Galactic Binary Residuals in LISA SGWB Amplitude Inference

Source Power Concentration and Spectral Degeneracy

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Outline

Outline

The Galactic confusion foreground

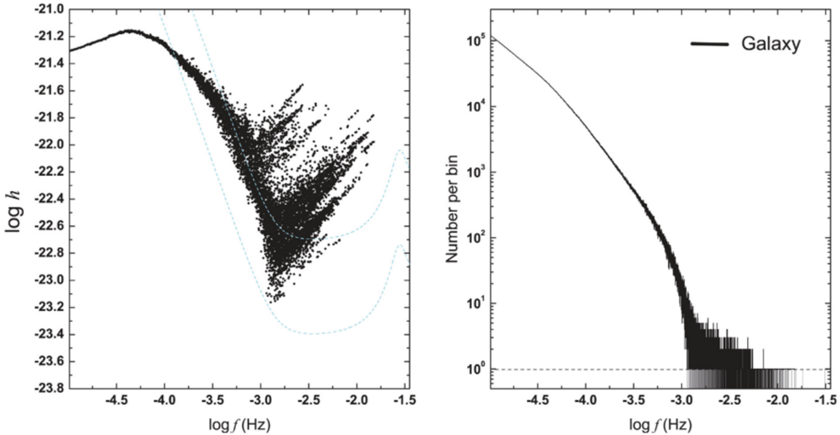


Figure: Yu & Jeffery, A&A (2010).

One residual, two statistical questions

Q1: Source discreteness

Fourth-order source statistic

Within one frequency bin

Many comparable sources
$\updownarrow$
a few dominant sources

How concentrated is the residual power?

Q2: Spectral degeneracy

Mean binned power

Across the frequency band

Residual spectrum
$\updownarrow$
SGWB spectrum

How does residual uncertainty affect the inferred SGWB amplitude?

From the Galactic foreground to a catalog residual

LDC2A Sangria injections

$\Downarrow$

Erebor comparison table

$\Downarrow$

Catalog residual

- Sources not recovered:
  - Recovery confidence $C_{\rm rec} < 0.9$
  - Injection–recovery overlap $\mathcal{O}_{\rm best} < 0.9$

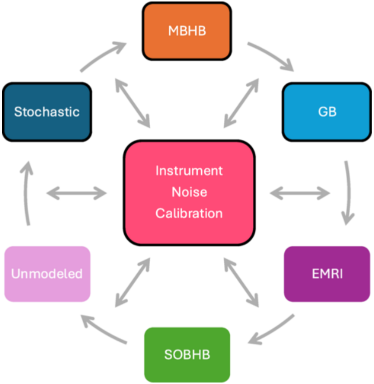
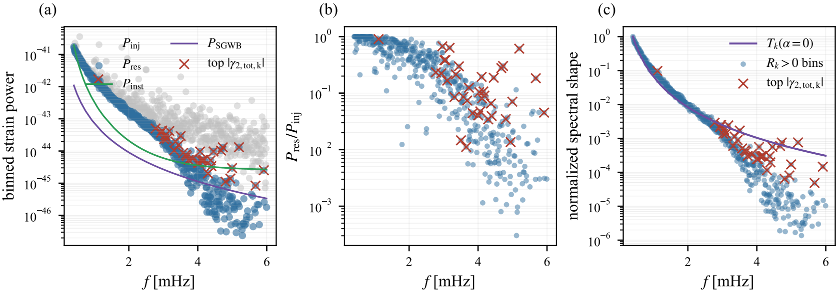


Figure: Katz et al., PRD (2025).

The residual and SGWB occupy the same frequencies



$$\Omega_{\rm GW}(f) = \Omega_0 \left(\frac{f}{f_{\rm ref}}\right)^{\alpha}, \ f_{\rm ref} = 3\,\rm mHz, \ S_h \propto \Omega_{\rm GW}/f^3.$$

$$\boxed{\text{Fiducial: } \Omega_0 = 10^{-11}, \ \alpha = 0}$$

R_k and $T_k(0)$ share a low-frequency shape.

