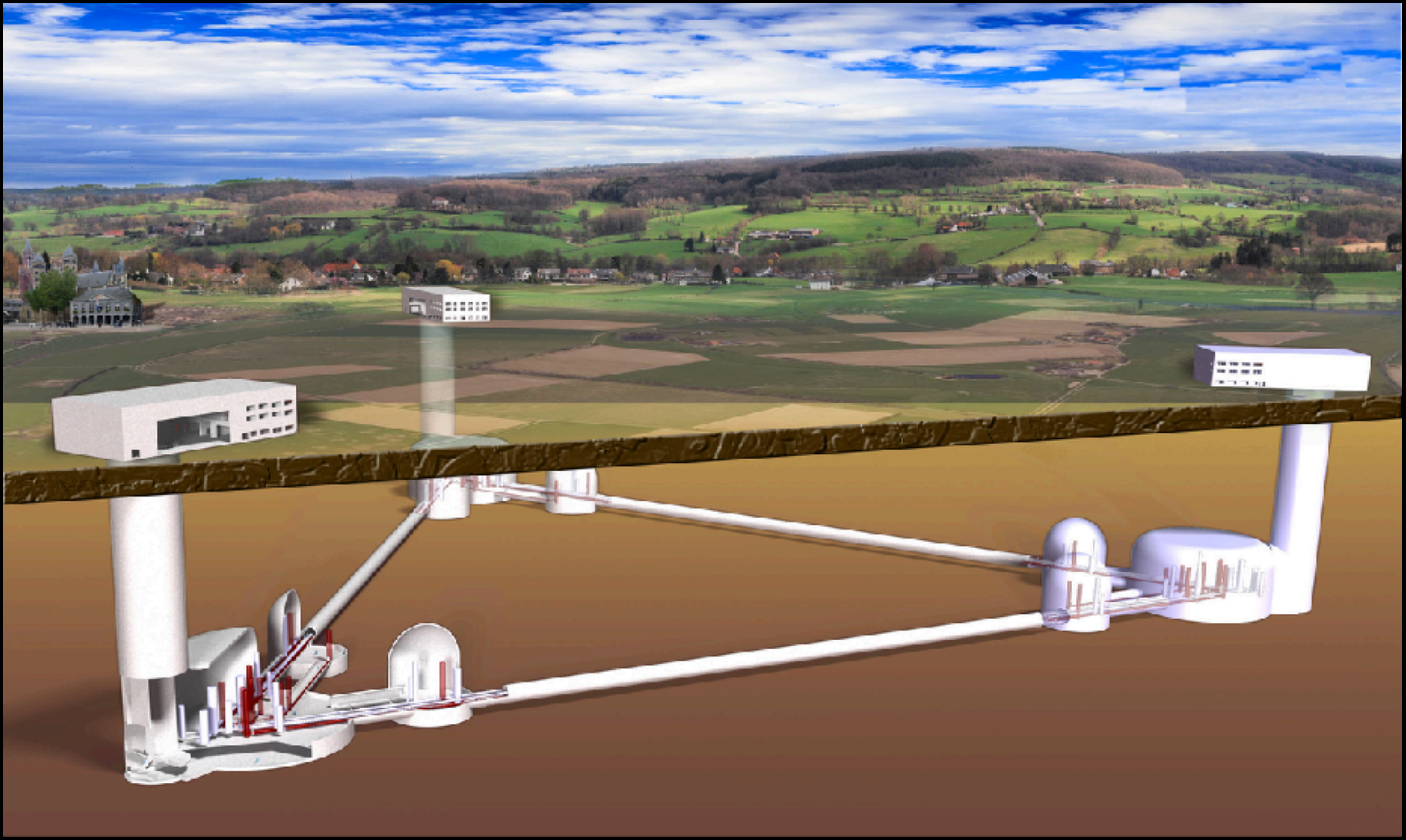
Over **1000** people from **100** institutions and **20** countries worldwide!

