

Gravitational Wave Observatories III: Ground Based Interferometers

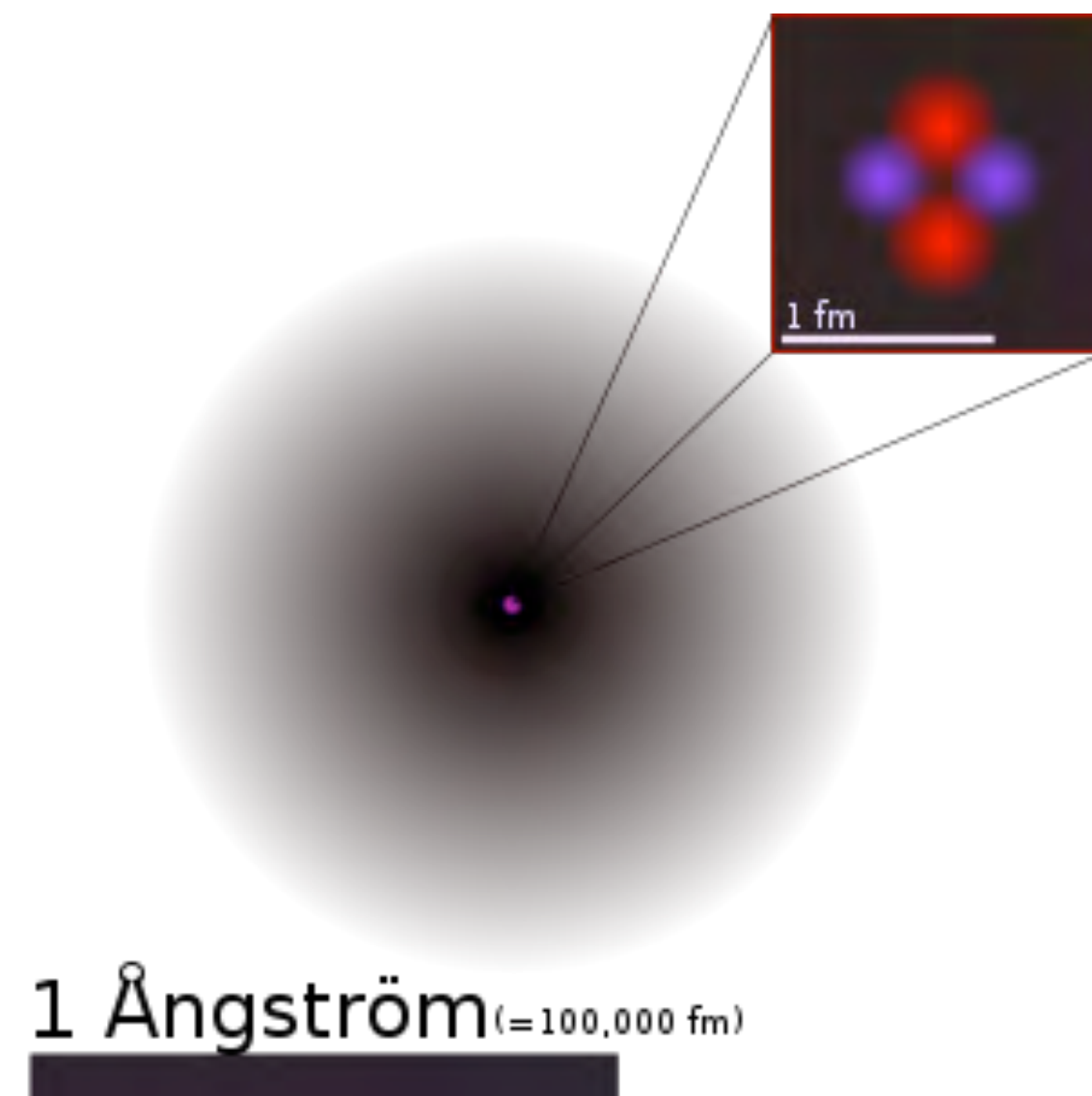
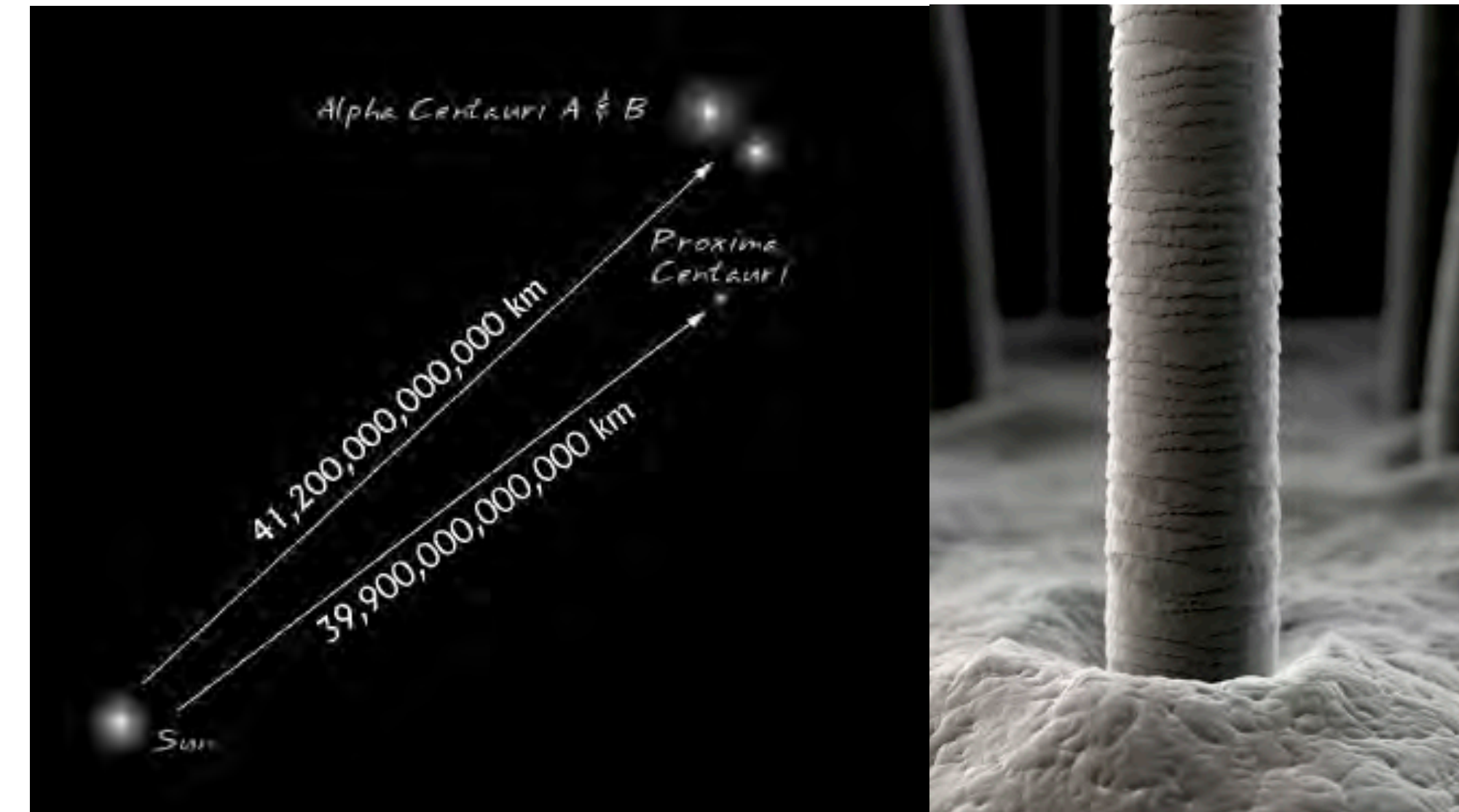
Neil J. Cornish

Outline

- Interferometer design
- Sources of noise
- LIGO data analysis, theory and search results
- Astrophysical rates

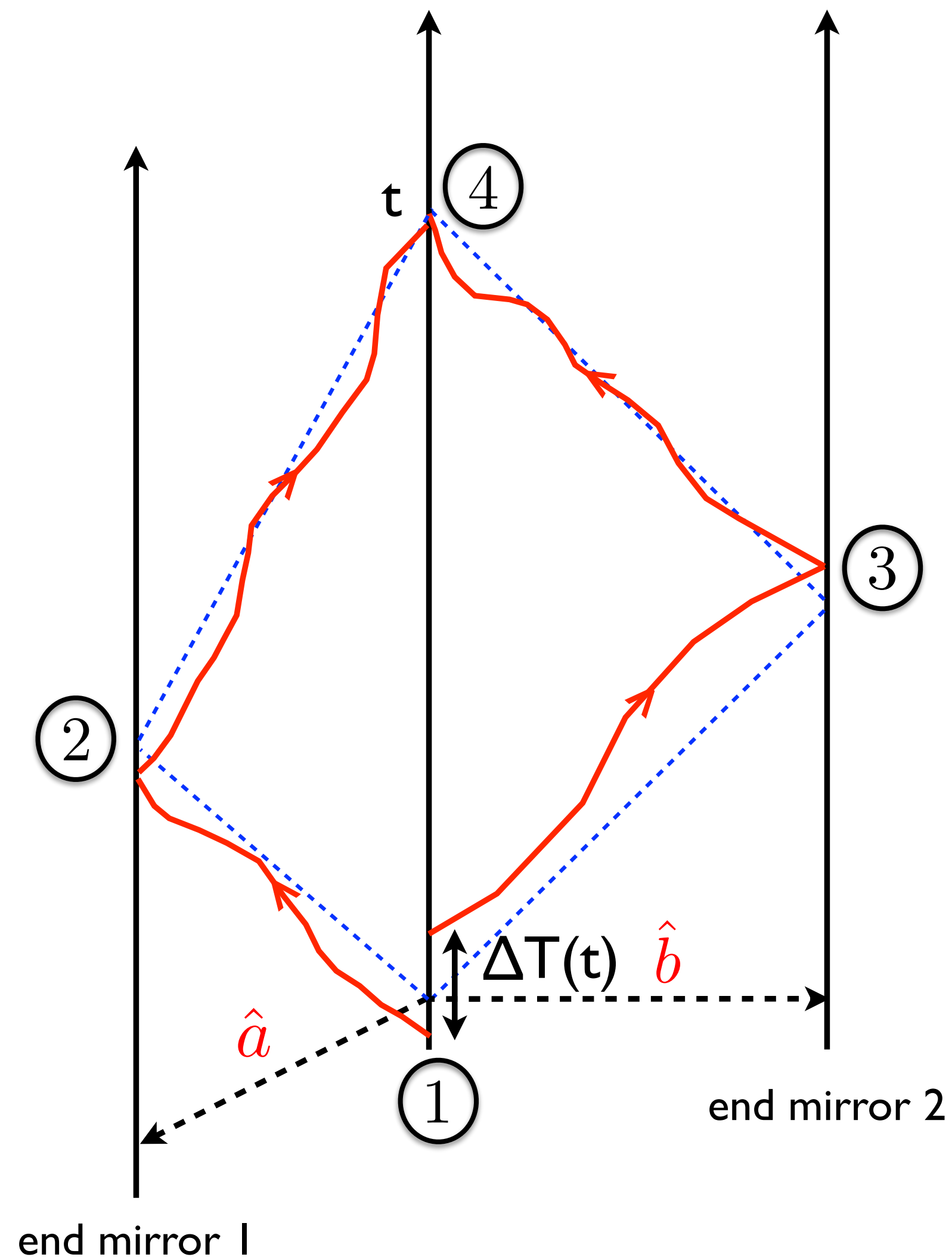


Gravitational Wave Telescopes



Interferometer Design

$$\Phi(t) = 2\pi\nu_0\Delta T(t)$$



Consideration 1

$$\Delta T \propto h L \quad \text{for} \quad f_{\text{gw}} < \frac{c}{L}$$

Want L as large as possible up to $L \sim \frac{c}{10^3 \text{ Hz}} = 300 \text{ km}$

Expensive!

Solution: folded arms

Consideration 2

$$\Phi \propto \nu_0 \Delta T$$

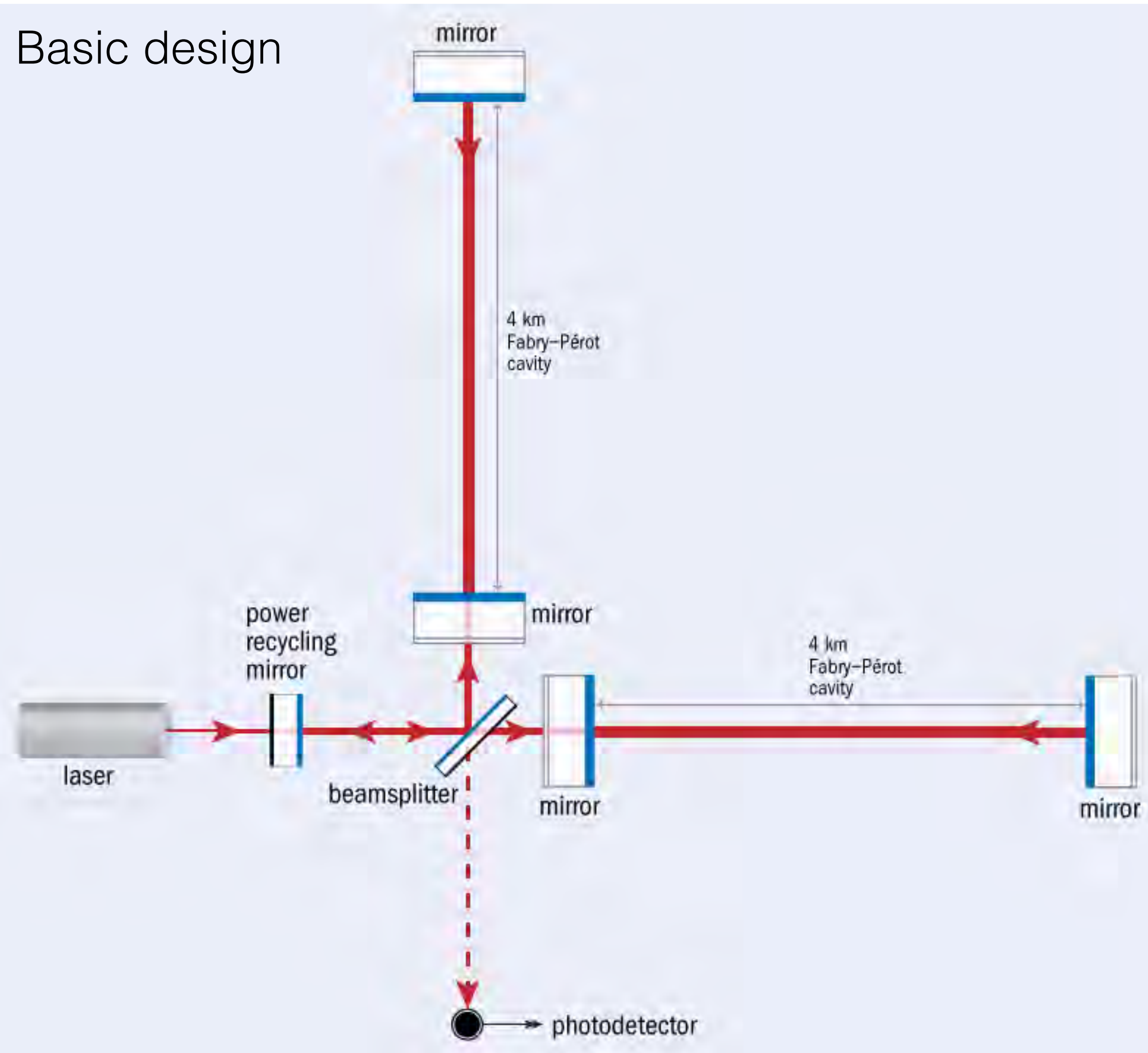
Fluctuations in Laser frequency can masquerade as GW signal

Partial Solution: Highly stable lasers

Solution: Michelson topology - cancel laser frequency noise

Interferometer Design

Basic design



The 4 km Fabry-Perot cavities effectively fold the arms

Can calculate the response using basic E&M, electric field transmission and reflection coefficients at each mirror. (See Maggiore's text)

In the long wavelength limit, phase shift is

$$|\Delta\Phi_{\text{FP}}| = \left(\frac{\nu_0 h L}{c} \right) \left[\frac{8\mathcal{F}}{\sqrt{1 + (f_{\text{gw}}/f_p)^2}} \right]$$

$$\mathcal{F} = \frac{\pi \sqrt{r_1 r_2}}{1 - r_1 r_2}$$

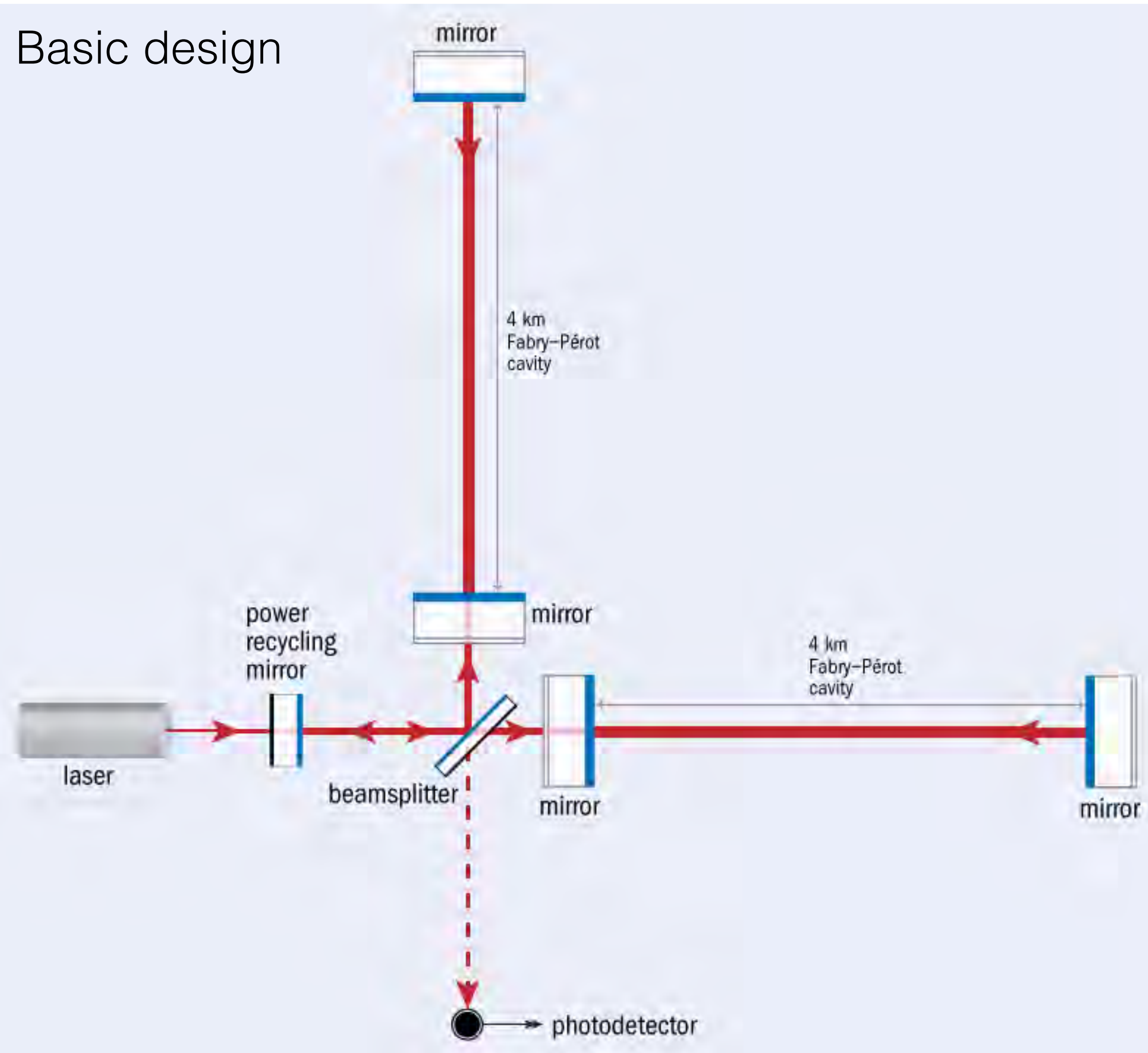
Cavity Finesse

$$f_p = \frac{1}{4\pi\tau_s} \approx \frac{c}{4\mathcal{F}L}$$

Pole frequency

Single Fabry-Perot Cavity

Basic design



$$|\Delta\Phi_{\text{FP}}| = \left(\frac{\nu_0 h L}{c} \right) \left[\frac{8\mathcal{F}}{\sqrt{1 + (f_{\text{gw}}/f_p)^2}} \right]$$

$$\mathcal{F} = \frac{\pi \sqrt{r_1 r_2}}{1 - r_1 r_2}$$

Cavity Finesse

$$f_p = \frac{1}{4\pi\tau_s} \approx \frac{c}{4\mathcal{F}L}$$

Pole frequency

Reflectivities are very close to unity

e.g. advanced LIGO $\mathcal{F} = 450$ $f_p = 42 \text{ Hz}$

Note that increasing the Finesse improves the low frequency sensitivity (good), but lowers the pole frequency (bad)

Advanced LIGO gets around this problem by using signal recycling

Michelson Interferometer with coupled Fabry-Perot Cavities

The actual LIGO design is much more complicated. FP cavities are coupled by a power recycling and signal recycling mirrors

There is a common mode and a differential mode

$$L_+ = \frac{L_1 + L_2}{2} \quad L_- = \frac{L_1 - L_2}{2}$$

Differential mode contains the GW signal

$$f_- = \frac{2}{4\pi L_+} \ln \left(\frac{1 - r_i r_s}{r_e r_i - r_e r_s (t_i^2 + r_i^2)} \right)$$

i = input mirror

e = end mirror

s = signal recycling mirror

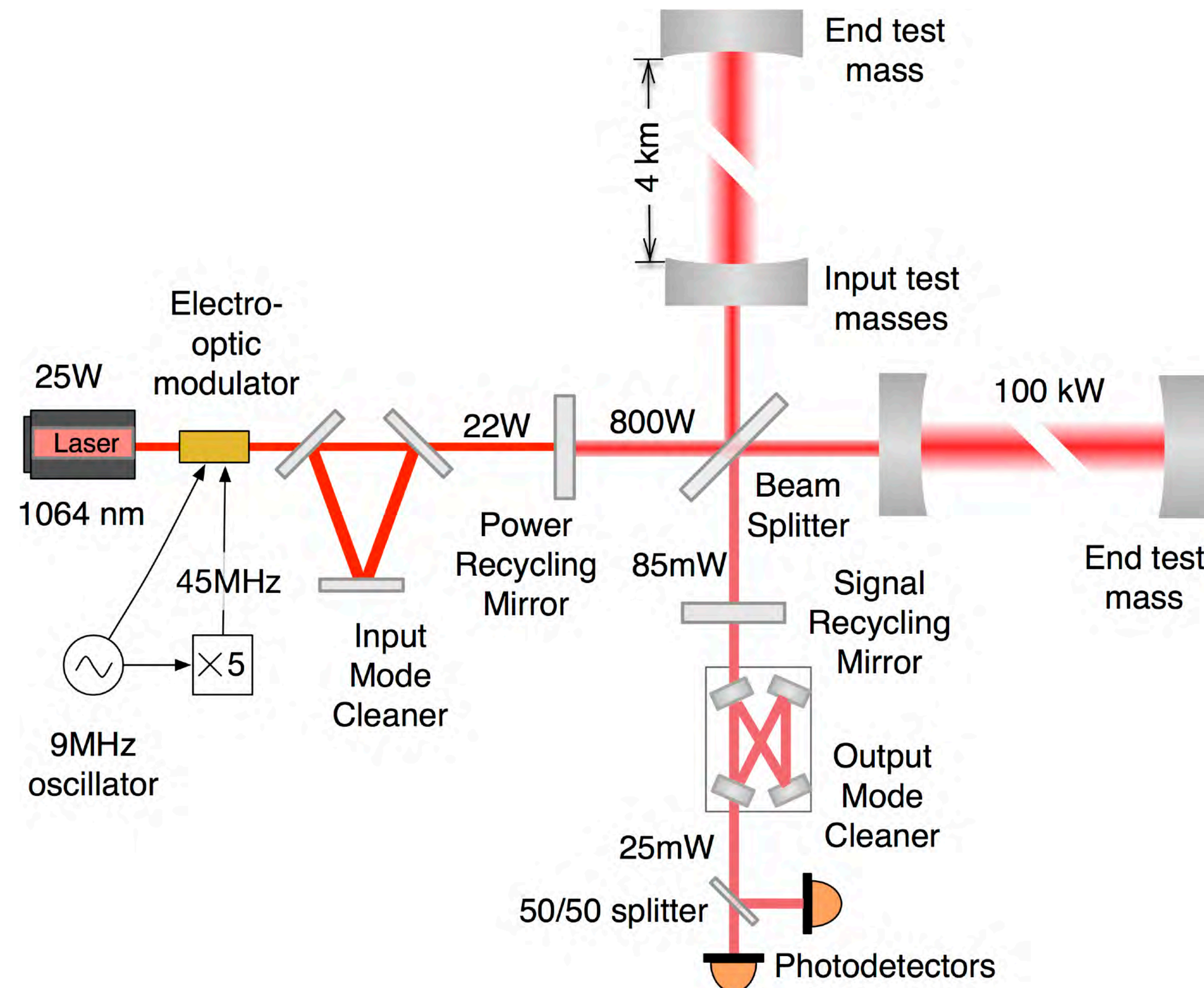
Advanced LIGO

$$f_- = 350 \text{ Hz}$$

Transfer function

$$\frac{1}{\sqrt{1 + (f_{\text{gw}}/f_-)^2}}$$

The gain from folding and recycling is now a complicated combination of terms. Comes out at a factor of $\sim 1,100$



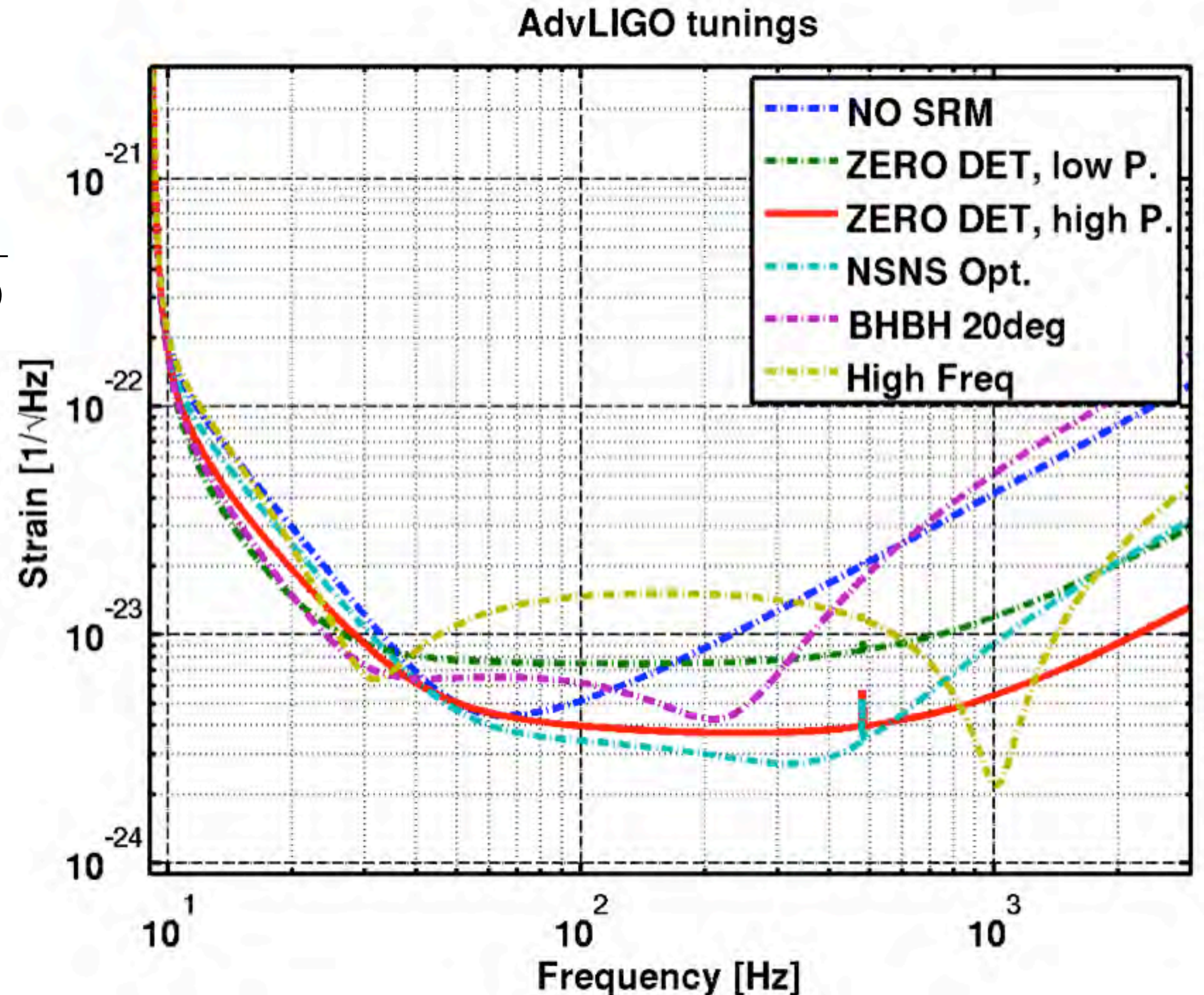
Signal recycling and response shaping

The cavity transfer function for the Michelson-Fabry-Perot topology with signal recycling allows us to shape the response and target particular signals by changing the distance to the signal recycling mirror

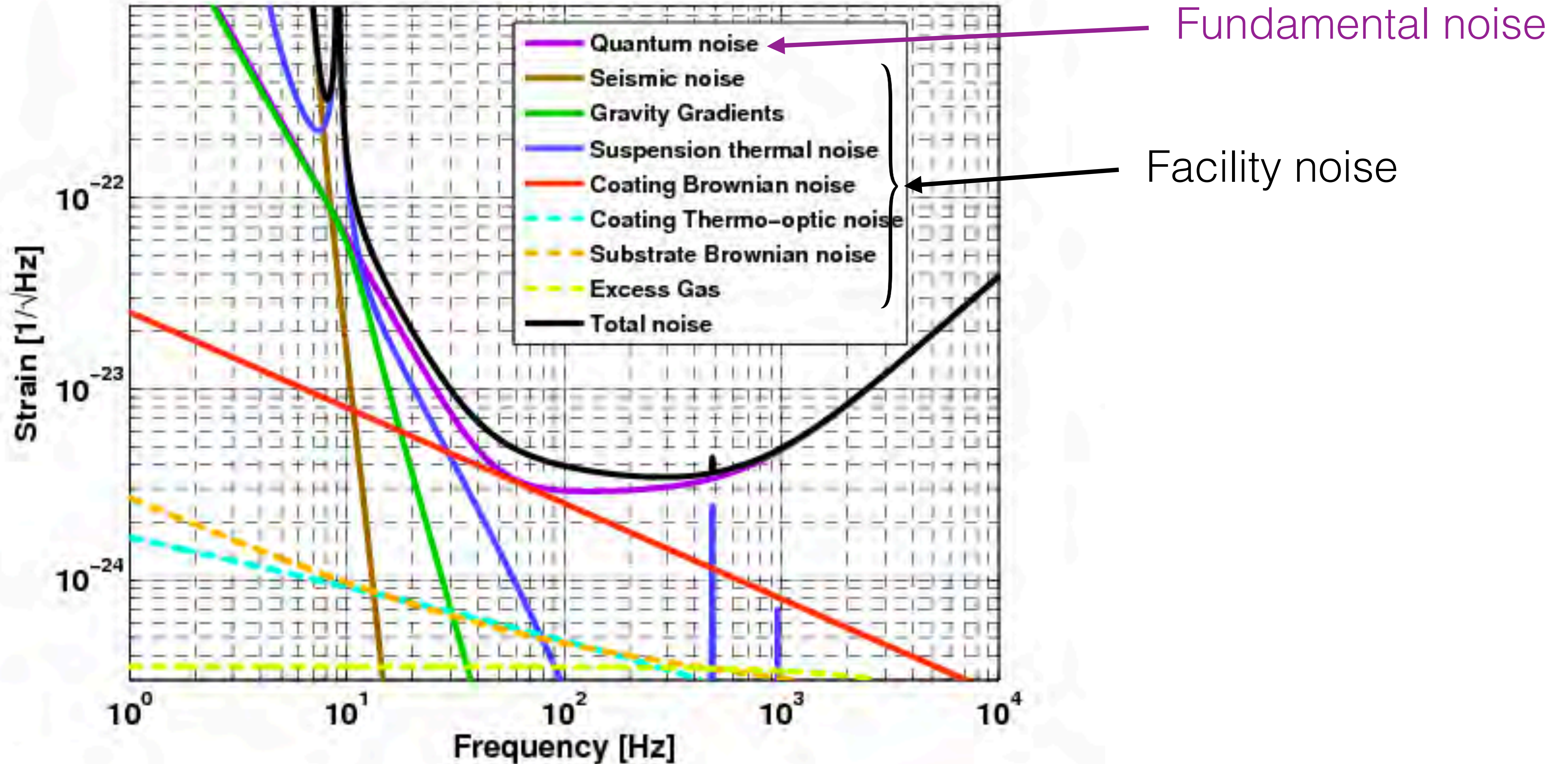
$$C(f) = \frac{t_s e^{-i(2\pi f \ell_s / c + \phi_s)}}{1 - r_s \left(\frac{r_i - e^{-4\pi i f L / c}}{1 - r_i e^{-4\pi i f L / c}} \right) e^{-2i(2\pi f \ell_s / c + \phi_s)}}$$

$$\phi_s = 2\pi \nu_0 \ell_s / c$$

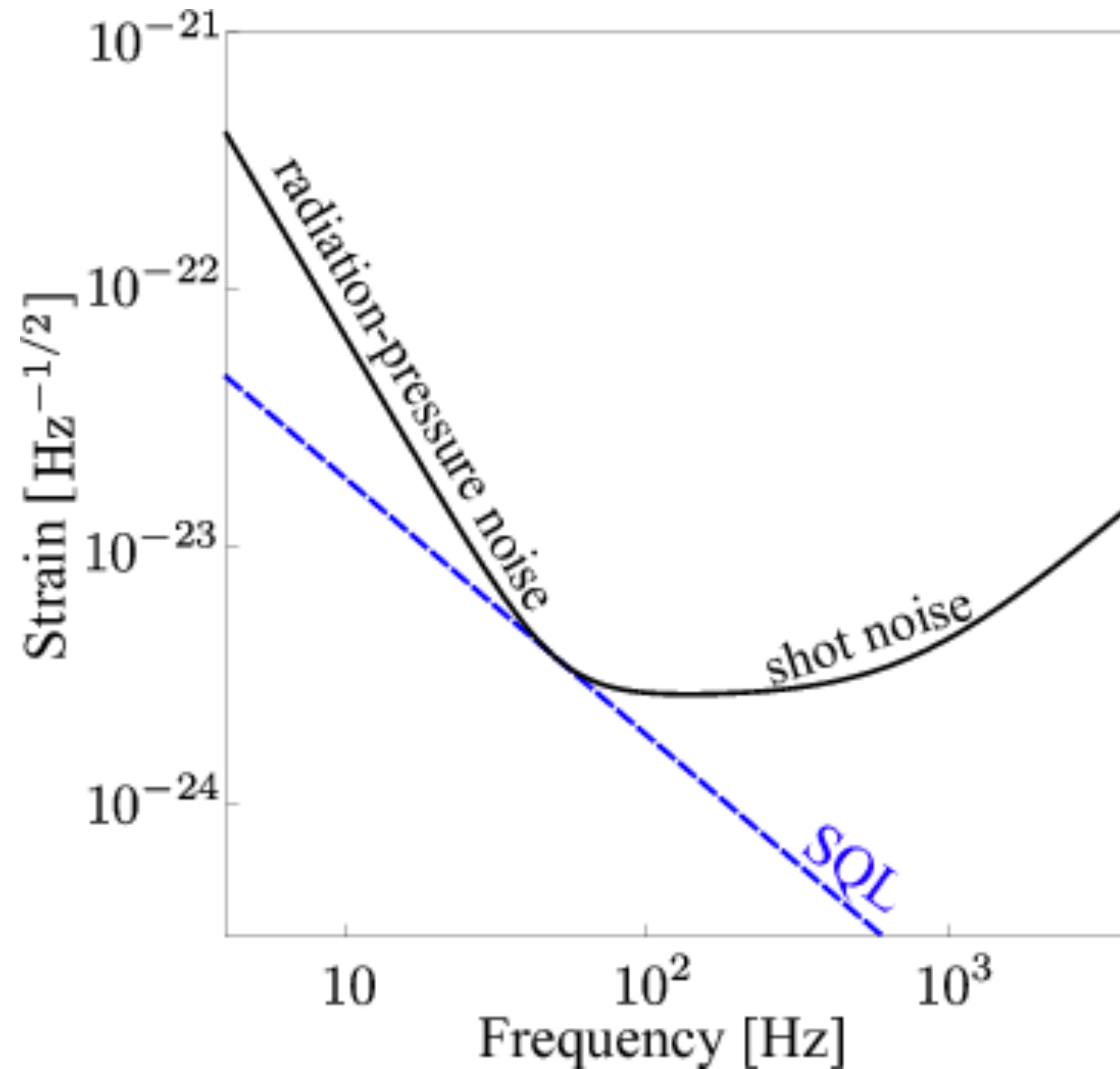
The pole frequency quoted on the last slide was for the zero detuned configuration



