Gravitational and (possible) electromagnetic signals from compact binaries

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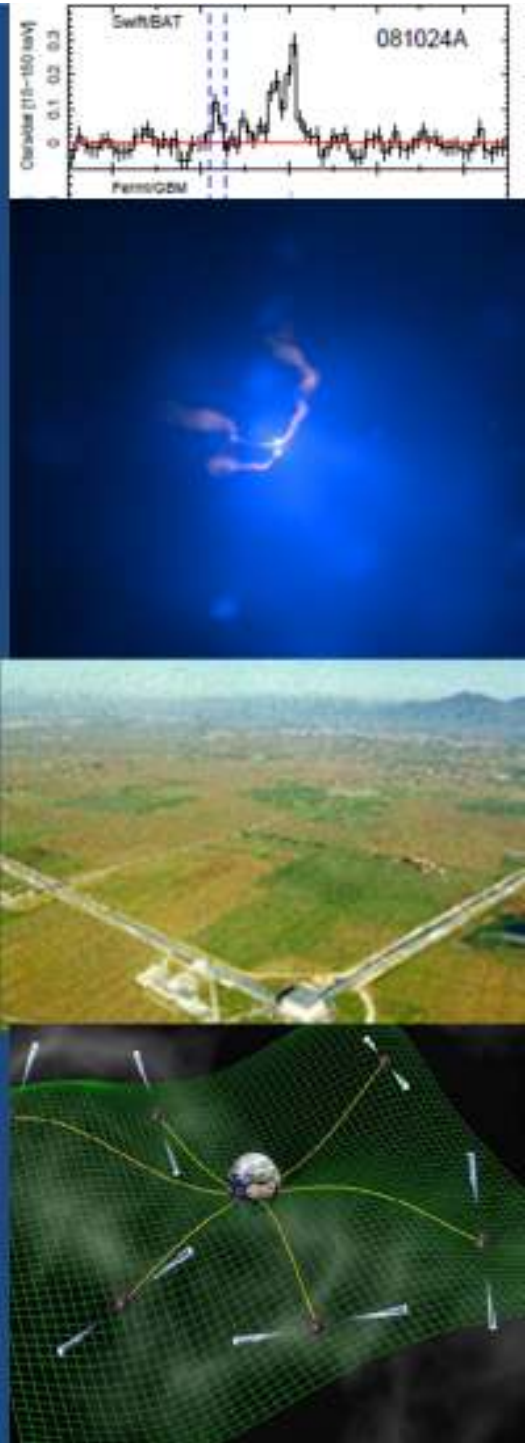
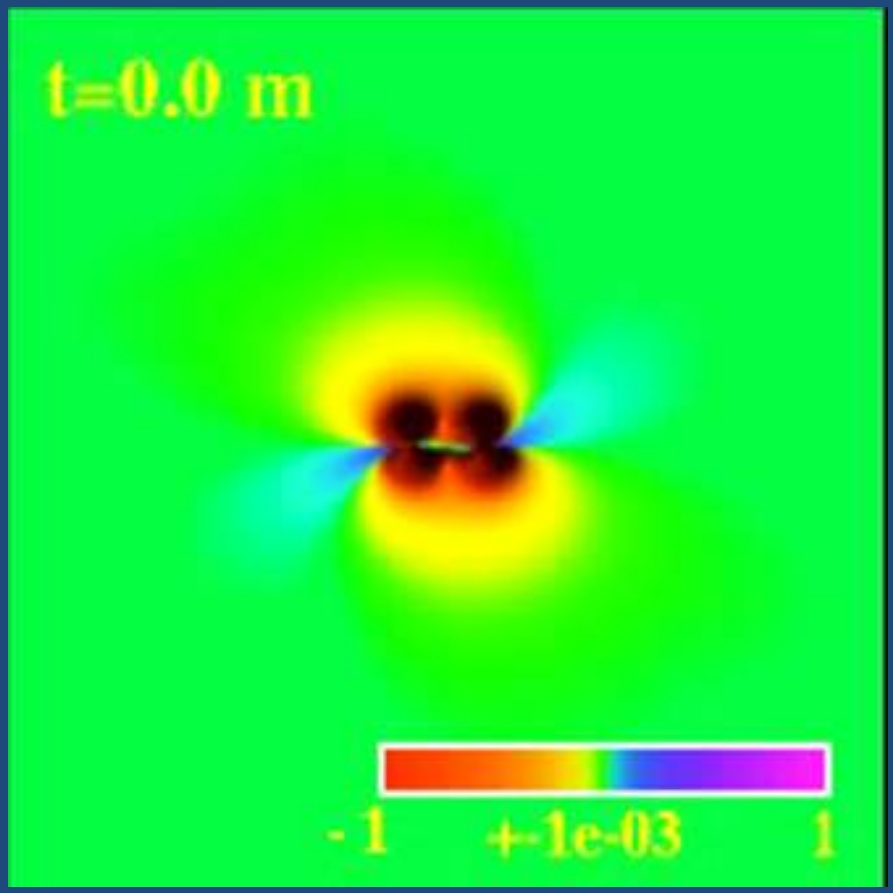
Underlying motivation…

- We know of a zoo of astrophysical systems emitting highly energetic EM signals (e.g. bursts, jets). Most however, are not well understood
  - Luminosities of ~ NS/secs hint of BHs & NSs
  - Collimations, strong directional dependence require mechanisms to act on long scales
  - As well, EM observations unfortunately tell ``the end of the story''
- Gravity plays a key role, and some systems also generate gravity waves which provide complementary information.
  - Just with standard EM efforts, 'models' are required to confront with signals.



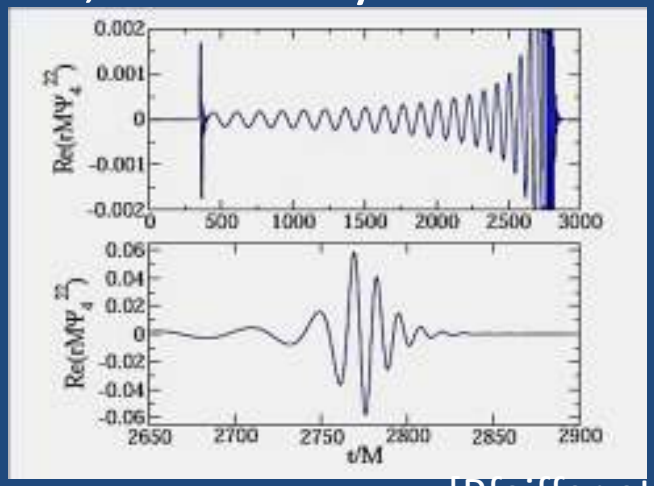
- To understand GW signals in the most dynamical phase → solve Einstein equations for target systems
- $G_{ab} = 8 \pi T_{ab}$ → just G_{ab} part 2nd order, nonlinear eqns.
  - Several length scales (source size, observer's location)
  - Relatively long time scales (though some can be addressed via perturbations)
  - Require complex simulations

As well, T_{ab} brings its own series of issues, but of crucial importance in a number of systems, and might help trigger more than one type of signal.



GWs and BHs, where are things (theory)?

- Gravitational waves from binary black holes, not overly 'complicated' by nonlinearities



[Pfeiffer et al]

- Radiation: convert ~ 5% of total intial mass and (late) angular momentum. (can be higher for 'tuned' collisions).
  - E_{GW} ~ 10^{58} ergs ($M_T/10^6\ M_{sun}$) in ~ 100 ($M_T/10^6\ M_{sun}$) secs
  - L_{GW} ~ $10^{25}\ L_{sun}$ *[or ~ $10^{7\text{-}9}\ L_{GRB}$]*

- Asymmetric scenarios give rise to kicks, these can be as large as 3-8 10^3 km/s! (claim Quasar SDSS J092712.65+294344.0)
  - Yet… these need some tweaking.
  - A few 100s km/s more typical. (Mech Energy~ 10^{53} ergs ($M_T/10^6\ M_{sun}$) >> SN !)

GWs, where are things (direct observations)? (or…what would it take to claim victory?)

- GWs (~ 2015?, ~2017?, ~ 2019….).
  - Theory results to prepare analysis of GWs and influence ongoing plans for future detector tweaks and designs
  - EM signals might help detection claim, and to remove degeneracies
  - What EM emissions might we expect? We already have possible EM observations!
  - Smoking guns to tell EM observations apart?

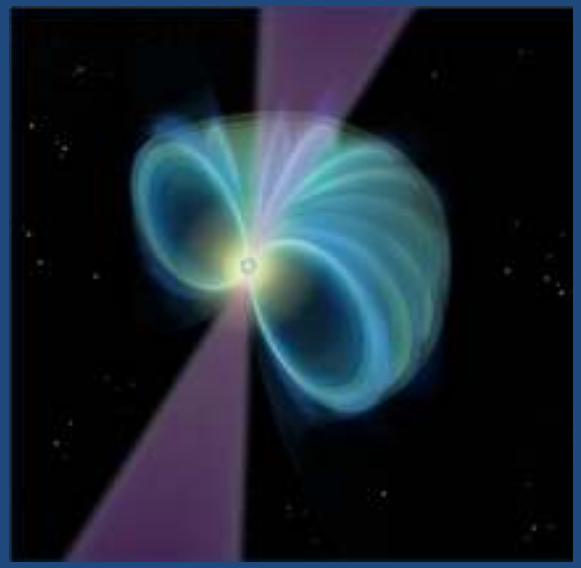
What's next?

- BBH: precision templates & efficient covering o parameter space
  - Data analysis challenges
  - Efficient analysis, rapid turn-around, *early warning*
- Beyond 'those' waves, there can `easily' be EM ones:
  - Just a fraction of energy released into surrounding gas/matter/fields can trigger an observable counterpart. e.g. GRBs, etc.
    - But what and how shines?
    - Are there characteristics tied to the orbital (GW) behavior?
    - Anything beyond SGRBs?

EM radiation

- Need to find what the right model is
  - microphysics, EM fields, what's outside compact objects?

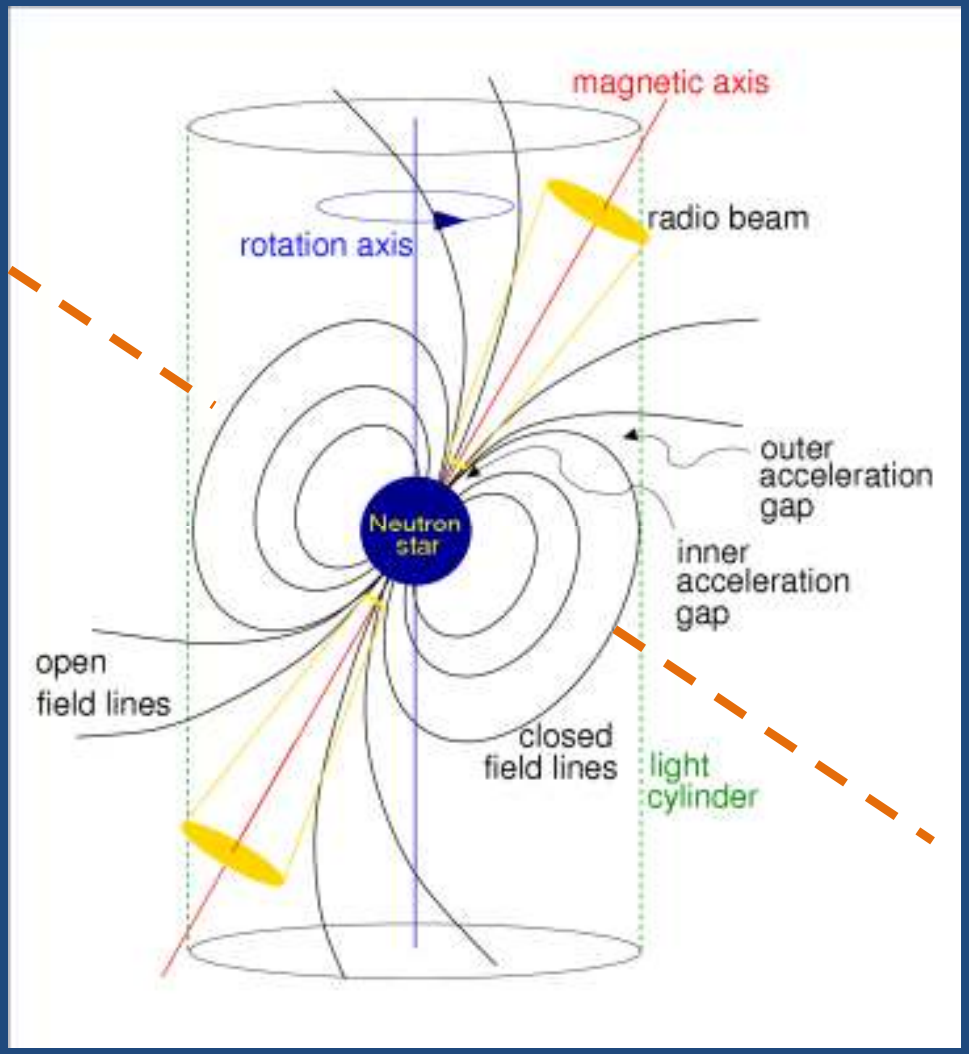
- So… let's start simple… consider a star and its dipole… Pulsars radiate….. Dipole radiation?



$$L \sim B^2 \Omega^4 R^6 \sin(x)^2$$

…but this doesn't seem right, (radio observations tell us so)

What is missing?



