Electromagnetic precursors to compact objects' mergers

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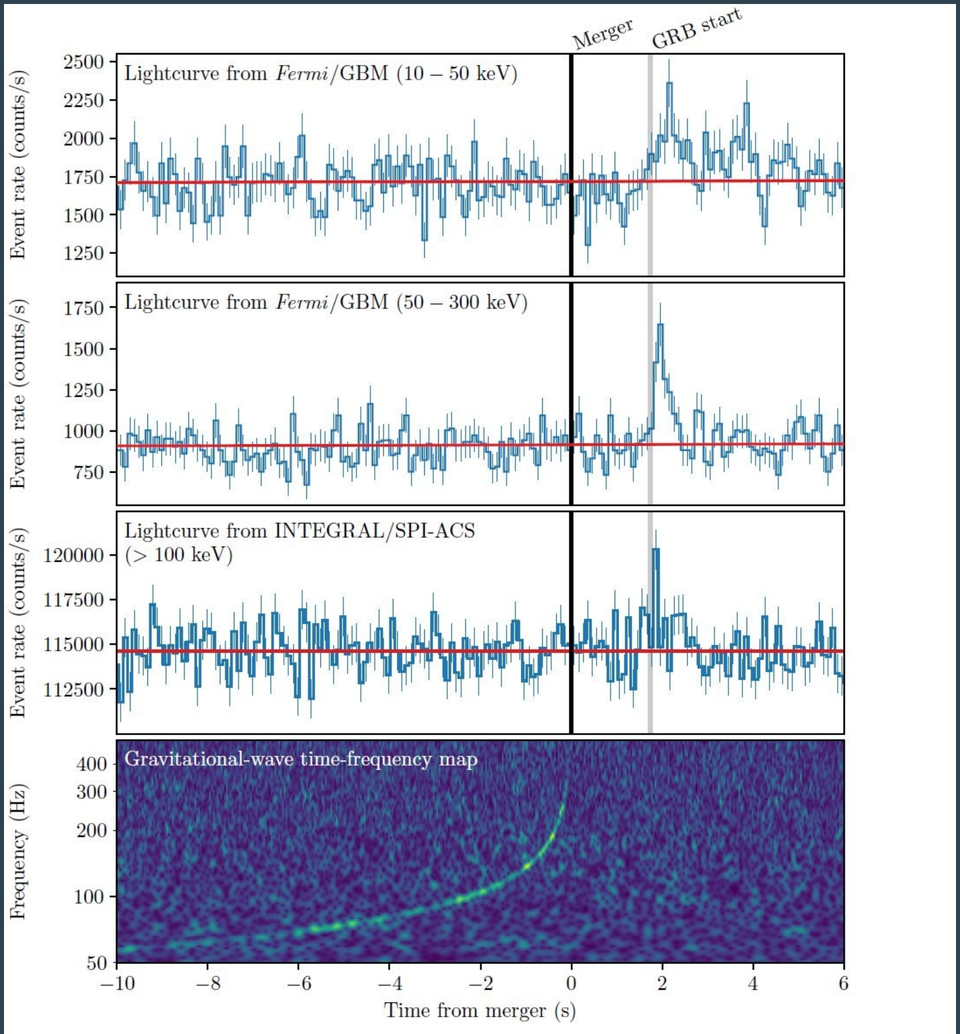
Neutron star-neutron star merger and Gamma-ray Burst Aug 17 2017



- both LIGO (both detectors) and VIRGO: NS-NS merger (masses “comme il faut", not clear if final BH is formed - too high freq.)
- Fermi gamma-ray satellite sees a Gamma Ray Burst 2 sec later
- Optical transient identified in a nearby galaxy (40 Mpc) few hours later - kilonova
- X-ray afterglow days later

Precursor emission - (?)

- Can emission be generated **before** the merger?
- Can we detect it?

Yes, and yes

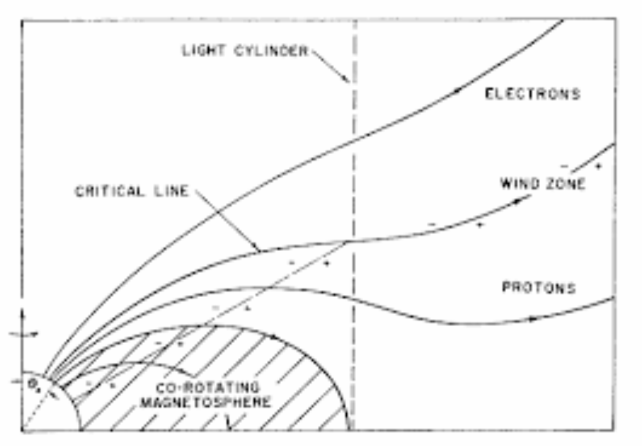
difficult, but these are beautiful physics problems

Plan of the talk

- Unipolar Inductor: expected power
- Generation of jets ***before*** NSs mergers (Alfven wings)
- “Dansing” NSs: pre-merger flares
- Generation of jets in NS-BH mergers
- Magnetic hair of black holes
- Cherenkov emission by uncharged Schwarzschild BH
- Observational strategies
- “To do” list

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

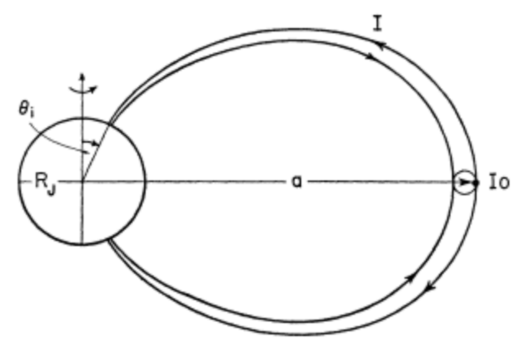


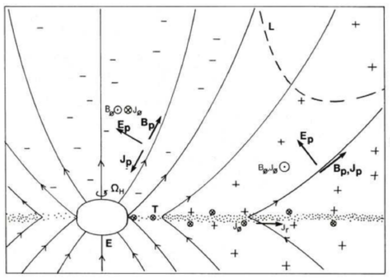
FIG. 2.—Current circuit in the meridian plane (not to scale)

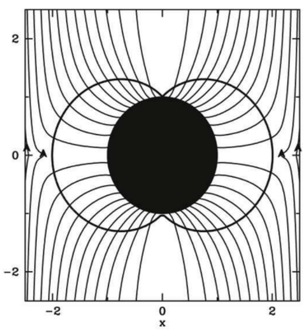
Linearly moving conductor generates EMF

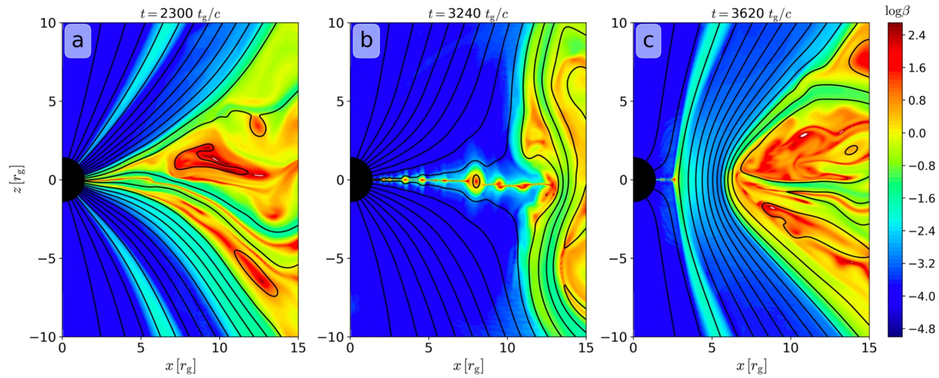
- In both cases parallel E-field is generated
- pulsars: $E_{||}$ is quickly killed due to vacuum breakdown
- Plasma is accelerated: pulsar emission and Jovian aurora

Extension to GR: BZ-effect

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







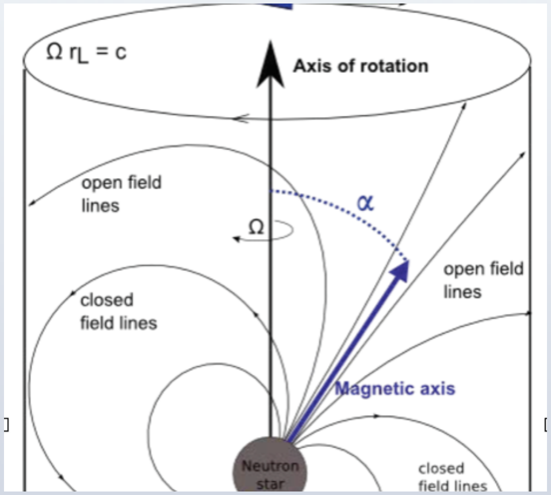
Chashkina + , 2021

Later: extension to GR:- linearly moving BH

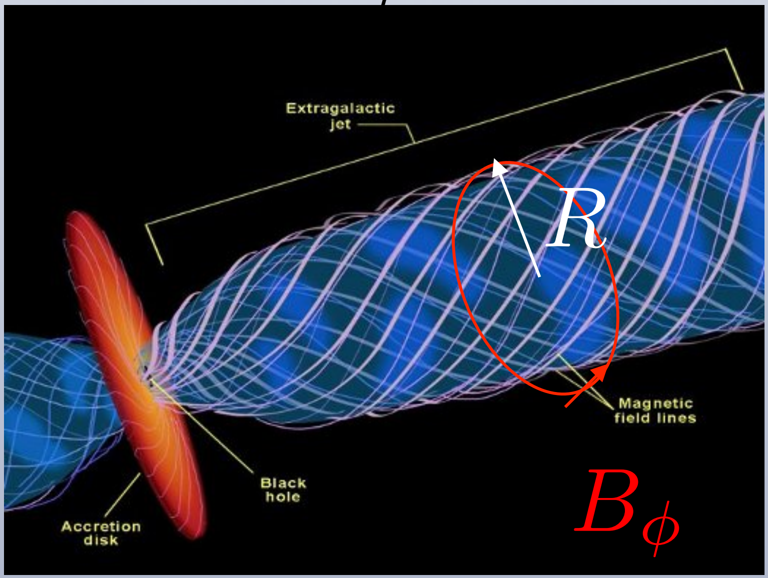
Power of relativistic unipolar inductor

- Expected power: $L \sim \frac{c}{4\pi}(\Delta\Phi)^2$
- **EM-dominated** relativistic sources, matter inertia not important
- $4\pi/c = 377$ Ohm - space is very bad conductor
- Potential: E-field times size: $\Delta\Phi \sim E \times l, E \sim \beta B$
  - linear: β, size *l*, B-field: $(\Delta\Phi) \sim \beta l B$
  - Rotating NS:
    - $\Delta\Phi \sim B_{NS} R_{NS}^3 (\Omega_{NS}/c)^2$
    - which is $\Delta\Phi \sim B_{LC} \times R_{LC}$

$\Delta\Phi \sim R_{LC} B_{LC}$



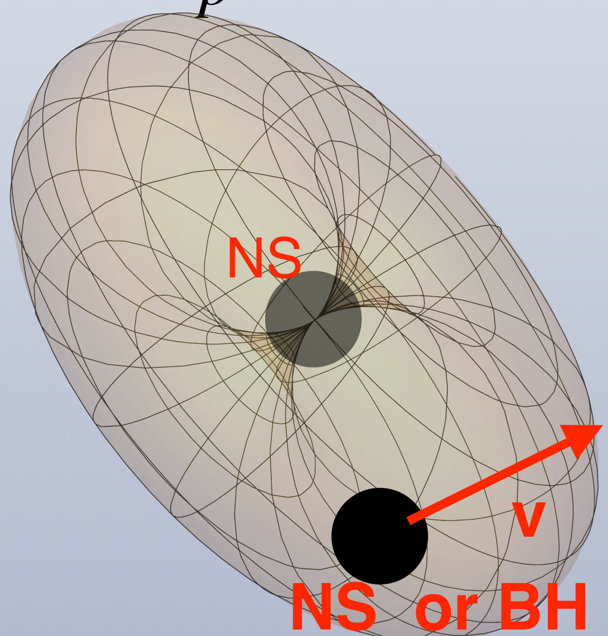
Eg, AGN jet $L \sim B_\phi^2 R^2 c \approx (\Delta\Phi)^2 c$

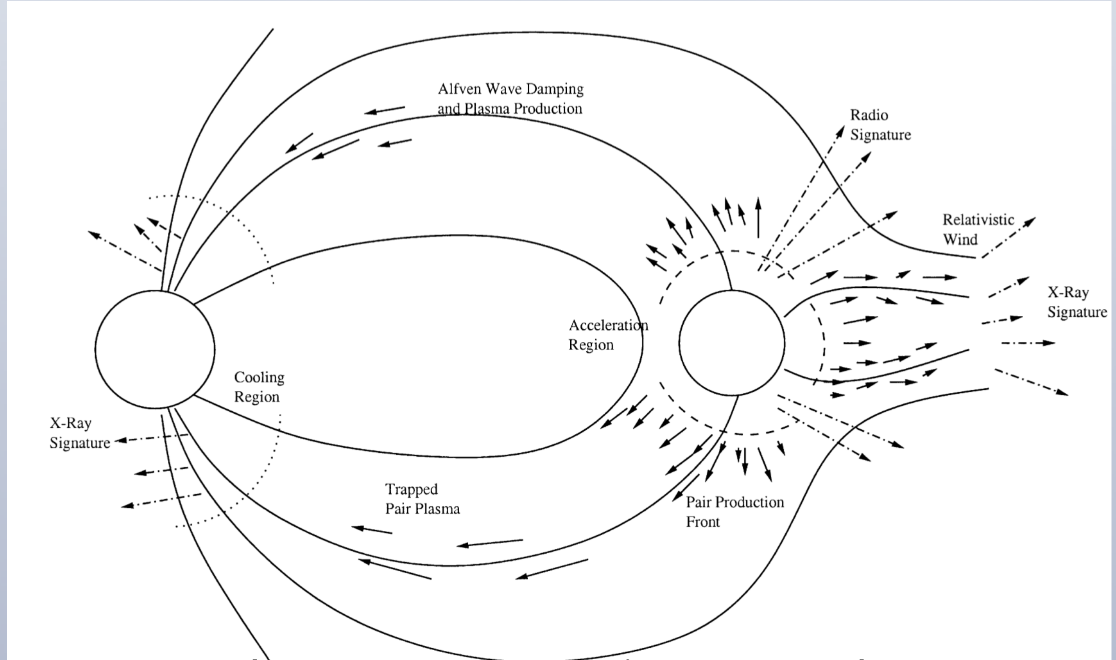


Relativistic Io-Jupiter
(linear motion through B-field)

Possible precursor emission

- Before merger a NS or BH moves through companion's B-field: what EM signal we expect?
- Old systems, not much gas around
- $B_{NS} \sim 10^{12}\,\mathrm{G}$
- $\sigma \equiv \frac{\omega_B^2}{\omega_p^2} \gg 1, v_A \sim c$ - all is relativistic (simple!)





