EVOLUTION OF BINARY COMPACT BODIES

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Carlos Palenzuela Luque
Max-Planck Institute, AEI, Golm (Berlin)

Overview

- Binary black holes
  - production of GWs
  - overview of the equations
  - waveforms and kicks
- Binary boson stars
  - modeling galaxy mergers
  - overview of the equations
  - head-on and orbital collisions
- Binary neutron stars
  - hot EOS and production of GRBs & GWs
  - overview of the equations
  - differences with the unmagnetized case
- Summary and conclusion

I. Binary Black Holes

- production of GWs
- overview of the equations
- waveforms and kicks

Binary BHs: motivation

maps of the sky

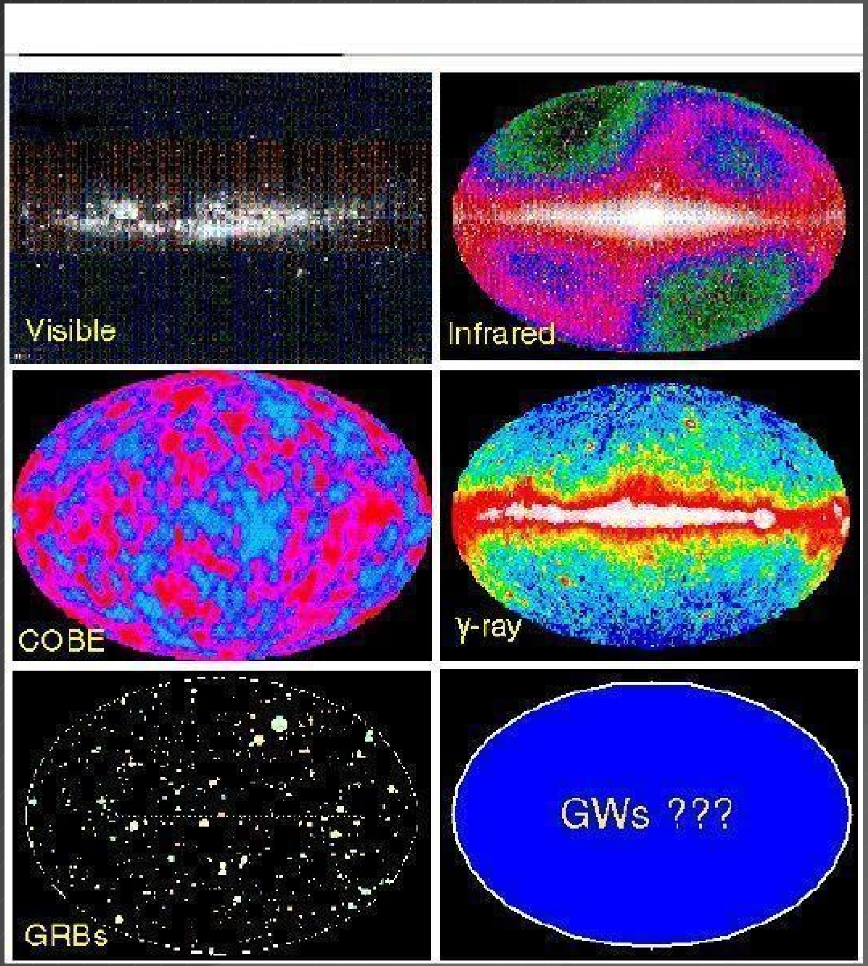
em force is much stronger

$F_{em} \sim 10^{40} F_g$

but the observable decays faster

EM : $E \sim 1/r^2$

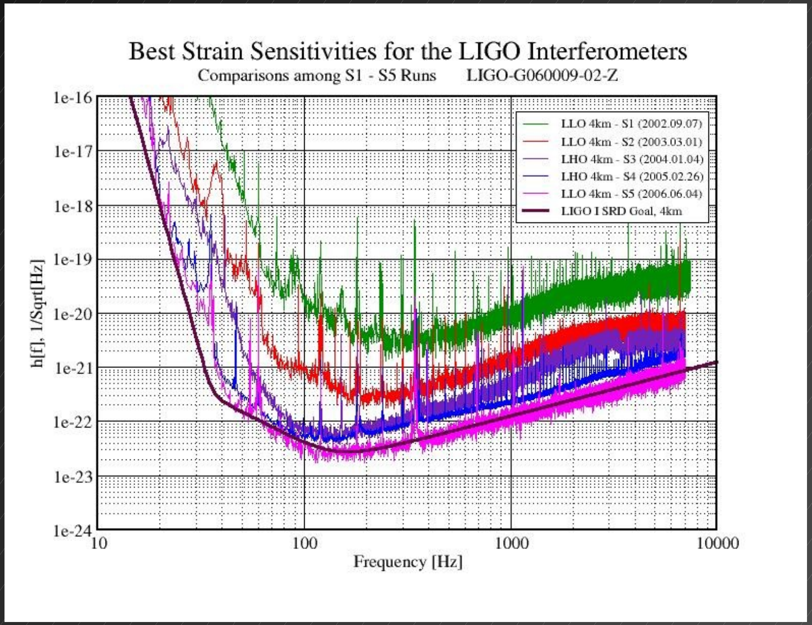
G : $h \sim 1/r$



Binary BHs: motivation

detectors of GWs based on interferometers are already operating

LIGO



VIRGO

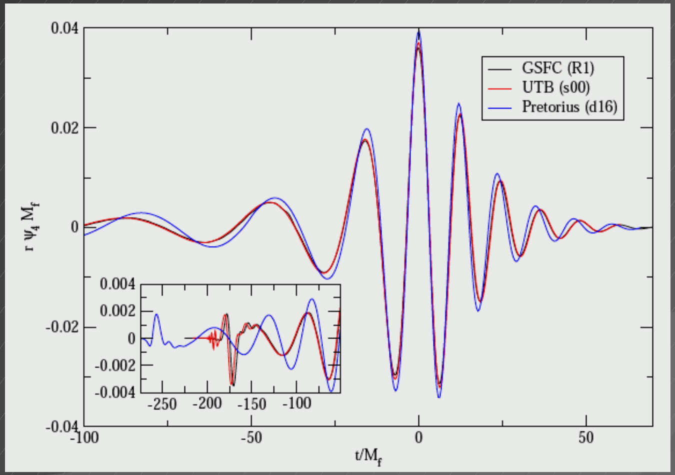
The sensitivity is enough to measure distance changes of 10^{-21} m.

Binary BHs: motivation

- The profile of the waves generated from the most promising sources (merger of black holes, neutron stars, …) are necessary.

4) With the current detectors, to filter the signal from the detector noise (are we seeing something?).

