Generic burst search

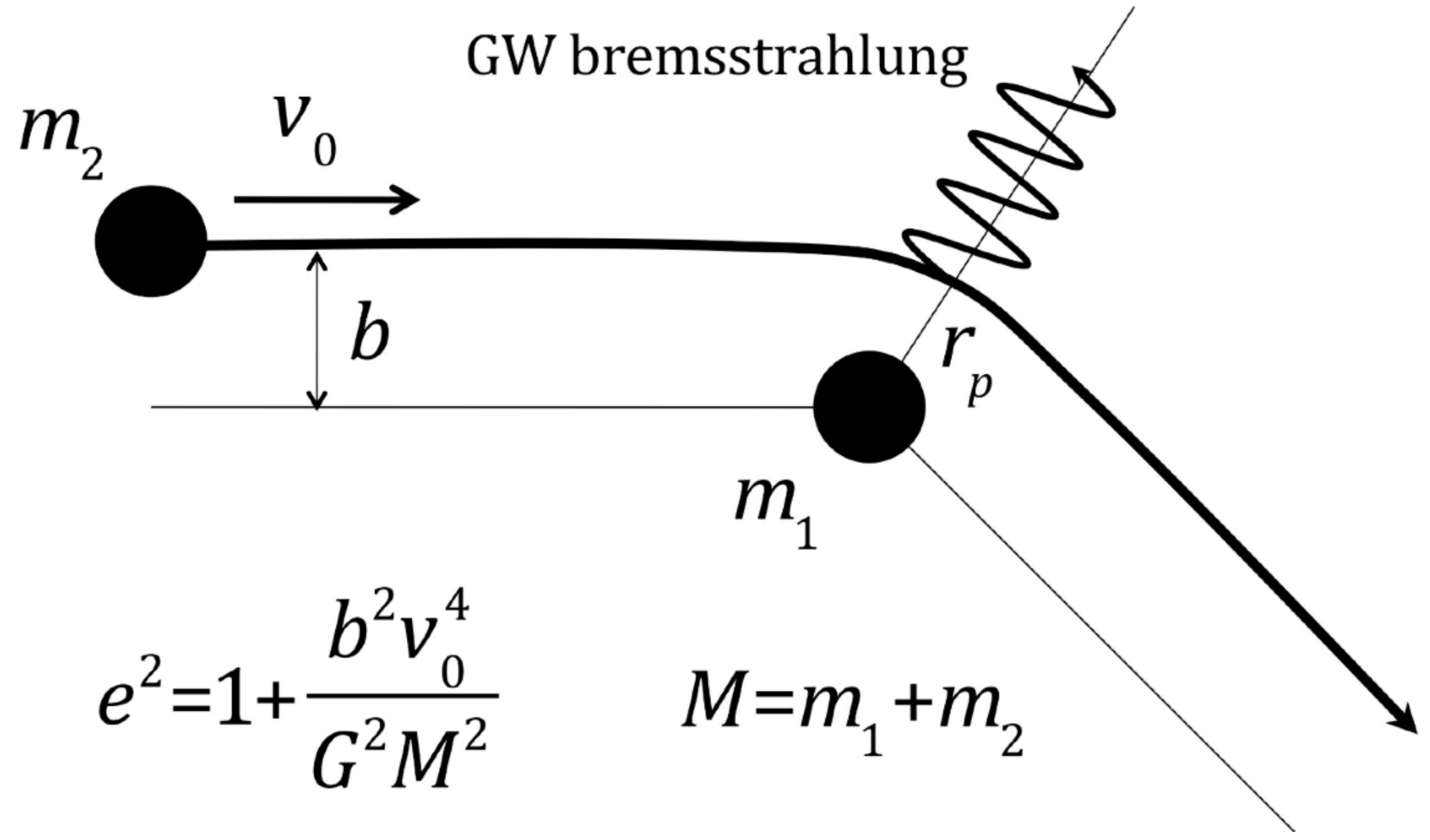
Neil Cornish

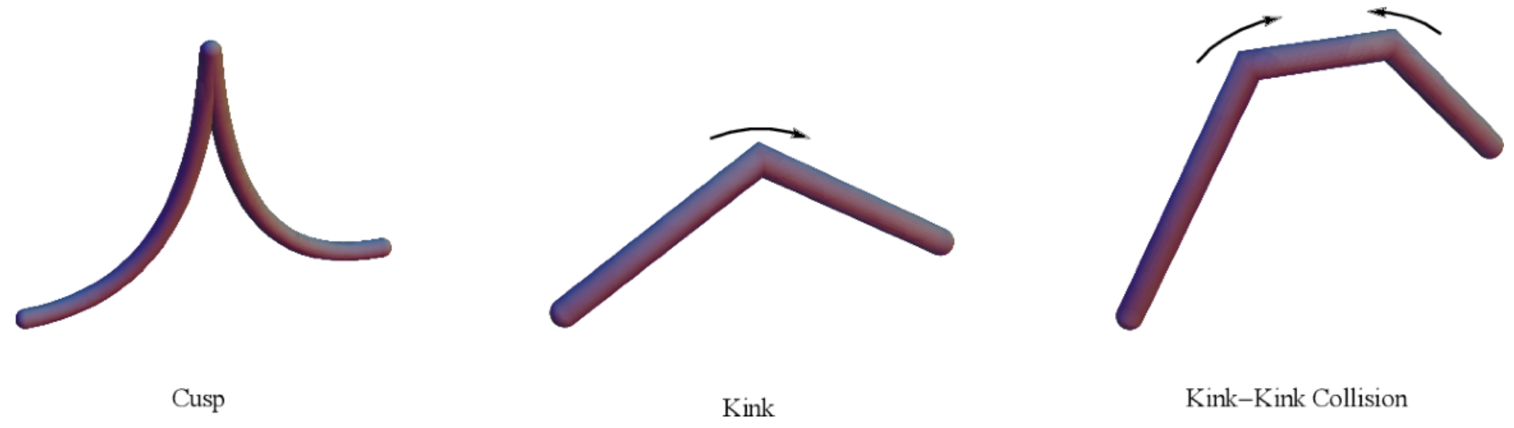
Outline

- Motivation
- LIGO Heritage
- PTAs: Earth terms and Pulsar terms
- Wavelet Based Search
- Spline Based Search
- Piecewise Linear Search
- Status and Plans

Motivation

- Theorized burst signals
  - Hyperbolic BH encounters
  - Highly eccentric BH binaries
  - Cosmic String cusps/kinks

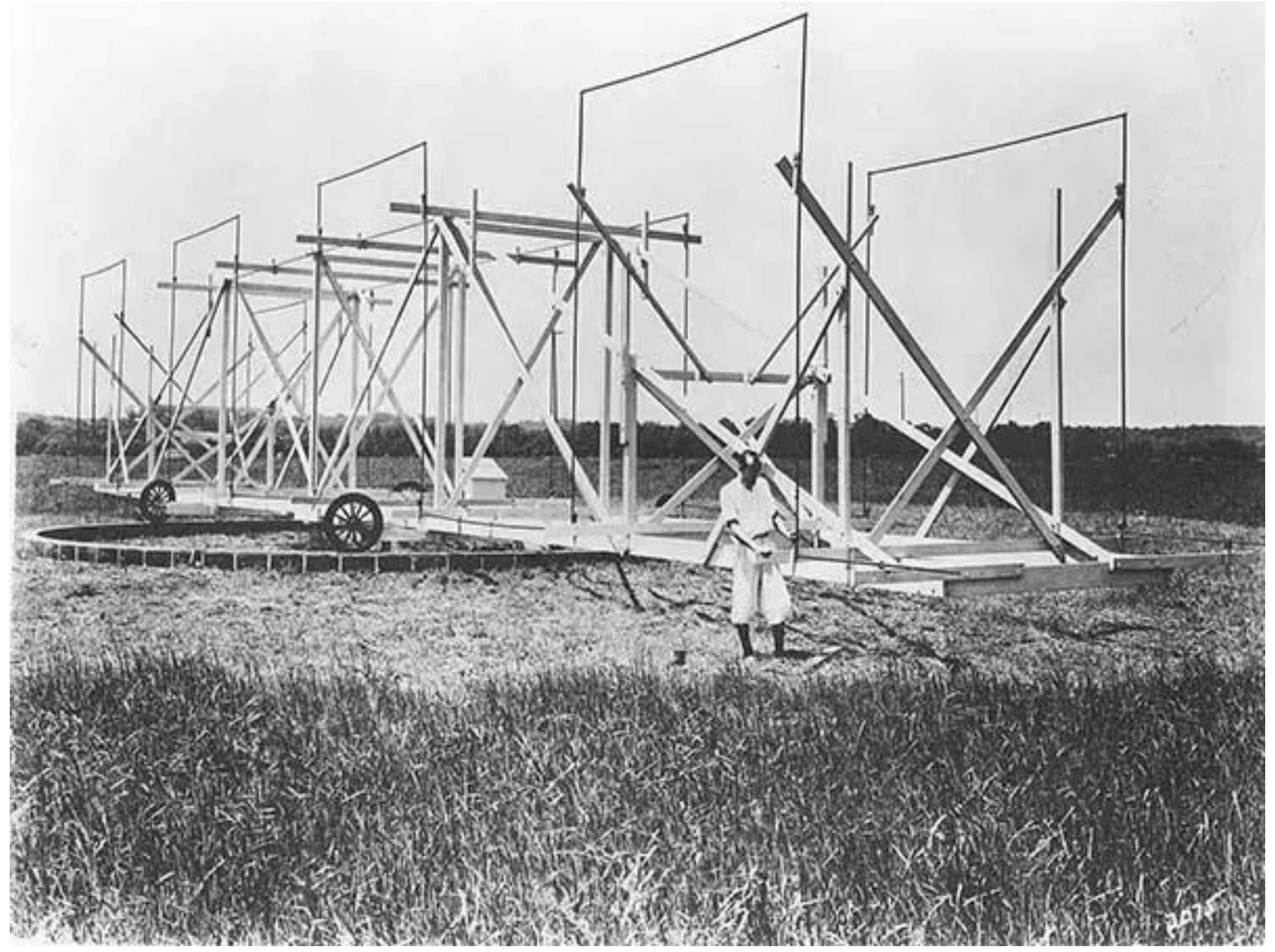




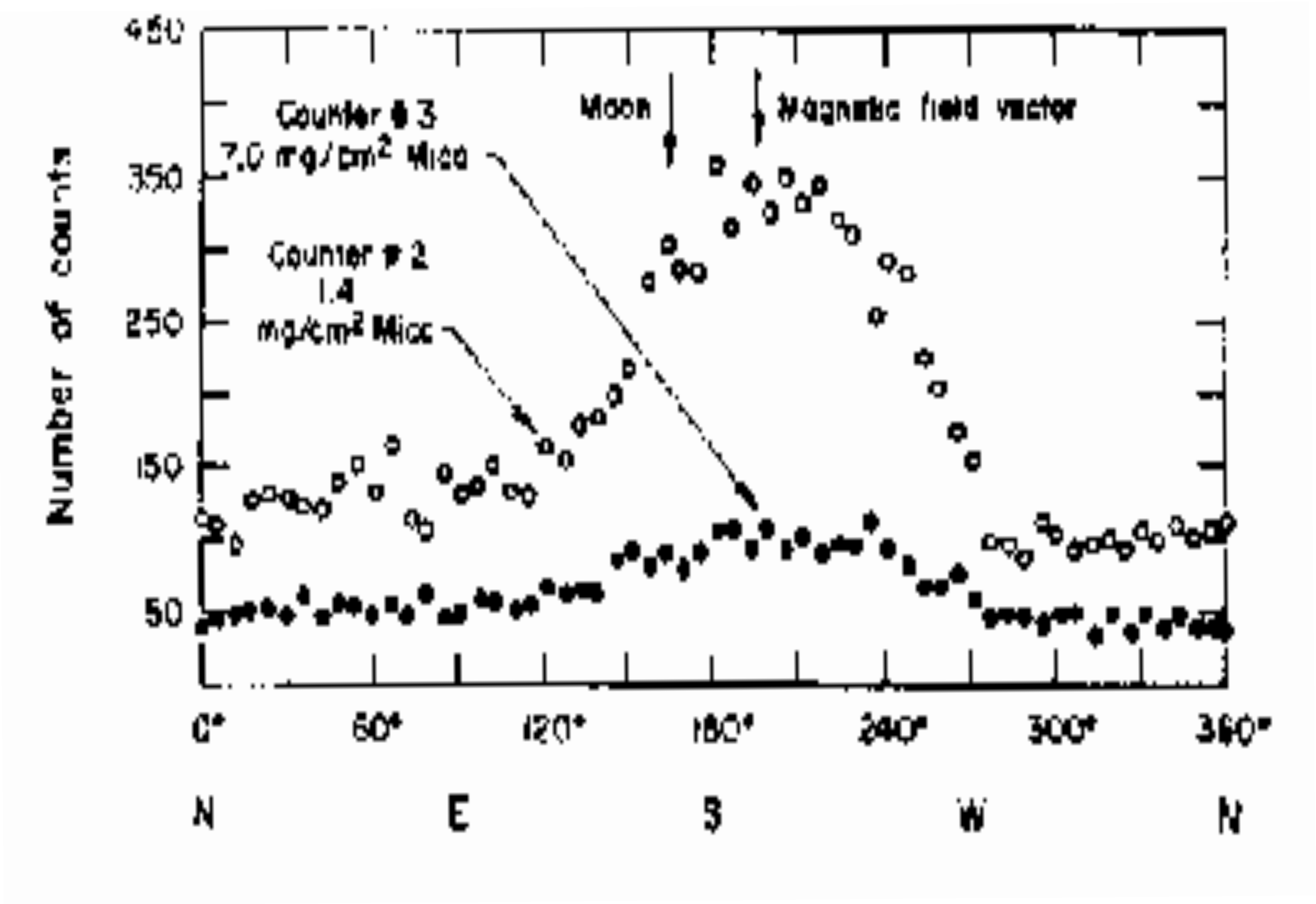
- Un-anticipated sources
  - Opening a new observational window

