Recovering Primordial Stochastic Gravitational Wave Backgrounds in the LISA Global Fit

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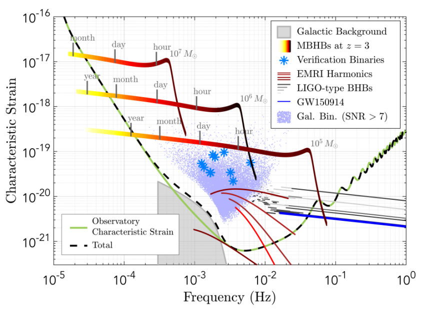
Outline

- LISA will see a lot of things
- (Explain data analysis??)
- Explain the Global Fit
- Eventual and current stochastic search strategy
- List current template bank
- Simulated data results
- Real global fit residuals

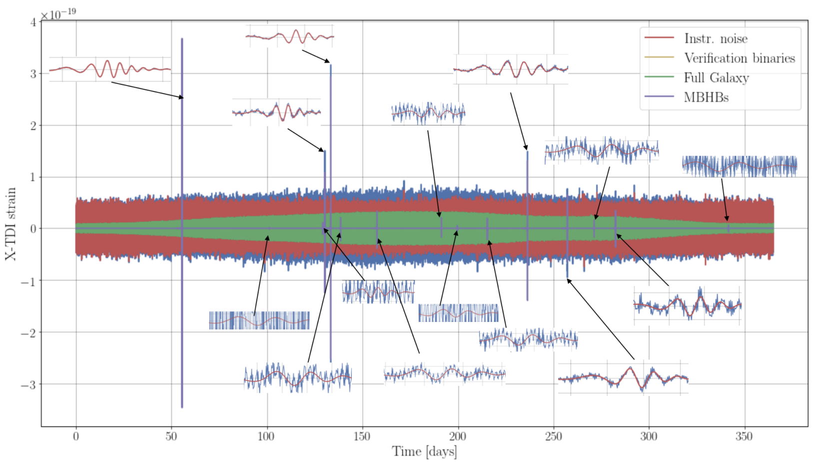
What will LISA see?

- Discrete sources **[Baker+ 2019]**
  - $\mathcal{O}(10^4)$ galactic binaries
  - Extreme mass-ratio inspirals
  - Black hole binaries
- Stochastic sources **[Cornish, Romano 2015]**
  - Unresolved GBs (Galactic foreground)
  - Unresolved BBHs (Extragalactic background)
  - **Primordial sources?**



[LISA Consortium 2017]

What does the data look like?



Why Fit Globally

Assuming Gaussian noise:

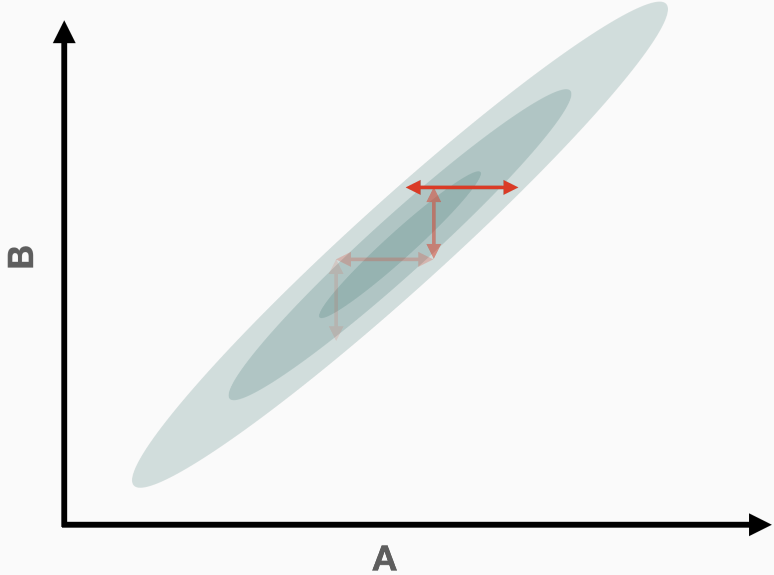
$$L(\mathbf{d}|\vec{\lambda}) = \frac{1}{\sqrt{(2\pi)^N |\mathbf{C}|}} e^{-\frac{1}{2}(\mathbf{d}-\mathbf{h})\mathbf{C}^{-1}(\mathbf{d}-\mathbf{h})}$$

