Journées LISA Observatoire

Magnetism in Galactic Binaries and Gravitational Waves detection by Lisa

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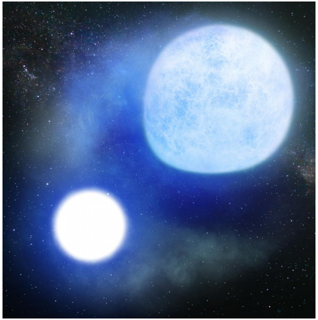


Illustration of a CGB system in tidal interaction.

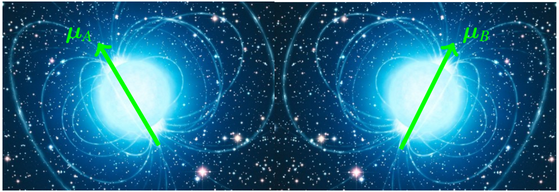
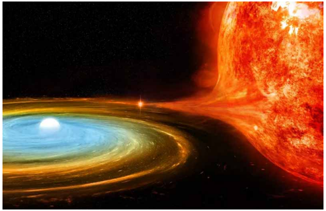


Illustration of a CGB system in magnetic interaction.

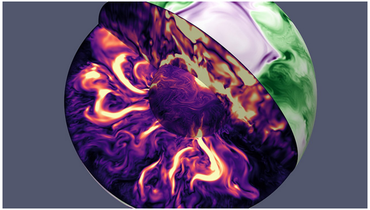
Physical properties

Binaries of **White Dwarfs**, **Neutron Stars**, and stellar-mass **black holes**, in various combinations, and within the galaxy.

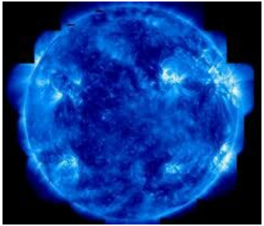
- **White Dwarfs** (WD), **Neutron Stars** (NS),
- **Radius**: $R_{\rm WD} \sim R_\oplus$ $R_{\rm NS} \sim 10\,{\rm km}$
- **Mass**: $M_{\rm WD} \lesssim M_\odot$ $M_{\rm NS} \gtrsim M_\odot$
- **Density**: $\rho_{\rm WD} \sim 1\,{\rm t/cm^3}$ $\rho_{\rm NS} \sim 10^9\,{\rm t/cm^3}$
- **Compacity** ($\Xi = GM/c^2R$):
  $\Xi_{\rm WD} \sim 10^{-3}$ $\Xi_{\rm NS} \sim 10^{-1}$
- **LISA frequency** ($\Phi = 10^{-1}$ Hz to $\Phi = 10^{-4}$ Hz):
  $a \sim 10^4 - 10^6\,{\rm km}$
  $P \sim 1\,{\rm min} - 10\,{\rm h}$
- **Magnetic fields** ($< 20\%$ WD and $< 10\%$ NS):
  $B_{\rm WD} \sim 10^6 - 10^9 G$ $B_{\rm NS} \sim 10^{14} - 10^{15} G$
- **Magnetic moments** ($\mu \propto BR^3$):
  $\mu_{\rm WD} \sim 10^{30} - 10^{33}\,{\rm A \cdot m^2}$ $\mu_{\rm NS} \sim 10^{29} - 10^{30}\,{\rm A \cdot m^2}$



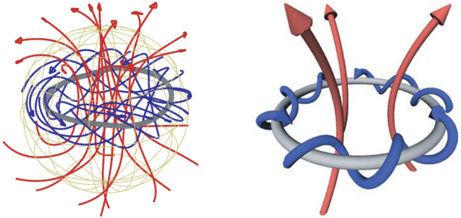
Merging scenario: MWD formed with cataclysmic variables, and magnetars formed with WD merger. Tout *et. al* (2008). MWD observed in detached system. Landstreet and Bagnulo (2020)



