Title: Binary black hole collision in a force-free environment

Date: Jun 26, 2010 11:10 AM

URL: http://pirsa.org/10060085

Abstract: In this work we investigate the electromagnetic radiation induced by a binary black hole merger when they are surrounded by a force-free environment (i.e. plasma with inertia terms negligible compared to the electromagnetic stresses). We discuss the relevance of this system for possible multimessenger astronomy with binary black holes.

Dual Jets from binary BHs

NRDA

June 26, 2010

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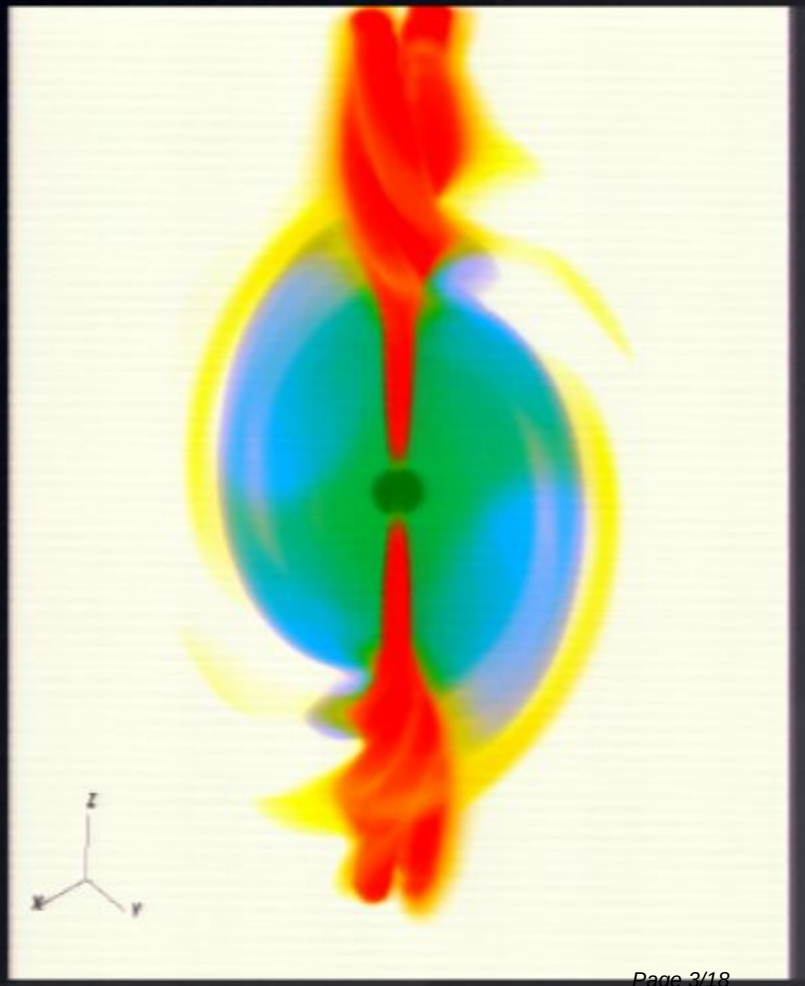
(arXiv:1005.1067 , arXiv:1006.????)

Motivation

- GW astronomy can measure very precisely the luminosity distance to the source
- EM counterpart would localize the source on the sky and redshift

- study systems emitting in both bands to extract more information

 * binary NS and mixed binaries
 * binary BH surrounded by matter



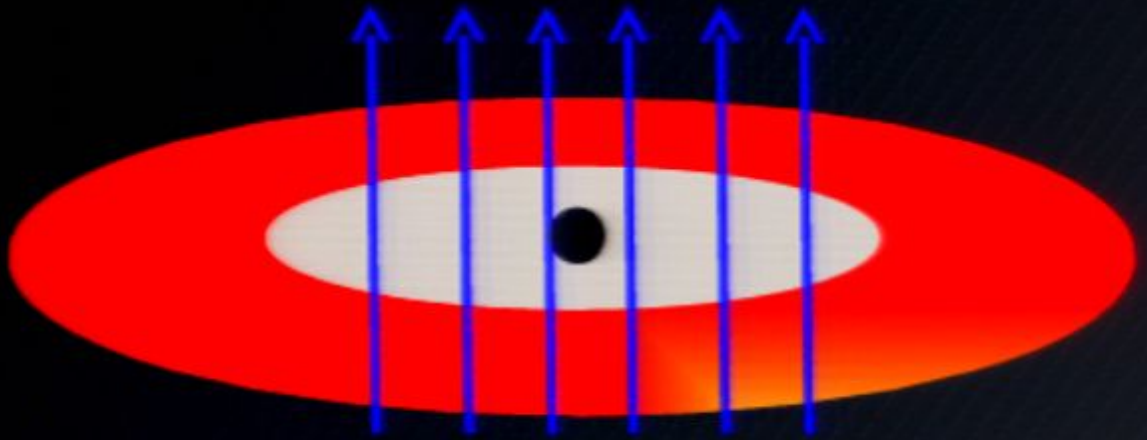
Merger of galaxies (I)

