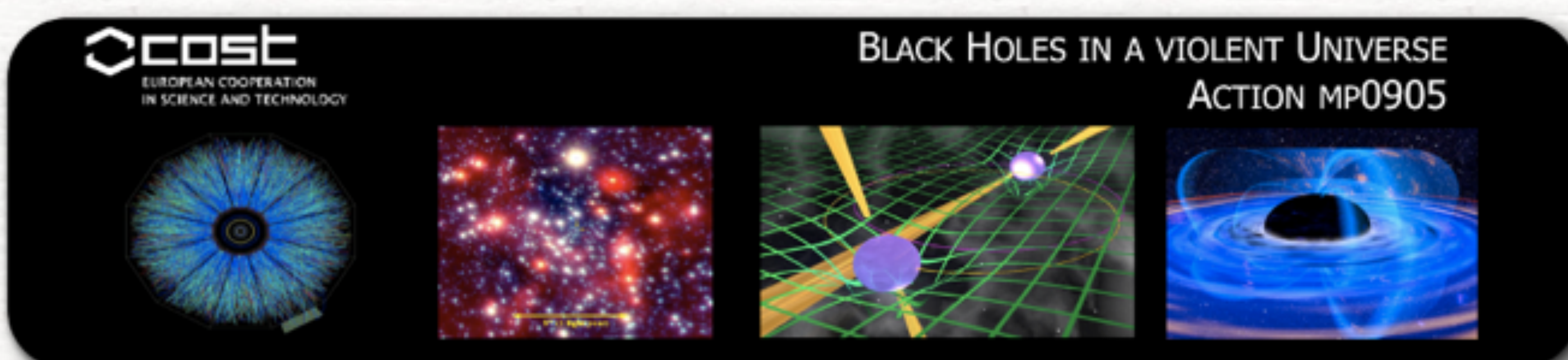
Simulating BH mergers and their EM emission

Luciano Rezzolla

Albert Einstein Institute, Potsdam, Germany

Dept. of Physics and Astronomy, Louisiana State Univ. Louisiana, USA



Valencia

15 Nov. 2010

Plan of the talk

Simulating BH binaries in NR

- ✳ final spin
- ✳ final recoil
- ✳ EM counterparts
  - ★ pre-merger
  - ★ post-merger

The two-body problem

Newtonian gravity: the eqs of motion derive from a force balance. The system **admits closed** orbits: the binary remains at a constant radius and analytic solution is simple.

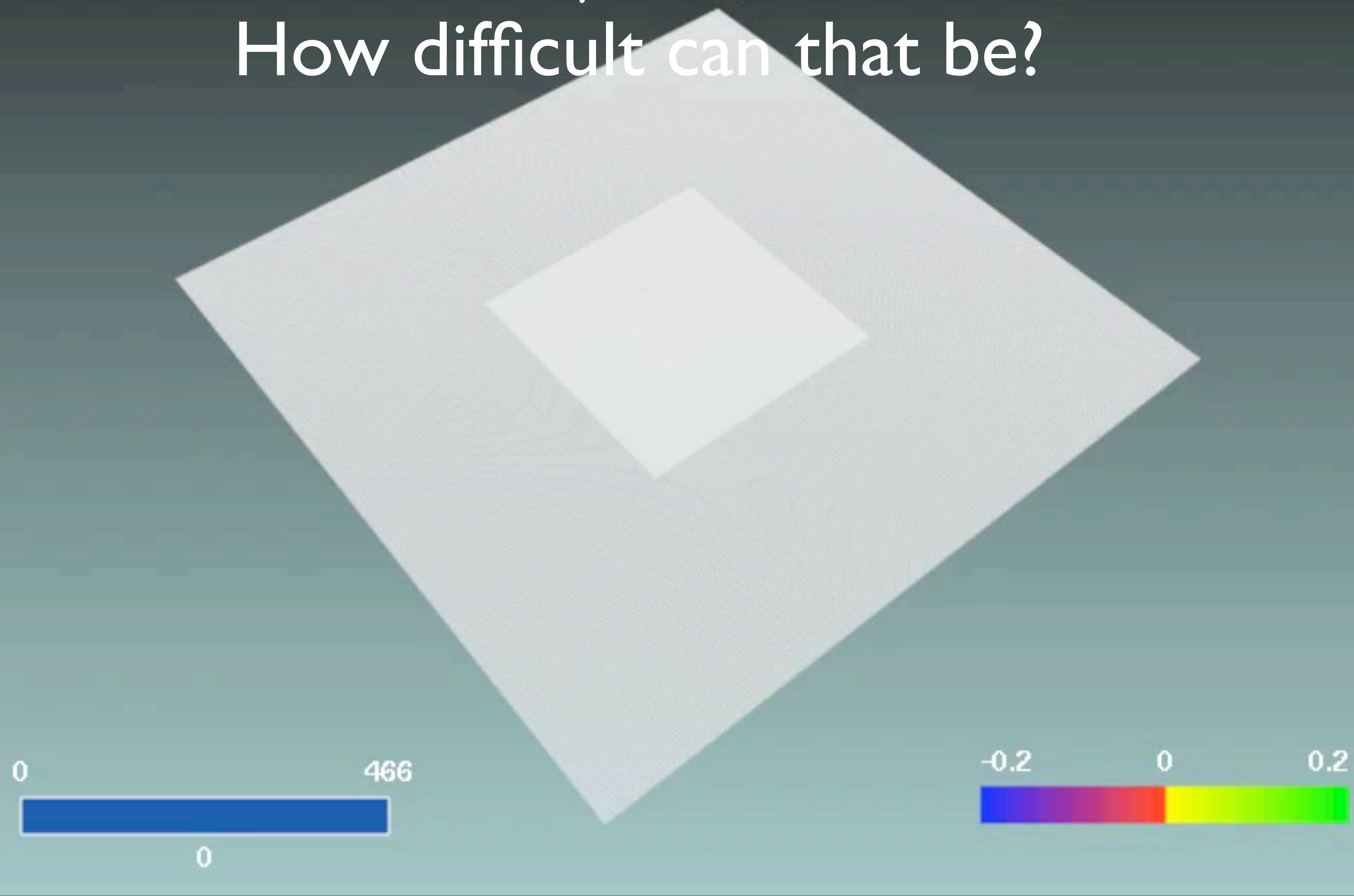
GR: the eqs of motion derive from the Einstein equations, which cannot be solved analytically in general.
The system **does not** admit **closed** orbits: the binary loses energy and angular momentum and will eventually merge.

NR: is employed when all other approximations (eg post-Newtonian expansion) are **known to fail**. Most useful to compute the **last few orbits** (~ i.e. 10-20) and use this information to "tune" different analytic approximations such as post-Newtonian/EOB: produce *"hybrid waveforms"*

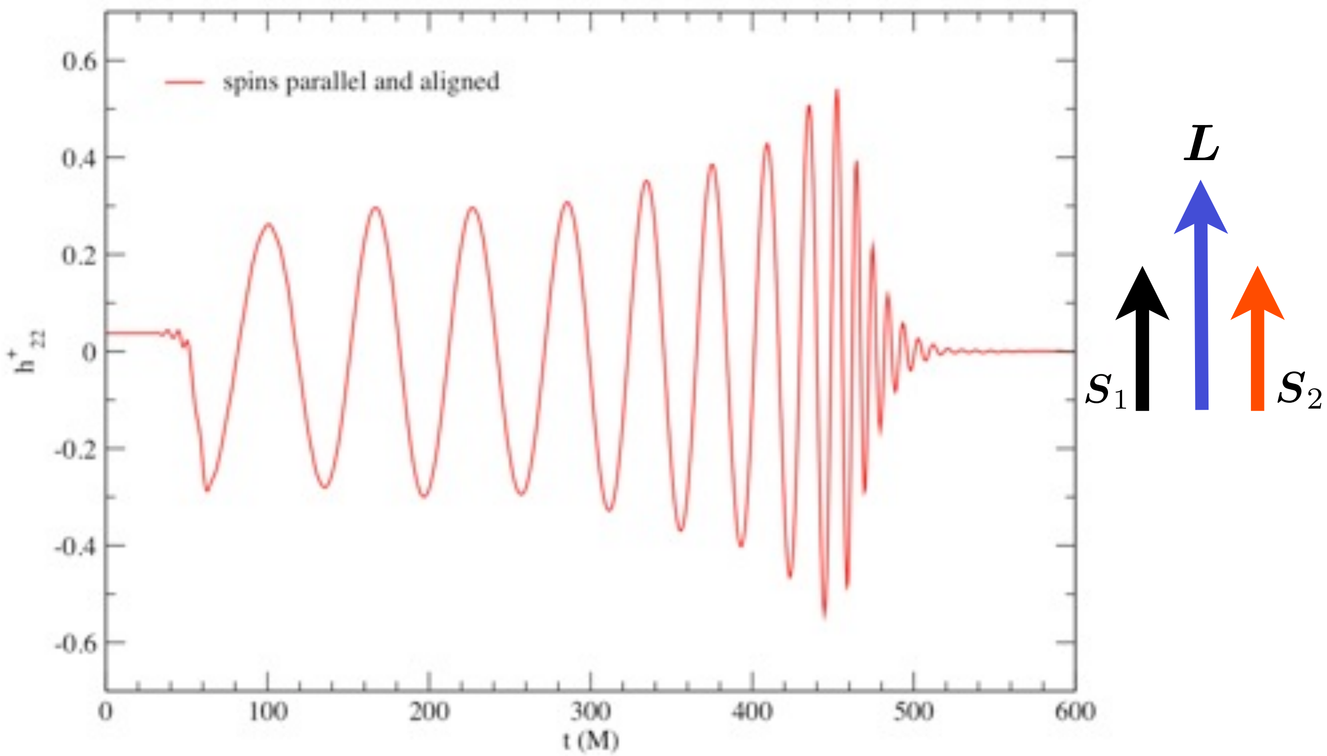
In vacuum the Einstein equations reduce to

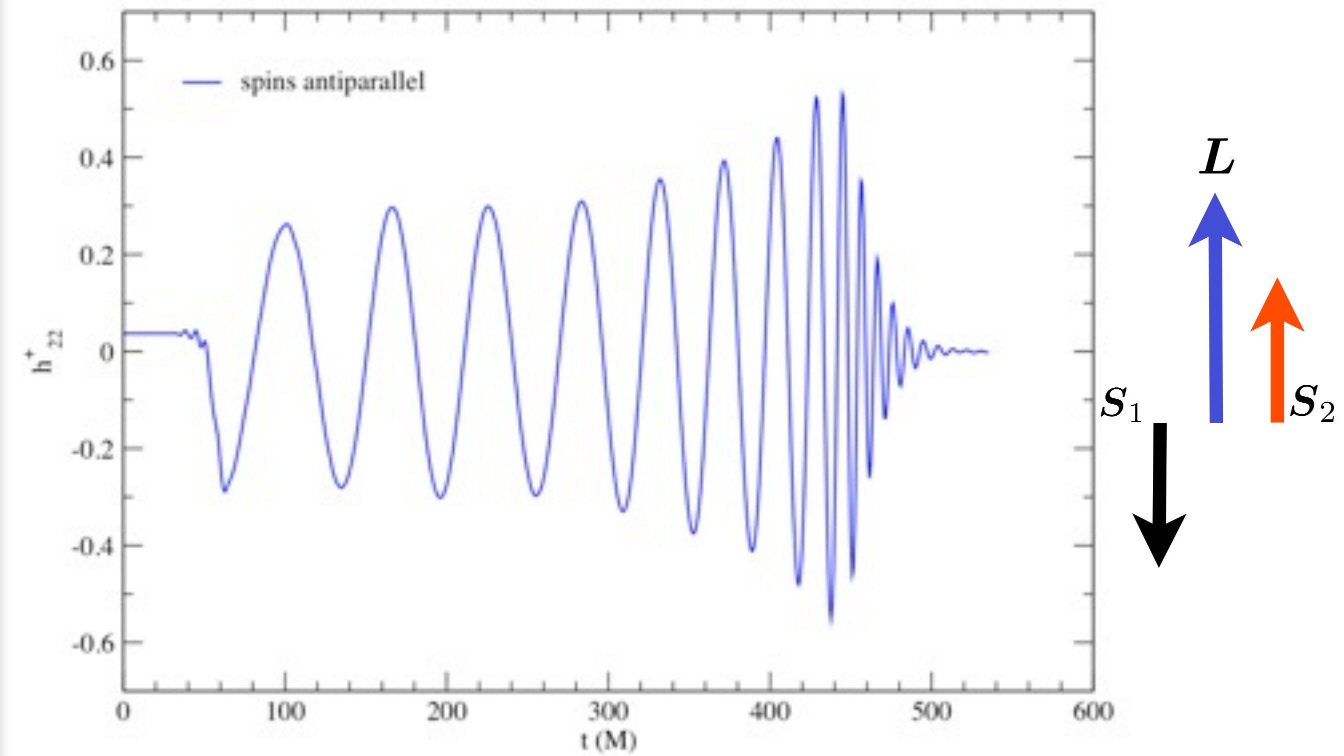
$$R_{\mu\nu} = 0$$

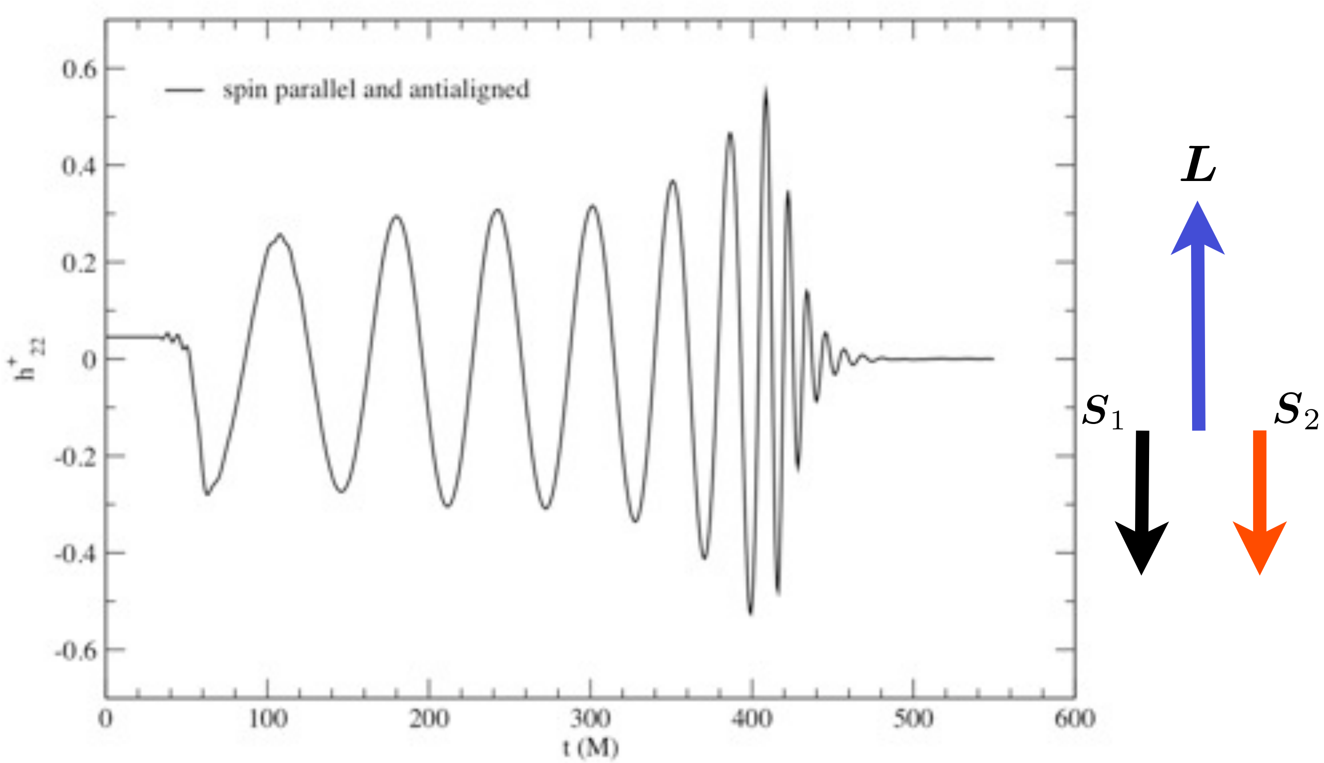
How difficult can that be?



Animation by Kaehler, Reisswig, LR







All the information is in the waveforms

- used in matched filtering techniques (data analysis)
- compute the physical/ astrophysical properties of the merger (kick, final spin, etc.)