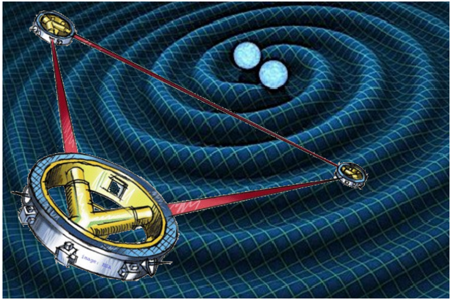
Turbulent dynamo in convective zone of progenitors or differentially rotating degenerate stars. Duncan *et. al* (1992); Raynaud *et. al* (2020); Reboul-Salze *et al.* (2021)

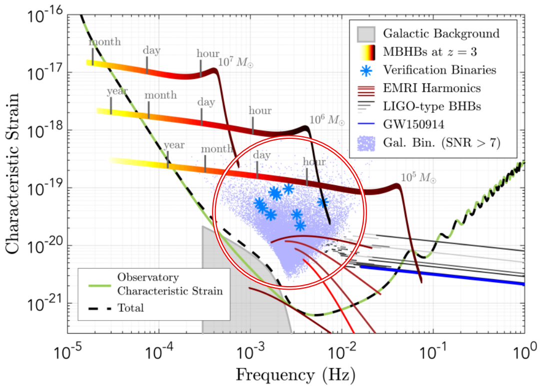


Flux conservation: MWD from main-sequence stars progenitors Ap, Bp for WDs, magnetars from O-type. Ferrario *et. al* (2005)



Fossil fields: Emergence of, large scale, strong, and stable dipolar fields. Braithwaite *et. al,* (2004); Duez & Mathis (2010)





Physics in strong field regime

1. **Cosmology**: How supermassive black holes *form* and *assemble*? What is the connection with *galaxy formation*?
2. **Fundamental Physics**: What is *nature of gravity* near black holes horizon?
3. **Astrophysics**: How galactic binaries *form* and *evolve*? Where are they *distributed* in the galaxy? What are the *mass distribution* and *internal structure*?

GW emitted by a binary system

Keplerian orbit

Oscillation at $2n \Longrightarrow$ circular orbit.

Modulation depends on $(e, \iota, \Omega, \omega)$.

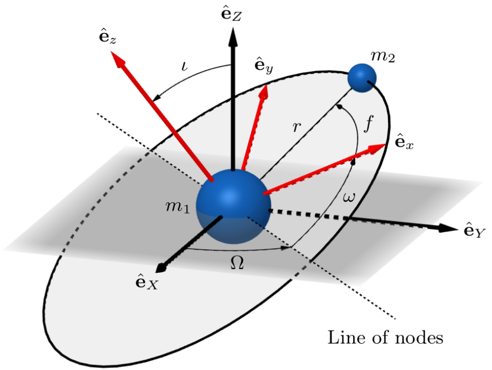
Amplitude depends on the shape (a, e).

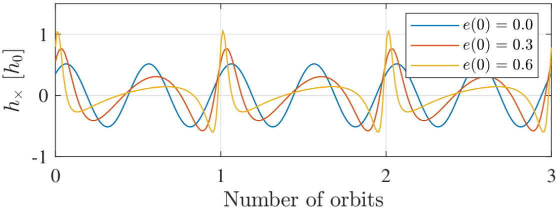
$$h_0 = 4\eta \left(\frac{p}{D}\right)\left(\frac{Gm}{c^2 p}\right)^2$$

- D: distance to the field point, *i.e.* $D = |\boldsymbol{x}|$,
- m: total mass, *i.e.* $m = m_1 + m_2$,
- η: symmetric mass ratio, *i.e.* $\eta = m_1 m_2 / m^2$
- p: semi-latus rectum, *i.e.* $p = a(1 - e^2)$.

