
UNIVERSITY OF BIRMINGHAM
GraWIToN
GW Initial Training Network
MARIE CURIE ACTIONS

Data analysis challanges in gravitational wave astronomy & "pills" of GW150914

Serena Vinciguerra
Supervisors: Ilya Mandel, John Veitch

26 May 2016

talk organisation

1. Speeding up the Bayesian Parameter for gravitational waves emitted by compact binary coalescences

- Introduction
- Motivation
- Procedure
- Results

2. “Pills” of GW150914

- The Discovery
- Main consequences

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Introduction: gravitational waves

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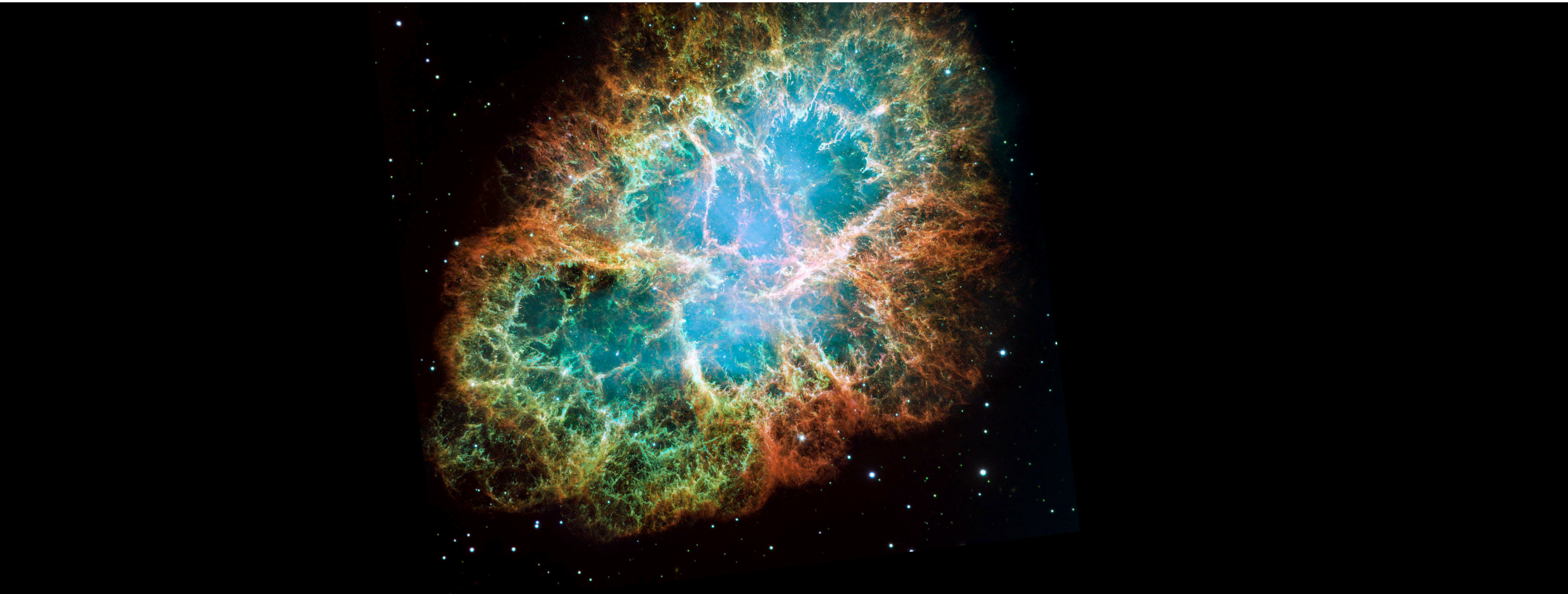
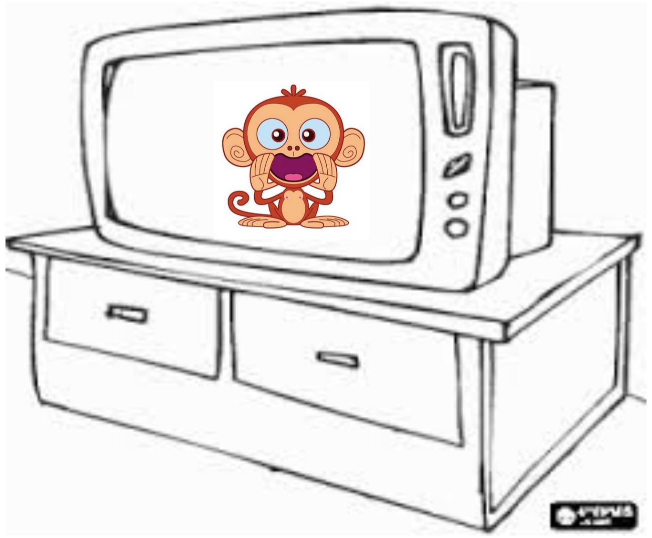
The first hints about the nature of the Universe which surrounded us came from deeply looking at the sky…



Introduction: gravitational waves

But how much would we be able to understand without hearing?



Introduction: gravitational waves

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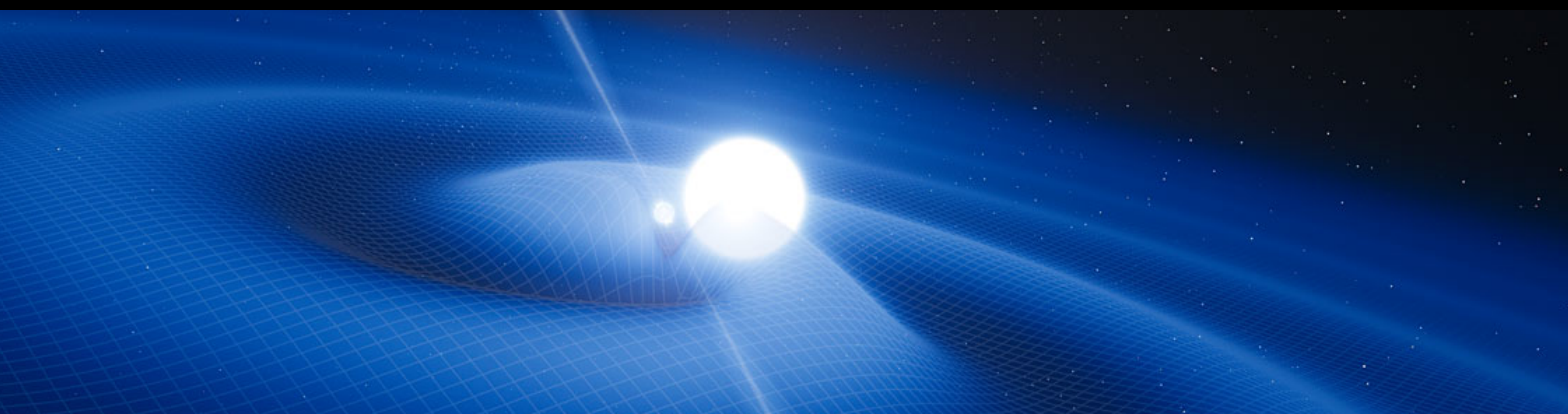
WHY DON'T ALSO LISTEN TO WHAT THE UNIVERSE IS TRYING TO TELL US?!

The **sound of the Universe.**

They are ripples in space-time which propagate from the source at the speed of light.

EINSTEIN FIELD EQUATIONS

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$



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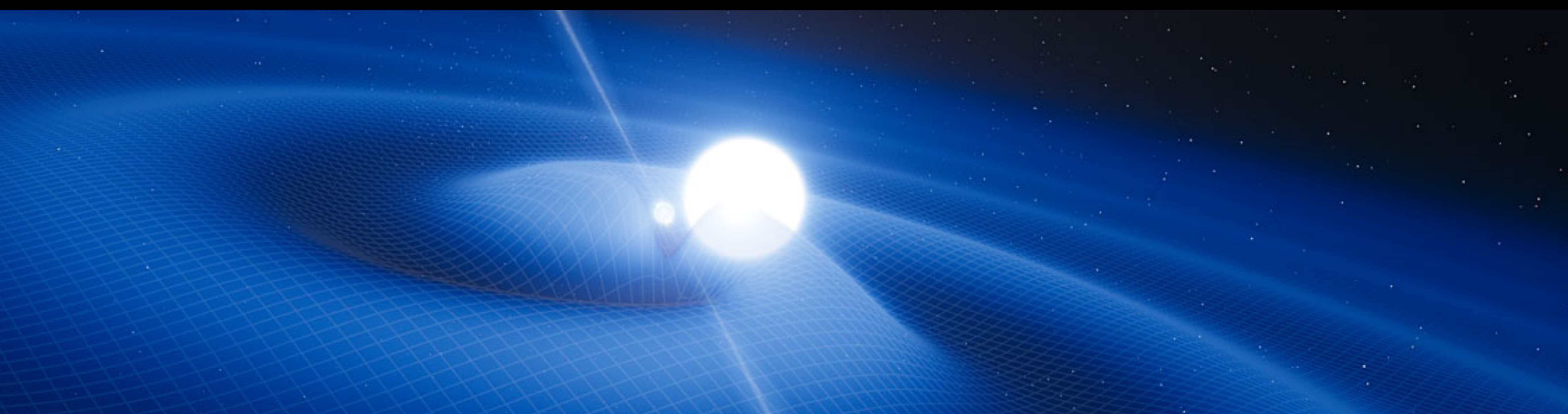

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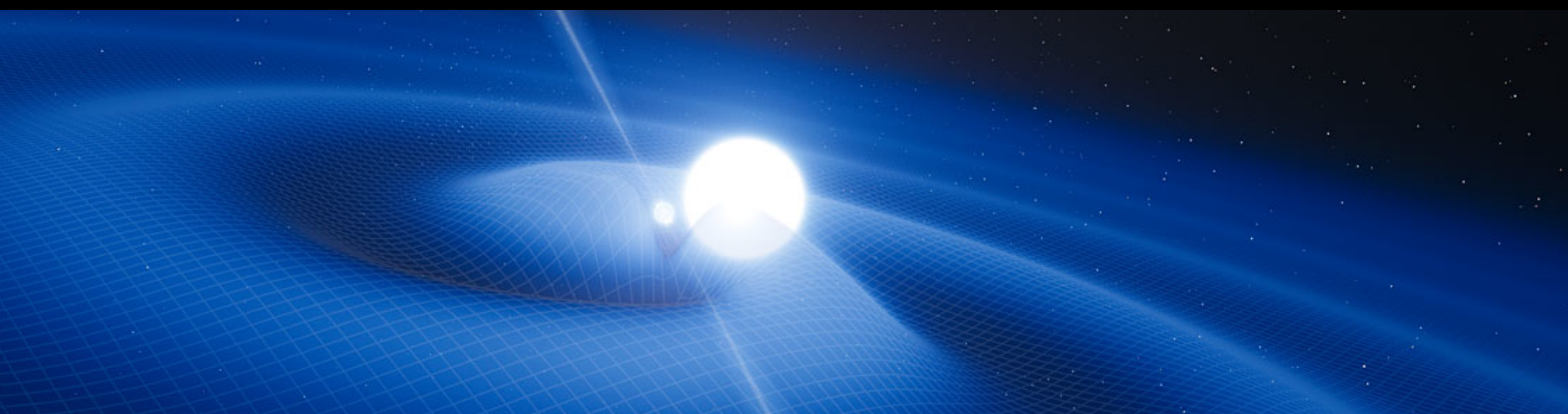

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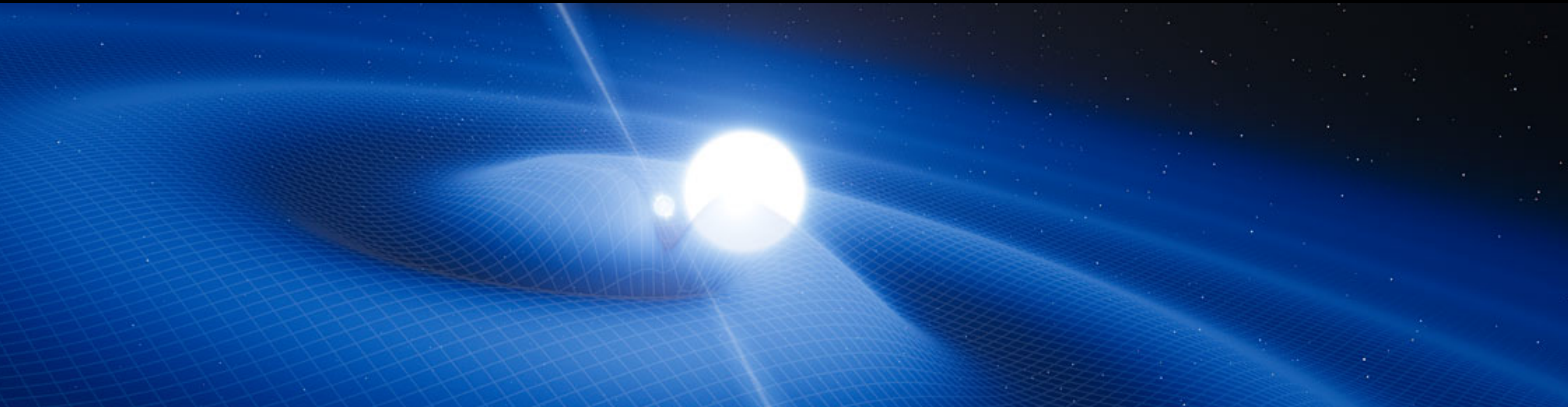
$$\boxed{h_{\mu\nu}(t,r) = 2\frac{G}{c^4}\frac{1}{r}\frac{\partial^2 I_{\mu\nu}}{\partial t^2}(t - \frac{r}{c})}$$



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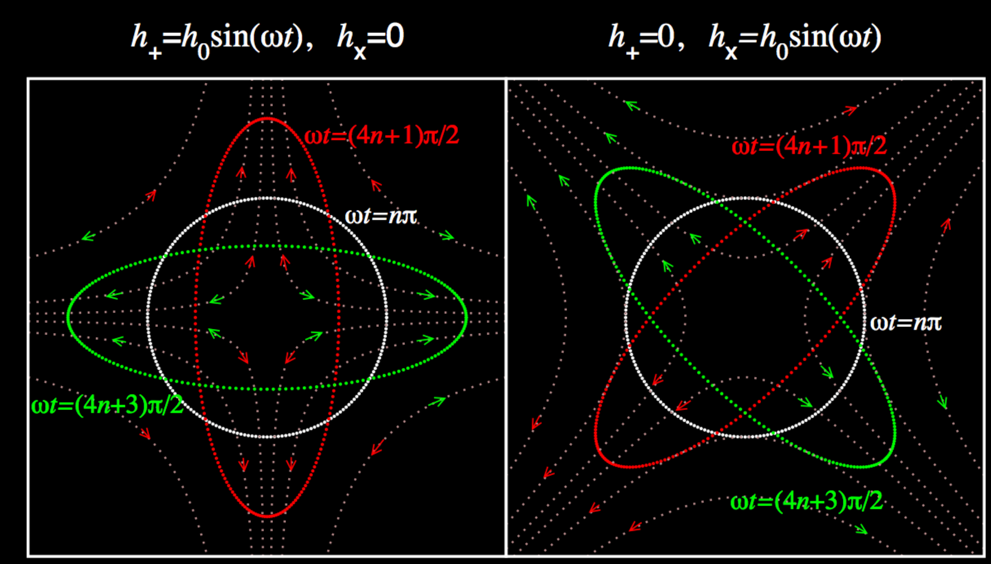
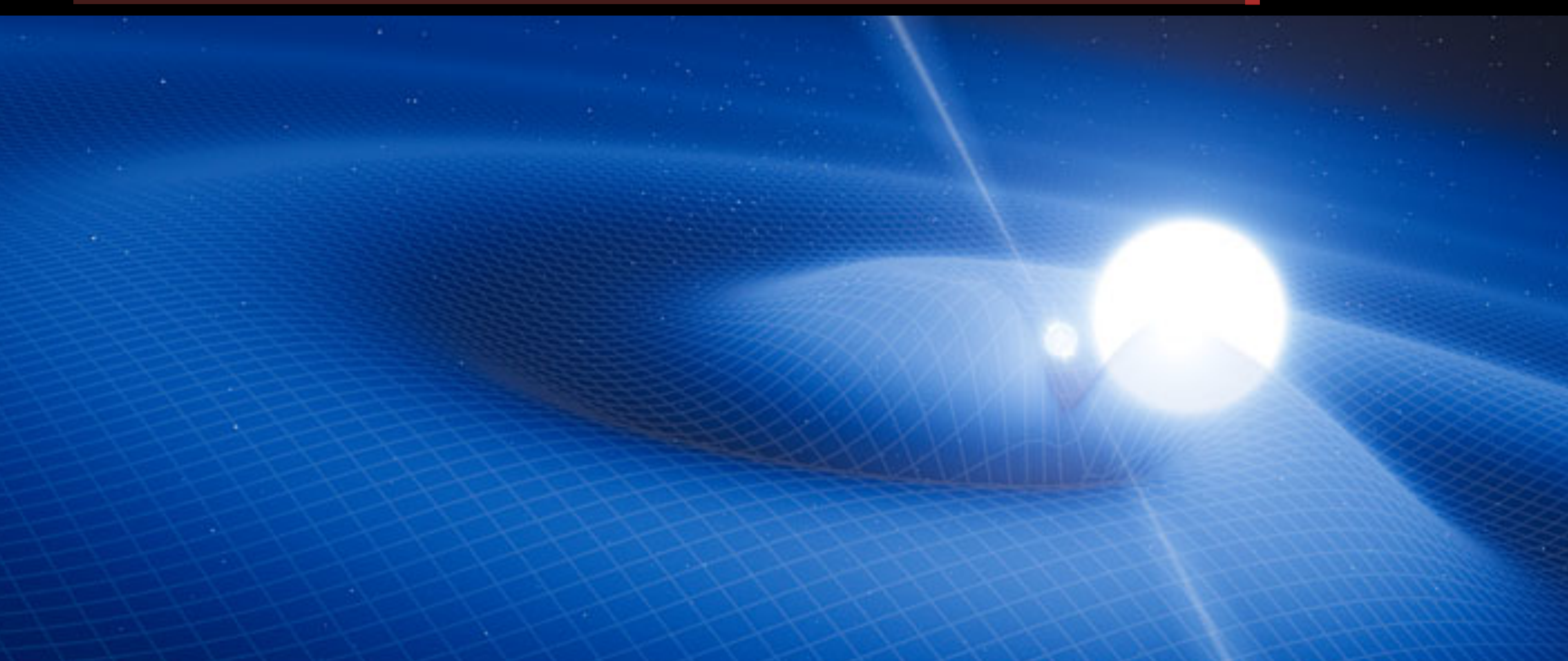
$$h_{\mu\nu}^{TT} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$