- NS isn't in vacuum. [Goldreich-Julian] Magnetosphere induced by e.g. pair creation
- Charges shorts out E.B → 'force free' condition

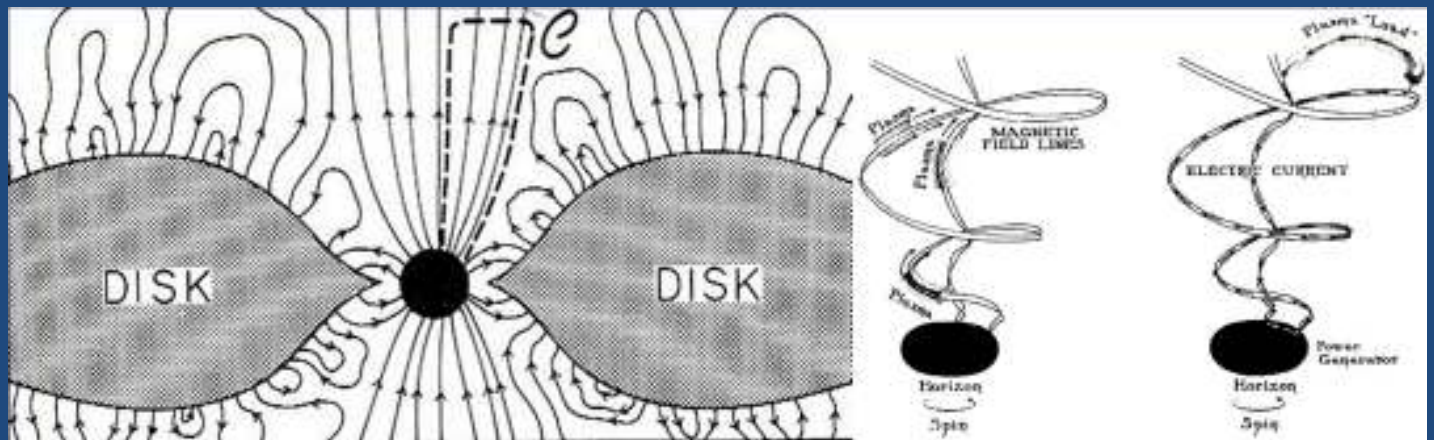
$$L \sim B^2 \Omega^4 R^6 [1+\sin(x)^2]$$

[Spitkovsky 2006]

- Plasma arguments are 'generic', enough that should be applicable in 'simpler' systems

'Blandford-Znajek' effect

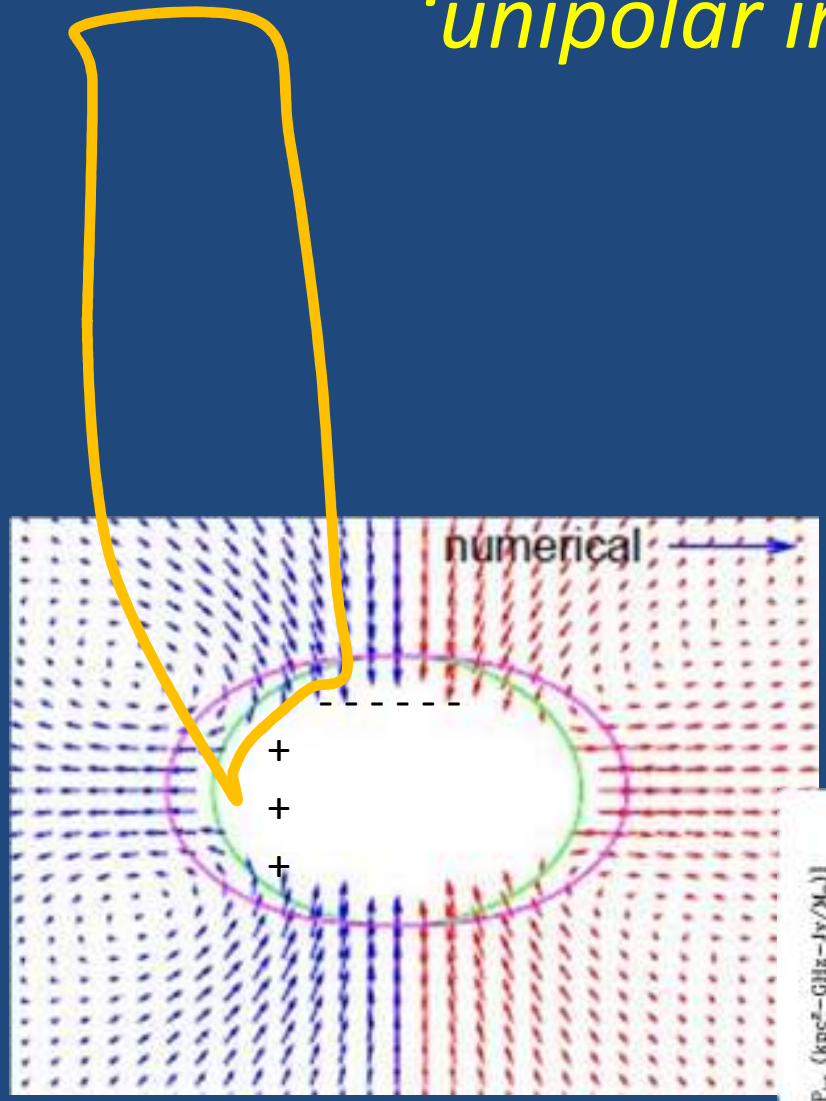
- Blandford-Znajek. Emmision mechanism for Kerr bh's surrounded by magnetic fields (anchored by an accretion disk)
- BH becomes surrounded by a tenuous conducting plasma with little inertia
- Blandford-Znajek: BH acquires and induced charge distribution, bh rotation provides an EMF with $V \sim B\,a \rightarrow L \sim (Ba)^2$
- *Binary black holes? -- PTA sources--*



[Goldreich-Julian, Blandford-Znajek]

simple picture from the membrane paradigm

'unipolar inductor'



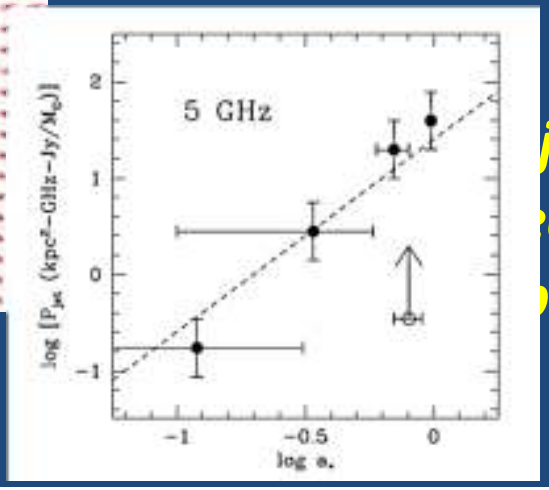
BH: (poor) conductor

Battery: Black hole's rotation

Plasma to close the circuit

Far load: to dissipate energy

$L \sim B^2 a^2$



just a picture,
ed full
are against

[Narayan-McClintock 2011]

First step: How to solve for this?

- Must add plasma effects to GR simulations
  - State of plasma?, Conductivity?....

First step: How to solve for this?

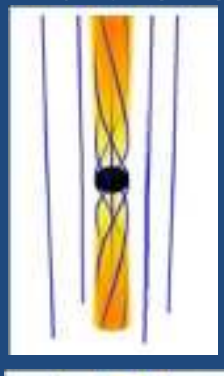
- $G_{ab} = T_{ab}$
- $\nabla_a F^{ab} = J^b$; $\nabla_a * F^{ab}$=0 ; J^a ?

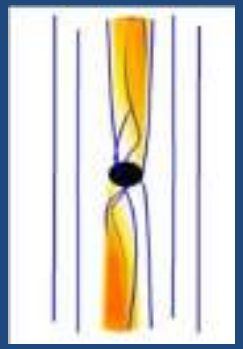
- *Further constraints*
- $F^{ab} * F_{ab} = 0$ $(orthogonality\ condition)$
- $F^{ab} F_{ab} > 0$ *(magnetically dominated)*
- $F_{ab} J^b$=0 *(Lorentz force =0)*

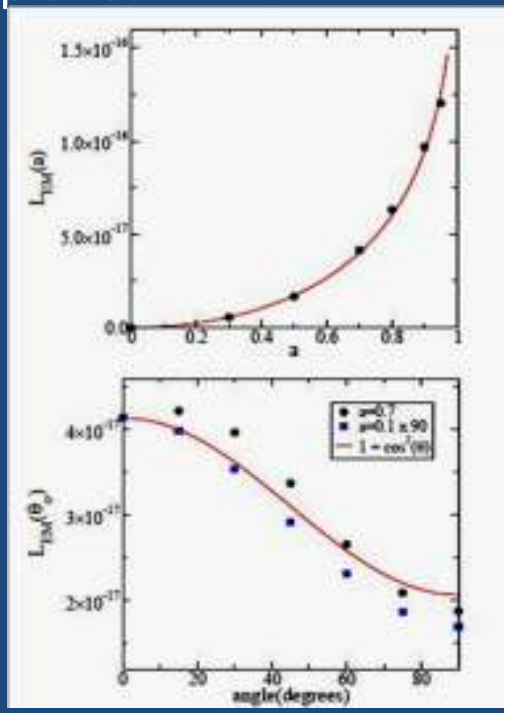
- ***IF*** *analogy can be pushed further*, there is little special about BH's rotation, any relative motion of conductor wrt ambient magnetic field would give and EMF

- Can this intuition be confirmed? And connection further exploited?

•we knew. $L \sim B^2 a^2$ in the aligned case [refined version Tchechovskoy,Narayan,McKinney 2010].





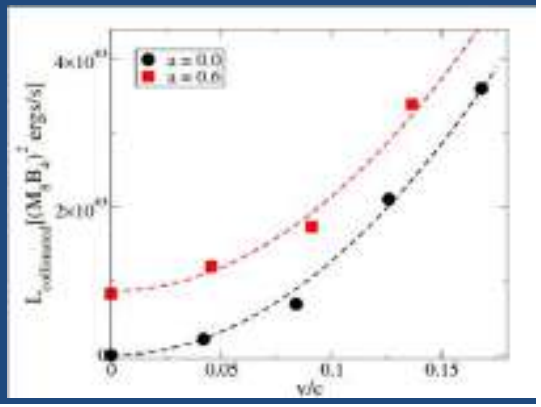


• For misaligned cases?
  - Poynting flux still there, along B
  - $L \sim B^2 a^2 (1 + \cos^2)$

  (can be predicted using Damour 74 + mp!)

