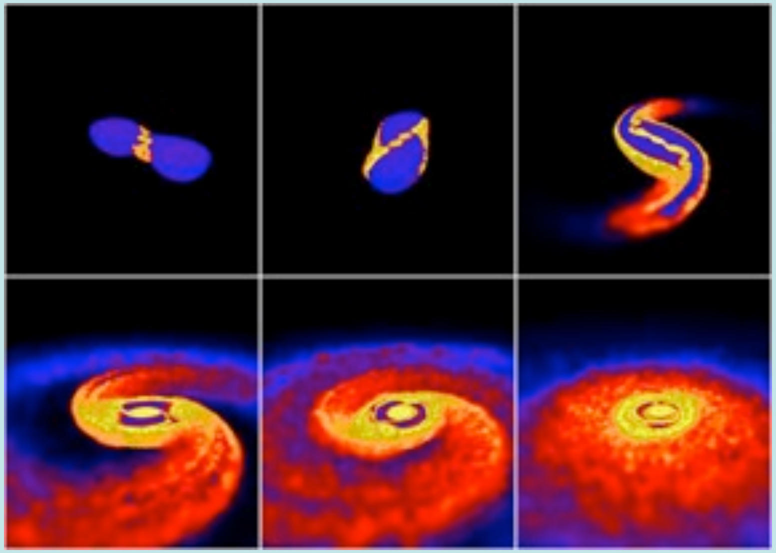
Electromagnetic hair of astrophysical black holes

Maxim Lyutikov (Purdue U.)

Collapse of a rotating NS into BH:

NS-NS mergers



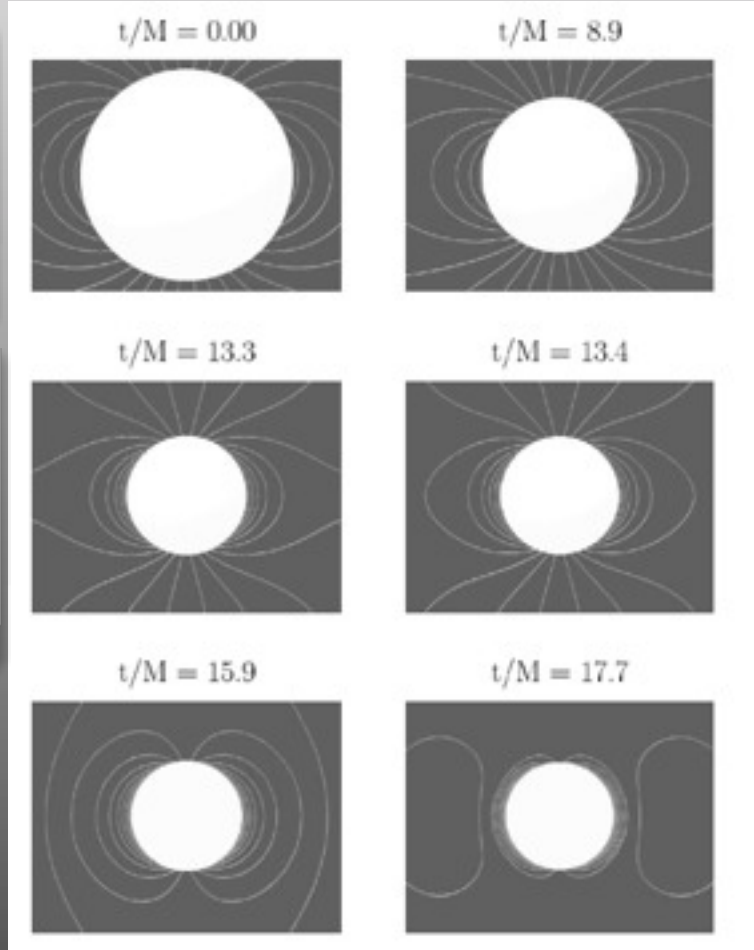
Transient NS ~ 100 msec

Rotating magnetized NS collapses into BH: what's the behavior of the magnetic field?

The “No hair” theorem

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

Collapse of a magnetized NS into BH in vacuum: B-field is lost on ~ dynamic time



Baumgarte & Shapiro, 2003

The "No hair" theorem

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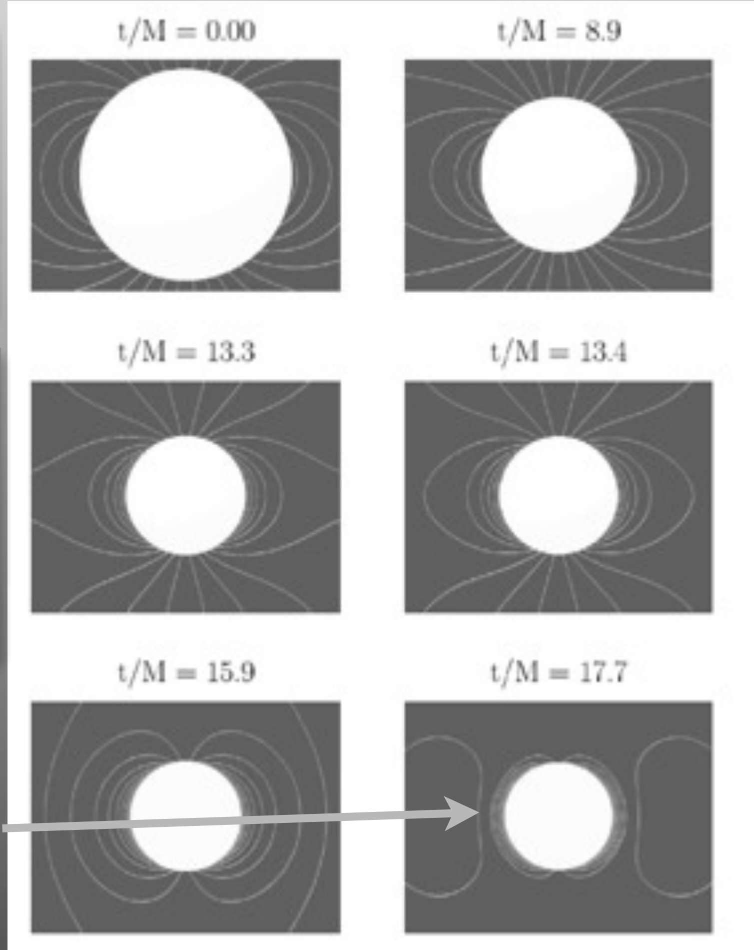
Such process is prohibited if outside is plasma



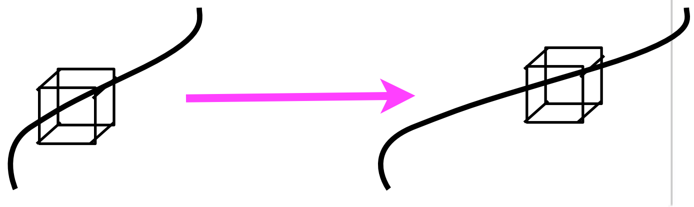
Baumgarte & Shapiro, 2003

Main point:

The proof of “no Hair” theorem assumes outside vacuum.

If outside plasma: **E.B** =0 - frozen-in B-field

This is a **topological** (not dynamic) constraint



- **Rotating** NS - unipolar inductor
  - generate plasma out of vacuum
  - have B-field lines open to infinity
- Blandford & Znajek: BHs do the same
- If a BH keeps producing plasma, like a NS, B-field cannot slide off. **E.B** =0: **field lines that connected NS surface to infinity, has to connect horizon to infinity**
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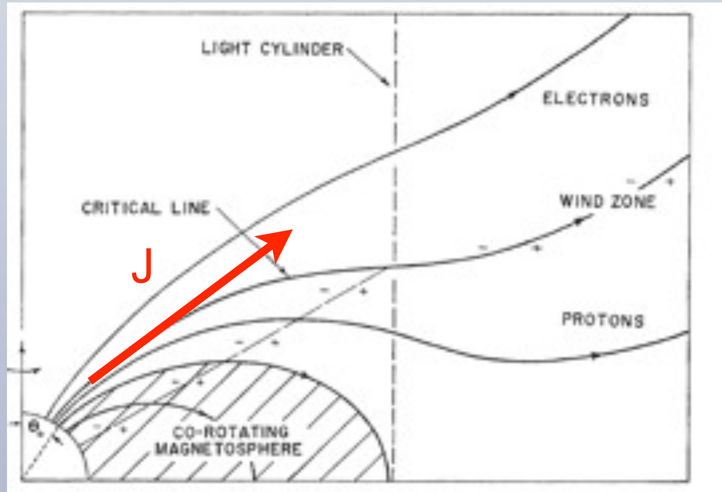


Goldreich & Julian, 1969

Main point:

- **The “no hair” theorem not applicable to collapse of rotating NSs: high plasma conductivity introduces topological constraint (frozen-in B-field).**

Conserved number: open magnetic flux:

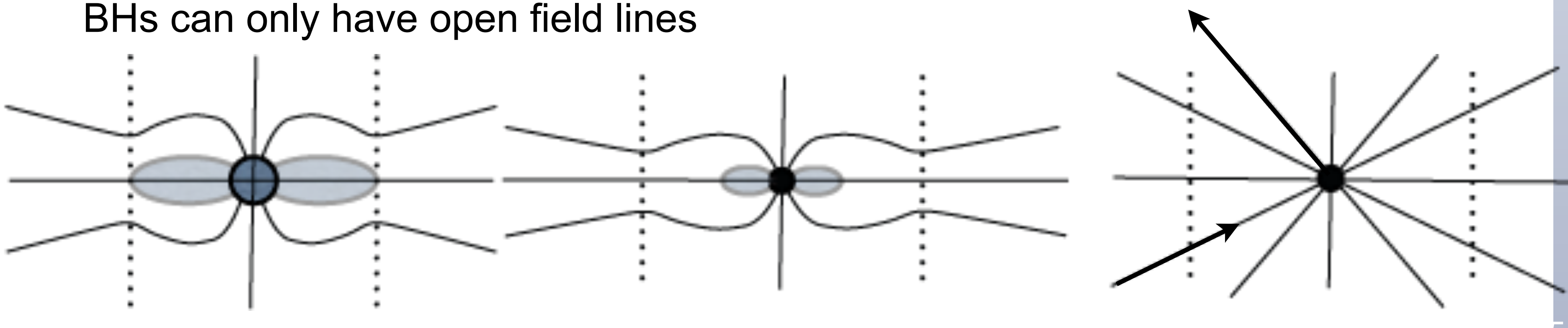
$$N_B = e\Phi_\infty/(\pi c\hbar)$$

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

Property of horizon measurable at infinity: BH hair

Countable BH hair!

