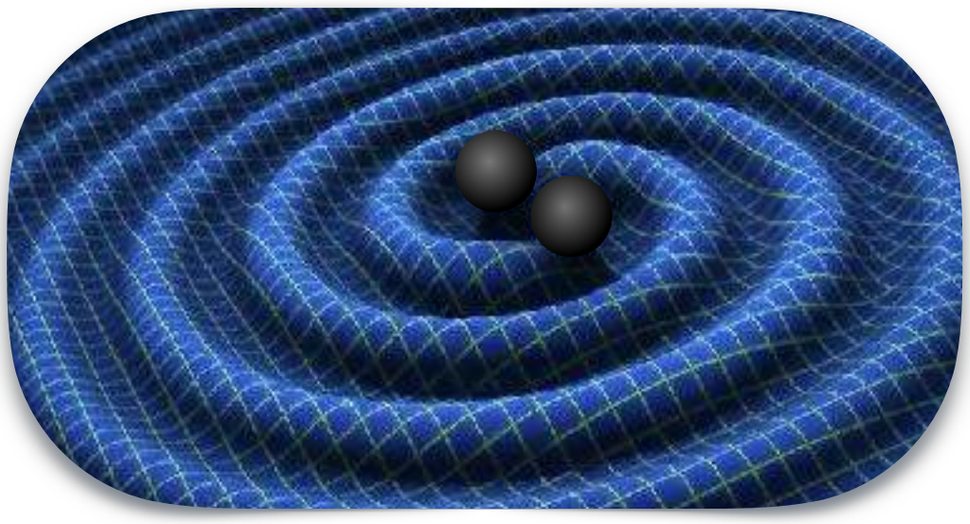
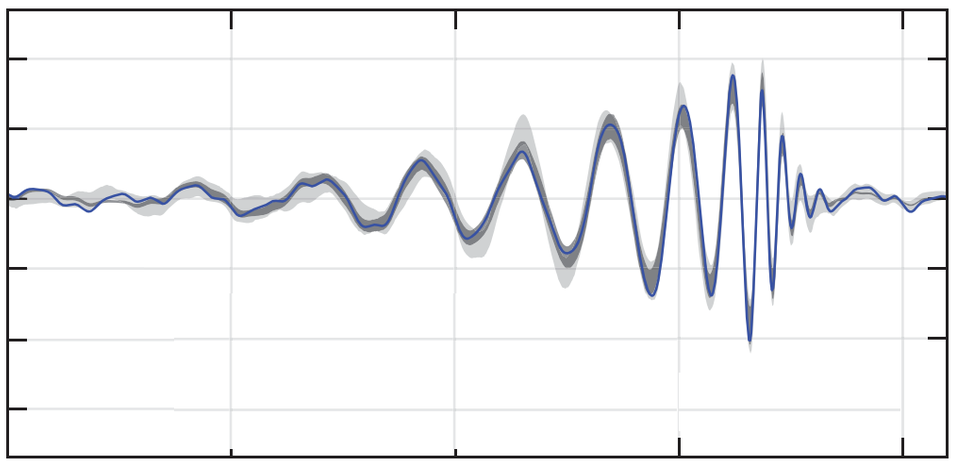
École Doctorale d'Astronomie & Astrophysique d'île-de-France

la Valse Hélicoïdale des Trous Noirs

How to make spacetime vibrate with dancing black holes ?



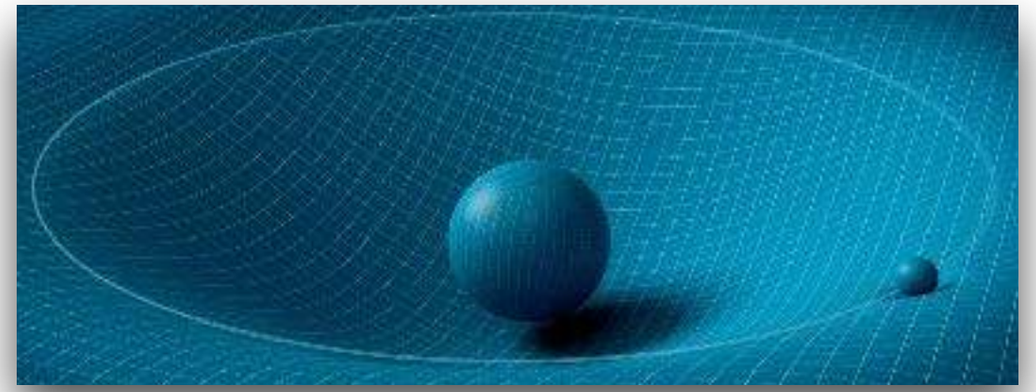


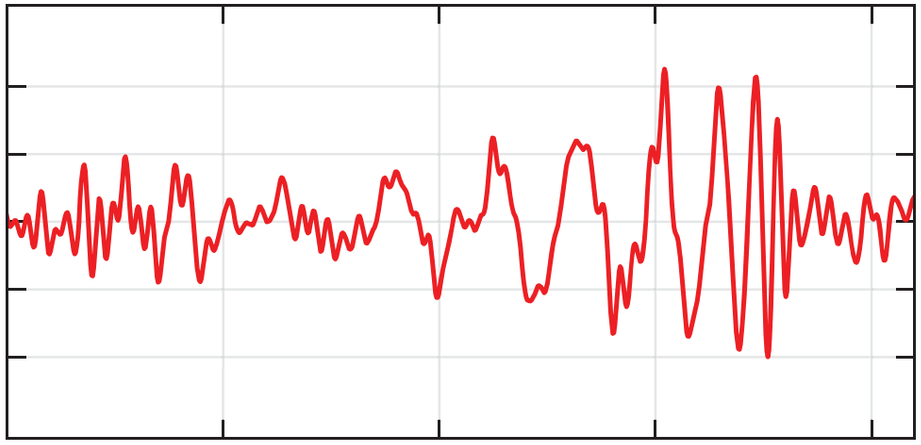
— Paul Ramond —

Laboratoire Univers et THéories

Summary

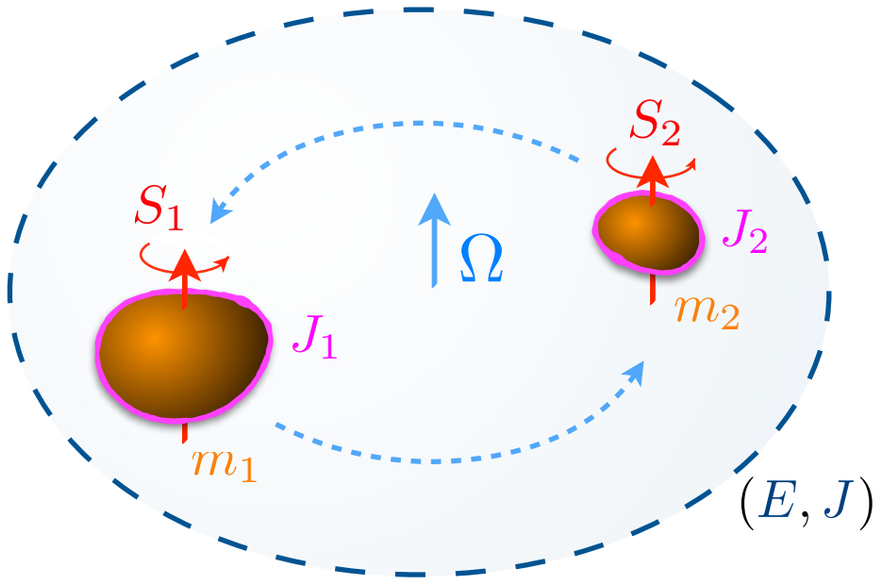
1. General Relativity





2. Gravitational Waves

3. My PhD



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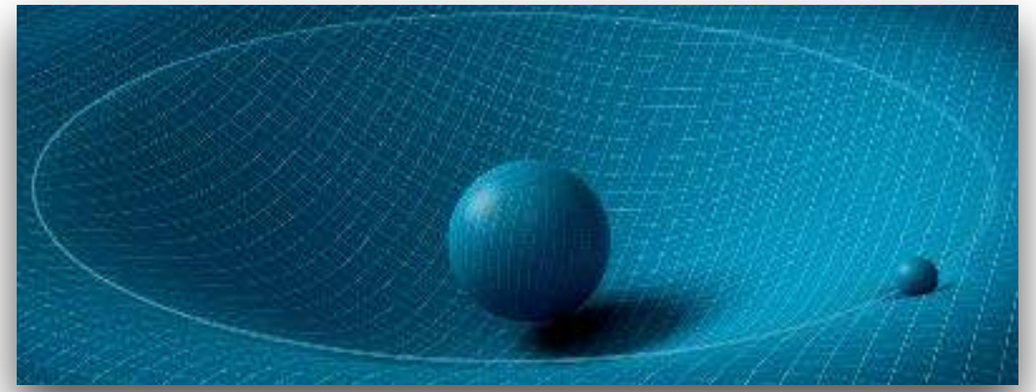

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General Relativity

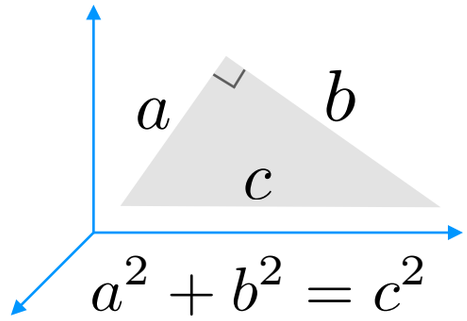
- Theory of **Space**, **Time** and **Gravitation**
- Formulated by **A. Einstein** between 1915 and 1918
- Never proved wrong (so far), **tested** in **strong** et **weak fields**
- Daily life application : **GPS, satellites** & interplanetary travel
- Contains **newtonian gravitation** and **special relativity**
- Corrects : **precession** of elliptic orbits, **time delay** of light, …
- New predictions : **black holes, expansion of the Universe,**…

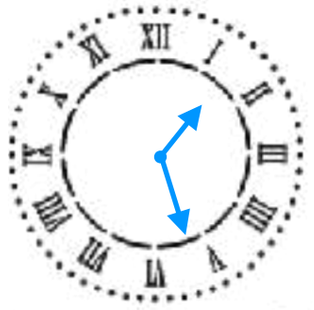
And Gravitational Waves !

