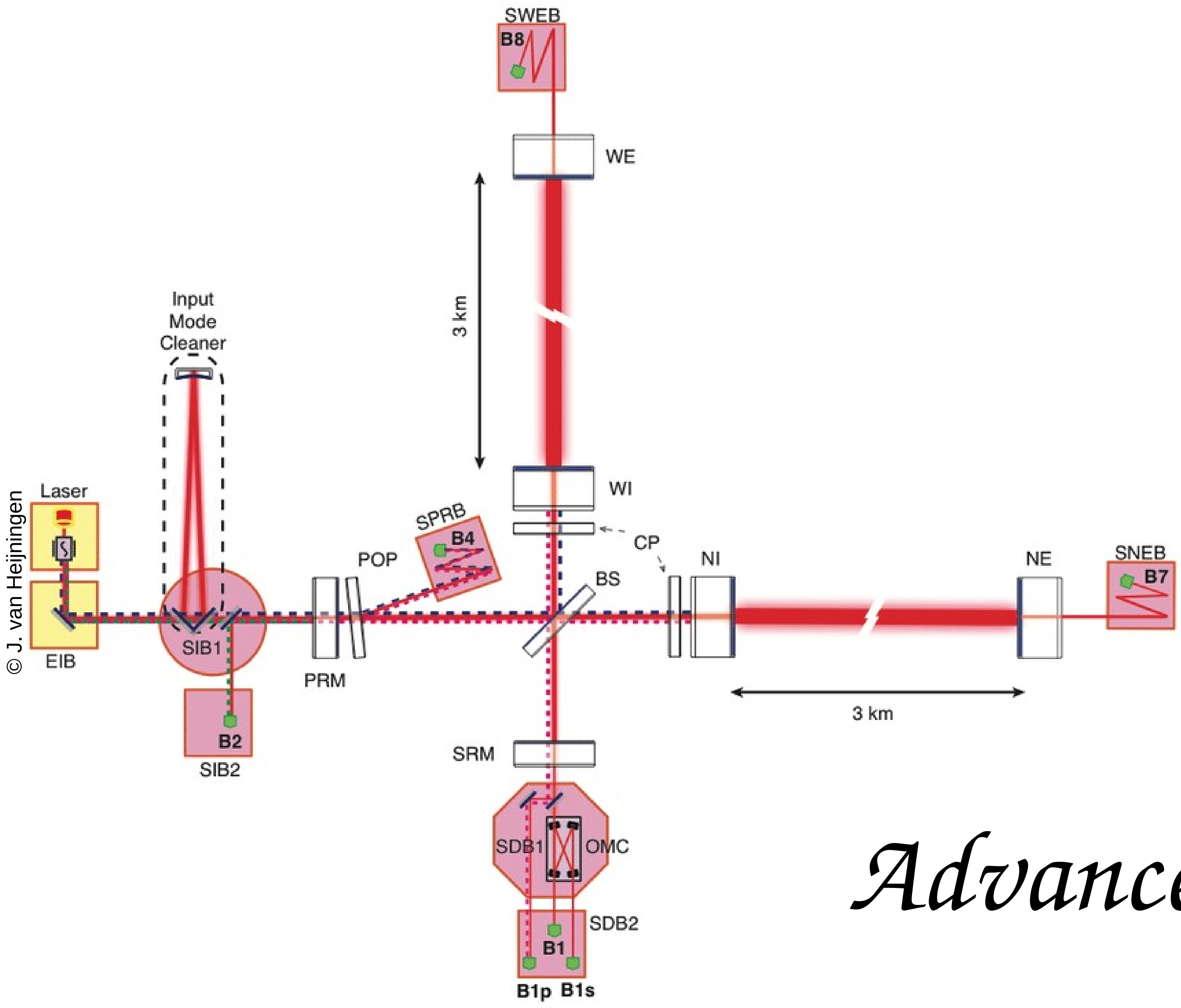
Searches for gravitational-wave signals with ground-based interferometers

Excluding CBC!

– Introduction: LIGO-Virgo gravitational-wave detectors

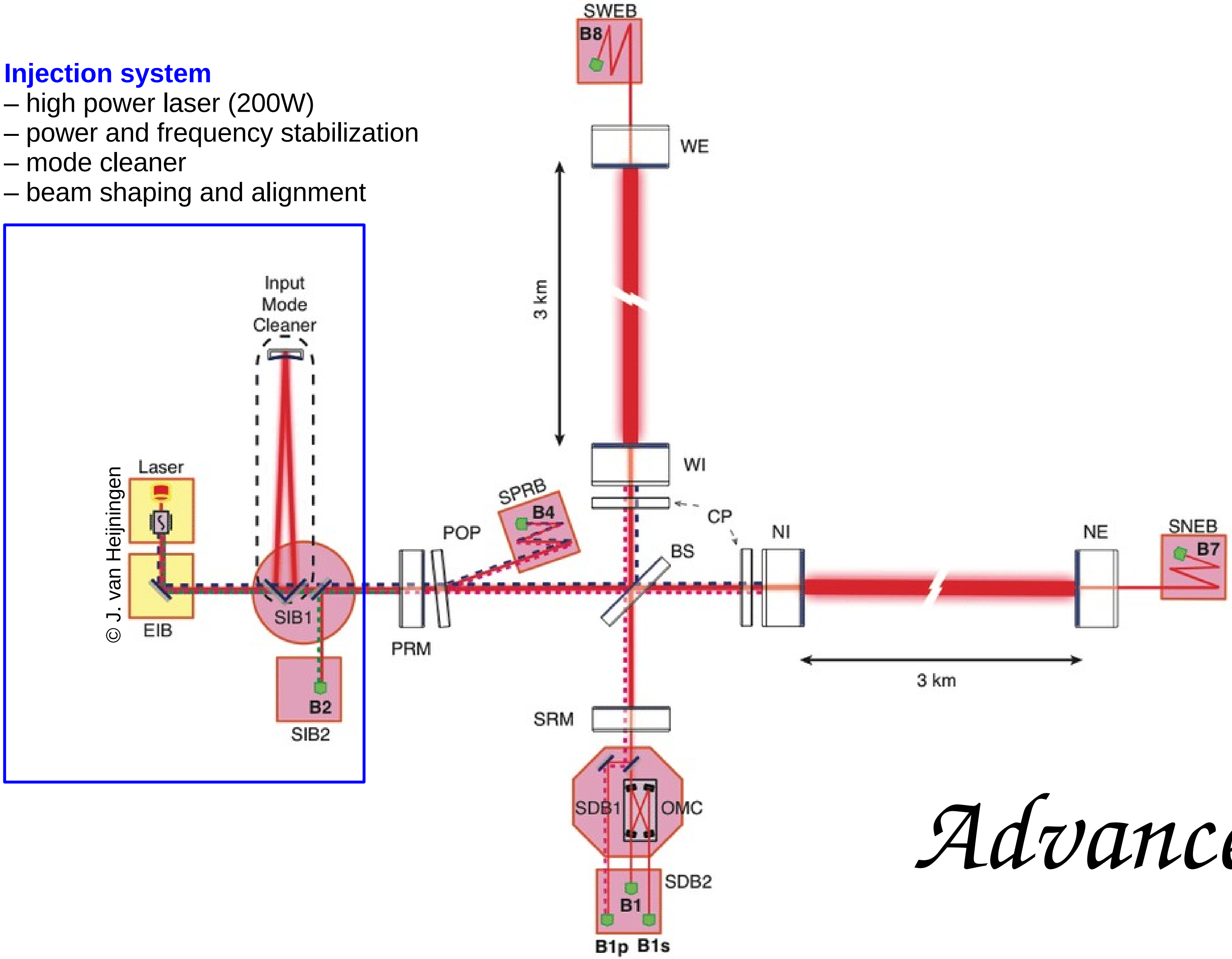
– Noise description

– Searching for:
  → transient signals
  → continuous signals
  → stochastic backgrounds



Advanced Virgo

Injection system
– high power laser (200W)
– power and frequency stabilization
– mode cleaner
– beam shaping and alignment



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Injection system
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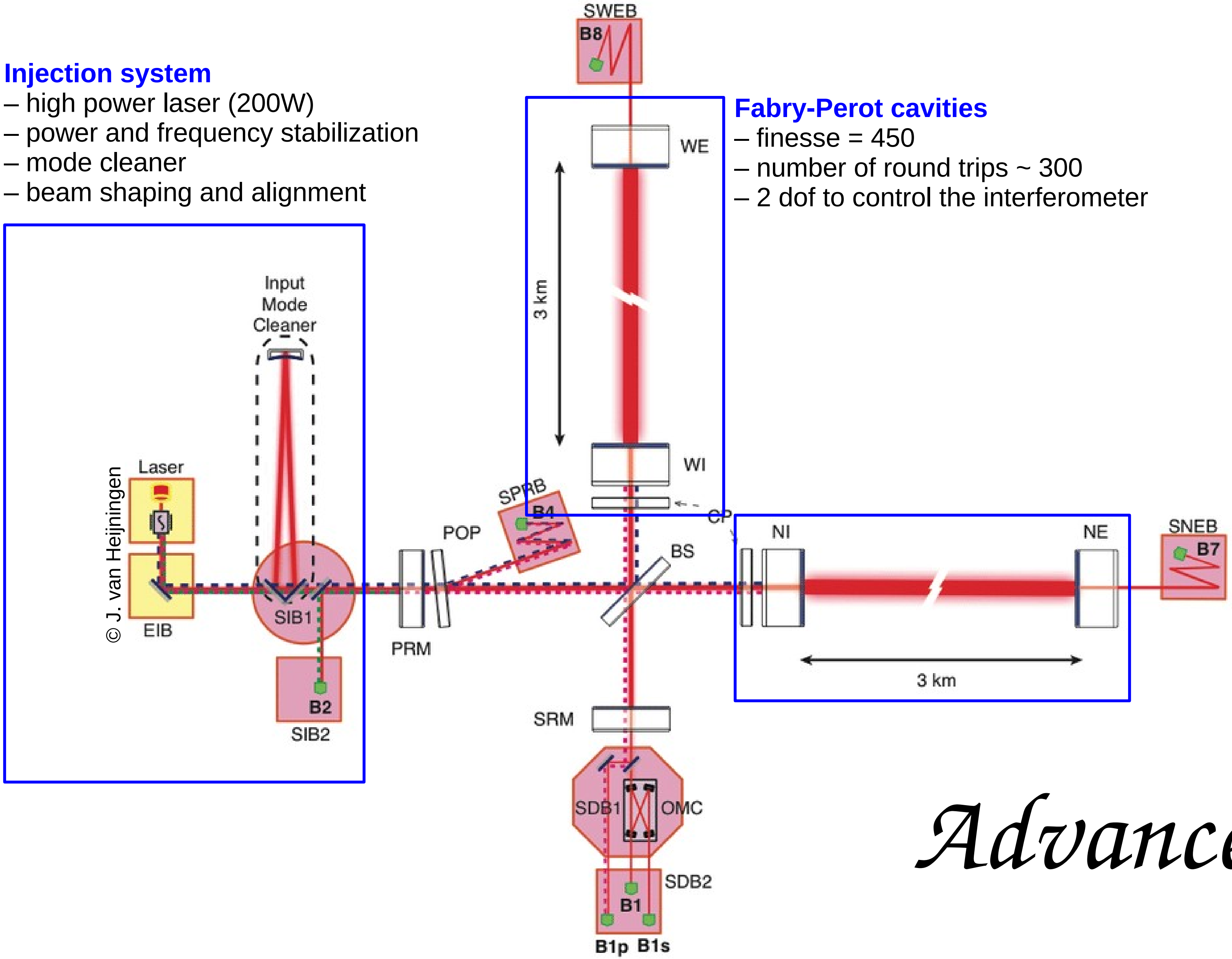
Fabry-Perot cavities
– finesse = 450
– number of round trips ~ 300
– 2 dof to control the interferometer



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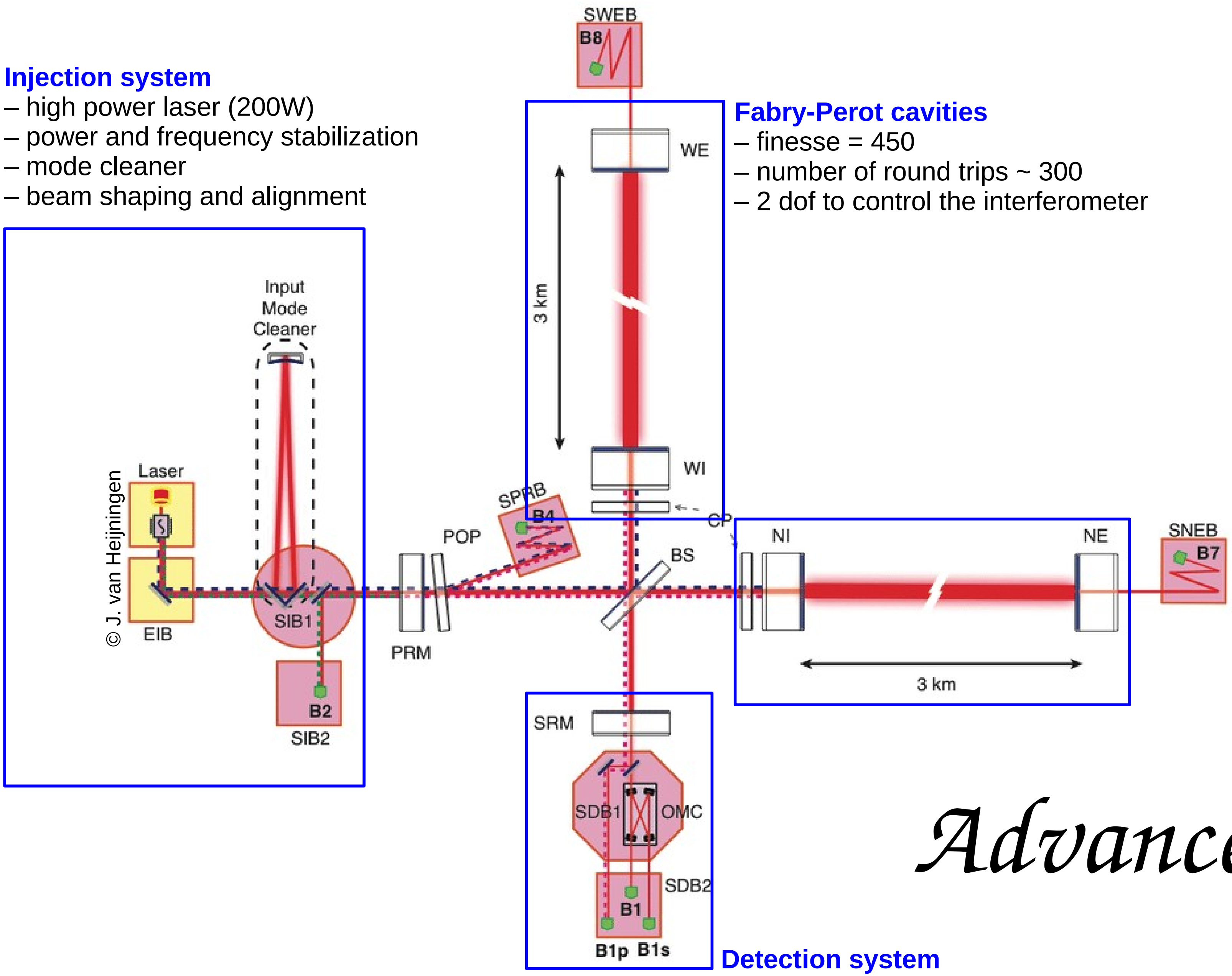

Detection system

Advanced Virgo

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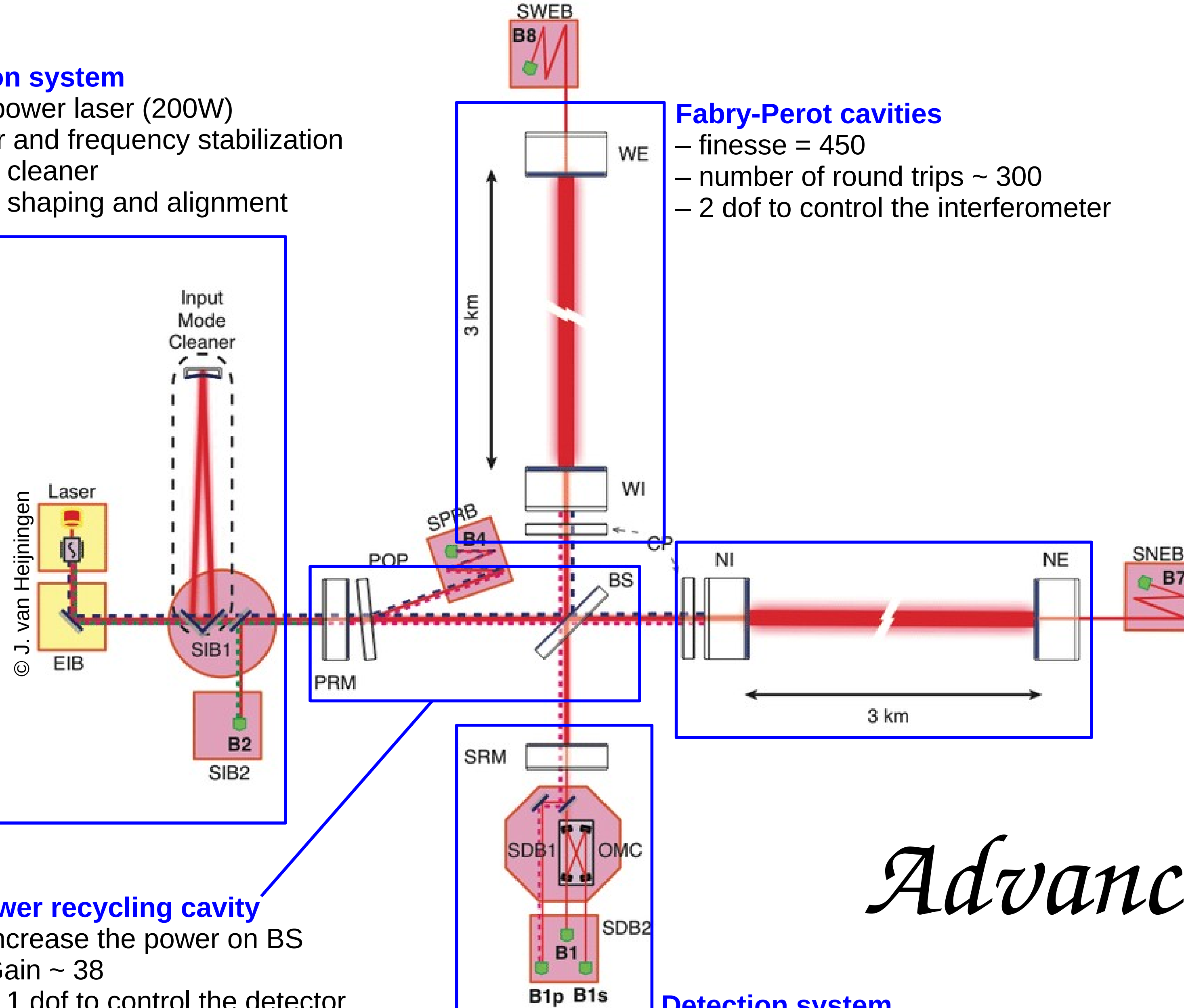

Power recycling cavity
– Increase the power on BS
– Gain ~ 38
– = 1 dof to control the detector

Detection system

Advanced Virgo

Injection system
- high power laser (200W)
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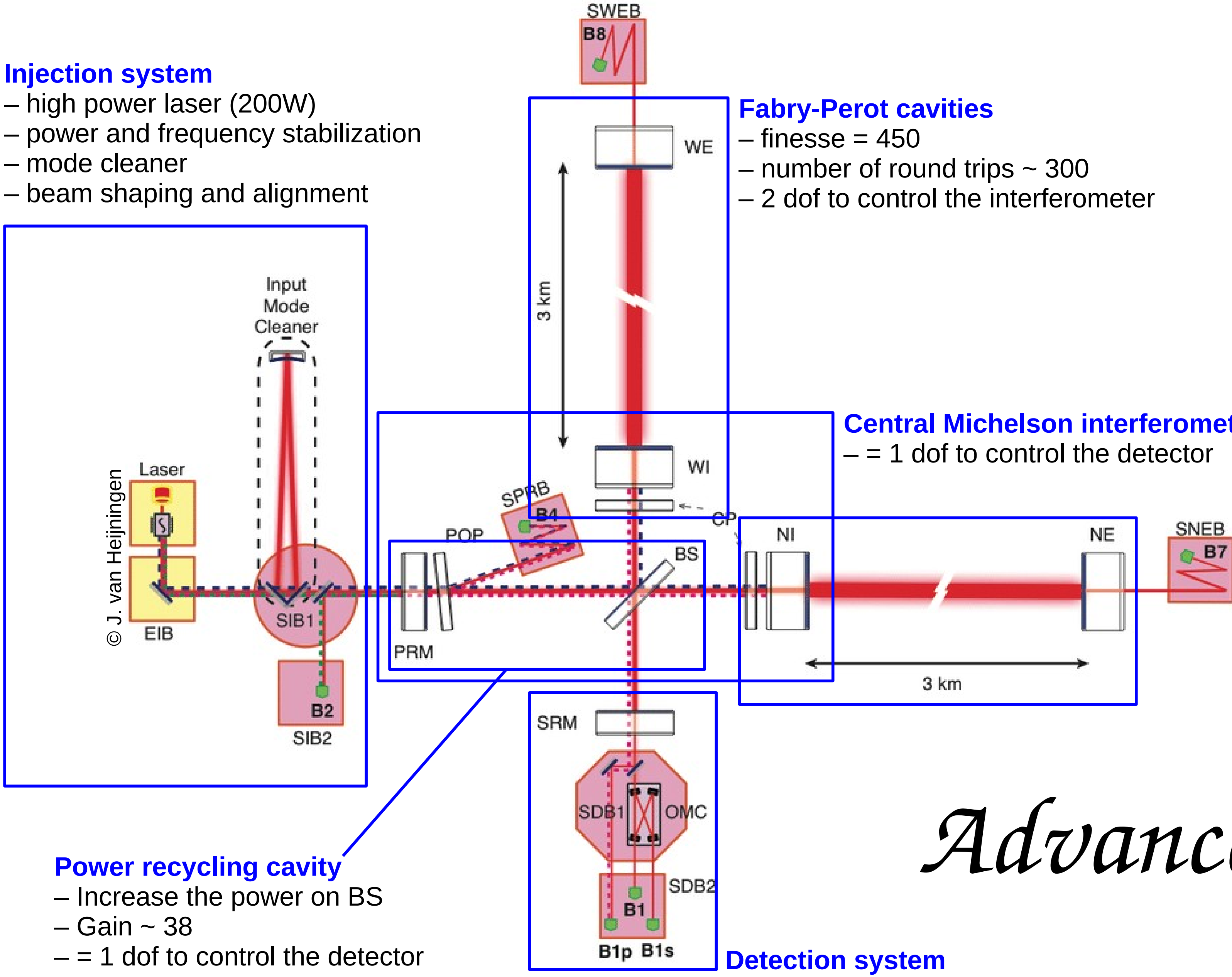
Fabry-Perot cavities
- finesse = 450
- number of round trips ~ 300
- 2 dof to control the interferometer

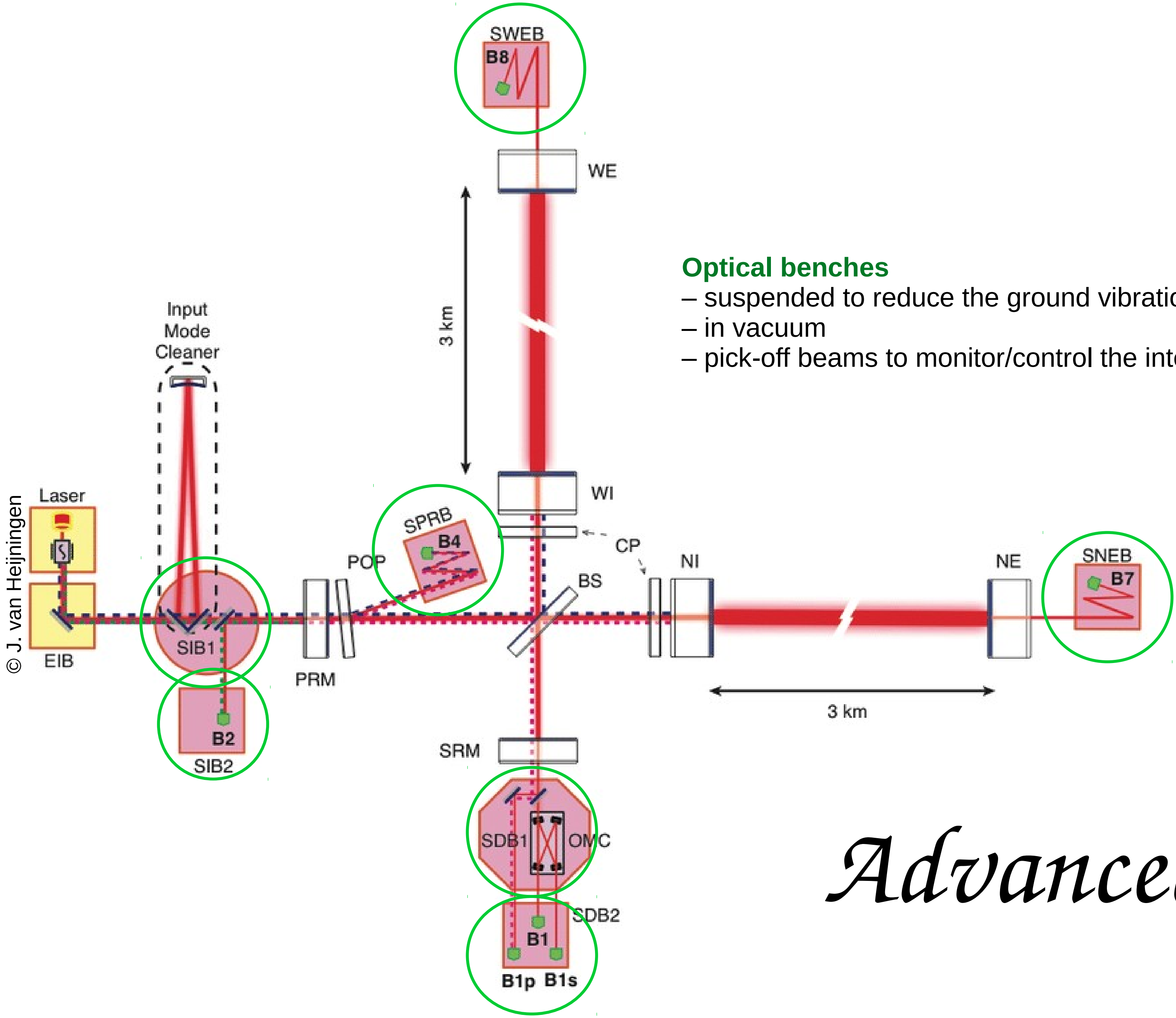
Central Michelson interferometer
- = 1 dof to control the detector

Power recycling cavity
- Increase the power on BS
- Gain ~ 38
- = 1 dof to control the detector

Detection system

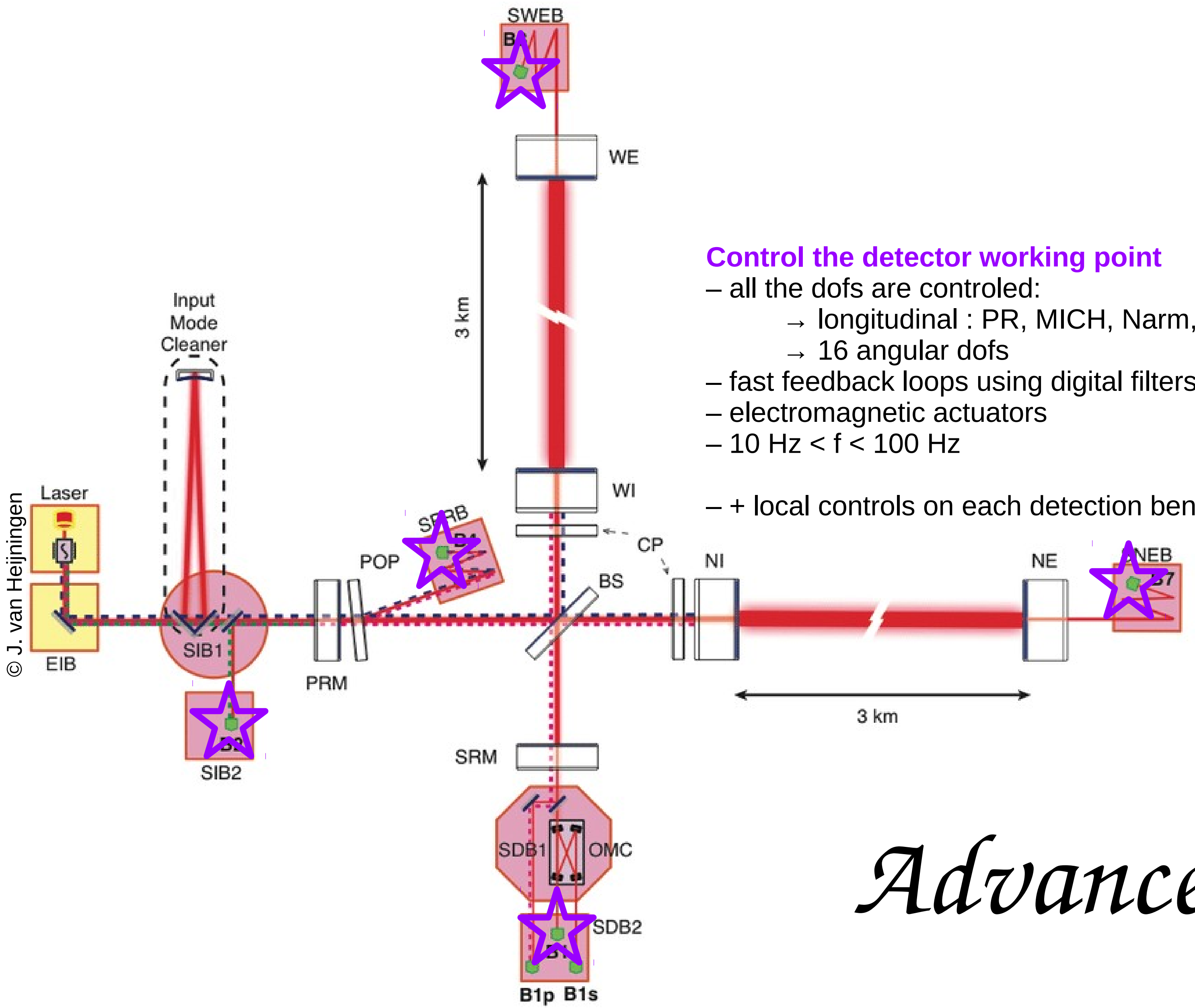


Advanced Virgo



Optical benches
– suspended to reduce the ground vibration
– in vacuum
– pick-off beams to monitor/control the interferometer

Advanced Virgo



Control the detector working point

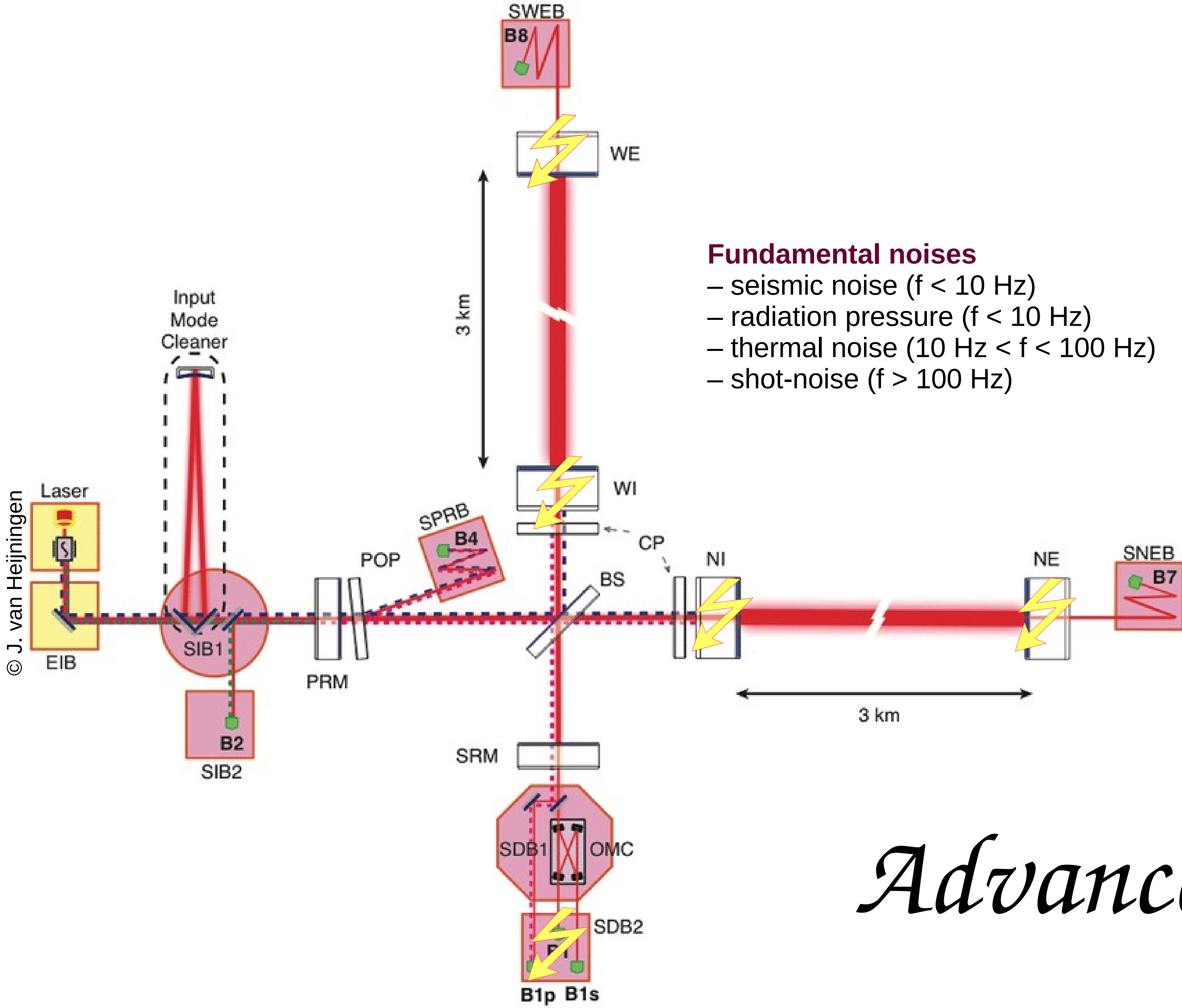
– all the dofs are controled:
  → longitudinal : PR, MICH, Narm, Warm
  → 16 angular dofs
– fast feedback loops using digital filters
– electromagnetic actuators
– 10 Hz < f < 100 Hz