Outline

From catalog sources to binned power

- Analysis band: 0.4–6.0 mHz
- $\Delta f = 10^{-5}\,\mathrm{Hz} \Rightarrow 560$ bins
- 487 bins with $R_k > 0$

Catalog residual template

$$R_k = \sum_{i \in k,\,\mathrm{res}} p_i$$

SGWB template

$$T_k(\alpha) = \sum_{j \in k} \frac{3H_0^2}{2\pi^2 f_j^3} \left(\frac{f_j}{f_{\mathrm{ref}}}\right)^{\alpha} \delta f_F$$

Mean binned power model

$$\boxed{\mu_k = P_{\mathrm{inst},k} + \Omega_0 T_k(\alpha) + \beta R_k}$$

Ω_0: SGWB amplitude (target).
β: residual-power factor (nuisance).

Ω_0–β degeneracy from the spectral overlap of T_k and R_k.

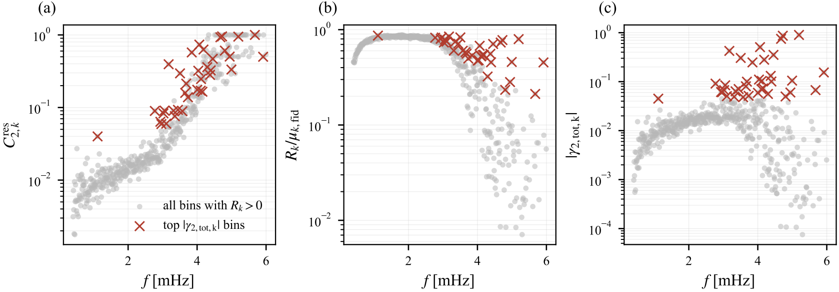
Prior width σ_β: $\beta = 1 \pm \sigma_\beta$.

How well must the residual power be known?

Source concentration and non-Gaussianity

Excess kurtosis γ_2: measures deviation from Gaussianity.
$\gamma_2 = 0$ for Gaussian; $\gamma_2 < 0$ means flatter-than-Gaussian tails.

$$\mathrm{C}_{2,\mathrm{k}} = \sum_{\mathrm{i}} \mathrm{w}_{\mathrm{i}}^2 \quad \Longrightarrow \quad \gamma_{2,\mathrm{res,k}} = -\frac{3}{2}\mathrm{C}_{2,\mathrm{k}} \quad \Longrightarrow \quad \gamma_{2,\mathrm{tot,k}} = \gamma_{2,\mathrm{res,k}} \left(\frac{\mathrm{R}_{\mathrm{k}}}{\mu_{\mathrm{k,fid}}}\right)^2$$



Median $|\gamma_{2,\mathrm{tot}}| \simeq 1.4 \times 10^{-2}$.

Quantifying the degeneracy: Fisher and marginalization

Spectral overlap $\rho_{\Omega\beta}$

Fisher elements:

$$A = \sum \frac{T_k^2}{\mathrm{Var}_k}, \quad B = \sum \frac{R_k^2}{\mathrm{Var}_k}$$

$$C = \sum \frac{T_k R_k}{\mathrm{Var}_k}$$

$$\rho_{\Omega\beta} = \frac{C}{\sqrt{AB}}$$

No-prior uncertainty increase

$$\boxed{I_0 = \frac{\sigma_{\Omega,\mathrm{marg}}}{\sigma_{\Omega,\mathrm{fixed}}} = \frac{1}{\sqrt{1-\rho_{\Omega\beta}^2}}}$$

- $\rho = 0 \;\Rightarrow\; I_0 = 1$: orthogonal.
- $|\rho| \to 1 \;\Rightarrow\; I_0 \to \infty$: degenerate.

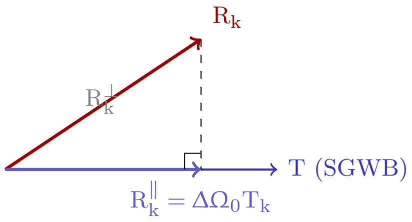
Prior width condition: $\beta = 1 \pm \sigma_\beta \;\Rightarrow\; B \to B + 1/\sigma_\beta^2$.

