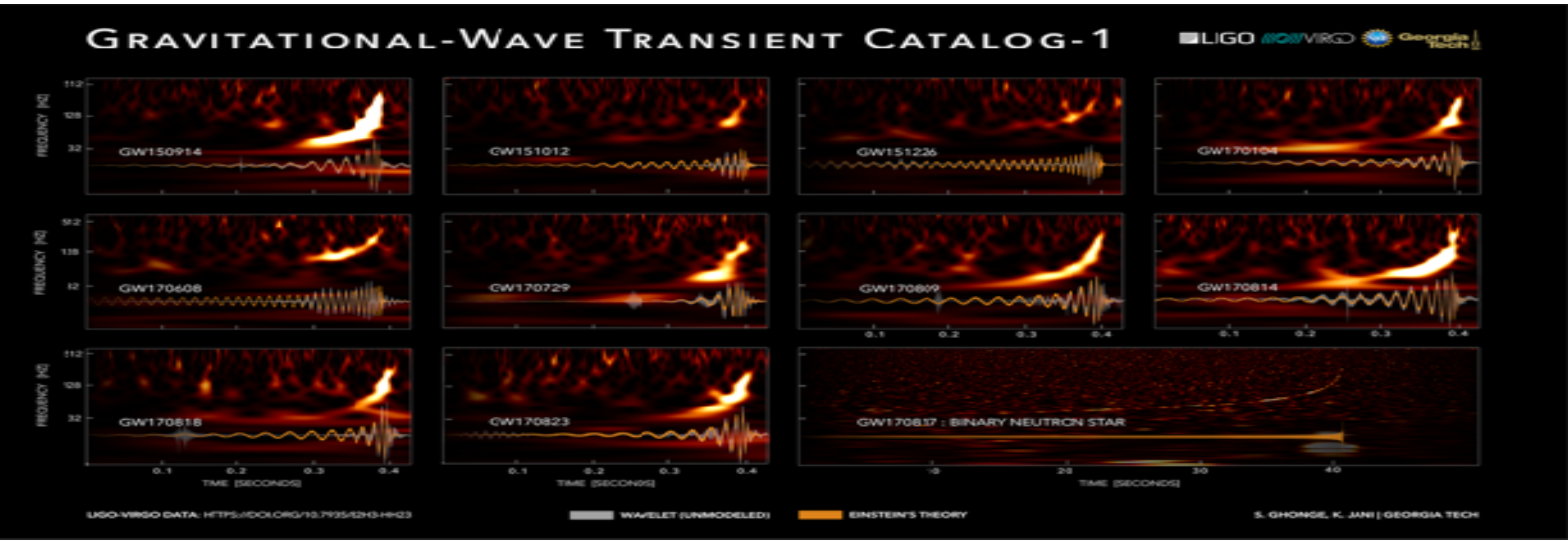
The Basics of compact binary searches



Ed Porter
APC/CNRS

LVC Open Data Workshop, APC-Paris, 8-10 April 2019

Topics Covered

- Part 1
  - Matched Filtering
  - CBC waveform modelling
  - Data treatment
- Part 2
  - O1/O2 detections
  - Fundamental physics and extreme matter
  - Astrophysics and Cosmology

Signal Processing and Matched filtering

What is matched filtering?

- GWs are analogous to 1D sound waves
- Optimal linear filter for weak signals buried in random Gaussian noise
- Also known as optimal or Wiener filtering
- Works by correlating a known signal model (template) with the data

Constructing the optimal linear filter

- Starting with data : $s(t) = h(t) + n(t) \quad , \; n(t) >> h(t)$

- Define the correlation between the data and a real filter as

$$C(\tau) = \int_{-\infty}^{\infty} dt\, s(t) F(t+\tau) = \int_{-\infty}^{\infty} df\, \tilde{s}(f) \tilde{F}^*(f) e^{2\pi i f \tau}$$

- To evaluate the signal-to-noise ratio (SNR), $\rho = \dfrac{S}{N}$

- we define the filtered signal

$$S = \langle C(\tau) \rangle = \int_{-\infty}^{\infty} df\, \langle \tilde{s}(f) \rangle\, \tilde{Q}^*(f) e^{2\pi i f \tau} = \int_{-\infty}^{\infty} df\, \tilde{h}(f) \tilde{Q}^*(f) e^{2\pi i f \tau}$$

- using $\langle n(t) \rangle = 0$

Constructing the optimal linear filter

- For stationary, Gaussian noise, the variance is

$$\left\langle N^2 \right\rangle = \left[\left\langle C^2(\tau)\right\rangle - \langle C(\tau)\rangle^2\right]_{h(t)=0} = \int_{-\infty}^{\infty} df df' \, \langle \tilde{n}(f)\tilde{n}*(f')\rangle \, \tilde{F}(f)\tilde{F}*(f')e^{2\pi\iota\tau(f-f')}$$

- Defining a two-sided power spectral density $\langle \tilde{n}(f)\tilde{n}*(f')\rangle = \delta(f-f')S_h(f)$

- we can now write $\left\langle N^2 \right\rangle = \int_{-\infty}^{\infty} df \, |\tilde{F}(f)|^2 S_h(f)$

- defining the SNR as $\rho = \dfrac{S}{N} = \dfrac{\int_{-\infty}^{\infty} df \, \tilde{h}(f)\tilde{F}*(f)e^{2\pi i f\tau}}{\left[\int_{-\infty}^{\infty} df \, |\tilde{F}(f)|^2 S_h(f)\right]^{1/2}}$

Constructing the optimal linear filter

- Defining a noise-weighted inner product

$$\langle a|b\rangle = 2\int_0^{\infty} \frac{df}{S_n(f)} \tilde{a}(f)\tilde{b}^*(f) + c.c.$$

- the SNR now becomes

$$\frac{S}{N} = \frac{\left\langle \tilde{h}(f)\,|\,S_n(f)\tilde{F}(f)e^{2\pi i f\tau}\right\rangle}{\left\langle S_n(f)\tilde{F}(f)\,|\,S_n(f)\tilde{F}(f)\right\rangle^{1/2}}$$

- To optimise the SNR, we require $\tilde{F}(f)\,||\,\tilde{h}(f)$
- allowing us to define the optimal linear filter as $\tilde{F}(f) = \frac{\tilde{h}(f)}{S_n(f)} e^{-2\pi i f\tau}$
- and the optimal SNR as $\rho_{opt} = \langle h|h\rangle^{1/2}$

Response to a GW

- The response at each detector is

$$h_i(t) = h_+(t+\tau_i)F_i^+ + h_\times(t+\tau_i)F_i^\times$$

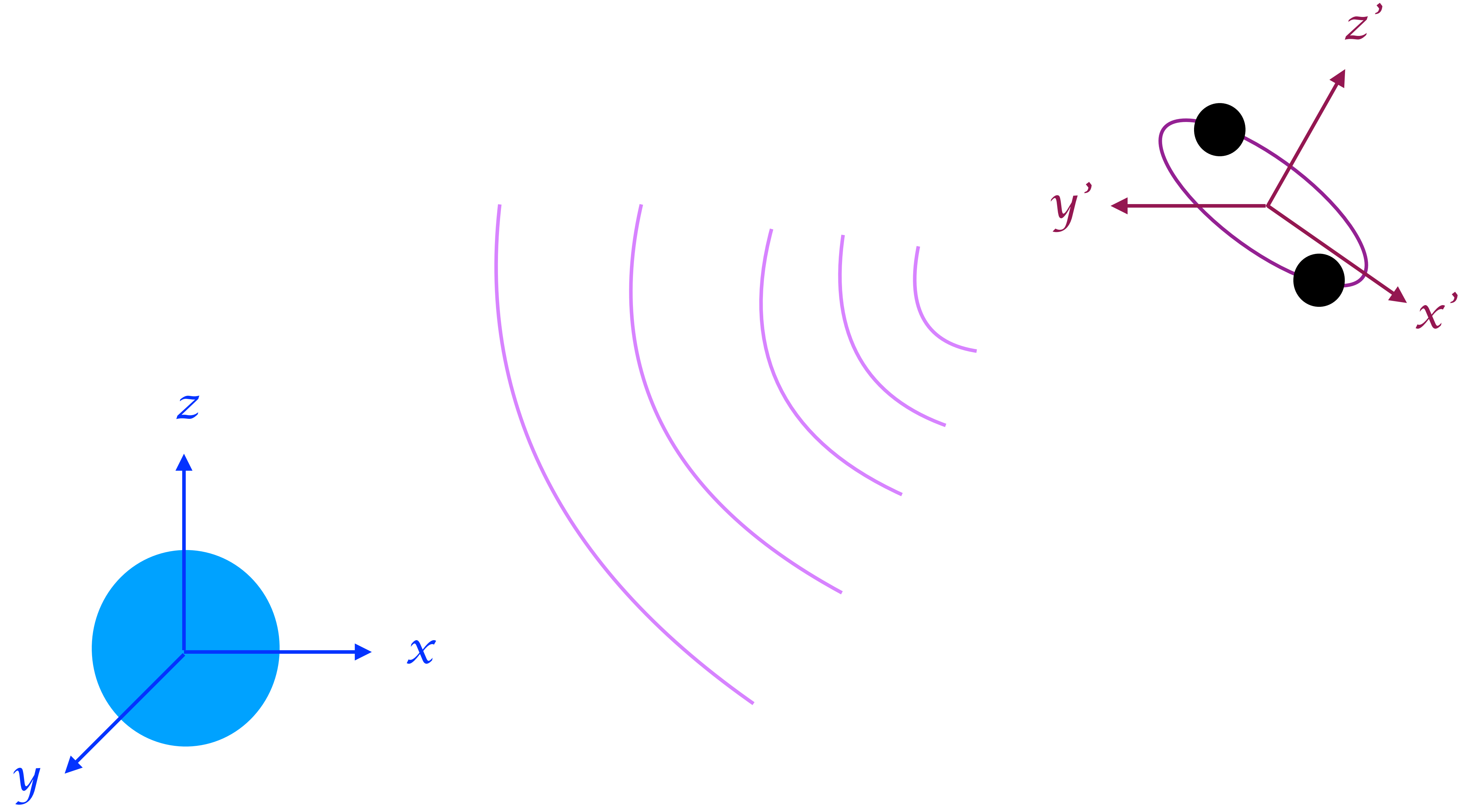
- where $(h_+, h_\times)$ are the GW polarisations

- and $(F^+, F^\times)$ are the detector pattern response

- In general, the GWs are defined by 15-17 parameters that we can define as extrinsic and intrinsic

Extrinsic Parameters (Positional)

$$h_i(t) = h_+(t+\tau_i)F_i^+ + h_\times(t+\tau_i)F_i^\times$$



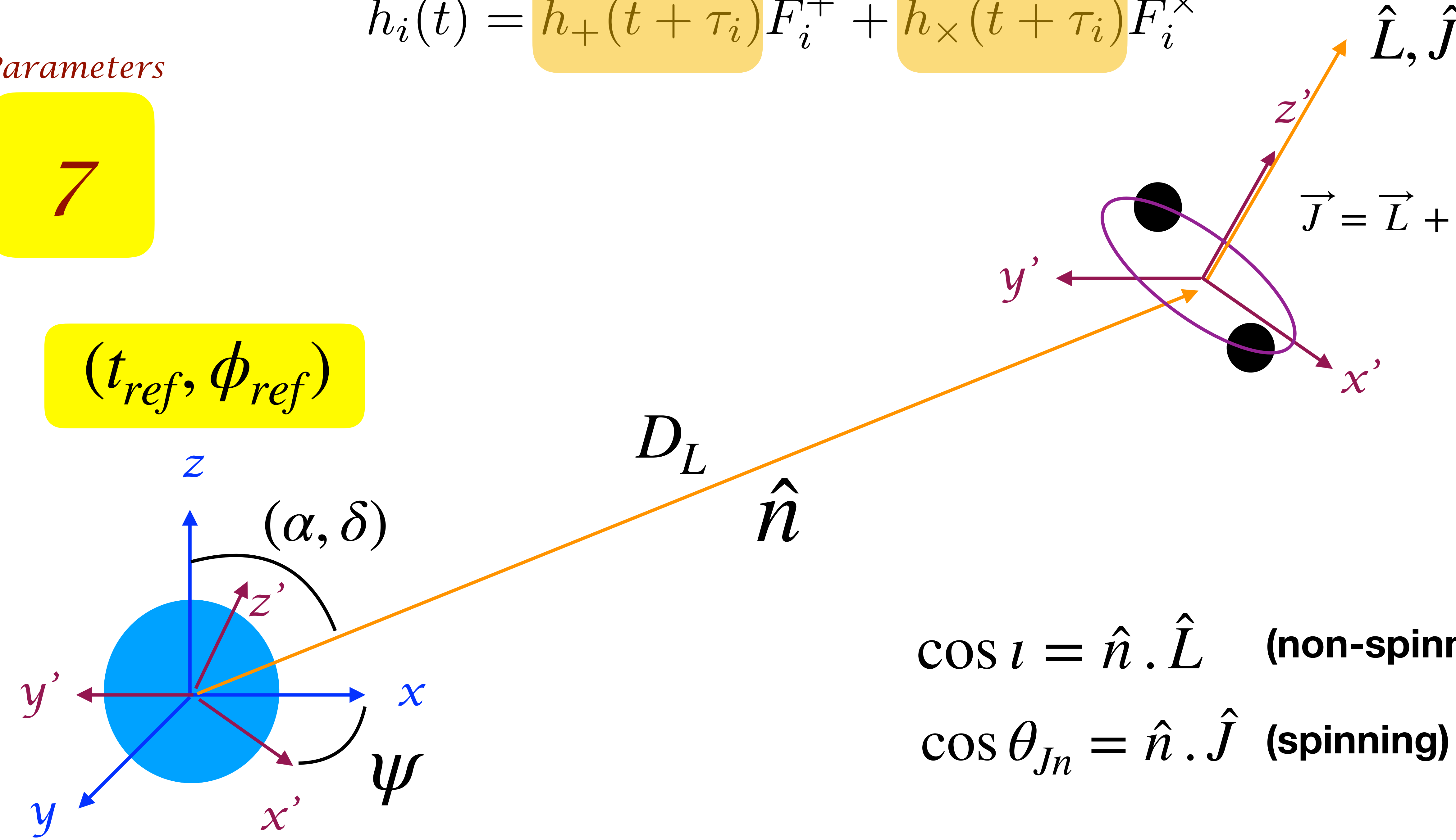
Reference Time and Phase

$$h_i(t) = h_+(t+\tau_i)F_i^+ + h_\times(t+\tau_i)F_i^\times$$

Parameters

7

(t_{ref}, ϕ_{ref})

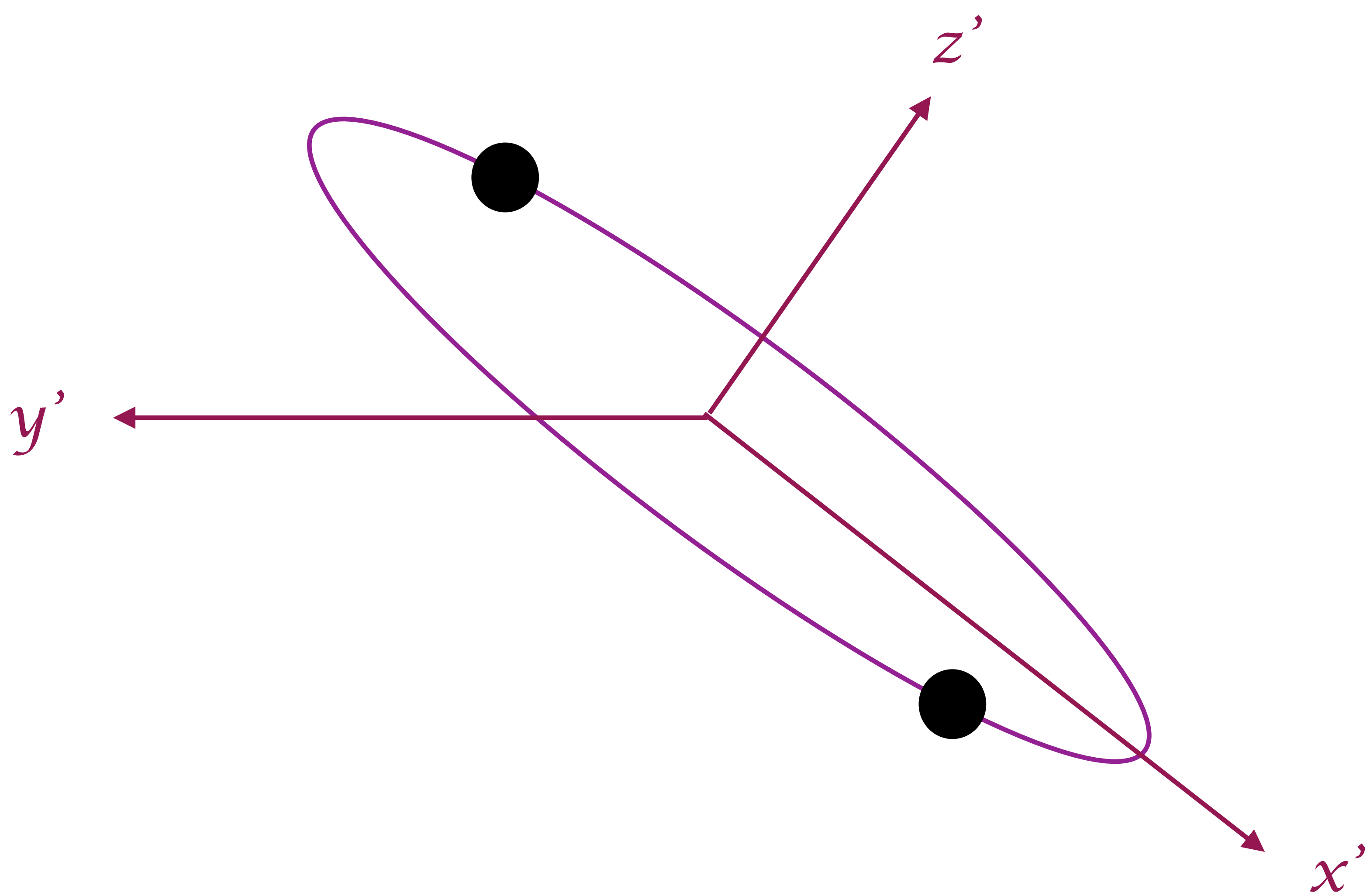


$\cos\iota = \hat{n}\,.\,\hat{L}$ **(non-spinning)**

$\cos\theta_{Jn} = \hat{n}\,.\,\hat{J}$ **(spinning)**

Intrinsic Parameters (Dynamical)

$$h_i(t) = h_+(t+\tau_i)F_i^+ + h_\times(t+\tau_i)F_i^\times$$



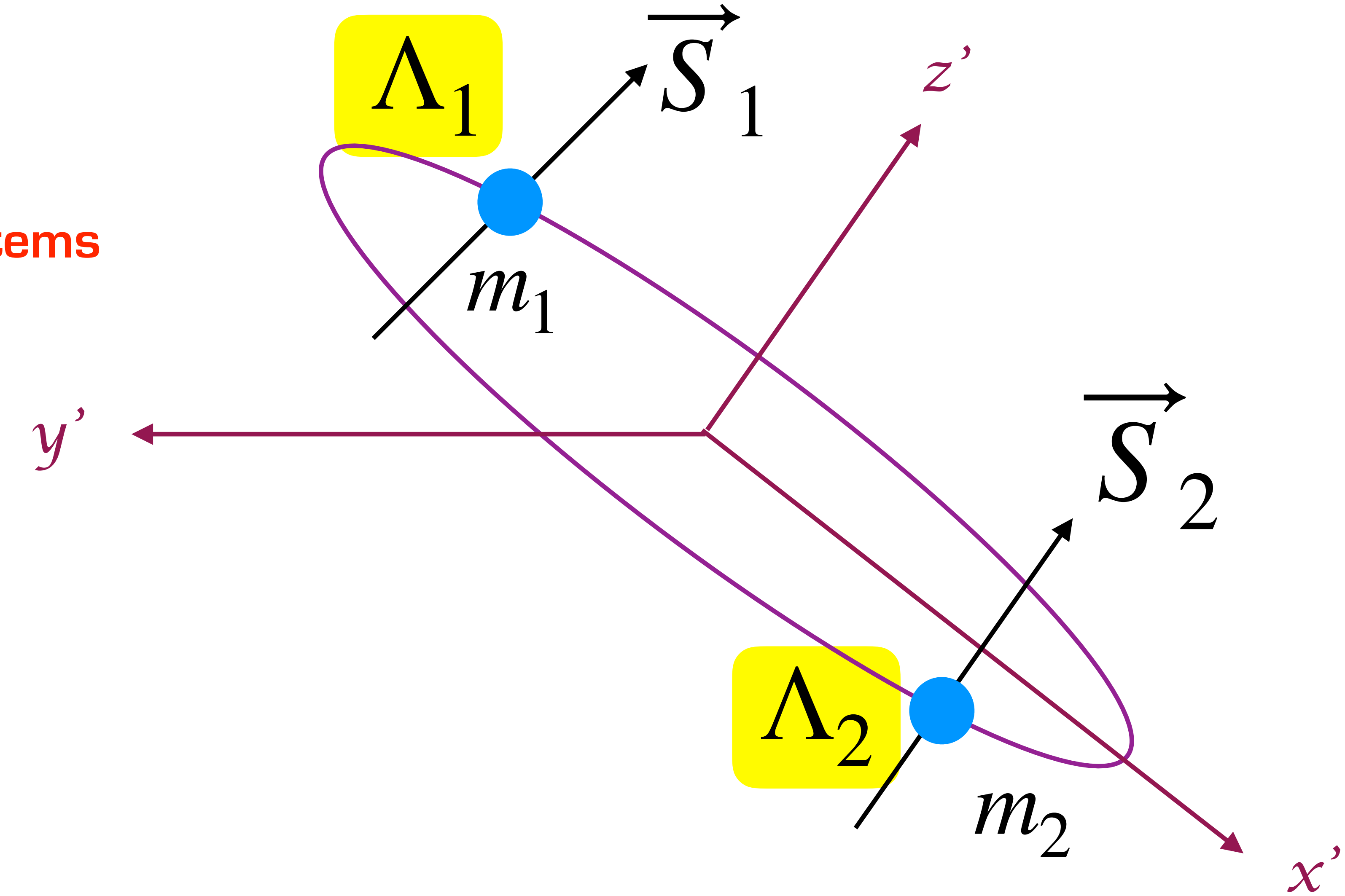
Intrinsic Parameters (Dynamical)

$$h_i(t) = h_+(t+\tau_i)F_i^+ + h_\times(t+\tau_i)F_i^\times$$

Parameters

17

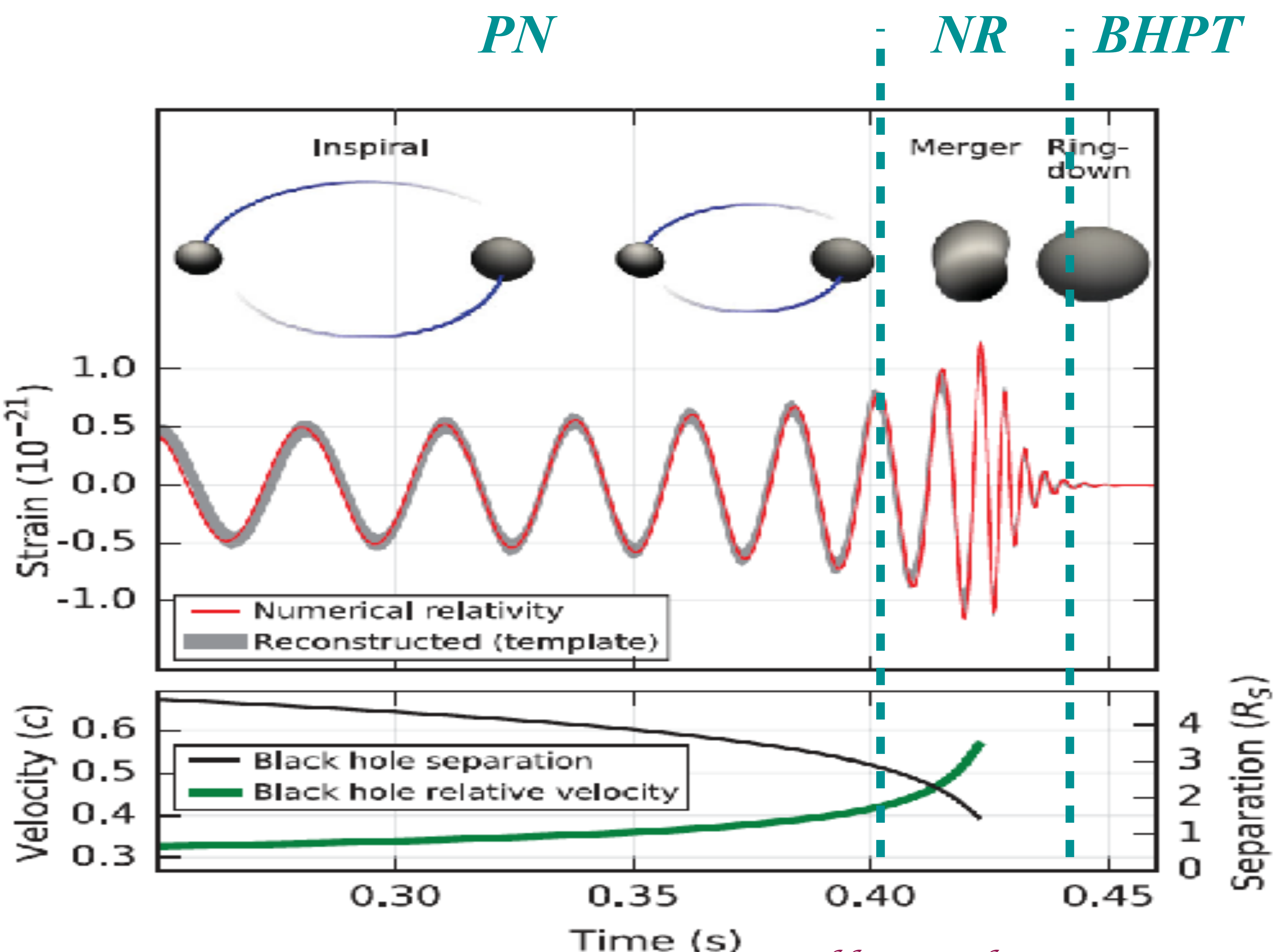
For BNS systems



Modelling the Phase

- Remember, matched filtering needs phase coherence
- Newtonian mechanics : analytic solution to 2-body problem, no solution to the generic 3-body problem
- GR : no solution to the 2-body problem
- Modelling requires a combination of analytic and numerical relativity

Time-Domain Morphology of a CBC Signal



Abbott et al, PRL 116, 061102 (2016)

Inspiral

- Wide separation, i.e. $v_{orb} \ll c$
- To start we can write the TD polarisations as

$$h_+(t) = \frac{2(1+\cos^2(\iota))m\eta}{D_L}\cos\Phi(t) \;\; , \;\; h_\times(t) = -\frac{4\cos(\iota)m\eta}{D_L}\sin\Phi(t)$$

- where $\eta = m_1 m_2/m^2$, and $\Phi(t) \equiv \Phi_{GW}(t) = 2\Phi_{orb}(t)$
- We can then write the GW phase as a PN expansion

$$\Phi(t) = \phi_N(t) + \phi_2(t) + \phi_3(t) + \ldots .$$

- in terms of a small parameter $v = (\pi m f)^{1/3}$, where f is the GW frequency, and the sub-script corresponds to the power of (v/c) correction

