Data analysis challenges in LISA inference

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A comparison

A recipe for disaster

Ground based (2G)

+

(+ noise)

Space based

+

+

(+ noise)

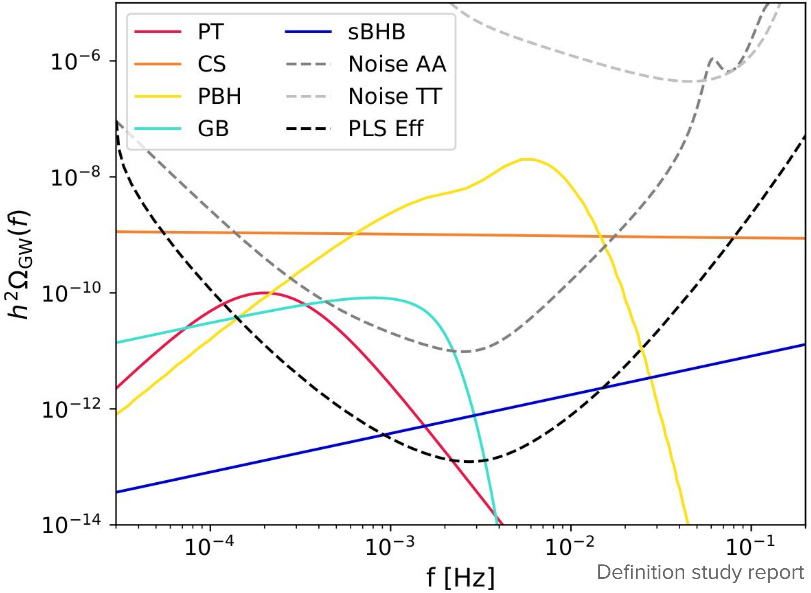
Pulsar Timing Array

+

(+ noise)

The upside down

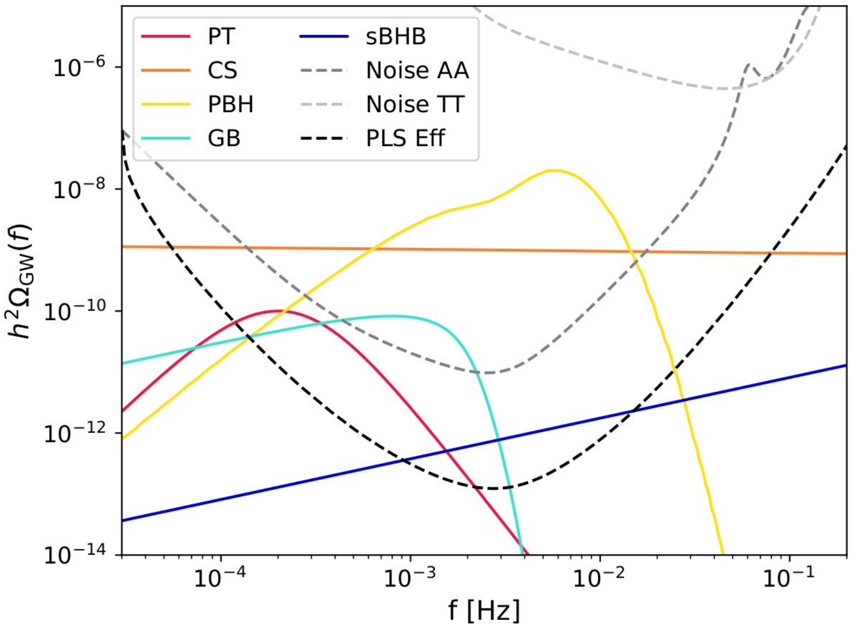
e.g. Braglia+ 2406.10048

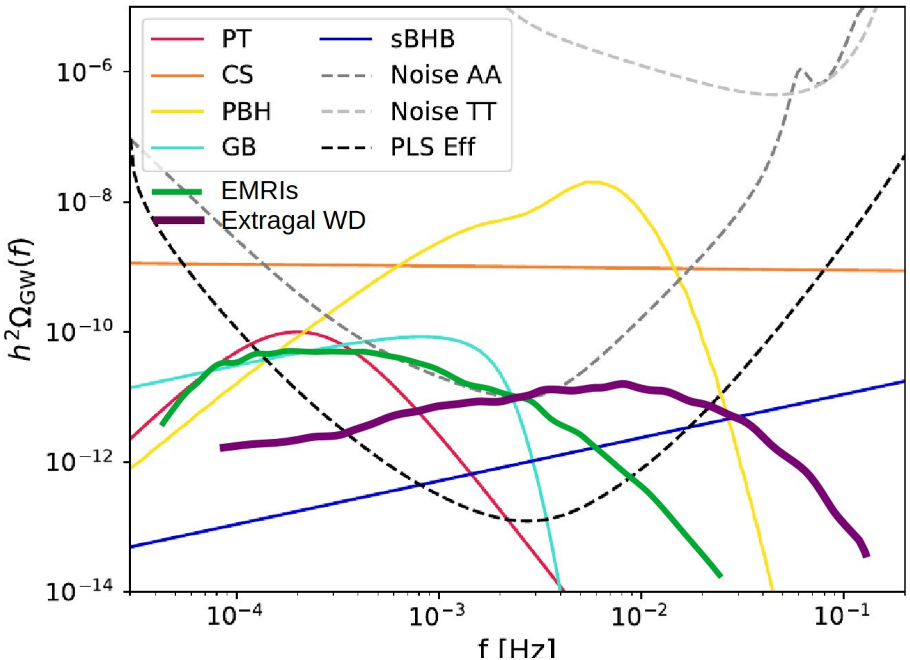


(+ noise)

Find the differences

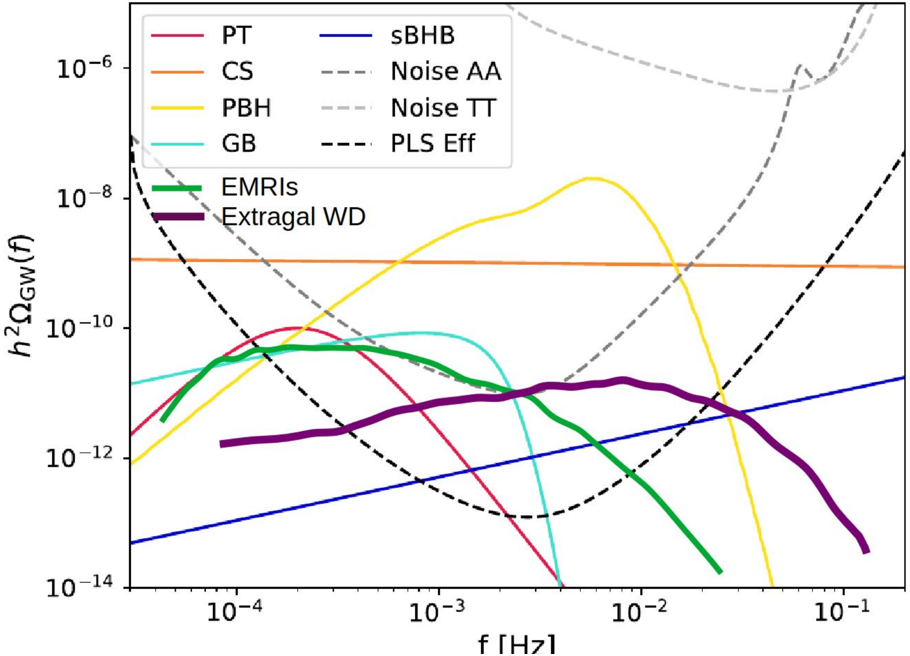
Ready for mixtures?

