Astrophysics of binary BH mergers: properties of the final BH and EM counterparts

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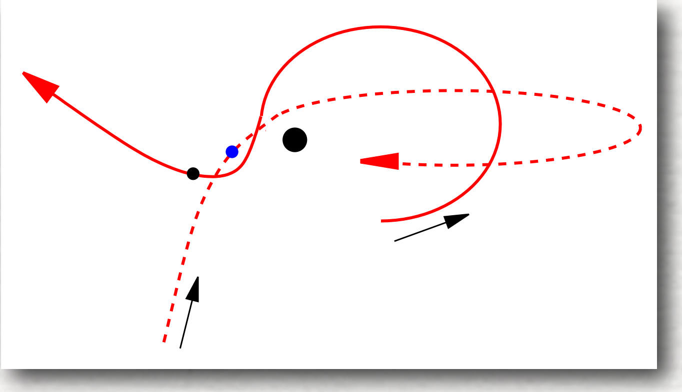


Plan of the talk

- Modelling of the product of binary mergers
  - ★ final spin vector
  - ★ radiated energy
  - ★ recoil

- EM counterparts
  - ★ inspiral and merger: BHs in uniform magnetic field
  - ★ impact of recoil on circumbinary disc

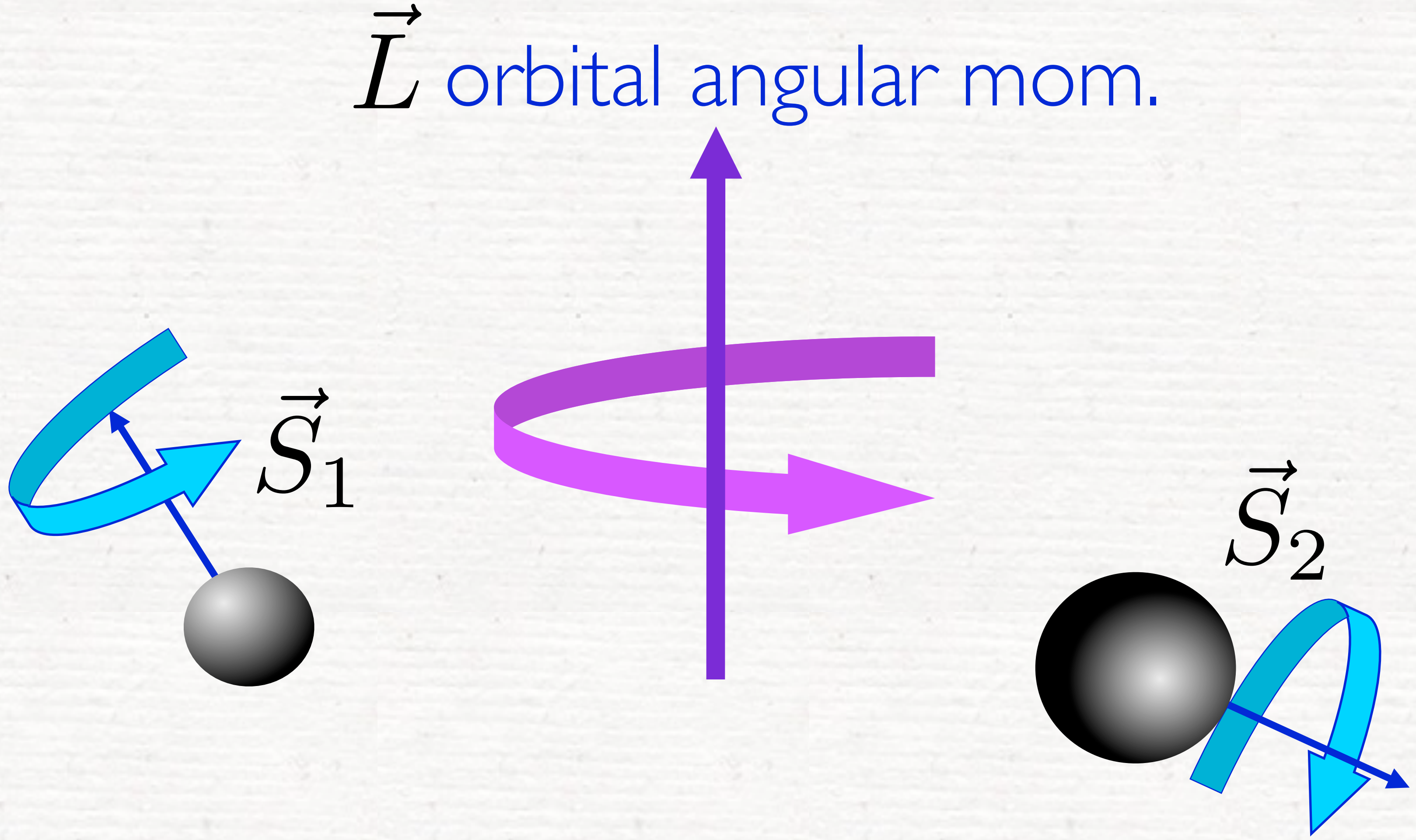
Modelling the final state

- 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 (BKL)
LR et al, 2007
Boyle et al, 2007
Marronetti et al, 2007
LR et al, 2007
Boyle et al, 2008
Baker et al, 2008
Lousto et al, 2008
Tichy & Marronetti, 2008
Kesden, 2008
Barausse, LR, 2009
Lousto et al. 2009

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

Before the merger...



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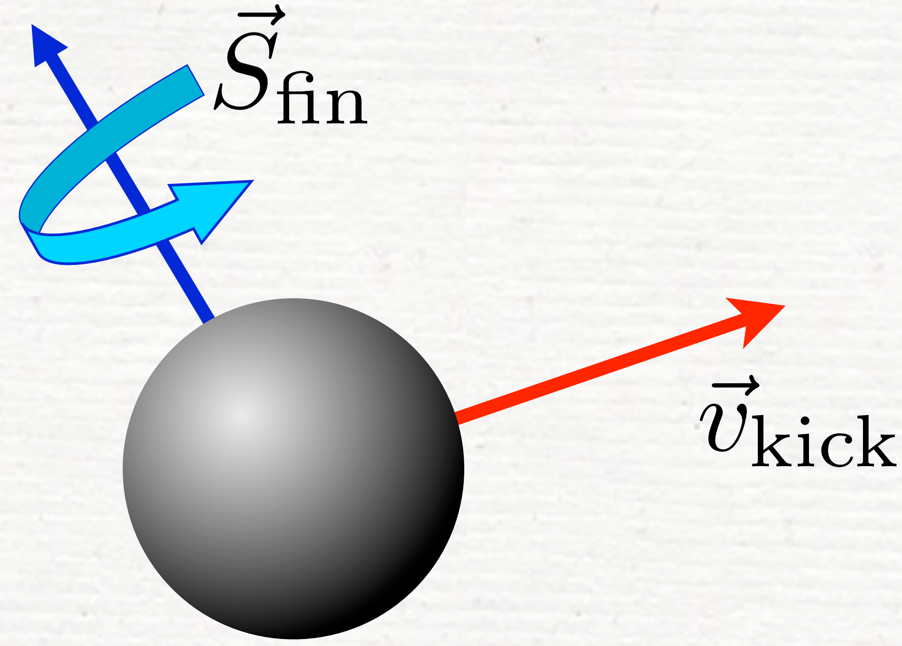
After the merger...



Can we map the initial configuration to a final one without performing a simulation?

The answer is yes! There are different ways of doing this with different levels of precision

There are several different attempts of doing this:

- “physically” motivated (LR et al. 2007a; 2007b; 2008)
- “test-particle” motivated (Buonanno, Kidder, Lehner 2007; Kesden 2008)
- “mathematically” motivated (Boyle, Kesden, Nissanke,2007, Boyle, Kesden 2008)
- abridged “mathemat”. motivated (Marronetti, Tichy, 2007, Tichy, Marronetti 2008)

Important requirements for the formula:

- **simple**, possibly algebraic
- use data for the binary at **large separations**
- as **generic** as possible (arbitrary masses and spins)
- **predictive** (should be deterministic not probabilistic)
- **improvable**

Hereafter I will concentrate on the work done at the AEI

E. Barausse, N. Dorband, D. Pollney, C. Reisswig, J. Seiler

Modelling the spin for *generic* binaries

LR et al (2008); LR et al (2008); LR et al (2008), Barausse, LR (0904.2577)

To do this we need to make 5 (reasonable) assumptions:

(i) the mass radiated in GWs can be neglected: $M_{\rm fin} = M$

$$M_{\rm rad}/M = 1 - M_{\rm fin}/M \approx 5 - 7 \times 10^{-2}$$

(ii) the final spin vector is expressed as the sum of the two initial spin vectors and of a third vector:

$$\boldsymbol{S}_{\rm fin} = \boldsymbol{S}_1 + \boldsymbol{S}_2 + \tilde{\boldsymbol{\ell}}$$

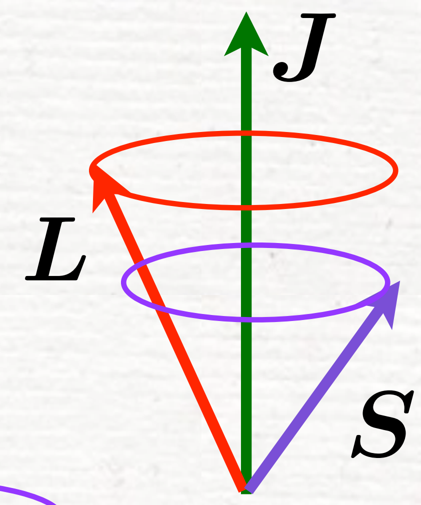
"third" vector is difference between initial orbital angular mom. and radiated one and is a "property" of the binary

$$\boldsymbol{L} + \boldsymbol{S}_1 + \boldsymbol{S}_2 = \boldsymbol{S}_{\rm fin} + \boldsymbol{J}_{\rm rad} \implies \tilde{\boldsymbol{\ell}} = \boldsymbol{L} - \boldsymbol{J}_{\rm rad}$$

Note that the vector norms $|\boldsymbol{S}_1|,\ |\boldsymbol{S}_2|,\ |\tilde{\boldsymbol{\ell}}|$ do not depend on the binary separation r (the vectors however do depend on r)

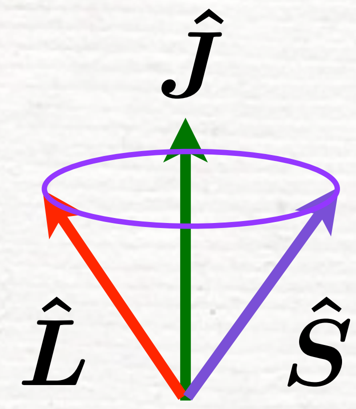
(iii) the final spin vector $\boldsymbol{S}_{\rm fin}$ *is parallel to initial total angular momentum:* $\boldsymbol{S}_{\rm fin} \parallel \boldsymbol{J}_{\rm in}$

where $\boldsymbol{J}_{\rm in} = \boldsymbol{J}(r_{\rm in}) \equiv \boldsymbol{S}_1(r_{\rm in}) + \boldsymbol{S}_2(r_{\rm in}) + \boldsymbol{L}(r_{\rm in})$



(iv) the angles between $\boldsymbol{L}$ *and* $\boldsymbol{S} \equiv \boldsymbol{S}_1 + \boldsymbol{S}_2$ *and between the spins* $\boldsymbol{S}_1, \ \boldsymbol{S}_2$ *are constant during the inspiral, while both* $\boldsymbol{L}$ *and* $\boldsymbol{S}$ *precess around* $\boldsymbol{J}$ *:*

$$\hat{\boldsymbol{L}} \cdot \hat{\boldsymbol{S}} = \text{const}\,; \quad \hat{\boldsymbol{S}}_1 \cdot \hat{\boldsymbol{S}}_2 = \text{const}$$



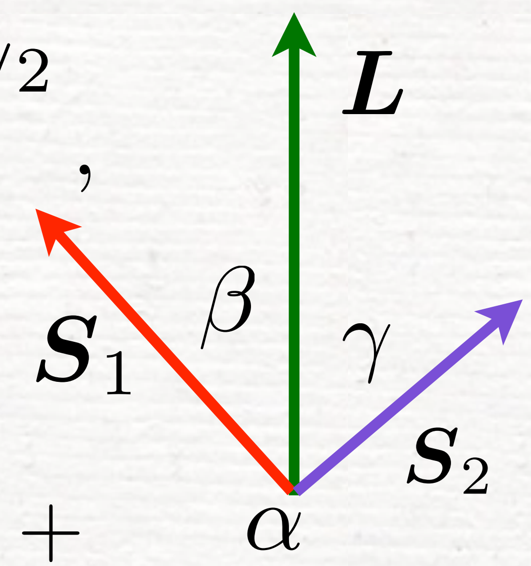
(v) When the initial spin vectors are equal and opposite and the masses are equal, the final spin is same as for zero spins

$$\boldsymbol{a}_{\rm fin}(\boldsymbol{a}_1 = -\boldsymbol{a}_2, q) = \boldsymbol{a}_{\rm fin}(\boldsymbol{a}_1 = 0 = \boldsymbol{a}_2, q)$$

Stated differently, equal-mass binaries with equal and opposite-spins behave as nonspinning binaries (Confirmed numerically).

Using these assumptions it is possible to write a unique expression for *the amount of angular momentum not radiated* and It is trivial to write the norm of the dimensionless spin vector as

$$|\boldsymbol{a}_{\rm fin}| = \frac{1}{(1+q)^2}\Big[|\boldsymbol{a}_1|^2 + |\boldsymbol{a}_1|^2 q^4 + 2|\boldsymbol{a}_2||\boldsymbol{a}_1|q^2\cos\alpha + 2\left(|\boldsymbol{a}_1|\cos\beta + |\boldsymbol{a}_2|q^2\cos\gamma\right)|\boldsymbol{\ell}|q + |\boldsymbol{\ell}|^2 q^2\Big]^{1/2},$$



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 "third" vector and hence the final spin is fully determined in terms of the 5 coefficients $s_4,\ s_5,\ t_0,\ t_2,\ t_3$ introduced for the aligned binaries.

Does this work?...

- Test against **equal-mass, unequal-spin aligned** binaries

$$a_1 \neq a_2, \qquad q = 1, \; (M_1 = M_2)$$

- Test against **unequal-mass, equal-spin aligned** binaries

$$a_1 = a_2 = a, \qquad q \neq 1, \; (M_1 \neq M_2)$$

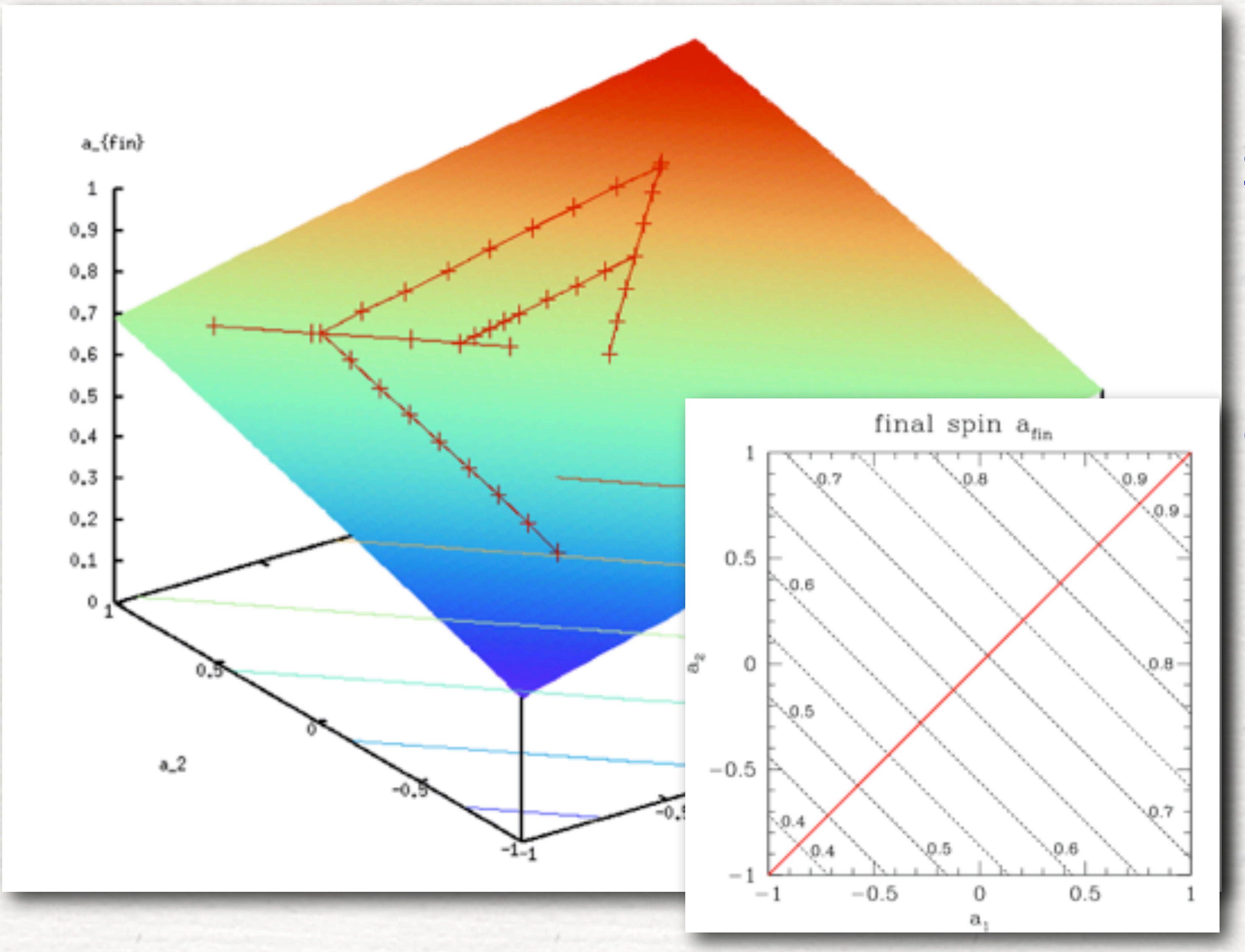
- Test against **generic** binaries

Equal-mass, unequal-spin binaries

The resulting expression is ($p_i = p_i(s4, s5, t0, t2, t3)$)

$$a_{\rm fin} = p_0 + p_1(a_1 + a_2) + p_2(a_1 + a_2)^2$$

with $\quad p_0 \simeq 0.6883;\ p_1 \simeq 0.1530;\ p_2 \simeq -0.0088$



- opposite spins same as non spinning
- monotonic behaviour
- final spin increases along the SW-NE diagonal
- minimum and maximum spin