7) With the advanced detectors, interpret the dynamics of the source (what are we seeing?).



I.Binary BHs: overview of equations

- Einstein equations in vacuum

$$R_{ab} = 0 = g^{cd}\,\partial_{cd}\, g_{ab} + \partial_a \Gamma_b + \partial_b \Gamma_a + \ldots$$

- Fix the gauge freedom to the harmonic coordinates

$$\Box\, x^a = - \Gamma^a = 0$$

- Harmonic formalism $\quad g^{cd}\,\partial^{cd}\, g_{ab} = \ldots$

  - set of wave-like equations for g_{ab}
  - the system is symmetric hyperbolic → well posed

I.Binary BHs: overview of code

- The well posedness at the continuous can be translated into stability at the numerical level (ie, errors are bounded) if:

- convert the second order system to first order

$$Q_{ab} = - n^c \partial_c g_{ab} \quad , \quad D_{iab} = \partial_i g_{ab}$$

- Method of Lines for the evolution: separate time and space discretization

  * third order RK for the time evolution
  * Space discrete operators satisfying Summation By Parts rule (ie, discrete equivalent of Integration By Parts)

I.Binary BHs: overview of code

- The equations are implemented in an infrastructure called “had” which provides:

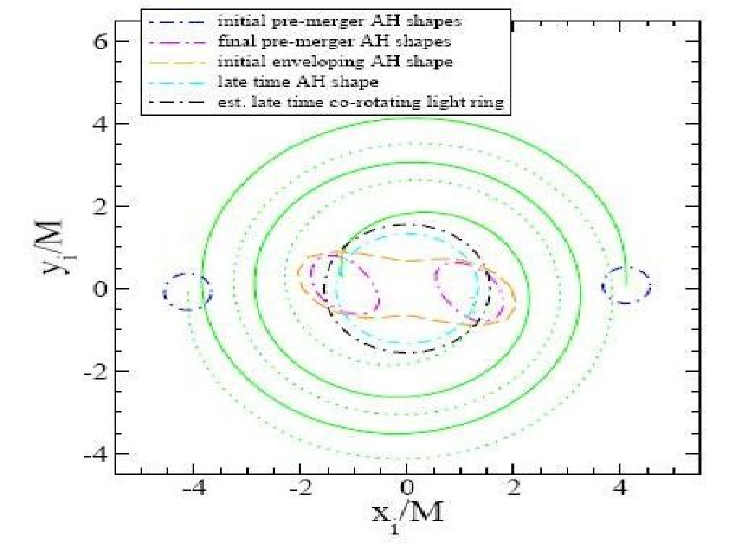
  - parallelization (ie, it can run in clusters of computers)

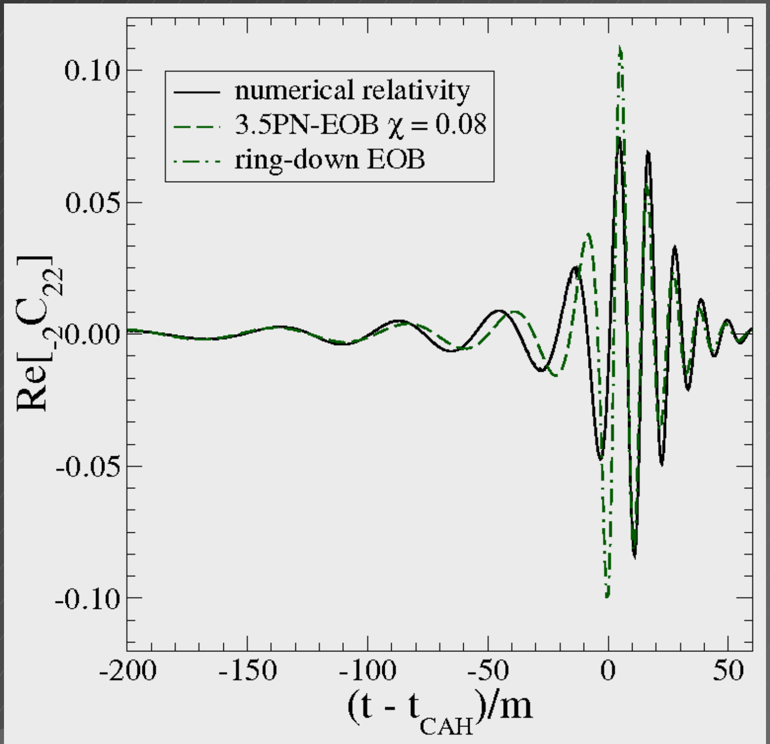
  - Adaptative Mesh Refinement (ie, it can increase the resolution locally by creating extra-grids)

