Searches for isotropic gravitational-wave backgrounds using ground-based interferometers

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“Data analysis challenges for stochastic GW backgrounds”
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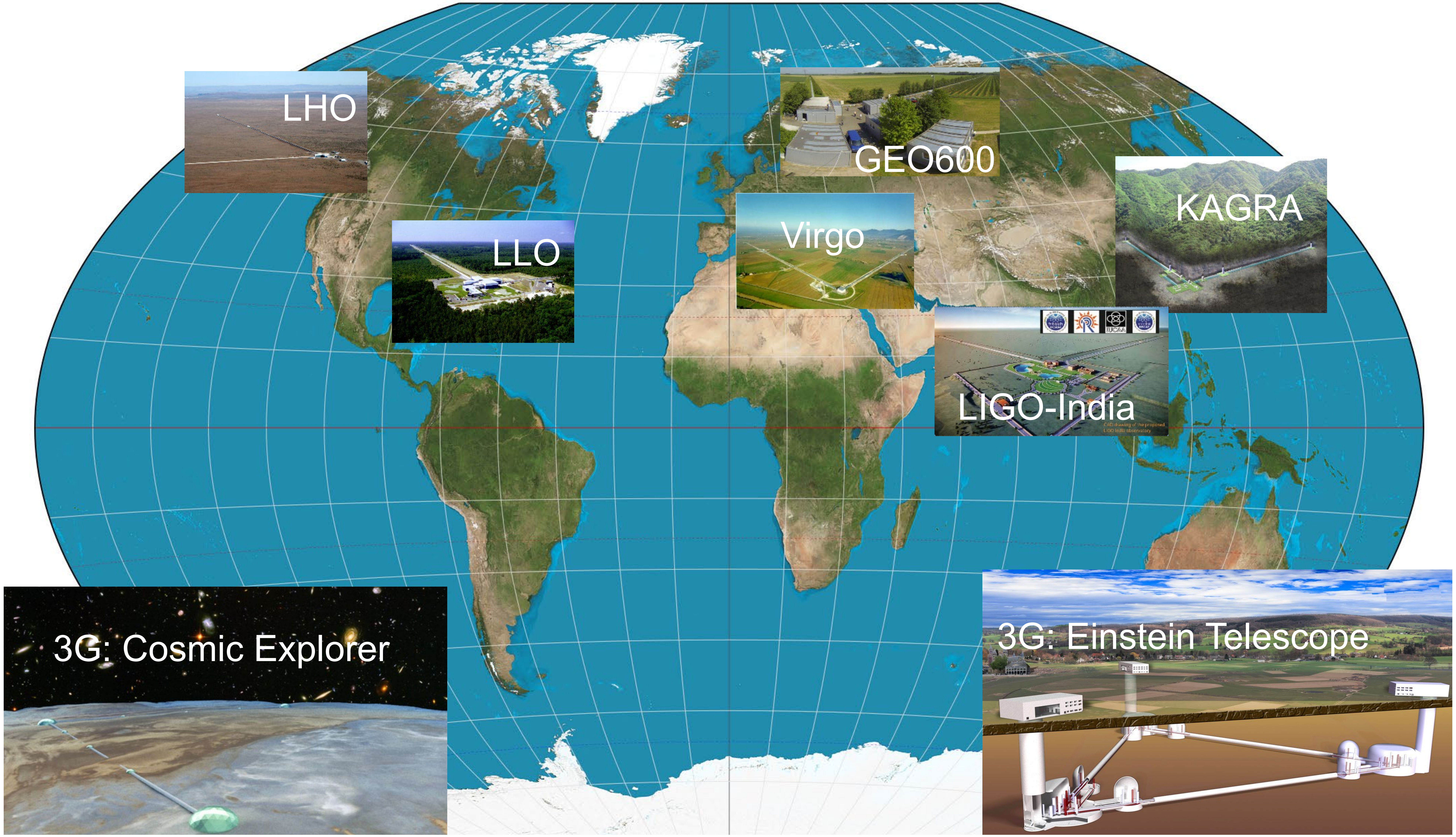
Outline / challenges

1. stochastic GW backgrounds in the LIGO-Virgo-KAGRA band are weak
2. detector noise is not stationary
3. detector noise is not Gaussian
4. potential contamination from correlated noise

- Discuss above in the context of LVK O3 stochastic search for an isotropic GWB
- Won’t talk about anisotropy or new methods (Jishnu’s and Vuk’s talks)
- Won’t talk about 3G detectors e.g., Cosmic Explorer, Einstein Telescope (Angelo’s talk)

Ground-based interferometers	LISA
km-long arms	million km-long arms
arm length << GW wavelength (“long wavelength approx”)	arm length ~ GW wavelength at high frequencies
trivial timing response to GWs	non-trivial timing response to GWs
noise dominated	signal dominated (galactic DWD is guaranteed stochastic foreground)
currently just backgrounds (no foregrounds)	both backgrounds and foregrounds
detector noise estimated from auto-power	detector noise inferred as part of the analysis
cross correlate data from multiple detectors	cross correlation not feasible (only one LISA)
“local fit”: separate searches for individual sources	“global fit”
hybrid frequentist-Bayesian analyses	Bayesian inference
potentially fix problems with instrument (on Earth)	can’t go to LISA to fix problems

Global network of ground-based detectors

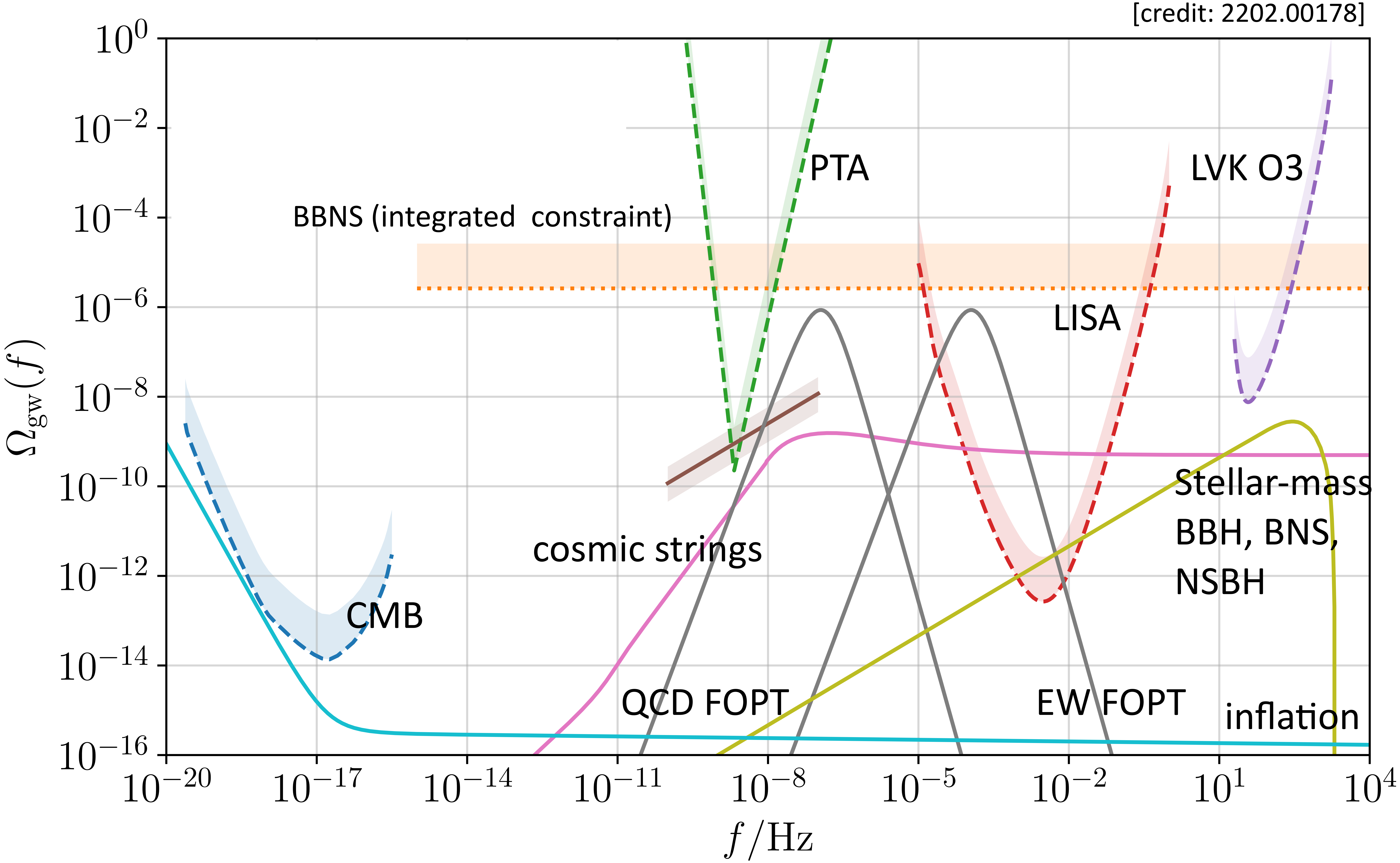


[credit: Vuk Mandic]

Some potential GWB signals

[credit: 2202.00178]

$$\Omega_{\mathrm{gw}}(f) \equiv \frac{1}{\rho_c}\frac{\mathrm{d}\rho_{\mathrm{gw}}}{\mathrm{d}\ln f}$$