Modelling the final state

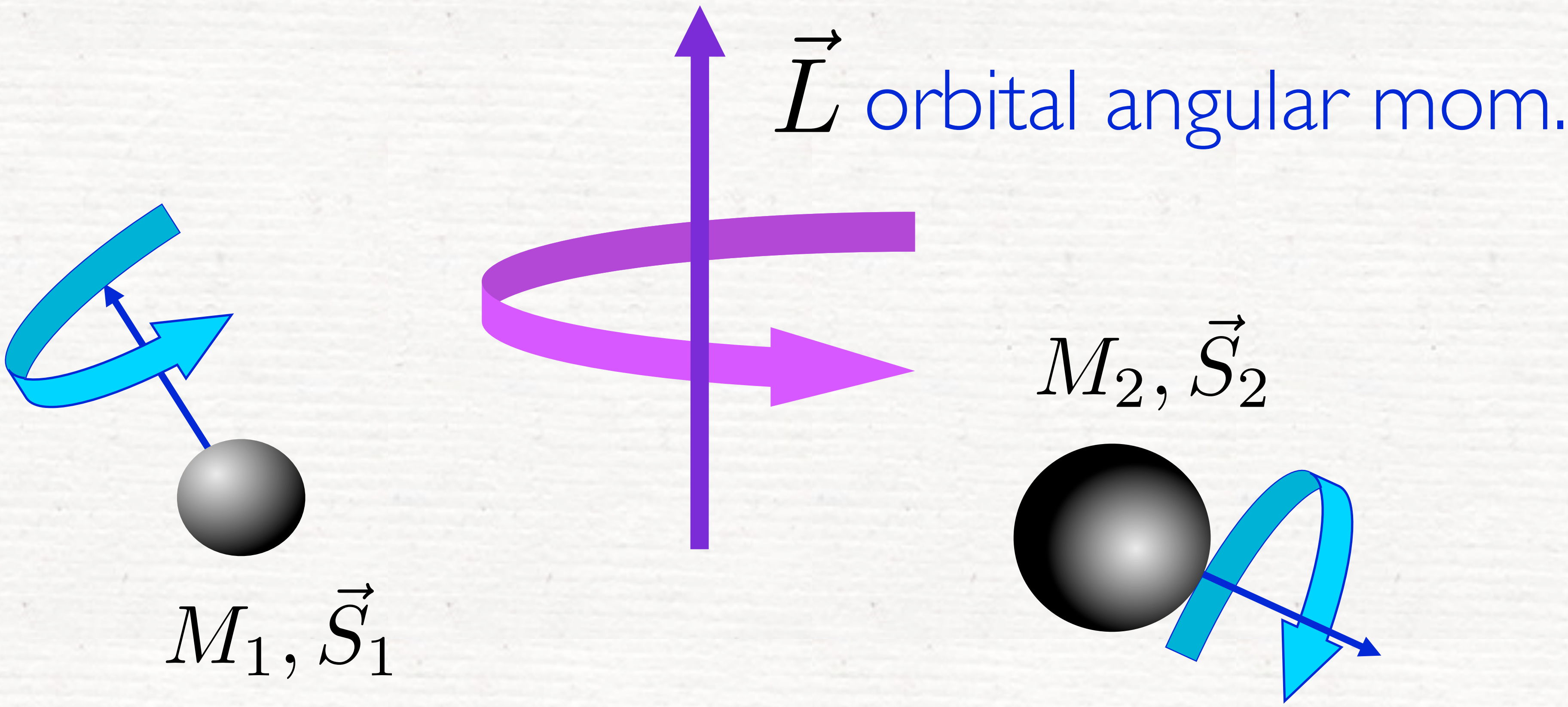
- final spin **vector**
- final recoil velocity

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
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
van Meter et al. 2010

Modelling the final state

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

Before the merger...

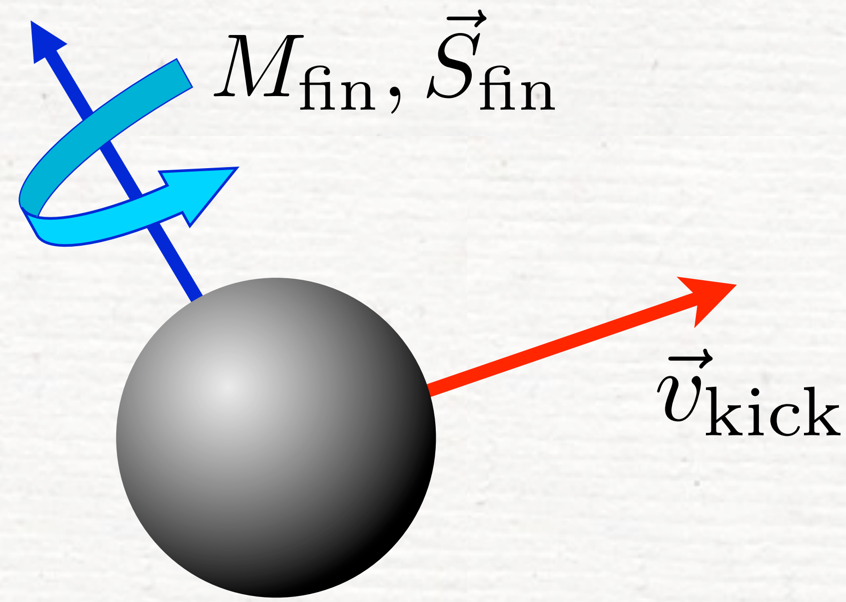


Modelling the final state

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

After the merger...

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



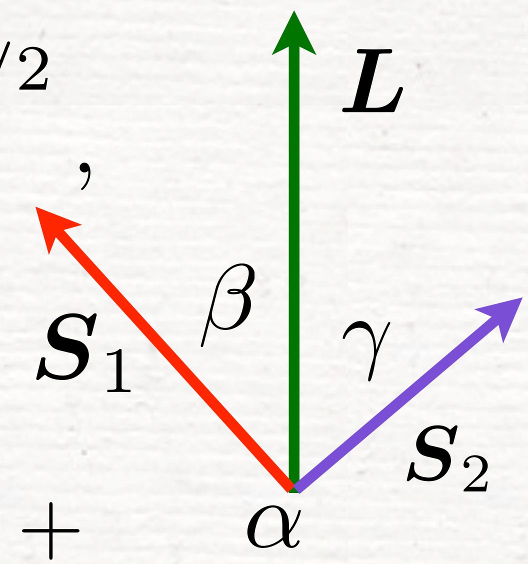
Buonanno et al. 2007
Boyle et al, 2007
Boyle et al, 2008
Tichy & Marronetti, 2008
Kesden, 2008
Lousto et al. 2009
van Meter et al. 2010
Kesden et al. 2010

The final BH has 3 specific properties: **mass, spin, recoil.**
Their knowledge is important for astrophysics and cosmology

- A lot of work, especially at the AEI, has gone into mapping the initial configuration to the final one without the need of performing a simulation.
- We can predict with **% precision** the **magnitude** and **direction** of the final **spin** as well as 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

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



where

$$|\boldsymbol{\ell}| = \frac{s_4}{(1+q^2)^2}\left(|\boldsymbol{a}_1|^2 + |\boldsymbol{a}_2|^2 q^4 + 2|\boldsymbol{a}_1||\boldsymbol{a}_2|q^2\cos\alpha\right) + \left(\frac{s_5\nu + t_0 + 2}{1+q^2}\right)\left(|\boldsymbol{a}_1|\cos\beta + |\boldsymbol{a}_2|q^2\cos\gamma\right) + 2\sqrt{3} + t_2\nu + t_3\nu^2\,.$$

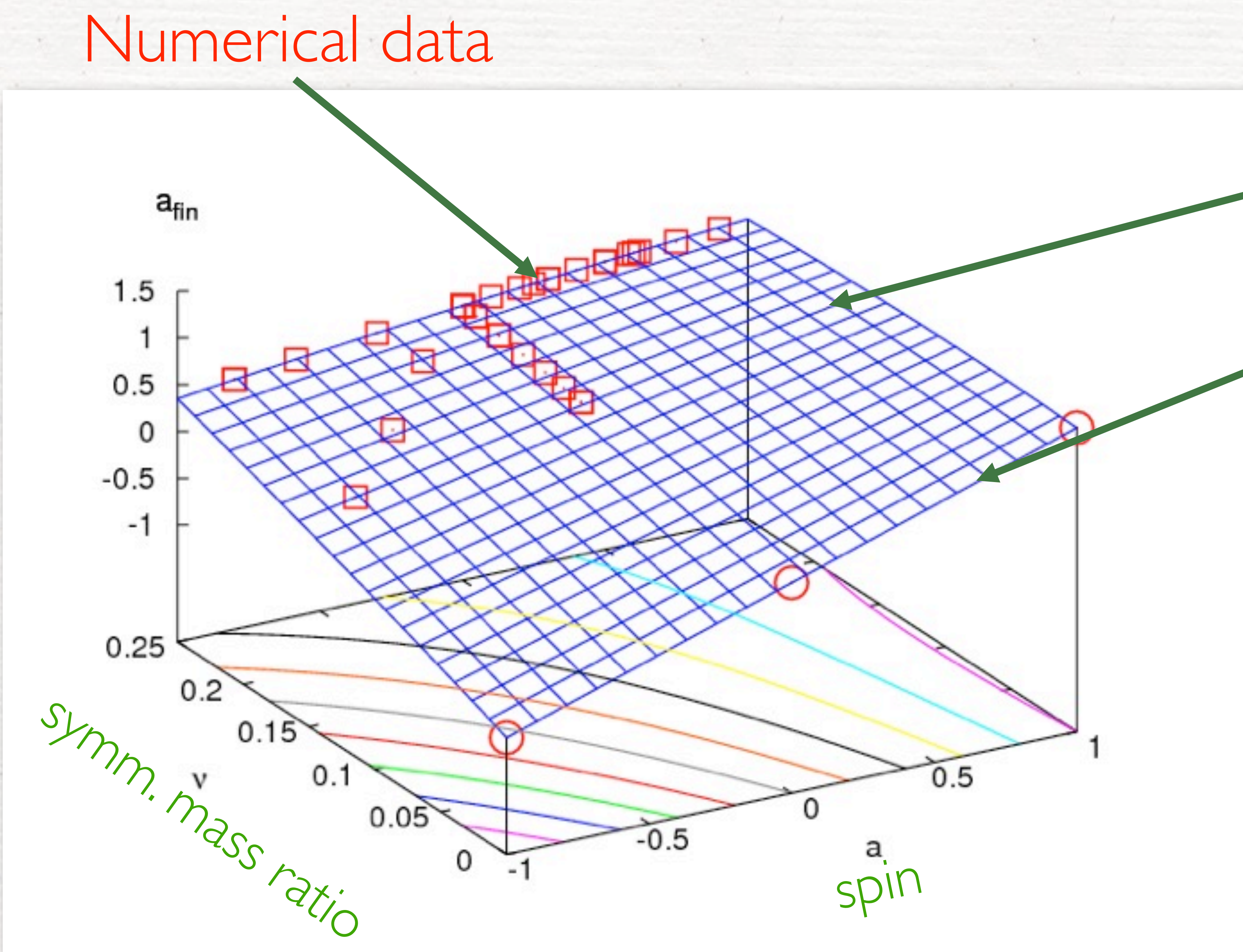
Note that the final spin is fully determined in terms of the 5 coefficients $s_4,\ s_5,\ t_0,\ t_2,\ t_3$ which can be computed via numerical simulations. The agreement with data is at % level!

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 ($\nu = M_1 M_2/(M_1+M_2)^2$)

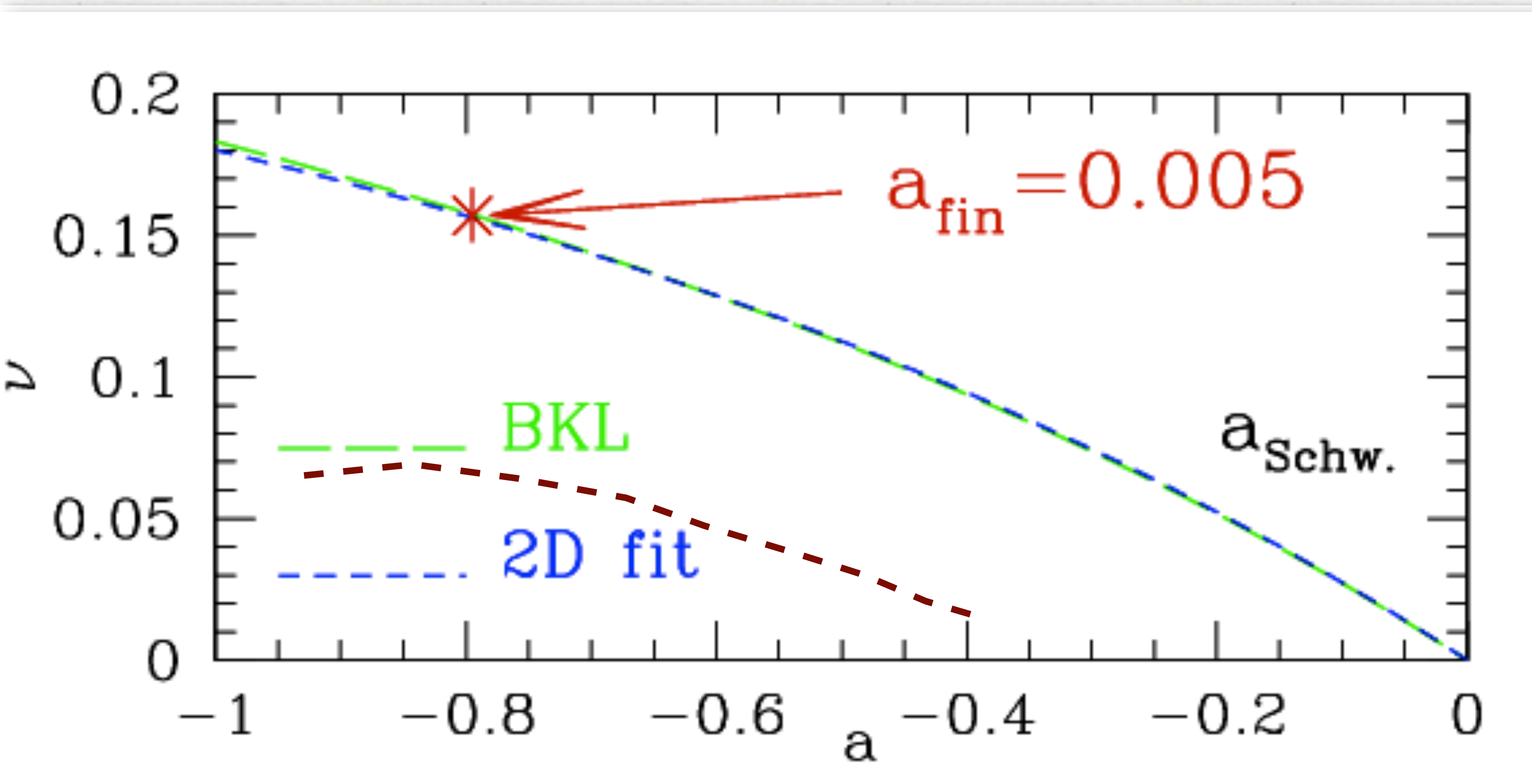
$$a_{\rm fin}(a,\nu) = a + s_4 a^2 \nu + s_5 a \nu^2 + t_0 a \nu + t_1 \nu + t_2 \nu^2 + t_3 \nu^3$$

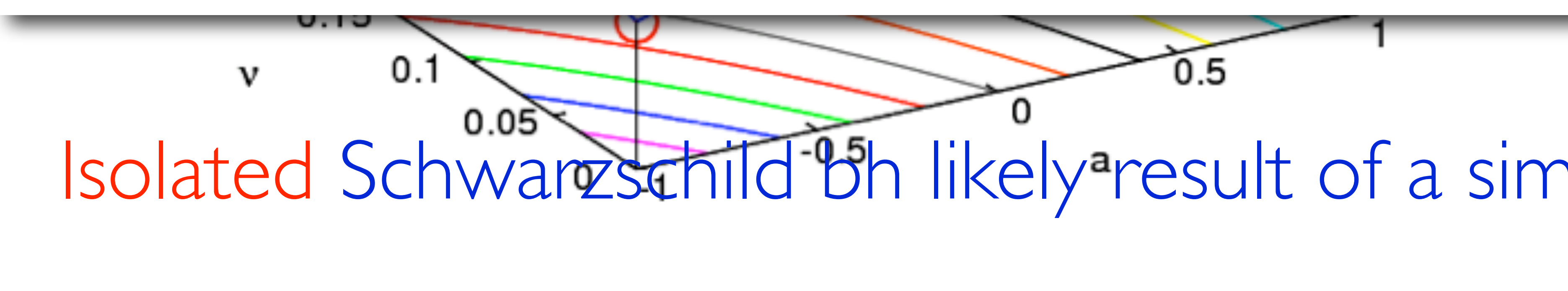


The functional dependence is simple enough that a low-order polynomial is sufficient

How to produce a Schwarzschild bh...

