Supermassive black hole binaries

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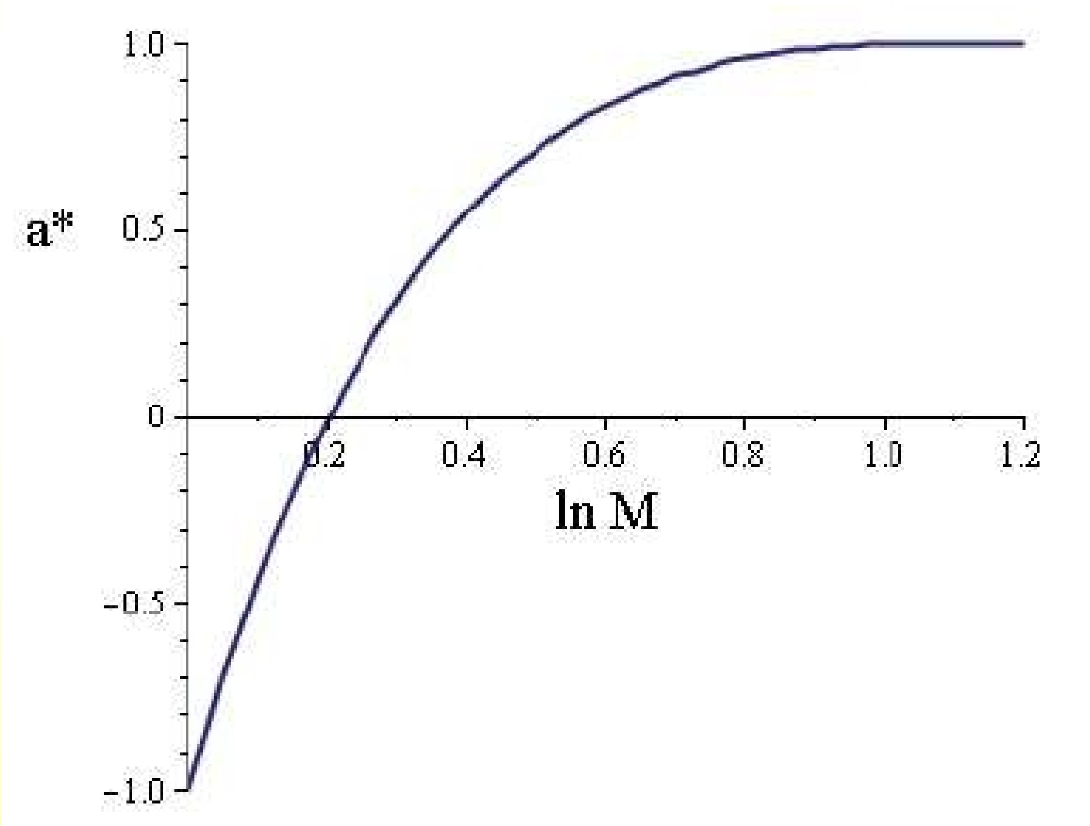
BHs rotate fast due to accretion

Bardeen accretion spins up BHs.

Mass increase by a factor of 3, when changing BHs spin from maximal counter-rotation to maximal rotation.

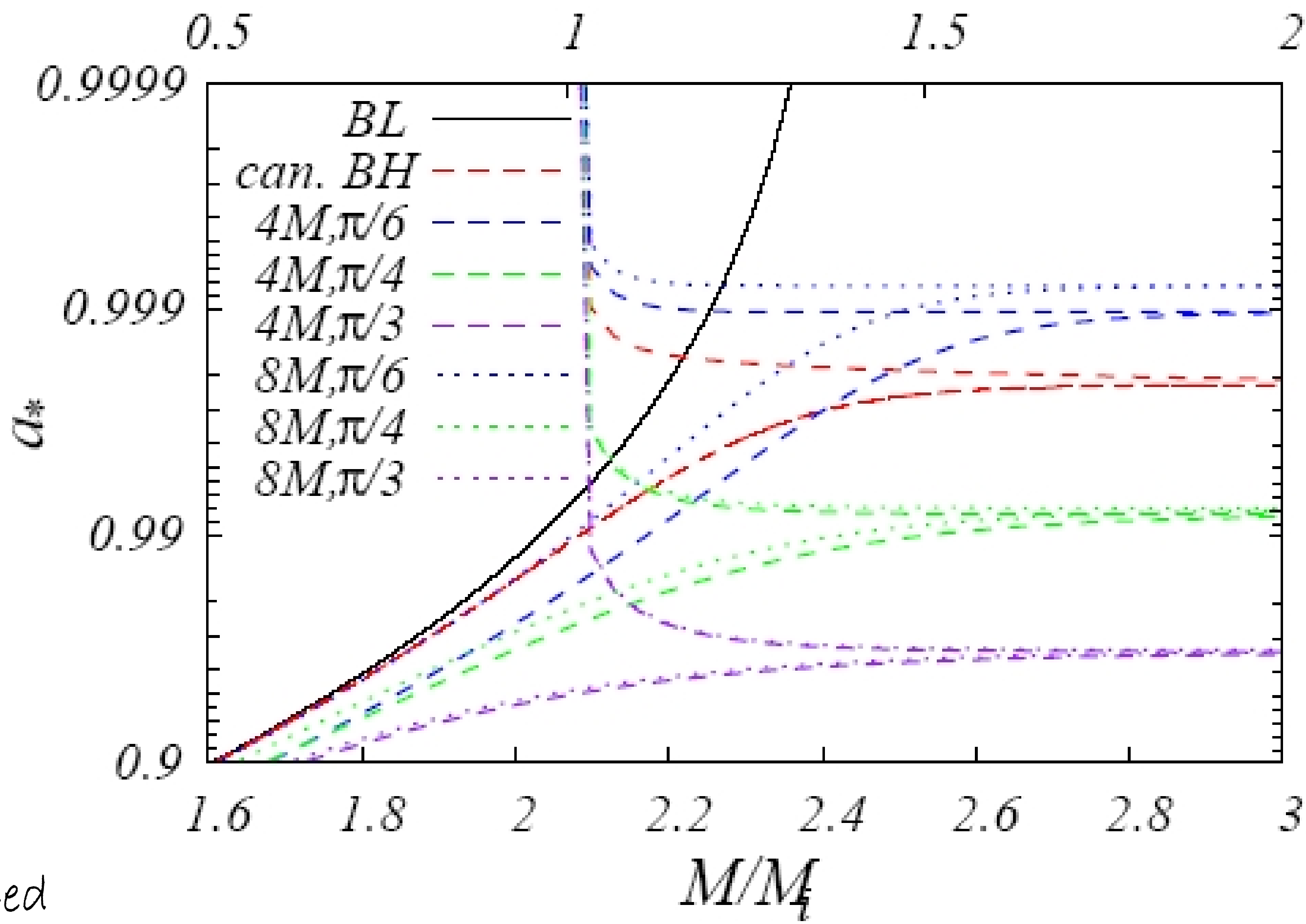
Efficiency of accreted rest mass conversion into outgoing electromagnetic radiation is 42.3%.