– + local controls on each detection bench

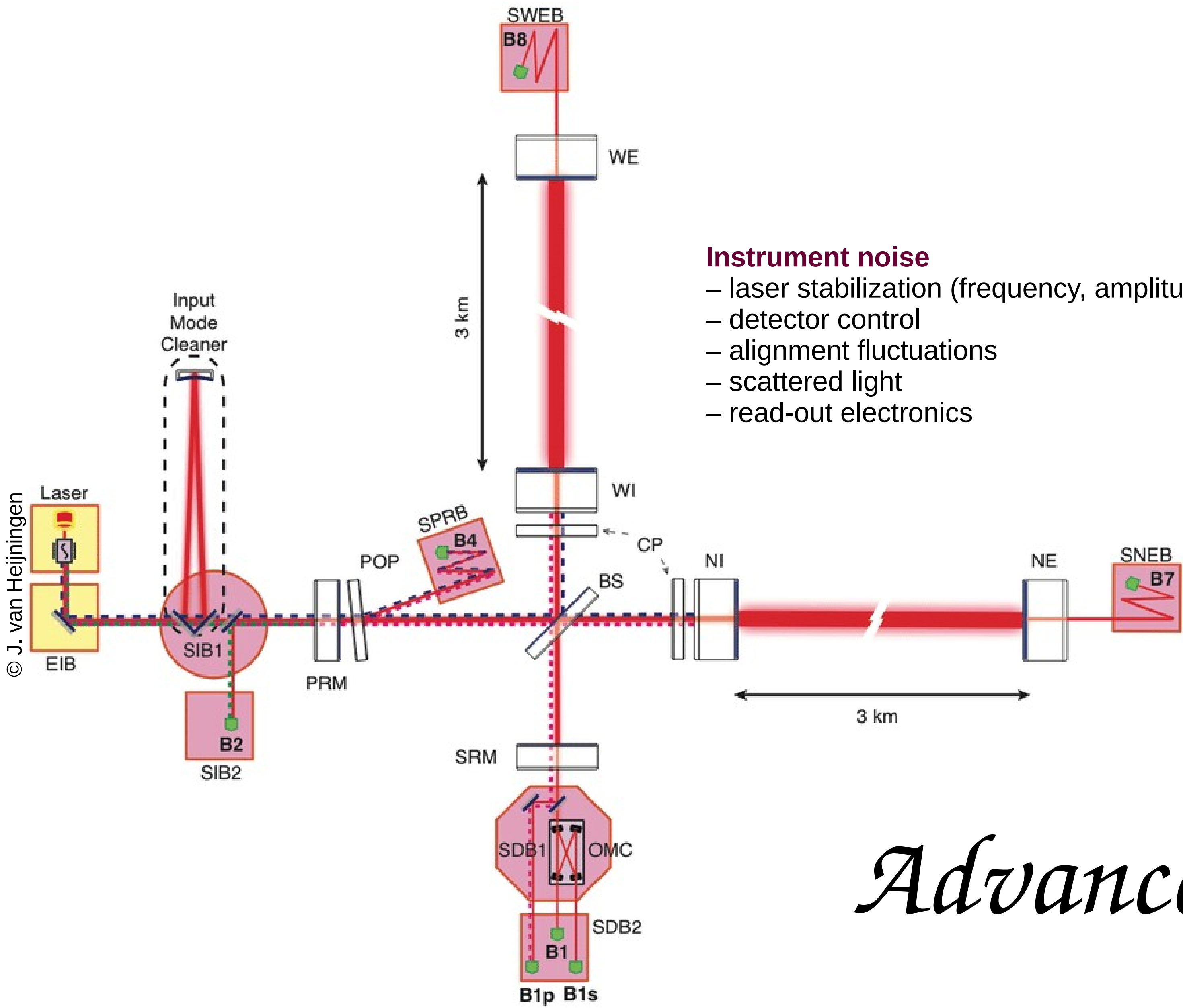
Advanced Virgo

Fundamental noises

– seismic noise (f < 10 Hz)
– radiation pressure (f < 10 Hz)
– thermal noise (10 Hz < f < 100 Hz)
– shot-noise (f > 100 Hz)

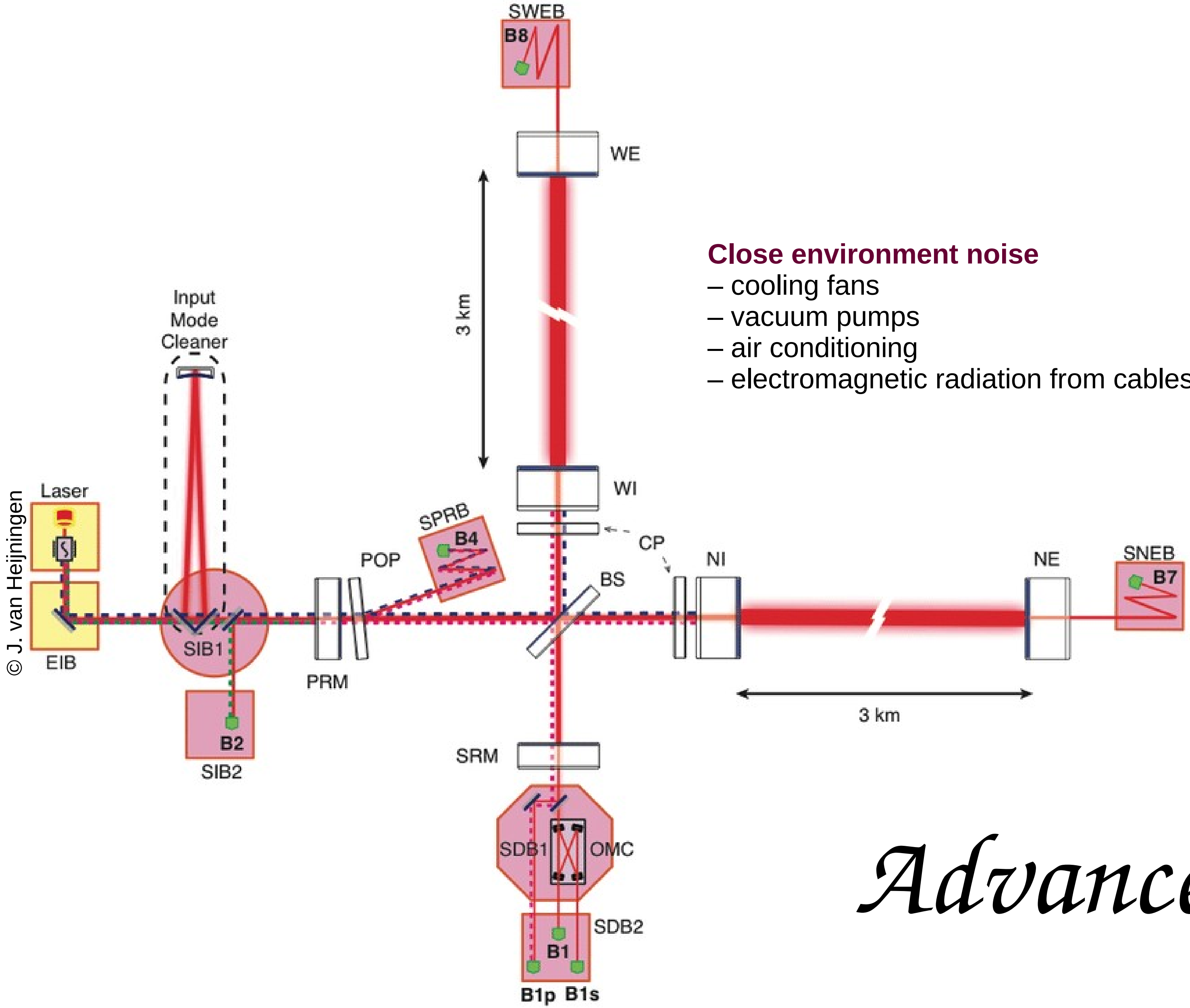


Advanced Virgo



Instrument noise
– laser stabilization (frequency, amplitude and jitter)
– detector control
– alignment fluctuations
– scattered light
– read-out electronics

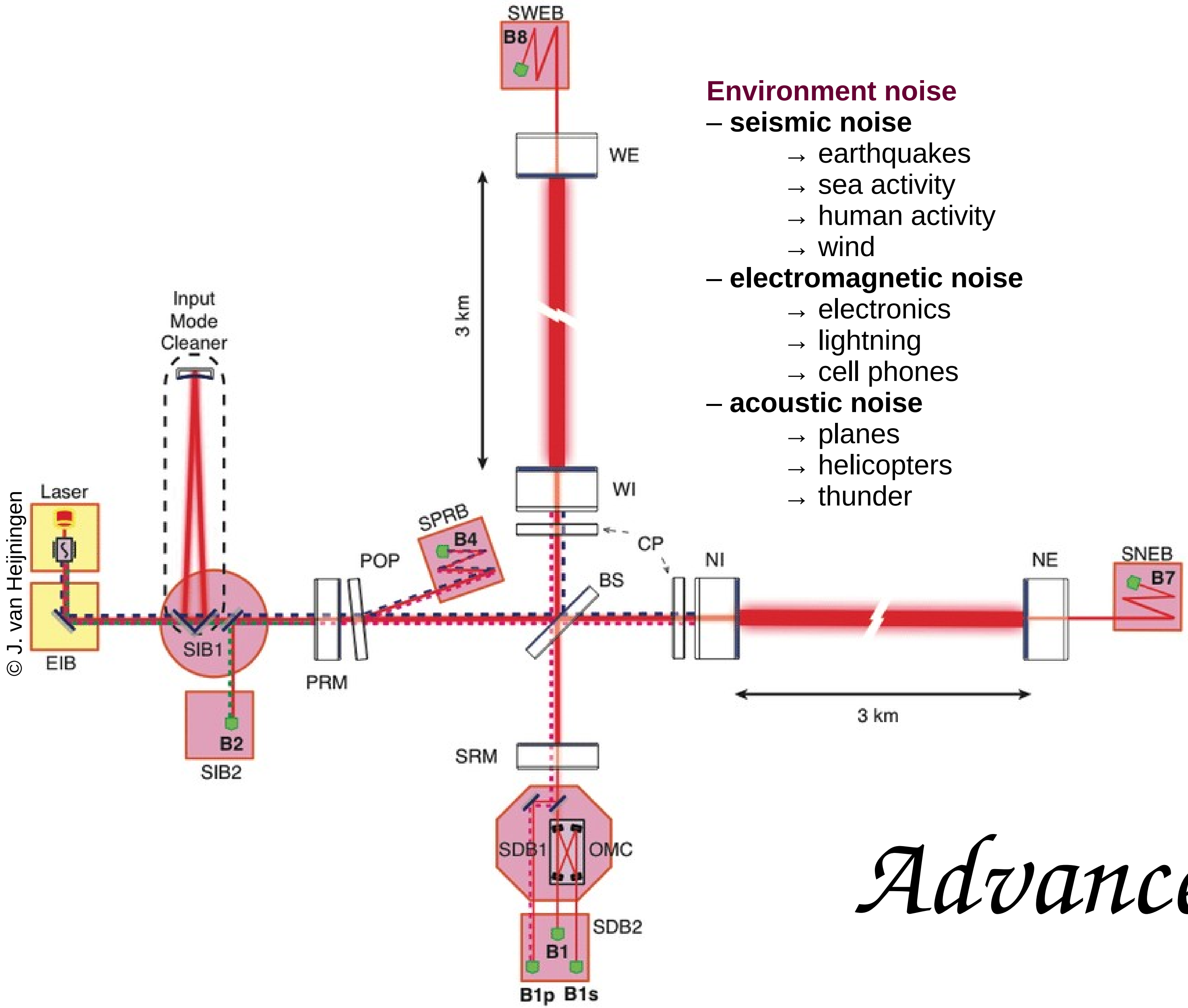
Advanced Virgo



Close environment noise

– cooling fans
– vacuum pumps
– air conditioning
– electromagnetic radiation from cables and electronics

Advanced Virgo



Environment noise

– **seismic noise**
  - → earthquakes
  - → sea activity
  - → human activity
  - → wind

– **electromagnetic noise**
  - → electronics
  - → lightning
  - → cell phones

– **acoustic noise**
  - → planes
  - → helicopters
  - → thunder

Advanced Virgo

Detector response:

$$\delta P_o = G_{PR} P_i C \frac{2\pi}{\lambda} \sin\left(\frac{4\pi}{\lambda}\Delta L_0\right) \frac{2F}{\pi} \delta\Delta L$$

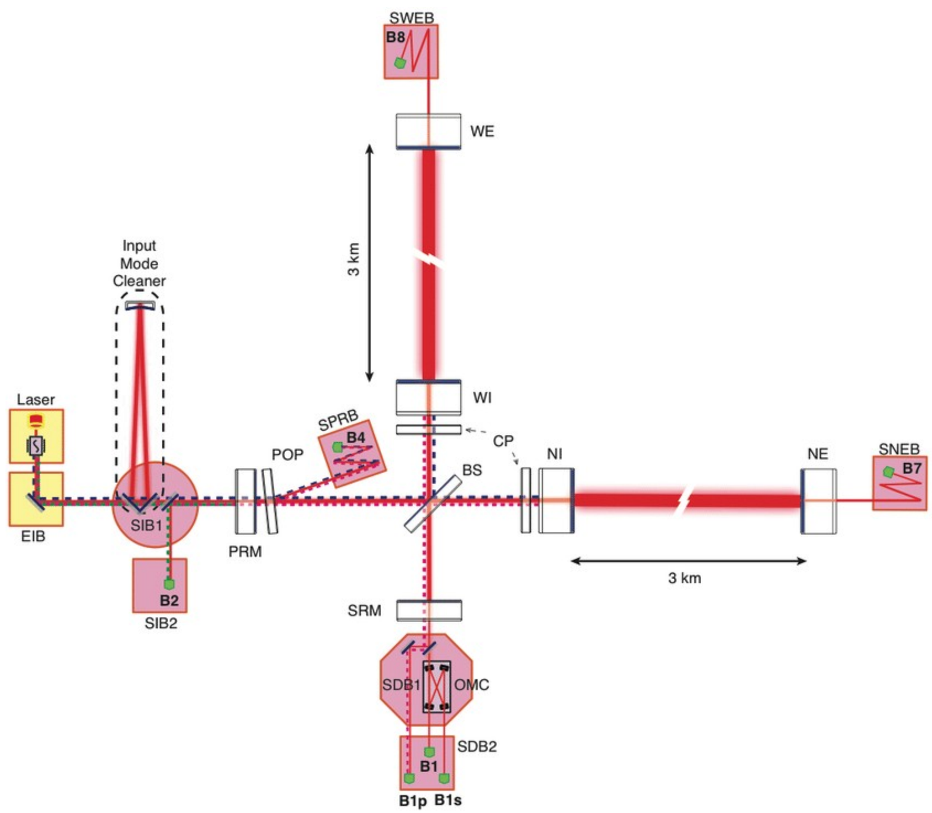
Typical shot noise at 50 mW:

$$\delta P_{shot} \sim 0.1\, nW$$

$$\delta\Delta L \sim 5\times10^{-20}\, m$$

Strain amplitude (reconstruction)

$$h = \frac{\delta\Delta L}{L_0} \sim 10^{-23}$$



$\lambda = 1064\, nm$

$P_i = 100\, W$

$\Delta L_0 = 10^{-11}\, m$

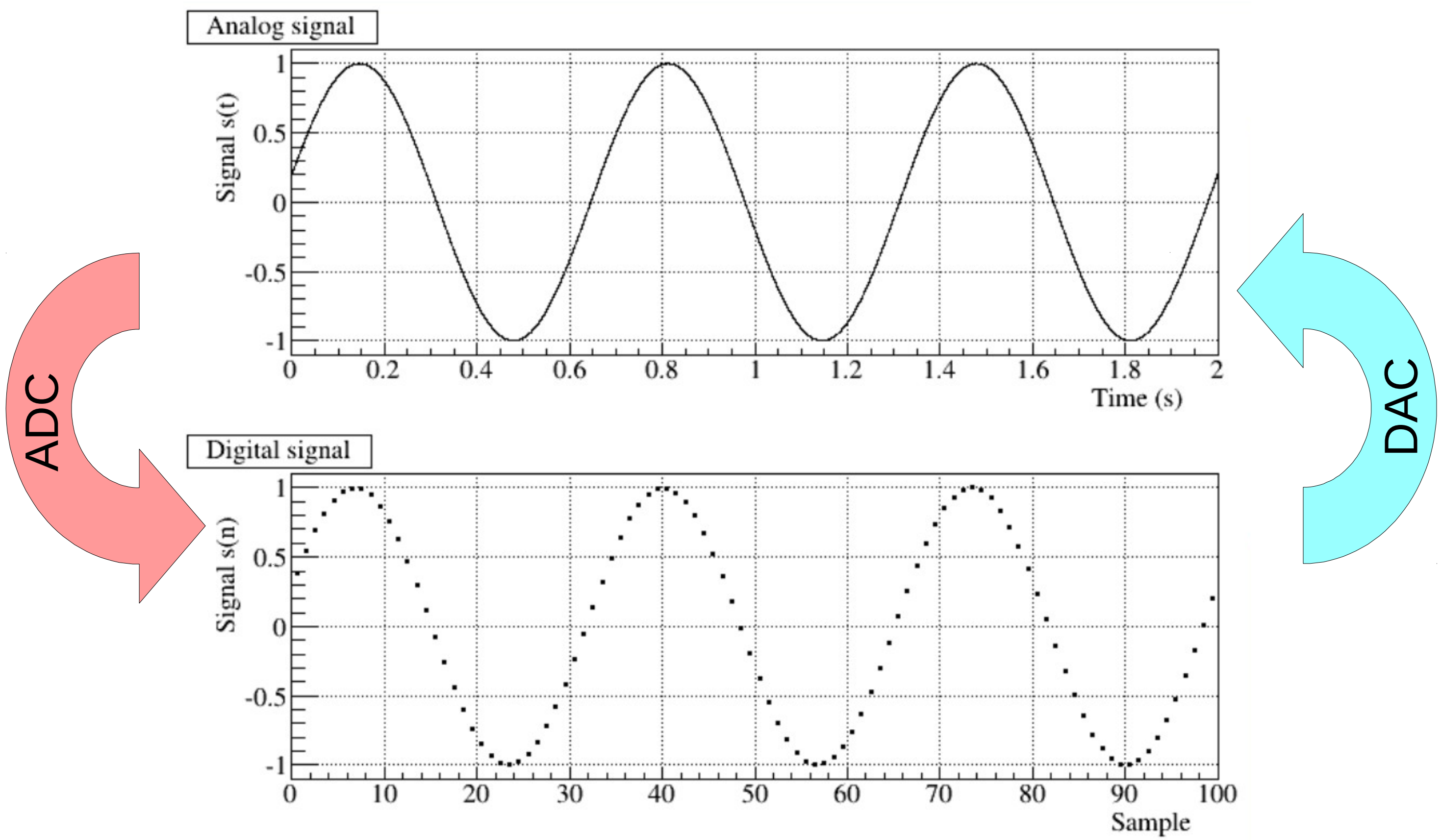
$F = 450$

$C = 1$

$G_{PR} = 38$

In reality the reconstruction is frequency dependent

Signal digitization



→ The photodiode analog signal (a voltage) is digitized

→ The signal is processed numerically

→ $h(t) \Rightarrow h[j] \quad t_{j+1} - t_j = 1/f_s$

→ The strain amplitude time series is saved to disk

Fourier transform

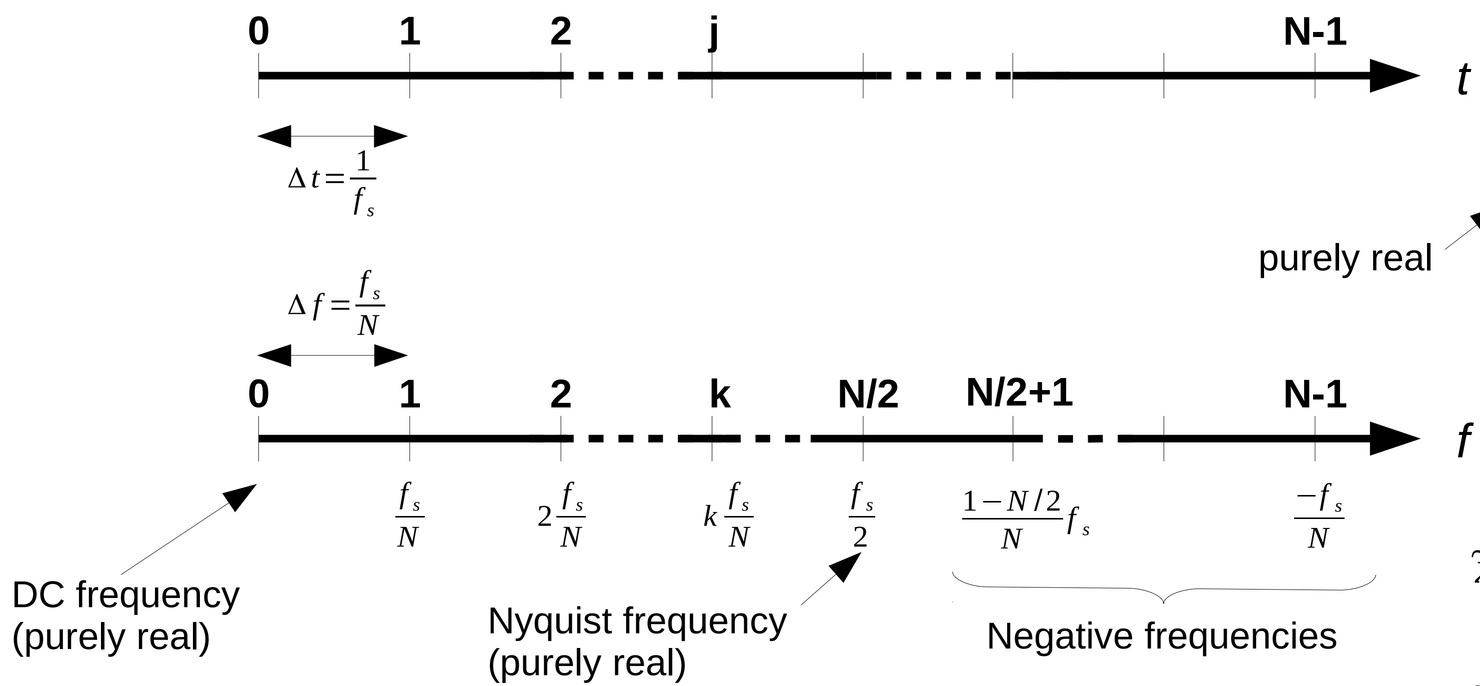
A time series *s(t)* can be projected over a basis of sinusoidal functions:

$$\tilde{x}(f) = \int_{-\infty}^{\infty} x(t) e^{-2i\pi ft} dt \qquad \text{(forward)}$$

$$x(t) = \int_{-\infty}^{\infty} \tilde{x}(f) e^{2i\pi ft} df \qquad \text{(backward)}$$

The signal is decomposed in characteristic frequencies

Discrete Fourier transform



$$x[j] = \frac{f_s}{N} \sum_{k=0}^{N-1} \tilde{x}[k] e^{+2i\pi kj/N}$$

$$\tilde{x}[k] = \frac{1}{f_s} \sum_{j=0}^{N-1} x[j] e^{-2i\pi kj/N}$$

$$\tilde{x}[k] = \tilde{x}^*[N-k]$$

Detector noise

Power spectral density (PSD)

$$\lim_{T \to \infty} \frac{1}{T} |\tilde{x}_T(f)|^2$$

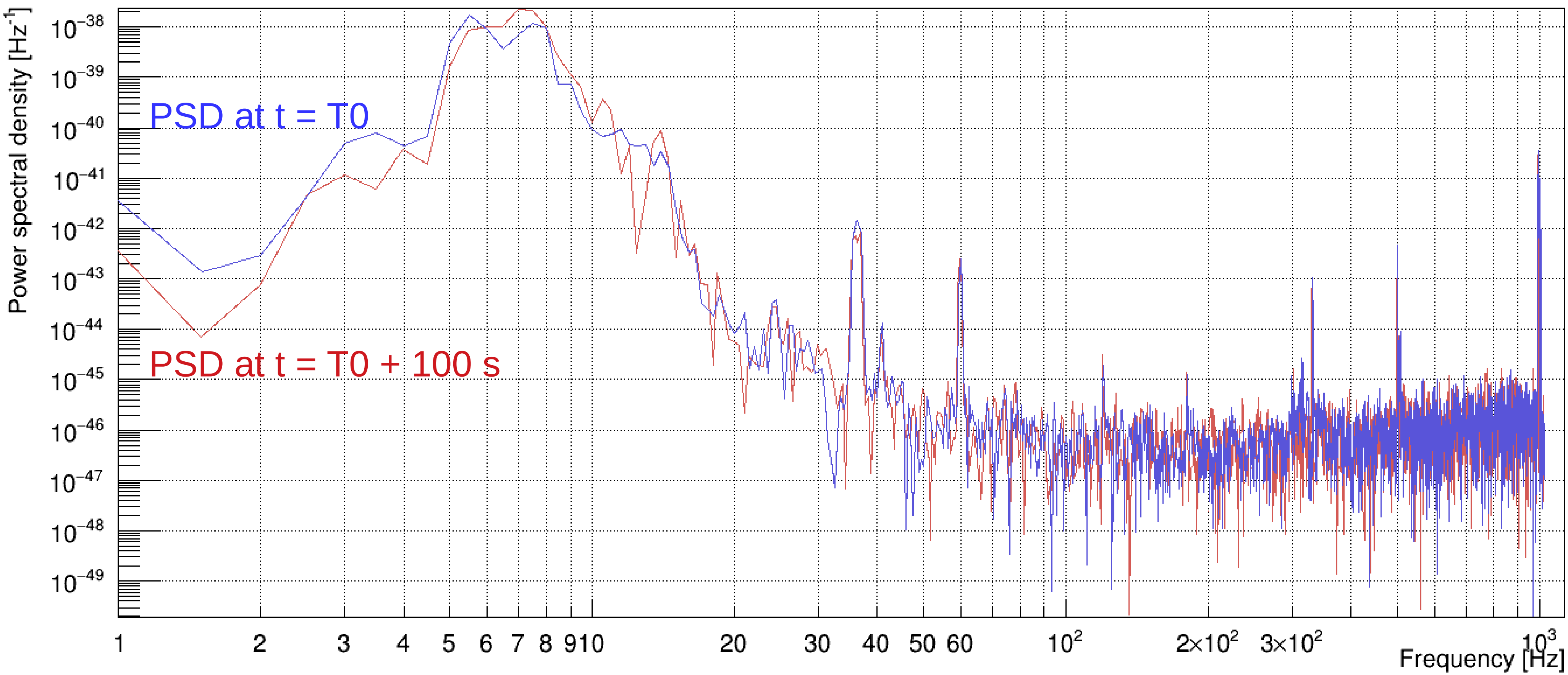
Estimator for a finite data set: **periodogram** $\frac{1}{T} |\tilde{x}_T(f)|^2$

The data must be windowed to prevent spectral leakage

$$\frac{1}{N f_s} \left| \sum_{j=0}^{N-1} x[j] w[j] e^{-2i\pi jk/N} \right|^2$$

→The frequency resolution is set by the number of points (N must be large)

Detector noise



→ LIGO h(t) data sampled at 2048 Hz
→ Periodogram evaluated over 2 seconds
→ N = 2048 x 2 = 4096 → df = 0.5 Hz

Detector noise

Power spectral density (PSD)

$$\lim_{T \to \infty} \frac{1}{T} |\tilde{x}_T(f)|^2$$

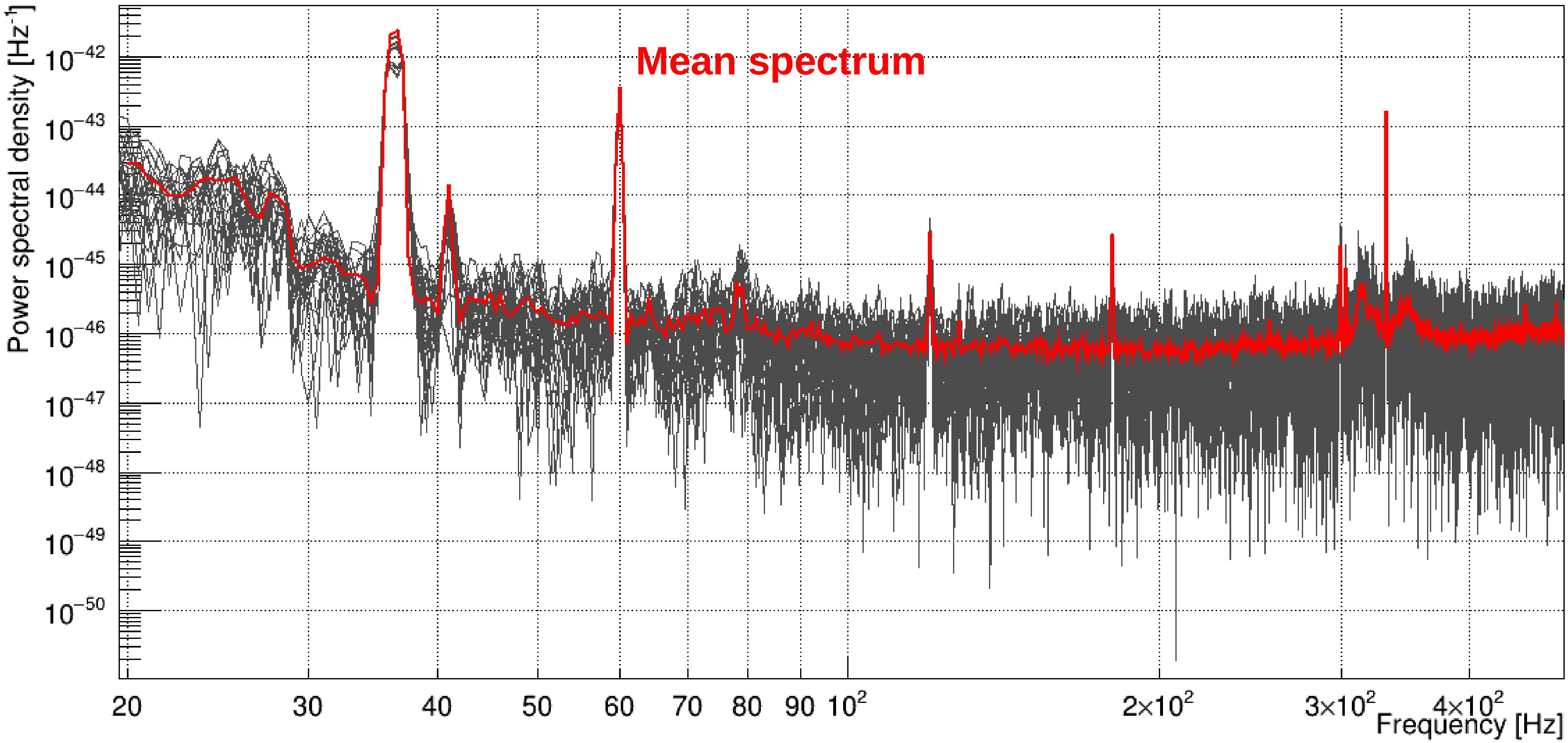
Estimator for a finite data set: **periodogram** $\frac{1}{T} |\tilde{x}_T(f)|^2$

The data must be windowed to prevent spectral leakage

$$\frac{1}{N f_s} \left| \sum_{j=0}^{N-1} x[j] w[j] e^{-2i\pi jk/N} \right|^2$$

Welch method: average multiple periodograms to reduce the variance

Detector noise

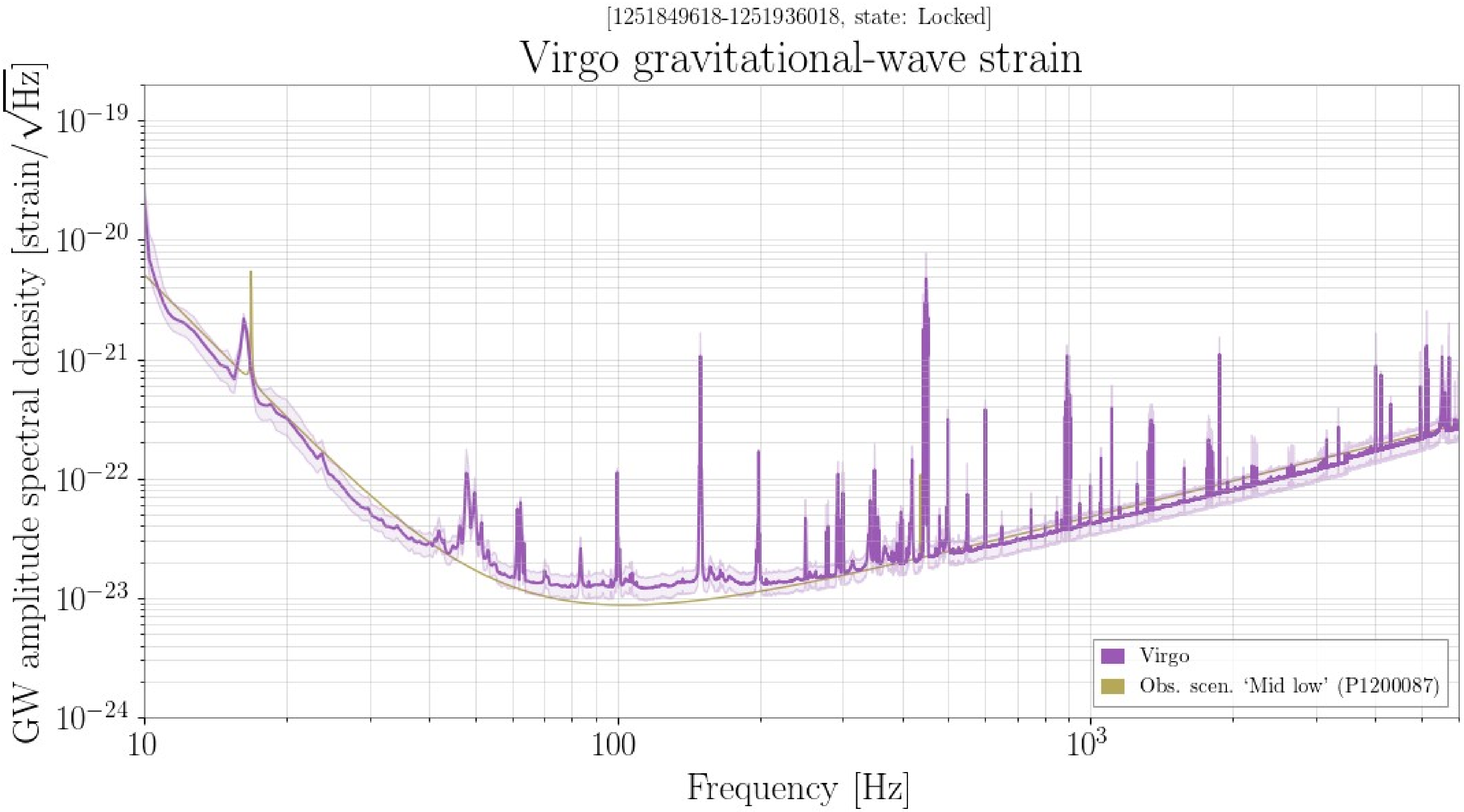


A lot of data must be considered to provide a reliable and precise estimate of noise:

→ maximize N for each periodograms

→ average many periodograms to reduce the variance

Detector noise floor



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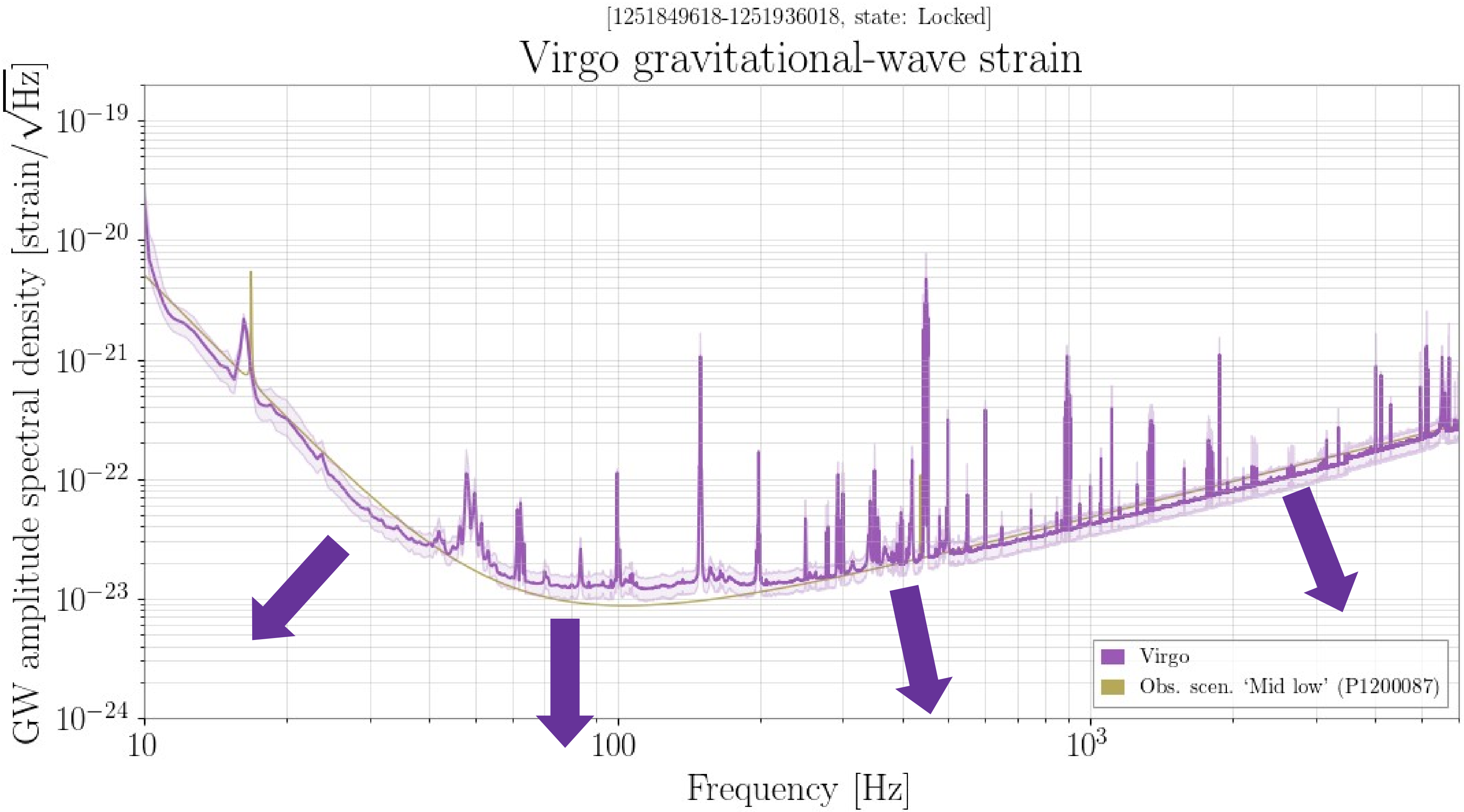
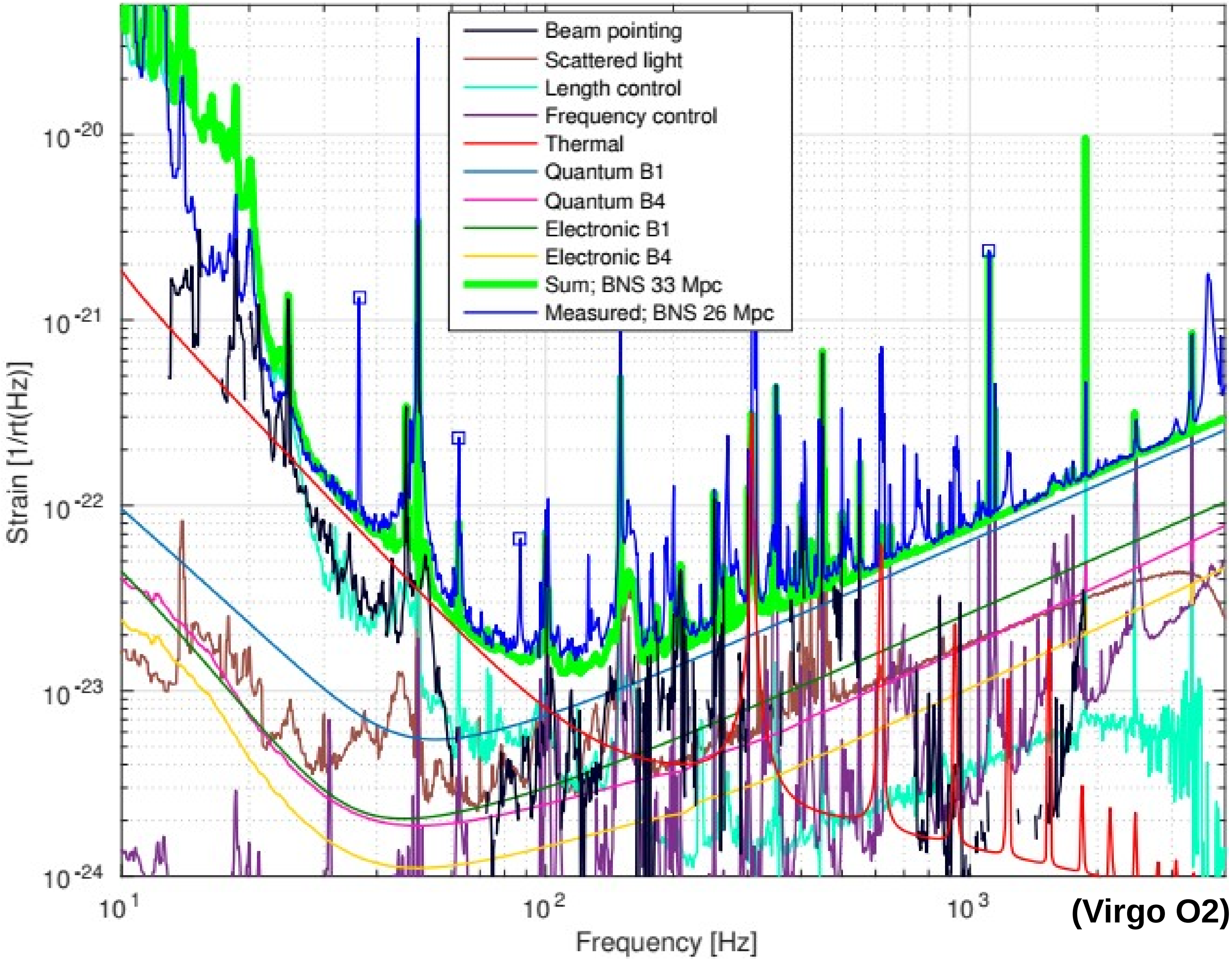


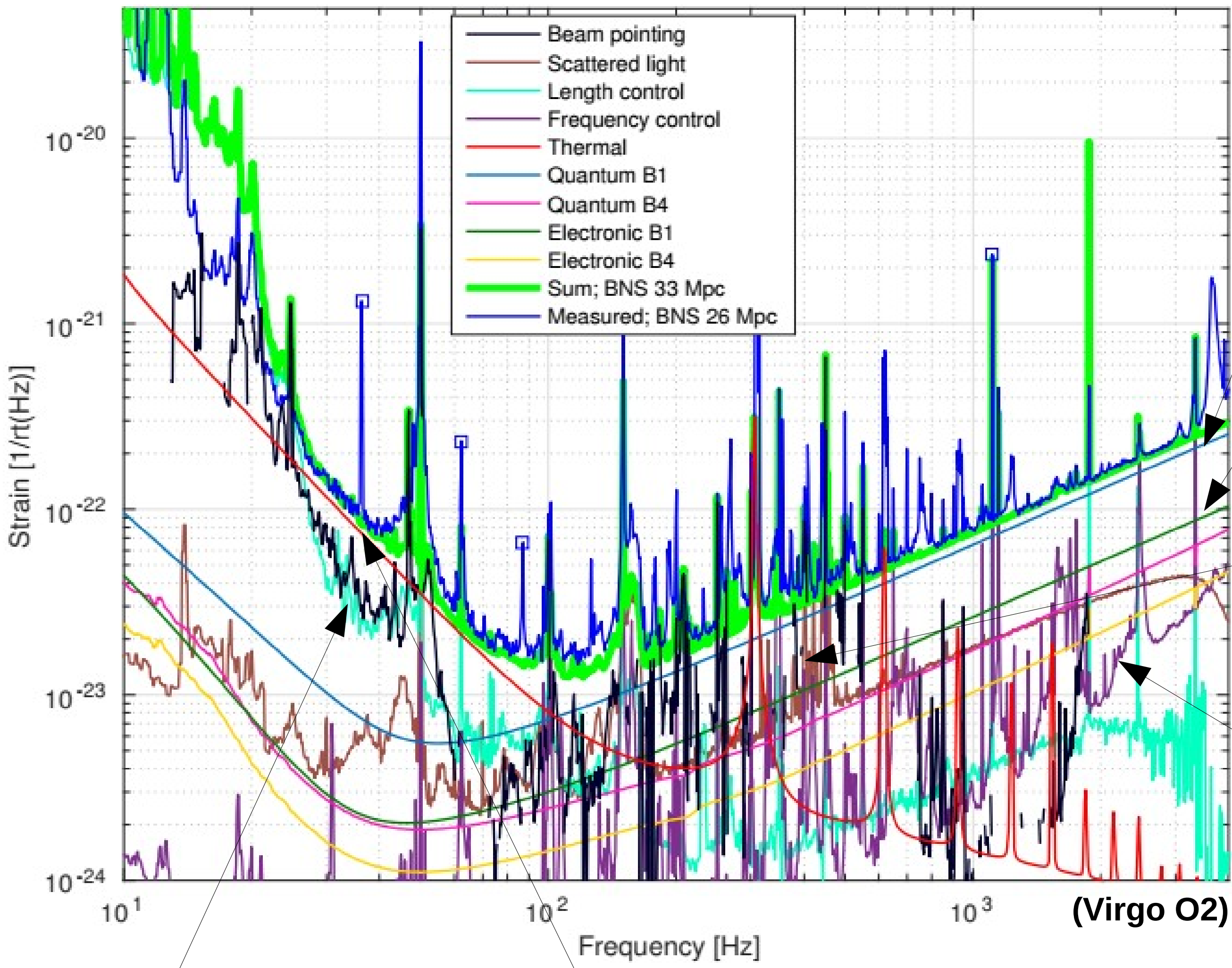
Noise hunt: bring the sensitivity curve down to the fundamental noise (seismic+thermic+quantum noise)

Detector noise floor



(Virgo O2)

Detector noise floor



Shot noise (analytical model)

$$\delta P_{shot} = \sqrt{\frac{2 P_0 \hbar c}{\lambda}}$$

PD electronic noise
measured with shutter closed

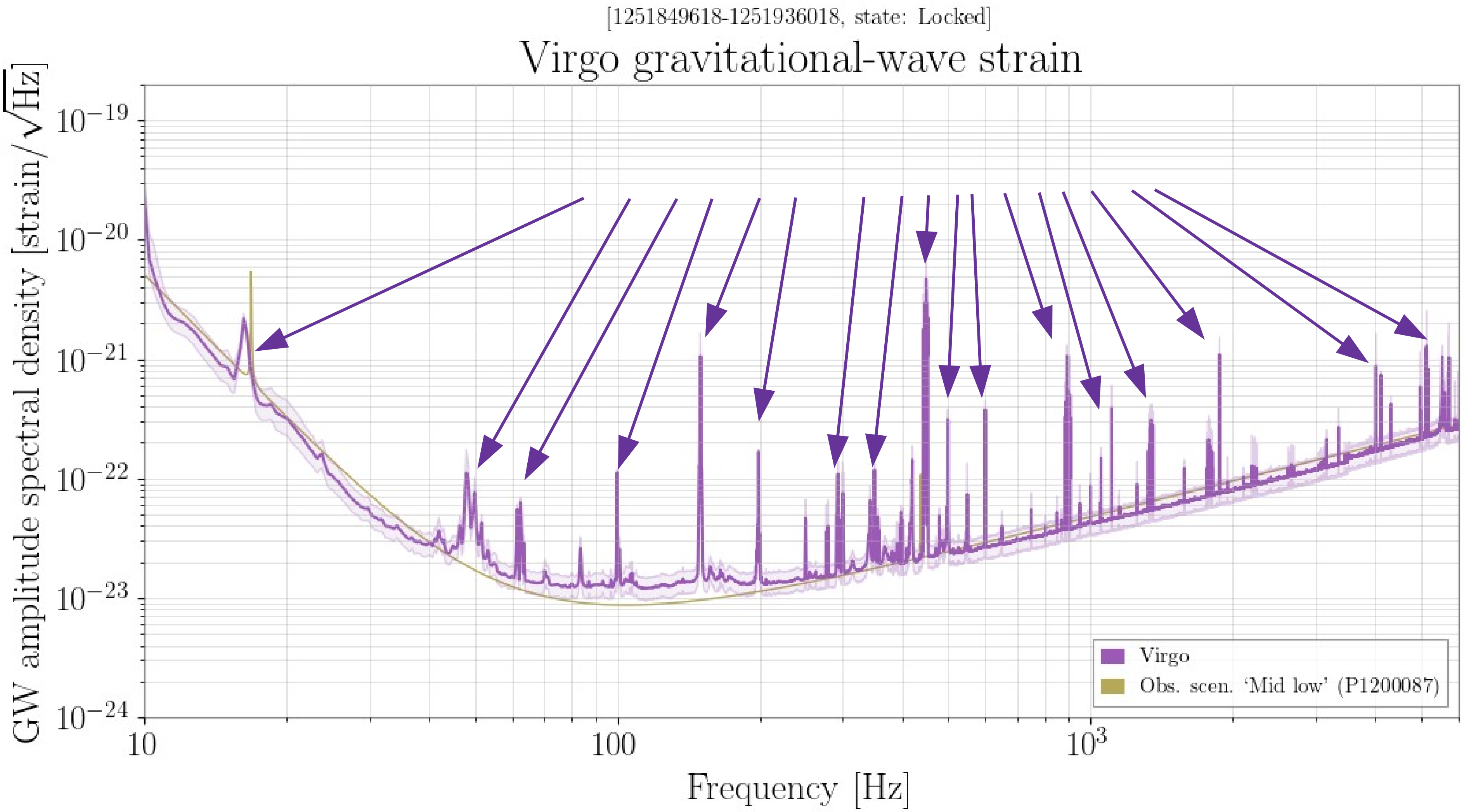
Scattered light
monitored using the DC power
In the central interferometer

Laser frequency control
(spectral lines)

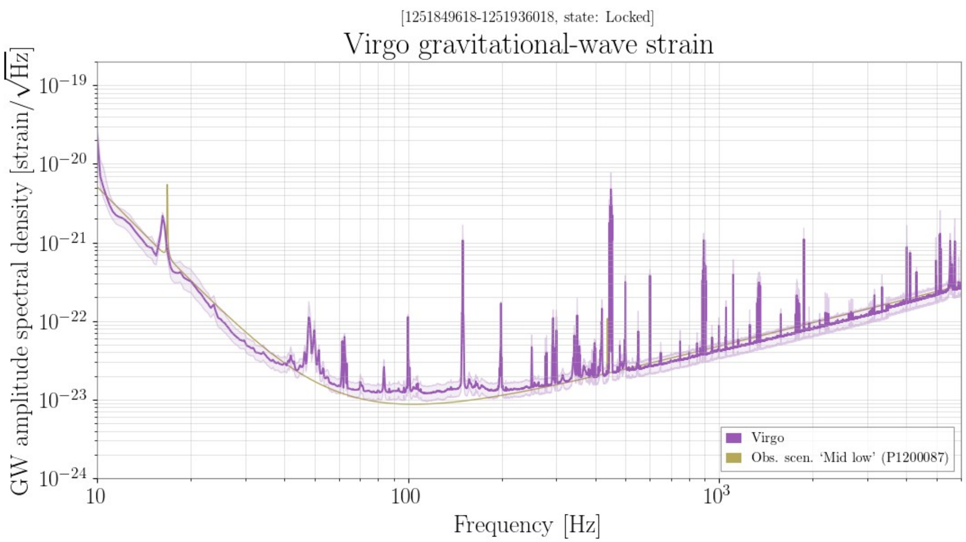
Control noise (MICH dof)
dominant for f < 25 Hz
(subtracted by active feed-forward)

Thermal noise from wire suspensions (steel in O2)
(analytical model)

Detector noise spectral structures



Detector noise spectral structures



→ **mechanical resonant modes** (mirror and suspensions): typical lorentzian spectral shape

→ **very narrow lines** associated to electronic devices

→ **line combs** often associated to digitized clocks

→ **Line harmonics** resulting of the coupling of 2+ frequencies

→ **Calibration lines** are intentionally injected to monitor the detector response

The line frequency can often be associated to electronic devices: cooling fans, vaccum pumps, water pumps, wi-fi, badges identification devices...

Spectral noise investigation is often based on a deep knowledge of the detector and its environment

Noise variations

The detector noise varies at all time scales during a LIGO-Virgo science run

O(run) → The detector performance is often improved during a run

O(1 month) → The data set often covers several seasons; the noise gets worse in winter

O(1 day) → Day/night variation (mostly temperature driven)

O(1 hour) → Environment (temperature, human activity, weather…)

O(<1 min) → Transient noise (so many sources!)

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Typically noise is estimated every few minutes

Welch method is biased by transient noise

→ Use a median estimator instead of mean

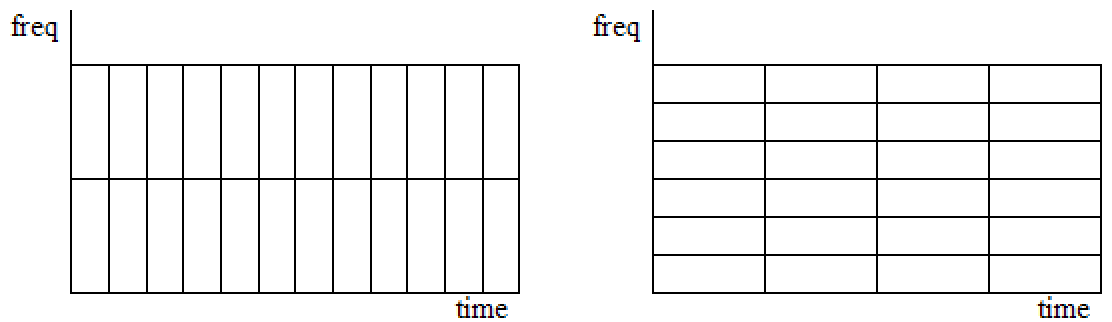
$$S_n(k) = Median_{0 \leq m < M} \left\{ \frac{1}{N f_s} \left| \sum_{j=0}^{N-1} x_m[j] w[j] e^{-2i\pi jk/N} \right|^2 \right\}$$

Spectrograms

Short Fourier transforms

$$X(\tau,\phi)=\int_{-\infty}^{+\infty} x(t)\,w(t-\tau,\phi)\,e^{-2i\pi\phi\tau}\,dt$$

Time-frequency analysis: the signal amplitude is computed in small regions in time and frequency

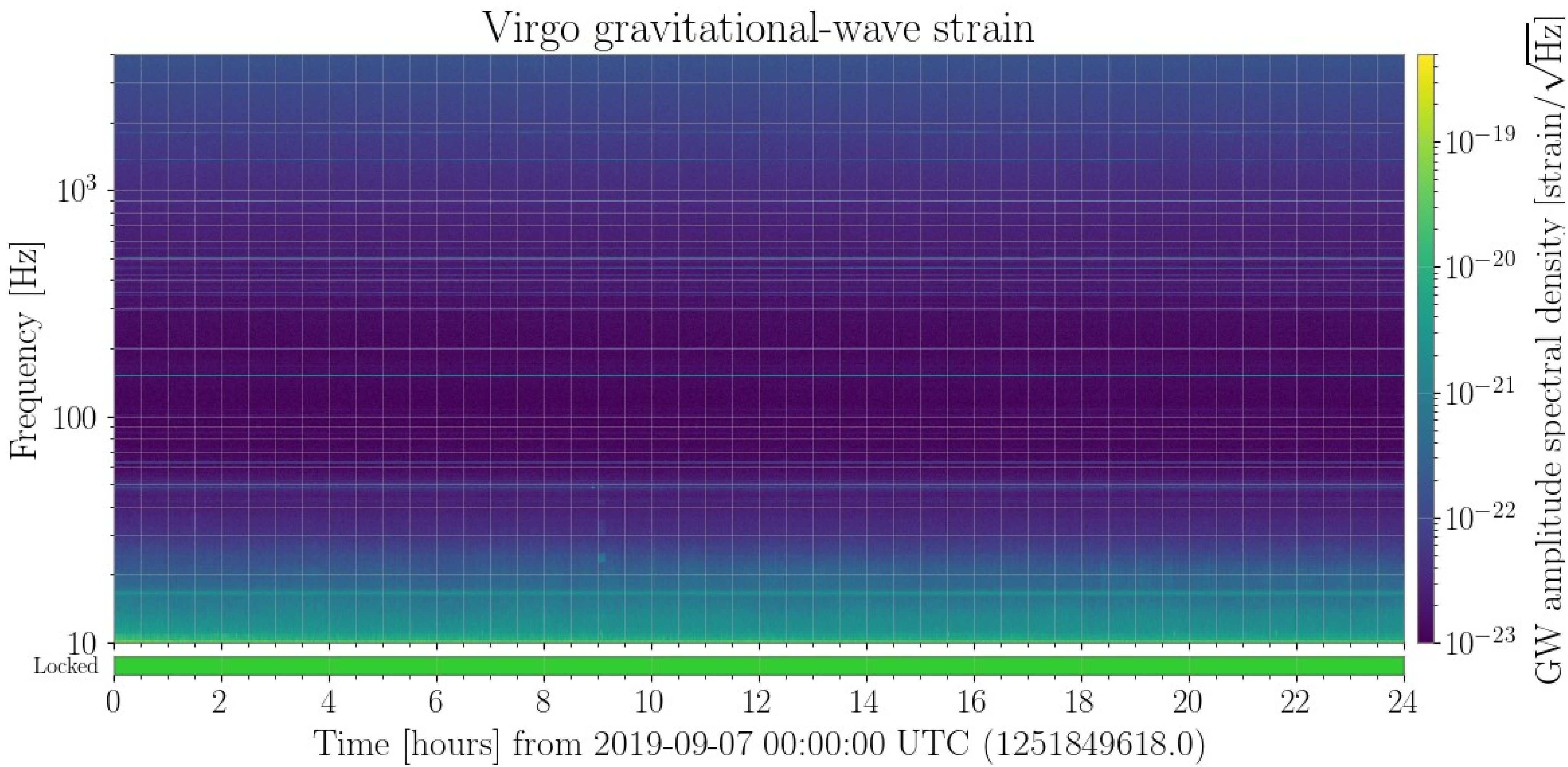


Heisenberg uncertainty principle: time and frequency resolutions are inversely proportional

Generalization of SFT: wavelet decomposition

Spectrograms

Short Fourier transforms $$X(\tau,\phi)=\int_{-\infty}^{+\infty} x(t)\,w(t-\tau,\phi)\,e^{-2i\pi\phi\tau}dt$$



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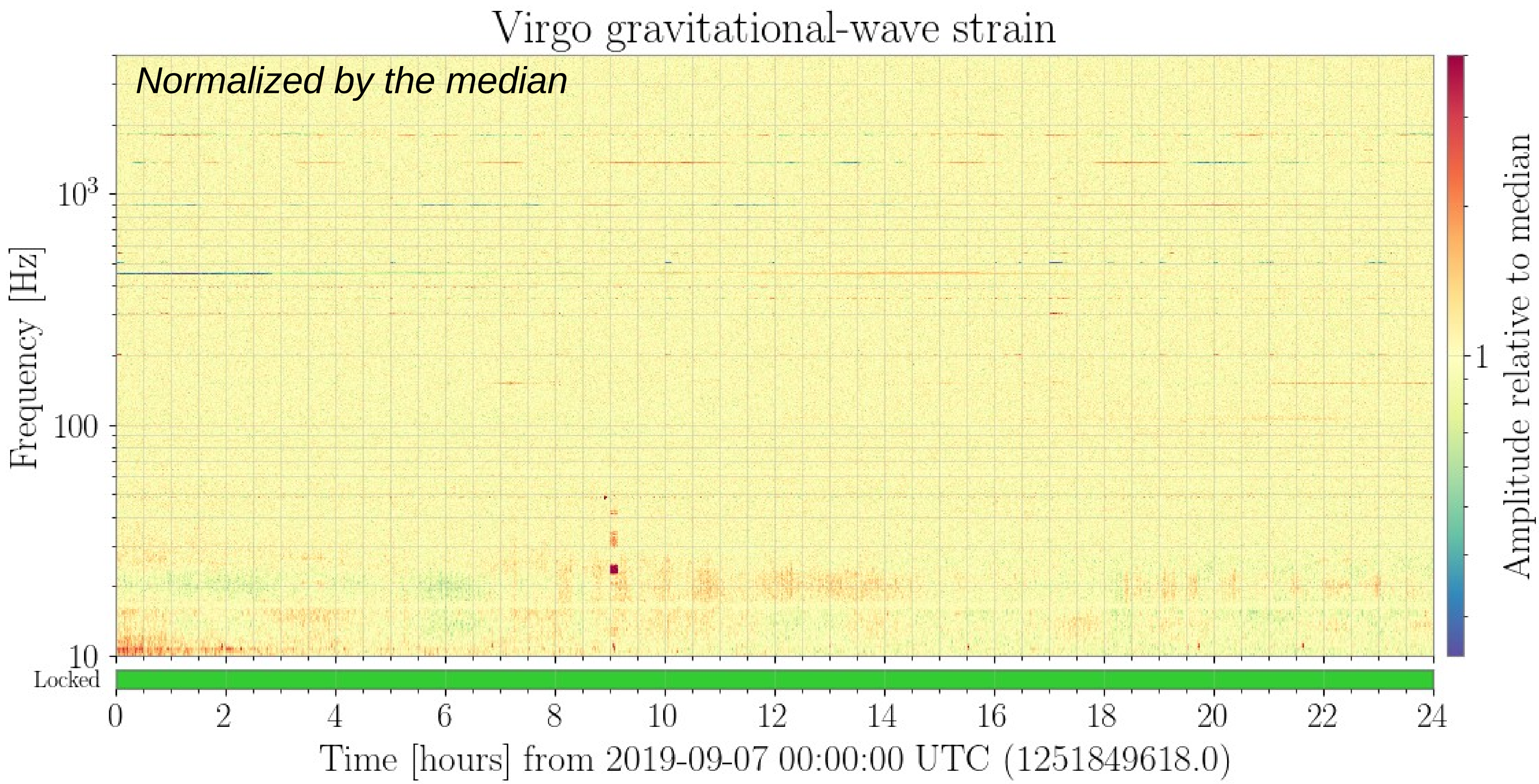
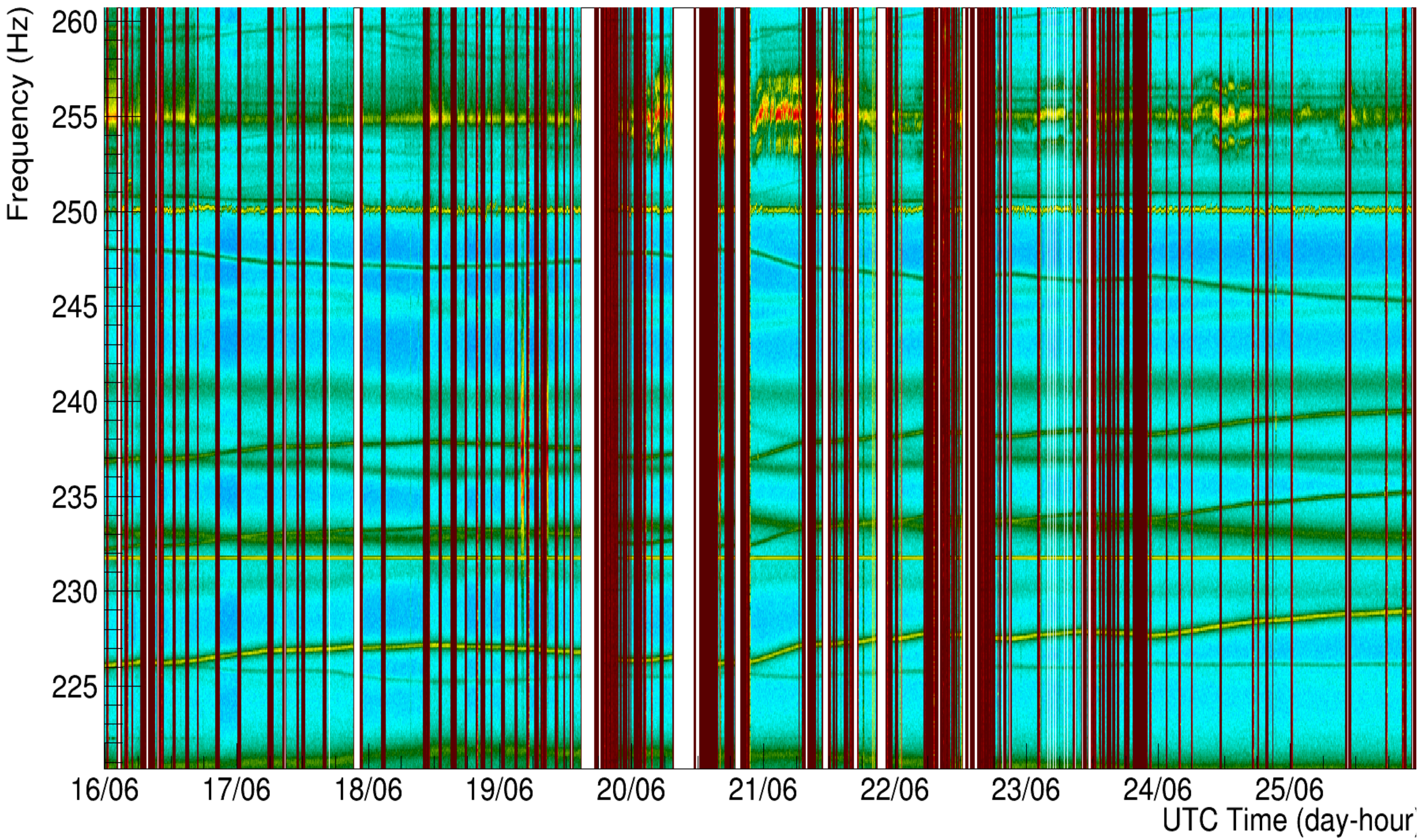


Wandering lines



Whitening

GW data must be whitened.

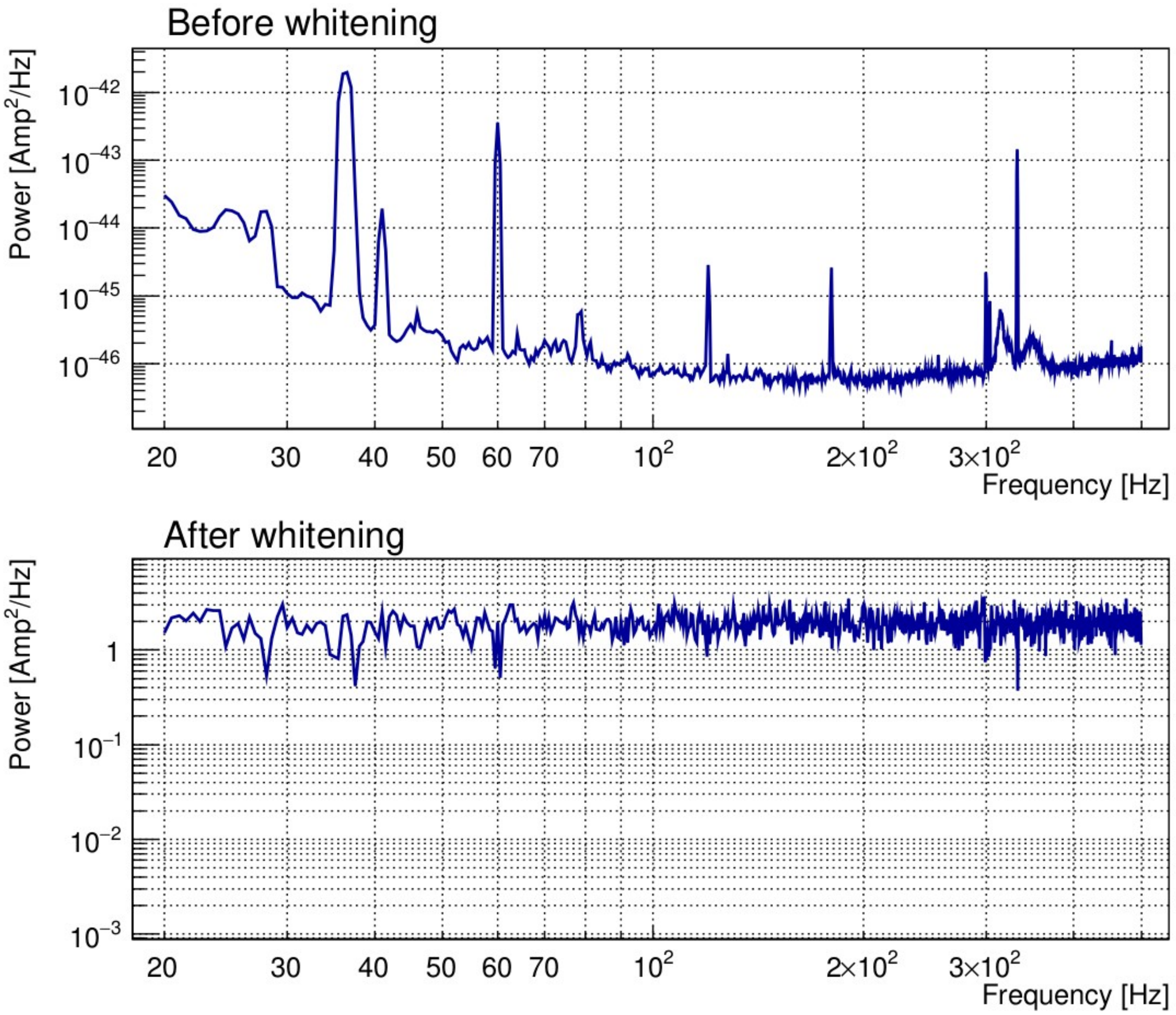
Several methods are used :
- reweighting of frequency bins

$$\tilde{x}(f) \rightarrow \frac{\tilde{x}(f)}{\sqrt{S_n(f)}}$$

- linear prediction

→ white noise is mandatory for a statistical interpretation of the data

→ measure of signal-to-noise ratio



Transient noise

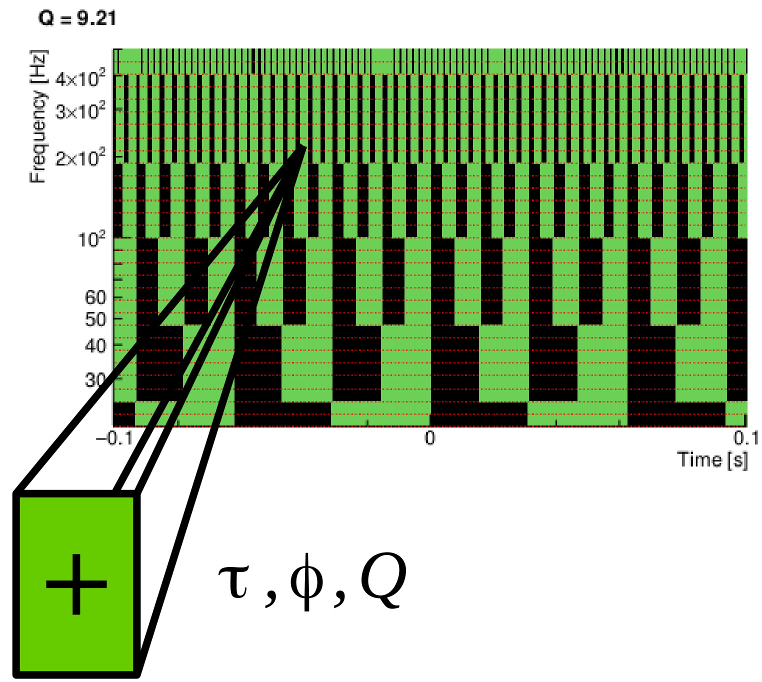
Example : Q-transform

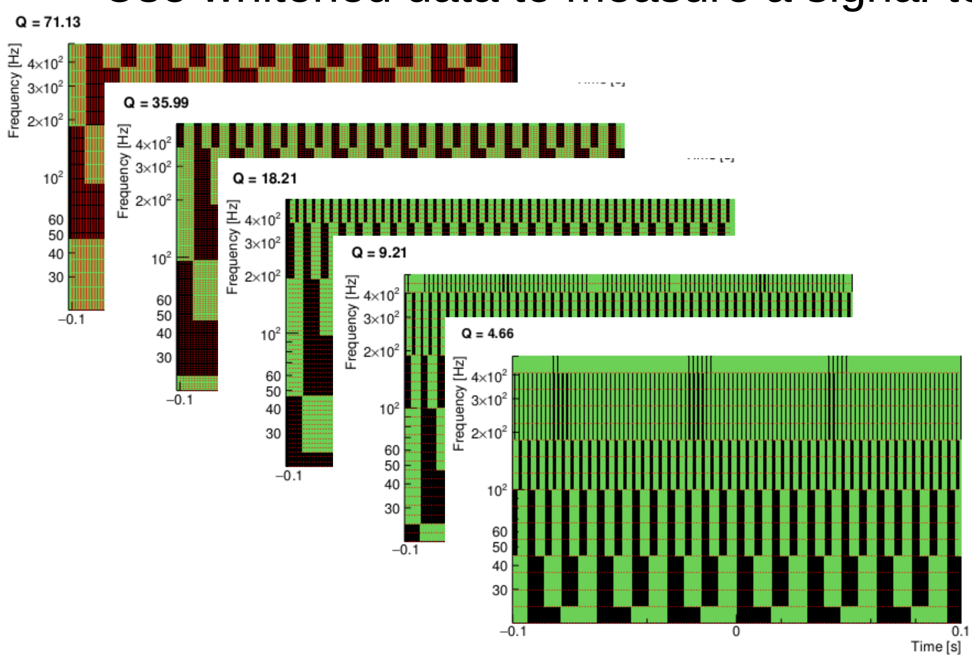
$$X(\tau,\phi,Q)=\int_{-\infty}^{+\infty} x(t)\,w(t-\tau,\phi,Q)\,e^{-2i\pi\phi\tau}\,dt$$

