Electromagnetic counterparts to loud gravitational wave events

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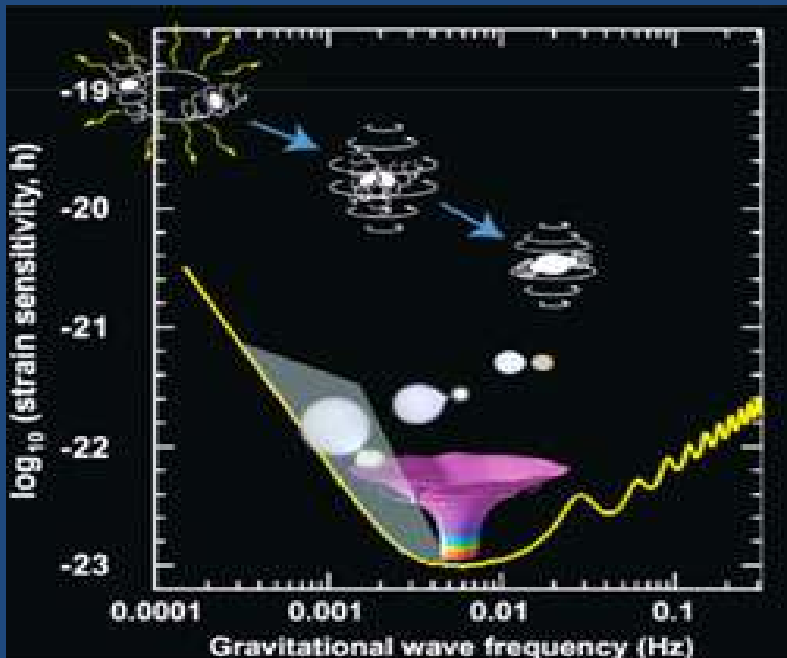
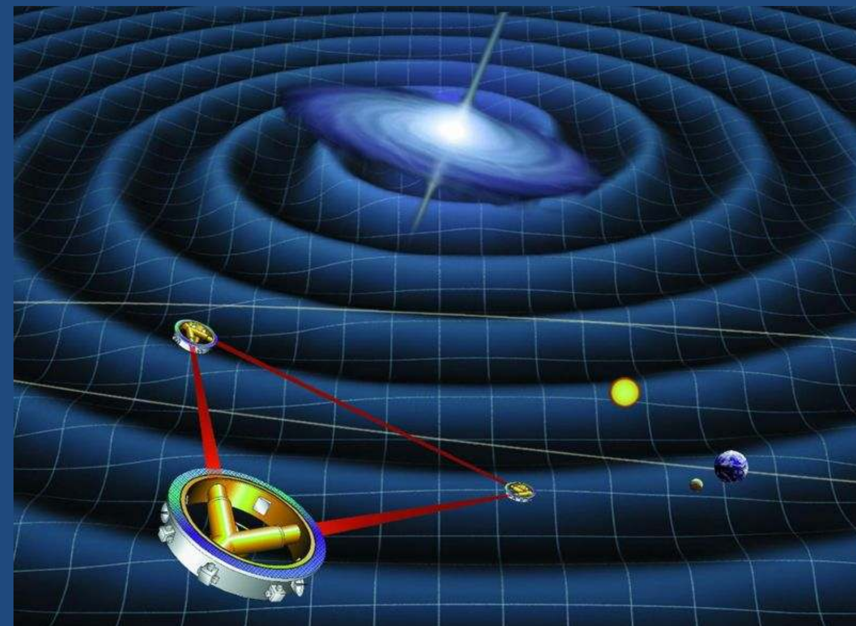
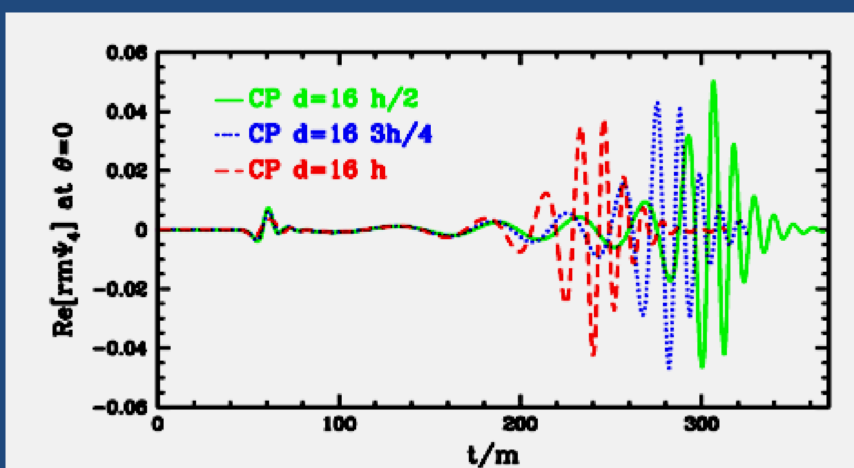
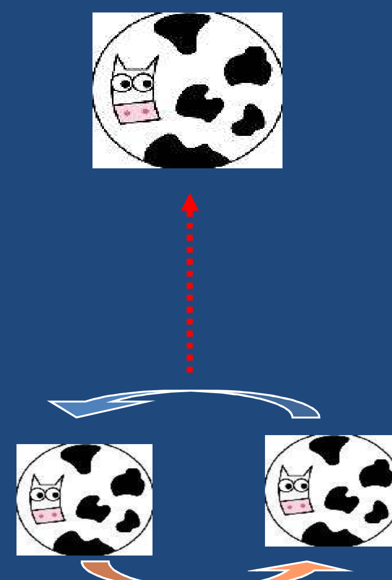
Driving goal I



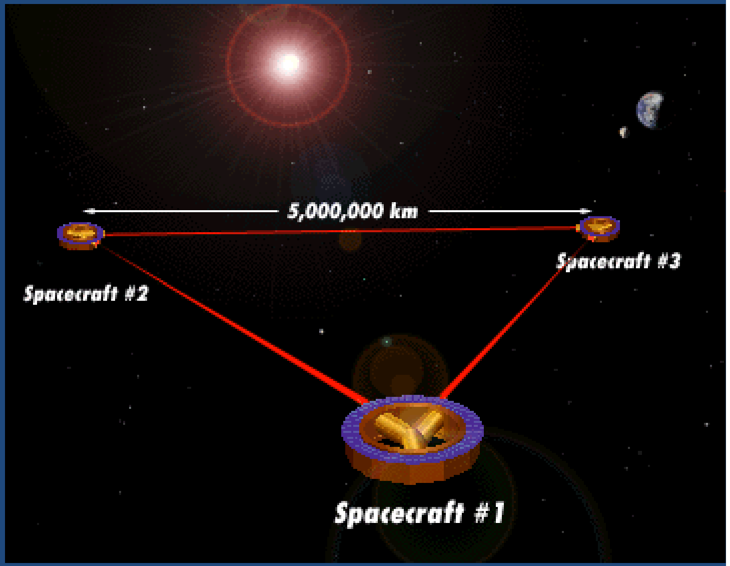






[Pretorius 05, …..]

Not so fast?



LISA: superb signal to noise ratio
[Phinney's, Baker's talks]

- waves will be ``seen'' directly and to very large redshifts (z~ 5-10 …)

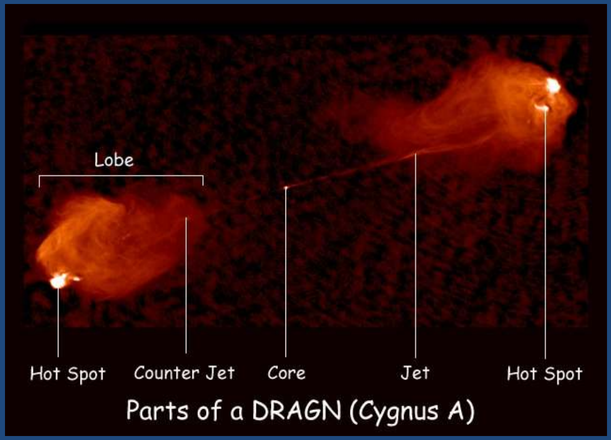
- Potential to do accurate astrophysics
- Potential to probe cosmology
- Potential to probe higher dimensional scenarios