Sources of Noise



Fundamental (quantum) noise

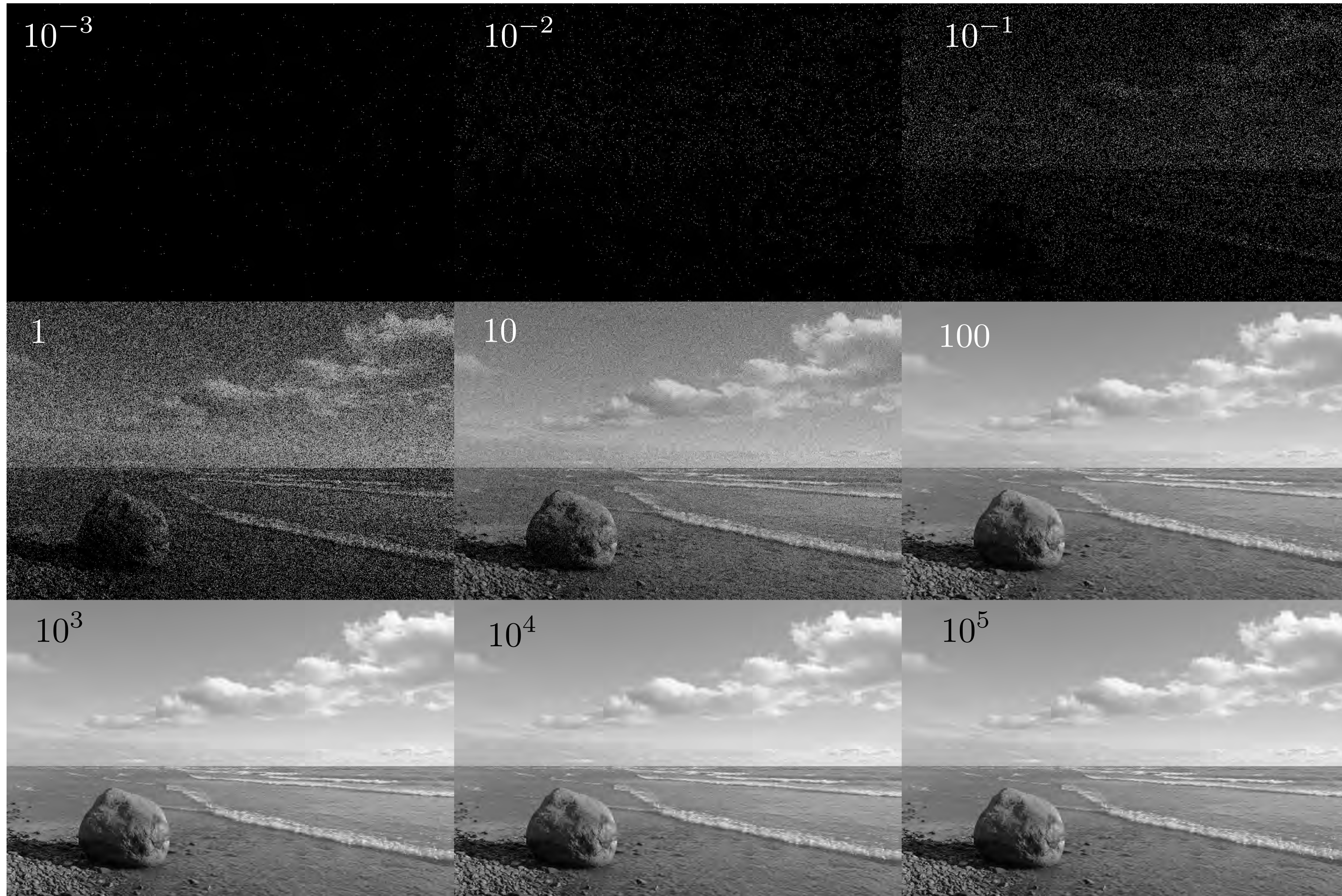


$$S_{\text{shot}}^{1/2} \propto \frac{1}{\sqrt{I_0}}$$

$$S_{\text{rp}}^{1/2} \propto \sqrt{I_0}$$

$$\text{SQL} \Delta \quad x \Delta p \geq \hbar$$

Shot noise: Digital camera, photons per pixel



$$S_{\text{shot}}^{1/2} \propto \frac{1}{\sqrt{I_0}}$$

Radiation pressure noise

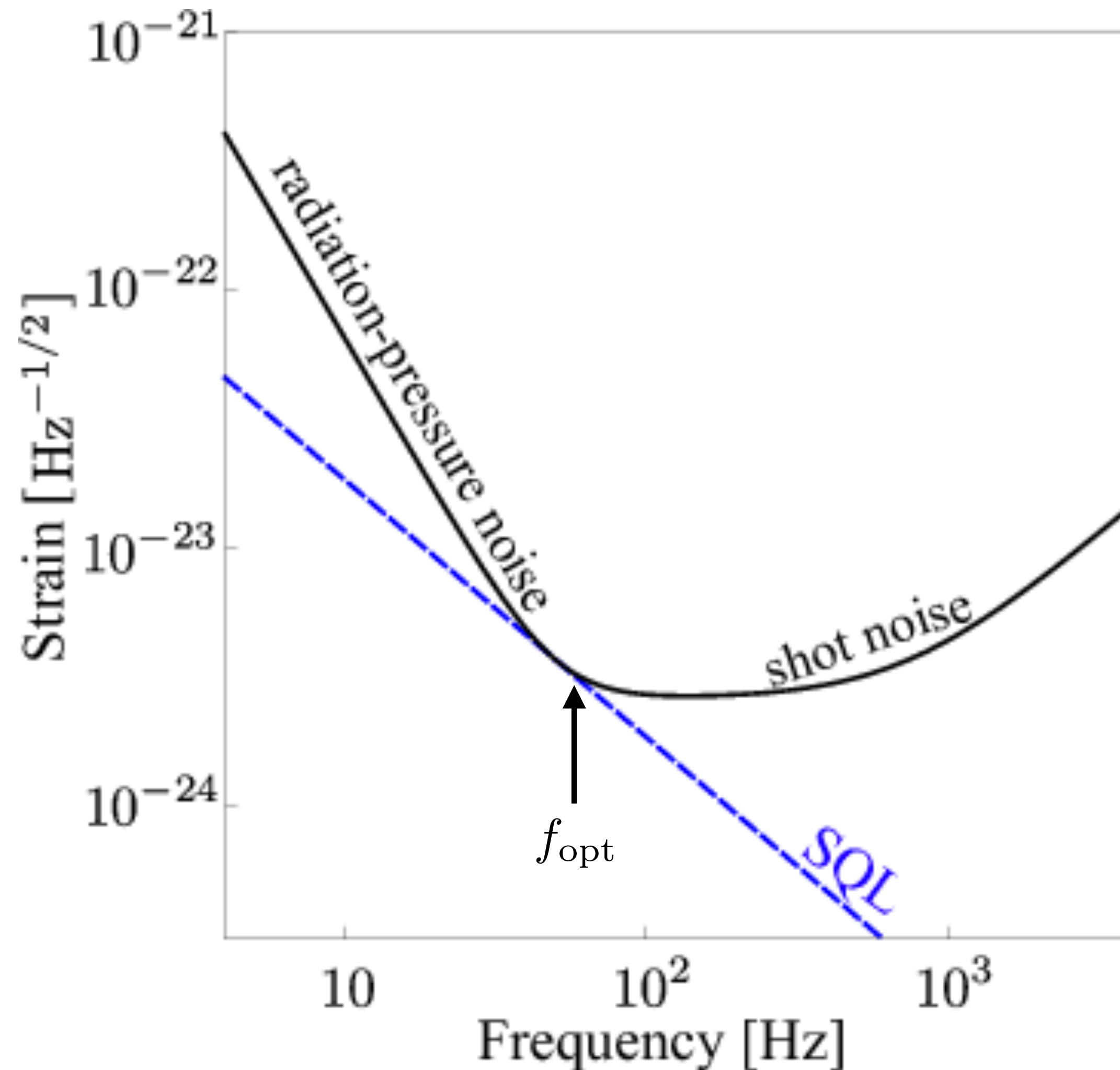
The test masses are essentially free (inertial) in the horizontal direction for frequencies above the pendulum frequency of the suspension

$$\ddot{x} = \frac{F_{\text{rad}}}{M}$$

$$\Rightarrow \quad \tilde{x} = -\frac{\tilde{F}_{\text{rad}}}{4\pi^2 f^2 M} \quad \mathbb{E}[\tilde{x}] = 0 \quad \mathbb{E}[\tilde{x}\tilde{x}^*] \propto \frac{I_0}{f^4 M^2}$$

$$\Rightarrow \quad S_{\text{rp}}^{1/2} \propto \frac{\sqrt{I_0}}{f^2 M}$$

Fundamental (quantum) noise



The intensity of the laser light is frequency dependent due to the cavity response

$$S_Q = \frac{\hbar}{\pi^2 f^2 M L^2} \left(\overset{\text{RP}}{\frac{I(f)}{\pi^2 f^2 M c}} + \overset{\text{Shot}}{\frac{\pi^2 f^2 M c}{I(f)}} \right)$$

$$I(f) \sim \frac{I_0}{1 + (f/f_-)^2}$$

SQL is reached when the Shot and RP contributions are equal (minimum of S_Q)

$$S_{\text{SQL}} = \frac{2\hbar}{\pi^2 f_{\text{opt}}^2 M L^2}$$

Standard Quantum Limit

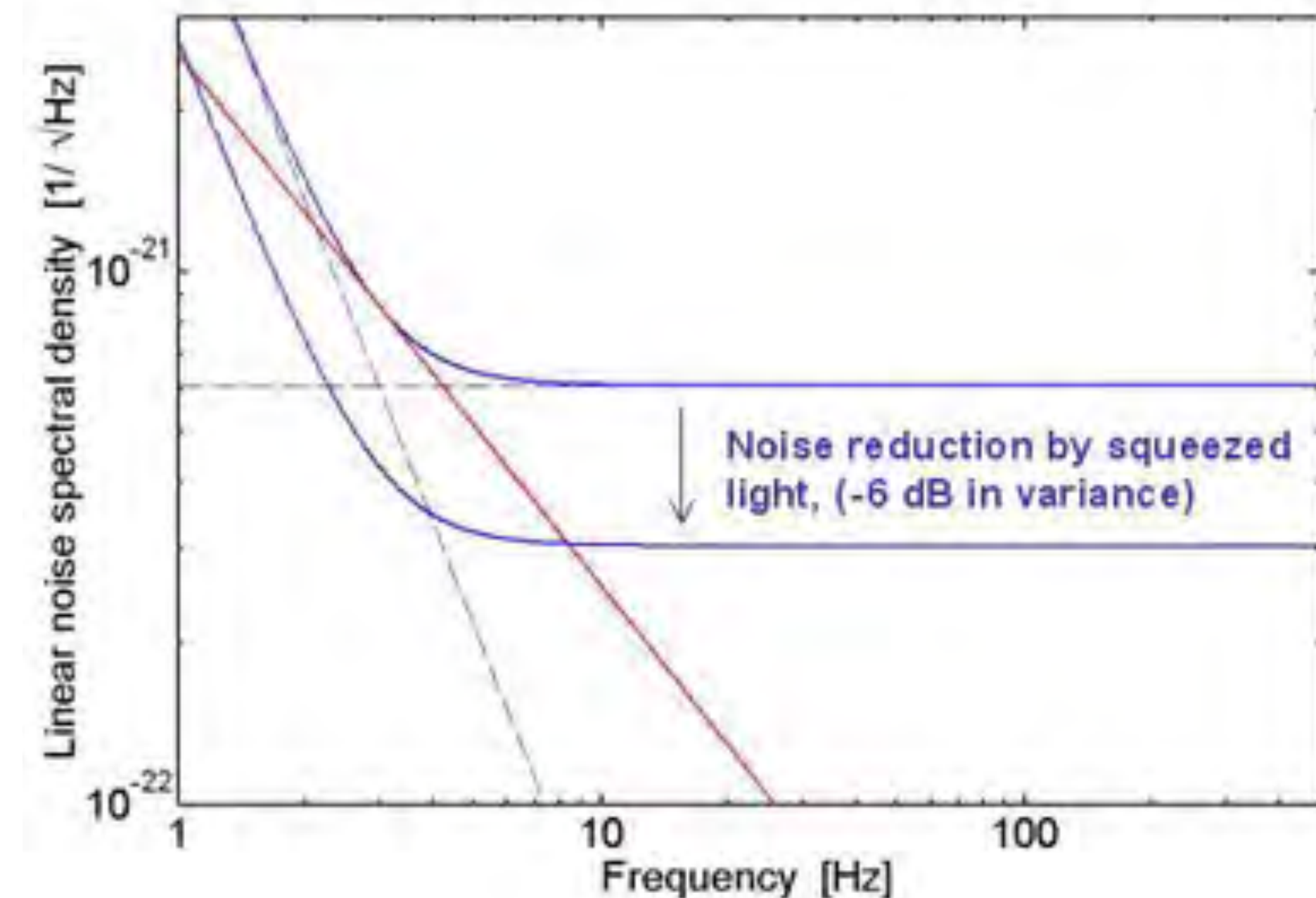
$$\text{SQL} \Delta x \Delta p \geq \hbar$$

$$S_{\text{SQL}} = \frac{2\hbar}{\pi^2 f_{\text{opt}}^2 M L^2}$$

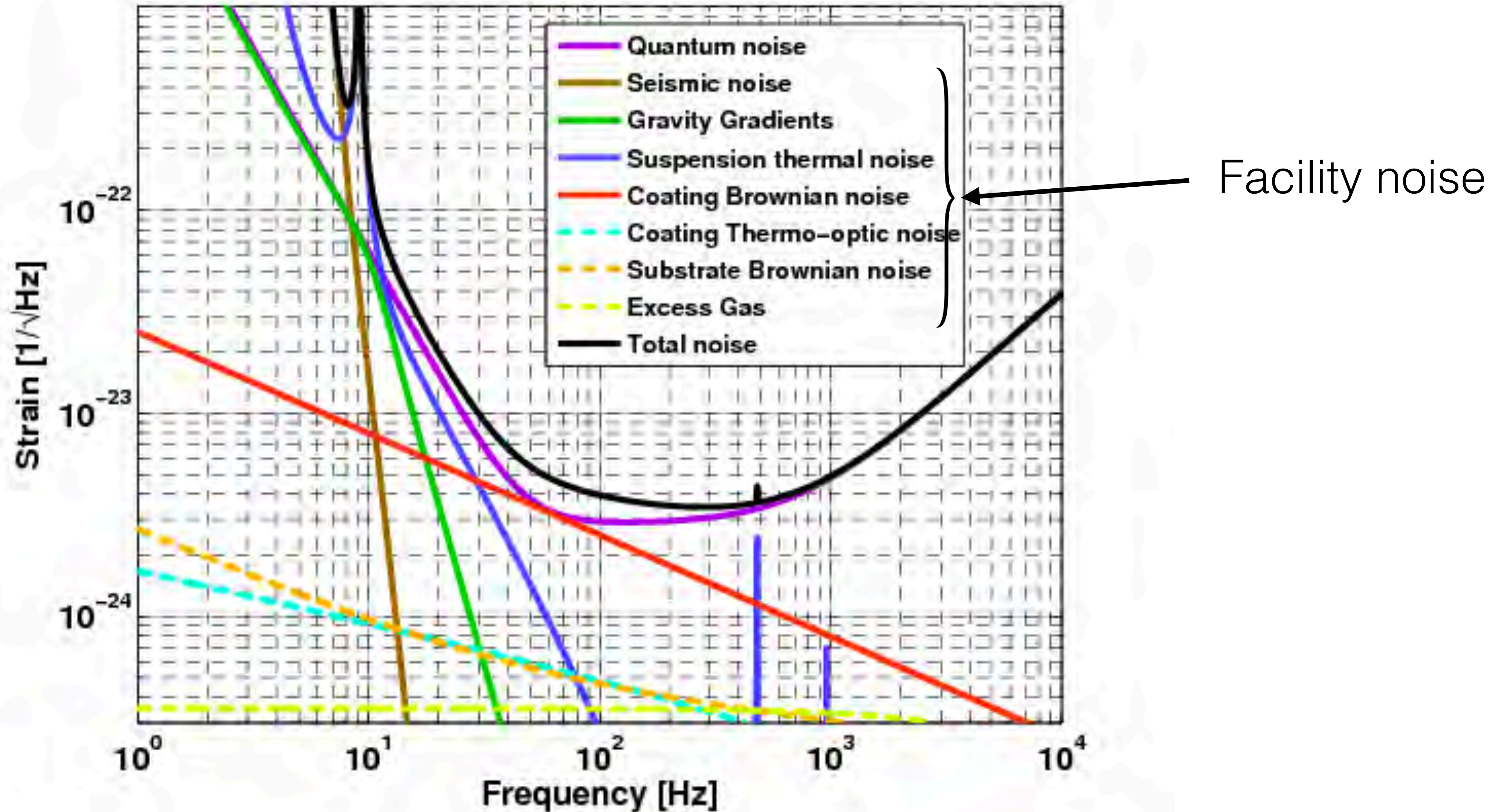
The SQL is not a fundamental limit to GW detector sensitivity

1) Measure momentum change rather than position change (speedmeter)

2) The RP and Shot noise can be made to be correlated. Allows us to reshape uncertainty ellipse using squeezed light (Quantum no-demolition measurement)



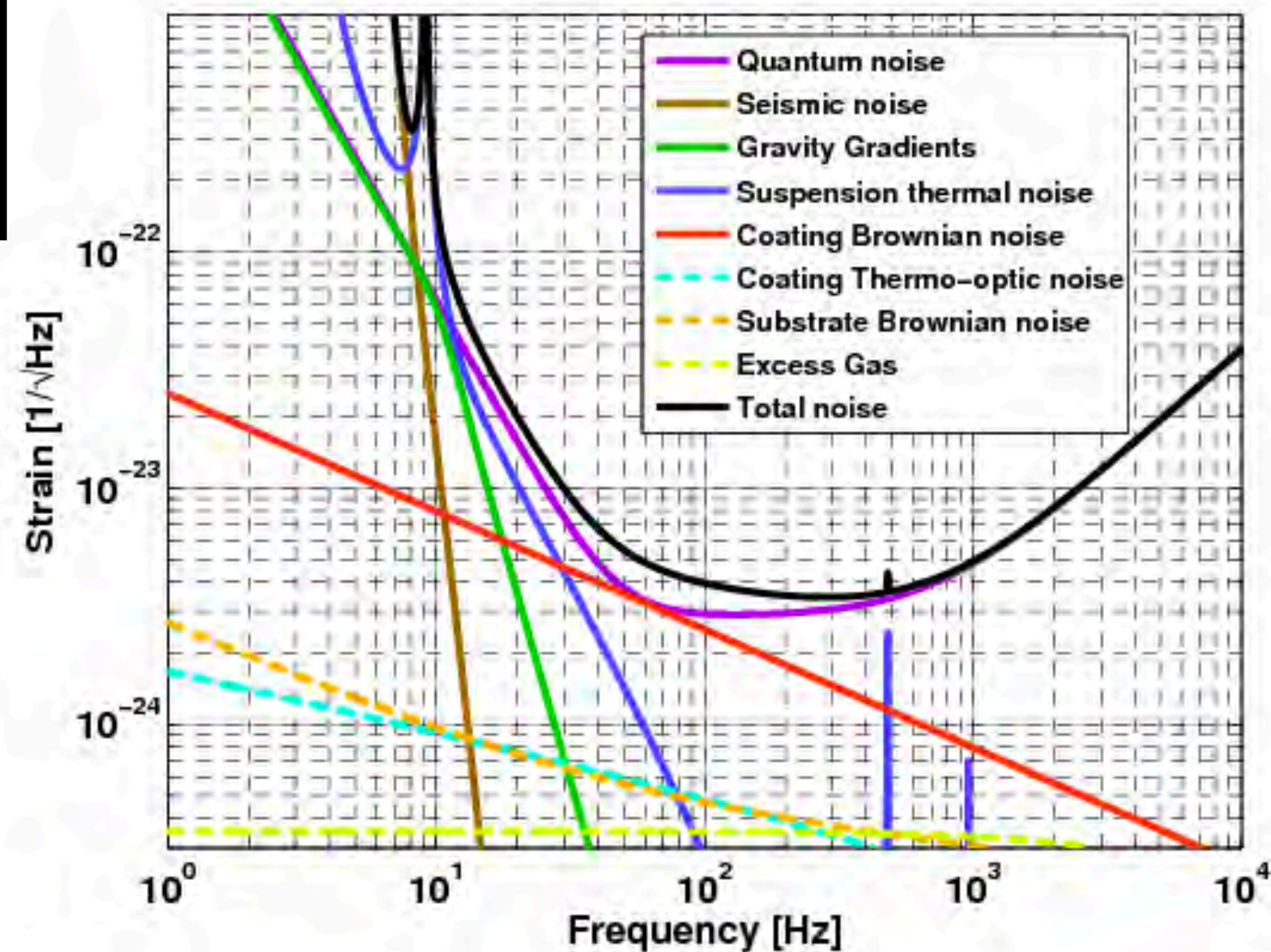
Facility Noise



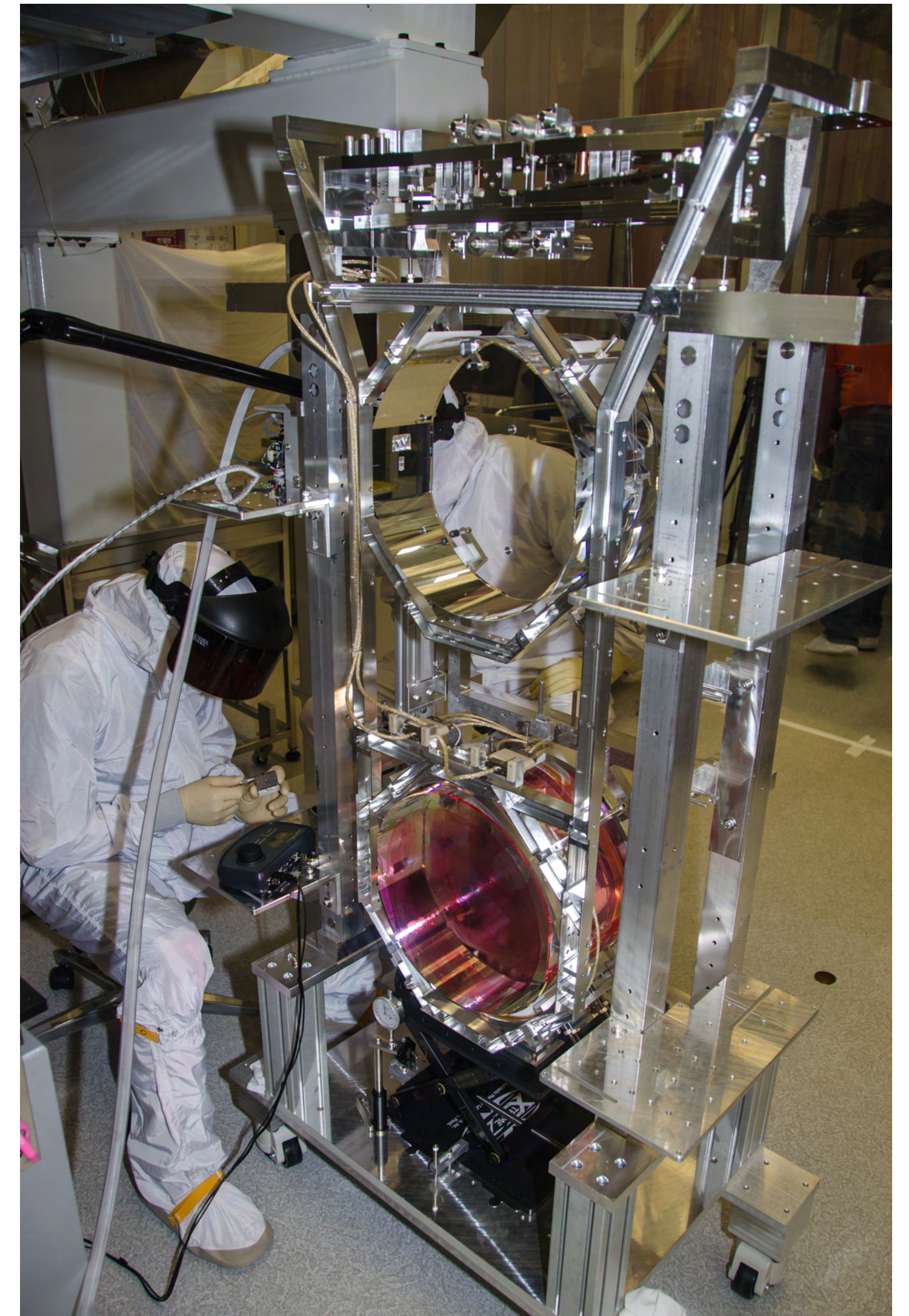
Seismic Noise

10^{10} too large

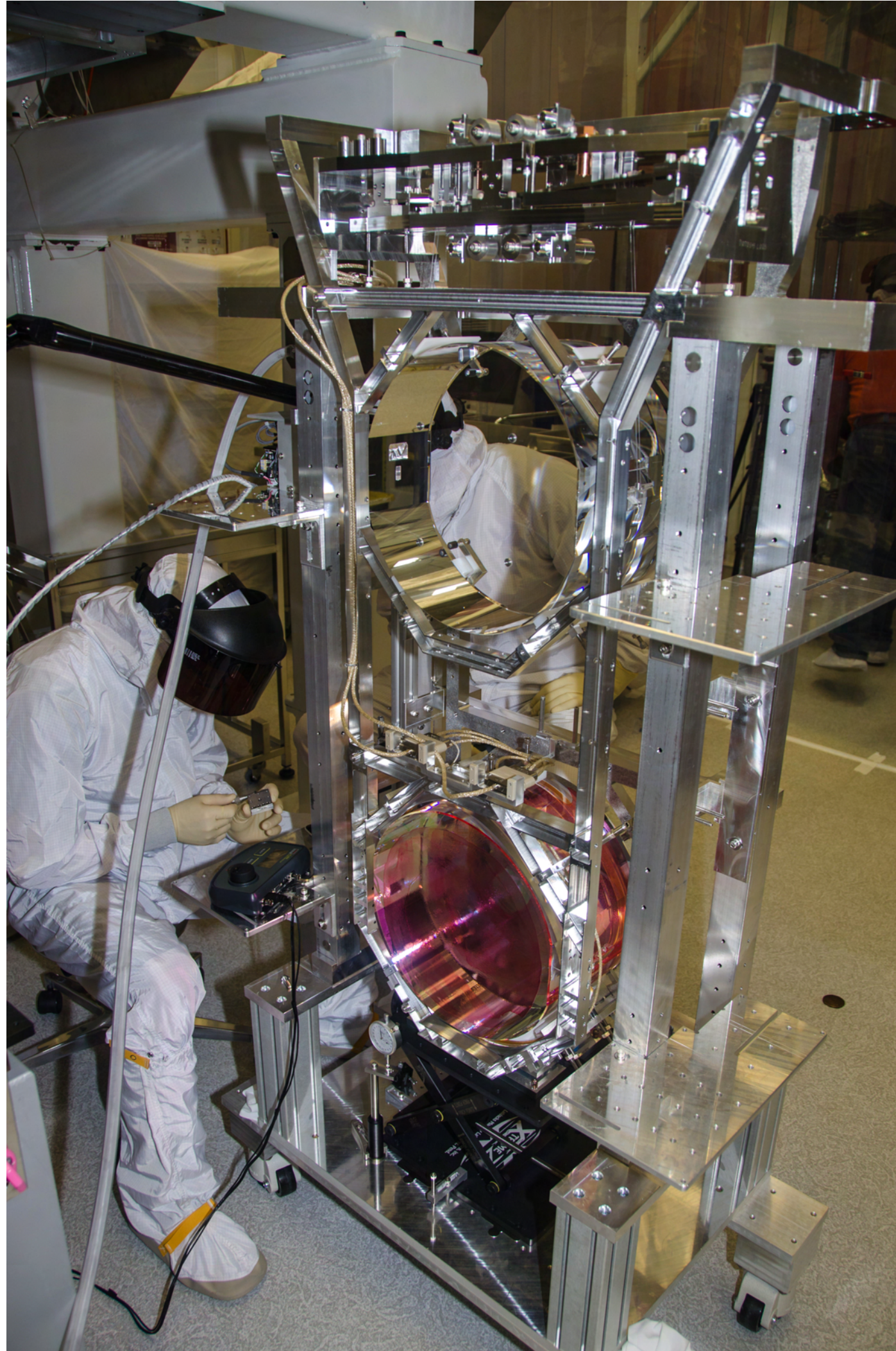
$$S_{\text{seis}}^{1/2} \sim 10^{-12} \left(\frac{10 \text{ Hz}}{f} \right)^2 \text{ Hz}^{-1/2}$$



Need one of these



Seismic Noise



$$S_{\text{seis}}^{1/2} \sim 10^{-12} \left(\frac{10 \text{ Hz}}{f} \right)^2 \text{ Hz}^{-1/2}$$

Single pendulum suspension

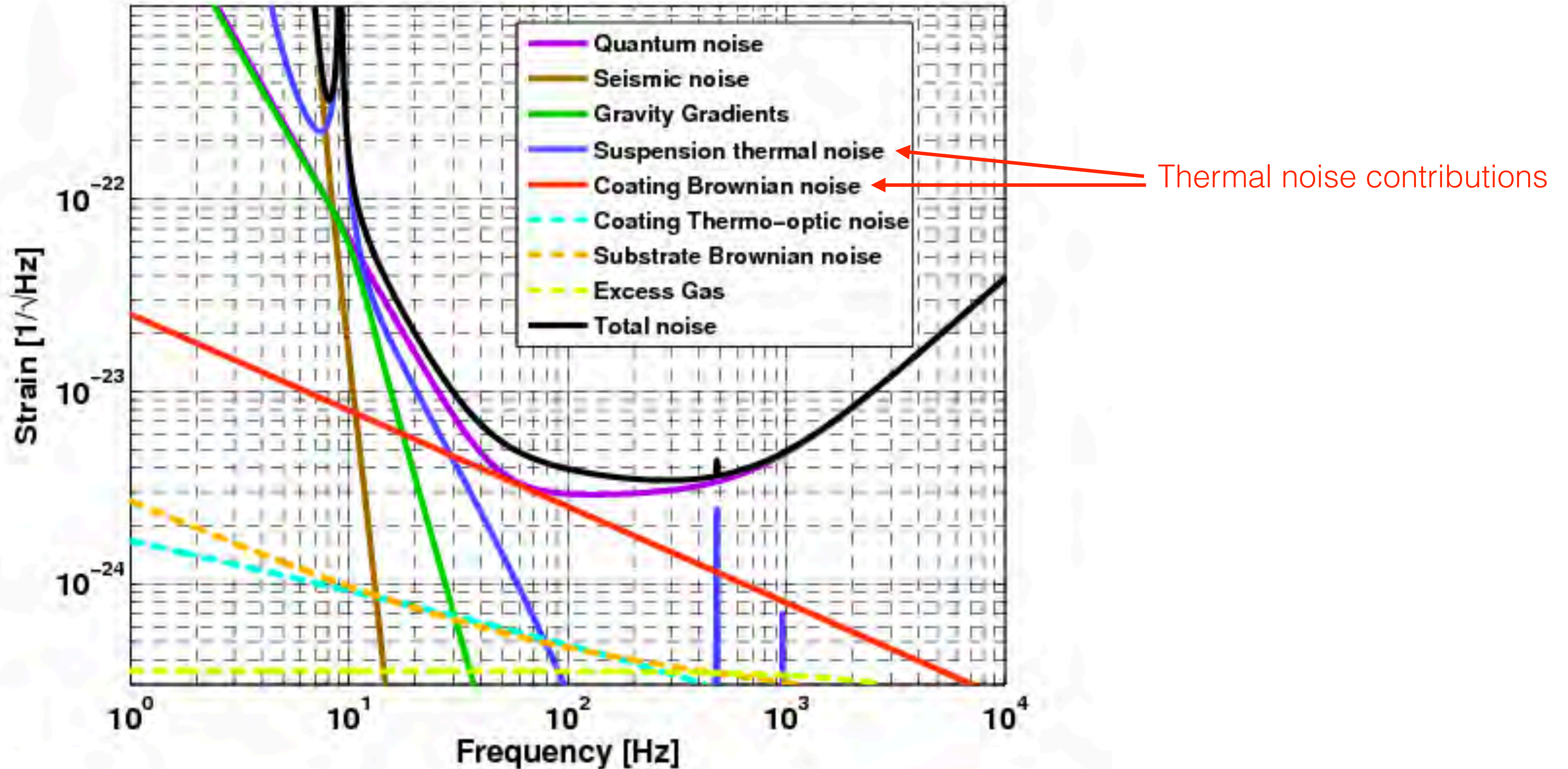
$$S_{\text{seis, filt}}^{1/2} = \frac{1}{|1 - (f/f_{\text{pend}})^2|} S_{\text{seis}}^{1/2} \quad f_{\text{pend}} \sim 1 \text{ Hz}$$

$$S_{\text{seis, filt}}^{1/2} \approx 10^{-12} \left(\frac{f_{\text{pend}}}{f} \right)^2 \left(\frac{10 \text{ Hz}}{f} \right)^2 \text{ Hz}^{-1/2}$$

aLIGO 5-stage pendulum suspension

$$S_{\text{seis, filt}}^{1/2} \approx 10^{-12} \left(\frac{f_{\text{pend}}}{f} \right)^{10} \left(\frac{10 \text{ Hz}}{f} \right)^2 \text{ Hz}^{-1/2}$$

Thermal Noise



Thermal Noise

Fluctuation-dissipation theorem: PSD of fluctuations of a system in equilibrium at temperature T is determined by the dissipative terms that return the system to equilibrium

$$S_T(f) = \frac{4k_B T}{(2\pi f)^2} \mathbb{R}[Y(f)]$$

For an *anelastic* spring with loss angle ϕ Hooke's law becomes $F = -k x (1 + i\phi)$

$$S_T(f) = \frac{k_B T}{2\pi^3 M f} \frac{f_{\text{res}}^2 \phi(f)}{(f_{\text{res}}^2 - f^2)^2 + f_{\text{res}}^4 \phi^2(f)}$$

Mirror Coating Thermal Noise

$$S_T(f) = \frac{k_B T}{2\pi^3 M f} \frac{f_{\text{res}}^2 \phi(f)}{(f_{\text{res}}^2 - f^2)^2 + f_{\text{res}}^4 \phi^2(f)}$$

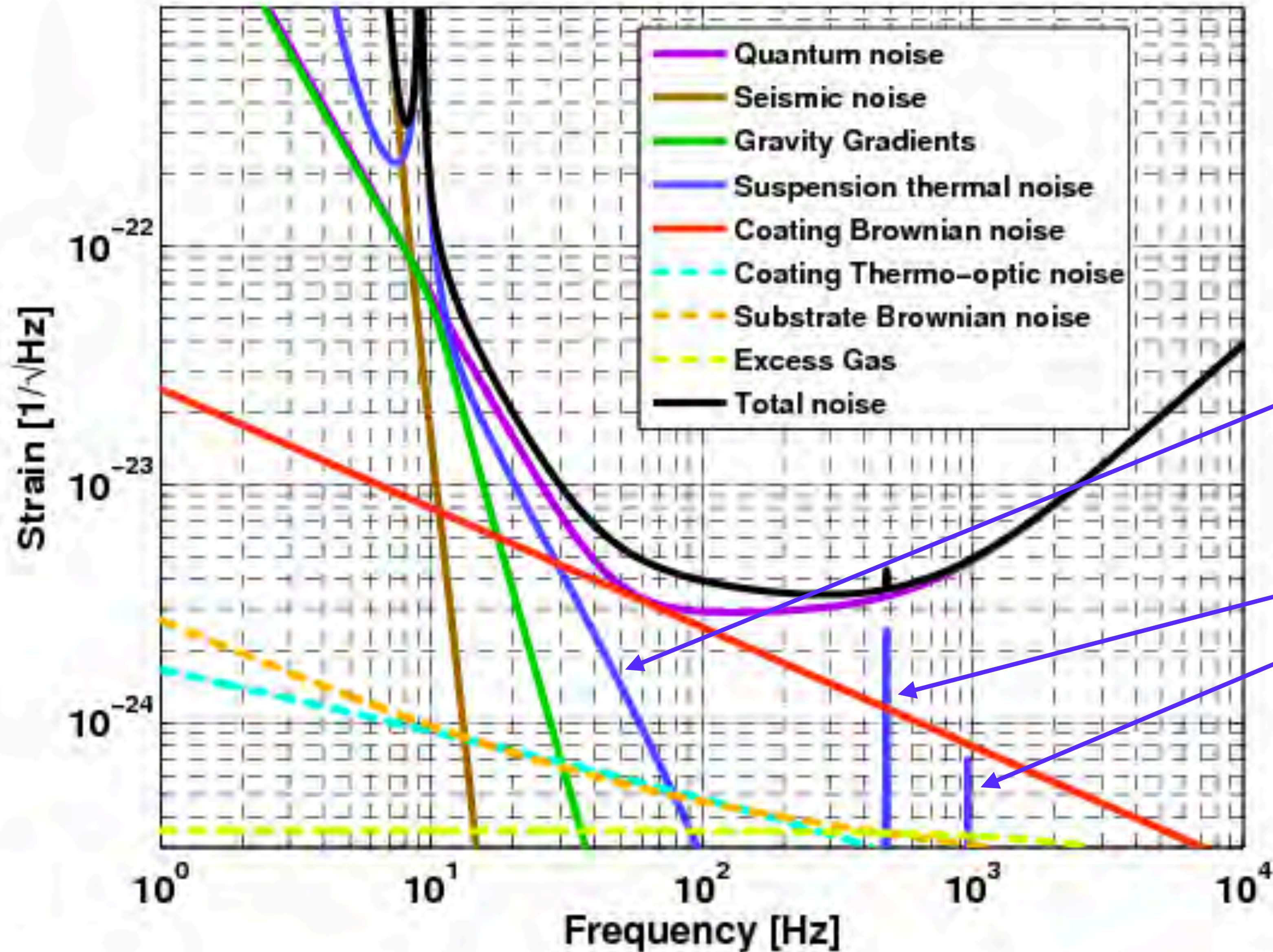
The resonant frequencies for the coatings are very high (tens of kHz), and the loss angle small (millionths)

$$S_{\text{MC}} = \left(\frac{2k_B T \phi}{\pi^3 M L^2 f_{\text{MC}}^2} \right) \frac{1}{f}$$

For advanced LIGO

$$S_{\text{MC}}^{1/2} = 2.5 \times 10^{-24} \left(\frac{100 \text{ Hz}}{f} \right)^{1/2} \text{ Hz}^{-1/2}$$

Suspension Thermal Noise



$$S_T(f) = \frac{k_B T}{2\pi^3 M f} \frac{f_{\text{res}}^2 \phi(f)}{(f_{\text{res}}^2 - f^2)^2 + f_{\text{res}}^4 \phi^2(f)}$$

Pendulum mode

$$f_{\text{pen}} = 9 \text{ Hz}$$

Violin modes

$$f_v = 500, 1000, \dots \text{ Hz}$$

Pendulum Suspension Thermal Noise

$$S_T(f) = \frac{k_B T}{2\pi^3 M f} \frac{f_{\text{res}}^2 \phi(f)}{(f_{\text{res}}^2 - f^2)^2 + f_{\text{res}}^4 \phi^2(f)}$$

$$f_{\text{res}} = f_{\text{pen}} \ll f$$

For advanced LIGO

$$S_{\text{pen}}^{1/2} = 3.5 \times 10^{-25} \left(\frac{100 \text{ Hz}}{f} \right)^{5/2} \text{ Hz}^{-1/2}$$

Violin mode Thermal Noise

$$S_T(f) = \frac{k_B T}{2\pi^3 M f} \frac{f_{\text{res}}^2 \phi(f)}{(f_{\text{res}}^2 - f^2)^2 + f_{\text{res}}^4 \phi^2(f)}$$

