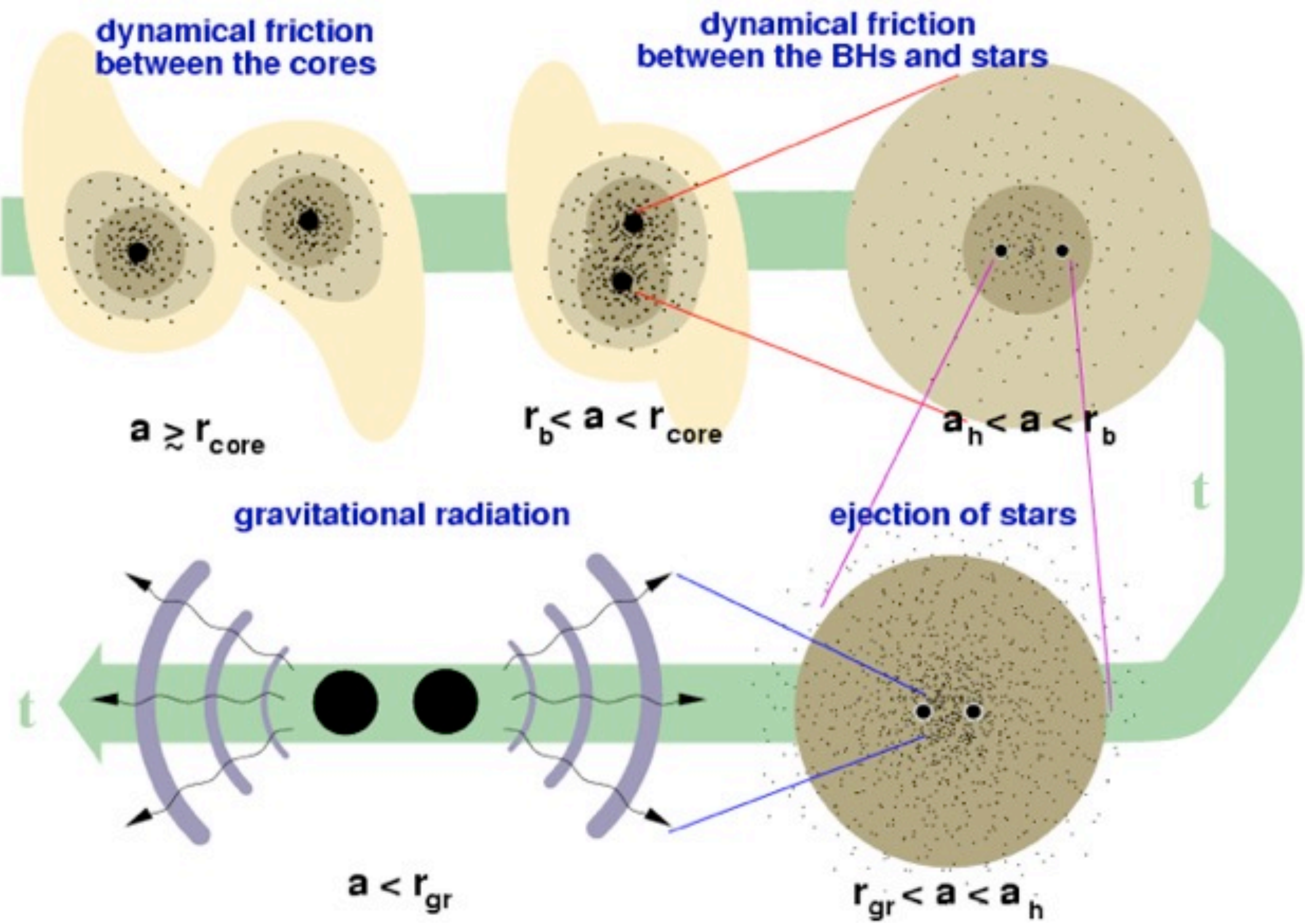
Electromagnetic signatures of merging and collapsing compacts

(for LISA and LIGO sources)

Maxim Lyutikov (Purdue U.)