Inspiral

- In the early inspiral, we can assume $\dot{f}_{orb}/f_{orb}^2 \ll 1$
- This allows us to use the energy balance equation $F(t) = -m\dfrac{dE(t)}{dt}$
- and calculate the phase evolution

$$\frac{d\phi}{dt} - \frac{v^3}{m} = 0$$

$$\frac{dv}{dt} + \frac{F(v)}{mE'(v)} = 0$$

$\Leftrightarrow$

$$t(v) = t_{ref} + m\int_v^{v_{ref}} dv\, \frac{E'(v)}{F(v)}$$

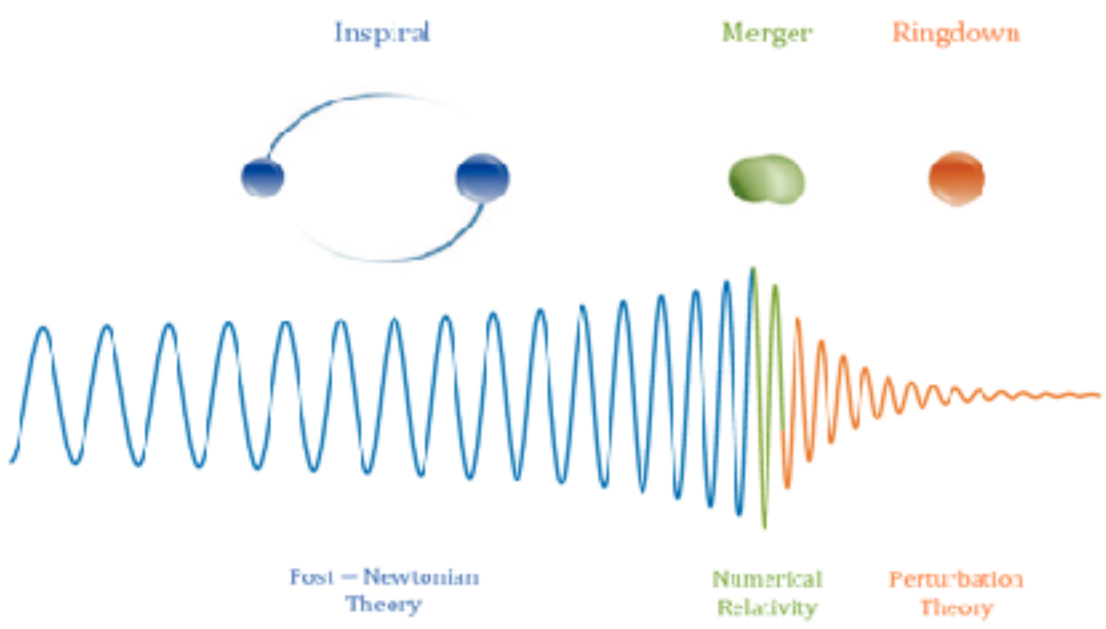
$$\phi(v) = \phi_{ref} + \int_v^{v_{ref}} dv\, v^3 \frac{E'(v)}{F(v)}$$

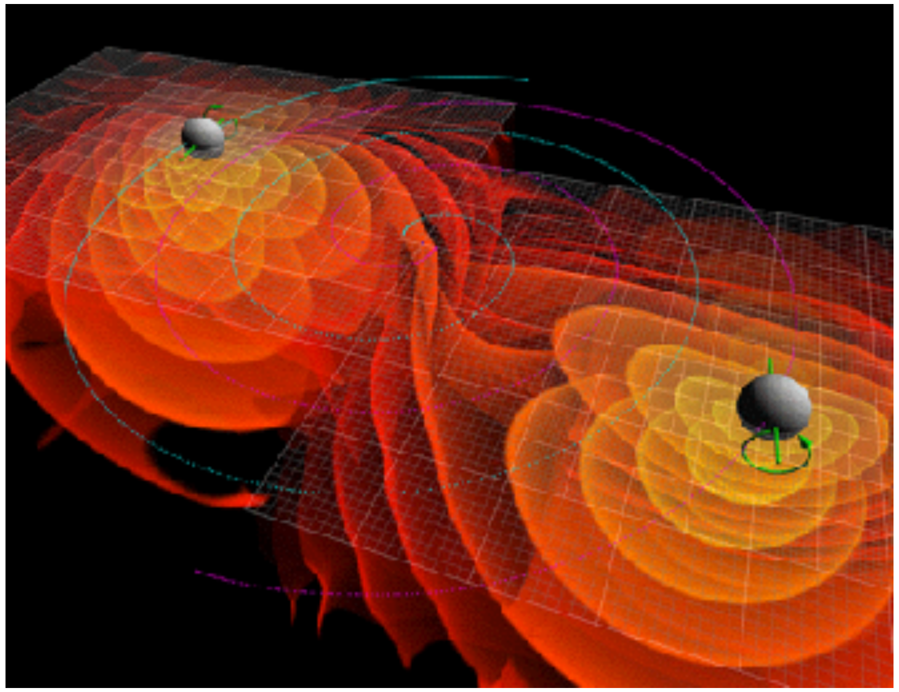
Limits of the PN expansion

- Both $E'(v)$ and $F(v)$ have a PN (power) series solution
- How we treat the ratio $E'(v)/F(v)$ leads to different PN families
- Each PN series is asymptotically divergent, meaning…
  - …different families have differing levels of accuracy,
  - …a higher approximation does not guarantee higher accuracy,
  - …the PN approximation should break down at the LSO $(\sim R=6M)$
  - …but in fact, breaks down much sooner $(R\sim 12M)$

Late Inspiral / Merger

- Both the late inspiral and merger need to solved numerically
- A relatively small number of cycles can take months to generate on a supercomputer



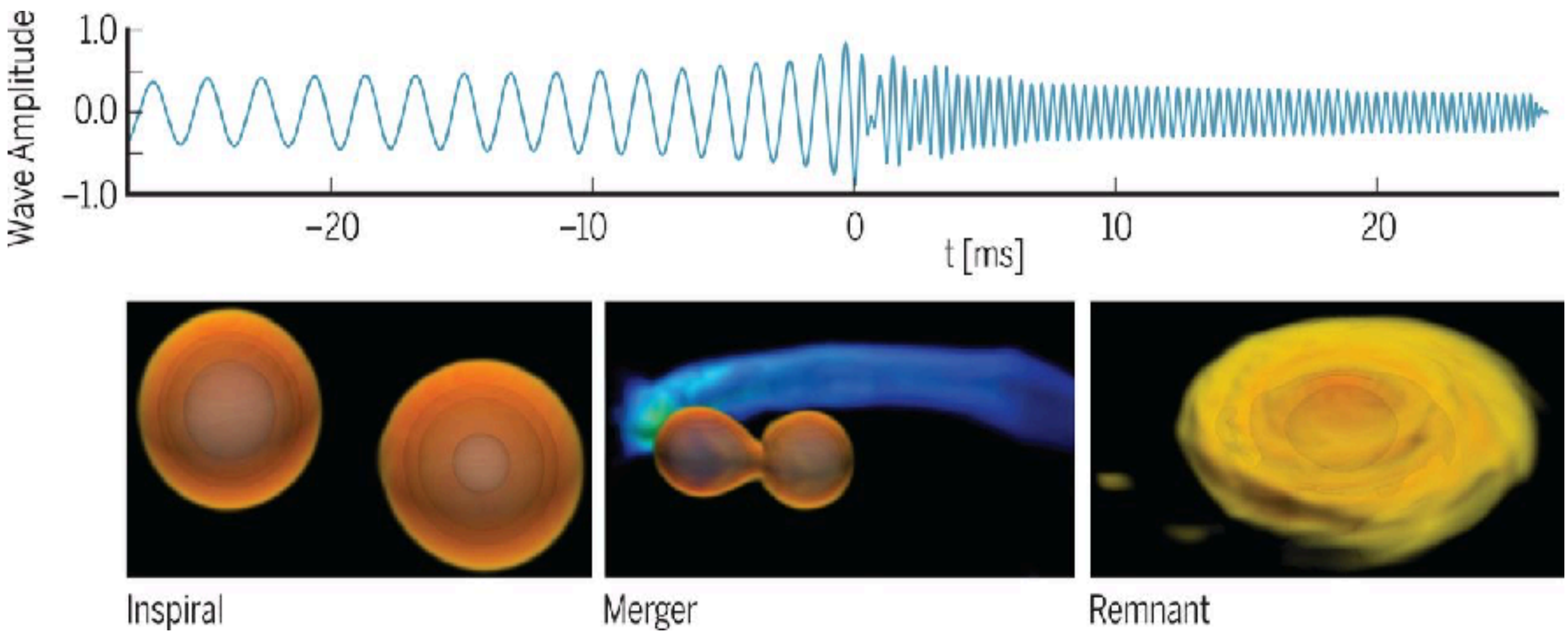


Late Inspiral / Merger

video of NR simulation by SXS

Late Inspiral / Merger

- NR becomes even more important as we try and simulate BNS and NSBH systems



B. Brugmann, Science 361, 336 (2018)

Ringdown

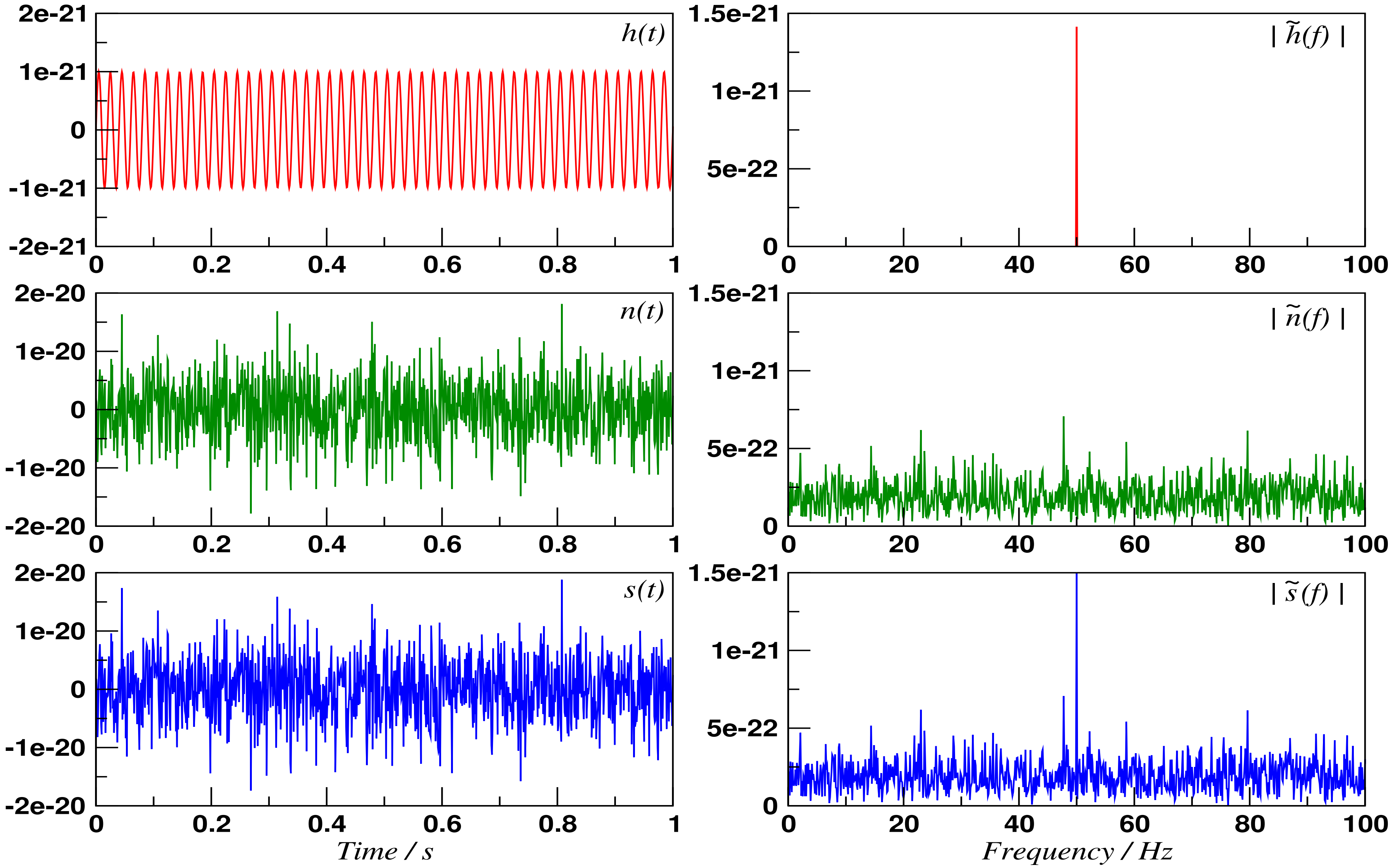
- The final black hole rings like a bell that's been struck
- An analytic solution exists using black hole perturbation theory
- The energy is radiated in a series of quasi-normal modes
- These modes can be used to test the no-hair theorem
- No evidence of the QNMs as of yet

Hybrid Waveforms

- NR waveforms are expensive to generate and use
- For efficient data analysis, we use approximate analytical solutions
  - EOB - solves Hamilton's equations along the trajectory. Calibrated using NR waveforms
  - IMRPhenom - frequency domain analytic waveform, also calibrated using NR waveforms
- As we don't know if our waveforms are perfectly accurate, different families allow us to keep systematics under control
- New waveform families include eccentricity, tidal forces, precession etc.

Treating the Data

- Easiest to work in Fourier domain
- e.g. Sine-wave with f=50 Hz buried in random Gaussian noise



Signal Only

Noise Only

Signal + Noise

Fourier Domain Waveforms

- Stationary phase approximation
- Start with a generalised Fourier integral $I = \int F(\omega)\, e^{i\,\varphi(\omega)}\, d\omega$
- Assume $F(\omega)$ varies slowly compared to $\varphi(\omega)$ .As the phase rapidly varies, the integral averages to zero except where $\varphi(\omega)$ has an extremum
- So find points where $d\varphi/d\omega = 0$ and Taylor expand the phase

$$\varphi(\omega) = \varphi(\omega_{sp}) + \frac{1}{2}\varphi^{''}(\omega - \omega_{sp})^2 + \ldots$$

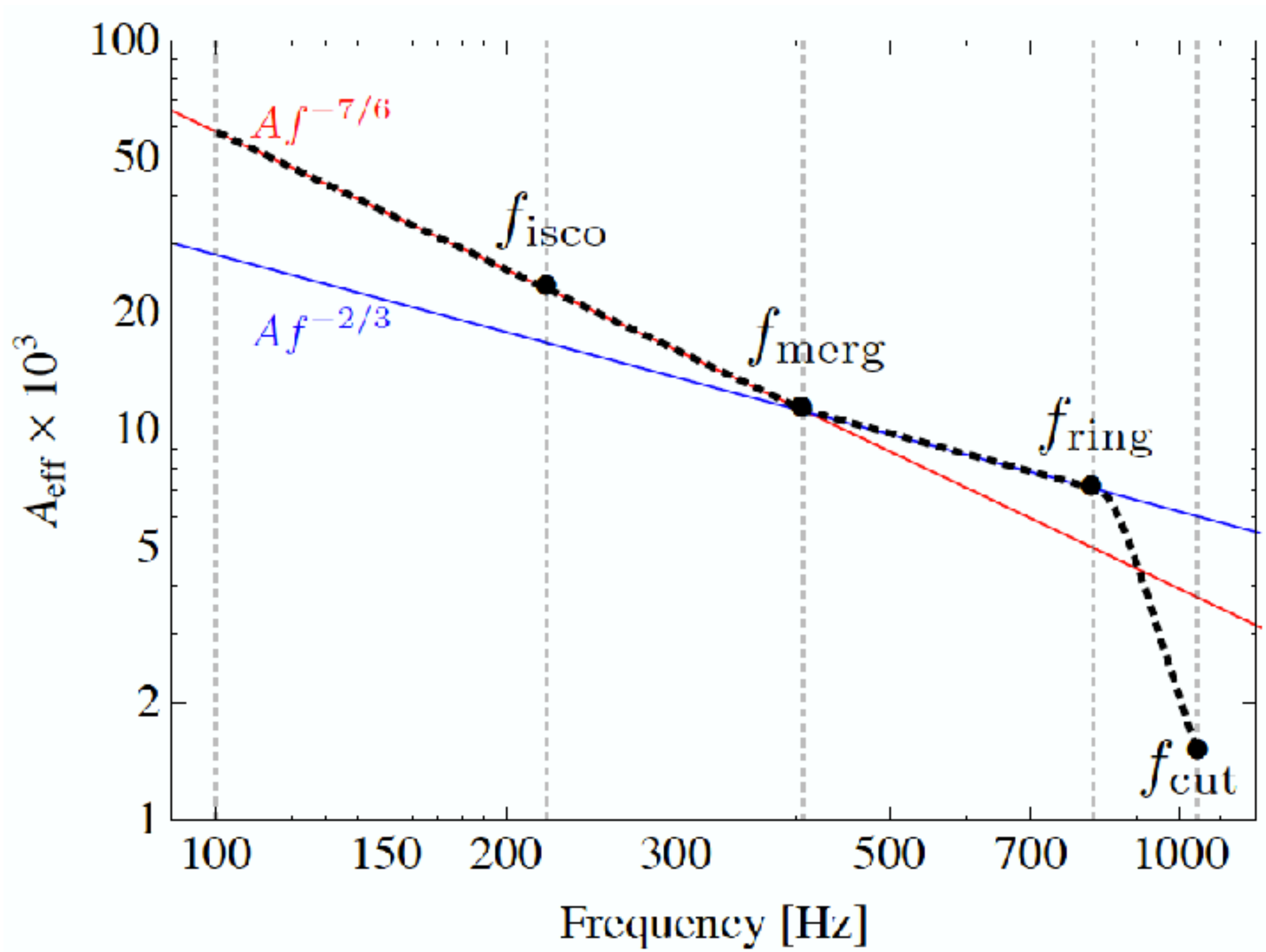
- Evaluate the integral in the vicinity of extrema, and sum if more than one saddle point

$$I = F(\omega_{sp})\, e^{i\,\varphi(\omega_{sp})} \int e^{\frac{i}{2}\,\varphi(\omega-\omega_{sp})^2}\, d\omega$$

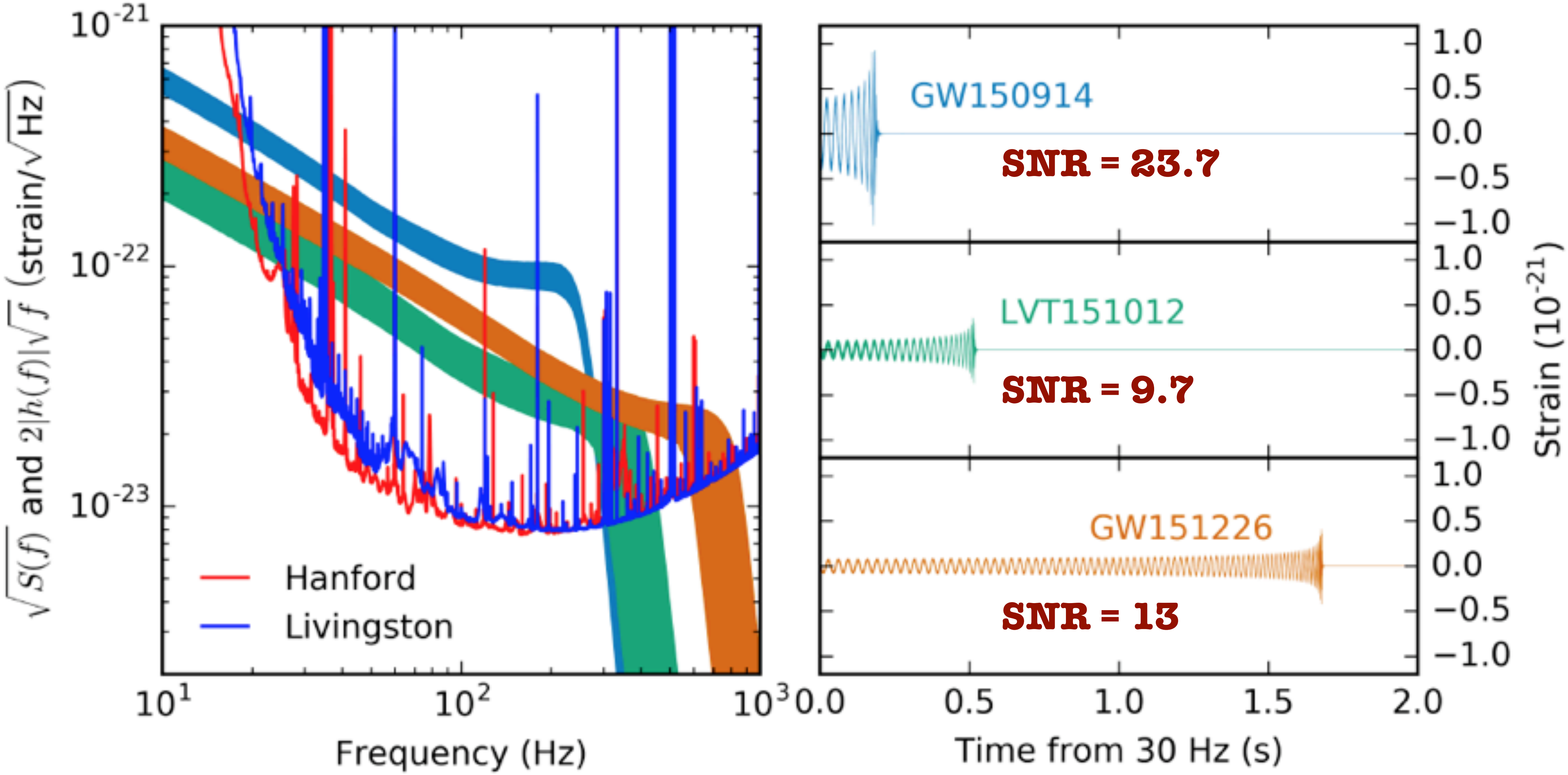
- Fresnel type integral with standard solution, leading to

$$\tilde{h}\left(f\right) = A\, f^{-7/6} e^{i\,\varphi\left(f\right)}$$

Frequency Domain CBC Waveform Morphology



Waveform Comparisons



Abbott et al, PRX 6, 041015 (2016)

Sampling the data

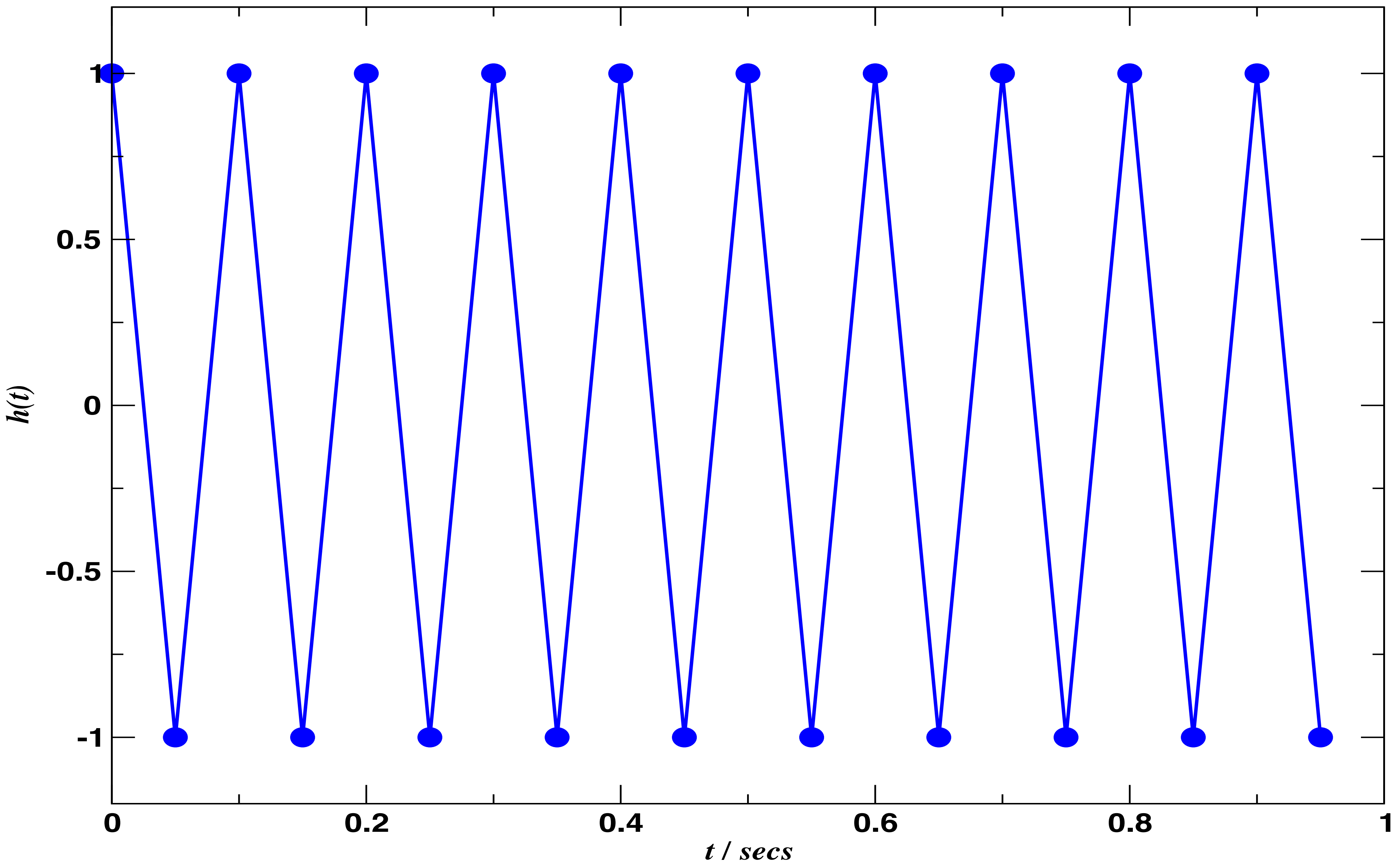
- Our analysis is best represented in the Fourier domain
- So given a continuous signal *h(t)*, the FT is $\tilde{h}(f) = \int_{-\infty}^{\infty} dt\, h(t) e^{-2\pi i f t}$
- However, we need a digital representation, i.e. $h(t) \Rightarrow h_j = h(t_j)$
- Given a sampling frequency f_s, we define $\Delta t = 1/f_s$
- With time domain data of N samples, total observation time $T_{obs} = N\,\Delta t$, the discrete FT is given by
- $\tilde{h}_k = \sum_{j=0}^{N-1} h_j e^{-2\pi i jk/N}$ where each sample has a frequency $f_k = k / T_{obs}$
- But how do we choose f_s ?