Things that go bump in the night

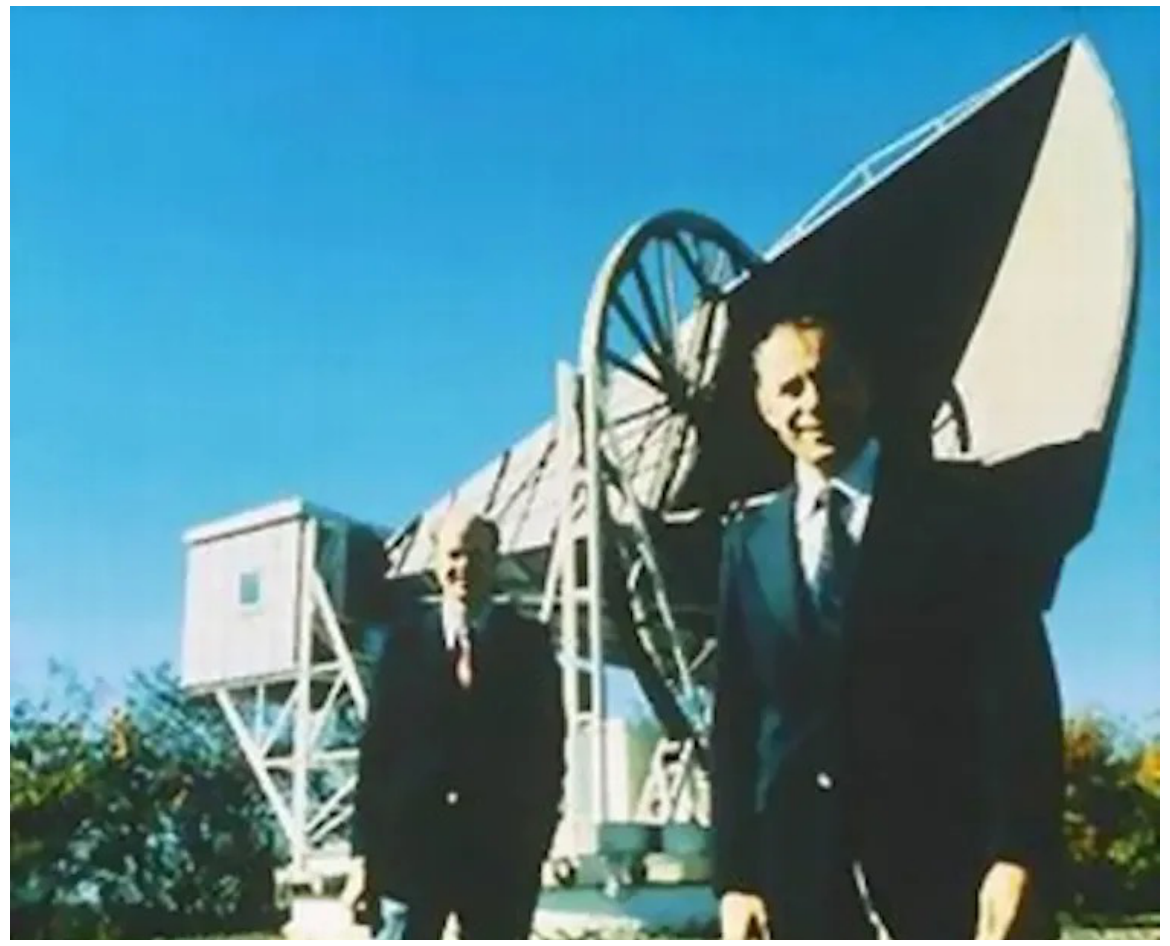
Cosmic Radio Waves 1933



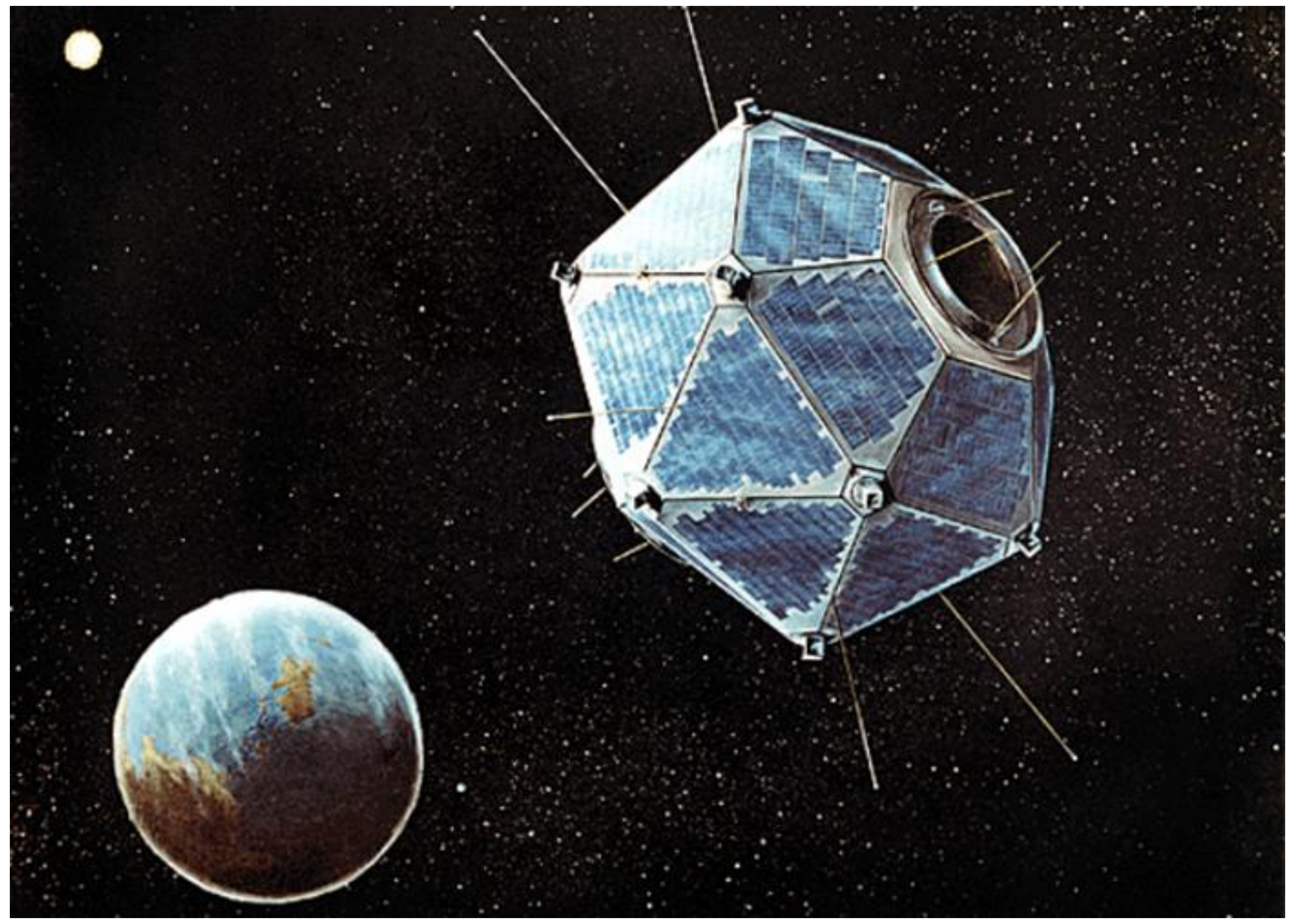
X-ray binaries 1962



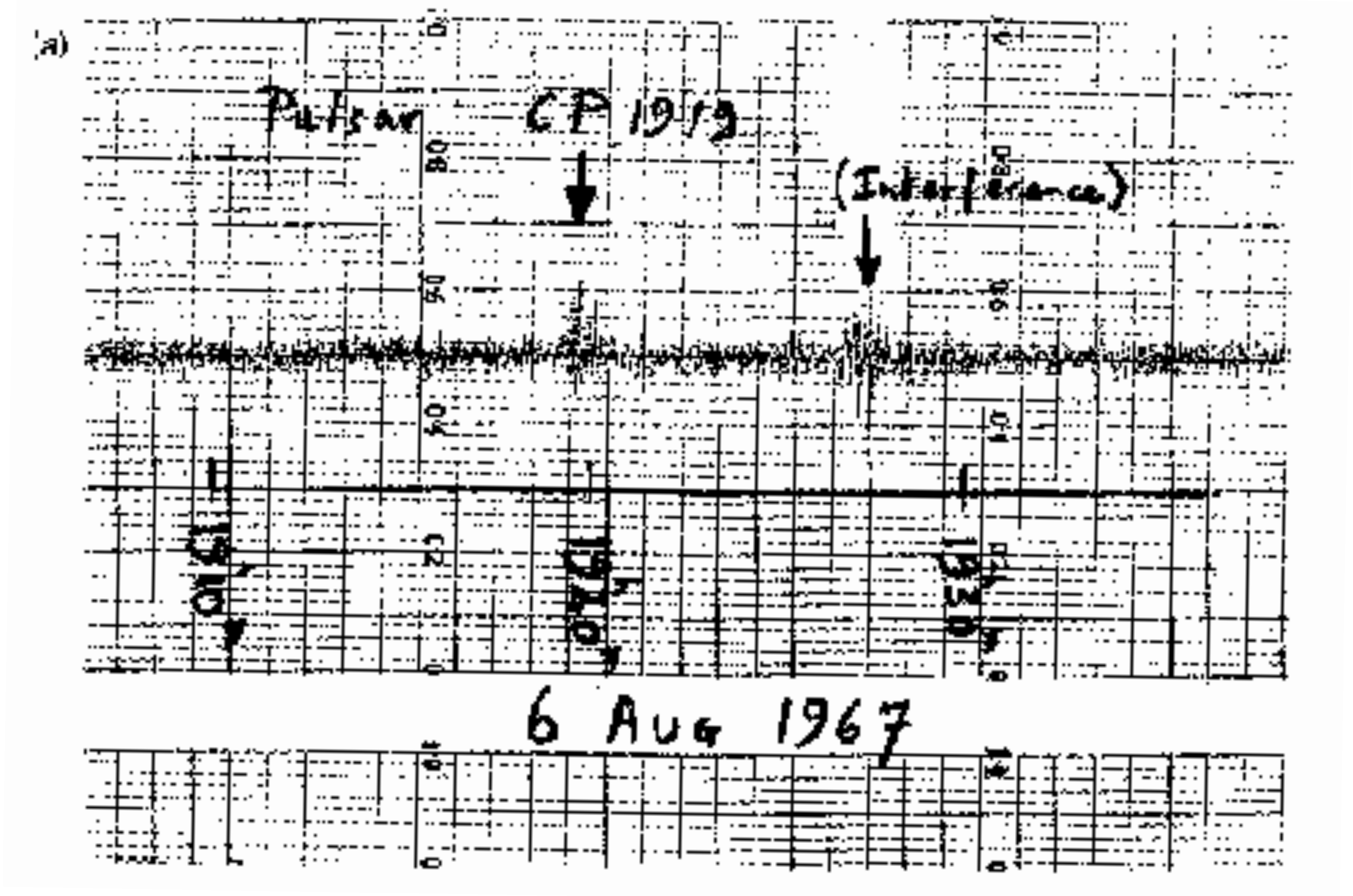
Microwave Background 1965



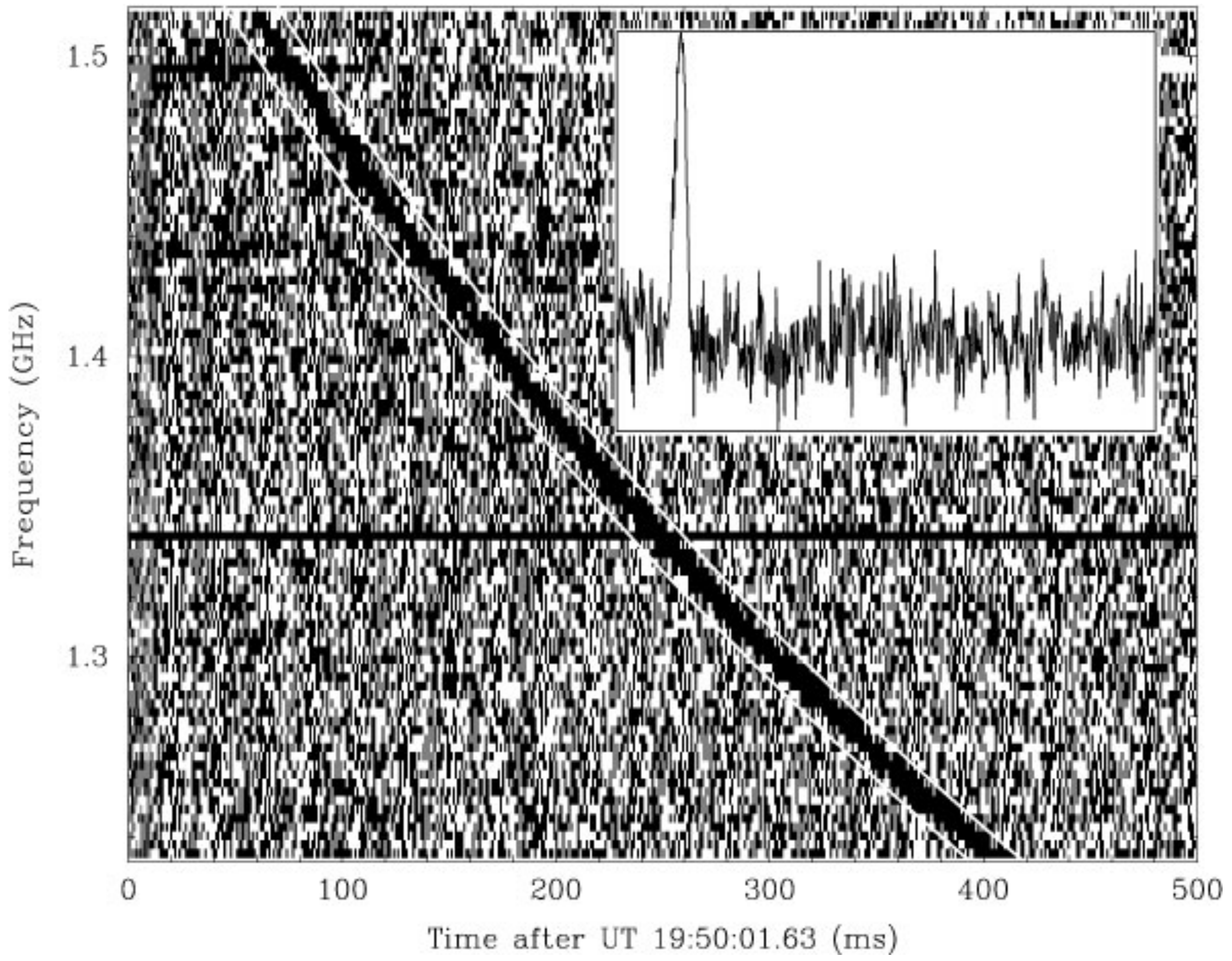
Gamma Ray Bursts 1967



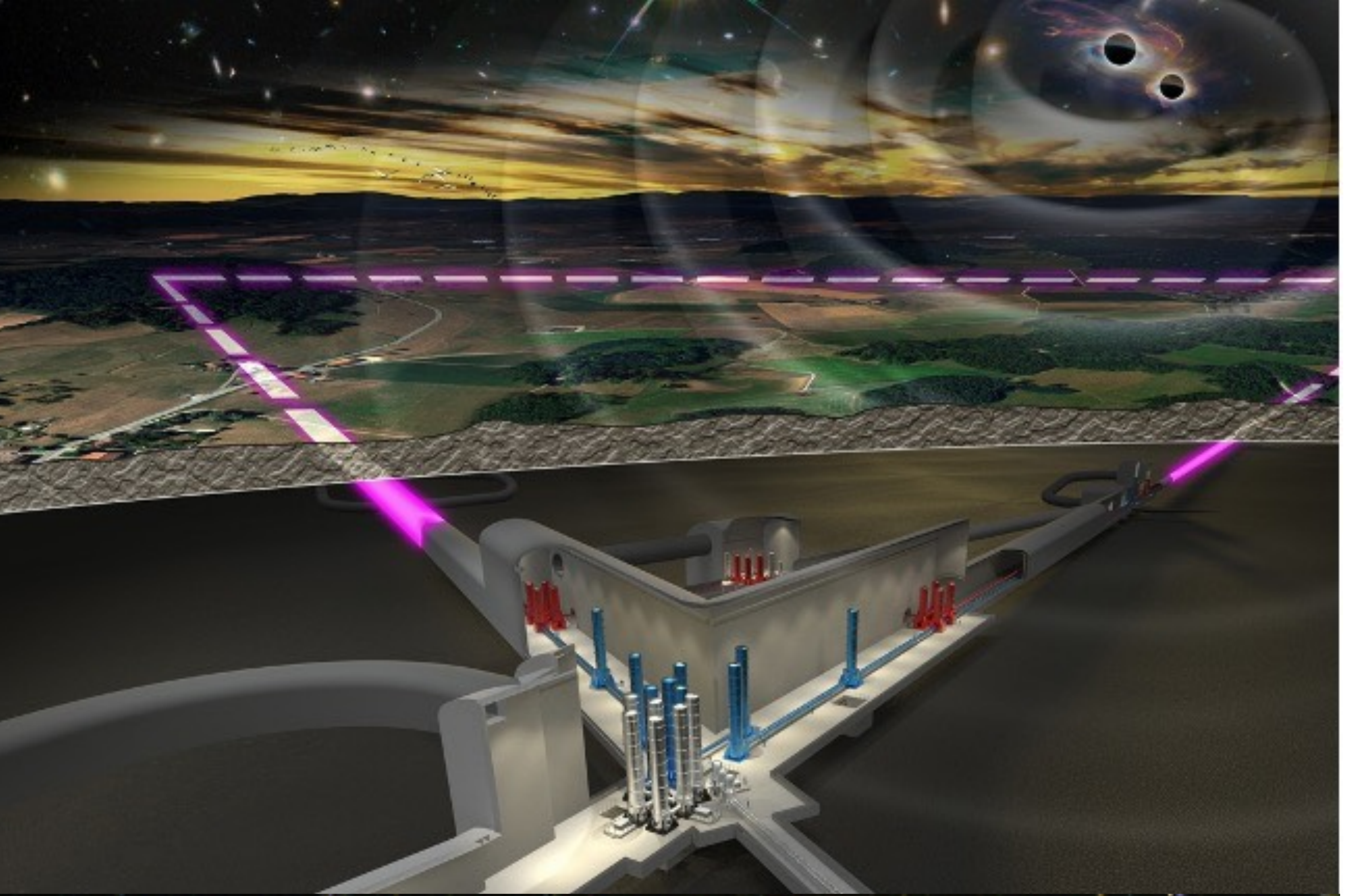
Radio Pulsars 1967

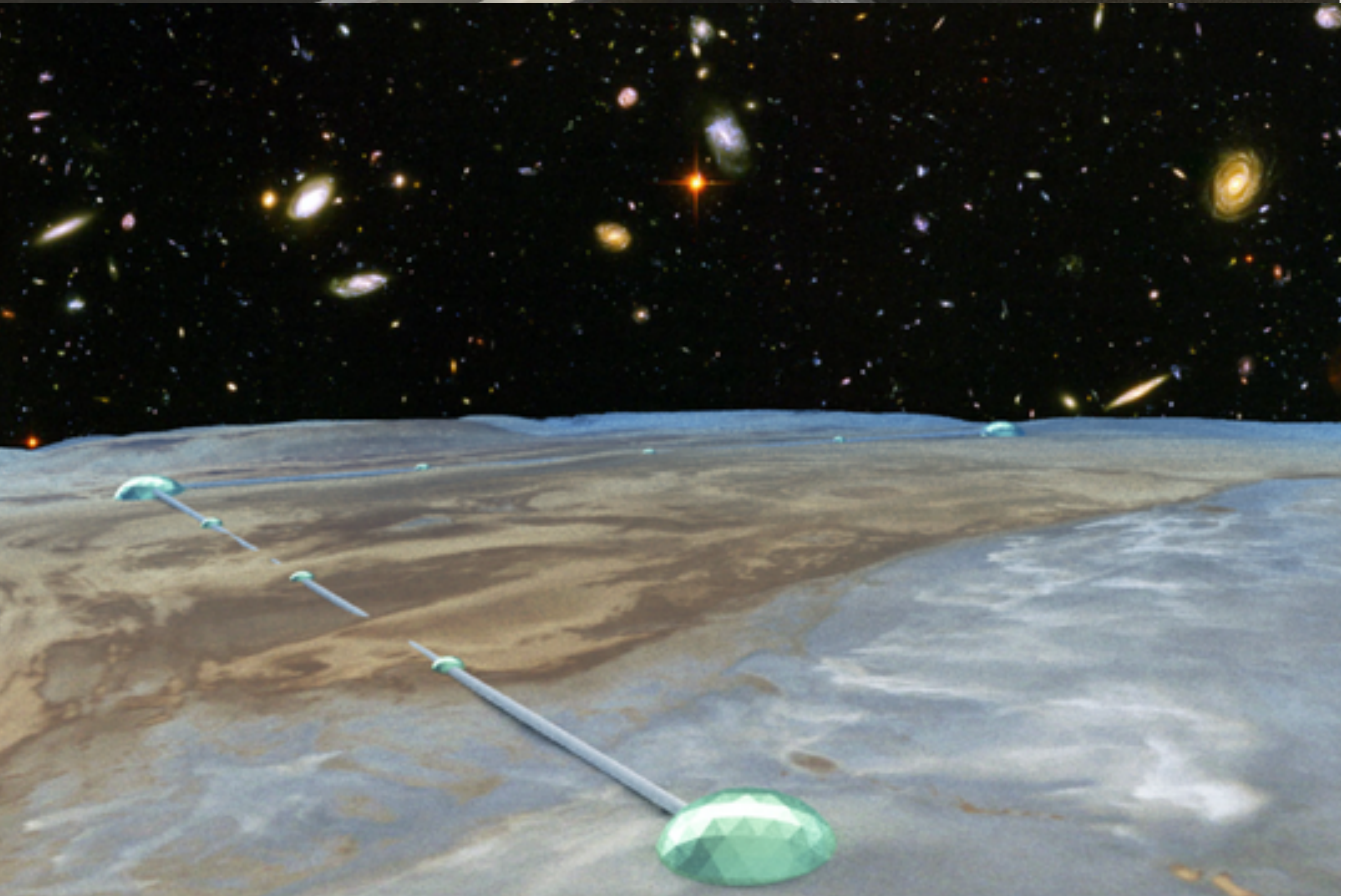


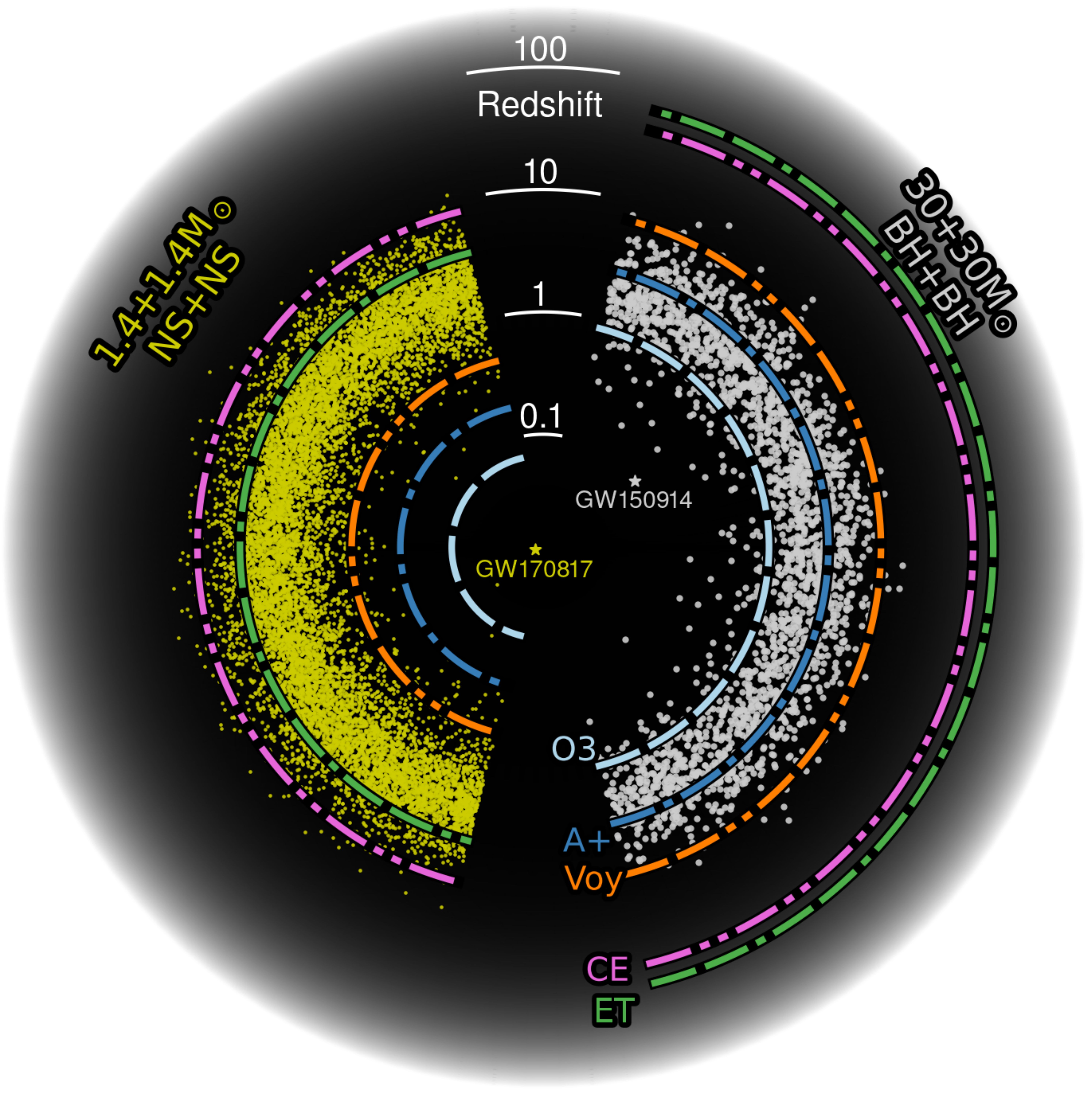
Fast Radio Bursts 2007