BHs can only have open field lines



Time-dependent Grad-Shafranov equation

Lyutikov 2011b

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

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

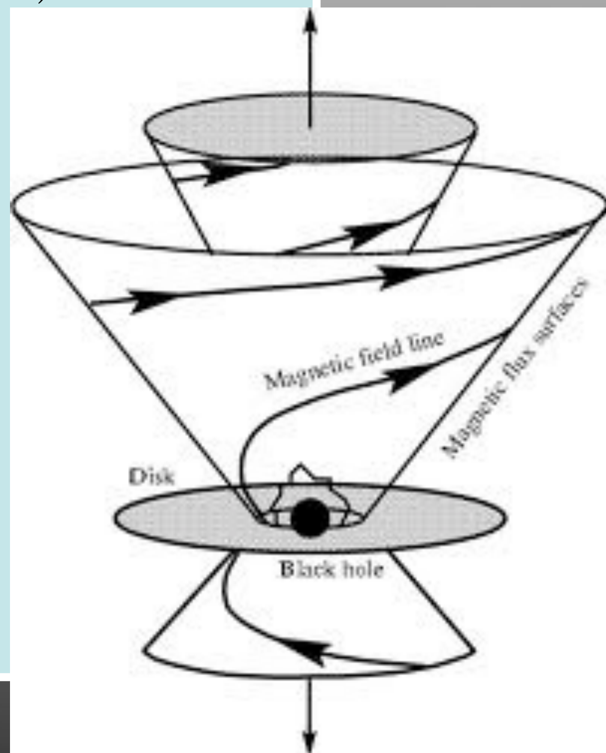
$$\partial_t^2 \Omega = \frac{\mathbf{B} \cdot \nabla (\mathbf{B} \cdot \nabla \Omega)}{B_p^2}$$

  - **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 split-monopole solution in Schwarzschild metric

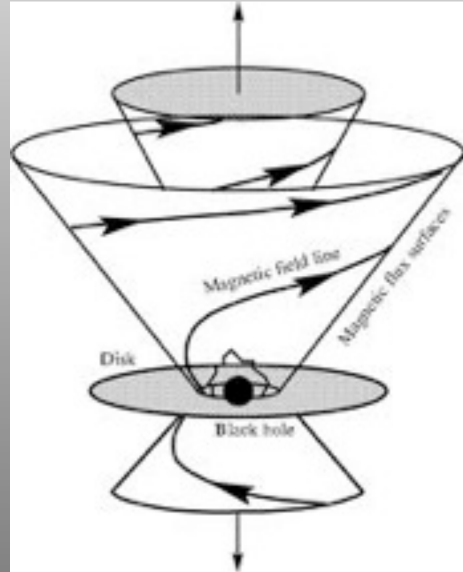
- Magnetosphere of collapsing NS:

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

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

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

$$B_s R_s^2 = const$$



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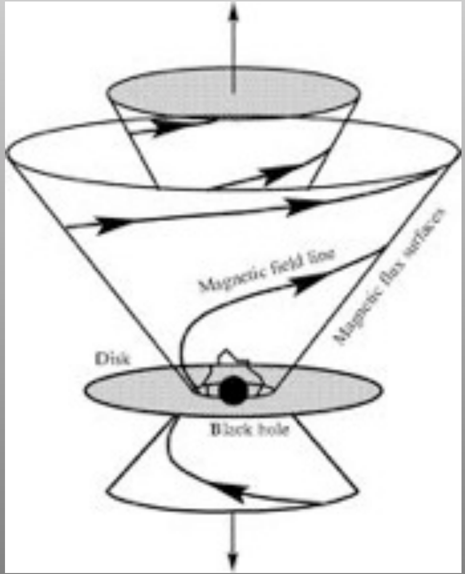

Take a relativistic object with monopolar B-field,
rotate it arbitrarily (slowly, a<< 1). The field will remain monopolar

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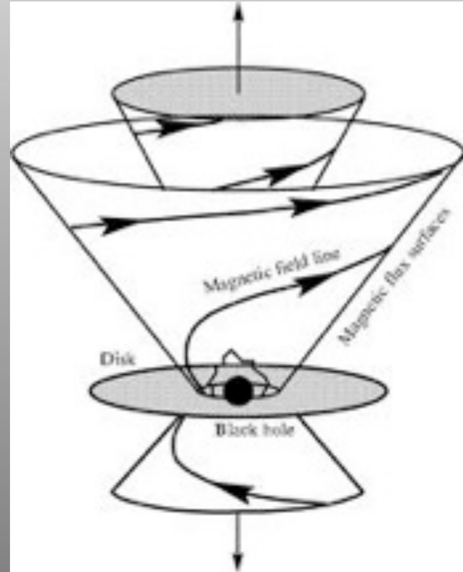

Take a relativistic object with monopolar B-field,
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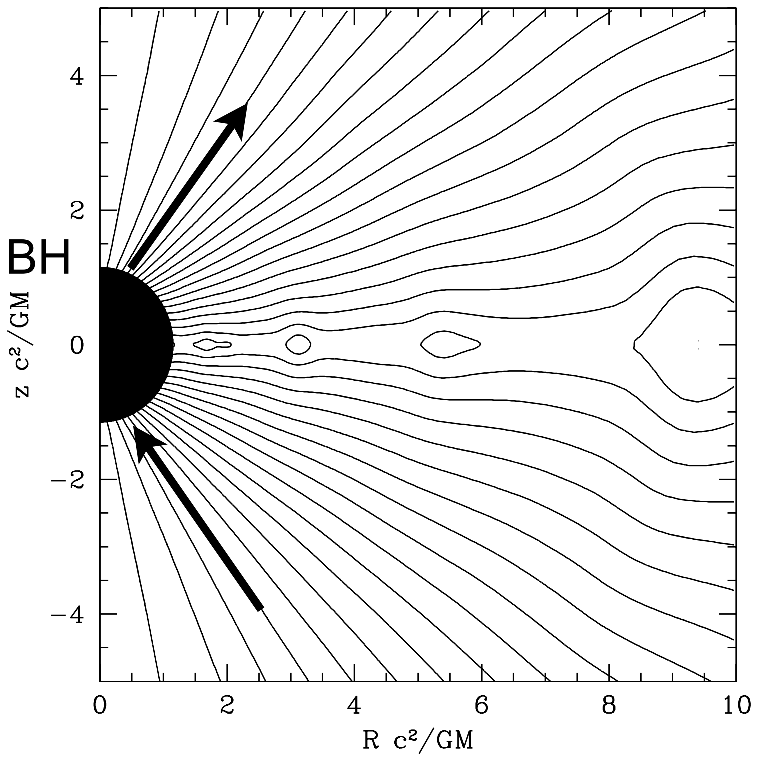
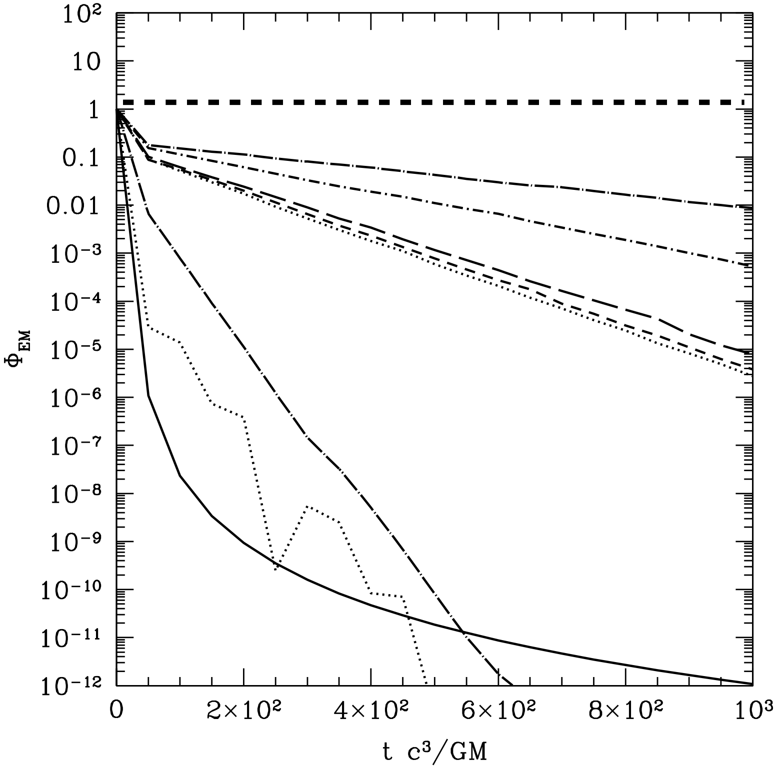
Nothing “bad” happens to poloidal fields during NS collapse