Very challenging data analysis problem – easily 10^5 parameters

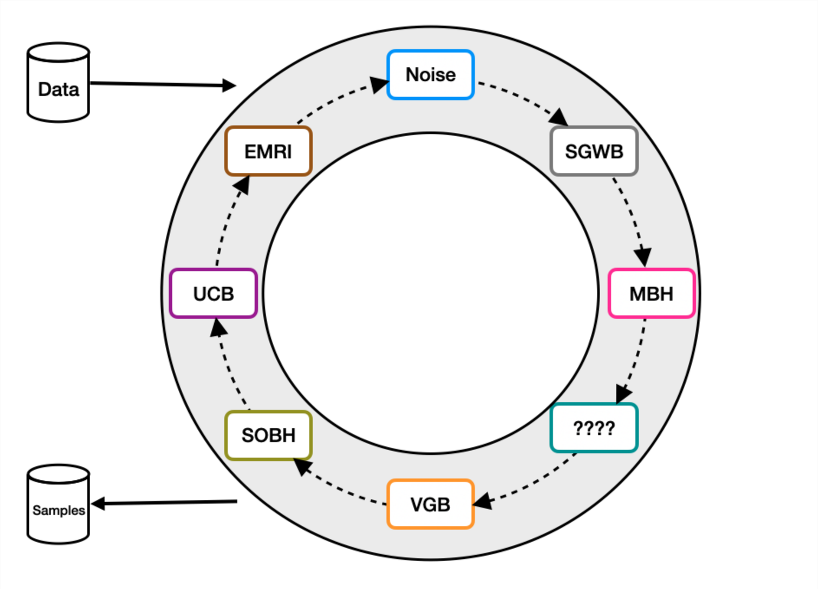
In principle, could split for each source

$$\log L = \langle d|h\rangle - \frac{1}{2}\langle h|h\rangle = \sum_i^M \log L_i - \frac{1}{2}\sum_{i\neq j}\langle h_i|h_j\rangle$$

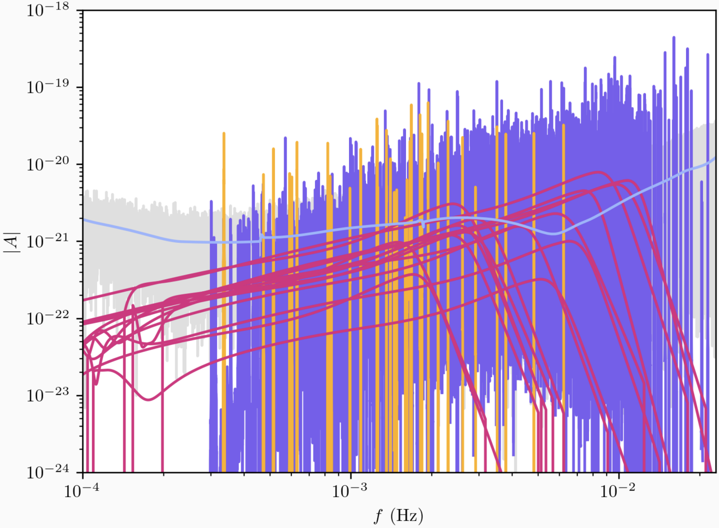
Blocked Gibbs sampling



Wheel



Sangria results ($50k on AWS!) [Littenberg, Cornish 2301.03673]



Current GLASS noise model

- Current residual is fit with independent Akima splines in TDI A and E channel
- Number of control points is varied (RJMCMC)
- **Ignores null channel!**

How do we detect an SGWB?

Use the covariance matrix, C.

