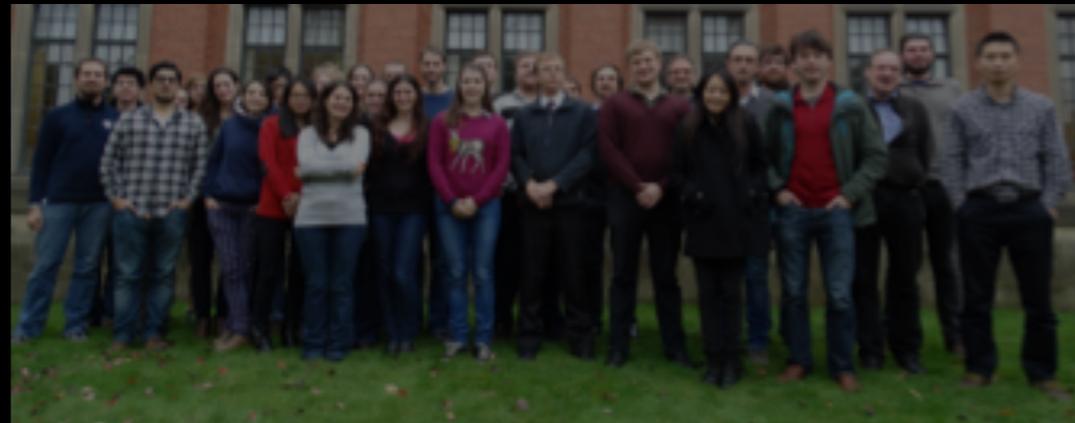




UNIVERSITY OF
BIRMINGHAM



GraWIToN 
GW Initial Training Network



**Data analysis challenges in
gravitational wave astronomy
&
"pills" of GW150914**

Serena Vinciguerra

Supervisors: Tlya 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



talk organisation

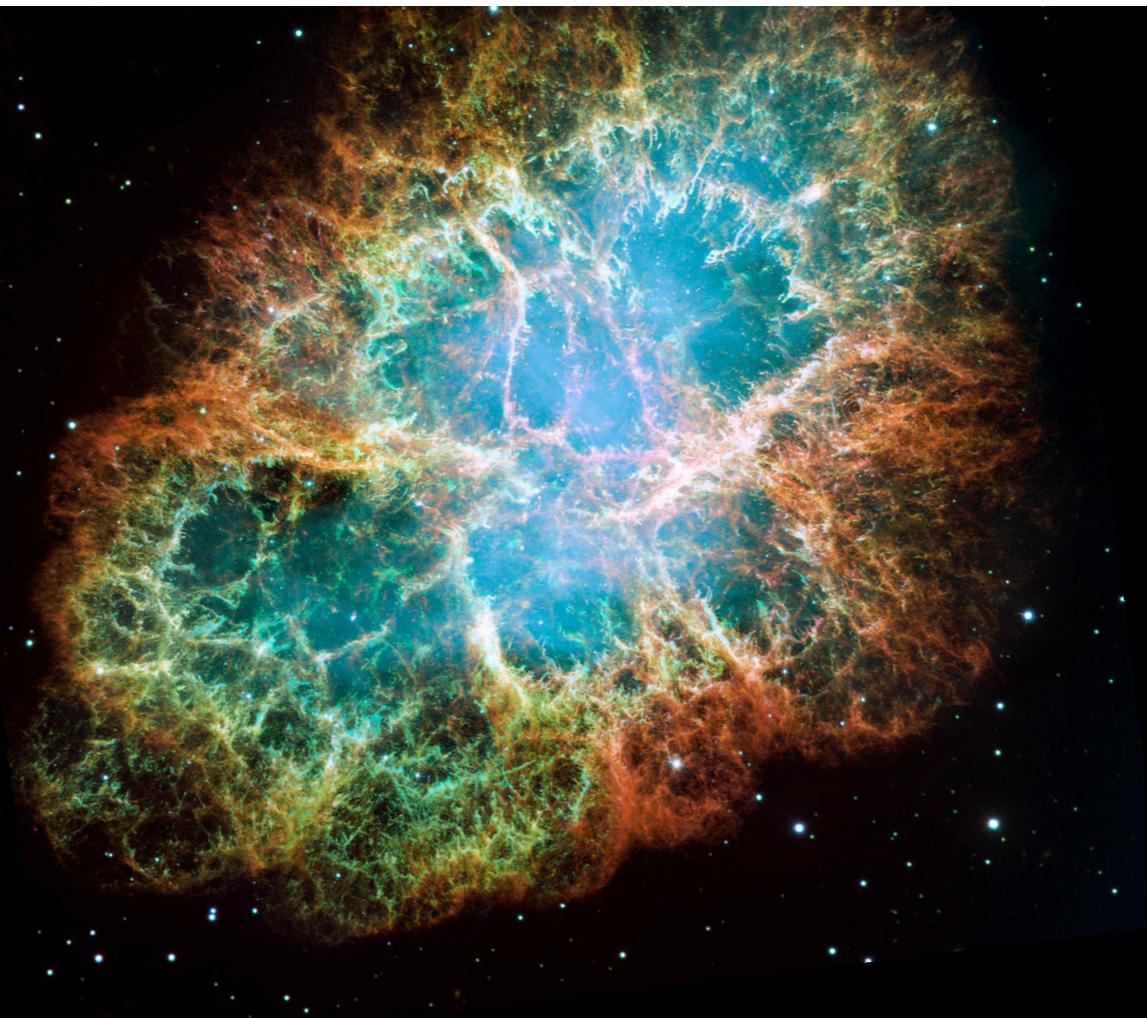
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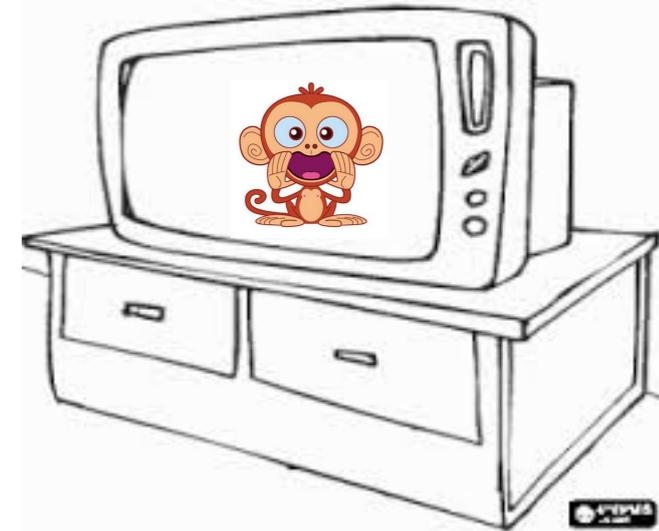
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The first hints about the nature of the Universe which surrounded us came from deeply looking at the sky...





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



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



Even invisible
things 'talk'!

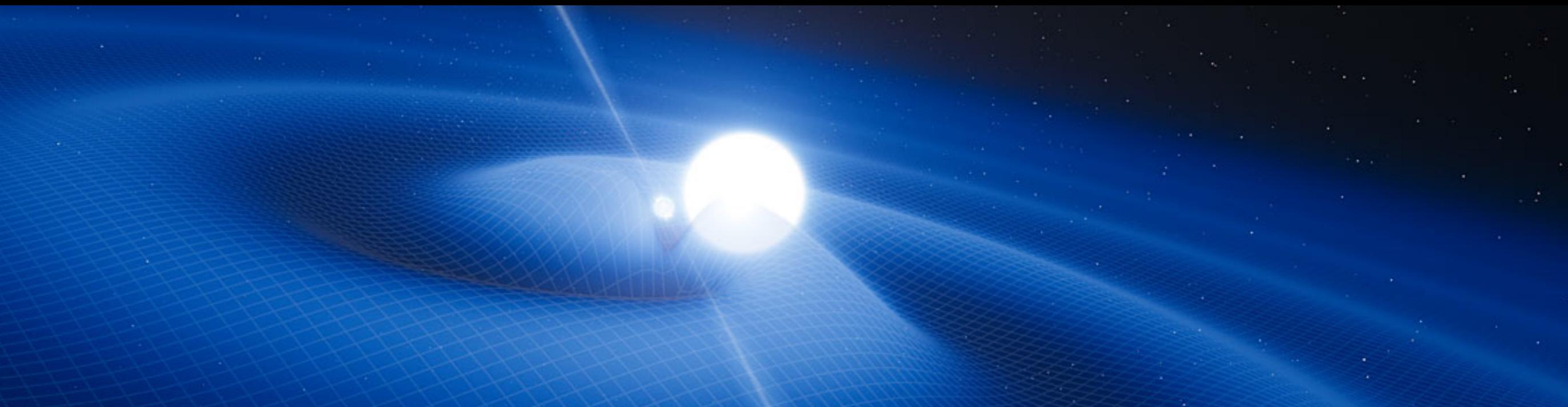


The sound of the Universe.

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

EINSTEIN FIELD EQUATIONS

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



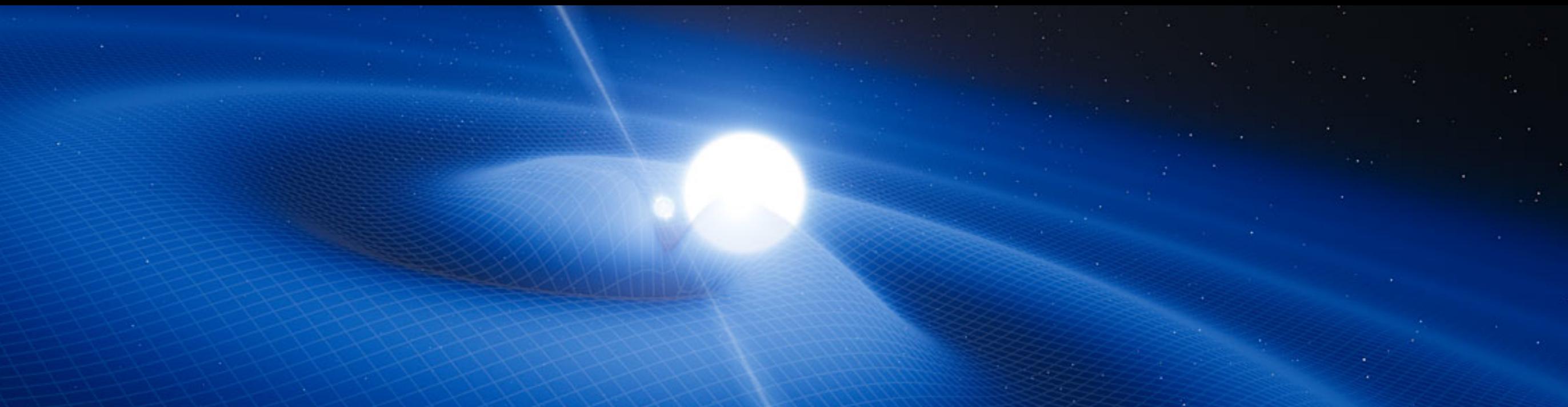
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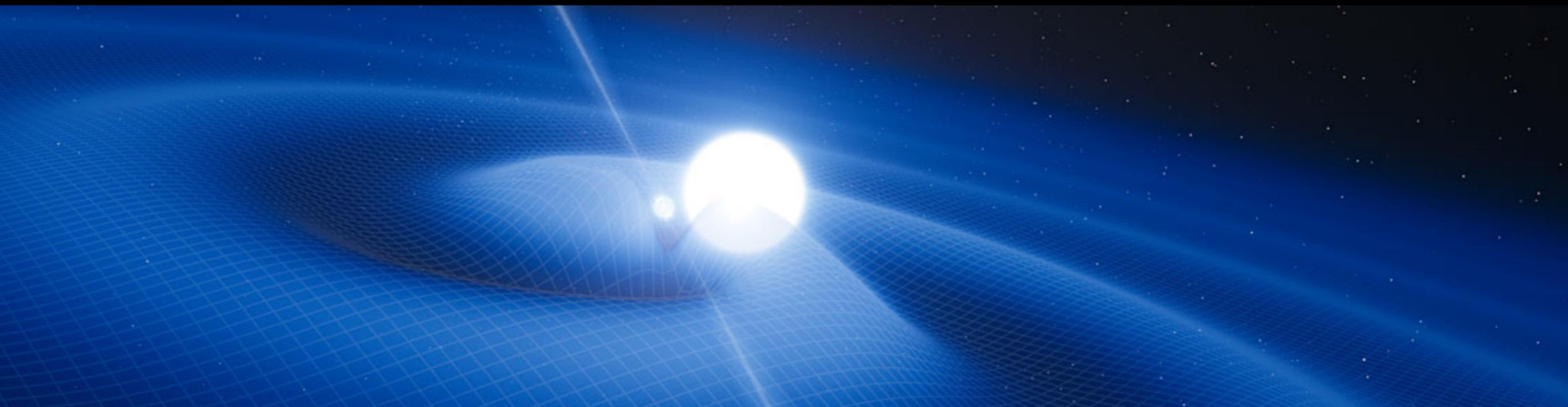
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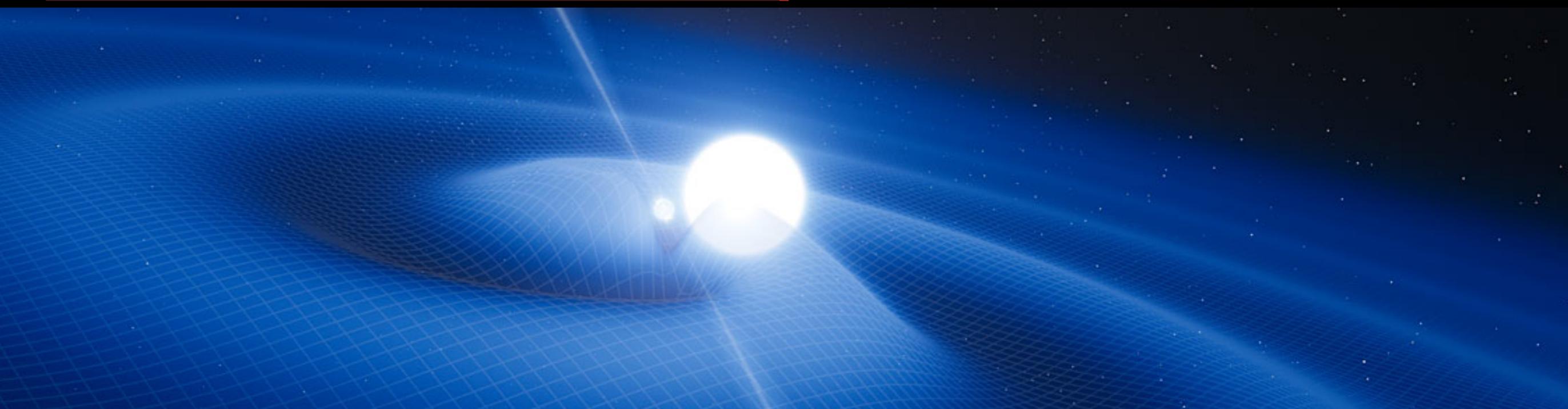
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$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Term connected to the space-time geometry

Term connected to the physical properties of the source

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



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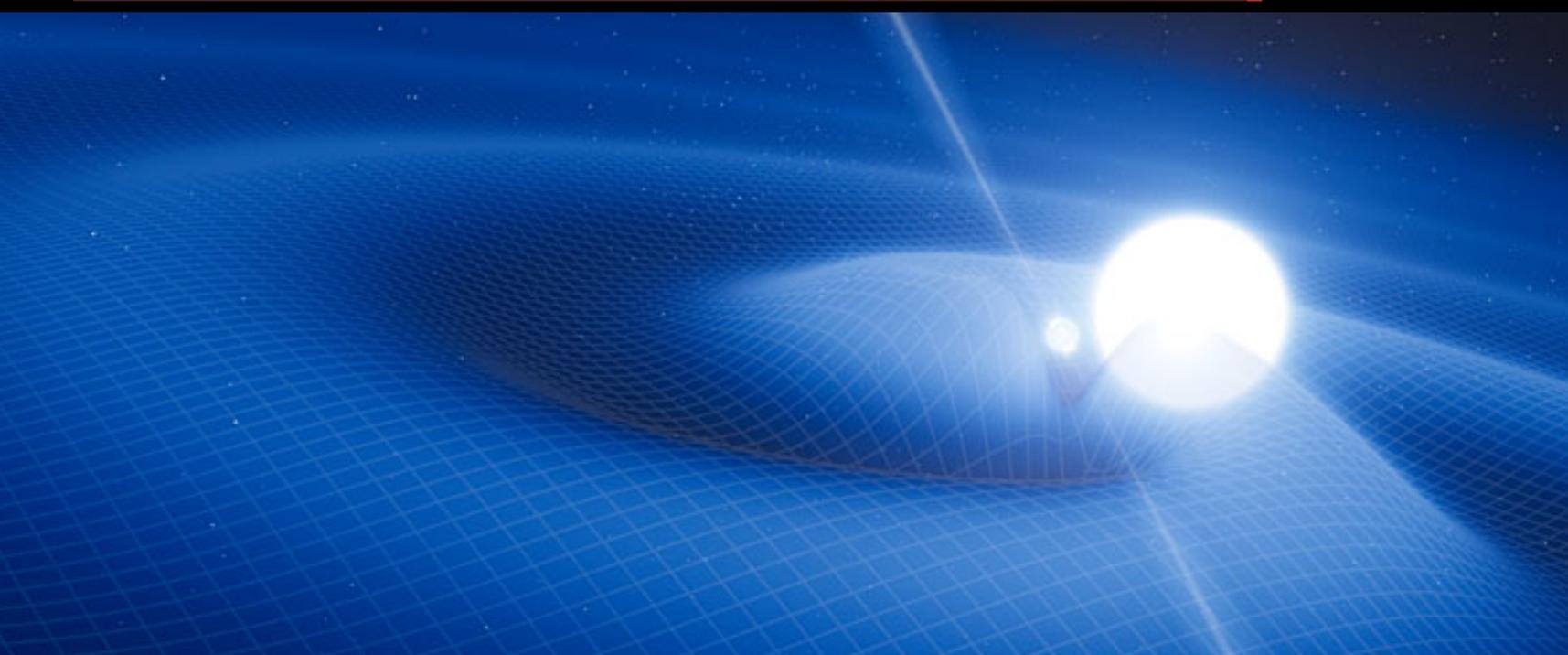
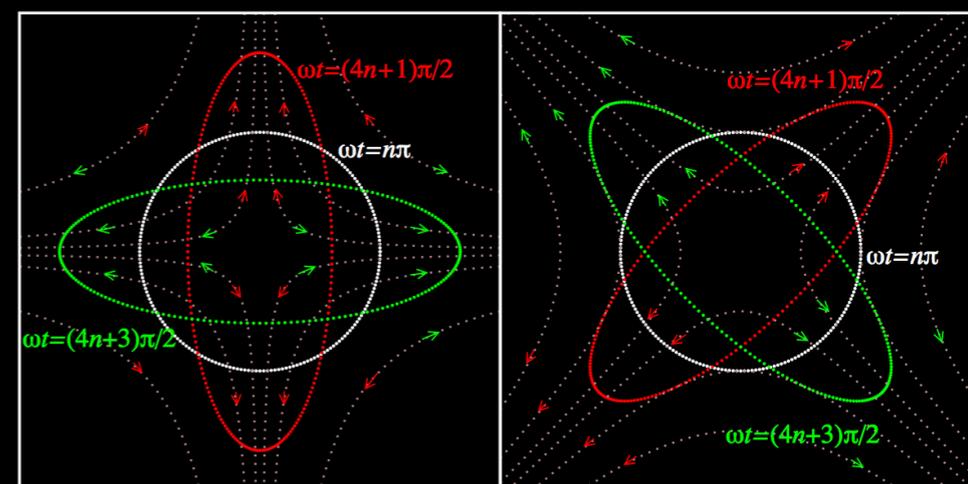
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$$h_{\mu\nu}(t, r) = 2 \frac{G}{c^4} \frac{1}{r} \frac{\partial^2 I_{\mu\nu}}{\partial t^2} \left(t - \frac{r}{c} \right)$$

