# Electromagnetic effects from binary Black Hole systems:

## correlations between GW and EM spectrum

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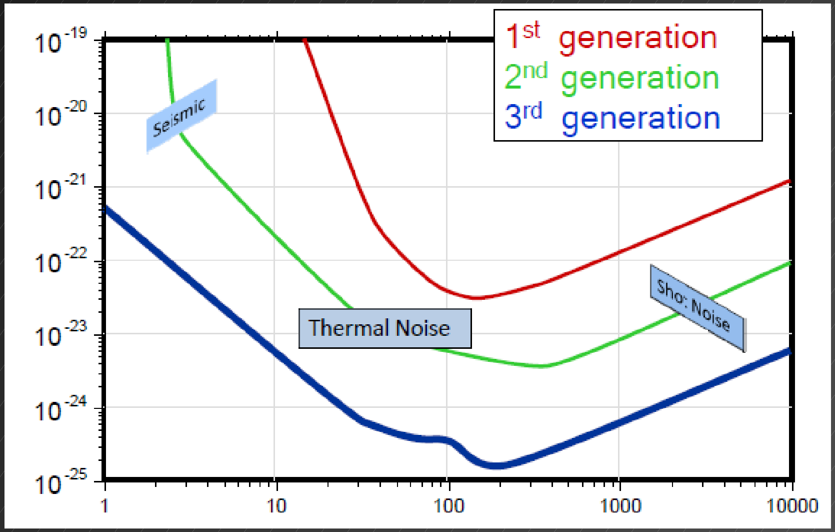
# Overview

- Motivation
  - correlations between the EM and GW spectrum
  - study the effects of the BBH mergers on the EM fields
- The evolution system
  - the Einstein-Maxwell equations
  - code implementations: GH and BSSN
- The binary BH in electrovacuum
  - the asymptotic state: Wald's solution
  - the non-spinning case; membrane paradigm model
  - the spinning case and the waveform corrrelations
- The next step; the force-free approximation
  - the single black hole case
  - preliminary results

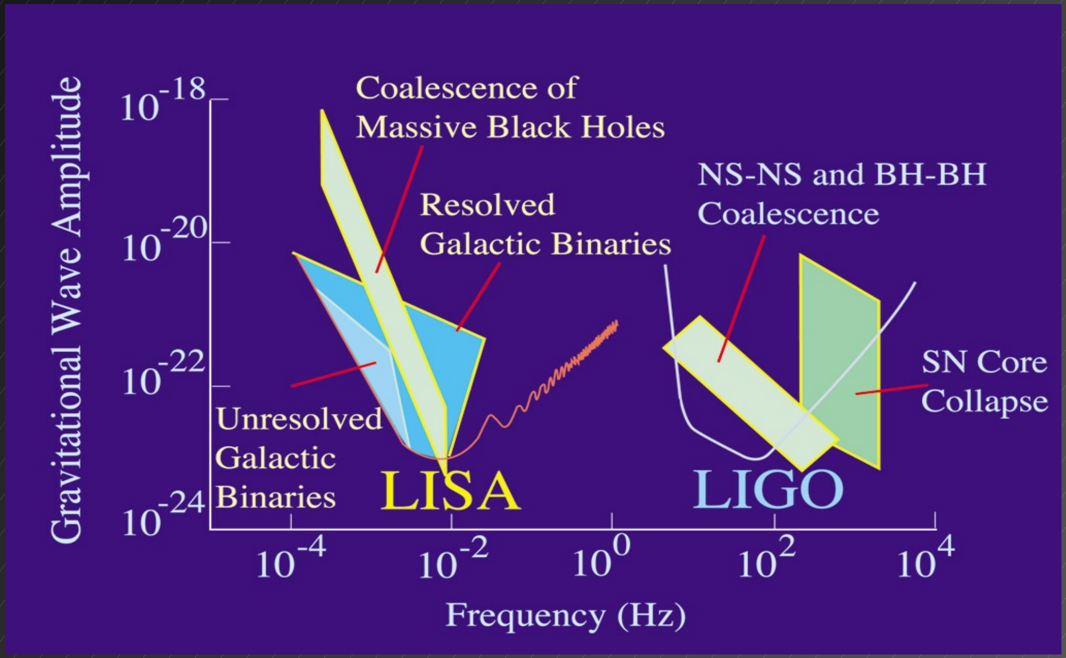
# I. Motivation:ground GW astronomy

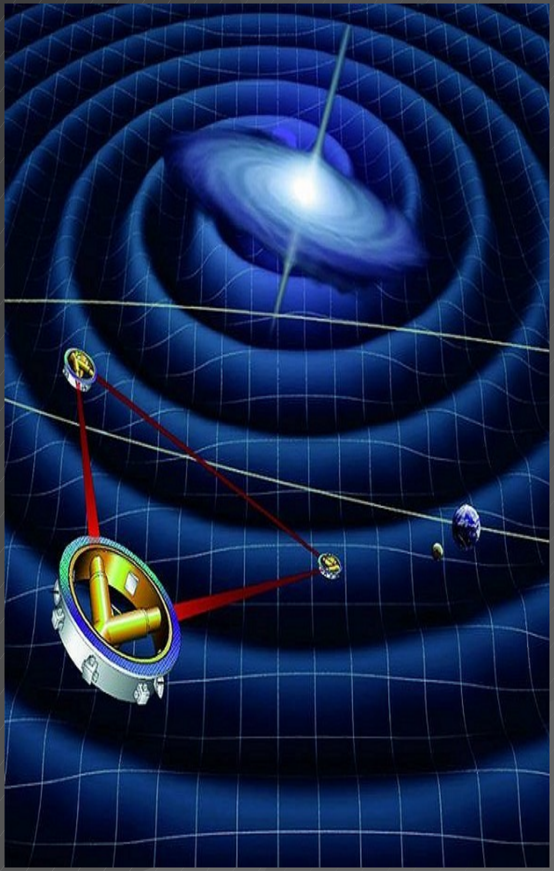
- the first generation of ground detectors of GW is already operating -LIGO-, second is being build, third is in project (ET)




