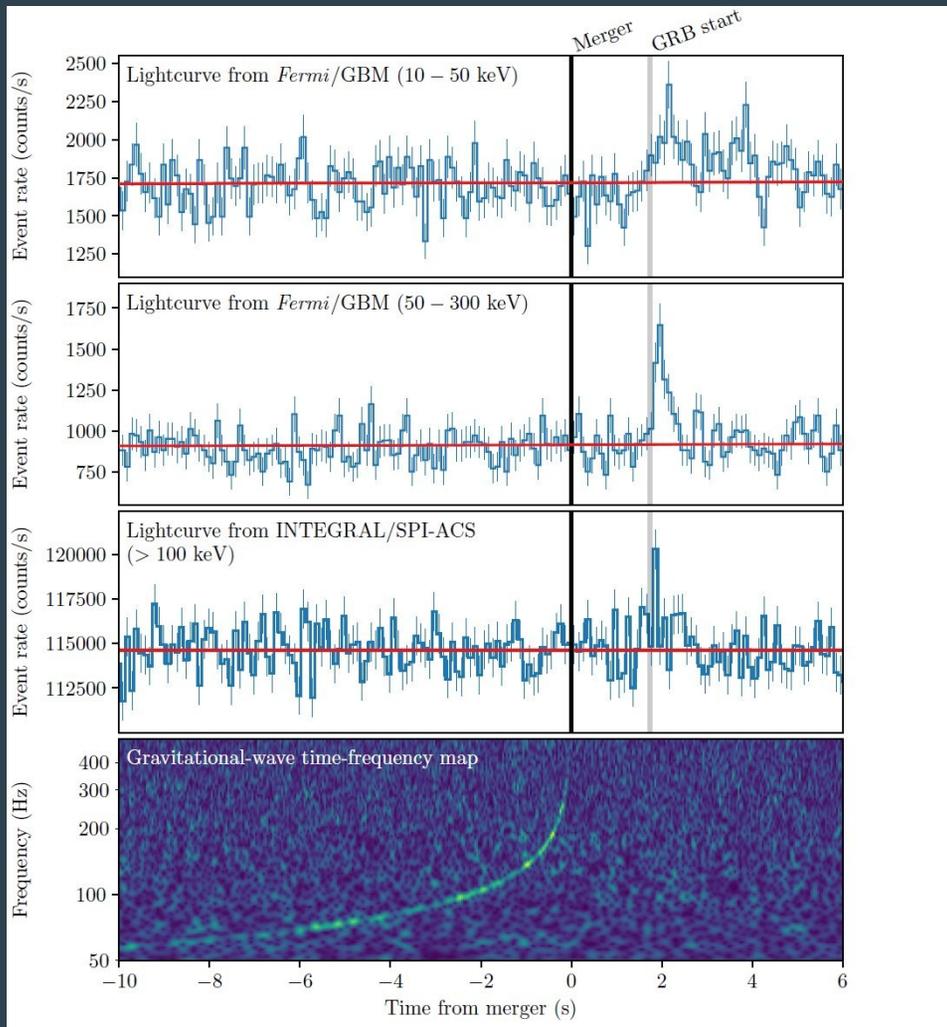


Electromagnetic precursors to compact objects' mergers

Maxim Lyutikov
Purdue University

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

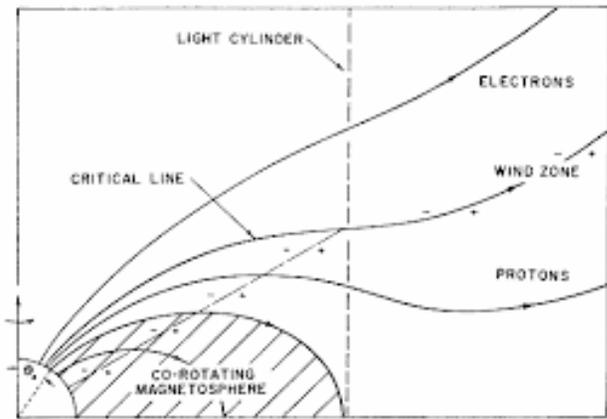
difficult, but these are
beautiful physics problems

Plan of the talk

- Unipolar Inductor: expected power
- Generation of jets **before** NSs mergers (Alfven wings)
- “Dancing” 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

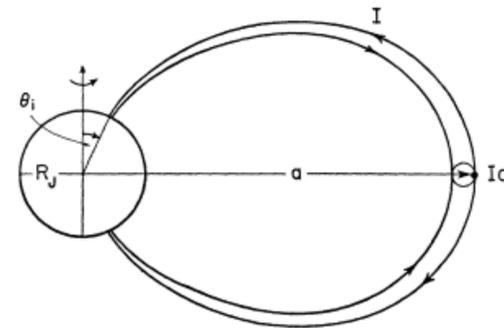


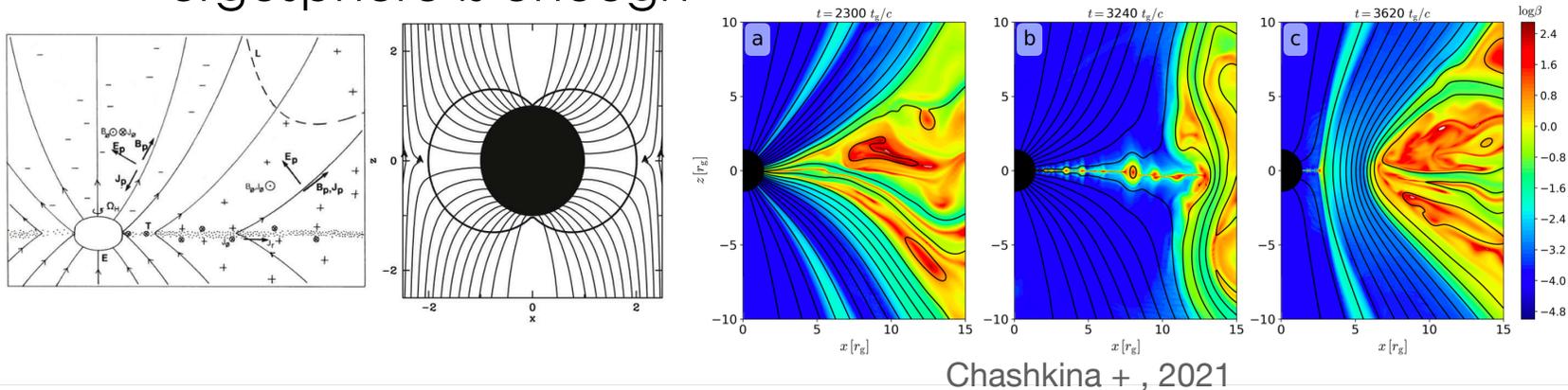
FIG. 2.—Current circuit in the meridian plane (not to scale)

Linearly moving conductor generates EMF

- In both cases parallel E-field is generated
- pulsars: E_{\parallel} 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)

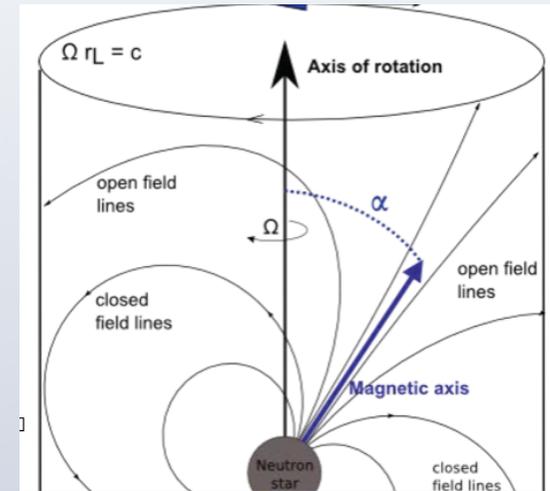


Later: extension to GR:- linearly moving BH

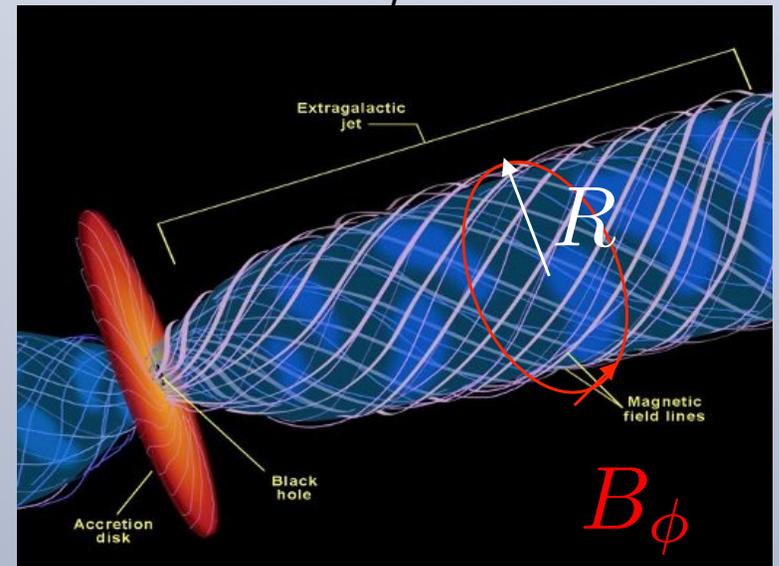
Power of relativistic unipolar inductor

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

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



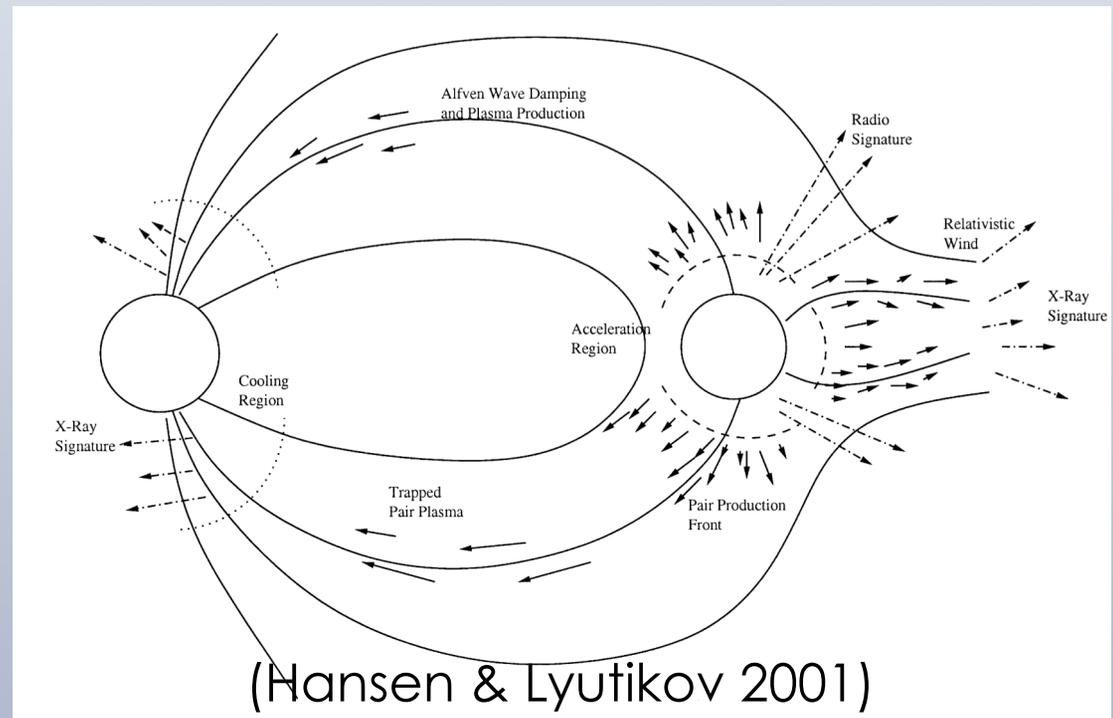
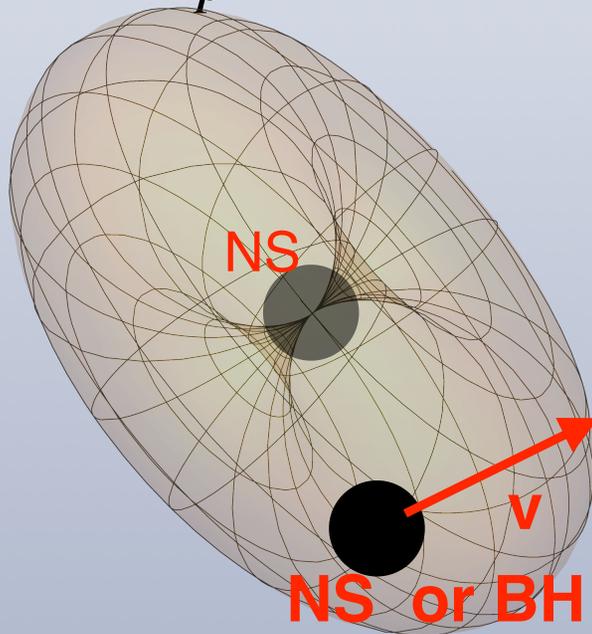
Eg, AGN jet $L \sim B_\phi^2 R^2 c \approx (\Delta\Phi)^2 c$



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
- $B_{NS} \sim 10^{12} \text{ G}$
- $\sigma \equiv \frac{\omega_B^2}{\omega_p^2} \gg 1, v_A \sim c$ - all is relativistic (simple!)

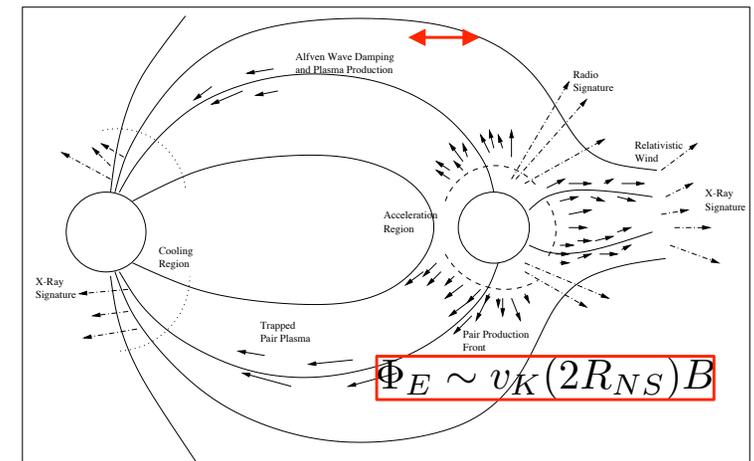
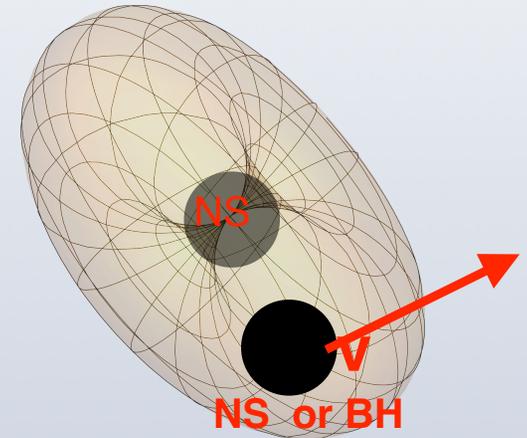