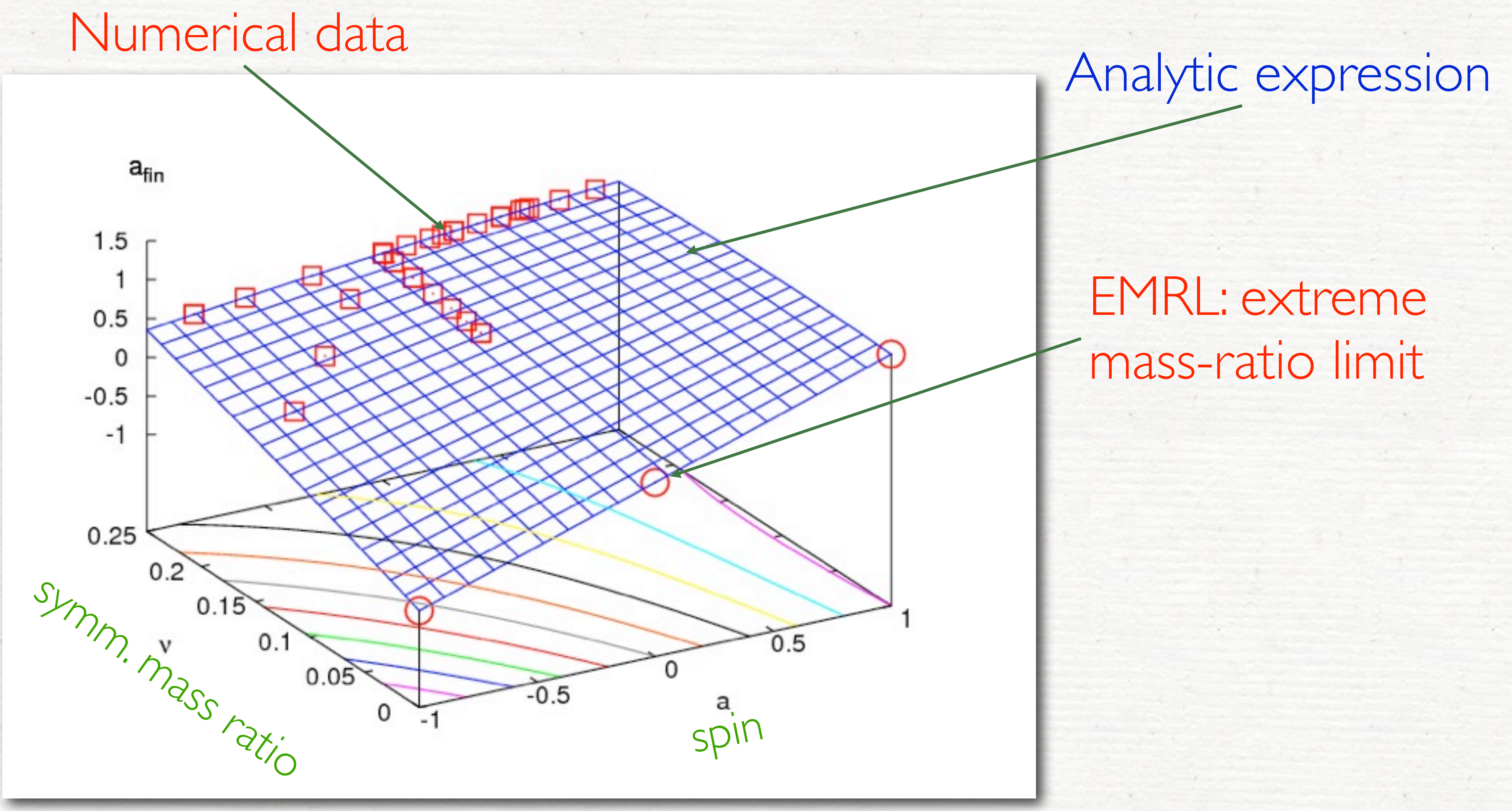
$$(a_{\rm fin})_{\rm min} \simeq 0.347$$

$$(a_{\rm fin})_{\rm max} \simeq 0.959$$

Unequal-mass, equal-spin binaries

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

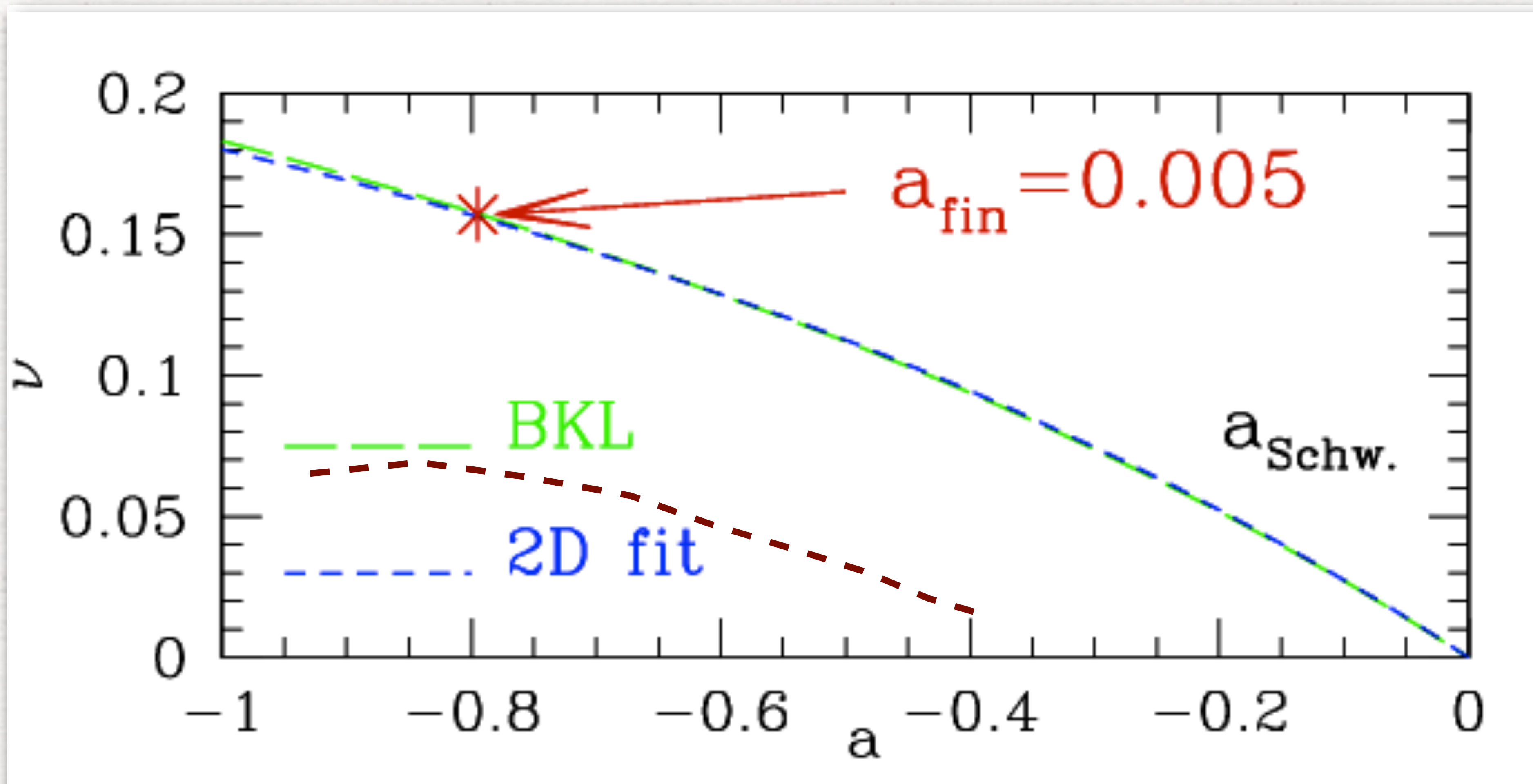
$$a_{\rm fin}(a,\nu) = a + s_4 a^2 \nu + s_5 a \nu^2 + t_0 a \nu + t_1 \nu + t_2 \nu^2 + t_3 \nu^3$$



How to produce a Schwarzschild bh...

The analytic expression allows to answer simply questions such as:

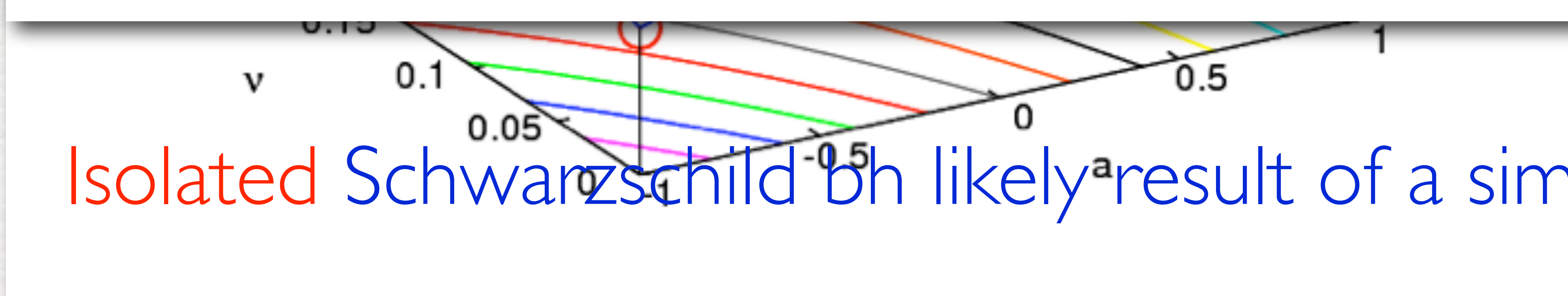
is it possible to produce a Schwarzschild bh from the merger of two Kerr bhs?



Find solutions for:

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

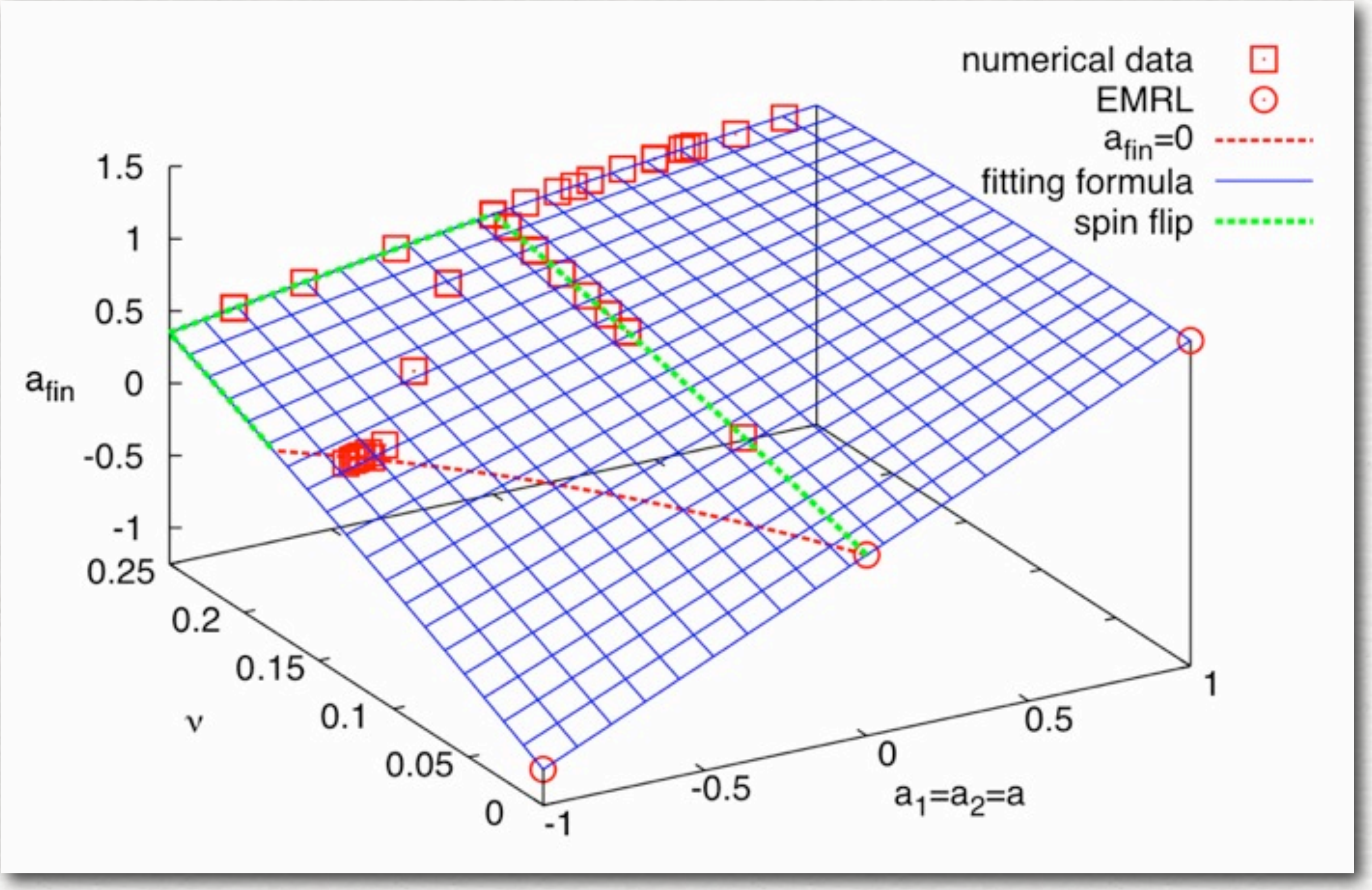
Unequal masses and spins antialigned to the orbital ang. mom. are necessary



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:

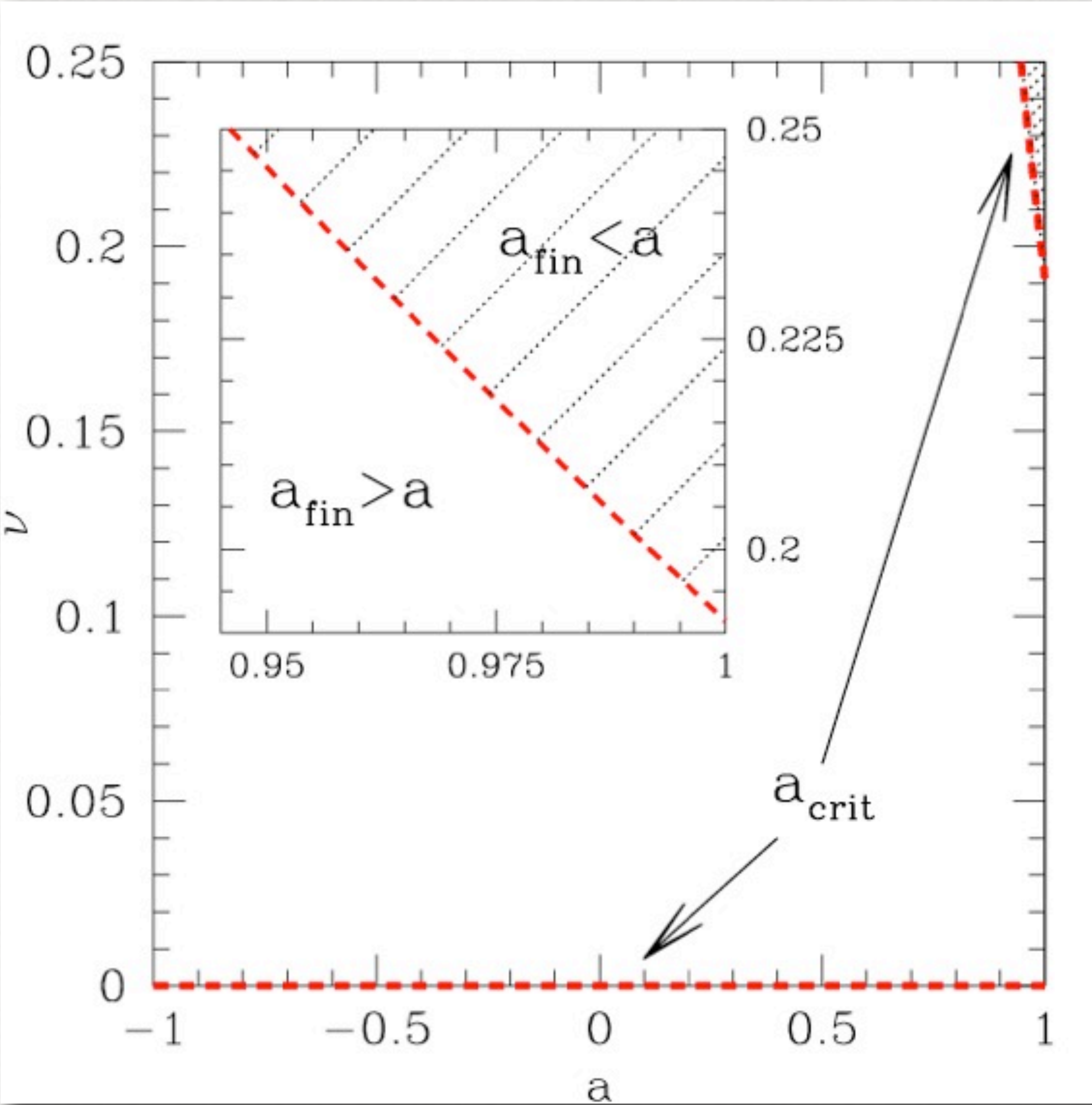
$$a_{\rm fin}(a,\nu)\,a < 0$$

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?