I. EM counterparts of BHs' mergers

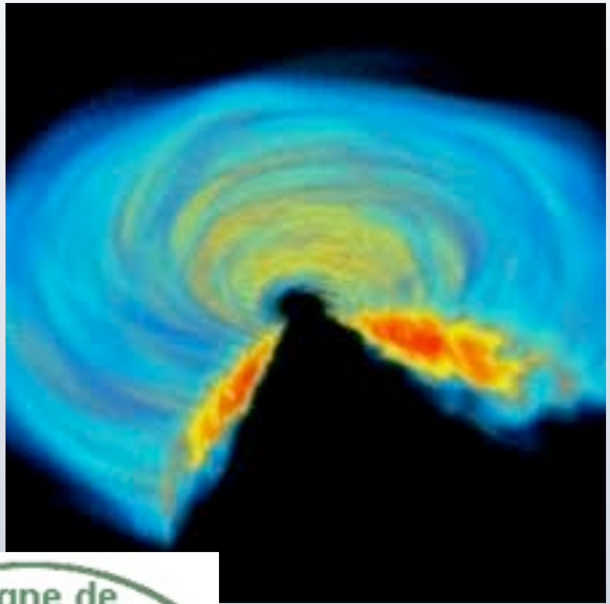
MERGING OF BHs DUE TO

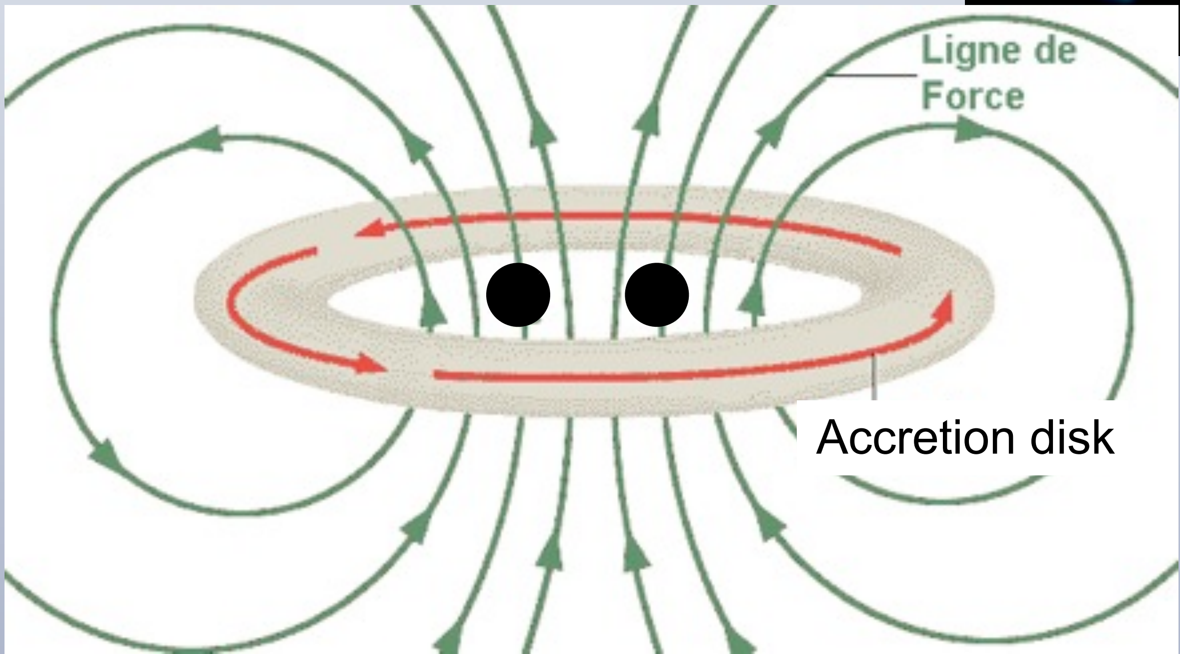


pict. by Zier

Disk generates B-field

- MRI - dynamo (Velikhov-Chandrasekhar-Balbus-Hawley)
- BHs move in B-field generated by the disk

