Generalizations of the Blandford-Znajek process

Carlos Palenzuela
Universitat de les Illes Balears
(Mallorca, SPAIN)

Universitat de les Illes Balears

UIB

Relativistic Jets (Krakow, Poland) April 20-24, 2015

Overview

I. Magnetized plasma interacting with a black hole:
  The standard Blandford-Znajek process

II. Generalizing the Blandford-Znajek process:
  misaligned, boosted and binary BHs

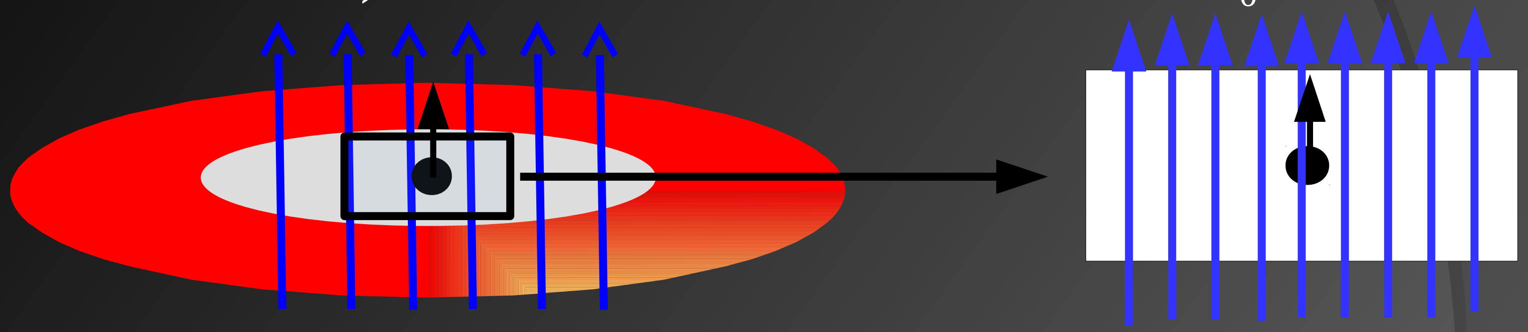
III. Magnetized plasma interacting with
  regular spacetimes

I. Magnetized plasma interacting with a (single,spinning,aligned,unboosted) black hole:

the standard Blandford-Znajek process

BH immersed in force-free plasma

- Kerr BH immersed in a strongly magnetized plasma (i.e., without the disk) such that far from the BH **B** ≈ B_0 ž ,**E**= 0



- Fluid + Maxwell equations in a curved background

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

- But, for very tenuous highly-magnetized plasma

  $\rho, P << B^2 \rightarrow \nabla_a T^{ab}{}_{(fluid)} << F^{ab} J_a \approx 0$

$\mathbf{E}\cdot\mathbf{J} = 0$, $q\,\mathbf{E} + \mathbf{J} \times \mathbf{B} = 0 \rightarrow E\cdot B=0$, $J_\perp = q\, E\times B / B^2$

The Blandford-Znajek process

- EM energy flux of a force-free plasma at the horizon of a stationary and axisymmetric spinning BH

$\Omega_F = F_{tr}/F_{r\Phi}$ constant along B

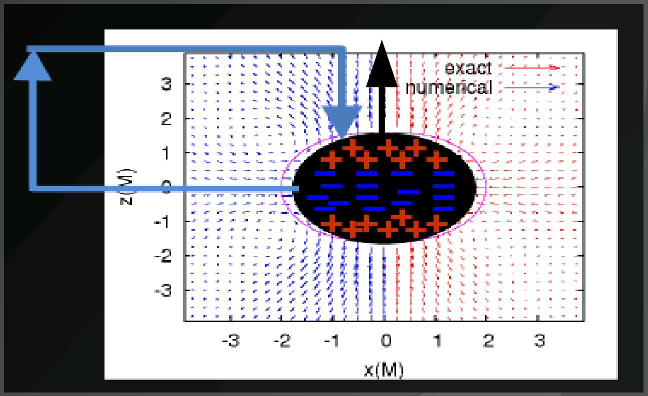
$\Omega_H = a/(2\,M\,r_H)$

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

- Analytical solution found by expanding the EM fields around a<<1, obtaining $\Omega_F \sim ½\,\Omega_H$ *(Blandford & Znajek,1977)* :

magnetic fields in force-free environments can extract rotational energy of the BH!!

$dE/dt \sim B^2\,a^2$ a=J/M<<1



- Membrane paradigm *(Damour 1978,Znajek 1978,Thorne, Price & MacDonald 1986)* endows a charge density to the horizon

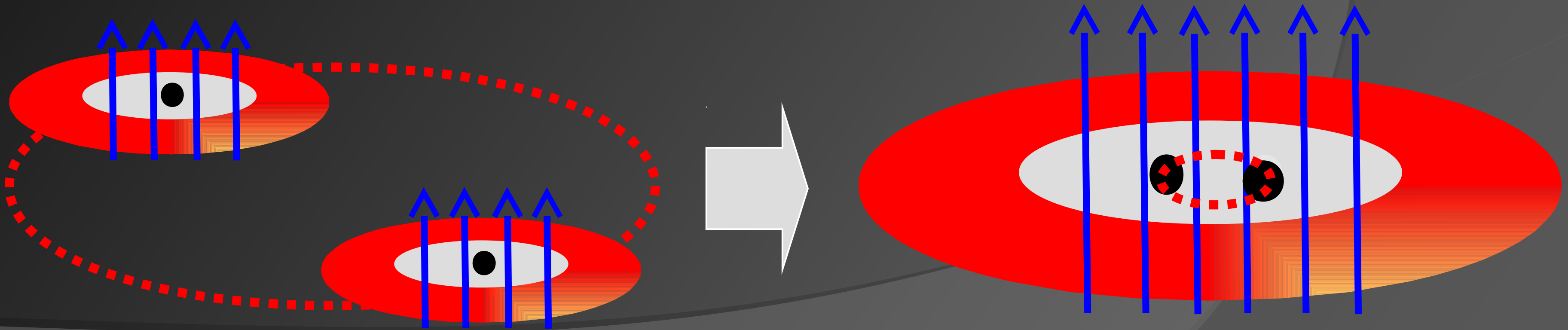
III. Generalizing the Blandford-Znajek process:

misaligned, boosted and binary BHs

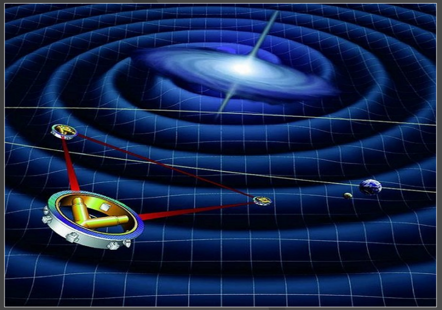
Motivation : merger of galaxies

- in the AGNs, SMBHs are surrounded by a disk of matter likely magnetized
- during the merger of galaxies, 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 BH binary is dominated by GW, opening the gap

