Coalescing binaries in numerical relativity: BH-BH

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Plan of the talk

- An (ultra) brief review of numerical relativity

- Selected topics on the dynamics of binary BHs
  - ✶final spin
  - ✶final recoil

- Selected topics on EM counterparts
  - ✶ pre-merger emission
  - ✶ post-merger emission

NR necessary to solve accurately this problem

NR solves Einstein equations in those regimes in which no approximation holds. We build codes which we consider our "**theoretical laboratories**"

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$$R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu} \qquad (\text{field eqs}: \ 6+6+3+1)$$

$$\nabla_\mu T^{\mu\nu} = 0 \ , \qquad (\text{cons. en./mom.}: \ 3+1)$$

$$\nabla_\mu (\rho u^\mu) = 0 \ , \qquad (\text{cons. of baryon no}: \ 1)$$

$$p = p(\rho, \epsilon, \ldots) \ . \qquad (\text{EoS}: \ 1+\ldots)$$

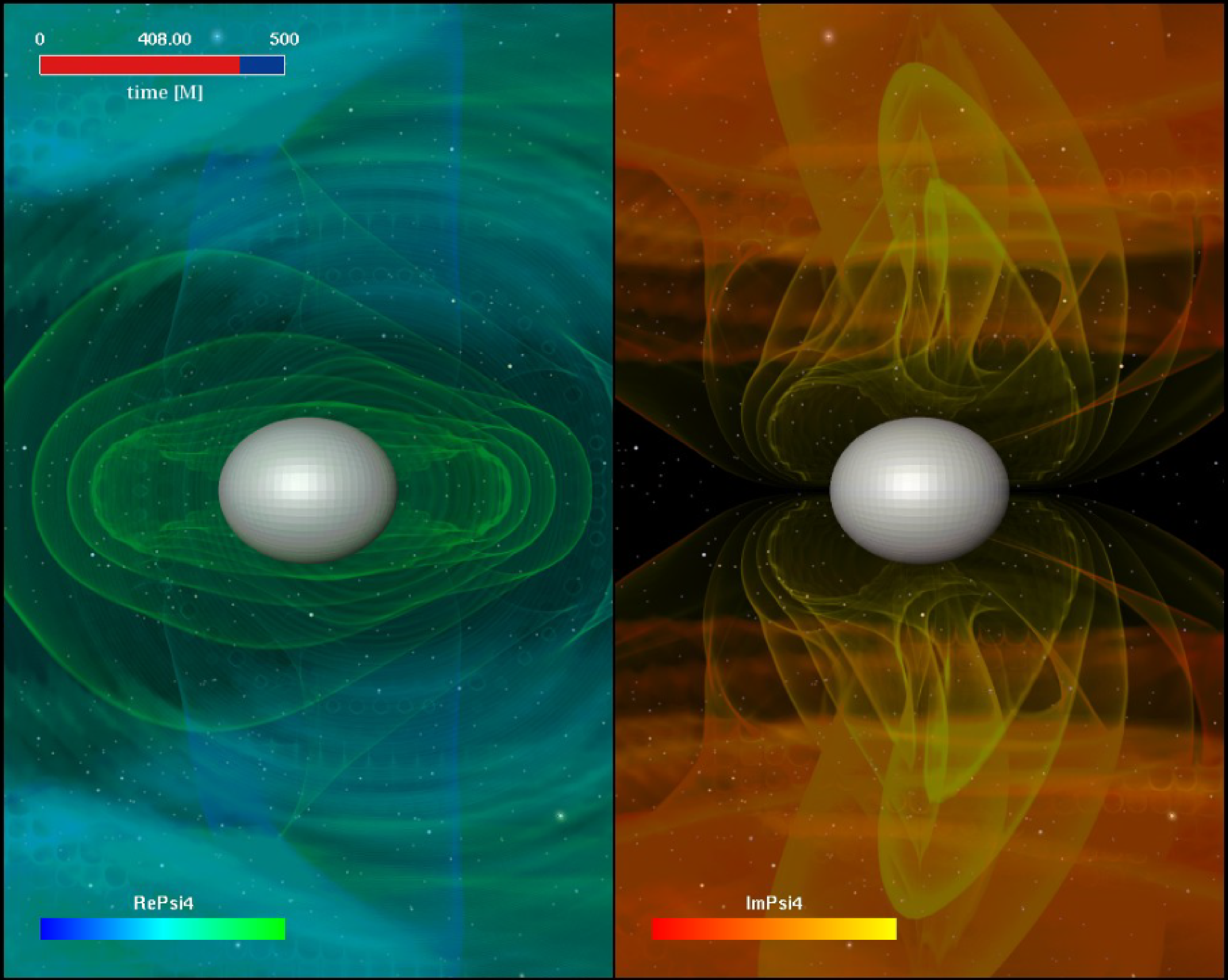
$$\nabla^*_\nu F^{\mu\nu} = 0, \qquad (\text{Maxwell eqs.}: \ \text{induction}, \ \text{zero div.})$$

$$T_{\mu\nu} = T^{\text{fluid}}_{\mu\nu} + T^{\text{em}}_{\mu\nu} + \ldots$$

Binary black holes have not been observed but they are expected to exist.

They are the strongest sources, though not the most common.

Binary Black Holes

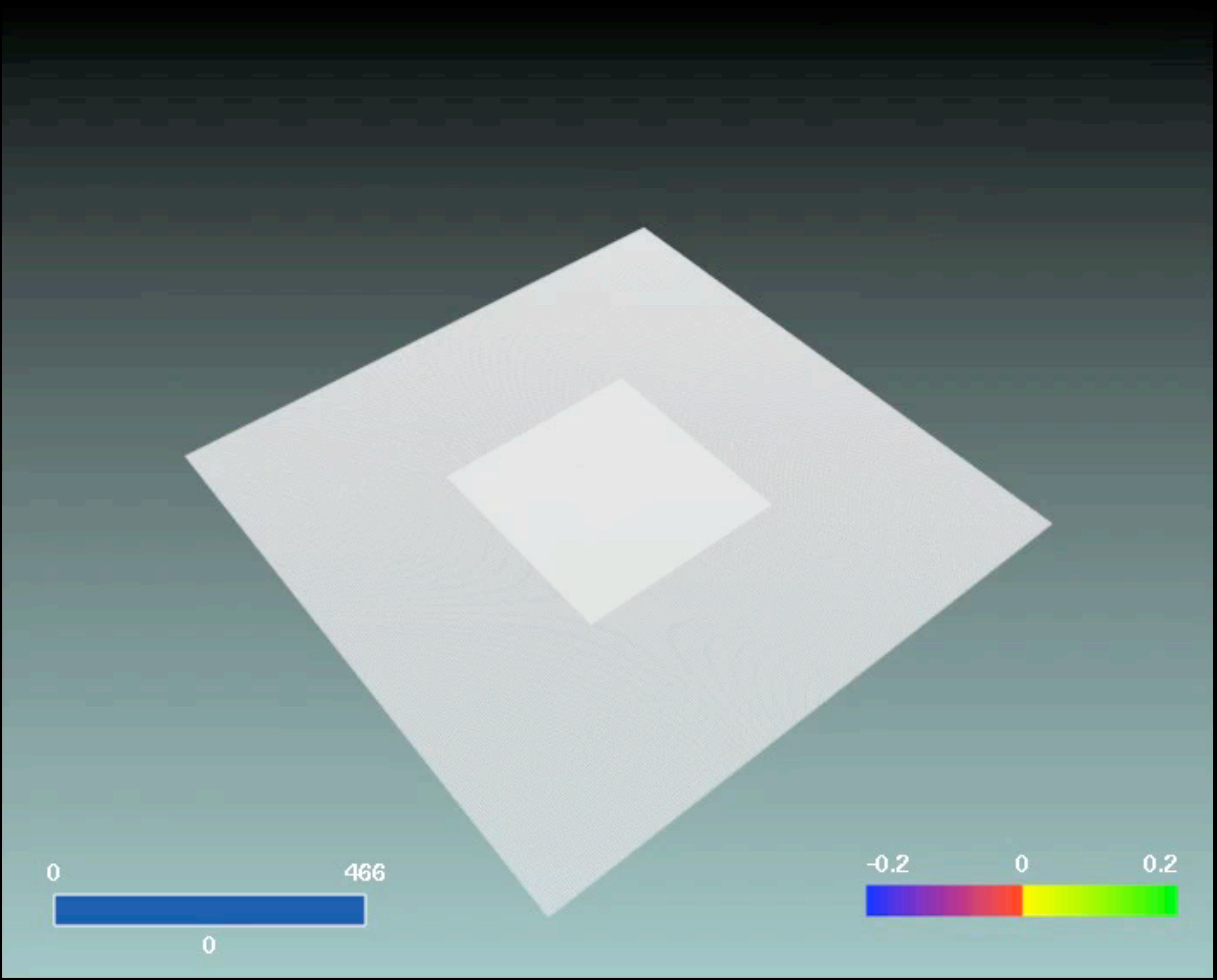


In vacuum the Einstein equations reduce to

$$R_{\mu\nu} = 0$$

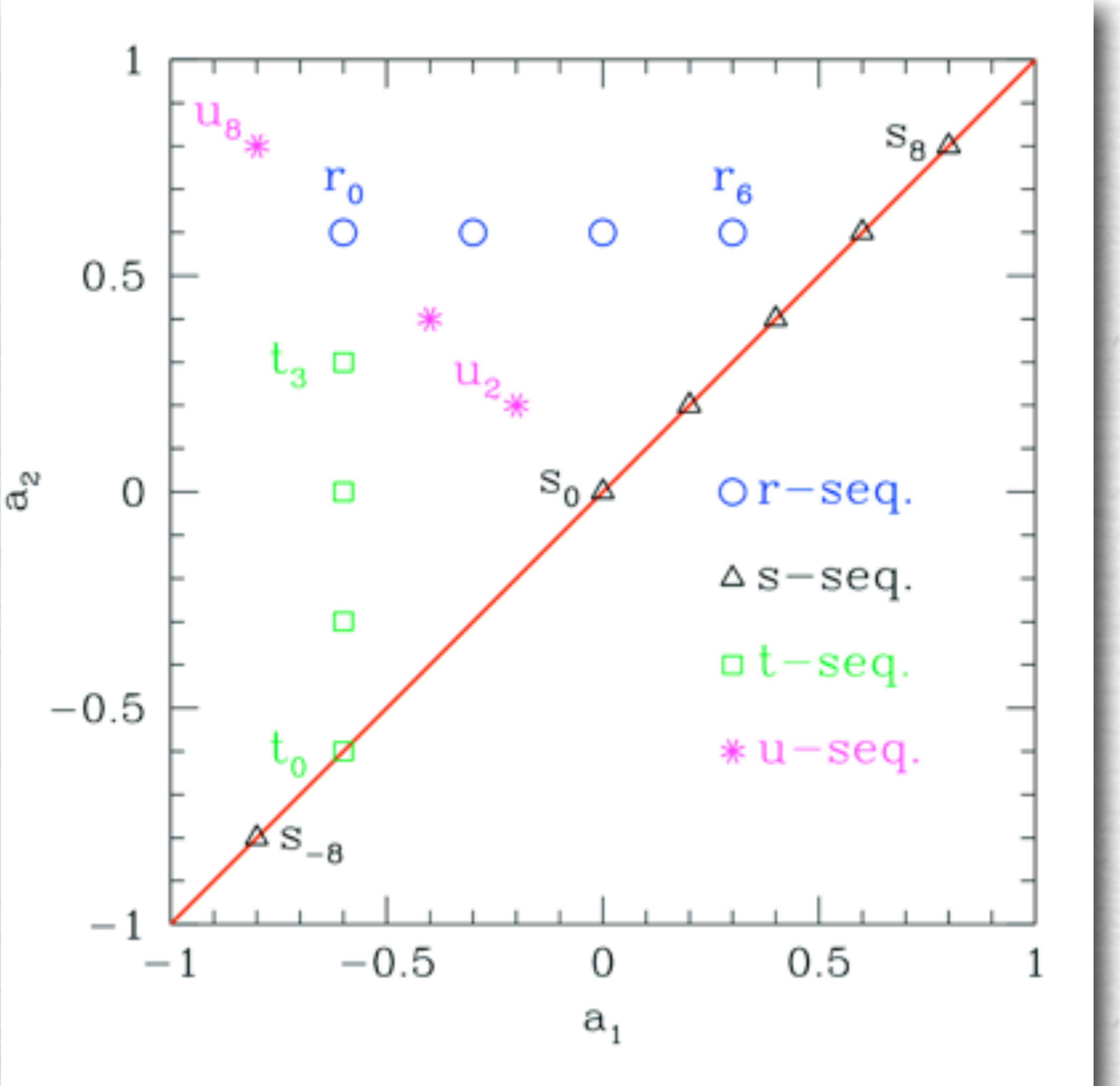
How difficult can that be?

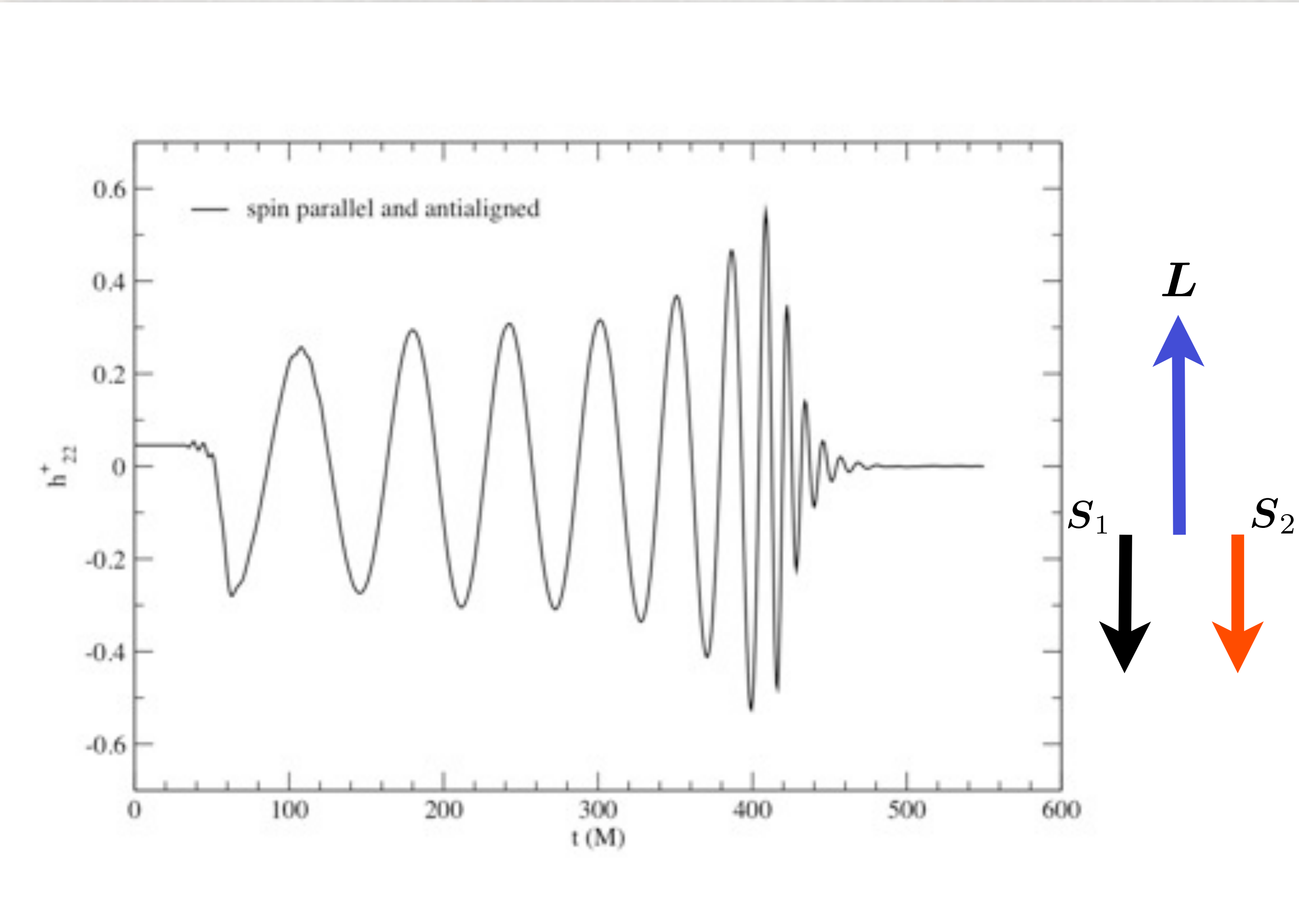
Animation by Kaehler, Reisswig, LR

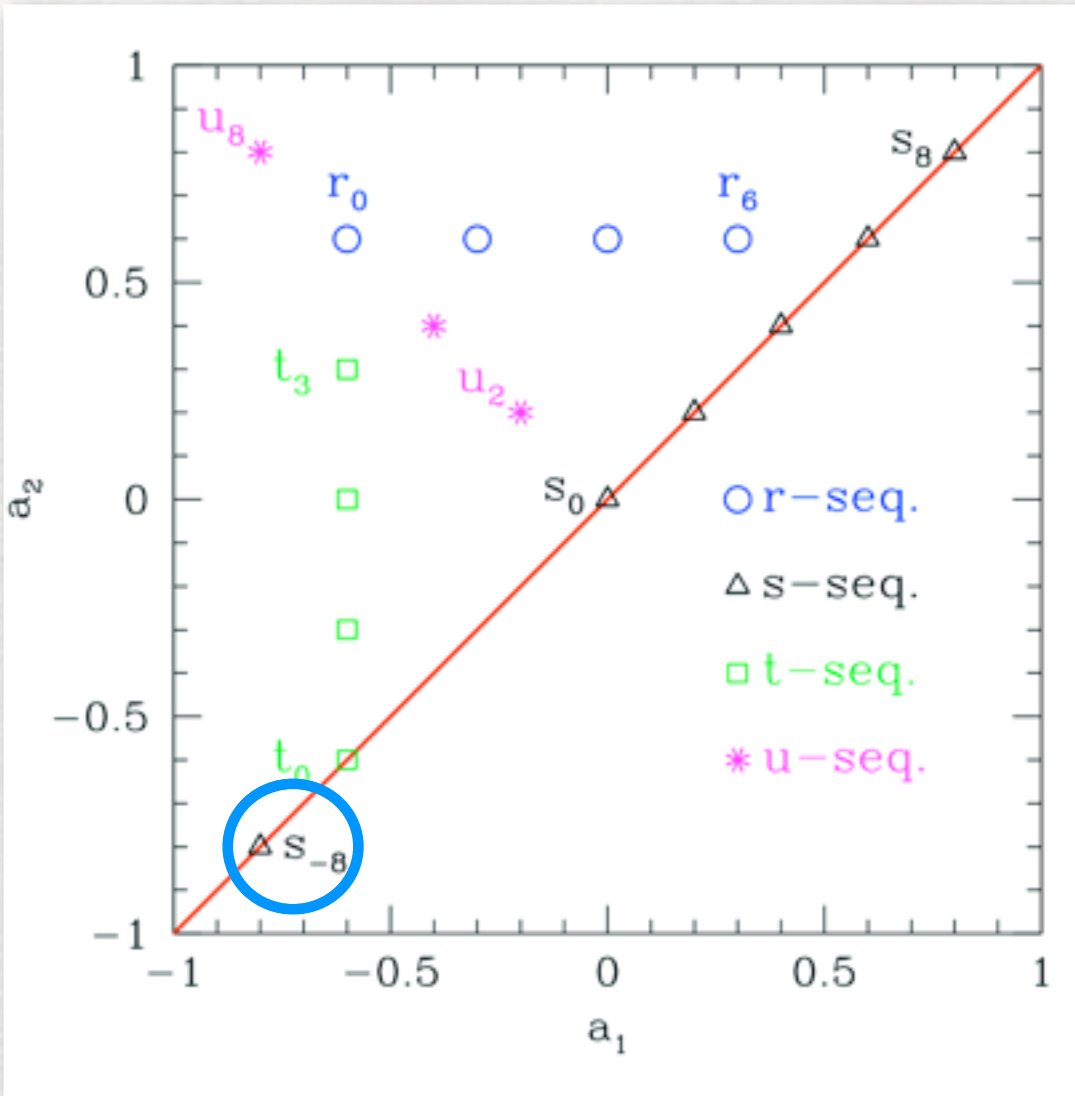

0
466
0
-0.2
0
0.2

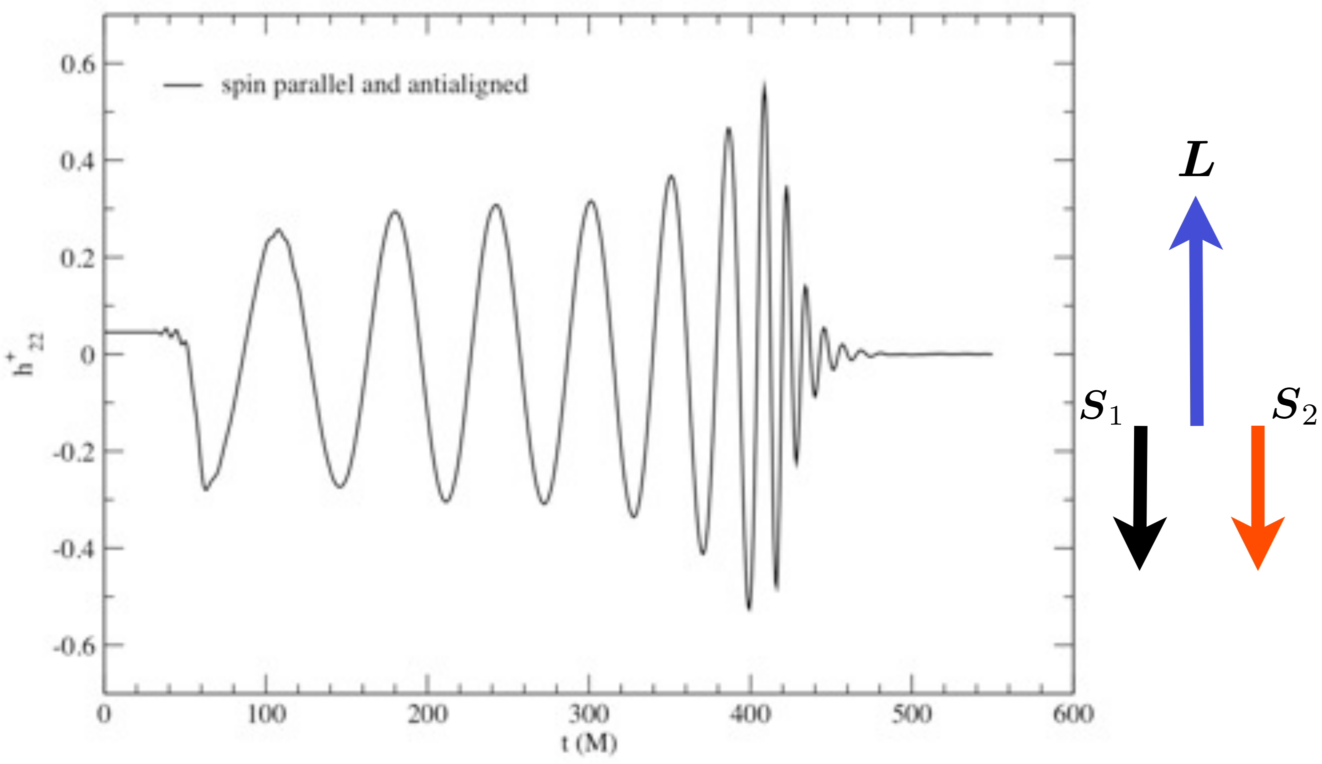
For a number of different reasons, **aligned binaries** (ie binaries with spins aligned with the orbital angular momentum) may be the most common ones in astrophysics.

The space of parameters is 2D and we refer to it as the "spin diagram"

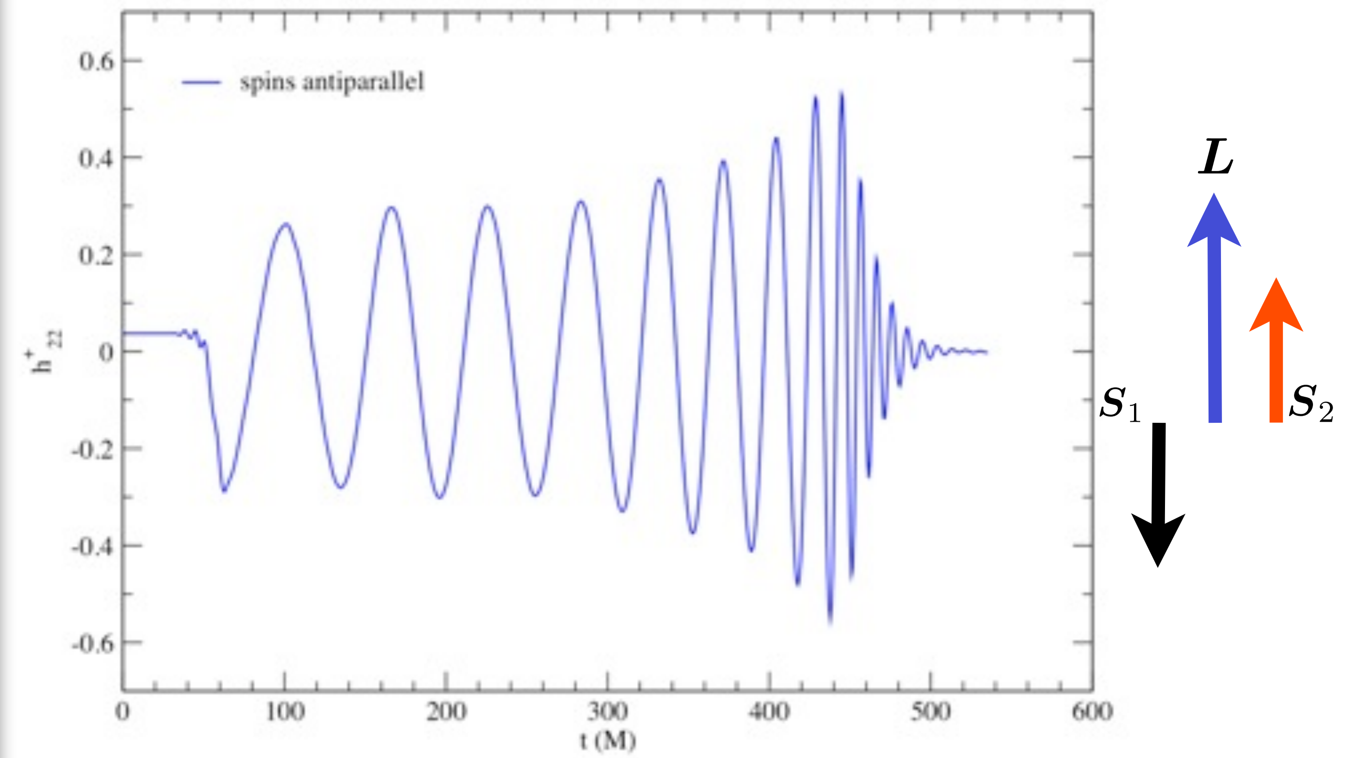



spin parallel and antialigned
h^+_{22}
t (M)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0
100
200
300
400
500
600
$\boldsymbol{L}$
$\boldsymbol{S}_1$
$\boldsymbol{S}_2$

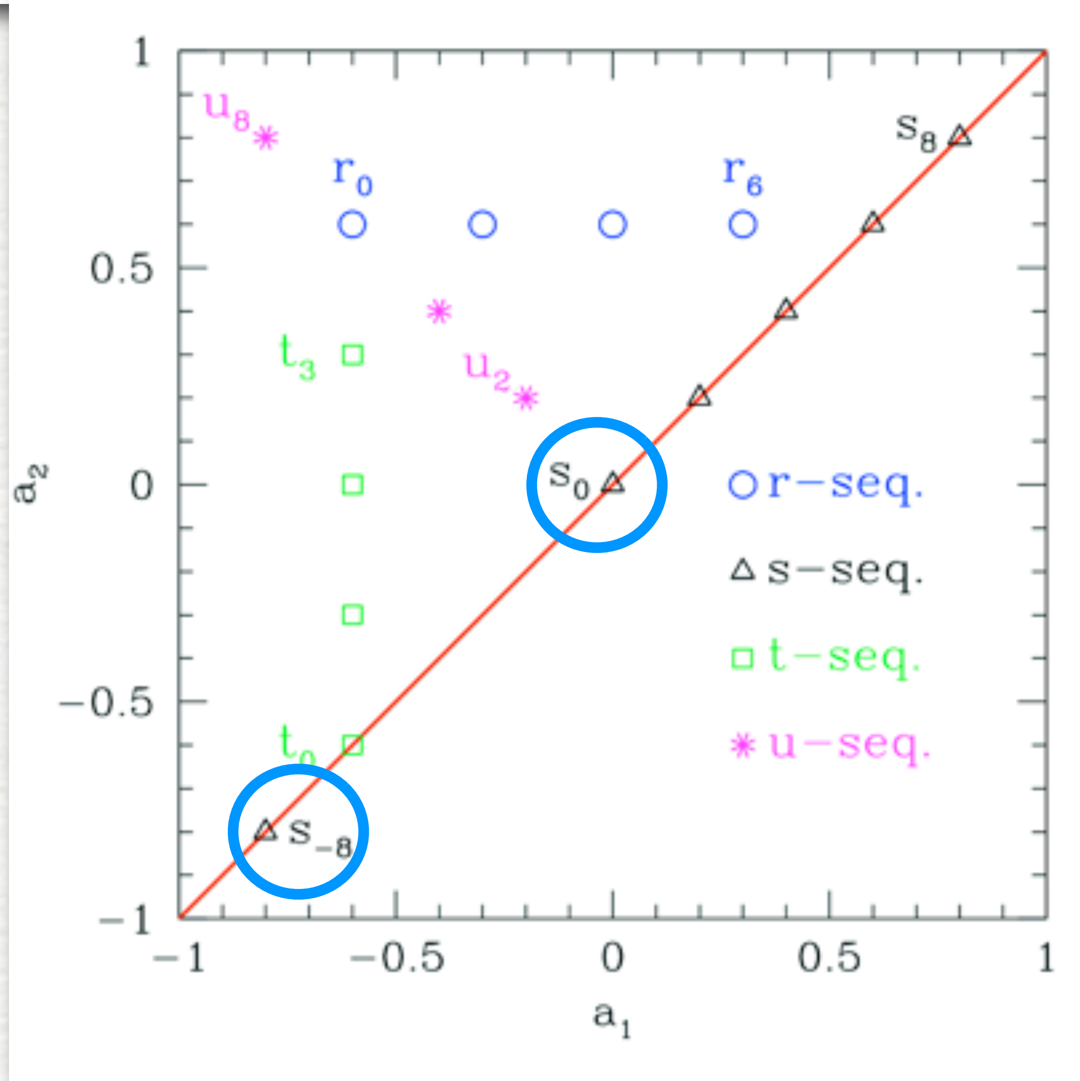

a_2
a_1
1
0.5
0
−0.5
−1
u_8
u_2
r_0
r_6
s_8
s_0
s_{-8}
t_3
t_0
r−seq.
s−seq.
t−seq.
u−seq.