Choose σ_β so that $I(\sigma_\beta) \leqslant r_{\max}$.

Outline

Omitting vs. marginalizing the residual

Wrong model: omit R_k

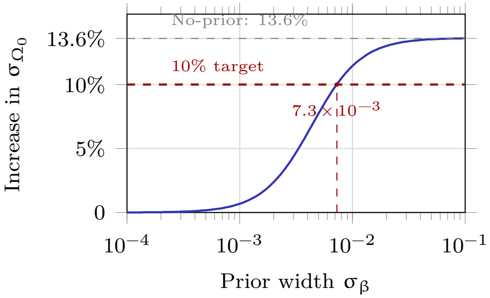


$$\Delta\Omega_0 = \frac{C}{A} \simeq 2.5 \times 10^{-11}$$

Residual absorbed as extra SGWB power.
$\Omega_{0,\mathrm{fit}} \simeq 3.5 \times 10^{-11}$ ($\Omega_{0,\mathrm{true}} = 10^{-11}$).

119.5× the fixed-β Fisher uncertainty.

Correct model: marginalize β

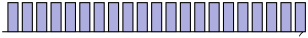


$\sigma_\beta \to 0 \Rightarrow I \to 1$ (fixed β).
$\sigma_\beta \to \infty \Rightarrow I \to I_0 = 1.136$ (no prior).

Robustness to unresolved sub-bin frequency structure

Catalog-to-Fourier mapping ($\Delta f = 10^{-5}$ Hz, $\delta f_F \simeq 3.2 \times 10^{-8}$ Hz, 315–316 modes/bin). Sets both R_k (mean) and mode-power variance (covariance).

Uniform within bin (coarse-grained reference)



schematic

Evenly distributed across ~315 modes.

Drift + Doppler (physically motivated)

schematic

Within chirp + annual Doppler range.

Mapping	$\min_k \nu_{\mathrm{eff},k}$	Inflation	$\sigma^{10\%}_{\beta,\max}$
Uniform within bin	~ 630	13.6%	0.0073
Drift + Doppler support	~ 93	11.2%	0.0145

ν_{eff}: moment-matched chi-square d.o.f. Closest-frequency stress test in backup.

Finite-source random-phase diagonal: 13.6% $\to$ 13.8%. Reference result not driven by Gaussian self-noise (diagonal only; cross-frequency covariance not included).

Outline

Summary

1. Residual omission causes parameter bias.
   The fitted Ω_0 absorbs residual power aligned with the SGWB template. $\Delta\Omega_0/\Omega_{0,\mathrm{true}} \simeq 2.5$.
2. Residual uncertainty propagates into SGWB uncertainty.
   Marginalizing β opens a spectral-degeneracy direction: 13.6% no-prior inflation, $\sigma^{10\%}_{\beta,\max} \simeq 0.0073$.
3. Gaussian residual self-noise does not drive the reference result.
   Finite-source random-phase diagonal covariance: $13.6\% \to 13.8\%$.

Reference case: $\alpha = 0$, $\Omega_0 = 10^{-11}$, all 560 bins, uniform within each bin.

Scope and future work

Current model

- Catalog residual from recovery-threshold classification
- Orbit-averaged scalar Michelson X power
- Independent complex Gaussian Fourier amplitudes
- Diagonal covariance fixed at the fiducial spectrum
- One residual normalization parameter β

Future work

- Global-fit residual realizations and subtraction uncertainty
- Time-dependent, multichannel TDI response
- Coherent cross-frequency and cross-channel covariance
- Flexible residual spectral and population-level model

Interpretation boundary

The reported numbers are conditional on a catalog-level scalar-power model; they are not a full coherent, multichannel LISA posterior forecast.

Thank You

Comments and questions are warmly welcome.