Newtonian Gravity

3D **euclidean** space

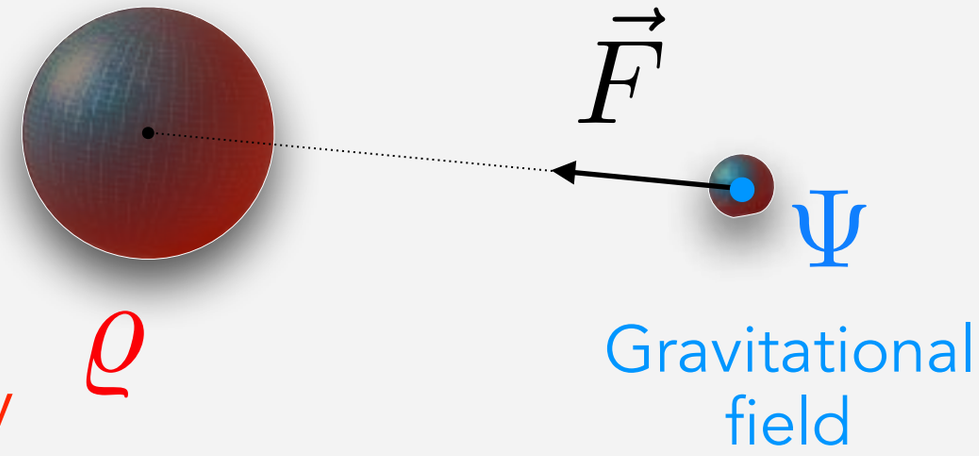
1D **universal** time





Gravitational Force

$$\vec{F} \propto \vec{\nabla}\Psi$$

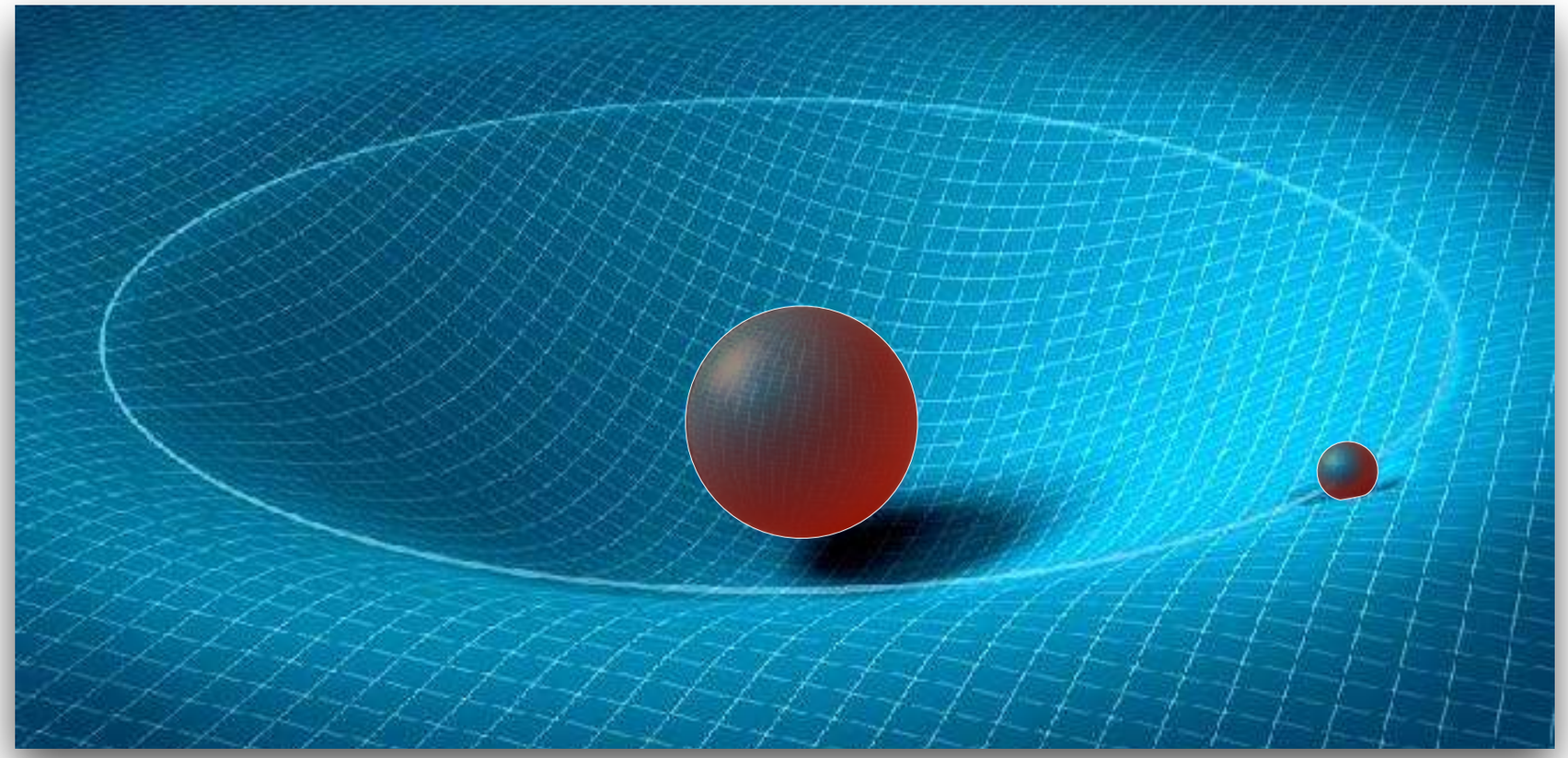


Poisson Equation $\Delta\Psi = 4\pi G\varrho$

General Relativity

Curved 4D Spacetime → g_{ab}

by mass/energy → T_{ab}



Einstein Equation $G_{ab} = 8\pi G\, T_{ab}$

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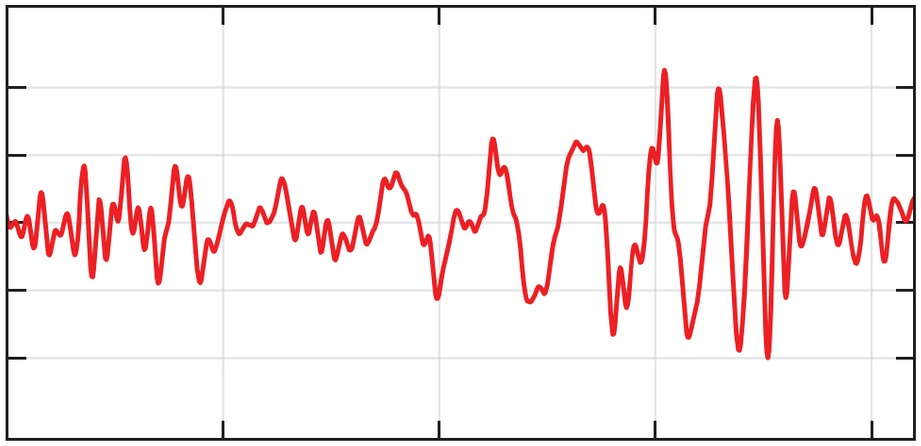

2. Gravitational Waves

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Gravitational Waves (GW) : theory

Flat spacetime $\longrightarrow$ $g_{ab} = \eta_{ab}$

+ small perturbation $\longrightarrow$ $g_{ab} = \eta_{ab} + h_{ab}$

… plug in Einstein Equations …

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Wave Equation $\Box \bar{h}_{ab} = -16\pi G T_{ab}$

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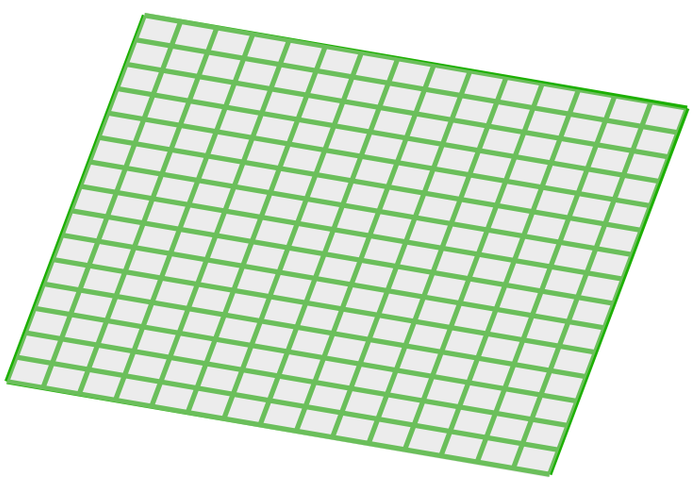

perturb

GW : astrophysical sources

Order of magnitude $$h \sim 10^{-21} \left(\frac{M}{10 M_\odot} \right) \left(\frac{100\mathrm{Mpc}}{R} \right) \left(\frac{v_a}{c} \right)^2$$

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$h \sim 10^{-21}$

For a typical system

→ of a few **stellar masses** within the **local group** **non-spherical** and **relativistic**

