Title: Electromagnetic precursors to compact mergers (and other EM-GR phenomena)

Speakers: Maxim Lyutikov

Series: Strong Gravity

Date: May 30, 2024 - 4:00 PM

URL: https://pirsa.org/24050096

Abstract: I will review various mechanisms and detection strategies of precursor emission to black holes and neutron stars mergers. I will also discuss other peculiar physical processes at the intersection of electromagnetism, classical General Relativity, and the physics of continuous media.

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Zoom link

arXiv:2402.16504

# Electromagnetic precursors to compact mergers (and other EM-GR phenomena)

Maxim Lyutikov (Purdue University)

# Outline

I. Relativistic unipolar inductor
   1. rotation and linear motion
   2. gaps/E-regions

II. NS-NS mergers
   1. draping
   2. double -magnetized (gaps)
   3. flares

III. BH-NS merger
   1. E-regions

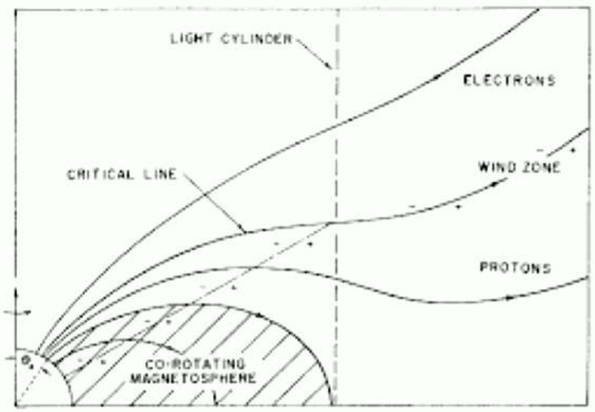
IV. NS to BH collapse
   I. prompt flash
   2. magnetic hair

V. Observational strategies

VI. Fun topics:
   I. Cherenkov emission by Schwarzschild BH
   II. Axion production by Schwarzschild BH

# The paradigm: relativistic Faraday's wheel/ unipolar inductor

- *Pulsar Electrodynamics*
  Goldreich & Julian, 1969




Rotating magnetized sphere generates EMF

- *Io, a jovian unipolar inductor*
  Goldreich & Lynden-Bell, 1969

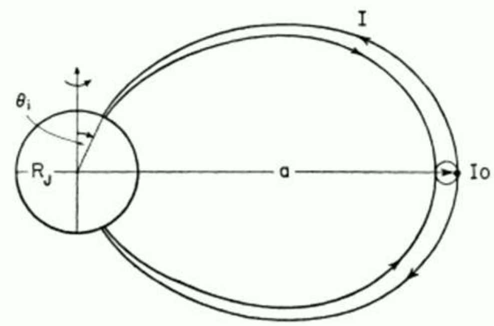


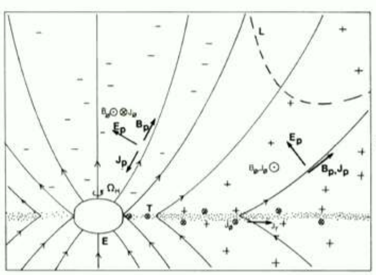

FIG. 2.—Current circuit in the meridian plane (not to scale)

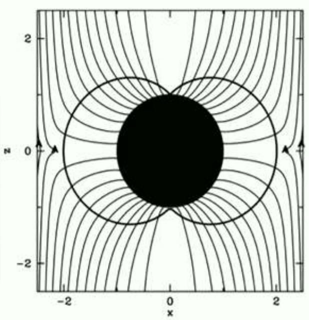
Linearly moving conductor generates EMF

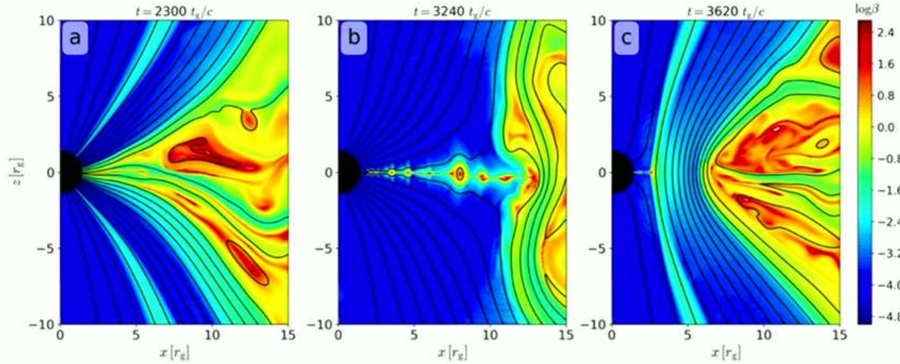
- In both cases parallel E-field is generated
- pulsars: $E_{||}$ is quickly killed due to vacuum breakdown
- Plasma is accelerated: pulsar emission and Jovian aurora

# Extension to GR. 1 BZ-effect

- Rotation: Blandford-Znajek
  - new effects at GR + EM + plasma
  - Rotating space ``drags'' B-field similar to metal plate
  - details are still debated (should a field line cross horizon, or ergosphere is enogh)








Chashkina + , 2021

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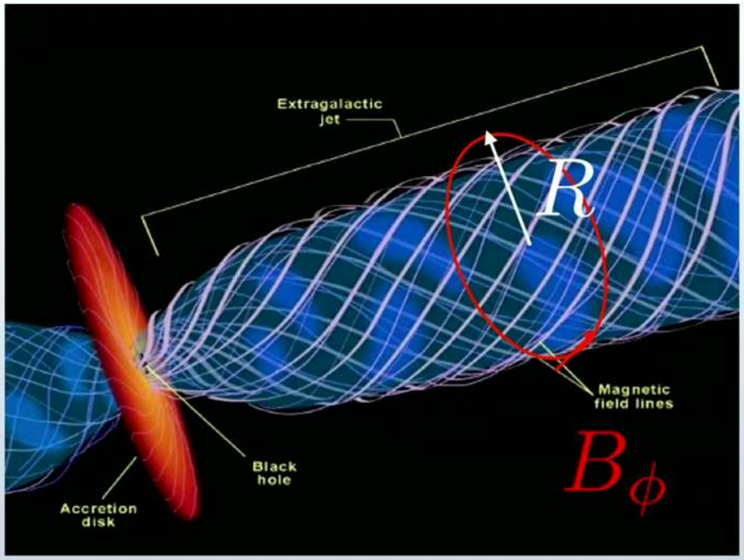
# Power of relativistic unipolar inductor