Introduction: compact binaries coalescences

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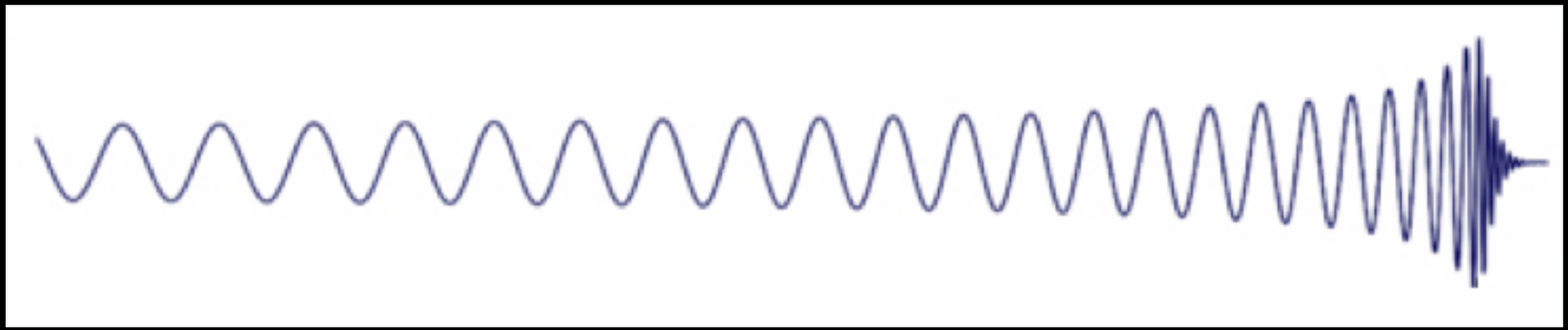
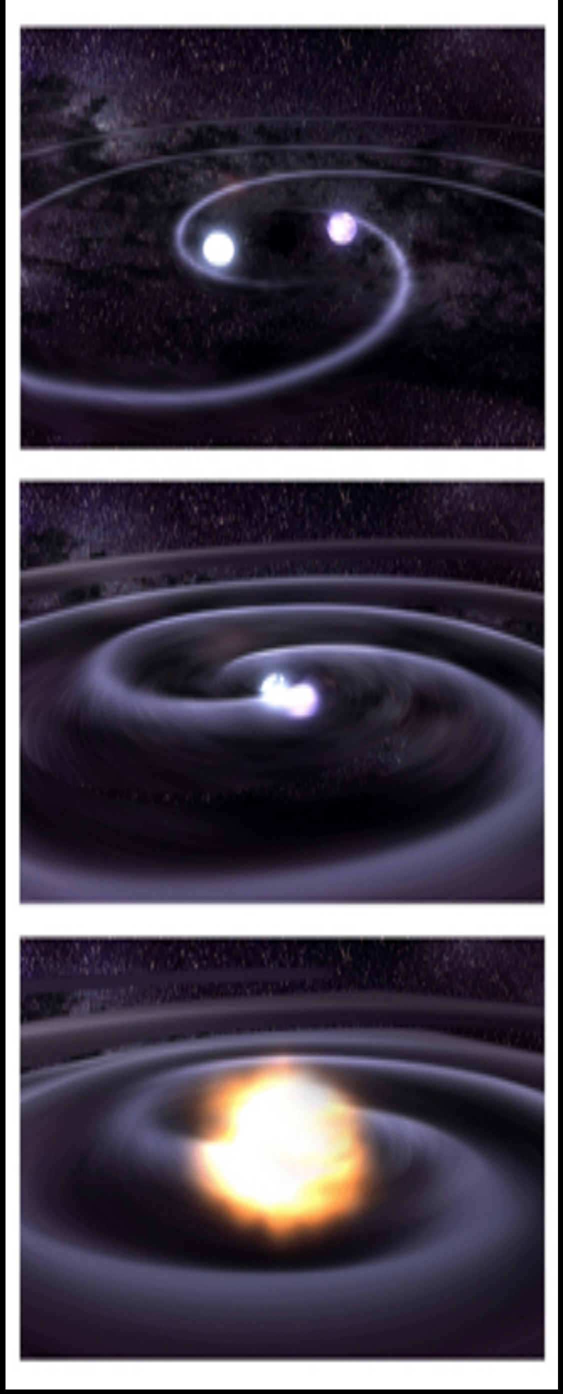
INTERESTING BINARIES:

- Neutron Star-Neutron Star [NS-NS];
- Neutron Star-Black Hole [NS-BH];
- Black Hole-Black Hole [BH-BH]

System	Masses (M_{sun})	Range (Mpc)	expected detection rate for aLIGO		
			low (yr^{-1})	realistic (yr^{-1})	high (yr^{-1})
NS-NS	1.4/1.4	200	0.4	40	400
NS-BH	1.4/10	410	0.2	10	300
BH-BH	10/10	970	0.4	20	1000





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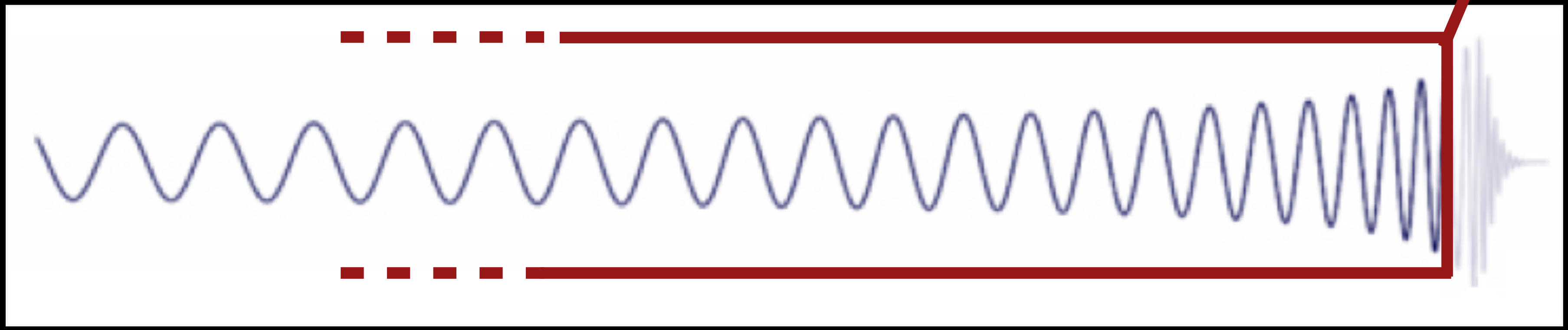

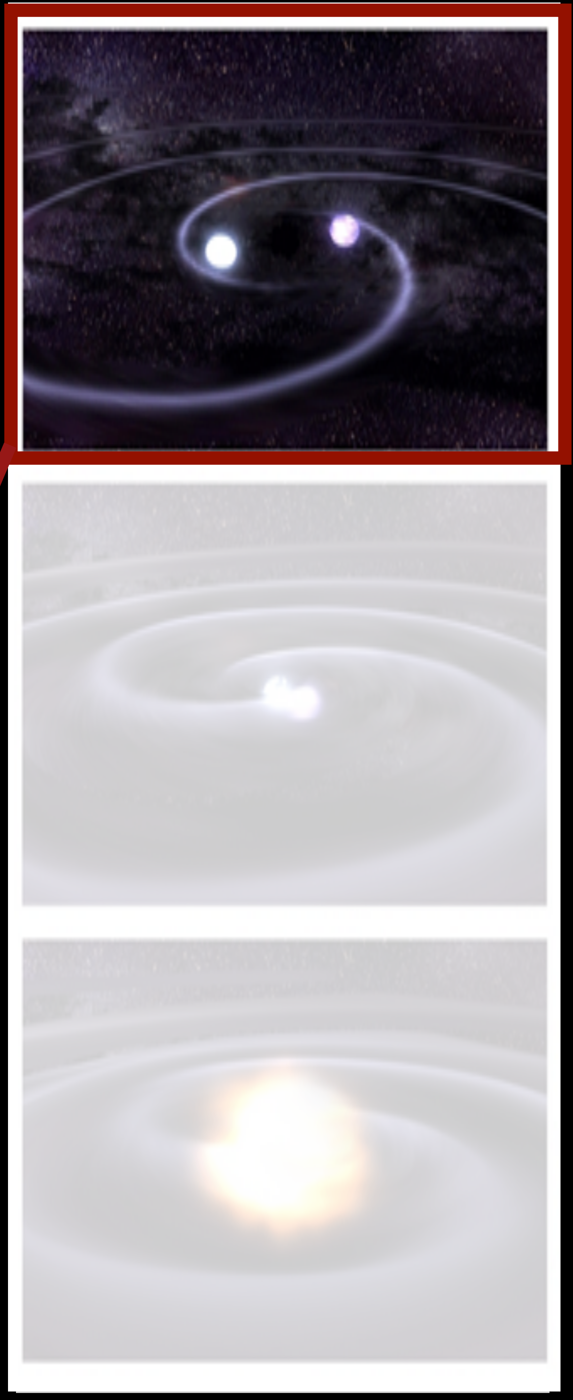

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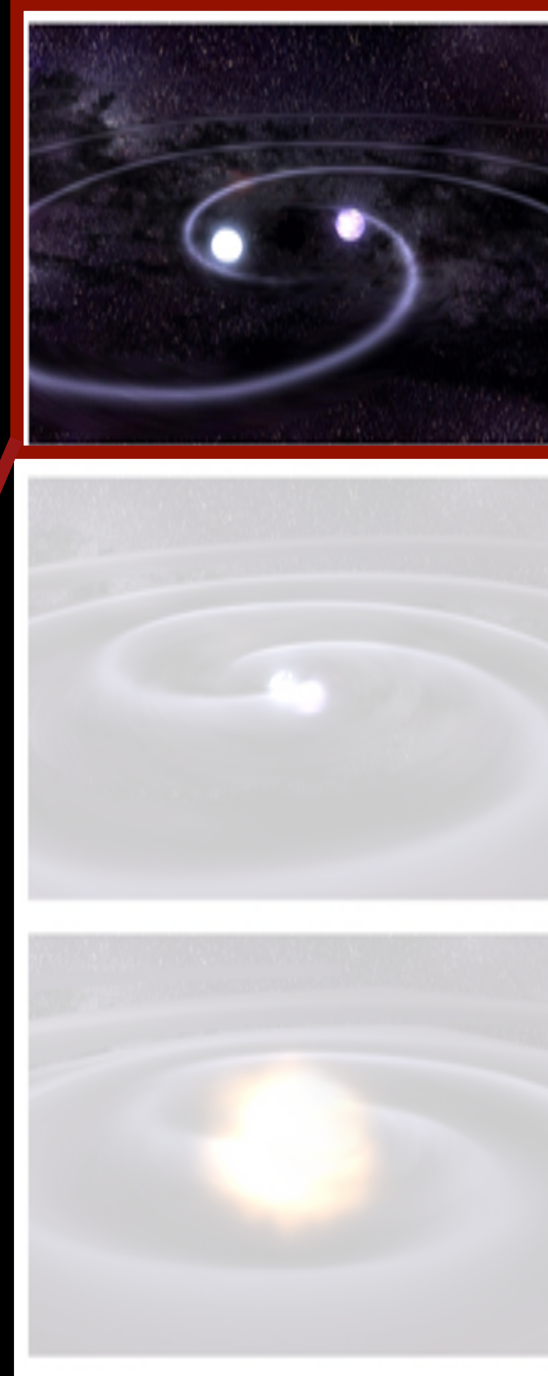

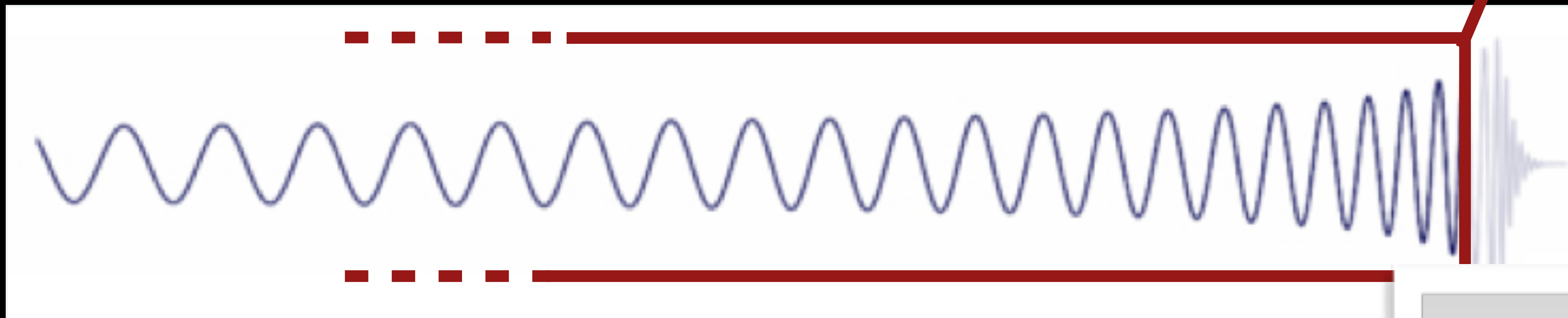

$$t_{inspiral} \propto f_{min}^{-8/3} \mathcal{M}^{-5/3}$$

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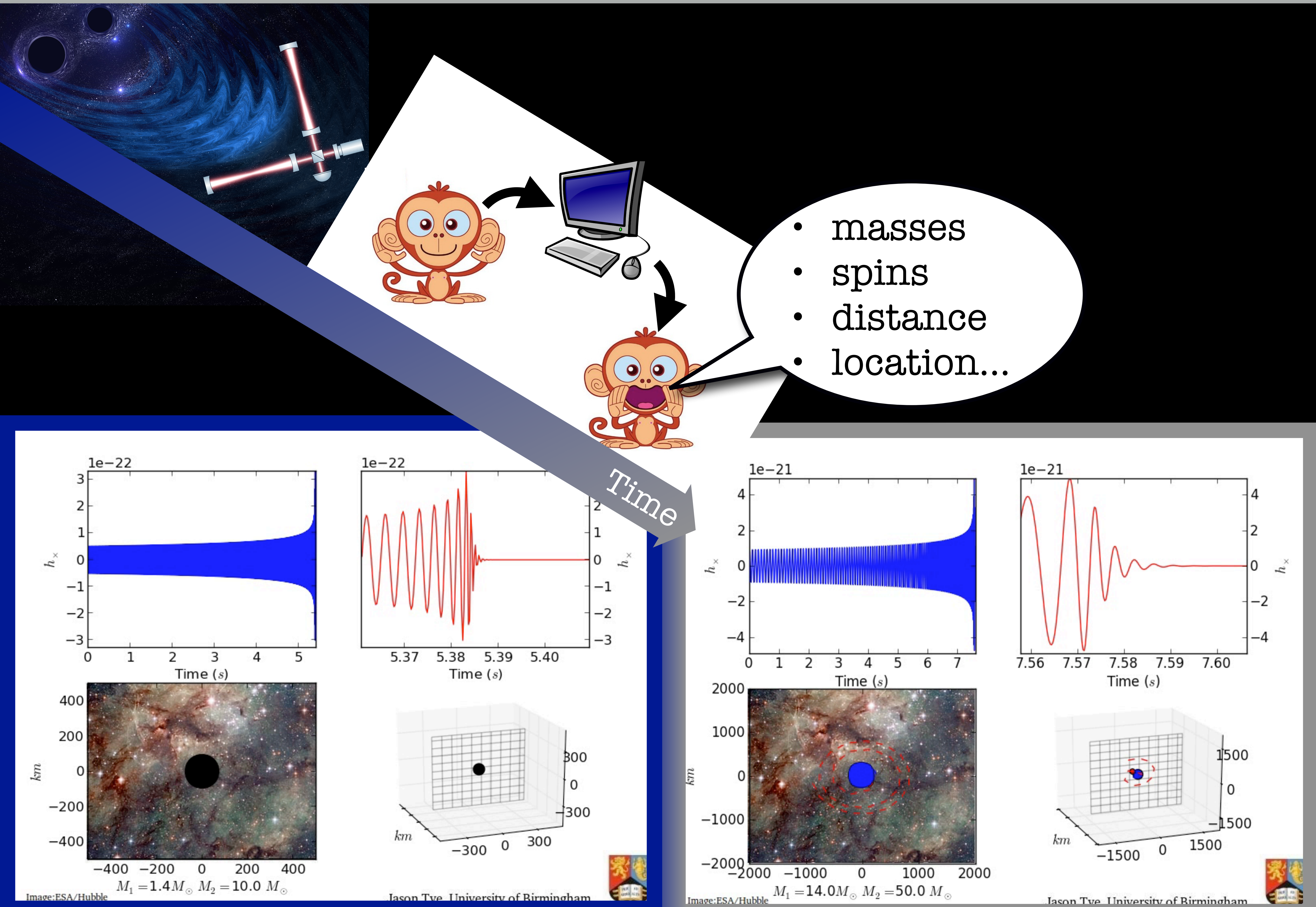
Motivation: parameter estimation



Motivation: parameter estimation

$$\mathbf{d} = \mathbf{h}(\boldsymbol{\theta}) + \mathbf{n}$$

masses, spins, distance, inclination,sky locations …

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Bayes theorem

$$\mathbf{d} = \mathbf{h}(\boldsymbol{\theta}) + \mathbf{n}$$

$\mathbf{d}$: data
$\mathbf{h}$: signal
$\mathbf{n}$: noise
$\boldsymbol{\theta}$: parameters
H: model

Priors

Likelihood

$$p(\boldsymbol{\theta}|\mathbf{d}, H) = \frac{p(\boldsymbol{\theta}|H)\,p(\mathbf{d}|\boldsymbol{\theta}, H)}{p(\mathbf{d}|H)}$$

Posterior

Evidence

GAUSSIAN NOISE

- zero mean
- known variance

$$p(\mathbf{d}|\boldsymbol{\theta}, H) \propto \exp\left[-\delta f \sum_{i=0}^{N} \frac{2|\tilde{d}(f_i) - \tilde{h}(\boldsymbol{\theta}, f_i)|^2}{S_n(f_i)}\right]$$

Motivation: future instrument sensitivities

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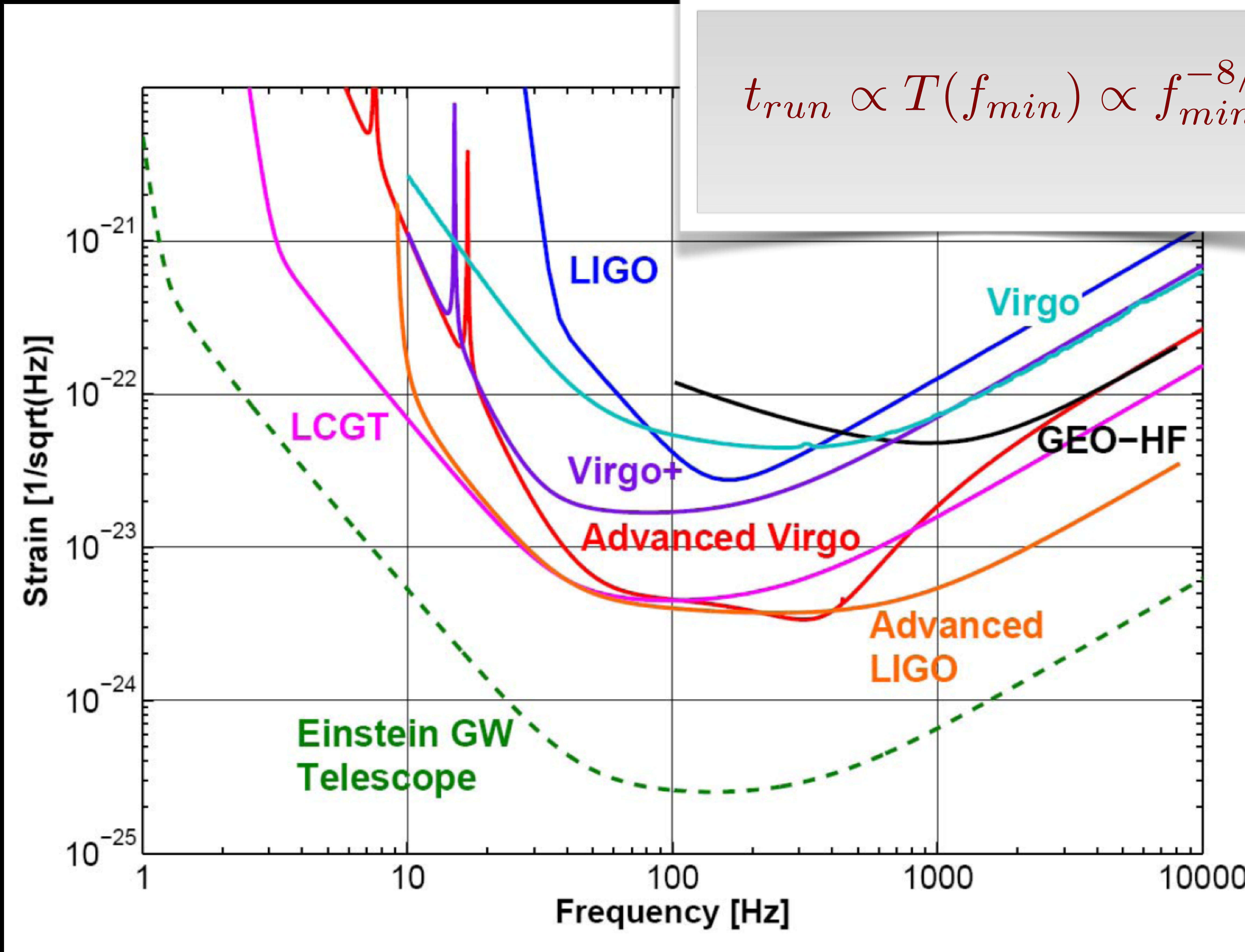
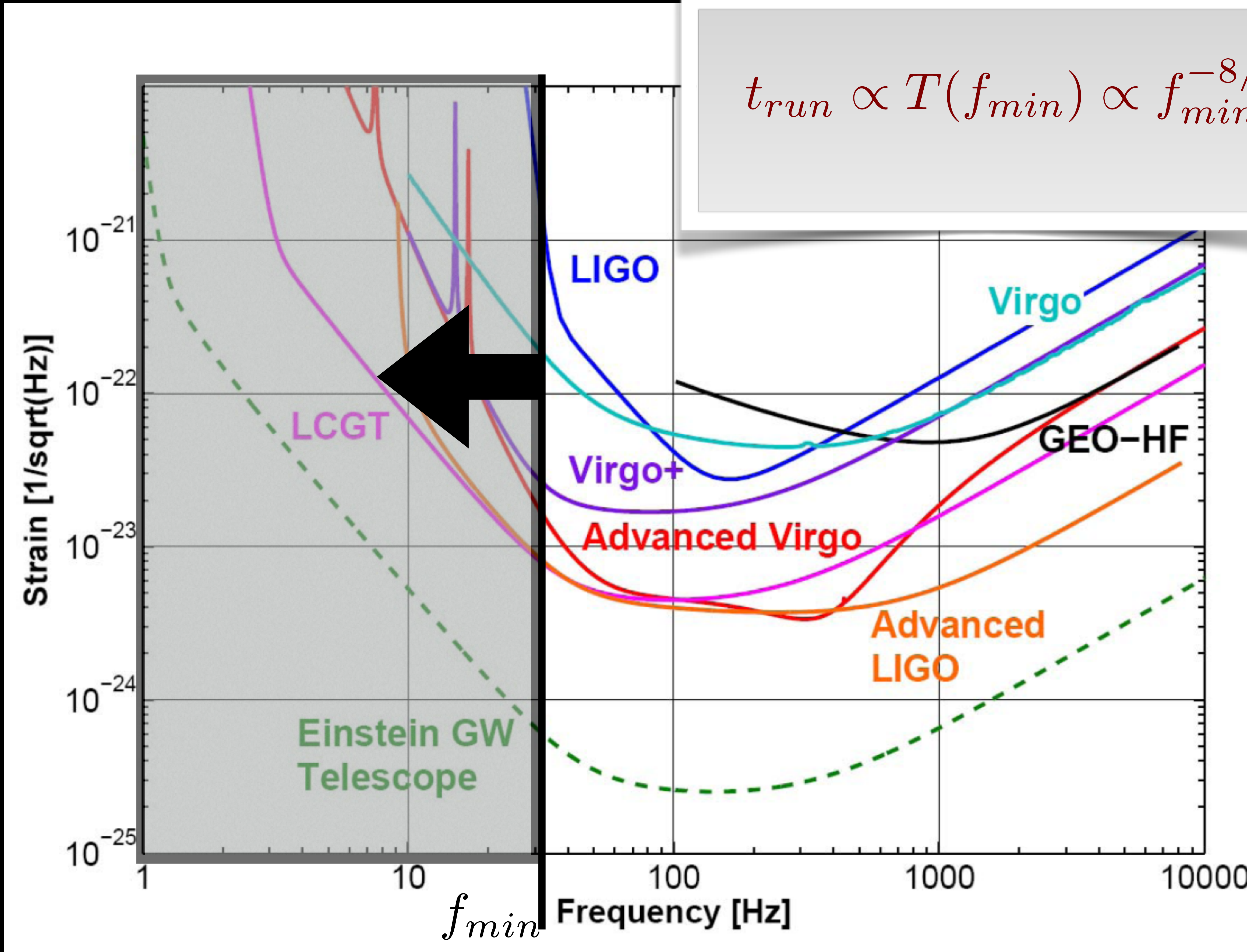