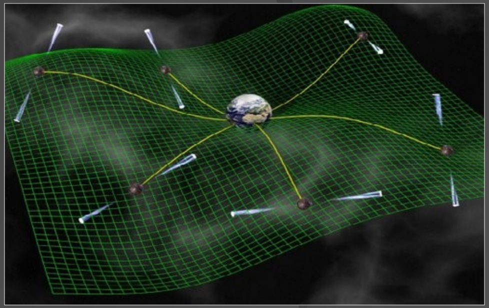


Multi-messenger astronomy

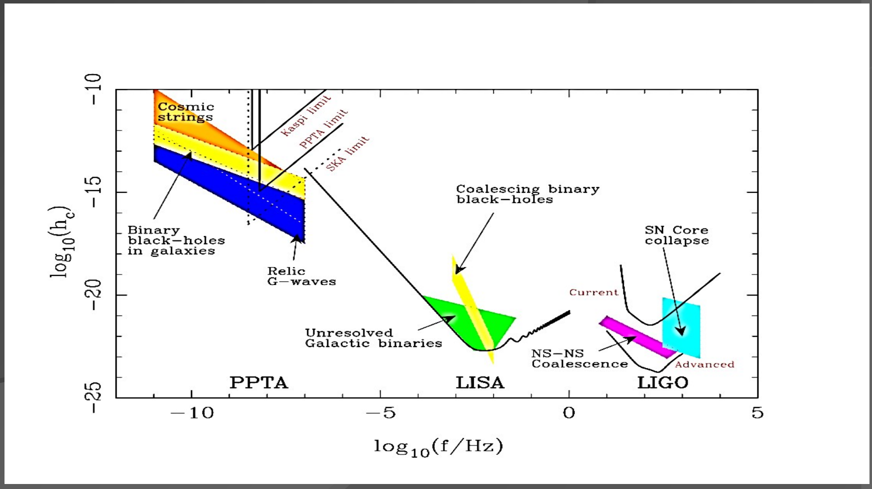


The merger of SMBHs will produce strong gravitational waves that could be measured by

- NGO/eLISA : interferometry between satellites following the earth around the Sun
- Pulsar Timing Array : GW affects the propagation of radio signal from pulsars to the Earth.



- Correlate EM & GW to extract more information from the system (progenitor, environment) and the physical processes involved (plasma physics, accretion,...)



GW on its way...and EM waves?

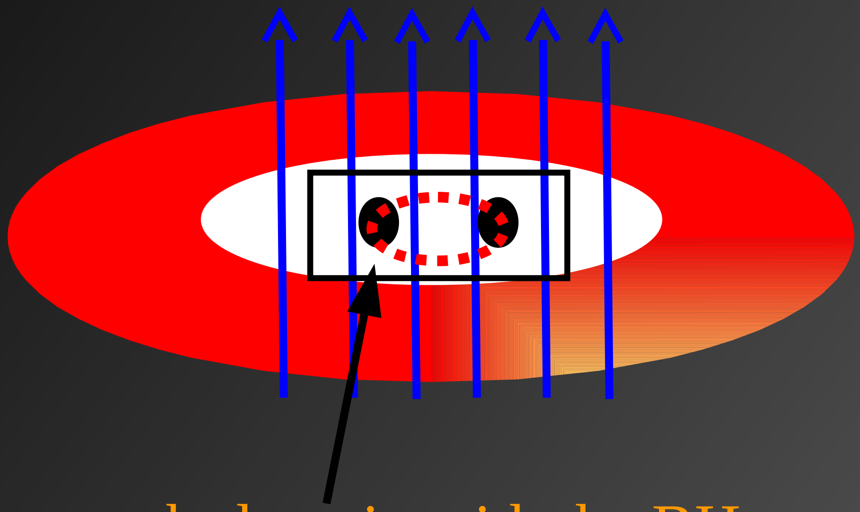
Zooming in on the black holes

Near the BHs the density in the cavity is so low that even moderate magnetic fields may dominate the fluid dynamics

$$\nabla_a T^{ab}_{(fluid)} << \nabla_a T^{ab}_{(EM)} \quad \rightarrow \quad F^{ab} J_a \approx 0$$

→ force-free environment influenced by BH dynamics

(CP++2010, Neilsen, CP ++2011, Moesta,CP++2012)



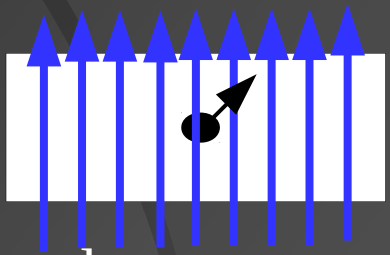
- sub-domain with the BHs, excluding the disk

- General Relativity for the evolution of the spacetime
- Force-free to describe the magnetically dominated plasma

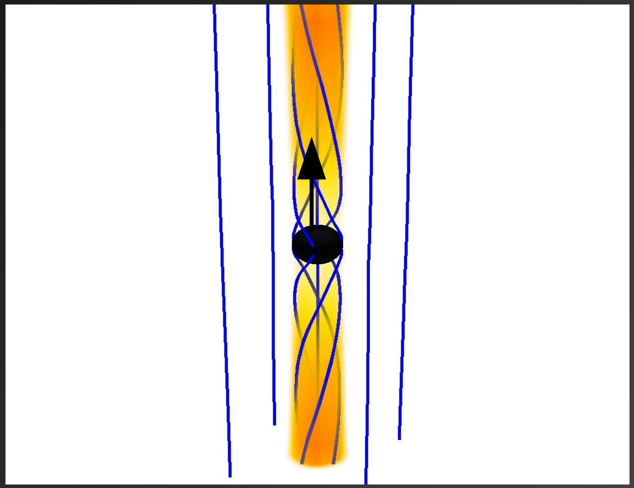
Einstein-Maxwell equations
+ Force-free condition

$$F^{ab} J_b = 0$$

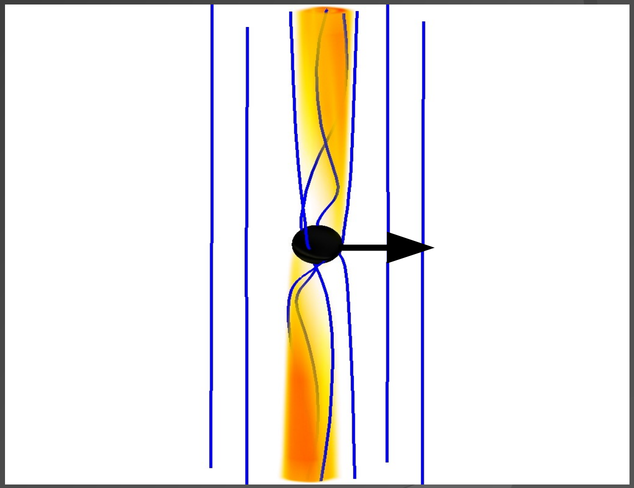
Single BHs in force-free environments : misaligned spinning case