Sampling the data

- Nyquist theorem prescribes how to digitally represent a continuous signal
- It defines a critical or Nyquist frequency taken to be the highest frequency content of the signal
- Define:
  - Nyquist frequency - $f_{Nyq} \equiv f_{max}$
  - Sampling frequency - $f_s \geq 2f_{Nyq}$
  - Sampling period - $\Delta t = 1/f_s$
- Sampling at less than twice the Nyquist frequency leads to "aliasing"
- For GWs, if the sampling frequency is $f_s = 4096\ Hz$, the highest frequency signal we can model is $f_{max} = 2048\ Hz$

Sampling the data

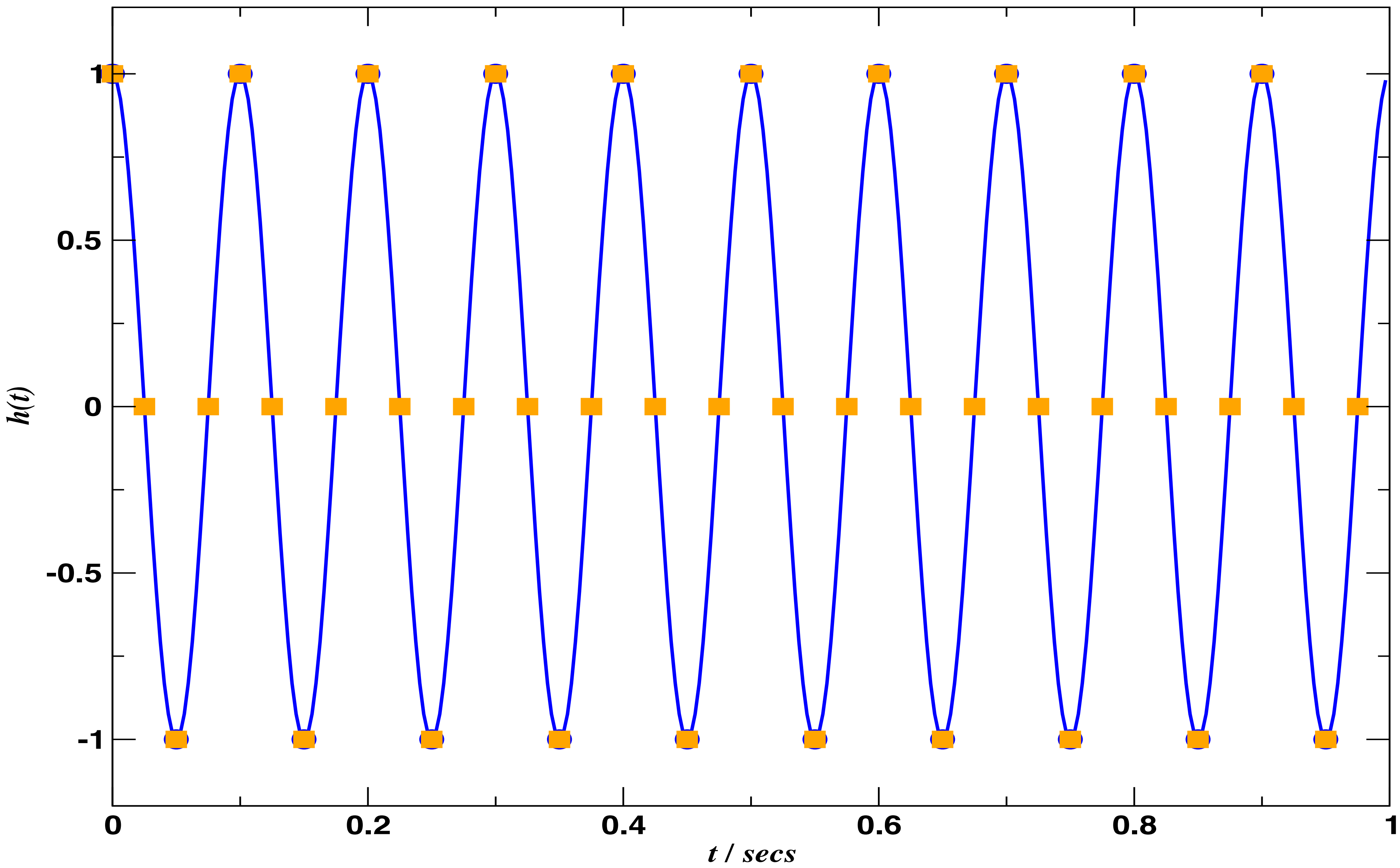
- Example : sine-wave with $f = 10\ Hz$, $T_{obs} = 1\ sec$, $dt = 1/f_s$



$f_s = 2f$

Sampling the data

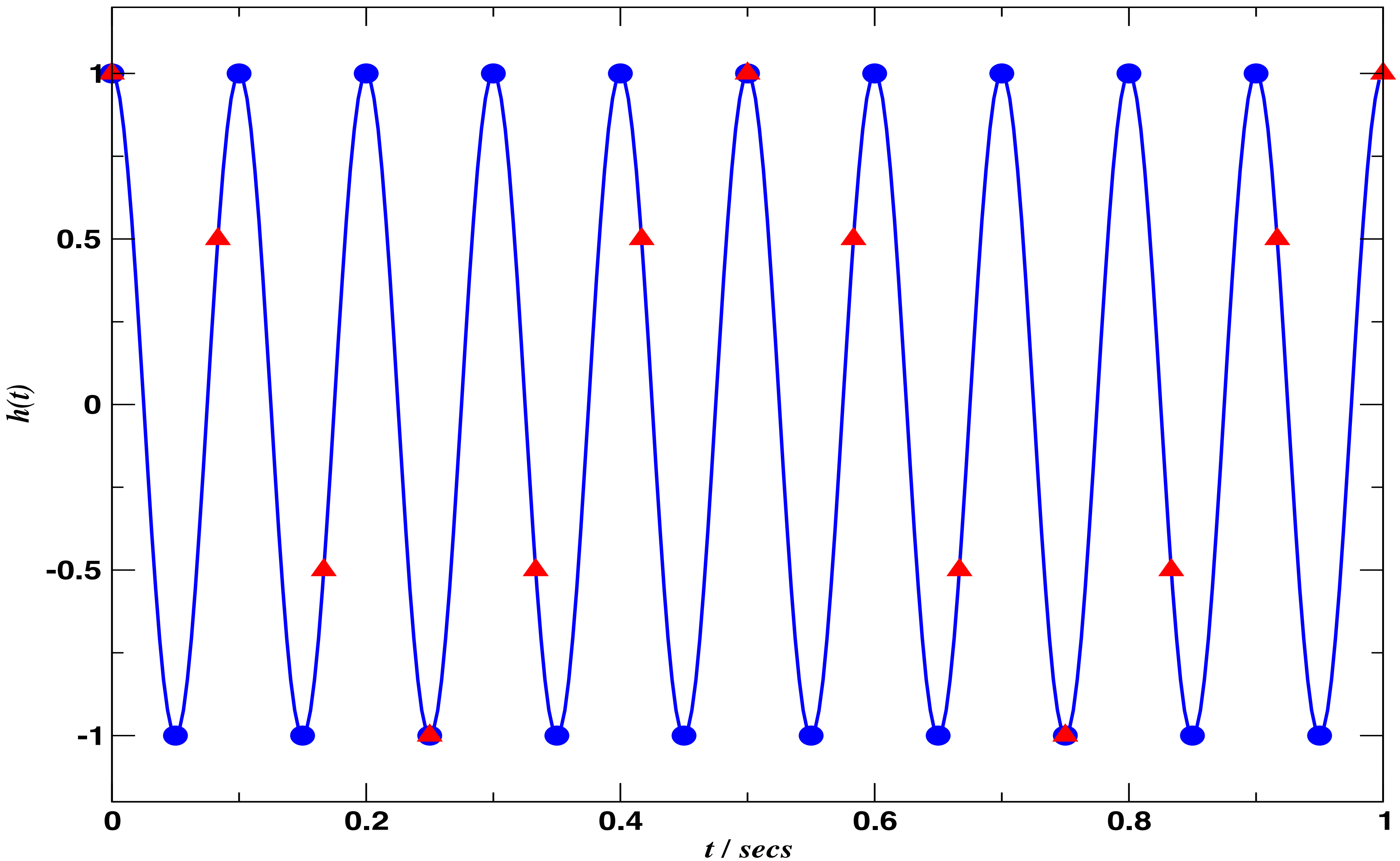
- If I oversample...?



$$f_s = 4f$$

Sampling the data

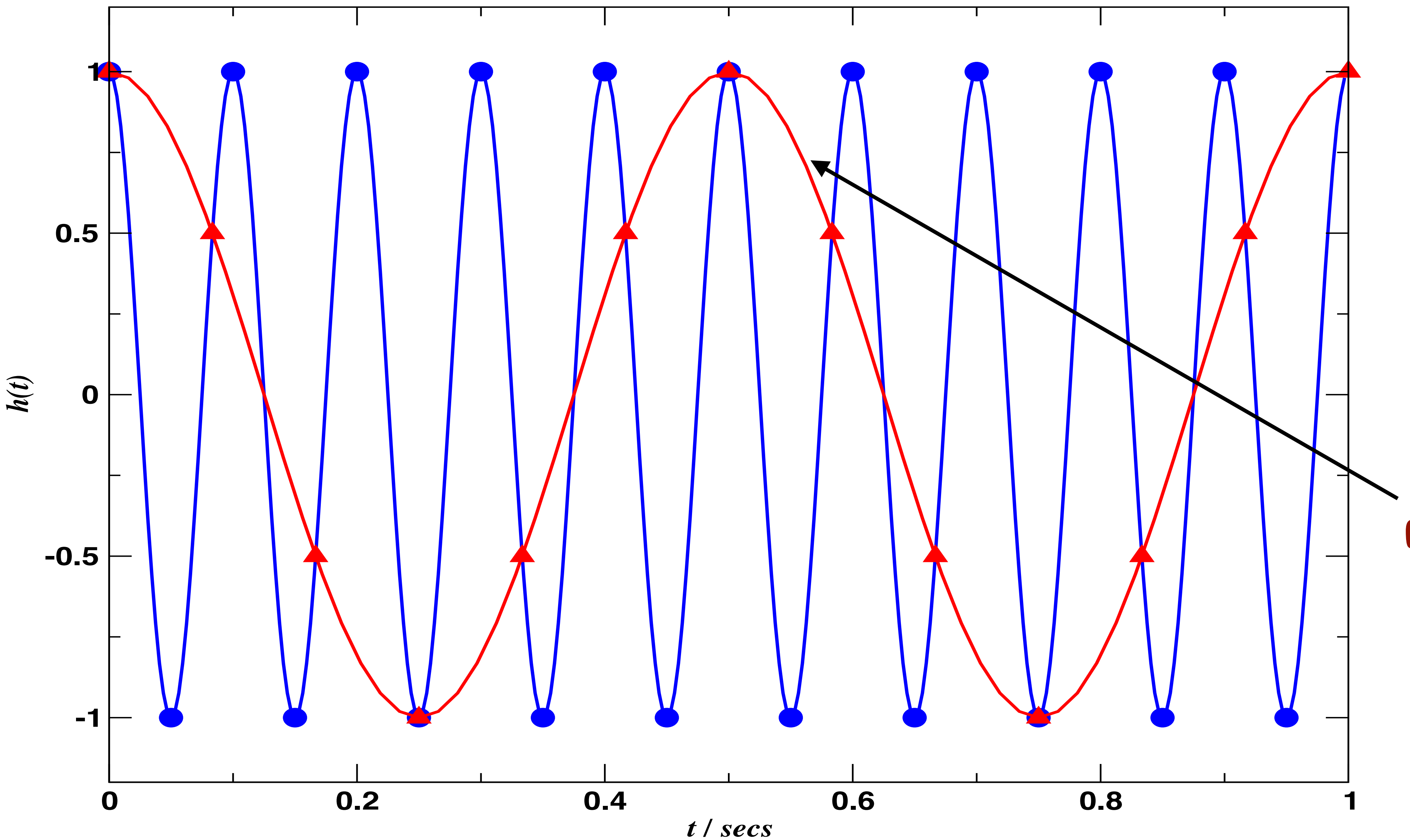
- and if I undersample...?



$f_s = 1.2f$

Sampling the data

- I get aliasing!!

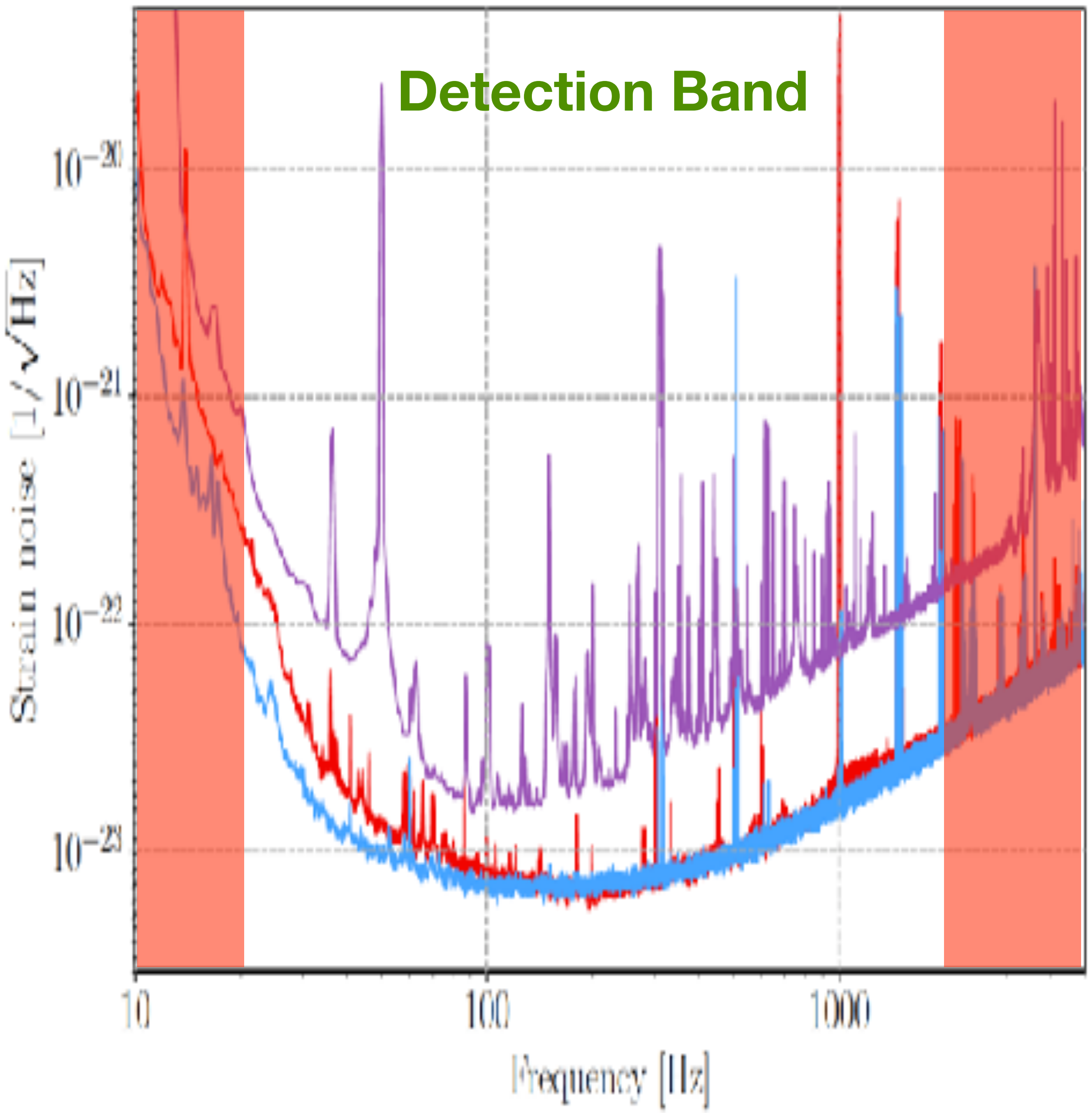


$f_s = 1.2f$

Corresponds to a wave at 2 Hz

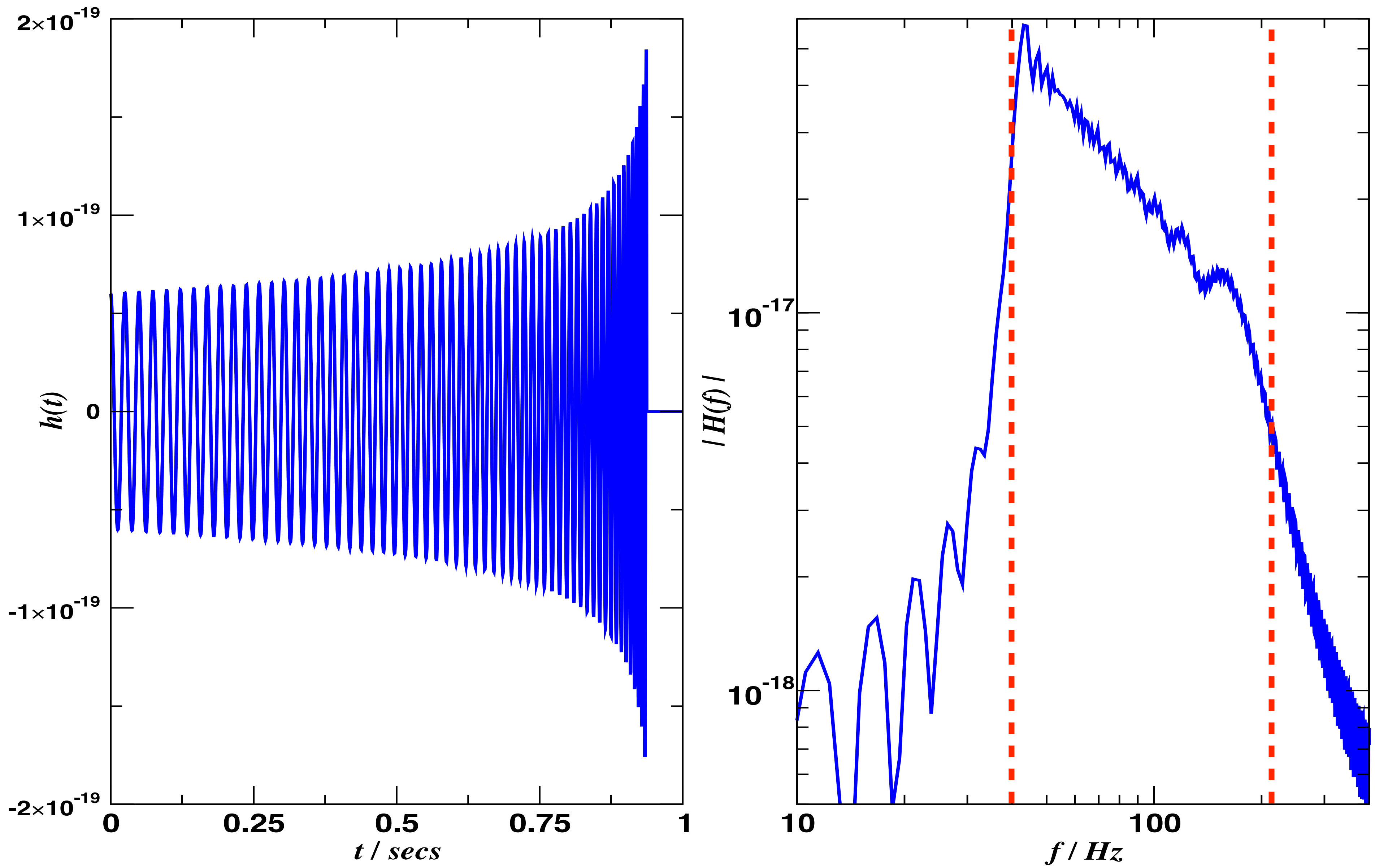
Low and High-band pass filtering

- Detectors very noisy below 20Hz and above 2kHz
- High pass filter > 20Hz
- Low pass filter < 2kHz



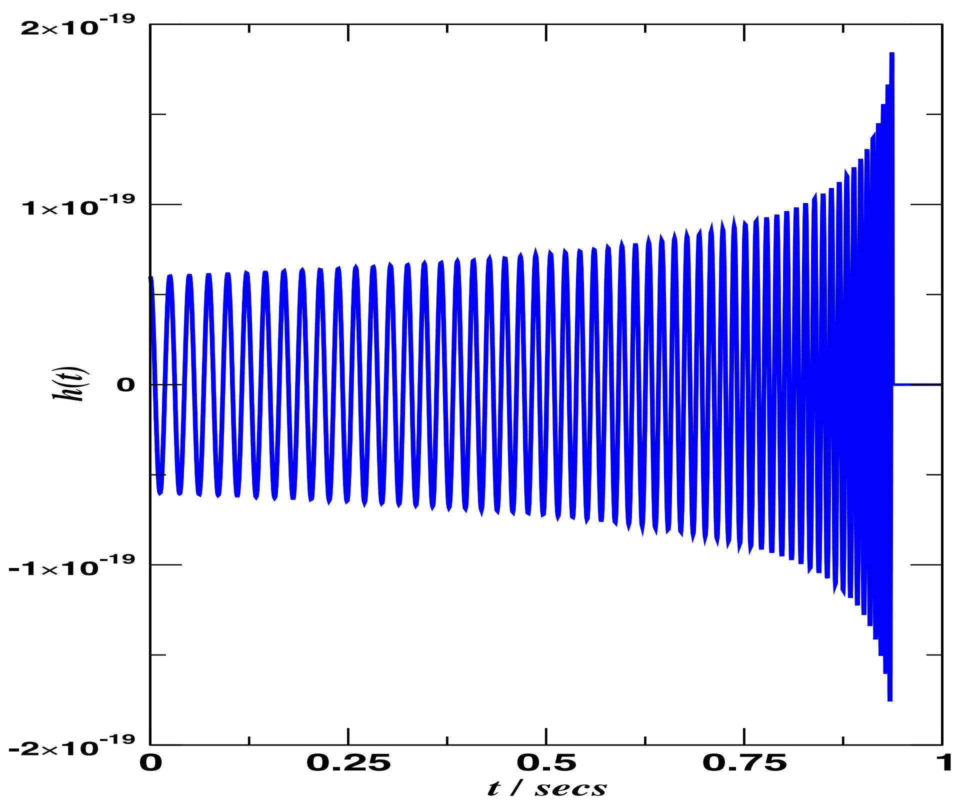
Windowing the data

large oscillations, spectral leakage…what's going on?



Windowing the data

- Our signal starts abruptly at t = 0, and finishes abruptly at t = 0.973 secs
- Equivalent to multiplying the signal with a rectangular window function
- and…..?



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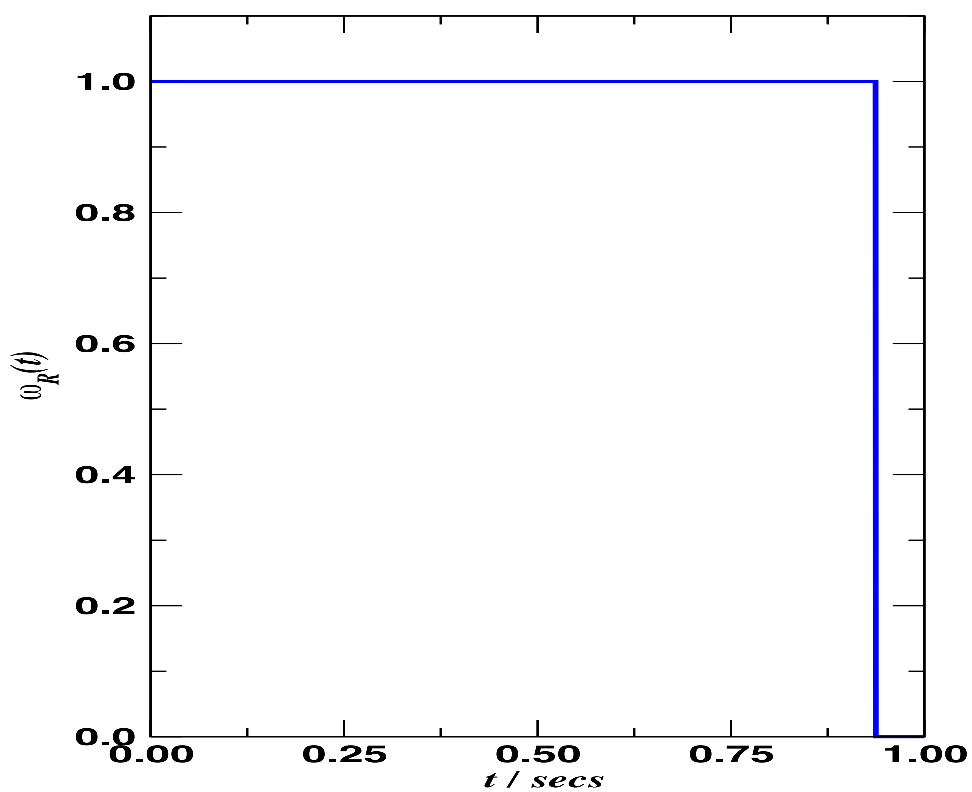
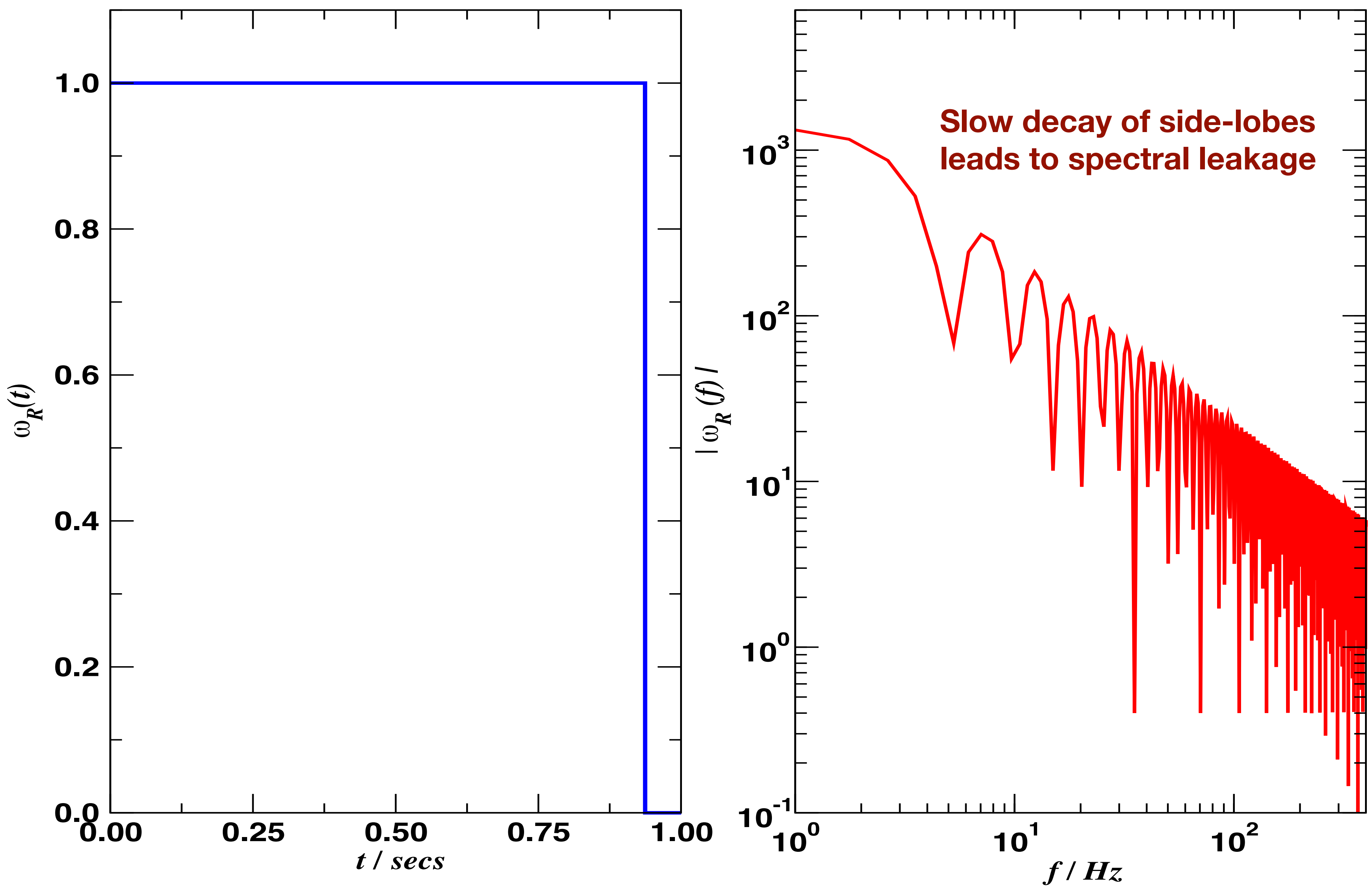