- Expected power: $L_U \sim \frac{c}{4\pi}(\Delta\Phi)^2$
- **EM-dominated** relativistic sources, matter inertia not important
- $4\pi/c = 377$ Ohm
- Potential E-field times size: $\Delta\Phi \sim E \times L, E \sim \beta B$
  - linear: $\beta$, size D, B-field: $(\Delta\Phi) \sim \beta L B$
  - Rotating NS: $\Delta\Phi \sim B_{NS} R_{NS}^3 (\Omega_{NS}/c)^2$ (Goldrech-Julian) (which is $\Delta\Phi \sim B_{LC} \times R_{LC}$ and $\beta \sim 1$)
  - open magnetic flux

$$L_{EM} \sim (\Phi_B \Omega)^2/c$$
$$\Phi_B \sim B R^2$$

Eg, AGN jet $L \sim B_\phi^2 R^2 c \sim \Phi_E^2 c$

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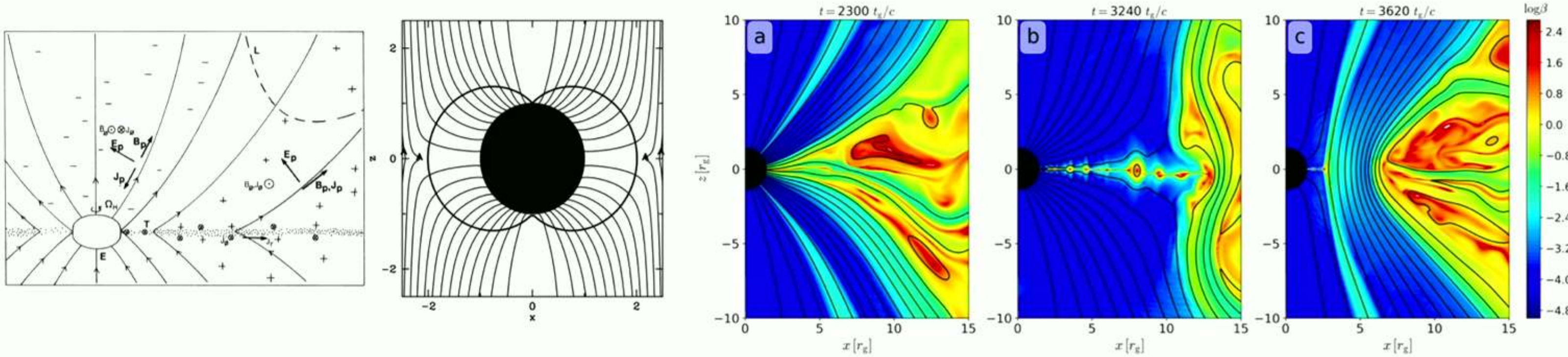

Chashkina + , 2021

Later: extension to GR. 2 - linearly moving BH

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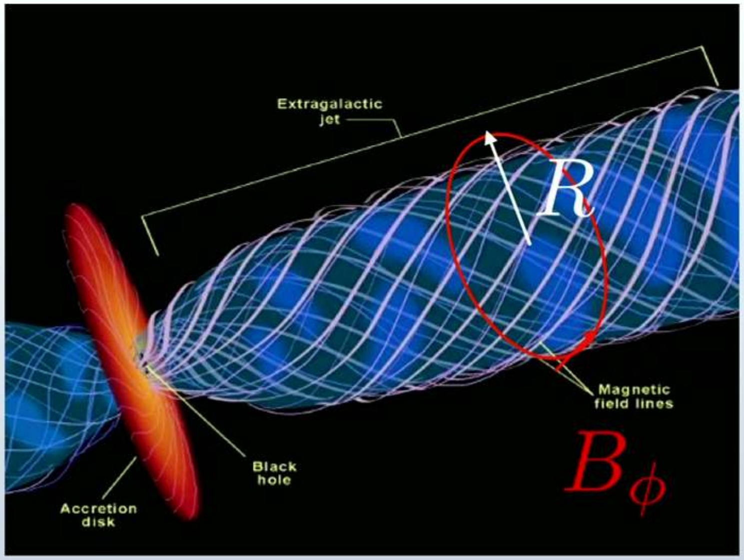
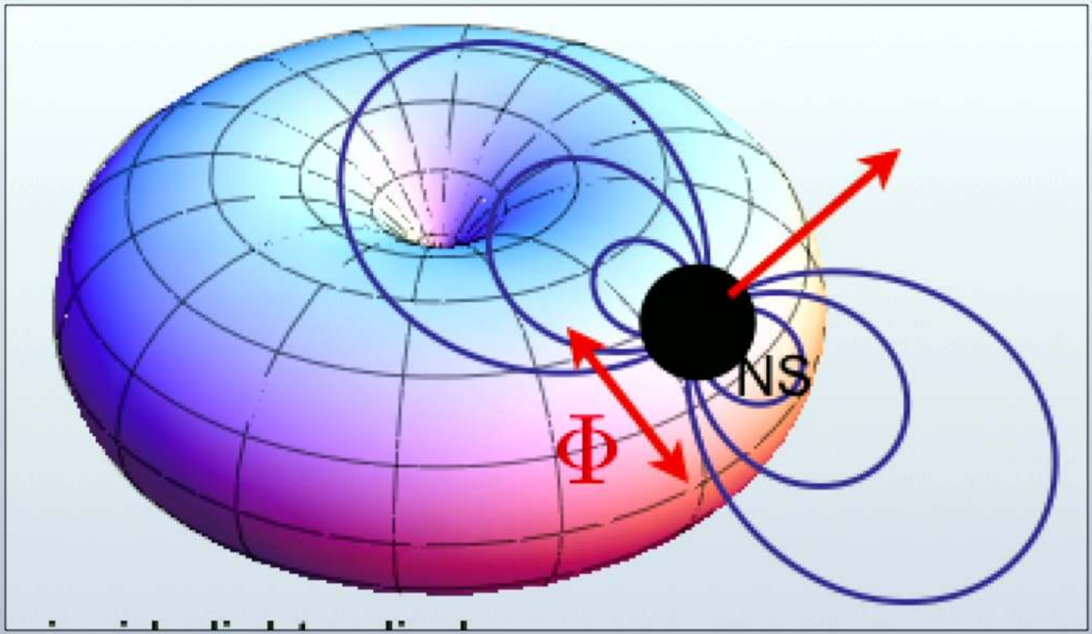


# II NS-NS mergers

Question 1: before merger a NS moves through companion's B-field: what we expect?