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Scan for the paper

Population Inference of Galactic Double White Dwarfs with Space-Based Gravitational-Wave Detections

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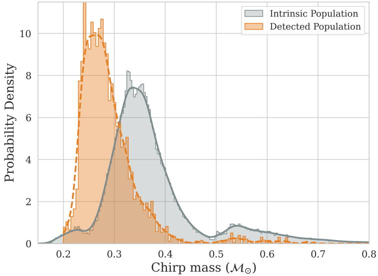
Science Motivation & Bayesian Framework

Scientific Motivation

- Space GW detectors (TianQin, LISA) will resolve $\sim 10^4$ double white dwarfs (DWDs).
- DWD populations constrain binary evolution models (e.g., common envelope efficiency).
- **Goal**: Recover Galactic DWD intrinsic population while correcting for selection effects.



Intrinsic (grey) vs. detected (orange) DWD chirp mass distribution under selection effects.

Hierarchical Bayesian Model

- Mixture model for chirp mass $\mathcal{M}$:

$$\pi(\mathcal{M} \mid \lambda) = \omega \pi_{\mathrm{PL}}(\mathcal{M} \mid \alpha) + (1-\omega) \pi_{\mathrm{G}}(\mathcal{M} \mid \mu, \sigma)$$

- Population parameters: $\lambda = (\omega, \alpha, \mu, \sigma)$

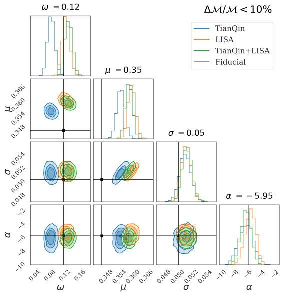
Key Results: Parameter Recovery & Optimal Threshold

Posterior Recovery

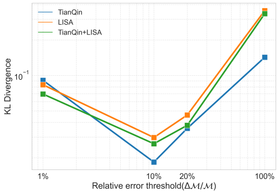
- HBI accurately recovers population parameters $(\omega, \mu, \sigma, \alpha)$ under selection effects.

Optimal 10% Threshold

- KL divergence (D_{KL}) quantifies recovery accuracy.
- **Minimum at 10%** relative error threshold for TianQin, LISA, and TianQin+LISA.
- Strict thresholds $(< 1\%)$ suffer from small-sample bias; relaxed $(< 100\%)$ suffer from noise.



(a) Posteriors $(\Delta\mathcal{M}/\mathcal{M} < 10\%)$

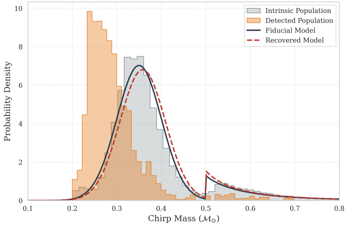


(b) KL Divergence vs. Error Threshold

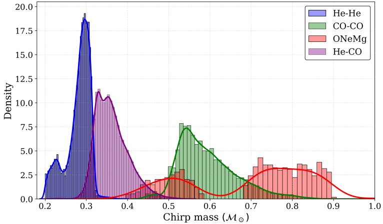
Population Recovery & Conclusions

Population Distribution Recovery

- Recovered model closely aligns with intrinsic population under 10% threshold.
- Power-law + Gaussian mixture model captures both low-mass tail and main peak.
- Mixture components reflect physical DWD sub-populations:
  - He-He ($\sim 0.3 M_\odot$), He-CO ($\sim 0.35 M_\odot$)
  - CO-CO ($\sim 0.55 M_\odot$), ONeMg ($\sim 0.8 M_\odot$)
- Connects global GW population inference with binary evolution physics.