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





Find solutions for:

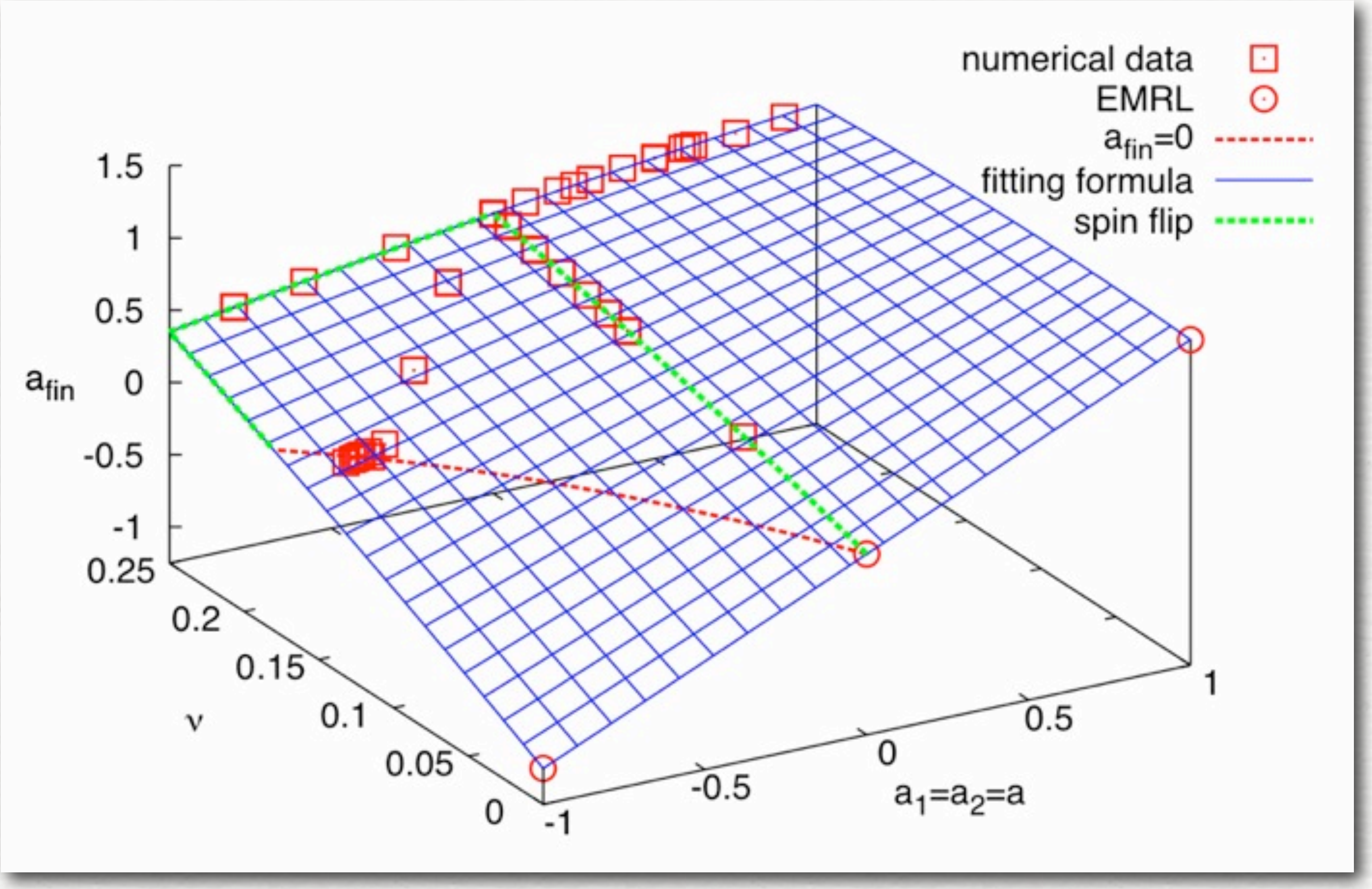
$$a_{\mathrm{fin}}(a,\nu) = 0$$

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:

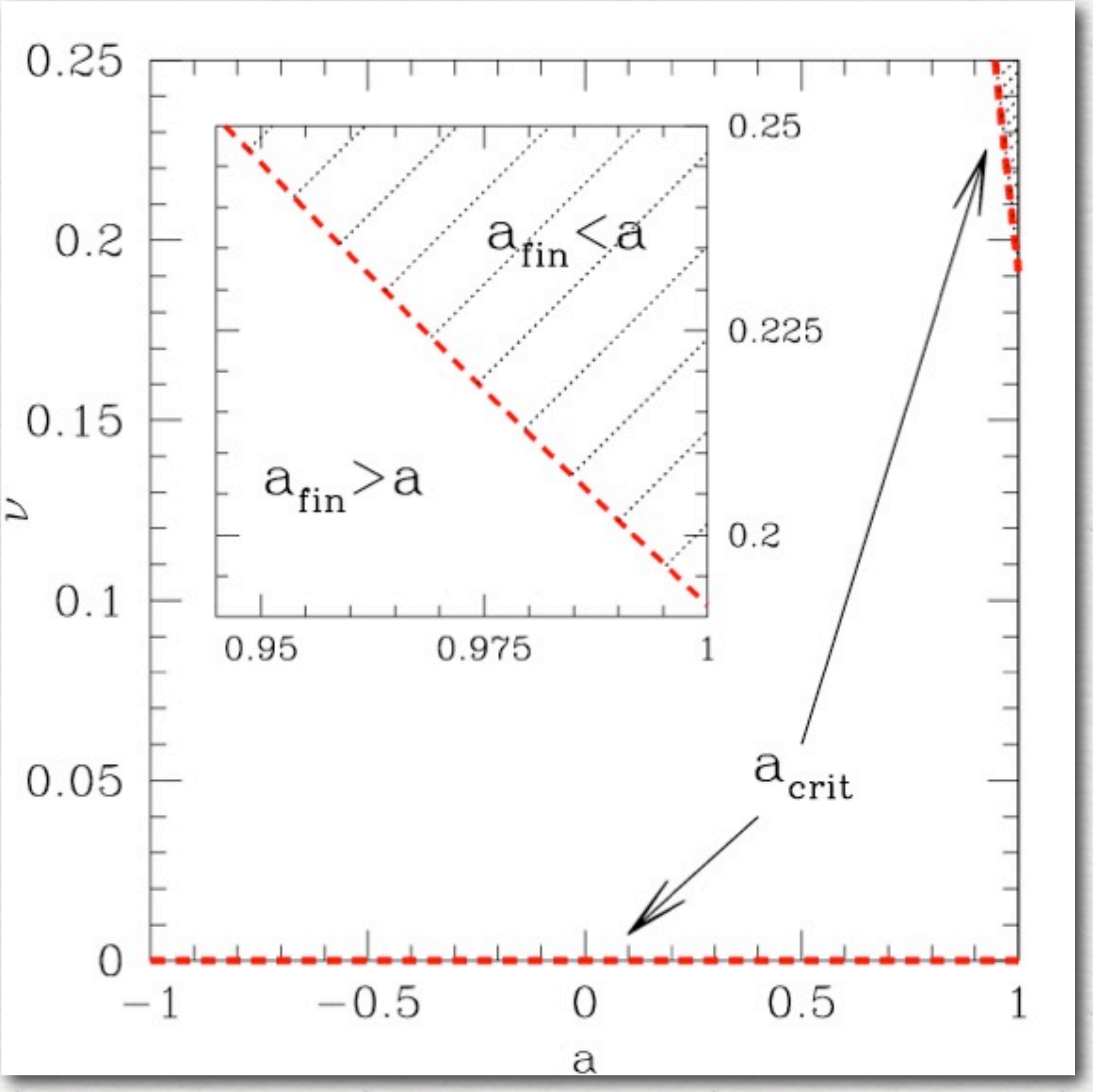
$$a_{\rm fin}(a,\nu)\,a<0$$

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

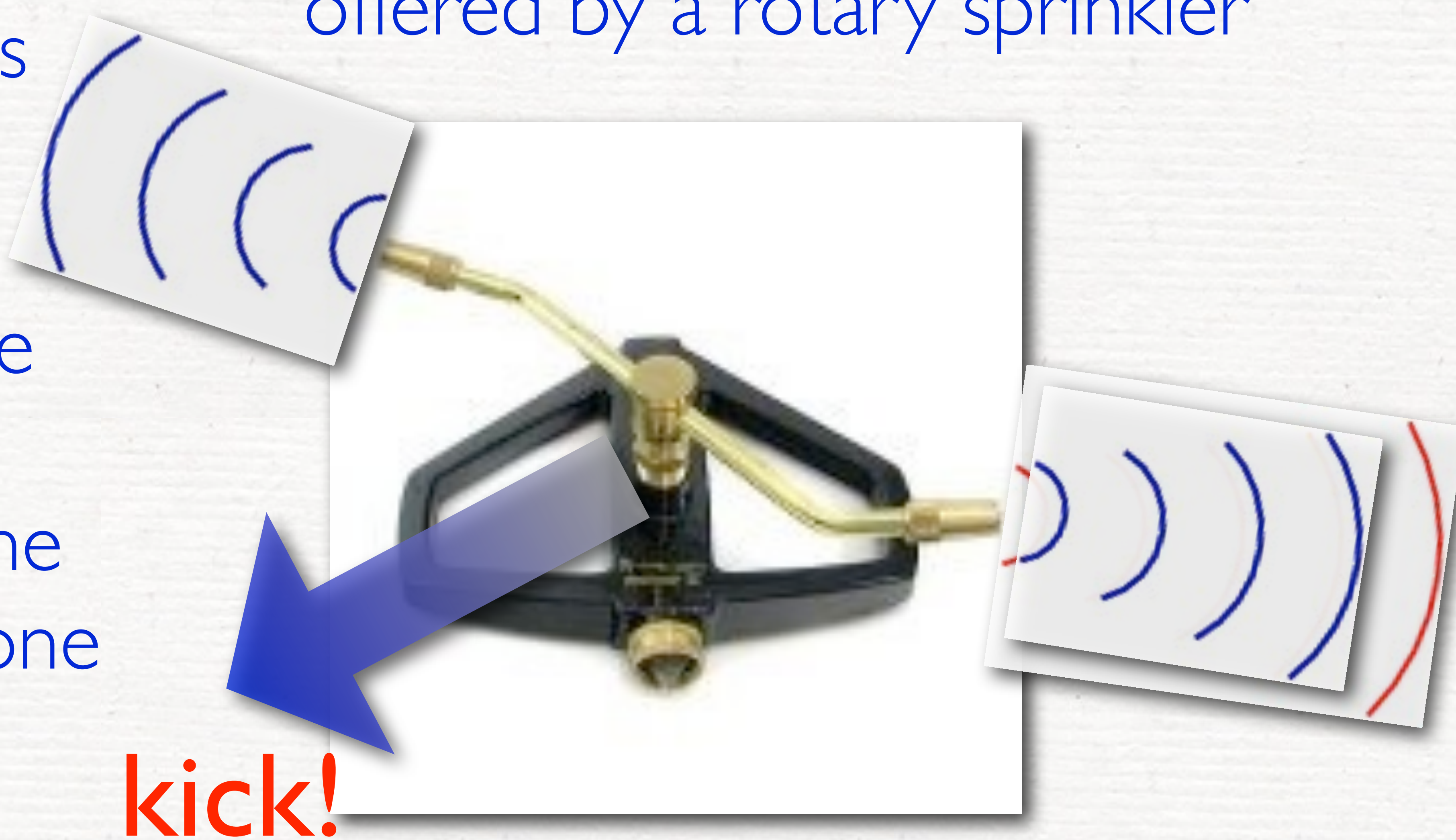
LR et al, 2007
Boyle et al, 2008
Baker et al, 2008
Lousto et al, 2008
Tichy & Marronetti, 2008
Kesden, 2008
Barausse, LR, 2009
Lousto et al. 2009
van Meter et al. 2010

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



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

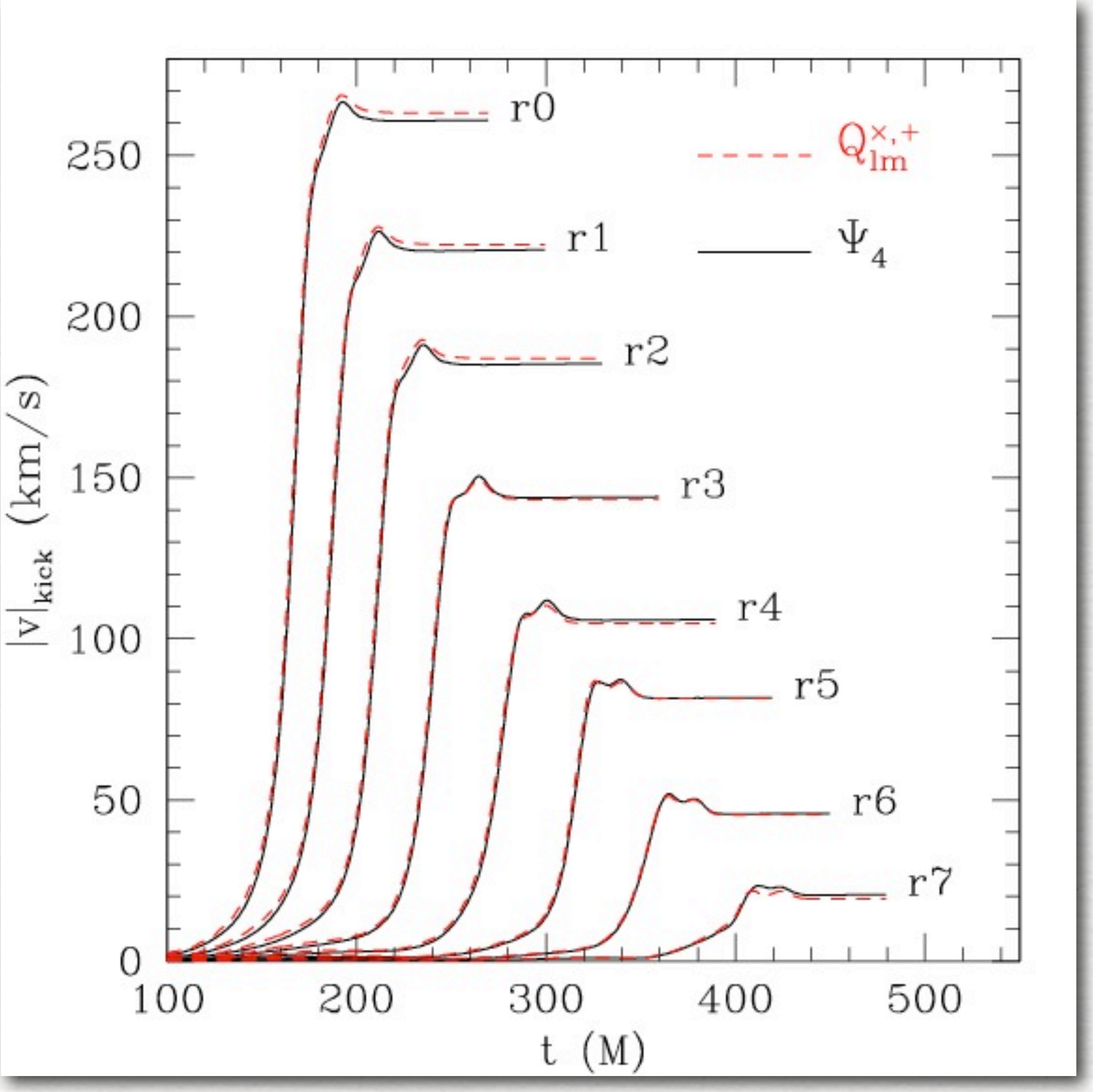
r0: ↑ ↓ (a_1/a_2=-4/4)

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

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

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

$$v_\| \simeq \frac{K_1\nu^2 + K_2\nu^3}{(1+q)}\left[q a_1^\perp \cos(\phi_1 - \Phi_1) - a_2^\perp \cos(\phi_2 - \Phi_2)\right]$$

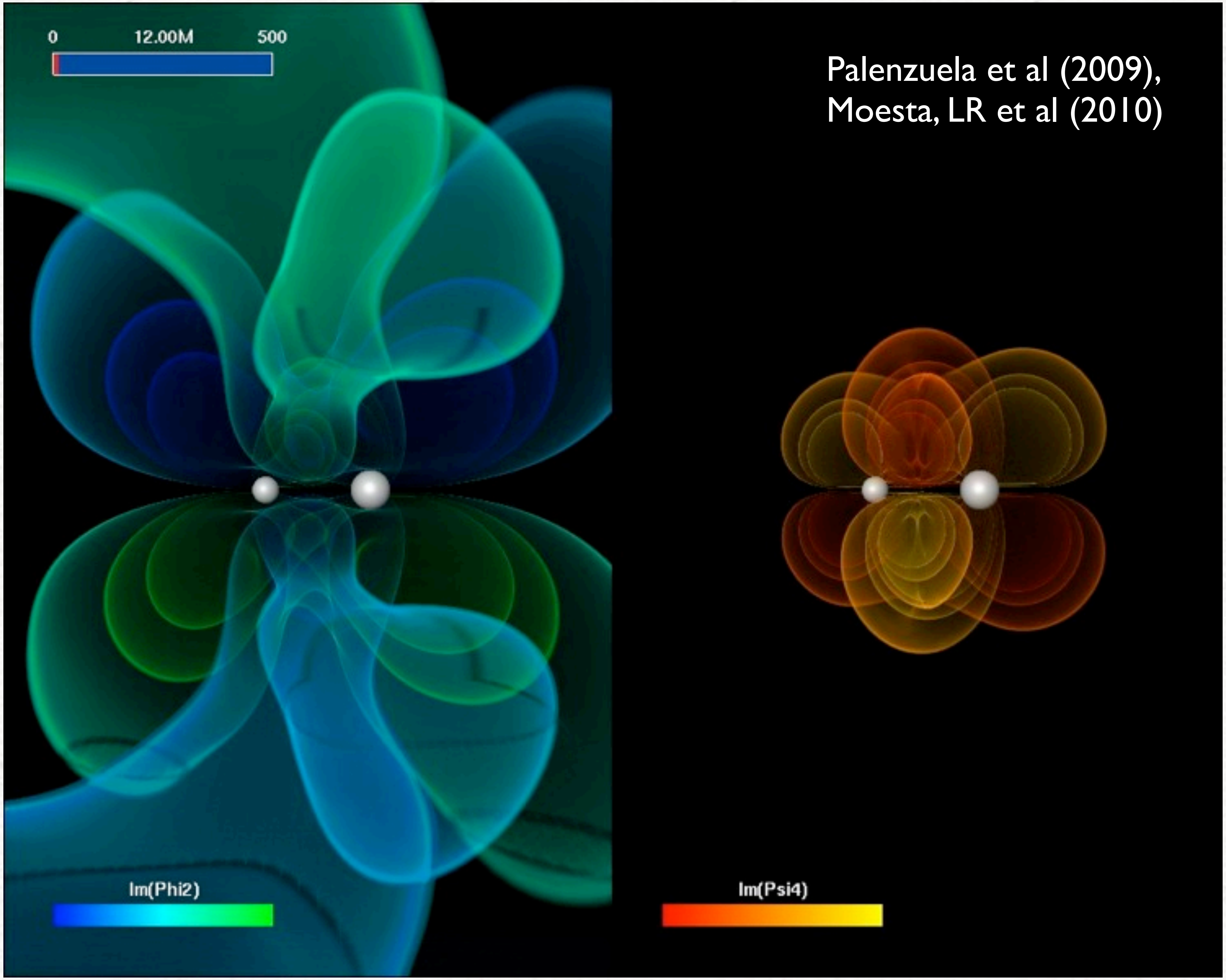
mass asymmetry $\lesssim 150 \mathrm{km/s}$