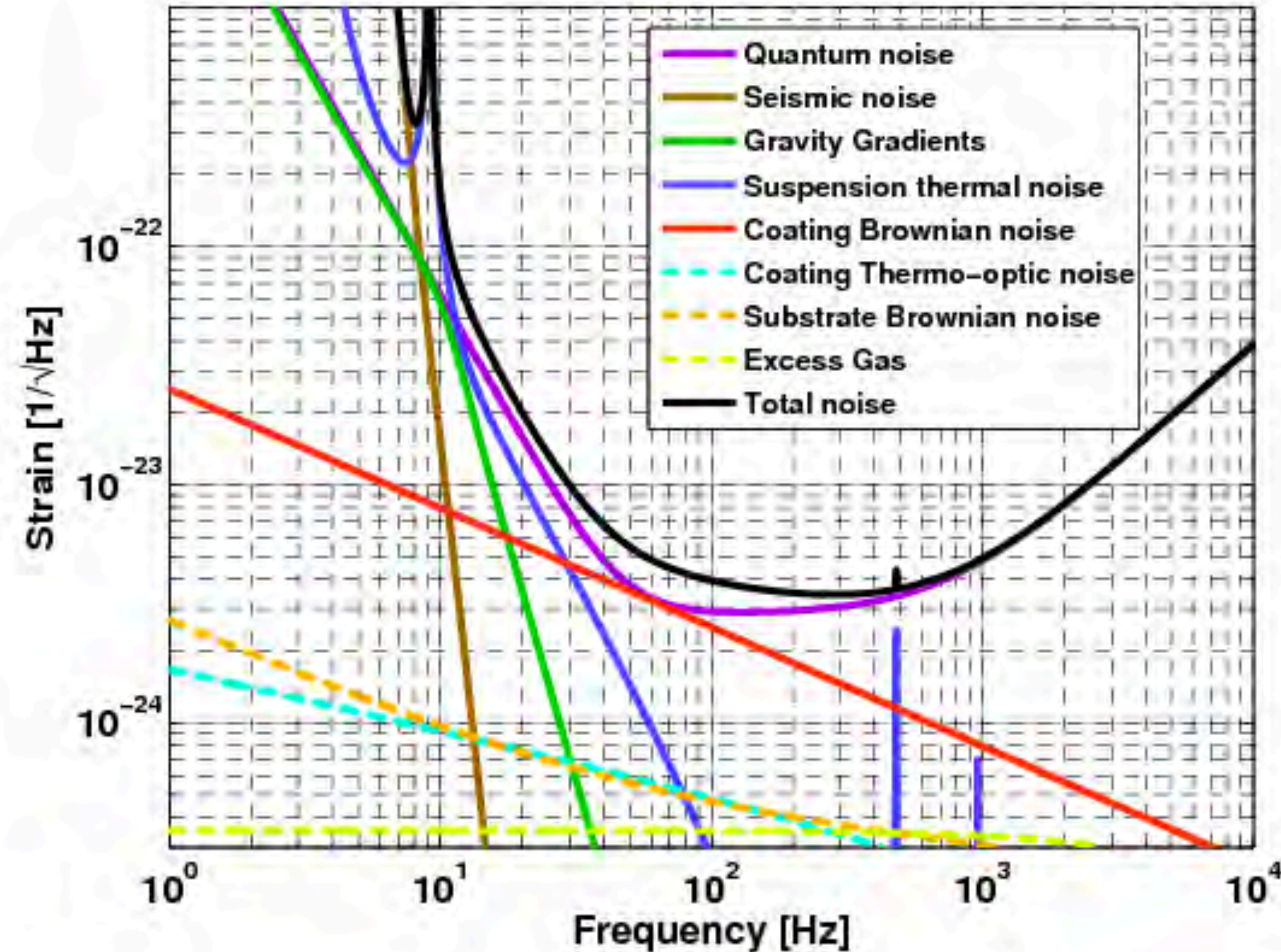
$$f_{\text{res}} = f_v = 500 \text{ Hz}, 1000 \text{ Hz}, \dots$$

For advanced LIGO, first harmonic

$$S_v^{1/2} = \frac{3 \times 10^{-24}}{1 + (f_v^2 - f^2)^2 / \delta f^4} \text{ Hz}^{-1/2}$$

$$\delta f = f_v \phi^{1/2} \approx 2 \text{ Hz}$$

Gravity Gradient Noise



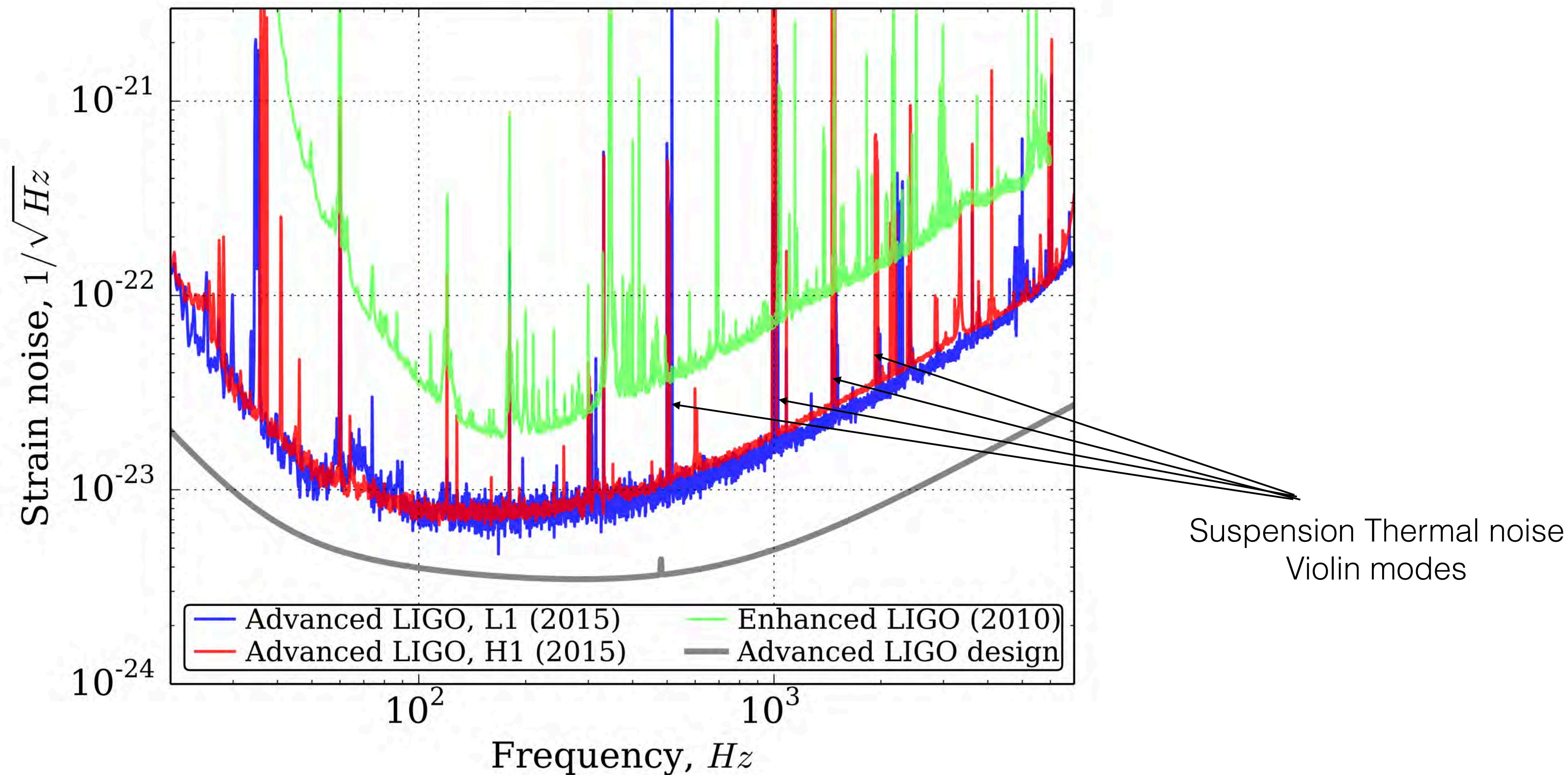
We can't escape Newton

$$\ddot{\mathbf{x}} = G \int \frac{\delta\rho(\mathbf{x}', t)}{|\mathbf{x} - \mathbf{x}'|^3} (\mathbf{x} - \mathbf{x}') d^3\mathbf{x}'$$

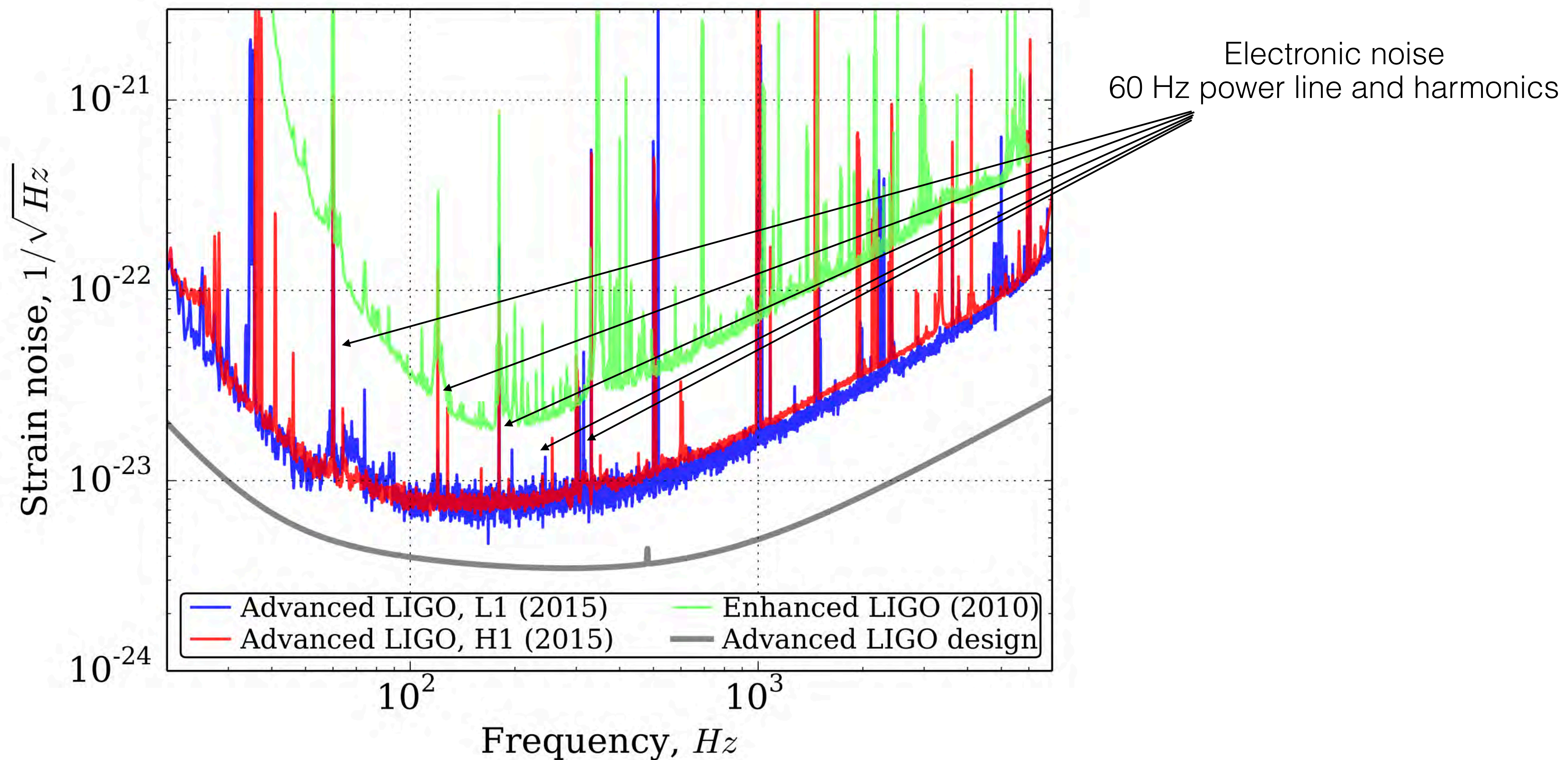


This is why we need LISA!

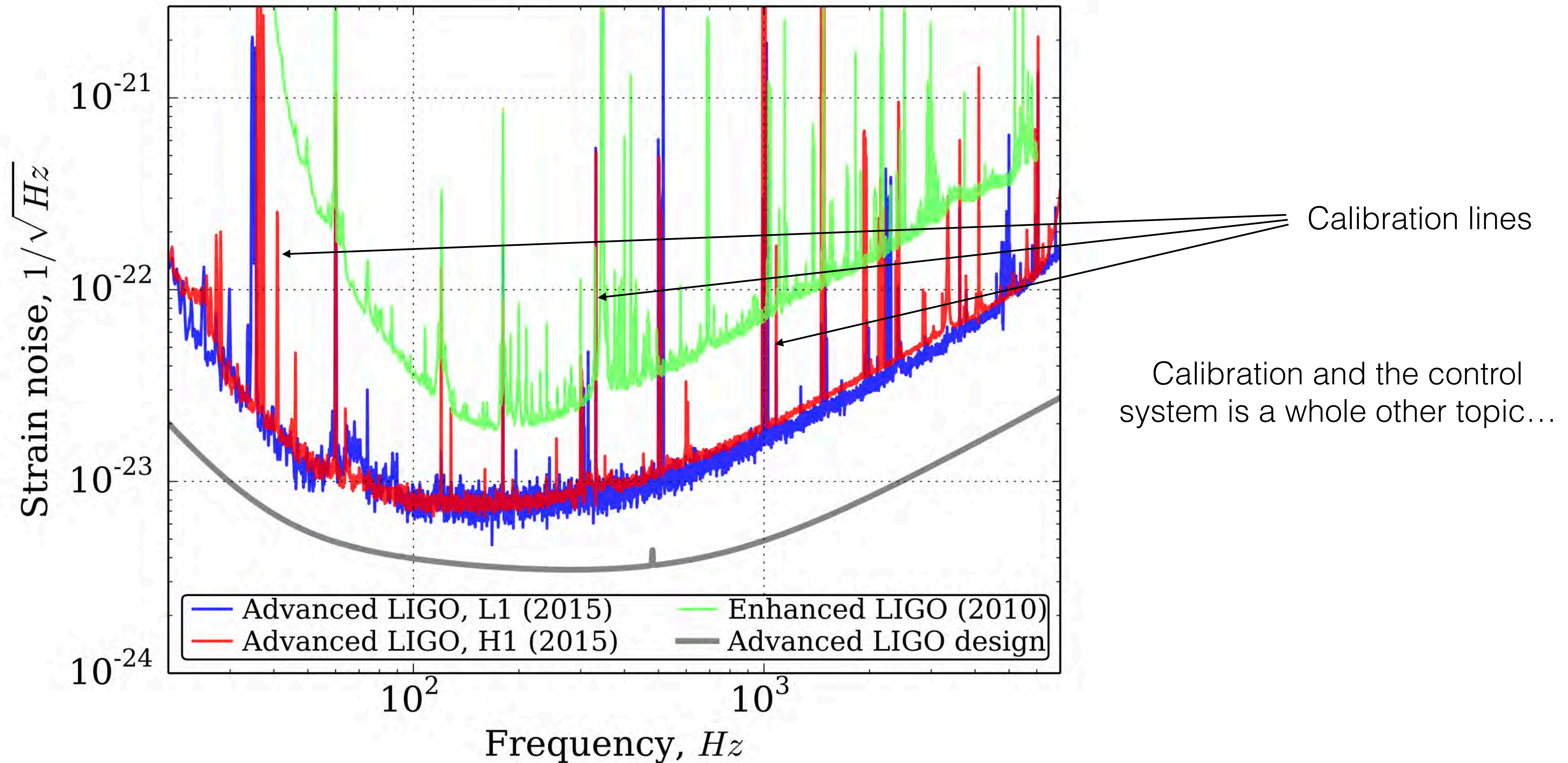
Real aLIGO noise spectra from O1



Real aLIGO noise spectra from O1



Real aLIGO noise spectra from O1/S6



LIGO searches for binary inspired signals

Recall: Likelihood for Stationary Gaussian Noise

$$p(\mathbf{d}|\vec{\lambda}) = \text{const.} \cdot e^{-\frac{\chi^2(\vec{\lambda})}{2}}$$

$$\chi^2(\vec{\lambda}) = (\mathbf{d} - \mathbf{h}(\vec{\lambda})|\mathbf{d} - \mathbf{h}(\vec{\lambda}))$$

$$(\mathbf{a}|\mathbf{b}) = 2 \int_0^\infty \frac{\tilde{a}(f)\tilde{b}^*(f) + \tilde{a}^*(f)\tilde{b}(f)}{S_n(f)} df$$

Suppose that we have two hypotheses:

H_1 : A signal with parameters $\vec{\lambda}$ is present

H_0 : No signal is present

Likelihood ratio:
$$\Lambda(\vec{\lambda}) = \frac{p(\mathbf{d}|\mathbf{h}(\vec{\lambda}), H_1)}{p(\mathbf{d}, H_0)}$$

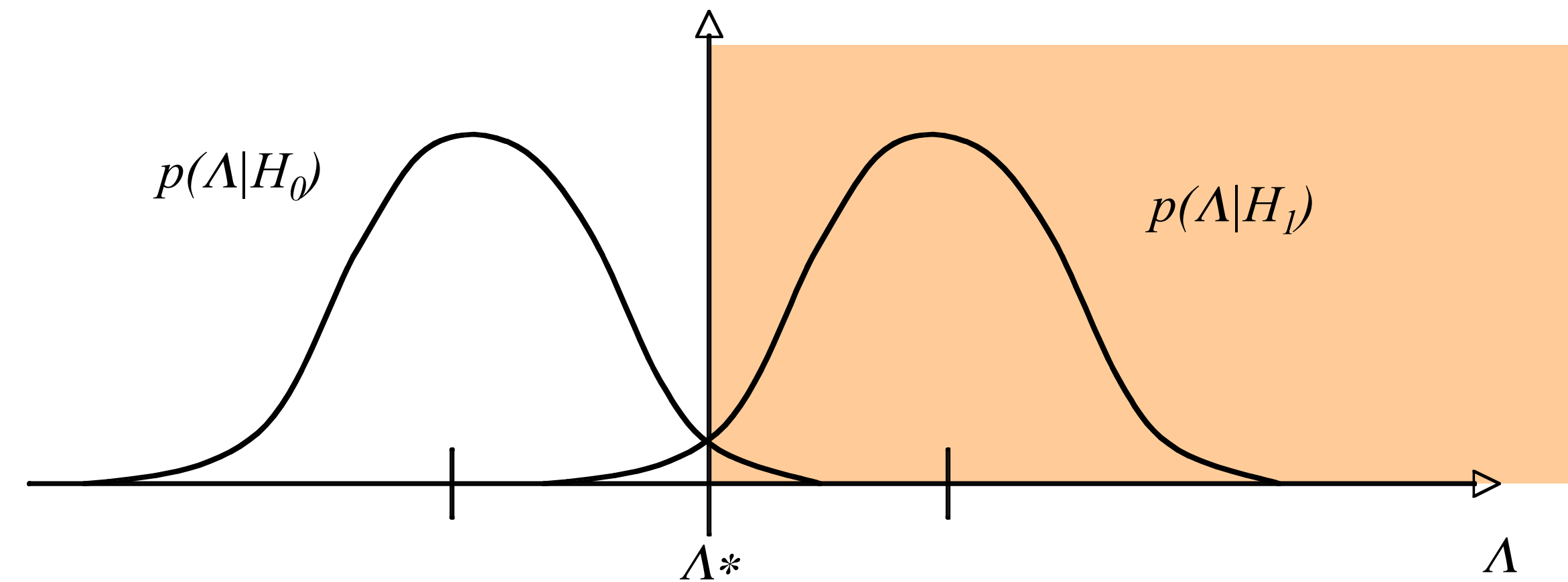
For Gaussian noise:
$$\Lambda(\vec{\lambda}) = e^{-(\mathbf{d}|\mathbf{h}) + \frac{1}{2}(\mathbf{h}|\mathbf{h})}$$

Frequentist Hypothesis Testing

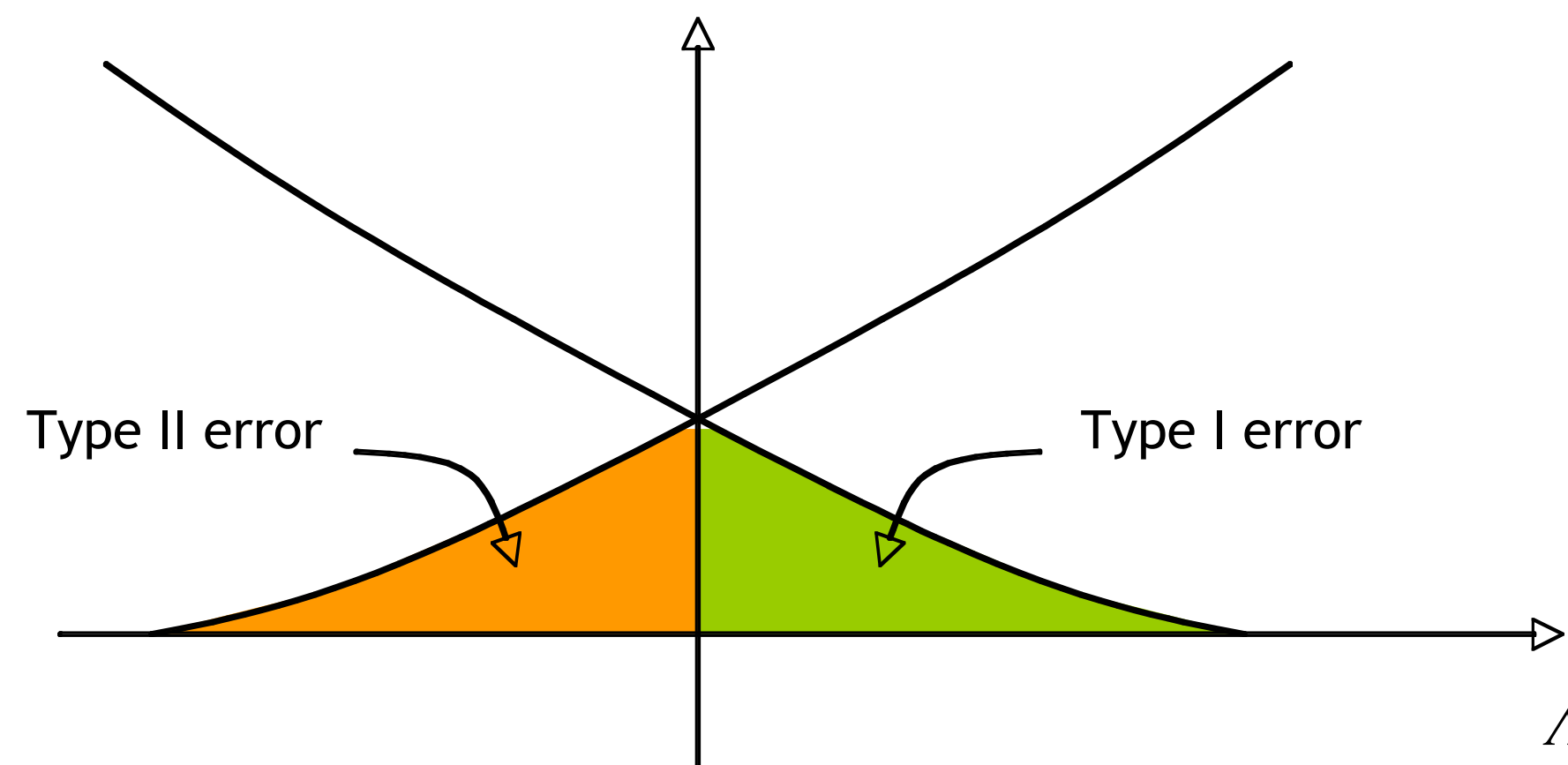
Λ – Detection Statistic

H_0 – Noise Hypothesis

H_1 – Noise + Signal Hypothesis



Set threshold Λ_* such that $\Lambda > \Lambda_*$ favors hypothesis H_1



Type I error - False Alarm

Type II error - False Dismissal

Neyman-Pearson Theorem

For a fixed false alarm rate, the false dismissal rate is minimized by the likelihood ratio statistic

$$\Lambda(\vec{\lambda}) = \frac{p(\mathbf{d}|\mathbf{h}(\vec{\lambda}), H_1)}{p(\mathbf{d}, H_0)}$$

The likelihood ratio is maximized over the signal parameters.

The rho statistic is often used in place of the likelihood ratio

$$\text{Writing } \mathbf{h} = \rho \hat{h} \text{ where } (\hat{h}|\hat{h}) = 1 \quad \Lambda(\vec{\lambda}) = e^{\rho(\mathbf{d}|\hat{h}) - \frac{1}{2}\rho^2}$$

$$\text{Maximizing wrt } \rho \quad \frac{\partial \Lambda(\vec{\lambda})}{\partial \rho} = 0 \quad \Rightarrow \quad \rho(\vec{\lambda}) = (\mathbf{d}|\hat{h}(\vec{\lambda}))$$

$$\log \Lambda(\vec{\lambda}) = \frac{1}{2}\rho^2(\vec{\lambda})$$

The rho statistic and SNR

The signal-to-noise ratio (SNR) is defined:

$$\text{SNR} = \frac{\text{Expected value when signal present}}{\text{RMS value when signal absent}}$$

In practice, the detector noise is not perfectly Gaussian, and variants of the rho statistic are now used, notably the “new SNR” statistic, introduced by B. Allen Phys.Rev. D71 (2005) 062001

$$= \frac{E[\rho]}{\sqrt{E[\rho_0^2] - E[\rho_0]^2}}$$

$$= (h|\hat{h})$$

$$= \sqrt{(h|h)}$$

$$\text{SNR}^2 = 4 \int_0^\infty \frac{|\tilde{h}(f)|^2}{S_n(f)} df$$

Matched Filtering = Maximum Likelihood

Convolve the data with a filter (template) K :

$$Y = \int dt \int du K(t - u) d(u)$$

$$\begin{aligned} \text{SNR} &= \frac{E[Y]}{\sqrt{E[Y_0^2] - E[Y_0]^2}} \\ &= \frac{2 \int_0^\infty df (\tilde{h}^*(f) \tilde{K}(f) + \tilde{h}(f) \tilde{K}^*(f))}{\sqrt{4 \int_0^\infty df |\tilde{K}(f)|^2 S(f)}} \end{aligned}$$

Maximizing the SNR yields

$$\tilde{K}(f) = \frac{\tilde{h}(f)}{S(f)} \quad \Rightarrow \quad Y = (\mathbf{d}|\mathbf{h}) = \rho \sqrt{(h|h)}$$

Frequentist Detection Threshold

For stationary, Gaussian noise the detection statistic ρ is Gaussian distributed.

For the null hypothesis we have $p_0(\rho) = \frac{1}{\sqrt{2\pi}} e^{-\rho^2/2}$

For the detection hypothesis we have $p_1(\rho) = \frac{1}{\sqrt{2\pi}} e^{-(\rho^2 - \text{SNR}^2)/2}$

Setting a threshold of ρ_* gives the false alarm and false dismissal probabilities

$$P_{\text{FA}} = \frac{1}{2} \text{erfc}(\rho_*/\sqrt{2})$$
$$P_{\text{FD}} = \frac{1}{2} \text{erfc}((\rho_* - \text{SNR})/\sqrt{2})$$

LIGO/Virgo analyses do not use SNR thresholds, but rather use False Alarm Rate thresholds

$$\text{FAR} = \frac{P_{\text{FA}}}{T_{\text{obs}}}$$

e.g. FAR = One in million years and an observation time of one year

$$P_{\text{FA}} = 10^{-6} \quad \text{aka} \quad 4.9 \sigma \quad \rho_* = 4.8$$

Grid Based Searches

Goal is to lay out a grid in parameter space that is fine enough to catch any signal with some good fraction of the maximum matched filter SNR

The match measures the fractional loss in SNR in recovering a signal with a template and defines a natural metric on parameter space:

$$M(\vec{x}, \vec{y}) = \frac{(h(\vec{x})|h(\vec{y}))}{\sqrt{(h(\vec{x})|h(\vec{x}))(h(\vec{y})|h(\vec{y}))}}$$

Taylor expanding $M(\vec{x}, \vec{x} + \Delta\vec{x}) = 1 - g_{ij}\Delta x^i \Delta x^j + \dots$

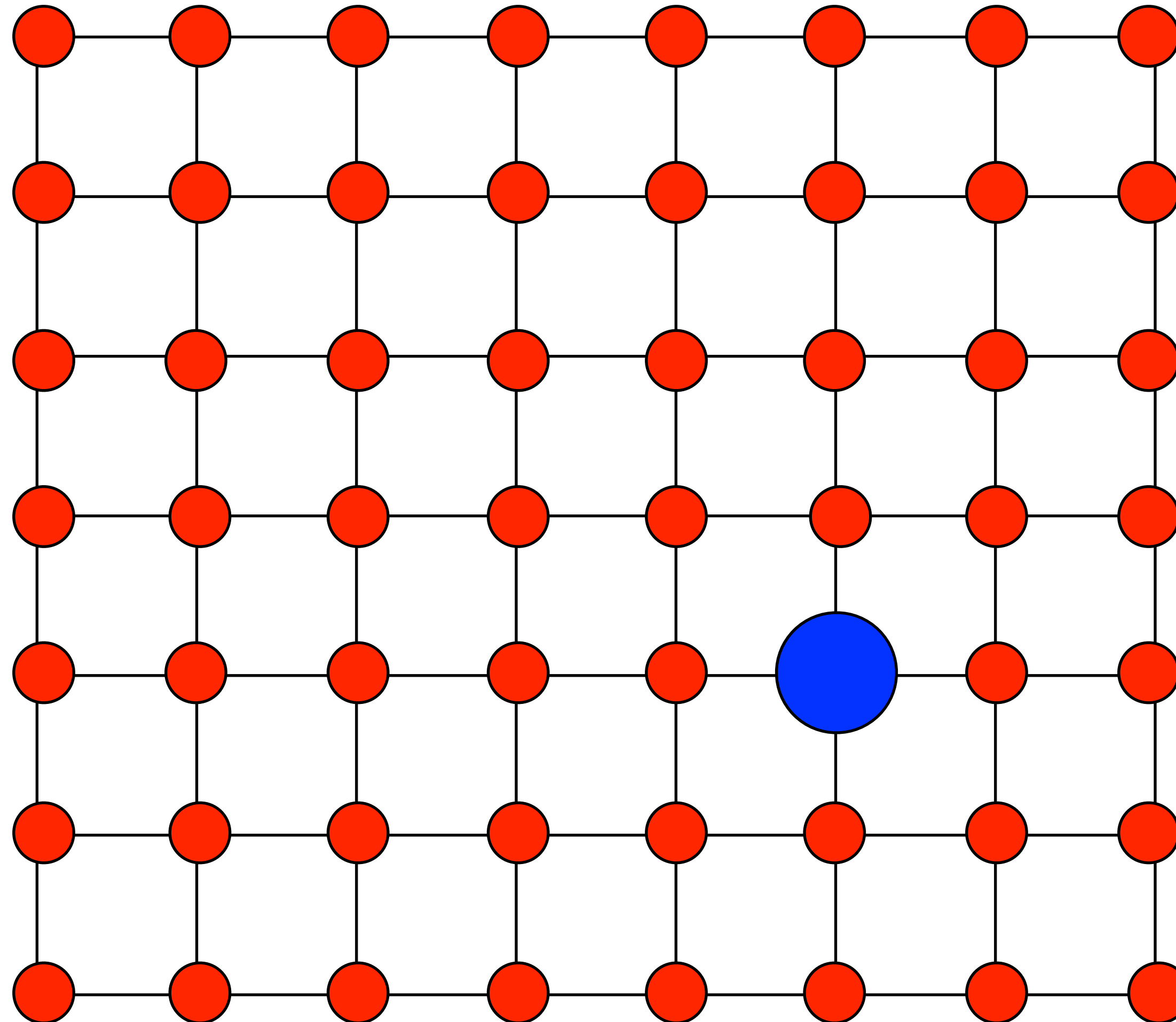
where $g_{ij} = \frac{(h_{,i}|h_{,j})}{(h|h)} - \frac{(h|h_{,i})(h|h_{,j})}{(h|h)^2}$ (Owen Metric)

Number of templates (for a hypercube lattice in D dimensions)

$$N = \frac{V}{\Delta V} = \frac{\int d^D x \sqrt{g}}{(2\sqrt{(1 - M_{\min})/D})^D}$$

Cost grows geometrically with D for any lattice

LIGO Style Grid Searches



Typically 2-3 dimensional, 1000's points

Reducing the cost of a search

In most cases it is possible to analytically maximize over 3 or more parameters

Distance:

The unit normalized template \hat{h} defines a reference distance \bar{D}

Scaling this template to distance D gives

$$h = \frac{\bar{D}}{D} \hat{h}$$

The distance is then estimated from the data as

$$D = \frac{\bar{D}}{(d|\hat{h})}$$

Reducing the cost of a search

Phase Offset:

Generate two templates $h(\phi = 0)$ and $h(\phi = \pi/2)$

$$\text{Then } (d|h)_{\max \phi} = \sqrt{(d|h(0))^2 + (d|h(\pi/2))^2}$$

Easy to see this in the Fourier domain.

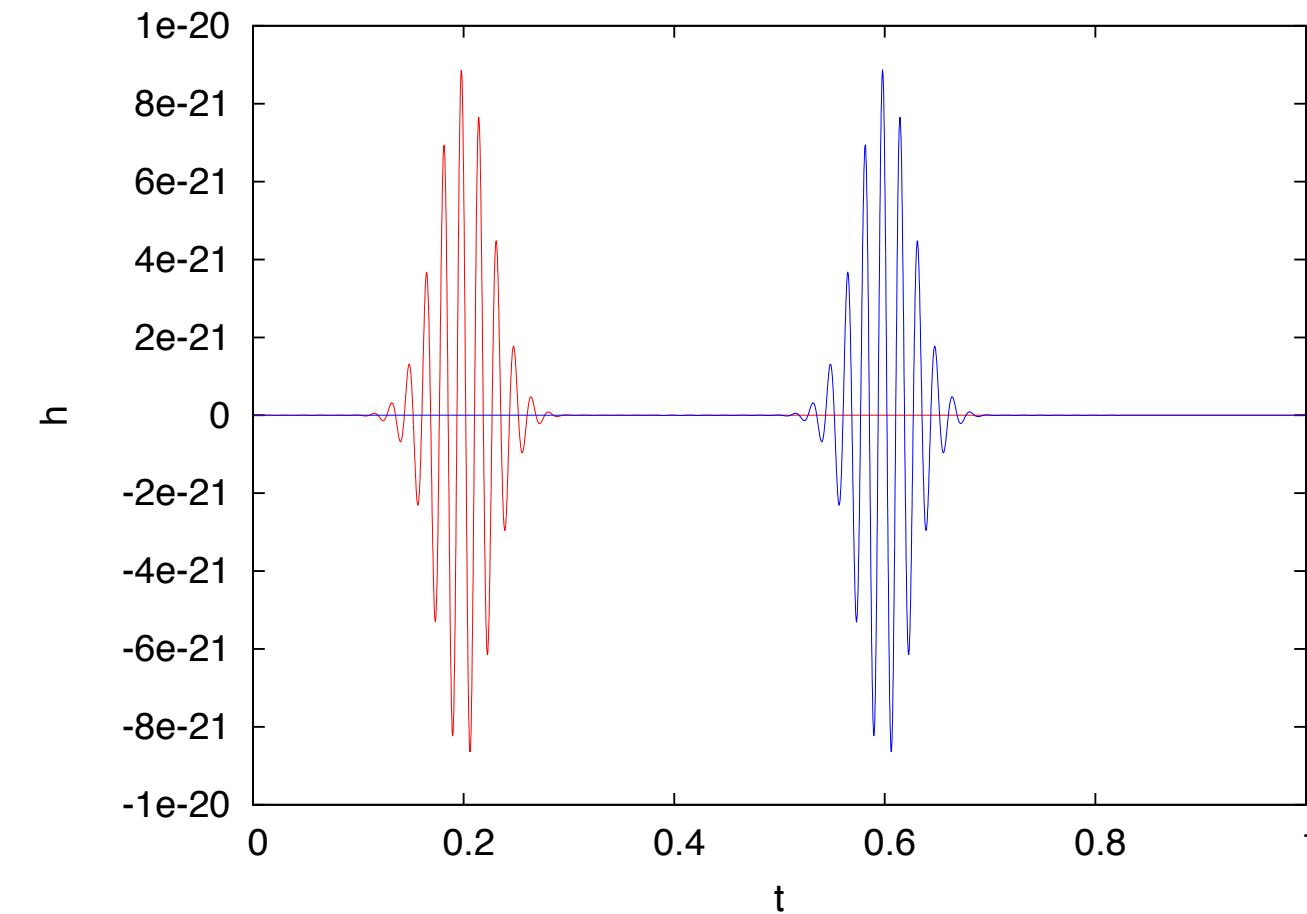
Suppose $\tilde{d} = \tilde{h}_0 e^{i\phi}$, then

$$(d|h(0)) = (h_0|h_0) \cos \phi$$

$$(d|h(\pi/2)) = (h_0|h_0) \sin \phi$$

Reducing the cost of a search

Time Offset:



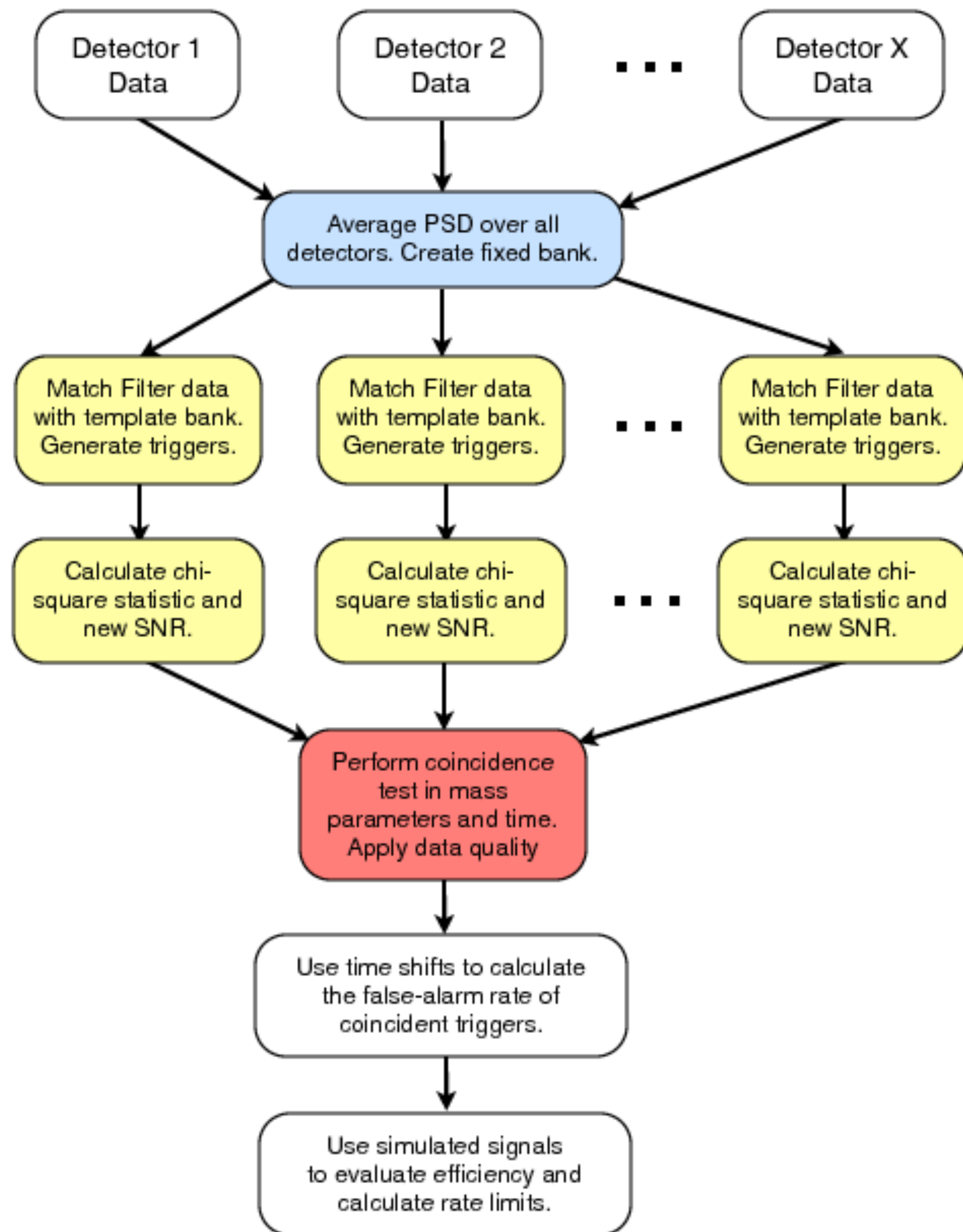
Fourier transform treats time as periodic - use this to our advantage