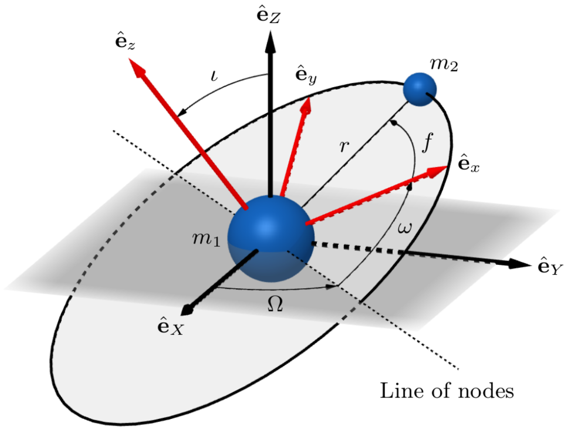
CGB, state of the art

- 1PN, 2PN, and 2.5PN corrections
  Lincoln and Will (1990)
- Dynamical Tides.
  Fuller *et. al* (2011), (2012), (2014)
- **Magnetic effects $\Longrightarrow$ Not investigated yet**



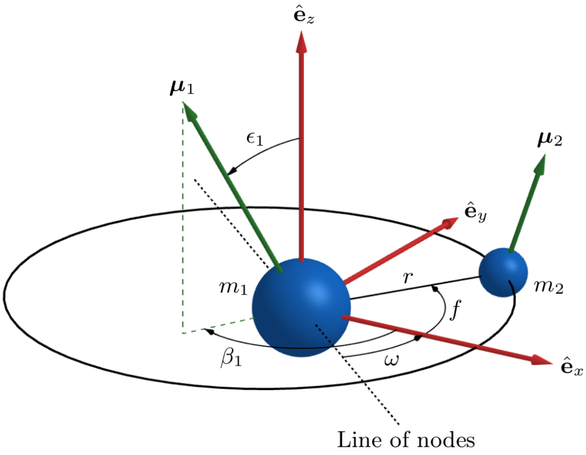


Orientation of the orbit



- **Semi-major axis**: a
- **Longitude of the pericenter**: $\varpi = \Omega + \omega$
- **Mean longitude**: $L = \varpi + M$
- **Eccentricity vector**: $z = e\,\exp(\mathrm{i}\varpi)$
- **Node vector**: $\zeta = \sin\left(\frac{\iota}{2}\right)\exp(\mathrm{i}\Omega)$

Orientation of magnetic moments



- Magnetic moments: $\boldsymbol{\mu}_1$ and $\boldsymbol{\mu}_2$
- Obliquities of the magnetic moment $\boldsymbol{\mu}_1$: ϵ_1, ϵ_2
- Precession angles of the magnetic moment $\boldsymbol{\mu}_1$: β_1, β_2

The magnetic dipole-dipole interaction

The rotational motion

$$\left\langle \frac{\mathrm{d}\epsilon_1}{\mathrm{d}t} \right\rangle_{\mathrm{M}} = \nu_1(a,e) f(\epsilon_1, \epsilon_2, \beta_1, \beta_2, \varpi),$$

$$\textit{idem} \text{ for } \left\langle \frac{\mathrm{d}\beta_1}{\mathrm{d}t} \right\rangle_{\mathrm{M}}, \left\langle \frac{\mathrm{d}\epsilon_2}{\mathrm{d}t} \right\rangle_{\mathrm{M}}, \text{ and } \left\langle \frac{\mathrm{d}\beta_2}{\mathrm{d}t} \right\rangle_{\mathrm{M}}$$

with

$$\nu_{1,2} = \left(\frac{\mu_0}{8\pi}\right)\left(\frac{\mu_1\mu_2}{S_{1,2}}\right)\frac{1}{a^3(1-e^2)^{3/2}}$$

- S_1: angular momentum of the primary,
- S_2: angular momentum of the secondary,
- a: semi-major axis,
- e: eccentricity,
- ϖ: longitude of the pericenter,