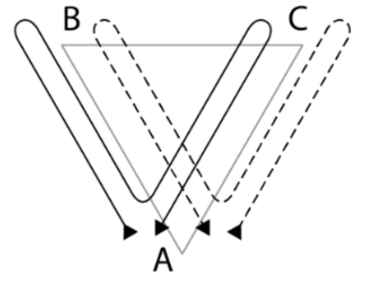
In the equal arm case ($i, j \in \{A, E, T\}$)

$$C_{ij} = \delta_{ij}(N_i + R_i S_i)$$

$$A = \frac{Z - X}{\sqrt{2}}$$

$$E = \frac{X - 2Y + Z}{\sqrt{6}}$$

$$T = \frac{X + Y + Z}{\sqrt{3}}$$

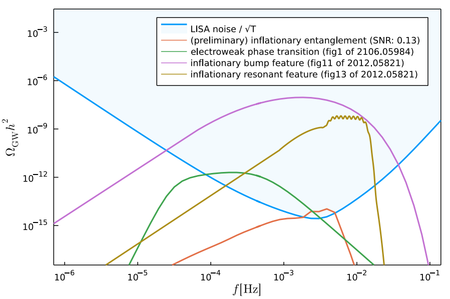


[Smith, Caldwell 1908.00546]

Many caveats! See Baghi+ 2302.12573, talks including Marc Lilley and Olaf Hartwig

Use stochastic templates

- Physically motivated background shapes – matched filtering in frequency domain **[Cornish, Romano 2016]**
- Decompose overlapping signals
- Automatic parameter inference and exclusion
- Work in time/frequency **[Digman, Cornish 2206.14813]**

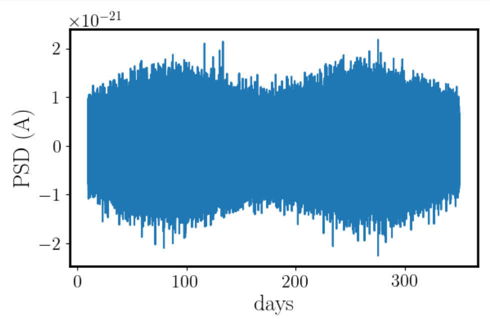


Prototype SGWB Recovery pipeline

Language	files	blank	comment	code
Python	27	481	885	5448
Jupyter Notebook	4	0	1664	655
C	1	52	143	454
make	1	0	0	3
SUM:	33	533	2692	6560

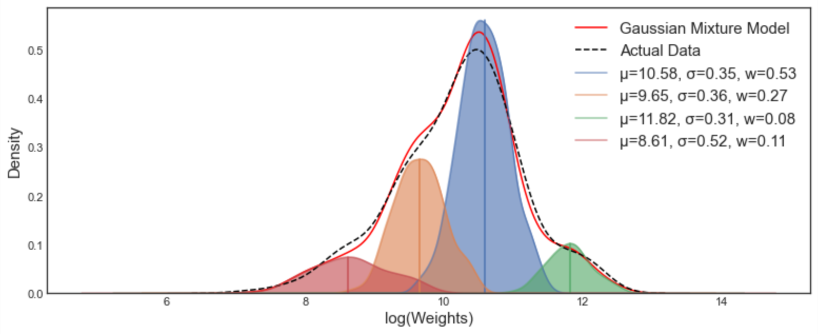
- Likelihood, templates, noise model implemented in C
- Use simple two-parameter noise model
- Data synthesis, bookeeping, sampling, plotting in Python
- Use `Eryn` parallel-tempered sampler [Karnesis+ 2303.02164]
- Use STFTs

Why STFTs?