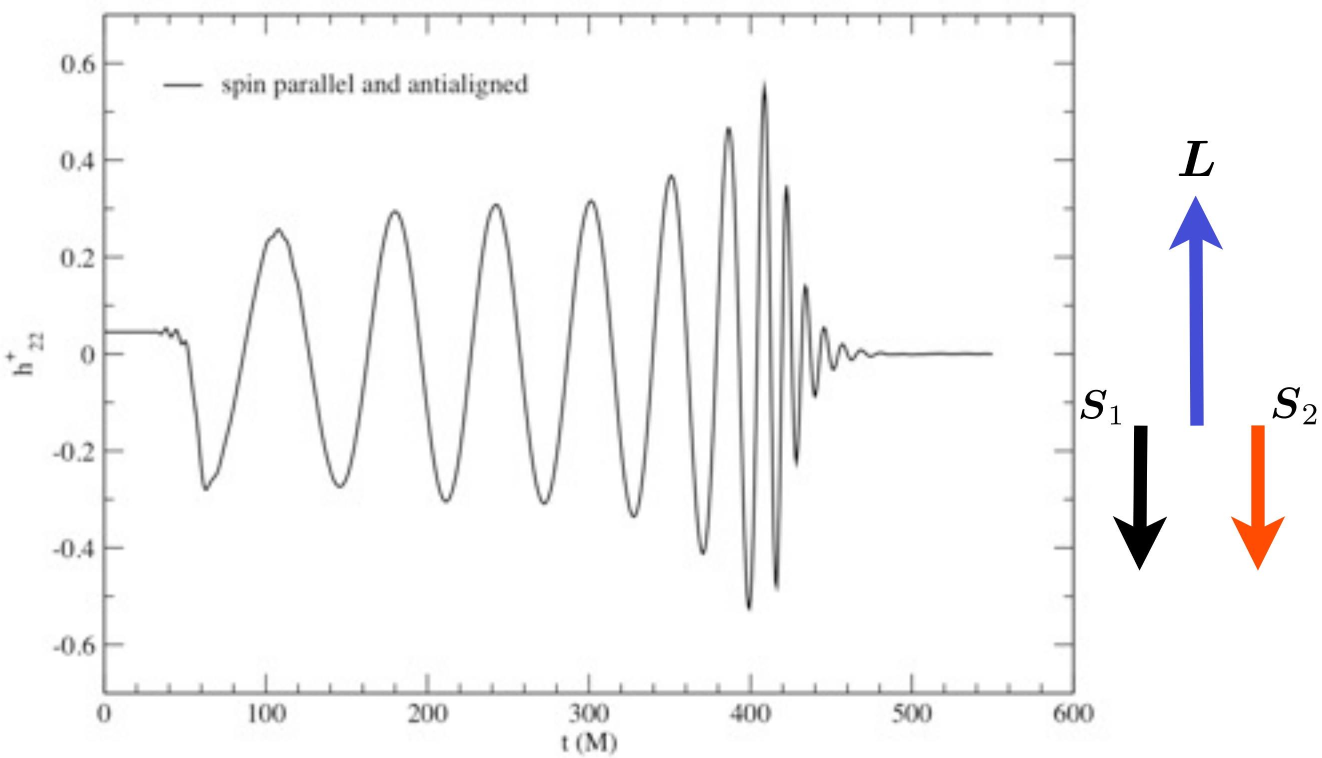
spin parallel and antialigned
h^+_{22}
t (M)
L
S_1
S_2

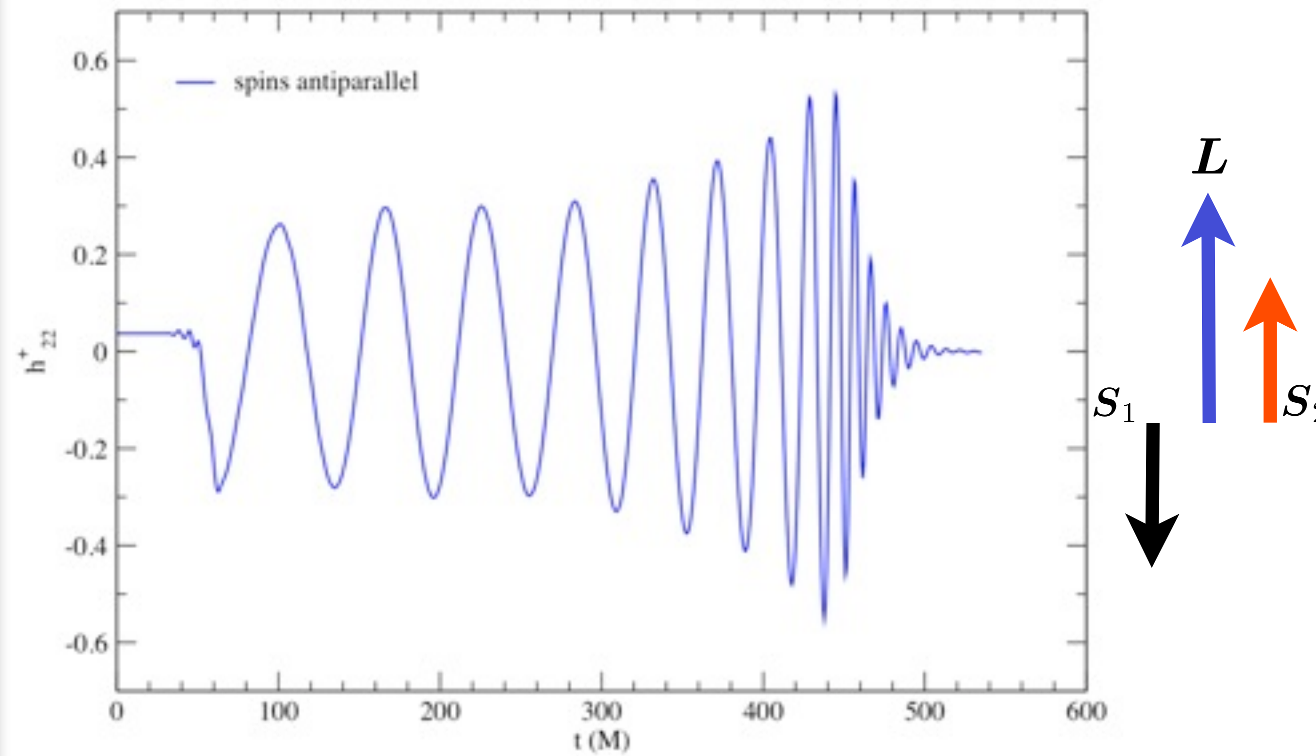


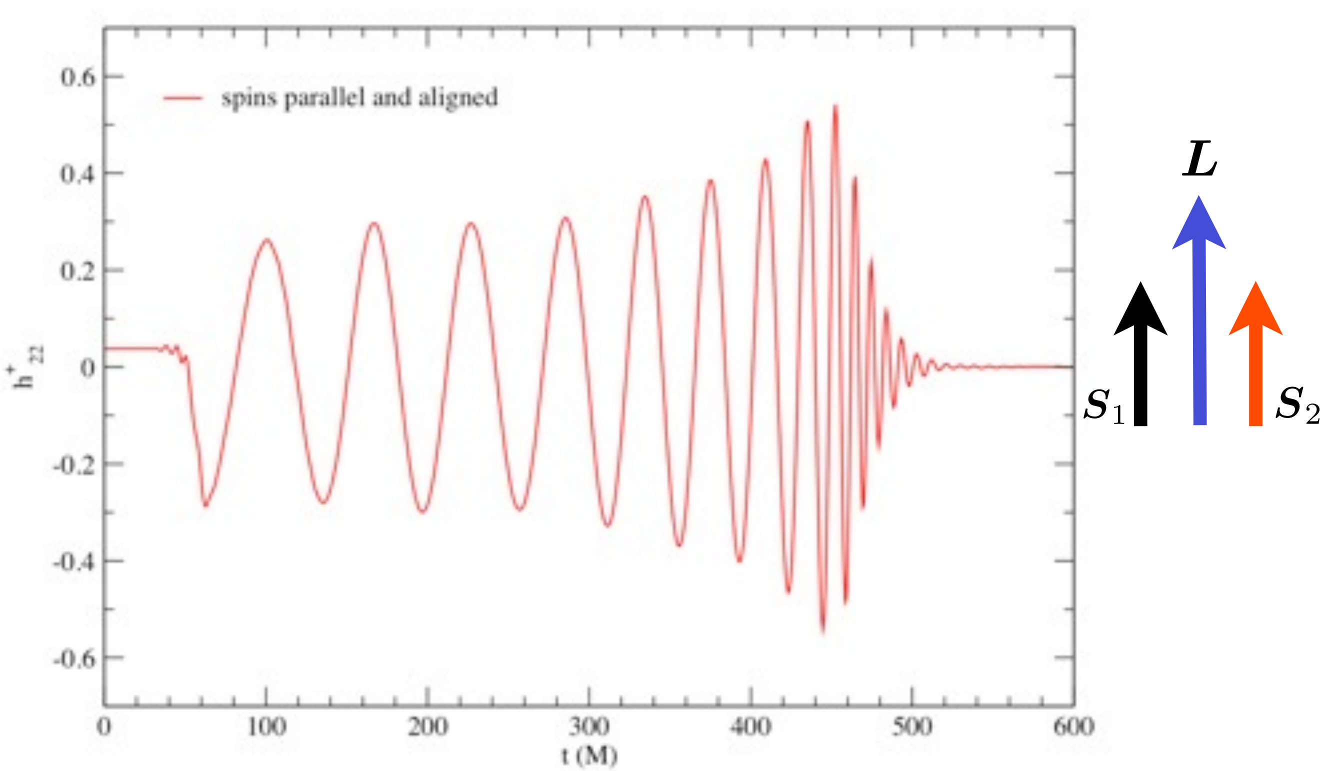
spins antiparallel
h^+_{22}
t (M)
L
S_1
S_2

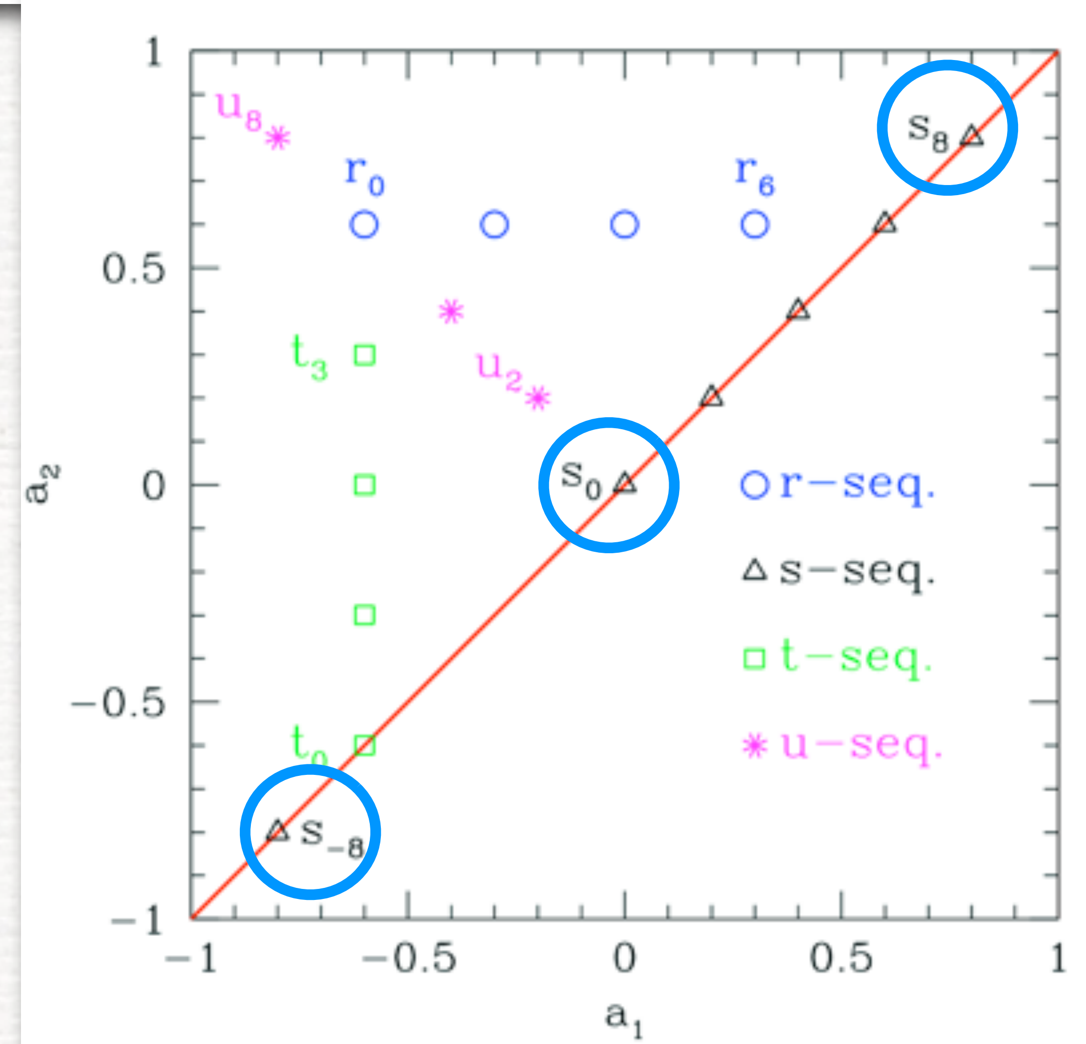


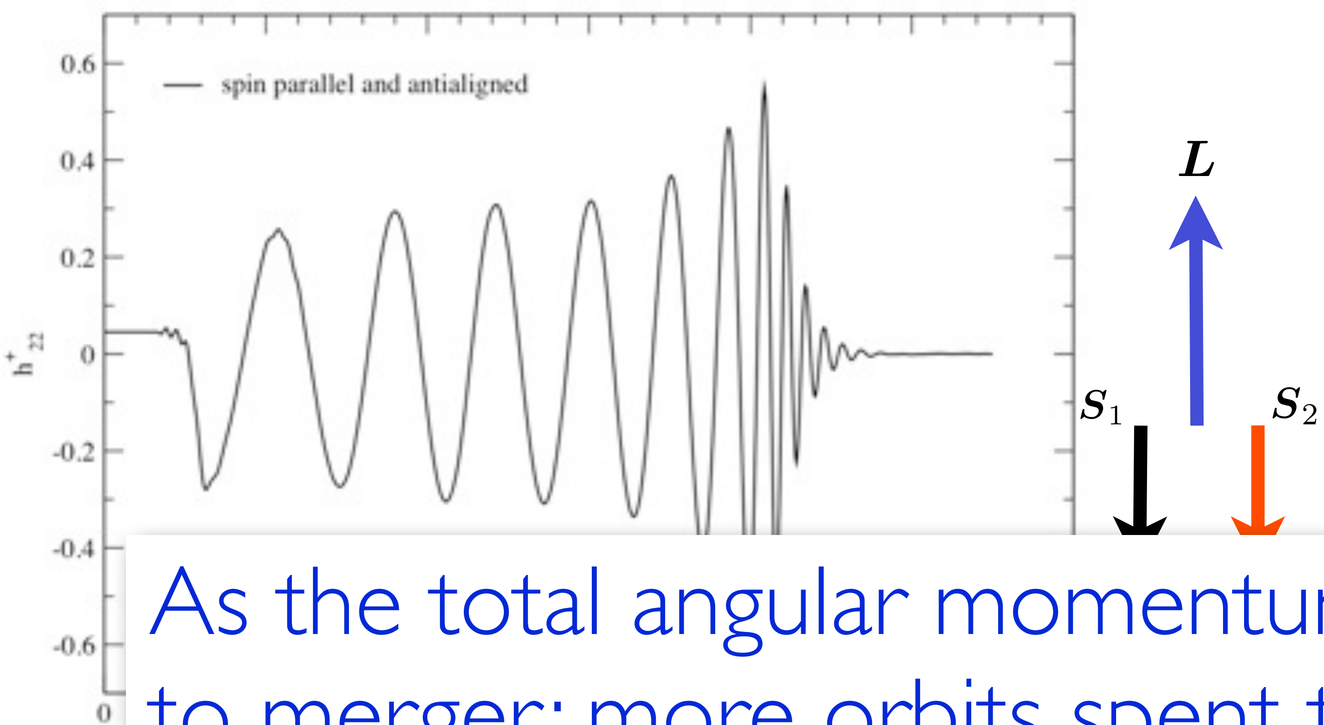
u_8
r_0
r_6
s_8
t_3
u_2
s_0
t_0
s_{-8}
r−seq.
s−seq.
t−seq.
u−seq.
a_1
a_2

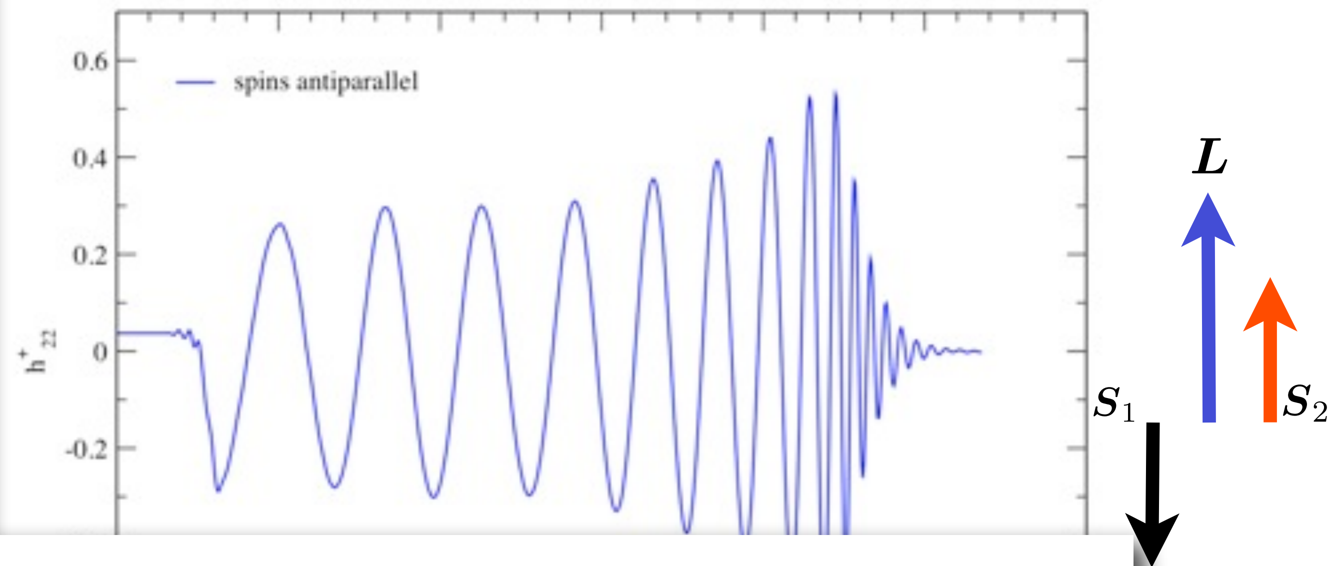

spin parallel and antialigned
h+22
t (M)
L
S1
S2


spins antiparallel
h+22
t (M)
L
S1
S2


spins parallel and aligned
h+22
t (M)
L
S1
S2

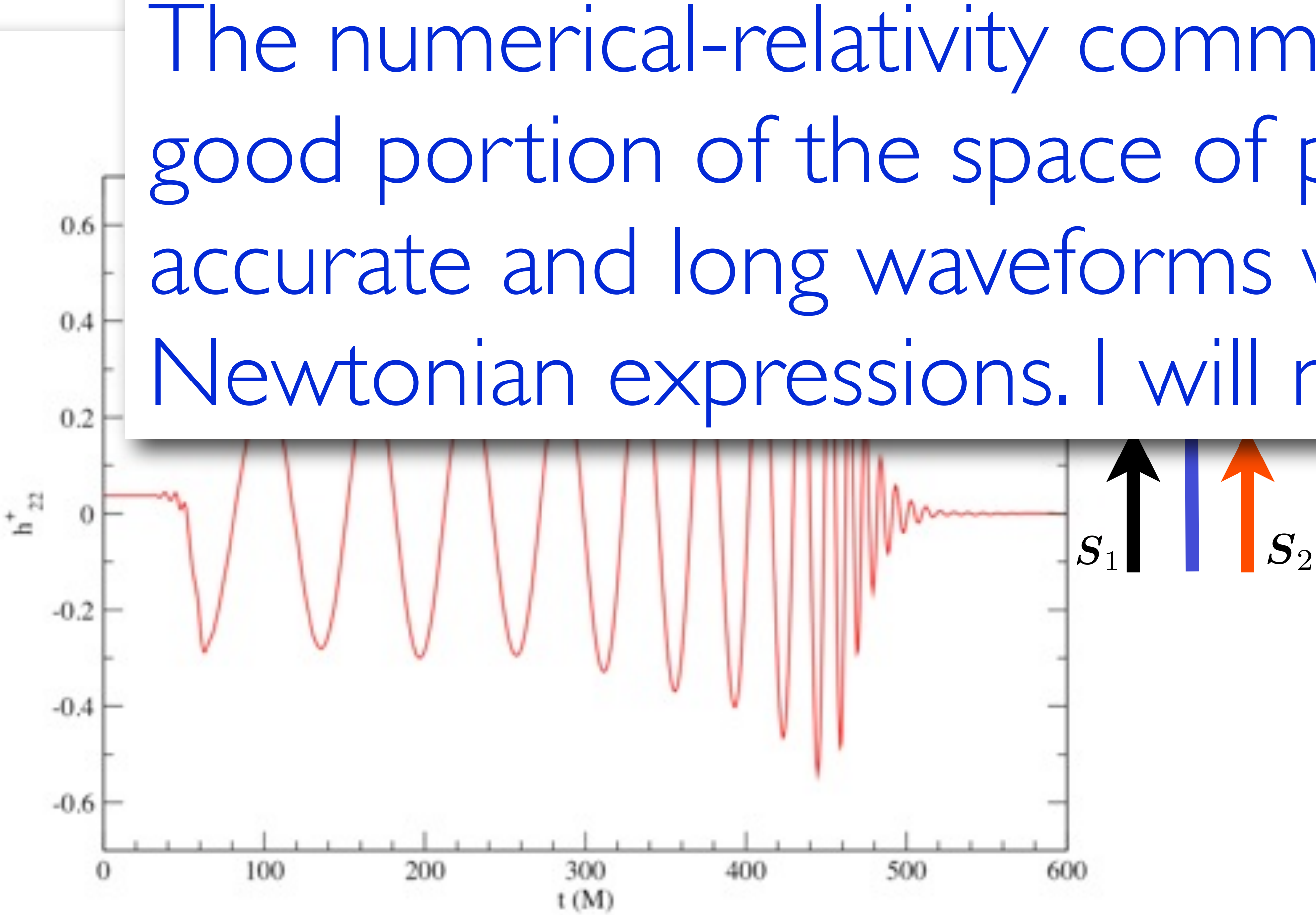

u8
r0
r6
s8
t3
u2
s0
t0
s-8
r−seq.
s−seq.
t−seq.
u−seq.
a2
a1

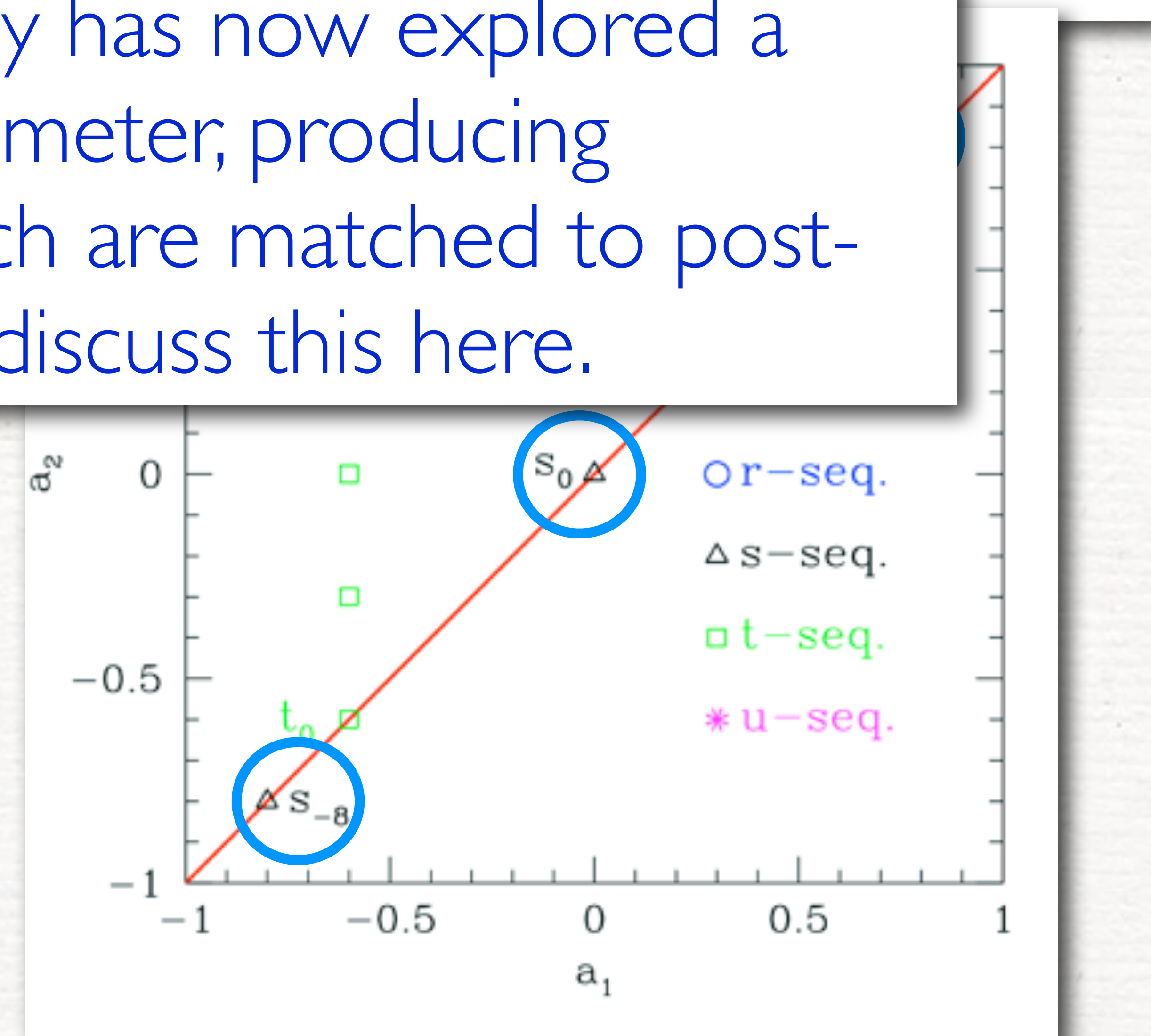




As the total angular momentum is increased, so is the time to merger: more orbits spent to lose angular momentum.

The numerical-relativity community has now explored a good portion of the space of parameter, producing accurate and long waveforms which are matched to post-Newtonian expressions. I will not discuss this here.

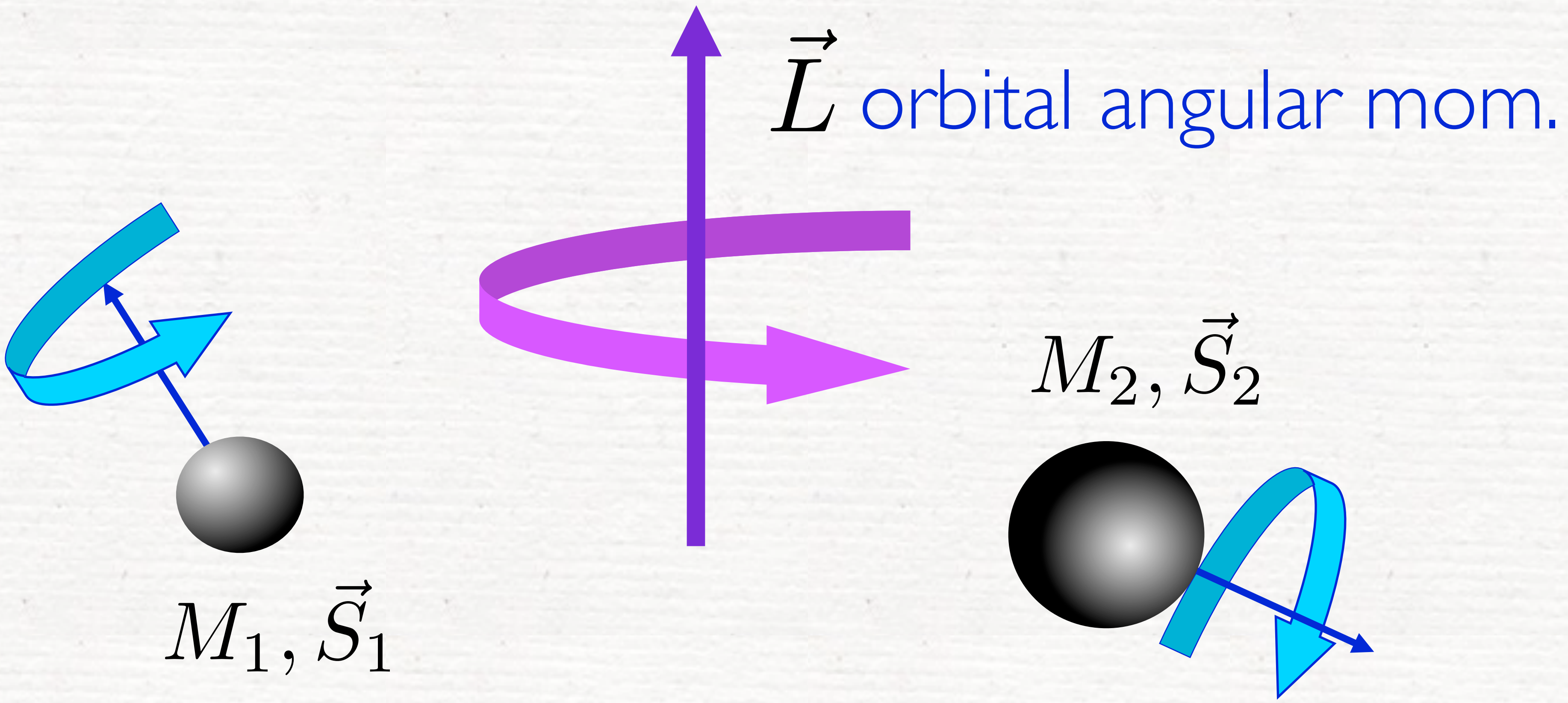




Modelling the final state

Consider BH binaries as "engines" producing a final single black hole from two distinct initial black holes

Before the merger...



The space of parameters is 7-dimensional (2 spin vectors, mass ratio) and tiny when compared to that of NSs

Modelling the final state

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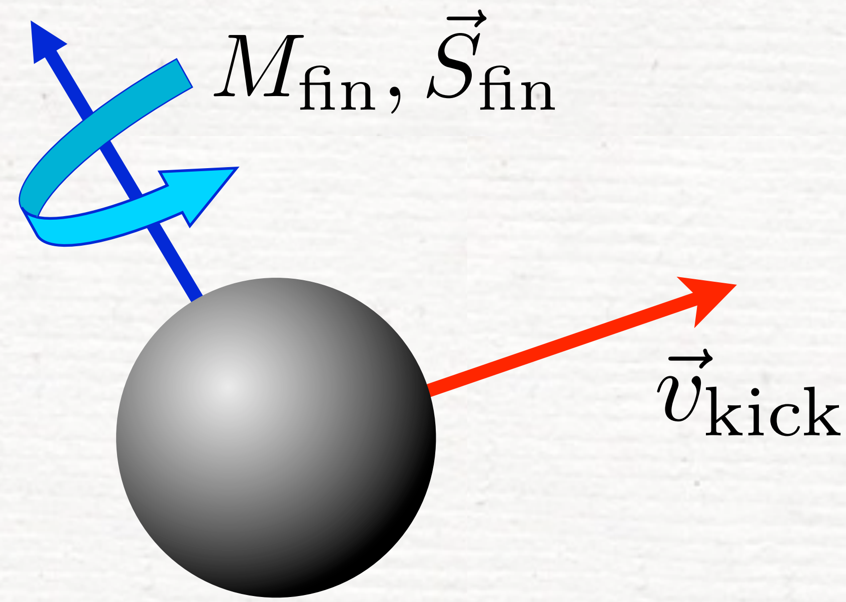
After the merger...

LR et al, 2007
LR et al, 2008
LR et al, 2008
LR, 2009
Barausse, LR 2009



Buonanno et al. 2007
Boyle et al, 2007
Boyle et al, 2008
Tichy & Marronetti, 2008
Kesden, 2008
Lousto et al. 2009
van Meter et al. 2010
Kesden et al. 2010

The final BH has 3 specific properties: **mass, spin, recoil.**

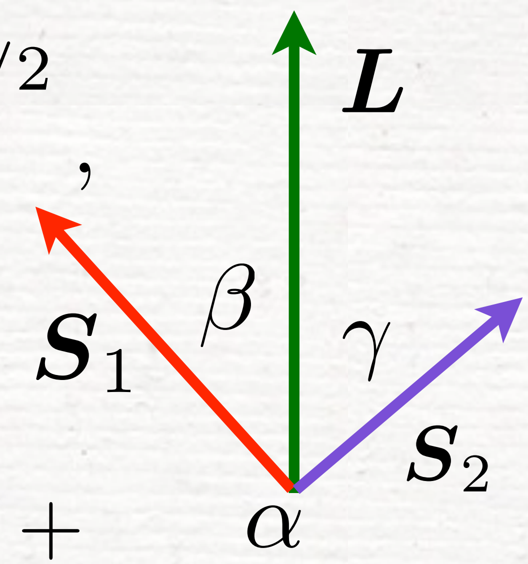
Their knowledge is important for astrophysics and cosmology

Can predict with **% precision** the **magnitude** and **direction** of final **spin** and the **magnitude** of the **kick** for arbitrary binaries.

Using a number assumptions derived from PN theory we have derived an **algebraic** expression for the **final spin** vector

$$|\boldsymbol{a}_{\rm fin}| = \tfrac{1}{(1+q)^2}\Big[|\boldsymbol{a}_1|^2 + |\boldsymbol{a}_1|^2 q^4 + 2|\boldsymbol{a}_2||\boldsymbol{a}_1|q^2\cos\alpha +$$

$$2\left(|\boldsymbol{a}_1|\cos\beta + |\boldsymbol{a}_2|q^2\cos\gamma\right)|\boldsymbol{\ell}|q + |\boldsymbol{\ell}|^2 q^2\Big]^{1/2},$$



where

$$|\boldsymbol{\ell}| = \frac{s_4}{(1+q^2)^2}\left(|\boldsymbol{a}_1|^2 + |\boldsymbol{a}_2|^2 q^4 + 2|\boldsymbol{a}_1||\boldsymbol{a}_2|q^2\cos\alpha\right) +$$

$$\left(\frac{s_5\nu + t_0 + 2}{1+q^2}\right)\left(|\boldsymbol{a}_1|\cos\beta + |\boldsymbol{a}_2|q^2\cos\gamma\right) + 2\sqrt{3} + t_2\nu + t_3\nu^2\,.$$

Note that the final spin is fully determined in terms of the 5 coefficients $s_4,\ s_5,\ t_0,\ t_2,\ t_3$ which can be computed via numerical simulations. The agreement with data is at % level!