"Chance favours the prepared mind" Pasteur, 1854






100
Redshift
10
1
0.1
1.4+1.4M☉
NS+NS
30+30M☉
BH+BH
GW150914
GW170817
O3
A+
Voy
CE
ET

If you don’t look, you won’t find it

Low probability, Big reward

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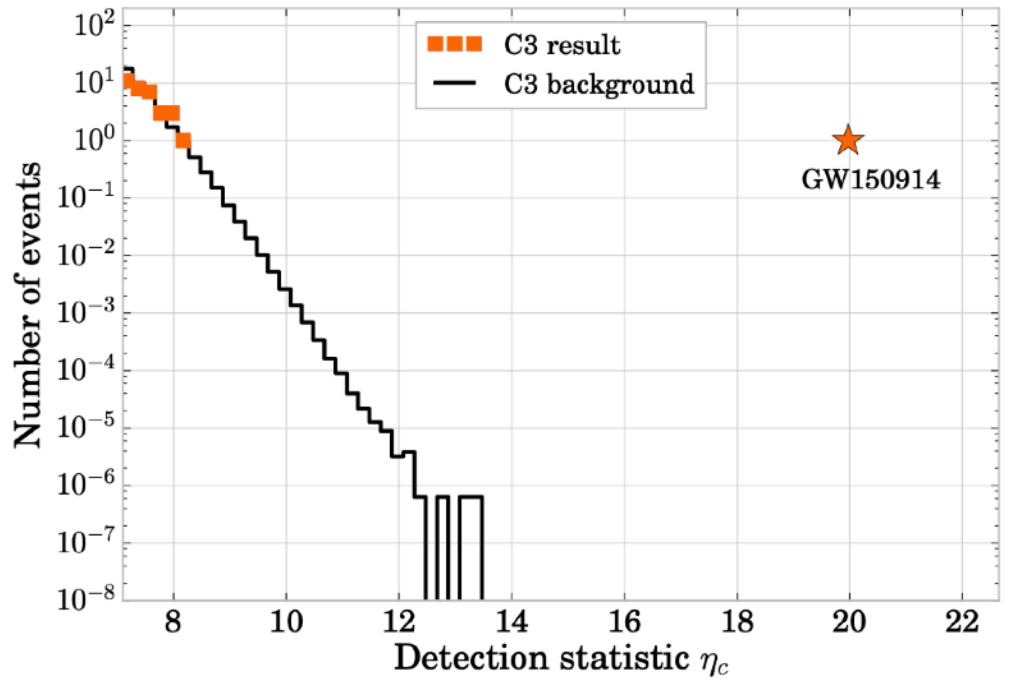
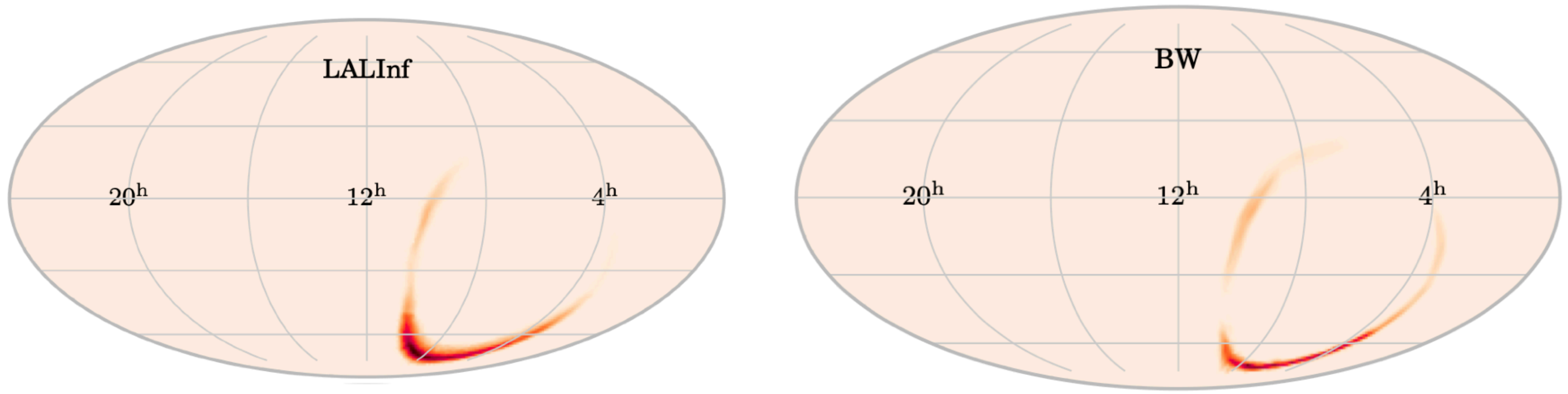
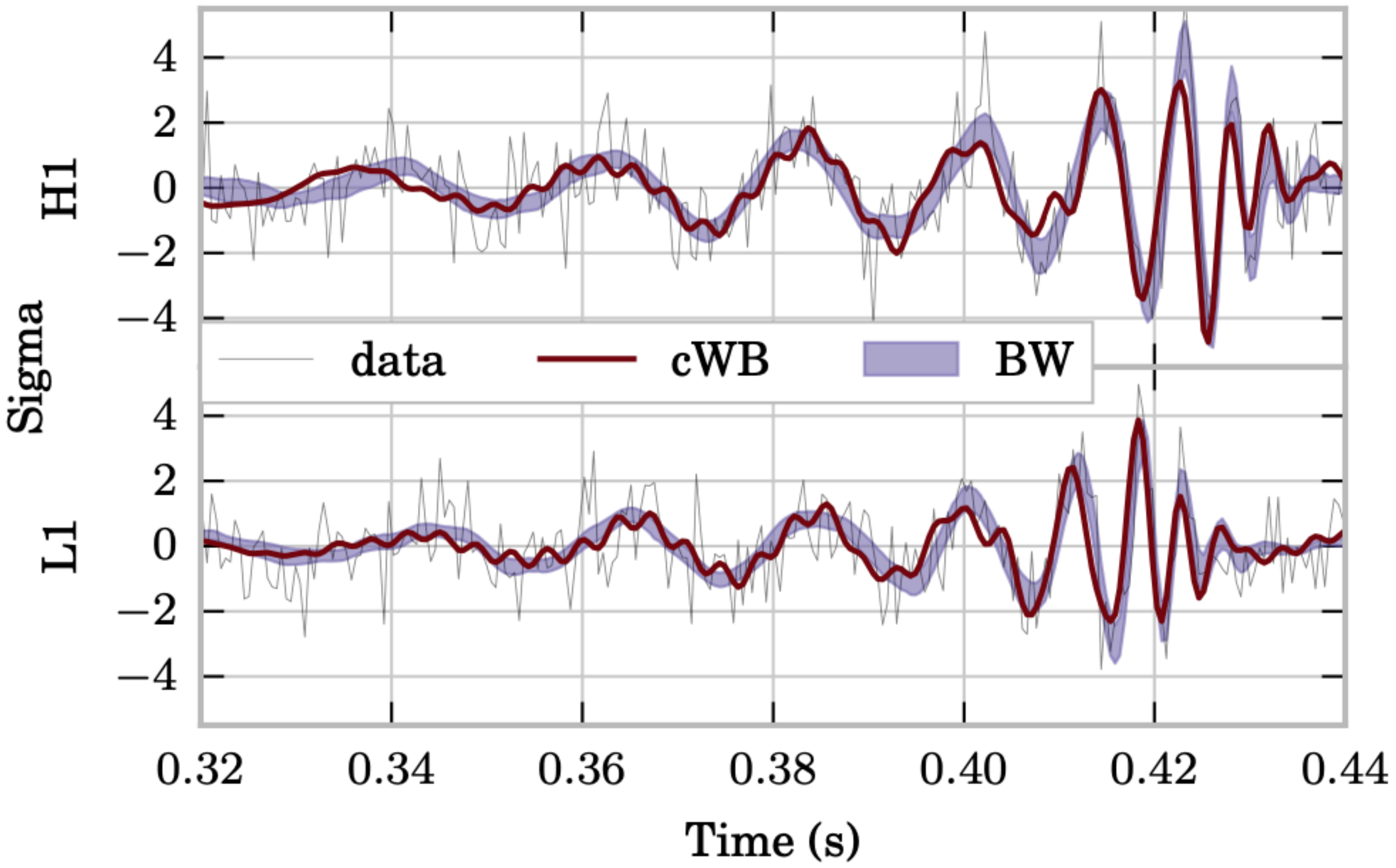
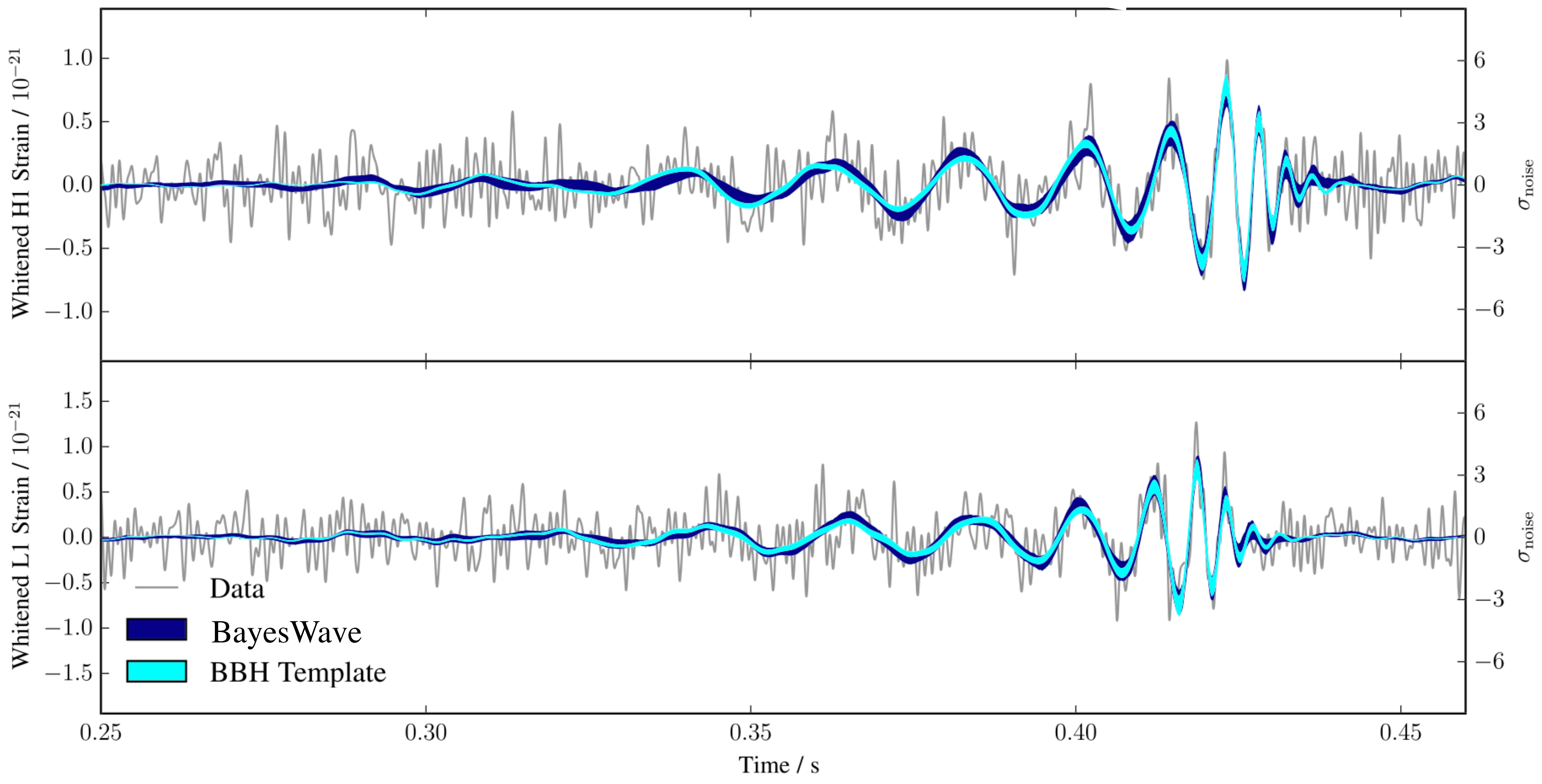
Model Agnostic Signal Reconstruction