NS-NS merger as relativistic Io-Jupiter

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

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

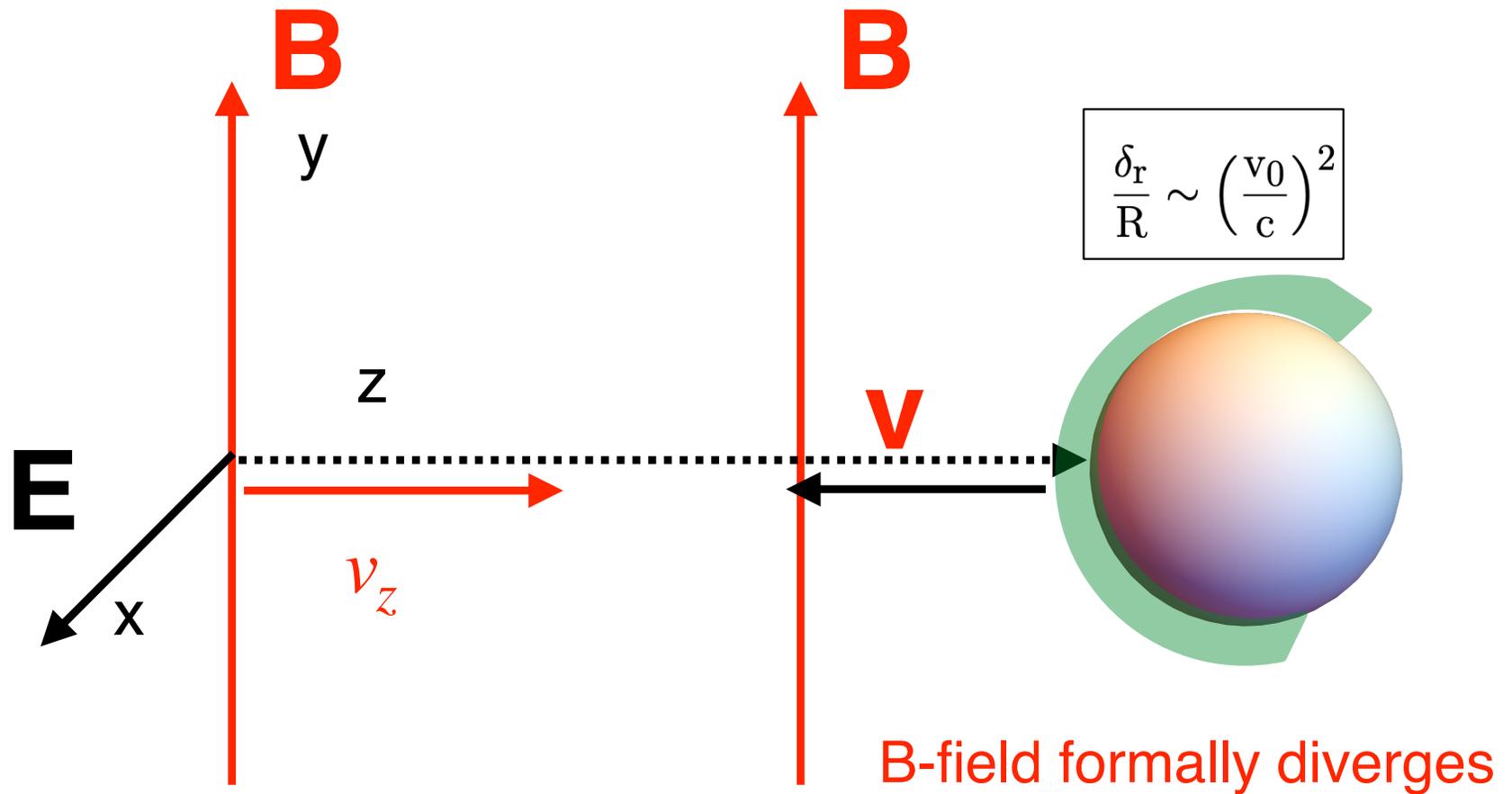
- Not very bright for all-sky X-ray telescopes, tens of Mpc (expected sources typically at ~ 200 Mpc)
- Unless coherent! - **Radio**
- $F_\nu \sim (\text{kilo}) - \text{Jansky}$ from Gpc
- That was the best model for the Lorimer Burst, not anymore, FRBs are not mergers, FRB rates \gg NS-NS mergers



Can emission be beamed?

Generation of jets *before* NSs mergers

Magnetic draping



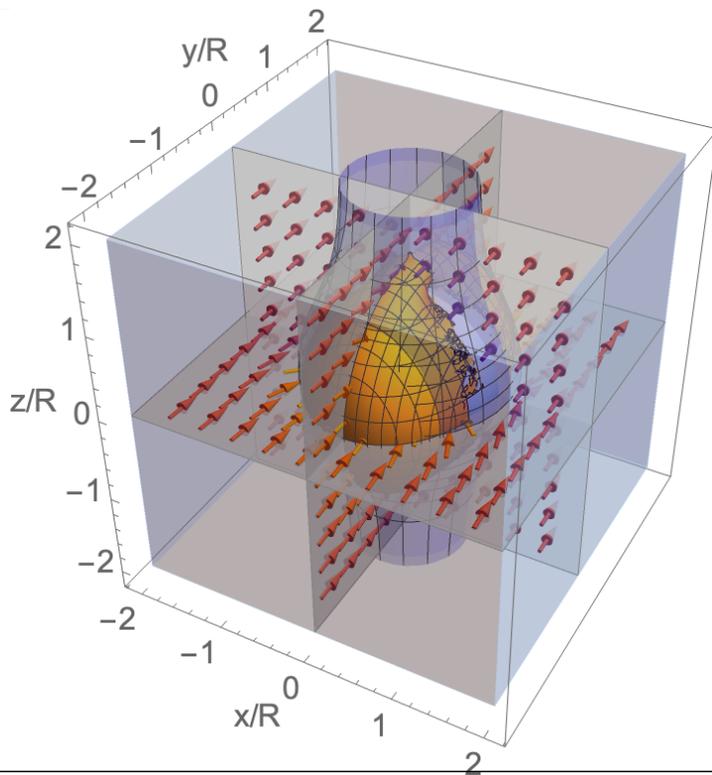
Steady state: $\partial_z E_x = 0: E_x = -v_z B_y = \text{const}$

Different ways to resolve the draping problem

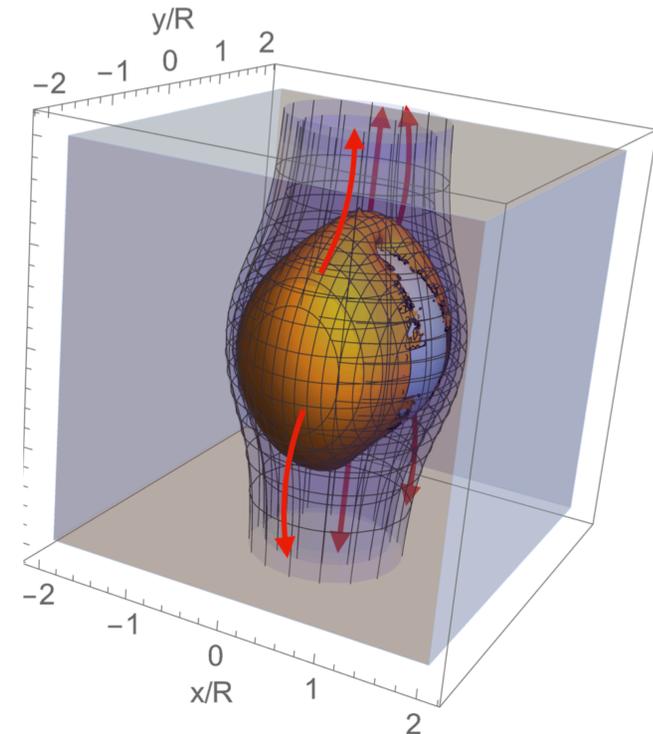
- Depletion layers in planetary-solar wind interaction
- Highly magnetized plasma has only fields (little charges only try to ensure $\mathbf{E} \cdot \mathbf{B} = 0$).
- The system **must** become dissipative:
- regions $\mathbf{E} \cdot \mathbf{B} \neq 0$
- regions with $E > B$

-> current j_{\parallel} , non-thermal emission

NS-NS mergers: dissipative B-field draping



- Magnetic draping (Lyutikov 2023).
metal sphere moving through B-field:
- Weak B-field in the bulk
 - \sim equipartition field in narrow layer
 - Generation of $\mathbf{E} \cdot \mathbf{B} \neq 0$, $|E| > |B|$



Double-jet structure is expected

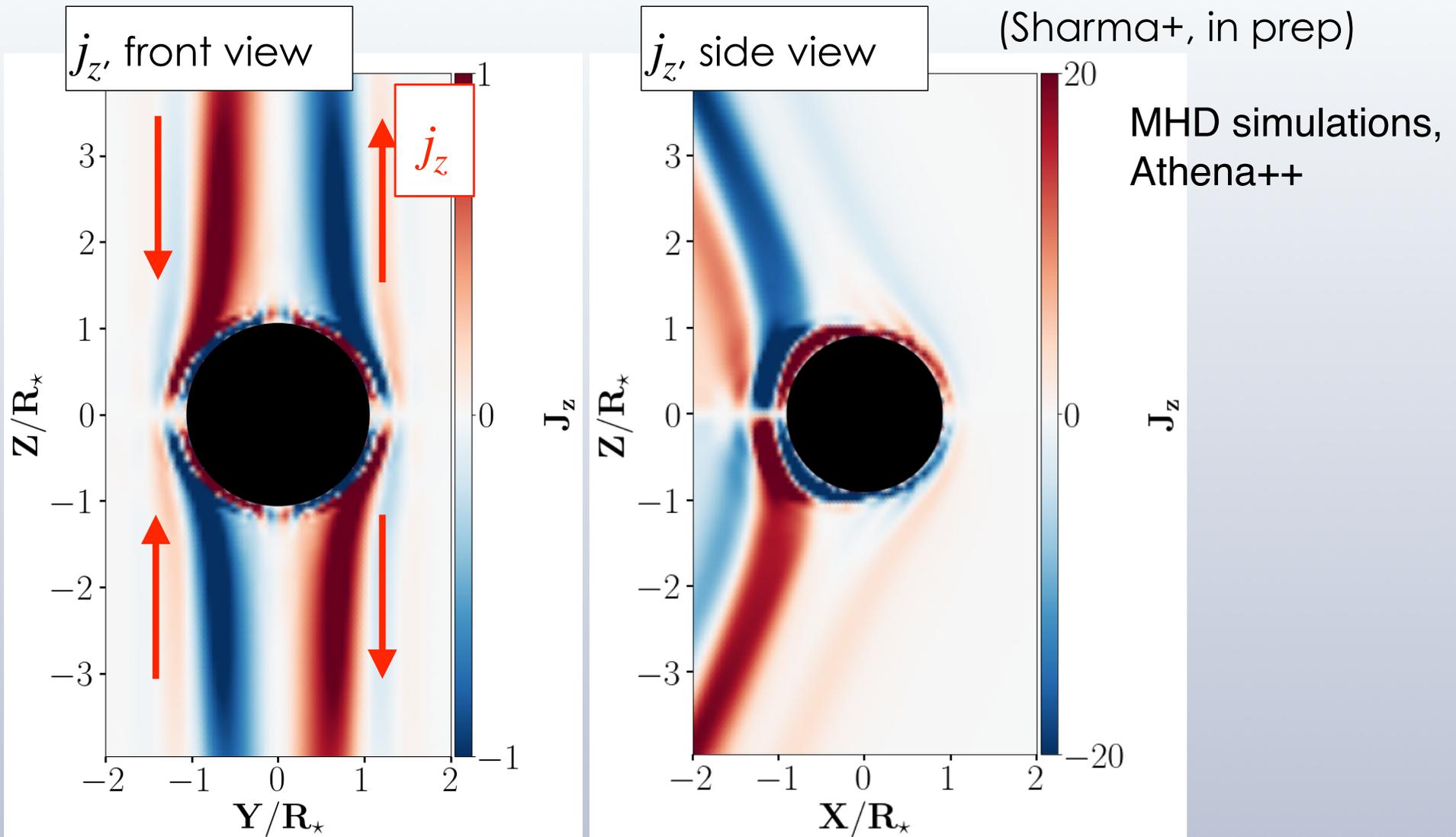
Relativistic sub-Alfvenic

- NS magnetosphere:

- $\beta_A = \sqrt{\frac{\sigma}{1 + \sigma}} \sim 1$

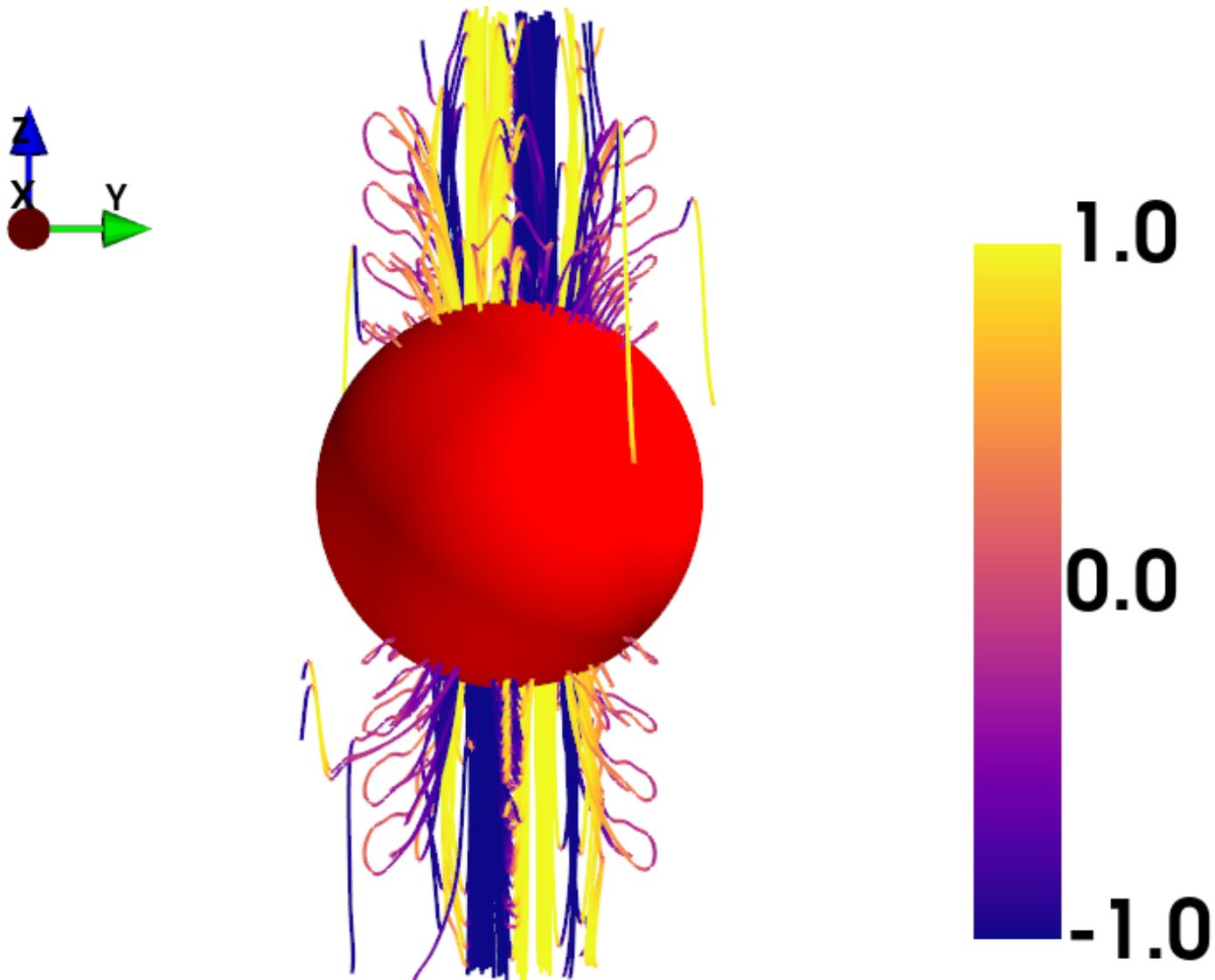
- $\beta \sim 1, \beta \leq \beta_A$

NS-NS mergers: dissipative B-field draping



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

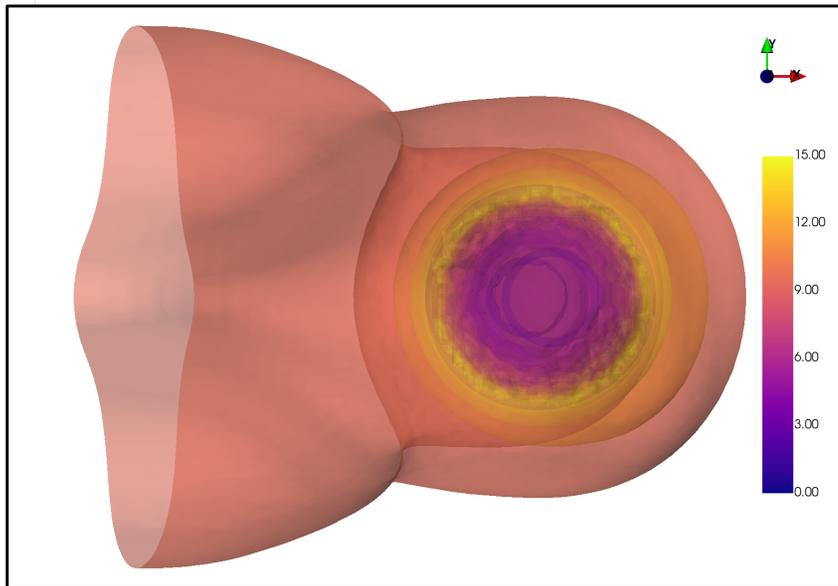
Double jets = Alfven wings



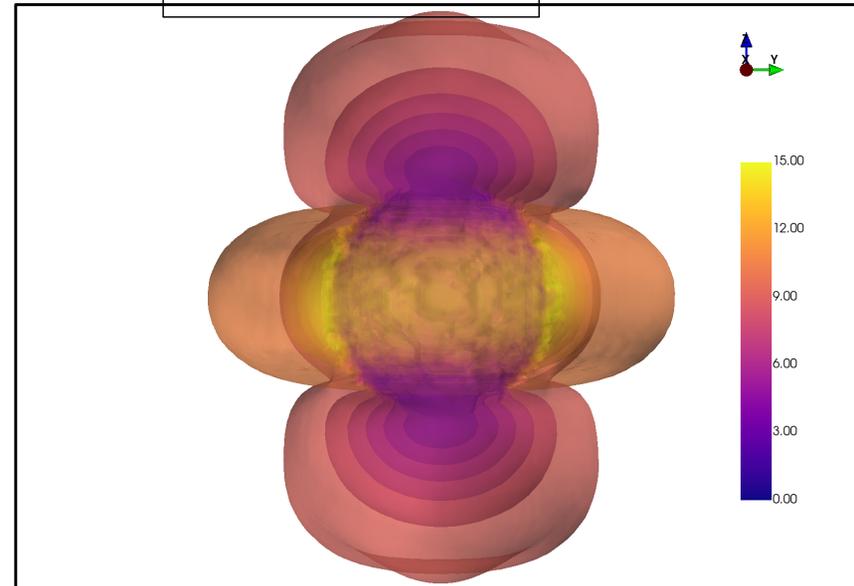
NS-NS mergers: dissipative B-field draping