- For moving cases?
  - From membrane paradigm → BH is a conductor. If moving through a B field, induce $E \sim v \times B$ → $EMF=V \sim (vB)$; $L \sim V^2$
  - Expect $L \sim v^2 B^2$

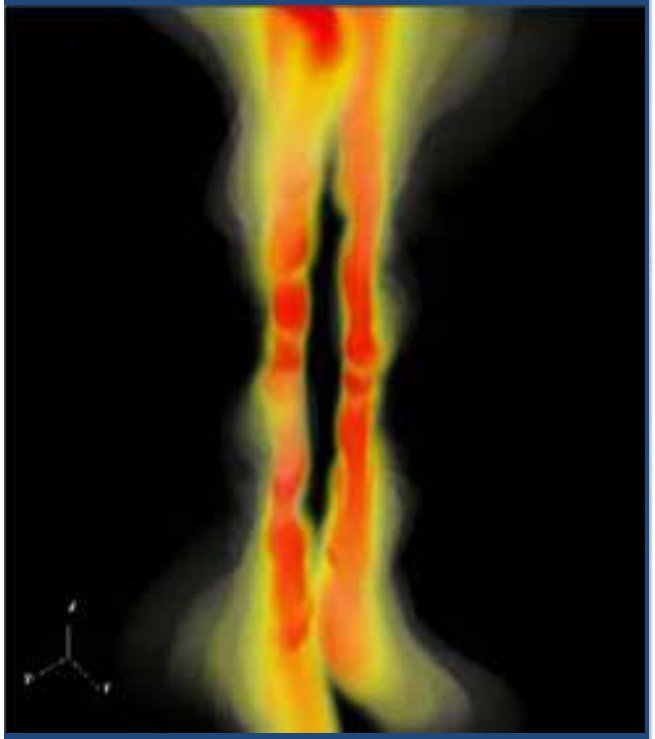
  (Can be predicted using theory of satellite propulsion Drell,Foley,Rudderman 65!)



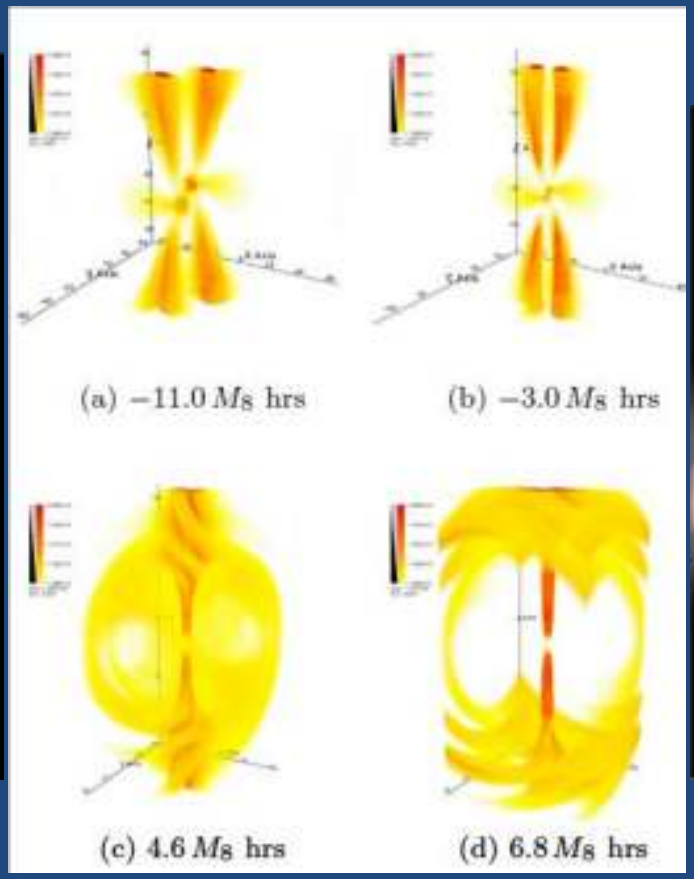
[Palenzuela,Garret,LL,Liebling, PRD 2010]

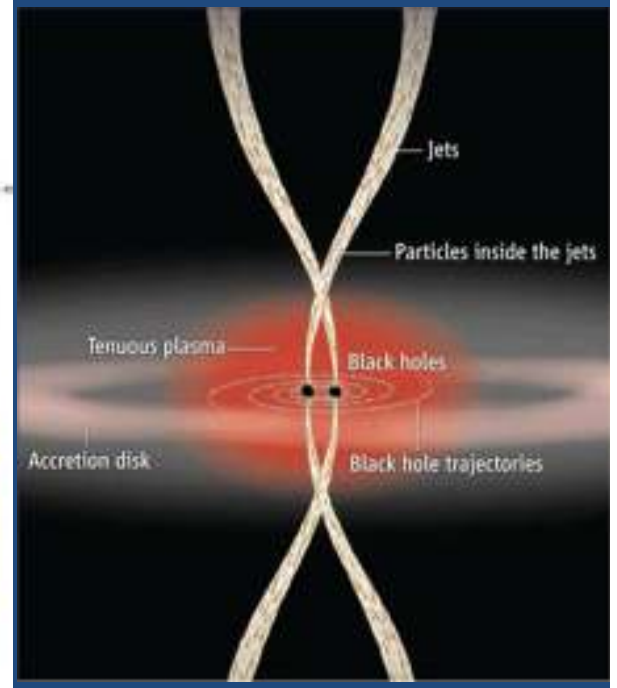
Onto the binary case: “Braided jets”

- Orbit → Black holes move through B. Hall effect analogue.
- As in previous cases, ‘circuit’ can be established due to charge separation
- Thus, expect Poynting flux through orbiting stages. Also contribution from standard BZ .

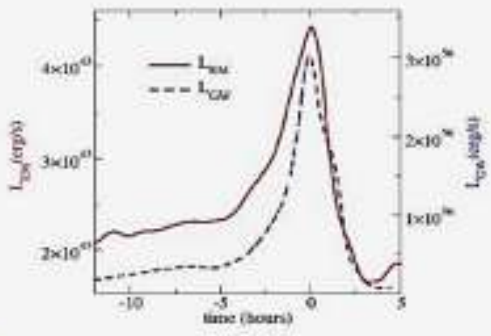


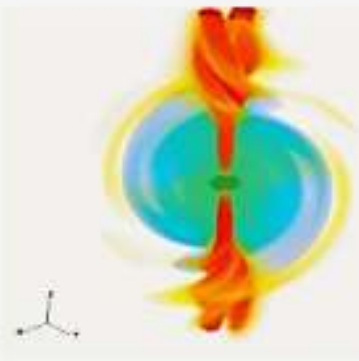
Poynting flux

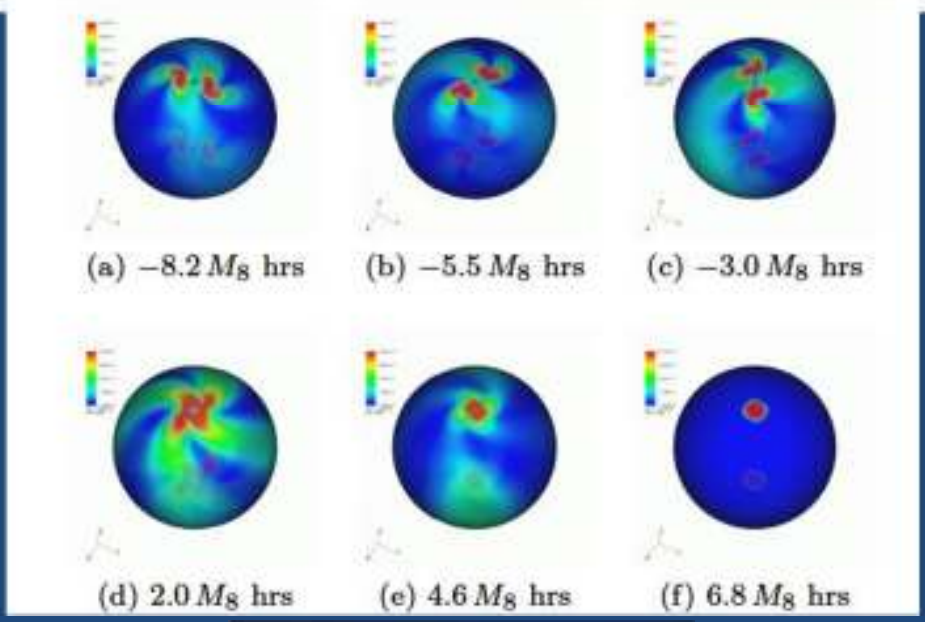




[Palenzuela,LL,Liebling , Science 2010]







Putting all together:

$L \sim (1 [a/0.6]^2 + 100 v^2) 10^{43}$ ergs $[M_8 B_4]^2$

* *EM flux acts as a "spacetime tracer"*
* *Can exploit 'standard' BBH results to predict much of the EM flux behavior. This system is very clean*

Multimessenger? : LISA & PTA for gravity waves

EM observations? 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 ?

Additional messages…

(i) spin isn't needed

(ii) a BH isn't needed (a star or satellite would do, eg. Io-Jupiter)

LIGO/VIRGO/KAGRA sources: NS-NS & BH-NS

Excellent sources of GWs [few to hundreds per year!];
Zoo of ingredients: Eqn of state [YITP-UWM,…] ? Role of magnetic fields [PI/CITA/LIU/BYU,…] ; neutrinos [YITP,Caltech/UW/CITA/CORNELL,….]?, configurations [UIUC,CWCC,…] *all can affect the dynamics at particular stages*

For grav waves.

Early pre-merger stages: PN is good enough [Blanchet,Faye….]
Late pre-merger: internal structure plays a role
Merger, postmerger: prompt vs. delayed collapse to a BH and other features, we could use to determine eqn of state.
Can different effects be disentangled?