Accretion and efficiency refined

Corrections from:

- photon capture
- open and closed magnetic fields
- inner truncation of the disk due to a jet



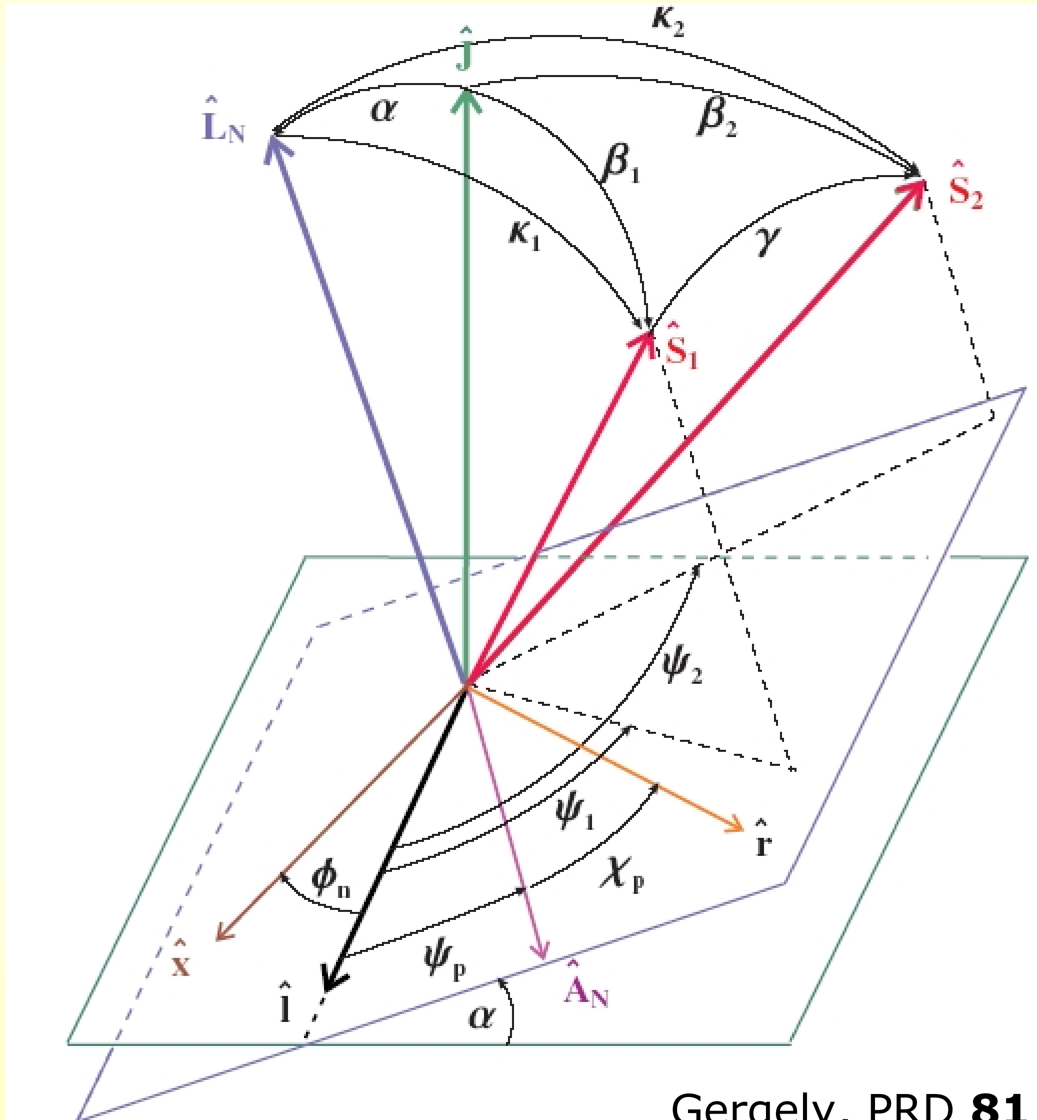
Spin limit

slightly reduced

Efficiency reduced to 25% - 35 %

Kovács, Gergely, Biermann, in preparation (2010)

A multitude of parameters



Gergely, PRD **81** 084025 (2010)

Conservative evolution

Independent variables:

1. orbital elements: [a_r (or E_N), e_r (or A_N), Euler angles ($-\phi_n$, ψ_p, α)]
2. spin angles [κ_i, ψ_i]
3. masses m_i, dimensionless spins χ_i, total angular momentum J