(Sharma+, in prep)

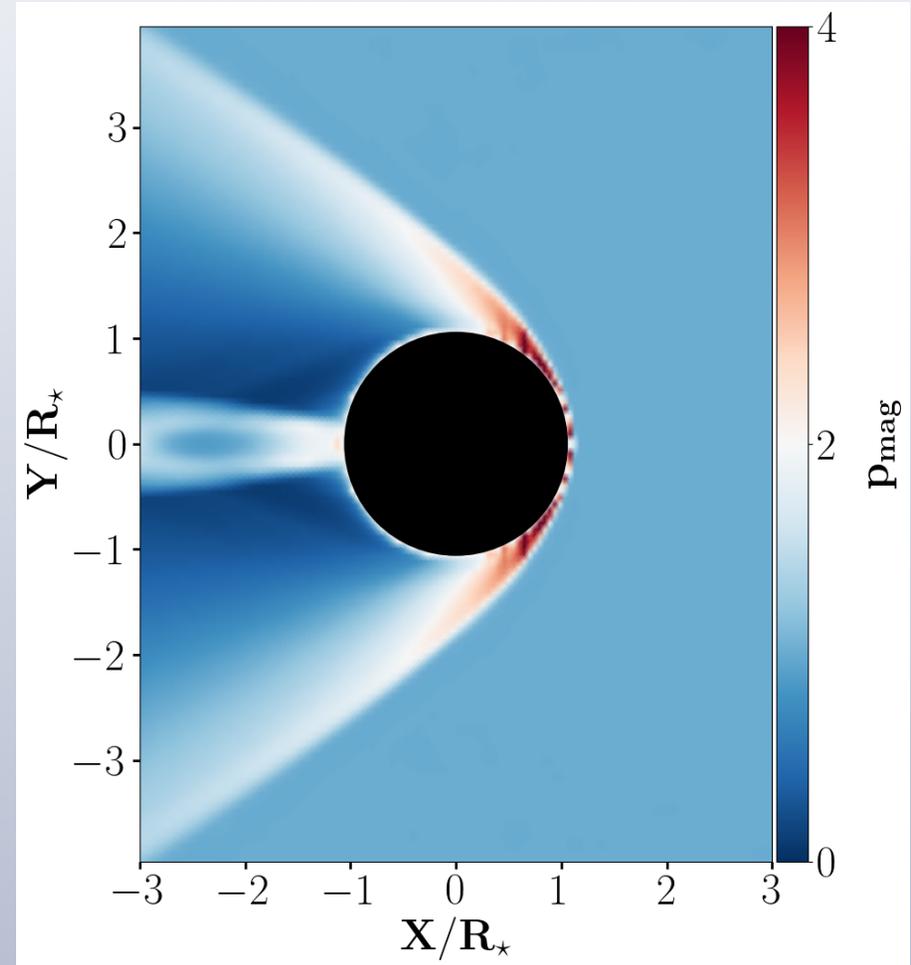
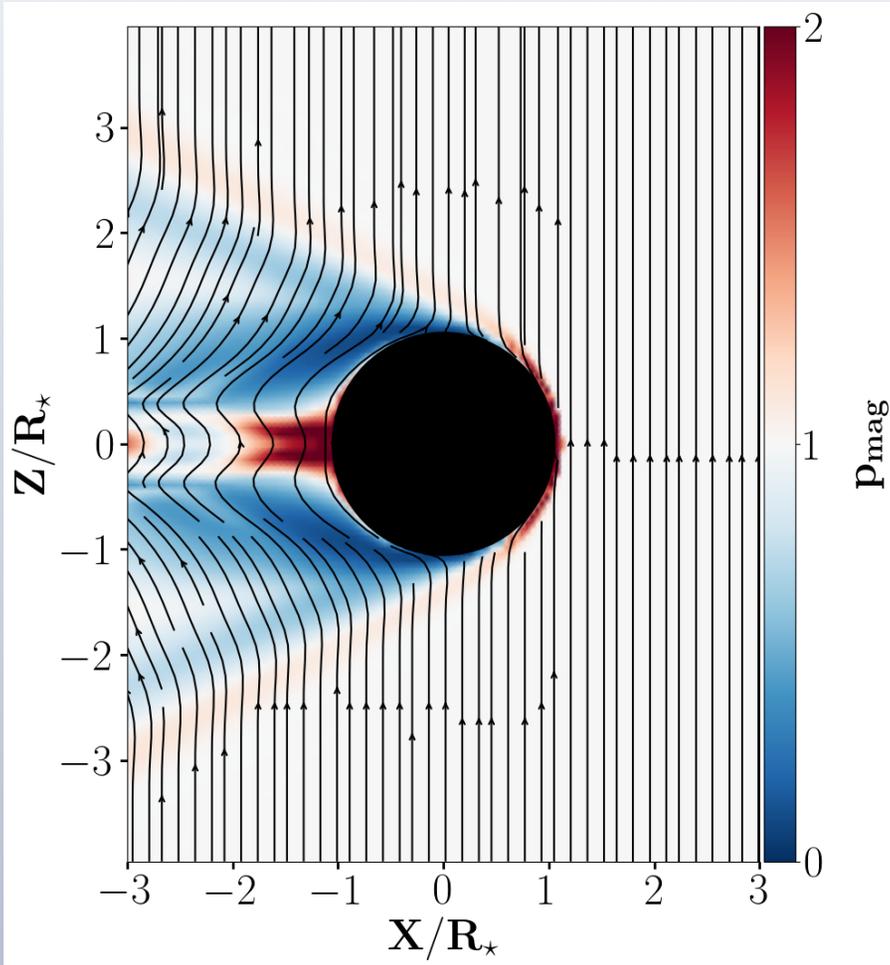
B^2 , top view



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)

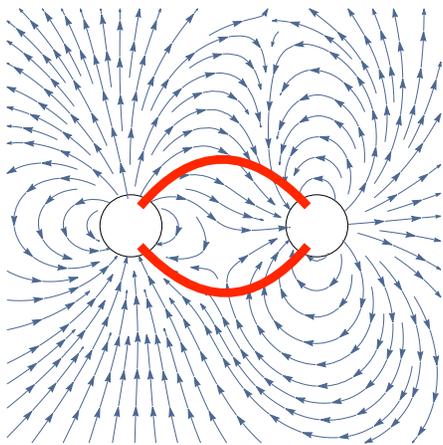
Double-magnetized spinning NS: *smooth* interaction of two magnetospheres

Lyutikov 2019

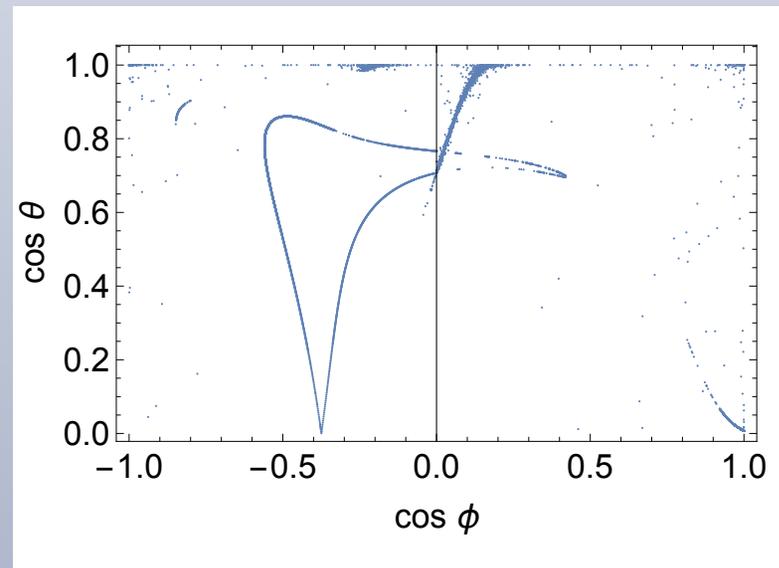
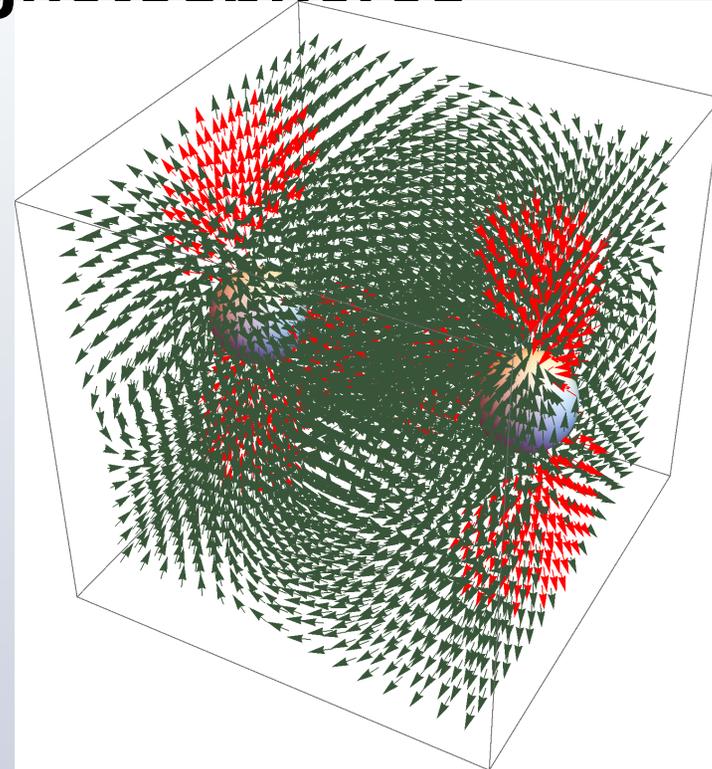
$$\mathbf{E} \cdot \mathbf{B} = -2(\mathbf{v}_1 \times \mathbf{B}_1) \cdot \mathbf{B}_2 \neq 0$$

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

Magnetic connection at co-rotation $\sim 10^{39}$ erg



(No need to diffuse through crust)

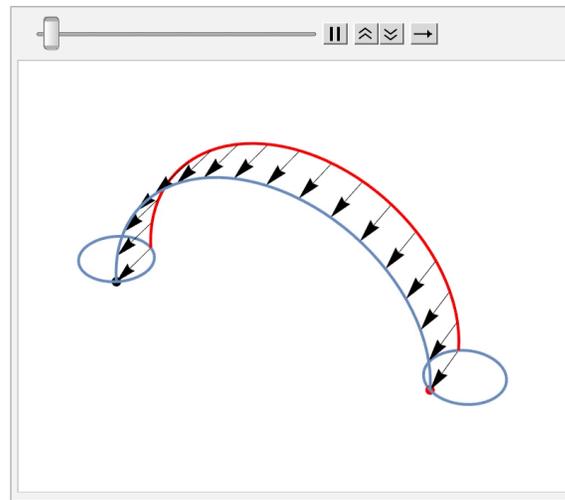
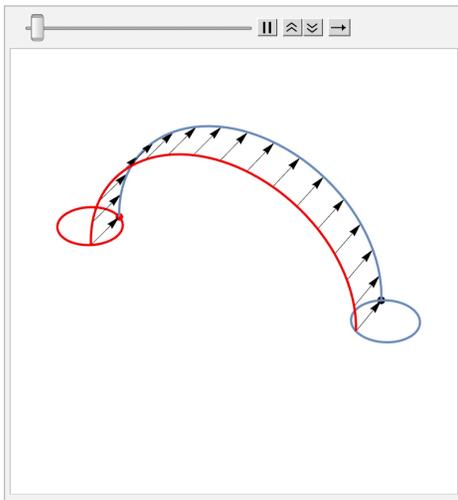


Flares!