The orbital motion

$$\left\langle \frac{\mathrm{d}L}{\mathrm{d}t} \right\rangle_{\mathrm{M}} \propto \nu(a,e) f(\epsilon_1, \epsilon_2, \beta_1, \beta_2),$$

$$\textit{idem} \text{ for } \left\langle \frac{\mathrm{d}z}{\mathrm{d}t} \right\rangle_{\mathrm{M}}, \left\langle \frac{\mathrm{d}\zeta}{\mathrm{d}t} \right\rangle_{\mathrm{M}} \text{ and } \left\langle \frac{\mathrm{d}\varpi}{\mathrm{d}t} \right\rangle_{\mathrm{M}}$$

with

$$\nu = \left(\frac{3\mu_0}{8\pi G}\right)\left(\frac{\mu_1\mu_2}{m_1 m_2}\right)\left(\frac{n}{p^2}\right)$$

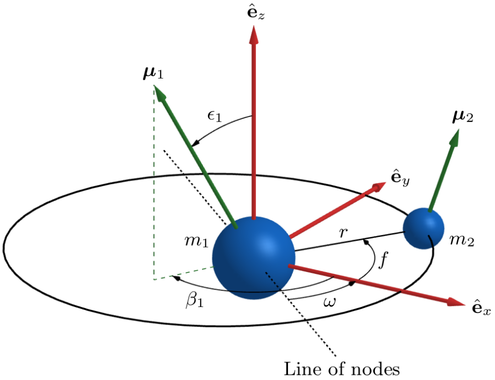
- μ_0: permeability of vacuum,
- m: total mass, *i.e.* $m = m_1 + m_2$,
- n: orbital mean motion, *i.e.* $n = \sqrt{Gm/a^3}$,
- p: semi-latus rectum, *i.e.* $p = a(1-e^2)$.

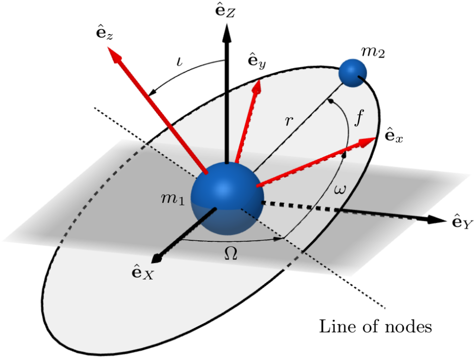
The rotational motion

- **Secular variations** of β_1 and β_2: $\boxed{\propto \nu_{1,2}\, t}$
- **Periodic oscillations** of ϵ_1, ϵ_2, β_1, and β_2.
  Amplitudes are independent of a.