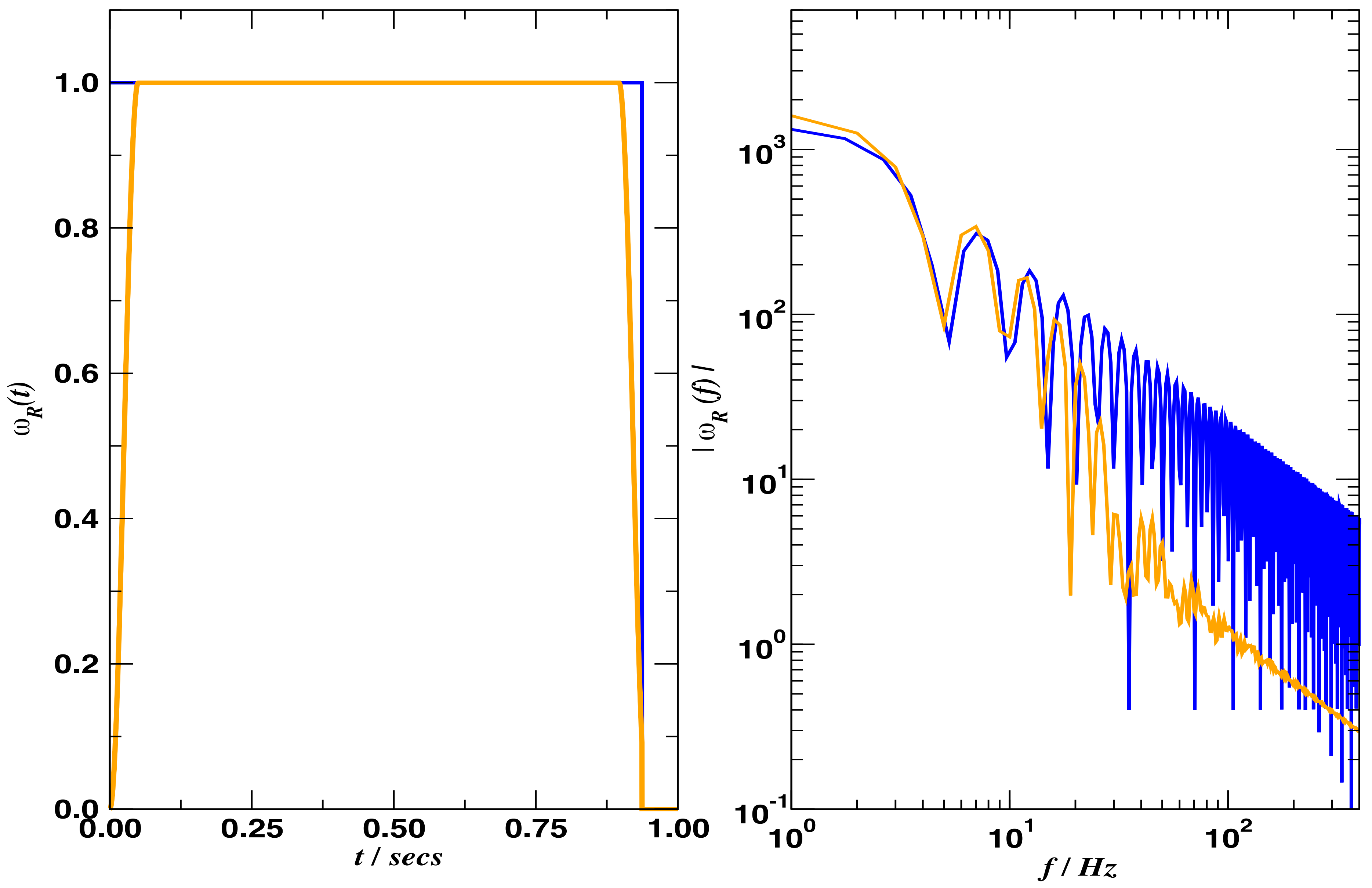
Windowing the data

FT of a rectangular window function



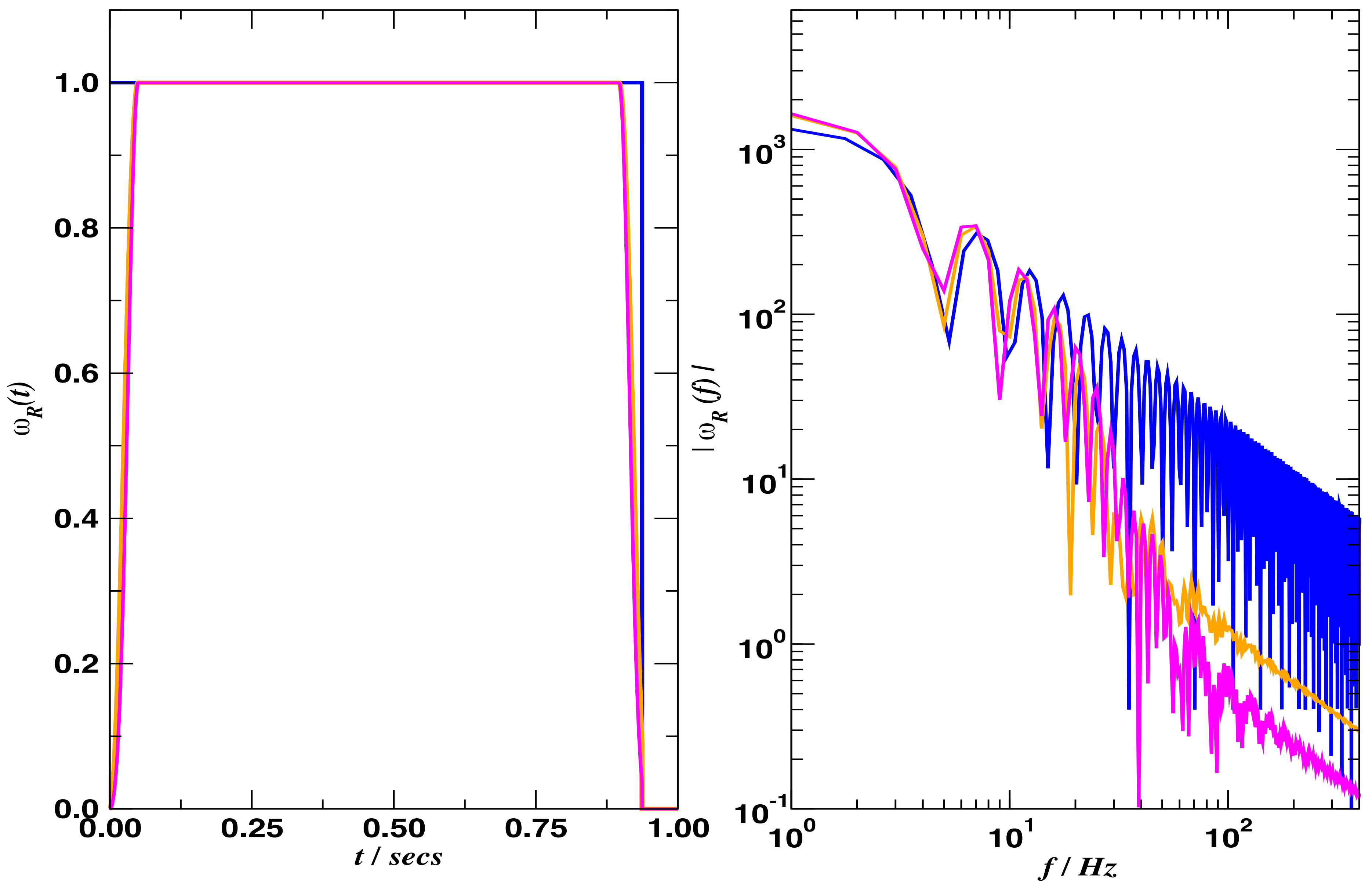
Windowing the data

FT of a Hanning window function



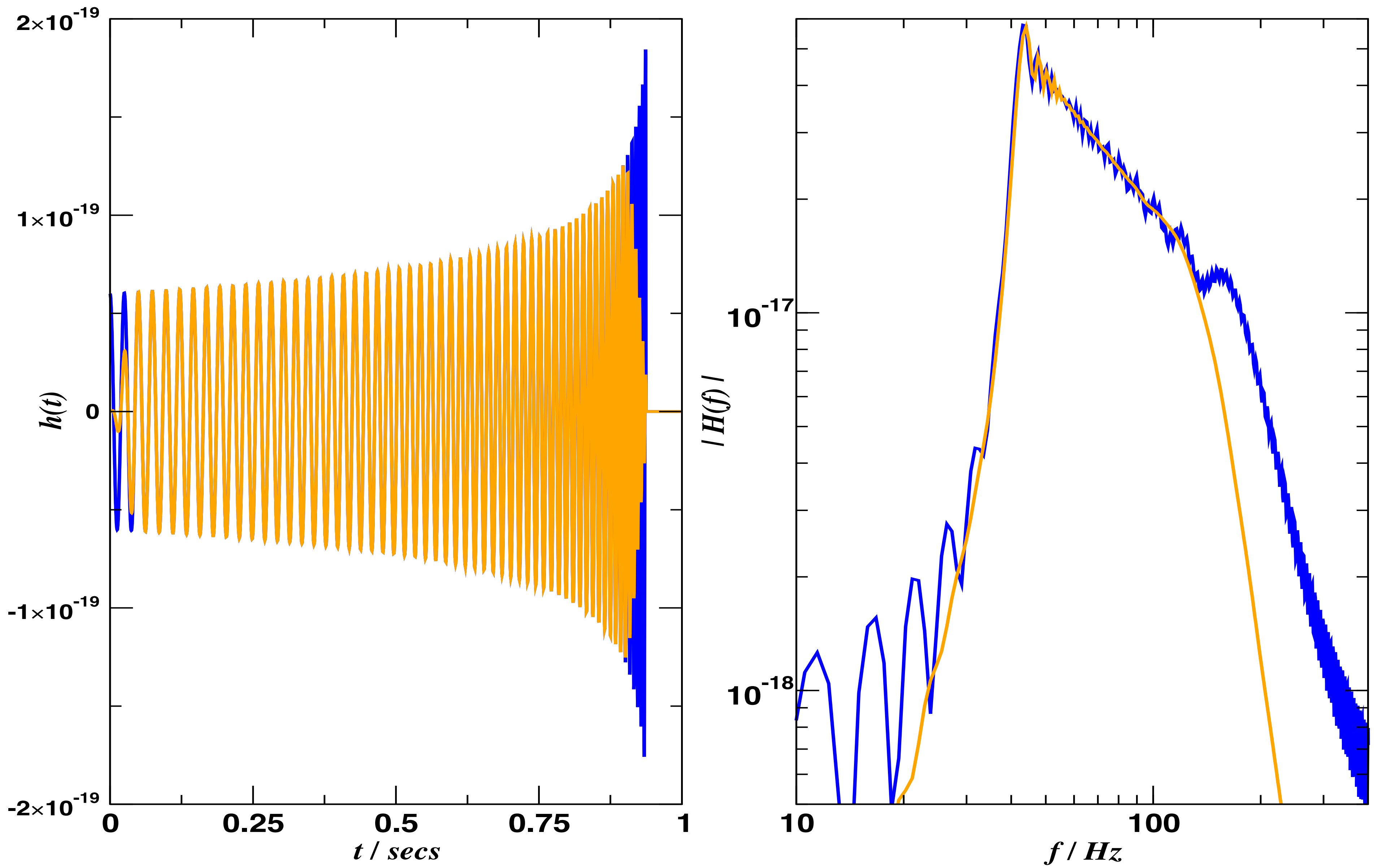
Windowing the data

FT of a Blackman window function



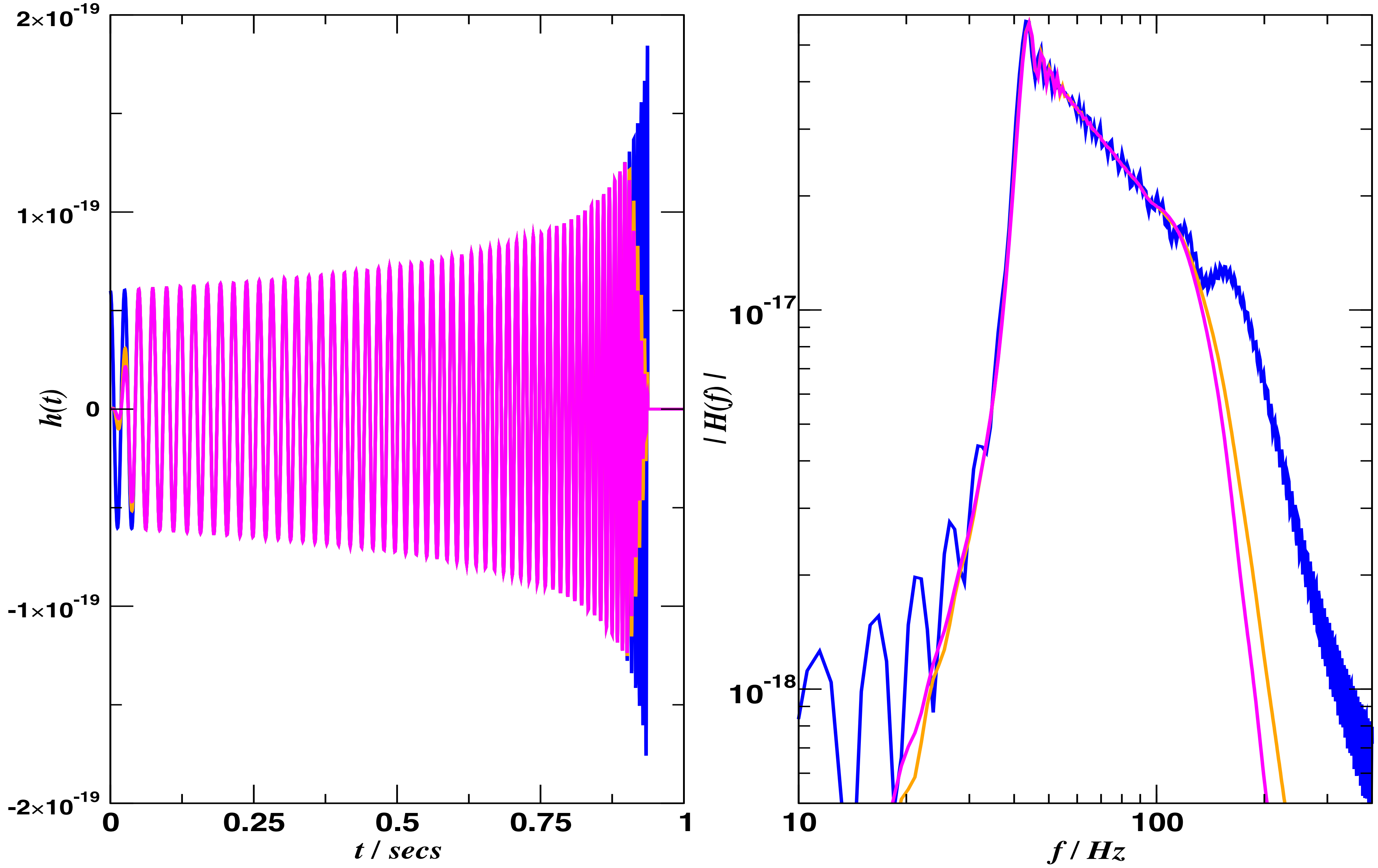
Windowing the data

FT of a chirp waveform using a Hanning window function



Windowing the data

FT of chirp waveform with a Blackman window function

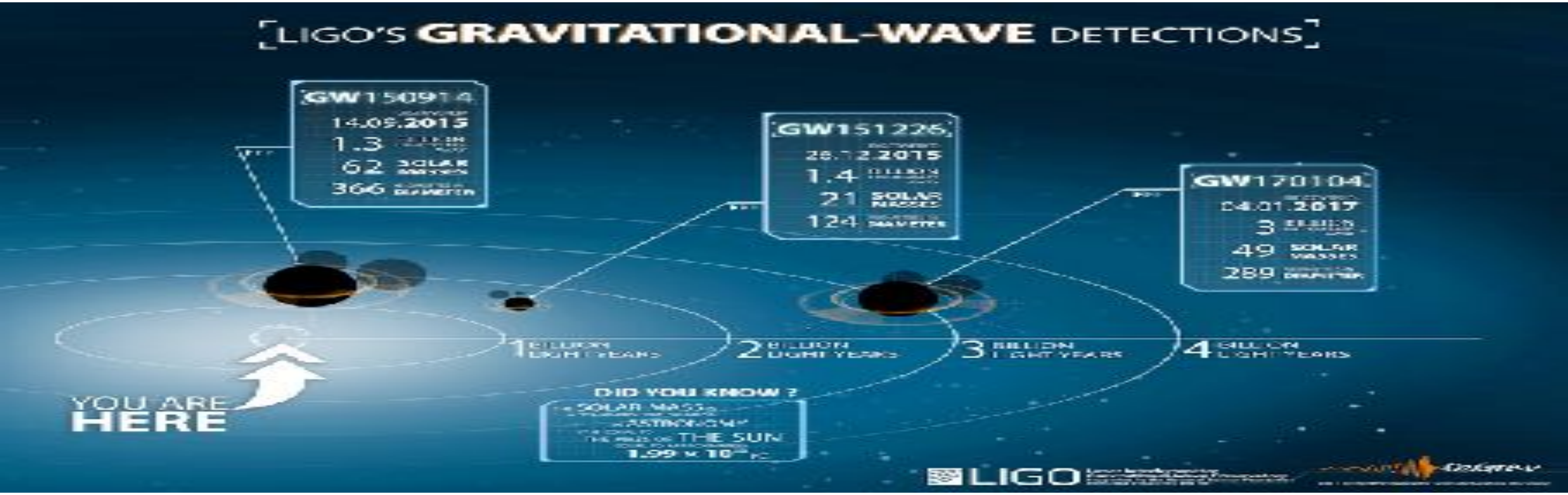


Matched Filtering

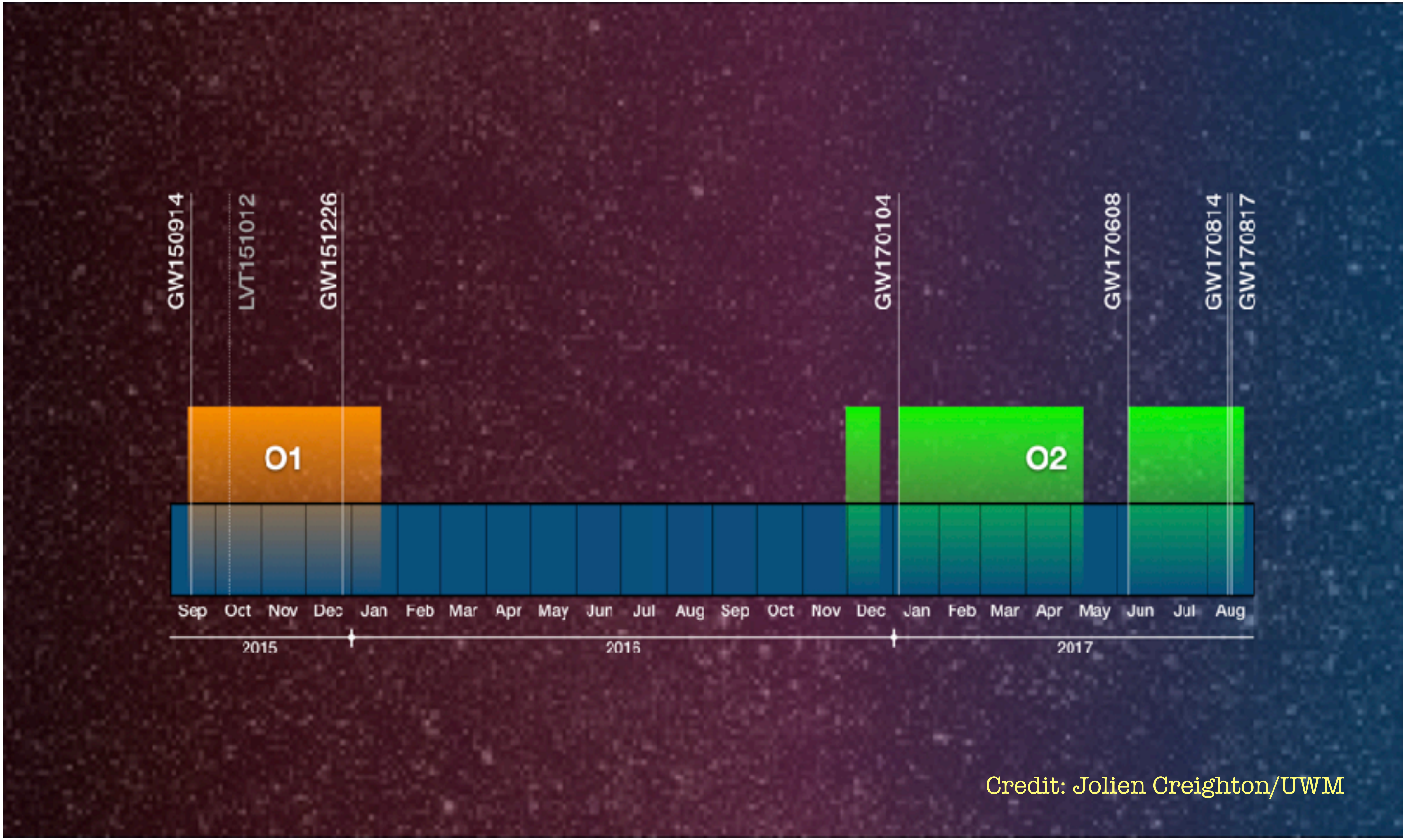
So, let's tie it all together....

3 short sims of waveform fitting

Advanced detector observation runs



O1/O2



GW150914
LVT151012
GW151226
GW170104
GW170608
GW170814
GW170817
O1
O2
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
2015
2016
2017
Credit: Jolien Creighton/UWM

GWTC-1 results

Event	$m_1/\mathrm{M}_\odot$	$m_2/\mathrm{M}_\odot$	$\mathcal{M}/\mathrm{M}_\odot$	χ_{eff}	$M_f/\mathrm{M}_\odot$	a_f	$E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$\ell_{\mathrm{peak}}/(\mathrm{erg\,s}^{-1})$	d_L/Mpc	z	$\Delta\Omega/\mathrm{deg}^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4} \times 10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	180
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7} \times 10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1555
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7} \times 10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.1^{+5.2}_{-3.9}$	$0.66^{+0.08}_{-0.10}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-0.9} \times 10^{56}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$	924
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.05}_{-0.1}$	$3.5^{+0.4}_{-1.3} \times 10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	396
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5} \times 10^{56}$	2750^{+1350}_{-1320}	$0.48^{+0.19}_{-0.20}$	1033
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9} \times 10^{56}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$	340
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5} \times 10^{56}$	580^{+160}_{-210}	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1 \times 10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7} \times 10^{56}$	1020^{+430}_{-360}	$0.20^{+0.07}_{-0.07}$	39
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9} \times 10^{56}$	1850^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$	1651

- 10 BBHs

Abbott et al, arXiv:1811.12907 (2018)

GWTC-1 results

Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	χ_{eff}	$M_f/M_\odot$	a_f	$E_{rad}/(M_\odot c^2)$	$\ell_{peak}/(\mathrm{erg\,s^{-1}})$	d_L/Mpc	z	$\Delta\Omega/\mathrm{deg}^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4} \times 10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	180
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7} \times 10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1555
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7} \times 10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.1^{+5.2}_{-3.9}$	$0.66^{+0.08}_{-0.10}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-0.9} \times 10^{56}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$	924
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.05}_{-0.1}$	$3.5^{+0.4}_{-1.3} \times 10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	396
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5} \times 10^{56}$	2750^{+1350}_{-1320}	$0.48^{+0.19}_{-0.20}$	1033
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9} \times 10^{56}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$	340
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GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1 \times 10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7} \times 10^{56}$	1020^{+430}_{-360}	$0.20^{+0.07}_{-0.07}$	39
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9} \times 10^{56}$	1850^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$	1651

- Massive energy output

Abbott et al, arXiv:1811.12907 (2018)

GWTC-1 results

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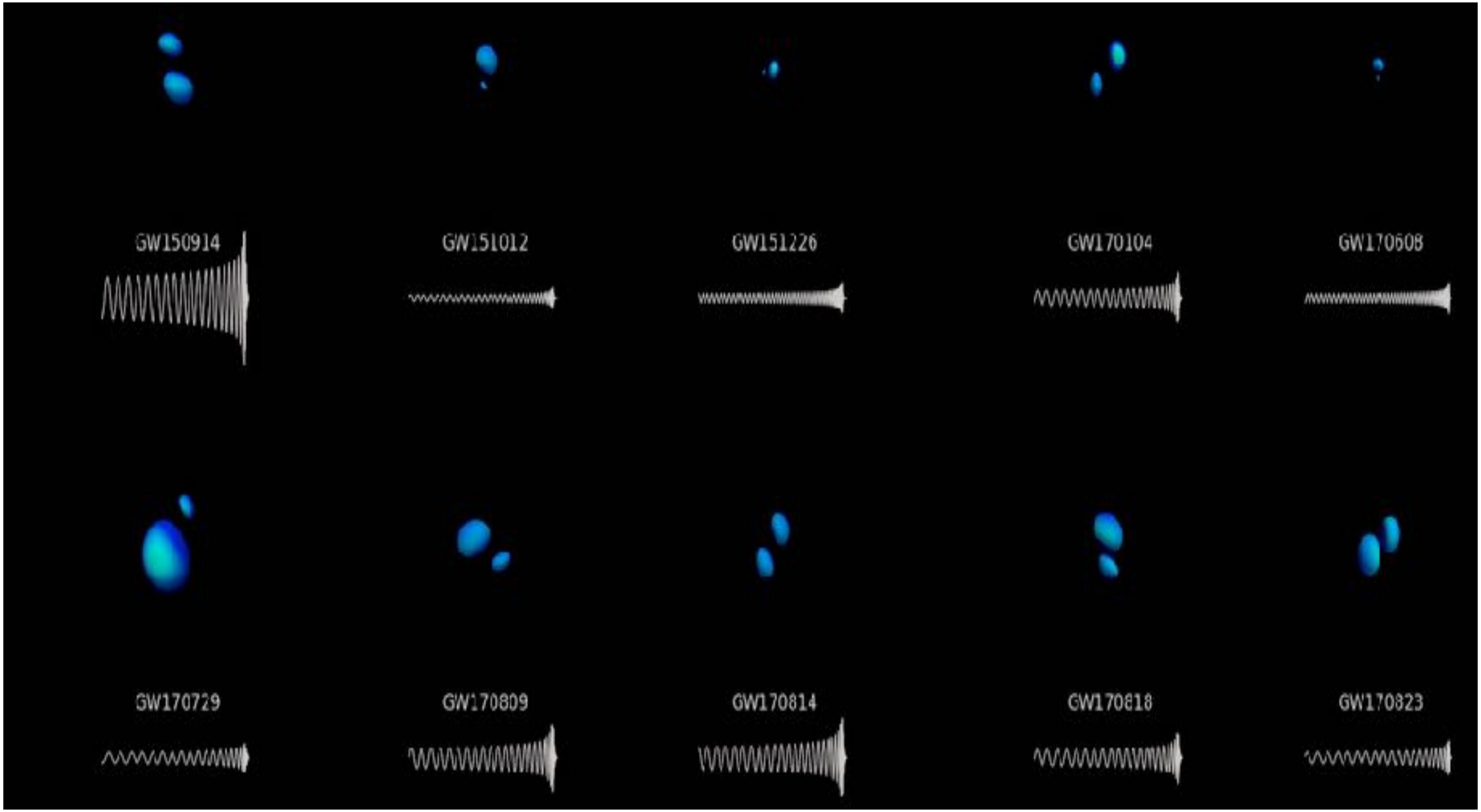
- Most massive and distant source