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

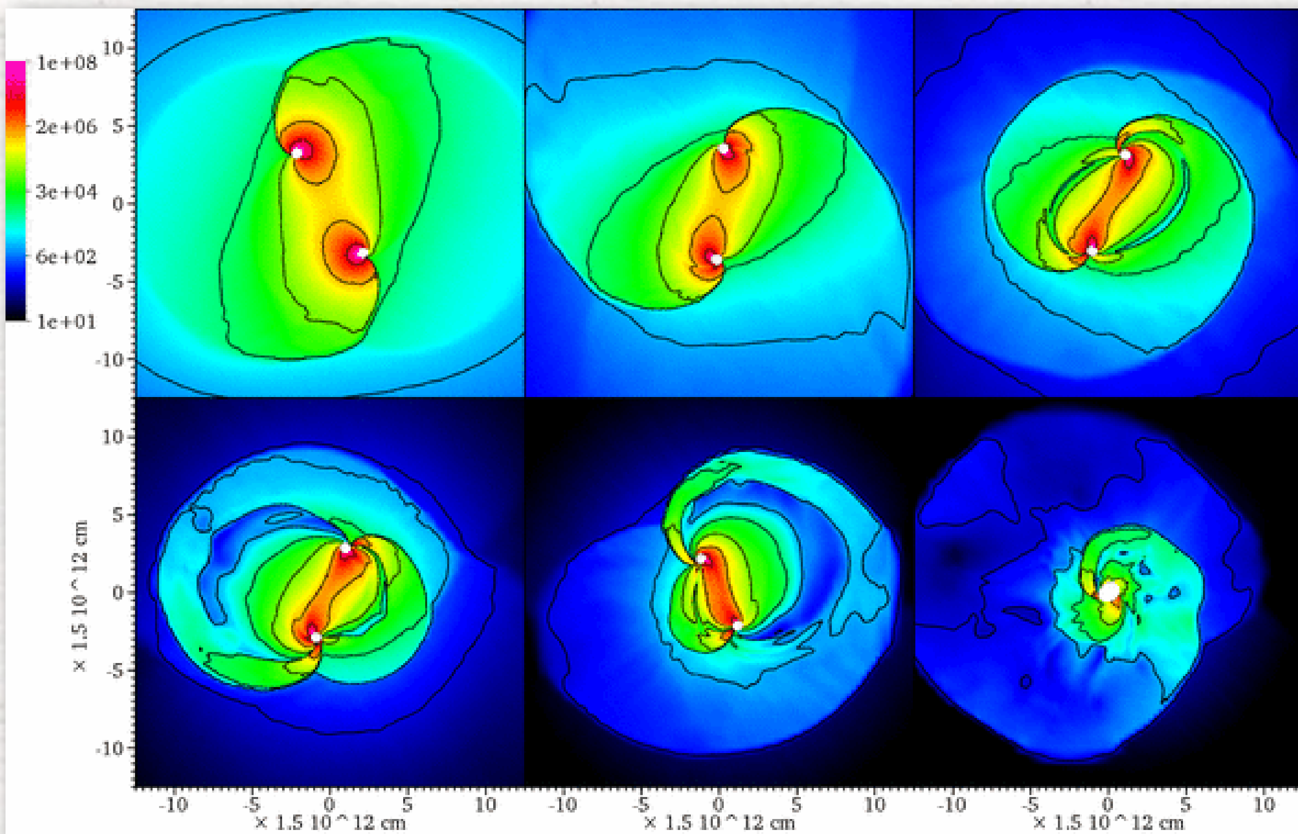
EM counterparts: pre-merger



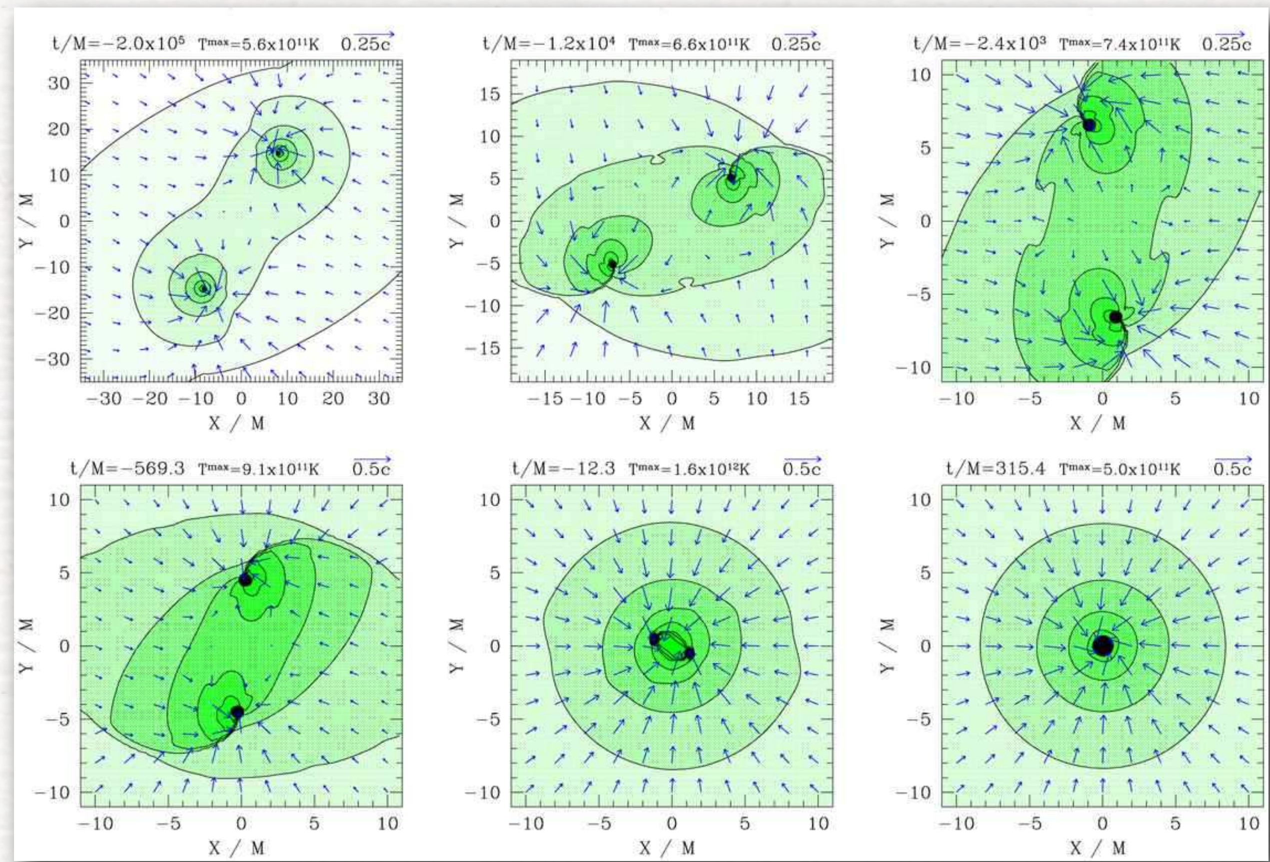
Approaches considered so far in NR:

- isotropic distribution of hot/dense gas surrounding the binary (Bode al. 2009; Farris et al. 2010)

Bremmsstrahlung (Bode, 2010)

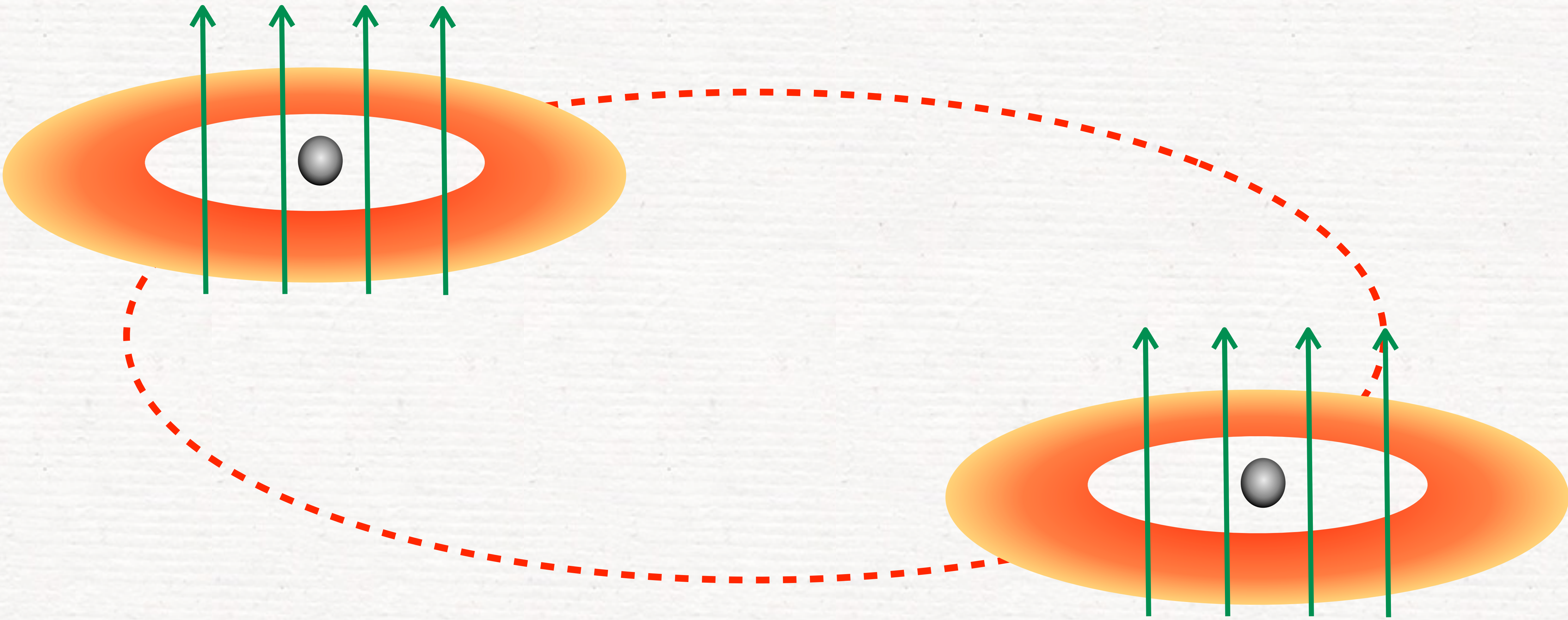


Temperature (Farris, 2010)

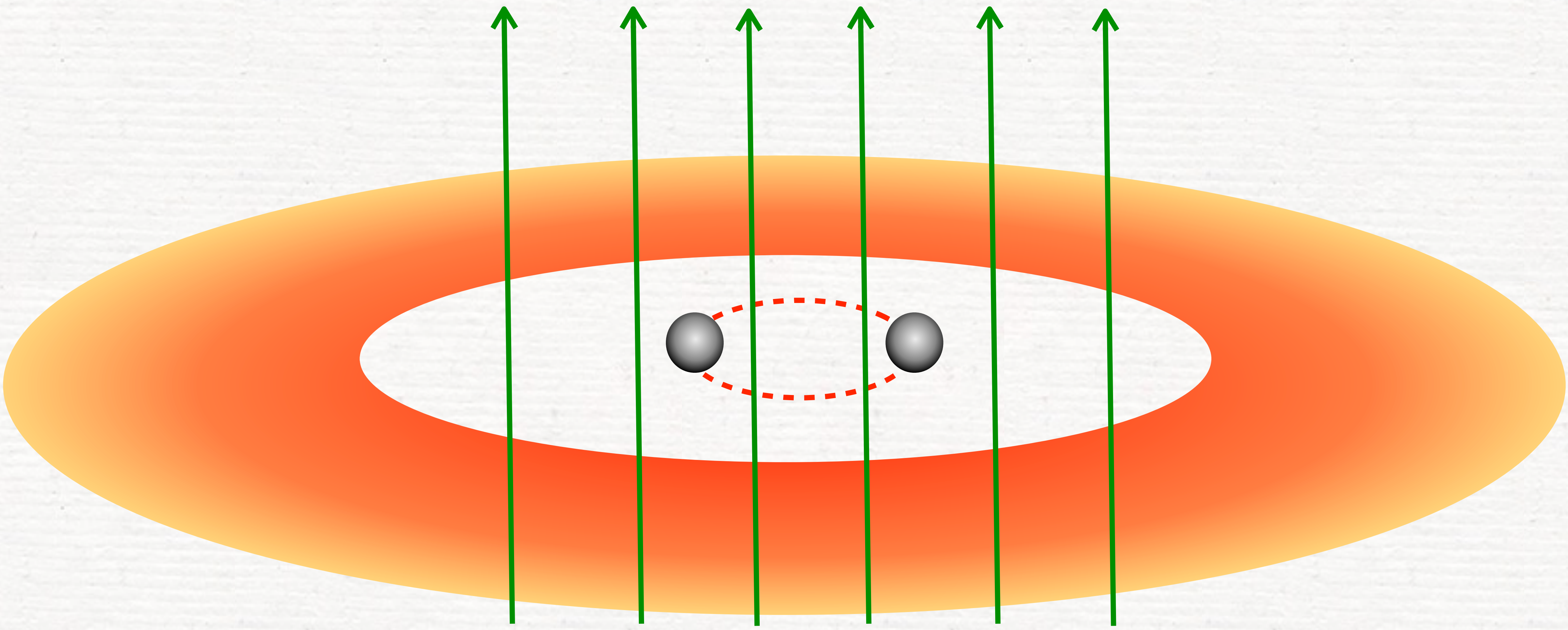


- distant circumbinary disc (the binary is essentially in vacuum) and coupling takes place via a plasma or EM fields (Palenzuela et al. 2009, 2010; Moesta et al. 2010)

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.

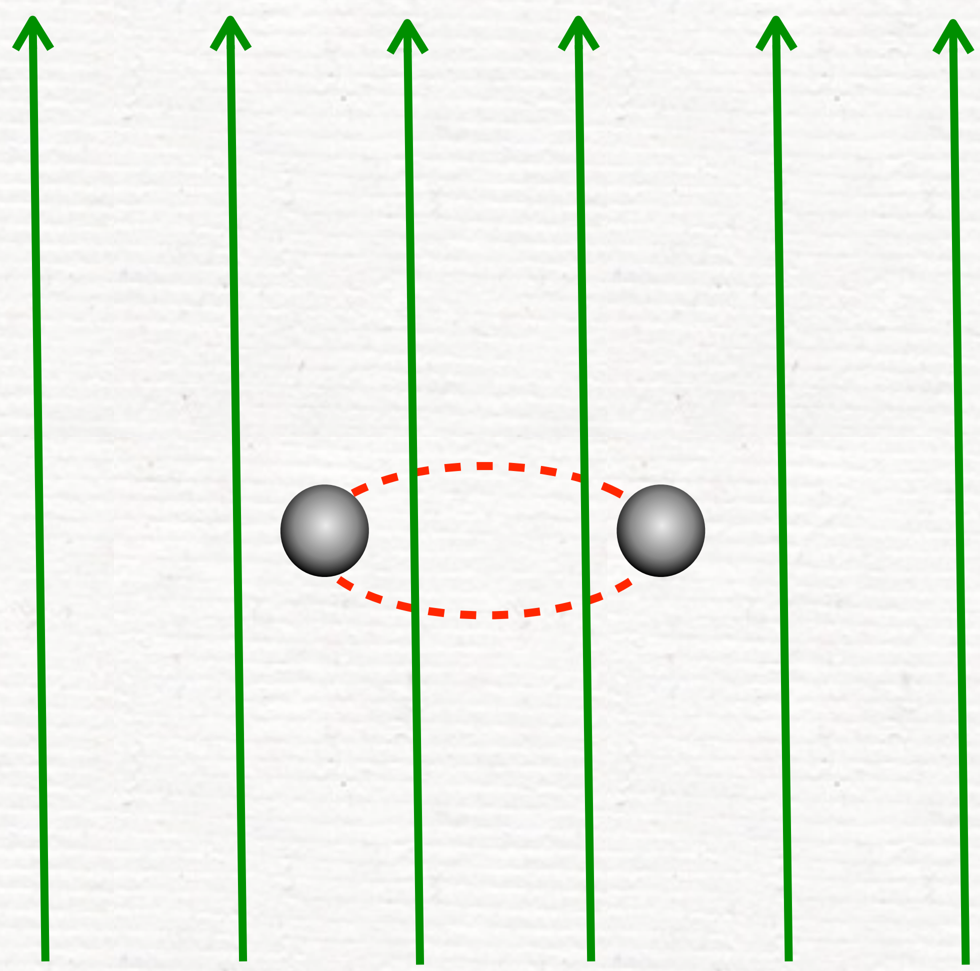


The massive **circumbinary disc** will follow the binary during the slow viscous evolution. When GW losses are large, the **circumbinary disc** will not follow the evolution and the binary will evolve in very tenuous gas. This could then produce an EM emission **BEFORE** the merger.



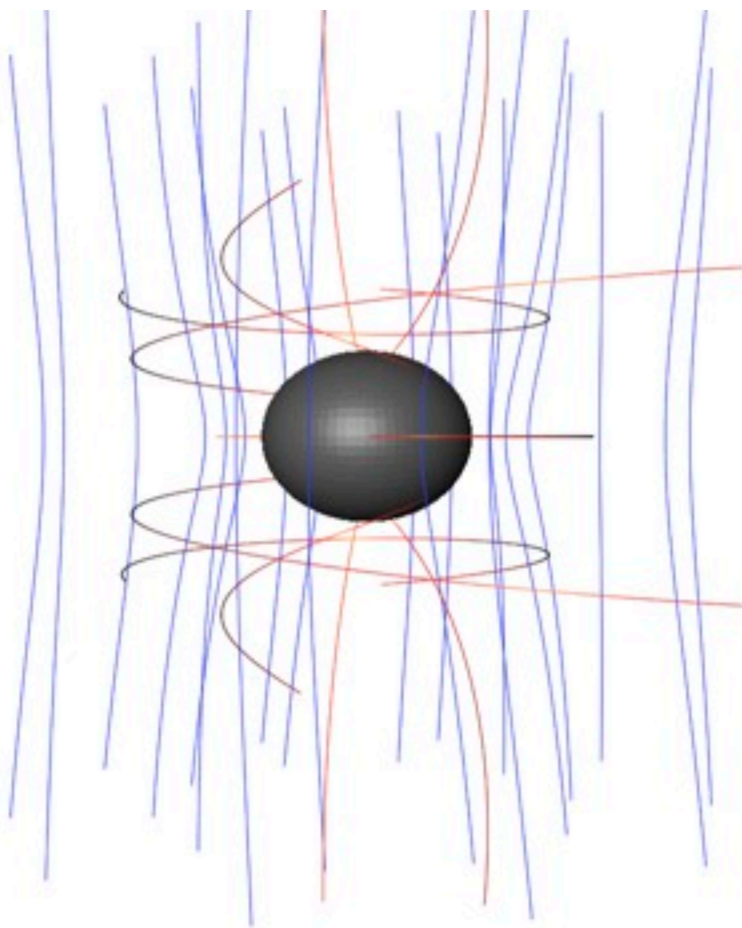
The massive **circumbinary disc** will follow the binary during the slow viscous evolution. When GW losses are large, the **circumbinary disc** will not follow the evolution and the binary will evolve in very tenuous gas. This could then produce an EM emission **BEFORE** the merger.