→ window width $\sim 1/\phi$

~ Short Fourier transform with a Gaussian window

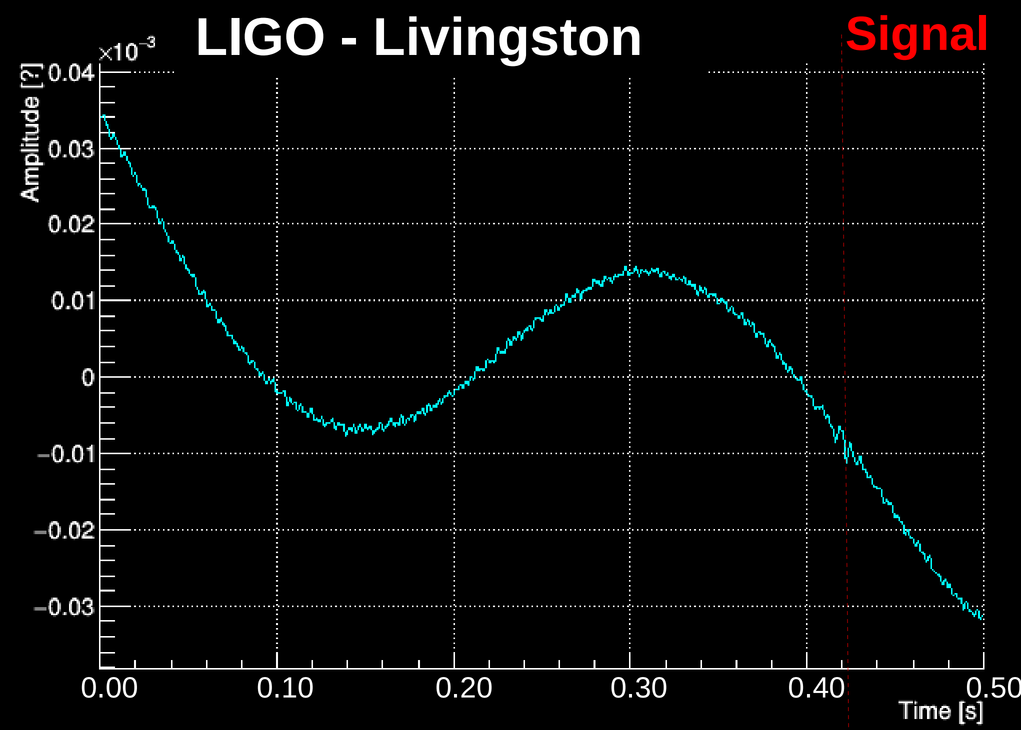
→ Use whitened data to measure a signal-to-noise ratio





GW150914

Output power



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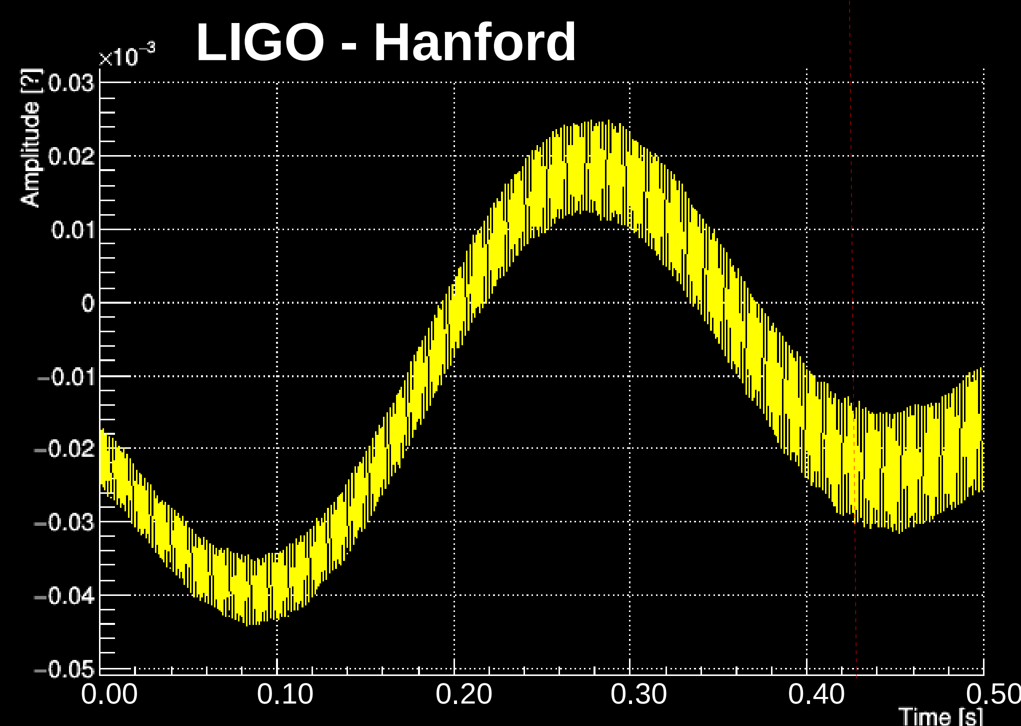
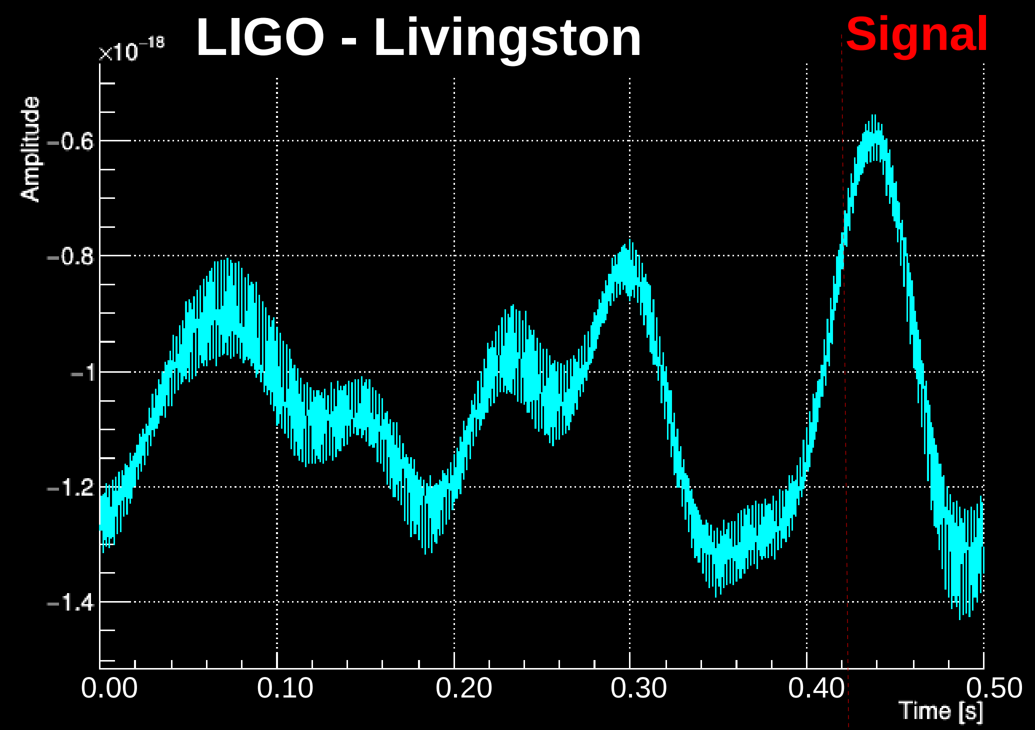


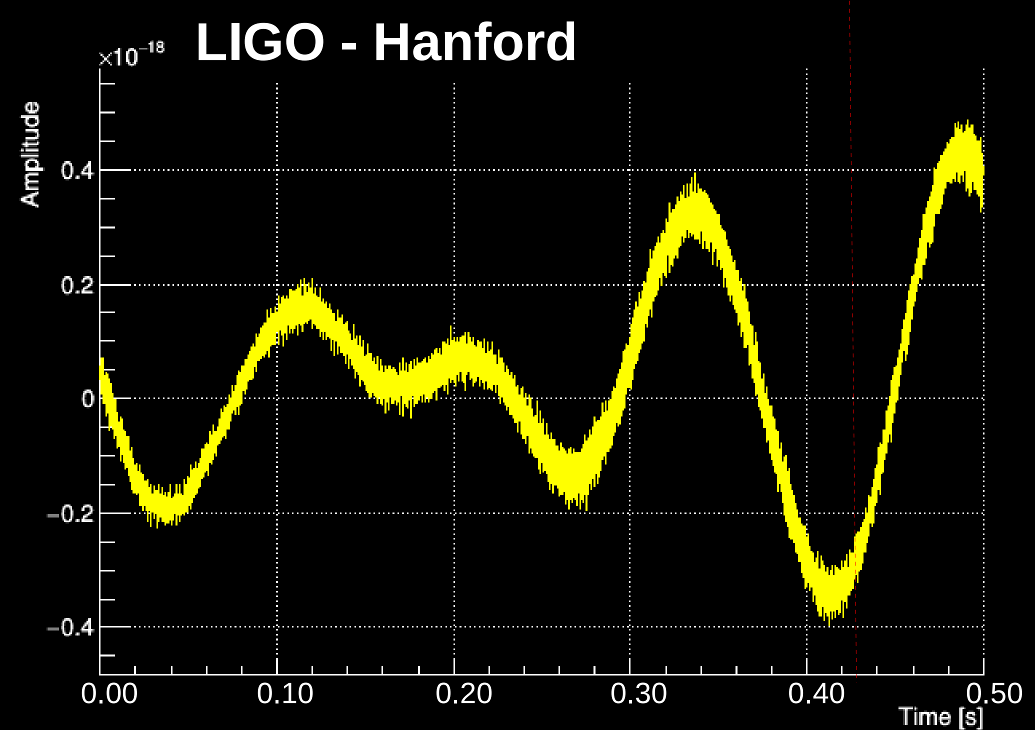
GW150914

$h(t)$

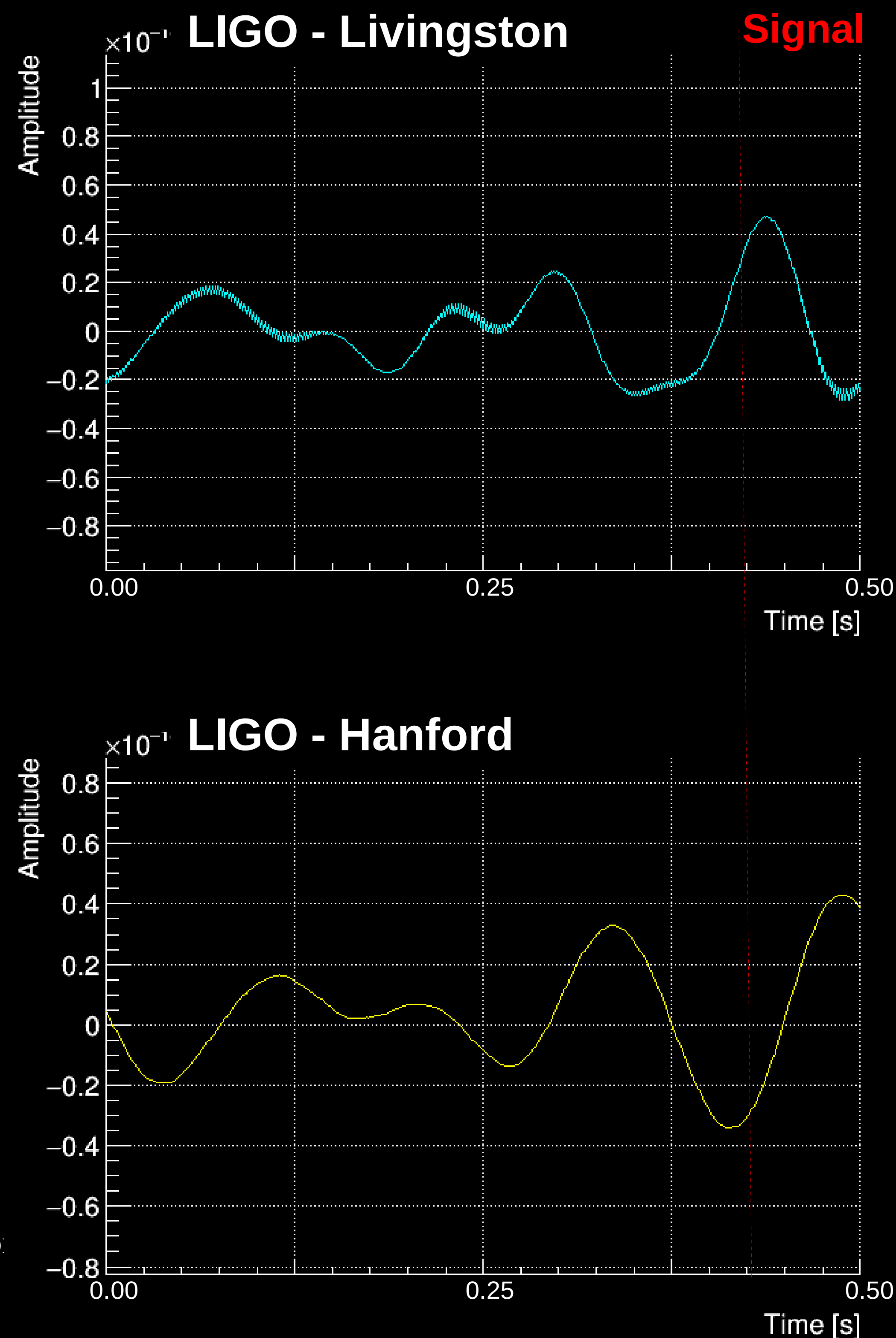


Data is calibrated
→ GW strain amplitude *h(t)*
(including high-pass filter f > 10 Hz)

$h(t)$

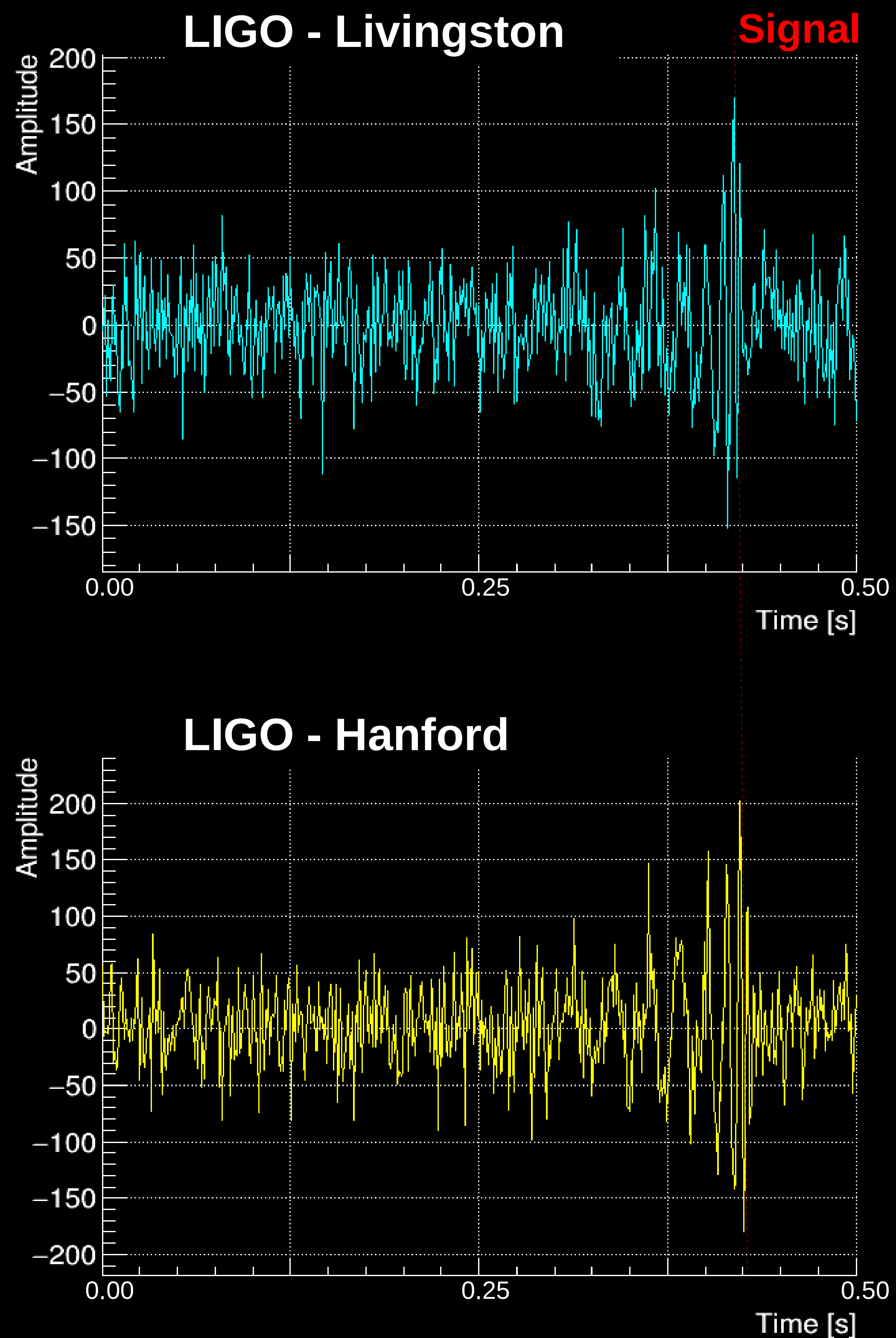


GW150914



Data are low-pass filtered
(here, < 500 Hz)

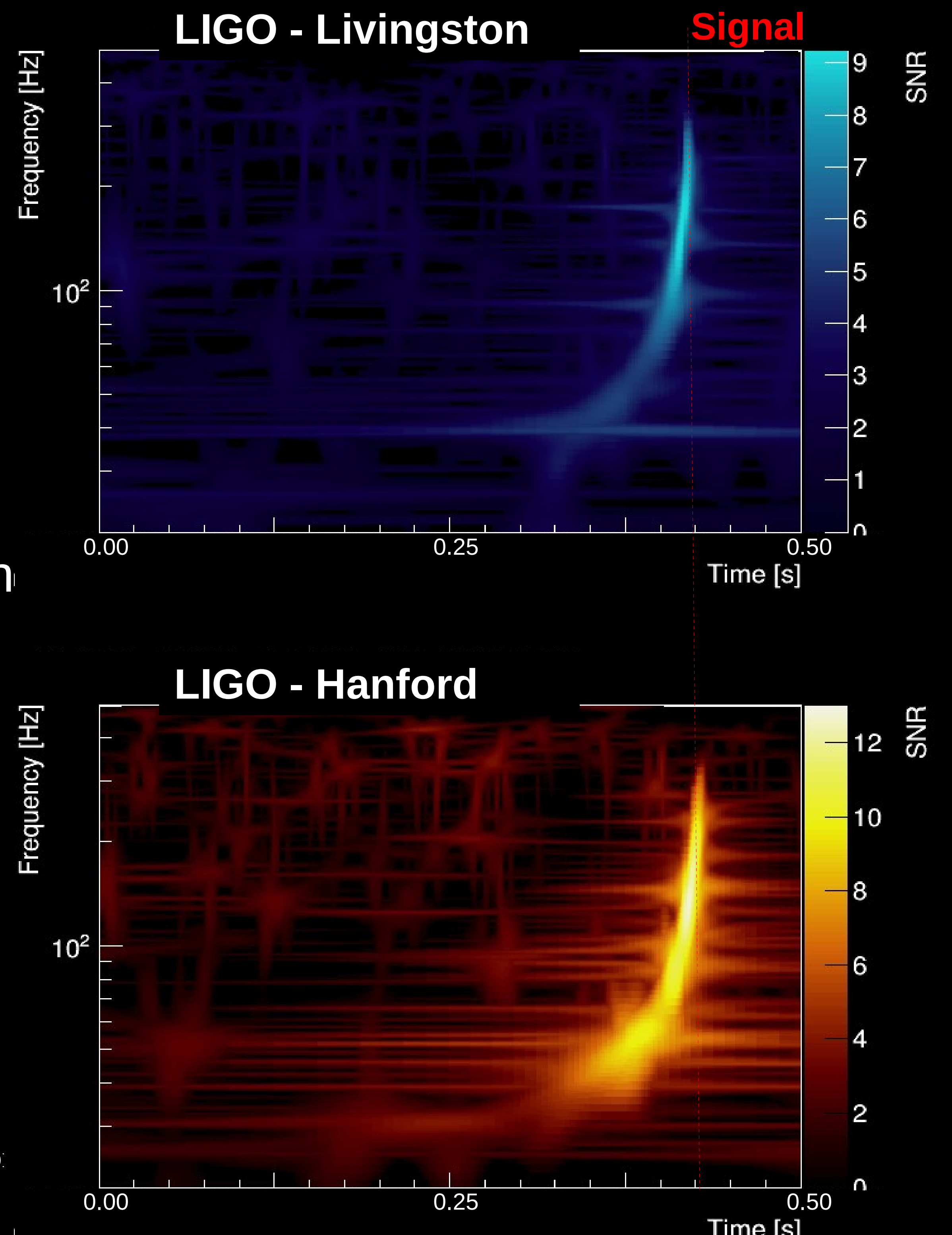
GW150914



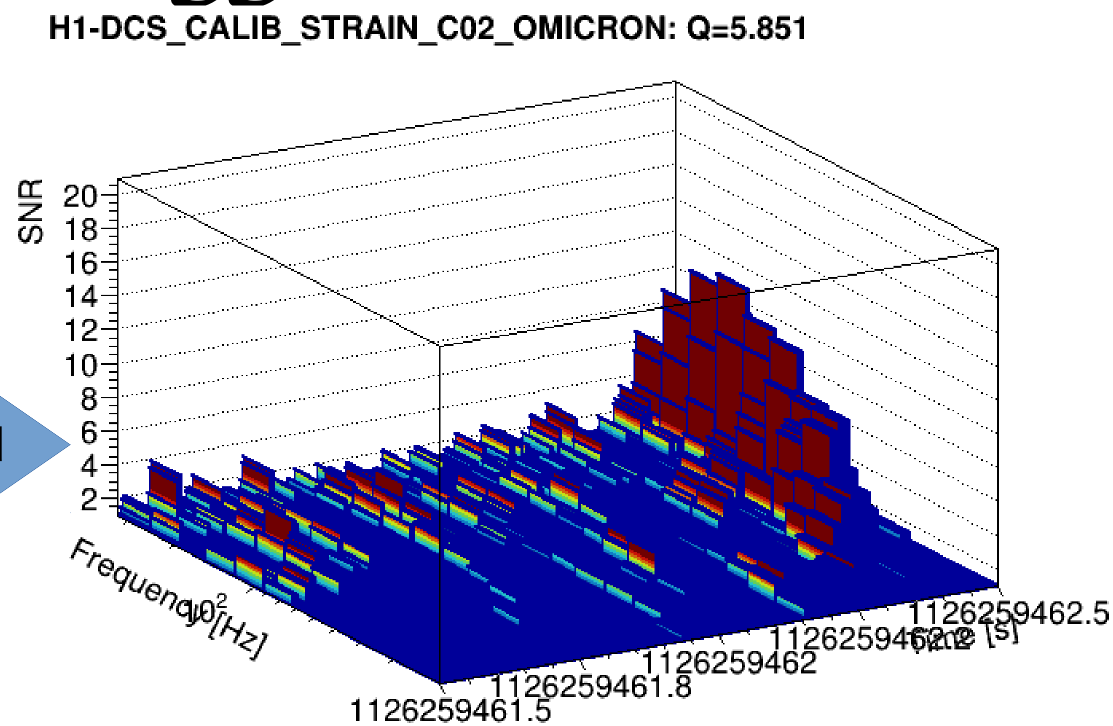
Data are whitened

GW150914

Time-frequency decomposition
(Short Fourier transforms)

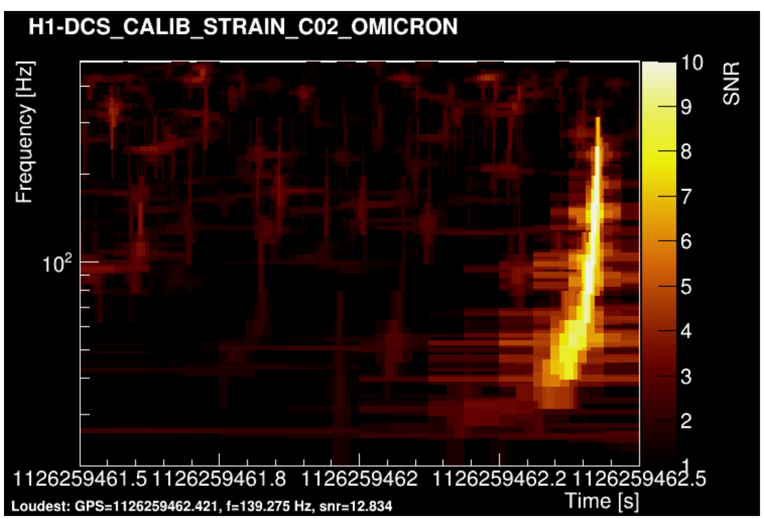


Transient triggers

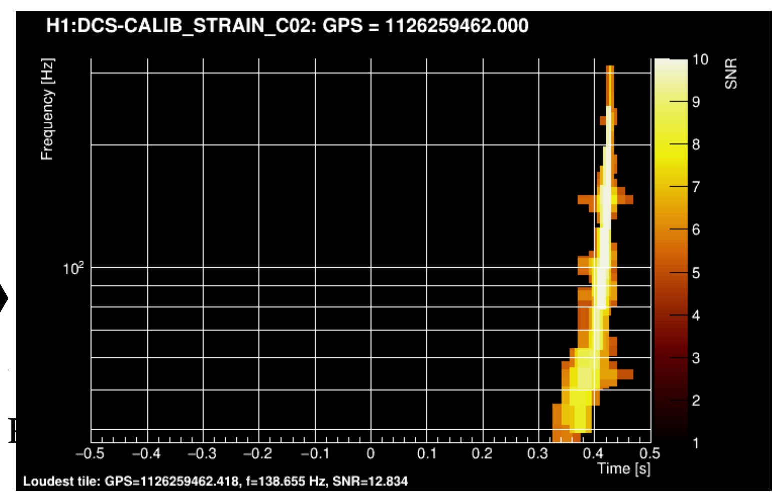


SNR threshold

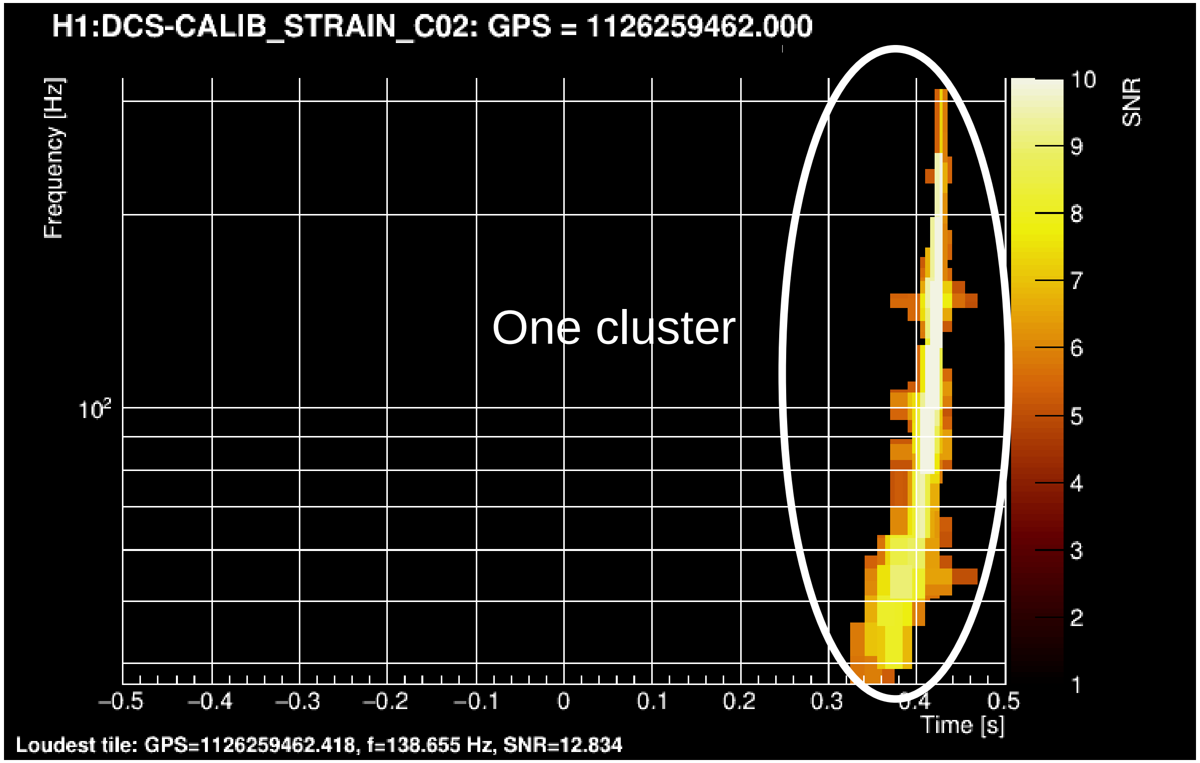
A trigger = a tile with a SNR value above a given threshold



SNR > 5



Transient triggers



Triggers are clustered in time

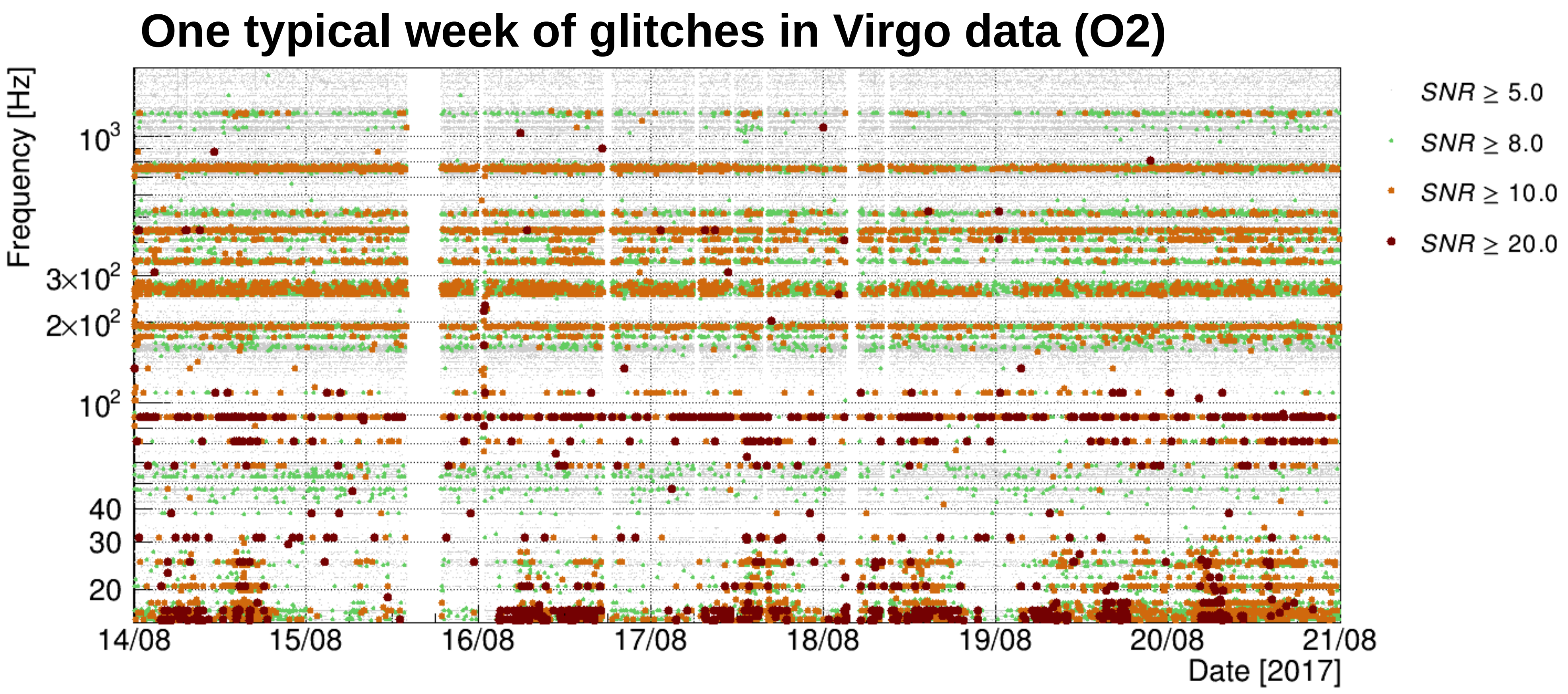
One cluster:
- time
- frequency
- SNR

→ given by the tile with the highest SNR

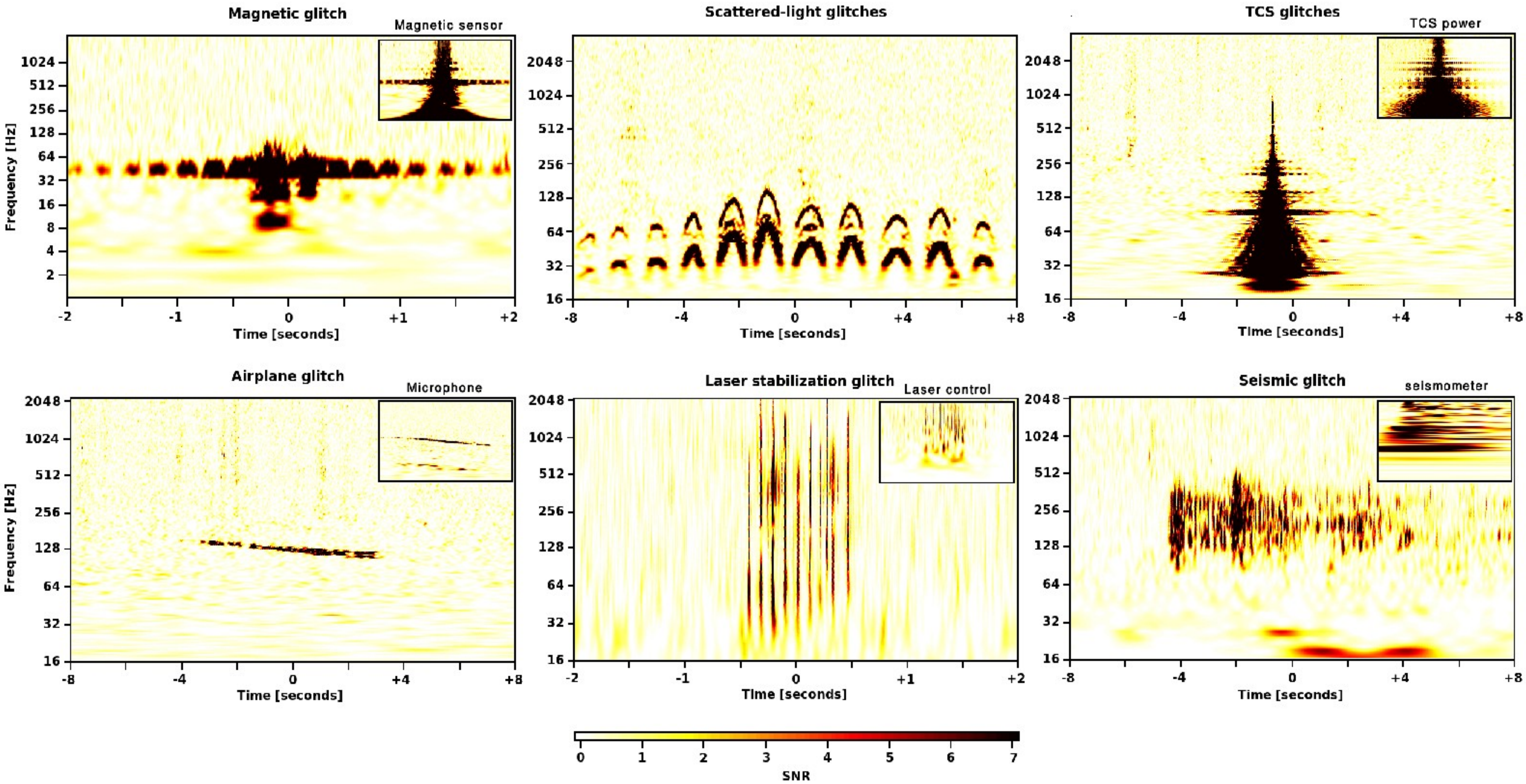
+ duration, bandwidth...