# I. Motivation: space GW astronomy

- space detector LISA in project
- use the pulsars as detectors



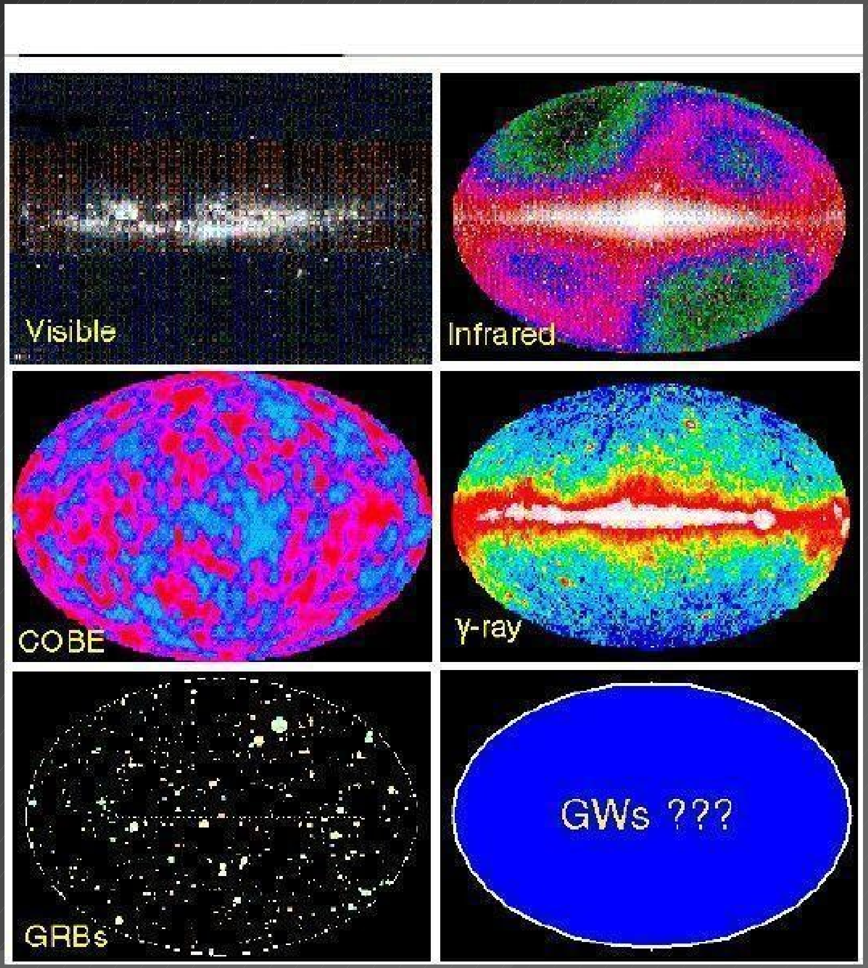



# I. Motivation: GW versus EM

- the GW astronomy will open a new window to see the universe

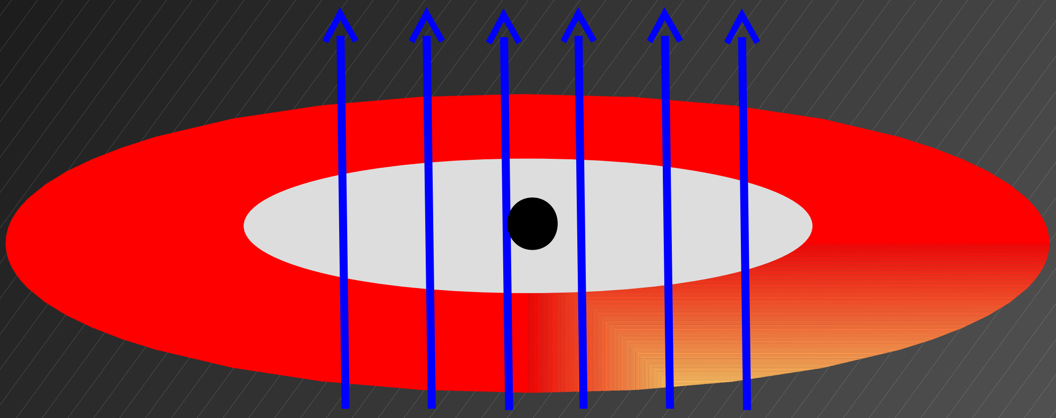
-most of the systems emitting GW waves also have EM bright

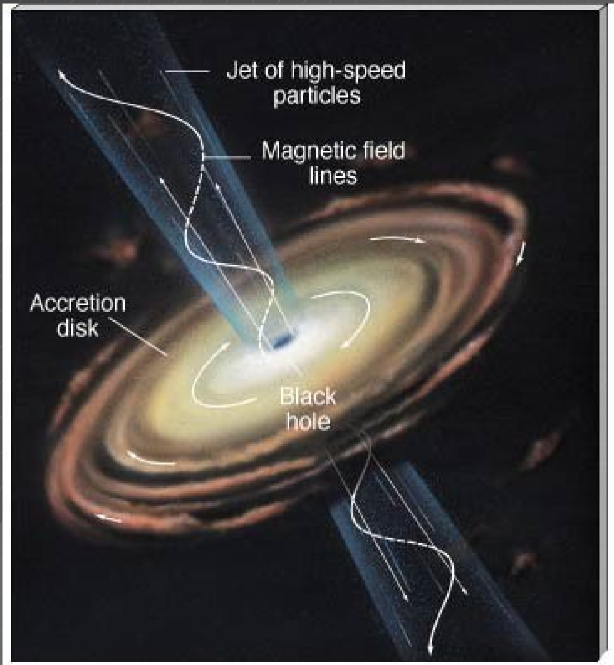
- opportunity to study simultaneously several bands and correlate the different spectrums



# I. Motivation : magnetic fields and BHs

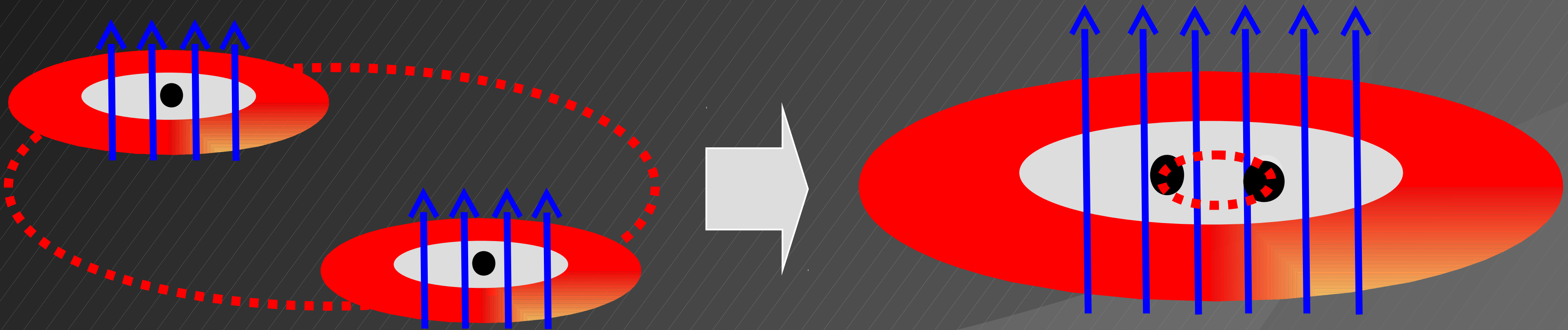
-observations indicate the presence of supermassive BHs in the center of galaxies, surrounded by gas and an accretion disk
- in the Active Galactic Nuclei (AGN), the BHs are surrounded by a disc of matter likely magnetized. The jets allows to bound the magnetic fields ($B_0 < 10^4$-$10^6$ Gauss) near the BH (Massi & Kaufman, A&A 477) .