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
 - $\omega_1 = -\omega_2$

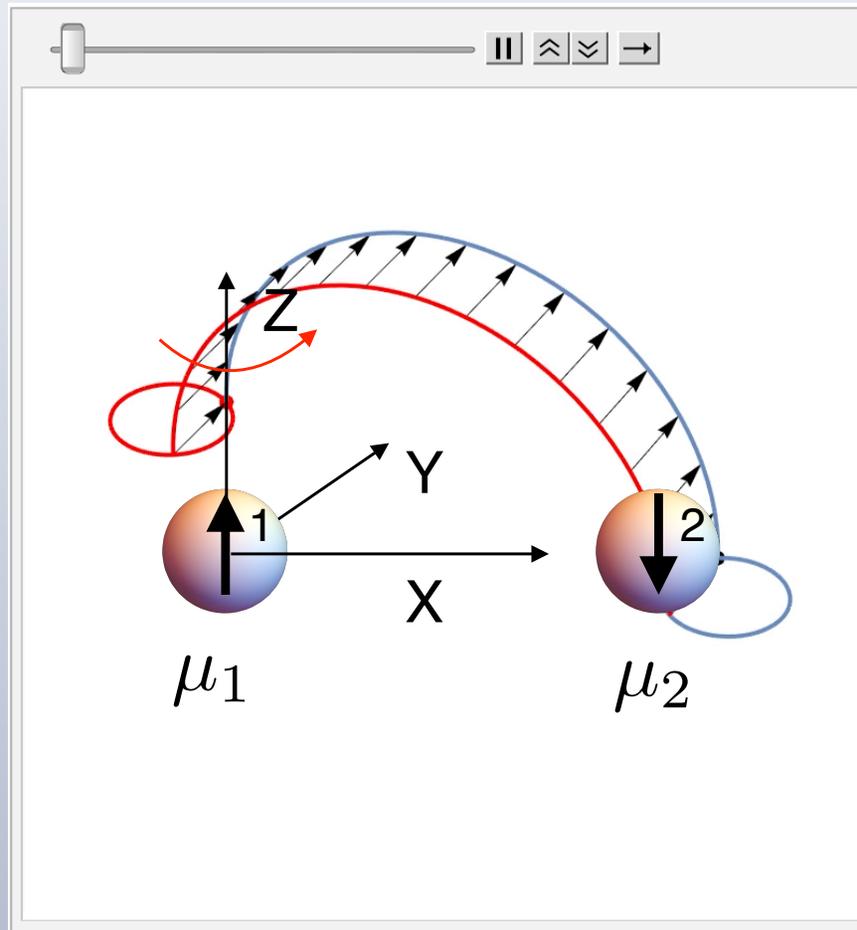
- NOT EXPECTED



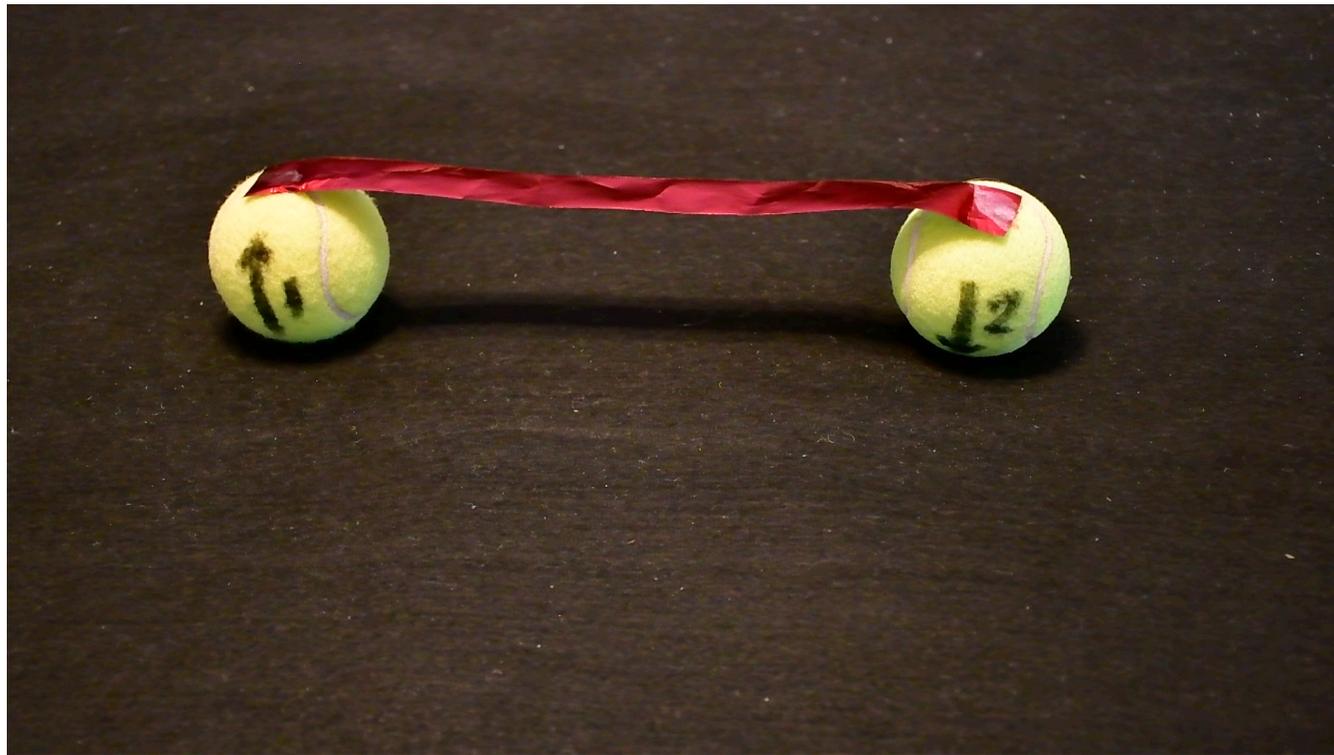
Basic-Z:

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

Dirac's belt



Y-spin



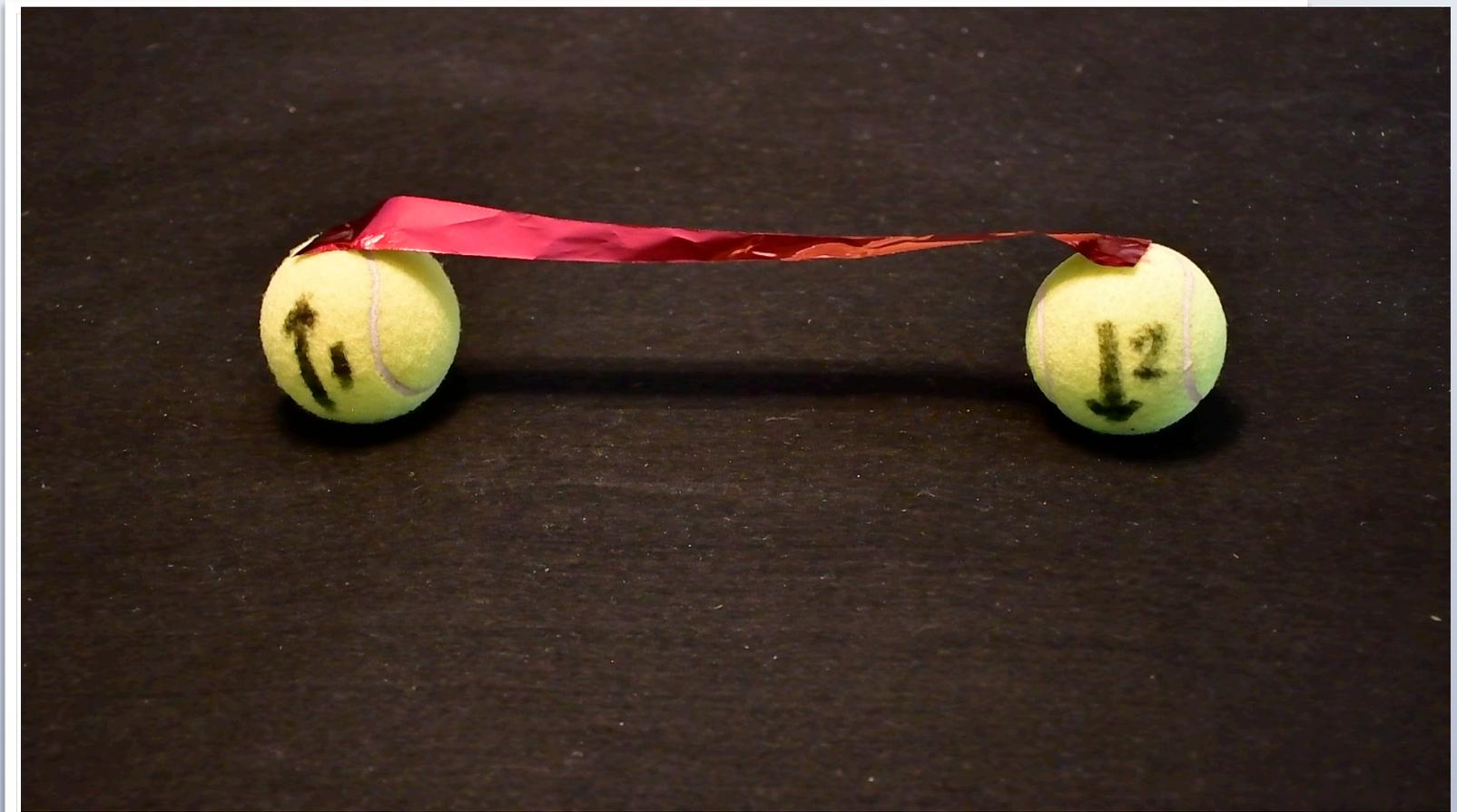
Cherkis & Lyutikov ApJ, 2021

Y-spin

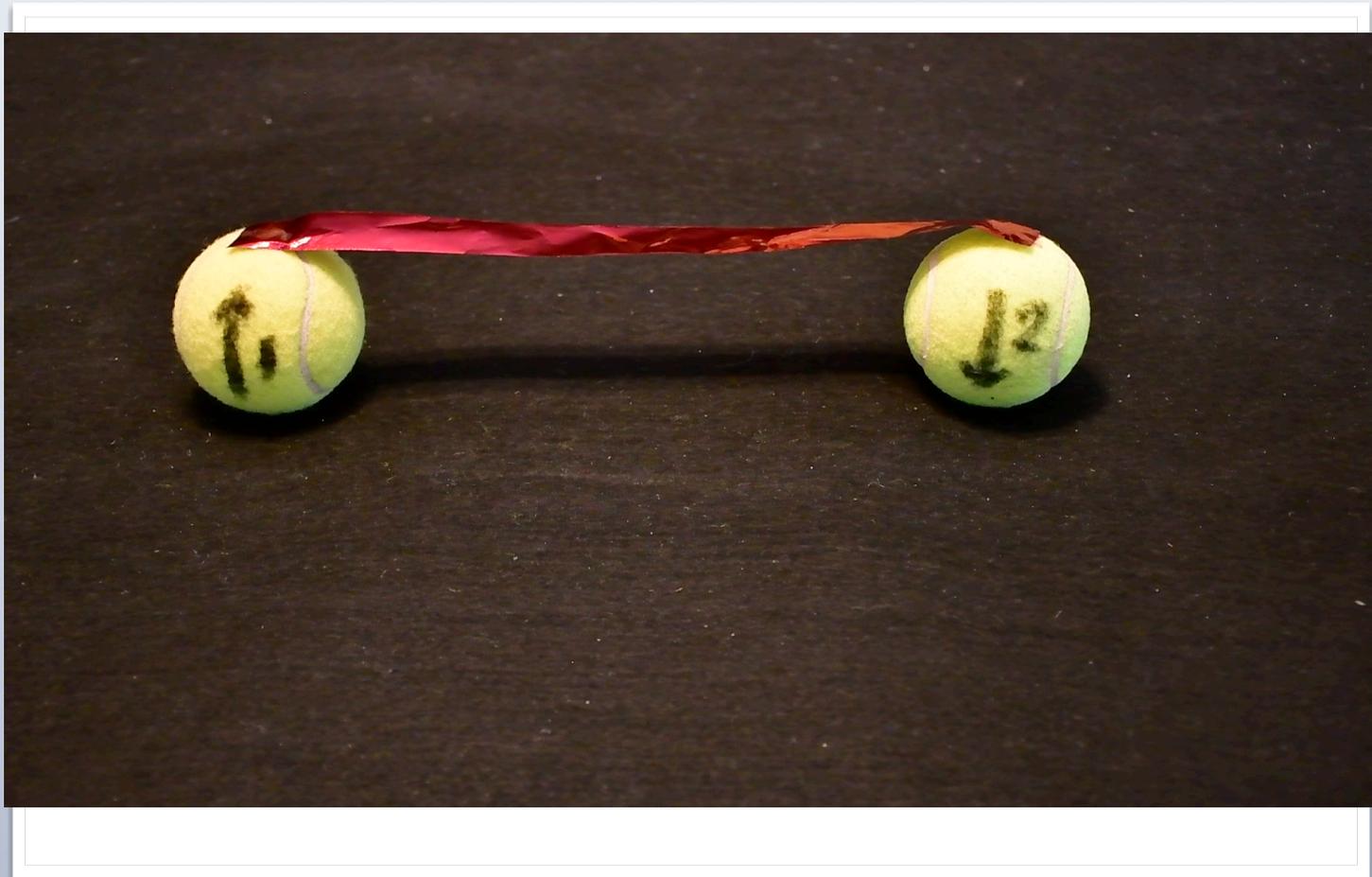


- Did you get the trick?

X-spin

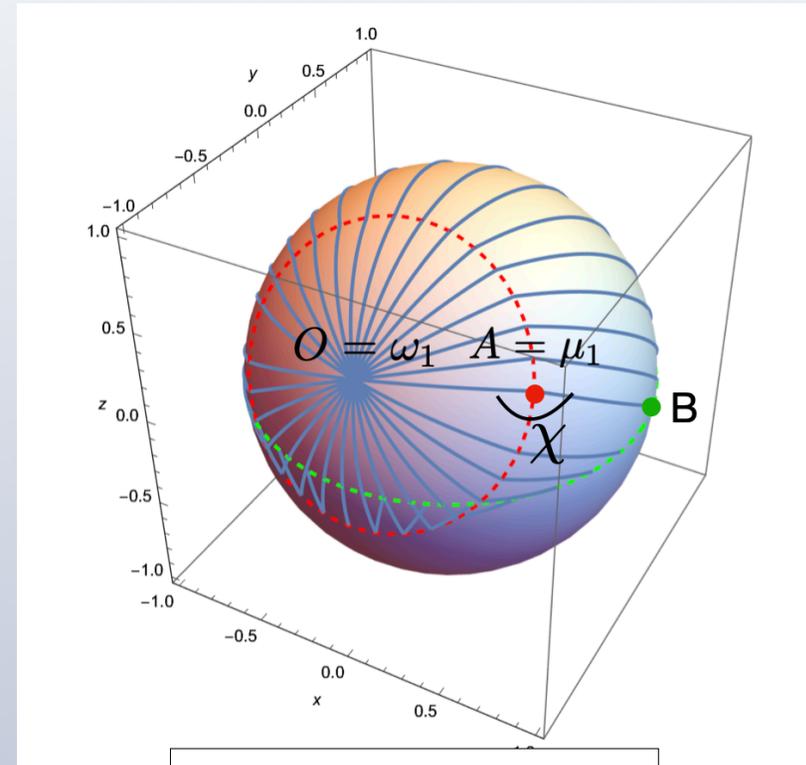


X-spin



Topology of magnetically coupled stars

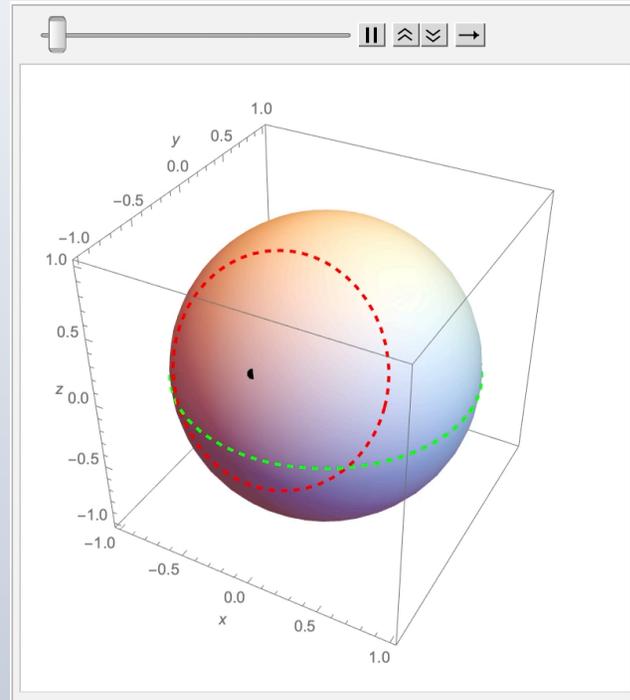
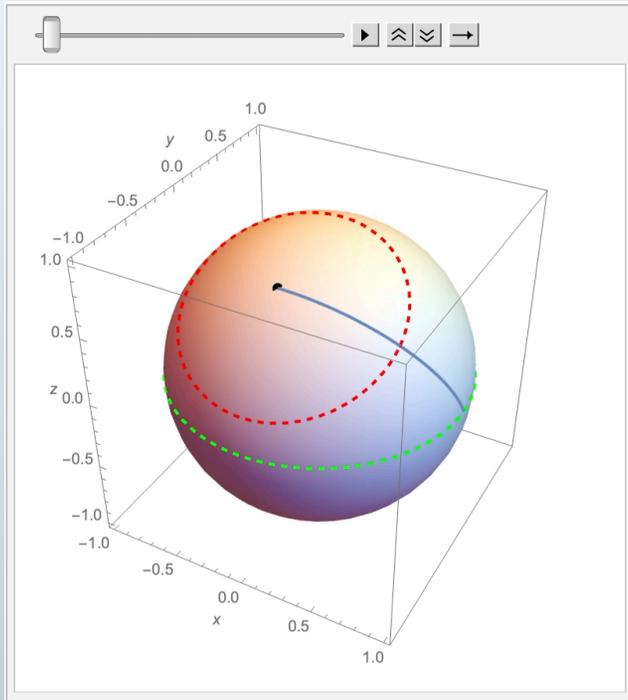
- Direction of B-field from #1 to #2: a path on 2-sphere
- Curl B is not important: each hair in a braid can be twisted: we are for **braiding**
- Need to track 3 points on the 2-sphere of B-direction to define braiding.