Triggers are saved to disk for further analysis

Transient triggers = glitches



Transient triggers = glitches



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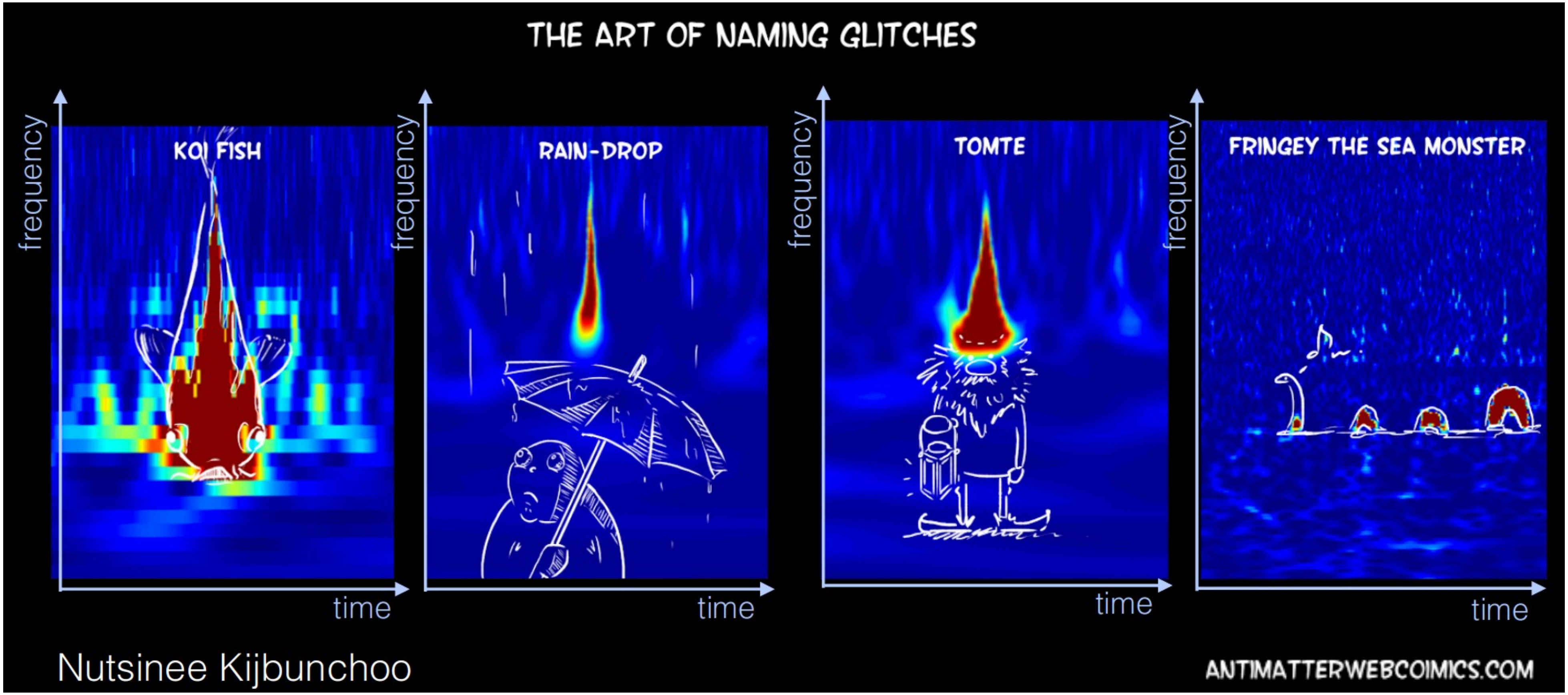
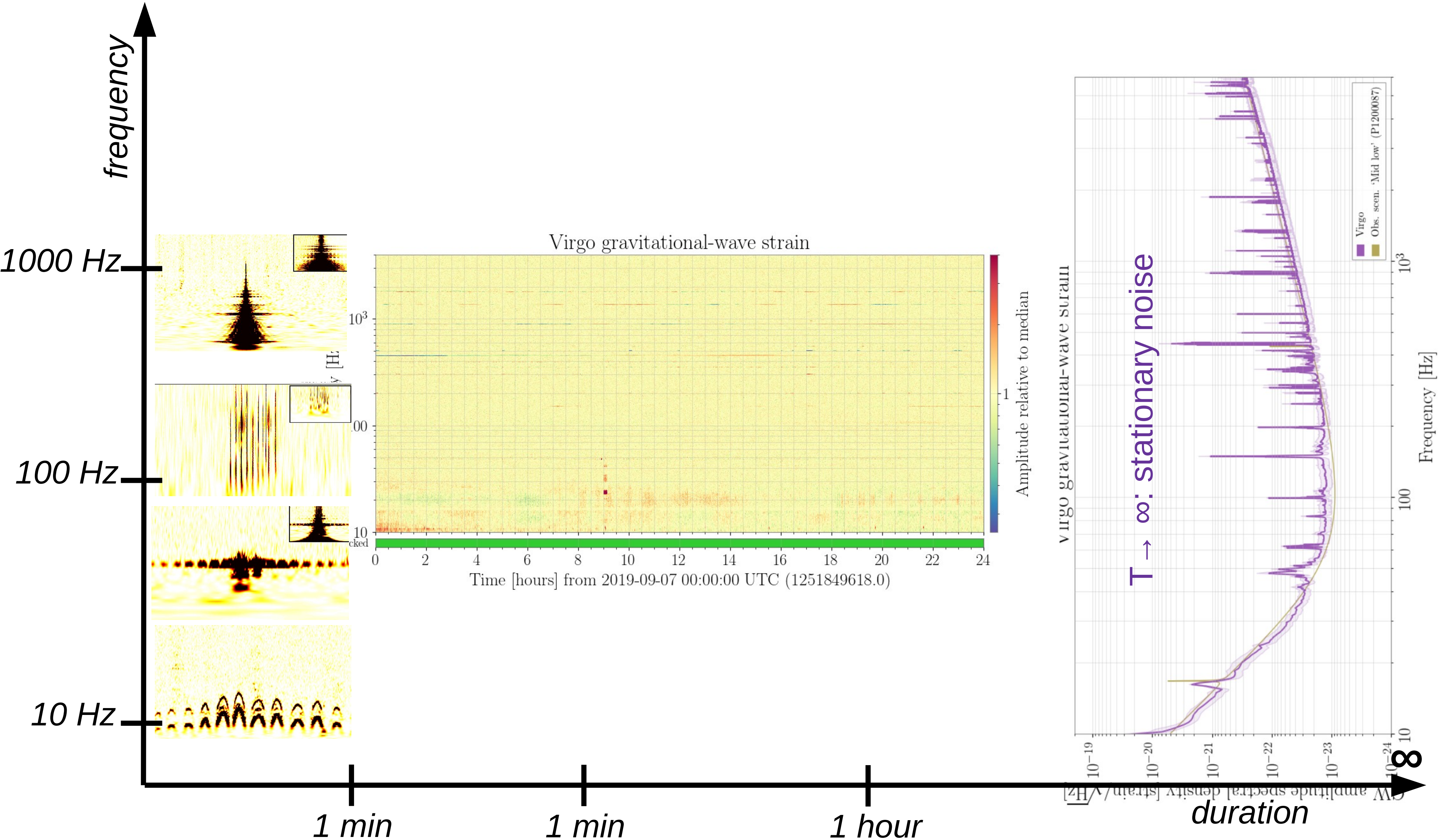
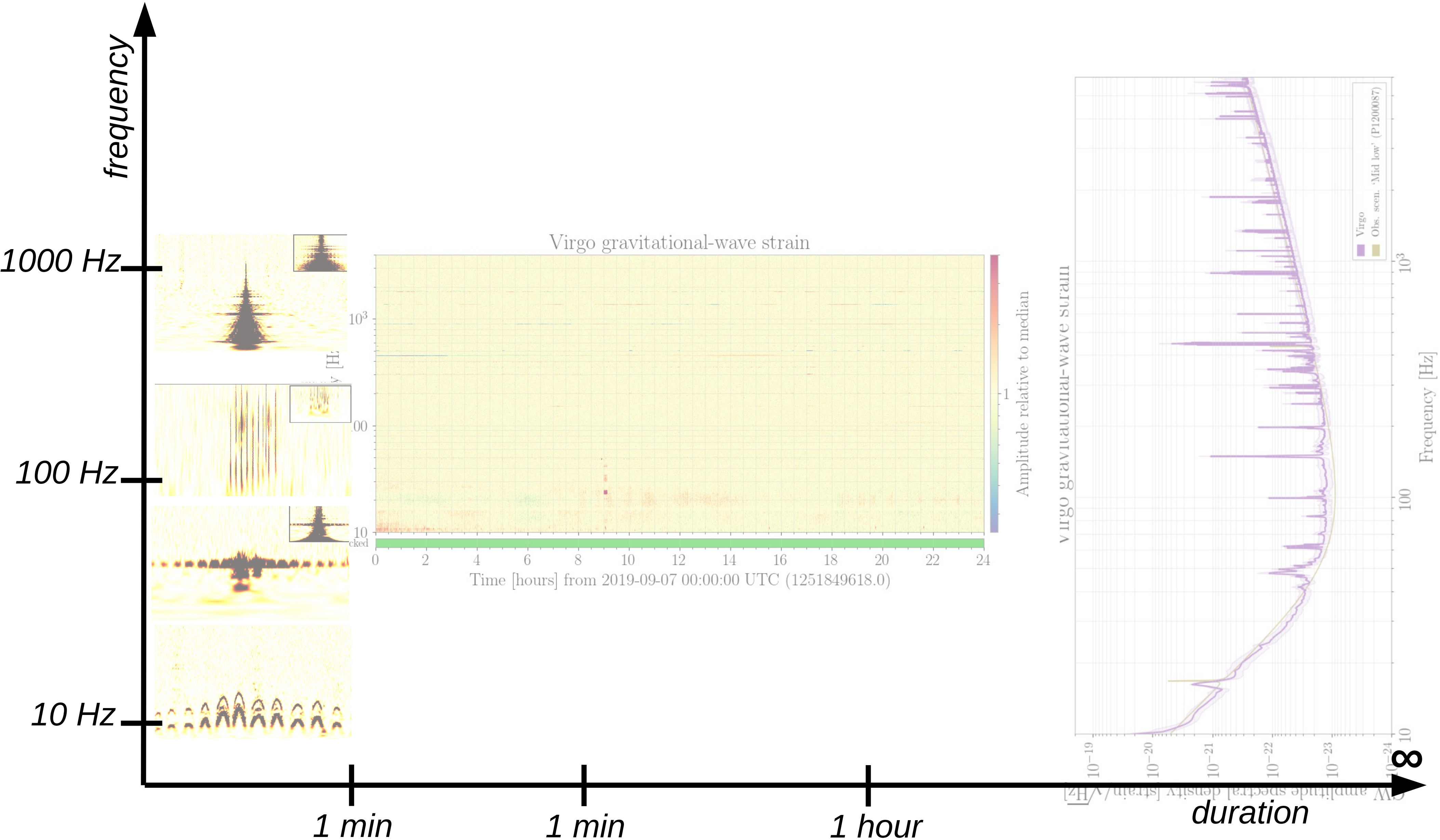


Noise summary

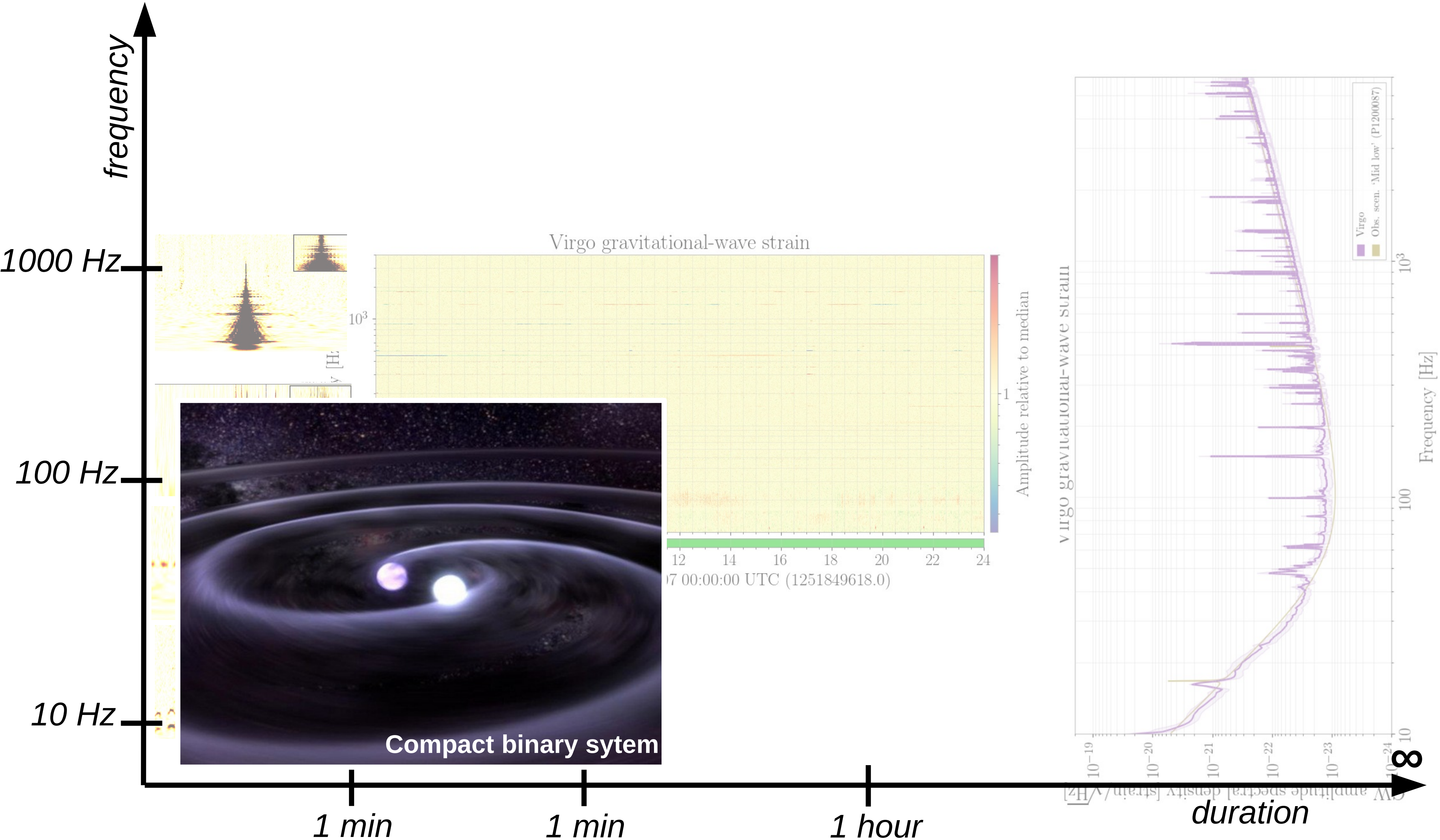


Gravitational-wave sources



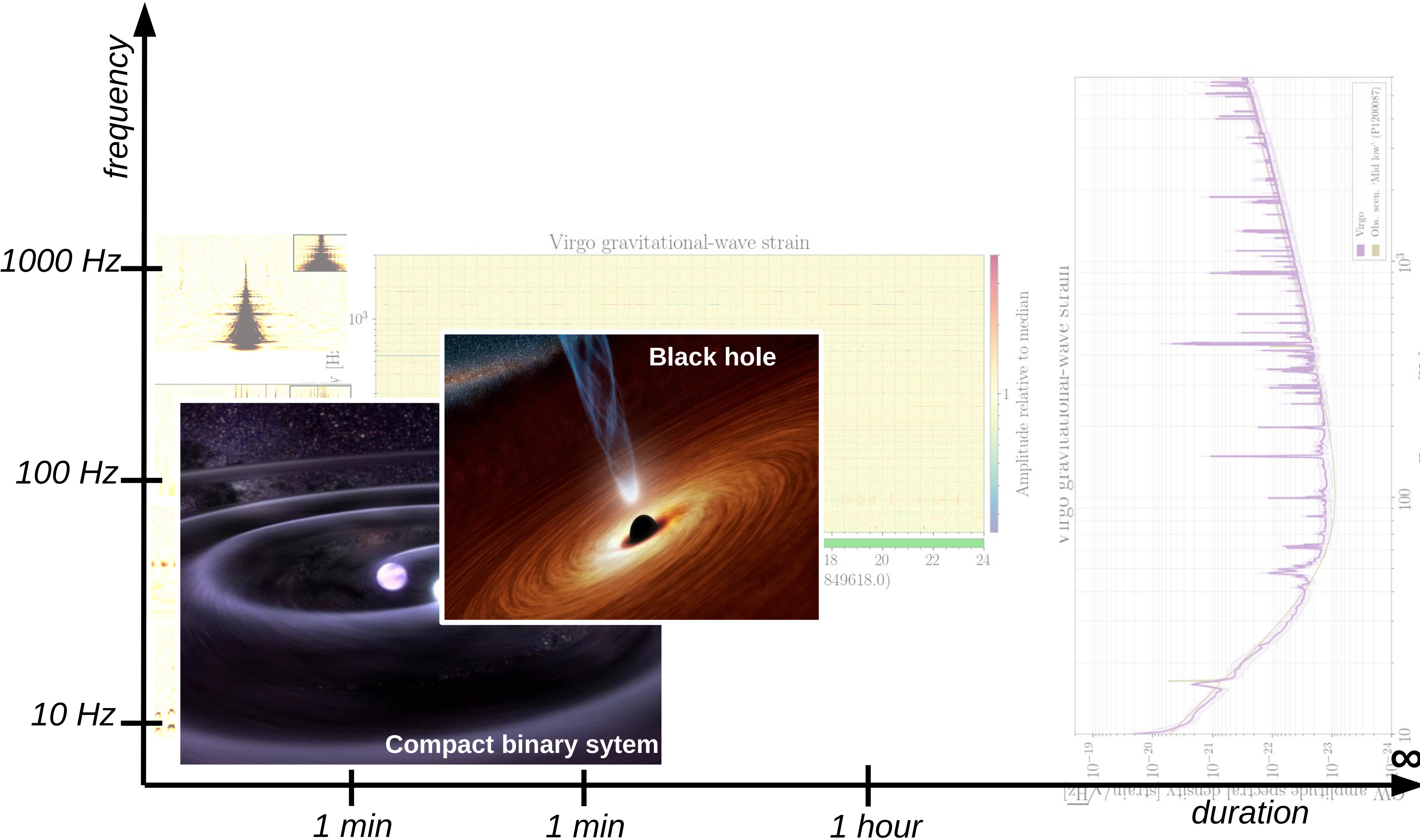
Gravitational-wave sources

Compact binary merger



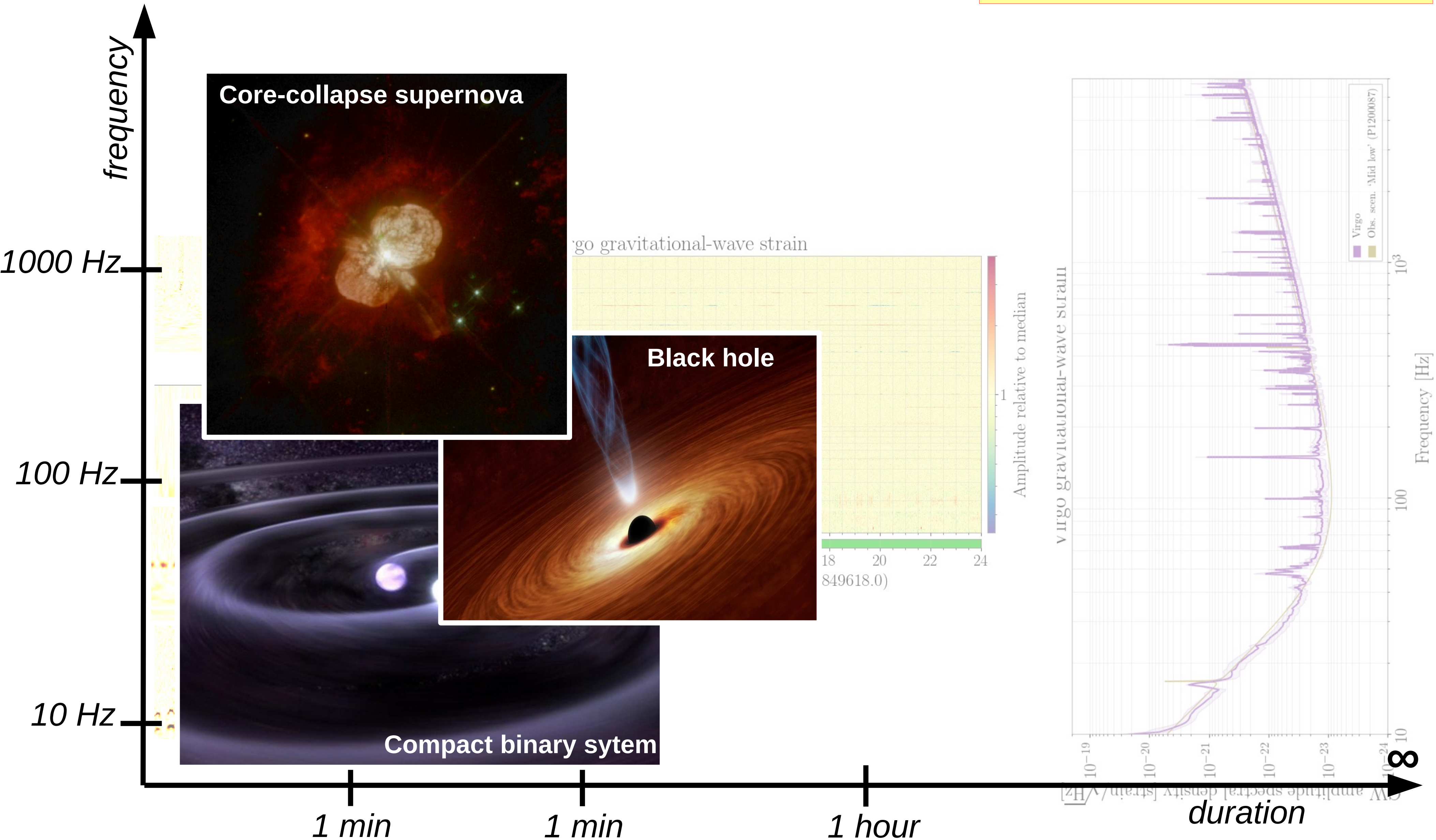
Gravitational-wave sources

Compact binary merger
Newly-formed black-holes



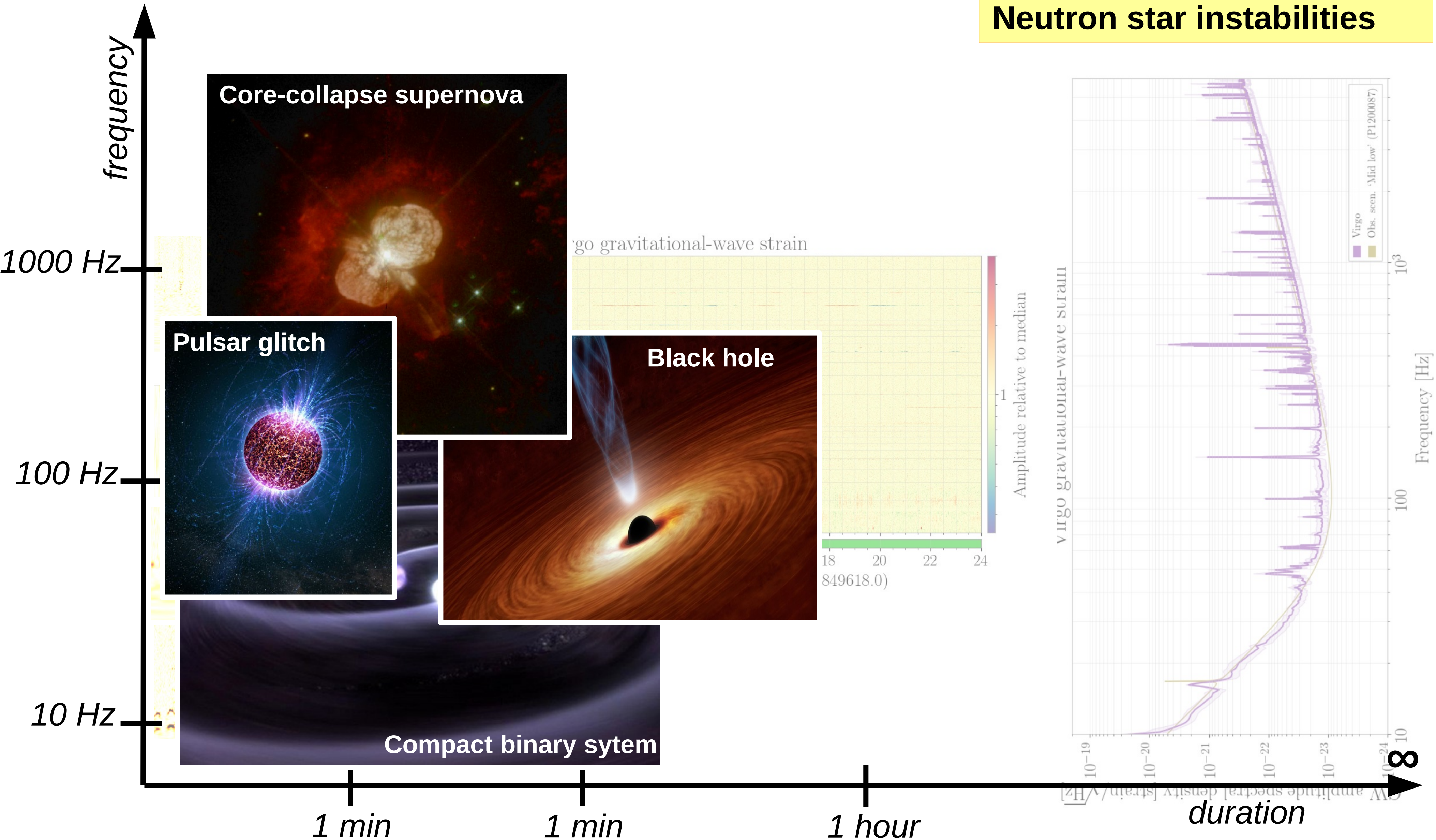
Gravitational-wave sources

Compact binary merger
Newly-formed black-holes
Core-collapse supernovae



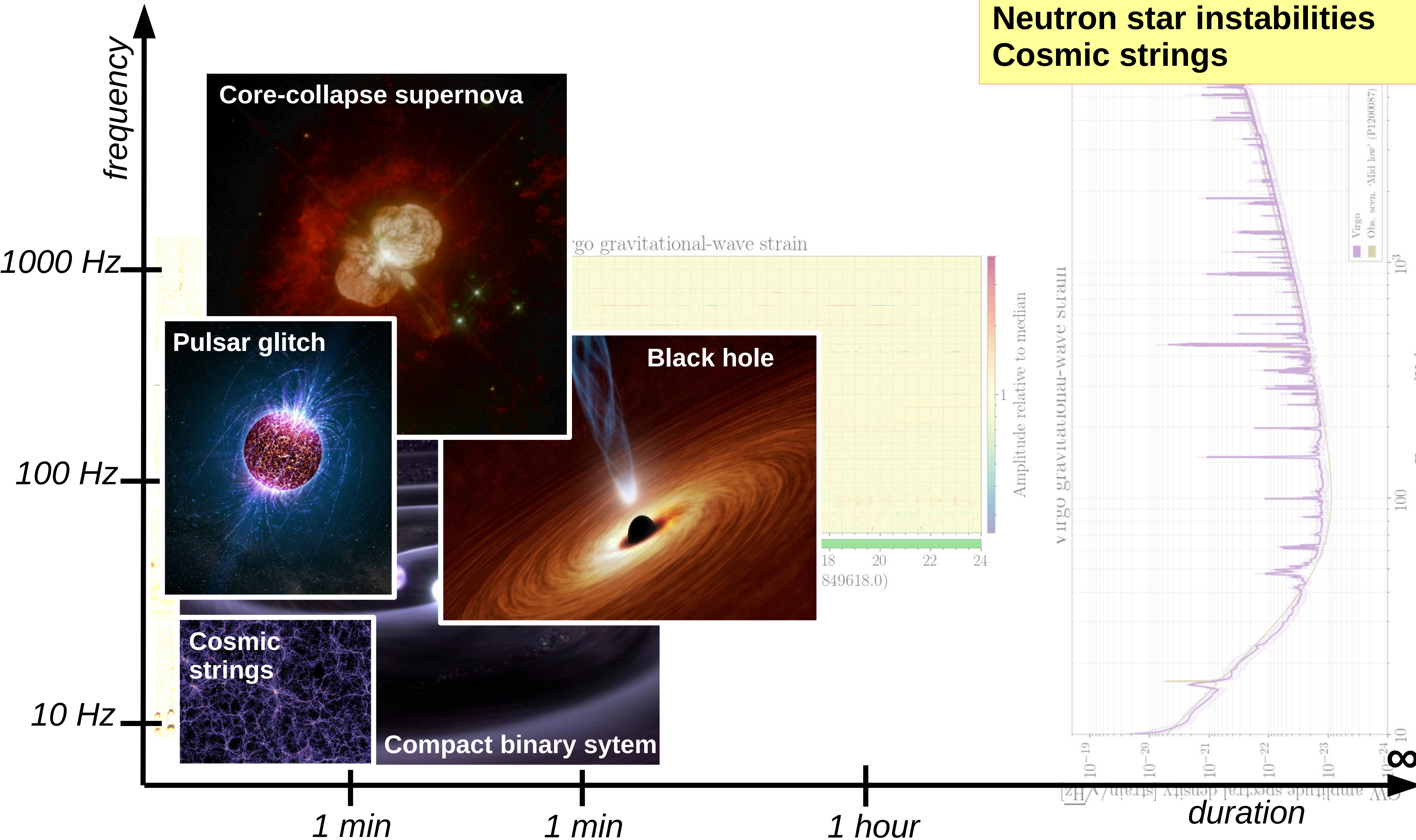
Gravitational-wave sources

Compact binary merger
Newly-formed black-holes
Core-collapse supernovae
Neutron star instabilities

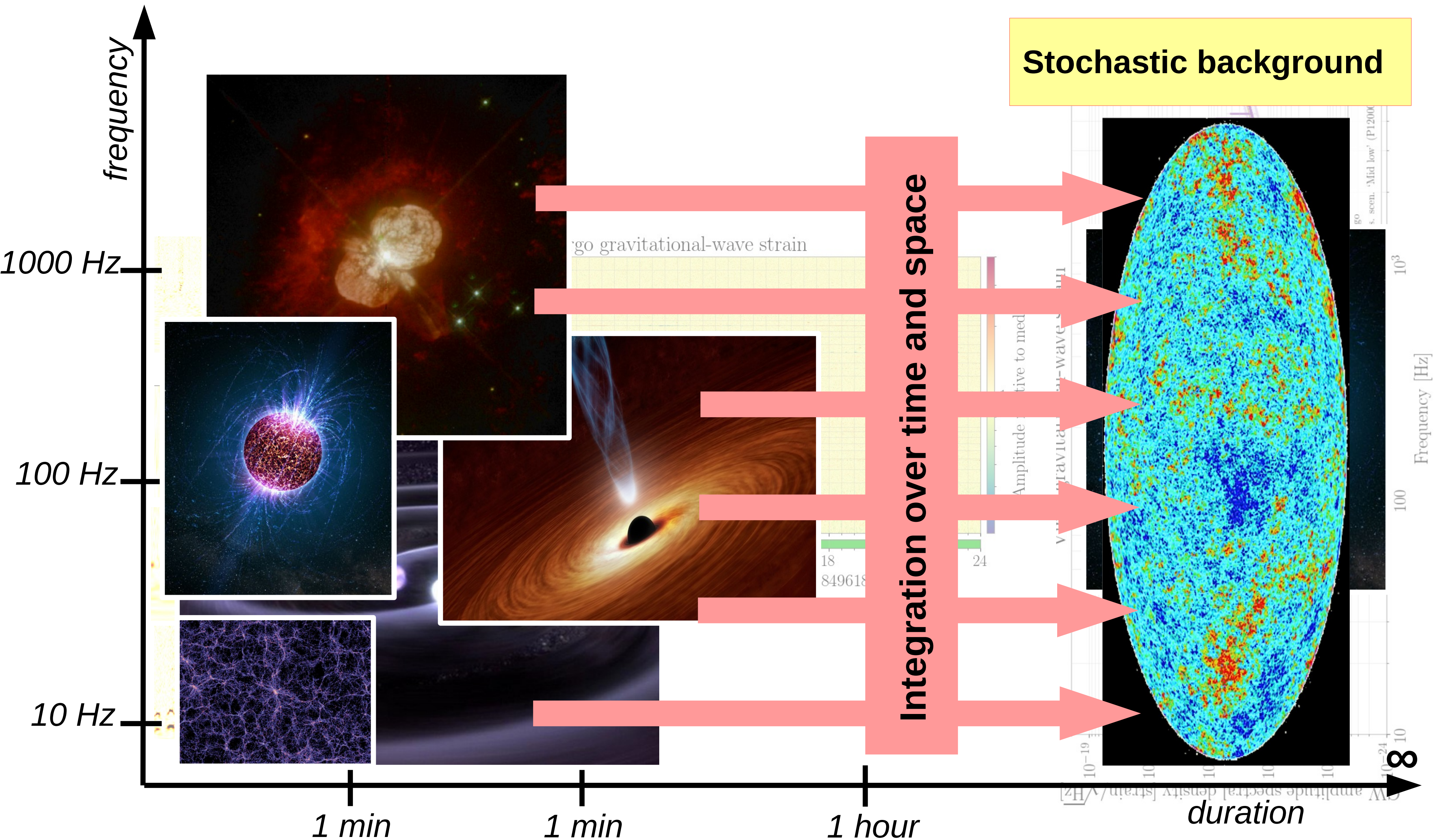


Gravitational-wave sources

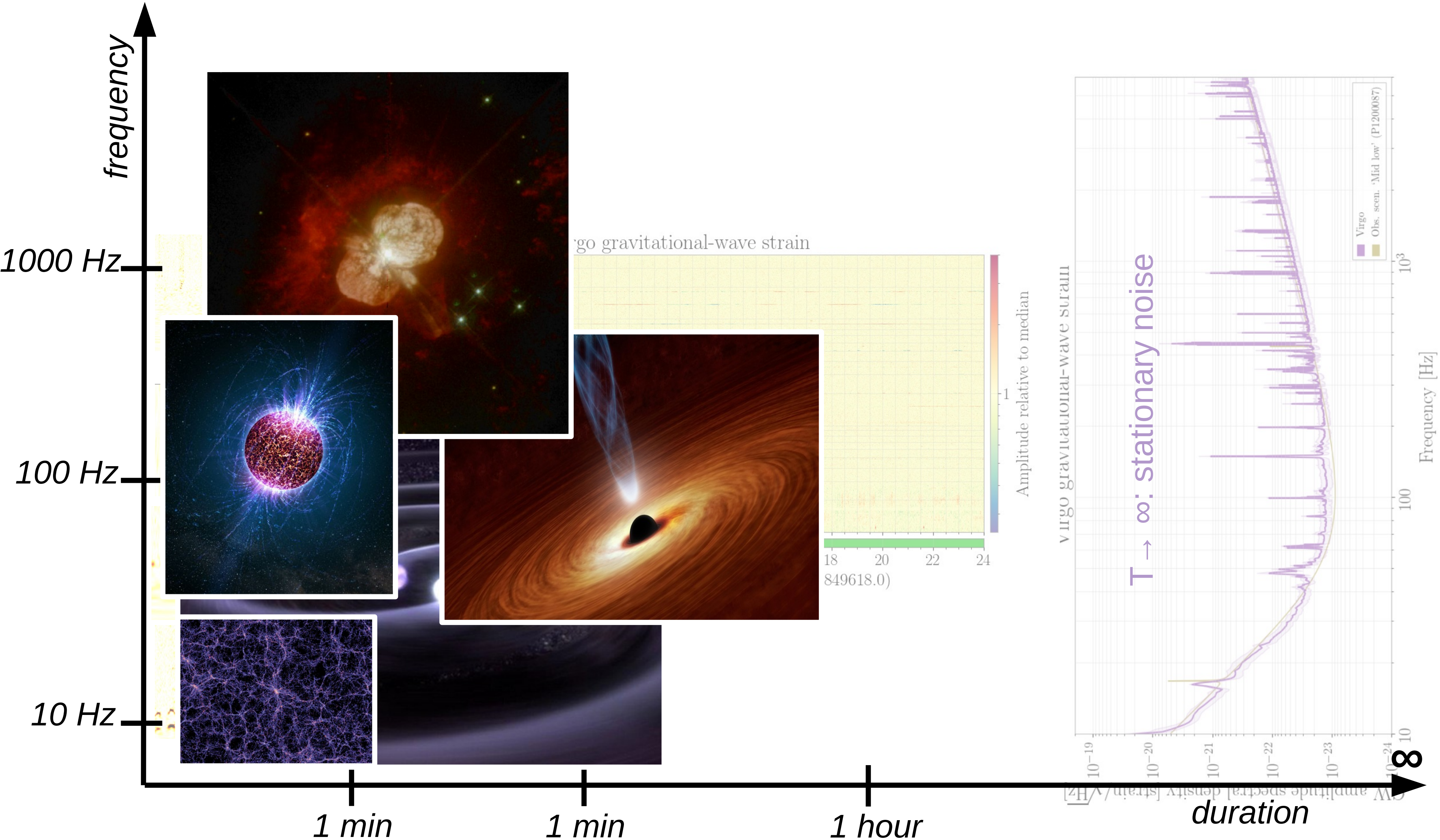
Compact binary merger
Newly-formed black-holes
Core-collapse supernovae
Neutron star instabilities
Cosmic strings