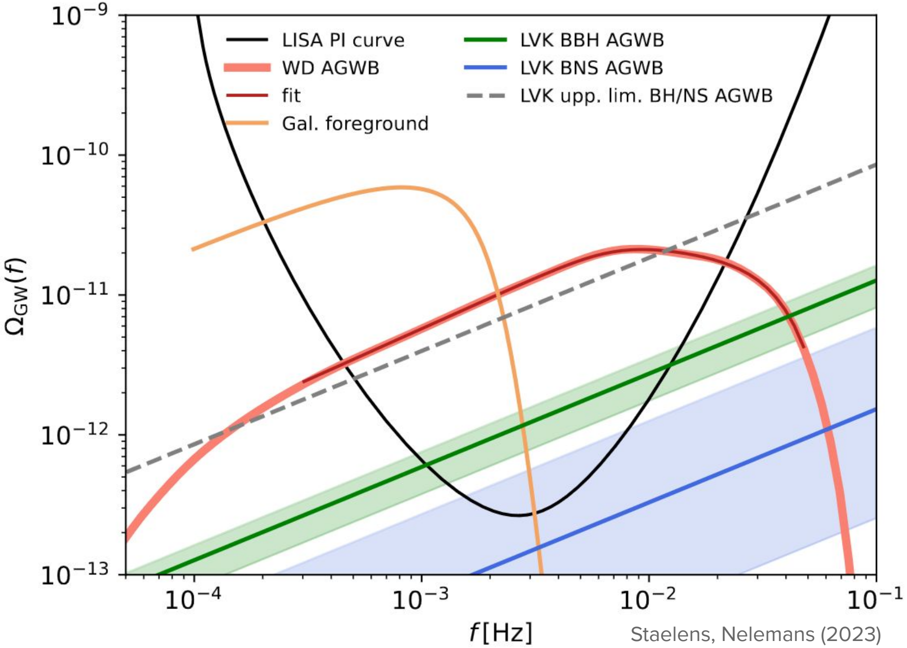




Find the differences

Ready for mixtures?

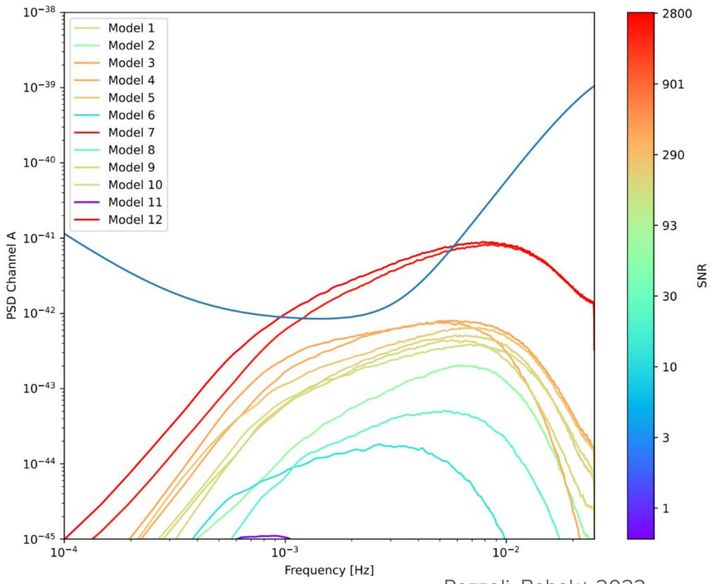




Staelens, Nelemans (2023)

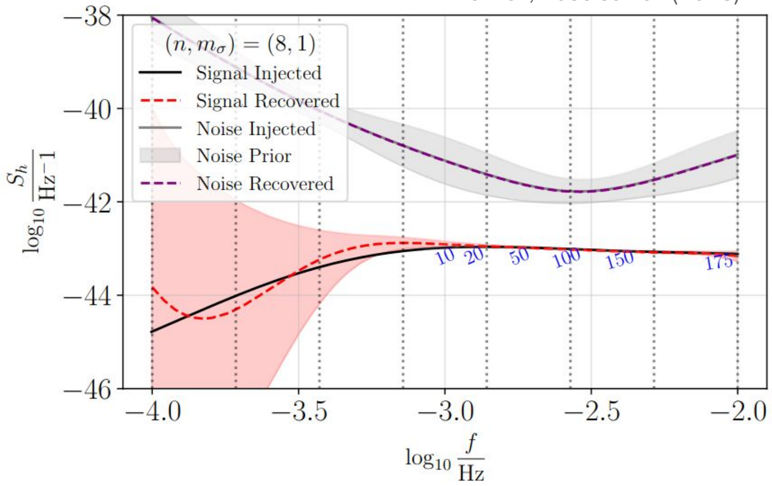
Collaborative effort is ongoing...

EMRI foregrounds
In unknown noise



Pozzoli, Babak+ 2023

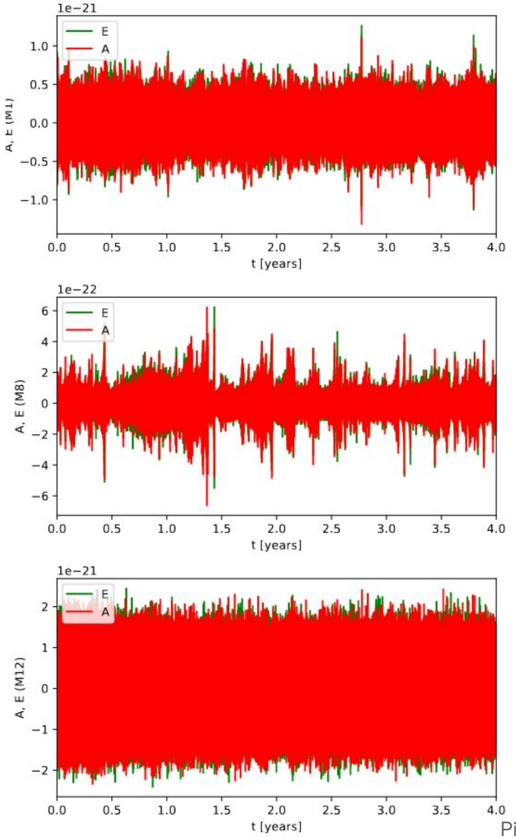
Pozzoli, Buscicchio+ (2023)