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For a typical system

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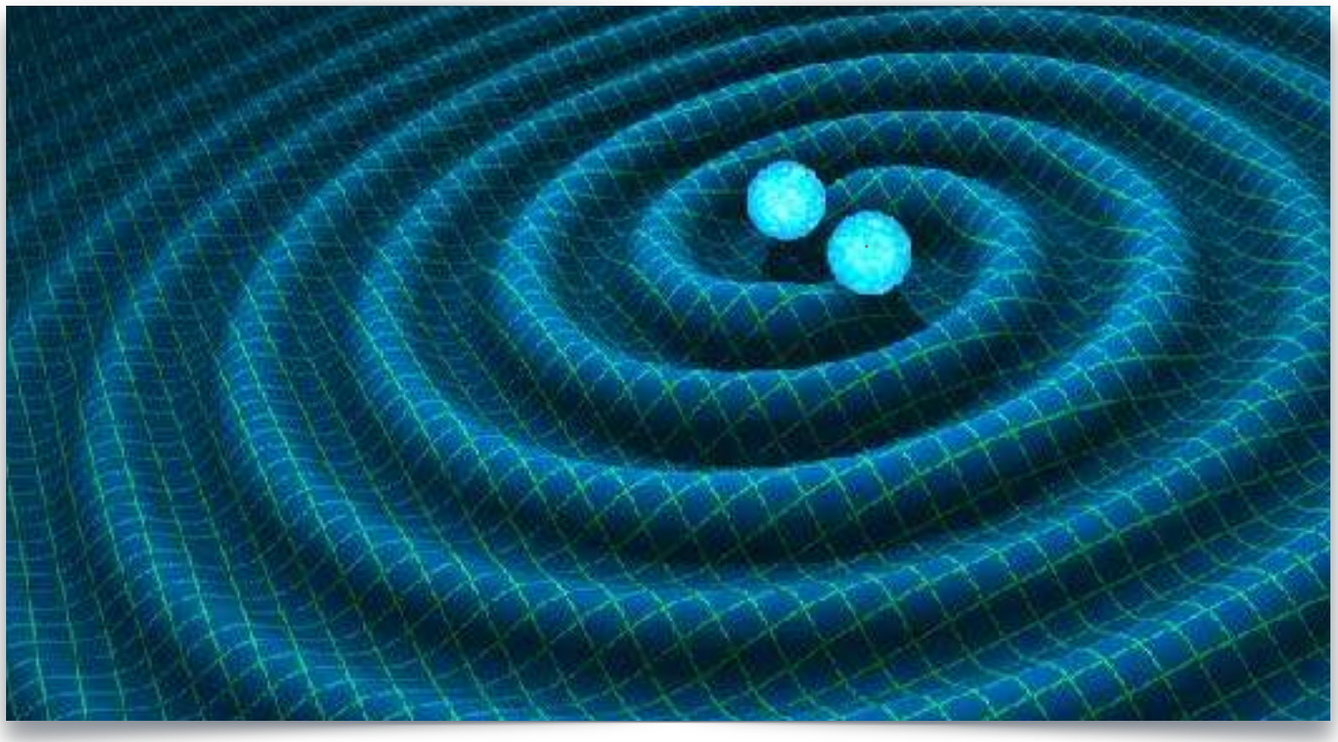
Most promising GW source :

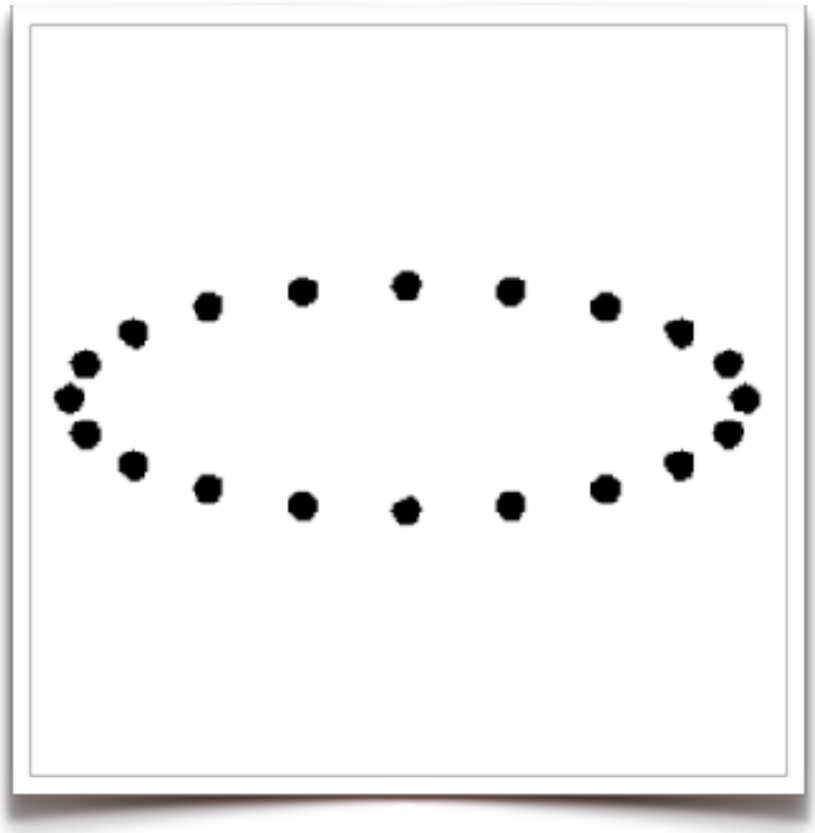
Binary system of Compact Objects

(Black Holes or Neutron Stars)

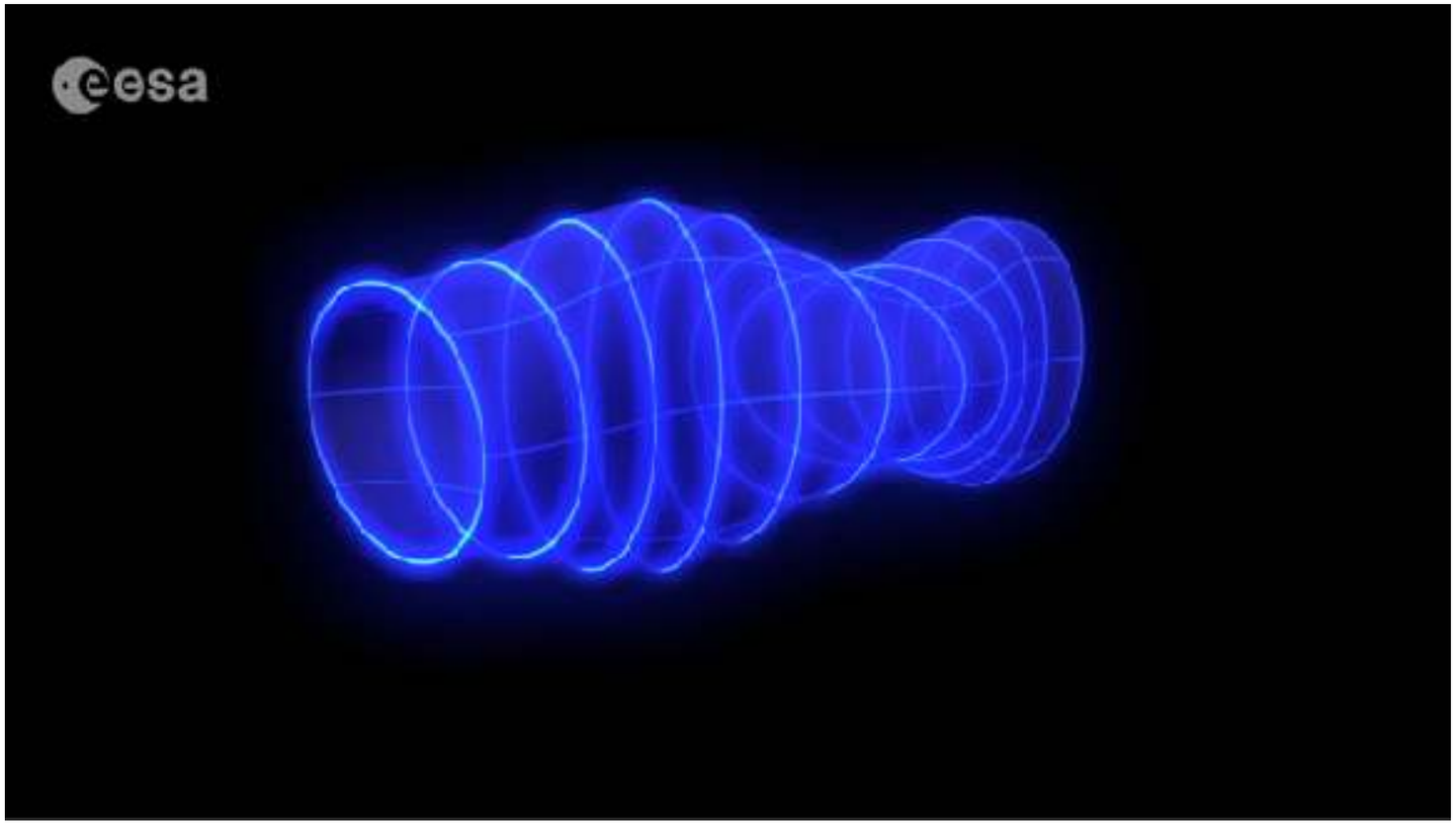


GW : interactions with matter

Effect of a **GW**
on **ring** of particles
(travelling perpendicularly)



Effect of a **GW** on multiple **rings**
(travelling perpendicularly)



GW : interactions with matter

Effect of a **GW** on **Earth** (vastly exaggerated)