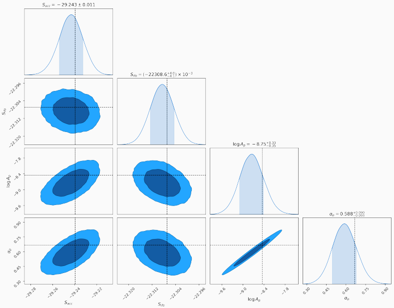
- Non-stationarity!
- Confusion noise is (close to) cyclo-stationary
- Instrument noise
- Isotropic SGWB posteriors modeled with GMMs

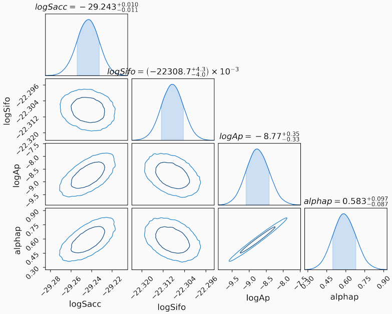
Gaussian Mixture Models



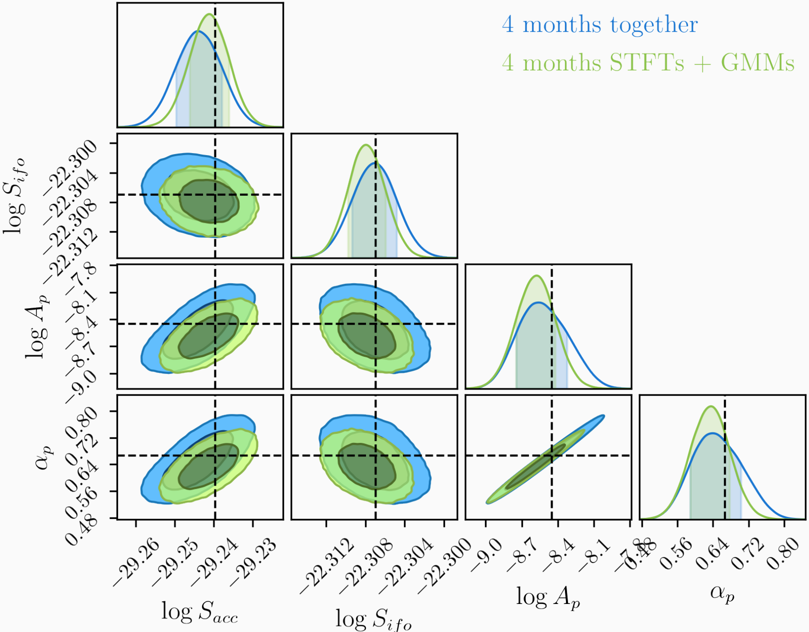
Gaussian Mixture Models

Posterior ⇒ Prior

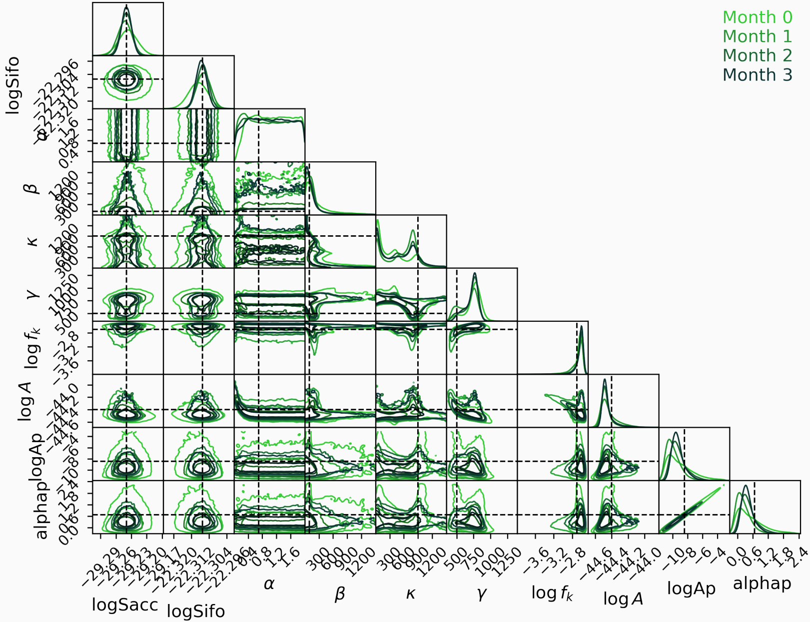




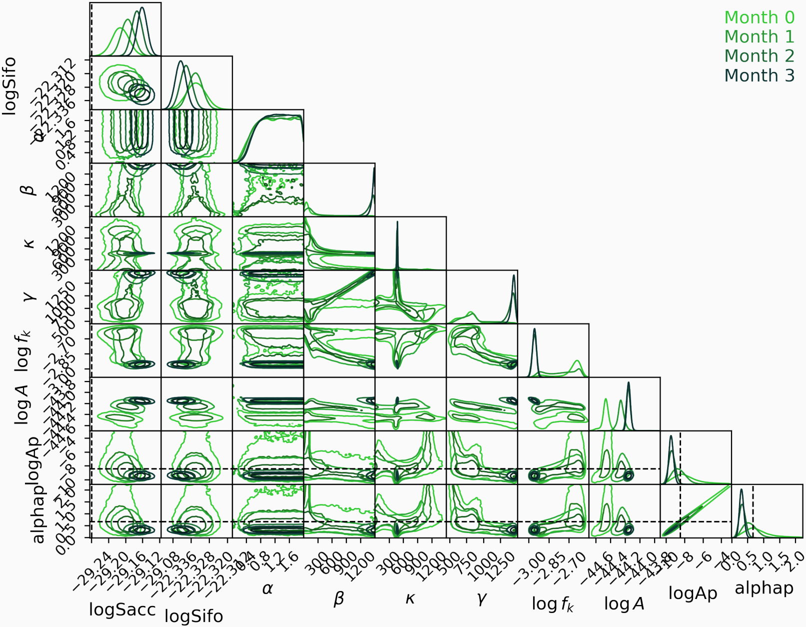
GMM comparison



Stationary "confusion noise" + powerlaw injection



