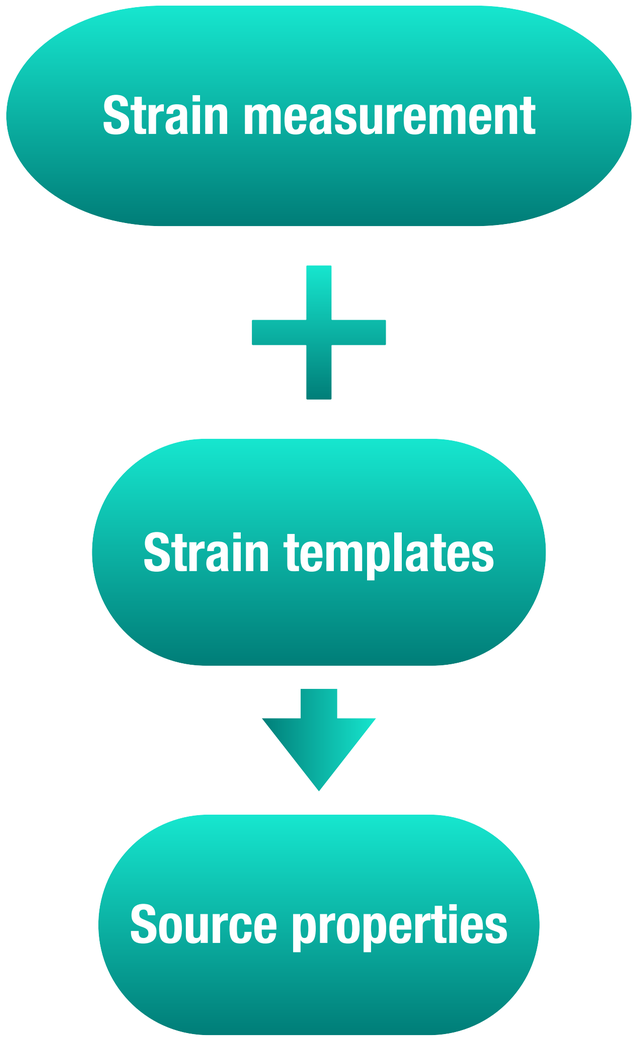
Gravitational-wave parameter inference with the Newman-Penrose scalar

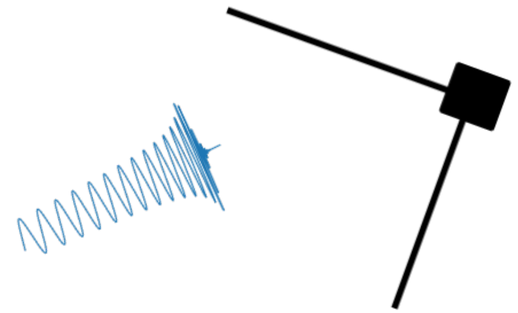
Juan Calderón Bustillo, Isaac C. F. Wong, Nicolas Sanchis-Gual, Samson H. W. Leong, Alejandro Torres-Forné, Koustav Chandra, José A. Font, Carlos Herdeiro, Eugen Radu, and Tjonnie G. F. Li

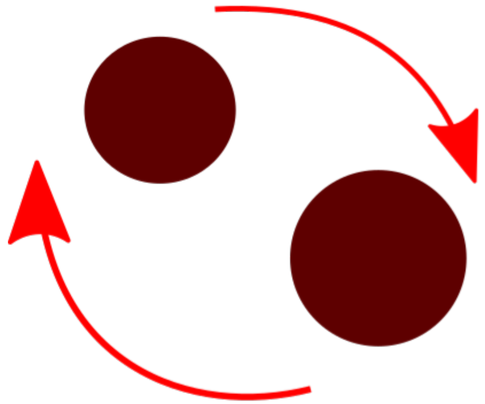
Speaker: Isaac C. F. Wong

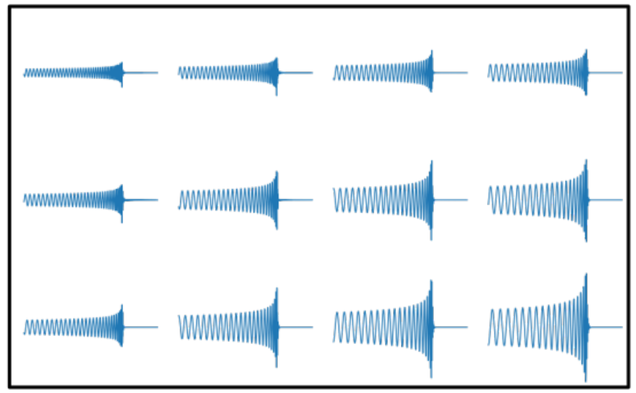
arXiv: 2205:15029

The usual way that we perform data analysis









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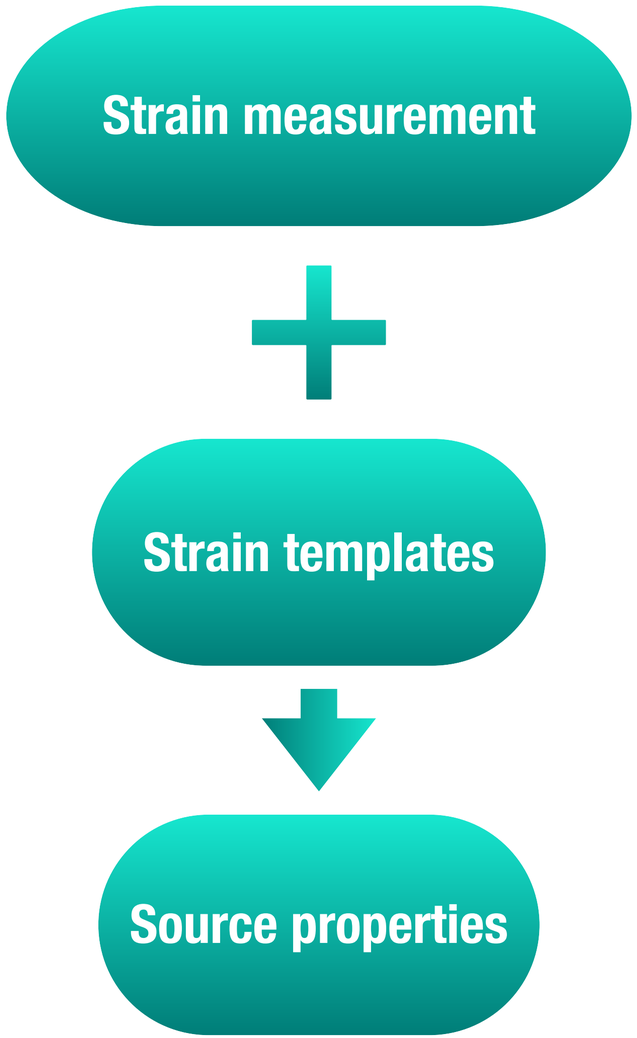

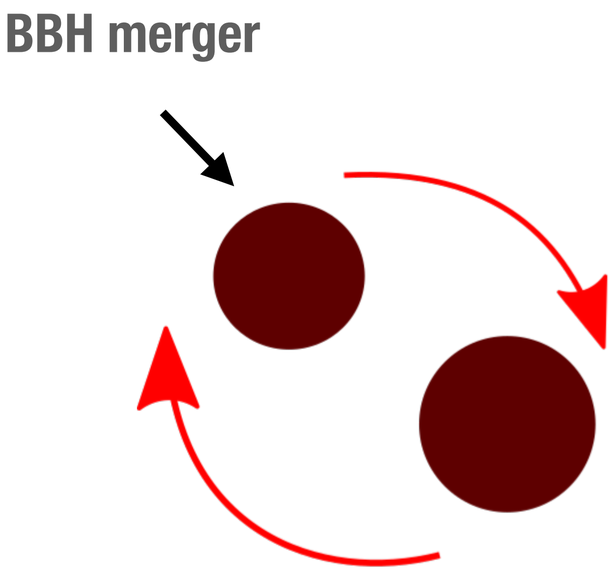

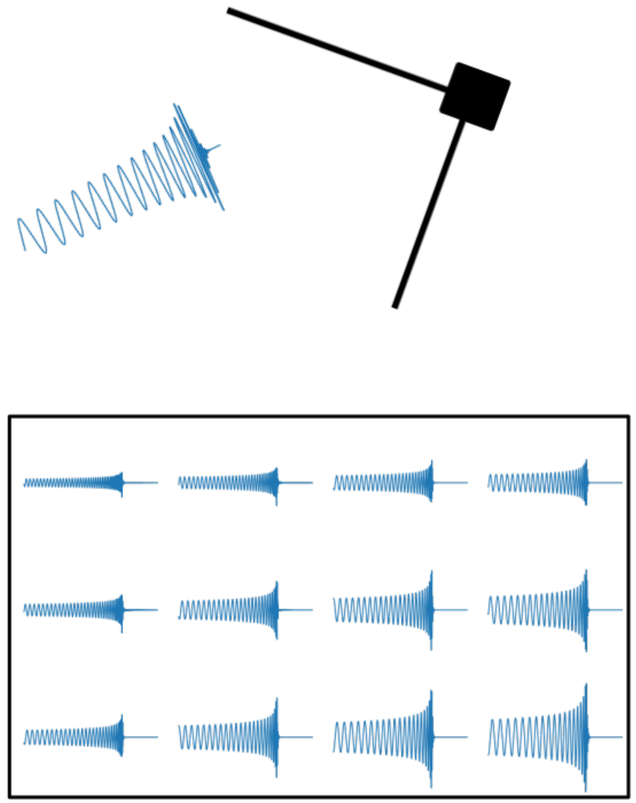

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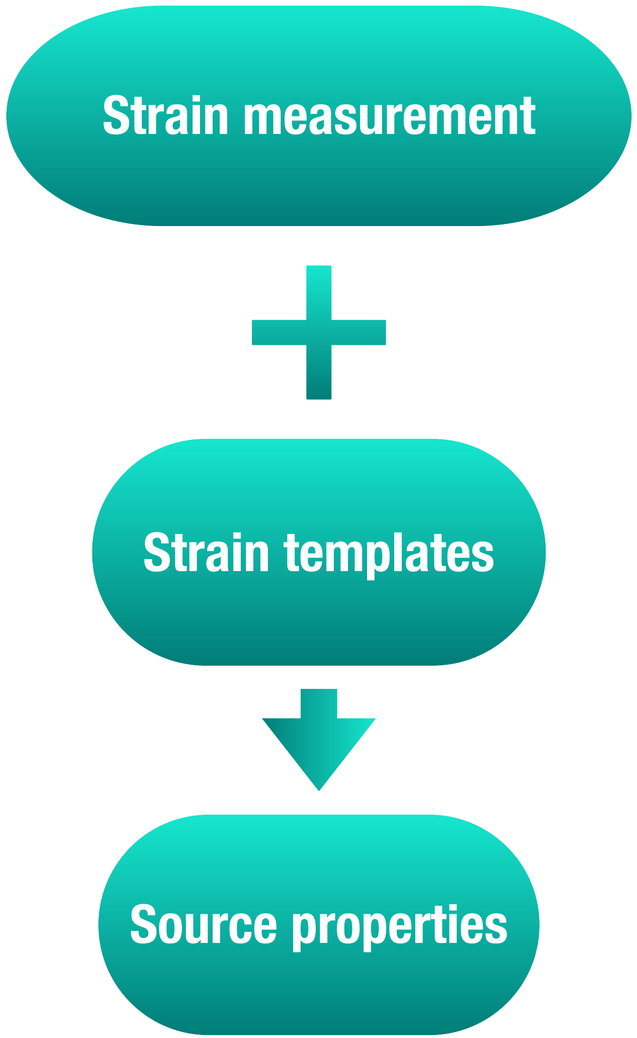