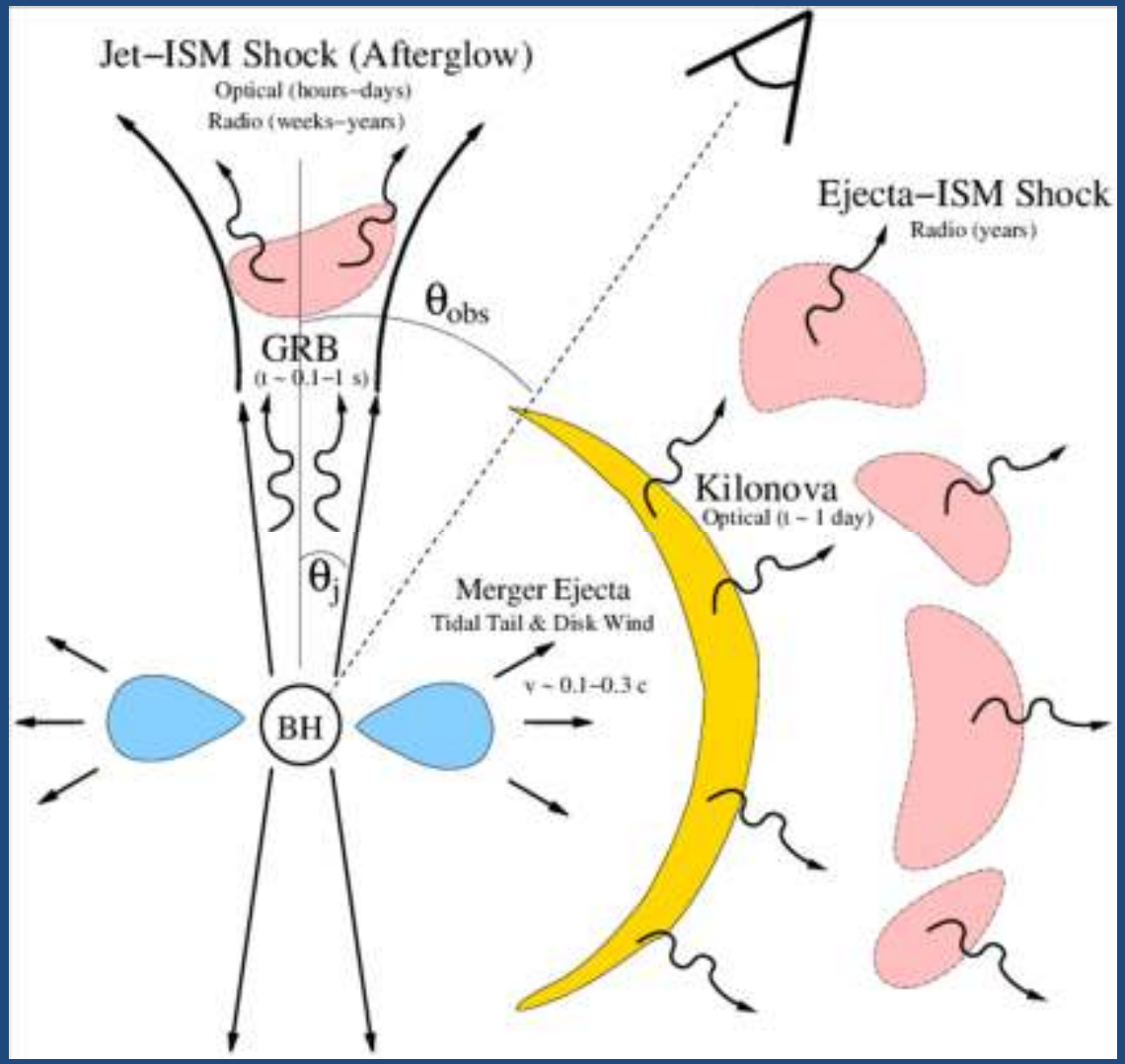
Beyond these, other key qns

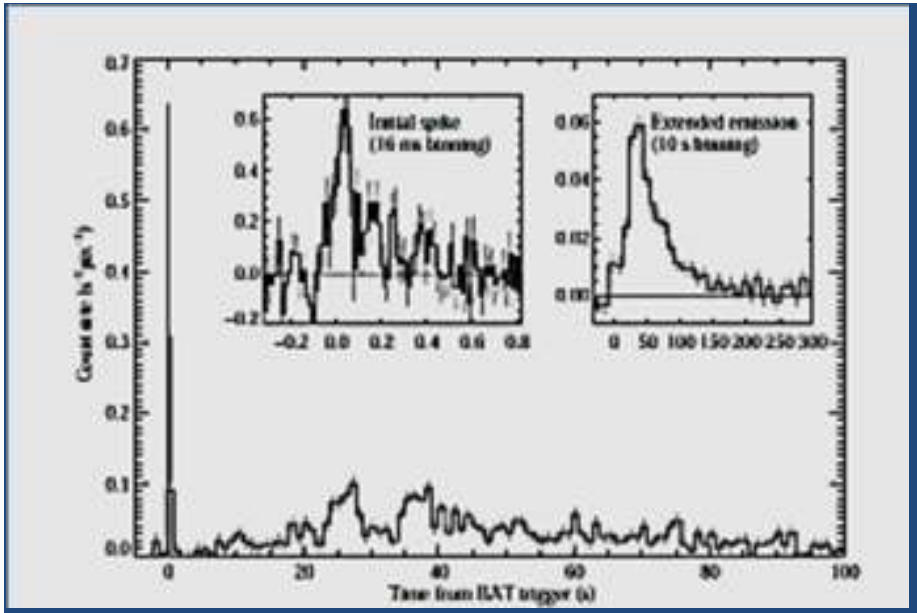
Does the merger give rise to a BH with sizeable disk?, what is its final spin, magnetic field strength /topology, etc?
All these connect directly with short GRBs models

EM connection?

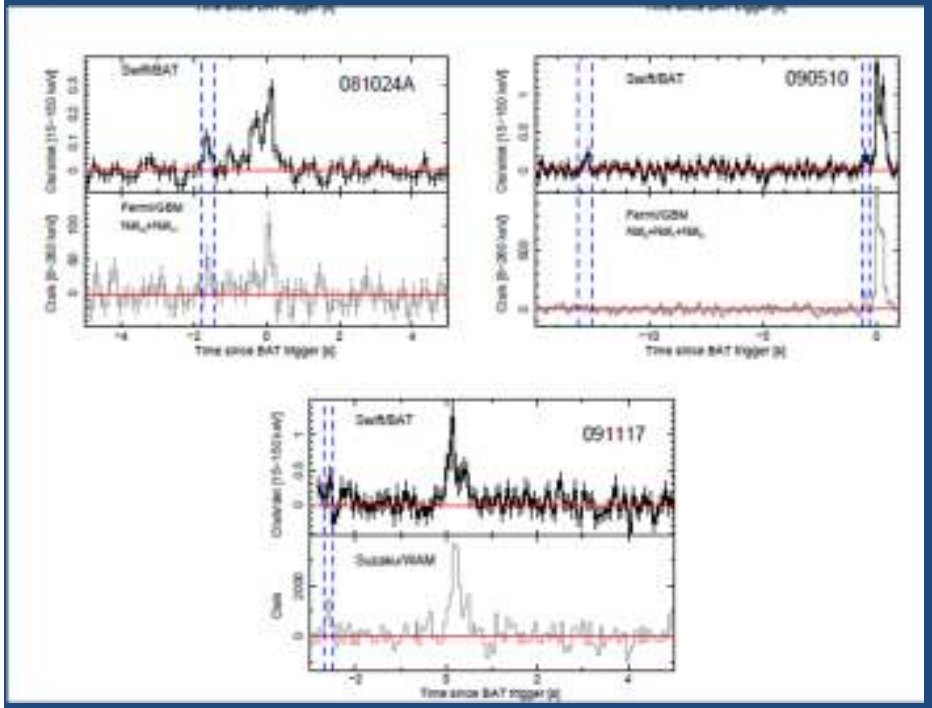
- Possible sources for sGRBS
  - Observations indicate old stellar population progenitors
  - Rates are consistent with estimates of non-vac. compact binaries
  - Rapid γ and X-ray variability -> small source. Huge luminosities and non-thermal spectrum -> ultrarelativistic. →powered by jets produced by rapid accretion onto a newly formed stellar-mass BH (or a rapidly rotating magnetar). Jet break → collimated outflows
  - A fraction show long, sustained emissions with total energy ~ the main burst itself (or higher)
  - a few seem to show activity prior to burst (?)
  - since collimated, where are 'orphan afterglows' ? (expected in radio).

sGRB ‘anatomy’





[Perley et al 09]



[Troja,Rosswog,Gehrels 10]

- GR080503. Extended emission for ~ 200secs. "Gap" between main burst and extended emission.
- Why 2 time scales? argument: r-processes from ejecta
- --though opacities have been underestimated [Kasen, Hungerford]
- Near IR observations perhaps… already measured! [Berger etal]
- ~10% of sGRBS seem to display pre-burst activity. Up to 10secs before the merger?!
- Why 2 time scales?

- Also, one expects there should be more than ‘sGRBS’ (and remember not all binaries might give sGRBS)
  - Strongest fields; extreme dynamics; what else is out there?
  - BH-disk & magnetar scenarios not mutually exclusive (NS-NS)

Regardless… GW observations will have a huge impact

- Do they really come from BH-NS / NS-NS?
- What is the ‘radiative’ process?
- What is the environment ?

- So… let’s try to put as much as we can together. GWs are coming, but EM observations have been with us for long
  - (dividing NSNS and BH-NS)

How to deal with them?

- Stress tensor T_{ab} sum of:

$$T^{\text{fluid}}_{ab} = [\rho_o (1+\epsilon) + P] u_a u_b + P g_{ab}$$
$$T^{\text{em}}_{ab} = F_a{}^c F_{bc} - \frac{1}{4} g_{ab} F^{cd} F_{cd} .$$

- Coupling: Ohm's law $J^a = q\, u^a + f(\sigma)\, (e^a + (e.b)\, b^a\, \lambda\,)$

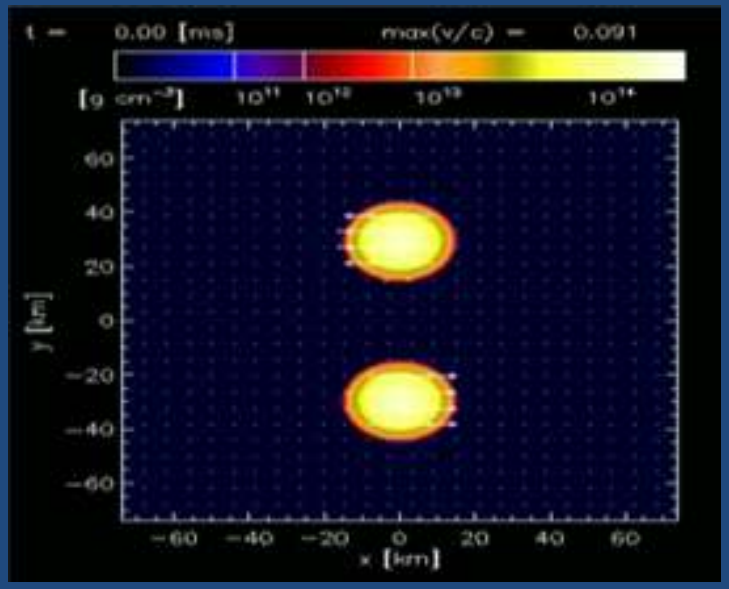
- Traditional way, concentrate on different limits:
  - Ideal MHD $f(\sigma) \rightarrow$ *infinity.* $F_{ab}\, u^b = 0$. Suitable for stars, outside of them?
    - B turns into a 'fluid' field, propagation speeds tied to u^a
  - Force free electrodynamics. Fluid's inertia is negligible $\rightarrow F_{ab}\, J^b = 0$ ($f_{lorentz}=0$)
    - *E,B independent fields, currents/charges implicitly considered.*
  - *Vacuum case* $\sigma = 0$.

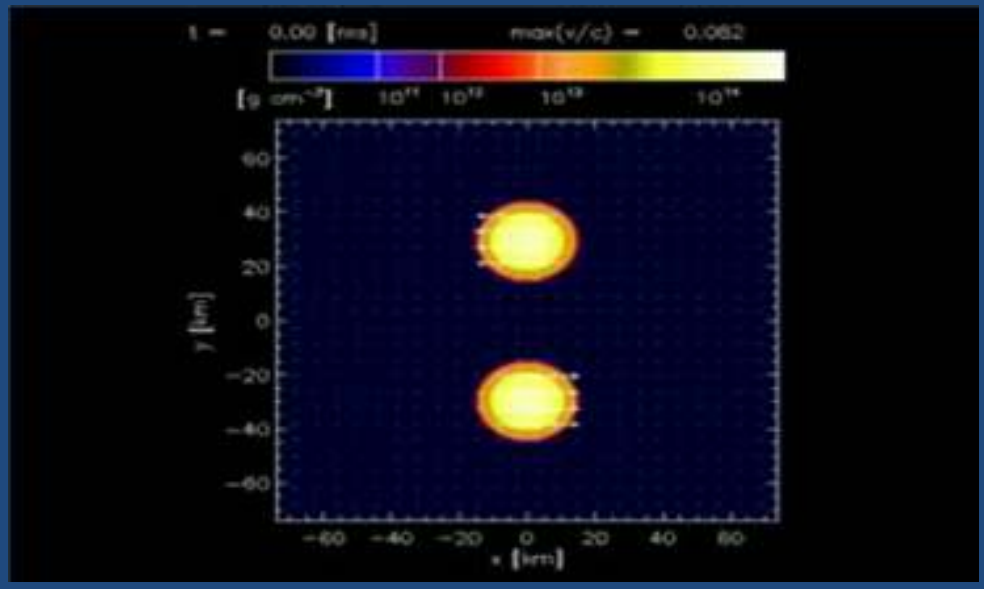
- σ *?* Values vary over huge scale range → numerically delicate *(but doable [Palenzuela '12, Palenzuela,LL,Ponce,Liebling,…'13])*