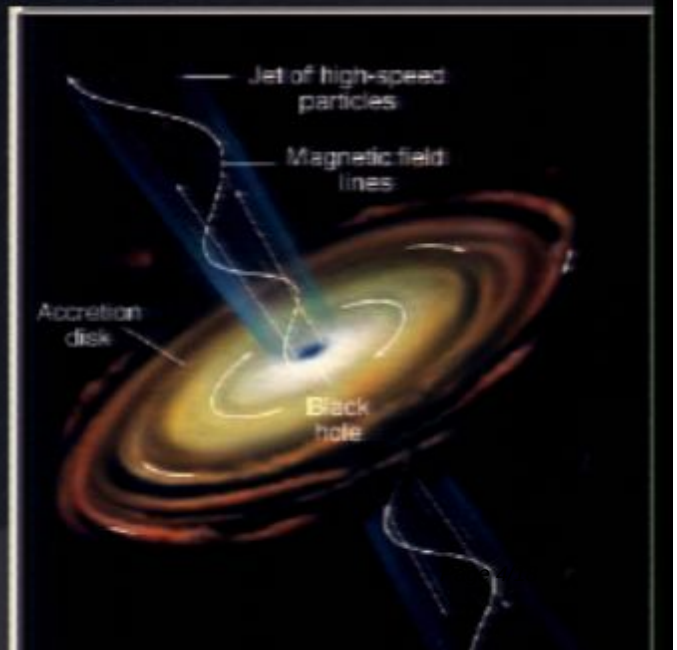
-observations indicate the presence of supermassive BHs in the center of galaxies, surrounded by gas and an accretion disk

- in the Active Galactic Nuclei (AGN), the BHs are surrounded by a disc of matter likely magnetized. For a $M=10^8 M_\Theta$

* bounded by the jets : $B_0 < 10^4$-10^6 G (near the BH)

* Eddington magnetic field : $B_0 \sim 10^5$ G



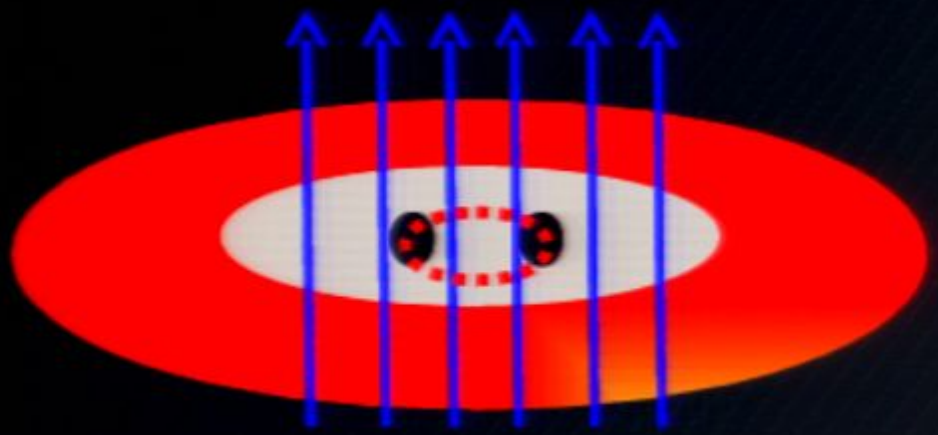


Merger of galaxies (II)

- the galaxies have undergone some mergers
- during the merger, the binary BH hollows the surrounding gas while its orbit shrinks, forming a circumbinary disk
- eventually, the dynamics of the binary decouples from the disk and is governed by GW emission

Electromagnetic Counterparts (I)

- the luminosity of the disk is modified by the binary BH dynamics
- the merger can enhance some Blandford-Znajeck mechanism
- study the correlations between GW & EM radiation