Keplerian orbits: all conserved

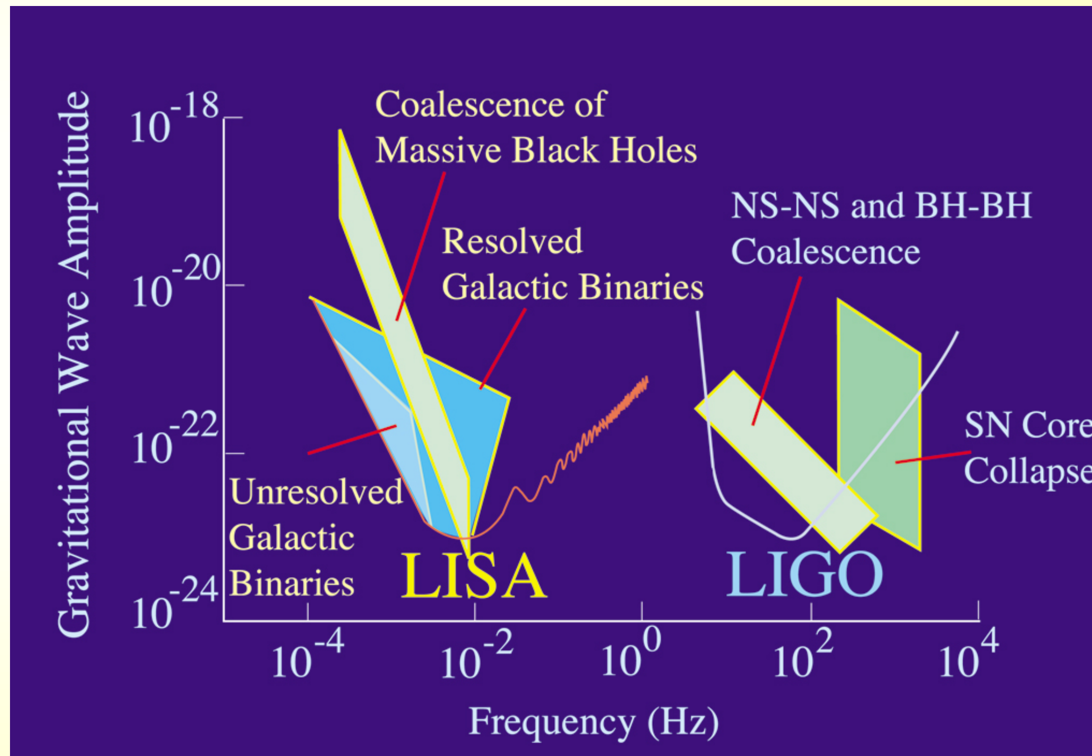
2PN orbits with SO, SS, QM: m_i, χ_i, J conserved; the rest evolve

–> system of first order ordinary differential equations

Gergely, arXiv: 1005.5330

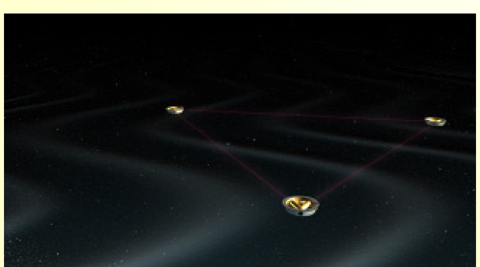
GW detection from BH binaries

2003 LIGO, VIRGO, GEO, TAMA Earth-based interferometric detectors operational (50– 2000 Hz)



2018+ LISA

(10^{-3} - 1 Hz)

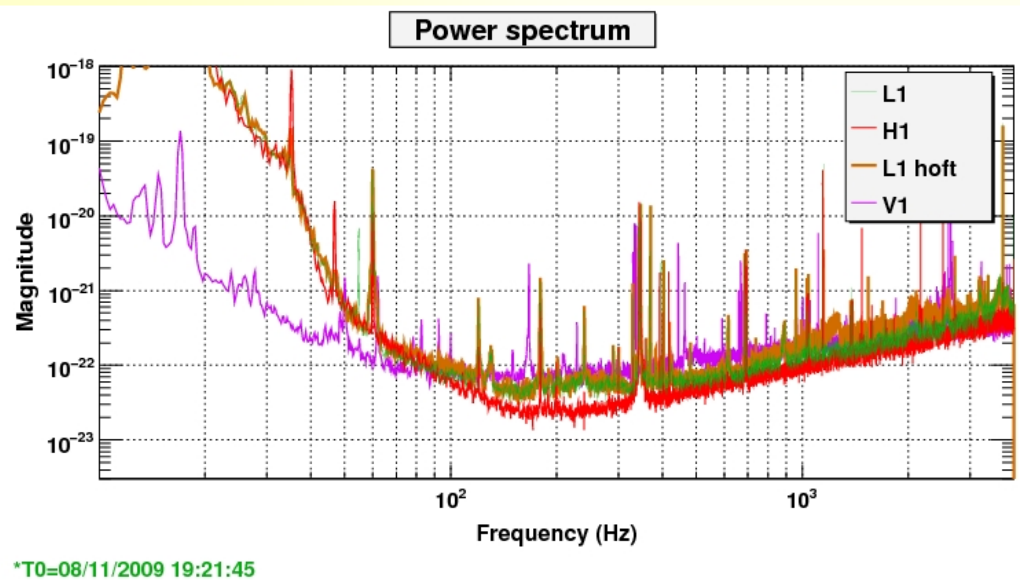


VIRGO

What had LIGO/Virgo not heard yet?

Two black holes, each of 2 ½ solar masses

Scott Hughes, http://web.mit.edu/sahughes/www/sounds.html



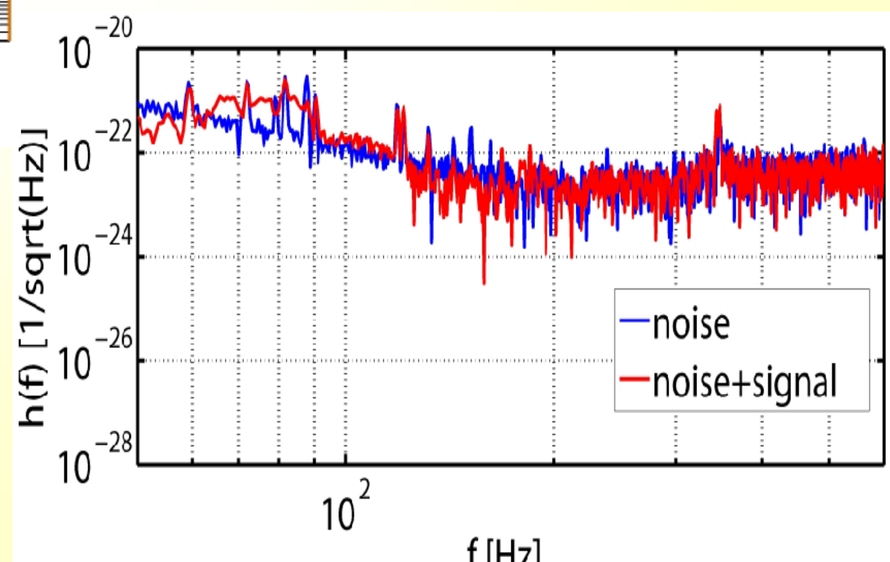
$$f_{wave} = \frac{c^3}{6^{3/2}\pi G M_\odot}\left(\frac{m}{M_\odot}\right)^{-1}$$