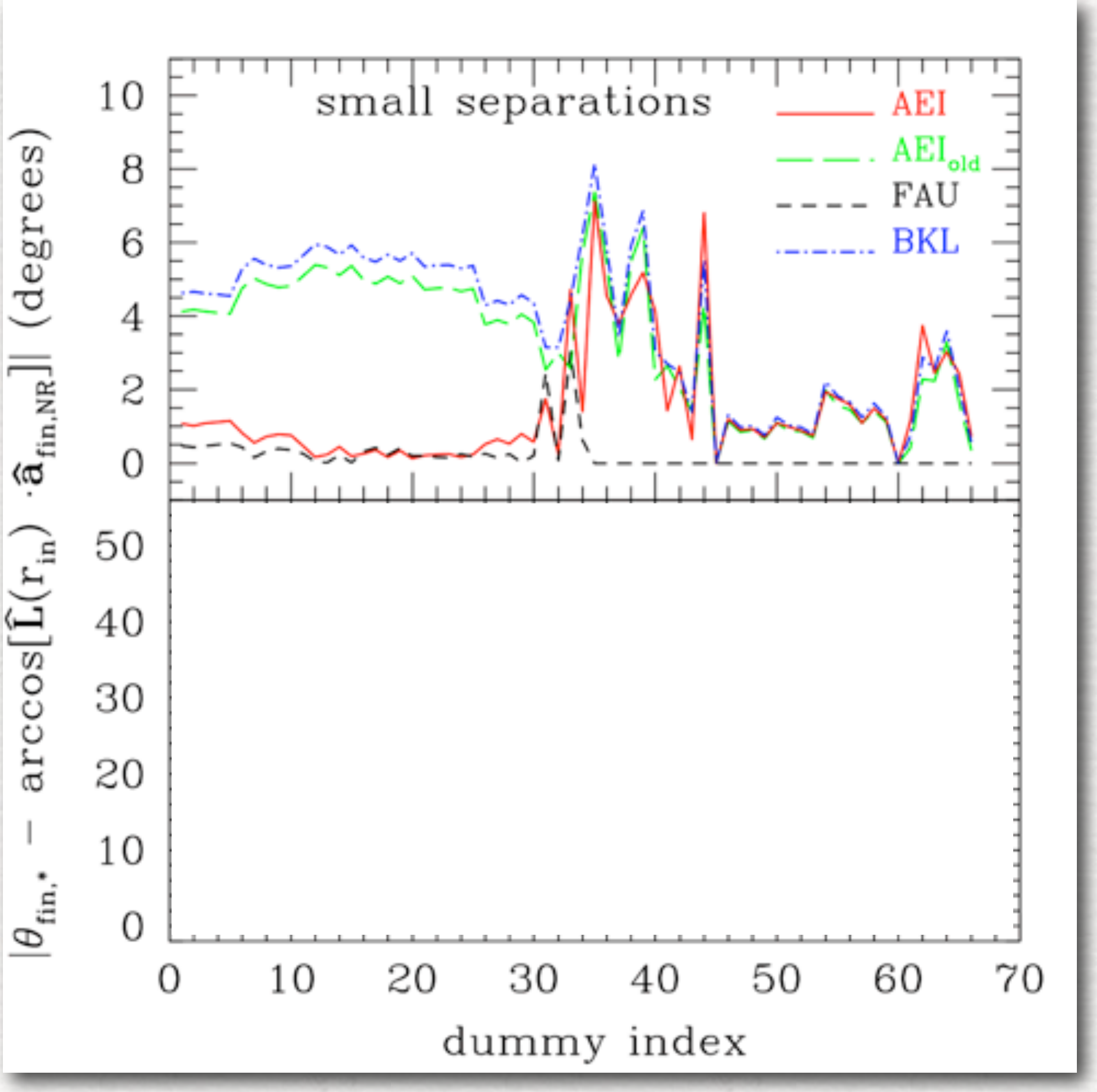


Just find solutions for:

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

Clearly, the merger of aligned BHs statistically, leads to a spin-up. This has impact on modelling the merger of cosmological supermassive BHs (Berti & Volonteri, 2008)

Predicting the final **direction**



All formulas have been tuned to reproduce the NR numerical relativity data from small separations with good precision.

When the input data is of a binary at large separation, all expression are bad. This is because the precession can modify the initial properties (ie α, β, γ) of the binaries.

We solve this problem with assumption (iii): $\boldsymbol{S}_{\rm fin} \parallel \boldsymbol{J}_{\rm in}$

Exact at 2.5 PN if q=0, 1 and SS coupling is neglected (Apostolatos et al '94). In general approximately valid unless initially: $\hat{\boldsymbol{L}} \approx -\hat{\boldsymbol{S}}$ ("transitional precession", with large change of $\hat{\boldsymbol{J}}$ when $\boldsymbol{L} \approx -\boldsymbol{S}$)

Radiated Energy

Reisswig, LR et al. 2009

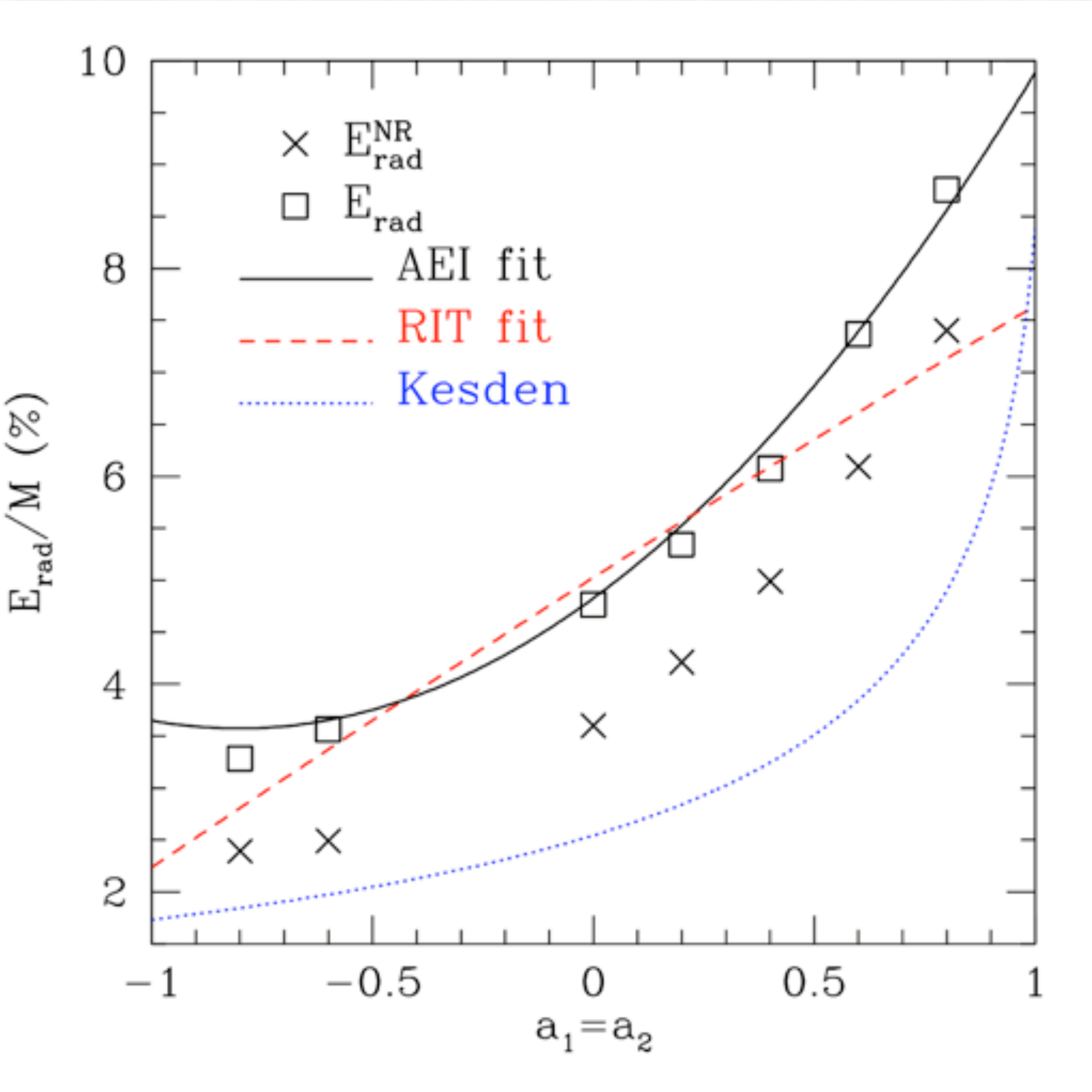
In a systematic investigation of equal-mass binaries with aligned spins we have computed the radiated energy as the sum of the energy lost from during the simulation (NR) from the initial separation D and the (PN) energy lost from infinity up to D

$$\begin{aligned} E_{\rm rad} &= E^{\rm NR}_{\rm rad} + E^{\rm PN}_{\rm rad}(\infty \to D) \\ &= M_{\rm ADM}(D) - M_{\rm fin} + E^{\rm PN}_{\rm rad}(\infty \to D) \end{aligned}$$

Both NR/PN terms can be expressed as a series of total spin, ie

$$E^{\rm NR,PN}_{\rm rad} = \sum_{i=0}^{N} p_i^{\rm NR,PN}(a_1 + a_2)^i$$

the coefficients have been obtained by fitting the numerical data and can be found in Reisswig et al. 2009 (PRD)



Some highlights:

$$E_{\rm rad}(a_{1,2} = -1)/M = 3.7\%$$

$$E_{\rm rad}(a_{1,2} = 0)/M = 4.8\%$$

$$E_{\rm rad}(a_{1,2} = 1)/M = 9.9\%$$

When considering only the NR contribution, the energy-loss budget gives:

- nonspinning contrib: $\sim 3.6\%$
- spin-orbit contrib: $\lesssim 3.0\%$
- spin-spin contrib: $\lesssim 2.0\%$

Aligned, maximally spinning BH binaries are among the most efficient sources of energy known!

Modelling the final state

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

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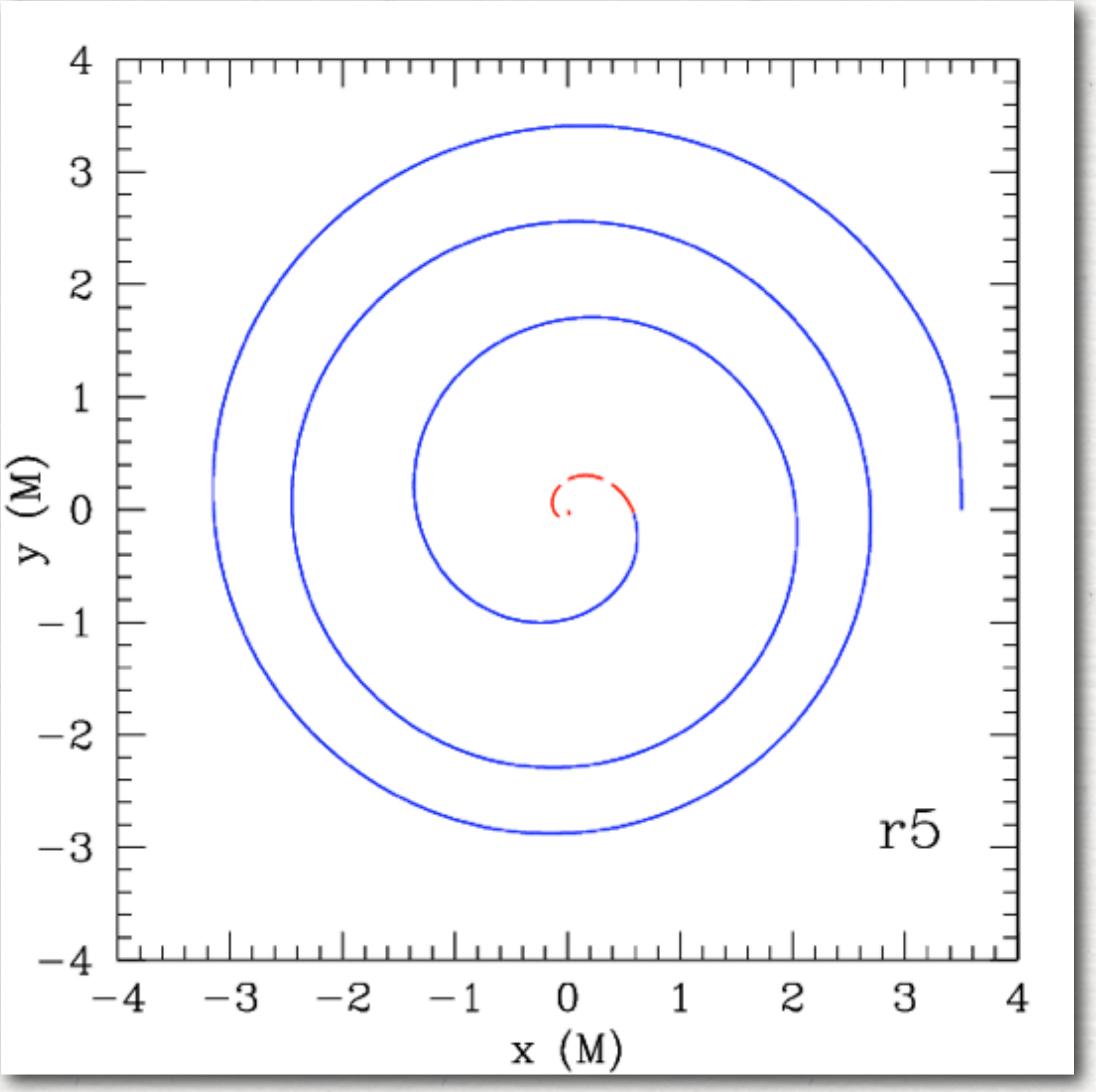
Being sensitive to the asymmetries in the system, the recoil velocity develops very rapidly in the final stages of the inspiral: i.e. during last portion of the last orbit!



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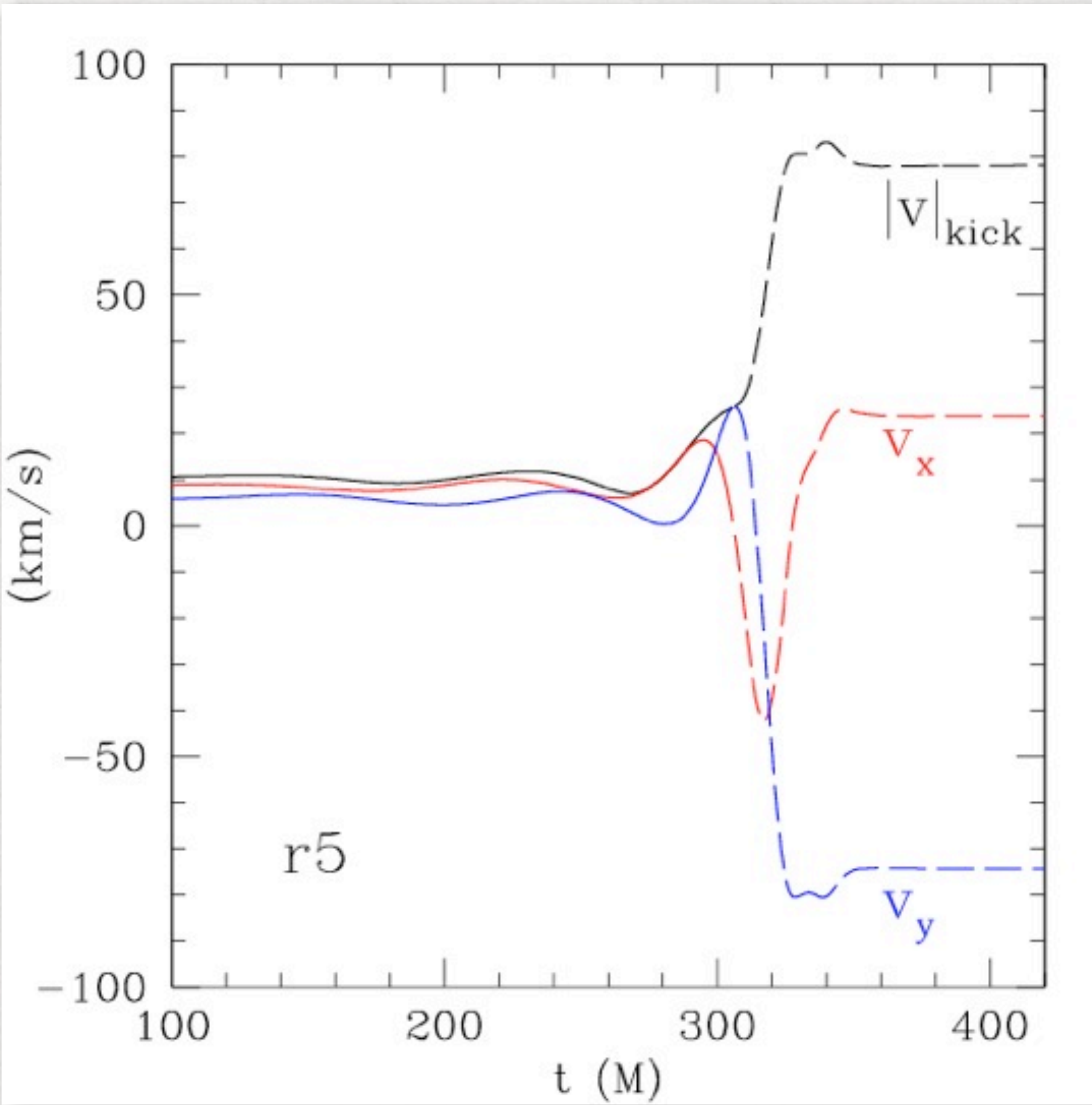


The details of the processes leading to the recoil are still, in great part, unclear. Subtle balances in the emission of different QNMs during the ringdown are behind the final kick vector.

What we know (now) of the kick

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

where

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

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

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

ν^2 ?

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

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

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

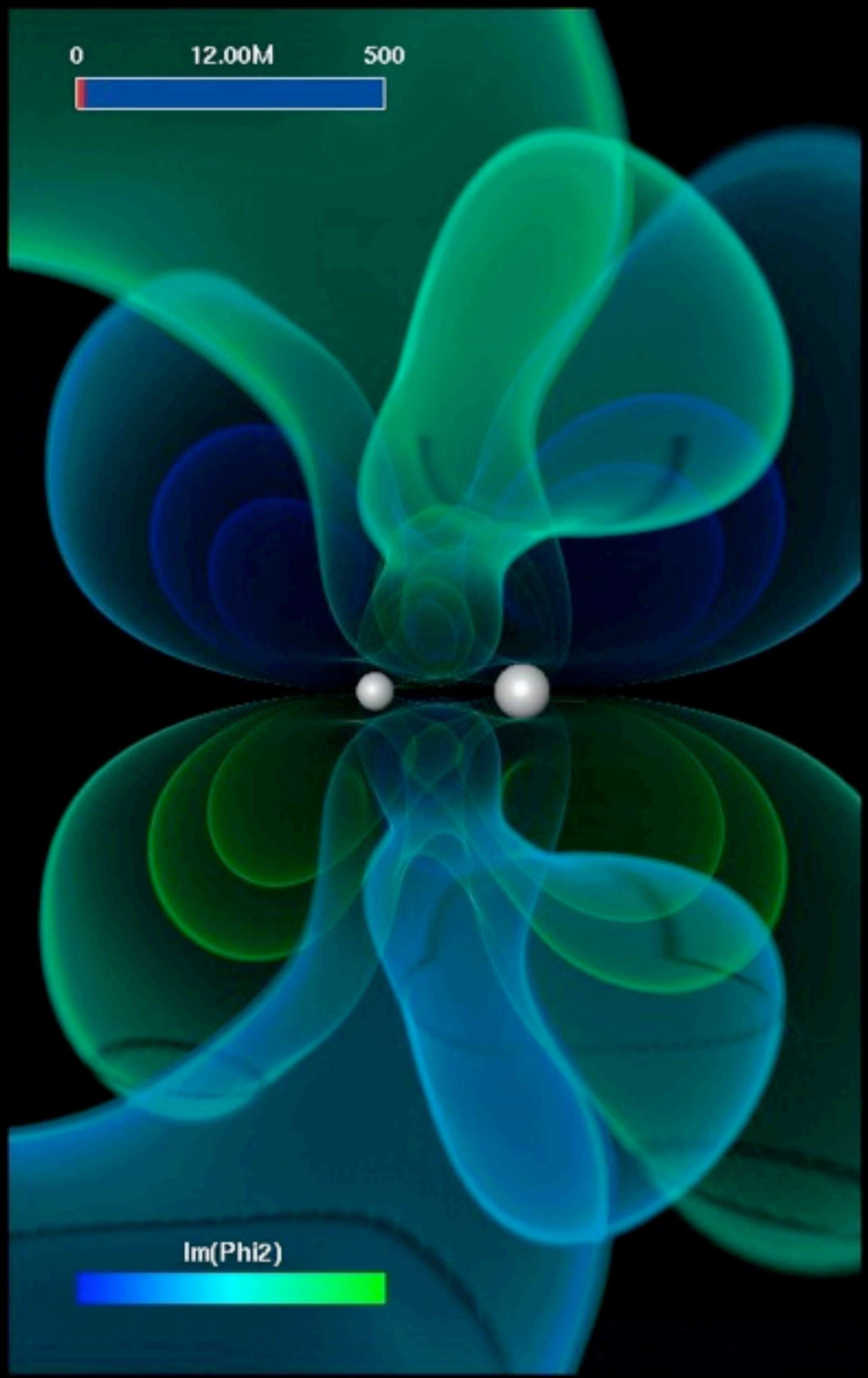
EM counterparts to BBH mergers

More recently we have started a systematic study of the possible electromagnetic (EM) signatures that could produced during the inspiral and merger of a binary of massive black holes.

