APS APRIL MEETING 2024

IMPACT OF NOISE TRANSIENTS ON GRAVITATIONAL-WAVE BURST DETECTION EFFICIENCY OF THE *BAYESWAVE* PIPELINE WITH MULTI-DETECTOR NETWORKS

3RD OF APRIL 2024

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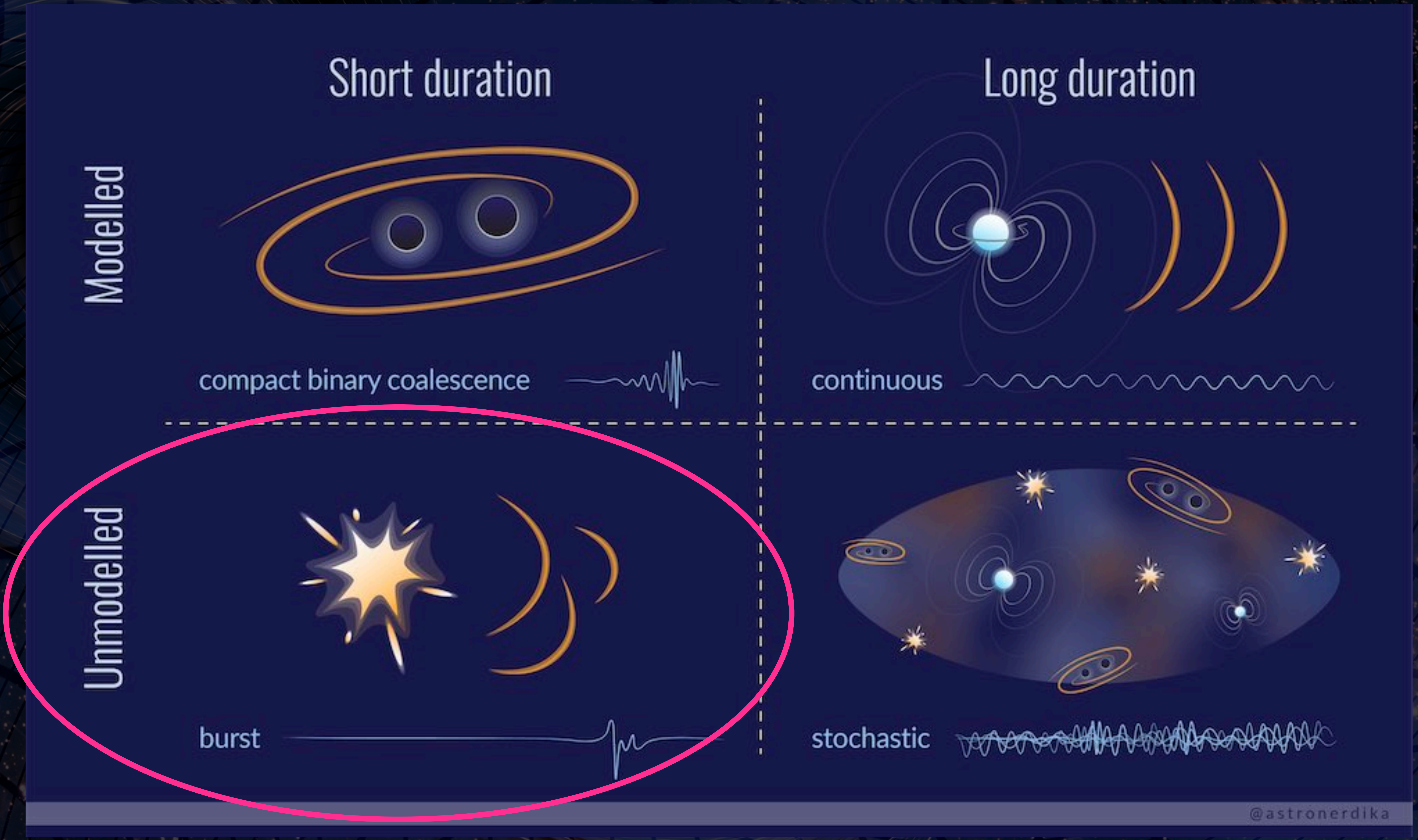
TYPES OF GW SOURCES

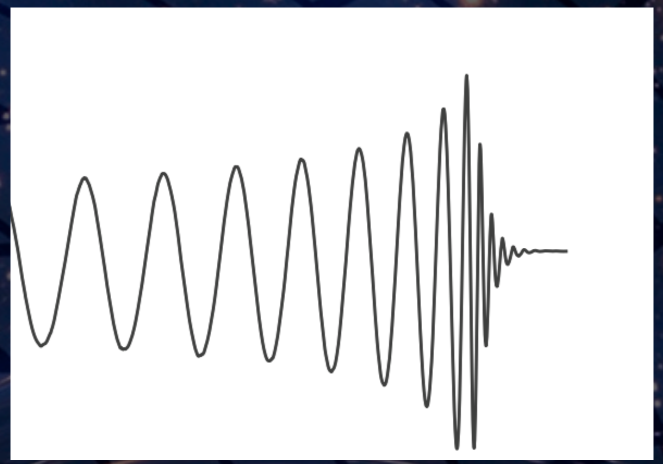


[Image credits: Shanika Galaudage]

WHAT IS IN THE DETECTOR DATA?

Data = Signal (maybe) + Noise

$\vec{s}$



$h(\vec{\theta})$

$\vec{n}$

Noise components:

$$\vec{n} = \overrightarrow{n_G} + \vec{g}$$

Stationary, Gaussian noise

Instrumental glitches (non-stationary, non-Gaussian)

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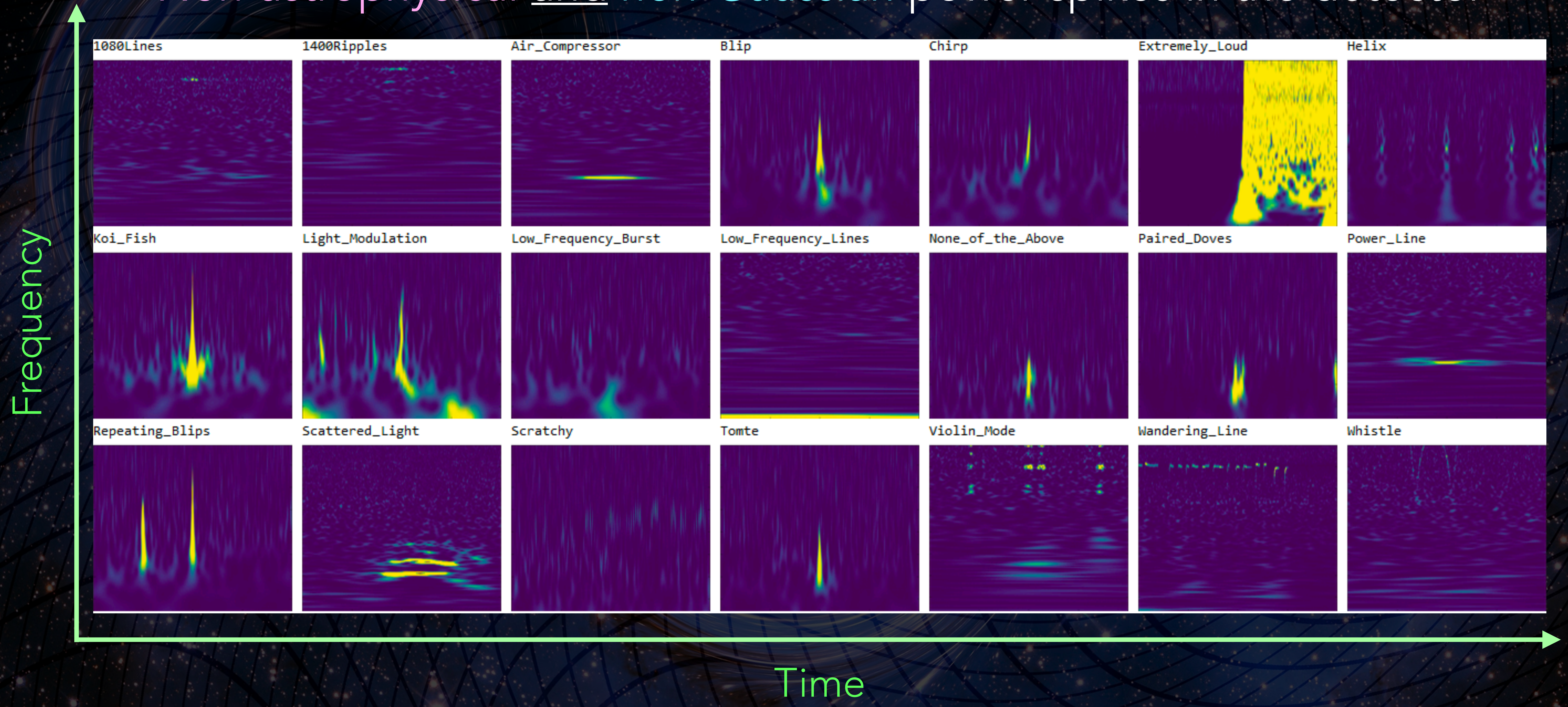
[Adapted from Meg Millhouse's slide]