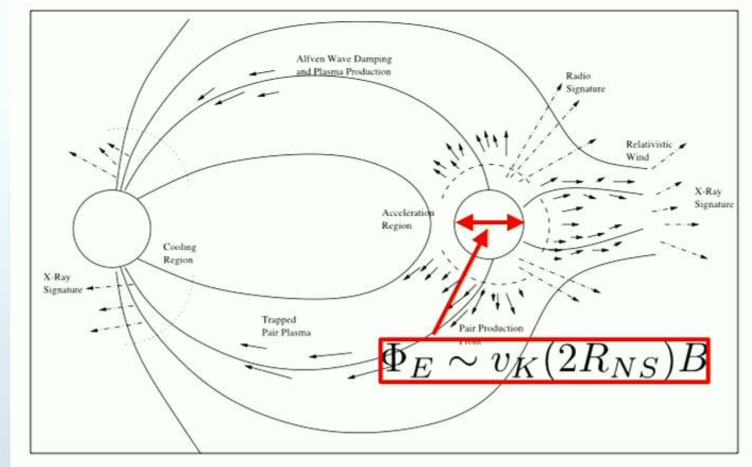


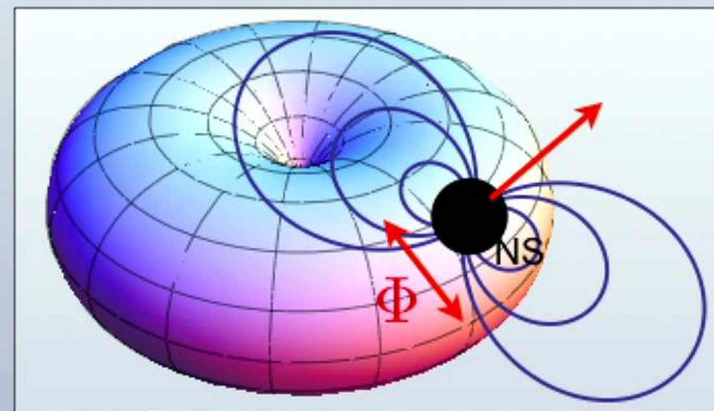
# Precursor emission to LIGO NS-NS events

- Hansen & Lyutikov 2001: NS in the B-field of companion

$$L \sim \frac{GM}{c} B_{NS}^2 \frac{R_{NS}^8}{a^7} \approx 10^{46}\, B_{12}^2\, a_6^{-7}\, \mathrm{erg}\, s^{-1}$$

- Not very bright... Unless coherent! - **Radio**
- $F_\nu \sim 10^3\,\mathrm{Jy\ from\ 1\ Gpc}$
- That was the best model for the Lorimer Burst, not anymore, FRBs are not mergers.
- Short GRBs from NS-NS merger need B-field amplification to ~ $10^{14}$ G

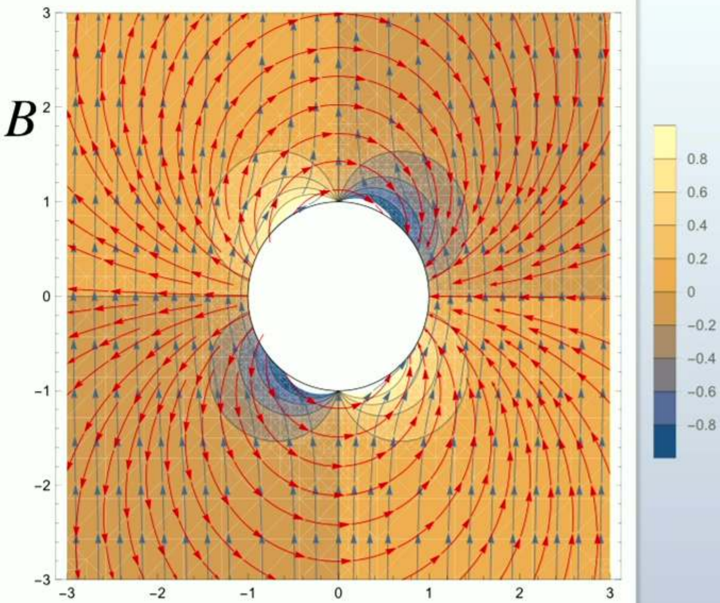


# NS moving through B-field: Creation of dissipative regions

Lyutikov 2018

- Try vacuum, if $\mathbf{E} \cdot \mathbf{B} \neq 0$ -> most likely a problem
- Electrodynamics ~ pulsars
  - Motional E-field
  - regions with $\mathbf{E} \cdot \mathbf{B} \neq 0$ and $E > B$
  - orbital modulation

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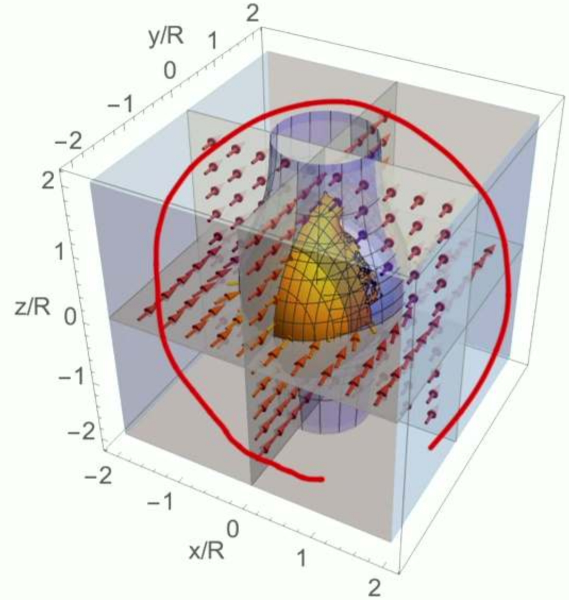
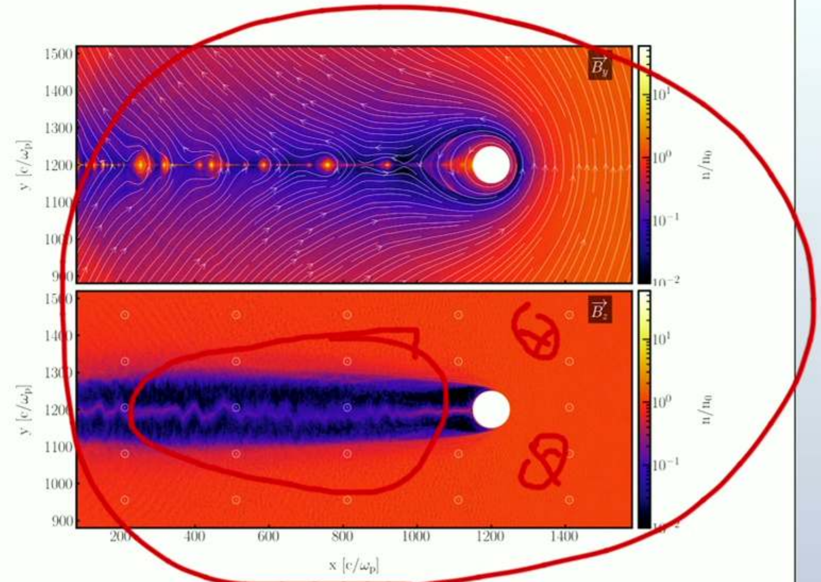
Lyutikov 2023