Compute the inverse Fourier transform of the product of the Fourier transforms:

$$(d|h)(\Delta t) = 4 \int \frac{\tilde{d}^*(f)\tilde{h}(f)}{S(f)} e^{2\pi i f \Delta t} df$$

Then if the template and data differ by a time shift: $d(t) = h(t - t_0)$

$$(d|h)_{\max t} = (d|h)(\Delta t = t_0)$$



Workflow for pyCBC search

Template bank constructed

Matched filtering is done per-detector (not coherent)

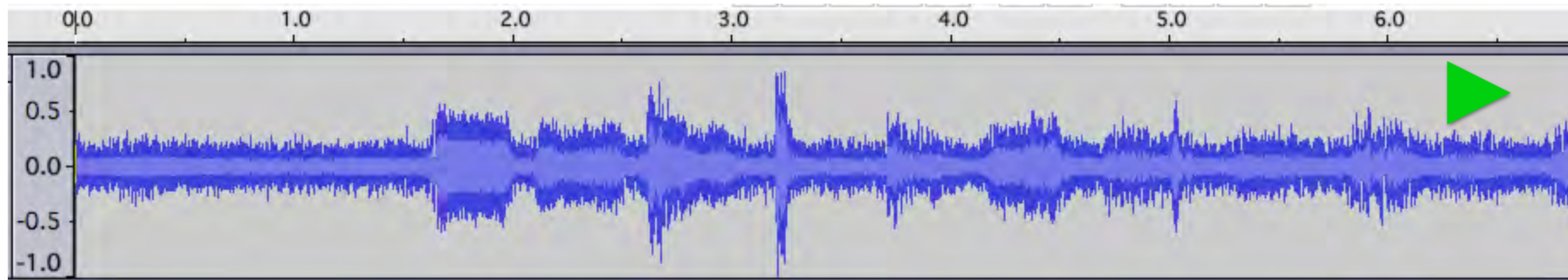
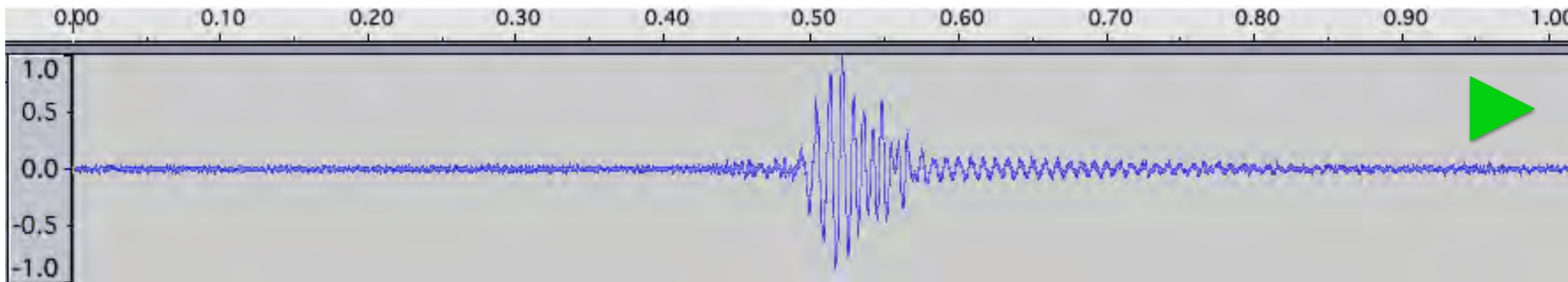
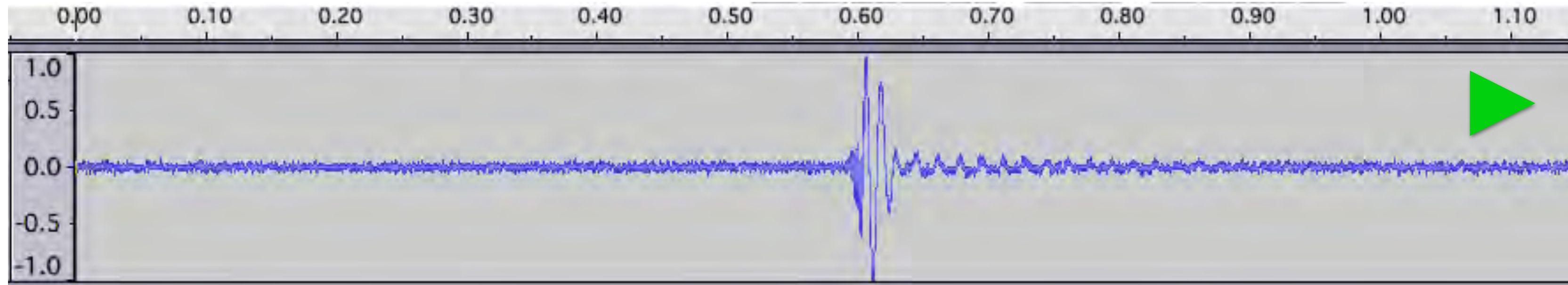
Detection statistic computed ("new SNR")

Coincidence in time/mass enforced
Data quality vetoes applied

Monte Carlo background to compute
FAR vs new SNR

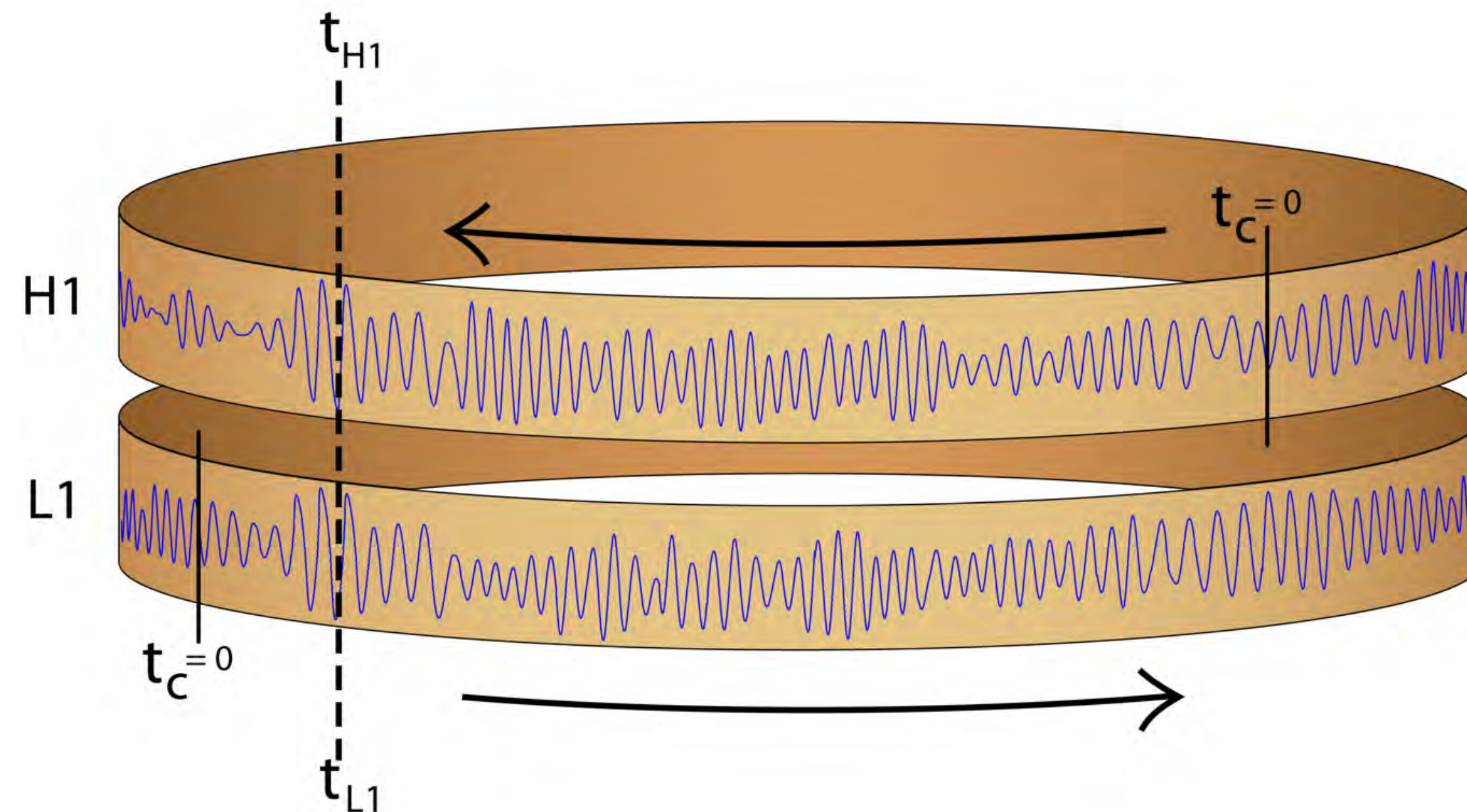
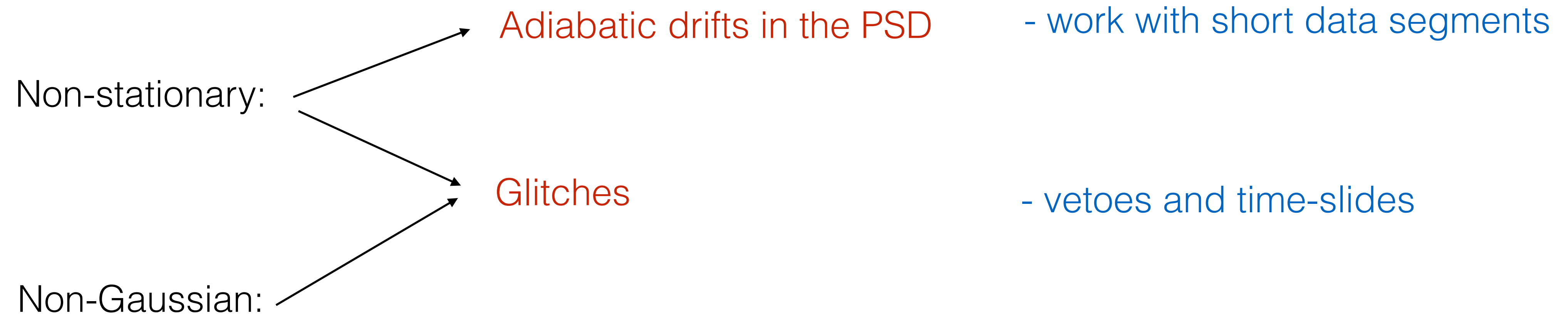
Things that go bump in the night

(Bandpass filtered, whitened, time domain)

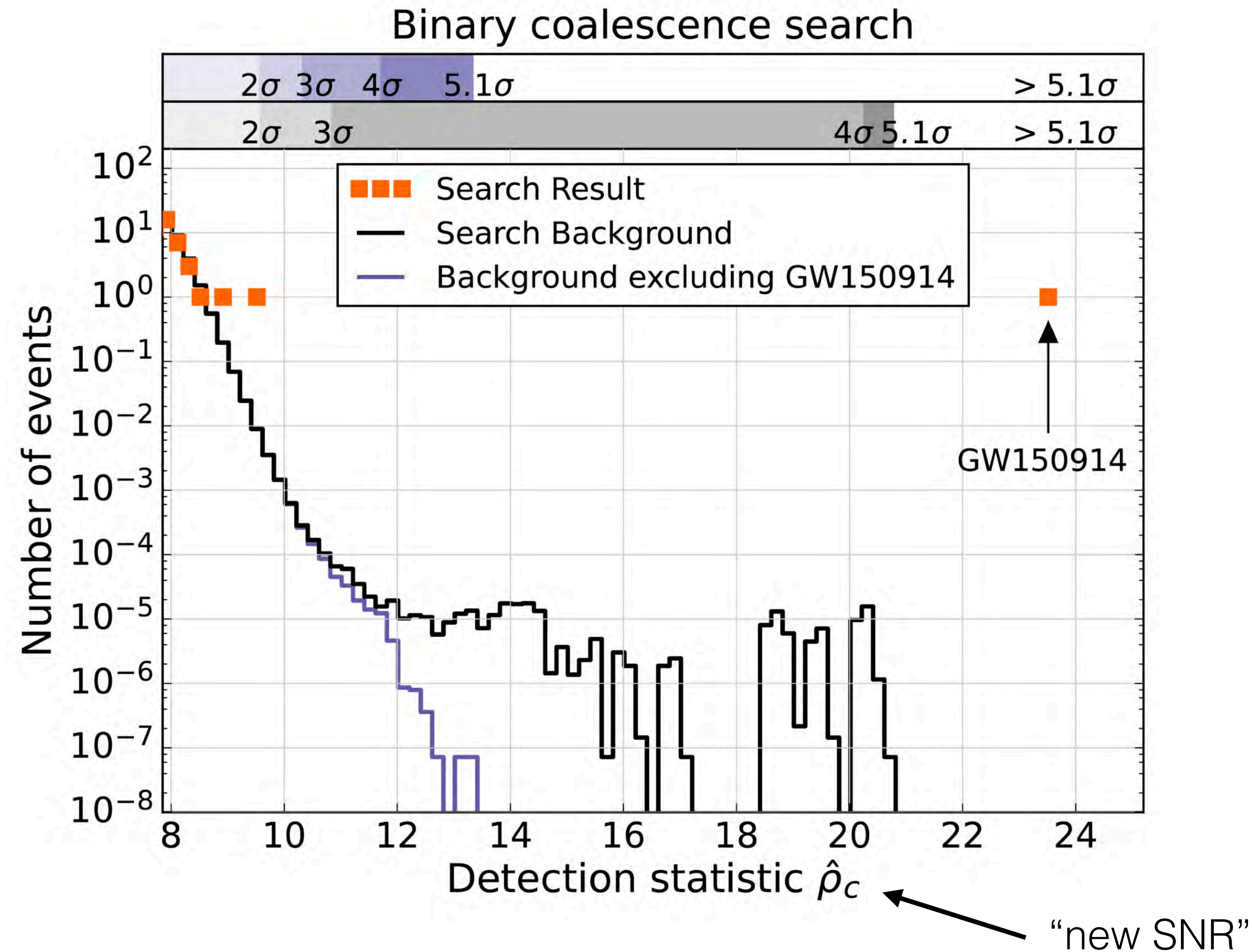


Samples from the Syracuse Audio Study of Glitches

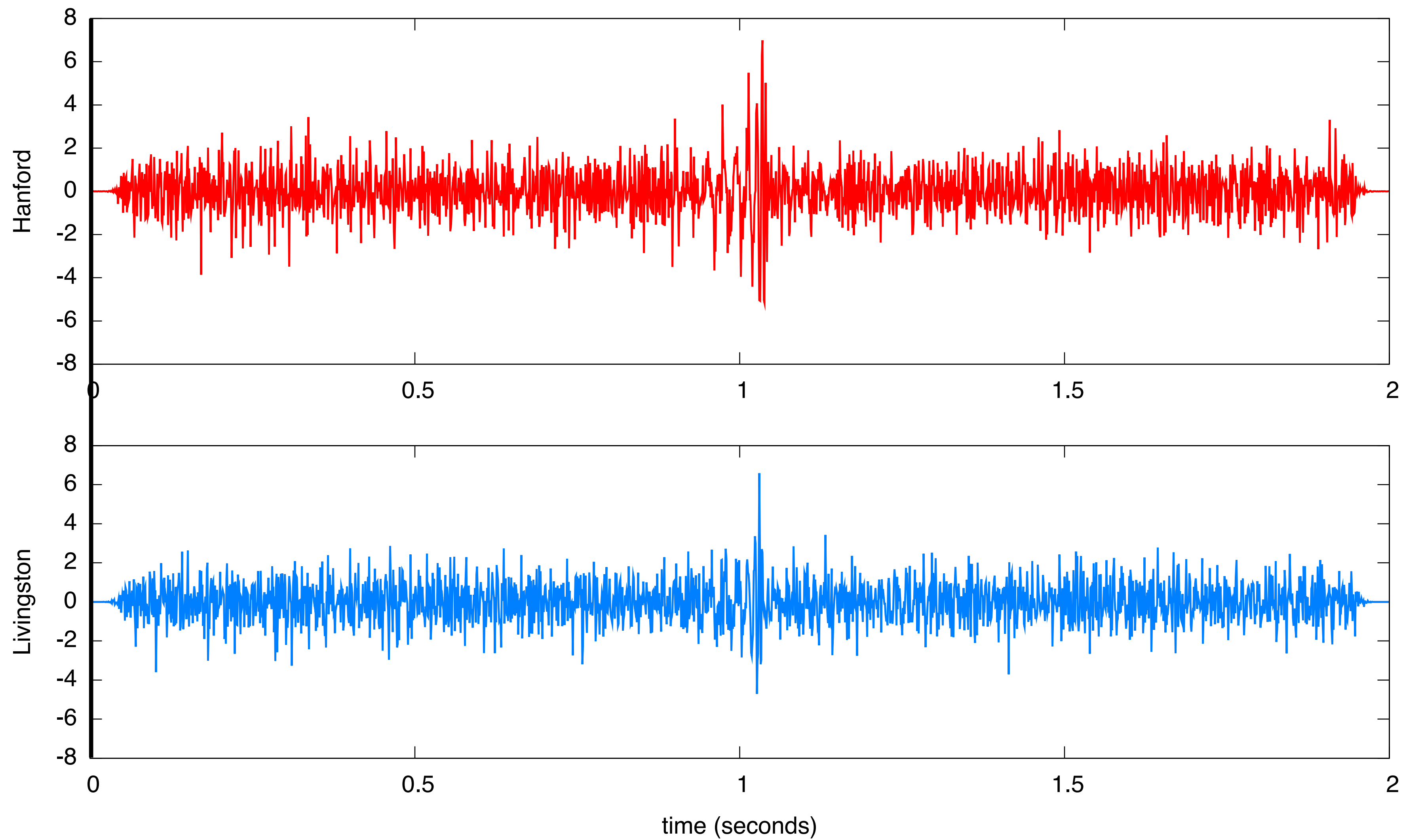
Contending with non-stationary, non-Gaussian noise



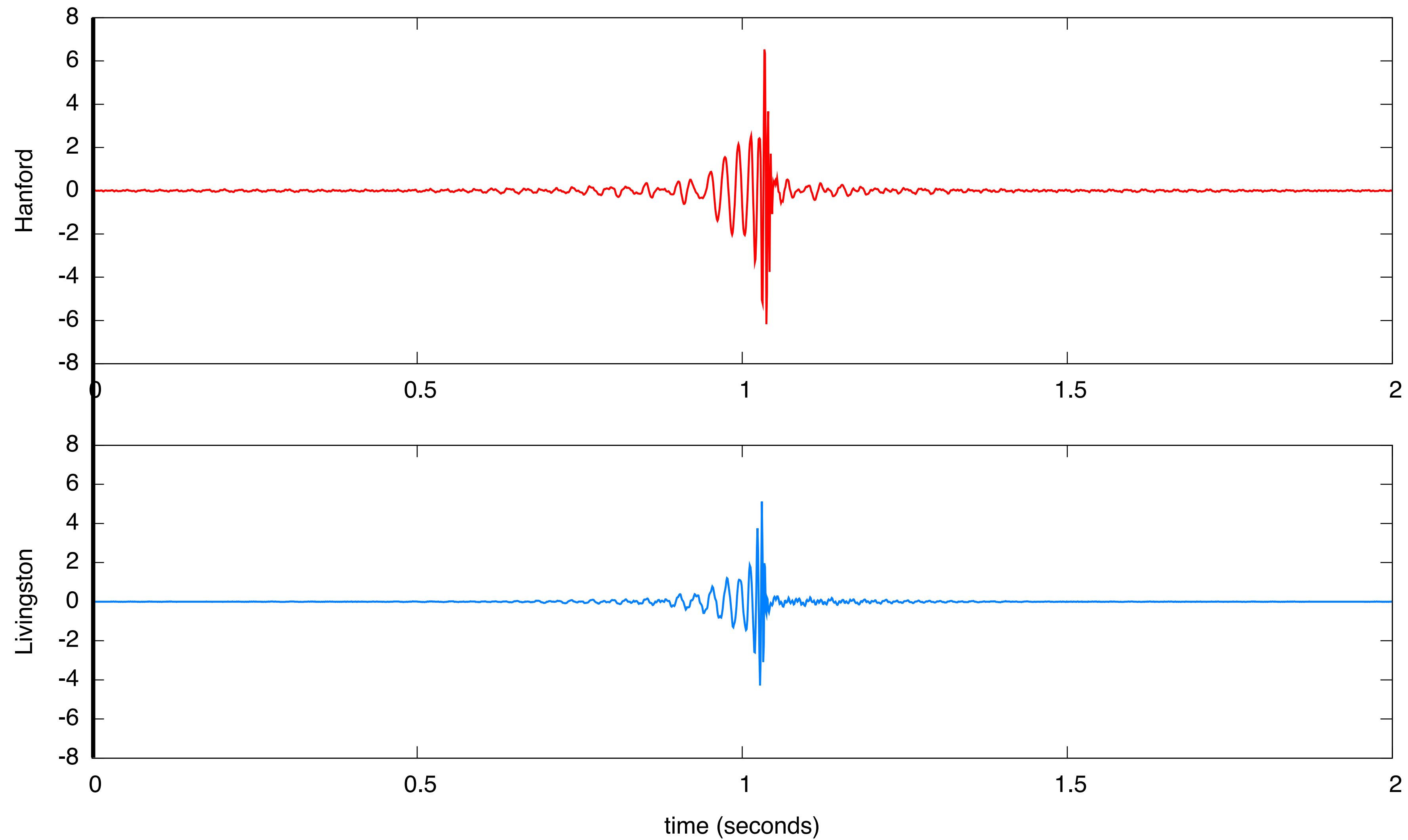
Analysis of 16 days of data from September 2015



Early Morning, September 14 2015



BayesWave reconstruction of the signal



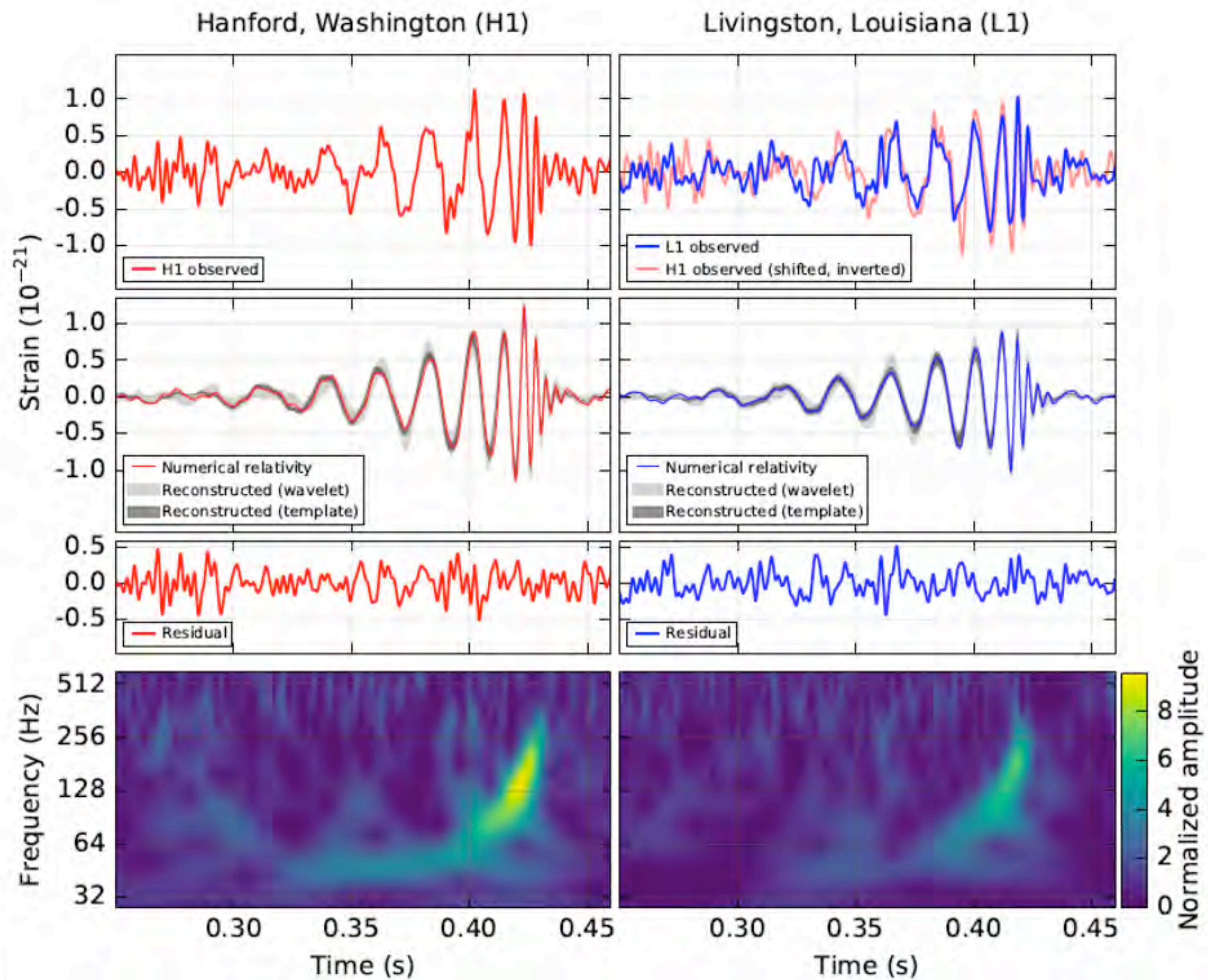
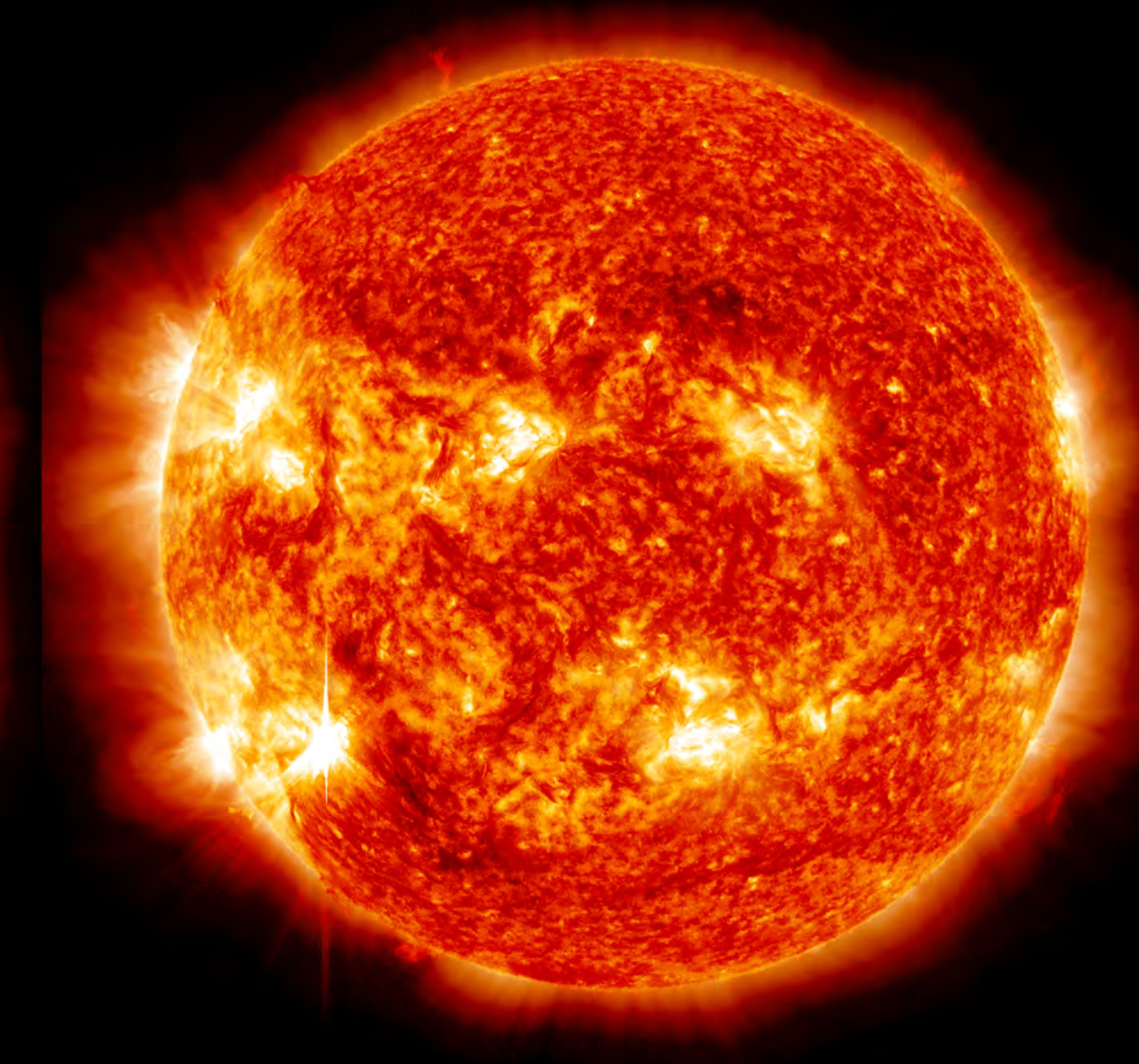
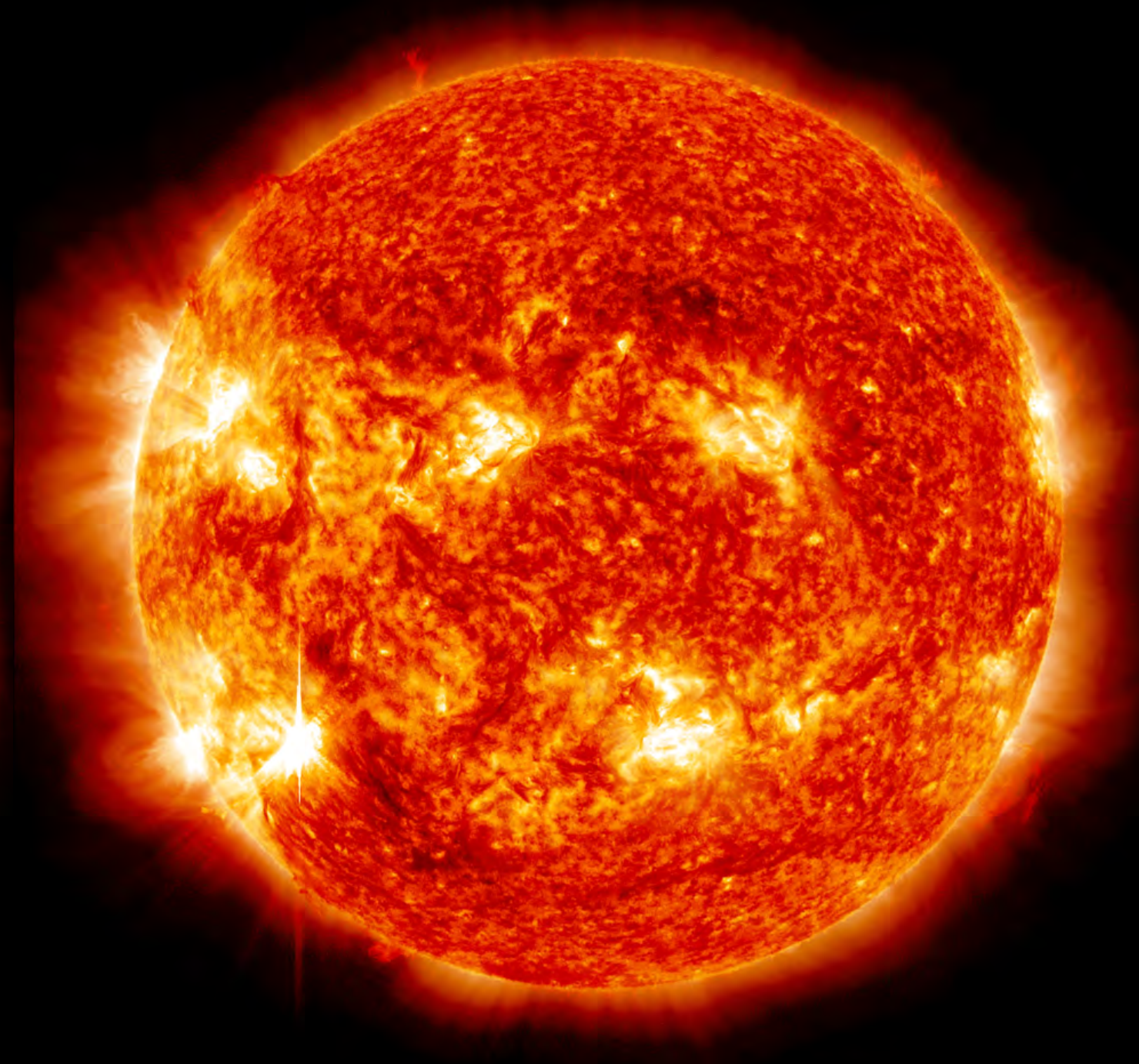
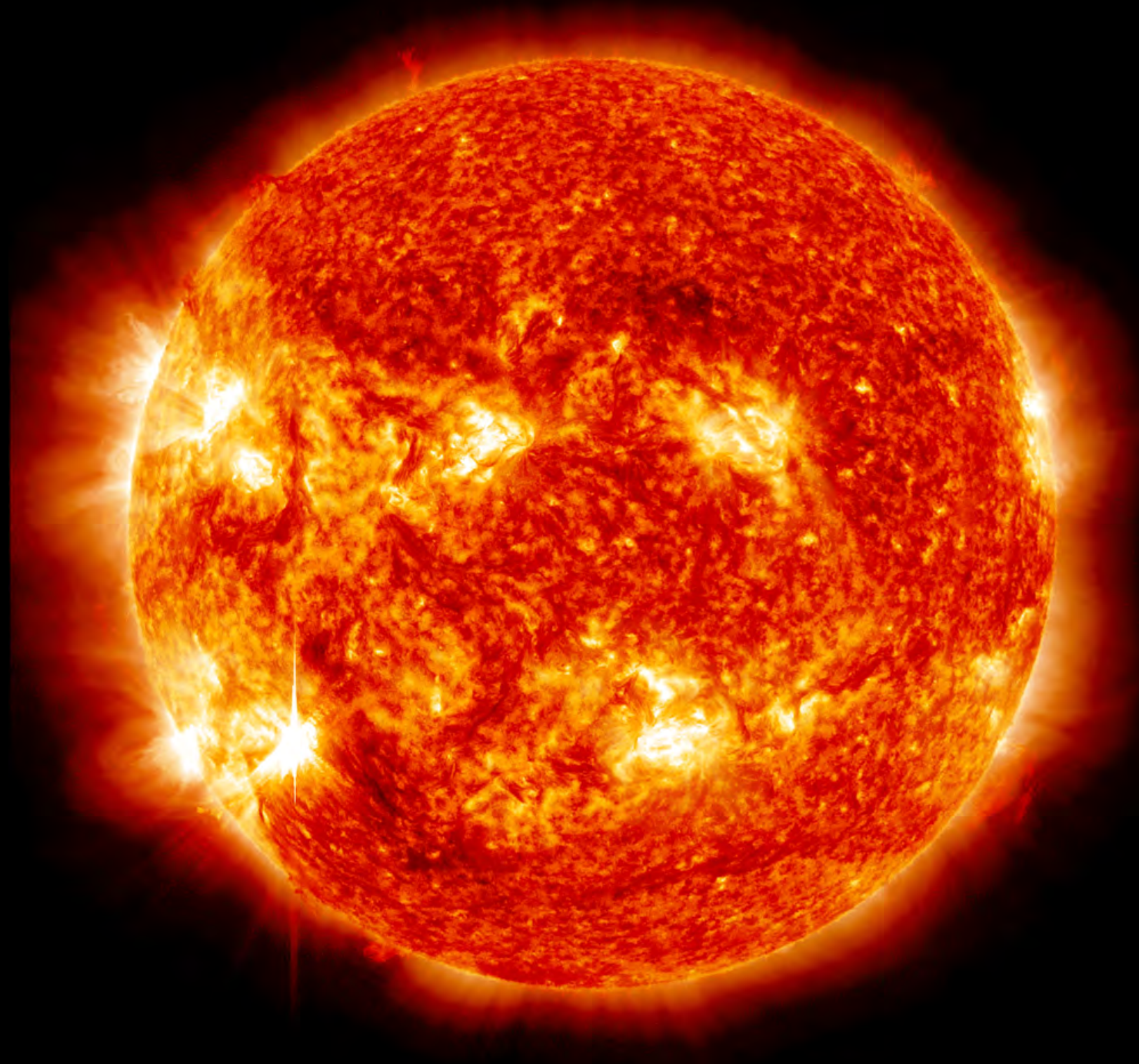


FIG. 1. The gravitational-wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (L1, right column panels) detectors. Times are shown relative to September 14, 2015 at 09:50:45 UTC. For visualization, all time series





"All the News
That's Fit to Print"

The New York Times

Late Edition
Today, some sunshine giving way to times of clouds, cold, high 28. Tonight, a flurry or heavier squall late, low 15. Tomorrow, windy, frig-

VOL. CLXV . . . No. 57,140 + © 2016 The New York Times NEW YORK, FRIDAY, FEBRUARY 12, 2016

Clinton Paints Sanders Plans



President Obama
@POTUS

Follow

Einstein was right! Congrats to @NSF and @LIGO on detecting gravitational waves - a huge breakthrough in how we understand the universe.