Future prospects for terrestrial gravitational wave astronomy

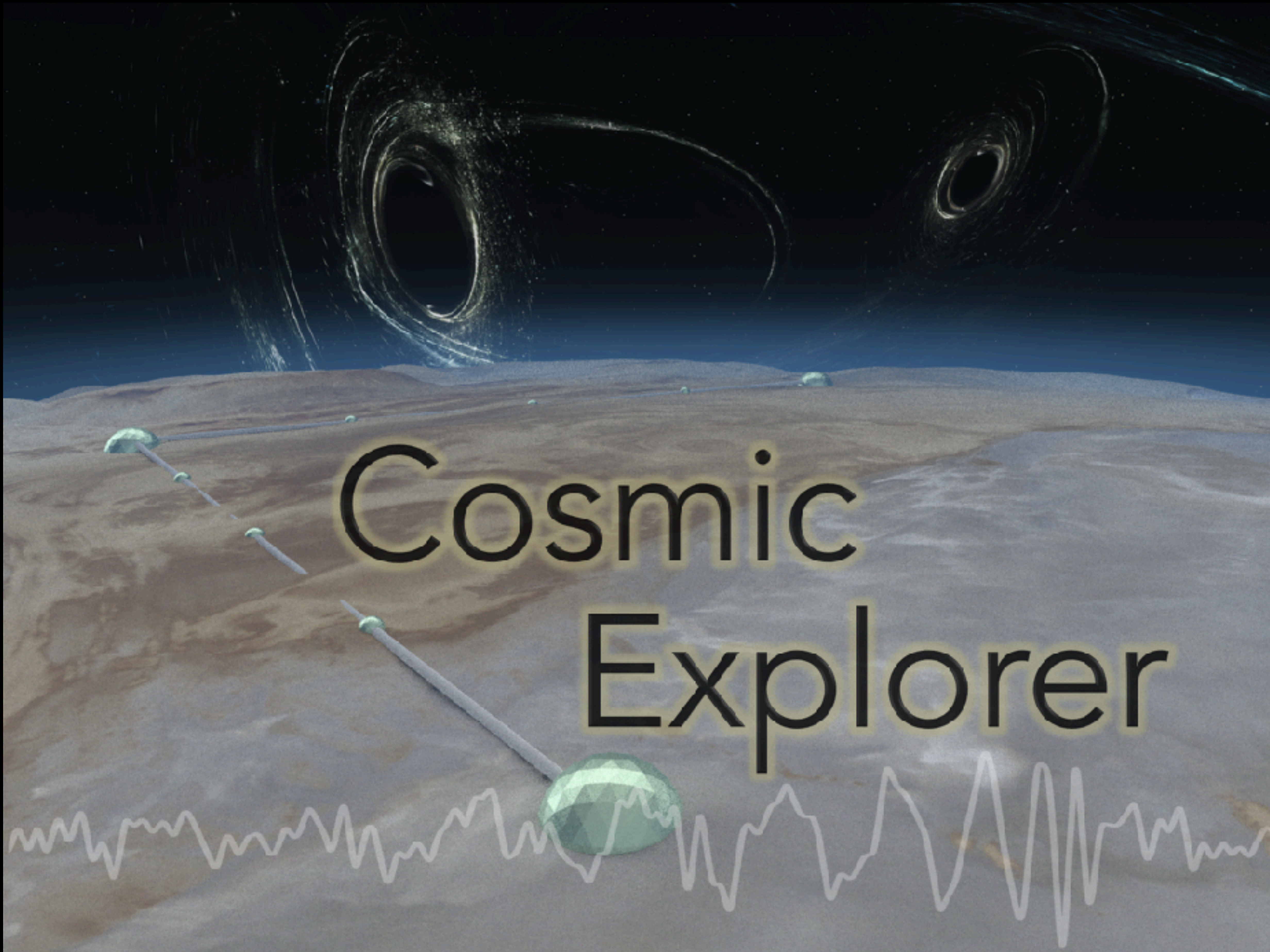


Hall and Evans, 2019

Einstein telescope

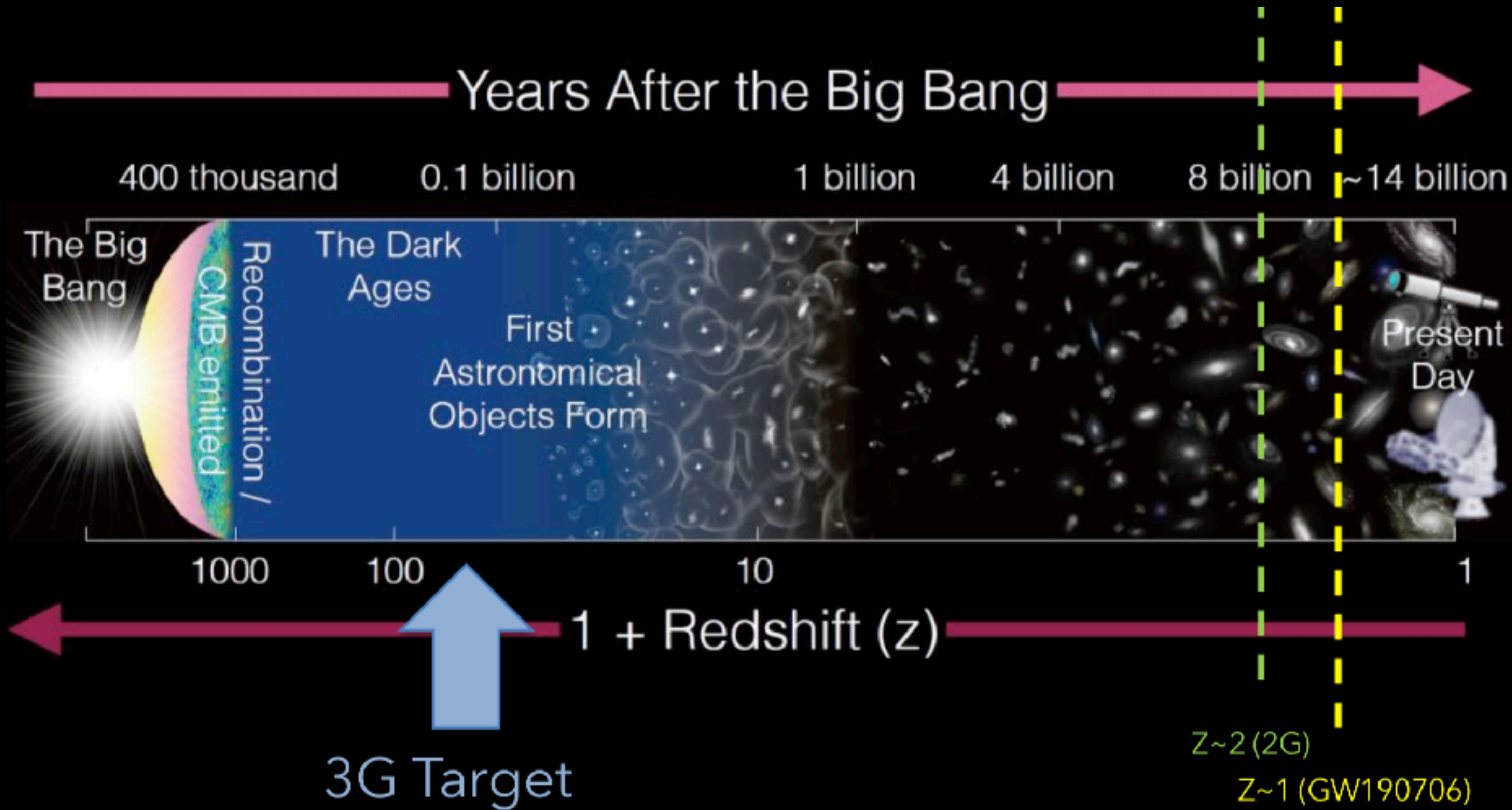


Source: http://www.et-gw.eu



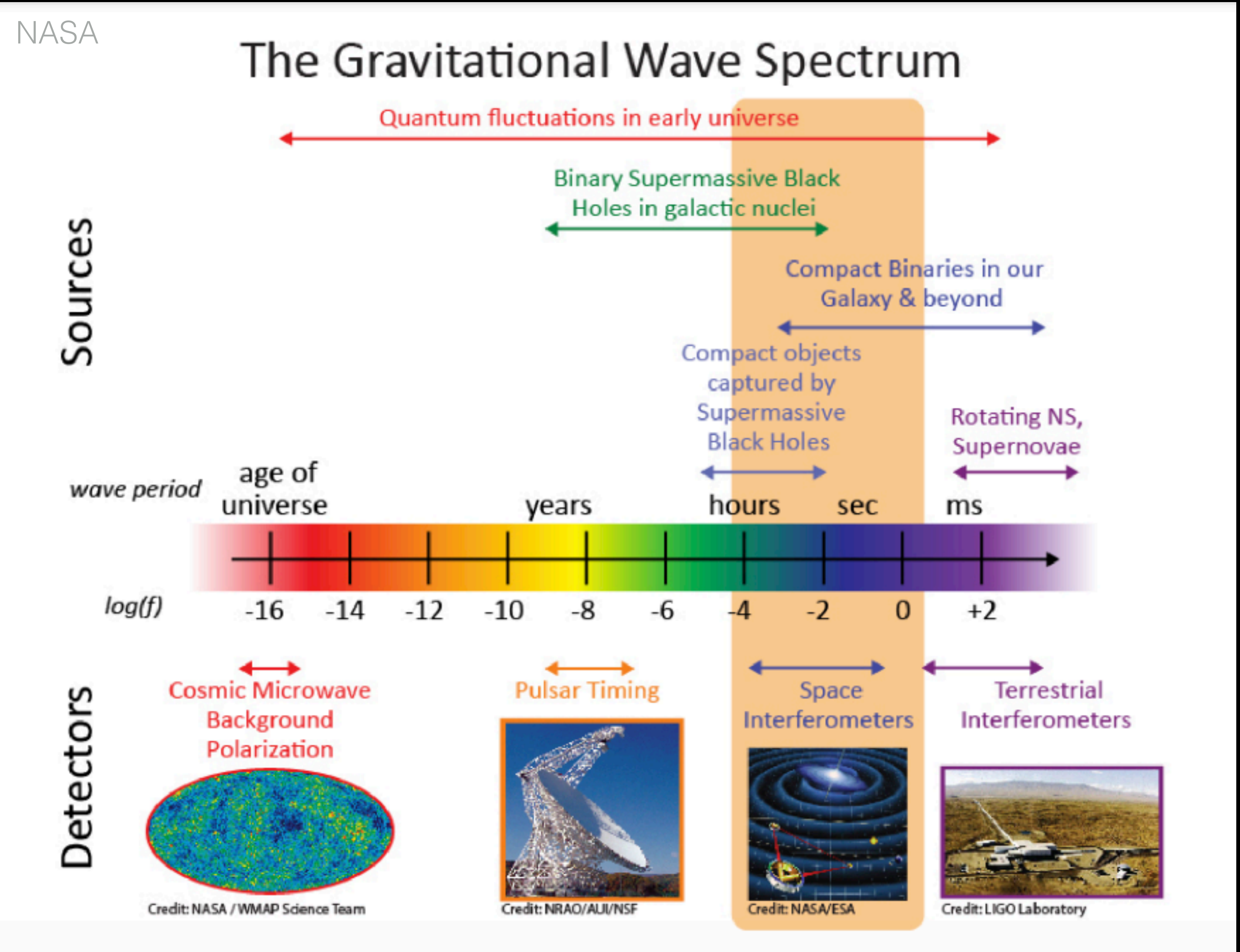
Source: cosmicexplorer.org

Source: cosmicexplorer.org

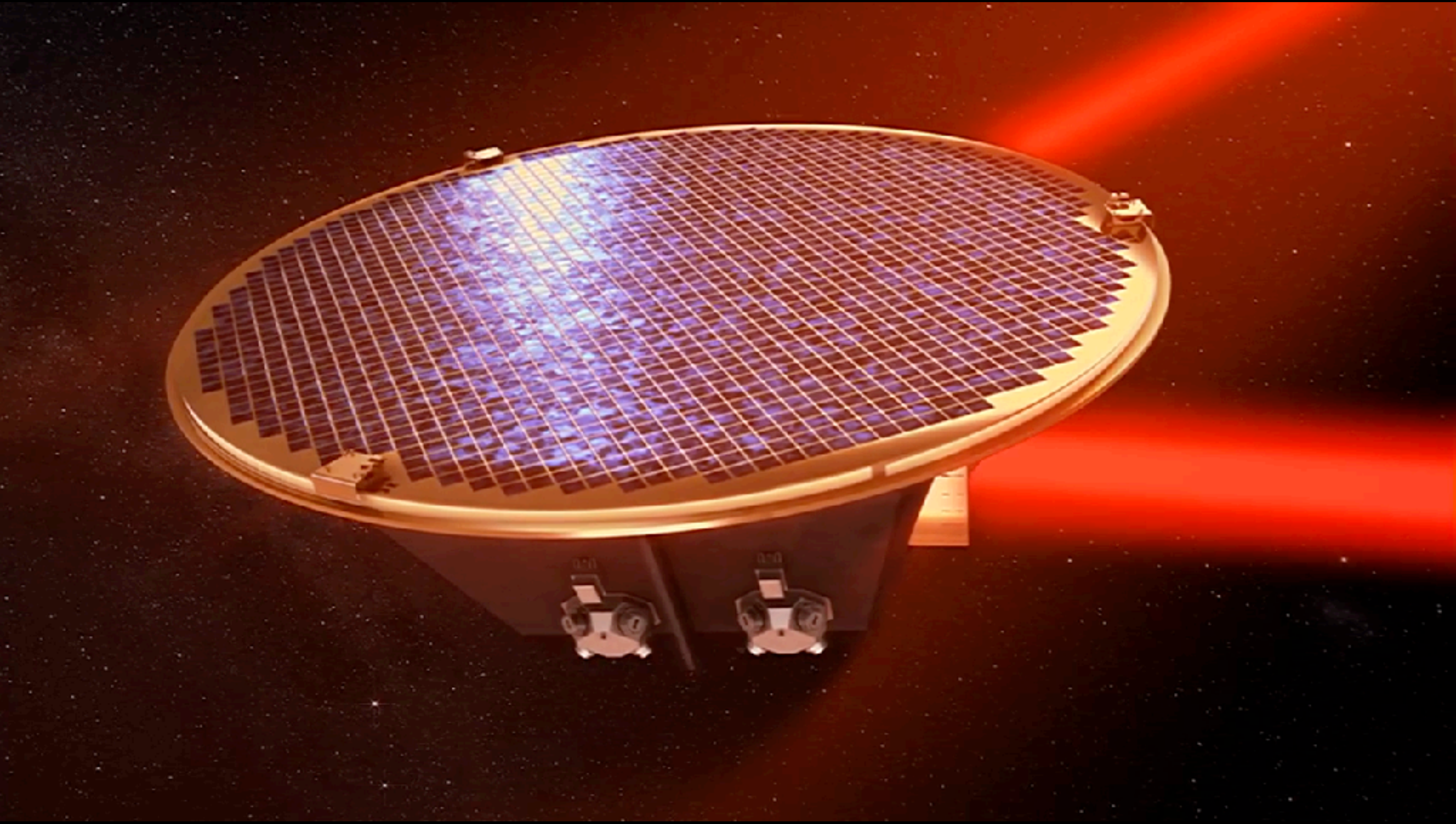


Slide by G. Losurdo

Beyond terrestrial detectors

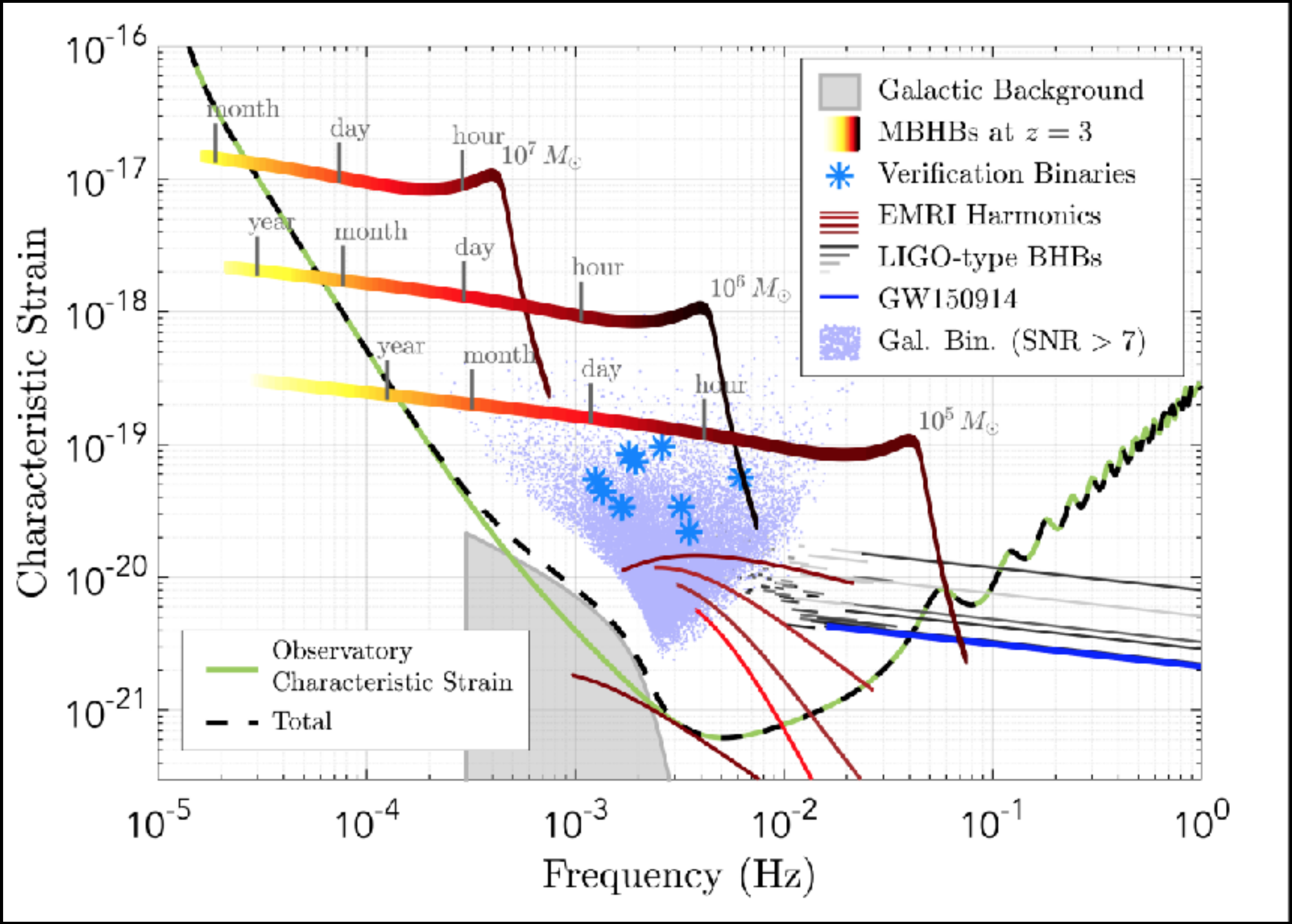


The LISA mission



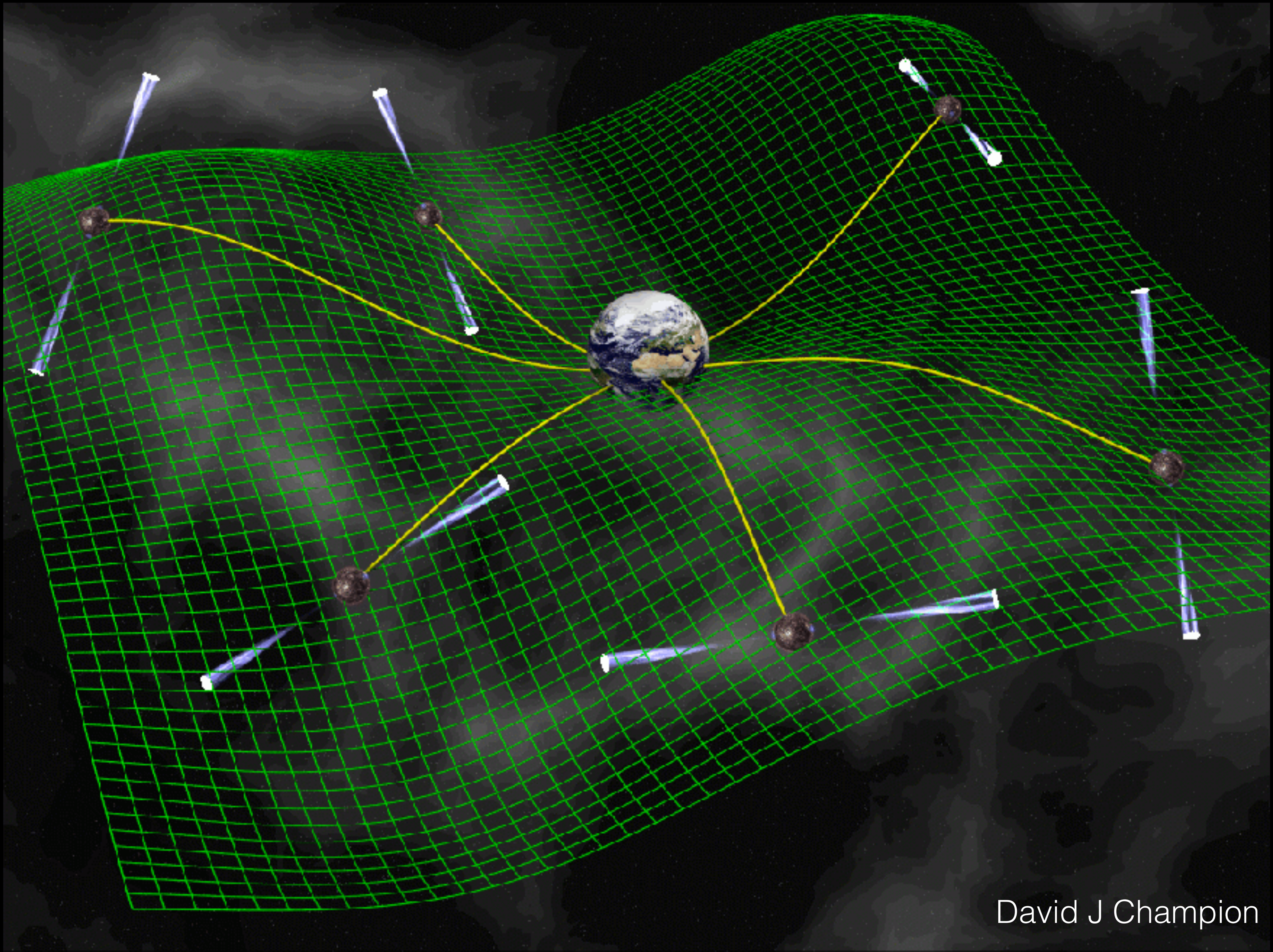
NASA

LISA discovery space



LISA core team + consortium - 2017

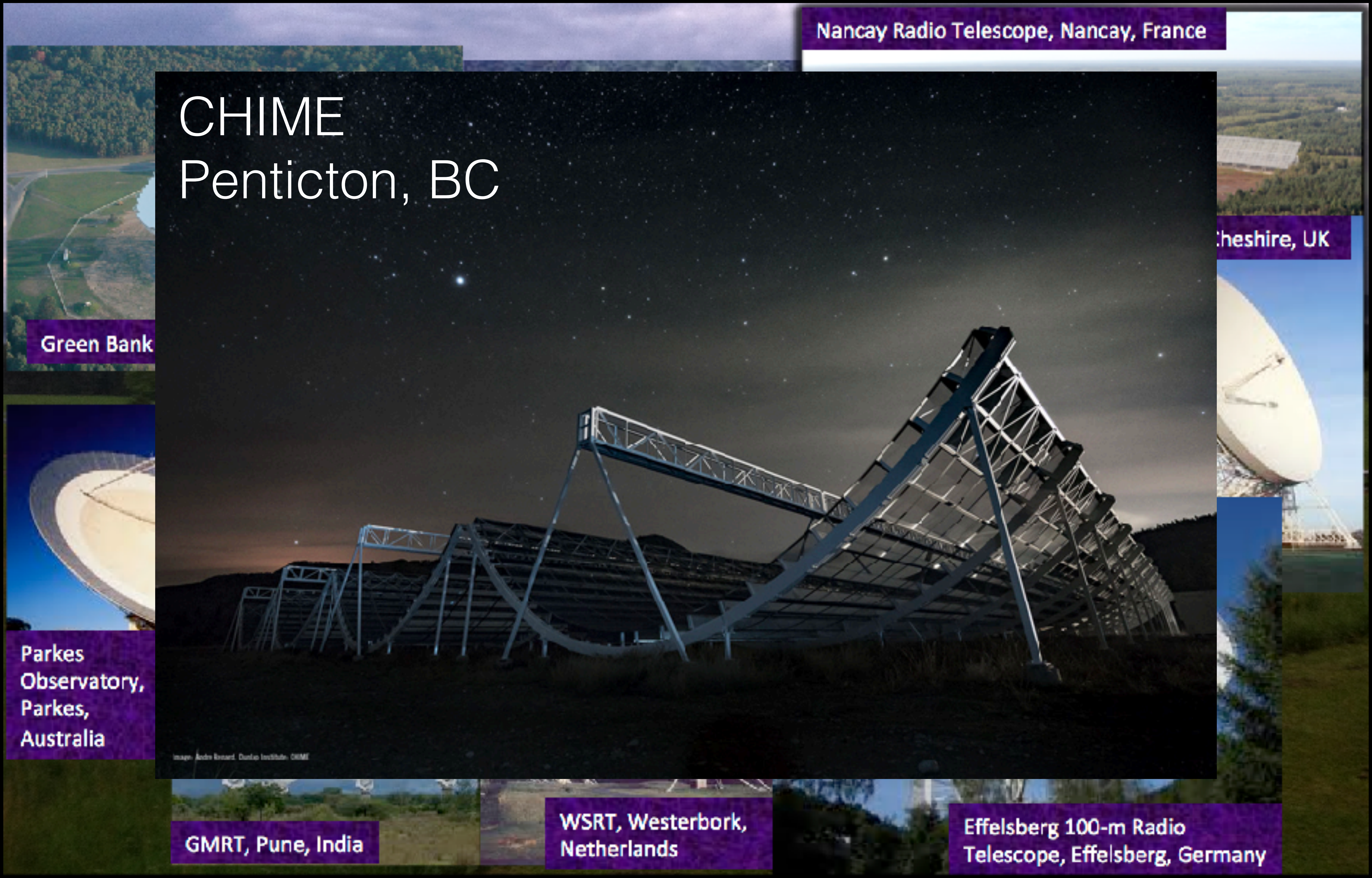
Pulsar Timing Arrays



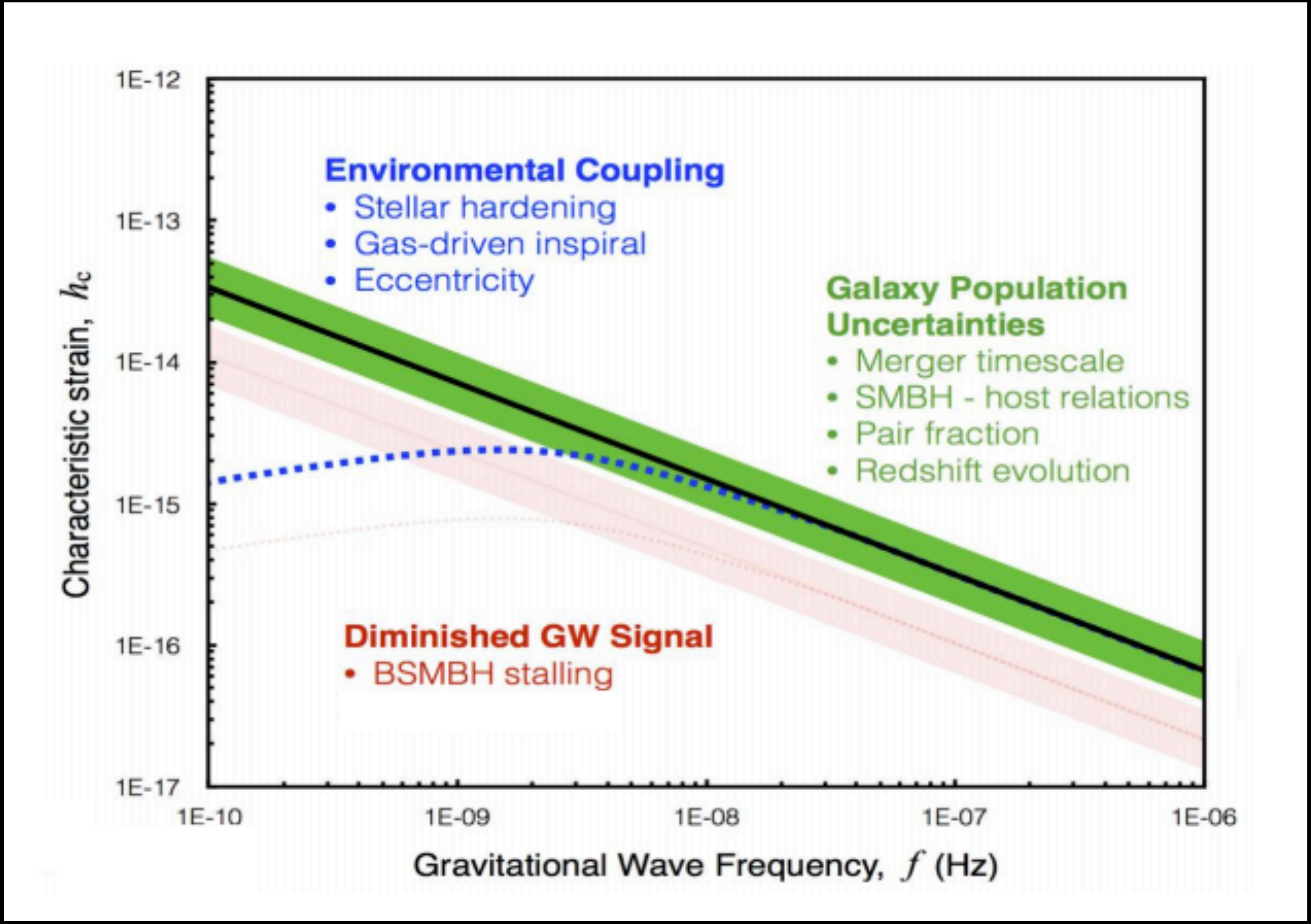
David J Champion

An International Radio Telescope Effort

An International Radio Telescope Effort

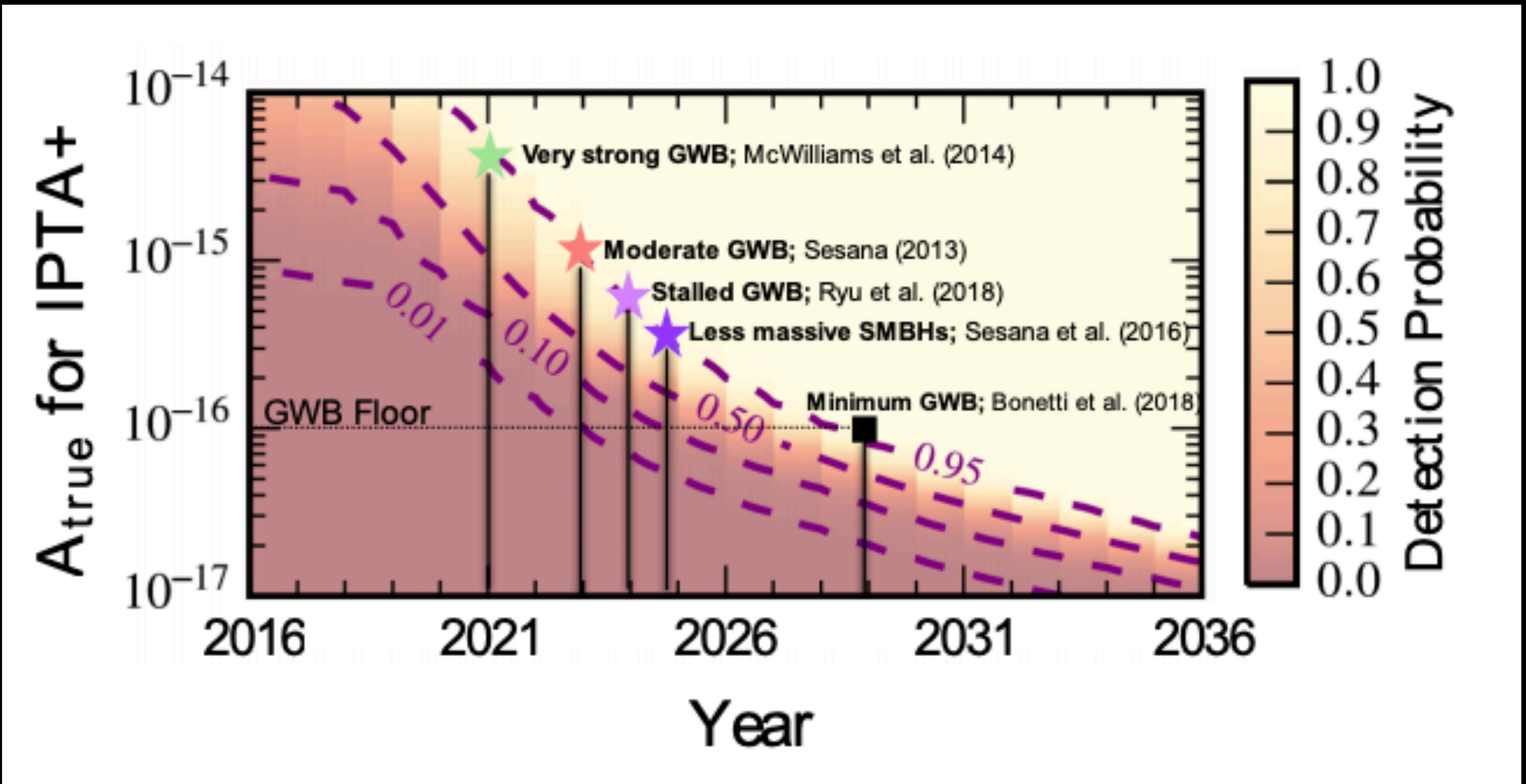


How do SMBHs get close enough to merge?

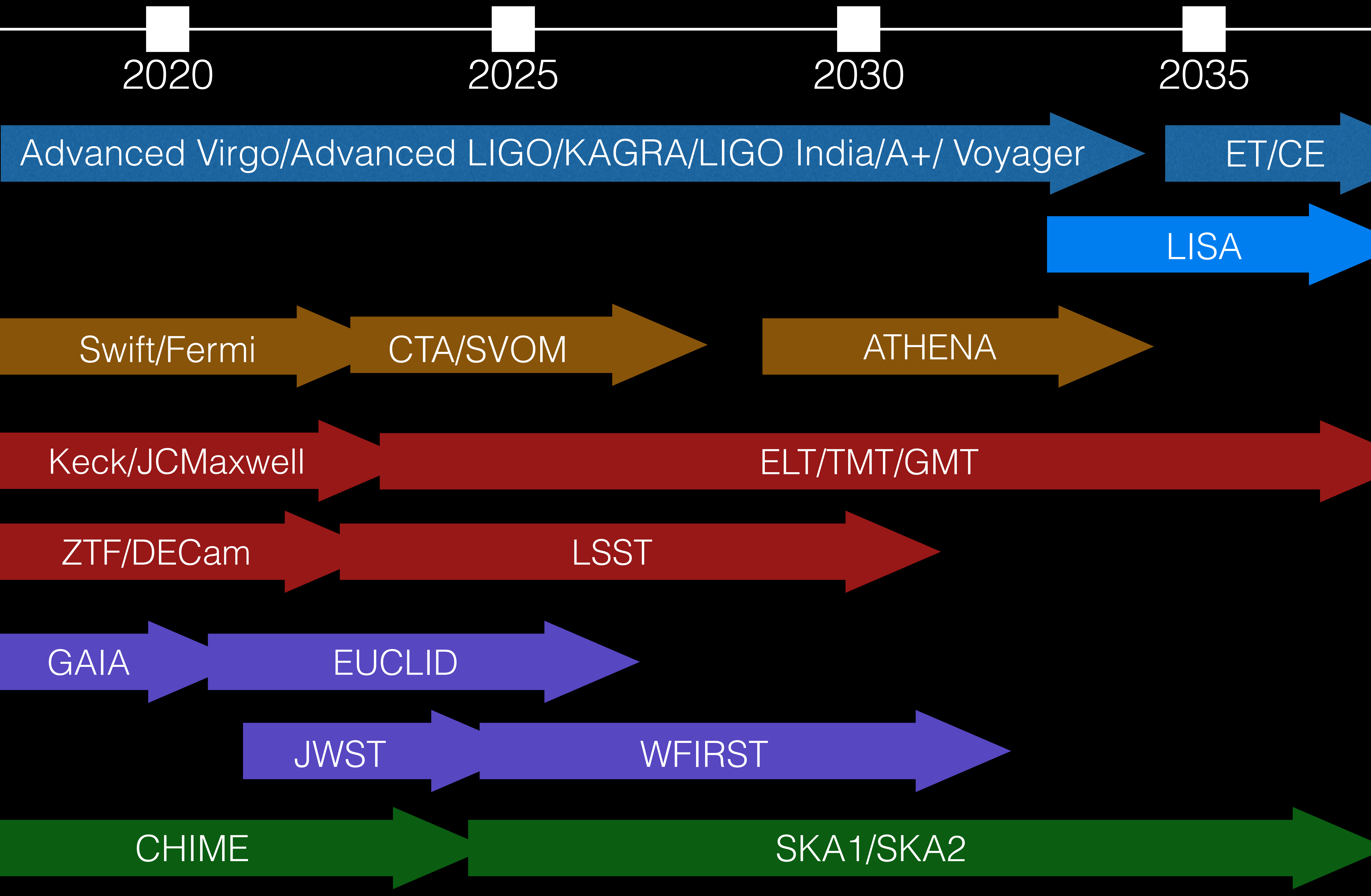


S. Burke Spolaor

IPTA detection prospects

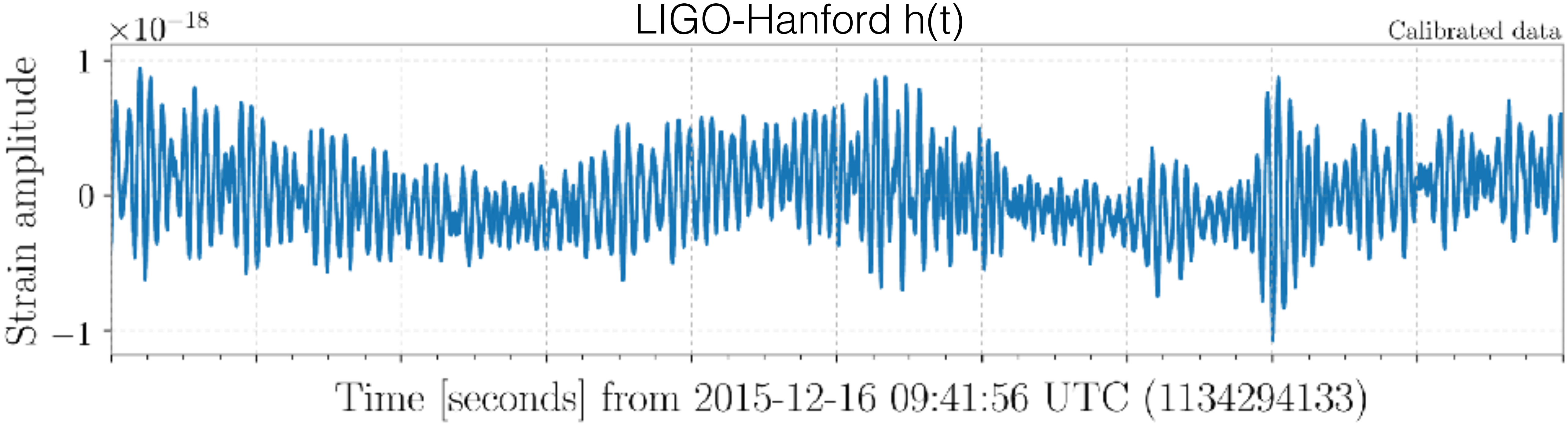


Future prospects: multi-messenger astronomy



If we have time:
Intro to GW detector data

What does GW detector data look like?



Made with GWpy!

What's in a GW data file?

meta: Meta-data for the file. This is **basic information** such as the GPS times covered, which instrument, etc.

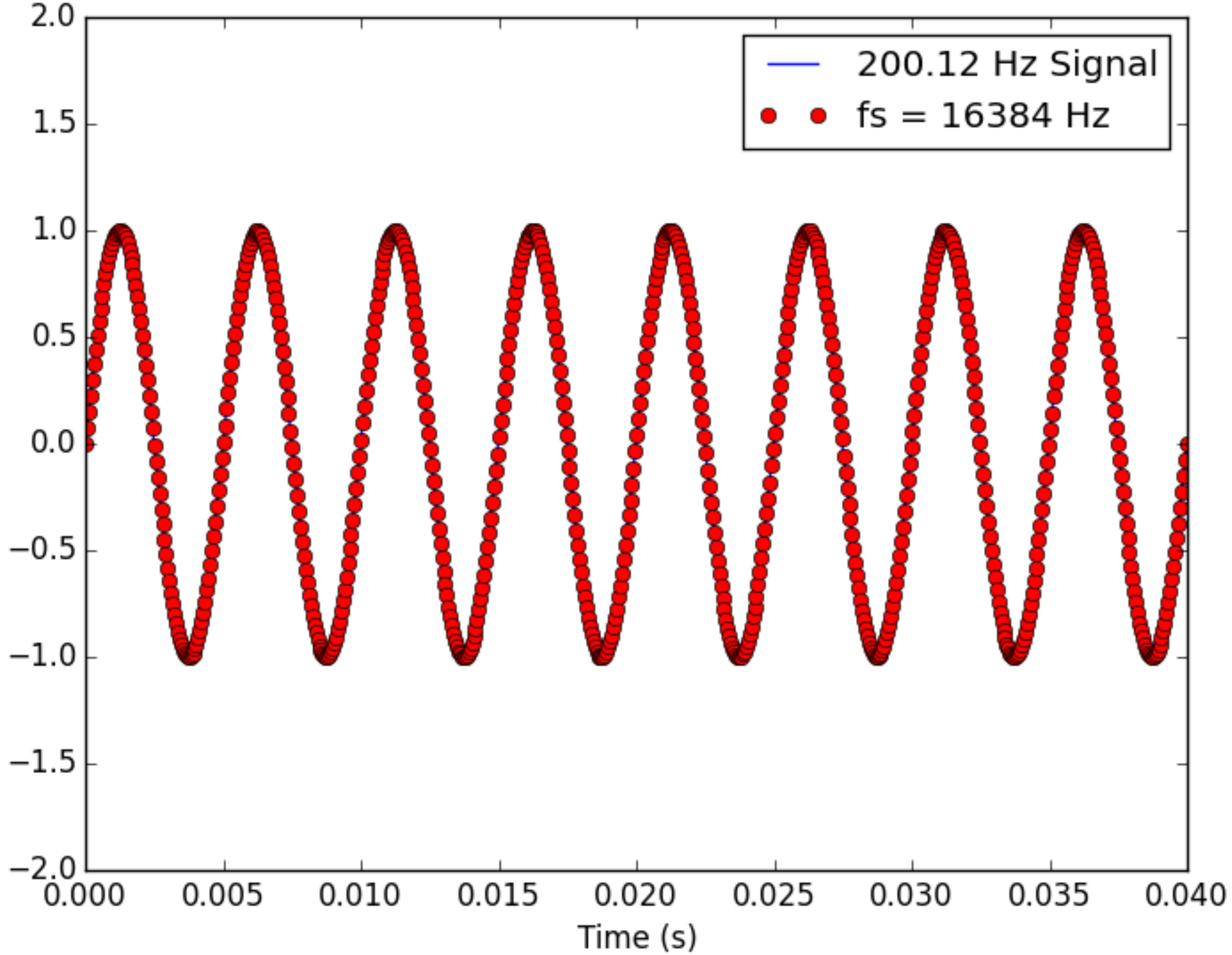
strain: Strain data from the interferometer. This is "the data", the **main measurement of spacetime strain** recorded by the LIGO detectors.

quality: A 1 Hz time series describing the **data quality** for each second of data.

h(t) **sampling rate** for LIGO detectors: 16384 Hz
Open data: 4096 Hz and 16384 Hz

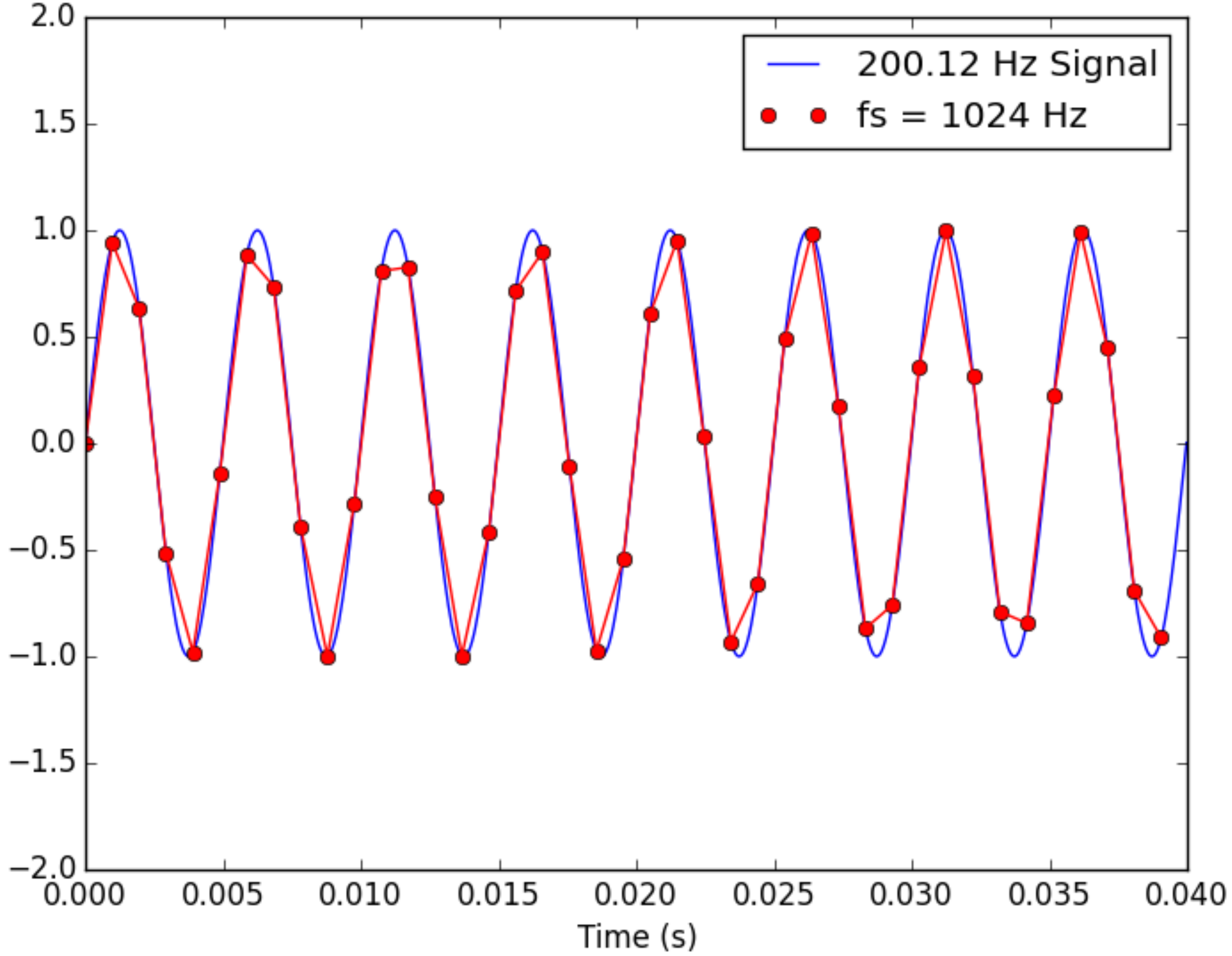
Why do we care about sampling rate, f_S ?