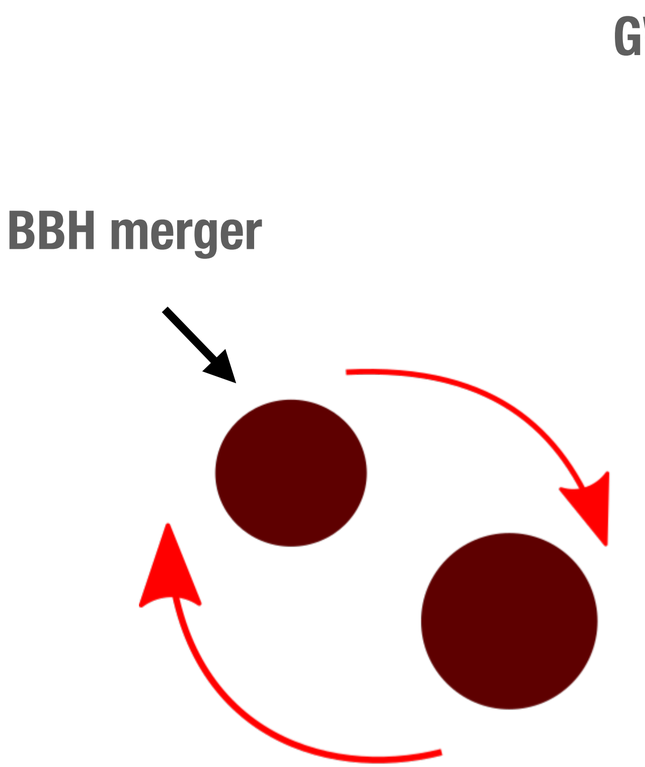

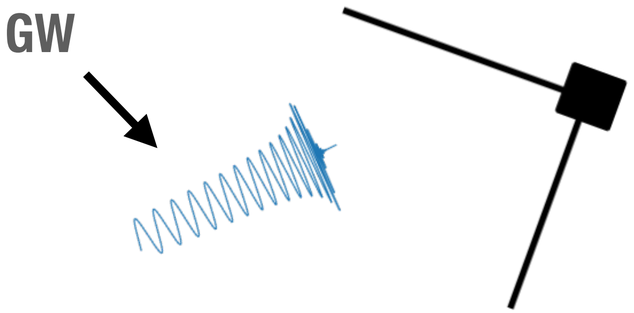

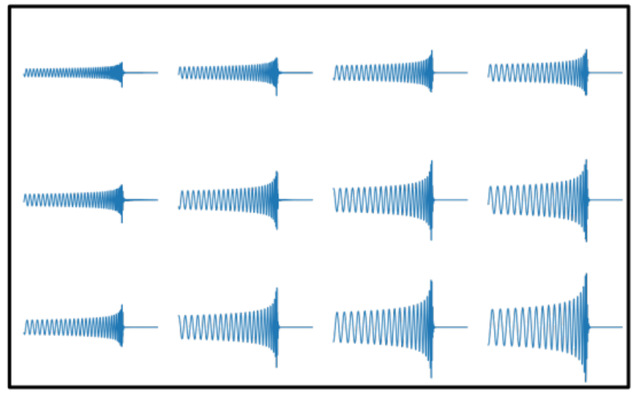

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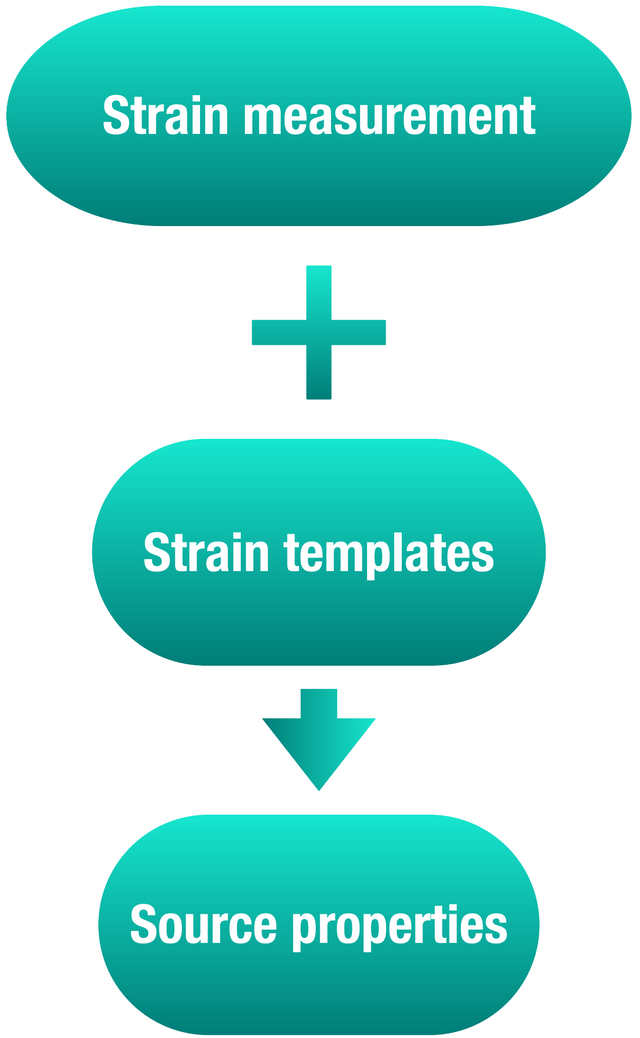
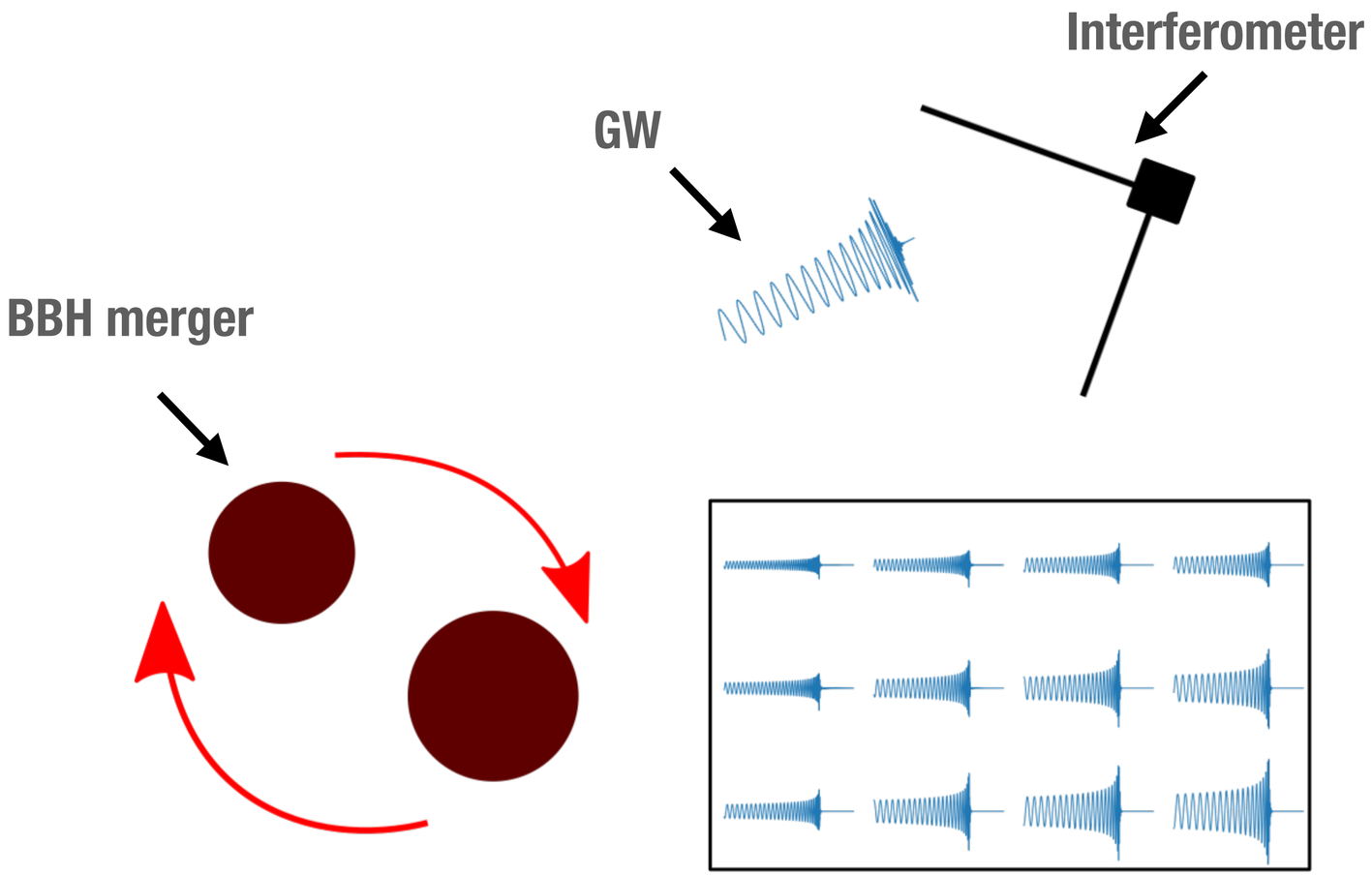




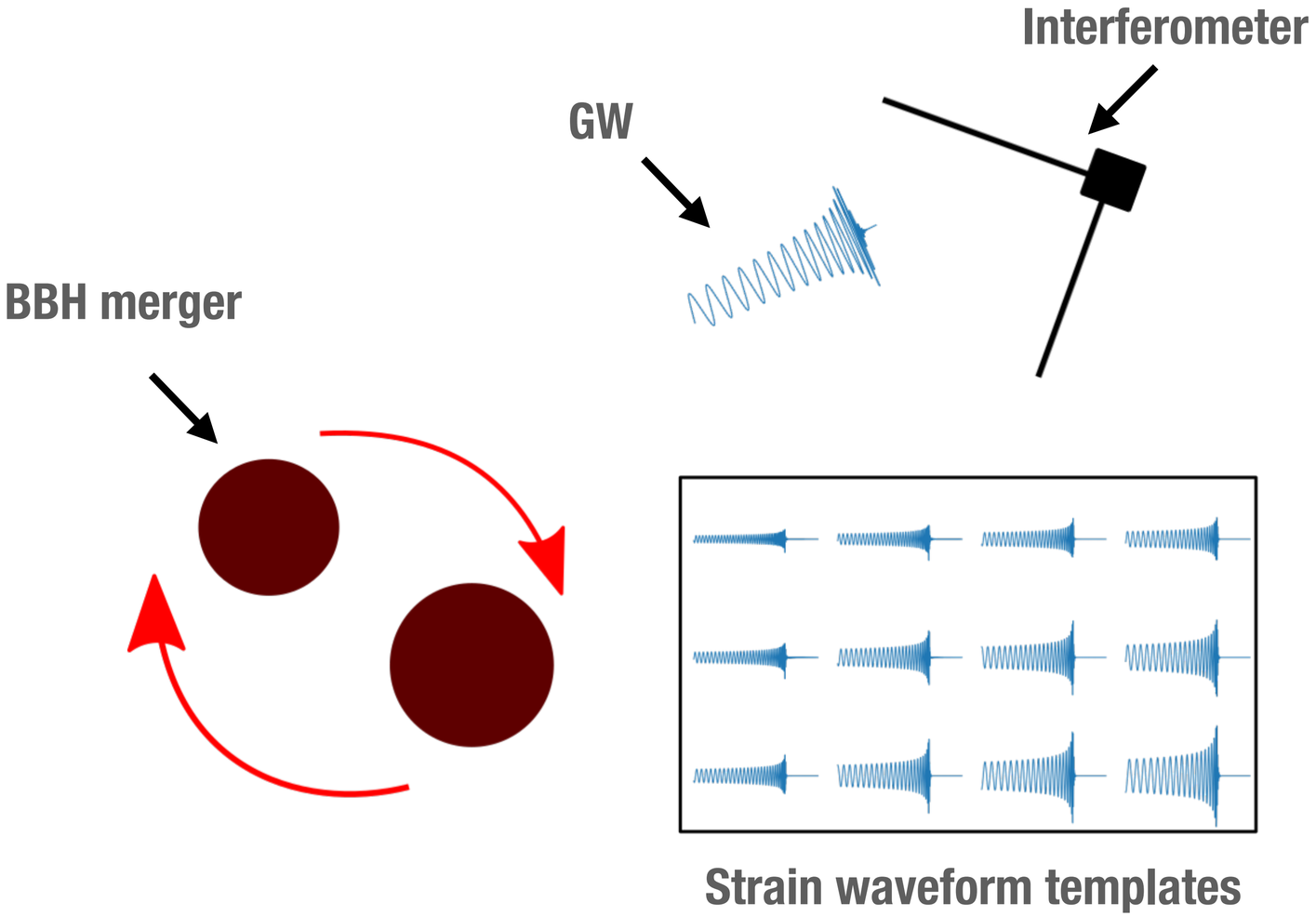
The usual way that we perform data analysis

Strain measurement

+

Strain templates

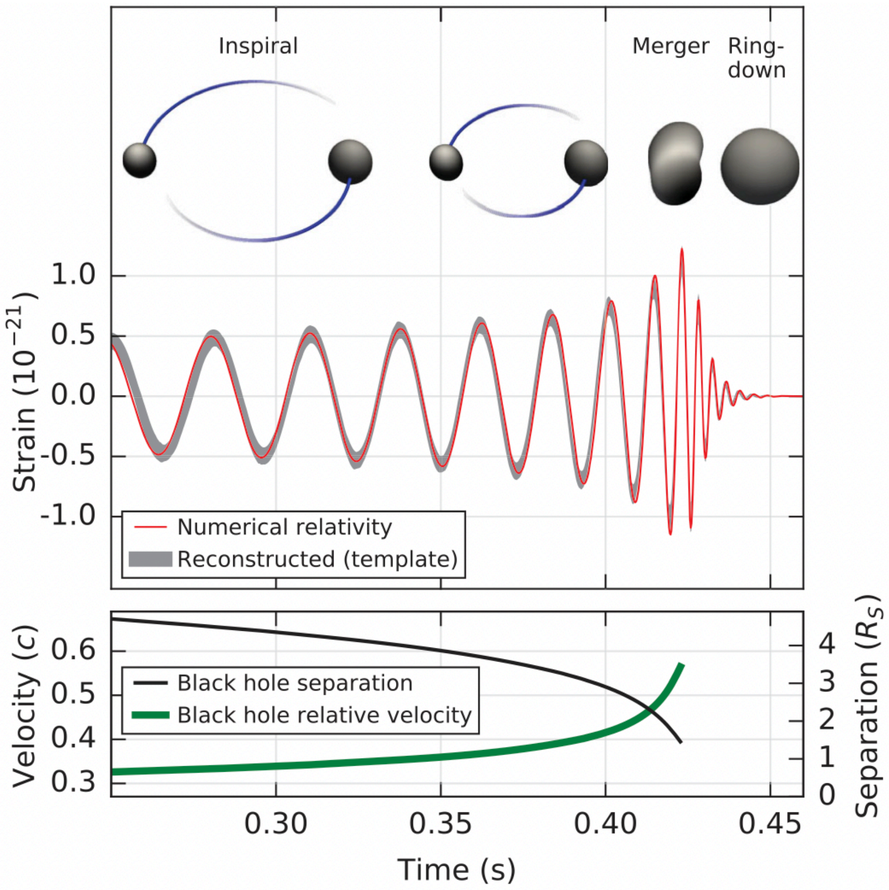
Source properties



We need NR simulations

Inspiral → **Post-Newtonian approximation/ Effective one-body formalism**

Merger & Ringdown → **Approximated models calibrated to NR simulations**

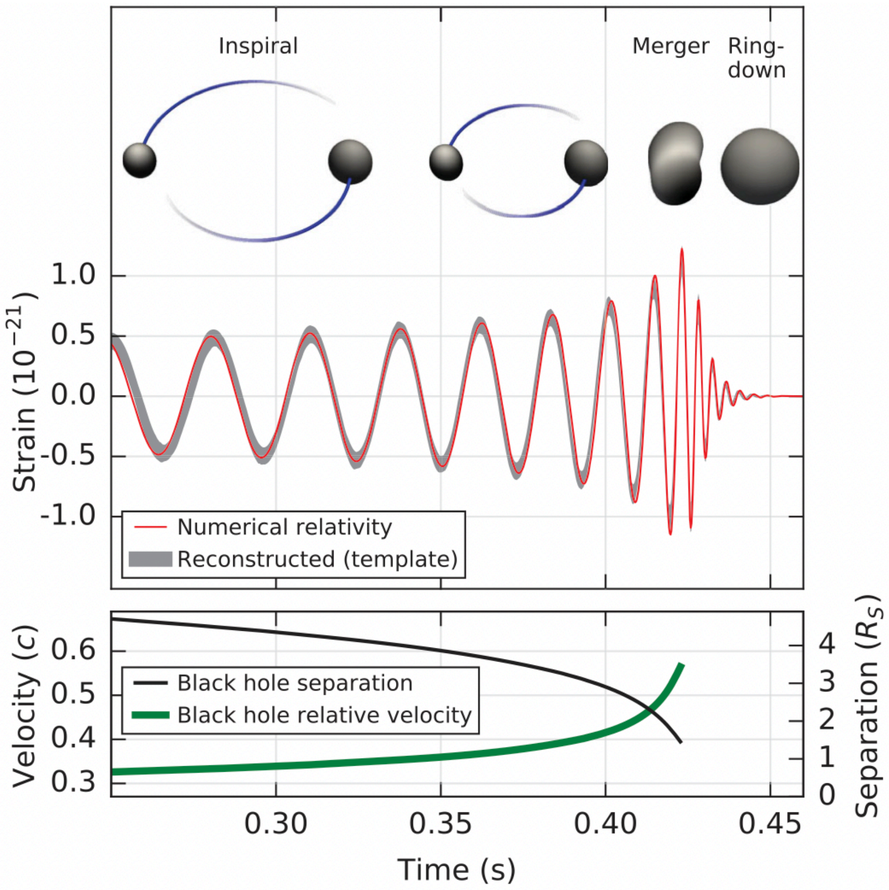


LIGO and Virgo Collaboration [1602.03837]