- Consider a single BH and vary the spin orientation wrt the asymptotic magnetic field
- There is still a rotation of the magnetic field lines and net extraction of BH rotational energy



a = 0.99, angle =0



a = 0.99, angle = 90 º

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

Single BHs in force-free environments : misaligned spinning case

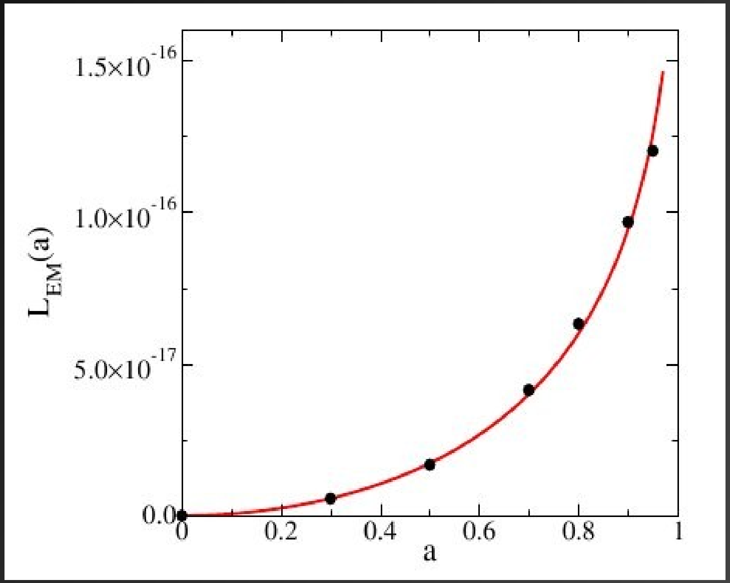
- Radiated power as a function of:

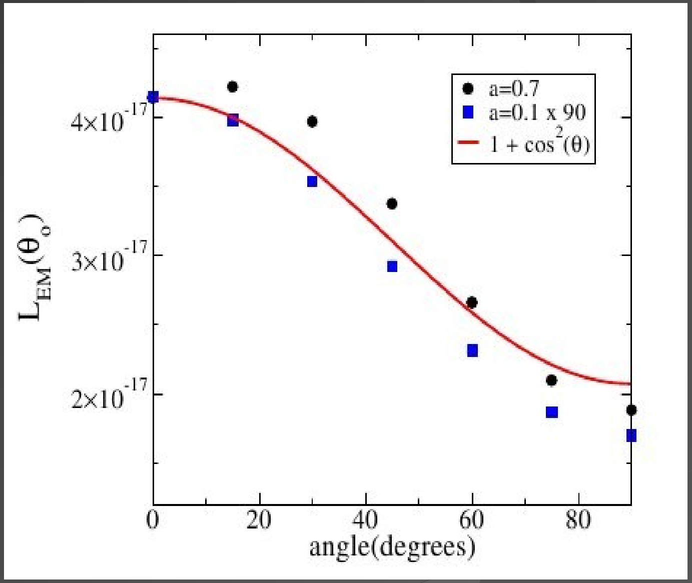
  -spin*(…,McKinney 2010,CP++ 2010)*

  $L \sim B^2 \Omega_H^{\ 2}$

  -inclination angle *(CP++2010)*

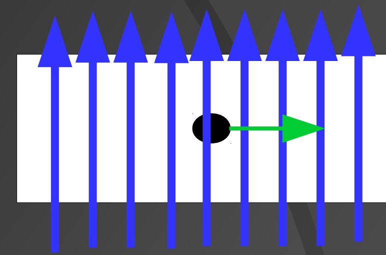
  $L \sim B^2 \Omega_H^{\ 2} (1 + \cos^2\theta)$



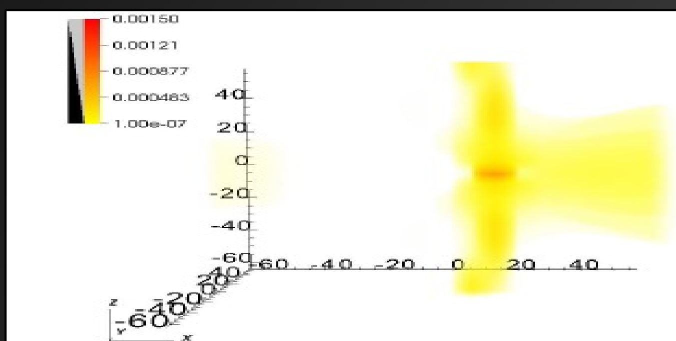


- In the case of pulsars, $L \sim B^2 R^6 \Omega^4 (1 + \sin^2\theta)$

Single BHs in force-free environments : boosted case



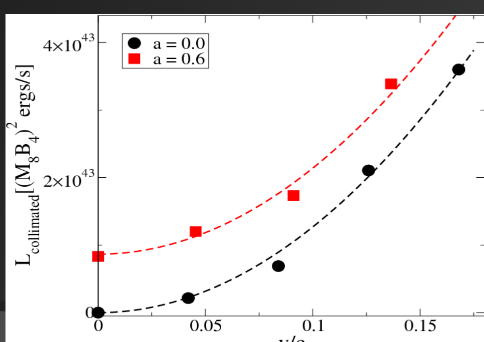
- Consider a BH with a relative motion wrt the asymptotic magnetic field.
- There is a collimated flux of energy along the magnetic field lines threading the horizon *(Neilsen,CP++ 2011)*



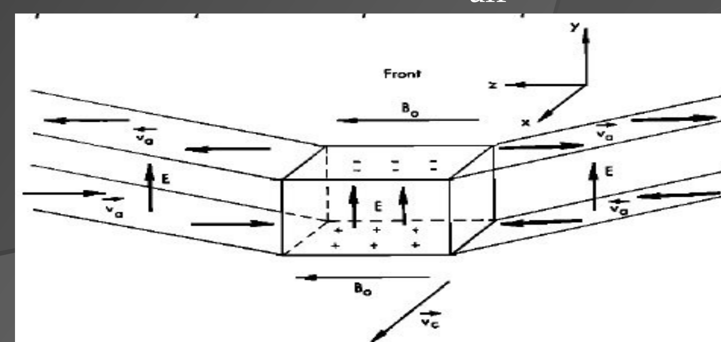
-propulsion of satellites in the ionosphere

(Drell,Foley,Rudderman 1965)