$$t_{run} \propto T(f_{min}) \propto f_{min}^{-8/3}$$

Motivation: future instrument sensitivities



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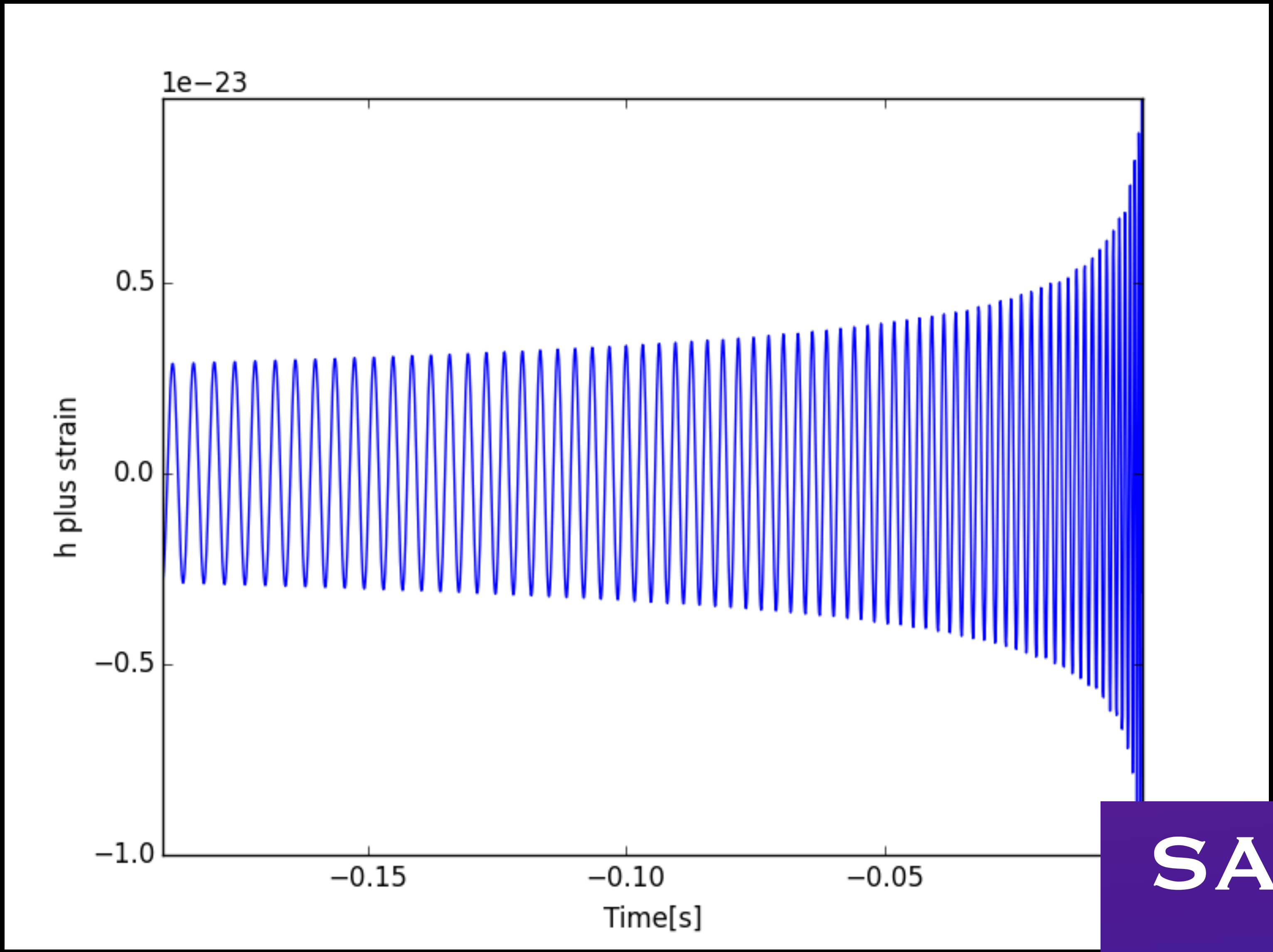
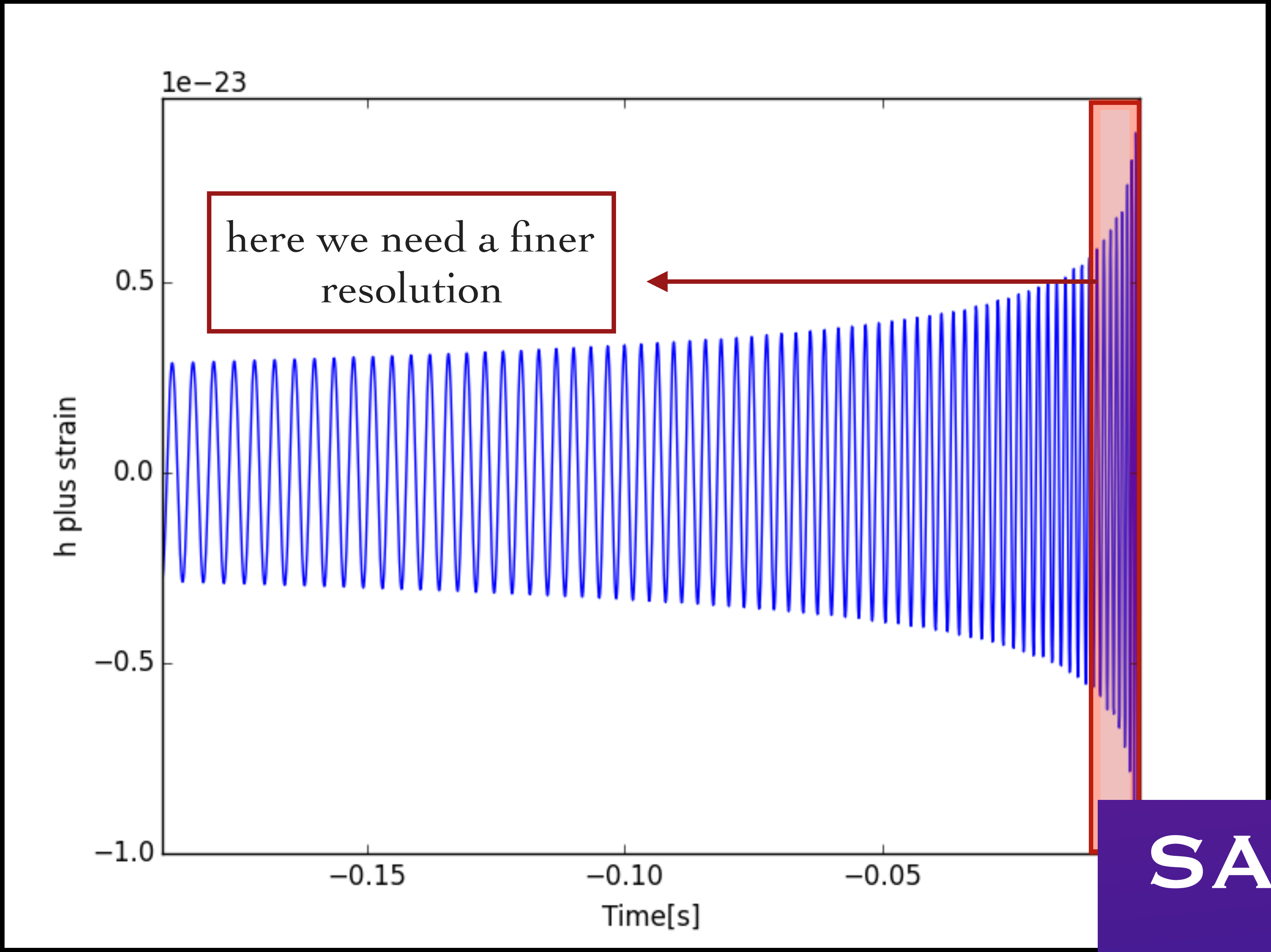
Procedure: multi-banding



SAMPLING THEORY

$$\delta t \leq (2f_{max})^{-1}$$

Procedure: multi-banding



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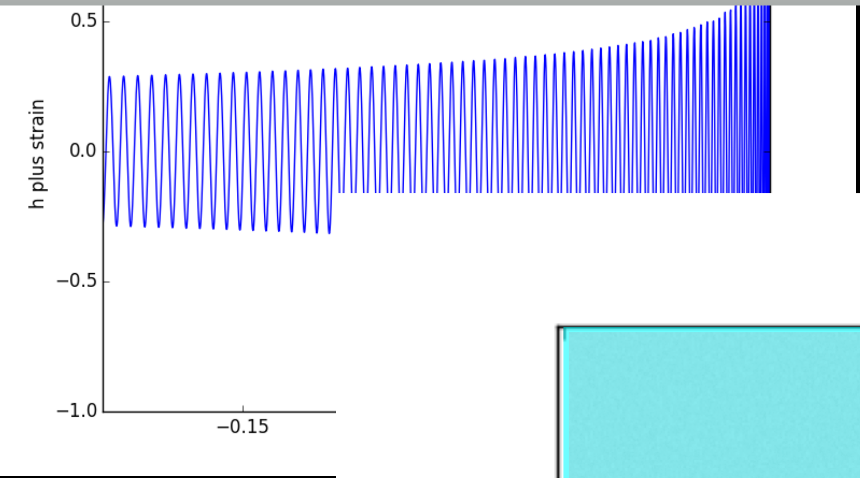
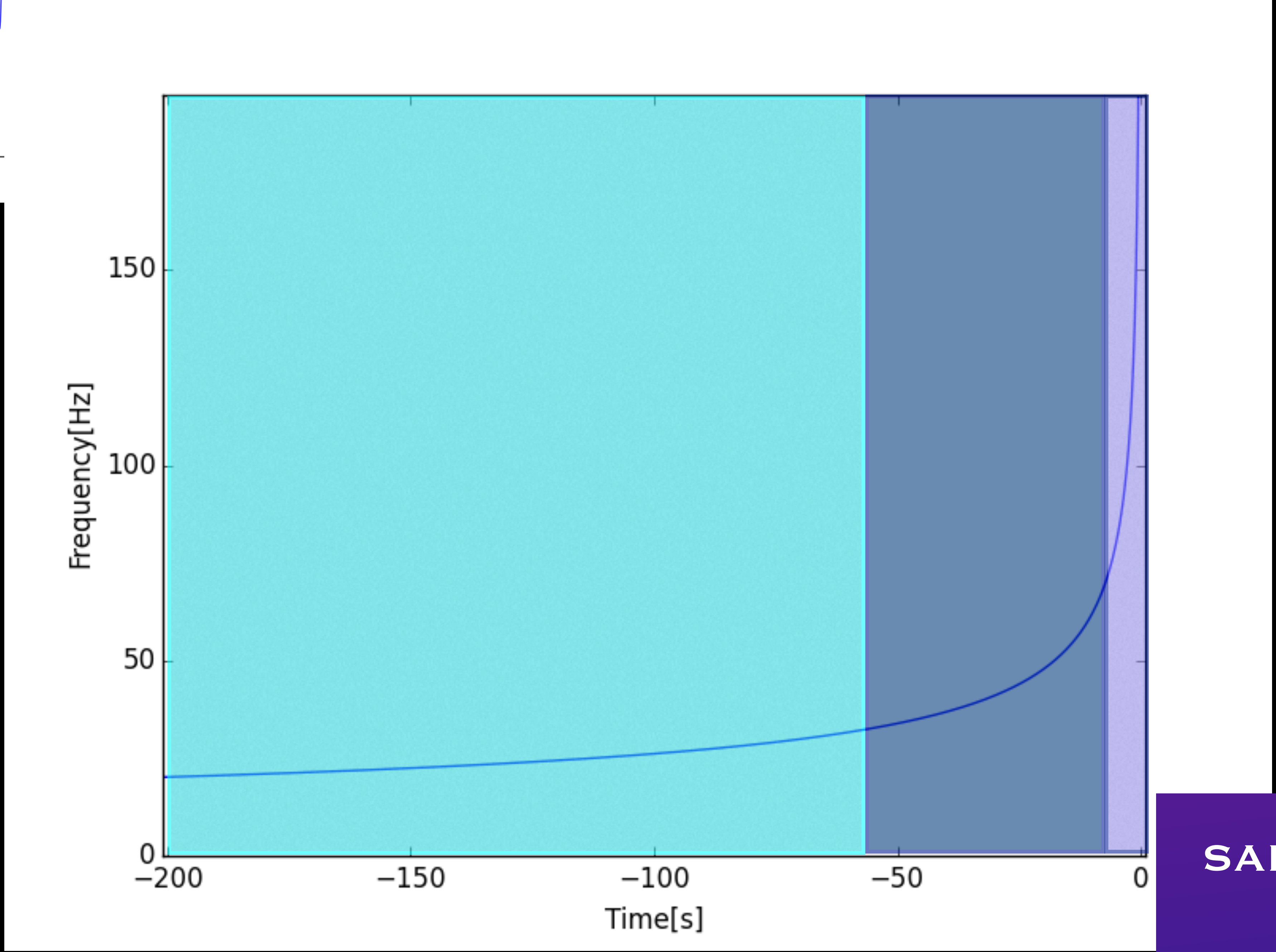
$$\delta t \leq (2 f_{max})^{-1}$$

$$\rightarrow \delta t(t) \leq (2 f_{max}(t))^{-1}$$

Procedure: multi-banding





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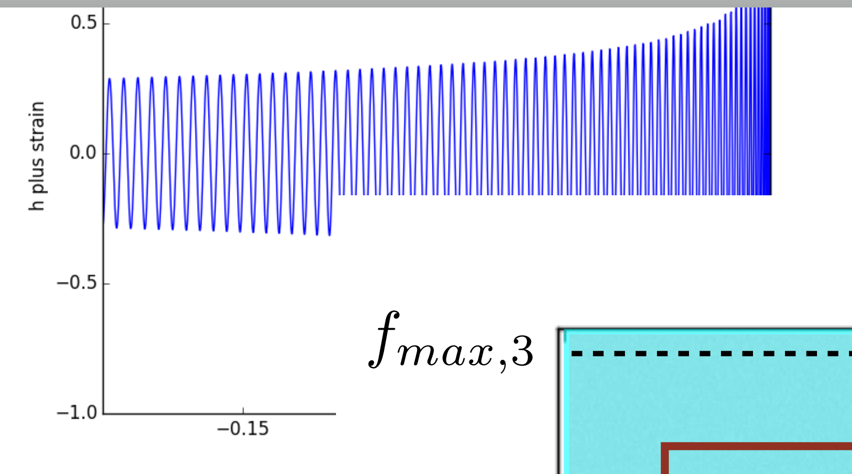