  - the region inside the Apparent Horizon is removed or “excised” from the computational domain; the information can not travel outside the black hole.

I.Binary BHs: some results

- Cases with equal mass, no spin :
  * simple results, match very well the post-newtonian





I.Binary BHs: some results

- Cases with unequal mass and/or spin :
  * waveforms relatively simple
  * the final black hole has a kick velocity depending on the masses and spin (due to the assymetry on the radiation of GW and the dragging due to the other black hole)
  * enough for a supermassive BH to scape from the center of its galaxy?

*

- up to 175km/s for non-spinning, unequal mass components
- typical values for spinning black holes of 100’s km/s, but can be as large as 4000km/s

II. Binary Boson Stars

- modelling galaxy mergers
- overview of the equations
- head-on collisions and orbital dynamics

II. Binary BSs: motivation

- compact bodies composed of a complex massive scalar field, minimally coupled to the gravitational field

-simple evolution equation for the matter
→ it does not tend to develop shocks
→ the "equation of state" is given by the potential

- model to study the two body interactions in GR
- alternative for supermassive black hole
- candidates for the dark matter in galaxy

Binary BSs: motivation

The bullet cluster

- stars observable in visible light, gravitationally slowed
- The hot gas seen in X-rays, electromagnetically slowed (much more than stars, red in the picture)
- the dark matter detected indirectly by gravitational lensing, interacts weakly and cross each other (blue in the picture)

Binary BSs: motivation

- most of the galaxies had at least one collision in its lifetime, producing other galaxies
-study the collisions of the models for galaxies (in this case, boson stars) and analyze the interactions and the final objects

Binary BSs: overview of the equations

- Lagrangian of a complex scalar field in a curved background (geometric units G=c=1)

$$\mathcal{L} = - R/(16\,\pi) \;+\; [g^{ab}\, D_a\varphi^*\, D_b\varphi + m^2\, |\varphi|^2/2\,]$$

R : Ricci scalar
g_{ab} : spacetime metric
φ, φ^* : scalar field and its conjugate complex
m : mass of the scalar field

Binary BSs: overview of the equations

- The Einstein-Klein-Gordon equations are obtained by varying the action with respect to g_{ab} and φ

  - EE with a real stress-energy tensor (quadratic)
  - KG : covariant wave equation with massive term

$$R_{ab} = 8\pi \, (T_{ab} - g_{ab} \, T/2)$$

$$T_{ab} = [D_a\varphi \, D_b\varphi^* + D_b\varphi \, D_a\varphi^* - g_{ab} \, (D^c\varphi \, D_c\varphi^* + m^2 \, |\varphi|^2) \,]/2$$