Power-law integrated sensitivity curves

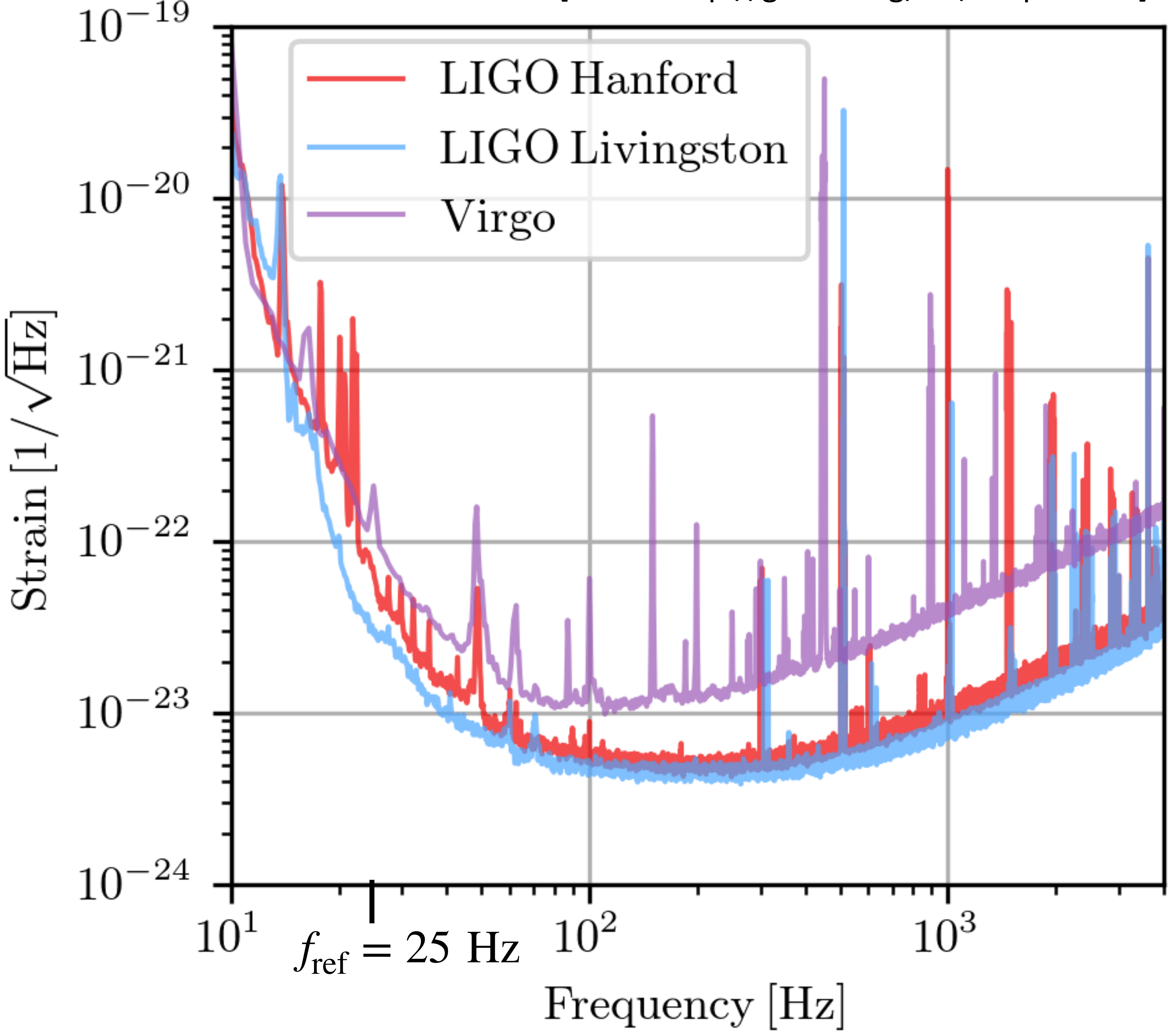
$$\Omega_{\mathrm{gw}}(f) \equiv \Omega_\alpha \left(\frac{f}{f_{\mathrm{ref}}}\right)^\alpha$$

$$\Omega_{\mathrm{PI}}(f) \equiv \max_\alpha \Omega_{\mathrm{gw}}(f)$$

O3 information

- Data taken by LIGO Hanford, LIGO Livingston, and Virgo detectors
- O3 split into two parts:
  - O3a: 1 Apr 2019 - 1 Oct 2019 (6 months)
  - O3b: 1 Nov 2019 - 27 Mar 2020 (~5 months)
- Total live time (before data quality cuts):
  - HL: 205.4 days
  - HV: 187.5 days
  - LV: 195.4 days
- "Flagship" search: unpolarized, isotropic, power-law $\Omega_{\rm gw}(f) = \Omega_{\rm ref}(f/f_{\rm ref})^\alpha$
  - $\alpha = 0$ for cosmological backgrounds
  - $\alpha = 2/3$ for binary inspiral
  - $\alpha = 3$ for ``generic" source (white strain noise)

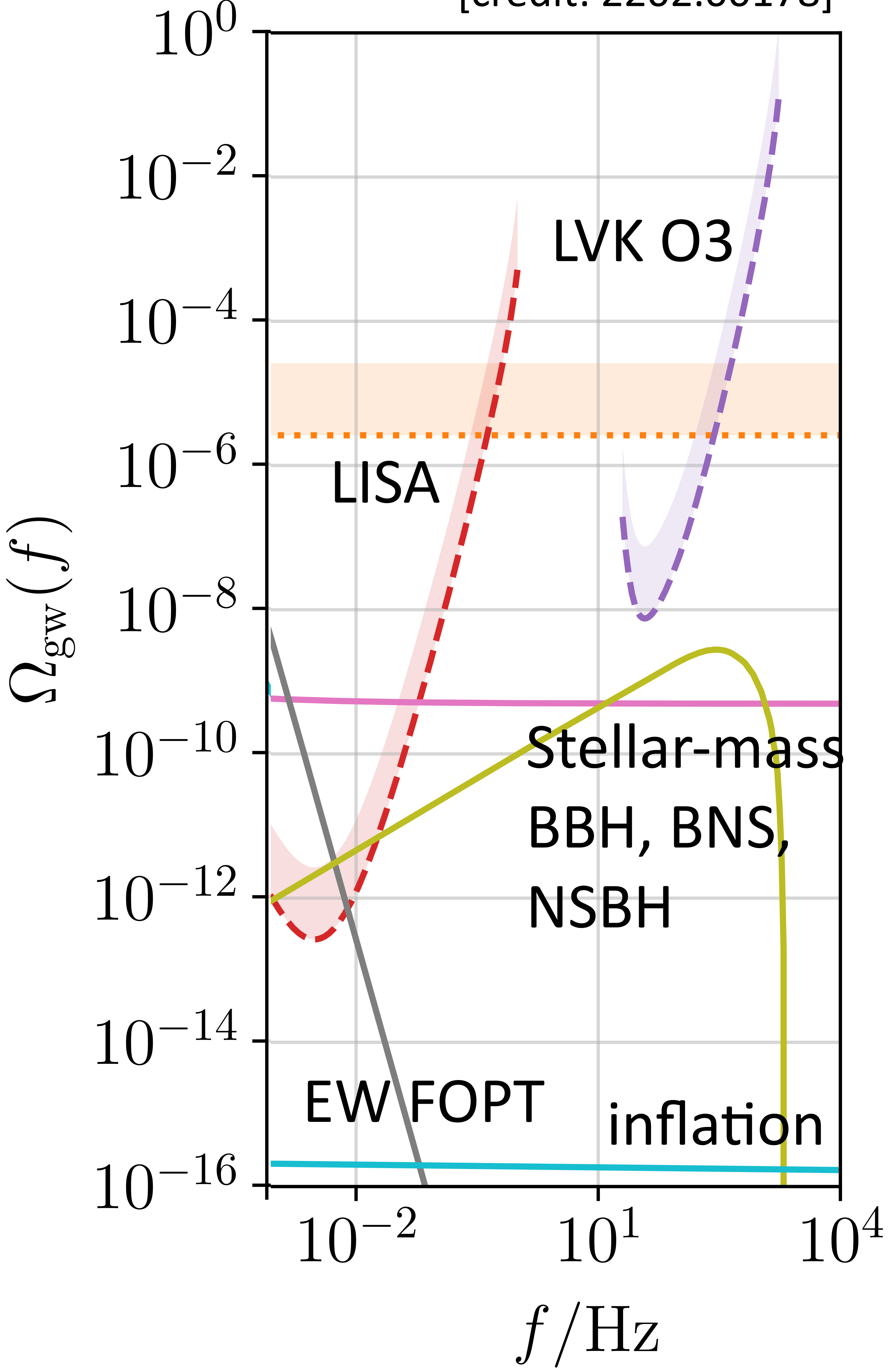
[credit: http://gwosc.org/O3/o3speclines]



Challenge 1: GWB signal is weak relative to noise

- in LVK band, amplitude of GWB << noise, unlike LISA or PTA searches for GWBs
- an optimal analysis should model GWB contribution to auto-power, BUT…
  - for a weak GWB, cross-power and estimates of auto-power are "sufficient statistics"
  - cross-correlation allows one to ``dig down" below noise
- weak-signal approx may break down for searches for intermittent GWBs (segment SNR ~ 1)
  - might need to model GWB contribution to auto-power estimates

[credit: 2202.00178]



Cross-correlation: basic idea

Data from two detectors:

$$d_1 = R_1\, h + n_1$$
$$d_2 = R_2\, \underset{\uparrow}{h} + n_2$$

common GW signal component

Expected value of cross-correlation:

$$\langle C_{12}\rangle = \langle d_1 d_2\rangle = R_1 R_2 \langle h^2\rangle + R_1 \cancelto{0}{\langle h n_2\rangle} + R_2 \cancelto{0}{\langle n_1 h\rangle} + \langle n_1 n_2\rangle = R_1 R_2 \langle h^2\rangle + \langle n_1 n_2\rangle$$

Assuming detector noise is uncorrelated:

$$\langle C_{12}\rangle = R_1 R_2 \langle h^2\rangle = \gamma_{12} S_h$$

Hybrid frequentist-Bayesian analysis for weak GWBs

Cross and auto-power
estimates for detectors I, J:

$$C_{IJ}(t;f) = \frac{2}{T}\mathrm{Re}[\tilde{d}_I^*(t;f)\tilde{d}_J(t;f)] \qquad P_I(t;f) = \frac{2}{T}|\tilde{d}_I(t;f)|^2$$