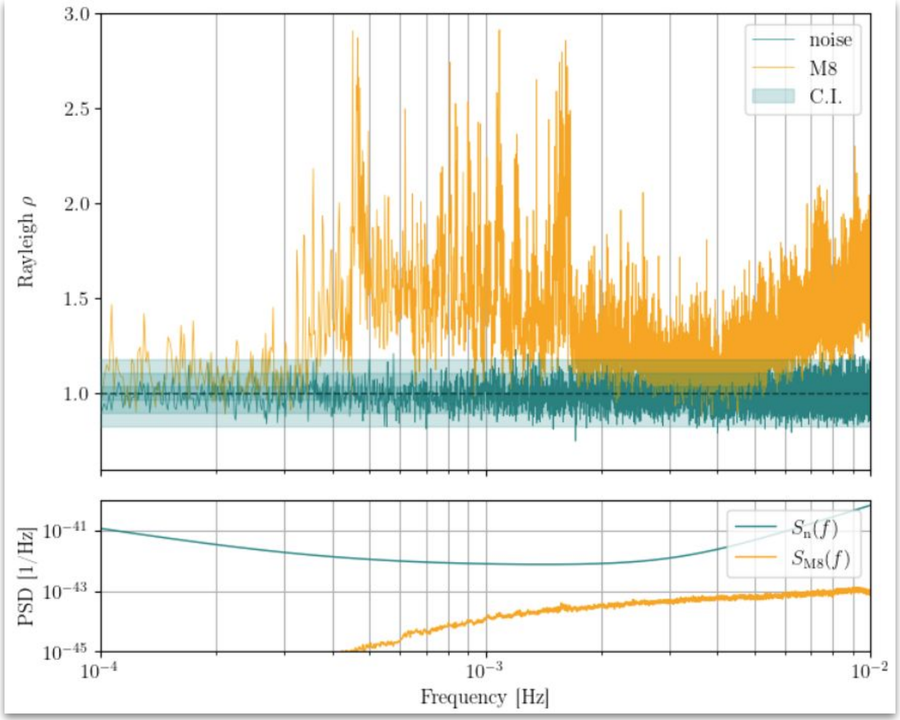
- Suitable for known & unknown global spectral shape
- Suitable for narrow spectral features
- Suitable for evidence-driven adaptive refinement

EMRI foregrounds

Stationary?



Piarulli, Buscicchio+ 2024



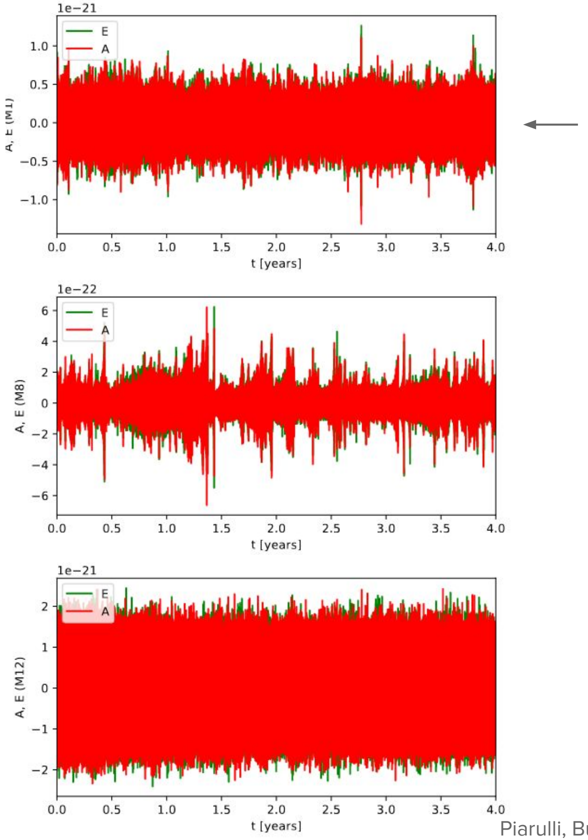
Non-stationary

Gaussian

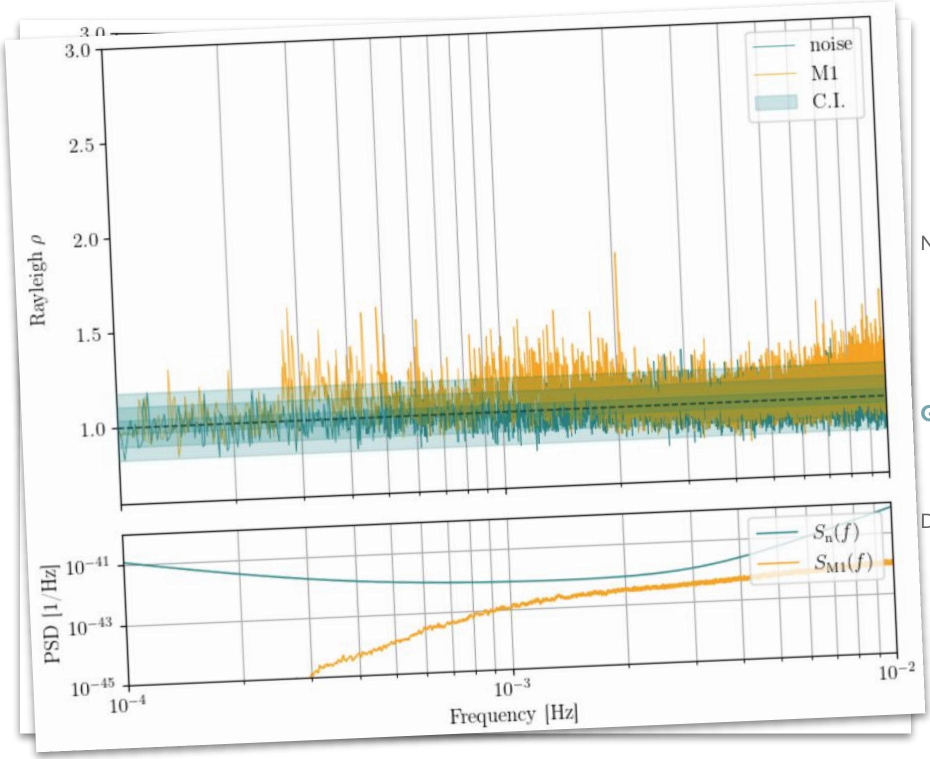
Deterministic

Piarulli, Buscicchio+ 2024

EMRI foregrounds
Stationary?