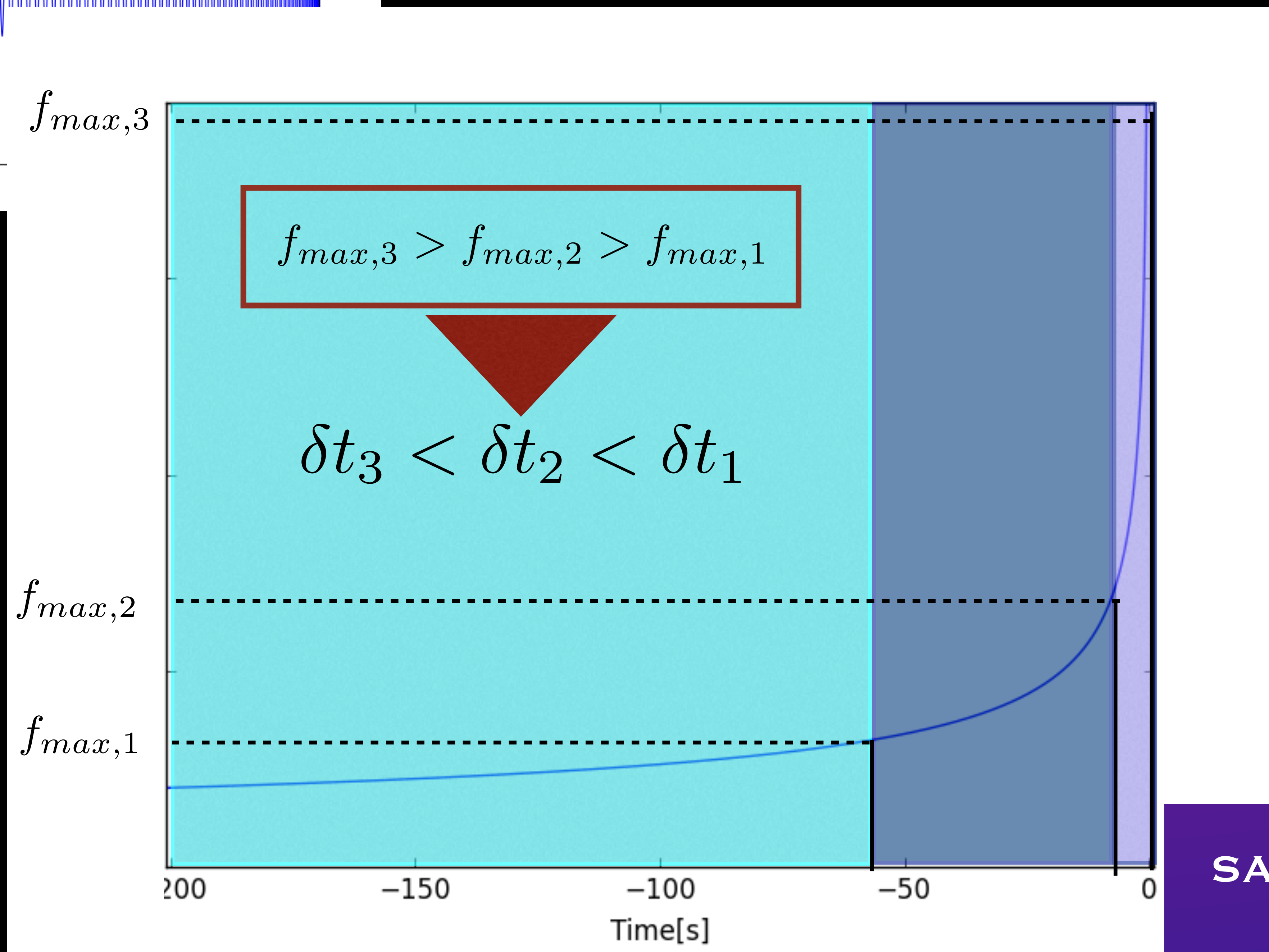

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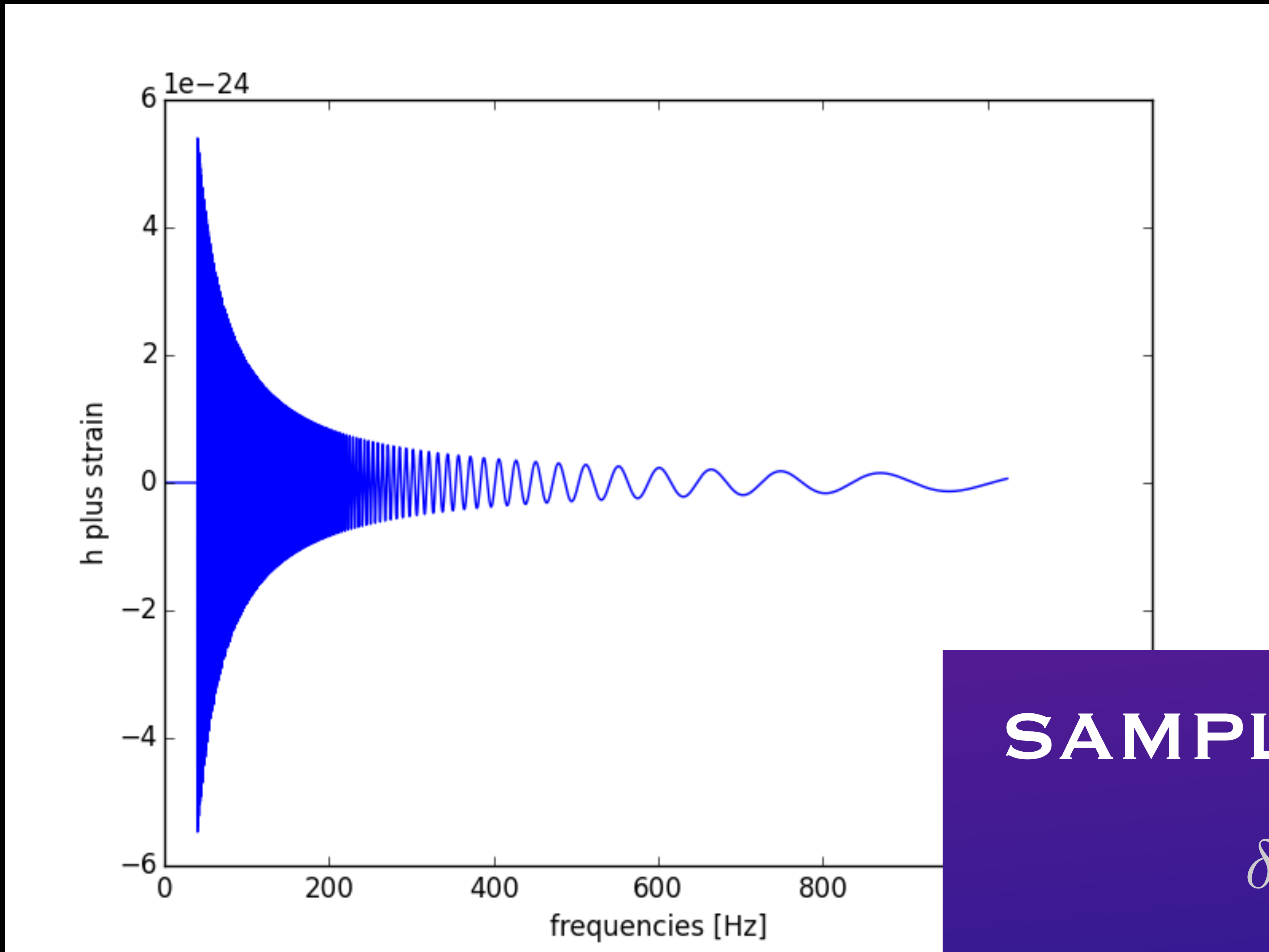

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$$\delta f \leq T[s]^{-1}$$

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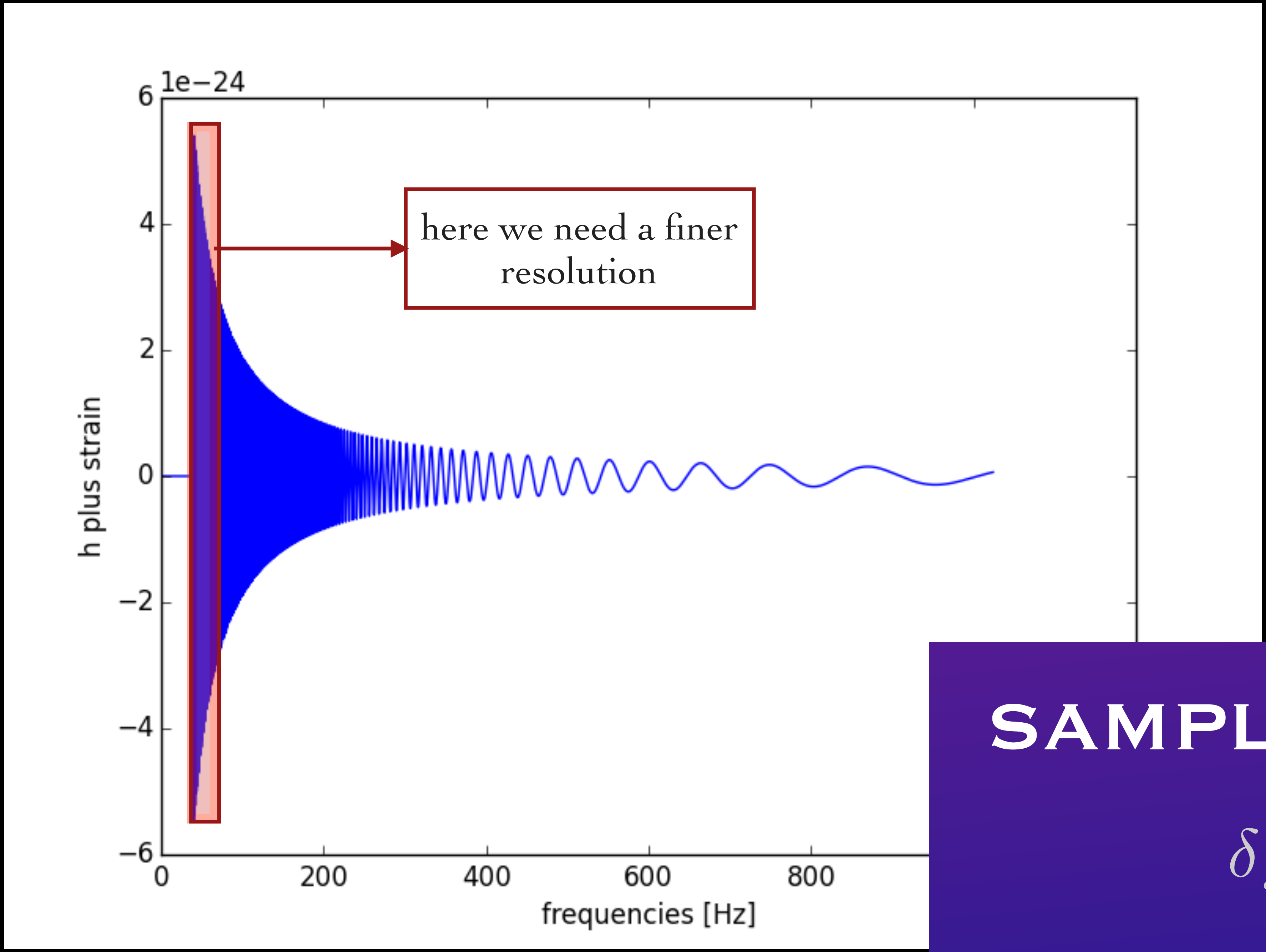

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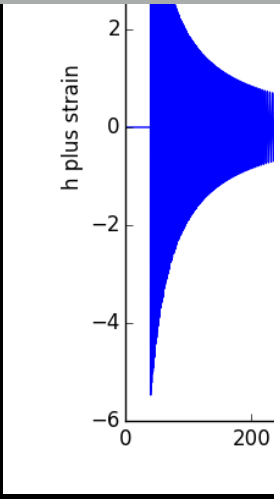

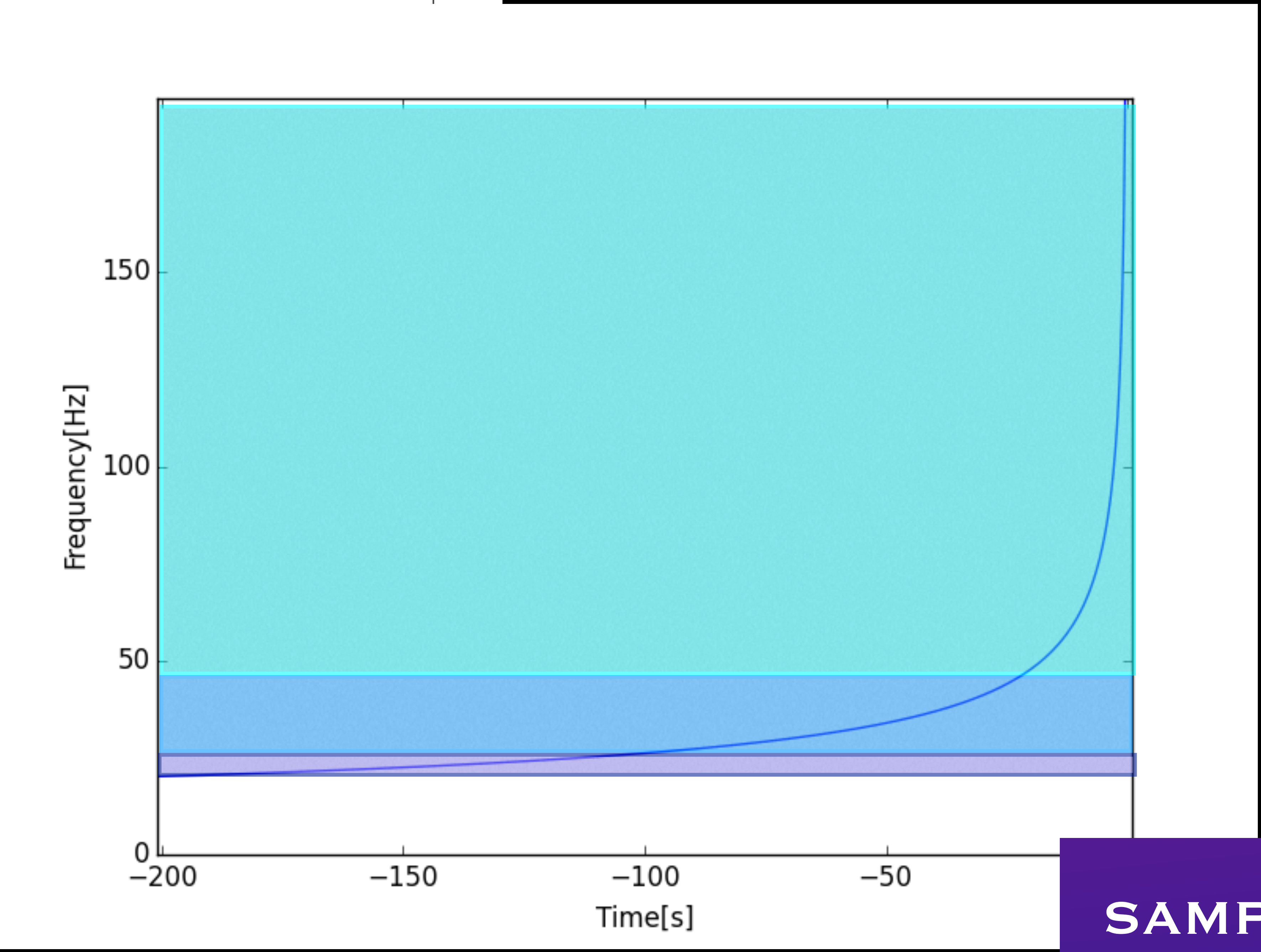

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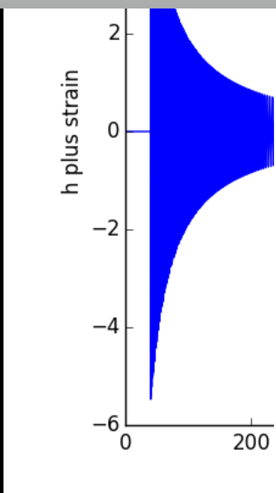