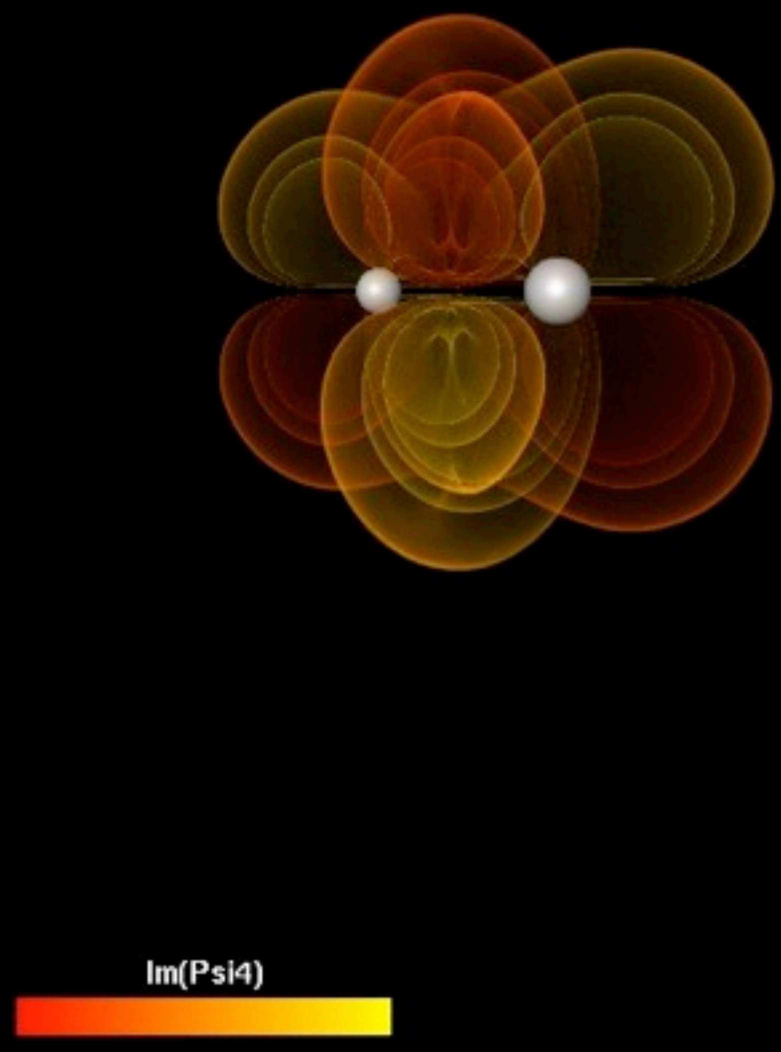
Two scenarios have been considered so far:

- ✶inspiral and merger: study binary in vacuum but within EM fields produced from circumbinary disc (Van Meter et al. 2009, Palenzuela et al. 2009a, 2009b, Bode et al. 2009)
- ✶postmerger: study effects on the circumbinary disc as a result of the recoil/change of mass (Lippai et al. 2008, Megevand et al 2008, Shields & Bonning 2008, Schnittman & Krolik 2008, Corrales et al. 2009, O'Neill et al. 2009, Rossi et al. 2009)

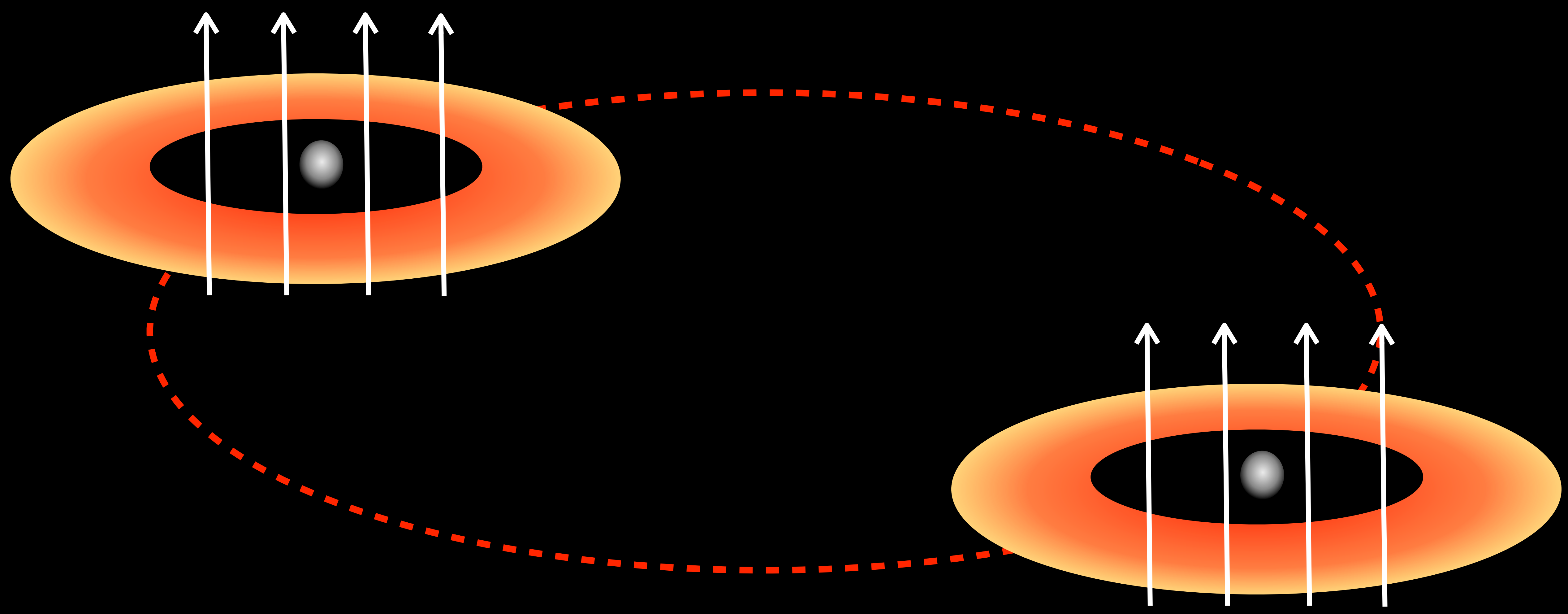
Inspiral and merger



Palenzuela et al (0905.1121)
Moesta, LR et al (submitted PRD)



The merger of two galaxies each hosting a massive BH will lead to a binary surrounded by a massive circumbinary disc which will follow the binary during the slow viscous-paced evolution. When GW losses are large, the circumbinary disc will not follow the evolution and the binary will evolve in very tenuous gas (Milosavljec & Phinney 2005).



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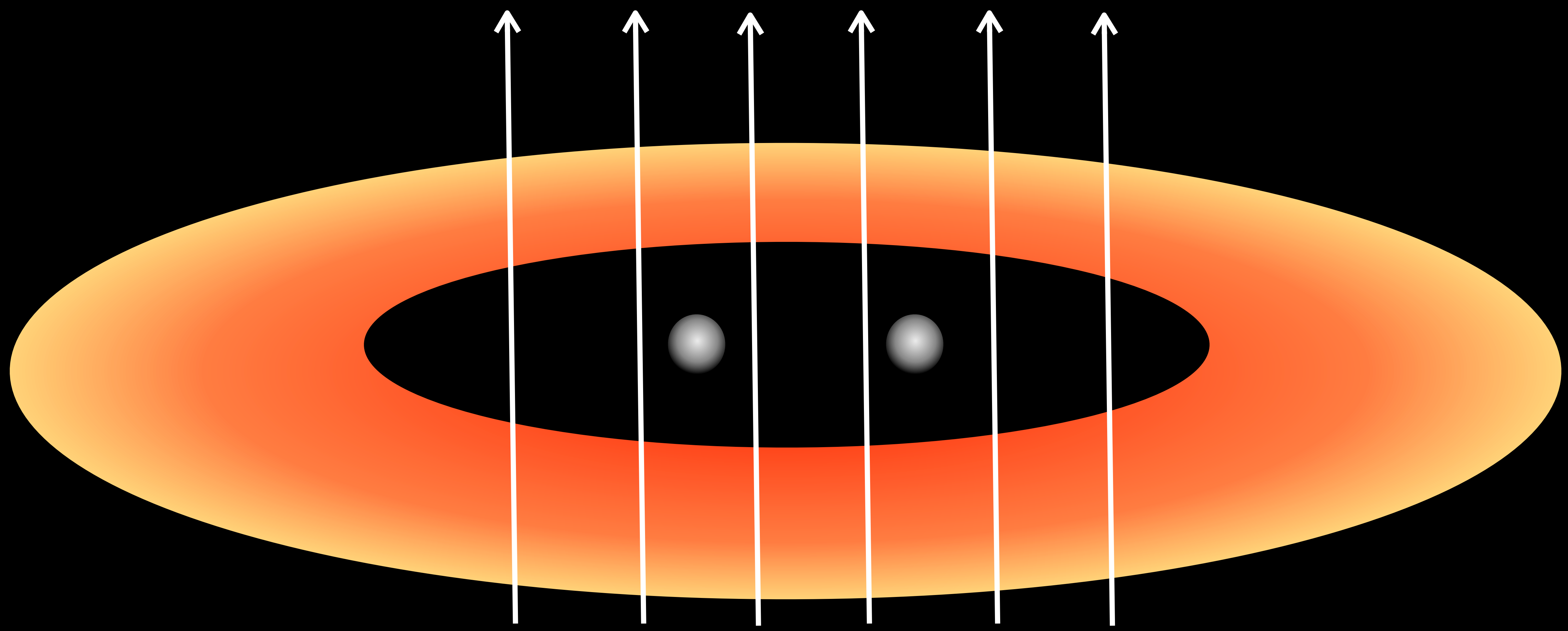

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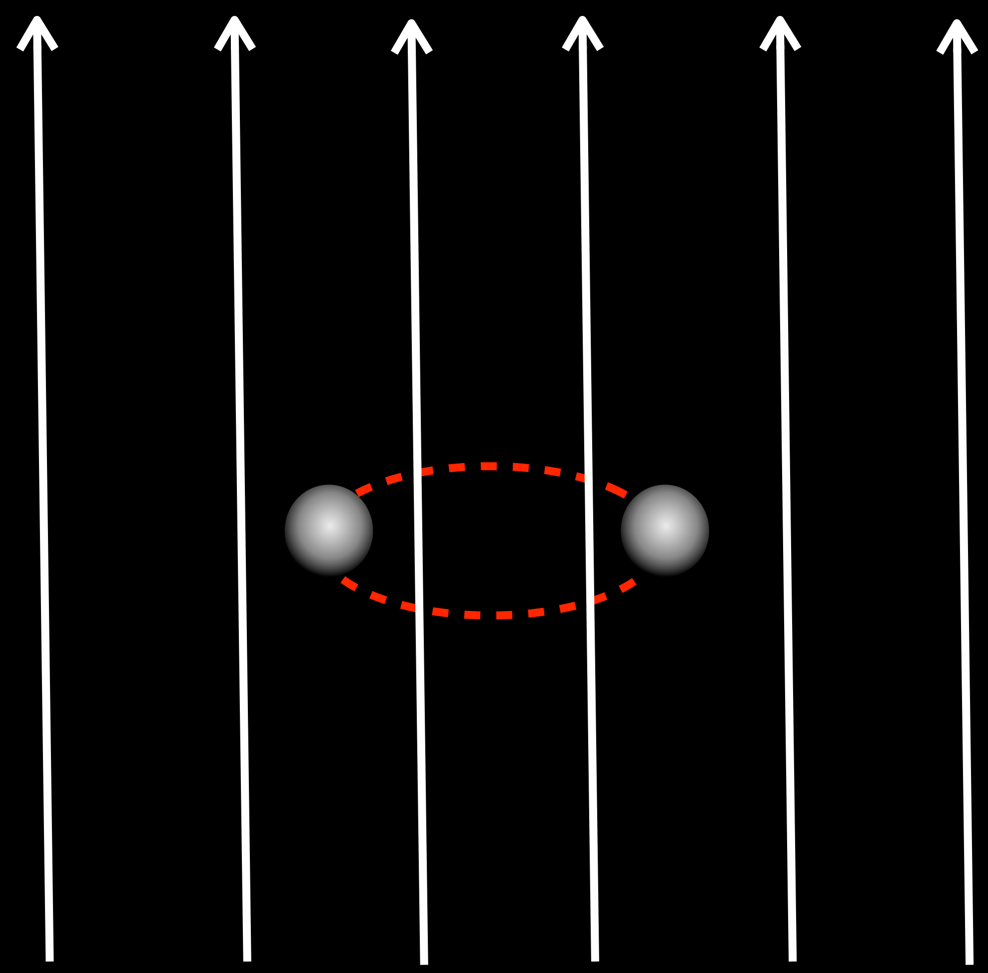
We next concentrate on what happens in vacuum in the vicinity of the two BHs



We solve Einstein eqs in vacuum but with a nonzero RHS

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

$$T_{\mu\nu} = F_{\mu\beta}F^{\beta\nu} - \frac{1}{4}(F^{\alpha\beta}F_{\alpha\beta})g_{\mu\nu}$$

where the Faraday tensor is a suitable combination of the electric (E) and magnetic fields

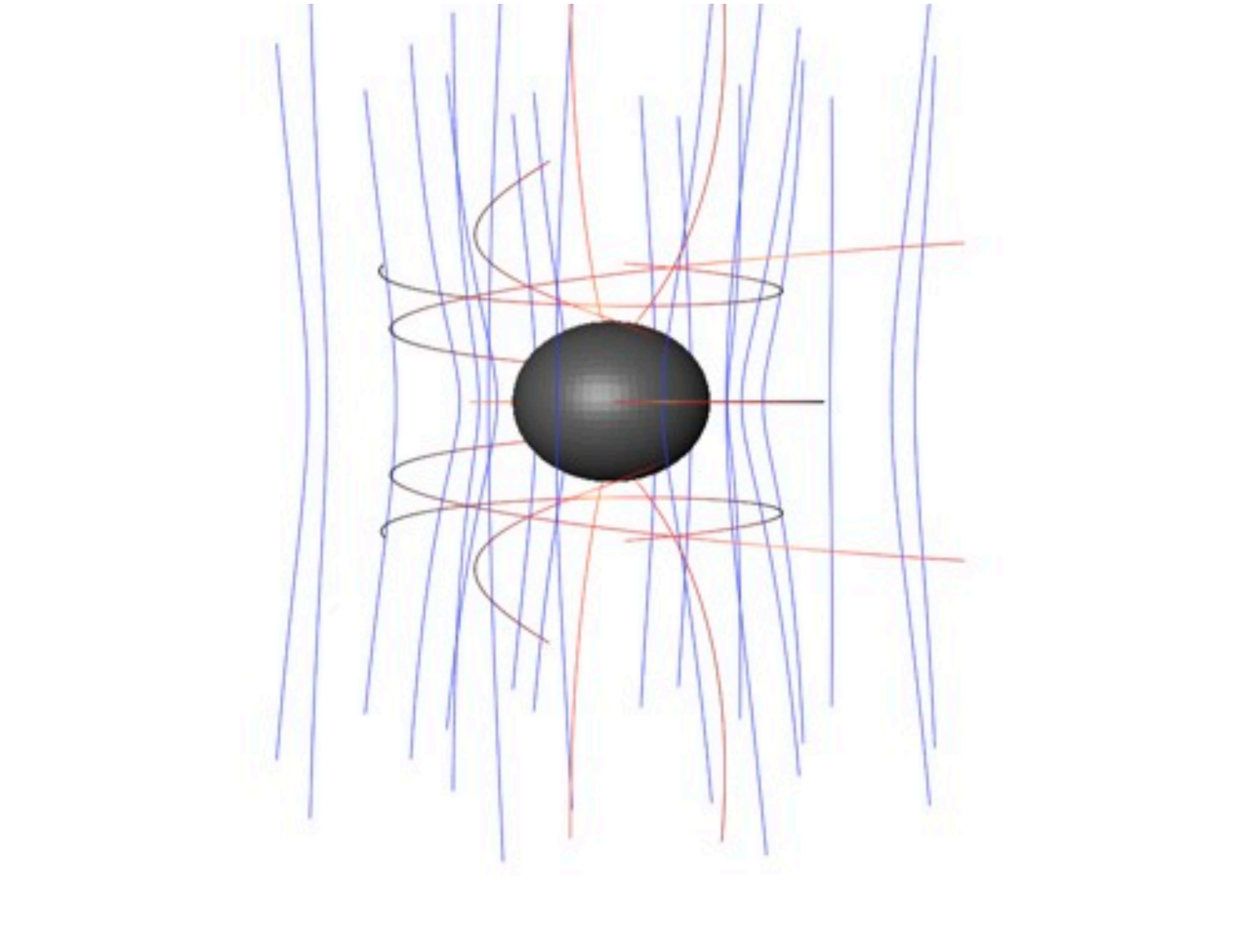
$$\begin{aligned} F^{\mu\nu} &= t^{\mu}E^{\nu} - t^{\nu}E^{\mu} + \epsilon^{\mu\nu\alpha\beta}\, B_{\alpha}\, t_{\beta}\,, \\ {}^{*}F^{\mu\nu} &= t^{\mu}B^{\nu} - t^{\nu}B^{\mu} - \epsilon^{\mu\nu\alpha\beta}\, E_{\alpha}\, t_{\beta}\,; \end{aligned}$$