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

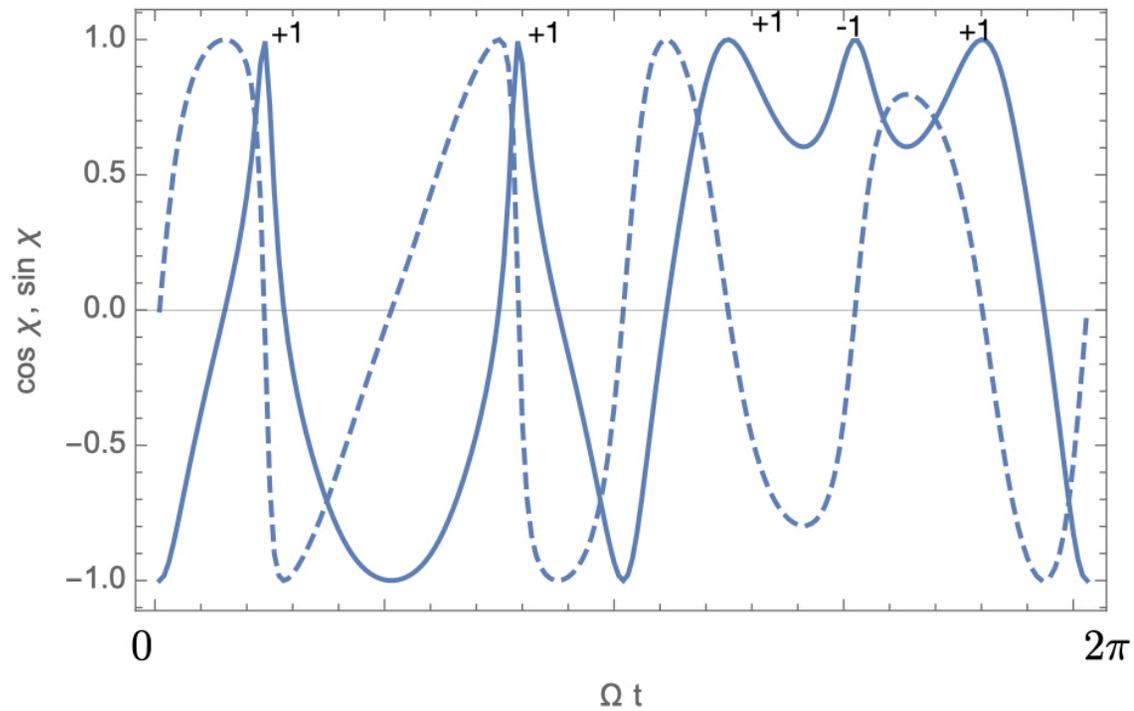
cut in the middle

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)

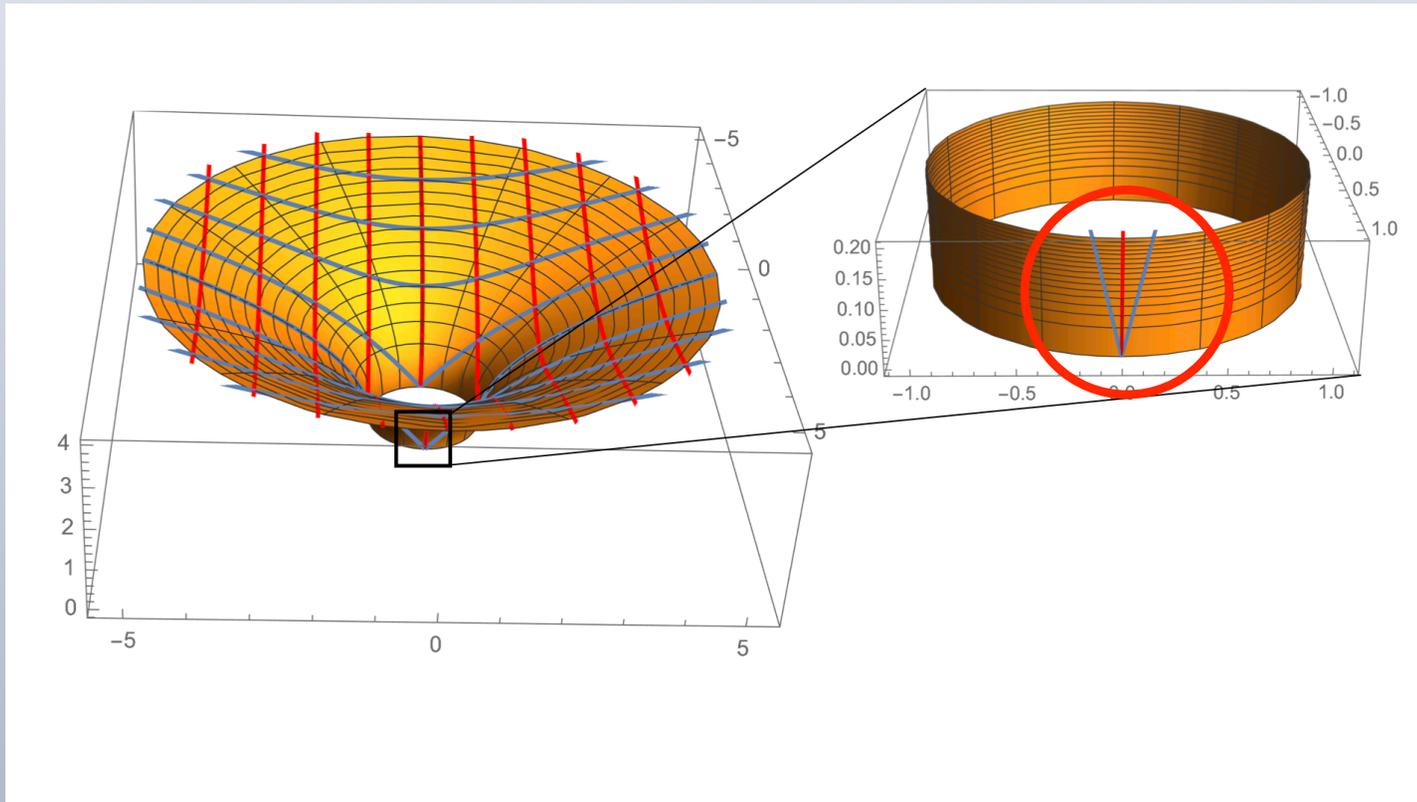
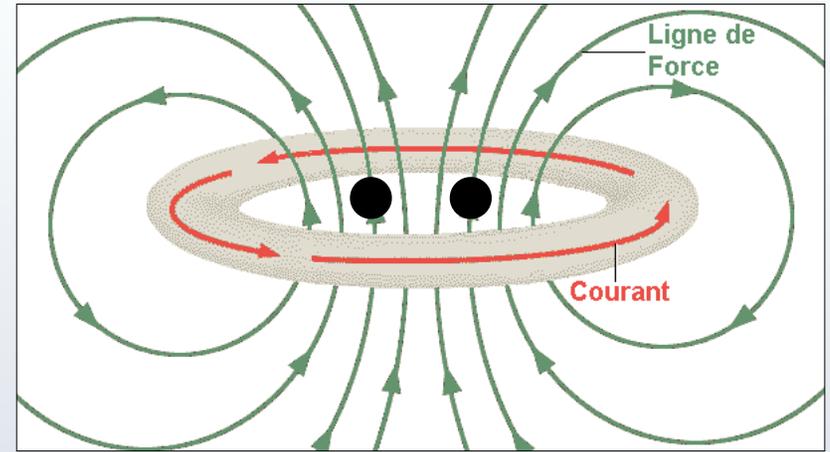
$$L_{B,c} = \frac{E_{B,c}}{r/c} = 10^{-1} \frac{B_{NS}^2 c R_{NS}^4 \omega^{4/3}}{(GM_{NS})^{2/3}} = 3 \times 10^{44} B_{12}^2 P_{s,-2}^{-4/3} \text{ erg s}^{-1}$$

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

BH-NS magnetospheric interactions
are inherently dissipative

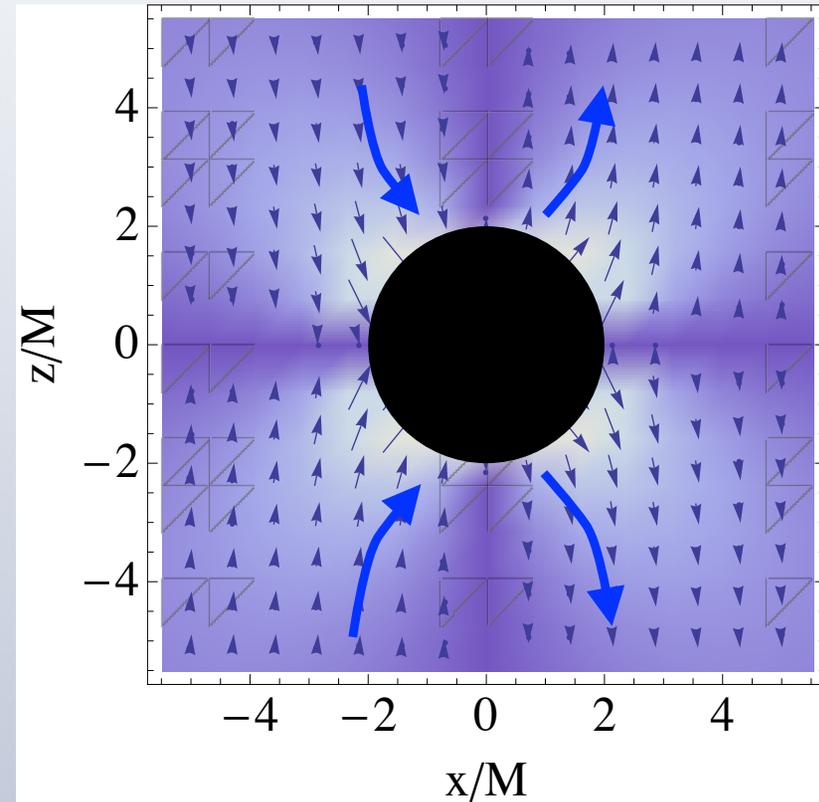
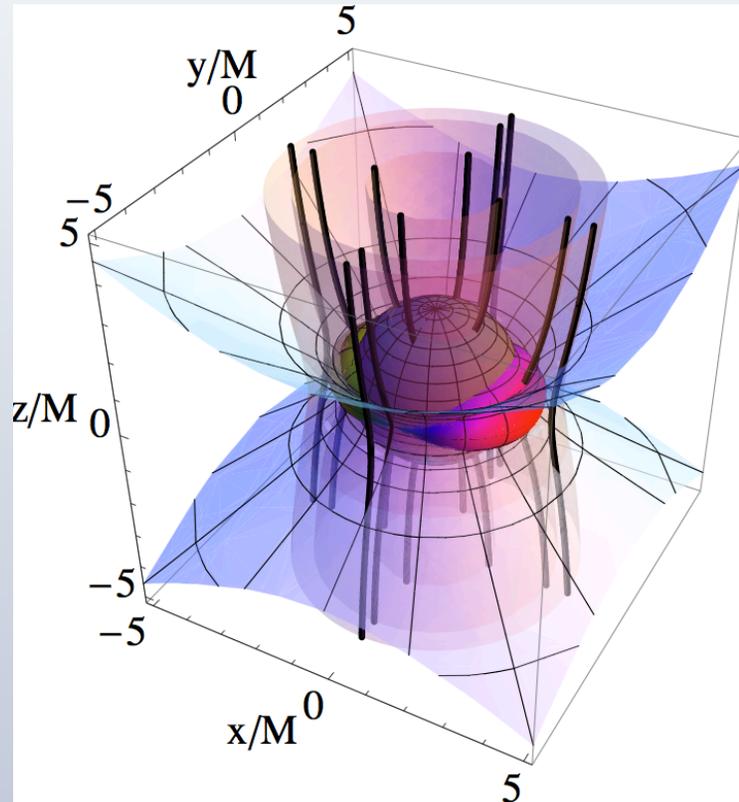
(and surprisingly, are expected to look similar
to single magnetized NS-NS)

A Schwarzschild BH
moving across B-field
generates
 $E \cdot B \neq 0$ and EM wind



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

Lyutikov 2011



$$I \sim \beta_0 M B_0$$

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

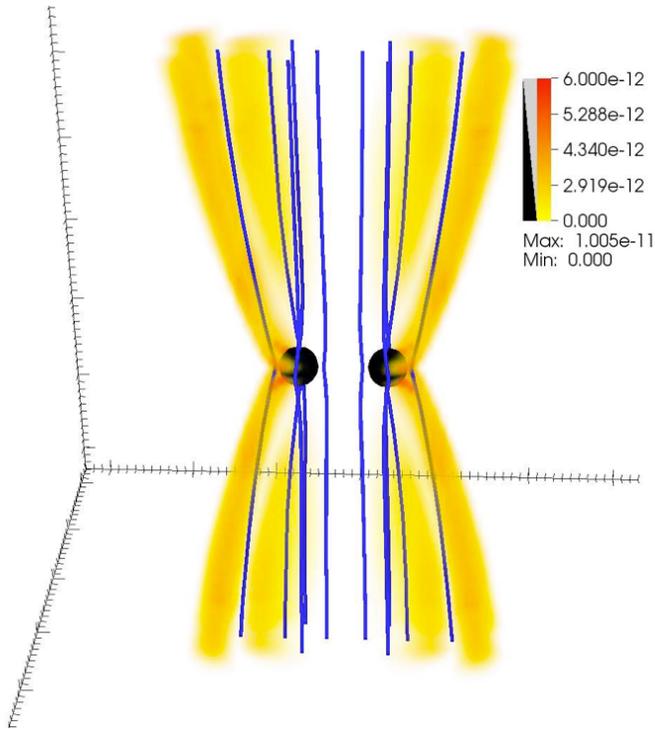
$$L_{EM,u} = \frac{(GM)^3 B_0^2}{c^5 R}$$

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 Alfvén wings - is surprising.
- ~ Membrane paradigm: BH is a bad conductor

Simulations

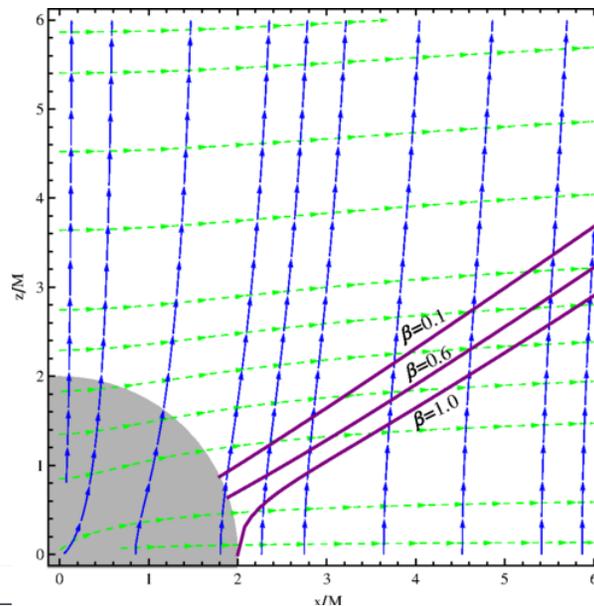
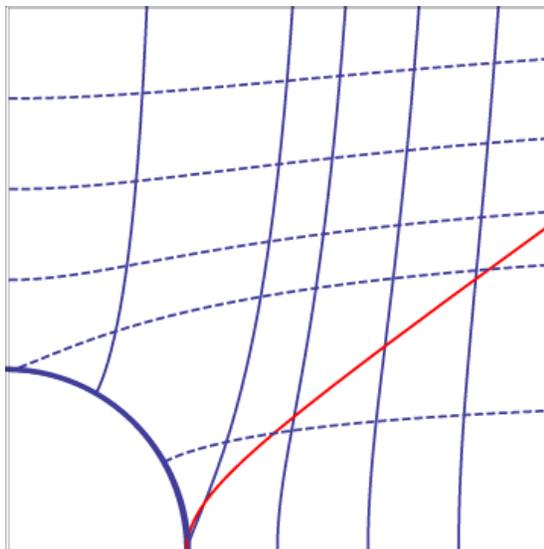
Charge density for head-on collision of two BH
Palenzuela et al



Morozova + 2013
spinning BH moving through B-field

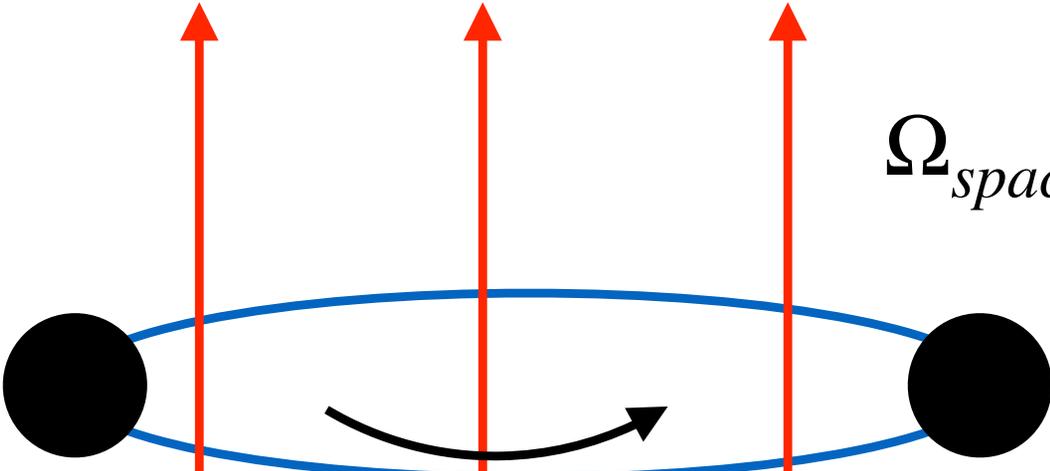
$$L = (c_1 \beta^2 + c_2 a^2) B^2 M^2$$

Rotation + linear motion



Two BHs in B-field

Lyutikov 2010


$$\Omega_{space} \sim \frac{(GM)^{3/2}}{c^2 R^{5/2}}$$
$$L_{EM} \sim \frac{(GM)^3}{c^5 R} B^2 \approx 10^{39} \text{ erg s}^{-1} b_3^2 m_6^2 (R_G/R)$$
$$E_{EM} \sim 10^{42-44} \text{ erg}$$