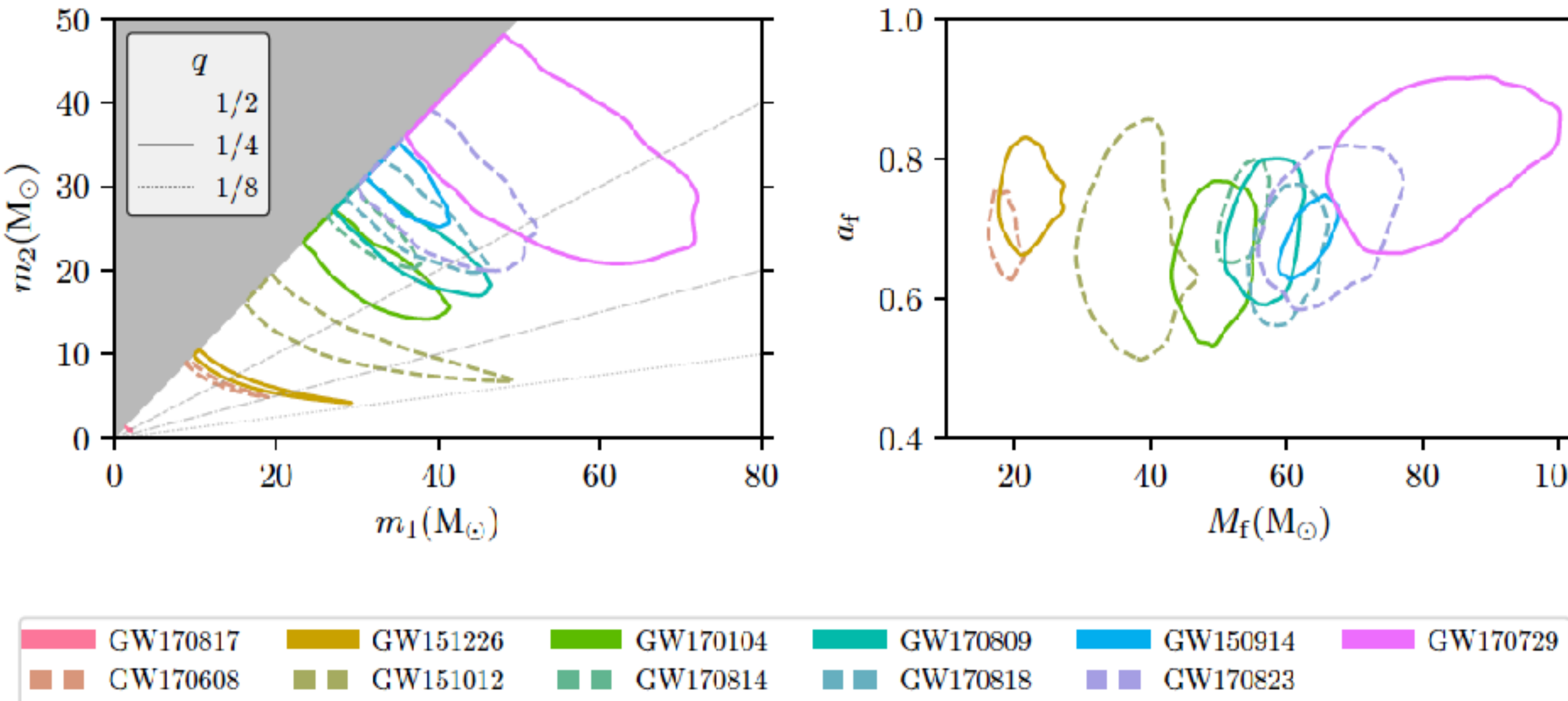
Abbott et al, arXiv:1811.12907 (2018)

GWTC-1 results



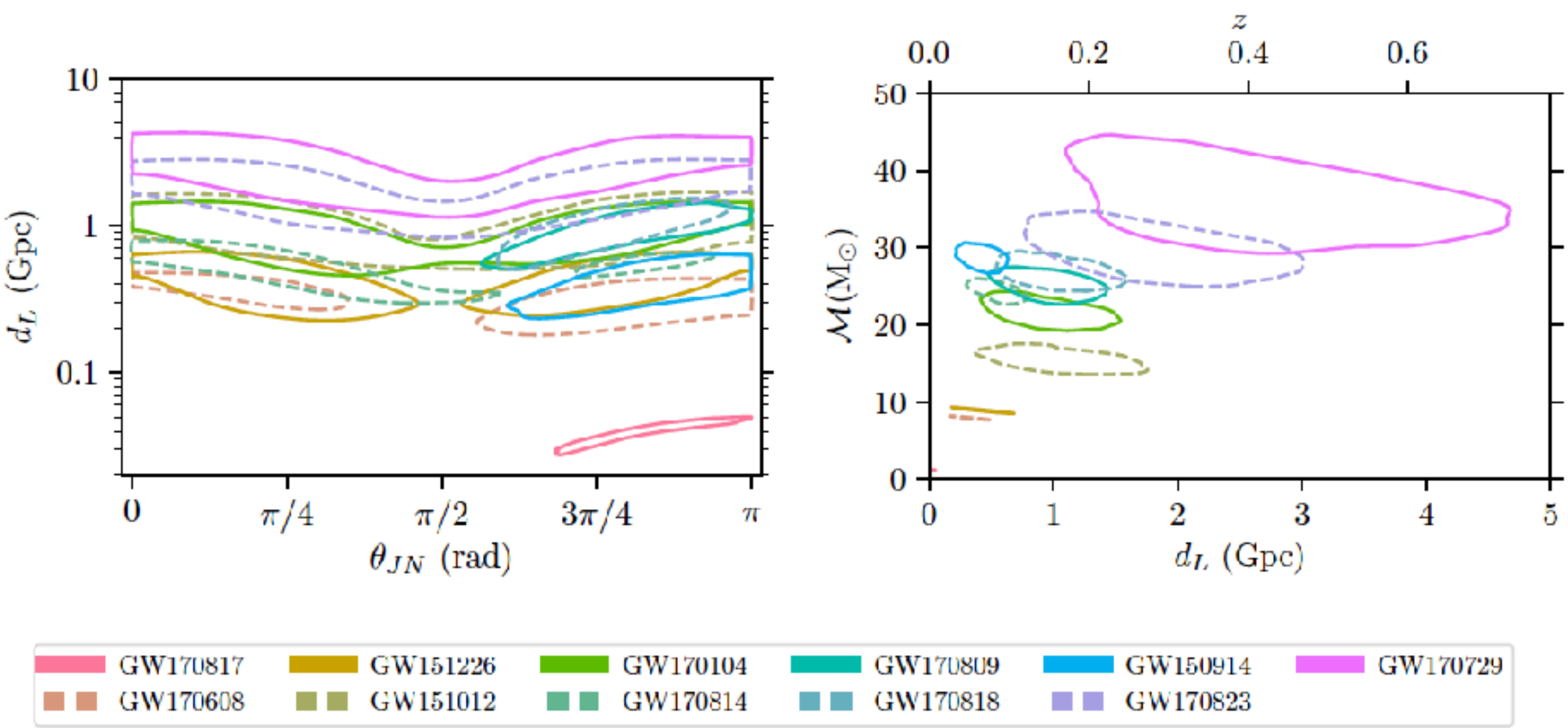
ligo.caltech.edu

BBH Masses



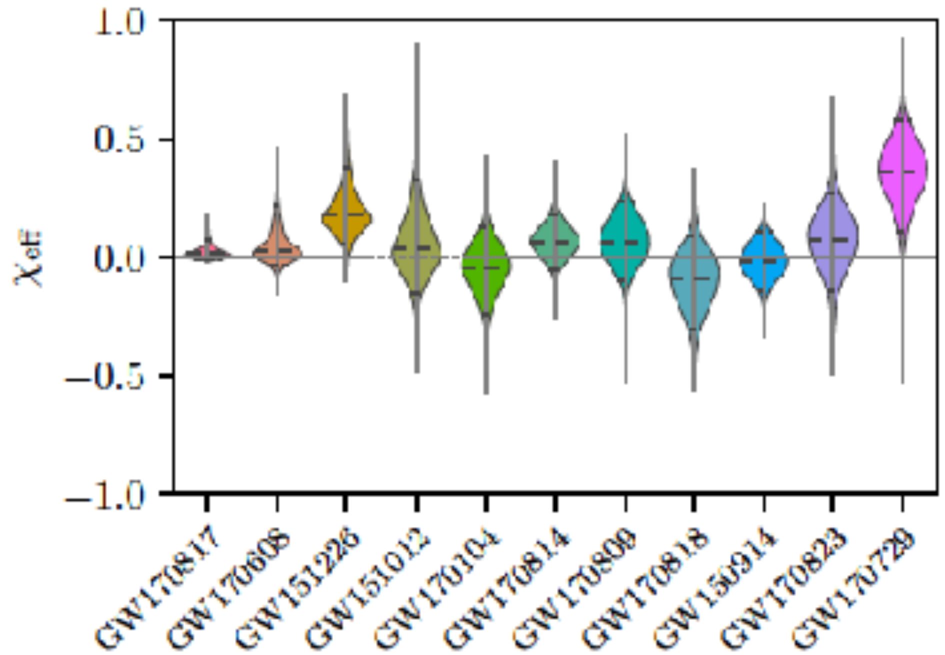
Abbott et al, arXiv:1811.12907 (2018)

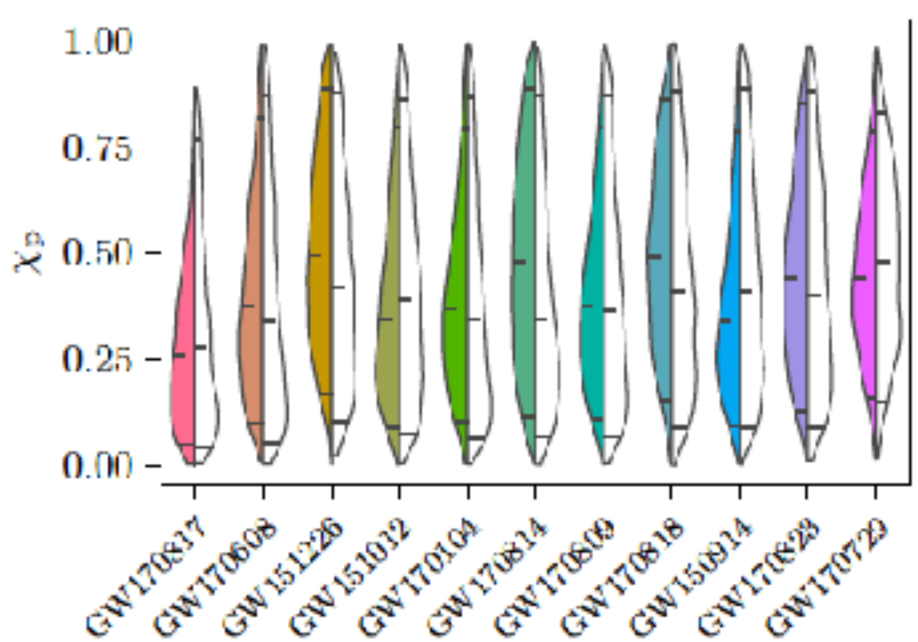
BBH Distance

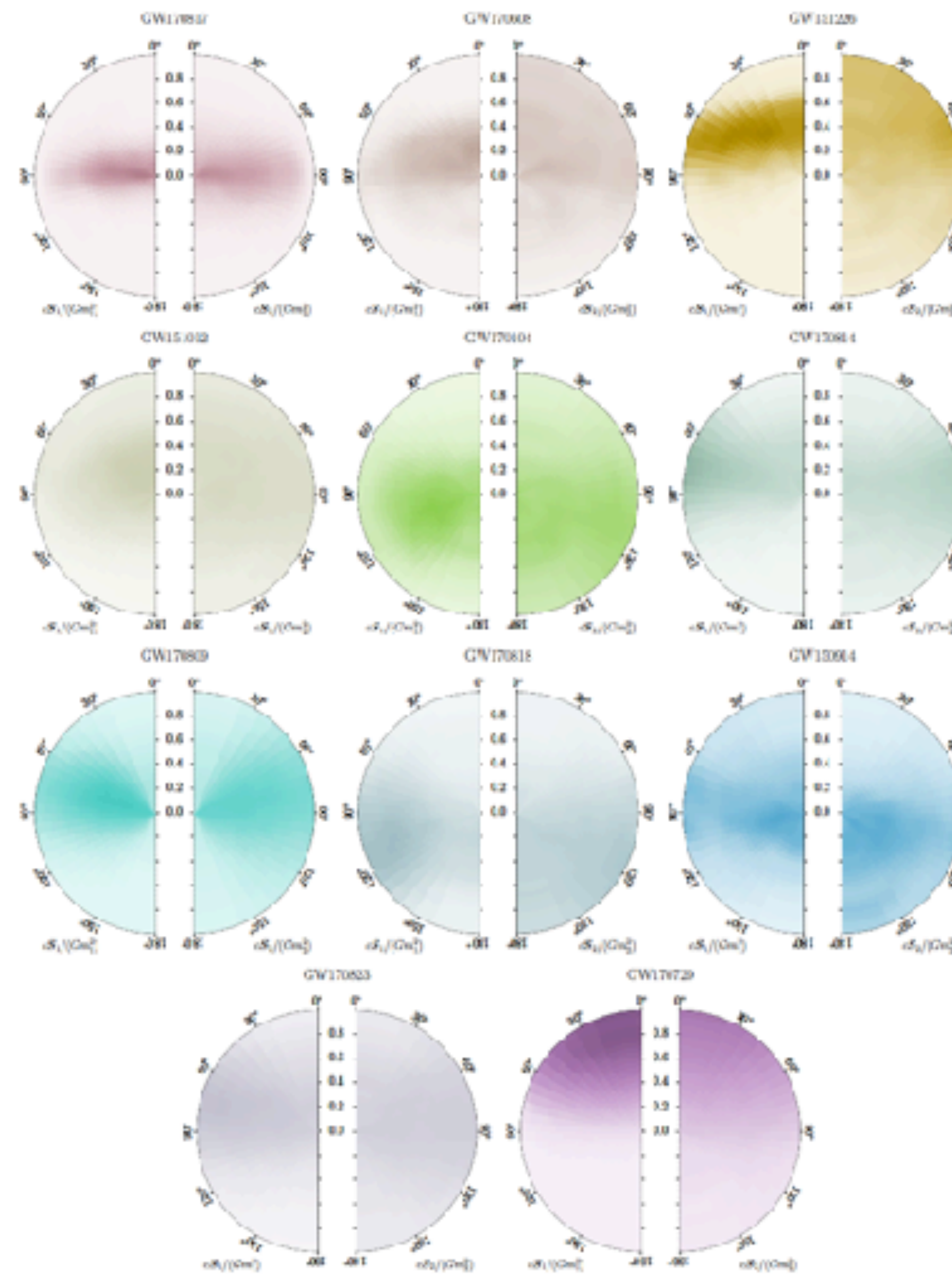


Abbott et al, arXiv:1811.12907 (2018)

BBH Spins







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GWTC-1 results

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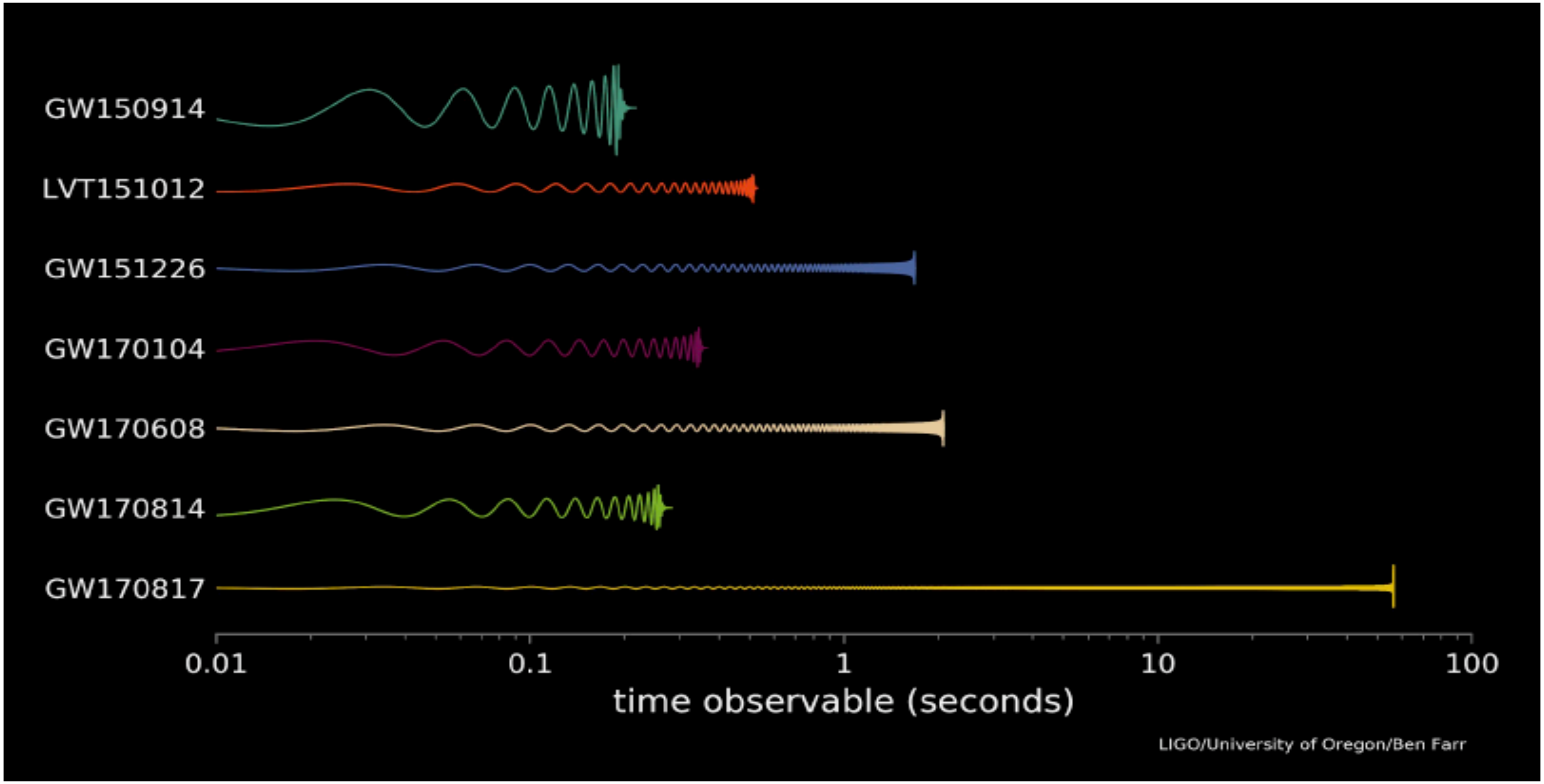
- 1st ever BNS and best resolved event

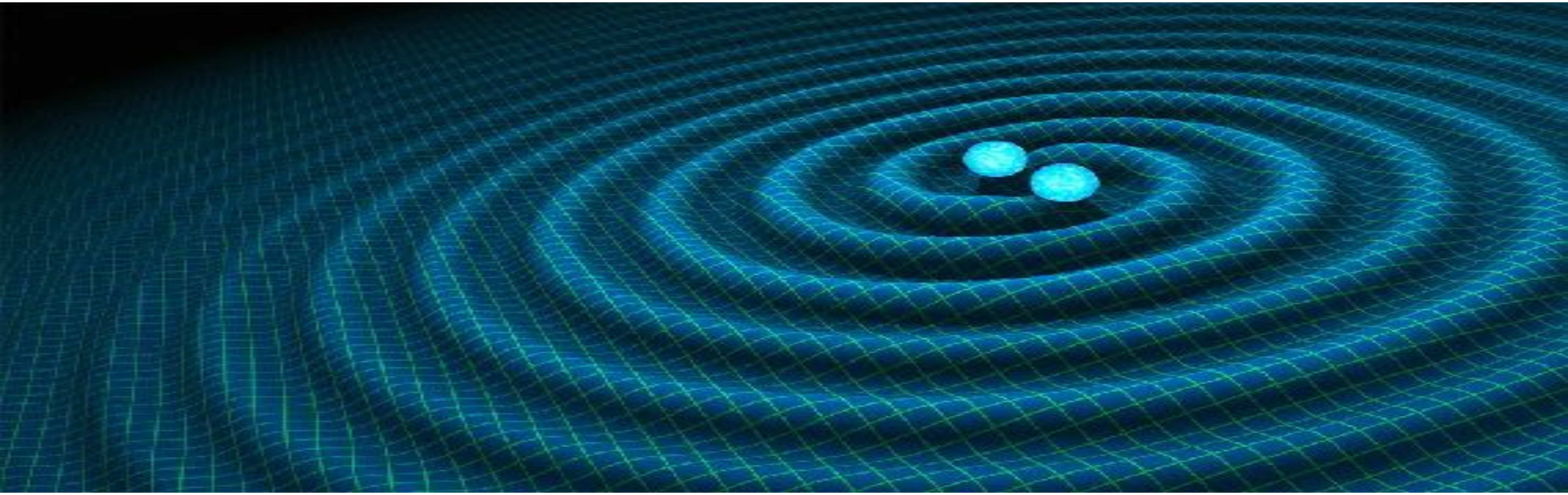
Abbott et al, arXiv:1811.12907 (2018)

Common question....

- ...how do we know GW170817 was a BNS?



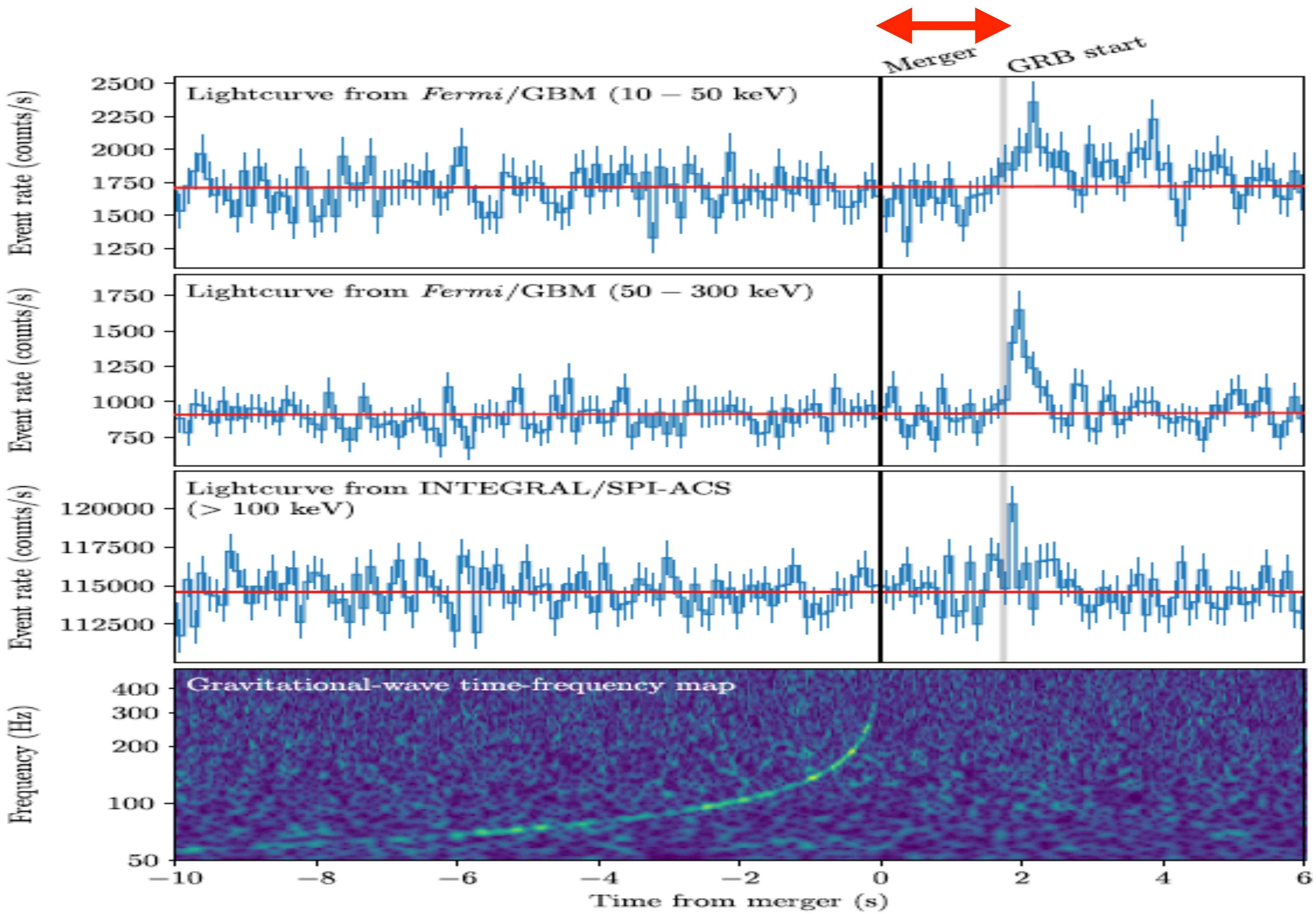
Gravitational Wave Astronomy



So, what can we do?

- Fundamental physics
- Astrophysics
- Extreme MatterCosmology
- Cosmology

Fundamental Physics



Abbott et al, ApJ Letters 848, L13 (2017)

Fundamental Physics

- The time delay between the GW and GRB detections over 1.3x10^8 Lyrs was (N.B. analysis allows for +/- 10 secs)

$$\Delta t = (1.74 \pm 0.05)\, s$$

- Defining the fractional difference between the speed of light and GWs as

$$\frac{c_g - c}{c} \approx c\frac{\Delta t}{D_L}$$

- We find the following constraint

$$-3 \times 10^{-15} \leq \frac{\Delta c}{c} \leq 7 \times 10^{-16}$$

- Large consequences for cosmological theories

Abbott et al, ApJ Letters 848, L13 (2017)

Fundamental Physics

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [42] Brans-Dicke/$f(R)$ [43, 44] Kinetic Gravity Braiding [46]	quartic/quintic Galileons [13, 14] Fab Four [15, 16] de Sitter Horndeski [45] $G_{\mu\nu}\phi^{\mu}\phi^{\nu}$ [47], Gauss-Bonnet
beyond H.	Derivative Conformal (20) [18] Disformal Tuning (22) DHOST with $A_1 = 0$	quartic/quintic GLPV [19] DHOST [20, 48] with $A_1 \neq 0$
	Viable after GW170817	Non-viable after GW170817

- with extension to: Einstein-Aether, Horava gravity, Generalised Proca, TeVeS, massive gravity, bigravity, multi-gravity, MOND-like theories

arXiv:1710.05901, 1710.06394, 1710.05893, 1710.05877….