THE PROBLEM: *INSTRUMENTAL GLITCHES*

Non-astrophysical and non-Gaussian power spikes in the detector



[Image from Gravity Spy]

BAYESWAVE: *ALGORITHM OVERVIEW*

- Unmodelled transient gravitational wave (burst) analysis algorithm
- Enables joint detection of instrumental glitches and GW bursts
- Reconstructs transient, non-Gaussian features in the data by summing a set of sine-Gaussian wavelets, with no *a priori* assumptions

Images courtesy of Meg Millhouse

BayesWave publications:
Cornish + Littenberg, Class. Quant. Grav 32, 130512 (2015)
Cornish et al., Phys. Rev. D 103, 044006 (2021)

BAYESWAVE: MODEL SELECTION

- Three independent models:
  - Signal plus Gaussian-noise model, $\mathscr{S}$
  - Glitch plus Gaussian-noise model, $\mathscr{G}$
  - Gaussian-noise only model, $\mathscr{N}$
- Compare models using the **Bayes Factor**

Bayesian evidence ratio between two models

$$\text{e.g. } \mathscr{B}_{\mathscr{S},\mathscr{G}} = \frac{p(\vec{s}\,|\,\mathscr{S})}{p(\vec{s}\,|\,\mathscr{G})}$$

If $\ln \mathscr{B}_{\mathscr{S},\mathscr{G}} > 0 \Rightarrow$ $\mathscr{S}$ is more strongly supported by data than $\mathscr{G}$

BAYESWAVE: ROLE IN GW BURST SEARCHES

- GWTC-1, -2 and -3:
  Assess consistency with matched-filter (model-based) searches
- O1, O2 and O3 all-sky burst searches:
  Follow-up trigger events found by coherent WaveBurst (cWB)
- Glitch subtraction
- PSD estimation

GWTC-1: Phys. Rev. X 9, 031040 (2019), **All-sky search O1:** Phys. Rev. D 95, 042003 (2017),
GWTC-2: Phys. Rev. X 11, 021053 (2021), **All-sky search O2:** Phys. Rev. D 100, 024017 (2019),
GWTC-3: arXiv:2111.03606 (2021). **All-sky search O3:** Phys. Rev. D. 104, 122004 (2021).

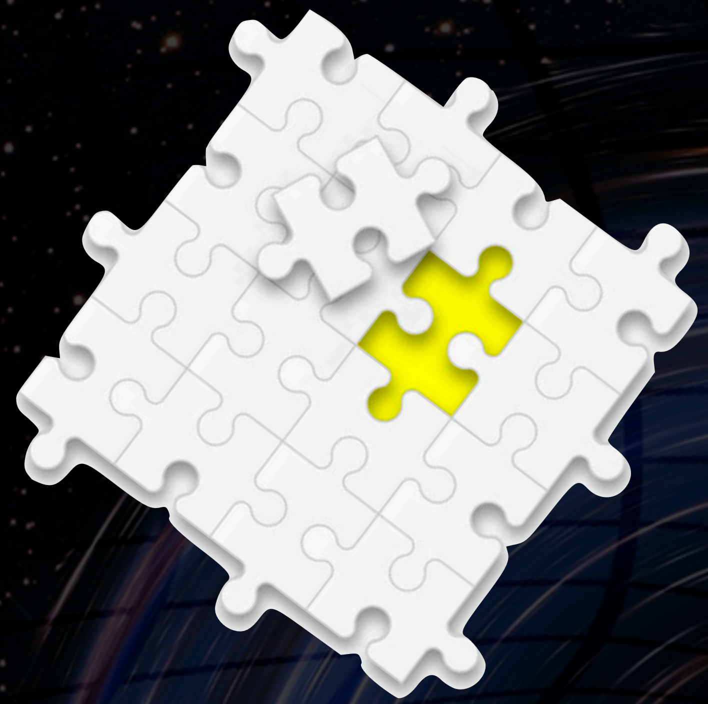
PREVIOUS WORK - PHYS. REV. D **103**, 062002

- *BayesWave's* detection statistics: $\ln \mathscr{B}_{\mathcal{S},\mathcal{G}}$
- Global detector network is expanding
- How does the size of the detector network affects $\ln \mathscr{B}_{\mathcal{S},\mathcal{G}}$?
- Analytically and empirically showed that $\ln \mathscr{B}_{\mathcal{S},\mathcal{G}}$ scales as
  - $\ln \mathscr{B}_{\mathcal{S},\mathcal{G}} \sim \mathscr{I} N \ln \mathrm{SNR}_{\mathrm{net}}$

    (i) $\mathscr{I}$: number of detectors

    (ii) N : number of wavelets (i.e. model complexity)

    (iii) $\mathrm{SNR}_{\mathrm{net}}$: signal-to-noise ratio



THE MISSING PUZZLE PIECE

- This work studies the improvement in $\ln \mathscr{B}_{\mathcal{S},\mathcal{G}}$ of astrophysical triggers with expanded detector networks
- BUT…
  Larger detector networks are more susceptible to instrumental glitches i.e. noisier detector backgrounds!