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

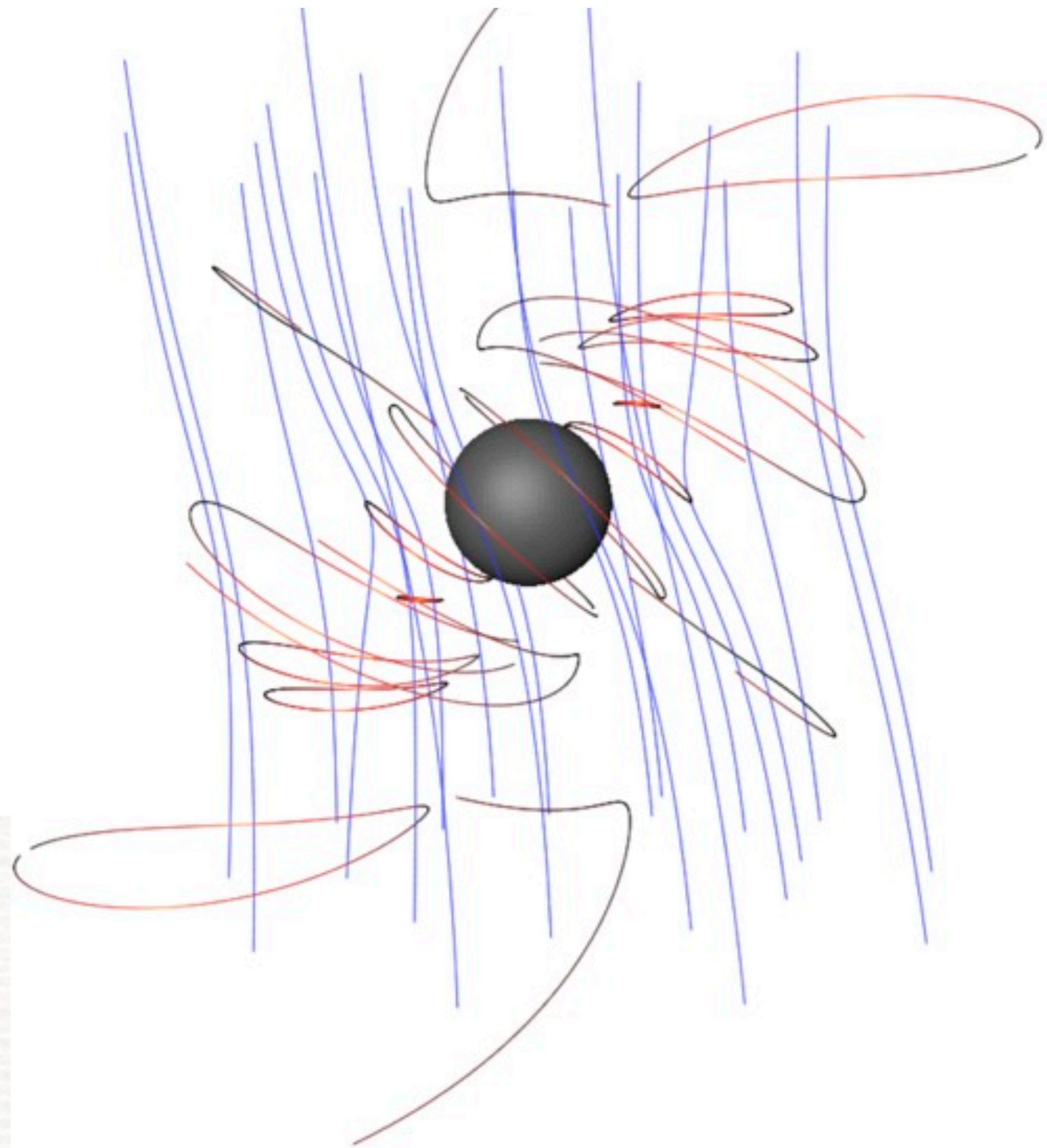


We have solved the full set of Einstein and Maxwell eqs in vacuum and computed the EM emission

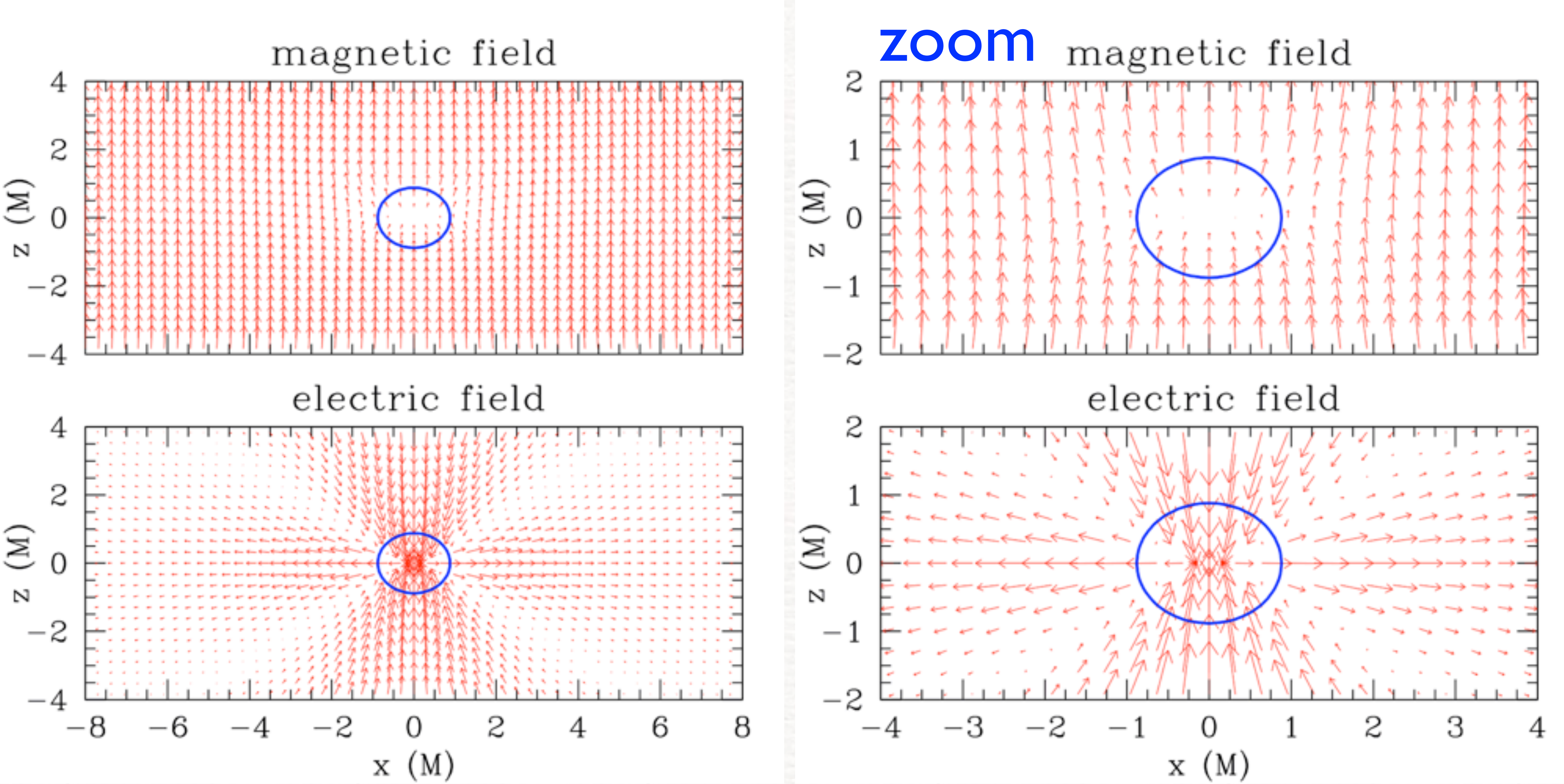
First a single BH in a uniform magnetic field



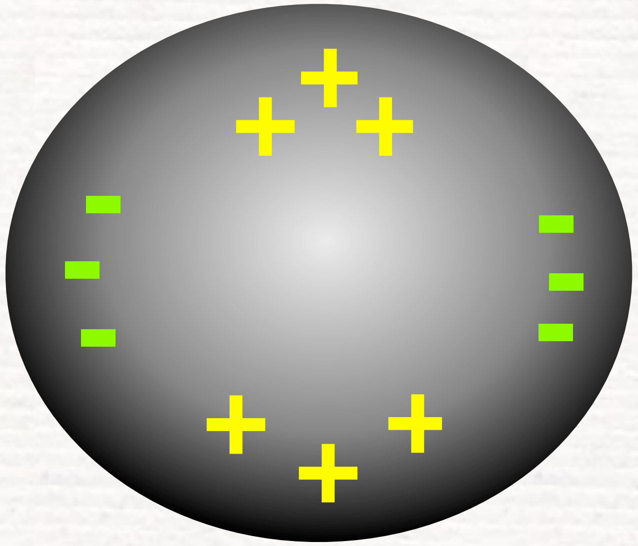
The magnetic field lines (blue) are distorted by spacetime curvature near the BH, while the electric field (red) is dragged by the spin (a=0.7)



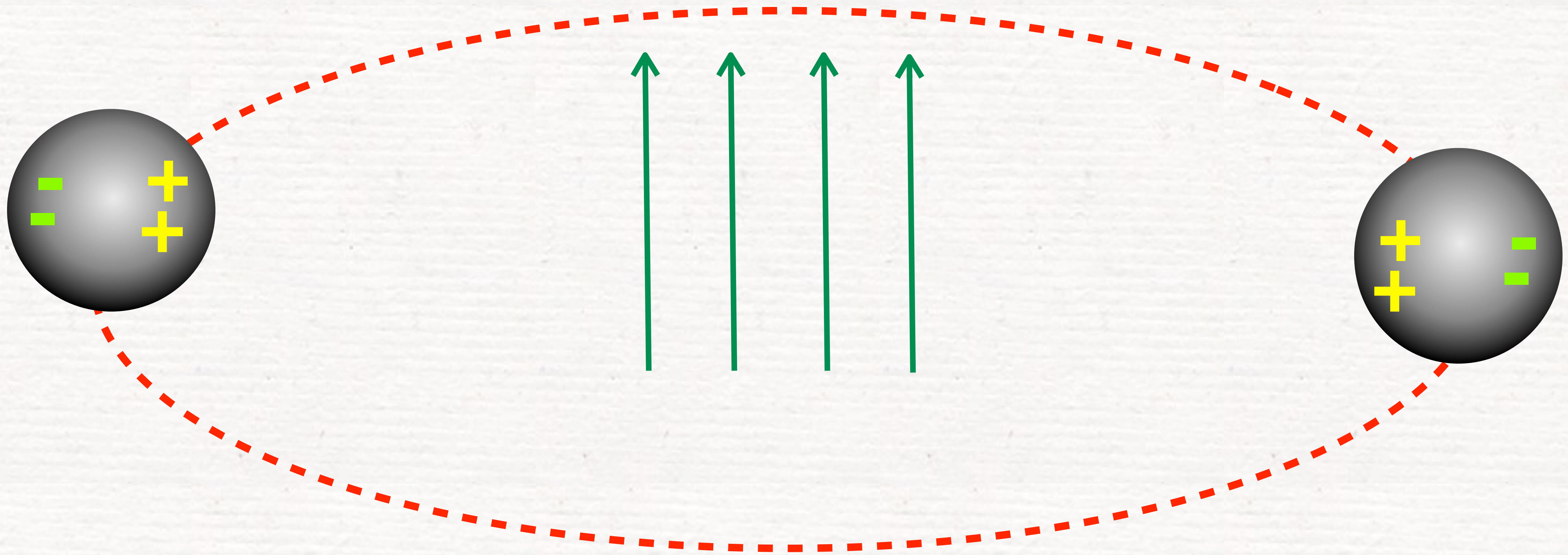
More complicated structure of EM fields for inclined spin



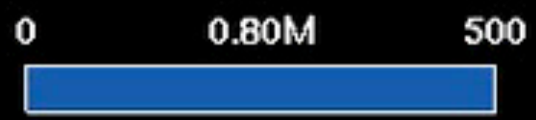
As in the "membrane paradigm", a rotating BH in a B-field generates an effective charge: **+** at the poles, **-** at the equator yielding a quadrupolar electric field



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

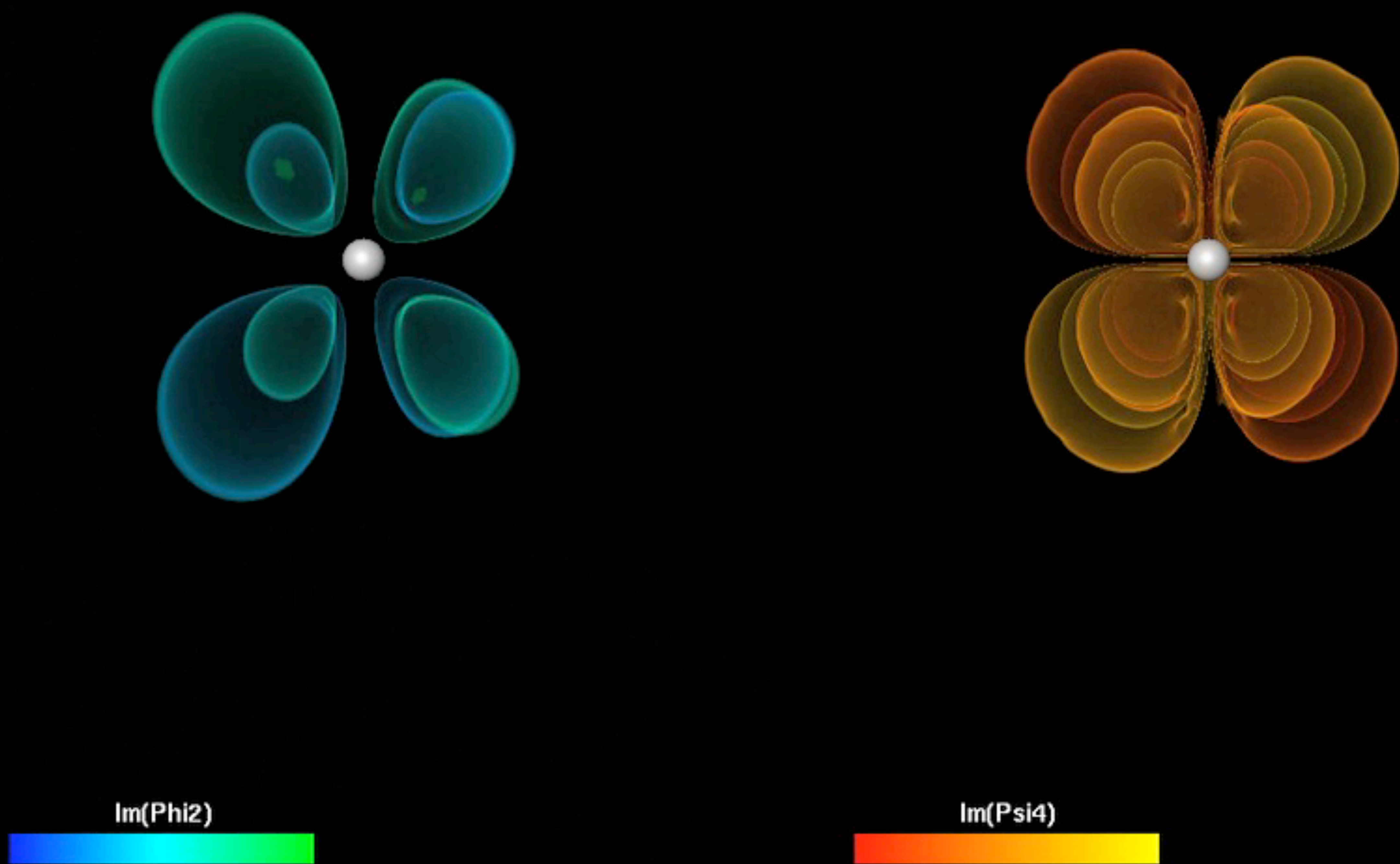


The two BHs are therefore like two dipoles moving in a magnetic field: they will produce a quadrupolar EM radiation. This has the same multipolar structure of GWs!