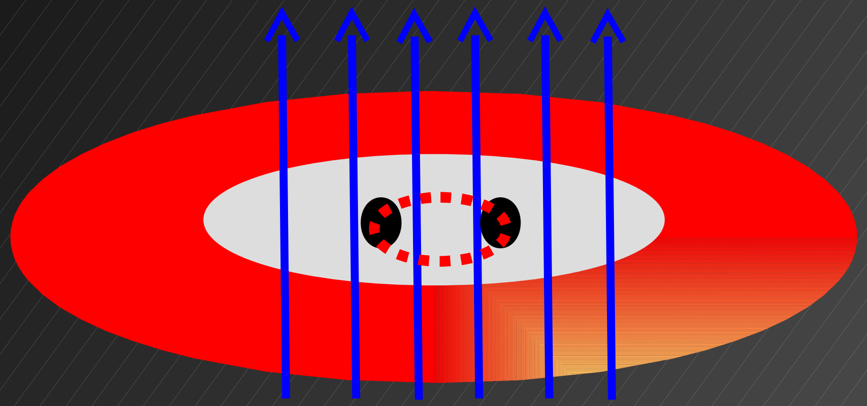
# I. Motivation : merger of galaxies

- the galaxies has undergone some mergers
- during the merger, the binary BH hollows the surrounding gas while their orbit shrinks, forming a circumbinary disk (Milosavljevic & Phinney, Astrophys. J. 622)
- eventually, the dynamics of the binary is dominated by GW

# I. Motivation : merger of galaxies

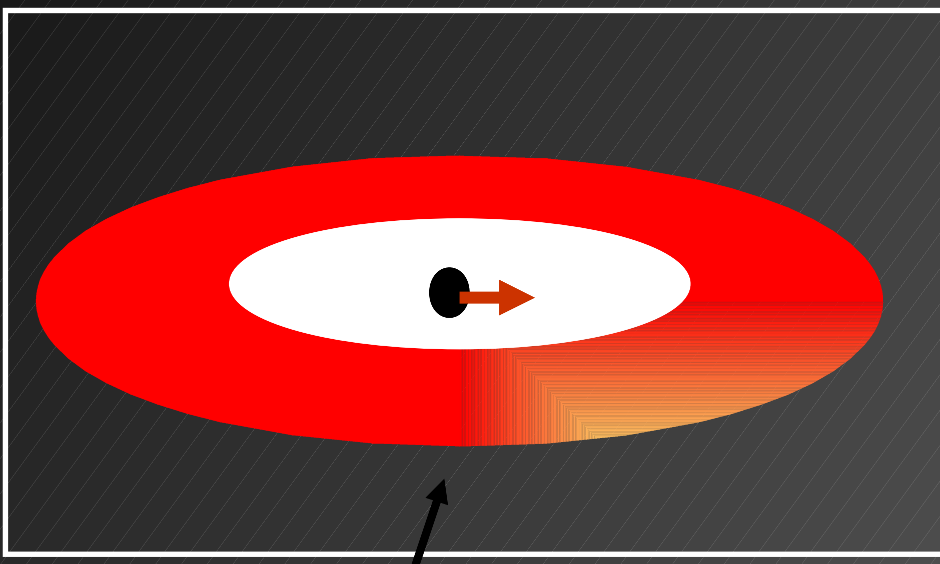
- the luminosity of the disk is modified by the binary BH dynamics
- the merger can enhanced some Blandford-Znajeck mechanism
- study the correlations between GW & EM radiation
- study systems with both bands to extract more information



- General Relativity for the evolution of the spacetime
- Maxwell equations for the evolution of the EM fields
- Hydrodynamics for the evolution of the disk
- Radiation processes due to the accretion, disk dynamic..

# I. Motivation : post-merger effects

- due to the merger processes, the BH:
  * losses few percent of the mass due to GW radiation
  * boosted with $v_{kick} \approx 100\text{-}3000$ Km/s
- the disk's dynamics is modified: perturbed disk get shocked (Zanotti,Rezzolla,DelZanna,CP ,MNRAS 2010 ) MOVIE!!

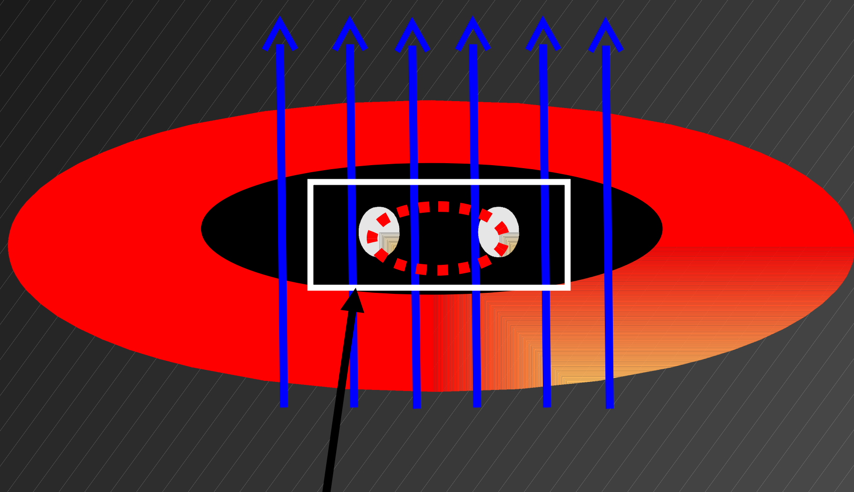


- all the domain with the final BH and the disk

- ~~General Relativity for the evolution of the spacetime~~
- ~~Maxwell equations for the evolution of the EM fields~~
- Hydrodynamics for the evolution of the disk
- ~~Radiation processes due to the accretion,disk dynamic…~~

# I. Motivation : pre-merger effects

- before/during the merger (CP et al. , PRL 2009):
 * study the effects of the binary BHs dynamics in the EM fields
 * the EM radiation may modify the disk structure, changing again its luminosity which can be observable
 * accretion of fossilized gas can trigger BZ type mechanisms



- sub-domain with the BHs, excluding the disk

- General Relativity for the evolution of the spacetime
- Maxwell equations for the evolution of the EM fields
- ~~Hydrodynamics for the evolution of the disk~~
- ~~Radiation processes due to the accretion, disk dynamic…~~

# II. The Einstein-Maxwell system

• Einstein equations with the EM stress energy tensor

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

$$T_{ab} = F_{ac}\,F^{c}{}_{b} - (F^{cd}F_{cd})g_{ab}/4$$

• Extended Maxwell equations with constraint dampings, written for the fields (E,B,Φ,Ψ)

$\nabla_a\,(F^{ab} + g^{ab}\,\Psi) = -I^b + \kappa\,n^b\,\Psi$ $F^{ab}$ : Maxwell tensor

$\nabla_a\,({}^*F^{ab} + g^{ab}\,\Phi) = \kappa\,n^a\,\Phi$ $I^b$ : current 4-vector

$\nabla_a\,I^a = 0$ $I^a = n^a\,q + J^a$ q : charge, $J^a$: 3-current

# II. The numerical code

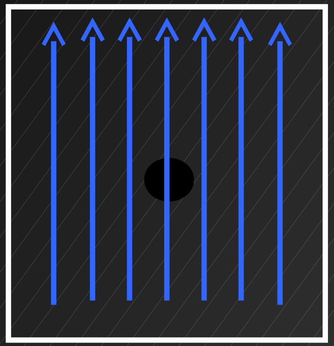
- Many scales in the problem → parallelization and AMR