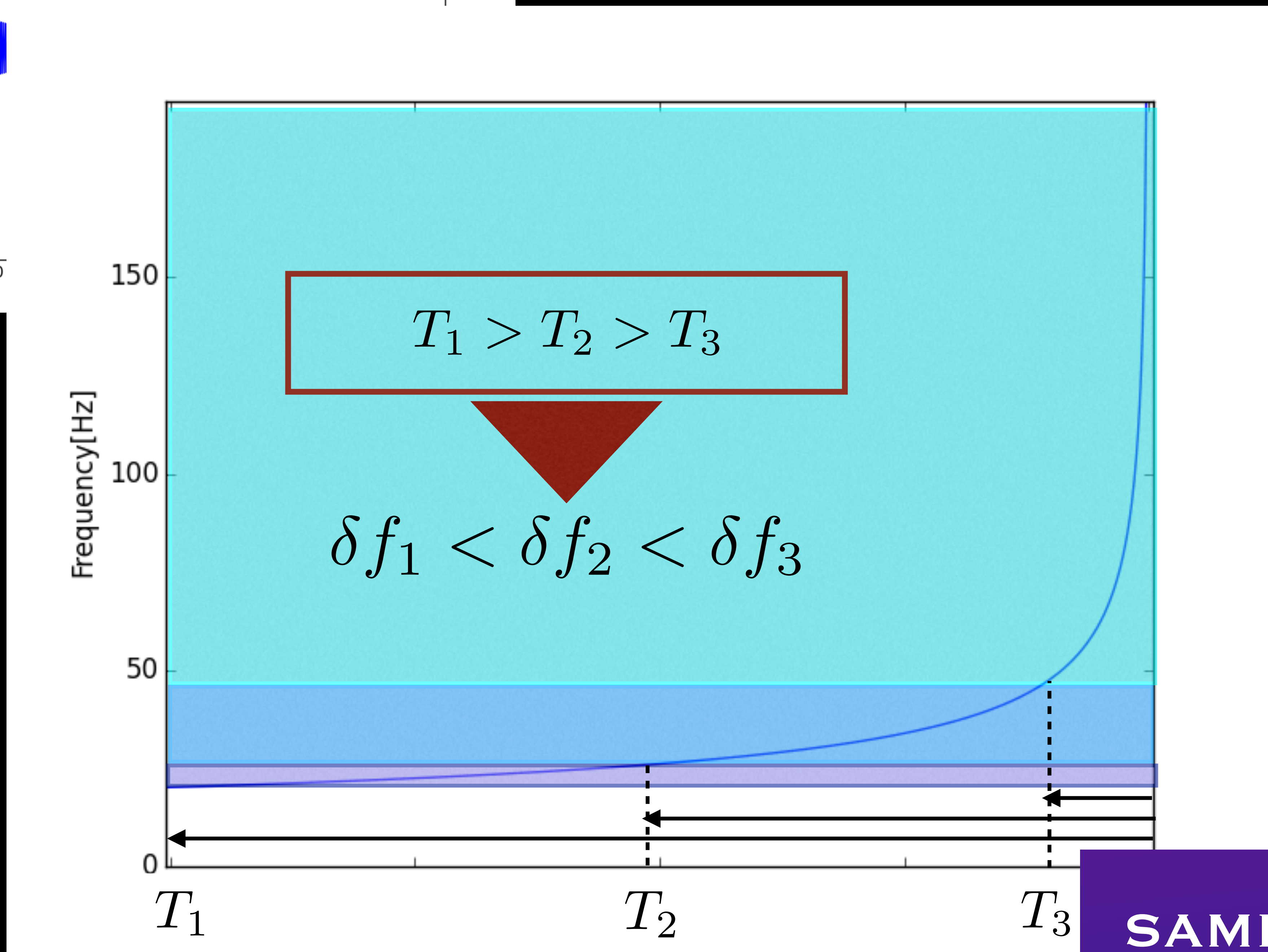

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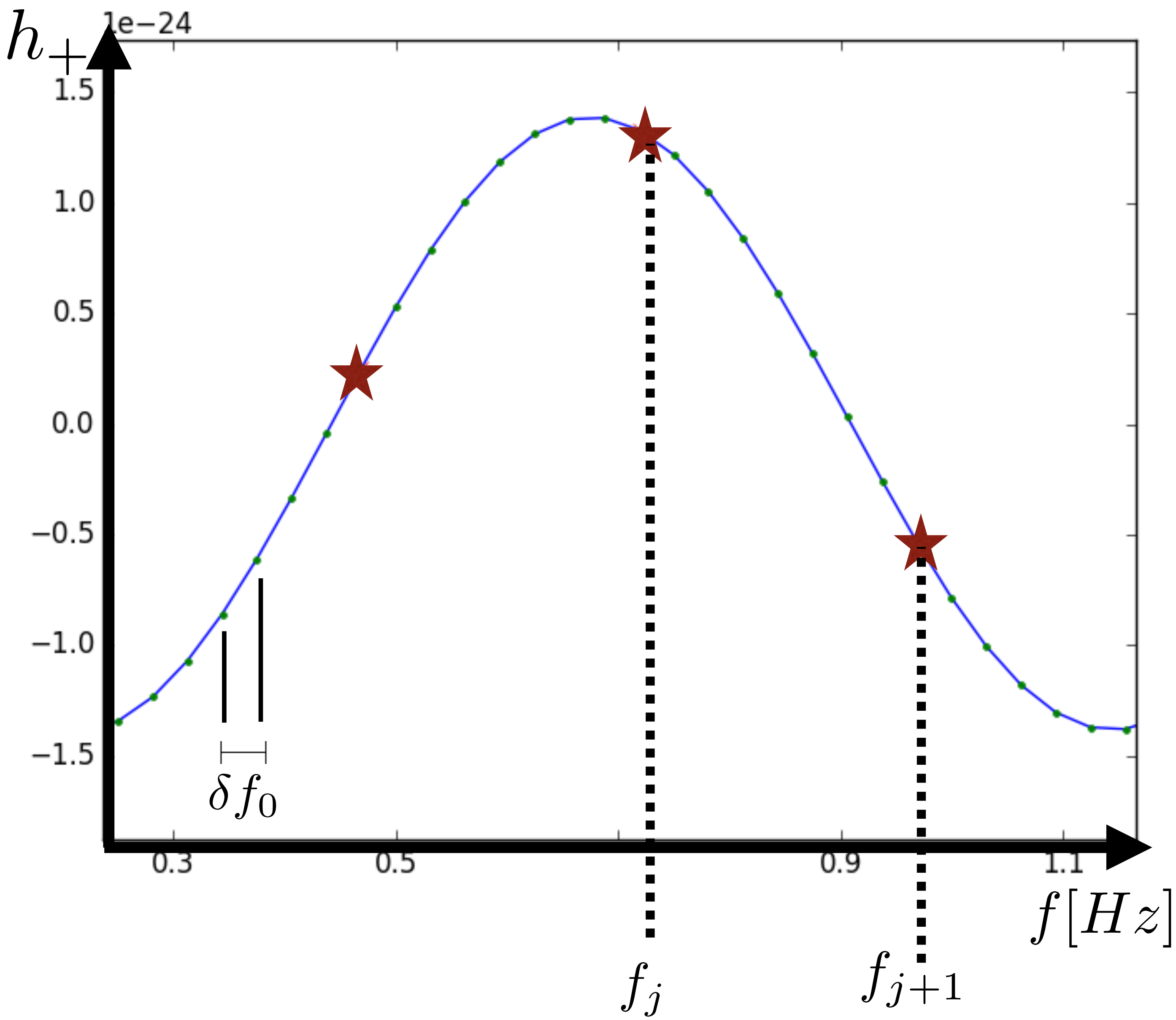
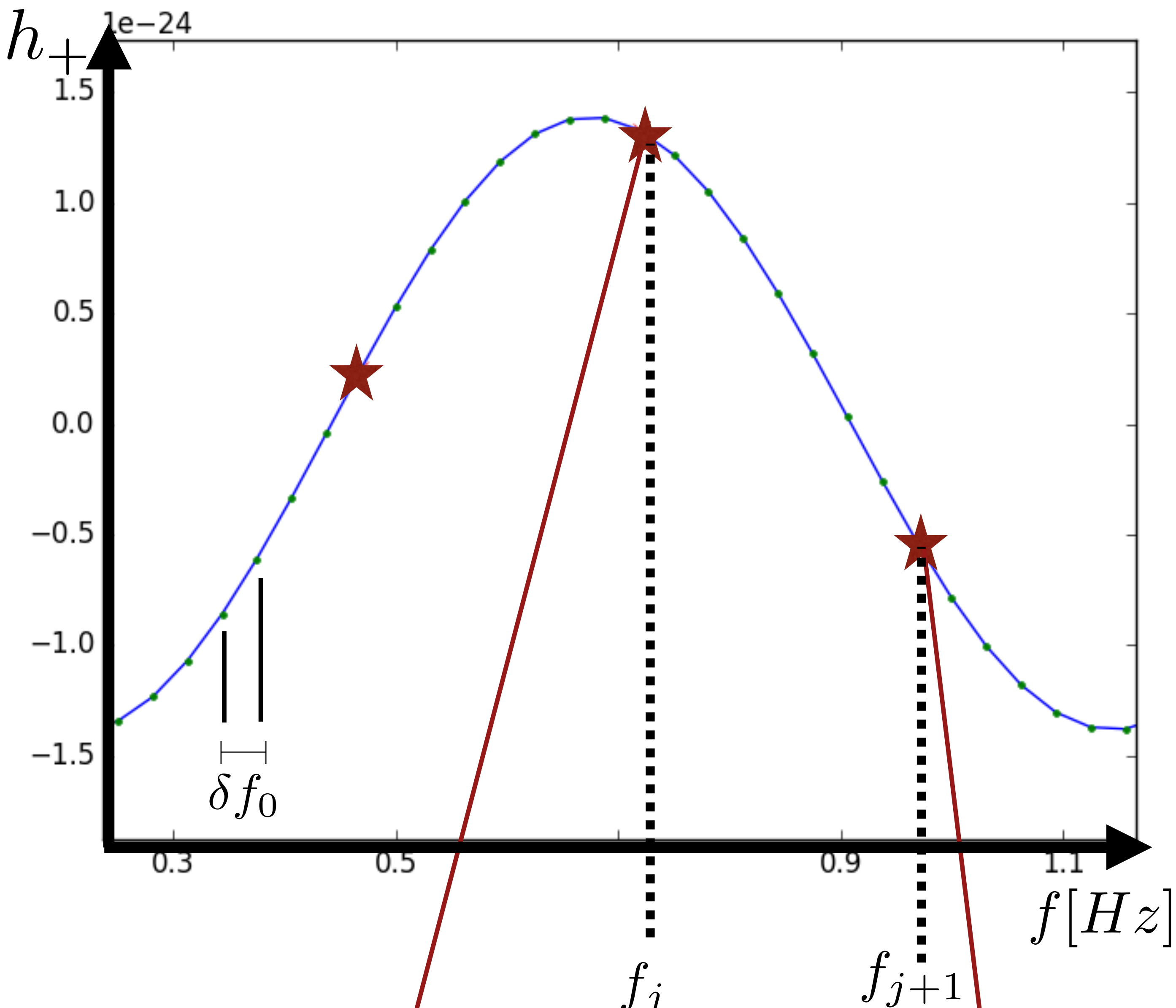
Procedure: Phase-Interpolation idea



$$\tilde{h}(\boldsymbol{\theta}, f) \sim A(\boldsymbol{\theta}, f) e^{i\psi(\boldsymbol{\theta}, f)}$$

Procedure: Phase-Interpolation idea



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$$\tilde{h}(f_j) \quad , \quad \tilde{h}(f_{j+1})$$

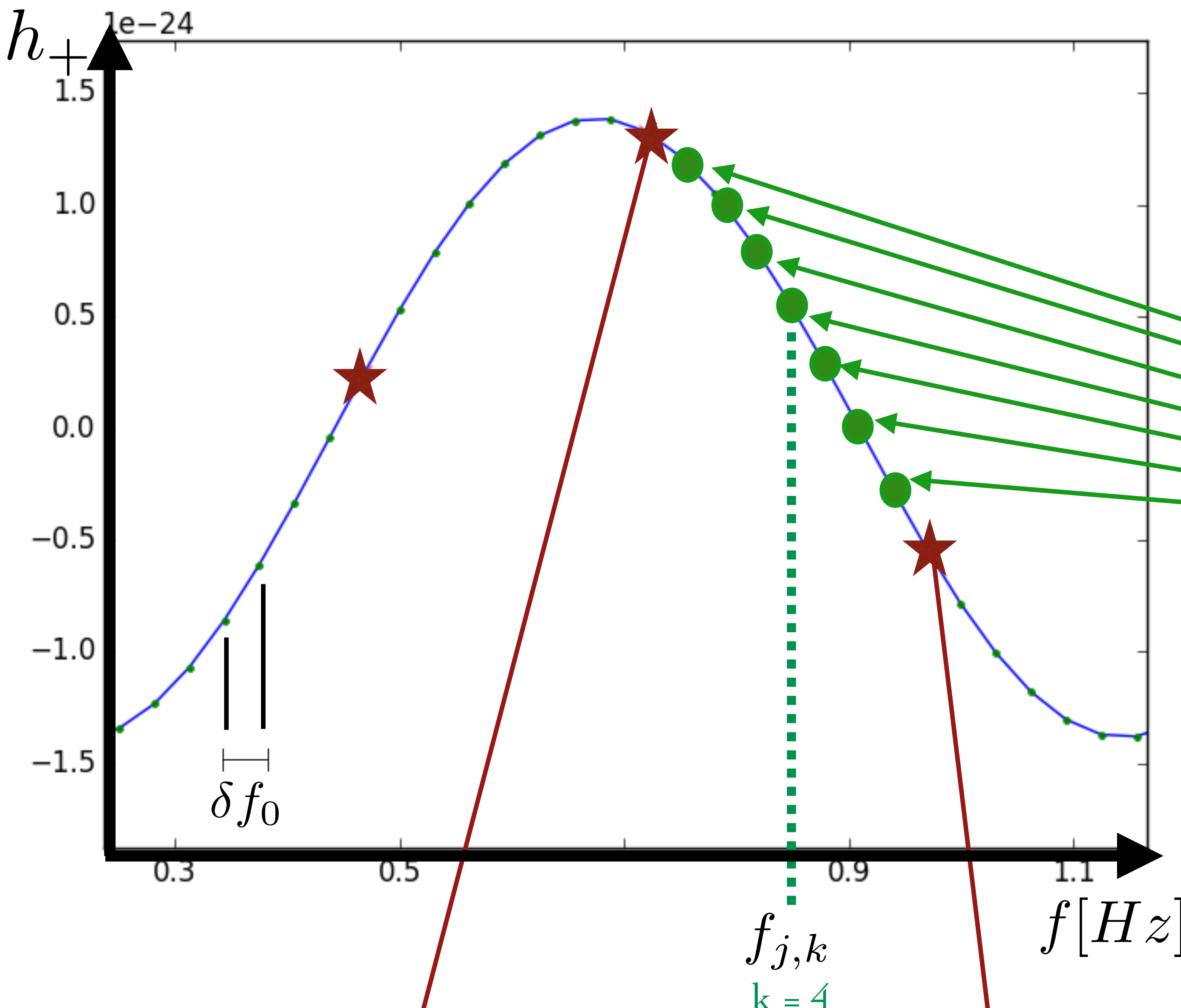
IN

$$\psi(f) = \int_{f_j}^{f} \frac{d\psi(\hat{f})}{d\hat{f}} \, d\hat{f}$$

$$\psi(f_{jk}) = \frac{\psi(f_{j+1}) - \psi(f_j)}{f_{j+1} - f_j} k\delta f_0$$

$$= \Delta\psi_j k$$

Procedure: Phase-Interpolation idea



$$\tilde{h}(\boldsymbol{\theta}, f) \sim A(\boldsymbol{\theta}, f) e^{i\psi(\boldsymbol{\theta}, f)}$$

$$\tilde{h}_{jk} \approx \chi_{jk} \equiv \tilde{h}(f_j) e^{i\Delta\psi_j k}$$

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Results: Gain in template generation

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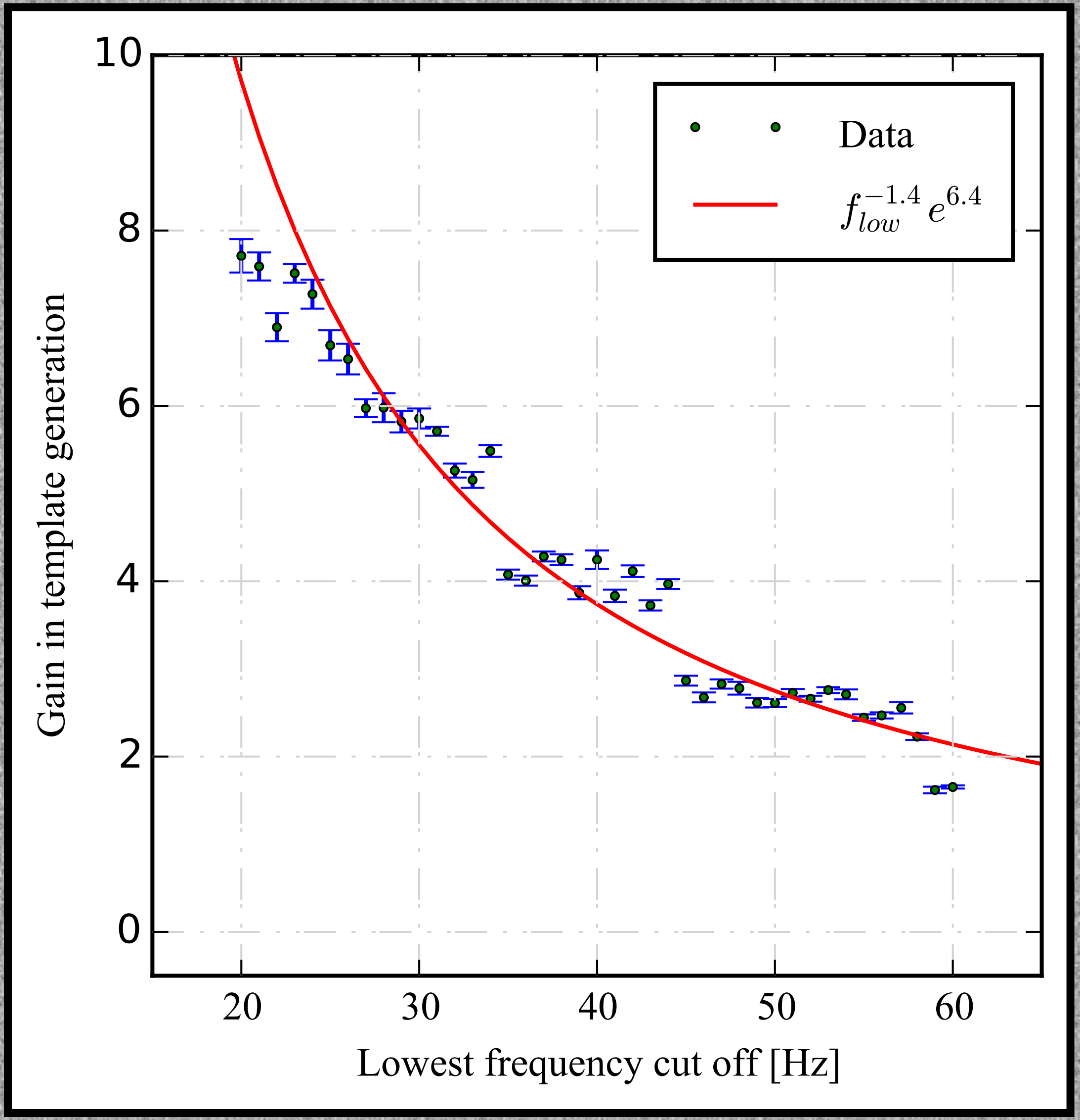
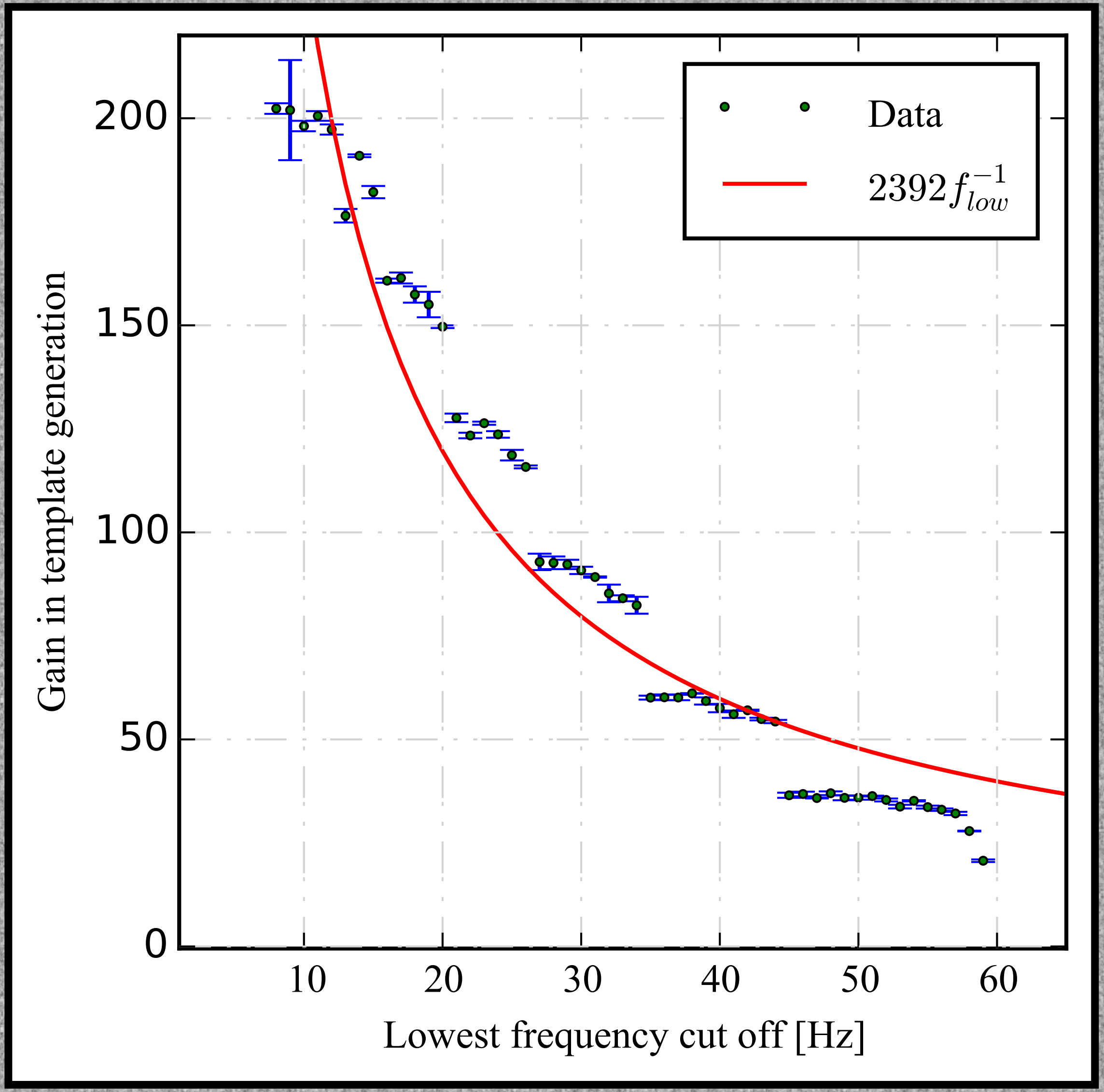
GW Initial Training Network



A simple waveform model (TaylorF2)

A complicate waveform model (IMRPhenomPv2)



Results: Gain in overall analysis

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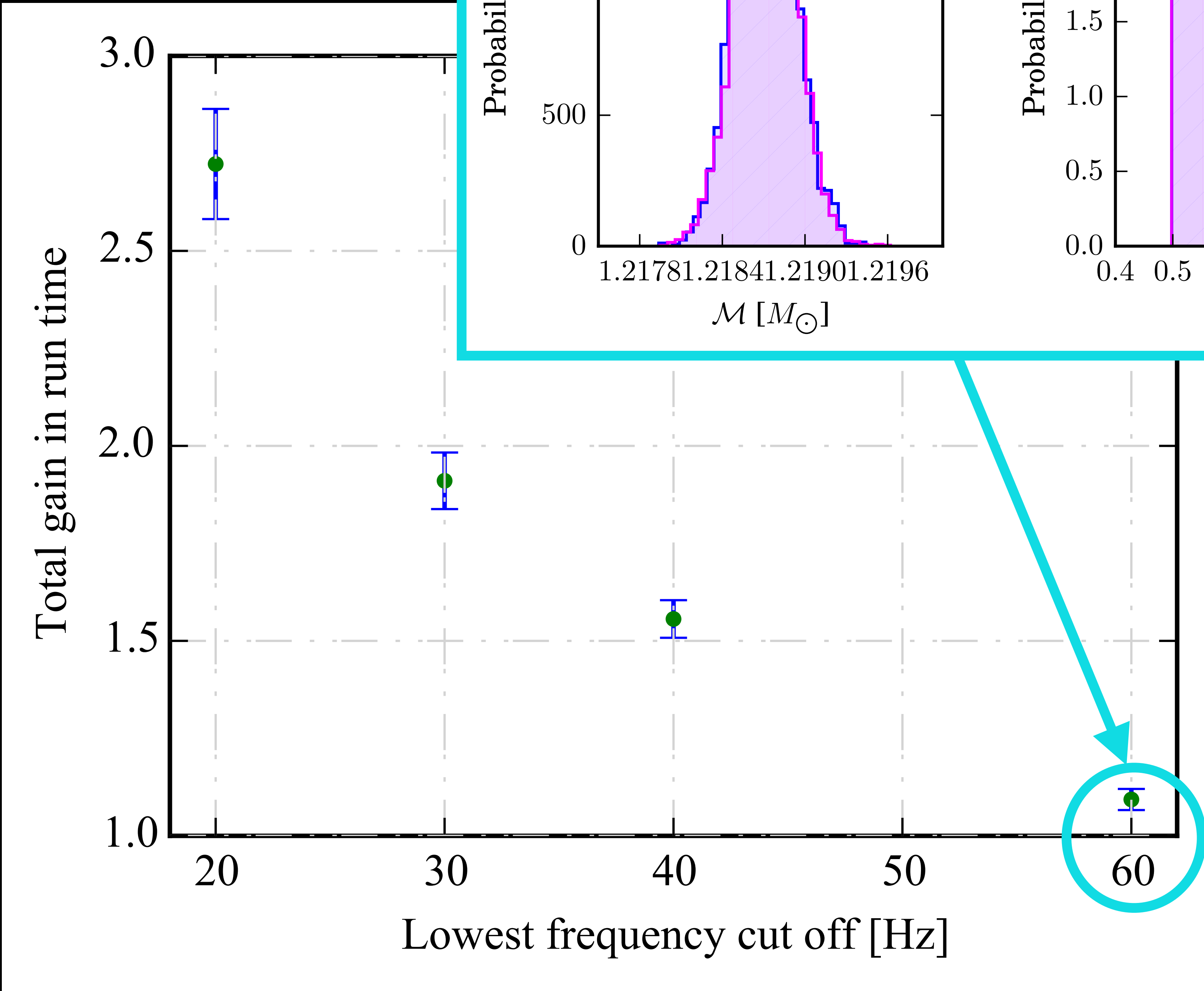