RETWEETS 7,787 LIKES 16,365

3:43 PM - 11 Feb 2016

as well, seizing an opportunity to talk about leaders she admired and turning it against Mr. Sanders by bashing his past criticism of President Obama — a remark that Mr. Sanders called a “low blow.”

With tensions between the two Democrats becoming increasingly obvious, the debate was full of new lines of attack from Mrs. Clinton, who faces pressure to

A worker installed a baffle in 2010 to control light in the Laser Interferometer Gravitational-Wave Observatory in Hanford, Calif.

Long in Clinton's Corner, Blacks Notice Sanders

By RICHARD FAUSSET
ORANGEBURG, S.C. — When Helen Duley was asked whom she would vote for in the South

Courted Hard in South Carolina, Loyalists

candidate she barely knew. “It makes me feel good,” she said, chuckling, “that young people are listening to the elderly people.” She now said she was an un-

Last Occu In Rural Is Coas

CARVE
BACKCOUNTRY BEHAVIOR
New MSU snow science research tracks decision-making process during backcountry skiing trips | CARVE

BOMBS AWAY
Montana State men set school record with 25 3s in win against NAU | SPORTS

BOZEMAN DAILY CHRONICLE
FRIDAY, FEBRUARY 12, 2016

Jury rules against woman in 'wrongful birth' case

By WHITNEY BERMES
Chronicle Staff Writer

A Gallatin County jury ruled against a Gardiner woman who was seeking money for her daughter born with cystic fibrosis. After about two hours of deliberations, the 12-person jury ruled that Livingston HealthCare nurse Peggy Scanlon and Bozeman OB/GYN Dr. William Peters did not violate their standard of care with Kerrie Evans.

The verdict came on the ninth day of the trial, held before Gallatin County District Judge Mike Salvagny. Evans sued in 2011 after her daughter, now 5, was born with cystic fibrosis. Evans' attorneys Casey Magan and Russ Waddell argued that during Evans' pregnancy, Evans had chorionic villus sampling (CVS), which is a type of test that can diagnose abnormalities.

That test came back with normal results, but after giving birth, Evans' daughter was diagnosed with cystic fibrosis, a genetic disease that affects respiratory and digestive systems. Evans argued that she was not given any information on cystic fibrosis screening, a different test that would have shown that both she and her husband were carriers for the gene that caused the genetic disorder in their child.

Had she known her daughter was going to be born with cystic fibrosis, Evans said she and her husband Joe would have terminated her pregnancy. “Kerrie Evans asked for (a cystic fibrosis) test. She walked out of that place thinking she was going to get that test,” Waddell said to the jury during closing arguments Thursday.

Kerrie Evans, center, talks with her attorneys after a 12-person jury ruled against her lawsuit on Thursday at the Gallatin County Law and Justice Center in Bozeman.

Einstein was right

'Now we can hear the universe': Einstein's gravity waves detected, MSU scientists members of discovery team



Astrophysicist Neil Cornish, co-director of Montana State University's xGravty Institute, and a team of 1,000 scientists worldwide, helped prove the existence of gravitational waves, predicted by Albert Einstein a century ago.

By GAIL SCHONTZLER
Chronicle Staff Writer

A century ago Albert Einstein predicted the existence of gravitational waves rippling through the universe, and on Thursday a team of 1,000 scientists worldwide — including Montana State University astrophysicist Neil Cornish — announced they found proof in the echo of a billion-year-old collision between two massive black holes.

“It’s great to finally be able to tell everybody,” said Cornish, 45, speaking in his native Australian accent, standing in line at The Daily Coffee Shop. “As the story broke on NPR and the New York Times’ front page, his cell phone was buzzing with friends texting congratulations and a USA Today reporter calling.

The discovery, originally all information came from different forms of light. Now we can listen to objects that don’t emit light, like black holes.

“It’s inaugurating an entirely new branch of astronomy. It’s akin to Galileo turning his telescope to the heavens.”

Cornish, co-director of MSU’s xGravty Institute, said he, his graduate student Margaret Millhouse and five MSU Ph.D. graduates will be named on scientific papers on the discovery, among more than 1,000 scientists in 16 countries, from Germany, Japan, France, Italy and Australia to the United States.

“This absolutely is a Nobel Prize-worthy discovery,” Cornish said, for the three “visitors” who have been working on it for decades — Kip Thorne and Ronald Drever of Caltech in Los Angeles and Ray Weiss of MIT in Boston. Weiss, in his 80s, is still out tinkering and trouble-shooting on the giant detectors, built in Hanford, Washington, and Livingston, Louisiana.

They’ve worked on this for 50 years,” Cornish said. “I think this is one of the most significant scientific discoveries in history.”

With FBI ring tightening, last Oregon occupiers surrender

Four holdouts in the armed takeover of national wildlife refuge give up on Thursday



Nevada Assemblyman John Moore speaks to reporters outside the Malheur Wildlife Refuge during the standoff near Burns, Ore., on Thursday.

By REBECCA BOONE AND MARTHA BELLISLE
Associated Press

BURNS, Ore. — With the FBI tightening its ring around them, the last four holdouts in the armed takeover of a national wildlife refuge in Oregon surrendered Thursday, ending a 41-day standoff that left one man dead and exposed simmering anger over the government’s control of vast expanses of Western land.

Federal authorities in six states also arrested seven other people accused of being involved in the occupation and brought charges against a leader of the movement who organized a 2014 standoff. Two more suspects remained at large.

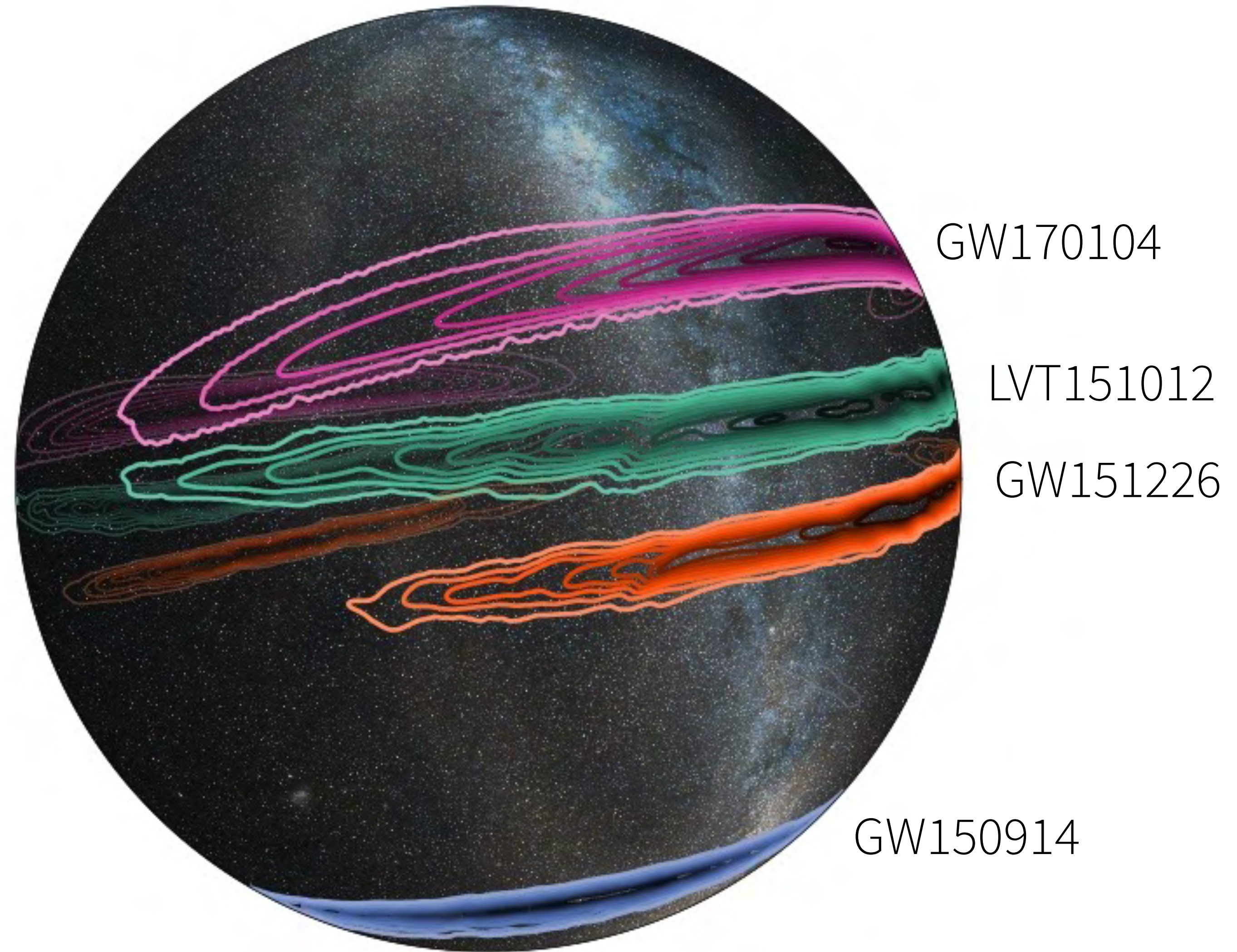
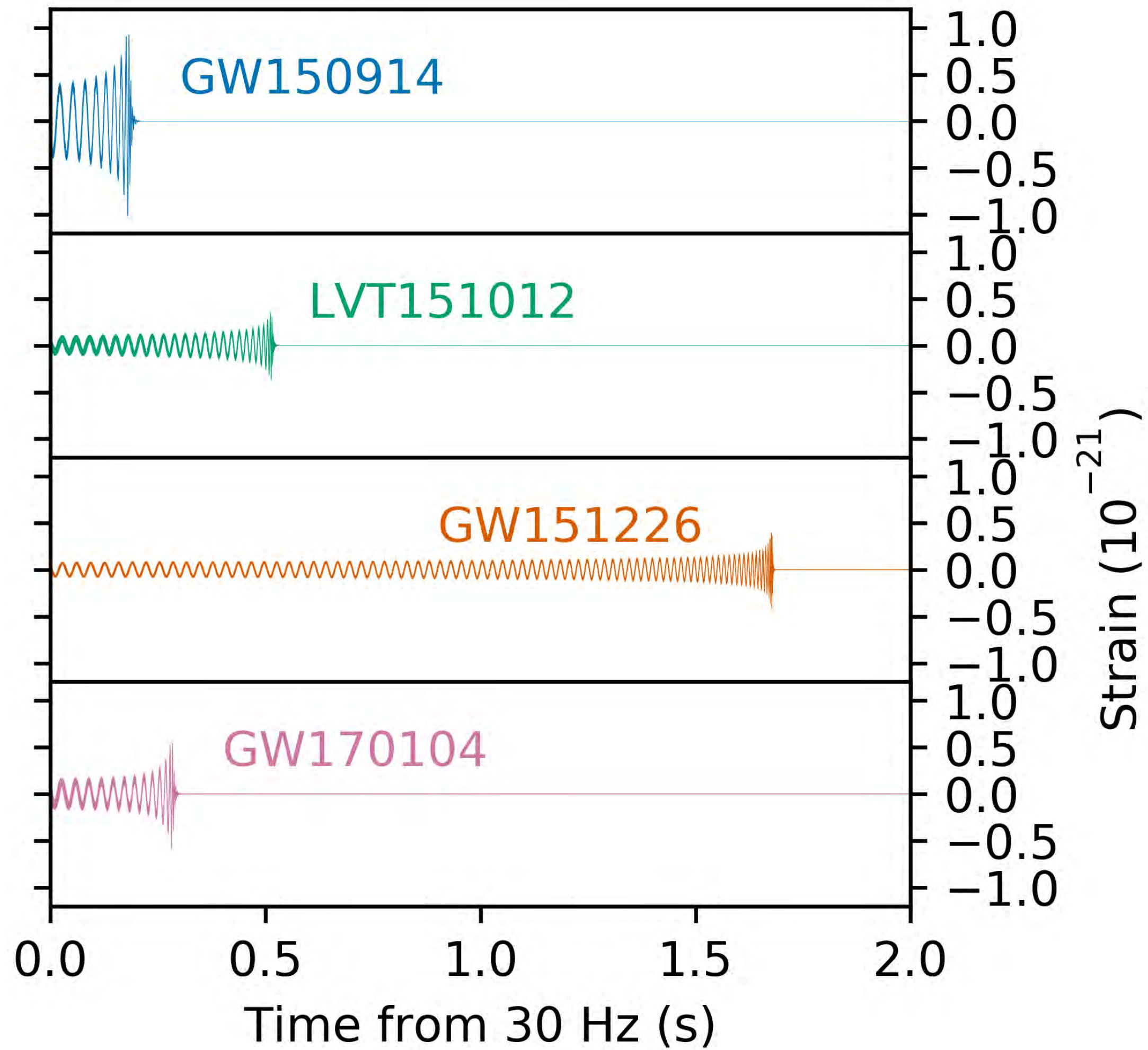
The last occupiers at the Malheur National Wildlife Refuge gave up without incident a day after federal agents surrounded the site.

Nearly residents were relieved. “I just posted bail on my Facebook,” said Julie Weikel, who lives next to the nature preserve. “And I think that says it all. I am so glad this is over.”

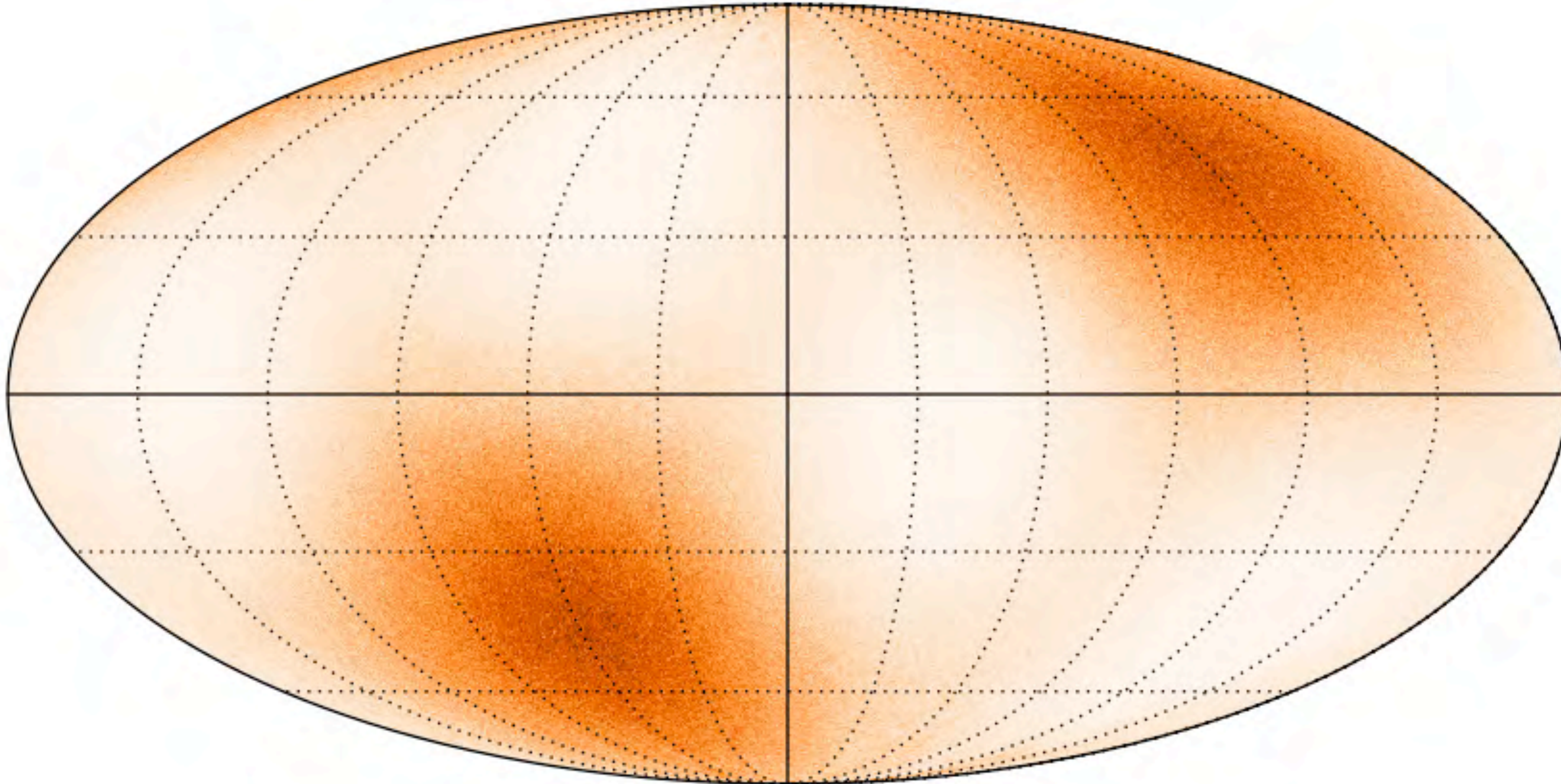
At least 25 people have now been indicted on federal charges of conspiracy to impede employees at the wildlife refuge from performing their duties.

Meanwhile, Cliven Bundy, who was at the center of the 2014 standoff at his ranch in Nevada, was arrested late Wednesday in Portland after encouraging the occupiers not to give up. Bundy is the father of Ammon Bundy, the jailed leader of the Oregon occupation.

LIGO detections to-date

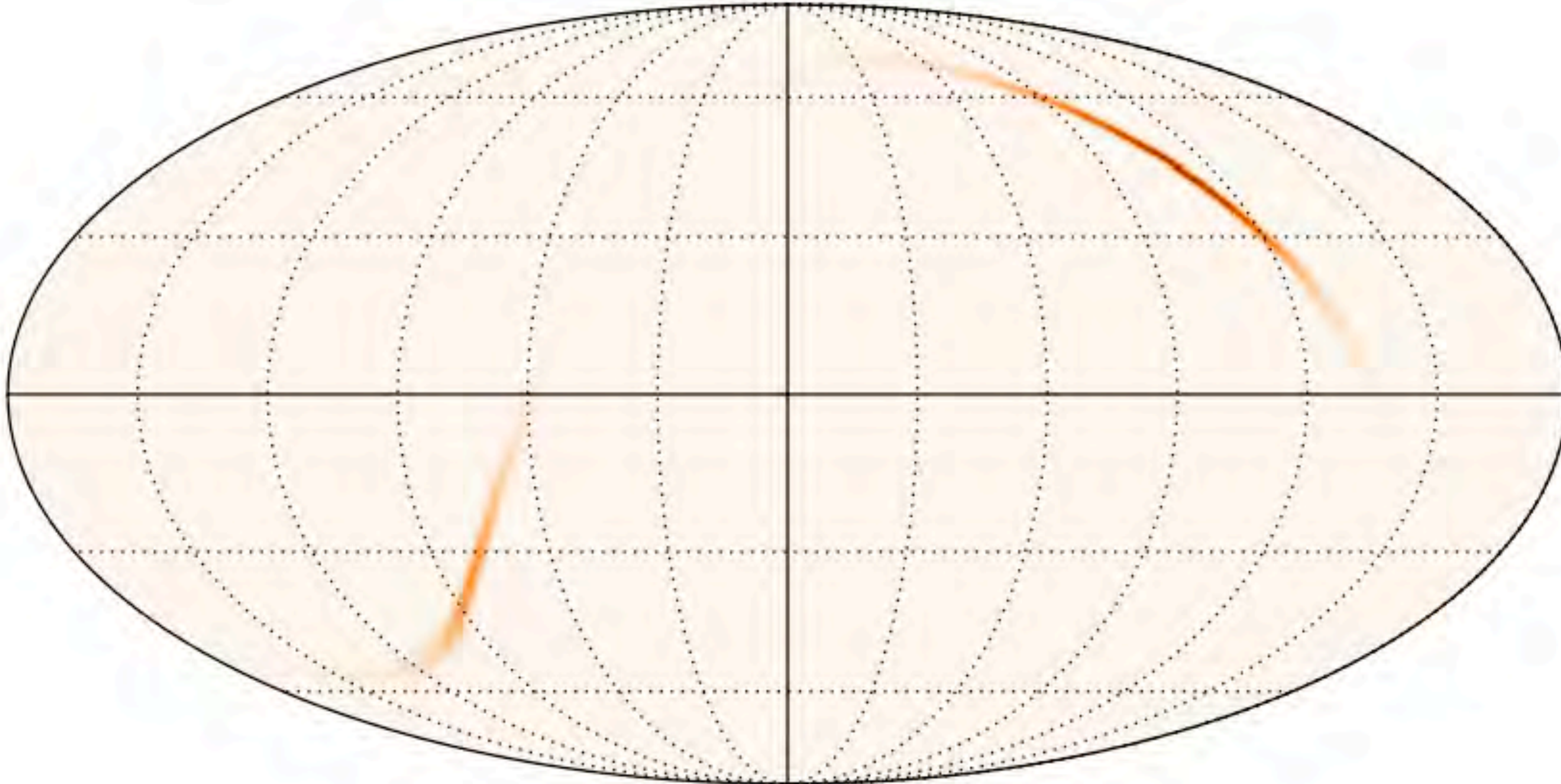


Triangulating the Source



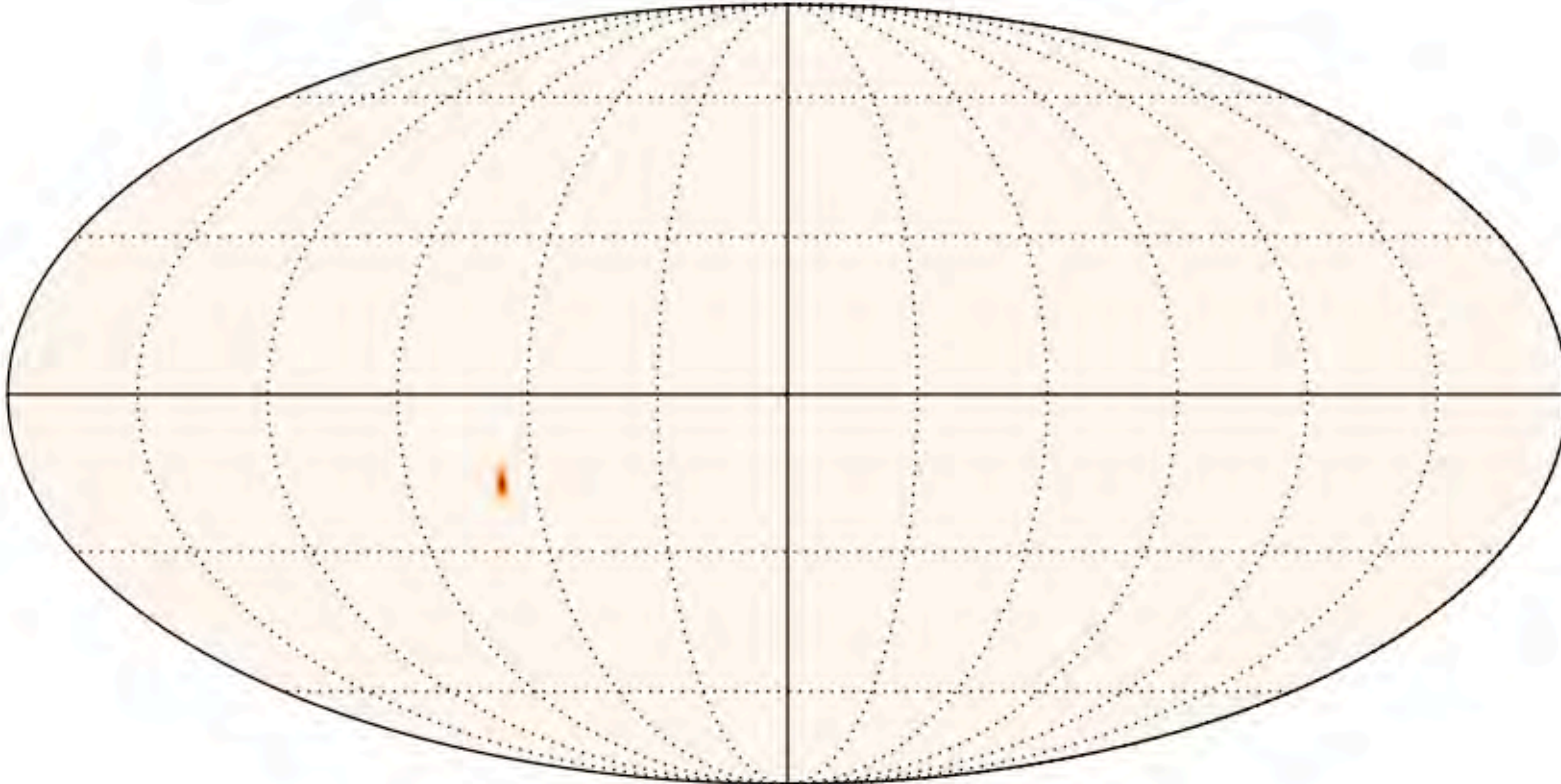
Hanford

Triangulating the Source



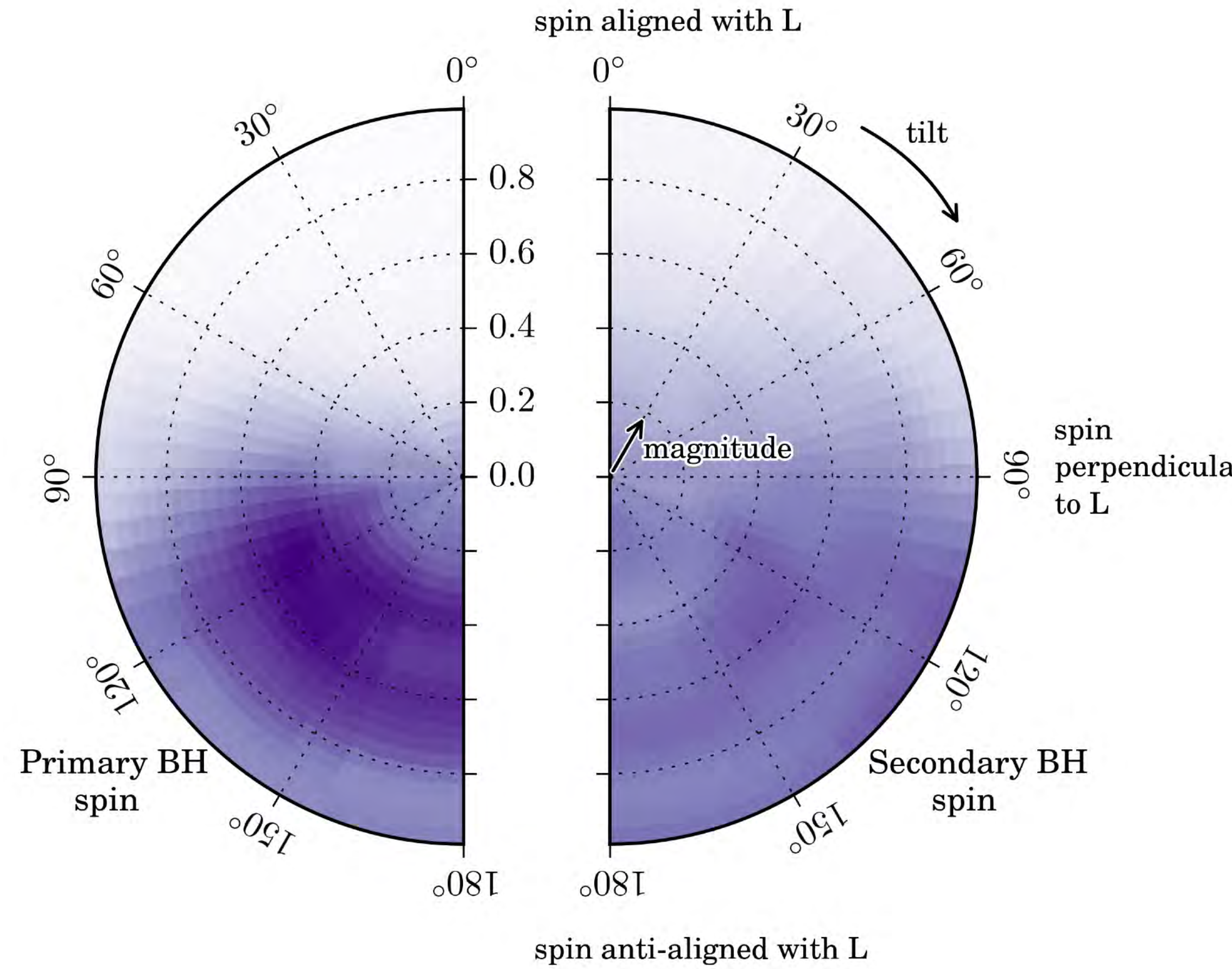
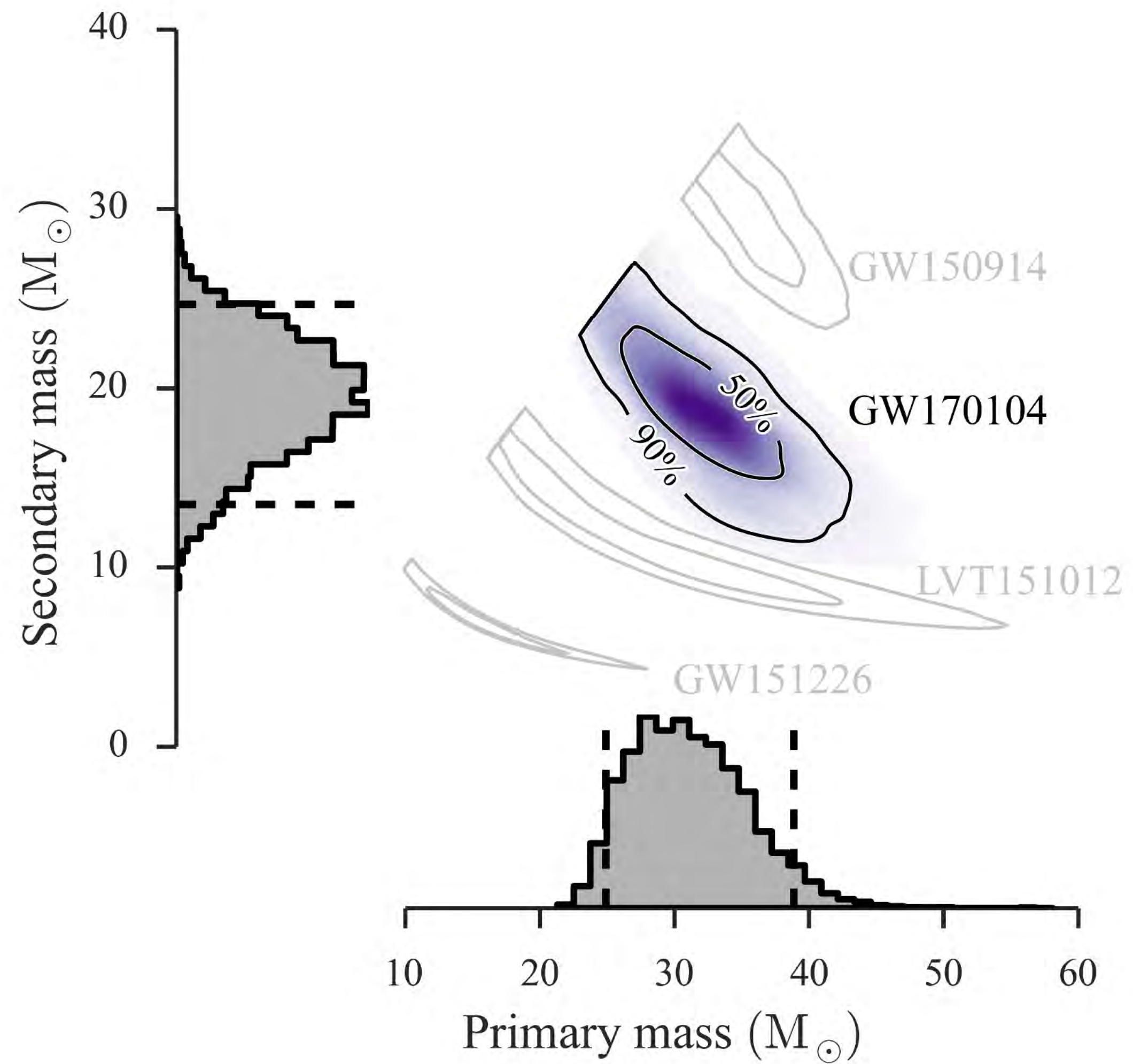
Hanford + Livingston

Triangulating the Source



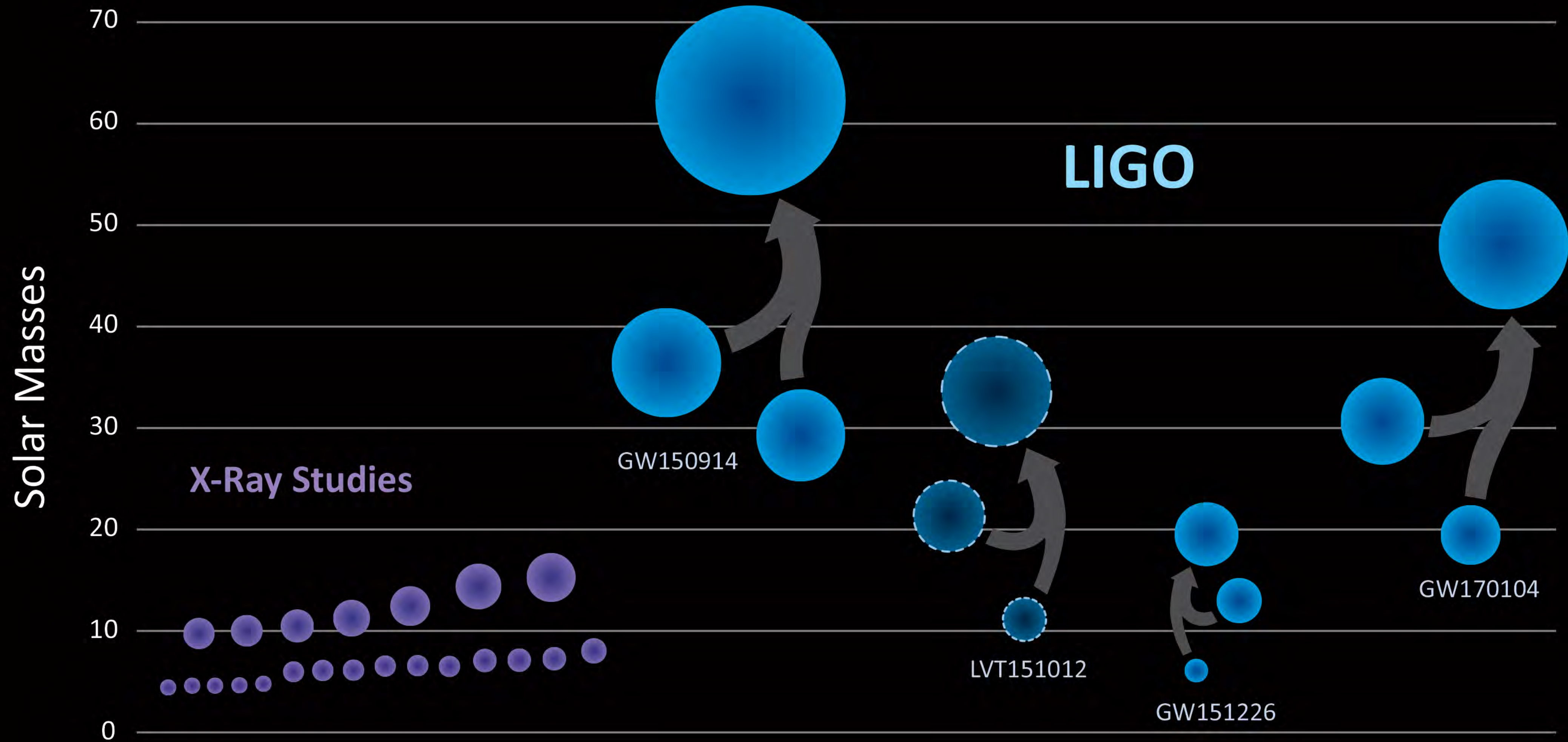
Hanford + Livingston + Virgo

Parameter estimation



GW170104

Black Holes of Known Mass



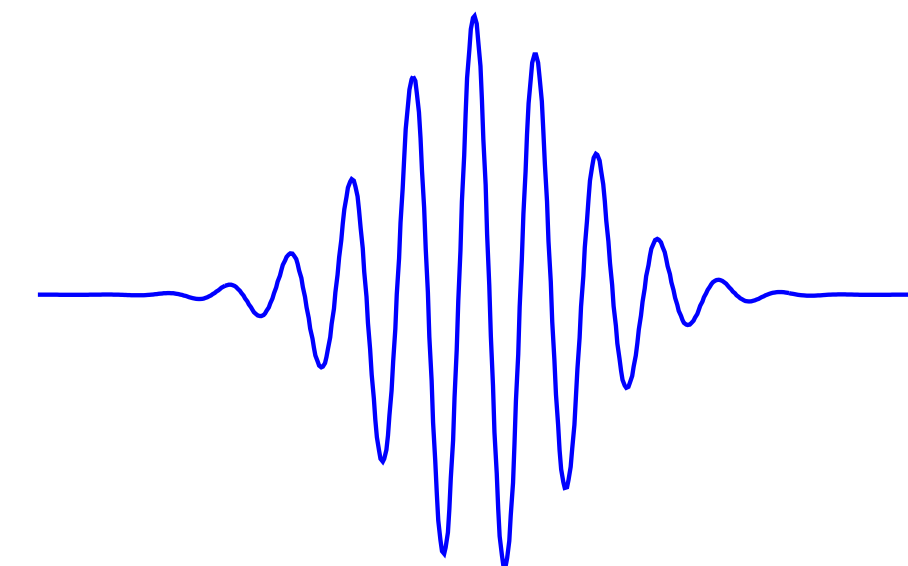
Detection without templates

BayesWave

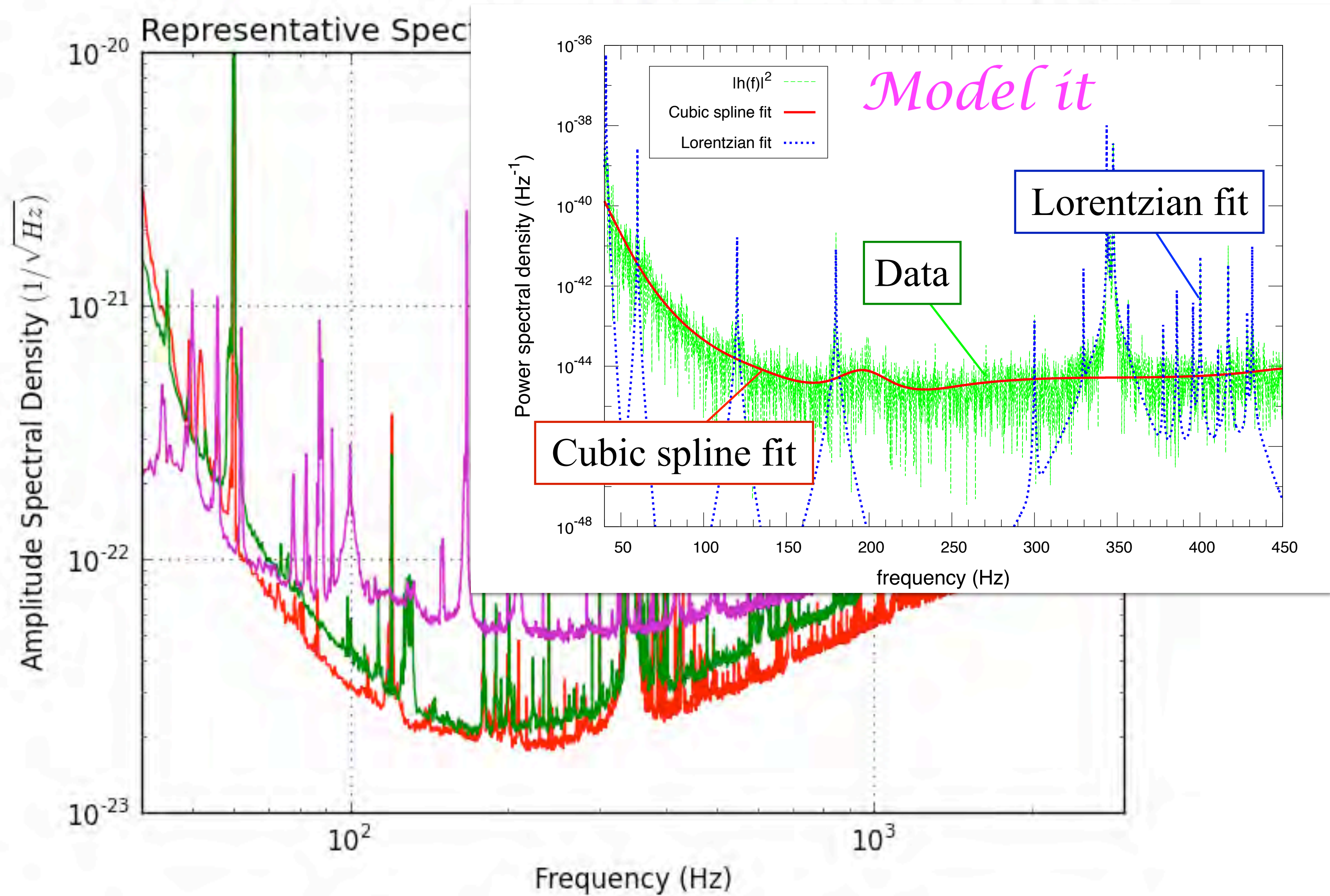
Cornish & Littenberg 2015

- Bayesian model selection
 - Three part model (signal, glitches, gaussian noise)
 - Trans-dimensional Markov Chain Monte Carlo
- Wavelet decomposition
 - Glitch & GW modeled by wavelets
 - Number, amplitude, quality and TF location of wavelets varies