Fundamental Physics

- Shapiro delay is defined as $$\Delta t_s = -\frac{1+\gamma}{c}\int_{r_e}^{r_o} U(r(l))dl$$
- γ is the PPN parameter parameterising a deviation from Einstein-Maxwell theory
- Conservative bound on $$\Delta\gamma = |\gamma_{GW} - \gamma_{EM}| \leq 2\frac{\Delta t}{\Delta t_s}$$
- is $-2.6 \times 10^{-7} \leq \Delta\gamma \leq 1.2 \times 10^{-6}$

- Newer result (S. Boran et al, 1710.06168) using more sophisticated dark matter halo model gives
$$\Delta\gamma \leq 3.9 \times 10^{-8}$$
- implying that MOND-like dark matter emulator theories are ruled out, as the GWs would have arrived 1000 days before the EM emission

Fundamental Physics

- Fourier domain waveform

$$\tilde{h}(f) = A(f)e^{i\Psi_{GR}(f)}$$

- GW inspiral phase to 3.5 PN order, i.e. ***(v/c)***^{7}

Einstein-Aether
Khronometric

Massive Graviton

$$\Psi_{GR}(f) = 2\pi f t_c + \phi_c - \frac{\pi}{4} + \frac{3}{128}\Big[\psi_0(\pi M f)^{-5/3} + \psi_1(\pi M f)^{-4/3} + \psi_2(\pi M f)^{-1}$$
$$\psi_3(\pi M f)^{-2/3} + \psi_4(\pi M f)^{-1/3} + \psi_5 + \psi_6(\pi M f)^{1/3} + \psi_7(\pi M f)^{2/3} + \Big]$$

Dynamical Chern-Simons

+ scalar-tensor theory at the -1PN order, i.e. $f^{-7/3}$

Fundamental Physics

- Set $\psi_k \rightarrow \psi_k \left(1 + \delta\psi_k\right)$

- Phenomenological phase

$$\Psi(f) = \Psi_{GR}(f) + \Psi_{NGR}(f)$$

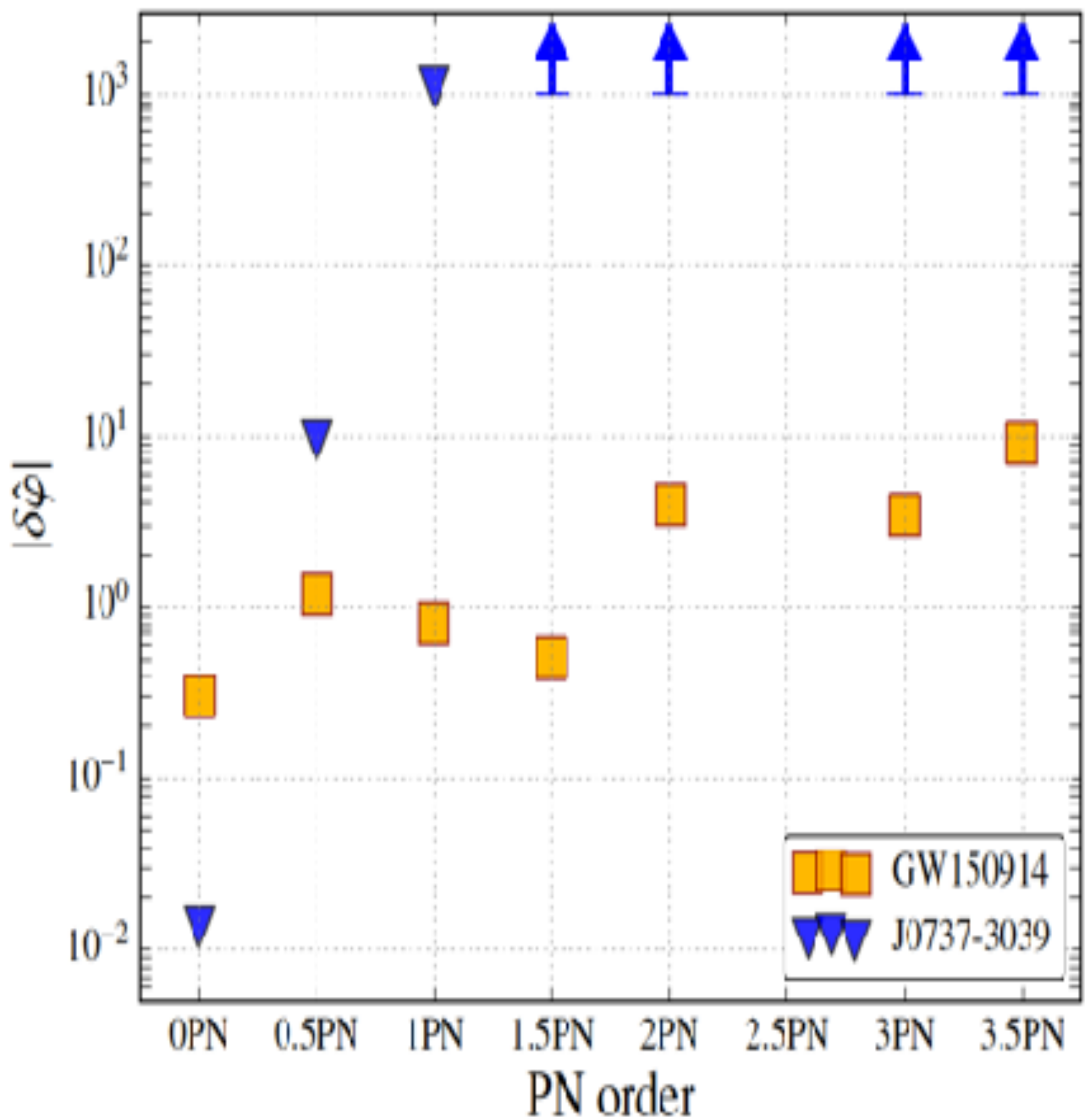
- Phenomenological waveform

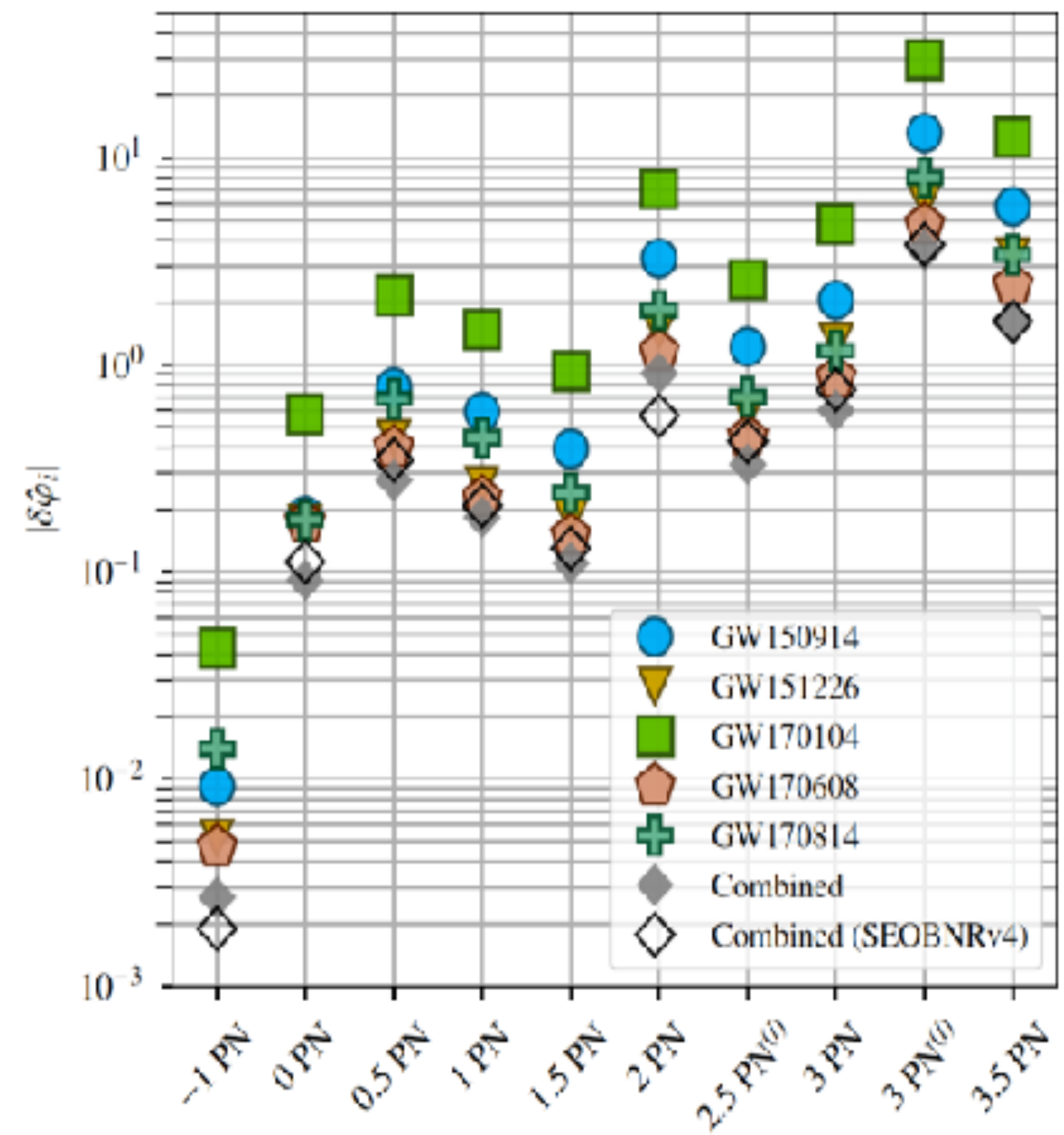
$$\tilde{h}(f) = A(f)e^{i\Psi_{GR}(f)}e^{i\Psi_{NGR}(f)}$$

- Has been demonstrated that it is enough to search for the dominant effect

Fundamental Physics

- Test of the PN approximation



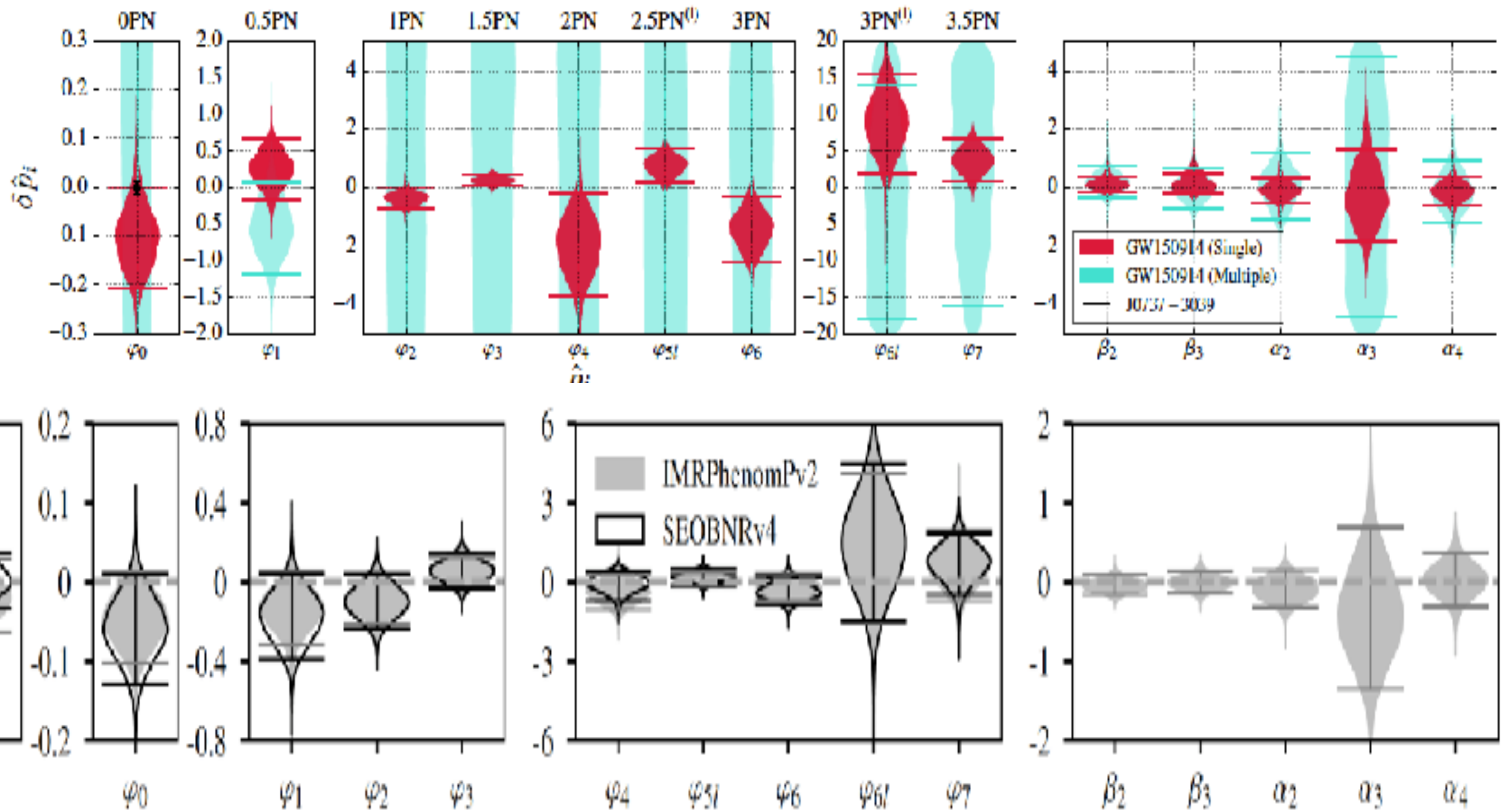


Abbott et al, arXiv:1903.04467

Fundamental Physics

If GR is correct, the deviation $\delta\hat{p}_i$ should be 0

GW150914



Abbott et al, arXiv:1903.04467

Fundamental Physics

- Assume a dispersion relationship of the form

$$E^2 = p^2c^2 + Ap^\alpha c^\alpha, \ \alpha \geq 0$$

- modifying the GW group velocity as

$$v_g/c = 1 + (\alpha - 1)AE^{\alpha-2}/2$$

- which changes the phase of the GW

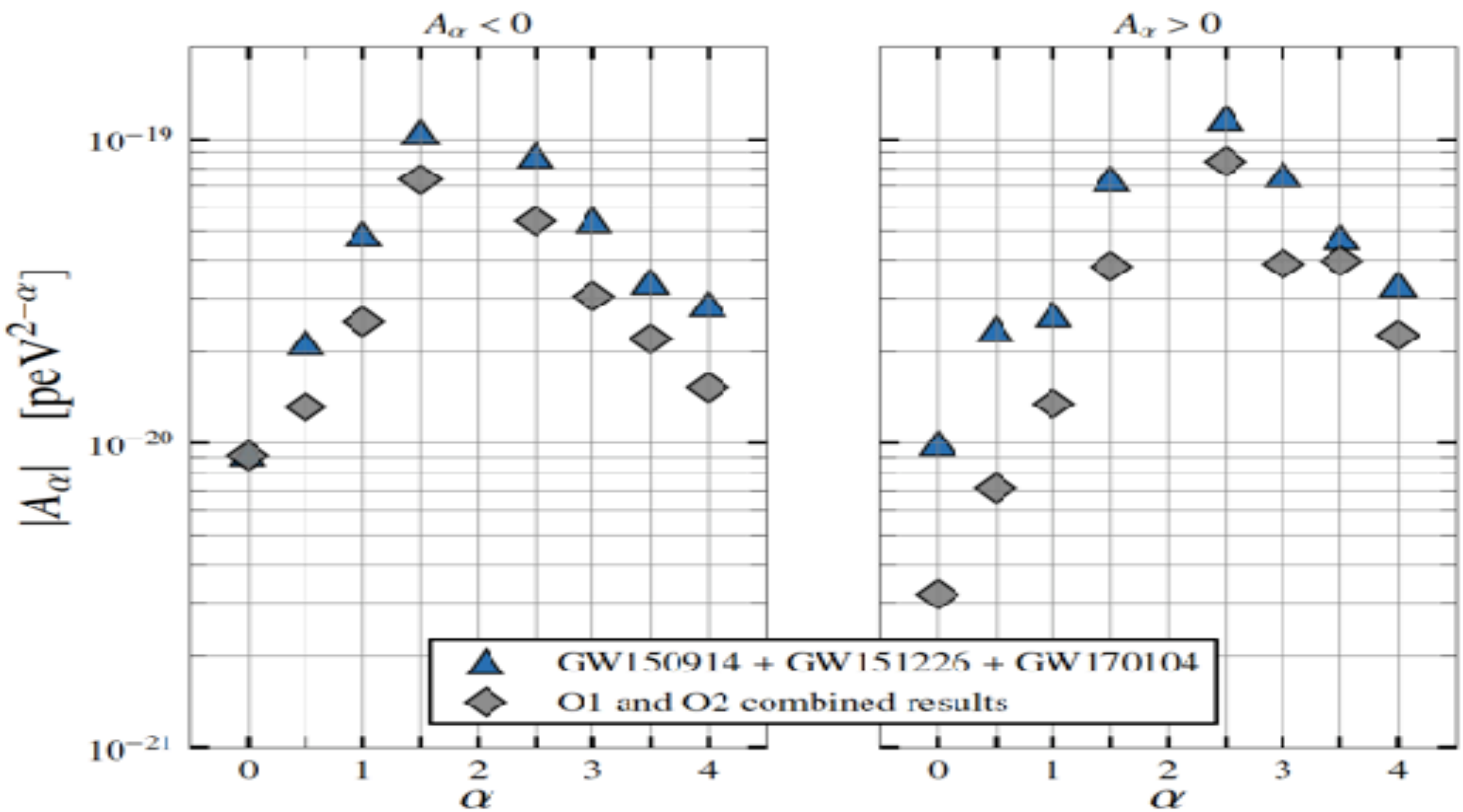
$$\delta\Psi = \begin{cases} \dfrac{\pi}{\alpha - 1}\dfrac{AD_\alpha}{(hc)^{2-\alpha}}\left[\dfrac{(1+z)f}{c}\right]^{\alpha-1} & \alpha \neq 1 \\ \dfrac{\pi AD_\alpha}{hc}\ln\left(\dfrac{\pi G\mathcal{M}^{\rm det}f}{c^3}\right) & \alpha = 1 \end{cases}$$

Abbott et al, PRL 118, 221101 (2017)

Fundamental Physics

- Can probe the following theories:
  - Double special relativity $A = \eta_{dsrt} \ , \ \ \alpha = 3$
  - Extra-dimensional gravity $A = -\alpha_{edt} \ , \ \ \alpha = 4$
  - Horova-Lifshitz gravity $A = \kappa_{hl}^4 \mu_{hl}^2 / 16 \ , \ \ \alpha = 4$
  - Massive gravity $A = (m_g c^2)^2 \ , \ \ \alpha = 0$
  - Multifractional spacetime $A = (-3^{1-\alpha/2}) 2 E_*^{2-\alpha} / (3 - \alpha) \ , \ \ \alpha = 2 - 3$

Fundamental Physics



- A_0 corresponds to a massive graviton
- O1/O2 results give $m_g \leq 5 \times 10^{-23}\, eV/c^2$ or $\lambda_g > 2.4 \times 10^{13}\, km$

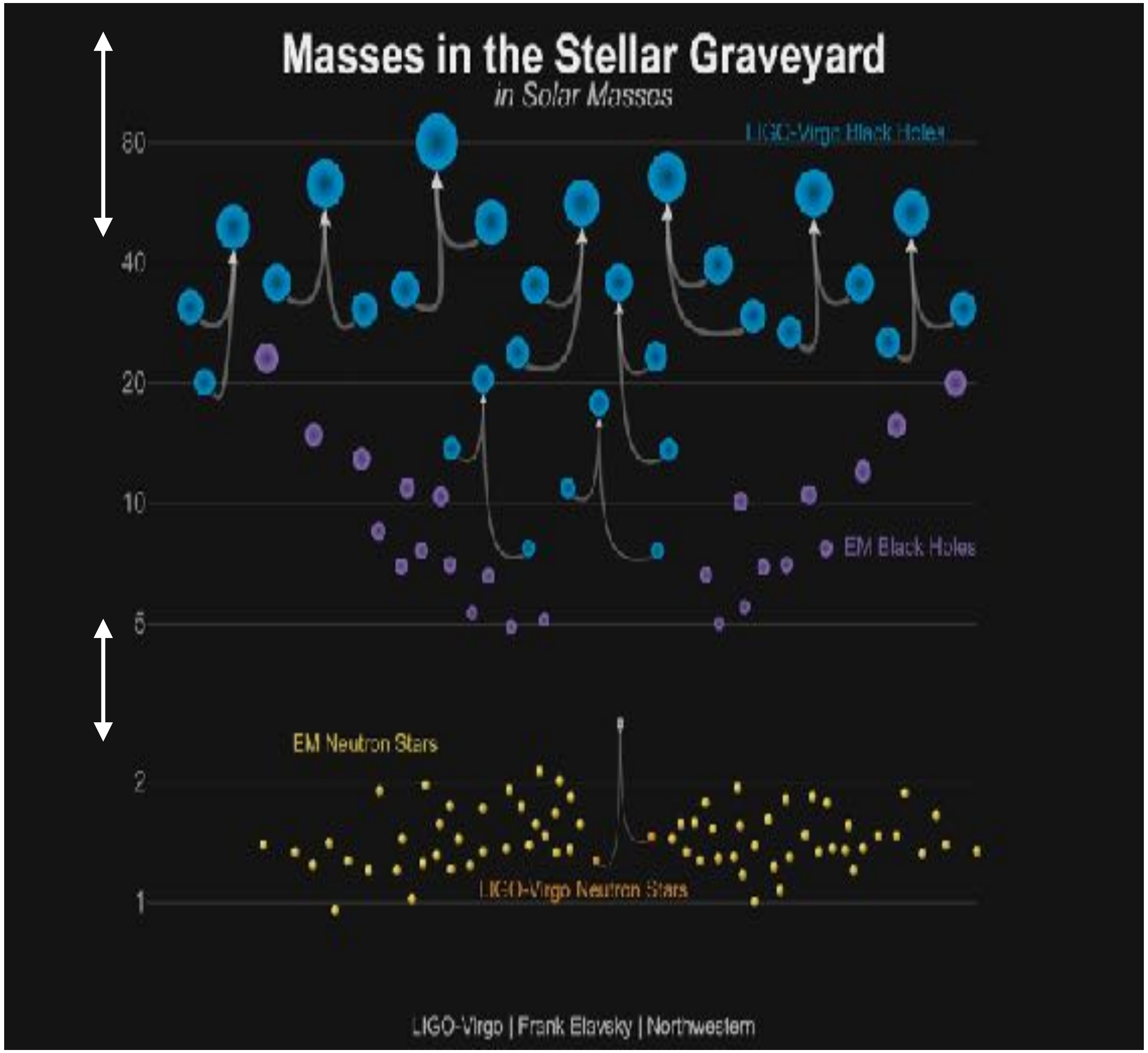
Abbott et al, arXiv:1903.04467

Astrophysics

- Uncertainty in formation channels
  - galactic field evolution
  - dynamical capture in globular clusters
- How does the common envelope phase actually work?
- Role of metallicity?
- Do natal kicks in SN play a role?
- How does mass transfer efficiency affect binary evolution?
- What is the merger rate for binary systems?

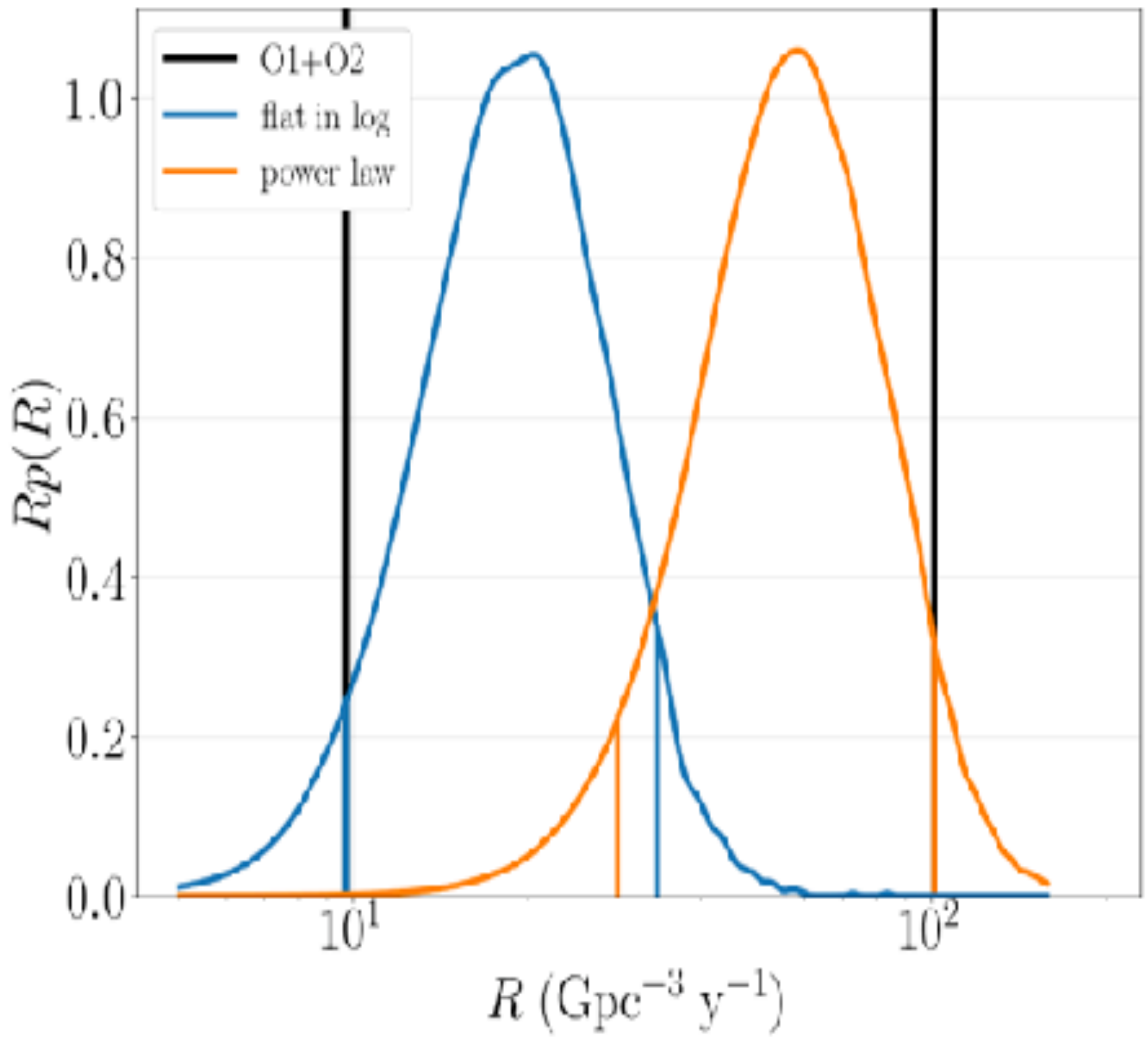
Astrophysics

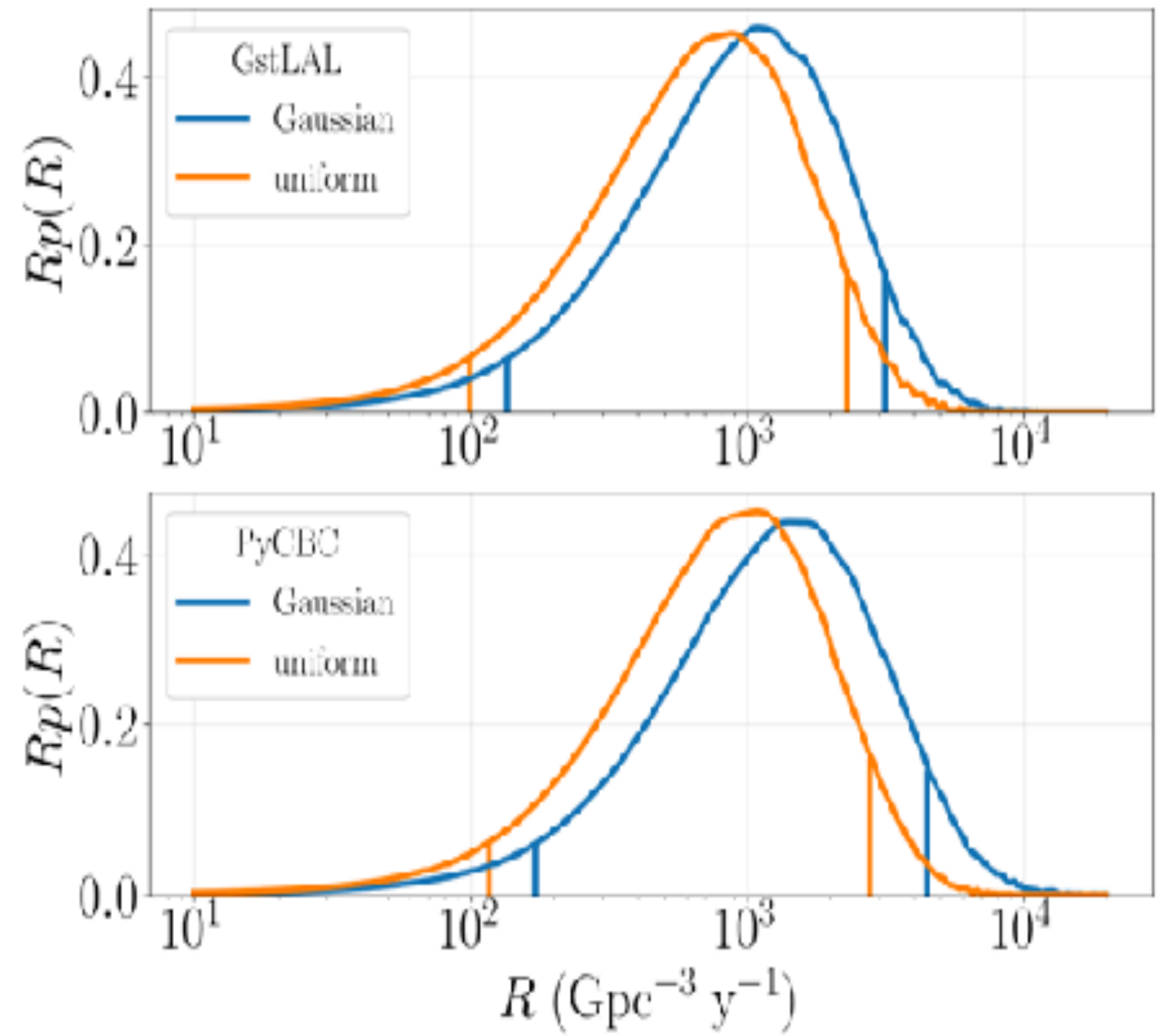
- Two possible mass gaps
  - >3 $M_\odot$: nuclear EOS
  - <5 $M_\odot$: binary evolution
  - > 50 $M_\odot$: PISN