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

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

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

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

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

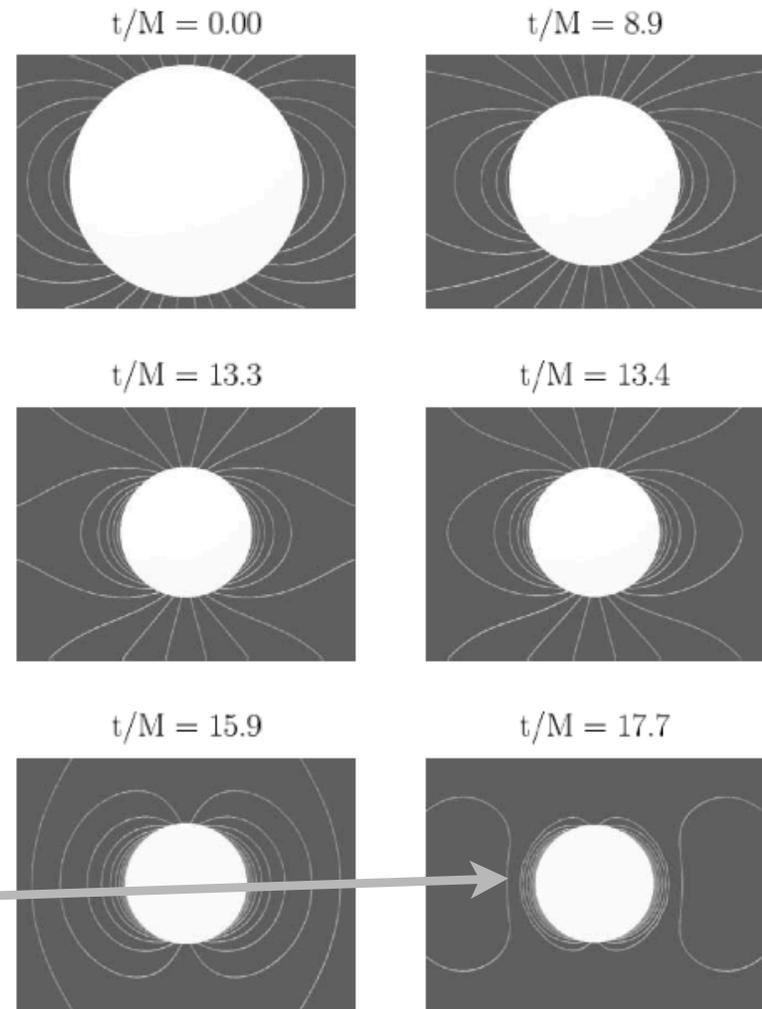
$$\Omega_H \approx \frac{\chi}{5} \frac{c^4 R_{NS}^2}{(GM_{NS})^2} \Omega_{NS} = 2.9 \times 10^3 \text{ rads}^{-1} \chi_{-1} P_{NS,-3}^{-1}$$

- $a = 0.04$ 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

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

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

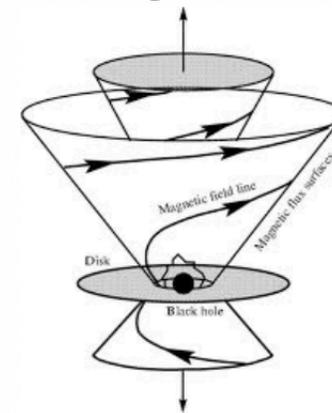
- Analytics: time-dependent B-field in Schwarzschild geom.

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

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

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

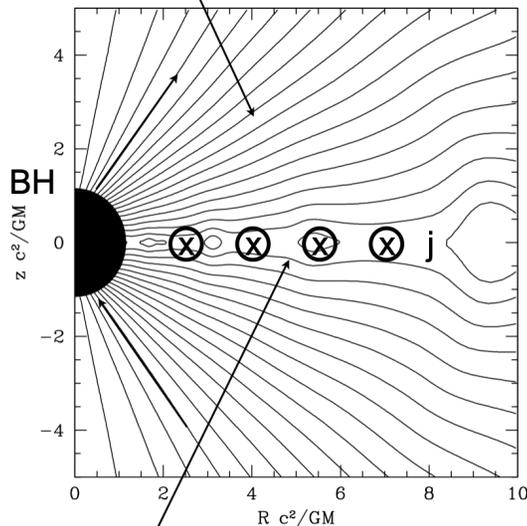
- Nonlinear, time-dependent solution in GR (small α)



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

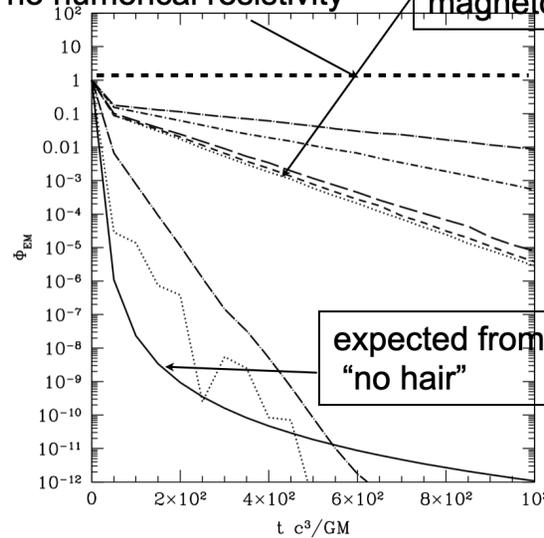
Slowly balding black holes, (Lyutikov and McKinney 2011)

Fields are NOT anchored
in heavy crust

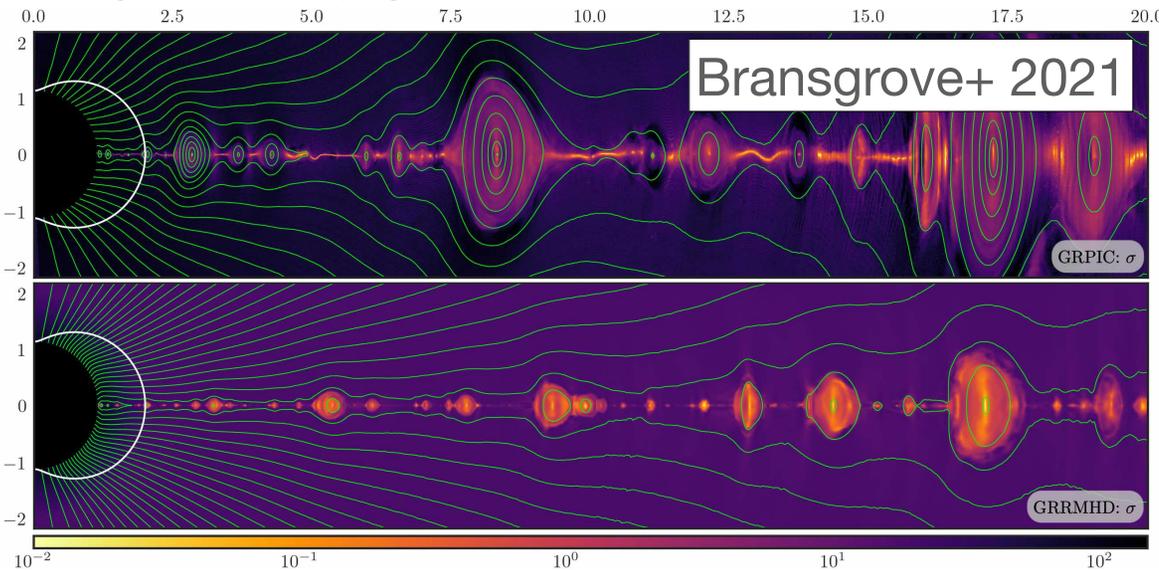


Tearing mode developing

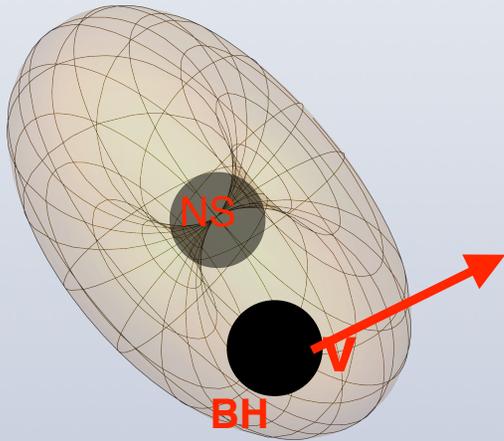
Expected for
no numerical resistivity



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

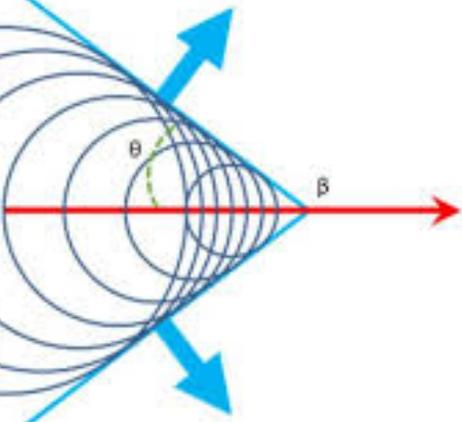
First example (?) of classical (not π^0), truly charge-neutral “particle” producing EM radiation

Cherenkov emission

- $\omega - k_{\parallel} v_{\parallel} = 0 \rightarrow \omega' = 0$ - in particle's frame radiation field is stationary
- In quantum language:

$$0 = mv_{recoil}^2/2 + \hbar\omega - ???$$

polarization shock front



Tamm & Frank, 1947

Доклады Академии Наук СССР
1947, т. XIV, № 1

ФИЗИКА

И. Е. ТАММ, аспирант Академии Наук СССР, и М. М. ФРАНК

КОГЕРЕНТНОЕ ИЗЛУЧЕНИЕ БЫСТРОГО ЭЛЕКТРОНА В СРЕДЕ

рими и распространяющихся со скоростью $\frac{c}{n}$. Легко видеть, что в направлении, образующем угол θ с осью z , или от перпендикулярности плоскостей волны будет иметь одинаковые фазы, если только ϵ и n удовлетворяют условиям:

$$\frac{c}{v} = \epsilon \cos \theta, \quad \sin \theta = \frac{1}{n}. \quad (1)$$

где $\theta = \frac{c}{v} - \frac{1}{n}$. Эти распространяющиеся в фазе волны обуславливают излучение в направлении θ , и во время полета для точек друг друга направленной радиации увеличивается интерференционной волна.

Условие (1) может быть выполнено только, если $\beta > \frac{1}{n}$, т. е. только в случае быстрого электрона и только в среде, в которой показатель преломления для рассматриваемых частот заметно больше единицы. Например, если $n = 1.55$ (вода, $\lambda = 5000 \text{ \AA}$), то электронная скорость не может быть меньше 200 КВ. Если же $\beta > \frac{1}{n}$, то равномерно движущийся электрон всегда излучает свет в направлении θ .

Перейдем к рассмотрению более детальной теории. Так как в данном случае мы имеем дело только с излучением, то сразу можно рассмотреть излучение, применив для этого обычные уравнения электродинамики. Поскольку, однако, существуют соотношения между поляризациями P и ϵ (электронной газой E):

$$\frac{\partial^2 P}{\partial t^2} + \sum_{\alpha} \nu_{\alpha} P_{\alpha} = \epsilon E,$$

где ν_{α} — собственные частоты молекулярных осцилляторов среды, и разлагаем все переменные, характеризующие поле, в интегралы Фурье:

$$E = \int K_{\omega} e^{i\omega t} d\omega; \quad P = \int P_{\omega} e^{i\omega t} d\omega \text{ и т. д.} \quad (2)$$

Для соотношения между P_{ω} и K_{ω} имеем:

$$P_{\omega} = (\epsilon^2 - 1) K_{\omega}, \quad (3)$$

где ϵ и ϵ^2 означают показатель преломления среды для частоты ω . С помощью (2) и (3) уравнения Максвелла приводятся к следующему виду:

$$\text{grad div } A_{\omega} - \Delta A_{\omega} = -\frac{4\pi}{c} A_{\omega} \text{ и } -\frac{4\pi}{c} A_{\omega} \text{ и т. д.} \quad (4)$$

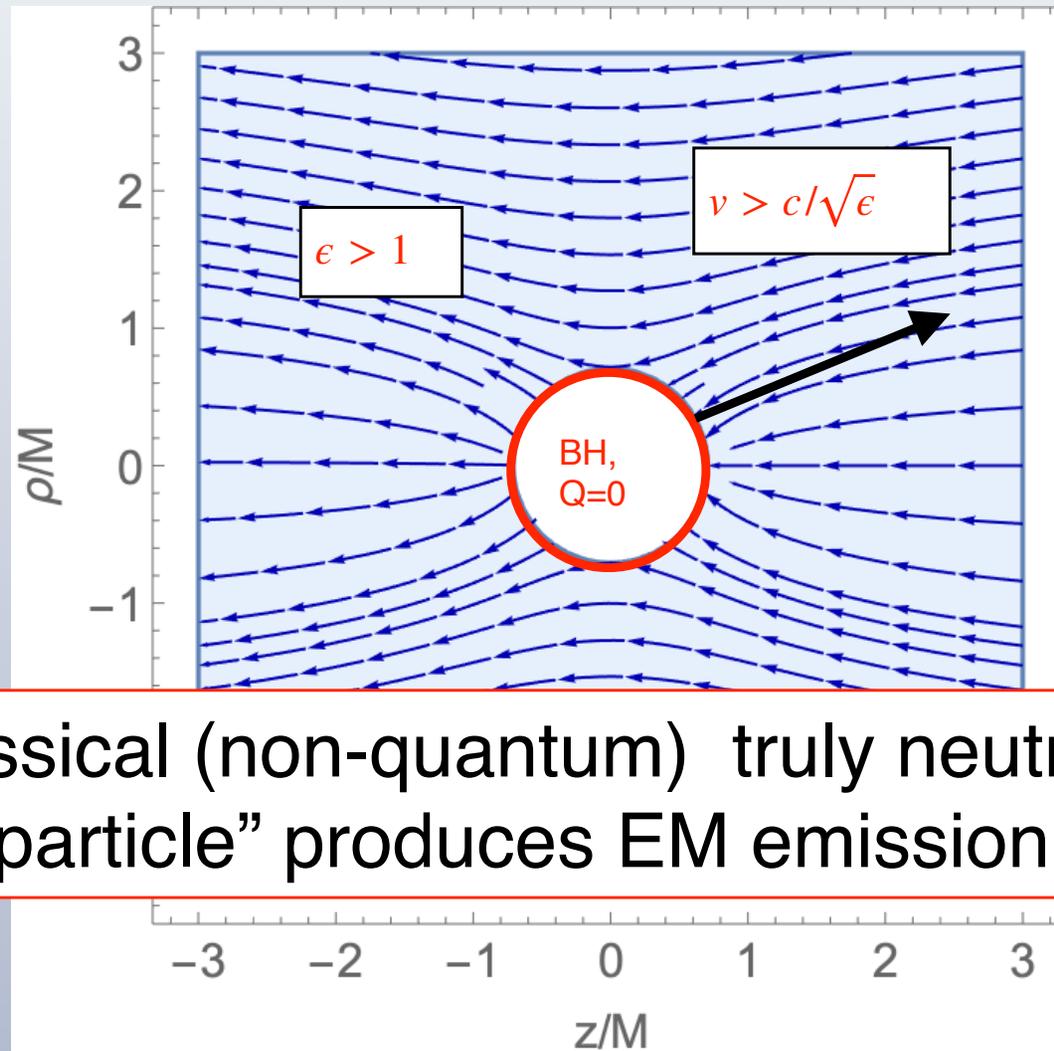
причем наложение ϵ на уравнения для K_{ω} приводит нас к известным соотношениям между скалярными и векторными потенциалами:

$$\Delta V_{\omega} + \epsilon^2 \Delta A_{\omega} = 0.$$

Электрон, движущийся в среде со скоростью v и постоянной скоростью ω , соответствует потенциалы типа $f_{\omega} e^{i\omega t - i k_{\parallel} z}$, где $k_{\parallel} = \frac{\omega}{v} - \frac{1}{n}$, $k_{\perp} = \frac{\omega}{c} \sqrt{1 - \frac{v^2}{c^2}}$ и $\epsilon = \epsilon(\omega)$ (1) (2) (3) (4) (5) (6) (7) (8) (9) (10) (11) (12) (13) (14) (15) (16) (17) (18) (19) (20) (21) (22) (23) (24) (25) (26) (27) (28) (29) (30) (31) (32) (33) (34) (35) (36) (37) (38) (39) (40) (41) (42) (43) (44) (45) (46) (47) (48) (49) (50) (51) (52) (53) (54) (55) (56) (57) (58) (59) (60) (61) (62) (63) (64) (65) (66) (67) (68) (69) (70) (71) (72) (73) (74) (75) (76) (77) (78) (79) (80) (81) (82) (83) (84) (85) (86) (87) (88) (89) (90) (91) (92) (93) (94) (95) (96) (97) (98) (99) (100) (101) (102) (103) (104) (105) (106) (107) (108) (109) (110) (111) (112) (113) (114) (115) (116) (117) (118) (119) (120) (121) (122) (123) (124) (125) (126) (127) (128) (129) (130) (131) (132) (133) (134) (135) (136) (137) (138) (139) (140) (141) (142) (143) (144) (145) (146) (147) (148) (149) (150) (151) (152) (153) (154) (155) (156) (157) (158) (159) (160) (161) (162) (163) (164) (165) (166) (167) (168) (169) (170) (171) (172) (173) (174) (175) (176) (177) (178) (179) (180) (181) (182) (183) (184) (185) (186) (187) (188) (189) (190) (191) (192) (193) (194) (195) (196) (197) (198) (199) (200) (201) (202) (203) (204) (205) (206) (207) (208) (209) (210) (211) (212) (213) (214) (215) (216) (217) (218) (219) (220) (221) (222) (223) (224) (225) (226) (227) (228) (229) (230) (231) (232) (233) (234) (235) (236) (237) (238) (239) (240) (241) (242) (243) (244) (245) (246) (247) (248) (249) (250) (251) (252) (253) (254) (255) (256) (257) (258) (259) (260) (261) (262) (263) (264) (265) (266) (267) (268) (269) (270) (271) (272) (273) (274) (275) (276) (277) (278) (279) (280) (281) (282) (283) (284) (285) (286) (287) (288) (289) (290) (291) (292) (293) (294) (295) (296) (297) (298) (299) (300) (301) (302) (303) (304) (305) (306) (307) (308) (309) (310) (311) (312) (313) (314) (315) (316) (317) (318) (319) (320) (321) (322) (323) (324) (325) (326) (327) (328) (329) (330) (331) (332) (333) (334) (335) (336) (337) (338) (339) (340) (341) (342) (343) (344) (345) (346) (347) (348) (349) (350) (351) (352) (353) (354) (355) (356) (357) (358) (359) (360) (361) (362) (363) (364) (365) (366) (367) (368) (369) (370) (371) (372) (373) (374) (375) (376) (377) (378) (379) (380) (381) (382) (383) (384) (385) (386) (387) (388) (389) (390) (391) (392) (393) (394) (395) (396) (397) (398) (399) (400) (401) (402) (403) (404) (405) (406) (407) (408) (409) (410) (411) (412) (413) (414) (415) (416) (417) (418) (419) (420) (421) (422) (423) (424) (425) (426) (427) (428) (429) (430) (431) (432) (433) (434) (435) (436) (437) (438) (439) (440) (441) (442) (443) (444) (445) (446) (447) (448) (449) (450) (451) (452) (453) (454) (455) (456) (457) (458) (459) (460) (461) (462) (463) (464) (465) (466) (467) (468) (469) (470) (471) (472) (473) (474) (475) (476) (477) (478) (479) (480) (481) (482) (483) (484) (485) (486) (487) (488) (489) (490) (491) (492) (493) (494) (495) (496) (497) (498) (499) (500) (501) (502) (503) (504) (505) (506) (507) (508) (509) (510) (511) (512) (513) (514) (515) (516) (517) (518) (519) (520) (521) (522) (523) (524) (525) (526) (527) (528) (529) (530) (531) (532) (533) (534) (535) (536) (537) (538) (539) (540) (541) (542) (543) (544) (545) (546) (547) (548) (549) (550) (551) (552) (553) (554) (555) (556) (557) (558) (559) (560) (561) (562) (563) (564) (565) (566) (567) (568) (569) (570) (571) (572) (573) (574) (575) (576) (577) (578) (579) (580) (581) (582) (583) (584) (585) (586) (587) (588) (589) (590) (591) (592) (593) (594) (595) (596) (597) (598) (599) (600) (601) (602) (603) (604) (605) (606) (607) (608) (609) (610) (611) (612) (613) (614) (615) (616) (617) (618) (619) (620) (621) (622) (623) (624) (625) (626) (627) (628) (629) (630) (631) (632) (633) (634) (635) (636) (637) (638) (639) (640) (641) (642) (643) (644) (645) (646) (647) (648) (649) (650) (651) (652) (653) (654) (655) (656) (657) (658) (659) (660) (661) (662) (663) (664) (665) (666) (667) (668) (669) (670) (671) (672) (673) (674) (675) (676) (677) (678) (679) (680) (681) (682) (683) (684) (685) (686) (687) (688) (689) (690) (691) (692) (693) (694) (695) (696) (697) (698) (699) (700) (701) (702) (703) (704) (705) (706) (707) (708) (709) (710) (711) (712) (713) (714) (715) (716) (717) (718) (719) (720) (721) (722) (723) (724) (725) (726) (727) (728) (729) (730) (731) (732) (733) (734) (735) (736) (737) (738) (739) (740) (741) (742) (743) (744) (745) (746) (747) (748) (749) (750) (751) (752) (753) (754) (755) (756) (757) (758) (759) (760) (761) (762) (763) (764) (765) (766) (767) (768) (769) (770) (771) (772) (773) (774) (775) (776) (777) (778) (779) (780) (781) (782) (783) (784) (785) (786) (787) (788) (789) (790) (791) (792) (793) (794) (795) (796) (797) (798) (799) (800) (801) (802) (803) (804) (805) (806) (807) (808) (809) (810) (811) (812) (813) (814) (815) (816) (817) (818) (819) (820) (821) (822) (823) (824) (825) (826) (827) (828) (829) (830) (831) (832) (833) (834) (835) (836) (837) (838) (839) (840) (841) (842) (843) (844) (845) (846) (847) (848) (849) (850) (851) (852) (853) (854) (855) (856) (857) (858) (859) (860) (861) (862) (863) (864) (865) (866) (867) (868) (869) (870) (871) (872) (873) (874) (875) (876) (877) (878) (879) (880) (881) (882) (883) (884) (885) (886) (887) (888) (889) (890) (891) (892) (893) (894) (895) (896) (897) (898) (899) (900) (901) (902) (903) (904) (905) (906) (907) (908) (909) (910) (911) (912) (913) (914) (915) (916) (917) (918) (919) (920) (921) (922) (923) (924) (925) (926) (927) (928) (929) (930) (931) (932) (933) (934) (935) (936) (937) (938) (939) (940) (941) (942) (943) (944) (945) (946) (947) (948) (949) (950) (951) (952) (953) (954) (955) (956) (957) (958) (959) (960) (961) (962) (963) (964) (965) (966) (967) (968) (969) (970) (971) (972) (973) (974) (975) (976) (977) (978) (979) (980) (981) (982) (983) (984) (985) (986) (987) (988) (989) (990) (991) (992) (993) (994) (995) (996) (997) (998) (999) (1000) (1001) (1002) (1003) (1004) (1005) (1006) (1007) (1008) (1009) (1010) (1011) (1012) (1013) (1014) (1015) (1016) (1017) (1018) (1019) (1020) (1021) (1022) (1023) (1024) (1025) (1026) (1027) (1028) (1029) (1030) (1031) (1032) (1033) (1034) (1035) (1036) (1037) (1038) (1039) (1040) (1041) (1042) (1043) (1044) (1045) (1046) (1047) (1048) (1049) (1050) (1051) (1052) (1053) (1054) (1055) (1056) (1057) (1058) (1059) (1060) (1061) (1062) (1063) (1064) (1065) (1066) (1067) (1068) (1069) (1070) (1071) (1072) (1073) (1074) (1075) (1076) (1077) (1078) (1079) (1080) (1081) (1082) (1083) (1084) (1085) (1086) (1087) (1088) (1089) (1090) (1091) (1092) (1093) (1094) (1095) (1096) (1097) (1098) (1099) (1100) (1101) (1102) (1103) (1104) (1105) (1106) (1107) (1108) (1109) (1110) (1111) (1112) (1113) (1114) (1115) (1116) (1117) (1118) (1119) (1120) (1121) (1122) (1123) (1124) (1125) (1126) (1127) (1128) (1129) (1130) (1131) (1132) (1133) (1134) (1135) (1136) (1137) (1138) (1139) (1140) (1141) (1142) (1143) (1144) (1145) (1146) (1147) (1148) (1149) (1150) (1151) (1152) (1153) (1154) (1155) (1156) (1157) (1158) (1159) (1160) (1161) (1162) (1163) (1164) (1165) (1166) (1167) (1168) (1169) (1170) (1171) (1172) (1173) (1174) (1175) (1176) (1177) (1178) (1179) (1180) (1181) (1182) (1183) (1184) (1185) (1186) (1187) (1188) (1189) (1190) (1191) (1192) (1193) (1194) (1195) (1196) (1197) (1198) (1199) (1200) (1201) (1202) (1203) (1204) (1205) (1206) (1207) (1208) (1209) (1210) (1211) (1212) (1213) (1214) (1215) (1216) (1217) (1218) (1219) (1220) (1221) (1222) (1223) (1224) (1225) (1226) (1227) (1228) (1229) (1230) (1231) (1232) (1233) (1234) (1235) (1236) (1237) (1238) (1239) (1240) (1241) (1242) (1243) (1244) (1245) (1246) (1247) (1248) (1249) (1250) (1251) (1252) (1253) (1254) (1255) (1256) (1257) (1258) (1259) (1260) (1261) (1262) (1263) (1264) (1265) (1266) (1267) (1268) (1269) (1270) (1271) (1272) (1273) (1274) (1275) (1276) (1277) (1278) (1279) (1280) (1281) (1282) (1283) (1284) (1285) (1286) (1287) (1288) (1289) (1290) (1291) (1292) (1293) (1294) (1295) (1296) (1297) (1298) (1299) (1300) (1301) (1302) (1303) (1304) (1305) (1306) (1307) (1308) (1309) (1310) (1311) (1312) (1313) (1314) (1315) (1316) (1317) (1318) (1319) (1320) (1321) (1322) (1323) (1324) (1325) (1326) (1327) (1328) (1329) (1330) (1331) (1332) (1333) (1334) (1335) (1336) (1337) (1338) (1339) (1340) (1341) (1342) (1343) (1344) (1345) (1346) (1347) (1348) (1349) (1350) (1351) (1352) (1353) (1354) (1355) (1356) (1357) (1358) (1359) (1360) (1361) (1362) (1363) (1364) (1365) (1366) (1367) (1368) (1369) (1370) (1371) (1372) (1373) (1374) (1375) (1376) (1377) (1378) (1379) (1380) (1381) (1382) (1383) (1384) (1385) (1386) (1387) (1388) (1389) (1390) (1391) (1392) (1393) (1394) (1395) (1396) (1397) (1398) (1399) (1400) (1401) (1402) (1403) (1404) (1405) (1406) (1407) (1408) (1409) (1410) (1411) (1412) (1413) (1414) (1415) (1416) (1417) (1418) (1419) (1420) (1421) (1422) (1423) (1424) (1425) (1426) (1427) (1428) (1429) (1430) (1431) (1432) (1433) (1434) (1435) (1436) (1437) (1438) (1439) (1440) (1441) (1442) (1443) (1444) (1445) (1446) (1447) (1448) (1449) (1450) (1451) (1452) (1453) (1454) (1455) (1456) (1457) (1458) (1459) (1460) (1461) (1462) (1463) (1464) (1465) (1466) (1467) (1468) (1469) (1470) (1471) (1472) (1473) (1474) (1475) (1476) (1477) (1478) (1479) (1480) (1481) (1482) (1483) (1484) (1485) (1486) (1487) (1488) (1489) (1490) (1491) (1492) (1493) (1494) (1495) (1496) (1497) (1498) (1499) (1500) (1501) (1502) (1503) (1504) (1505) (1506) (1507) (1508) (1509) (1510) (1511) (1512) (1513) (1514) (1515) (1516) (1517) (1518) (1519) (1520) (1521) (1522) (1523) (1524) (1525) (1526) (1527) (1528) (1529) (1530) (1531) (1532) (1533) (1534) (1535) (1536) (1537) (1538) (1539) (1540) (1541) (1542) (1543) (1544) (1545) (1546) (1547) (1548) (1549) (1550) (1551) (1552) (1553) (1554) (1555) (1556) (1557) (1558) (1559) (1560) (1561) (1562) (1563) (1564) (1565) (1566) (1567) (1568) (1569) (1570) (1571) (1572) (1573) (1574) (1575) (1576) (1577) (1578) (1579) (1580) (1581) (1582) (1583) (1584) (1585) (1586) (1587) (1588) (1589) (1590) (1591) (1592) (1593) (1594) (1595) (1596) (1597) (1598) (1599) (1600) (1601) (1602) (1603) (1604) (1605) (1606) (1607) (1608) (1609) (1610) (1611) (1612) (1613) (1614) (1615) (1616) (1617) (1618) (1619) (1620) (1621) (1622) (1623) (1624) (1625) (1626) (1627) (1628) (1629) (1630) (1631) (1632) (1633) (1634) (1635) (1636) (1637) (1638) (1639) (1640) (1641) (1642) (1643) (1644) (1645) (1646) (1647) (1648) (1649) (1650) (1651) (1652) (1653) (1654) (1655) (1656) (1657) (1658) (1659) (1660) (1661) (1662) (1663) (1664) (1665) (1666) (1667) (1668) (1669) (1670) (1671) (1672) (1673) (1674) (1675) (1676) (1677) (1678) (1679) (1680) (1681) (1682) (1683) (1684) (1685) (1686) (1687) (1688) (1689) (1690) (1691) (1692) (1693) (1694) (1695) (1696) (1697) (1698) (1699) (1700) (1701) (1702) (1703) (1704) (1705) (1706) (1707) (1708) (1709) (1710) (1711) (1712) (1713) (1714) (1715) (1716) (1717) (1718) (1719) (1720) (1721) (1722) (1723) (1724) (1725) (1726) (1727) (1728) (1729) (1730) (1731) (1732) (1733) (1734) (1735) (1736) (1737) (1738) (1739) (1740) (1741) (1742) (1743) (1744) (1745) (1746) (1747) (1748) (1749) (1750) (1751) (1752) (1753) (1754) (1755) (1756) (1757) (1758) (1759) (1760) (1761) (1762) (1763) (1764) (1765) (1766) (1767) (1768) (1769) (1770) (1771) (1772) (1773) (1774) (1775) (1776) (1777) (1778) (1779) (1780) (1781) (1782) (1783) (1784) (1785) (1786) (1787) (1788) (1789) (1790) (1791) (1792) (1793) (1794) (1795) (1796) (1797) (1798) (1799) (1800) (1801) (1802) (1803) (1804) (1805) (1806) (1807) (1808) (1809) (1810) (1811) (1812) (1813) (1814) (1815) (1816) (1817) (1818) (1819) (1820) (1821) (1822) (1823) (1824) (1825) (1826) (1827) (1828) (1829) (1830) (1831) (1832) (1833) (1834) (1835) (1836) (1837) (1838) (1839) (1840) (1841) (1842) (1843) (1844) (1845) (1846) (1847) (1848) (1849) (1850) (1851) (1852) (1853) (1854) (1855) (1856) (1857) (1858) (1859) (1860) (1861) (1862) (1863) (1864) (1865) (1866) (1867) (1868) (1869) (1870) (1871) (1872) (1873) (1874) (1875) (1876) (1877) (1878) (1879) (1880) (1881) (1882) (1883) (1884) (1885) (1886) (1887) (1888) (1889) (1890) (1891) (1892) (