AIM OF THIS WORK

- To study the overall performance of *BayesWave* by accounting for the noise background
- Compare performance between:
  - Hanford-Livingston (HL), 2-detector network
  - Hanford-Livingston-Virgo (HLV), 3-detector network

FALSE ALARM PROBABILITY, P_{FA}

/measure of detection significance/

a function of detection statistics ($\ln \mathscr{B}_{\mathcal{S},\mathcal{G}}$)

Probability that a trigger with a given $\ln \mathscr{B}_{\mathcal{S},\mathcal{G}}$ is a false alarm

Lower P_{FA} = Higher astrophysical significance

DETECTION EFFICIENCY P_{det}

/figure of merit for *BayesWave's* overall performance/

Probability of detecting an astrophysical event with a given significance (P_{FA})

EFFICIENCY CURVES

To characterise

DETECTION EFFICIENCY P_{det}

as a function of

FALSE ALARM PROBABILITY P_{FA}

EFFICIENCY CURVE "RECIPE"

2 COMPONENTS:

(1) **NOISE BACKGROUND MEASUREMENTS** → P_{FA}

- Distribution of *BayesWave*'s detection statistics $\ln \mathscr{B}_{\mathcal{S},\mathcal{G}}$ for **non-astrophysical triggers**

(2) **ASTROPHYSICAL MEASUREMENTS** → P_{det}

- As above, but for **astrophysical triggers**

EFFICIENCY CURVE:
(1) NOISE BACKGROUND MEASUREMENT

EFFICIENCY CURVE:
(1) NOISE BACKGROUND MEASUREMENT

STEP 1: Obtaining detection statistics for background triggers

- Down-select triggers from the Coherent WaveBurst (cWB) trigger lists of O3a time-slide data
- Selected triggers satisfy the cWB nominal significance threshold: $\rho \geq 7$
- Analyse triggers using *BayesWave* to get $\ln \mathcal{B}_{\mathcal{S},\mathcal{G}}$

Method adapted from Kanner et al, Phys. Rev. D 93, 022002 (2016)

EFFICIENCY CURVE:
(1) NOISE BACKGROUND MEASUREMENT

STEP 1: Down-selecting background triggers

- From Coherent WaveBurst (cWB) trigger lists of O3a time-slide data

Stage 1 down-selection:

Triggers satisfying $\rho \geq 7$

- $\sim 2 \times 10^3$ triggers for HL
- $\sim 7 \times 10^3$ triggers for HLV

Stage 2 down-selection:

Keep only a fraction of $\rho \geq 7$ triggers (randomly selected)

- 45% of HL → 1008 triggers
- 15% of HLV → 1134 triggers

Method adapted from Kanner et al, Phys. Rev. D 93, 022002 (2016)

EFFICIENCY CURVE:
(1) NOISE BACKGROUND MEASUREMENT

STEP 2: Identifying Gaussian-noise-like background triggers

- Events more consistent with the Gaussian-noise model, $\mathscr{N}$ than the Gaussian-noise plus signal model, $\mathscr{S}$:

$$\ln \mathscr{B}_{\mathscr{S},\mathscr{N}} - \Delta \ln \mathscr{B}_{\mathscr{S},\mathscr{N}} \leq 0$$

- Meaningless to compare odds between signal and glitch models via $\ln \mathscr{B}_{\mathscr{S},\mathscr{G}}$
- Cannot remove from dataset as they still satisfy $\rho \geq 7$
- Assign arbitrarily low detection statistics: $\ln \mathscr{B}_{\mathscr{S},\mathscr{G}} = -500$
- **THIS APPLIES TO ALL EVENTS IN THIS STUDY!**

EFFICIENCY CURVE:
(1) NOISE BACKGROUND MEASUREMENT

STEP 3: Calculate P_{FA} as a function of $\ln \mathscr{B}_{\mathcal{S},\mathcal{G}}$

P_{FA}
/probability of false alarm/

Fraction of non-astrophysical triggers detected above a given $\ln \mathscr{B}_{\mathcal{S},\mathcal{G}}$ threshold

EFFICIENCY CURVE:
(1) NOISE BACKGROUND MEASUREMENT

STEP 3: Calculate P_{FA} as a function of $\ln \mathscr{B}_{\mathcal{S},\mathcal{G}}$

P_{FA}
/probability of false alarm/

Per-trigger probability (i.e. fraction) of non-astrophysical triggers detected above a given $\ln \mathscr{B}_{\mathcal{S},\mathcal{G}}$ threshold

Why not False alarm RATE (FAR)?

- FAR is a time-averaged quantity
- The timescales of HL and HLV time-slide background data are different

- P_{FA} is time-independent and marginalises over the number of triggers analysed is more suitable for comparison between the two networks

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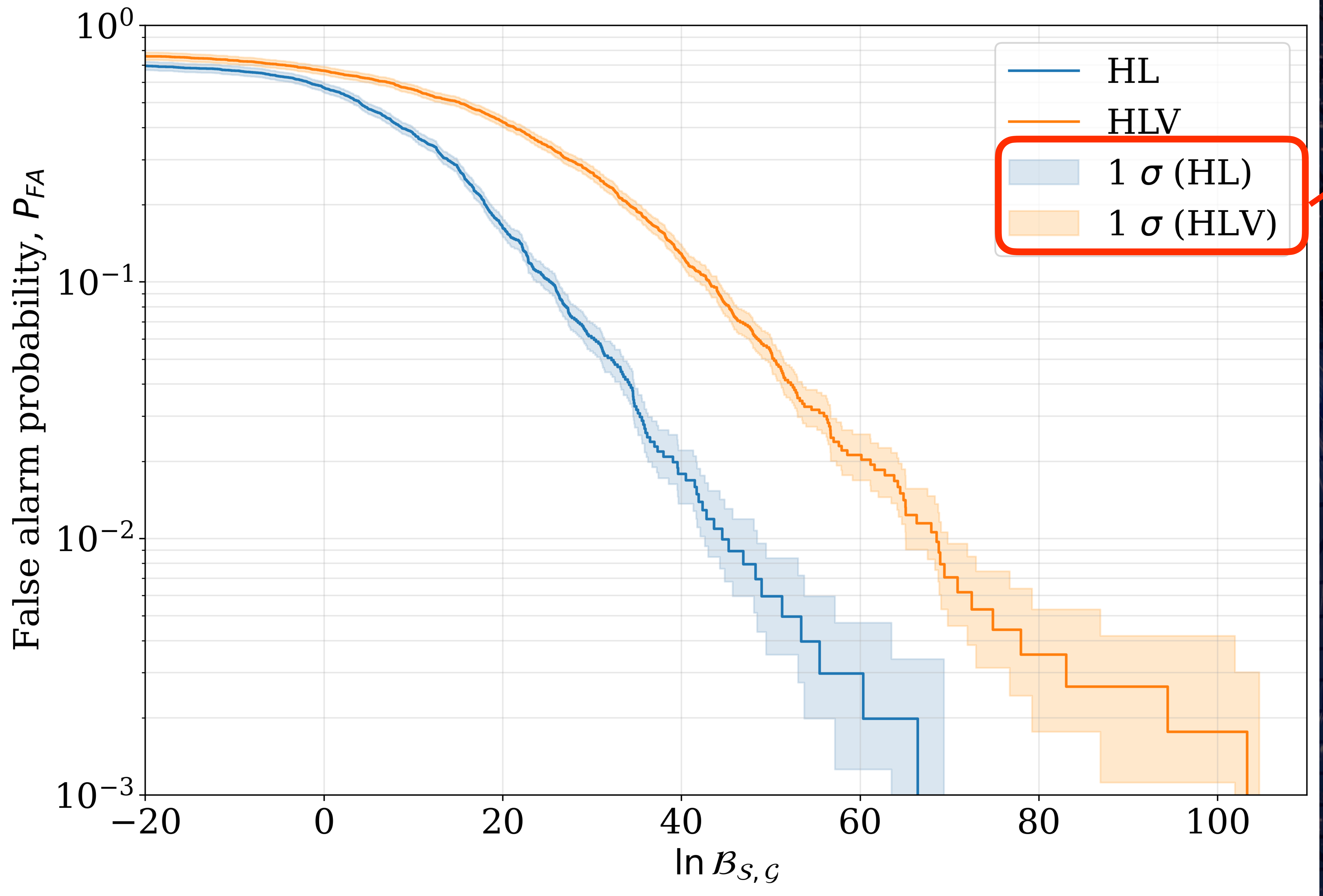
EFFICIENCY CURVE:
(1) NOISE BACKGROUND MEASUREMENT



STEP 3: Error bars

Assume Poisson process

s.t.