$$g^{ab} \, D_a \, D_b \, \varphi = m^2 \, \varphi$$

II.Binary BS: ID for a single BS

1) static spherically symmetric spacetime in isotropic coordinates

$$ds^2 = - \alpha^2 dt^2 + \Psi^4 (dr^2 + r^2 d\Omega^2)$$

2) harmonic time dependence of the complex scalar field

$$\varphi = \varphi_0(r) e^{-i\omega t}$$

3) maximal slicing condition

$$trK = \partial_t trK = 0$$

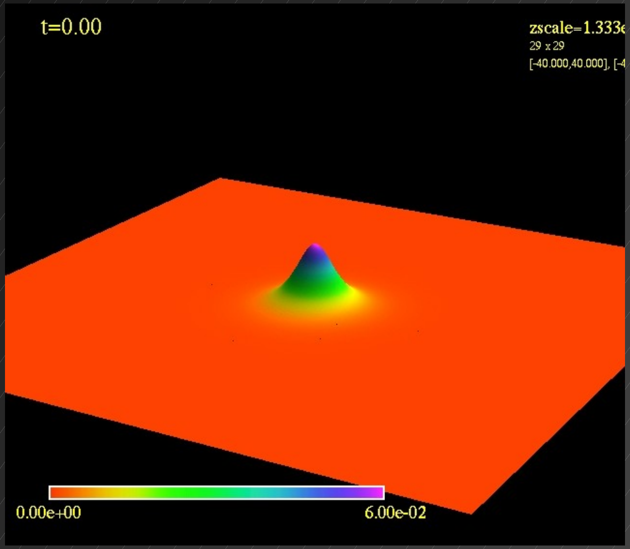
II. Binary BS: ID for a single BS

- Substitute previous ansatzs in EKG

  → set of ODE's, can be solved for a given $\varphi_0(r=0)$

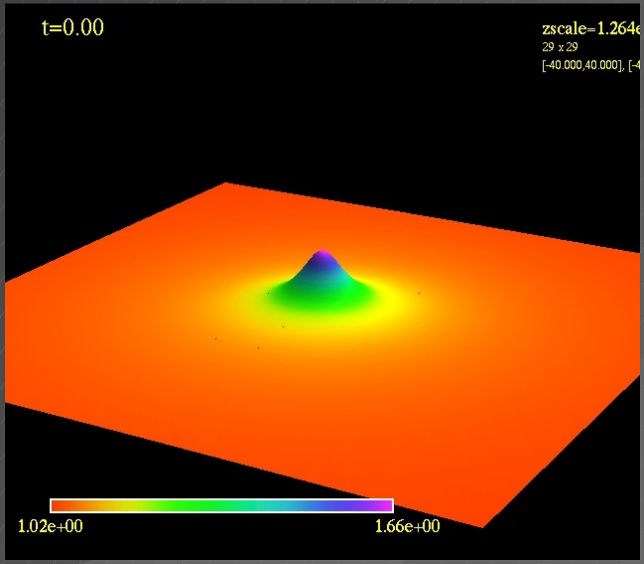
  → eigenvalue problem for $\{\omega : \alpha(r), \Psi(r), \phi_0(r)\}$

- stable configurations for $M_{max} \leq 0.633/m$



φ_0

g_{xx}

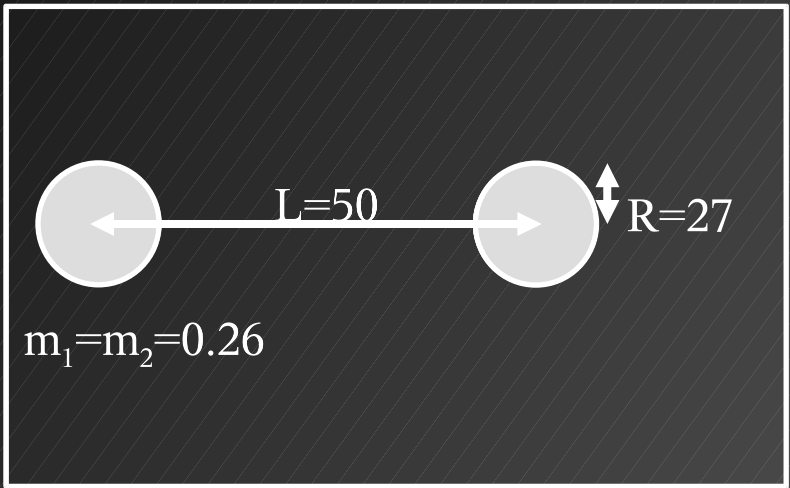


II. Binary BS: some results

- Superposition of two single boson stars

$$\varphi = \varphi_1(r - r_1)\, e^{-i\omega t} + \varphi_2(r - r_2)\, e^{-i(\varepsilon\omega t+\delta)}$$

$\varepsilon = \pm 1$: boson/antiboson
δ : phase difference



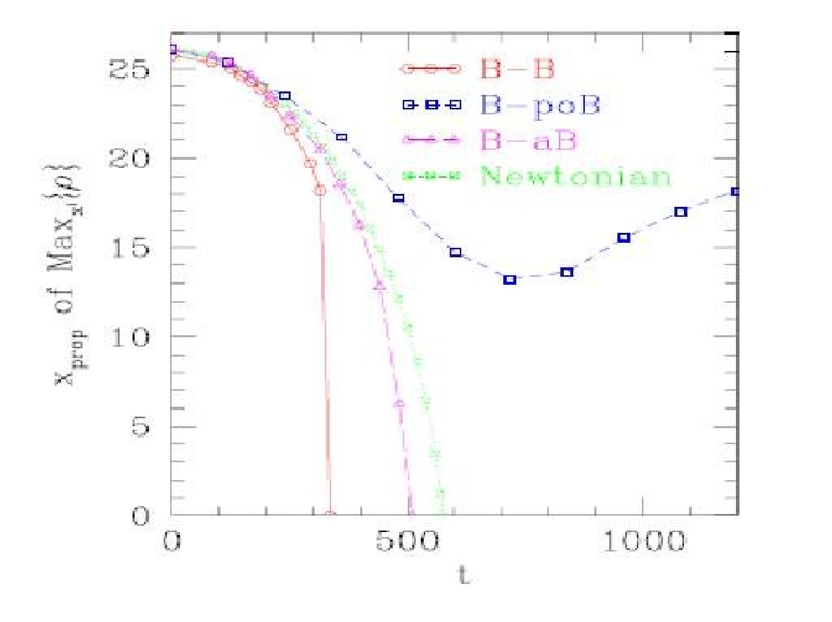
Configurations

- Boson/boson pair : $\varepsilon = +1, \delta = 0$
- Boson/antiboson pair : $\varepsilon = -1, \delta = 0$
- Boson/boson in op. of phase pair : $\varepsilon = +1, \delta = \pi/2$

- Movie reminder!!