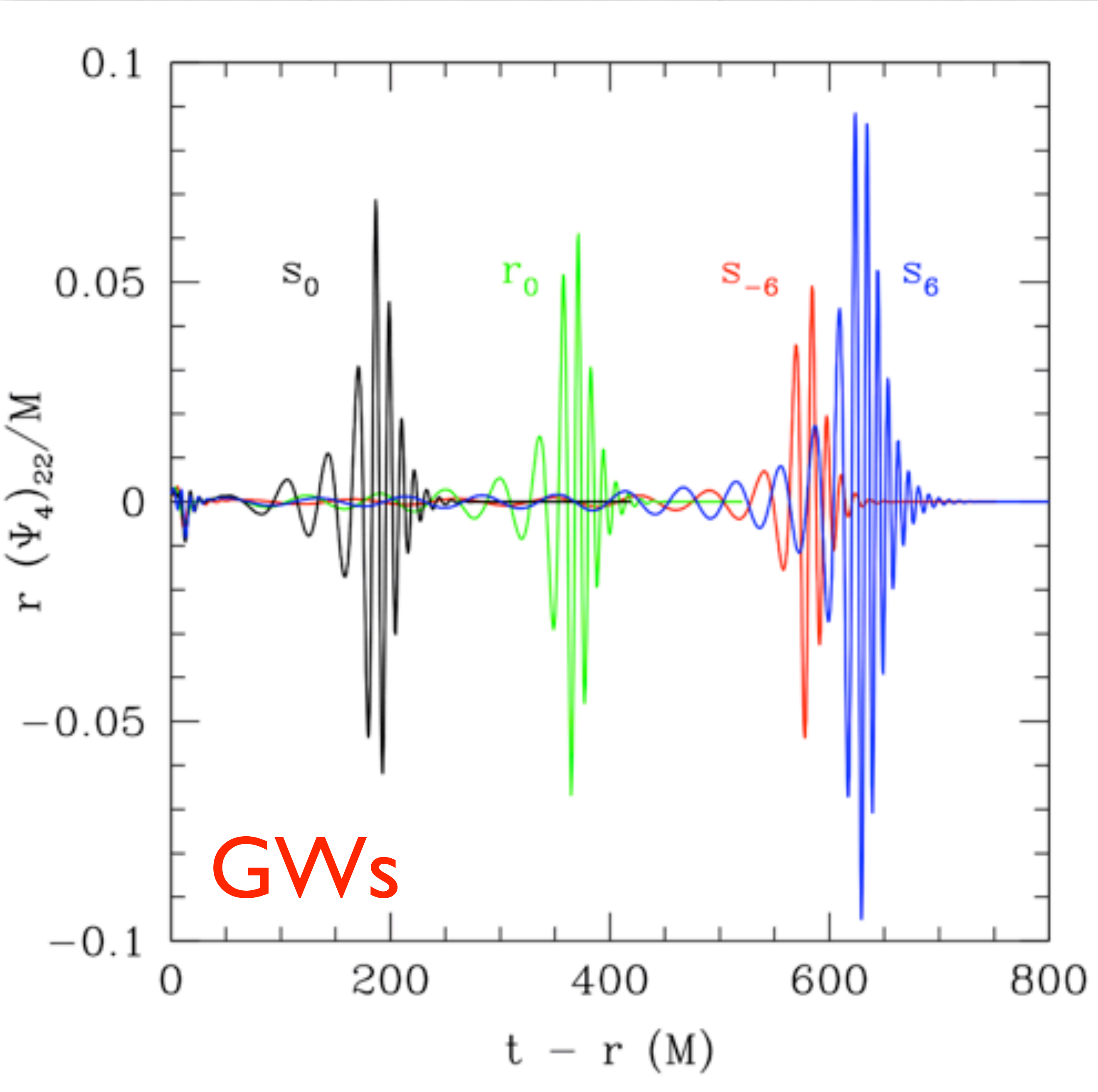
Animations: Koppitz, LR Moesta

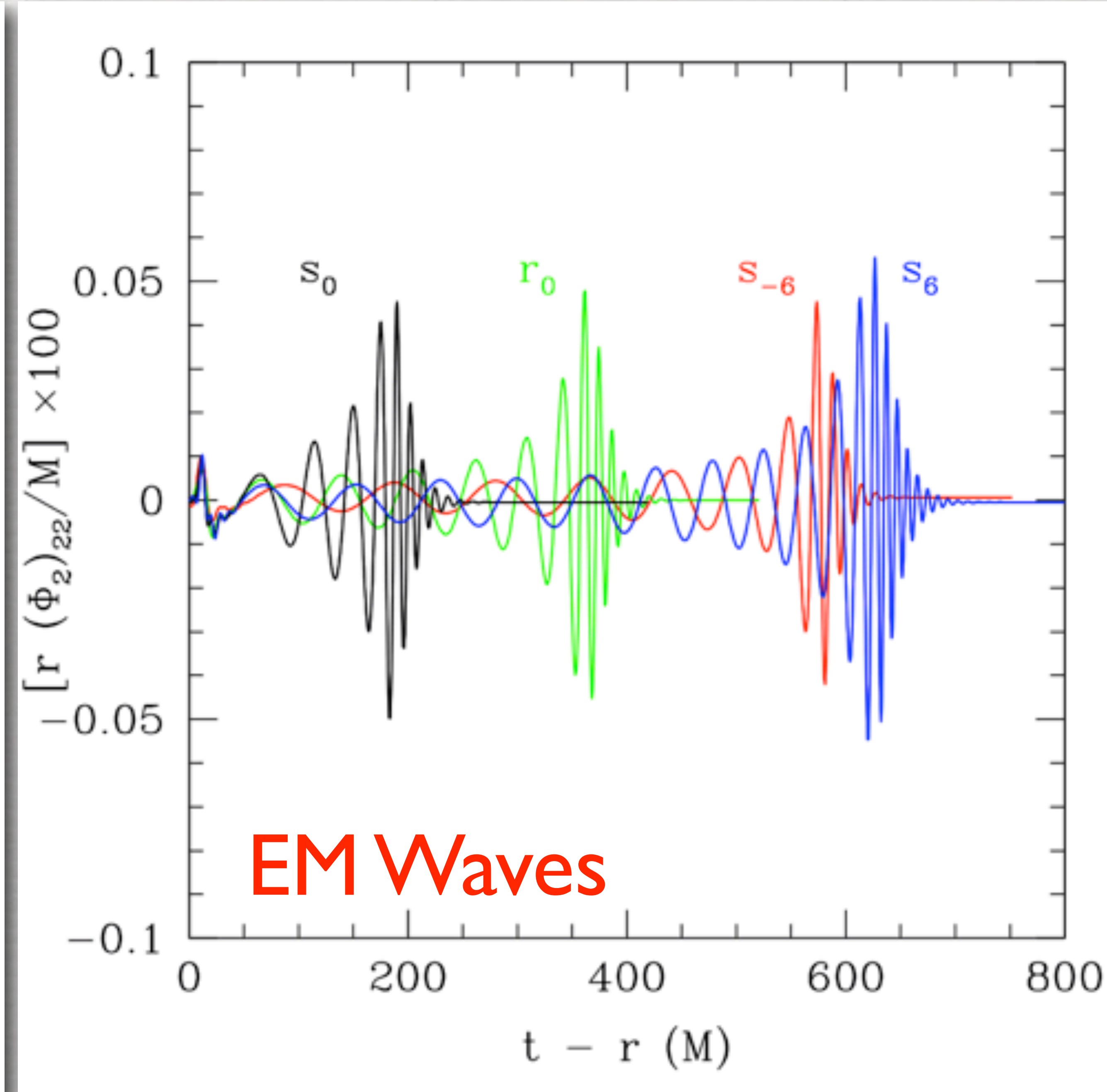
Simulation of an equal mass binary system with nonspinning BHs: left part measures EM fields, right one measures GWs

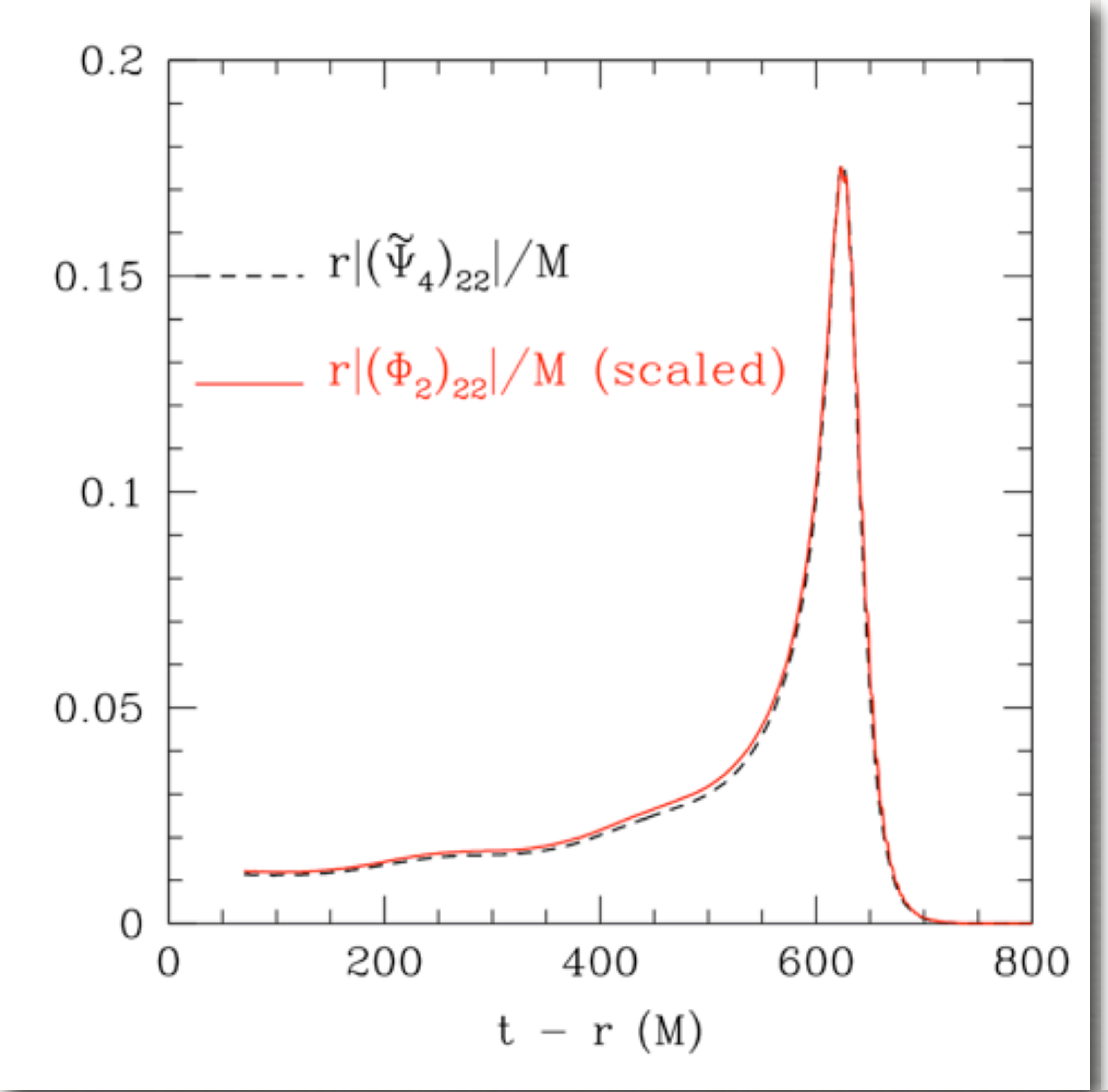


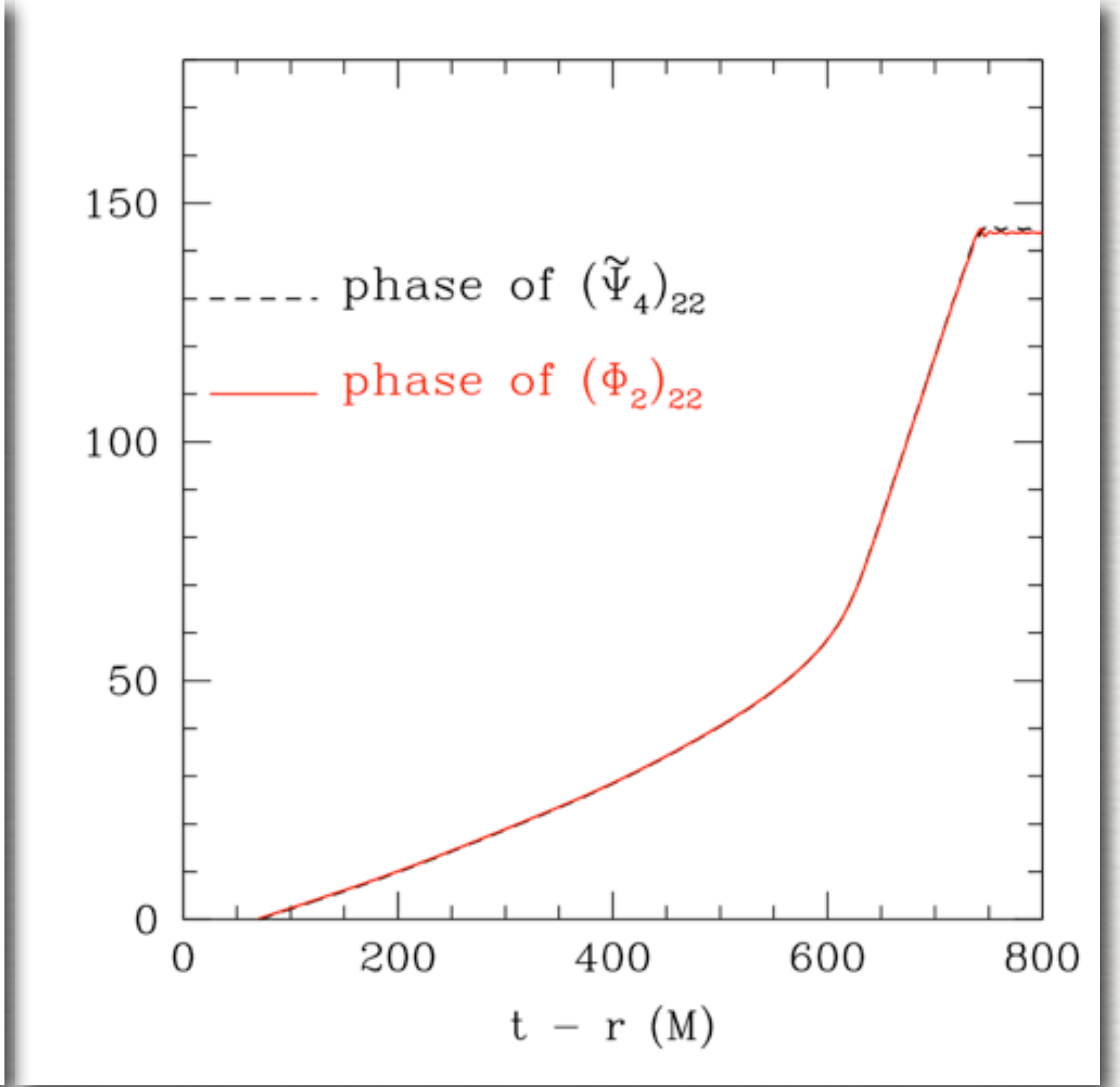
GW, EM radiation computed via Newman-Penrose scalars, ie projection of the Weyl curvature scalar and Faraday tensor onto outgoing null tetrad

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









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?

$$\frac{E^{\rm rad}_{\rm EM}}{M} \simeq 10^{-11} \left(\frac{M}{10^8\ M_\odot}\right)^2 \left(\frac{B}{10^4\ {\rm G}}\right)^2 ,$$

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

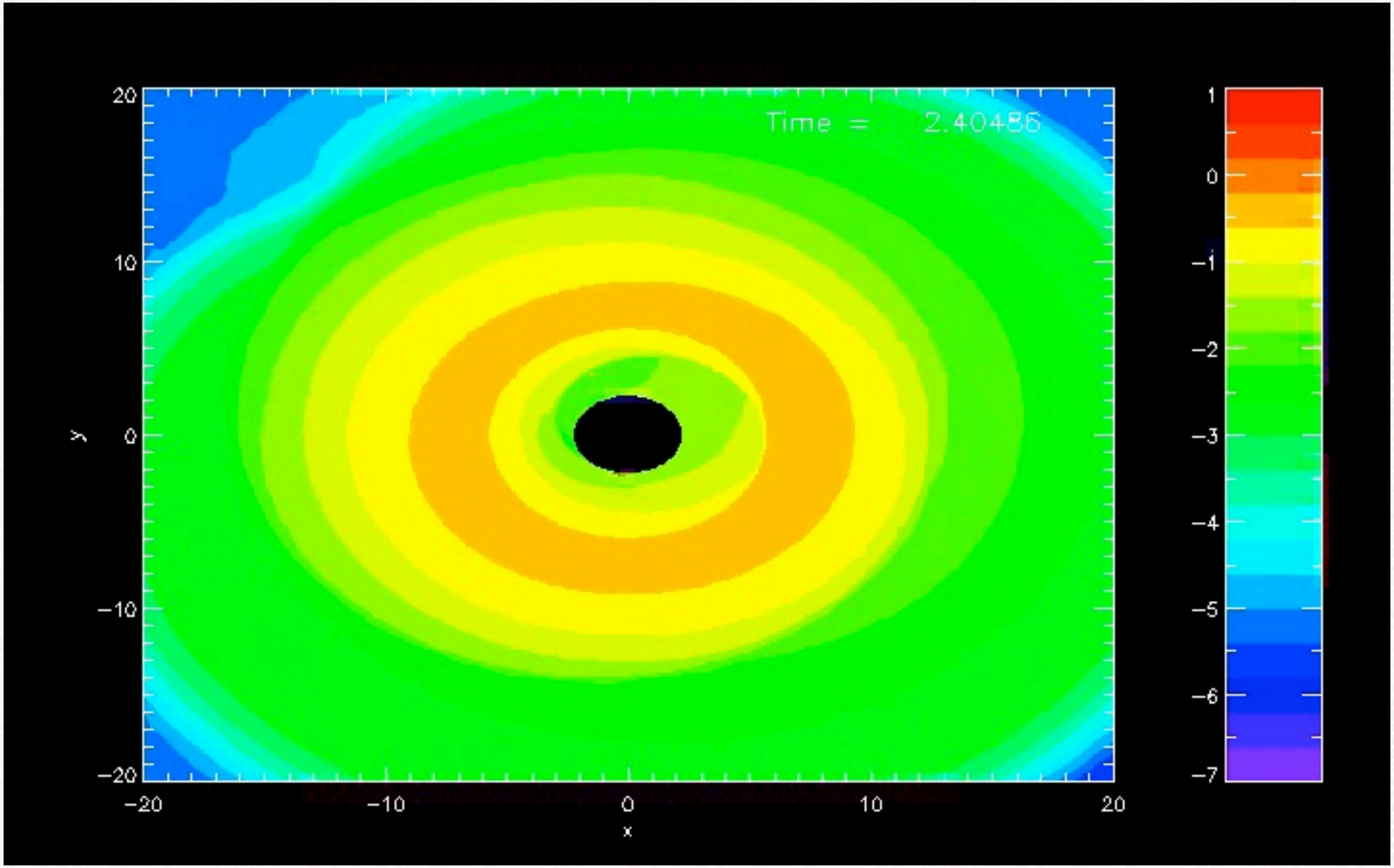
$$\frac{E^{\rm rad}_{\rm EM}}{E^{\rm rad}_{\rm GW}} \simeq 10^{-9} \left(\frac{M}{10^6\ M_\odot}\right)^2 \left(\frac{B}{10^4\ {\rm G}}\right)^2 .$$