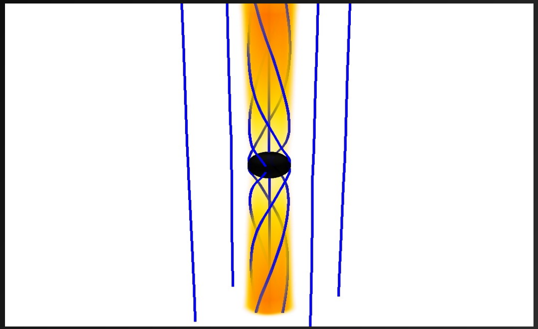
$$L \sim B^2 (v/v_{alf})^2$$

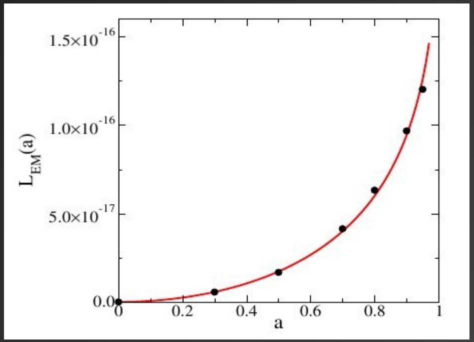


$$L \sim B^2 v^2$$



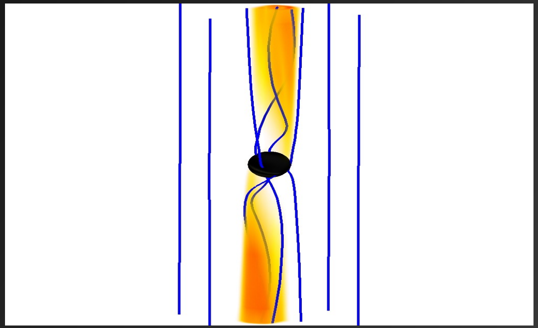
Single BH in force-free environments

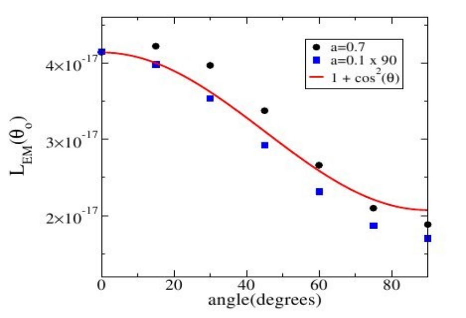




$L_{spin} \sim B^2\Omega_H^{\ 2} \quad a \leq 1$

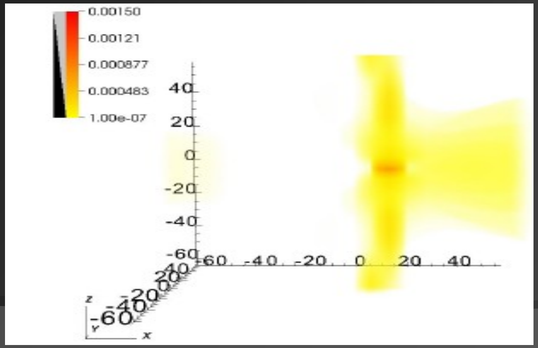
(…,McKinney 2010, CP ++ 2010)

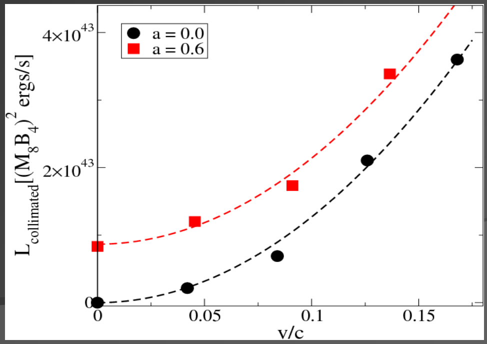




$L_{spin} \sim (1+\cos^2\theta)\, B^2\Omega_H^{\ 2}$

(CP ++ 2010, Gralla++ 2015)





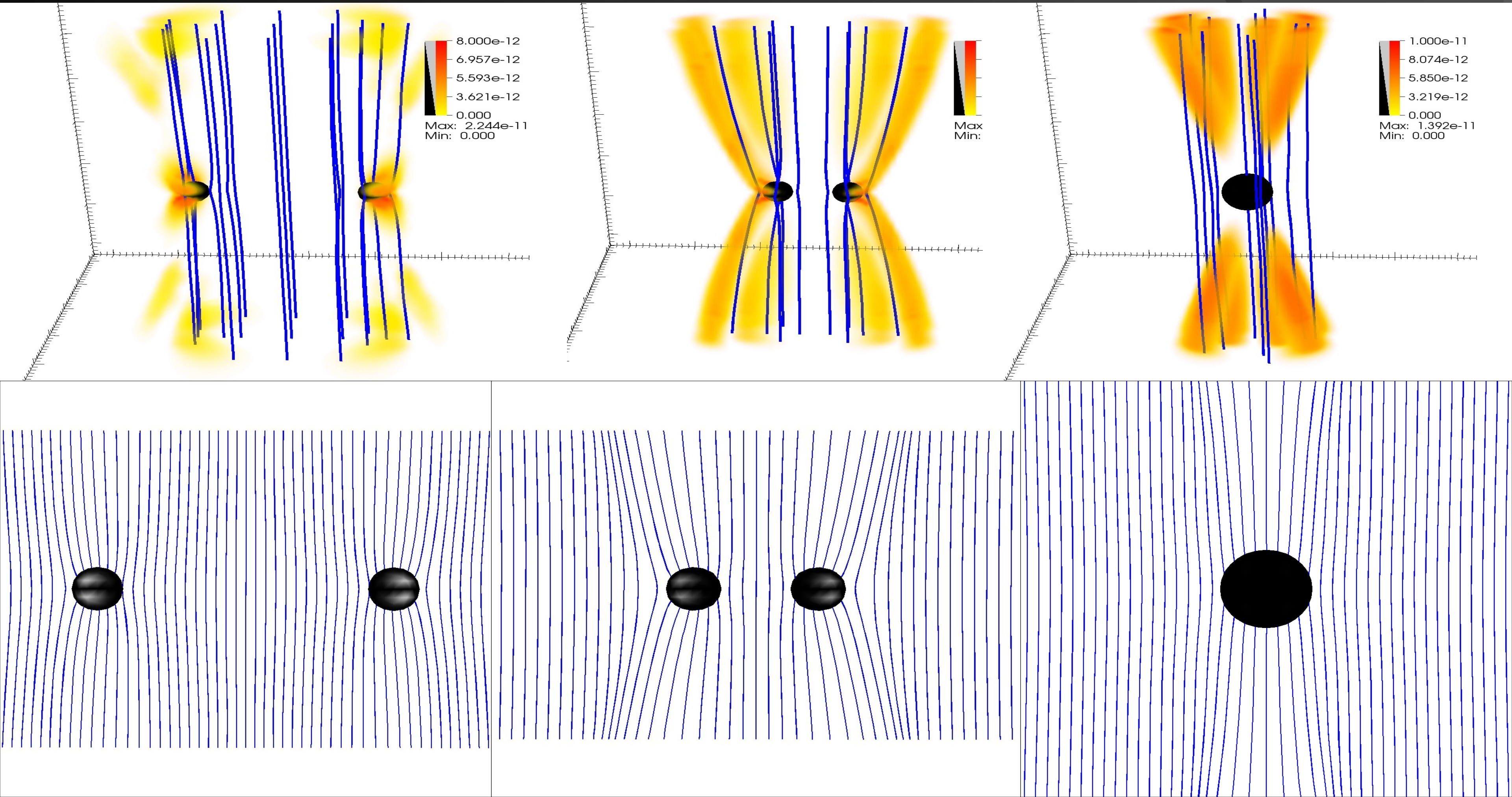
$L_{boost} \sim B^2\, v^2$

$L_{total} \sim L_{spin} + L_{boost}$

(Neilsen,CP ++ 2011, Penna 2015)