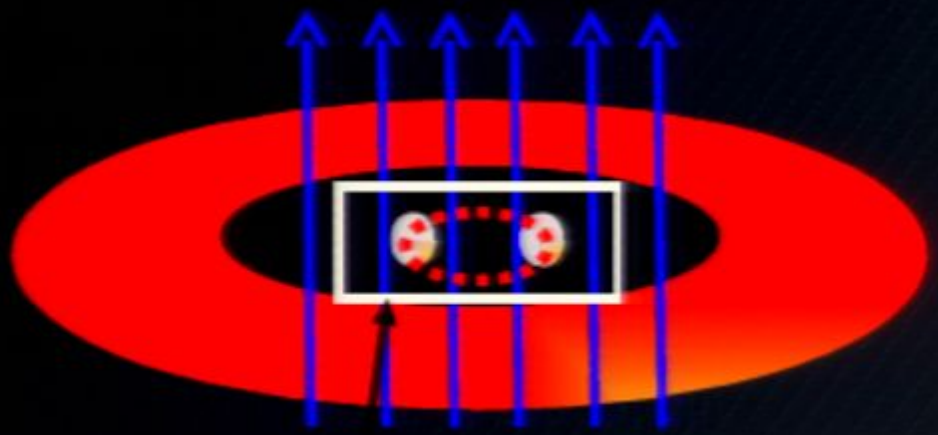


- General Relativity for the evolution of the spacetime
- Maxwell equations for the evolution of the EM fields
- Hydrodynamics for the evolution of the plasma
- Radiation processes due to the accretion, disk dynamic..

Electromagnetic Counterparts II

- after the merger :
  * study the dynamics of the disk perturbed by the final BH

- before/during the merger :
  * study the effects of the binary BHs dynamics in the EM fields



- 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
- Force-free approximation for the plasma
- ~~Radiation processes due to the accretion, disk dynamic~~…

The Einstein-Maxwell system

- Einstein equations

$$R_{ab} - R\, g_{ab}/2 = 0 \qquad R_{ab} = R_{ab}\,(\partial_{cd} g_{ab}, \partial_{c} g_{ab}, g_{ab})$$

- Maxwell equations , with F the Maxwell tensor
  I the current 4-vector

$$\nabla_a F^{ab} = -I^b \qquad F^{ab} = n^a E^b - n^b E^a + \varepsilon^{abc} B_c$$

$$\nabla_a {}^*F^{ab} = 0 \qquad \partial_t E - \nabla \times B = -J\,,\ \nabla \cdot E = q$$

$$\partial_t B + \nabla \times E = 0,\quad \nabla \cdot B = 0$$

The force-free approximation

- If B and the black hole spin are large enough (i.e.,$B \approx 0.2$ T for $M \approx 10^8 M_\odot$, $a>0.7$), the induced E will accelerate charged particle to high enough energies that will radiate photons decaying into electron-positron pairs.
- The time average of this cascade process will be a magnetosphere full of a tenuous plasma, which can support charges and currents but with negligible inertia

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

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

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

The Blandford-Znajek mechanism

- By using these conditions, assuming axisymmetry and stationarity, we can compute the electromagnetic energy flux

$$F_E = 2(B^r)^2 \Omega_F r \left(\frac{a}{2Mr} - \Omega_F\right) \sin^2\theta - B^r B^\phi \Omega_F \Delta \sin^2\theta.$$

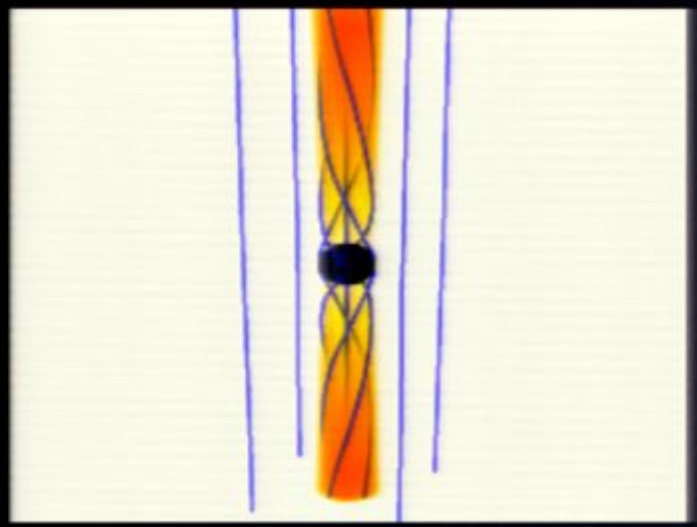
- at the AH, $\Delta=0$ and we define the rotation frequency of the BH like $\Omega_H = a/(2*M*r_H)$