# Even with plasma: Draping of merging NS

- **EM interaction of merging neutron stars is necessarily dissipative due to formation of draping layer, $E_{||}$ and/or $E > B$**

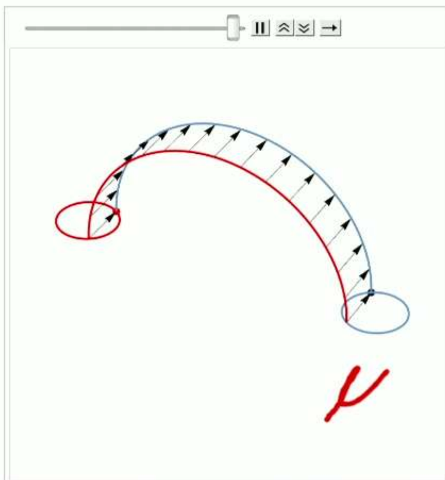


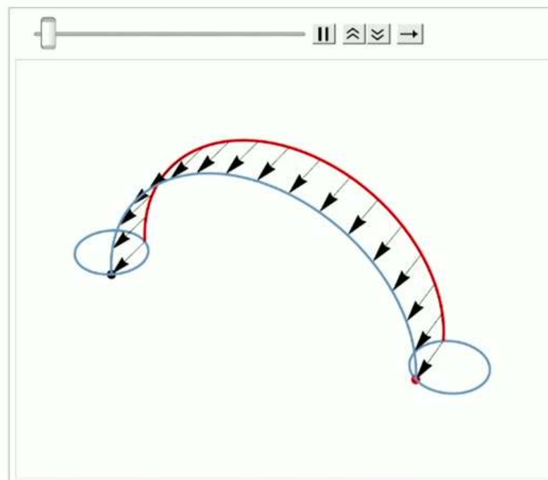




Sironi+, in prep.

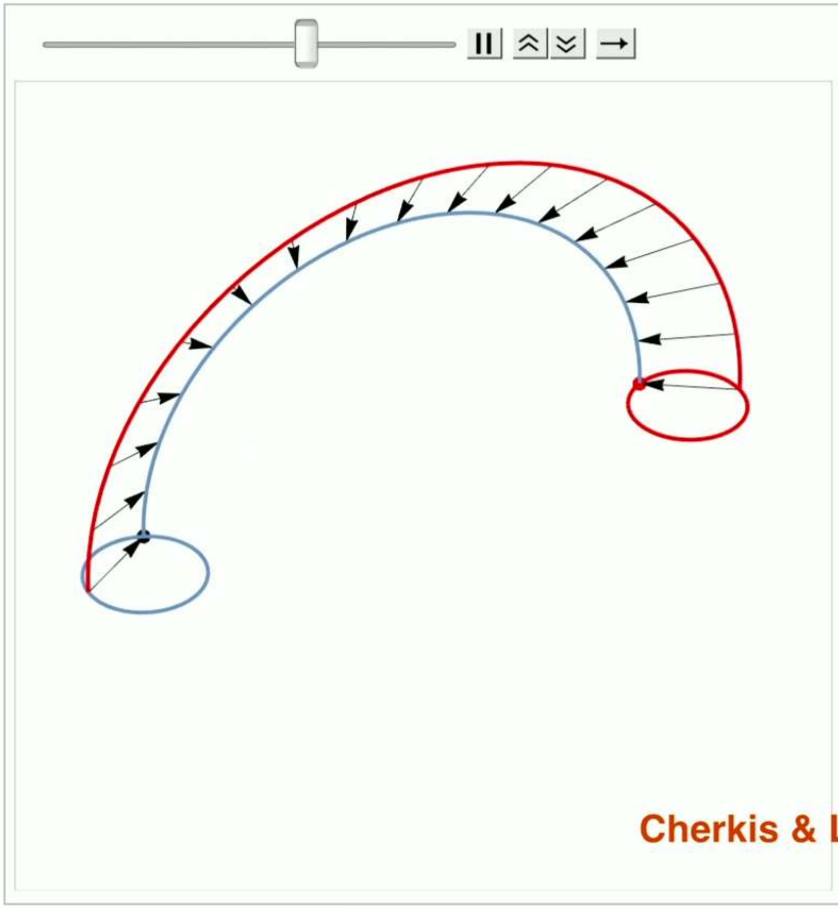
# Flares!

- Store energy **slowly** in connected magnetospheres – release explosively
- **Combination of spins and orbital motion can "unwind"**
- Special configurations of interacting NSs
  - Fully locked
  - $\text{omega}_1 = -\text{omega}_2$





# Basic-Z: $\omega_1 + \omega_2 = 2\Omega$



Cherkis & Lyutikov ApJ, 2021

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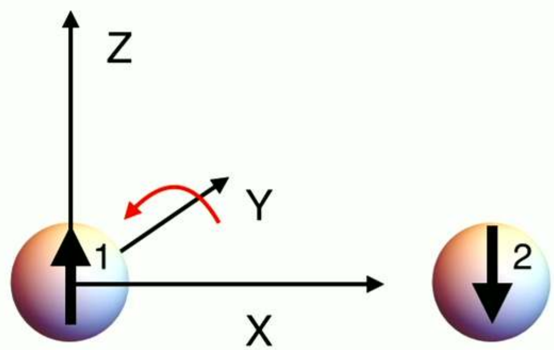
# Y-spin