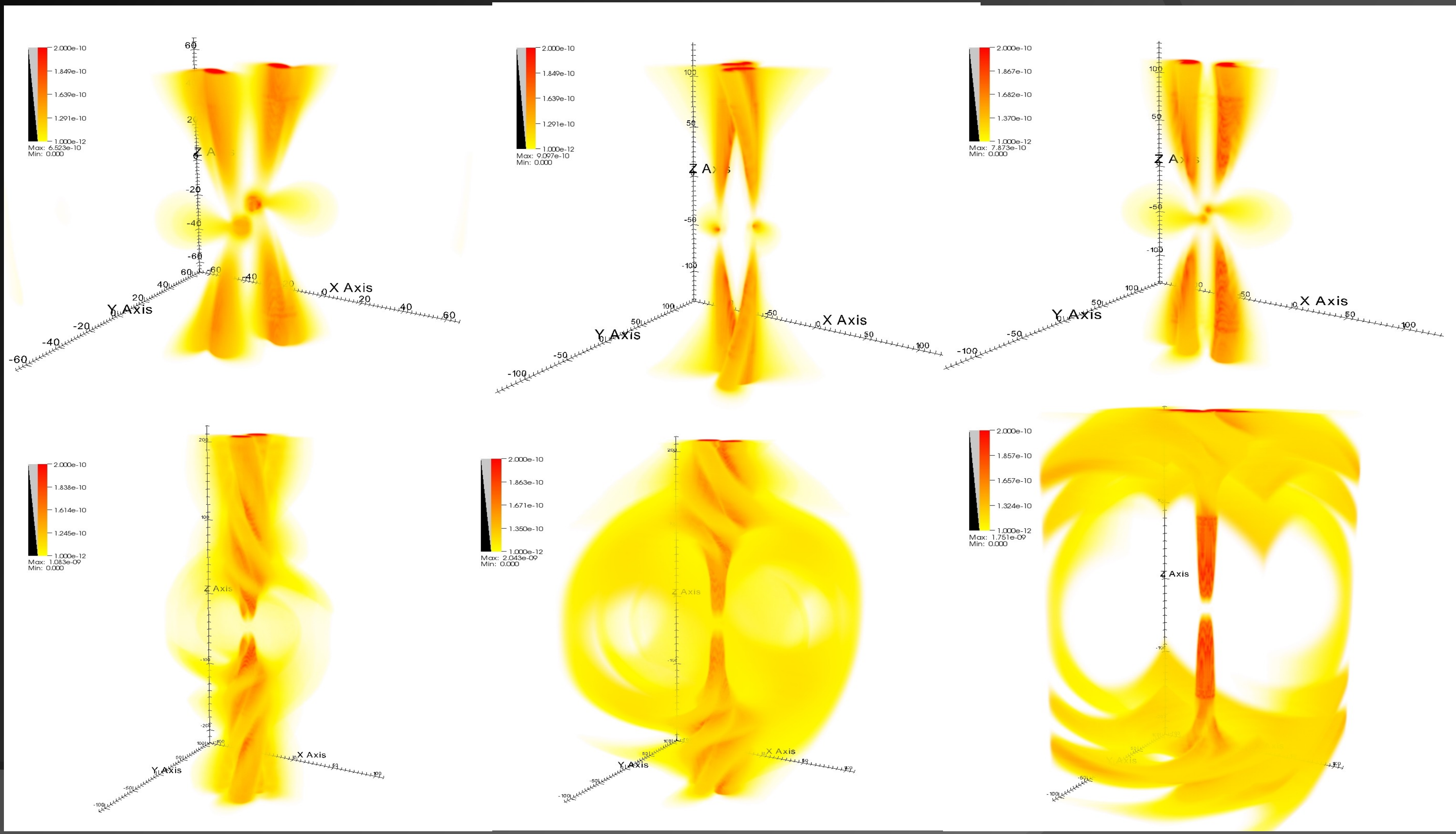
Binary black holes : head on

- Head-on binary BH produces two collimated jets



Binary black hole coalescence

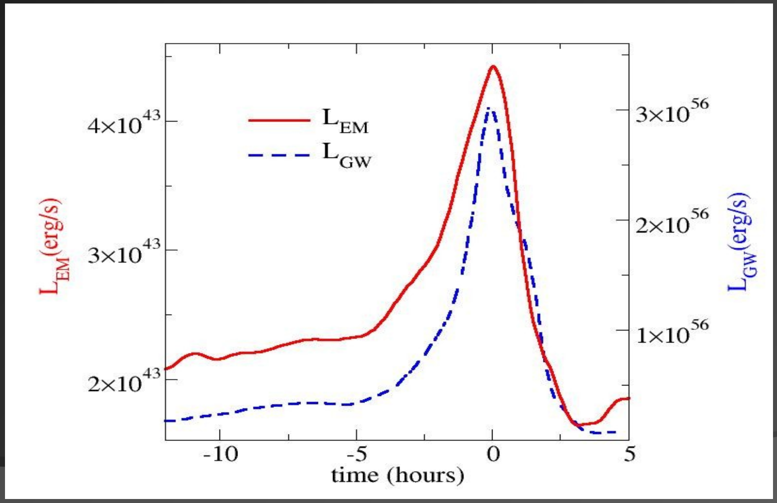
- Inpiral and merger of a binary BH system produce a dual jet

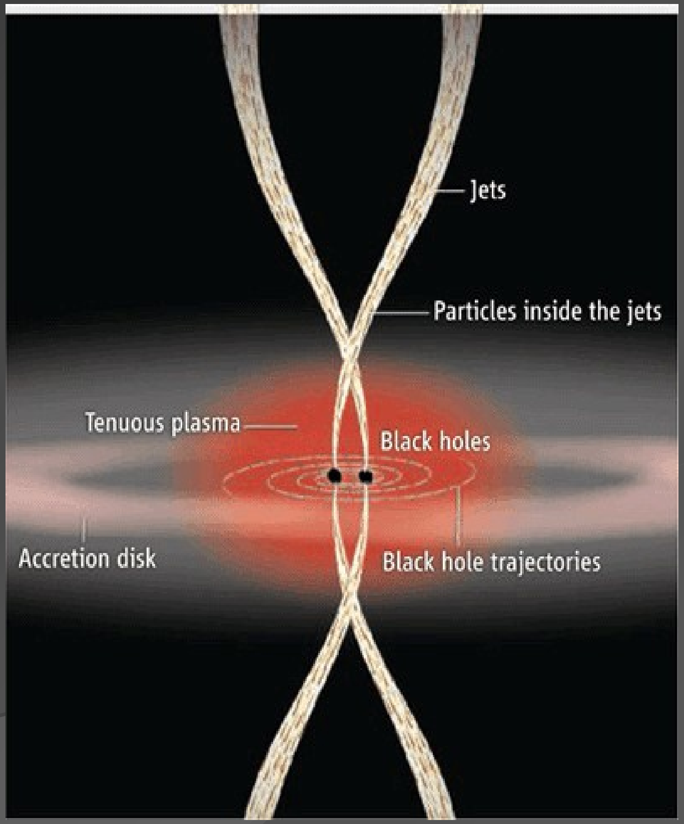


Binary BHs in force-free environment

The EM power ~ $(B\ v)^2 \sim 1/r$, while that the GW power goes like ~ $1/r^5$. A significant amount of EM energy is radiated days/weeks before the merger, while most of the GW is emitted during the last day *(CP++ 2010)*