Simulations *(Lyutikov & McKinney, 2011)*

-Split-monopole magnetosphere

- Slow balding





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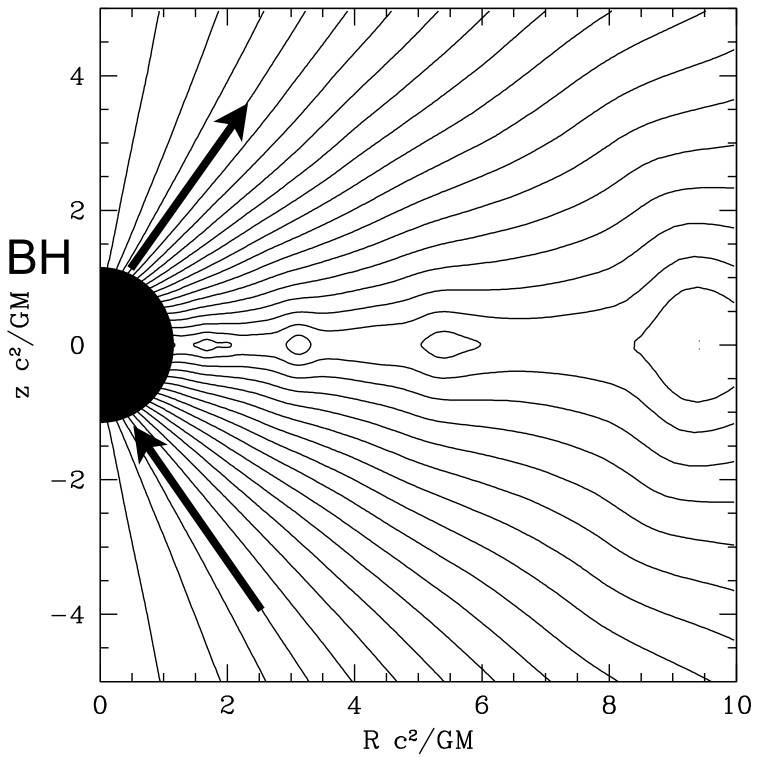

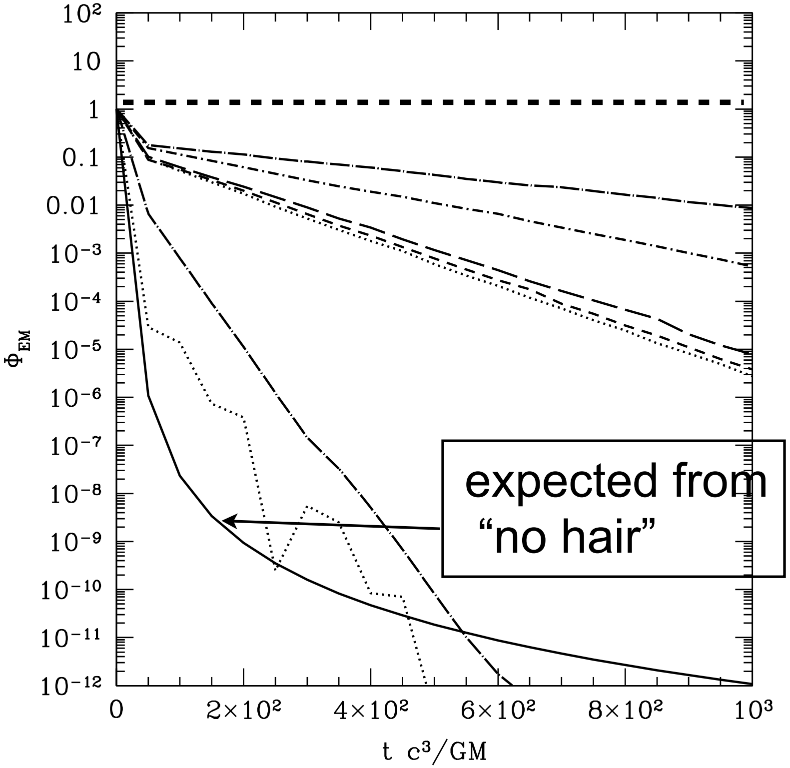

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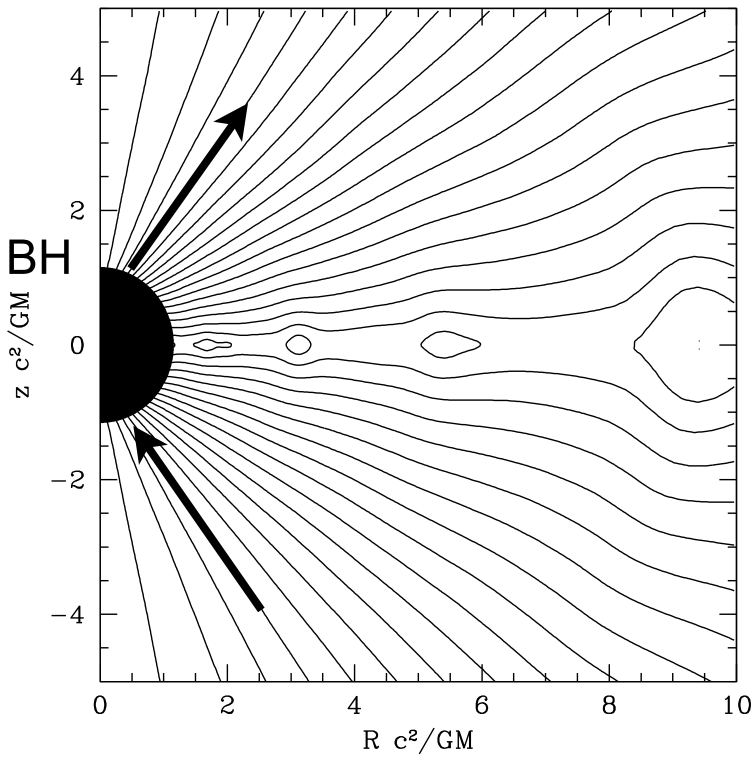