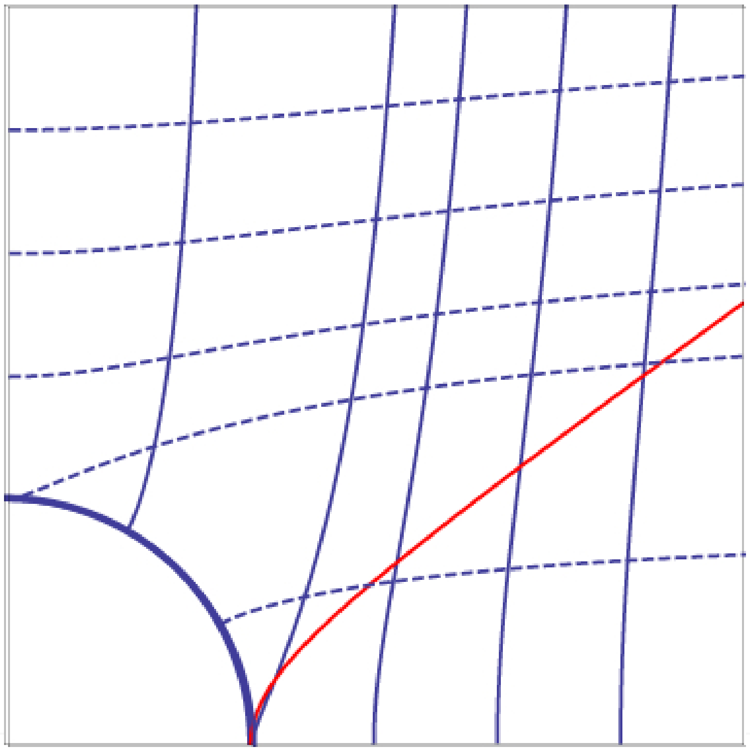




Non-zero second EM invariant

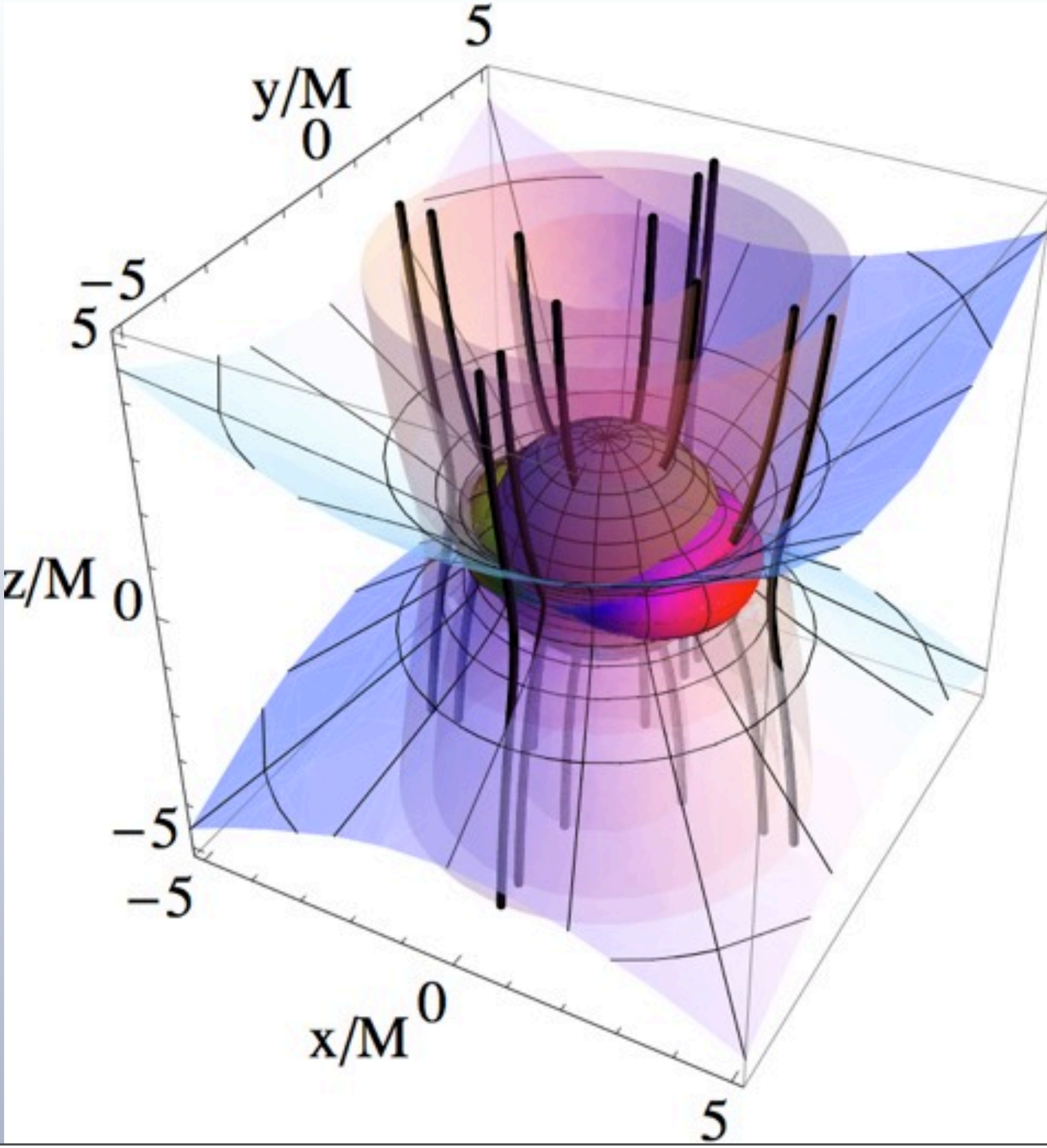
- **BH moving across B-field: parallel E-field is generated**
- Non-zero second EM invariant