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

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

EM counterparts: post-merger

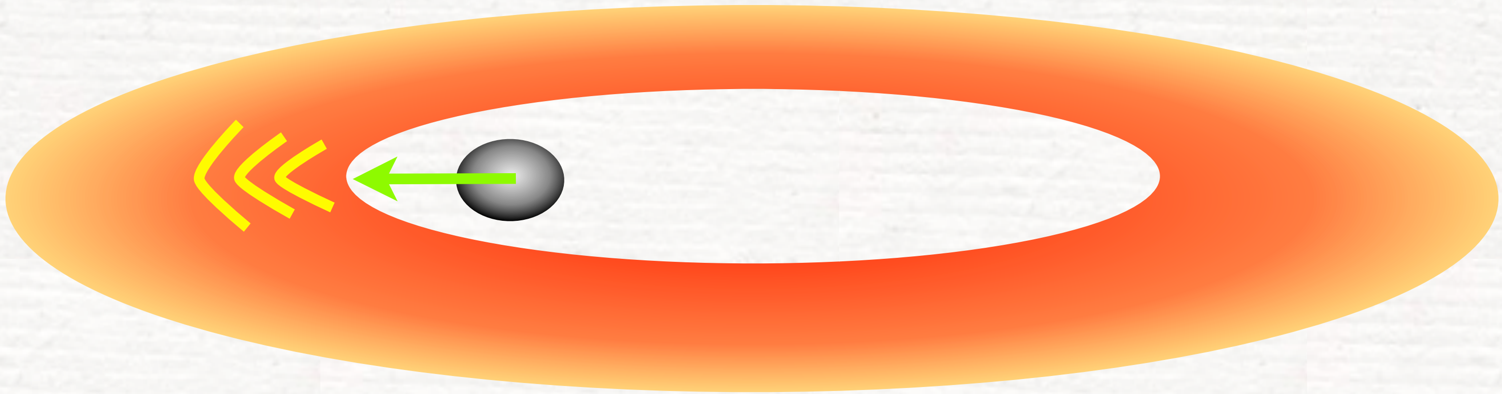
Zanotti, et al., A&A (2010)



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 et al 2008; O'Neill et al 2009; Megevand et al 2009; Corrales et al 2009; Rossi et al 2009

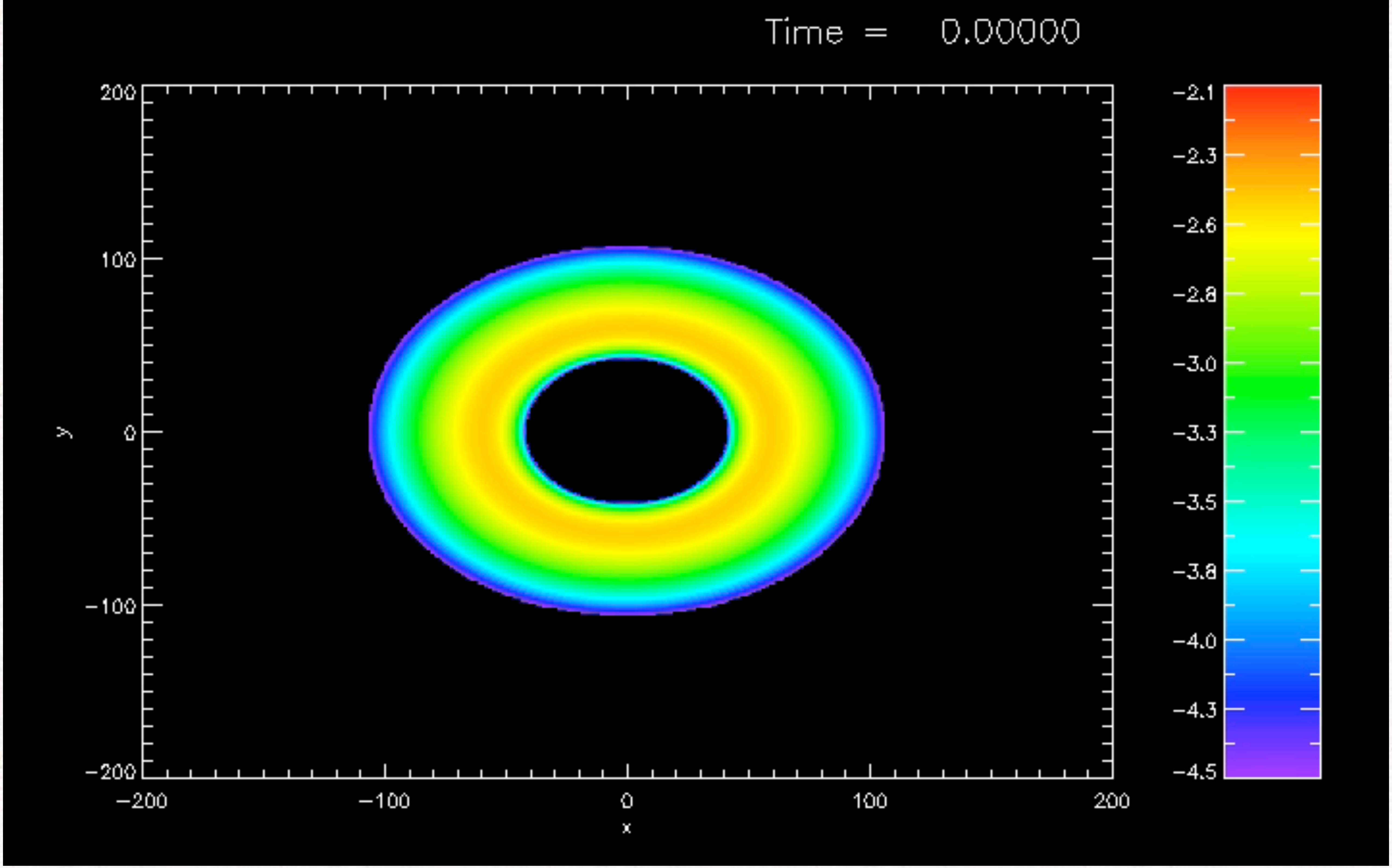


Pros of our approach:

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

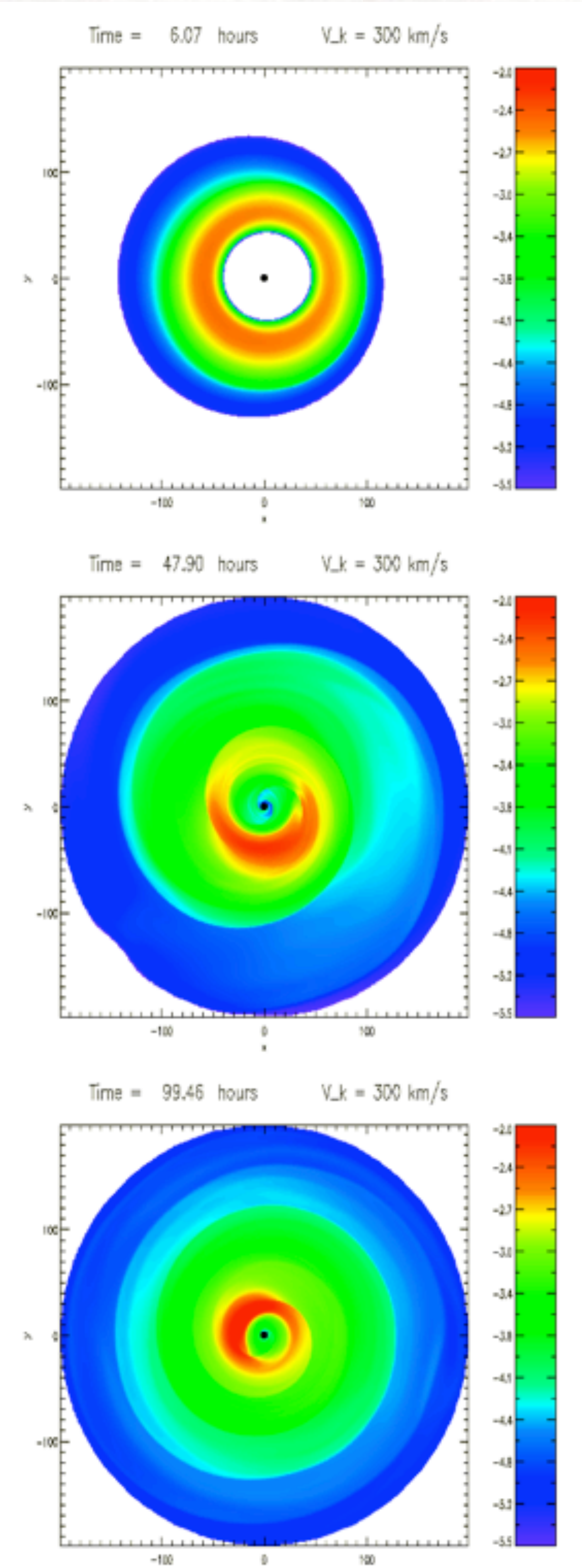
Cons of our approach:

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



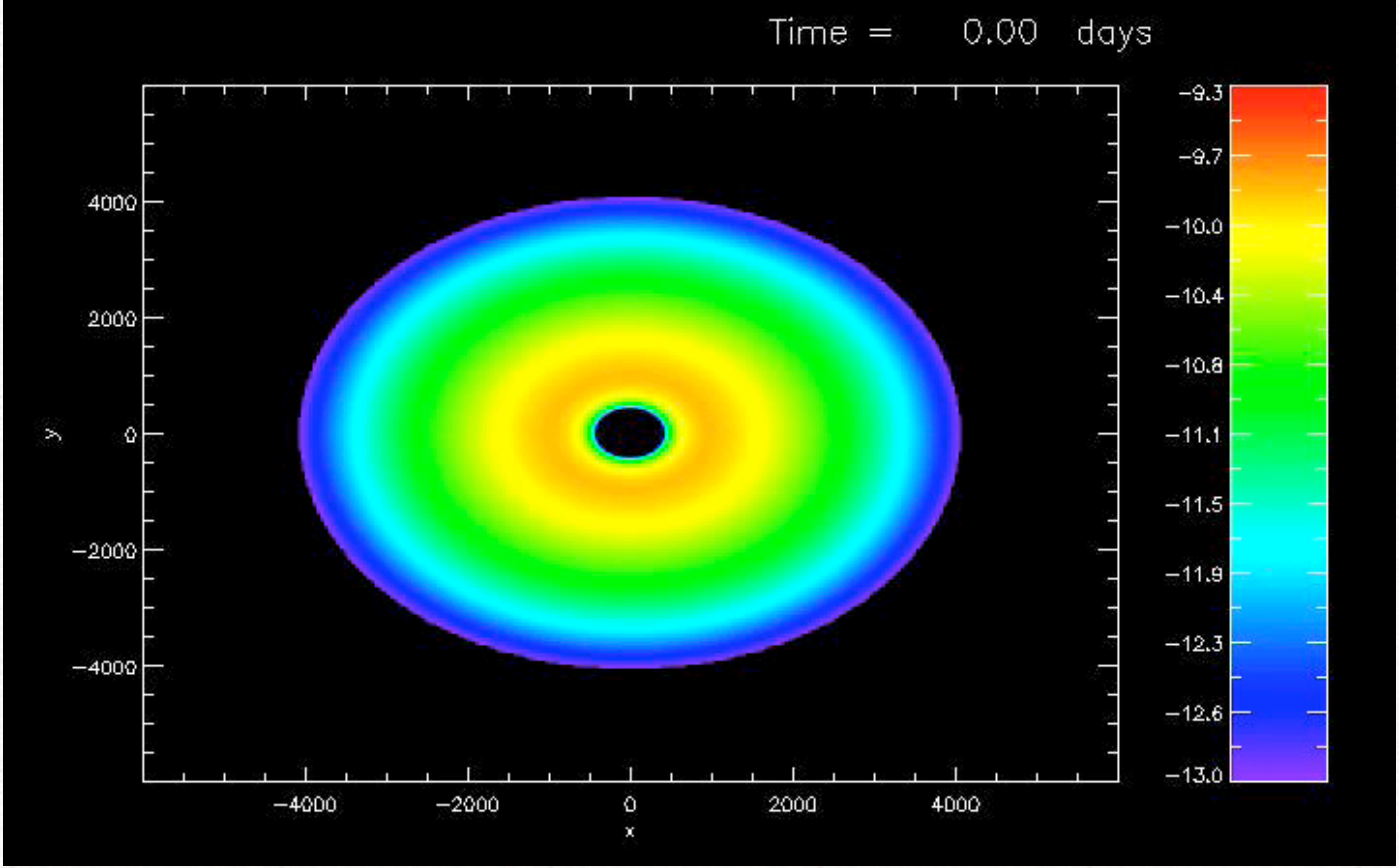
Small disc and recoil of 500 km/s.

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



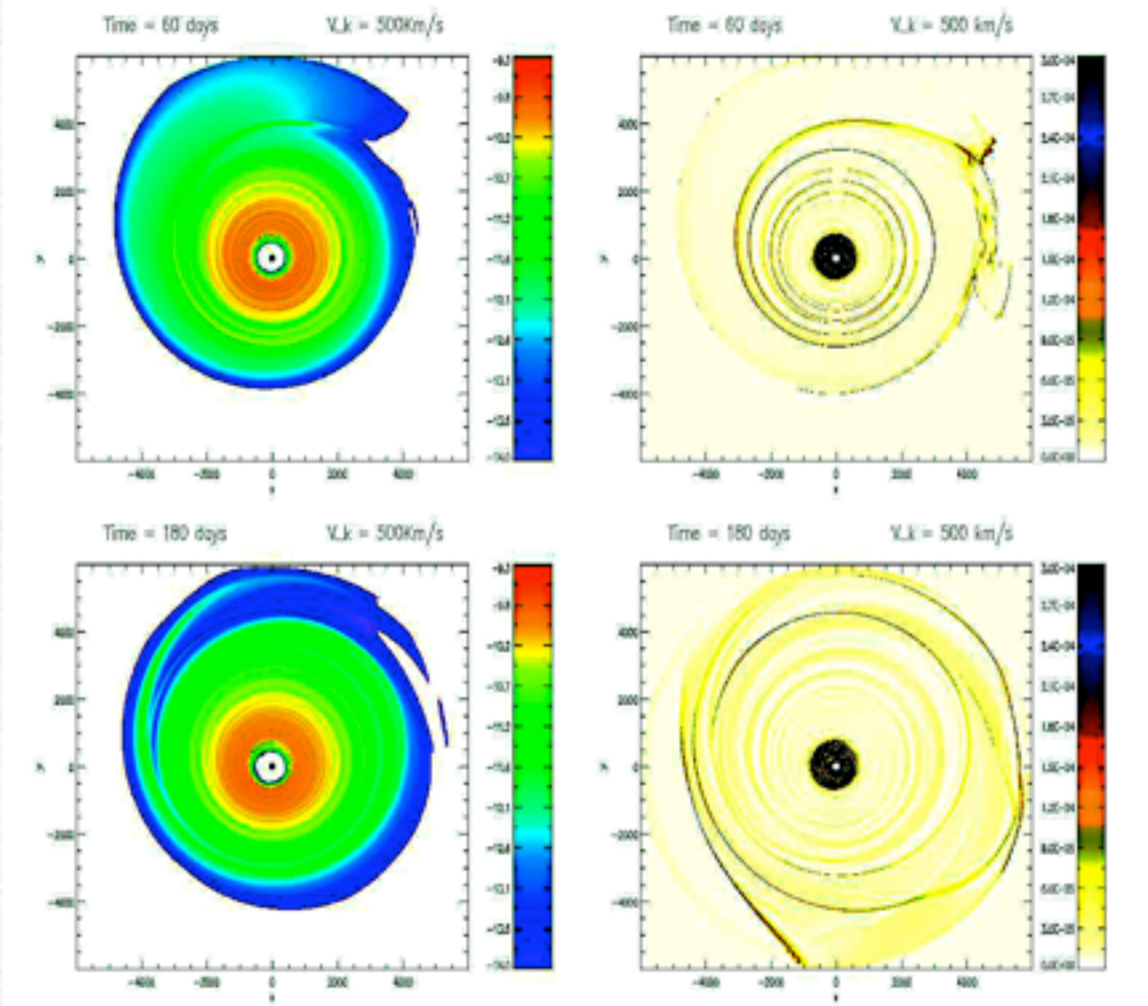
Small disc and kick of 500 km/s

- 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)

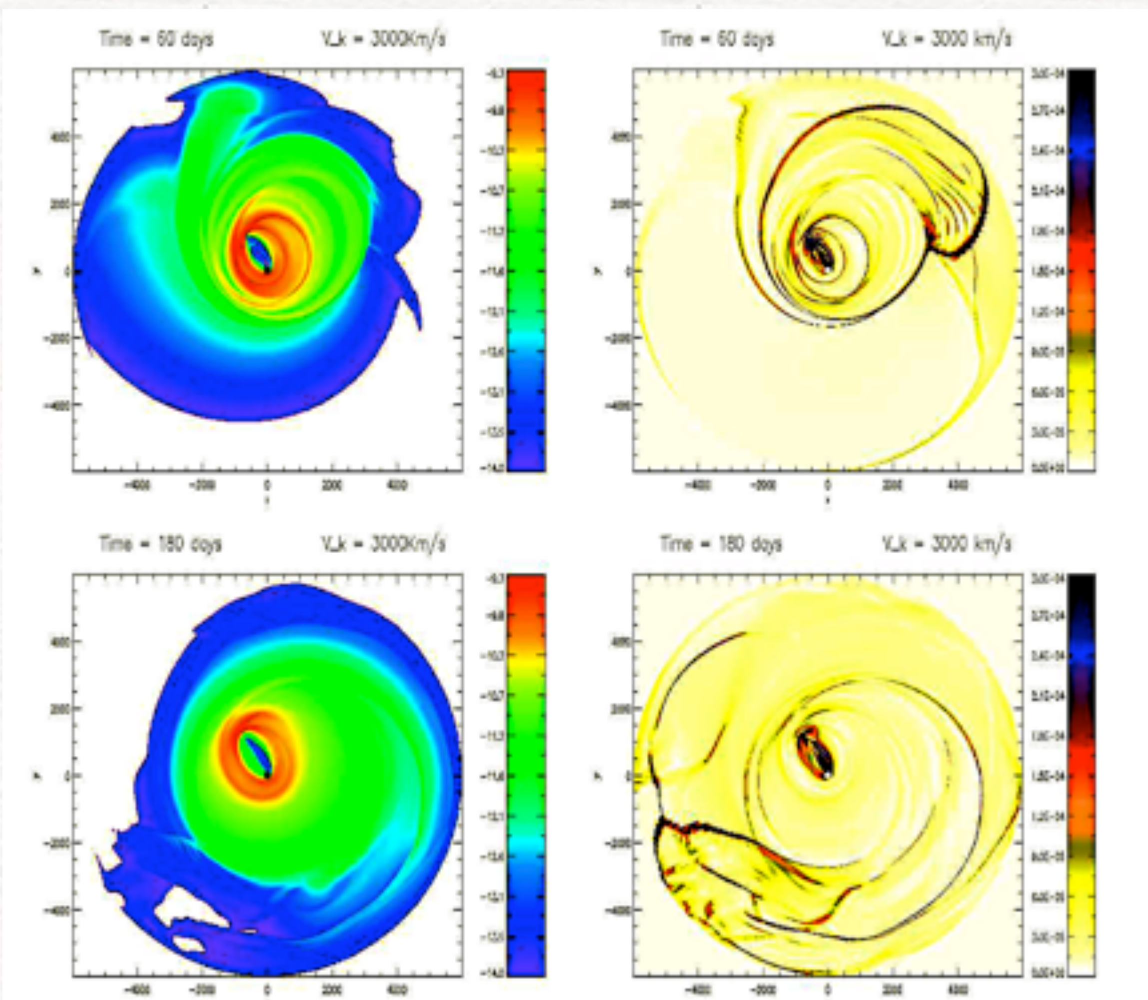


Large disc and recoil of 3000 km/s.