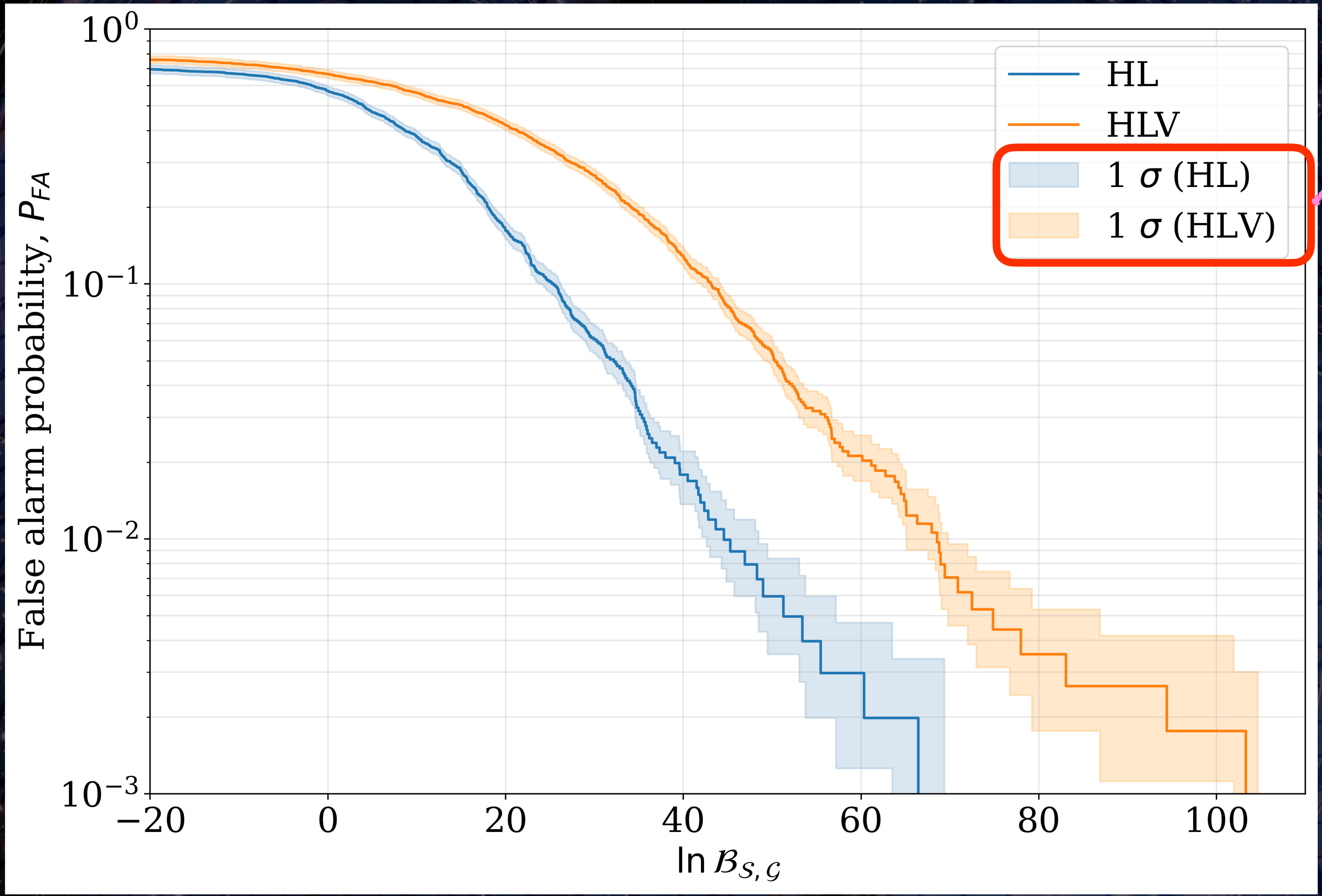
1-σ in background event counts, $n = \sqrt{n}$

$\therefore$

1-σ in P_{FA} is $\dfrac{\sqrt{n}}{N}$

N: Total number of triggers (1008 in HL, 1134 in HLV)

EFFICIENCY CURVE:
(1) NOISE BACKGROUND MEASUREMENT



Poisson uncertainty region

Assuming background noise is a Poisson process

P_{FA} in HLV is <u>higher than HL</u> for all $\ln \mathscr{B}_{\mathcal{S},\mathcal{G}}$

i.e. HLV background is NOISIER than HL

EFFICIENCY CURVE:
(2) ASTROPHYSICAL MEASUREMENTS: PHENOMENOLOGICAL INJECTIONS

EFFICIENCY CURVE: (2) ASTROPHYSICAL MEASUREMENTS

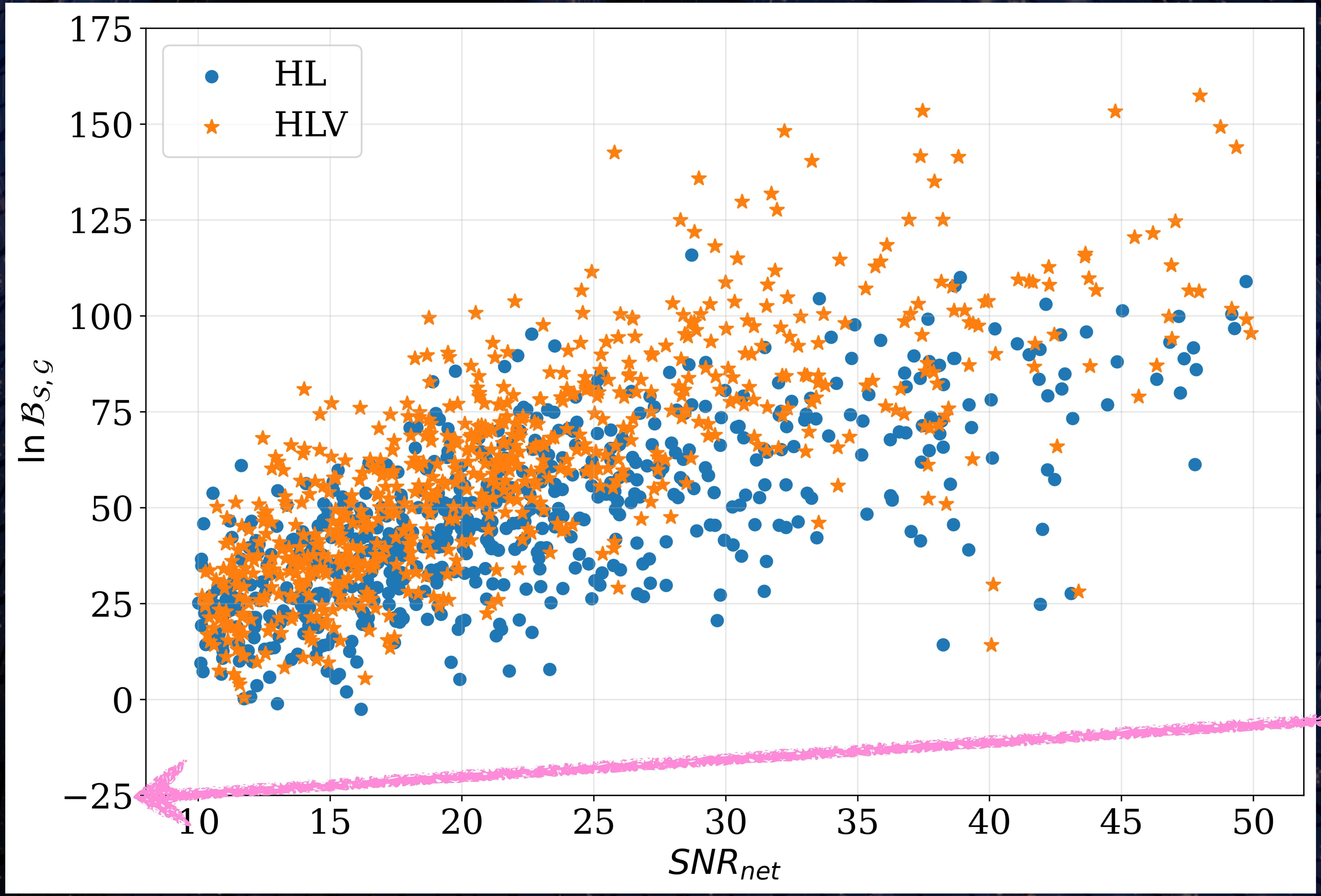
Properties of Injection Set 1 (IS1)