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

$$h_+ = h_0 \sin(\omega t), \quad h_\times = 0$$

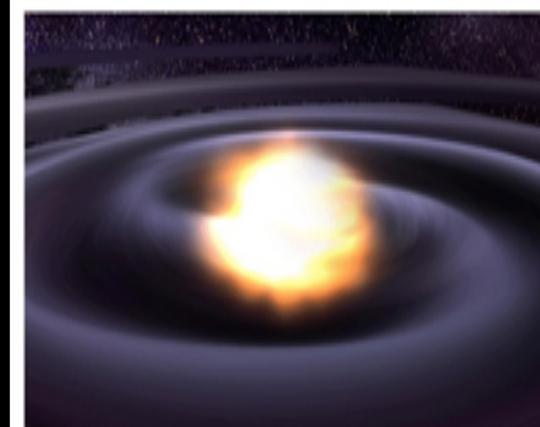
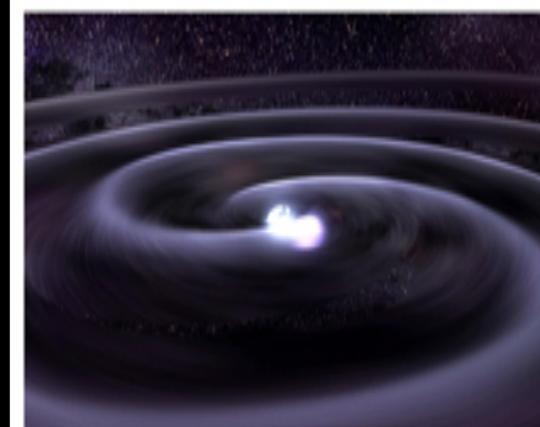
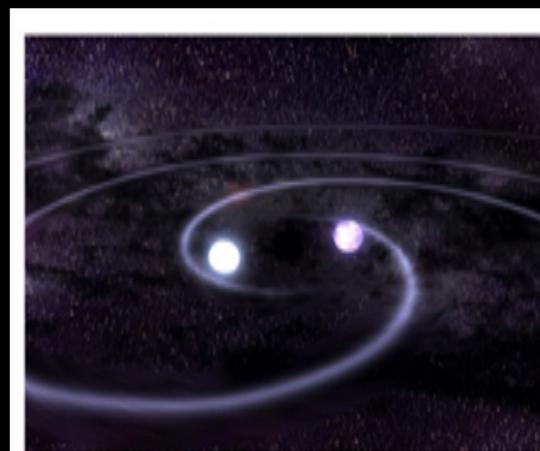
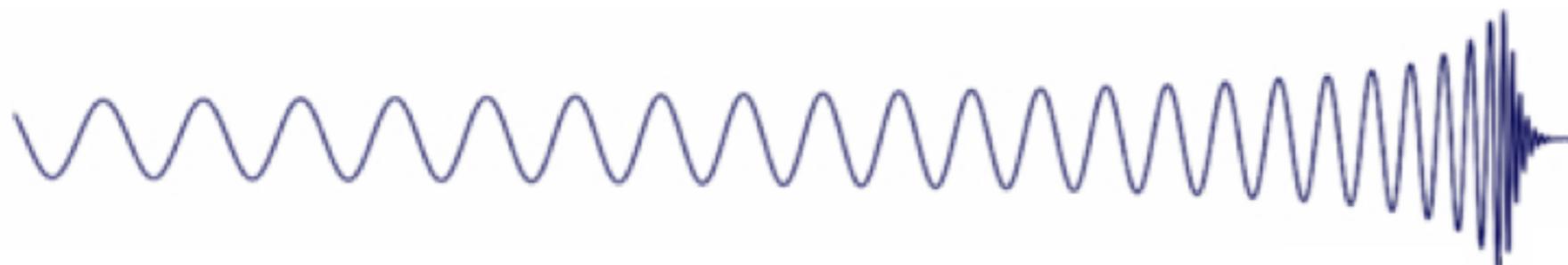
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INTERESTING BINARIES:

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

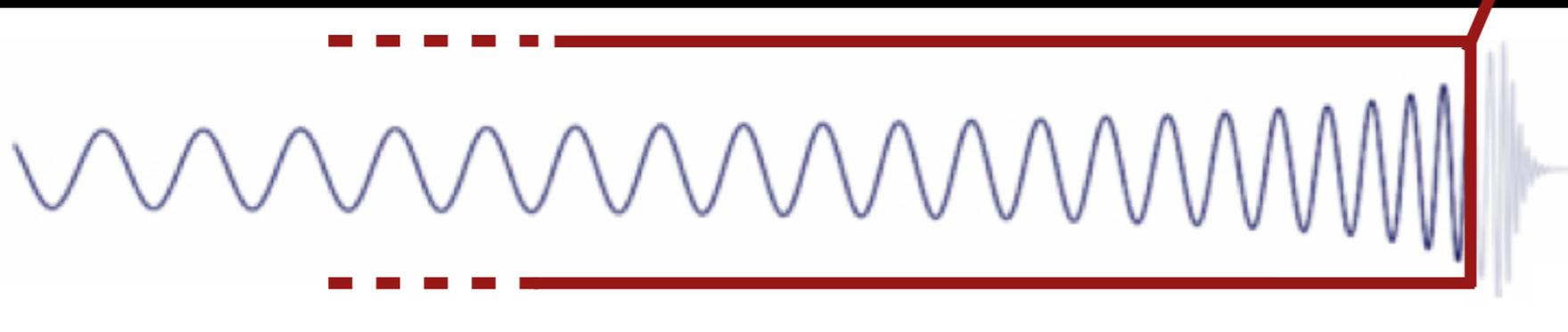
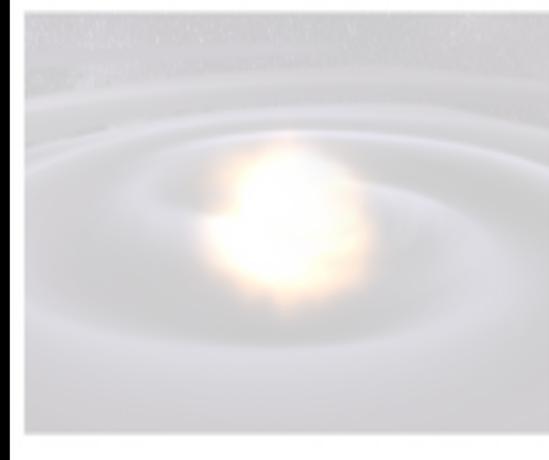
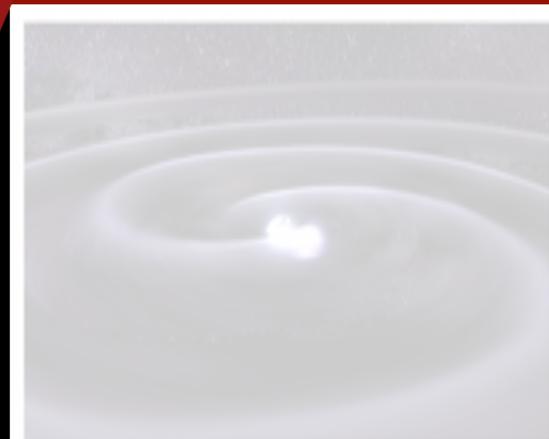
System	Masses (M_{sun})	Range (Mpc)	expected detection rate for aLIGO		
			low (yr^{-1})	realistic (yr^{-1})	high (yr^{-1})
NS-NS	1.4/1.4	200	0.4	40	400
NS-BH	1.4/10	410	0.2	10	300
BH-BH	10/10	970	0.4	20	1000



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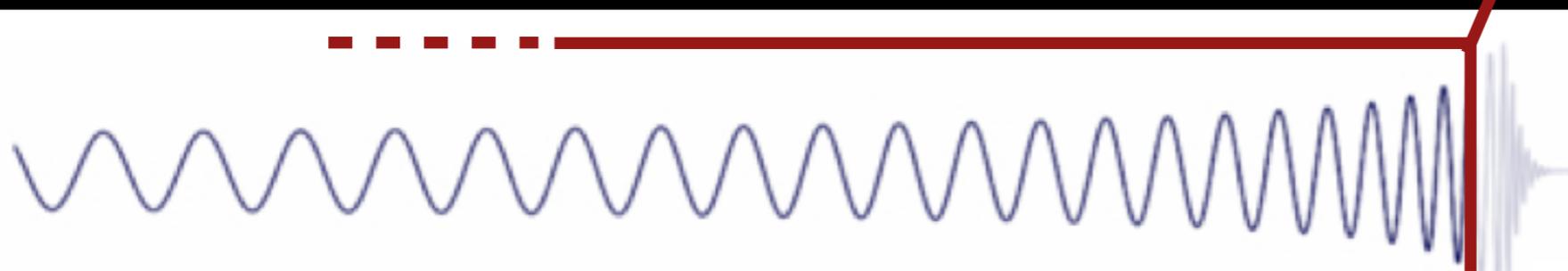
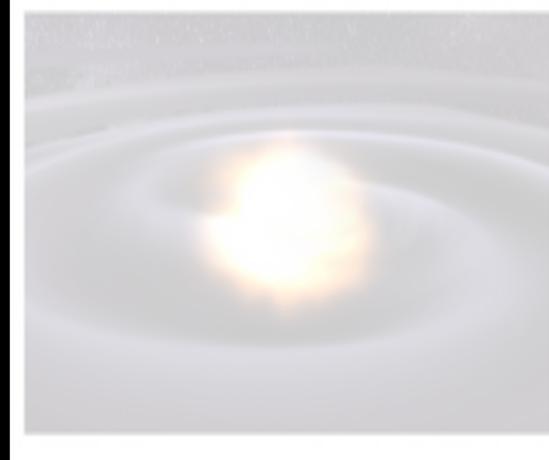
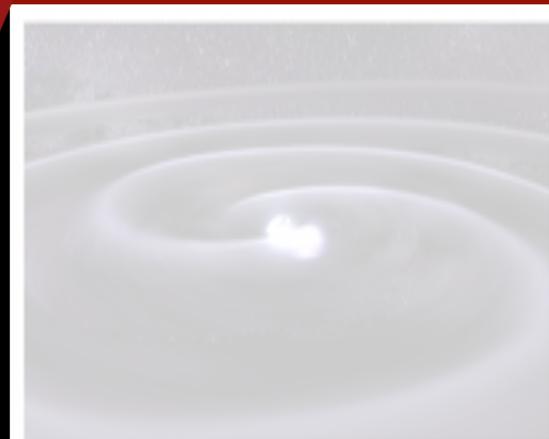
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$$t_{\text{inspiral}} \propto f_{\text{min}}^{-8/3} \mathcal{M}^{-5/3}$$

talk organisation

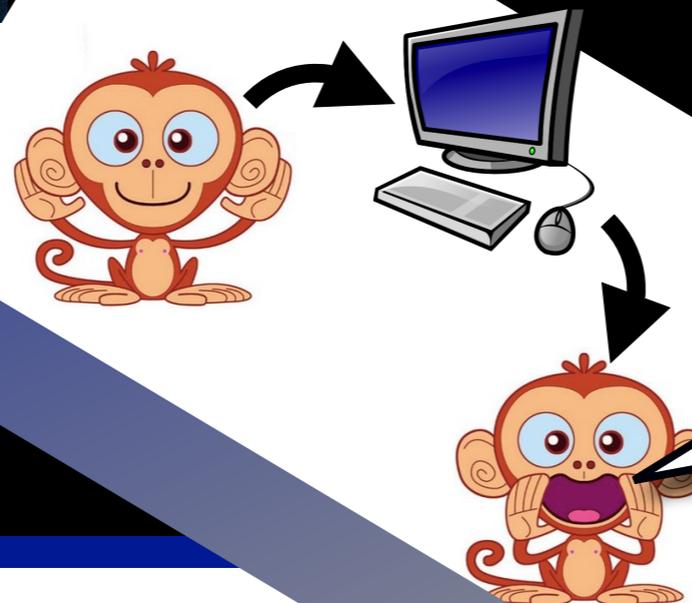
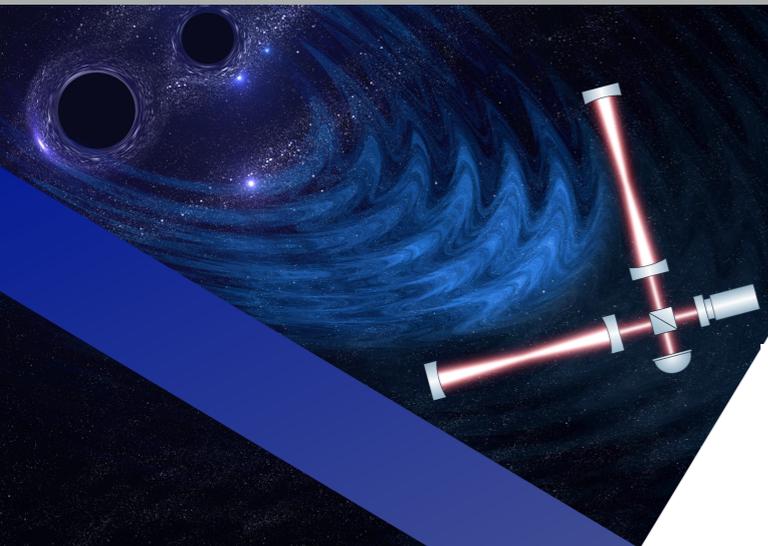
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Motivation: parameter estimation



- masses
- spins
- distance
- location...

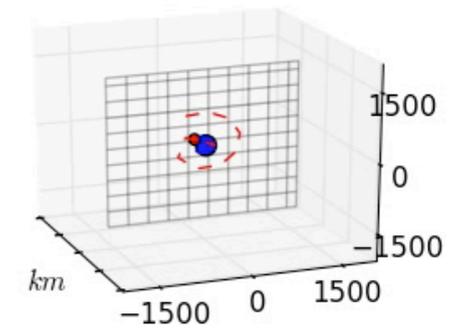
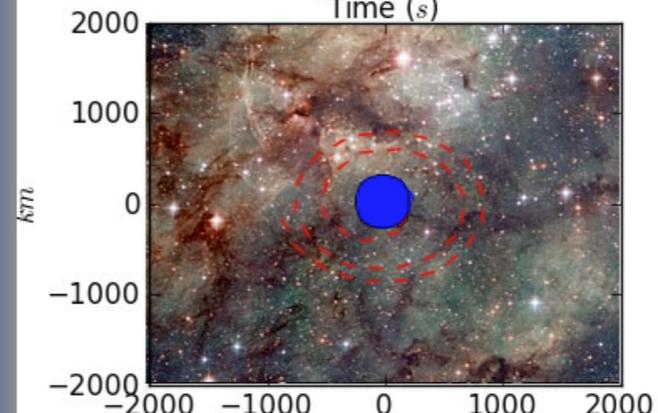
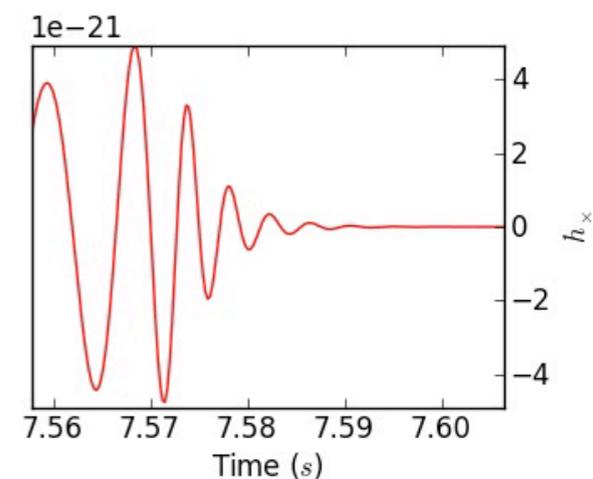
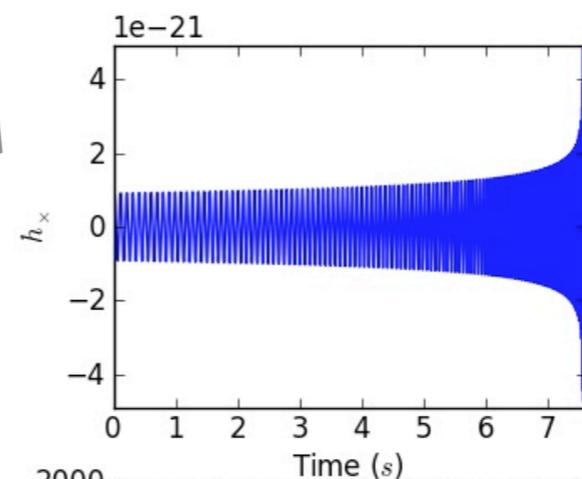
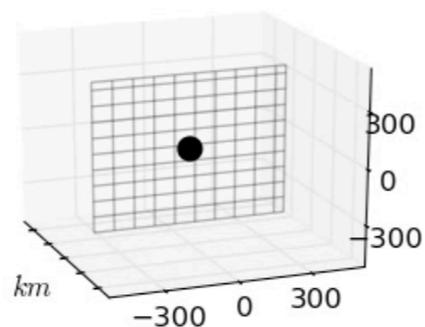
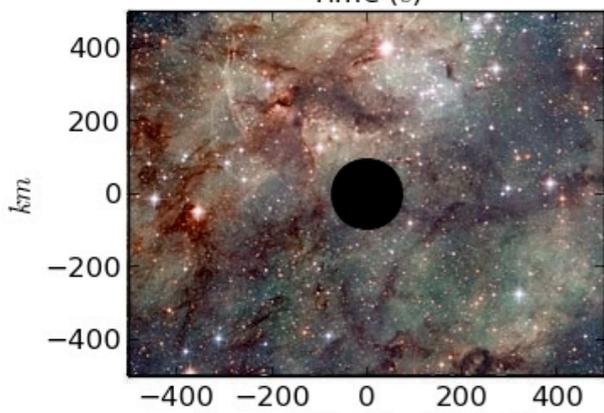
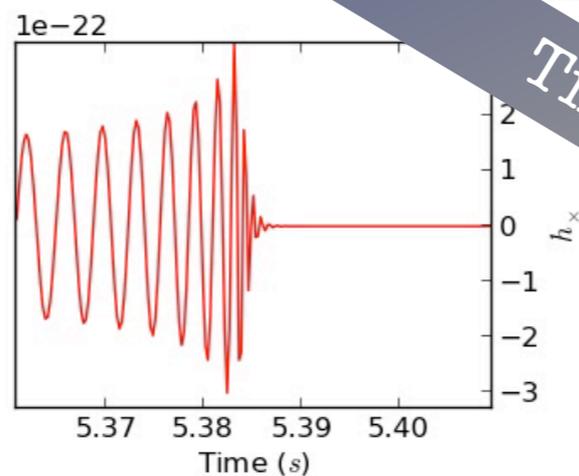
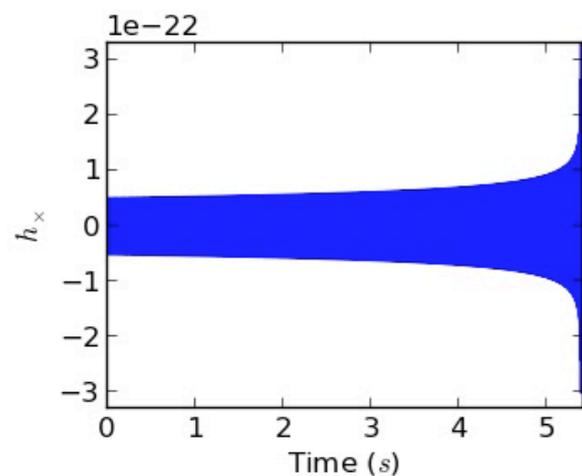