Piarulli, Buscicchio+ 2024



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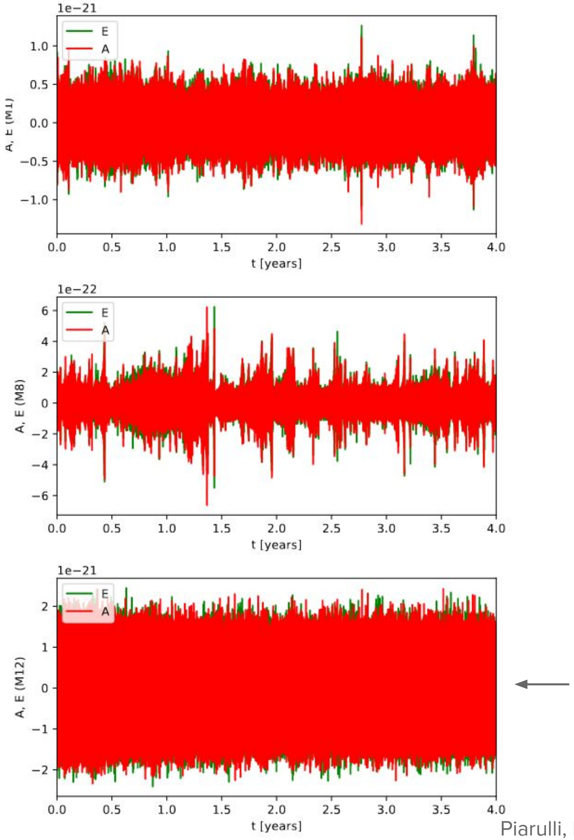
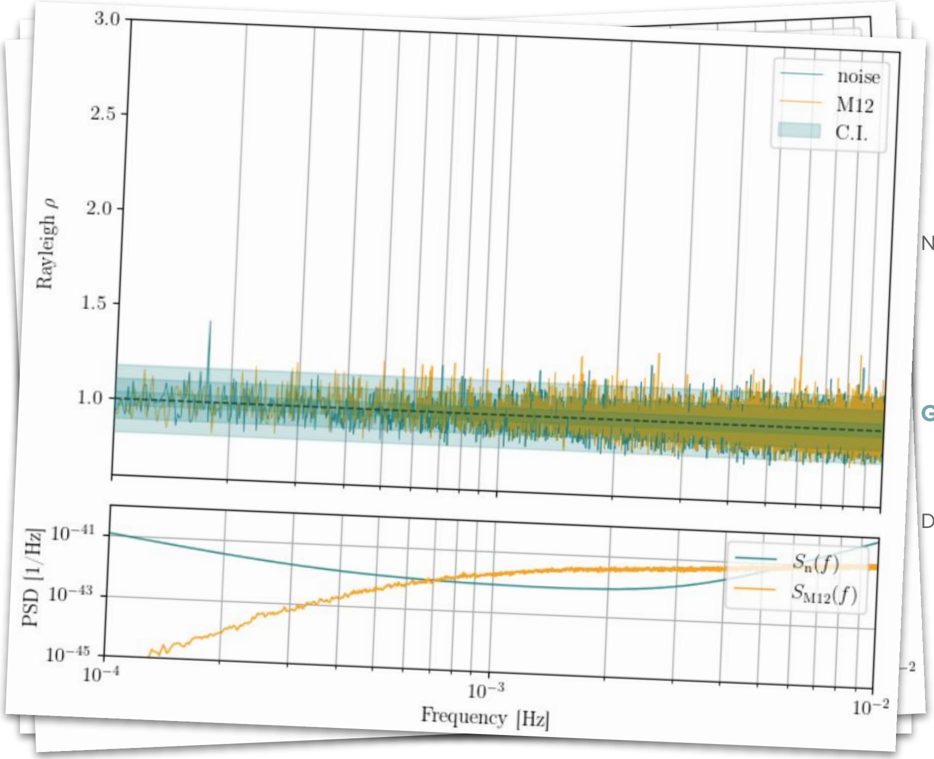
EMRI foregrounds
Stationary?



Piarulli, Buscicchio+ 2024



Non-stationary

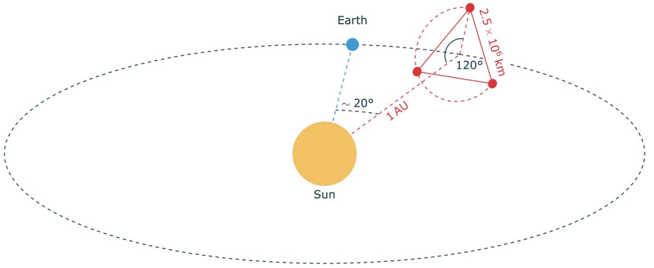
Gaussian

Deterministic

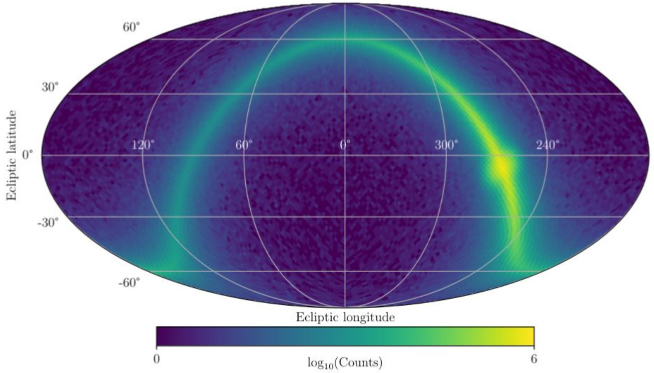
Piarulli, Buscicchio+ 2024

DWD foreground

Cyclostationary



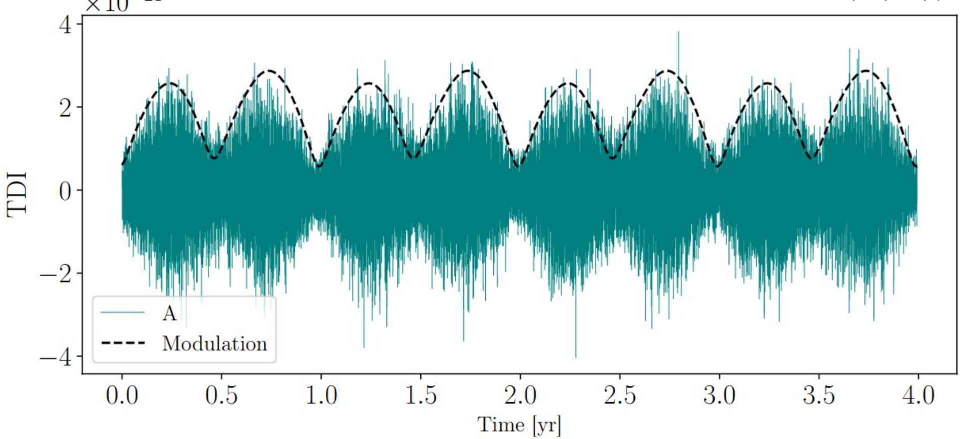
+



=

$$1/T_{\text{mission}} \leq 2/T_{\text{orb}} \ll f_s \ll 1/\Delta t$$

Buscicchio, Klein+ (in prep)



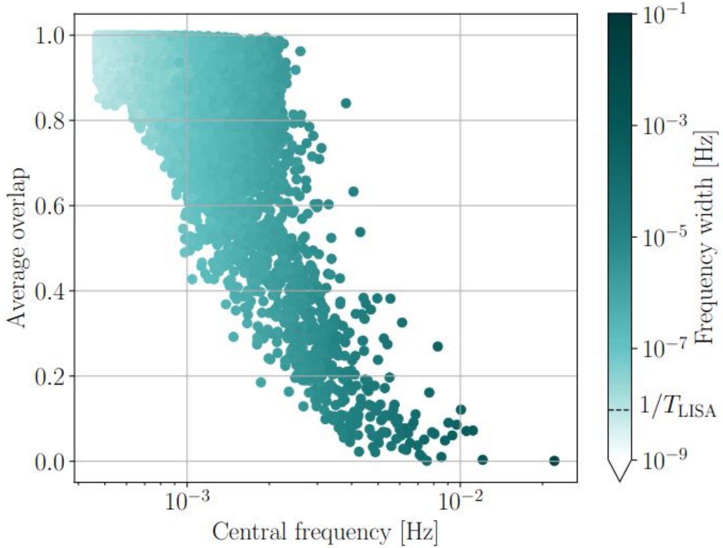
$$\mathcal{C}(f, f') = \sum_{n=-\infty}^{\infty} \gamma_n \, |\mathbf{J}| \, \delta\left(f - f' + \frac{n}{T_l}\right) S\left(\frac{f + f'}{2}\right)$$