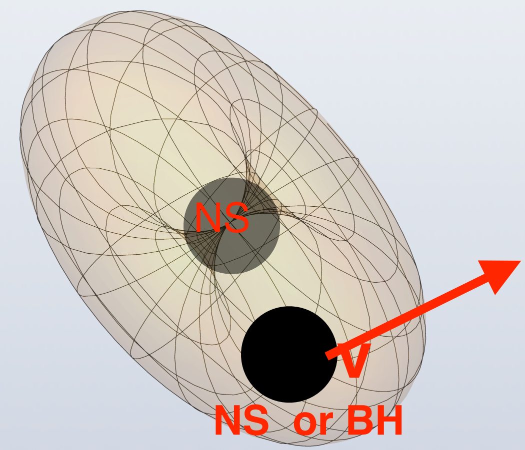
(Hansen & Lyutikov 2001)

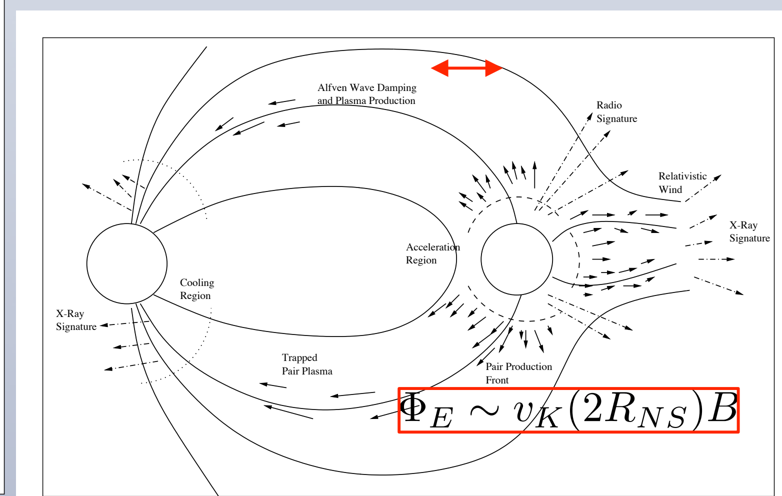
NS-NS merger as relativistic Io-Jupiter

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

$$L \sim (v_K/c)^2 B^2 R_{NS}^2 c \approx 10^{44}\,\mathrm{erg\,s^{-1}} \left(\frac{R_{NS}}{a}\right)^7$$

- Not very bright for all-sky X-ray telescopes, tens of Mpc (expected sources typically at ~ 200 Mpc)
- Unless coherent! - **Radio**
- $F_\nu \sim (kilo) - Jansky$ from Gpc
- That was the best model for the Lorimer Burst, not anymore, FRBs are not mergers, FRB rates >> NS-NS mergers

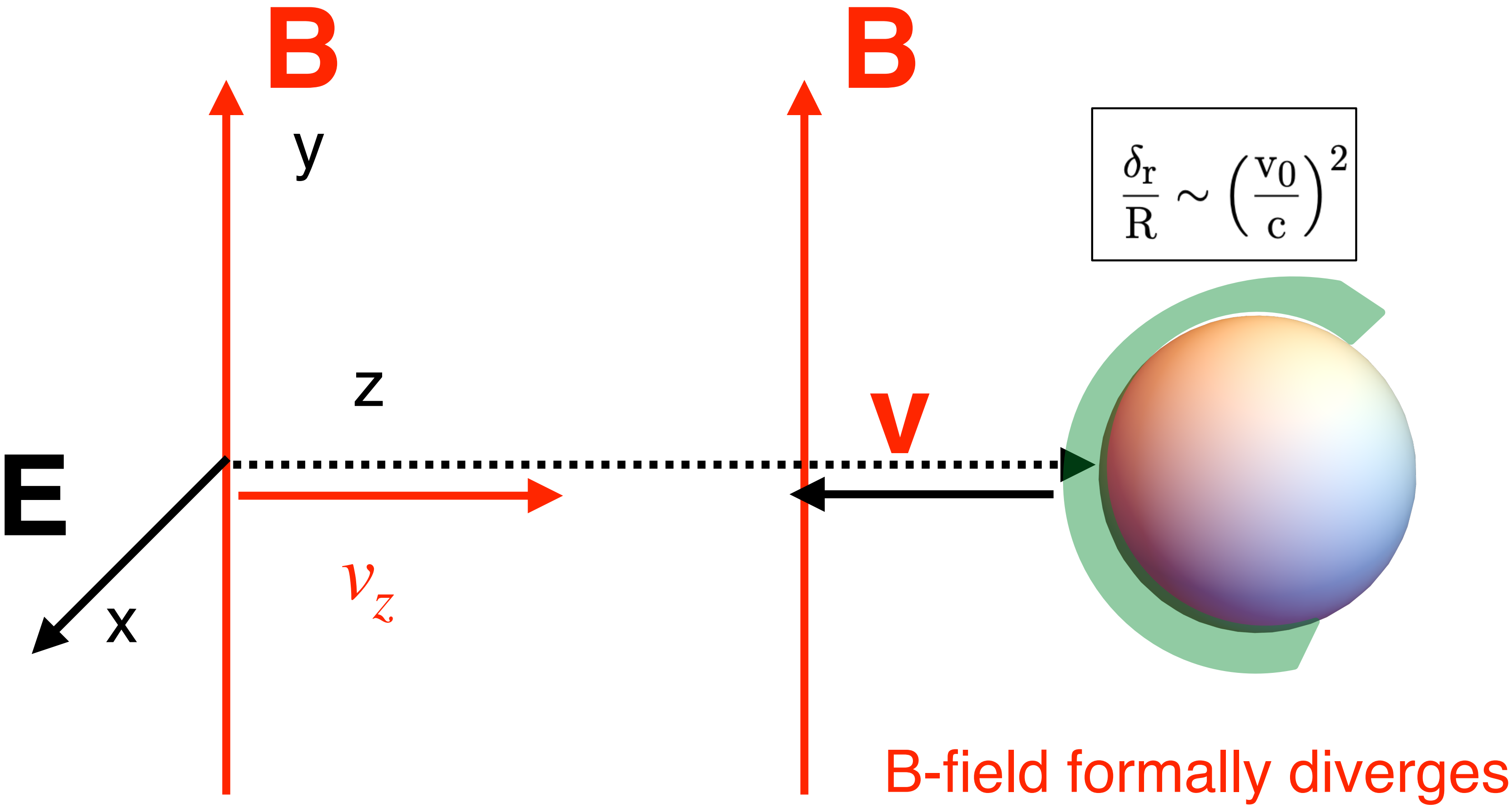




Can emission be beamed?

Generation of jets *before* NSs mergers

Magnetic draping

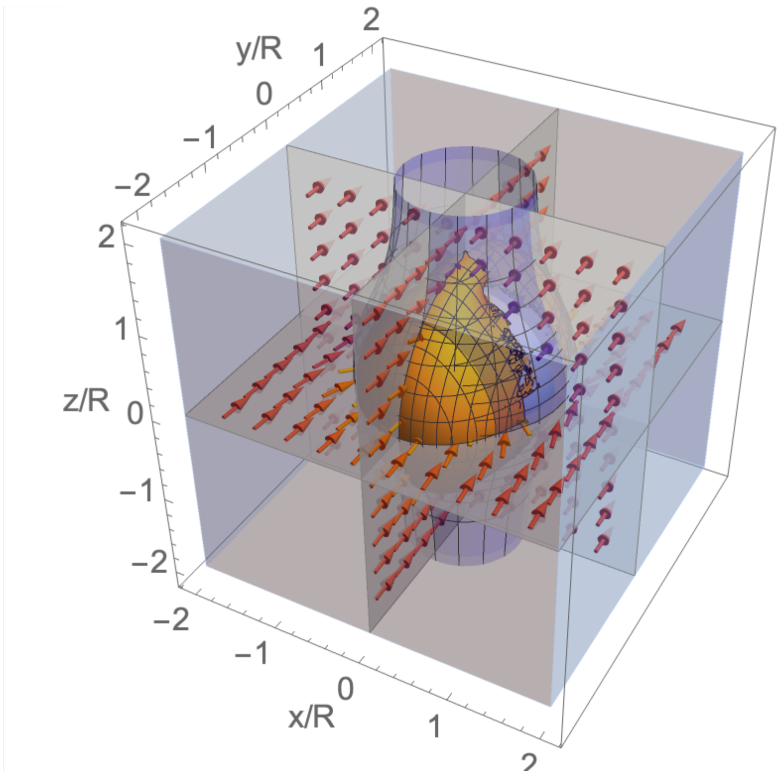


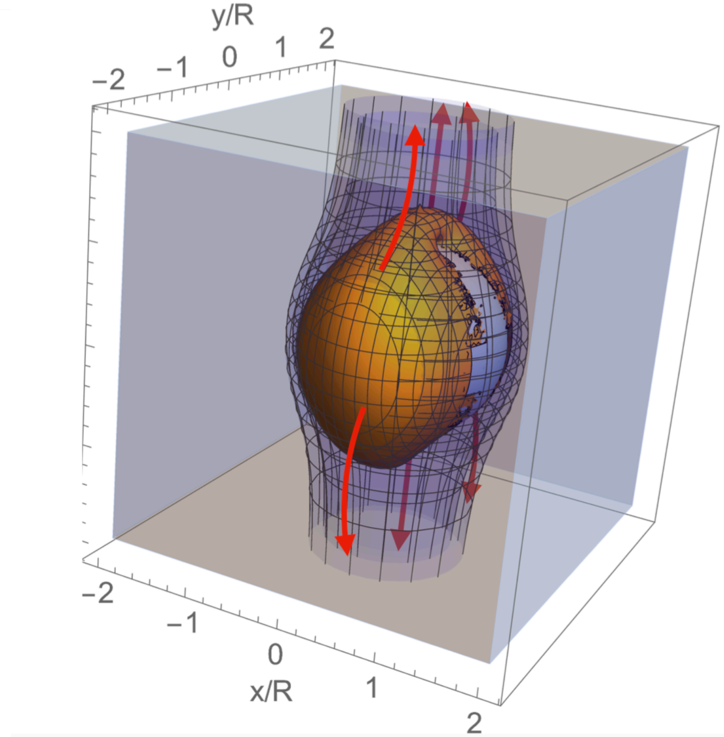
Steady state: $\partial_z E_x = 0$: $E_x = -v_z B_y = \text{const}$

Different ways to resolve the draping problem

- Depletion layers in planetary-solar wind interaction
- Highly magnetized plasma has only fields (little charges only try to ensure **E.B**=0).
- The system **must** become dissipative:
- regions $\mathbf{E} \cdot \mathbf{B} \neq 0$ -> current $j_{||}$, non-thermal emission
- regions with E>B

NS-NS mergers: dissipative B-field draping





Magnetic draping (Lyutikov 2023).
metal sphere moving through B-field:

- Weak B-field in the bulk
- ~ equipartition field in narrow layer
- Generation of $\mathbf{E} \cdot \mathbf{B} \neq 0$, $|E| > |B|$

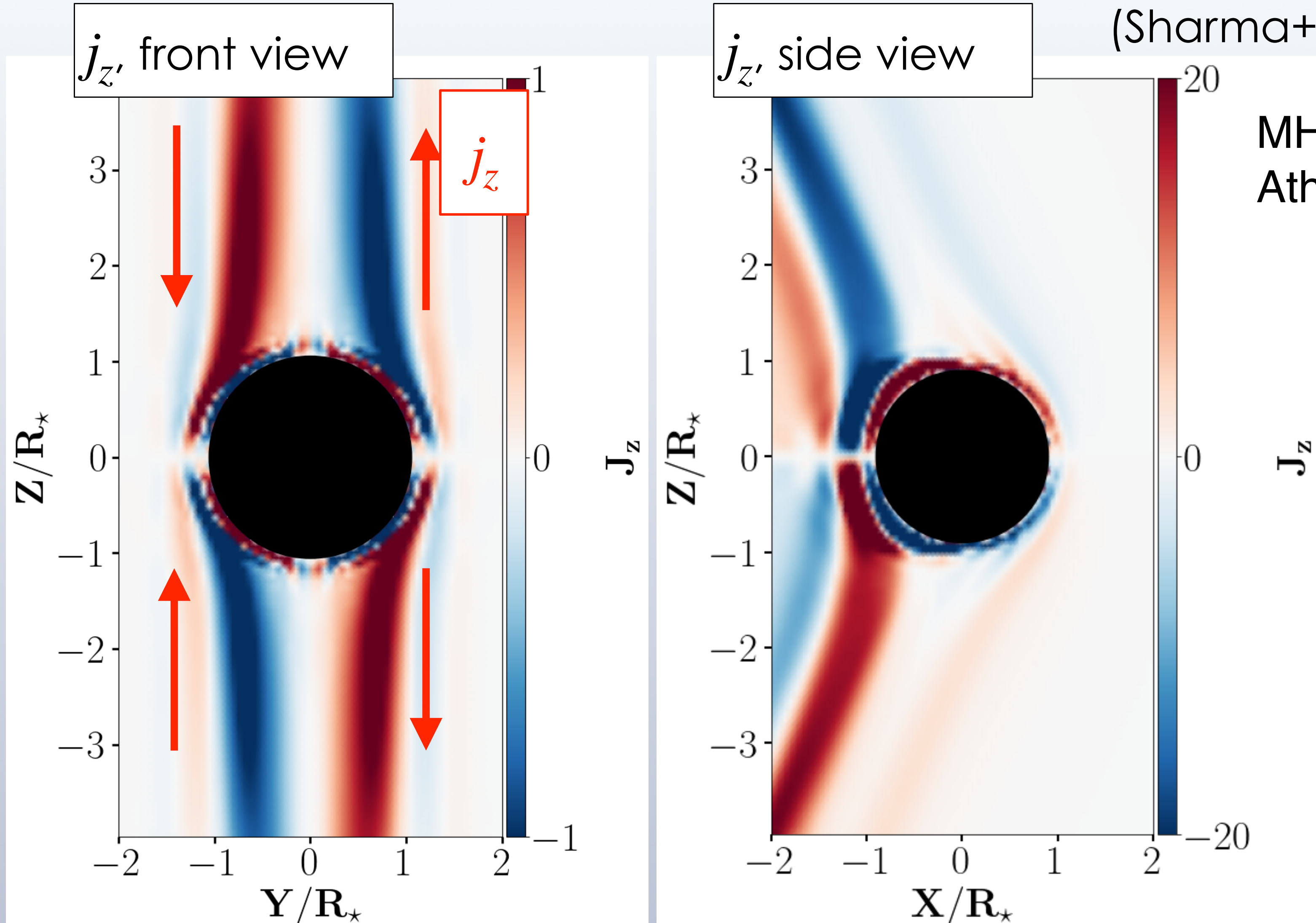
Double-jet structure is expected

Relativistic sub-Alfvenic

- NS magnetosphere:
- $\beta_A = \sqrt{\frac{\sigma}{1+\sigma}} \sim 1$
- $\beta \sim 1,\ \beta \leq \beta_A$

NS-NS mergers: dissipative B-field draping

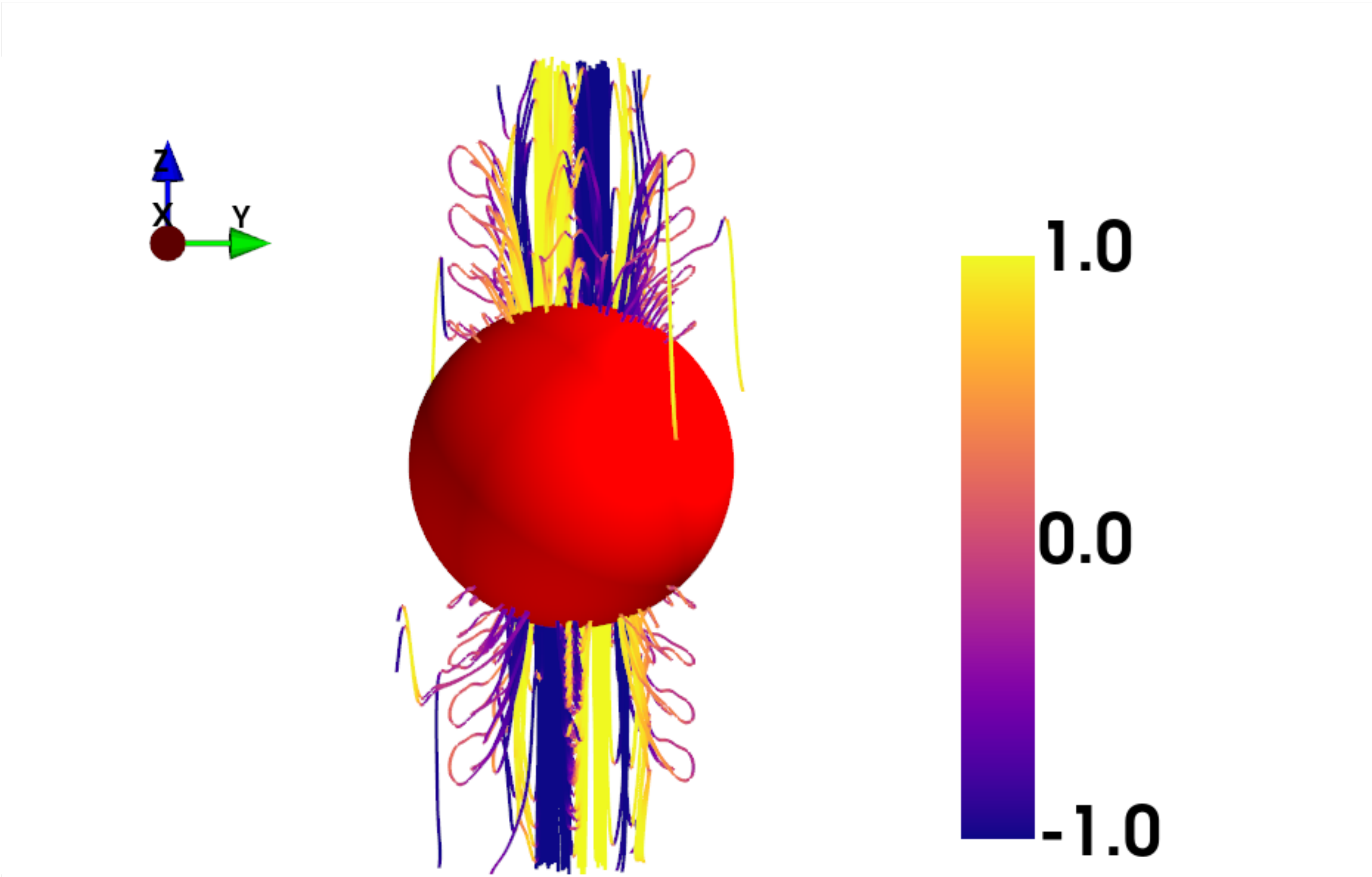
(Sharma+, in prep)