Discrete Time Samples



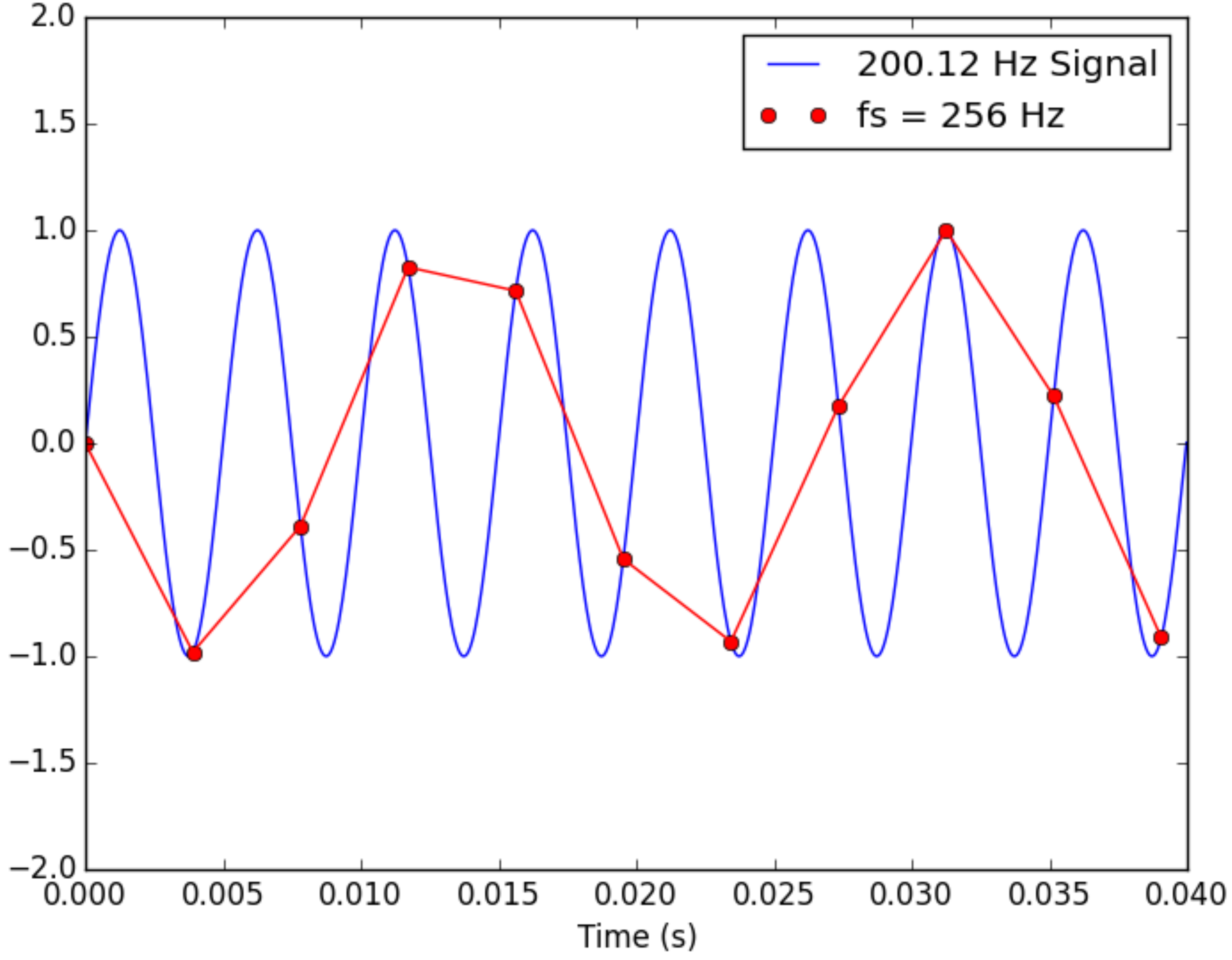
Slide from J. Kanner

Discrete Time Samples



Slide from J. Kanner

Discrete Time Samples



Slide from J. Kanner

Nyquist Frequency

- Nyquist Frequency = $\frac{f_s}{2}$
- Data can only accurately represent frequency content below the *Nyquist frequency*
- Higher frequency signals will be lost or "aliased" to lower frequencies

Introduction to GWpy

A python package for gravitational-wave astrophysics

https://gwpy.github.io

Heavily dependent on numpy, scipy, astropy, matplotlib

Provides intuitive object-orientated methods to access GW detector data, process, and visualize them

Not specific to GW data other than data access routines

Slide from D. Macleod

GWpy Quickstart

Import the class that represents the data you want to study

```
>>> from gwpy.timeseries import TimeSeries
```

Fetch some open data from the OSC

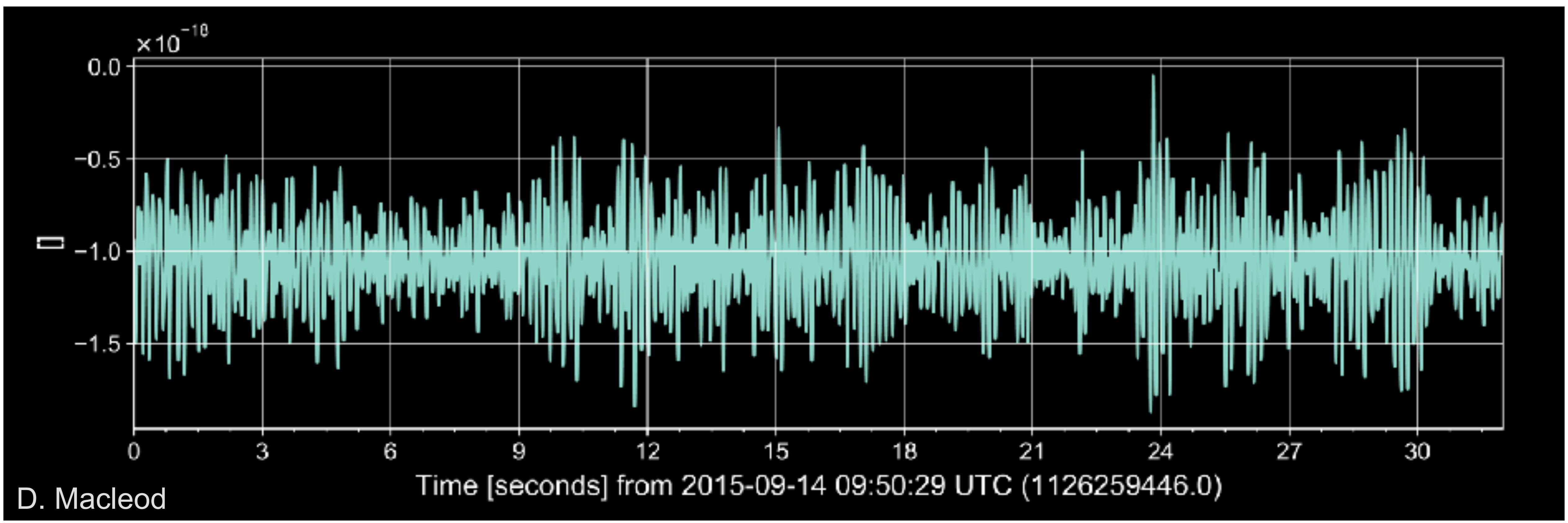
```
>>> data = TimeSeries.fetch_open_data('L1', 'Sep 14 2015 09:50:29', 'Sep 14 2015 09:51:01')
```

Make a plot

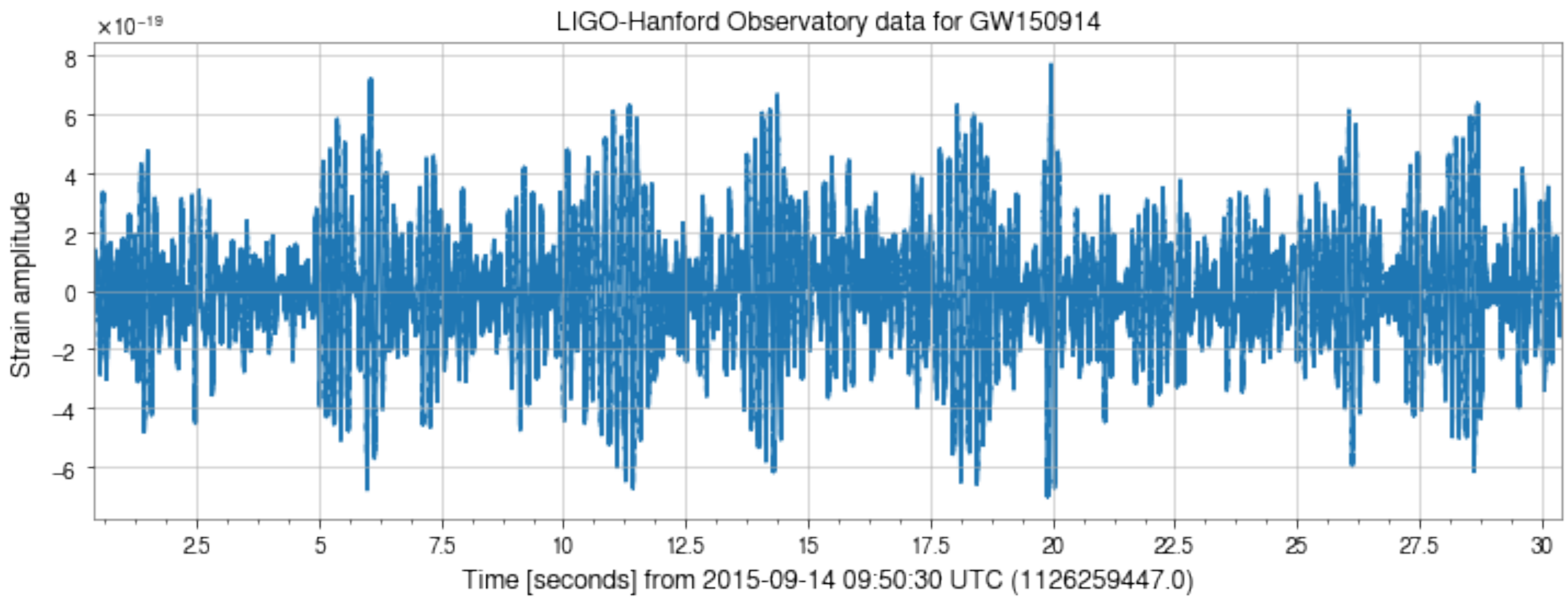
```
>>> plot = data.plot()
```

Display the plot

```
>>> plot.show()
```



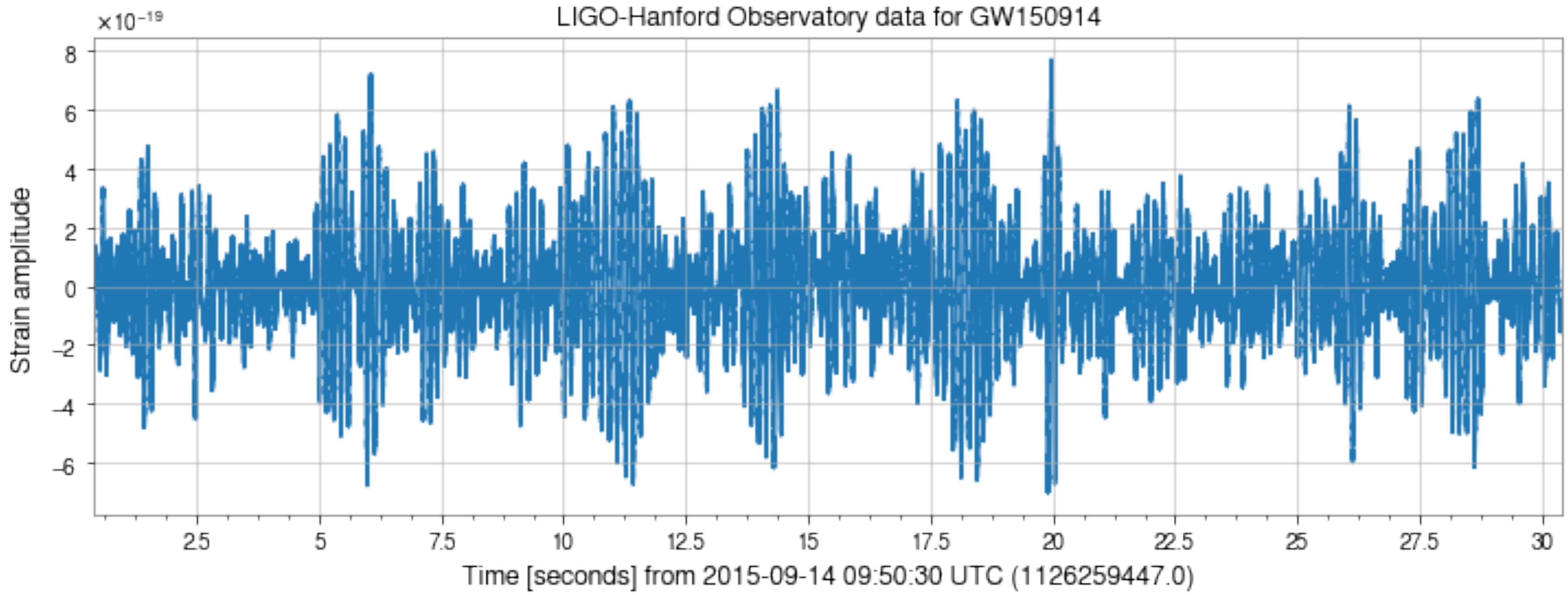
Time domain



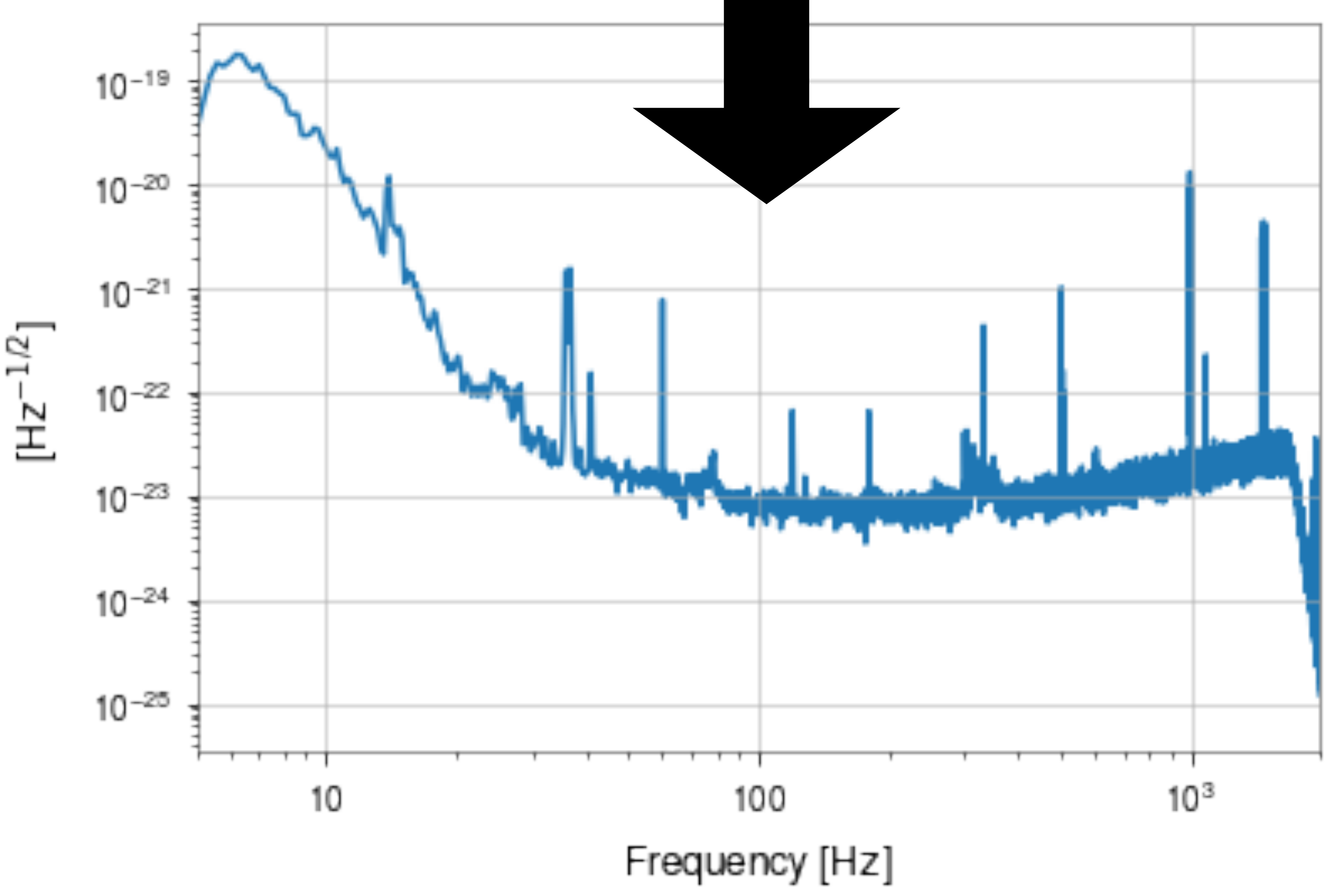
LIGO-Hanford Observatory data for GW150914
×10⁻¹⁹
8
6
4
2
0
-2
-4
-6
Strain amplitude
2.5
5
7.5
10
12.5
15
17.5
20
22.5
25
27.5
30
Time [seconds] from 2015-09-14 09:50:30 UTC (1126259447.0)

Time domain ➔ Frequency domain

Time series (strain vs time)



Amplitude spectral density ($Hz^{-\frac{1}{2}}$ vs. frequency)



The Fourier Series

Any function can be represented as a sum of sines and cosines (with some coefficients that can also be functions).

$$f(x) = \sum_{n=0}^{\infty} A_n \cos\left(\frac{n\pi x}{L}\right) + \sum_{n=1}^{\infty} B_n \sin\left(\frac{n\pi x}{L}\right)$$

The Fourier Transform

When we transform our function or time (or space) into the "frequency domain", we are **projecting f(x) onto an orthogonal basis of sines and cosines**.

Fourier transform

$$\tilde{x}(f) = \int_{-\infty}^{\infty} dt\, x(t) e^{-i2\pi f t}$$

The Fourier Transform

When we transform our function or time (or space) into the "frequency domain", we are **projecting f(x) onto an orthogonal basis of sines and cosines**.

Fourier transform

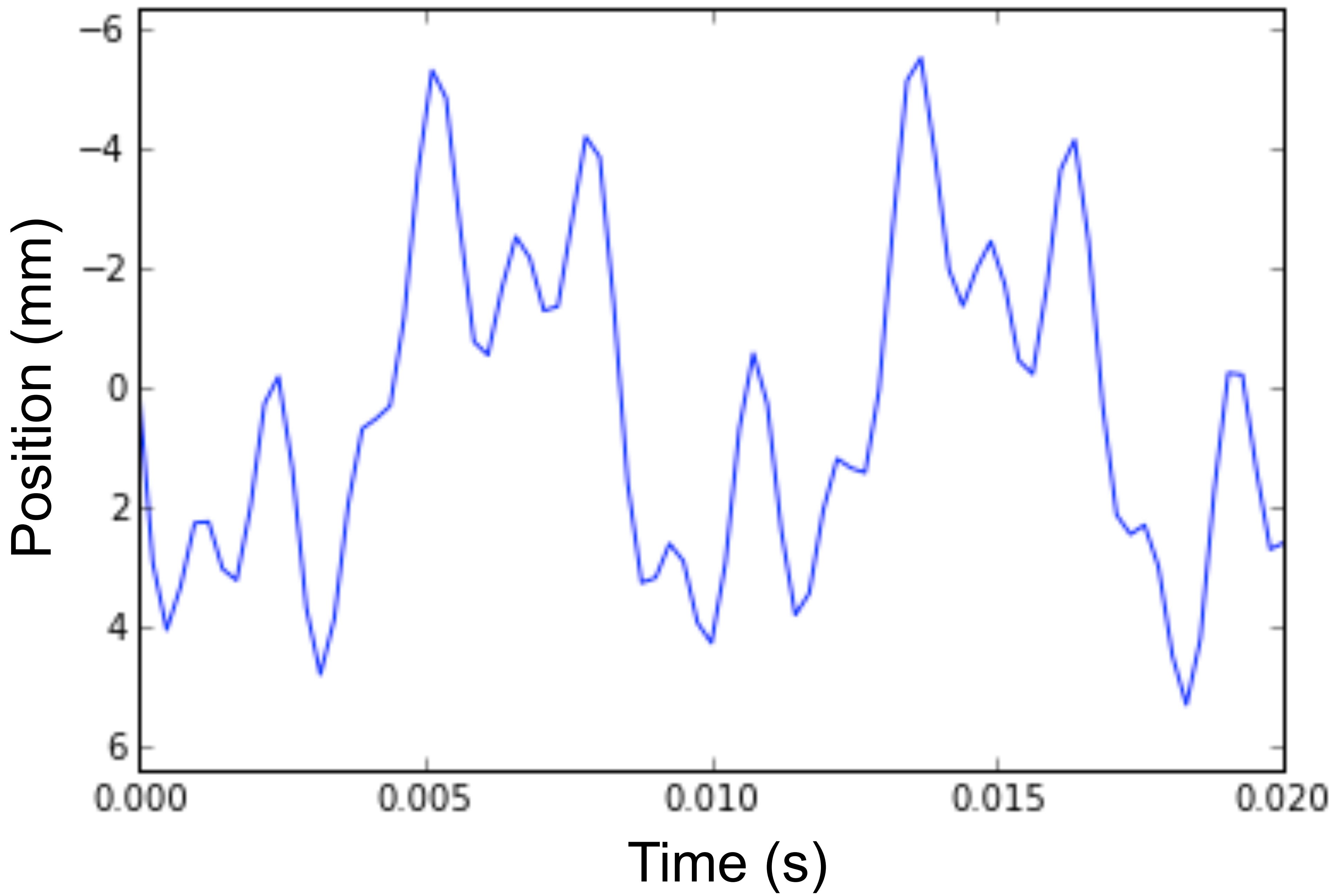
$$\tilde{x}(f) = \int_{-\infty}^{\infty} dt\, x(t) e^{-i2\pi f t}$$

Inverse Fourier transform

$$x(t) = \int_{-\infty}^{\infty} df\, \tilde{x}(f) e^{i2\pi f t}$$

Another way to think about it: when we take a Fourier transform **we are decomposing the function into its component frequencies**.

How would you describe this function?