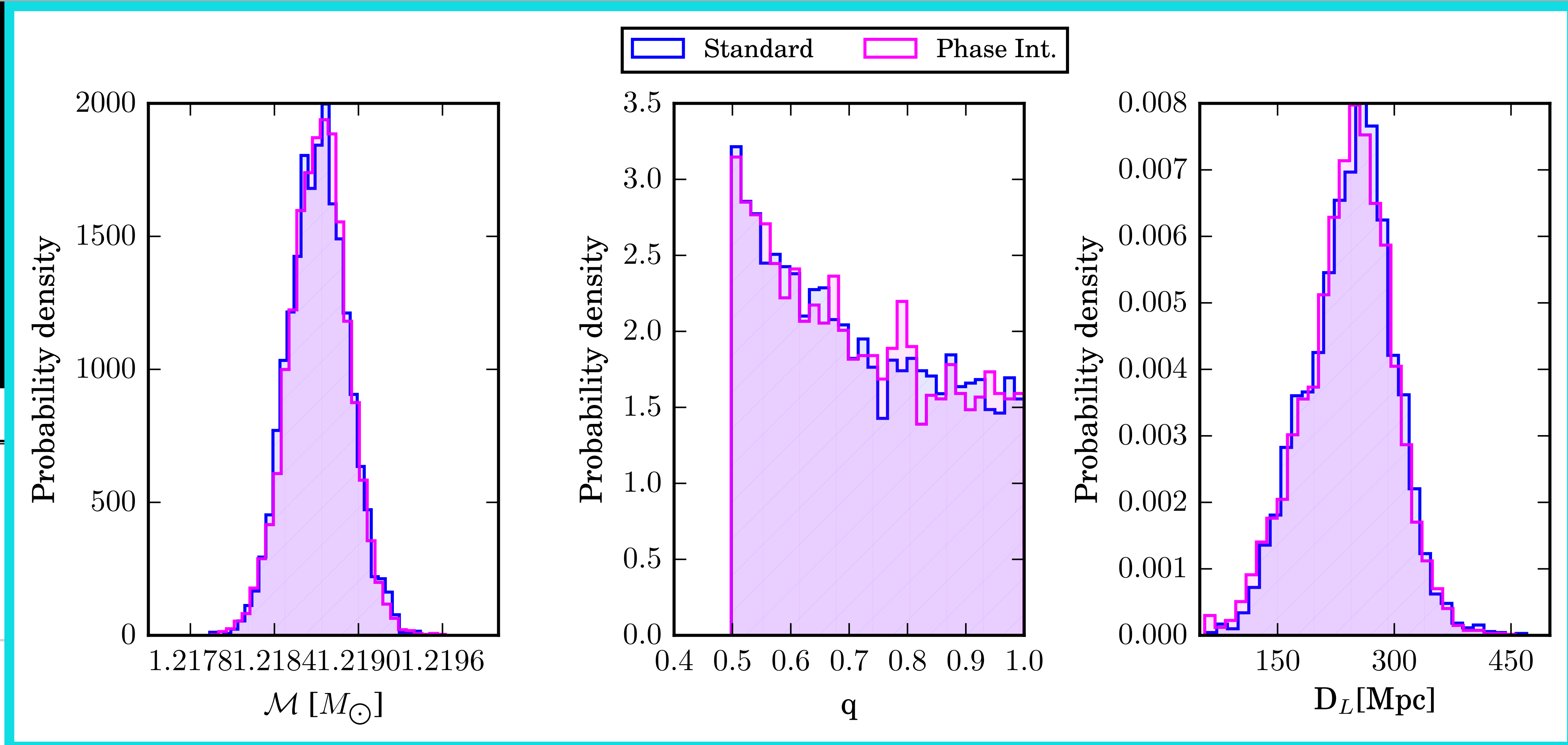

Conclusion

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GW Initial Training Network

The sampling procedure can be notedly optimised by adapting the step accordingly to the expected signal frequency evolution.

Useful method for now and future generations of interferometers.

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PER ARDUA AD ALTA

The discovery: GW150914

GraWIToN

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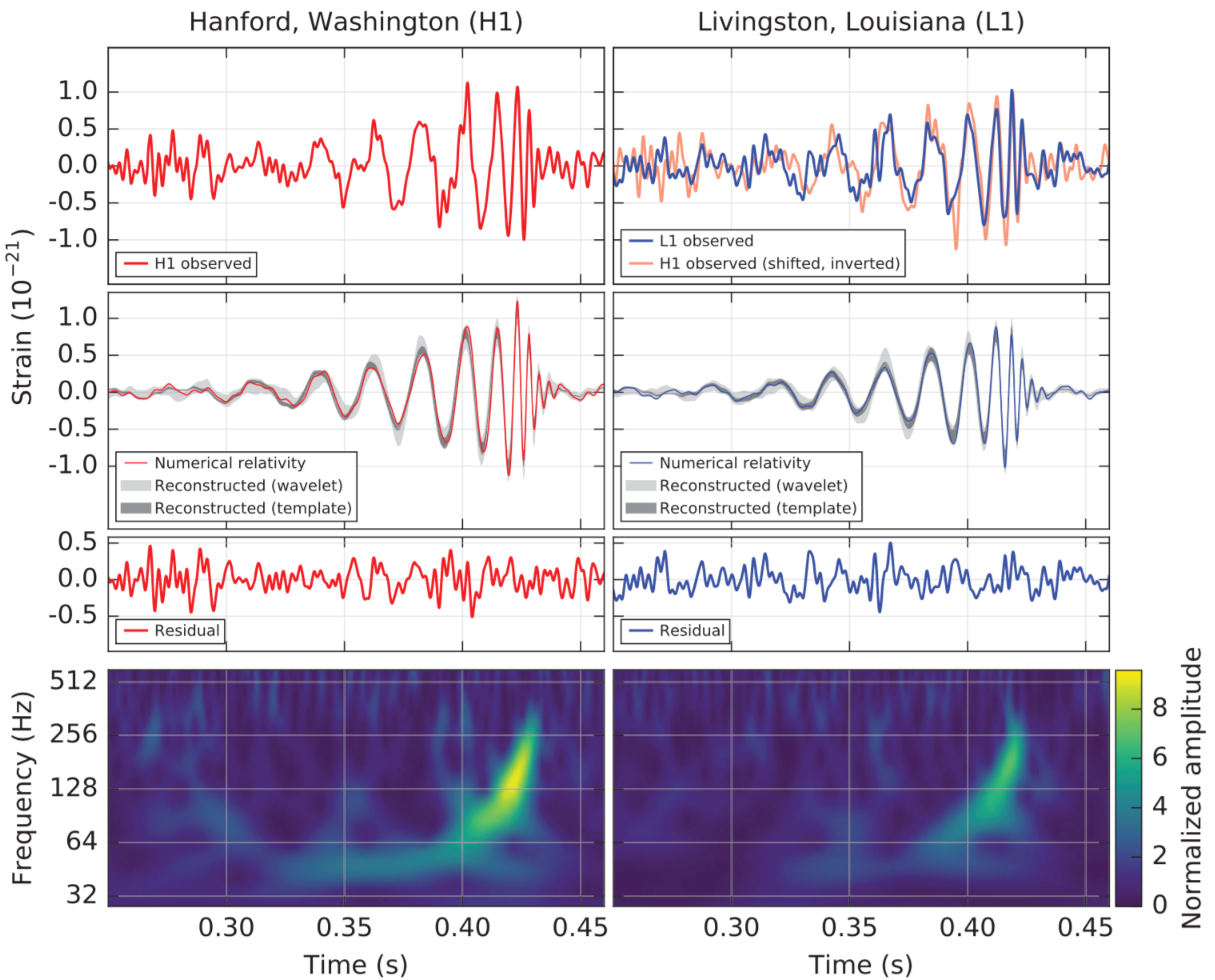
GW Initial Training Network

The discovery: GW150914

The discovery: GW150914

The GW astronomy has begun!

The discovery: GW150914



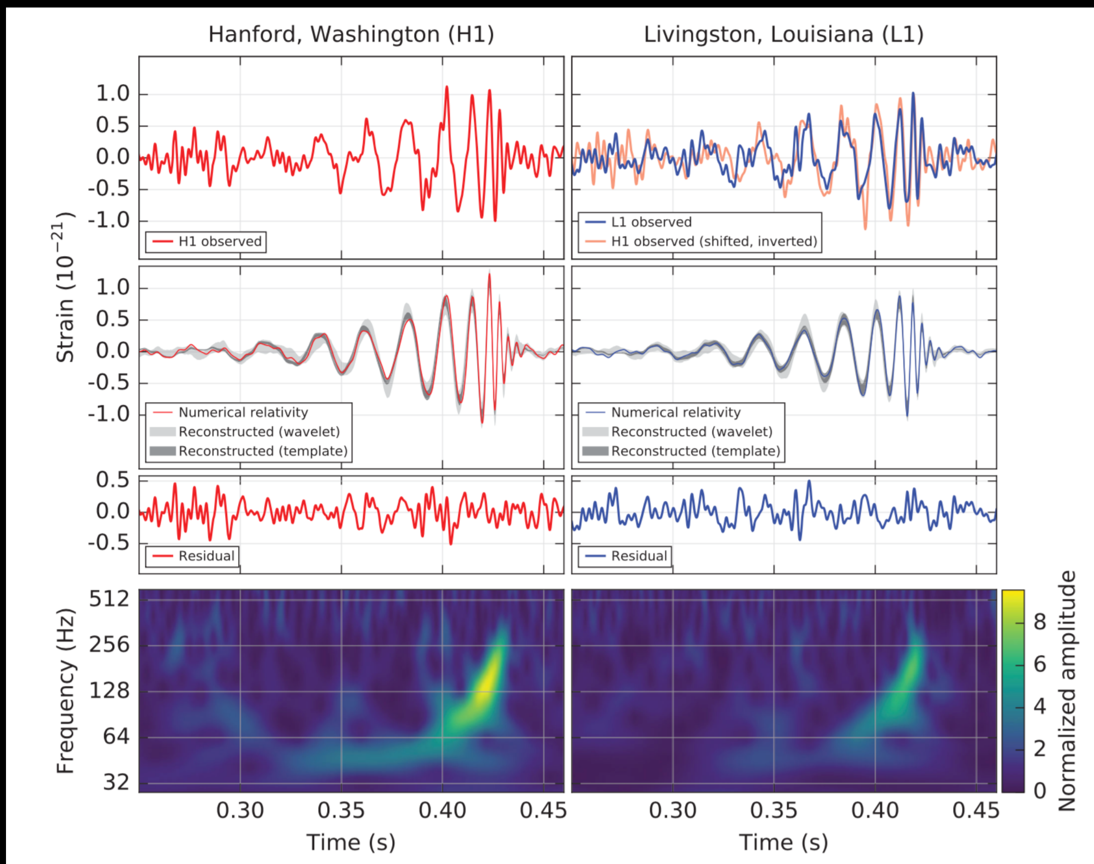
Data

Reconstructed waveform

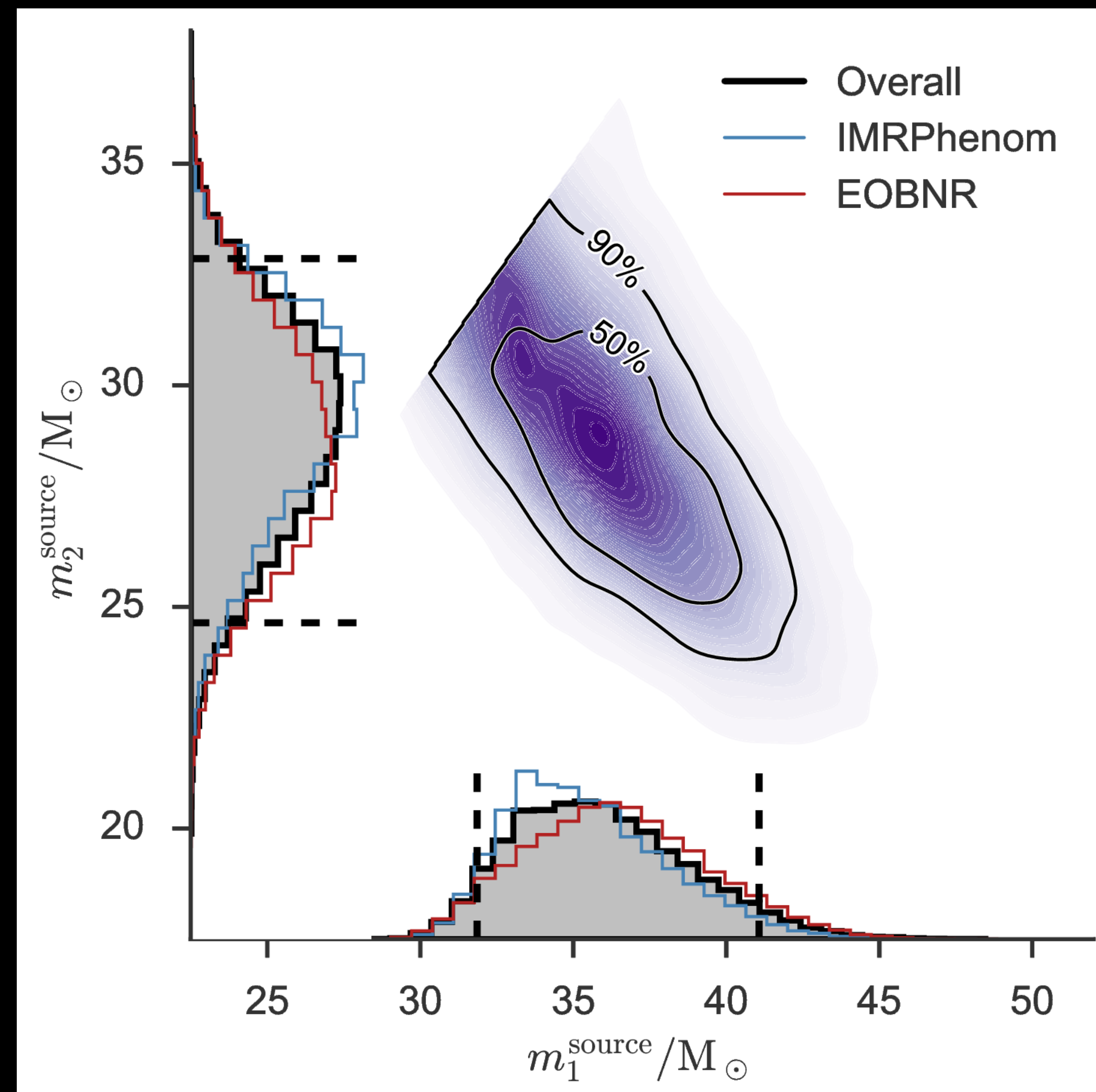
Time-frequency representation

Imagini: LVC

The discovery: GW150914



Paremeter estimation



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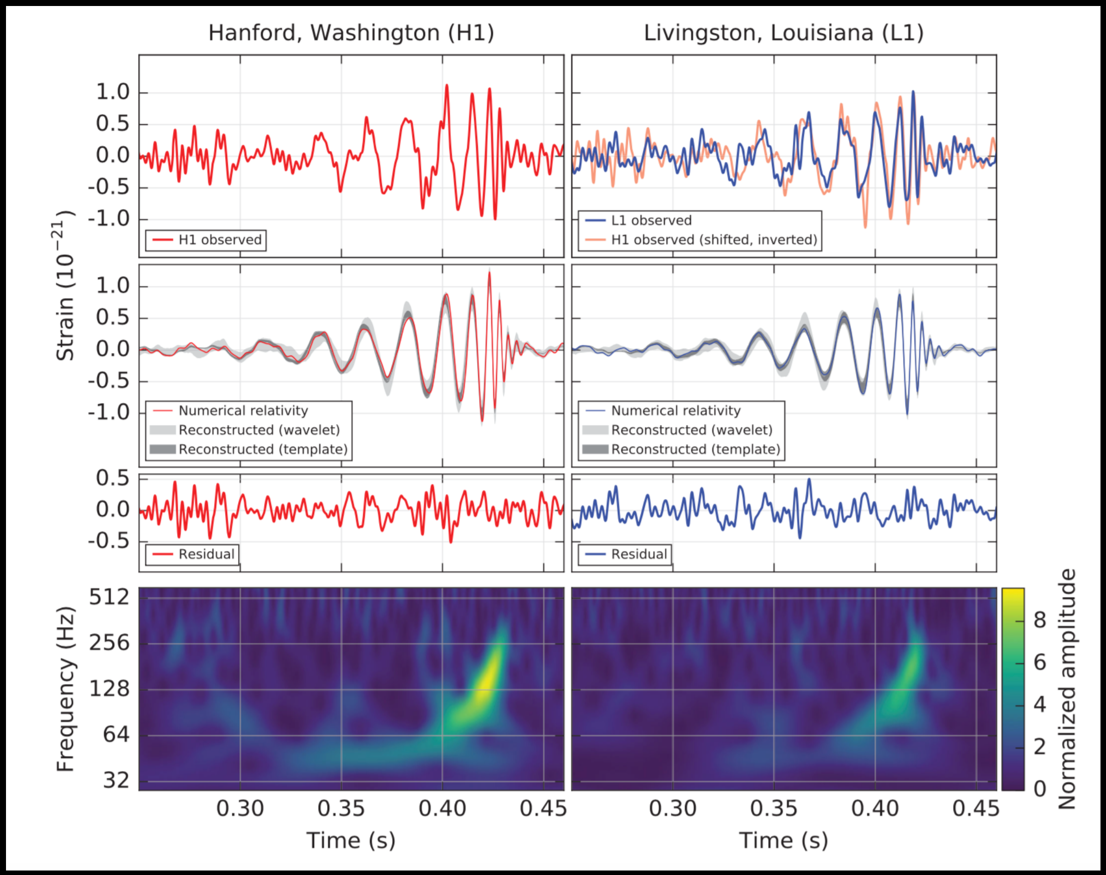