Estimator of $\Omega_{\mathrm{GW}}(f)$ and
its variance (weak-signal):

$$\hat{\Omega}_{\mathrm{GW},IJ}(t;f) = \frac{C_{IJ}(t;,f)}{\gamma_{IJ}(f)S_0(f)} \qquad \sigma^2_{\mathrm{GW},IJ}(t;f) \approx \frac{1}{2T\Delta f}\,\frac{P_I(t;f)P_J(t;f)}{\gamma^2_{IJ}(f)S_0^2(f)}$$

$$S_0(f) = \frac{3H_0^2}{10\pi^2 f^3}$$

Likelihood function
for model $\Omega_{\mathrm{GW}}(f)$:

$$p(\hat{\Omega}_{\mathrm{GW},IJ}(f)\,|\,\vec{\lambda}) \propto \exp\left[-\frac{1}{2}\sum_{IJ}\sum_{f}\frac{\left(\hat{\Omega}_{\mathrm{GW},IJ}(f) - \Omega_{\mathrm{model}}(f\,|\,\vec{\lambda})\right)^2}{\sigma^2_{\mathrm{GW},IJ}(f)}\right]$$

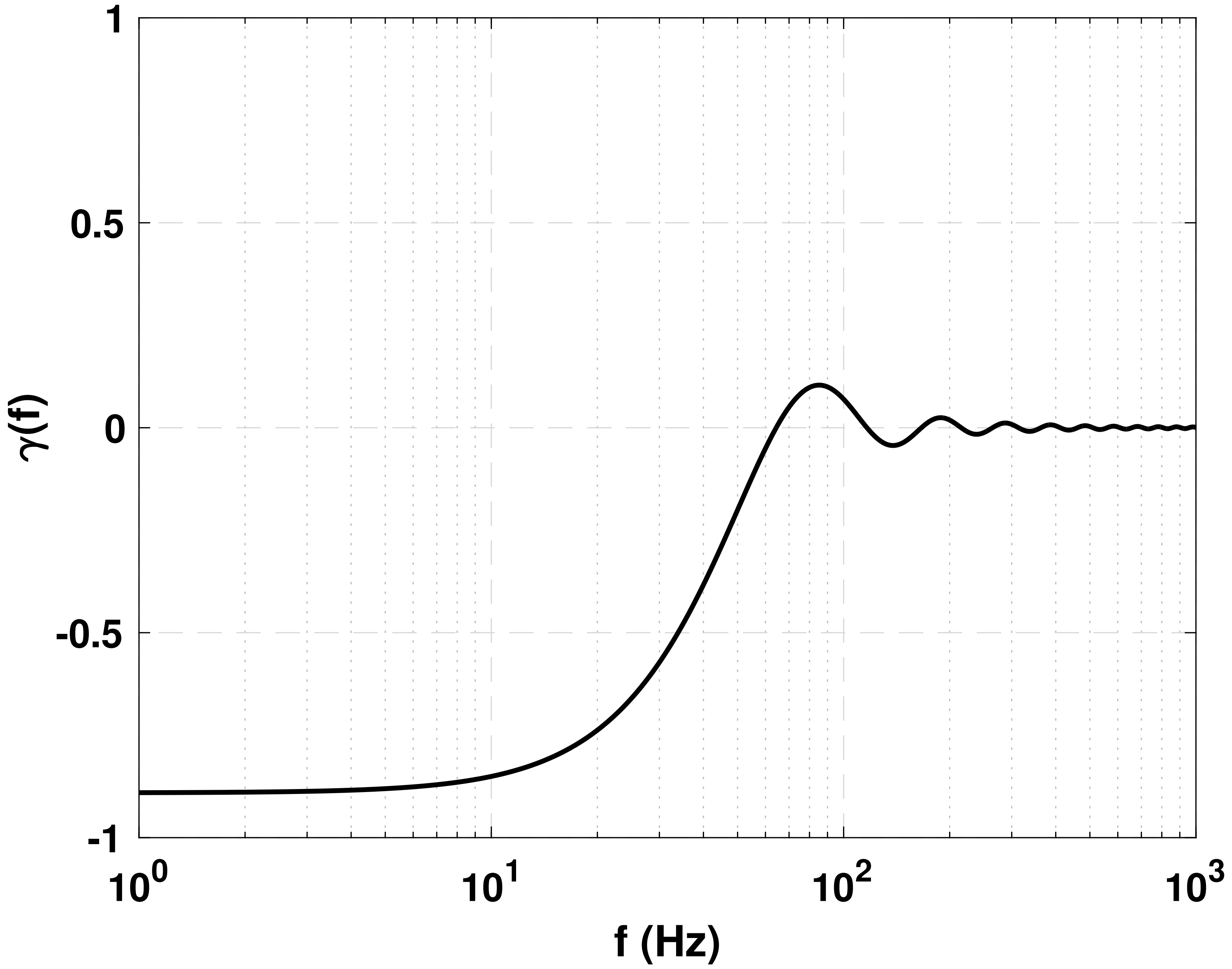
where

$$\hat{\Omega}_{\mathrm{GW},IJ}(f) = \frac{\sum_t \Omega_{\mathrm{GW},IJ}(t;f)/\sigma^2_{\mathrm{GW},IJ}(t;f)}{\sum_t 1/\sigma^2_{\mathrm{GW},IJ}(t;f)} \qquad \frac{1}{\sigma^2_{\mathrm{GW},IJ}(f)} = \sum_t \frac{1}{\sigma^2_{\mathrm{GW},IJ}(t;f)}$$

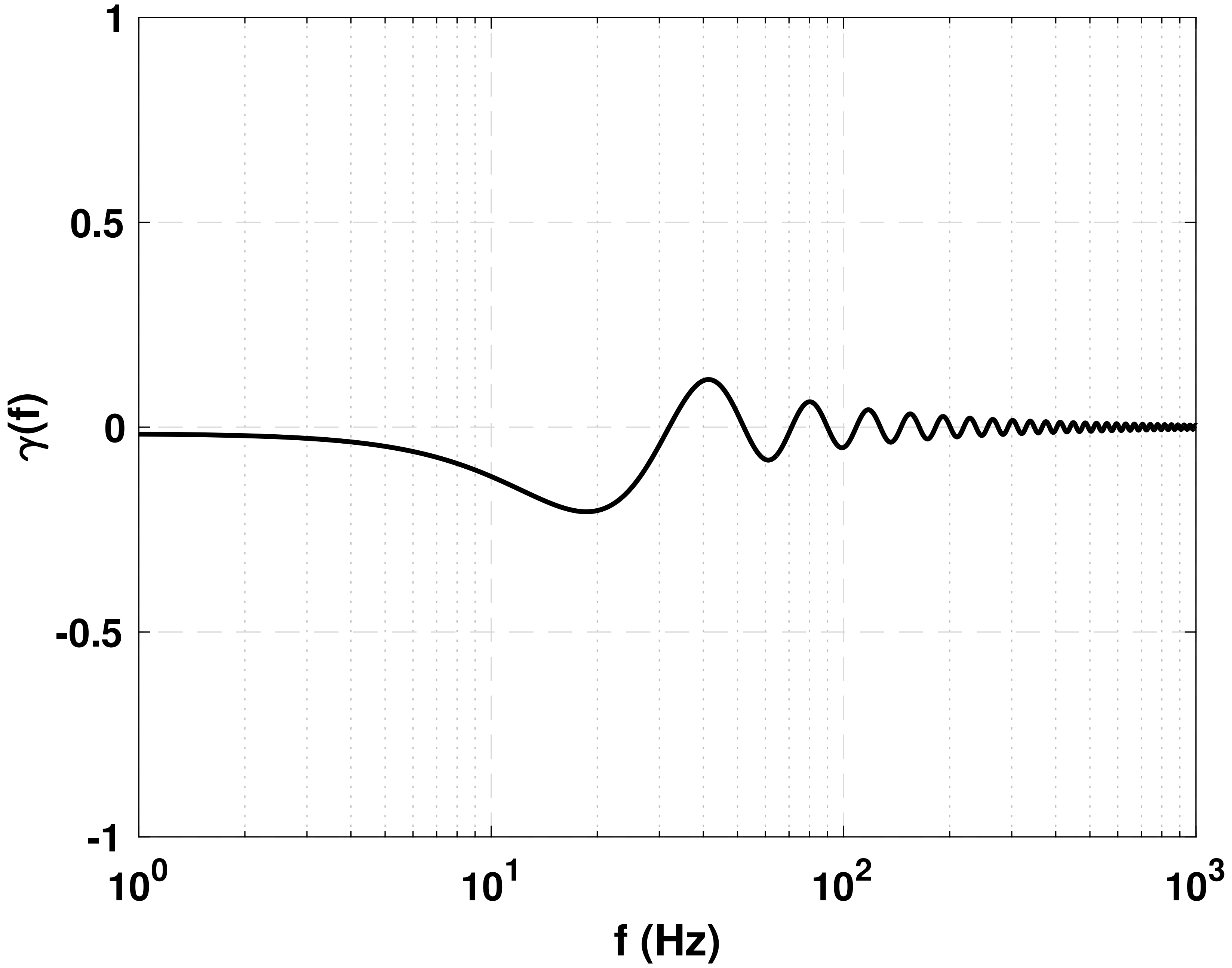
Overlap functions for cross-correlated data

$C_{IJ}(f) = \gamma_{IJ}(f) S_h(f)$ where $\gamma_{IJ}(f) = \frac{5}{8\pi} \sum_A \int \mathrm{d}\hat{k}\, F_I^A(\hat{k}) F_J^A(\hat{k}) e^{-i2\pi f \hat{k}\cdot(\vec{x}_I - \vec{x}_J)}$