$$F_E|_{r=r_H} = 2(B^r)^2 \Omega_F r_H (\Omega_H - \Omega_F) \sin^2\theta.$$

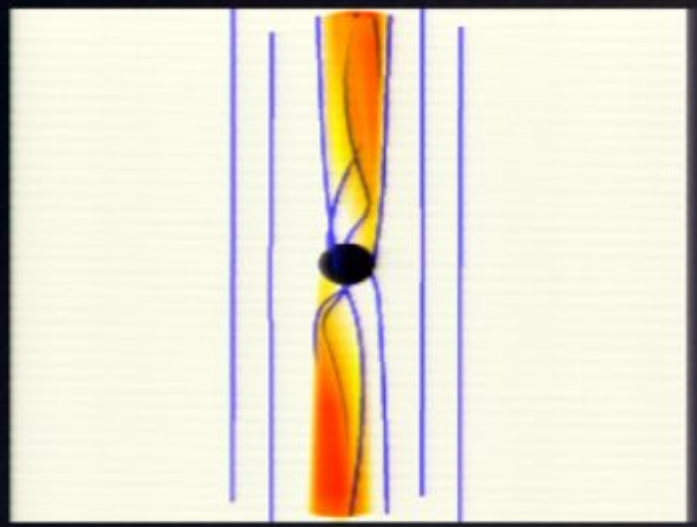
so if $B^r>0$ and $0<\Omega_F<\Omega_H$, there will be an outward energy flux at the AH

Single black holes

- There is a rotation of the EM field lines and an extraction of energy → Blandford-Znajek mechanism