II. Binary BS: some results

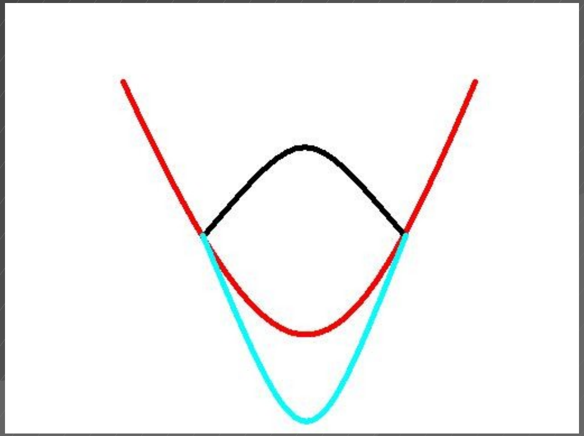
- It can be explained with a simple energy argument



$$\tau = \tau_1 + \tau_2 + \Delta_0 * \cos[(1-\varepsilon)\,\omega t + \delta)$$

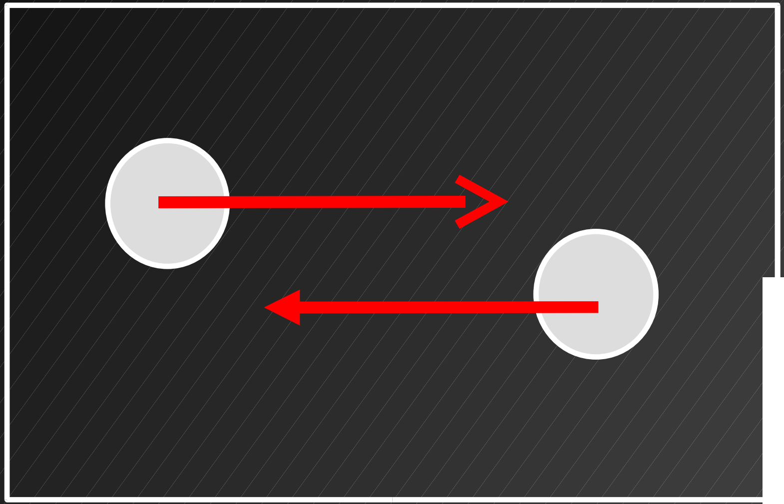
$$\tau_{b\text{-}b} = \tau_1 + \tau_2 + \Delta_0$$

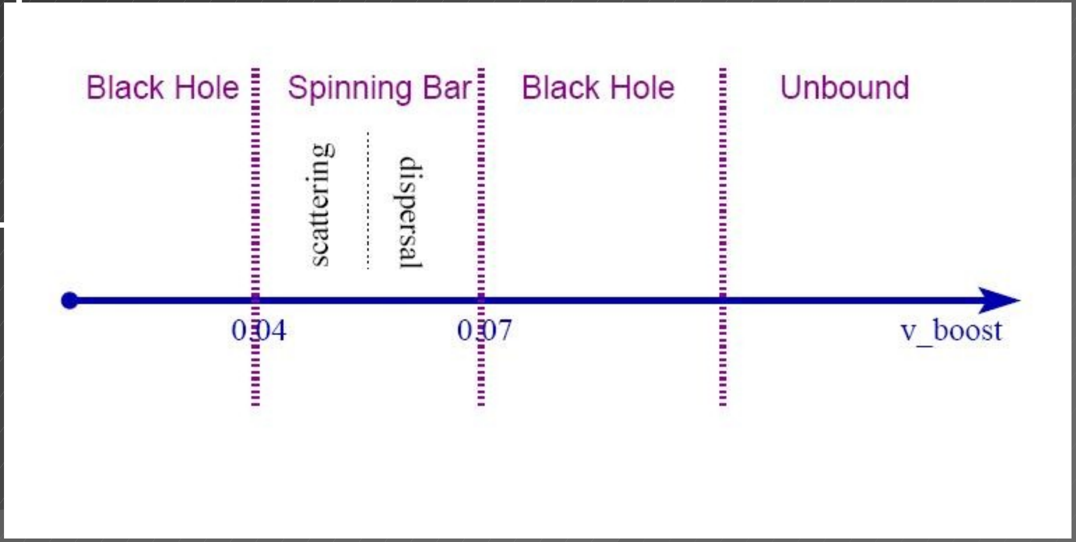
$$\tau_{b\text{-}opb} = \tau_1 + \tau_2 - \Delta_0$$



II. Binary BS: some results

- head-on with a constant parameter impact but changing the velocity (movie)





- Movie reminder!!