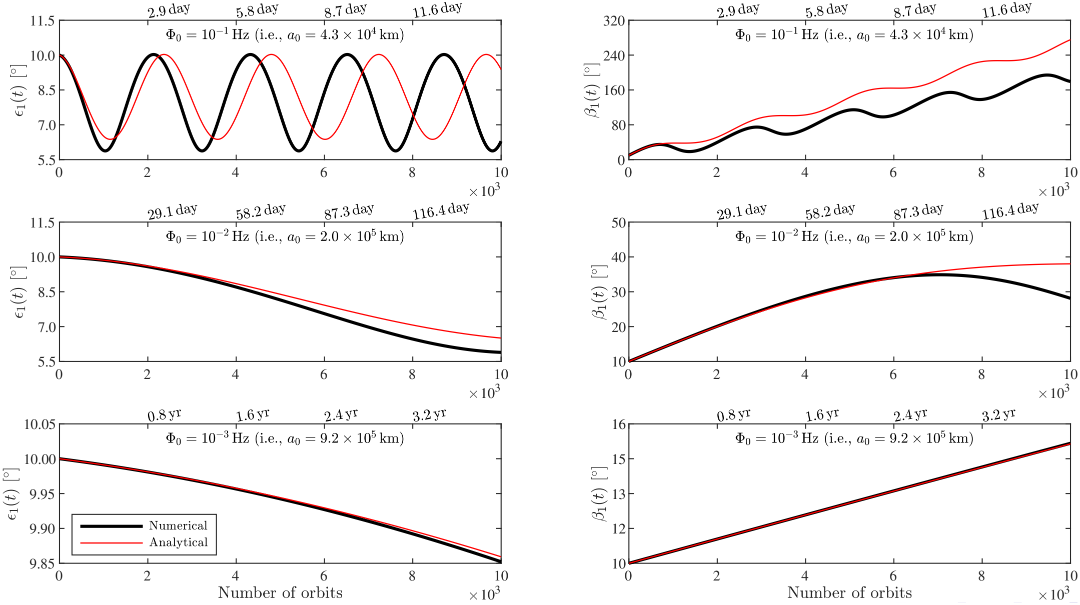
The orbital motion

- **Secular variation** of L, ϖ: $\boxed{\propto (n+\nu)\, t}$, $\boxed{\propto \nu\, t}$
- **Periodic oscillations** of ι, Ω, L, and ϖ.
  Amplitudes depend on $\dot\beta_1$, $\dot\beta_2$, and $\dot\varpi_{\rm GR}$.





Orientation of primary's magnetic moment



Effect of the magnetic dipole-dipole interaction on the orbit

- **Purely oscillating solutions**:

$$\iota(t) = \iota_0 + \widetilde{\iota}_{\rm M}(t)$$
$$\Omega(t) = \Omega_0 + \widetilde{\Omega}_{\rm M}(t)$$

- Oscillating signatures $\widetilde{\iota}_{\rm M}$ and $\widetilde{\Omega}_{\rm M}$ made of 2 sinusoids:

$$\propto \Theta_1 \sin\left[(\dot{\varpi}_{\rm GR} + \dot{\varpi}_{\rm M} + \dot{\beta}_1)t + \dots\right] + \Theta_2 \sin\left[(\dot{\varpi}_{\rm GR} + \dot{\varpi}_{\rm M} + \dot{\beta}_2)t + \dots\right] + \dots,$$

- Amplitude of oscillations:

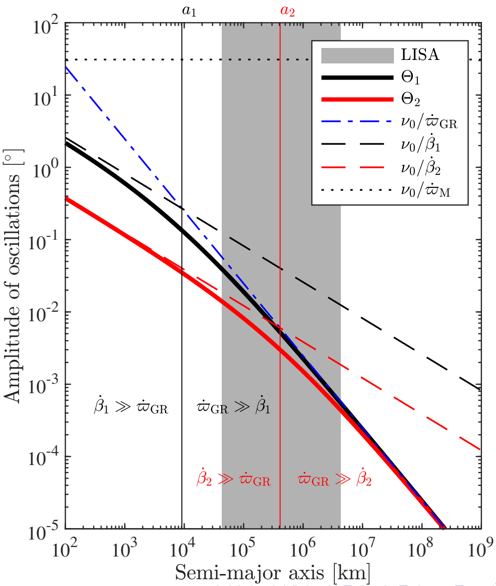
$$\Theta_{1,2} = \frac{\nu}{\dot{\varpi}_{\rm GR} + \dot{\varpi}_{\rm M} + \dot{\beta}_{1,2}}$$

$\Longrightarrow$ Oscillations too small to be detected ?