a = 0.99, angle =0



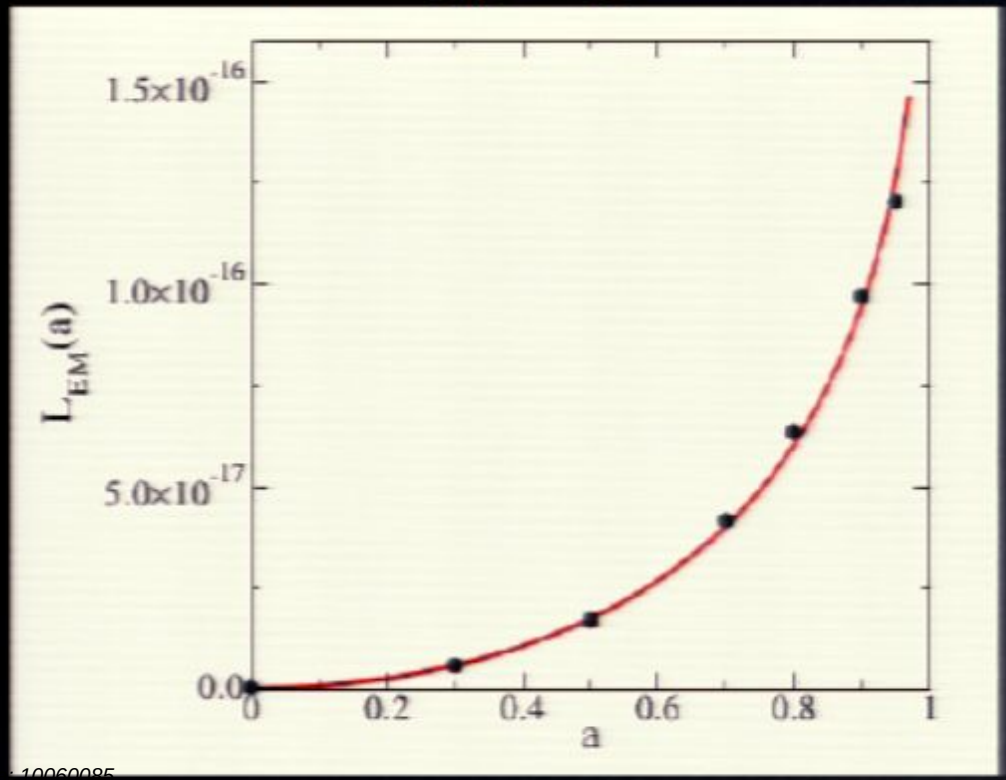
a = 0.99, angle = 90°

$M = 10^8 M_\odot$, $B = 10^4$ G

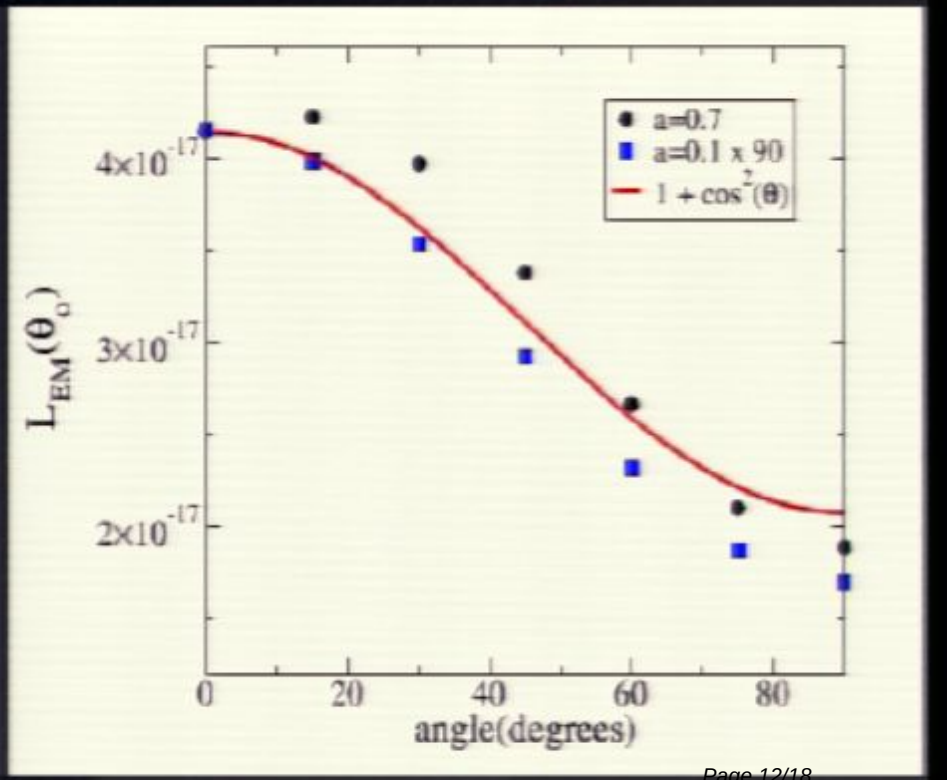
Single black holes