II. Binary Neutron Stars

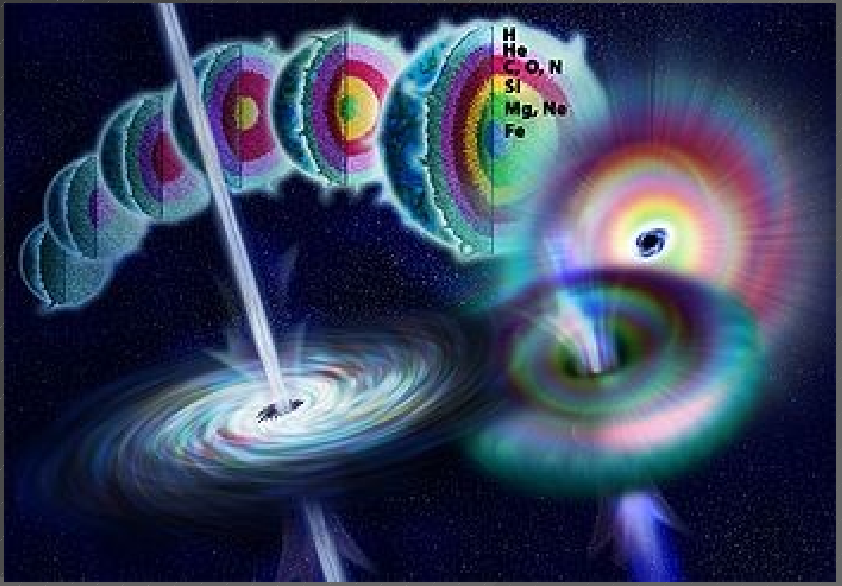
- hot EOS and production of GRBs & GWs
- overview of the equations
- differences with the unmagnetized case

Binary NSs: motivation

-- sources of gravitational waves (ie, not so strong but more frequent than the black holes)

- NS have large magnetic fields (10^{12} G) : the (short) Gamma Ray burst seems to be produced by extracting energy from the black holes

-the radiation give information about the equation of state of hot neutron star.



Binary NSs : overview of the equation

- Maxwell equations for the EM fields

$\nabla_a F^{ab} = -J^b$ F^{ab} : Faraday tensor

$\nabla_a {}^*F^{ab} = 0$ J^b : current 4-vector

- Einstein equations for the gravity

$G_{ab} = 8 \pi T_{ab}$ G_{ab} : Einstein tensor

- Hydrodynamic equations for the (ideal) fluid

$\nabla_a T^{ab} = 0$ T^{ab} : stress-energy tensor (ideal fluid + Maxwell)

$$T_{ab} = [\rho(1+\varepsilon) + P]u_a u_b + P g_{ab} + F_{ac} F^c{}_b - (F_{cd}F^{cd})g_{ab}/4$$

Binary NSs : overview of the equation

- ionized plasma behaves almos like a perfect conductor
  ideal MHD limit ($\sigma \rightarrow \infty$)

$$\nabla_a(\rho\, u^a) = 0 \qquad \nabla_a T^{ab} = 0 \qquad \nabla_a {}^*F^{ab} = 0$$

$$T_{ab} = [\rho\,(1 + \varepsilon) + p + b_c b^c]\, u_a\, u_b + [p + b_c b^c/2]\, g_{ab} - b_a b_b$$

$$p=p(\rho,\varepsilon)$$

ρ: rest mass density, ε: internal energy, p: pressure

u_a :four-velocity of the fluid

b_a: magnetic field (measured in the comoving frame)

Binary NSs : overview of the code

- Some technical details of the code

* High-Resolution Shock Capturing (HRSC) methods
  - PPM reconstruction (more accurate results)
  - HLLE flux formulae (no characteristic decomposition needed)

* Low density (atmosphere) in all the domain, set to 10^{-8} (no influence on the dynamics)
* Outflow boundary conditions

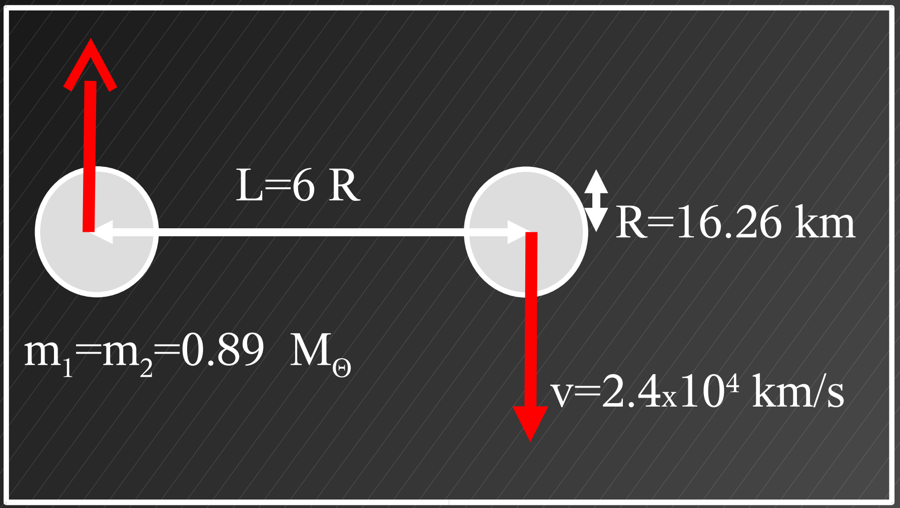
* Equation Of State (EOS)