We need NR simulations

Surrogate models

Interpolated using a set of NR simulations



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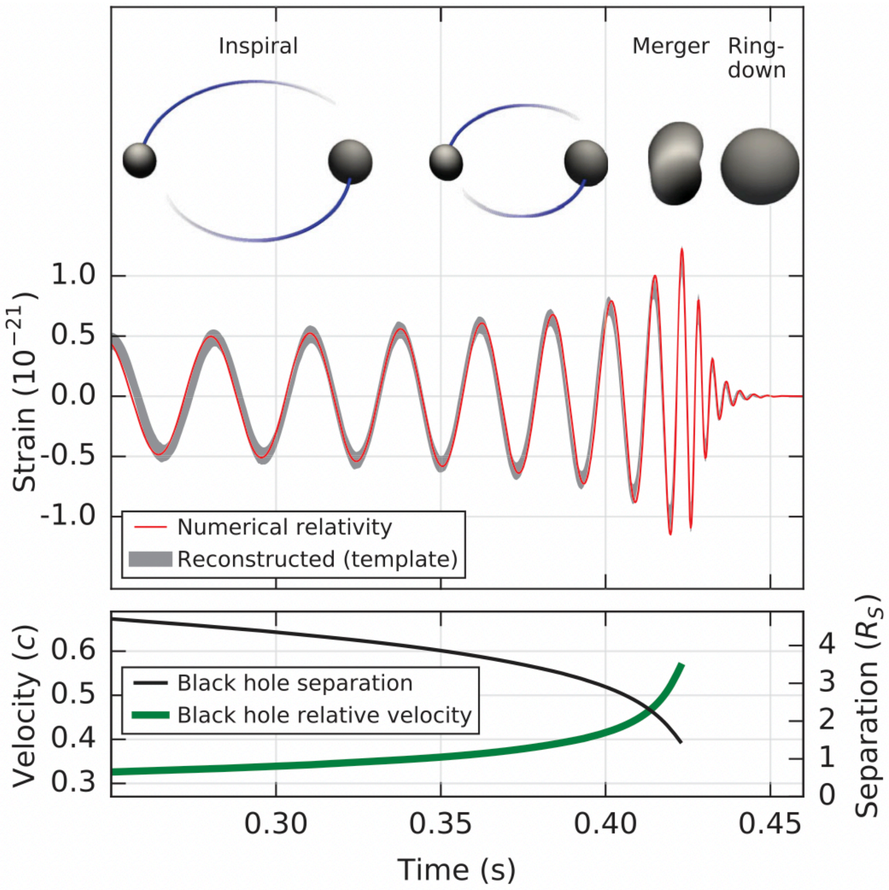
We need NR simulations

Highly eccentric & precessing → **NR simulation**

Exotic compact objects → **NR simulation**



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We need NR simulations

Inspiral	Post-Newtonian approximation/ Effective one-body formalism
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Highly eccentric & precessing	NR simulation
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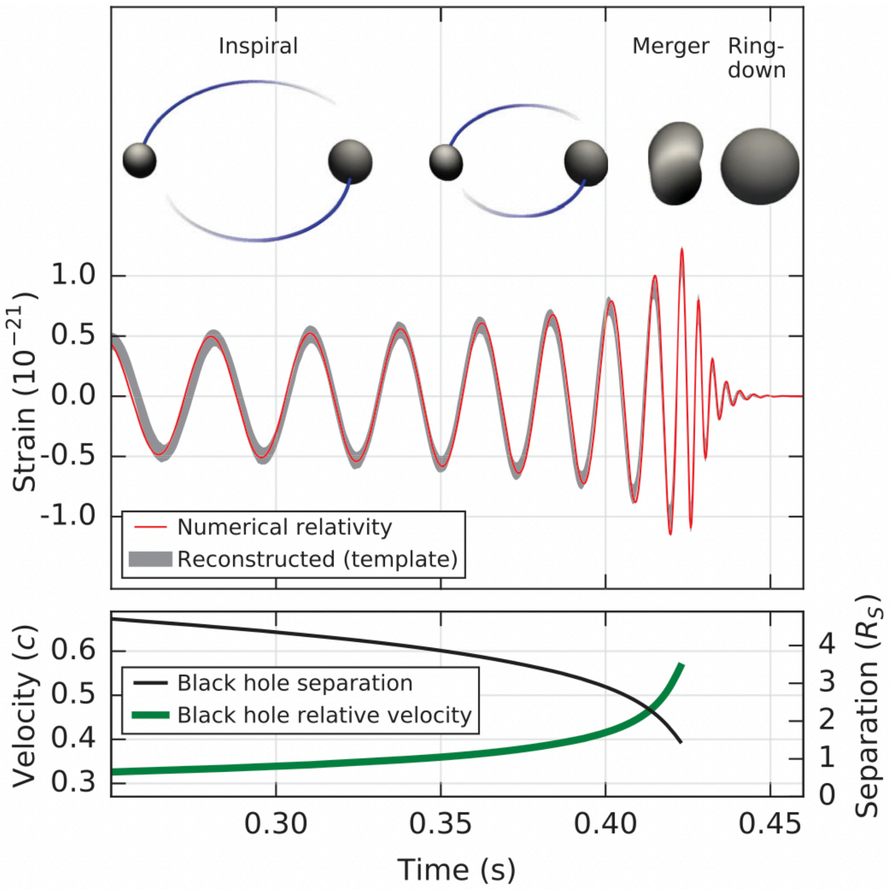

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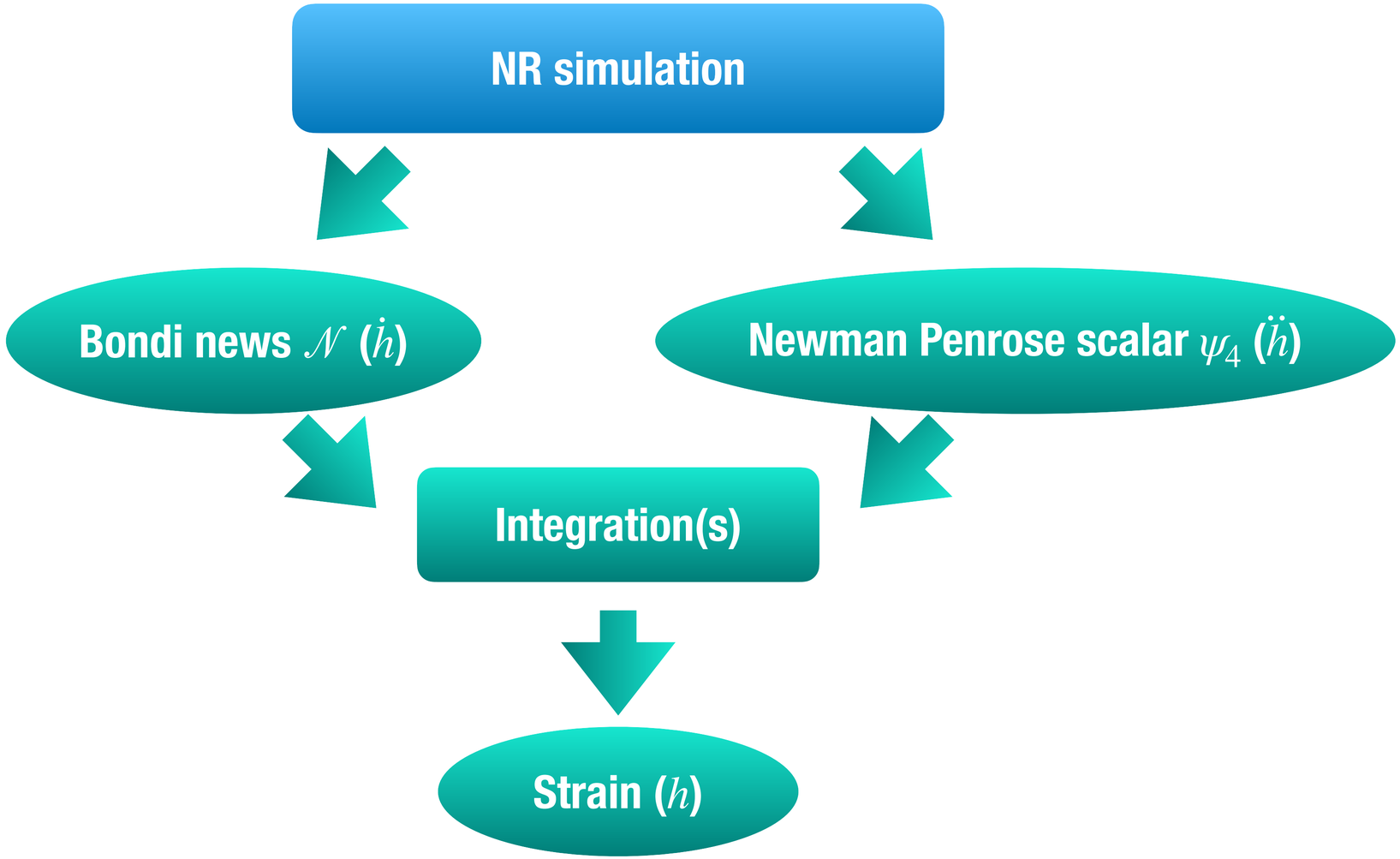
But… NR simulations do not give strain



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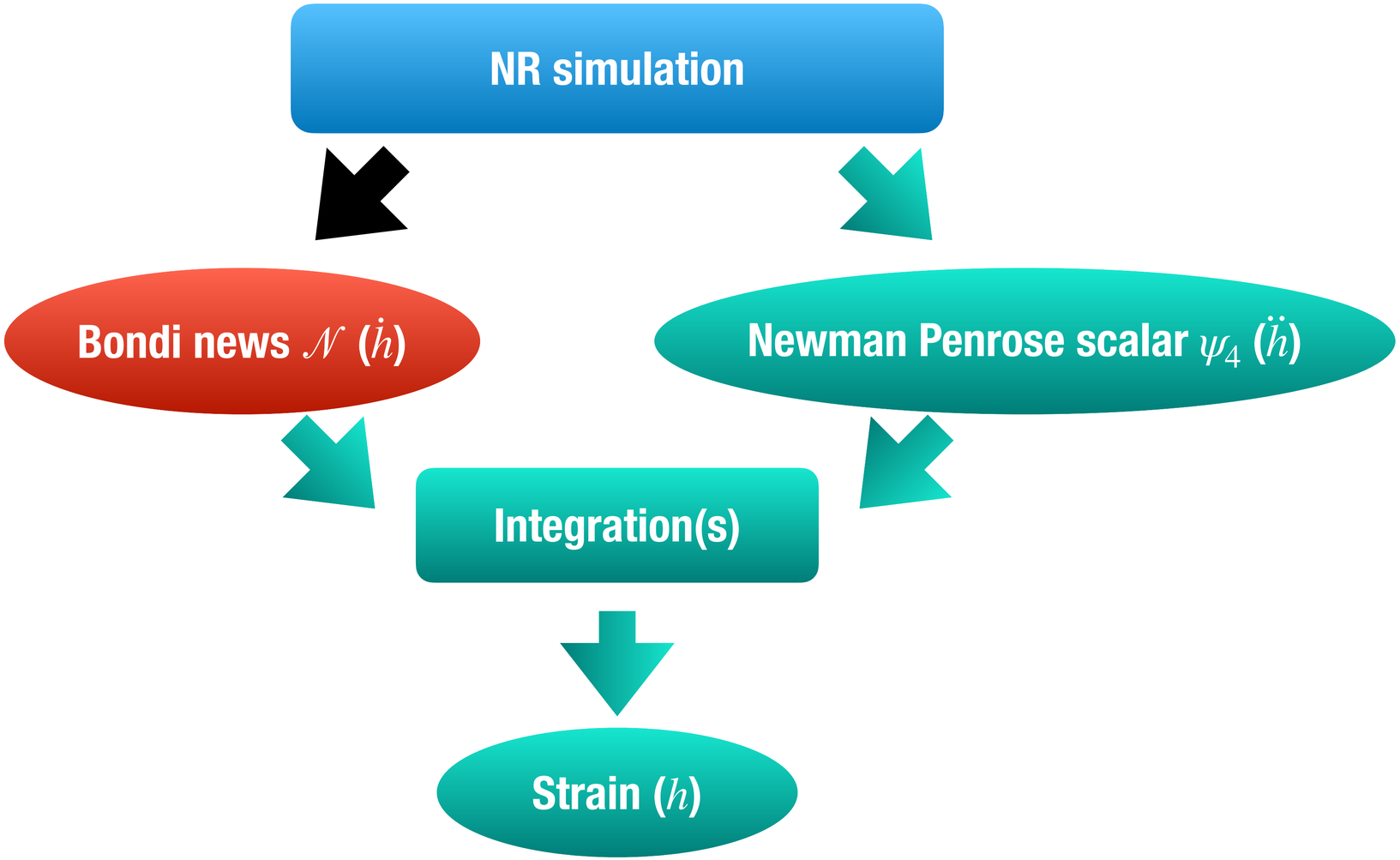