MHD simulations,
Athena++

- Relativistic sub-Alfvenic flow
- Double jets are generated (Alfven wings)
- Emitted power collimated, Radio like in pulsars

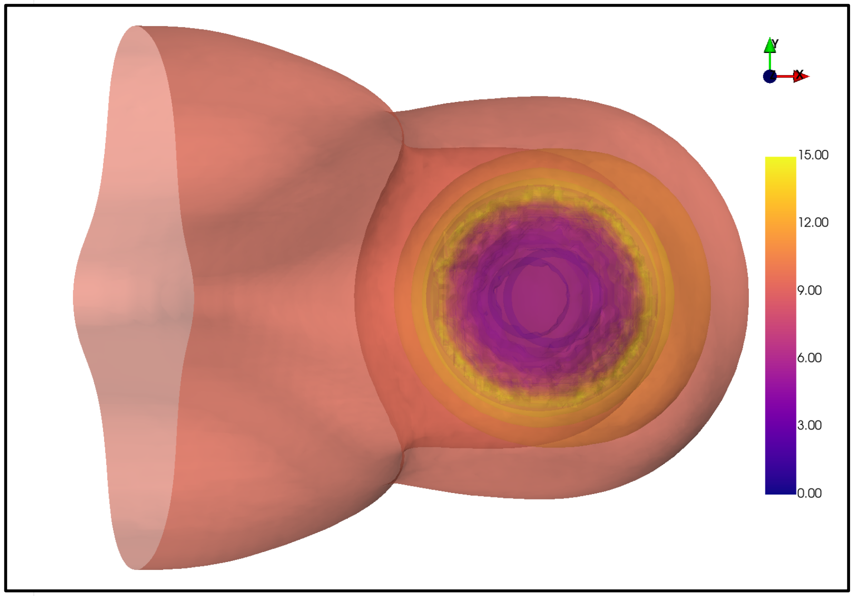
Double jets = Alfven wings



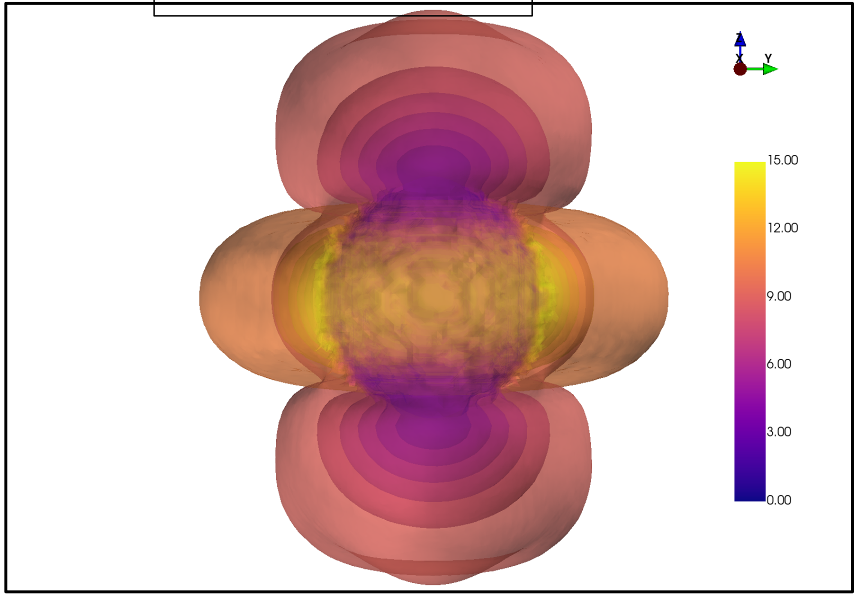
NS-NS mergers: dissipative B-field draping

(Sharma+, in prep)

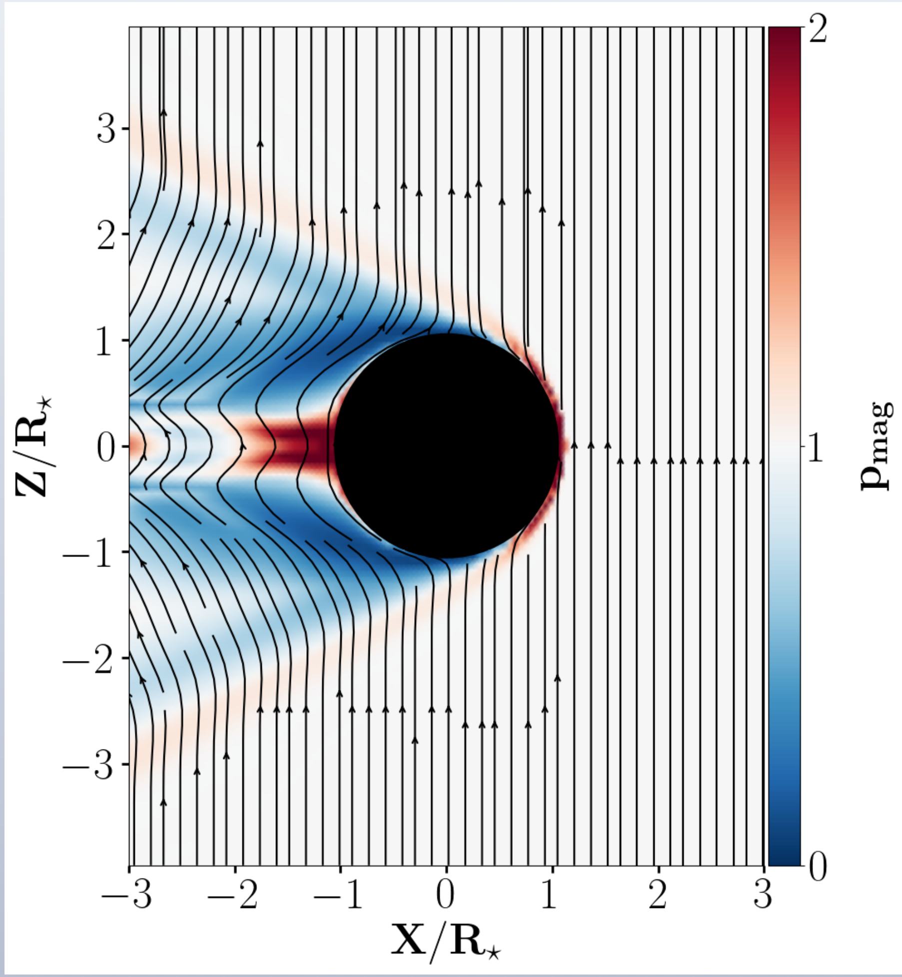
B^2, top view

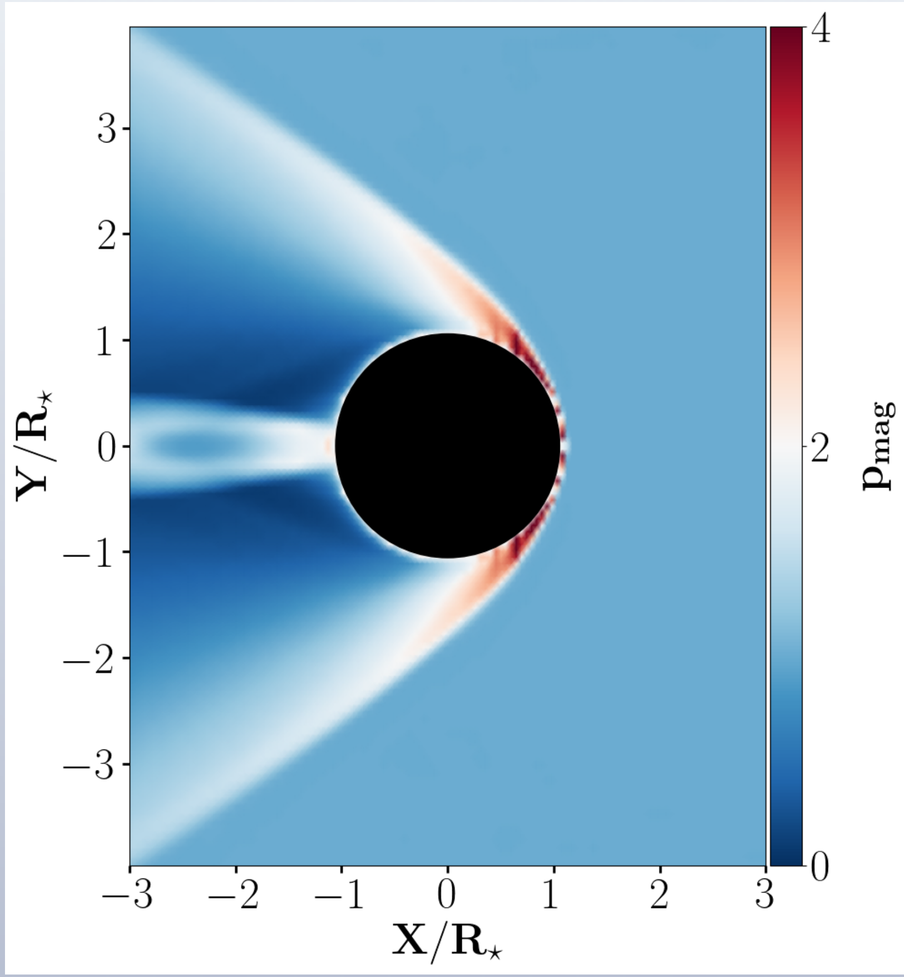


B^2, front view



Supersonic: just shocks





Power will follow the current

- Expected beaming of radiation
- Current instabilities: production of coherent emission
- modulation at orbital frequency
- Coherent radio? - Coherent radio!!

Mergers of binary NSs (both magnetized)

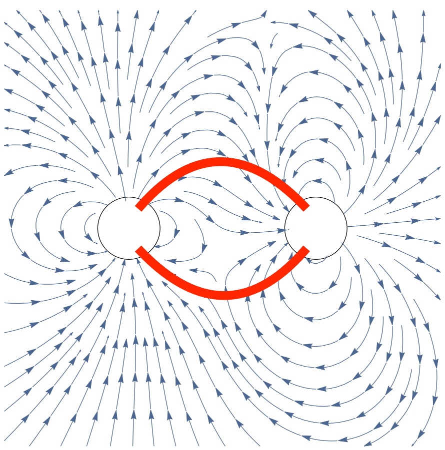
Double-magnetized spinning NS: *smooth* interaction of two magnetospheres

Lyutikov 2019

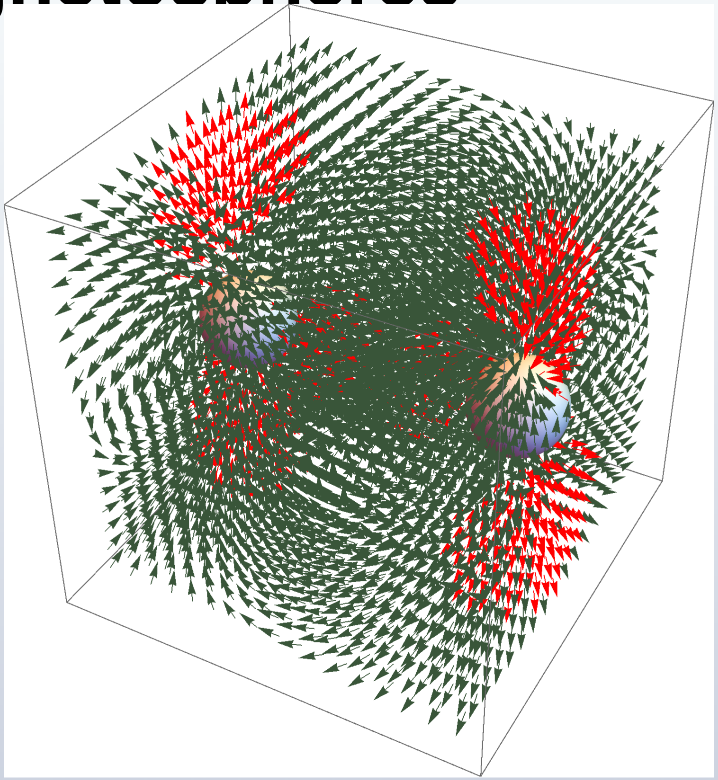
$$\mathbf{E}\cdot\mathbf{B} = -2(\mathbf{v}_1 \times \mathbf{B}_1)\cdot\mathbf{B}_2 \neq 0$$

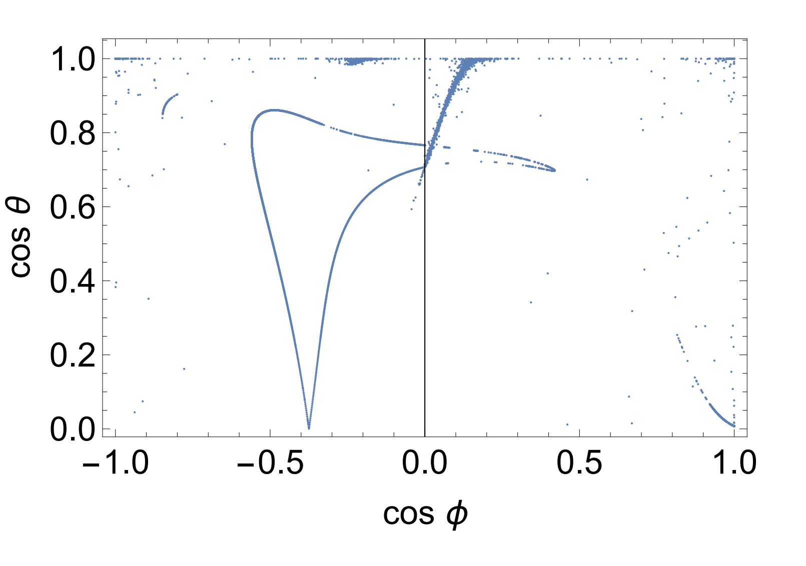
- gaps!
- Emission along B-field with largest $E_{||}$ (?)
- Modulated at orbital
- Power larger by a/R_{NS}

Magnetic connection at co-rotation ~ 10^{39} erg



(No need to diffuse through crust)



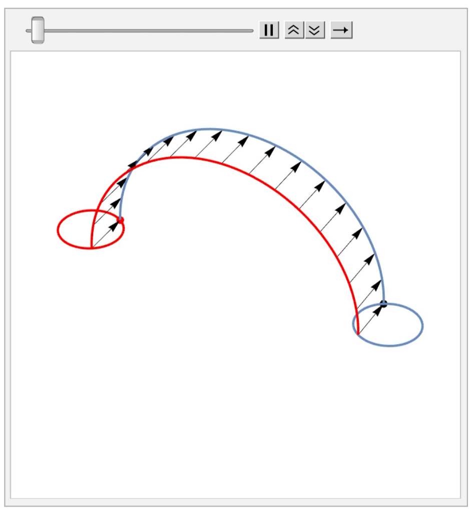


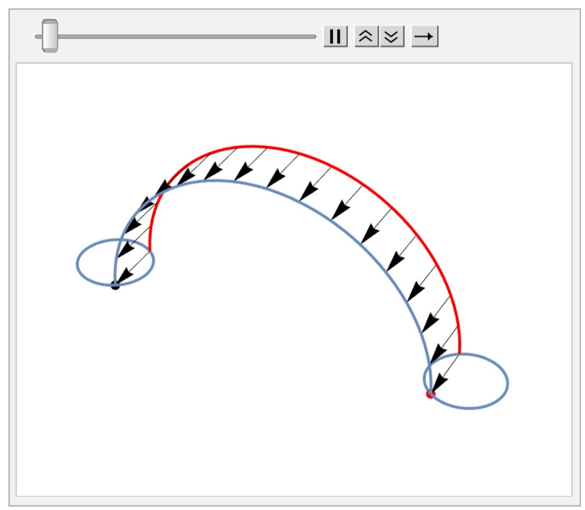
Flares!