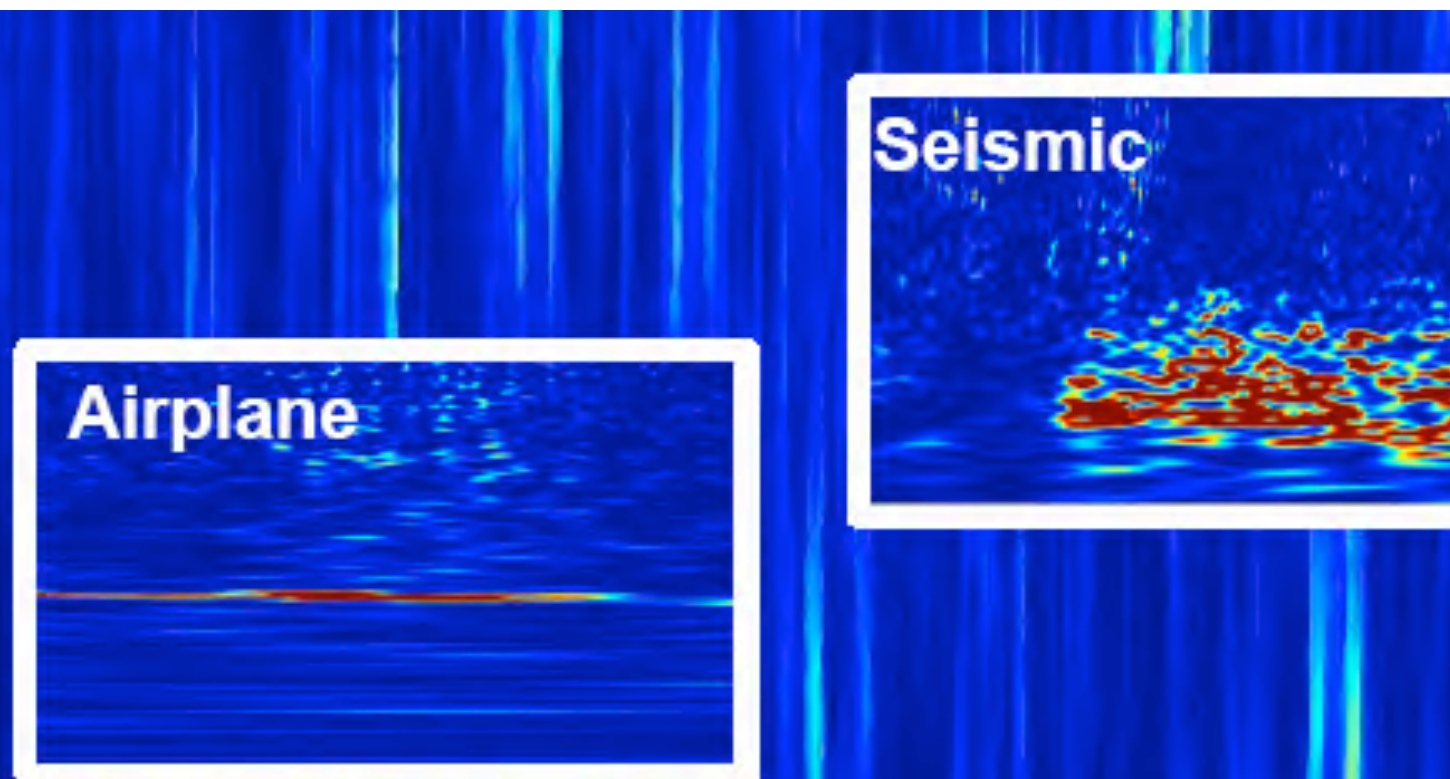
Continuous Morlet/Gabor Wavelets



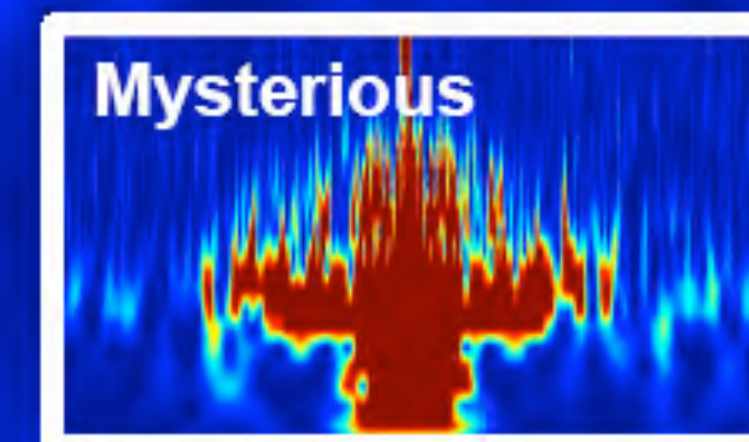
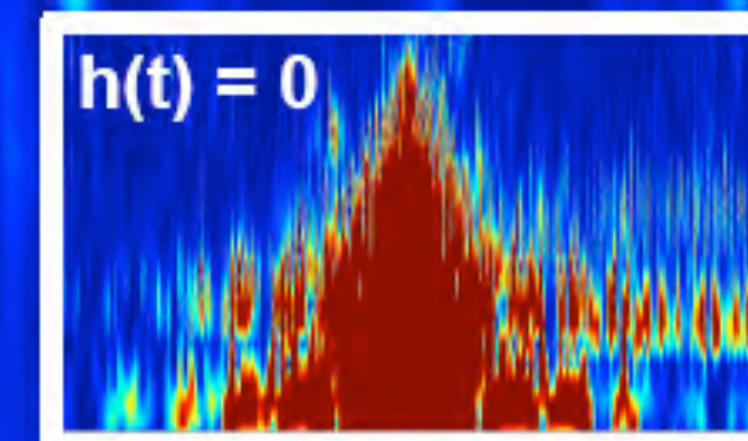
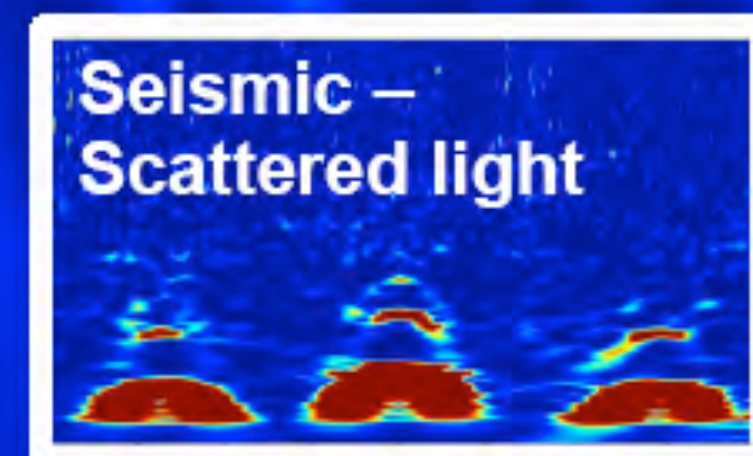
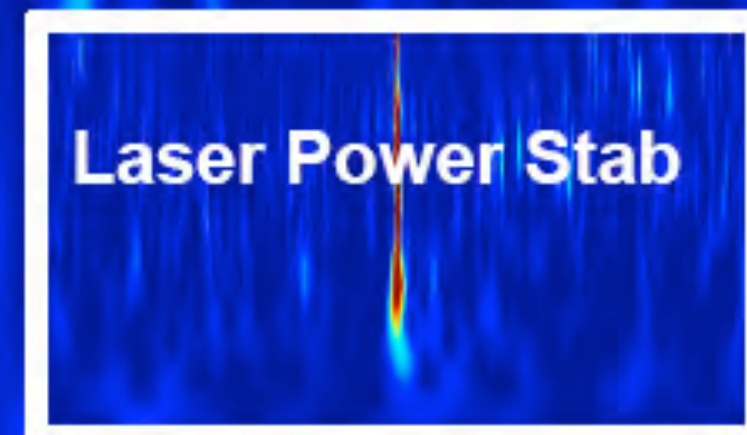
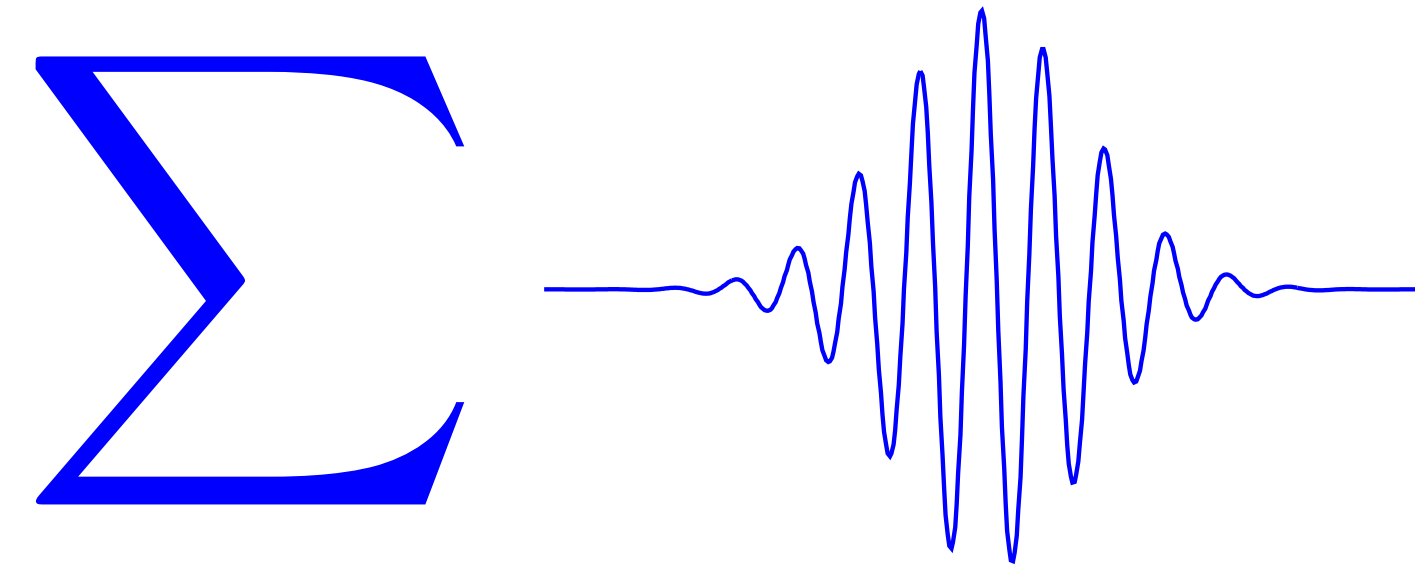
Lines and a drifting noise floor



Glitches



Model these too

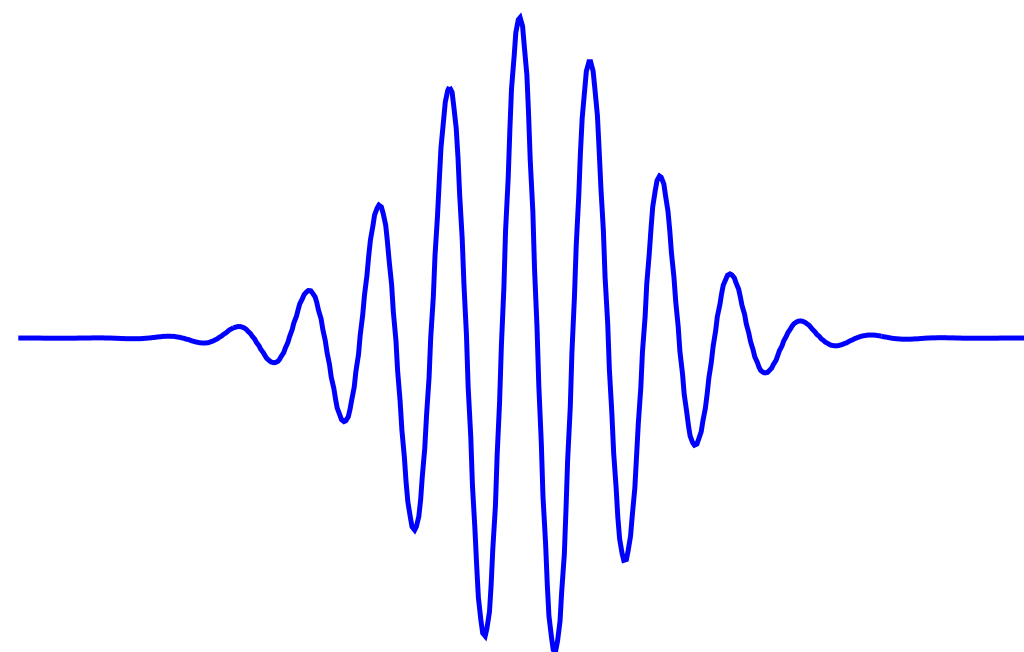


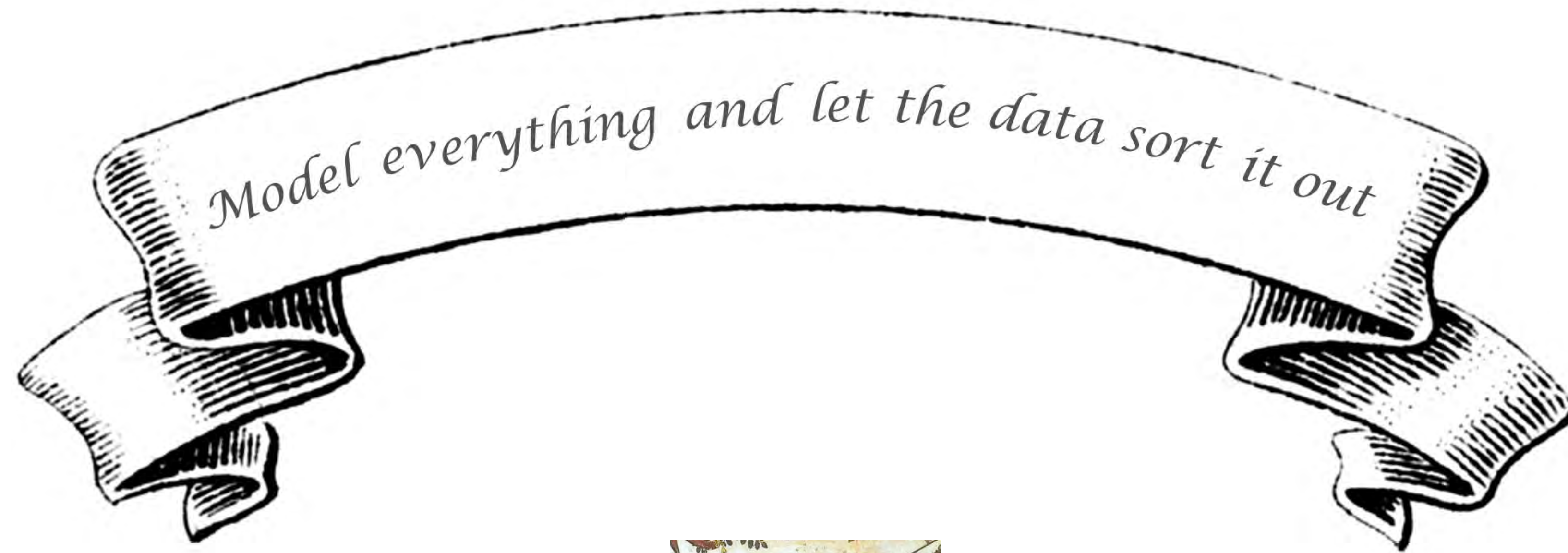
Gravitational Waves

and model these



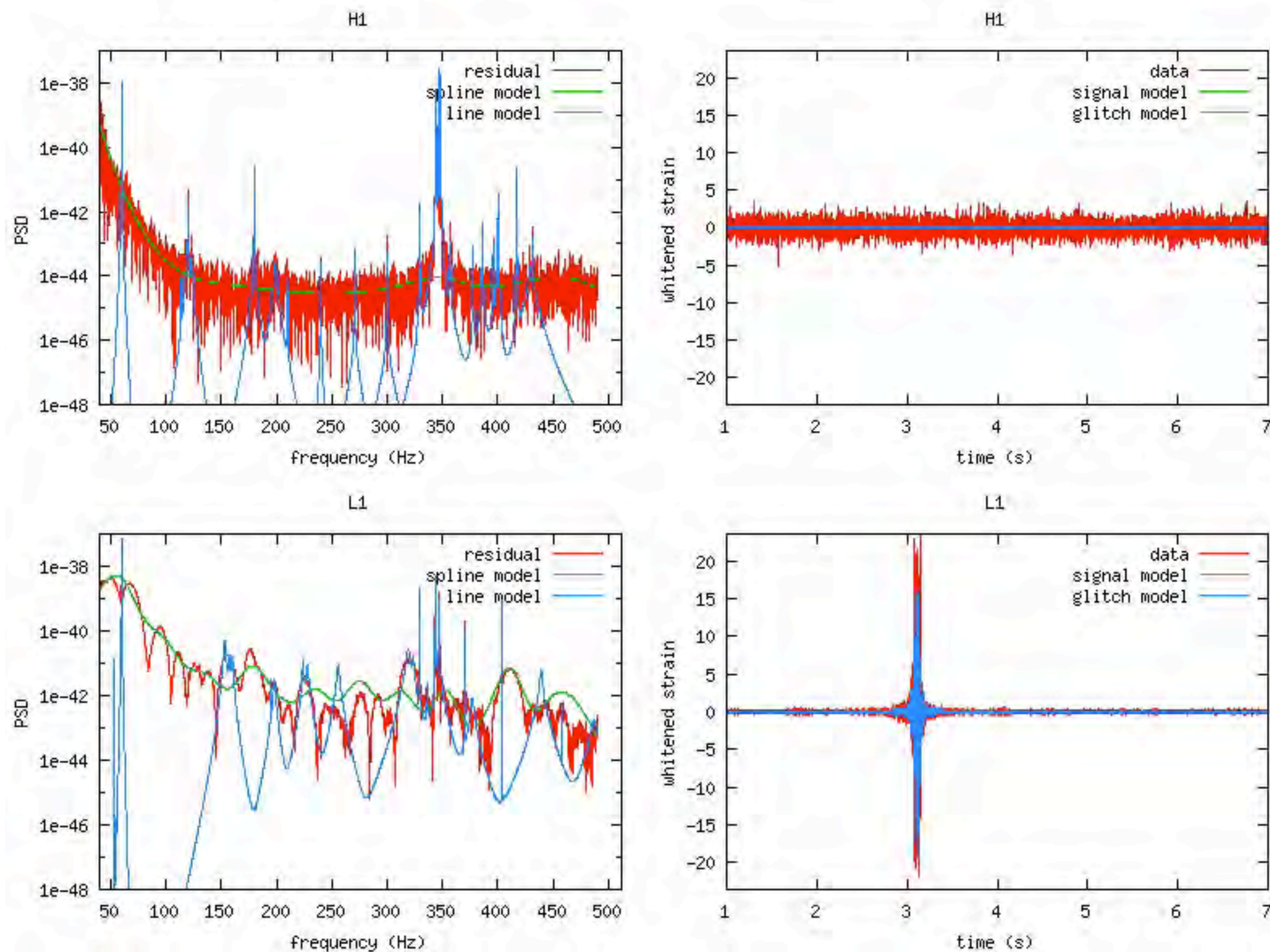
Σ



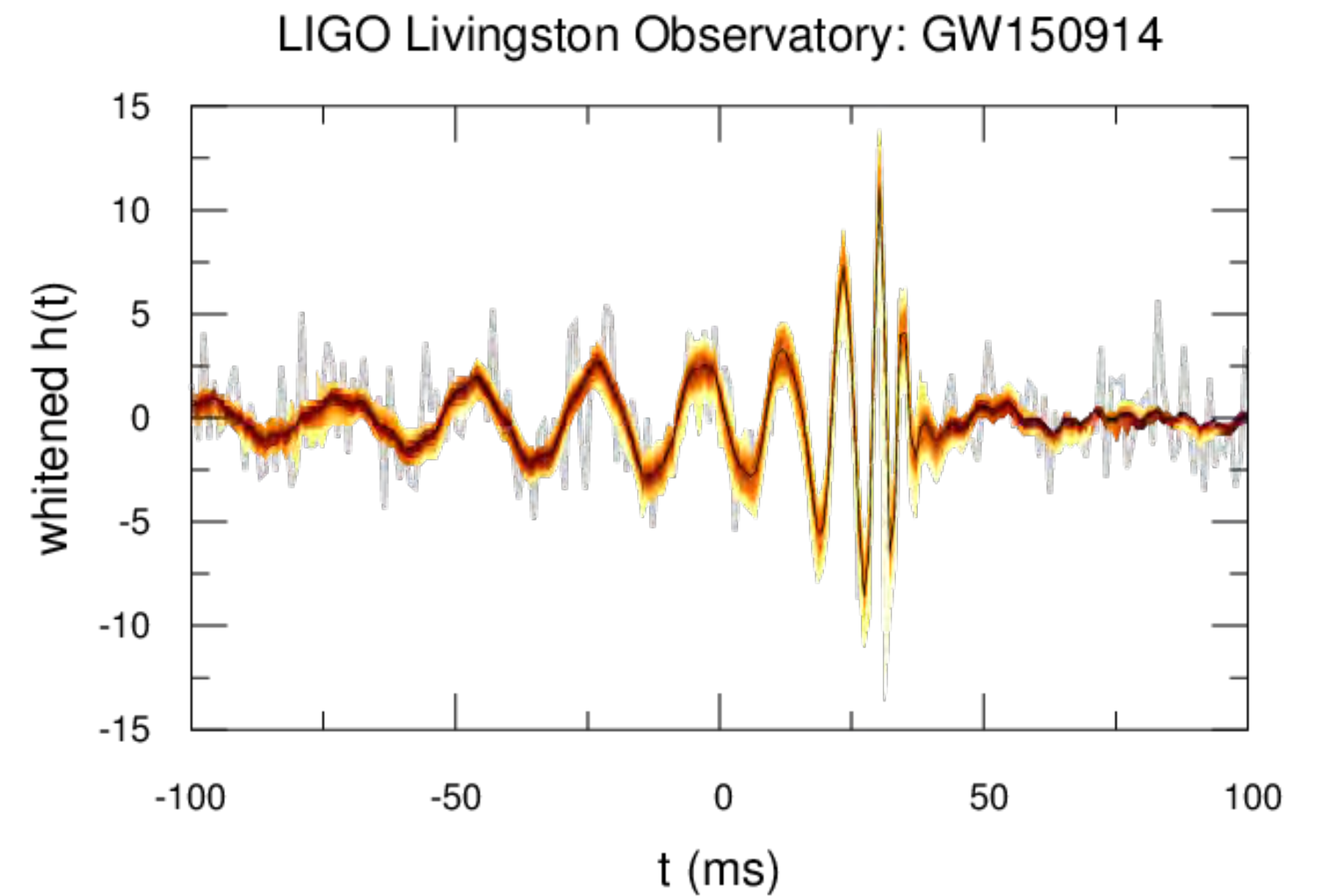
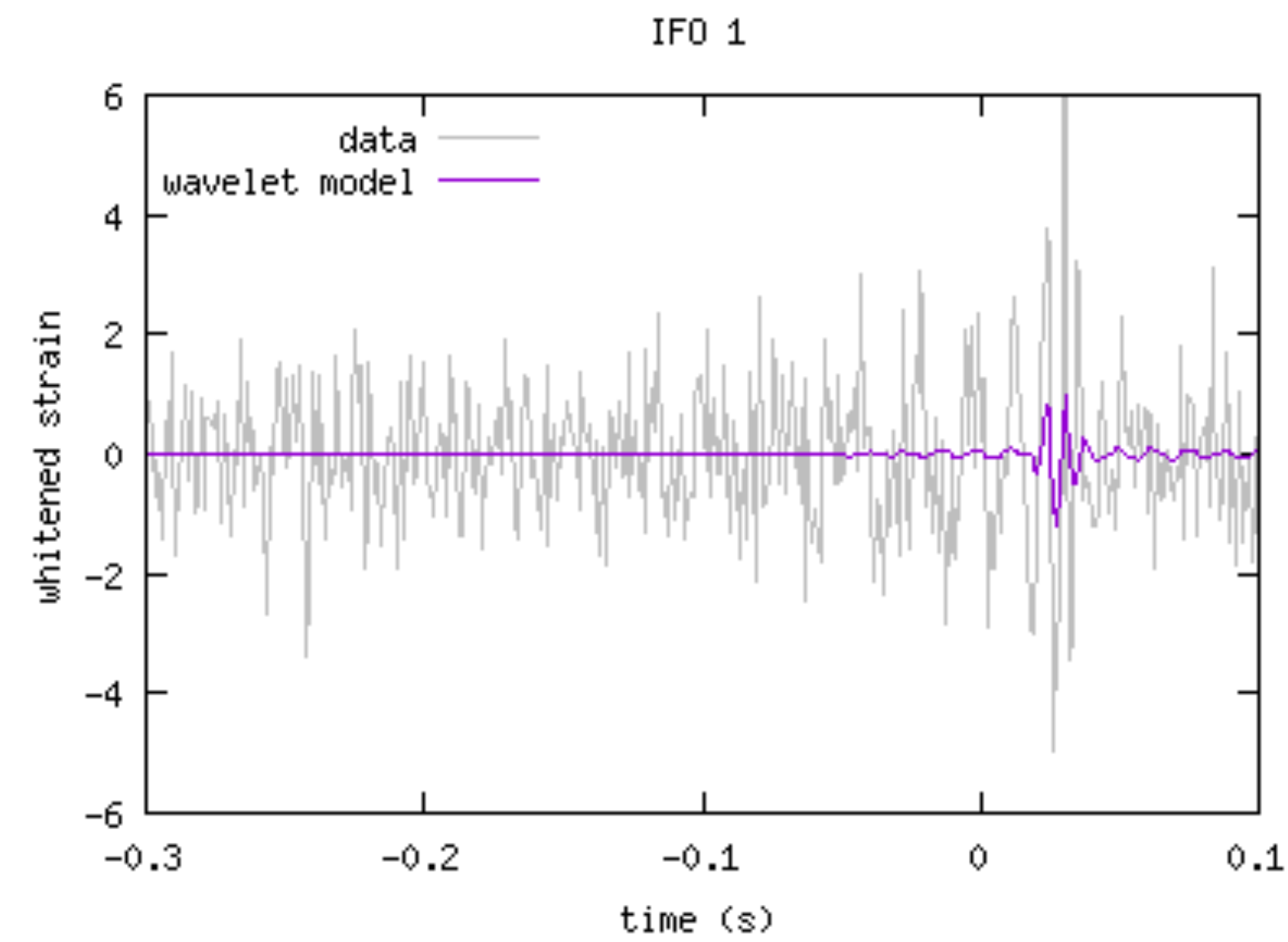
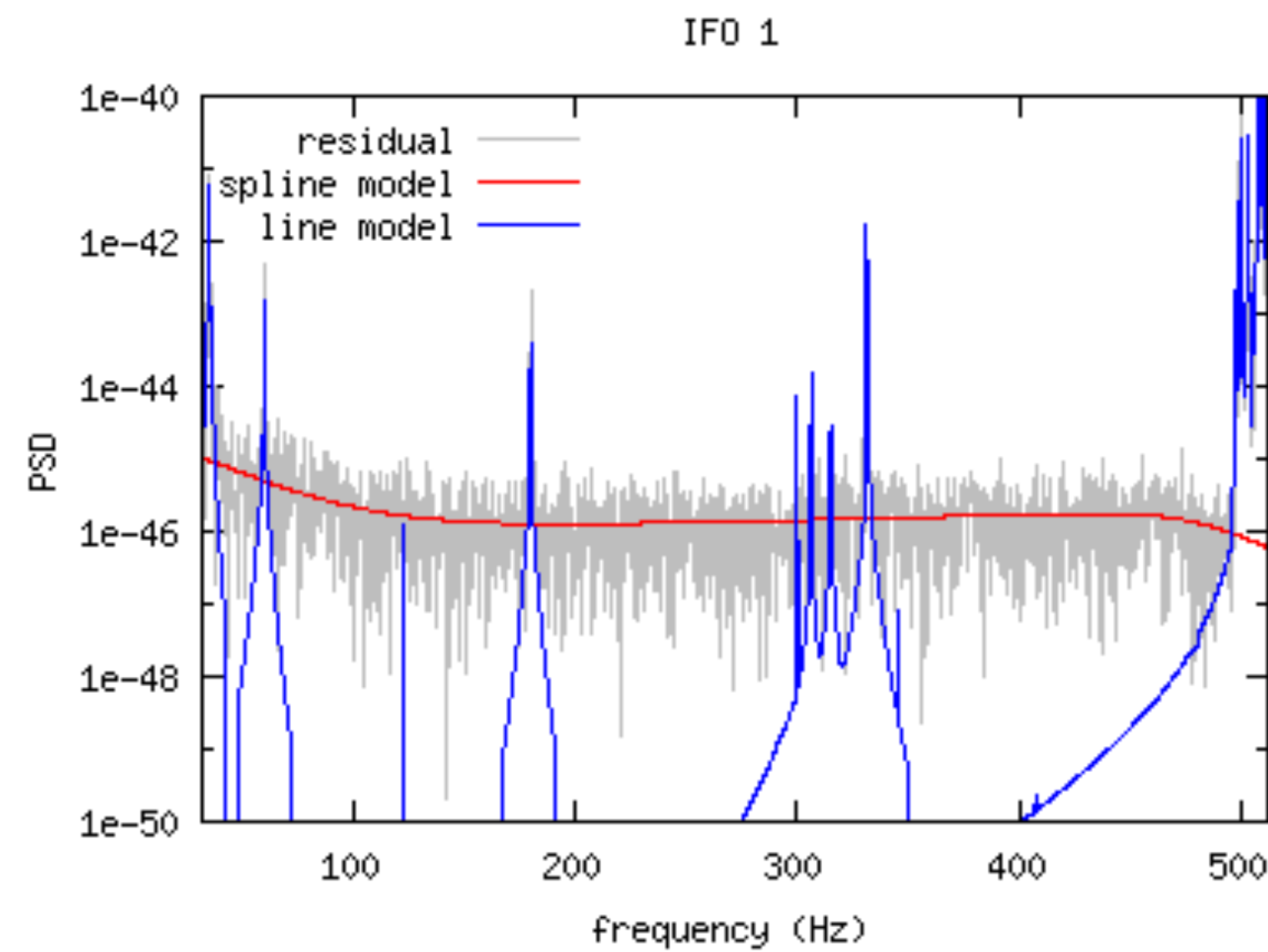
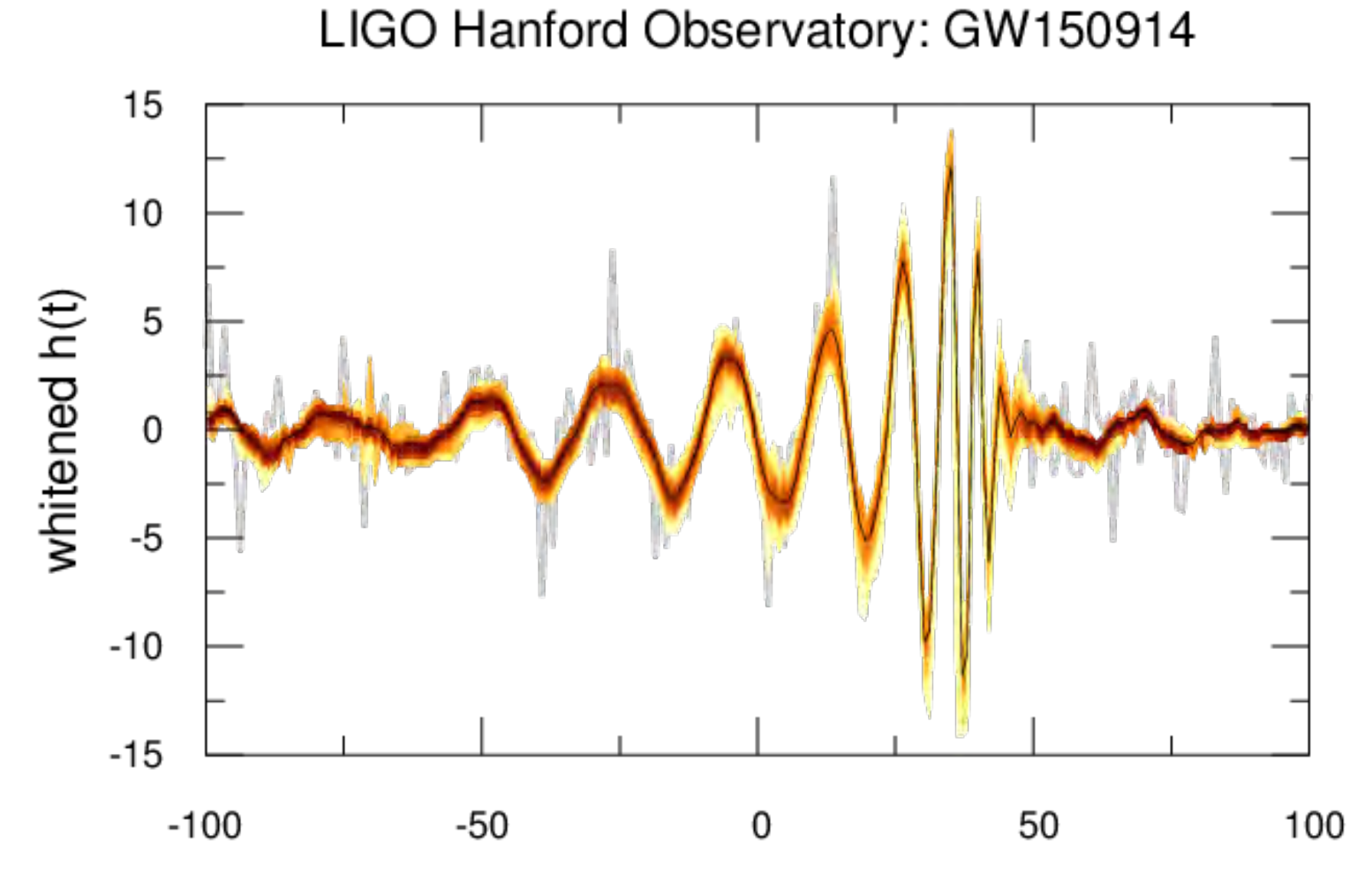
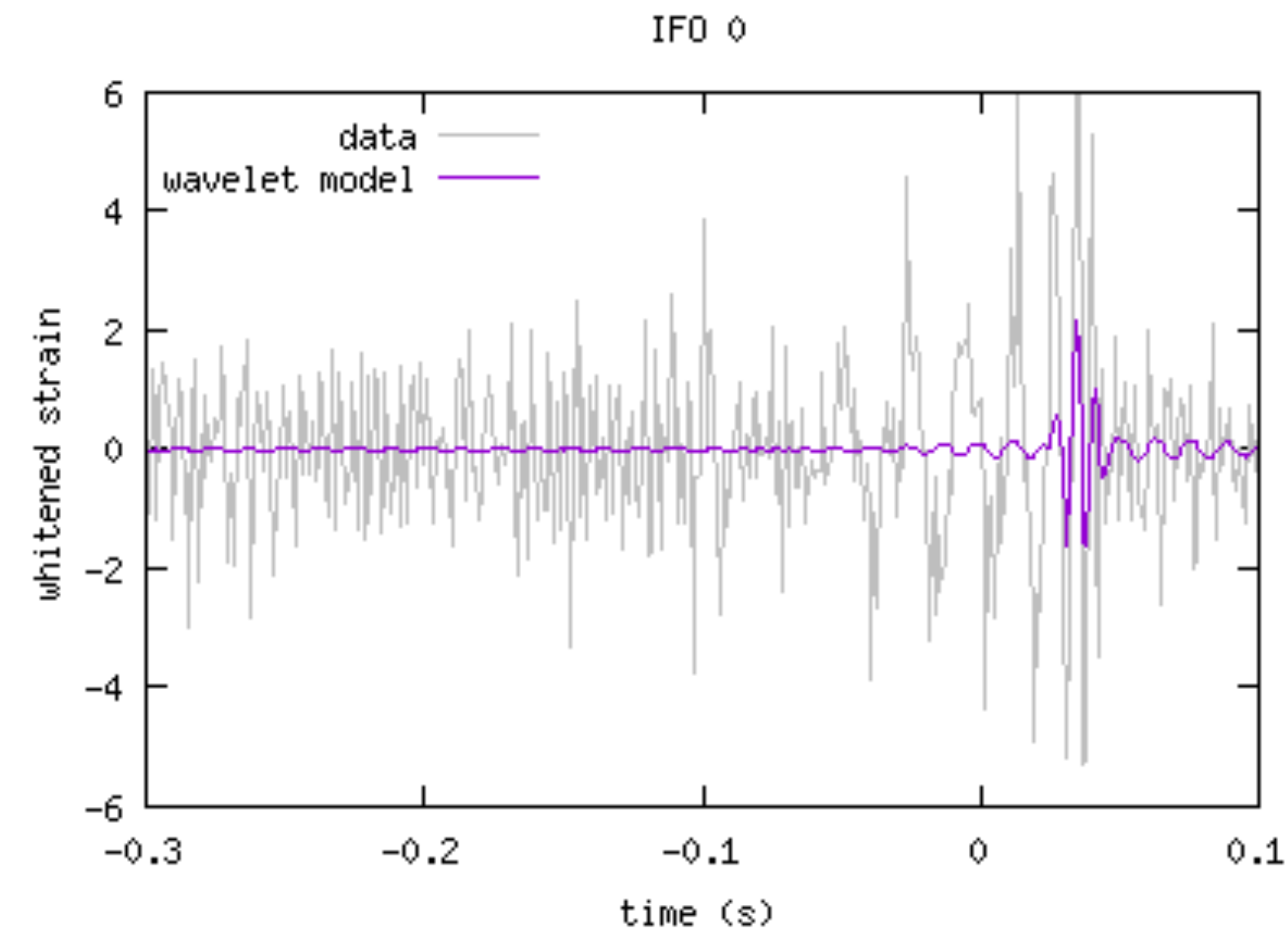
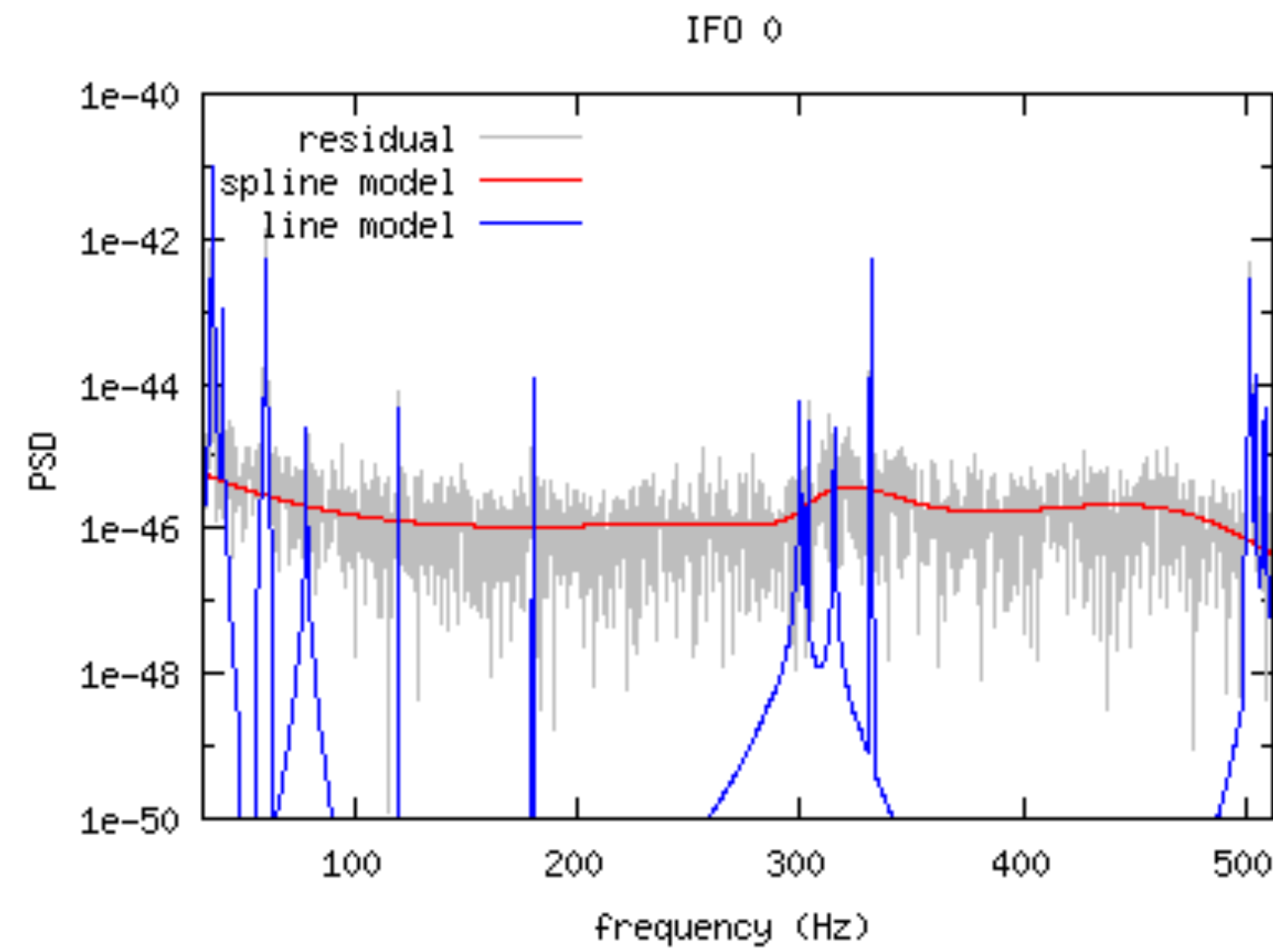


“Caedite eos. Novit enim Dominus qui sunt eius” Arnaud Amalric
(Kill them all. For the Lord knoweth them that are His.)