NS-NS

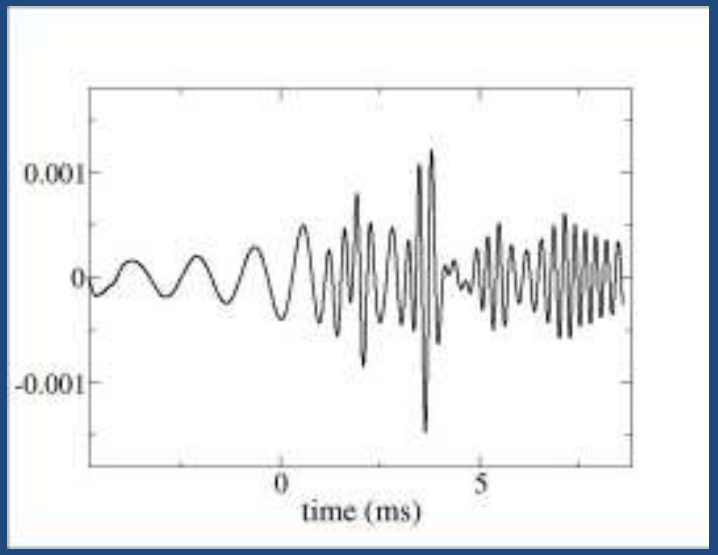
- Gravity waves can tell the EOS. Radius/Mass measurable to ~ 1% [Read et al]

- Degeneracies? Magnetic fields can play a role –*after merger*-- [Ioka-Taniguchi '01; Anderson et.al., UIUC,YITP,AEI,…]. Cooling? [Sekiguchi+]
- Angular mom transport, reduction of thermal pressure, …



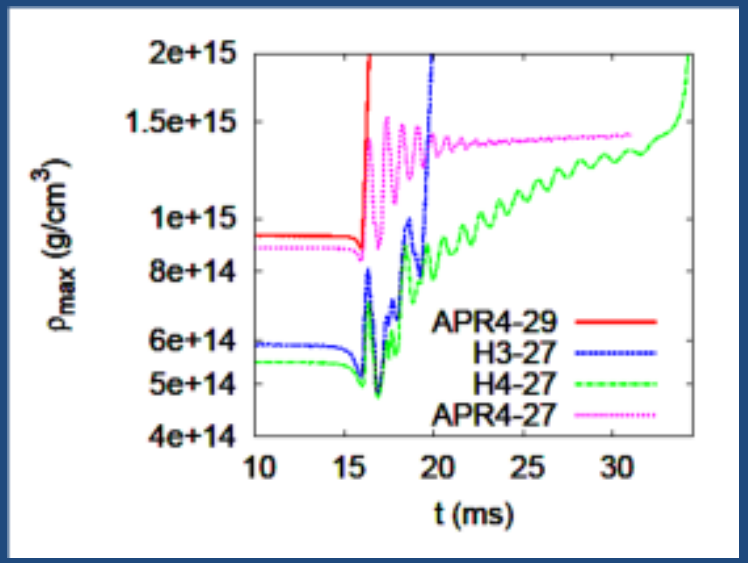


waves

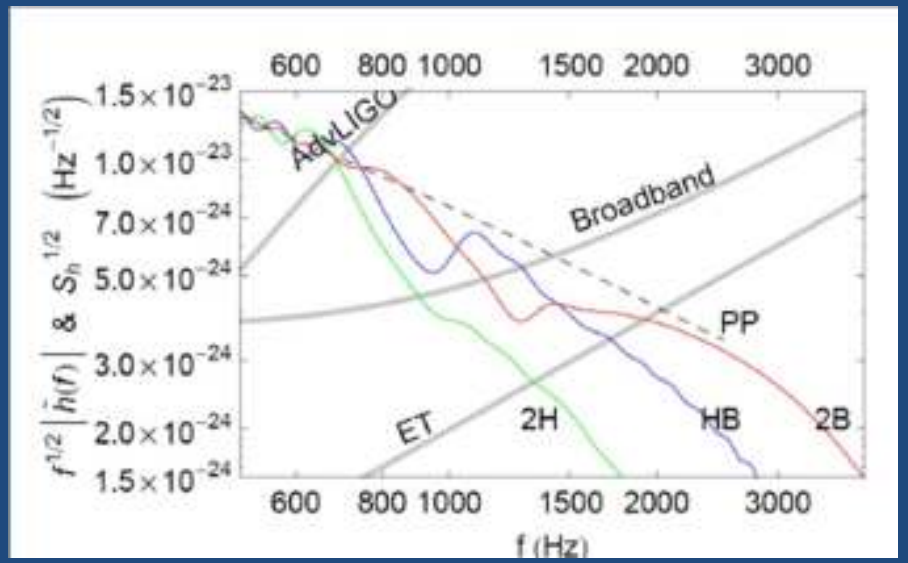


[Palenzuela et.al]

- Early on PN is enough
- then tidal effects visible, nonlinear effects
- then ‘bar’ structure. Strongly dependent on masses/EOS and more



[Hotokezaka et al 2012]

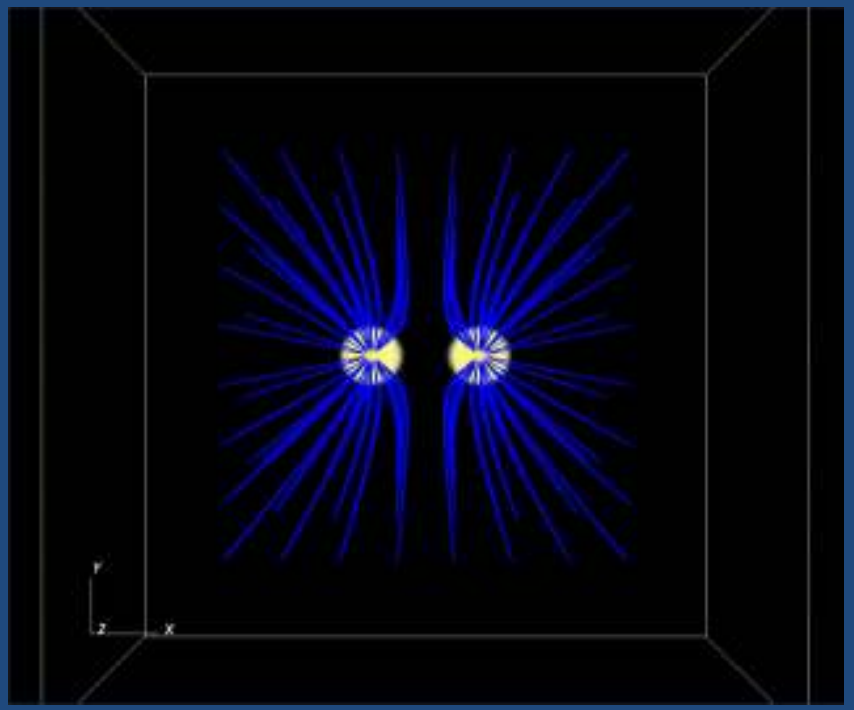


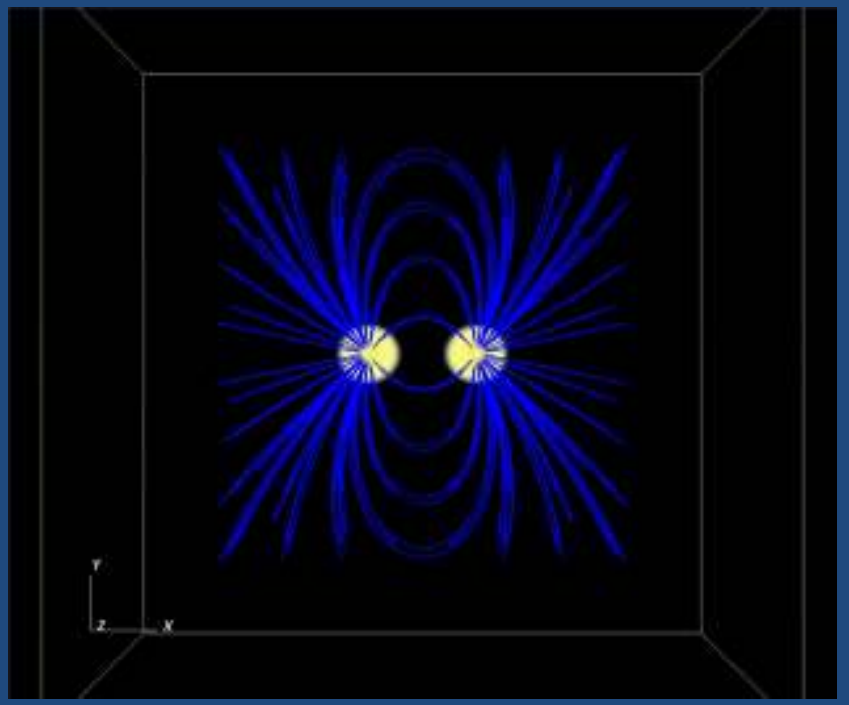
[Markakis et.al 2011], also Bausswein et al

NS-NS: what else can they do?

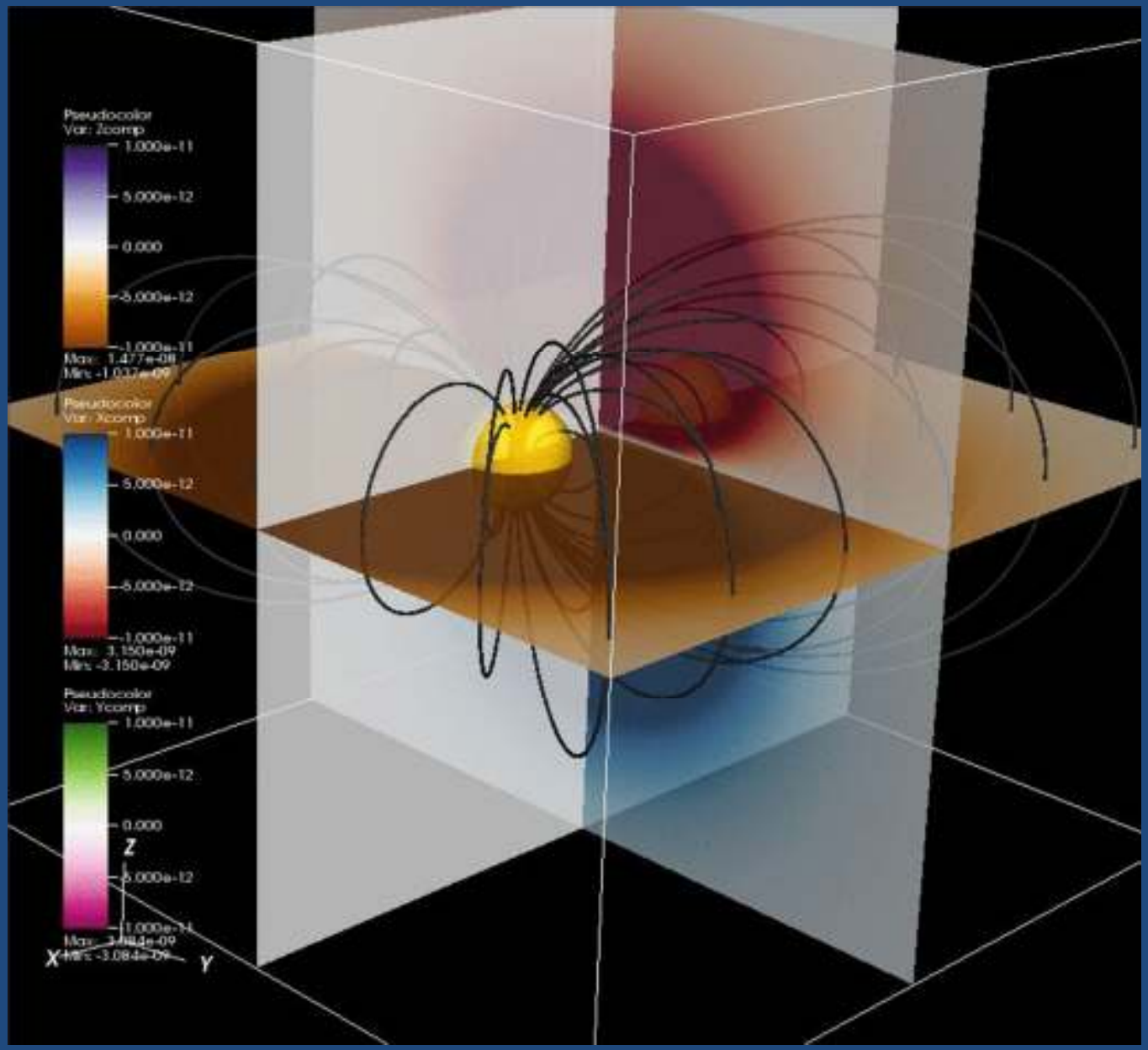
- These undergo a massive collision. Binding energy ~ $10^{52\text{-}53}$ ergs
- Such collision can 'pump up' fields to magnetar levels
- Possible channel for GRBs.
  - Disk size? OK*, but 'central' BH is mass bounded*
  - *final BH spin lower*? Stars aren't highly spinning.