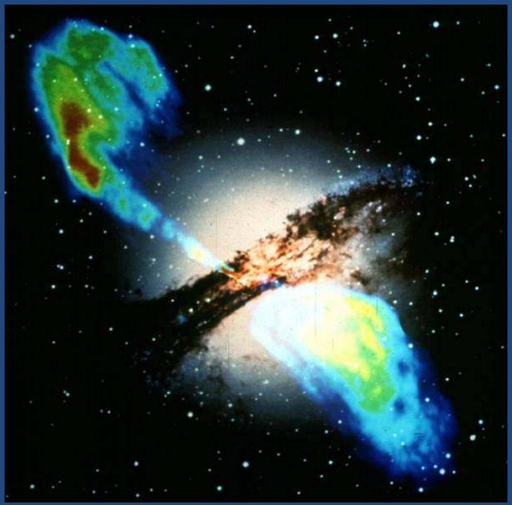
•However:
- localization to ~ square degrees [Cutler's talk; Holtz-Hughes]
- distance obtained is redshift dependent

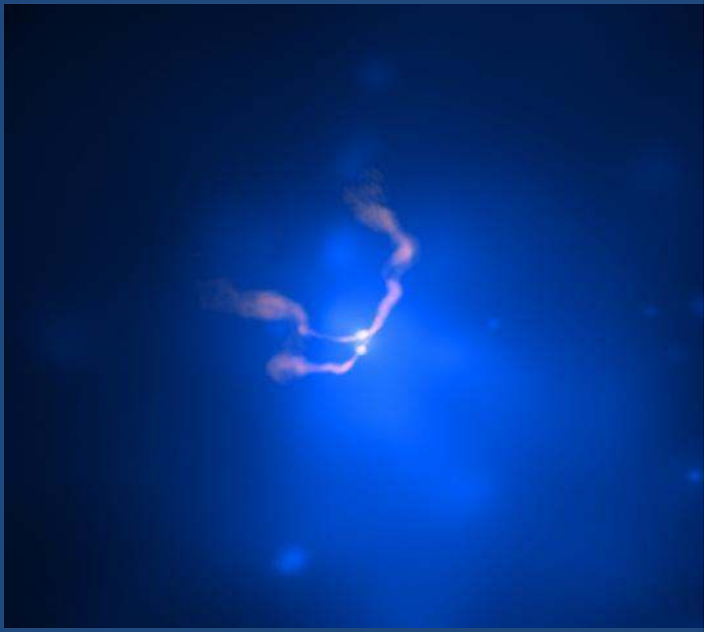
An electromagnetic counterpart resolve these issues

Nature cooperates…

- Understand both gravitational and electromagnetic wave emissions from key systems
  - Binary black holes interacting with surrounding media







10^{51} Ergs routinely inferred… even some 10^{61} ergs ?!

Studying relevant systems (BBH)

- Deal with spacetime curvature
  - Einstein equations. That's the 'solved' part! (ie… if you 'think' about it.. NR can give the answer)

- Black holes… are not really quite in vacuum…must deal with fields describing gas and electromagnetic fields
  - Poorly understood systems [we don't control the experiment]
  - Matter, what matter ?
  - Electromagnetic fields?
  - Emission process?

[Schnittman's talk]

Two fronts.

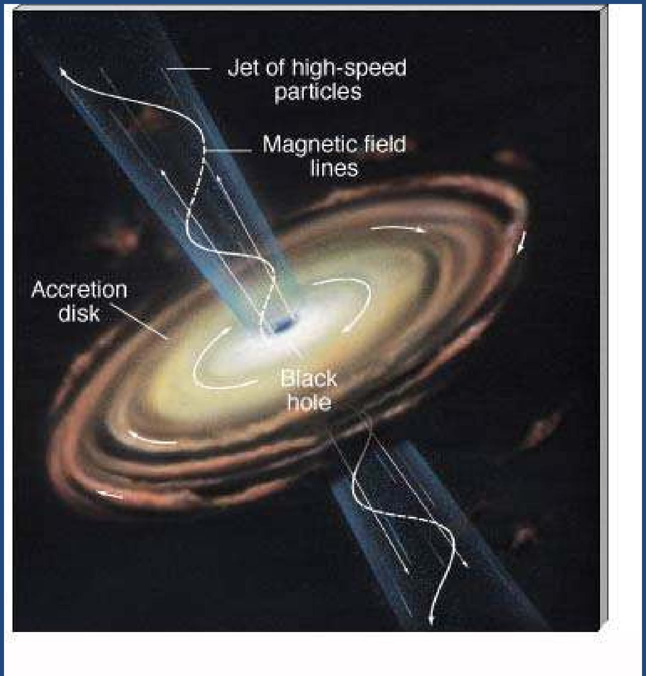
(circumbinary picture [complementary to Bogdanovic])

- Pre/prompt/post - merger emissions?
  - (pre/prompt) Binary black holes as EM field stirrers
  - (post) Binary black holes as bullies for matter

Merger of galaxies

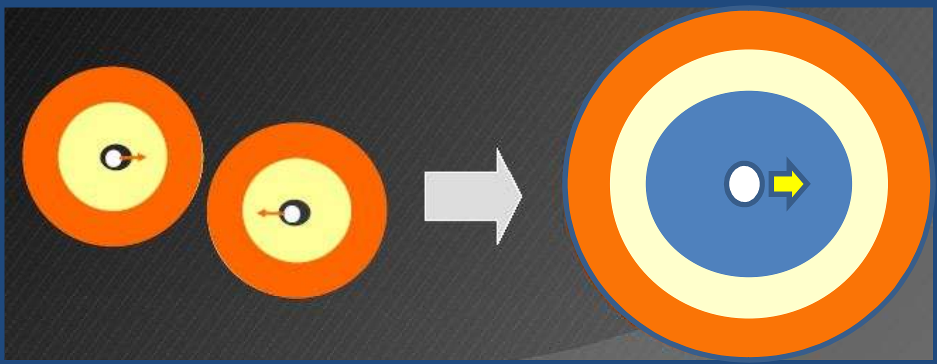
-observations indicate the presence of supermassive BHs in the center of galaxies, surrounded by gas and an accretion disk
- these galaxies have undergone mergers → binary black hole merger

- further, AGNs → BHs are surrounded by a disc of matter likely magnetized.



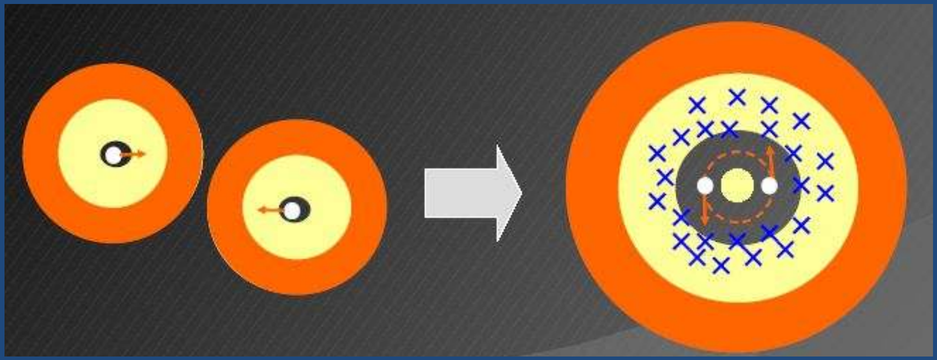
Binary black holes and emissions

- Different possible options.
  - Postmerger events from circumbinary disks around BHs



[Milosavljevic-Phinney;
Lipai-Loeb;
Lipai et.al,
Bonning et.al;
Bode et.al;
O'Neil et. al;
Megevand et.al;
Corrales et.al, etc.]

  - Pre/merger events from gas/plasmas in between BHs / torques on disk



[Armitage et.al;
MacFadyen et.al.;
Dotti et.al;
Chang. et.al.;
Palenzuela et.al.;
Bode et.al…]

After merger consequences

- Circumbinary disk ‘knows’ a merger takes places ‘after the fact’
  - ~ 5% energy radiated, most during last orbit: gravitational potential weakens ‘suddenly’
  - Recoil in a given direction

in both cases, the disk needs to readjust

Approach: GR+Hydrodynamics

- Einstein equations
  - Generalized Harmonic formulation: $\nabla^a \nabla_a x^u = H^u$
  - Constraints : $C_a = \Gamma_a + H_a$
  - Einstein eqns: $R_{ab} = \nabla_{(a} C_{b)} + {}^{TR}T_{ab} + \kappa\{2n_{(a}C_{b)} - g_{ab} n^c C_c\}$
  - Expressed in terms of g_{ab}; H_a *from stationary solution.*
  - *Cowling approximation is enough.*

- GRHydro:
  - Eqns determined by: $\nabla_a T^{ab} = 0 \quad ; \quad \nabla_a(\rho u^a) = 0$

$$T_{ab} = (\rho_0(1+\varepsilon) + P)u_a u_b + P g_{ab} + F_a^c F_{bc} - \tfrac{1}{4} F^{cd} F_{cd}$$

  - Expressed in terms of *conservative variables, (use of HRSC)*
  - Eqn of state: $P = (\Gamma - 1)\rho_o \varepsilon \qquad (though,\ P = k\rho_0^{\Gamma}\ for\ ID)$
  - Present case $\Gamma=5/3$, ideal MHD eqns. Results for B=0.