$$m_{f_{wave}=2000\ \mathrm{Hz}} = 2.19\,M_\odot$$

$$m_{f_{wave}=600\ \mathrm{Hz}} = 7.31\,M_\odot$$

$$m_{f_{wave}=80\ \mathrm{Hz}} = 54.97\,M_\odot$$

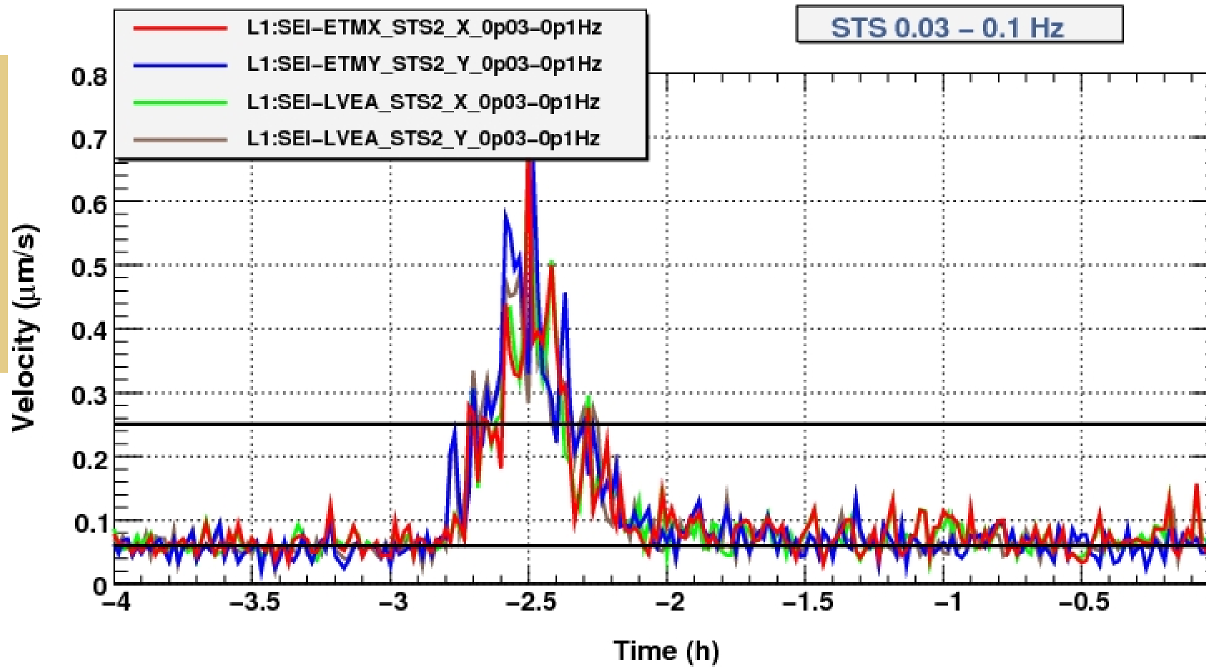
$$m_{f_{wave}=50\ \mathrm{Hz}} = 87.94\,M_\odot$$