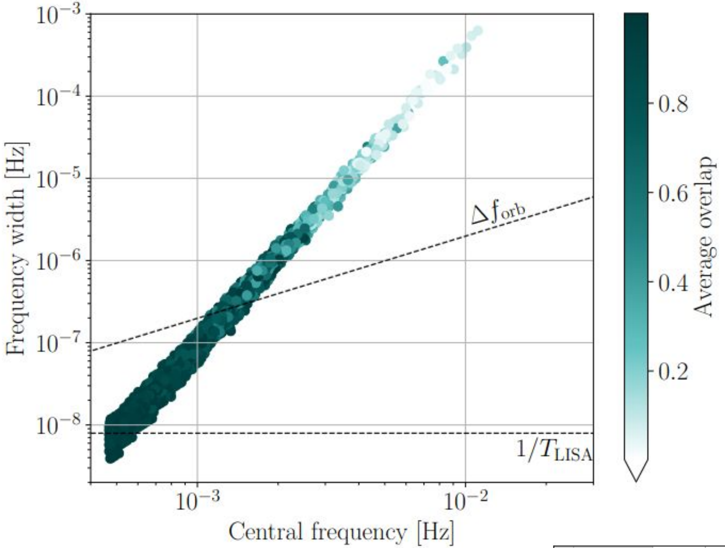
Sidenote: Time-domain windowing and gaps have similar effect

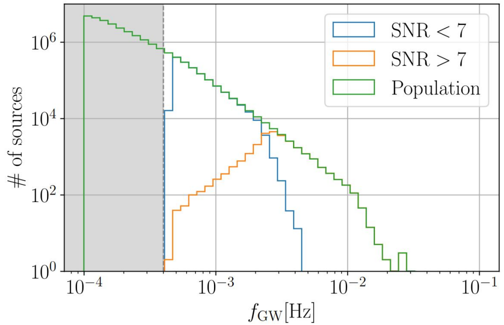
DWD foreground

Cyclostationary

Buscicchio, Klein + (in prep)

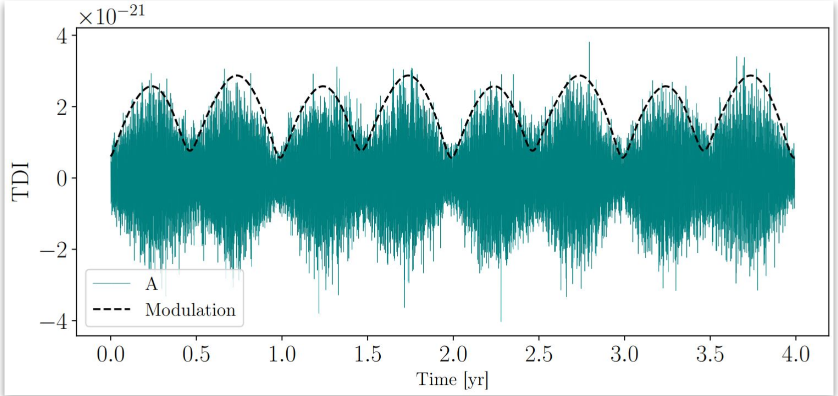






DWD foreground

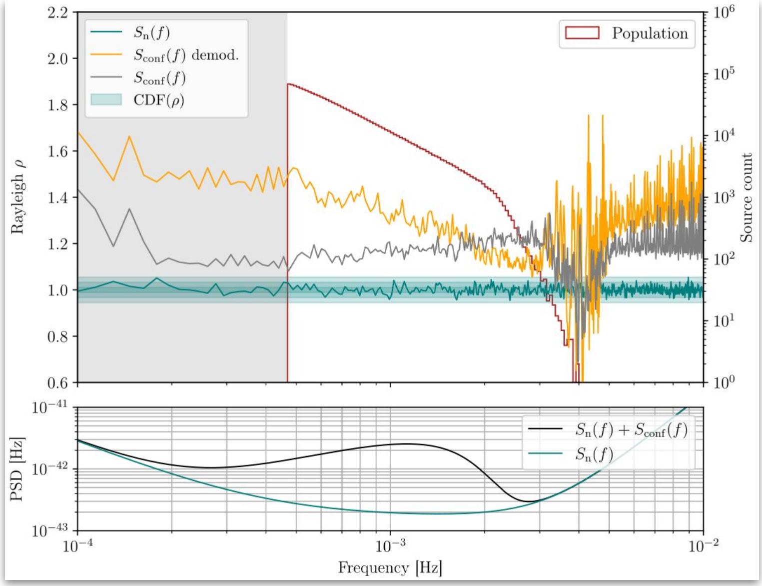
Cyclostationarity



Buscicchio, Klein+ (in prep)

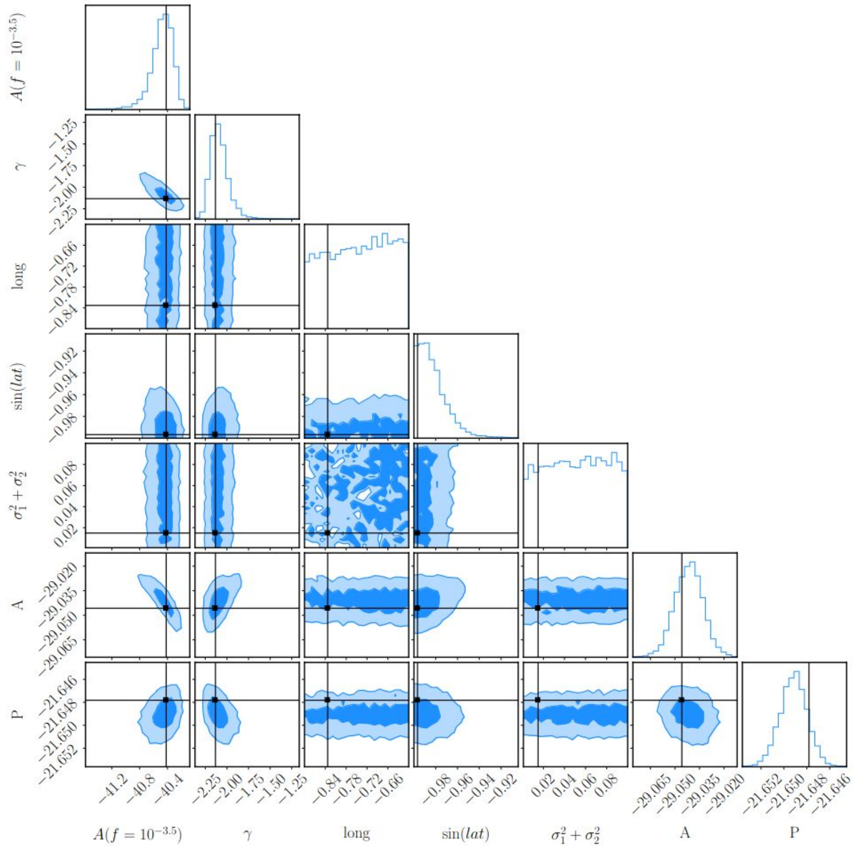
Heavy-tailed likelihoods for the characterization of stochastic gravitational wave background signals