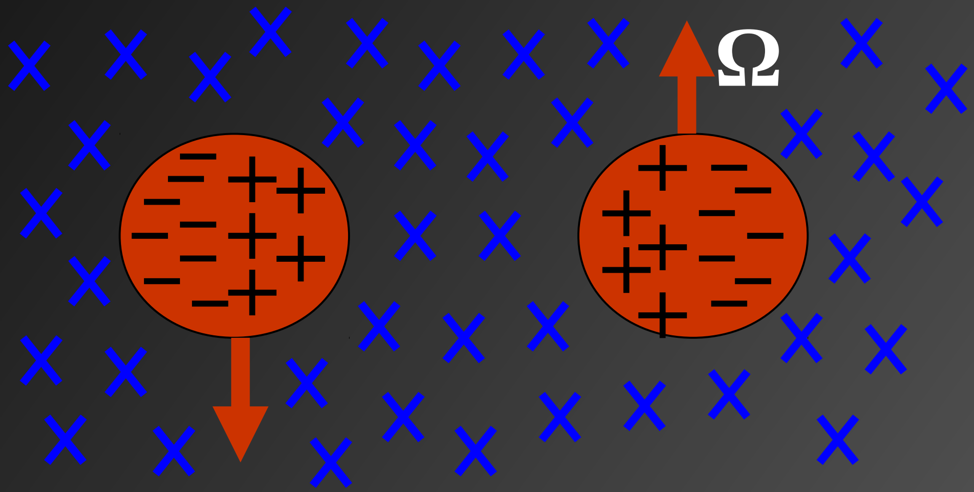
- dual jet structure during inspiral, join into a single jet after merge
- diffuse quadrupolar luminosity





Note 1: Membrane paradigm

- simple model based on the membrane paradigm can explain the different cases (see Penna's talk this morning).

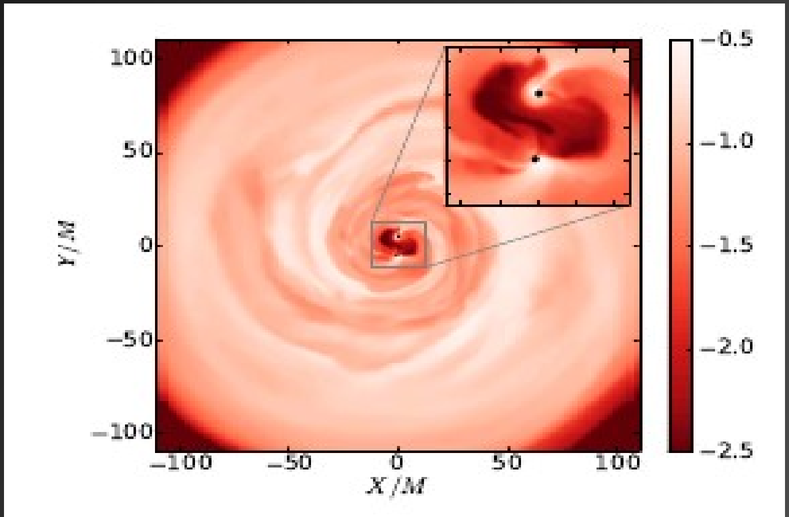


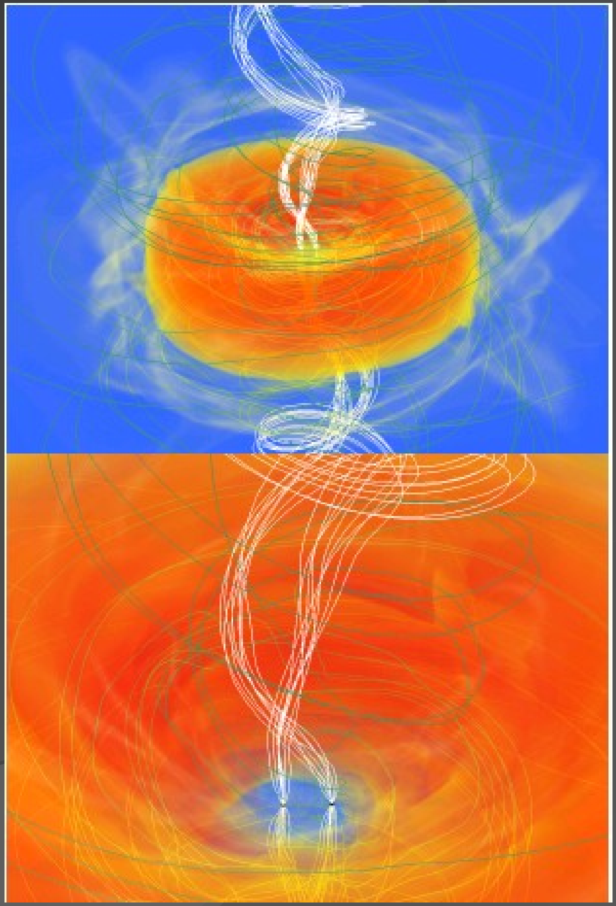
* there is a induced charge separation that can sustain a current and dissipate energy in the force-free medium

Note 2 : comparison with full MHD

- Inspiral during the decoupling phase with full relativistic spacetime and MHD with radiation for the thick disk (H/R~0.3) via "consistent" cooling *(Farris et al, 2012, Gold et al 2013)*

  - accretion through two spiral arms
  - dual jet structure!!





IV. Magnetized plasma interacting with regular spacetimes

Power sourcing the BZ mechanism

- Where is the energy coming from?
  - AH casually disconnected.