Gravitational-wave sources



Transient gravitational waves



Transient gravitational waves

Burst searches

→ Compact binary merger
 – for low-mass systems, less sensitive than a template search
 – signal reconstruction → deviation from GR

→ Core-collapse supernovæ
 – iconic burst source
 – different GW signatures (rotating core collapse / neutrino-driven SN)
 – model/simulation are incomplete
 – use ad-hoc models (damped sine, white-noise burst)

→ Pulsar glitches
 – cause is unclear: crust fragmentation, stellar interior dynamic

→ Cosmic strings
 – simple waveform model → template search

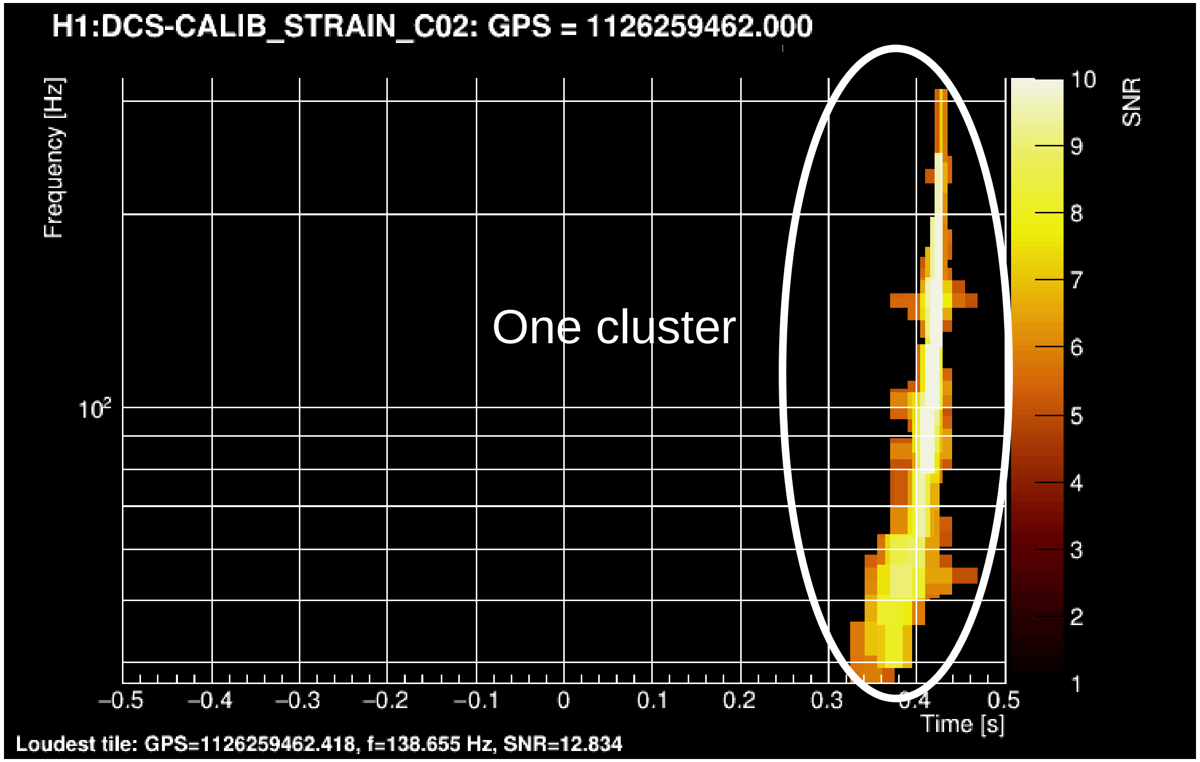
Goals

1/ make a detection
2/ reconstruct the waveform
3/ extract the source parameters

Transient gravitational waves

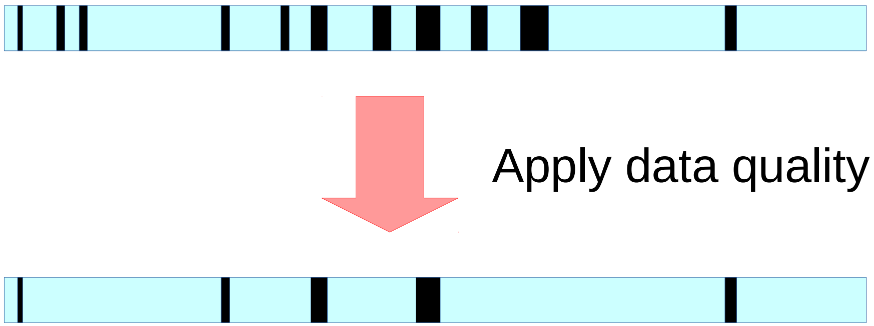
Burst searches

→ Several search pipelines were developed, all of them based on time-frequency analysis



How to separate a true signal from a glitch?

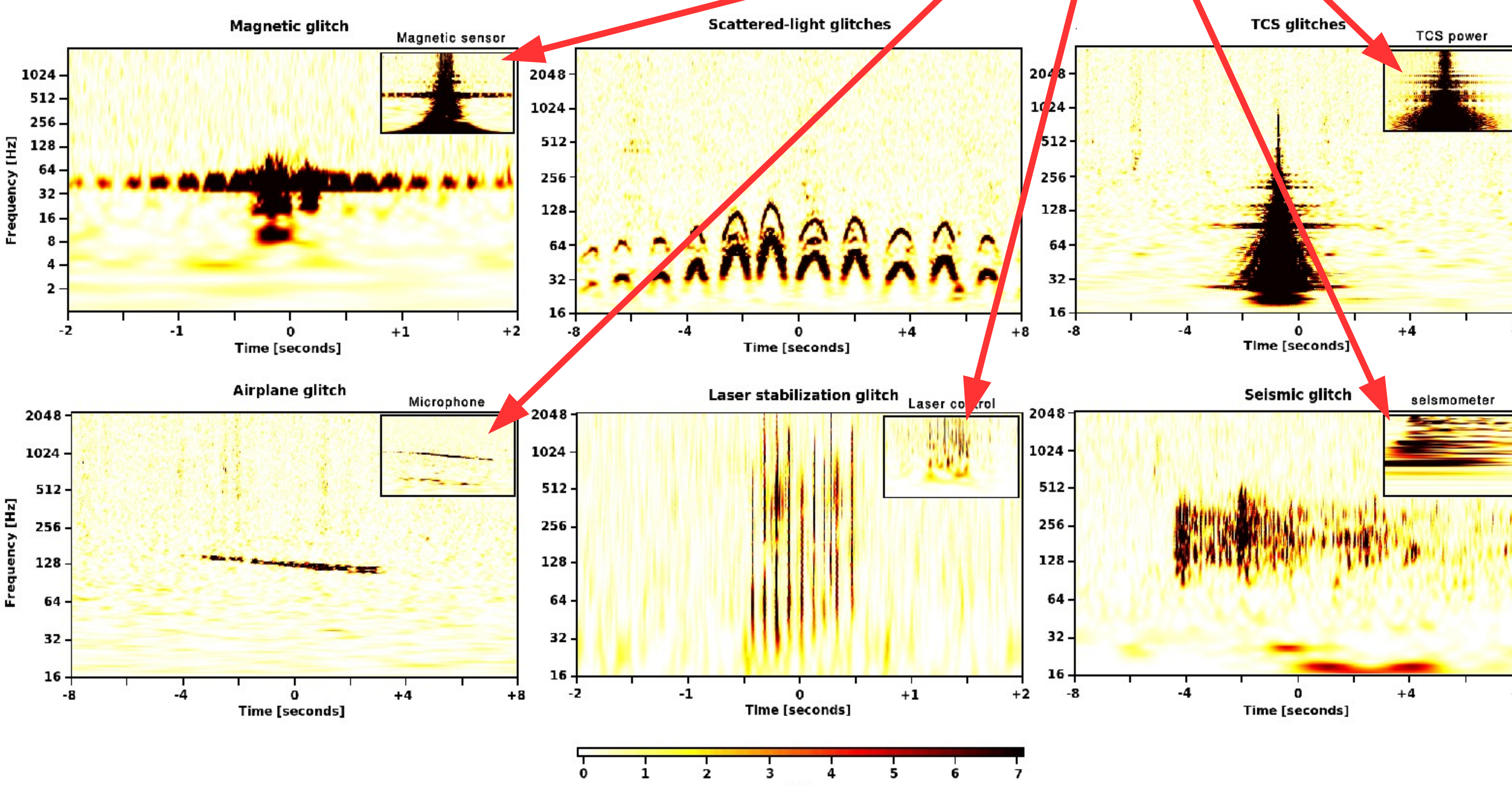
Background reduction



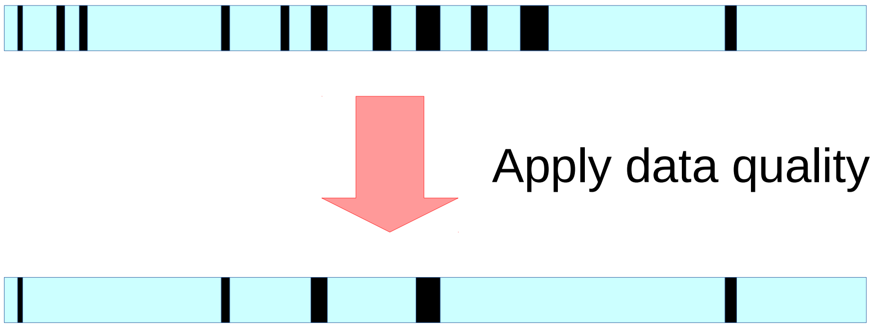
Pipeline triggers

Apply data quality vetoes based on noise investigation

Auxiliary channels are used to witness transient noise and veto the resulting events



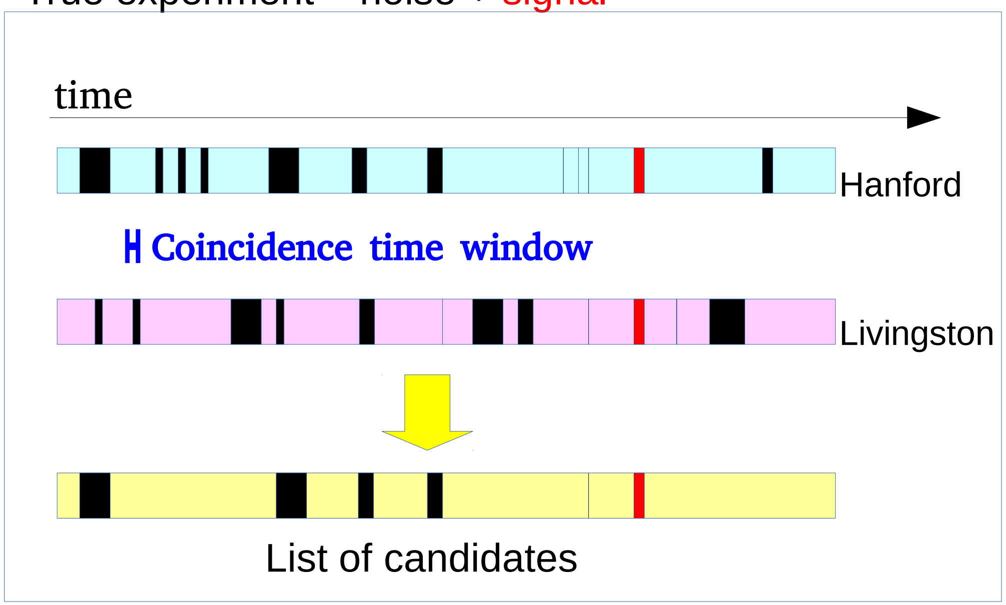
Background reduction



Pipeline triggers

Apply data quality vetoes based on noise investigation

True experiment = noise + signal

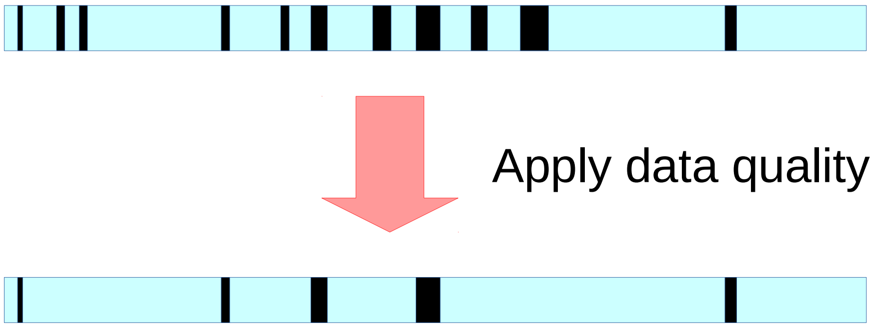


Coincidence between detectors

Coincidence rate:

$$R_{coinc} \sim R_H R_L \Delta t_{win}$$
$$\sim (1\,Hz) \times (1\,Hz) \times (10^{-2}\,s) = 10^{-2}\,Hz$$

Background estimation



Pipeline triggers

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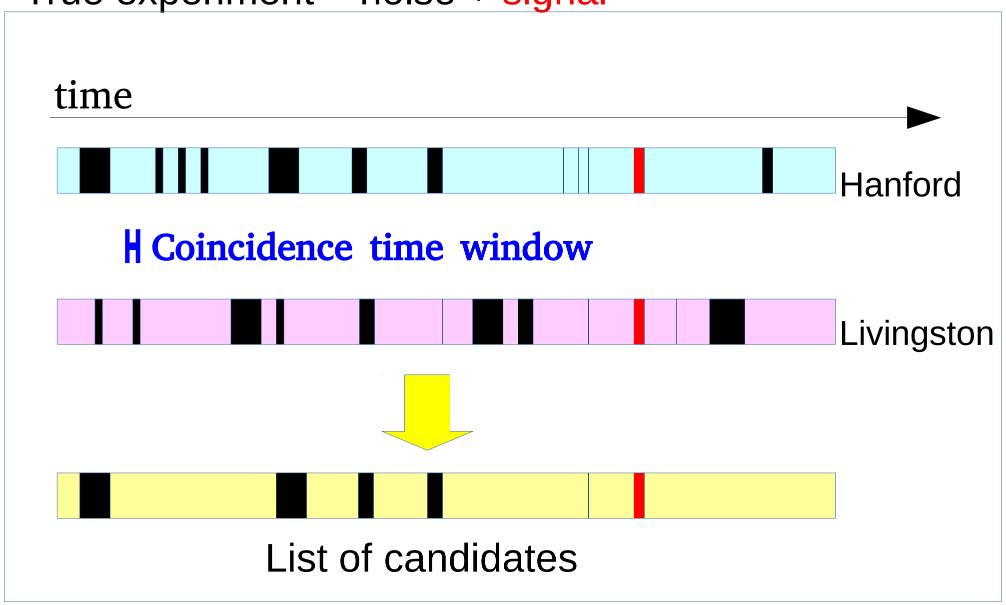
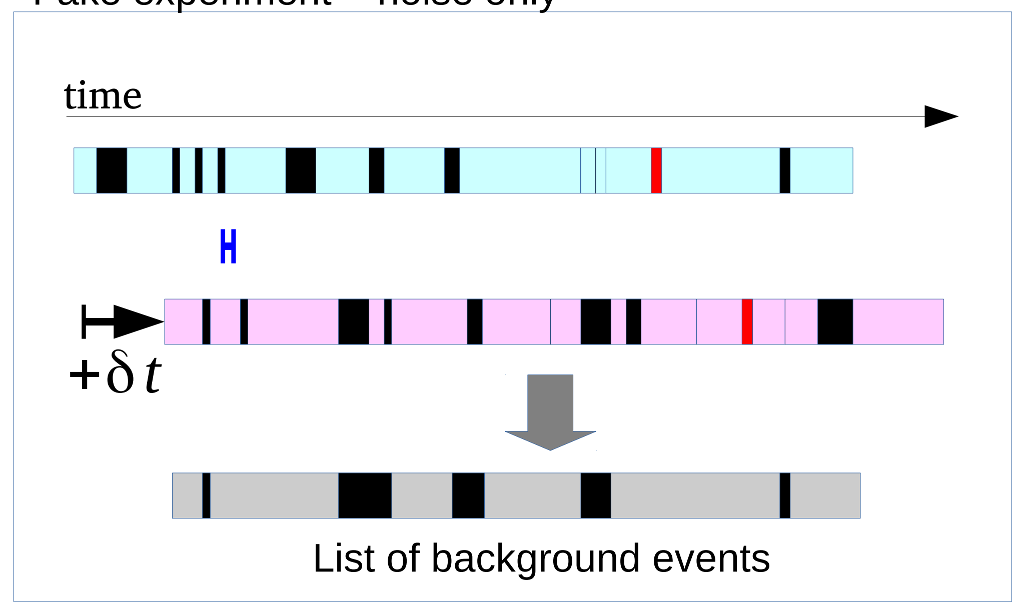


Fake experiment = noise only

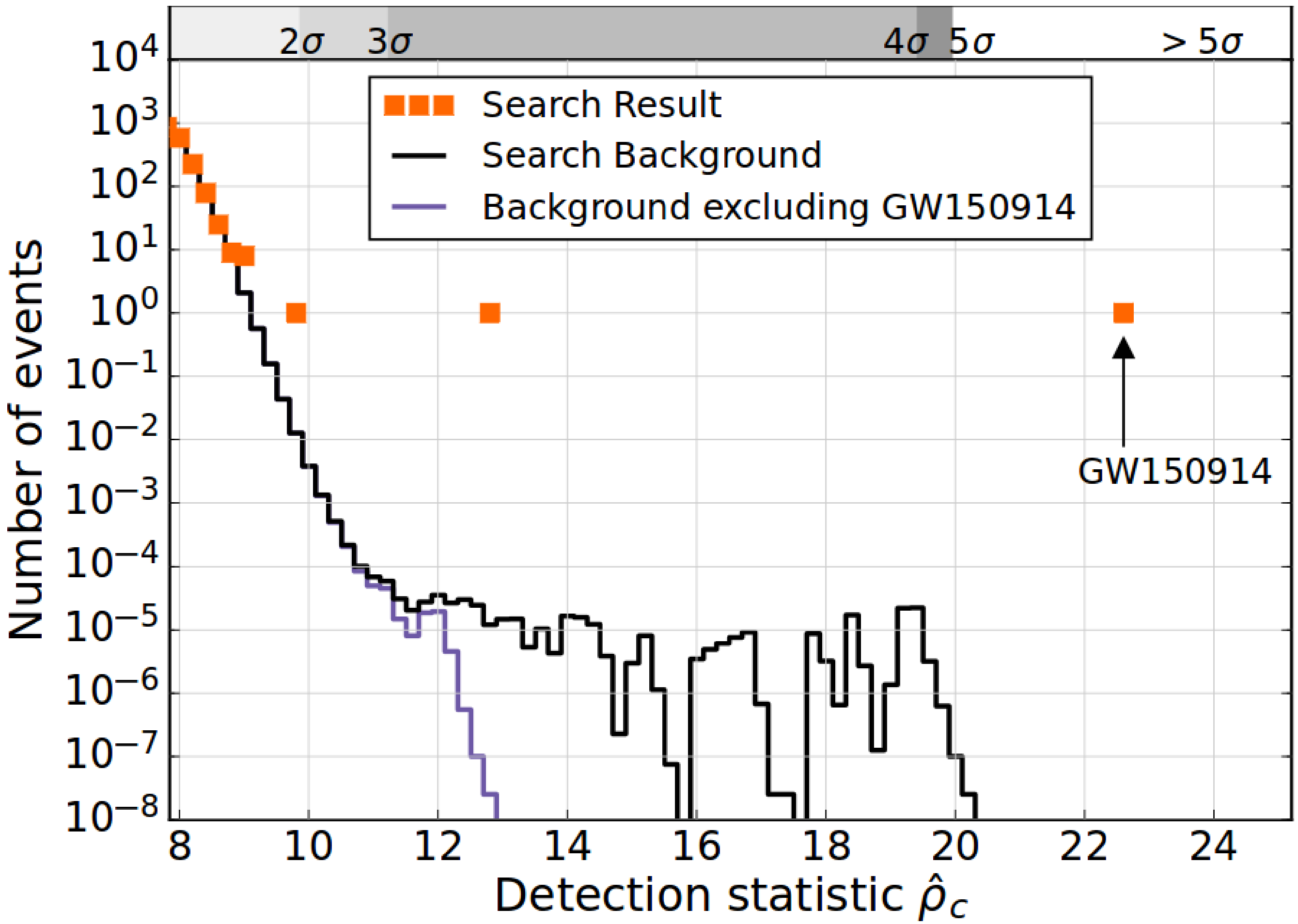


Coincidence rate:

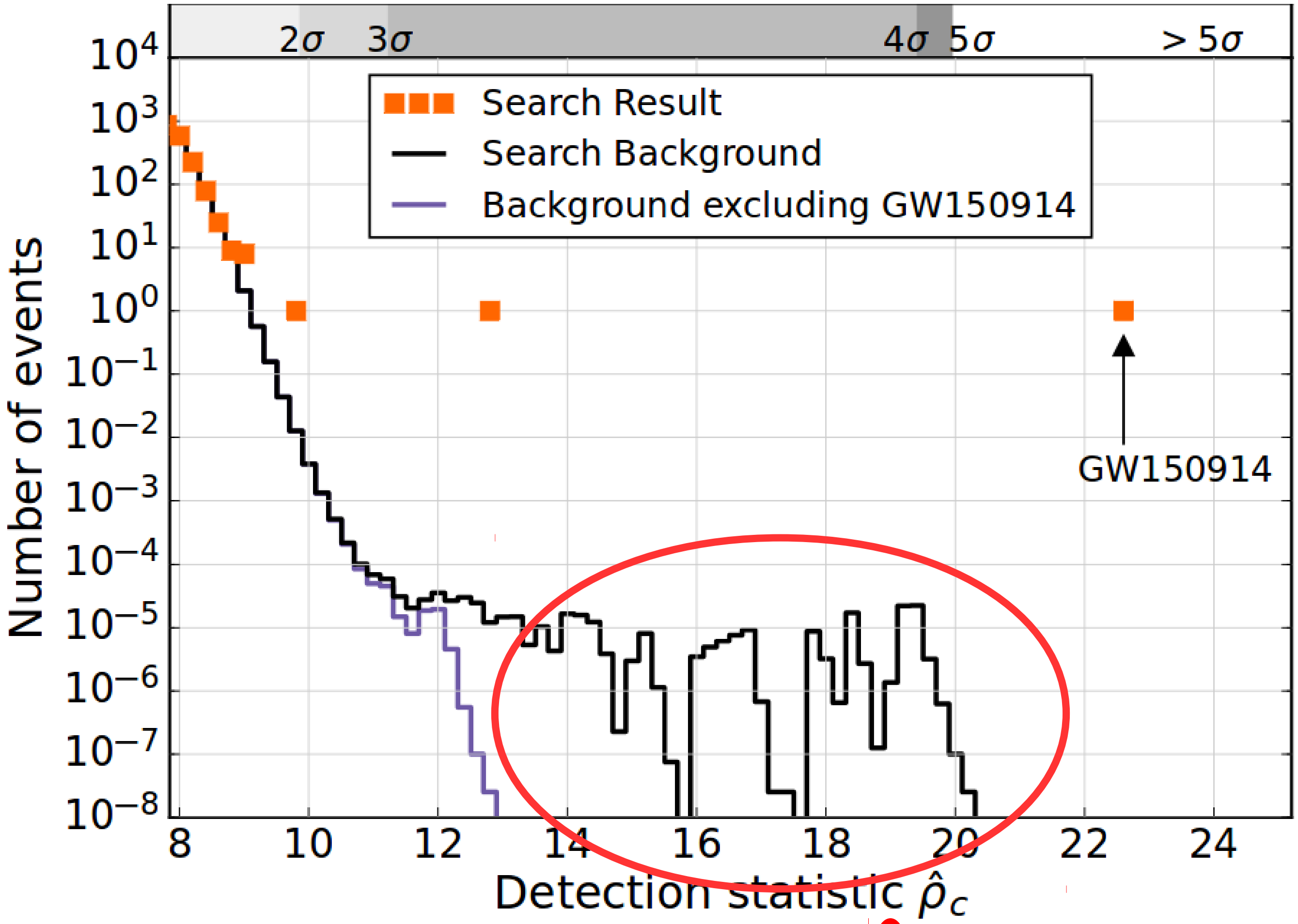
$$R_{coinc} \sim R_H R_L \Delta t_{win}$$
$$\sim (1\,Hz) \times (1\,Hz) \times (10^{-2}\,s) = 10^{-2}\,Hz$$

A very large number of fake experiments can be simulated using multiple offsets O(1,000,000)

Background & detection

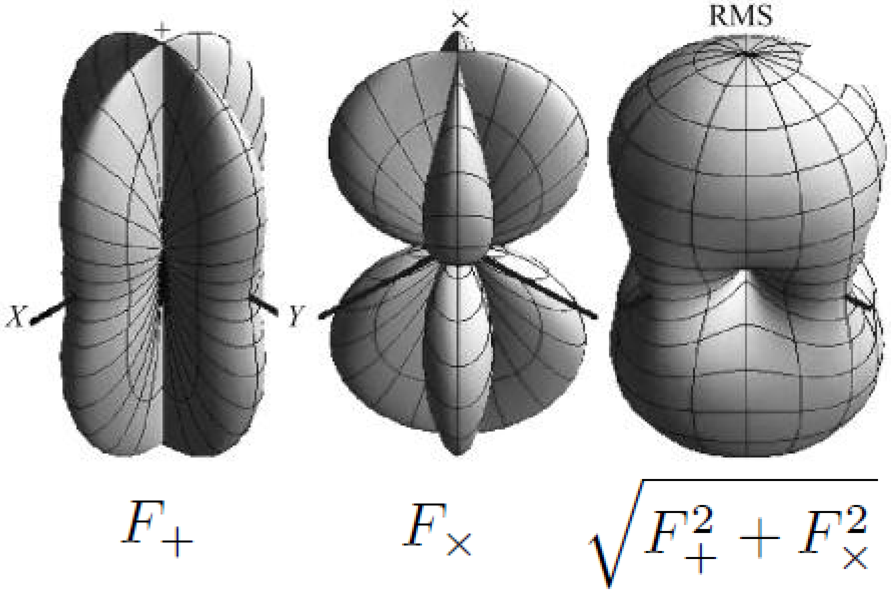


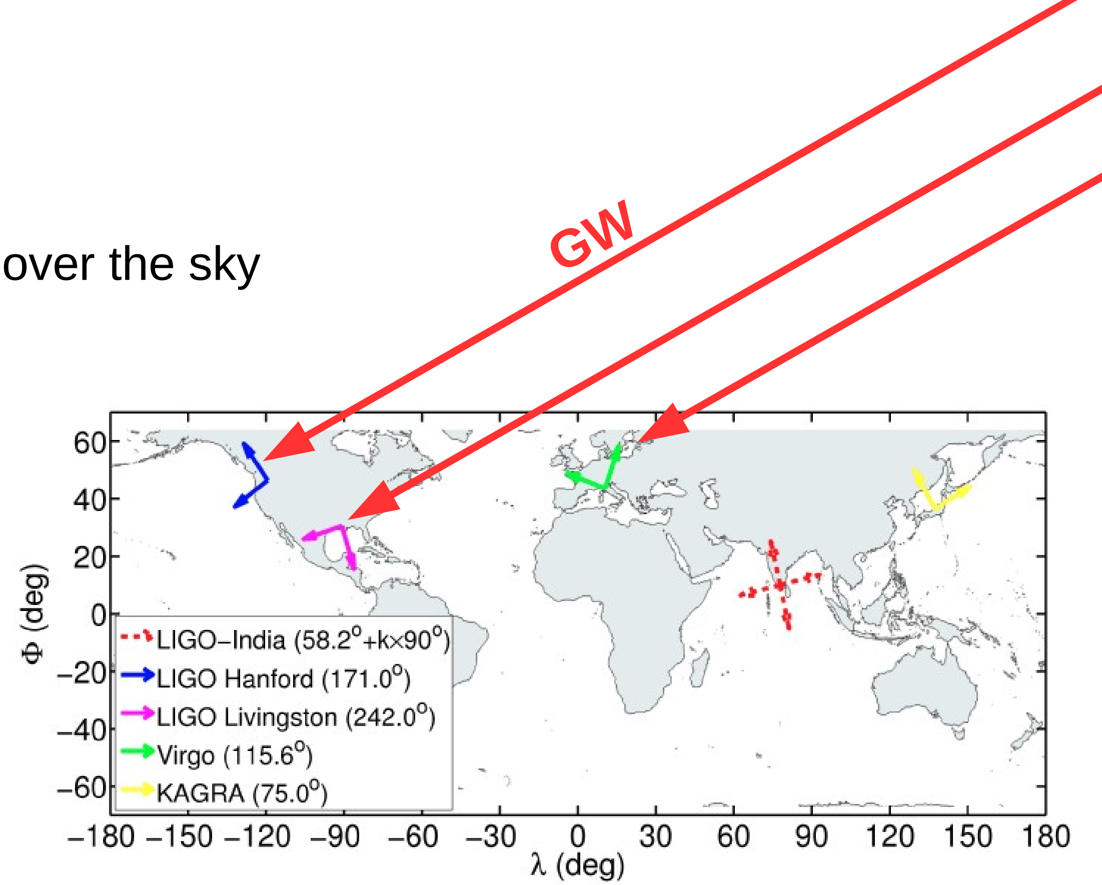
Background & detection



Coherent search

The sensitivity of the detector is not uniform over the sky





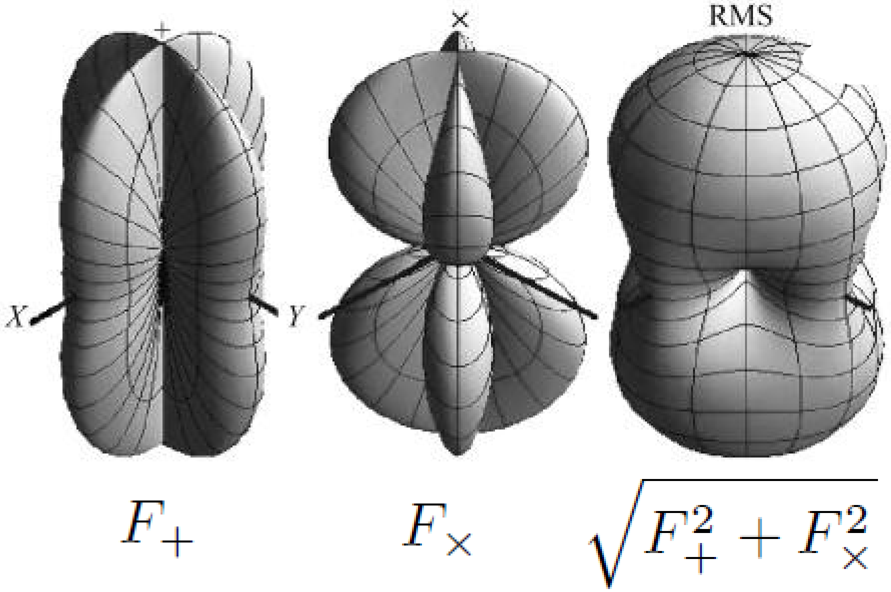
$$GW(t) = F_+(t, ra, dec, \Psi) \times h_+(t) + F_x(t, ra, dec, \Psi) \times h_x(t)$$

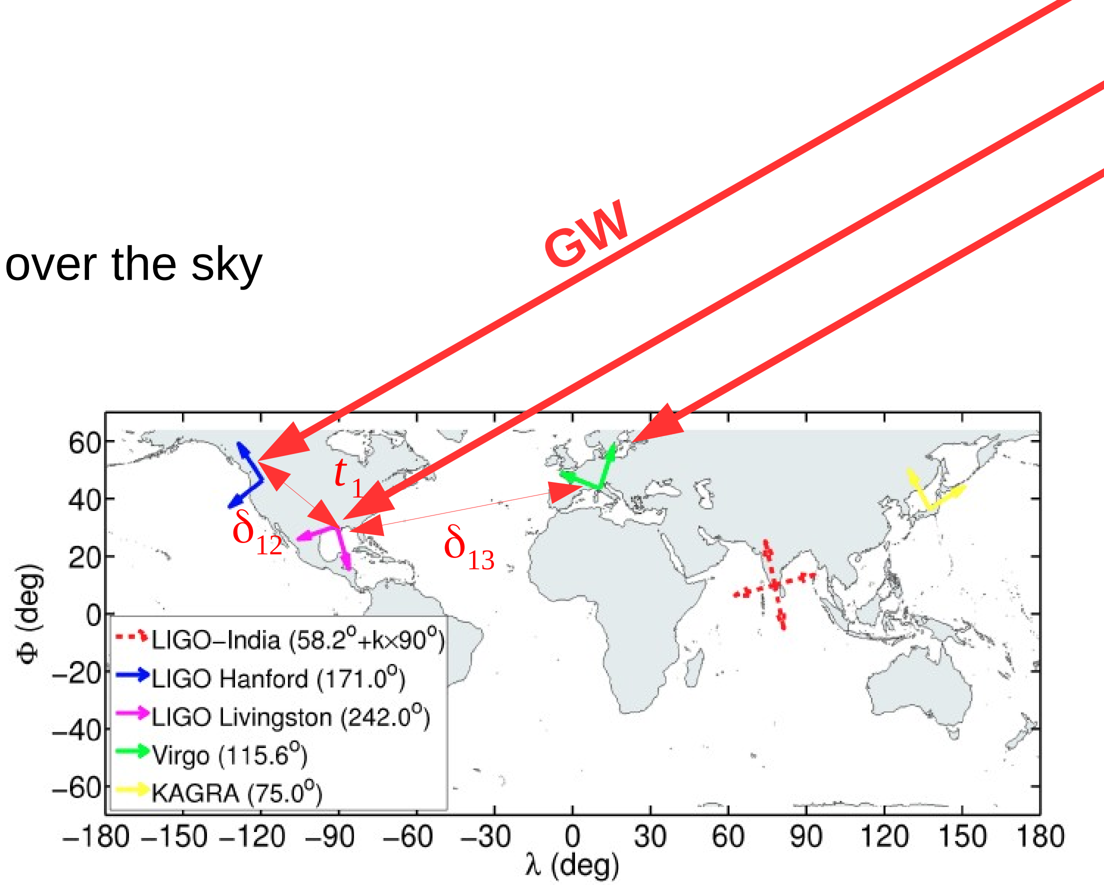
Source position — Source polarization angle