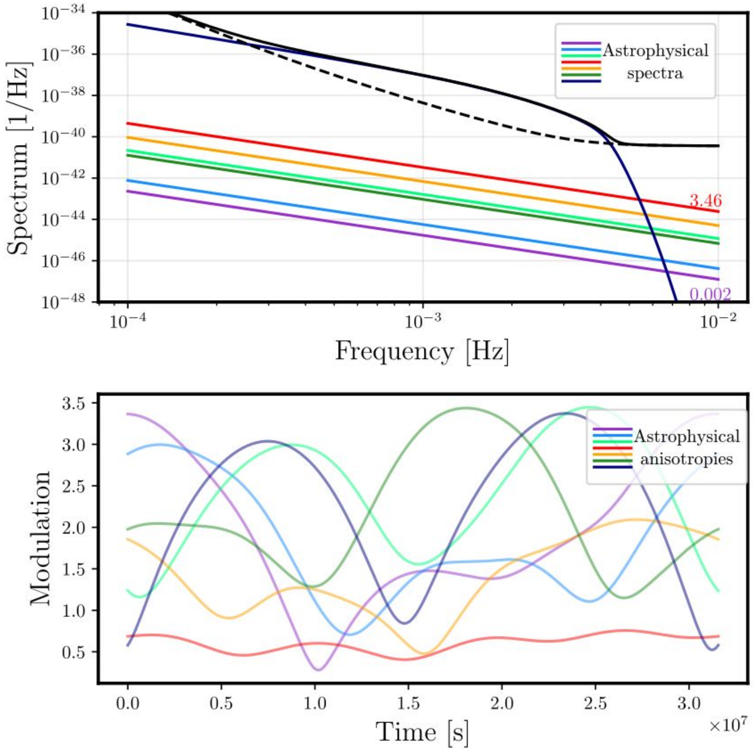
Karnesis, Buscicchio+ (in prep)



Cyclostationary spectra

An intermediate step

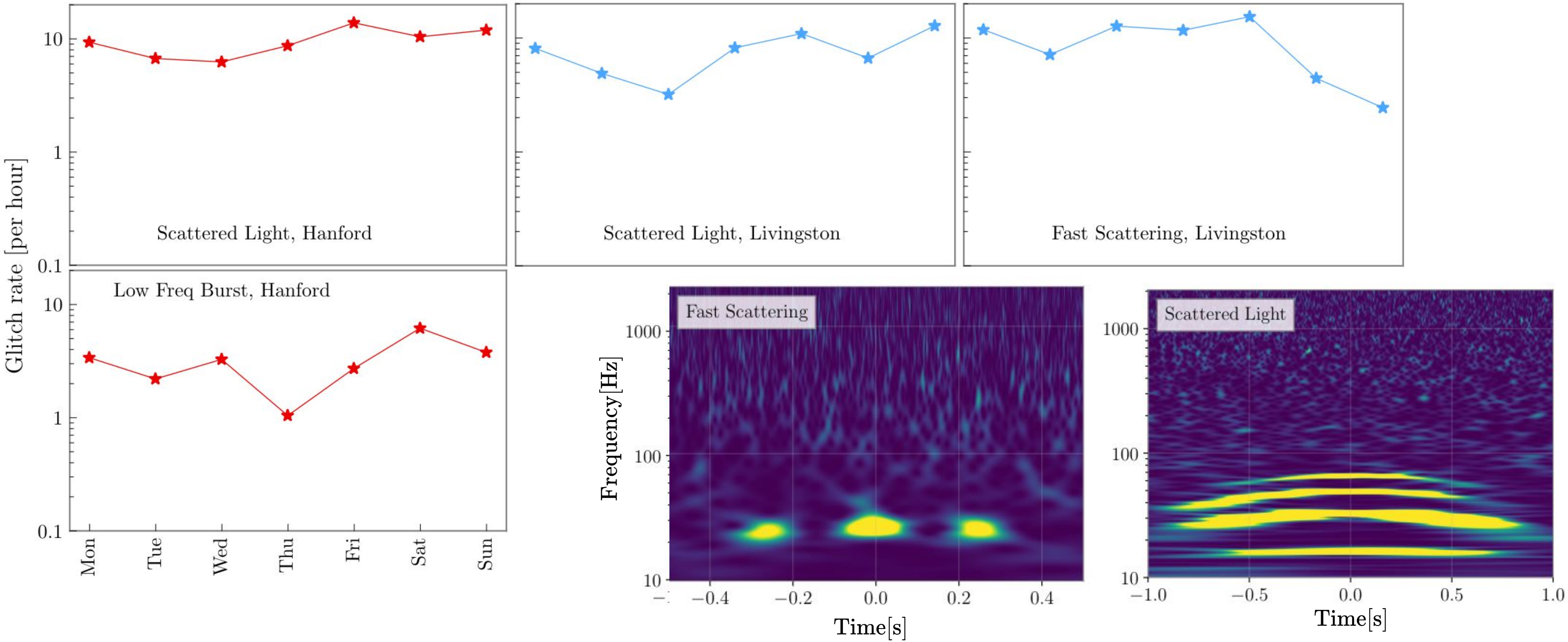




Pozzoli, Buscicchio+ (in prep)
see also Digman, Cornish (2022)

The junkyard
A quick digression

Glanzer+ (2023)