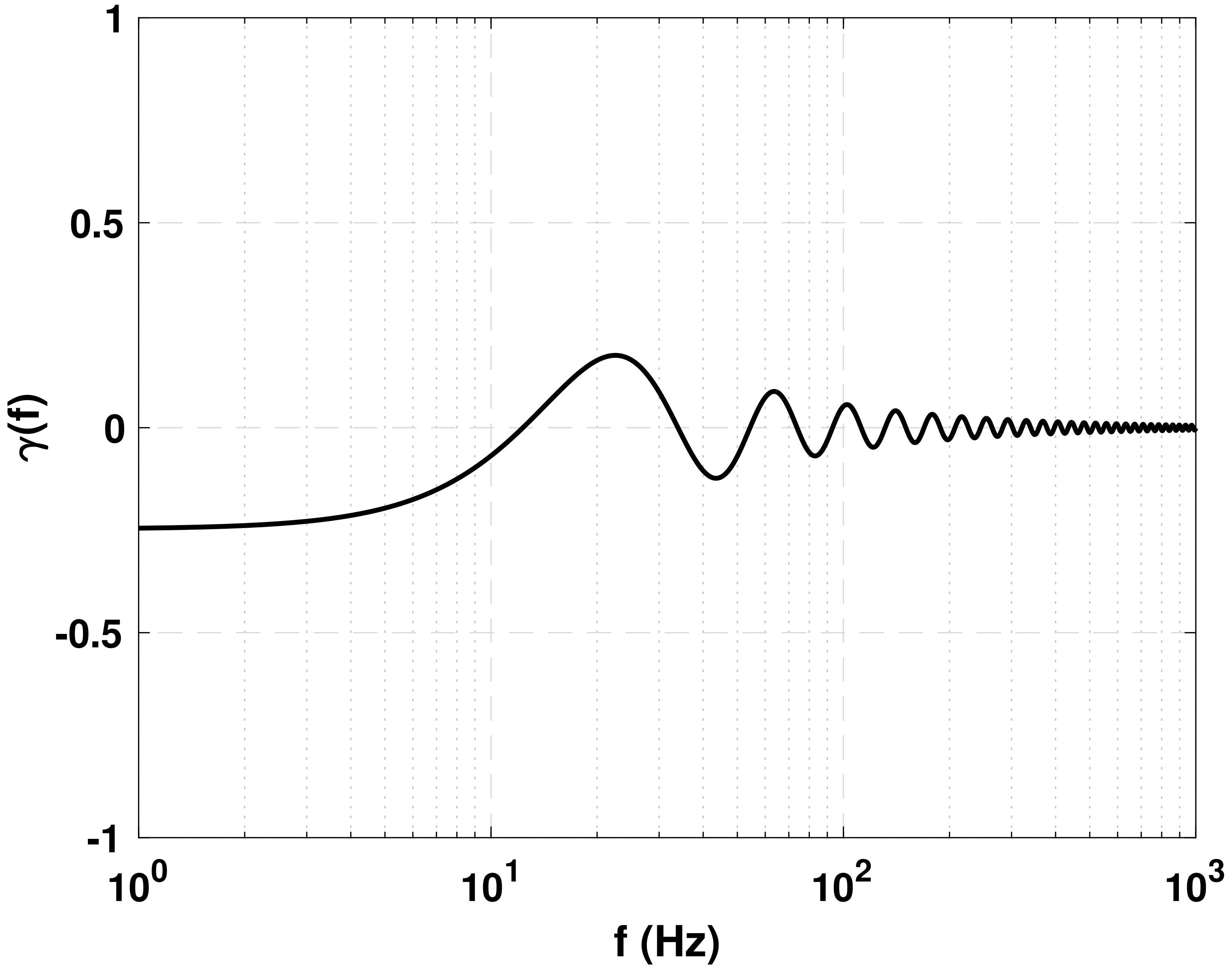
LIGO Hanford - LIGO Livingston



LIGO Hanford - Virgo



LIGO Livingston - Virgo



- overlap functions reduce frequency band where most of the SNR is accumulated
- extent of sensitive frequency band depend on spectral index:
  - 20-100 Hz for $\alpha = 0$; 20-100 Hz for $\alpha = 2/3$; 20-400 Hz for $\alpha = 3$

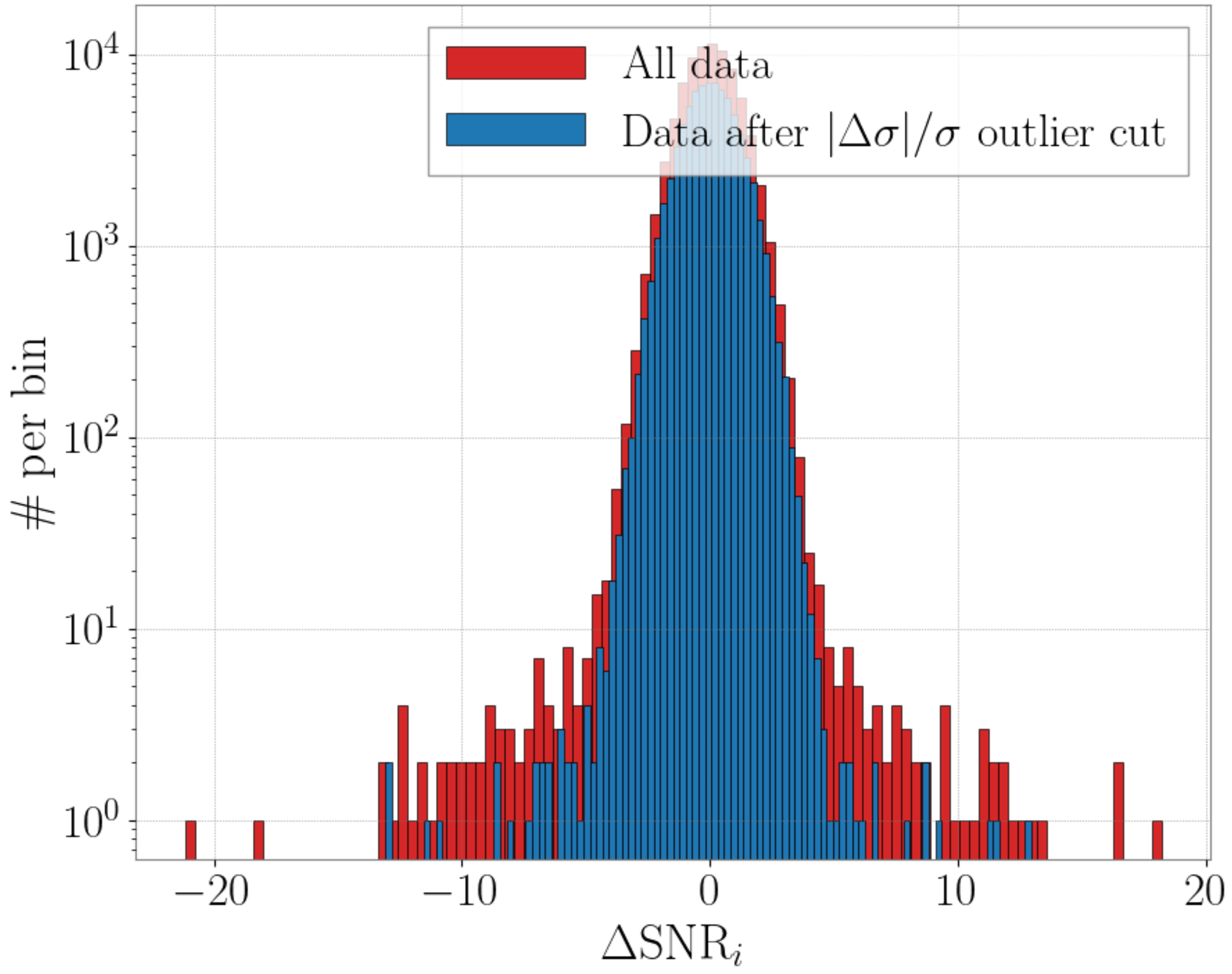
Challenge 2: detector noise is not stationary

- interferometers are non-stationary on ~ minutes time scale
  - break year-long observation into short duration segments (192 s for O3)
  - compare estimated power spectra in neighboring segments with that in analysis segment
  - reject segment if

$$\frac{|\Delta\sigma|}{\sigma} \equiv \frac{|\sigma_{\mathrm{neighbor}} - \sigma_{\mathrm{analysis}}|}{\sigma_{\mathrm{analysis}}} > 0.20$$

- effective at removing noisy segments
- lose ~20% of available live-time from $\Delta\sigma$-cut:
  - 17.9% for HL
  - 22.1% for HV
  - 21.9% for LV

[credit: 2303.15696]