LR et al, 2007, LR et al, 2008, LR et al, 2008, LR, 2009, Barausse, LR 2009

Unequal-mass, aligned binaries

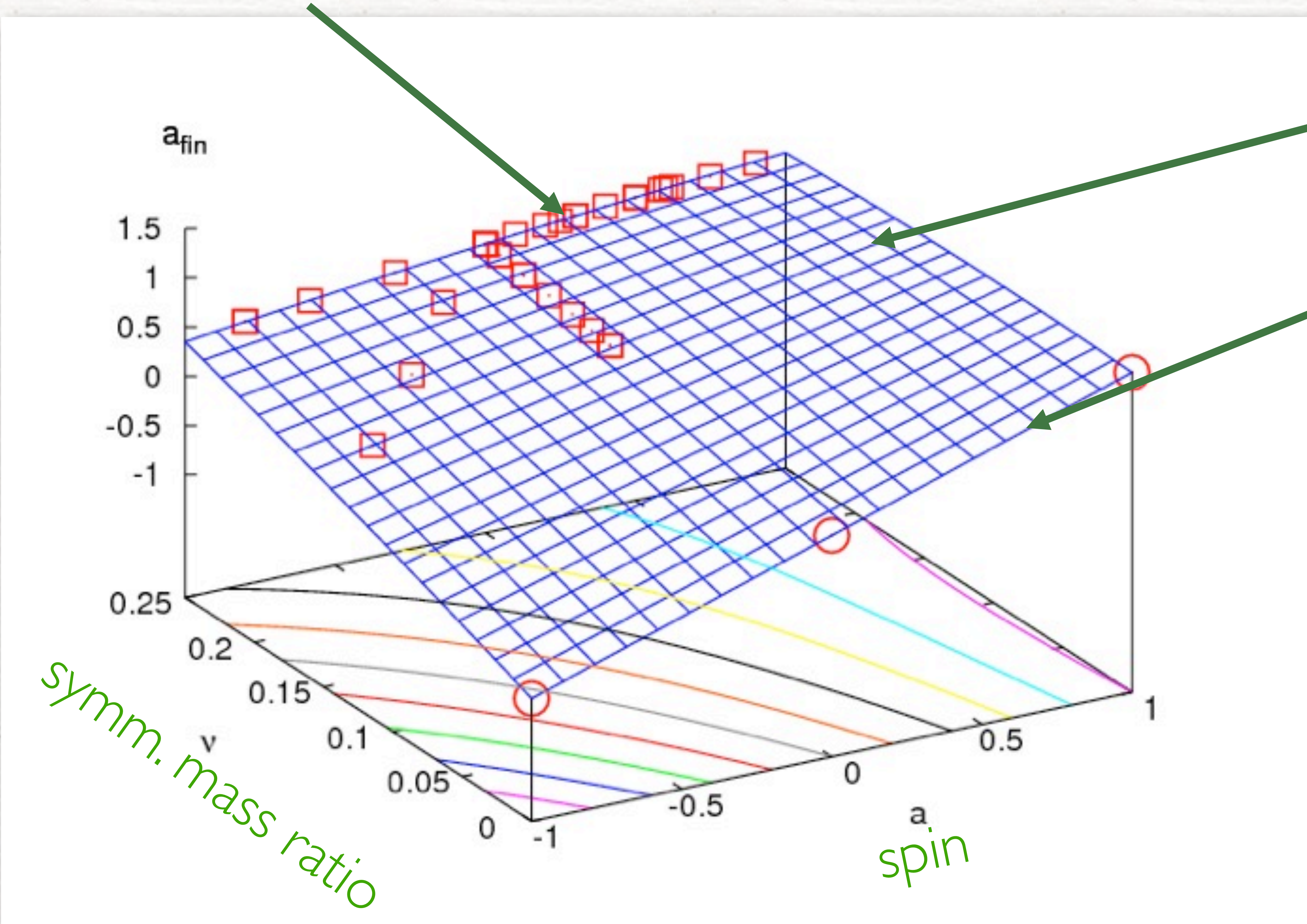
The resulting expression is ($\nu = M_1 M_2/(M_1+M_2)^2$)

$$a_{\rm fin}(a,\nu) = a + s_4 a^2 \nu + s_5 a \nu^2 + t_0 a \nu + t_1 \nu + t_2 \nu^2 + t_3 \nu^3$$

Numerical data

Analytic expression

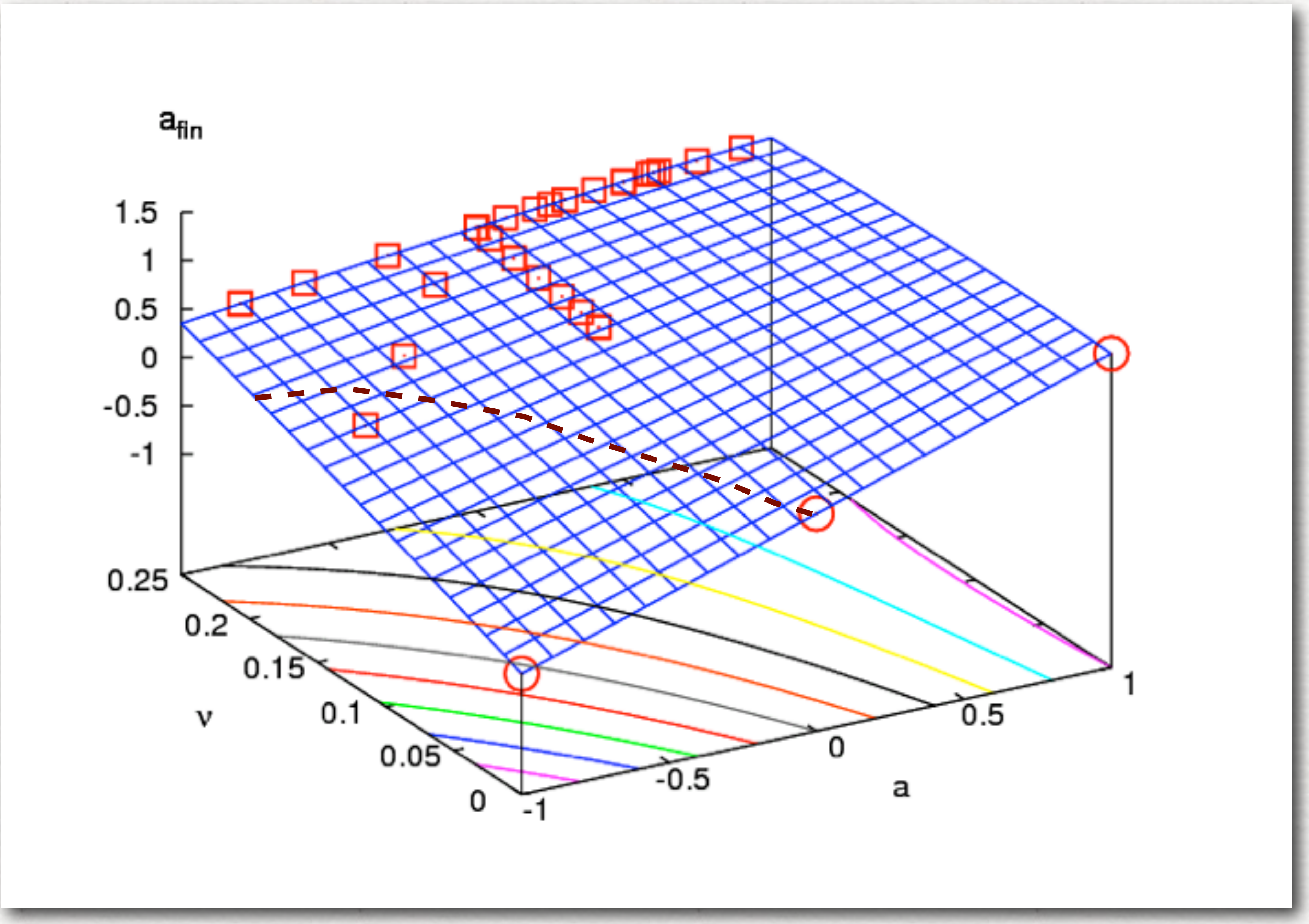
EMRL: extreme mass-ratio limit



The functional dependence is simple enough that a low-order polynomial is sufficient

How to produce a Schwarzschild bh...

Is it possible to produce a Schwarzschild bh from the merger of two Kerr bhs?



Find solutions for:

$$a_{\rm fin}(a,\nu) = 0$$

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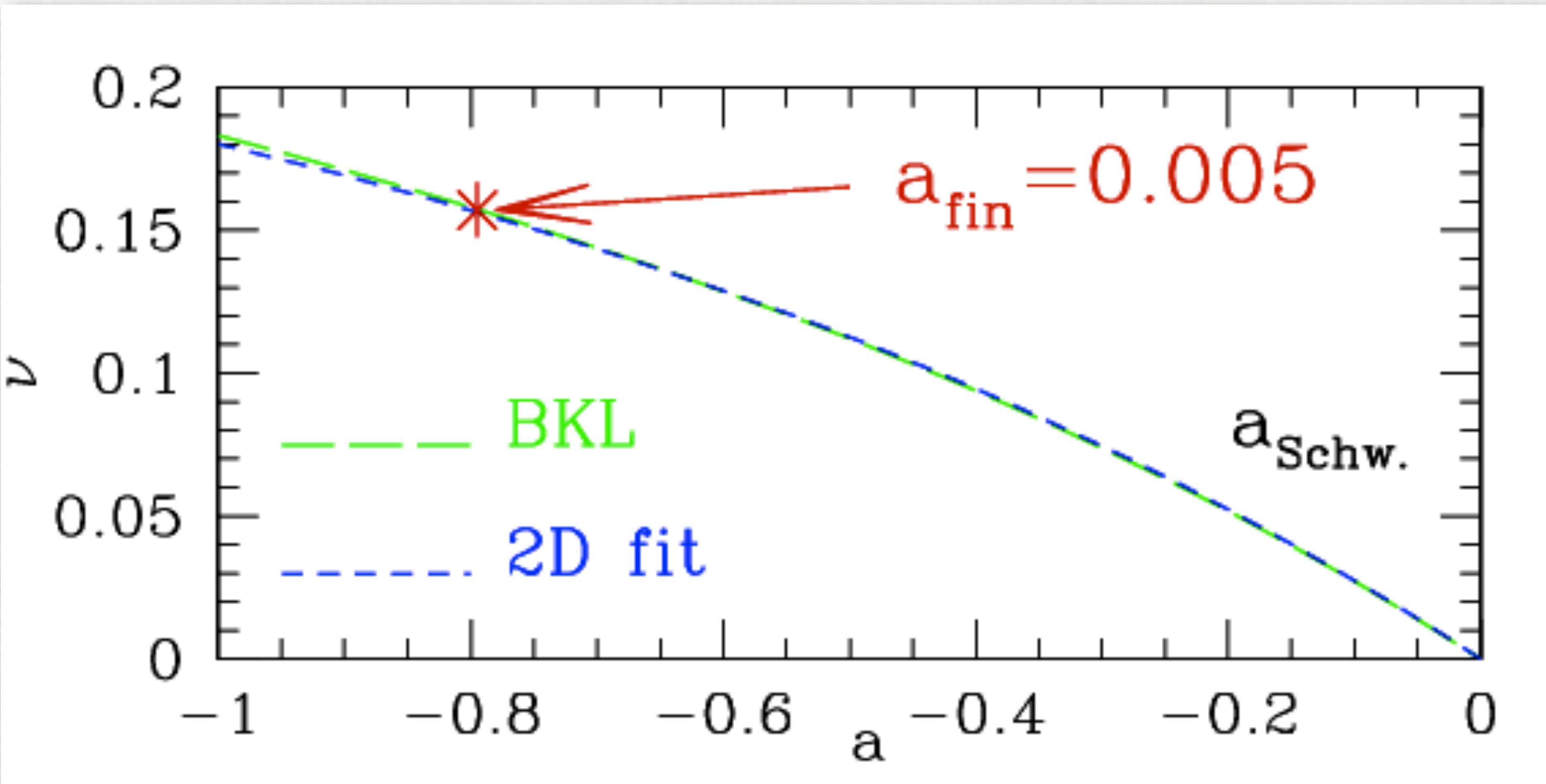


Find solutions for:

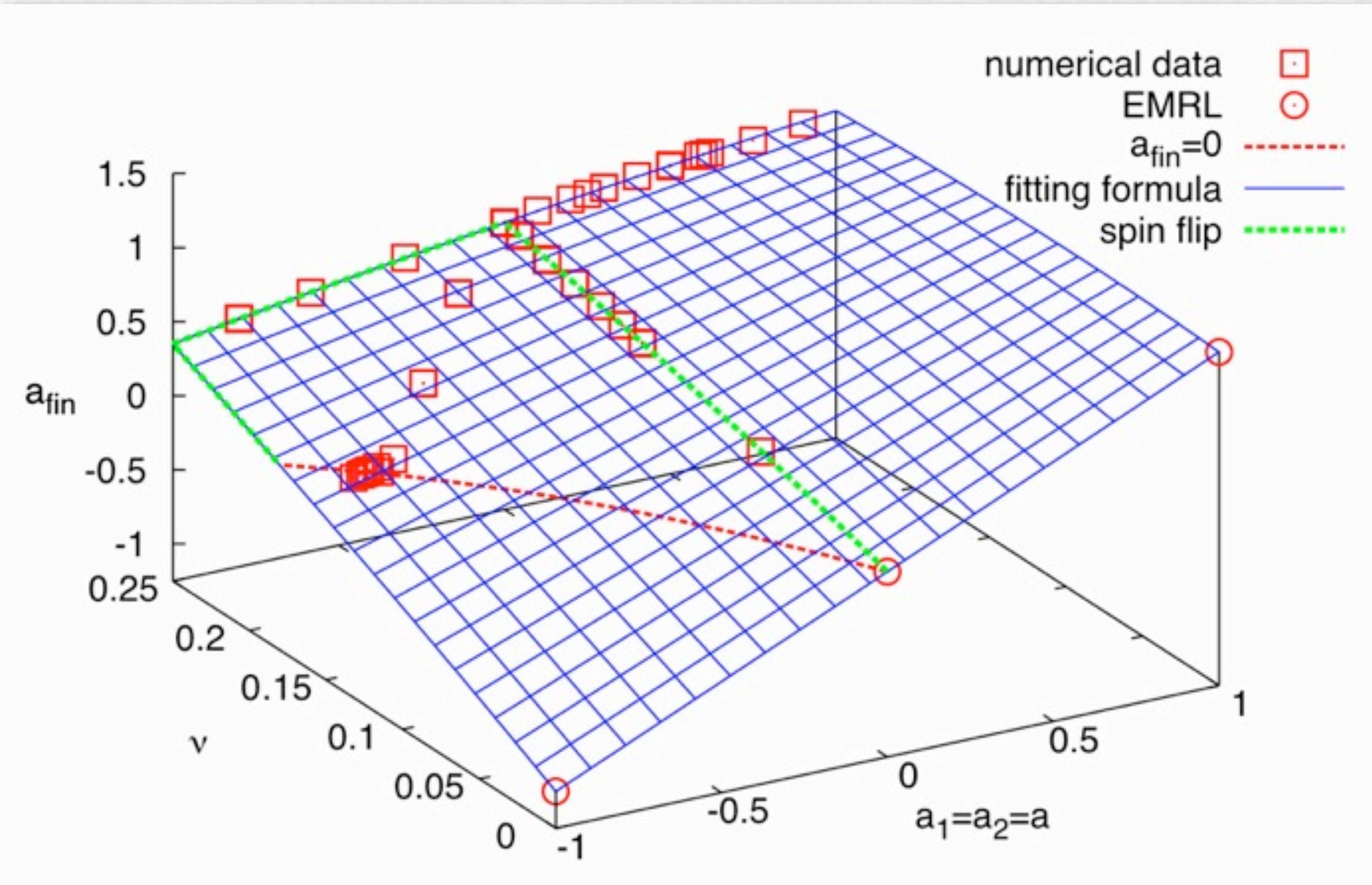
$$a_{\text{fin}}(a,\nu) = 0$$

Unequal masses and spins antialigned to the orbital ang. mom. are necessary

Isolated Schwarzschild bh likely result of a similar merger!

How to flip the spin...

In other words: under what conditions does the final black hole spin a direction which is opposite to the initial one?



Find solutions for:

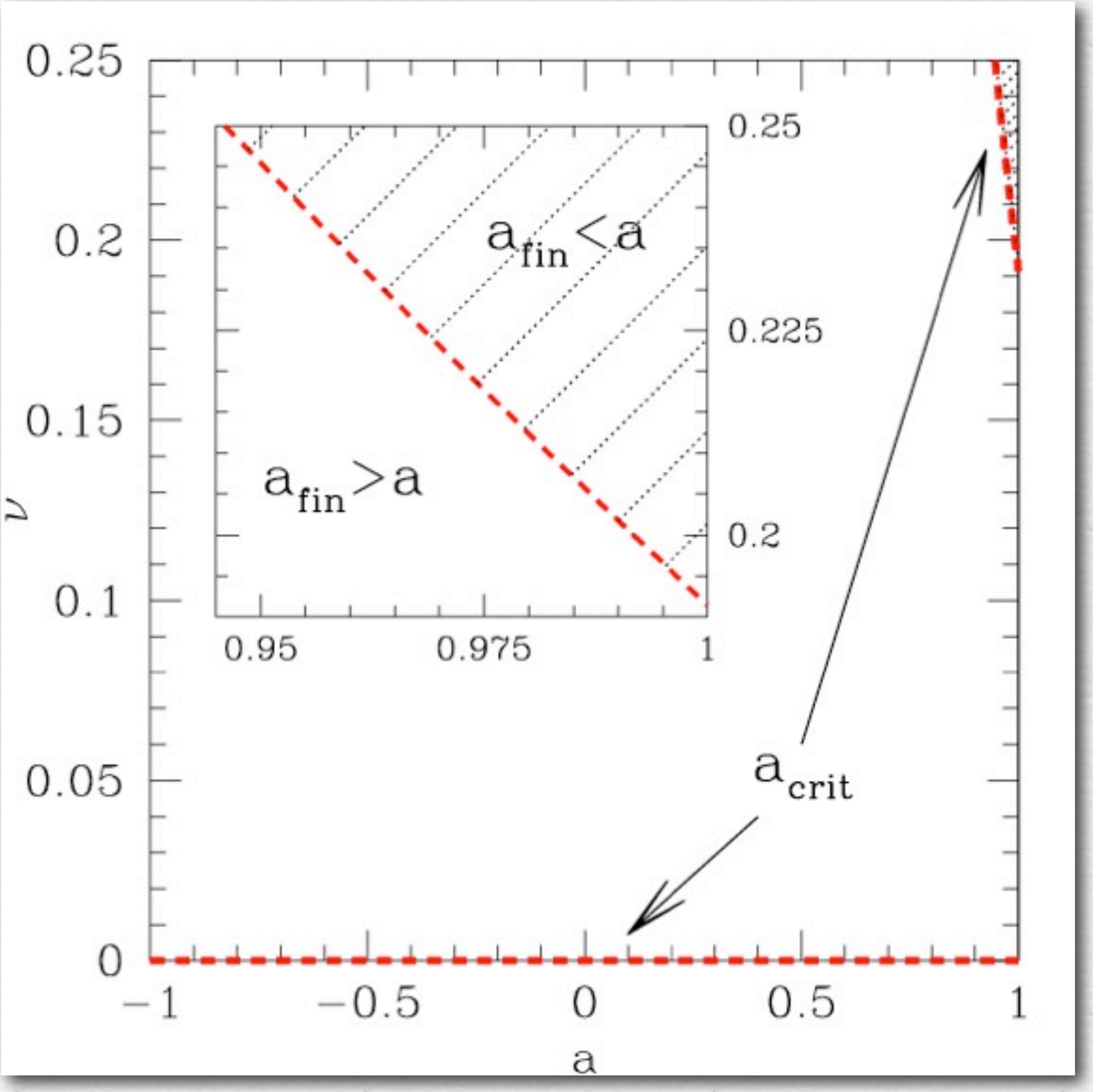
$$a_{\rm fin}(a,\nu)\,a < 0$$

Spin-flips are possible if:

- initial spins are antialigned with orbital angular mom.
- small spins for small mass ratios
- large spins for comparable masses

Spin-up or spin-down?...

Similarly, another basic question with simple answer: does the merger generically spin-up or spin-down?



Just find solutions for:

$$a_{\rm fin}(a,\nu) = a$$

Clearly, the merger of aligned BHs statistically, leads to a **spin-up.** Note however that for very high spins, the merger actually leads to a spin down: no naked singularities are expected.

Modelling the final state

- final spin **vector**
- final recoil velocity

Campanelli et al, 2006
Campanelli et al, 2007
Baker et al, 2008
Gonzalez et al, 2007
LR et al, 2007
Hermann et al, 2007
Buonanno et al. 2007
LR et al, 2007
Boyle et al, 2007
Marronetti et al, 2007

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Baker et al, 2008
Lousto et al, 2008
Tichy & Marronetti, 2008
Kesden, 2008
Barausse, LR, 2009
Lousto et al. 2009
van Meter et al. 2010

Understanding the recoil

At the end of the simulation and unless the spins are equal, the final black hole will acquire a recoil velocity: aka "kick".

The emission of GWs is beamed and thus asymmetrical: the linear momentum radiated at an angle will not be compensated by the momentum after one orbit.

A simple mechanic analogue is offered by a rotary sprinkler

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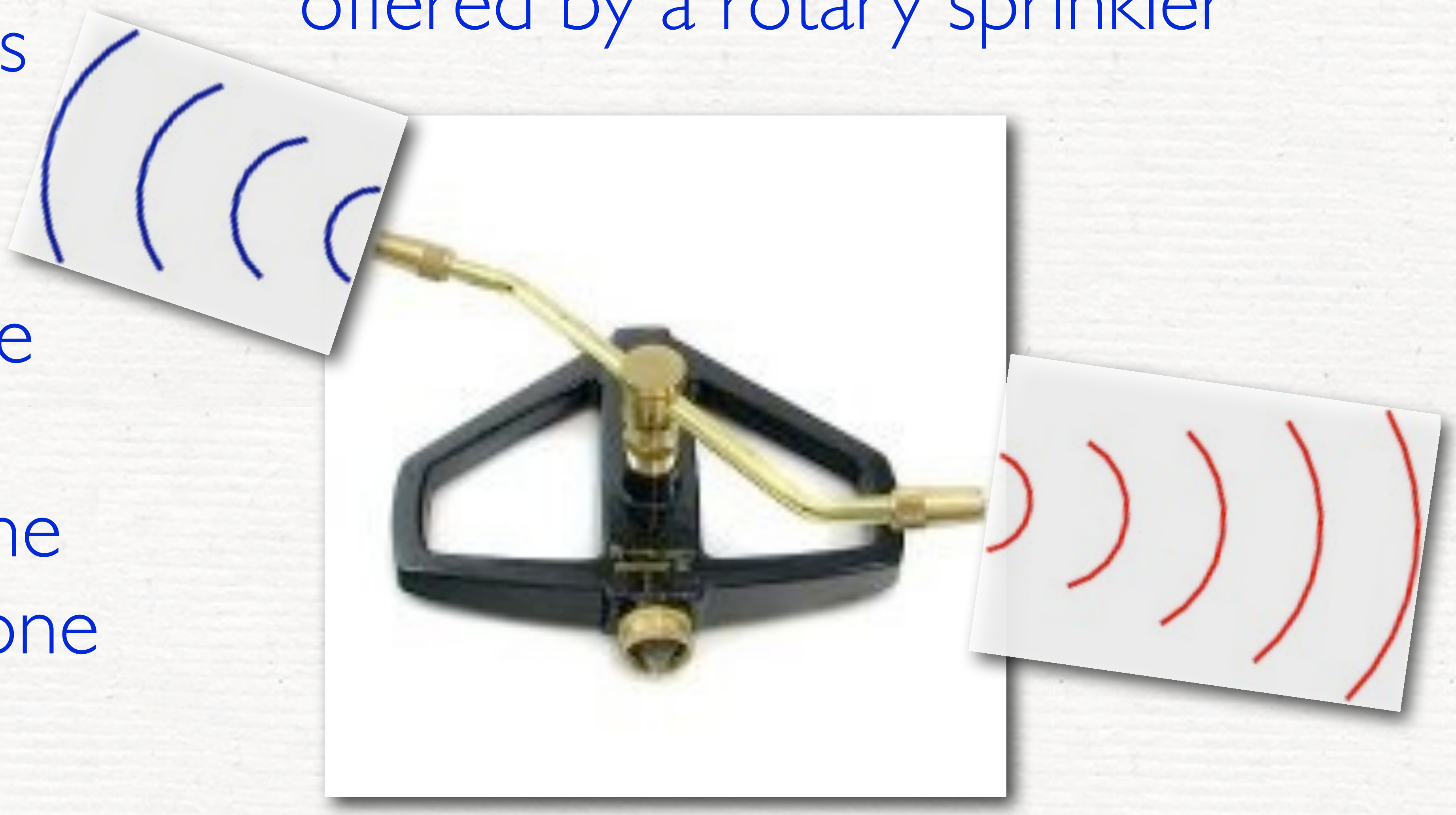

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A simple mechanic analogue is offered by a rotary sprinkler

Consider a sequence of spinning BHs in which one of the spins is held fixed and the other one is varied in amplitude

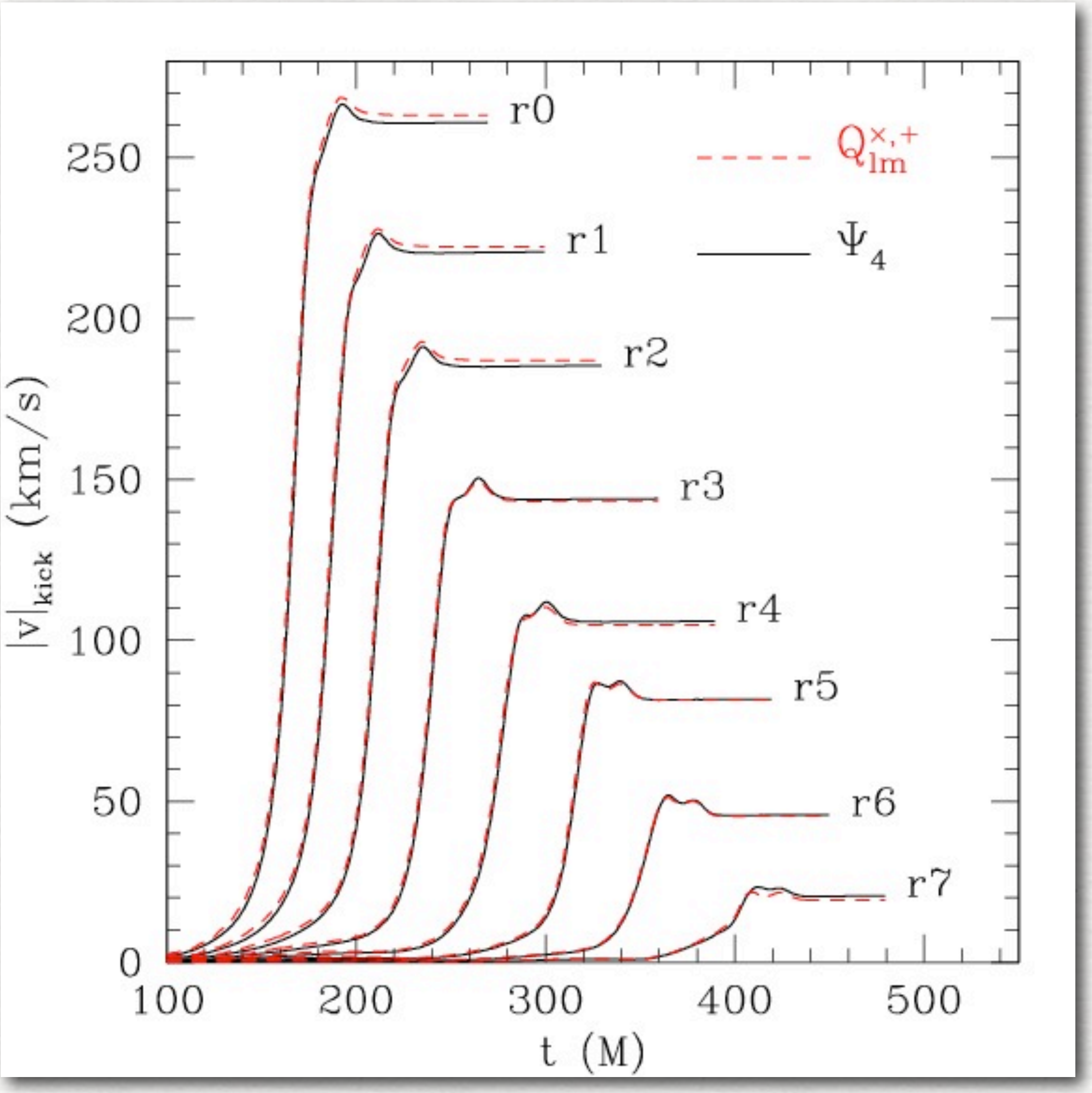
r0: ↑ ↓ (a_1/a_2=-4/4)

r2: ↑ ↓ (a_1/a_2=-2/4)

r4: ↑ . (a_1/a_2=-0/4)

r6: ↑ ↑ (a_1/a_2=2/4)

r8: ↑ ↑ (a_1/a_2=4/4)



What we know (now) of the kick

$$v_{\rm kick} = v_m \boldsymbol{e}_1 + v_\perp \left(\cos(\xi)\boldsymbol{e}_1 + \sin(\xi)\boldsymbol{e}_2\right) + v_\| \boldsymbol{e}_3$$

where

$$v_m \simeq A\nu^2\sqrt{1-4\nu}(1+B\nu)$$

$$v_\perp \simeq c_1 \frac{\nu^2}{(1+q)}\left(qa_1^\| - a_2^\|\right) + c_2\left(q^2(a_1^\|)^2 - (a_2^\|)^2\right)$$

$$v_\| \simeq \frac{K_1\nu^2 + K_2\nu^3}{(1+q)}\left[qa_1^\perp \cos(\phi_1 - \Phi_1) - a_2^\perp \cos(\phi_2 - \Phi_2)\right]$$

LR 2008 (review)
van Meter et al. 2010

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mass asymmetry $\lesssim 150\mathrm{km/s}$