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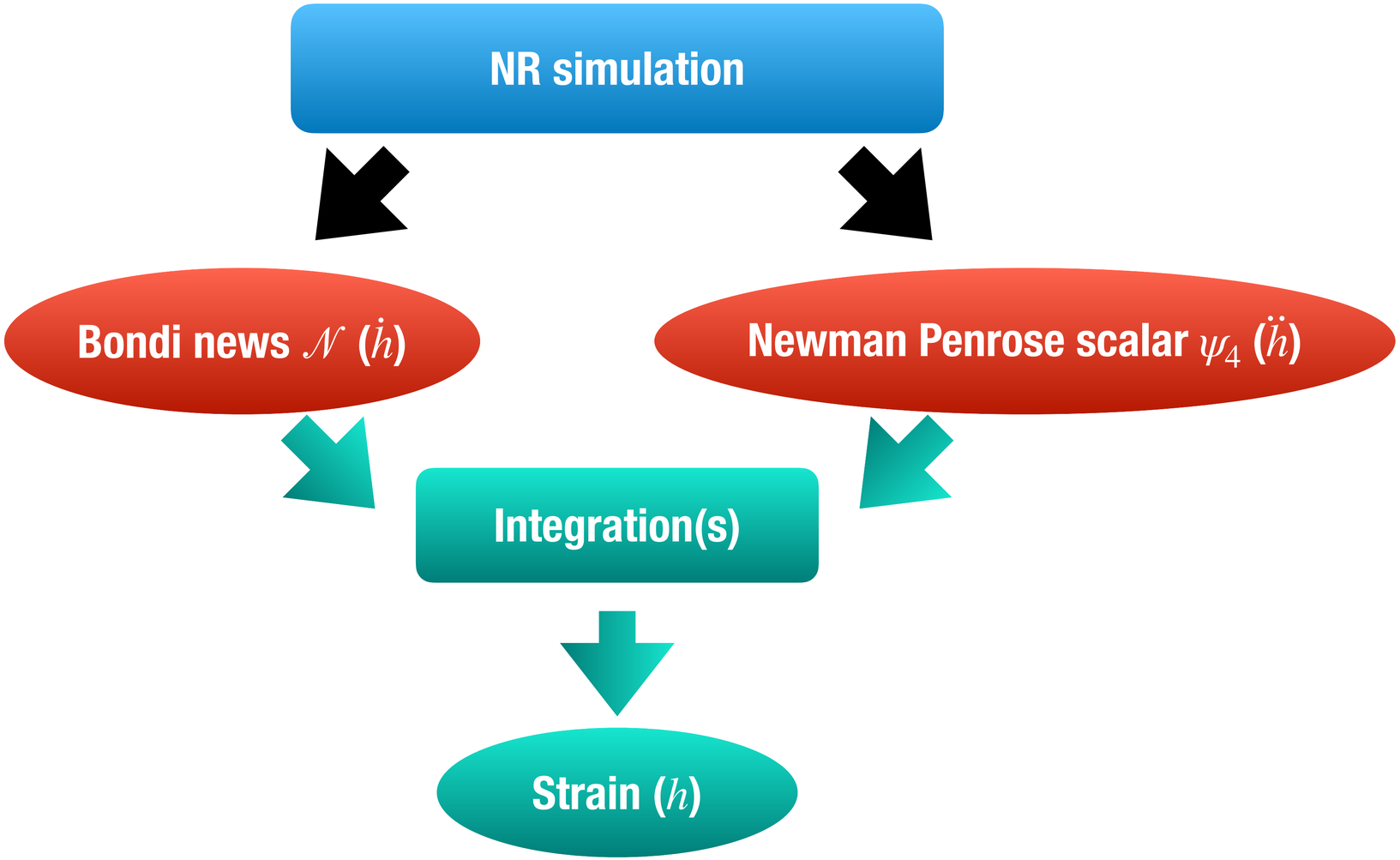

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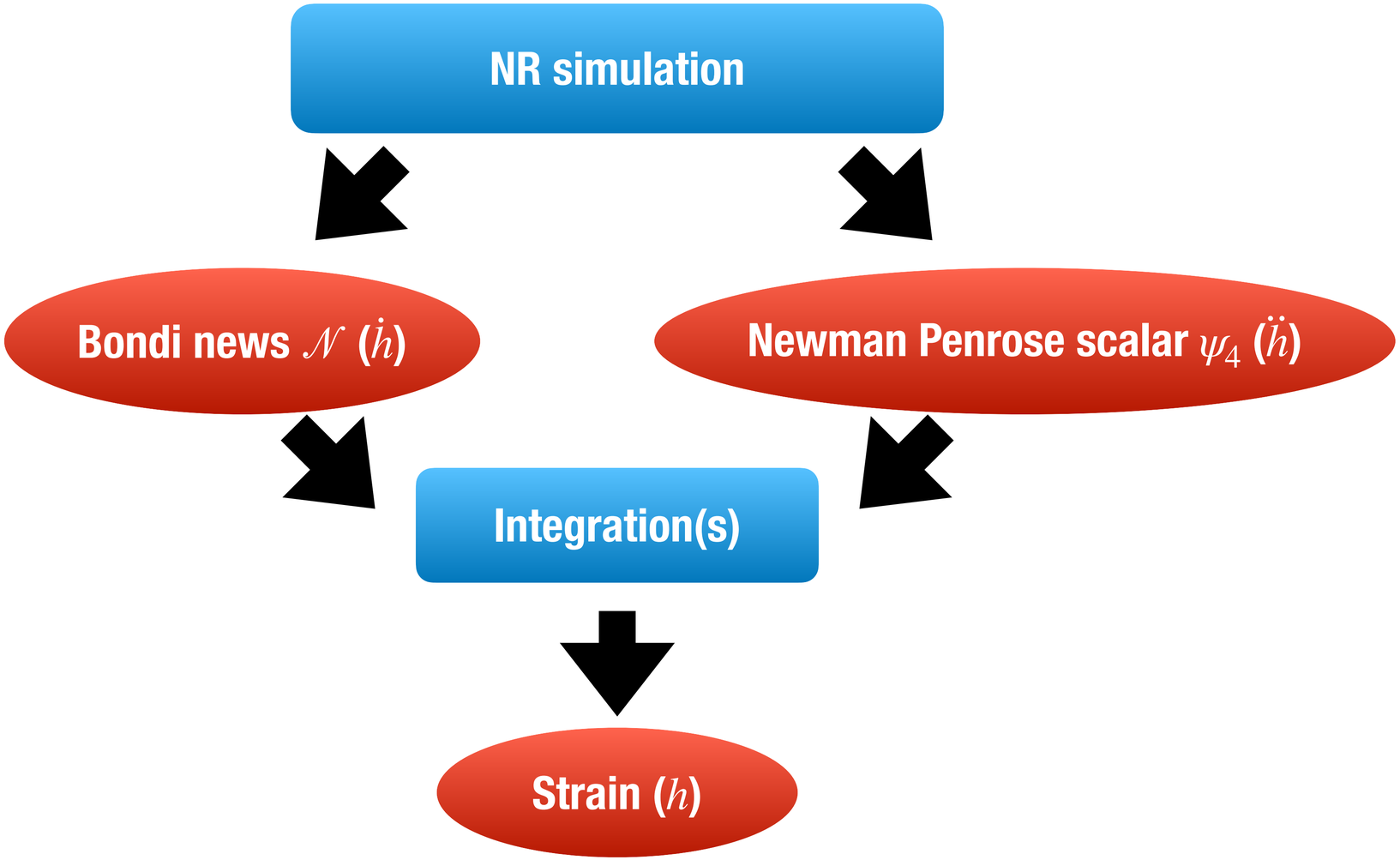
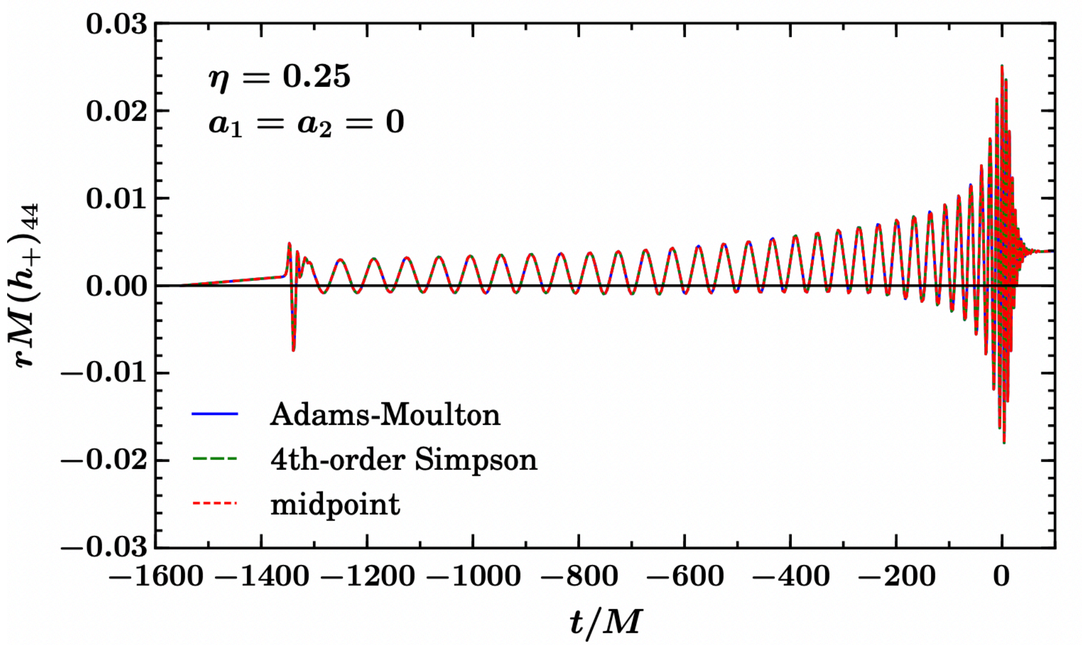


Caveats

Time-domain integration

$$h = h_+ - ih_\times = \int_{-\infty}^{t} dt' \int_{-\infty}^{t'} dt'' \psi_4$$



Reisswig + Pollney (2011) [1006.1632]

Caveats

Time-domain integration

Discretely sampled

Finite length

Numerical noise

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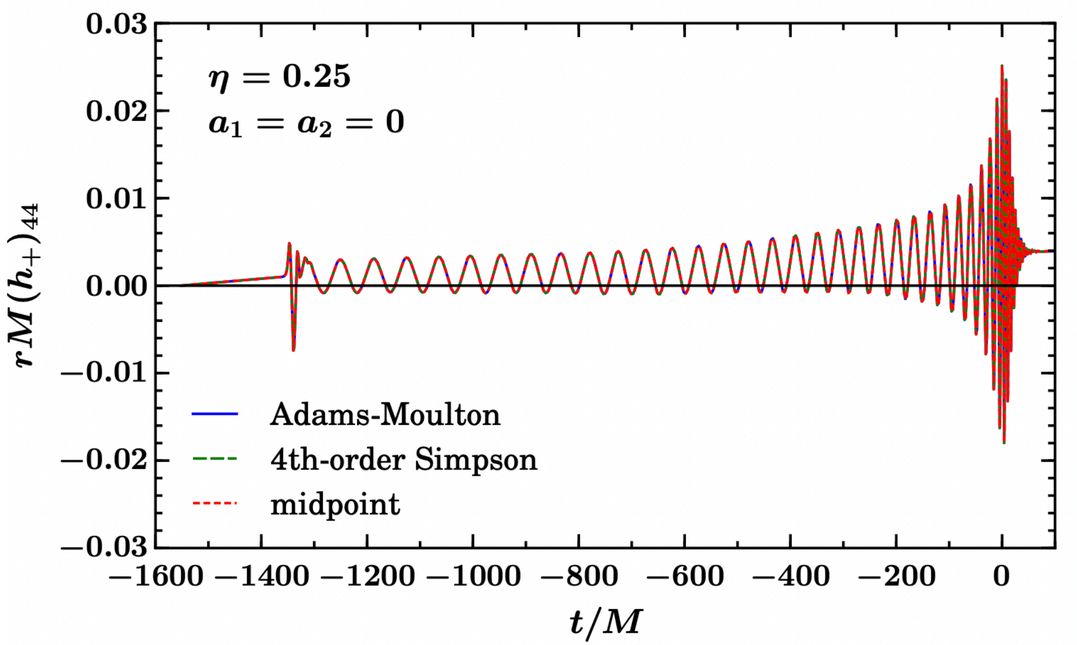

