Extracting energy from black holes in force-free environments:

generalizations of the Blandford-Znajek process

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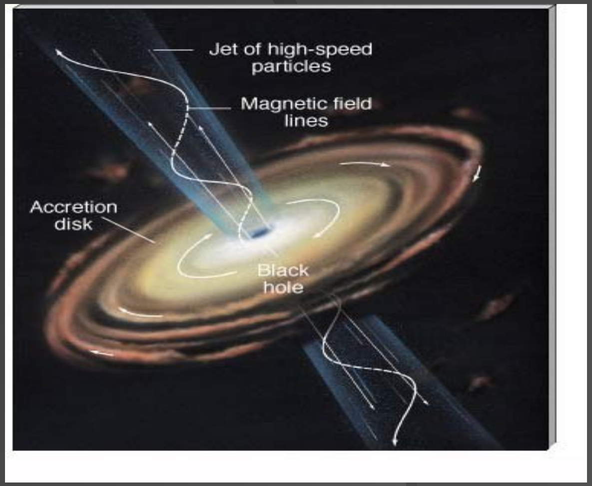
November 12, 2014

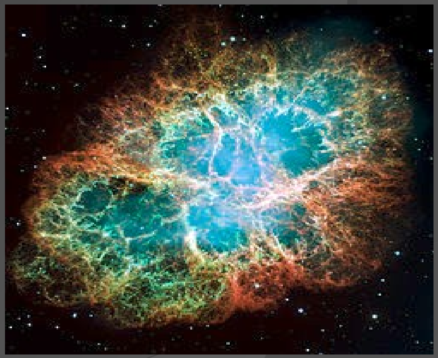
Searching for the power source

- what is the source that powers jets
  in disks accreting onto black holes?

  * binding energy of the accreting gas
  * rotational energy of the BH



- Crab Nebula powered by the rotational
  energy of a Neutron Star through
  relativistic particles and EM fluxes.



- Is there a similar process for Black Holes? How general it is?

Overview

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

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

III. Magnetized plasma interacting with
regular spacetimes

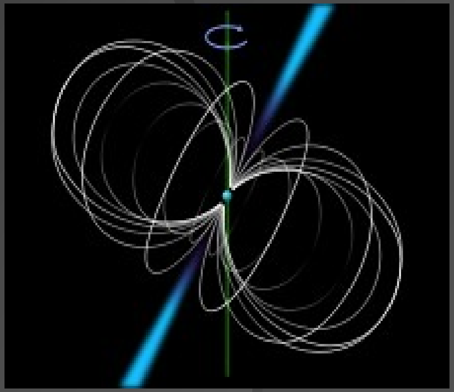
IV. Summary

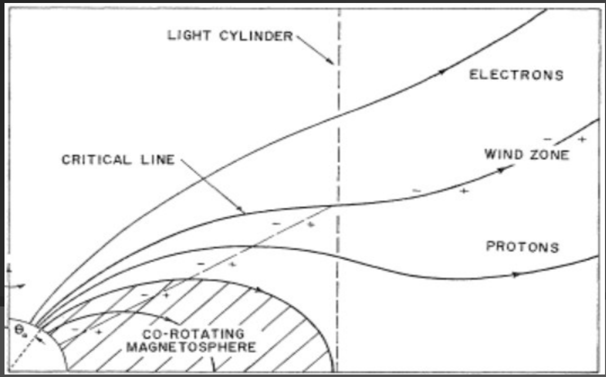
I. Magnetized plasma interacting with a black hole:

the standard Blandford-Znajek process

Magnetized spinning neutron stars

- Pulsar : highly magnetized, rotating NS emitting a beam of electromagnetic radiation
- easy solution assuming electrovacuum exterior
- $E \bullet B \neq 0$ outside the star, so the electric force pulls out electrons from the NS surface and fills the magnetosphere with low density plasma *(Goldreich & Julian 1969)*
- the magnetosphere is magnetically dominated, so it is forced to co-rotate with the star (up to the Light Cylinder)





EM luminosity *(Spitkovsky 2006)*

(Poynting flux)

$$L \sim B^2 R^6 \Omega^4 (1 + \sin^2\theta)$$

plasma vacuum

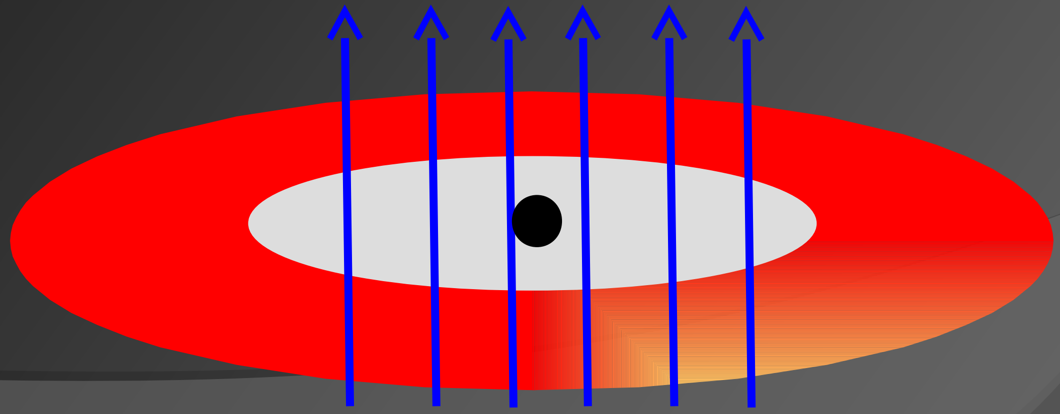
BH immersed in external EM field

- BH : stationary axisymmetric solution of the EE in vacuum, described by mass M and angular momentum $a=J/M^2$

"radius" = Apparent Horizon (AH) $r_H = M + (M^2 - a^2)^{1/2}$

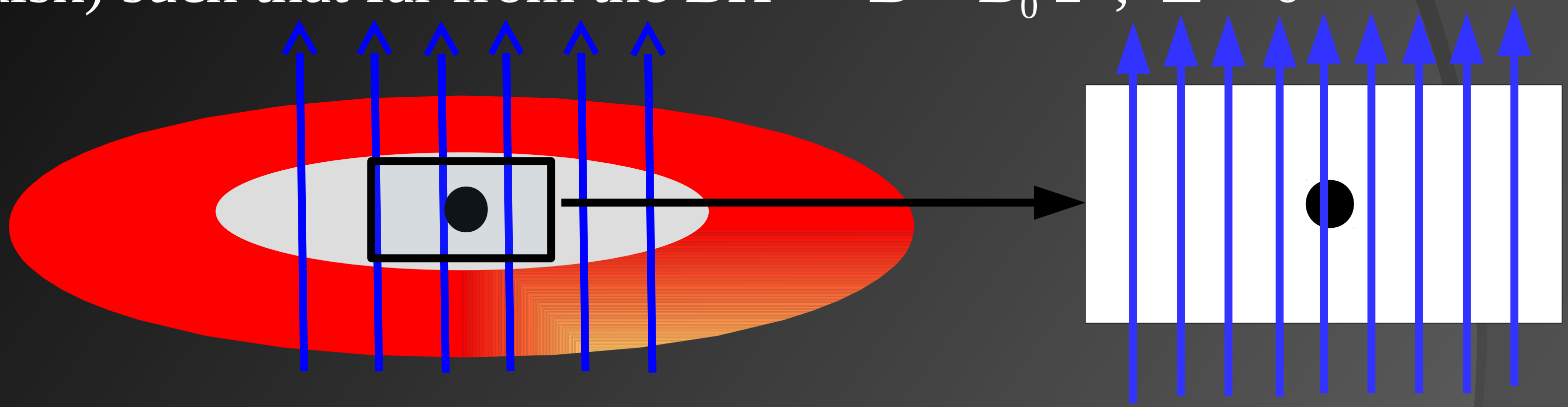
"angular velocity" = ZAMOS at the AH $\Omega_H = a/(2\,M\,r_H)$

- Study the possible extraction of rotational energy from a spinning BH through the EM fields sourced by an accretion disk



Modelling the BH magnetosphere: electrovacuum

- Kerr BH immersed in magnetic fields (i.e., without the disk) such that far from the BH $\mathbf{B} \approx B_0\, \check{z}$, $\mathbf{E} = 0$



Maxwell equations without neither charges nor currents in a curved background

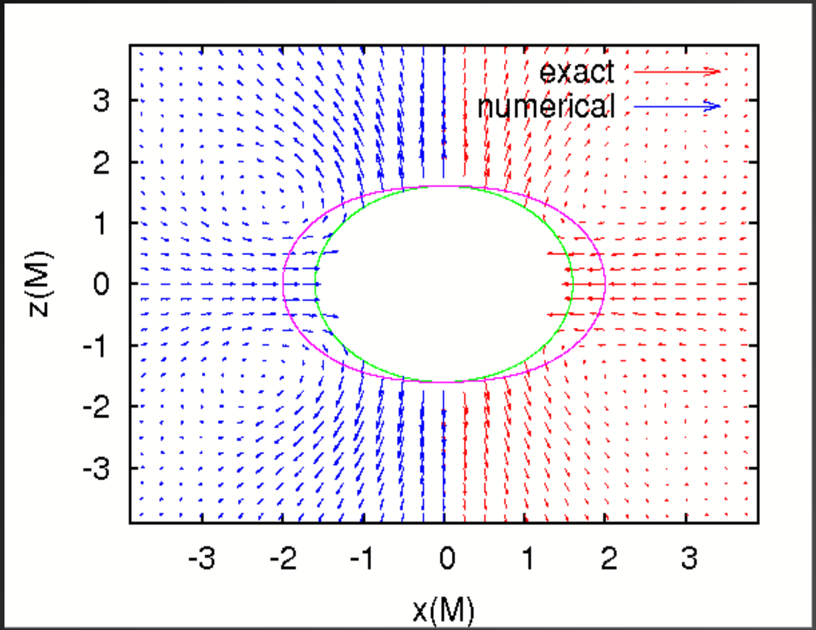
$\nabla_a F^{ab} = -I^b = 0$ Maxwell tensor $F^{ab} = n^a E^b - n^b E^a + \epsilon^{abc} B_c$