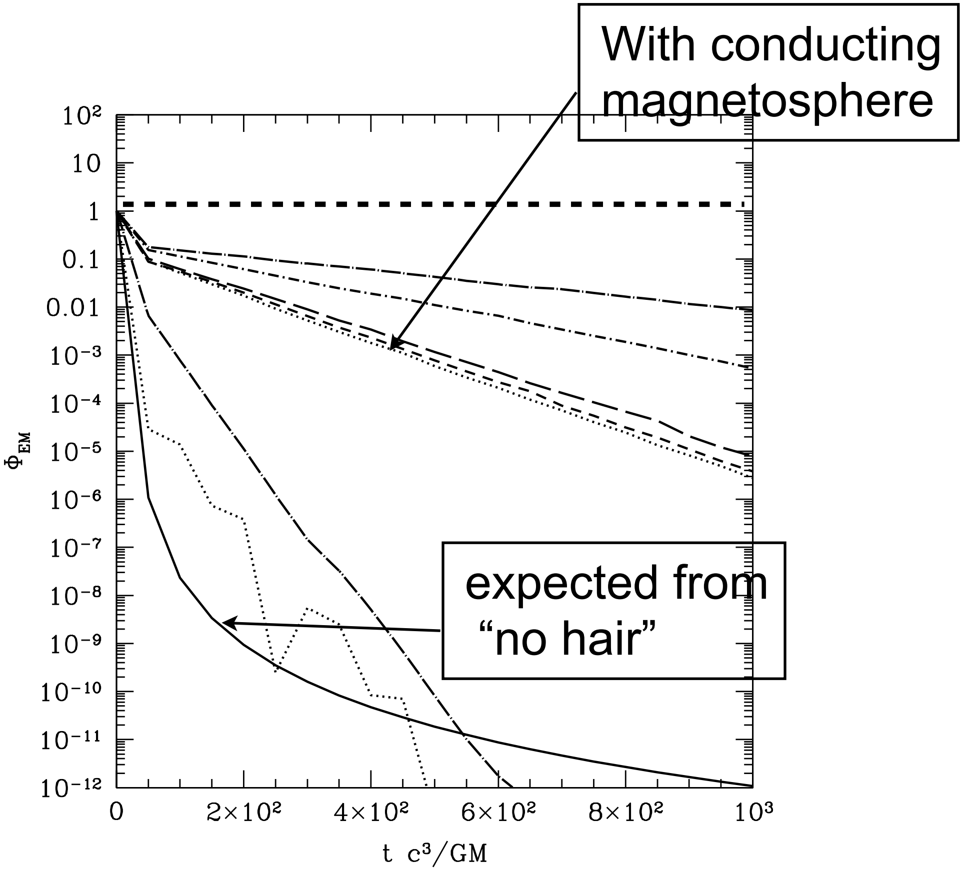

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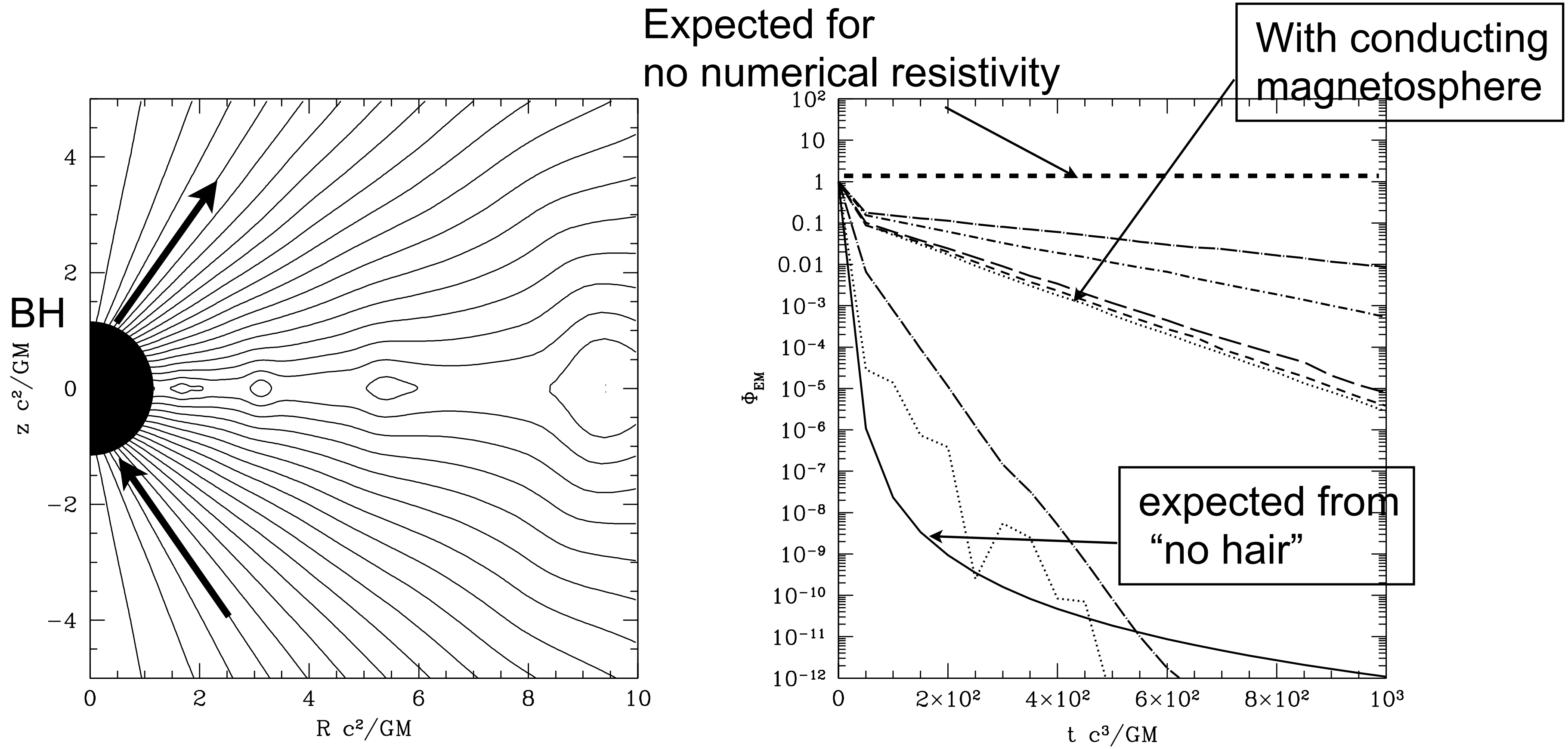

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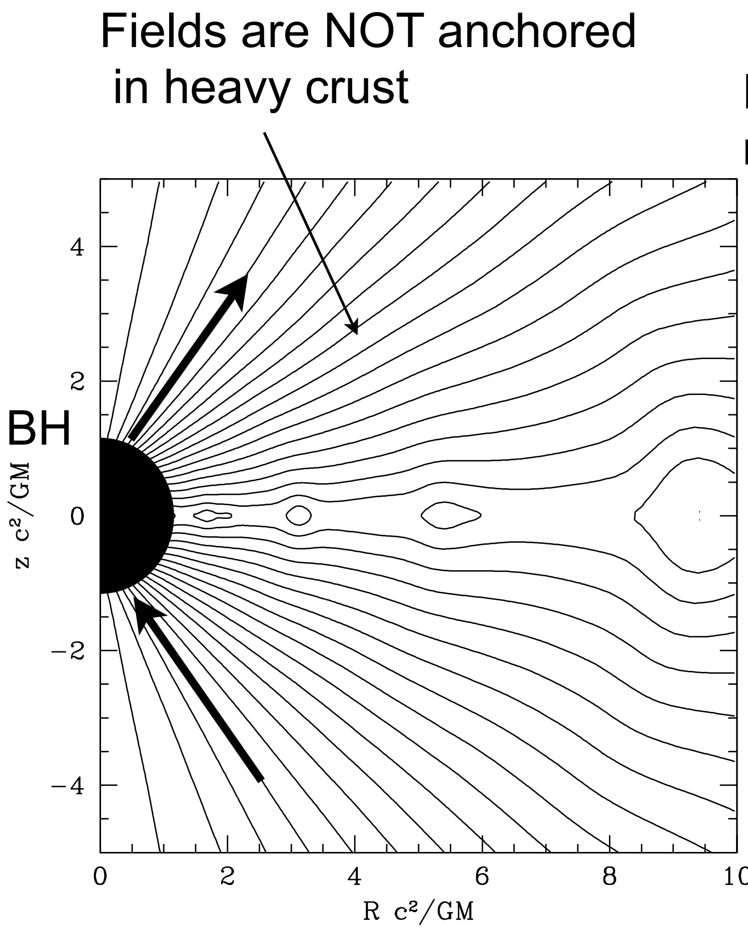