(a) Recovered distribution vs. intrinsic & detected sample



(b) Intrinsic chirp mass distribution by stellar type

Backup Slides

All-bin Fisher details

Gaussian residual amplitudes

Residual distribution	$\lvert\rho_{\Omega\beta}\rvert$	I_0	$\sigma_\beta^{10\%}$	Min. d.o.f.
Uniform within each bin	0.475	1.136	0.00728	~ 630
Intrinsic drift + Doppler	0.438	1.112	0.01451	~ 93
Closest Fourier frequency	0.308	1.051	No prior	~ 3.3

- Uniform finite-source diagonal check: $I_0 = 1.138$ and $\sigma_\beta^{10\%} = 0.00698$.
- Reference case: $\Omega_{0,\mathrm{fid}}/\sigma_{\Omega,\mathrm{fixed}} = 47.9$.
- The 73 bins with $R_k = 0$ add $F_{\Omega\Omega}$ but not $F_{\Omega\beta}$ or $F_{\beta\beta}$.
- Reference omitted-residual shift: $\Delta\Omega_{\mathrm{bias}}/\sigma_{\Omega,\mathrm{fixed}} = 119.5$.

Overall noise-amplitude uncertainty

$$\mu_k = \eta P_{\mathrm{inst},k} + \Omega_0 T_k + \beta R_k, \qquad \eta_{\mathrm{fid}} = 1$$

Quantity	Fixed η	η marginalized
$\Omega_{0,\mathrm{fid}}/\sigma_{\Omega,\mathrm{fixed}}$	47.9	17.0
I_0 from marginalizing β	1.136	1.130
$\sigma_\beta^{10\%}$	0.00728	0.00848

Uncertainty in the overall instrumental-noise amplitude affects the absolute Ω_0 constraint more than the relative cost of marginalizing β.

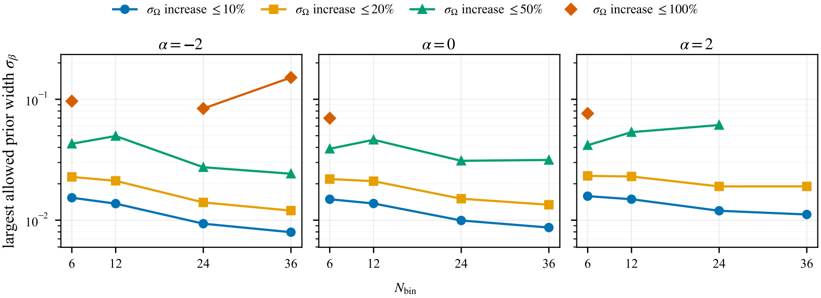
Selected frequency subsets

487 bins with $R_k > 0$, ranked by $|\gamma_{2,\mathrm{tot},k}|$:

α	N_{bin}	$\Omega_{0,\mathrm{fid}}/\sigma_{\Omega,\mathrm{fixed}}$	I_0	$\sigma_\beta^{10\%}$
−2	6	1.28	2.36	0.015
−2	36	6.98	2.03	0.008
0	6	2.29	3.04	0.015
0	12	4.73	1.84	0.014
0	24	7.62	1.97	0.010
0	36	9.98	1.76	0.009
2	6	4.52	2.90	0.016
2	36	17.51	1.42	0.011

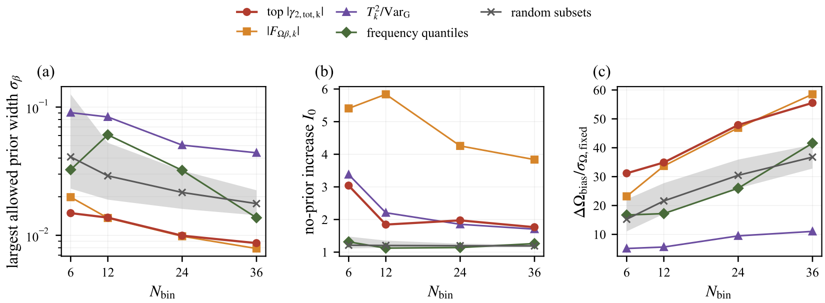
The ranking selects bins where the random-phase source discreteness remains least diluted; it does not rank the spectral overlap itself.

Prior widths for selected subsets



$\alpha = -2, 0, 2$; thresholds of $10\%, 20\%, 50\%, 100\%$. Open triangles indicate that no informative prior is required.