$\nabla_a {}^*F^{ab} = 0$ current 4-vector $I^a = n^a q + J^a$

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

I. Kerr+B = unstable to pair production !

- Assuming stationarity ($\partial_t \rightarrow 0$) axisymmetry ($\partial_\varphi \rightarrow 0$) and J=q=0, there is a solution for a BH immersed in a external magnetic field aligned with the spin in terms of the Killing vectors (*Wald 1974*)



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

- Total Poynting flux = 0
  (the EM fields can not extract energy from the BH)

- there is an induced E field with

$$E \cdot B \neq 0$$

unstable to pair production!!

magnetized tenuous plasma surrounding the BHs

Modelling the magnetosphere: ideal MHD

- Coupling between EM fields and the plasma (perfect fluid)

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

$$\nabla_a T^{ab}=0 \text{ for the fluid } + \text{Maxwell for the EM fields}$$

$$\partial_t B + \nabla \times E = 0 \qquad E = -v \times B$$

Magnetic fields anchored in the plasma

- If $p \gg B^2$ the EM will follow the fluid motion
- If $p \ll B^2$ the fluid will move according to the EM dynamics

Modelling the magnetosphere: the force-free approximation

- For very tenuous highly-magnetized plasma

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

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

$$\mathbf{E}\cdot\mathbf{J} = 0 \quad , \quad q\,\mathbf{E} + \mathbf{J} \times \mathbf{B} = 0 \rightarrow \boxed{\begin{array}{c} E\cdot B=0 \\ J_\perp = q\, E\times B / B^2 \end{array}}$$

- the plasma only supplies charges and determines the current of the EM fields, but it does not appear directly in the equations

The Blandford-Znajek mechanism

- Under these conditions, we can compute the EM energy flux ($F_E \sim -T^r_t \sim ExB$) around a BH

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

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

- At the AH, $\Delta=0$ and we can use that the rotation frequency of the BH is $\Omega_H = a/(2\,M\,r_H)$

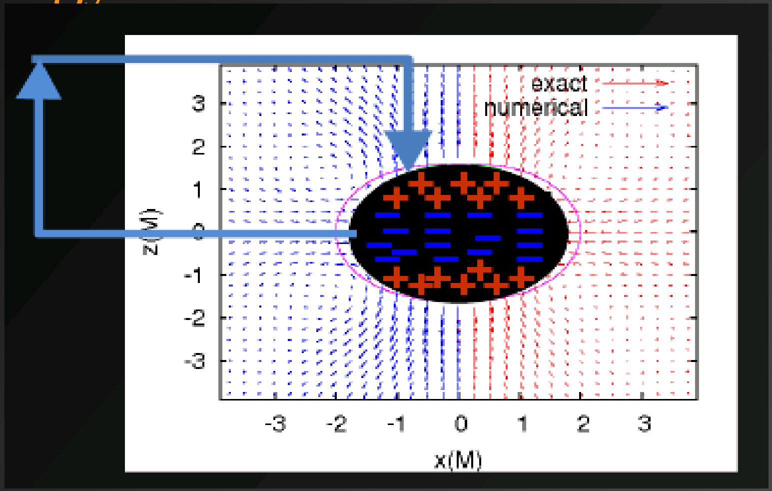
$$F_E\big|_{r=r_H} = 2\,(B^r)^2\,\Omega_F\,r_H\,(\Omega_H - \Omega_F)\,sin^2\theta.$$

- if $0<\Omega_F<\Omega_H$ (for $B^r \neq 0$) there will always be an outward energy flux at the AH!!

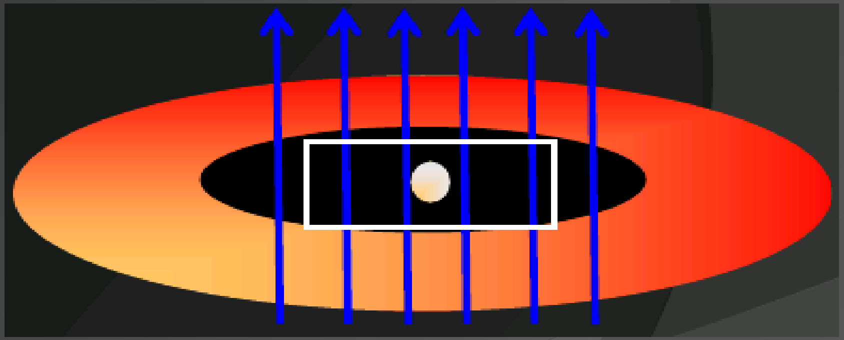
EM energy extraction from a single BH

- Wald's solution is force-free for a Schwarzschild BH.
- A solution was found analytically 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!!



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



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

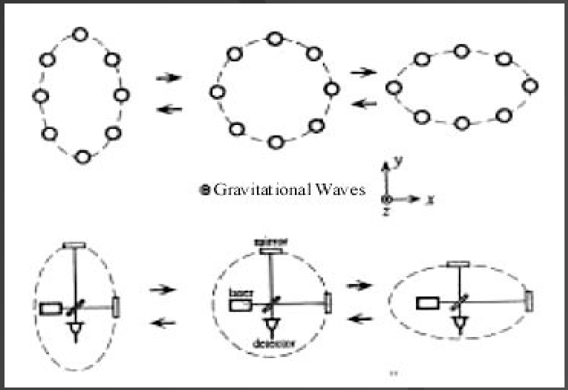
III. Generalizing the Blandford-Znajek process:

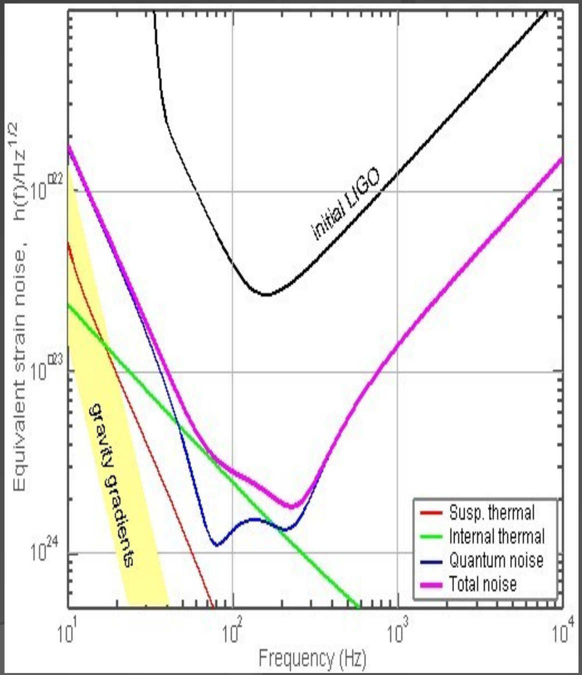
misaligned, boosted and binary BHs

Detectors of GW

- Detect the GWs produced during the coalescence of binary compact objects by measuring changes in the relative distances between perpendicular arms

$$h \sim \Delta L/L$$

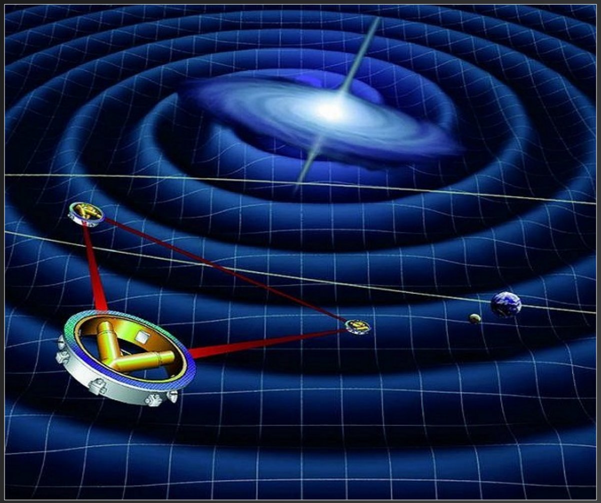


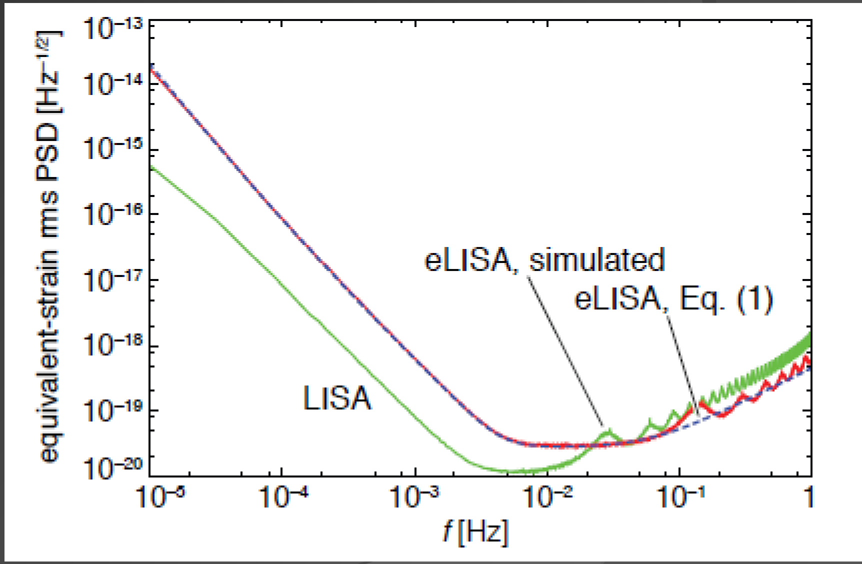


Sensitive band M~1-100 $M_\odot$

Detectors of GW in the space (I)

- NGO/eLISA : satellites following the earth around the Sun and measuring distance by interferometry between two arms. Continued by the ESA and expected to be launch at 20XX?.