Image:ESA/Hubble $M_1 = 1.4 M_\odot$ $M_2 = 10.0 M_\odot$

Jason Tye, University of Birmingham

Image:ESA/Hubble $M_1 = 14.0 M_\odot$ $M_2 = 50.0 M_\odot$

Jason Tye, University of Birmingham

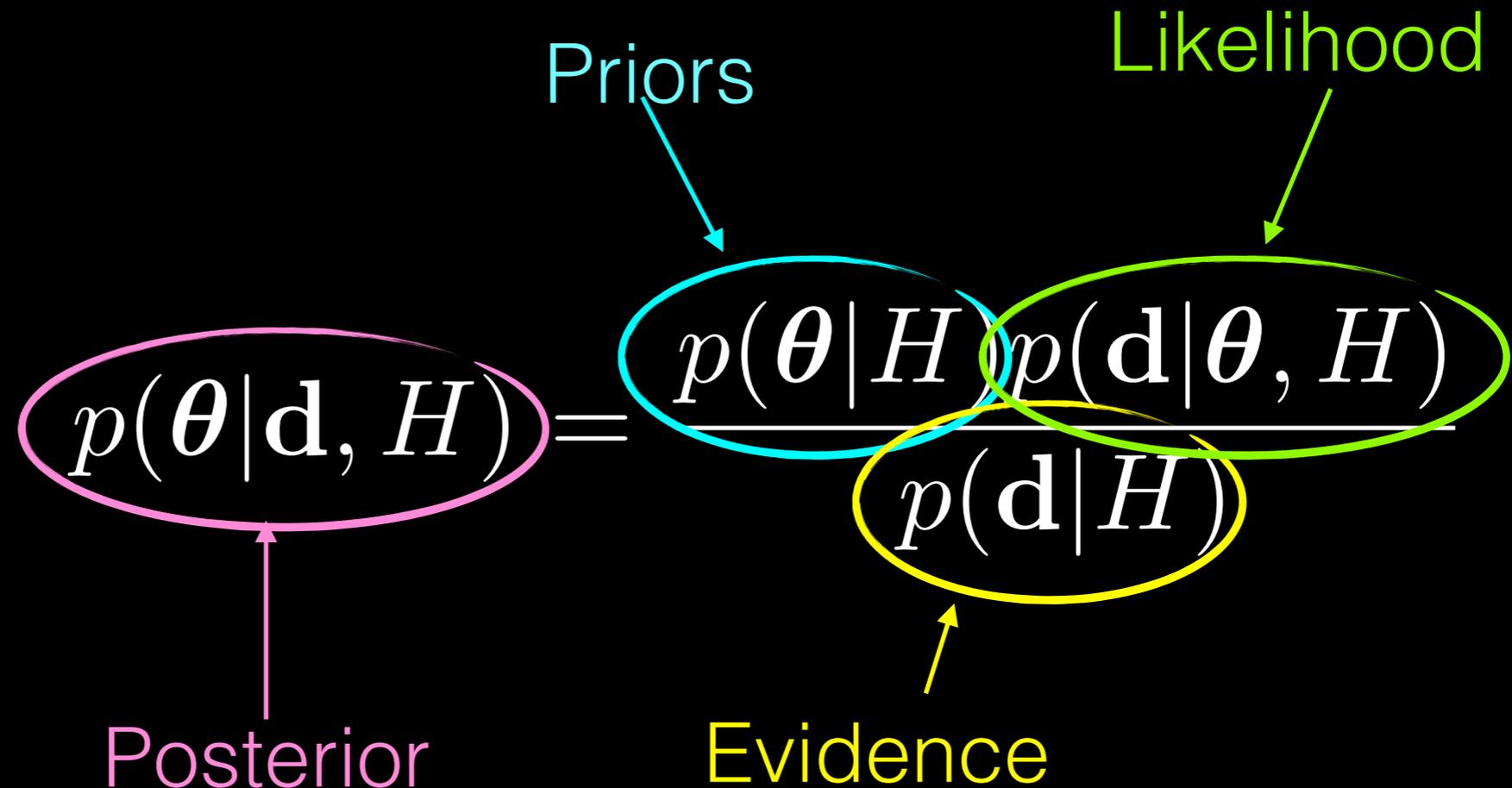
$$\mathbf{d} = \mathbf{h}(\boldsymbol{\theta}) + \mathbf{n}$$

masses, spins, distance, inclination, sky locations ...

BAYES THEOREM

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

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



The diagram illustrates Bayes Theorem with the following components and labels:

- Prior** (blue arrow): $p(\boldsymbol{\theta}|H)$
- Likelihood** (green arrow): $p(\mathbf{d}|\boldsymbol{\theta}, H)$
- Evidence** (yellow arrow): $p(\mathbf{d}|H)$
- Posterior** (pink arrow): $p(\boldsymbol{\theta}|\mathbf{d}, H)$

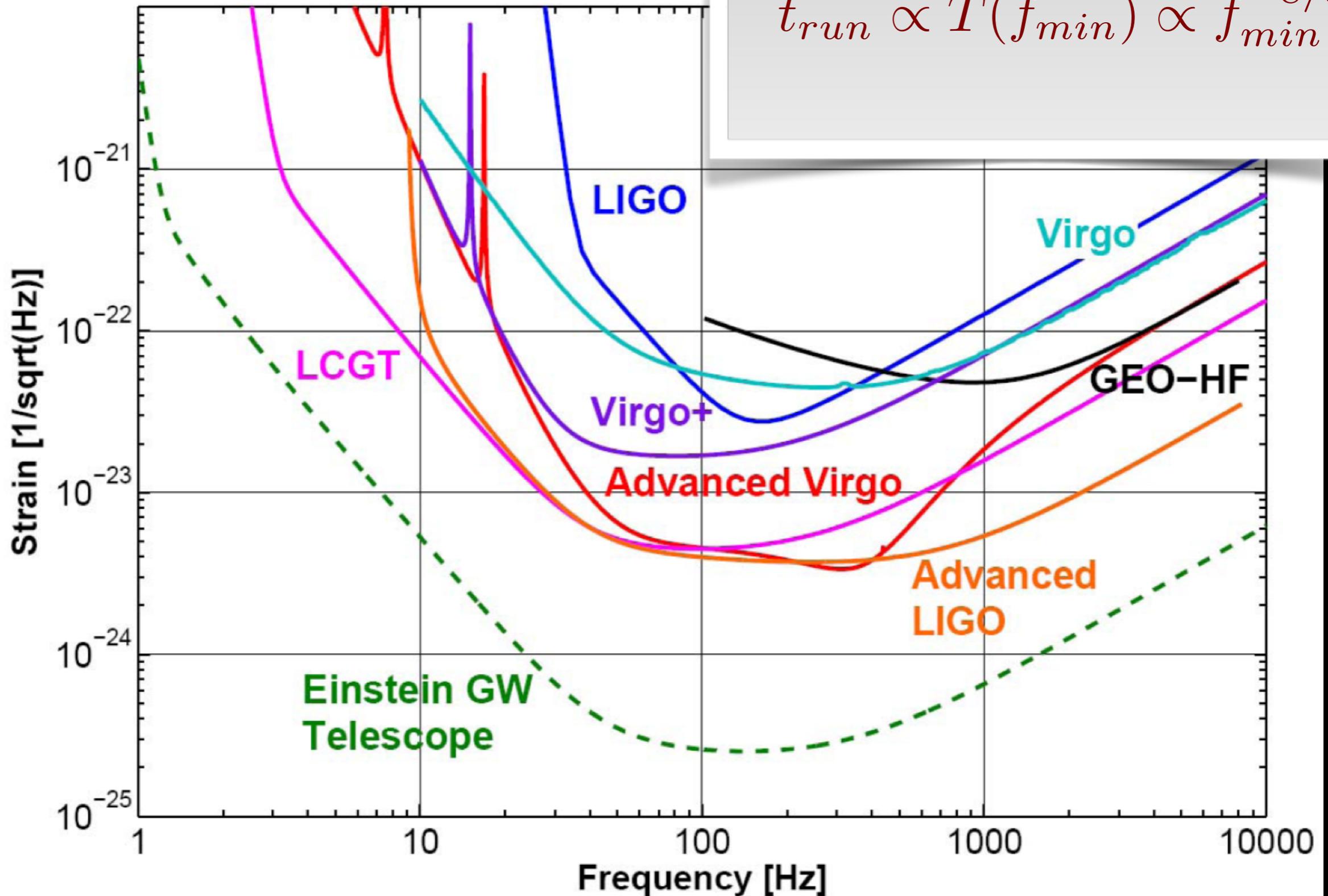
$$p(\boldsymbol{\theta}|\mathbf{d}, H) = \frac{p(\boldsymbol{\theta}|H) p(\mathbf{d}|\boldsymbol{\theta}, H)}{p(\mathbf{d}|H)}$$

GAUSSIAN NOISE

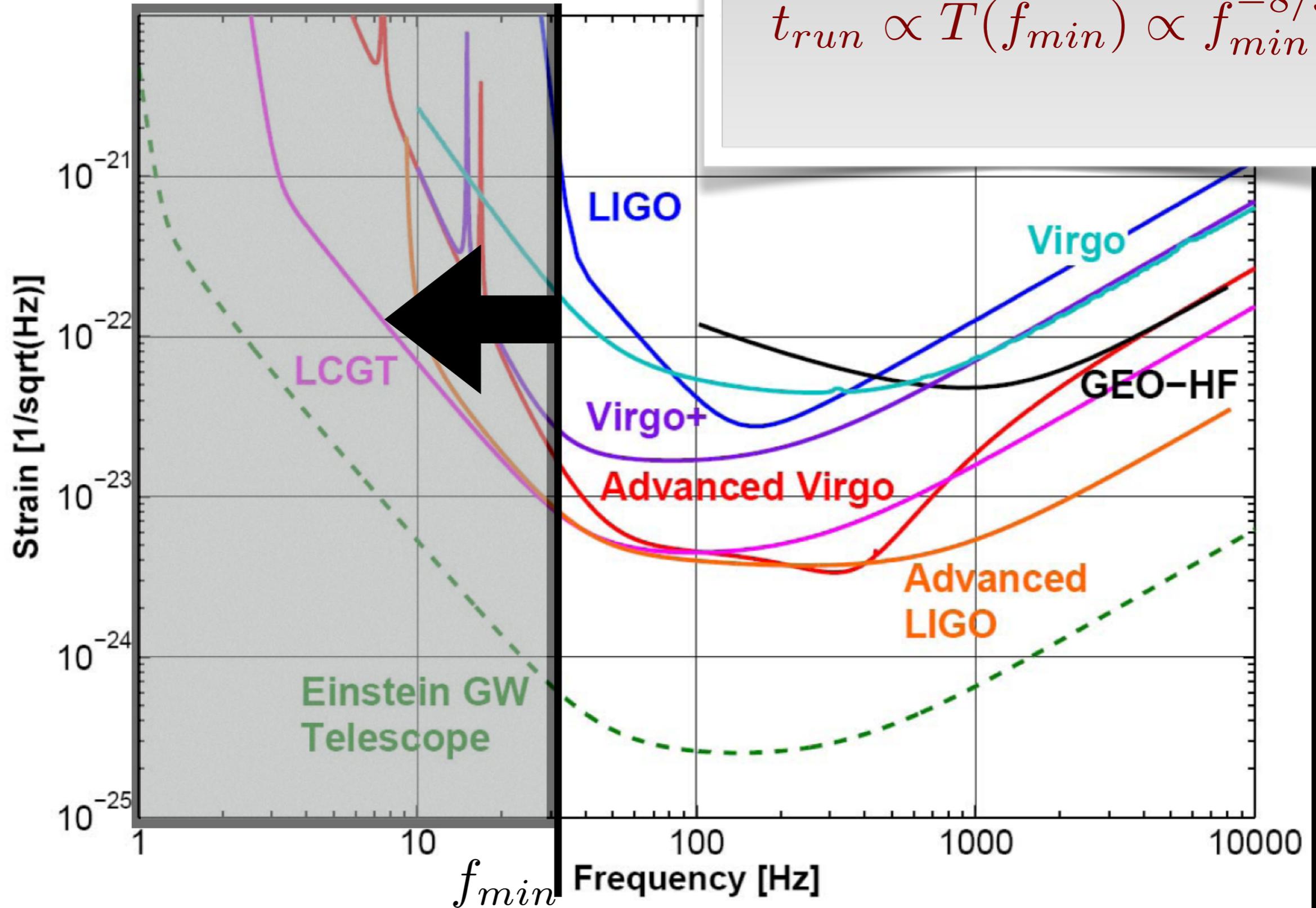
- zero mean
- known variance

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

Motivation: future instrument sensitivities



Motivation: future instrument sensitivities



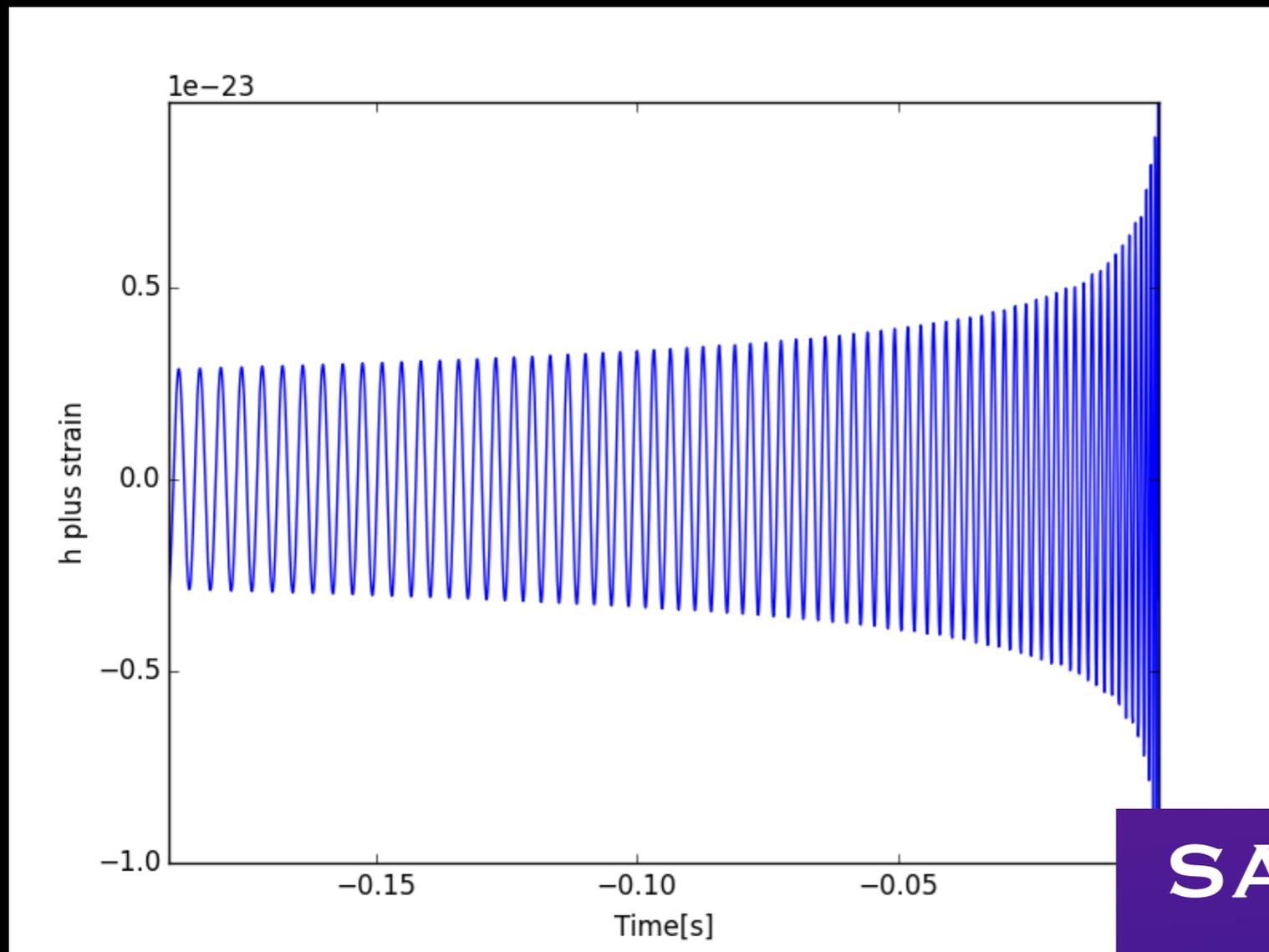
talk organisation

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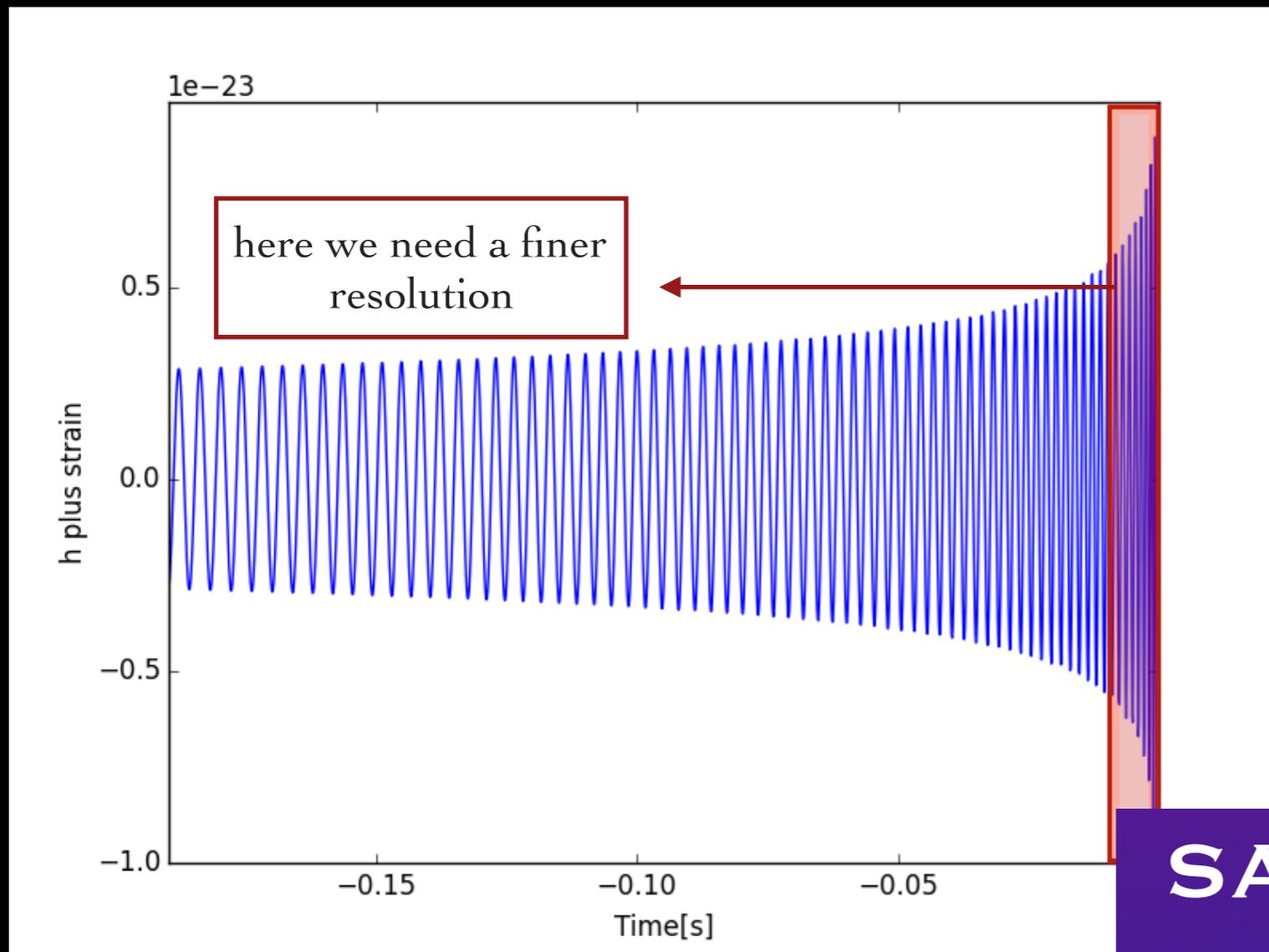
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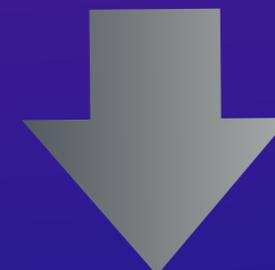
SAMPLING THEORY