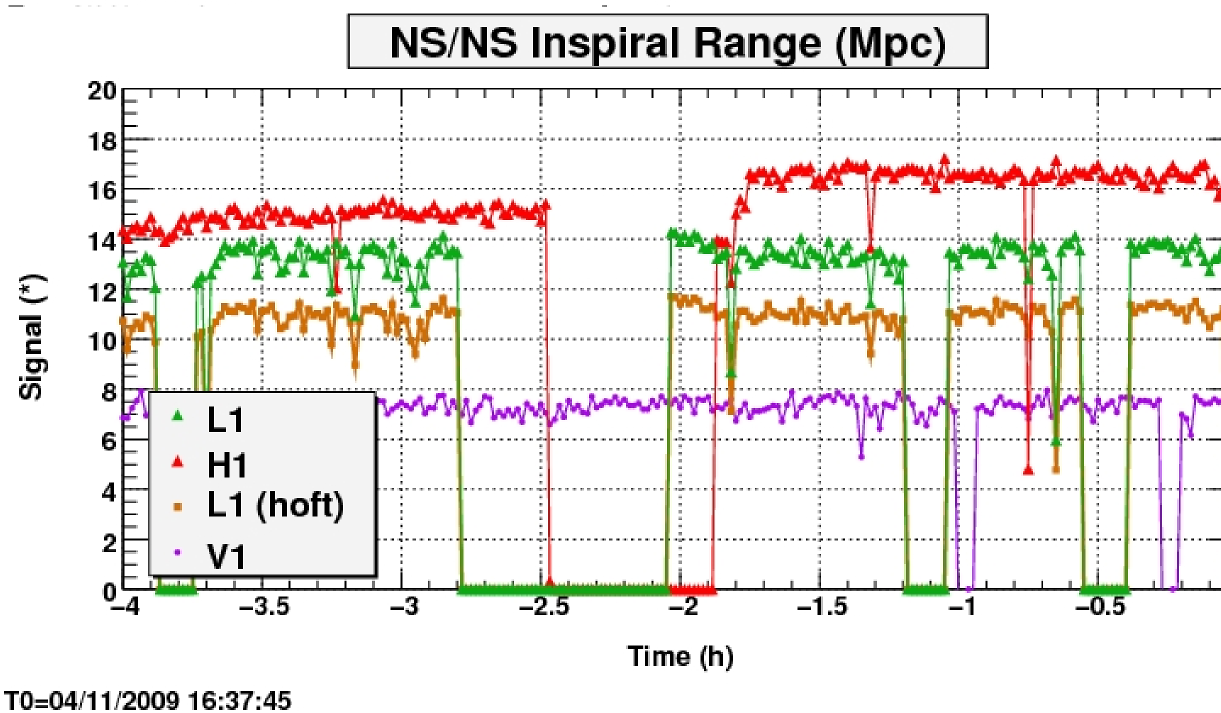


Earthquakes, storms and waves

large sensitivity =
large instability

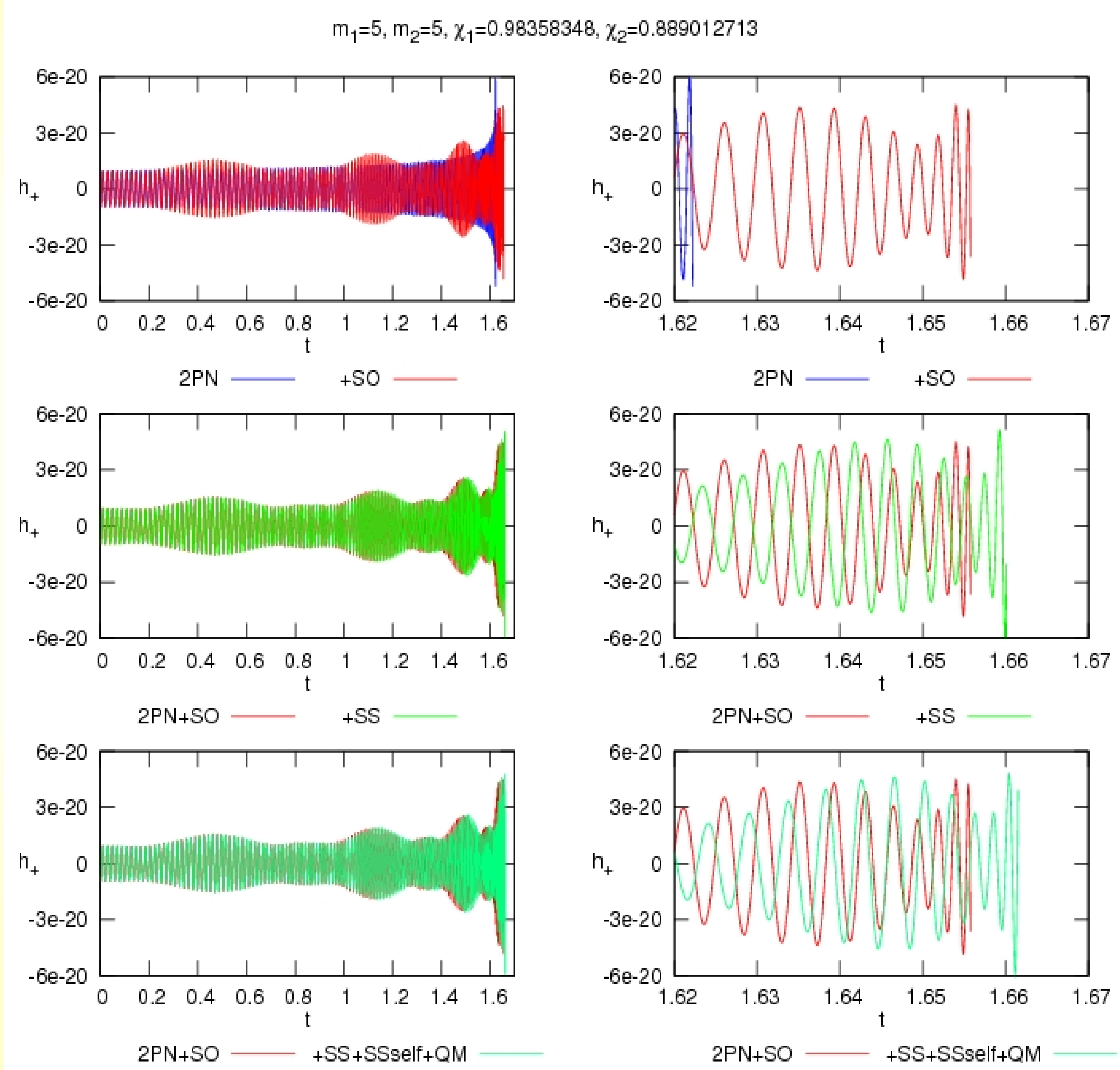
Costa Rica
earthquake
4.9 Richter scale





More accurate waveforms: equal mass

by adding
self-spin
and
quadrupole
-monopole
terms
(both 2PN
contrib.)