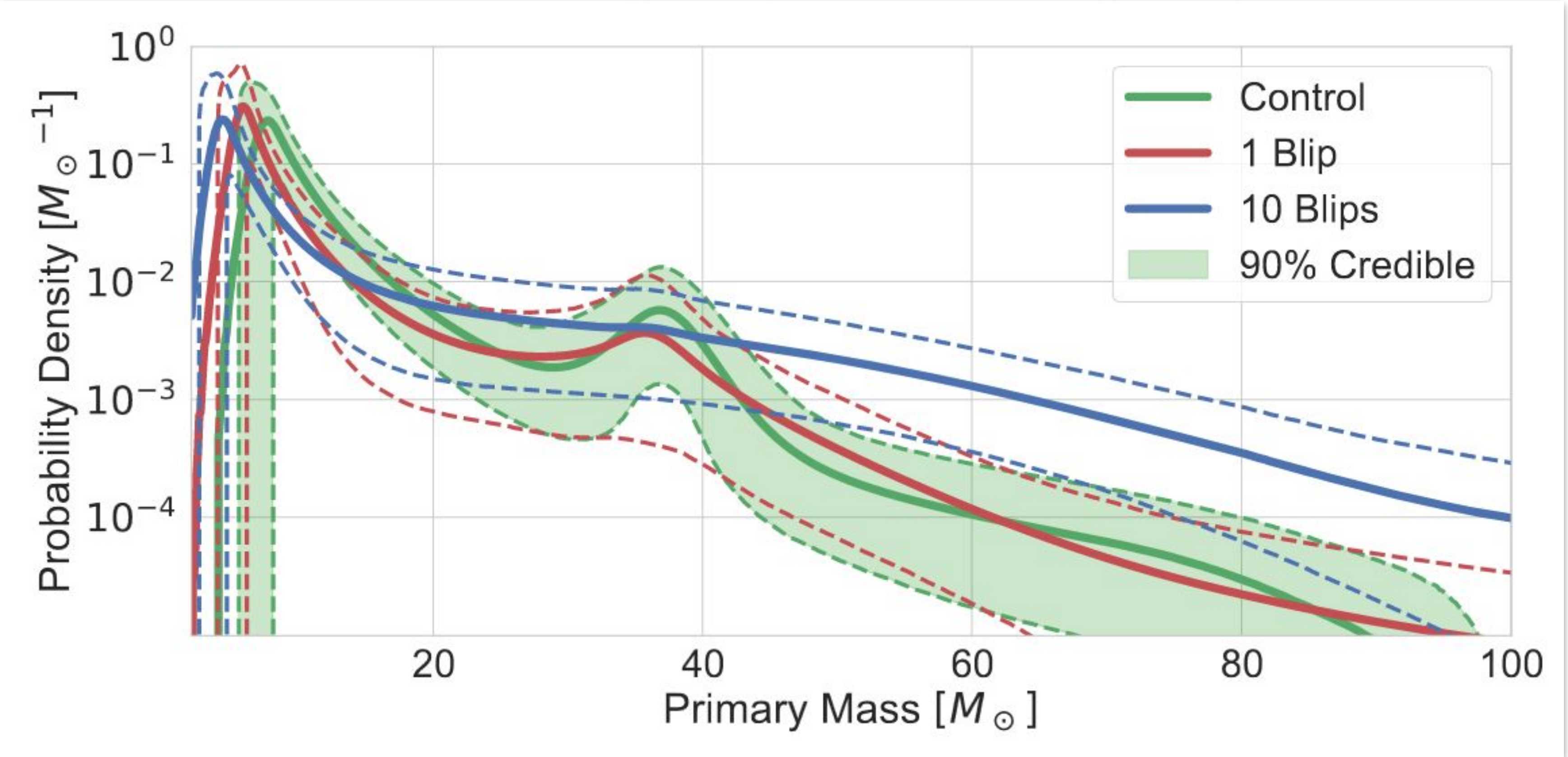


Any plan for gating in LISA? Line notching?

The junkyard

Why important?

Heinzel+ (2023)



Thanks!
Questions?

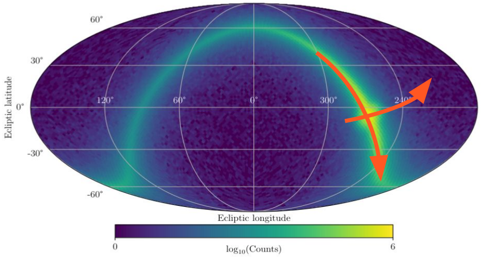
Backup slides

Cyclostationarity
The key ingredient

Pozzoli, Buscicchio+ (in prep)

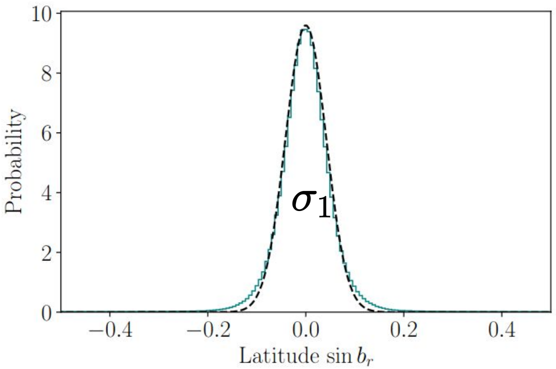
$$\int_{\mathbb{R}} d\theta_N \int_{\mathbb{R}} d\phi_N \; p(\theta_N,\phi_N) e^{in\theta_N} e^{im\phi_N} = \exp\left[-\frac{1}{4}\left(m^2+n^2\right)\sigma_+^2 + \frac{1}{4}\left(m^2-n^2\right)\sigma_{-,c}^2 + \frac{mn}{2}\sigma_{-,s}^2\right] e^{in\theta_M} e^{im\phi_M}$$

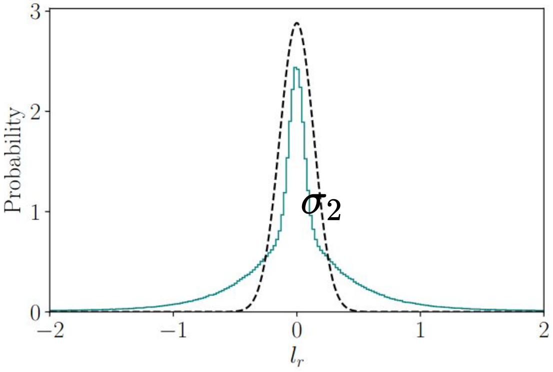
$$\sigma_+^2 = \sigma_1^2 + \sigma_2^2,$$
$$\sigma_{-,c}^2 = \left(\sigma_1^2 - \sigma_2^2\right)\cos 2\beta,$$
$$\sigma_{-,s}^2 = \left(\sigma_1^2 - \sigma_2^2\right)\sin 2\beta.$$



$$\phi_X(t) = E\left[e^{itX}\right]$$

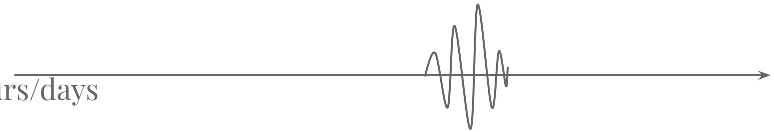
- **Characteristic function over integers!**
  - exists analytical for many probability distributions
  - closed upon mixing
- Smoothly interpolates pixel and spherical harmonics decomposition





Non-gaussian SGWB

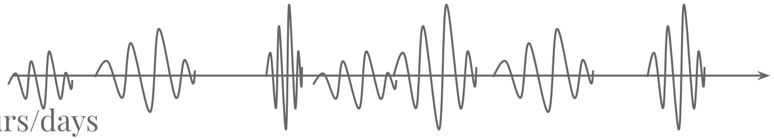
Draw the line where you need to



hours/days

Is it stochastic?

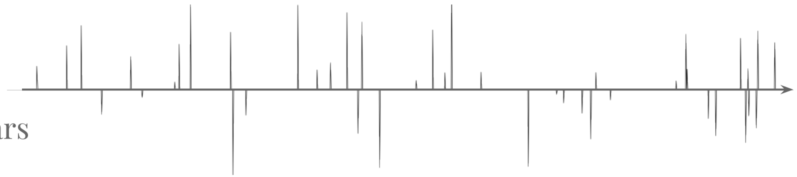
Individual event
param. est.



hours/days

Is it stochastic?

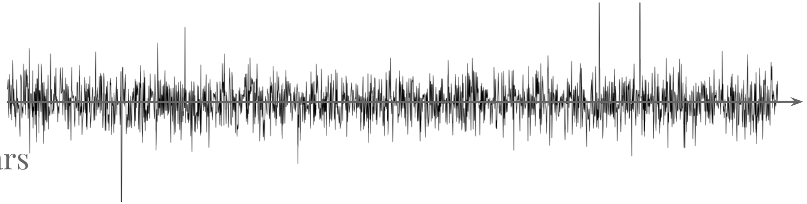
Overlapping event
param. est.



years

Is it deterministic?

Non-Gaussian
param. est.



years

Is it deterministic?

Gaussian SGWB
param. est.

