SN2025gw, Warsaw

DEDICATED-FREQUENCY ANALYSIS OF GRAVITATIONAL-WAVE BURSTS FROM CORE COLLAPSE SUPERNOVAE

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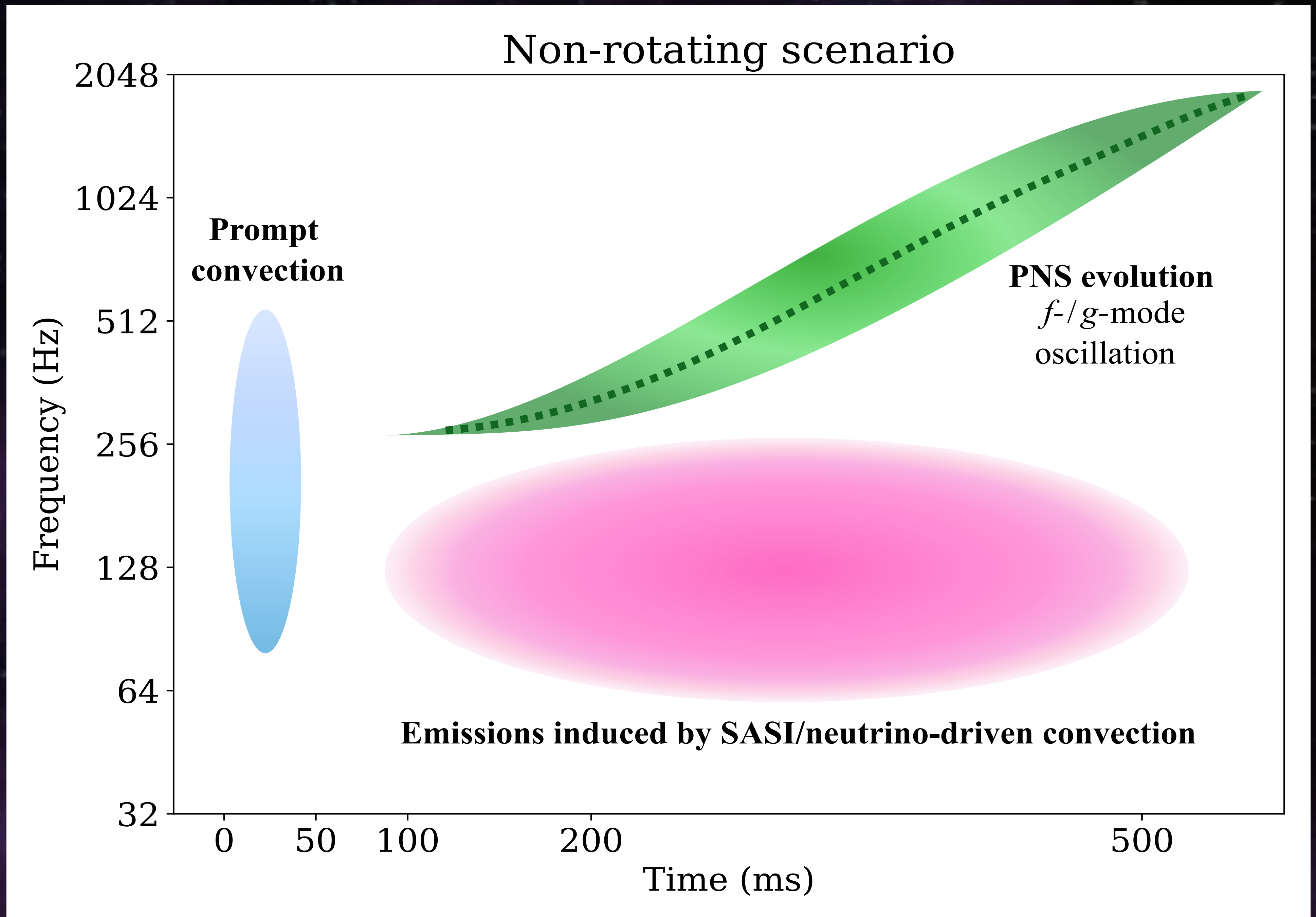
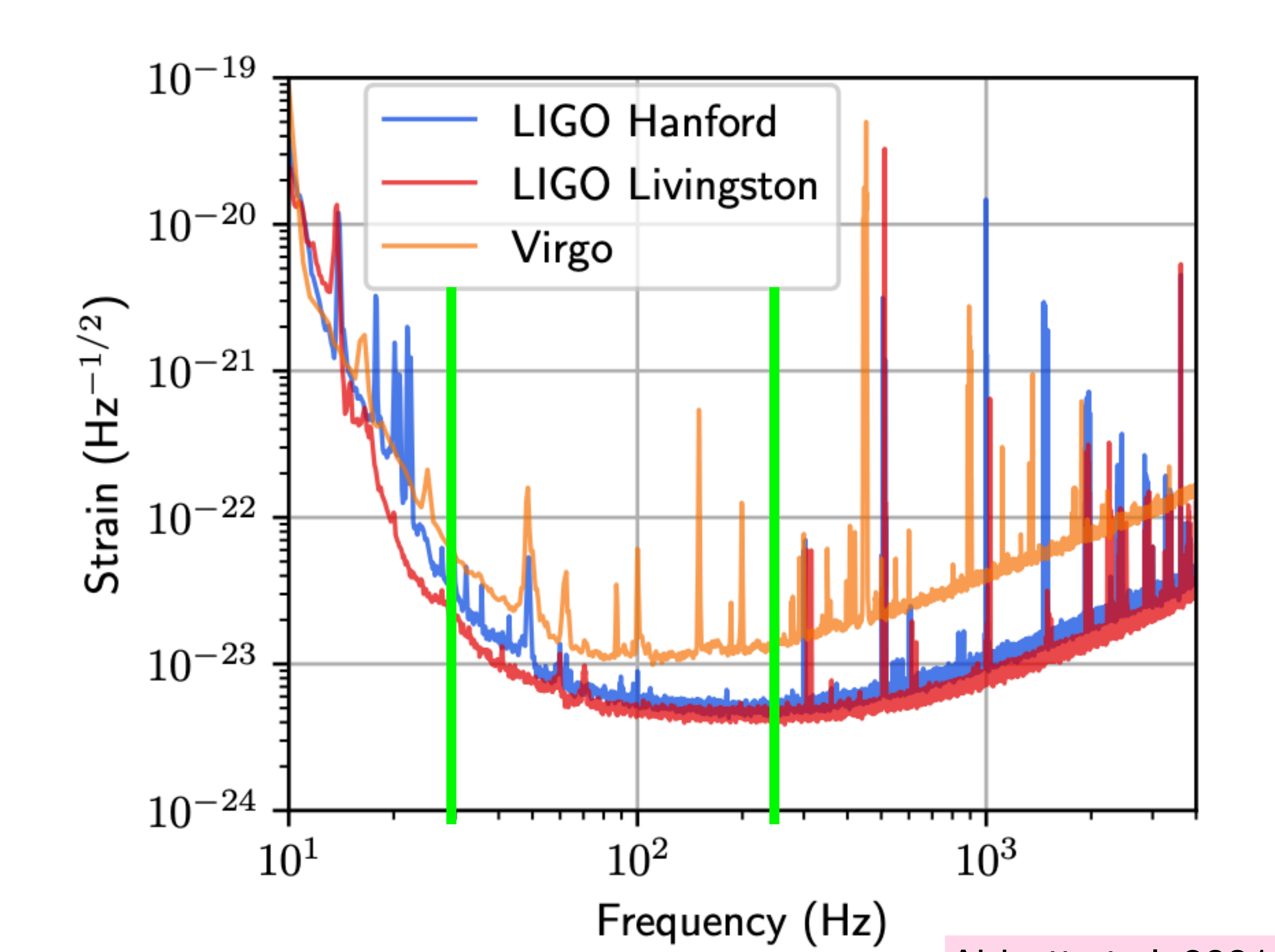
TALK OVERVIEW

- GW signatures from core-collapse supernova (CCSN)
- Introducing the **dedicated-frequency framework**
- Analysis pipelines: coherent WaveBurst and *BayesWave*
- Use-cases and workflow
- Applications of the low-frequency follow-up
- Applications of the high-frequency follow-up
- Conclusion

CCSN GW SIGNATURES

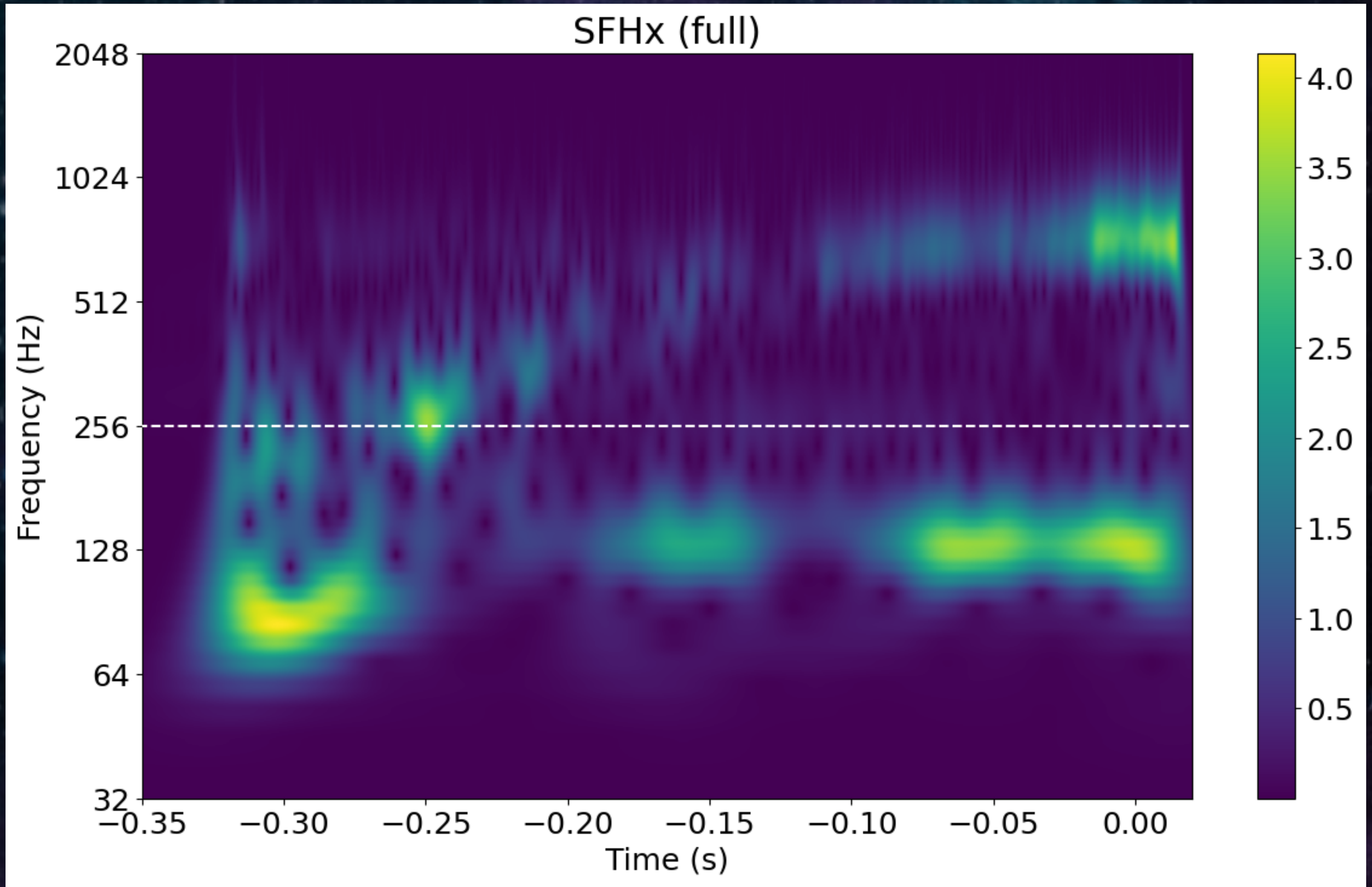
- **High-frequency** (~ 400-2000 Hz)
  - ✓ Protoneutron star (PNS) oscillations
  - ✓ Constrains PNS structure and EOS, but does not imply explosion
- **Low-frequency** ($\lesssim 250$ Hz)
  - ✓ Standing accretion shock instability (SASI) and neutrino-driven convection
    - Instabilities drive explosion
  - ✓ Within the most sensitive band of LIGO/Virgo