GW150914 first detected by generic wavelet reconstruction techniques, coherent Wave Burst and BayesWave







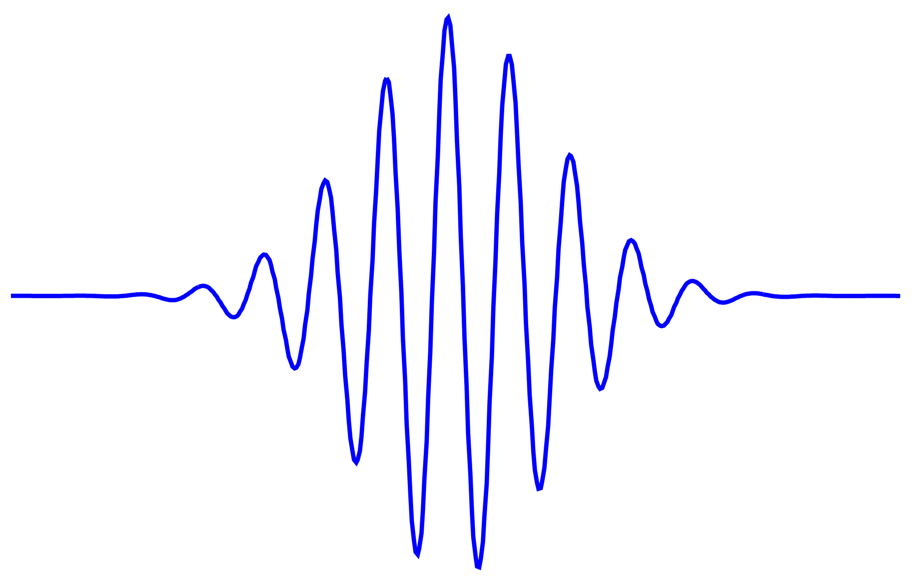


Detection without templates

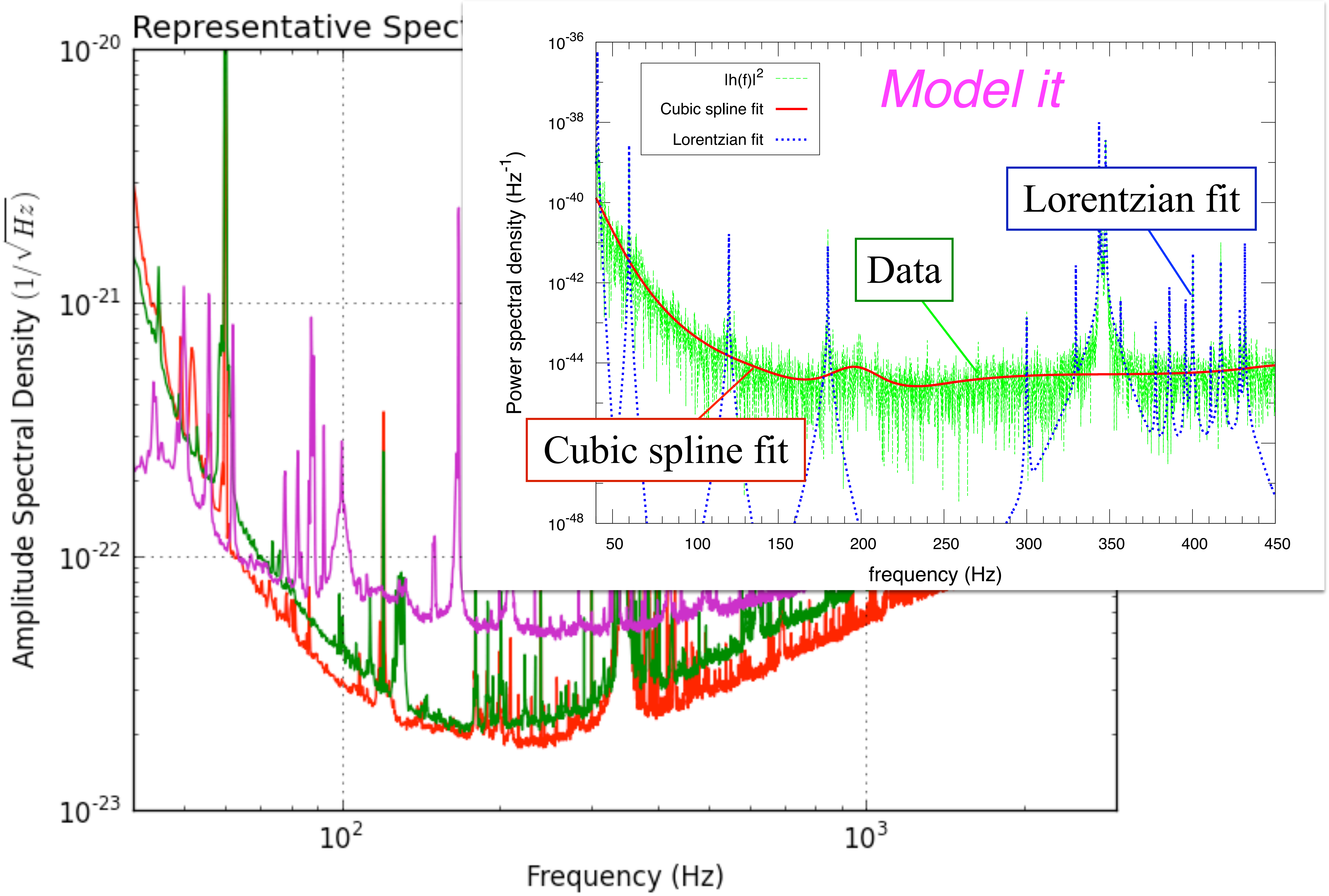
BayesWave

- Bayesian model selection
  - Three part model (signal, glitches, gaussian noise)
  - Trans-dimensional Markov Chain Monte Carlo
- Wavelet decomposition
  - Glitch & GW modeled by wavelets
  - Number, amplitude, quality and TF location of wavelets varies