- Method of Lines for the evolution
  - * 3rd-4th order RK for the time integration
  - * 4th order space discretization

| | GH | BSSN |
|---|---|---|
| Infrastructure | Had | Cactus |
| Singularity | Excision | Puncture approach |
| Gauge | Harmonic | 1+log lapse<br>Gamma freezing |

# III. Asymptotic state: Wald's solution

- study first the asymptotic stationary state, after the merger



- Exact solution (Wald 1974) for a BH immersed in a external magnetic field aligned with the spin (test field, valid in this case $M = 10^8\, M_\Theta$, $B = 10^4$ G)

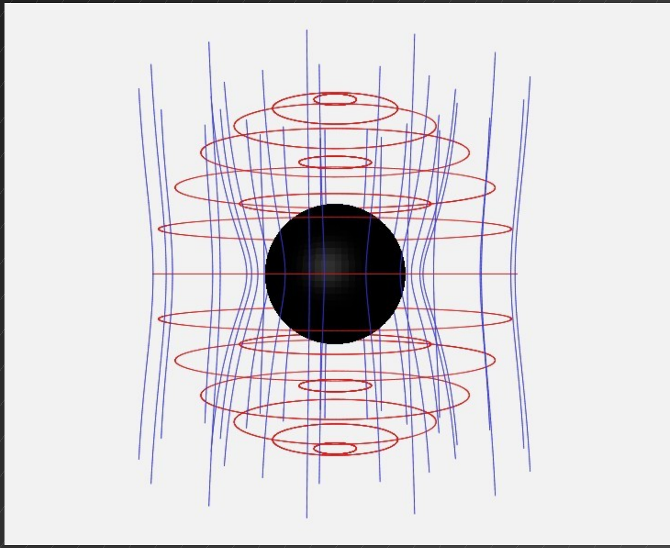
$$F = \tfrac{1}{2} B_0 (d\Psi + 2J/M\, d\eta)$$

$\Psi$ axial KV, $\eta$ timelike KV

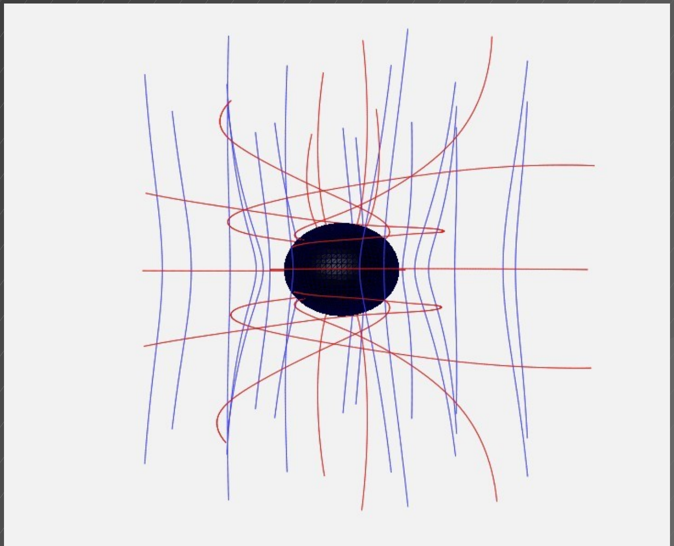
- Near the black holes, the magnetic fields from the disk, in the stationary state, tend to Wald's solution (King, Lasota & Kundt 1975)

# III. Asymptotic state: evolution

- consider a domain close to the BH without the disk
- set the magnetic field from the 'far away' disk by:
    * an initial EM field $\mathbf{B} \approx B_0\, \check{z}$ , $\mathbf{E} = 0$
    * consistent boundary conditions
- evolve the Einstein-Maxwell system until the stationary state