GW : ground based detectors

LIGO and VIRGO

Michelson Interferometers

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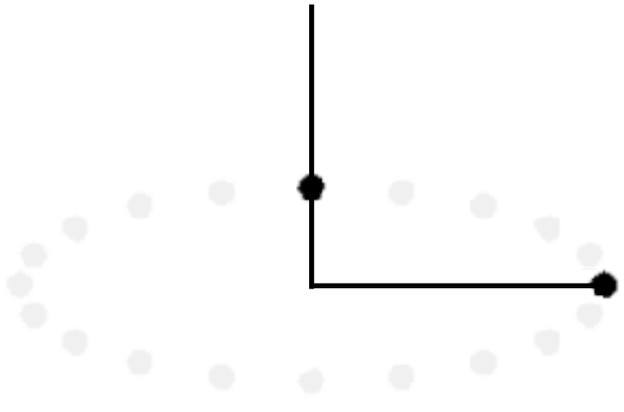
Michelson Interferometers

3-4 km vacuum tunnels with laser beam bouncing off of mirrors

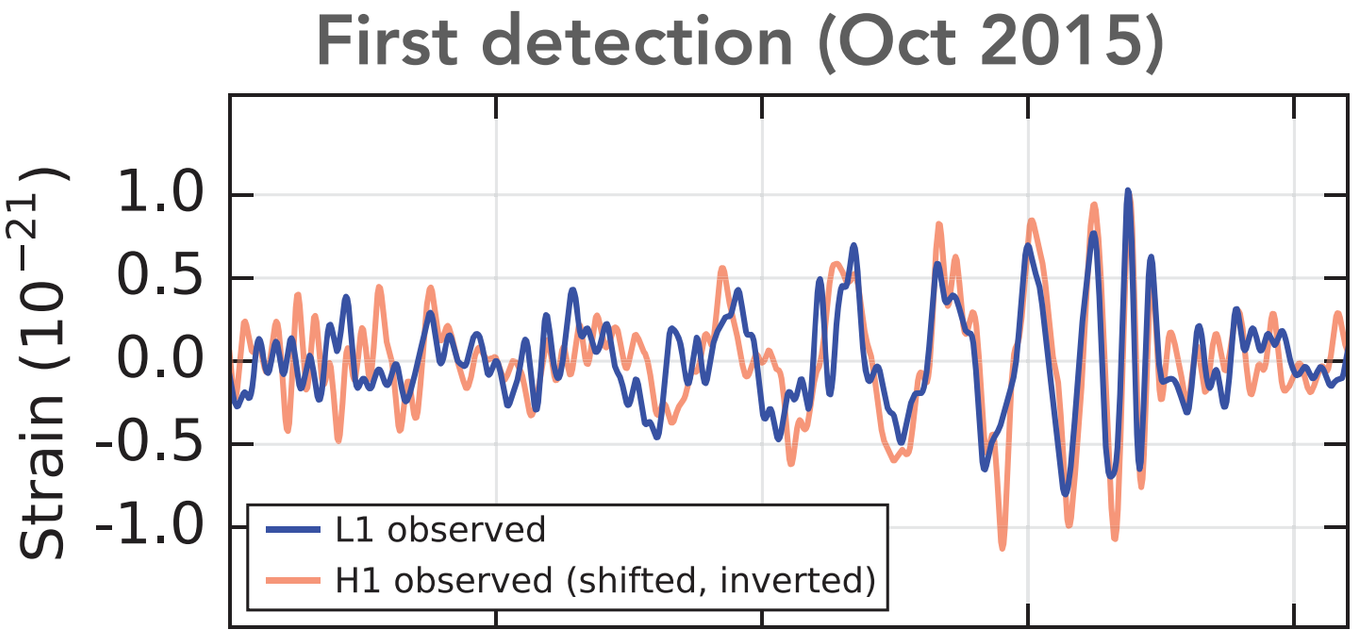


Arm length variation for typical OG

$$\Delta L \approx 4.10^{-19}\mathrm{m}$$

Earth-Moon distance with 0.1 Å accuracy…

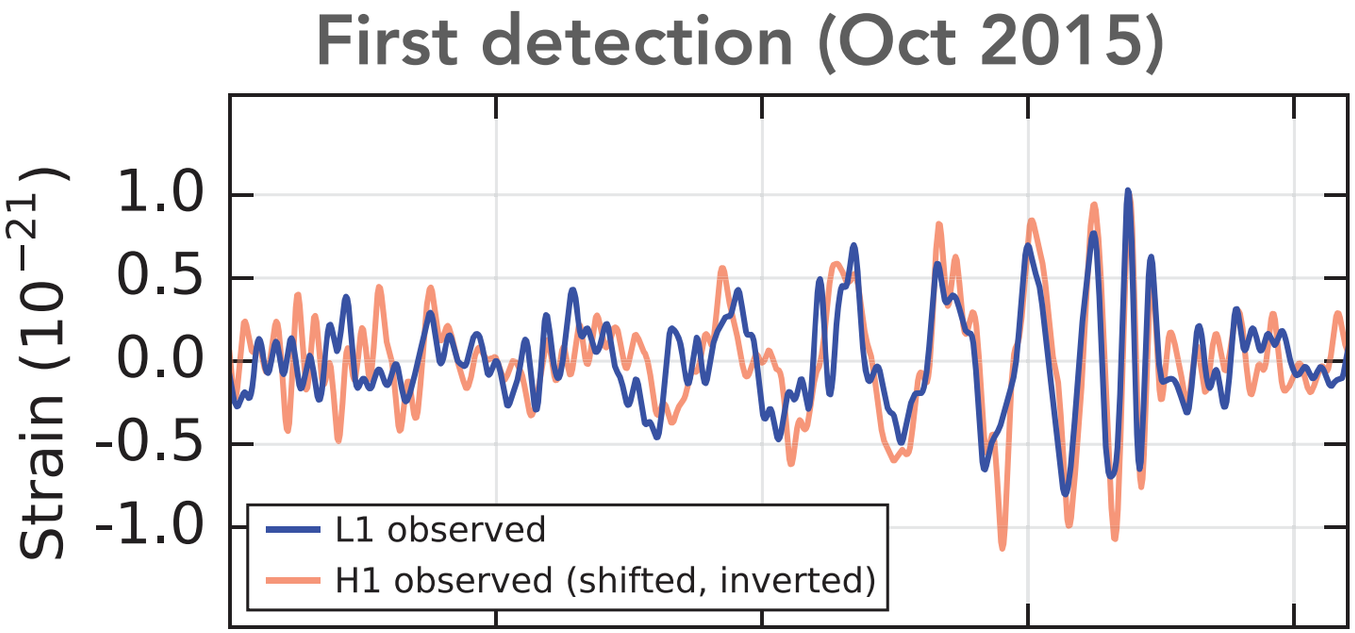
GW : first detections



PRL 116, 061102 (2016)

How to infer physical parameters from the GW ?

GW : first detections



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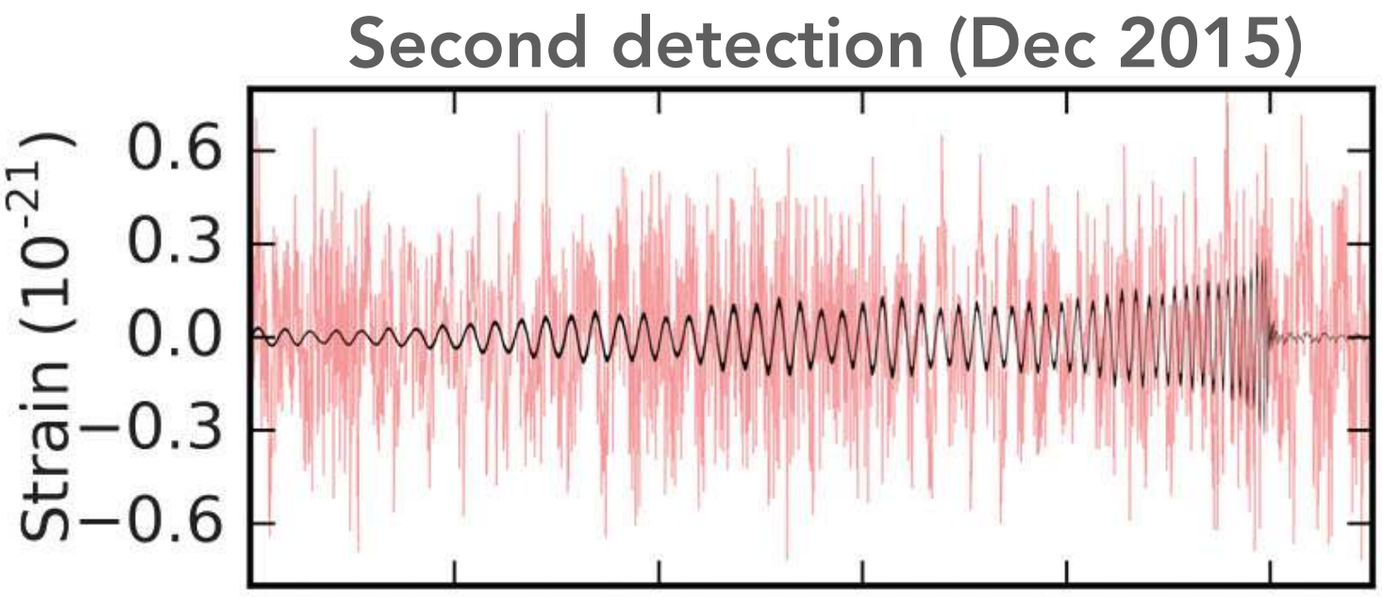

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How to extract the GW from the noise ?