Real global fit residual + powerlaw injection



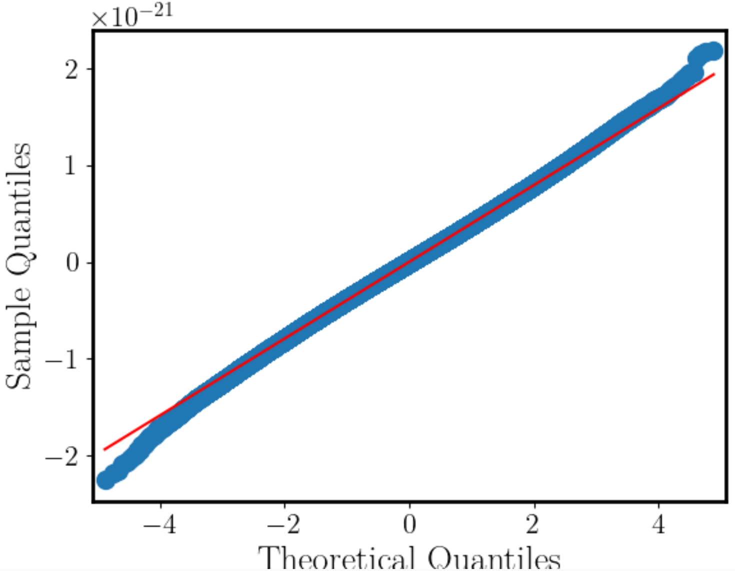
Preliminary Conclusions

- Primordial SGWBs can be constrained in presence of non-stationary components
- Modeling the non-stationarity helps constrain primordial signals
- Analytic model for confusion noise doesn't match
- Likely other un-modeled populations too [Littenberg, Breivik in prep]
- Anisotropies not fully exploited (BLIP [Banagiri+ 2103.00826])