non spinning

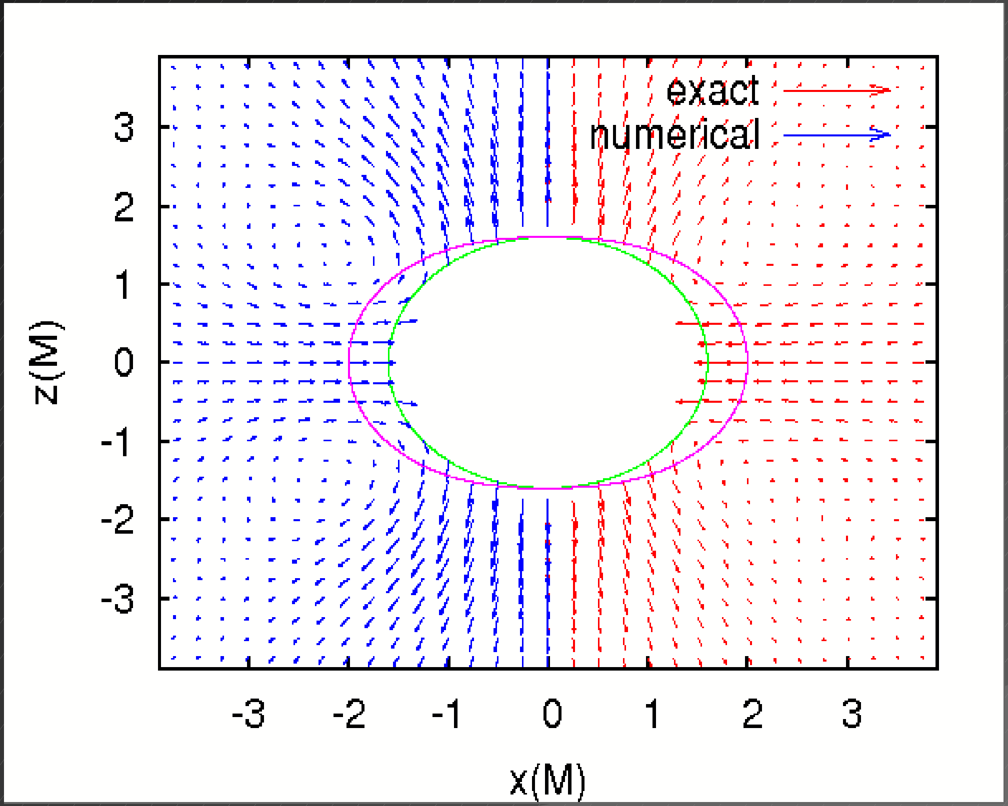


spin a=0.7

# III. Asymptotic state: evolution

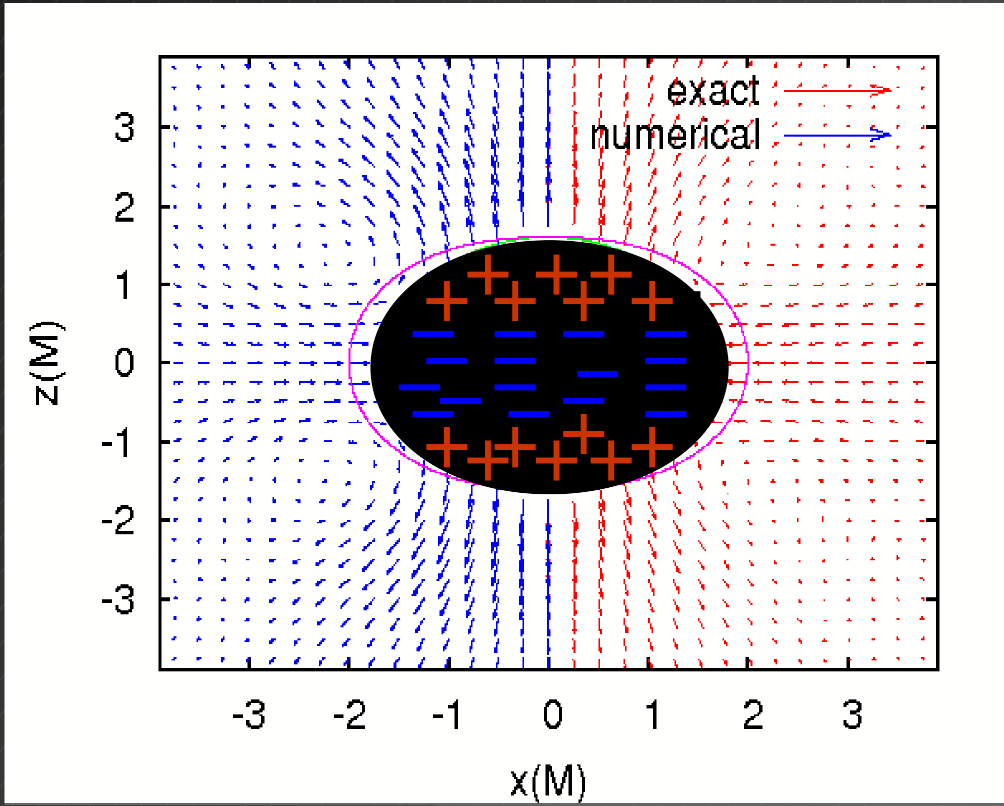
- fixed spacetime: Kerr in Kerr-Schild coordinates

electric field for spinning case (a=0.7)



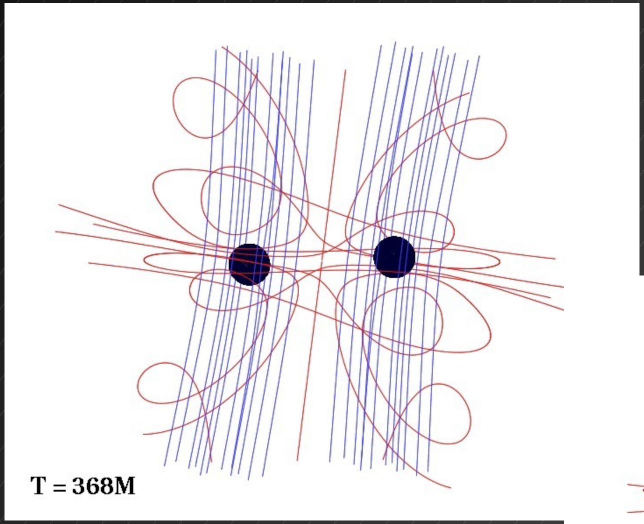
# III. Asymptotic state: evolution

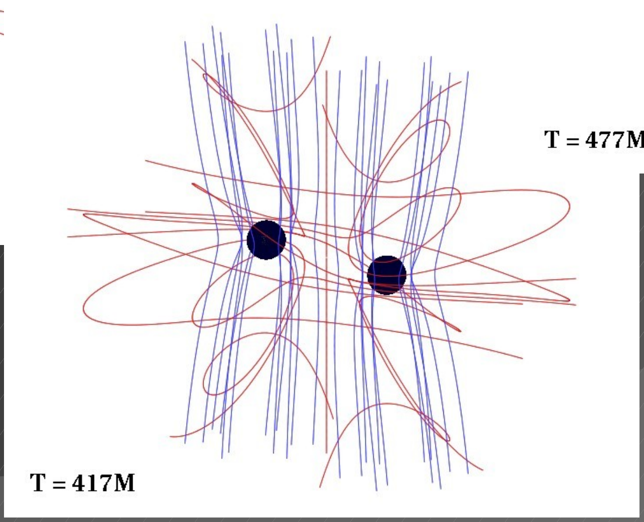
- membrane paradigm (Thorne,Price,MacDonald 1986): density charge endowed to the Apparent Horizon

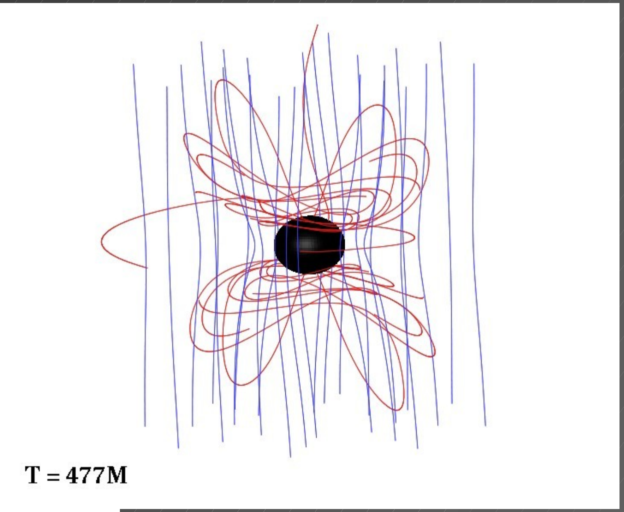


# IV. Binary BHs (non-spining)

- study the last orbits and merger of the binary black holes
- set the initial data with a binary BHs in quasi-circular orbits and add the magnetic fields like before