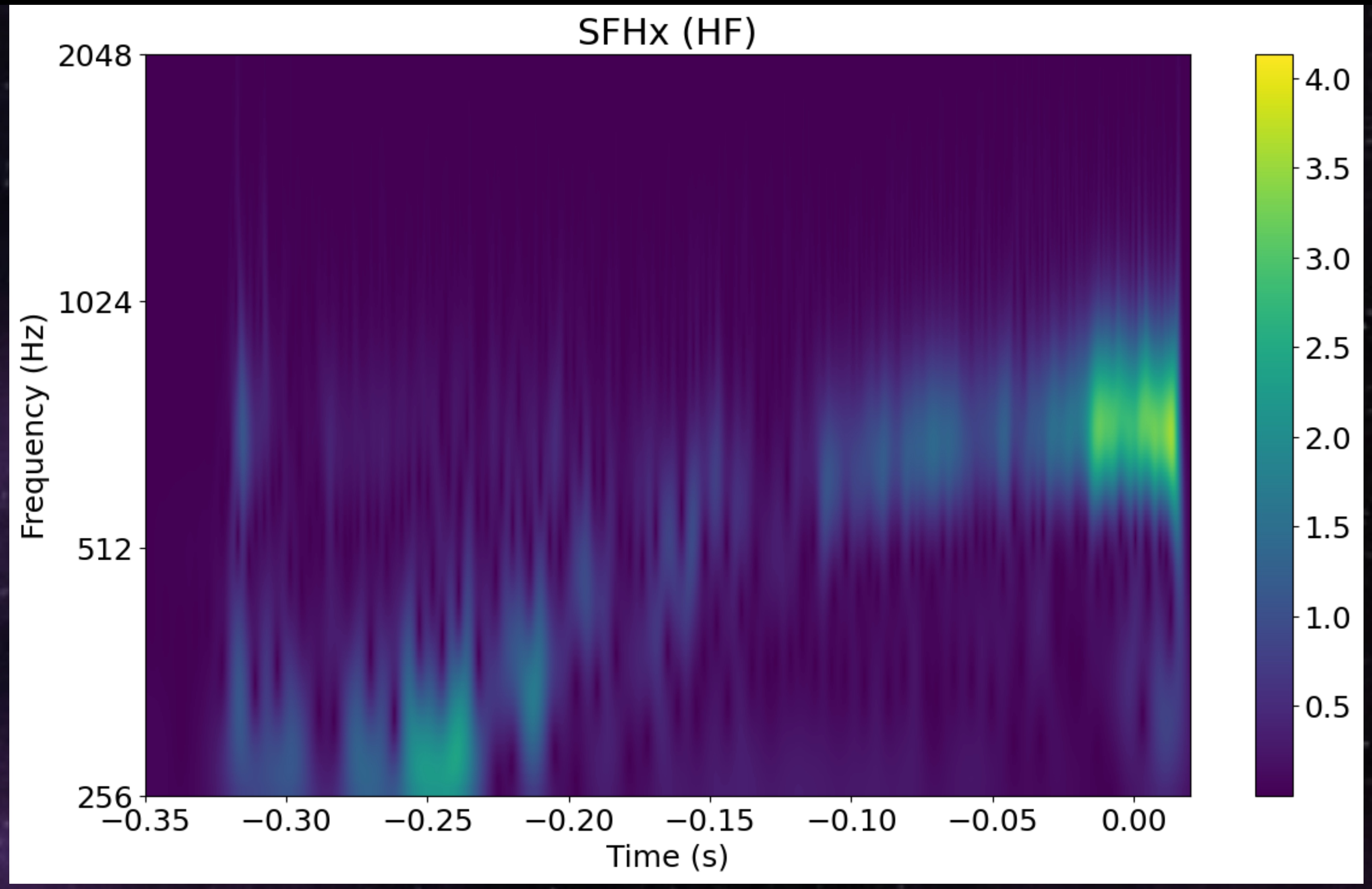
Abbott et al. 2021

DEDICATED-FREQUENCY FRAMEWORK

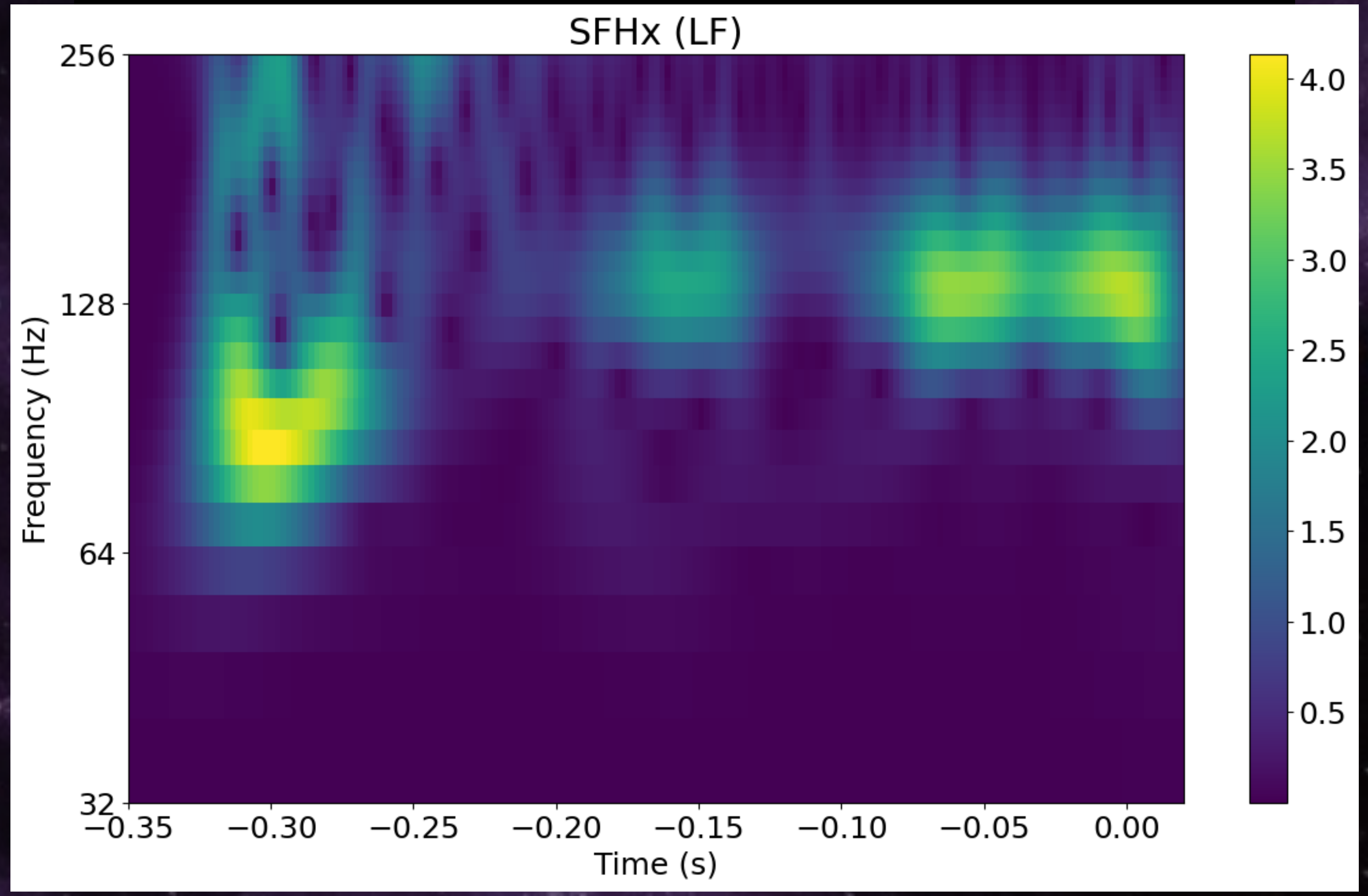


Full-band analysis : 32 - 2048 Hz

High-frequency (HF) : 256 - 2048 Hz



Low-frequency (LF) : 32 - 256 Hz

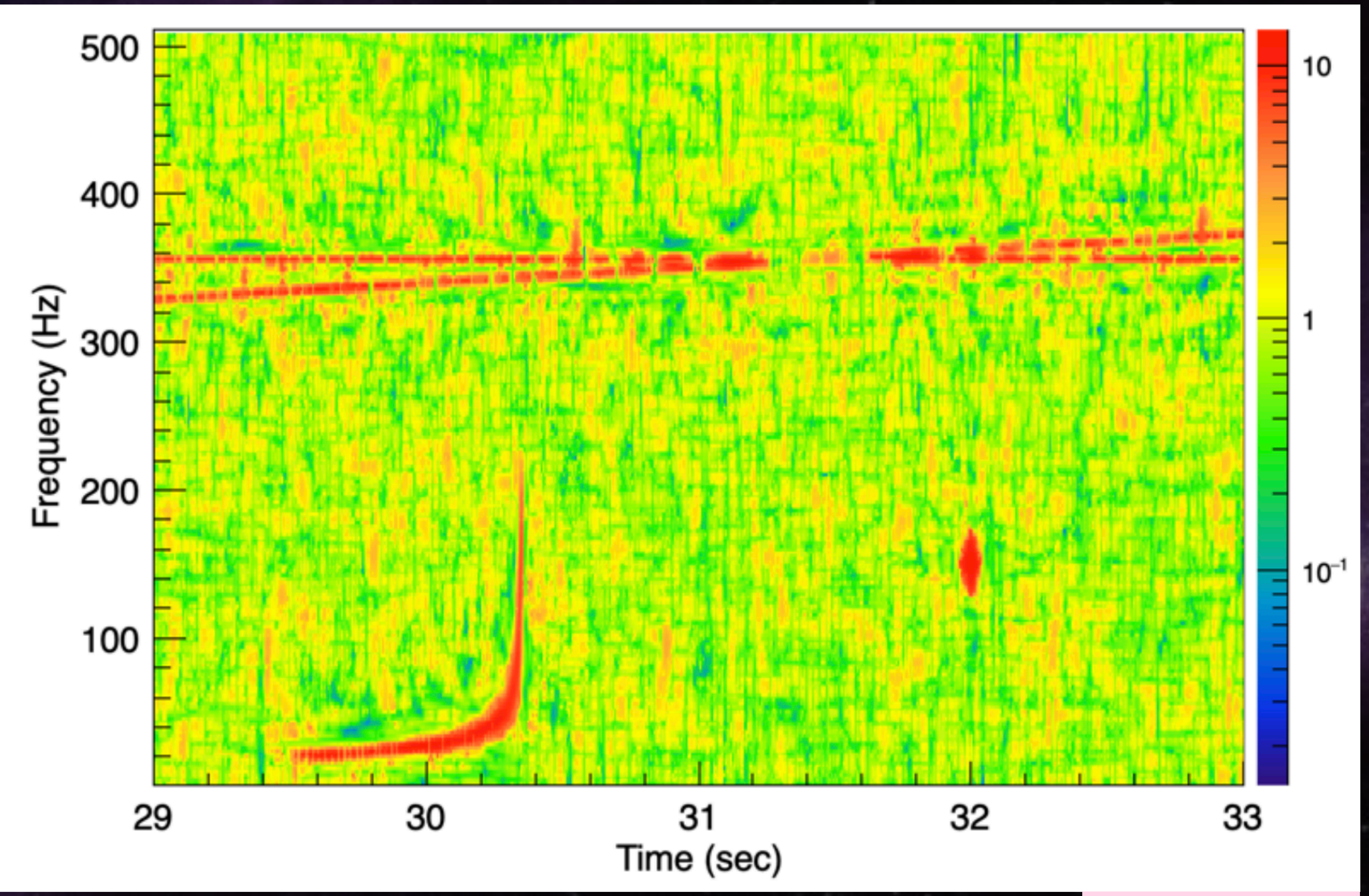


Szczepańczyk and Zanolin, Galaxies 10 (2022) 3, 70

Coherent WaveBurst (cWB)

(See Sergey's talk on Friday 25/07)

- Uses a time-frequency (TF) transform called *WaveScan*
- Both cross-power and excess power statistics used for efficient selection of transient events.
- Statistic scales with coherent energy in the network: $\eta_r \sim \mathrm{SNR}_{\mathrm{net}}$



Klimenko 2022

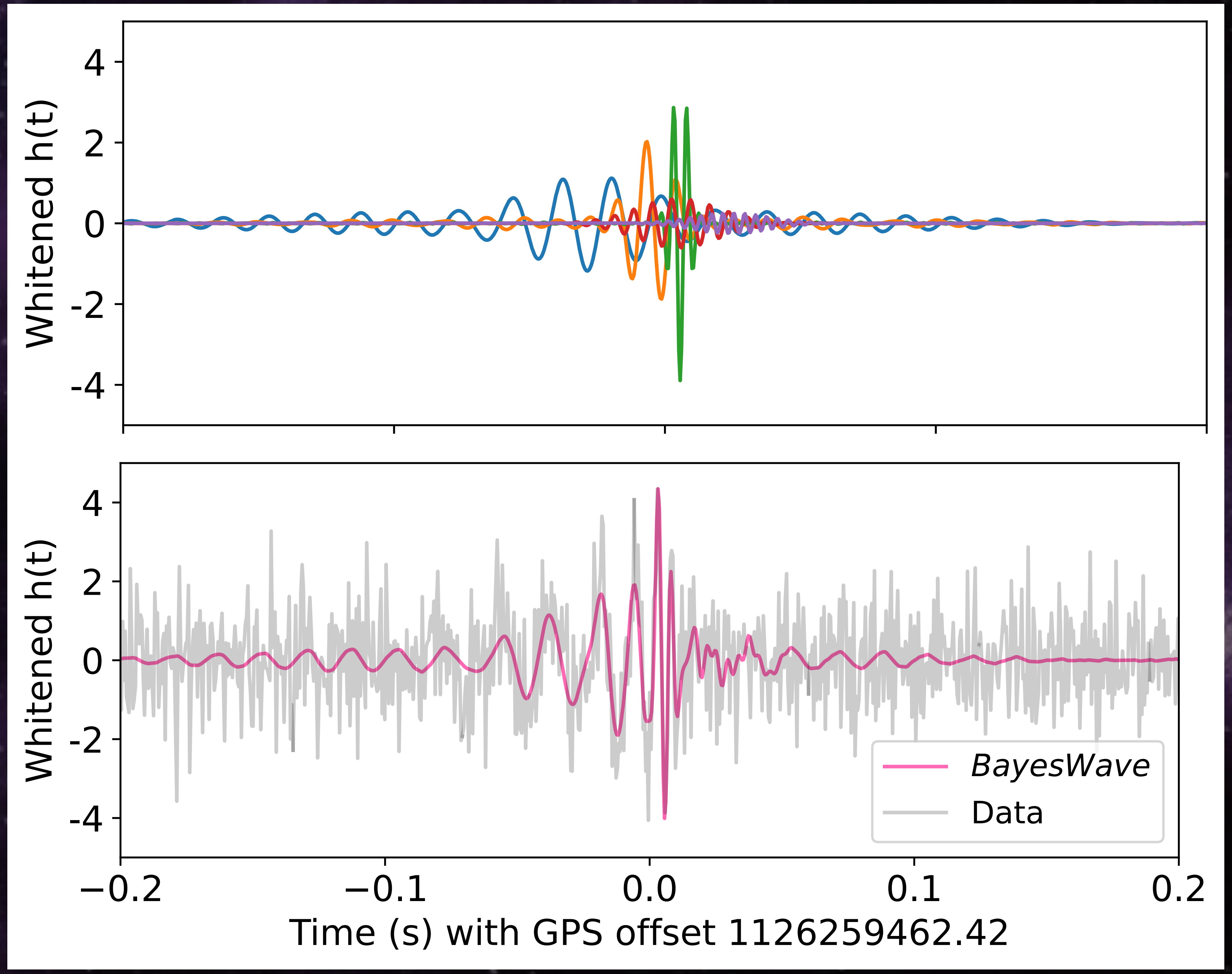
[Slide adapted from Tanmaya Mishra]

S. Klimenko et al. Phys. Rev. D 93, 042004 (2016)

BayesWave

- **R**econstruction of coherent signals $\mathscr{S}$ and non-coherent glitches $\mathscr{G}$ using sine-Gaussian wavelets
- Uses Bayes factor to compare the evidence between signals, glitches and Gaussian noise
- Statistic scales with model complexity, size of detector network *and* network signal-to-noise ratio:

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