- Further, magnetospheres can interact (uu/ud)





[Palenzuela,LL,Liebling,Ponce…]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Min: -1.037e-09
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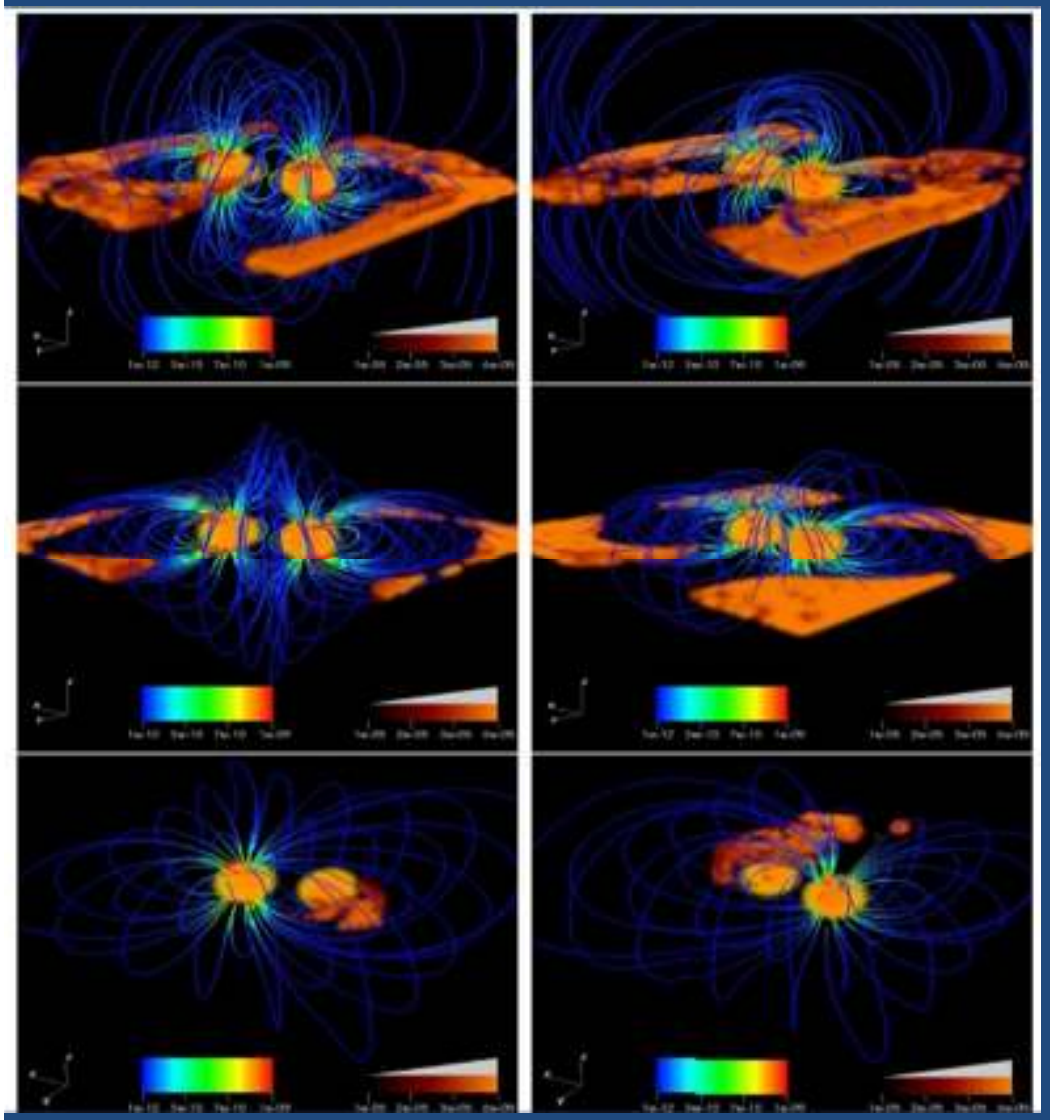
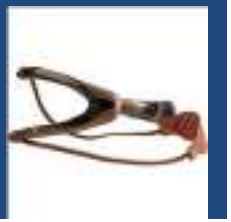
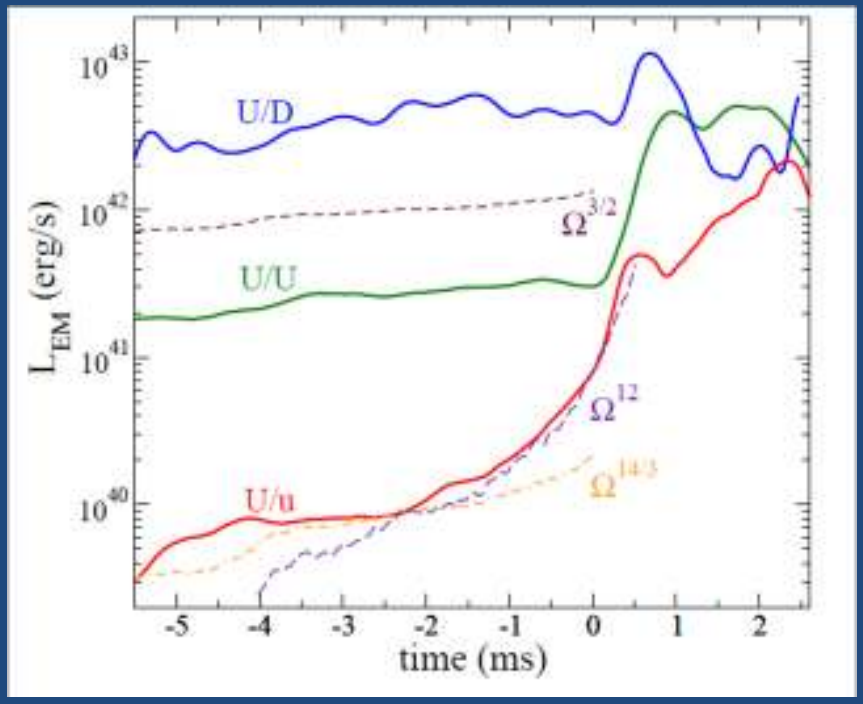


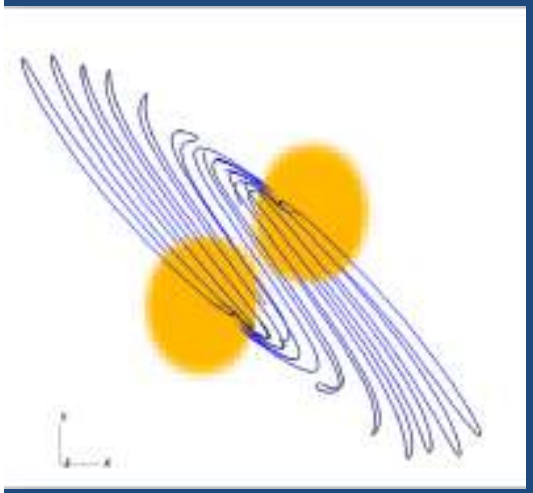
Current sheets, tied to:
Particle acceleration and
high energy emission
from pulsars, gamma rayy
flares, etc
[Uzdenski,McKinney,Spitkovsky
….]

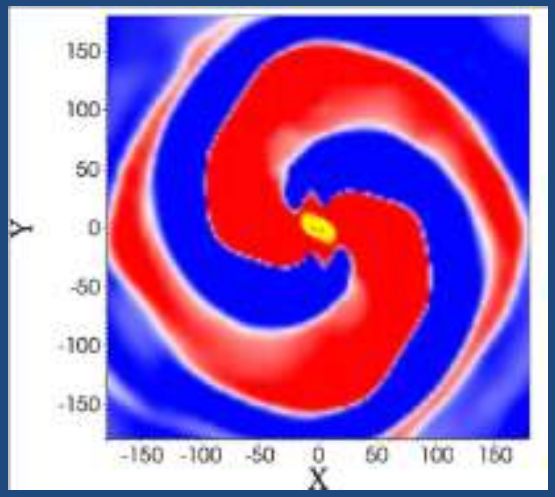
Here: structure tied to orbital
dynamics, ``spacetime tracer''



Energetics: B = 10^{11} G. equal mass 1.4 M_O





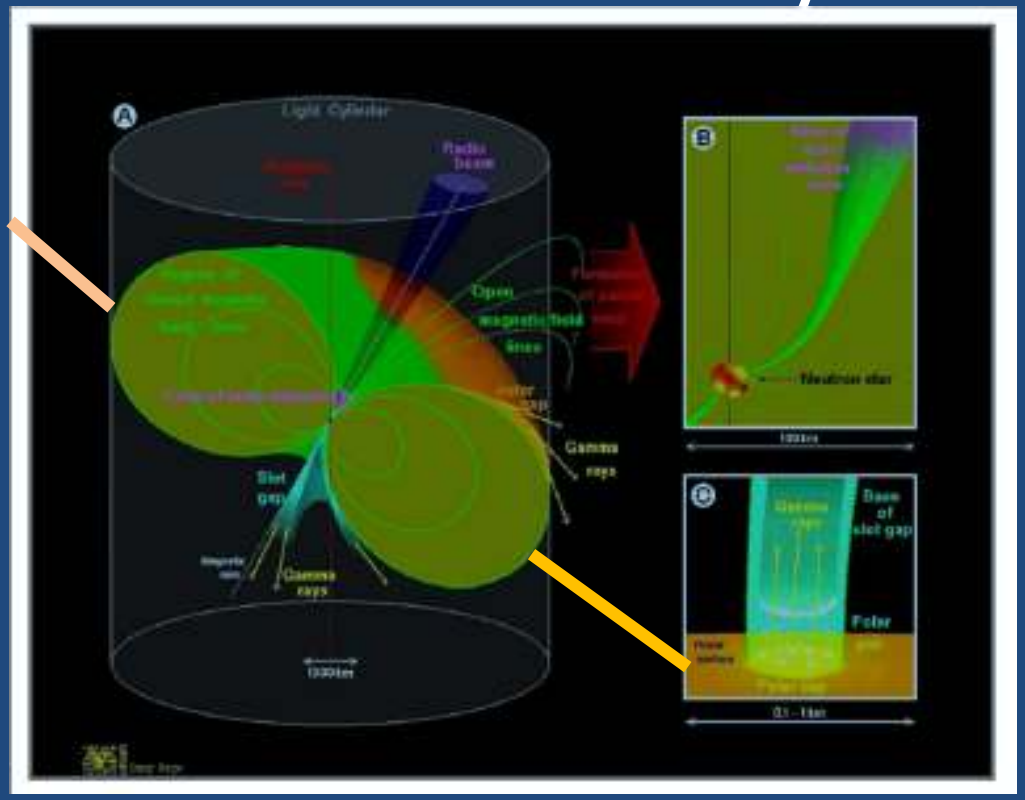


- Basic argument:
  $L \sim B^2 (R/a)^6 v^2 \sim B^2 \Omega^{14/3}$
  or … $\sim B^2 \Omega^{10/3}$
- Reconnections in missaligned case gives rise to stronger output
- Merger forces reconnections in generic scenarios

Radiation? Acceleration of charged particles; coherent radiation in radio. Optically thick -> black body radn

[c.f. Sironi-Spitkovsky]

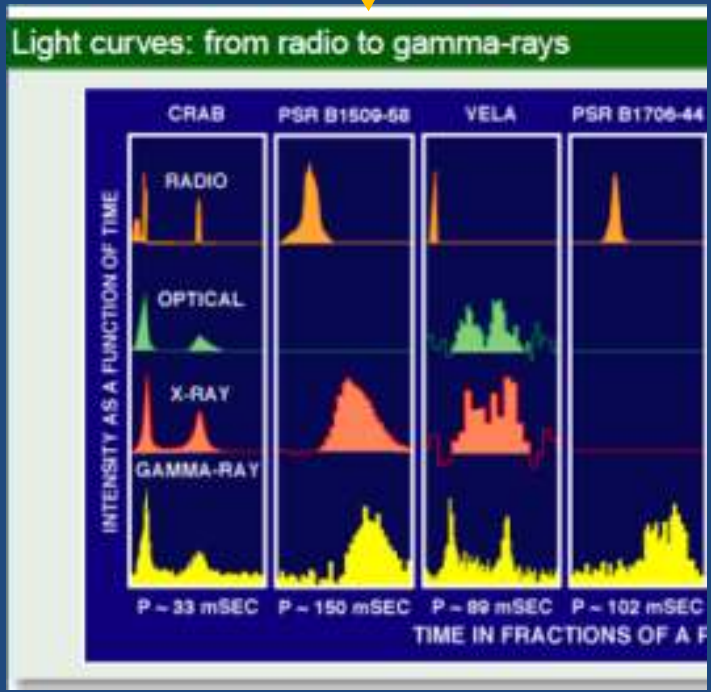
Guidance system. Pulsars



High energy emissions?