- The radiated power as a function of

the spin $L_{EM} \sim \Omega_H^2$

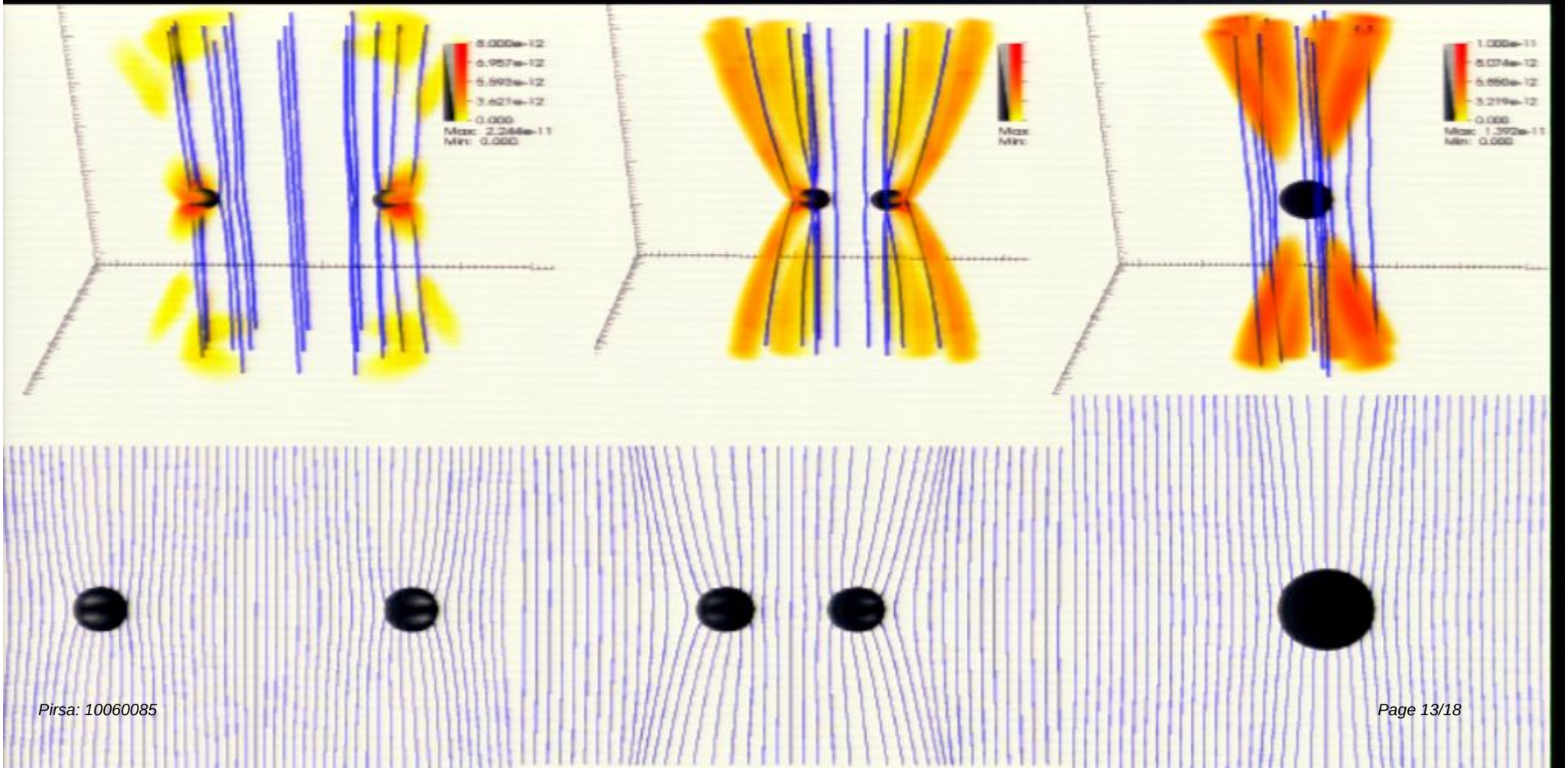


the inclination angle



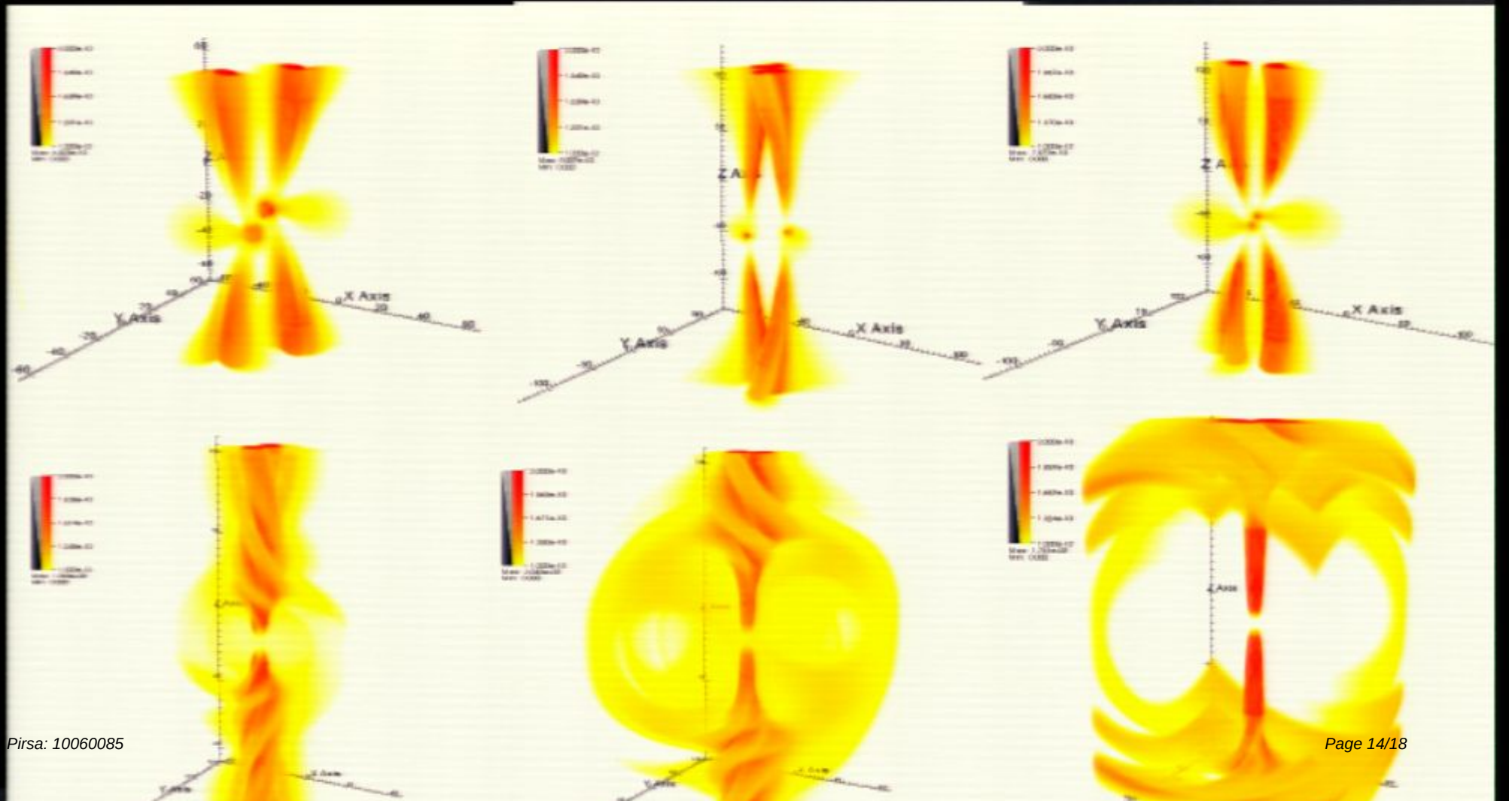
Binary black holes : head on

