Title: Recent results from simulating accretion and jets in strong gravity environments

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Abstract:

# Electromagnetic precursors of compact binary mergers

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February 15, 2010

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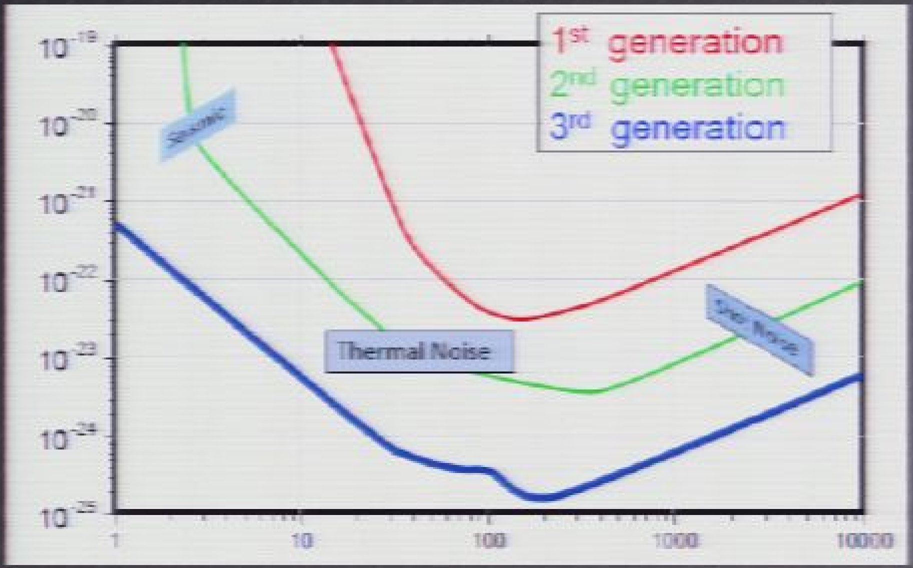
# Overview

* I. Introduction
  - correlations between the EM and GW spectrum
* II. EM precursors for LISA
  (supermassive black holes and the merger of galaxies)
  - electrovacuum environment
  - force-free environment
* III. EM precursor for LIGO
  (binary neutron stars and mixed binaries)
* IV. Summary

# I. INTRODUCTION

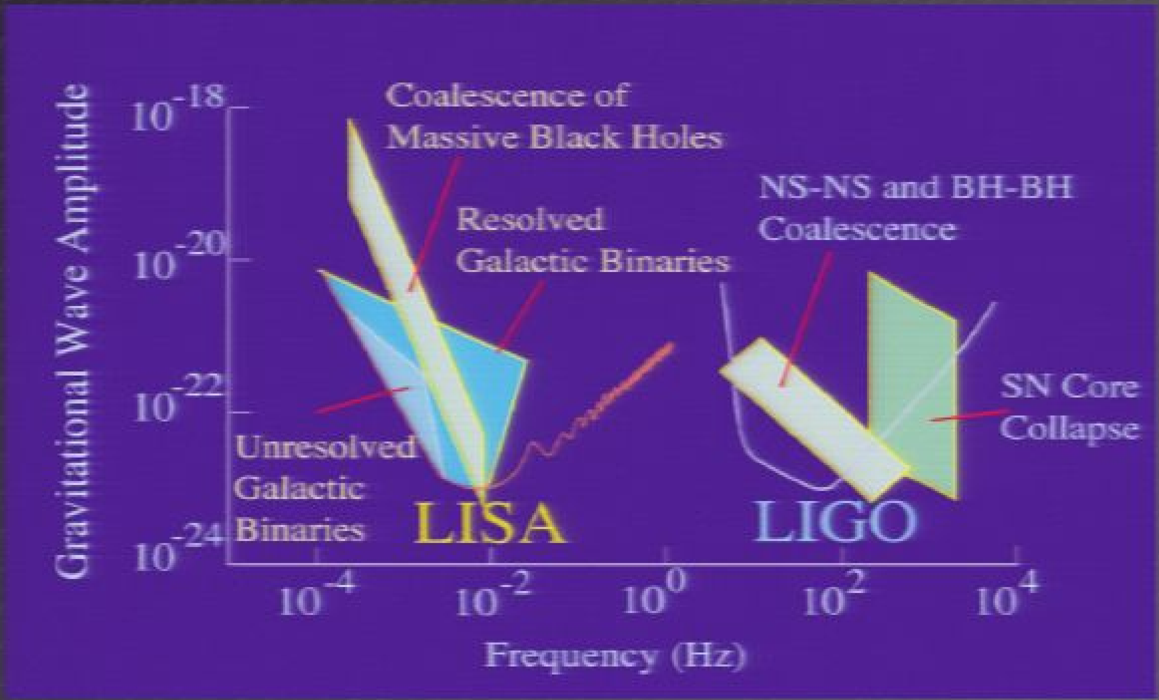
# I. GW astronomy (on the ground)

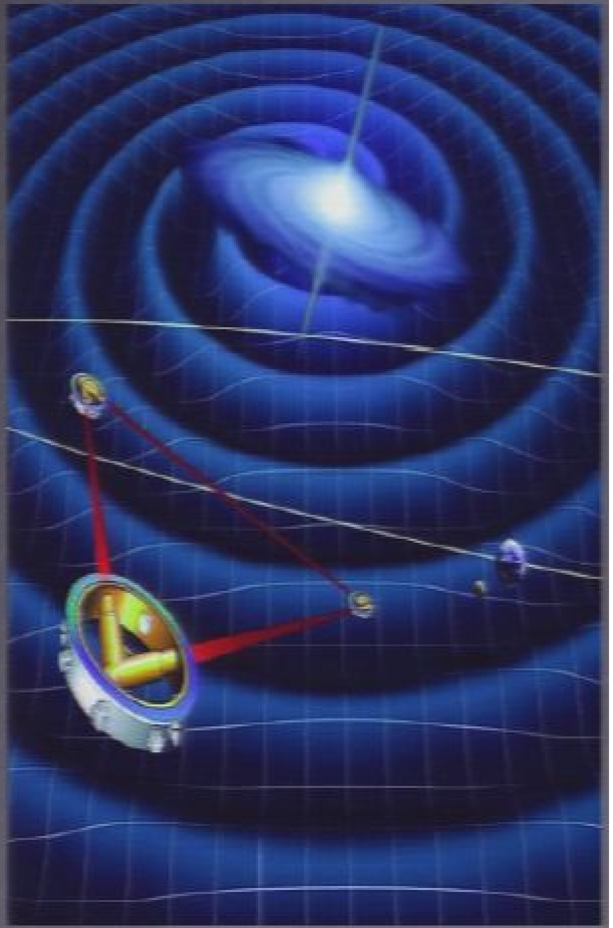
- the first generation of ground detectors of GW is already operating -LIGO-, second is being build, third is in project (ET)




# I. GW astronomy (on the space)

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



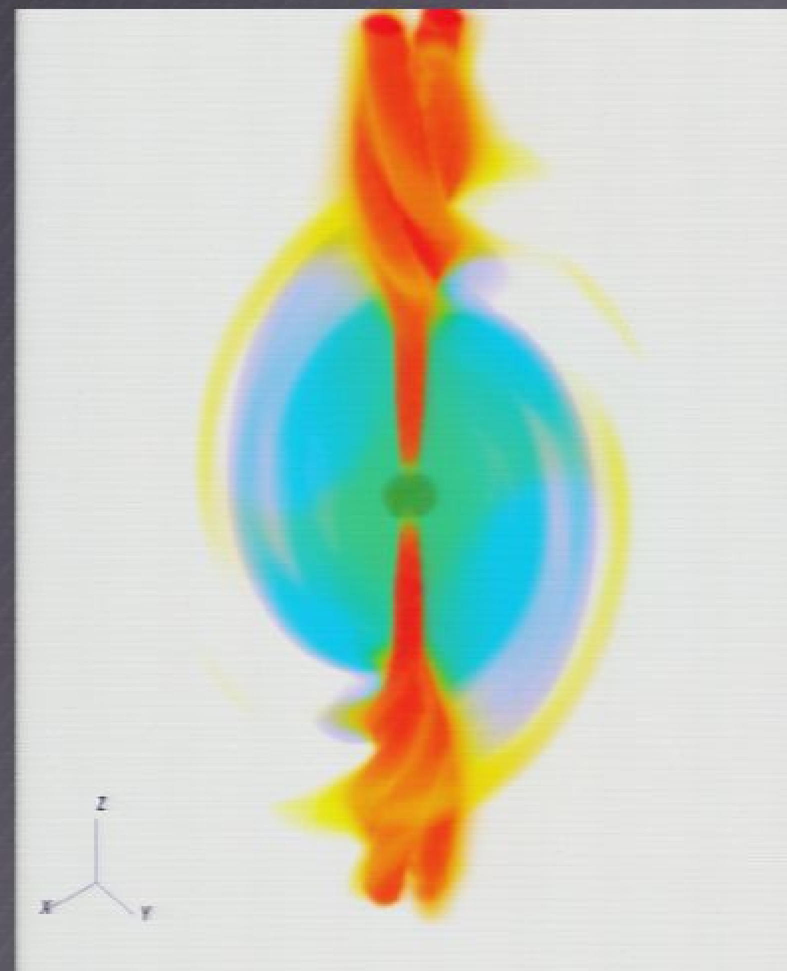



# I. EM counterparts

- study systems emitting in both bands (GW and EM) to extract more information

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

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



# II. EM PRECURSORS FOR LISA

## Supermassive black hole binaries

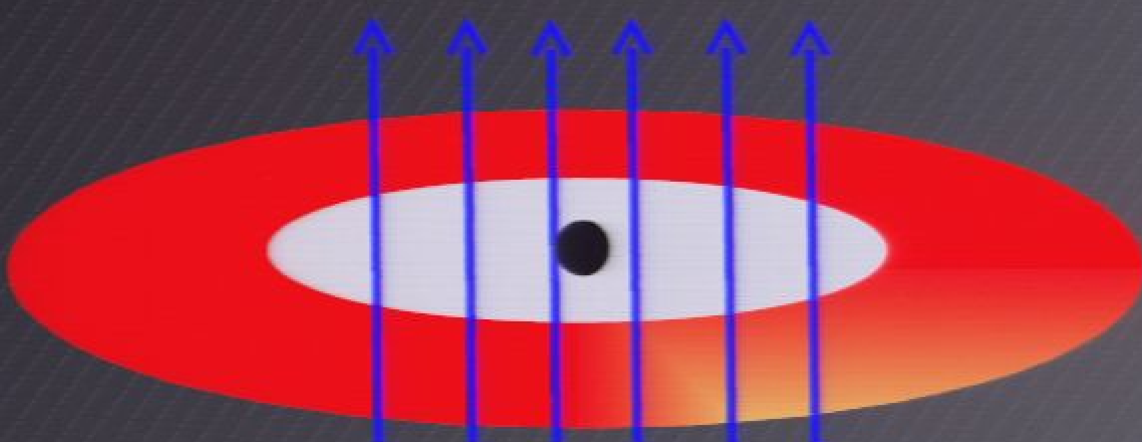
# II. Supermassive BH & EM fields

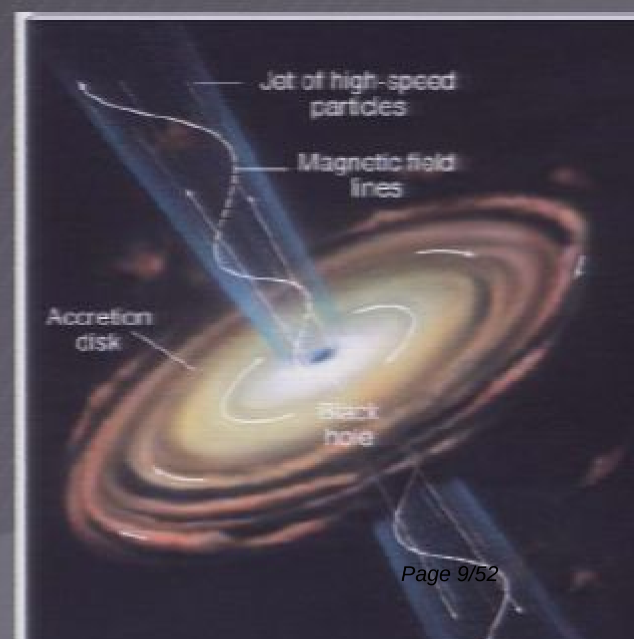
-observations indicate the presence of supermassive BHs in the center of galaxies, surrounded by gas and an accretion disk

- 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





# II. 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, opening the gap

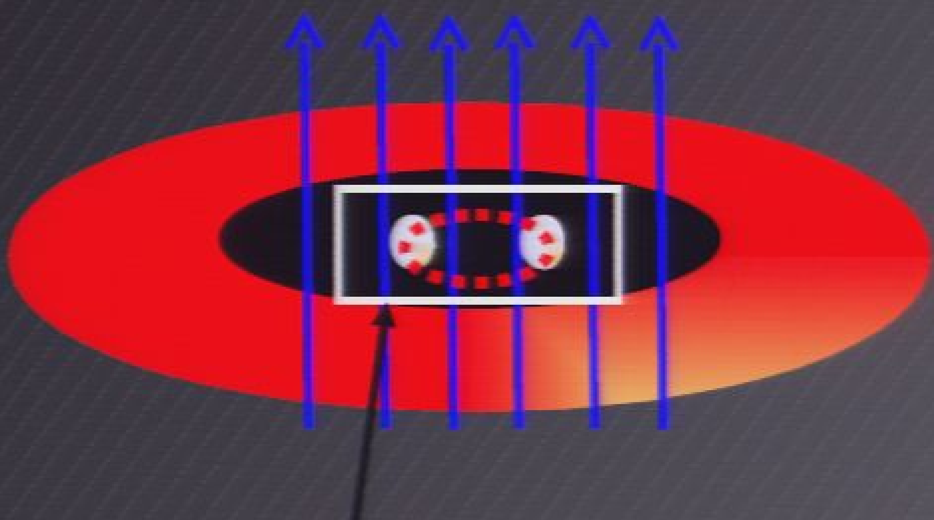
# II. Merger of galaxies

- the merger can enhanced some Blandford-Znajeck mechanism
- the luminosity of the disk is modified by the binary BH dynamics
- 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..