The Maxwell eqs express then the conservation of this tensor and are extended to include constraint damping terms

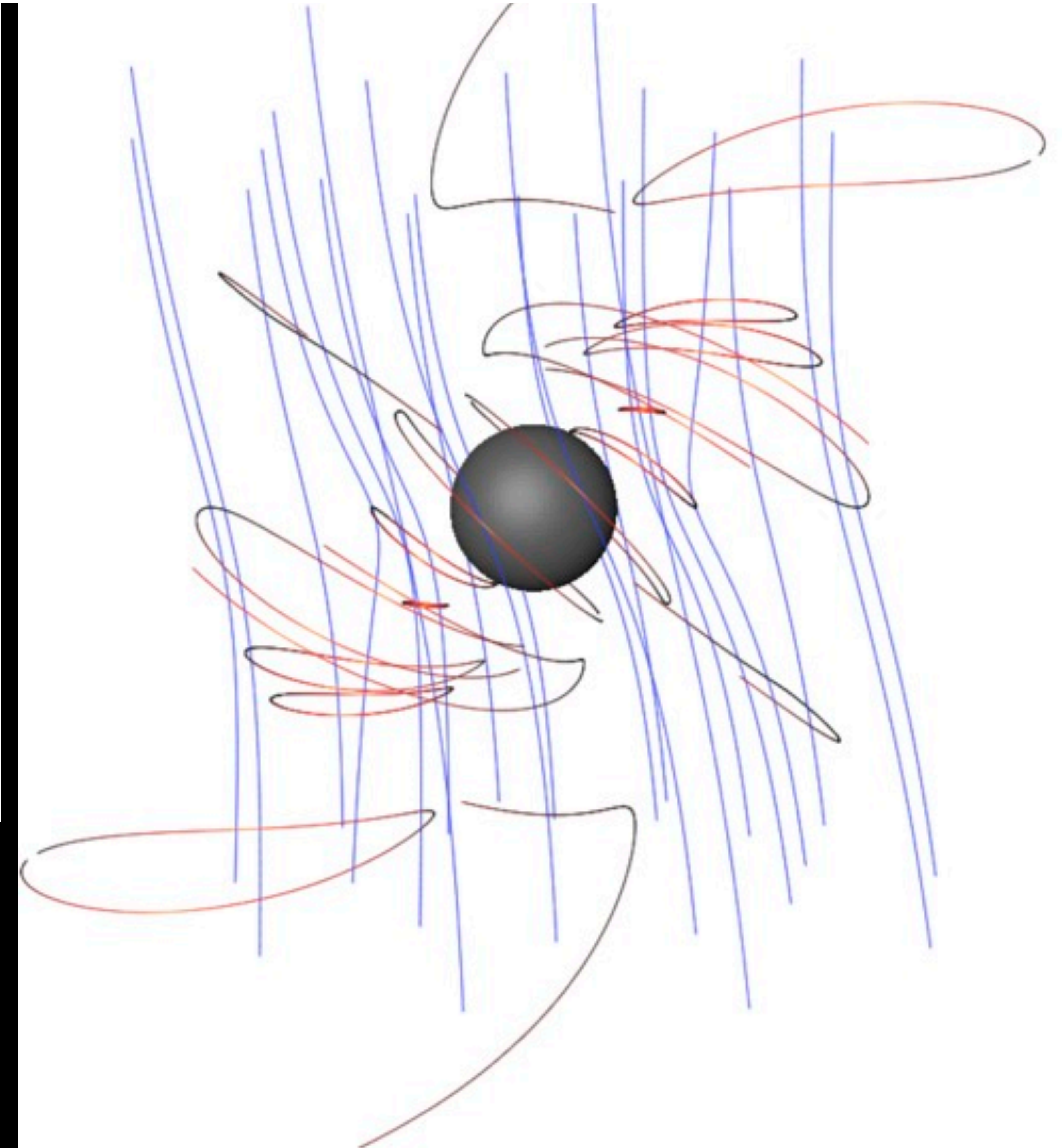
$$\nabla_{\mu}(F^{\mu\nu} + g^{\mu\nu}\psi) = kn^{\nu}\psi$$

$$\nabla_{\mu}({}^{*}F^{\mu\nu} + g^{\mu\nu}\phi) = kn^{\nu}\phi$$

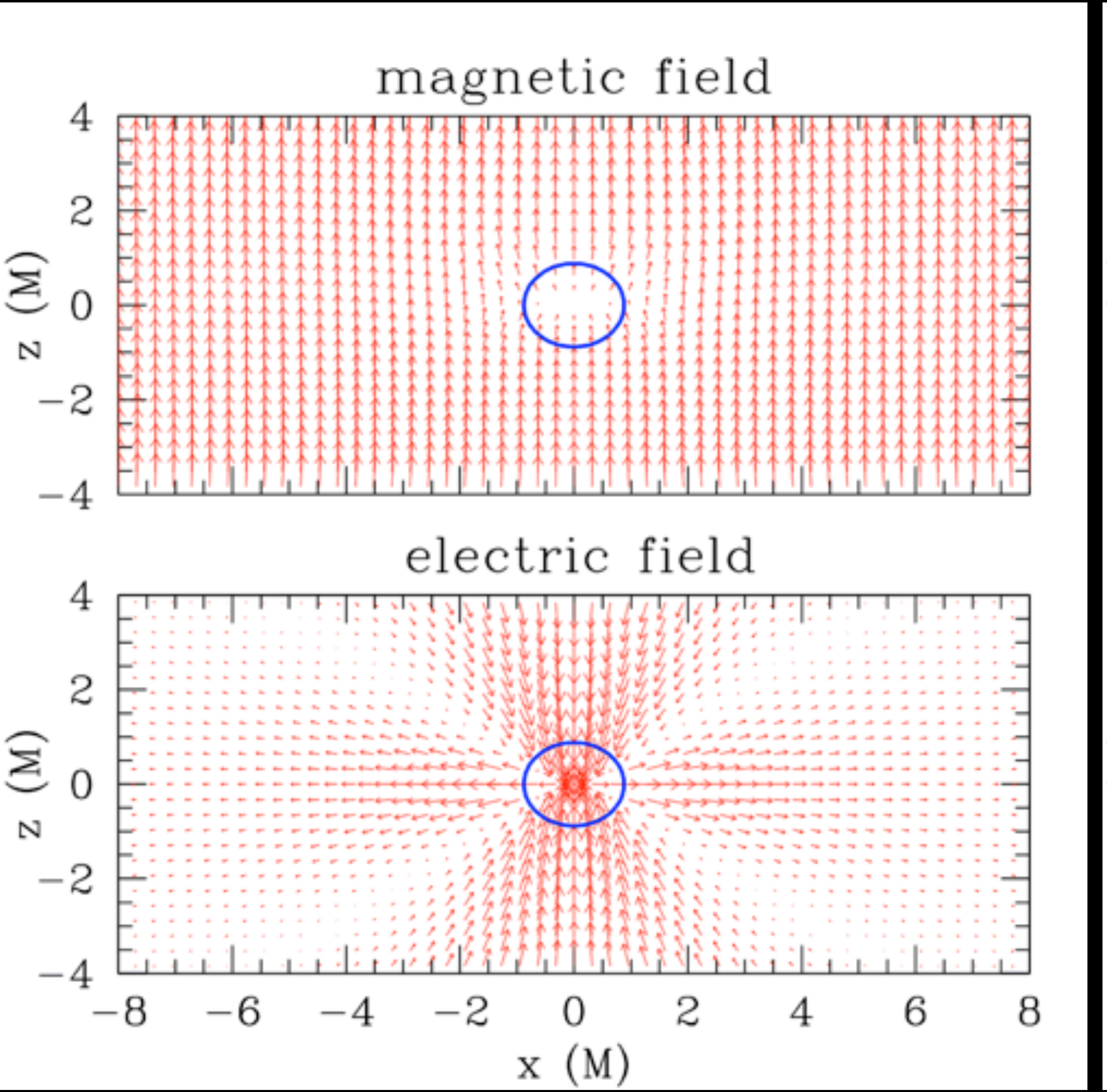
First a single BH in a uniform magnetic field

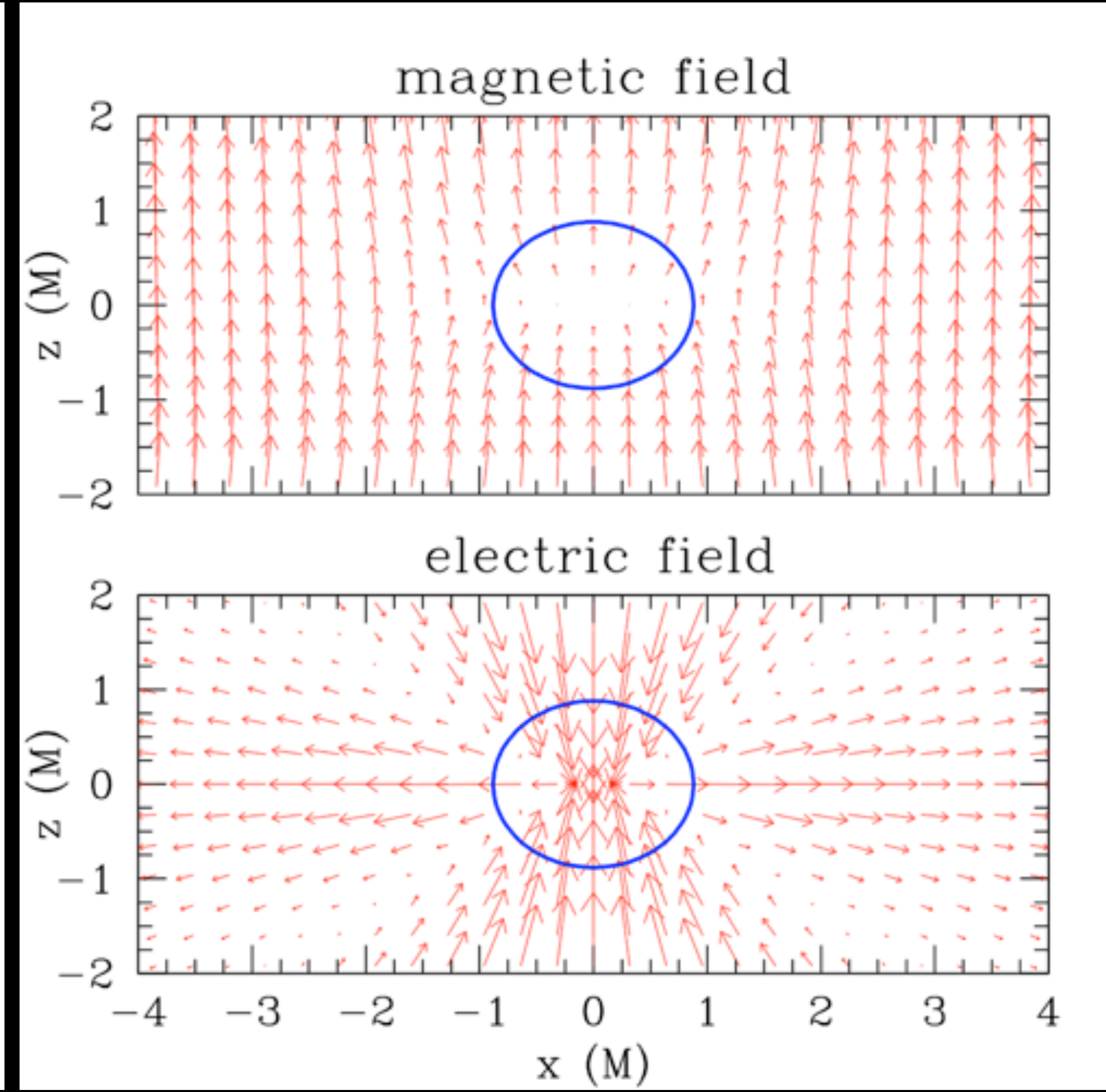


The magnetic field lines (blue) are distorted by spacetime curvature near the BH, while the electric field (red) is dragged by the spin (a=0.7)

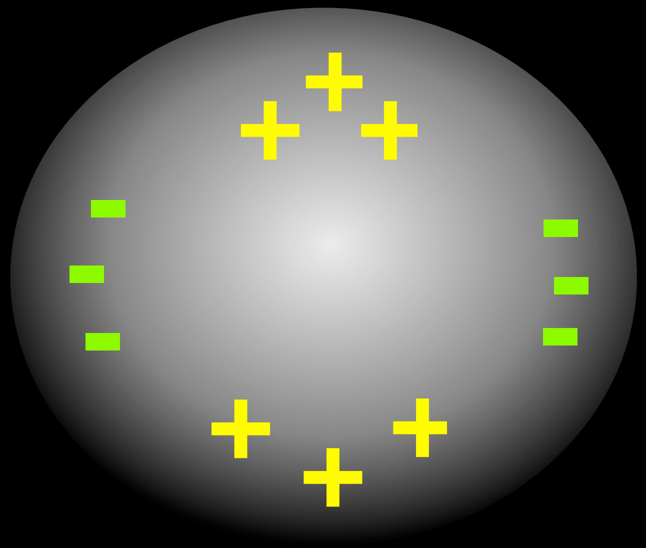


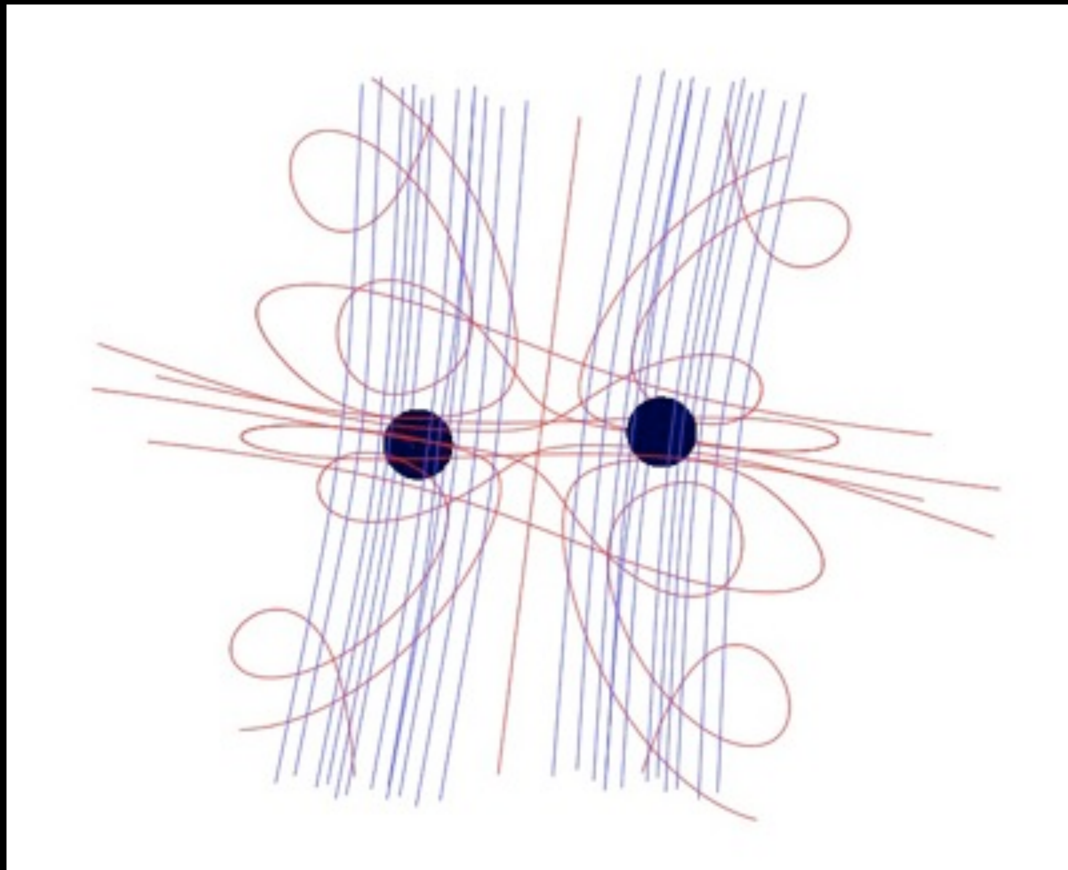
More complicated structure of EM fields for inclined spin