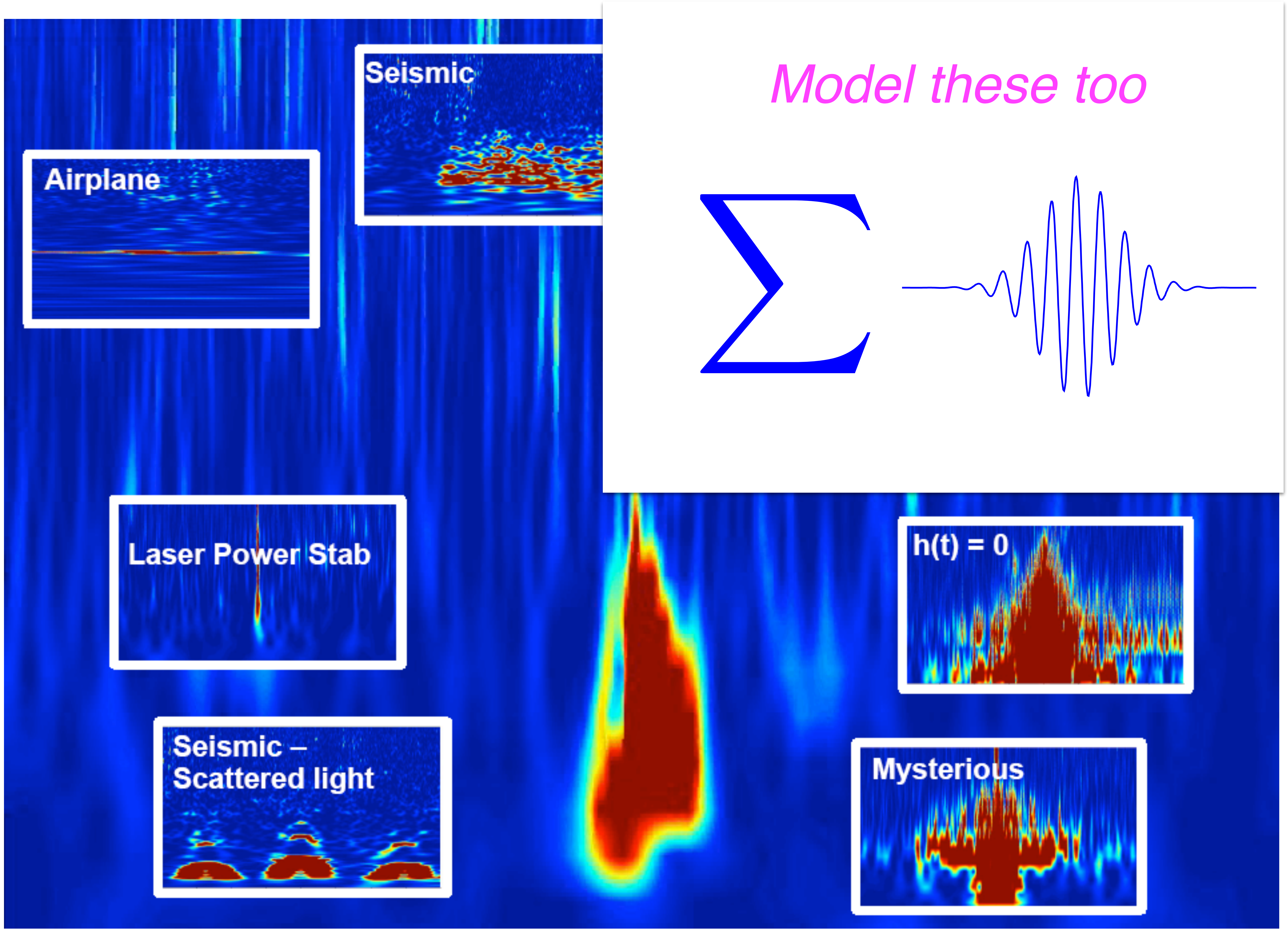
Continuous Morlet/Gabor Wavelets



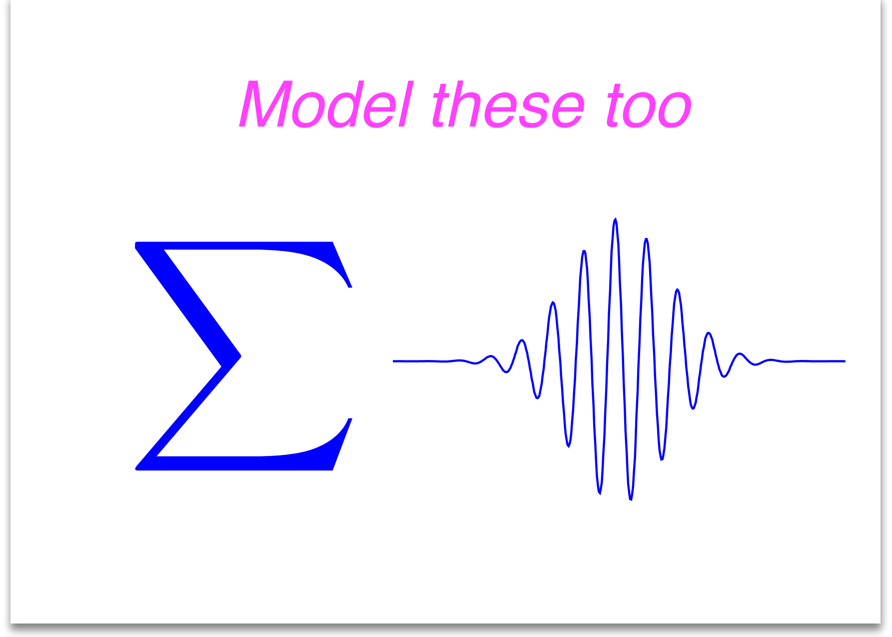
Lines and a drifting noise floor

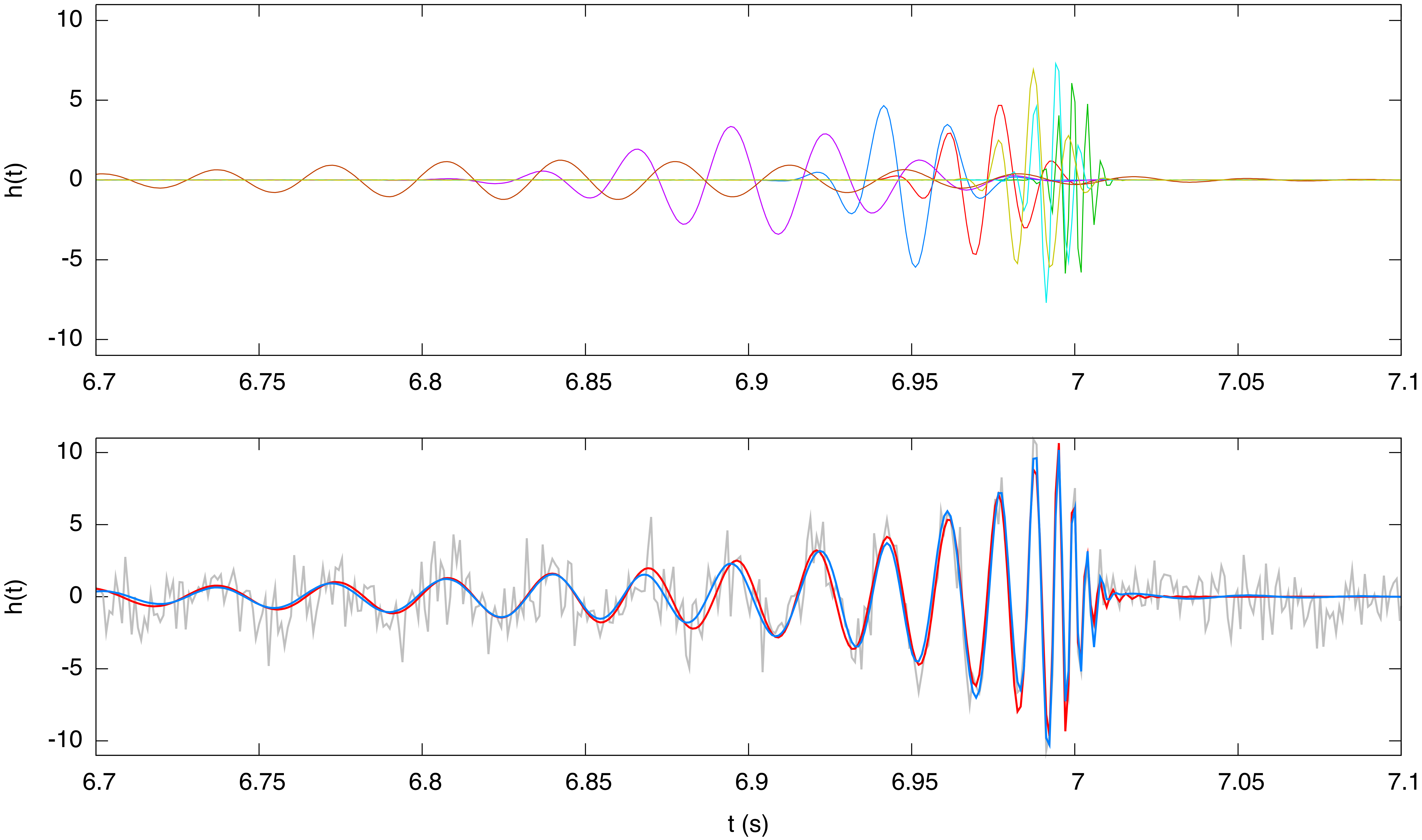


Glitches


Seismic
Airplane
Model these too
Laser Power Stab
h(t) = 0
Seismic –
Scattered light
Mysterious

Gravitational Waves

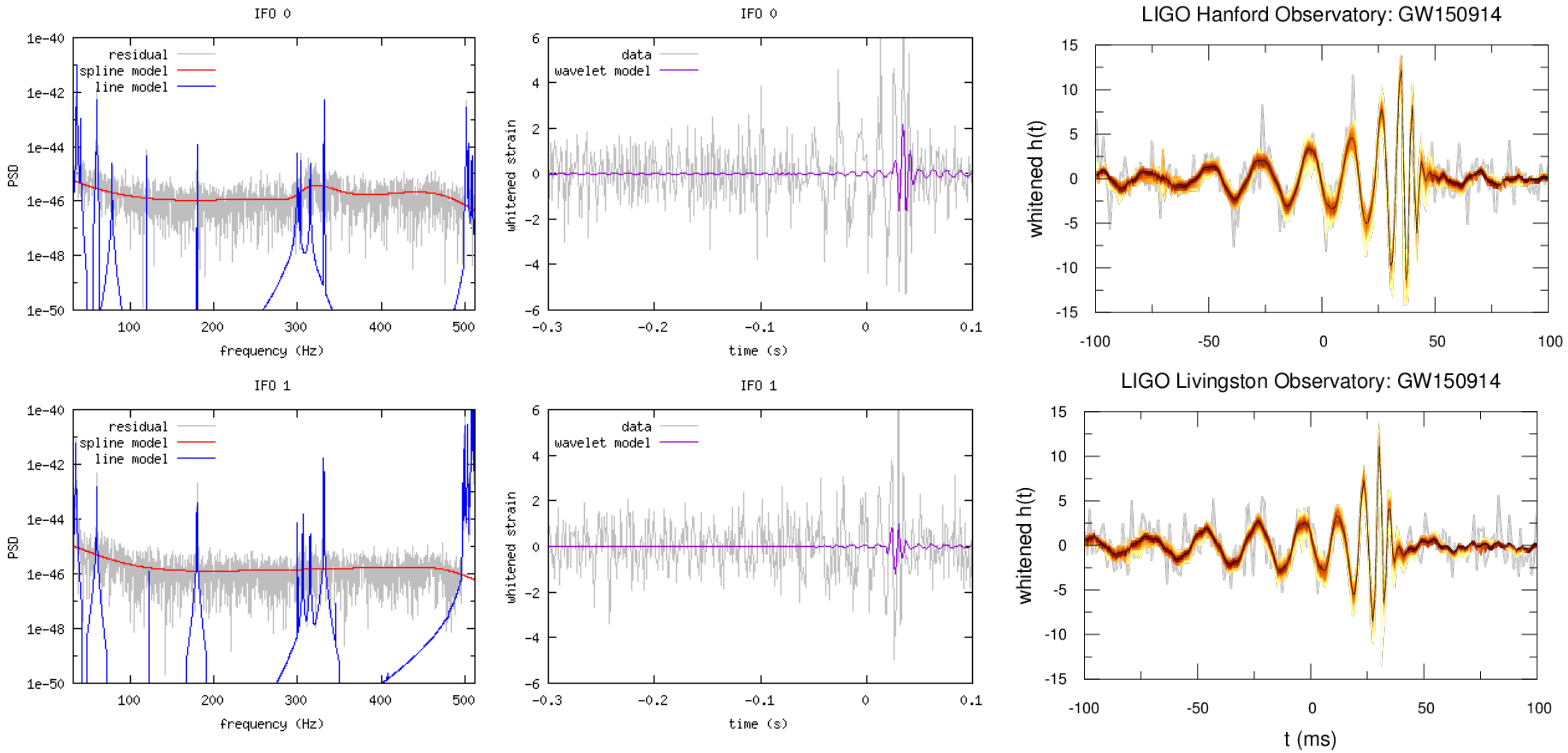




injected

recovered

Reconstructing GW150914 with wavelets



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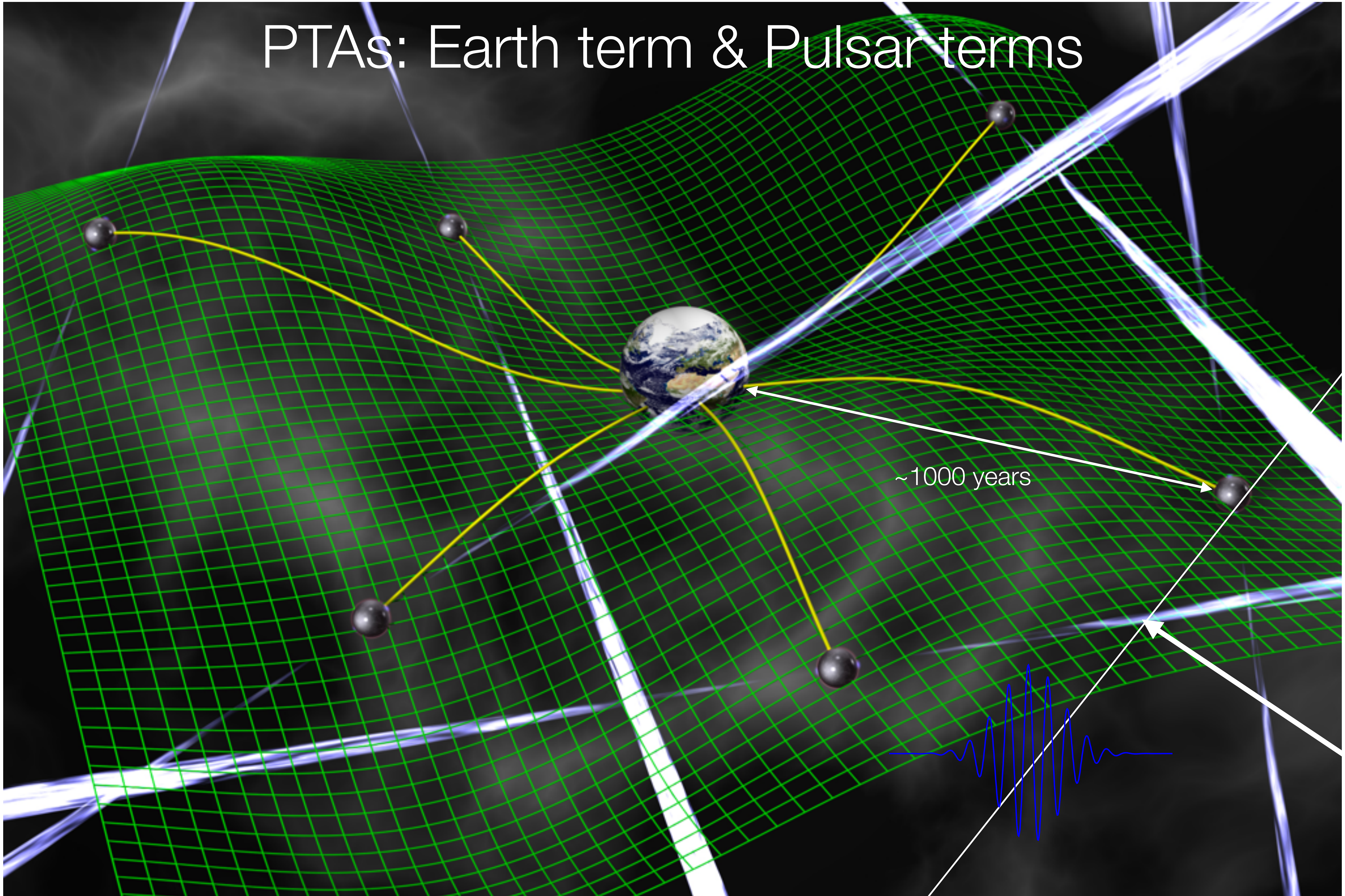
PTAs: Earth term & Pulsar terms



PTAs: Earth term & Pulsar terms

$$T_{\text{burst}} \leq T_{\text{obs}}$$

We define bursts are being short duration compared to our data span - months to years

For a given burst, will either detect the Earth term or the pulsar term in one pulsar

$$\mathrm{S/N}_{\text{Earth}} \simeq \sqrt{N_p}\, \mathrm{S/N}_{\text{pulsar}} \quad \Rightarrow \quad V_{\text{Earth}} = N_p^{3/2}\, V_{\text{pulsar}}$$

$$T_{\text{pulsar}} \simeq N_p\, T_{\text{obs}}$$

$$\Rightarrow \quad \text{Detections}_{\text{Earth}} \simeq \sqrt{N_p}\, \text{Detections}_{\text{pulsar}}$$

But, difficult to say if pulsar term bursts are signals or noise transients

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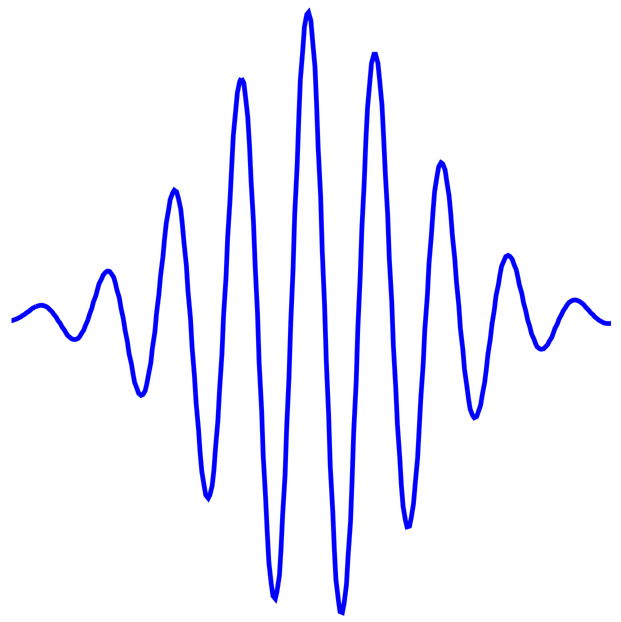
BayesWave for PTAs

[Ellis & Cornish arXiv 1601.00650]

[Becsy & Cornish arXiv 2011.01942]

$$H_+(t) = \sum_{i=0}^{N} \Psi(t, t_i, f_i, \tau_i, A_+, \phi_+)$$



$$H_\times(t) = \sum_{i=0}^{N} \Psi(t, t_i, f_i, \tau_i, A_\times, \phi_\times)$$

$$\Psi(t, t_i, f_i, \tau, A, \phi) = A\, e^{(t-t_i)^2/\tau^2} \cos(2\pi f_i (t - t_i) + \phi)$$

No pulsar term. Also have noise transient model in each pulsar.
Same form as signal model but not correlated across the array.

Can also have elliptically polarized model with $A_\times = \epsilon A_+$, $\phi_\times = \phi_+ + \pi/2$.