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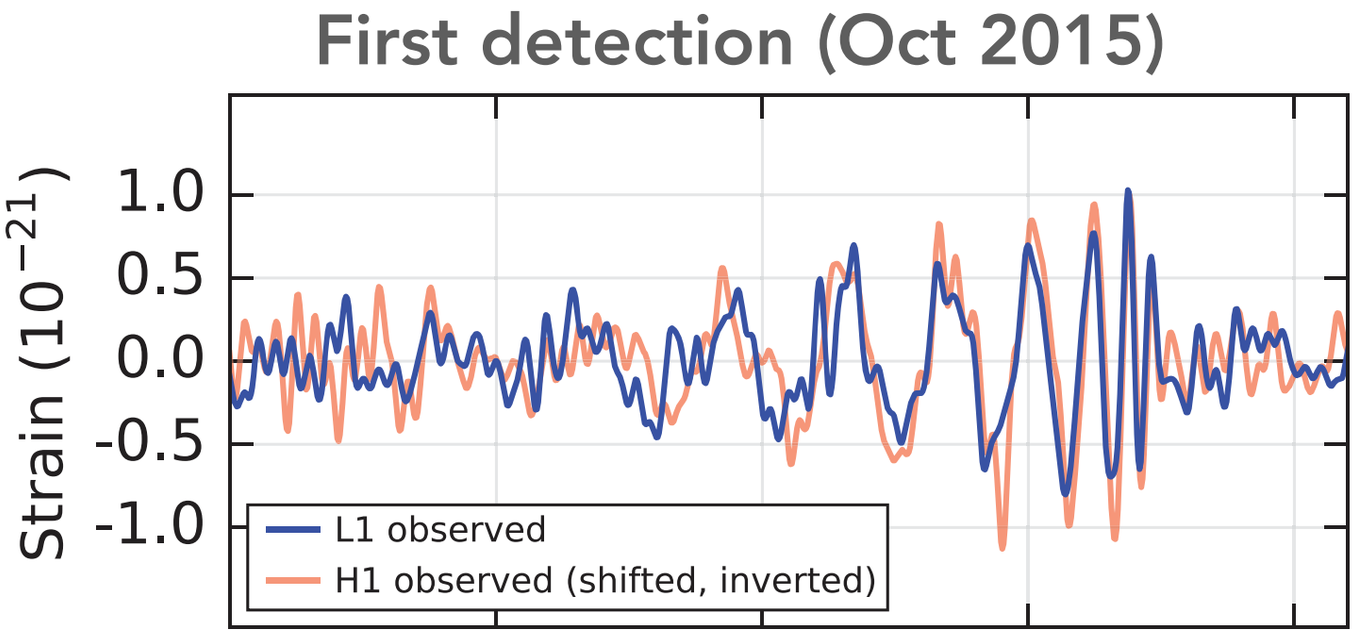

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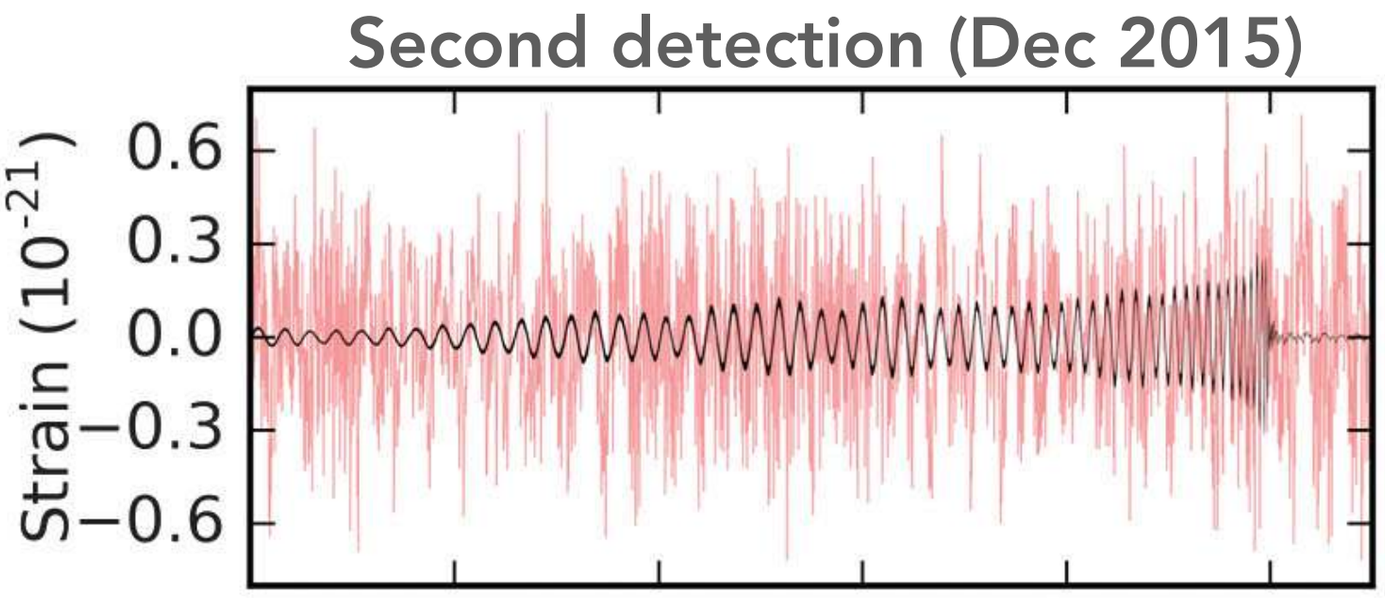

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How to infer physical parameters from the GW ?

Using GW templates !

How to extract the GW from the noise ?

GW : templates

Ex : for a binary system of two black holes

Step 1. Model a binary system of black holes at distance D , with mass M

GW : templates

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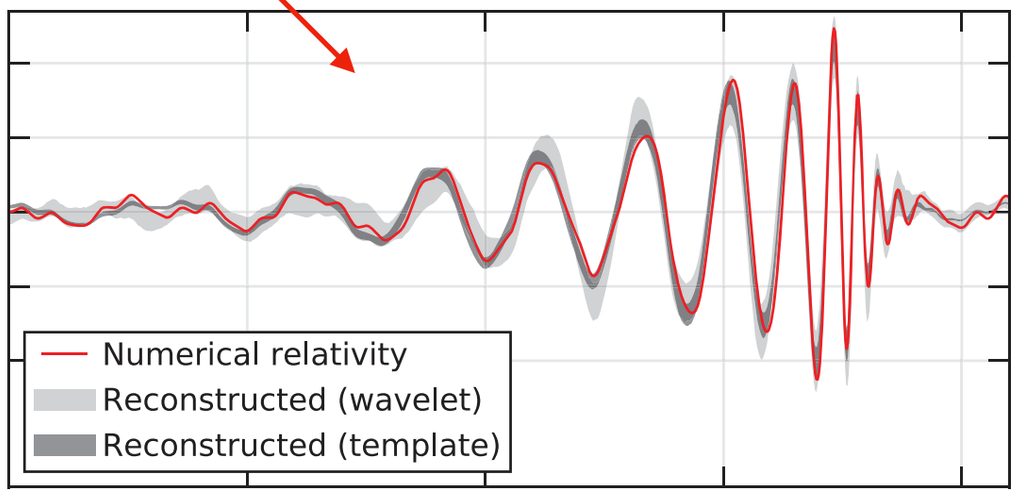
Step 2. Construct GW template :
solve GW equation for this system

$$\Box \bar{h}_{ab} = -8\pi G T_{ab}$$



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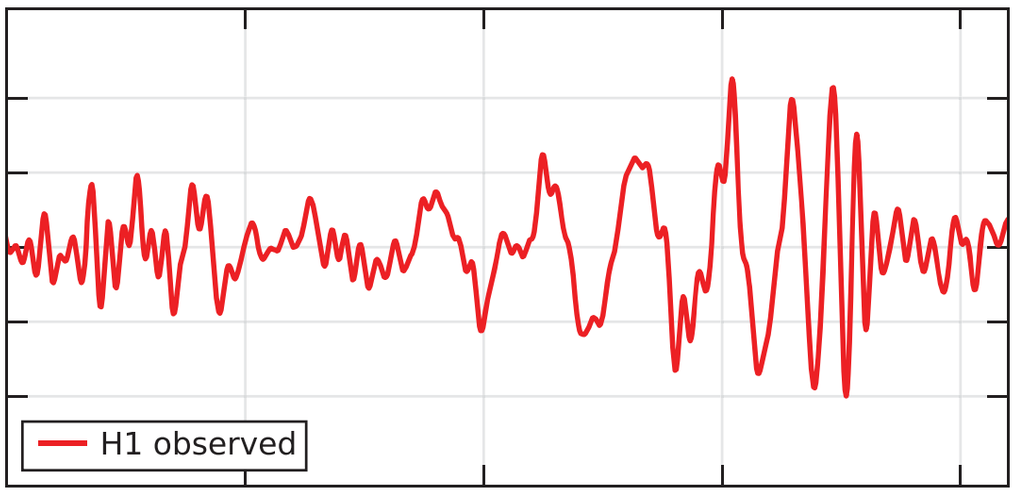
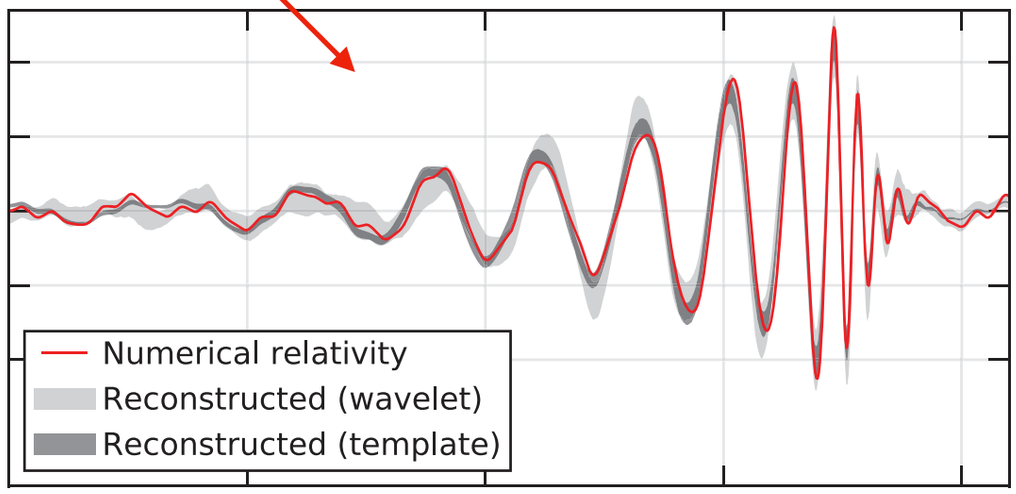
Step 3. Match detector signal with template bank to <u>detect</u>