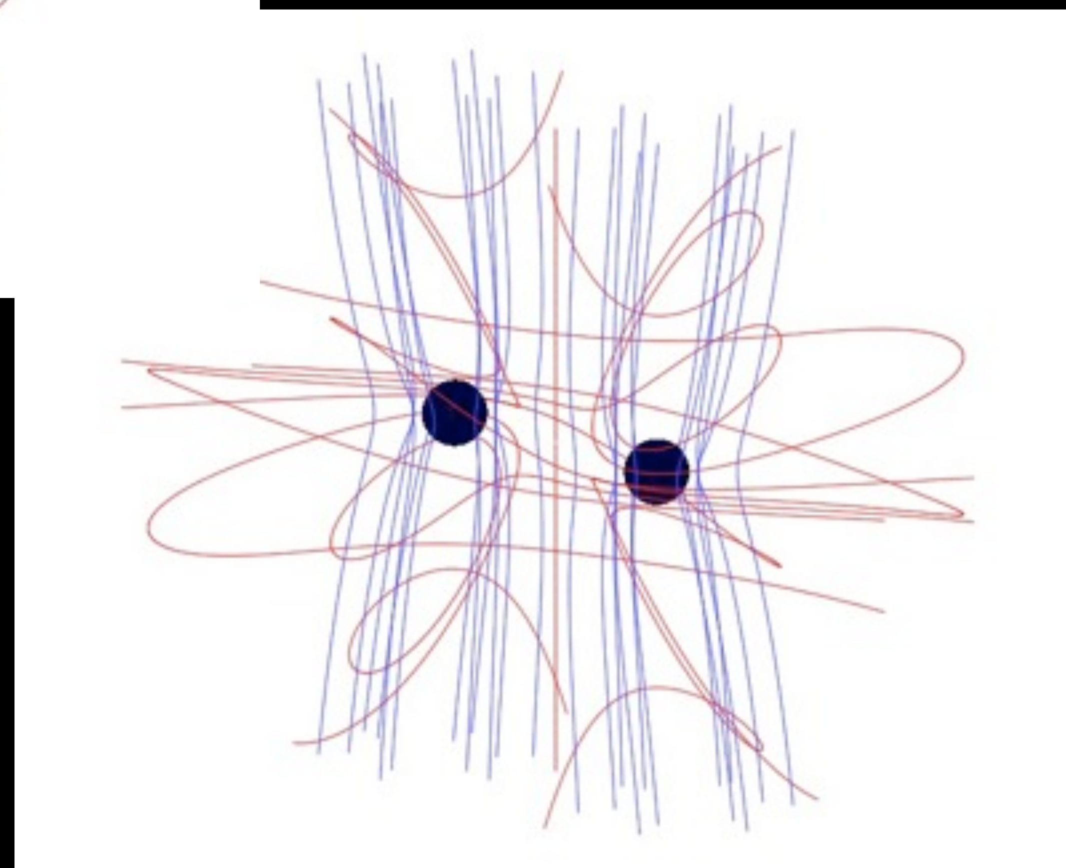


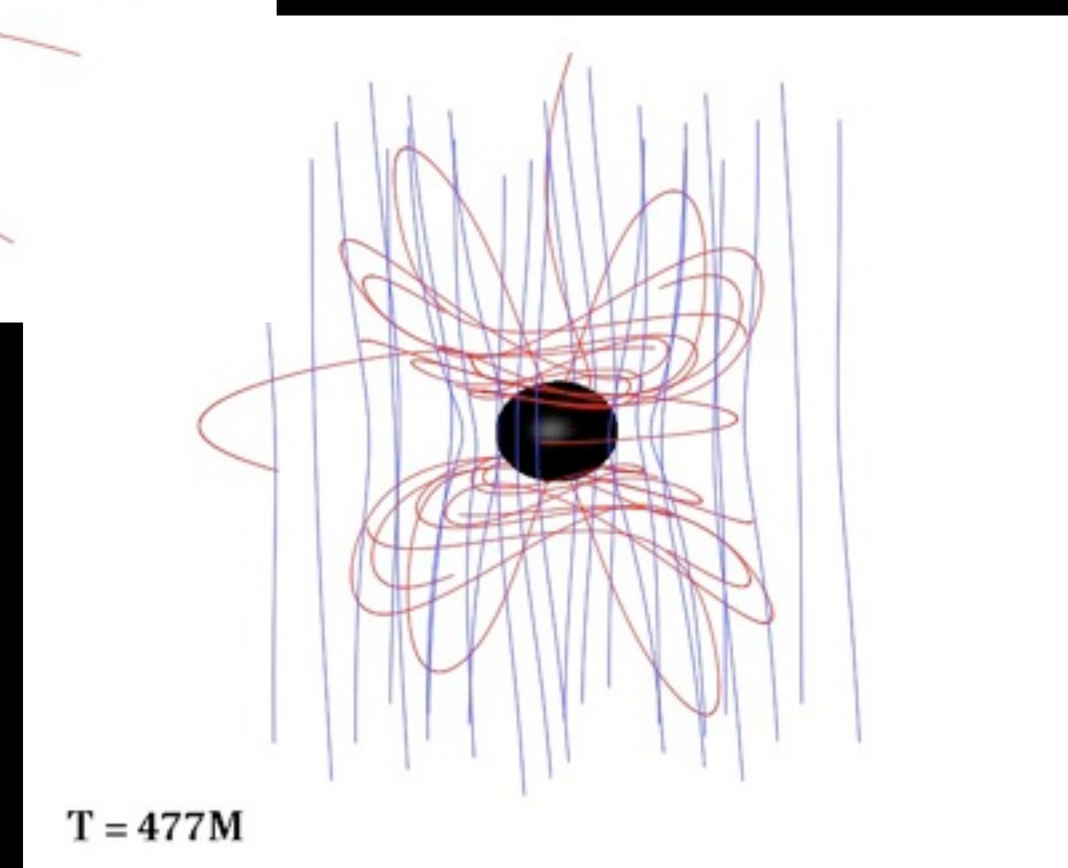
The small-scale electric field is quadrupolar: the horizon has an effective charge: + at the poles, - at the equator (membrane paradigm)





Similar distortions of the EM field lines are present also in the case of a binary and further enahanced by the orbital motion.



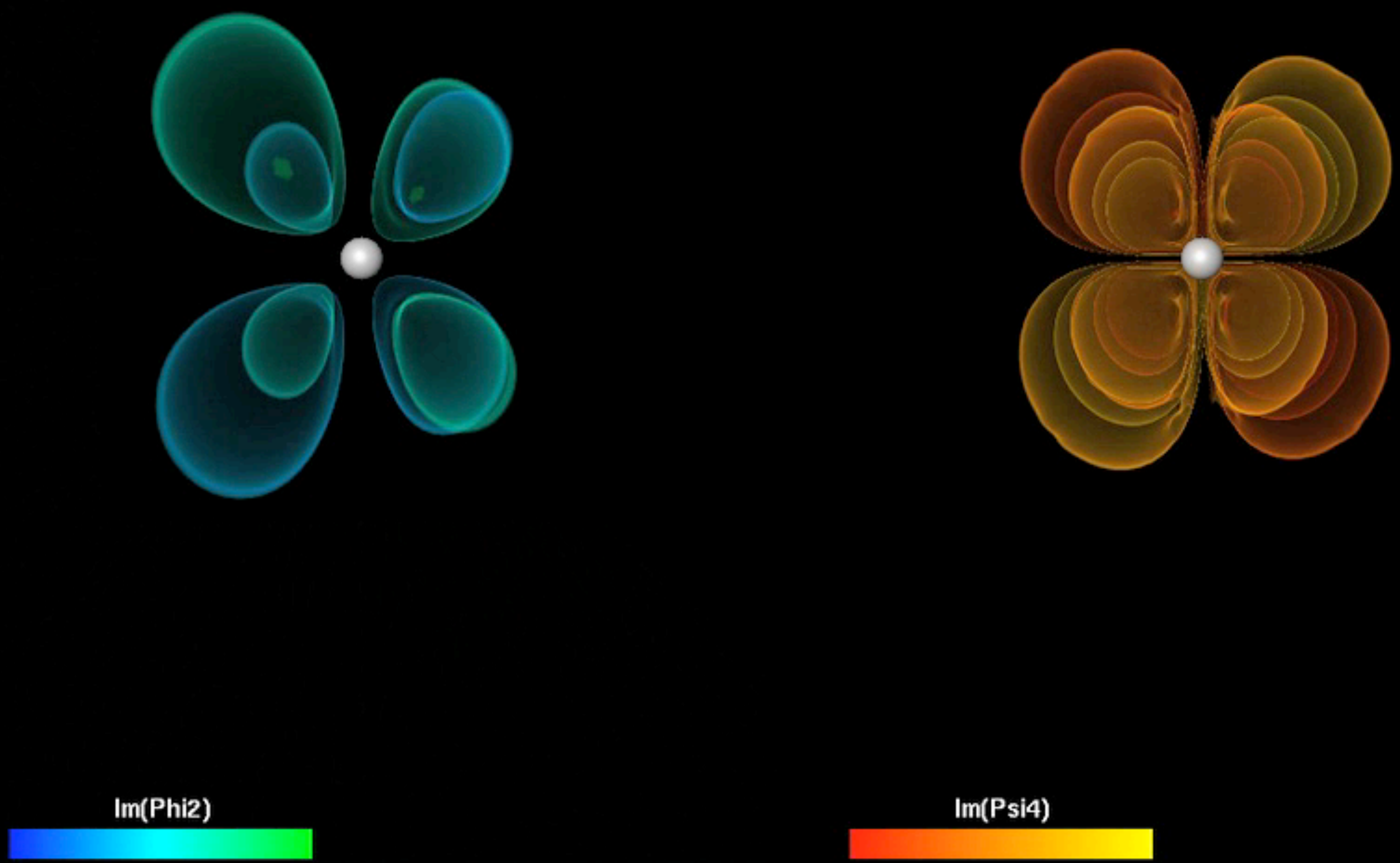


After the merger one recovers the stationary configuration already observed for a single spinning BH.

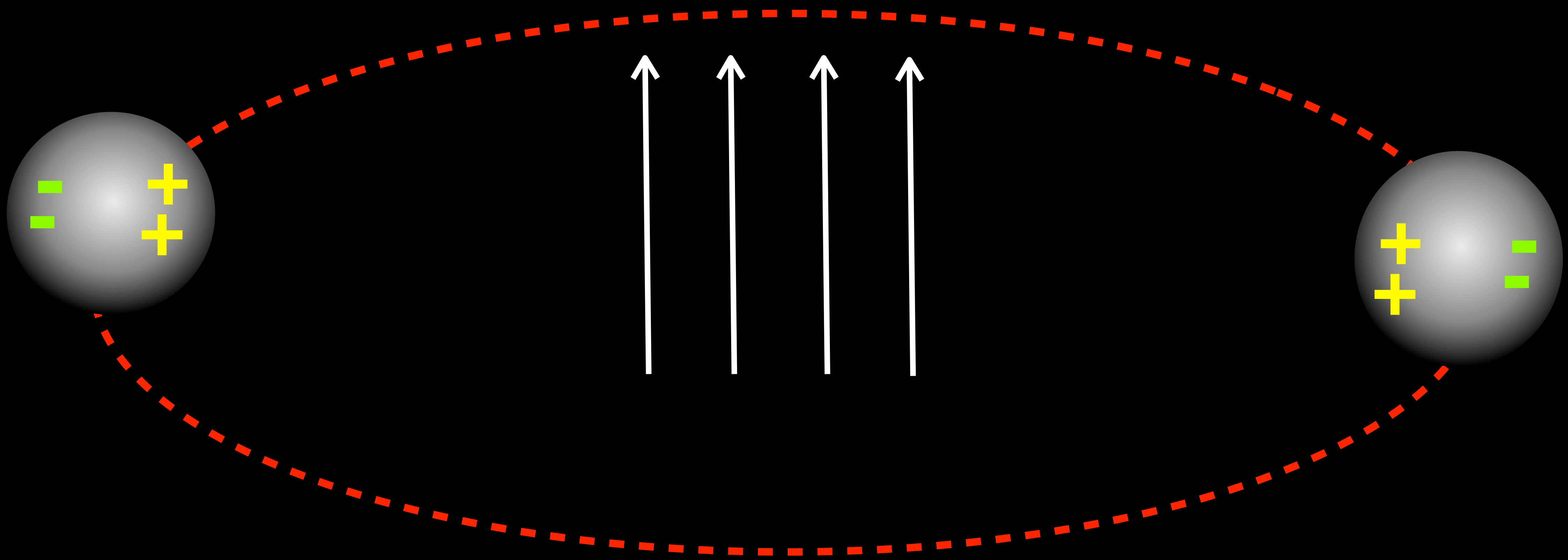
GW, EM radiation computed via Newman-Penrose scalars, ie projection of the Weyl curvature scalar and Farady tensor onto outgoing null tetrad

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

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



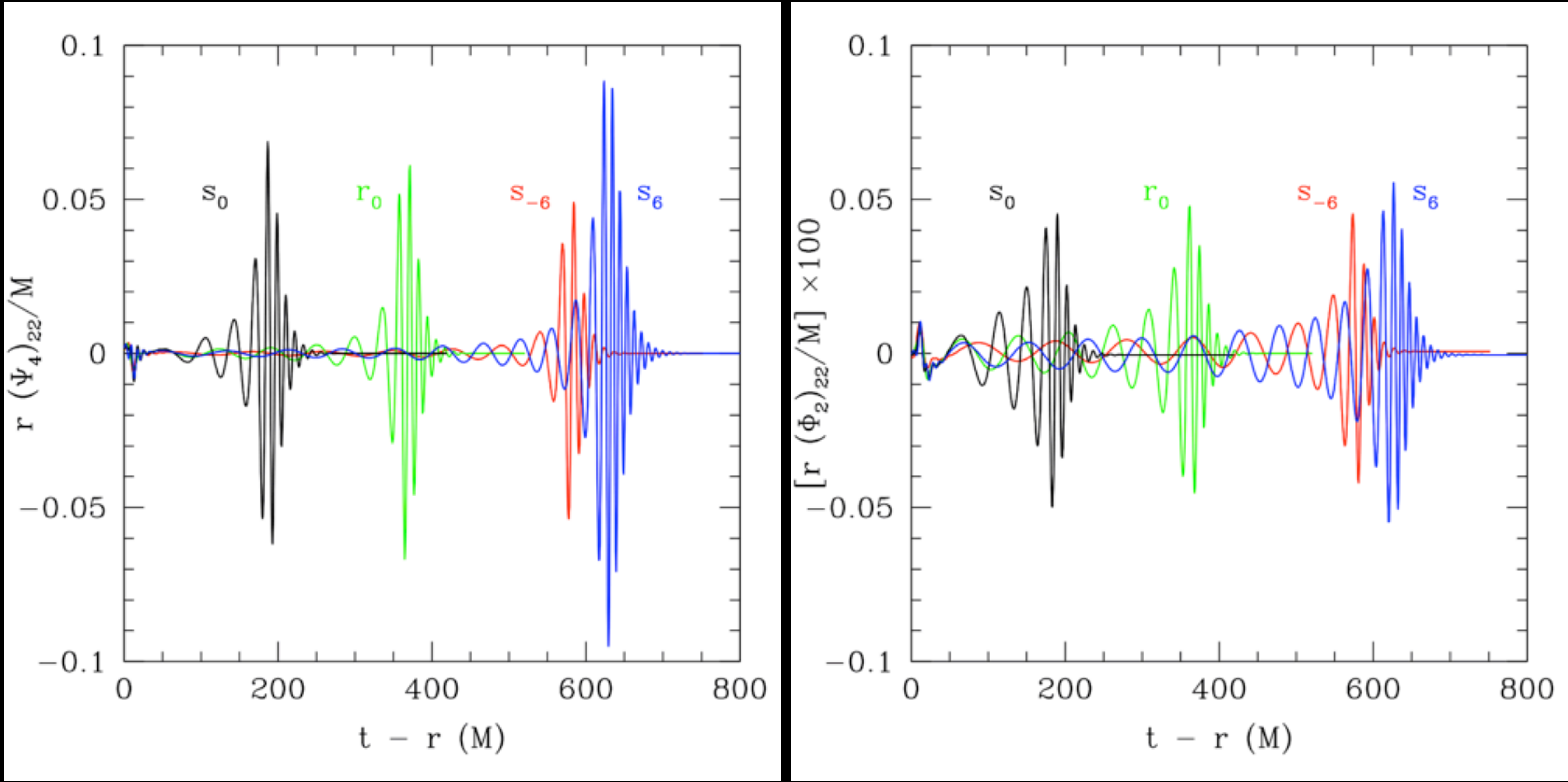
When moving across the vertical magnetic field the two BHs behave like conductors subject to the Hall effect: a dipolar charge develops.