Dependence on frequency-bin selection



Gray bands: 16th–84th percentiles from 200 random subsets at each $\mathrm{N_{bin}}$; they show variation across frequency subsets, not measurement uncertainty.

Source concentration and Fourier covariance

Distinct but connected statistical objects

$\gamma_{2,\mathrm{tot}}$ describes the distribution of an auxiliary, response-averaged random-phase source sum. It does not determine the full cross-frequency covariance of Fourier power.

- C_2 and $\gamma_{2,\mathrm{tot}}$ are used to characterize source discreteness.
- For the uniform-within-bin mapping, $\mathrm{C}_{2,\mathrm{k}}$ determines the finite-source diagonal correction to the mode-power covariance.
- The all-bin Fisher result uses a fixed Gaussian mode-power covariance; the finite-source check changes 13.6% to 13.8%.
- Subsets are ranked by $|\gamma_{2,\mathrm{tot},\mathrm{k}}|$ only to select bins where the random-phase signature remains least diluted.

Random phase model derivation

Model: $x_{res} = \sum_i x_i$, $x_i = \sqrt{2p_i}\cos\phi_i$, $\phi_i \sim U(0, 2\pi)$ i.i.d.

Moments of a single term: $\langle\cos\phi\rangle = 0$, $\langle\cos^2\phi\rangle = \frac{1}{2}$, $\langle\cos^4\phi\rangle = \frac{3}{8}$.

$$\langle x_i\rangle = 0, \quad \langle x_i^2\rangle = p_i, \quad \langle x_i^4\rangle = \tfrac{3}{2}p_i^2$$

$$\kappa_{4,i} = \langle x_i^4\rangle - 3\langle x_i^2\rangle^2 = -\tfrac{3}{2}p_i^2$$

Cumulants add for independent variables: $\kappa_{4,res} = -\frac{3}{2}\sum_i p_i^2$, $\sigma_{res}^2 = \sum_i p_i$.

Excess kurtosis: $\gamma_{2,res} = \dfrac{\kappa_{4,res}}{\sigma_{res}^4} = -\dfrac{3}{2}\dfrac{\sum p_i^2}{(\sum p_j)^2} = \boxed{-\dfrac{3}{2}C_2}$

Note: p_i already contains orbital average $\rightarrow$ x_{res} is auxiliary response-averaged source sum, not time-dependent Michelson strain.

Noise dilution step-by-step

Setup: $x = x_{\rm res} + x_{\rm G}$ ($x_{\rm G}$ approx. Gaussian). Cumulants add for independent variables.
Gaussian properties: $\kappa_{4,\rm G} = 0$.

$$\kappa_{4,\rm tot} = \kappa_{4,\rm res} = \gamma_{2,\rm res}\,\sigma^4_{\rm res}$$
$$\sigma^2_{\rm tot} = \sigma^2_{\rm res} + \sigma^2_{\rm G}$$

Dilution formula:

$$\gamma_{2,\rm tot} = \frac{\kappa_{4,\rm tot}}{\sigma^4_{\rm tot}} = \gamma_{2,\rm res}\,\frac{\sigma^4_{\rm res}}{(\sigma^2_{\rm res} + \sigma^2_{\rm G})^2} = \gamma_{2,\rm res}\left(\frac{\sigma^2_{\rm res}}{\sigma^2_{\rm tot}}\right)^2$$

Identifying $\sigma^2_{\rm res} = R_{\rm k}$, $\sigma^2_{\rm tot} = \mu_{\rm k,fid}$: $\boxed{\gamma_{2,\rm tot,k} = \gamma_{2,\rm res,k}\,(R_{\rm k}/\mu_{\rm k,fid})^2}$.