ligo.caltech.edu

Astrophysics

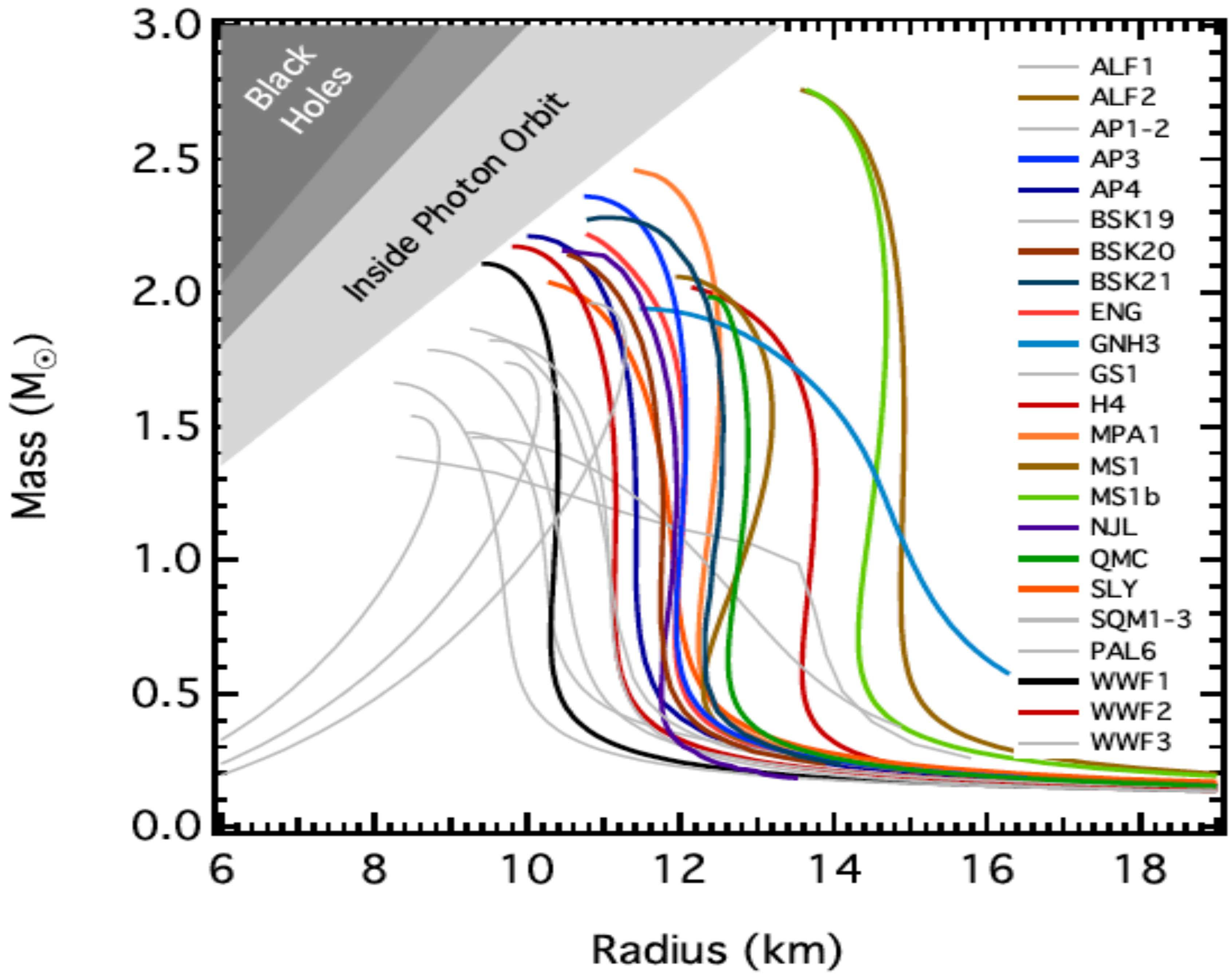




$9.7 - 101\, Gpc^{-3}yr^{-1}$

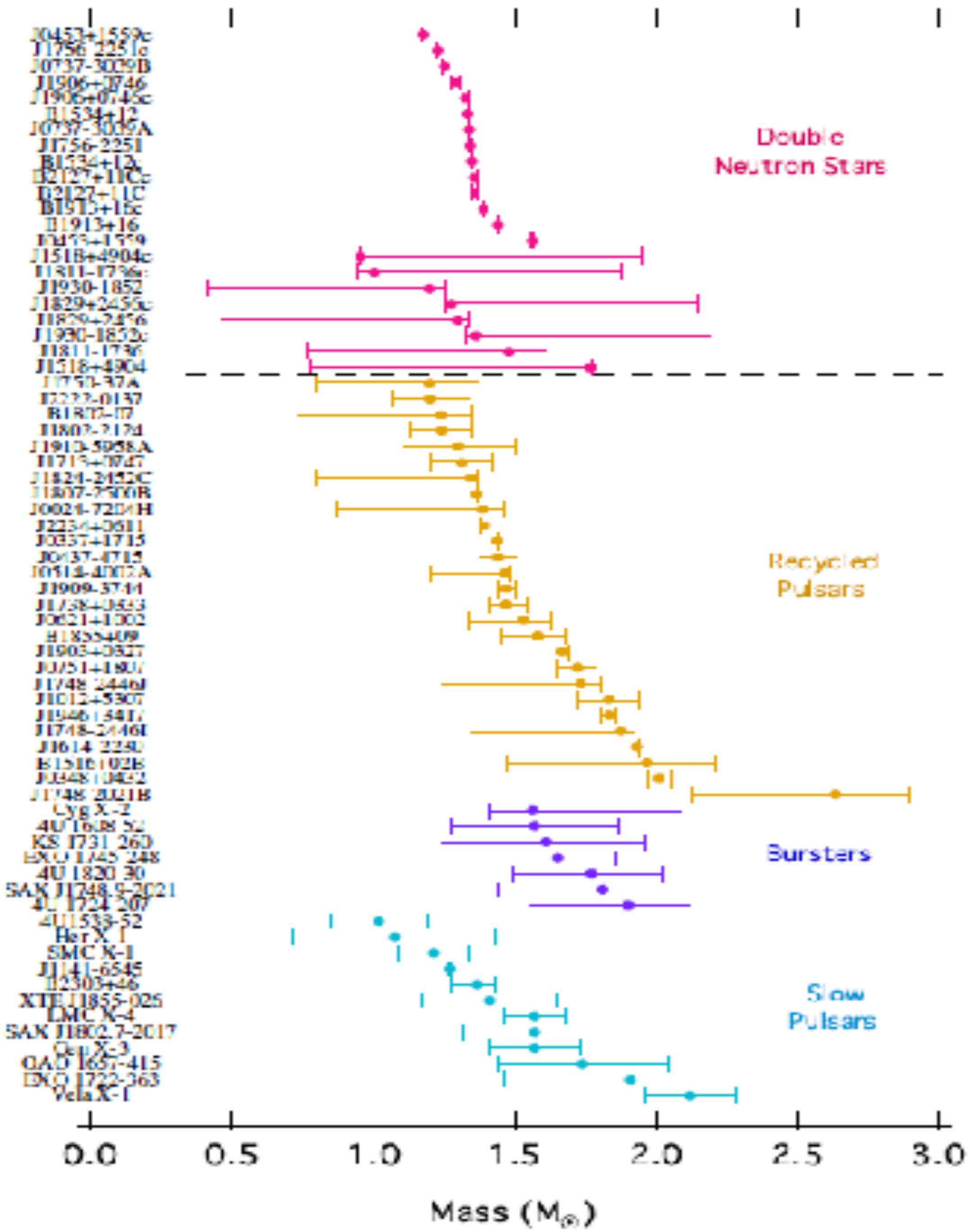
$110 - 3840\, Gpc^{-3}yr^{-1}$

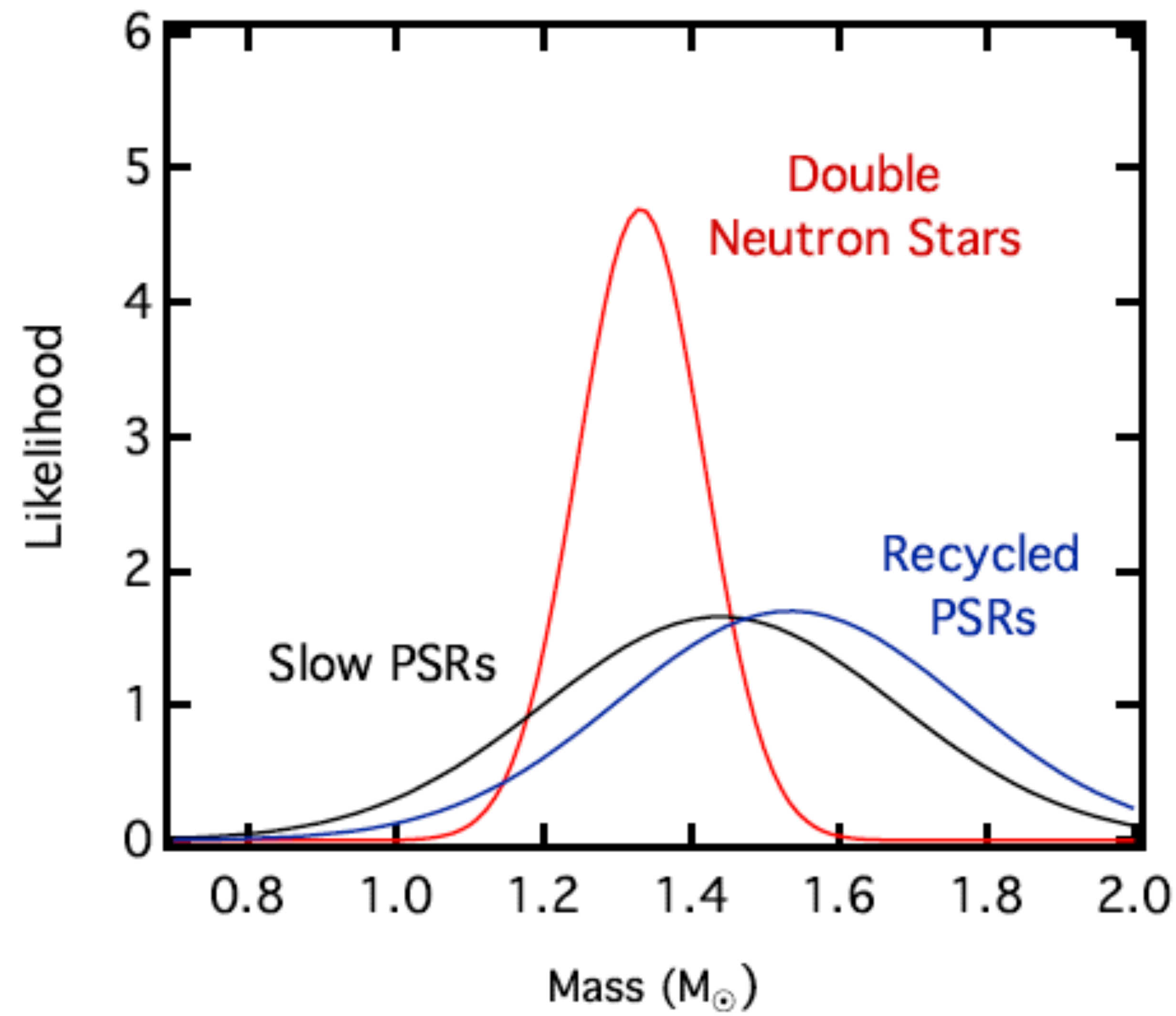
Extreme Matter



Özel & Freire, Ann.Rev.Astron.Astrophys 54, 401 (2017)

Extreme Matter

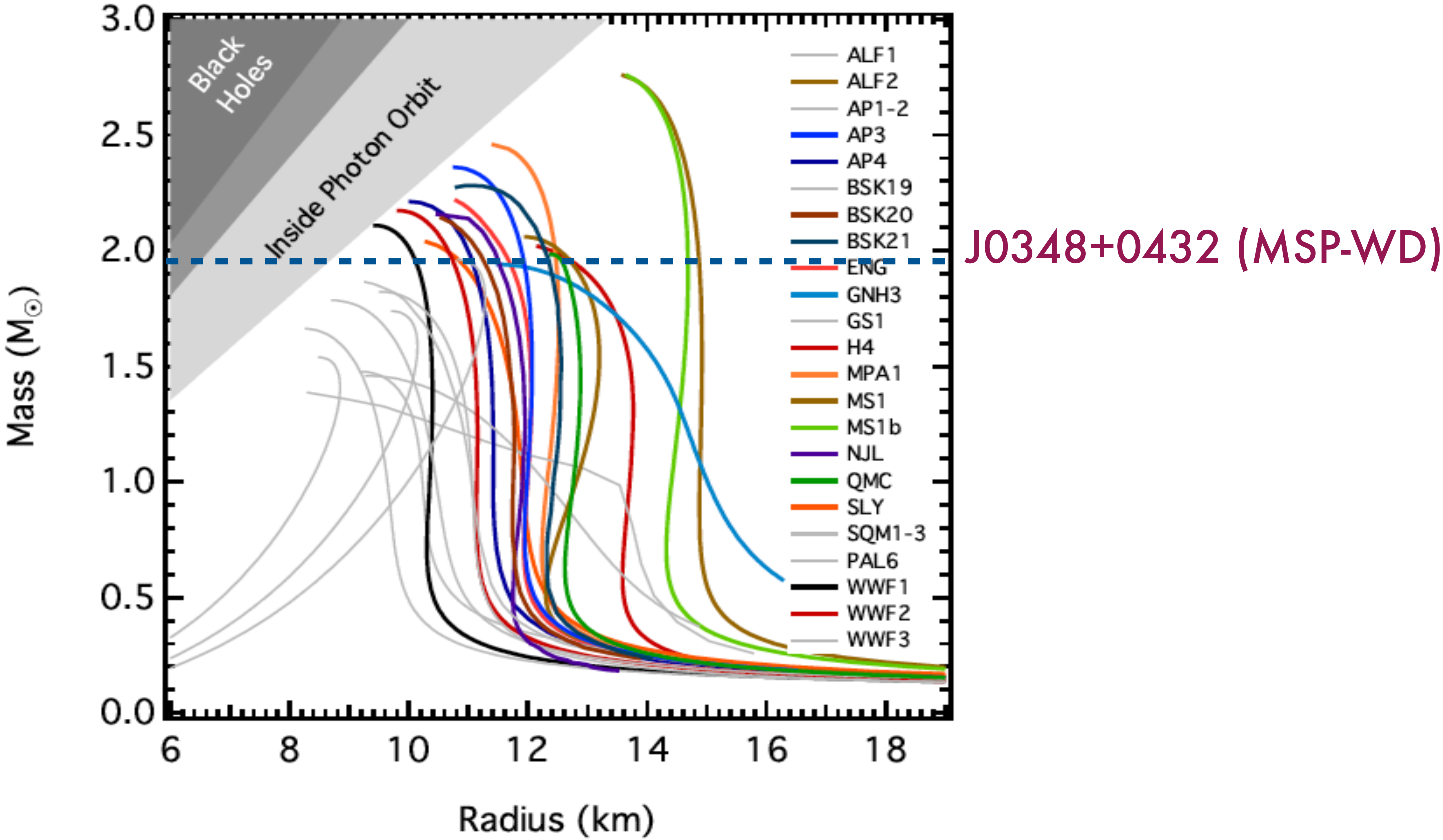




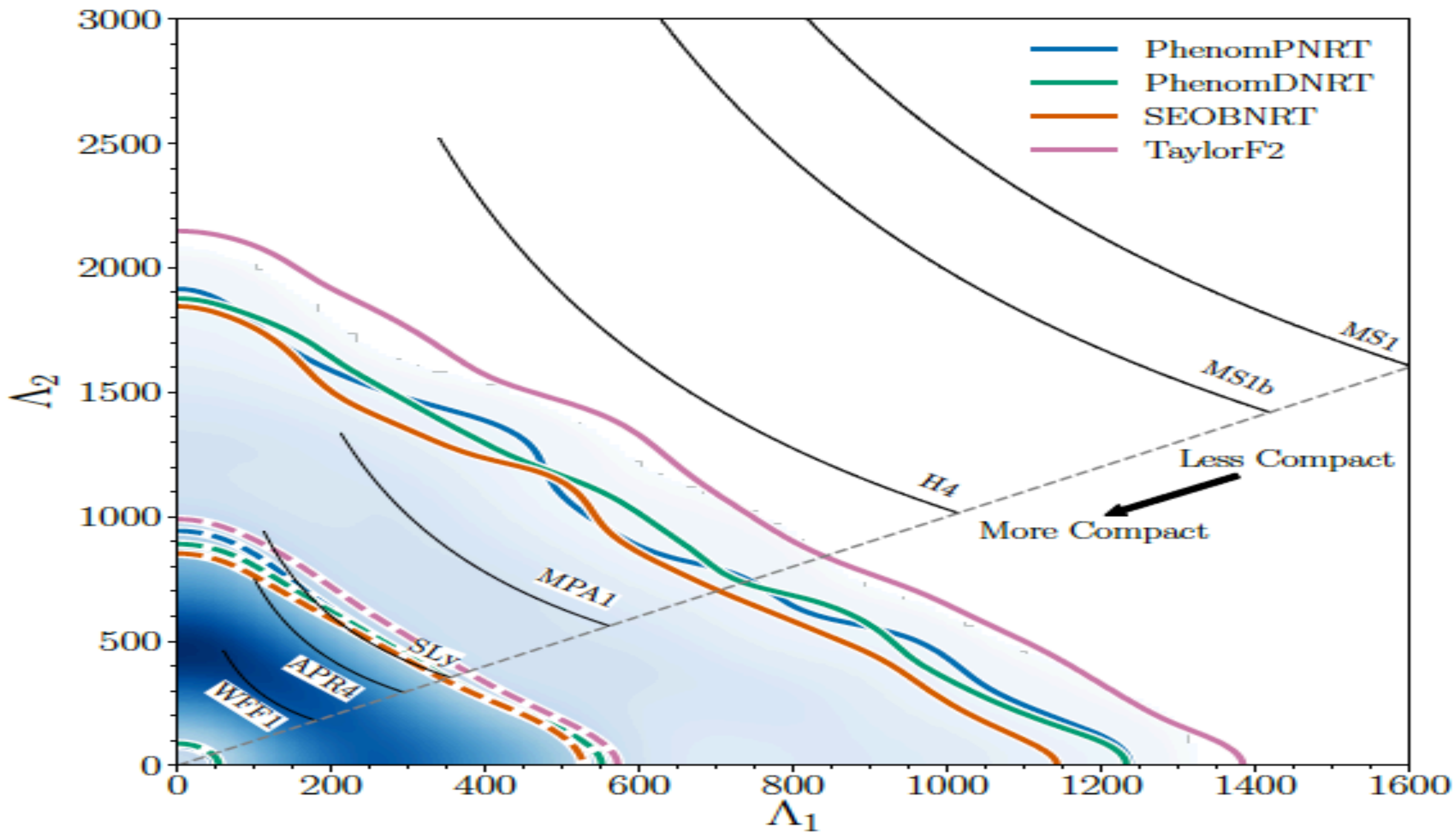
J0348+0432 : 2.01±0.04 $M_\odot$

Özel & Freire, Ann.Rev.Astron.Astrophys 54, 401 (2017)

Extreme Matter



Extreme Matter

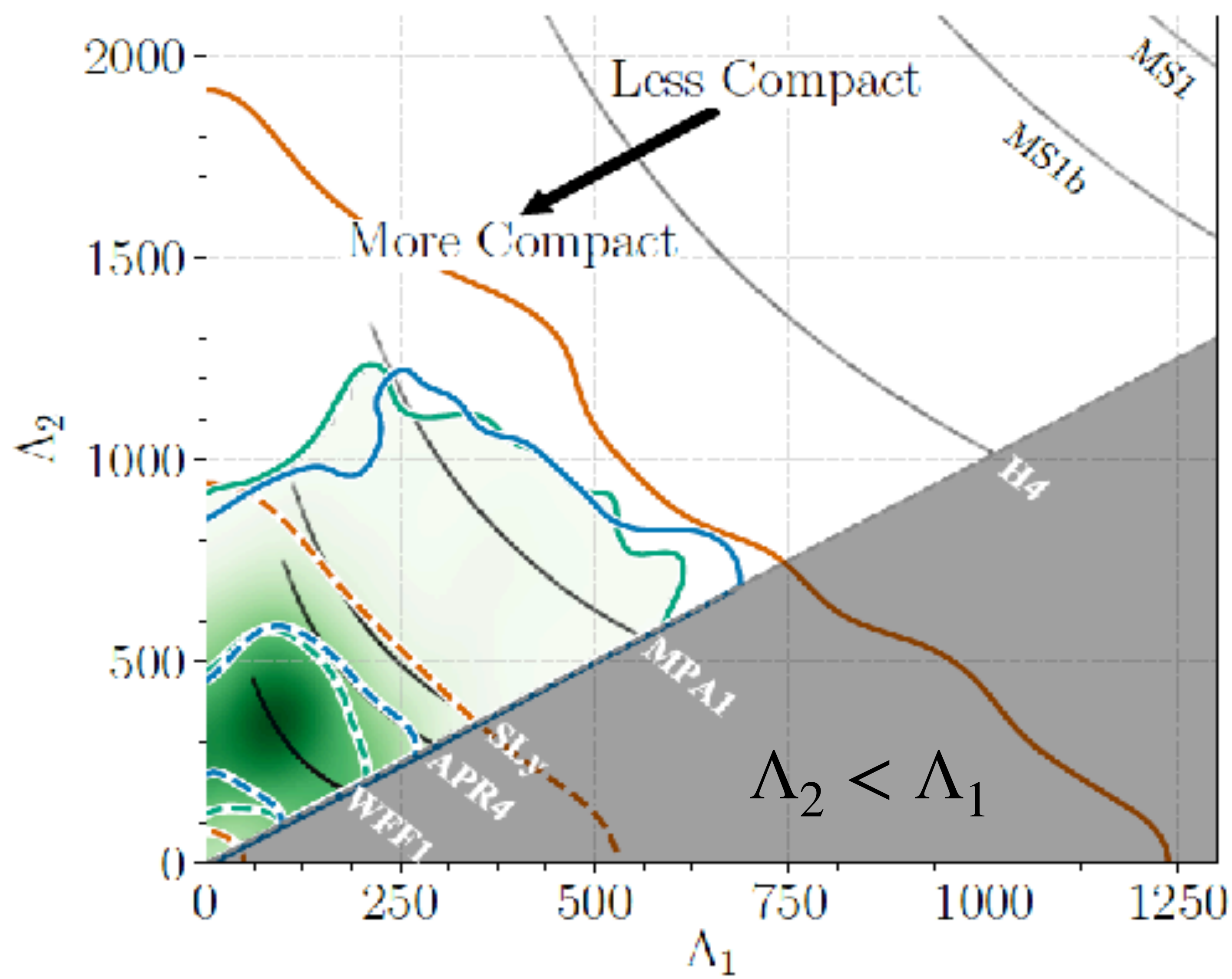


- New analysis beginning at 23 Hz (~1500 extra cycles) with better modelling
- No assumption on binary components
- No assumptions on EOS - independent variation
- sky error reduced to 16 deg² (using sky position given by SSS17A/AT 2017 gfo)
- Bound on Λ_1 - Λ_2 is 20% smaller

Abbott et al, arXiv:1805.11579 (2018)

Extreme Matter

- **Assume 2 NSs with identical EOS**
- **2 EOS methodologies**
  - **EOS-insensitive :**
    i. $\Lambda_a(\Lambda_s, q)$
    ii. Λ - C
  - **Parameterised EOS (no max mass)**
    i. Spectral parameterisation
  - **Original detection results**
- **90% CI for Λ_1 - Λ_2 shrinks by ~3**

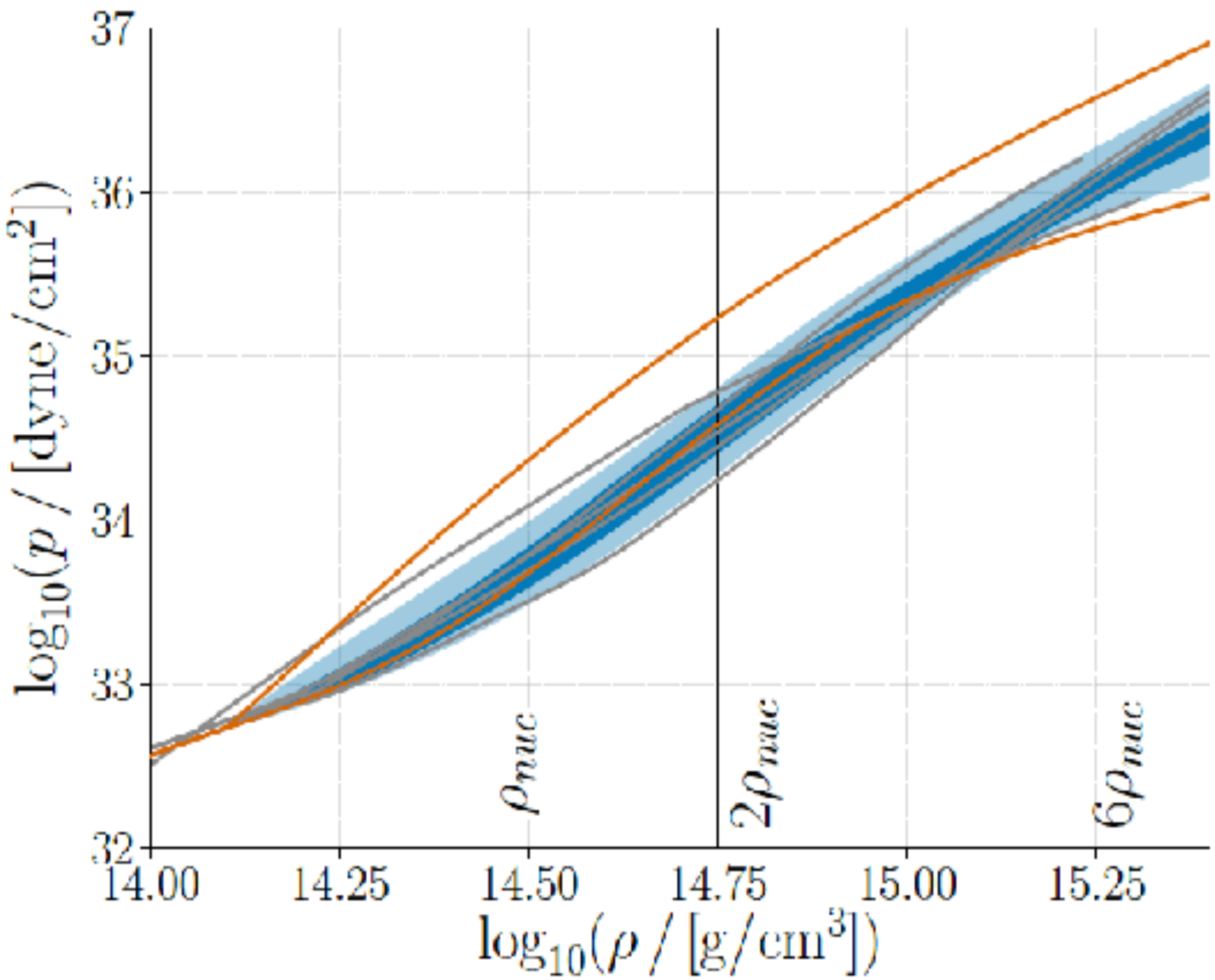


$$\Lambda_{1.4} = 190^{+390}_{-120}$$

Abbott et al, arXiv:1805.11581 (2018)