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



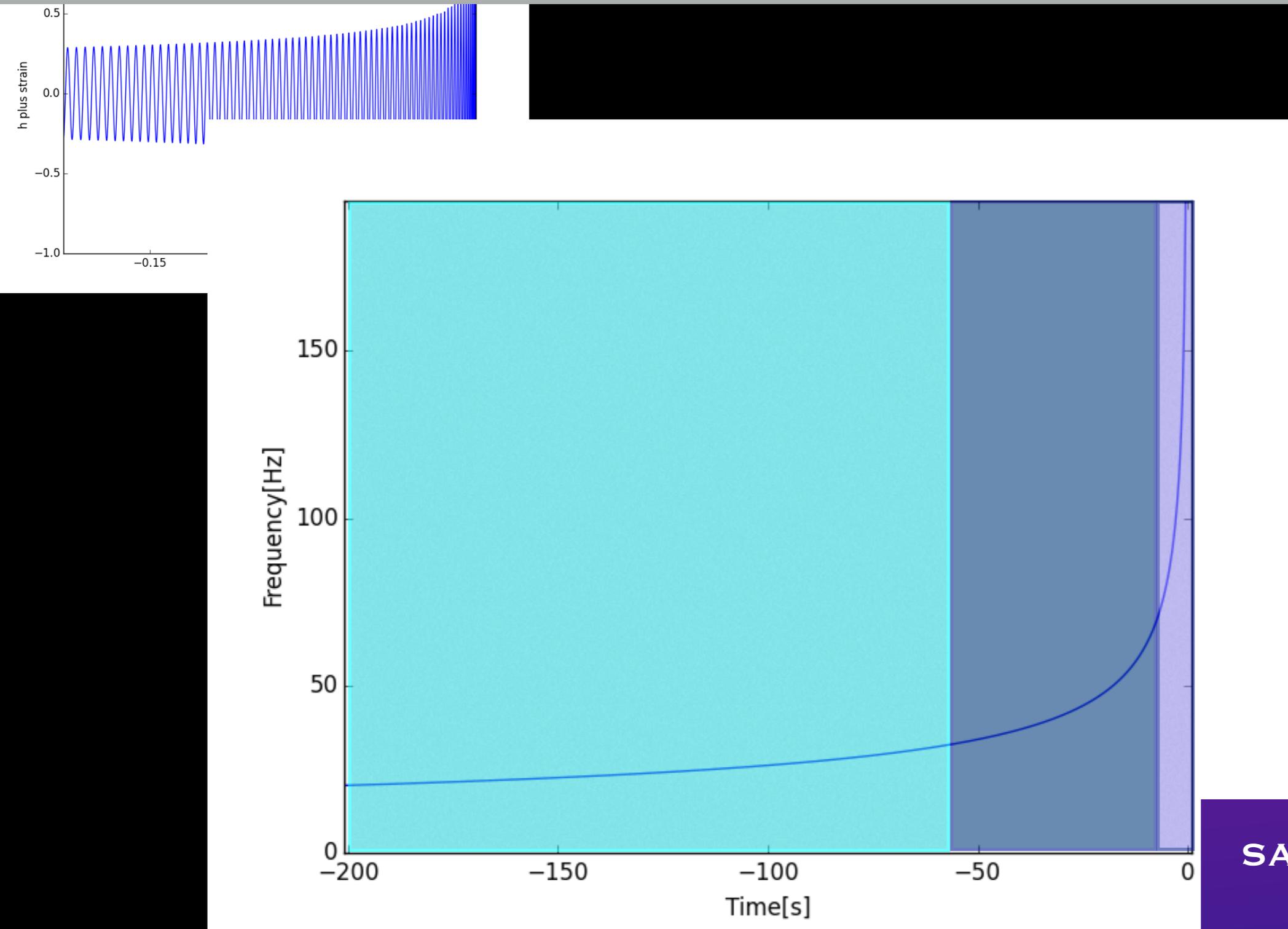
SAMPLING THEORY

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



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

Procedure: multi-banding



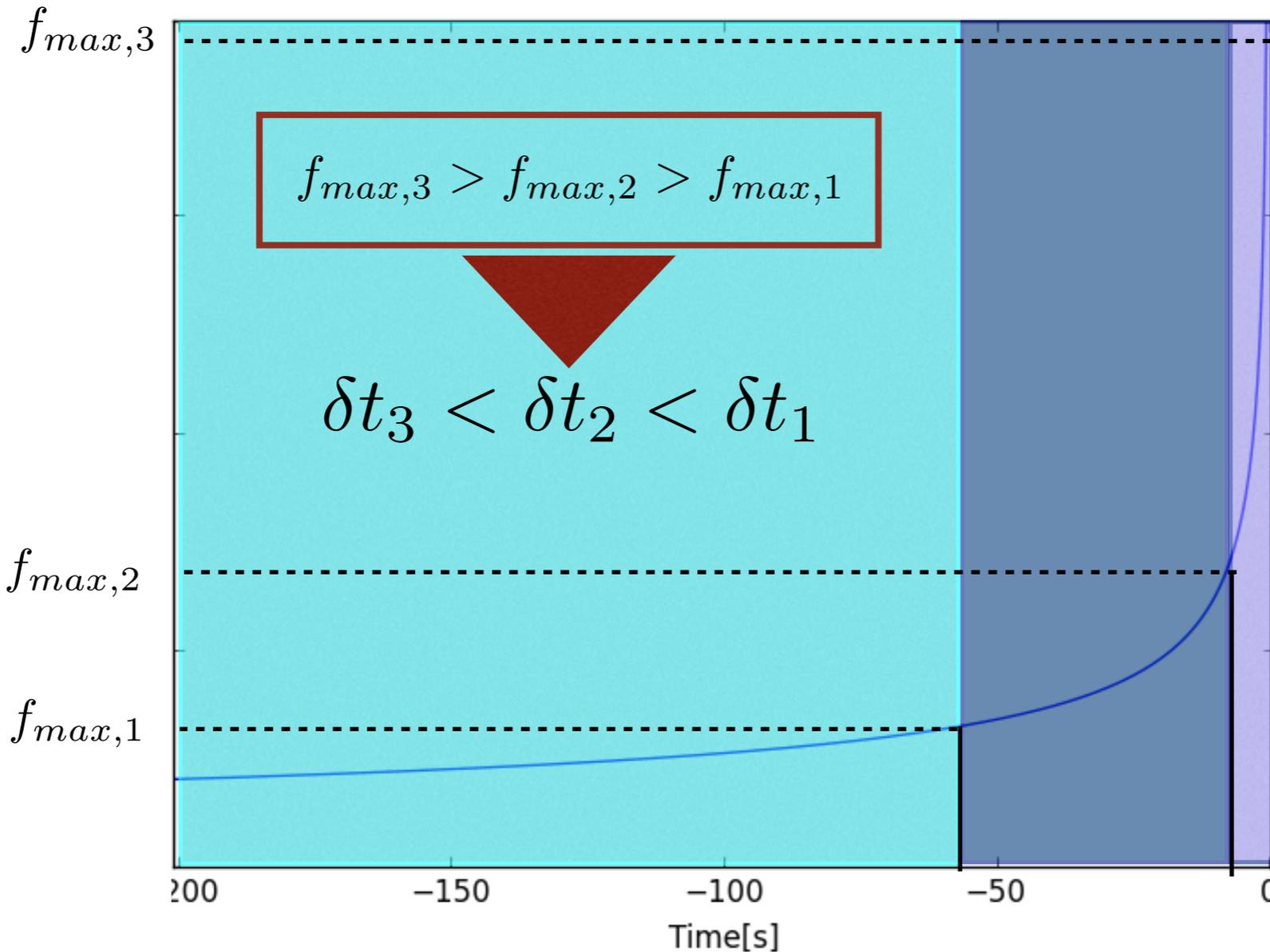
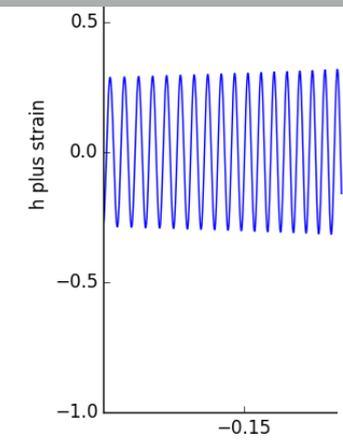
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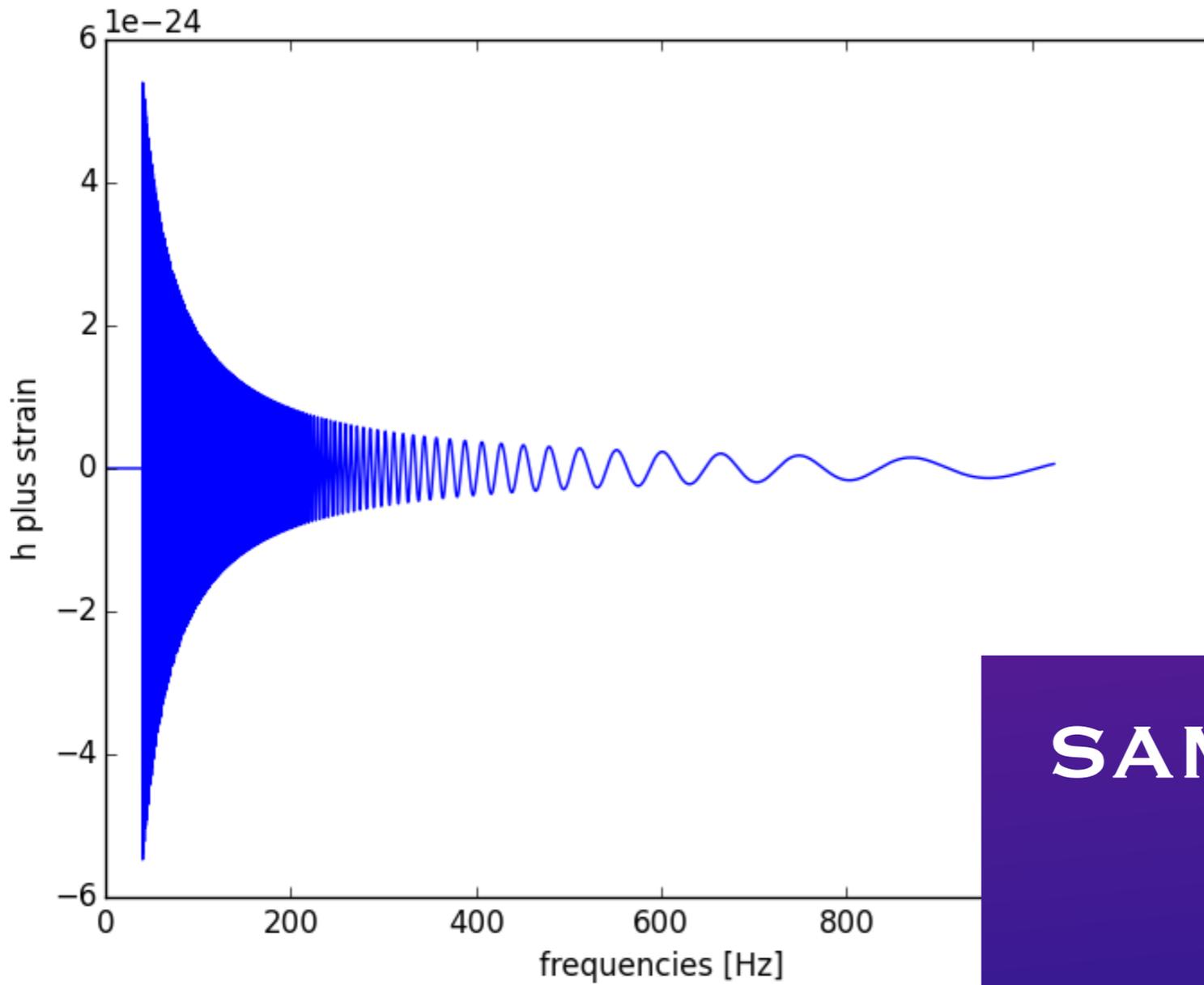


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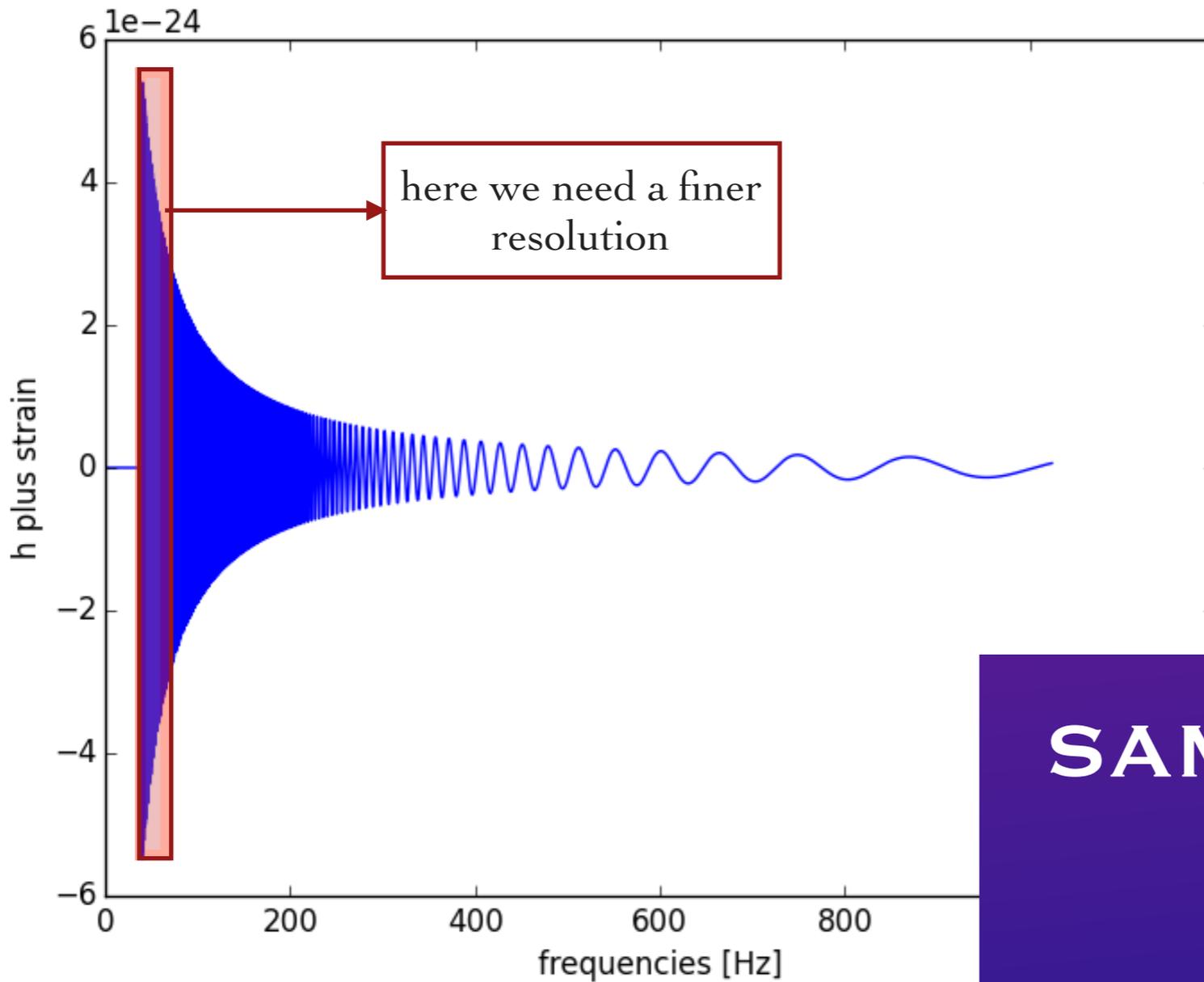


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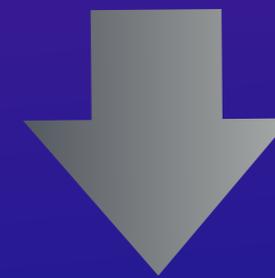
SAMPLING THEORY

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



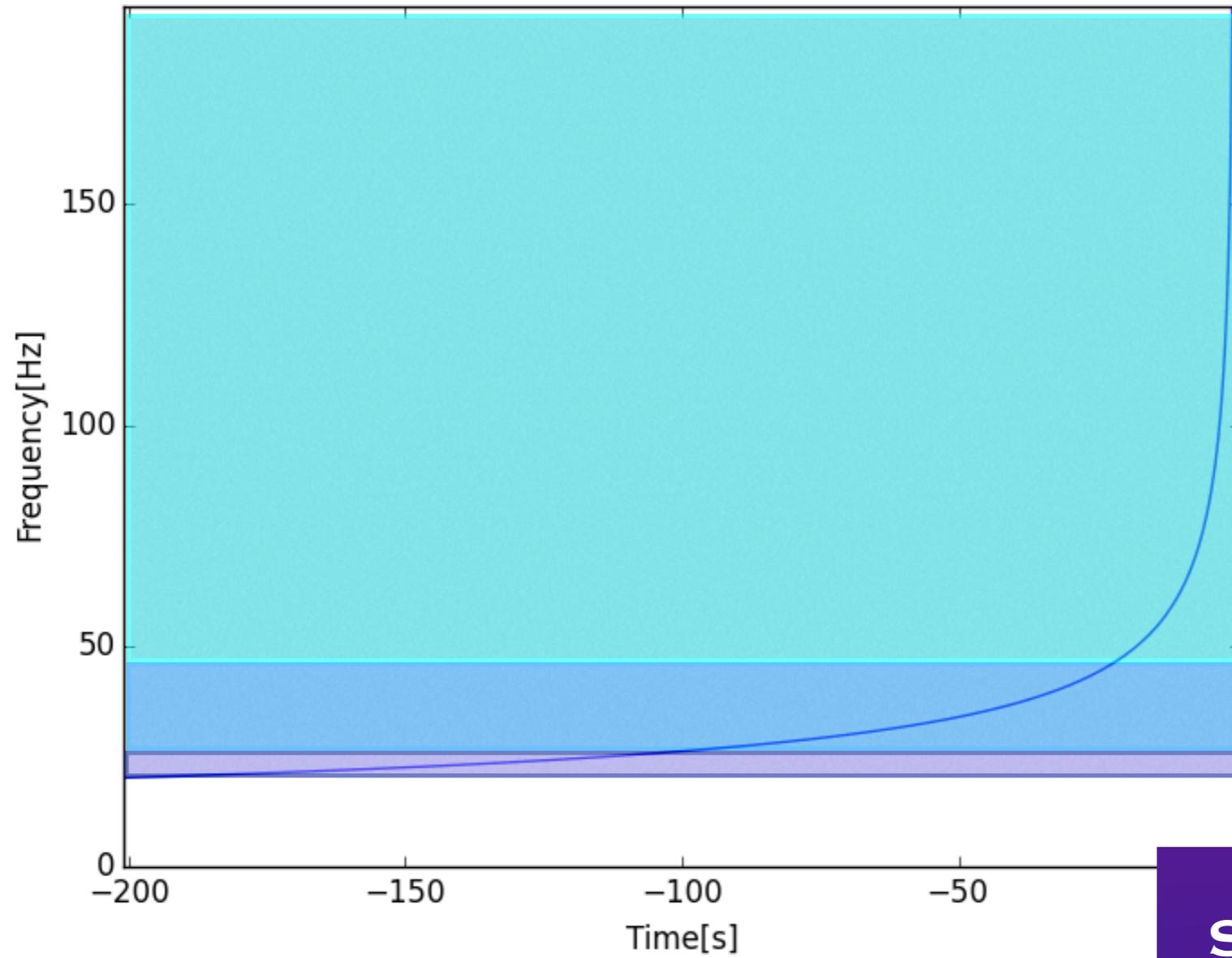
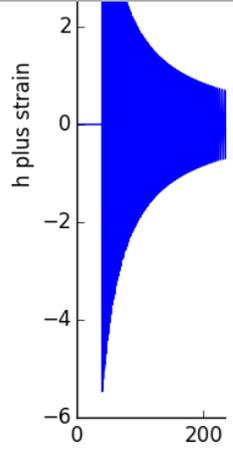
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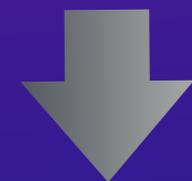
$$\rightarrow \delta f(t) \leq (T(t))^{-1}$$