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mass asymmetry $\lesssim 150\text{km/s}$

spin asymmetry; contribution **off** the plane $\lesssim 450\text{km/s}$

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mass asymmetry $\lesssim 150 \mathrm{km/s}$

spin asymmetry; contribution **off** the plane $\lesssim 450 \mathrm{km/s}$

spin asymmetry; contribution **in** the plane $\lesssim 3500 \mathrm{km/s}$

LR 2008 (review)
van Meter et al. 2010

However, there is more than just the final recoil velocity

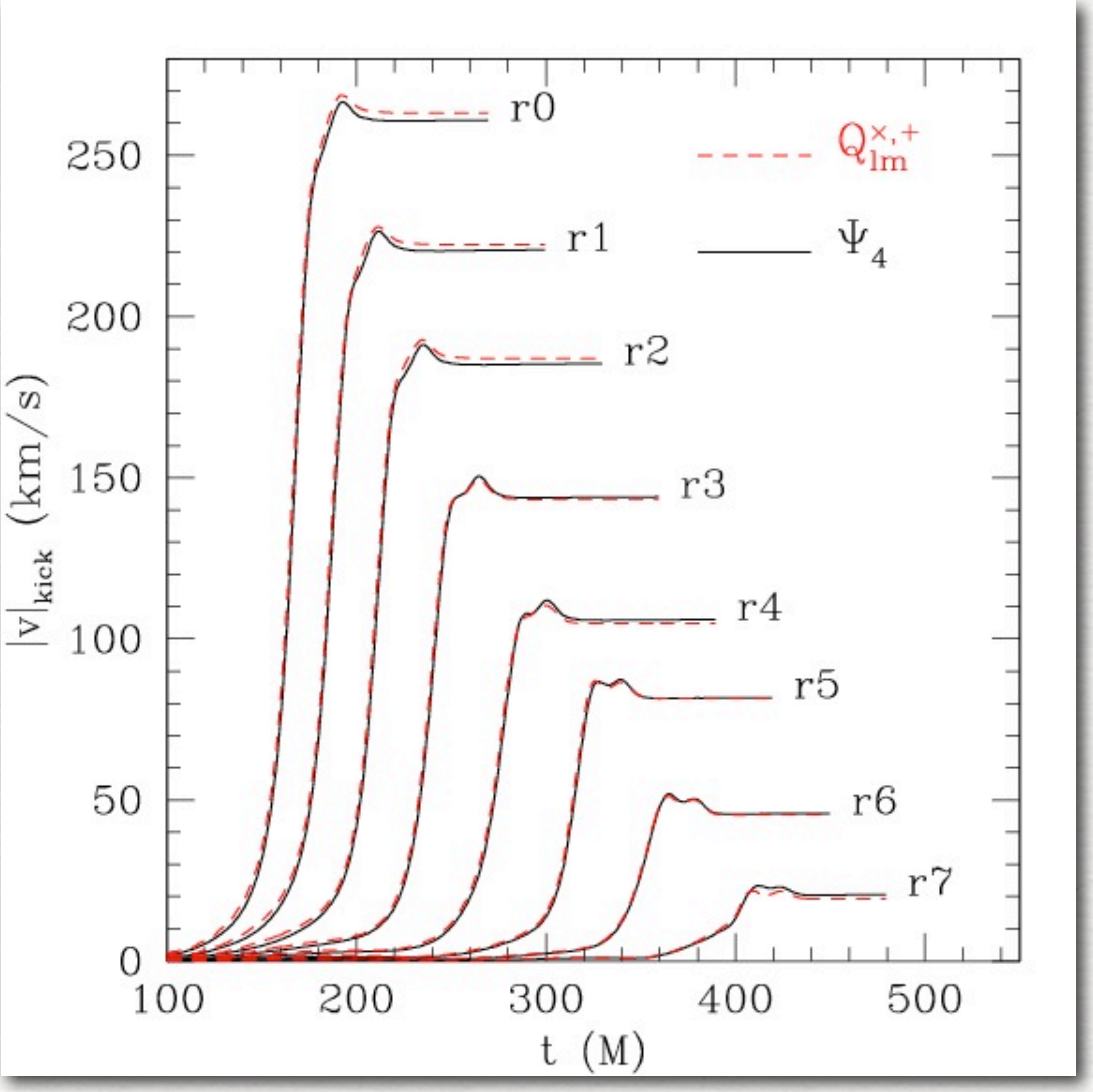
r0: (a$_1$/a$_2$=-4/4)

r2: (a$_1$/a$_2$=-2/4)

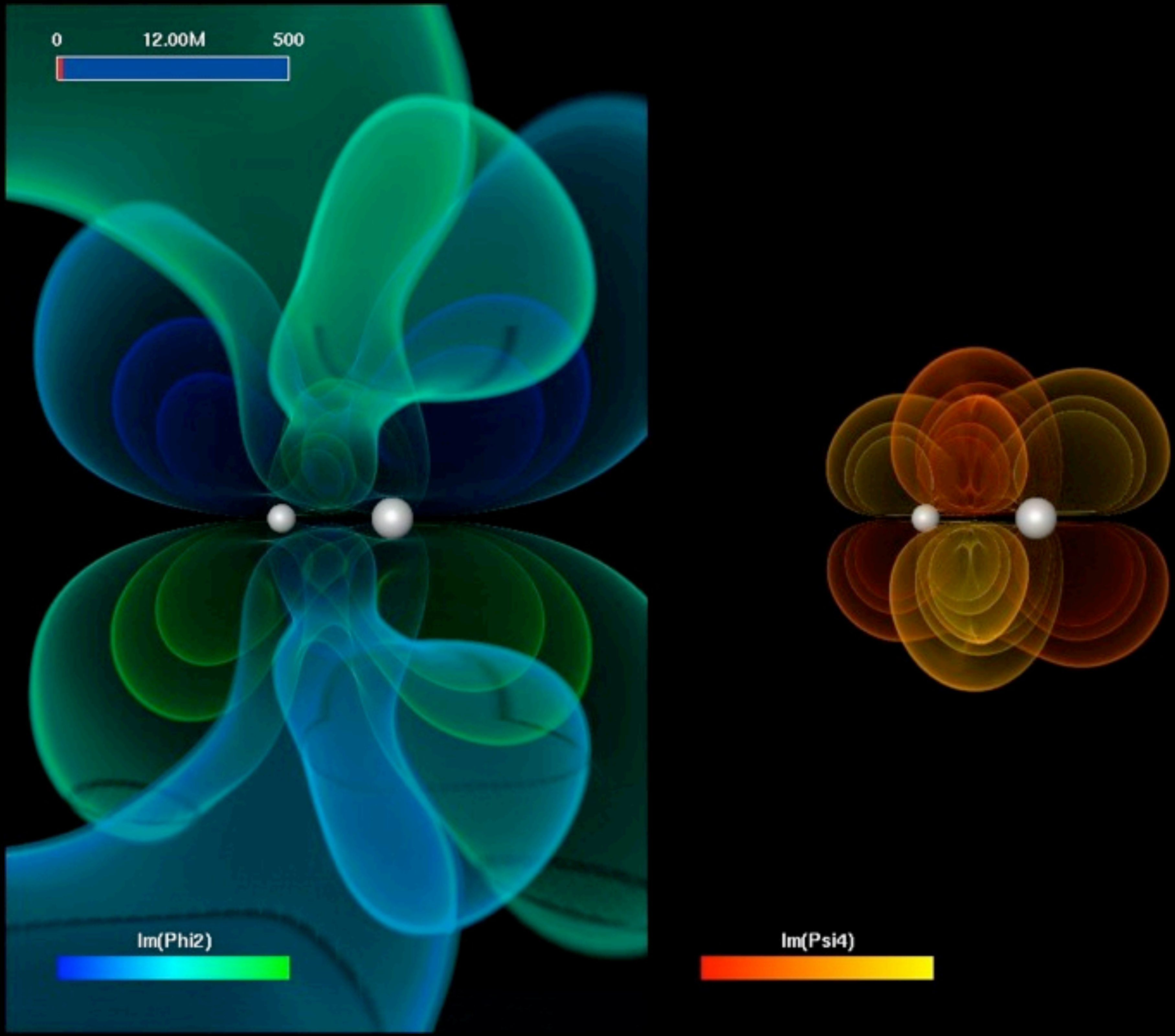
r4: (a$_1$/a$_2$=-0/4)

r6: (a$_1$/a$_2$=2/4)

r8: (a$_1$/a$_2$=4/4)



Before the merger...



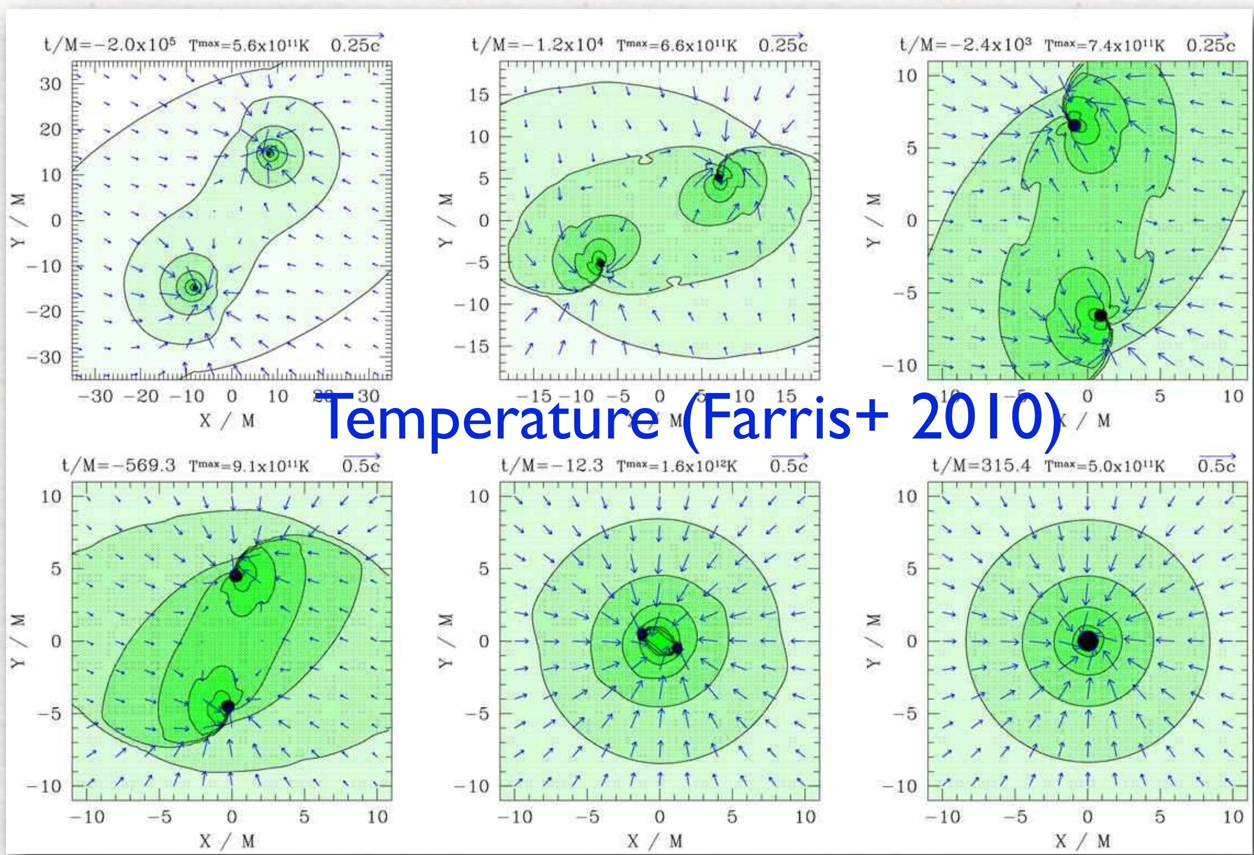
Approaches considered so far in NR:

- Our knowledge of the conditions that lead to a massive binary black-hole system to coalesce are still not settled (e.g. final pc or mpc problem).
- The situation is even more complicated when the binary is just a few orbits away from merger.
- Essentially we don't know what to expect and different scenarios have been considered:
  - isotropic distribution of hot/dense gas surrounding the binary (Bode+ 2009, 2011; Farris+ 2009, 2011)
  - distant circumbinary disc (the binary is essentially in vacuum) and coupling takes place via a plasma or EM fields (Palenzuela+ 2009, 2010a,b; Moesta, LR+ 2010, 2011, Alic, LR+ 2012)

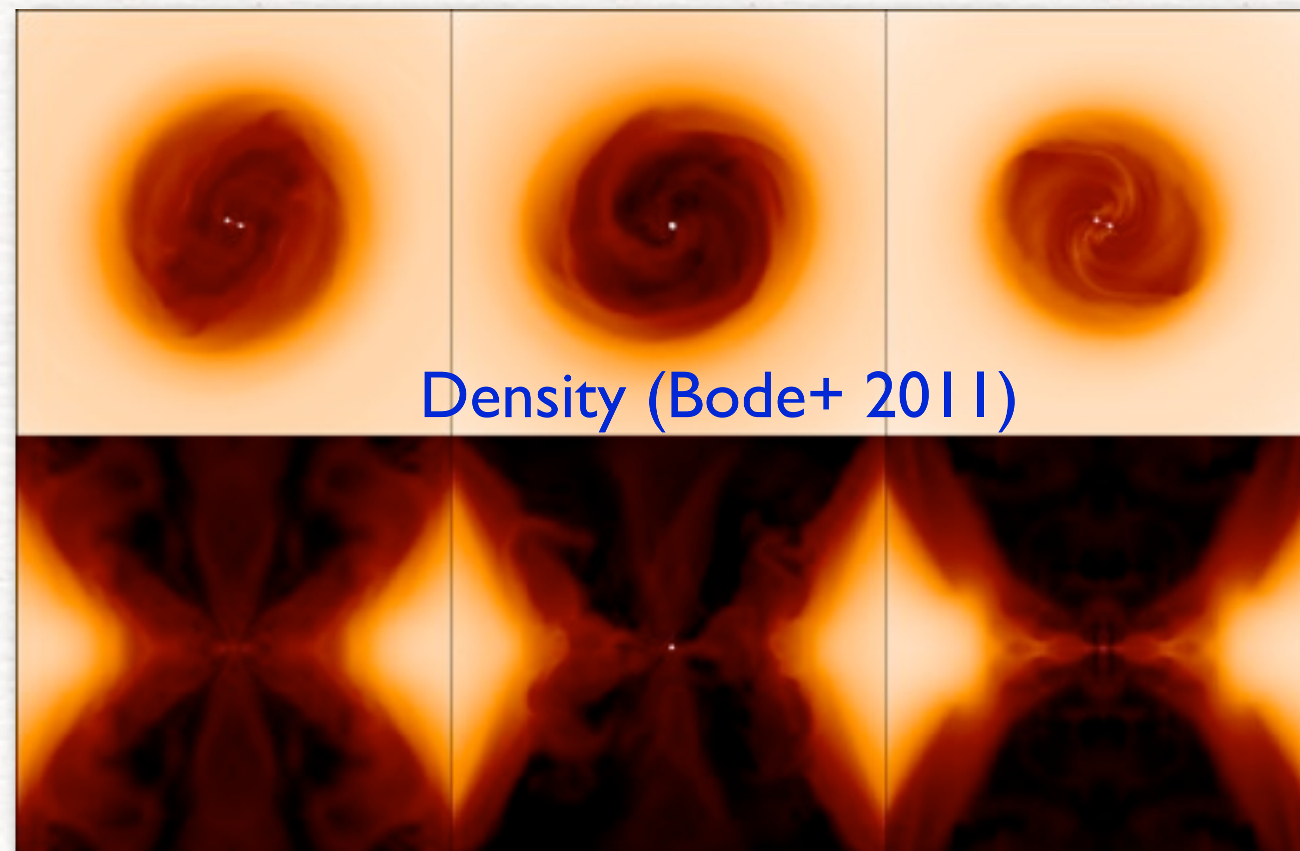
Final inspiral in hot/dense **accretion**

Farris+ 09,10, 11
Bode+ 10, 11, Bogdanovic+ 10

Lacking a precise prescription about the matter conditions around the binary soon before the merger, simulations have considered extreme scenarios of "hot dense clouds" or massive disk accretion



Temperature (Farris+ 2010)



Density (Bode+ 2011)

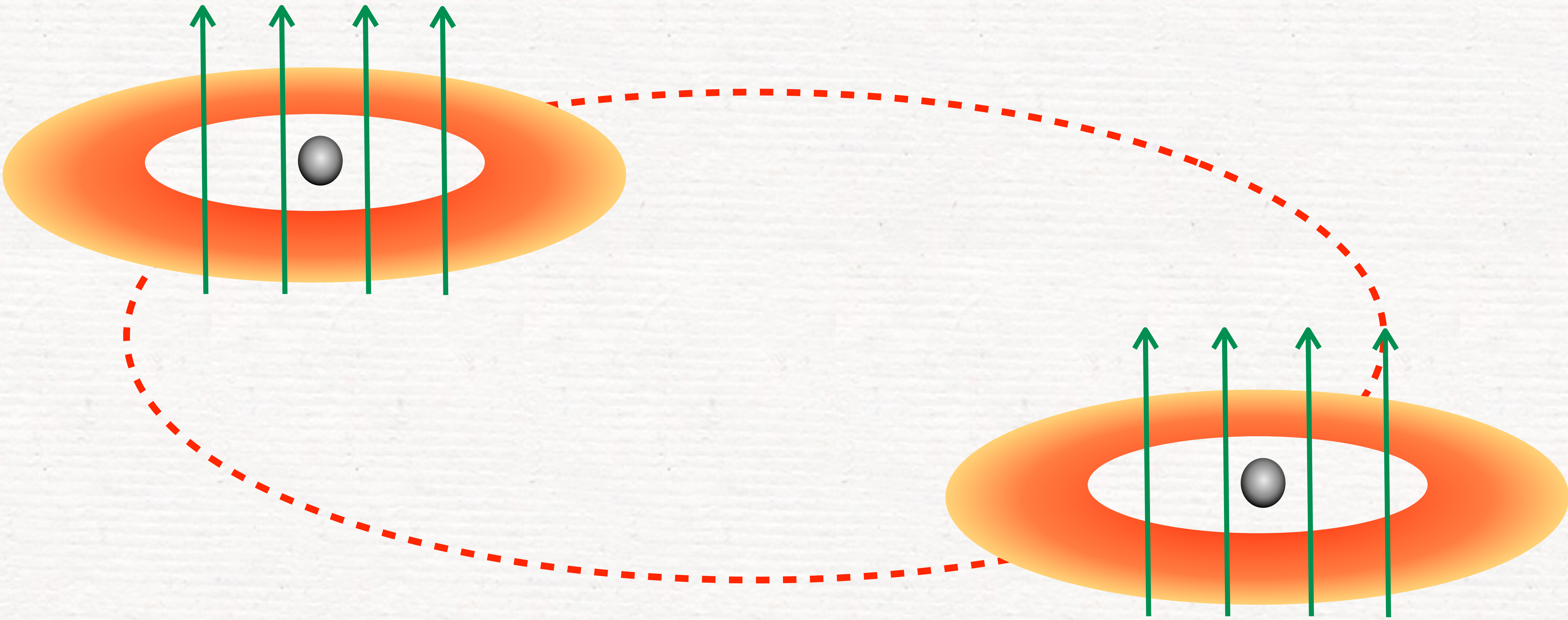
Within the "arbitrary" setup, the matter is evolved consistently but the bremsstrahlung luminosity is computed a-posteriori with crude estimates

$$L_{\rm brem} \approx 1.6\times10^{35}\,{\rm erg\,s^{-1}} \left(\frac{f_{\rm gas}}{10^{-5}}\right)^2 \left(\frac{\rho_{\rm disk}}{3.5\times10^{-11}{\rm g\,cm^{-3}}}\right)^2 \left(\frac{R}{10\,M}\right)^3 \left(\frac{T_e}{10^{10}\,{\rm K}}\right)^{1/2} \left[1+4.4\times\left(\frac{T_e}{10^{10}\,{\rm K}}\right)\right]_{5.4} M_7^3$$

Final inspiral in **vacuum**

Palenzuela+2010, Moesta, LR+ 2011

The massive **circumbinary disc** will follow the binary during the slow viscous evolution. When GW losses are large, the **circumbinary disc** will not follow the evolution and the binary will evolve in very tenuous gas. This could then produce an EM emission BEFORE the merger.



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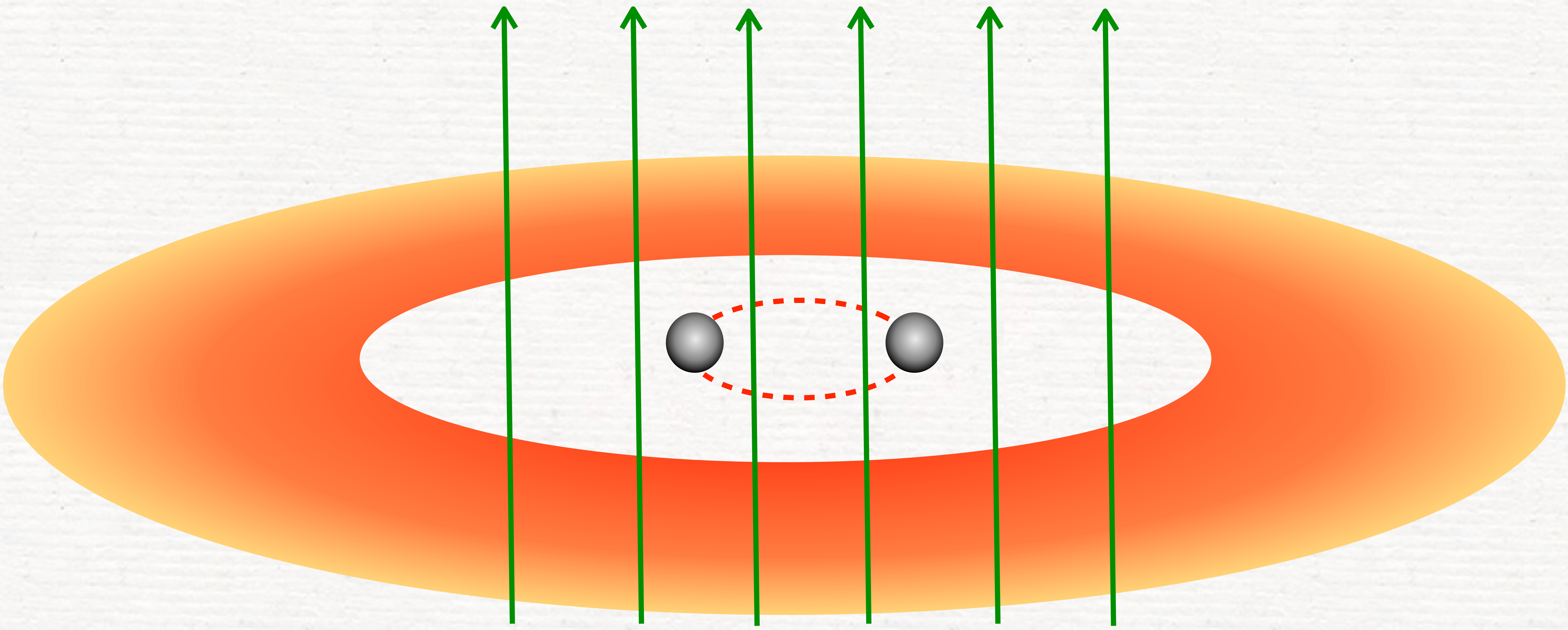
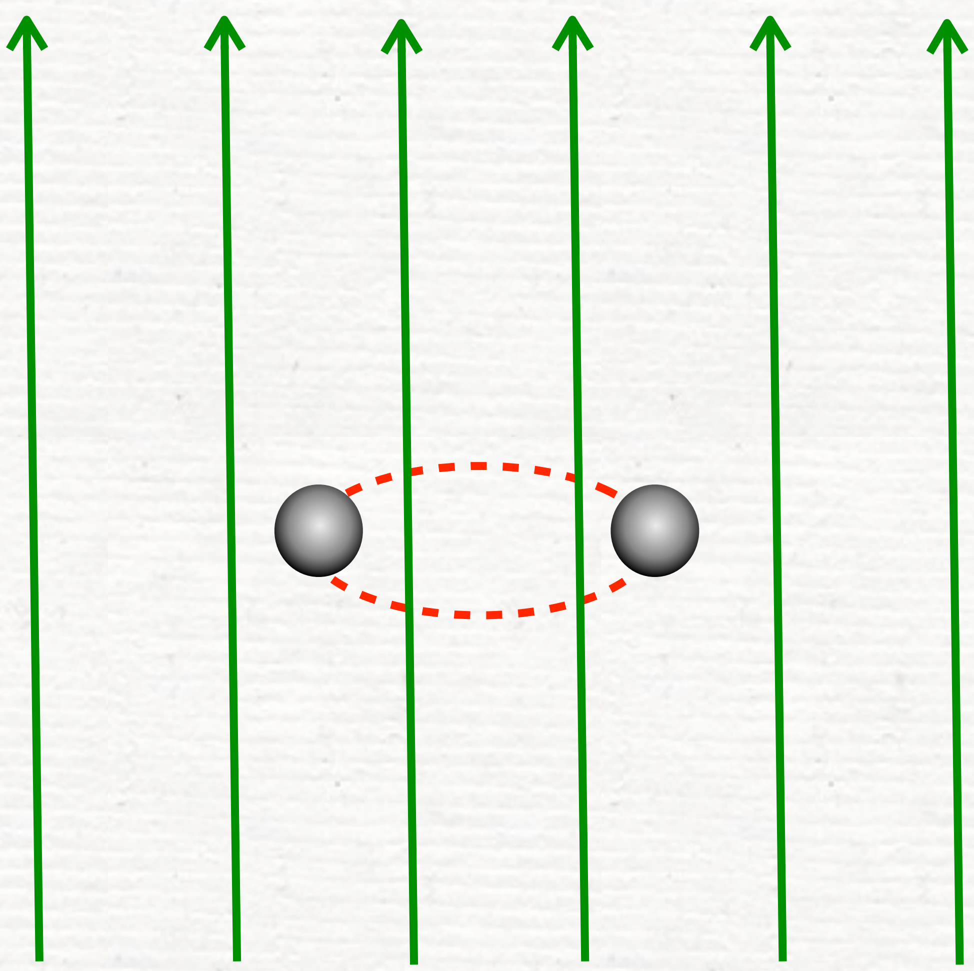


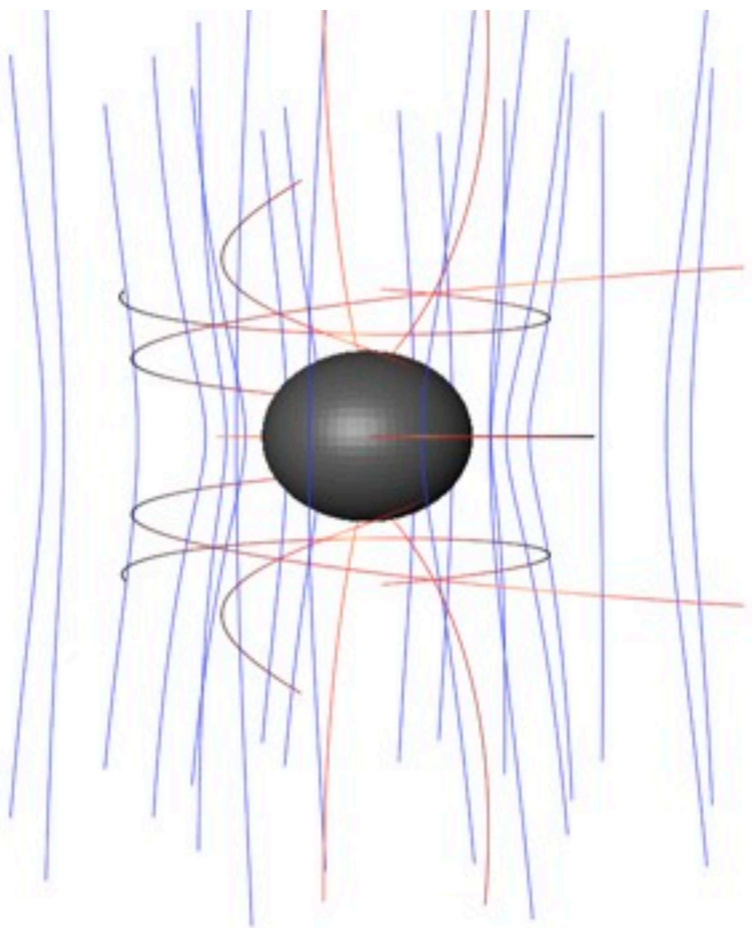
The massive **circumbinary disc** will follow the binary during the slow viscous evolution. When GW losses are large, the **circumbinary disc** will not follow the evolution and the binary will evolve in very tenuous gas. This could then produce an EM emission **BEFORE** the merger.

We considered what happens in vacuum in the vicinity of the two BHs when this is threaded by a uniform magnetic field

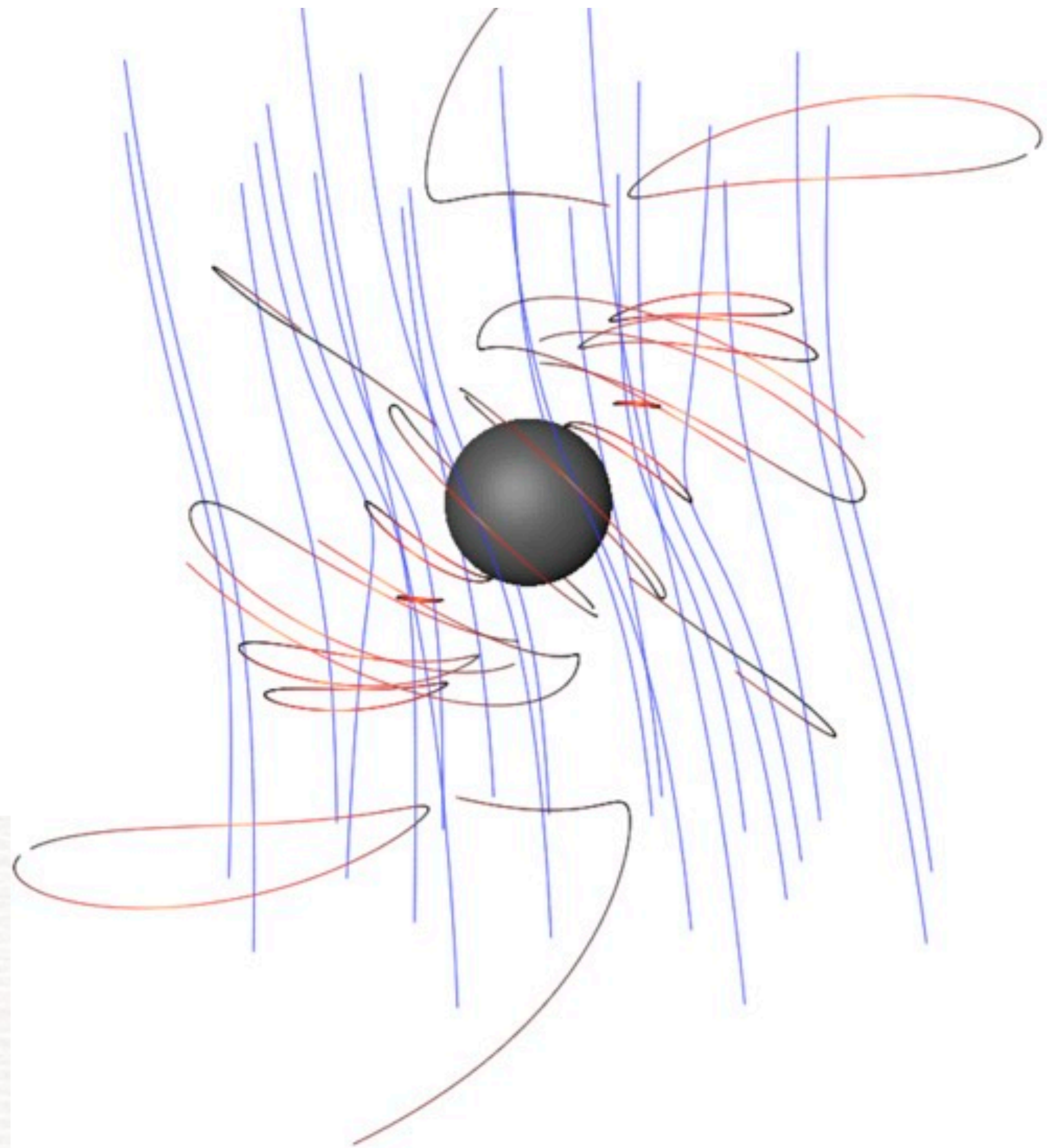


We have solved the full set of Einstein and Maxwell eqs in vacuum and computed the EM emission

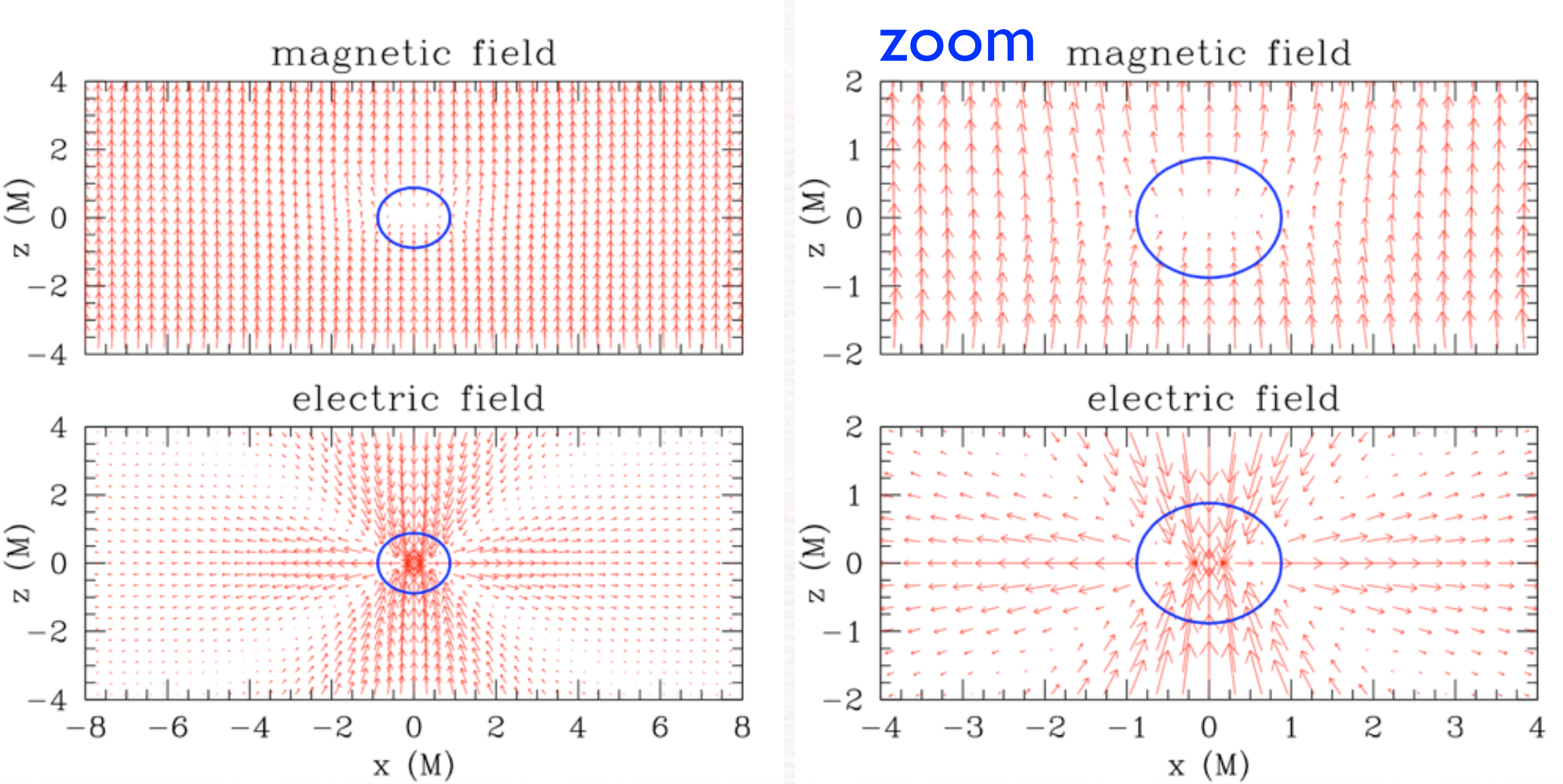
First a single BH in a uniform magnetic field