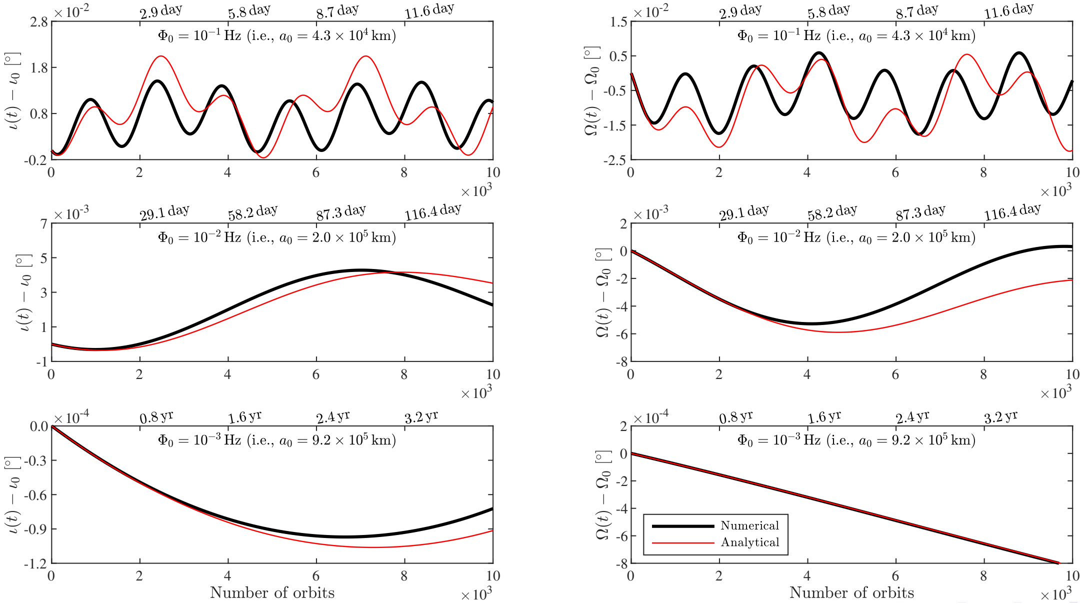
- **Secularly changing solution**:

$$L(t) = L_0 + \widetilde{L}_{\rm M}(t) + (n_0 + \dot{L}_{\rm GR} + \dot{L}_{\rm M})t - \frac{3n_0}{4a_0}\dot{a}_{\rm GR}t^2$$
$$\varpi(t) = \varpi_0 + \widetilde{\varpi}_{\rm M}(t) + (\dot{\varpi}_{\rm GR} + \dot{\varpi}_{\rm M})t$$

$\Longrightarrow$ Only the secular drift can be retained.



Inclination and longitude of the node



Relative error on $h = (h_+, h_\times)$:

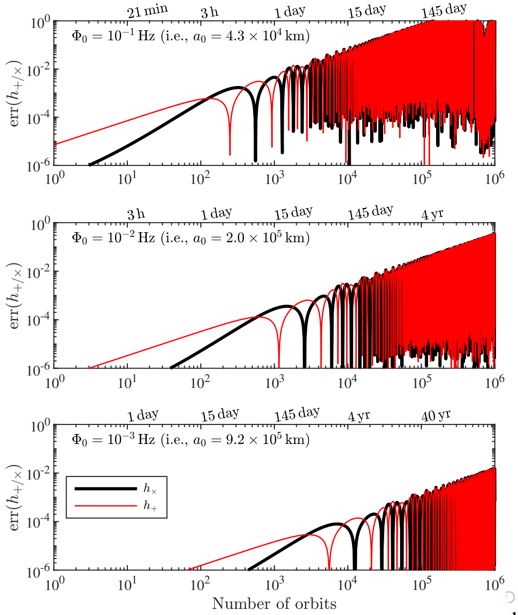
$$\mathrm{err}(h) = \frac{|h_{\mathrm{GR+M}} - h_{\mathrm{GR}}|}{h_{\mathrm{GR+M}}}$$

- h_{GR}: mode with GR effects only.
- $h_{\mathrm{GR+M}}$: mode with GR and magnetism for 2 WDs with $B_1 = B_2 = 10^9$ G.

$\Longrightarrow$ 0.01% error in 4 years for $\Phi_0 = 10^{-3}$ Hz,

$\Longrightarrow$ **1% error** in **4 years** for $\Phi_0 = 10^{-2}$ Hz,

$\Longrightarrow$ **100% error** in **145 days** for $\Phi_0 = 10^{-1}$ Hz !