A different perspective

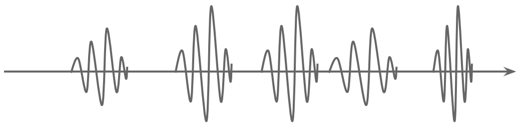
Campbell processes (Van Kampen 1981)

$$H_1 : s = n + g + h$$
$$H_0 : s = n$$

Data model

$$s_i^{\mathcal{A}} = g_i^{\mathcal{A}} + h_i^{\mathcal{A}} + n_i^{\mathcal{A}}$$

$$h^{\mathcal{A}}(t) = \sum_{\sigma=1}^{N} u^{\mathcal{A}}(t - \tau_\sigma; \theta_\sigma)$$



Where do you draw the line?
Confusion noise

Non-gaussian SGWB

An effective theory: Part 1

$$\hat{Y}(s) = \frac{1}{2}[\check{\mathbb{C}}_g]^{\mathcal{A}\mathcal{B}}_{ij}\,\mathfrak{s}^{\mathcal{A}}_i \mathfrak{s}^{\mathcal{B}}_j + \chi_h \sum_{n=1}^{\infty} \frac{1}{n!} \check{\Gamma}^{\mathcal{A}_1 \cdots \mathcal{A}_n}_{i_1 \cdots i_n}\, \mathfrak{s}^{\mathcal{A}_1}_{i_1} \cdots \mathfrak{s}^{\mathcal{A}_n}_{i_n}$$

Buscicchio, Ain+ (2022)

Free field

Interactions

Non-gaussian SGWB

An effective theory: Part 1

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Buscicchio, Ain+ (2022)

Free field

Interactions

Nothing more than **population model**

Vertices

$$\Gamma^{\mathcal{A}_1\cdots\mathcal{A}_n}(t_1,\cdots,t_n) = \rho\int\left\langle\prod_{k=1}^{n}u^{\mathcal{A}_k}(t-t_k;\hat{\theta})\right\rangle_{\hat{\theta}} dt$$

Extremely fast to evaluate

Non-gaussian SGWB

An effective theory: Part 1

$$\hat{Y}(s) = \frac{1}{2}[\check{\mathbb{C}}_g]^{\mathcal{AB}}_{ij}\mathfrak{s}^{\mathcal{A}}_i\mathfrak{s}^{\mathcal{B}}_j + \chi_h \sum_{n=1}^{\infty}\frac{1}{n!}\check{\Gamma}^{\mathcal{A}_1\cdots\mathcal{A}_n}_{i_1\cdots i_n}\mathfrak{s}^{\mathcal{A}_1}_{i_1}\cdots\mathfrak{s}^{\mathcal{A}_n}_{i_n}$$

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Extremely fast to evaluate

Generating functional of connected diagrams

$$W[J] = \langle e^{\mathrm{i}J_{\mathcal{A}_k}u^{\mathcal{A}_k}}\rangle$$

One current per detector

Non-gaussian SGWB

An effective theory: Part 1

$$\hat{Y}(s) = \frac{1}{2}[\check{\mathbb{C}}_g]^{\mathcal{AB}}_{ij}\mathfrak{s}^{\mathcal{A}}_i\mathfrak{s}^{\mathcal{B}}_j + \chi_h \sum_{n=1}^{\infty}\frac{1}{n!}\check{\Gamma}^{\mathcal{A}_1\cdots\mathcal{A}_n}_{i_1\cdots i_n}\mathfrak{s}^{\mathcal{A}_1}_{i_1}\cdots\mathfrak{s}^{\mathcal{A}_n}_{i_n}$$

Buscicchio, Ain+ (2022)

Free field

Interactions

Nothing more than **population model**

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Extremely fast to evaluate

Generating functional of connected diagrams

$$W[J] = \langle e^{\mathrm{i}J_{\mathcal{A}_k}u^{\mathcal{A}_k}}\rangle$$

One current per detector

Unfortunately: if the noise hypothesis is not under control (you cannot switch off the SGWB), poor performances.

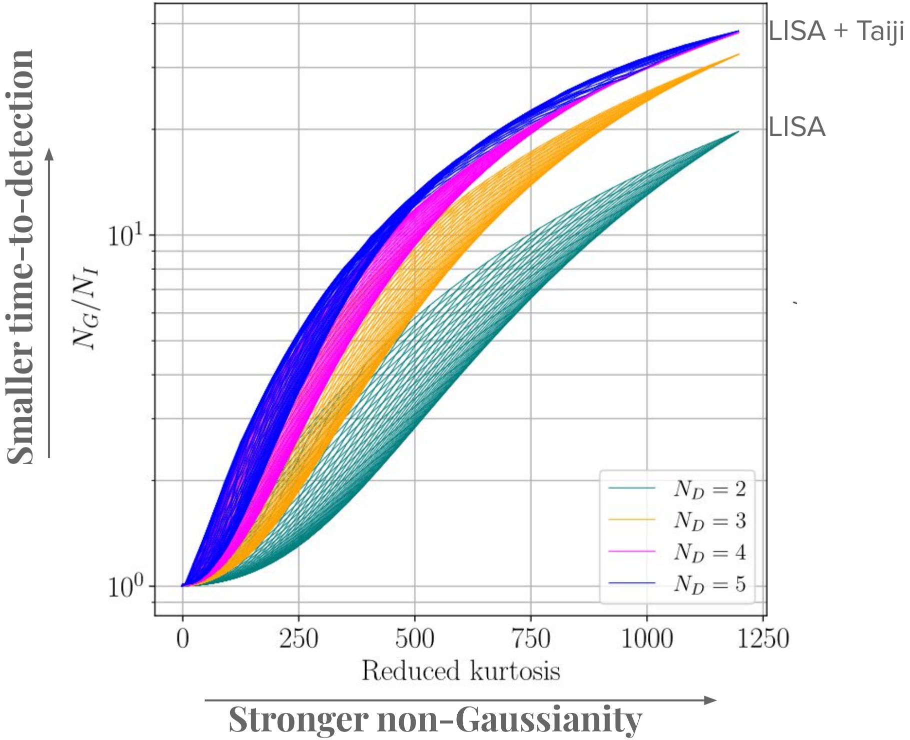
Non-gaussian SGWB

An effective theory: Part 2

Ballelli, Buscicchio+ (2023)

Theorem III.1. *For a given statistics* $\mathcal{S}(u^1, \cdots, u^{N_D})$, *where* $u^{\mathcal{A}} = h^{\mathcal{A}} + n^{\mathcal{A}}$, *if* $n^{\mathcal{A}}$ *are statistically independent stochastic variables (i.e., the noise in our context) with non-zero even momenta and zero odd momenta, we consider the formal Taylor expansion in powers of* $u^{\mathcal{A}}$. *A modified statistics where under* $\mathcal{H}_0$ *terms with non-zero expectation values are canceled while preserving others is*

$$\mathcal{S}_s(u^1, \cdots, u^{N_D}) = \mathcal{S}\left(u^1, \cdots, u^{N_D}\right) + \\ -\frac{1}{N_D} \sum_{\varepsilon_1=-1,1} \cdots \sum_{\varepsilon_{N_D}=-1,1} \mathcal{S}\left(\varepsilon_1 u^1, \cdots, \varepsilon_{N_D} u^{N_D}\right) . \quad (28)$$



Robust to noise mismodelling