Cornish and Littenberg, Class. Quant. Grav 32, 130512 (2015)

ANALYSIS PIPELINE

Coherent WaveBurst (cWB)

- ✓ Fast and computationally efficient
- ✓ Able to analyse large datasets
- ✓ **<u>In this work:</u>**
  Used to identify eligible candidates for dedicated-frequency followup

→

BayesWave

- ✓ Computationally expensive due to extensive parameter space sampling
- ✓ Typically used to follow-up existing (e.g. cWB) triggers
- ✓ **<u>In this work:</u>**
  Follows up cWB candidates in both the full-band and LF/HF

USE-CASES

To detect and characterize frequency-specific GW signatures e.g. in CCSNe;

a follow-up to GW candidates that satisfy the standard detection threshold

WORKFLOW

Full-band analysis of candidates with cWB

cWB candidates with $\mathrm{FAR} \leq 1\mathrm{yr}^{-1}$

BayesWave follow-ups

Full-band + low-frequency (**LF**) and/or high-frequency (**HF**)

Kanner *et al.*, Phys, Rev. D. 93, 022002 (2016) + LVK all-sky short GW burst searches

PART I:
APPLICATIONS OF THE LF FOLLOW-UP

Can we constrain explosion models of CCSNe detections in practical observing scenarios?

ANALYSIS DATASET

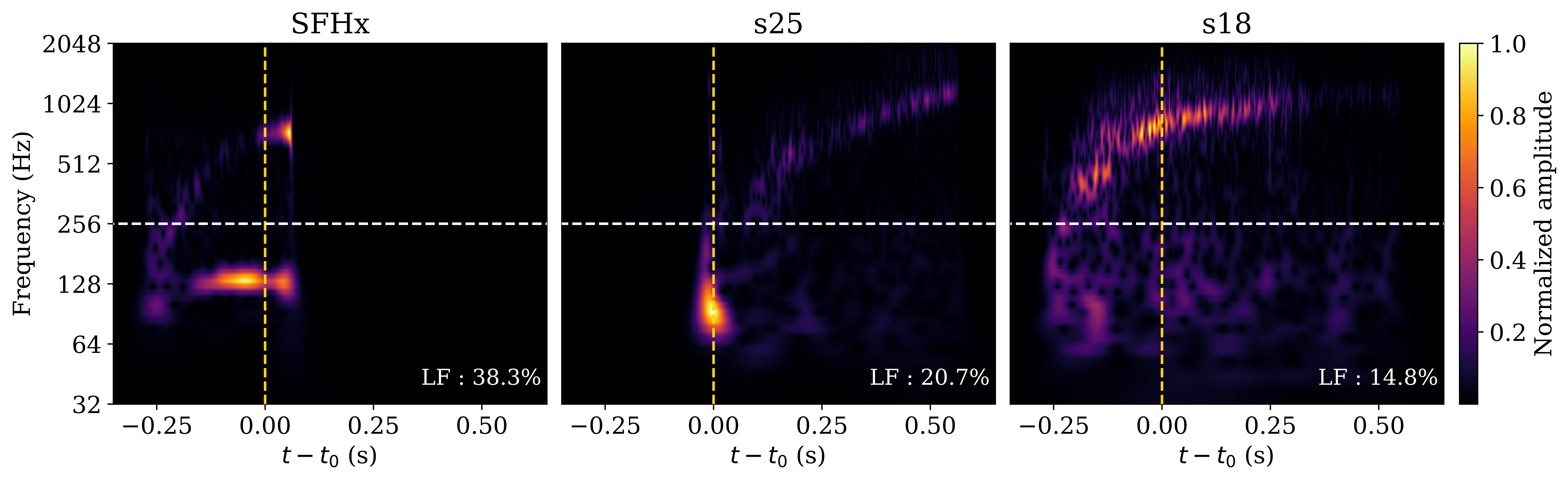
- GW waveforms from five non-rotating and solar metallicity 3D CCSN models:

	Progenitor mass ($M_\odot$)	SASI/neutrino-driven convection?	Average LF power (%)
SFHx (Kur+16)	15	Yes	36.6
s25 (Rad+19)	25	Yes	19.4
D15-3D (Mez+20)	15	Yes	18.4
mesa20_pert (Oco+18)	20	Yes	16.2
s183d (Pow+18)	18	No	14.9

- Injected into O3 data of the Hanford-Livingston (HL) two-detector network

SN 2023ixf, ApJ 985 183 (2025) - see also Yanyan's talk (Tue 22/07)

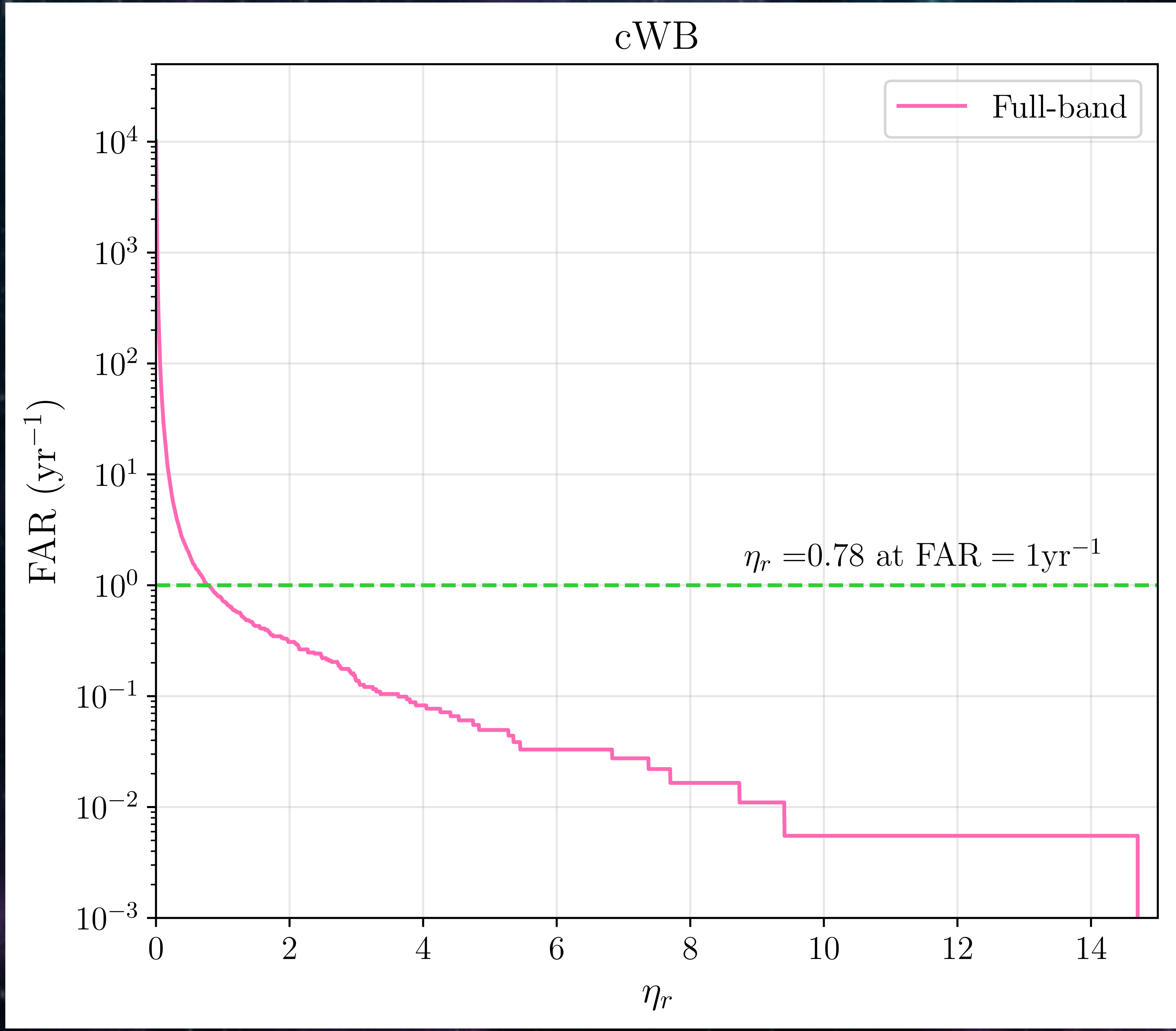
VISUALISING CCSN WAVEFORMS

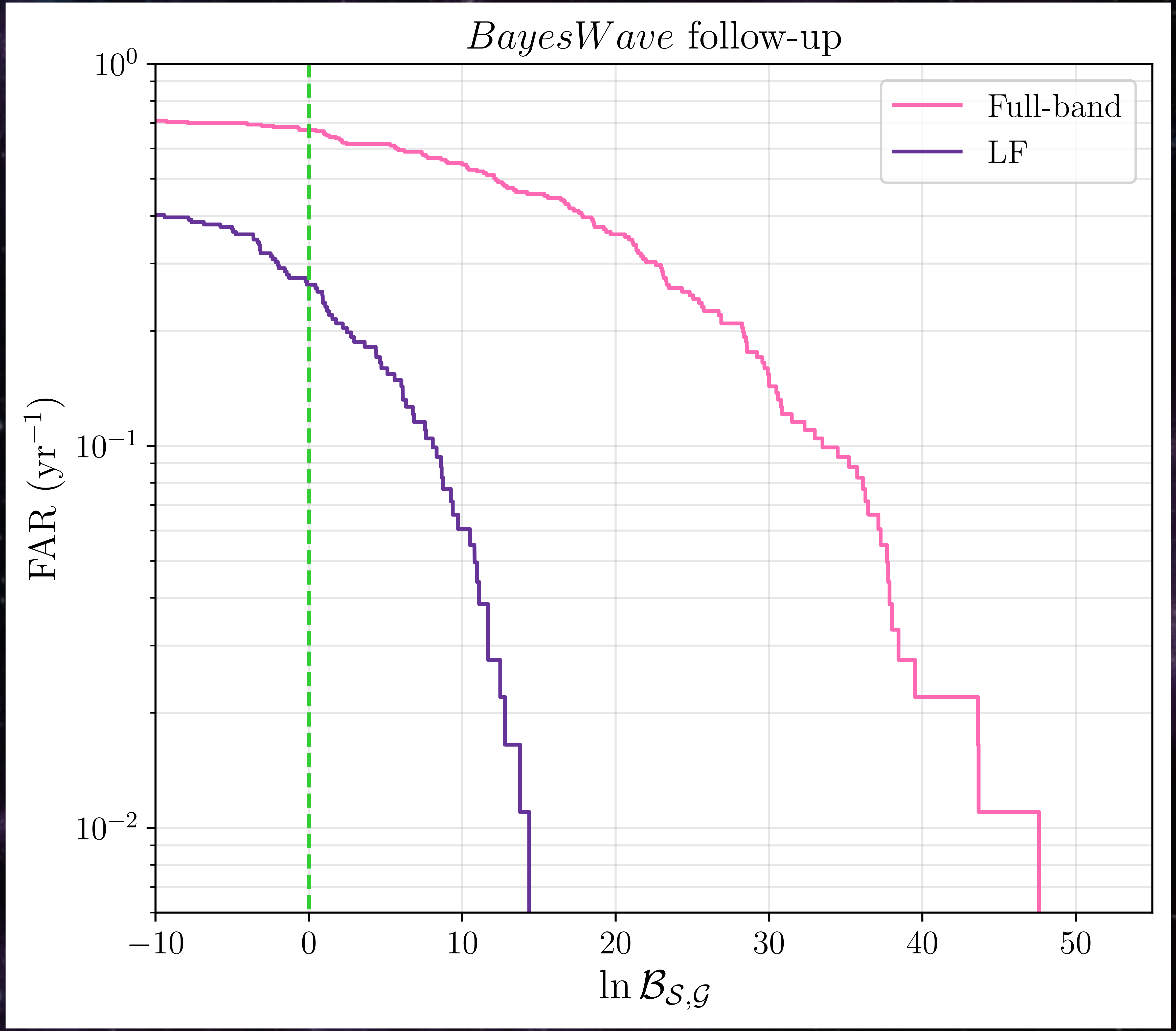


Time-frequency spectrograms of SFHx, s25 and s18

Continuous-wavelet transform: see Henshaw et al. (2025) arXiv:2402.16533

BACKGROUND MEASUREMENTS (O3 HL NETWORK)