Cherkis & Lyutikov 2021

- Store energy **slowly** in connected magnetospheres – release explosively
- **Combination of spins and orbital motion can “unwind”**
- Special configurations of interacting NSs
  - Fully locked
  - $omega_1$= - $omega_2$

- NOT EXPECTED

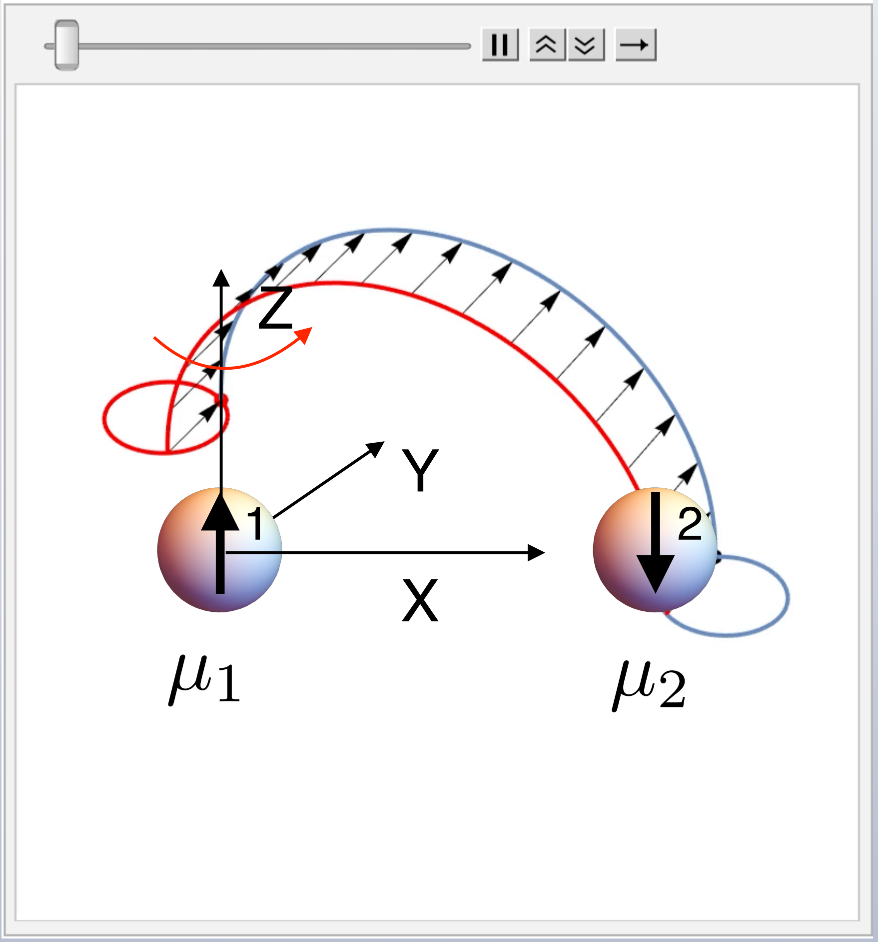




Basic-Z:

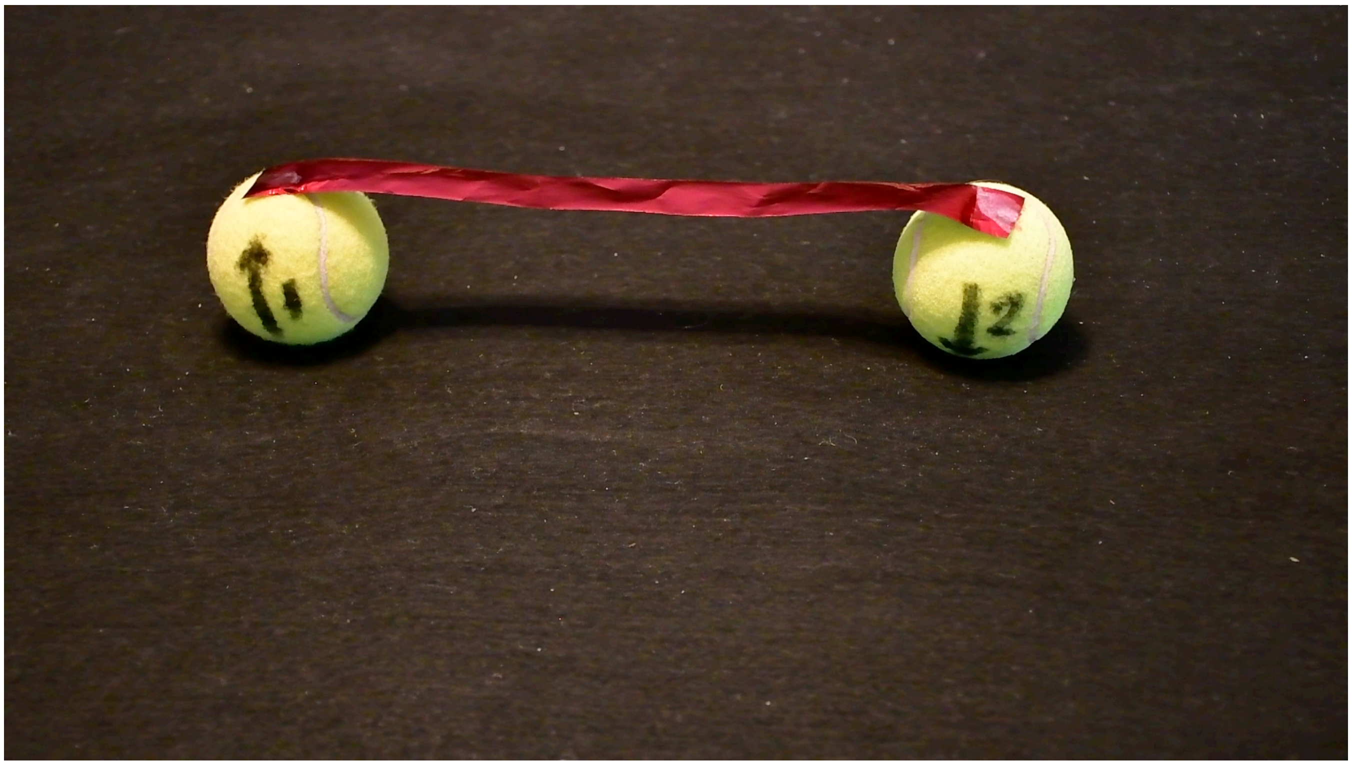
$$\omega_1 + \omega_2 = 2\Omega$$

Dirac's belt



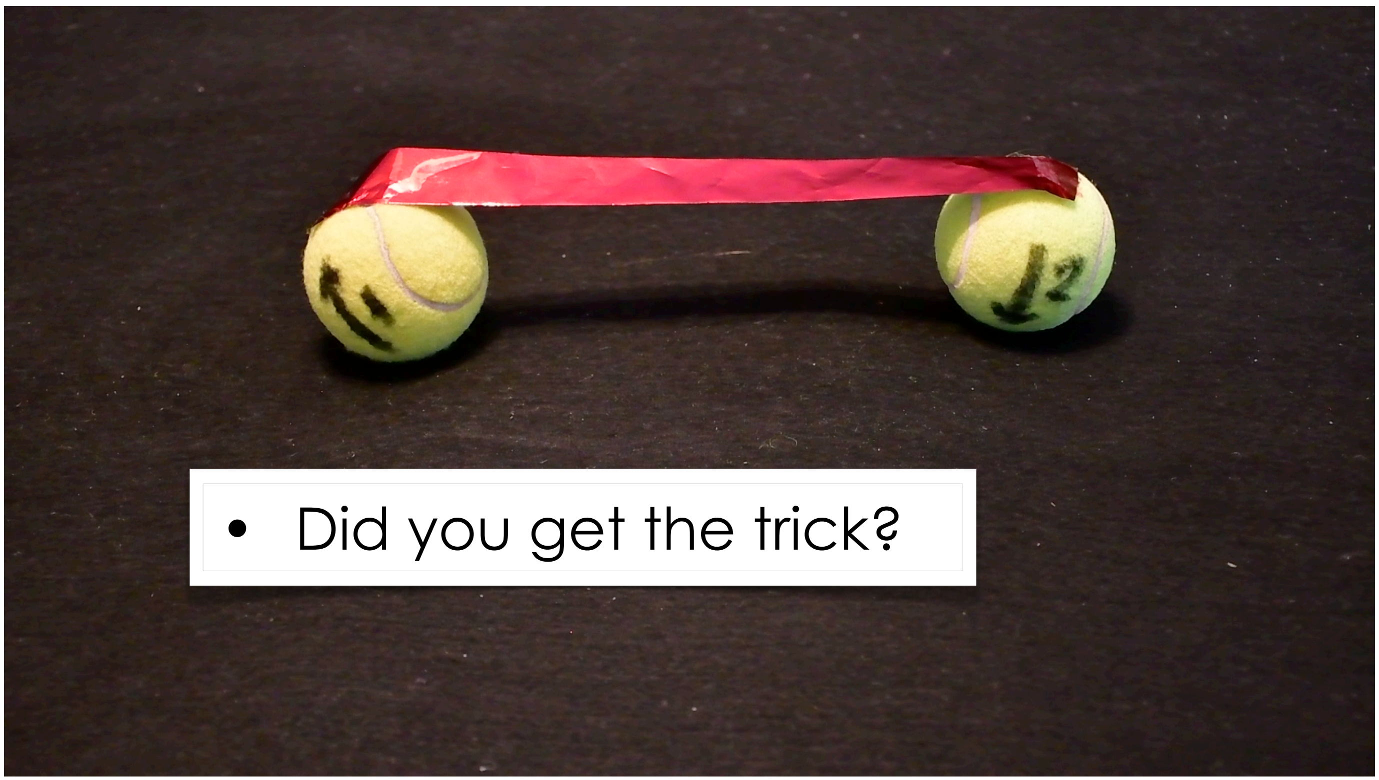
Cherkis & Lyutikov ApJ, 2021

Y-spin



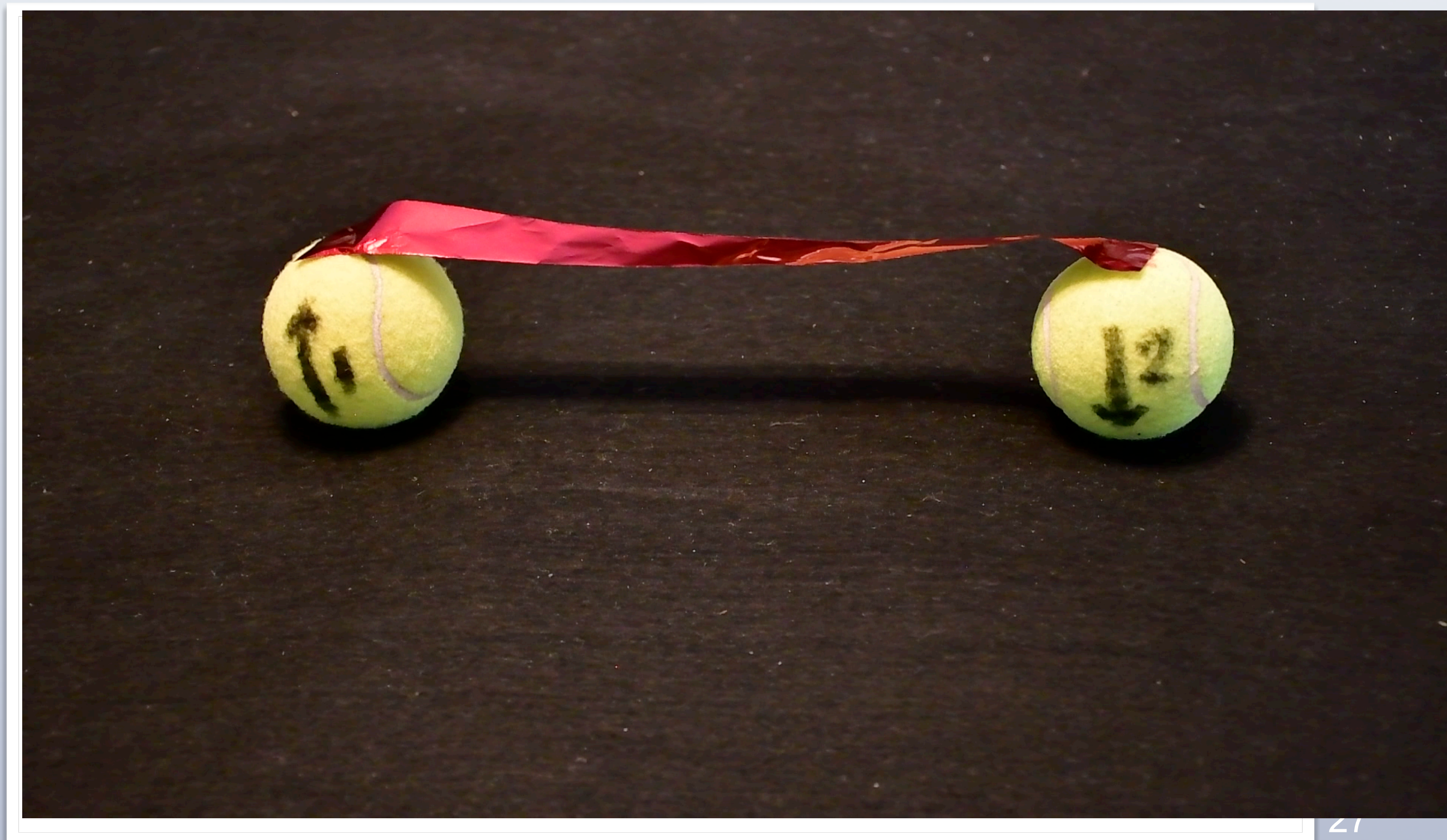
Cherkis & Lyutikov ApJ, 2021

Y-spin

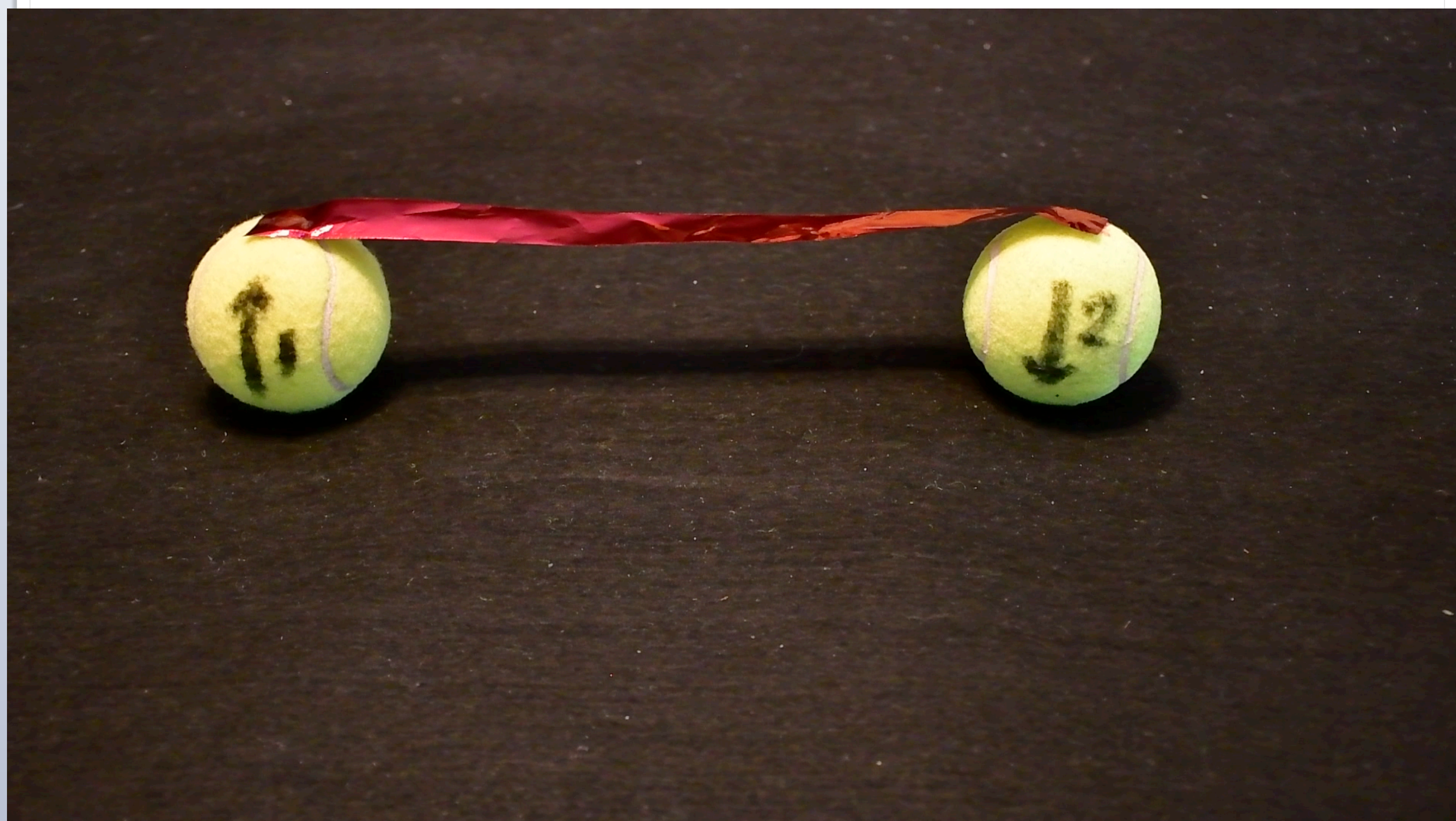


- Did you get the trick?