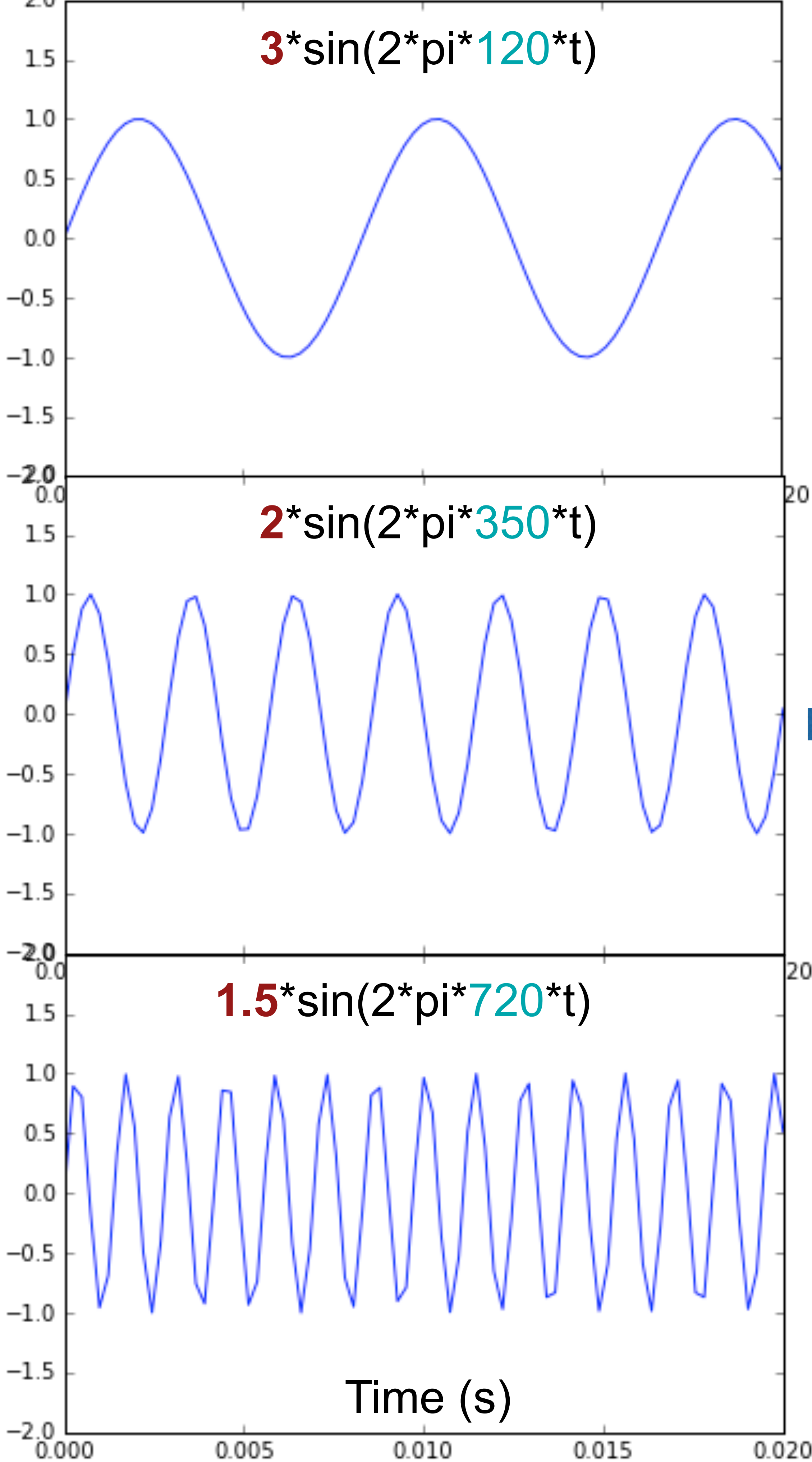
2 sinusoids

3 sinusoids

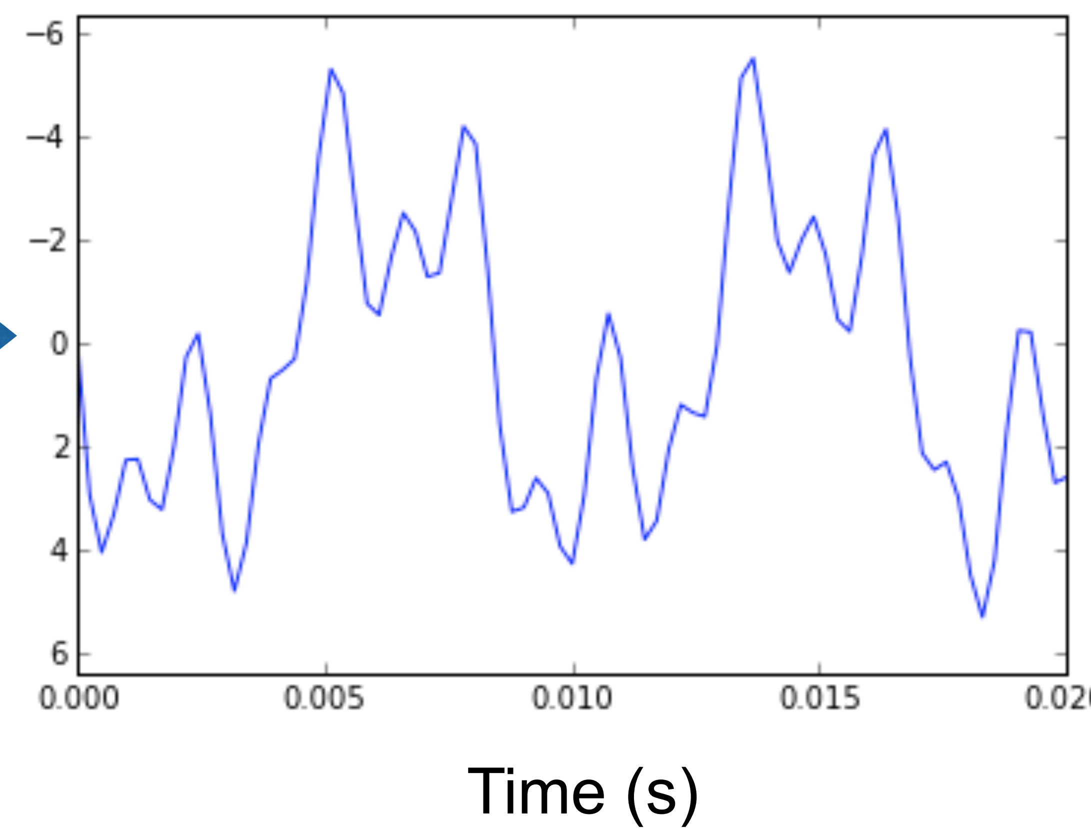
4 sinusoids

5 sinusoids

Slide from J. Kanner

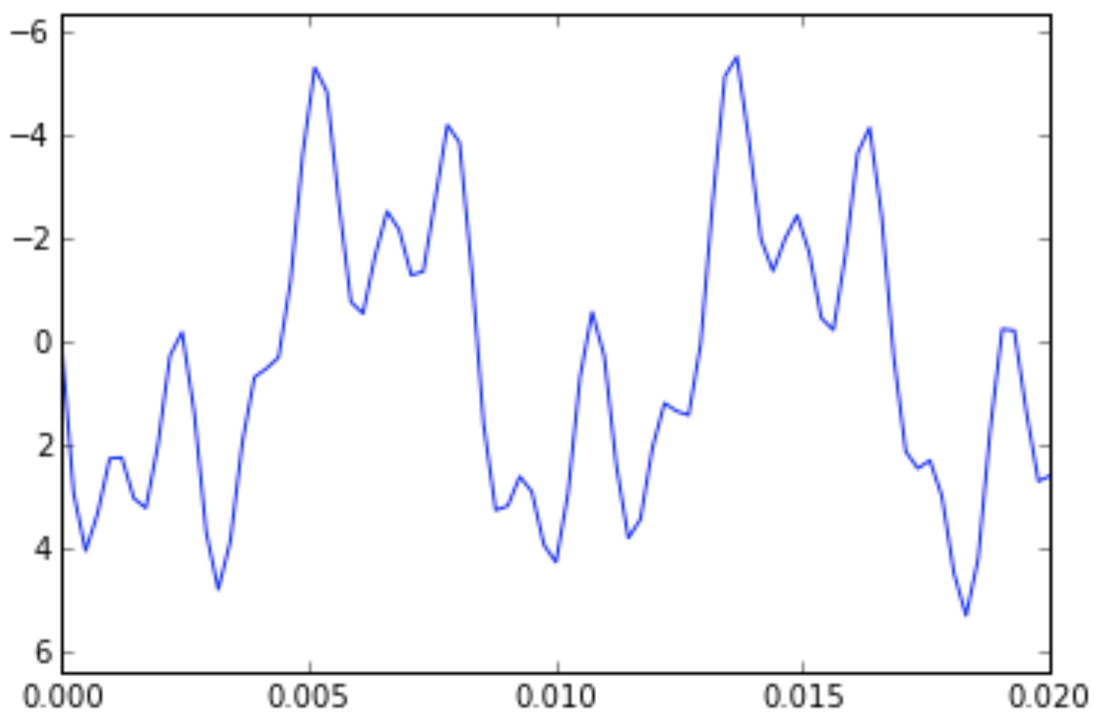


Our original function



Slide from J. Kanner

Time Domain

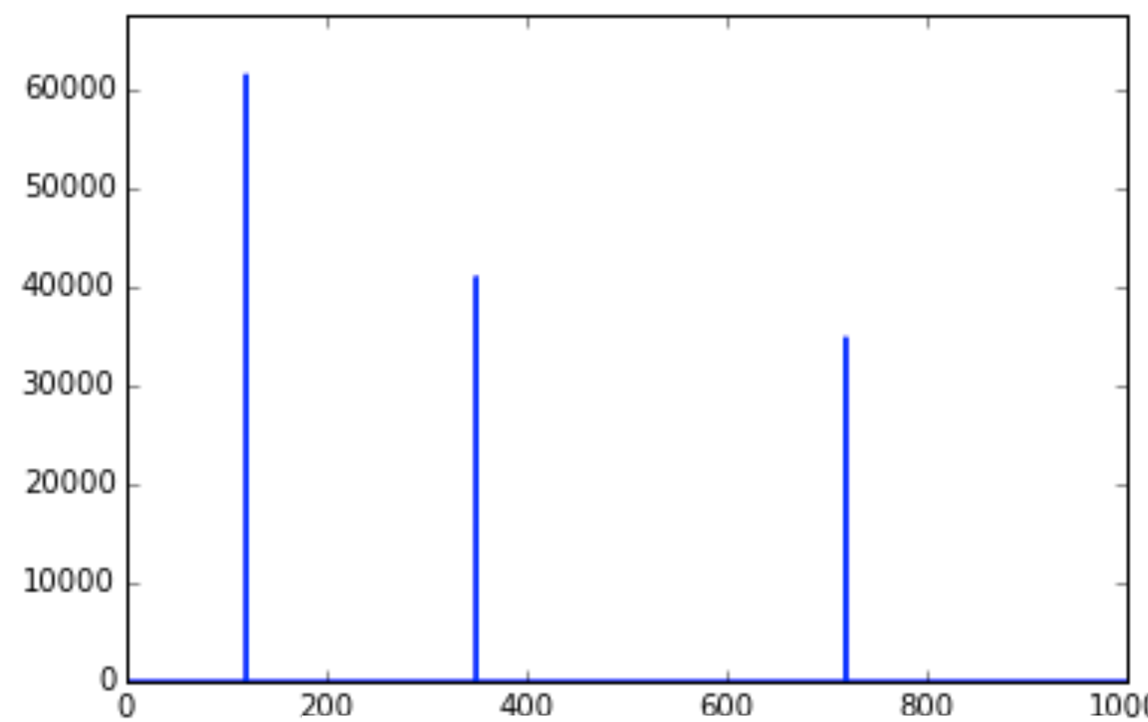


Time (s)

h(t) – Position as a function of time

h(t) = 3 * sin(2*pi*120*t) +
2 * sin(2*pi*350*t) +
1.5* sin(2*pi*720*t)

Frequency Domain



Frequency (Hz)

H(f) – Amplitude as a function of frequency

|H(120 Hz)| = 3
|H(350 Hz)| = 2
|H(720 Hz)| = 1.5
H(f) = 0 otherwise

Fourier Transform

Slide from J. Kanner

Power Spectral Density

Parseval's theorem:

$$\int_{-\infty}^{\infty} dt\, |x(t)|^2 = \int_{-\infty}^{\infty} df\, |\tilde{x}(f)|^2$$

$\Rightarrow$ Total energy in the data can be calculated in either time domain or frequency domain

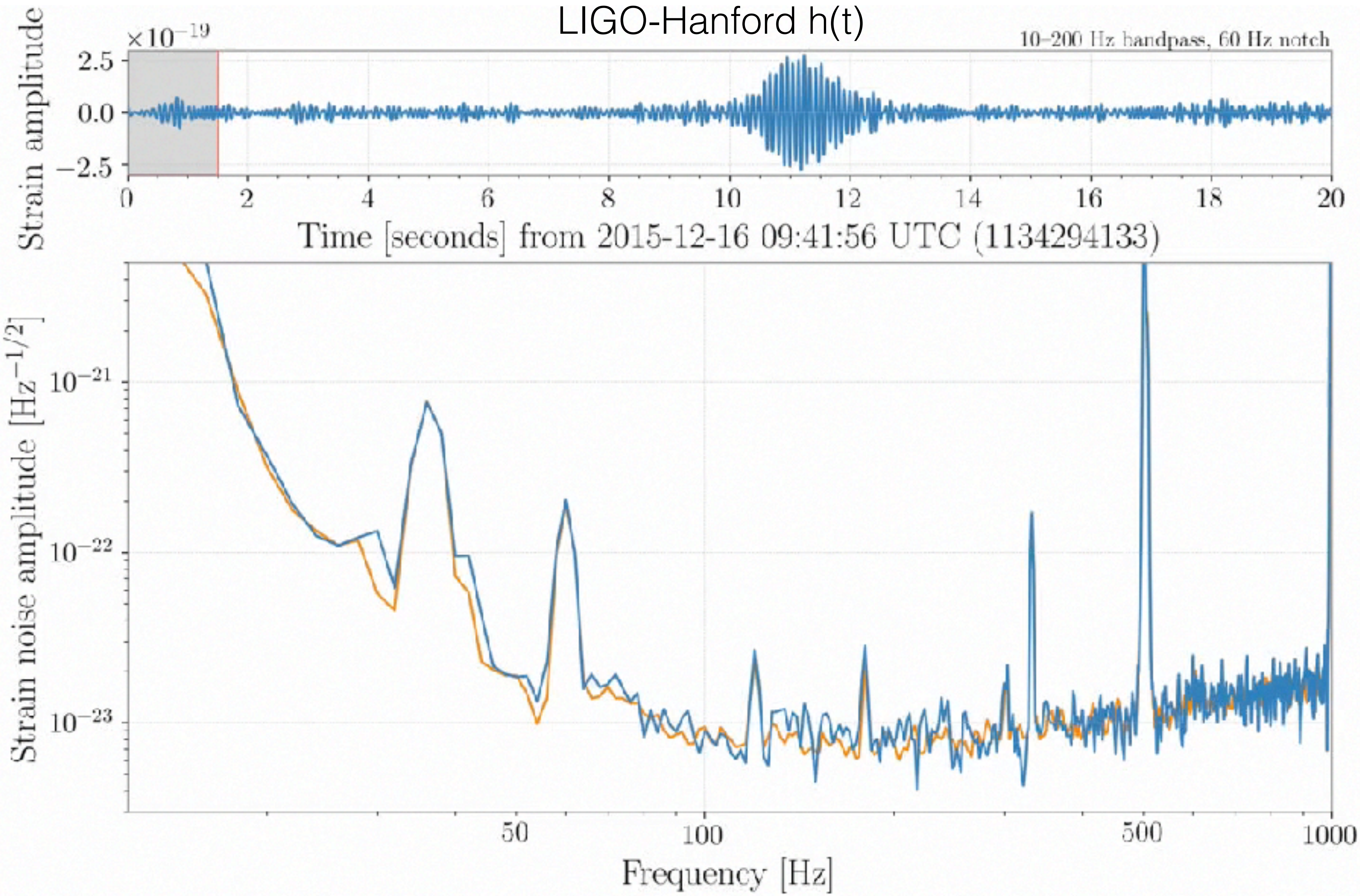
Units:

$|\tilde{x}(f)|^2$ Energy spectral density
(normalize by 1/T to get power)
Signal energy per unit frequency (per Hz)

$|\tilde{x}(f)|$ $\propto$ Amplitude spectral density
(sqrt of power for each discrete frequency)
Signal amplitude per unit frequency (per *sqrt Hz*)

Slide adapted from P. Shawhan

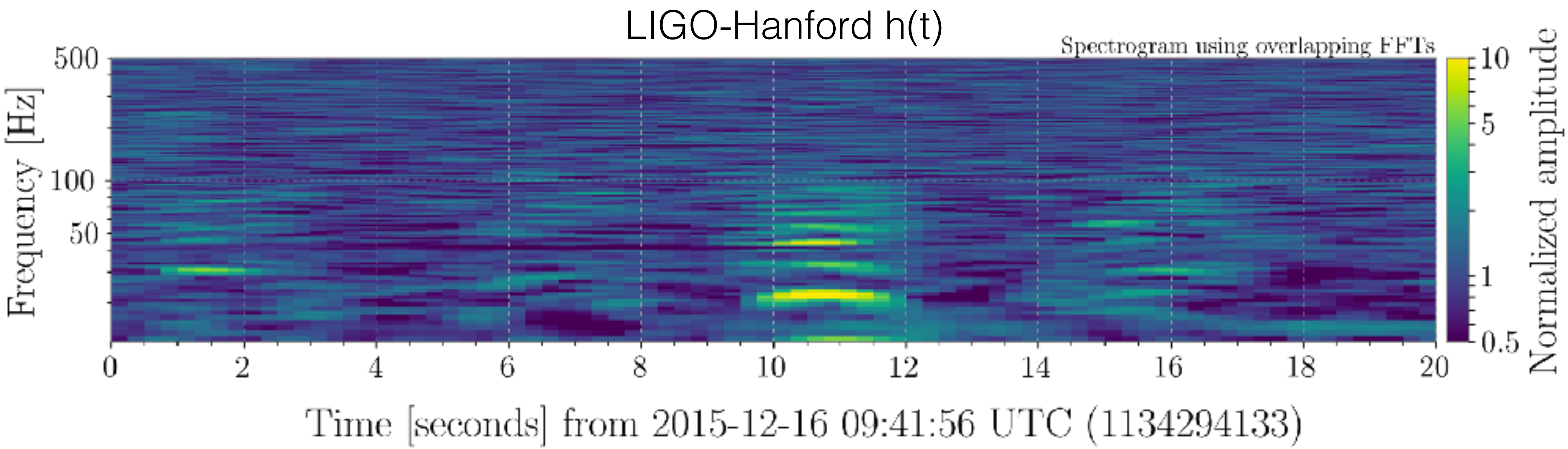
LIGO data in time and frequency



Made with GWpy by Duncan Macleod. Code: https://git.io/gwpy-ligo-scattering-animation

0.5 second FFT; 5 averages covering 1.5 seconds; 50% overlap

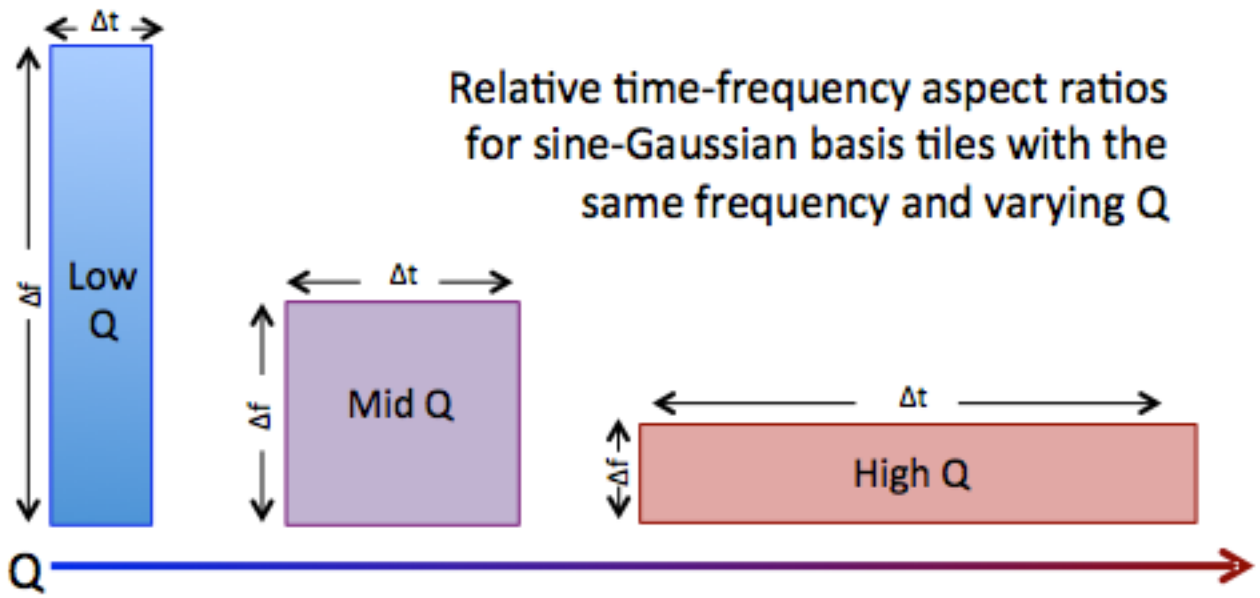
Time-frequency spectrogram



Made with GWpy by Duncan Macleod

The Q transform

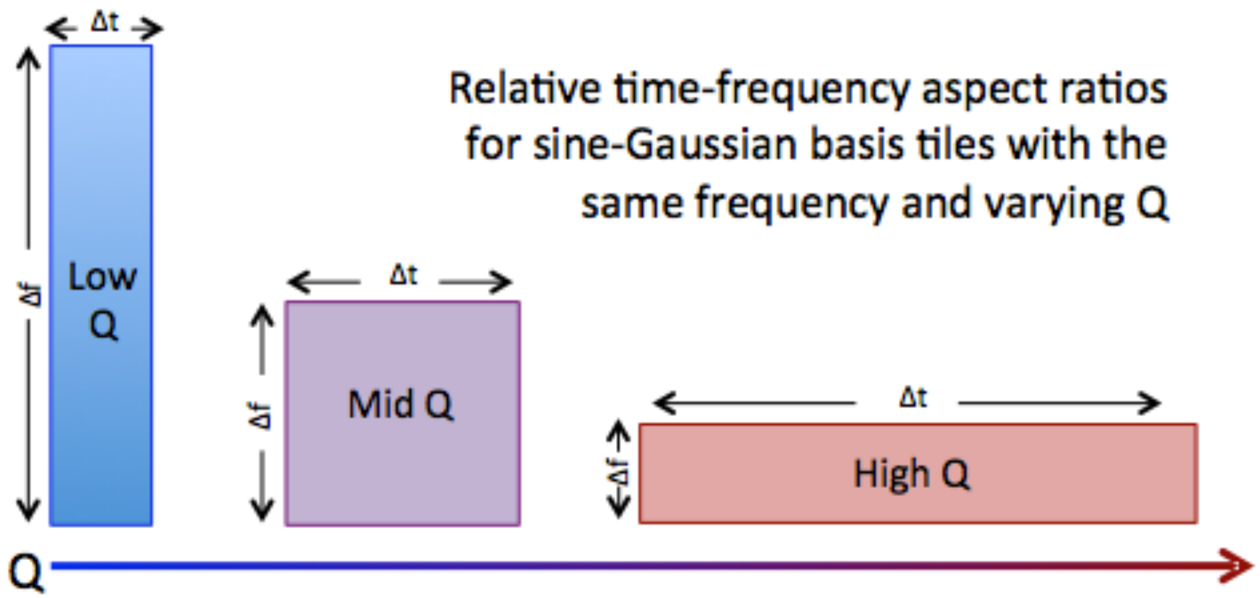
S. Chatterji et al. CQG (2010)
Images: McIver