# II. EM counterpart: precursors

- before/during the merger (CP,Lehner et al, PRL09,Science10):
  * study the effects of the binary BHs dynamics in the EM fields
    - the EM radiation may modify the disk structure
    - the EM radiation can be transferred to particles and produced an observable emission



- 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

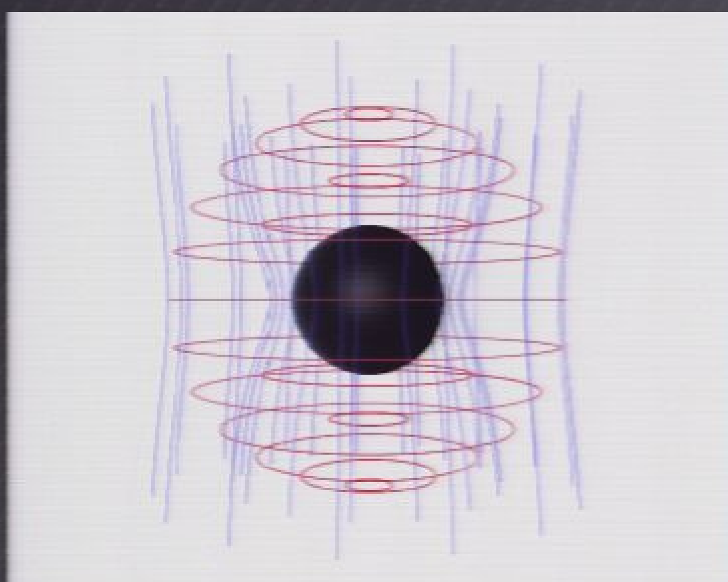
# II. The numerical code

- 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

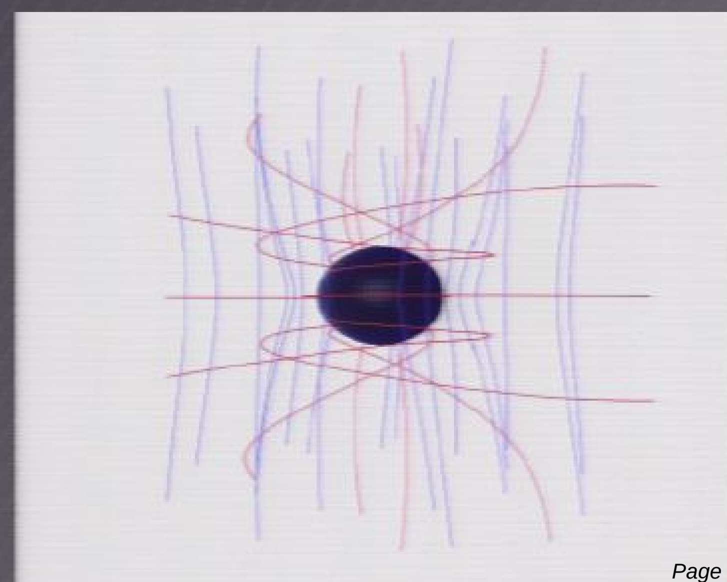
| | GH | BSSN |
|---|---|---|
| Infrastructure | Had | Cactus/Had |
| Singularity | Excision | Puncture approach |
| Gauge | Harmonic | 1+log lapse<br>Gamma freezing |

# II. Electrovacuum (J=q=0)

- 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

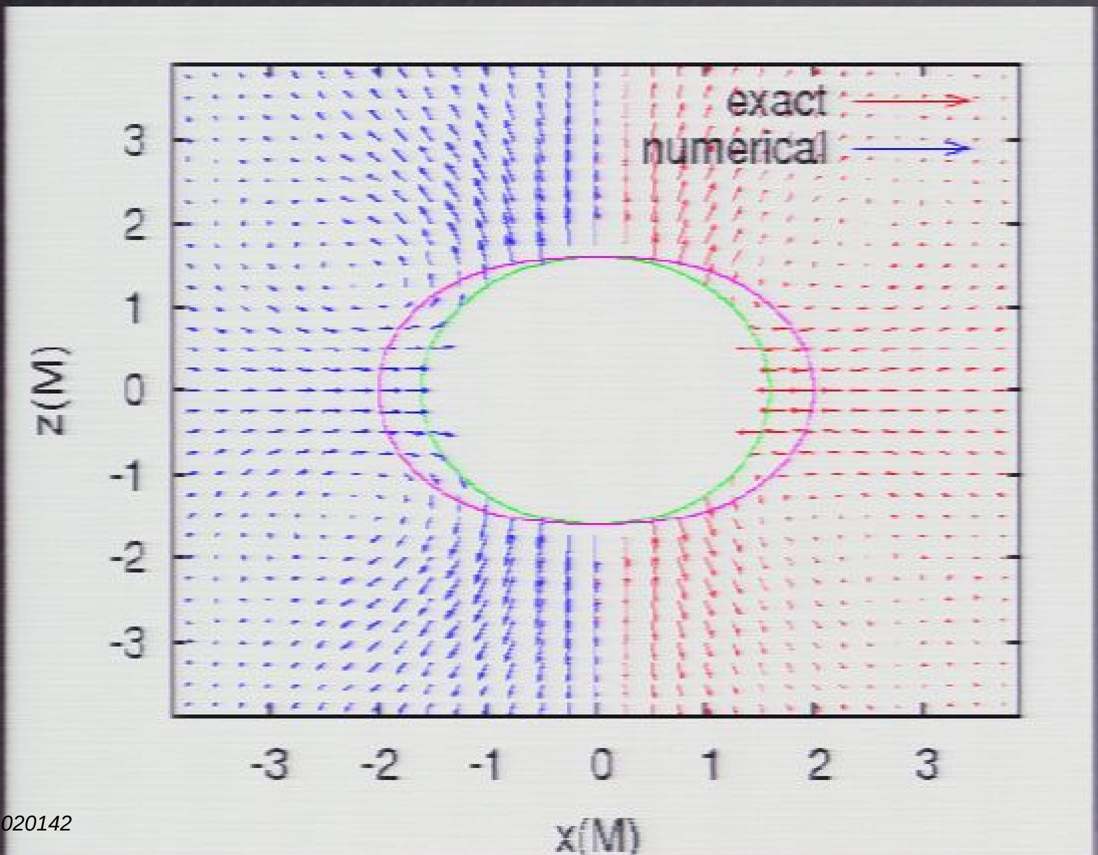


spin a=0.7

# II. Electrovacuum (single BH)

- fixed spacetime: Kerr in Kerr-Schild coordinates

electric field for spinning case (a=0.7)



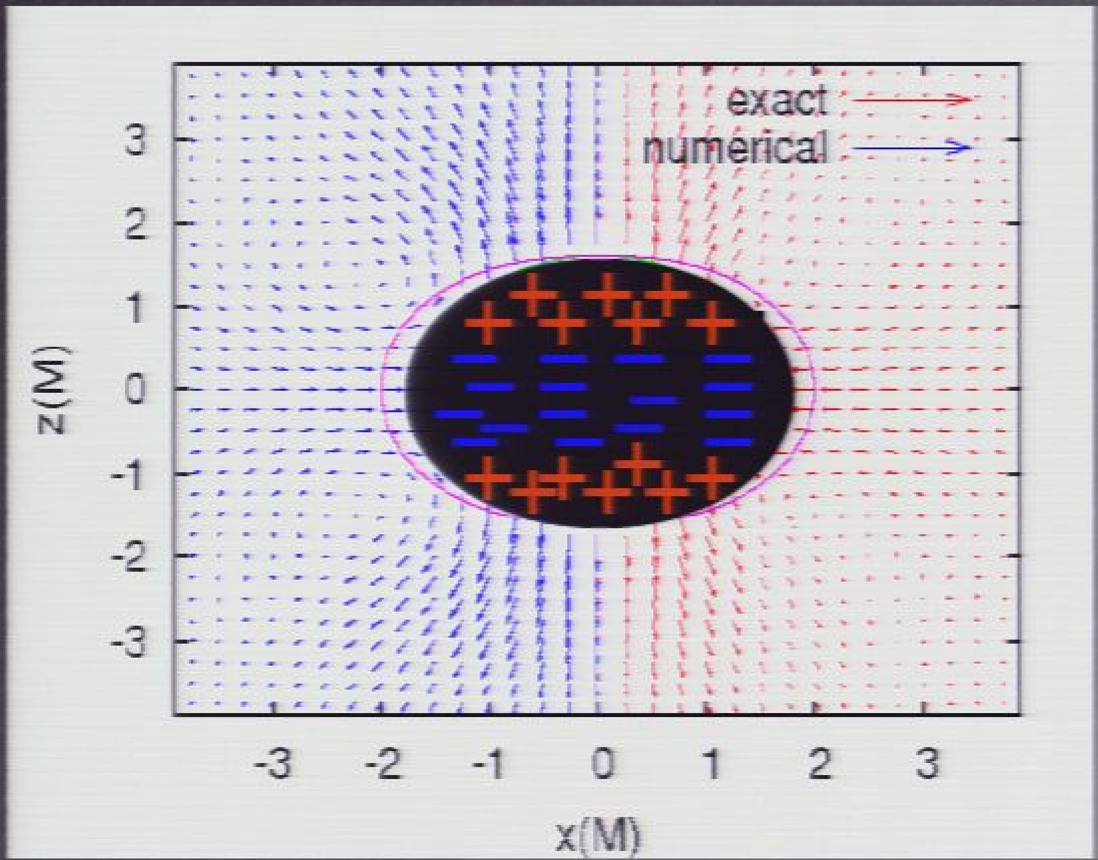

- Exact solution for a BH immersed in a external magnetic field aligned with the spin (Wald 1974)

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

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

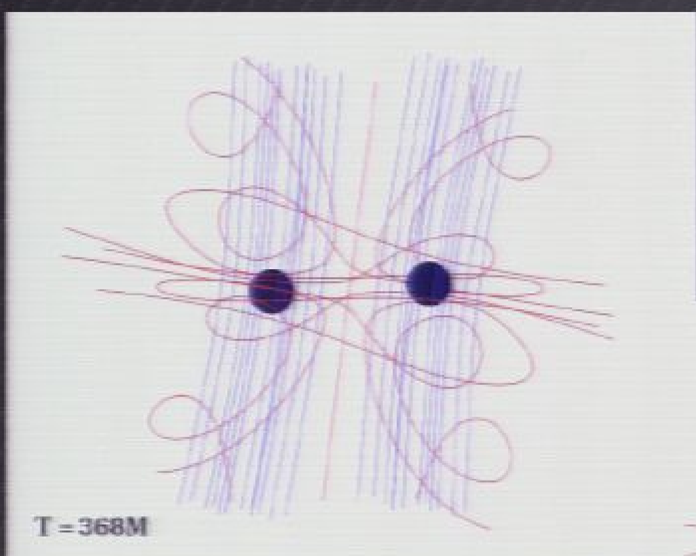
# II. Electrovacuum (single BH)