- The EM radiation propagates along the magnetic field lines



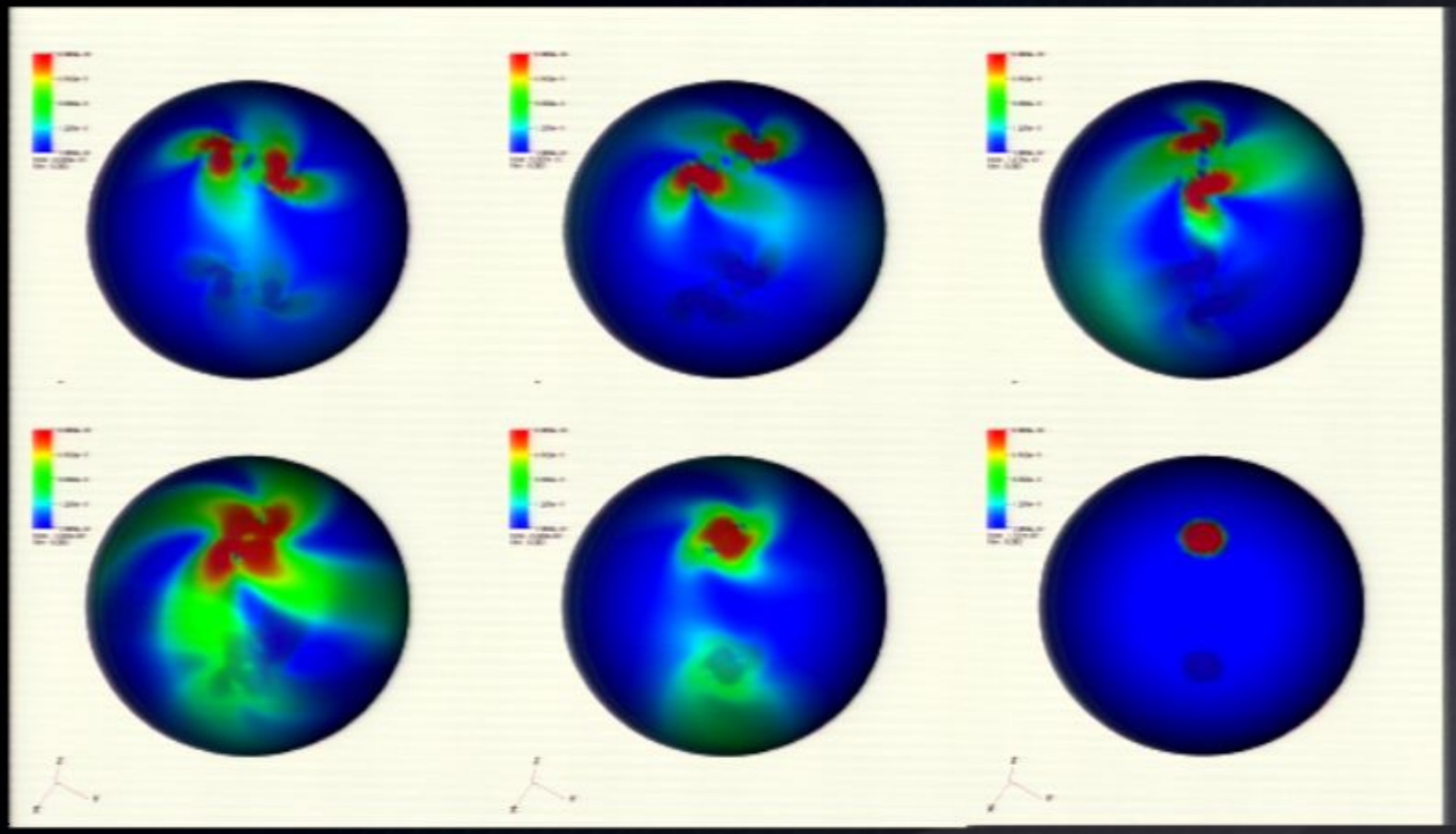
Binary black holes : inspiral-merger

- The EM radiation is collimated !!