The signal is coherent between detectors, the noise is generally not

Coherent search

The sensitivity of the detector is not uniform over the sky





$$GW_1(t_1) = F_{+1}(t_1, ra, dec, \Psi) \times h_+(t_1) + F_{\times 2}(t_1, ra, dec, \Psi) \times h_\times(t_1)$$

$$GW_2(t_2) = F_{+2}(t_2, ra, dec, \Psi) \times h_+(t_2) + F_{\times 2}(t_2, ra, dec, \Psi) \times h_\times(t_2)$$

$$GW_3(t_3) = F_{+3}(t_3, ra, dec, \Psi) \times h_+(t_3) + F_{\times 3}(t_3, ra, dec, \Psi) \times h_\times(t_3)$$

$$\Rightarrow GW_1(t_1) + GW_2(t_1 + \delta_{12}) + GW_3(t_1 + \delta_{13})$$

Coherent search

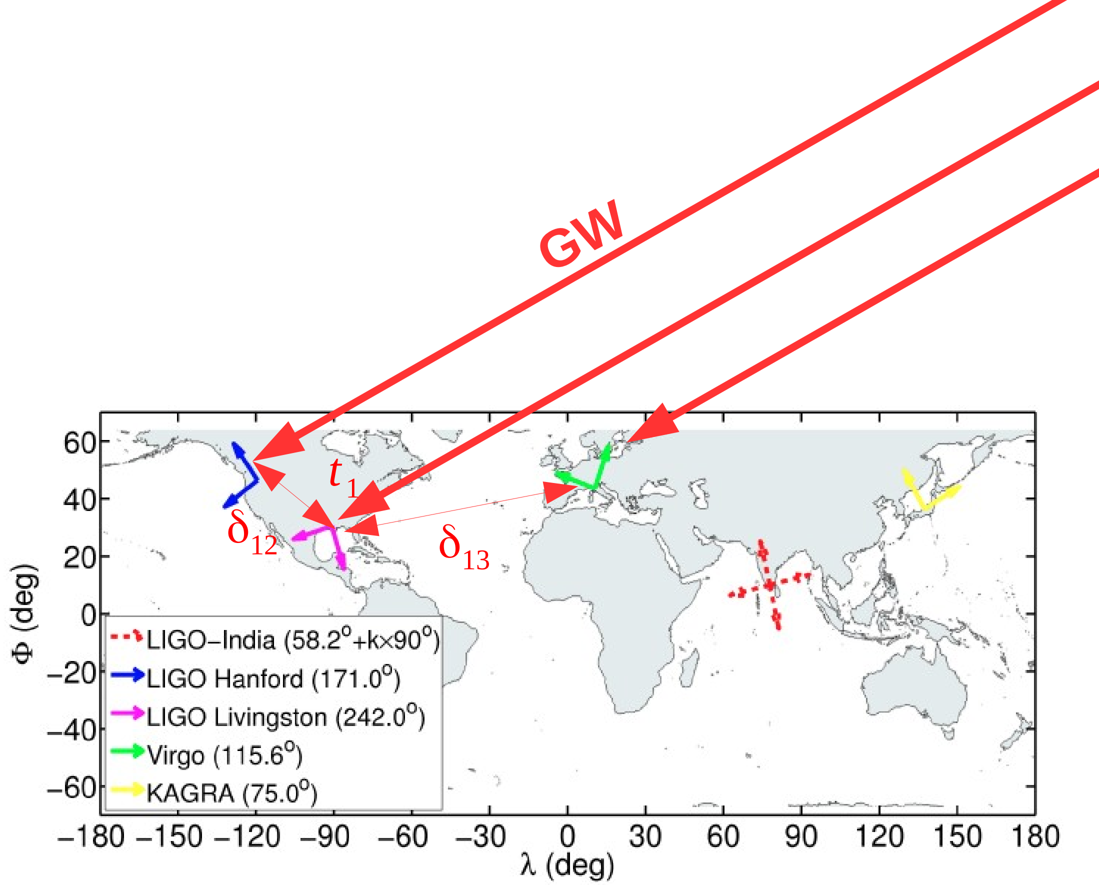
A coherent data stream is considered:

$$h_{coh} = h_1(t) + h_2(t+\delta_{12}) + h_3(t+\delta_{13})$$

The times of arrival are unknown:

$$|\delta_{12}| < \delta_{12}^{max} (=10\,ms) \quad |\delta_{13}| < \delta_{13}^{max} (=27\,ms)$$

Multiple values of δ must be tested
such that the coherent SNR is maximized



→ To optimize the computing, the coherent burst pipeline time-shifts time-frequency maps

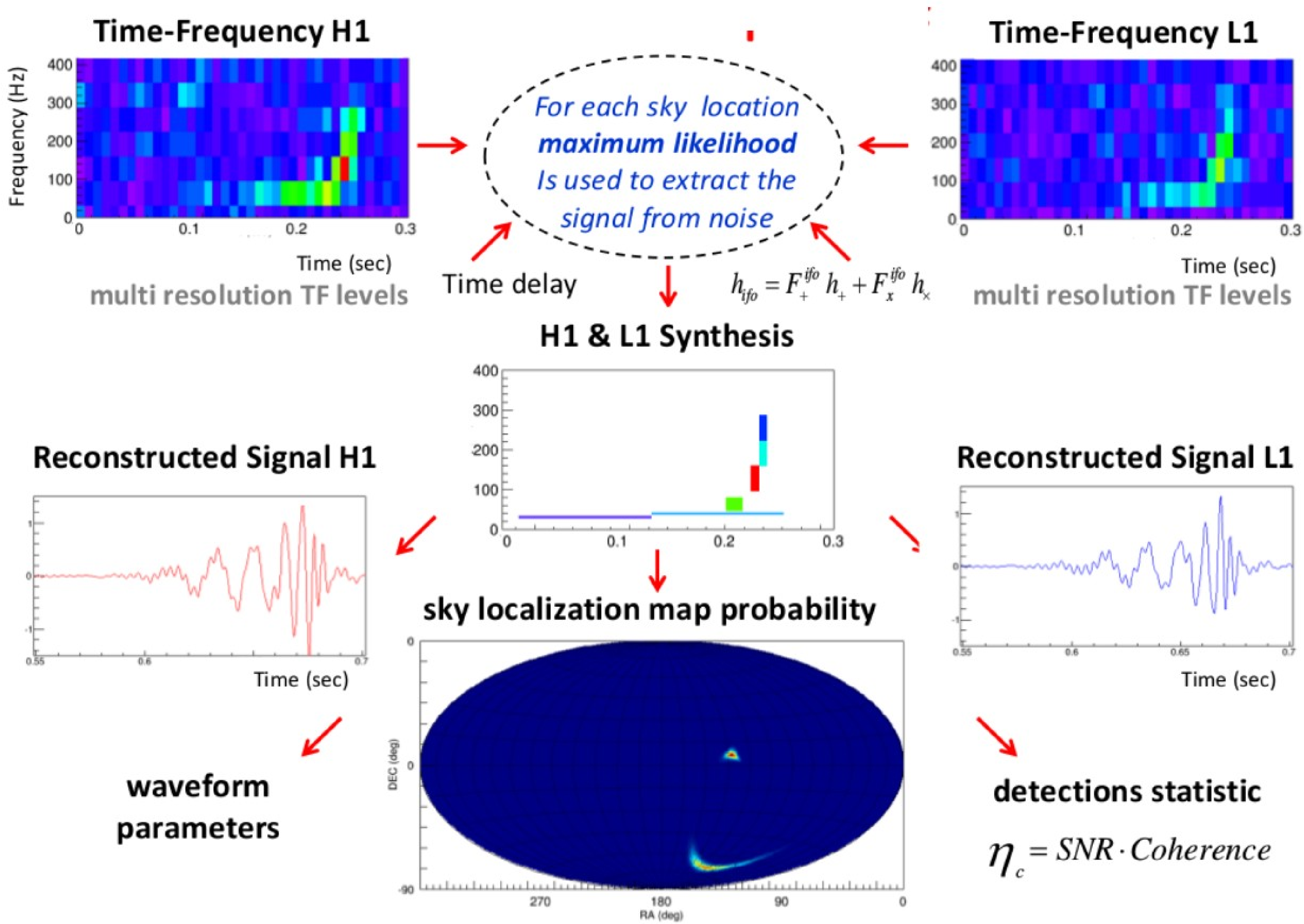
→ Maximum-likelihood-ratio method

→ Null data stream to reject spurious events

→ The network sensitivity is not limited by the least sensitive detector

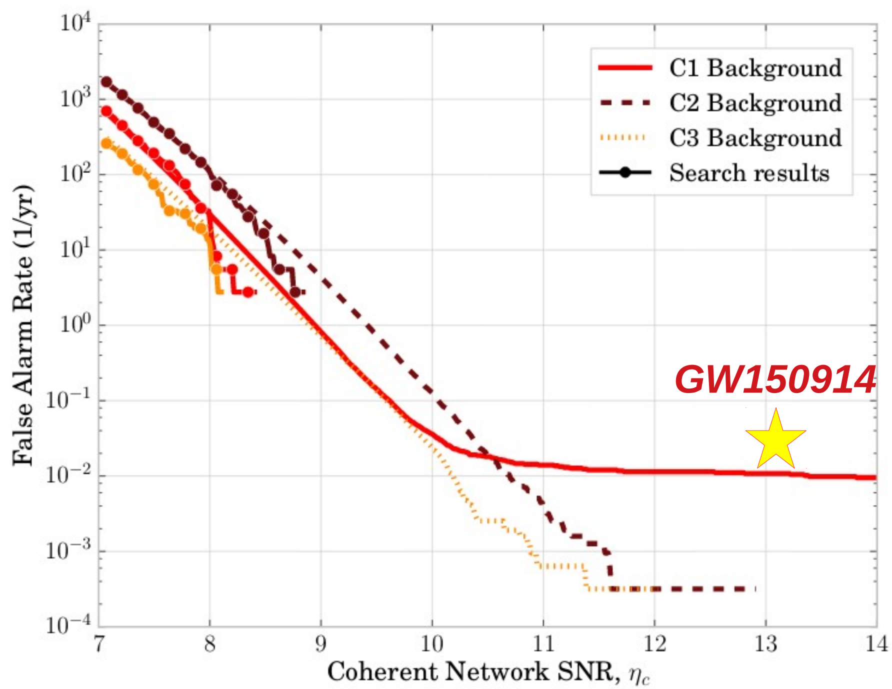
→ Source location is reconstructed

Coherent-wave burst pipeline

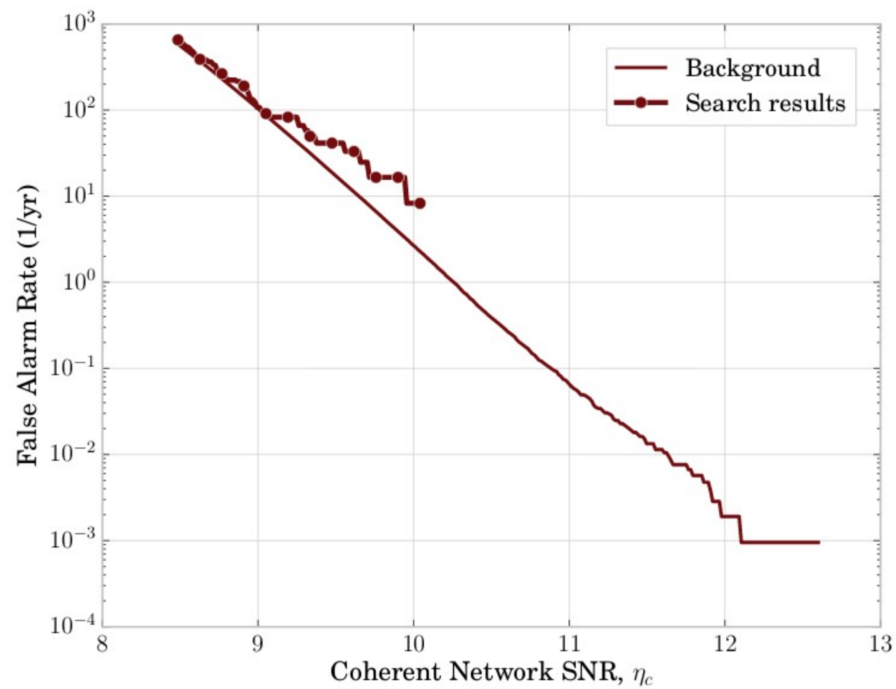


Coherent search results (O1)

C1: low-Q events (short-duration & wide-band)
C3: events for which the frequency increases with time
C2: any other events

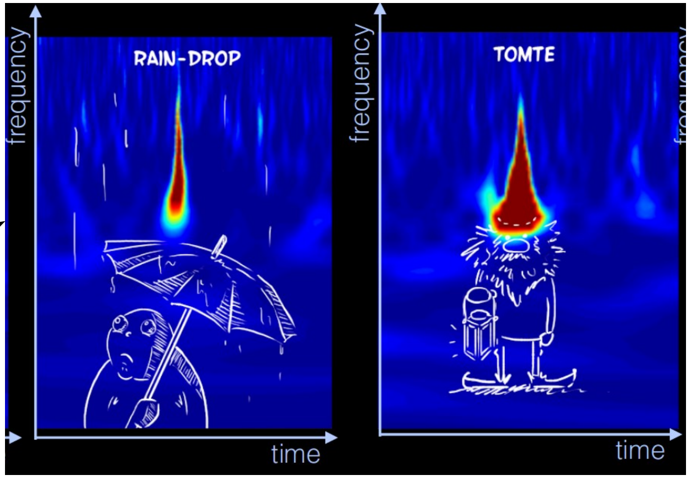


f < 1024 Hz



f > 1024 Hz

Coherent search results (O1)



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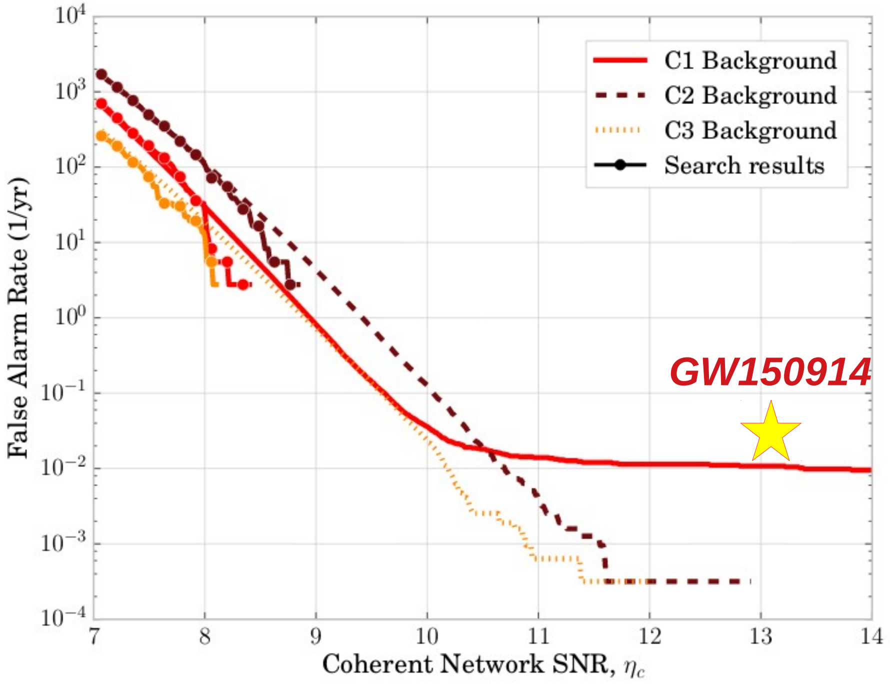
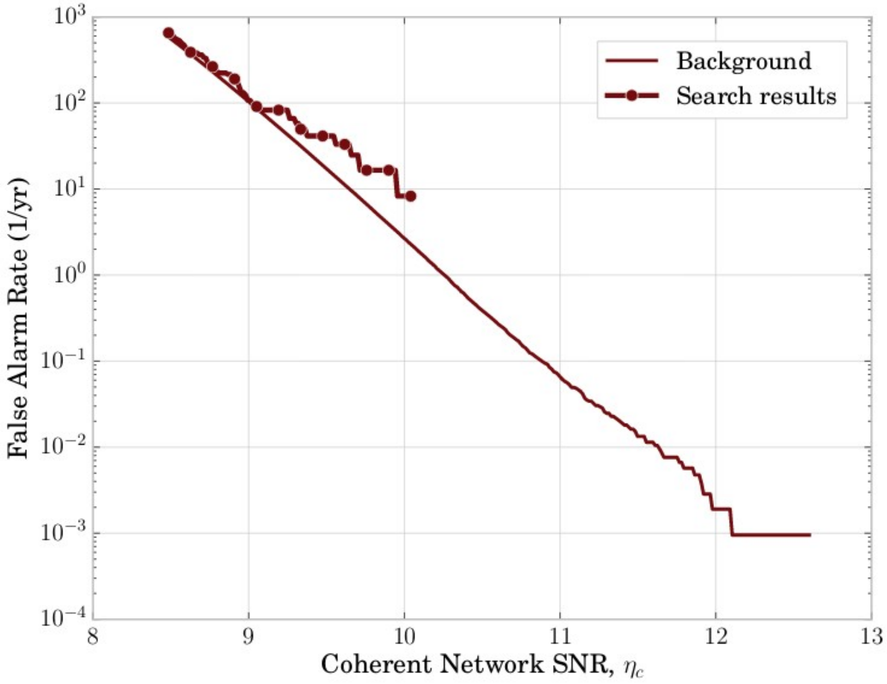
C2: any other events



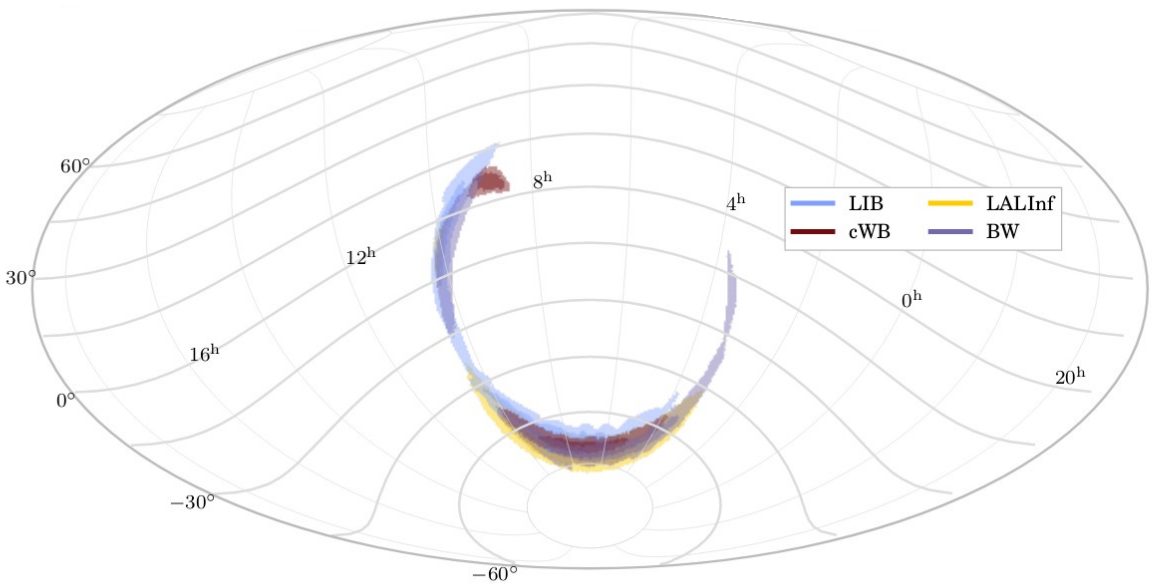


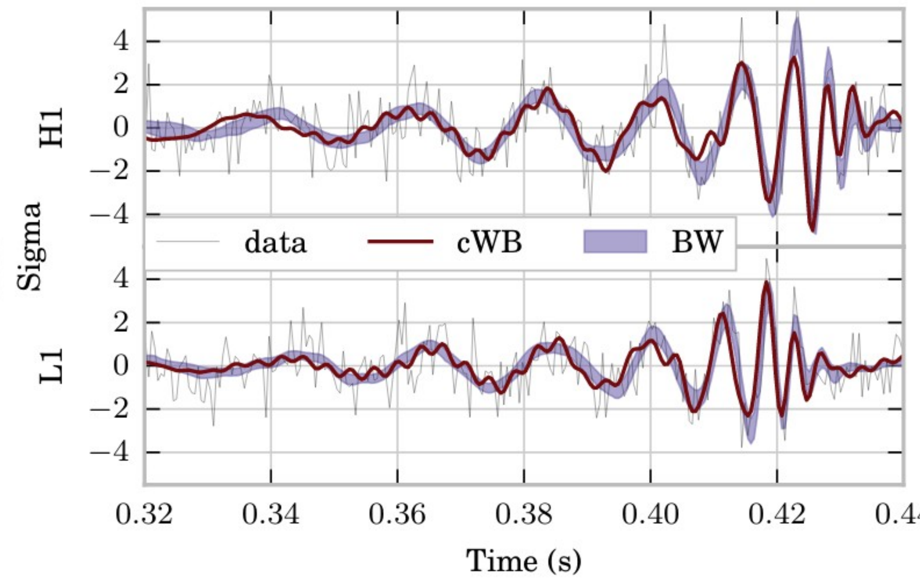
f < 1024 Hz

f > 1024 Hz

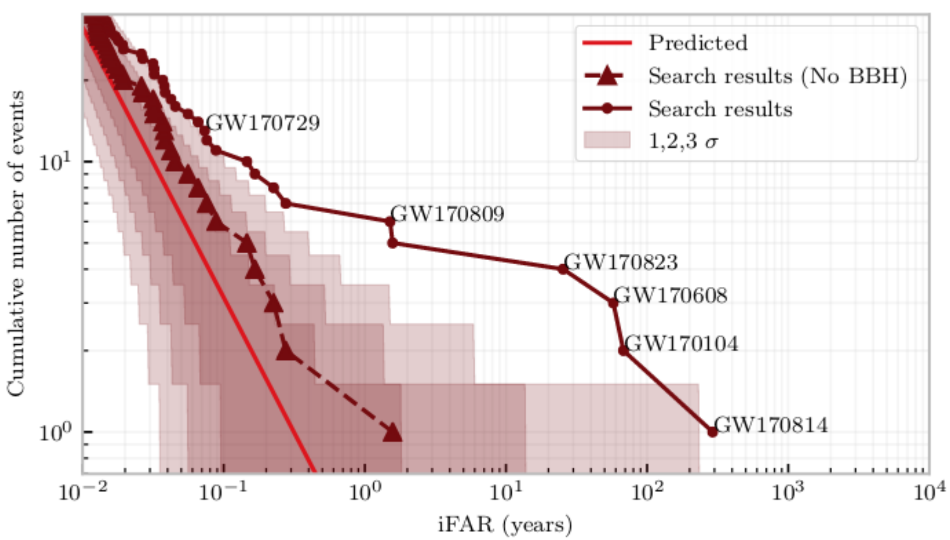
Coherent search results (O1)

Parameter estimation for GW150914

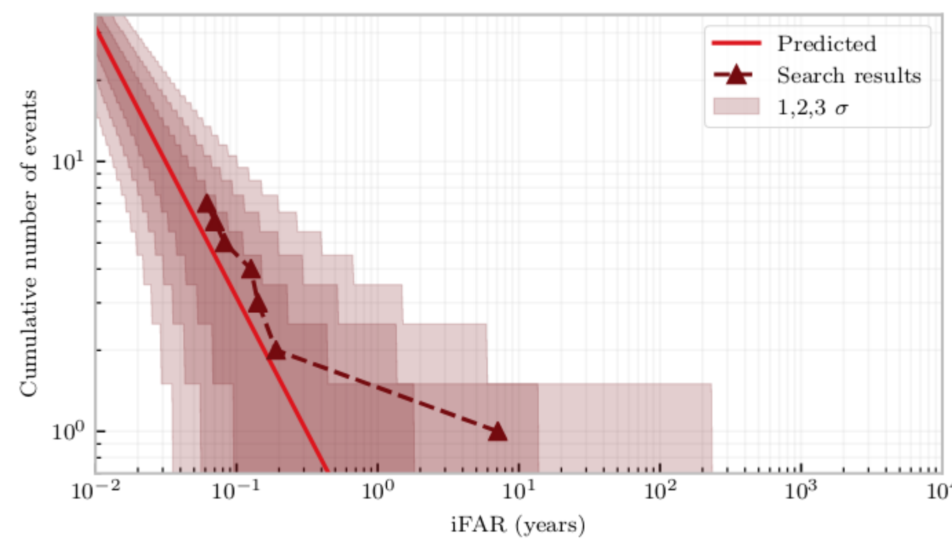




Coherent search results (O2)



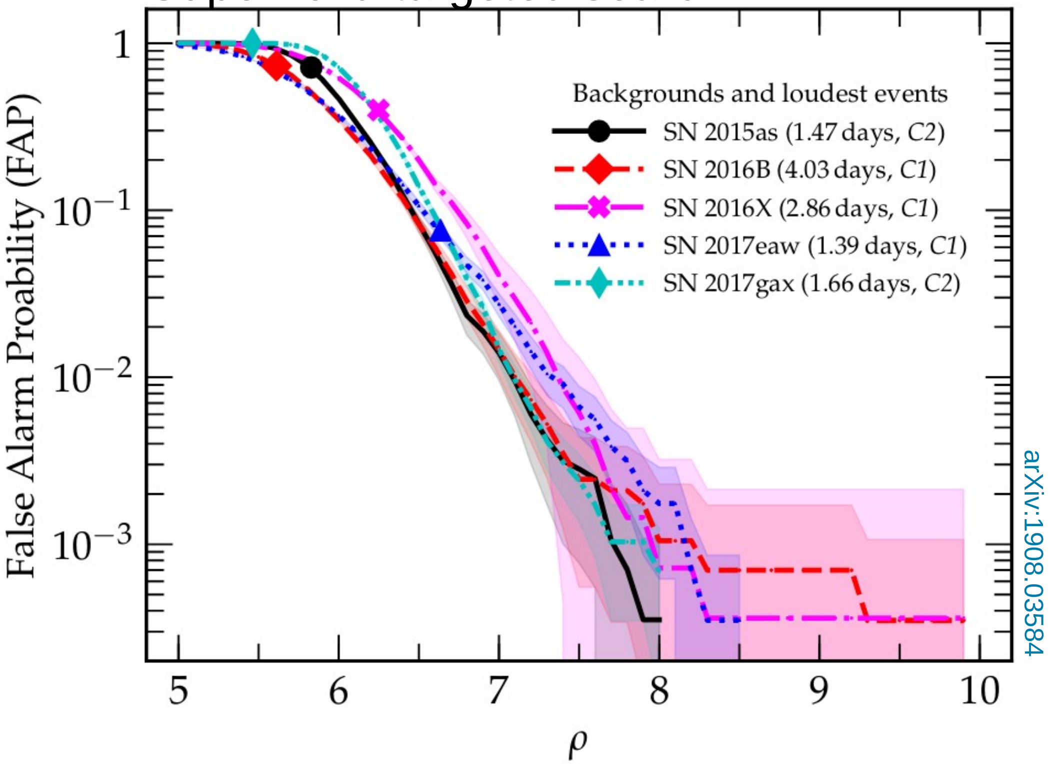
f < 1024 Hz



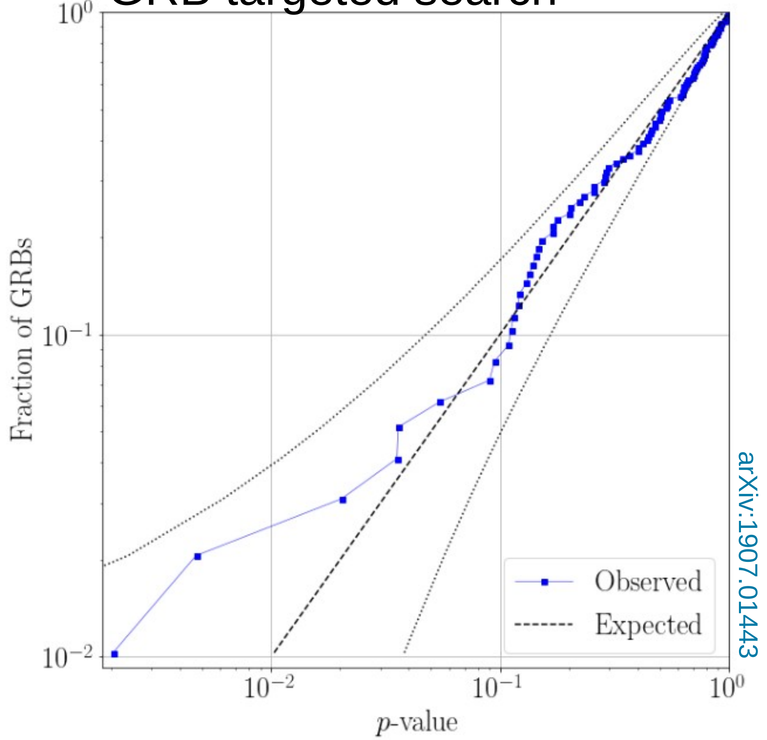
f > 1024 Hz

Targeted burst searches

Supernova targeted search



GRB targeted search



See also: GW + high-energy neutrino trigger coincidence

Low-latency searches

GW ID	Event Time UTC	Final status	Source Classification	Triggers		Latency (min)	
				Search(es)[a]	Online FAR (yr^{-1})	GraceDb submission	Initial GCN notice
G268556 GW170104	2017-01-04 10:11:58	Confident	BBH EM-Bright: 0%	**PyCBC**, cWB GstLAL, oLIB	1.9[b]	264	395
G270580	2017-01-20 12:30:59	Retracted	Burst EM-Bright: N/A	**cWB**	5.0	2	67
G274296	2017-02-17 06:05:53	NFI	Burst EM-Bright: N/A	**cWB**	5.4	715	813
G275404	2017-02-25 18:30:21	NFI	NS-BH EM-Bright: 90%	**PyCBC**, GstLAL	6.0	<1	24
G275697	2017-02-27 18:57:31	NFI	BNS EM-Bright: 100%	**PyCBC**, GstLAL, MBTAOnline	4.5	<1	27
G277583	2017-03-13 22:40:09	NFI	Burst EM-Bright: N/A	**cWB**	2.7	3	30
G284239	2017-05-02 22:26:07	NFI	Burst EM-Bright: N/A	**oLIB**	4.0	12	963
G288732 GW170608	2017-06-08 02:01:16	Confident	BBH EM-Bright: 0%	**PyCBC**, cWB, GstLAL[c]	2.6[b]	650	818
G296853 GW170809	2017-08-09 08:28:22	Confident	BBH EM-Bright: 0%	**GstLAL**, cWB MBTAOnline	0.2	<1	49
G297595 GW170814	2017-08-14 10:30:44	Confident	BBH EM-Bright: 0%	**GstLAL**, oLIB, PyCBC, cWB[d]	1.2×10^{-5}	<1	31
G298048 GW170817	2017-08-17 12:41:04	Confident	BNS EM-Bright: 100%	**GstLAL**[d], PyCBC	1.1×10^{-4}	6	27[e]
G298389	2017-08-19 15:50:46	NFI	Burst EM-Bright: N/A	**oLIB**	4.9	16	192
G298936 GW170823	2017-08-23 13:13:59	Confident	BBH EM-Bright: 0%	cWB, oLIB, **GstLAL**, PyCBC, MBTAOnline	5.5×10^{-4}	<1	22
G299232	2017-08-25 13:13:37	NFI	NS-BH EM-Bright: 100%	**MBTAOnline**[f]	5.3	<1	25

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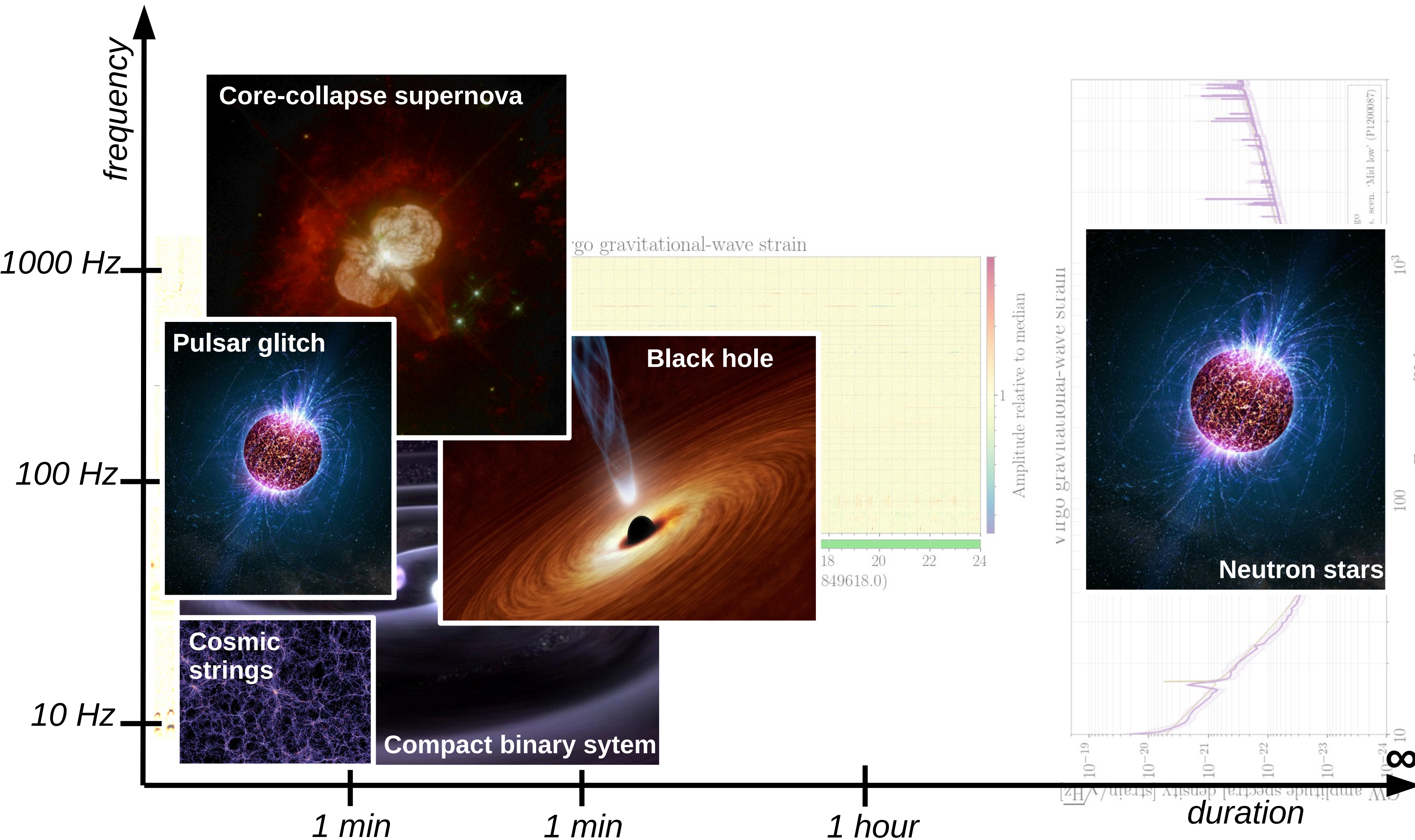
Continuous gravitational waves



Continuous gravitational waves

Gravitational-wave radiation from a time-varying quadrupolar mass-moment:

$$h_{\mu\nu}=\frac{2G}{rc^4}\frac{d^2}{dt^2}[I_{\mu\nu}]$$

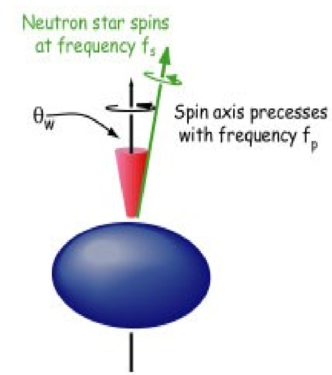
Rapidly-rotating neutron star with ellipticity

$$h\approx 1.1\times 10^{-24}\left(\frac{r}{1\,kpc}\right)^{-1}\left(\frac{f_{GW}}{1\,kHz}\right)^{2}\left(\frac{\epsilon}{10^{-6}}\right)\left(\frac{I_{zz}}{10^{38}\,kg\cdot m^2}\right)$$

$$f_{GW}=2f_{rot}$$

Mass asymmetry:

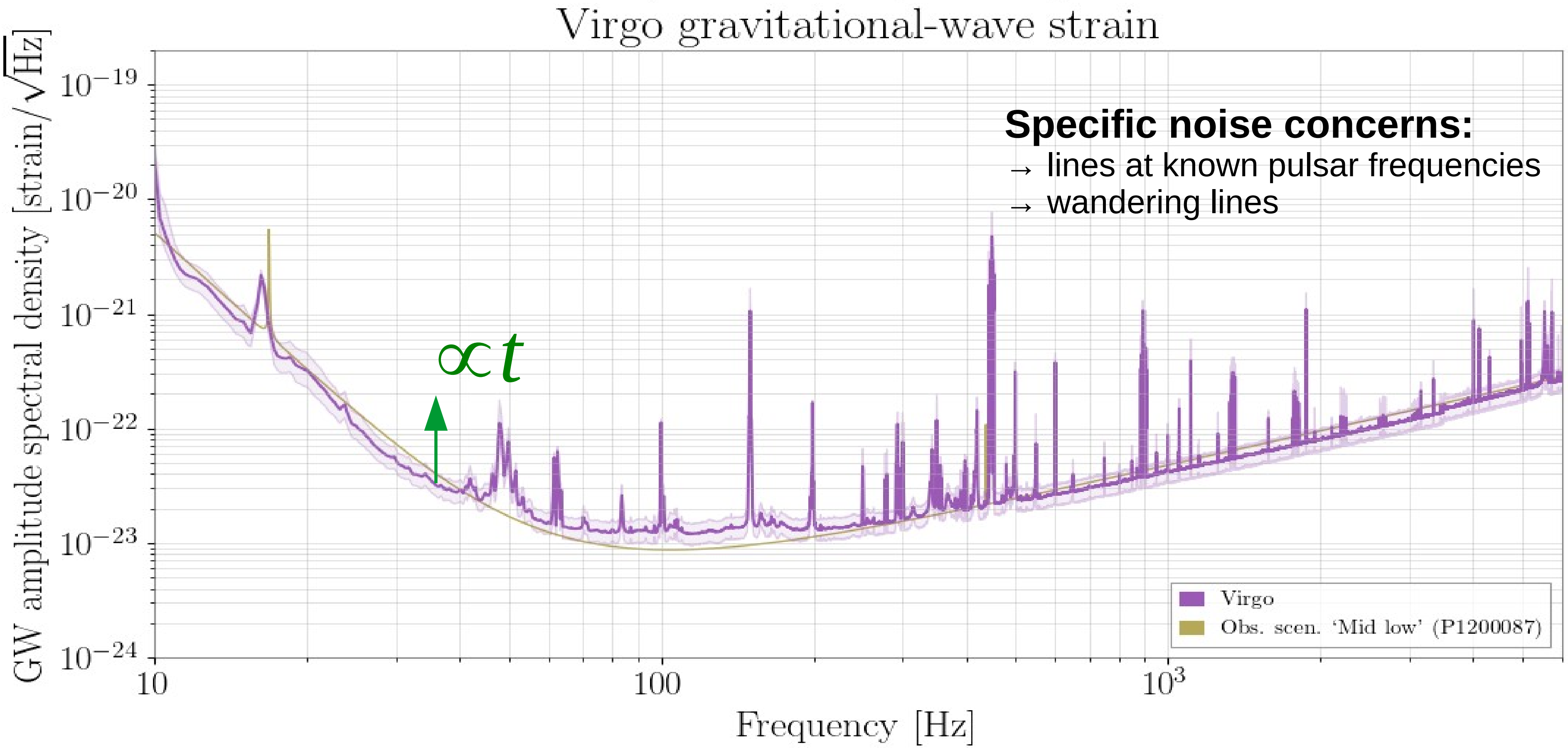
→ distortion due to elastic stresses or magnetic field
→ distortion due to matter accretion
→ free precession around rotation axis
→ excitation of long-lasting oscillations (e.g. r-modes)



Continuous gravitational waves

→ The continuous gravitational waveform is well modeled by a sinusoidal wave

$$h(t) = h_0 \left(F_+(t, \alpha_0, \delta_0, \psi) \frac{1+\cos^2(\iota)}{2} \cos(\Phi(t)) + \right.$$
$$\left. + F_\times(t, \alpha_0, \delta_0, \psi) \cos(\iota) \sin(\Phi(t)) \right) \; ,$$



Continuous gravitational waves

→ The continuous gravitational waveform is well modeled by a sinusoidal wave

→ Rupture point of neutron star matter
- Normal nuclear matter $\epsilon < 10^{-5}$
- Hybrid (hadron-quark core) $\epsilon < 10^{-3}$
- Quark star $\epsilon < 10^{-1}$

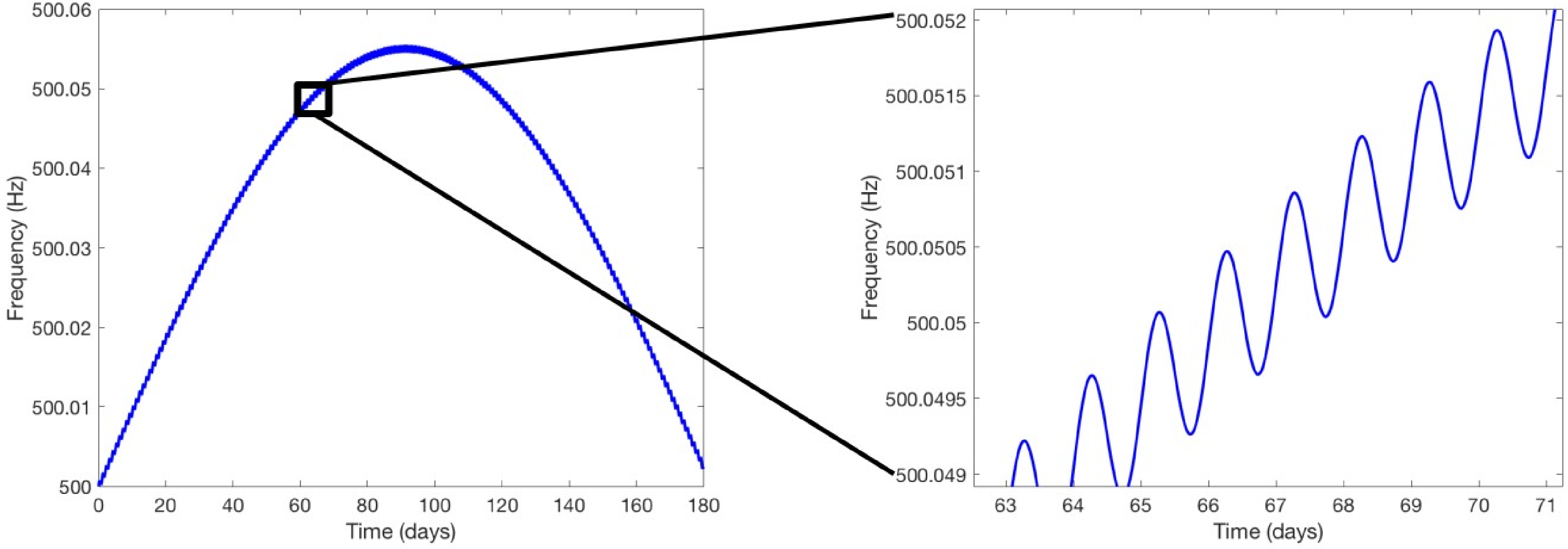
→ Gravitational-wave frequency
- Tri-axial ellipsoid $f_{GW} = 2 f_{rot}$
- r-mode fluid oscillations $f_{GW} \approx 4/3 f_{rot}$
- free-precession $f_{GW} = f_{rot} \pm f_{pre}$

→ The science of continuous waves
- Neutron star equation of state, maximum mass, spin and ellipticity
- Exotic state of matter
- Tests of general relativity
- Neutron star dynamics

Continuous gravitational waves

The gravitational waveform is Doppler-modulated by the Earth rotational & orbital motion

→ <u>you need to correct for that for every sky location you observe</u>



Continuous gravitational waves

Targeted search
→ known pulsars
→ "know" everything

Directed search
→ region of interest (galactic center, Sco-X1)
→ "know" something

All-sky search
→ "know" nothing

→ **Computational cost**

Continuous gravitational waves

Targeted search
→ known pulsars
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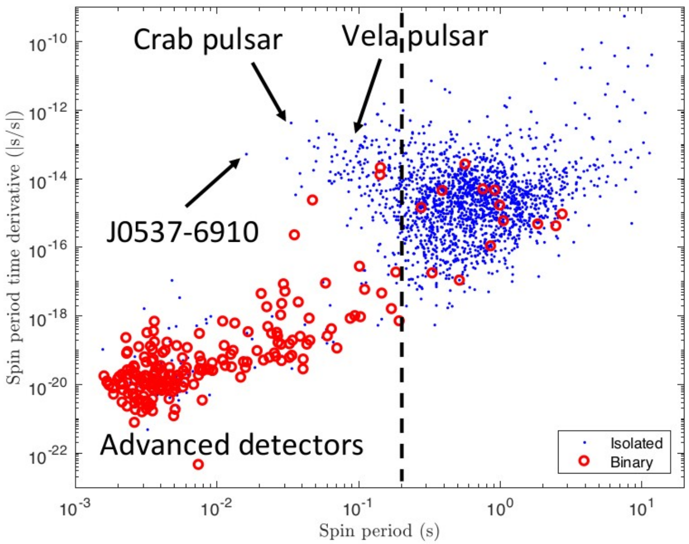
Computational cost



~ 600 known pulsars spinning faster than 5 Hz

~ Almost half of them are in binary systems

Neutron stars spin down
→ result of gravitational radiation

Spin-down ($\dot{f}_{rot}$) limit can be used to place constraints on GW emission → useful benchmark

Continuous gravitational waves

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→ "know" everything

Directed search
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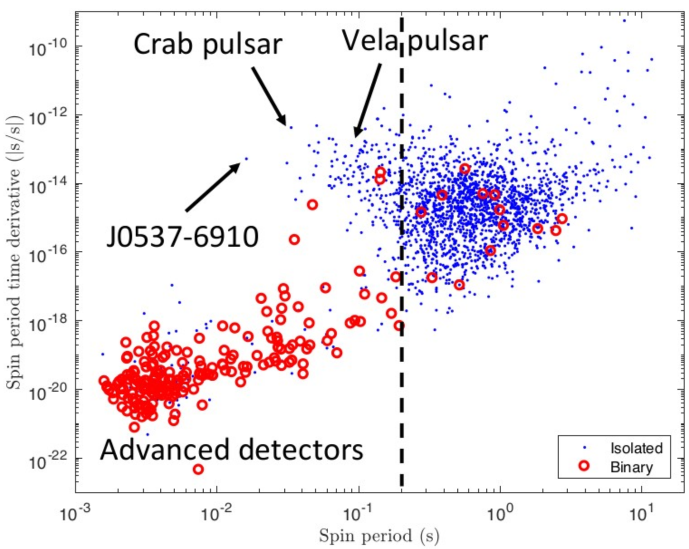
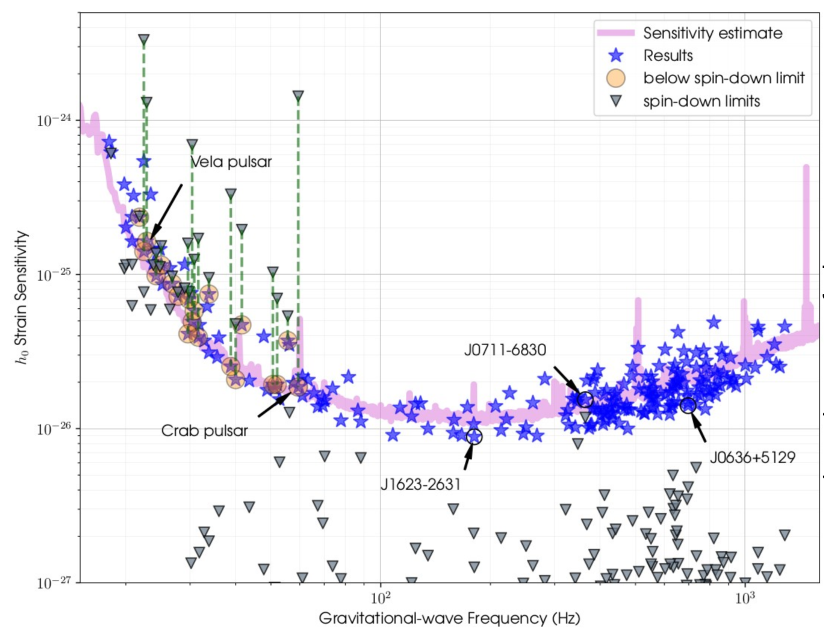
All-sky search
→ "know" nothing

Computational cost





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Continuous gravitational waves

Targeted search
→ known pulsars
→ "know" everything

Directed search
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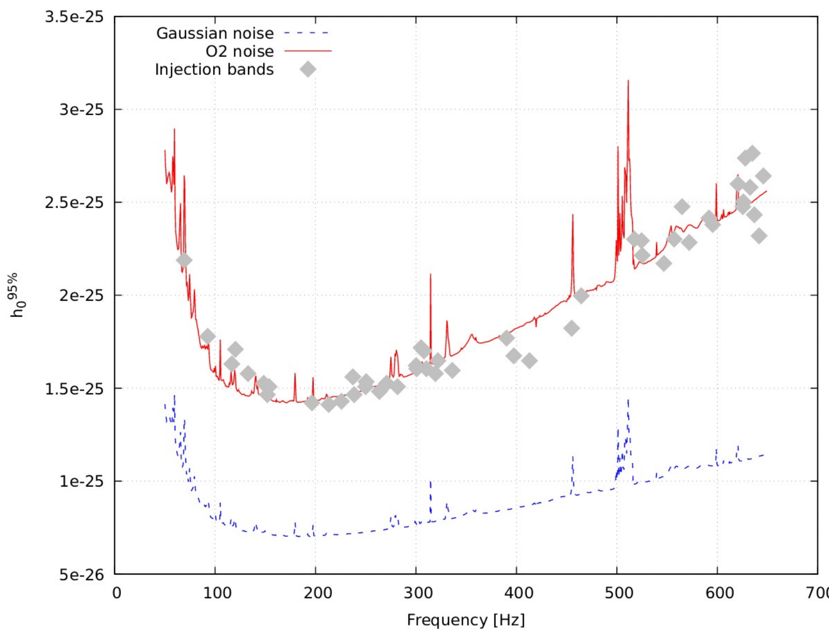
All-sky search
→ "know" nothing

Computational cost



arXiv:1906.12040

Low-mass X-ray binary Scorpius X-1

Continuous gravitational waves

Brute-force (and very expensive) search over a huge parameter space:

→ gravitational-wave frequency (LIGO-Virgo sensitive band)
→ frequency derivative (~$\pm 10^{-8}$ Hz/s)
→ sky location (all-sky)
→ source inclination and polarization angle (anything)
→ signal phase (anything)

(more parameters for binary systems !!!)

Continuous gravitational waves

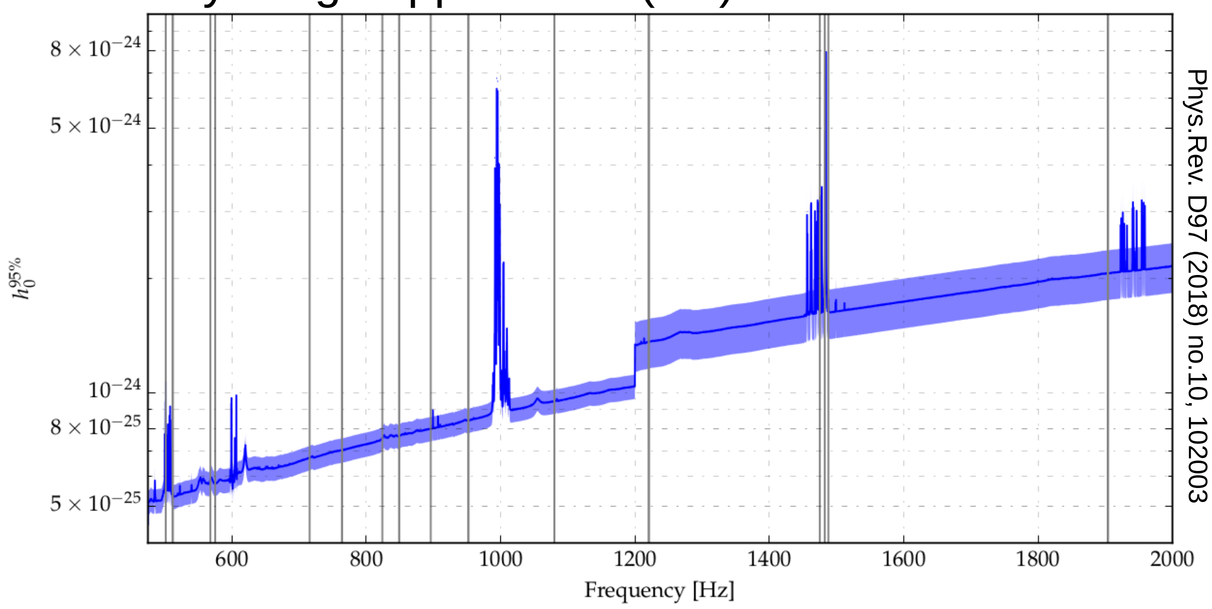
Targeted search
→ known pulsars
→ “know” everything

Directed search
→ region of interest (galactic center, Sco-X1)
→ “know” something

All-sky search
→ “know” nothing

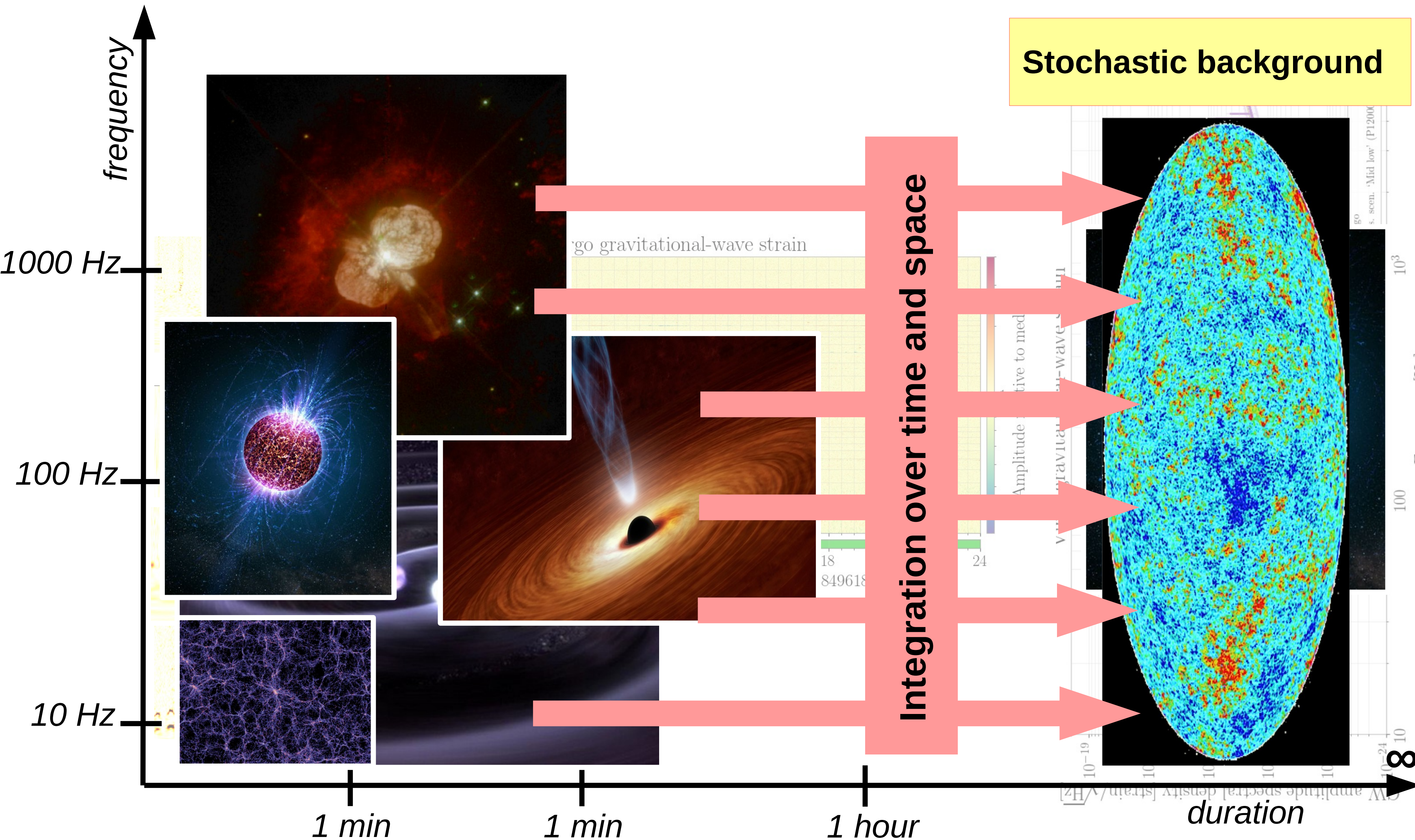
Computational cost

SkyHough upper limits (O1)



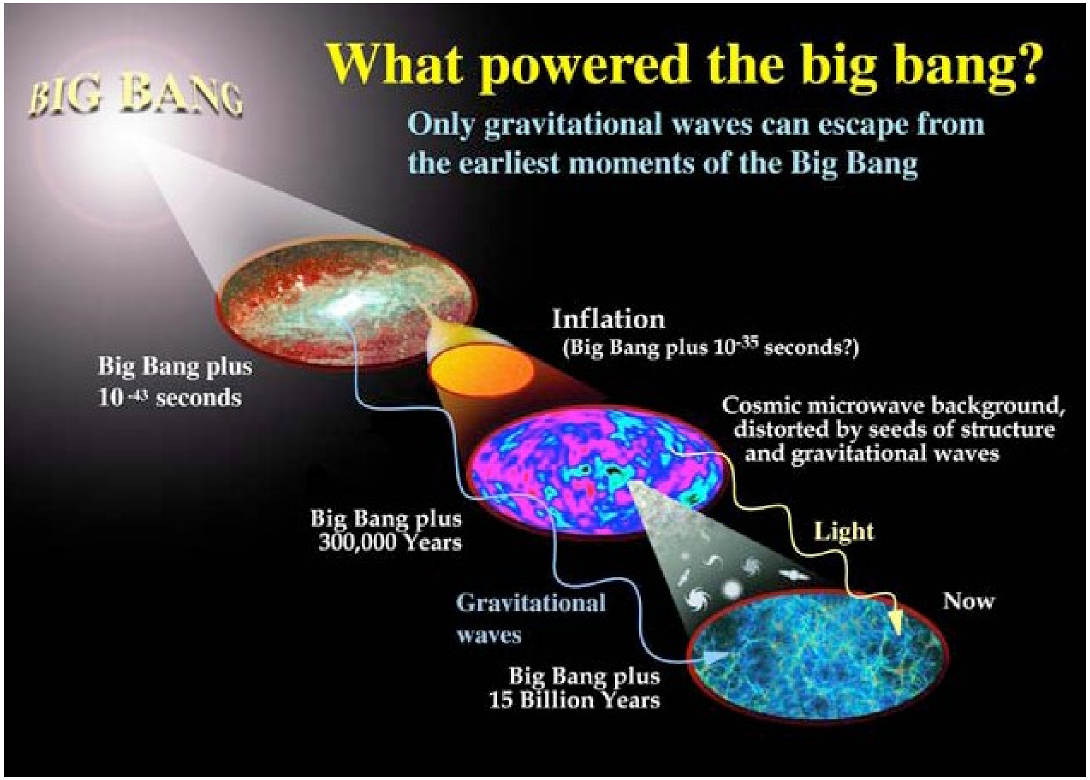
Phys.Rev. D97 (2018) no.10, 102003

Stochastic background



Stochastic background

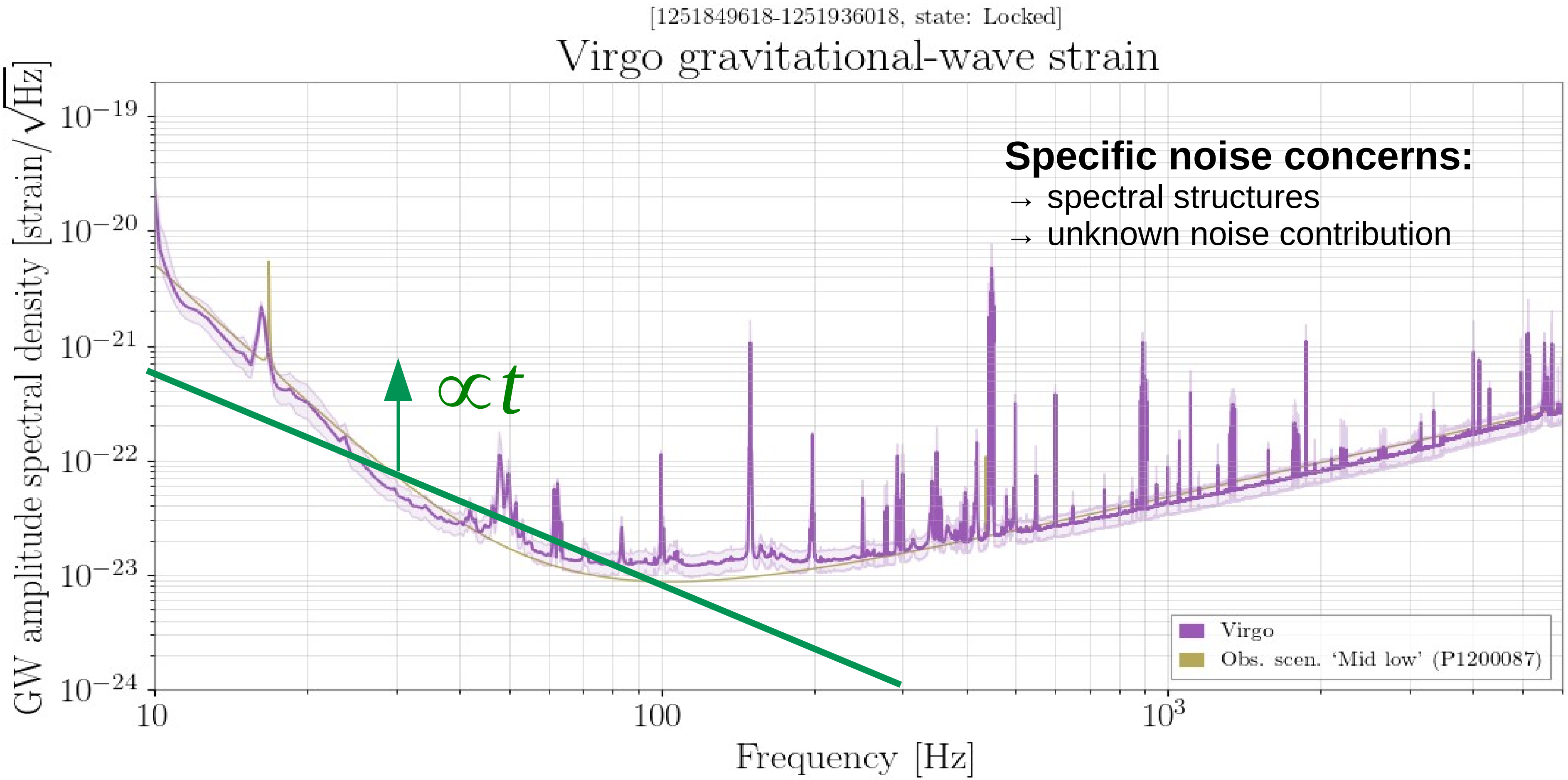
- Incoherent superposition of many unresolved sources.
- Cosmological:
  - Inflationary epoch, preheating, reheating
  - Phase transitions
  - Cosmic strings
  - Alternative cosmologies
- Astrophysical:
  - Supernovae
  - Magnetars
  - Binary black holes
- Potentially could probe physics of the very-early Universe.



$$\Omega_{GW}(f) = \frac{f}{\rho_c}\frac{d\rho_{GW}}{df}$$

Stochastic background

→ A physical gravitational-wave spectrum is produced by the superposition of astrophysical (or cosmological) sources



Stochastic background

Assumption : stationary, unpolarized, and Gaussian stochastic background

→ Cross correlate the output of detector pairs to eliminate the noise

$$h_i = n_i + GW_i$$

$$\langle h_1, h_2 \rangle = \langle GW_1, GW_2 \rangle + \underbrace{\langle n_1, GW_2 \rangle}_{0} + \underbrace{\langle GW_1, n_2 \rangle}_{0} + \underbrace{\langle n_1, n_2 \rangle}_{0}$$

With $\langle x_1, x_2 \rangle = \int_{-\infty}^{+\infty} \tilde{x}_1^*(f)\, \tilde{Q}(f)\, \tilde{x}_2(f)\, df$

Optimal filter:

$$\tilde{Q}(f) \propto \frac{\gamma(f)\,\Omega_{GW}(f)}{f^3 S_{n,1}(f)\, S_{n,2}(f)}$$

overlap of antenna pattern

GW spectrum $\Omega_{GW}(f) = \Omega_\alpha f^\alpha$

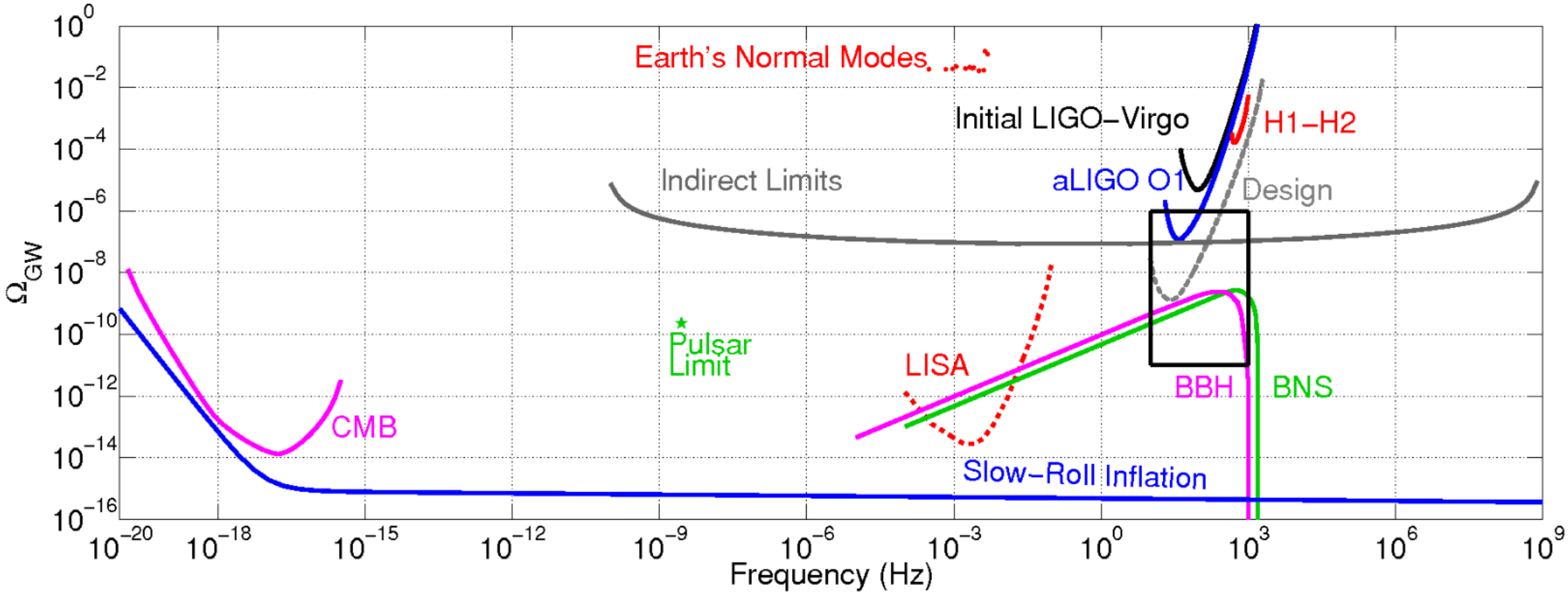
Detector PSDs

O1 isotropic search, for $\alpha = 0$: $\Omega_{GW}(25\,Hz) < 6.0 \times 10^{-8}$

PRL.118.121101 (2017)

Stochastic background

Use astrophysical (/cosmological) models to predict expected backgrounds and amplitude → constraints on models



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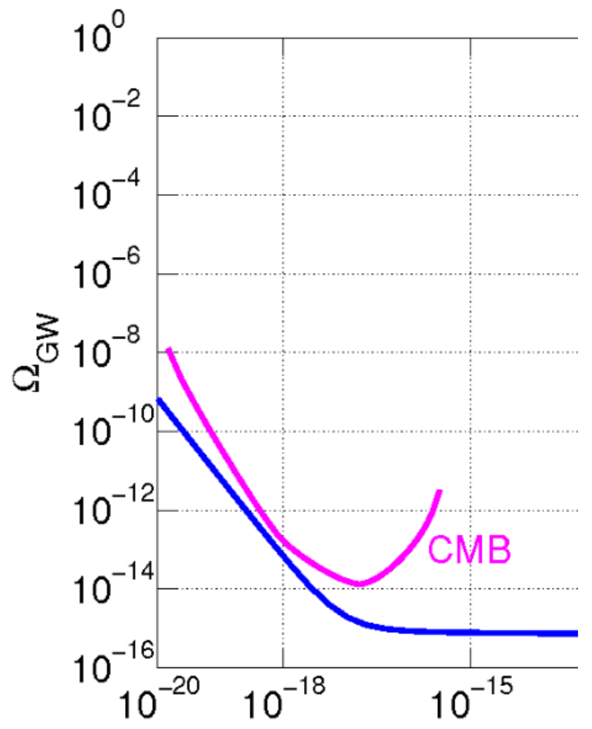

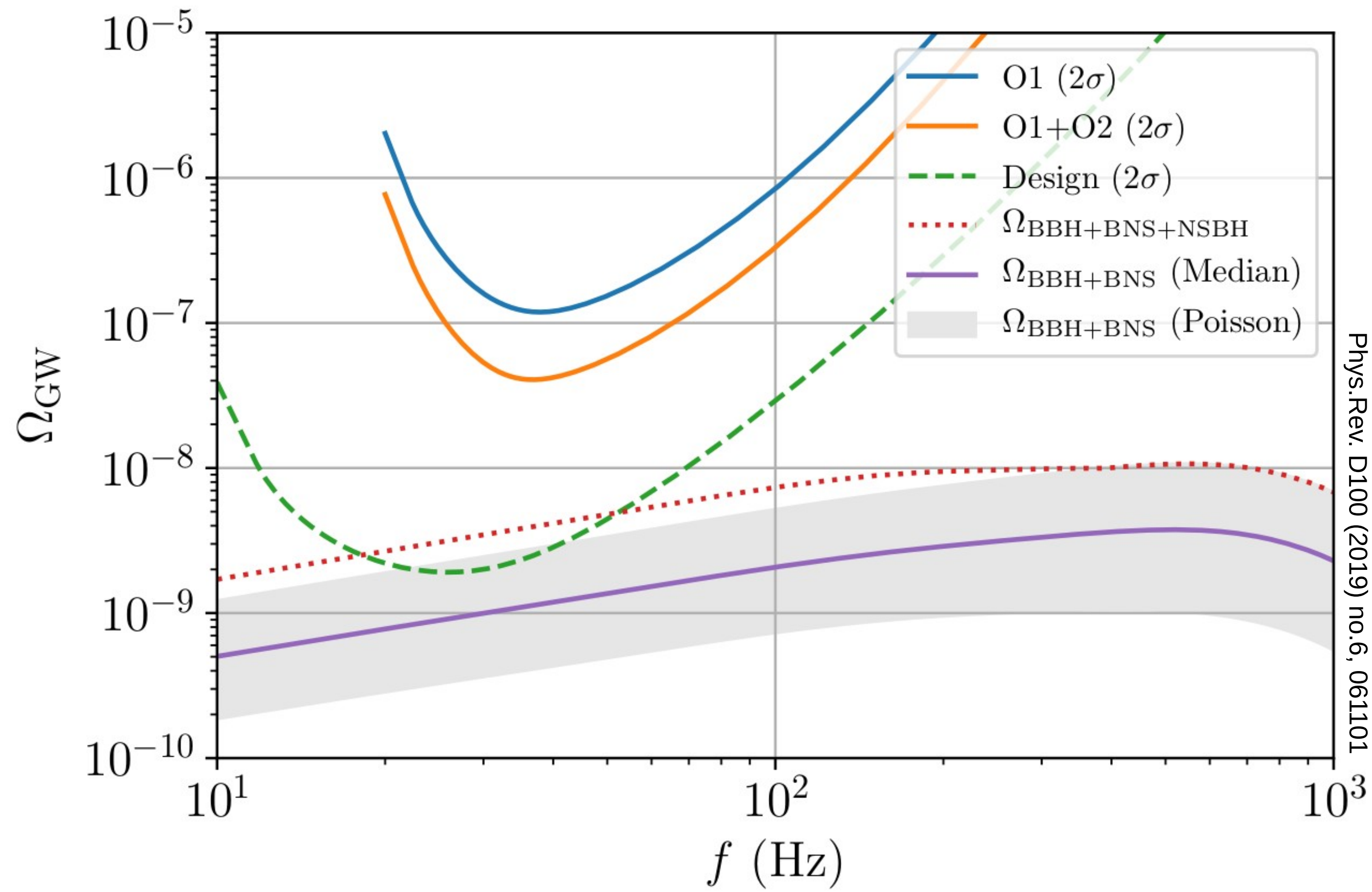

Conclusions

O3:

→ The LIGO-Virgo O3 run started on Apr. 1st 2019
→ The detectors improved their sensitivity (/O2)
→ The first half of the run is completed, offline data analyses are on-going

Burst:

→ 1 single public alert so far (excluding CBC): it has been retracted
→ Lots of work on transient noise to maximize the search sensitivity
→ Great hopes to witness THE supernova of the 21st century

Continuous waves:

→ keep digging the noise...

Stochastic background:

→ BBH/BNS background is not far…
→ Challenge: identify the source