Can use shape/projection decomposition and pre-computed inner products to speed up the likelihoods

Continuous wavelets, unevenly sampled data

Similar to how we model the stochastic background $\mathbf{h} = \mathbf{aF}$

$$a_n^c \cos(2\pi nt/T) + a_n^s \sin(2\pi nt/T)$$

$$p(\mathbf{d}\,|\,\mathbf{a}) = \frac{\mathbf{1}}{\det(\mathbf{2}\pi\mathbf{C})^{\mathbf{1/2}}} \exp\left(-\frac{\mathbf{1}}{\mathbf{2}}(\mathbf{d} - \mathbf{aF})^{\mathbf{T}}\mathbf{C}^{-\mathbf{1}}(\mathbf{d} - \mathbf{aF})\right)$$

$$p(\mathbf{a}) = \frac{1}{\det(2\pi\boldsymbol{\phi})^{1/2}} \exp\left(-\frac{1}{2}\mathbf{a}^T\boldsymbol{\phi}^{-1}\mathbf{a}\right)$$

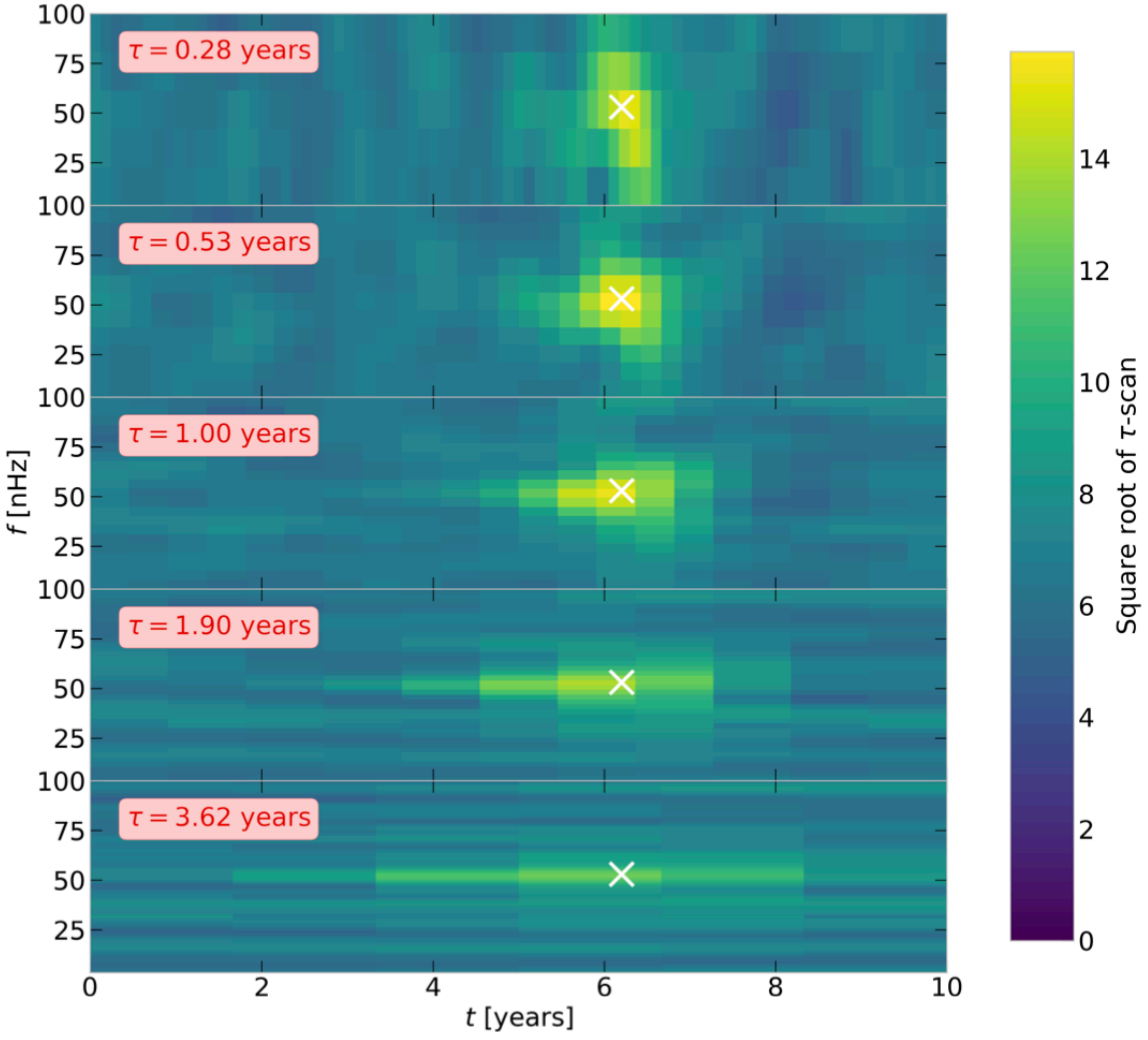
Integrate out the Fourier amplitudes $\mathbf{a}$

$$p(\mathbf{d}\,|\,\mathbf{S_h}) = \frac{\mathbf{1}}{\det(\mathbf{2}\pi\tilde{\mathbf{C}})^{\mathbf{1/2}}} \exp\left(-\frac{\mathbf{1}}{\mathbf{2}}\mathbf{d}\,\tilde{\mathbf{C}}^{-\mathbf{1}}\,\mathbf{d}\right)$$

$$\mathbf{C}^{-1} \to \tilde{\mathbf{C}}^{-1} = \mathbf{F}^T\mathbf{C}^{-1}\mathbf{F} + \boldsymbol{\phi}^{-1}$$

BayesWave for PTAs

[Becsy & Cornish arXiv 2011.01942]

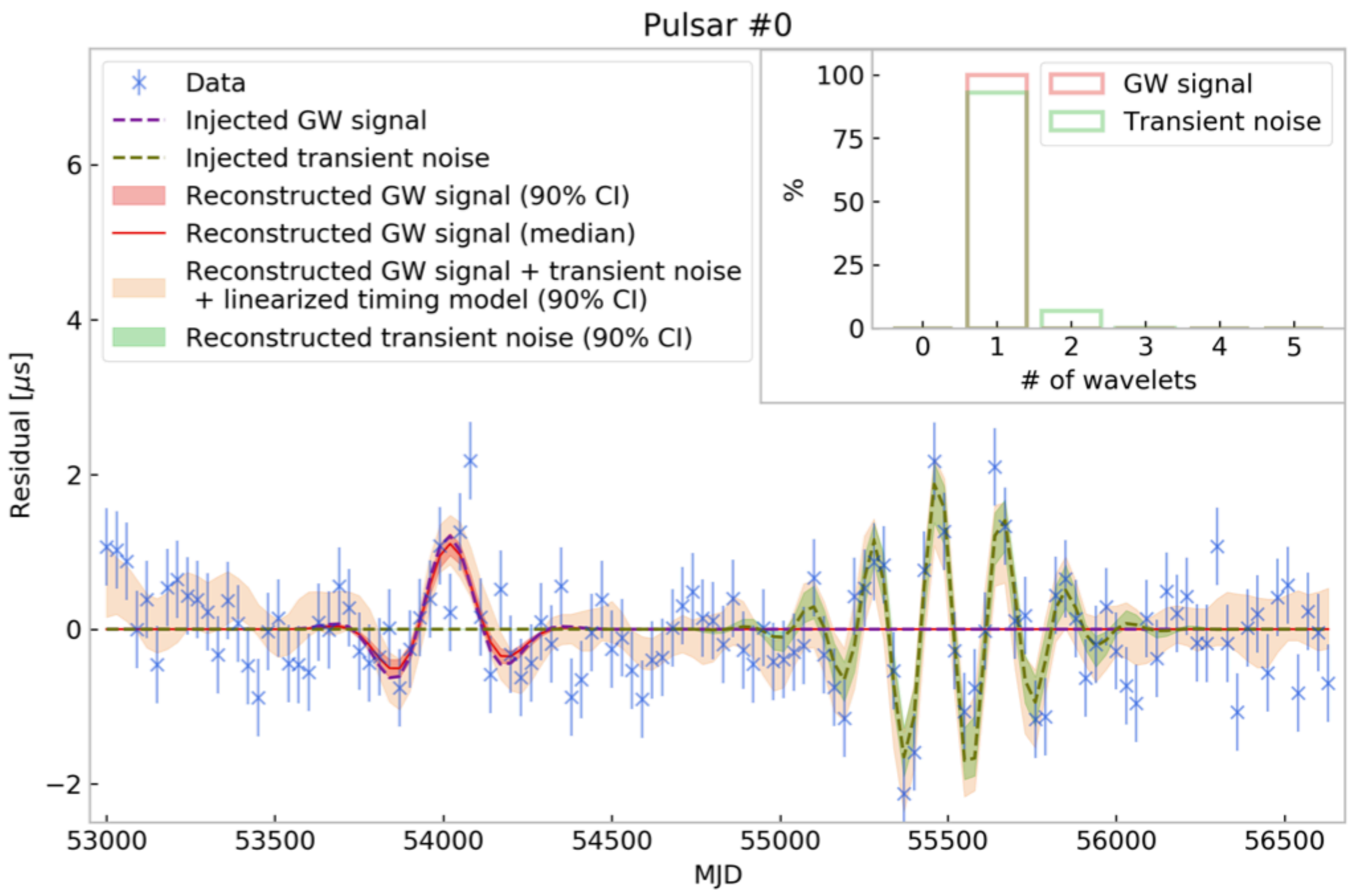


$$P(t,f) = (d \,|\, \Psi(t,f,\tau))^2$$

Use a variety of proposals, including tau-scans of the data in each pulsar. Shown is a tau scan of a simulated white noise burst

BayesWave for PTAs

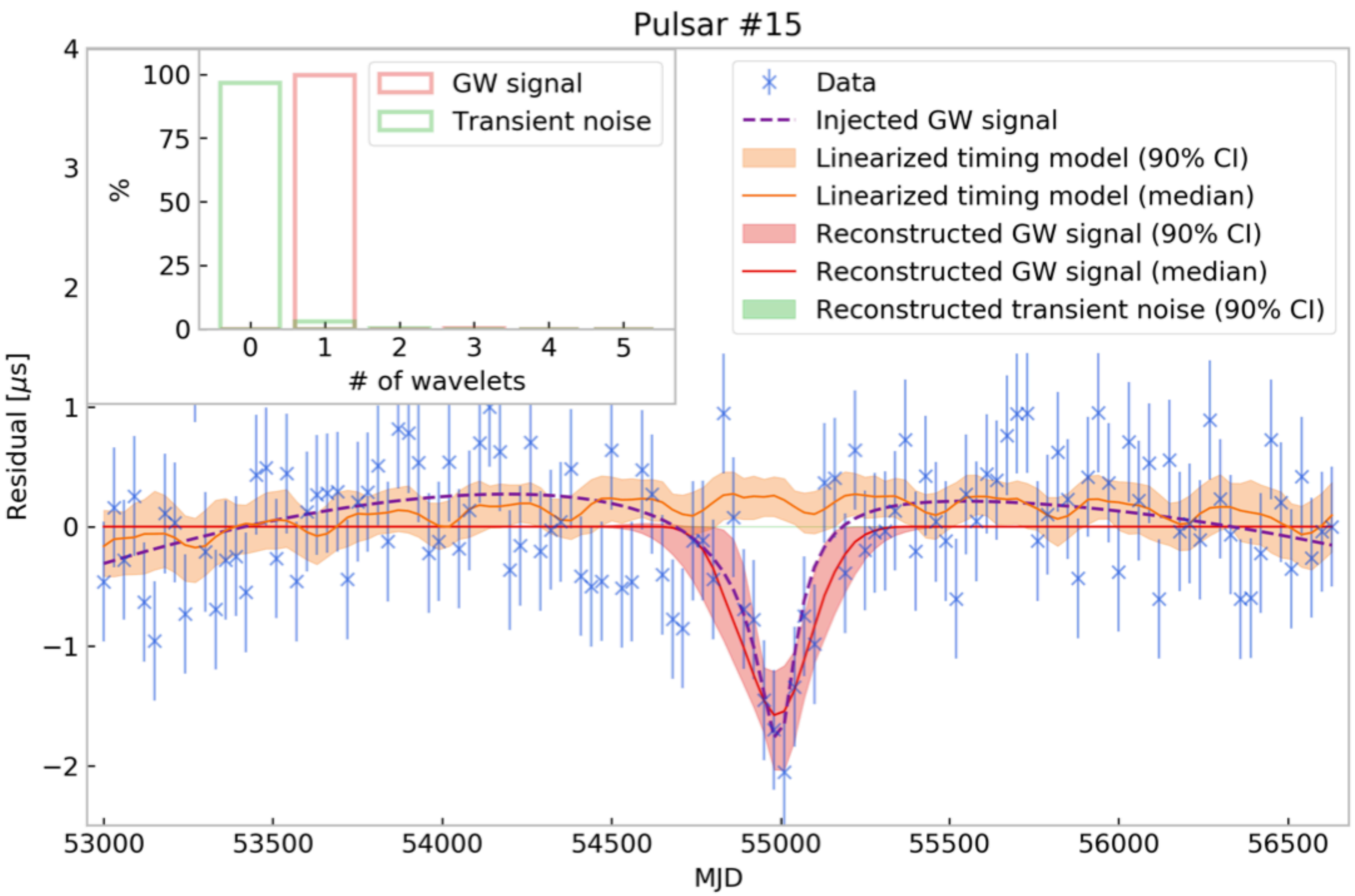
[Becsy & Cornish arXiv 2011.01942]



Example where we are able to detect a signal and a noise transient simultaneously

BayesWave for PTAs

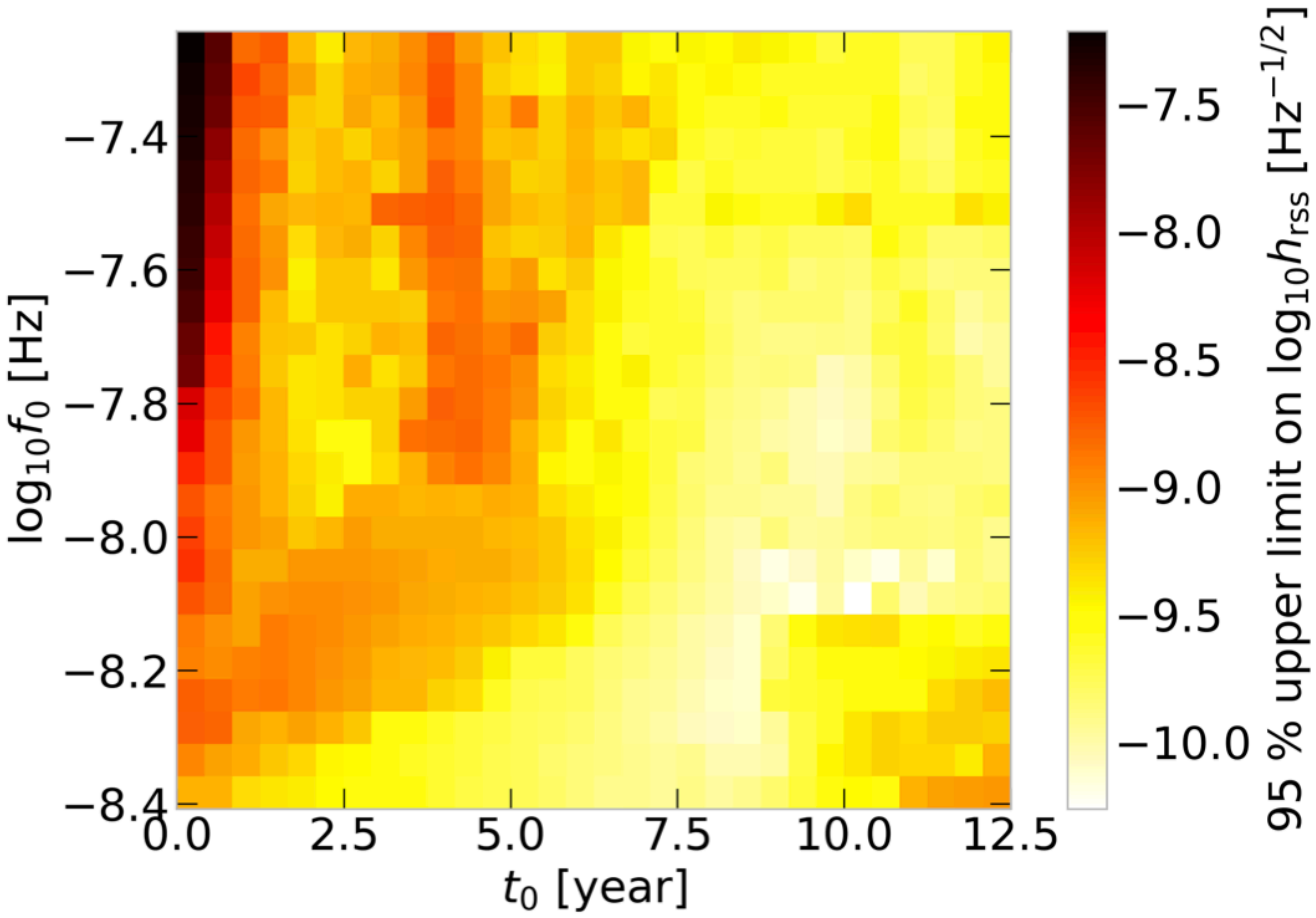
[Becsy & Cornish arXiv 2011.01942]