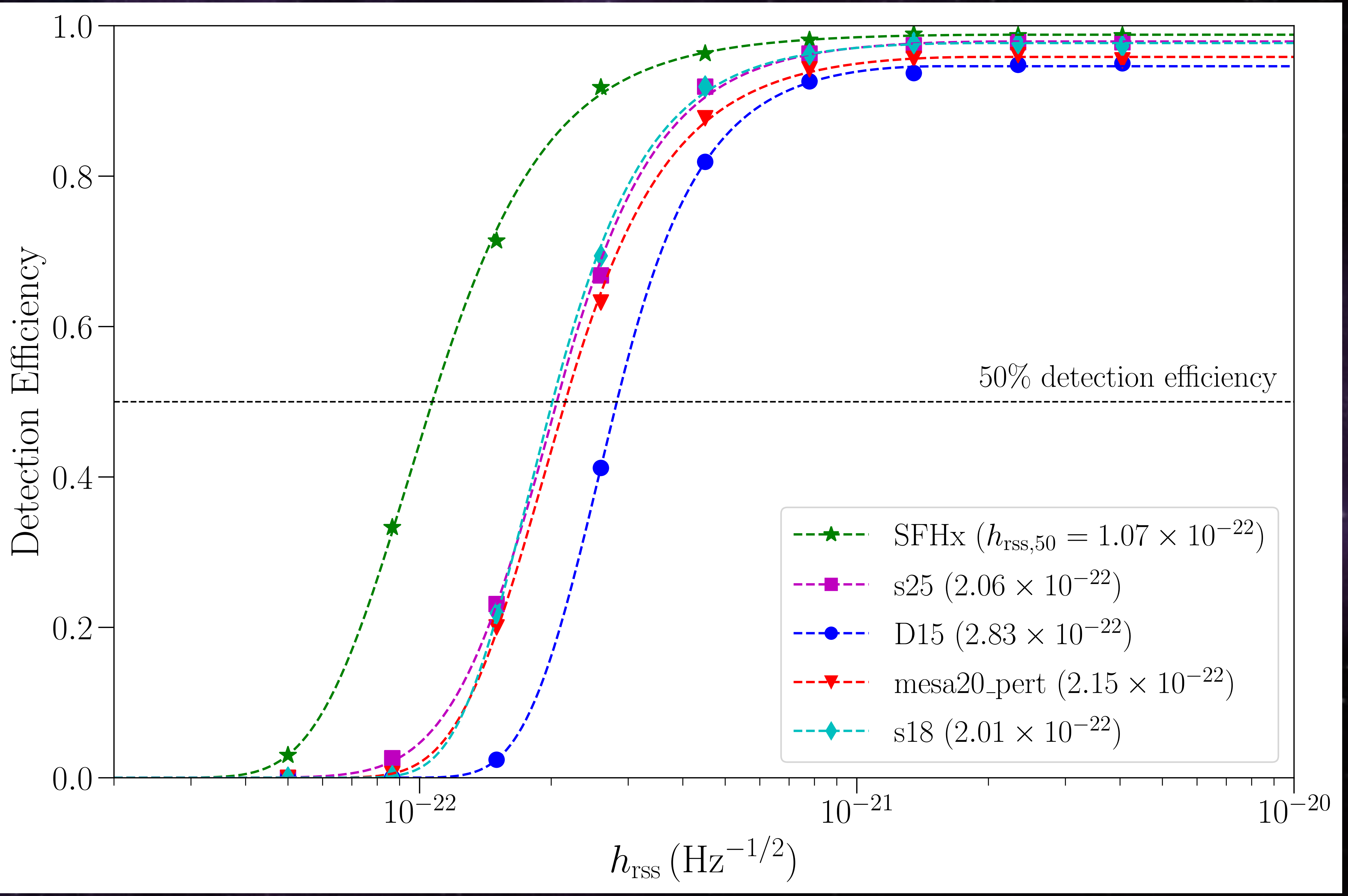




See Marco Drago's talk for more details on FAR & background measurements (Thu 24/07)

AMPLITUDE OF CCSN INJECTIONS

- Aim of the dedicated-frequency analyses is to follow-up "standard" *detection* candidates
- Detection = events with FAR below the nominal threshold (1 yr^{-1}) in the cWB full-band analysis
- Inject signals at $h_{rss,50}$ to ensure the events are detectable
- *BayesWave* only follows up injections with with cWB FAR $\leq 1\ yr^{-1}$



INJECTED DISTANCE

$$r^2 = \frac{GE_{\mathrm{GW}}}{\pi^2 c^3 h_{\mathrm{rss}}^2 f_0^2}$$

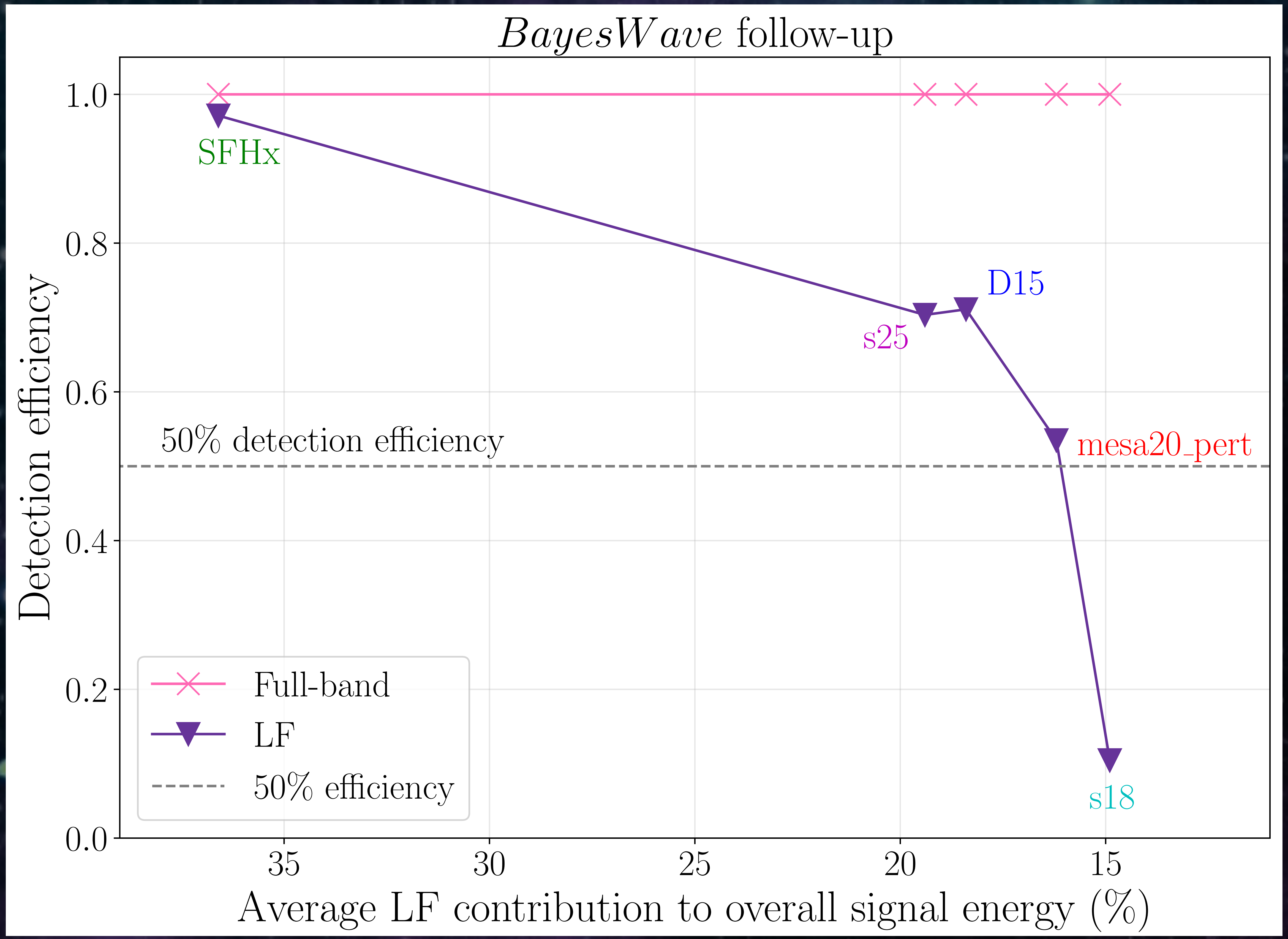
Assume $f_{\mathrm{peak}} \approx f_0$

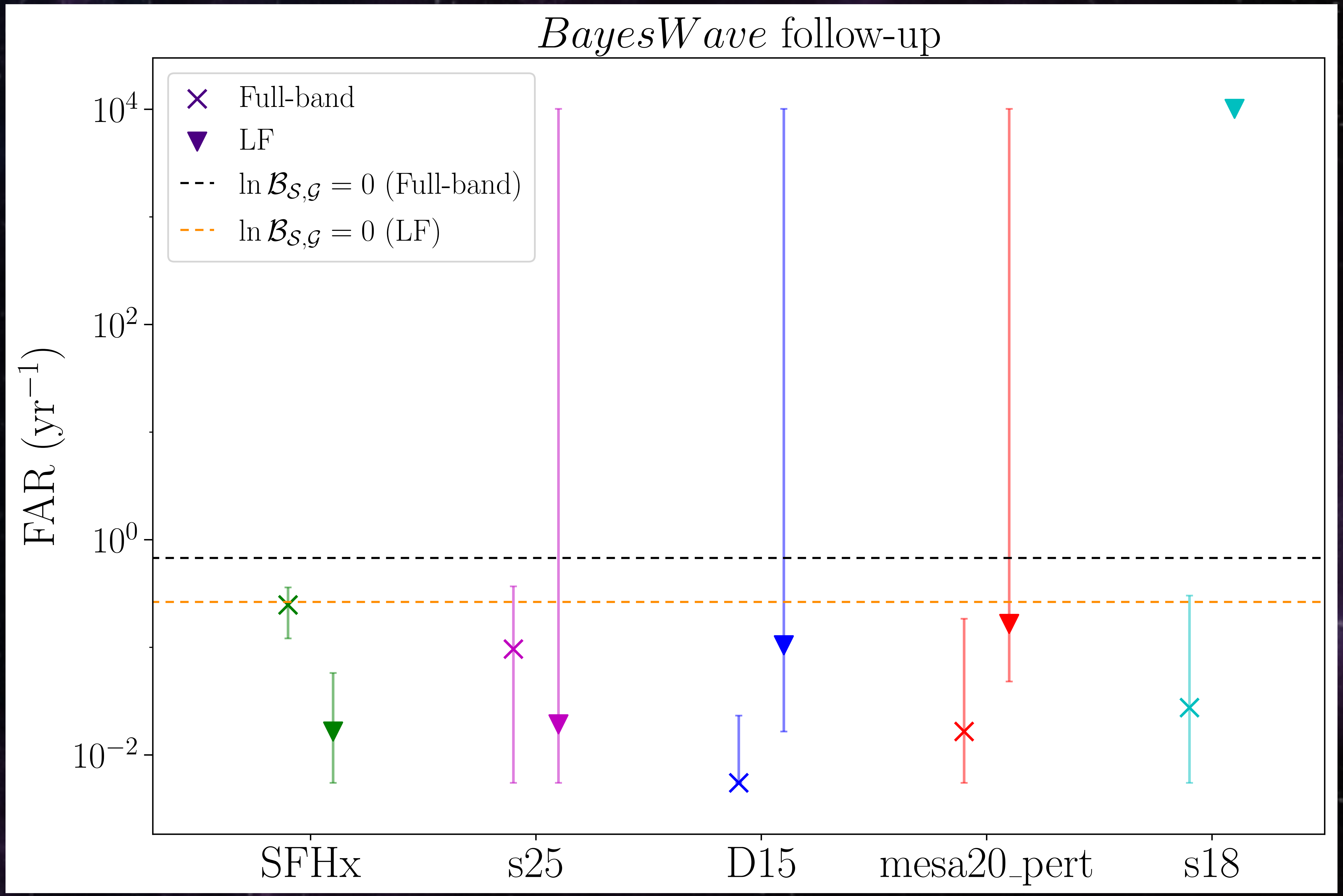
Model	E_{GW} $[M_\odot c^2]$	f_{peak} [Hz]	$h_{\mathrm{rss},50}$ $[\mathrm{Hz}^{-1/2}]$	r_{50} [kpc]
SFHx	1.1×10^{-9}	267	1.07×10^{-22}	7.8
s25	2.7×10^{-8}	1132	2.06×10^{-22}	4.9
D15	8.9×10^{-9}	1102	2.83×10^{-22}	2.1
mesa20_pert	9.4×10^{-10}	1103	2.15×10^{-22}	0.9
s18	1.6×10^{-8}	818	2.01×10^{-22}	5.3