[Megevand et.al 2009]

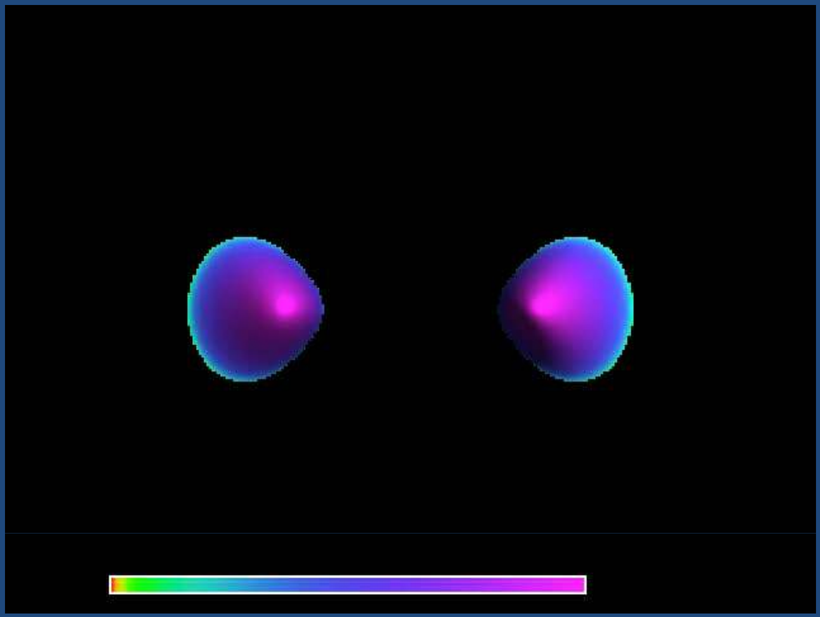
‘kicked black holes’ retaliate

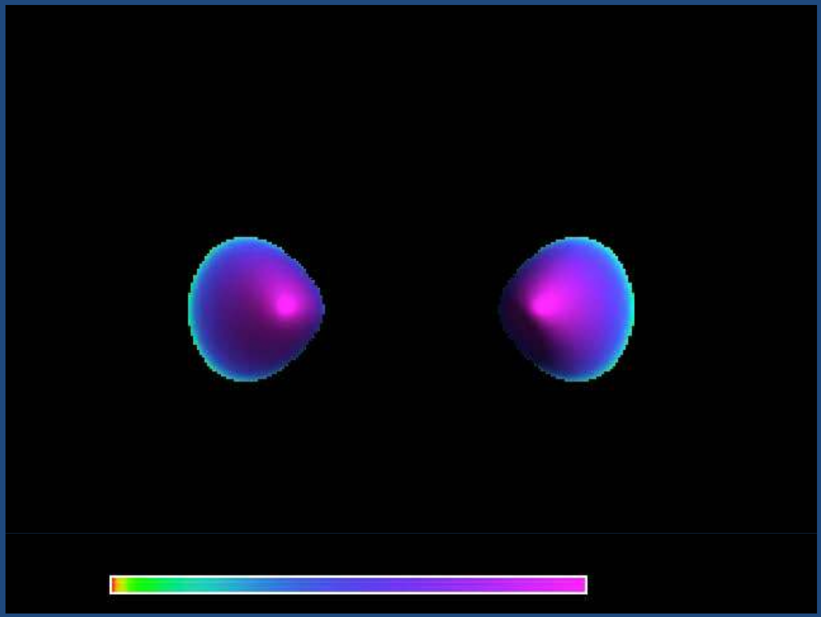
- Both mass reduction and recoil speed have an impact on the disk’s behavior. Relevant quantities: v_{kick} ; v_{sound} ; $v_{orbital}$

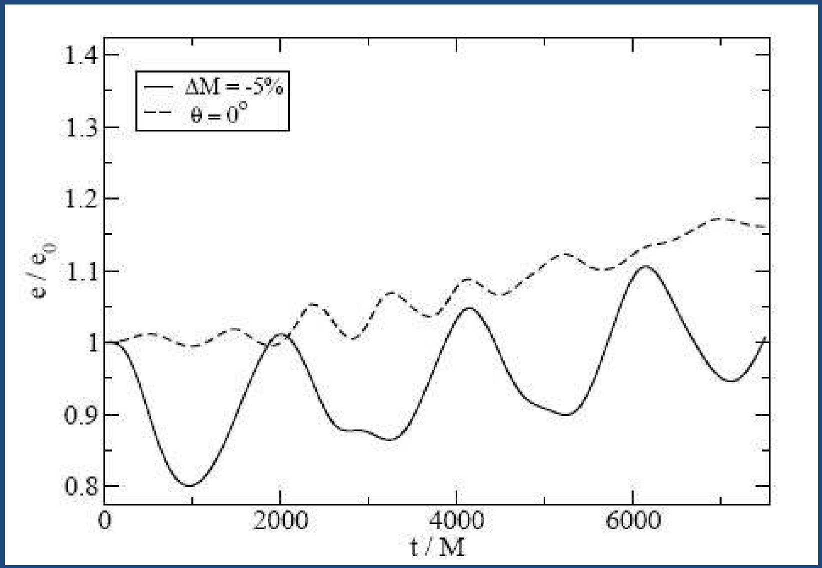
- If shocks develop → shock energy onto the disk → can induce EM signals

  - *from there on… take your pick…*
    - Lipai et. al. : prompt and in the UV
    - Bonning et. al. : delayed and in soft Xrays
    - Phinney et. al. : not kicks but mass reduction, significant output
    - O’Neil et. al. : not kicks but mass reduction, lowering of luminosity