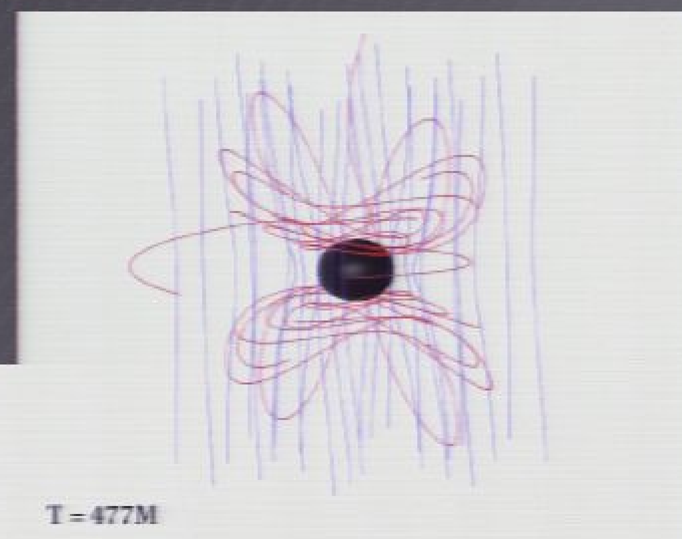
- membrane paradigm (Thorne,Price,MacDonald 1986): density charge endowed to the Apparent Horizon

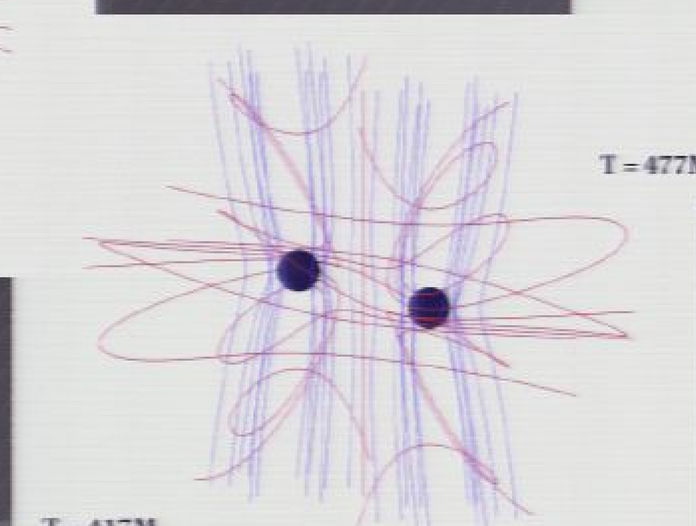


# II. Electrovacuum (binary BHs)

- 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



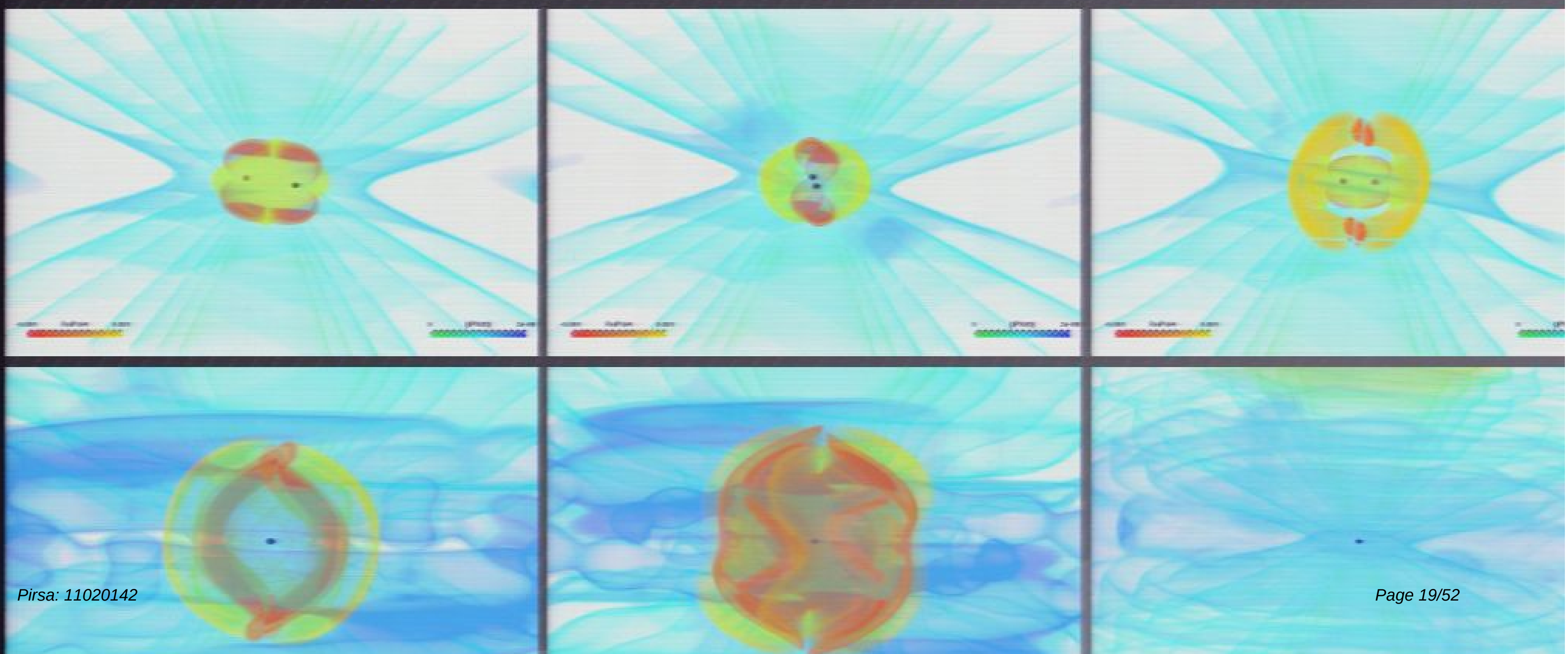



# II. Electrovacuum (binary BHs)

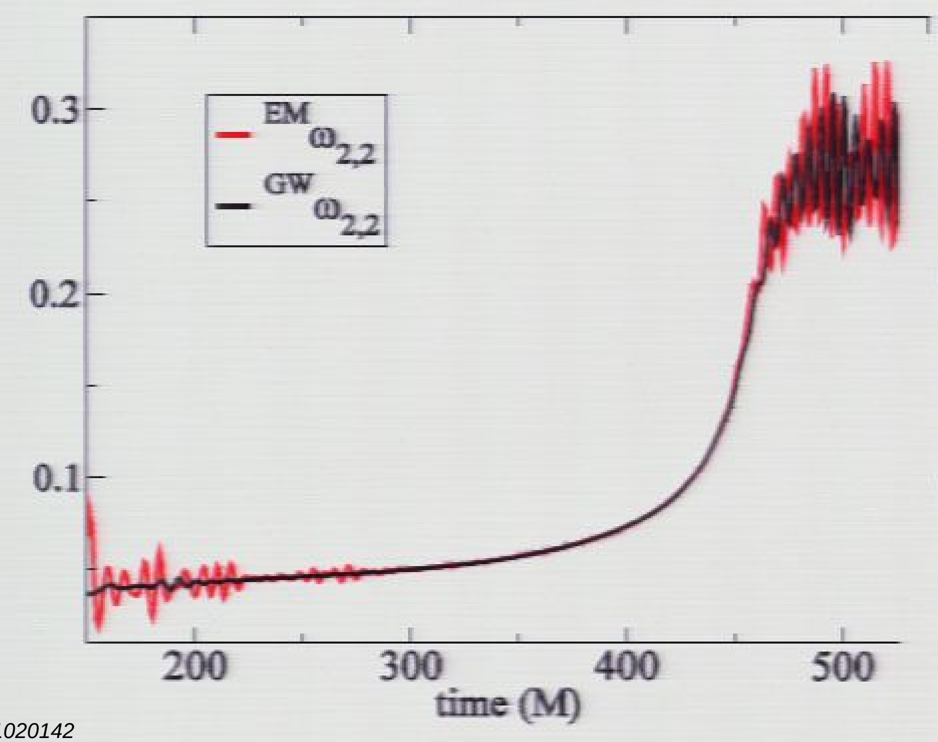
- compute the GW & EM radiations via Newman-Penrose scalars

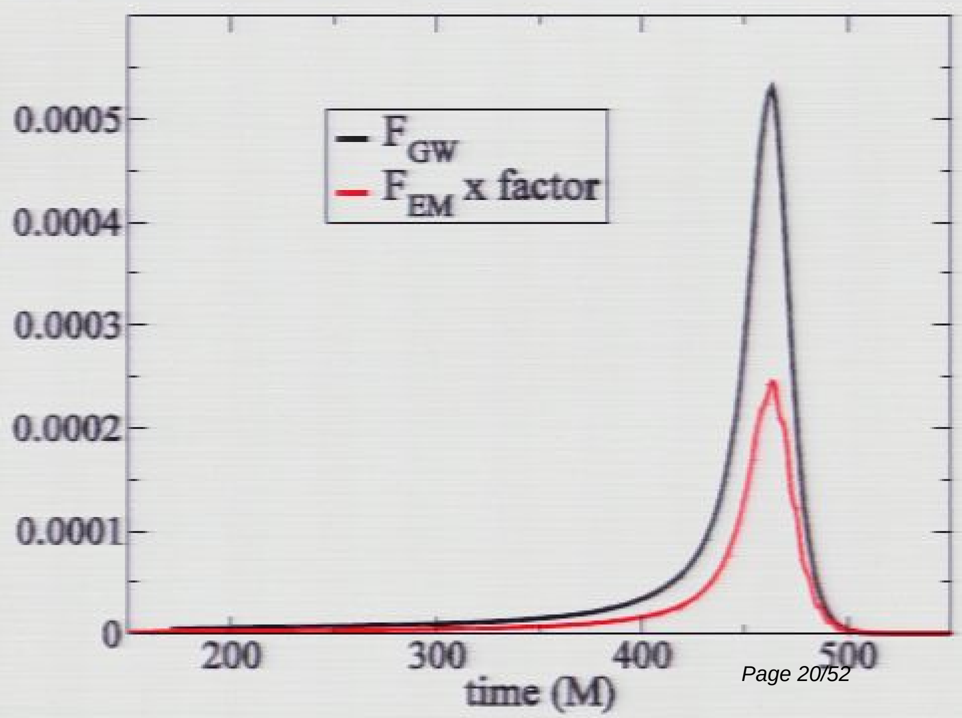
$$\Psi_4 = R_{abcd}\, k^a\, {}^*m^b\, k^c\, {}^*m^d \qquad \Phi_2 = F_{ab}\, k^a\, {}^*m^b$$



# II. Electrovacuum (binary BHs)

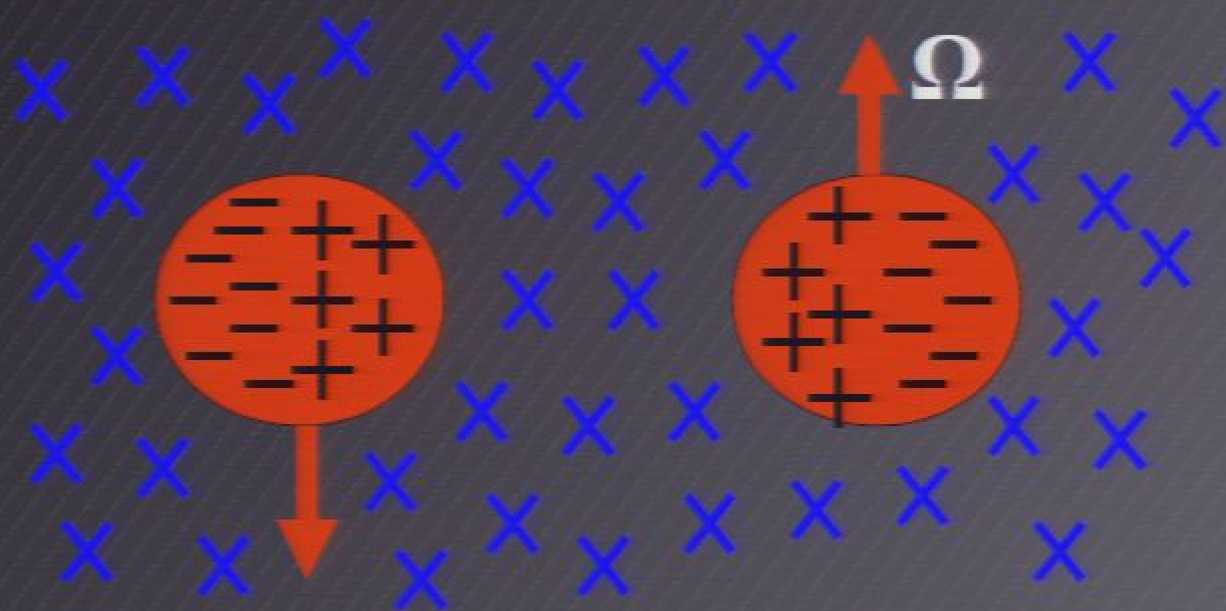
- mode decomposition shows a quadrupolar nature for both the GW and EM modes → the EM radiation mimics the GW
- the modes have the same frequency and radiated energy shape