- **Phenomenological binary black hole (BBH) waveforms**
- **Injected into** randomly selected segments throughout all of **O3a**
- 790 injections, all satisfying $\mathrm{SNR}_{\mathrm{net}} \geq 10$

  c.f. Only followed-up cWB (background) events with $\rho \geq 7$

EFFICIENCY CURVE: (2) ASTROPHYSICAL MEASUREMENTS

Distribution of IS1 injections



Consistent with previous work:

$$\ln \mathscr{B}_{\mathcal{S},\mathcal{G}} \sim \mathcal{I} N \ln \mathrm{SNR}_{\mathrm{net}}$$

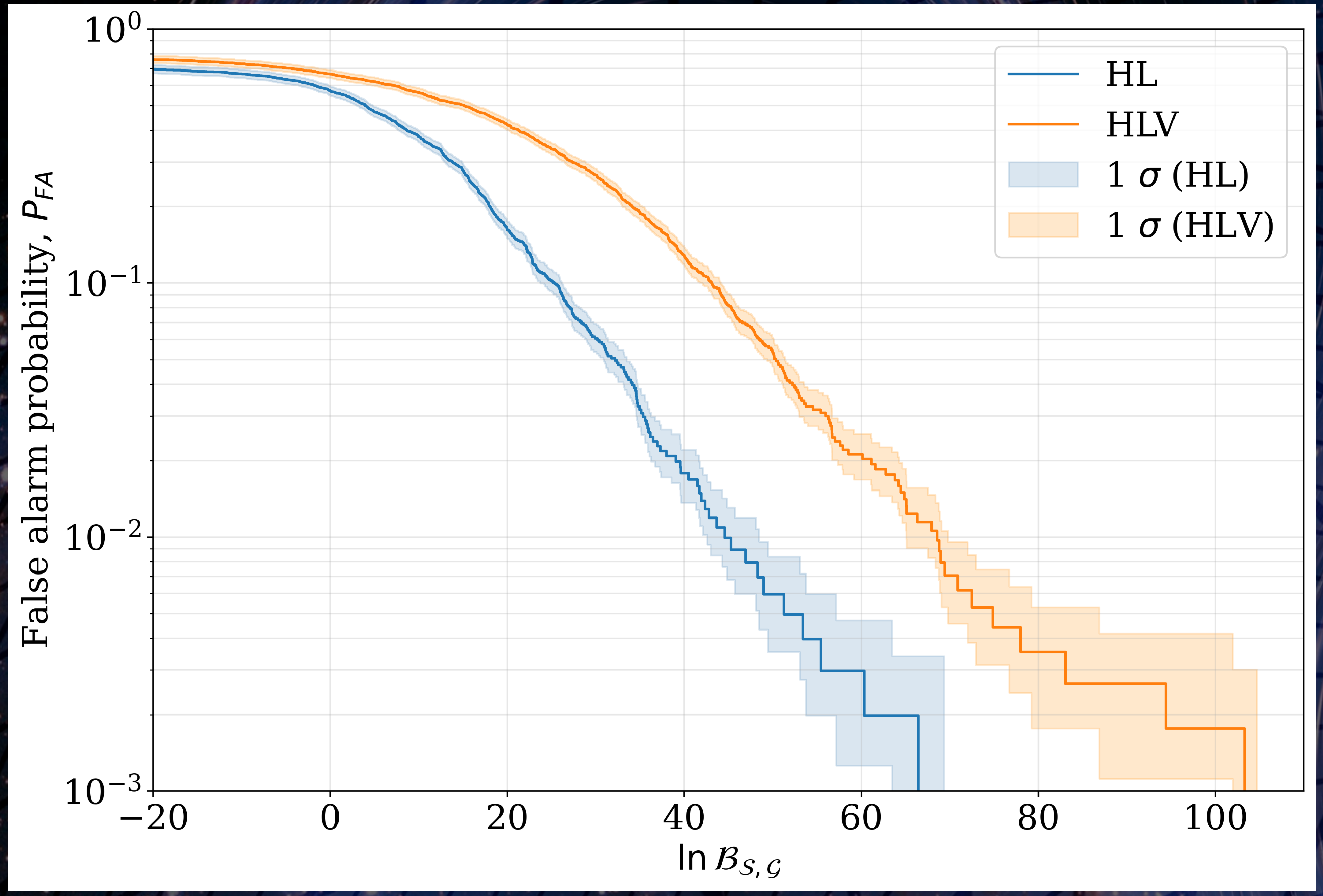
$\ln \mathscr{B}_{\mathcal{S},\mathcal{G}} = -500$ events not shown