Gergely, Veréb, Udvari, Keresztes, Raffai,

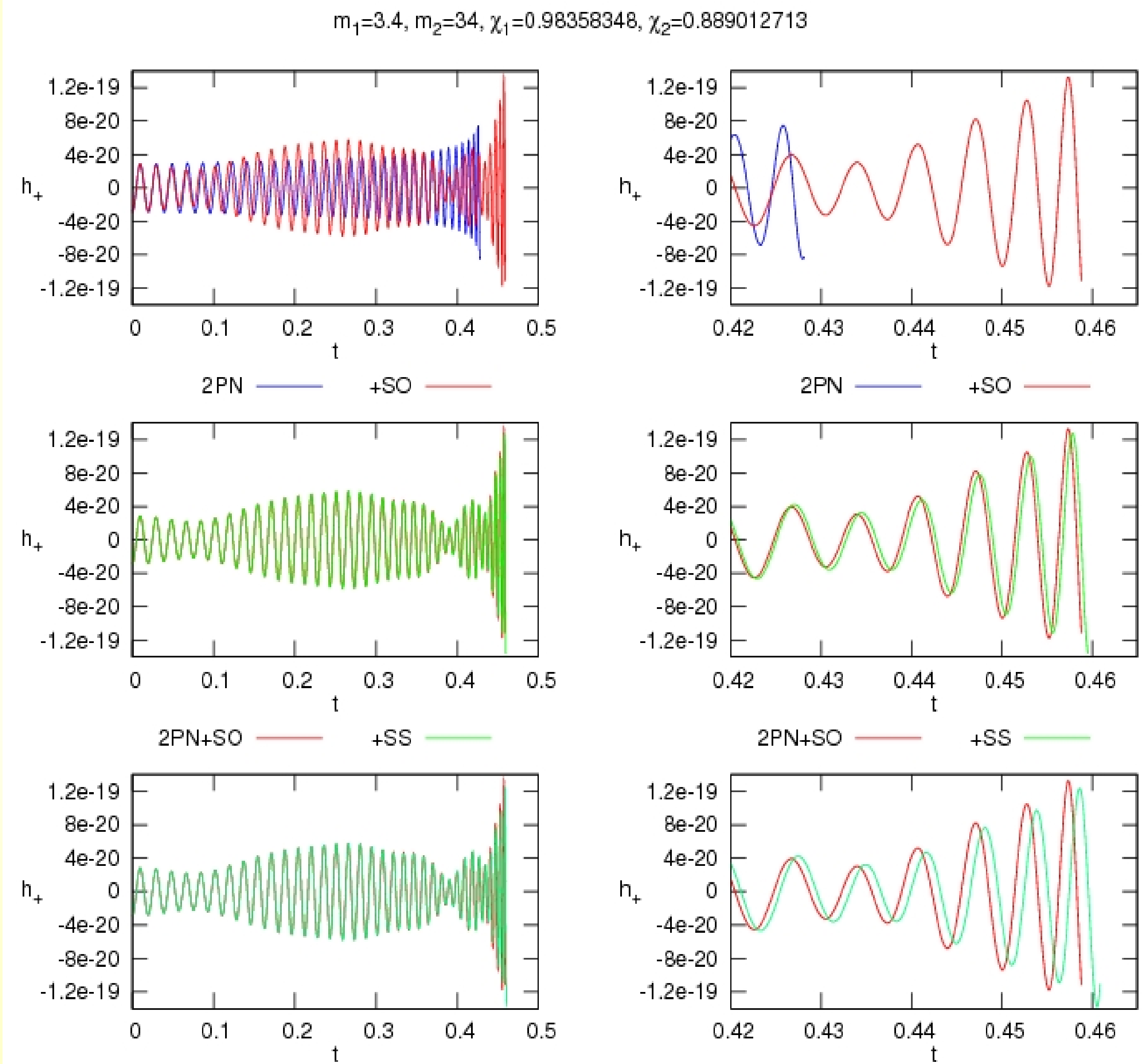
in preparation (2010)

More accurate WFs: unequal mass

by
adding
self-spin
and
quadrupole
-monopole
terms

mass ratio

$\nu=0.1$



Supermassive black hole binaries

- SMBHs are frequent in the Universe, each galaxy has them in the center
- Galaxies collide frequently
- SMBH binaries arise, their dissipative evolution driven by gravitational radiation
- 3 regimes: inspiral, merger/plunge, ringdown
- low mass SMBH binaries, source for

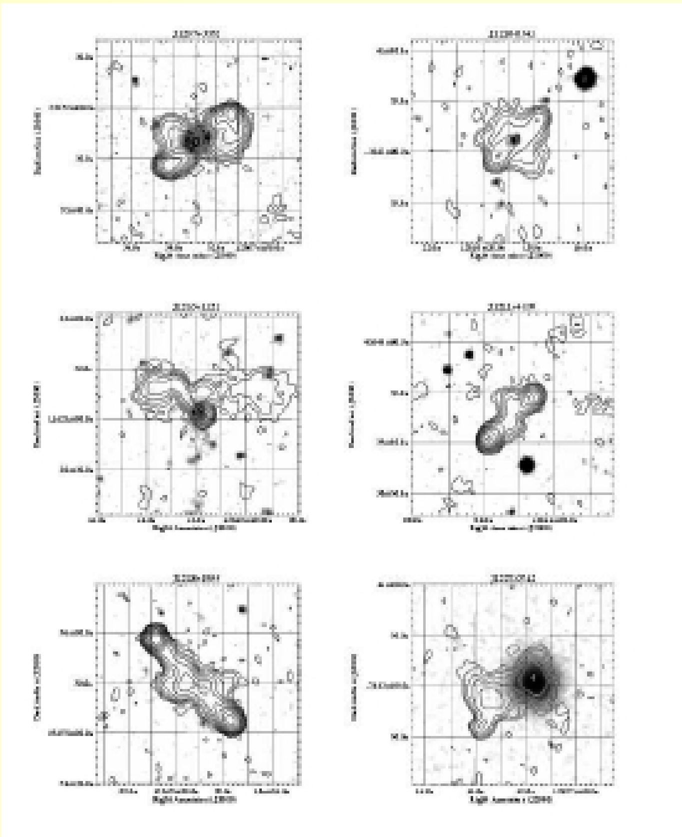
$$f_{wave} = \frac{c^3}{6^{3/2}\pi G M_\odot}\left(\frac{m}{M_\odot}\right)^{-1}$$