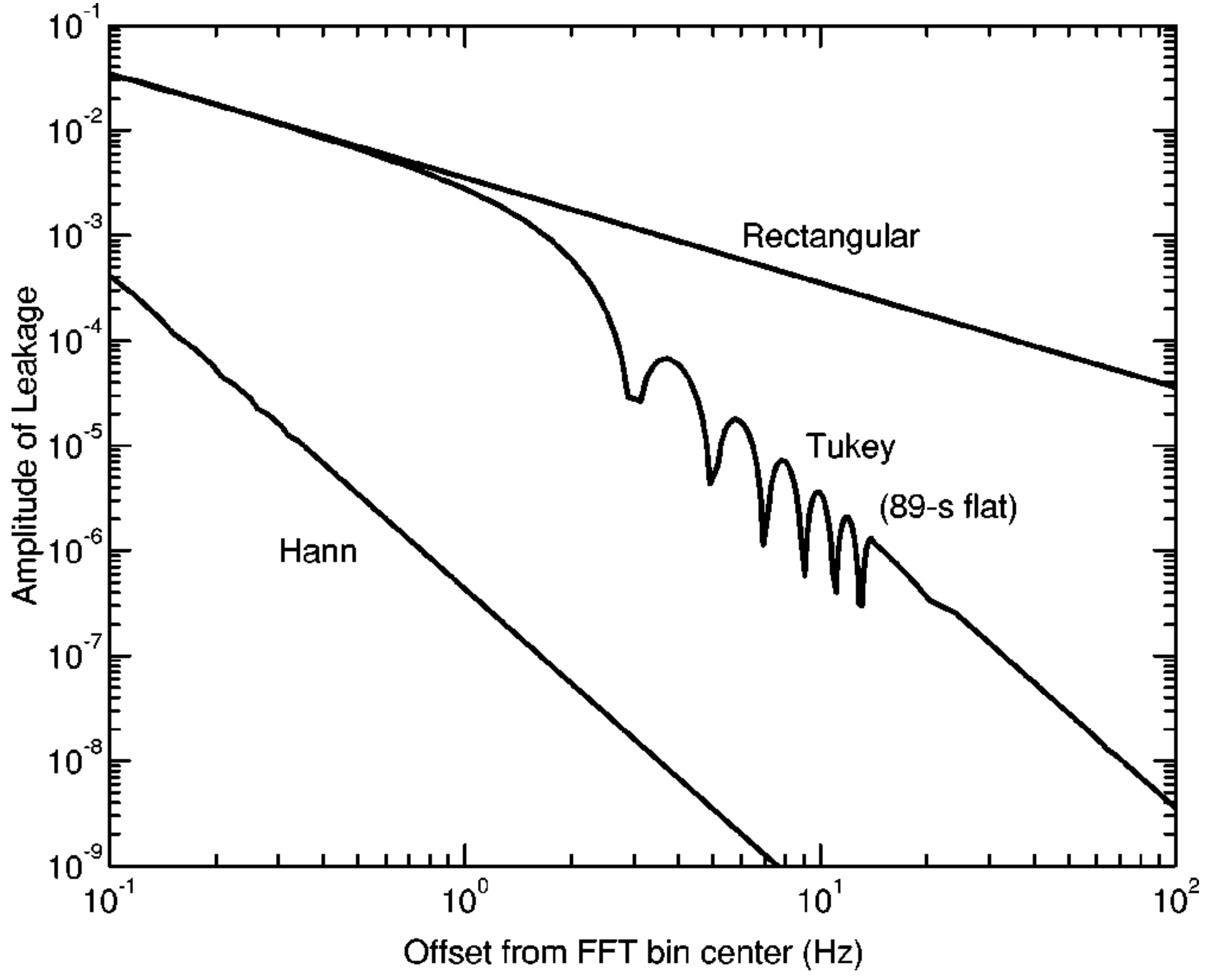


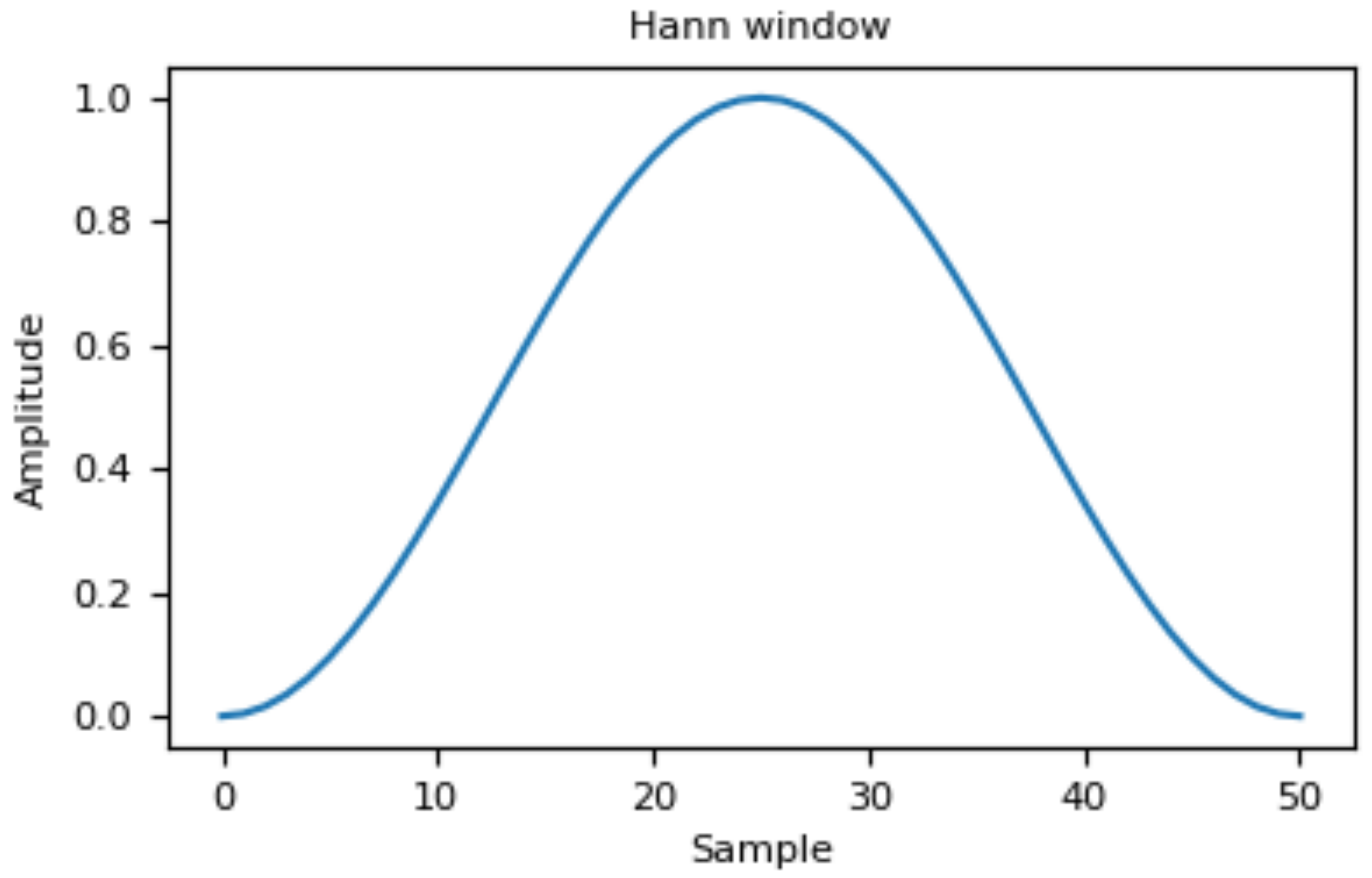
$$\Delta\mathrm{SNR}_i = \frac{\hat{\Omega}_i - \Omega_{\mathrm{opt}}}{\sigma_i}$$

Challenge 3: detector noise is not Gaussian

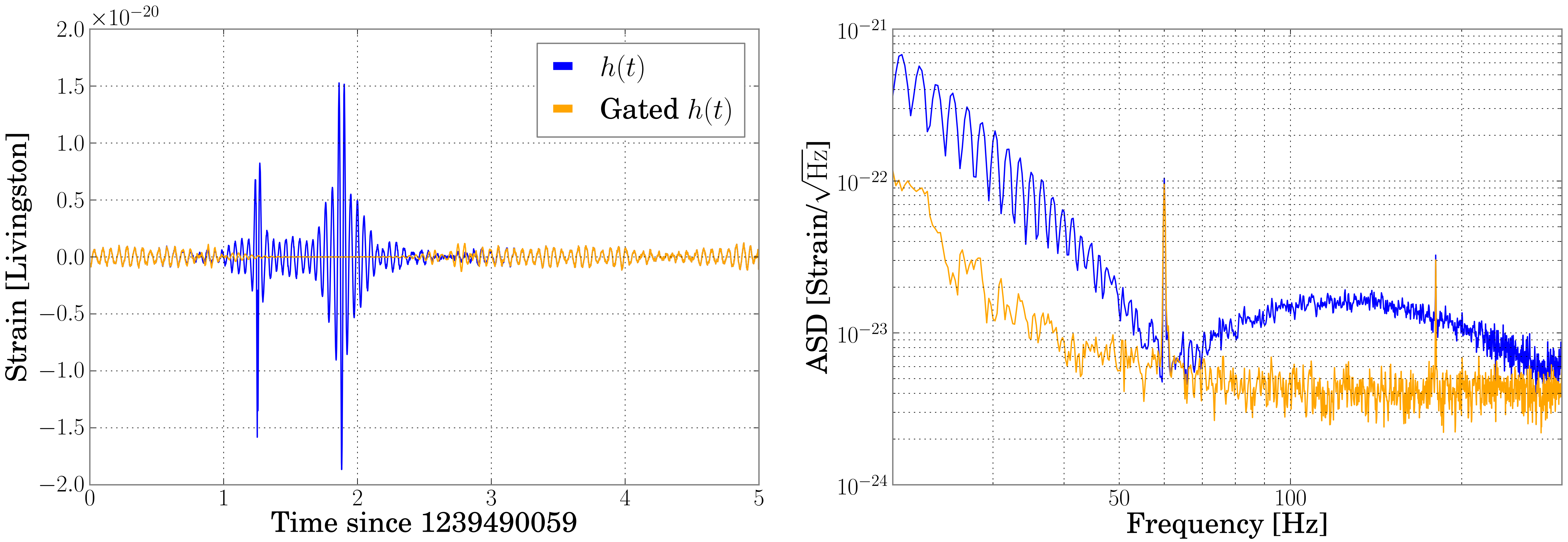
- power from strong “lines” (nx60 Hz, calibration, violin modes, …) may leak into nearby freq bins
  - Hann window data, 50% overlap
  - notch lines in frequency domain
  - O3: lose 3.2% HL, 9.3% HV, 5.9% LV of freq band <300 Hz
- large glitches in LHO, LLO were an issue for O3:
  - $\Delta\sigma$ cut removes more than 50% of segments!!
  - “gating” required (notch bad data with inv Tukey window)
  - gating bad data leads to loss of only 0.4% of data for LHO, 1% for LLO (not needed for Virgo)
  - gating doesn’t introduce spurious correlations
- new features often arise with each observing run!!

[credit: S1 stochastic paper]