Fourier-mode covariance construction

Sangria parameters: $N = 6\,307\,200$, cadence $5\,\mathrm{s}$, $T_{obs} = 31\,536\,000\,\mathrm{s}$, $f_j = j/T_{obs}$, $\delta f_F = 3.17 \times 10^{-8}\,\mathrm{Hz}$.
Independent Gaussian Fourier-mode powers: $\langle \widehat{S}_j \rangle = S_j$, $\mathrm{Cov}(\widehat{S}_j, \widehat{S}_{j'}) = S_j^2 \delta_{jj'}$.
Binned power: $\widehat{V}_k = \delta f_F \sum_{j \in \mathcal{J}_k} \widehat{S}_j$, $\mu_k = \delta f_F \sum_j S_j$, $\mathrm{Var}_G = (\delta f_F)^2 \sum_j S_j^2$.
PSD decomposition: $S_j = S_{inst}(f_j) + \Omega_0 \mathcal{T}_j(\alpha) + \beta S_{res,j}$.
Three residual Fourier distributions (same total catalog power):

- Uniform: $\nu_{eff} \approx 2M_k \approx 630$ (CLT well-satisfied)
- Drift+Doppler (chirp+Doppler broadening): $\nu_{eff} \approx 93$
- Closest-frequency: $\nu_{eff} \approx 3.3$ (Gaussian approximation weakest; limiting case)

The assigned powers determine both R_k in the mean and the covariance; drift–Doppler intervals can transfer power between neighboring bins.

Residual covariance model dependence

Let G_j be the instrumental+SGWB spectral density and H_j the residual spectral density at Fourier frequency j.

Gaussian residual amplitudes

$$\mathrm{Var}(\widehat{S}_j) = (G_j + H_j)^2$$

Includes the H_j^2 variance from Gaussian residual amplitudes.

Finite-source random phase

$$\mathrm{Var}(\widehat{S}_j) = (G_j + H_j)^2 - C_{2,k} H_j^2$$

Uniform distribution; diagonal correction.

Fixed residual Fourier realization

$$\mathrm{Var}(\widehat{S}_j) = G_j^2 + 2G_j H_j$$

Conditional on a fixed residual Fourier realization.

Residual distribution	Gaussian	Finite source	Fixed residual
Uniform within each bin	13.6%	13.8%	21.0%
Intrinsic drift + Doppler range	11.2%	—	21.1%
Closest Fourier frequency	5.1%	—	21.0%

Interpretation

The uniform all-bin increase changes by only 0.2 percentage points under the finite-source diagonal correction.

Prior widths for the uniform-within-bin mapping: 0.00728 (Gaussian), 0.00698 (finite source), and 0.00258 (fixed residual). None includes coherent cross-frequency covariance.

Instrumental-noise convention

Long-wavelength single-Michelson noise:

$$\mathrm{S_{inst}(f) = \frac{20}{3L^2}\left[P_{OMS}(f) + \frac{4P_{acc}(f)}{(2\pi f)^4}\right], \quad L = 2.5 \times 10^9\,m}$$

OMS (position noise):
$\mathrm{P_{OMS}(f) = (1.5 \times 10^{-11}\,m)^2\,Hz^{-1}\left[1 + (2.0 \times 10^{-3}\,Hz/f)^4\right]}$
Acceleration noise: $\mathrm{P_{acc}(f) =}$
$\mathrm{(3.0 \times 10^{-15}\,m\,s^{-2})^2\,Hz^{-1}\left[1 + (0.4 \times 10^{-3}\,Hz/f)^2\right]\left[1 + (f/8.0 \times 10^{-3}\,Hz)^4\right]}$
Convention: $20/3 = 1/\mathcal{R}^{\mathrm{X}}_{\mathrm{LW}}$ converts to equivalent incident strain, same as $\mathrm{p_i}$ and SGWB template. $\mathrm{P_{inst,k} = \delta f_F \sum_{j \in \mathcal{J}_k} S_{inst}(f_j)}$.