Procedure: multi-banding



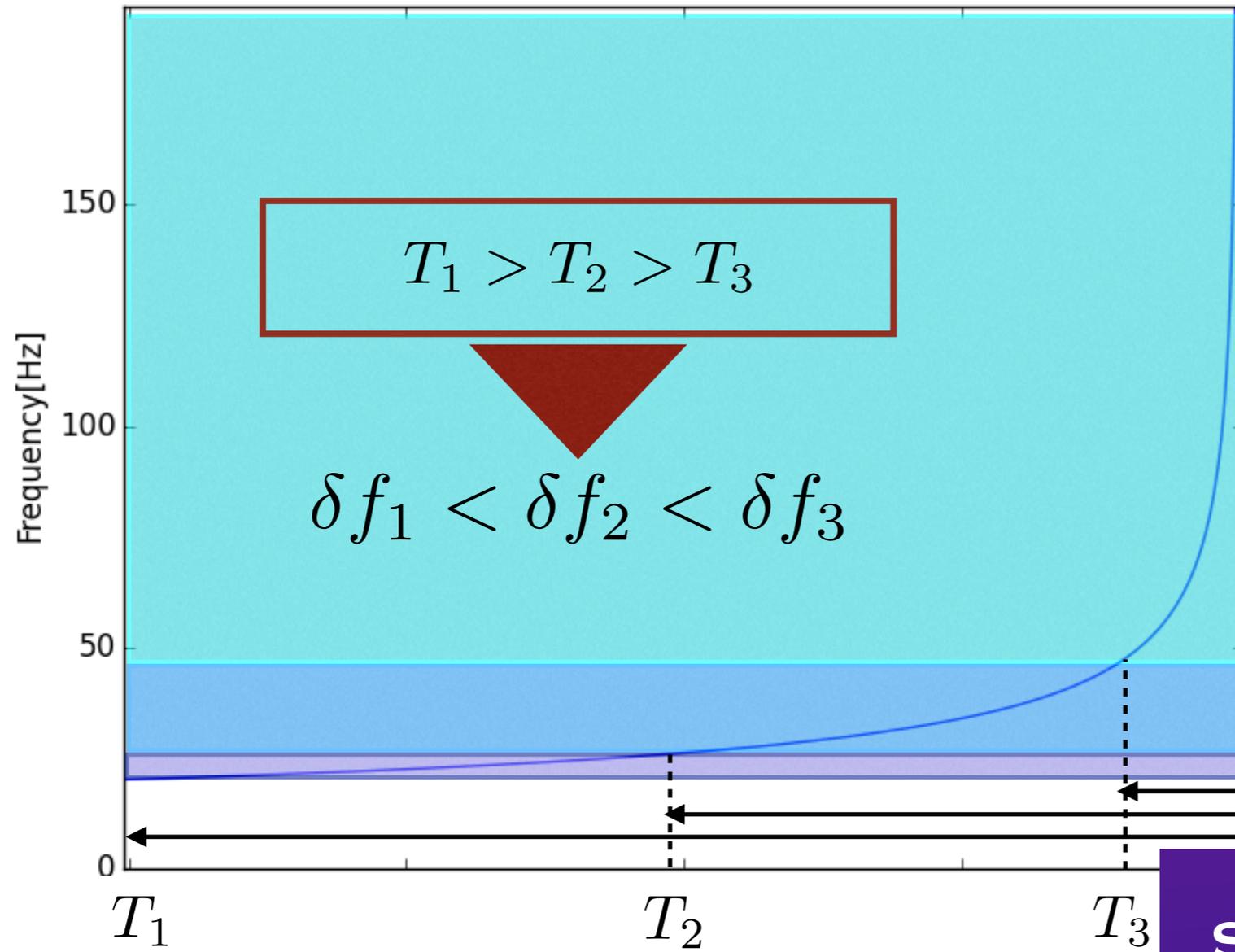
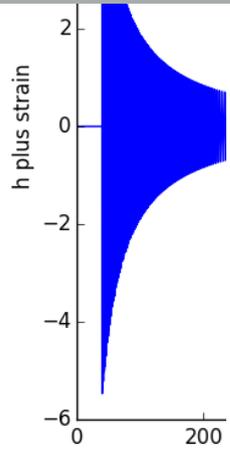
SAMPLING THEORY

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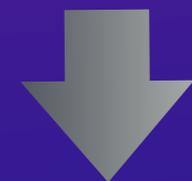
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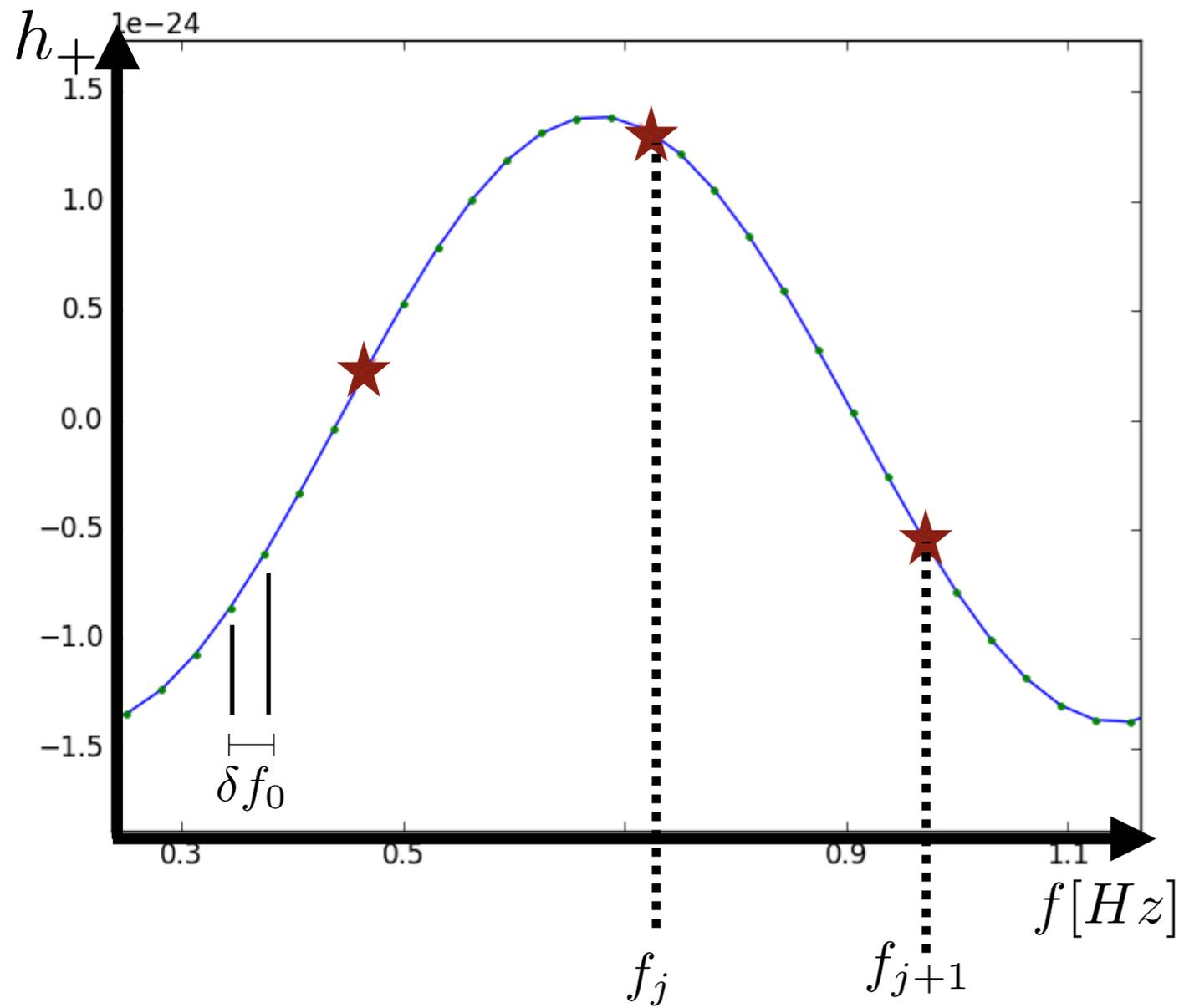
SAMPLING THEORY

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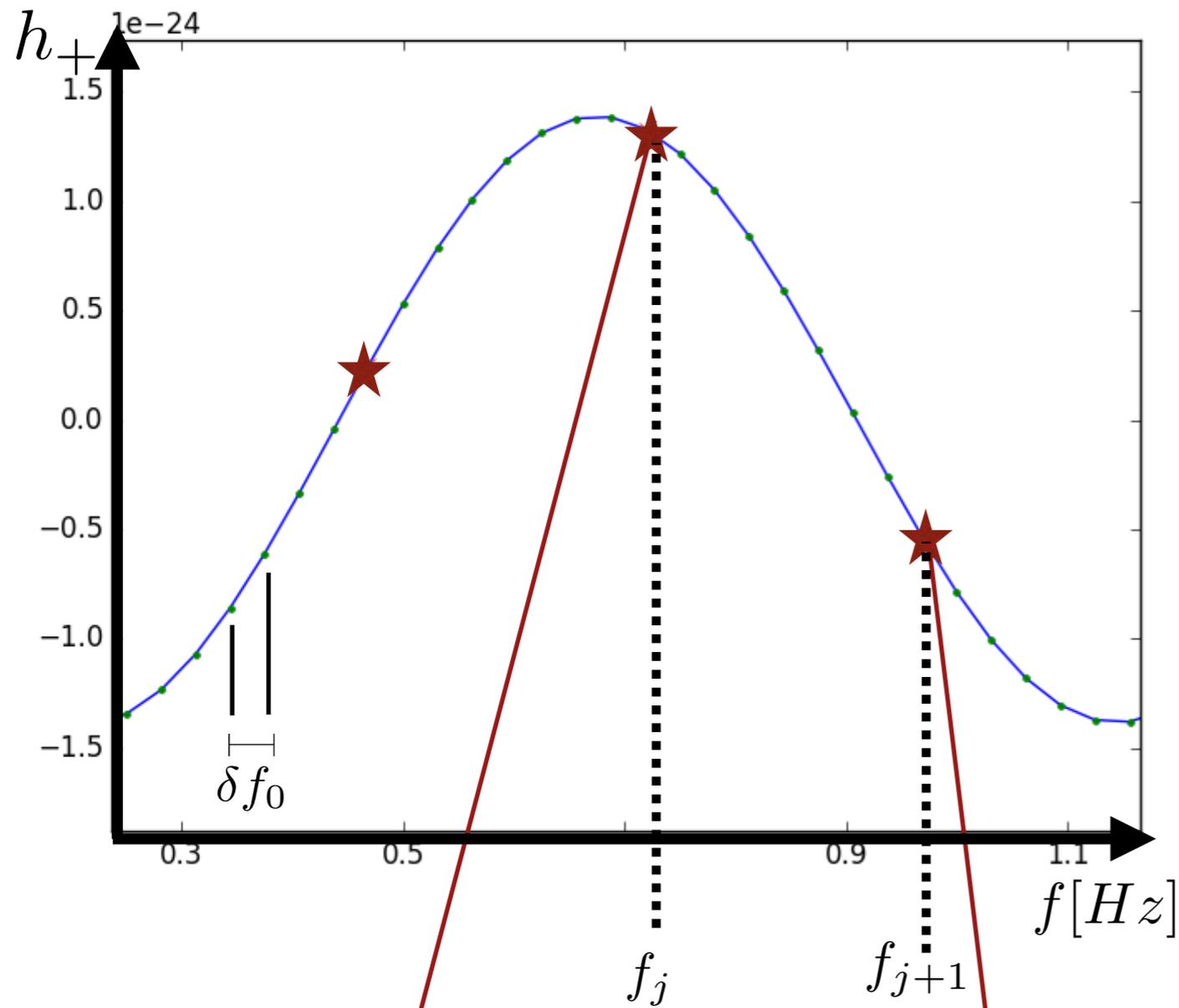
$$\rightarrow \delta f(t) \leq (T(t))^{-1}$$

Procedure: Phase-Interpolation idea



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

Procedure: Phase-Interpolation idea

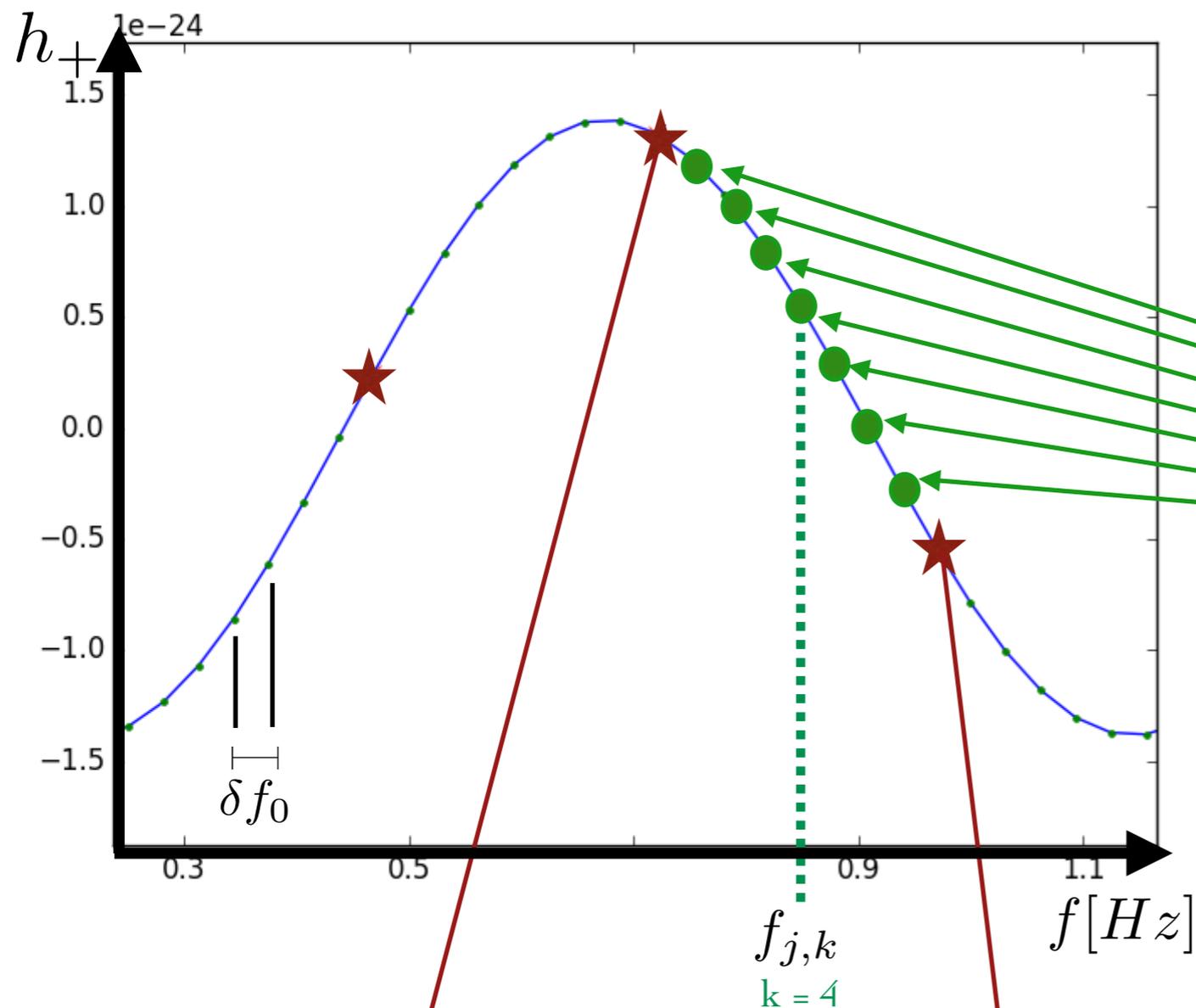


$$\tilde{h}(\theta, f) \sim A(\theta, f) e^{i\psi(\theta, f)}$$

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

$$\begin{aligned} \psi(f_{jk}) &= \frac{\psi(f_{j+1}) - \psi(f_j)}{f_{j+1} - f_j} k \delta f_0 \\ &= \Delta\psi_j k \end{aligned}$$

Procedure: Phase-Interpolation idea



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

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

OUT

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

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

$$= \Delta\psi_j k$$

IN

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

talk organisation

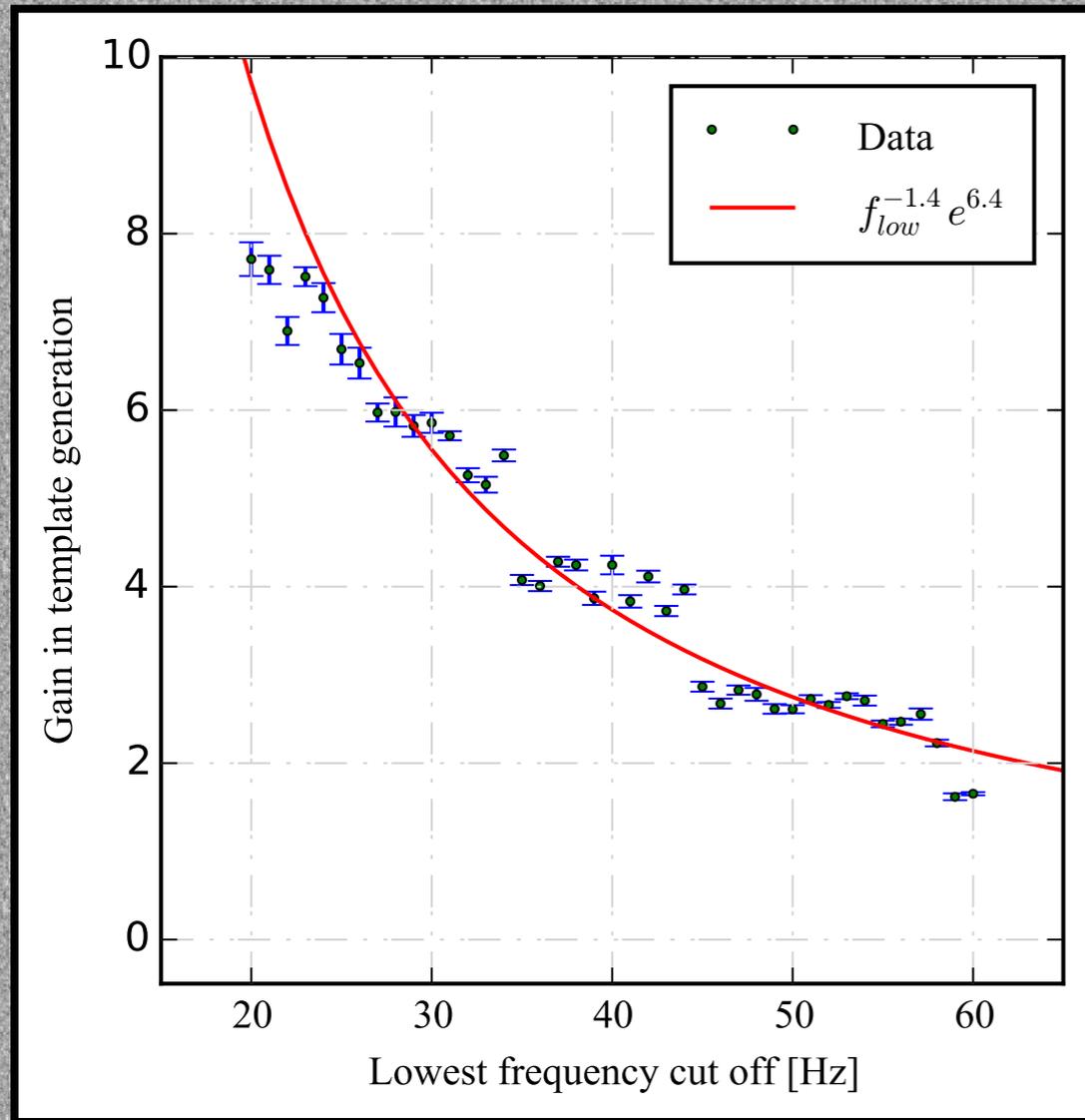
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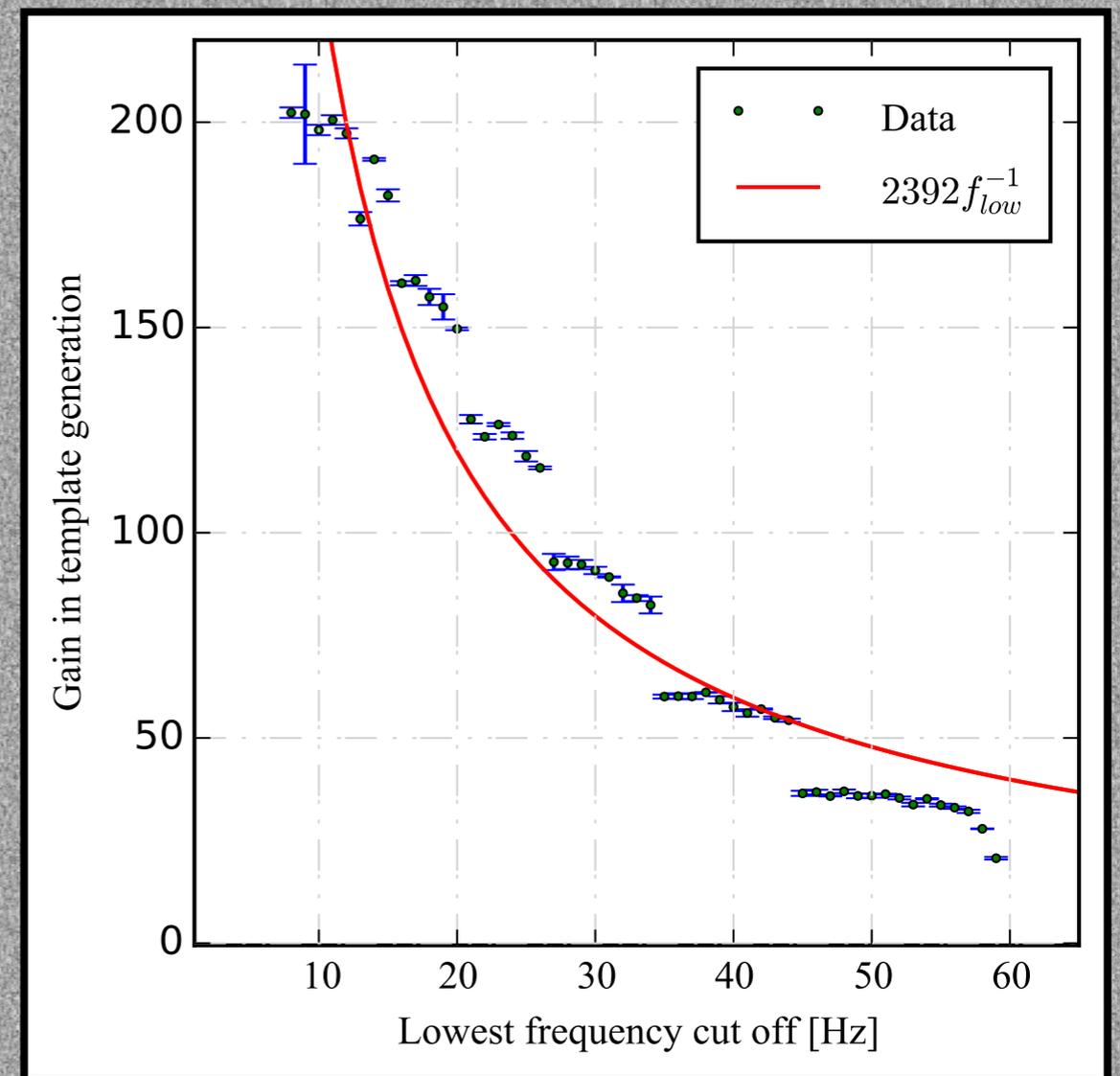
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Results: Gain in template generation