$$\mathbf{E} \cdot \mathbf{B} = -\cos\phi \sin 2\theta \, \beta_0 B_0^2 \frac{M}{r}$$



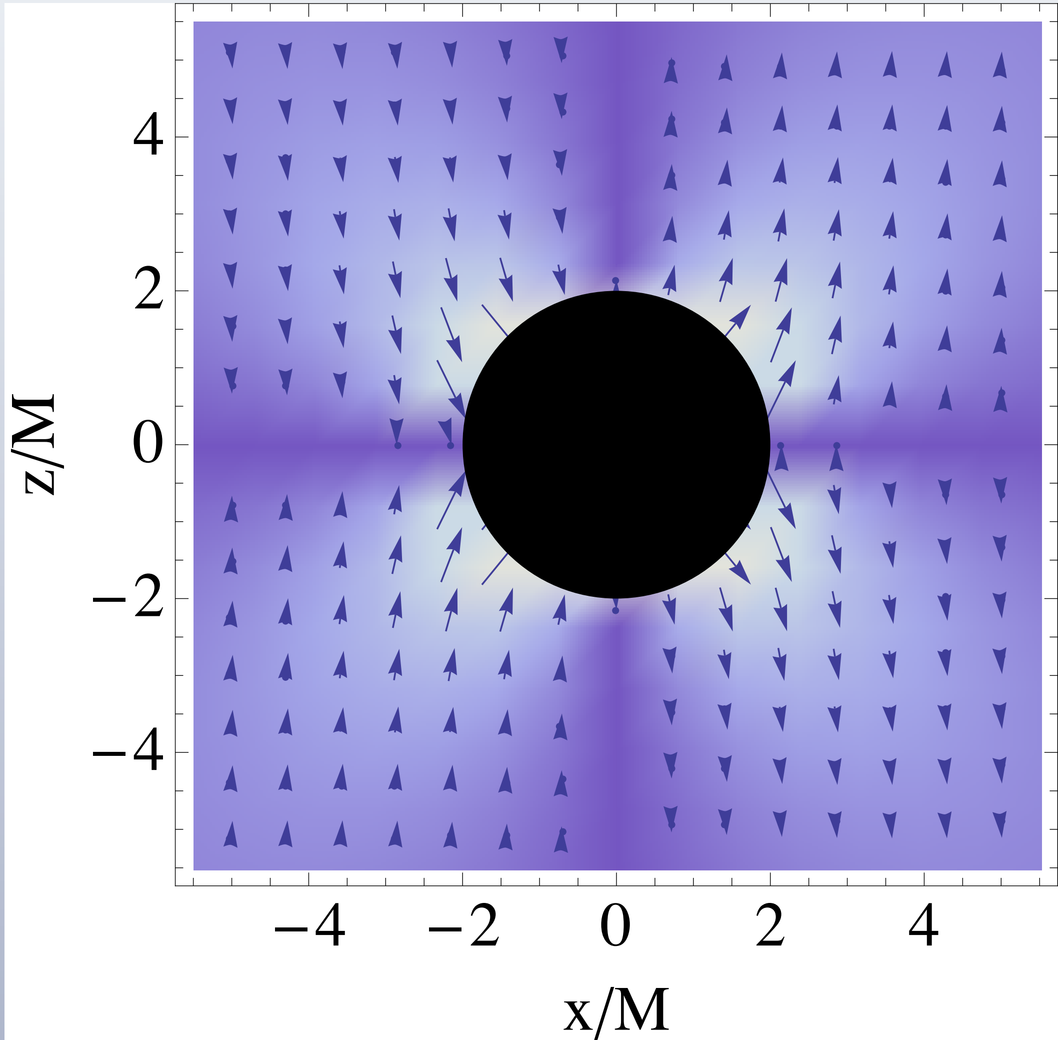
$$\rho_{\rm ind} = \frac{1}{4\pi} \nabla \cdot \mathbf{E}_{\|}$$