# II. Electrovacuum (binary BHs)

- simple model based on the membrane paradigm

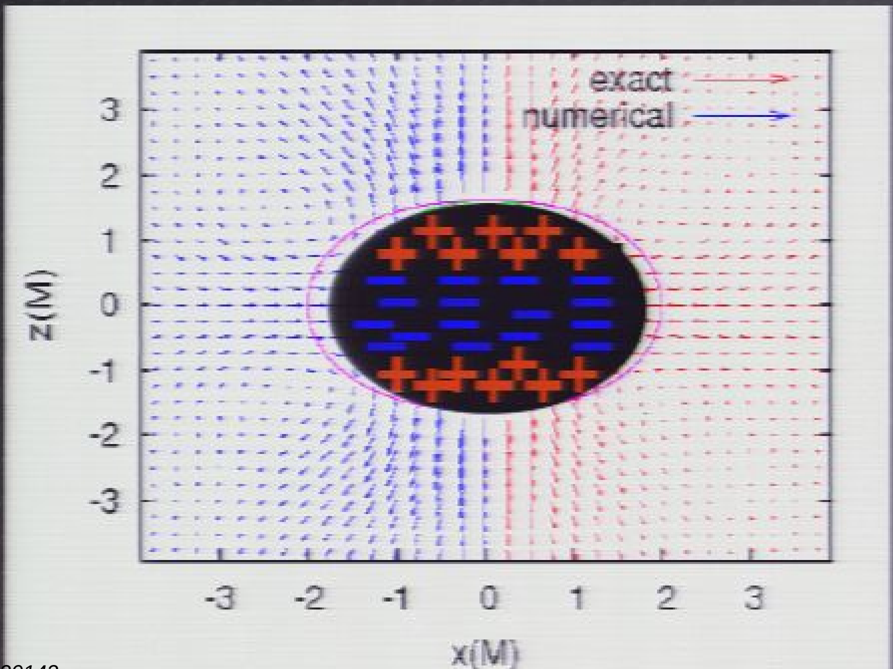



* there is a induced charge separation→ electric quadrupole

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

# II. Kerr+B = unstable to pair production !

- Wald solution by assuming J=q=0, stationarity ($\partial_t \rightarrow 0$) and axisymmetry ($\partial_\varphi \rightarrow 0$), for a BH inmersed on a external magnetic field aligned with the spin




- the EM fields can not extract energy from a stationary BH

- there is an induced E field with

$$E \cdot B \neq 0$$

- unstable to pair production : magnetized tenuous plasma surrounding the BHs

# II. The Force-free approximation

- Spinning BH + magnetic field → surrounded tenuous plasma

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

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

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

$$J_\perp = q\, E \times B / B^2$$

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

# II. The Blandford-Znajek mechanism

- By using these conditions, we can compute the EM energy flux around a BH

$F_E \sim -T^r_t$

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

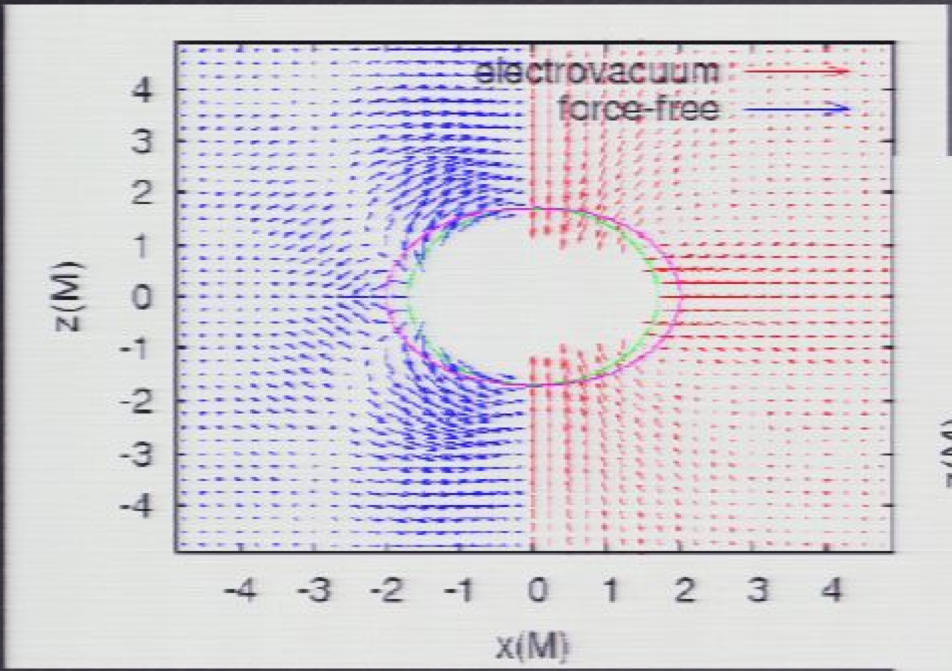
- at the AH, $\Delta$=0 and we define the rotation frequency of the BH like $\Omega_H = a/(2*M*r_H)$

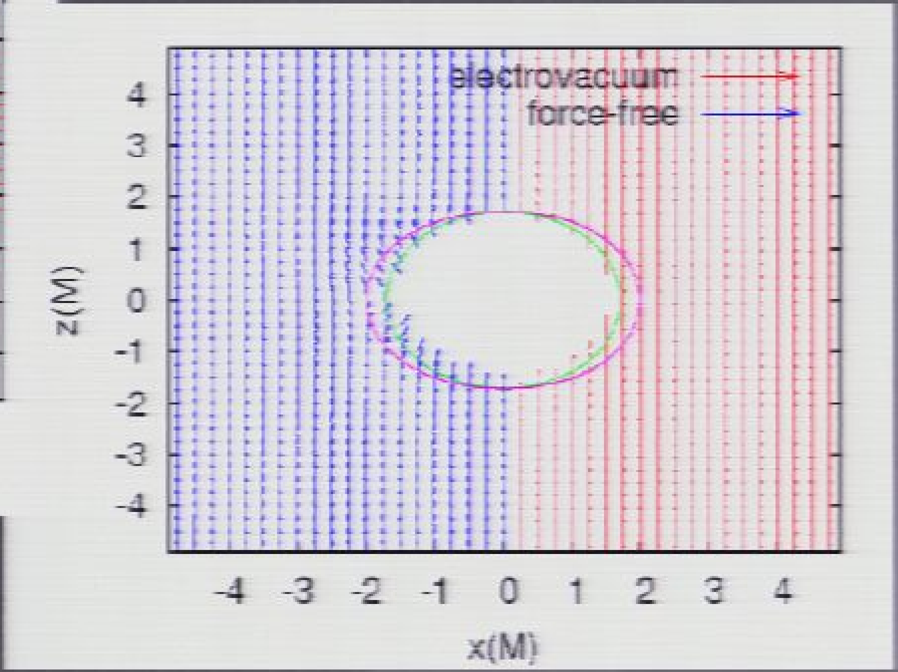
$$F_E|_{r=r_H} = 2 (B^r)^2 \Omega_F r_H (\Omega_H - \Omega_F) \sin^2\theta.$$

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

# II. Force-free versus Electrovacuum

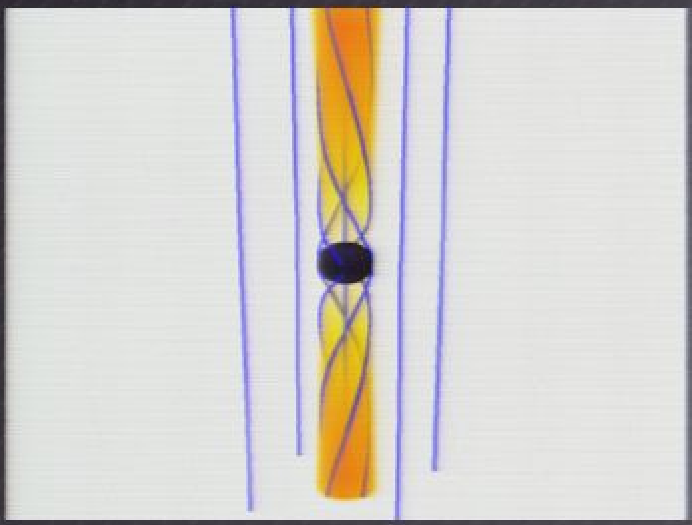
- Electric and magnetic fields for electrovacuum and force-free



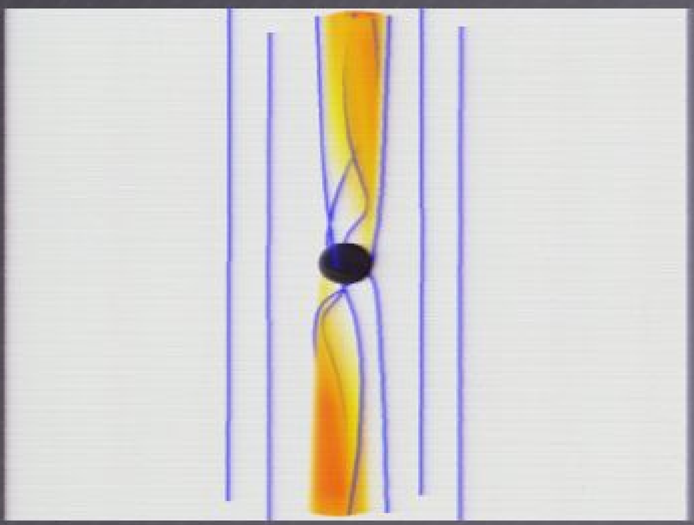



# II. Force-free (single BHs)

- 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°

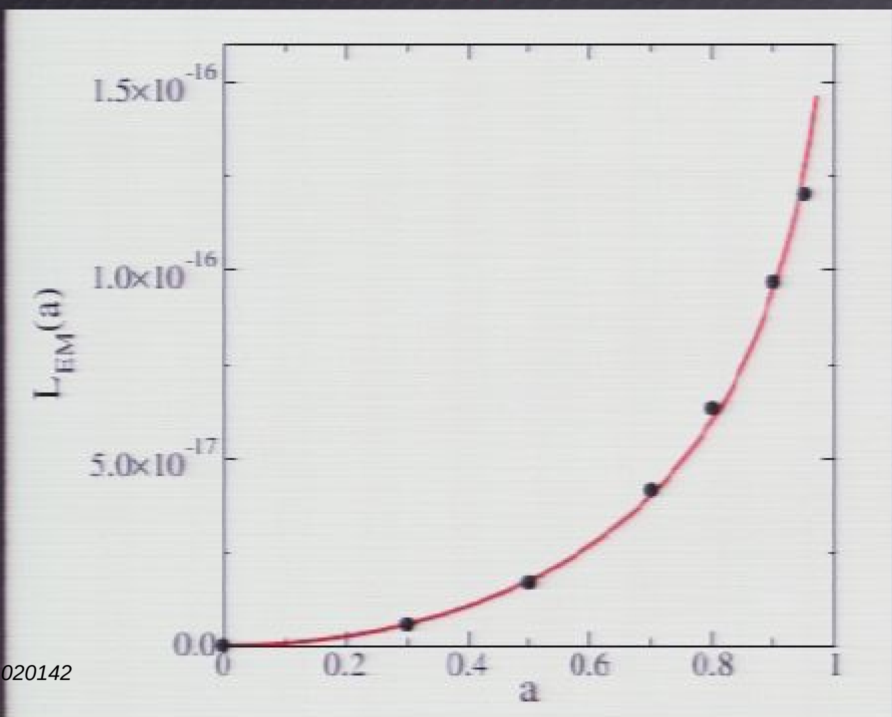
$M = 10^8 M_\Theta$ , $B = 10^4$ G

# II. Force-free (single BH spinning)

- The radiated power as a function of

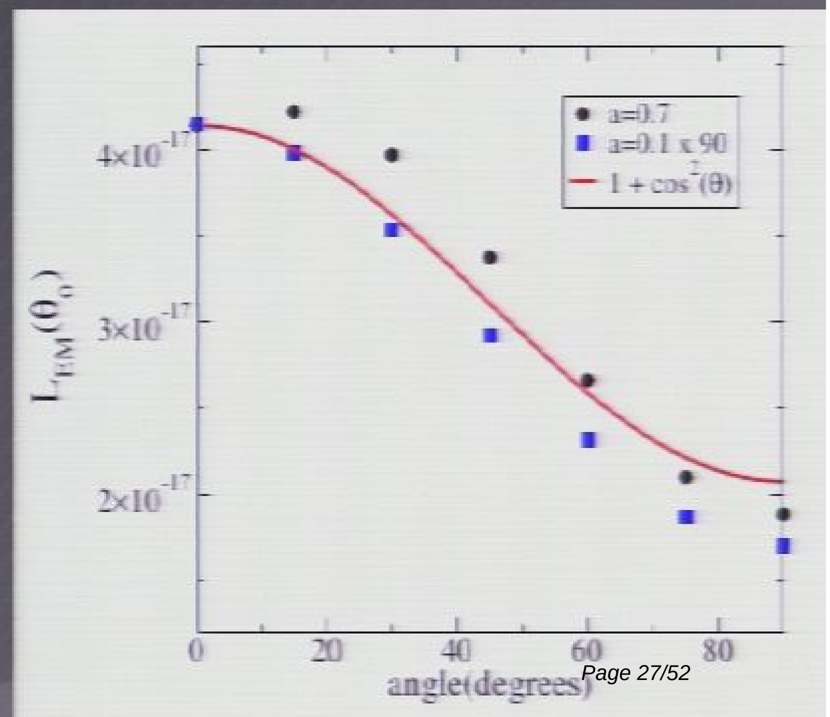
-the spin (Mckinney2010)

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




-the inclination angle (new!)