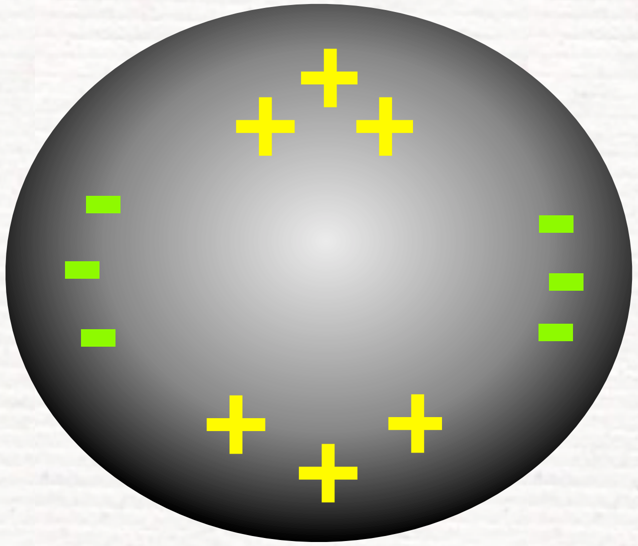
The magnetic field lines (blue) are distorted by spacetime curvature near the BH, while the electric field (red) is dragged by the spin (a=0.7)



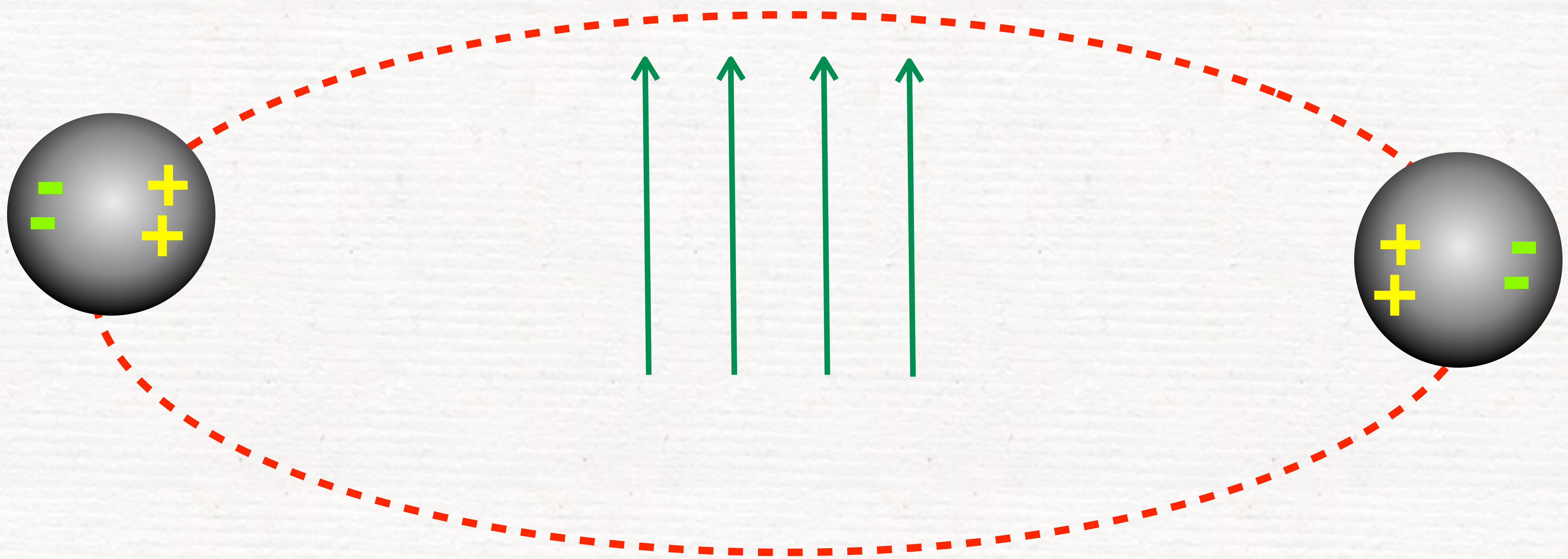
More complicated structure of EM fields for inclined spin



As in the "membrane paradigm", a rotating BH in a B-field generates an effective charge: **+** at the poles, **-** at the equator yielding a quadrupolar electric field



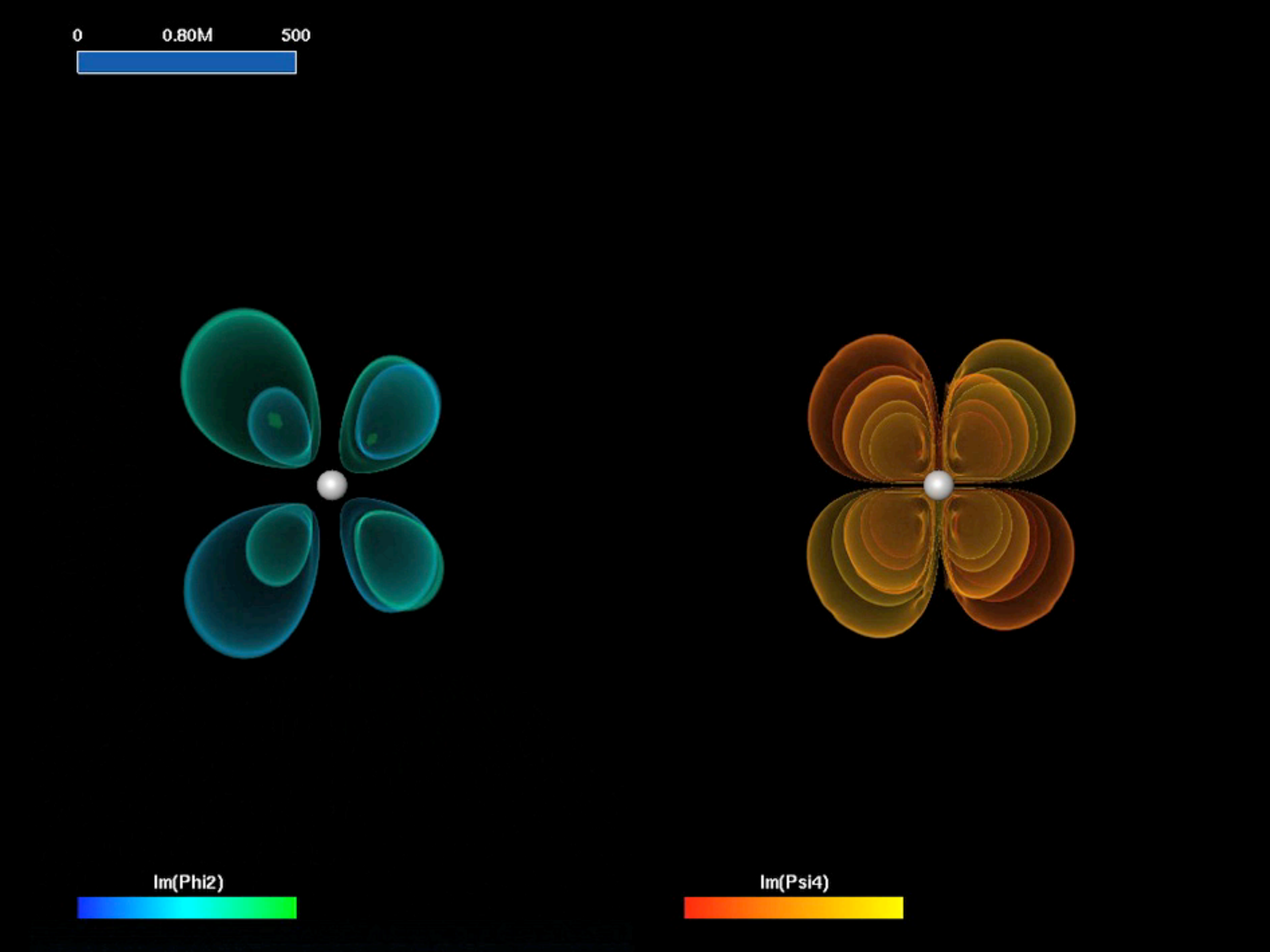
When moving across the vertical magnetic field the two BHs behave like conductors subject to the Hall effect: a dipolar charge develops.



The two BHs are therefore like two dipoles moving in a magnetic field: they will produce a quadrupolar EM radiation. This has the same multipolar structure of GWs!

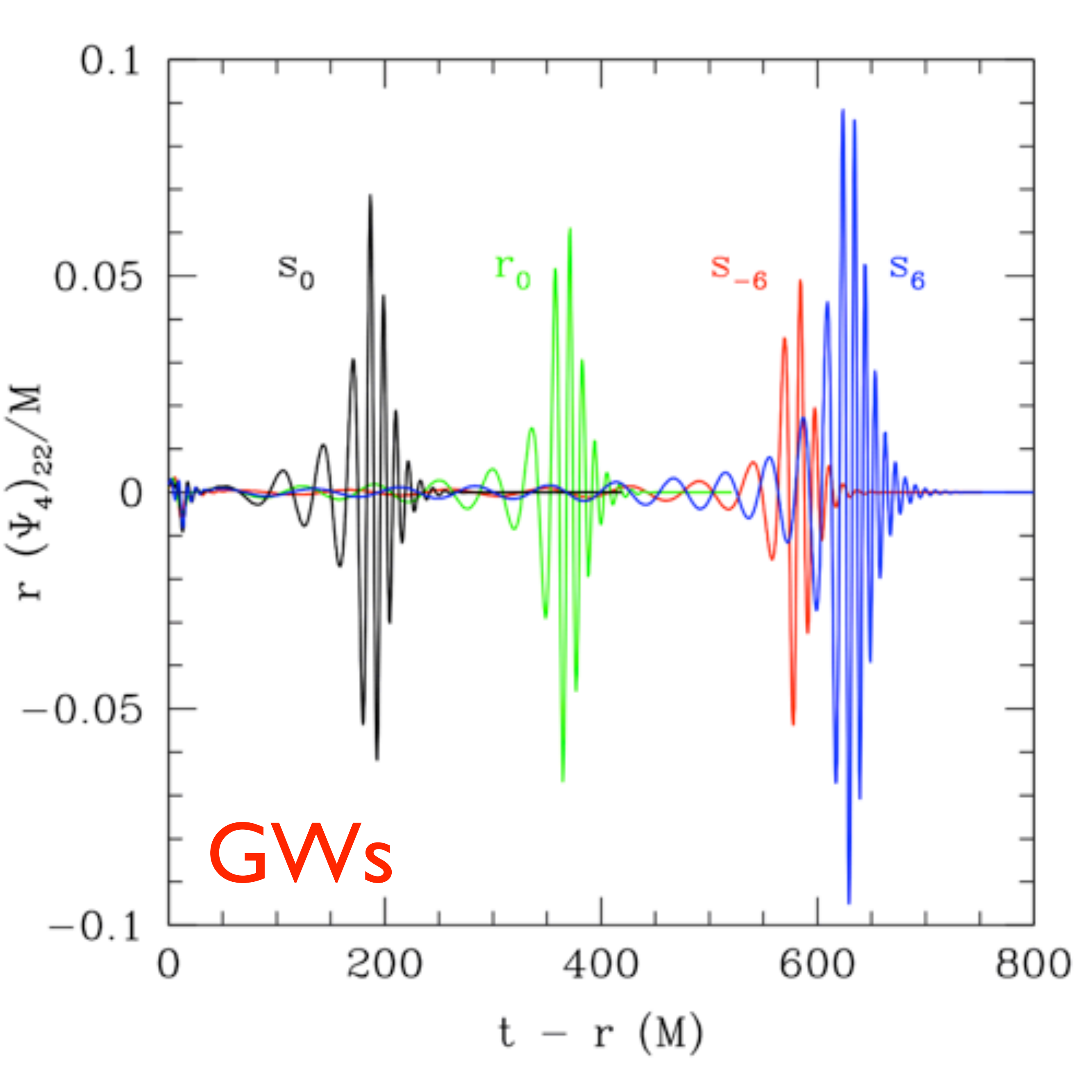
Animations: Koppitz, LR Moesta

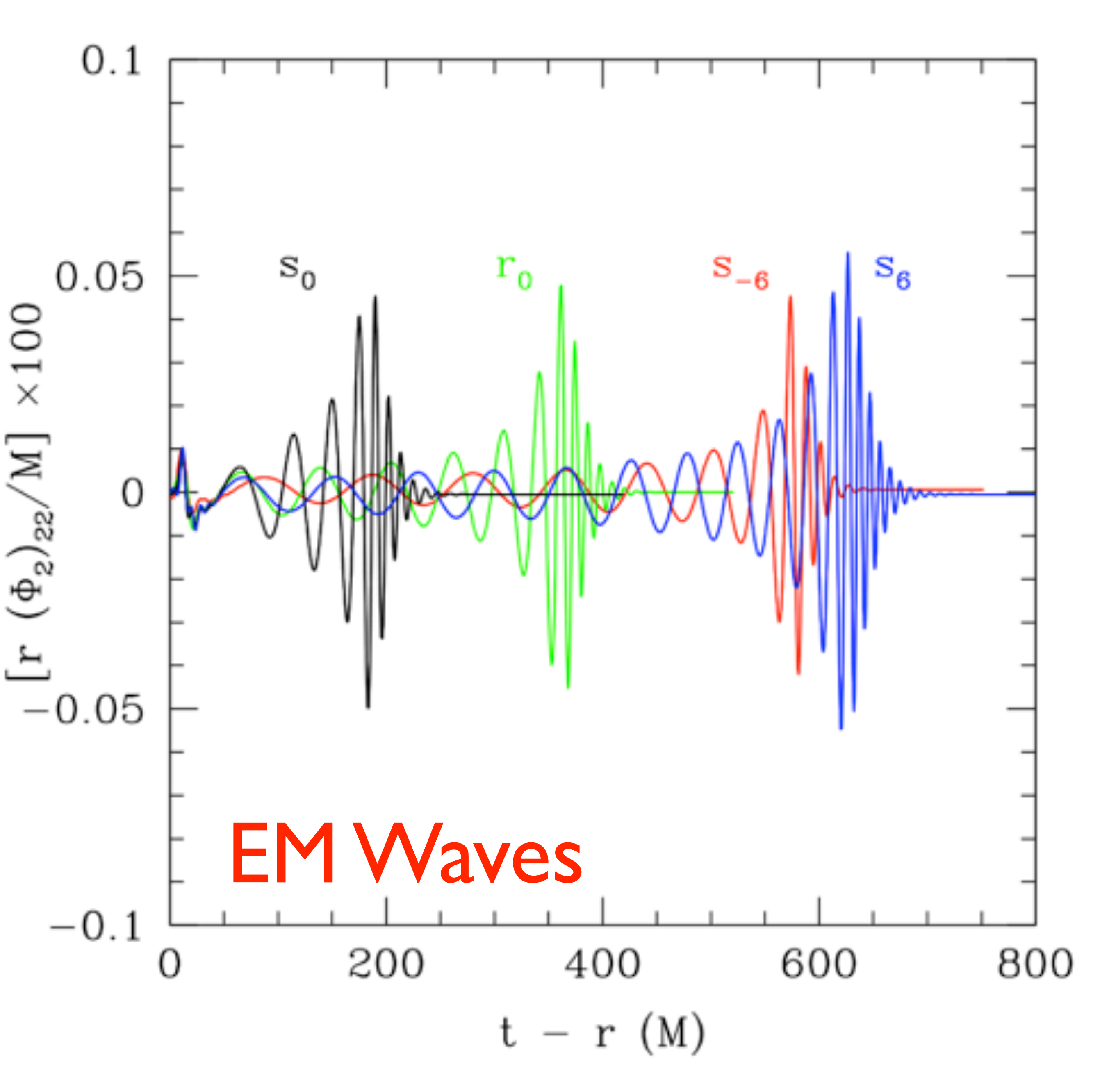
Simulation of an equal mass binary system with nonspinning BHs: left part measures EM fields, right one measures GWs

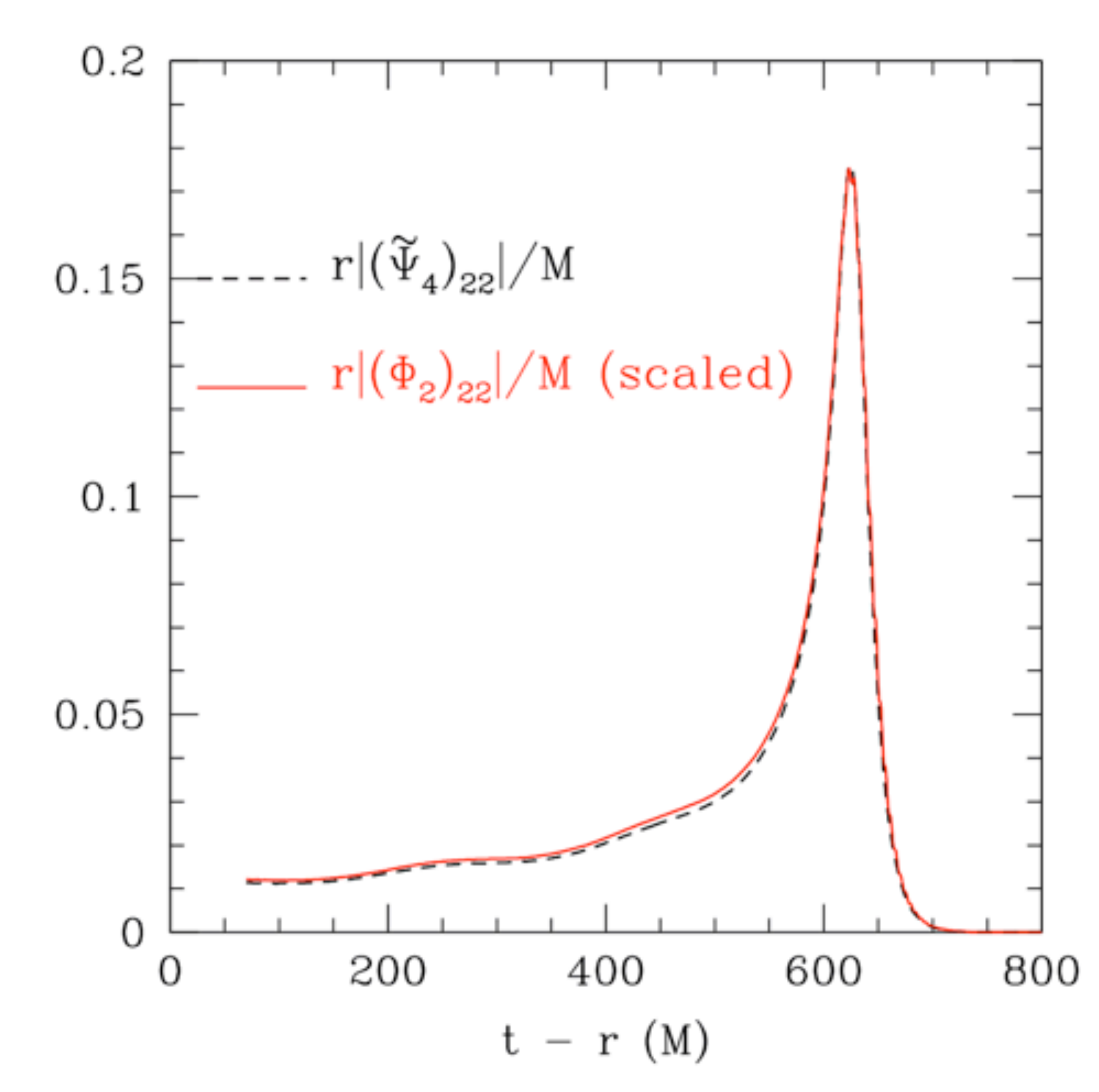

0
0.80M
500
Im(Phi2)
Im(Psi4)

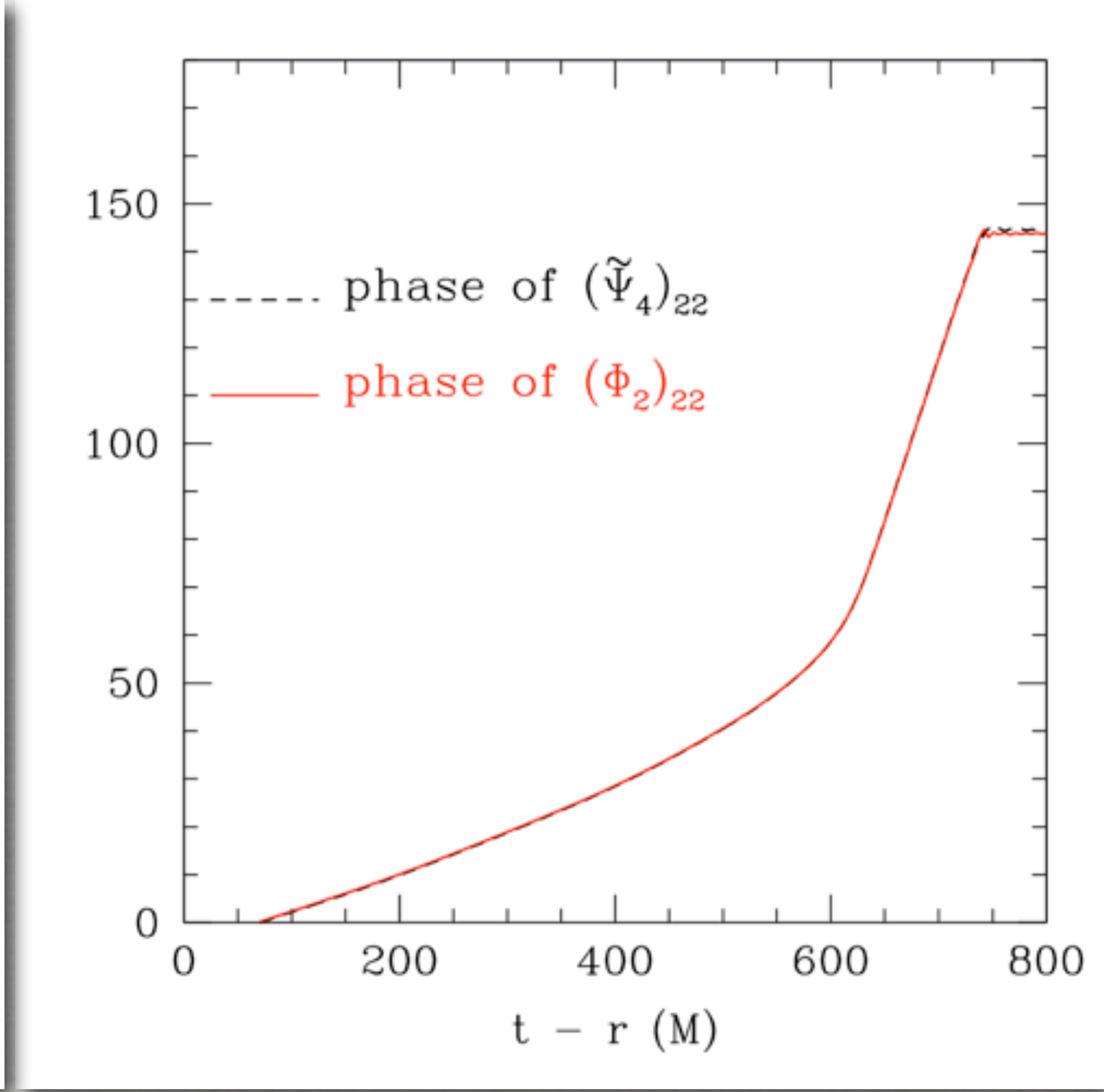
GW, EM radiation computed via Newman-Penrose scalars, ie projection of the Weyl curvature scalar and Faraday tensor onto outgoing null tetrad

$$\Psi_4 = R_{\alpha\beta\mu\nu} k^{\alpha *} m^{\beta} k^{\mu *} m^{\nu} \qquad \Phi_2 = F_{\alpha\beta} k^{\alpha *} m^{\beta}$$









The amplitude evolution in the two channels and lowest mode (l=m=2) has the same features: steep rise at merger followed by QNM ringdown

Phase evolution is identical: EM signal develops with the same freq. as the GW one: ie EM radiation just induced by BBH orbital motion

How efficient is this emission?

$$\frac{E^{\rm rad}_{\rm EM}}{M} \simeq 10^{-15}\left(\frac{M}{10^8\ M_\odot}\right)^2\left(\frac{B}{10^4\ {\rm G}}\right)^2,$$

Recalling that for nonspinning BHs: $E^{\rm rad}_{\rm GW}/M \simeq 5\times 10^{-2}$ the relative efficiency is

$$\frac{E^{\rm rad}_{\rm EM}}{E^{\rm rad}_{\rm GW}} \simeq 10^{-13}\left(\frac{M}{10^8\ M_\odot}\right)^2\left(\frac{B}{10^4\ {\rm G}}\right)^2.$$

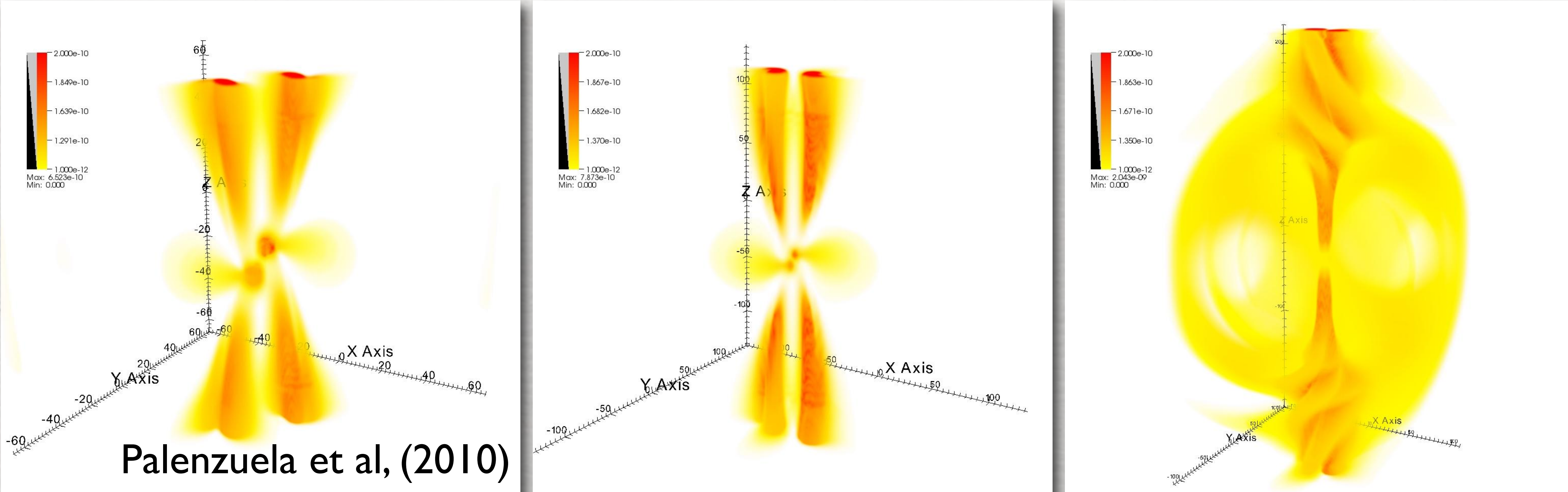
Undetectable for **realistic** fields but **detectable** for **unrealistic** fields (B~10^{10} G). Note that the amount of energy lost is large but at ultra-low freqs. It is unclear direct detection is possible

$$f_{\rm B} \simeq (100\,M)^{-1} \simeq 10^{-2}\left(\frac{10^6\,M_\odot}{M}\right)$$

Extension to a force-free regime

Recent progress (Palenzuela 2010a, b, Neilsen 2010) has been made extending the treatment in electrovacuum to a regime where charges are present but the force-free condition is imposed, ie we consider a tenuous charged plasma in which particles can be displaced but not accelerated: $E^k B_k = 0$

If the B-field is (asymptotically) uniform, "dual jets" are produced both by the motion of the BHs and by their spin.