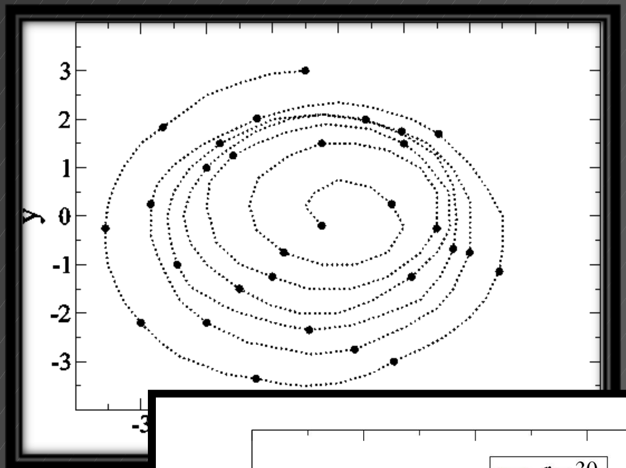
- Ideal gas EOS $p = (\Gamma-1)\,\rho\,\varepsilon$ for evolution ($\Gamma=2$)
- polytropic EOS $p = \kappa\,\rho^{\Gamma}$ for the initial data ($\kappa=1$, $\Gamma=2$)

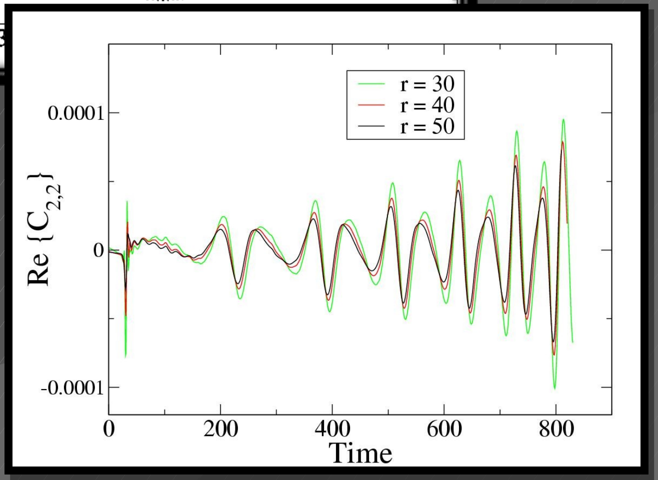
Binary NSs : some results

- Binary NS forming a black hole at the merger

  - initial data obtained by superposition of boosted NS
  - roughly 7 orbits before merger



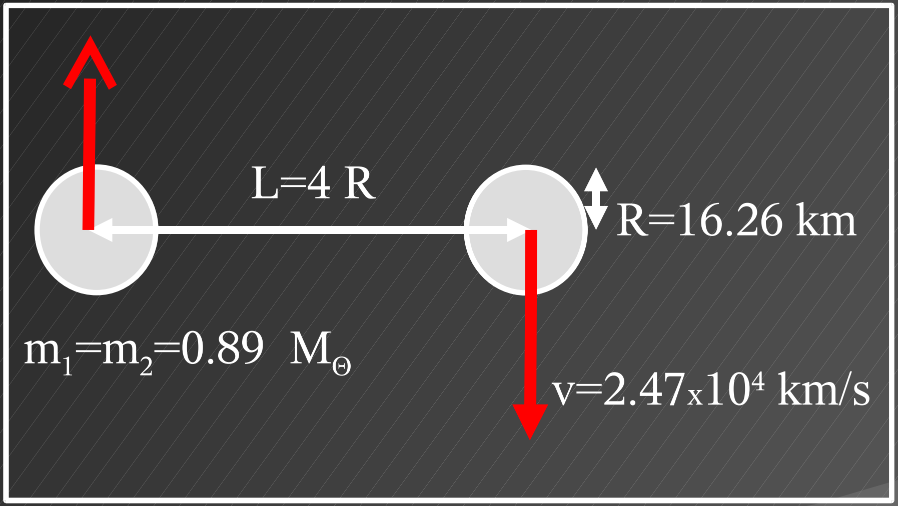




Binary NSs : some results

- Binary NS merge into a Differentially Rotating NS collapsing to a BH at late times (without magnetic fields)

 - observed magnetic fields in NS from 10^{12}- 10^{16} (magnetars)
 - differences in the simulations coming from B (ie, waveforms)??
 - initial data without magnetic field , short separation



Binary NSs : some results

- Stages of the evolution in the non-magnetized case

Stage 1. NS merge forming an unstable bar

Stage 2. The unstable bar expels matter forming an hypermassive (ie, supported by rotation) differentially rotating NS

Stage 3. The DRNS losses angular momentum and energy, collapsing to a BH

- Movie reminder!!

Binary NSs : some results

- Stages of the evolution in the magnetized case

Stage 1. NS merge forming an unstable bar

Act1. Magnetic repulsion delays the merger

Act2. Rapid growth of the magnetic strength due to Kelvin-Helmotz instability
(shear energy in the interface→ magnetic energy)

- Movie reminder!!