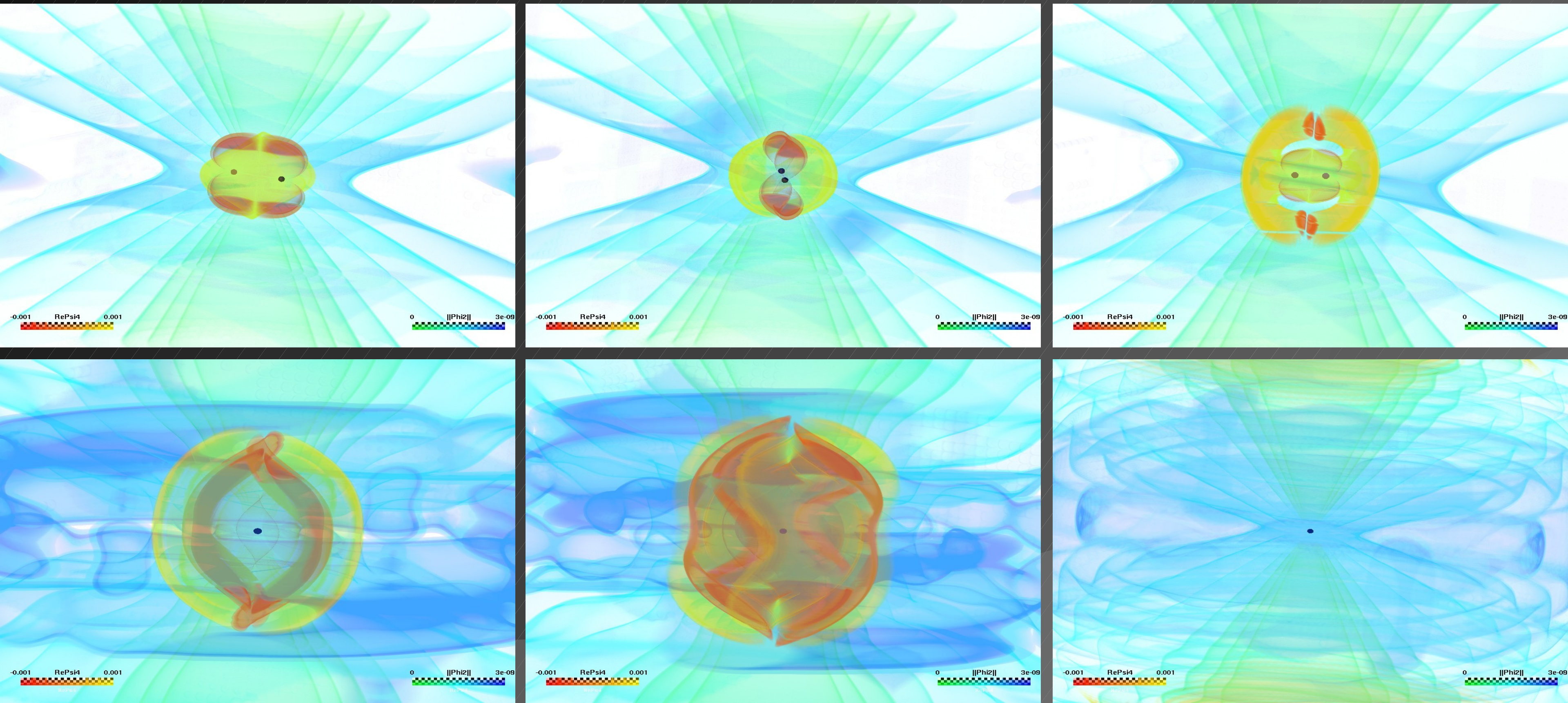



# IV. Binary BHs (non-spining)

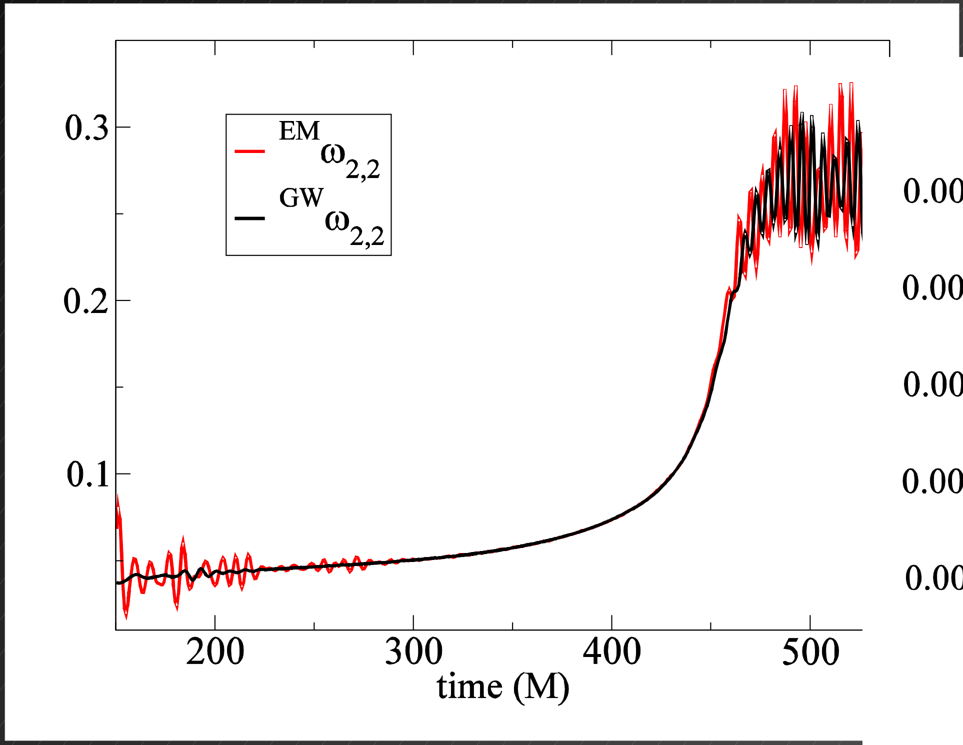
- compute the GW & EM radiations via Newman-Penrose scalars

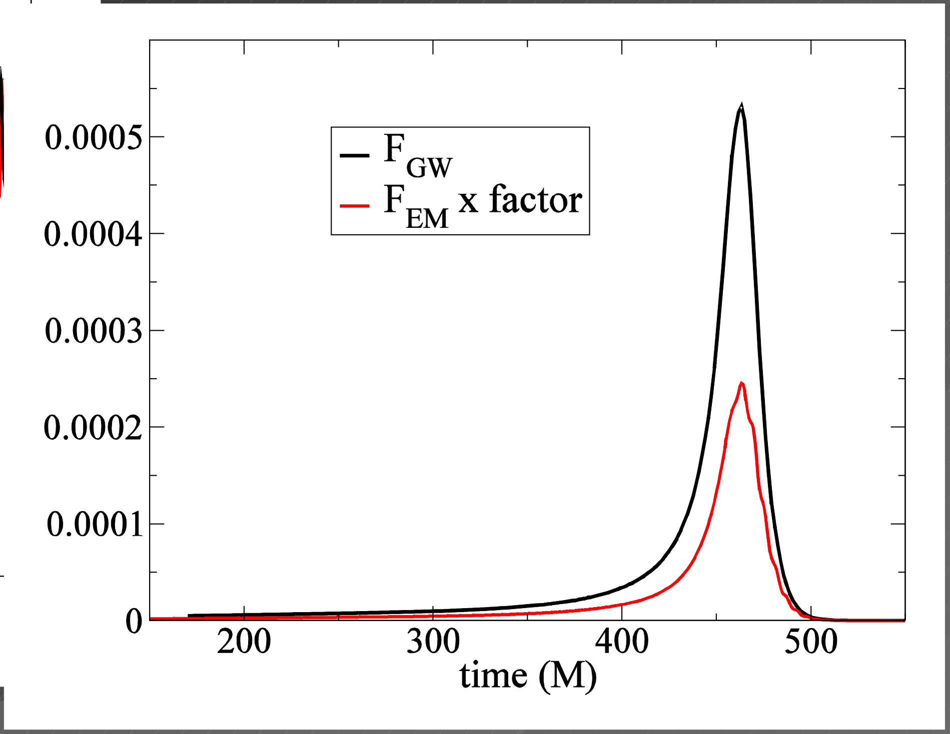
$\Psi_4 = R_{abcd}\ k^a\ {}^*m^b\ k^c\ {}^*m^d$ $\Phi_2 = F_{ab}\ k^a\ {}^*m^b$ MOVIE!!