Symmetry preserving cases

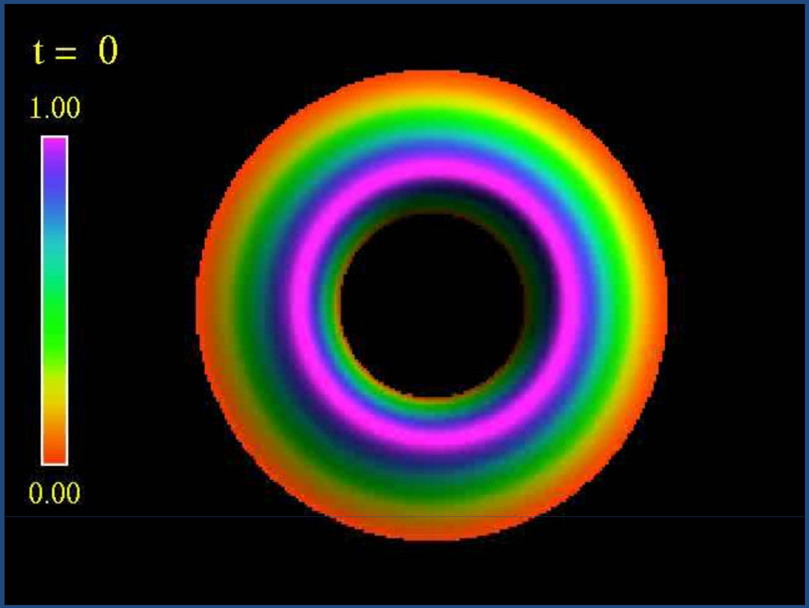


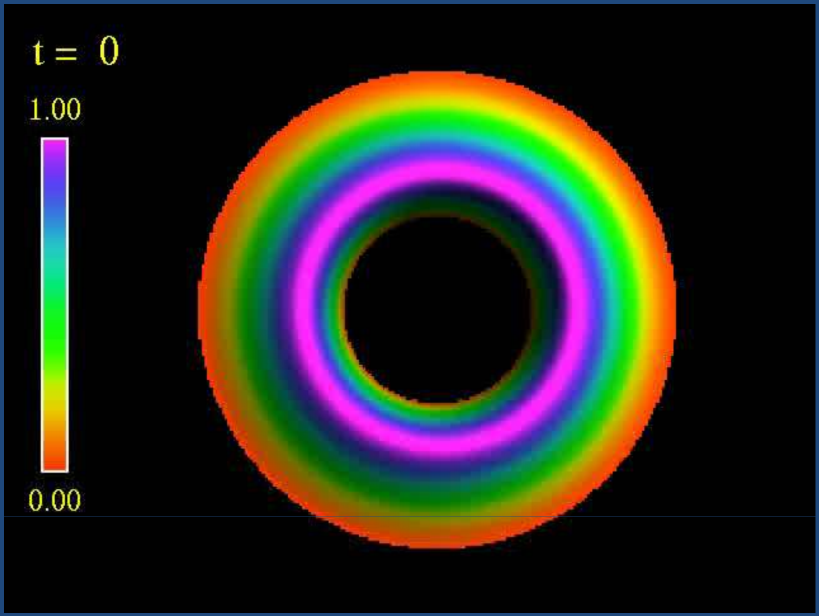


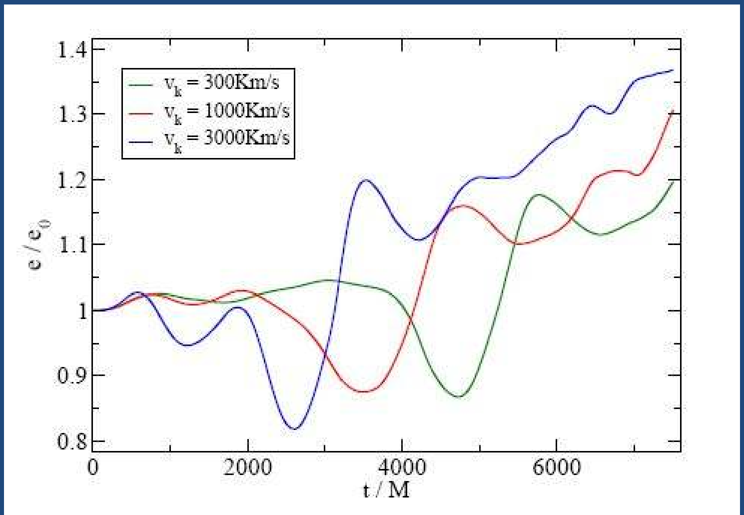


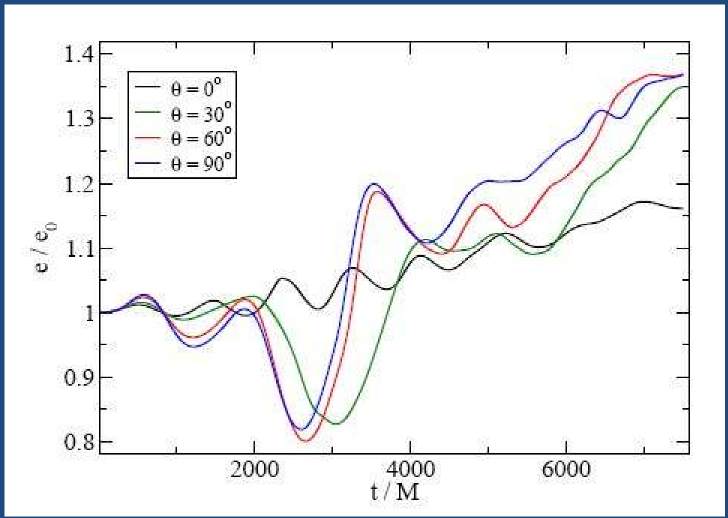
- Internal energy reduction (same with pressure, temperature).
- Possible reduction in disk luminosity initially, but oscillates.
- Time variability governed by the disk's period

Symmetry breaking cases









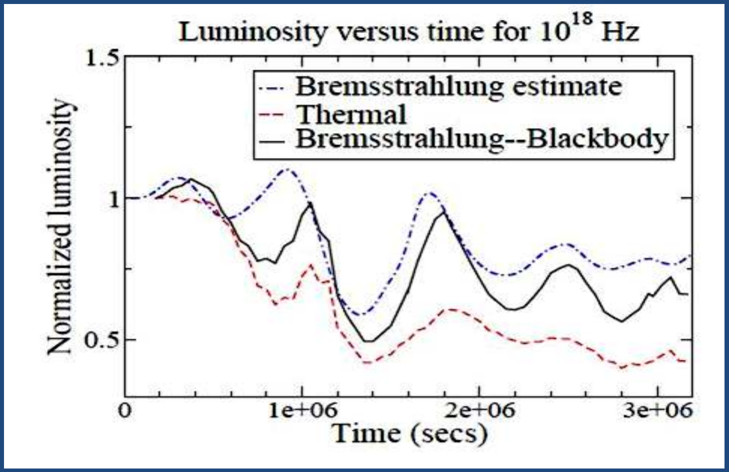
- In all cases, significant heating of disk is induced
  - Robust behavior
  - Time of ‘swing’ appearance
    - $T \sim 5200 - 912 \ln ((v_k)_{\rightarrow} /300 \text{ km/s})$
  - Strong (short) variability would certainly impart its characteristics to EM production process

  - Caveats:
    - Long term behavior, influenced by Papalaziou-Pringle ‘instability’
      - $T \sim T_{ref} - (2/w) \ln ((v_k)_{\rightarrow} / v_{ref})$, $w \sim 0.45$ (too high!)
    - Ongoing work on thin disk to remove this issue.
    - Role of Magnetic fields might be important.
    - Role of cooling important!
    - Particular emission process?

Taking images..

Radiation transfer eqn:

$$\frac{d\,I_{\upsilon}}{d\lambda} = -p^{a}u_{a}(\eta_{0} - \chi_{0}I_{\upsilon})$$



Options:

Brehmstralung-blackbody model

η brehmstralung emmisivity

χ modified Krammer's opacity law

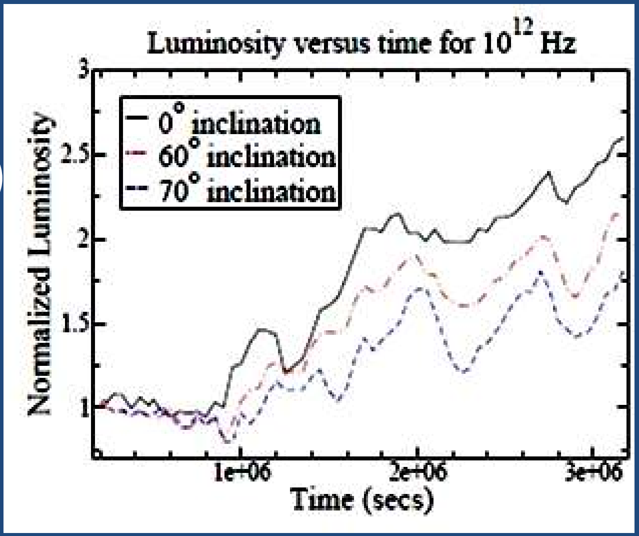
Thermal model

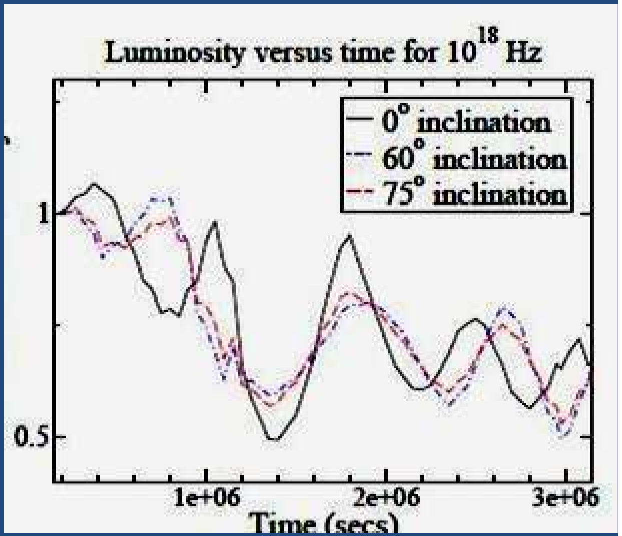
η Kirchoff's law η=χ (Planck law)