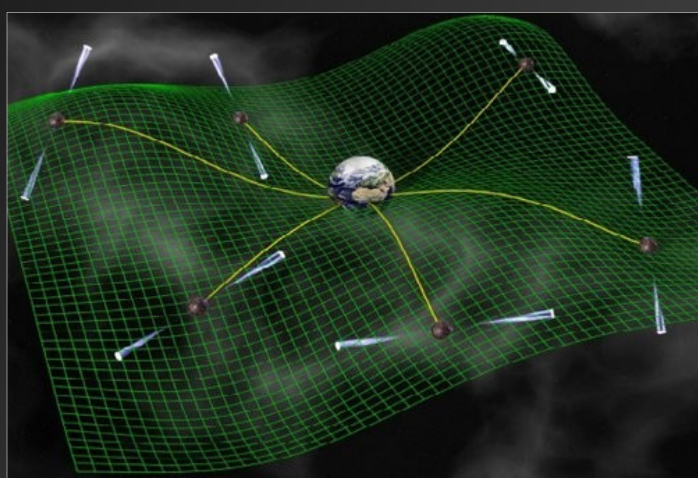


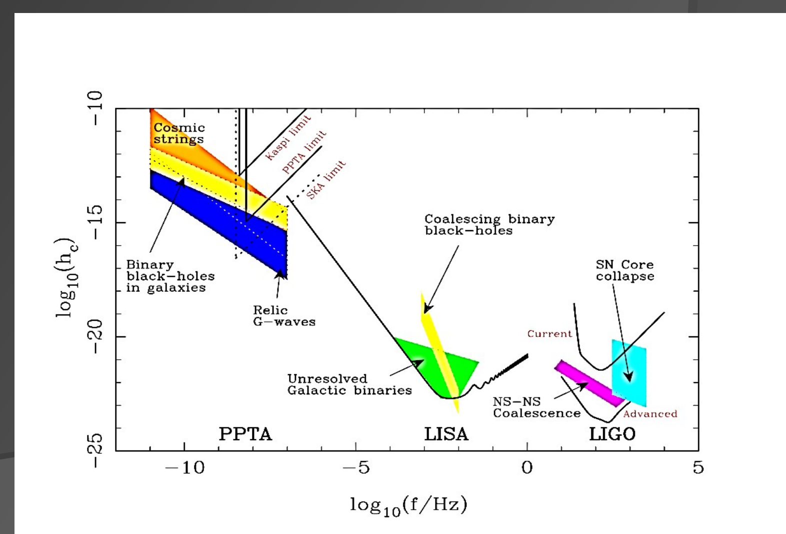
(Amaro-Seoane et al, 2012)

Sensitive band $M \sim 10^4 - 10^7\ M_\odot$

Detectors of GW in the space (II)

- Pulsar Timing Array : GW affects the propagation of radio signal from pulsars to the Earth. IPTA collects data from an array of millisecond pulsars in 10^{-9}-10^{-6}Hz.
  -Distinguish individual source and possible EM counterparts for $z \leq 1.5$ *(Tanaka,Menou,Haiman 2011)*
  -Improve sensitivity with future FAST and SKA

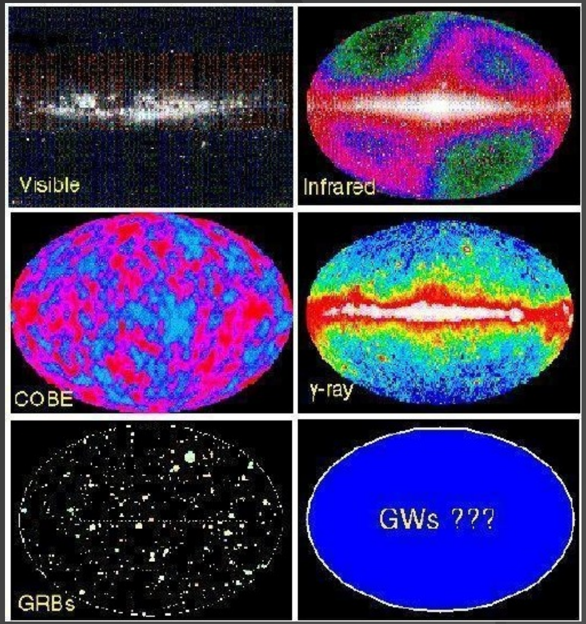




Sensitive to 10^{8}-10^{10} M_{Θ}

Multi-messenger astronomy

- Correlate information from different channels; electromagnetic waves, gravitational waves and (possibly) neutrinos



Gravitational waves

-Tell us about large masses
-Travel directly to us
-Easy to determine distance
-Hard to determine sky location
-Impossible to measure redshift

EM waves

-Tell us about particles
-Often modified in transit
-Hard to determine distance
-Easy to determine sky location
-Easy to measure redshift

Electromagnetic counterparts

- GWs would allow to study GR in the strong field regime (alternative theories of gravity, population studies, test models of galaxy mergers, formation channels, determine the EoS at high densities ↔ nuclear interactions...)
- EM counterpart would allow to extract more information from the system (progenitor, environment) and the physical processes involved (plasma physics, accretion,...)

- Standard sirens *(Schutz 1986, Holz&Hughes 2005)*

  - analogous to the standard candles SNe

GW luminosity distance~1-10% (limited by gravitational lensing)

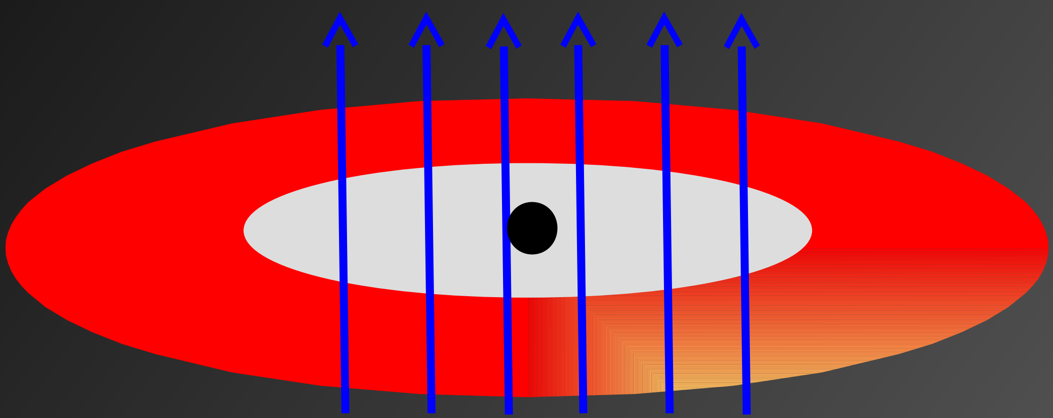
EM counterpart to localize the source in the sky and redshift

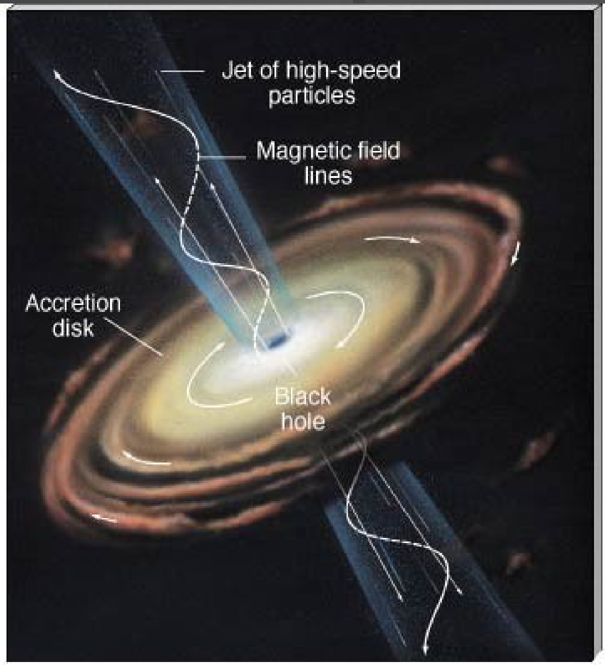
study the distribution of dark energy

Systems emitting in multiple bands

- 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 $M=10^8 M_\odot$

* bounded by the jets the : $B_0 < 10^4\text{-}10^6$ G (near the BH)
* Eddington magnetic field : $B_0 \sim 10^5$ G



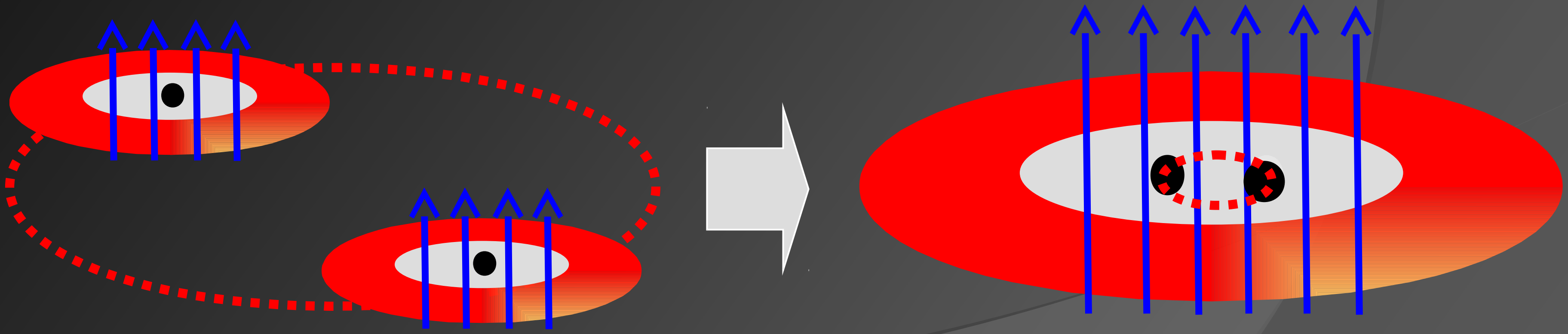


Motivation : merger of galaxies

- 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)