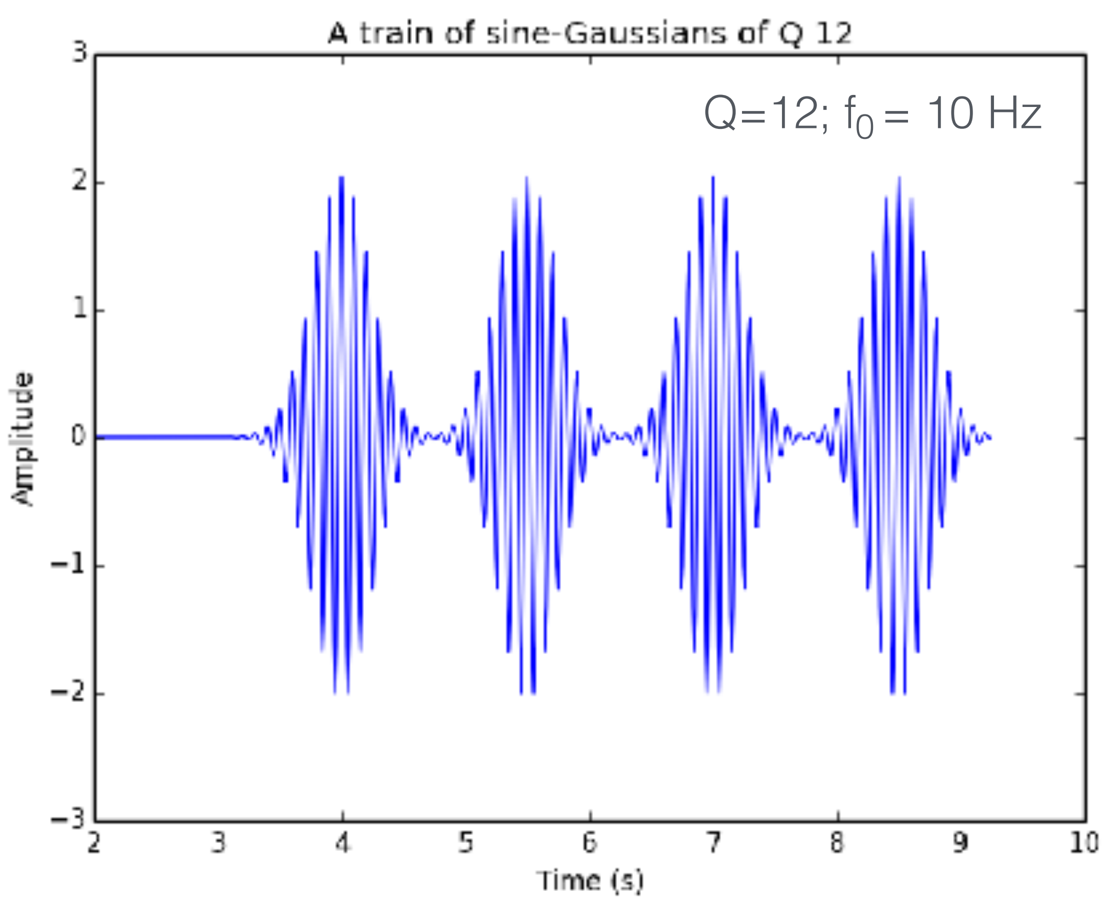
$$Q = \frac{f_0}{\Delta f}$$

The Q transform

S. Chatterji et al. CQG (2010)
Images: McIver



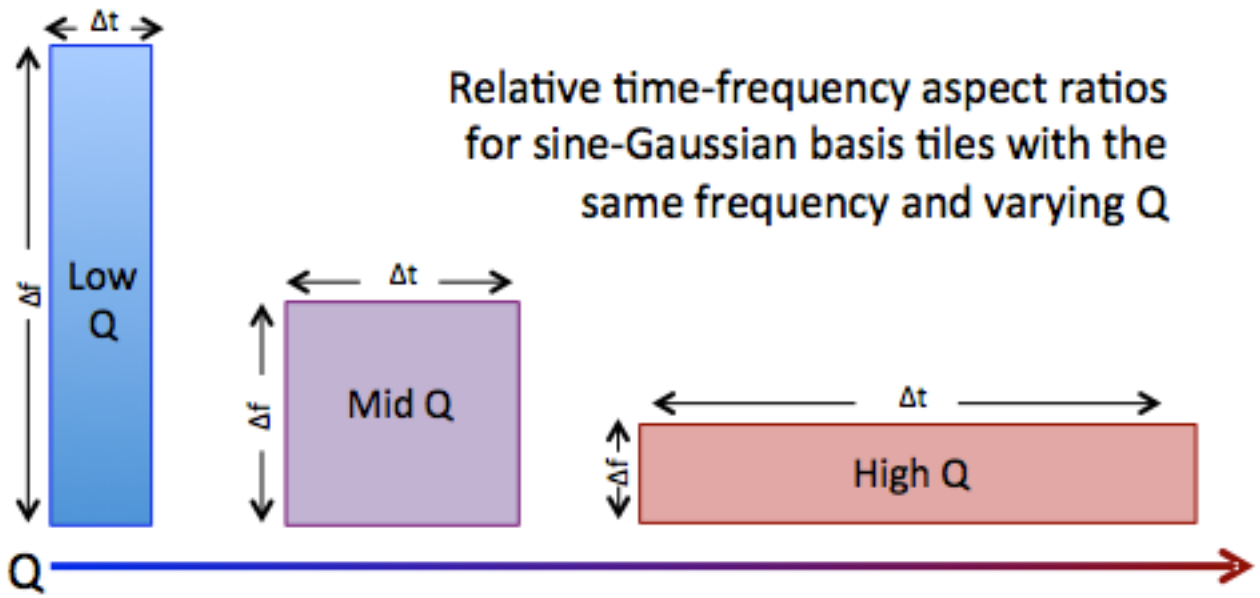
$$Q = \frac{f_0}{\Delta f}$$

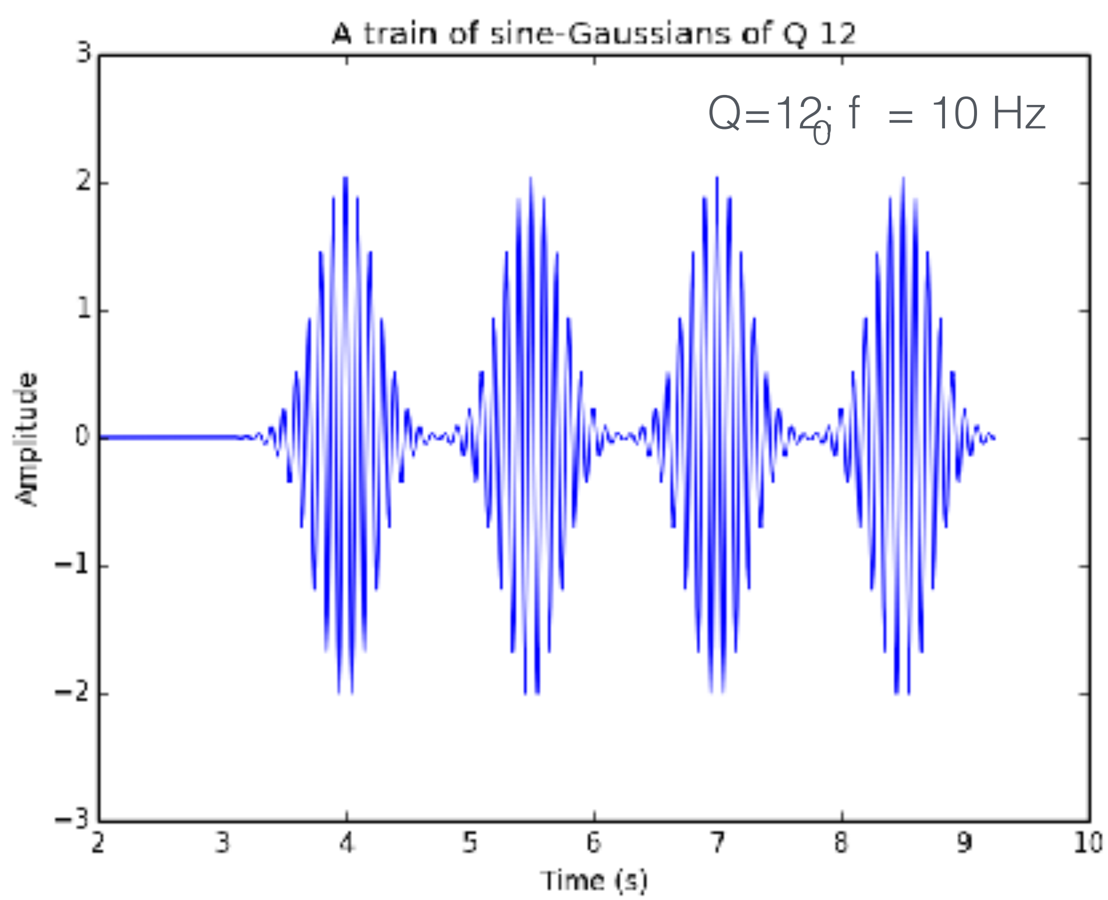


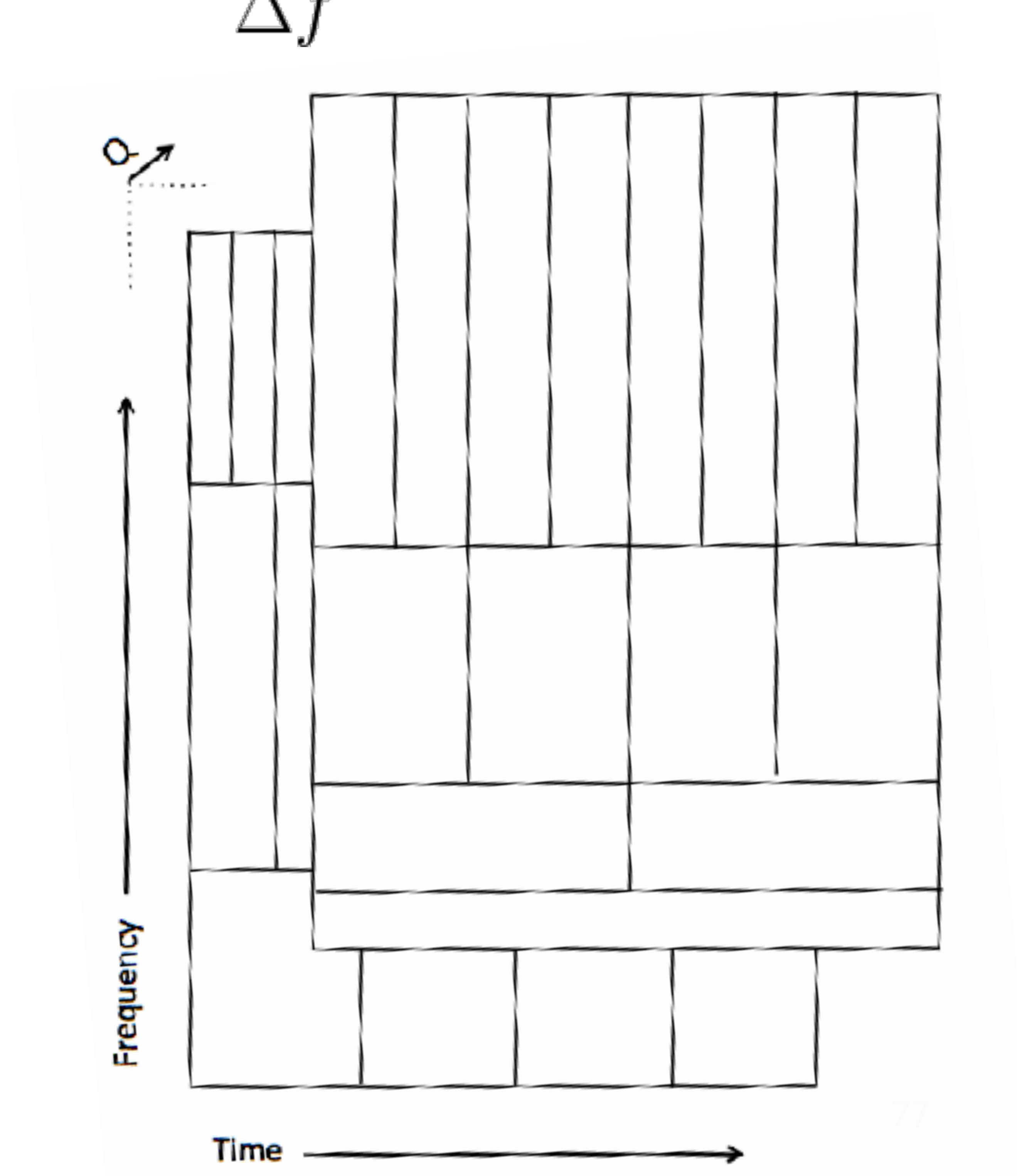
The Q transform

S. Chatterji et al. CQG (2010)
Images: McIver

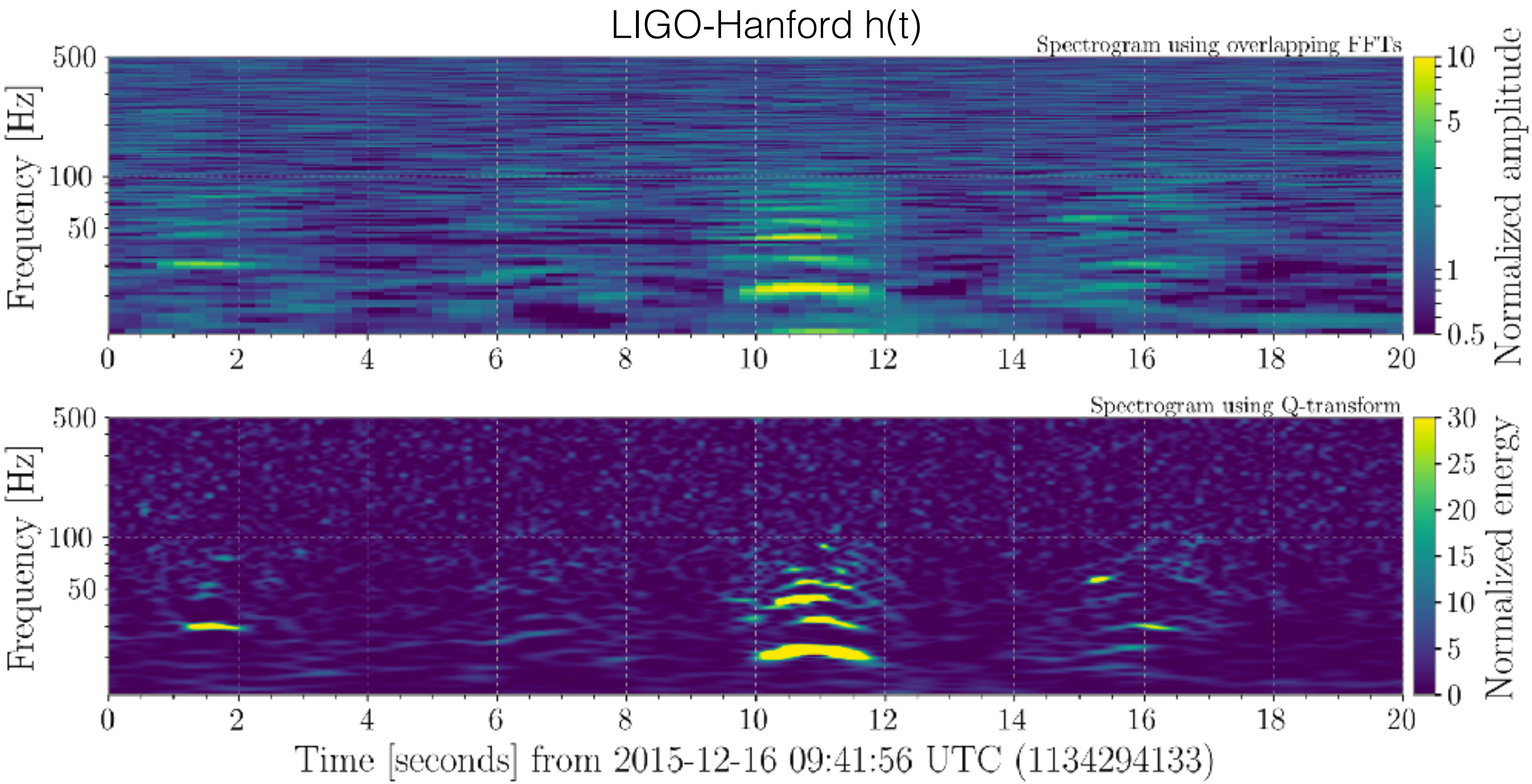
$$Q = \frac{f_0}{\Delta f}$$





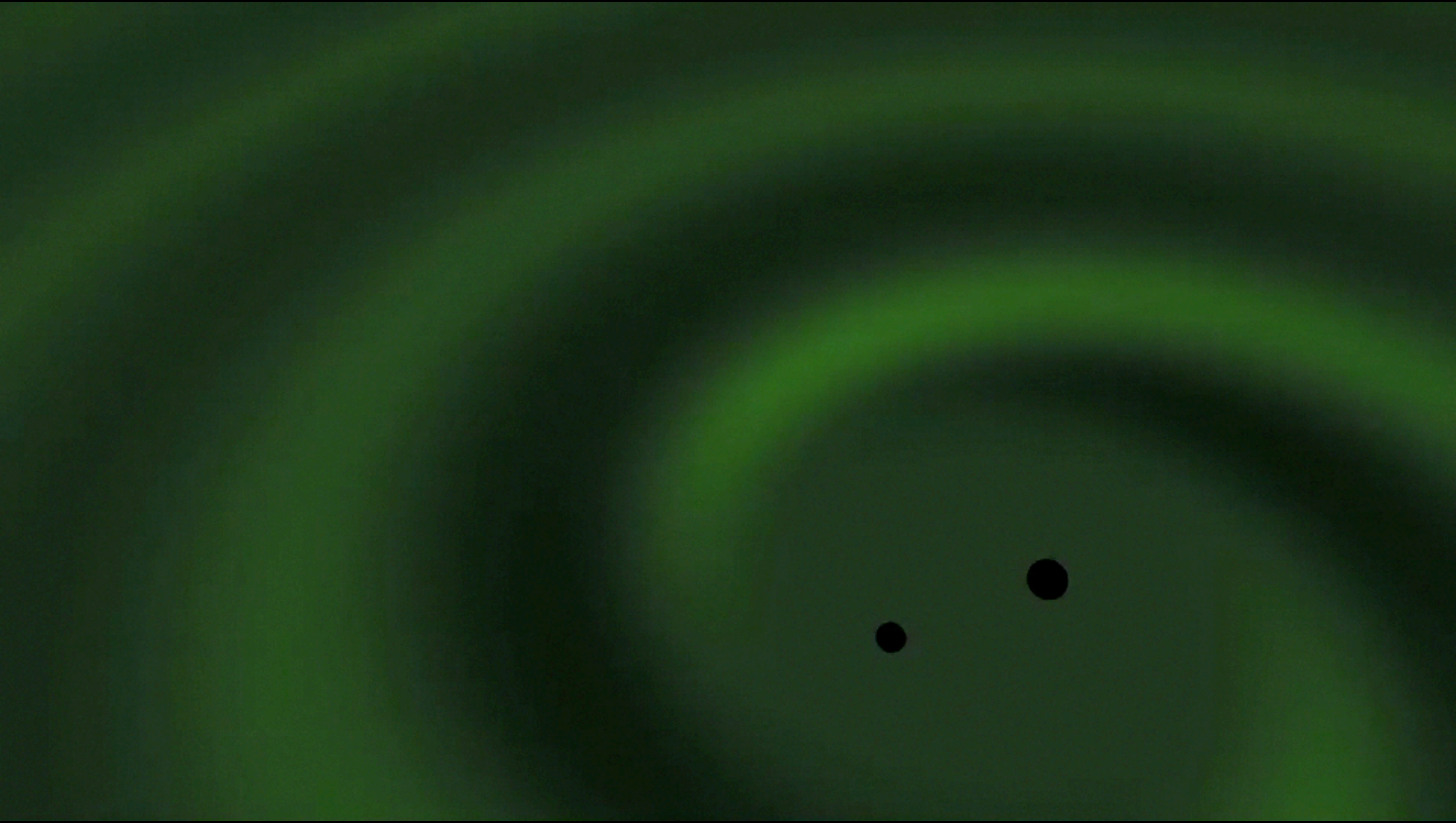


Time-frequency spectrograms



Made with GWpy by Duncan Macleod

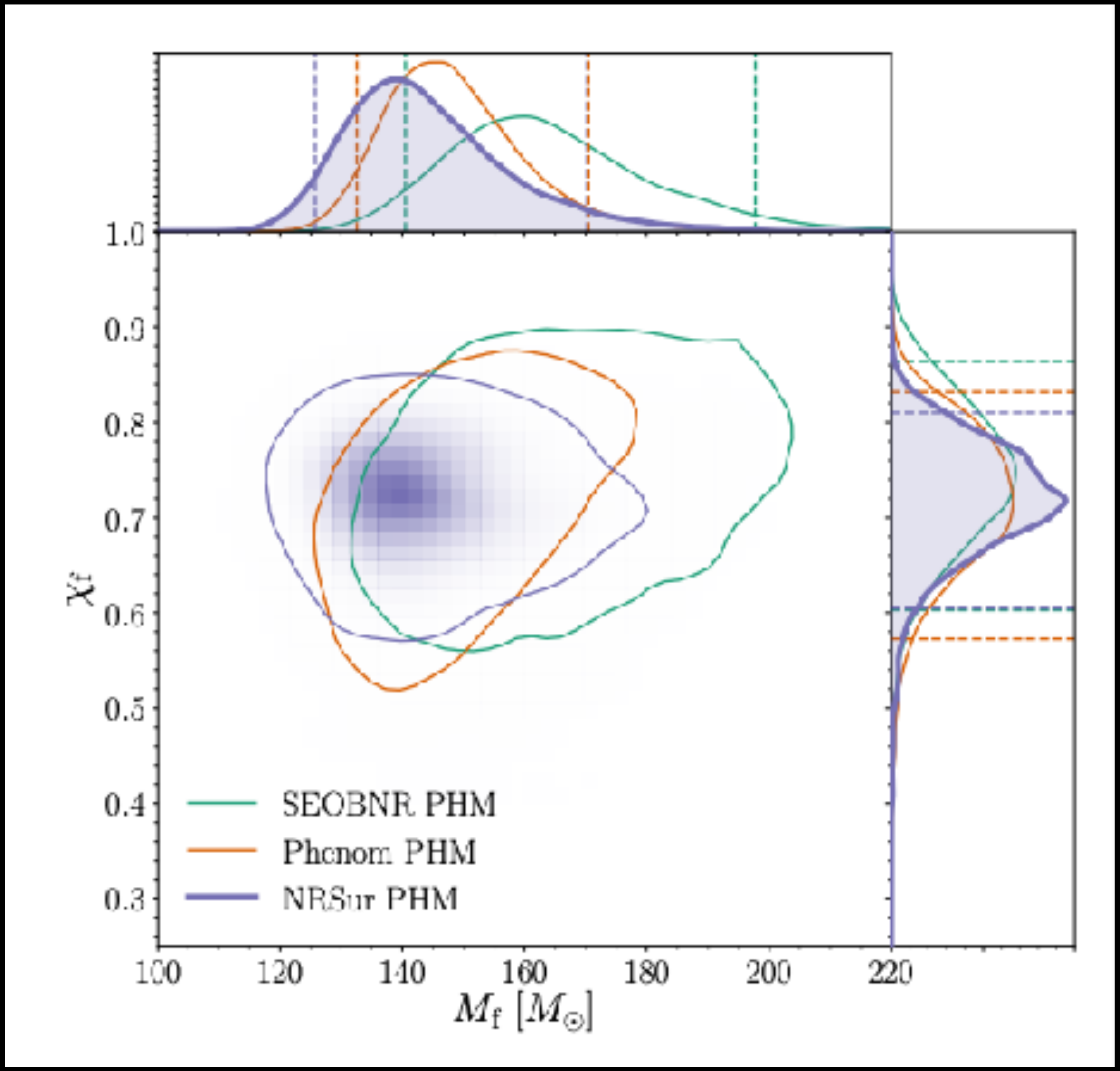
Extra slides


LIGO/Caltech

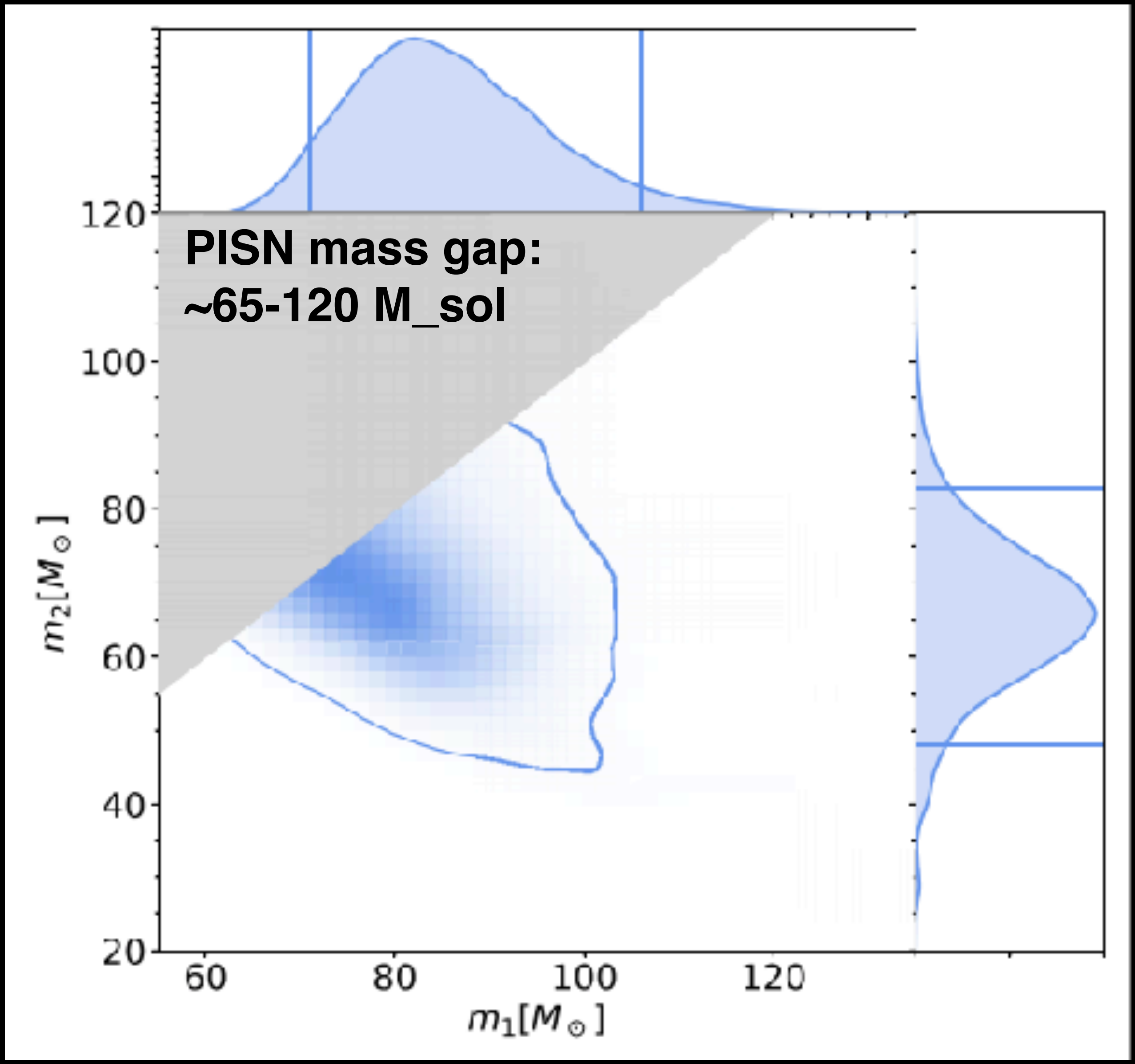
Major result from O3: GW190521

85, 66 solar mass BBH: First intermediate mass black hole detection!