Palenzuela et al, (2010)

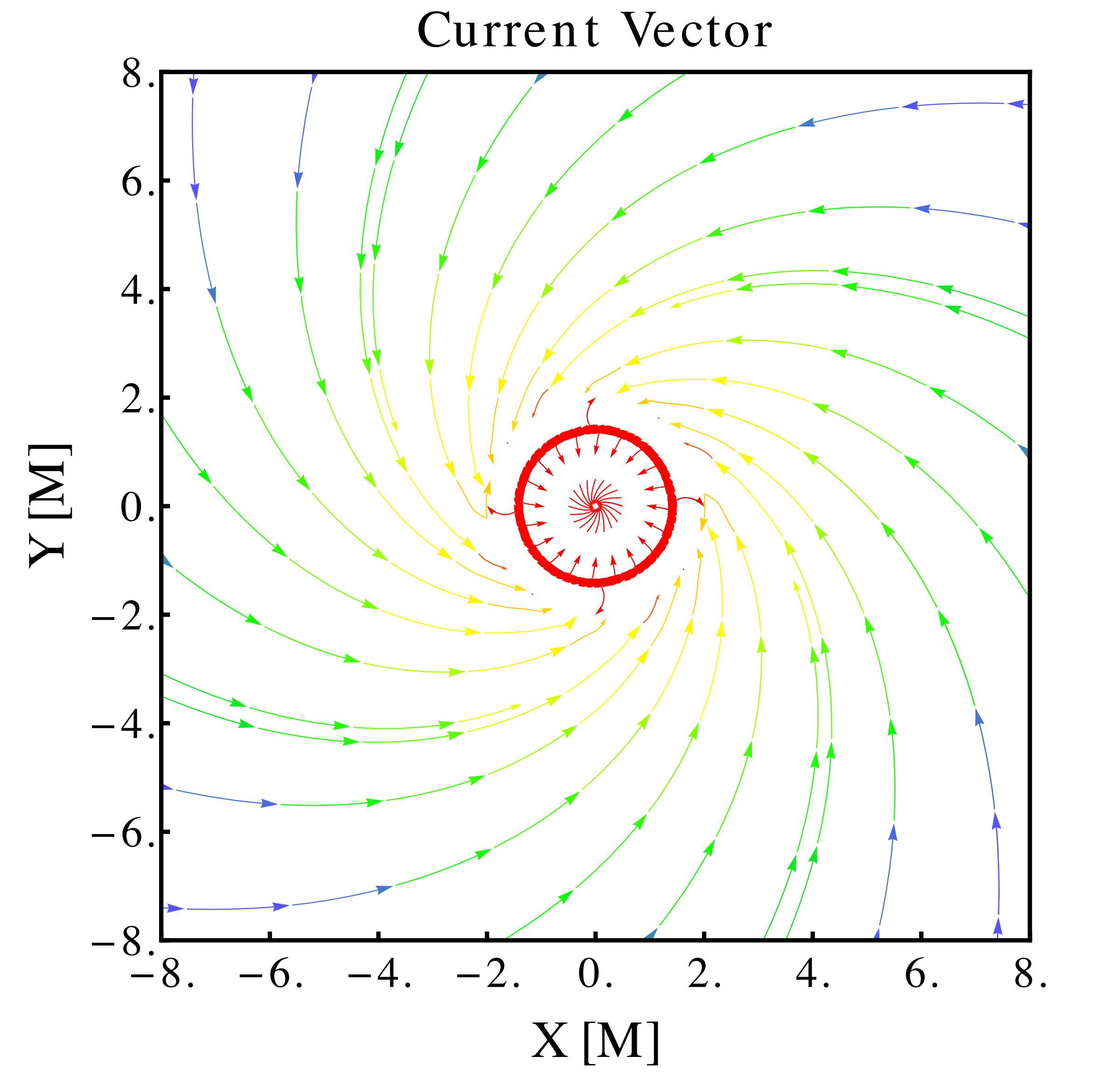
Extension to a force-free regime

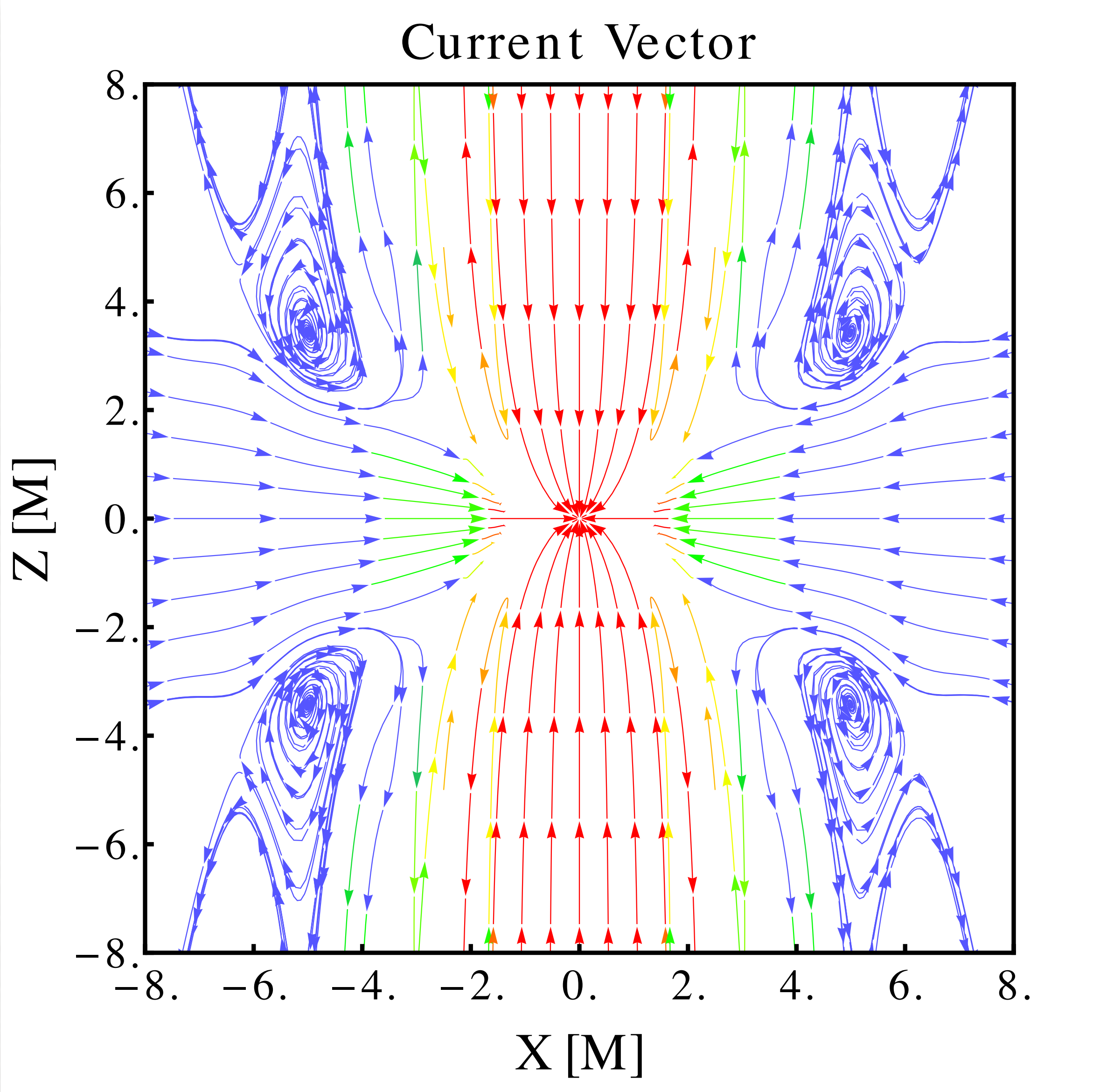
Moesta, LR +(2011)
Alic, LR + (2012)

We have revisited the works of Palenzuela et al and made a number of changes/improvements to their treatment:

- numerical methods: enforcement of the force-free condition based on continuos "driver" prescription
- measurements of the EM luminosity
  - Newmann-Penrose scalars and Poynting vector
  - suitably removing non-radiative background contributions coming from choice of magnetic field

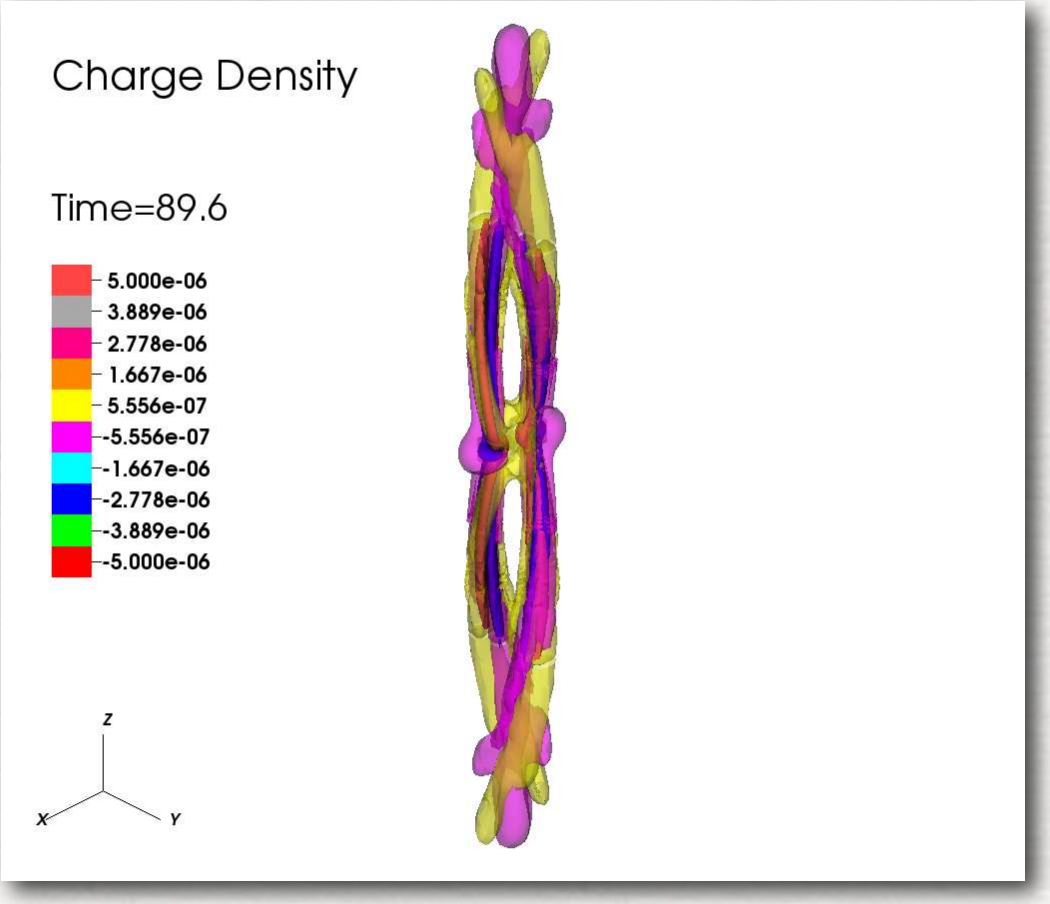
BH magnetosphere: currents



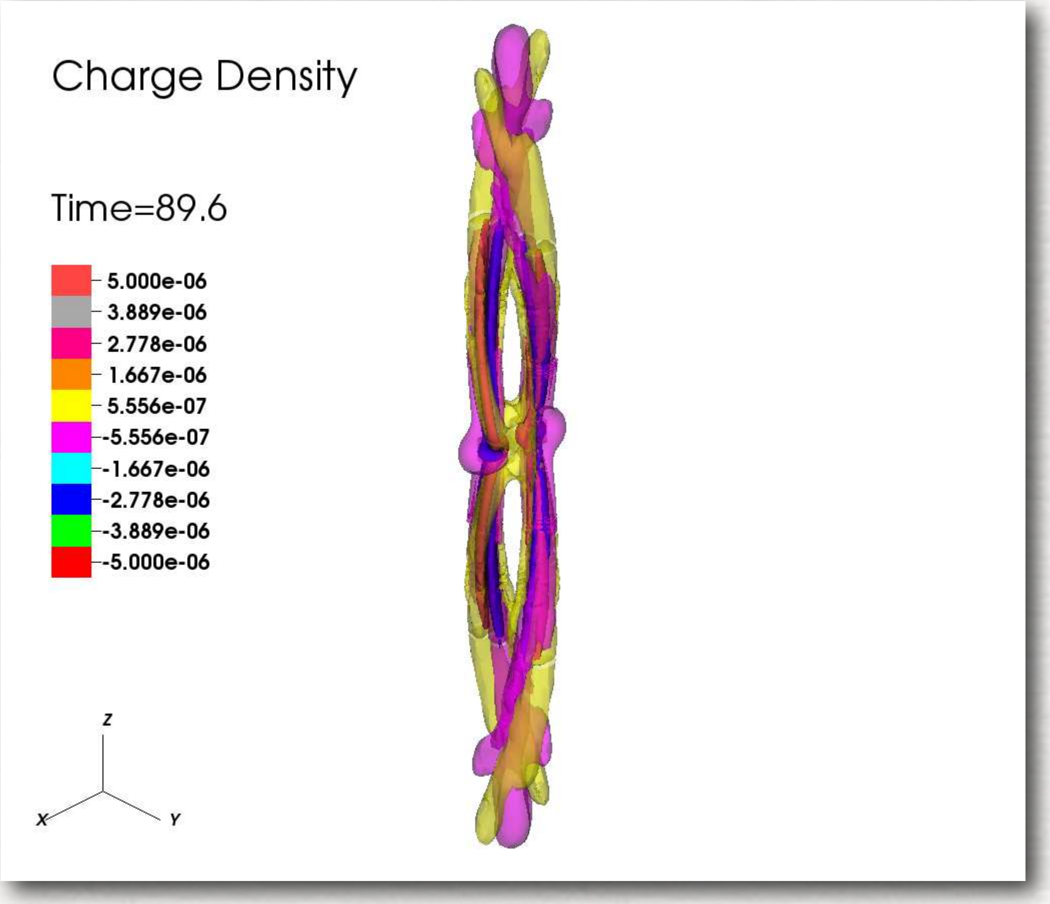


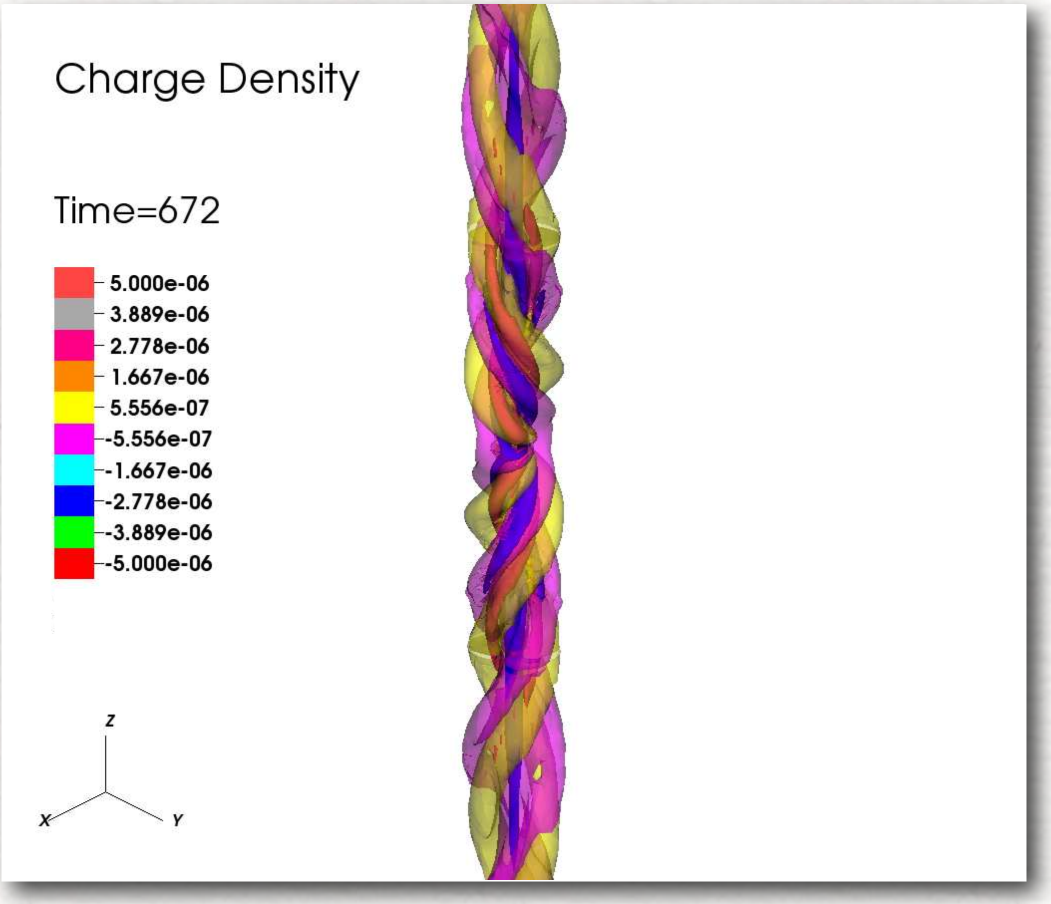
- Electric currents for a single spinning BH on the (x,y) and (x,z) planes, at $t=102M$ (solution has reached stationary state).
- Our "driver" approach provides an accurate current distribution, in agreement with the magnetosphere of a rotating BH obtained as a solution of the Grad-Shafranov eq.

BBH inspiral/merger: charge distribution

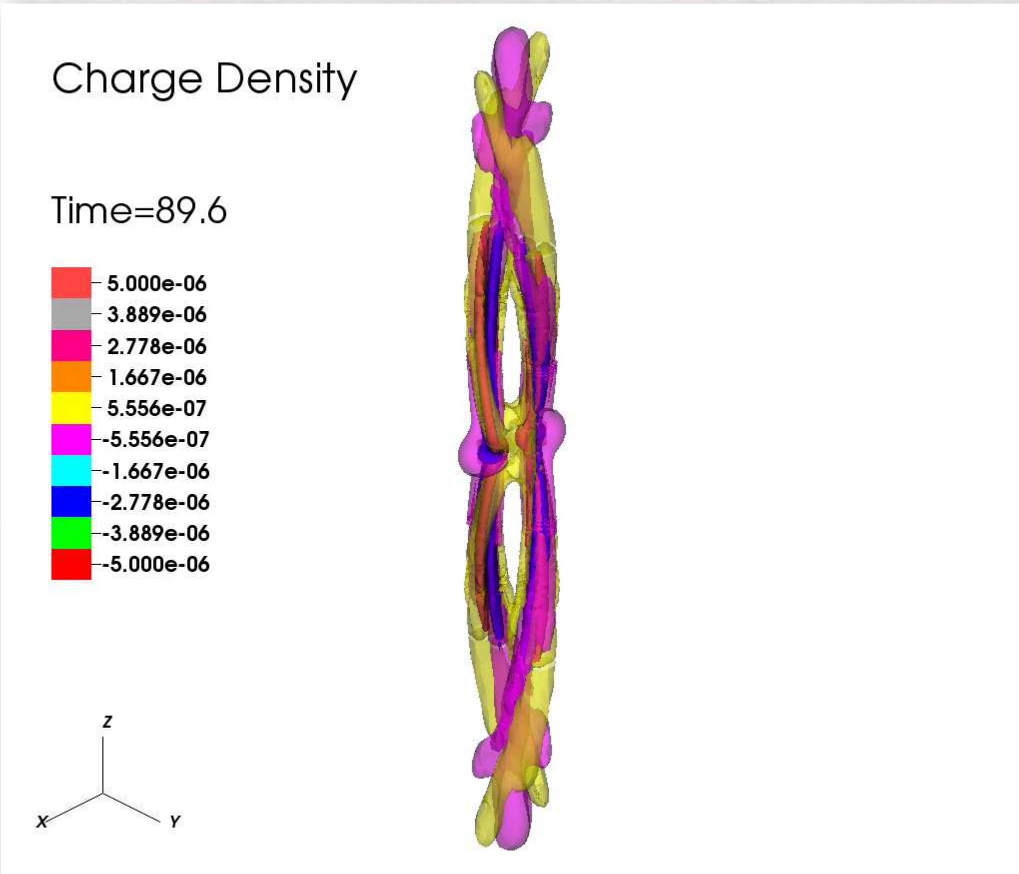


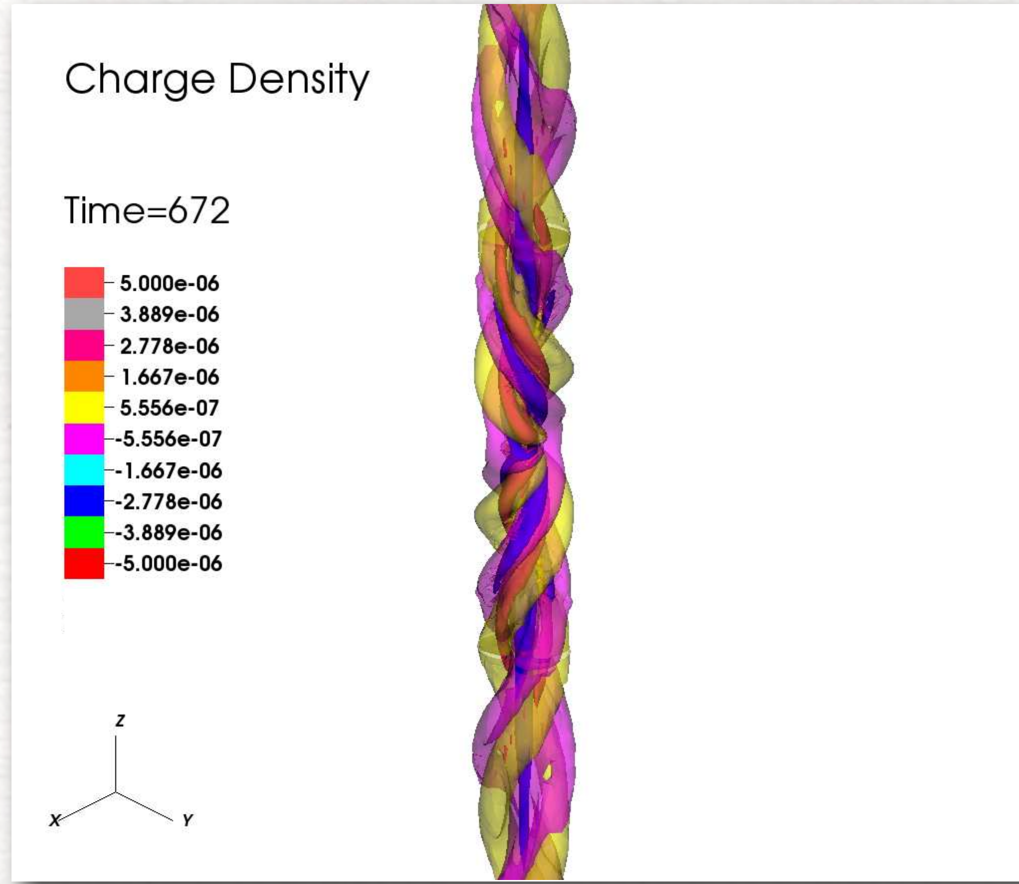
BBH inspiral/merger: charge distribution

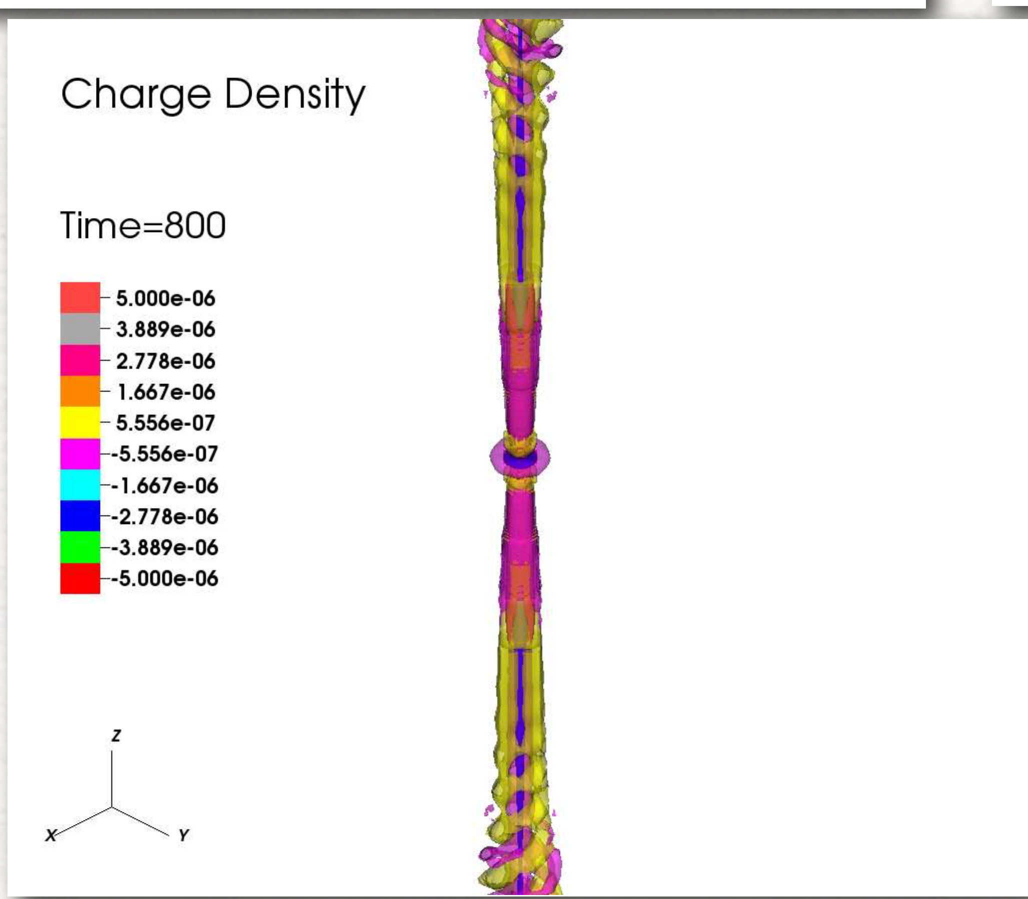




BBH inspiral/merger: charge distribution

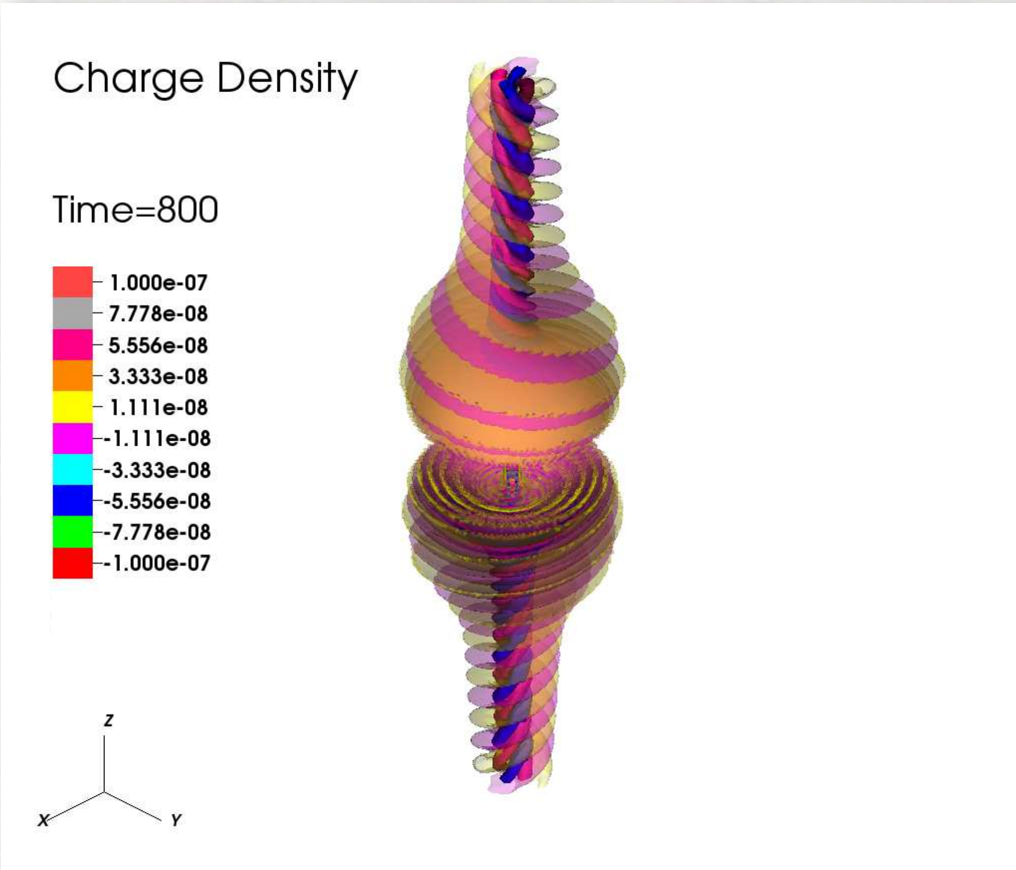


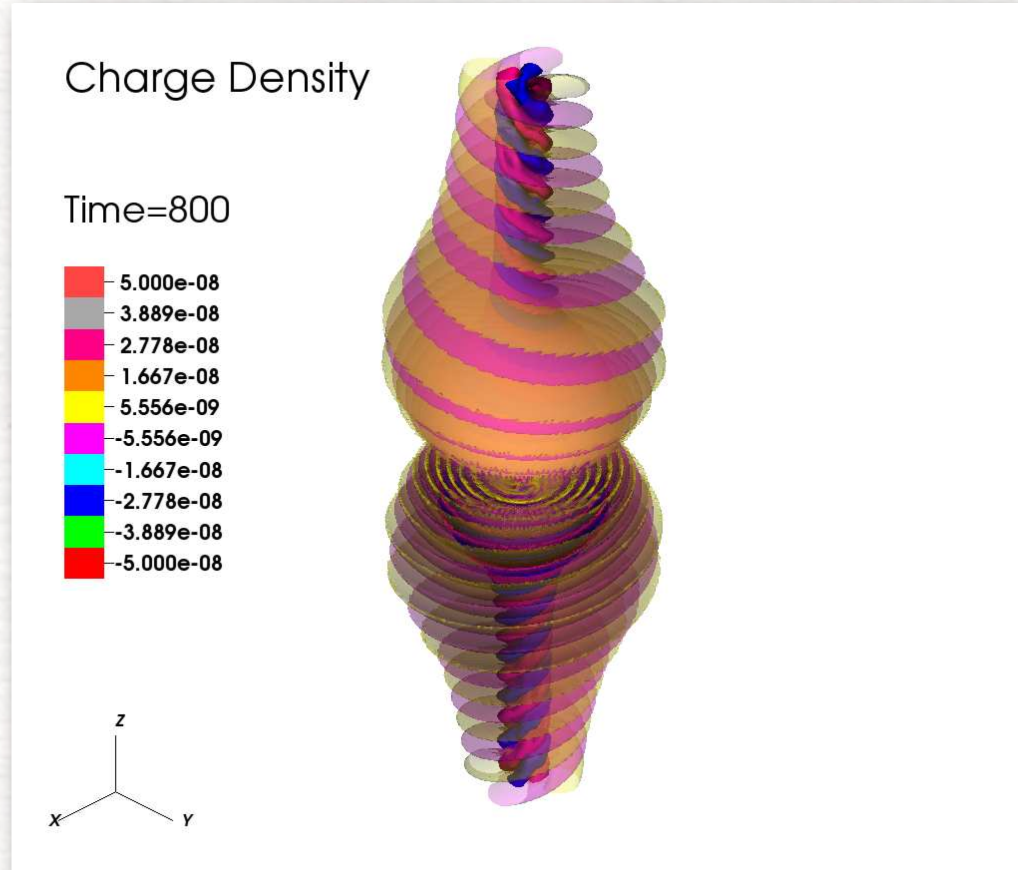


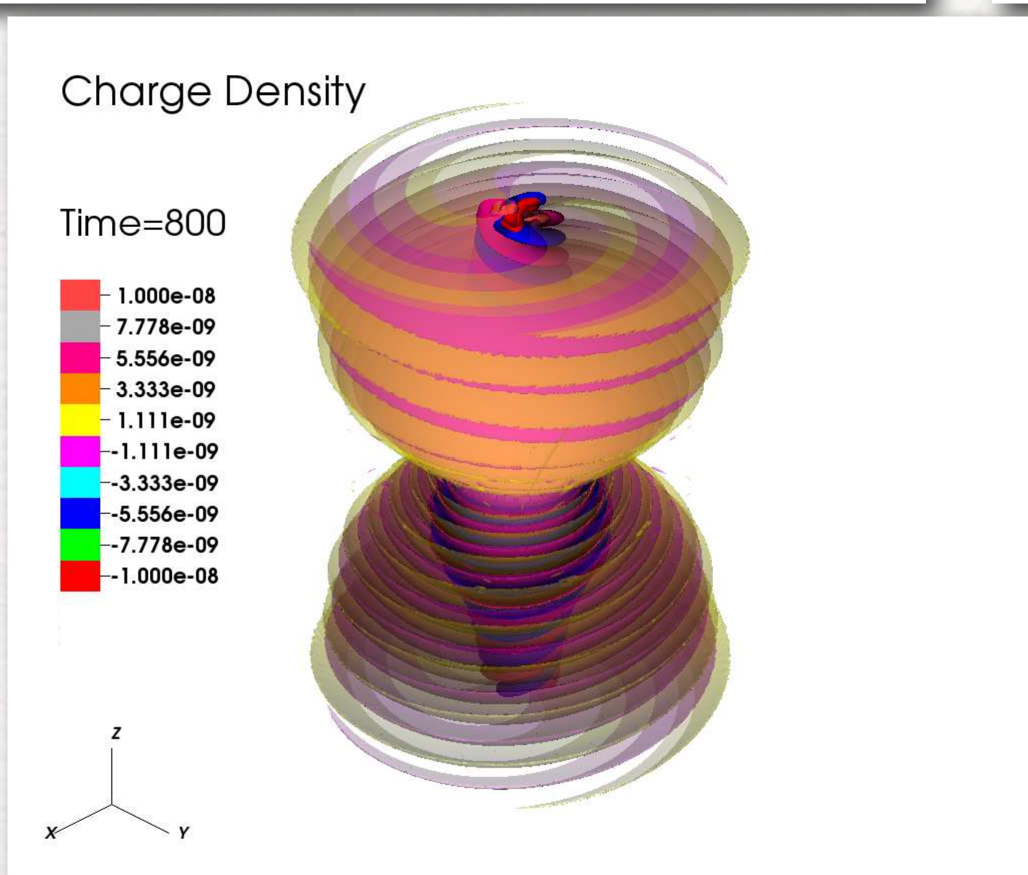


The 3D distribution shows a double-helical symmetry, which could lead to particle acceleration processes, that could cascade into less energetic charges and lead to detectable emission.