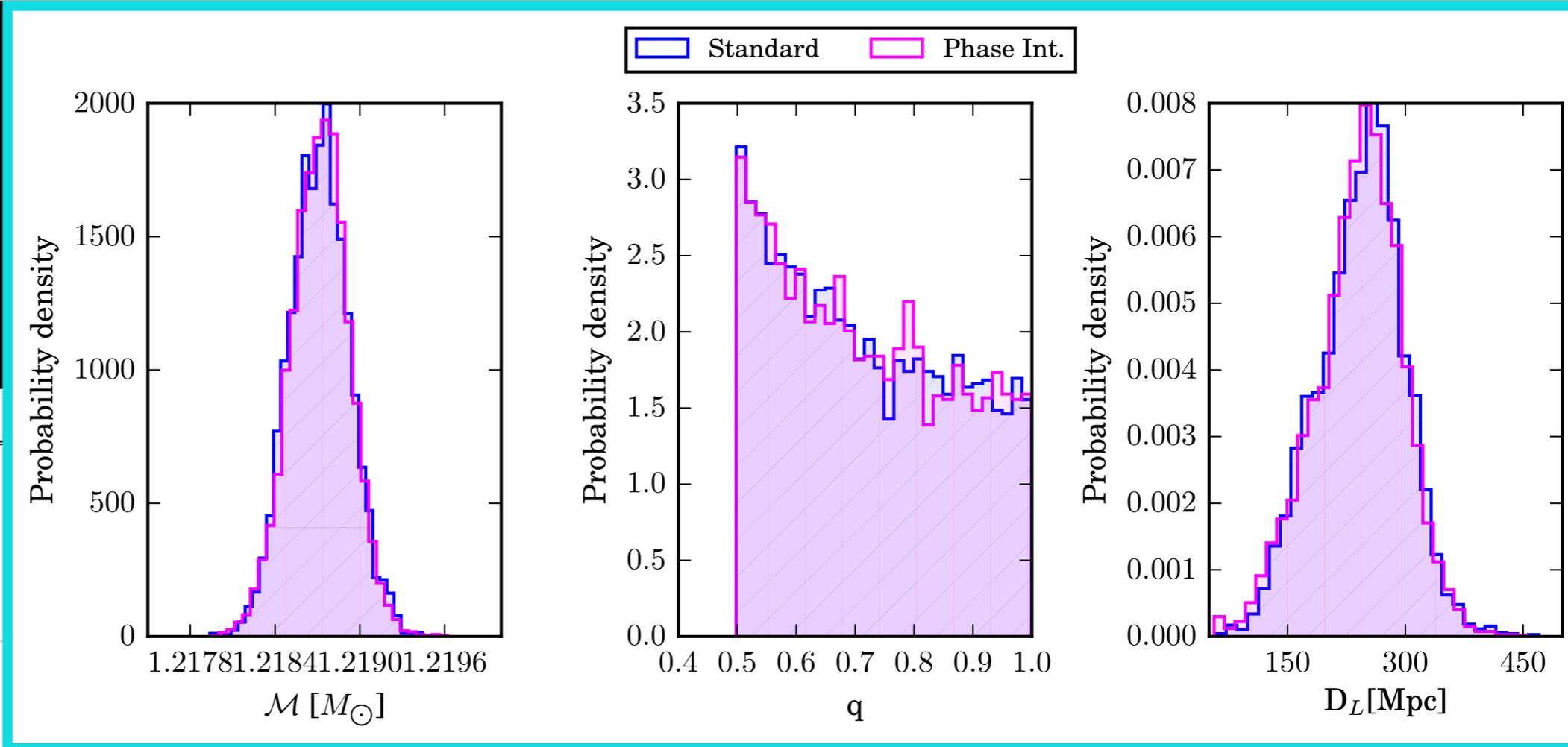
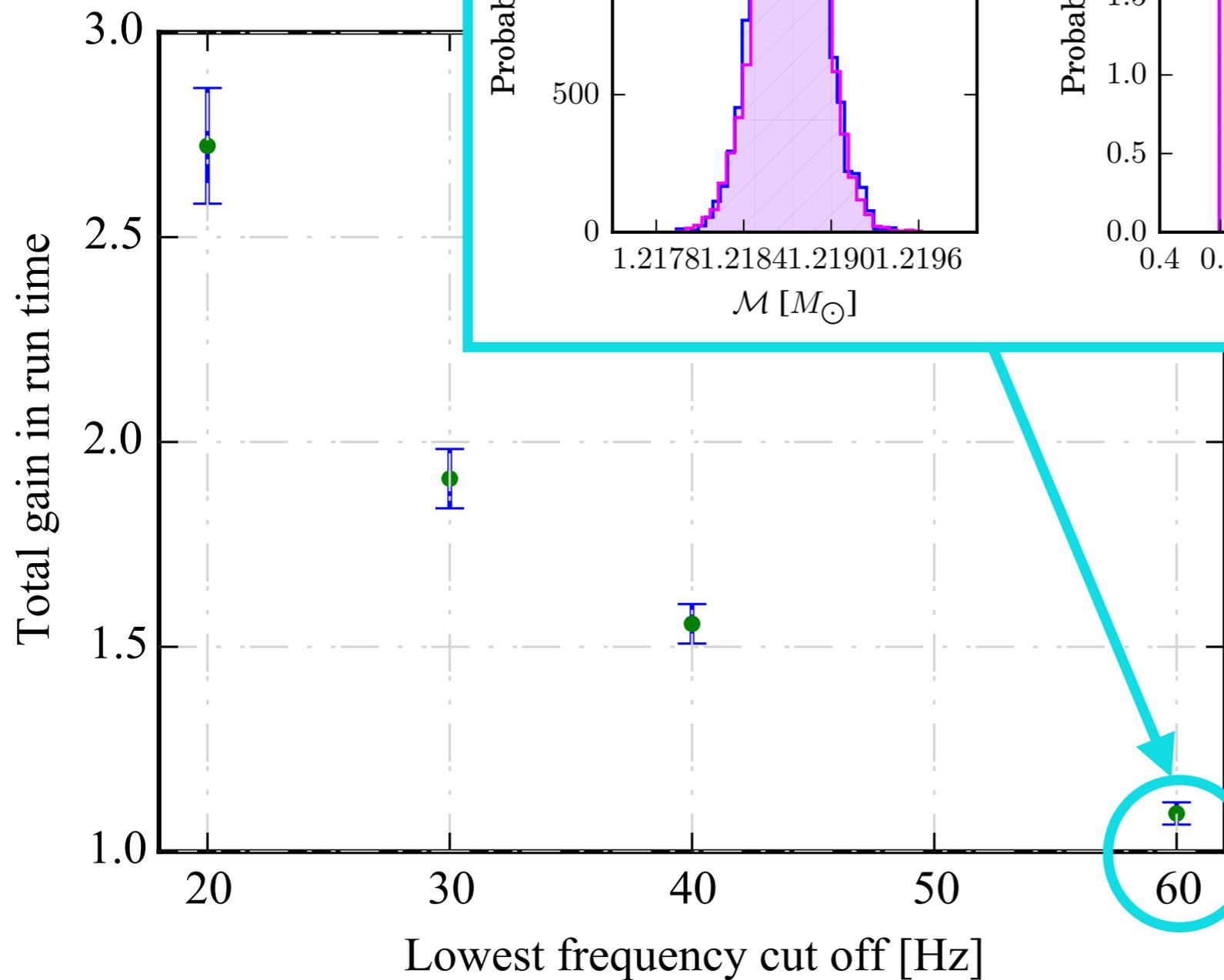


A simple waveform model
(TaylorF2)

A complicate waveform model (IMRPhenomPv2)



Results: Gain in overall analysis



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

Useful method for now and future generations of interferometers.





talk organisation

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The Discovery: GW150914



GraWIToN



GW Initial Training Network

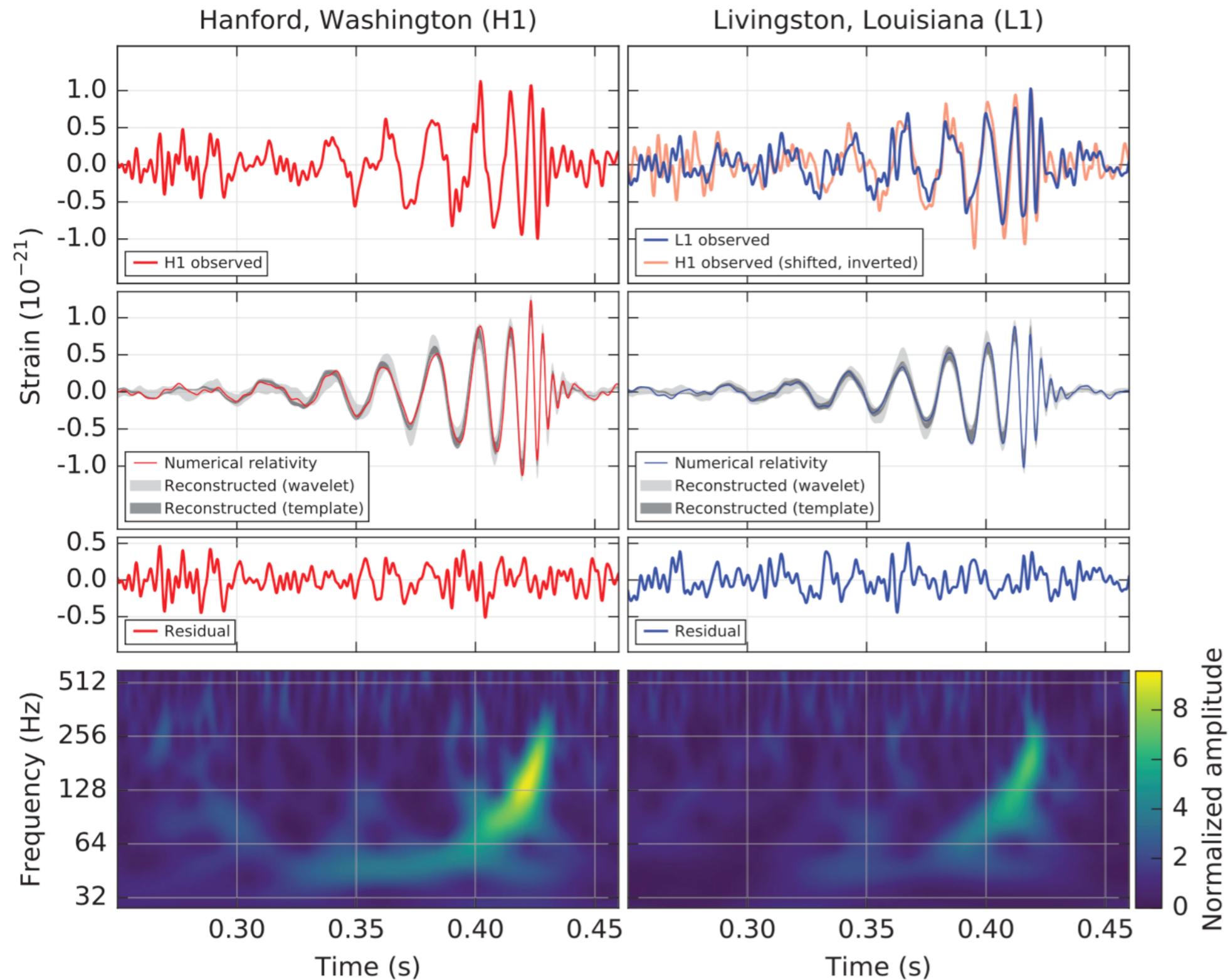
The Discovery: GW150914



The Discovery: GW150914

The GW astronomy has begun!