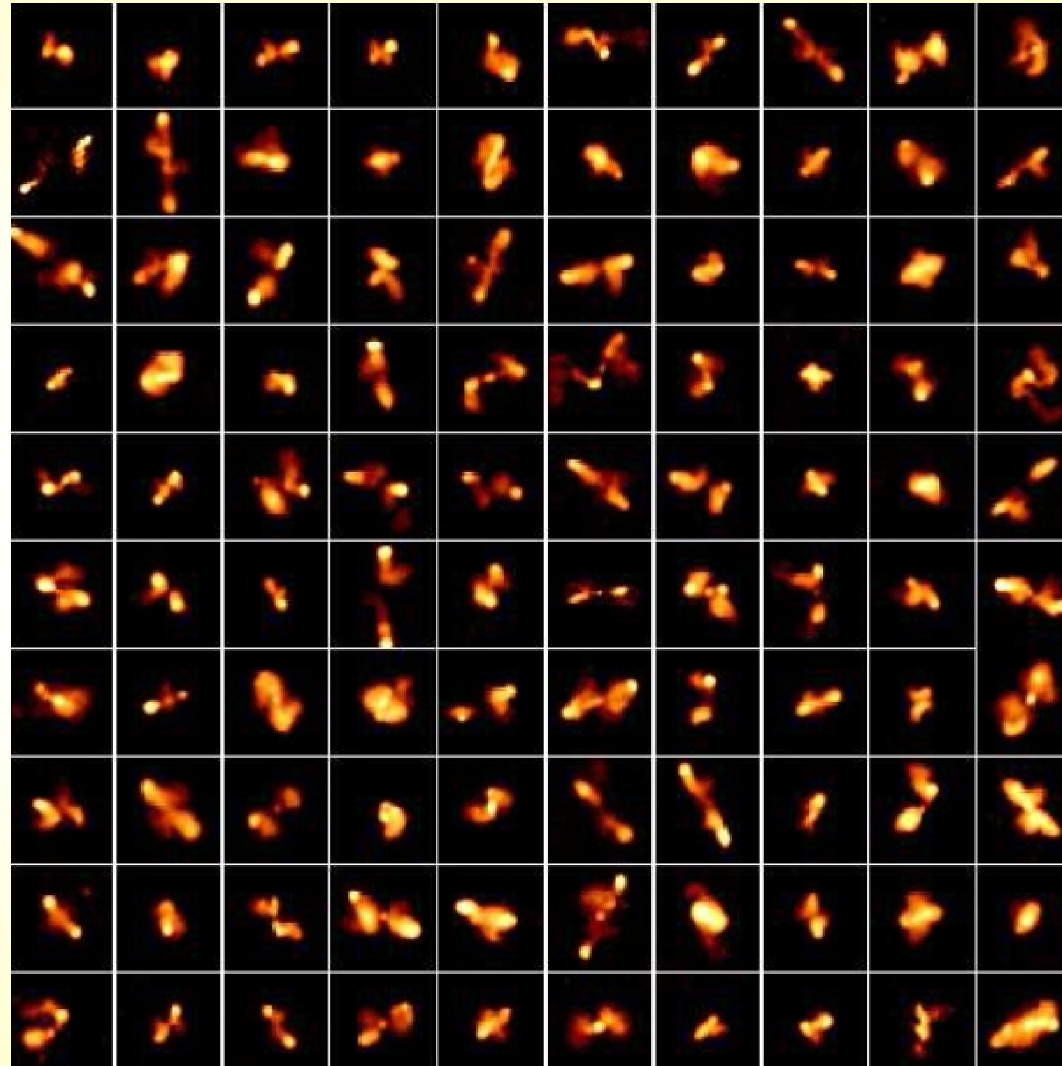
$$m_{f_{wave}=10^{-3}\,\mathrm{Hz}} = 4.38 \times 10^6\, M_\odot$$

$$m_{f_{wave}=1\,\mathrm{Hz}} = 4380\, M_\odot$$

Intermidiate Mass BH: do they exist?

X-shaped radio galaxies





Cheung, C. C. :The Astronomical Journal, 133, 2097-2121 (2007), arXiv:astro-ph/0701278v3

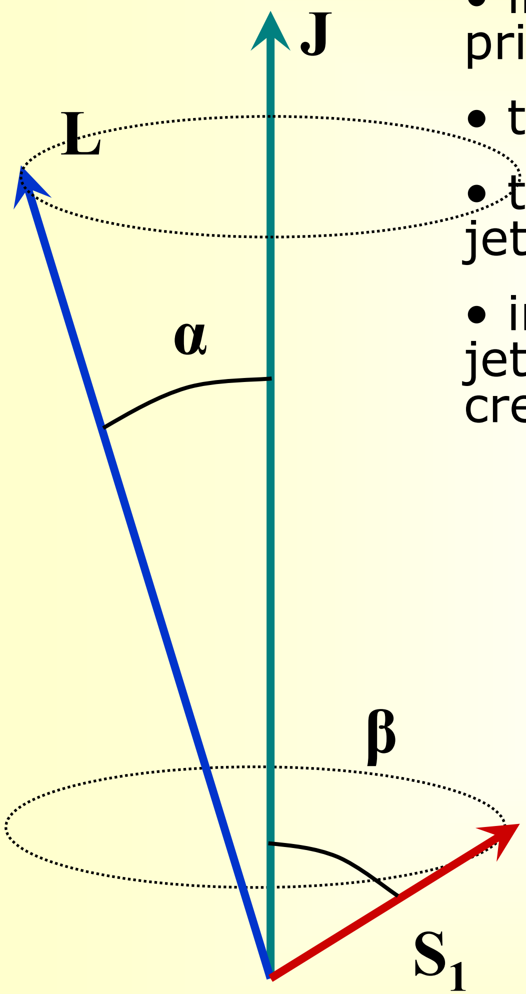
Explanations

1. Galaxy harbouring twin AGNs
2. Back-flow diversion models
3. Rapid jet reorientation (spin-flip) models
4. Jet-shell interaction model

The spin-flip model can explain most of the observations (excepting cases, when the jets are aligned with the principal axes of the host elliptical, then 4. can)

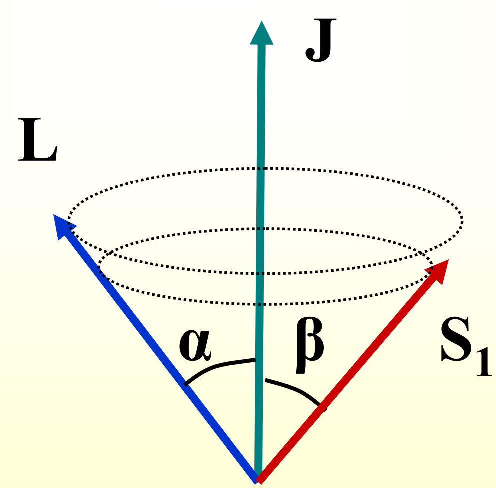
Gopal-Krishna, Biermann, Gergely, Wiita, in preparation (2010)