Zeroth-order in eccentricity: $$\begin{cases} h_+ = h_0(1+\cos^2\iota)\cos(\phi + \Phi t + \dot{\Phi} t^2) + \mathcal{O}(e), \\ h_\times = -2h_0 \cos\iota \sin(\phi + \Phi t + \dot{\Phi} t^2) + \mathcal{O}(e), \end{cases}$$

where the **main frequency** and the **frequency shift** are given by

$$\Phi = 2n\left(1 + \frac{\dot{L}_{\rm GR}}{n} + \frac{\dot{L}_{\rm M}}{n}\right), \qquad \dot{\Phi} = -\frac{3n}{4a}\,\dot{a}_{\rm GR}$$

$\Longrightarrow$ **Magnetism must be used for physical interpretation** of the **main frequency**, if

$$\frac{\sigma_\Phi}{\Phi} < \frac{\dot{L}_{\rm M}}{n} \qquad \dot{L}_{\rm M} = 2\nu\left(1 + \sqrt{1-e^2}\right)\cos\epsilon_1 \cos\epsilon_2,$$

that is to say, if

$$\boxed{\frac{\sigma_\Phi}{\Phi} < 6.8\times 10^{-7}} \qquad \text{for } \Phi = 10^{-1}\,\text{Hz and } B_1 = B_2 = 10^9\,\text{G}.$$

$\Longrightarrow$ Uncertainty for **Verification binaries** between 10^{-6} to 10^{-9} !

$\Longrightarrow$ **EM+GW observations to determine magnetism at zeroth-order in eccentricity**.

First-order in eccentricity: $$\begin{cases} h_+ = \frac{9}{4} h_0 e (1+\cos^2\iota)\cos(\phi' + \Phi' t) + \ldots + \mathcal{O}(e^2), \\ h_\times = -\frac{9}{2} h_0 e \cos\iota \sin(\phi' + \Phi' t) + \ldots + \mathcal{O}(e^2), \end{cases}$$

where the **frequency** is given by

$$\Phi' = 3n\left(1 + \frac{3\dot{L}_{\rm GR} - \dot{\varpi}_{\rm GR}}{3n} + \frac{3\dot{L}_{\rm M} - \dot{\varpi}_{\rm M}}{3n}\right),$$

$\Longrightarrow$ **Magnetism must be used for physical interpretation** of the **frequency**, if

$$\frac{\sigma_{\Phi'}}{\Phi'} < \frac{3\dot{L}_{\rm M} - \dot{\varpi}_{\rm M}}{3n} \qquad 3\dot{L}_{\rm M} - \dot{\varpi}_{\rm M} = 2\nu\left(2 + 3\sqrt{1-e^2}\right)\cos\epsilon_1 \cos\epsilon_2,$$

that is to say, if

$$\boxed{\frac{\sigma_{\Phi'}}{\Phi'} < 5.6 \times 10^{-7}} \qquad \text{for } \Phi' = 10^{-1}\,\text{Hz and } B_1 = B_2 = 10^9\,\text{G}.$$

$\Longrightarrow$ Magnetism determined **from GW observations alone** by combining Φ and Φ' !

Conclusion

- Are verification binaries magnetic?
  $\Longrightarrow$ Testing the dipole-dipole interaction.

- Is magnetism still degenerated with the main frequency at linear order in e?
  $\Longrightarrow$ Harmonics at frequencies $3n$ and n.

Collab. with Etienne Savalle and Aurélien Hees

- Non-adiabatic MHD interaction e.g., unipolar induction mechanism.
  $\Longrightarrow$ Requires only one magnetic body.
  $\Longrightarrow$ Loss of energy that can compete with 2.5PN terms.
  $\Longrightarrow$ Secular deformations of the orbit.

Collab. with Antoine Strugarek

- Dynamical tides and MHD interaction
  $\Longrightarrow$ Magneto-gravito-inertial-waves
  $\Longrightarrow$ Toward a coherent vision (internal structure, magnetism, and dynamics) of CGB