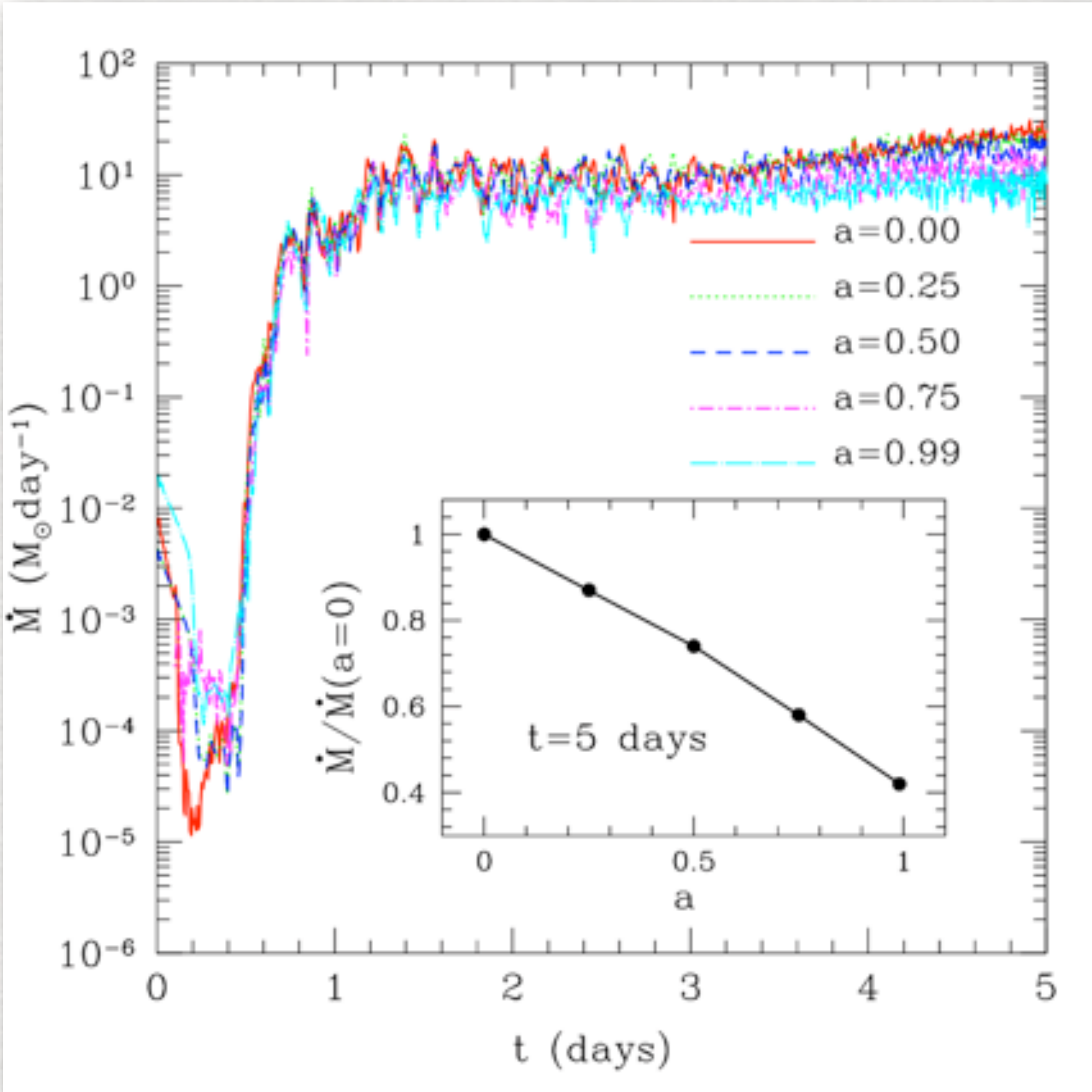
Time is in days for a BH of mass~ $10^6\,M_\odot$



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

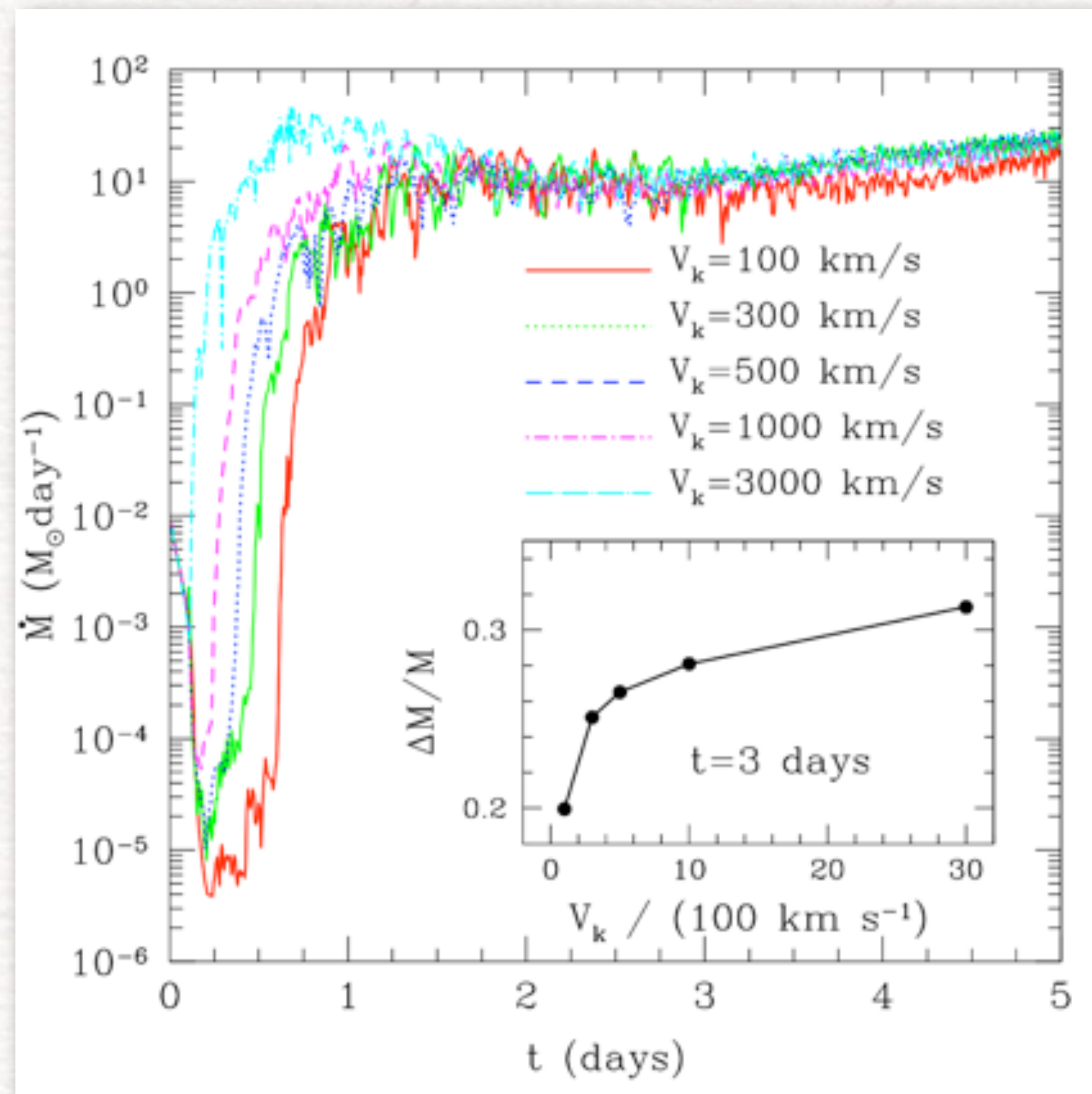


Large disc and kick of 3000 km/s: the spiral structure is never formed although strong shocks appear



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

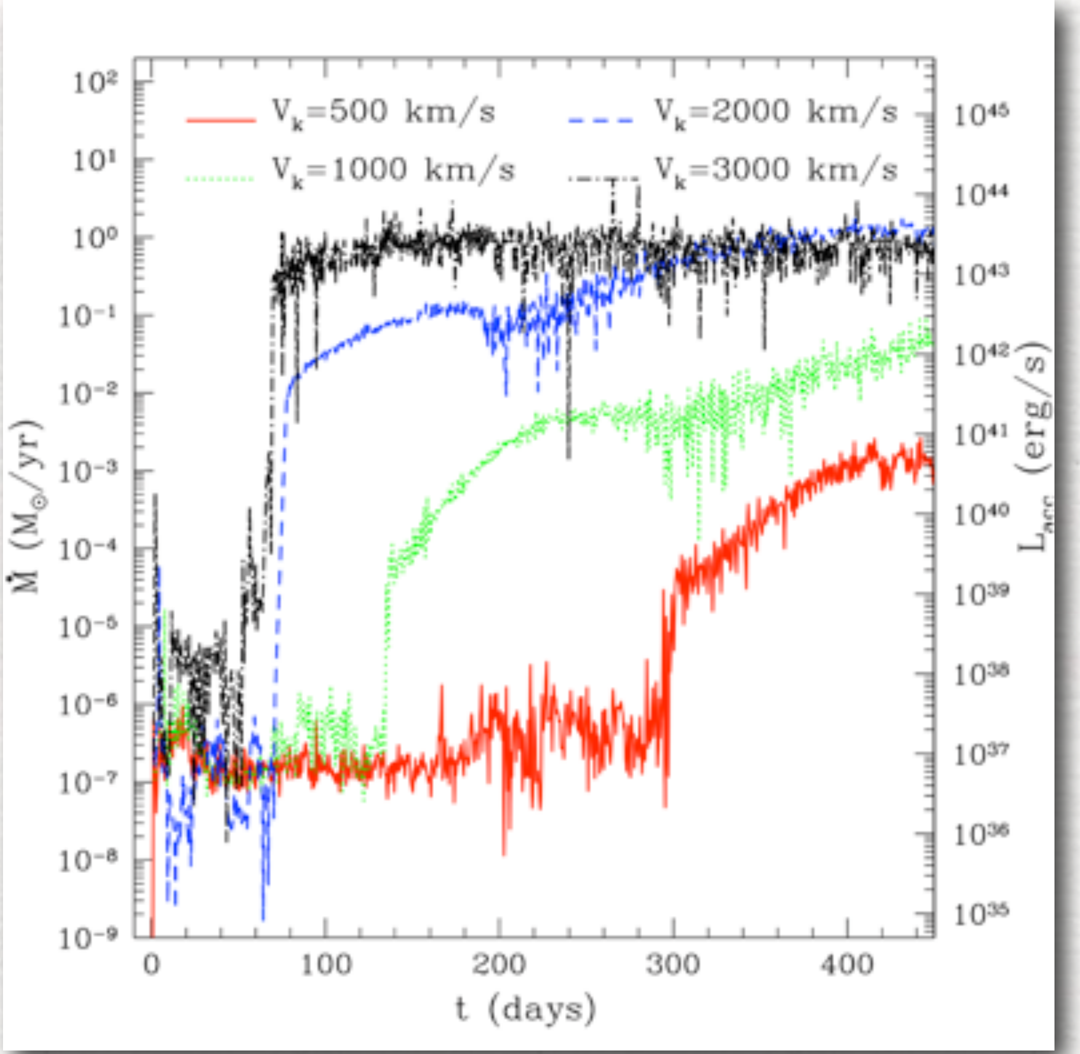
- the spin has little influence on the disc but the accretion rate is smaller for rapidly spinning BHs
- a larger kick anticipates the increase in the accretion rate and the total mass accreted



Luminosities

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

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



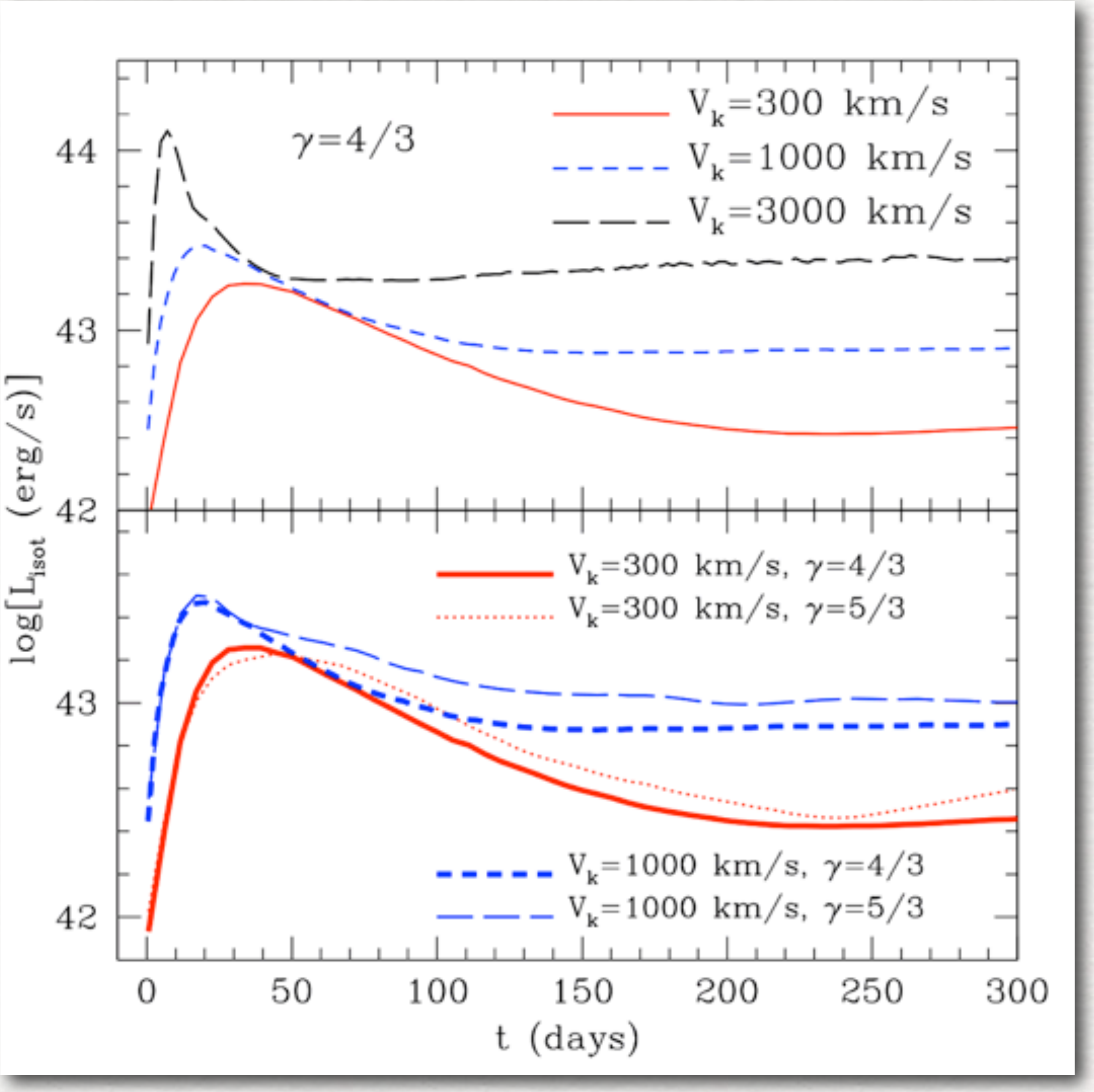
This estimate is popular but not realistic: cooling times of ~ few sec!

Another simple estimate comes from the accretion luminosity

$$L_{\rm acc} = \eta \dot{M} c^2 \simeq 0.001 \dot{M} c^2$$

again unrealistic since no radiation transfer is taken into account and the flow is therefore super-Eddington

Main results



- A more accurate estimate of the luminosity assumes all the changes in temperature due to a compression will be dissipated as radiation (cf 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.

Summary

✶Mapping initial binary to final spin/recoil is done to % precison

✶Aligned BH binaries are reasonably well understood

- space of parameters is degenerate for antialigned configs
- 50% of spinning binaries can be detected as nonspinning
- ↑↑ are 3 times louder than ↓↓: 30 times more likely to be detected

✶EM counterparts associated to mergers:

- A lot of work has already been done: mostly what is doable
- 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. However, more physics is needed.
- need to go from "*doing what is doable*" to "*doing what is realistic*"

Our ability of computing EM counterparts is only as good as our models for the initial conditions: we need more astrophysics input