	SFHx	s25	D15	mesa20_pert	s18
Supernova	s15	s25	C15	m20p	s18
SN 2019ehk	6.57	3.11	0.52	0.77	3.05
SN 2019ejj	7.94	2.73	1.73	0.85	2.68
SN 2019fcn	7.40	1.86	0.84	0.64	0.83
SN 2019hsw	5.60	2.82	2.24	0.76	3.85
SN 2020oi	6.53	1.96	1.15	0.70	1.71
SN 2020cxd	**8.90**	**3.15**	**2.74**	**0.95**	**4.74**
SN 2020dpw	8.66	2.86	2.46	0.85	4.30
SN 2020fqv	6.86	2.90	2.38	0.82	4.17

Szczepańczyk et al. Phys. Rev. D 110, 042007 (2024)

RESULTS - DETECTABILITY

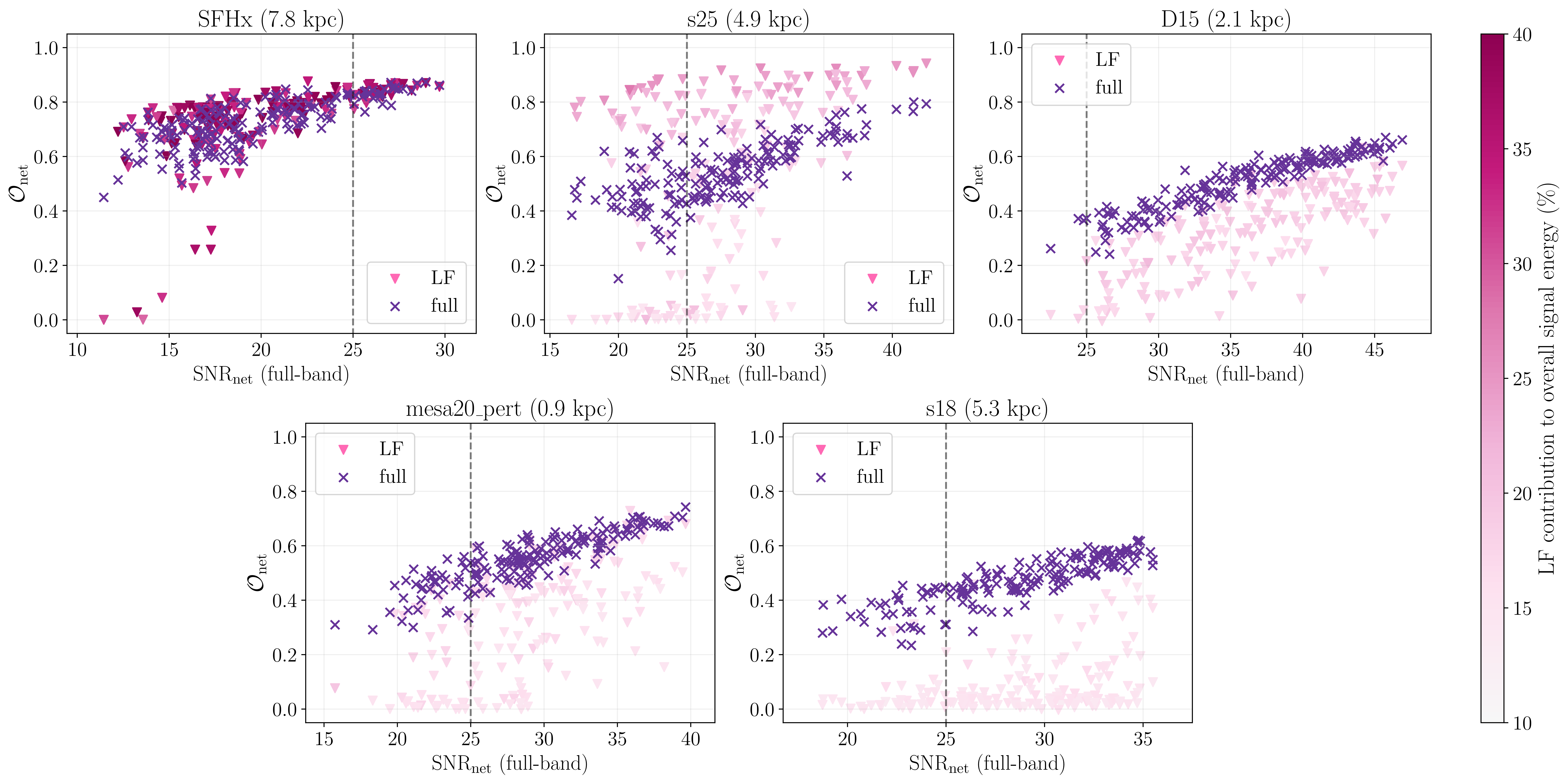




Decreasing LF power

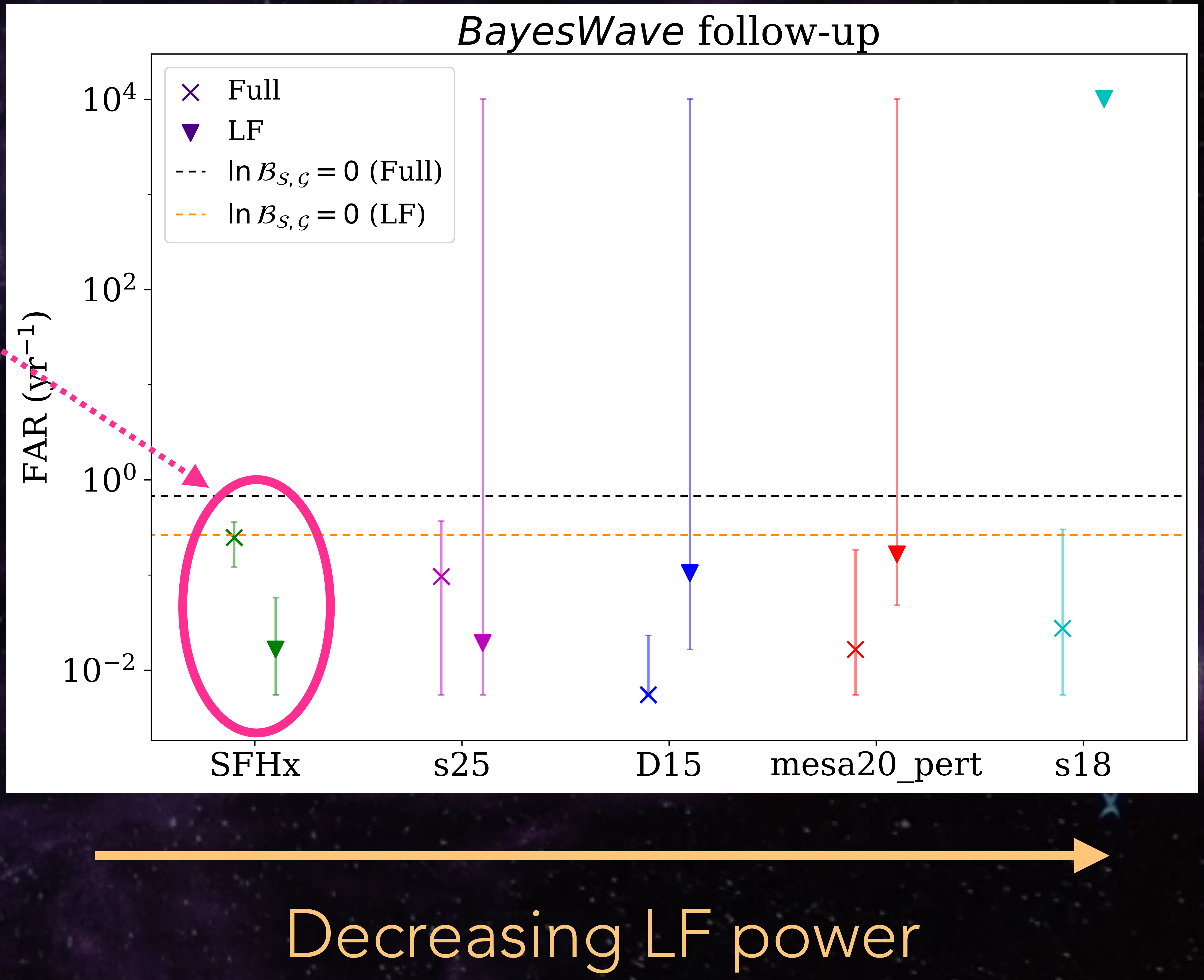
Decreasing LF power

RESULTS - RECONSTRUCTION ACCURACY



IMPLICATIONS

- CCSNe models with higher LF content have better detectability with the LF follow-ups
- BUT… the LF detectability is not guaranteed for CCSN models with moderate LF content e.g. s25, D15, mesa20_pert
- What does this mean?
  - ★ A successful LF detection is useful for constraining the CCSN explosion model
  - ★ Unsuccessful detection ≠ no LF emission

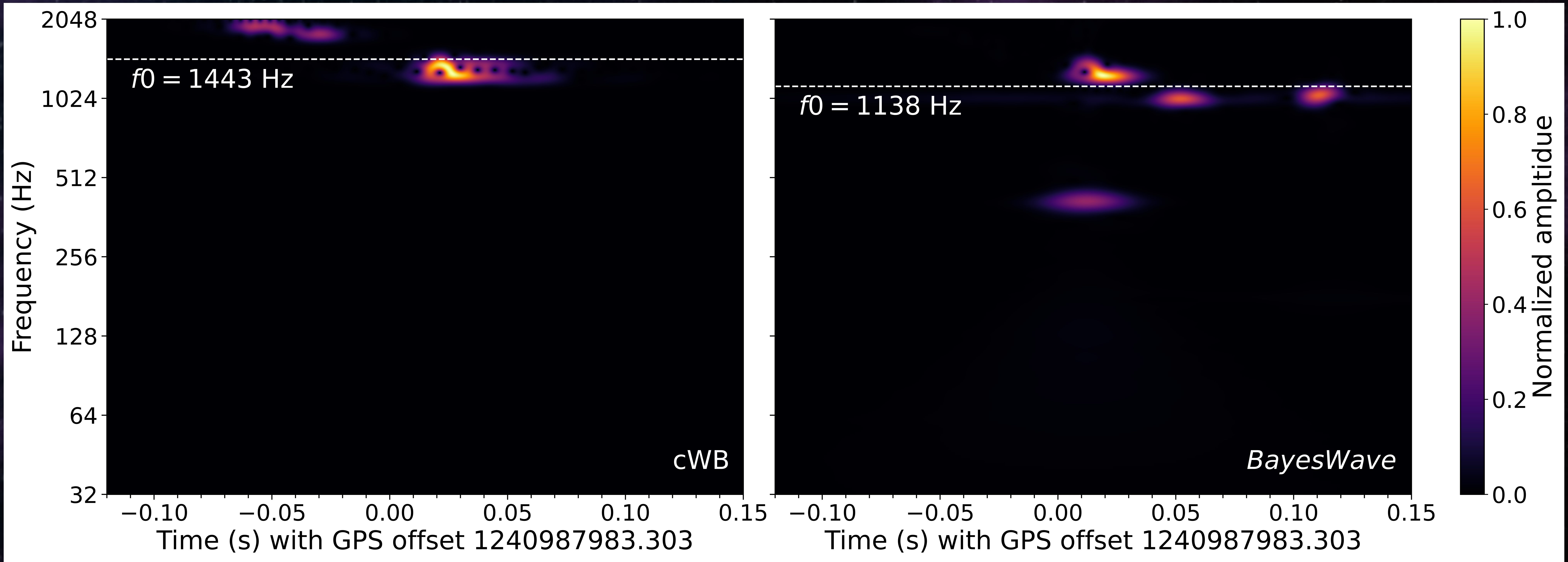


PART II:
APPLICATIONS OF THE HF FOLLOW-UP

Can we enhance detection significance of a candidate that only has high-frequency power, by ignoring all low-frequency data contributions?