Cherkis & Lyutikov ApJ, 2021

# Y-spin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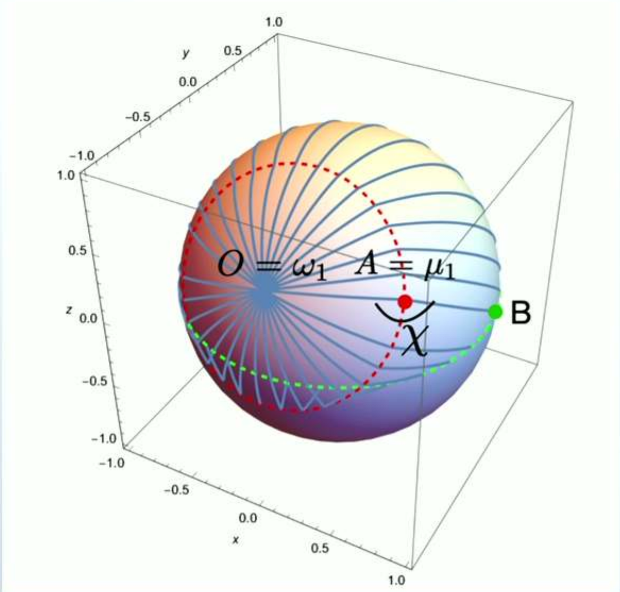
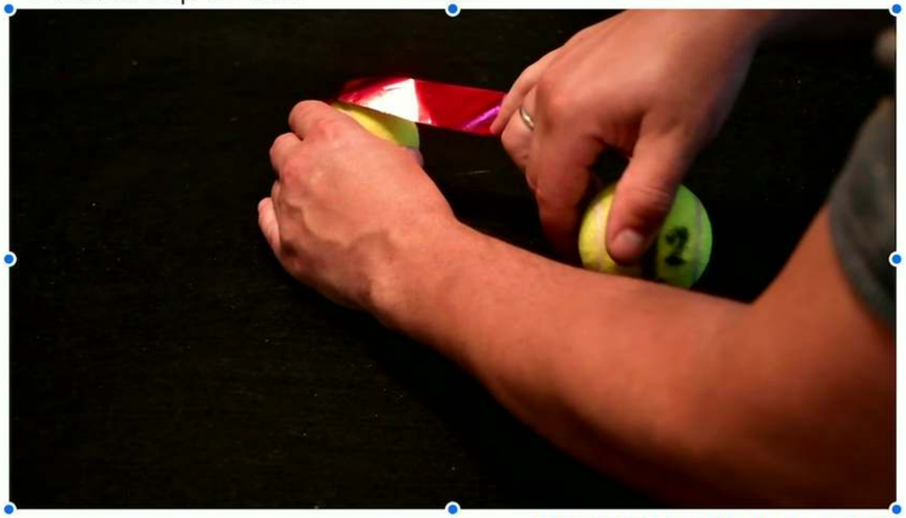
# Topology of magnetically coupled stars

- Direction of B-field from #1 to #2: a path on 2-sphere
- Curl B is not important: each hair in a braid can be twisted: we are for **braiding**
- Need to track 3 points on the 2-sphere of B-direction to define braiding.




O - omega of 1
A- mu of 1
B: radius 1-2

# Y-spin



Cherkis & Lyutikov ApJ, 2021

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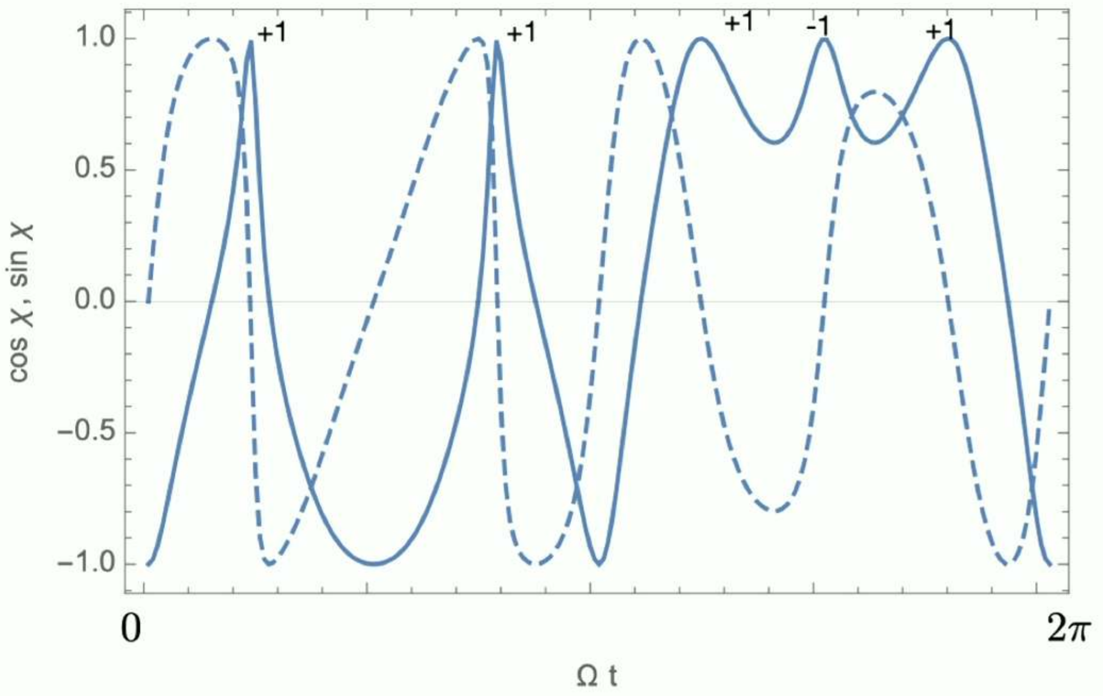
# Counting twists

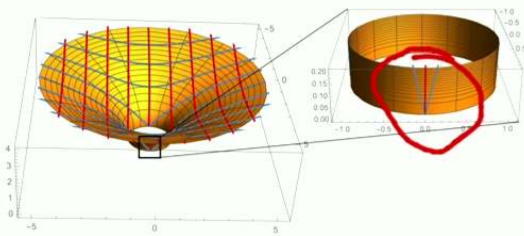


# III. BH-NS merger
# (and supermassive BH-BH)

# Extension to GR. 2: Linear unipolar inductor: Schwarzschild BH moving across B-field generates EM wind

Lyutikov 2011
Palenzuela +2010

- Linear motion: A Schwarzschild BH moving across B-field generates E.B !=0 and EM wind