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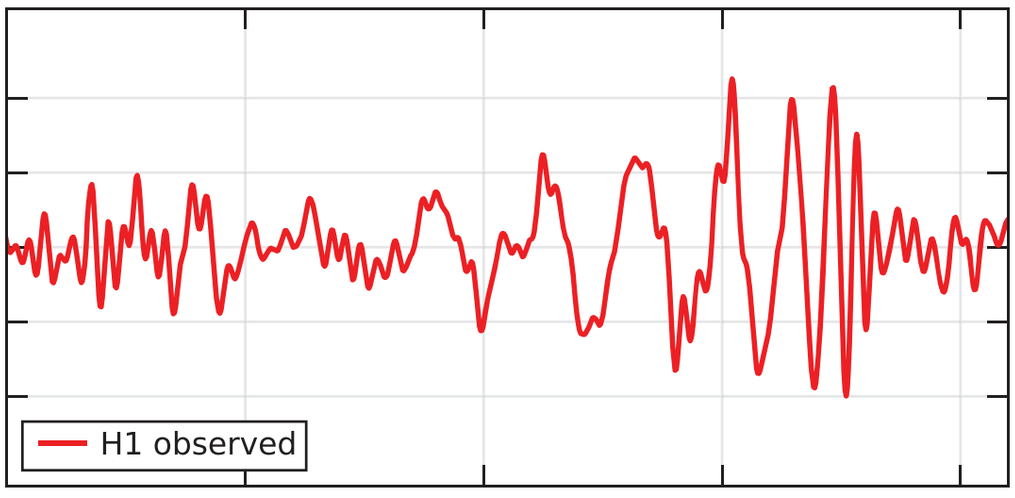
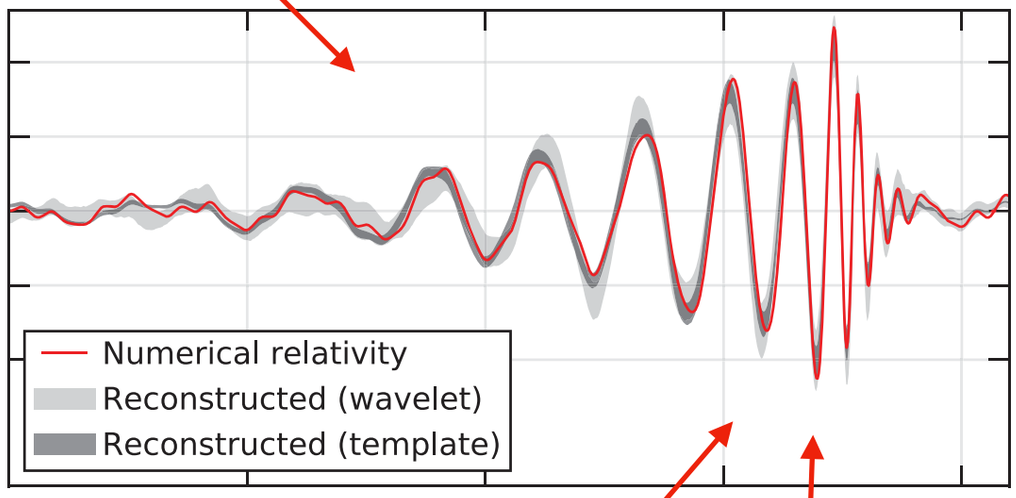




$$D = \frac{5c}{24\pi^2} \frac{\dot{f}}{f^3 A}$$

$$M = \left[\frac{5}{96} \frac{c^5}{G\pi^{8/3}} \frac{\dot{f}}{f^{11/3}} \right]^{3/5}$$

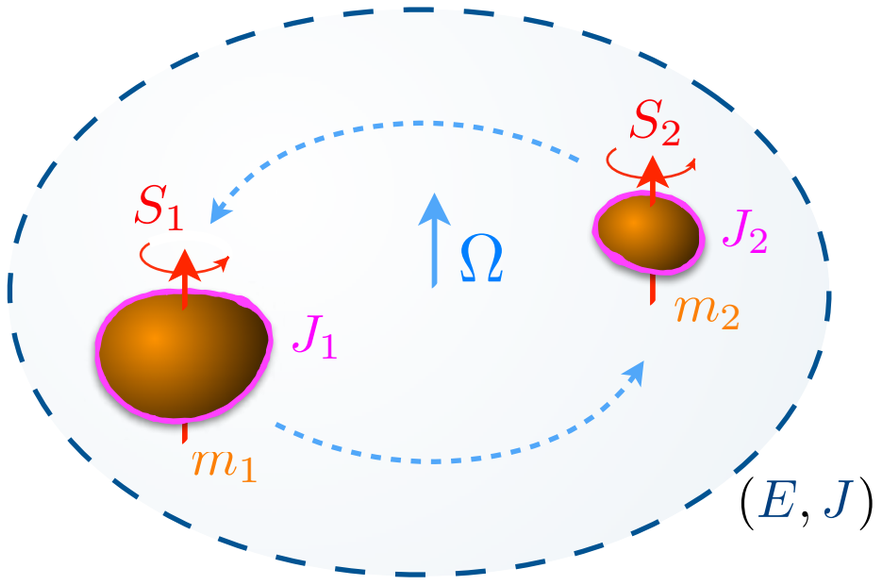
Step 4. Match with best template to extract source data

Summary

1. General Relativity

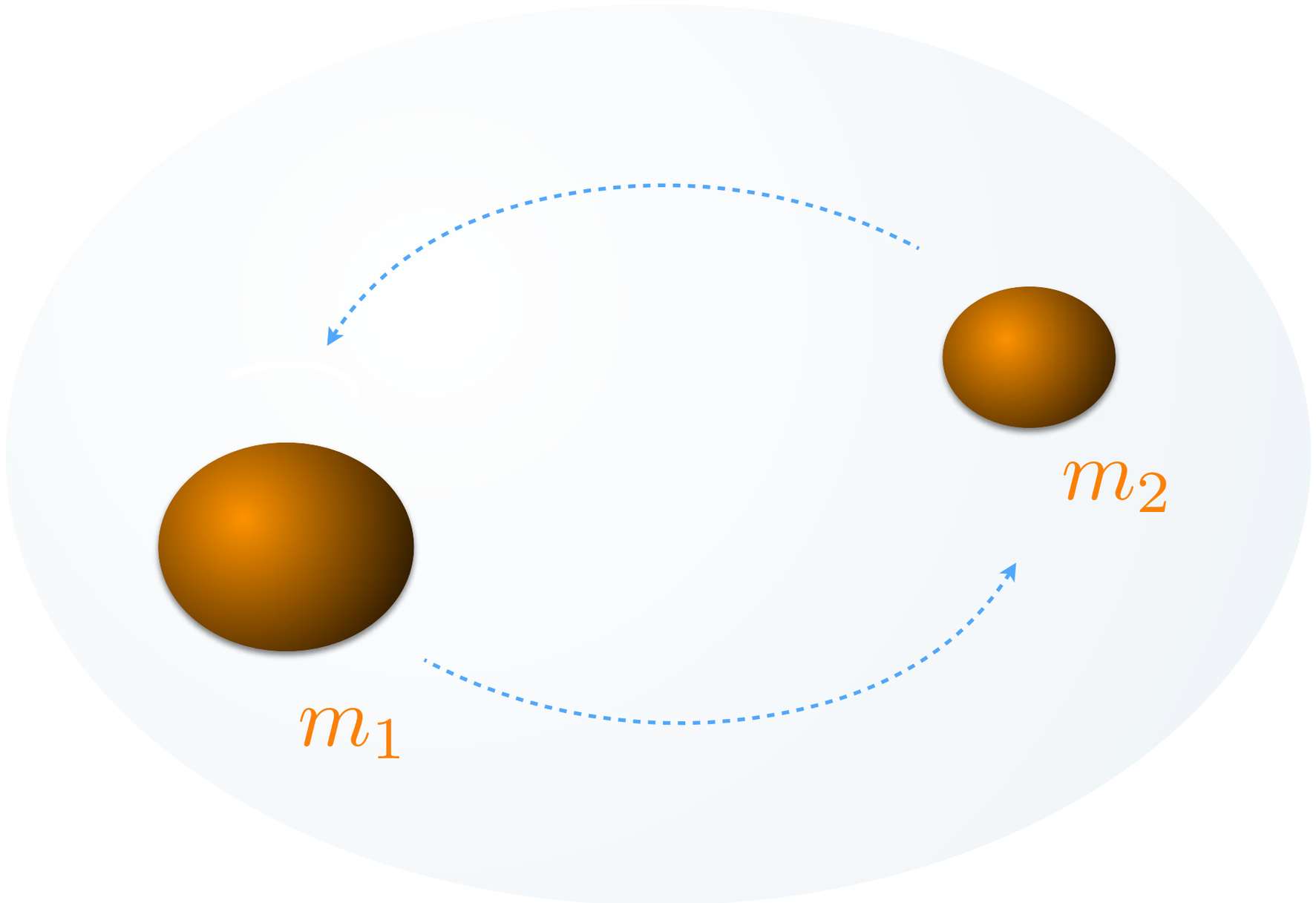
2. Gravitational Waves

3. My PhD



Model of binary system 1.0

Step 1. Refined model of binary systems of compact objects (NS or BH)