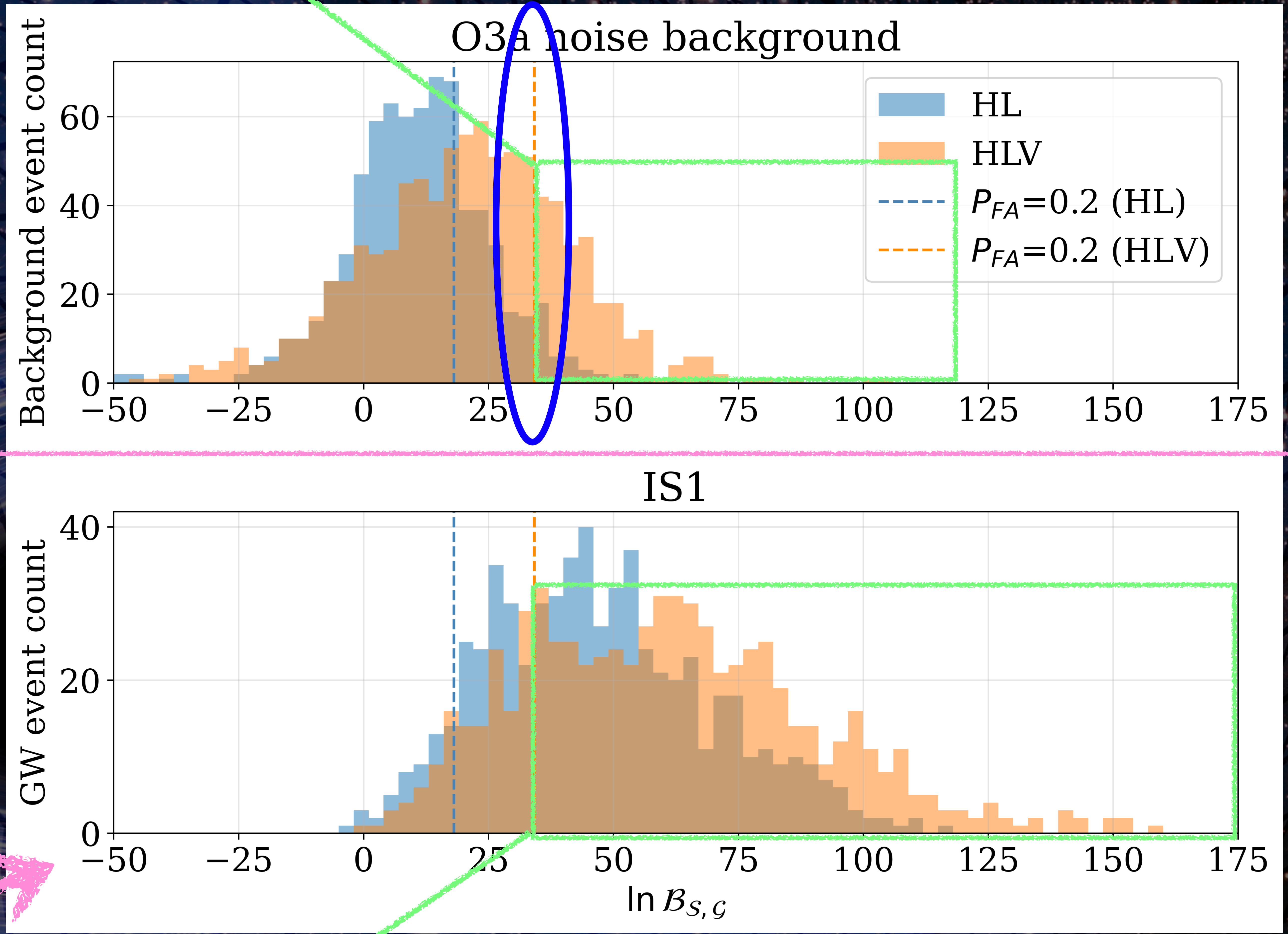
CONSTRUCTING EFFICIENCY CURVE

$P_{\mathrm{FA}} = 0.2$

/probability of false alarm/

Fraction of non-astrophysical triggers detected above a given $\ln \mathscr{B}_{\mathcal{S},\mathcal{G}}$ threshold





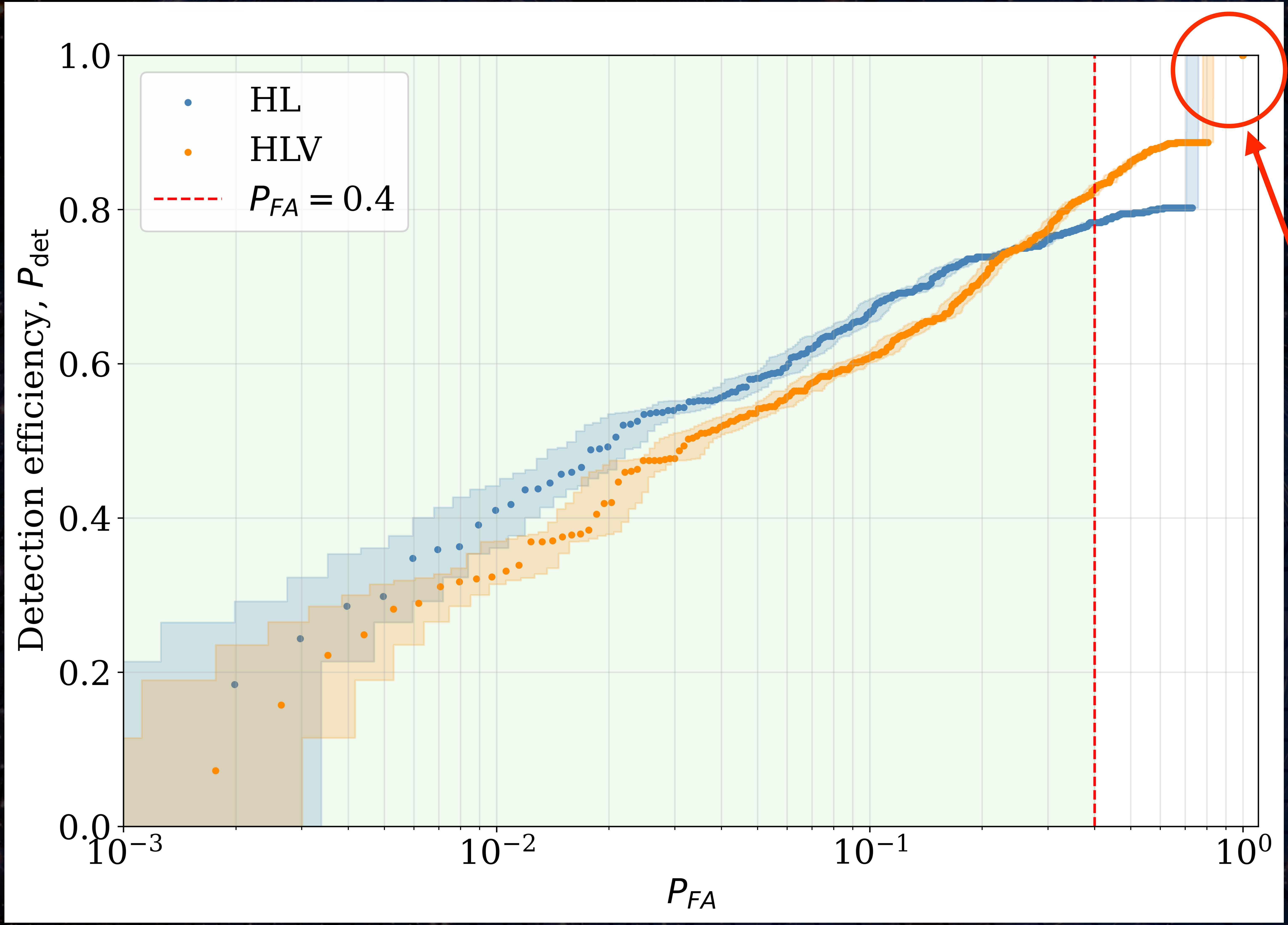
Again, $\ln \mathscr{B}_{\mathcal{S},\mathcal{G}} = -500$ events not shown

P_{det}

/Detection efficiency/

Fraction of astrophysical events detected with significance i.e. $P_{\mathrm{FA}} \geq 0.2$