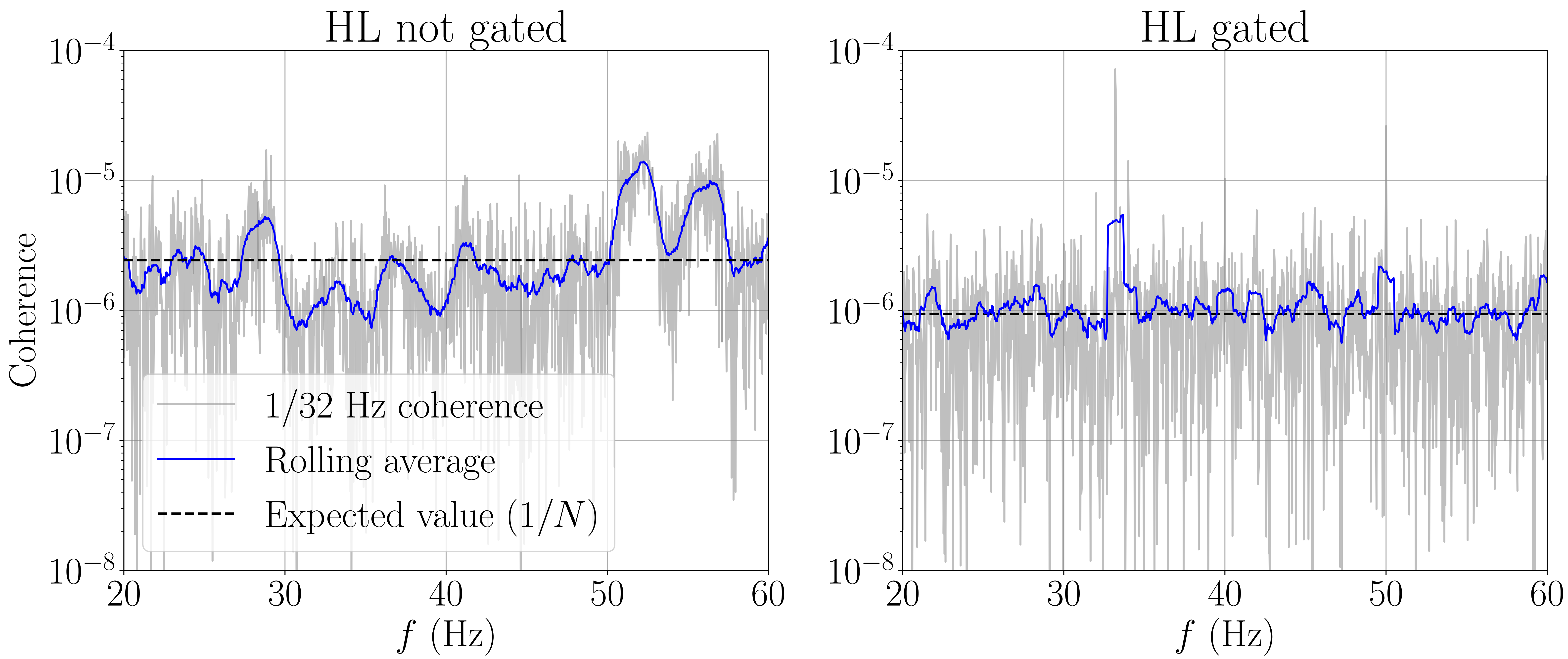




Example of gated vs non-gated data



[credit: LIGO P2000546-v2]

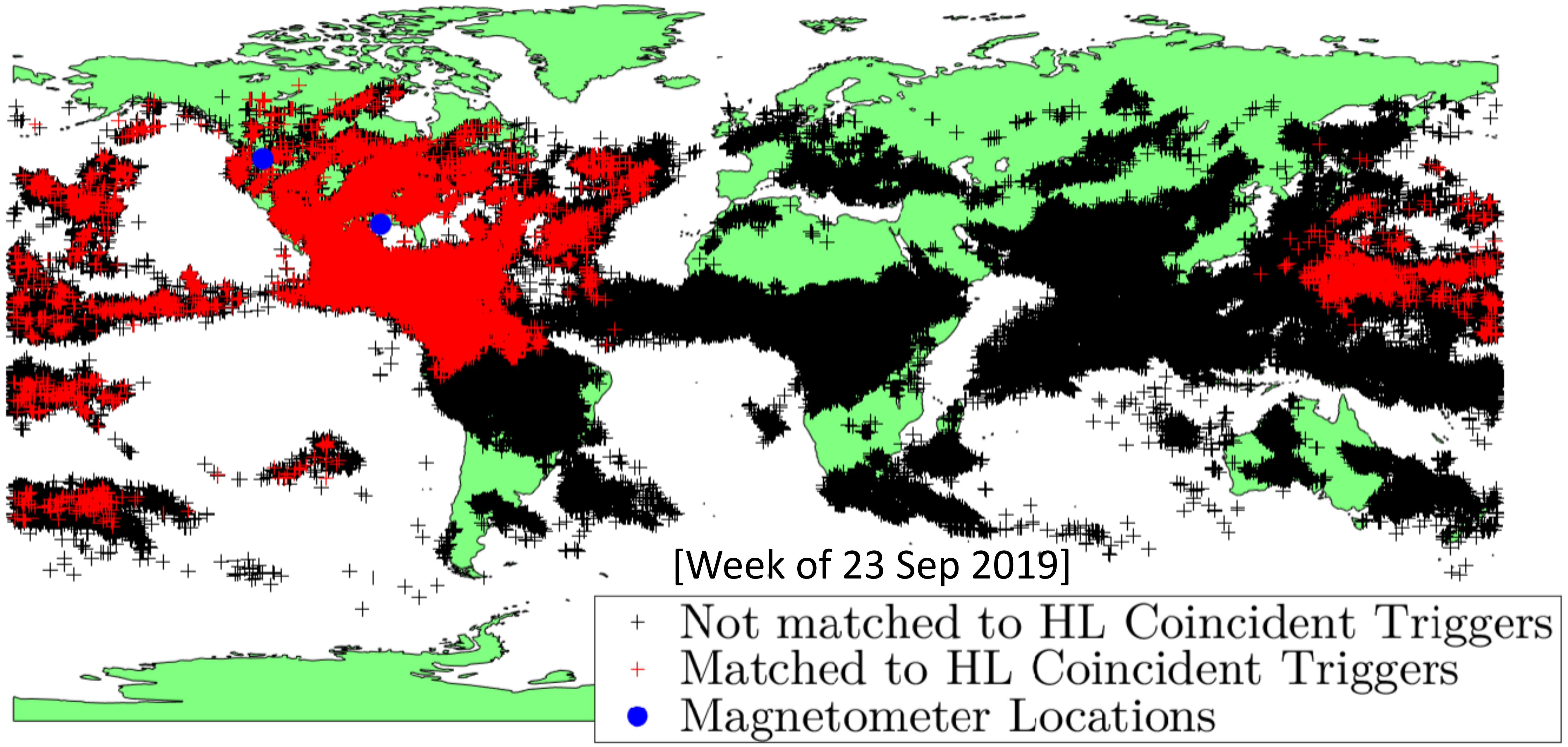


[credit: O3 isotropic paper]

$$\Gamma_{IJ} = \frac{\langle |\tilde{d}_I^*(f)\tilde{d}_j(f)|^2 \rangle}{\langle |\tilde{d}_I(f)|^2 \rangle \langle |\tilde{d}_J(f)|^2 \rangle}$$

Challenge 4: potential contamination from correlated noise

- global magnetic field fluctuations are correlated across large distances
- monitored by low-noise magnetometers installed at each site
- past analyses calculated magnetic noise budget
- for O3, also calculated Bayes factor for “magnetic correlation” model



[Week of 23 Sep 2019]

[credit: 2209.00284]

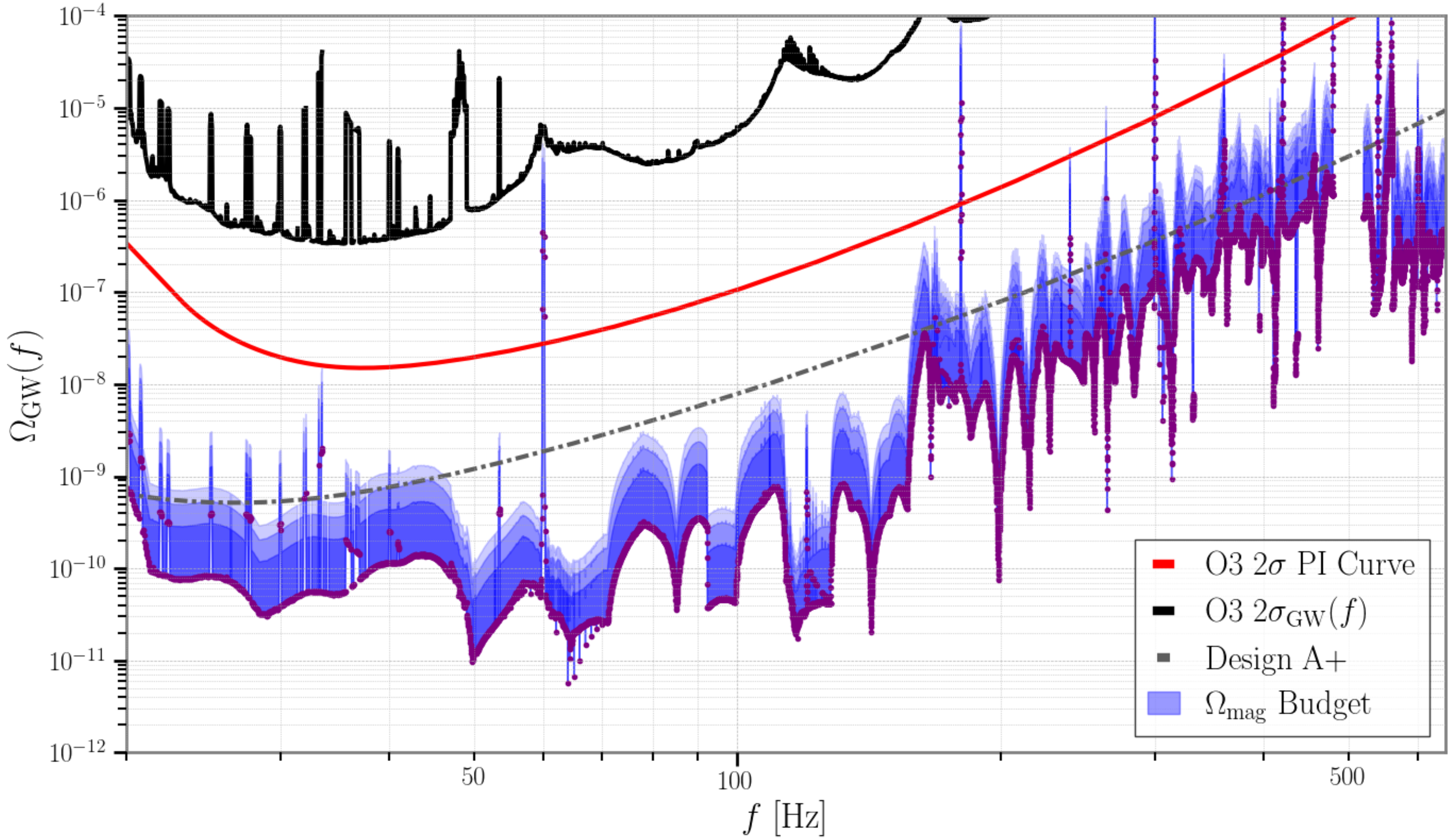
$$\hat{\Omega}_{\mathrm{mag},IJ}(f\,|\,\vec{\lambda}) = \frac{2}{T}\frac{|T_I(f)|\,|T_J(f)|\,\mathrm{Re}[\tilde{m}_I^*(f)\tilde{m}_J(f)]}{\gamma_{IJ}(f)S_0(f)}$$