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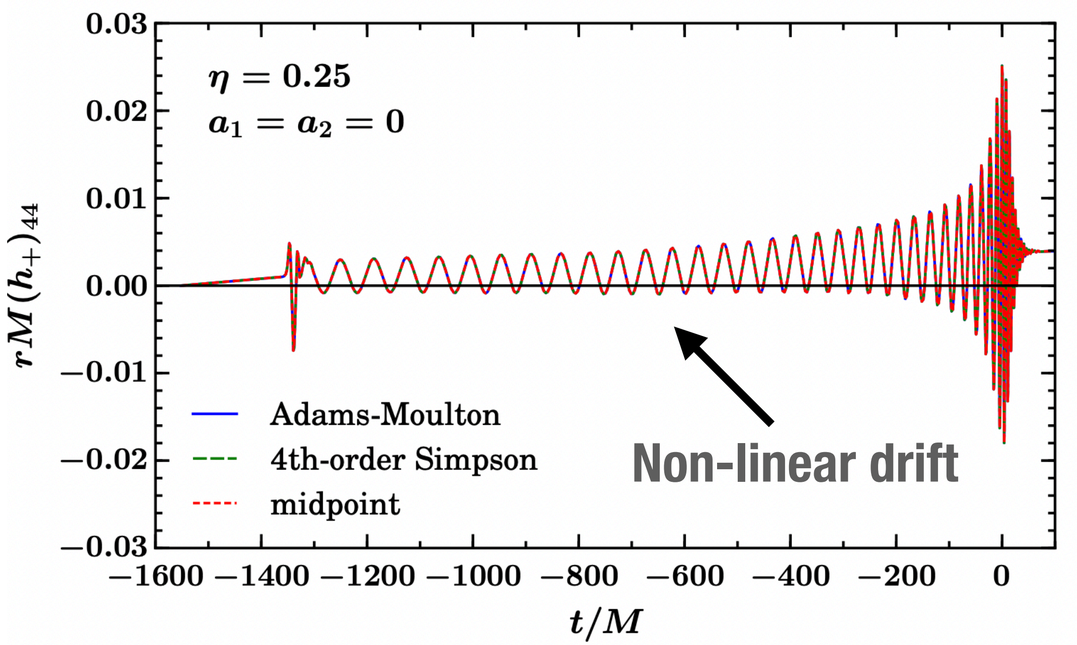
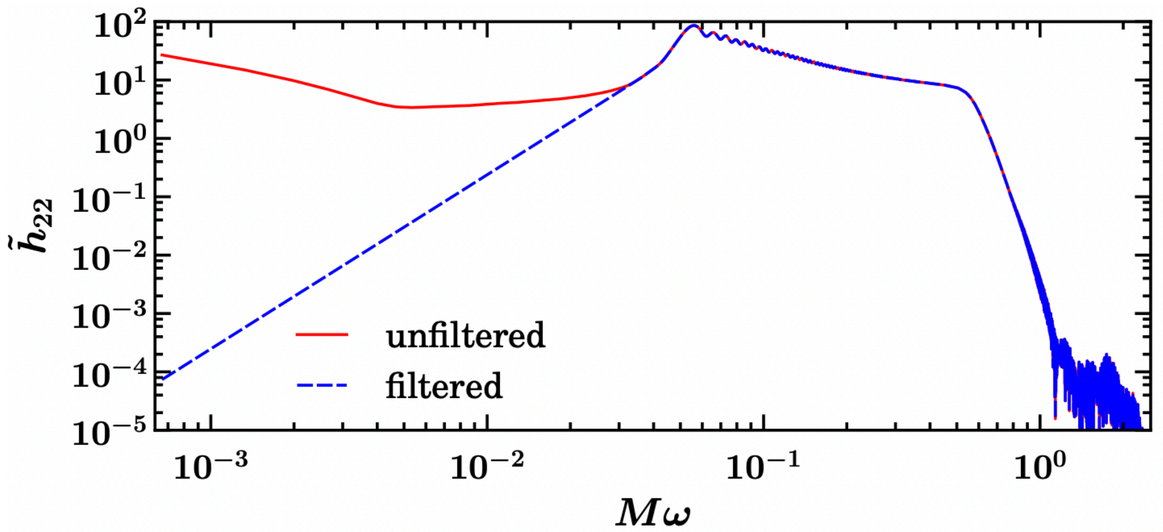


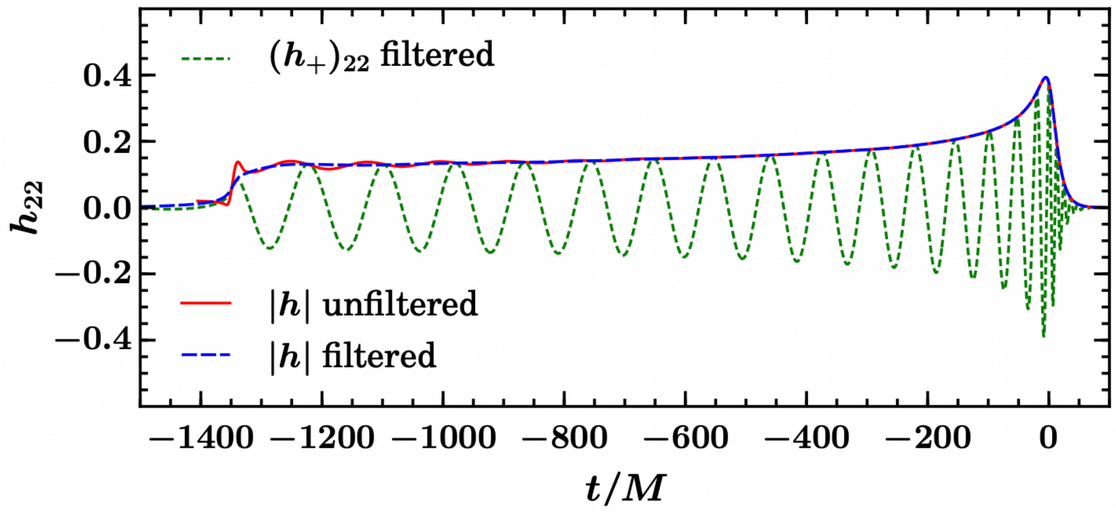
Reisswig + Pollney (2011) [1006.1632]

Caveats

Frequency-domain integration

$$h = h_+ - ih_\times = \mathscr{F}^{-1}\left[-\frac{1}{\omega^2}\tilde{\psi}_4(\omega)\right]$$





Reisswig + Pollney (2011) [1006.1632]

Caveats

- **Frequency-domain integration**
  - **Spectral leakage**
  - **Aliasing**

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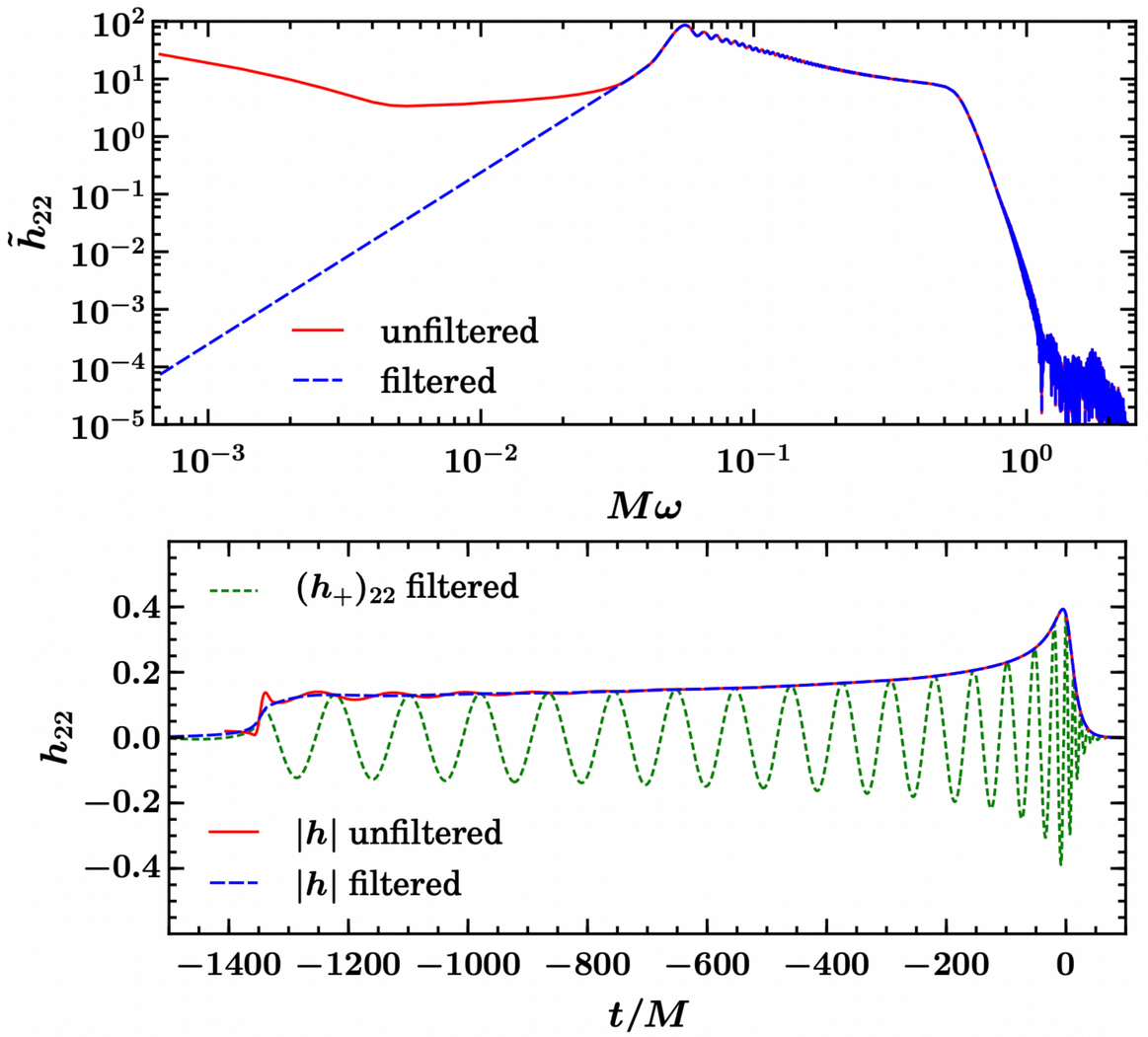

Reisswig + Pollney (2011) [1006.1632]

Caveats

- Frequency-domain integration
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- High-pass filters
- Fixed frequency integration

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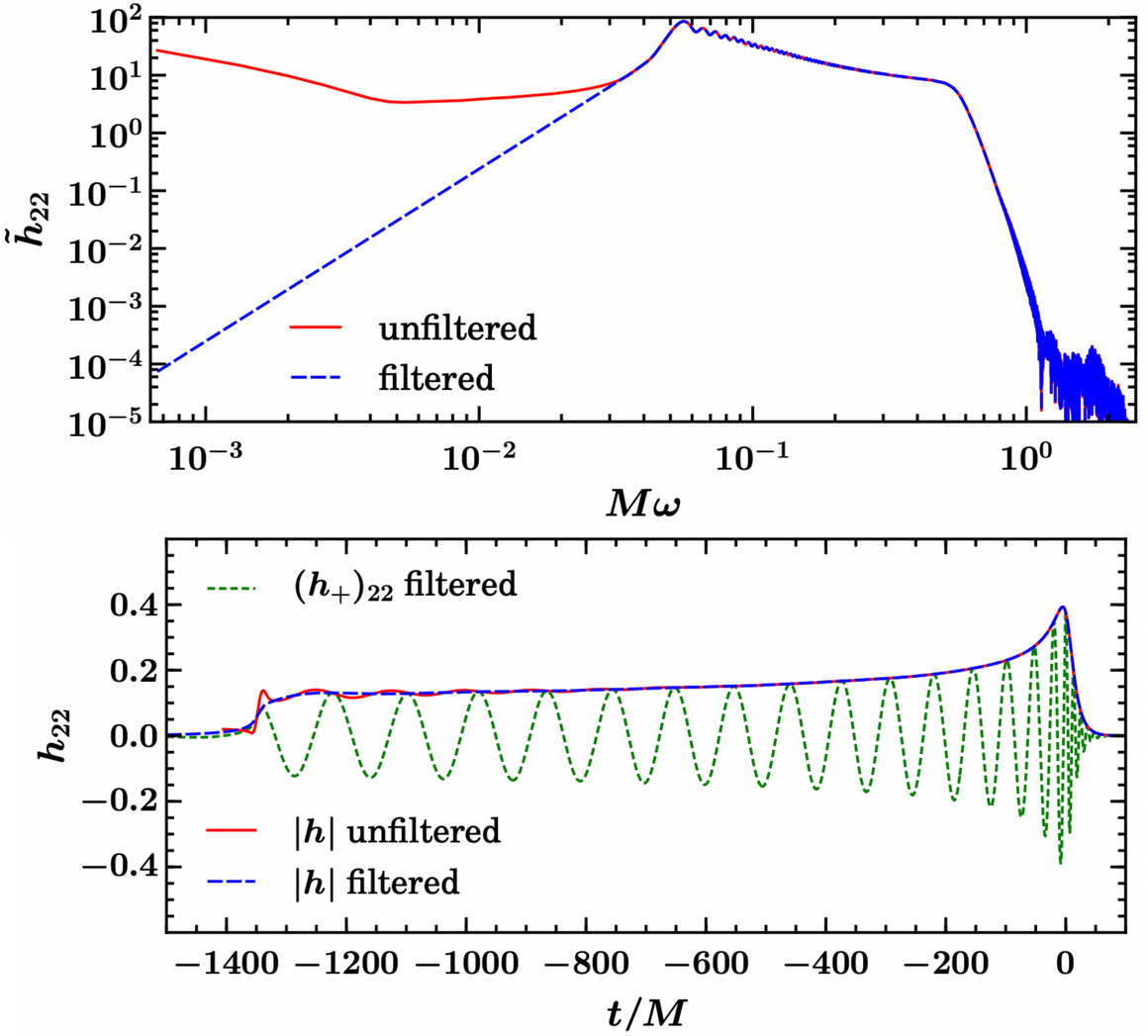

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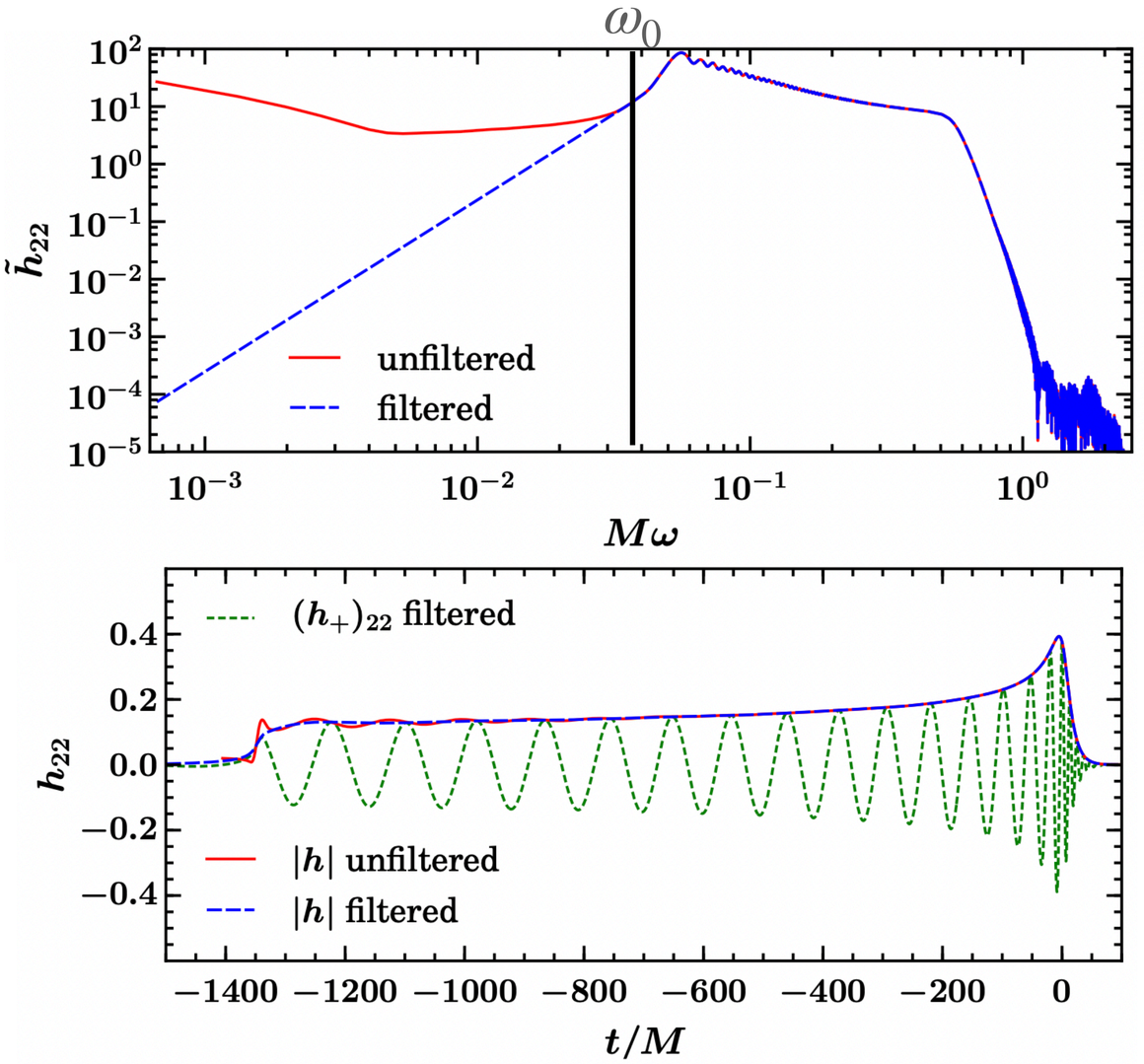