BBH inspiral/merger: charge distribution

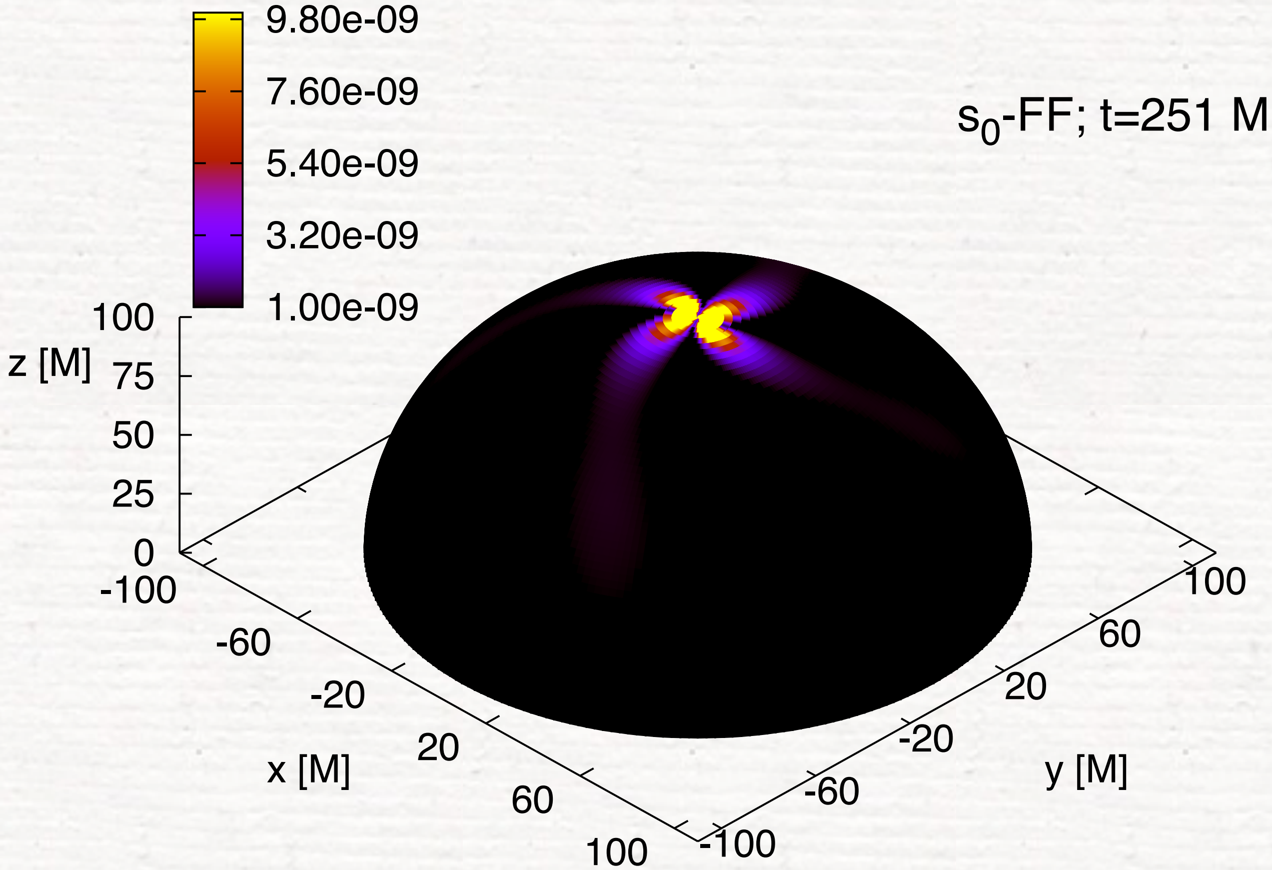


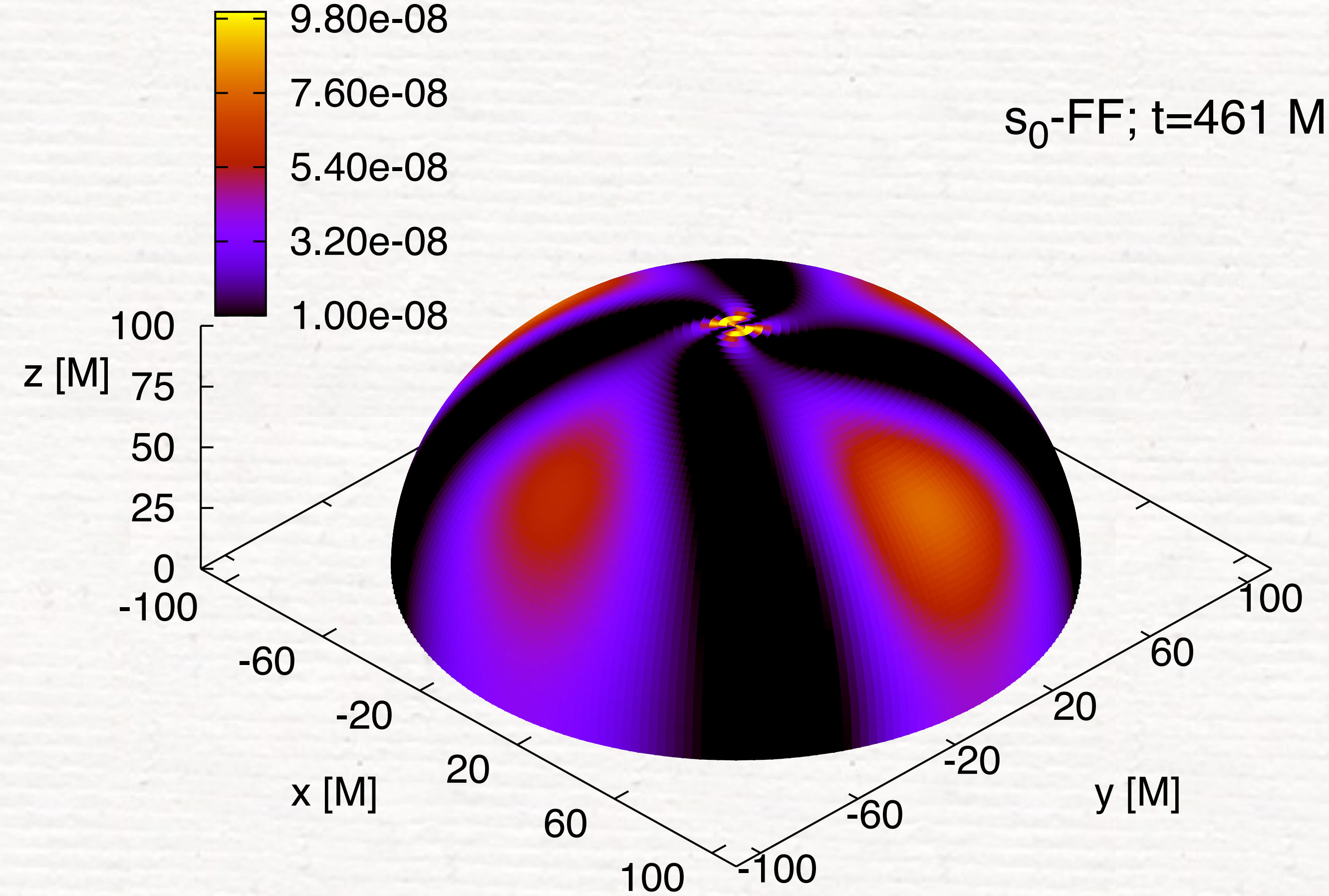


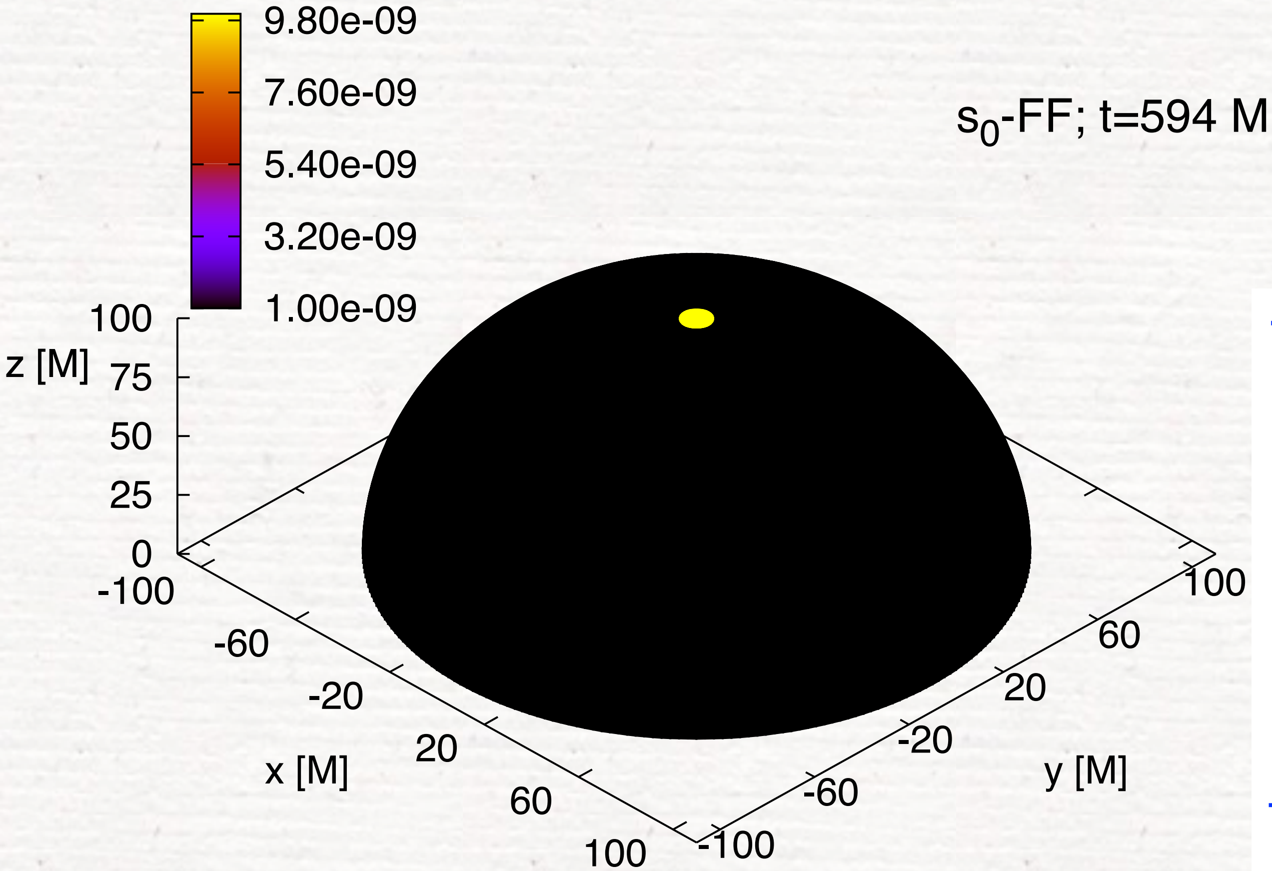


The distribution is not restricted to a small cylindrical area around the two BHs, but it extends in the whole region which is causally connected. Assessing astrophysical consequences requires moving away from FF approx.

BBH inspiral/merger: EM luminosity

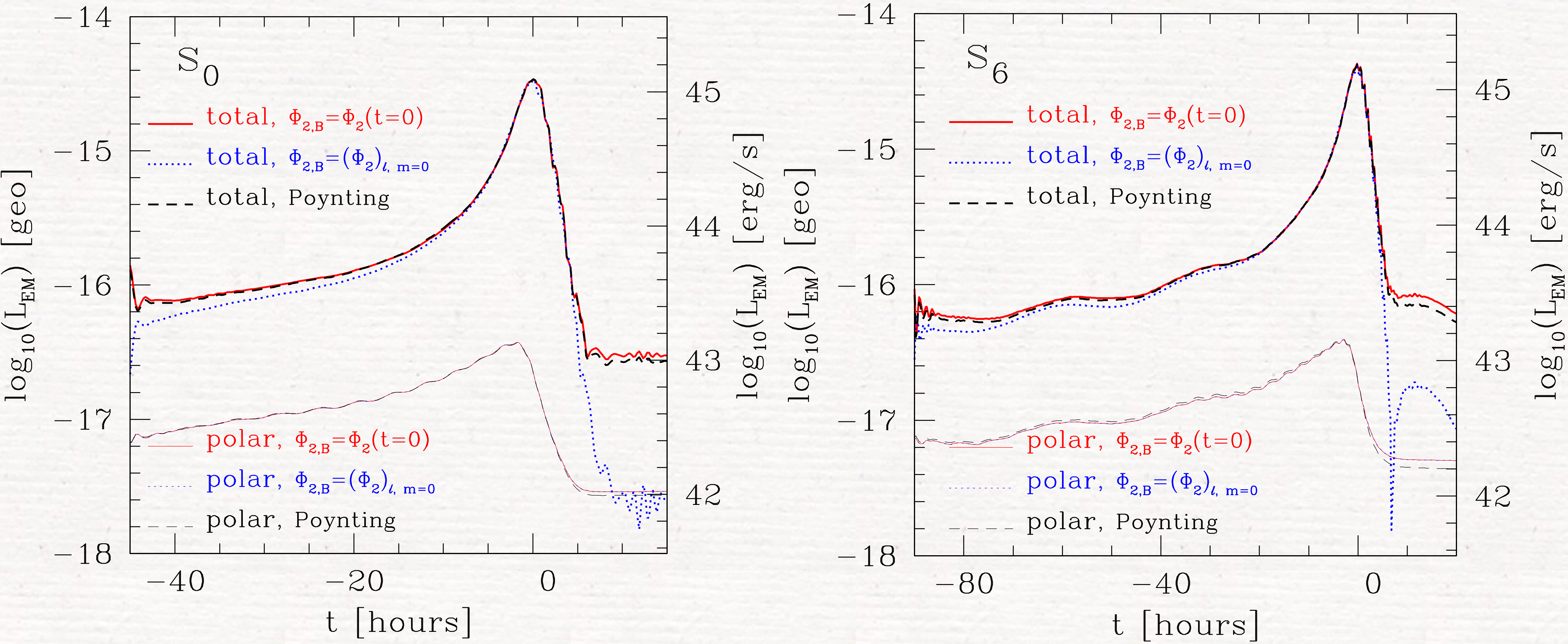






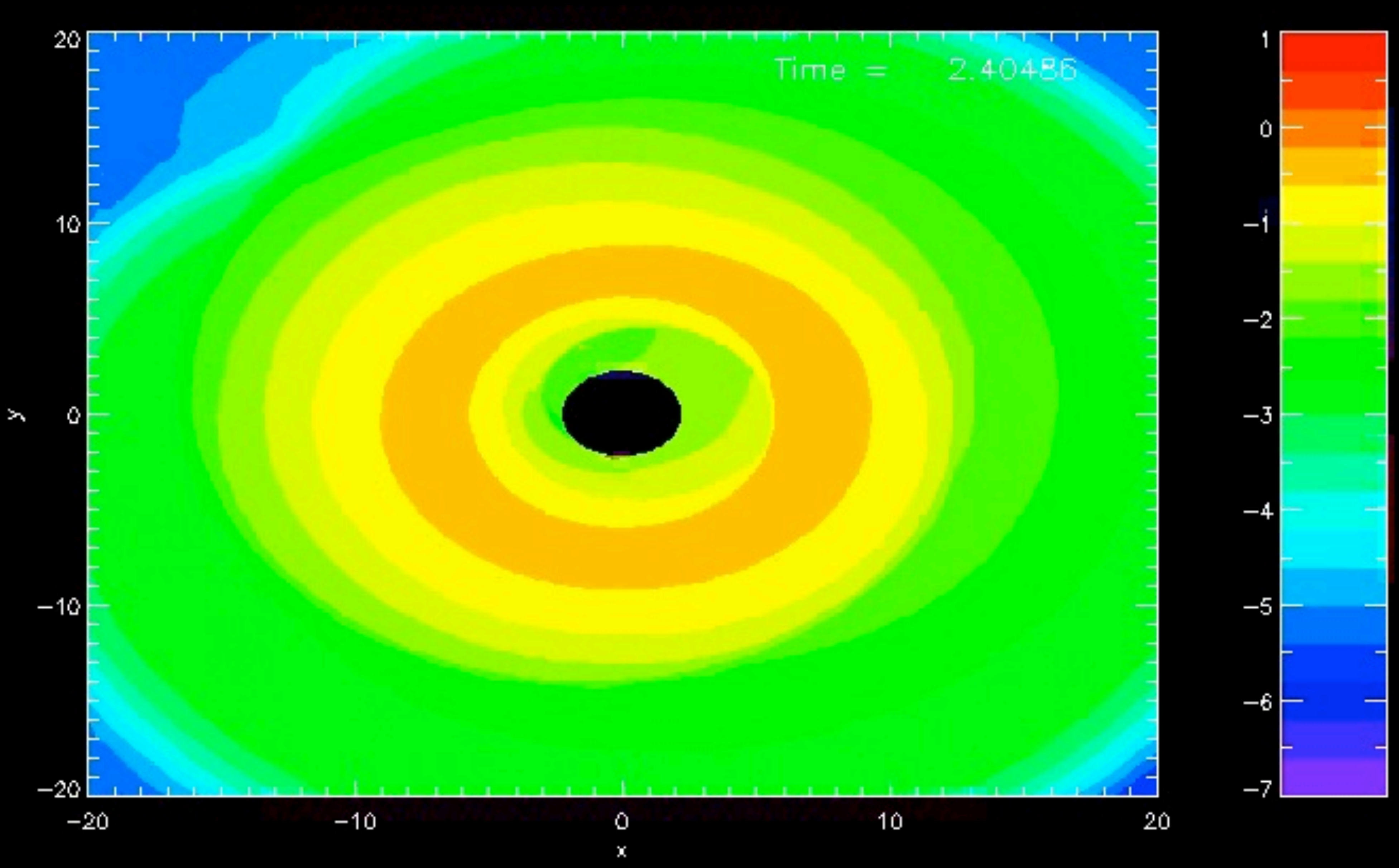
The angular distribution of emitted radiation, projected on a 2-sphere, shows two jets but also two extended lobes which rotate at the same frequency as the binary.

Properties of the EM luminosity



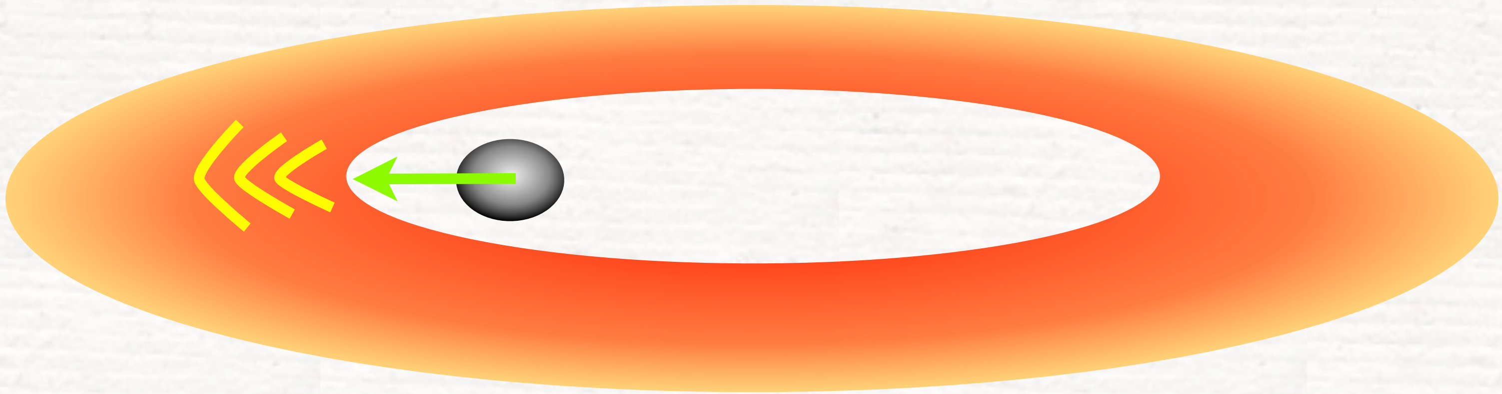
Luminosity for a non-spinning (left) and a spinning (right) binary black hole configuration, with total mass $M = 10^8\, M_\odot$, in a uniform magnetic field of $B_0 = 10^4\, G$.

After the merger...



Investigate the dynamics of the circumbinary disc after the merger, when the final BH has a recoil and a smaller mass.

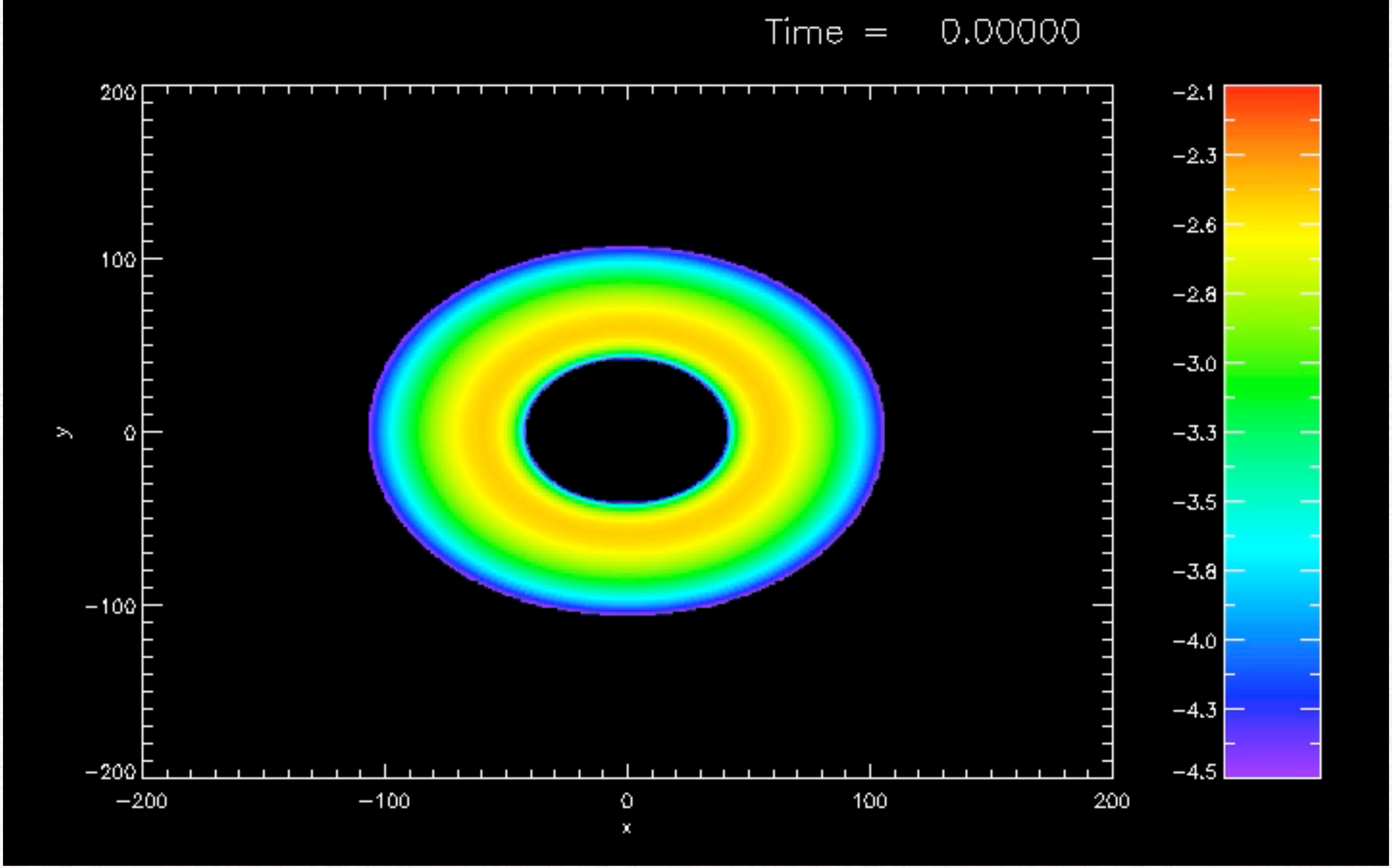
Large literature already:



Lippai+ 2008;
O'Neill+ 2009;
Megevand+ 2009;
Corrales+ 2009;
Rossi+ 2009,
Zanotti, LR+ 2010; 2011

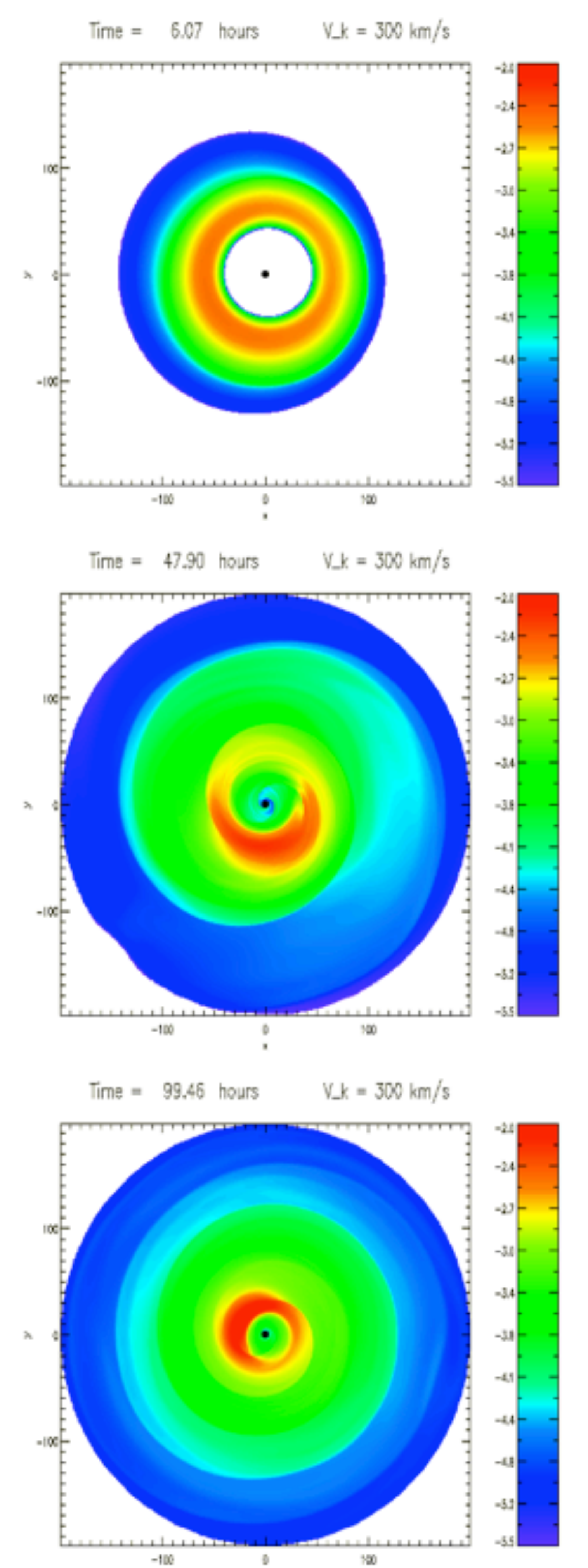
I will concentrate on the results of Zanotti, LR+, 2010, 2011

- the simulations are in general relativity (vs Newtonian)
- the initial data is self-consistent describing tori in equilibrium
- consider large set of tori (small tori with sizes of ~ 100M and large tori with sizes of ~ 1000M)
- frame comoving with the black hole
- consider different values of black hole's spins



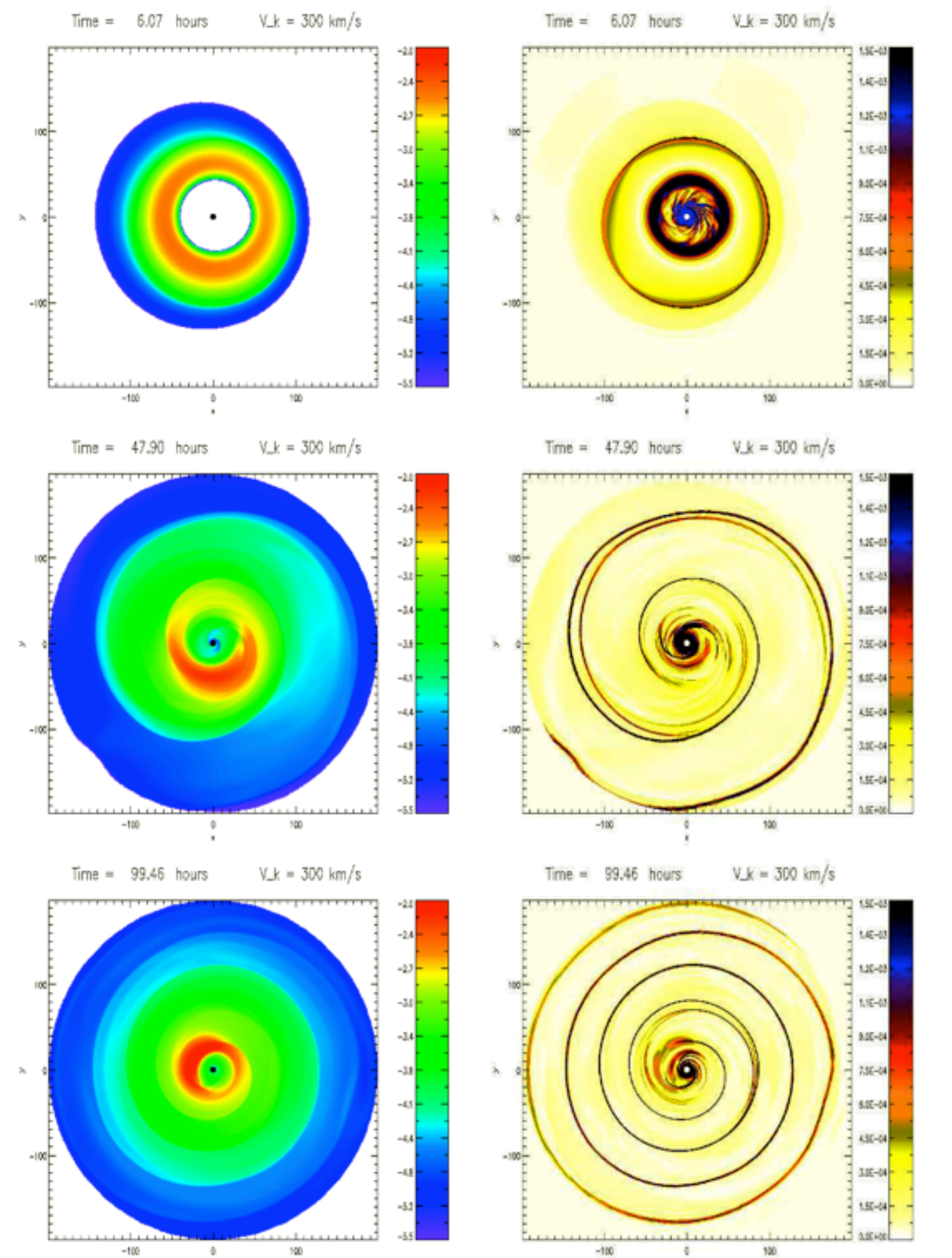
Small disc and recoil of 500 km/s.