EFFICIENCY CURVES OF HL AND HLV



1-σ P_{FA} **POISSON UNCERTAINTY REGION**

same as background measurement

Cluster of Gaussian-noise-like events with

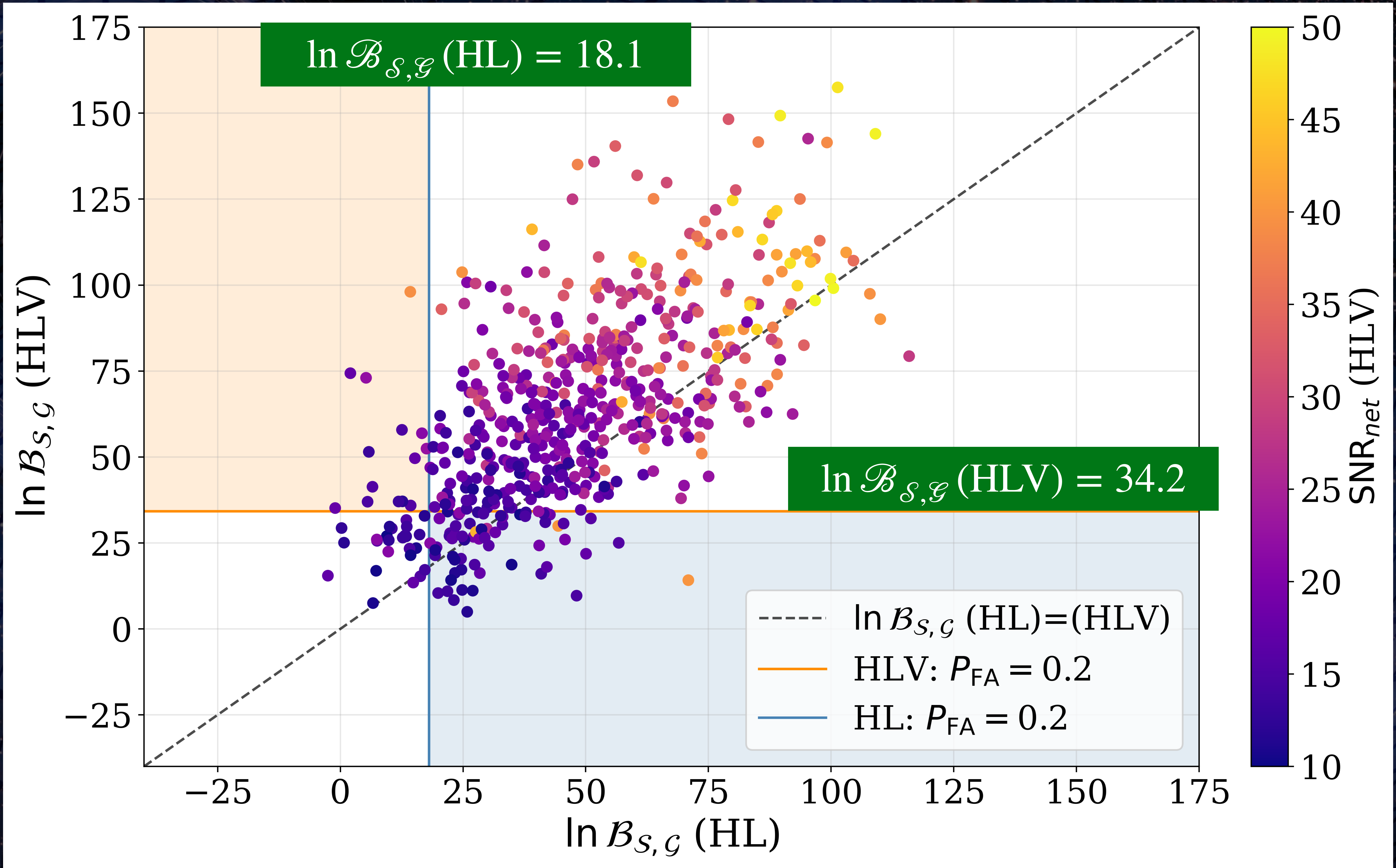
$\ln \mathscr{B}_{\mathscr{S},\mathscr{G}} = -500$ and $P_{\mathrm{FA}} = 1$

(i.e. minimal detection significance)

Practically meaningful regime $P_{\mathrm{FA}} \leq 0.4$

No significant difference between P_{det} of HL and HLV

P_{FA} AND $\ln \mathscr{B}_{\mathscr{S},\mathscr{G}}$ COMPARISON



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INJECTION SET 2 (IS2)
O3-LIKE CBC INJECTIONS

(1) A consistency check

(2) To measure *BayesWave*'s detection significance of O3 GW candidates

Using the HL and HLV backgrounds measured in this study

O3-LIKE CBC INJECTIONS

Properties of Injection Set 2 (IS2)

- **Off-source waveforms:**
  - Waveform parameters sampled from matched-filter posteriors of O3 GW events
  - Injected in the proximity of the actual event
- **18 GW events, each with 50 off-source waveforms**
  - Only follow-up injections with $\mathrm{SNR}_{\mathrm{net}} \geq 10$

O3-LIKE CBC INJECTIONS

Properties of Injection Set 2 (IS2)

- **Off-source waveforms:**
  - Waveform parameters sampled from matched-filter posteriors of O3a/O3b candidate GW events, injected in the proximity of the actual event
  - Consistency test candidates in GWTC-2/GWTC-3
- 17 candidates from O3a, 5 candidates from O3b
  ** O3b waveforms are injected into random segments of O3a data
- 50 off-source waveforms per GW candidate
  i.e. (17+5) x 50 = 1100 injections in IS2

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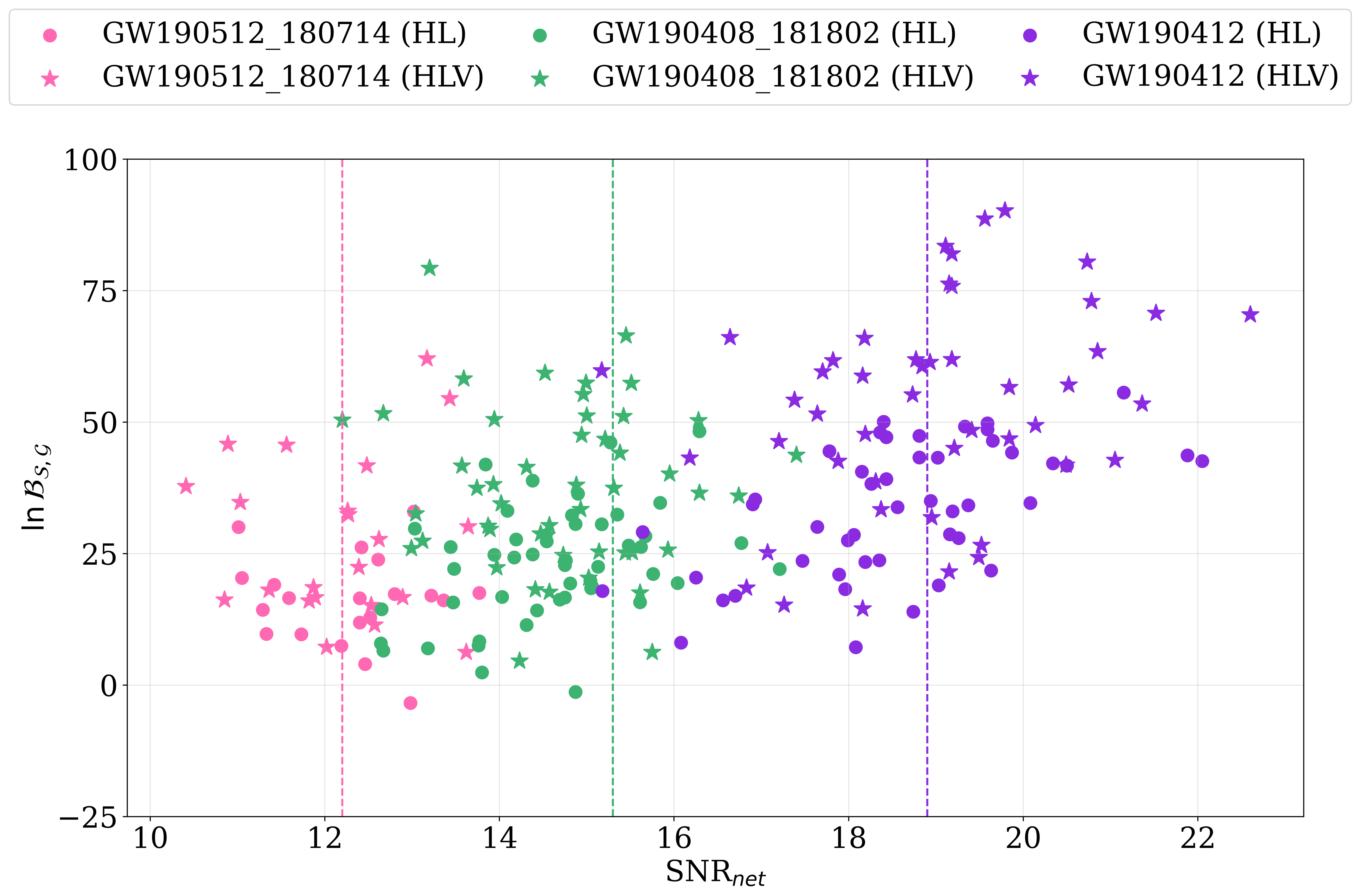
O3-LIKE CBC INJECTIONS