χ Krammer's opacity law

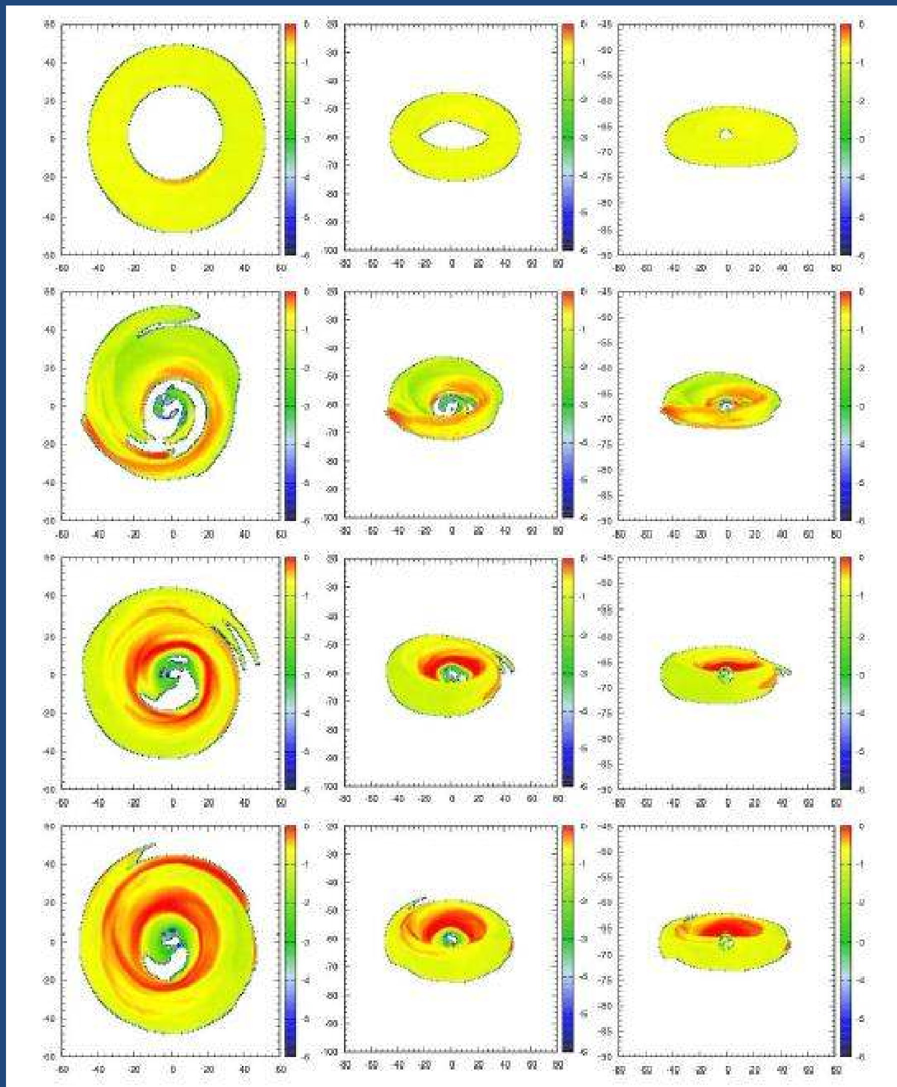
Brehmstralung vanilla

$\int \rho^{2} T\, dV$

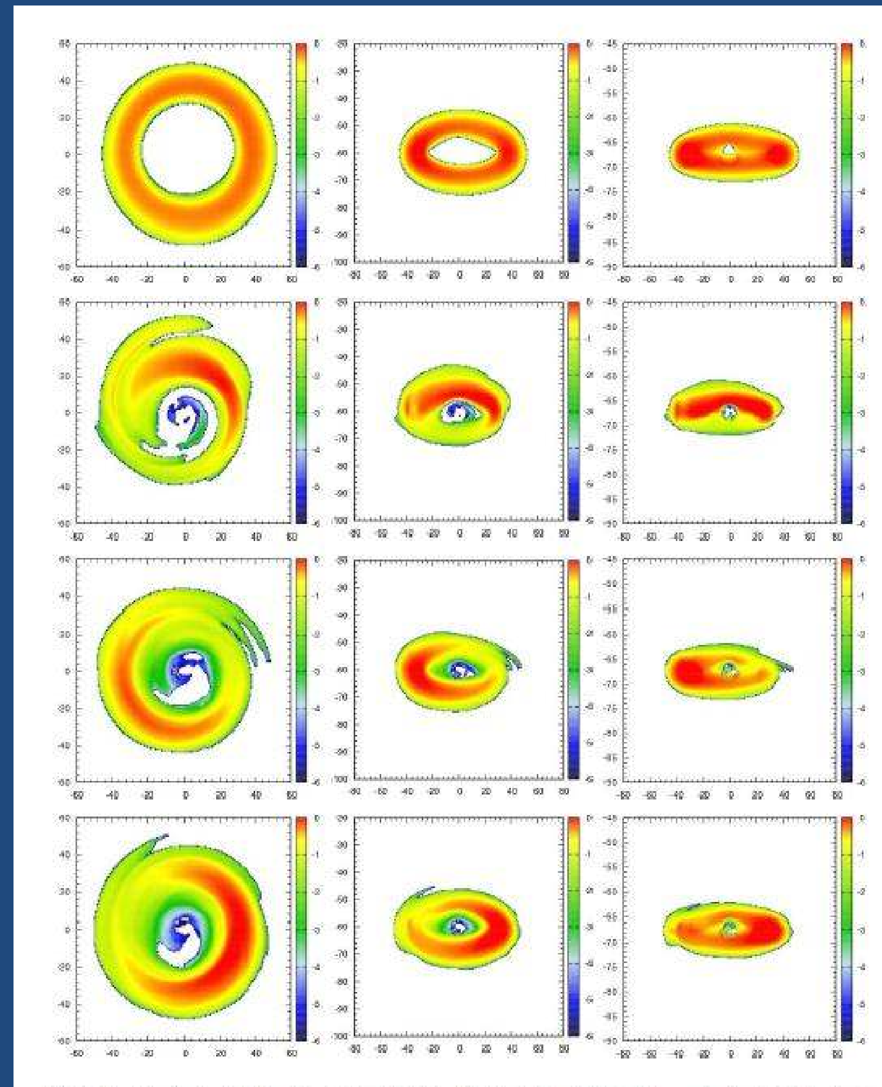




[a la, Schnittman; Noble]



Infrared



Xrays

[Anderson et.al, 2009]

Conclusion (I)

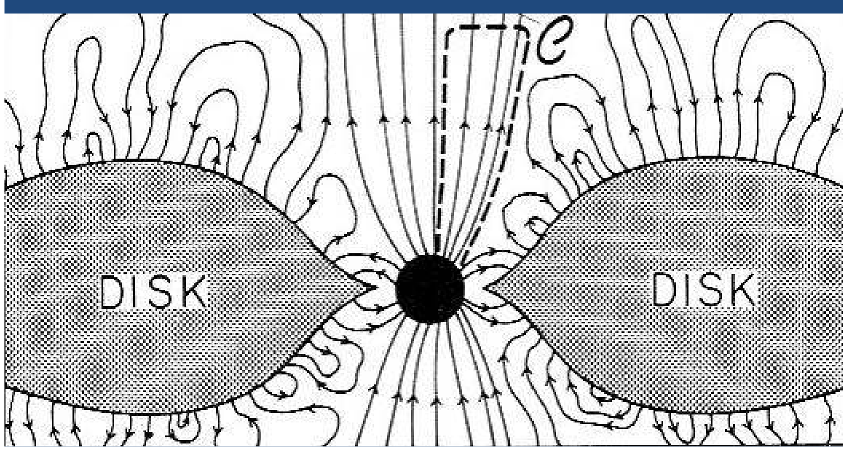
- BH recoil can produce observable consequences by affecting the disk.
- However… it might be too late, need to roll a dice with 10^5 faces!

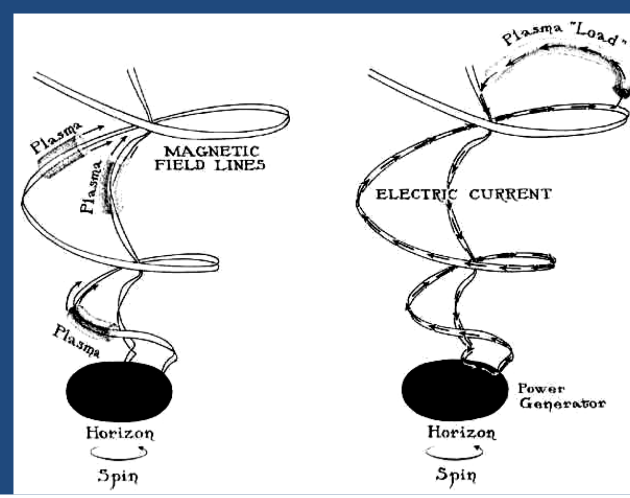
Binary black holes as blenders.
A new spin on an old story (though without spin)

How does the curvature/dynamics influence EM fields?