Detection of a hyperbolic BH scattering event. Note the interplay with the timing model

BayesWave for PTAs

[Becsy & Cornish arXiv 2011.01942]



Upper limits as a function of time and frequency using a signal-free 12.5 year Astro4Cast simulated data set

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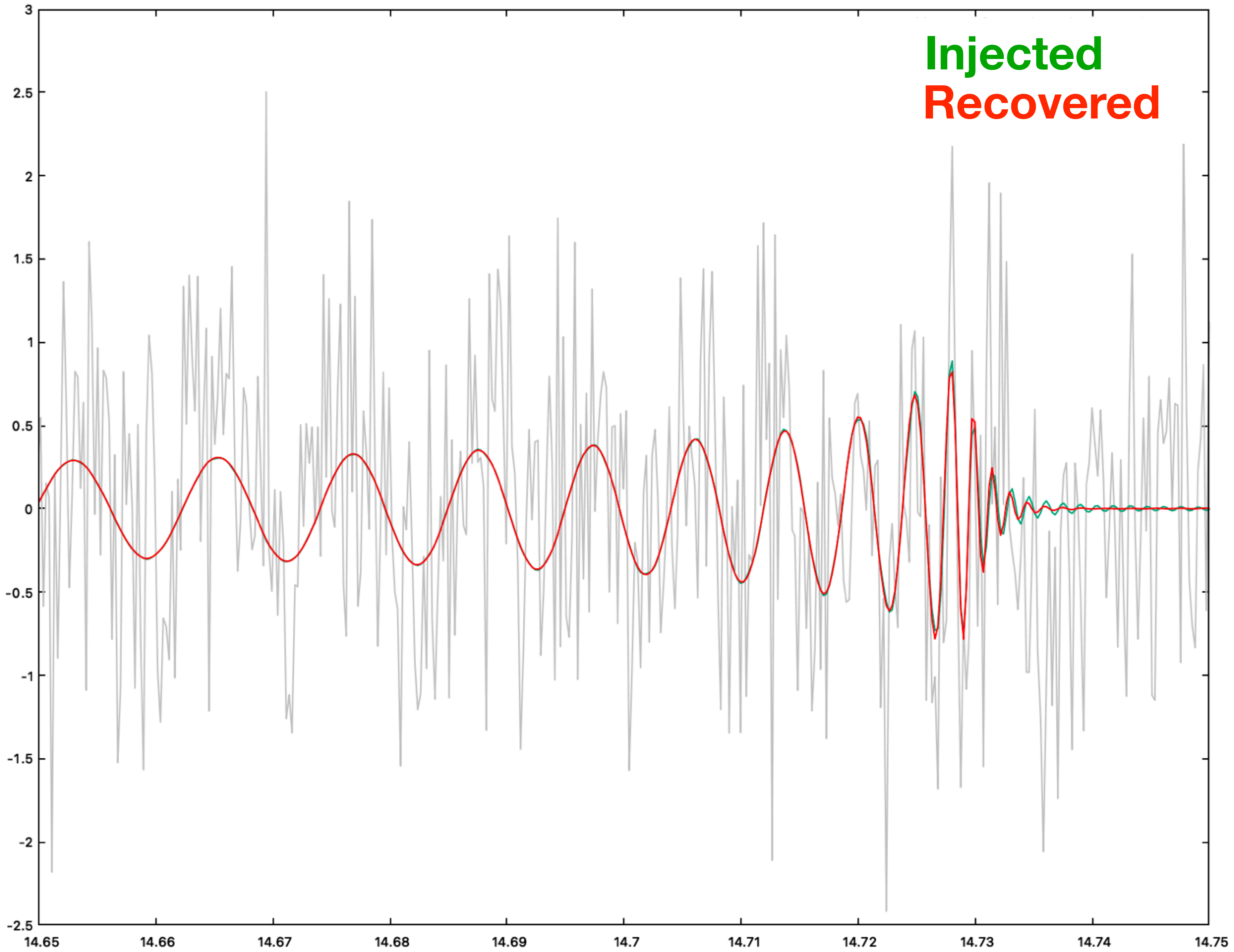
BayesWaveVoices - LIGO (Gupta & Cornish)

$$h(t) = \sum_n A_n(t) \cos \Phi_n(t)$$

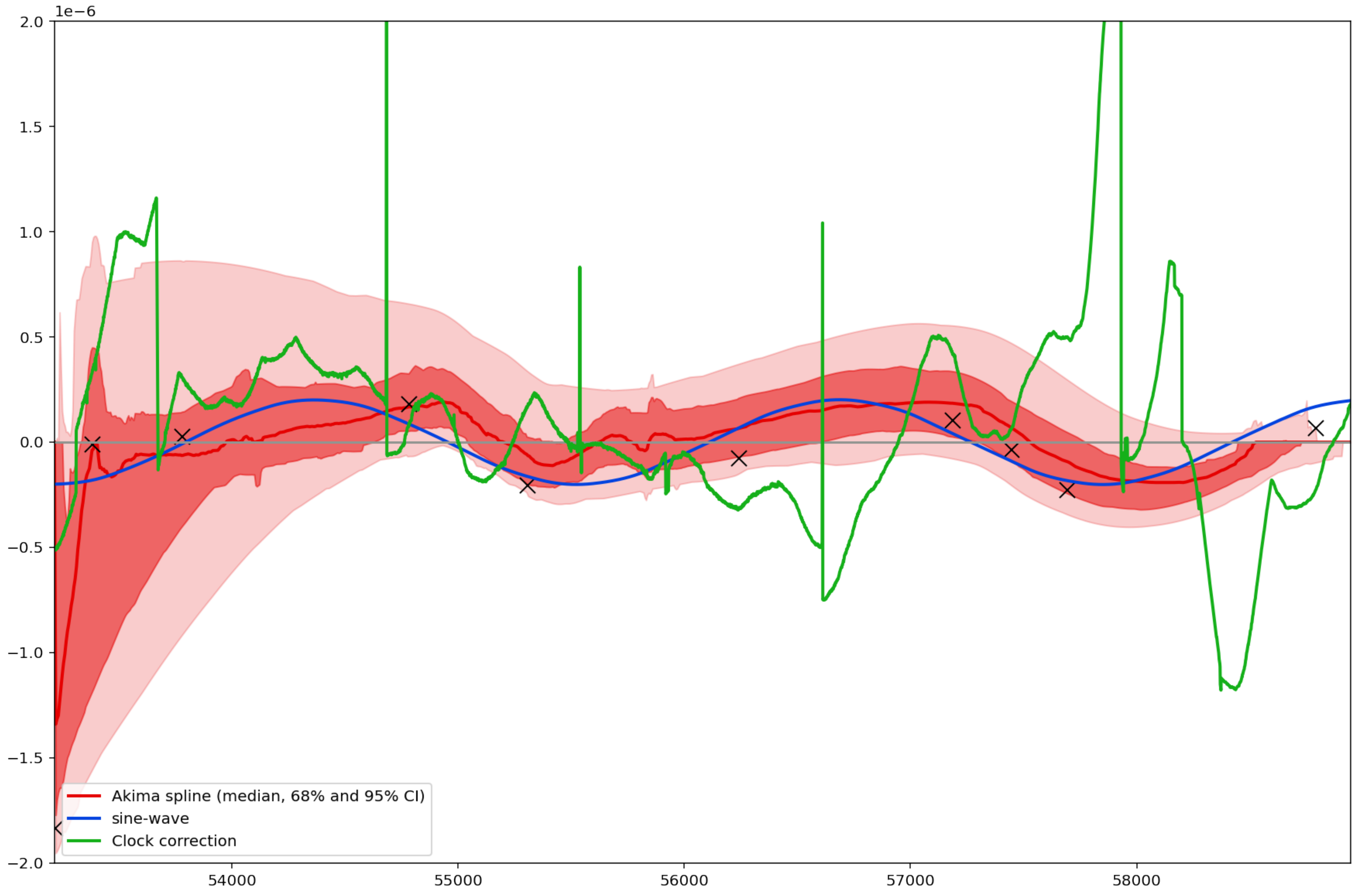
$$\Phi_n(t) = \phi_0 + 2\pi \int^t f_n(t')\, dt'$$

The amplitude evolution $A_n(t)$ and frequency evolution $f_n(t)$ modeled by trans-dimensional Akima splines



Amplitude and frequency share same start and end times (spline knots)

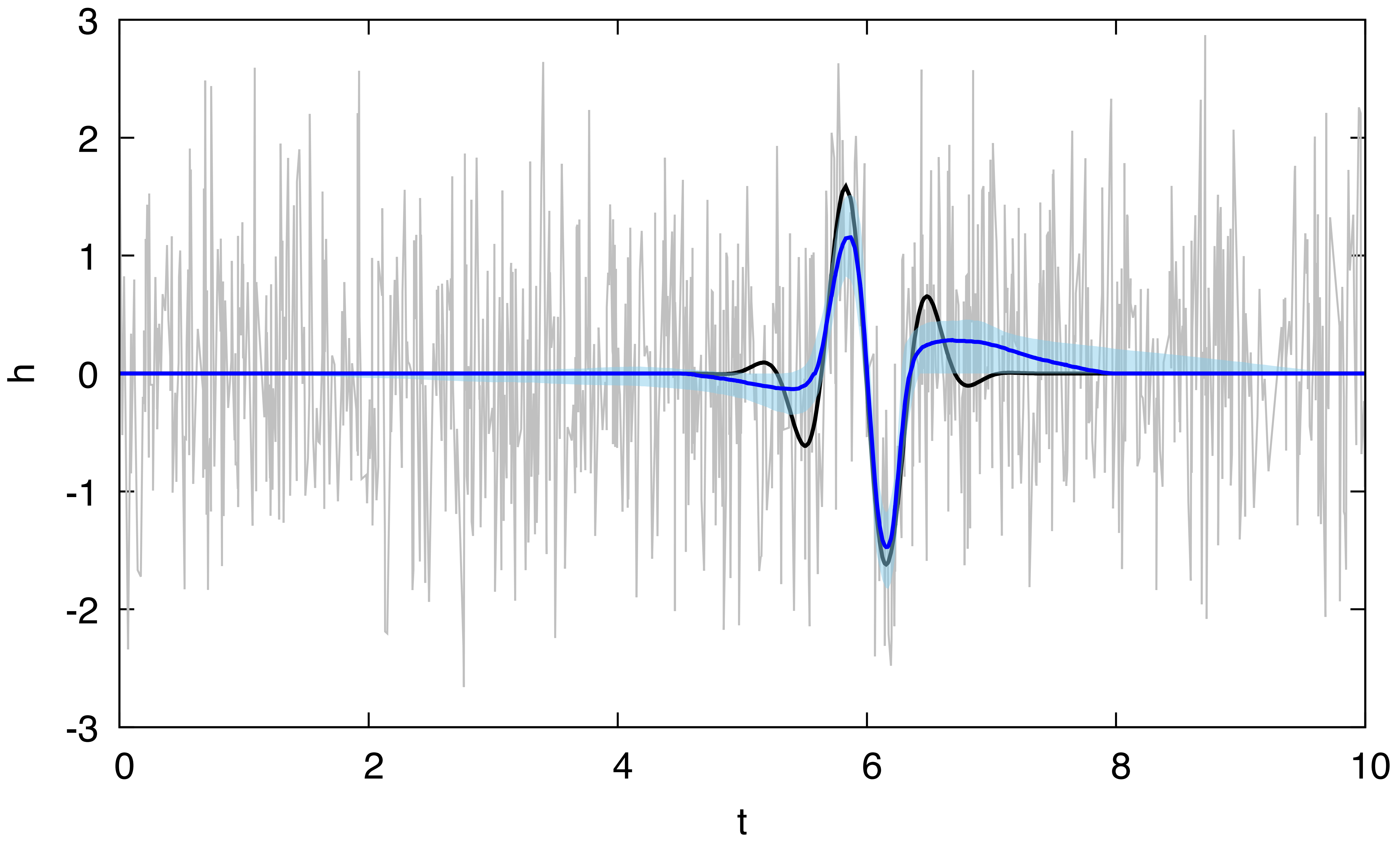
Monopole Akima Spline (Becsy & Cornish)



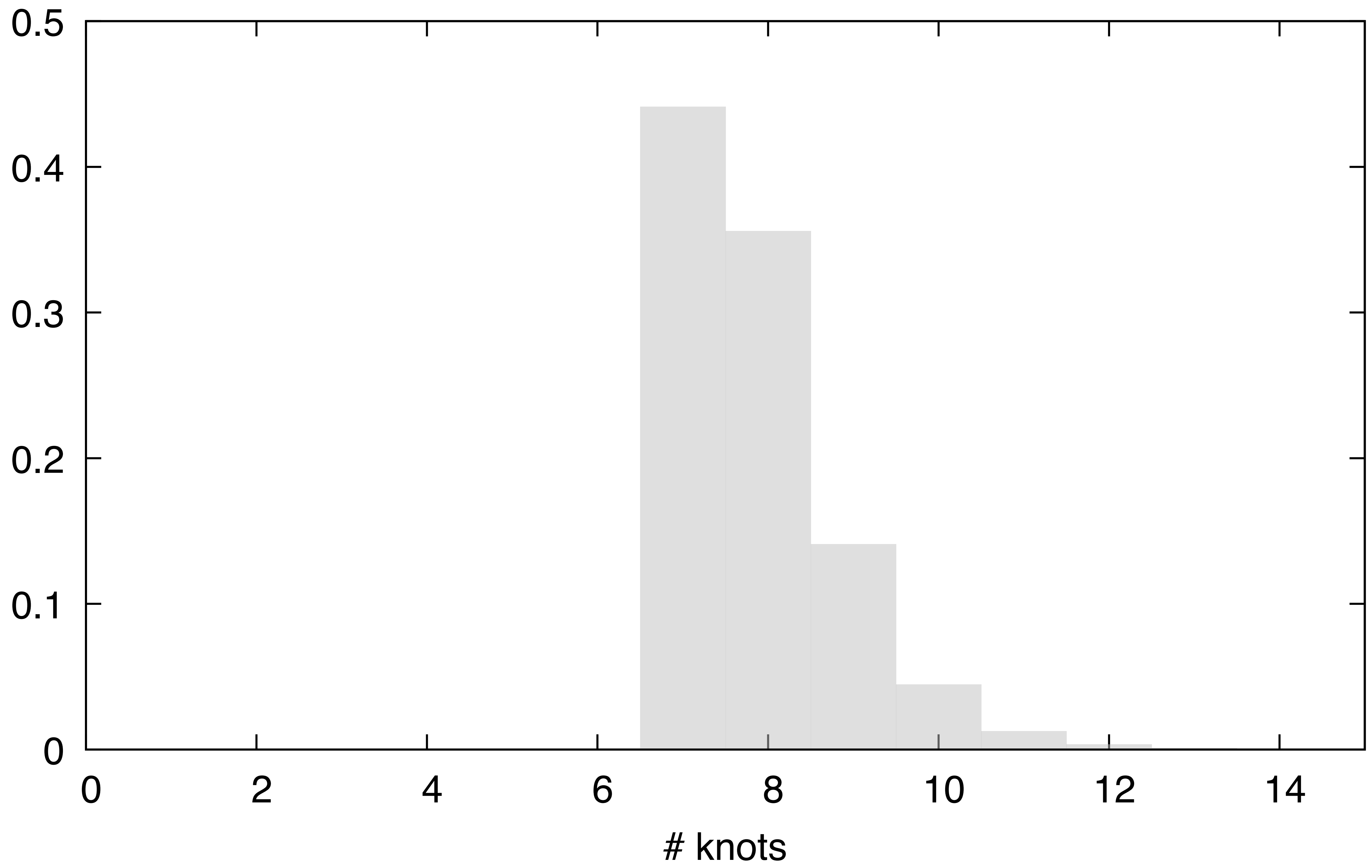
Trans-dimensional Akima spline used for the monopole

Modify code to have two copies - one for $h_+(t)$ and one for $h_\times(t)$ and include antenna patterns. Becomes a GW burst search.