$L \sim 1+\cos^2\theta$



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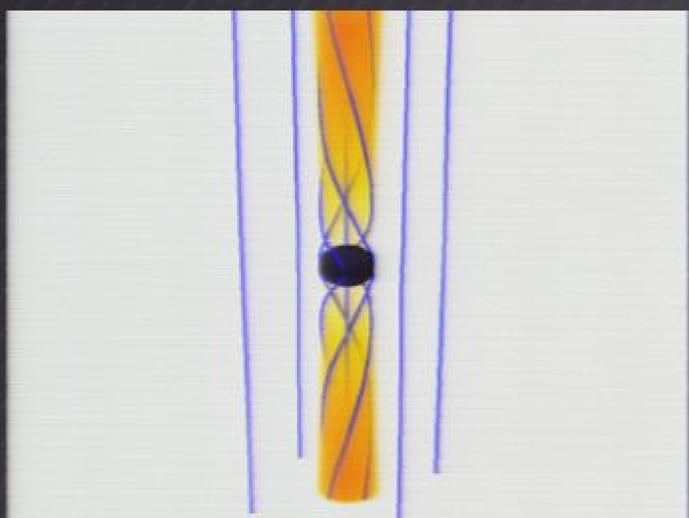
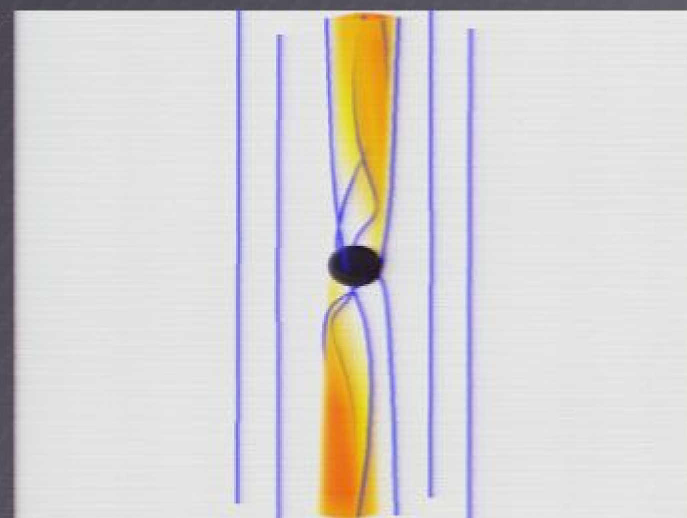


a = 0.99, angle =0



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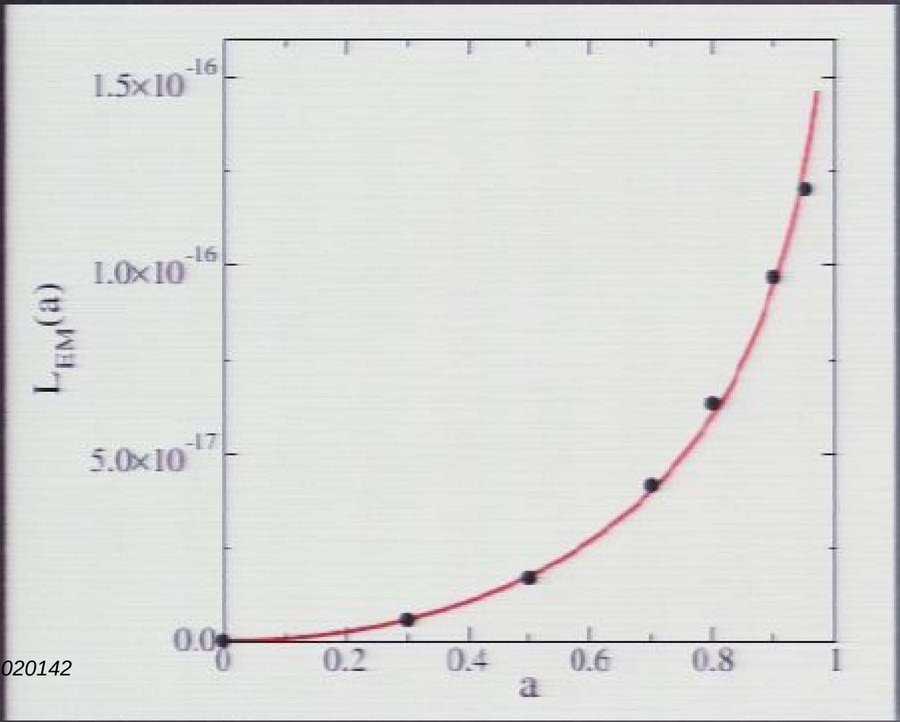
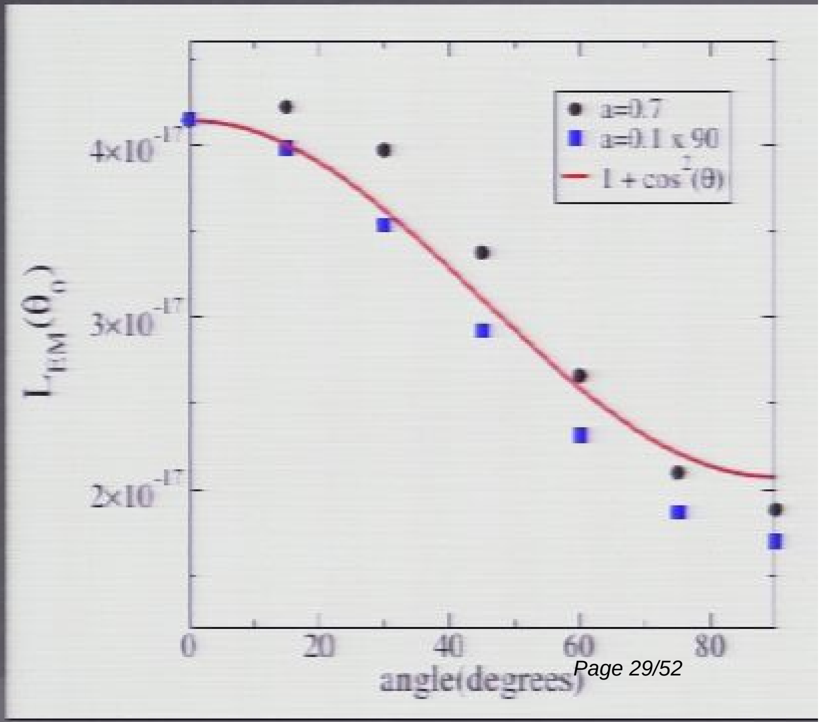
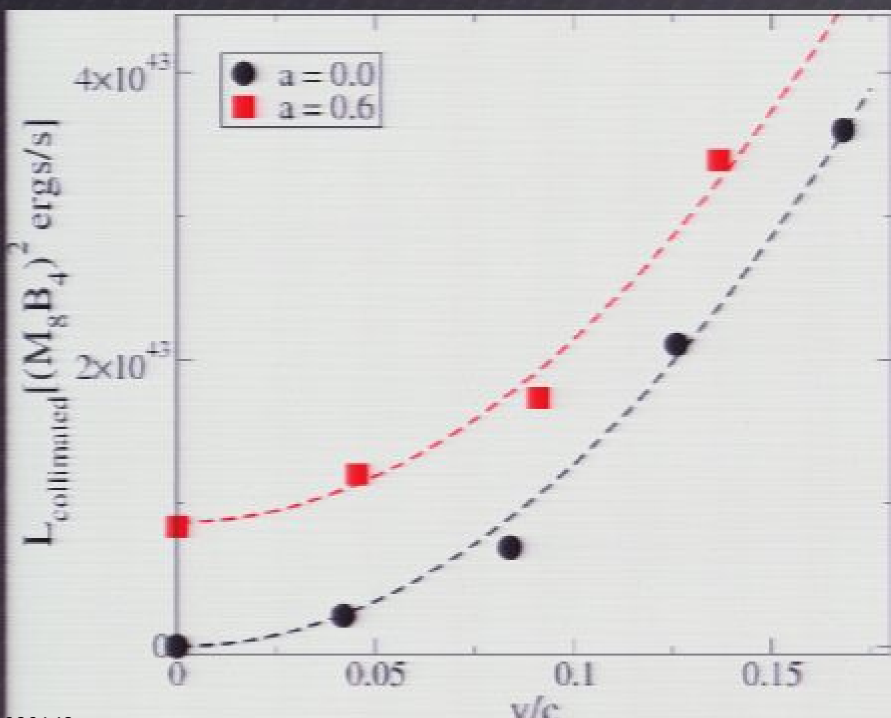