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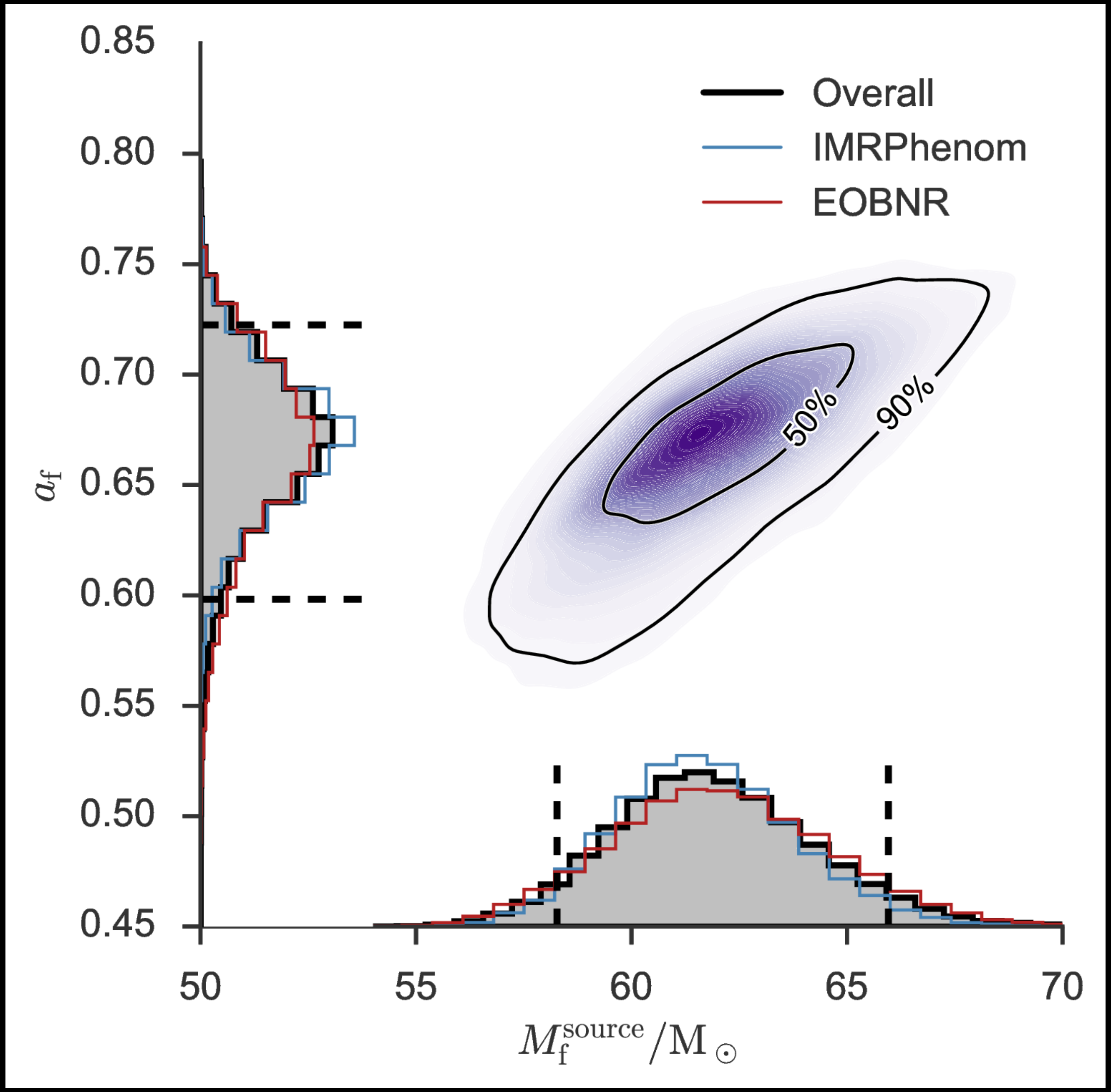

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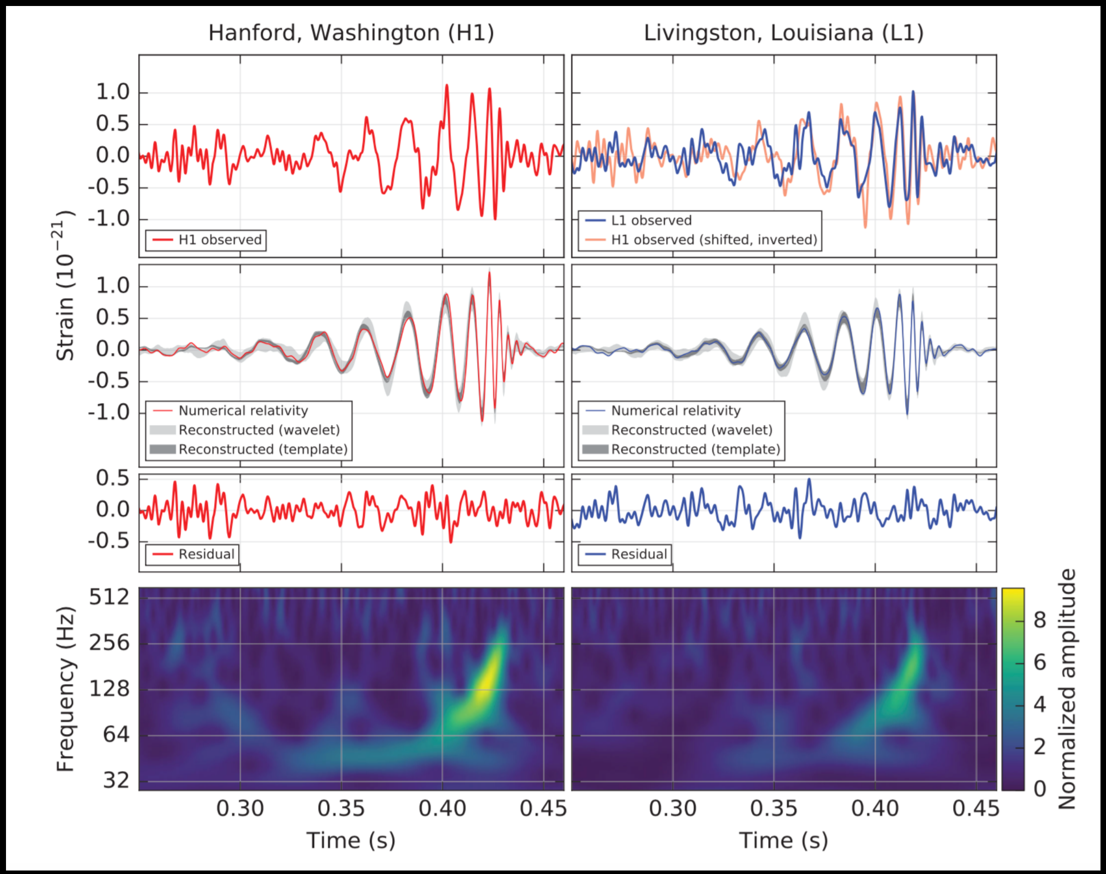

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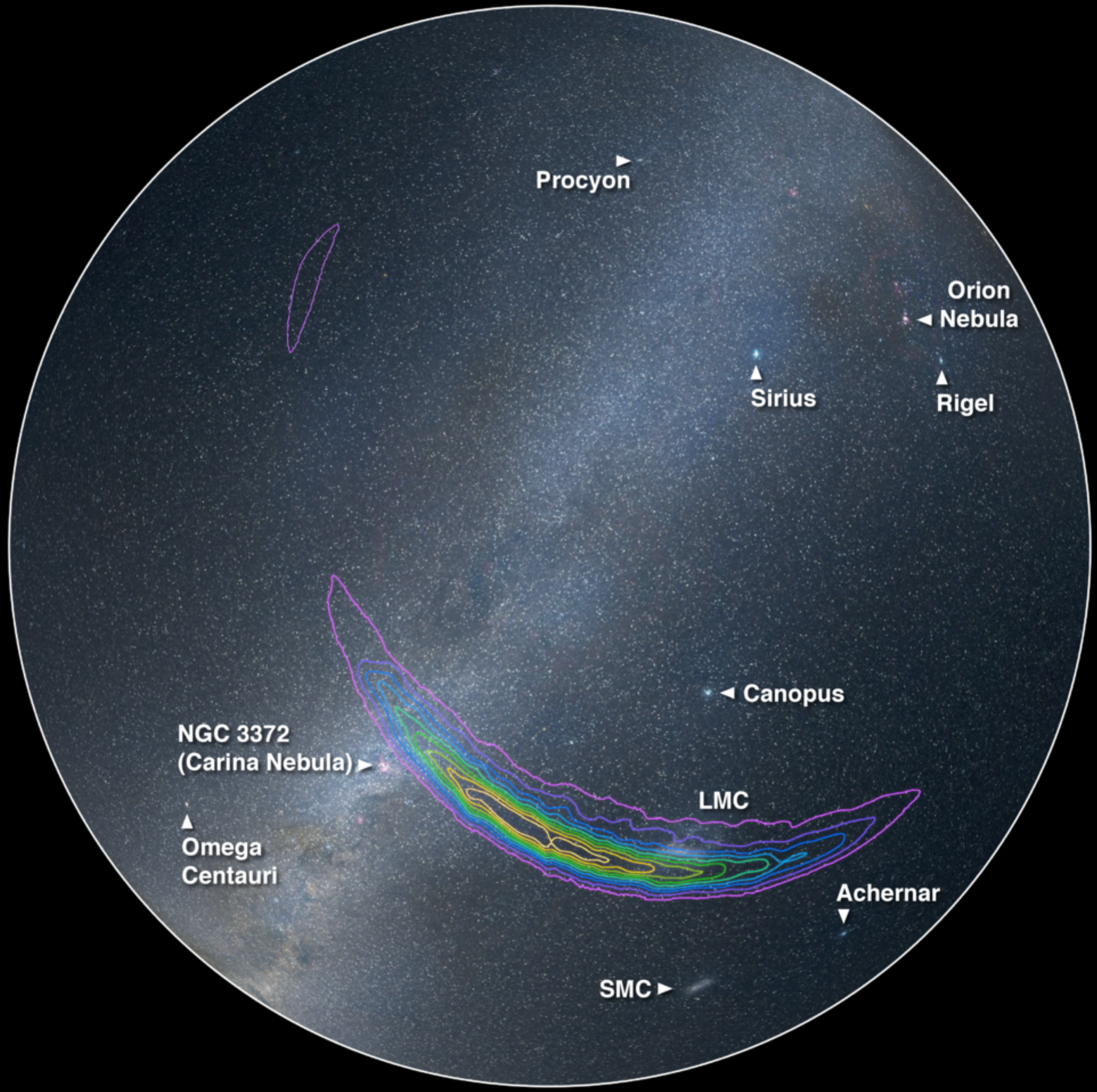


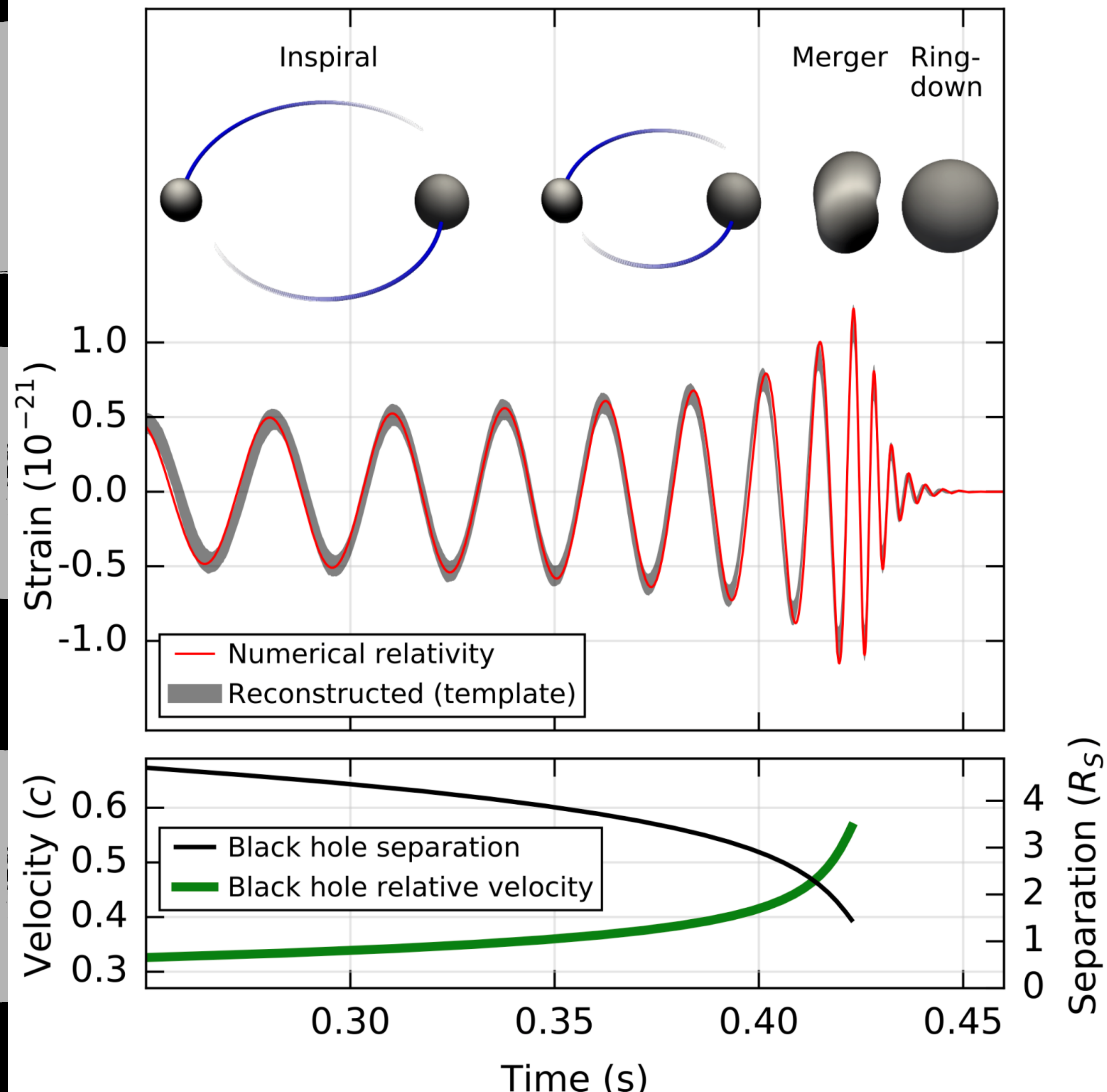
Imagini: LVC

The discovery: GW150914

The 3 stages of coalescence

Reconstructed waveform

Velocity and separation between the 2 initial BHs



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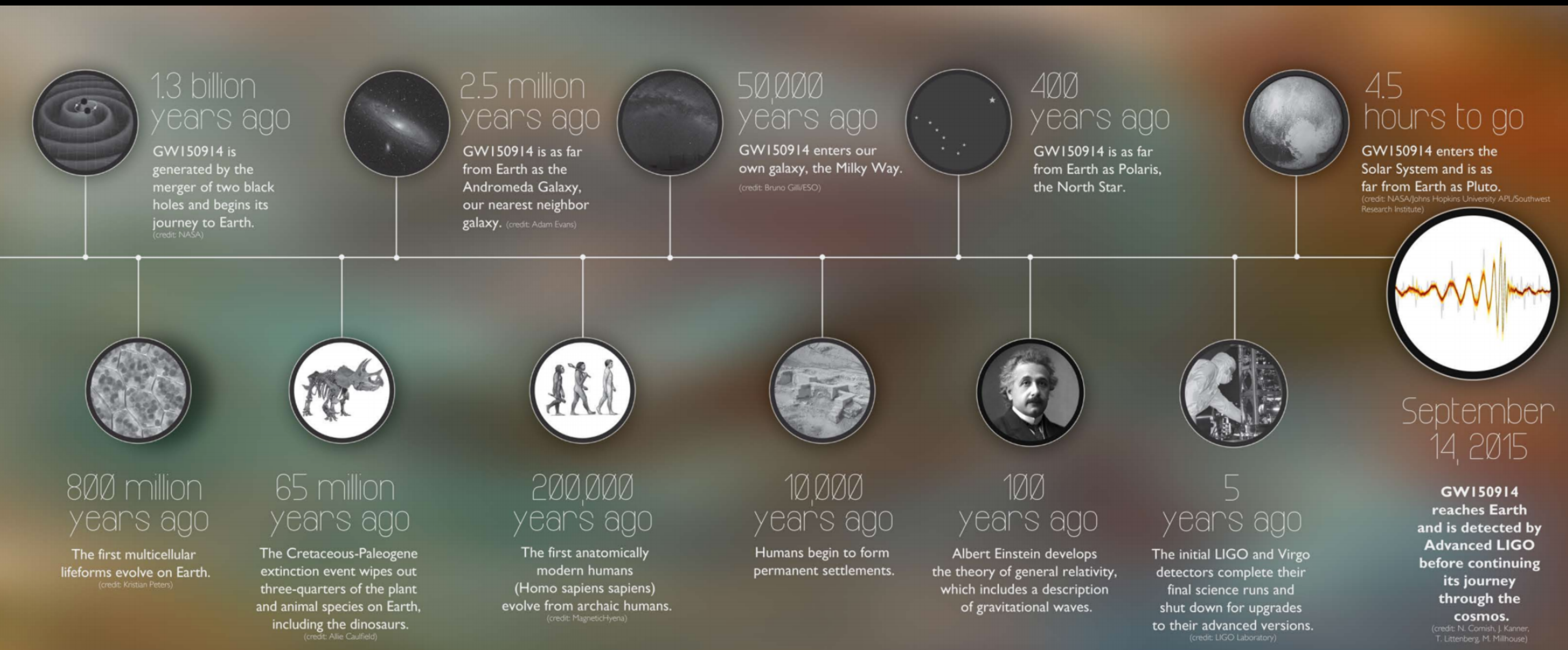
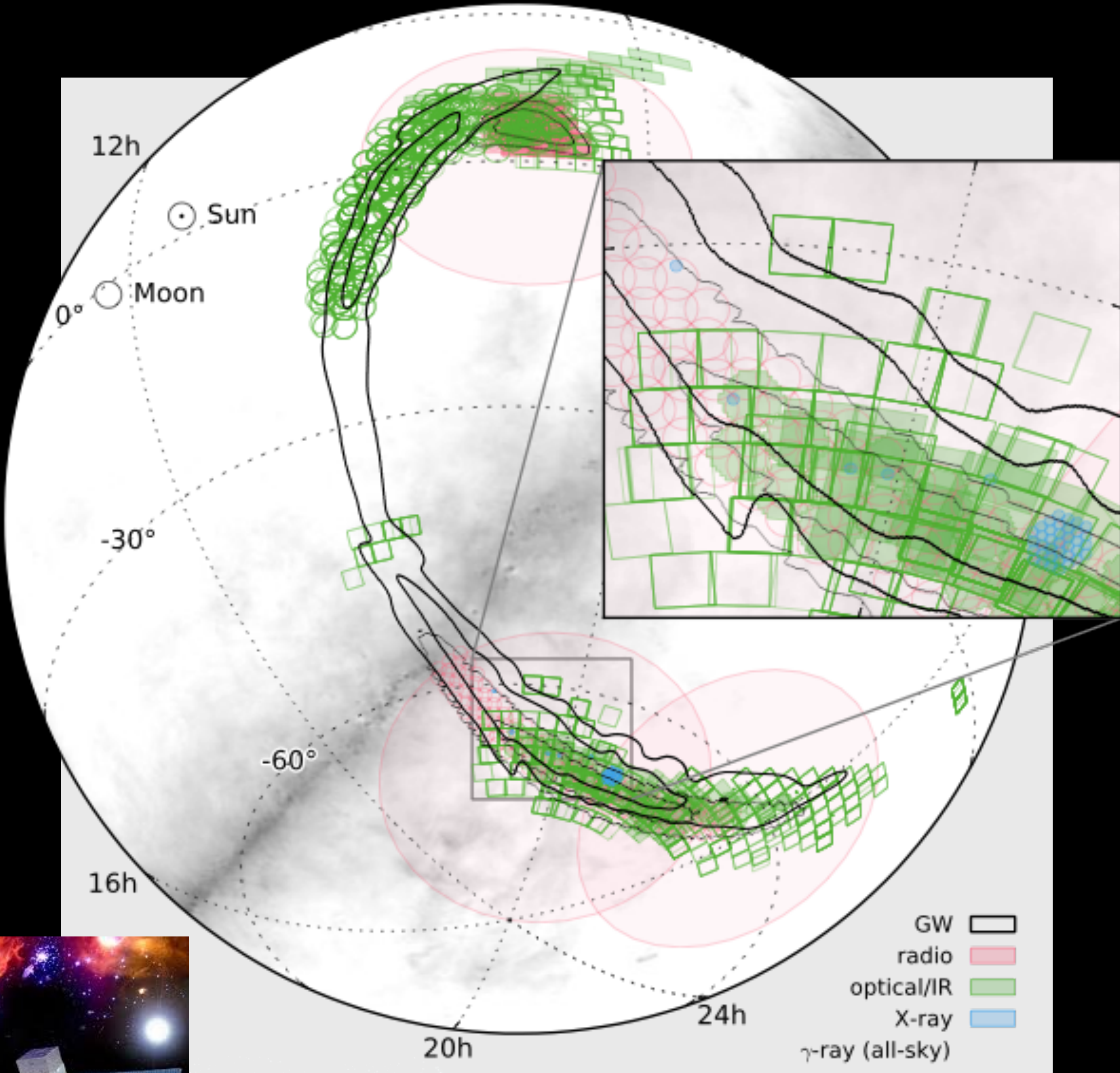


The discovery: GW150914



Follow up coverage area

Fermi detected a weak signal, not confirmed by INTEGRAL

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Main consequences

GraWIToN

GW Initial Training Network

Main consequences

WHAT DID GW150914 TELL US?