LOUDEST EVENT OF SN 2019fcn

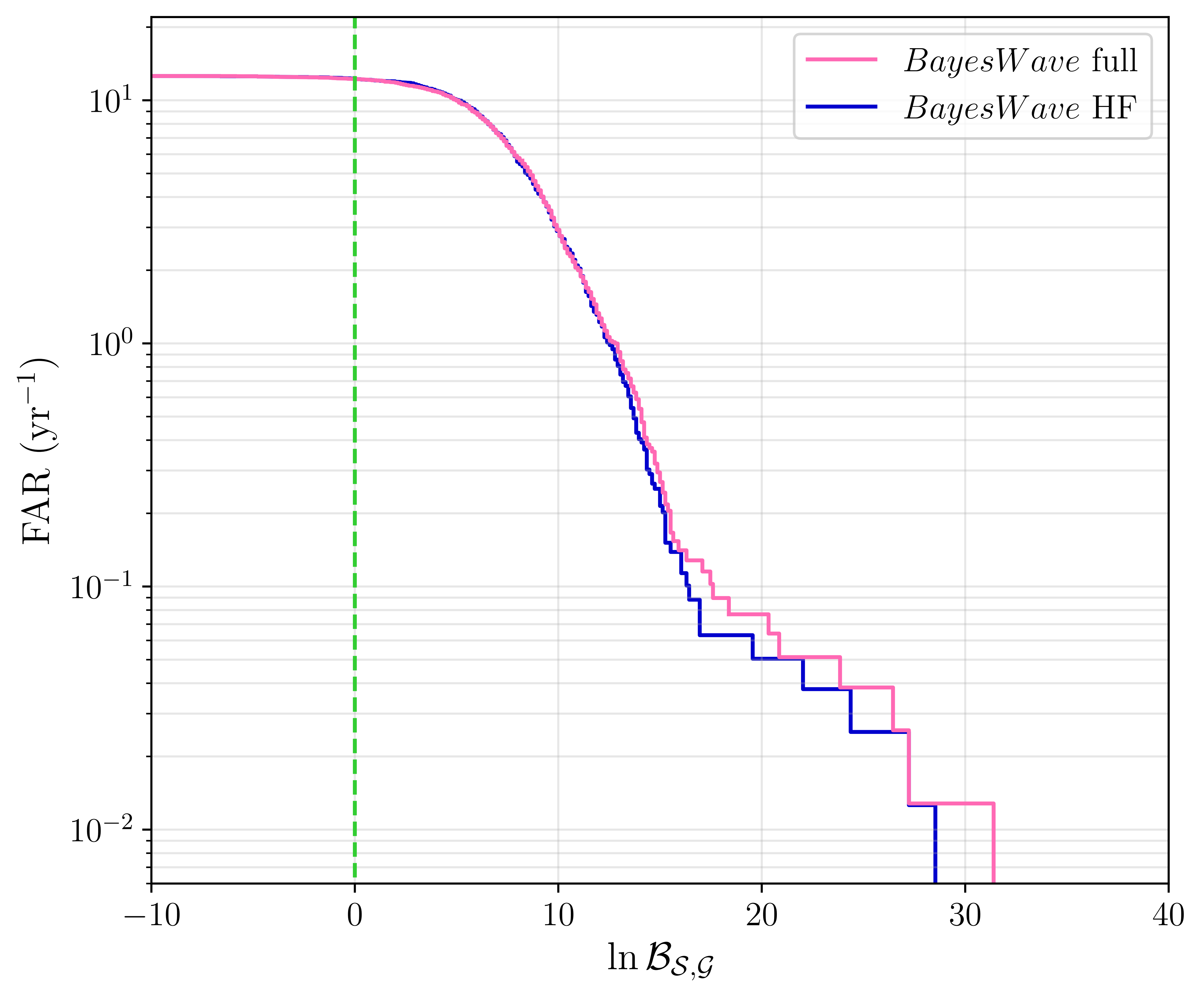
- Recognised as a trigger by both cWB <u>and</u> *BayesWave*
- $\mathrm{FAR} = 22\,\mathrm{yr}^{-1}$, lowest among other CCSN loudest events in O3
- Only has high-frequency power, with central frequencies ~1000 Hz



SIGNIFICANCE ANALYSIS

Pipeline	Full			HF		
	η_c	$\ln \mathcal{B}_{\mathcal{S},\mathcal{G}}$	FAR (yr^{-1})	η_c	$\ln \mathcal{B}_{\mathcal{S},\mathcal{G}}$	FAR (yr^{-1})
cWB	6.7	-	22.1	-	-	-
BayesWave	-	$\boxed{7.5}$	$\boxed{6.4}$	-	$\boxed{8.6}$	$\boxed{4.9}$

- *BayesWave* full-analysis follow-up reduces FAR
- *BayesWave* HF follow-up further reduces the FAR



cWB results quoted from Szczepańczyk et al. Phys. Rev. D 110, 042007 (2024)