X-spin

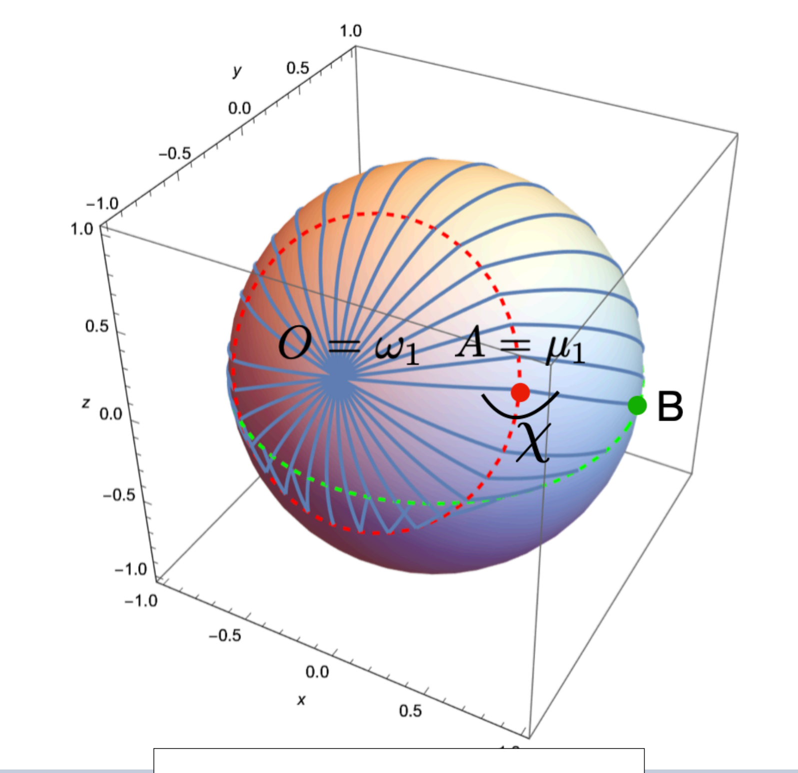


X-spin



Topology of magnetically coupled stars

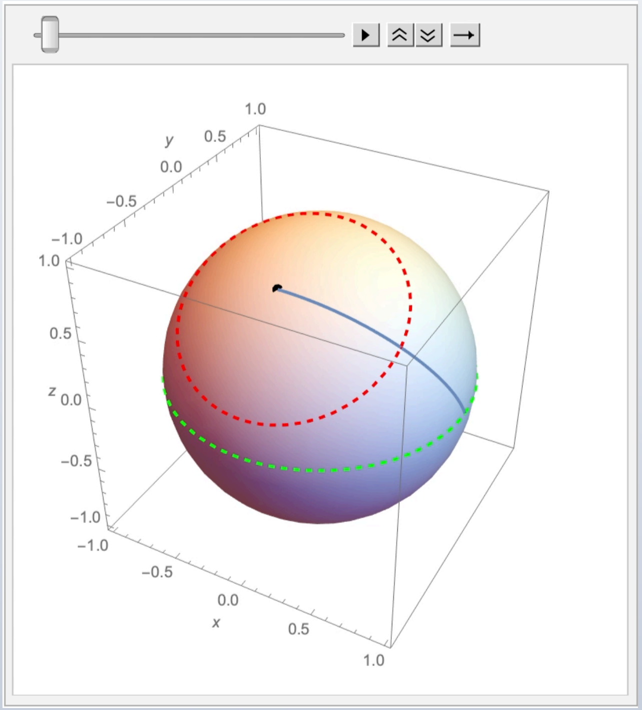
- Direction of B-field from #1 to #2: a path on 2-sphere
- Curl B is not important: each hair in a braid can be twisted: we are for **braiding**
- Need to track 3 points on the 2-sphere of B-direction to define braiding.

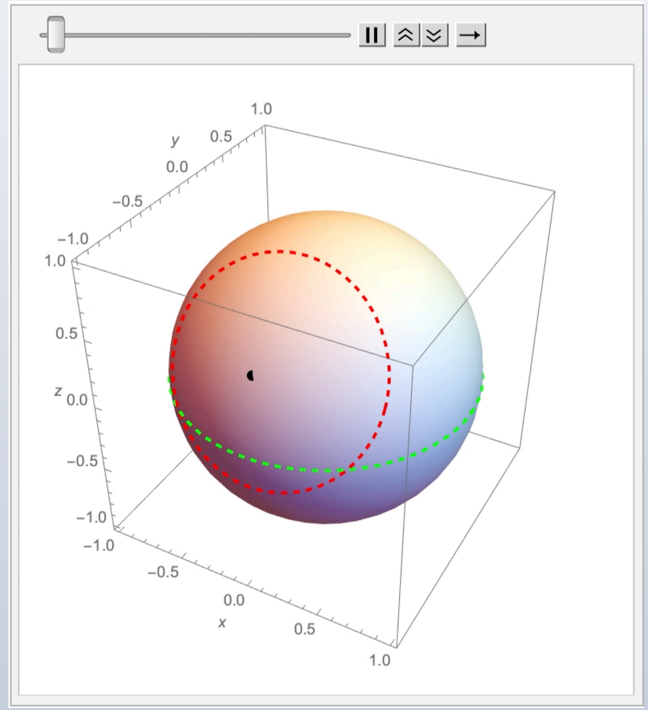


O - omega of 1
A- mu of 1
B: radius 1-2

cut in the middle

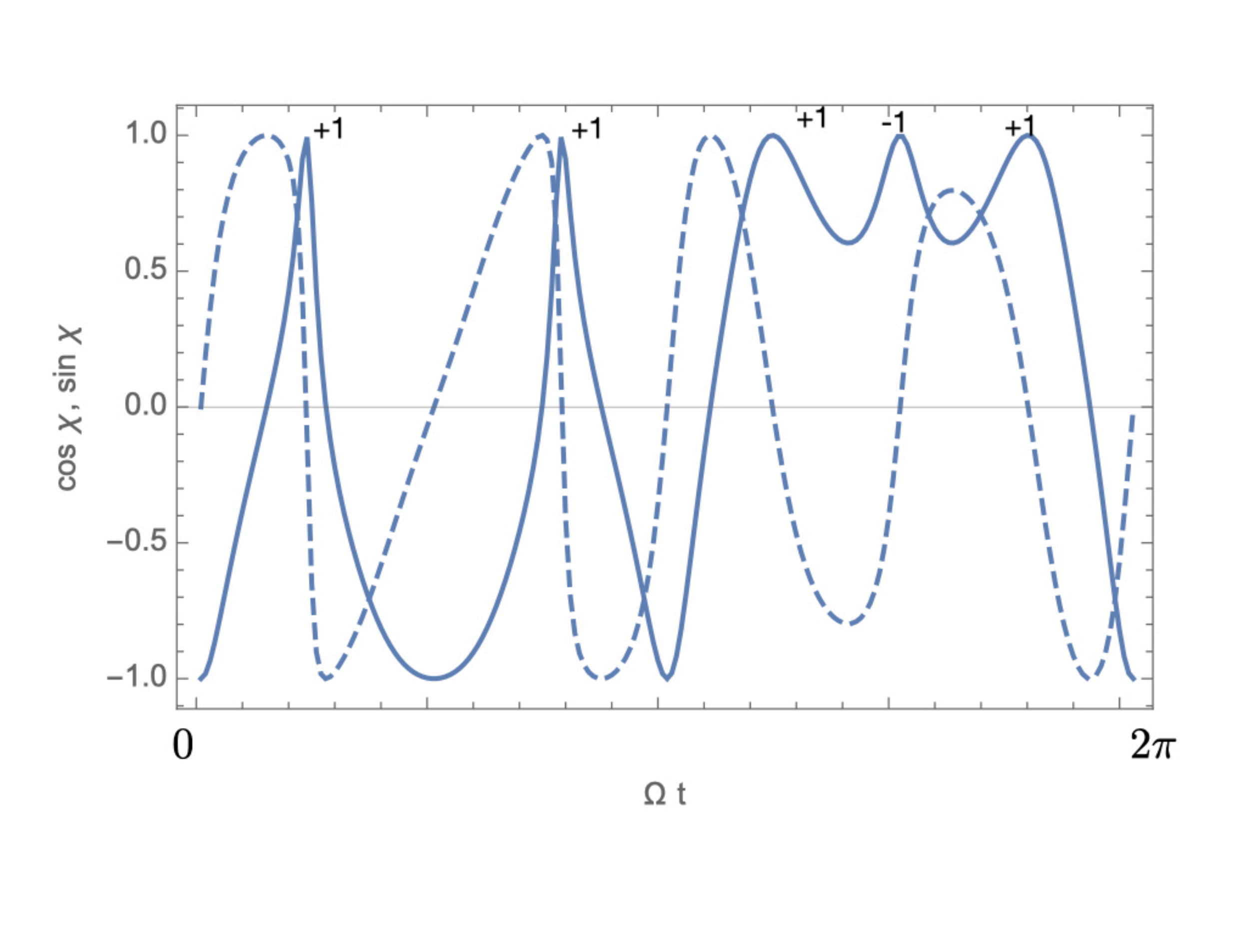
Topology of magnetically coupled stars





- Recall Y-spin: topological bifurcation (when points A & B overlap)
- Recall X-spin: depending on phase the angle may or may not flip

Counting twists



Precursors to LIGO

- There is one global untwisting resonance

$$\omega_1 + \omega_2 = 2\Omega$$

  - For 10 msec pulsar, 2:1 resonance at (-2) seconds
- There are numerous locally untwisting braids
  - Can produce (differently) modulated signals
  - May release a fraction of total connected B-field energy (twisted by ~1)

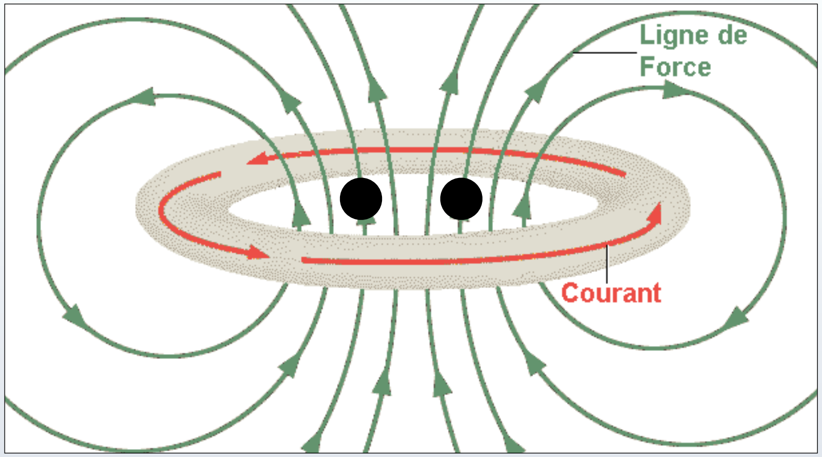
$$L_{B,c} = \frac{E_{B,c}}{r/c} = 10^{-1}\frac{B_{NS}^2 c R_{NS}^4 \omega^{4/3}}{(GM_{NS})^{2/3}} = 3\times 10^{44} B_{12}^2 P_{s,-2}^{-4/3}\,\mathrm{erg\,s^{-1}}$$

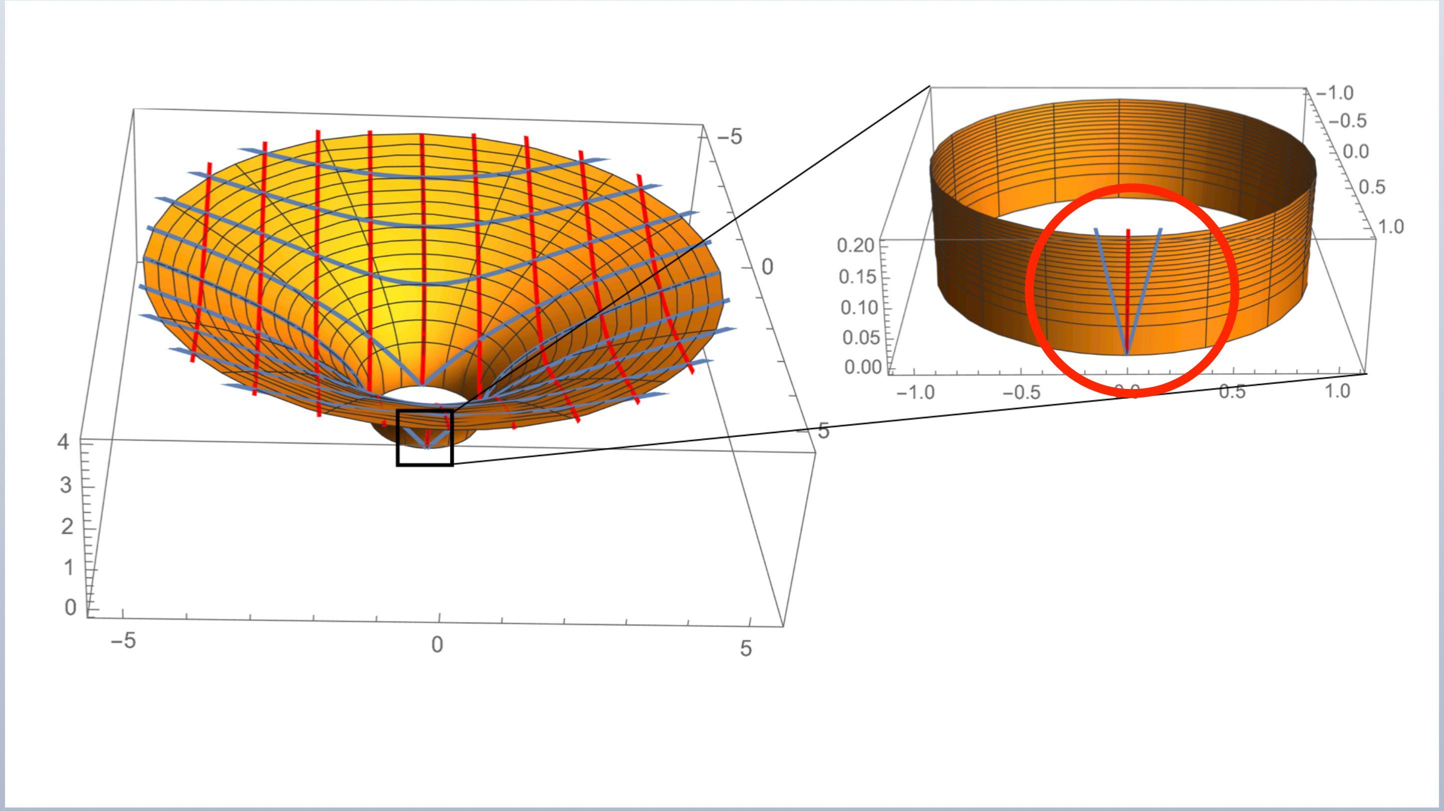
  - Higher resonances can be as efficient: amount of connected flux
  - Numerous **periodic**, and changing, signals expected.