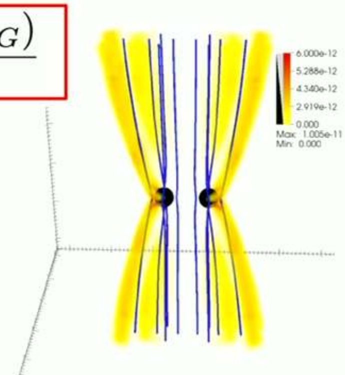


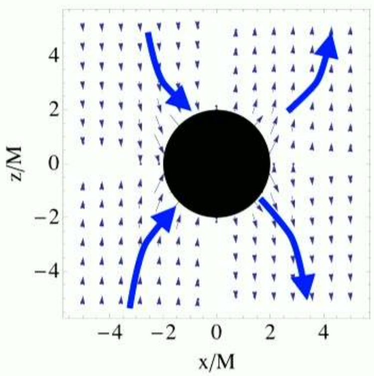
$$\mathbf{E}\cdot\mathbf{B} = -\cos\phi\sin 2\theta\,\beta_0 B_0^2 \frac{M}{r}$$

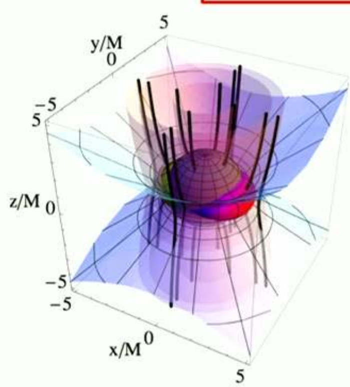
$$\rho_0 = \frac{B_0(v_0/R_G)}{2\pi c}$$

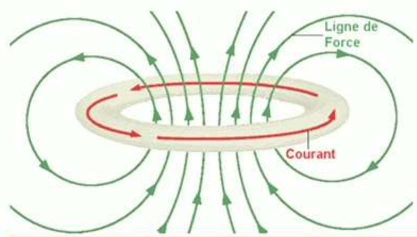
$$L_{EM} \approx M^2 \beta_0^2 B_0^2$$

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






– BH-BH merger ($B_0$ from disk)

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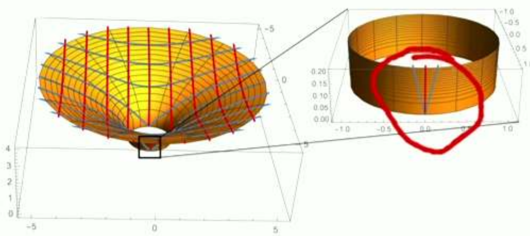

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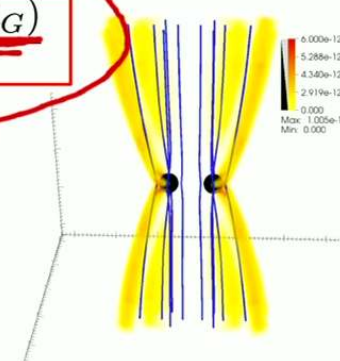

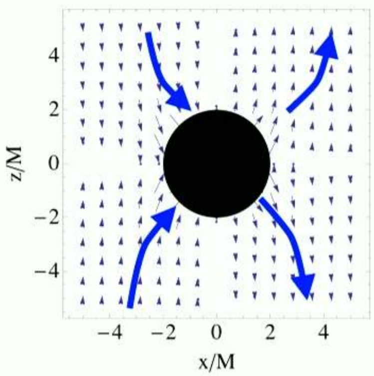


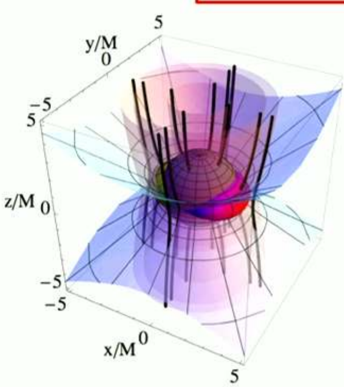


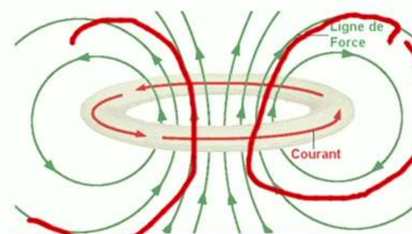


- BH-BH merger ($B_0$ from disk)

# Early stage of NS collapse: pulsar-like EM signal during prompt collapse - not much

- Power increases but collapse time is very short

$$L_{NS} \sim B_{NS}^2 R_{NS}^2 c \left(\frac{R_{NS}\Omega}{c}\right)^4$$

$$L \sim L_{NS} \left(\frac{R}{R_{NS}}\right)^{-4}$$

$$t_{col} \sim \sqrt{R_{NS}^3/(GM_{NS})} \sim 0.1\text{msec}$$ (rotational support will prolong)

- After NS collapse, the BH rotates with smaller frequency!

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

- a = 0.04 for a ms - NS slows down!

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# Magnetic hair of BHs

Lyutikov 2011
Lyutikov+2012
Bransgrove+ 2021

- **Loop-hole in "NO-HAIR" theorem: frozen-in B-fields**
- **Hair are conserved (in ideal plasma)**

$$N_B = e\Phi_\infty/(\pi c\hbar) = B_{NS} e R_{NS}^3 \Omega_{NS}/(c^2\hbar) = 10^{41}\frac{B_{NS}}{10^{12}\mathrm{G}}\frac{P_{NS}}{1\mathrm{msec}}$$

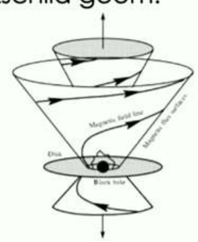
- **No prompt EM pulse due to "released" B-field**

- Analytics: time-dependent B-field in Schwarzschild geom.

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

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

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



- Nonlinear, time-dependent solution in GR (small a)

- **arbitrary $\Omega(t,\theta)$ in Schwarzschild metric**
  - **Alfven mode propagating *along* (!) B-field**
- **BH *slows down* during collapse (! - anti-skater)**
- **Released spin-down power is small $\sim L_{sd}R_{NS}/c$**

- **Magnetic hair** *(Slowly balding black holes, Lyutikov and McKinney 2011)*
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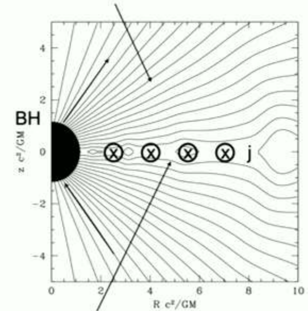