- Gap models
- Reconnection at current sheets
- …etc

handwavyness



But, they do even more…

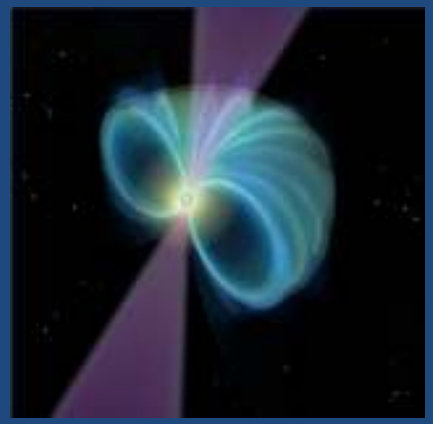
- As they merge, magnetic fields increase by orders of magnitude [Rosswog-Price, Anderson et al, AEI, …]

- Merged object is a hypermassive neutron star. Is it surrounded by plasma? A few ms afterwards

- Depending on the masses and eos: prompt or delayed collapse, even ‘stable’ configuration. (one can make several scenarios for GRBs fit here)

Single star collapse

- How does a star collapses and looses hair?
- What is the EM energetic behind it?
- When and how does it take place
  - *Old friend (aligned case)*
  - *$L \sim B^2 \Omega^4 R^6$*



Ang. Mom cons: *$\Omega \sim R^{-2}$* ; *Flux cons: $B \sim R^{-2}$*

→ *$L \sim L_o/R^6$* → *expect $5^6 \sim 10^4$ increase*

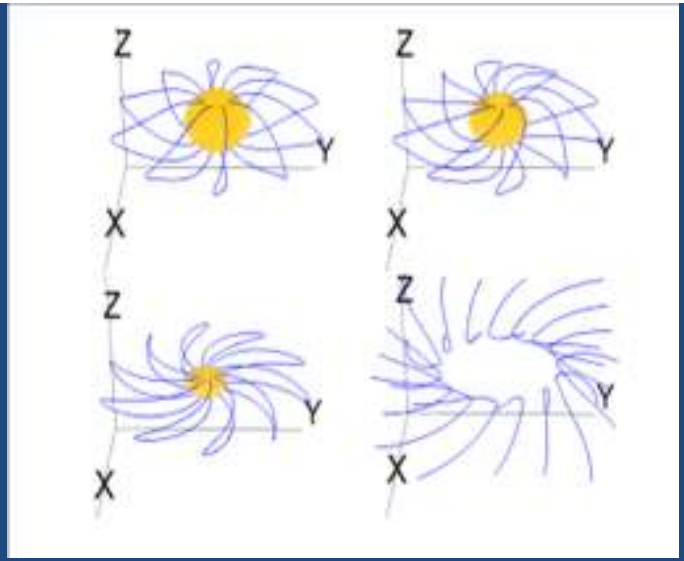
But… ignoring GR here, and assuming quasi-adiabatic process

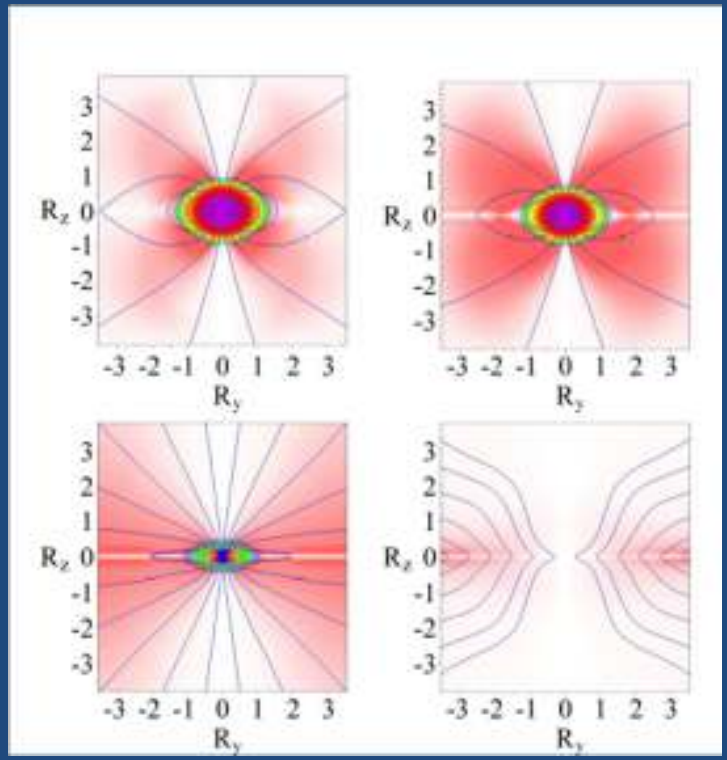
- Light cylinder closes in, but fields take time to adjust → differential rotation

- Region with 'open field lines' grows

- Field lines reconnect and GR has something to say on how.
  - L ~ 10^{49} erg/s $[B15]^2$ *[can it be the burst?, baryon loading?...]*

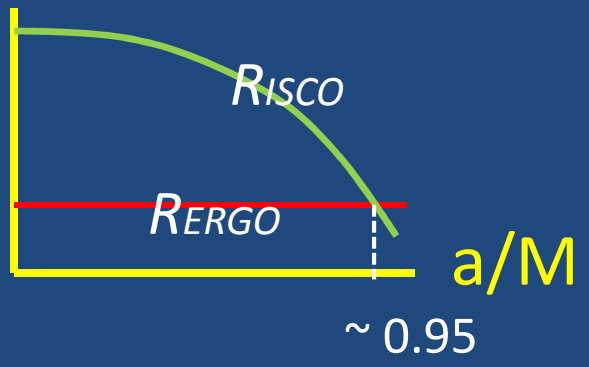
[LL,Palenzuela,Liebling,Thompson,Hanna '12]





BH-NS…

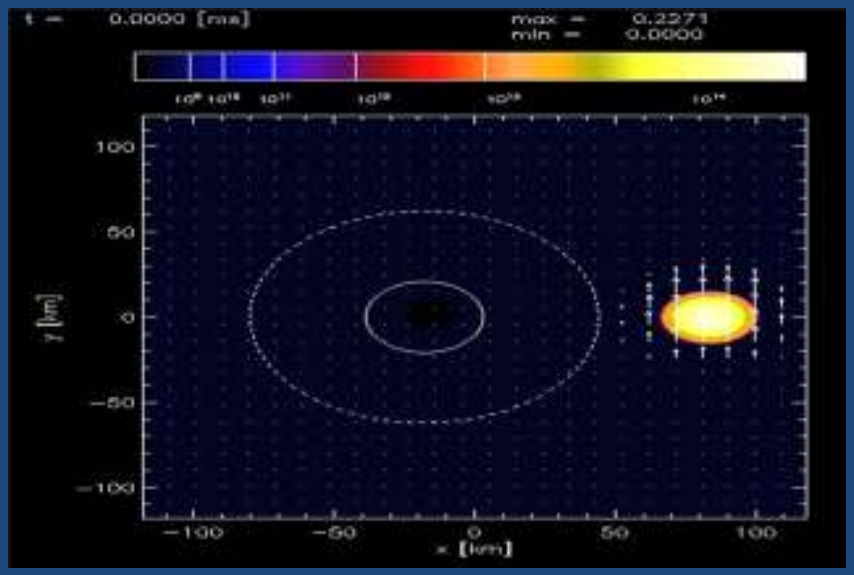
- Key aspects in the dynamics?
  - Roche vs. ISCO
  - R_{isco} =

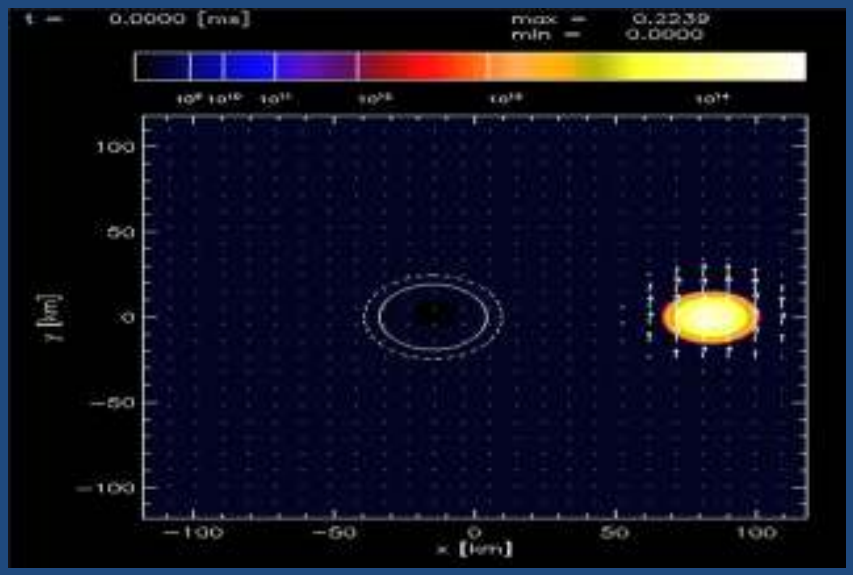


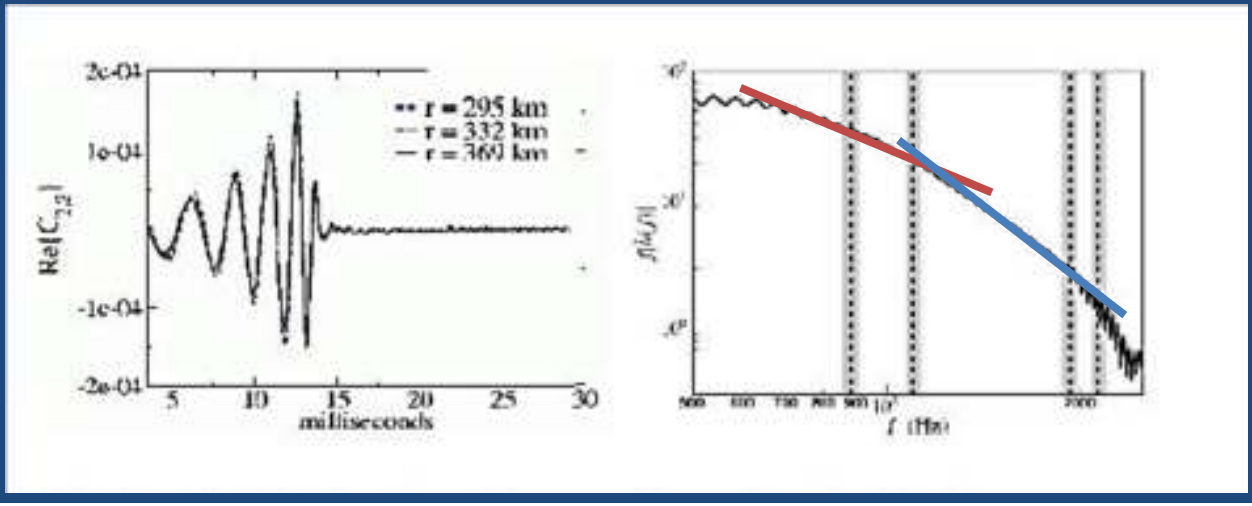
  - Final disk size?
    - Dependent on mass ratio, bh spin, if you want a sGRB better have high spin/or pray for low ratios [Shibata etal,Shapiro etal,Chawla etal,Foucart etal]
    - Magnetic fields not a huge effect, but topology? [Chawla et.al 2010,Etienne et al 2011]
    - Spin/Orbit missalignment? –significant differences only for large angles-- [Foucart 2010]