$$\rho_0 = \frac{B_0 (v_0 / R_G)}{2\pi c}$$


5
y/M
0
−5
5
z/M
0
−5
−5
x/M
0
5

Large scale currents

$$I \sim \beta_0 M B_0$$



$$L_{EM} \approx M^2 \beta_0^2 B_0^2$$

$$L_{EM,u} = \frac{(GM)^3 B_0^2}{c^5 R}$$

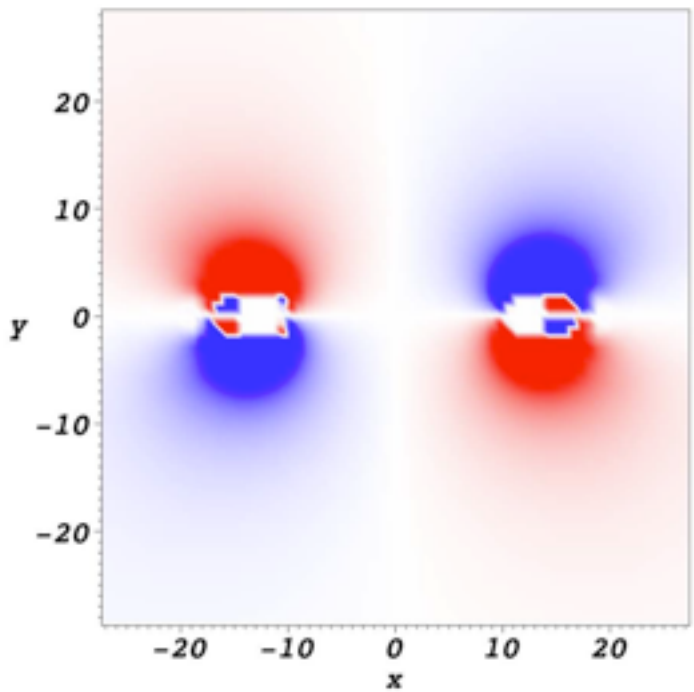
Luminosity and total energy

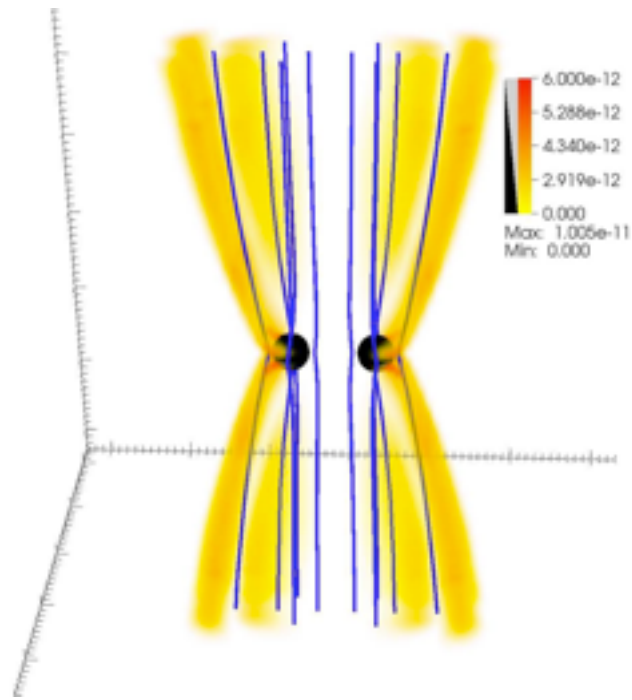
$$L_{EM} \approx \eta_E \frac{(GM)^2 m_p}{\xi_d^2 \sigma_T c R} \sim 10^{38}\,\mathrm{erg s}^{-1} m_6^2 \eta_{E,-1}$$

$$E_{EM} \approx \frac{(GM)^2 m_p \xi_d \eta_E}{c^2 \sigma_T} \approx 10^{43} - 10^{45} m_6^2 \mathrm{erg}$$

- Luminosity is low, unless M = 10^8 M_{Sun}
- Since inspiraling is slow, total energy is fairly large (wind-driven cavities?)