Mass of final BH unequivocally >100 M_sol
~8 solar masses of energy released in GWs!



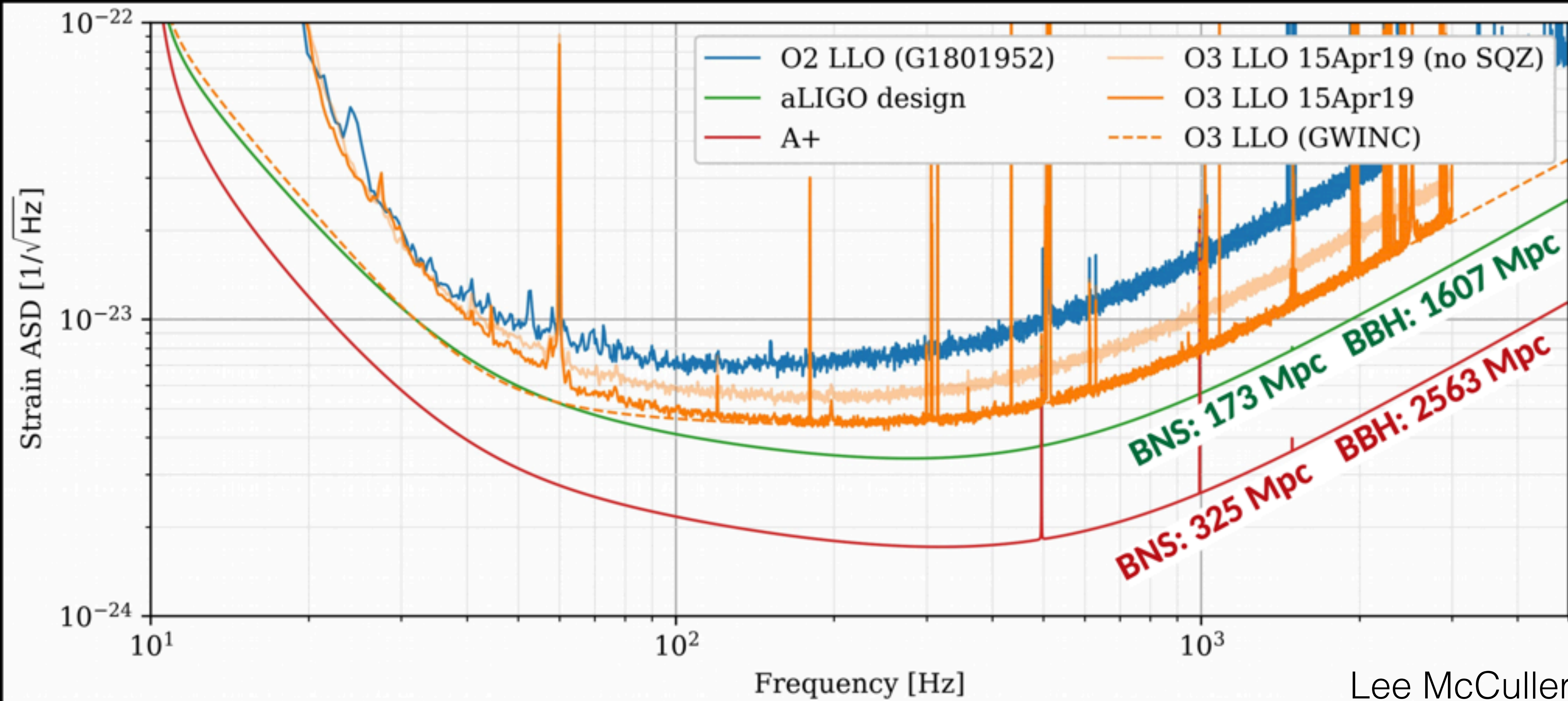
Primary mass in PISN mass gap!
0.32% probability below 65 M_sol



arxiv 2009.01190

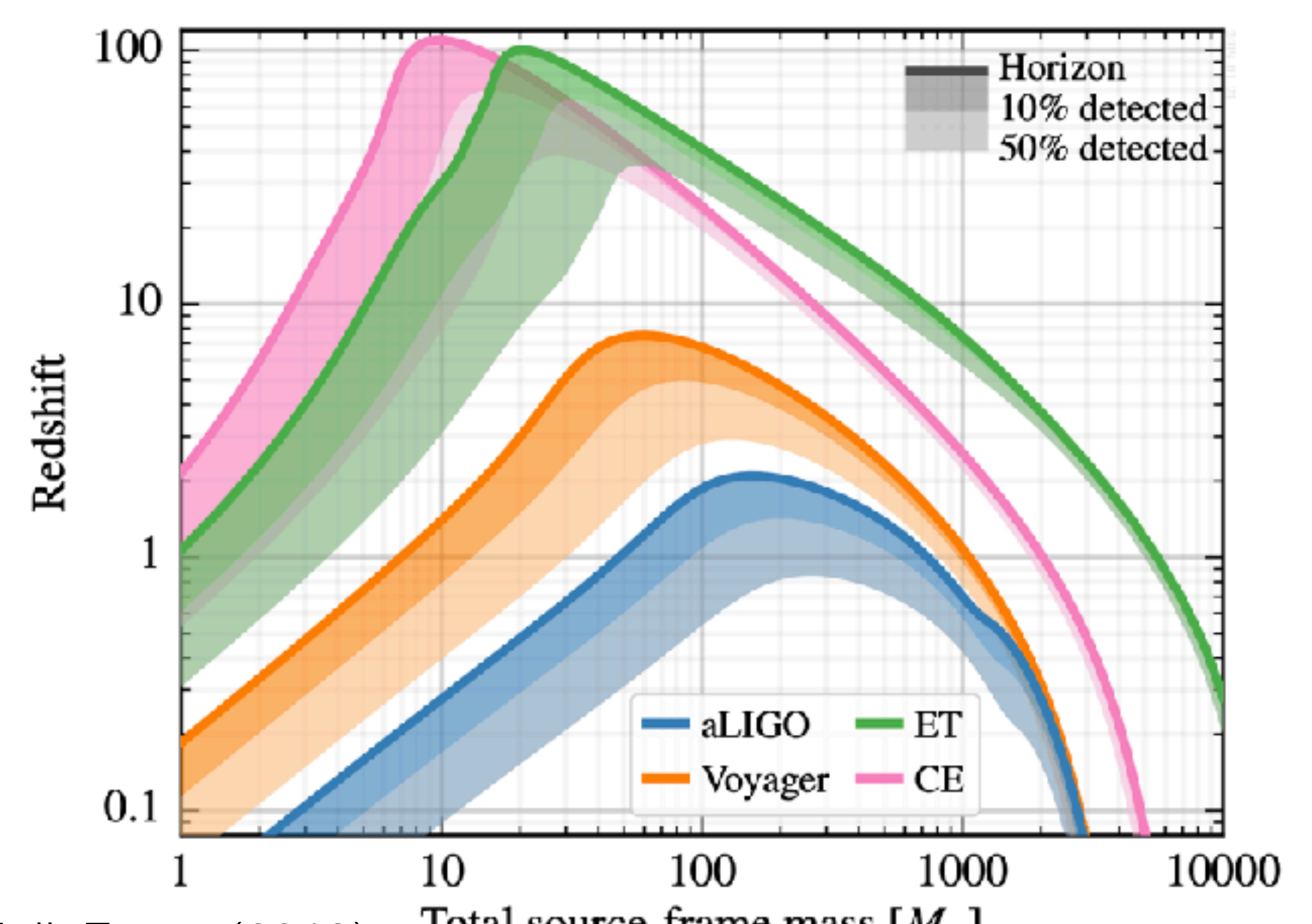
A+ by the mid 2020s

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



Lee McCuller

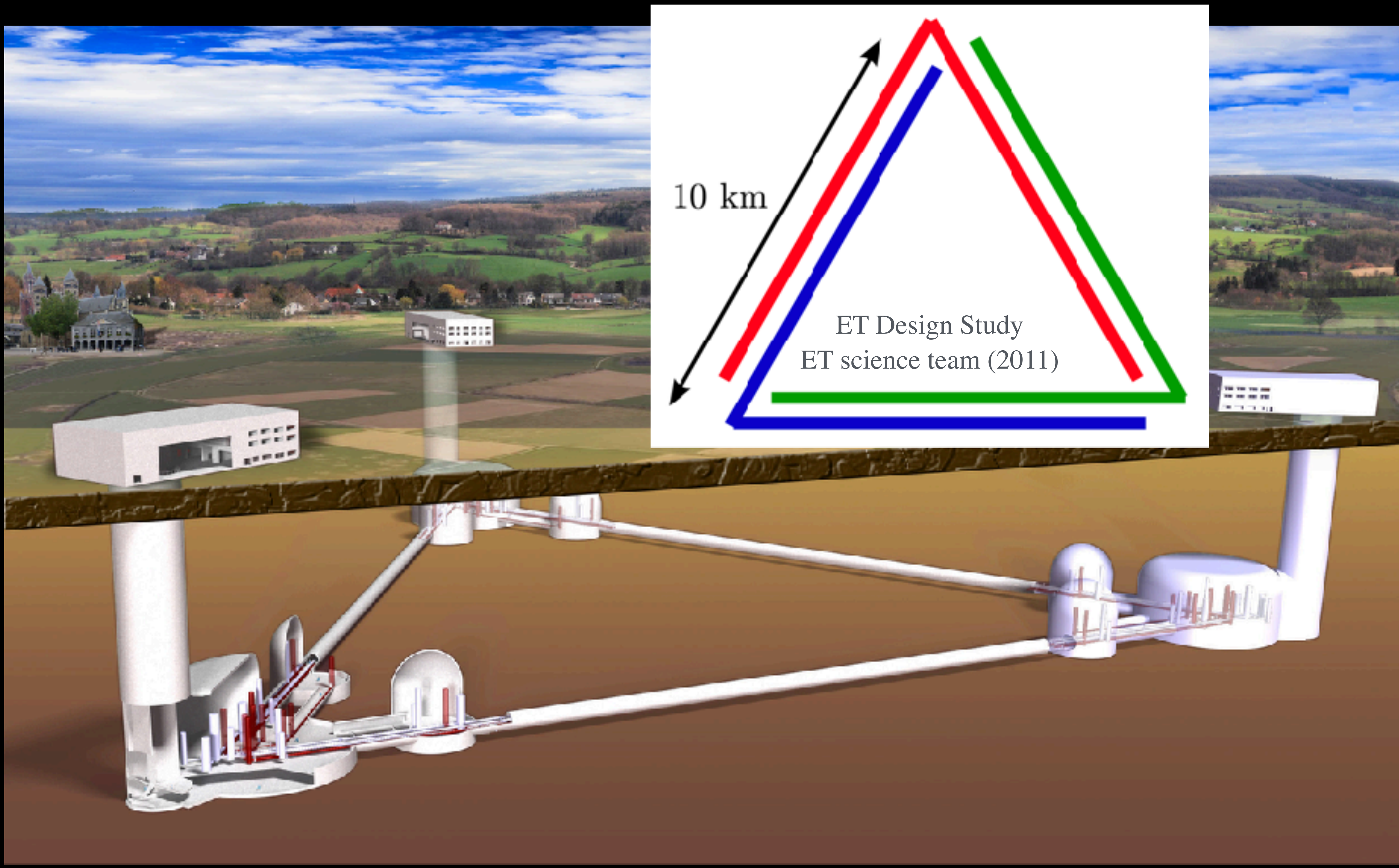
Detector range



Iall, Evans (2019)

- Thousands of high SNR events
- Precise tests of GR in highly curve spacetime
- New GW sources at high frequencies, including CCSNe
- All stellar-mass BBH mergers in the visible Universe!

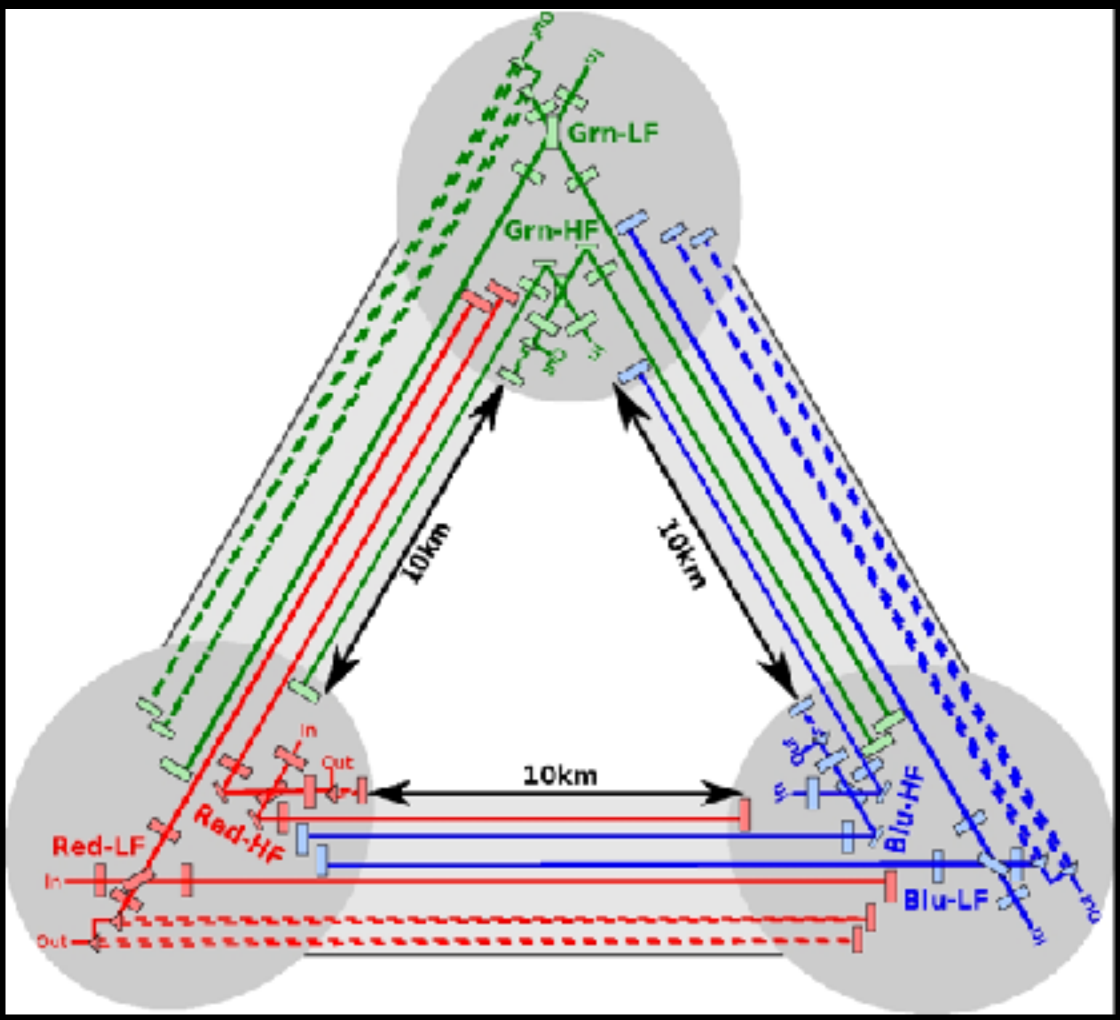
Einstein telescope

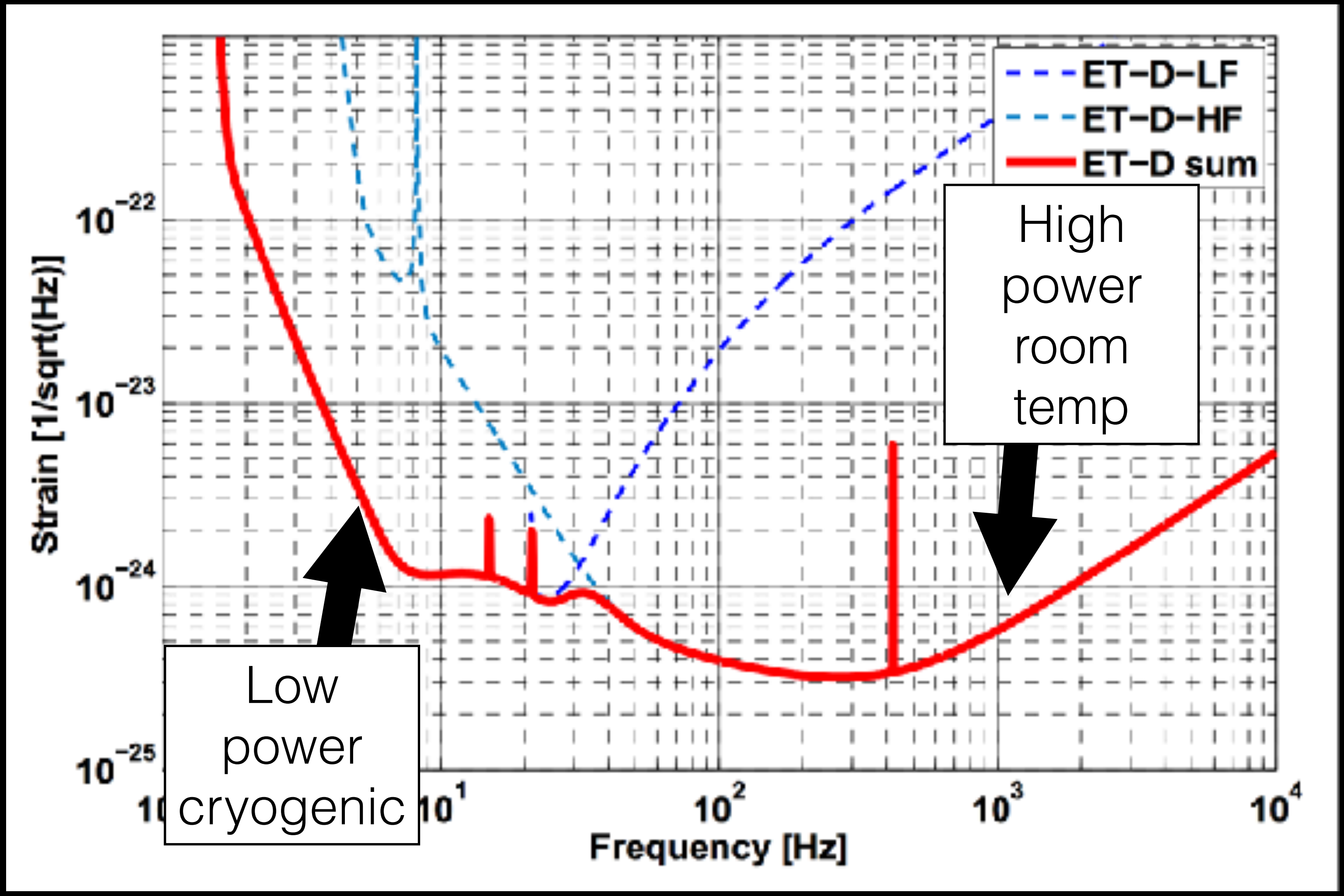


Source: http://www.et-gw.eu

Einstein telescope

Three detectors…**Six interferometers**

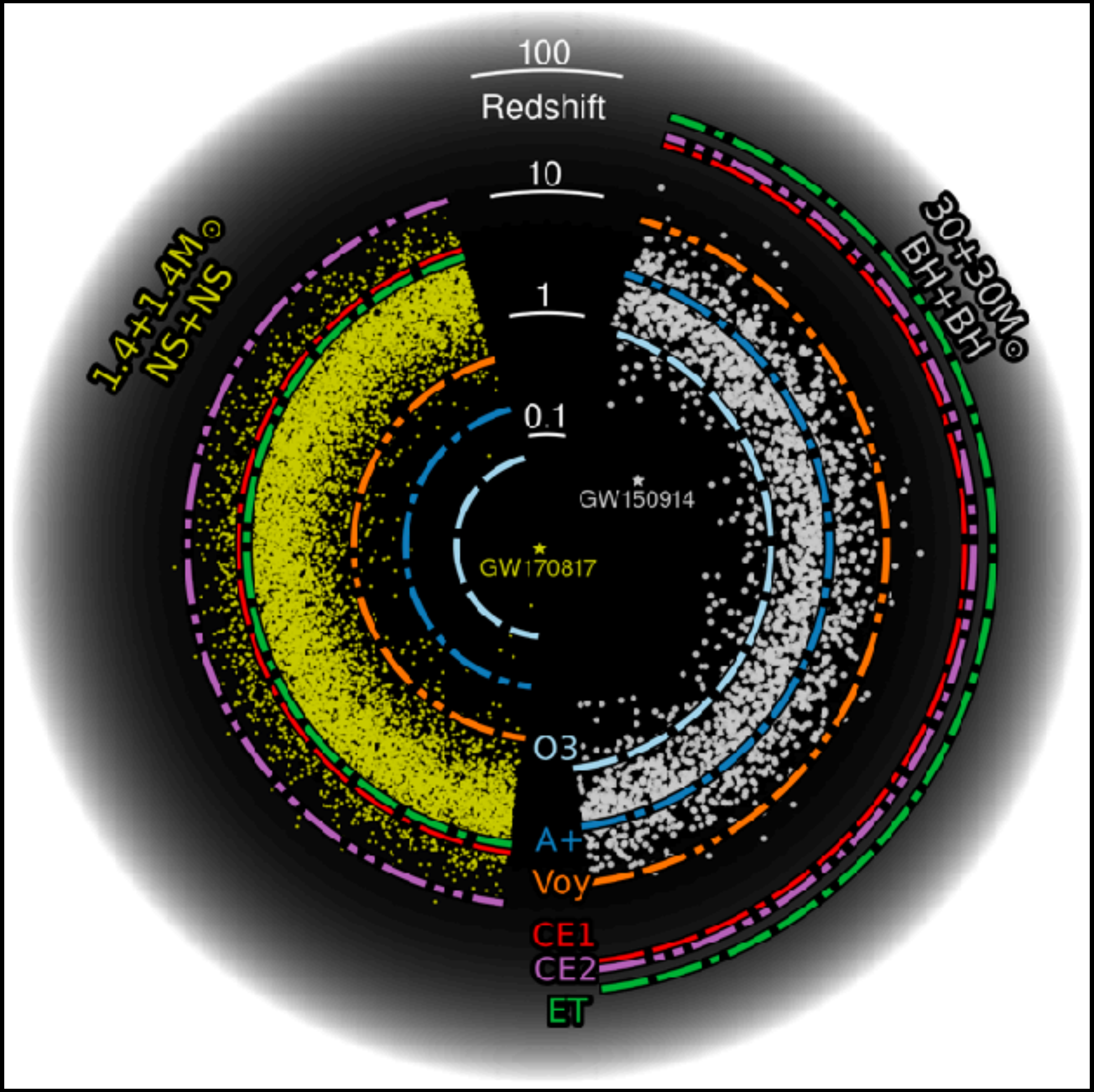




Source: http://www.et-gw.eu

ET Design Study, ET science team (2011)

The range of next generation GW detectors

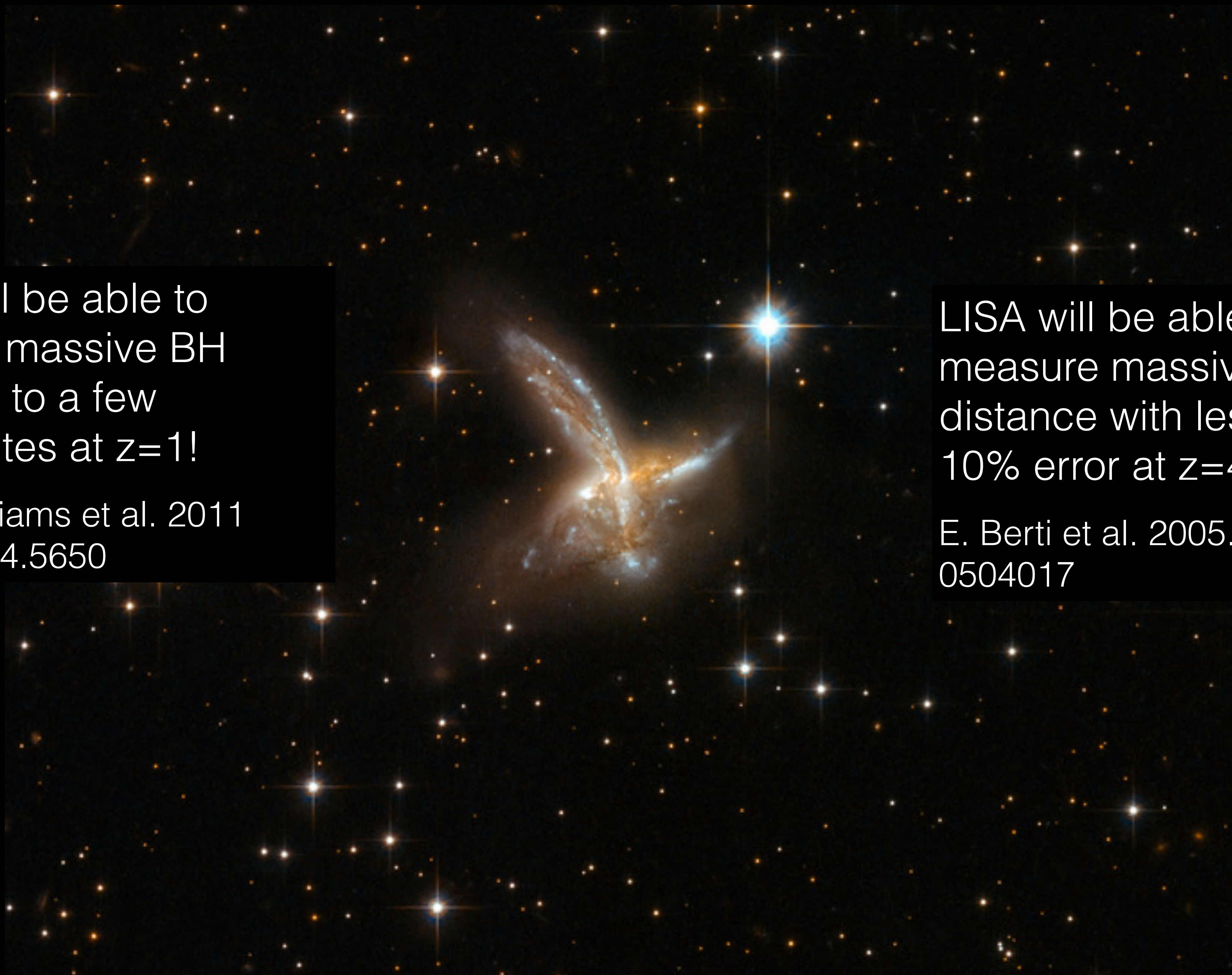


Hall and Evans, 2019

Galaxy formation and evolution

LISA will be able to localize massive BH sources to a few arcminutes at z=1!