BH-NS magnetospheric interactions are inherently dissipative

(and surprisingly, are expected to look similar to single magnetized NS-NS)

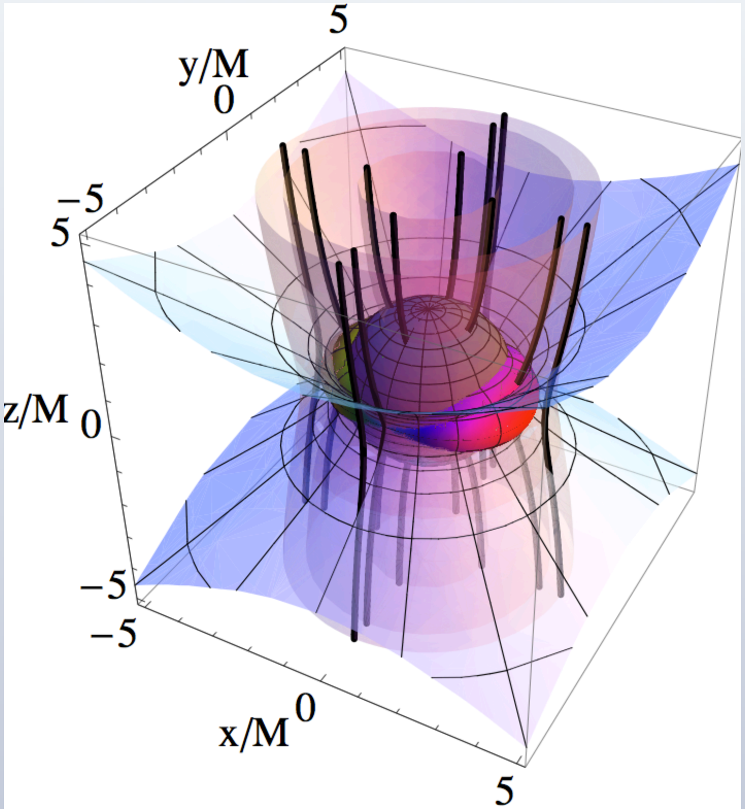
A Schwarzschild BH moving across B-field generates E.B !=0 and EM wind

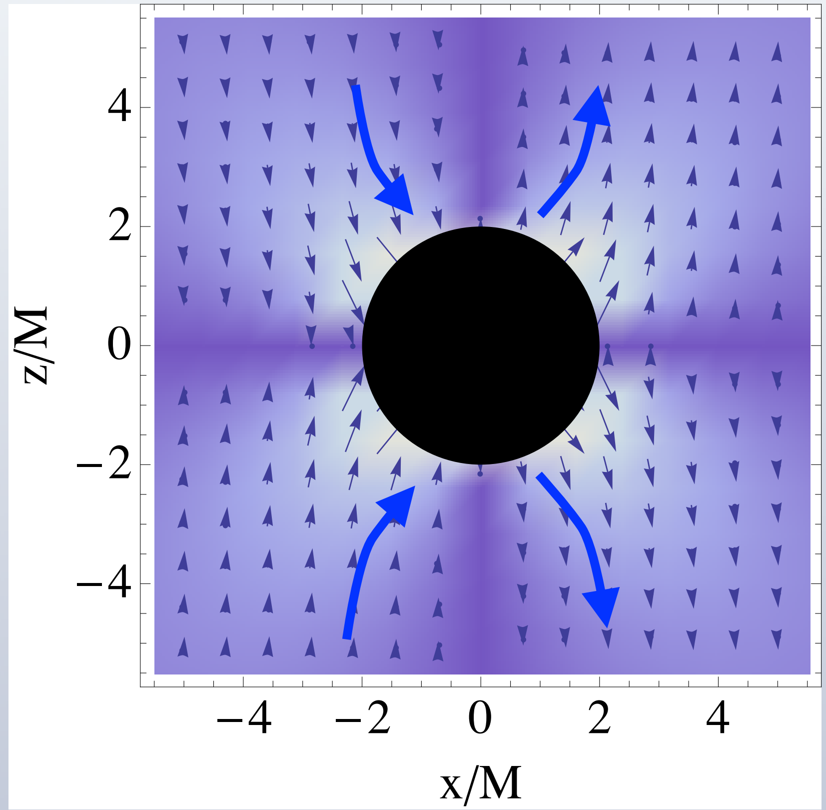




regions of $E_{||}$ and E>B - Alfven wings again!!!

Lyutikov 2011





$$I \sim \beta_0 M B_0$$

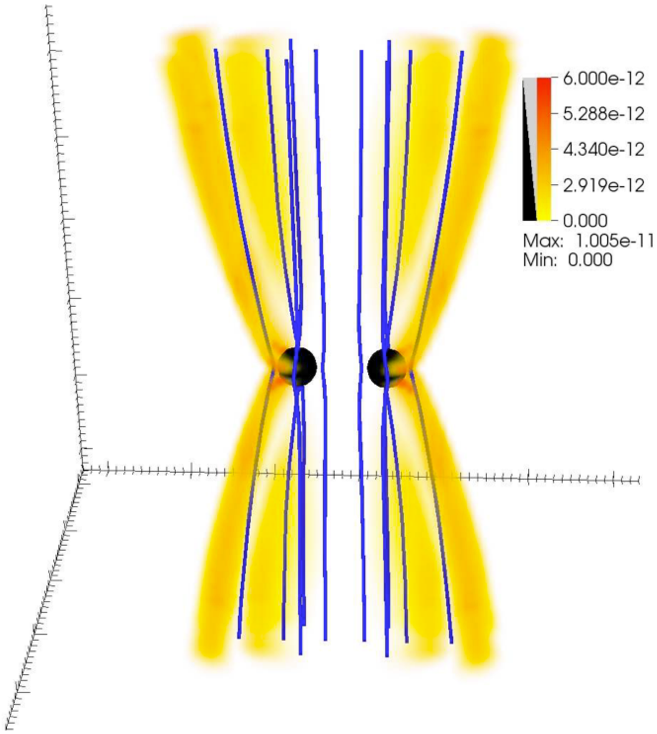
$$L_{EM} \approx M^2 \beta_0^2 B_0^2$$

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

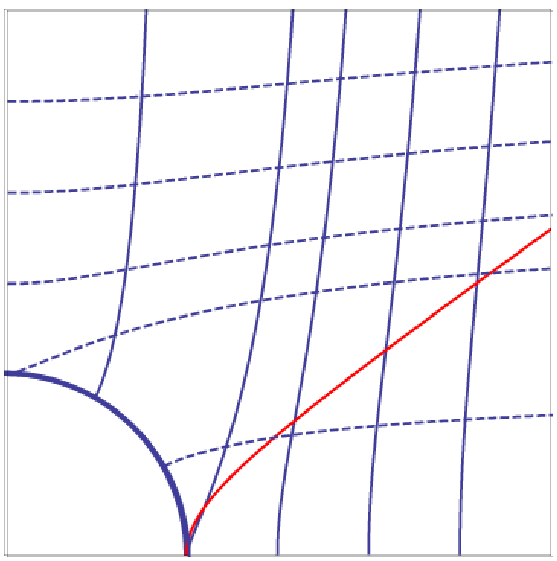
Similarity between NS and BH moving through B-field

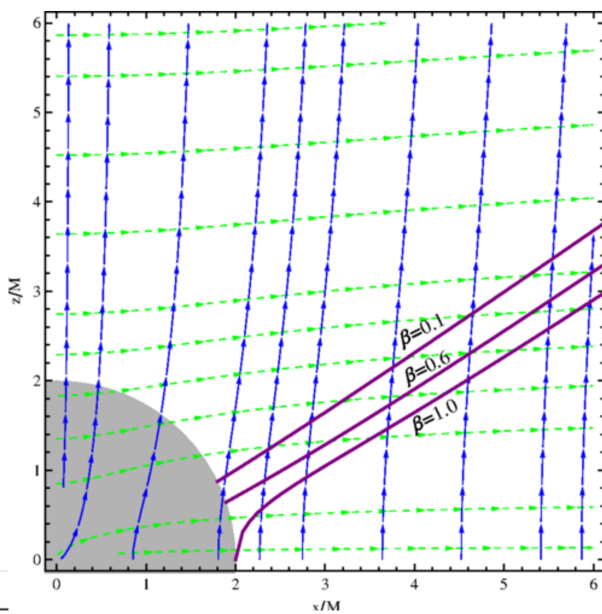
- Similarity between metal sphere moving through magnetized plasma and vacuum BH moving through B-field - both create Alfven wings - is surprising.
- ~ Membrane paradigm: BH is a bad conductor

Simulations



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





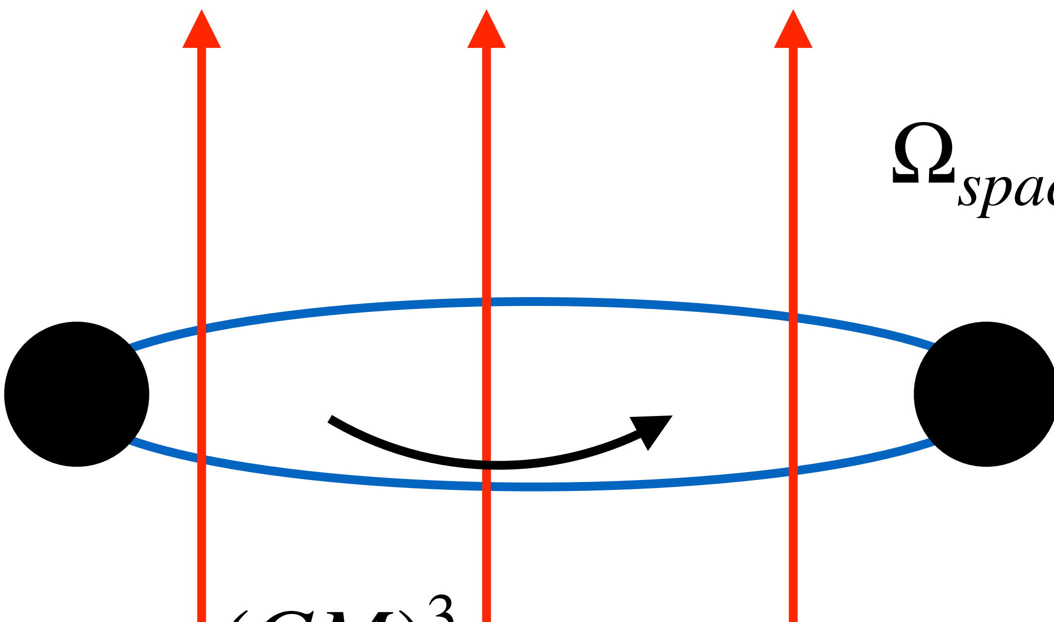
Morozova + 2013
spinning BH moving through B-field

$$L = (c_1\beta^2 + c_2 a^2)B^2M^2$$

Rotation + linear motion

Two BHs in B-field

Lyutikov 2010



$$\Omega_{space} \sim \frac{(GM)^{3/2}}{c^2 R^{5/2}}$$

$$L_{EM} \sim \frac{(GM)^3}{c^5 R} B^2 \approx 10^{39}\,\mathrm{erg\,s^{-1}} b_3^2 m_6^2 (R_G/R)$$

$$E_{EM} \sim 10^{42-44}\,\mathrm{erg}$$

EM emission during NS to BH collapse

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

- Power increases but collapse time is very short

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

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

$$t_{col} \sim \sqrt{R_{NS}^3/(GM_{NS})} \sim 0.1\mathrm{msec}$$

(rotational support will prolong)

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

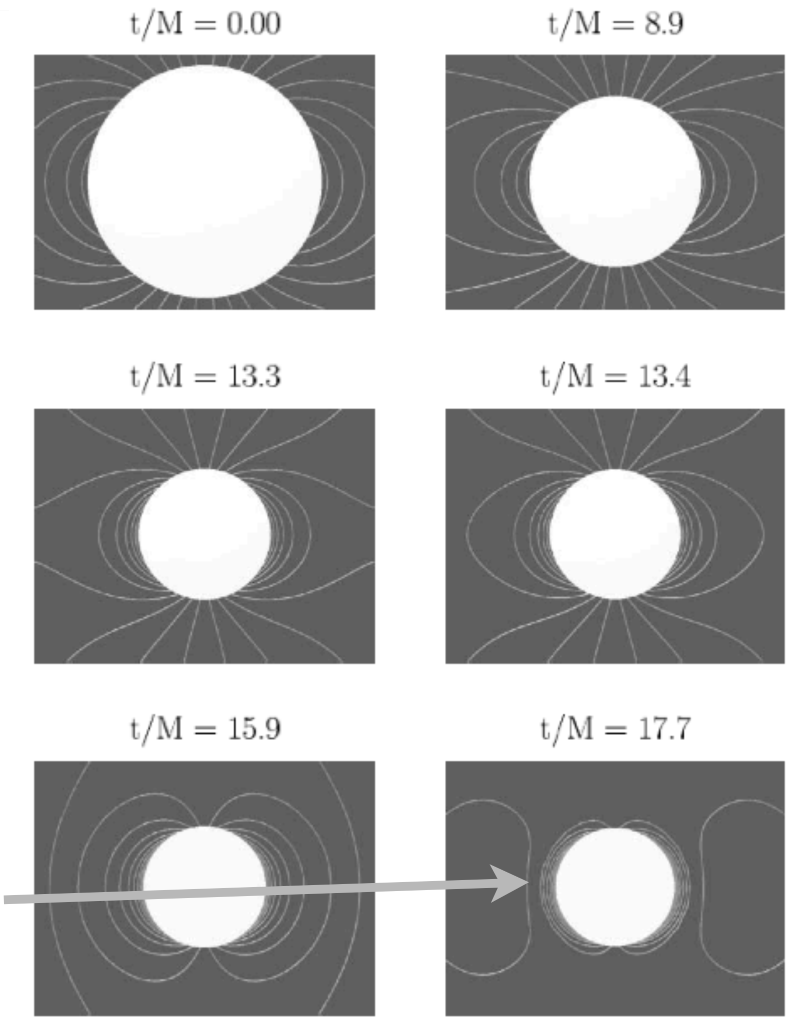
$$\Omega_H \approx \frac{\chi}{5}\frac{c^4 R_{\rm NS}^2}{(GM_{\rm NS})^2}\Omega_{\rm NS} = 2.9\times10^3 \mathrm{rads}^{-1}\chi_{-1}P_{\rm NS,-3}^{-1}$$

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

What happens to B-field at the moment BH is formed?

