

Bayesian analysis of pulsar timing arrays

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NanoGRAV meeting, 2008

Bayes theorem

- For any statistical inference problem, Bayes theorem can be used:
- $P(\text{par} \mid \text{data}) = \frac{1}{N} P(\text{data} \mid \text{par}) P_0$
- Need $P(\text{data} \mid \text{par})$ to do inference.
- For PTA, assume a Gaussian model (for now. . .)

Inference model

- Construct $P(\text{data} \mid \text{par})$ from model
- Deterministic sources (parameters contain all information)
- Stochastic sources (parameters contain statistical information)

- $P(\vec{\theta} \mid \vec{\delta t}) \sim$
$$\sqrt{\frac{1}{\det C}} \exp \left[(TR_{\text{obs}} - TR_{\text{fit}})^T C^{-1} (TR_{\text{obs}} - TR_{\text{fit}}) \right]$$

Sources

- Deterministic: $\delta t = A \sin(\omega t + \phi)$ (a simple sine)
- Everything that can be “fit for”: period derivative, Shapiro delay, equipment zero resets. . .

- Stochastic: $S(f) = A^2$ (white noise spectrum)
- GWB (power-law spectrum), pulsar timing noise (uncertain spectrum)

Bayesian inference strategy

- Construct a likelihood function $P(a, b, .. | \text{data})$
- Marginalize unwanted parameters (integrate likelihood/posterior)
- Plot the marginalized probability distribution

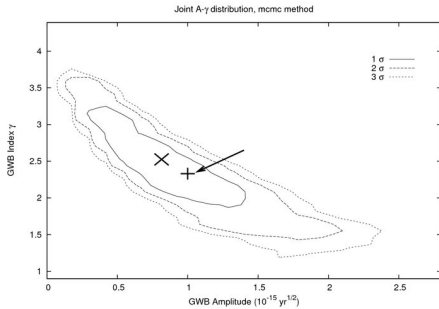
Sources

- Treat all parameters equal: integrate uninteresting parameters
- $P(A_{\text{GW}}, \gamma_{\text{GW}}, N_{\text{PN}}, \text{QSD}, \dots) \rightarrow P(A_{\text{GW}}, \gamma_{\text{GW}})$

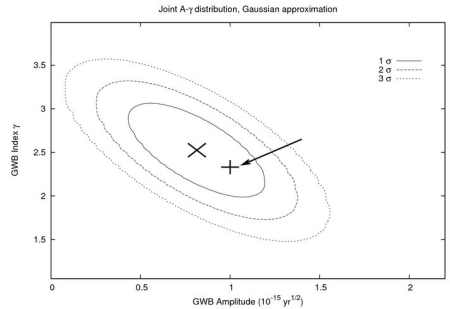
Marginalization (integrations)

- Linear: analytical (easy)
- Other: numerical (hard)

10yr, 100ns, monthly obs

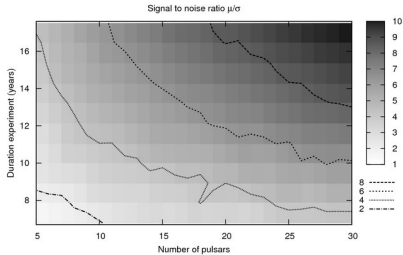


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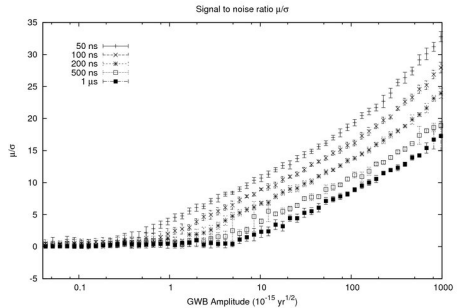


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Parameter studies



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Advantages

Our algorithm

- Does not rely on estimators - Explores the full likelihood function
- Measures simultaneously amplitude and slope of GWB
- Deals easily with unevenly sampled data, variable number of tracked pulsars, etc.
- Deals easily with systematics, like quadratic spindowns, zero resets, pointing errors, . . . of known functional form