Extreme Matter

Now assume spectral parameterisation + maximum NS mass = 1.97 $M_\odot$

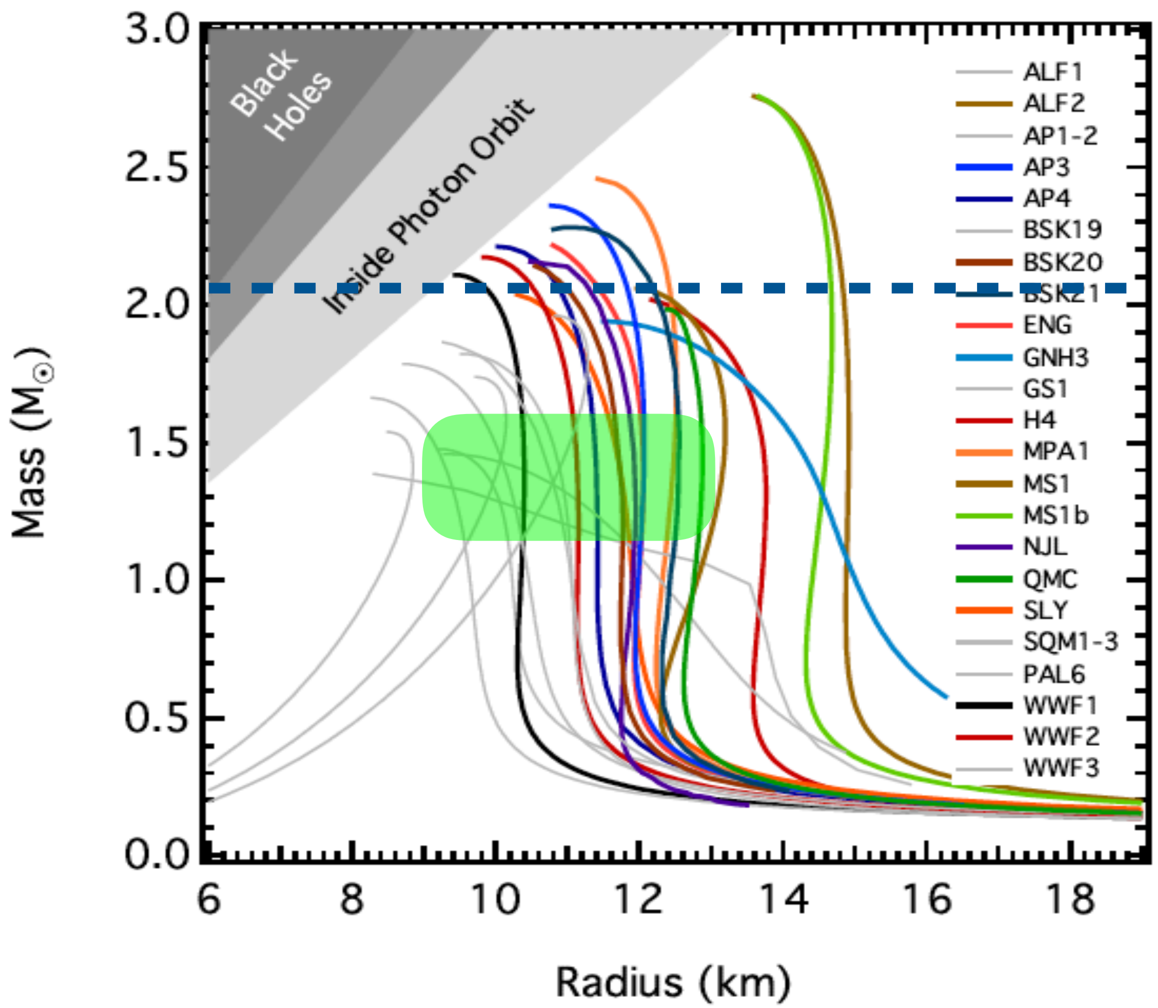


$$p(2\rho_{nuc}) = 3.5^{+2.5}_{-1.7} \times 10^{34}\, dyne\, cm^{-2}$$

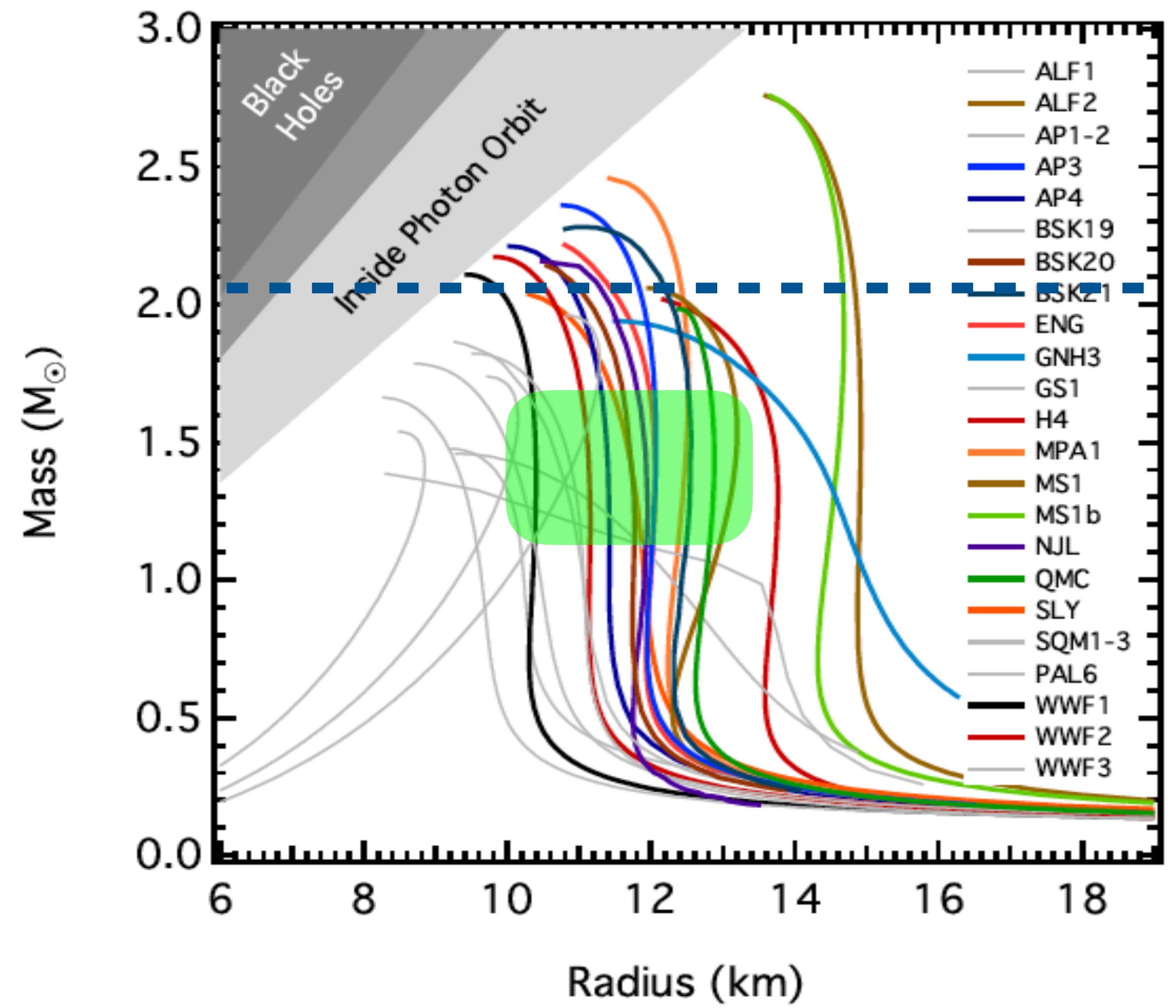
Abbott et al, arXiv:1805.11581 (2018)

Extreme Matter

EOS-ins



Spec.Param + min. NS mass

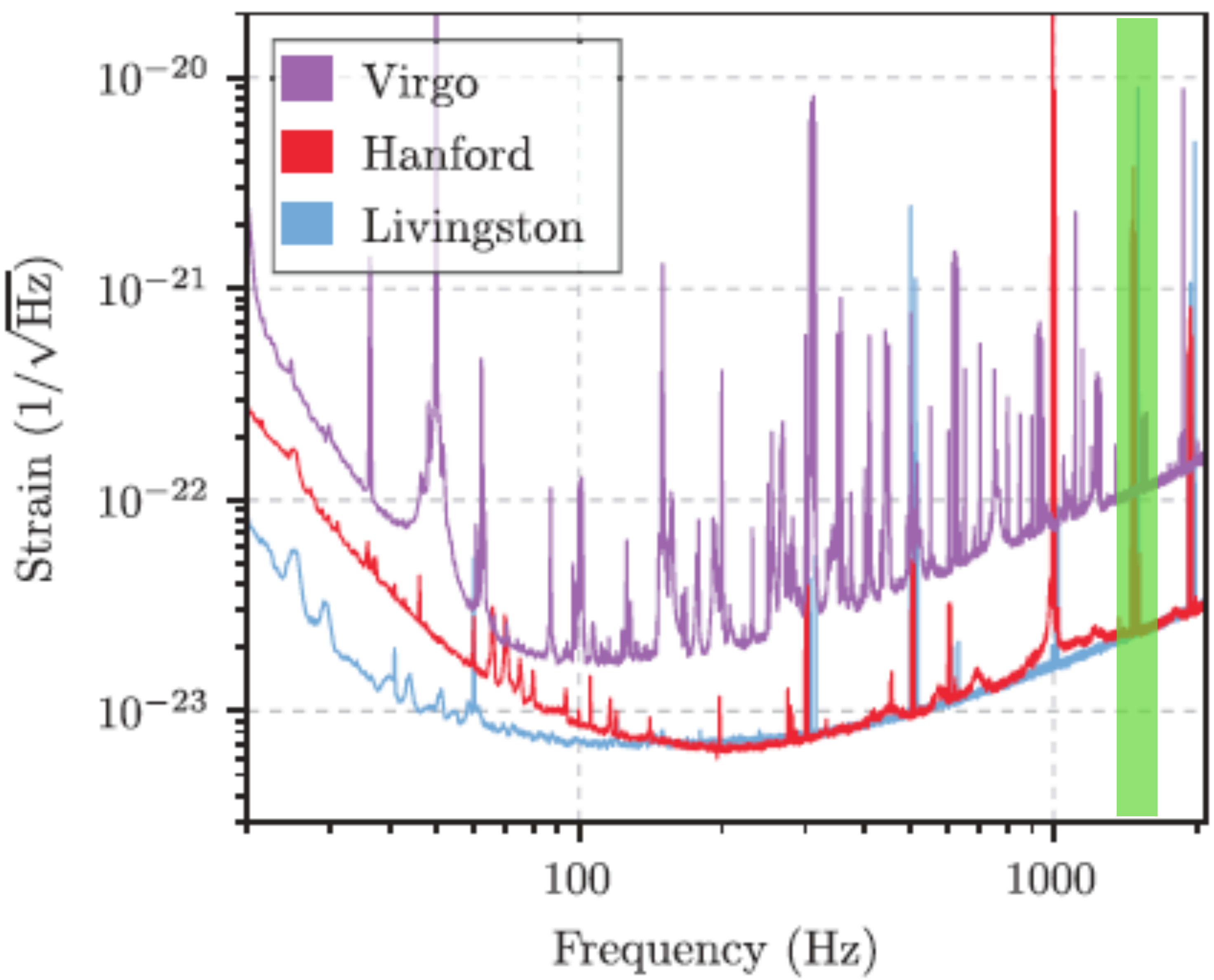


GW + EM gives much tighter constraint

Extreme Matter

Q:So what is the remnant of the merger?

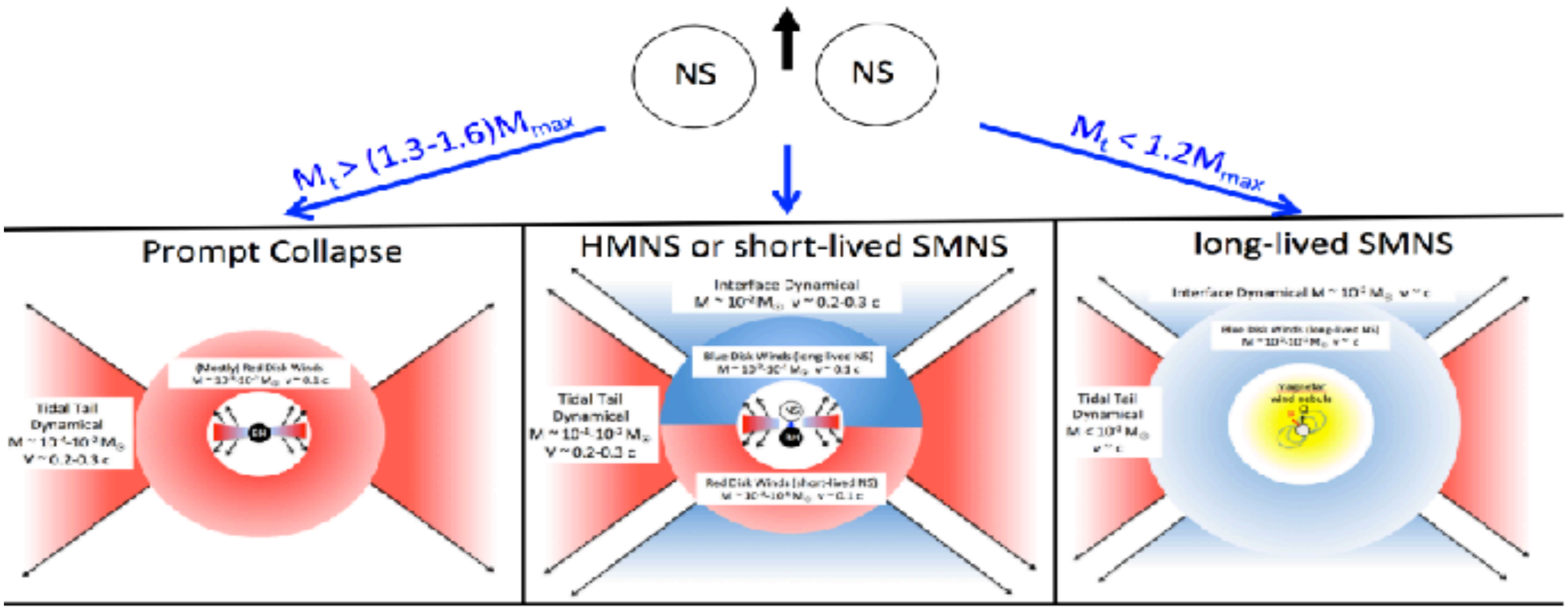
A:From GWs - we don't know. High frequency signal dominated by photon shot noise



Extreme Matter

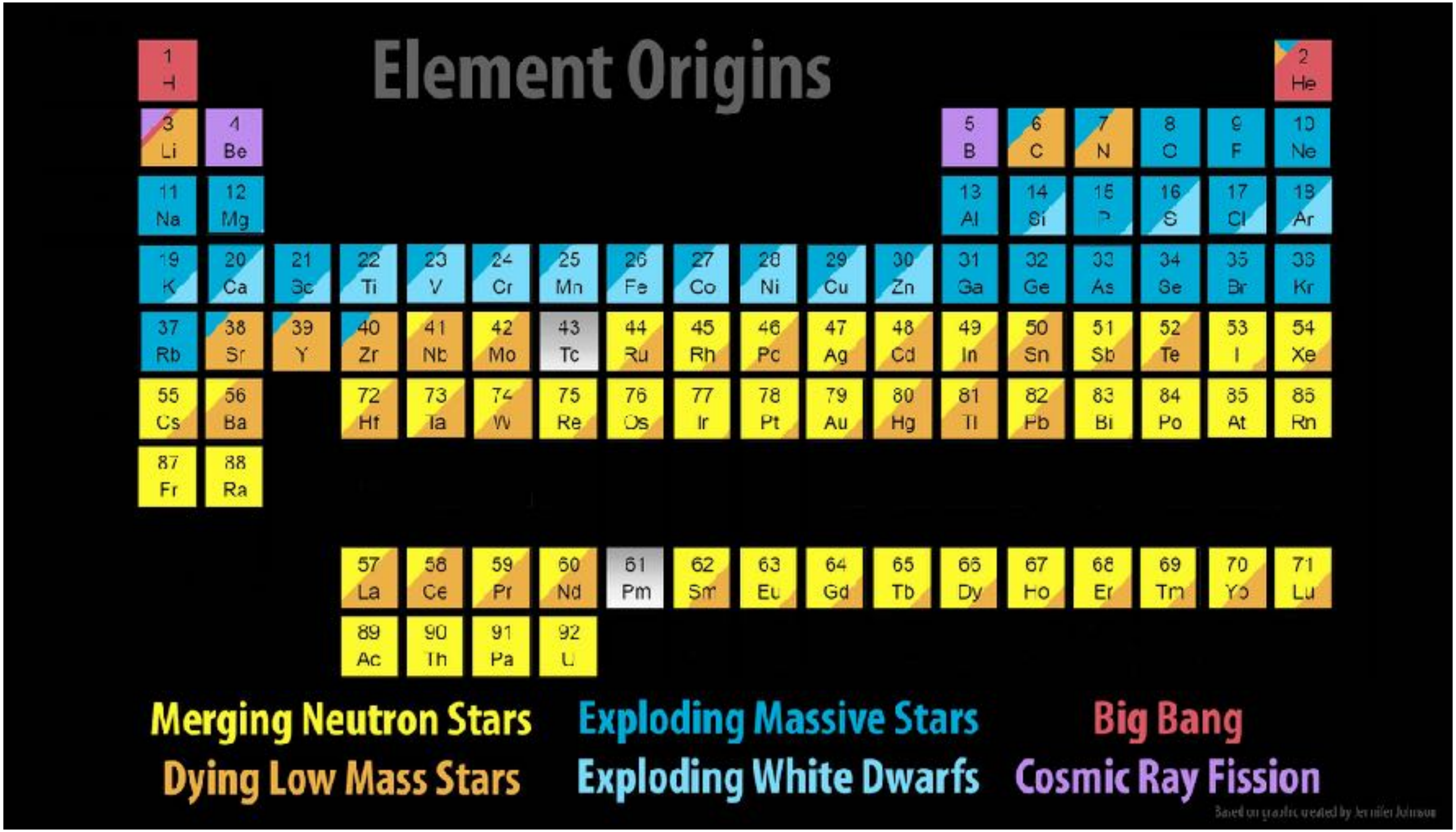
Q: So what is the remnant of the merger?

A: From EM - unclear! Some people believe prompt collapse to BH, others believe in the formation of a transient hypermassive NS



Margalit et al (2017)

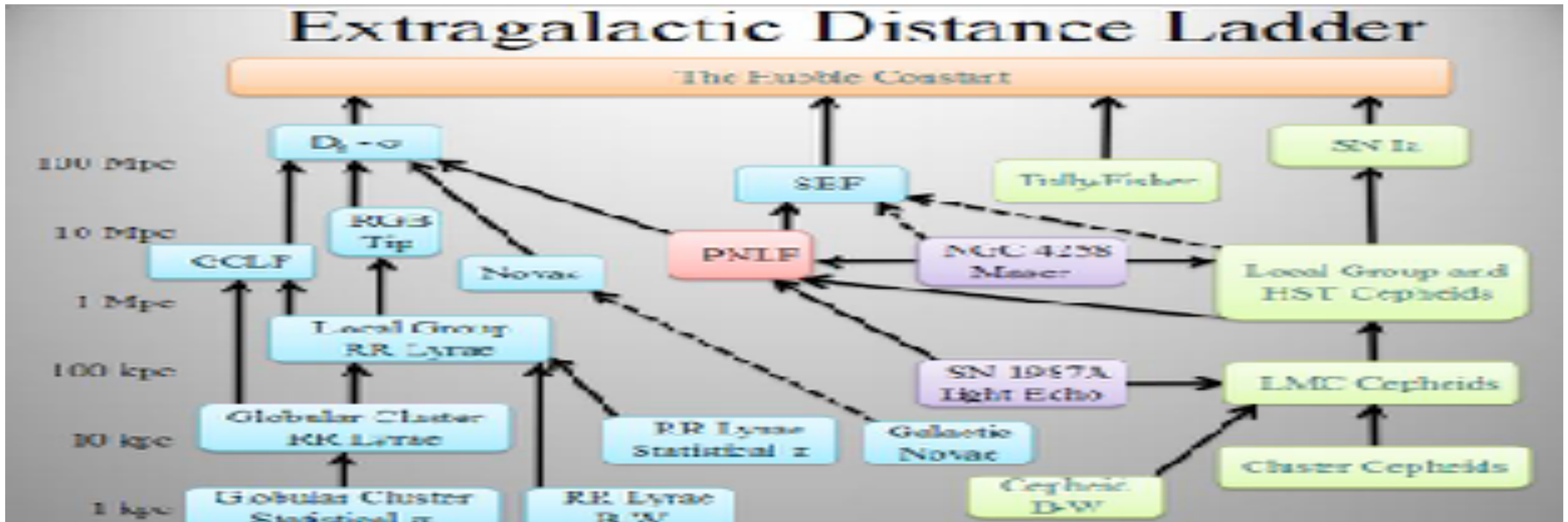
Extreme Matter



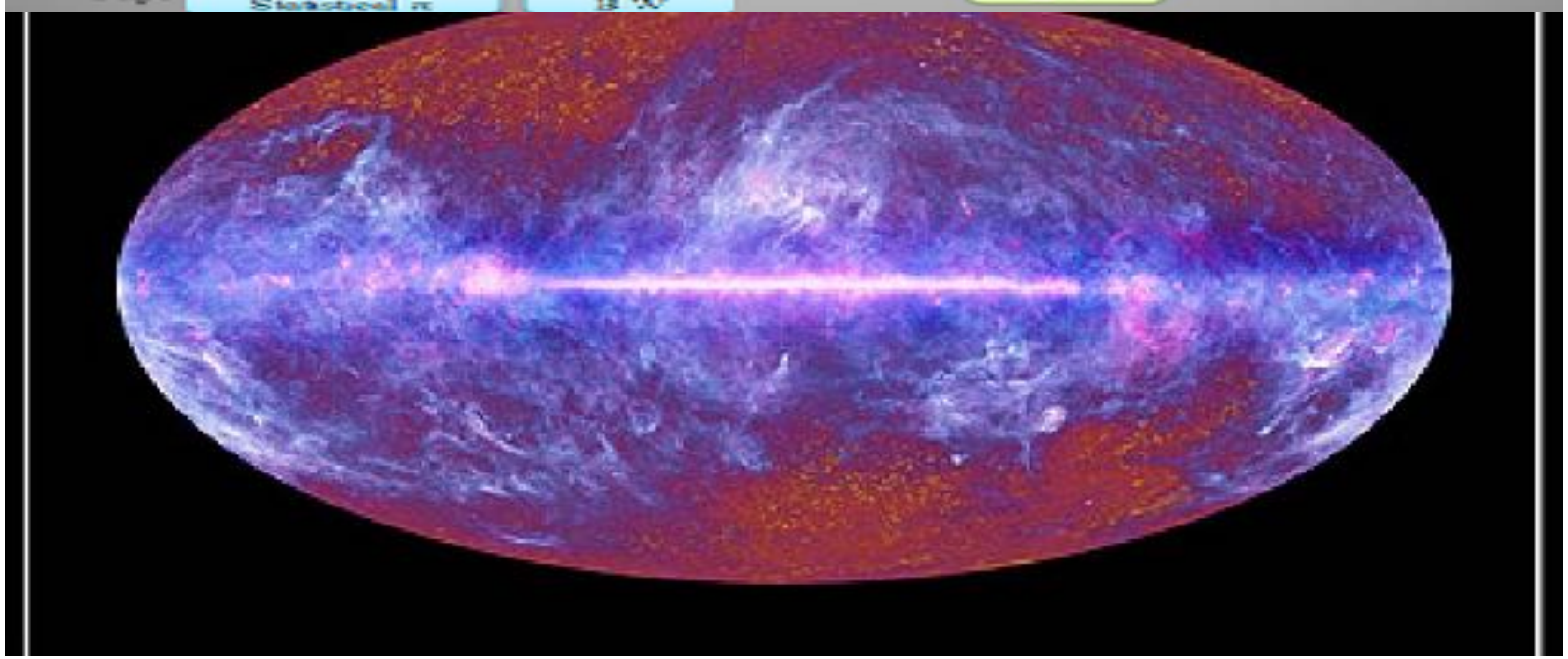
Credit: Jennifer Johnson/SDSS

Cosmology

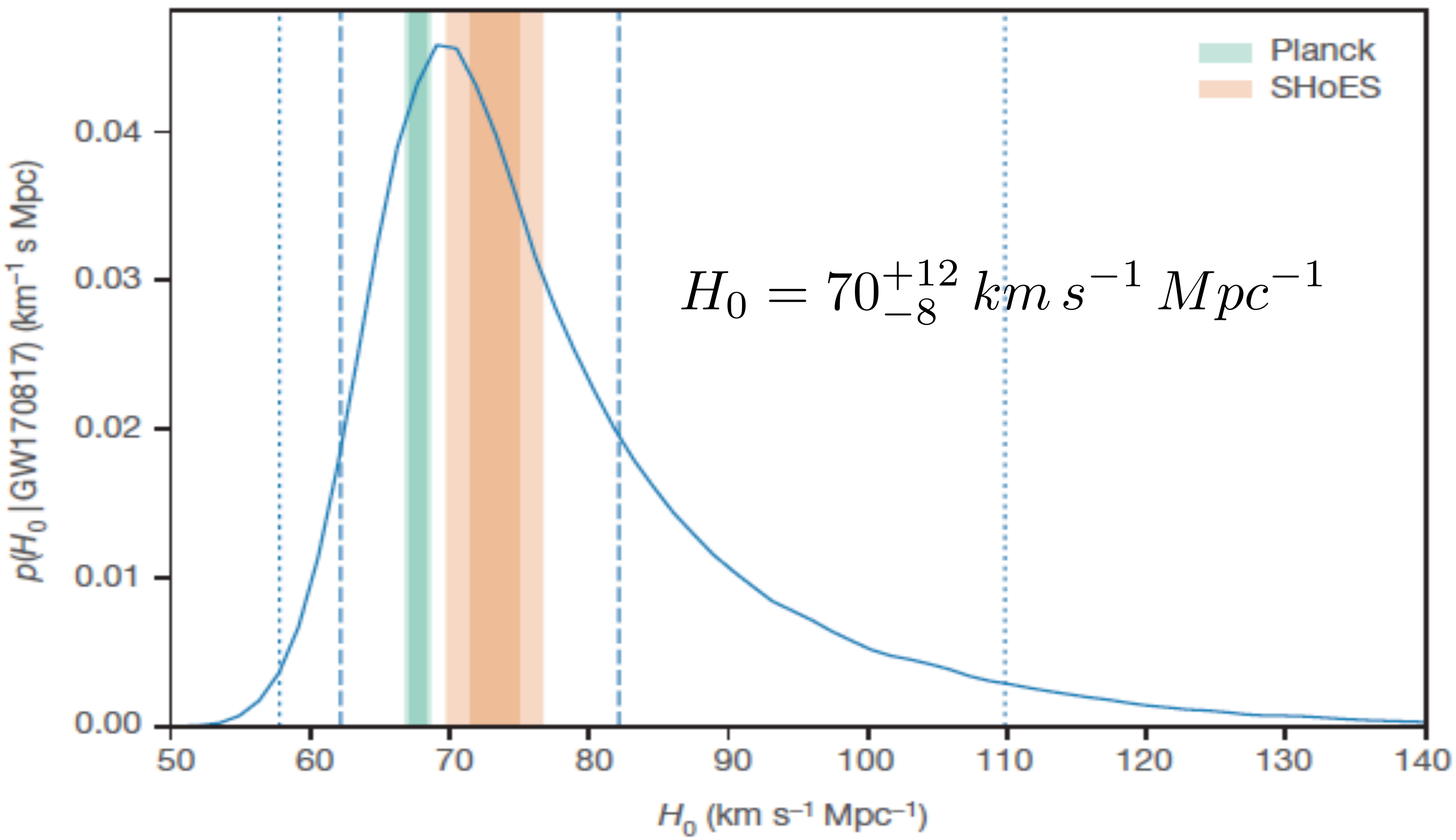
Astrophysics



Cosmology



Cosmology



- **N.B. No cosmic distance ladder needed!!**
- **GW astronomy measures luminosity distance directly over cosmic scales**

Abbott et al, Nature (2017)

Conclusion

- Very exciting time
- Thank you for attending the workshop