The Discovery: GW150914

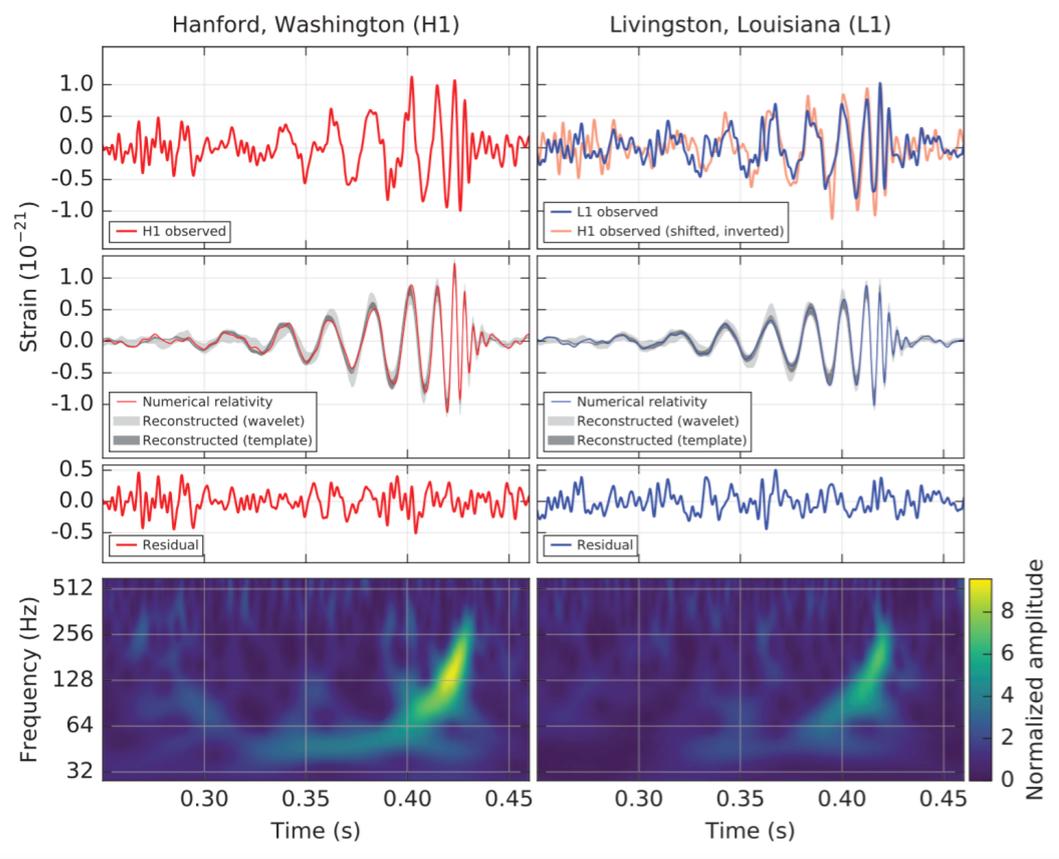


Data

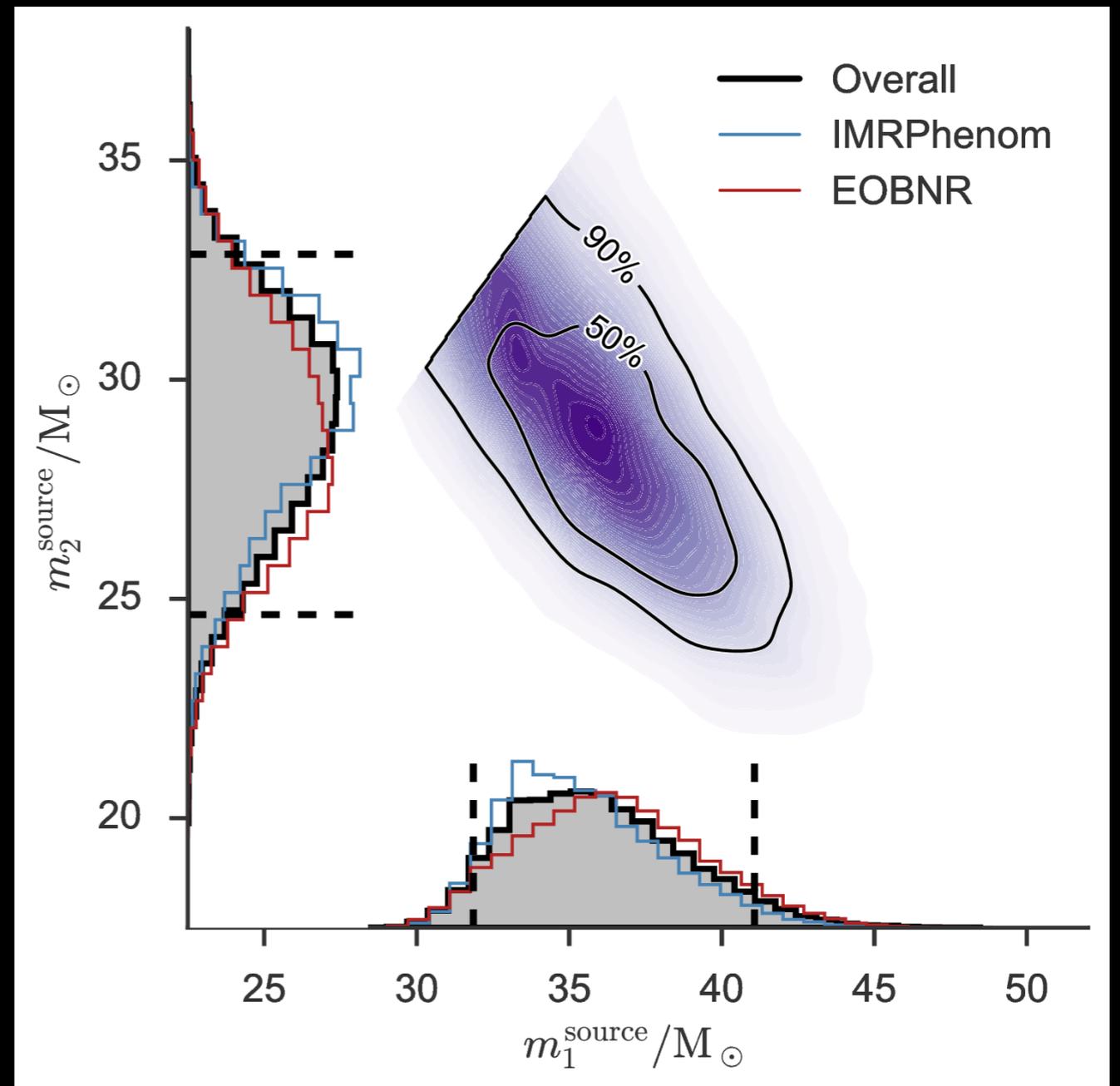
Reconstructed
waveform

Time-frequency
representation

The Discovery: GW150914

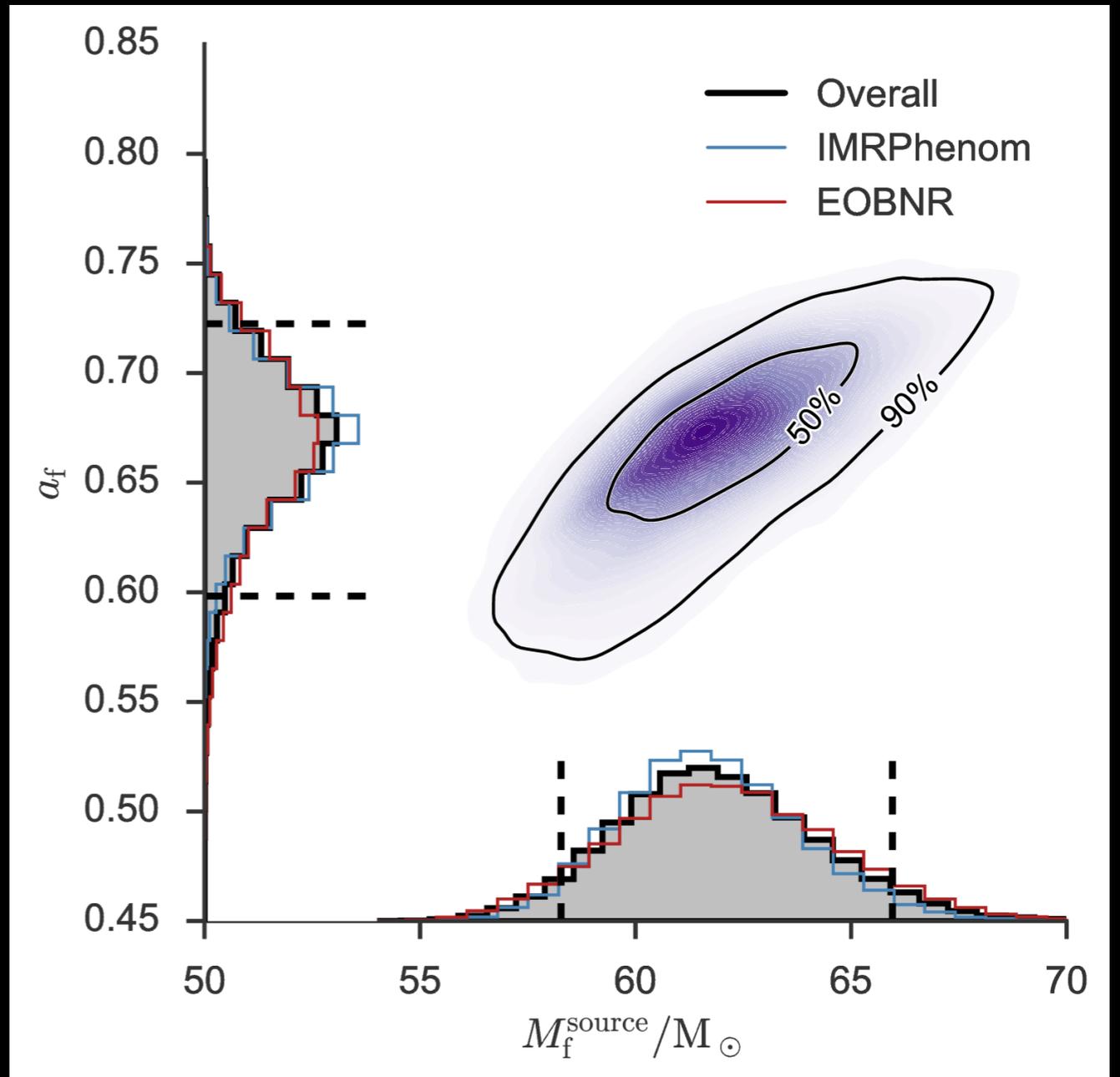
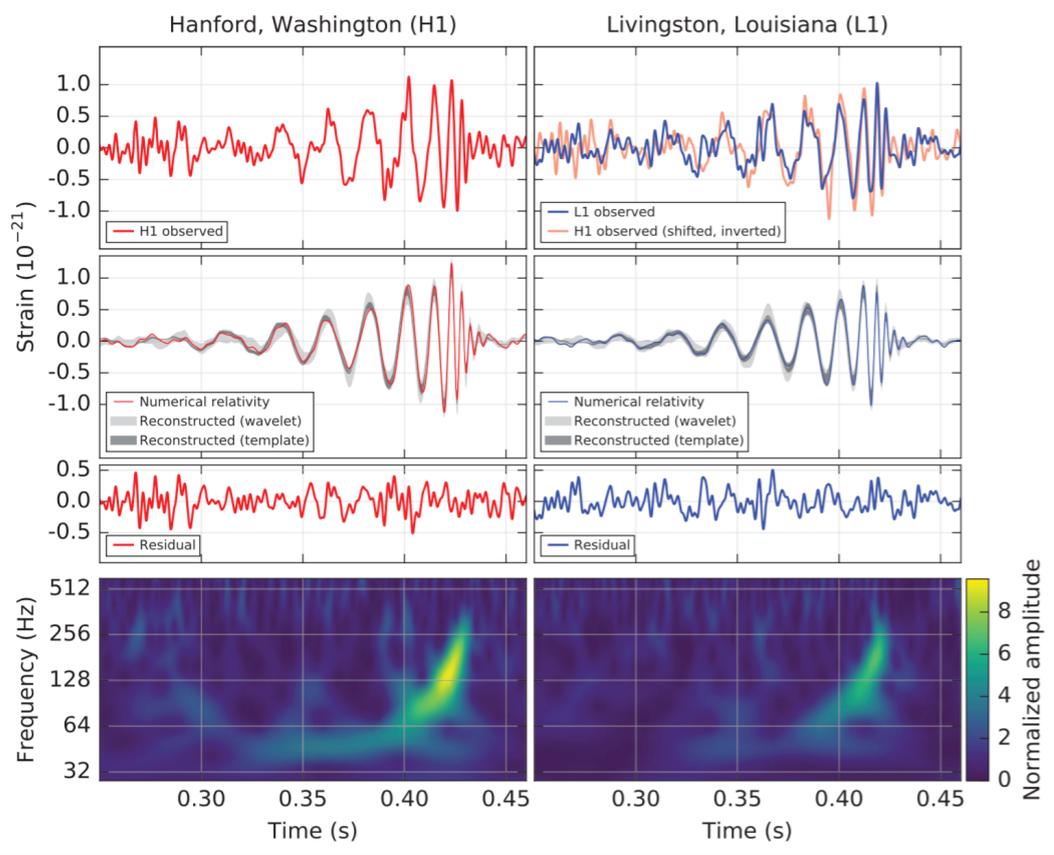


Parameter estimation



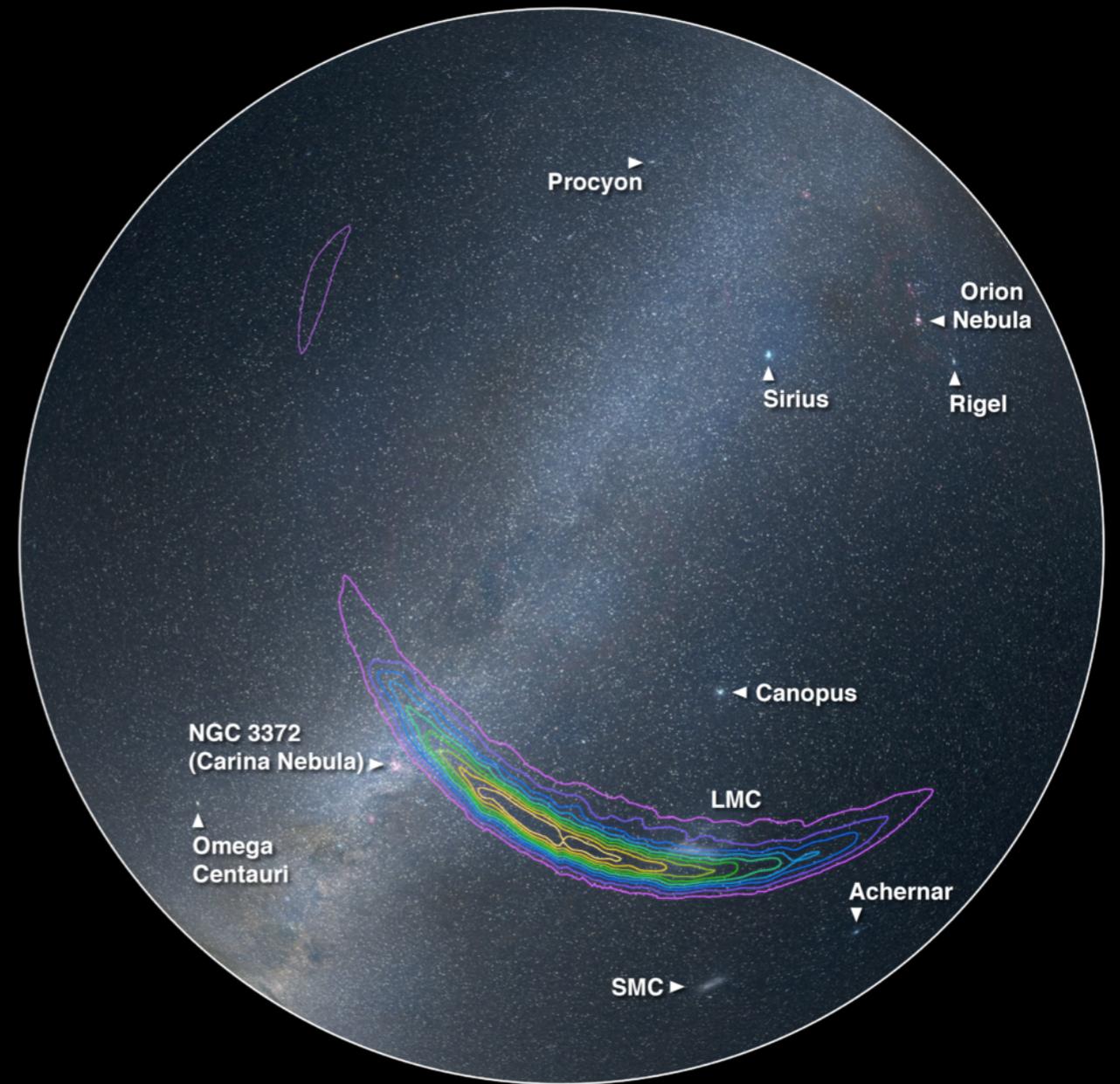
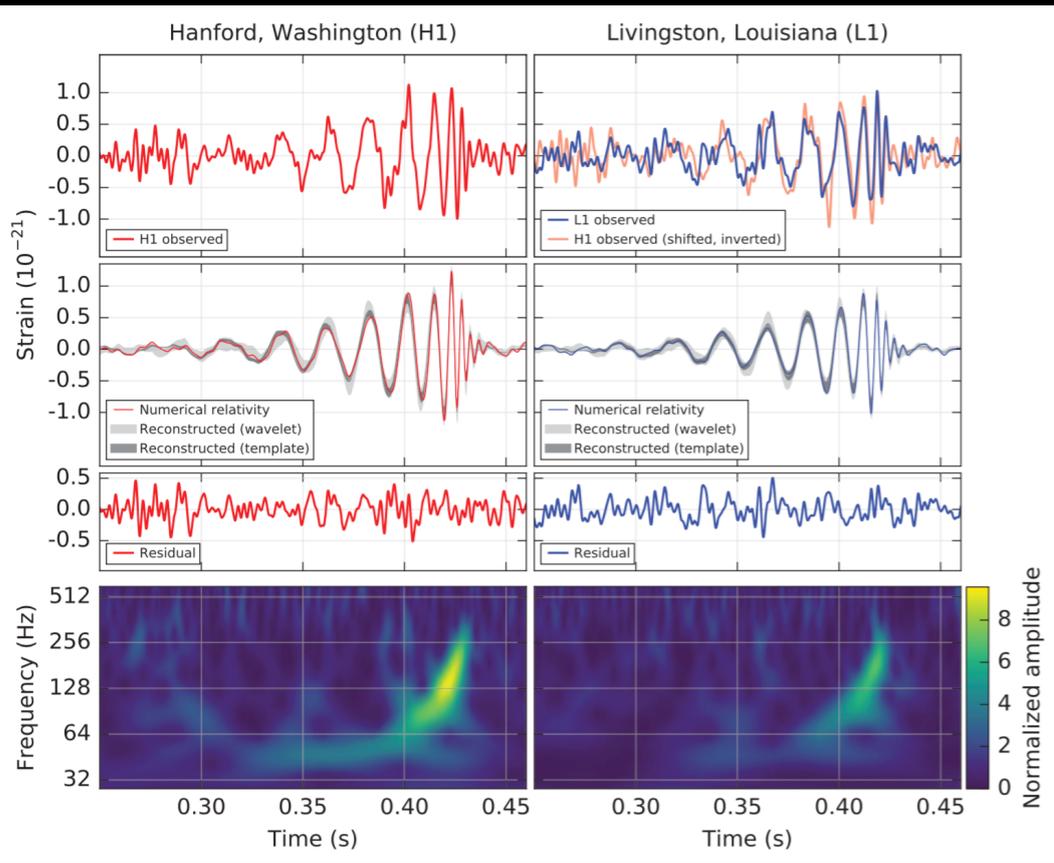
The Discovery: GW150914

Parameter estimation



The Discovery: GW150914

Parameter estimation



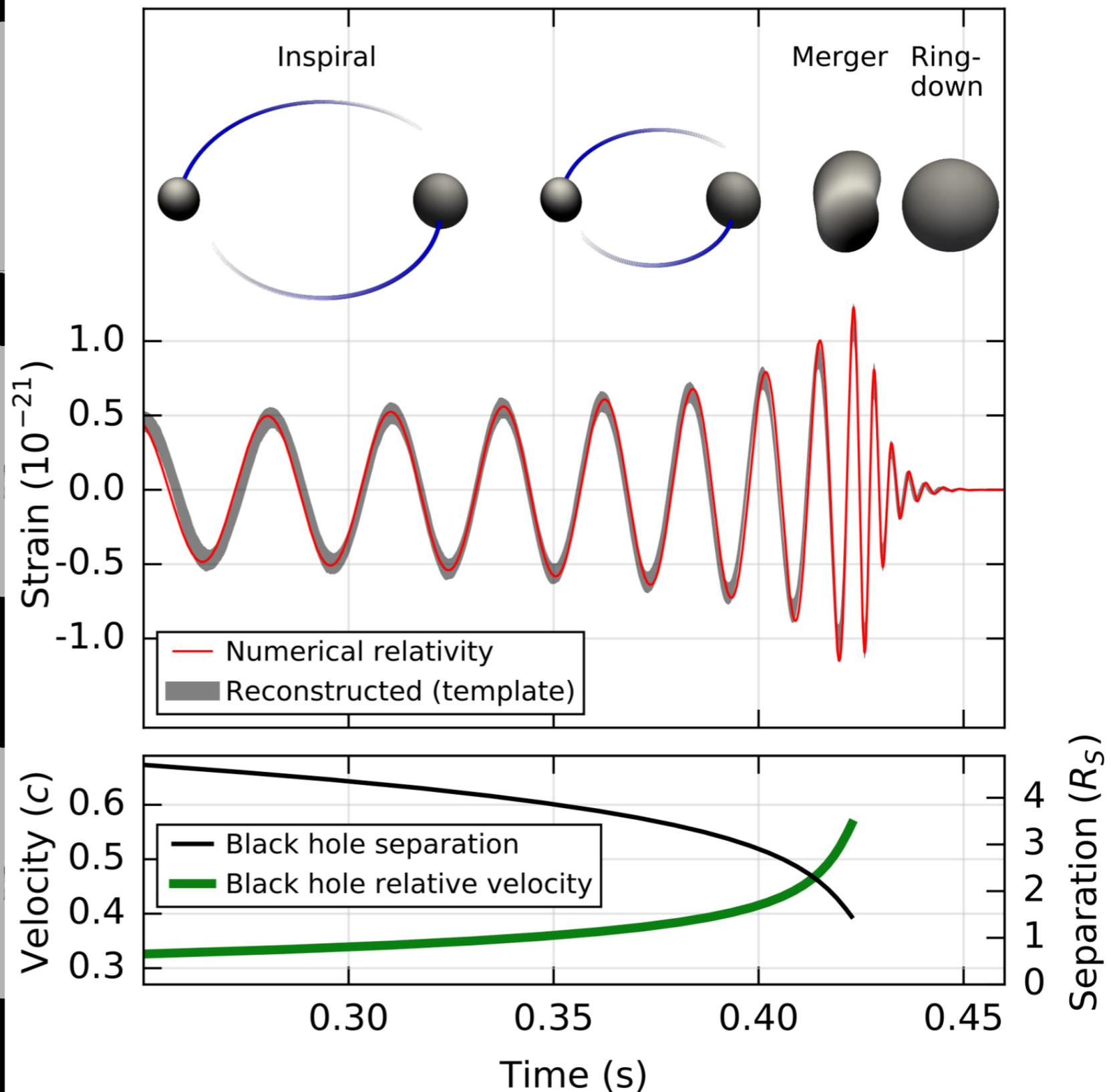
The Discovery: GW150914

The 3 stages of coalescence

Reconstructed waveform

Velocity and separation between the 2 initial BHs

Imagine: LVC



The Discovery: GW150914



1.3 billion years ago

GW150914 is generated by the merger of two black holes and begins its journey to Earth.
(credit: NASA)



2.5 million years ago

GW150914 is as far from Earth as the Andromeda Galaxy, our nearest neighbor galaxy.
(credit: Adam Evans)



50,000 years ago

GW150914 enters our own galaxy, the Milky Way.
(credit: Bruno Gill/ESO)



400 years ago

GW150914 is as far from Earth as Polaris, the North Star.



4.5 hours to go

GW150914 enters the Solar System and is as far from Earth as Pluto.
(credit: NASA/Johns Hopkins University APL/Southwest Research Institute)



September 14, 2015

GW150914 reaches Earth and is detected by Advanced LIGO before continuing its journey through the cosmos.

(credit: N. Cornish, J. Kanner, T. Littenberg, M. Millhouse)



800 million years ago

The first multicellular lifeforms evolve on Earth.
(credit: Kristian Peters)



65 million years ago

The Cretaceous-Paleogene extinction event wipes out three-quarters of the plant and animal species on Earth, including the dinosaurs.
(credit: Allie Caulfield)



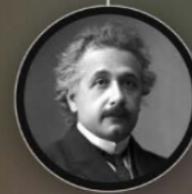
200,000 years ago

The first anatomically modern humans (*Homo sapiens sapiens*) evolve from archaic humans.
(credit: Magnetic-Hyena)



10,000 years ago

Humans begin to form permanent settlements.