Filtering Injection Set 2 (IS2)

- **Non-detections:**
  - Only follow-up injections with $\mathrm{SNR}_{\mathrm{net}} \geq 10$
  - 4 (low match-filter SNR) GW candidates removed $\because \leq 25$ (less than half of) off-source waveforms satisfy *BayesWave*'s detection criteria
- **Gaussian-noise-like injections**
  - Assign arbitrarily low detection statistics: $\ln \mathscr{B}_{\mathscr{S},\mathscr{G}} = -500$

O3-LIKE CBC INJECTIONS

Visualising distributions of off-source injections



Median match-filter SNR

GW190512_180714 → 12.2

GW190408_181802 →15.3

GW190412 → 18.9

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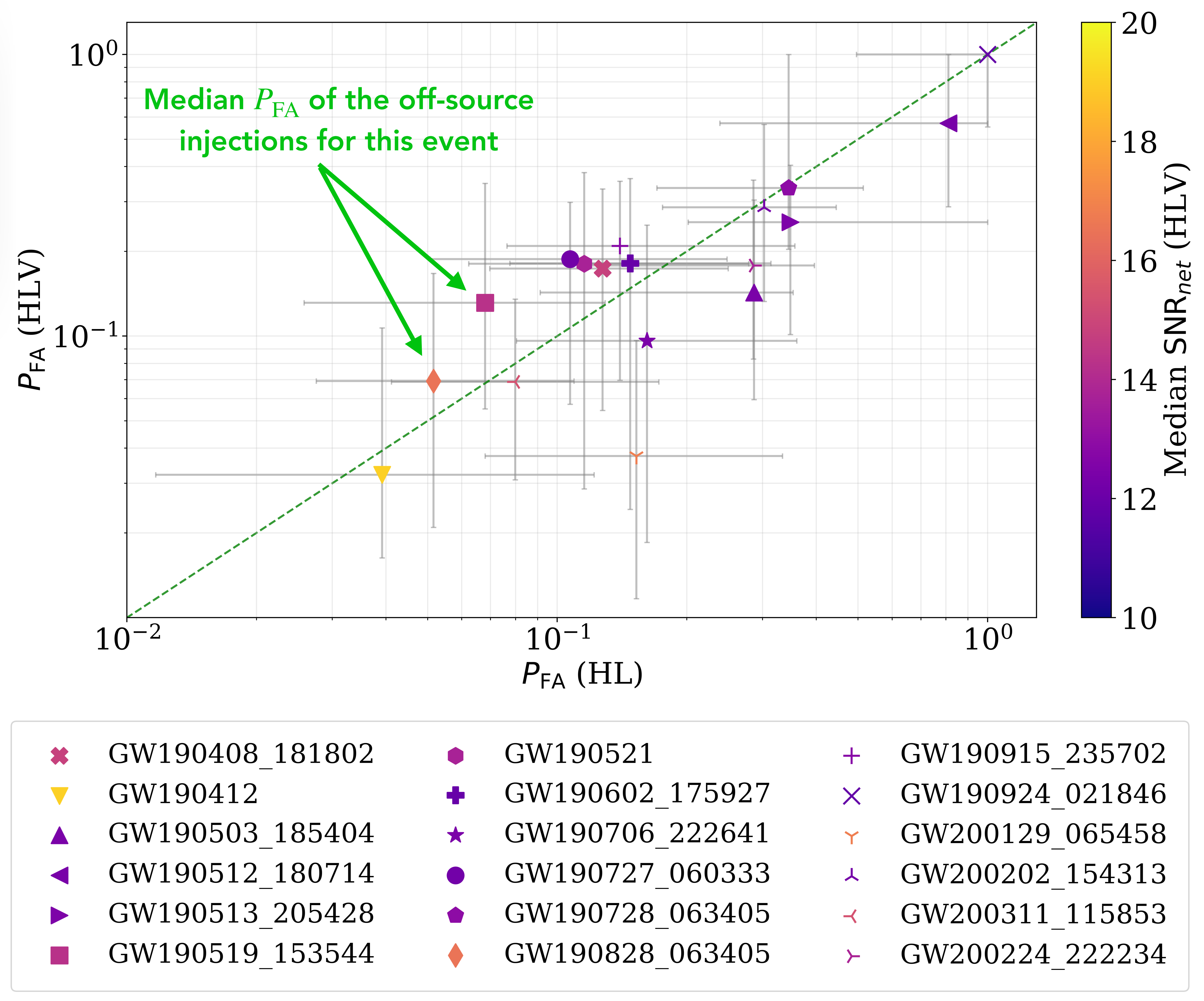
P_{FA} comparison - HLV vs. HL

18 O3-LIKE CBC INJECTIONS

Error bars

IQR of P_{FA} within each GW candidate

All events are detected with comparable significance between HL and HLV



SUMMARY OF RESULTS

- **Both the phenomenological BBH injections (IS1) and O3-like events (IS2) show comparable *BayesWave* performance with HL and HLV**
  - Although $\ln \mathscr{B}_{\mathcal{S},\mathcal{G}}$ increases with more detectors,
    false alarm probability P_{FA} is also higher (i.e. noisier detector backgrounds)
    ∴ Larger detector networks need to attain higher $\ln \mathscr{B}_{\mathcal{S},\mathcal{G}}$ to achieve the same significance (P_{FA}) as smaller networks

- **Findings consistent with:**
  - LVK O3 all-sky burst search (Phys. Rev. D **104**, 122004)
  - ML-enhanced cWB burst search, Szczepańzyk et al. (2023)

@AstroOrca

KEY TAKEAWAY

BayesWave's detection efficiency is comparable for two- and three-detector networks

because

more frequent glitches in expanded detector networks offsets the advantage of higher detection statistics ($\ln \mathscr{B}_{\mathscr{S},\mathscr{G}}$)

Link to arXiV

Accepted PRD - arXiv:2403.16837 (2024)