- Blandford-Znajek. “Penrose” process for Kerr bh’s surrounded by magnetic fields (anchored by the disk)

- Stray charges accelerate → pair production cascade. BH becomes surrounded by a tenuous conducting plasma with little inertia





[Goldreich-Julian, Blandford-Znajek]

Approach: Force-free electrodynamics

$$\nabla_a T^{ab}=0 \quad \rightarrow \quad \nabla_a T^{ab}{}_{(fluid)} = -\nabla_a T^{ab}{}_{(em)} = -F^{ab}J_a$$

$$\text{if} \quad \rho, P << B^2 \quad \text{then} \quad \nabla_a T^{ab}{}_{(fluid)} << F^{ab}J_a \approx 0$$

$$\mathbf{E}\cdot\mathbf{J} = 0 \quad , \quad q\,\mathbf{E} + \mathbf{J} \times \mathbf{B} = 0 \rightarrow \mathrm{E}\cdot\mathrm{B} = 0$$

Stationary spacetime:

(Gammie,McKinney 04)

$$E \bullet B = 0 \rightarrow F_{ab} * F^{ab} = 0 \rightarrow A_{\phi,\theta}A_{t,r} - A_{t,\phi}A_{\phi,r} = 0$$

so

$$\Omega_F \equiv -A_{t,r}/A_{\phi,r} = -A_{t,\theta}/A_{\phi,\theta} = \frac{F_{tr}}{F_{r\phi}} = \frac{F_{t\theta}}{F_{\theta\phi}}$$

$$E_{,t} = 2\pi\int_0^\pi \sqrt{-g}\,F_E\,d\theta \quad (with \quad F_E = -T_t^r)$$

$$\rightarrow F_E = 2(B^r)^2\Omega_F r(a/2Mr - \Omega_F)\sin^2(\theta) - B^r B^\theta \Delta \sin^2(\theta)$$

thus,

$$F_E\big|_{r=r_H} = 2(B^r)^2\Omega_F r_H(\Omega_H - \Omega_F)\sin^2(\theta)$$

$$\Rightarrow for \quad 0 < \Omega_F < \Omega_H \quad and \quad B^r \neq 0 \quad energy\ out\ of\ horizon$$

Plasma is crucial for this to happen

Examples…

- Kerr in vacuum and FF immersed in uniform field

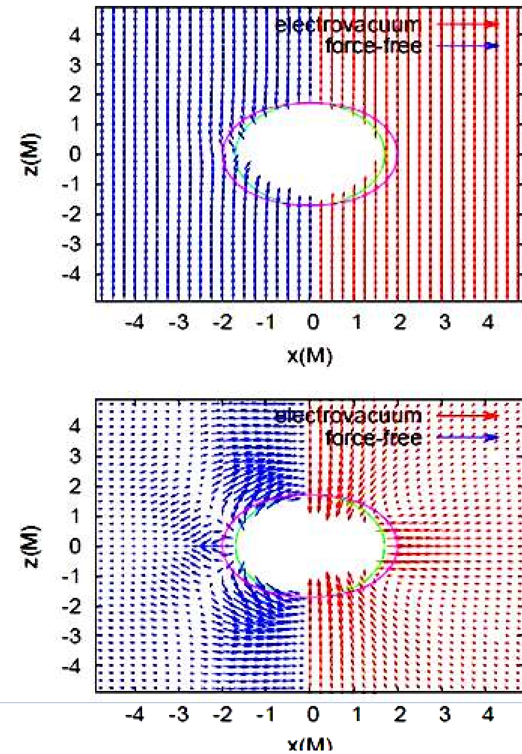
- In vacuum → no radiation

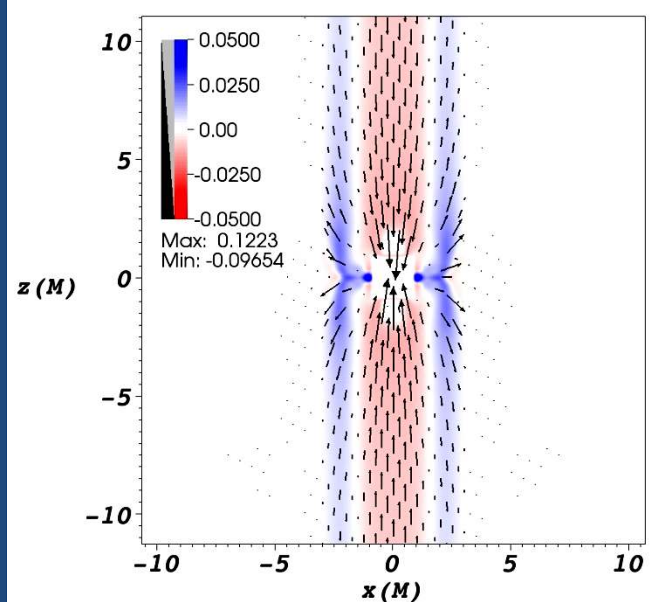
- With plasma → currents on the horizon ‘complete the circuit’

Membrane paradigm: wrt asymptotic observers, circuit moves through a B field → EMF produced.

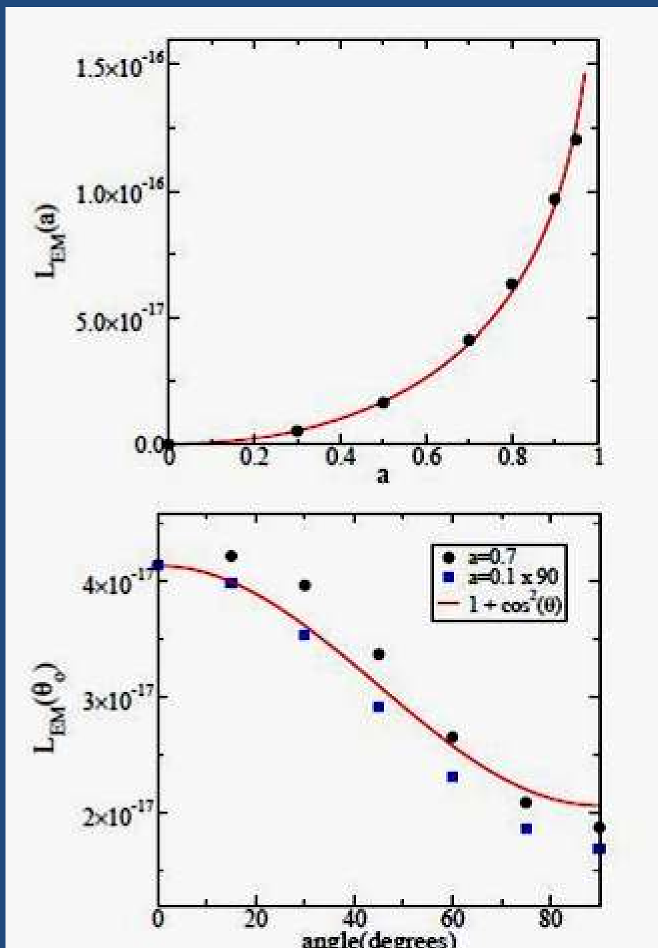
BH becomes the battery.

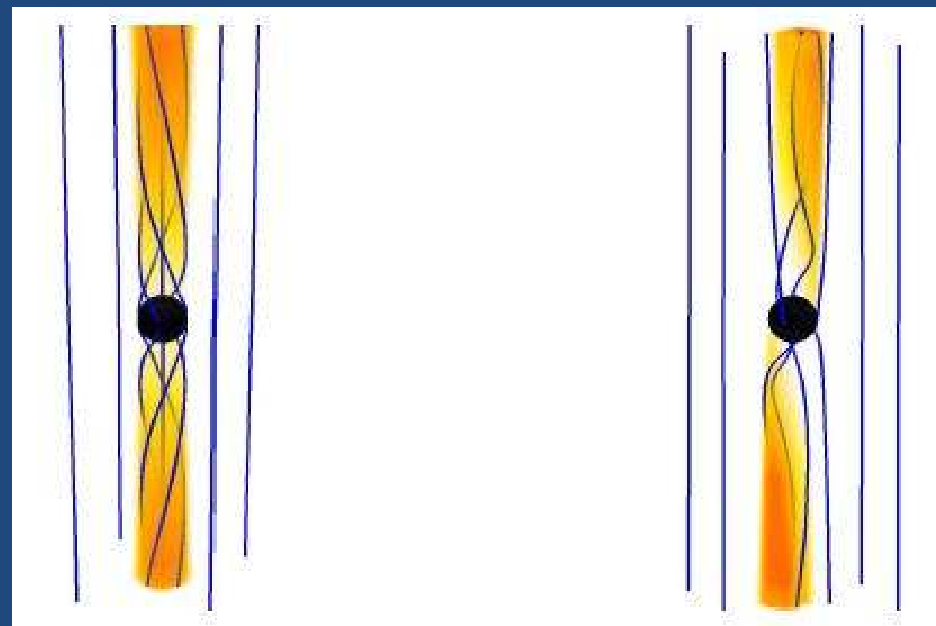
[Damour,Phinney,Thorne,McDonald…]





Single BHs, disk alignment?