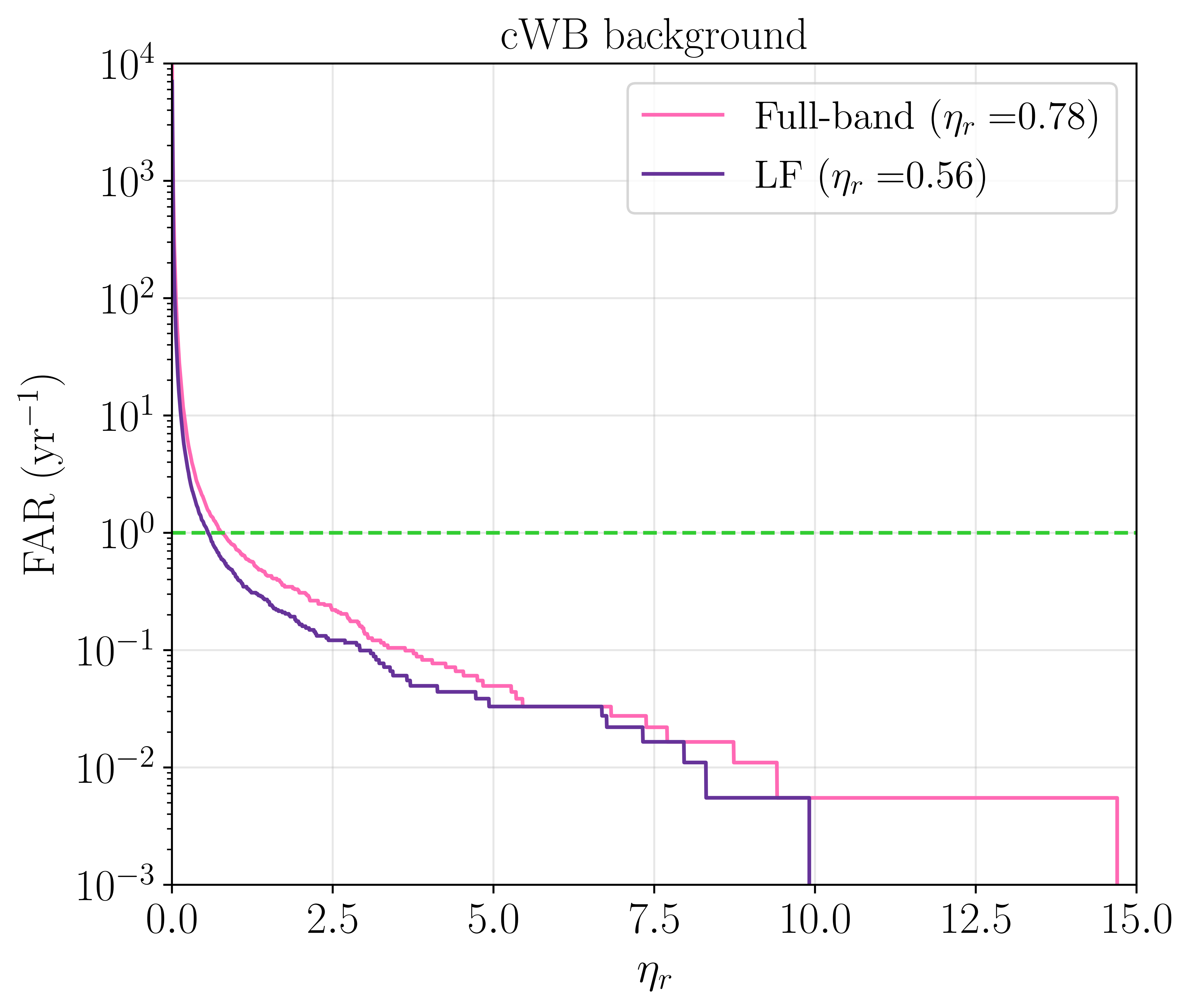
SUMMARY

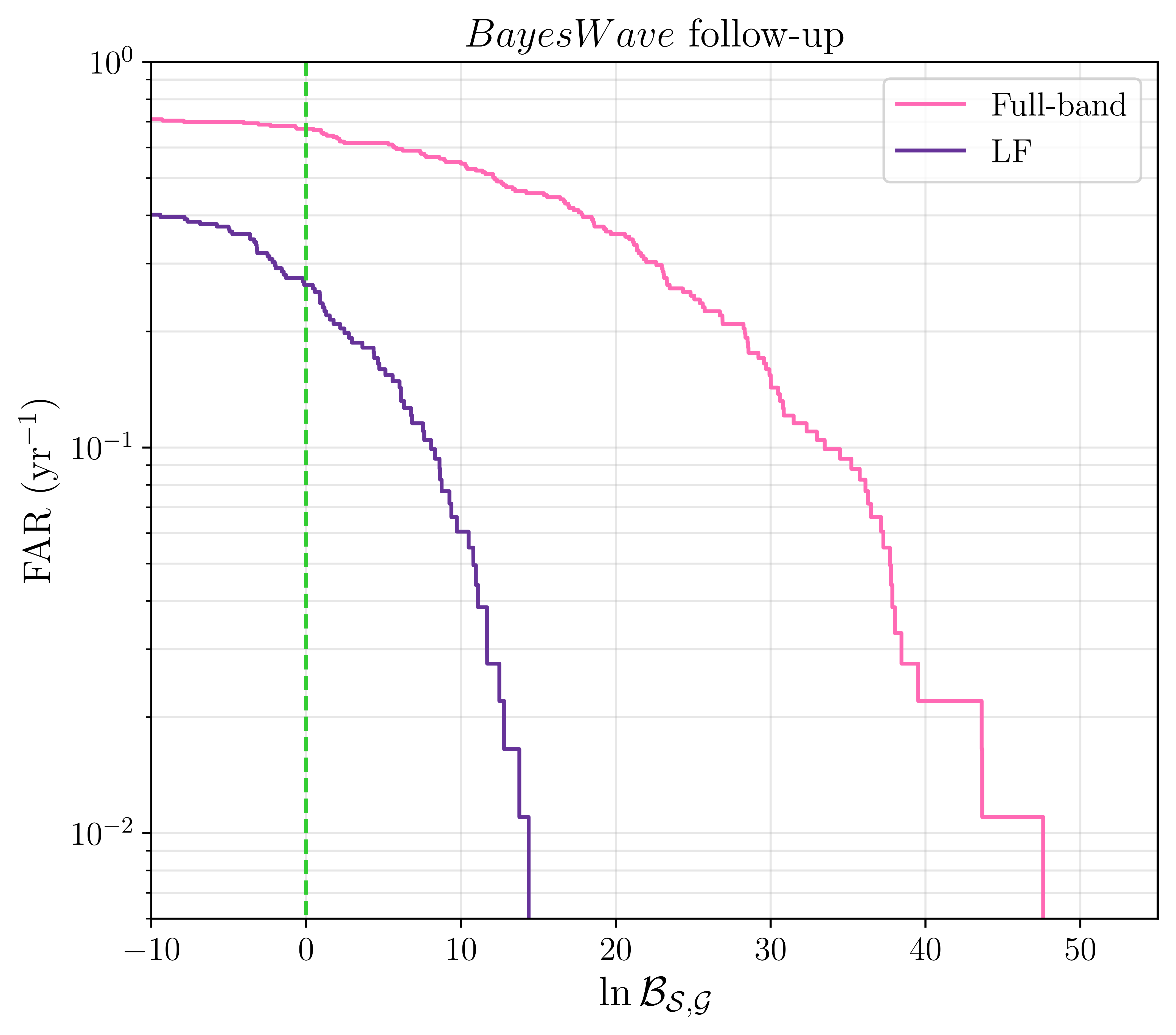
- We demonstrated applications of the dedicated-frequency framework with the hierarchical cWB+*BayesWave* pipeline
- Low-frequency follow-ups ($32 - 256$ Hz) are useful for constraining CCSN explosion models, when there is a successful detection
- High-frequency follow-ups ($256 - 2048$ Hz) can be used to enhance detection significance of a trigger with minimal low-frequency power
- **Going forward:**
  - ✦ How can we tune cWB for independent dedicated-frequency follow-ups?
  - ✦ Could repeat this analysis for HF looking for high-frequency features?
  - ✦ Suggestions for other features to follow-up?

SUPPLEMENTARY SLIDES

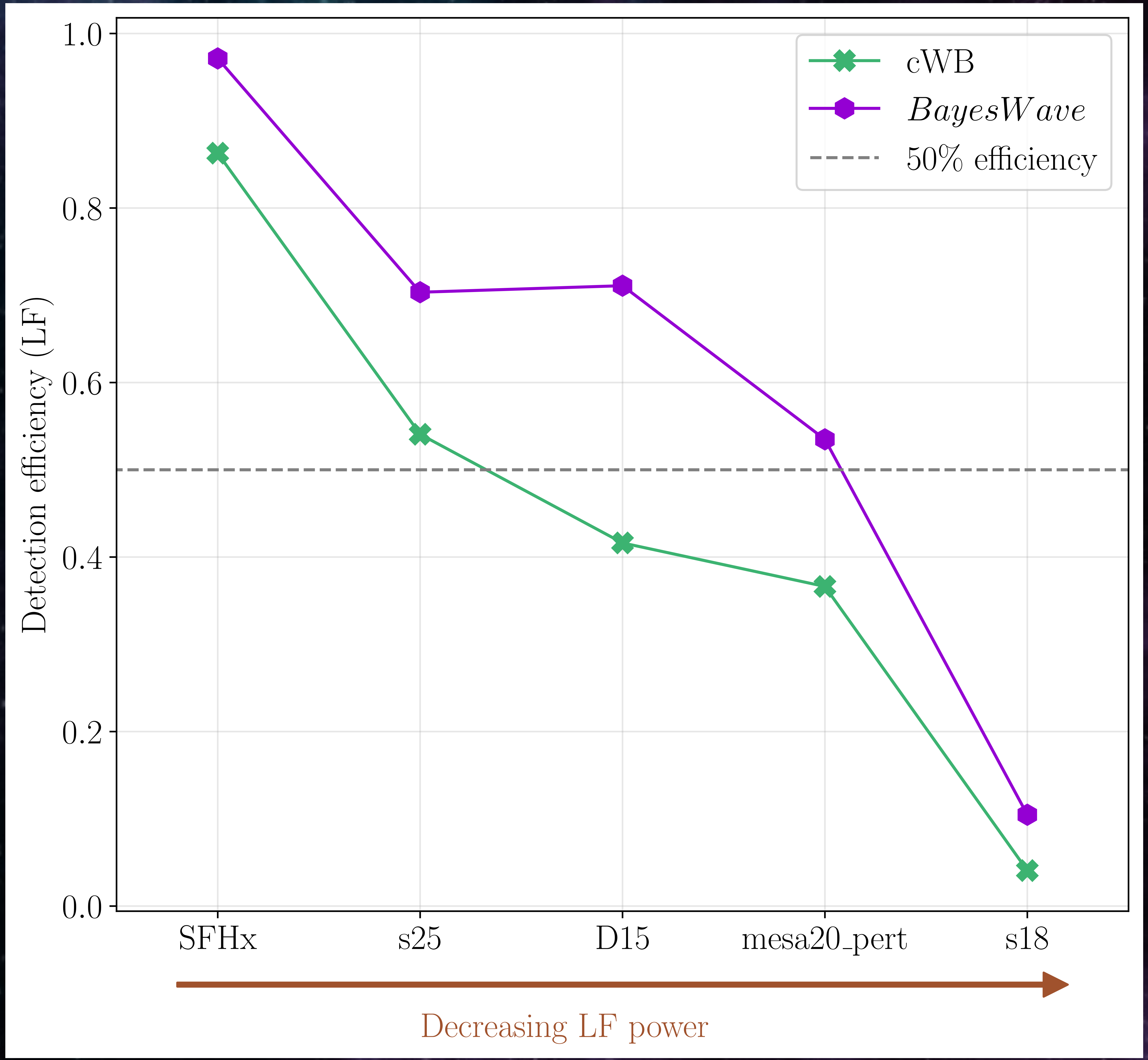
cWB LF analysis

LF BACKGROUND MEASUREMENTS

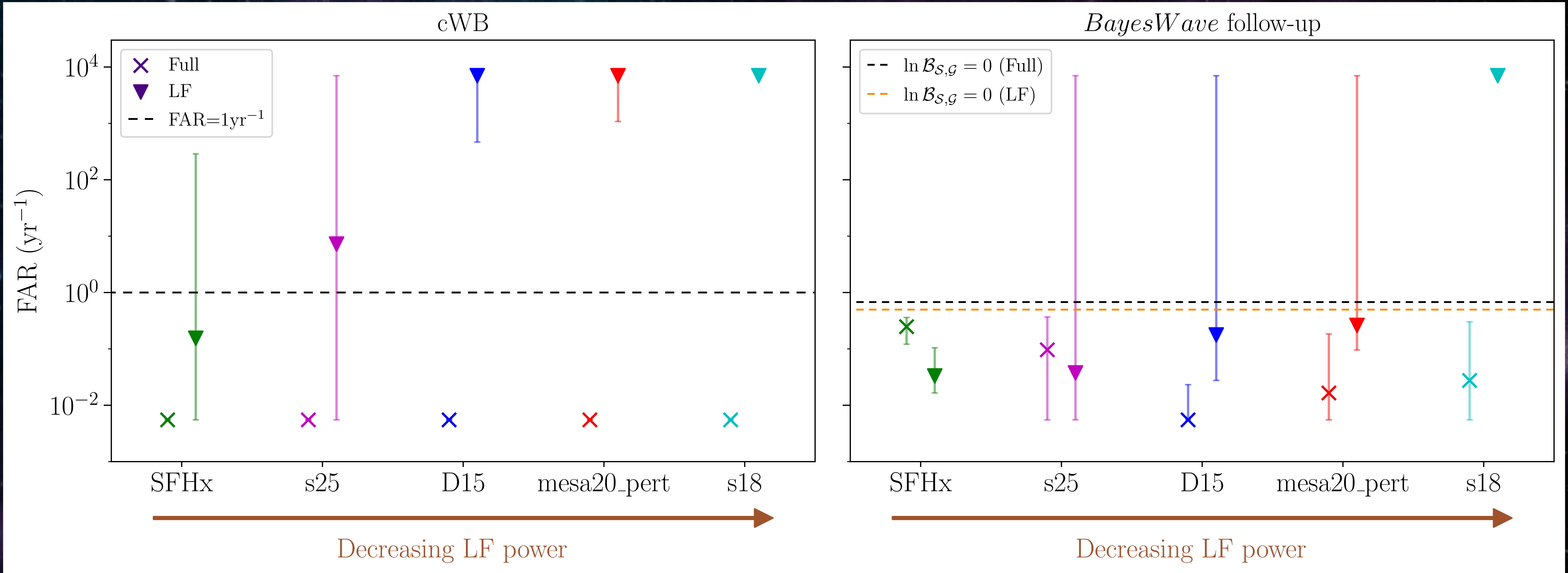




LF DETECTION EFFICIENCY



FAR COMPARISON



HF SIGNIFICANCE ANALYSIS:
A HEURISTIC EXPLANATION

Bayesian evidence for model $\mathscr{M}$:

$$p(\vec{d}\,|\,\mathscr{M}) \approx \frac{\Delta V}{V}$$

ΔV : posterior volume V : prior volume

Bayes factor, $\mathscr{B}_{\mathrm{full,HF}} = \dfrac{\Delta V_{\mathrm{full}}}{\Delta V_{\mathrm{HF}}} \dfrac{V_{\mathrm{HF}}}{V_{\mathrm{full}}}$

Similar reconstruction: $\dfrac{\Delta V_{\mathrm{full}}}{\Delta V_{\mathrm{HF}}} \approx 1$ and by definition $V_{\mathrm{full}} > V_{\mathrm{HF}}$

which results in $\mathscr{B}_{\mathrm{full,HF}} < 0$ (in favour of HF)