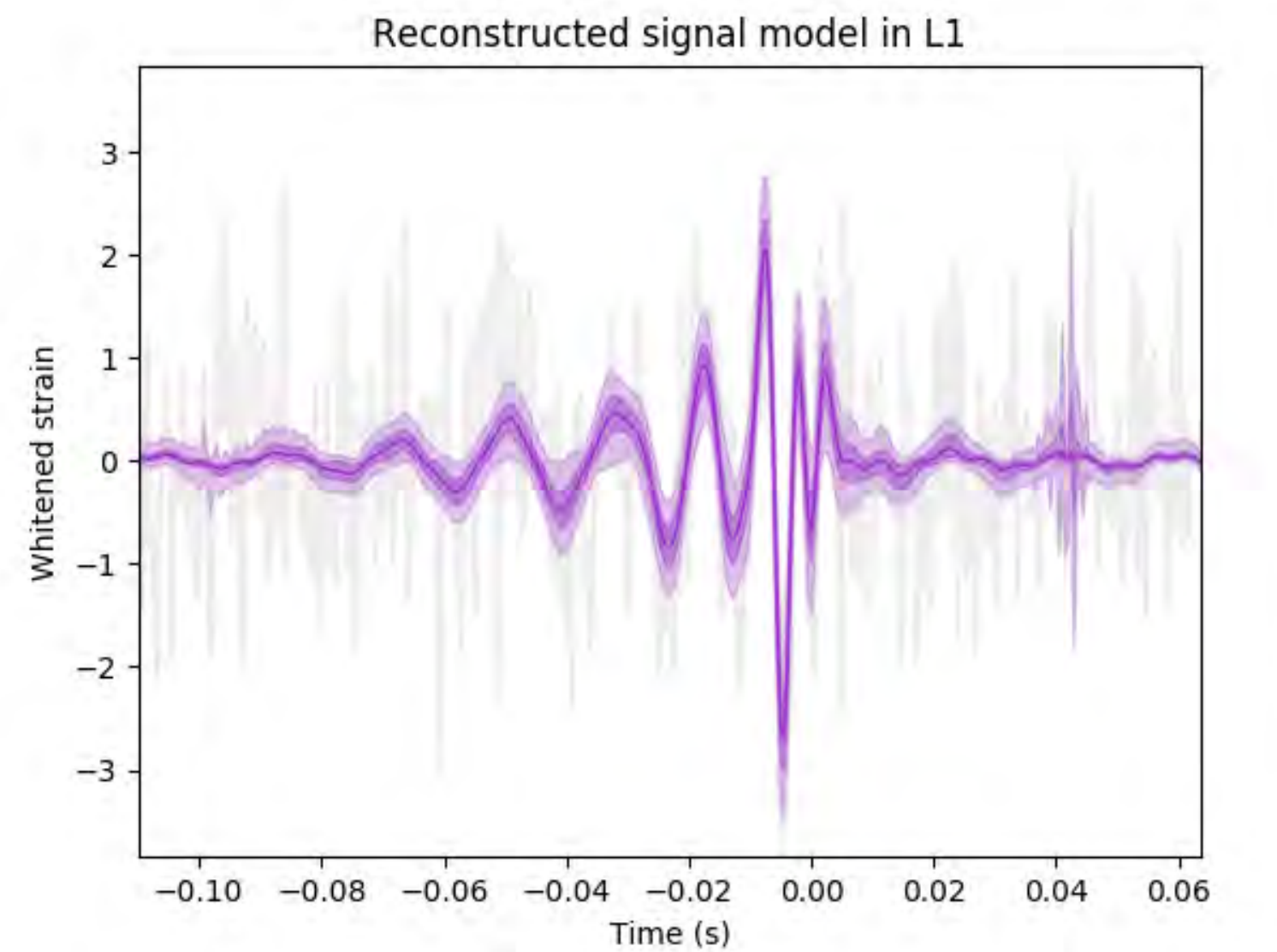
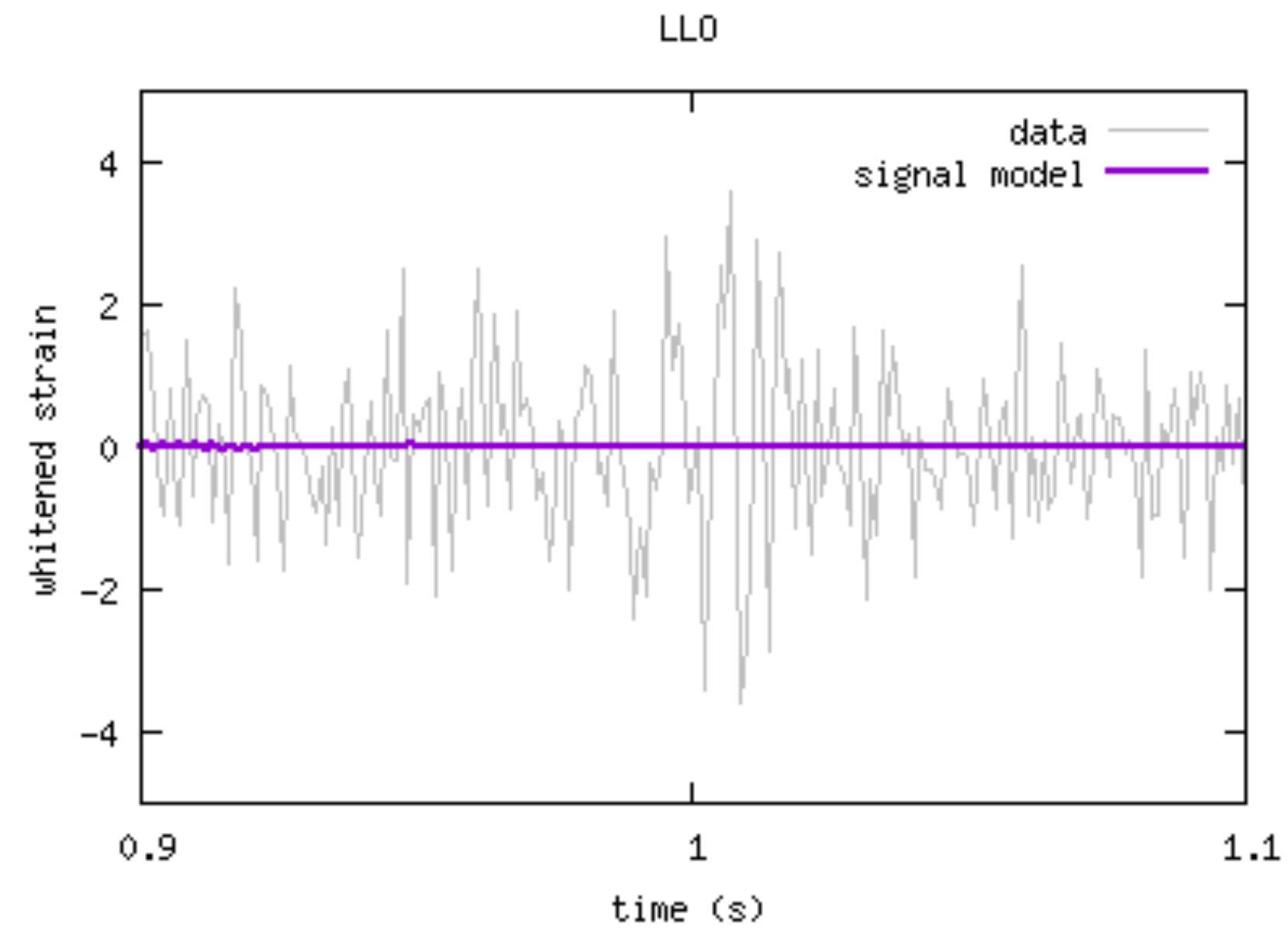
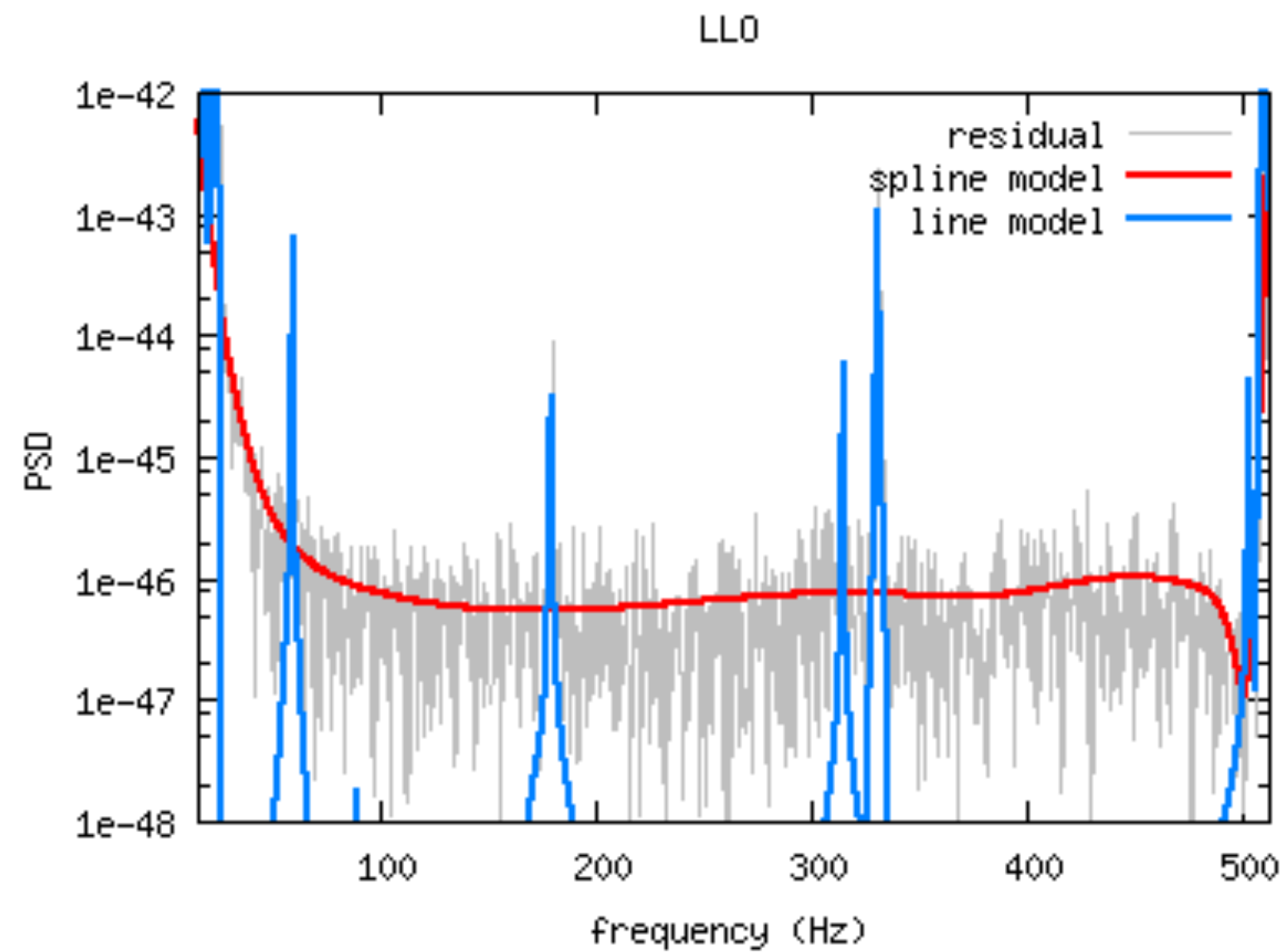
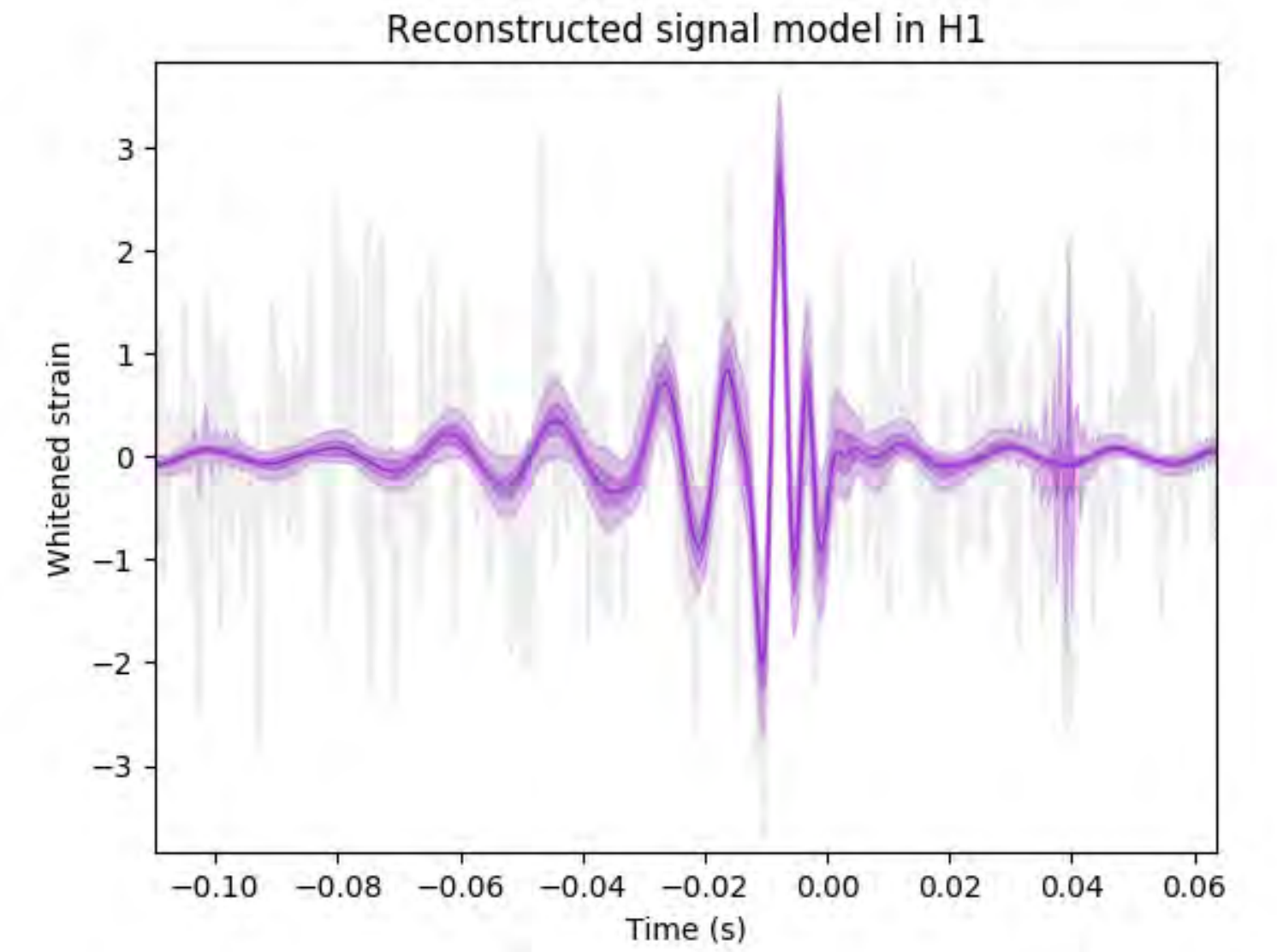
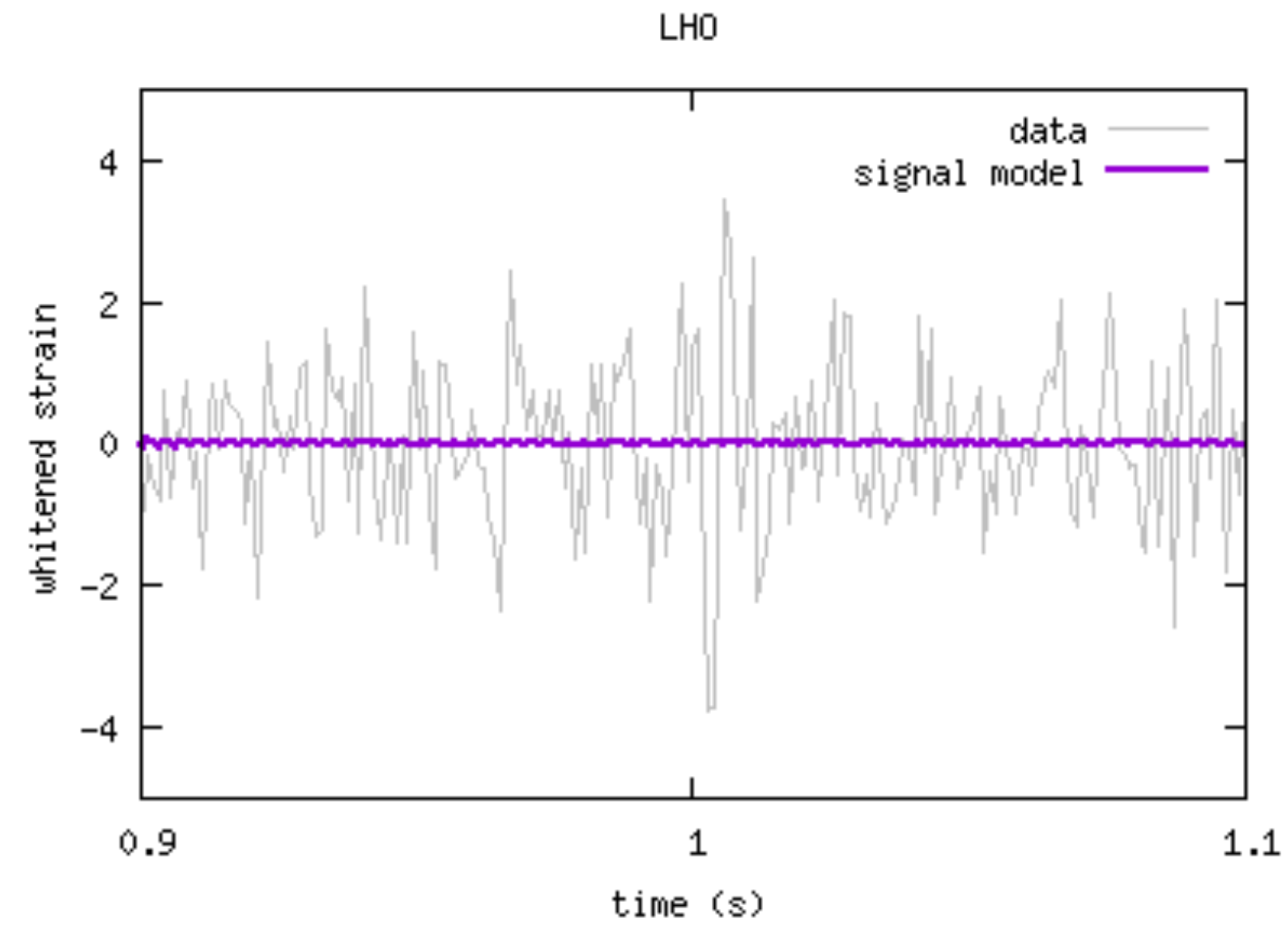
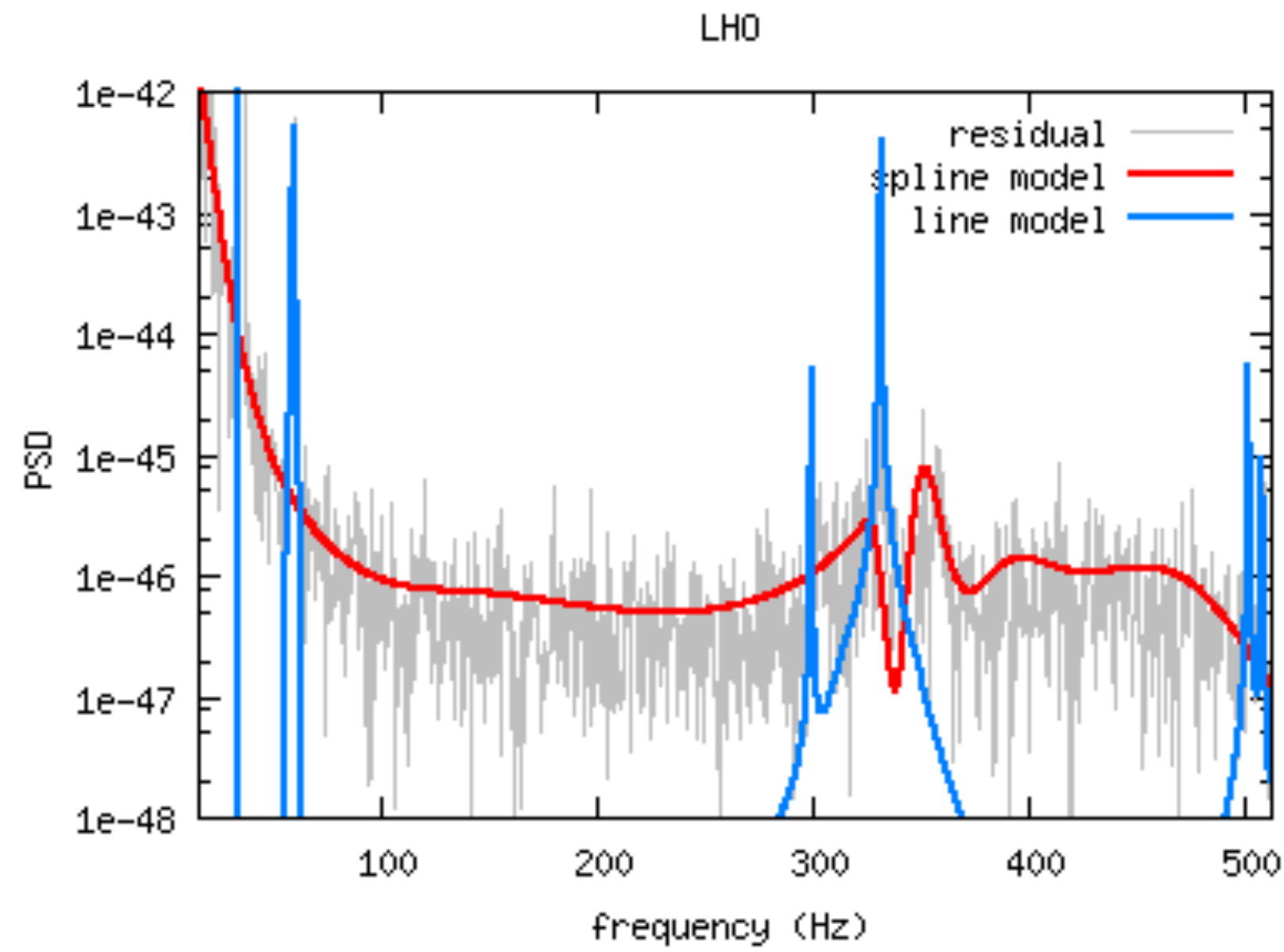
Example from LIGO's S5 science run

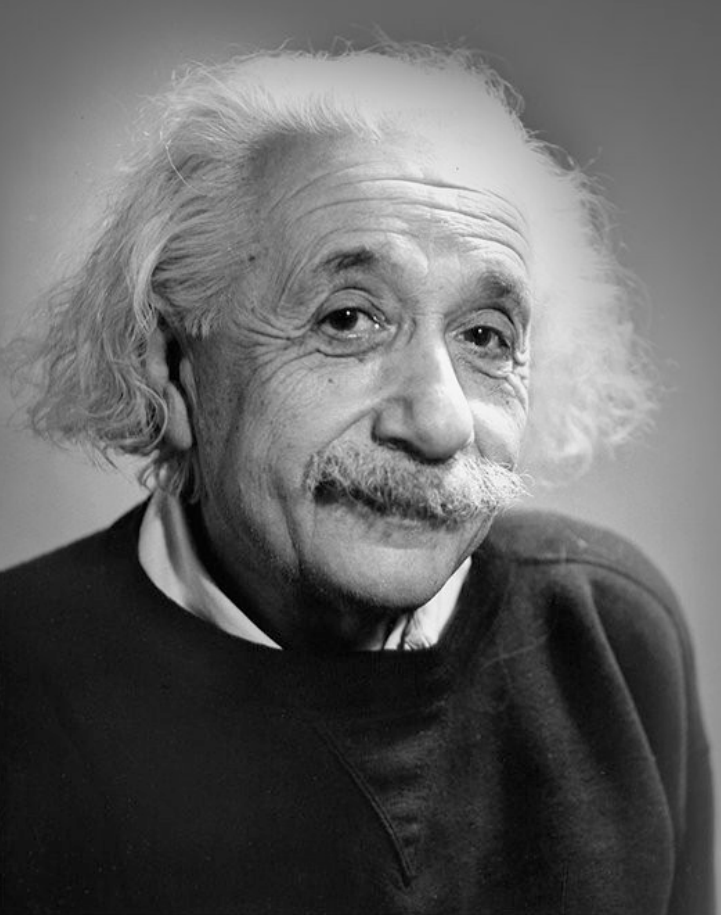


Reconstructing GW150914 with wavelets

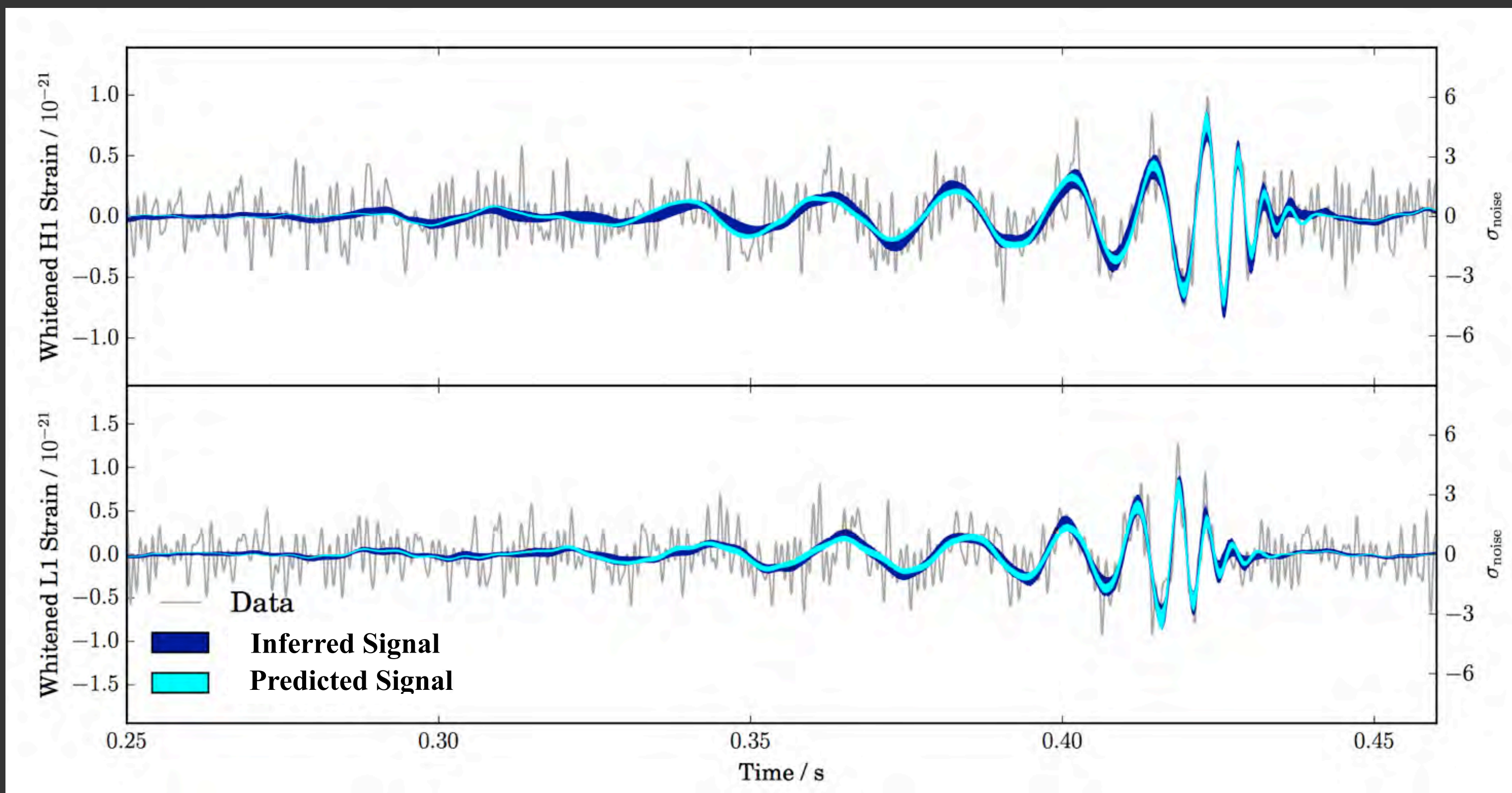


Reconstructing GW170104 with wavelets

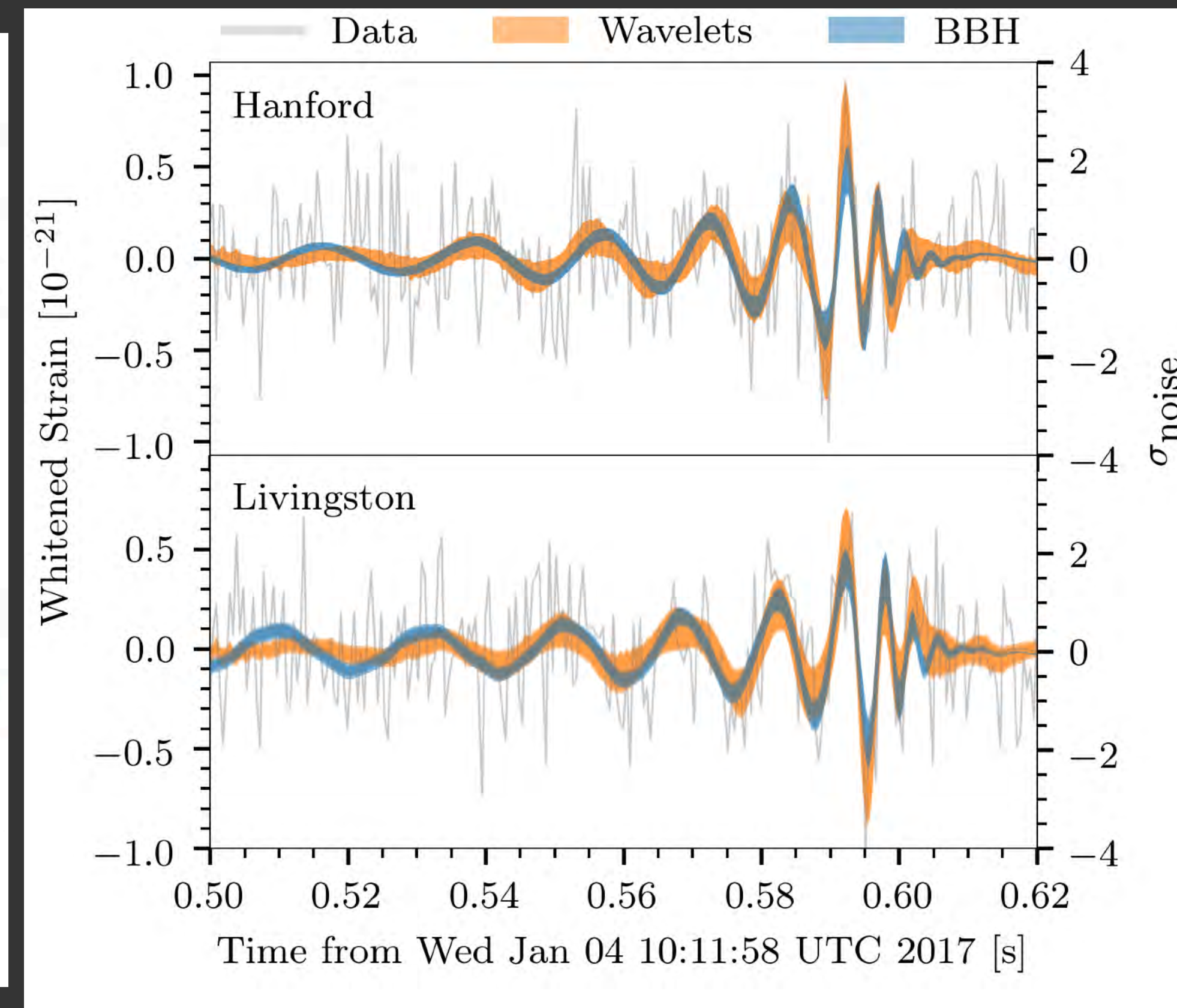




Match GR prediction

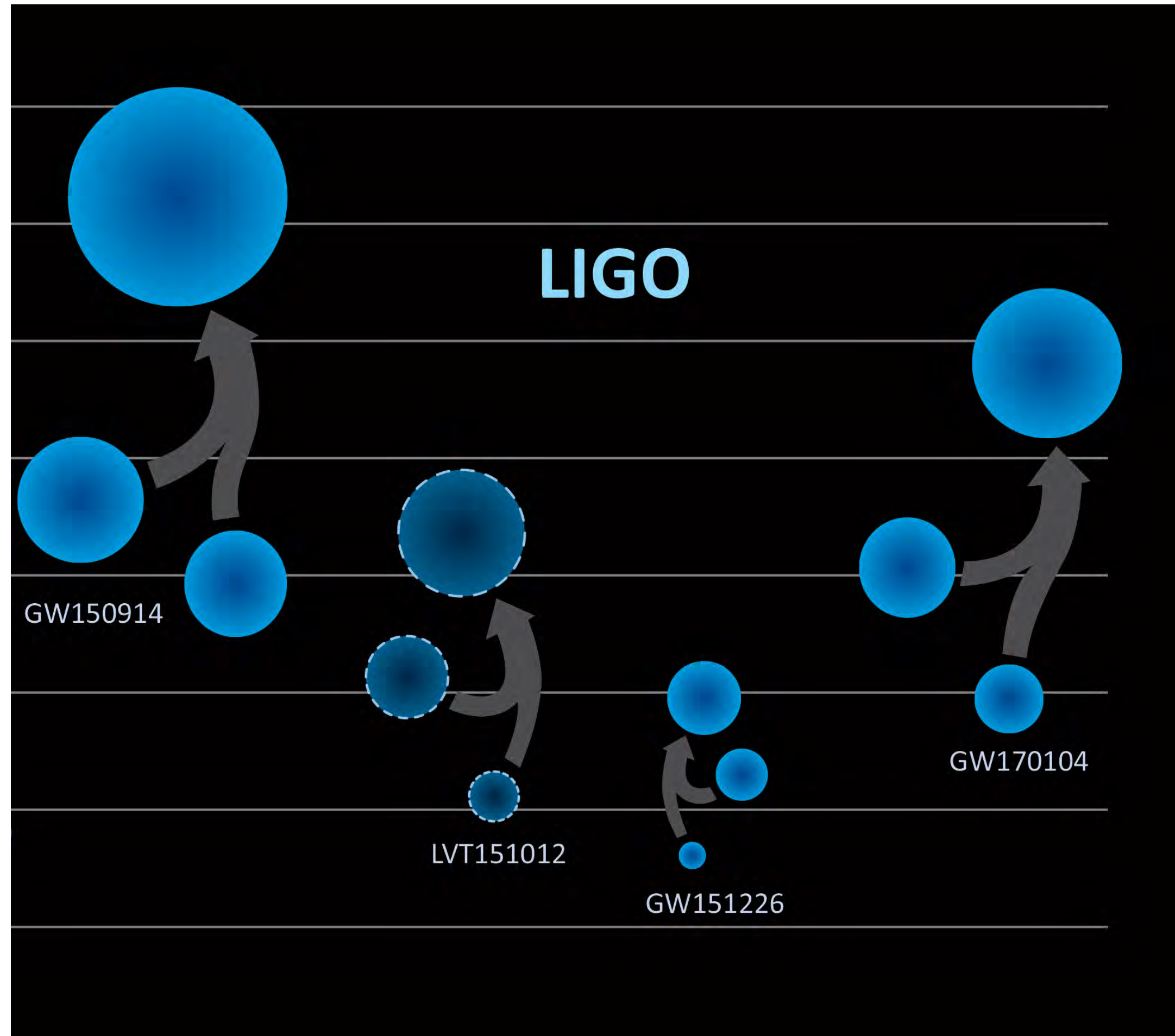


GW150914



GW170104

Astrophysical Inference



Would like to know merger rate to constrain population synthesis models. Even better, would like to know merger rate as a function of mass, spin, redshift etc