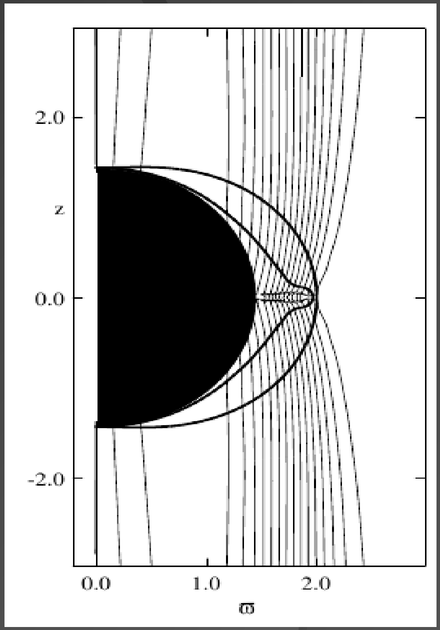
-Apparent Horizon (AH) : light surfaces are trapped

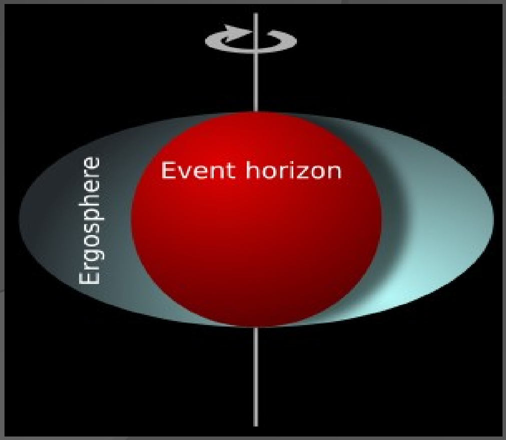
$$r_H = M + (M^2 - a^2)^{1/2}$$

- Ergosphere: region where all the physical observers are forced to rotate (frame-dragging)

$$r_{ergo} = M + (M^2 - a^2 \cos^2\theta)^{1/2}$$

particles can have negative energy!!



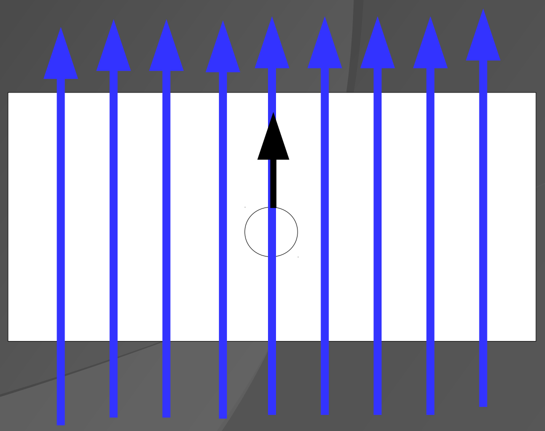


Regular spacetimes with rotation

- Where is the energy coming from?
  - study regular spacetimes (ie,without horizon) with and without ergosphere, generated by solving rotating NS with constant density.

  a) highly compact solutions M/R < 0.44
  b) may present ergospheres

  - we will assume that a "dark" fluid is deforming the space-time, and will only consider the evolution of the force-free fields in this curved background
  -i.e., without any direct coupling between the EM and the "dark" star- *(Ruiz,CP++2012)*



BZ in regular spacetimes

• Generalize the BZ power formula to any stationary and axisymmetric spacetimes, described by the Lewis-Papapetrou metric

$$ds^2 = -\alpha^2\, dt^2 + g_{\phi\phi}\,(d\phi - \omega\, dt)^2 + g_{rr}\, dr^2 + g_{\theta\theta}\, d\theta^2\,,$$

ω = angular velocity ZAMO (frame-dragging)

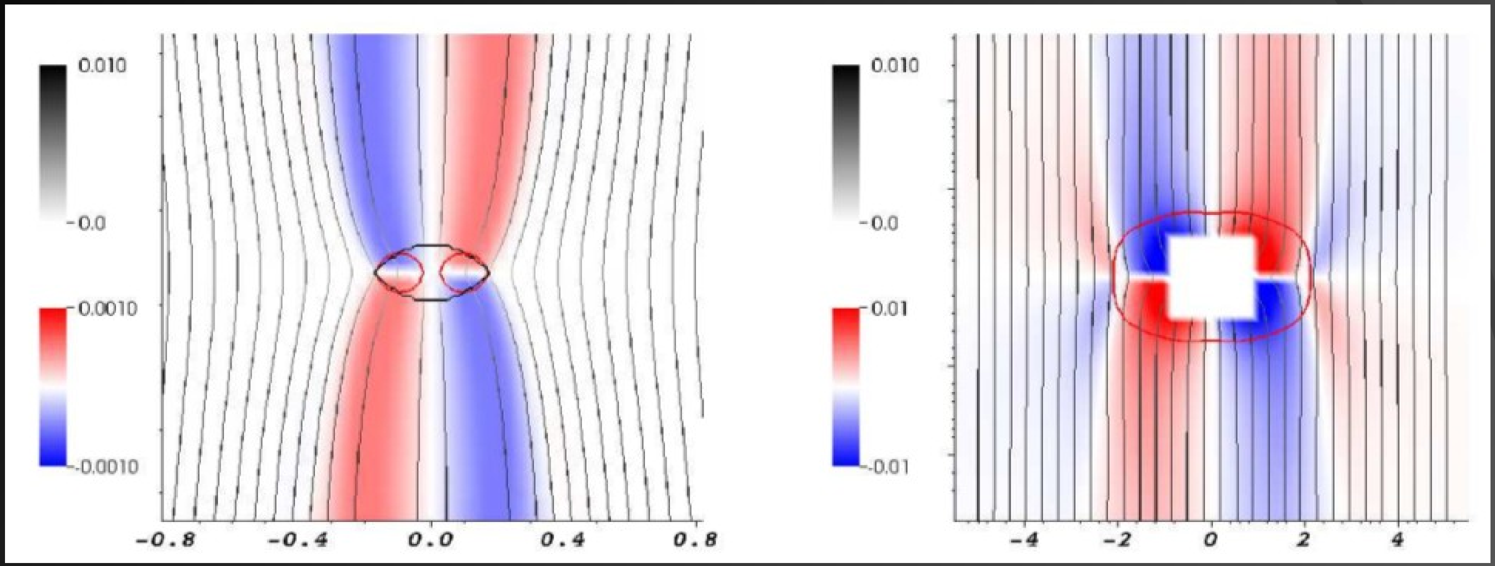
• Solutions of "dark stars" with adimensional spin $a=J/M^2=0.9$ and compactness depending on the metric potential V_o