Magnetic hair of black holes

“Black holes have no hair”



Such process is prohibited if outside is plasma

Baumgarte & Shapiro, 2003

Magnetic hair of BHs

Lyutikov 2011
Lyutikov+2012
Bransgrove+ 2021

- **Loop-hole in "NO-HAIR" theorem: frozen-in B-fields**
- **Open field lines remain on the BH**
- **Hair are conserved (in ideal plasma)**

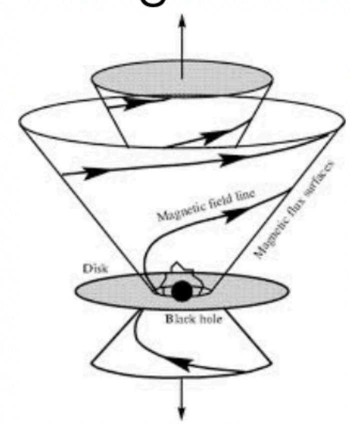
$$N_B = e\Phi_\infty/(\pi c\hbar) = B_{NS} e R_{NS}^3 \Omega_{NS}/(c^2\hbar) = 10^{41} \frac{B_{NS}}{10^{12}\mathrm{G}} \frac{P_{NS}}{1\mathrm{msec}}.$$

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

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

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

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

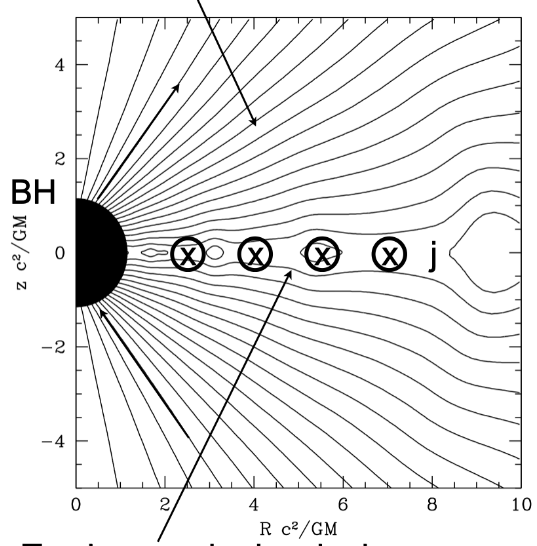


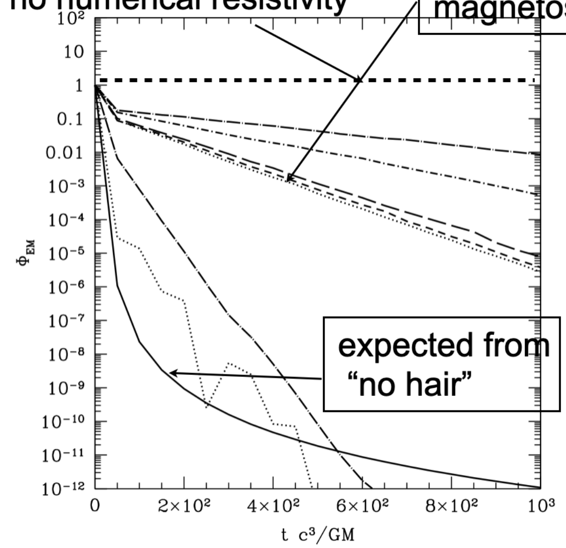
- Nonlinear, time-dependent solution in GR (small a)

-

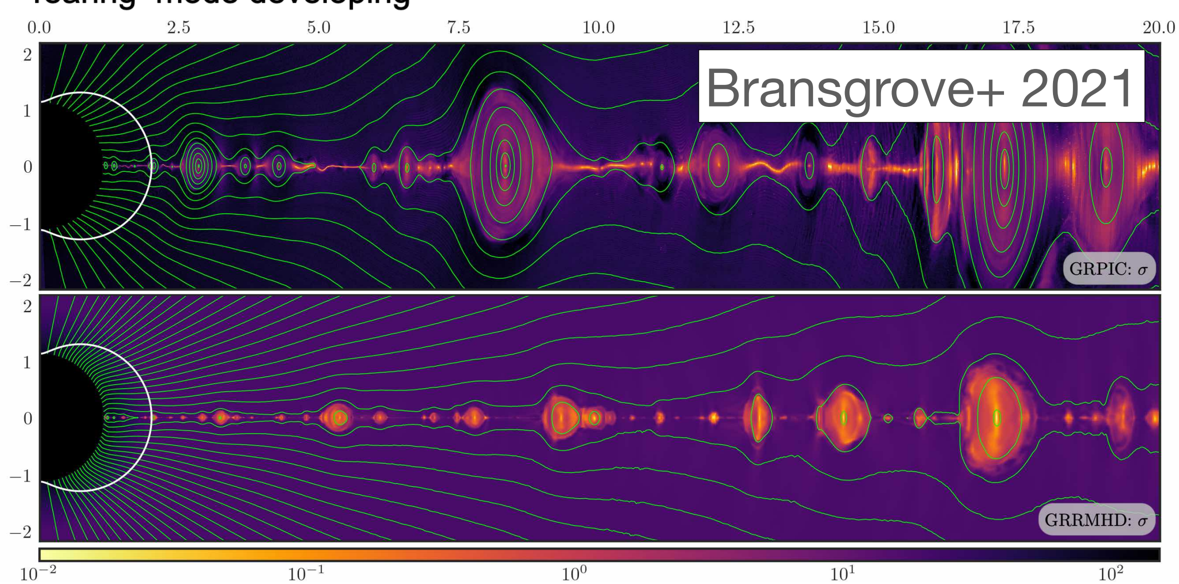
- **arbitrary $\Omega(t,\theta)$ in Schwarzschild metric (monopolar geom.)**
  - **fully nonlinear Alfven mode**

Slowly balding black holes,
(Lyutikov and McKinney 2011)

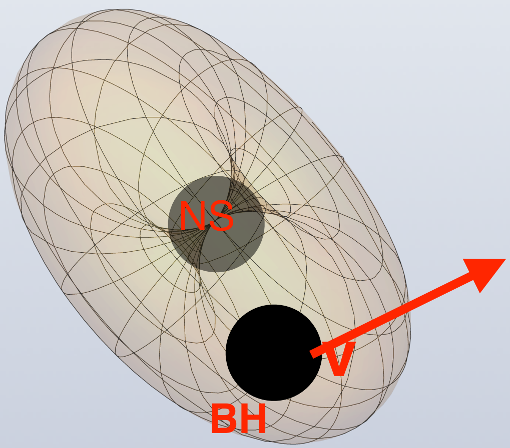




It seems B-field slides off fairly fast…
It's a statement about the resistivity of the equatorial current sheet



Cherenkov emission by Schwarzschild (uncharged) BH



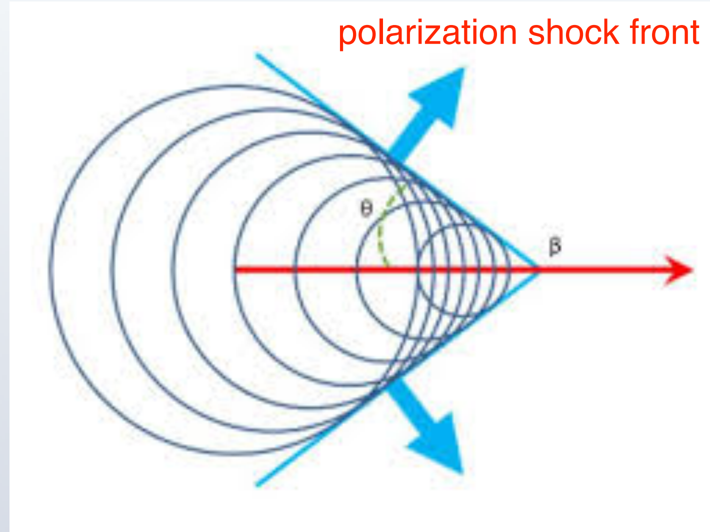
Uniting vol. II and vol. VIII

GR/EM and physics of continuous media

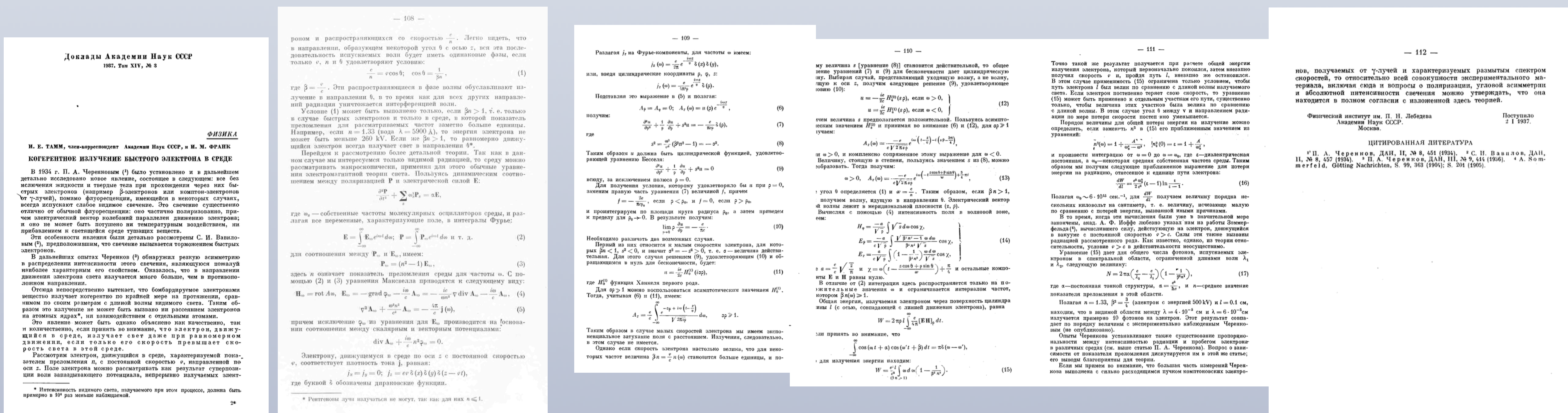
First example (?) of classical (not π^0), truly charge-neutral "particle" producing EM radiation

Cherenkov emission

- $\omega - k_{\|} v_{\|} = 0 \rightarrow \omega' = 0$ - in particle's frame radiation field is stationary ….
- In quantum language: $0 = mv^2_{recoil}/2 + \hbar\omega$- ???



Tamm & Frank, 1947


Доклады Академии Наук СССР
1937. Том XIV, № 3

ФИЗИКА

И. Е. ТАММ, член-корреспондент Академии Наук СССР, и И. М. ФРАНК

КОГЕРЕНТНОЕ ИЗЛУЧЕНИЕ БЫСТРОГО ЭЛЕКТРОНА В СРЕДЕ

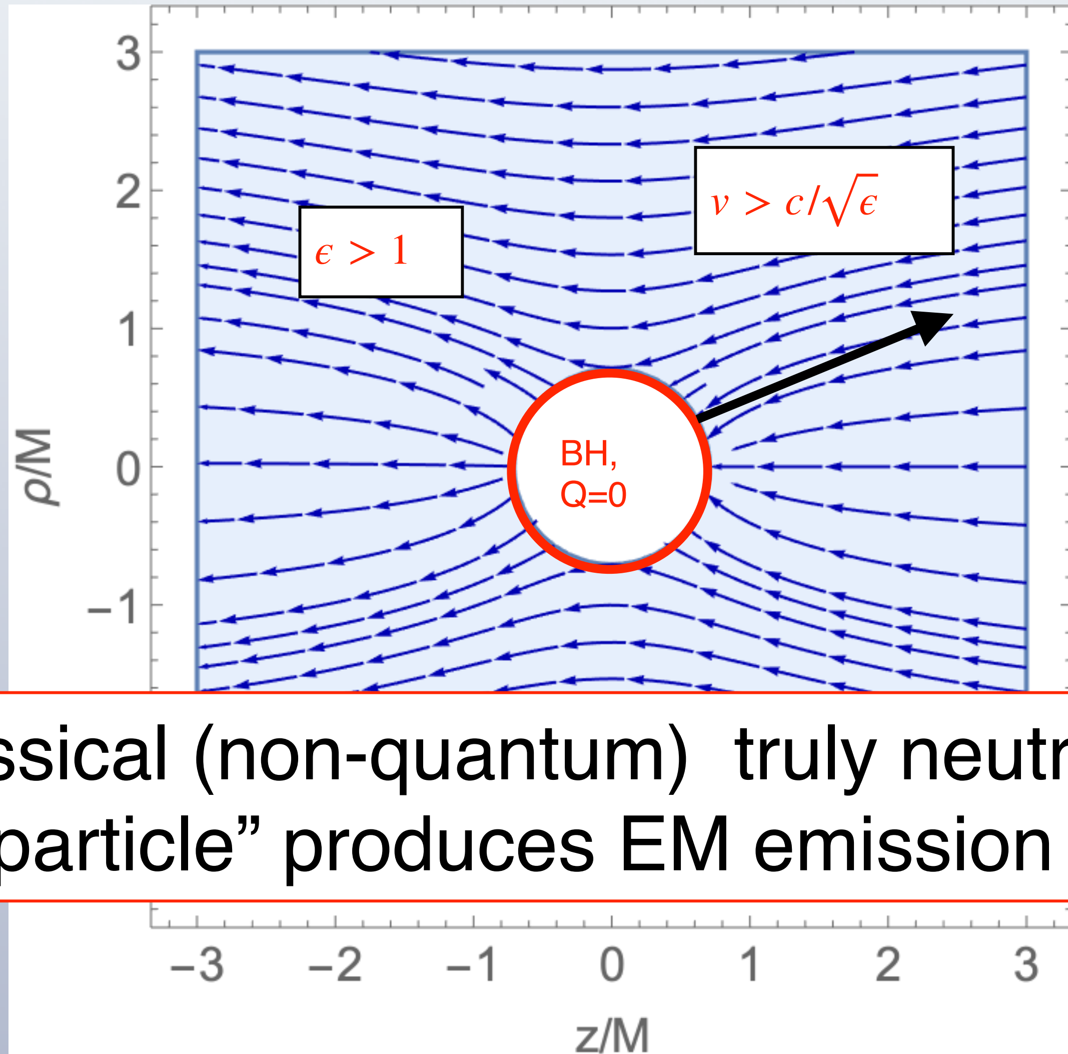
В 1934 г. П. А. Черенковым (1) было установлено и в дальнейшем детально исследовано новое явление, состоящее в следующем: все без исключения жидкости и твердые тела при прохождении через них быстрых электронов (например β-электронов или комптон-электронов от γ-лучей), помимо флуоресценции, имеющейся в некоторых случаях, всегда испускают слабое видимое свечение. Это свечение существенно отлично от обычной флуоресценции: оно частично поляризованно, причем электрический вектор колебаний параллелен движению электрона; и оно не может быть потушено ни температурным воздействием, ни …

Collective emission by the particles of the medium

- If we have a medium with n> 1 (v_{phase}<c). Eg. EM waves at $\omega_B > \omega$
- Uncharged BH moving with v> c/n produces Cherenkov emission in external magnetic field.

Khlebnikov & Lyutikov 2025

Schwarzschild (uncharged) BH moving in dielectric in B-field will produce Cherenkov emission



Classical (non-quantum) truly neutral "particle" produces EM emission

BH: there is no source for EM emission! (??)