Model of binary system 2.0

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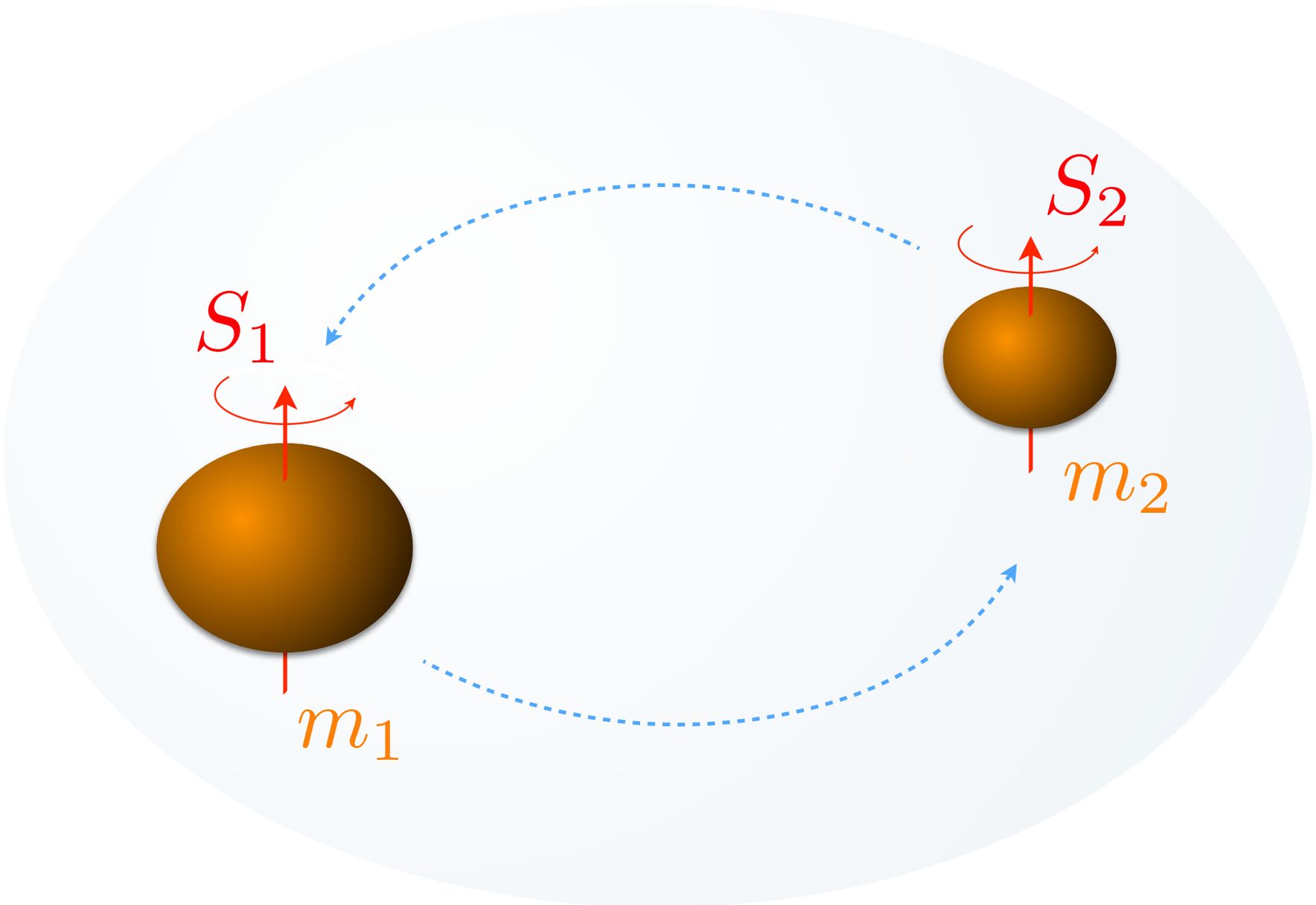

Model of binary system 3.0

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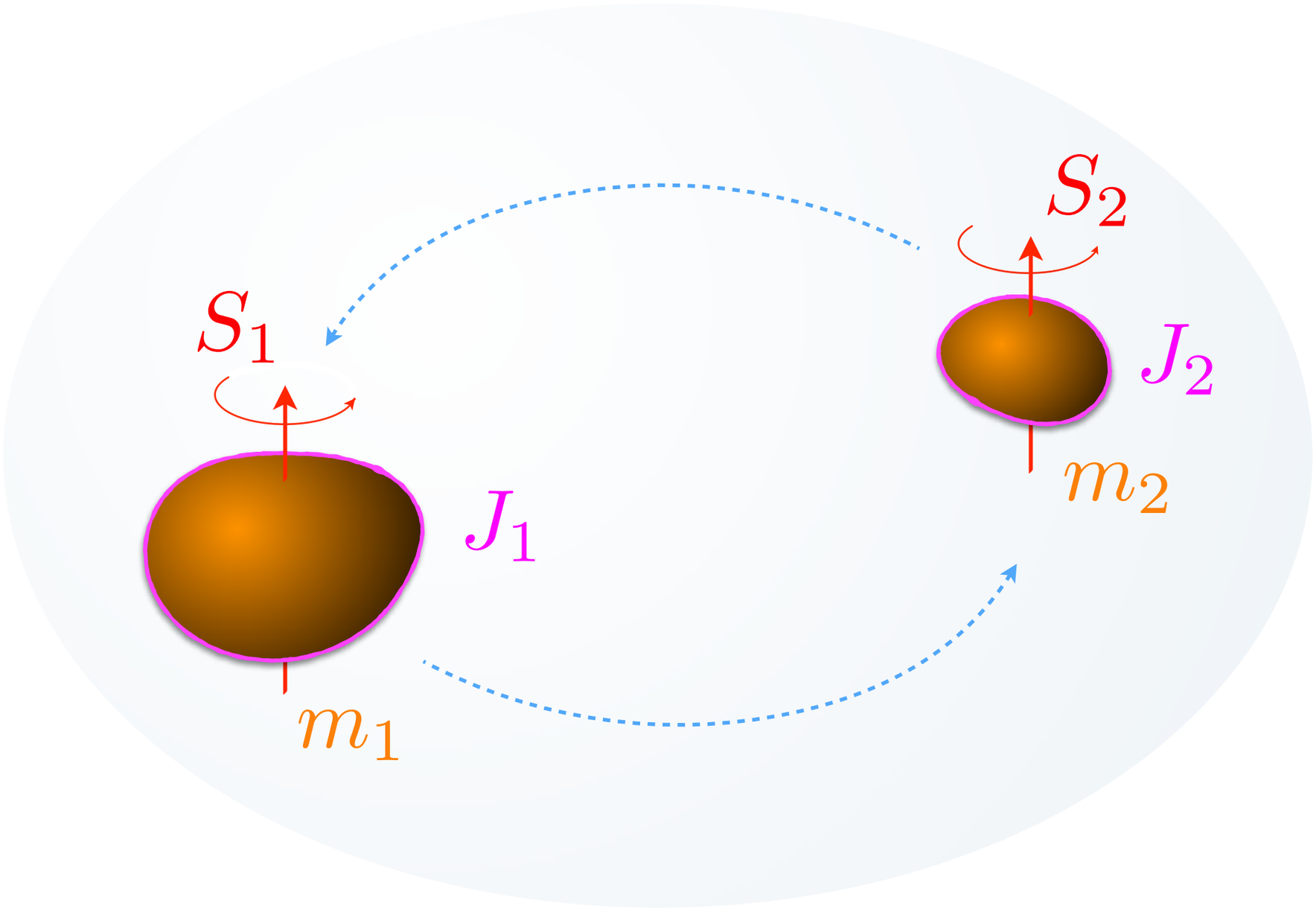