Simulations





Charge density for head-on
collision of two BH
Palenzuela et al

The triangle anomaly and baryo-genesis

- Standard model of particle physics: non-zero second Poincare EM invariant leads to the appearance of sources of topological vector currents

$$J_\nu = A^\mu ({}^*F_{\mu\nu})$$

$$J_0 = \mathbf{A} \cdot \mathbf{B} = 0$$

$$J_i = \mathbf{E} \times \mathbf{A} + \frac{A_0}{\alpha}\mathbf{B}$$

$$J_{\mu;\mu} = -\frac{7}{4} \sin 2\theta \cos\phi B_0 E_0 \frac{M}{r} = \frac{7}{4}\mathbf{E} \cdot \mathbf{B}$$

- NB: Helicity J_0=0, **E*B** != 0 due to $J_{i,i}$

- **E*B** ~ 1/r - nonlocal $\Delta N_B \propto (?) = \int d^4x J_{\mu\mu}$

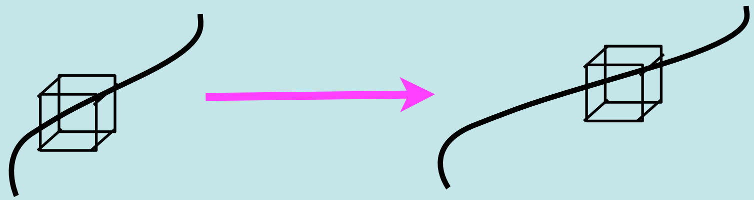
II. Slowly balding black holes

(NS collapse into BH)

"No hair theorem": not applicable to collapsing NSs.

“No hair theorem”: Isolated BH is defined by mass, angular momentum and electric charge.

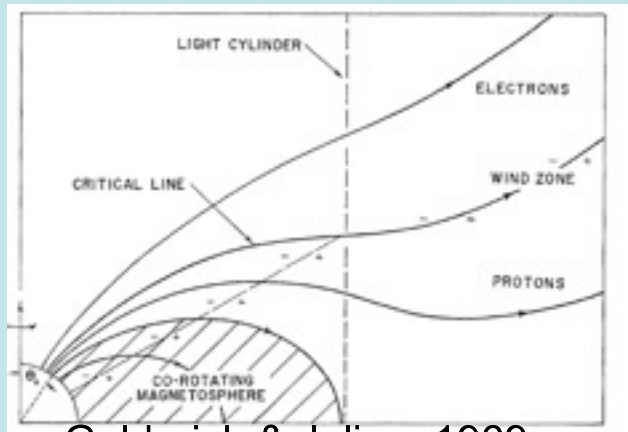
The proof assumes outside vacuum.



Plasma: **E.B** =0: frozen-in B-field

Rotating NS:

- generate plasma out of vacuum
- generate currents that open fields to infinity



Goldreich & Julian, 1969

BH rotates with finite

$$\Omega_H \approx \frac{\chi}{5}\frac{c^4 R_{\rm NS}^2}{(GM_{\rm NS})^2}\Omega_{\rm NS} = 2.9\times 10^3 {\rm rad s}^{-1}\chi_{-1}P_{{\rm NS},-3}^{-1}$$

(a = 0.04 for a ms NS, slows down!)

If a BH keeps producing plasma, like a NS, B-field cannot slide off.

Field lines that connected NS surface to infinity, has to connect horizon to infinity