$$T_I(f) = \kappa_I\left(\frac{f}{10\ \mathrm{Hz}}\right)^{\beta_I}$$

transfer function from magnetometer to GW channel

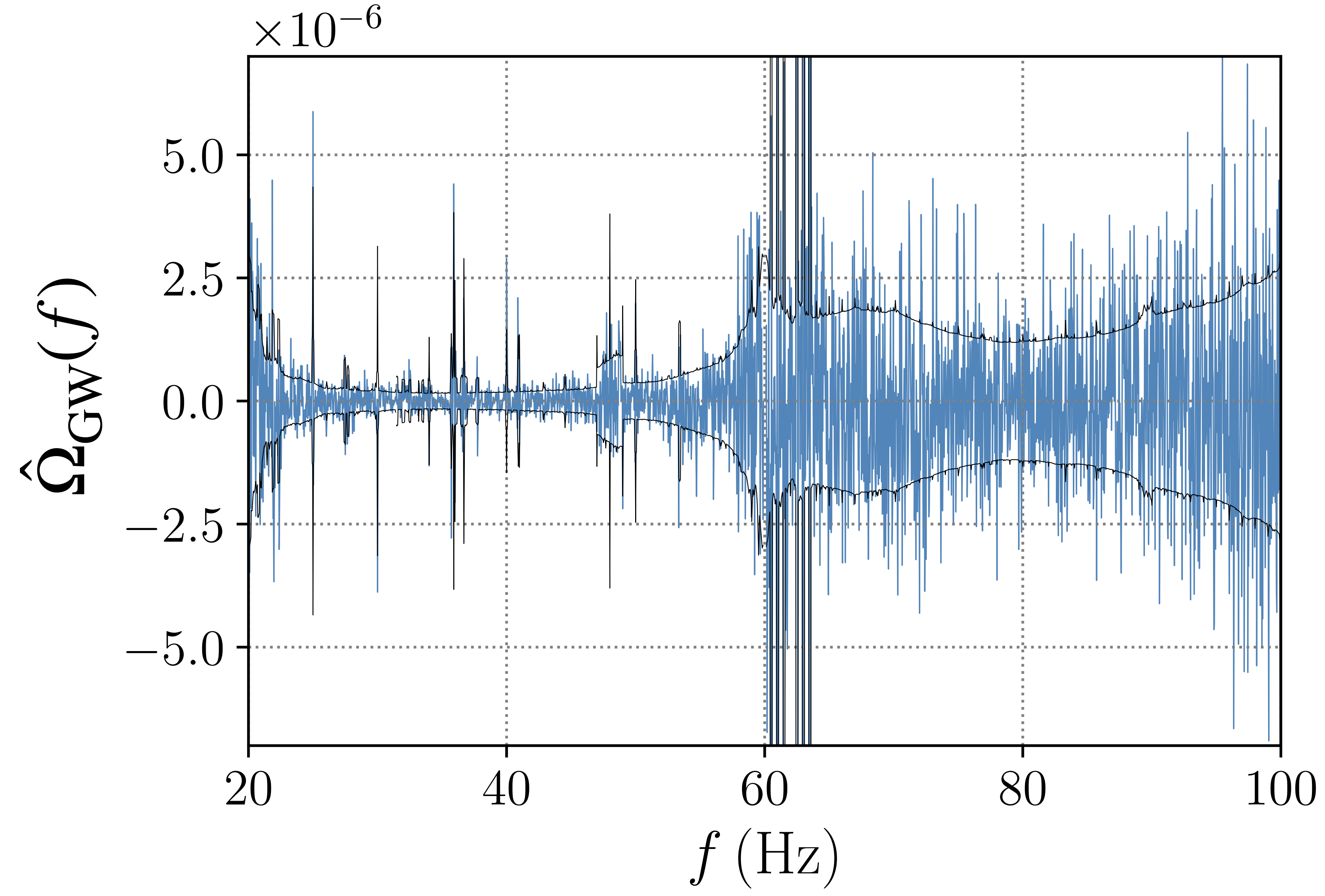
magnetic noise budget (O3 and beyond)

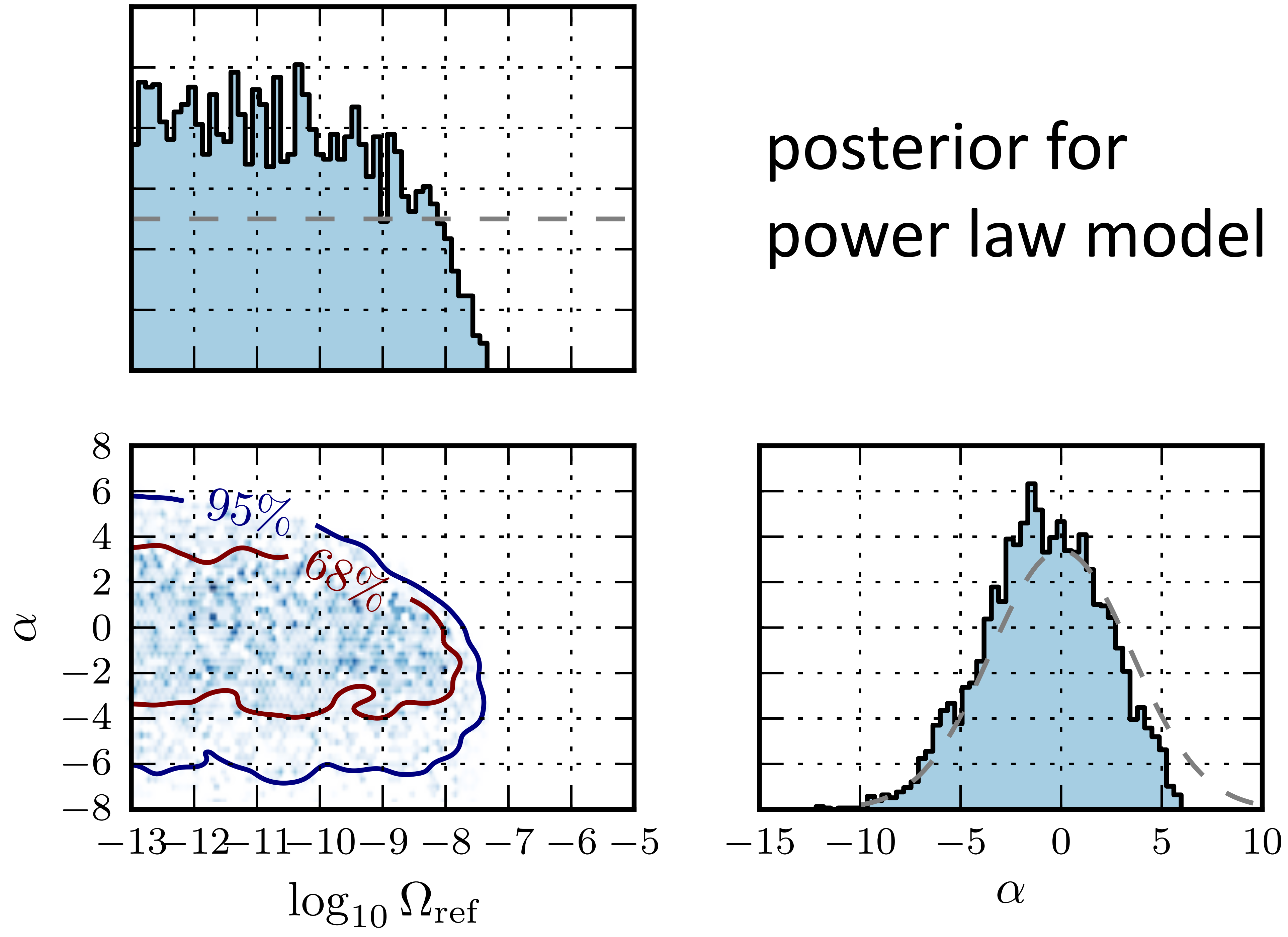
[credit: 2209.00284]



O3 results (standard isotropic search; power law model)

H,L,V combined $\Omega_{\rm GW}(f)$ cross-correlation spectrum





posterior for
power law model

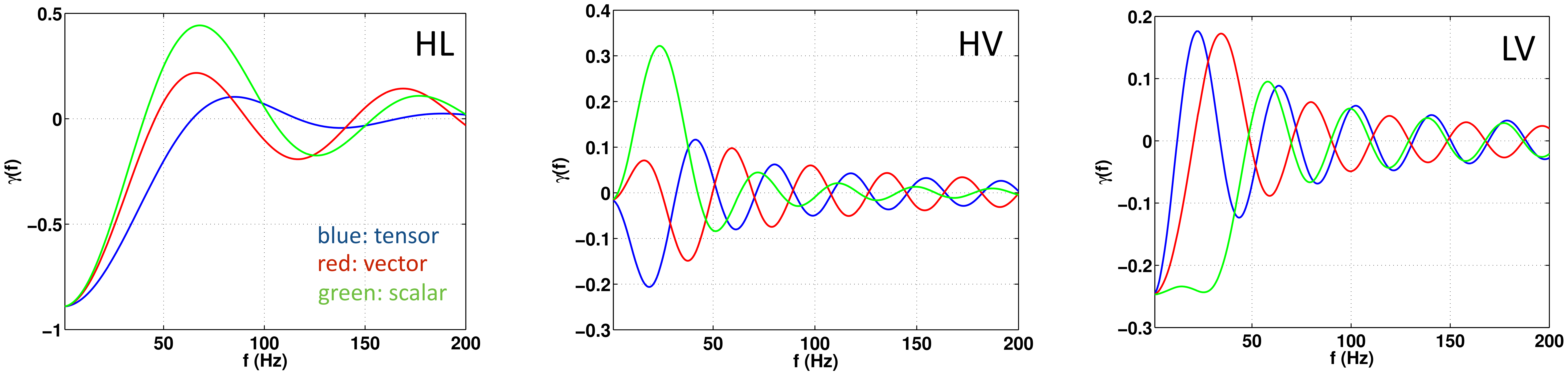
ULs
(95%)