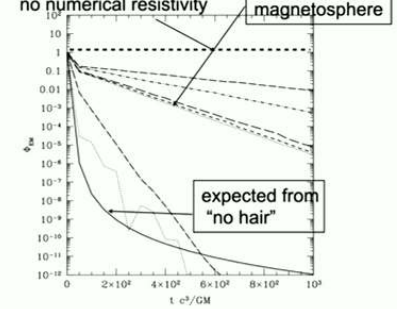


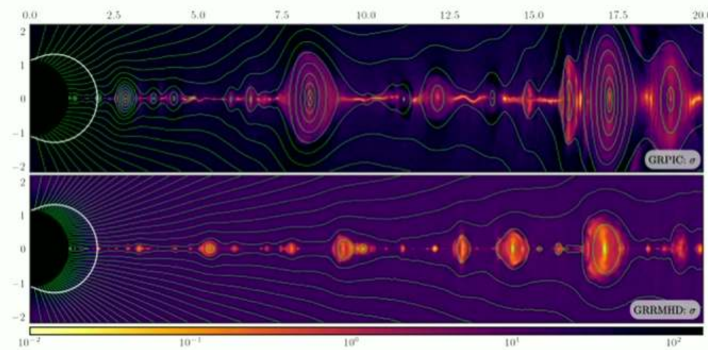

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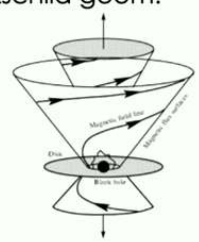

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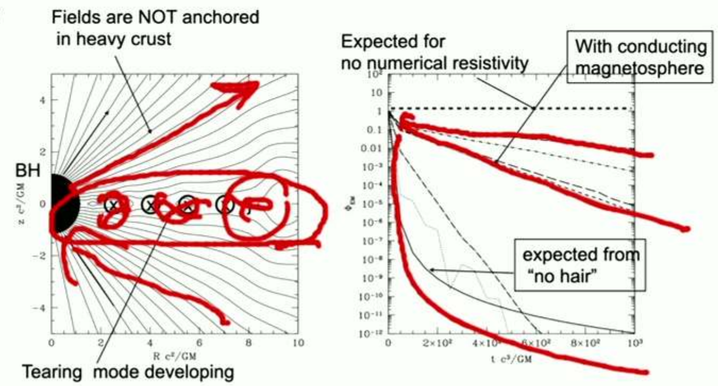
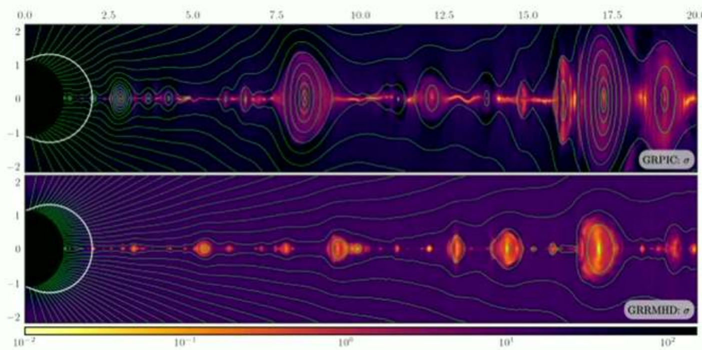
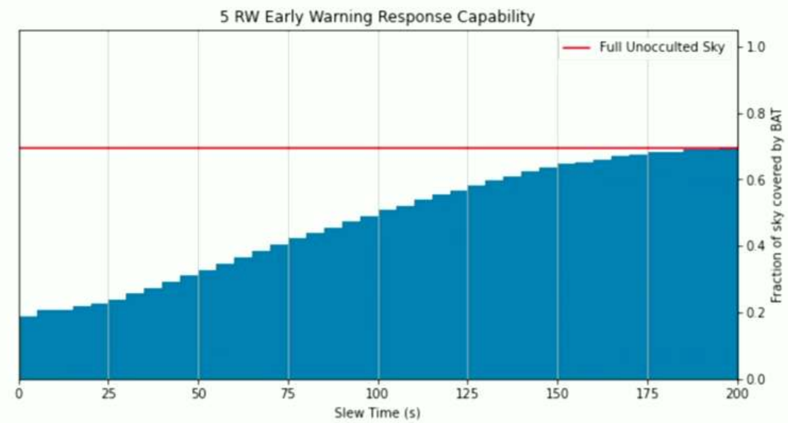


# Best chance to detect LIGO precursors: low frequency radio

- **Expected EM power of precursor emission is mild,** $\leq 10^{43}(-t/msec)^{-7/4}$ **erg/s**
  - **flares: pre-merger flashes at spin+ and orbital beats:** $n(\omega_1+\omega_2)=m\Omega$, **$10^{45}$ erg/s**
  - **beaming in high energy needed**
  - **LIGO early warning: up to a minute,**
  - **~10 sec before merger, 100 deg$^2$**
- **Optical**
  - **flashes of** $m \sim 15$
  - **LSST image will be only in one plate**
  - **Readout While Exposing mode**
- **Radio:**
  - **Jansky-level flashes** $F_{\nu,peak} = 0.5\,\mathrm{Jy}\eta_{R,-3}\nu_9^{-1}d_{200}^{-2}$
  - **delayed by ~** $\Delta t = 14\,\mathrm{sec}\nu_9^{-2}d_{200}$
  - **LOFAR & MWA: "see" whole sky, but need to**




SWIFTGUANO: Fraction of sky BAT can cover as a function of latency

# VI Fun topics

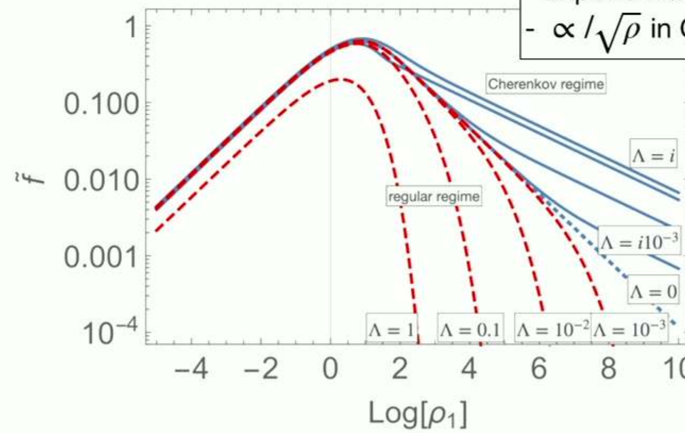
# Cherenkov emission by Schwarzschild BH