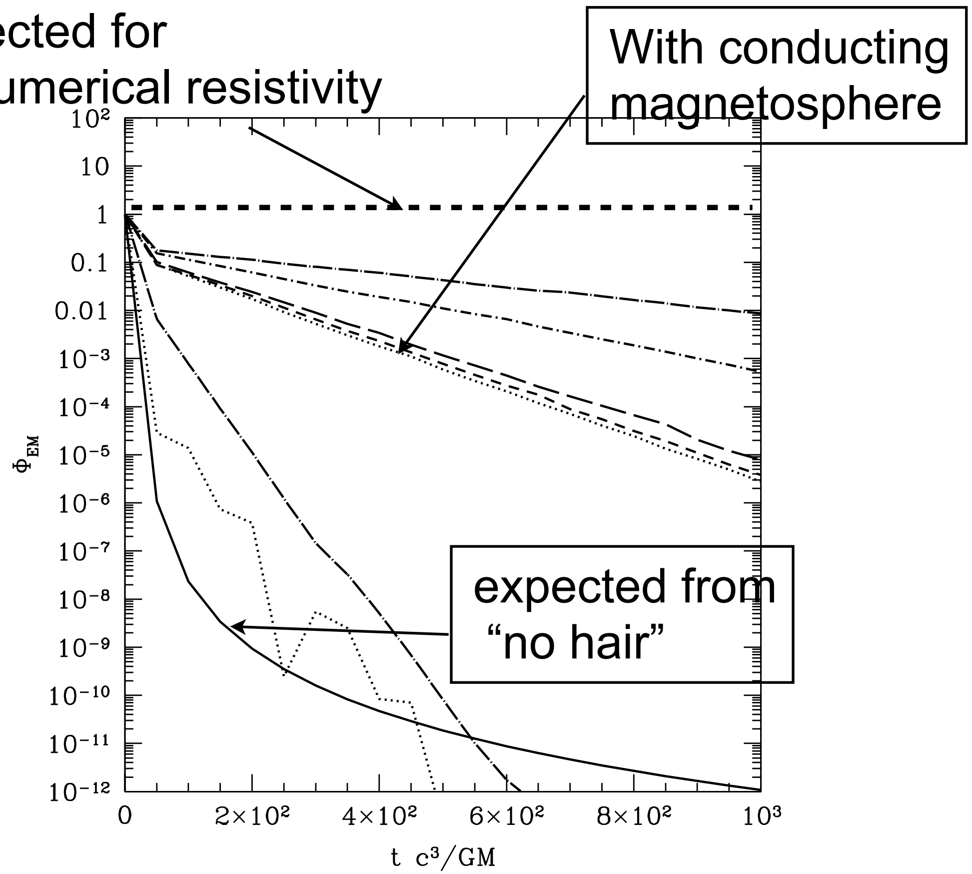

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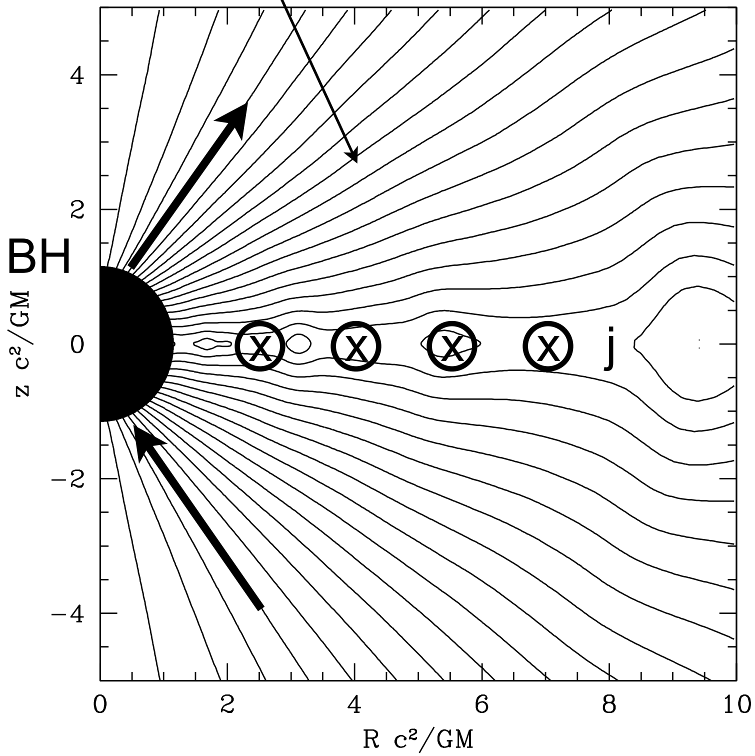
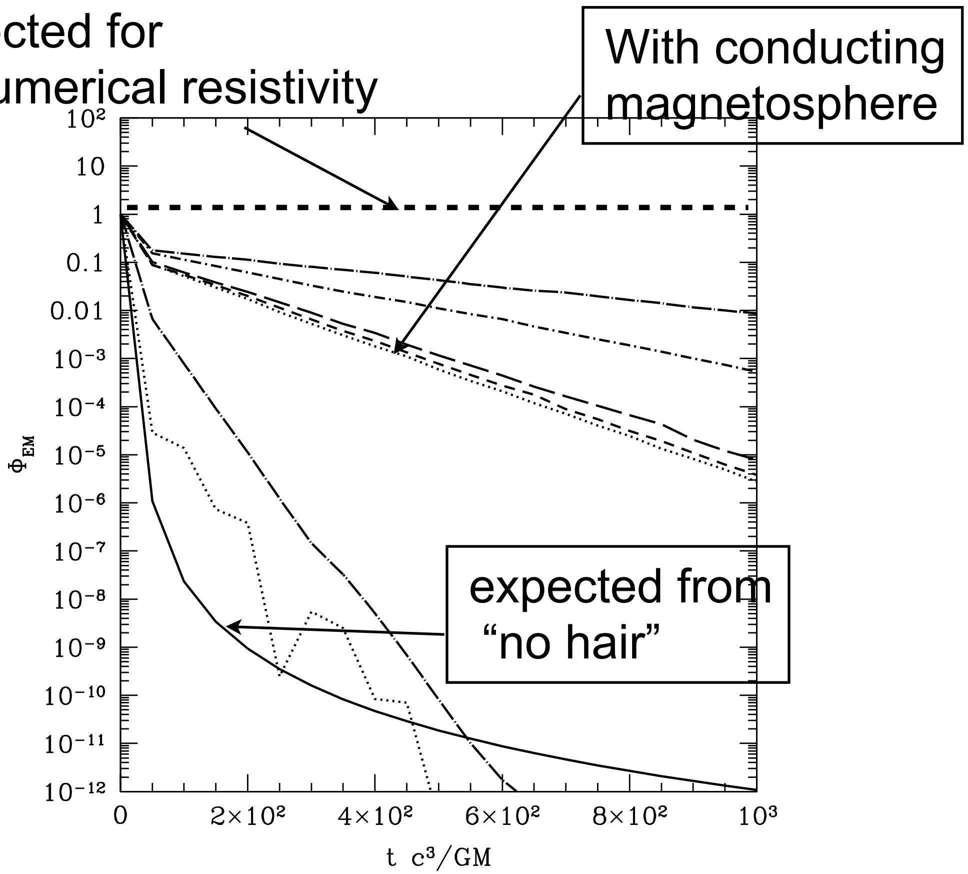
Fields are NOT anchored in heavy crust



Expected for no numerical resistivity



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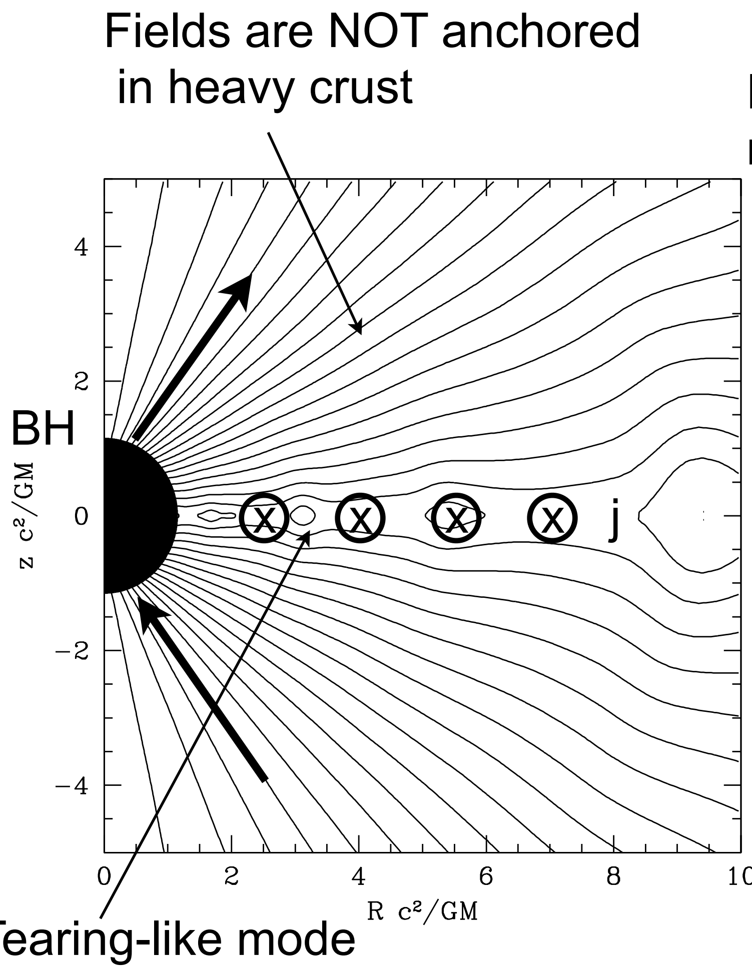