Many cool techniques being developed to do this using things like Gaussian processes

Only have time to discuss the total merger rate

Astrophysical Rate Limits

Even without a detection we can produce interesting astrophysical results such as bounds on the binary merger rate for NS-NS

Expect binary mergers to be a Poisson process. If the expected number of events is λ , then the probability of detecting k events is

$$p(k|\lambda) = \lambda^k e^{-\lambda} / k!$$

If the event rate is R [$\text{Mpc}^{-3} \text{ year}^{-1}$], and the observable 4-volume is VT [$\text{Mpc}^3 \text{ year}$]

$$\lambda = R VT$$

The probability of observing zero events ($k=0$) is then

$$p(R) = VT e^{-R VT}$$

Follows from $p(0|\lambda) = p(R) dR = e^{-R VT}$

Astrophysical Rate Limits

$$p(R) = VT e^{-RVT}$$

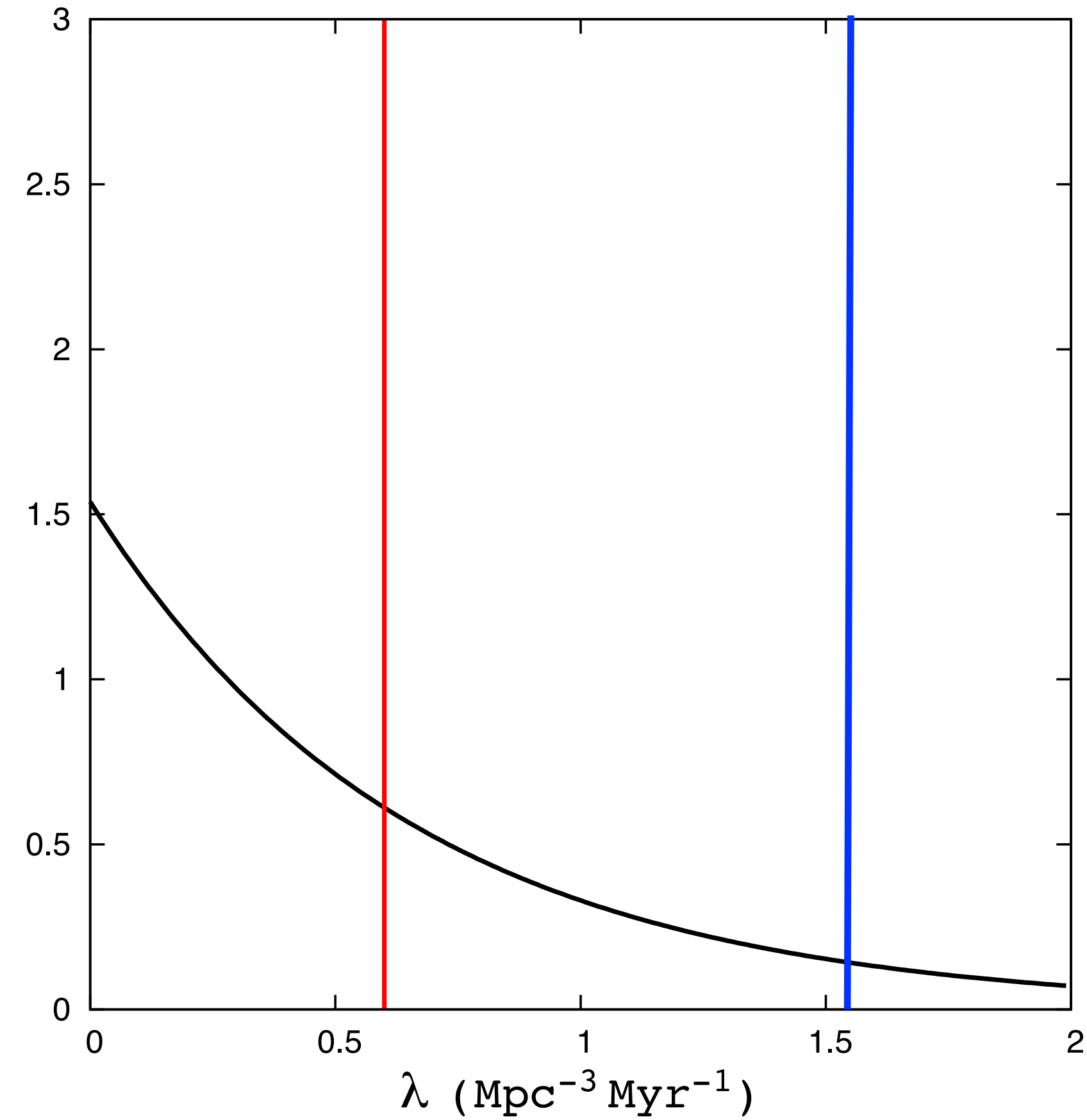
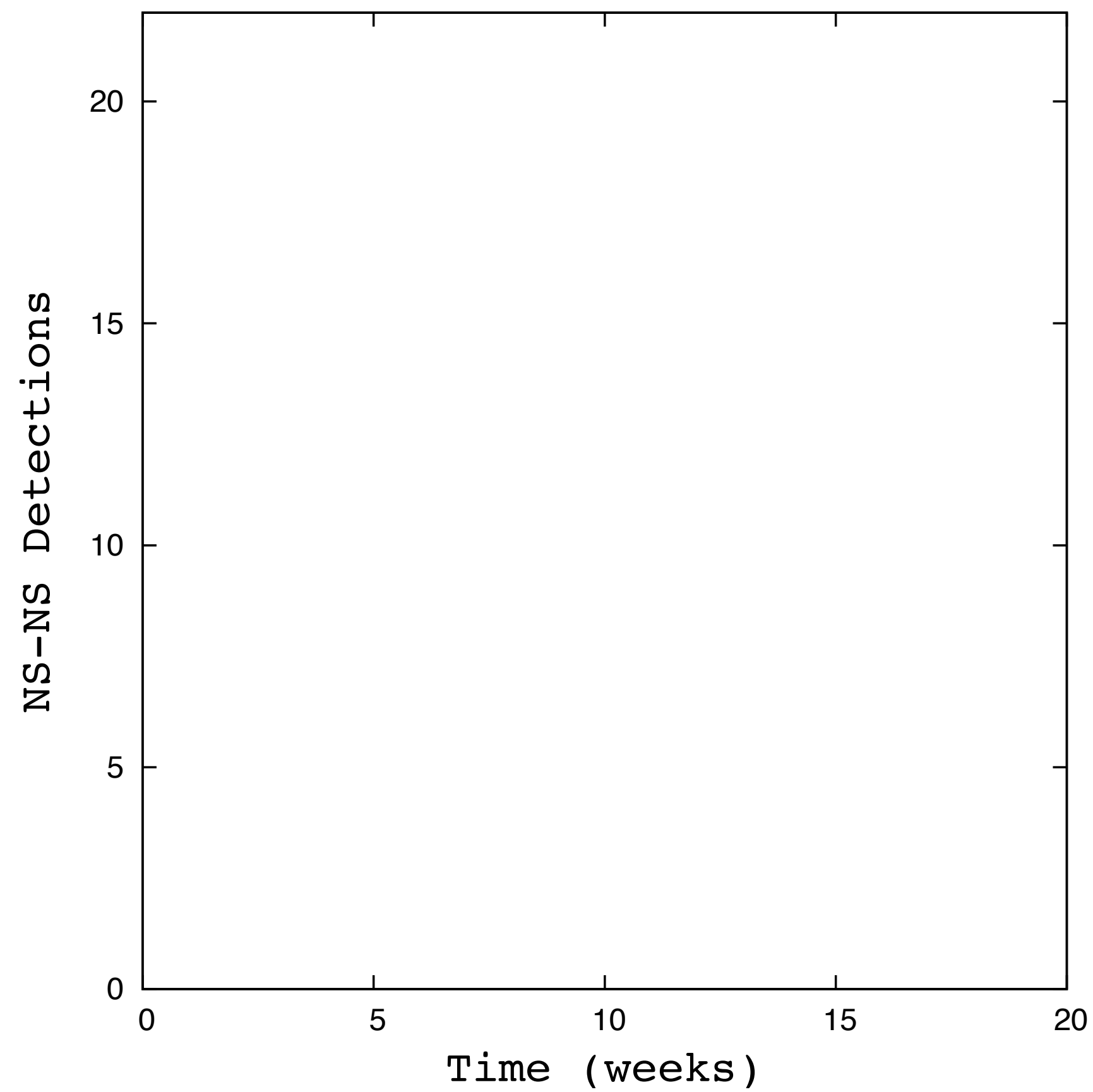
The probability distribution is peaked at a rate of zero. A 90% rate upper limit can be computed:

$$\int_0^{R_*} p(R) dR = 1 - e^{-R_*VT} = 0.9$$

$$\Rightarrow R_*VT = \ln(0.1)$$

$$\Rightarrow R_* = \frac{2.3}{VT}$$

e.g. NS-NS Merger Rate, aLIGO at design sensitivity $V = \frac{4\pi}{3}(200 \text{ Mpc})^3$



Truth

90% upper limit

Week 1

Astrophysical Rate Limits

When a signal is detected the probability distribution for the rate is no longer peaked at zero. For example, with a single detection ($k=1$) we have

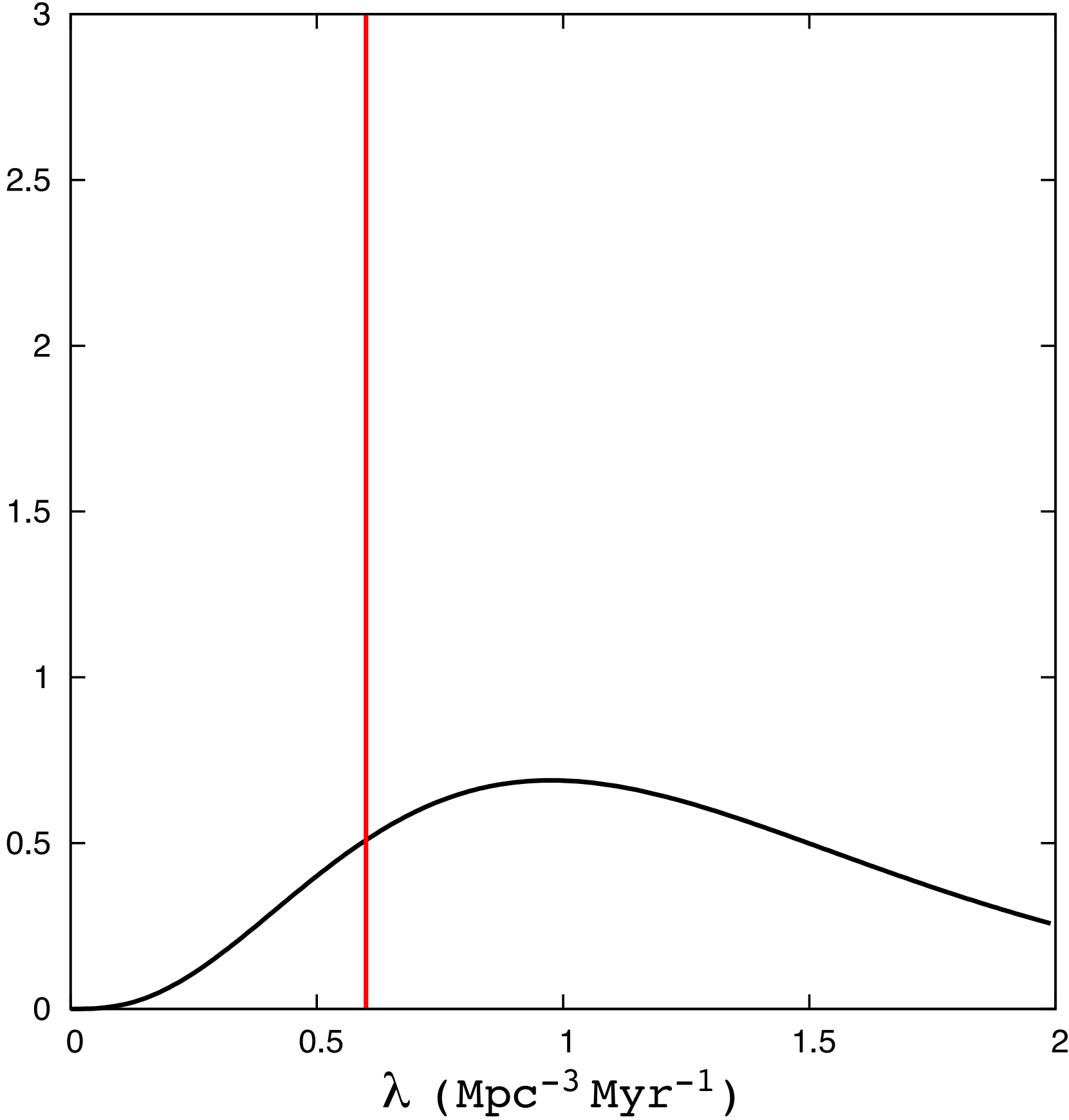
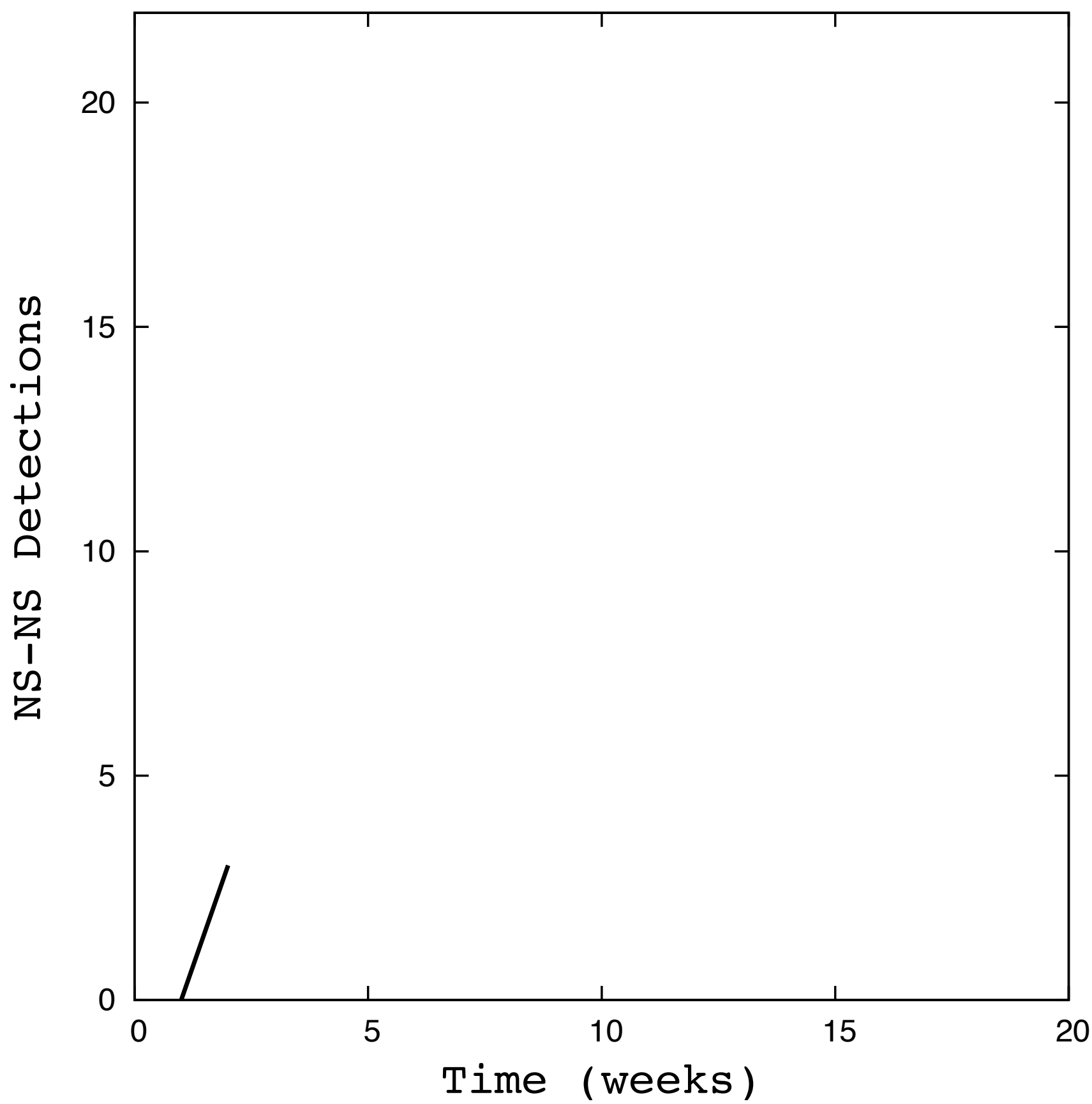
$$p(R) = R(VT)^2 e^{-RVT}$$

This distribution is peaked at

$$R = \frac{1}{VT}$$

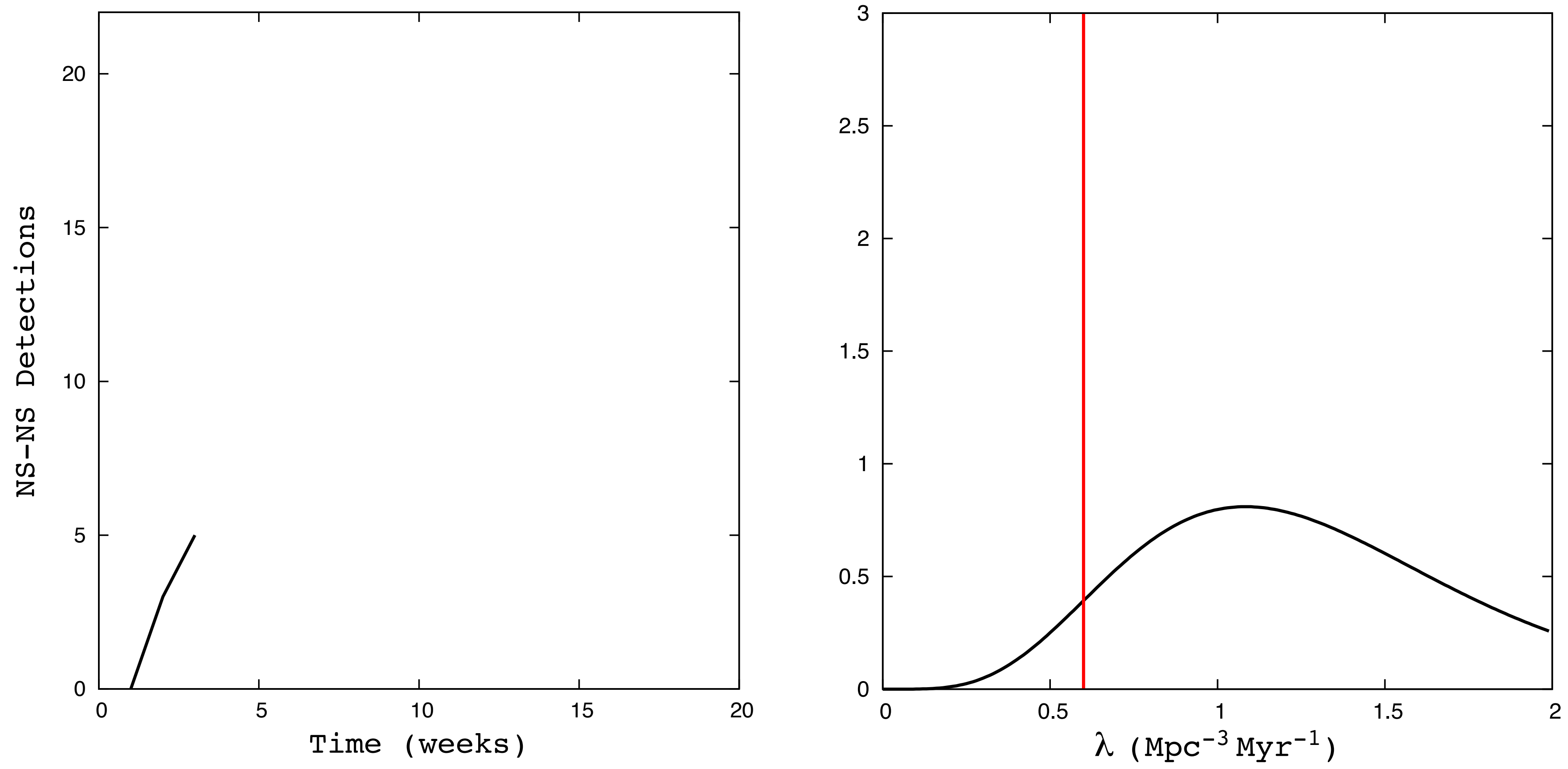
The 90% confidence interval now sets upper **and** lower limits on the merger rate.

Simulated NS-NS Merger Rate Constraints



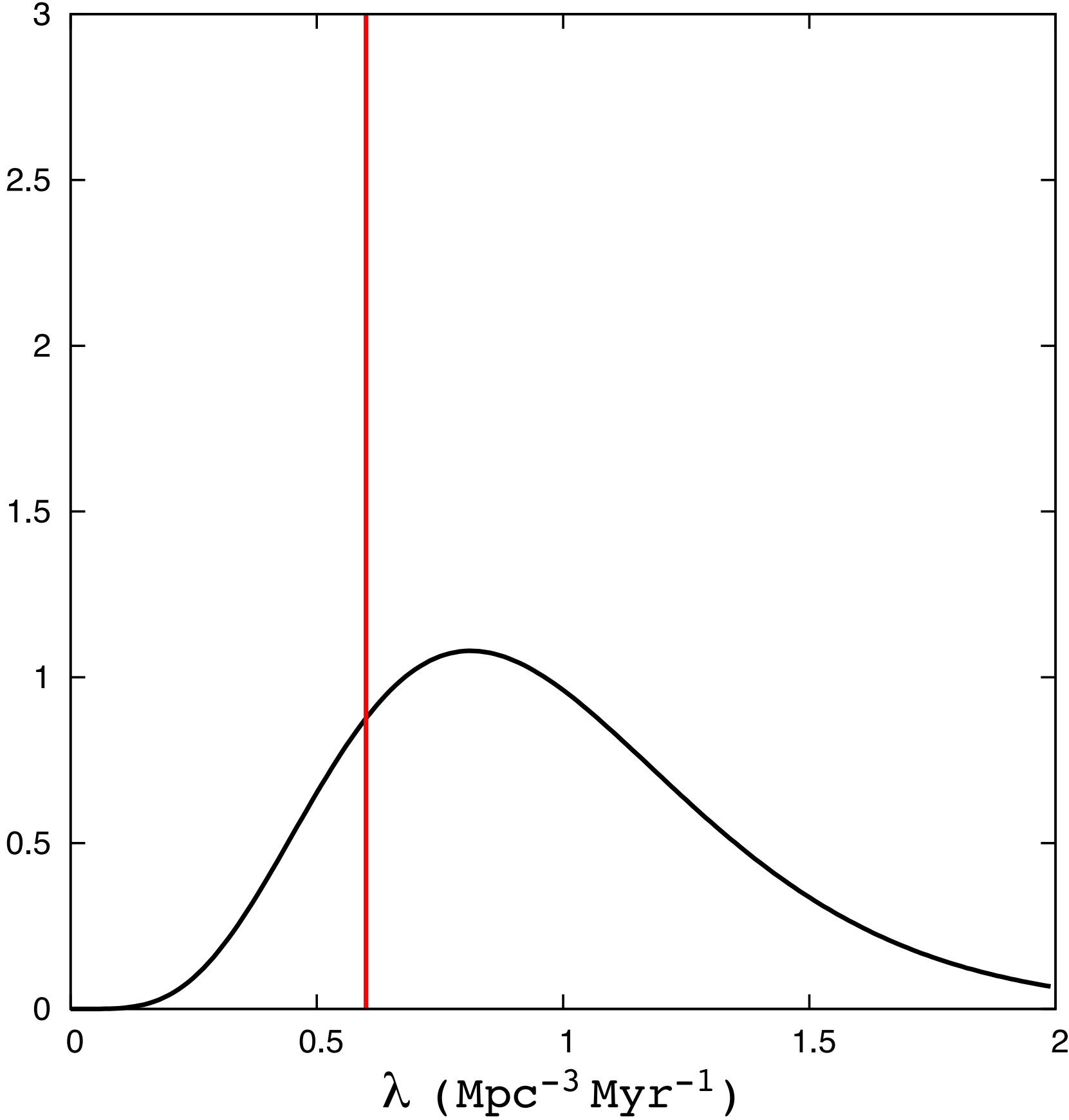
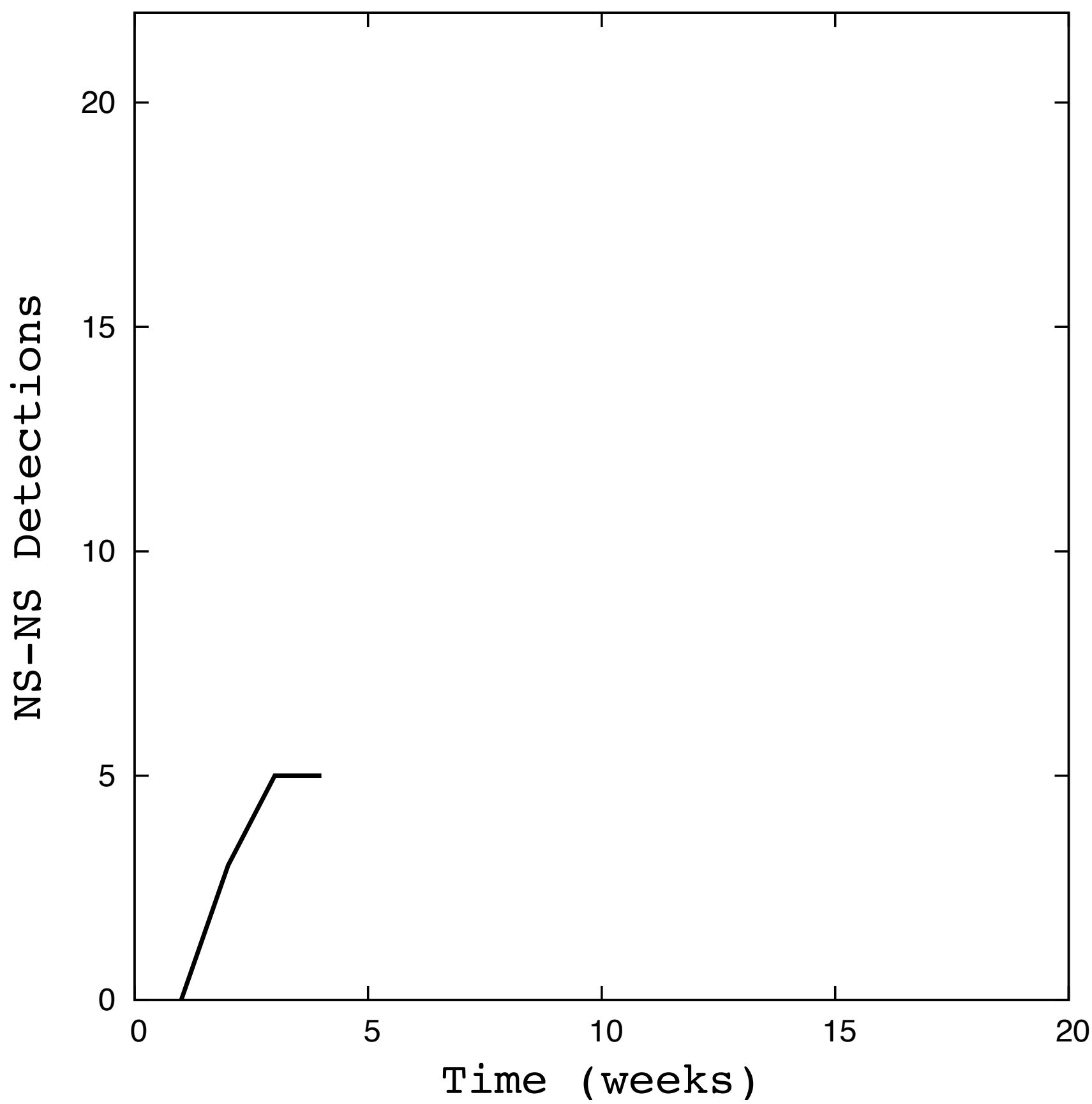
Week 2

Simulated NS-NS Merger Rate Constraints



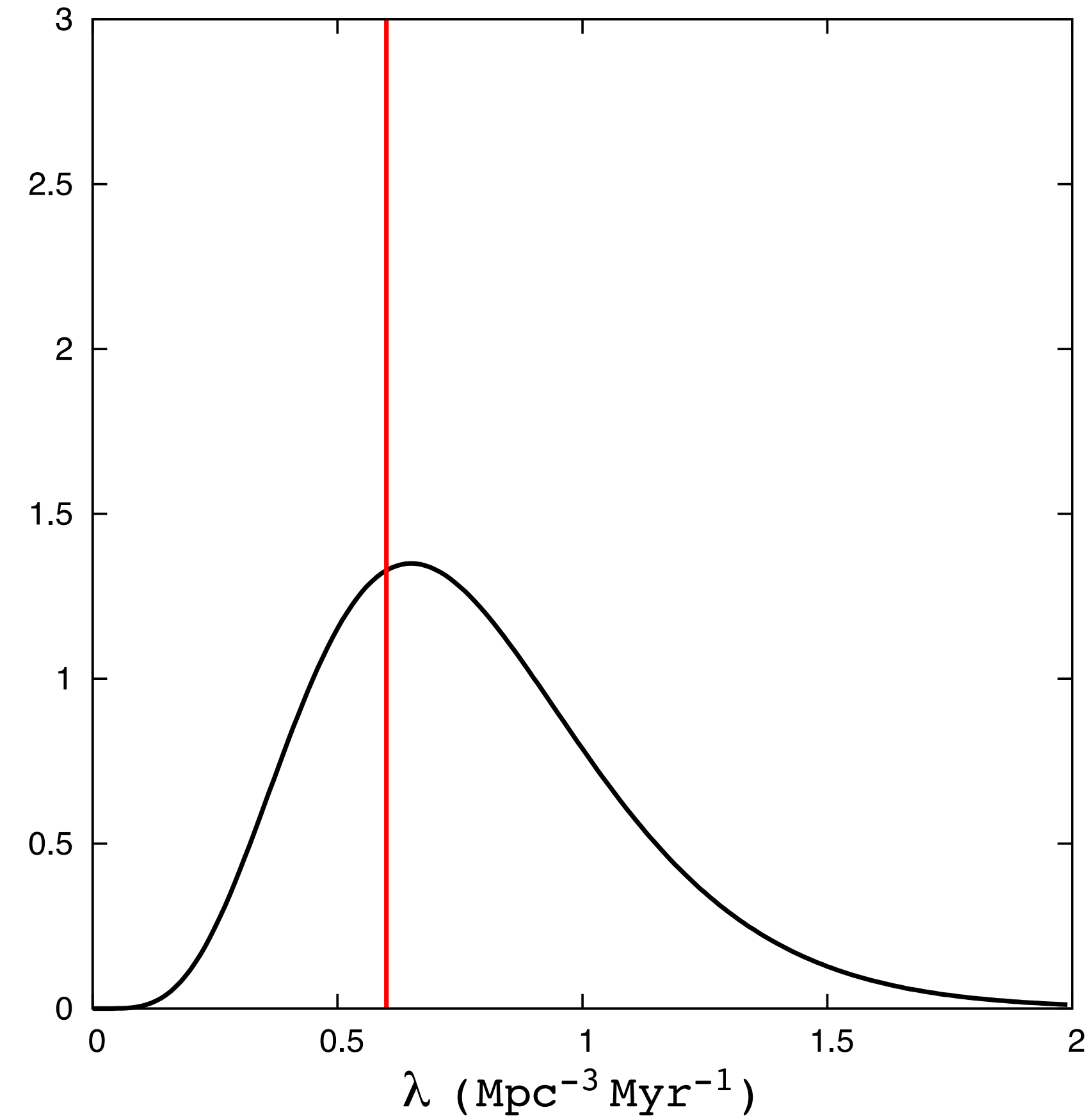
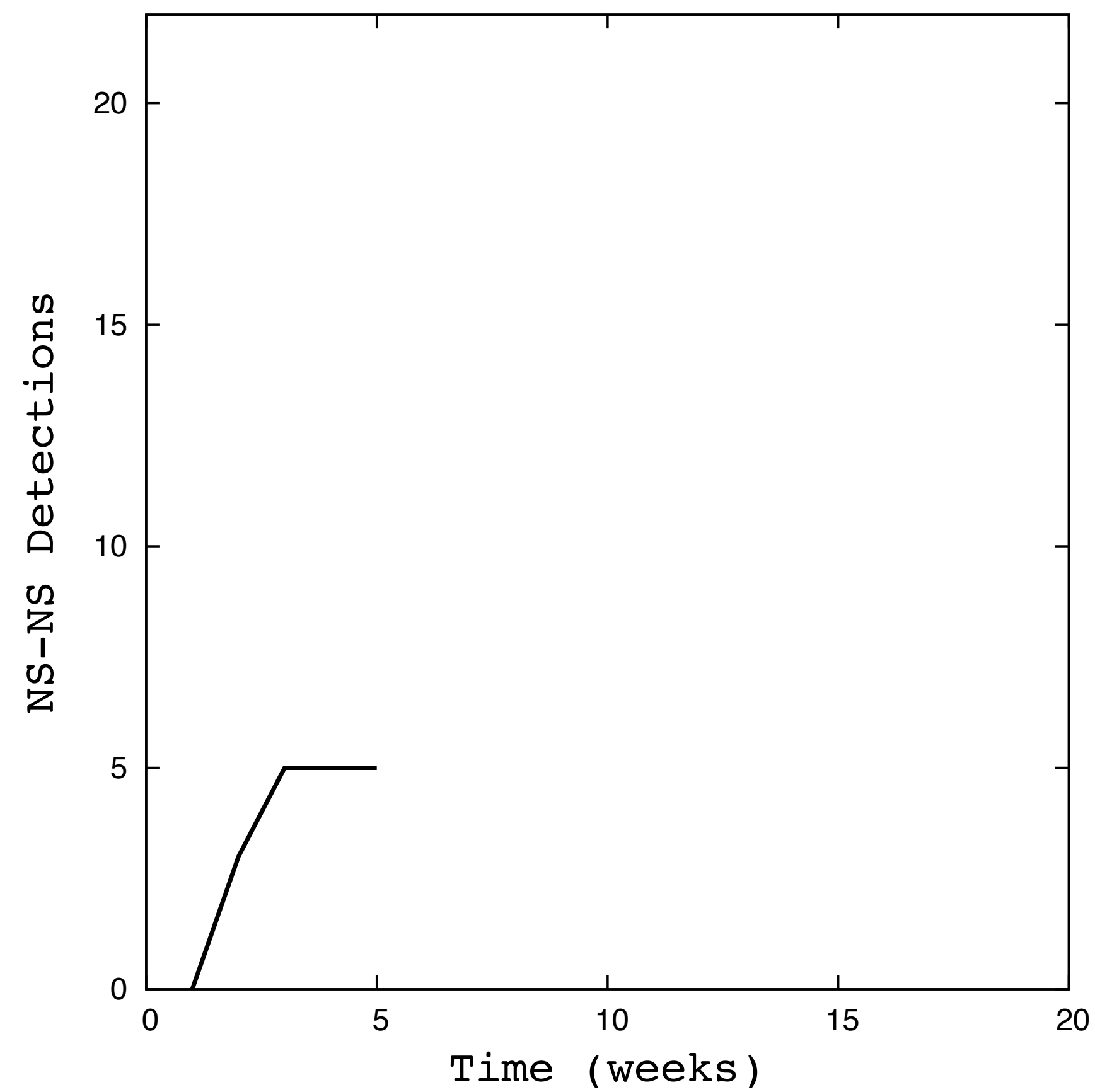
Week 3

Simulated NS-NS Merger Rate Constraints



Week 4

Simulated NS-NS Merger Rate Constraints



Week 5

Simulated NS-NS Merger Rate Constraints