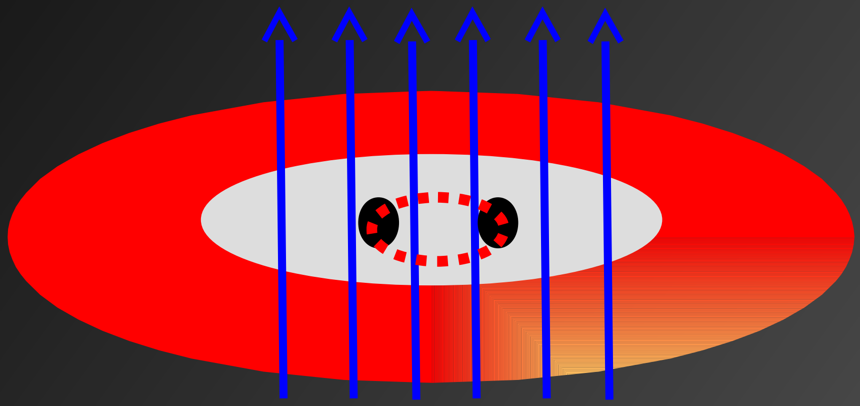
- eventually, the dynamics of the BH binary is dominated by GW, opening the gap



Motivation : merger of galaxies

- the luminosity of the disk is modified by the binary BH dynamics
- the merger can triger/enhanced the 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 disk
- Radiation processes due to the accretion, disk dynamic..

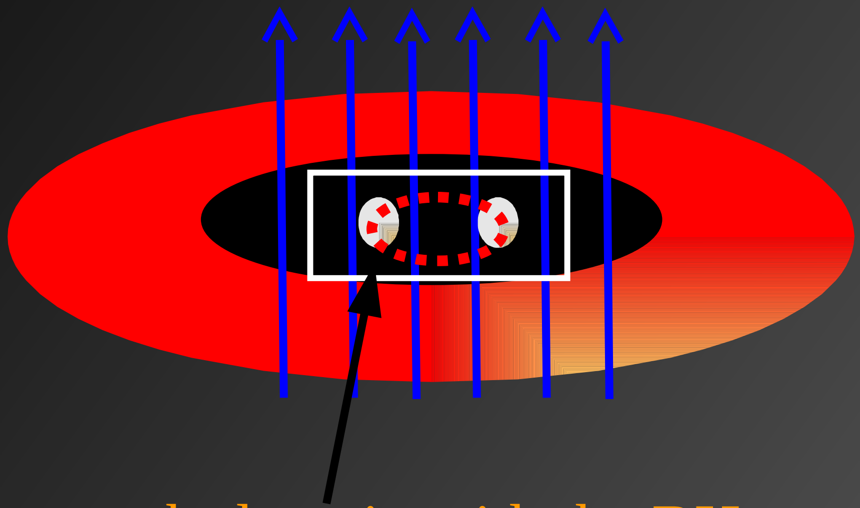
Zooming in on the black holes

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 et al 2010, Neilsen & CP et al 2011, Moesta & CP et al 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

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

The numerical algorithm

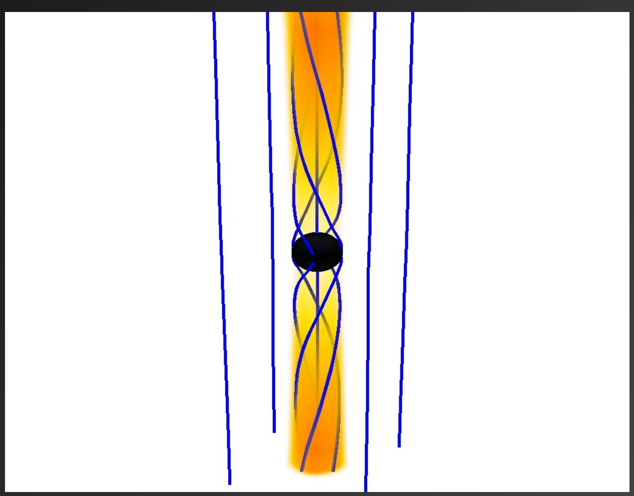
- Many scales in the problem → parallelization and AMR via “had”

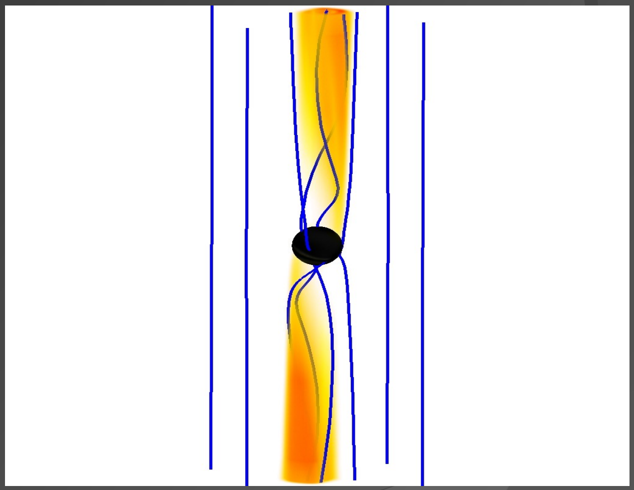
- Method of Lines for the evolution
  - * 3^{rd} order RK for the time integration
  - * 4^{th} order space discretization

Formulation	GH	BSSN
Infrastructure	Had	Had
Singularity	Excision	Puncture approach
Gauge	Harmonic	1+log lapse Gamma freezing

Single BHs in force-free environments : misaligned spinning case

- Consider first a single BH and vary the spin orientation wrt the asymptotic value of the magnetic field
- There is rotation of the EM field lines and net extraction of BH rotational energy → Blandford-Znajek mechanism





- 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

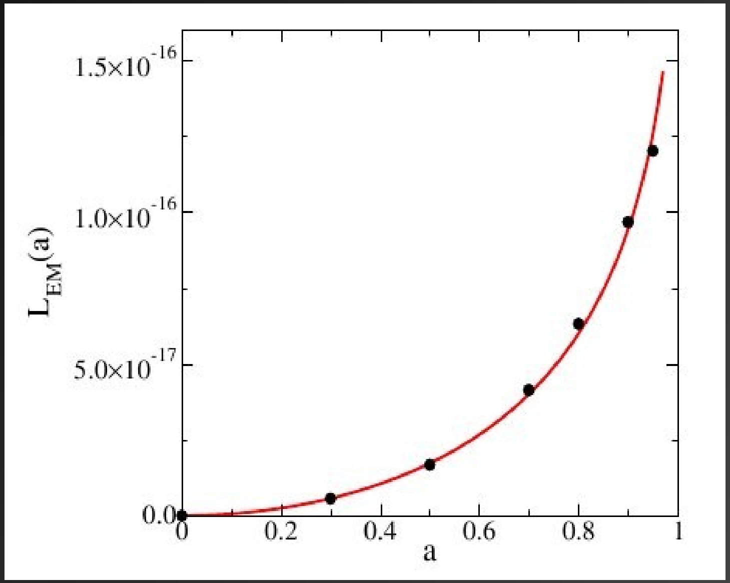
- Radiated power as a function of:

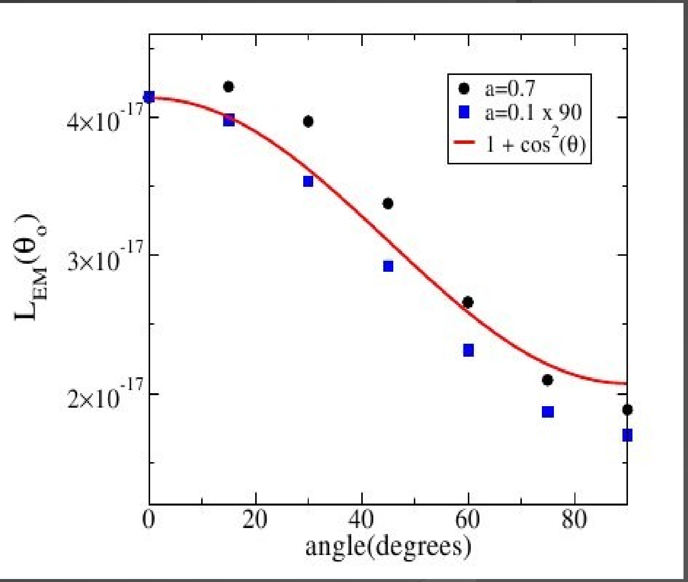
-the spin *(Mckinney 2010)*

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

-the inclination angle *(new!)*

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



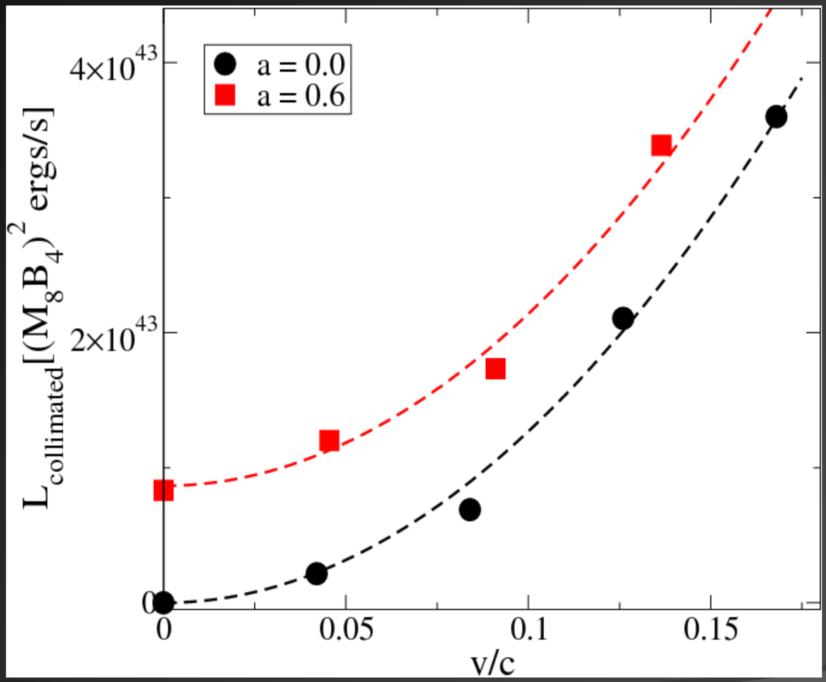


- In the case of pulsars, $L \sim B^2 R^6 \Omega^4 (1 + \sin^2\theta)$

Single BHs in force-free environments : boosted spinning case

- Consider a BH with a relative motion wrt the magnetic field.
- The resulting radiated power is a function of:

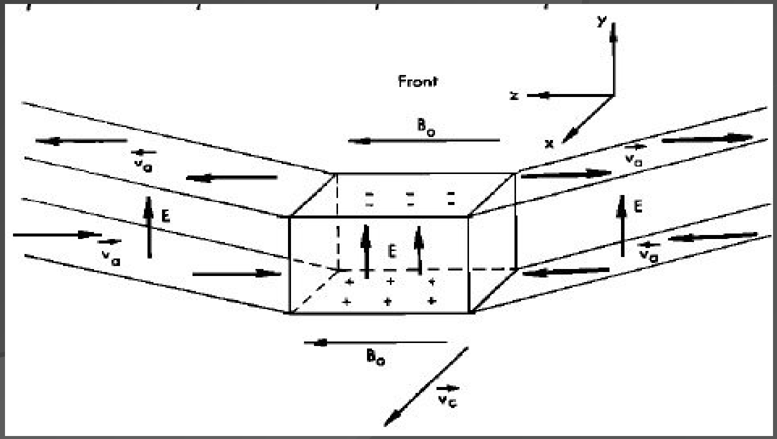
-the boost velocity $L \sim B^2 v^2$ *(new?)*



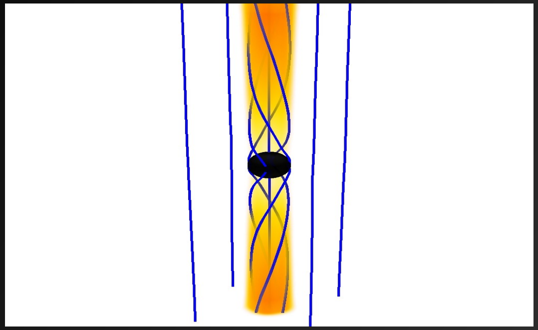
propulsion of satellites in the ionosphere

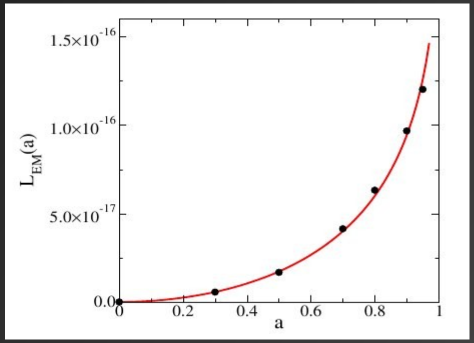
(Drell,Foley,Rudderman 1965)

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



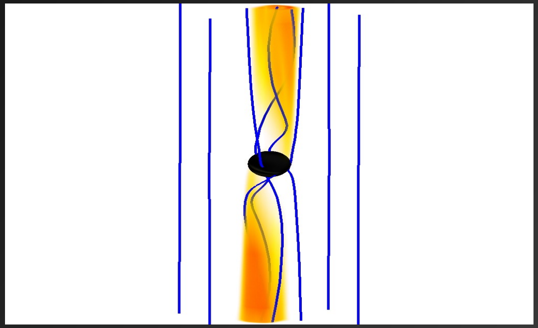
Single BH in force-free environments

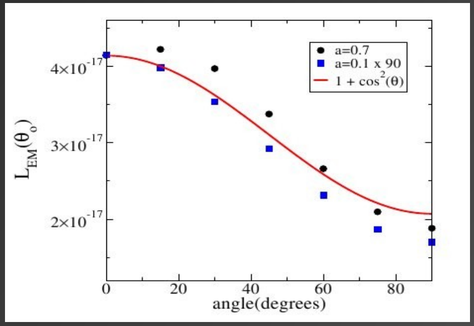




$L \sim B^2 a^2 \qquad a \leq 1$

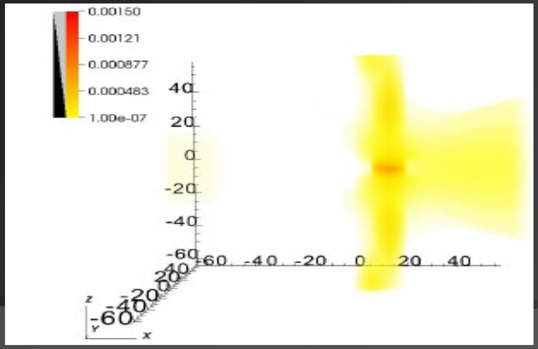
(McKinney 2010)

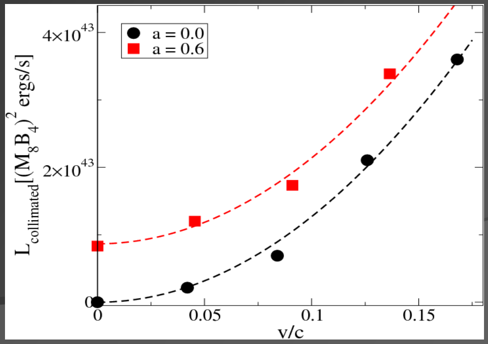




$L \sim (1 + \cos^2\theta)\, B^2 a^2$

(CP et al. 2010)





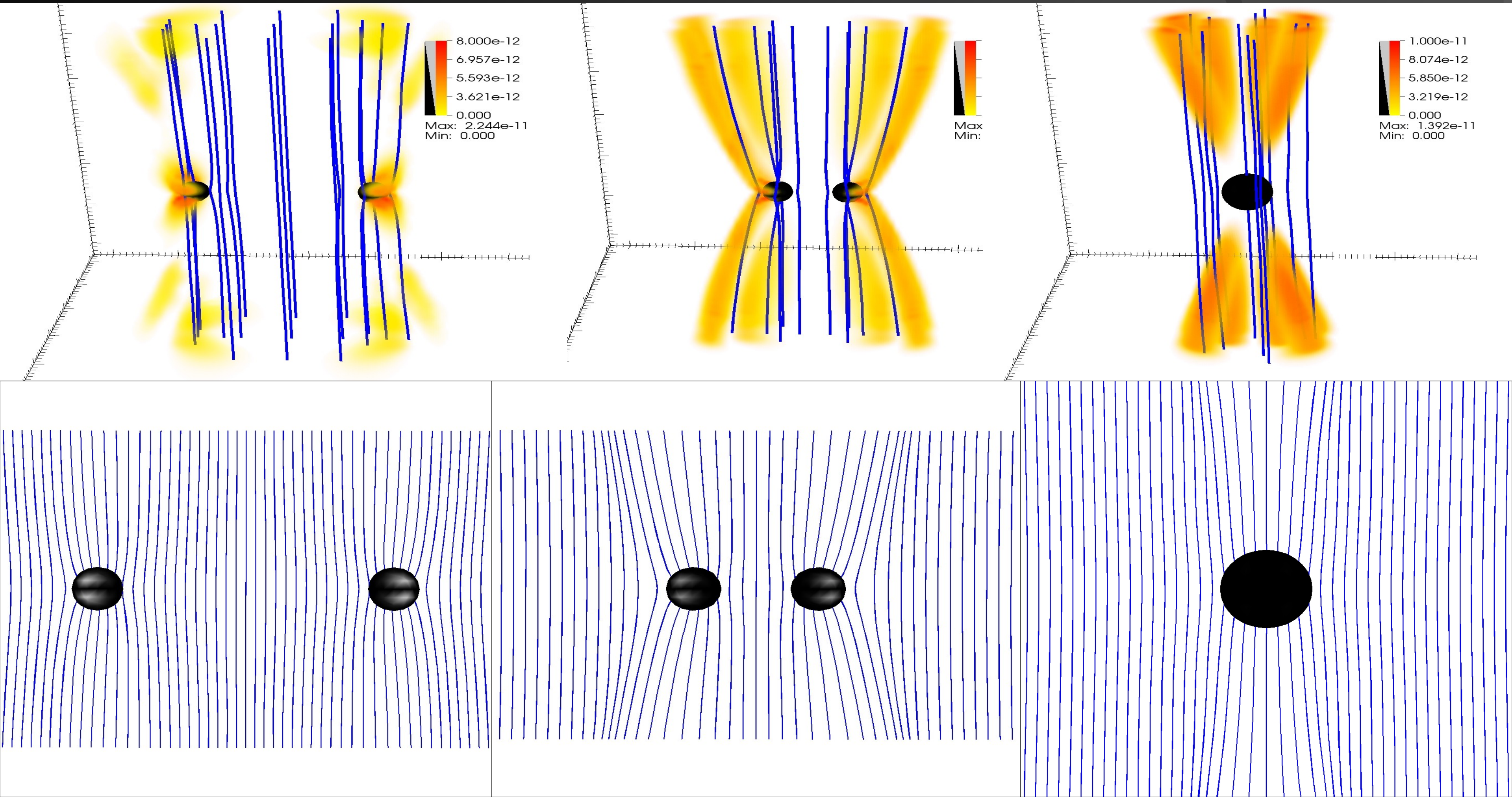
$L_{boost} \sim B^2 v^2$

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

(Neilsen,CP et al.2011)