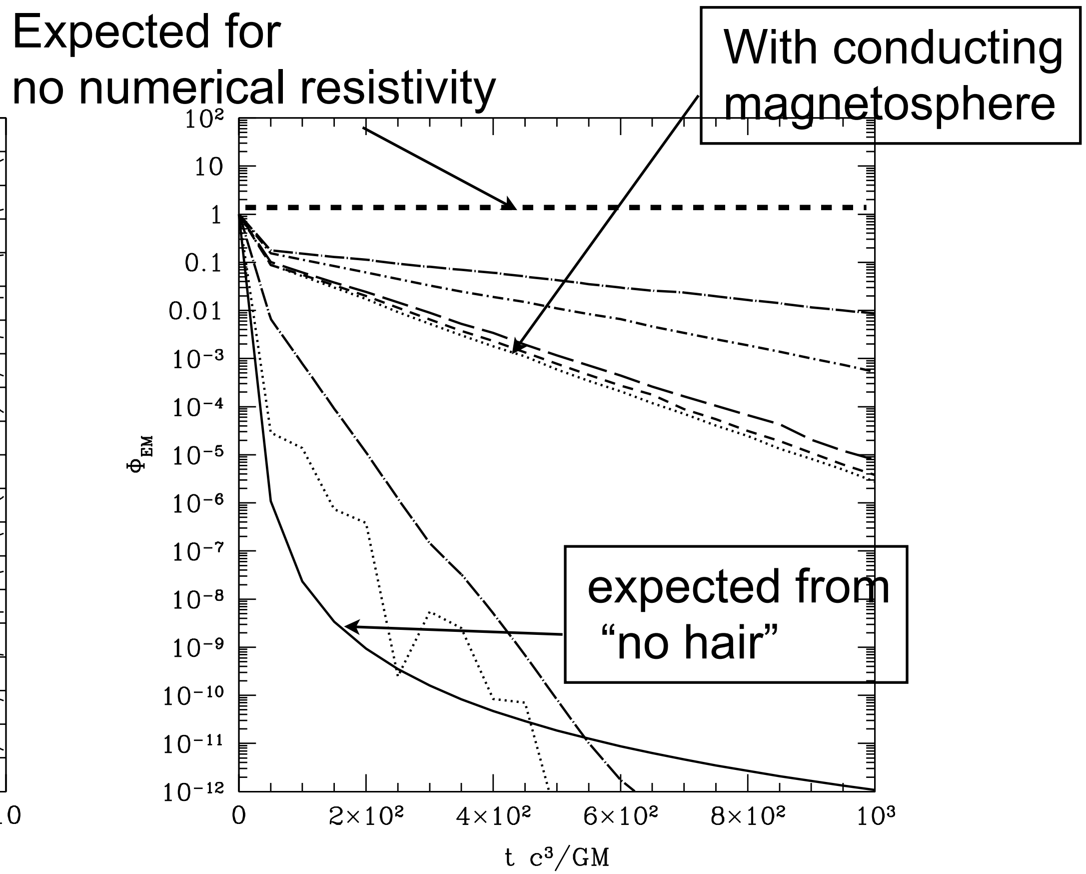

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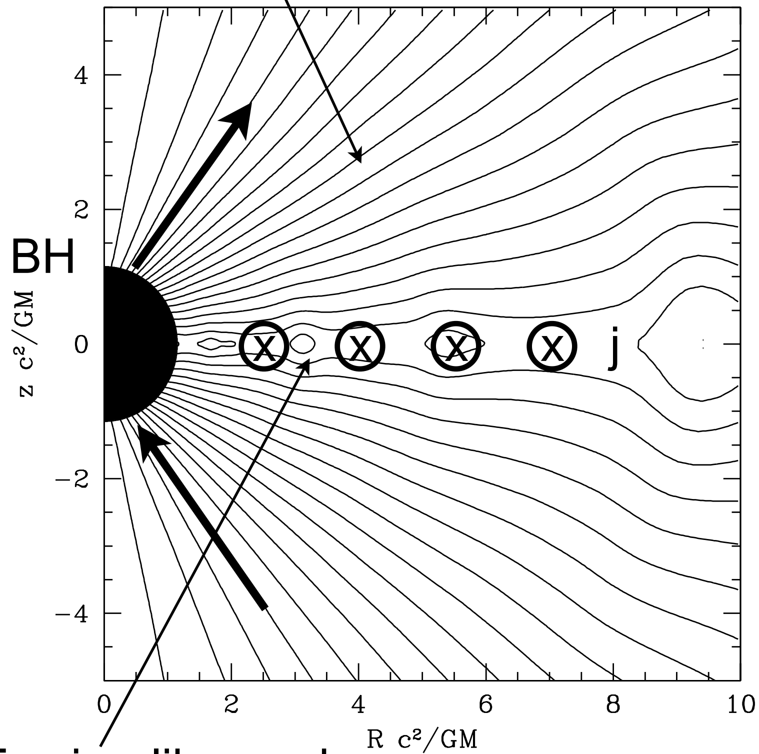
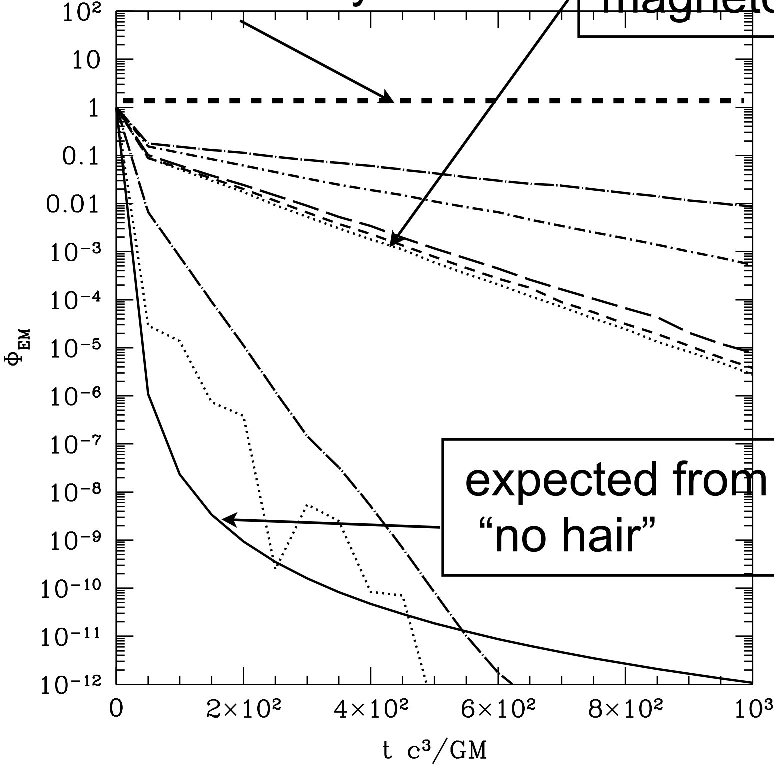


Tearing-like mode

Expected for no numerical resistivity

With conducting magnetosphere



expected from "no hair"

Fields are contained by the equatorial current, just like in BZ, but this current is self-produced

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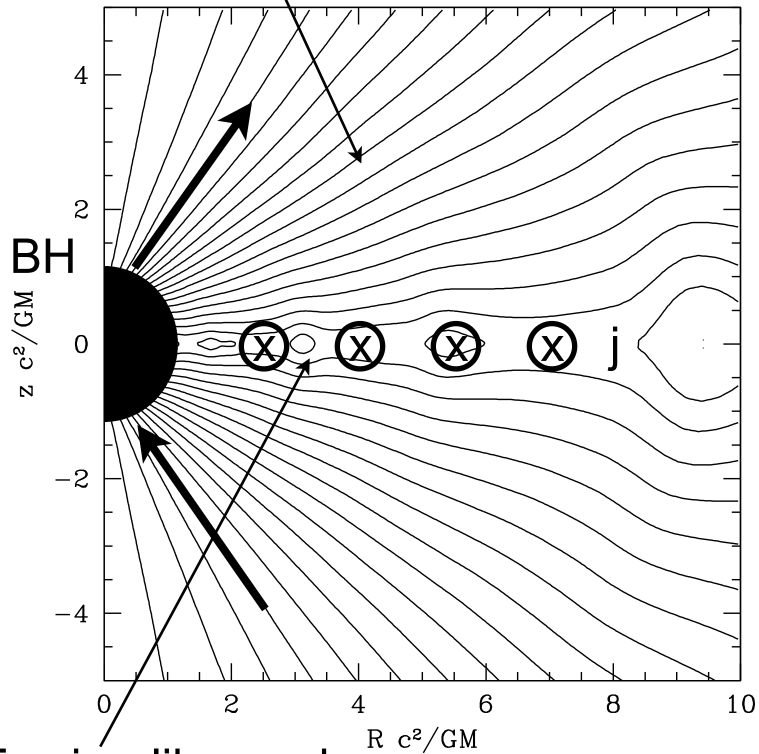

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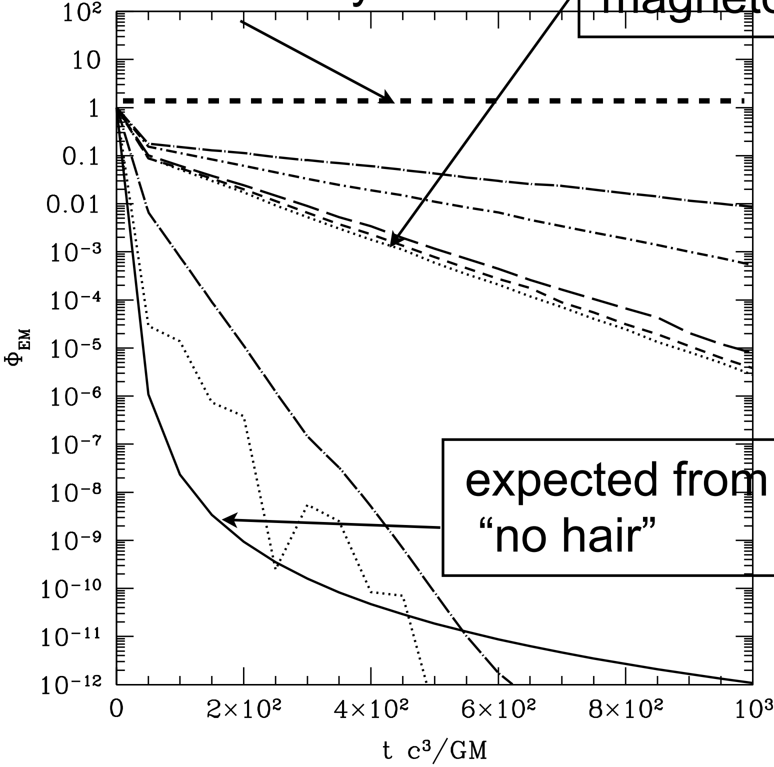

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BZ parabolic solution: switch-off the disk -> relaxes to split monopole

Slowly balding black holes

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

Field structure relaxes to split monopole

No need to anchor B-field into the heavy crust

Isolated BH acts as a pulsar, spins down electromagnetically, generates Poynting wind.

$$L \sim \frac{2}{3c}\left(\frac{\Phi\Omega_{BH}}{4\pi}\right)^2$$

Slow hair loss on **resistive** time scale - hard to predict

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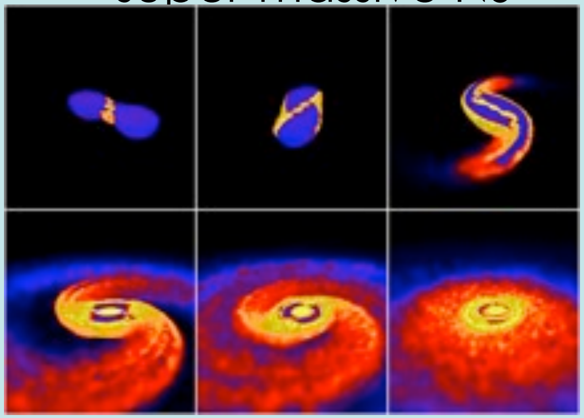
NB: Pair production by rotating BH on field lines penetrating the horizon is the key assumption of the Blandford-Znajek mechanism

The electromagnetic model of short GRBs

B-field in NS-NS mergers: super-massive NS and/or BH-torus

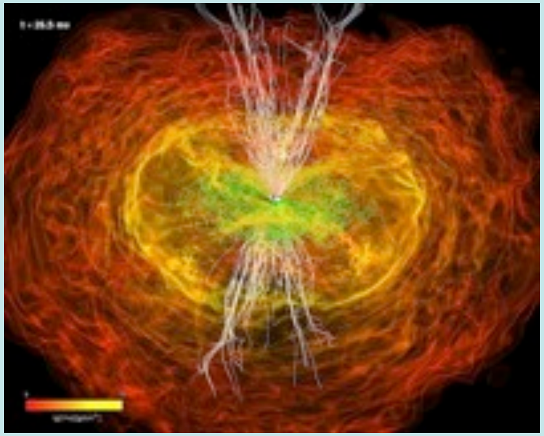
super-massive NS



Transient NS ~ 100 msec

Price & Rosswog

BH-torus, ~ 100 msec



Rezzolla et al

B ~ 10^{15}-10^{16} G

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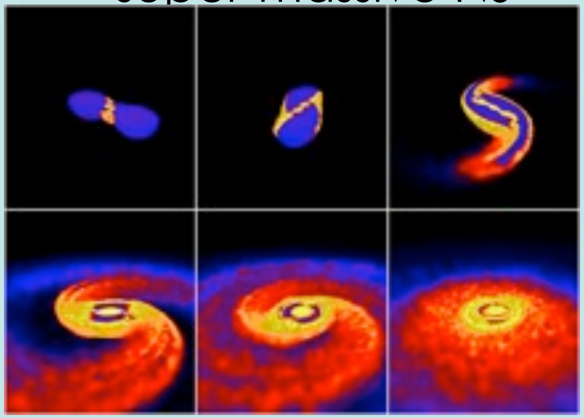

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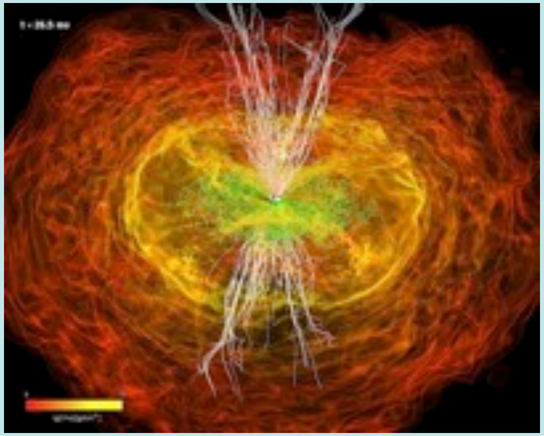

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What happens after NS and disk collapse into BH?
Open magnetic flux is conserved.