# II. Force-free (single BH boosted)

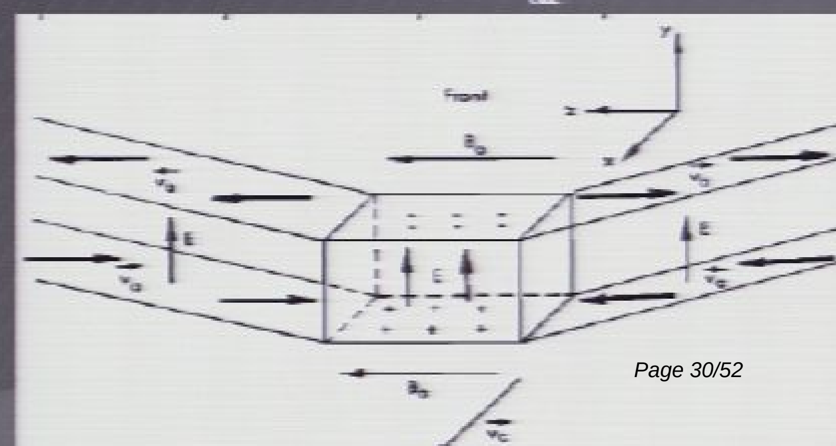
- The radiated power as a function of

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



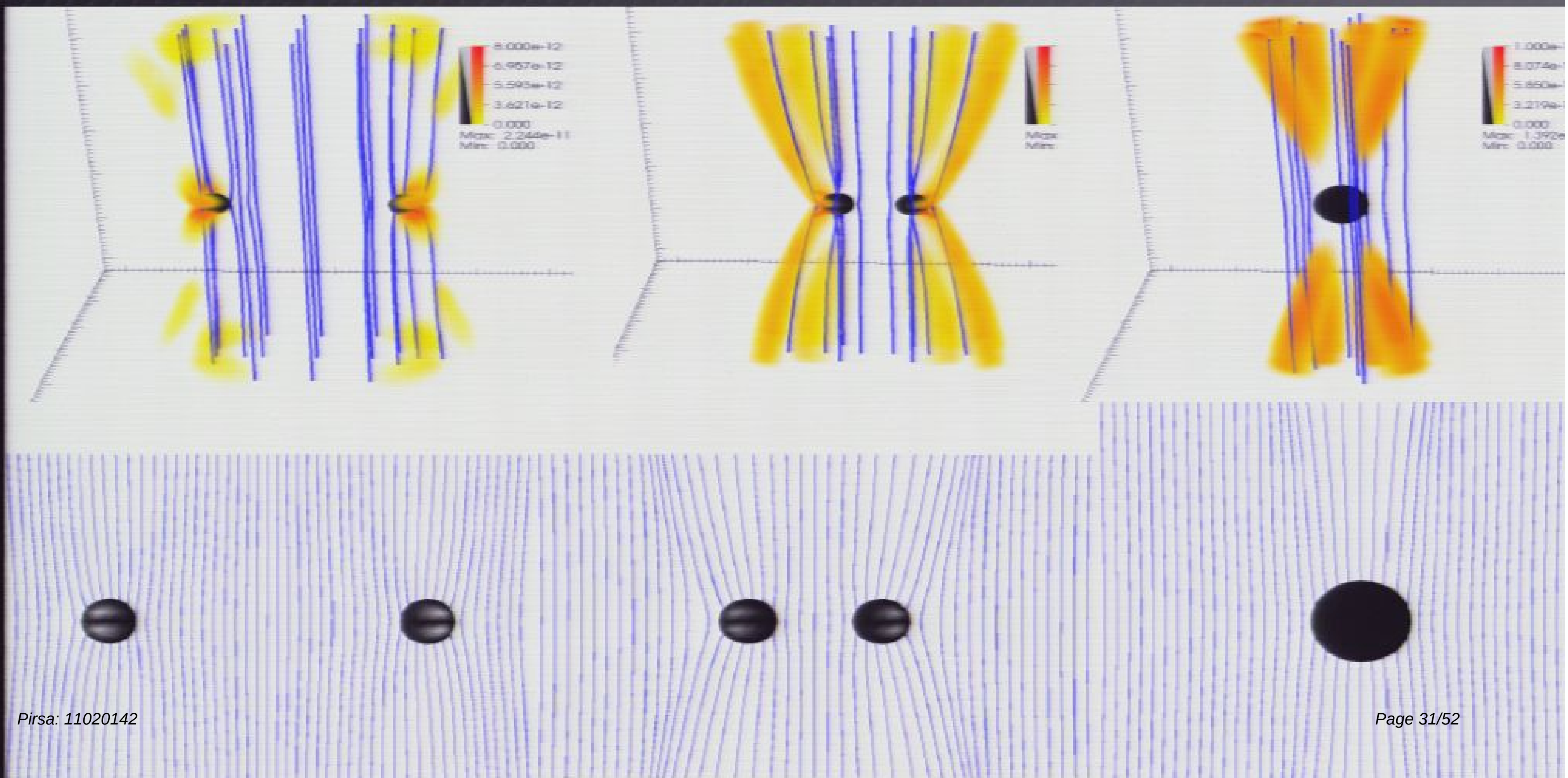

Drell,Foley,Rudderman(1965)
propulsion of satellites in
the ionosphere

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



# V. Force-free (binary BHs:head on)

- The EM radiation propagates along the magnetic field lines



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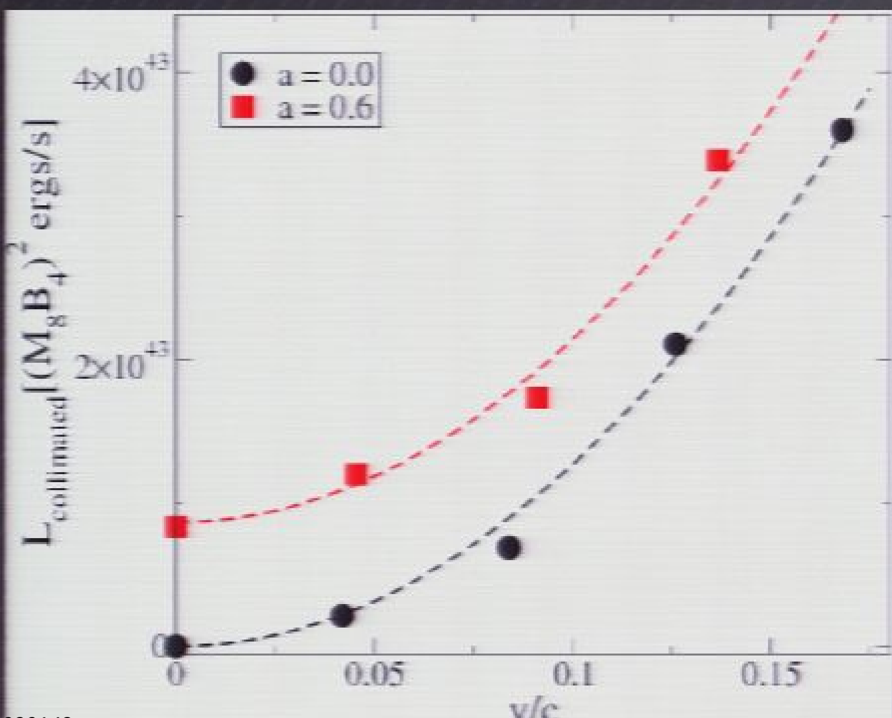


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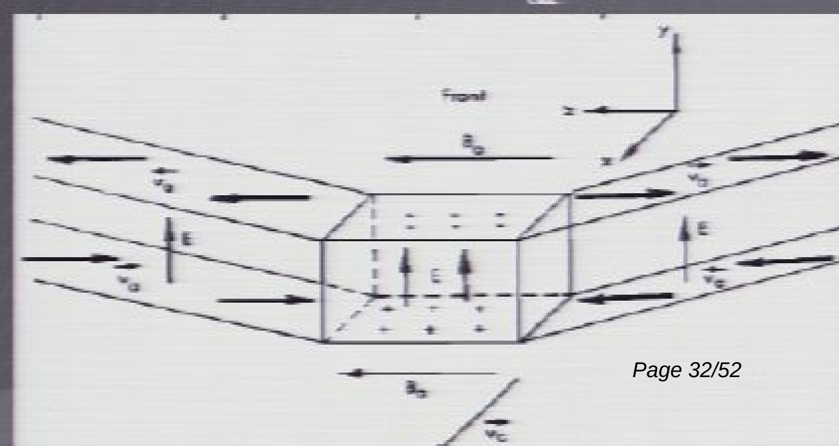

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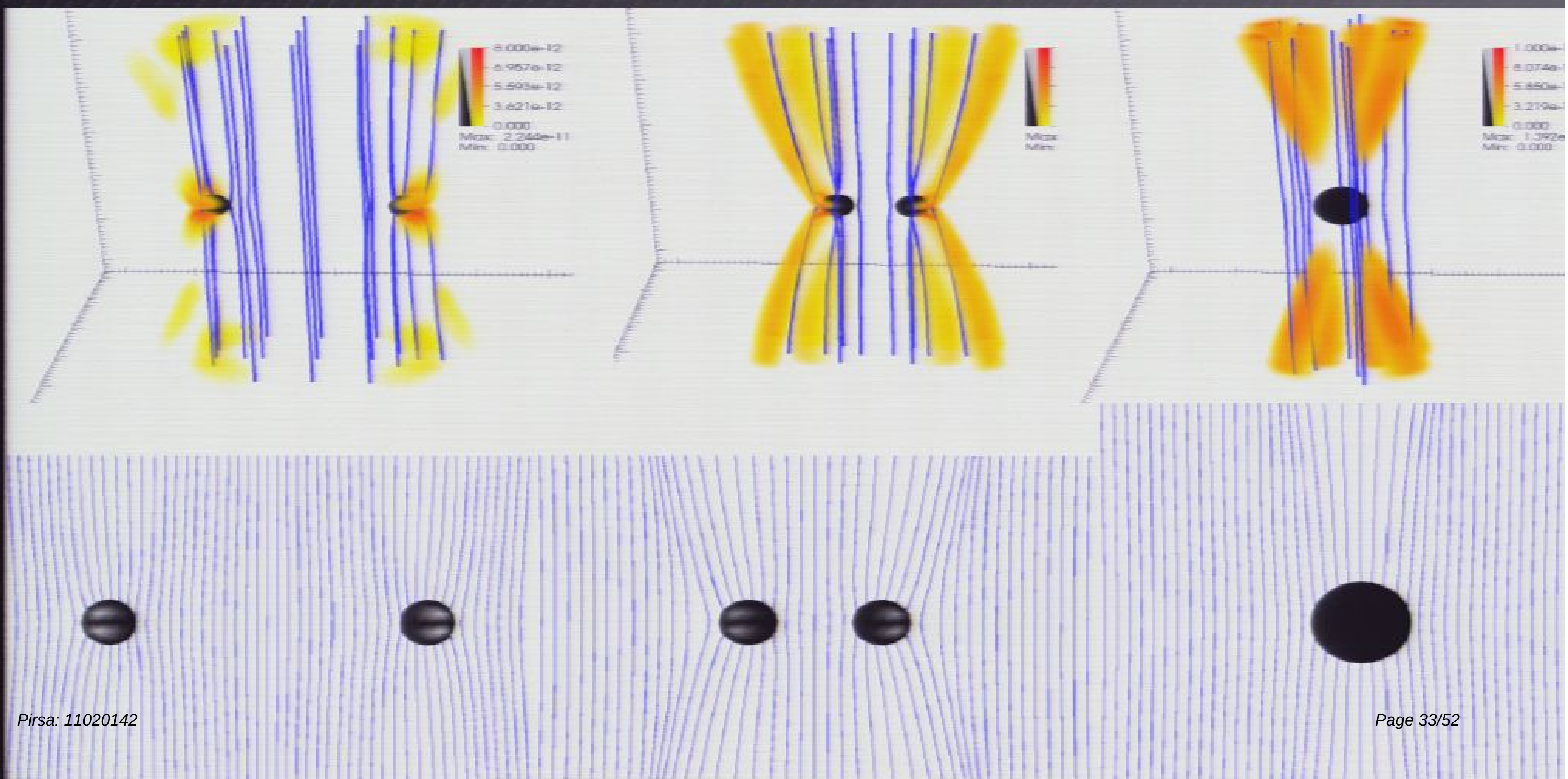
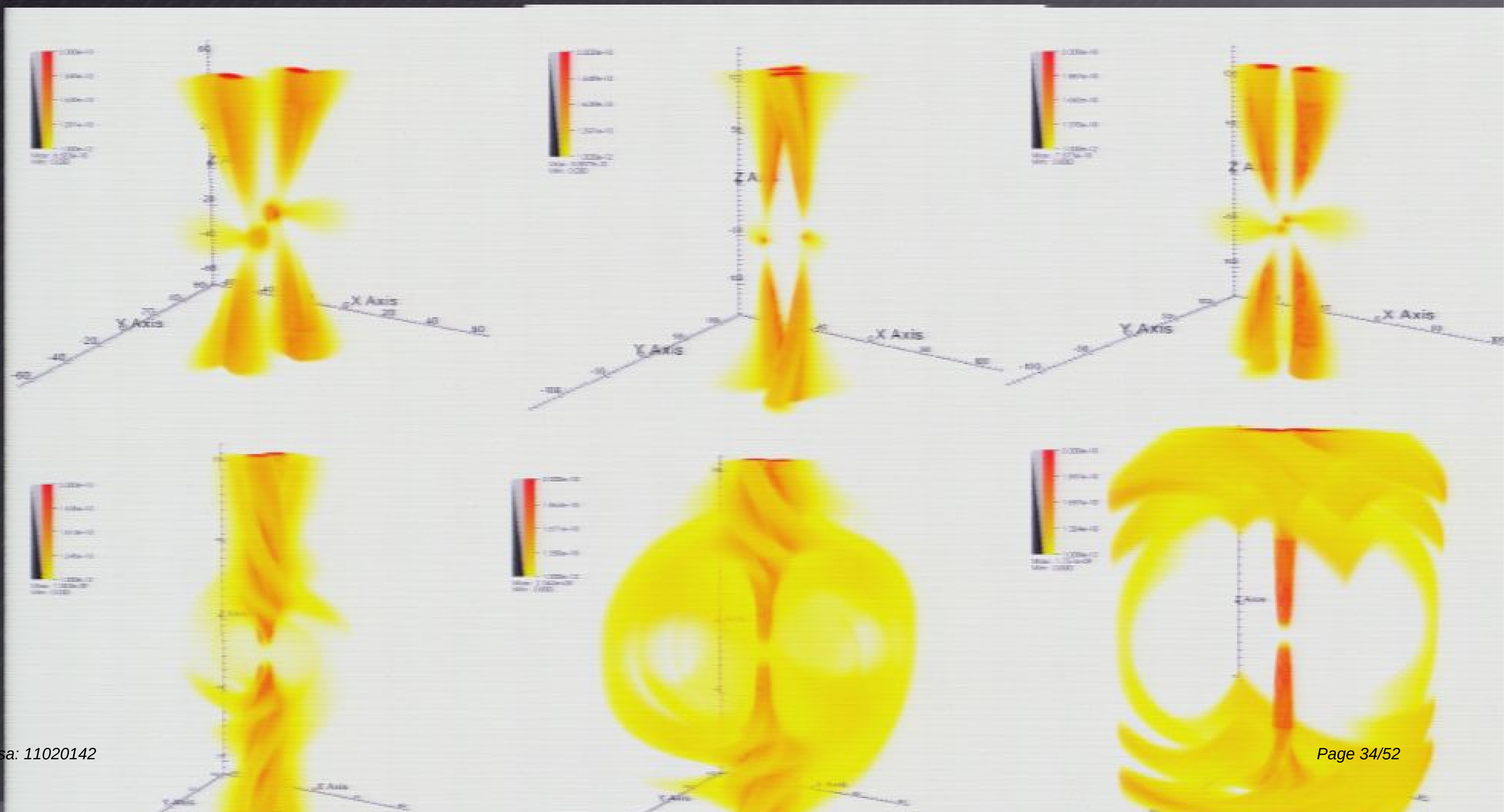