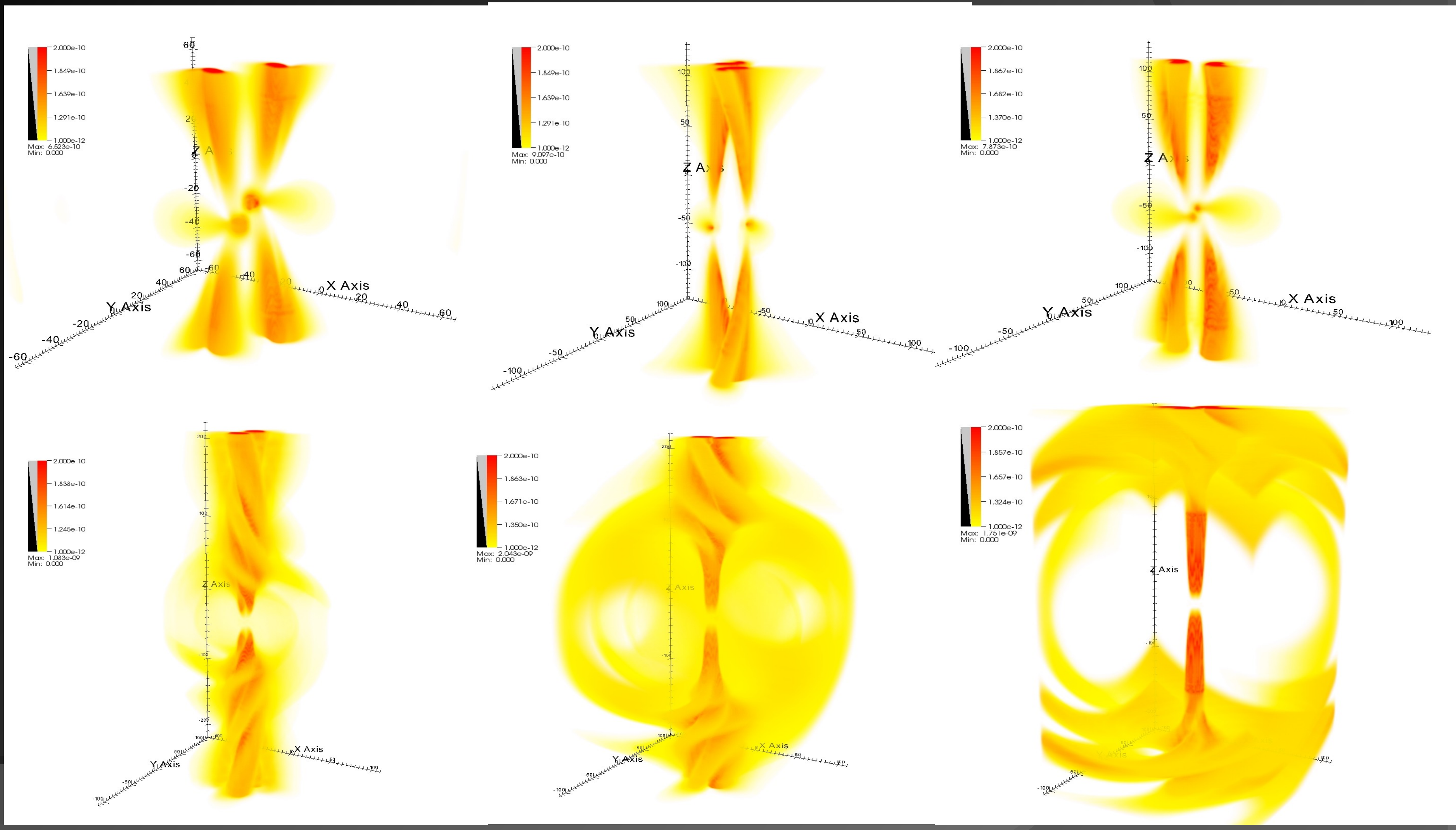
Binary black holes : head on

- Consider a head-on binary BH. Radiation is collimated



Binary BHs in force-free environment

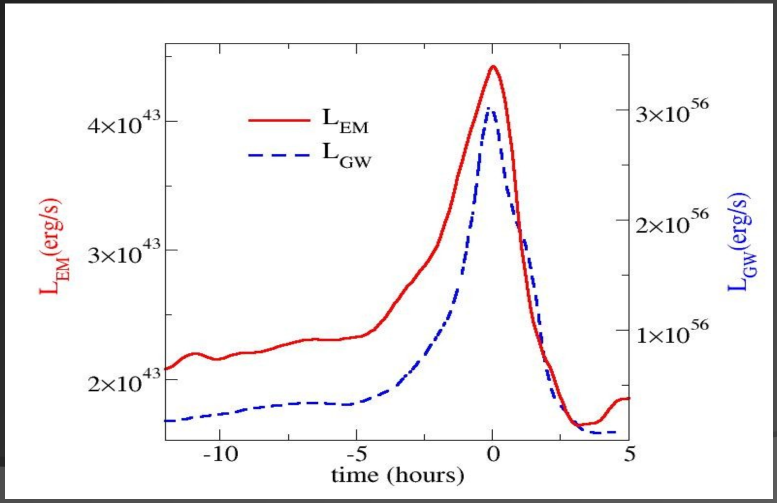
- Consider a binary during coalescence

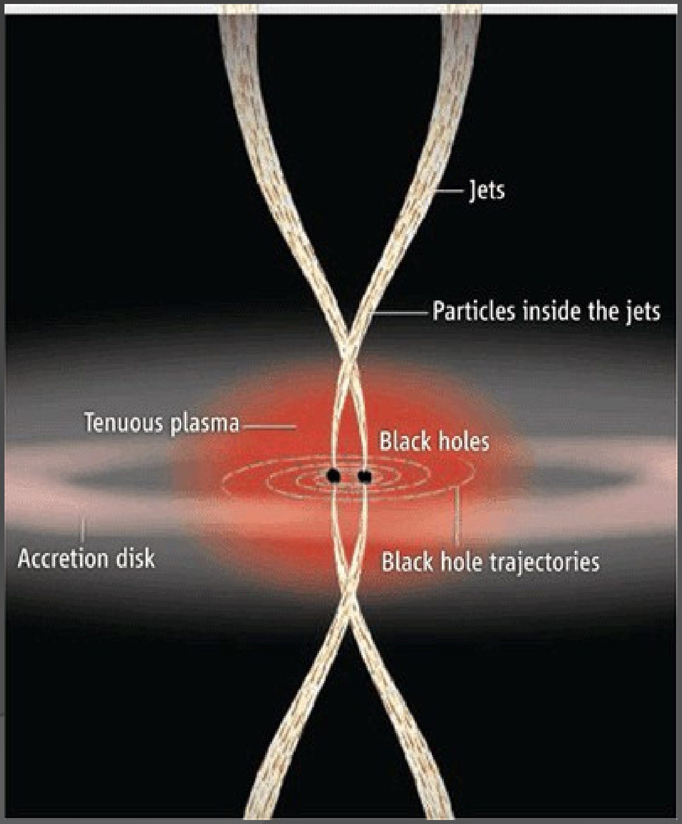


Binary BHs in force-free environment

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 et al, 2010)*

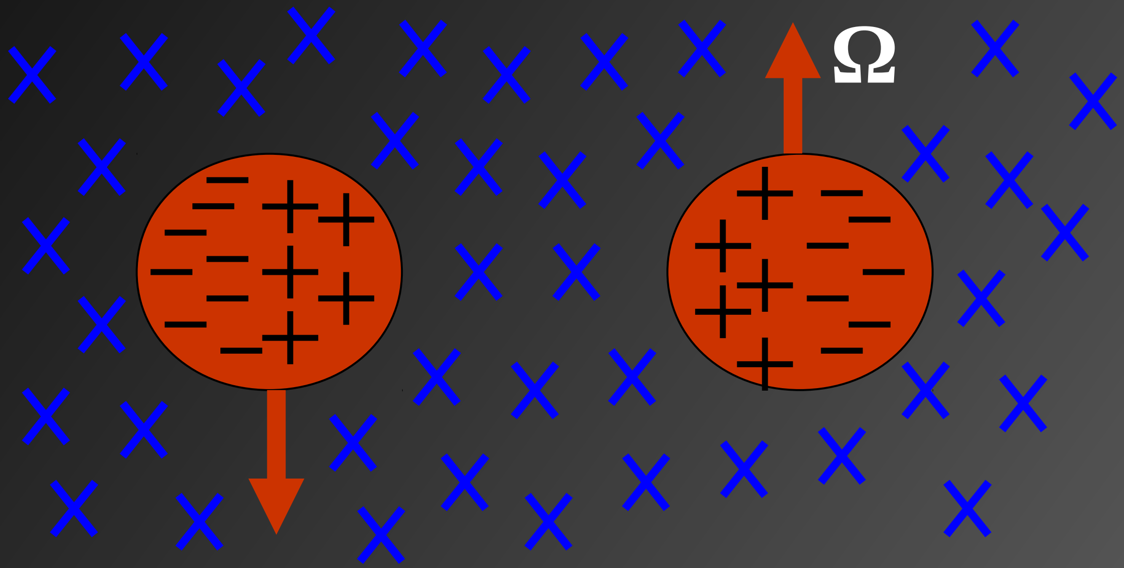
- dual jet structure during inspiral, join into a single jet after merge
- diffuse quadrupolar luminosity