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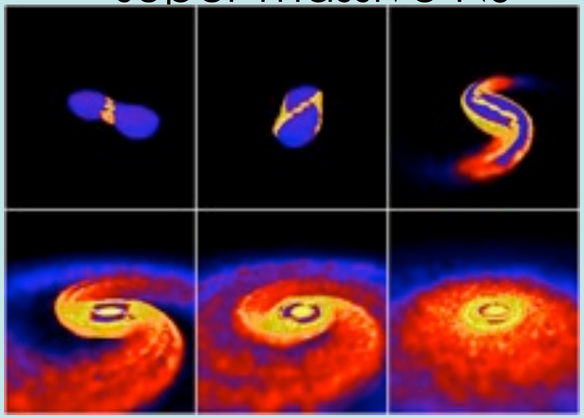

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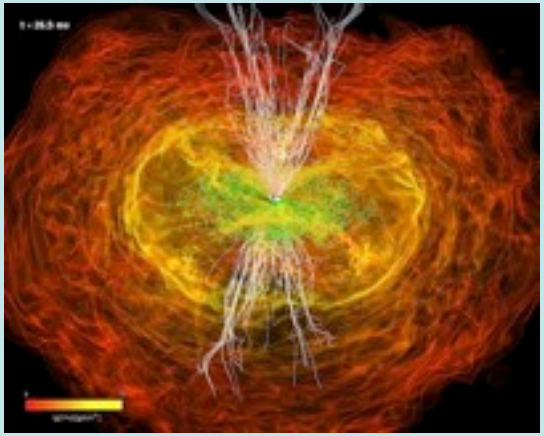

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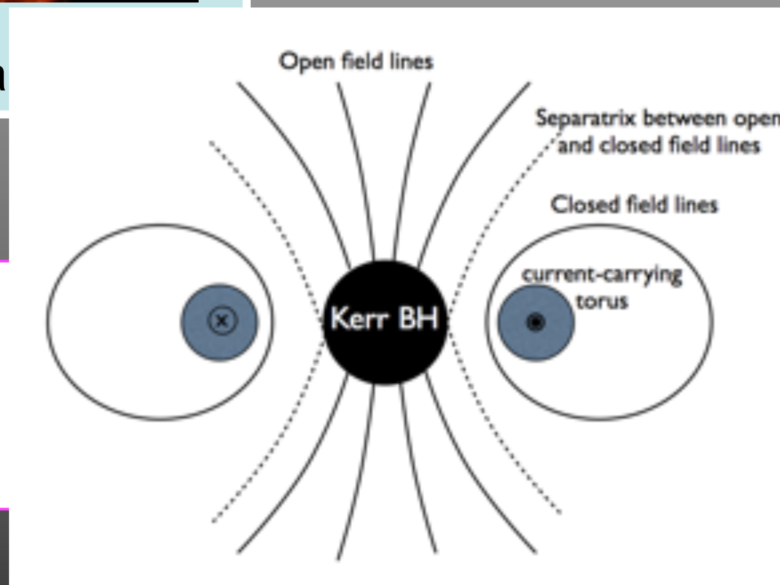
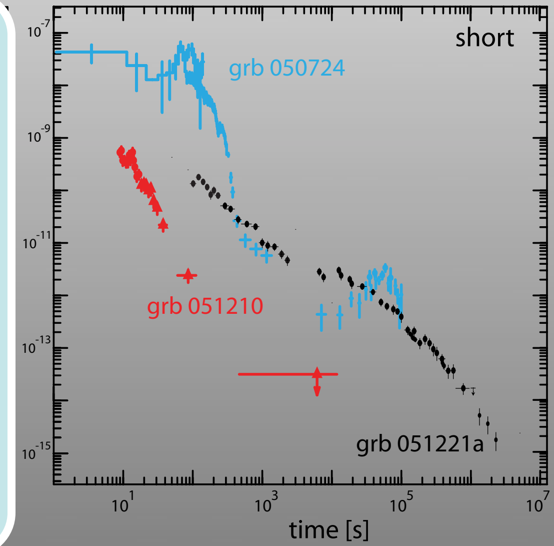


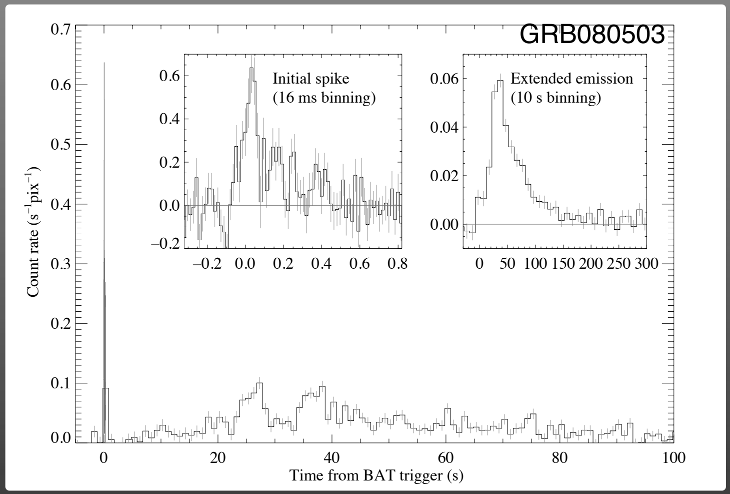
NS-NS merger as central engine of short GRBs, prompt tails, supernova-less long GRBs and late flares

Active stage of NS-NS merger takes 10-100 msec, then collapse into BH. Very little mass is ejected.

Many short GRBs have long 100 sec tails, energetically comparable to the prompt spike.

Many GRBs have late time flares, 10^5 sec

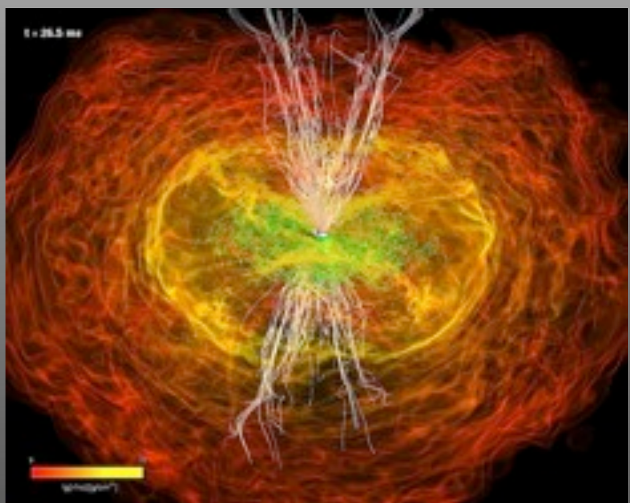




100 sec tail has ~ 30 times more energy than the prompt spike

The electromagnetic model of short GRBs

- NS-NS merger generates B ~ 10^{15} G in the torus around BH (Rezzolla et al.)
- BH-torus launches a jet along the axis: prompt spike
- After ~ 100 msec torus collapse, isolated BH spins down electromagnetically, produces **equatorially-collimated** flow, $L \propto \sin^2\theta$: prompt tail
- **Tail is more energetic**, but de-boosted for axial observer



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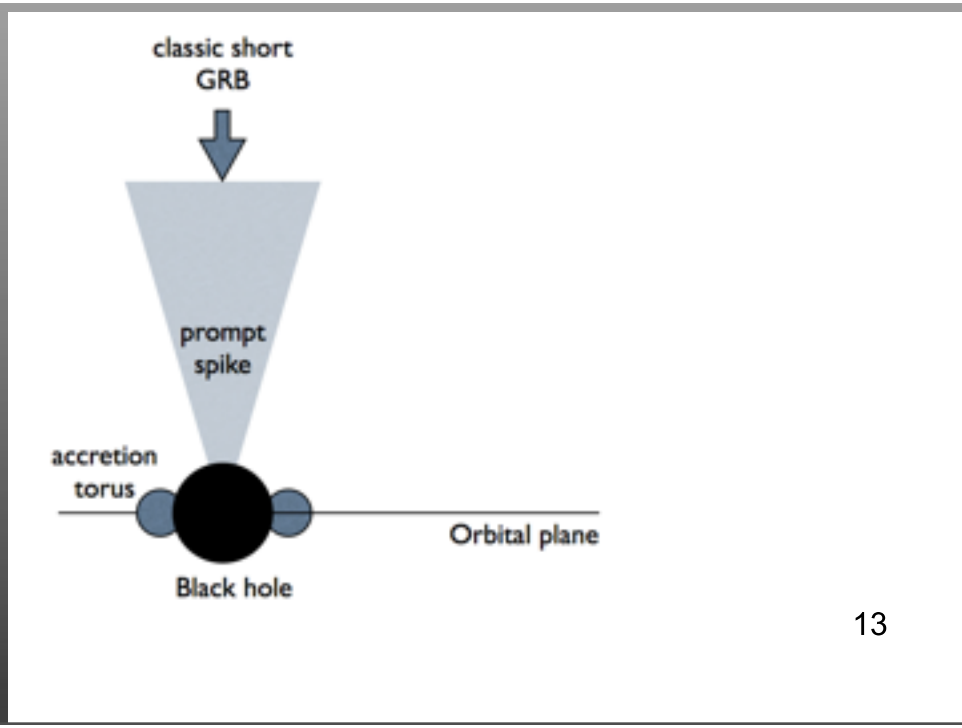