# IV. Binary BHs (non spinning)

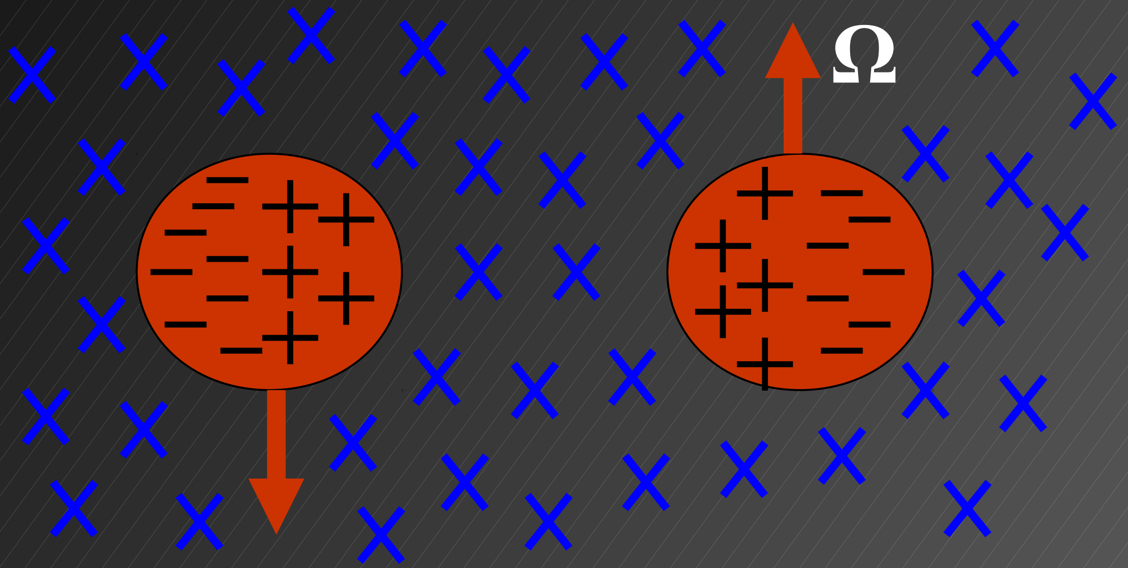
- mode decomposition shows a quadrupolar nature for both the GW and EM modes
- the modes have the same frequency and radiated energy



# IV. Binary BHs (non spinning)

- simple model based on the membrane paradigm



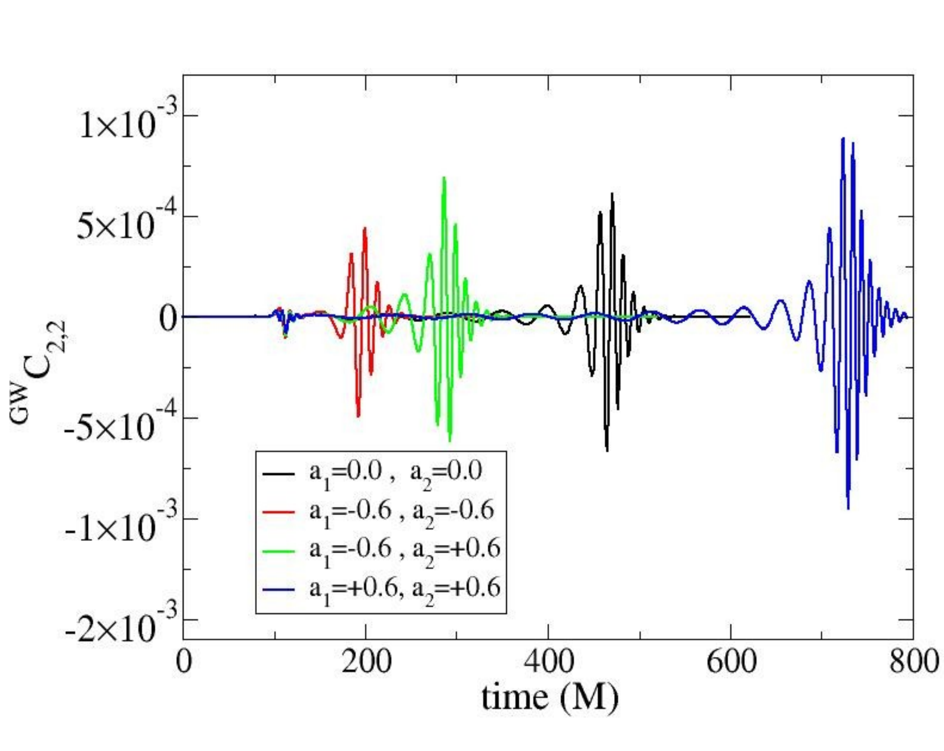

* there is a induced charge separation → electric quadrupole

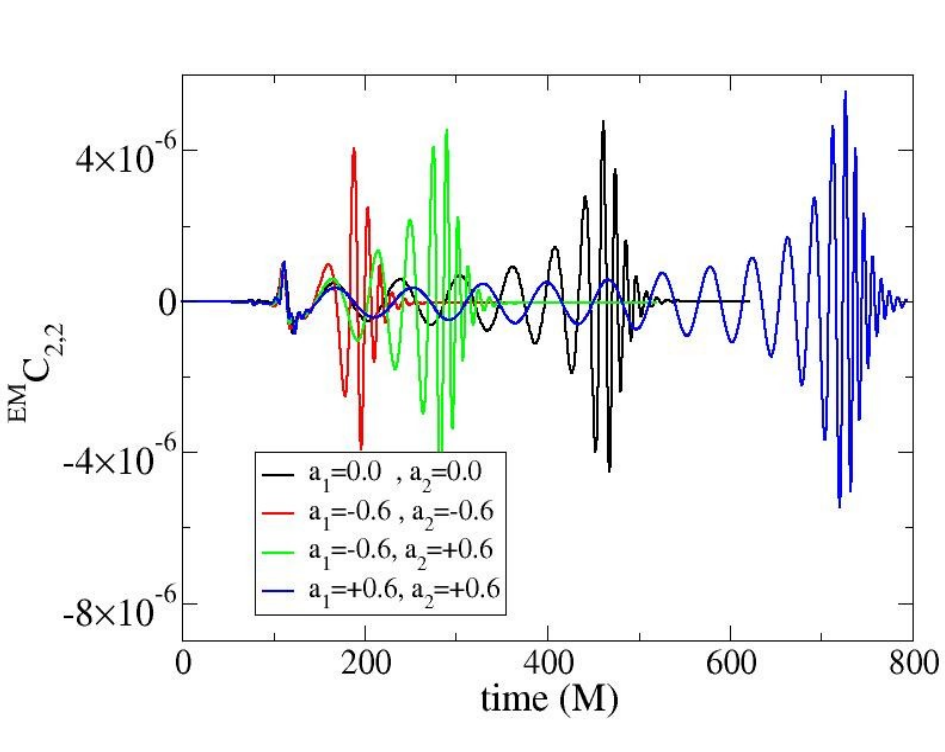
$$E,B \sim \sin^n \theta \cdot \cos(2\,\Omega\, t)$$

# IV. Binary BHs (spinning!!)

- consider several spinning-cases

1) $a_1=0, a_2=0$
2) $a_1=-0.6, a_2=-0.6$
3) $a_1=-0.6, a_2=+0.6$
4) $a_1=+0.6, a_2=+0.6$



# IV. Summary Binary BHs + EV

- the EM radiation mimics the GW one!
- the efficency of the EM radiation depends strongly on the intensity of the magnetic fields

$$E^{GW} / M = 5 \times 10^{-2}$$

$$E^{EM} / M = 5 \times 10^{-15} \qquad \text{for } B = 10^4 \text{ Gauss}$$

- the energy radiated directly in EM waves seems low to modify the disk dynamics for the inferred magnetic fields
- there is no vacuum!! Enhancement of the (extraction of energy due to) Blandford-Znajeck mechanism near the merger?