	Uniform prior			Log-uniform prior		
α	O3	O2 [43]	Improvement	O3	O2 [43]	Improvement
0	1.7×10^{-8}	6.0×10^{-8}	3.6	5.8×10^{-9}	3.5×10^{-8}	6.0
2/3	1.2×10^{-8}	4.8×10^{-8}	4.0	3.4×10^{-9}	3.0×10^{-8}	8.8
3	1.3×10^{-9}	7.9×10^{-9}	5.9	3.9×10^{-10}	5.1×10^{-9}	13.1
Marg.	2.7×10^{-8}	1.1×10^{-7}	4.1	6.6×10^{-9}	3.4×10^{-8}	5.1

[credit: O3 isotropic paper]

O3 results (search for alternative polarization modes)

- simple modification: just swap out tensor ORFs with vector and scalar ORFs



ULs
(95%)

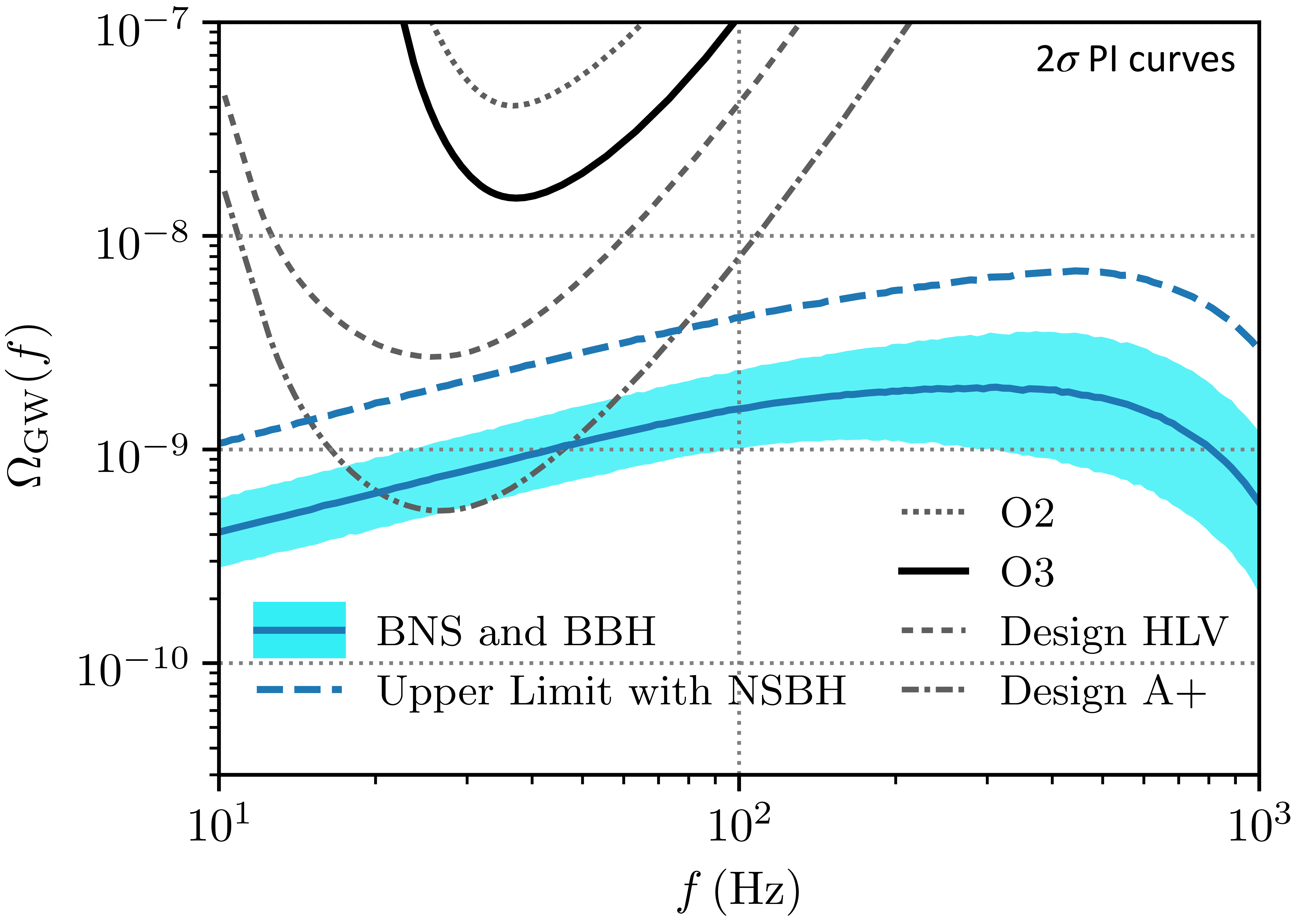
Polarization	O3	O2 [43]	Improvement
Tensor	6.4×10^{-9}	3.2×10^{-8}	5.0
Vector	7.9×10^{-9}	2.9×10^{-8}	3.7
Scalar	2.1×10^{-8}	6.1×10^{-8}	2.9

[credit: O3 isotropic paper]

O3 results (prospects for CBC background detection)

- detection of individual CBCs + assumptions about merger rate density -> revised estimate of CBC background
- CBC background probably not detectable by end of O4 unless new methods used (see Vuk's talk)

[credit: O3 isotropic paper]



O3 results (constraining the BBH merger rate history R(z))

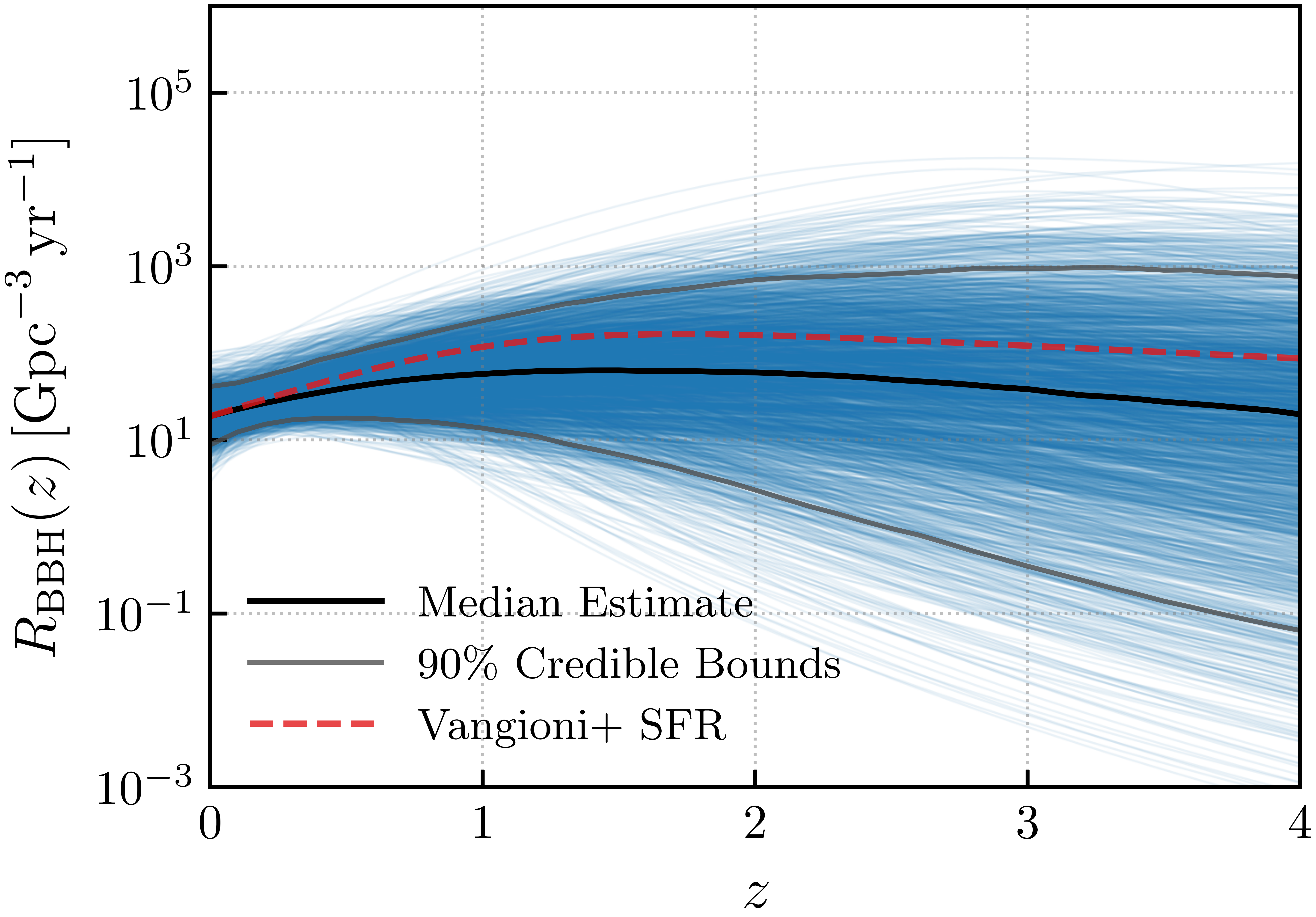
- constrain parameters describing BBH mass distribution and merger rate history using a joint CBC + stochastic analysis

$$p_{\mathrm{BBH}}(\{d\} \mid \overrightarrow{\lambda}_{\mathrm{BBH}})\, p_{\mathrm{stoch}}(\hat{\Omega}^{IJ}_{\mathrm{GW}} \mid \overrightarrow{\lambda}_{\mathrm{BBH}})$$

evaluated using
posterior samples
for masses and redshifts
of O3a BBH detections

parameters defining
empirical form of BBH
mass distribution and
merger rate history

[credit: O3 isotropic paper]



Summary

1. even the "simplest" LVK search for an isotropic GWB has challenges
2. new challenges seem to arise with each observation run!!
3. nonetheless, improvements in detector -> lower ULs

   $\Omega_{\rm gw} \lesssim 10^{-9}$ - 10^{-8} (for O3) vs. $\Omega_{\rm gw} \lesssim 40$ (for S1, twenty years ago)

4. new search methods may be needed to accelerate detection (e.g., intermittent search for population of BBH mergers)