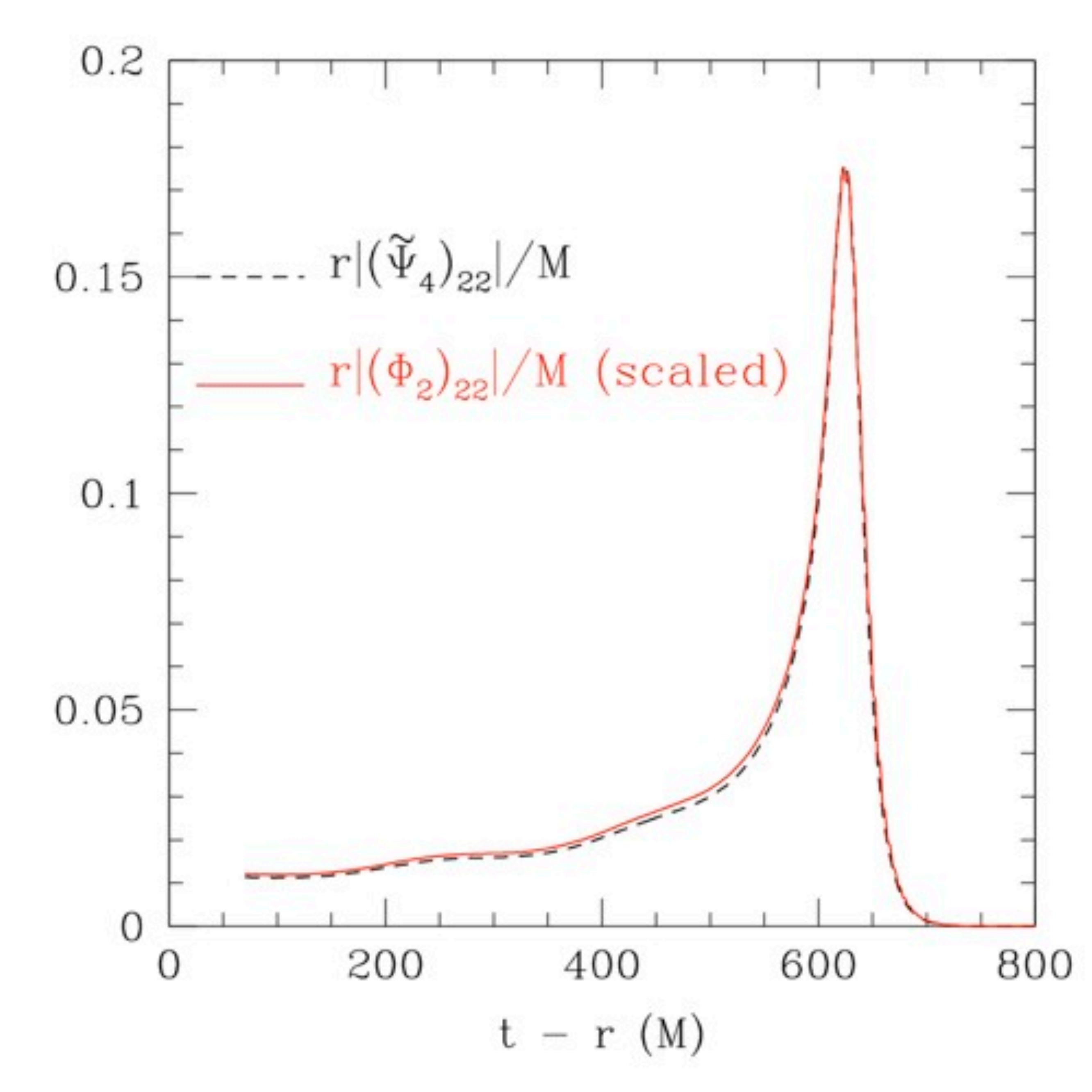


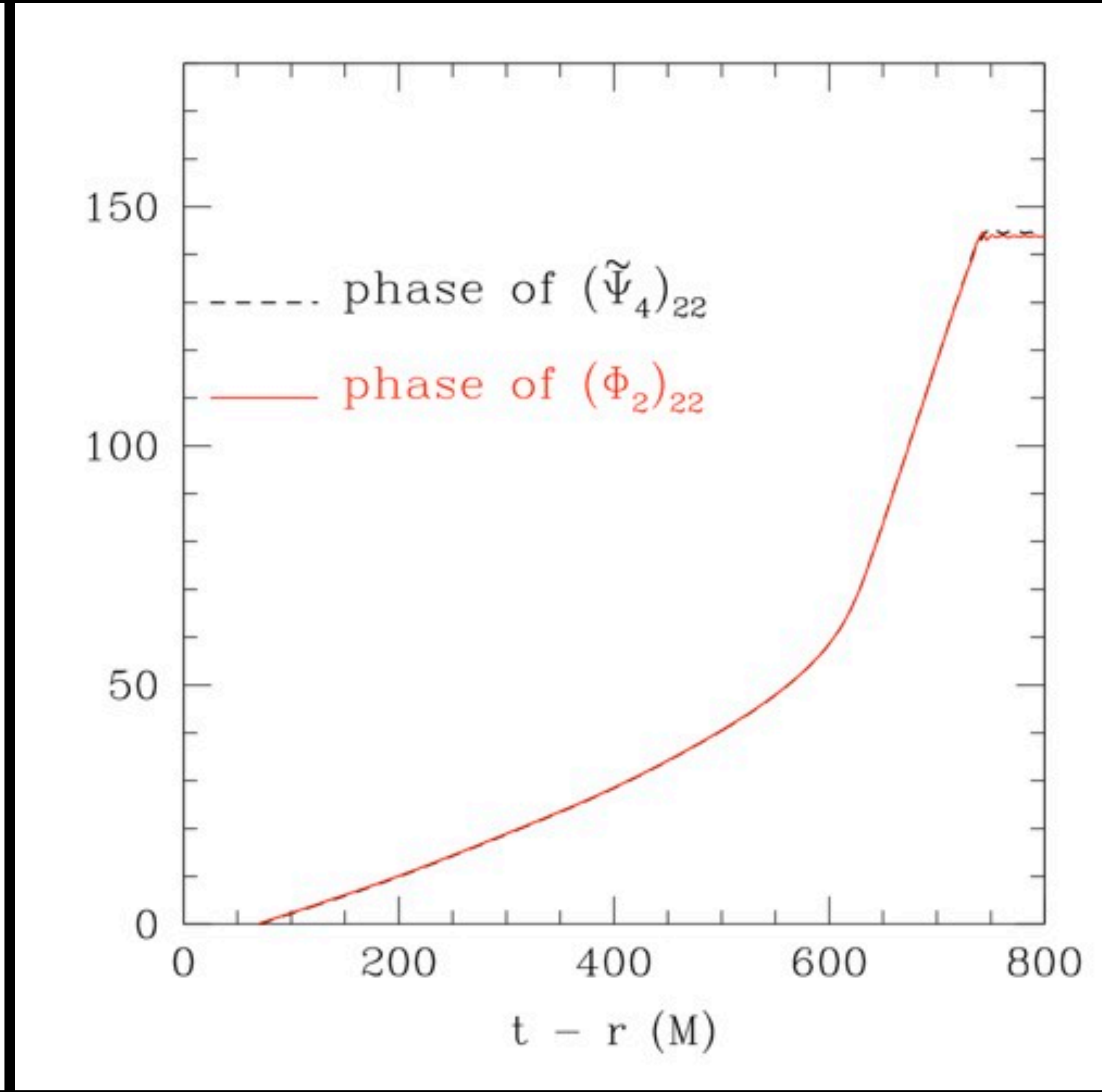
The two BHs are therefore like to dipoles moving in a magnetic field: they will produce a quadrupolar electric radiation

GW, EM radiation computed via Newman-Penrose scalars, ie projection of the Weyl curvature scalar and Farady 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: $E^{\rm GW}_{\rm rad}/M \simeq 5 \times 10^{-2}$
the relative efficiency is

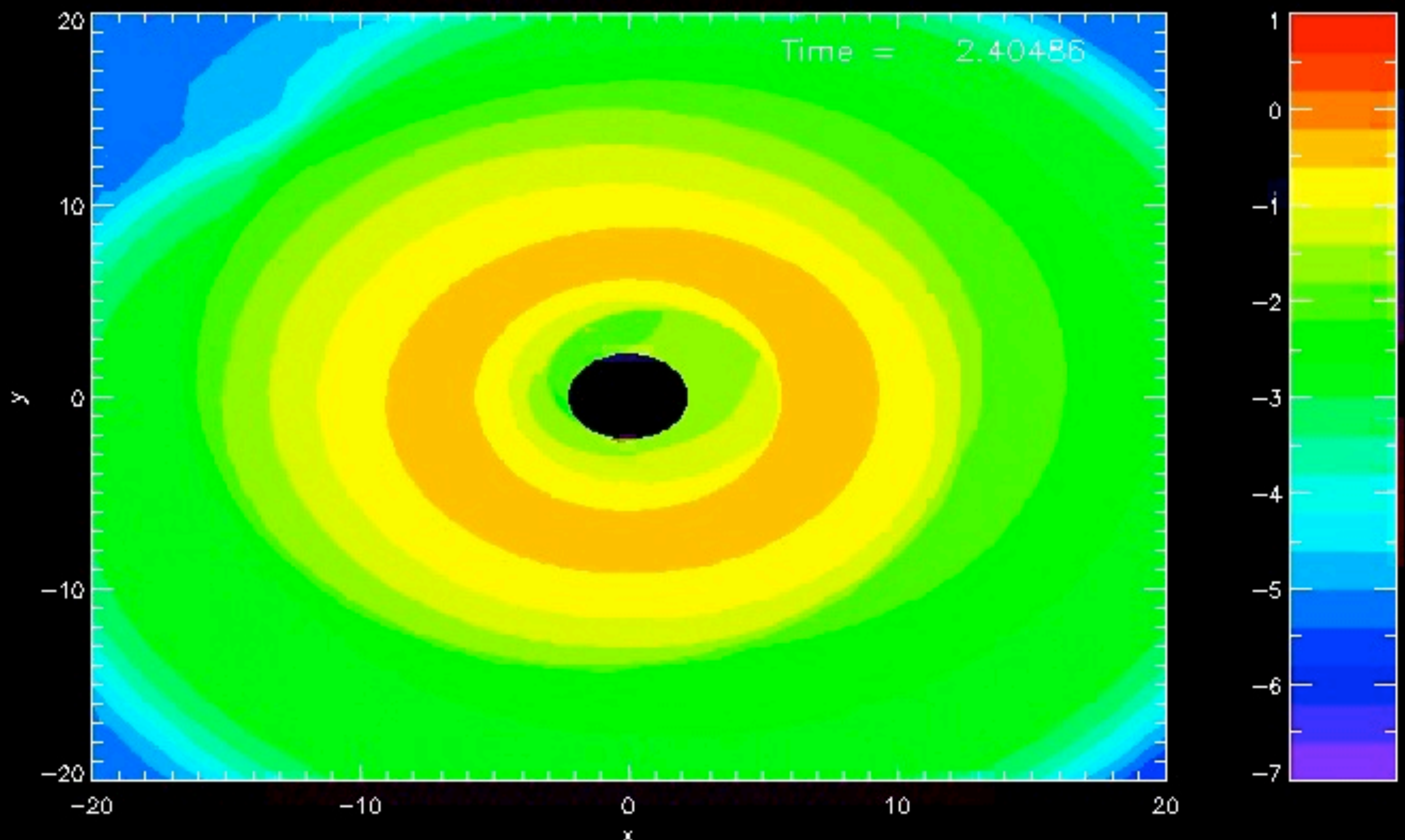
$$\frac{E^{\rm rad}_{\rm GW}}{E^{\rm rad}_{\rm GW}} \simeq 10^{-13} \left(\frac{M}{10^8\ M_\odot}\right)^2 \left(\frac{B}{10^4\ {\rm G}}\right)^2 .$$

Undetectable for realistic fields but detectable for unrealistic fields ($B \sim 10^{10}$ G). Furthermore, the emission is at ultra-low radio freqs. Unclear direct detection is possible

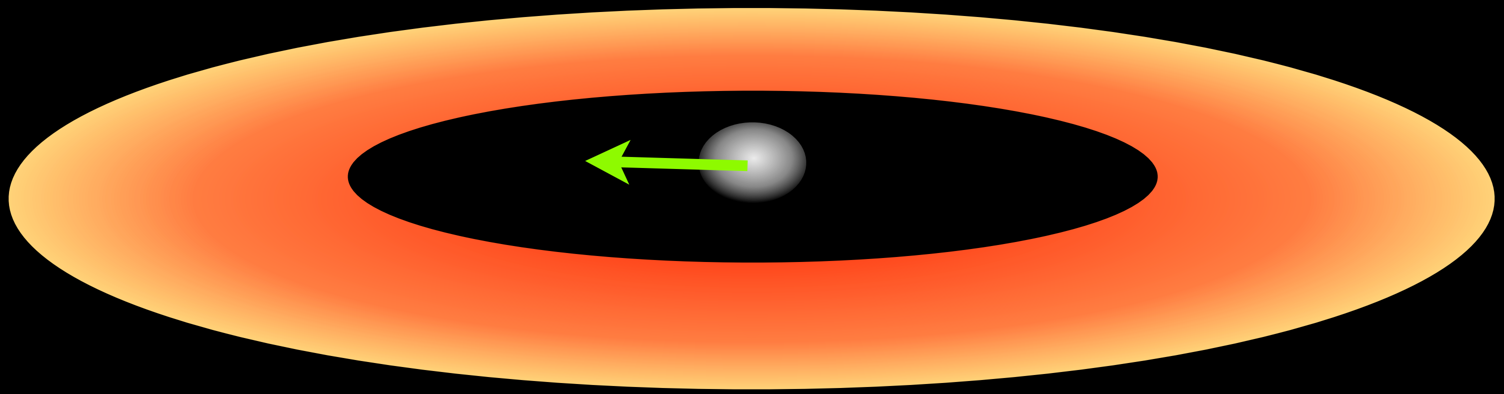
$$f_{\rm B} \simeq (40\, M)^{-1} \simeq 10^{-4} \left(\frac{10^8 M_\odot}{M}\right)\ {\rm Hz}$$

Postmerger evolution

Zanotti, LR et al (in progress)



We have investigated the dynamics of the circumbinary disc when the merger has taken place and the final BH has a recoil and a smaller mass.

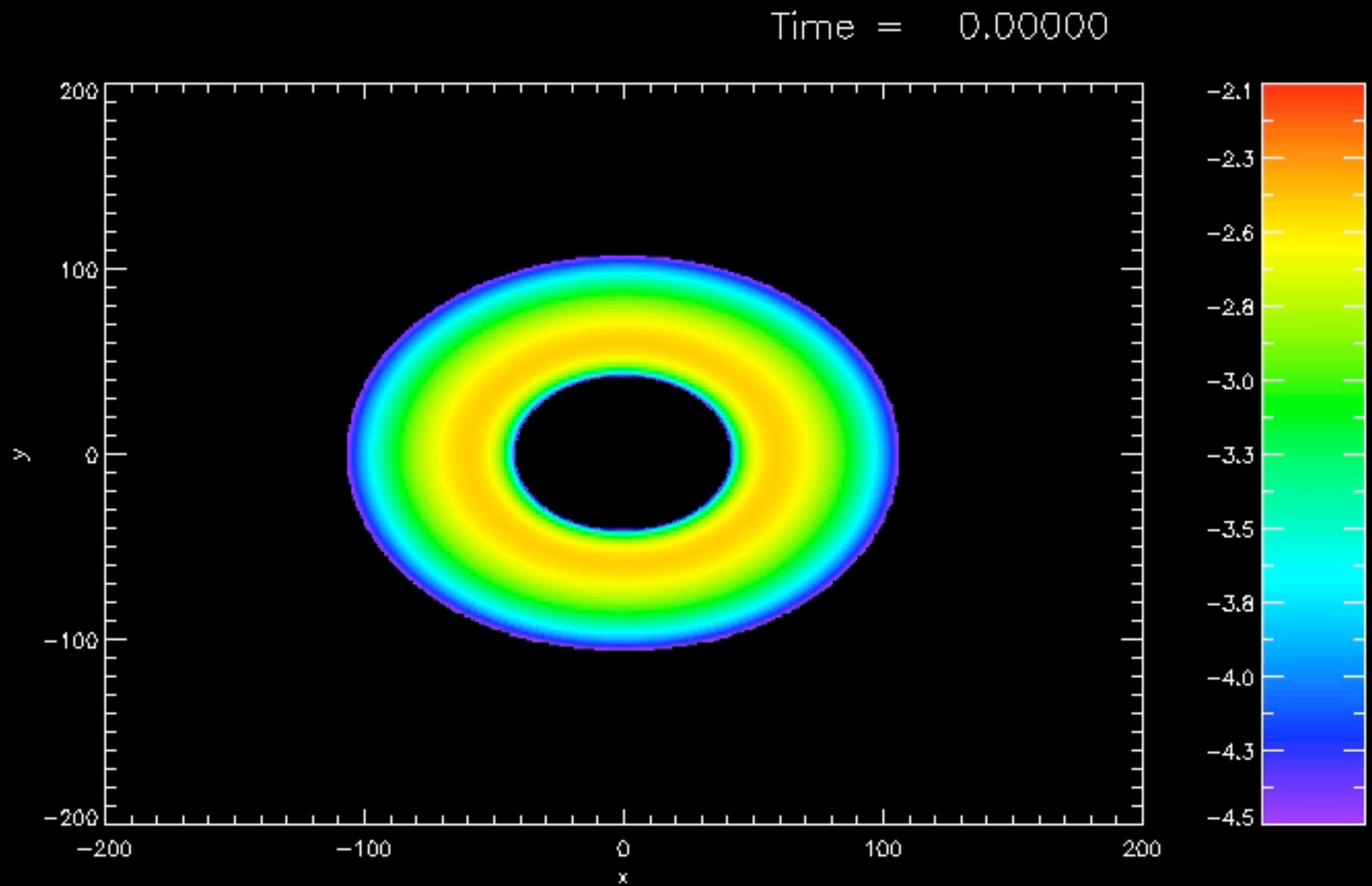


Pros of our approach:

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

Cons of our approach:

- restricted to 2D (kick in the plane of the disc)
- ignore magnetic fields and radiation transport