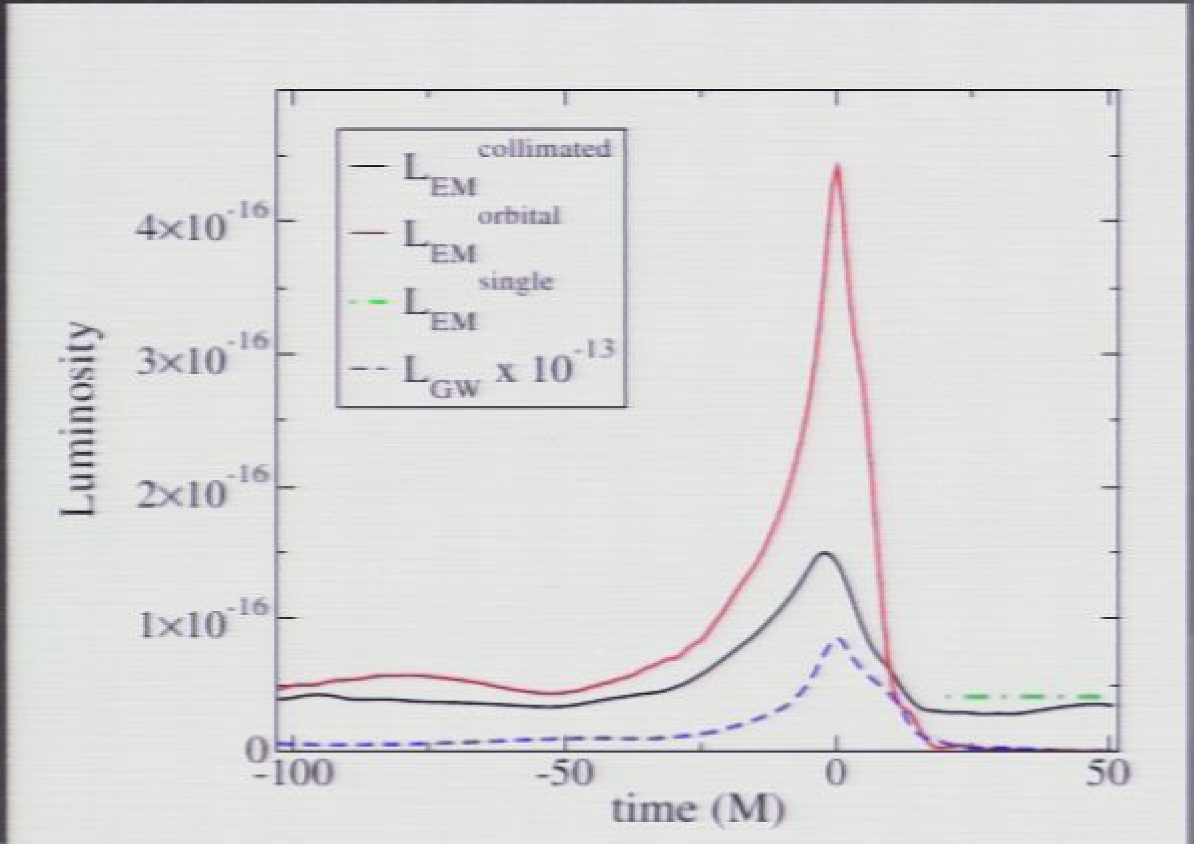
# II. Force-free (binary Bhs :orbitting)

- The EM radiation is collimated !!



# II. Force-free (binary BHs)

- 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



# III. EM PRECURSORS FOR LIGO

## Binary Neutron Stars
## and Binary Neutron Star-Black Hole

# III. Binary NS and mixed binaries

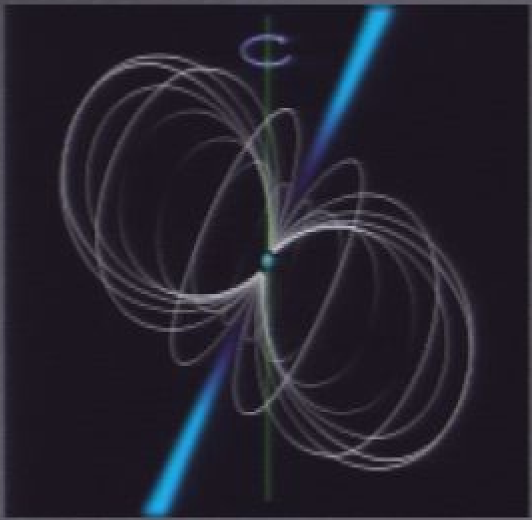
-Advance LIGO will be able to detect ~10 binary NS mergers and 1 BH-NS merger per year.


- The NS are compact objects of $R \sim 10$ km and $M \sim 1.5\text{-}2\ M_\odot$ containing magnetic fields ranging from $B \sim 10^8\text{-}10^{12}$ G

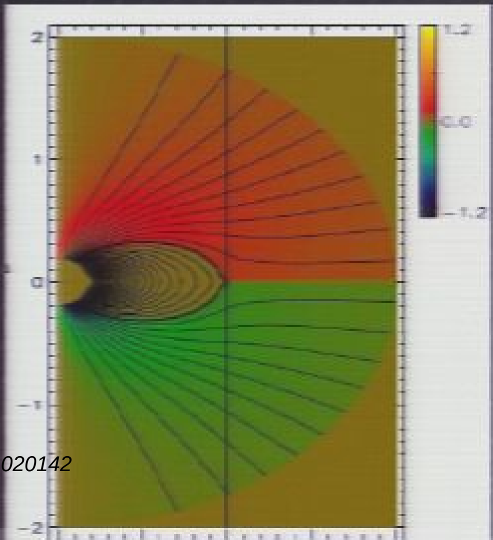
- These mergers will form a BH surrounded by a massive accretion disk, which is the scenario expected to produce short Gamma Ray Burst.

# III. Pulsars

- highly magnetized, rotating NS emitting a beam of electromagnetic radiation.




- The emission is produced at the magnetosphere which is described with the force-free approximation



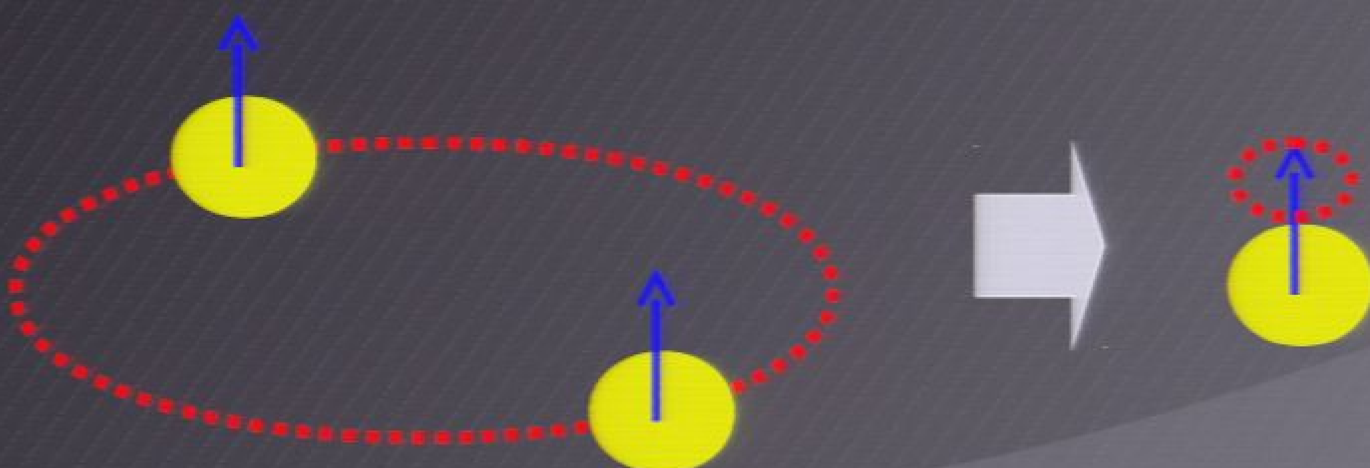
The EM luminosity for the pulsar (Spitkovsky 2006)

$$L \sim \mu^2 \Omega^4 (1 + \sin^2\theta)$$

# III. Binary NS

- Consider a binary magnetized NS in quasicircular orbits; each NS will have a magnetosphere described with force-free

- The interaction of the magnetospheres
  a)change the topology of the magnetic field lines (reconnections)
  b) produce current sheets and dissipation regions



# III. Hybrid method (MHD-forcefree)

- Solve the MHD fluid equations everywhere → good description of the magnetic fields in the interior of the star

$$T_{ab} = [\rho(1 + \varepsilon) + p]\, u_a u_b + p\, g_{ab} + {}^{em}T_{ab}$$

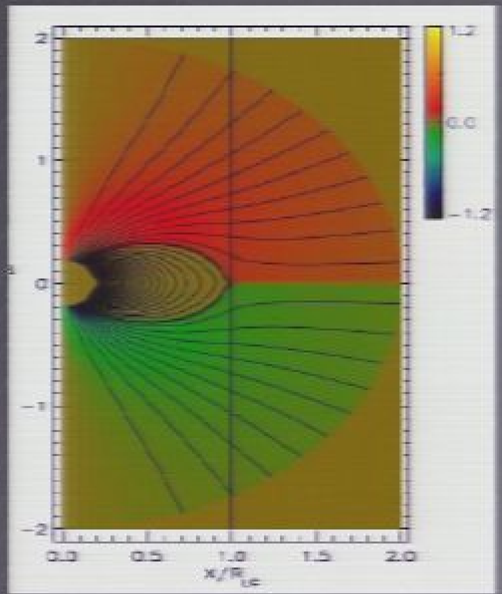
$\rho$ density, $\varepsilon$ internal energy, $u_a$ velocity, p pressure

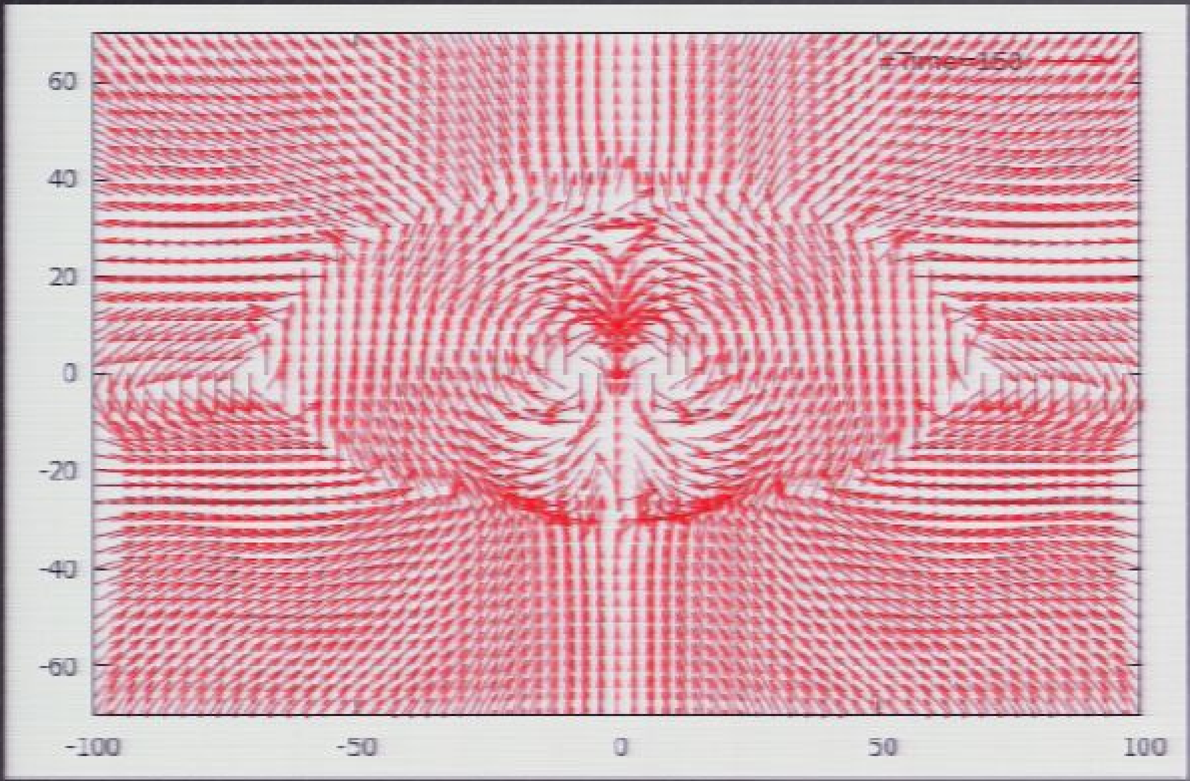
- Match the ideal MHD equations to the force-free equations at the surface of the star