- we knew. P ~ B^2 a^2 in the aligned case [Tchechovskoy,Narayan,McKinney 2010].

- For misaligned case?
  - Poynting flux still there, along B
  - P ~ B^2 a^2 $(1 + \cos^2)$

[Palenzuela,Garret,LL.Liebling, to be subm]

Onto binaries

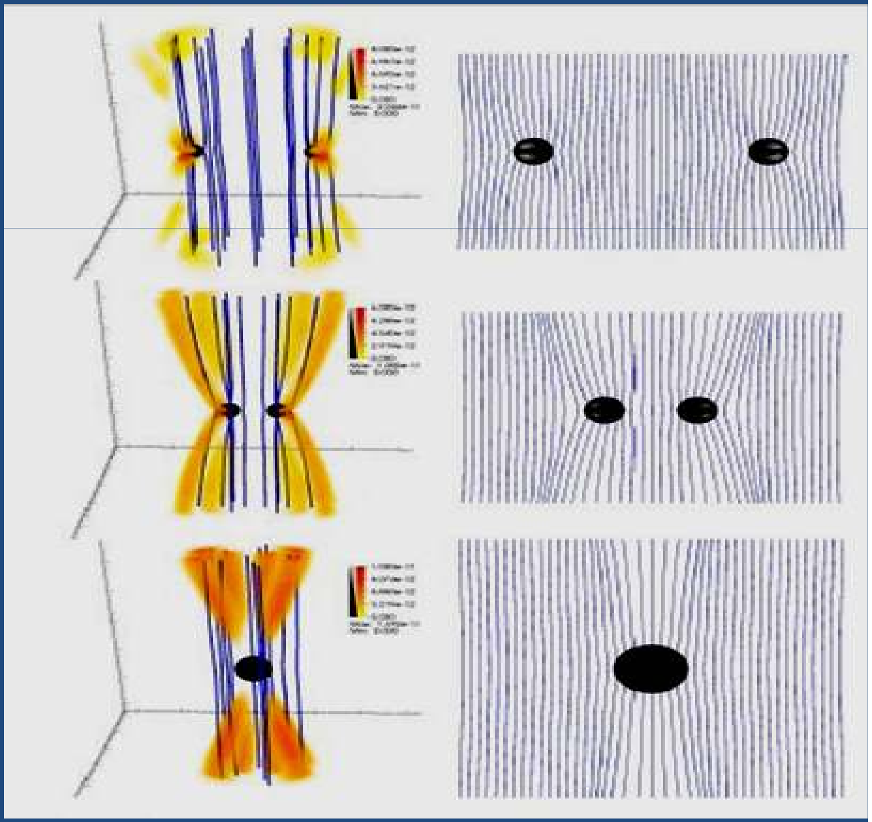
- Head on & quasicircular, equal mass. *non-spinning*

- Magnetic field as given by a 'circular loop' at far distances ~ constant within computational domain

- Field strength ~ 10^4G
  - For this value, if $M_T=10^8 M_O$, EM Energy dens ~ 10^{-16} [$1/M^2$]
    - → EM fields won't affect binary dynamics, but the other way around

Head-on case.

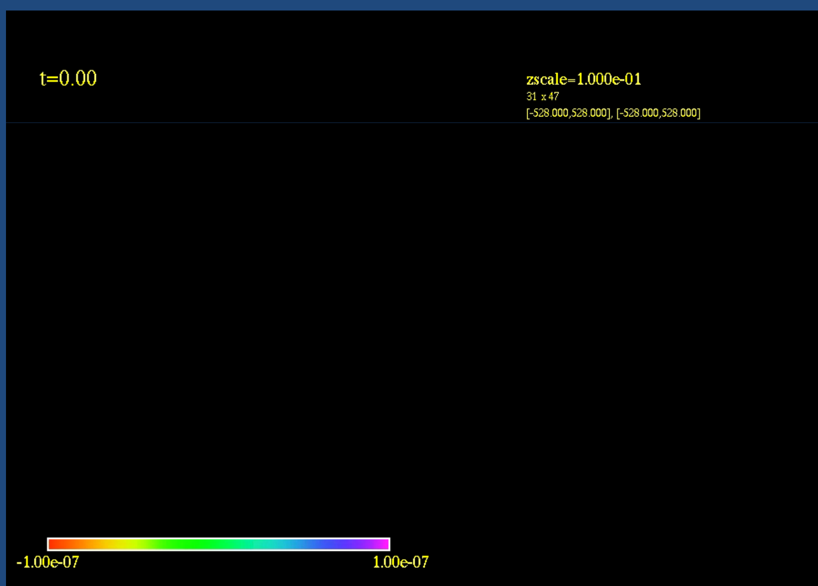
- Poynting flux,
  - What sources it ?
    - field lines tension/breaking as BH pulls them
    - Membrane paradigm: “Charge” separation induced by “Hall effect” , thus circuit is still there and still moving through B.
    - Poynting flux induced, though shuts off after merger