•The EM energy flux density for this metric is

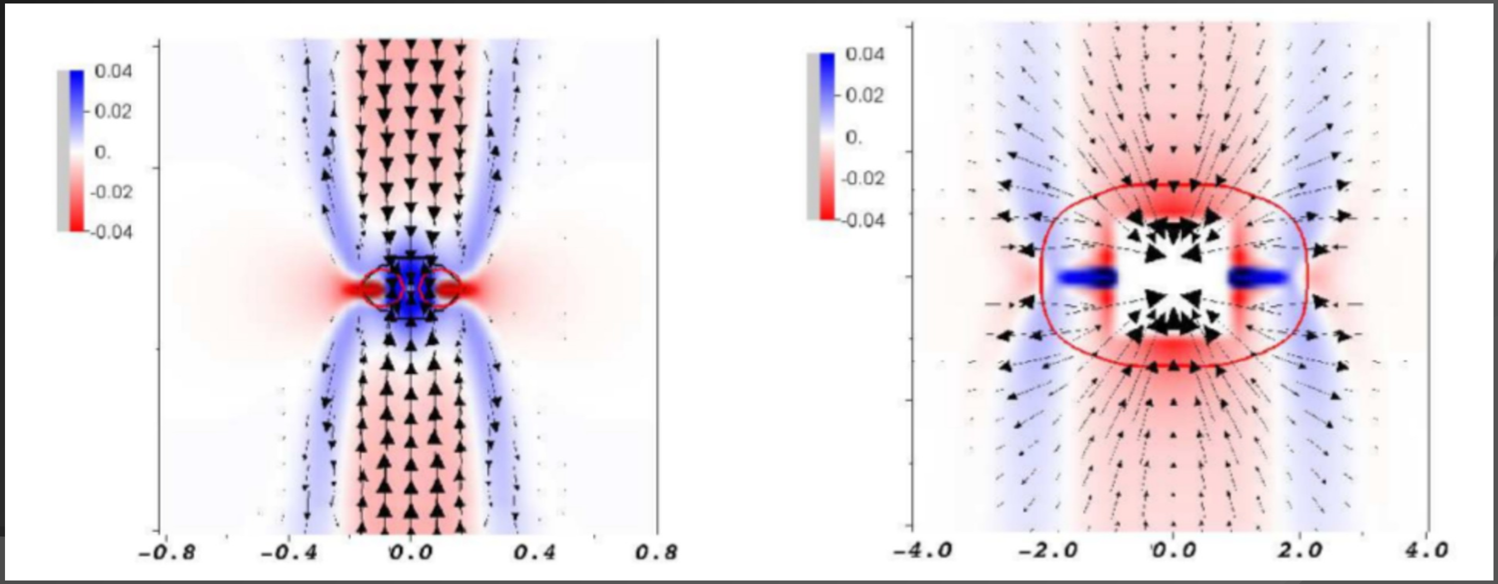
$\Omega = F_{tr}/F_{r\Phi}$ constant along B

$$S^r_\xi = -\frac{\Omega}{2\,\pi}\, B^r\, B^\phi\, \alpha^2\, g_{\phi\phi}$$

Regular spacetimes vs BHs

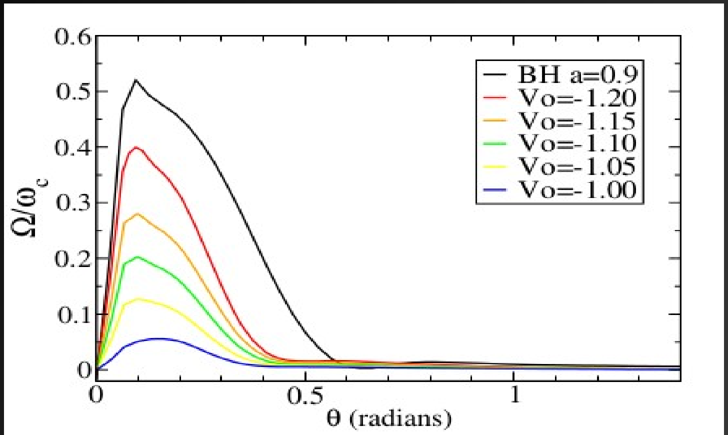


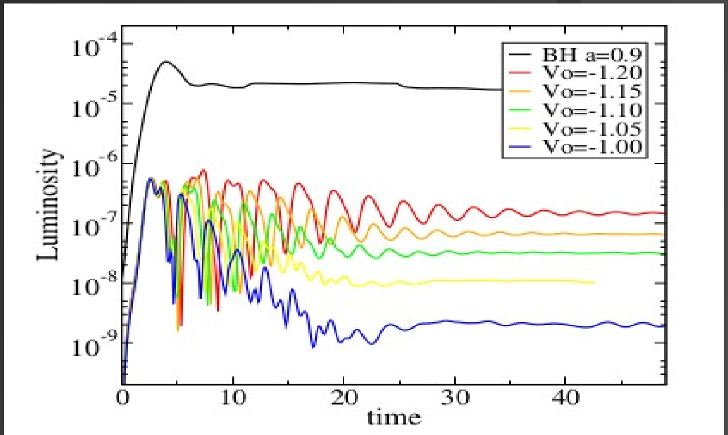
Magnetic Fields

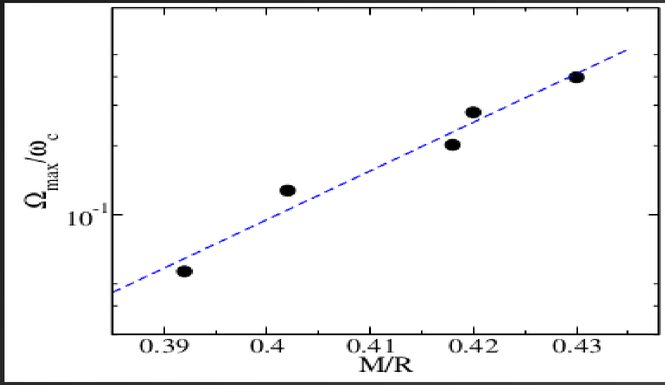


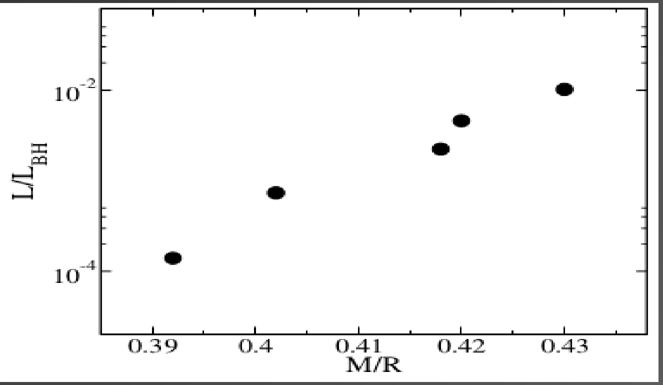
Currents and charges

BZ in regular spacetimes









$$\Omega/\omega_c \approx A\, e^{\lambda\, M/R},$$

$$B^\phi \approx -f\,\Omega B^r,$$

$$S^r_\xi = -\frac{\Omega}{2\pi} B^r B^\phi W^2 \approx \frac{f\Omega^2}{2\pi} (B^r)^2 W^2 \approx \frac{A f \omega_c^2}{2\pi} (B^r)^2 W^2 e^{2\lambda M/R},$$

Summary

- A force-free environment can extract both the rotational and the translational kinetic energy of a BH → in a binary, it will produce a dual jet with some features that could be detectable

- A force-free environment can extract rotational (and probably translational) kinetic energy of "compact" regular spacetime
  → the key ingredient seems to be the ergosphere