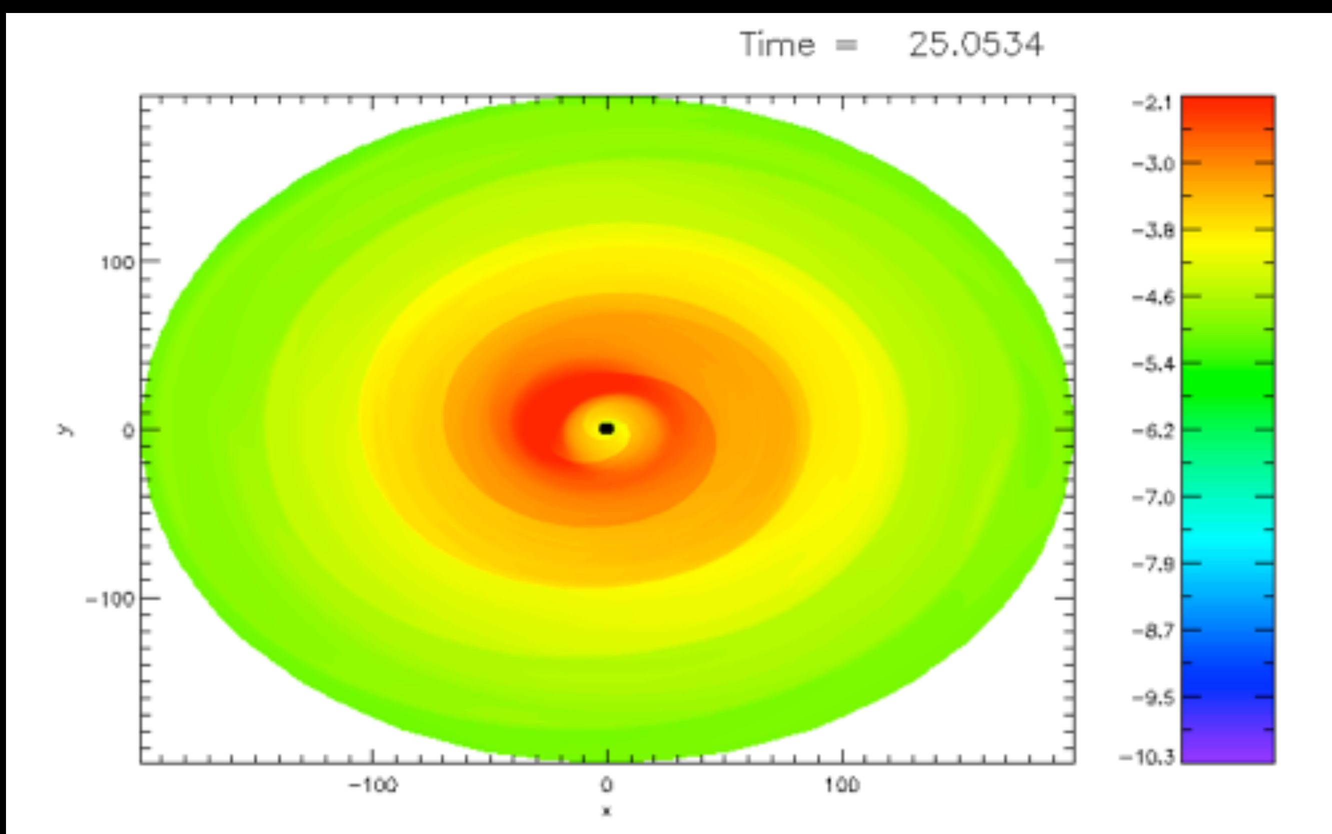


Time is in days for a BH with $10^6\, M_\odot$

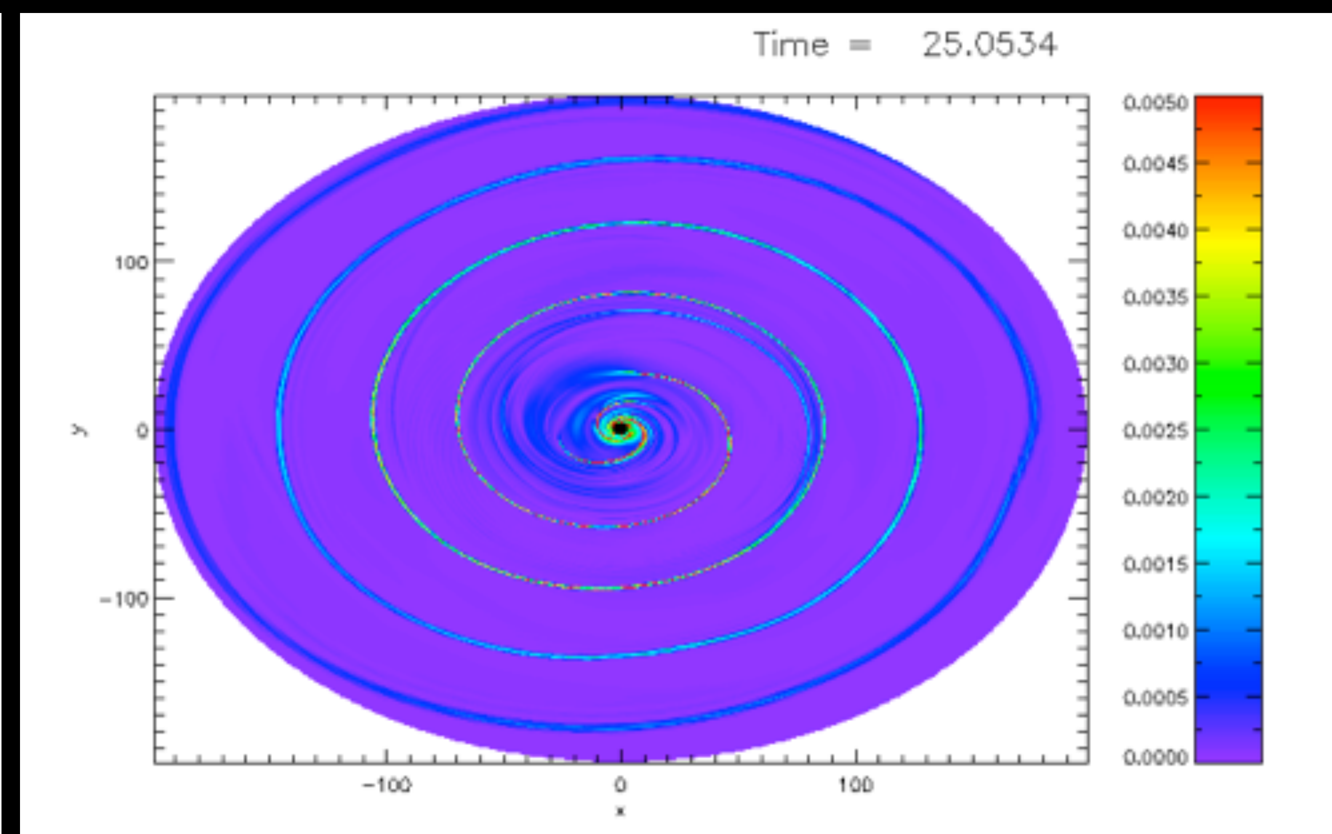
The evolution is over 30 dynamical times

Main results

- recovered most of the phenomenology already observed in Newtonian collisionless discs (Lippai et al. 2008) and in Newtonian fluid discs (Corrales et al. 2009, Rossi et al. 2009)
- spiral shocks are produced and and propagate outwards. Care when finding shocks: we use a sophisticated "shock detector"



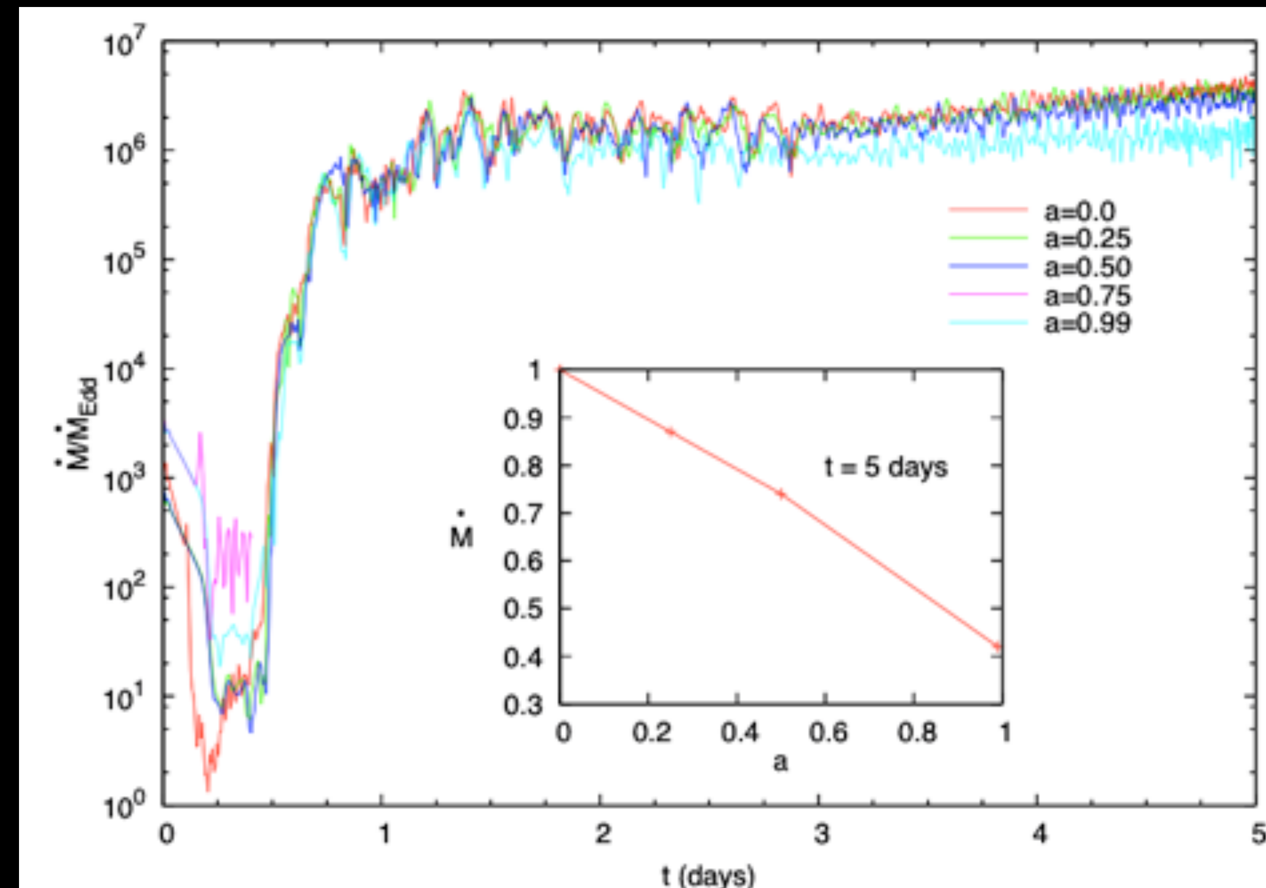
rest-mass density



shock-detector

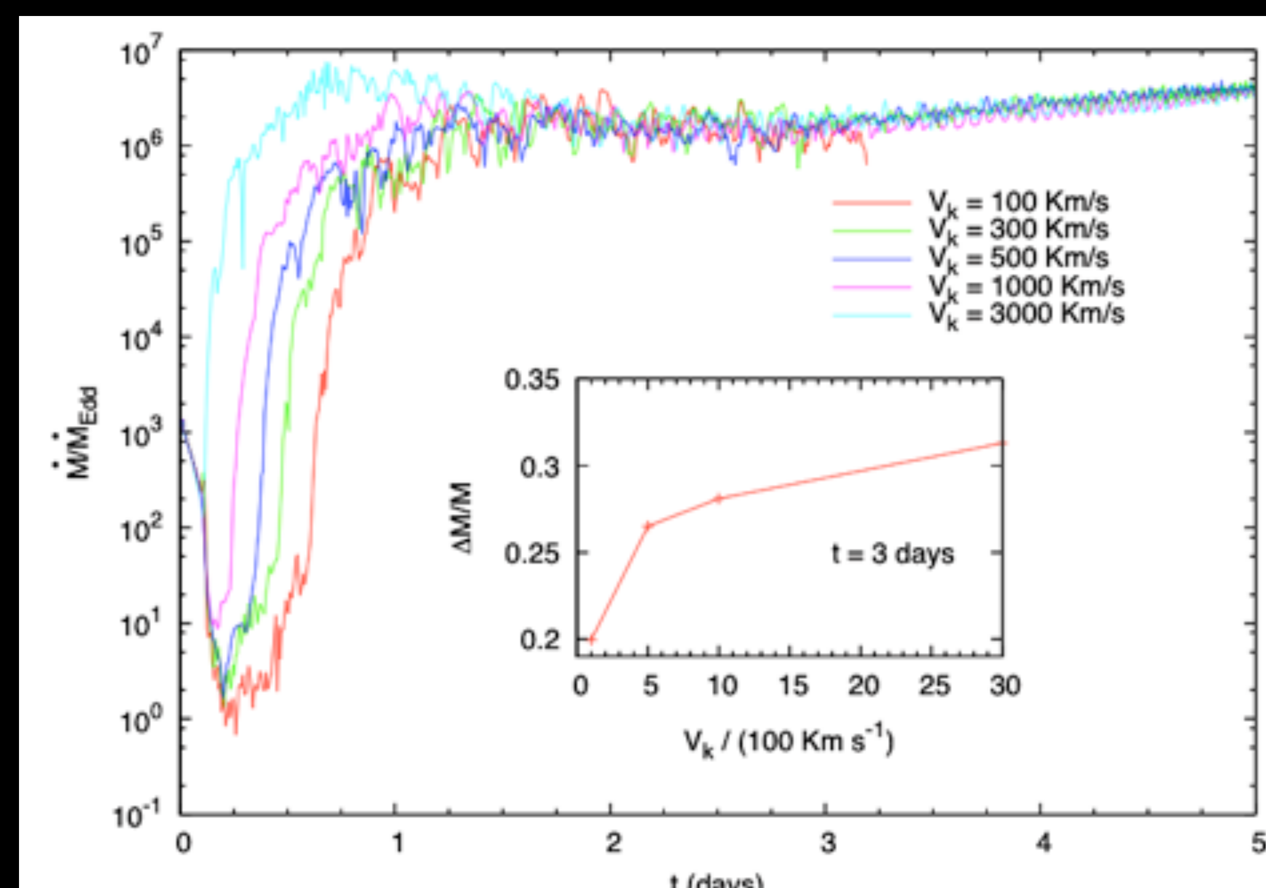
Main results

- the black hole spin has little influence on the dynamics of the disc



- the mass loss in the BH only excites epicyclic oscillations

the accretion rate increases as the torus falls into the BH



- the final stages of the accretion will see an enhanced luminosity followed by cutoff: unique signature

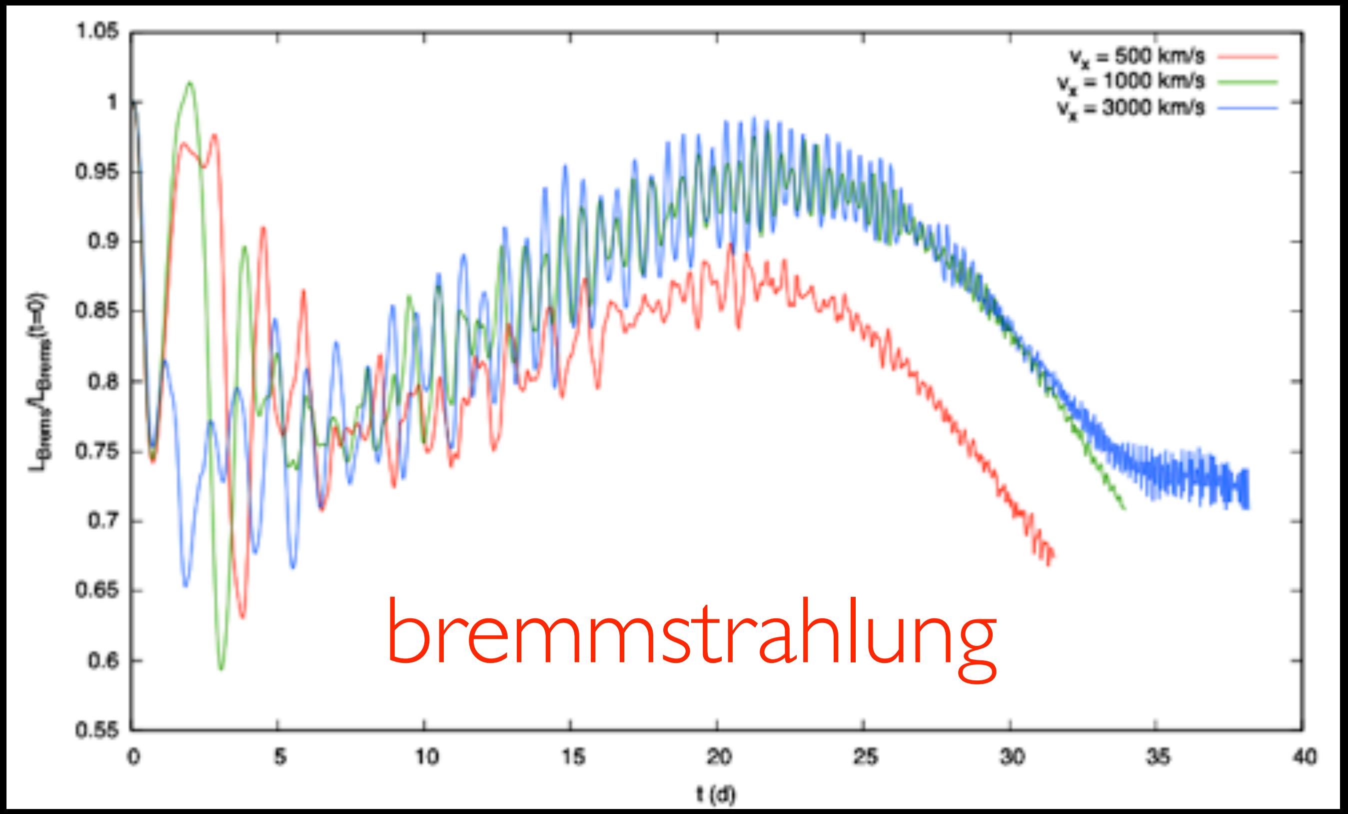
Main results

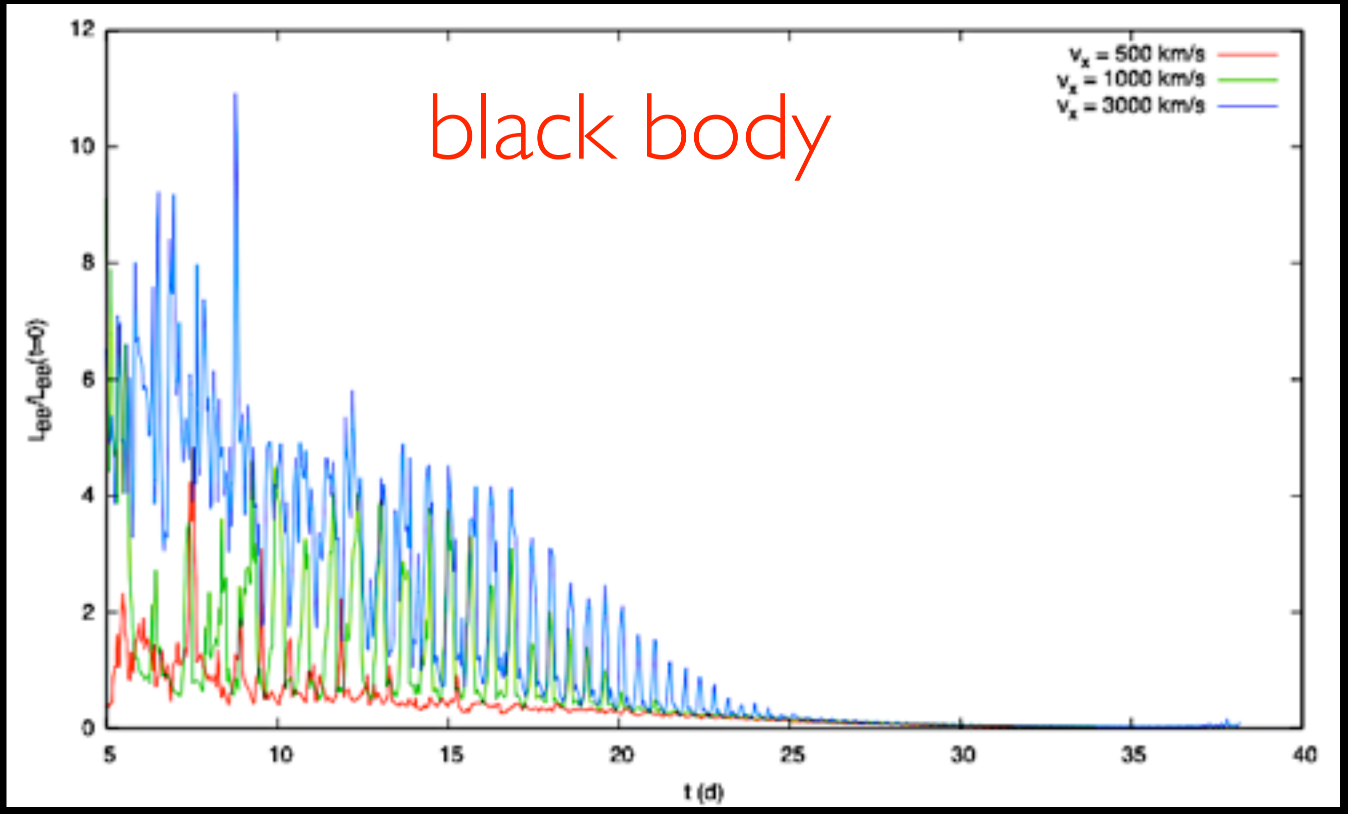
- bremstrahlung radiation is larger for larger kicks. Increases initially as denser material is accreted and vanes with vanishing of mass in the torus

- black body radiation is also larger for larger kicks

- in both cases the luminosity is modulated by the oscillations of the torus with amplitude variation of a few

- these results are consistent but doubtful till radiation is accounted for (super Eddington regimes





Conclusions

✳Several approaches are possible to model analytically the final spin vector from the inspiral and merger of BBHs

✳Derived an algebraic expression for the final spin for generic configurations with ~1% (5%) precision in the modulus (direction). Simplest and most accurate so far.

✳Modelling of the recoil not yet robust. Largest kicks are fine but statistical modelling of low mass ratio problematic. New results will come soon.

✳We are exploring the EM counterparts associated to BBHs.

- EM fields around BHs can be perturbed and lead to EM radiation but with small losses for realistic magnetic fields.
- recoil-induced perturbations on the disc lead to large and likely detectable accretion rates. However, more physics is needed.