# V. The Force-free approximation

- BH + magnetic field → unstable to pair production : magnetized plasma is surrounding the BHs

$$\nabla_a T^{ab} = 0 \quad \rightarrow \quad \nabla_a T^{ab}{}_{(fluid)} = -\nabla_a T^{ab}{}_{(em)} = -F^{ab} J_a$$

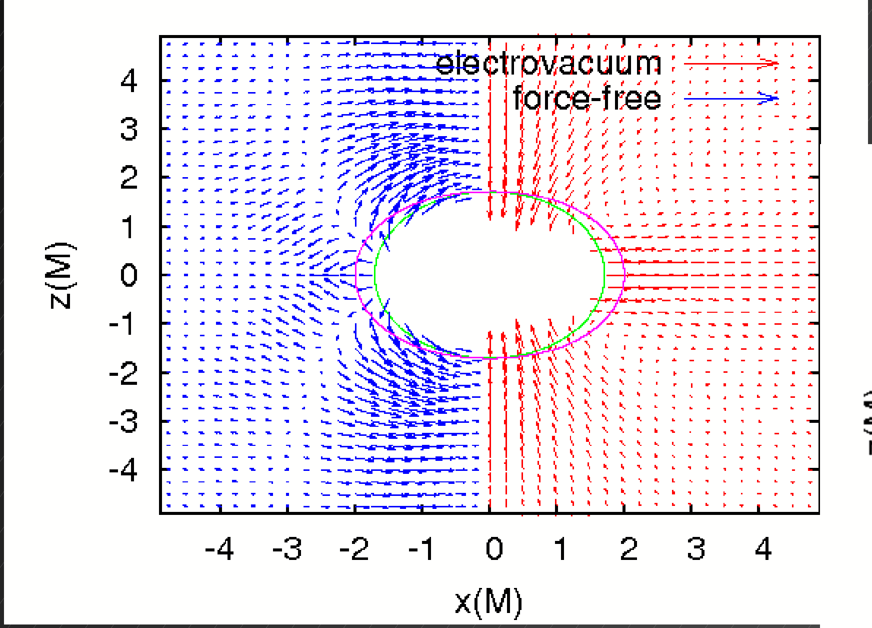
$$\text{if} \quad \rho, P \ll B^2 \quad \text{then} \quad \nabla_a T^{ab}{}_{(fluid)} \ll F^{ab} J_a \approx 0$$

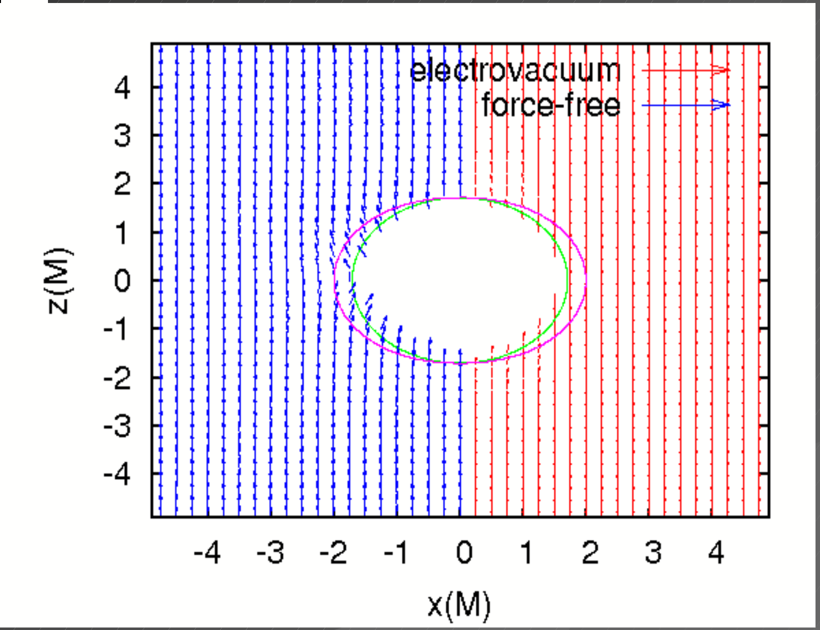
$$\mathbf{E} \cdot \mathbf{J} = 0 \quad , \quad q\,\mathbf{E} + \mathbf{J} \times \mathbf{B} = 0$$

- Fluid without fluid : the plasma only supplies charges and determines the dynamic of the EM fields, but it does not appear in the equations

# V. Single black holes

- Electric and magnetic fields for electrovacuum and force-free

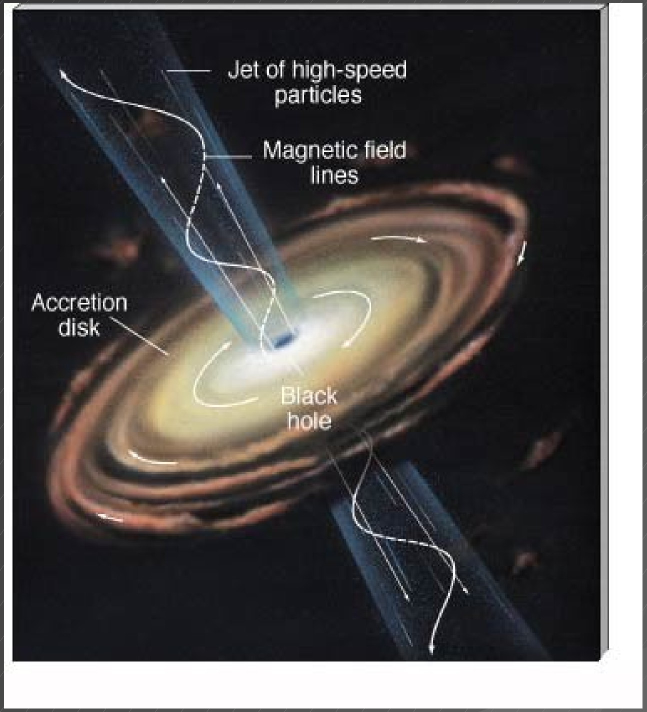


# V. Binary black holes

- The EM radiation seems to be collimated in the force-free case

MOVIES



# Summary

- we have evolved and analyzed the effects on the EM fields of the last orbits of a binary BH

-In electrovacuum (first step):
  * EM radiation profile quite tied to the BBH dynamics
  * the radiated EM energy low to modify the disk dynamics

-In force-free (more realistic):
  * Enhancement of the Blandford-Znajeck mechanism near the merger?
  * Collimation of the radiation?