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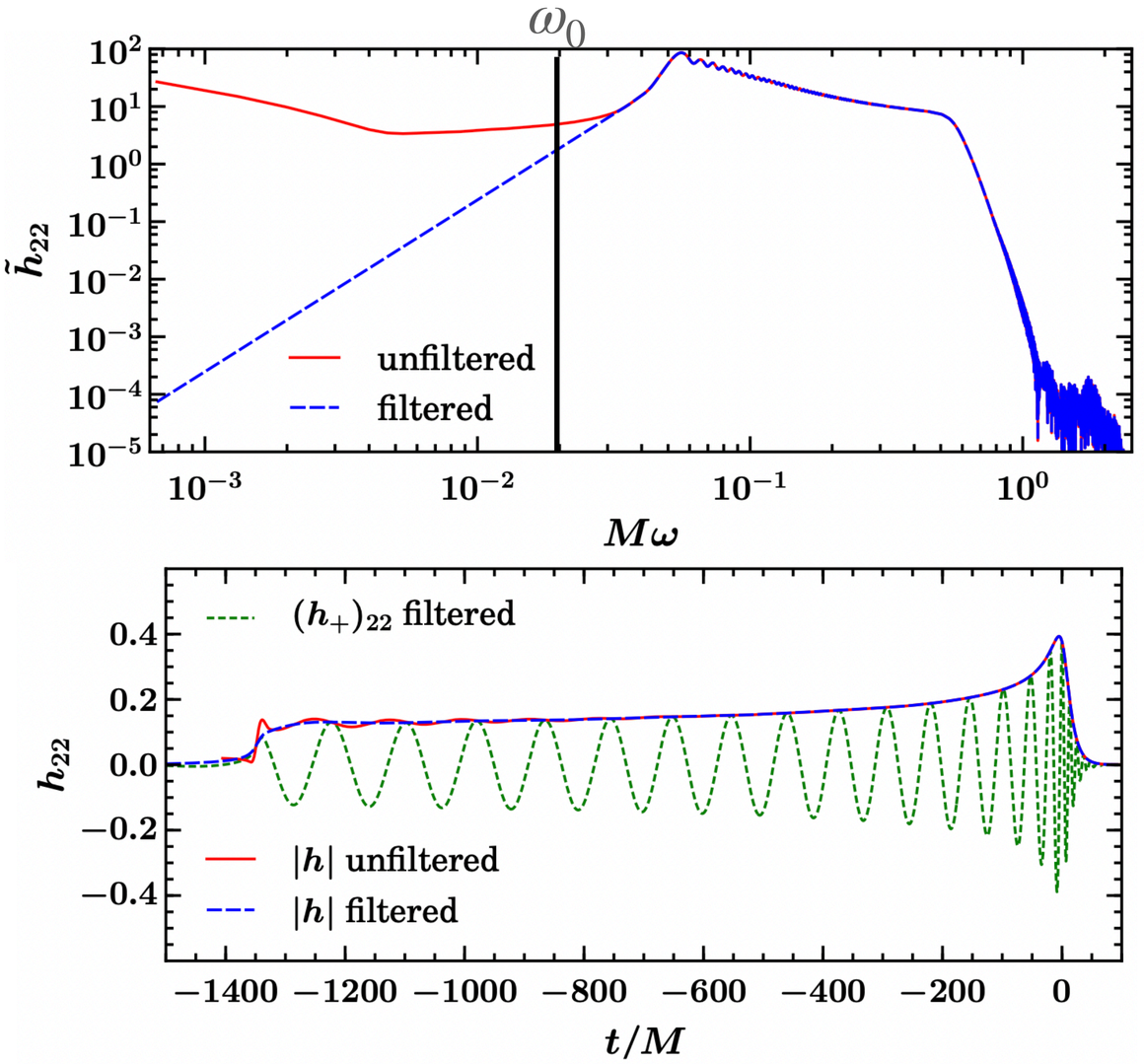

Reisswig + Pollney (2011) [1006.1632]

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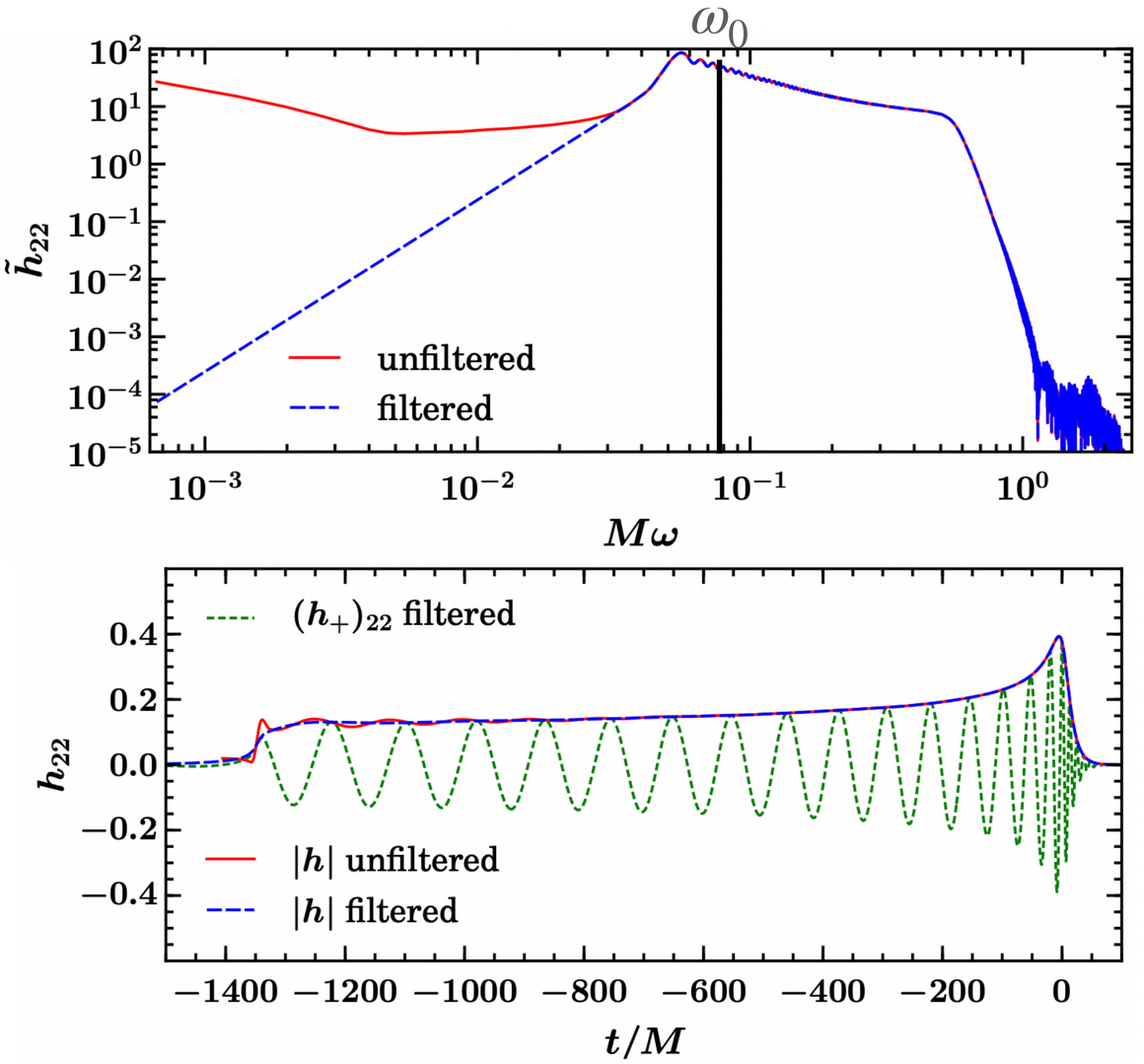


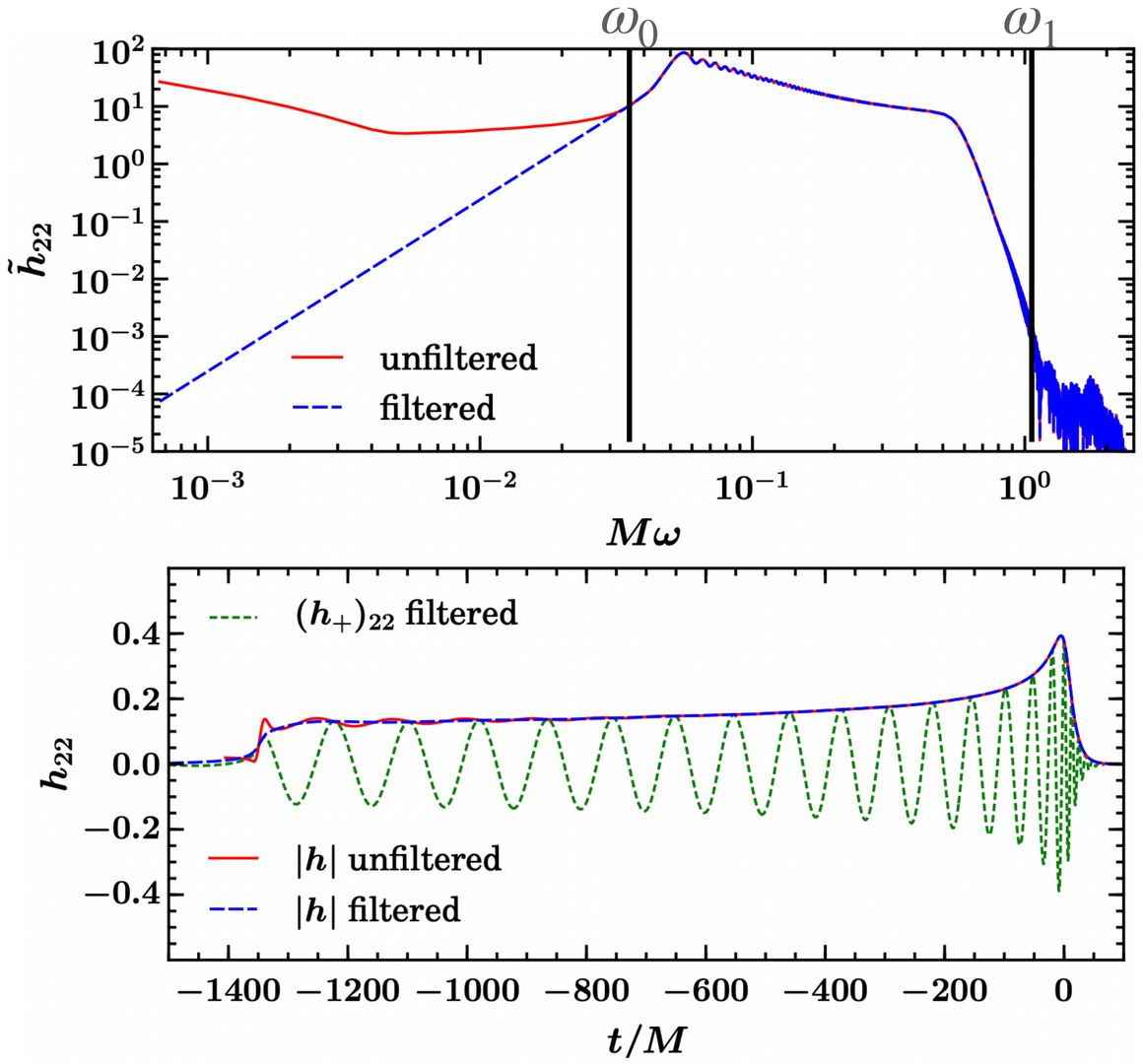
Reisswig + Pollney (2011) [1006.1632]

Caveats

Frequency-domain integration

Initial orbital frequency

Ringdown frequency



Reisswig + Pollney (2011) [1006.1632]