Time is in days for a BH of mass~ $10^6\, M_\odot$



Small disc and kick of 500 km/s

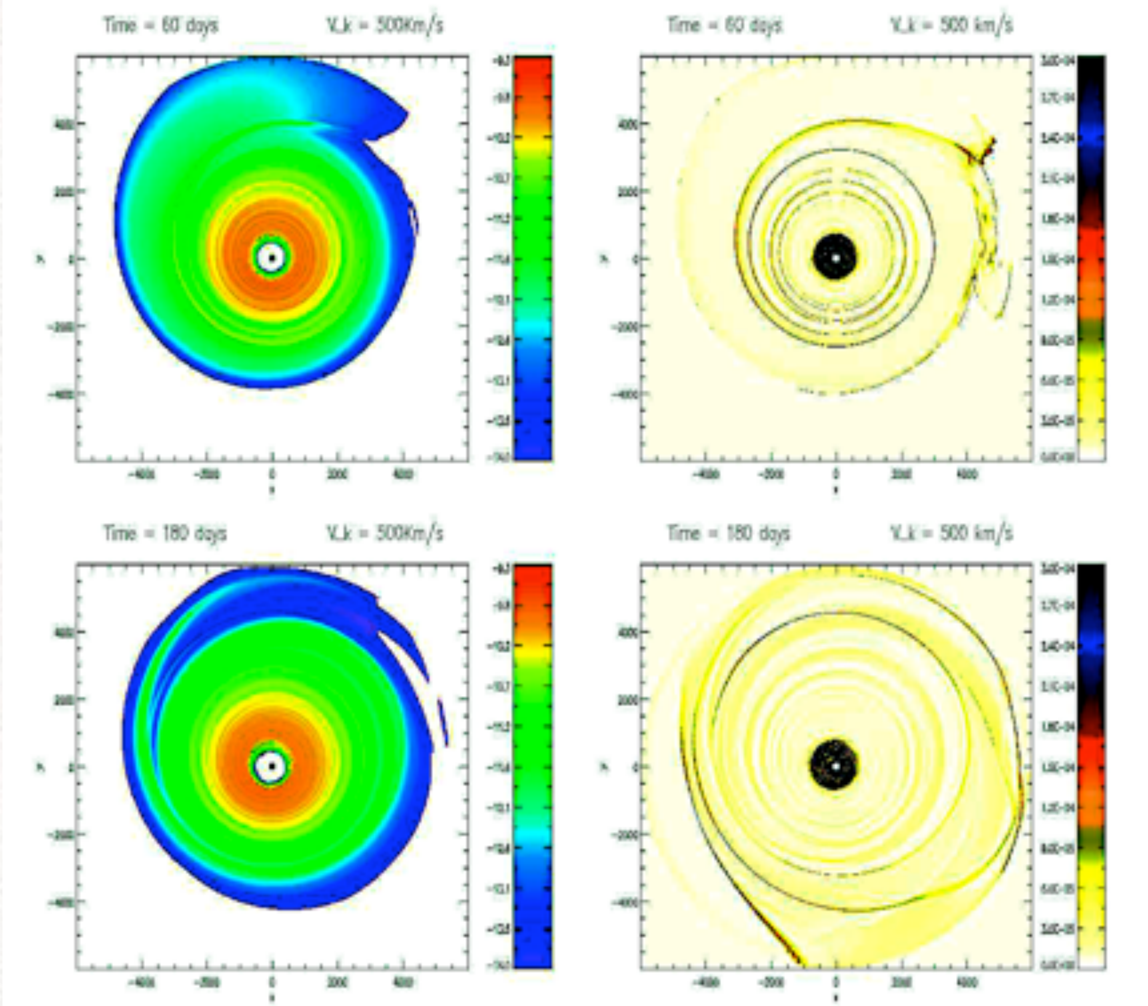
Zanotti, LR+ (2010)



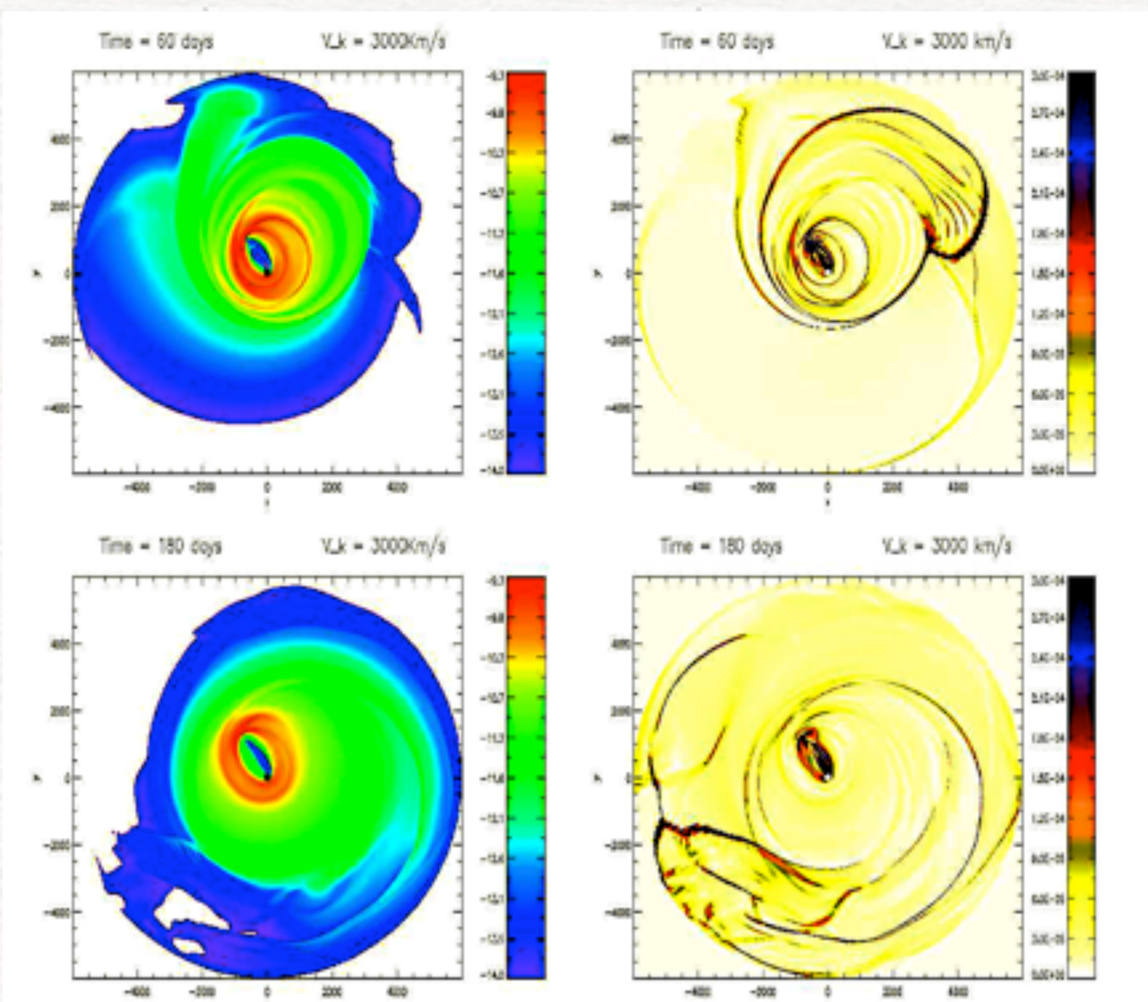
Small disc and kick of 500 km/s

Zanotti, LR+ (2010)

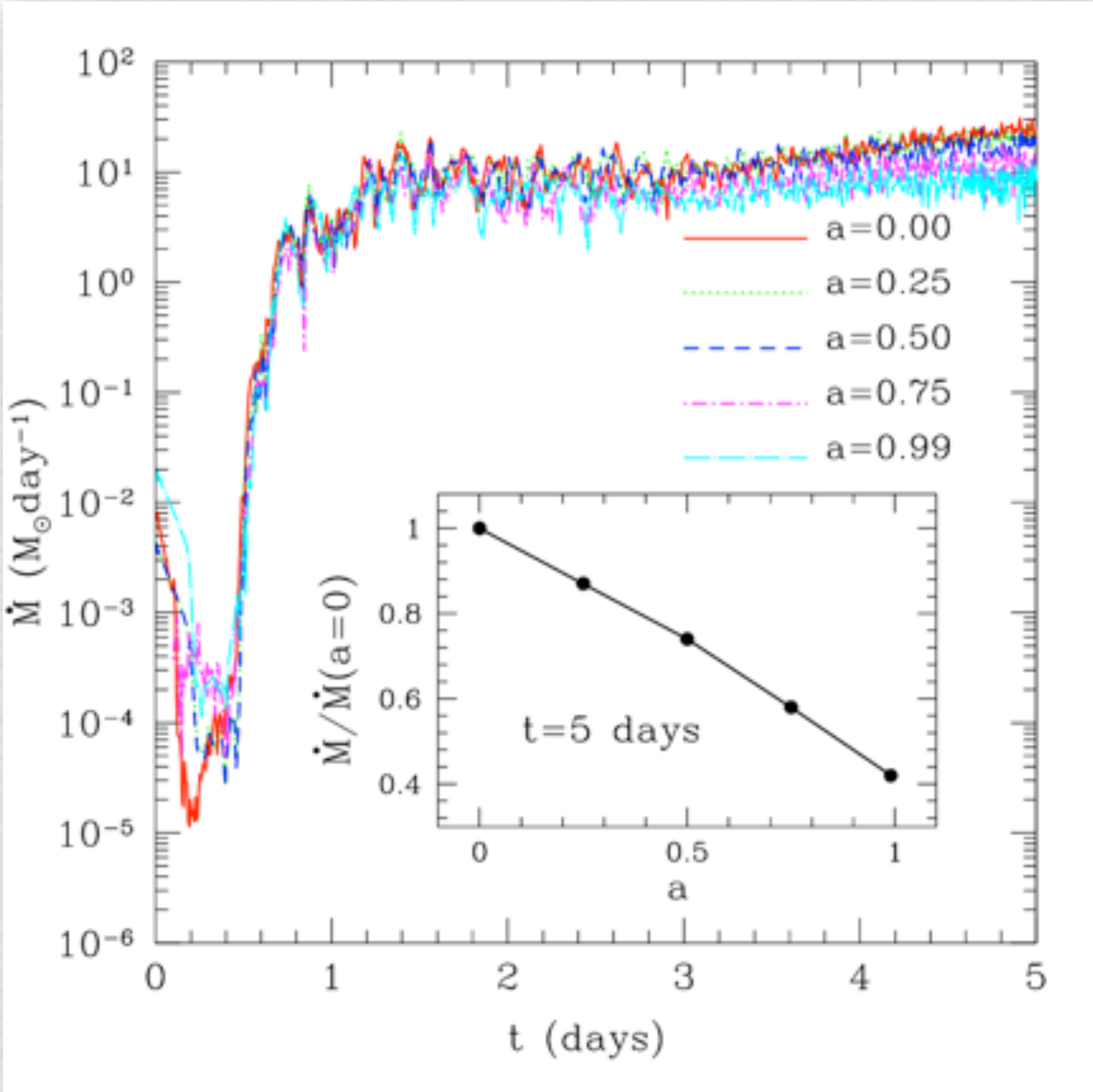
- spiral shocks are produced and and propagate outwards.
- detecting shocks needs lots of care and bad choices may lead to wrong results
- recovered most of the phenomenology observed in Newtonian collisionless discs (Lippai et al. 2008) and in Newtonian fluid discs (Corrales et al. 2009, Rossi et al. 2009, O'Neill et al 2009)



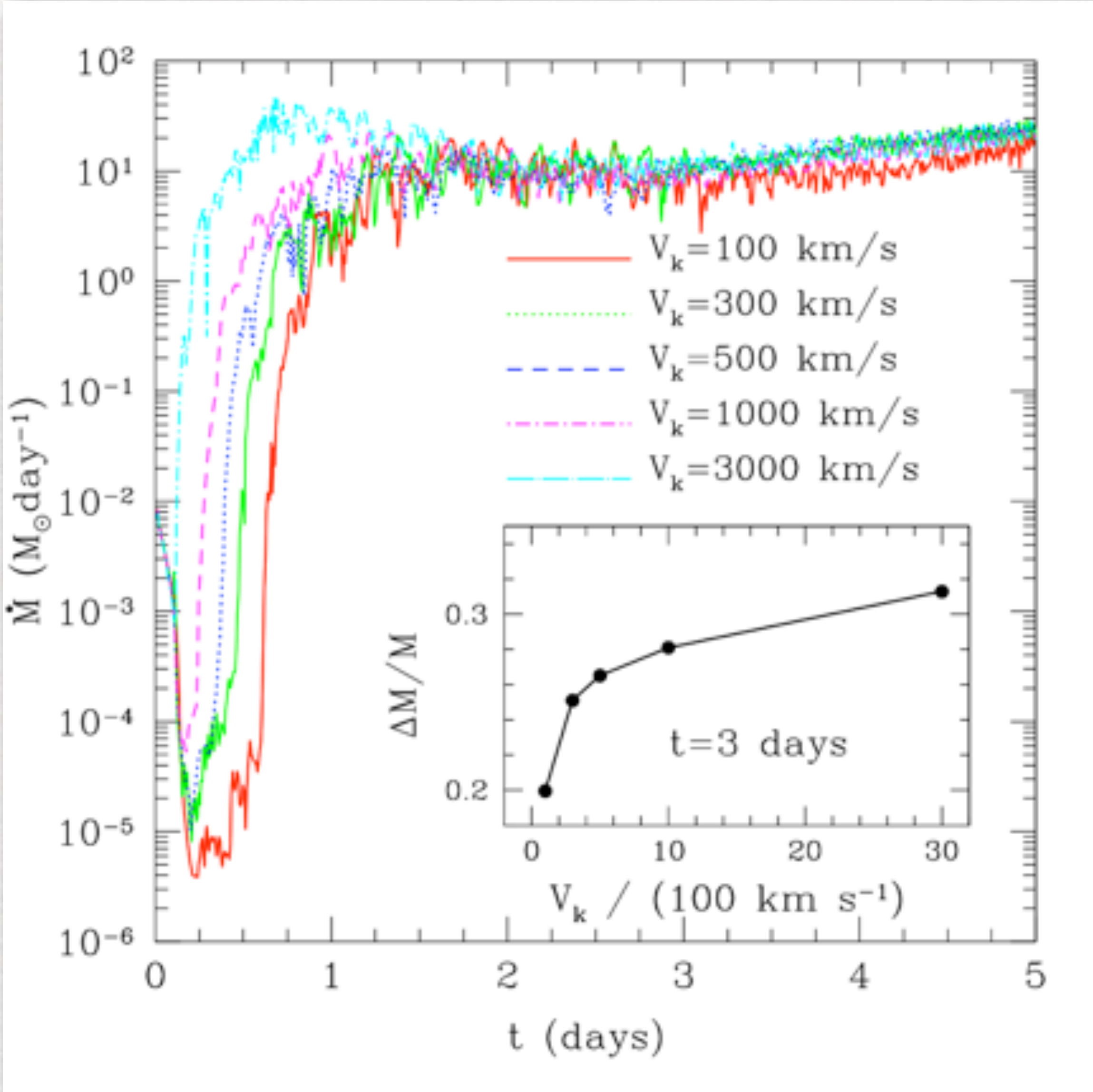
Large disc and kick of 500 km/s: the spiral structure is formed but short-lived



Large disc and kick of 3000 km/s: the spiral structure is never formed although strong shocks appear



- the accretion rate increases dramatically (super-Eddington) the torus falls into the BH
- the mass loss in the BH only excites epicyclic oscillations

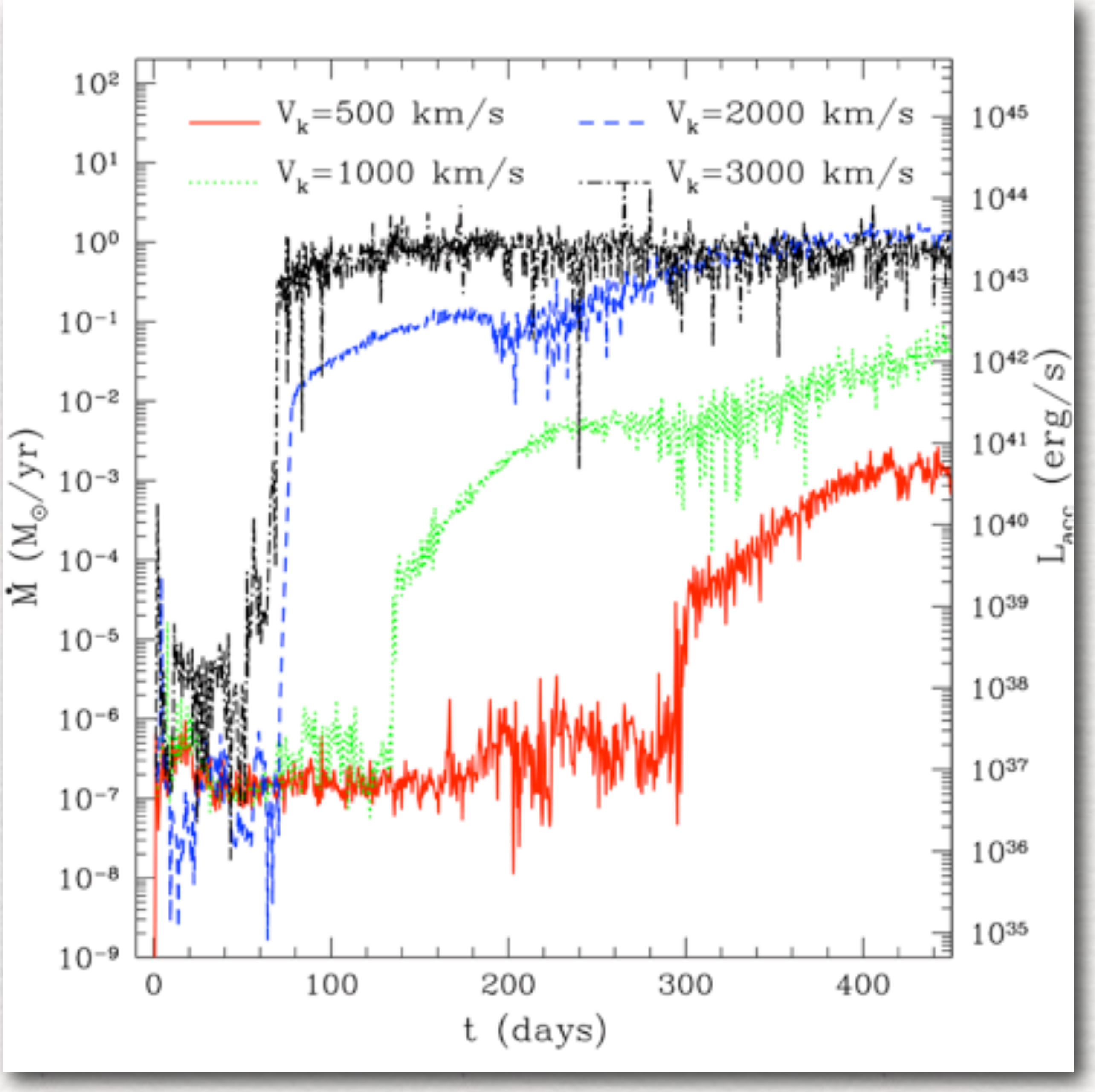


- the spin has little influence on the disc but the accretion rate is smaller for rapidly spinning BHs
- a larger kick anticipates the increase in the accretion rate and the total mass accreted

Bremsstrahlung luminosity

Given a hot, ionized plasma, there will be a bremsstrahlung emissivity produced by electron-proton collisions:

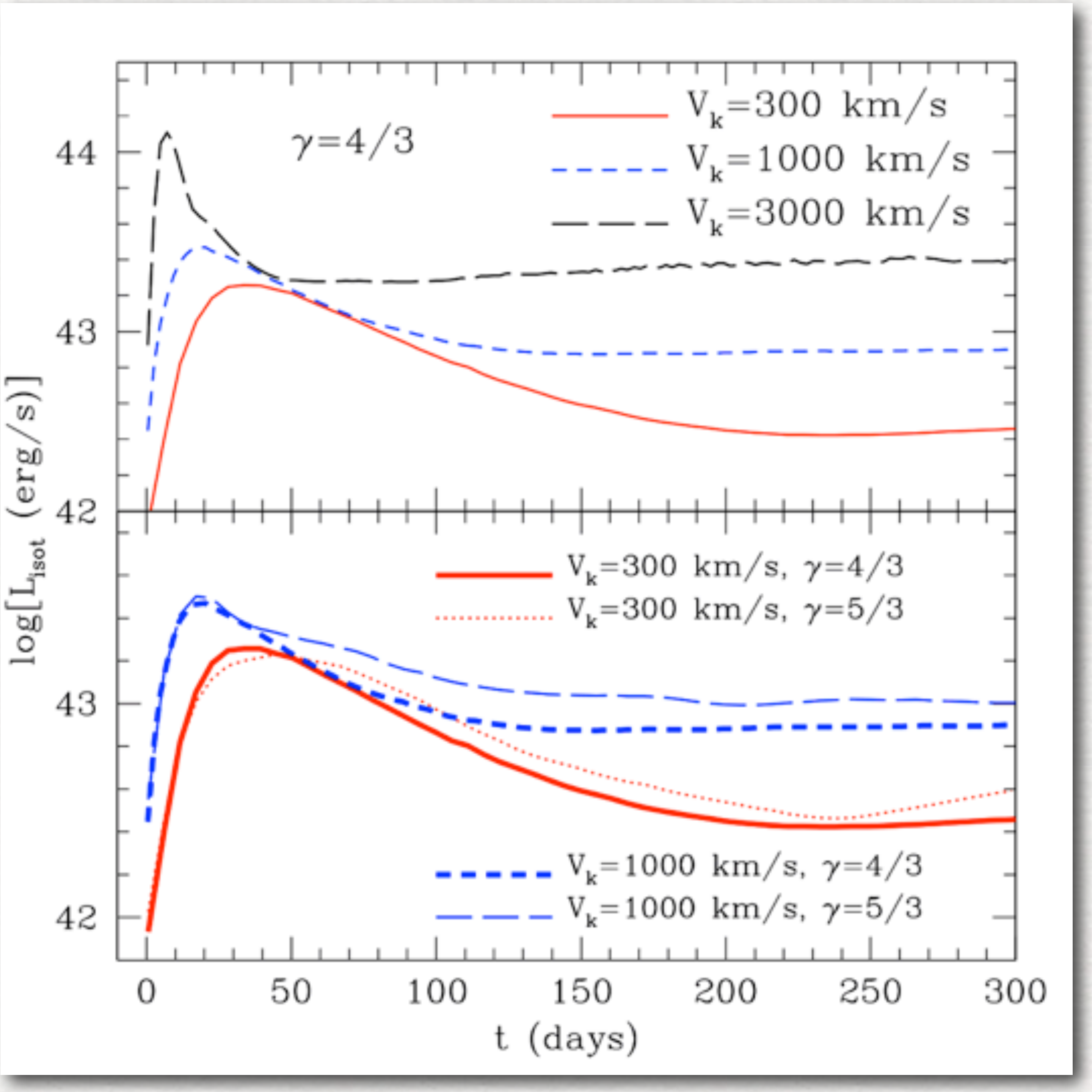
$$L_{\rm BR} \simeq 3 \times 10^{78} \int \left(T^{1/2}\rho^2\Gamma\sqrt{\gamma}dx^3\right)\left(\frac{M_\odot}{M}\right) \quad \frac{\rm erg}{\rm s}$$



This estimate is popular because simple but not self-consistent because it does not account for back-reaction of radiation.

Furthermore it is not realistic since the cooling times of ~ few sec! Yet, it is widely used

Isothermal luminosity

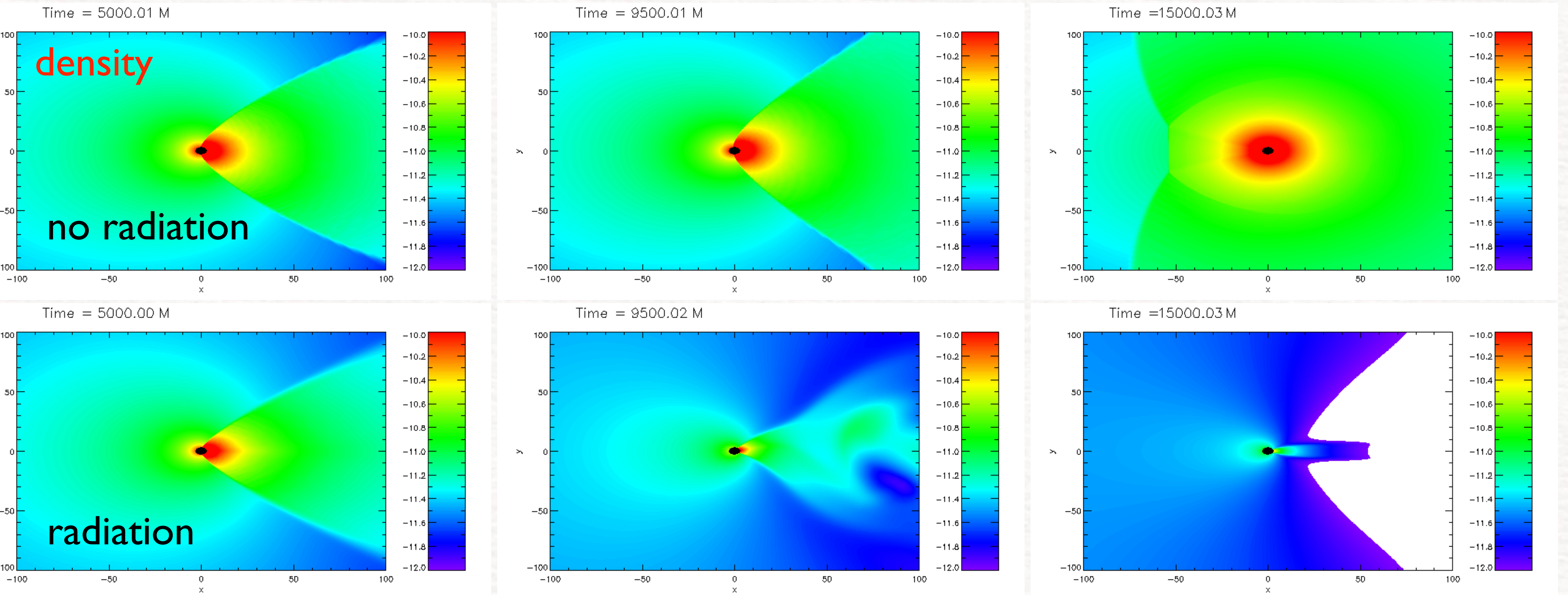


- A more accurate estimate of the luminosity assumes all the changes in temperature due to a compression will be dissipated as radiation (Corrales et al. 2009)
- The luminosity reaches a peak value above **$L \simeq 10^{43}$ erg/s** at about ~ **20 d** after merger for a binary with **$M \simeq 10^6 M_\odot$**. The emission persists for several days at values which are a factor of a few smaller.

Towards radiative transfer: optically thick regime

Zanotti, LR+ (2011)

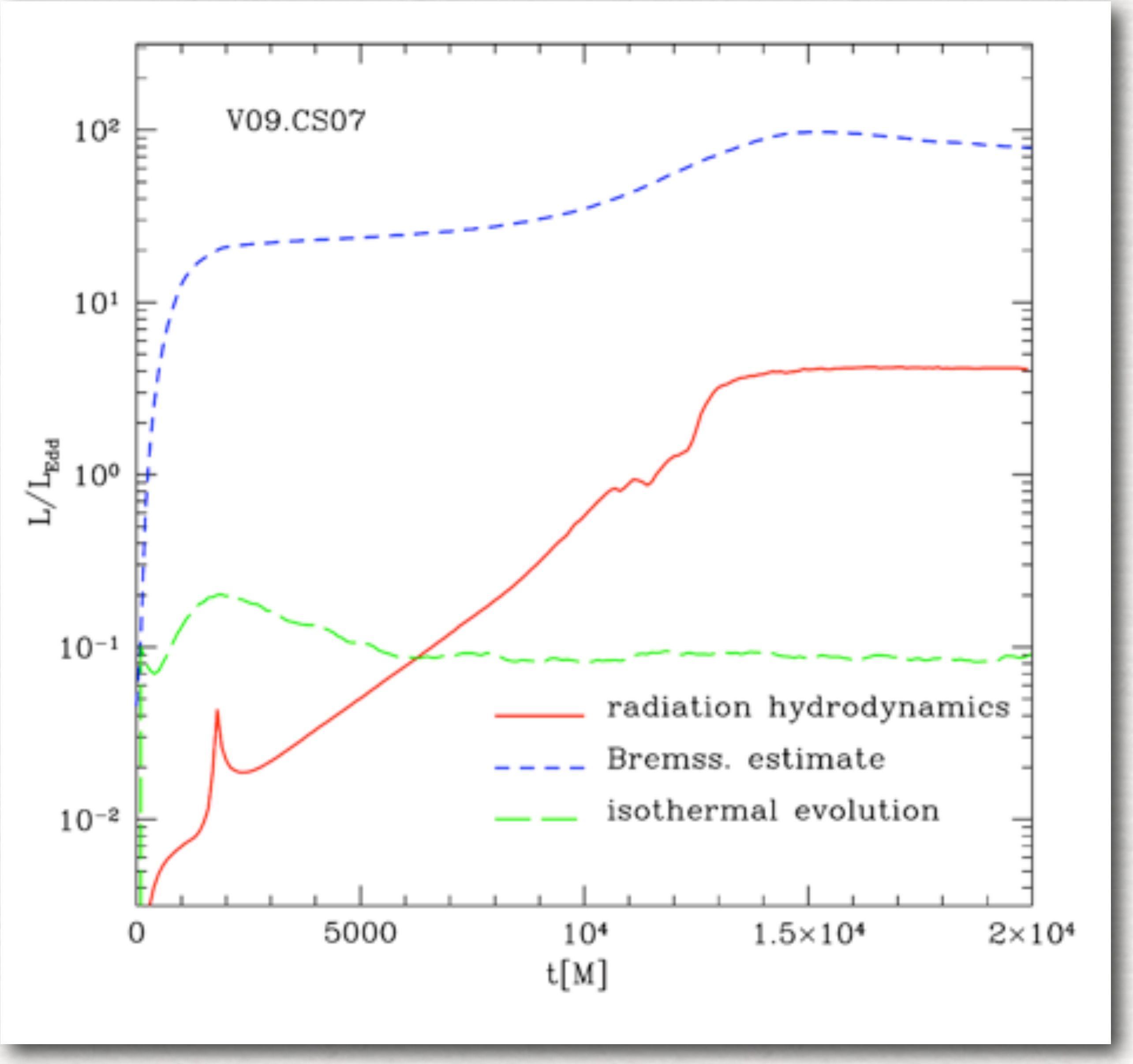
We have extended our code to account also of radiative effects in general relativity and in an optically-thick regime. First study has been the Bondi-Holy accretion flow onto BHs.



Radiation pressure reduces density near BH and accretion. At stationarity: $\dot{M}/\dot{M}_{\rm Edd} \simeq 7;\ L/L_{\rm Edd} \simeq 4;$

Self-consistent luminosities

Zanotti, et al., (2011)



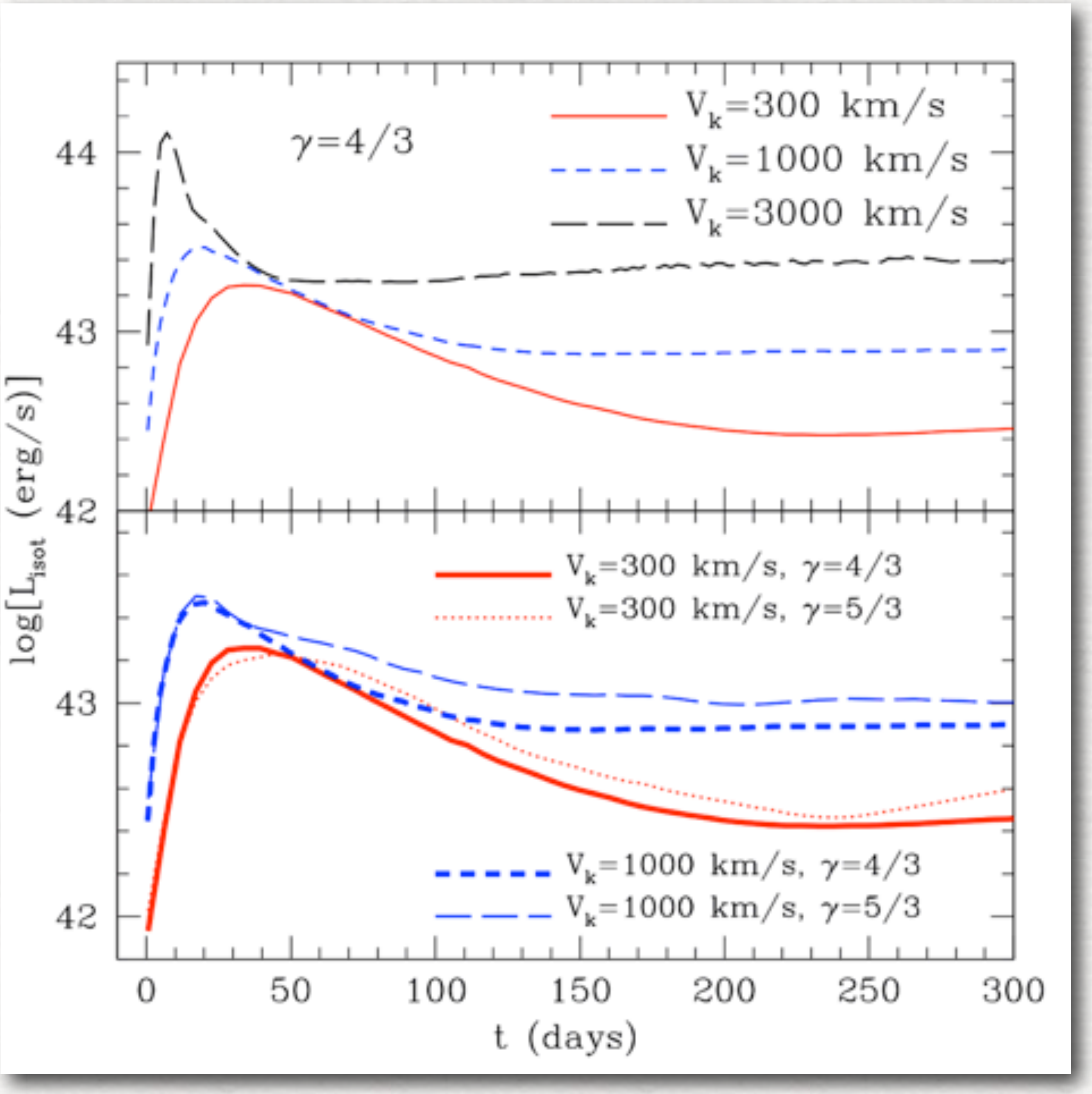
With the possibility of computing self-consistent luminosities in an optically-thick regime we have compared different prescriptions in a Bondi-Hoyle accretion.

The results are:

- Bremsstrahlung estimate is ~ 20 times larger than correct estimate
- isothermal evolution is ~ 45 times smaller than correct estimate

Self-consistent luminosities

Zanotti, LR + (2011)



With the possibility of computing self-consistent luminosities in an optically-thick regime we have compared different prescriptions in a Bondi-Hoyle accretion.

The results are:

- Bremsstrahlung estimate is ~ 20 times larger than correct estimate
- isothermal evolution is ~ 45 times smaller than correct estimate

- Hence, for the same accretion rates in Zanotti (2010), the peak luminosity of **$L \simeq 10^{43}$ erg/s** is amplified of ~ one order of magnitude.

Summary

- Binary black holes represent the strongest sources of GWs, although not the most common (no astronom. evidence yet).
- Numerical relativity is now able to compute the inspiral and merger over the large majority of the space of parameters.
- EM counterparts are possible when matter or EM fields are present. The signal could be challenging to detect.
- EM fields around BHs can be dragged and lead to EM radiation but losses are small for realistic magnetic fields.
- Recoil-induced perturbations on the disc lead to large and likely detectable accretion rates. More physics is needed.
- A lot more can be done to model EM counterparts; observations can help constrain the scenarios that are realistic.