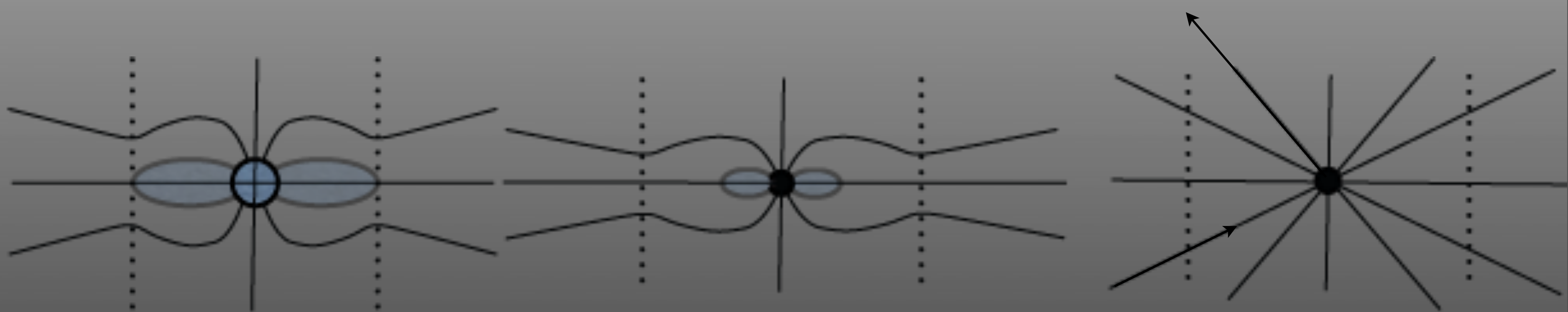
No hair theorem not applicable: high plasma conductivity introduces topological constraint (frozen-in B-field).

Conserved number: open magnetic flux:

$$N_B = e\Phi_\infty/(\pi c\hbar)$$

$$\Phi_\infty \approx 2\pi^2 B_{NS} R_{NS}^3/(P_{\rm NS} c)$$

BH's hair!



Time-dependent Grad-Shafranov equation

Lyutikov 2011b

- **Two types of time-dependent:**
  - **variable current** for given shape of flux surfaces

$$\varpi^2 \nabla \left(\frac{1-\varpi^2\Omega^2}{\varpi^2} \nabla P \right) + \frac{4I(\nabla P \cdot \nabla I)}{(\nabla P)^2} + \varpi^2 \Omega (\nabla P \cdot \nabla \Omega) = 0$$

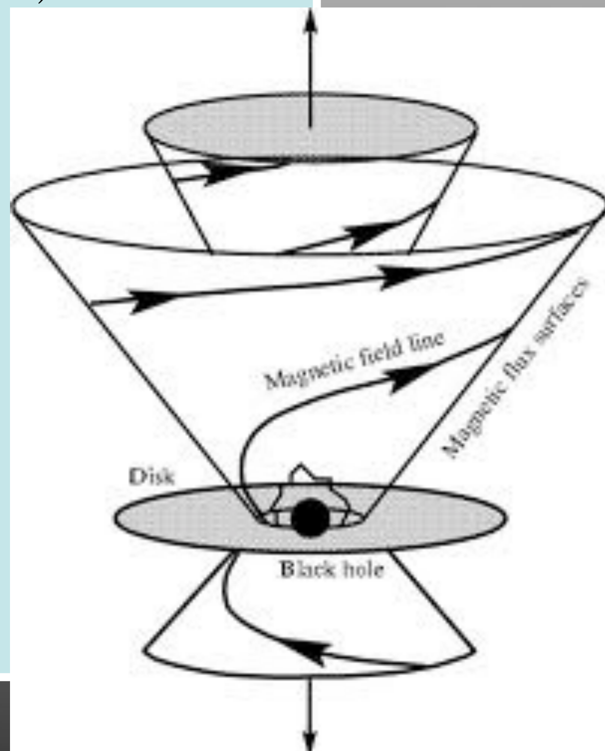
$$\partial_t^2 \Omega = \frac{\mathbf{B} \cdot \nabla (\mathbf{B} \cdot \nabla \Omega)}{B_p^2}$$

  - **motion of flux surfaces**

$$\Delta^* P - \partial_t^2 P + \frac{4I(\nabla P \cdot \nabla I)}{(\nabla P)^2} - 2\partial_t \left(\frac{I^2 \partial_t P}{(\nabla P)^2} \right) = 0$$

$$F'(\nabla P)^2 = 2I\partial_t P$$

$$\partial_t I = \frac{1}{2} \Delta^* F$$



Time-dependent Michel's solution in Schwarzschild metric

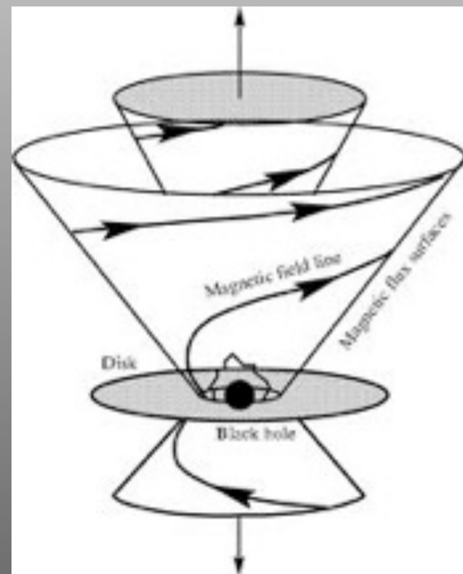
- Magnetosphere of collapsing NS:

$$B_\phi = -\frac{R_s^2 \Omega \sin\theta}{\alpha r} B_s, \quad B_r = \left(\frac{R_s}{r}\right)^2 B_s,$$