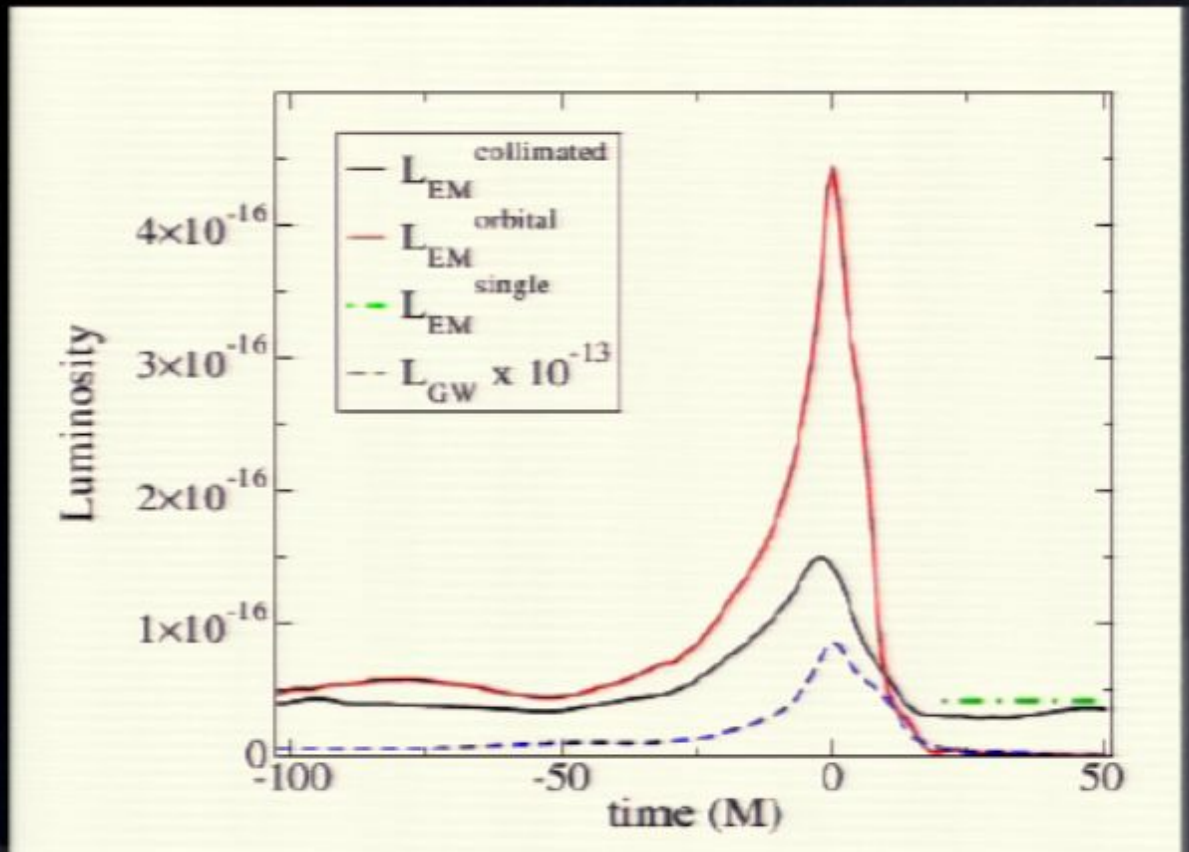
Binary black holes : inspiral-merger

- Transition from m=2 to m=0 (decays to Blandford-Znajek)



Binary black holes : inspiral-merger

- The EM power ~ $(B\Omega R)^2$, while the GW power ~ $M^2R^4\Omega^6$.
- A significant amount of EM energy is radiated days/weeks before the merger, while most of the GW is emitted during the last day



Summary

- we have evolved EE + Maxwell + force-free to study the effects of the binary BH dynamics on the EM fields

- collimated EM energy radiation even if the BHs are not spinning.

- significant isotropic EM radiation at the merger

- there are still a lot of things to do...

Binary black holes : inspiral-merger

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