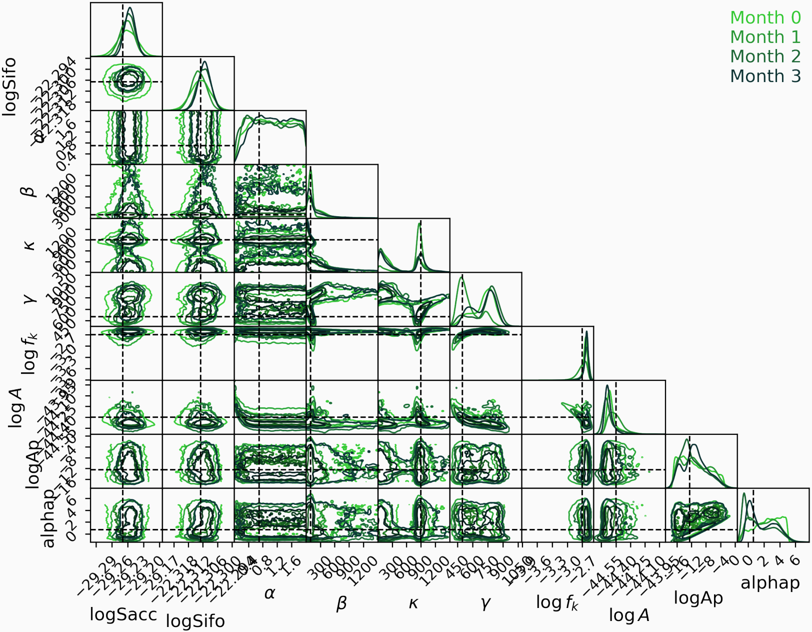
Future work

- Explore covariances in cosmological templates
- Expand the template library
- Inference during future `GLASS` runs
- Work with a better noise model?
- Switch to wavelet domain
- Use normalizing flows?

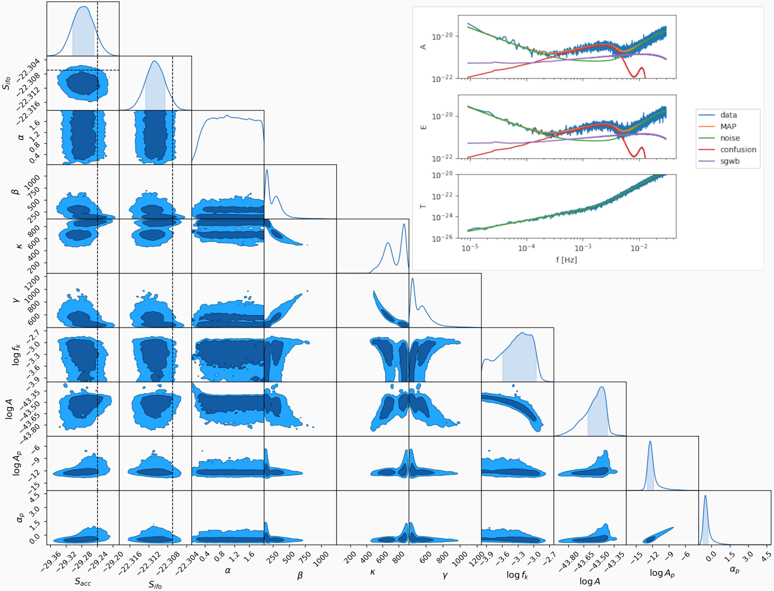
Confusion QQ plot



Injection simulating confusion noise



Real global fit residual, powerlaw upper limit (One STFT)



SGWB from P_ζ:

$$\Omega_{\rm GW}(k) =$$

$$c_g\Omega_{r,0}\int_0^{1/\sqrt{3}}\mathrm{d}d\int_{1/\sqrt{3}}^{\infty}\mathrm{d}s\,P_\zeta\left[\frac{\sqrt{3}k}{2}(s+d)\right]P_\zeta\left[\frac{\sqrt{3}k}{2}(s-d)\right]T(d,s)$$

$$T_{\rm RD}(d,s) = 36\frac{(d^2-1/3)^2(s^2-1/3)^2(d^2+s^2-2)^4}{(s^2-d^2)^8}\times$$

$$\left[\left(\log\frac{1-d^2}{|s^2-1|}+\frac{2(s^2-d^2)}{d^2+s^2-2}\right)^2+\pi^2\theta(s-1)\right]$$

$$c_g\Omega_{r,0}h^2 = 1.6\times 10^{-5}$$

GB skymap