- Solve the force-free equations in the magnetospheres → good description of the EM fields in the exterior of the star

# III. Pulsars

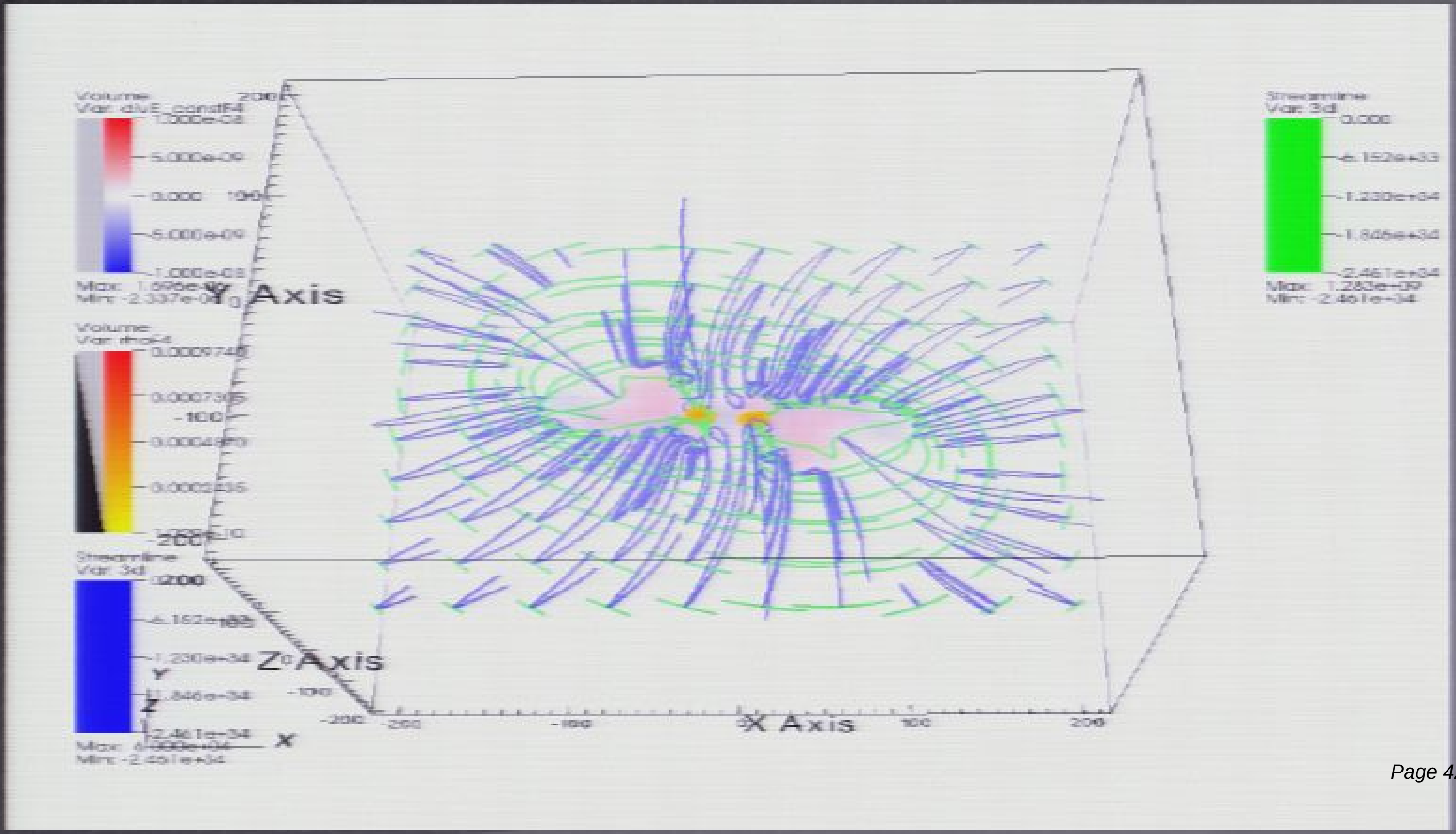
- Set a magnetized rotating NS to test the hybrid approach



# III. Binary NS

- Set a magnetized binary non-spinning NS with the magnetic moments up/up



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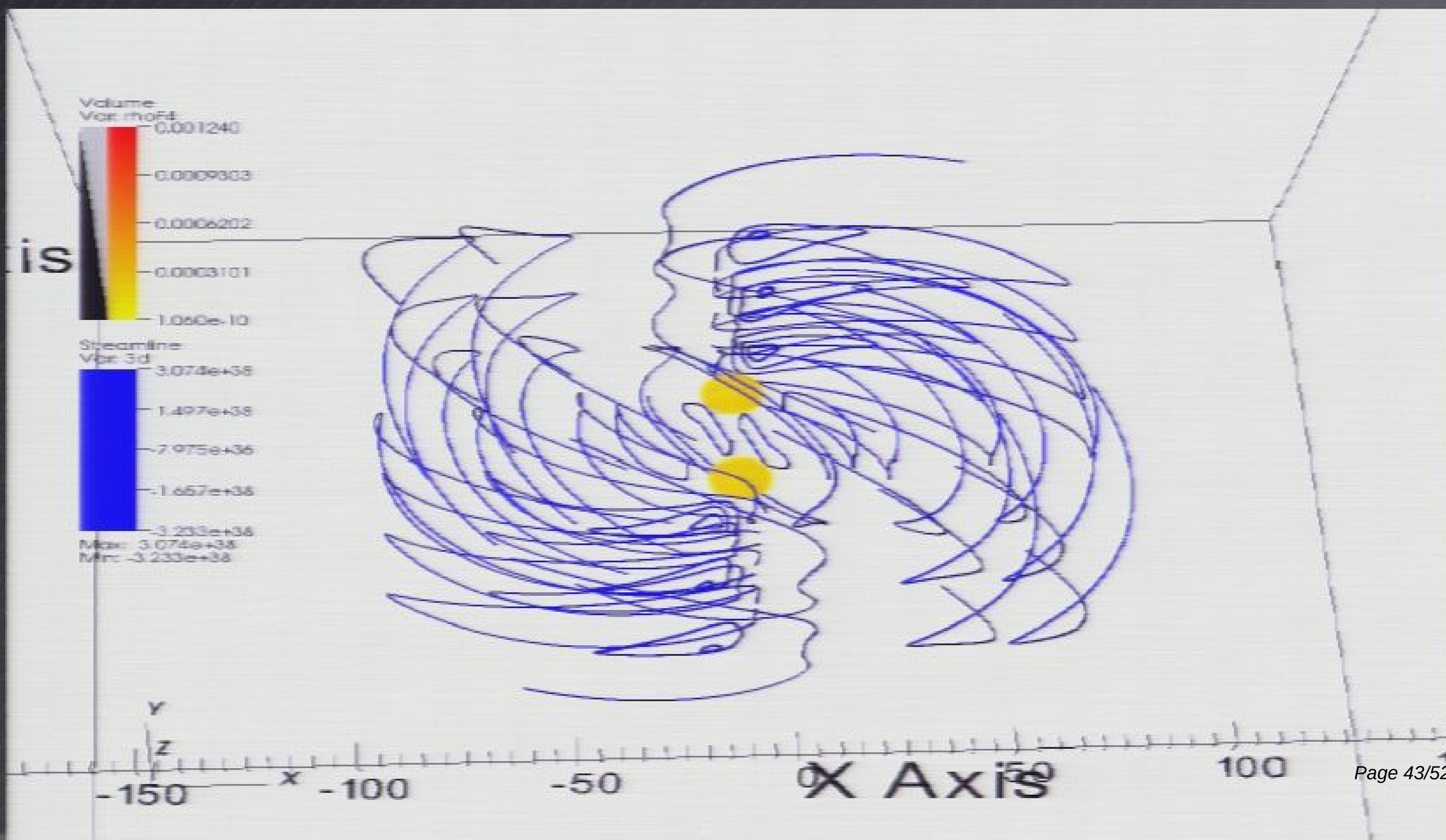

# IV. Summary

- Different EM counterparts (precursors)
  - supermassive binary Bhs for LIGO.
  - binary NS for LISA

- The force-free regime is a good approximation in both cases

- In the binary BHs, the magnetic field is external (produced by a disk) and extracts energy from both the rotational and kinetical energy of the BHs.

- In the binary NS, the magnetic field is internal and the interaction of the magnetospheres changes the topology of the EM fields

# IV. Summary

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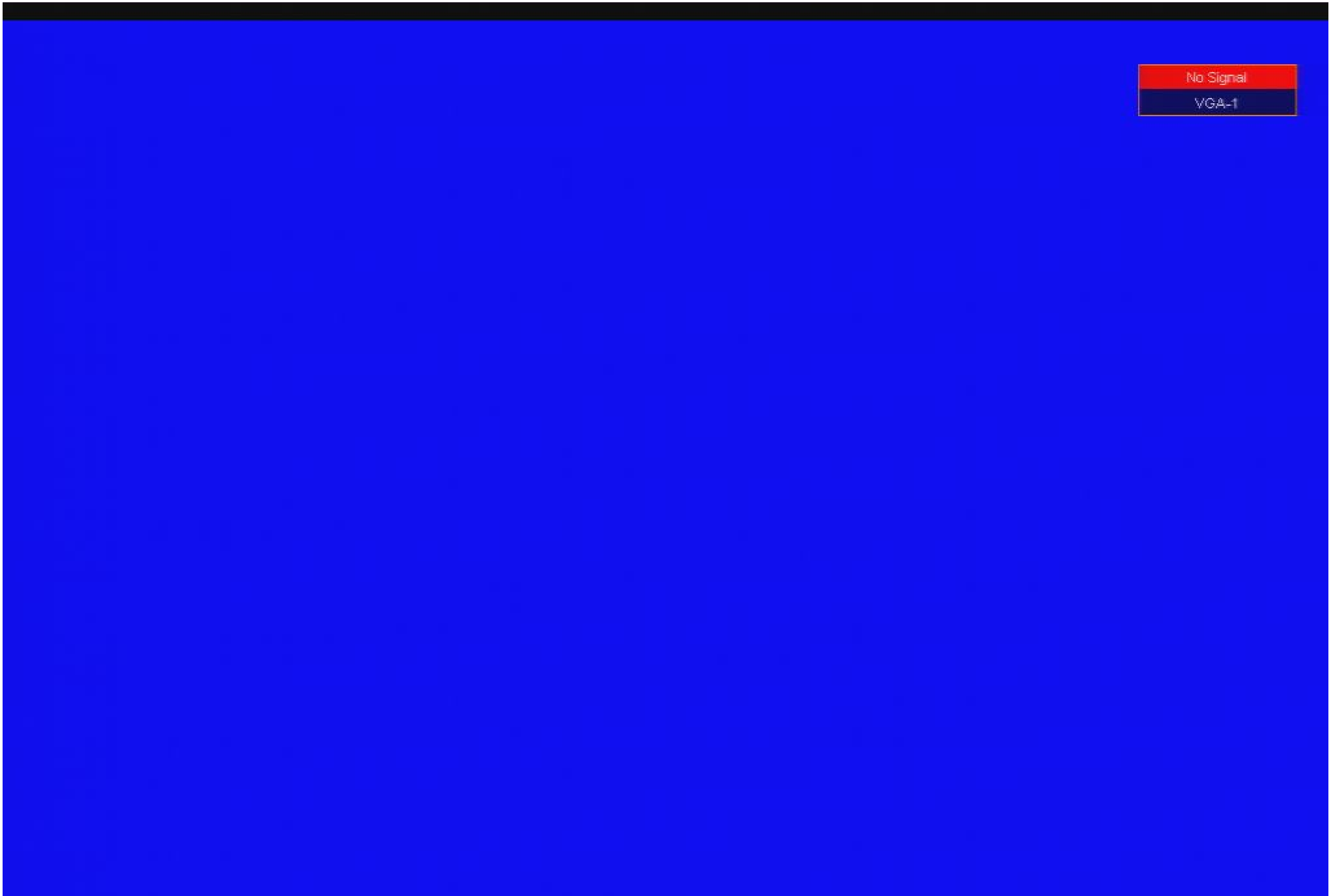
No Signal
VGA-1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