100 years ago

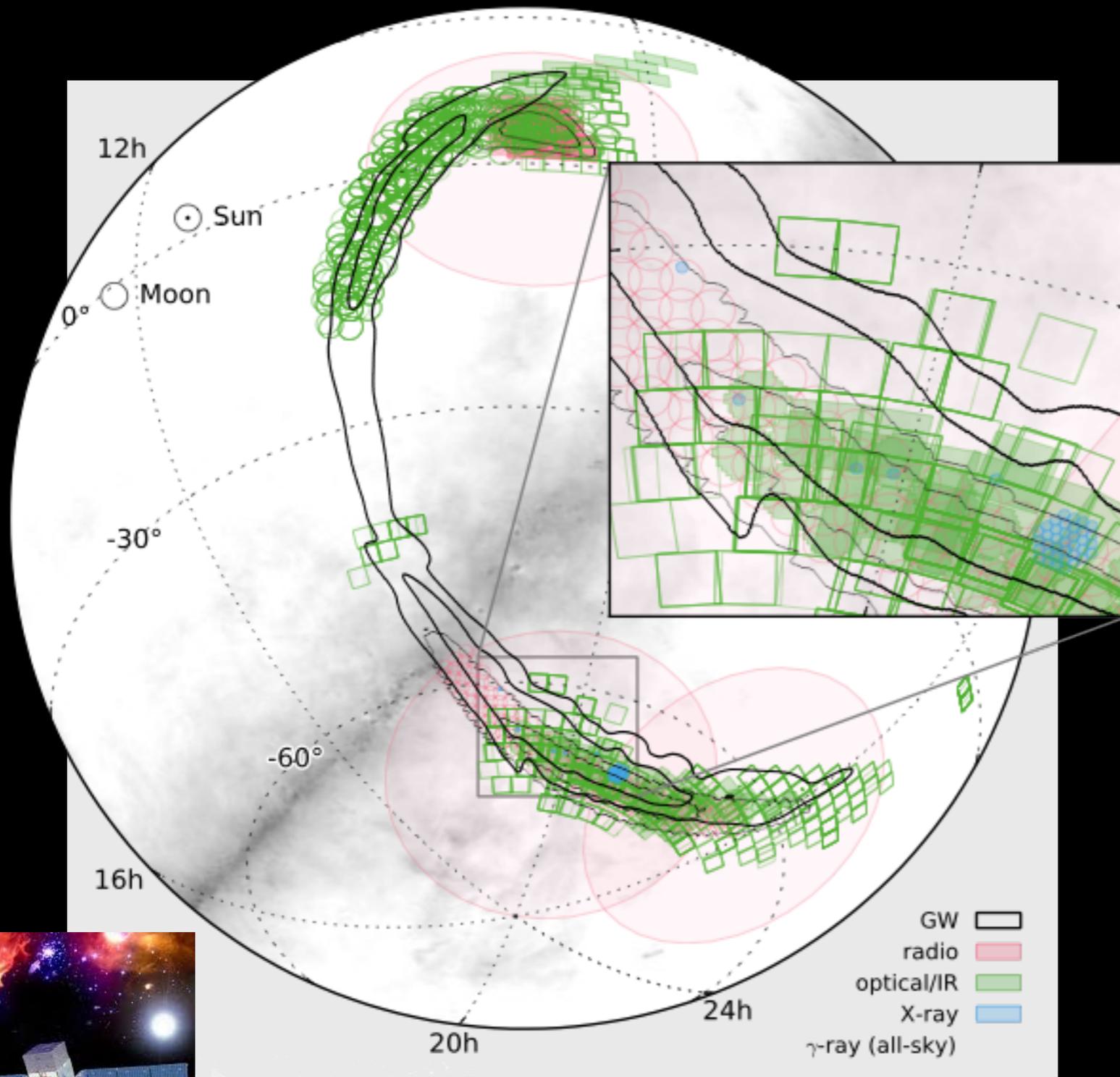
Albert Einstein develops the theory of general relativity, which includes a description of gravitational waves.



5 years ago

The initial LIGO and Virgo detectors complete their final science runs and shut down for upgrades to their advanced versions.
(credit: LIGO Laboratory)

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!



Main consequences

These are the most massive stellar BHs ever
seen

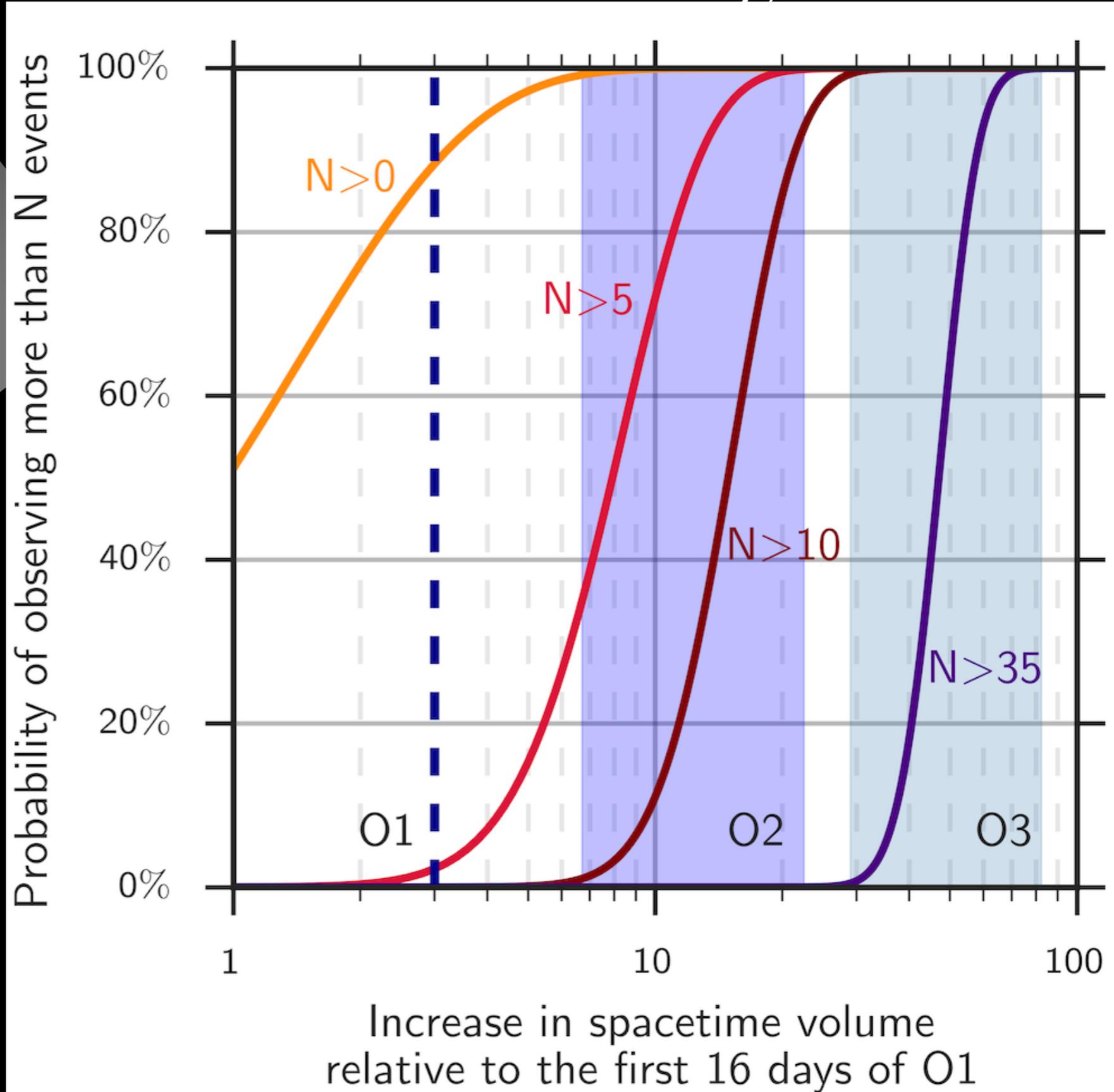
Weak winds -> Low metallicity

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

This is the first detection of signals
emitted by black holes

Main consequences

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





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GraWIToN



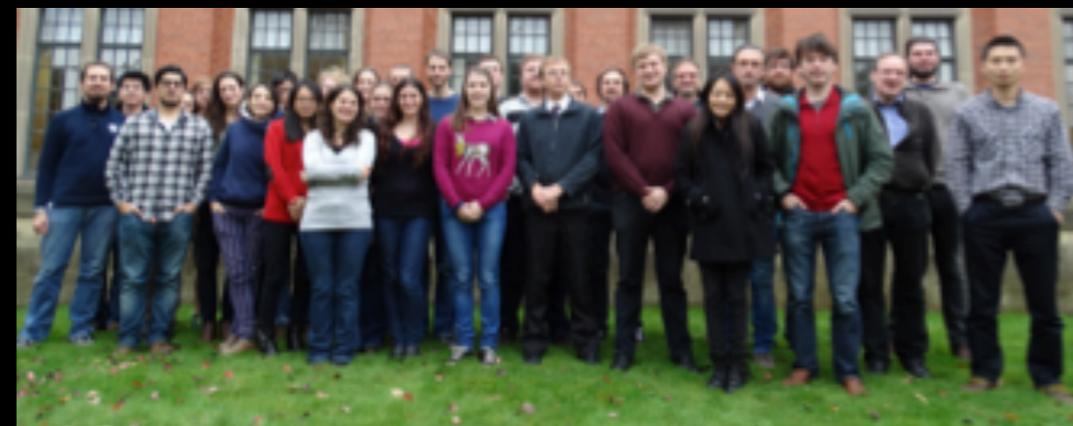
GW Initial Training Network

*Serena Vinciguerra 26 May 2016
Supervisors: Tlya Mandel, John Veitch*

Thank you for your attention

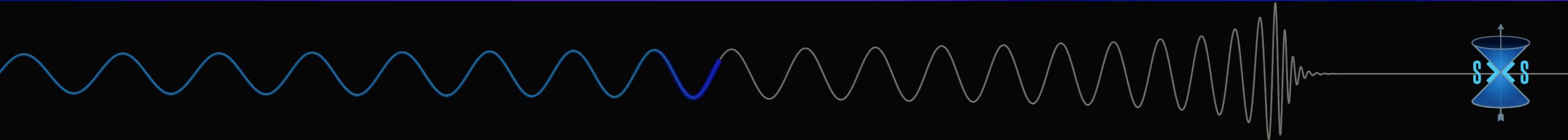
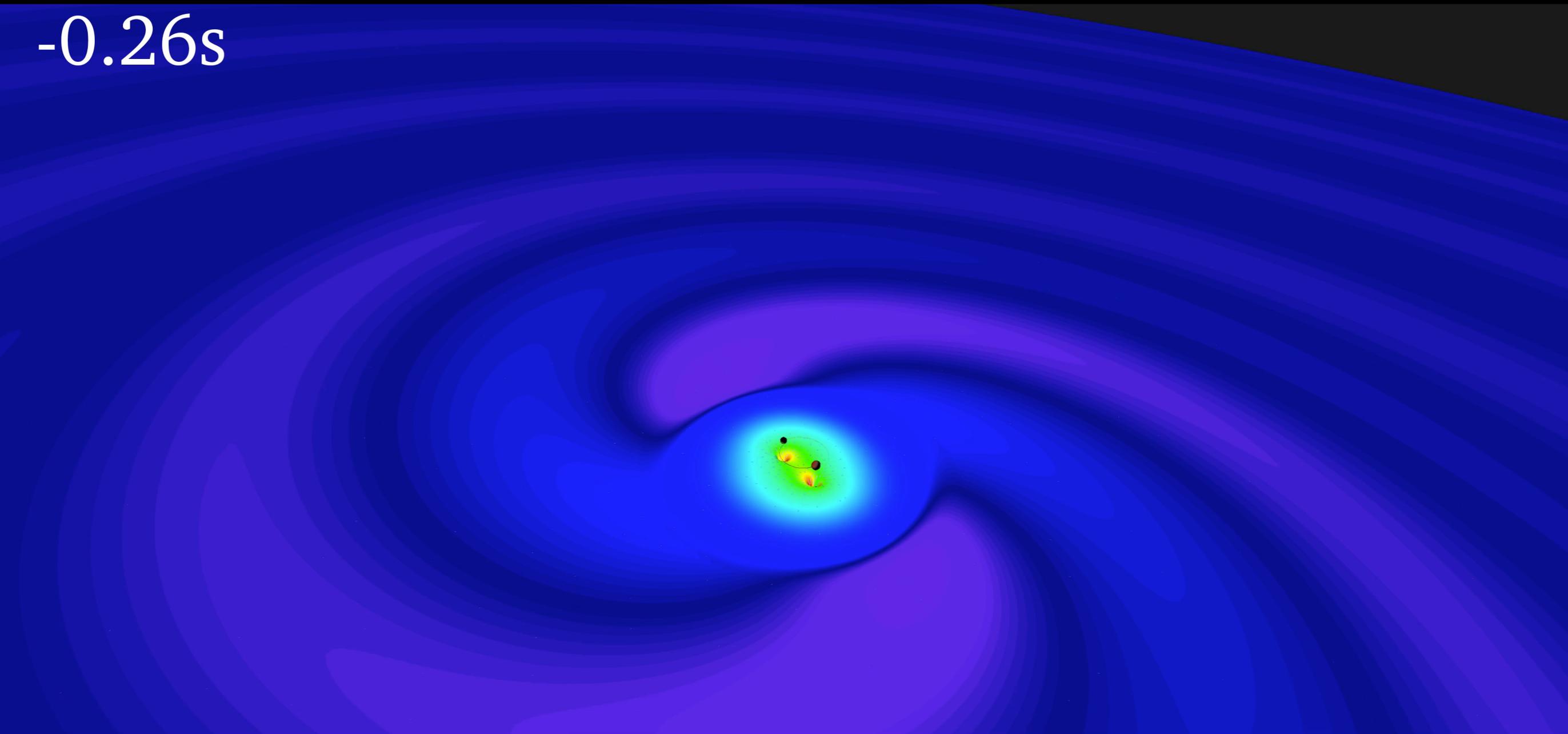
Thanks I. Mandel, J. Vetch, A. Freise, M. Branchesi and W. Far

Shree



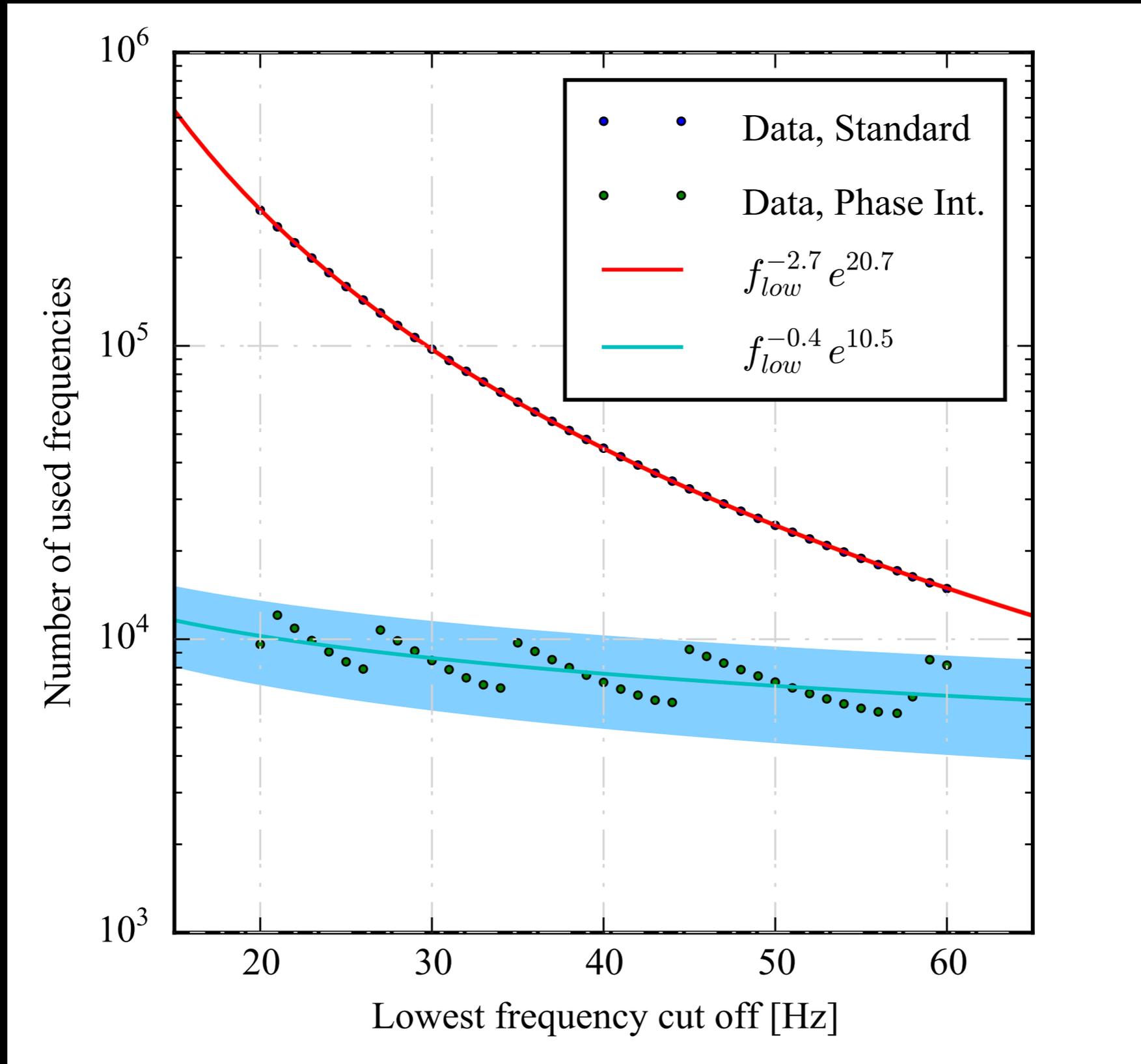
The Discovery: GW150914

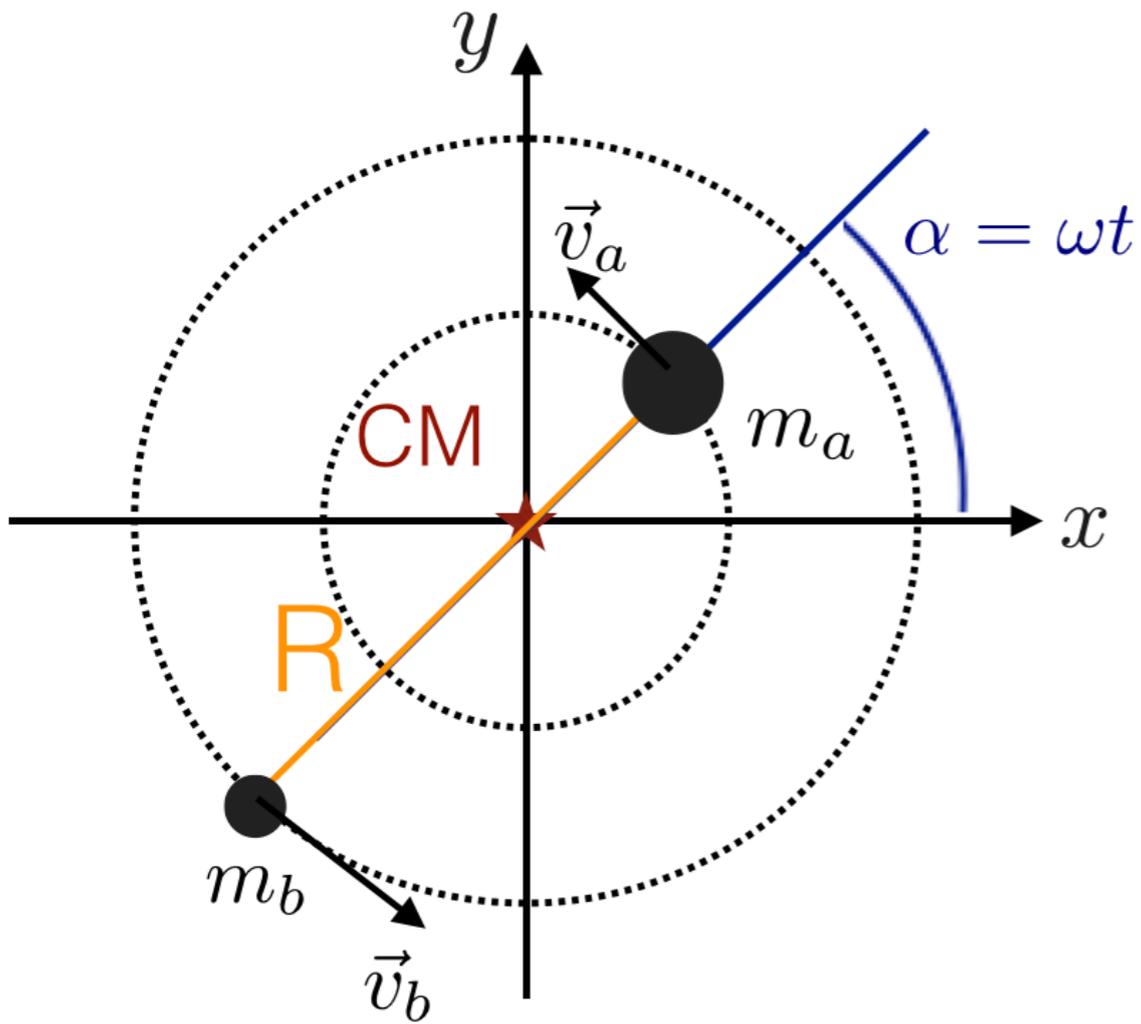
-0.26s



Video prodotto da: SXS

Results: Number-Gain in template generation





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

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

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

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

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

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