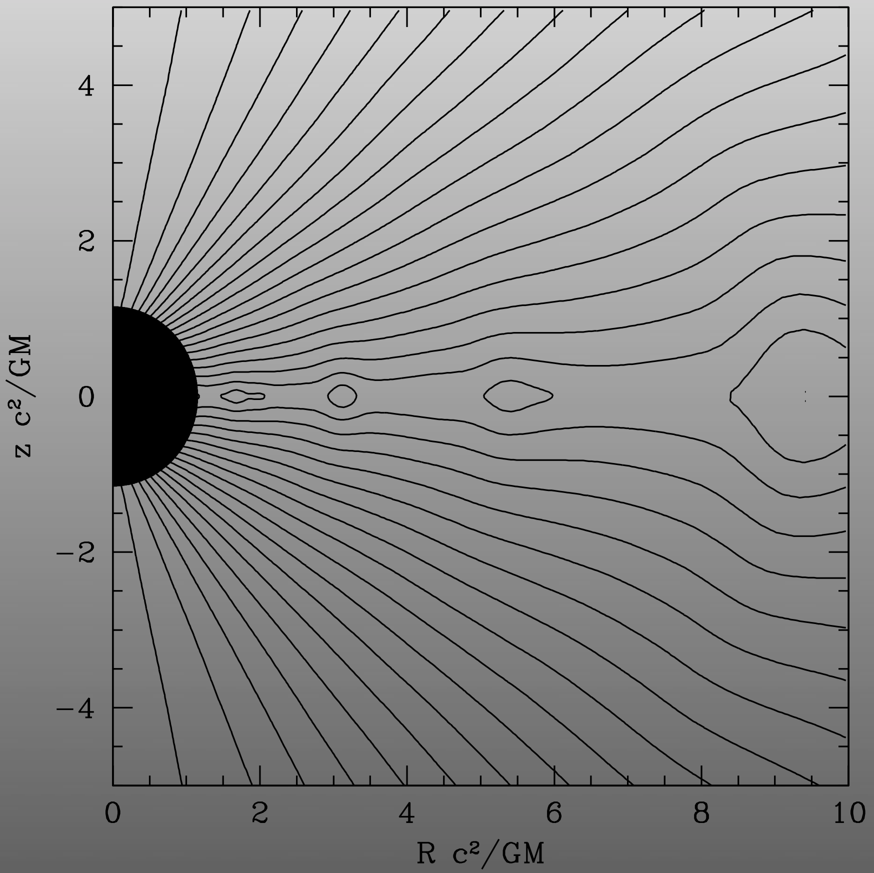
$$E_\theta = B_\phi, \quad j_r = -2\left(\frac{R_s}{r}\right)^2 \frac{\cos\theta \Omega B_s}{\alpha}$$

$$\Omega \equiv \Omega\left(r - t + r(1-\alpha^2)\ln(r\alpha^2)\right) \quad \alpha = \sqrt{1 - 2M/r}$$

$$B_s R_s^2 = const$$



Simulations (McKinney)



-Split-monopole magnetosphere

- Slow balding

As long as BH can produce pairs, open B-field does not slide off.

Field structure relaxes to split monopole

Isolated BH acts as a pulsar, spins down electromagnetically, generates Poynting wind (jets?).

Slow hair loss on **resistive** time scale

Application to GRBs

Shorts and Longs are very similar, even though the progenitors are very different.

Late times ($t > 10^5$ sec)- FS dominated -OK

But prompt and early afterglows? (Plateaus, flares)

Formation of magnetized BH that retains it's B-field for a long time and spins-down electromagnetically

Millisecond magnetar (but: monopolar spindown is more efficient that dipolar). Need dynamo to bring $B \sim 10^{14}$ G.

Early afterglows from internal dissipation in the wind (Lyutikov 2009)