1. Stellar black holes as massive as 30 and 60 solar masses exist

2. Binary black holes exist and can merge within Hubble time

3. We expect to detect soon many of such events!

Video: SXS

Main consequences

These are the most massive stellar BHs ever seen

Weak winds -> Low metallicity

The further away we look, the greater the number of expected events

This is the first detection of signals emitted by black holes

Image: NASA, C. Reed

Main consequences

We are going to see a lot of them!!!

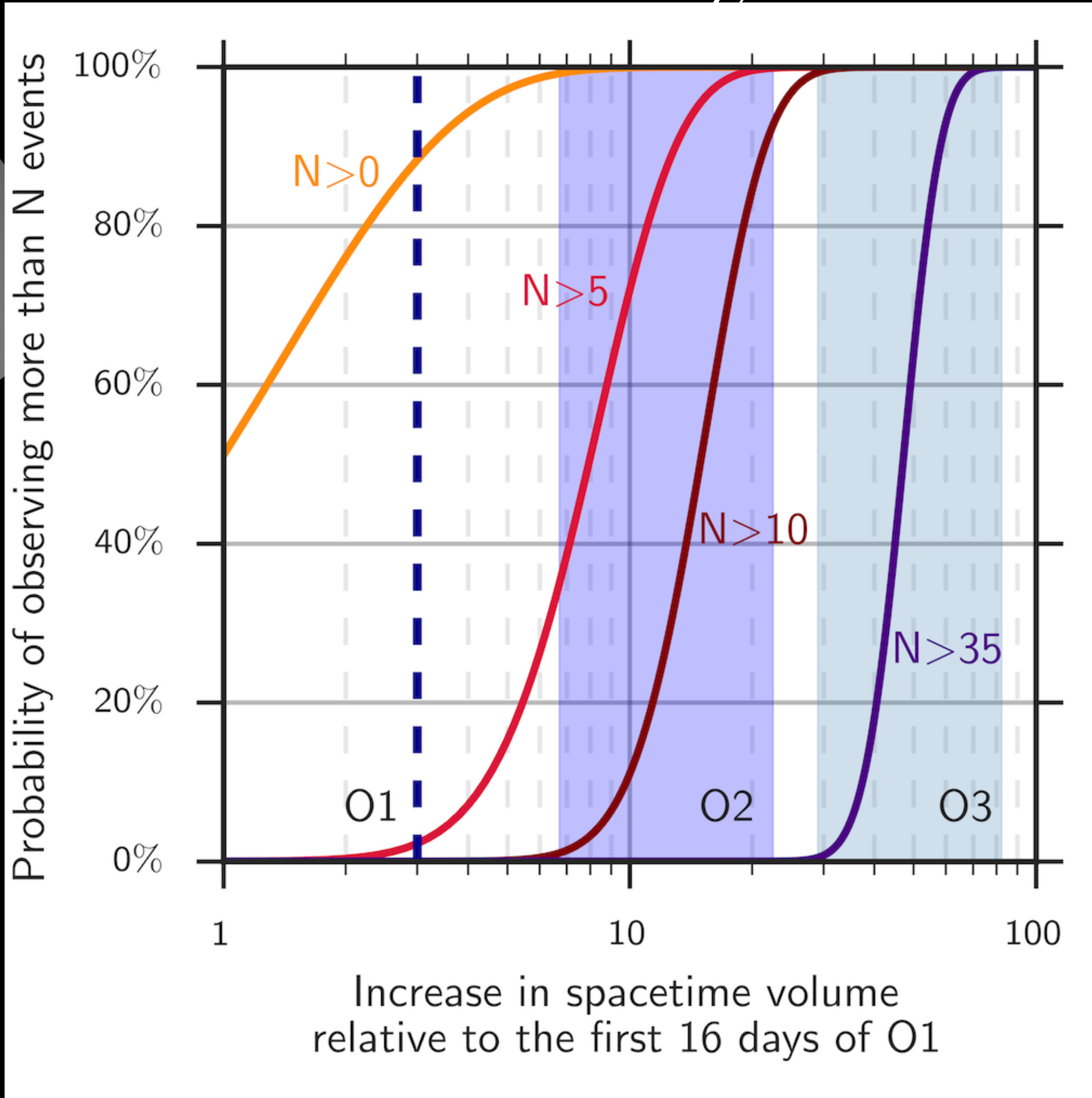
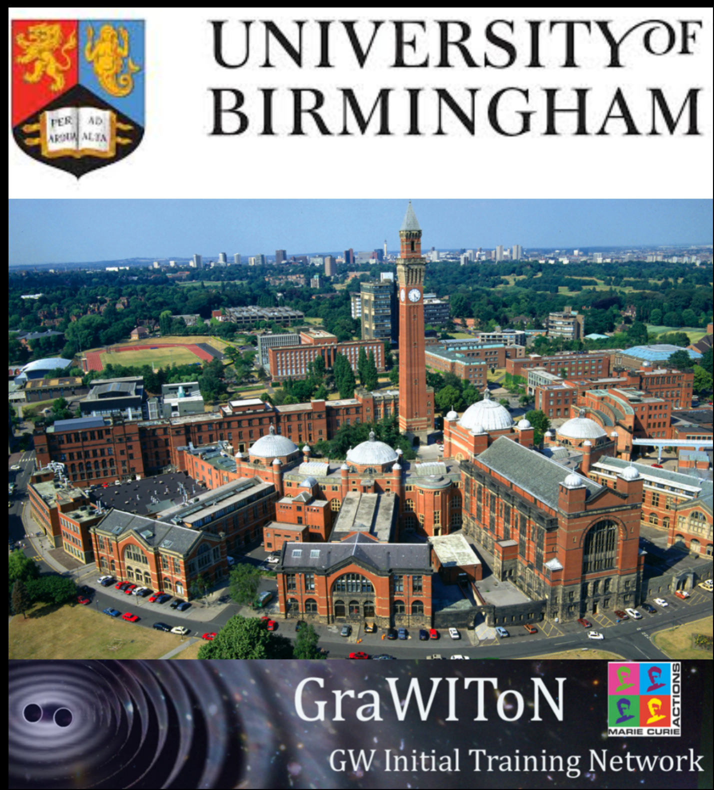


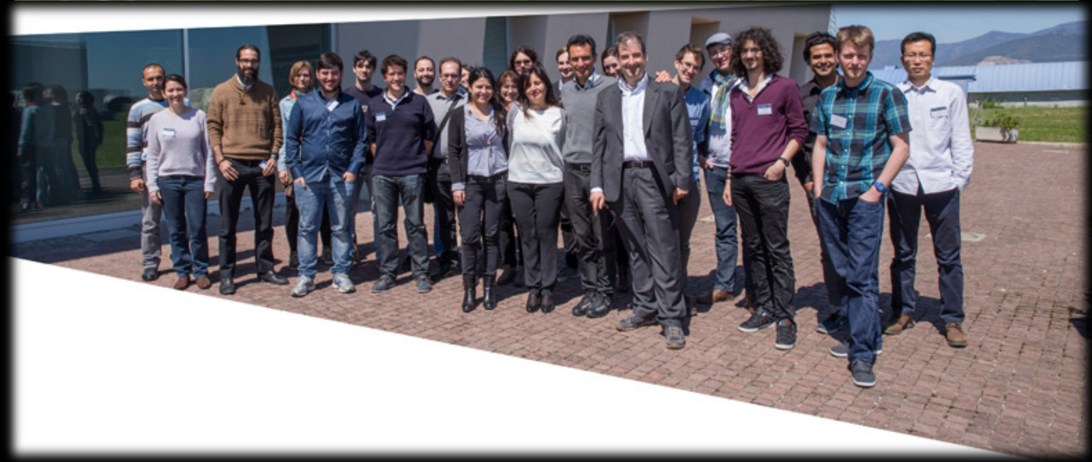
Image: LVC



Serena Vinciguerra 26 May 2016

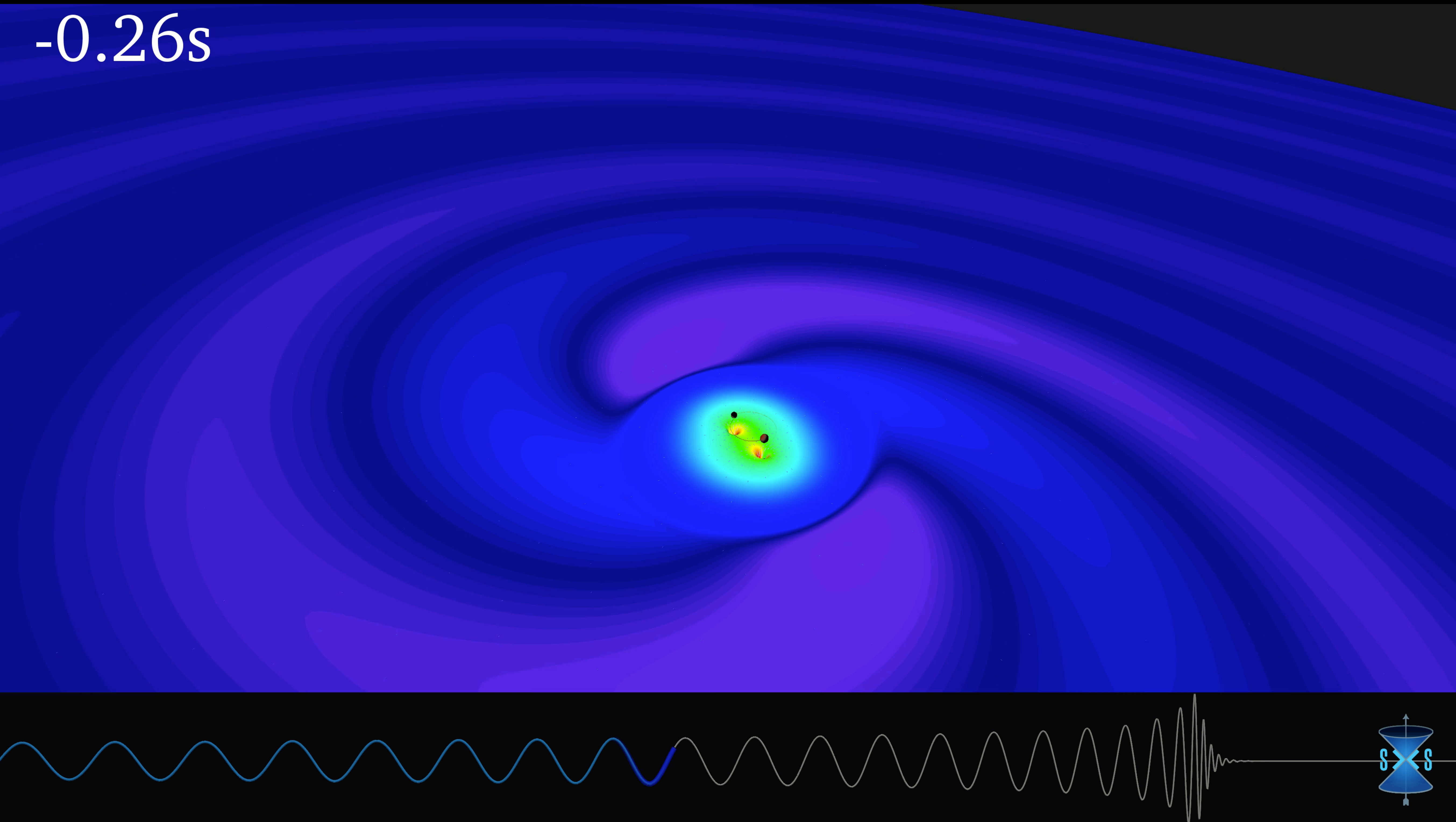
Supervisors: Ilya Mandel, John Veitch

Thank you for your attention



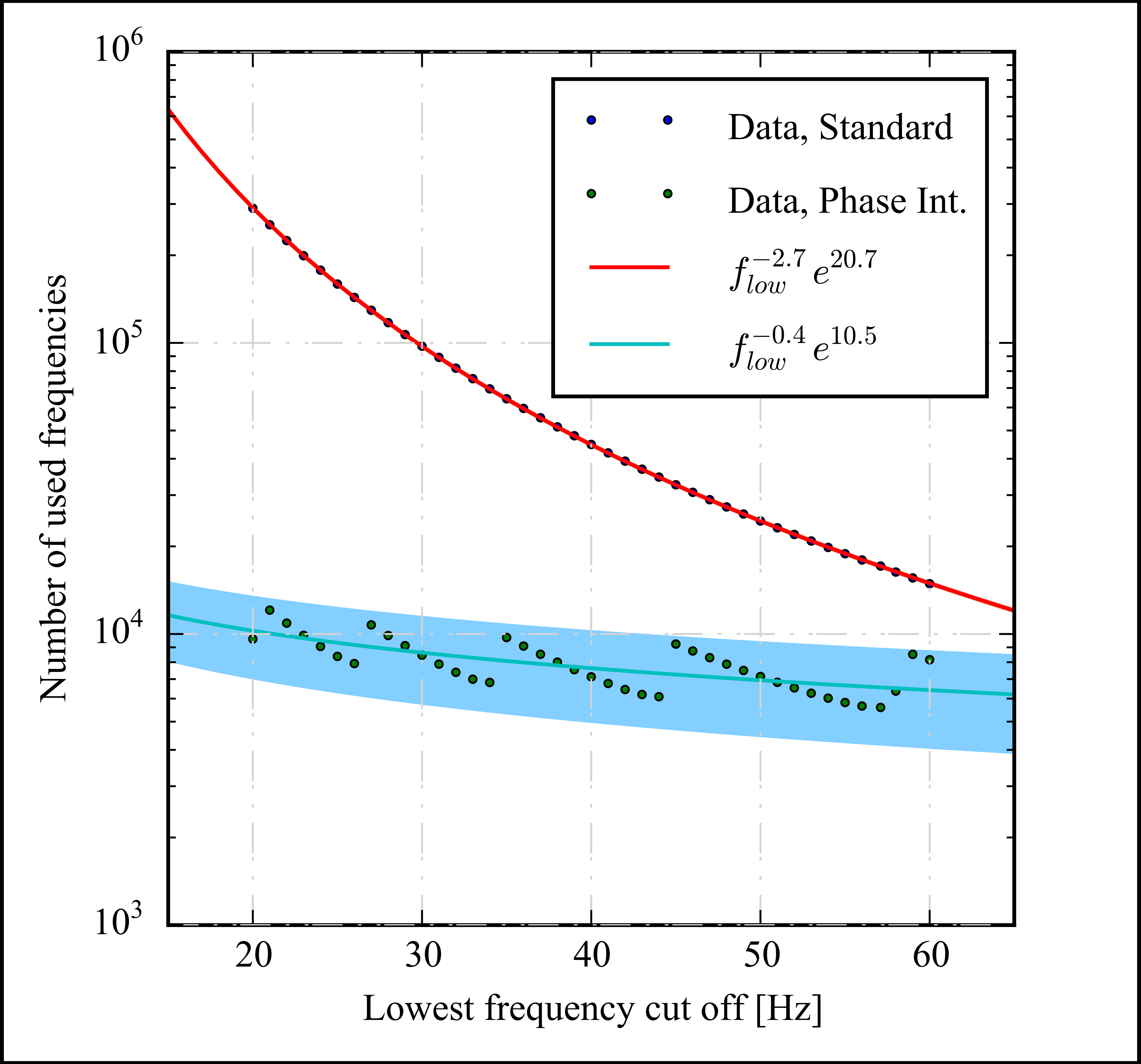
Thanks I. Mandel, J. Vetch, A. Freise, M. Branchesi and W. Far

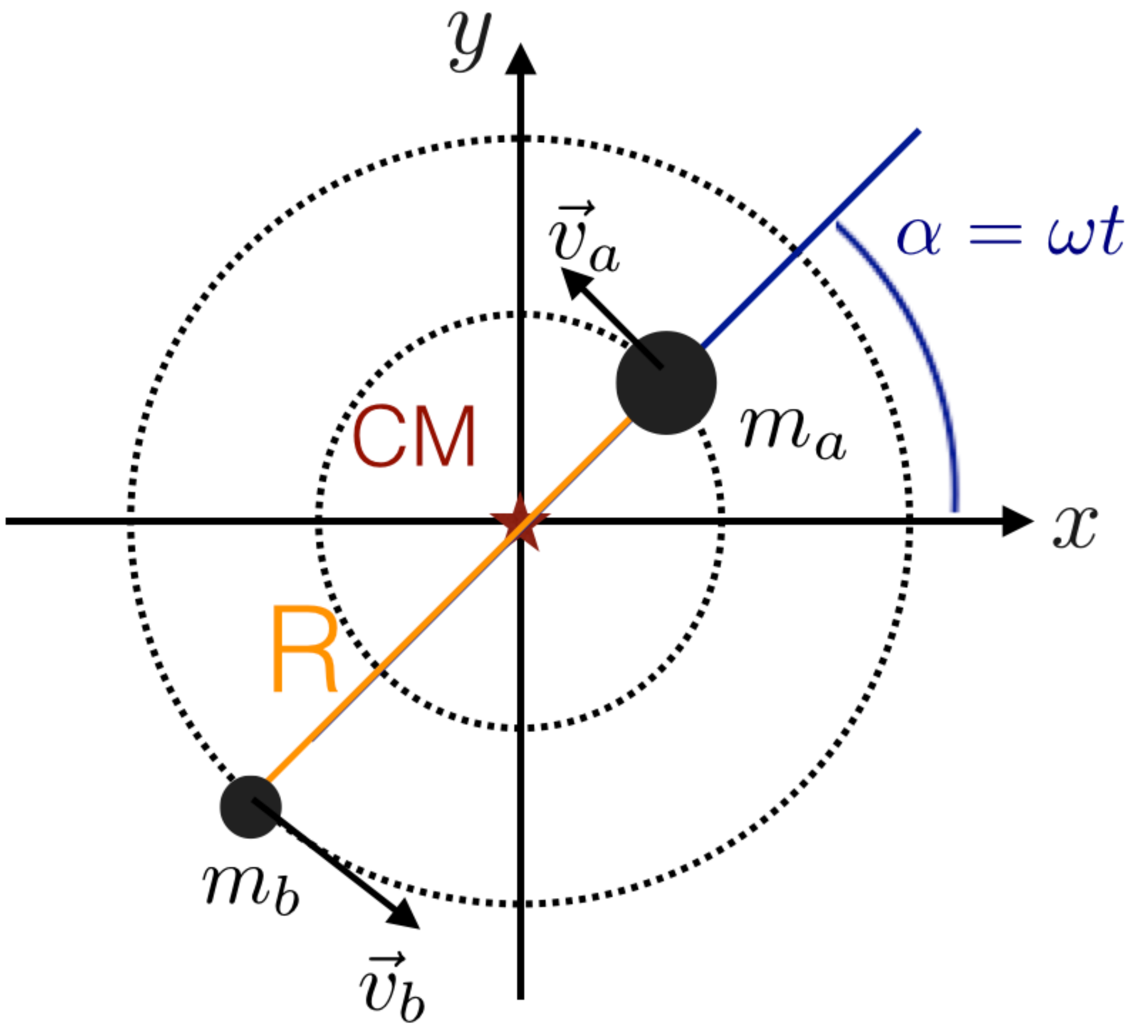
The discovery: GW150914



Video prodotto da: SXS

Results: Number-Gain in template generation





$$\vec{x}_a = R\frac{m_b}{m_a + m_b}[\cos\alpha, \sin\alpha,]$$

$$\vec{x}_b = R\frac{m_a}{m_a + m_b}[-\cos\alpha, -\sin\alpha,]$$

$$h_{\mu\nu}(t, r) = 2\frac{G}{c^4}\frac{1}{r}\frac{\partial^2 I_{\mu\nu}}{\partial t^2}(t - \frac{r}{c})$$

$$h_+ \propto \frac{\mathcal{M}^{5/3}}{r}\cos(2\omega t)$$

$$h_+ \propto \frac{\mathcal{M}^{5/3}}{r}\sin(2\omega t)$$

$$\mathcal{M} = \frac{(m_a m_b)^{3/5}}{(m_a + m_b)^{1/5}}$$