Fisher matrix construction

Setup: $\theta = (\Omega_0, \beta)$, covariance diagonal and fixed at fiducial.

$$F_{ij} = \sum_k \frac{(\partial_{\theta_i}\mu_k)(\partial_{\theta_j}\mu_k)}{\mathrm{Var}_G(\widehat{V}_k)}, \qquad \partial_{\Omega_0}\mu_k = T_k(\alpha), \quad \partial_\beta \mu_k = R_k$$

Element	Expression
$A = F_{\Omega\Omega}$	$\sum_k T_k^2/\mathrm{Var}_G(\widehat{V}_k)$
$B = F_{\beta\beta}$	$\sum_k R_k^2/\mathrm{Var}_G(\widehat{V}_k)$
$C = F_{\Omega\beta}$	$\sum_k T_k R_k/\mathrm{Var}_G(\widehat{V}_k)$

Gaussian prior $\beta = 1 \pm \sigma_\beta$: $B \to B_\sigma = B + 1/\sigma_\beta^2$. Fixed β: $\sigma_{\Omega,\mathrm{fixed}} = A^{-1/2}$. Marginalized: $\sigma_{\Omega,\mathrm{marg}} = \sqrt{B_\sigma/(AB_\sigma - C^2)}$.

Uncertainty increase and prior-width condition

Uncertainty inflation: $I^2(\sigma_\beta) = AB_\sigma/(AB_\sigma - C^2)$, $\quad B_\sigma = B + 1/\sigma_\beta^2$.
No-prior limit: $I_0 = 1/\sqrt{1-\rho^2}$ with $\rho = C/\sqrt{AB}$.
Prior-width condition $I(\sigma_\beta) \leqslant r_{\max}$:

$$B + \frac{1}{\sigma_\beta^2} \;\geqslant\; \frac{C^2}{A\,(1 - r_{\max}^{-2})}$$

- If $B \geqslant C^2/[A(1 - r_{\max}^{-2})]$: no informative prior needed
- Otherwise: $\sigma_{\beta,\max} = \left[C^2/(A(1-r_{\max}^{-2})) - B\right]^{-1/2}$

Thresholds: $r_{\max} = 1.1, 1.2, 1.5, 2.0$ $(10\%, 20\%, 50\%, 100\%)$.
Omitted-residual bias: $\Delta\Omega_{\rm bias}/\sigma_{\Omega,\rm fixed} = \beta_{\rm fid}\, C/\sqrt{A}$. (Linearized shift — distinct from marginalization penalty.)

Random-phase moment comparison

Procedure: 5×10^4 realizations per bin, 487 bins with $R_k > 0$. For each, draw $\phi_i \sim U(0, 2\pi)$ i.i.d., compute $x_{res} = \sum_i \sqrt{2p_i} \cos\phi_i$, estimate γ_2 from sample moments.

Metric	Value
Pearson $r(\gamma_{2,MC}, \gamma_{2,res})$	0.9991
$RMS(\Delta\gamma_2)$	1.78×10^{-2}
95th percentile $\lvert\Delta\gamma_2\rvert$	3.71×10^{-2}
Range of $\gamma_{2,res}$	[−1.5, 0]

Wider scatter at small C_2: sampling variance near Gaussian limit.
$corr(\Delta\gamma_2, C_2) = 0.036$ — no systematic bias.

Analysis settings reference

Setting	Value
Catalog data	LDC2A Sangria + Erebor comparison table
Response	Orbit-averaged Michelson X, $\mathcal{R}_{\mathrm{LW}}^{\mathrm{X}} = 3/20$
Frequency range	0.4–6.0 mHz
Bin width Δf	10^{-5} Hz (560 bins)
Observation	$T_{\mathrm{obs}} = 31\,536\,000\,\mathrm{s}$, cadence 5 s
Fourier modes per bin	315 or 316
Recovery criteria	$C_{\mathrm{rec}} \geqslant 0.9$, $\mathcal{O}_{\mathrm{best}} \geqslant 0.9$
Fiducial SGWB	$\Omega_0 = 10^{-11}$, $\alpha = -2, 0, 2$, $f_{\mathrm{ref}} = 3\,\mathrm{mHz}$
H_0	$67.4\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$
Noise model	Long-wavelength single-Michelson form
Covariance	Gaussian-amplitude; finite-source and fixed-residual compar
Fisher parameters	(Ω_0, β), Gaussian prior on β
Thresholds $r_{\max}$	1.1, 1.2, 1.5, 2.0