S. McWilliams et al. 2011 arXiv 1104.5650

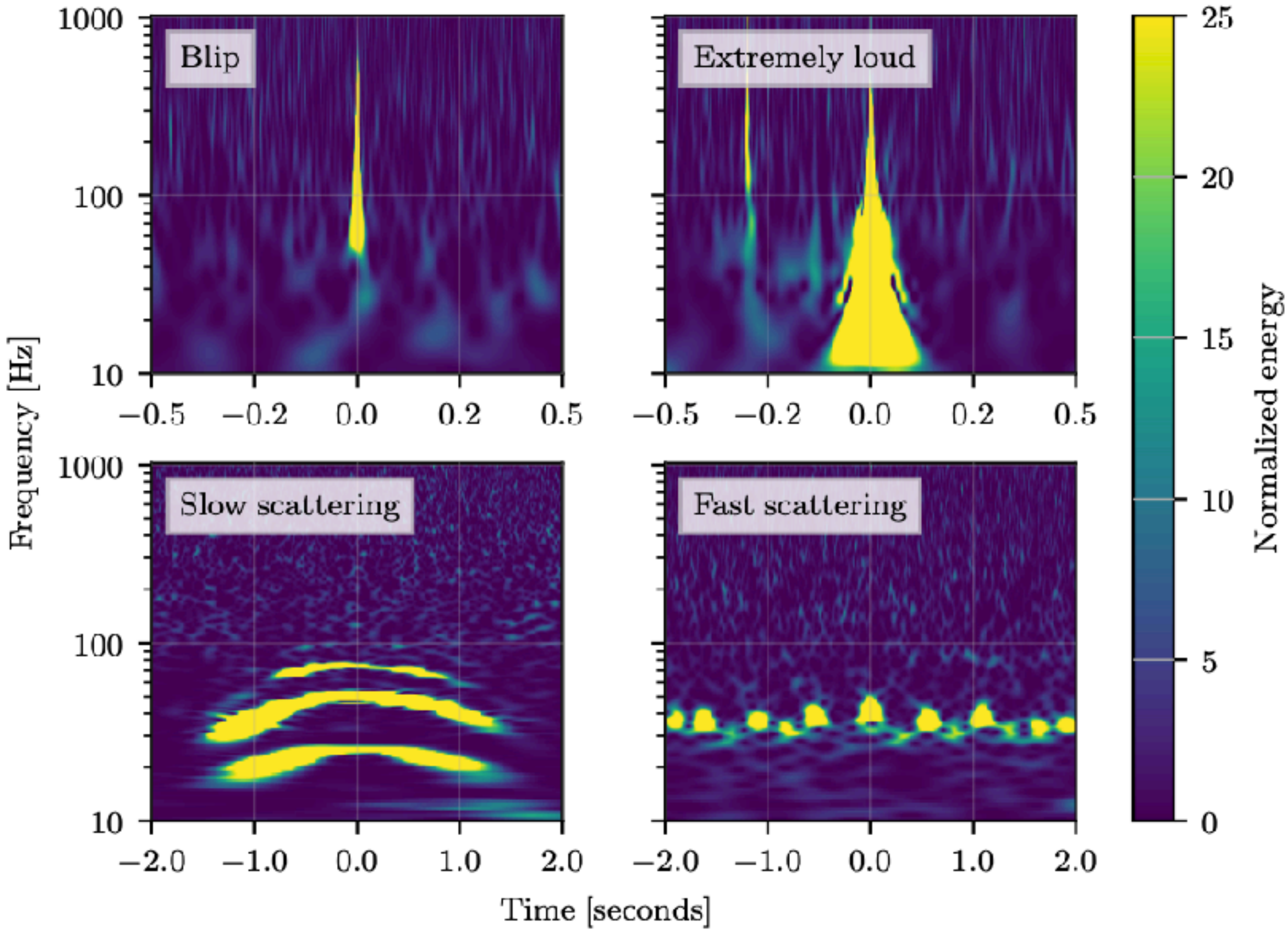


LISA will be able to measure massive BH distance with less than 10% error at z=4!

E. Berti et al. 2005. arXiv 0504017

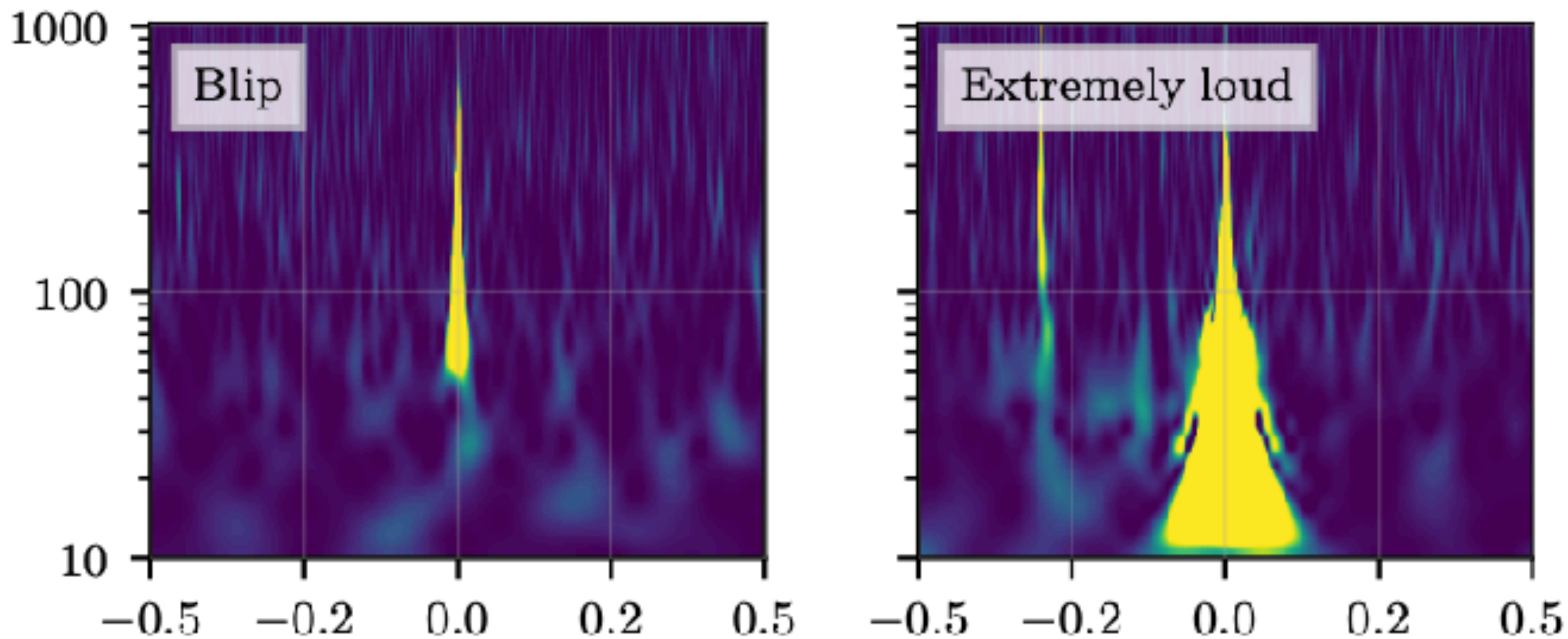
Hubble Interacting Galaxy ESO 593-8. Image: hubblesite.org

"Worst offender" glitches



Davis et al. CQG 2021

"Worst offender" glitches



Blips
- Few known witnesses
- Shared time-frequency morphology with high mass CBC signals

Extremely loud
- Much more common in O3 than in O2 for LIGO detectors
- Few clear witnesses
- Pollute PSD estimation

Davis et al. CQG 2021

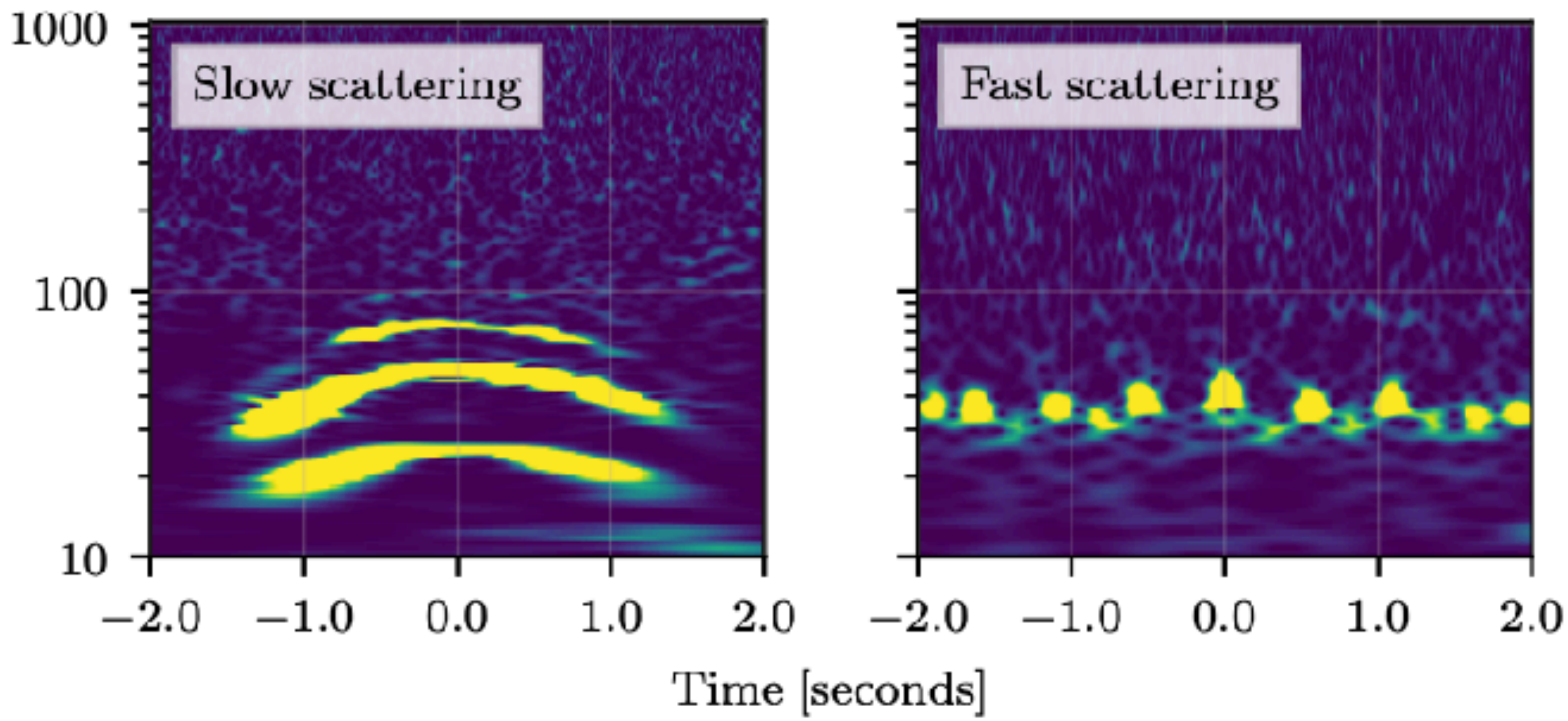
“Worst offender” glitches

Slow scattering

- Well understood witnesses and coupling
- Still difficult/impractical to veto because they are at times so frequent

Fast scattering

- Modulated fast scattering
- Troublesome for lower mass CBC templates
- Most comment LIGO-Livingston: thought to be understood for O3



Davis et al. CQG 2021

Estimating the PSD

Step 0: Take a **Fast Fourier Transform (FFT)**, which is any algorithm useful for quickly estimating the **Discrete Fourier Transform** that describes a **discrete time series**.

$$X_k = \sum_{n=0}^{N-1} x_n \cdot e^{-\frac{i2\pi}{N}kn}$$
$$= \sum_{n=0}^{N-1} x_n \cdot [\cos(2\pi kn/N) - i \cdot \sin(2\pi kn/N)],$$

Need to shift our thinking to discretized data; **frequency bins instead of continuous smooth sinusoids**

Estimating the PSD

Step 1: Apply a window to your data (if it's linear! as a time series is) to prevent **spectral leakage** from the assumption the signal is periodic.

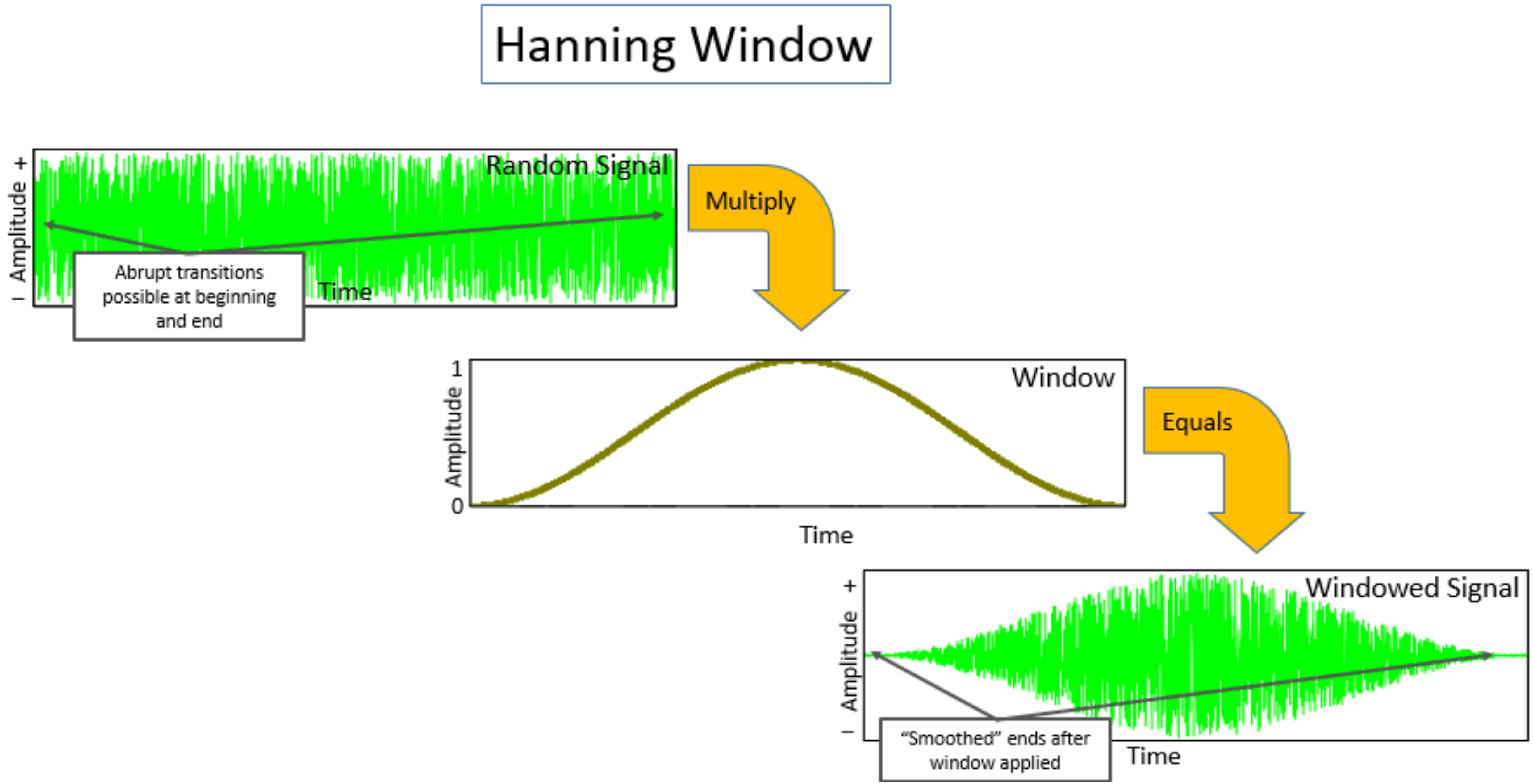


Image: Siemens.

Estimating the PSD

A single windowed FFT is unbiased (i.e. will give the correct mean PSD), but has **high variance**.

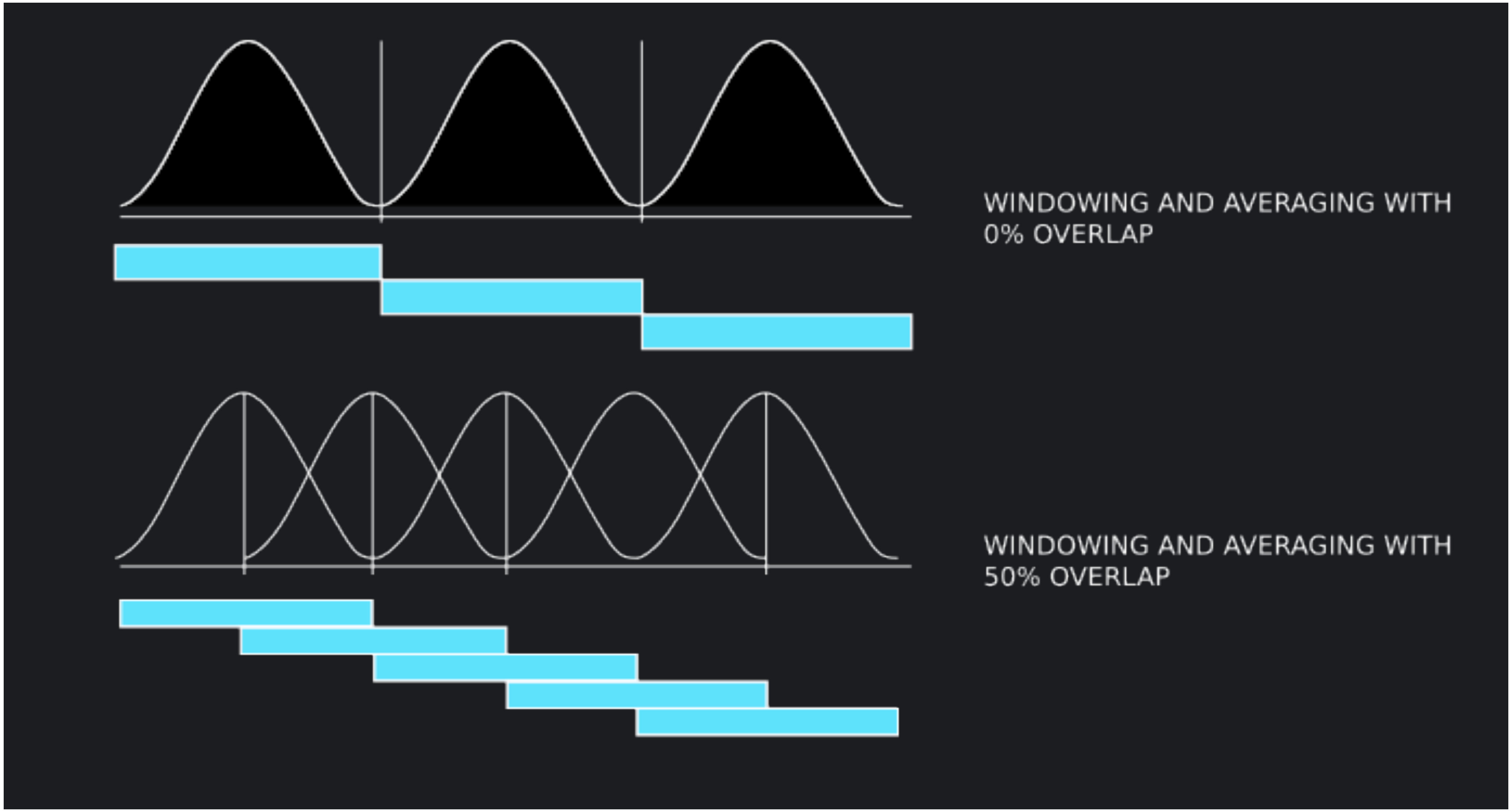
Solution: average several FFTs!

Step 2: Divide your data into shorter time segments; take a windowed FFT of each, and average these together.

Note you lose some frequency resolution this way.

Welch's method averages the mean value for each frequency bin across FFTs, with some overlap in the data analyzed.

Averaging FFTs



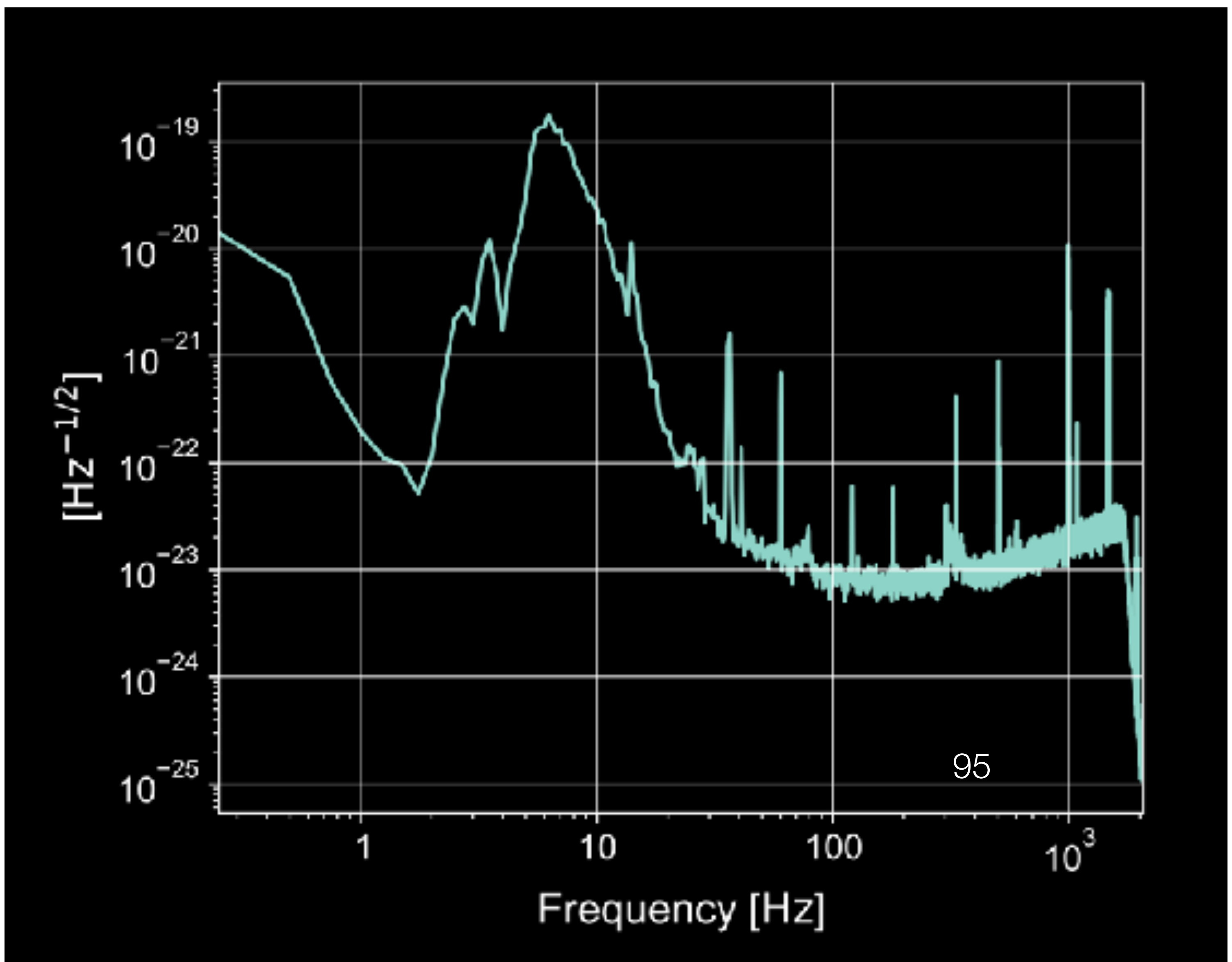
https://www.dewesoft.com/pro/course/spectral-analysis-using-the-fft-29?page=10

Signal processing with GWpy

GWpy provides **FFT wrappers** to estimate frequency-domain content of data:

FFT length (s) ↘ ↙ Overlap between averages (s)

```
>>> asd = data.asd(4, 2)
```



Can also specify:

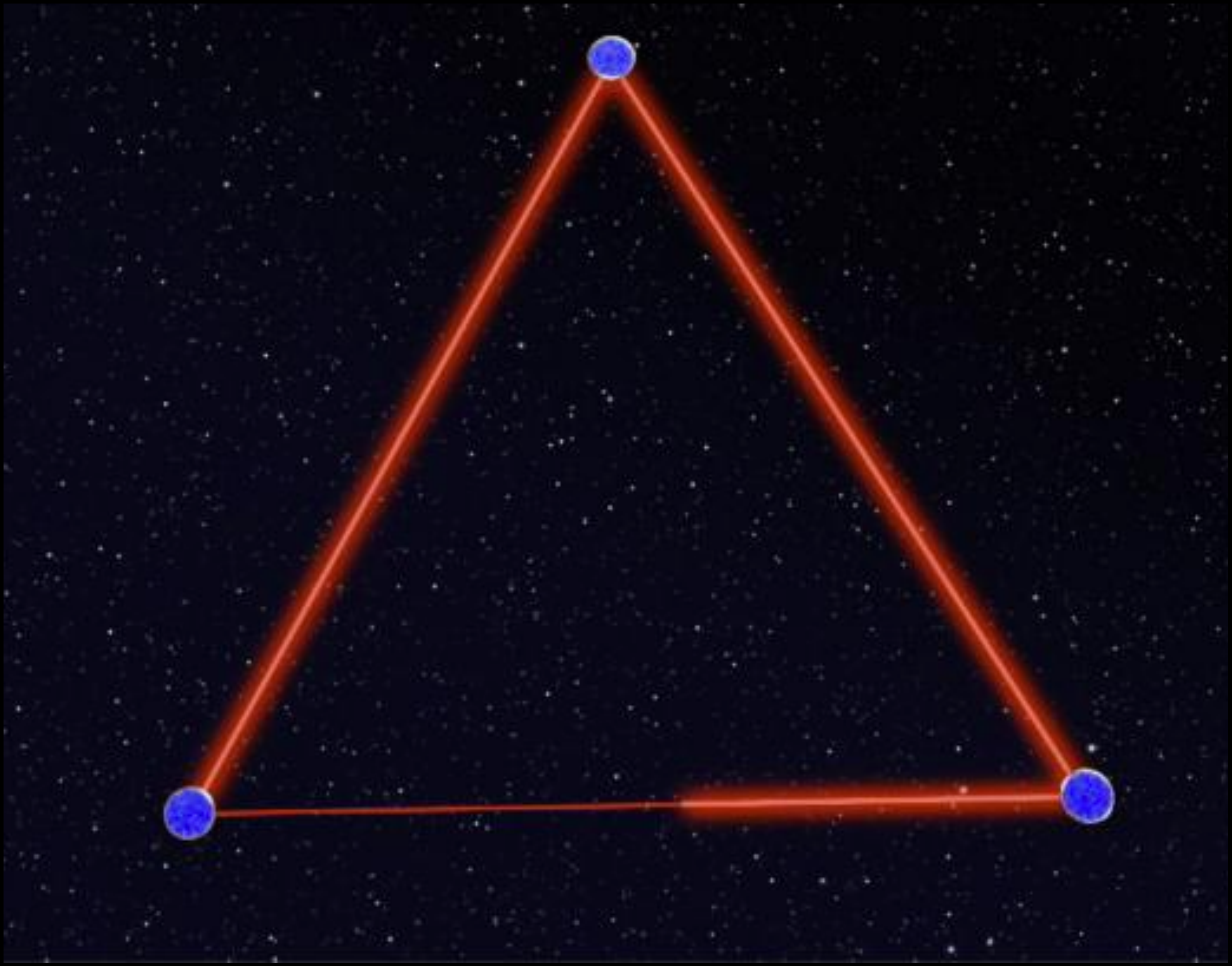
Time window
(default = Hanning)

Averaging method
(default = Welch)

The LISA mission

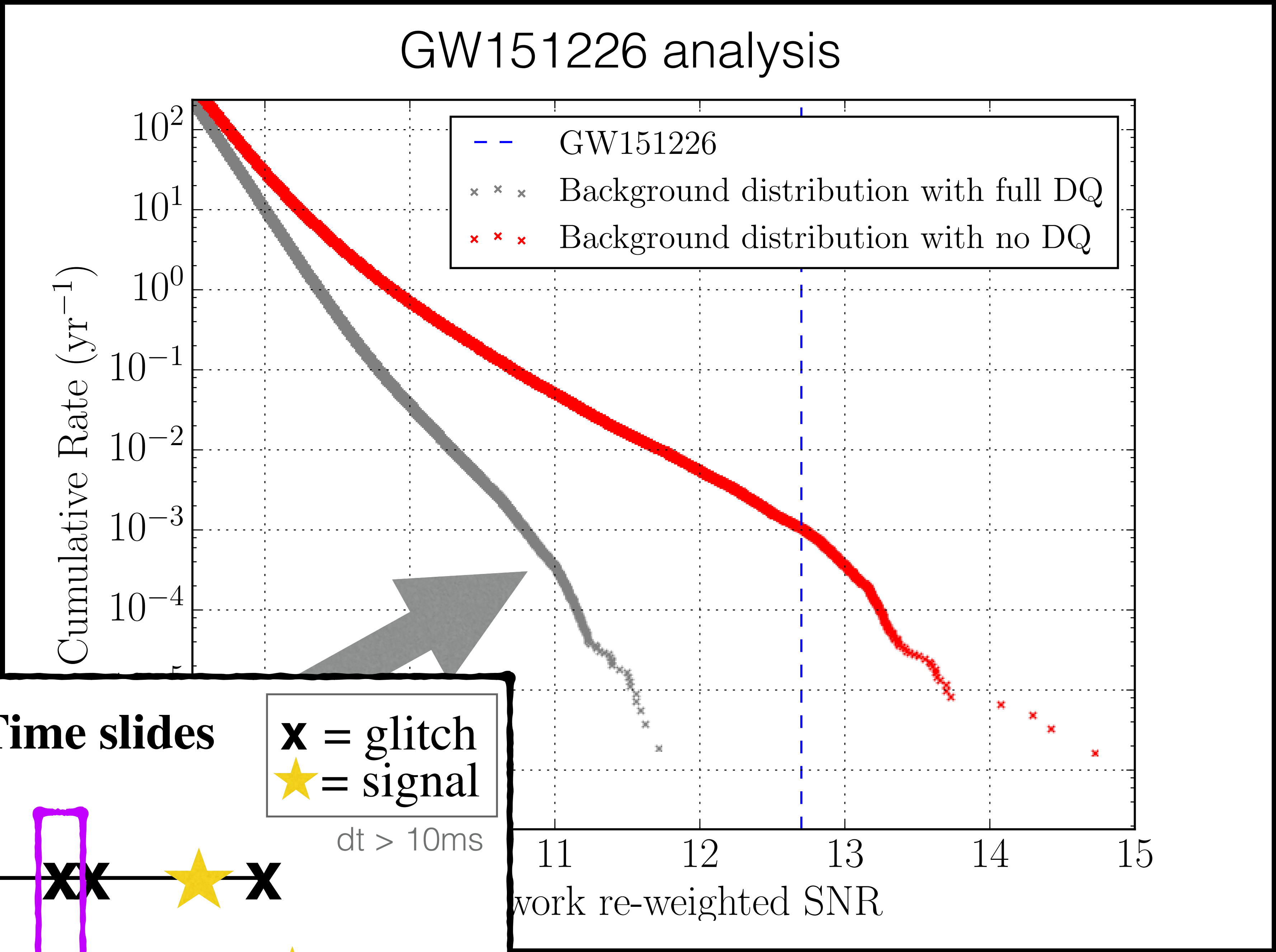
NASA

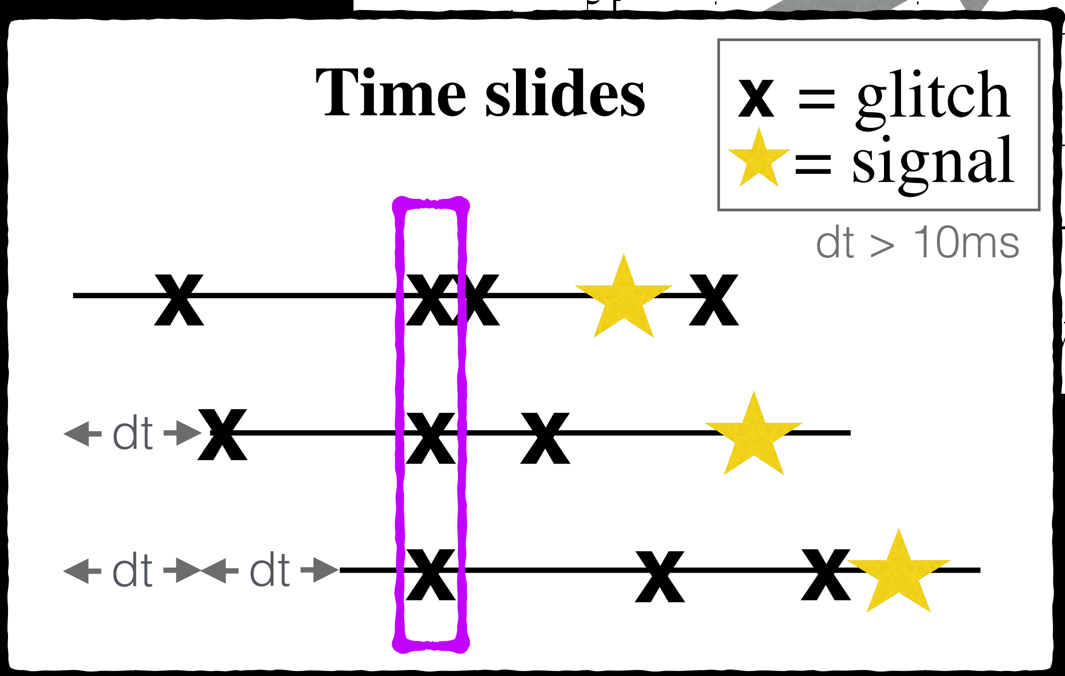
Beyond terrestrial detectors



ESA

The significance of a detected event



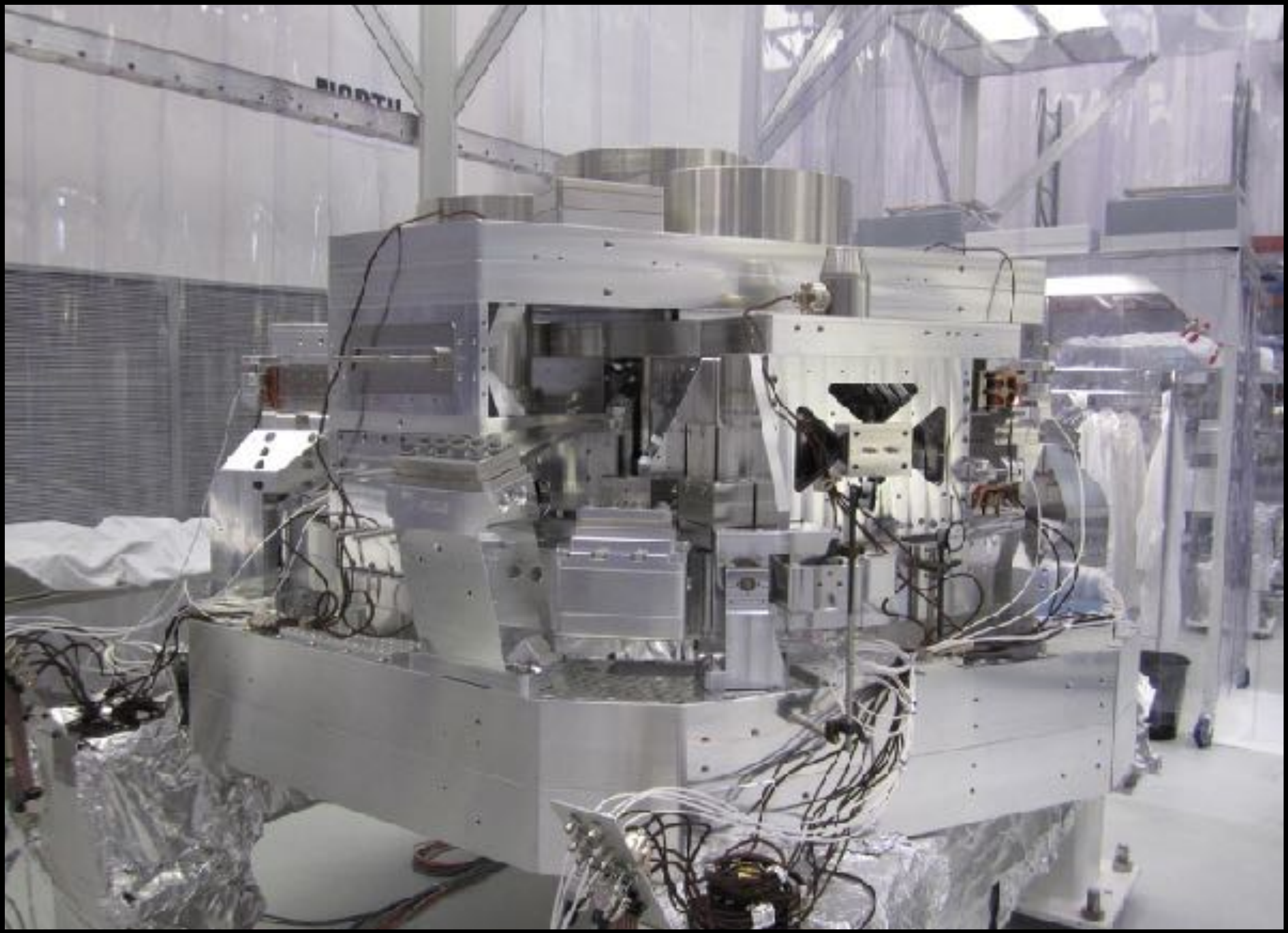


B.P Abbott et al. CQG (2018)

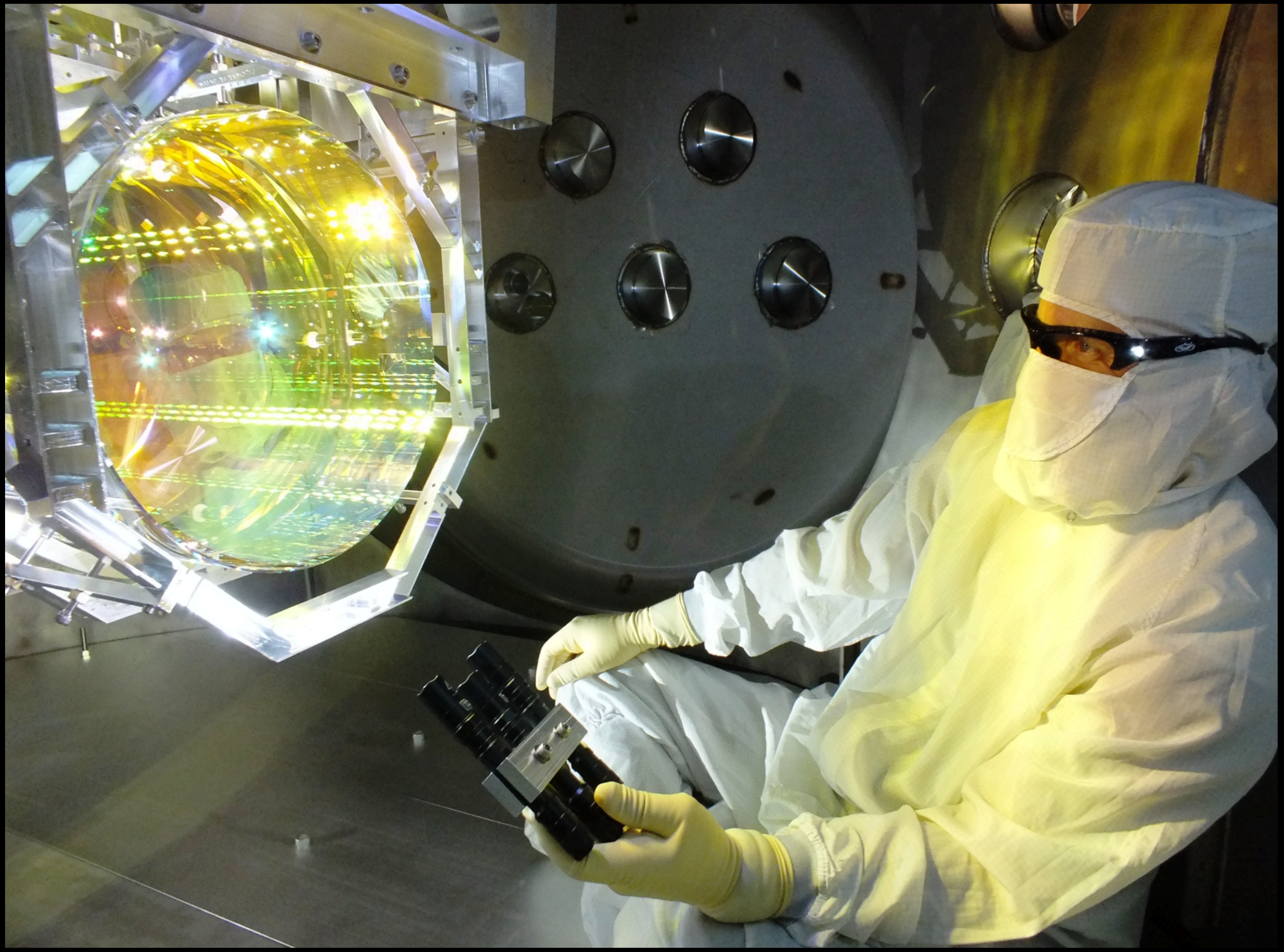
Dynamics of dead stars

Seismic isolation: active isolation

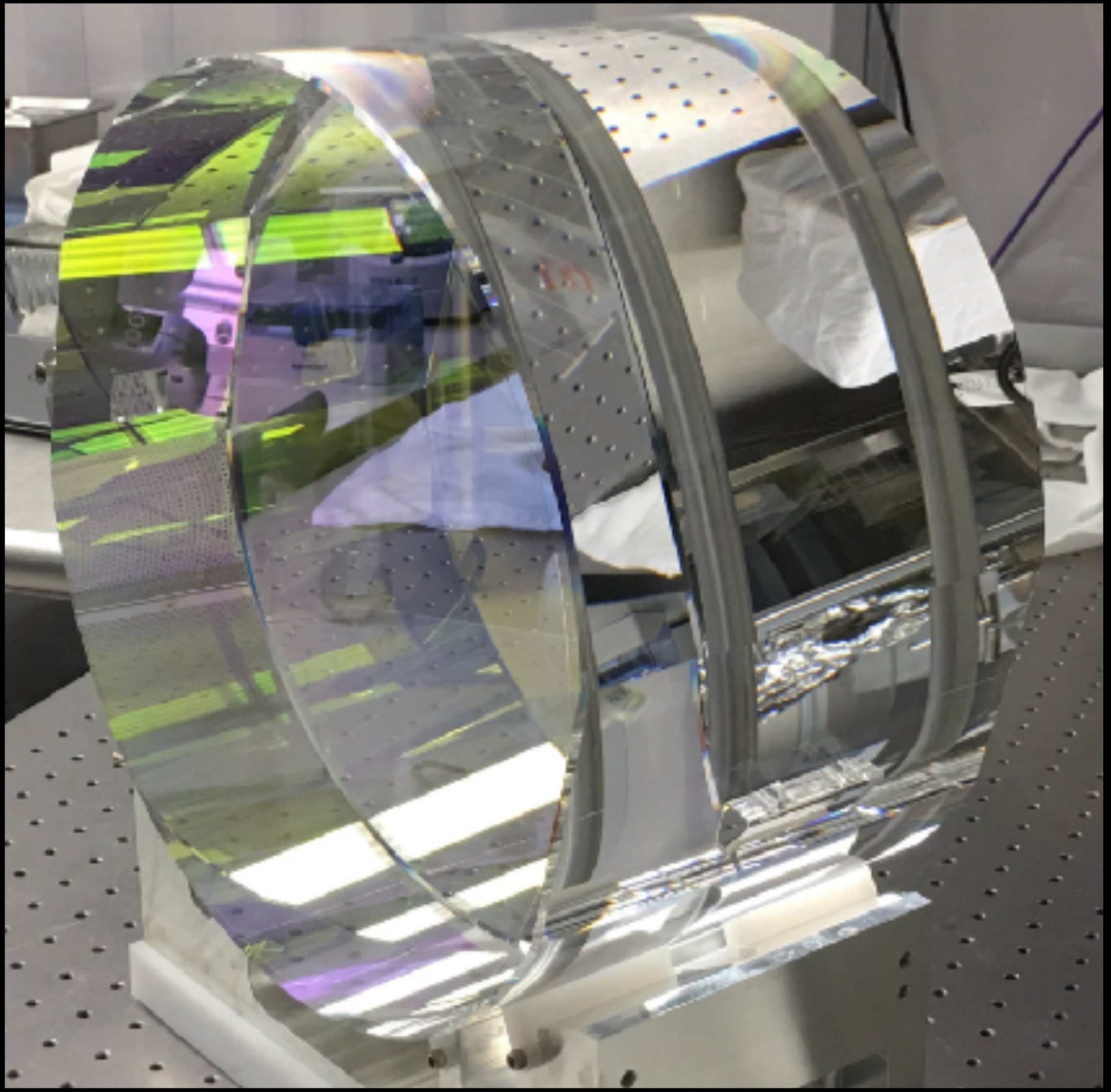
LIGO/Caltech



Advanced LIGO optics



M. Heintze

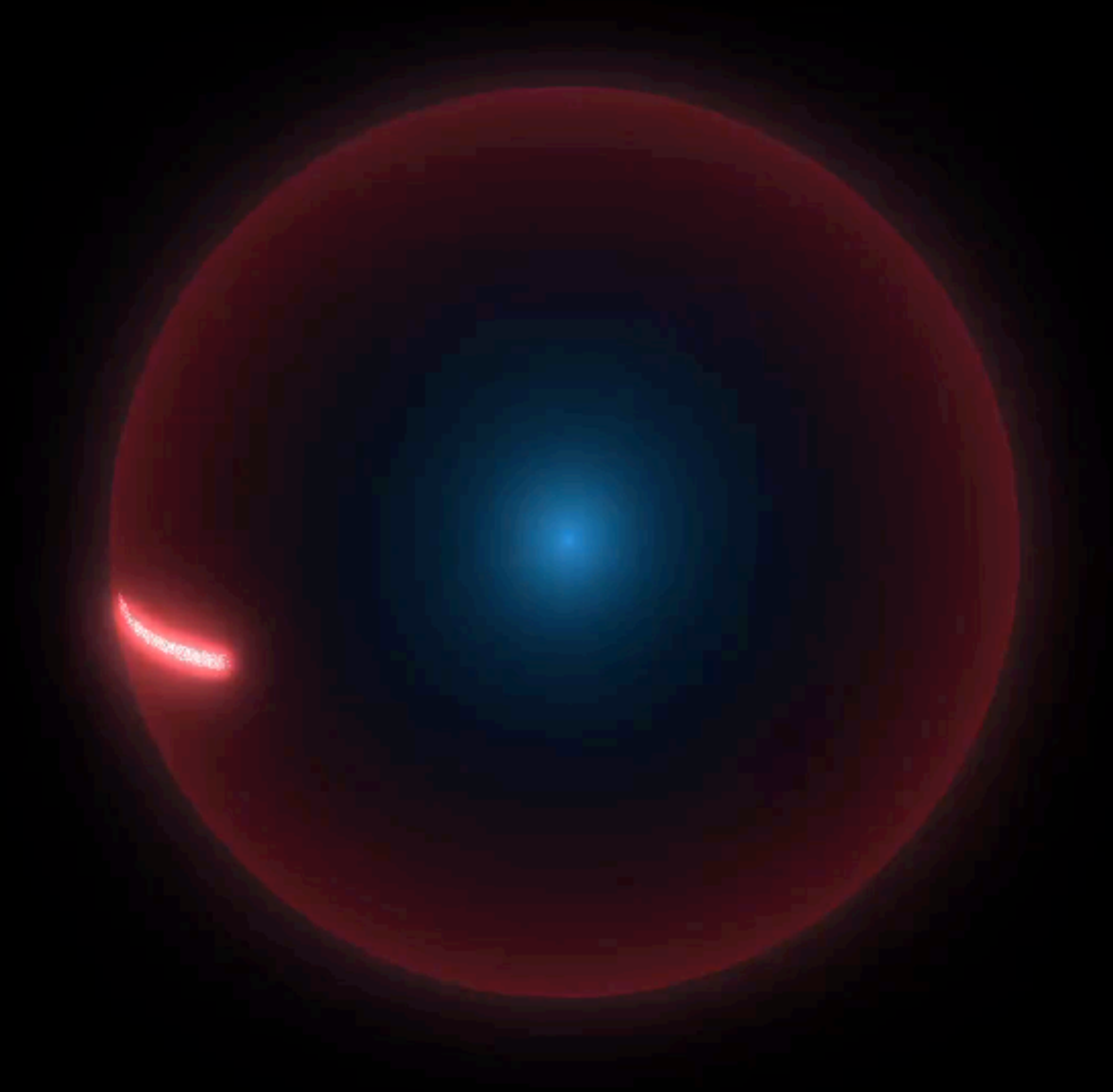


K. Toland

The Advanced LIGO input laser

M. Heintze

How sensitive is the LIGO experiment?



LIGO/Caltech