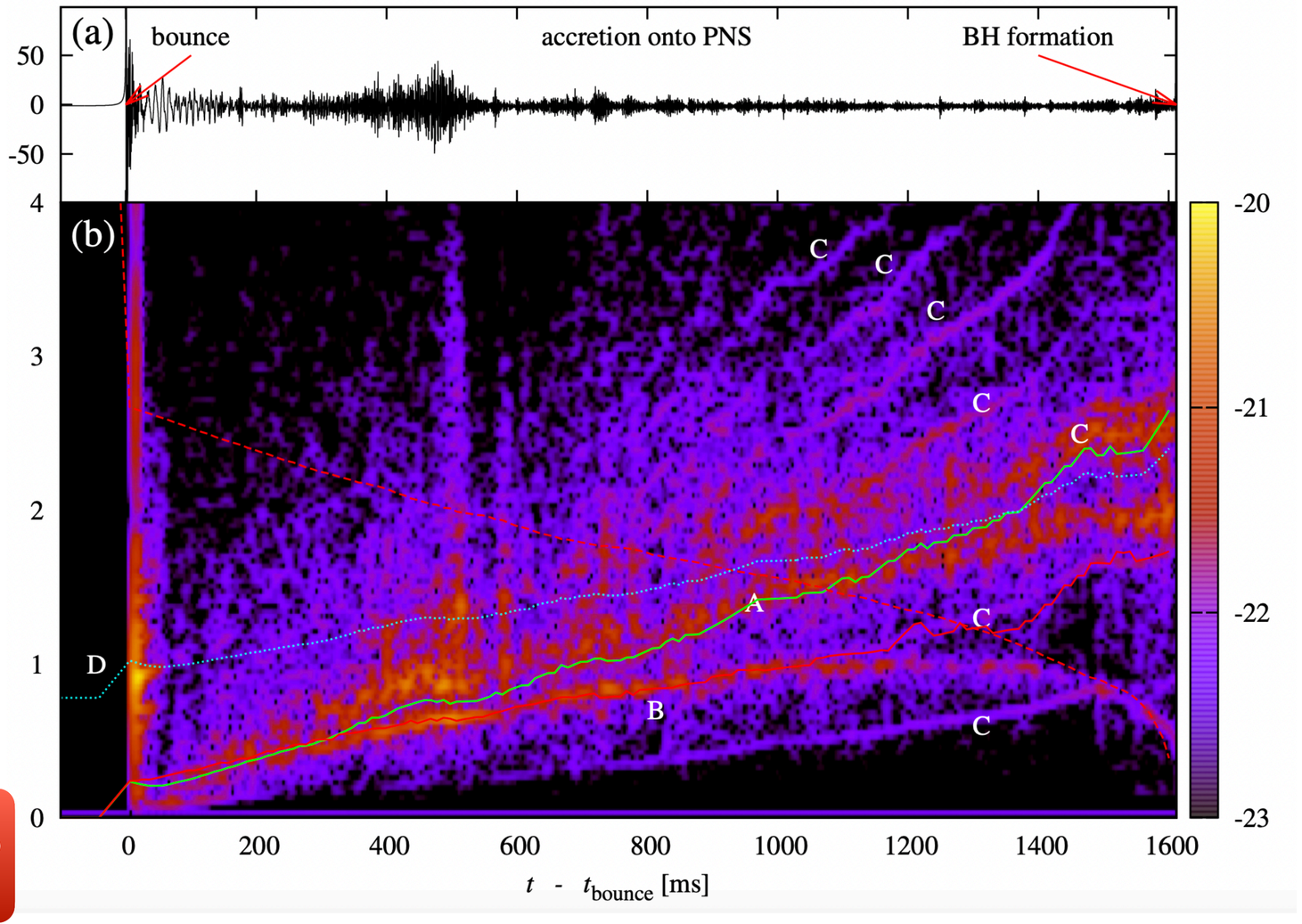
Caveats

Frequency-domain integration

Eccentric systems?

Core-collapse supernova?

What if there is no natural way to choose ω_0?



Pablo etal. (2013) [1310.8290]

Parameter inference with ψ_4

Not to do the integration!

Parameter inference with ψ_4

Not to do the integration!

Strain

$$d(t) = h(t) + n(t)$$

Strain data

Parameter inference with ψ_4

Not to do the integration!

Strain

$$d(t) = h(t) + n(t)$$

Strain data

Strain waveform

Parameter inference with ψ_4

Not to do the integration!

Strain

$$d(t) = h(t) + n(t)$$

Strain data — Strain waveform — Noise

Parameter inference with ψ_4

Not to do the integration!

Strain

$$d(t) = h(t) + n(t)$$

Strain data | Strain waveform | Noise

Second order finite difference

ψ_4

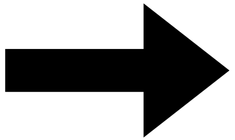
$$(\delta^2 d)(t) = \Psi_4(t) + (\delta^2 n)(t)$$

Ψ_4 data | Ψ_4 waveform | Ψ_4 noise

Caution:
For brevity, the antenna pattern function is omitted

Parameter inference with ψ_4

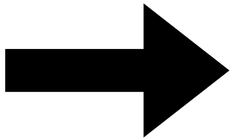
Strain data d



$$d_{\Psi_4}[m] = \frac{d[m+1] - 2d[m] + d[m-1]}{(\Delta t)^2}$$

Parameter inference with ψ_4

Strain data d



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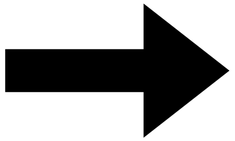
Noise PSD $S_n[k]$



$$S_{n_{\Psi_4}}[k] = \frac{1}{(\Delta t)^4}\left(6 - 8\cos\frac{2\pi k}{M} + 2\cos\frac{4\pi k}{M}\right) S_n[k]$$

Parameter inference with ψ_4

Strain data d

$$d_{\Psi_4}[m] = \frac{d[m+1] - 2d[m] + d[m-1]}{(\Delta t)^2}$$

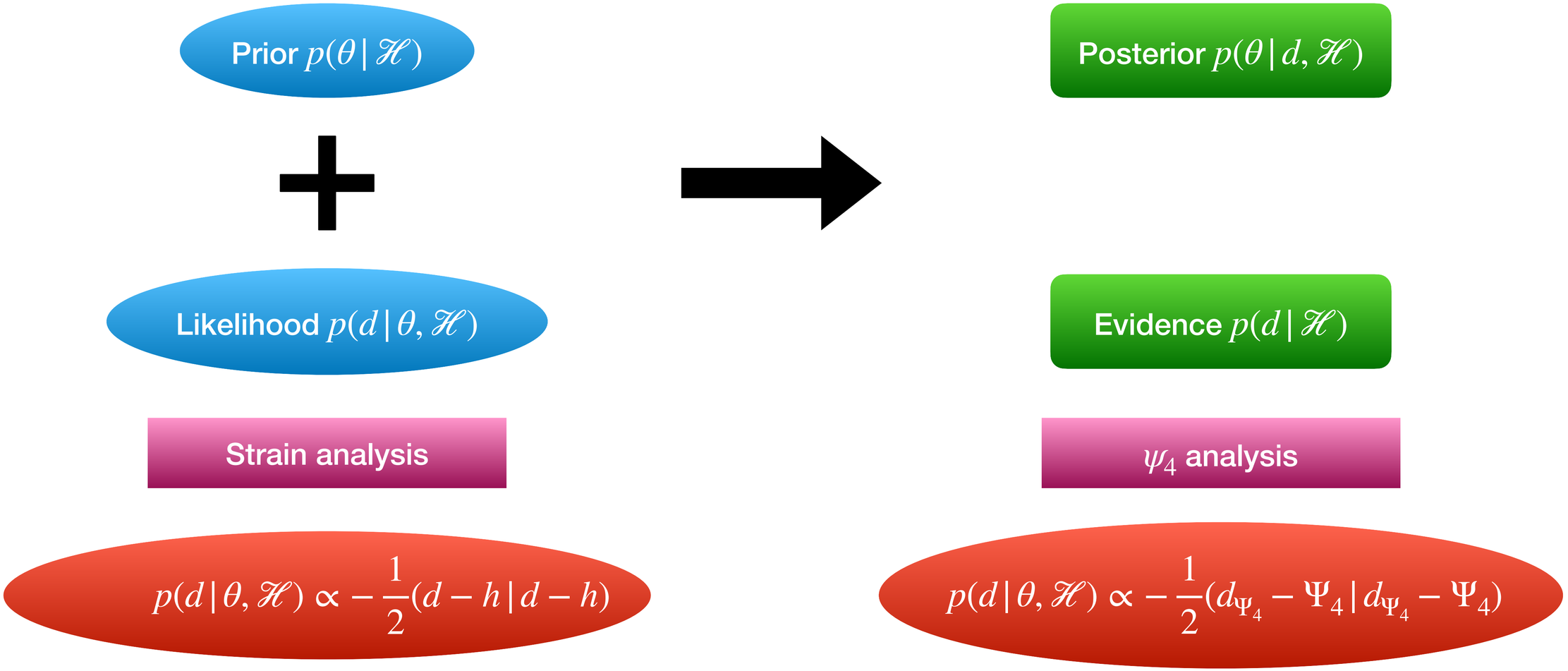
Noise PSD $S_n[k]$

$$S_{n_{\Psi_4}}[k] = \frac{1}{(\Delta t)^4}\left(6 - 8\cos\frac{2\pi k}{M} + 2\cos\frac{4\pi k}{M}\right) S_n[k]$$

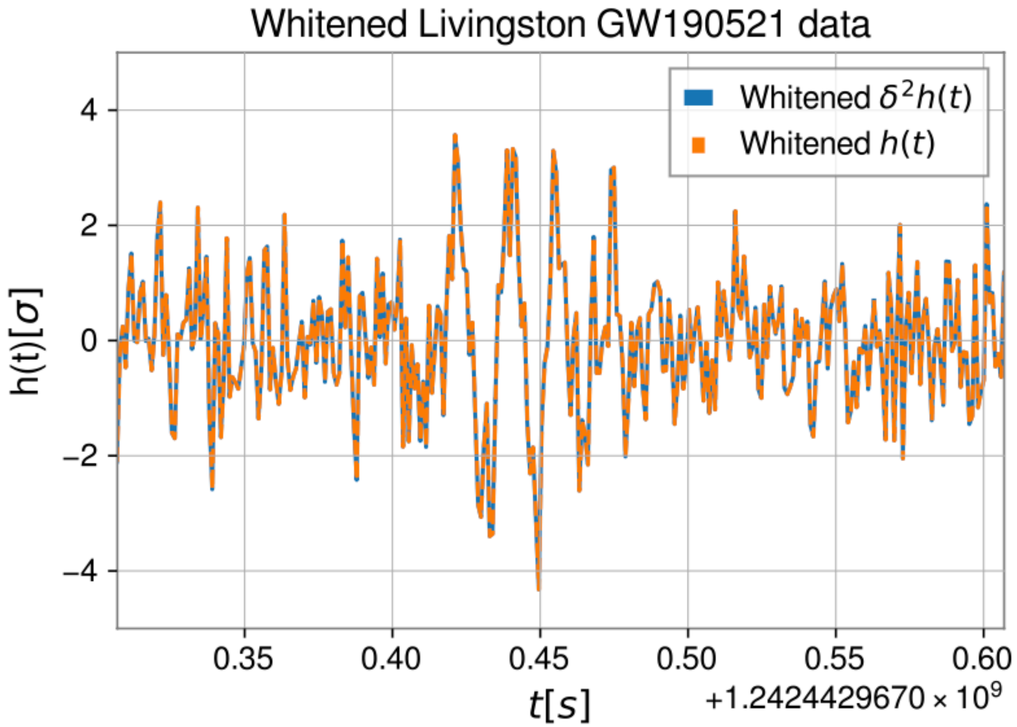
Strain template h

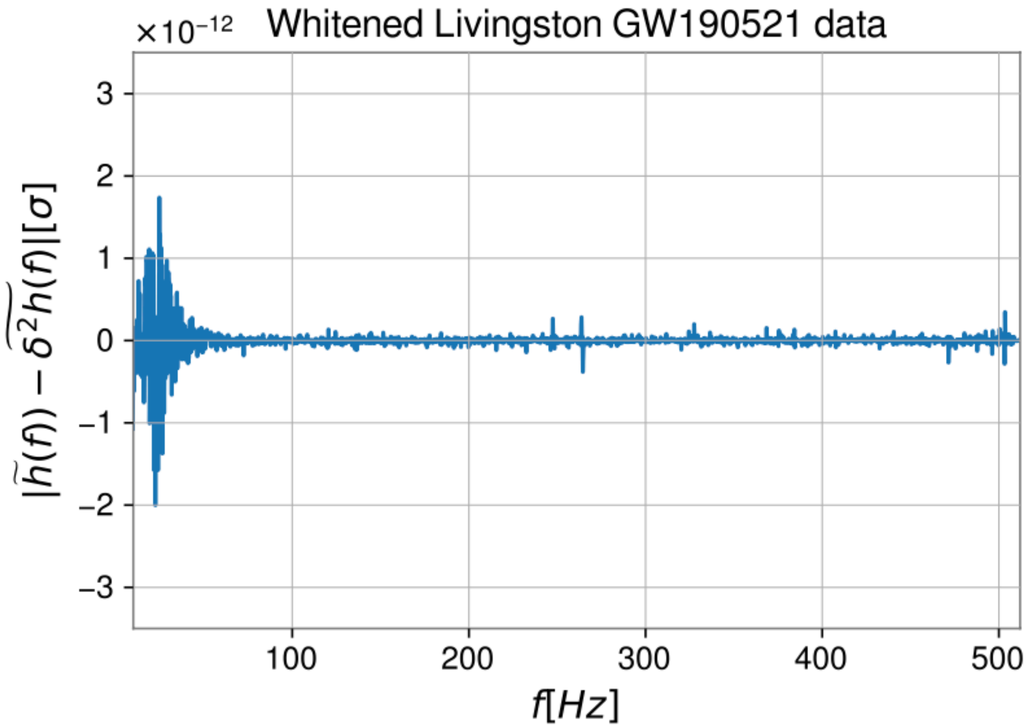
$$\tilde{\Psi}_4 = \frac{1 - \cos(2\pi k \Delta f \Delta t)}{2\pi^2 (k \Delta f \Delta t)^2} \tilde{\psi}_4[k]$$