    - Timescales? Accretion rate? Magnetic field redistribution/enhancement?
    - Long term behavior? , ejecta, …

- Take a ‘sample’ case
  - $M_{NS} = 1.44\ M_o$; $M_{BH} = 7\ M_{o;}$ $a = \{0, 0.5\}$, $B = \{0, 10^{12}\}G$





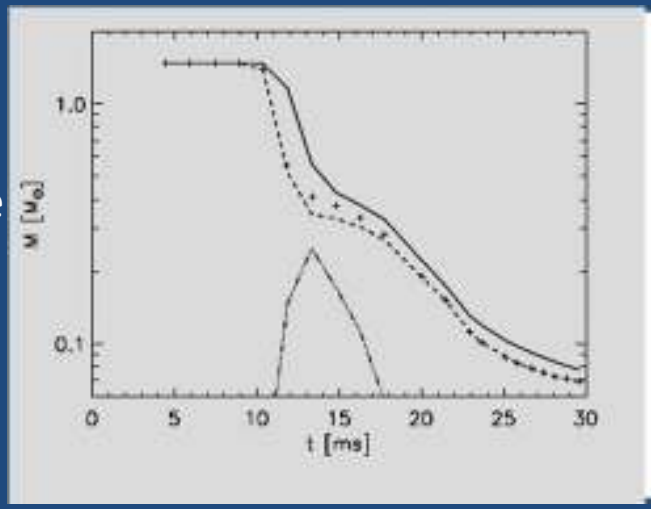


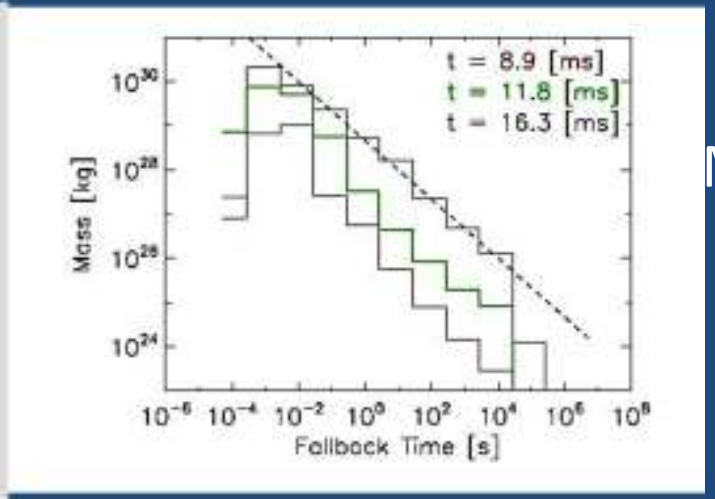
Slopes: -1/6 (pre-isco),
-3/5 (pre-QNM)

[see Lackey etal, ‘13]

- But waves aren't necessarily the 'sexiest' outcomes...

__ Mass
>isco +
-- < v_escape
X 4 unbound



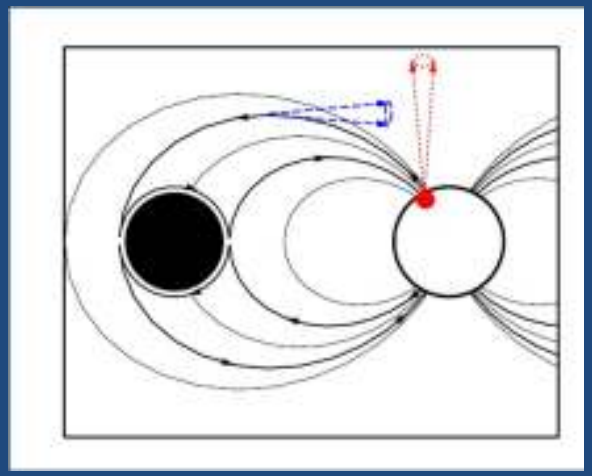


$M_{,t} \sim t^{-5/3}$

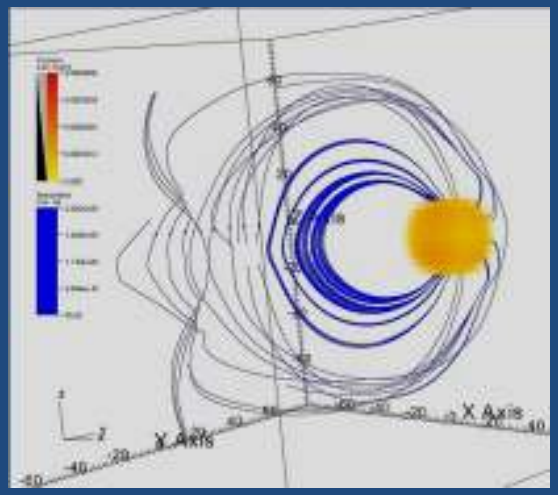
- 99% material 'back' by 10s; 99.99% in 3hrs. More mass, if magnetized, after ~ 30ms (angular momentum redistributed)
- Final BH spin ~0.56 (rough estimates possible)
- 10^{-2}-10^{-1}s hyperaccretion. Fireball model?
- <10^{2}s sufficient mass falls back for emissions through r-procs (opacity?)
- ~ 10^{-2} M_o still around for GRB models.
- MUST make contact with 'fixed background' sims [Narayan,Broderick]

Further fun...(spin is optional)

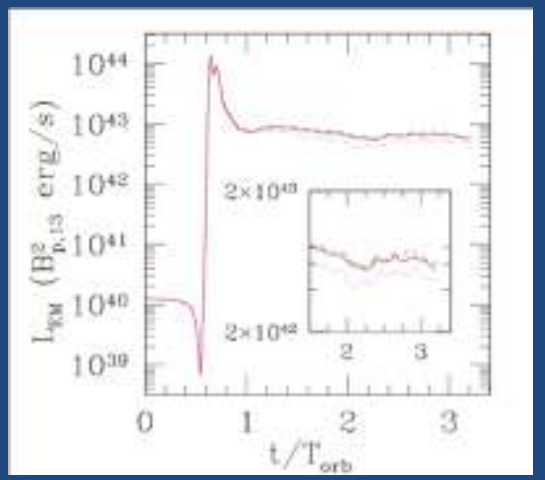
Before the merger….BH moves on NS generated field.



[McWilliams-Levi ‘11]



[Anderson,Palenzuela,LL,Liebling,…’11]



[Paschalidis,Etienne,Shapiro ‘13]

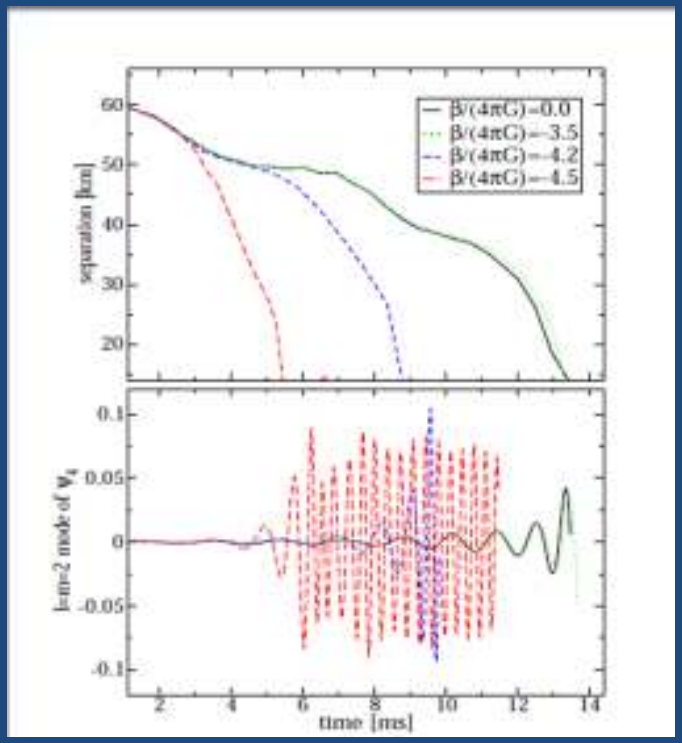
$L \sim B^2v^2$ ($v^2 \sim r^{-1}$, $B^2 \sim r^{-6}$) but $B_o \sim 10^{12}$G -> $L_p \sim 10^{42\text{-}44}$ erg/s

--- synchro/curvature radiation is possible

--- further phenomena : reconnections, joule heating, etc.

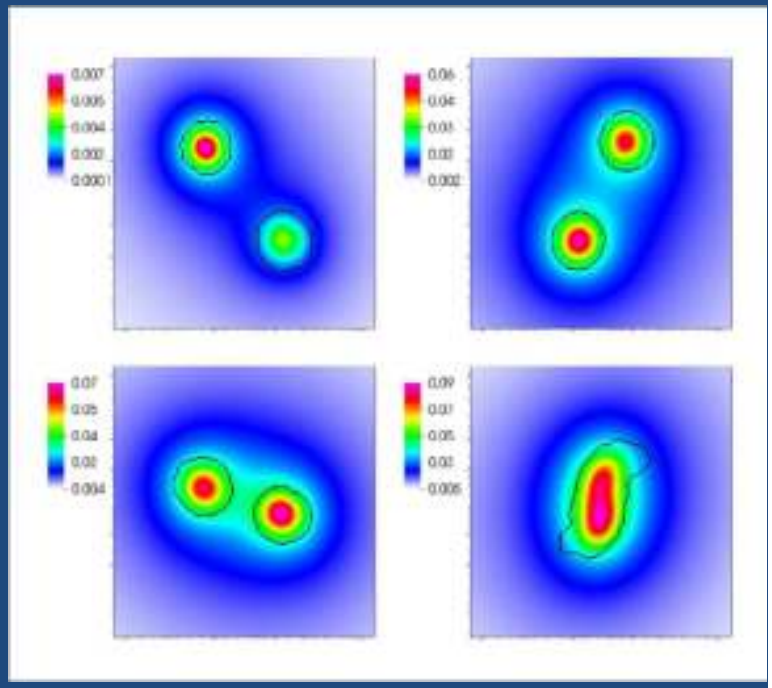
What is GR is not correct?
GWs will tell us so, but maybe also EM waves

- Scalar-tensor theories [Fierz-Jordan-Brans-Dicke,Damour-Esposito-Farese,…]
  - Gravity mediated by usual tensor degrees of freedom + a non-minimally coupled scalar field
  - Basics of these theory arise naturally within string theory
  - New phenomenology :
    - Dipole radiation
    - Spontaneous scalarization → provides a non-trivial ‘scalar charge’ to compact stars
    - While significantly constrained by solar and pulsar tests, interesting parameter space remains
    - Non-linear interactions largely unexplored → more ‘generic’ scalarization possible! [Barausse etal, Sotiriou etal]



- Dipole radiation modifies dynamical behavior.
- Important deviations from GR behavior (eg separation and grav wave signals)

- Interaction between differently scalarized stars induces a dynamical readjustment of charges to become equal



[Barausse,Palenzuela,Ponce,LL 2013]

- GWs for BH-NS & NS-NS are ‘roughly’ at hand. Depending on the qn… things are good, OK, or incomplete
- Considering further physics illustrates several channels for further interesting physics that can trigger EM counterparts
- Rich scenarios for theorists to ‘make stuff up’, already definitive connections with observations!
- → differences between BH-NS & NS-NS, at least intriguing prospects for differentiating EM signals already