My PhD : relate global and local properties

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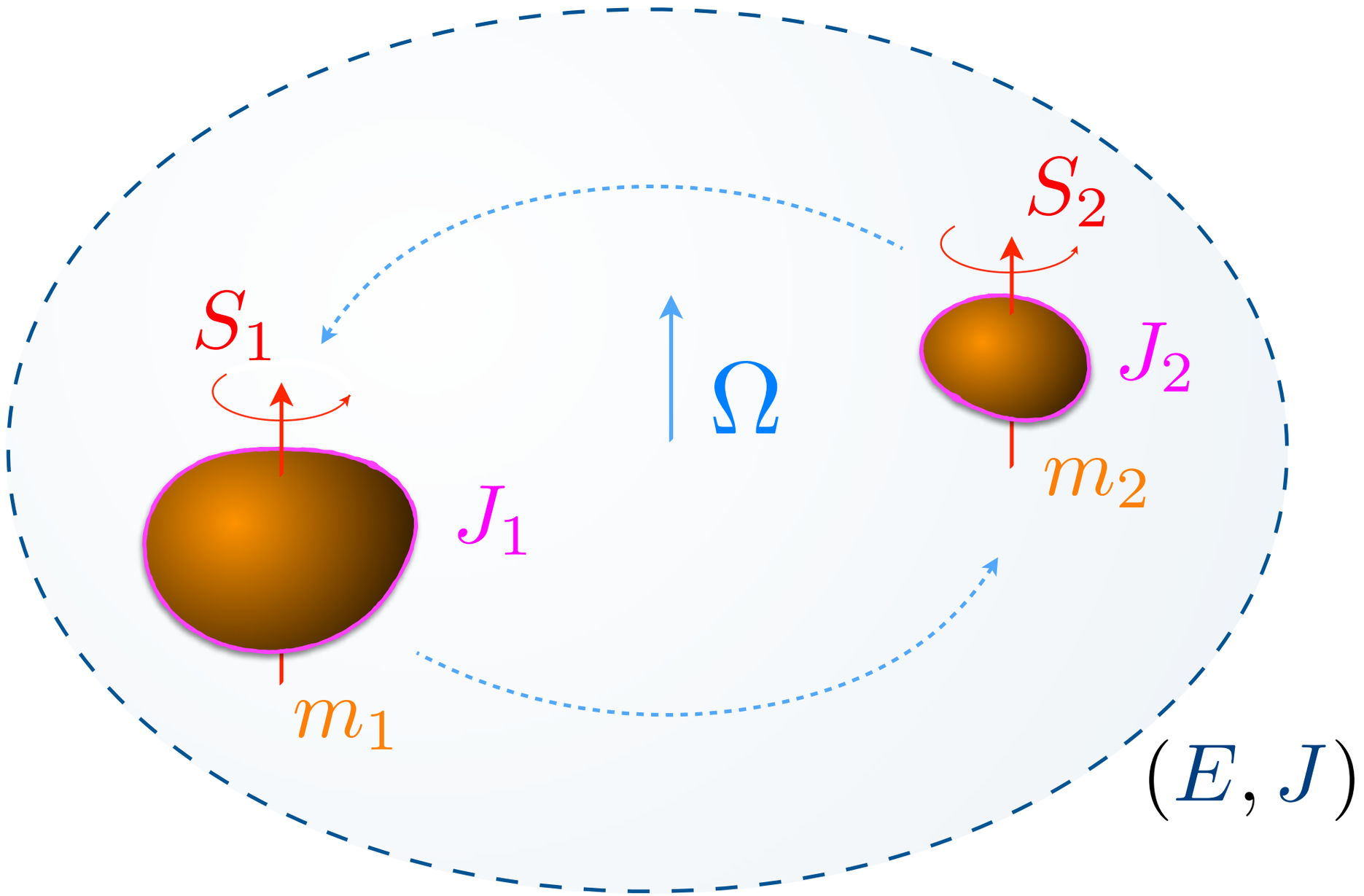
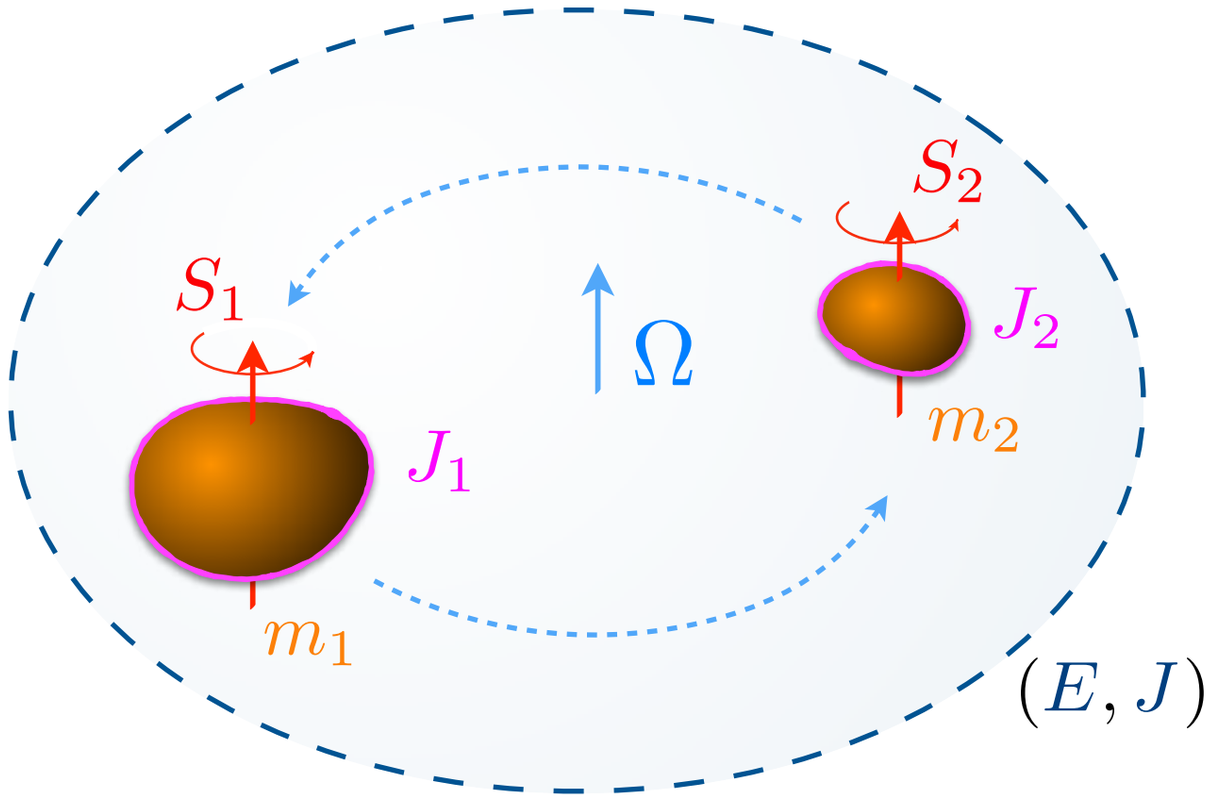


First law of black hole mechanics

Equation relating

(E, J, Ω) to (m_i, S_i, J_i)

First law of black hole mechanics



$$\delta M - \Omega \delta J = \sum_{i=1,2} \boxed{|k|\,\delta m_i} + \boxed{|\nabla k|\,\delta S_i} + \boxed{|\nabla\nabla k|\,\delta J_i}$$

2012 ***2018*** ***2020***

(done this year) *(if all goes well!)*

Thank you !

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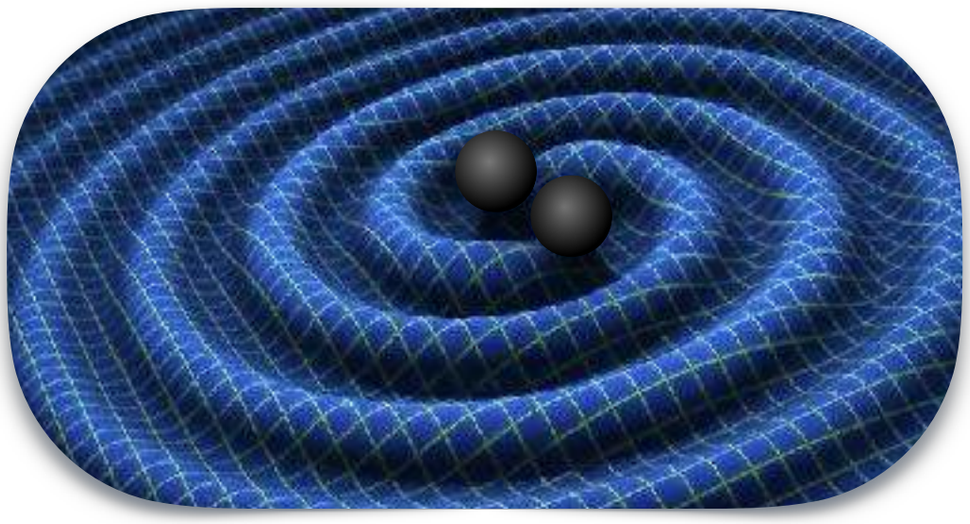

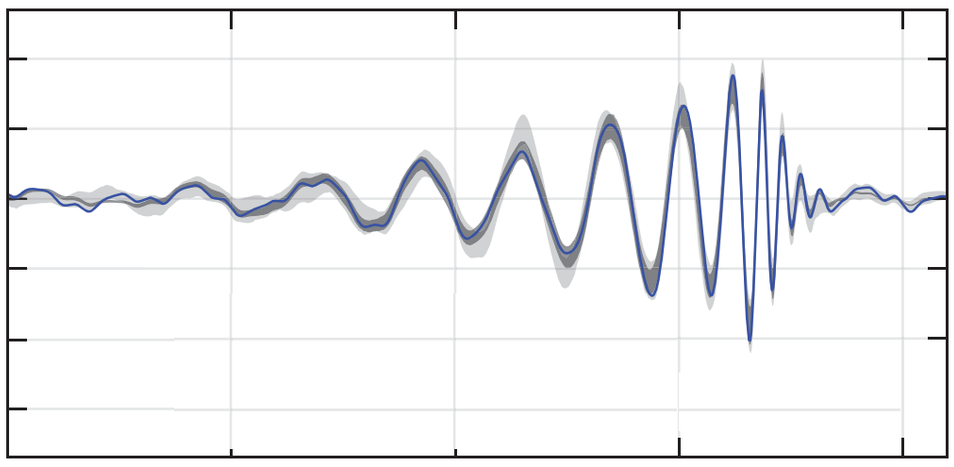

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