Parameter inference with ψ_4



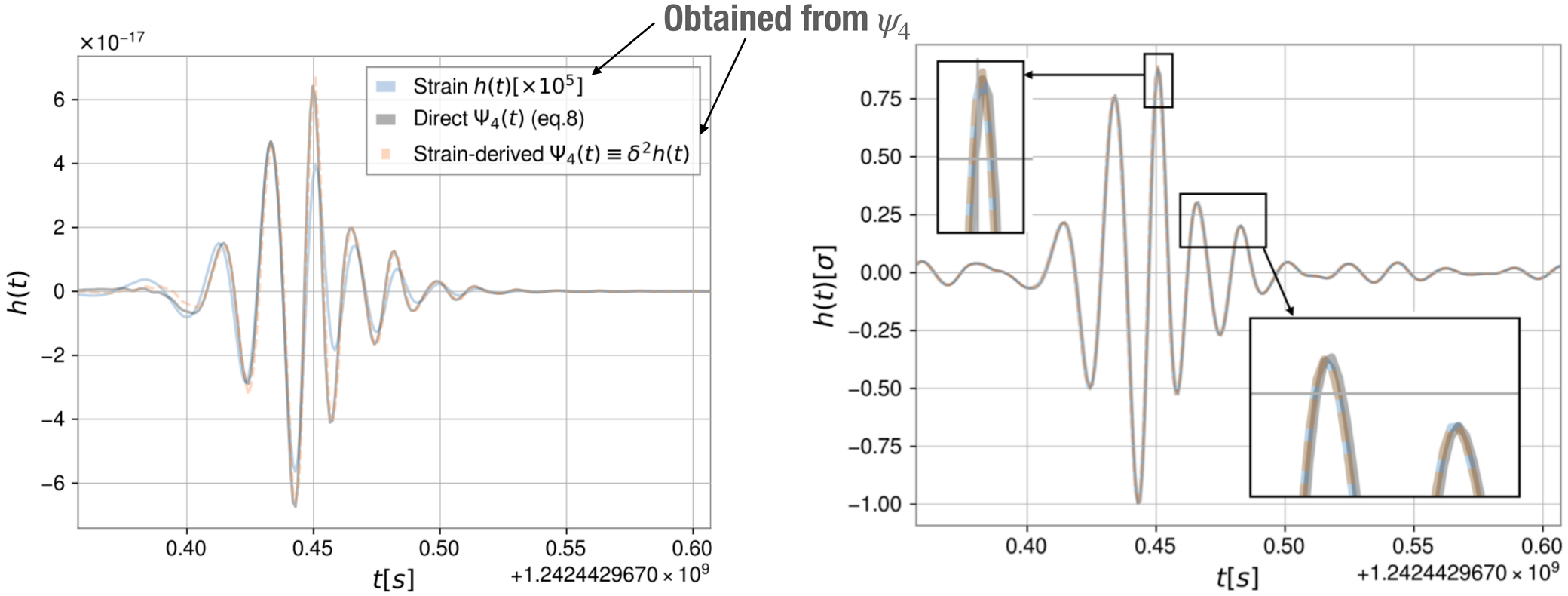
Testing the formalism with the whitened data





Testing the formalism with the whitened data

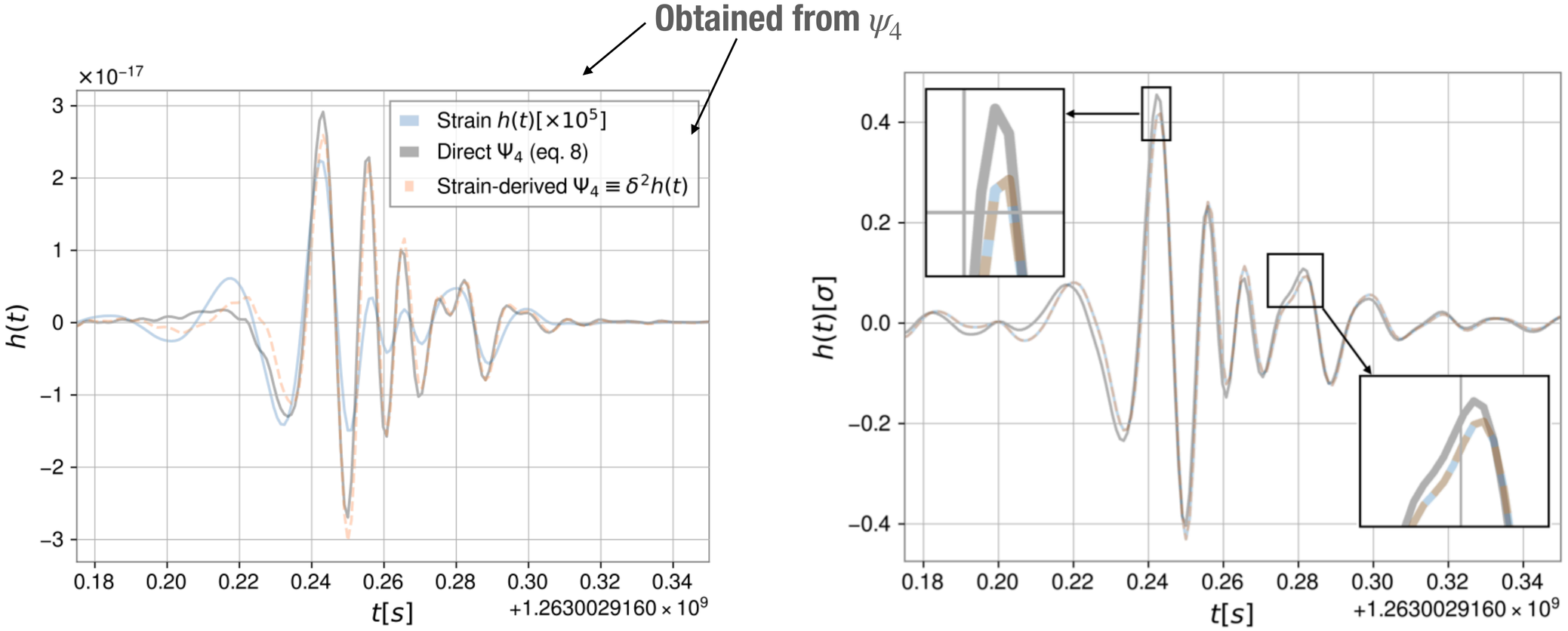
Appropriate ω_0



Head-on Proca-star merger consistent with GW190521

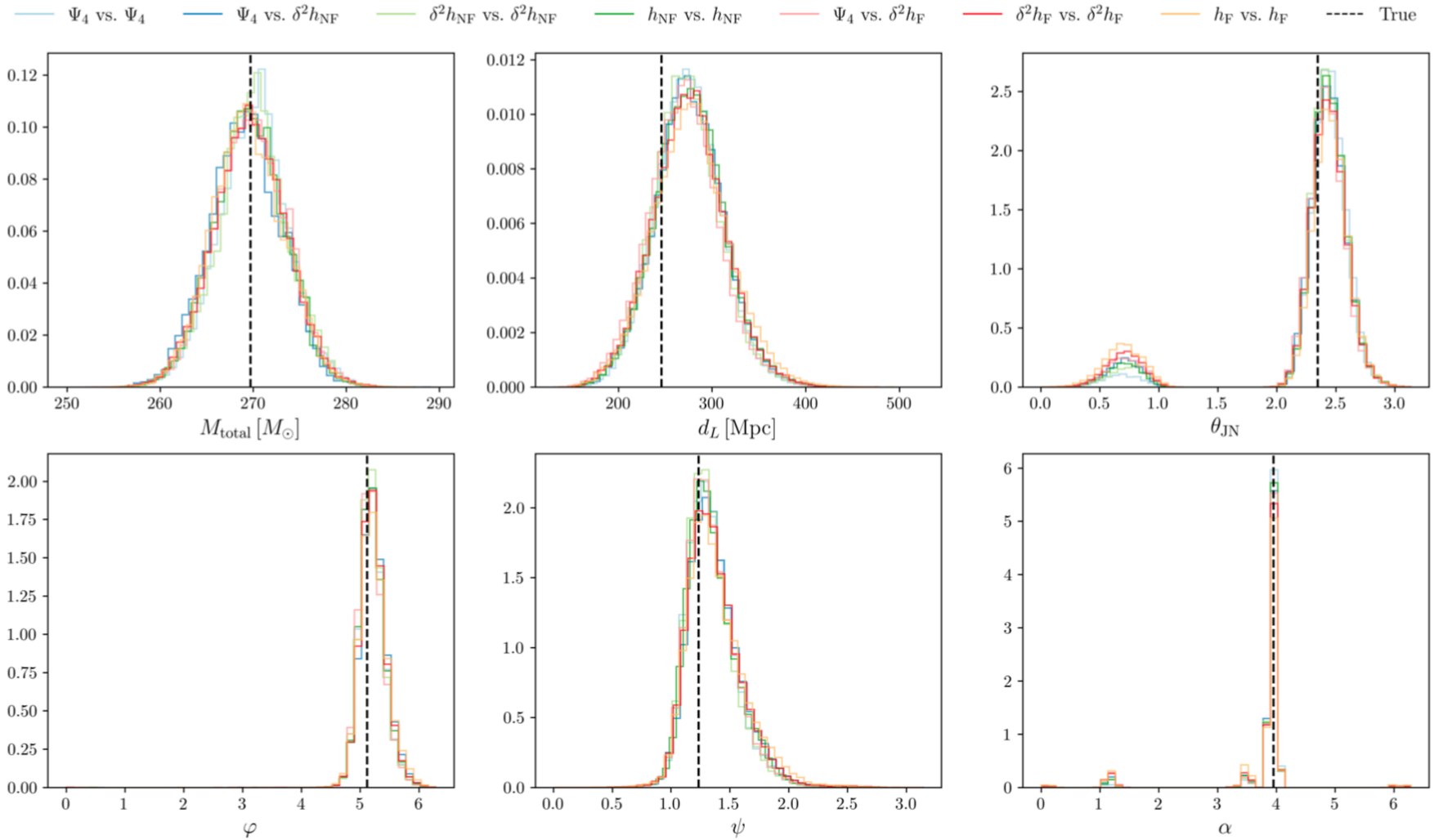
Testing the formalism with the whitened data

Too aggressive ω_0



Head-on Proca-star merger consistent with S200114f

Testing the formalism with parameter estimation



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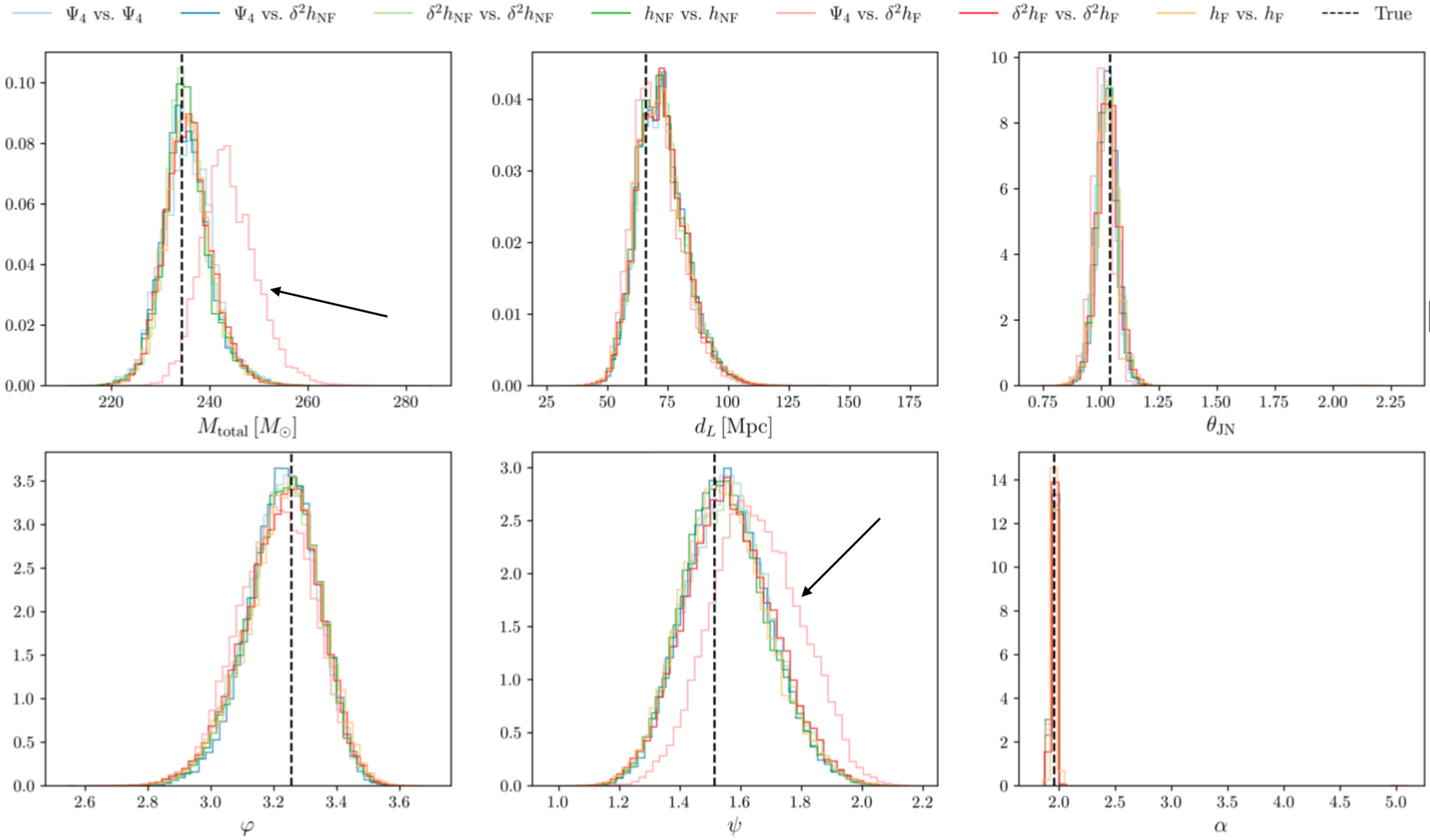

Inject ψ_4

Recover with $\delta^2 h_F$

Head-on Proca-star merger consistent with S200114f

Conclusion

- We propose a statistical framework to perform data analysis directly with ψ_4
- Time-integration of ψ_4 suffers from several issues, such as
  - amplifying the numerical noise that leads to a non-linear drift
  - the choice of frequency cutoff in the filter might not be trivial
- We show that the systematic induced by the integration can have huge impacts on data analysis
- Direct parameter inference with ψ_4 avoids the artefacts from performing numerical integration

Backup slides

Impact on model selection

Waveform model		GW190521		S200114f	
Injection	Template	$\log \mathcal{B}$	$\log \mathcal{L}_{\max}$	$\log \mathcal{B}$	$\log \mathcal{L}_{\max}$
Ψ_4	Ψ_4	94.1	123.2	90.0	124.2
Ψ_4	$\delta^2 h_{\rm NF}$	93.9	123.2	89.9	124.0
$\delta^2 h_{\rm NF}$	$\delta^2 h_{\rm NF}$	93.8	123.1	89.2	123.9
$h_{\rm NF}$	$h_{\rm NF}$	93.6	123.1	89.3	123.8
Ψ_4	$\delta^2 h_{\rm F}$	93.6	122.9	83.9	117.8
$\delta^2 h_{\rm F}$	$\delta^2 h_{\rm F}$	92.4	121.5	64.1	98.2
$h_{\rm F}$	$h_{\rm F}$	92.2	121.5	64.1	98.3