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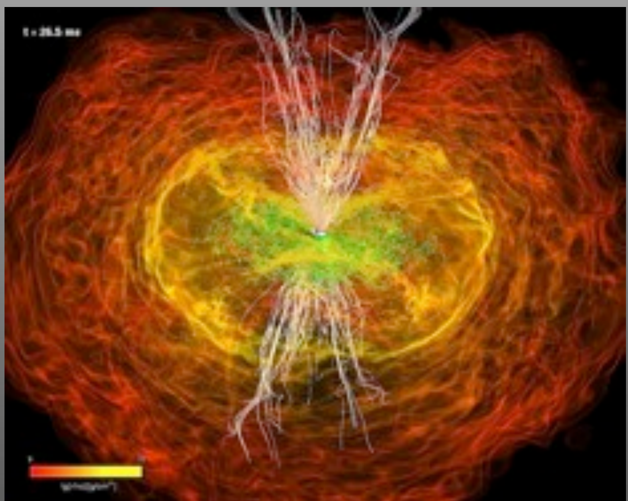

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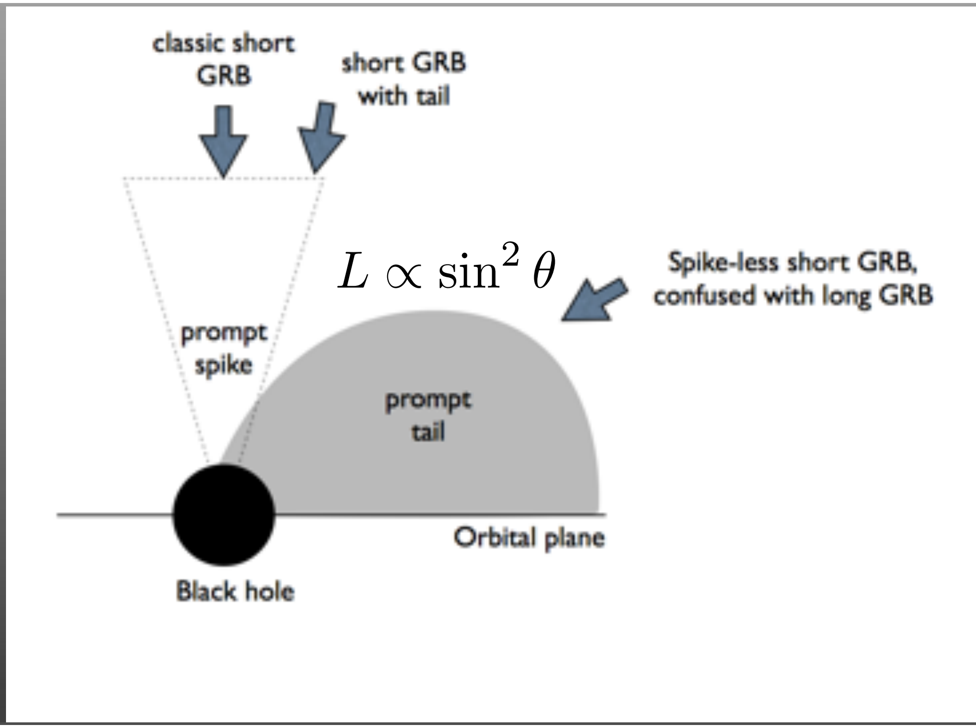

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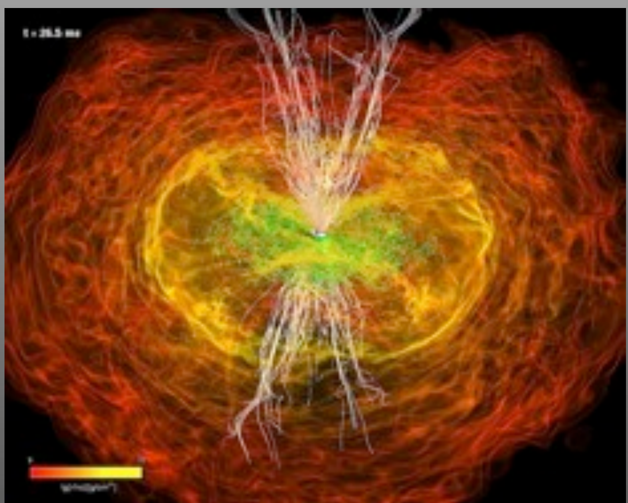

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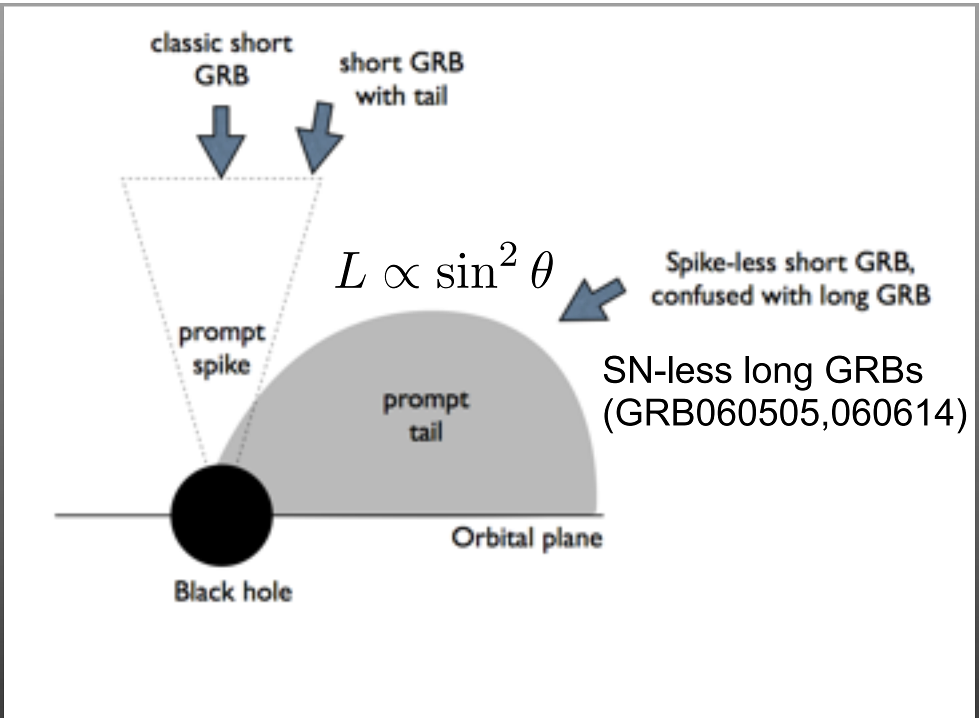


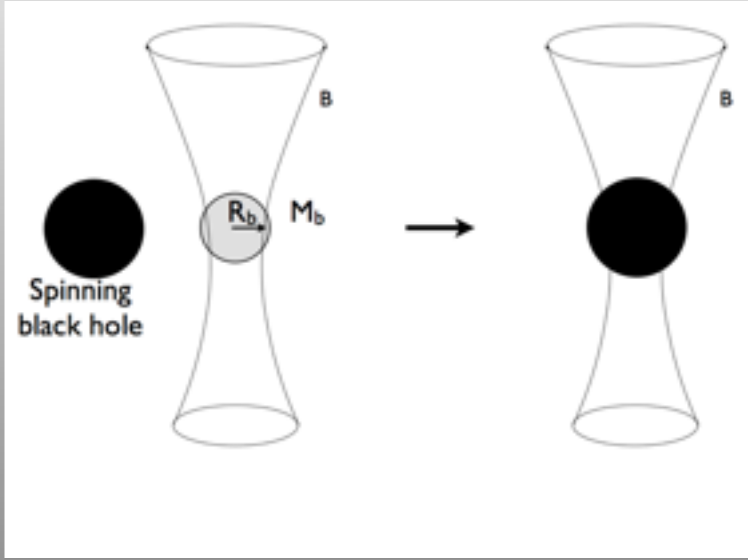
Episodic accretion: flares

Accretion of magnetized blobs

$$\frac{E_{EM}}{M_b c^2} = \frac{2}{3c}\left(\frac{\Phi_b \Omega_{BH}}{4\pi}\right)^2 \frac{\tau_{rec}}{M_b c^2} \geq 1$$

Accretion can be super-efficient (for long retention time-scales)

Need 10^{-5} M_{Sun} blob to produce
L ~ 10^{48} erg/s flare



Episodic accretion: average power

$$\frac{L_{EM}}{\dot{M} c^2} = \frac{2}{3c}\left(\frac{\Phi_b \dot{n} \tau_{rec} \Omega_{BH}}{4\pi}\right)^2 \frac{1}{\dot{M} c^2} \geq 1$$

Steady-state accretion can be super-efficient

Conclusion: BH hair

- The "no hair theorem" is not applicable to rotating magnetized NSs collapsing into BH: open magnetic field lines are retained
- "Balding", loss of open magnetic field lines, occurs on long resistive, not short dynamical, time scales
- Isolate BHs spin down electromagnetically
- May explain long prompt tails and late flares in short GRBs
- Some long GRBs are mis-identified short, SN-less ones