Akima Splines For Bursts



Here $h(t)$ is built directly from an Akima spline
Simulated SG burst has $S/N = 10$



Using GSL the minimum number of knots is 7

Akima Spline Burst Search (Becsy & Cornish)

Could model the two polarizations directly, or model the amplitude and frequency evolution like we do with BayesWaveVoices

Can also search for elliptically polarized signals:

$$h_+(t) \to \tilde{h}_+(f) \to i\epsilon\tilde{h}_+(f) \to h_\times(t)$$

Use Akima spline interpolation to over-sample $h_+(t)$ on a evenly spaced grid of times then linearly interpolate $h_+(t)$ and $h_\times(t)$ for each pulsar

Can use QuickCW tricks to pre-compute inner products. Note that even the sky location becomes a cheap projection parameter since no pulsar terms

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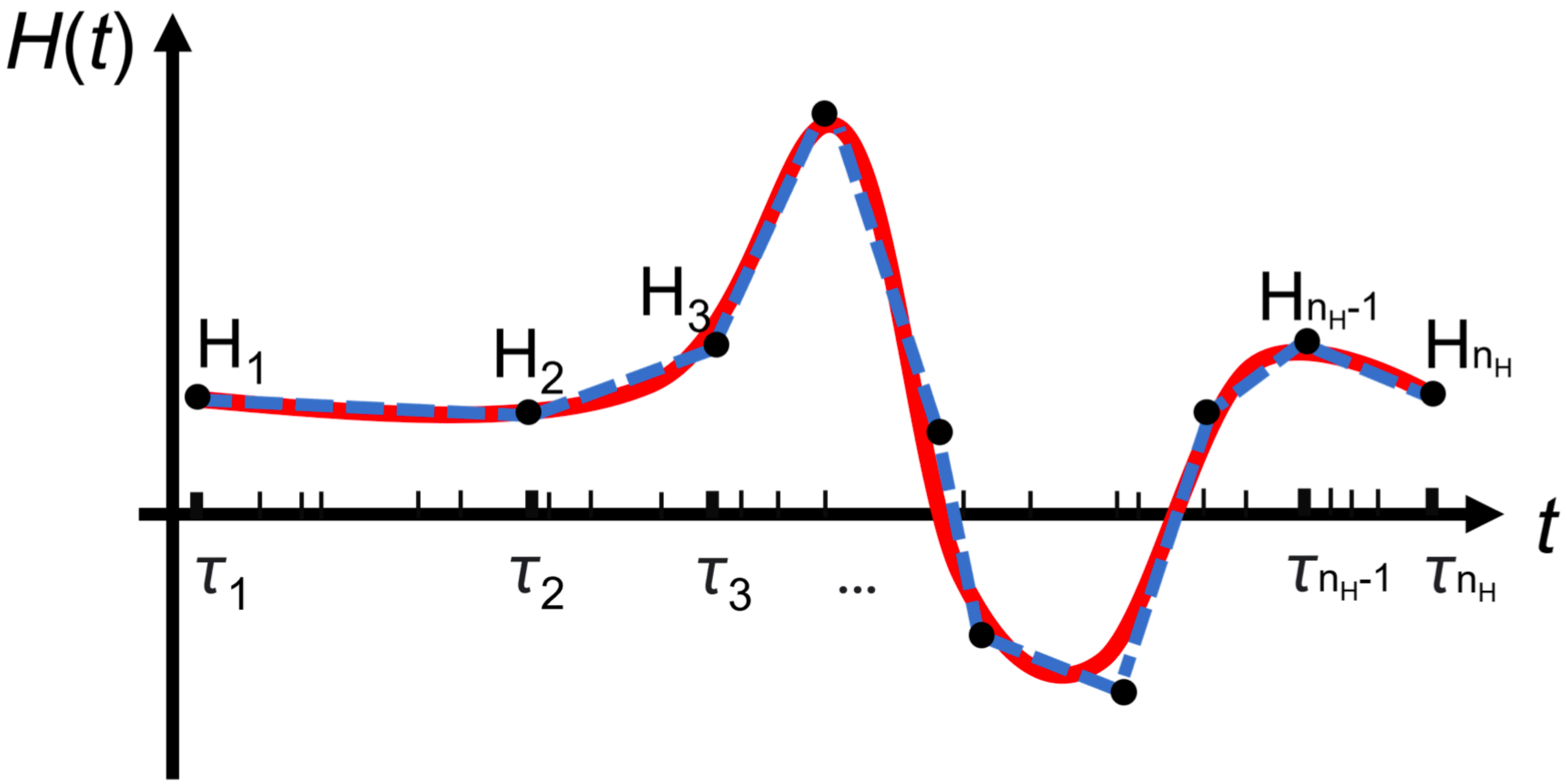
Line Segment Model

[Deng, Becsy, Siemens, Cornish & Madison, arXiv 2306.17130]

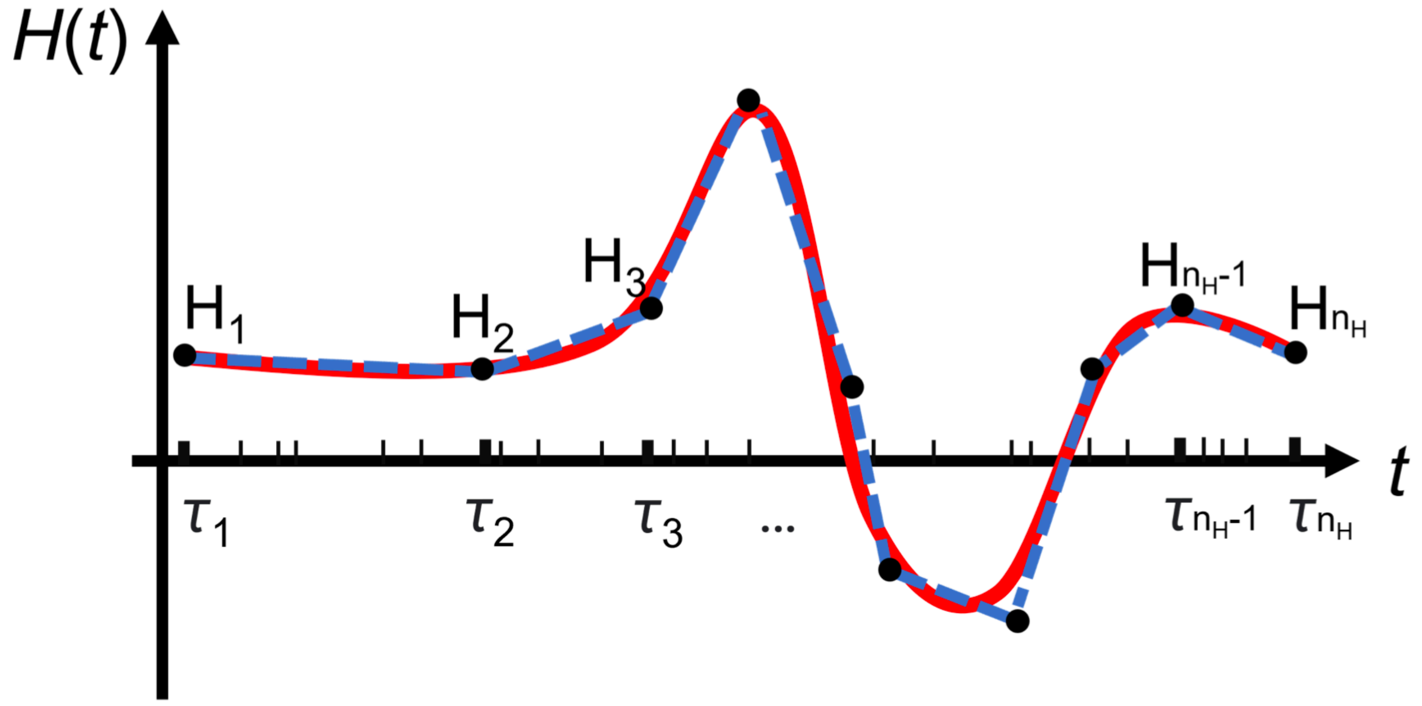


In current version, locations and number of control points is fixed (will RJMCMC this next)

Seems like a downgrade versus the wavelet to smooth spline models, so why do it?

Line Segment Model

[Deng, Becsy, Siemens, Cornish & Madison, arXiv 2306.17130]



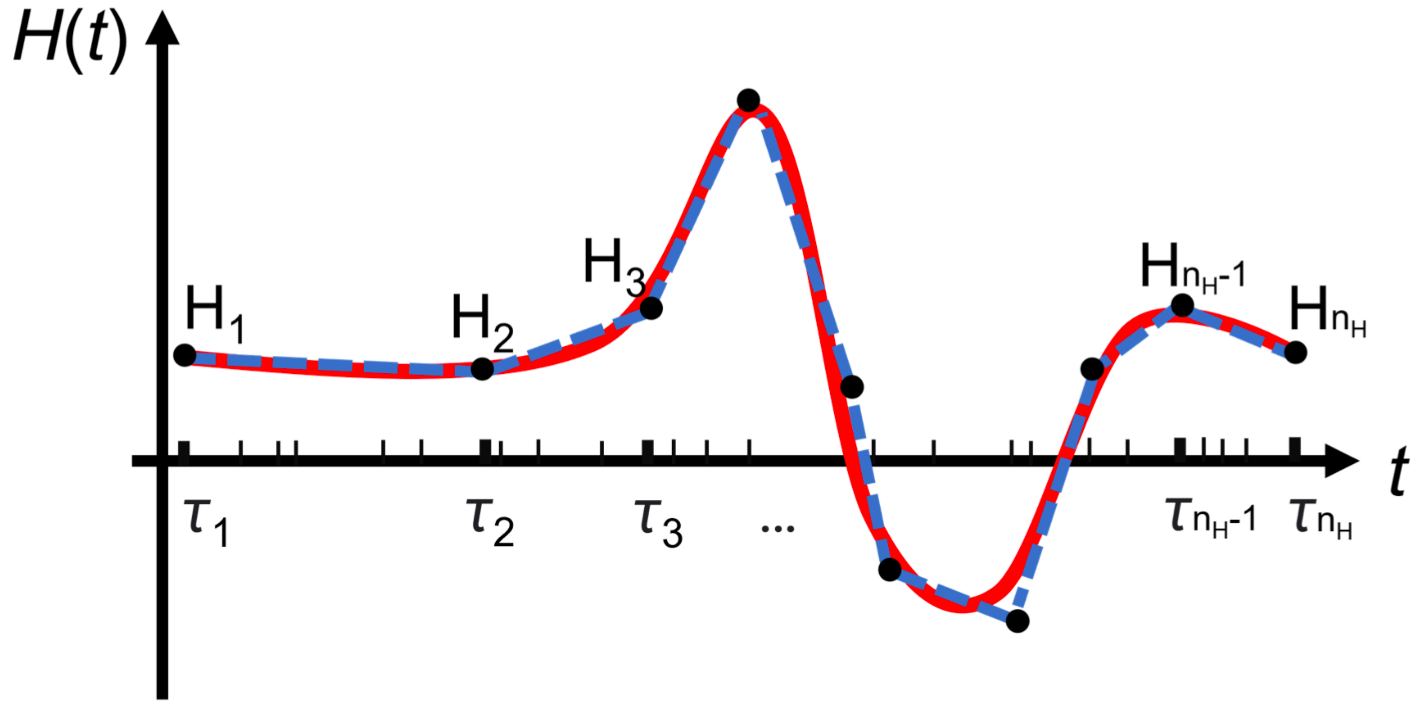
Linear interpolation

$$\begin{pmatrix} H^+(t_1) \\ H^+(t_2) \\ \vdots \\ H^+(t_{n_{toas}-1}) \\ H^+(t_{n_{toas}}) \end{pmatrix} \approx \begin{pmatrix} \frac{\tau_2-t_1}{\tau_2-\tau_1} & \frac{t_1-\tau_1}{\tau_2-\tau_1} & 0 & \cdots & 0 & 0 \\ \frac{\tau_2-t_2}{\tau_2-\tau_1} & \frac{t_2-\tau_1}{\tau_2-\tau_1} & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & \frac{\tau_{n_H}-t_{n_{toas}-1}}{\tau_{n_H}-\tau_{n_H-1}} & \frac{t_{n_{toas}-1}-\tau_{n_H-1}}{\tau_{n_H}-\tau_{n_H-1}} \\ 0 & 0 & 0 & \cdots & \frac{\tau_{n_H}-t_{n_{toas}}}{\tau_{n_H}-\tau_{n_H-1}} & \frac{t_{n_{toas}}-\tau_{n_H-1}}{\tau_{n_H}-\tau_{n_H-1}} \end{pmatrix} \begin{pmatrix} H_1^+ \\ H_2^+ \\ \vdots \\ H_{n_H-1}^+ \\ H_{n_H}^+ \end{pmatrix} \equiv P_I \mathbf{H}^+$$

$$\begin{aligned} h_I &\approx F_I^+ P_I \mathbf{H}^+ + F_I^\times P_I \mathbf{H}^\times \\ &= \left(F_I^+ P_I \quad F_I^\times P_I\right) \begin{pmatrix} \mathbf{H}^+ \\ \mathbf{H}^\times \end{pmatrix} \equiv S_I \mathbf{H} \end{aligned}$$

Line Segment Model

[Deng, Becsy, Siemens, Cornish & Madison, arXiv 2306.17130]



Marginalize over $\mathbf{H}$

$$\mathcal{L}(\boldsymbol{r}|\boldsymbol{\eta},\theta,\phi,q) = \int \mathcal{L}(\boldsymbol{r}|\boldsymbol{\eta},\theta,\phi,\mathbf{H})\pi(\mathbf{H}|q)\mathrm{d}\mathbf{H}$$

$$= \int \mathcal{N}(\boldsymbol{r}|\boldsymbol{C}) \frac{\exp\left[[\![\boldsymbol{r}|\mathbf{S}]\!]\,\mathbf{H} - \frac{1}{2}\mathbf{H}^{\top}\left([\![\mathbf{S}|\mathbf{S}]\!] + \boldsymbol{Q}^{-1}\right)\mathbf{H}\right]}{\sqrt{\det\left(2\pi\boldsymbol{Q}\right)}}\mathrm{d}\mathbf{H}$$

$$= \mathcal{N}(\boldsymbol{r}|\boldsymbol{C}) \frac{\exp\left(\frac{1}{2}[\![\boldsymbol{r}|\mathbf{S}]\!]\,\boldsymbol{\Sigma}^{-1}[\![\mathbf{S}|\boldsymbol{r}]\!]\right)}{\sqrt{\det\left(\boldsymbol{Q}\boldsymbol{\Sigma}\right)}}, \qquad \boldsymbol{\Sigma} \equiv [\![\mathbf{S}|\mathbf{S}]\!] + \boldsymbol{Q}^{-1}$$

We don't have to explicitly search over the amplitudes $H_i^{+}, H_i^{\times}$, so fast!

Can reconstruct the signal from the posterior samples (analogous to how we integrate out the coefficients of the Fourier expansion of the GW background)

Burst Search Outlook

- Two burst search pipelines (wavelet and line segment) are under development and will soon be applied to the NASOGrav 15-yr data set
- Akima spline based search built using QuickCW + Akima monopole codes is under development
- Exploratory runs using wavelet and line segment approaches are staring now