Note 1: Membrane paradigm

- simple model based on the membrane paradigm

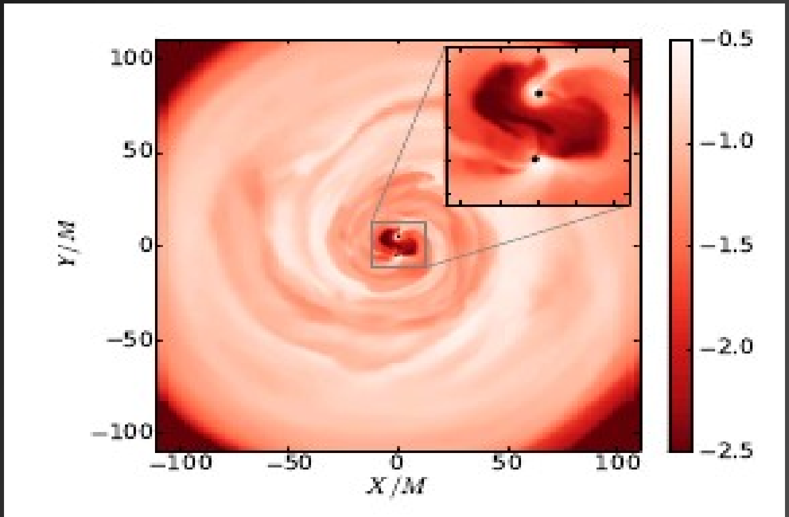


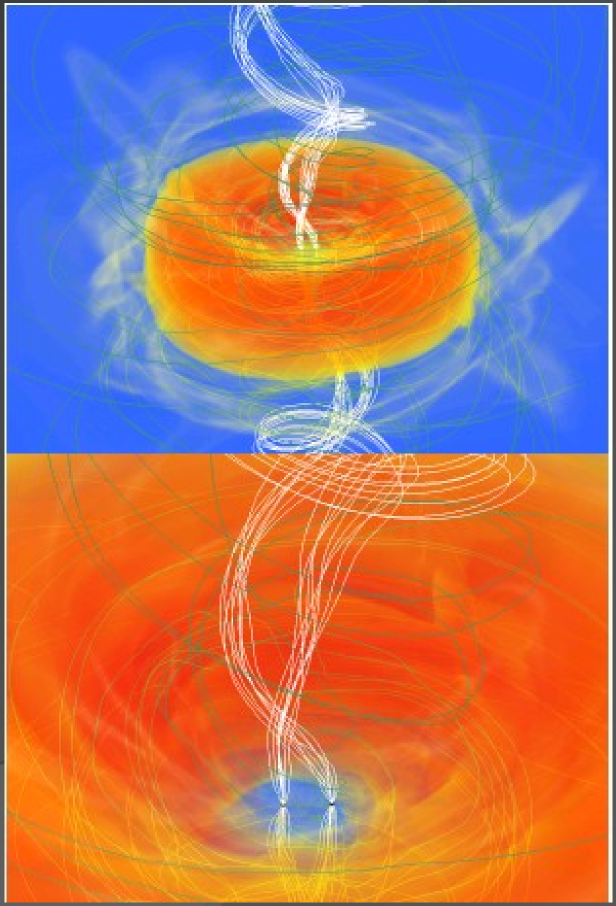
* there is a induced charge separation that can sustain a current and dissipate energy in the force-free medium

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..

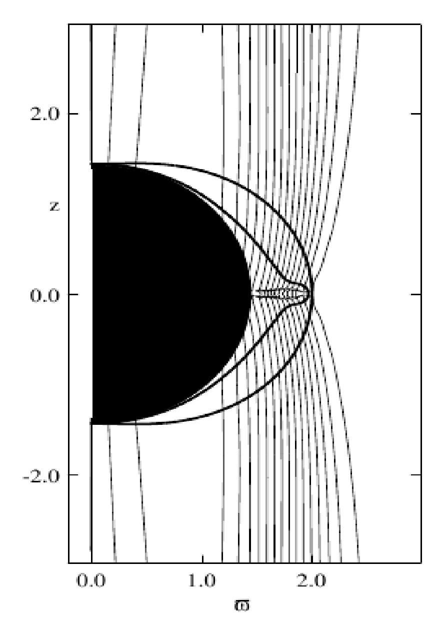
-Apparent Horizon (AH) : light surfaces are trapped

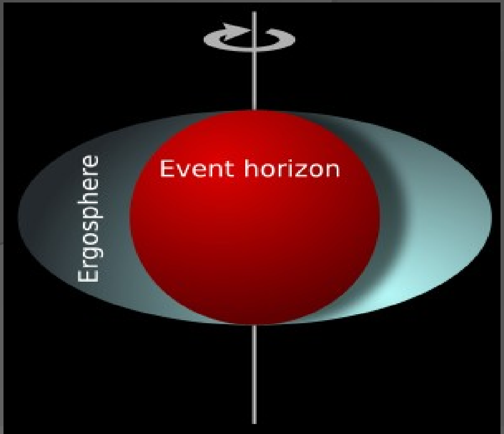
$$r_H = M + (M^2 - a^2)^{1/2}$$

- 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 “spinning” spacetimes

- Where is the energy coming from?
  - study regular spacetimes 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 ”fluid of the star)

BZ in regular spacetimes

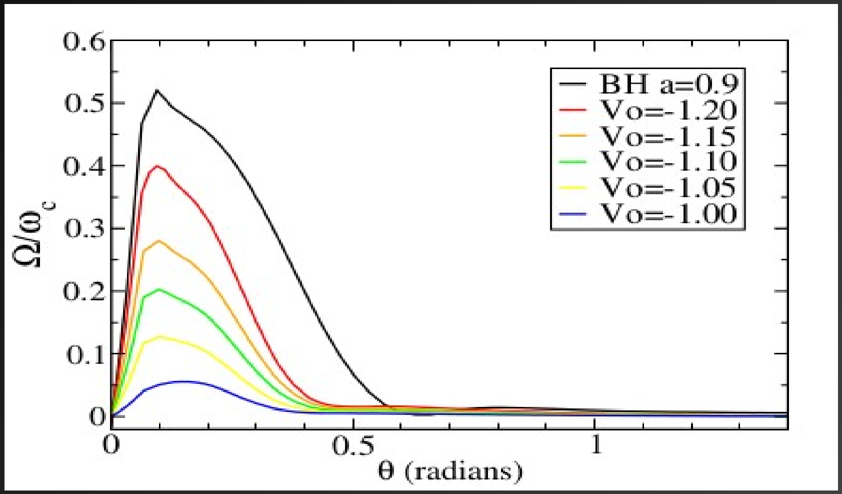
- Generalize the BZ power formula to any stationary and axisymmetric spacetimes, described by the Lewis-Papapetrou metric

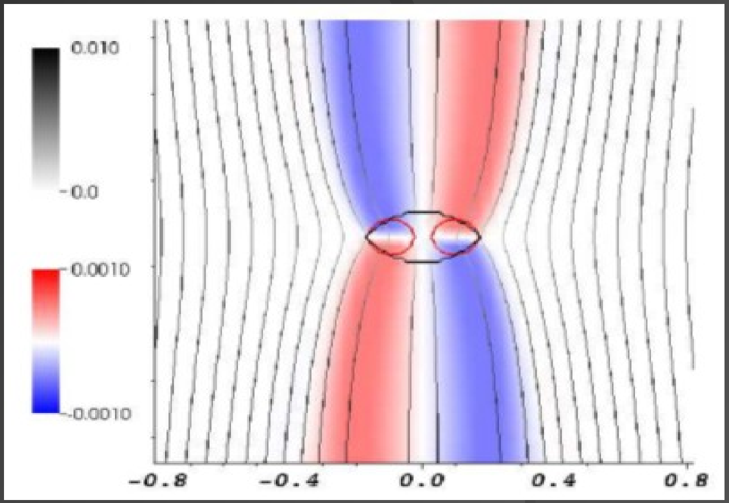
$$ds^2 = -\alpha^2\, dt^2 + g_{\phi\phi}\,(d\phi - \omega\, dt)^2 + g_{rr}\, dr^2 + g_{\theta\theta}\, d\theta^2\,,$$

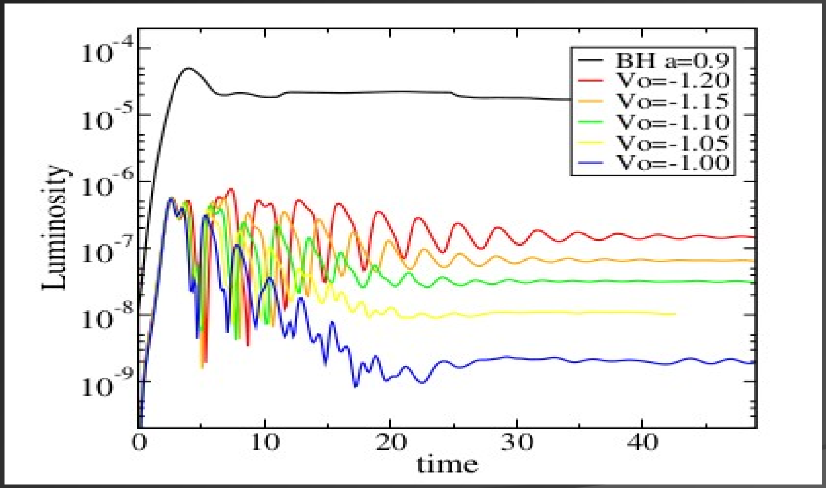
The EM energy flux density for this metric is

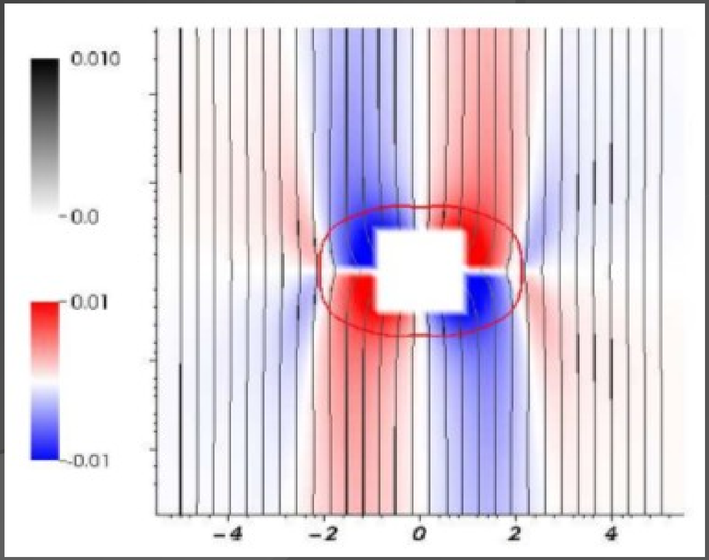
$$S^r_\xi = -\frac{\Omega}{2\,\pi}\, B^r\, B^\phi\, \alpha^2\, g_{\phi\phi}$$