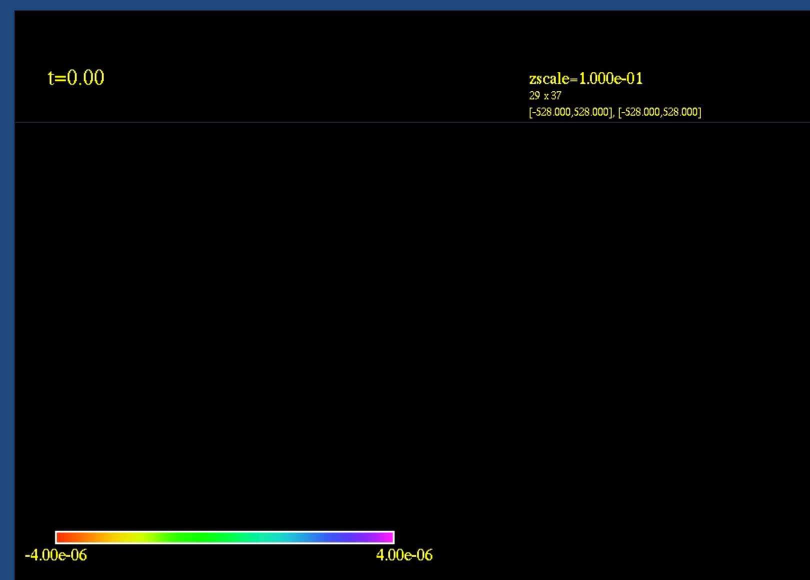


Onto the binary case

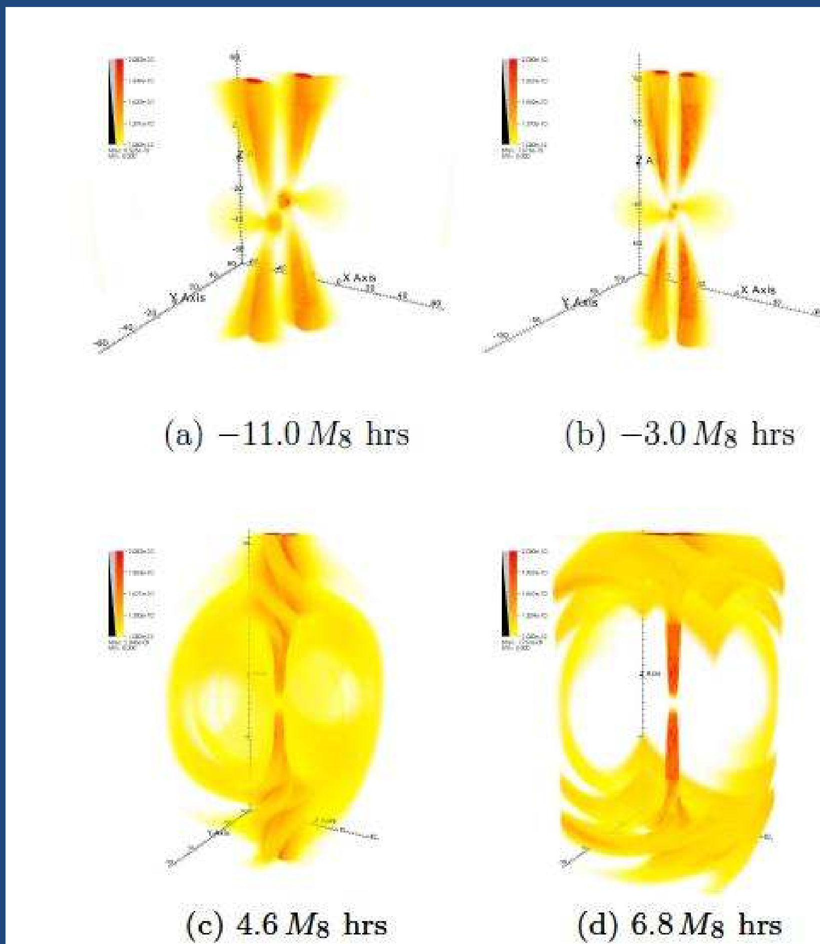
- Orbit → Black holes move through B. As in head-on case, ‘circuit’ can be Established due to charge separation (see in vacuum case already, [Palenzuela et.al. Moesta et.al.])

- Thus, expect Poynting flux through orbiting stages. Also at late time (BZ).



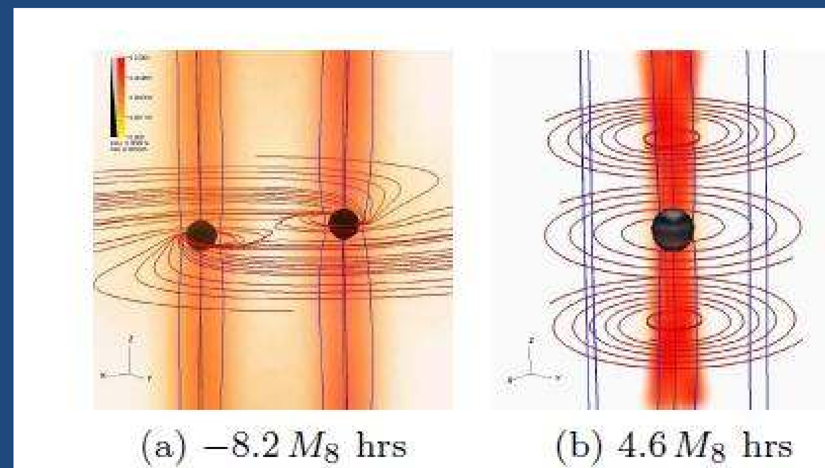


[Palenzuela,LL,Liebling , Science 2010]



(a) $-11.0\,M_8$ hrs (b) $-3.0\,M_8$ hrs

(c) $4.6\,M_8$ hrs (d) $6.8\,M_8$ hrs

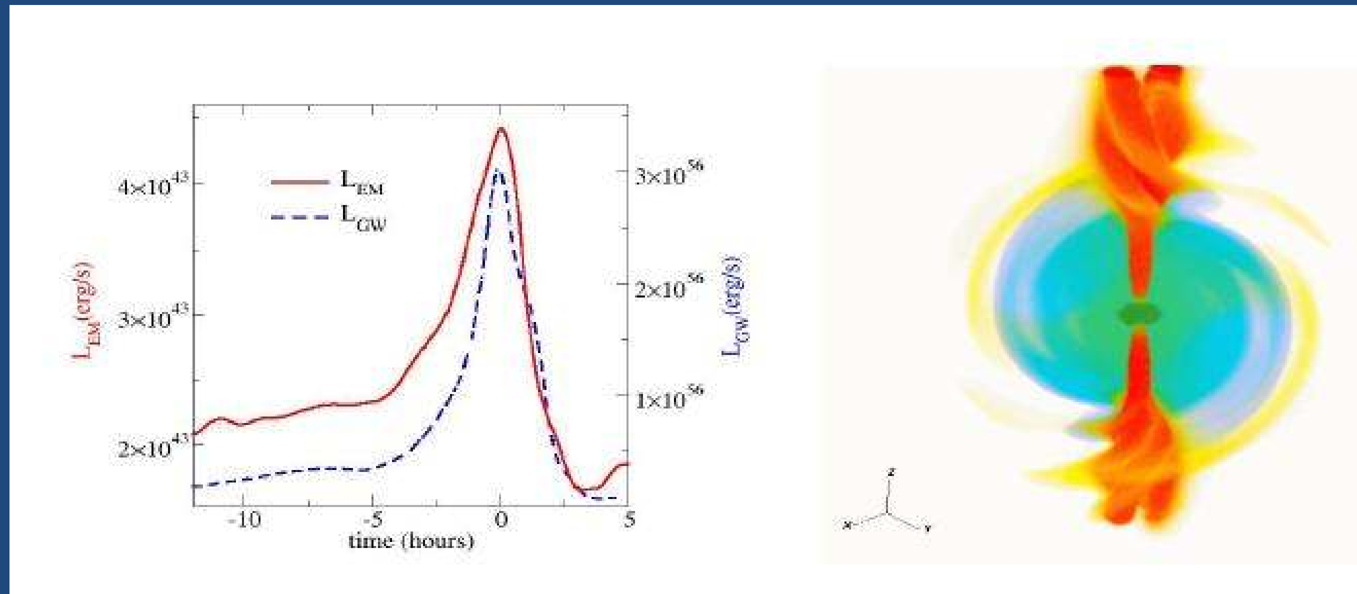


(a) $-8.2\,M_8$ hrs (b) $4.6\,M_8$ hrs

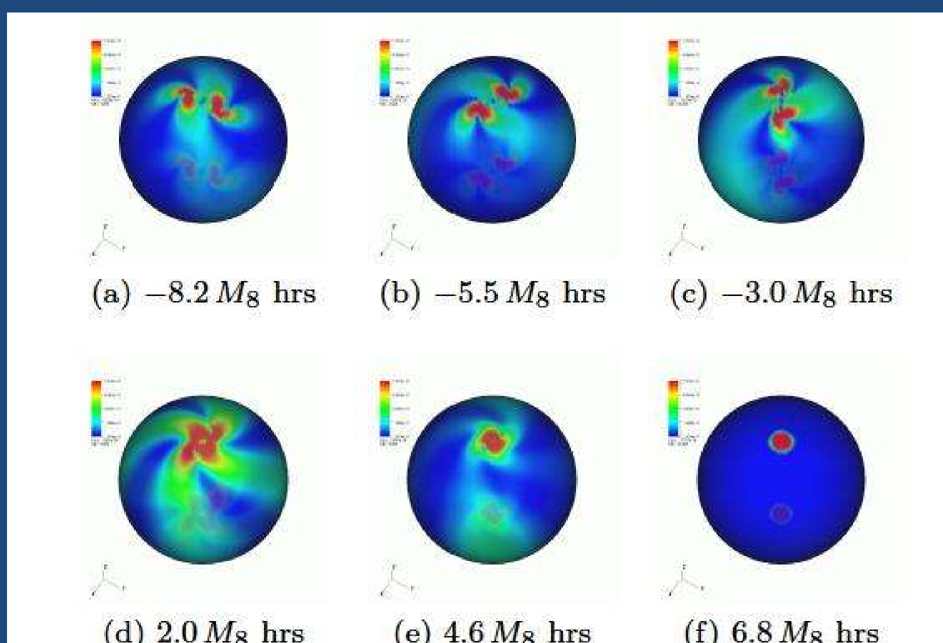
Ω_F this need not make sense!

Poynting flux

- Energy flux:



- Strong emission throughout. Burst around merger epoch



m=2 → 0 transition

Distributed energy output

- Making contact with astro… recall $(R_{orb}\ \Omega_{orb}) < 1$

- GW energy flux ~ $R^4_{orb}\ \Omega^6_{orb}\ M^2$ --strong emission--

- EM energy flux ~ $(R_{orb}\ \Omega_{orb})^2\ B^2$ --weaker but sustained, doesn't shut off after merger--

- Spinning case will have BZ on top. Also, particularly 'cute' scenarios should show an interesting phenomenology

- For 10^4G, $10^8 M_O$ flux ~ $10^{43\text{-}44}$ ergs. IF Poynting flux energy efficiently transferred to observable emissions, interesting pre/post merger observations possible; to z=1 ?