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

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
 - $(g^{\mu\nu} - (\epsilon - 1)u^\mu u^\nu) A_{\nu,\mu} = 0$ - separates polarization and dispersion
- choice of velocity field: “straight” motion

In isotropic coordinates (closest analogue of Cartesian)

- The only case of no emission: locally $\mathbf{v} \parallel \mathbf{B}$
- There is emission for \perp propagation,
- Effective source is **distributed**:

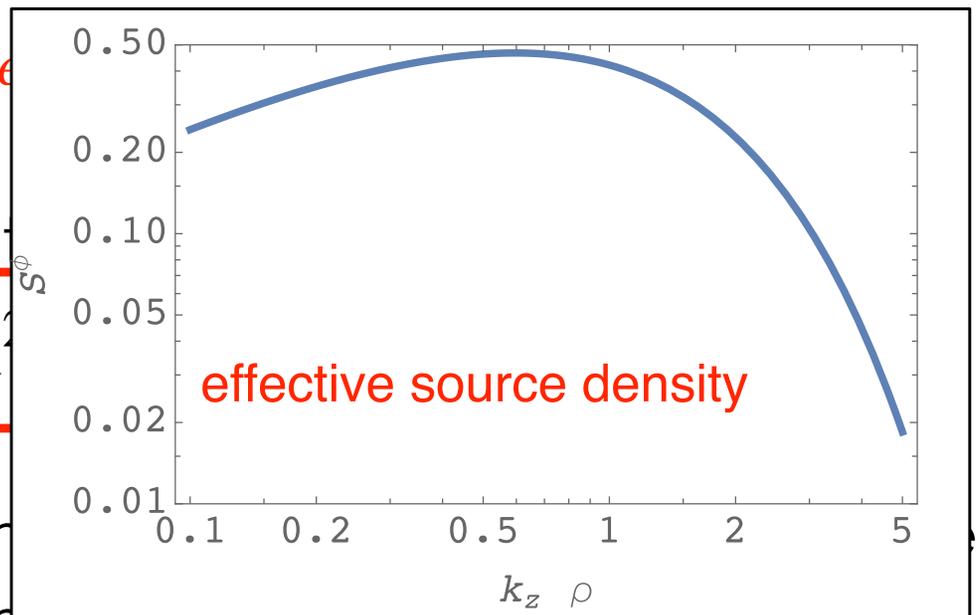
$$S^\phi = \frac{\rho (2z^2 - \rho^2)}{(\rho^2 + z^2)^{5/2}} \times MB_0 \beta^2 \gamma^2 (\epsilon)$$

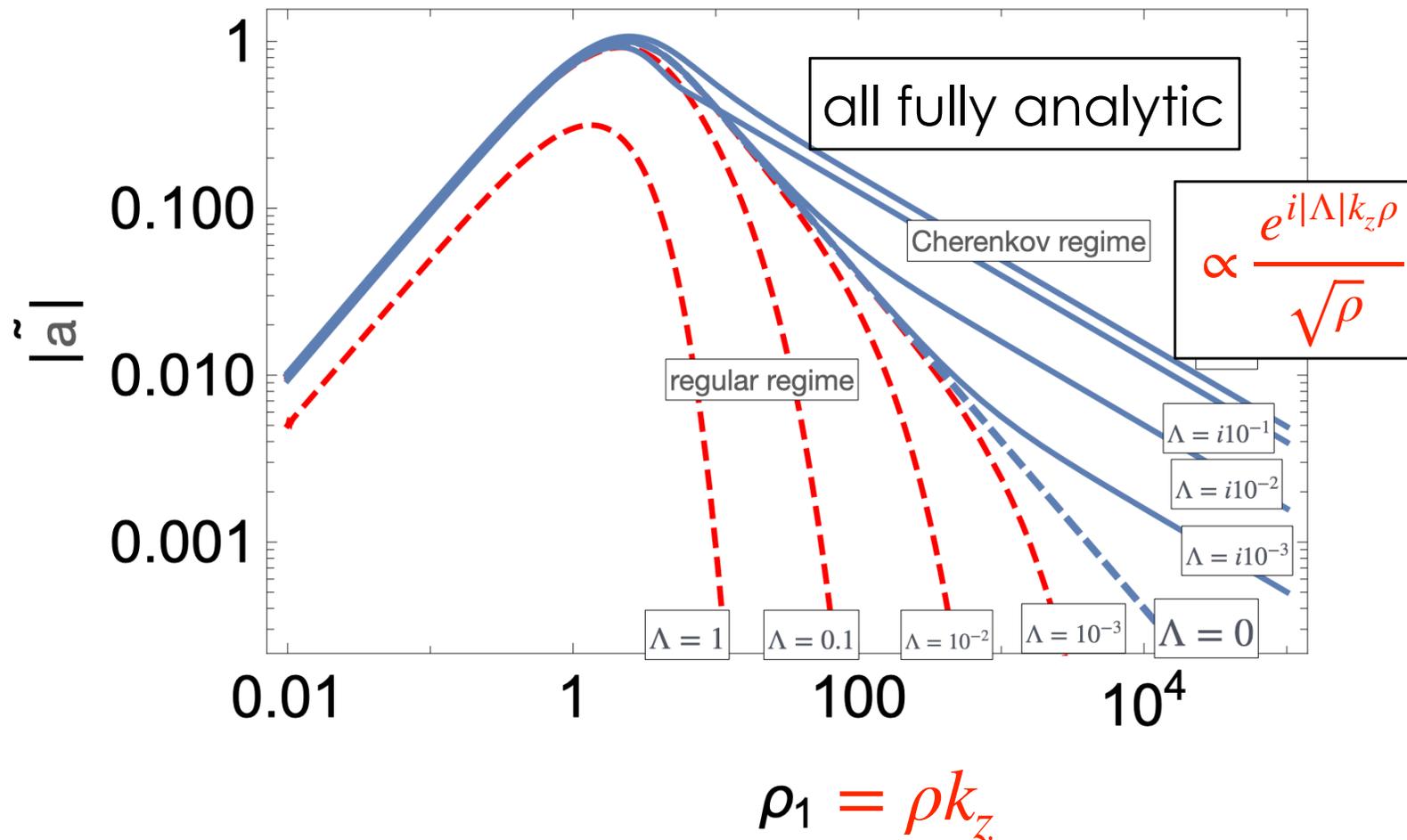
- different k_z are sourced at

- Cherenkov parameter: Λ
- Cherenkov regime

- $\delta A \propto K_1(\Lambda k_z \rho)$ - exponential decay of cylindrical wave in Cherenkov regime

- Causality: Landau-like rule (Laplace, not Fourier, for emission in complex k_z -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

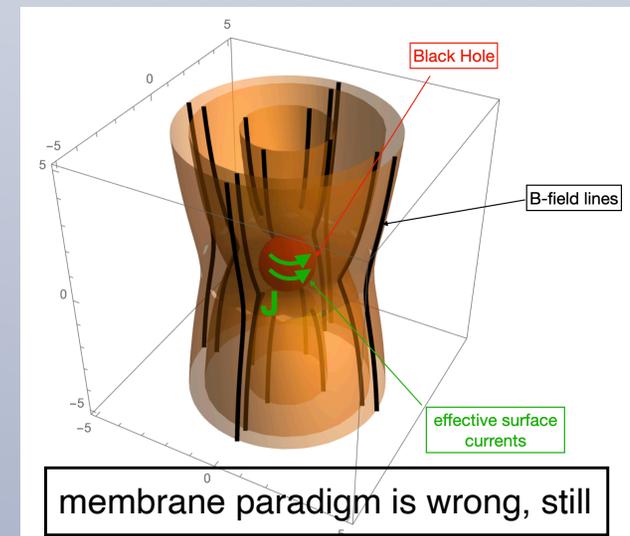
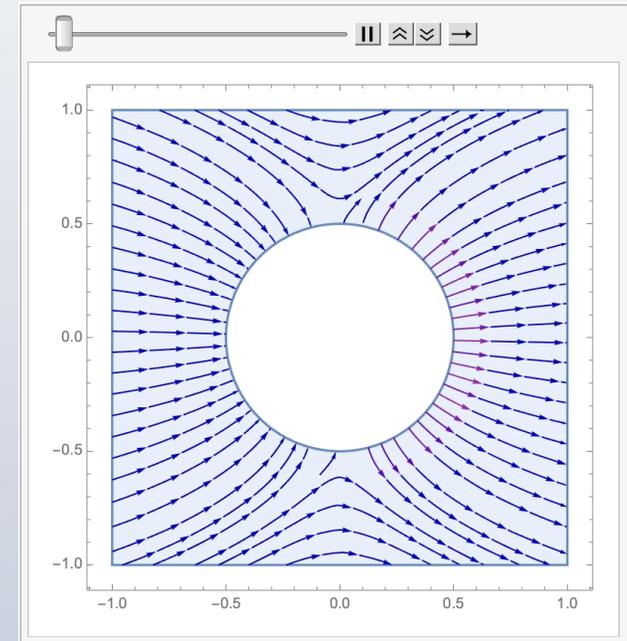
Another new cute effect: extra emission by BH evaporating in B-field:

- Time-dependent distortion of B-field by gravity: emission

$$L_B \approx B_0^2 R_g^2 c \frac{1}{(\tau_H \omega)^{2/3}} \frac{d\omega}{\omega}$$

$$\tau_H = \frac{5120\pi G^2 M_0^3}{c^4 \hbar} - \text{Hawking time}$$

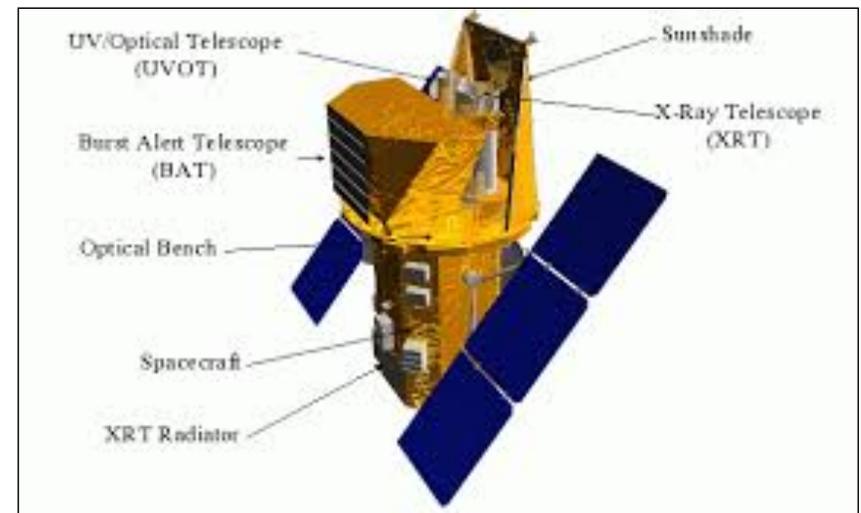
- What is the correct metric for evaporating BH?



Chances/strategies to detect precursors

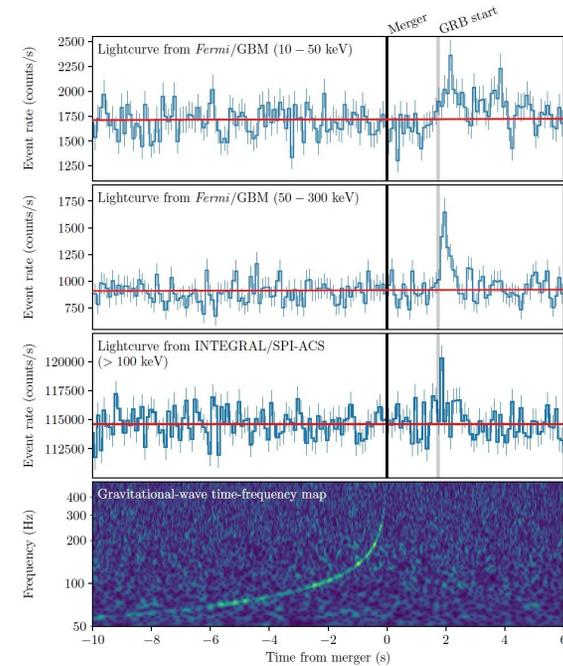
Do we have a chance to detect precursor emission?

- Bright (X-ray all-sky monitors): ≤ 10 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
 - $F_{\nu,peak} = 0.5 \text{ Jy} \eta_{R,-3} \nu_9^{-1} d_{200}^{-2}$
 - delayed by $\sim \Delta t = 14 \text{ sec} \nu_9^{-2} d_{200}$



5 RW Early Warning Response Capability



SWIFT GUANO: Fraction of sky BAT can cover as a function of latency

To do:

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

extra slides

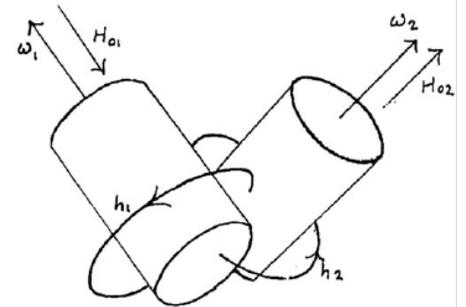
GW150914 and the EM signal

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

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

$$\Phi_B \sim B_{BH} R_{BH}^2$$

$$B_{BH} \sim 10^{12} \text{ G}$$



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...)

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

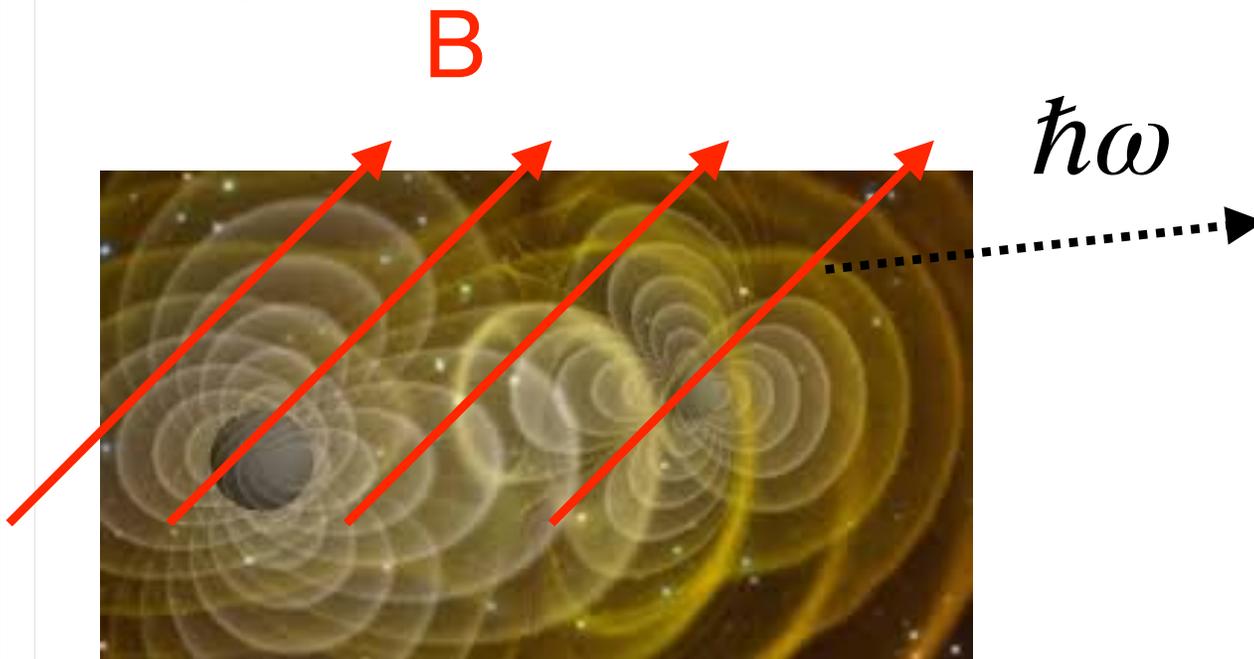
- Association of GW150914 with Fermi signal is unlikely.**
- N.B. A critically spinning BH in critical (Schwinger) B-field will have critical E-field, but inductive, **not** electrostatic. BH charge will be lost not by attraction of opposite charges, but by the loss of magnetic flux.

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 \rightarrow BH collapse



- $L_B \approx h_{+,x}^2 (B_0 R_g)^2 c = 5 \times 10^{46} \text{ erg s}^{-1} \times (h/0.1)^2 (B/B_Q)^2 (M/M_\odot)^2$

- $\frac{E_B}{E_{GW,1}} \approx \frac{B_0^2 R_g^3}{Mc^2} \sim 3 \times 10^{-12} (B/B_Q)^2 (M/M_\odot)^2$