Binary NSs : some results

- Stages of the evolution in the magnetized case

Stage 2. The unstable bar expels matter forming an hypermassive (ie, supported by rotation) DRNS

Act1. Differential rotation winds up the magnetic field, producing and amplifying a toroidal magnetic component

Act2. Tayler's instabilities

A) induces a m=1 mode which offsets the center of mass of the star with respect to the origin

B) magnetic bouyancy instability which sheds fluid in the low density regions

Binary NSs : some results

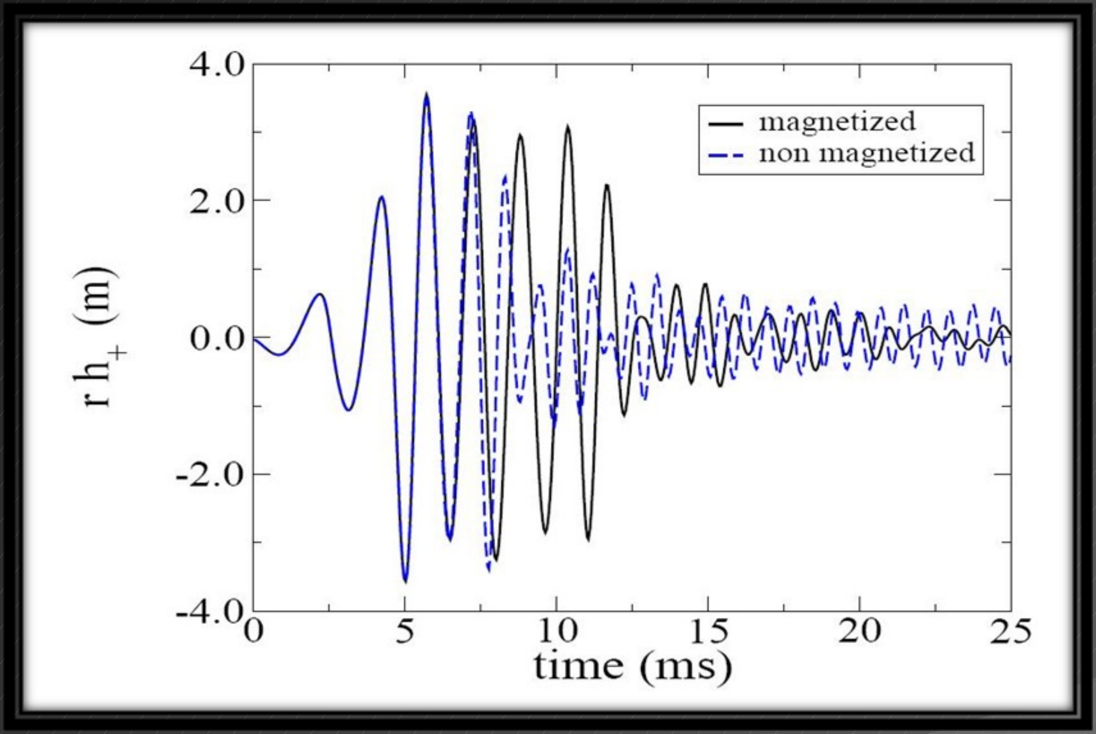
- Stages of the evolution in the magnetized case

Stage 3. The DRNS losses angular momentum and energy, collapsing to a BH

Act1. Growth on the field due to the compression of the field lines

Binary NSs : some results

- These differences in the dynamics are significant and measurable in the gravitational radiation



Summary

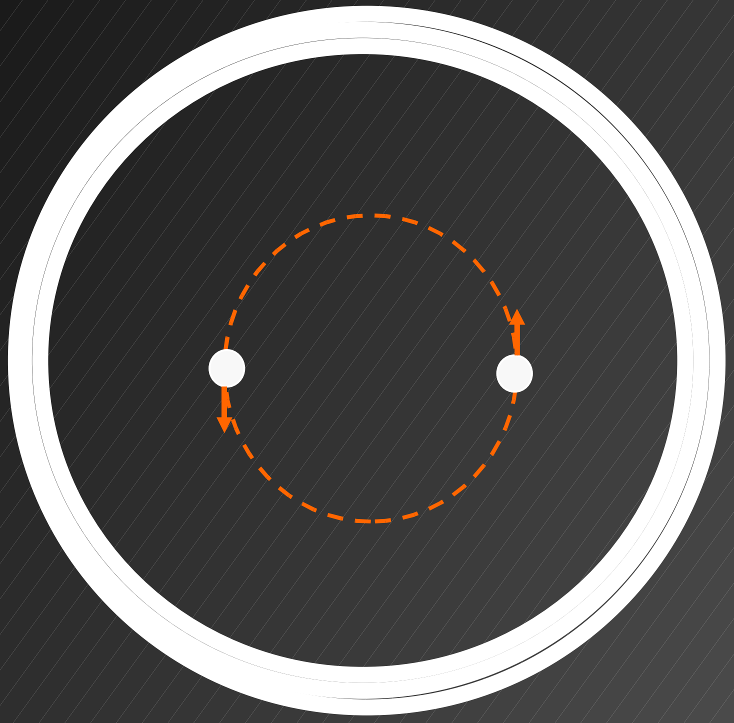
- The waveforms from the binary black holes are being computed, although the parameter space is large (masses and spin)
    * why the supermassive black holes does not escape from the center of galaxies?

-The boson stars are interesting candidates for the dark matter
    * do they form a stable single object after the merger?

-The first stepts in binary neutron star with full GR are done, but still missing:
    * realistic equation of state
    * more resolution to get accurate results (turbulence!)
    * add the transport of neutrinos generated at the merger

I.Binary BHs: extracting energy with electromagnetic fields

-what happens if there is a circumvalance magnetized disk during the merger?



-First approximation: the region inside the disk is vacuum

- add the Maxwell equations to evolve the EM fields without sources

- add the contribution of the em fields to the stress energy tensor

- Correlations between gravitational radiation and the em radiation during the merger

Movie (work in progress)