BZ in regular spacetimes

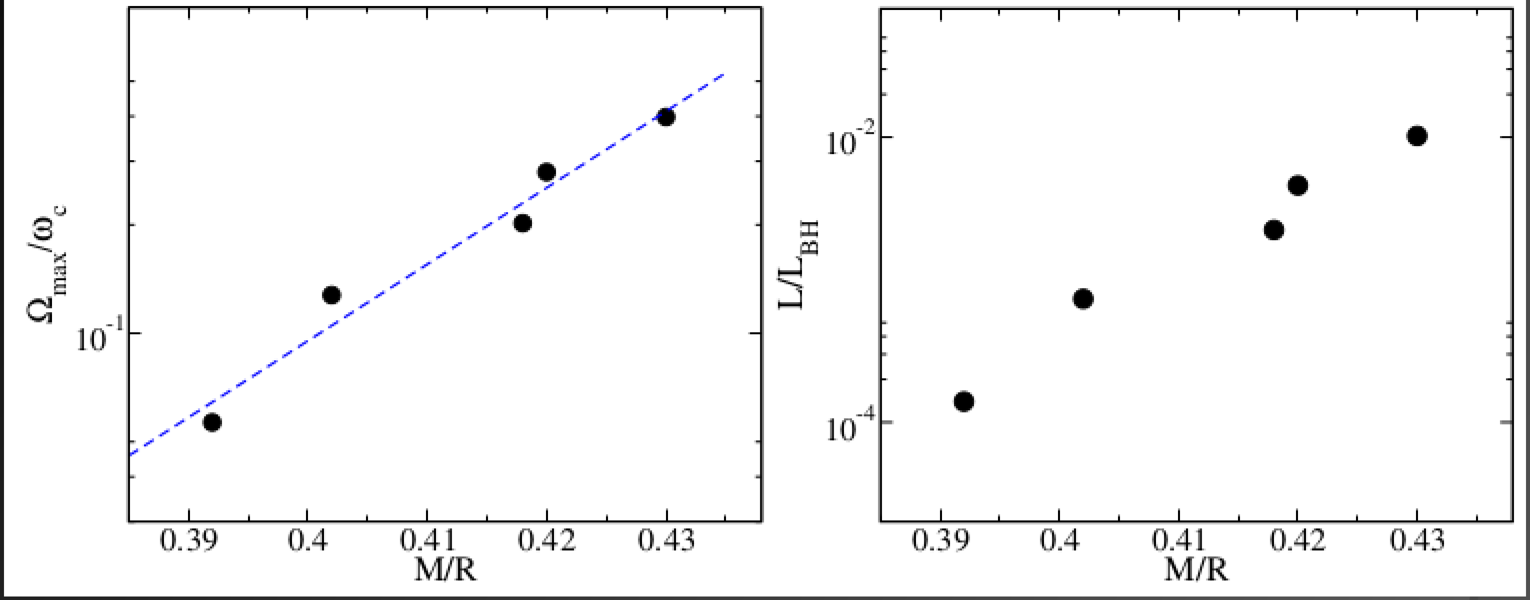








BZ in regular spacetimes



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

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

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

Summary

- A force-free environment can extract both the rotational and the translational kinetic energy of a BH
- In the case of a binary, it will produce a dual jet with some features that could be detectable
- The key ingredient seems to be the ergosphere

Supermassive black hole mergers

- observations indicate the presence of supermassive BHs in the center of galaxies (Kormendy & Richstone 95), surrounded by gas and an accretion disk

- in the Active Galactic Nuclei (AGN), the BHs are surrounded by a disc of matter likely magnetized

- galaxies has undergone some merger during their lifetimes

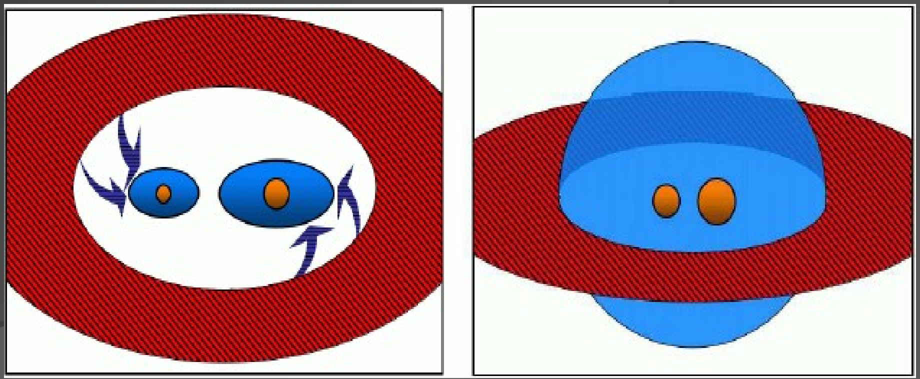
- Galaxy mergers involves a very large range of scales, going from galaxy merger ~ 10^2 $(M/10^6 M_\Theta)$ kpc to binary BH dynamics dominated by GW emission ~ 10^{-3} $(M/10^6 M_\Theta)$ pc

The gas surrounding the binary BHs

- The stellar and gaseous environment extracts the angular momentum from the binary until gravitational radiation becomes important and induces the coalescence (Begelman et al 80, Roos 81, Merrit & Milosavljevic 95)

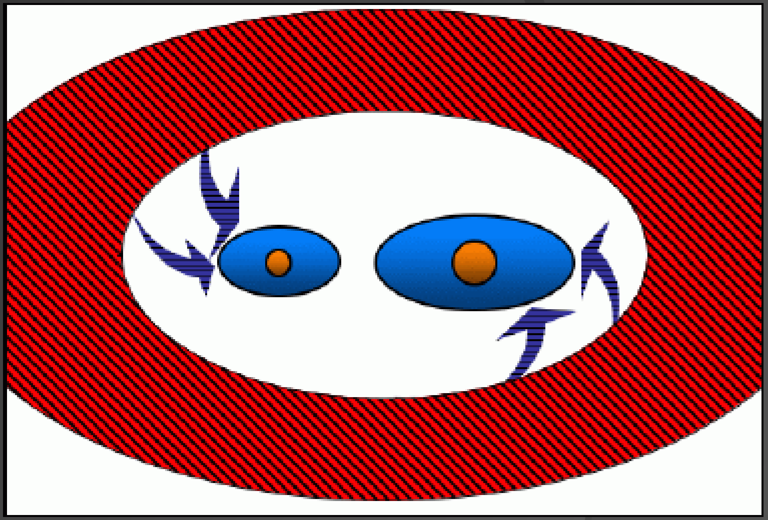
- Depending on the balance between heating and cooling mechanism in the accretion disk (Bogdanovic et al 2009)
  - radiative inefficient accretion flows (RIAF) → hot gas cloud
  - efficient cooling → circumbinary disk

Study numerically the EM (from the environment) and GWs (from the binary) emitted during coalescence in these two scenarios!!



The circumbinary disk

- If the gas is not so tenuous the ions and electrons are thermally coupled → can cool efficiently through the electrons



- Gas settles into a geometrically thin circumbinary disk, rotationally supported radially, and pressure supported vertically in the central part

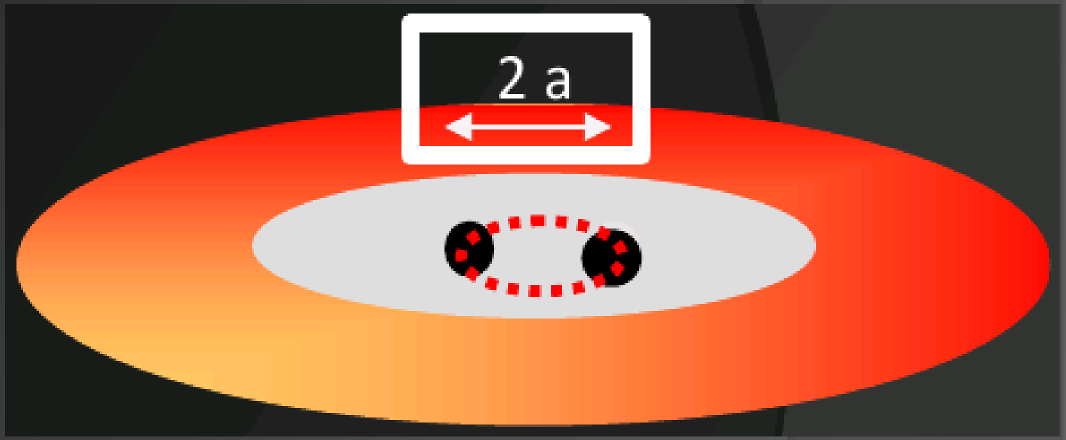
- The binary torques can evacuate most of the gas near the binary, producing a hollowed region with a surface density much smaller than in the disk (Armitage and Natarajan 2002; Milosavljevic and Phinney 2005; MacFadyen and Milosavljevic 2008; Cuadra et al. 2009)

Circumbinary disk dynamics

For r<<a the gas accretes into the BH, creating a hollowed region. The disk is truncated at the inner edge, where the binary torques ~ viscous stresses (Milosavljevic and Phinney 2005 and references therein)

$$t_{GW} = \frac{5\, c^5\, a^4}{64\, G^3\, M^3} \frac{(1+q)^2}{q} \sim a^4$$

$$t_{visc} = \frac{2\, r^2}{3\, \nu(r)} \sim r^2$$



- - early inspiral $t_{GW} >> t_{visc}$ → disk's edge follows the binary with r_{edge} ~ few a (Newtonian)
  - decoupling time $t_{GW} \sim t_{visc}$ (Relativistic fluid)
  - late inspiral $t_{GW} << t_{visc}$ → disk radius frozen (Fully relativistic)