- First example (?) of classical (not π^0), truly charge-neutral "particle" producing EM radiation
- Maxwell + GR + medium
- We are solving homogeneous Maxwells' equation $\hat{L}[g_{\mu\nu}, u^\mu]A = 0$, no source
- $A = A_0 + A_{BH} + \delta A \propto M$

external B-field

distorsions due to BH

perturbations

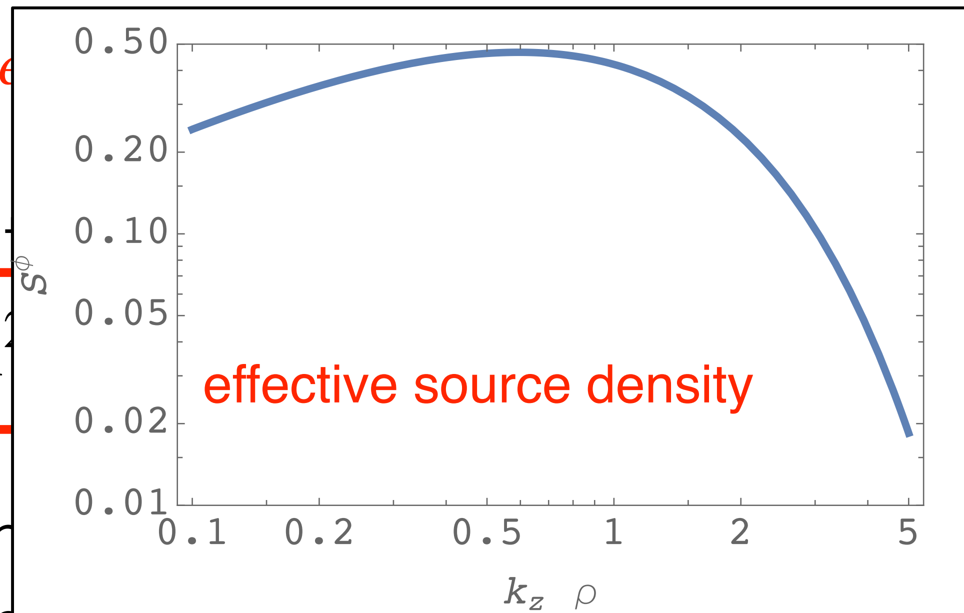
- perturbations of distortions
  - decay exponentially in ρ in normal regime
  - wave-like in Cherenkov regime
- choice of gauge is super-important
  - $\left(g^{\mu\nu} - (\epsilon - 1)u^\mu u^\nu\right) A_{\nu,\mu} = 0$ - separates polarization and dispersion
- choice of velocity field: "straight" motion

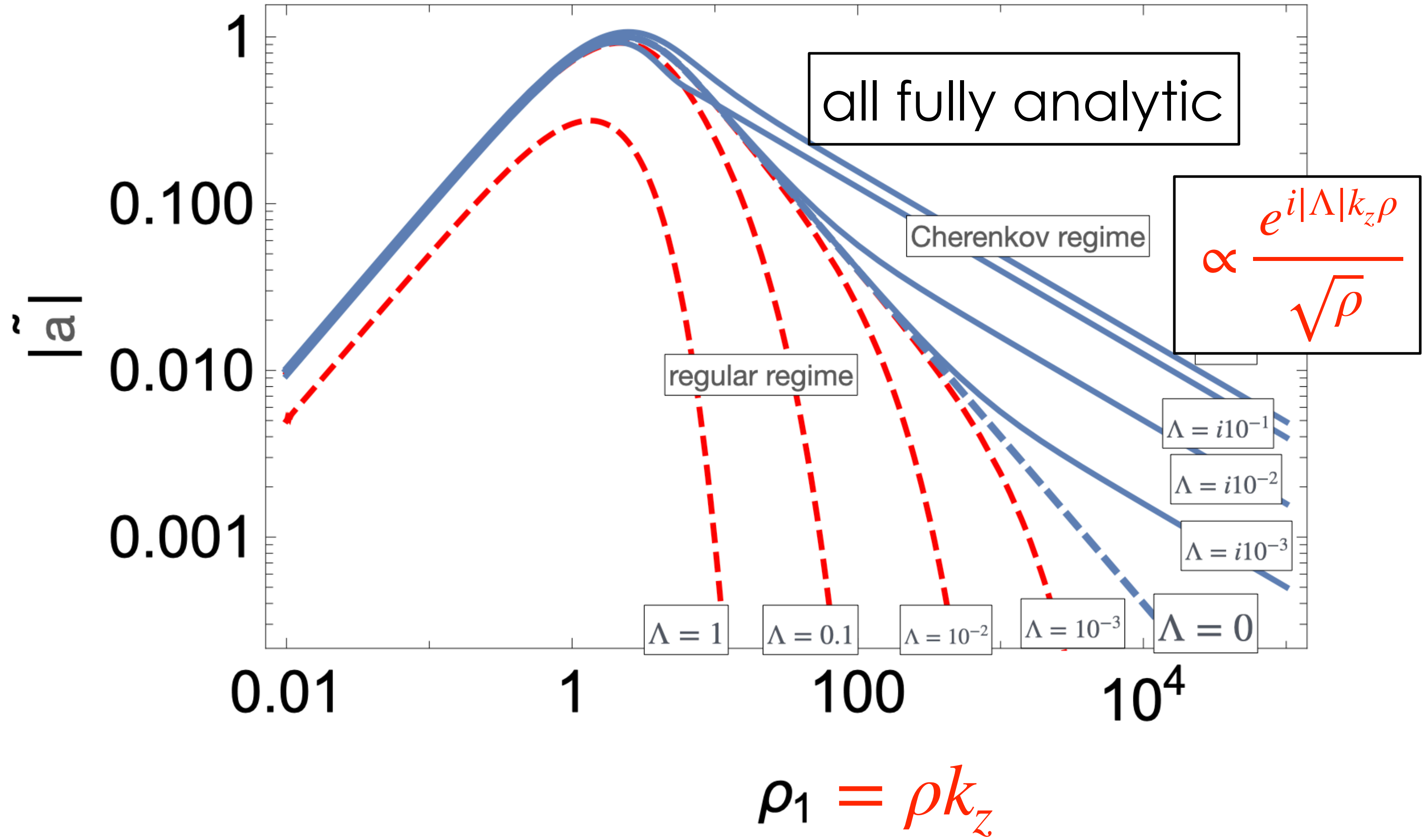
In isotropic coordinates (closest analogue of Cartesian)

- The only case of no emission: locally **v** | | **B**
- There is emission for | | propagation,
- Effective source is **distributed**:

$$S^{\phi} = \frac{\rho\left(2z^2 - \rho^2\right)}{\left(\rho^2 + z^2\right)^{5/2}} \times MB_0\beta^2\gamma^2(e$$

- different k_z are sourced at
- Cherenkov parameter: Λ^2
Cherenkov regime
- $\delta A \propto K_1(\Lambda k_z \rho)$ - exponen ,
cylindrical wave in Cherenkov regime
- Causality: Landau-like rule (Laplace, not Fourier, for emission in complex k-plane)



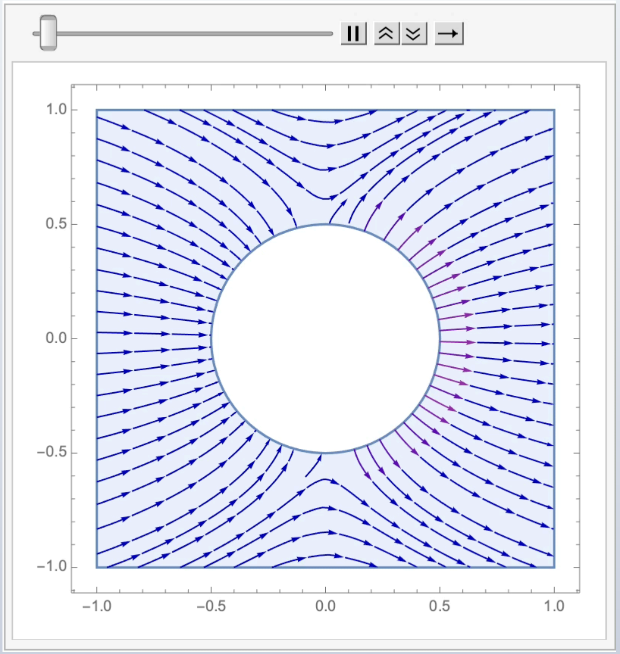


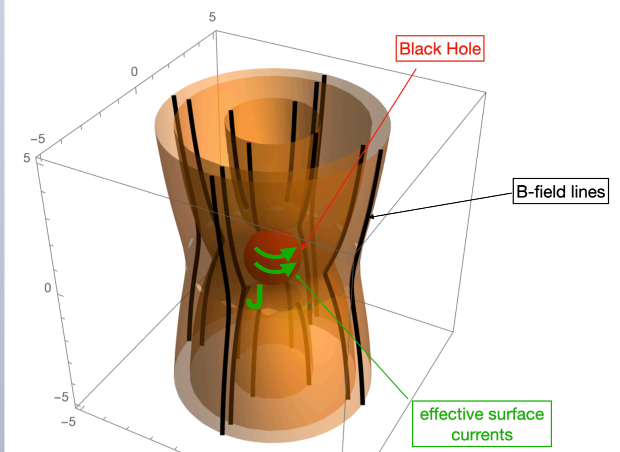
- Power: $L \approx R_G^2 B^2 c \times \frac{dk}{k}$
- Observability:
  - not stellar, need $\lambda \geq R_S$
  - primordial BHs- smaller power $\sim 10^{35}$ erg/s

Lyutikov, in prep

Another new cute effect: extra emission by BH evaporating in B-field:

- Time-dependent distortion of B-field by gravity: emission
- $$L_B \approx B_0^2 R_g^2 c \frac{1}{(\tau_H \omega)^{2/3}} \frac{d\omega}{\omega}$$
- $\tau_H = \dfrac{5120 \pi G^2 M_0{}^3}{c^4 \hbar}$ - Hawking time
- What is the correct metric for evaporating BH?



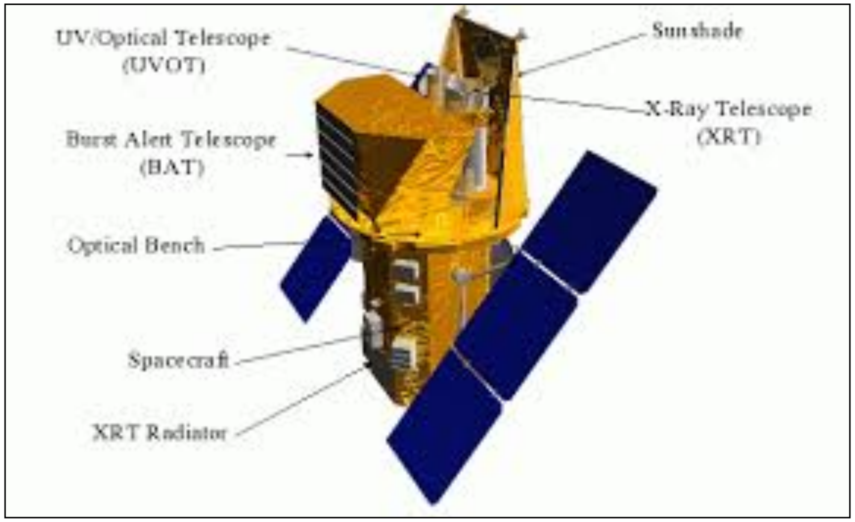


membrane paradigm is wrong, still

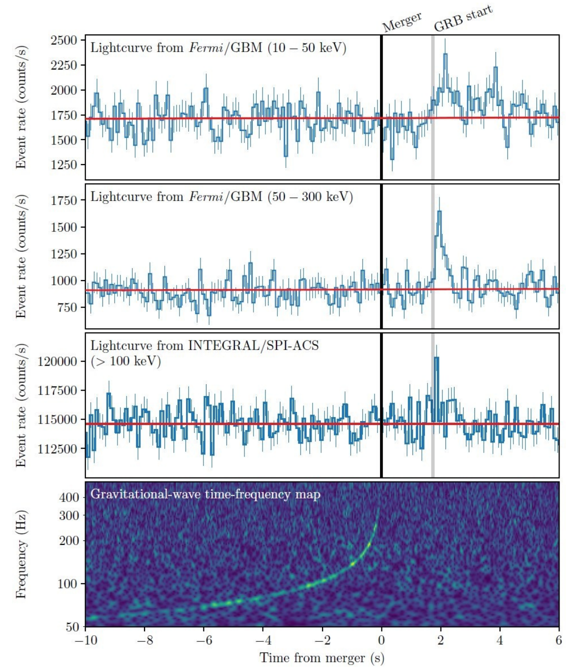
Chances/strategies to detect precursors

Do we have a chance to detect precursor emission?

- Bright (X-ray all-sky monitors): $\leq 10\,\mathrm{Mpc}$
- Bursty (small average power, but high peak power)
- Modulated is good (can pick modulated signal from below noise)
- Early warning (so can slew)
- Time-machine



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 ~ $\Delta t = 14\,\mathrm{sec}\,\nu_9^{-2}d_{200}$

5 RW Early Warning Response Capability

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

To do:

- Alfven wings in PIC 3D:
  - Shoot a NS across B-field
  - Shoot a BH across B-field

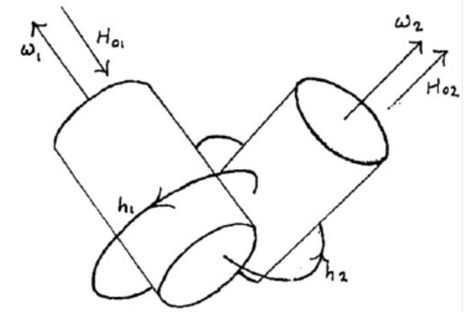
extra slides

GW150914 and the EM signal

- GW150914: claimed EM signal of 10^{49} erg/s

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

$$\Phi_B \sim B_{BH} R_{BH}^2 \longrightarrow B_{BH} \sim 10^{12}\,\mathrm{G}$$



Herzenberg dynamo

- Such fields are **not expected** on BHs
  - Herzenberg dynamo? - No, BHs are bad conductors
  - Charged BH? (surface **electrostatic** E-field of 5% of Schwinger…)

$$Q_{BH} = GM\sqrt{L_{EM}}/c^{5/2} = 5 \times 10^{16}\,\mathrm{coulombs}$$

- **Association of GW150914 with Fermi signal is unlikely.**

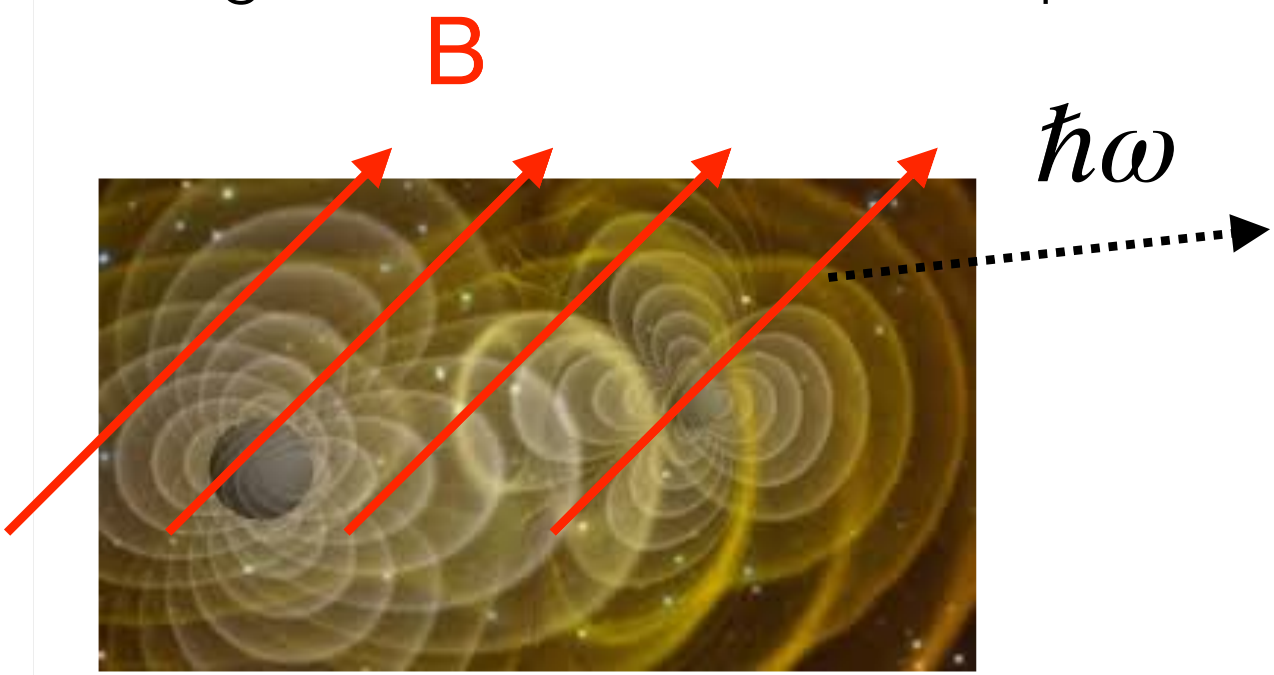
- N.B. A critically spinning BH in critical (Schwinger) B-field will have critical E-field, but inductive, **not** electrostatic. BH charge will be lost not by attraction of opposite charges, but by the loss of magnetic flux.

Membrane paradigm is wrong

- Horizon is a null surface
- Extended horizon is a time-like surface
- Different mathematical structure
- Eg: Parker/Bondi solution **cannot** be formulated as boundary value problem: it's a critical point flow

Also: Gertsenshtein-Zeldovich effect

- Coupling of gravitational waves to magnetic field
- Ring-down after NS -> BH collapse



- $L_B \approx h^2_{+,\mathrm{x}}(B_0 R_g)^2 c = 5 \times 10^{46}\,\mathrm{erg\,s^{-1}} \times (h/0.1)^2 (B/B_Q)^2 (M/M_\odot)^2$
- $\dfrac{E_B}{E_{GW,r}} \approx \dfrac{B_0^2 R_g^3}{Mc^2} \sim 3 \times 10^{-12} (B/B_Q)^2 (M/M_\odot)^2$