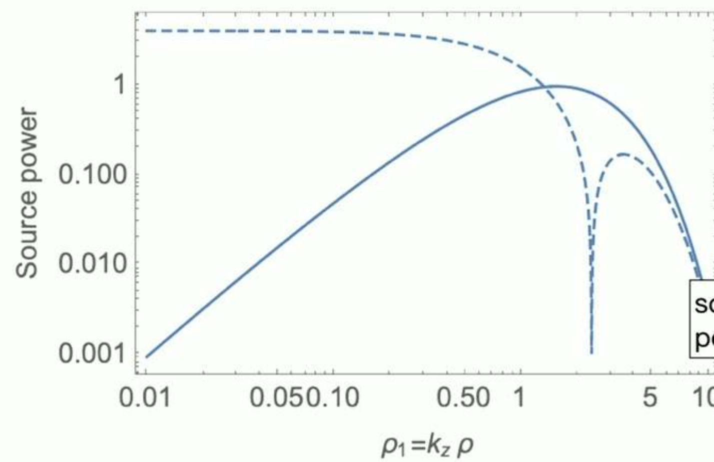
**Cherenkov emission by Schwarzschild BH**

- $L_{Ch} \propto (\epsilon - 1) \times B_0 \times (GM) \times \beta$
- No source!
- Distributed effective source
- BH induces superluminal EM perturbations
- Distributed effective source $\rho \sim 1/k_z$
- Spectrum $L_{CH} \propto \frac{dk_z}{k_z}$
- Even BH moving along the B-field emits (except

EM emission by purely charge-neutral "particle".

Fluctuating EM fields: as function of $\rho_1 = \rho k_z$
- Exponentially decaying for normal regime
- $\propto /\sqrt{\rho}$ in Cherenkov regime



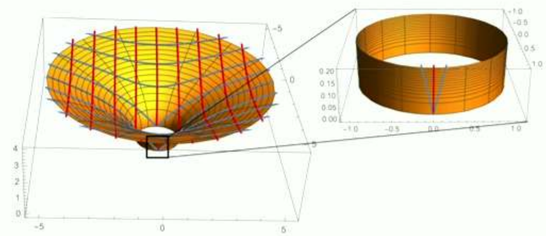



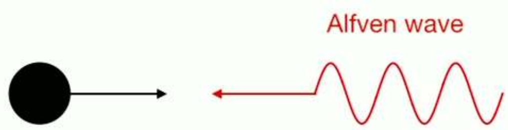

source powers for parallel and perpendicular propagation

# Axion production by Schwarzschild BH

- BH in crossed E &B -> $\mathbf{E}\cdot\mathbf{B} \neq 0$

Lyutikov 2108.06364






Oscillating $\mathbf{E}\cdot\mathbf{B}$ -> The triangle anomaly

- Axion-photon coupling $\mathscr{L}_{a\gamma} = g_{a\gamma} a\, \mathbf{E}\cdot\mathbf{B}$
- Coupling is non-local

$$\mathbf{E}\cdot\mathbf{B} = -\frac{M\sin(2\theta)\cos(\phi)}{r} B_0 E_0$$

- time-dependent
- plasma may not have time to screen

- topological current

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

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

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

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

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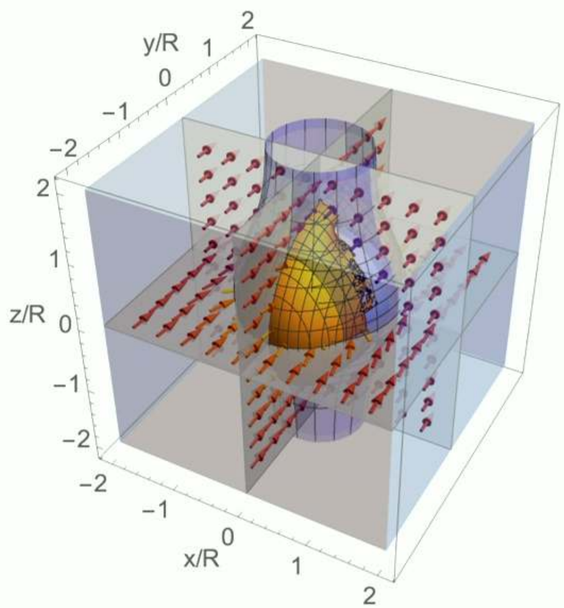
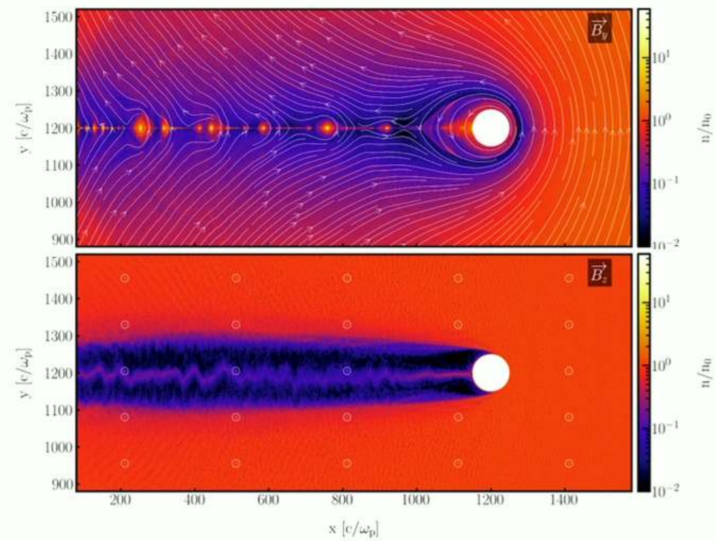
# Even with plasma: Draping of merging NS

- **EM interaction of merging neutron stars is necessarily dissipative due to formation of draping layer, $E_{||}$ and/or $E > B$**




Sironi+, in prep.

# Axion production by Schwarzschild BH

- BH in crossed E &B -> $\mathbf{E} \cdot \mathbf{B} \neq 0$

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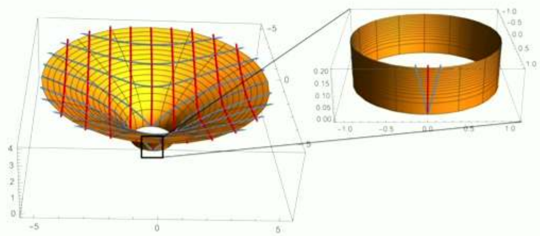

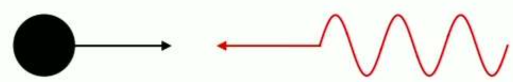


Oscillating $\mathbf{E} \cdot \mathbf{B}$ -> The triangle anomaly