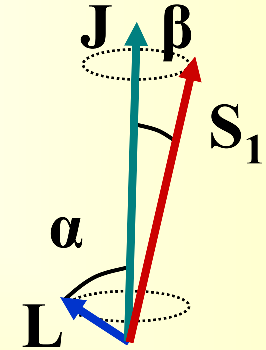
Conservative + dissipative dynamics



- initially the galactic BH has conserved spin → the primary jet can form
- the two galaxies collide → spin precession starts
- the spin aligns to the original **J** direction → the second jet starts to form
- in the intermediate phase when the spin precesses, no jet formation mechanism, the precessing magnetic field creates a wind, sweeping away the base of the old jet

Gergely, Biermann ApJ **697** 1621 (2009)





Key elements: (i) typically the BHs are not equal mass, $m_2 << m_1$, neglect $S_2 \sim m_2^2$

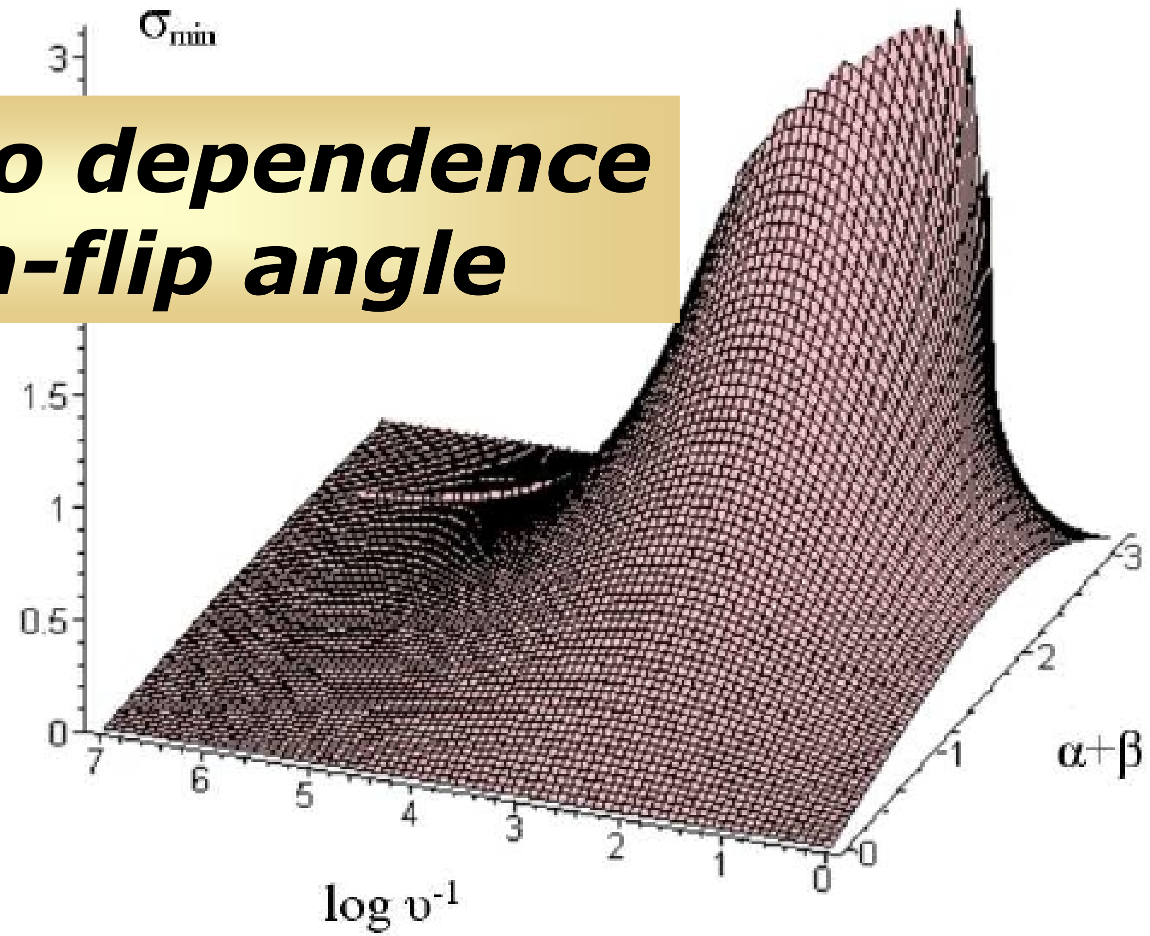
(ii) the direction of J is conserved, (iii) the magnitude of S_1 is conserved → spin-flip

How large is the spin-flip ?

$$\tan\alpha \approx \frac{\sin(\alpha+\beta)}{\chi_1^{-1}\varepsilon^{-1/2}\nu + \cos(\alpha+\beta)}$$

For an initial configuration of 0.005 pc (such that $\varepsilon \equiv \varepsilon^* = 10^{-3}$) and mass ratio $\nu = 10^{-1}$, the initial misalignment between $\mathbf{L}$ and $\mathbf{J}$ is $\alpha_{initial} \approx 18°,\ 10°,\ 0°$ for the dominant spin in the plane of orbit, spanning 45° degrees with the plane of orbit and perpendicular to the plane of orbit (such that $\alpha + \beta = 90°,\ 45°,\ 0°$), respectively. Then $\beta_{initial} = 72°,\ 35°,\ 0°$. For the same mass ratio and relative configurations, the angle α at the end of the PN epoch (at $\varepsilon = 10^{-1}$) becomes $\alpha_{final} \approx 73°,\ 35°,\ 0°$, respectively. This can be translated into a misalignment between $\mathbf{S_1}$ and $\mathbf{J}$ of $\beta_{final} = 17°,\ 10°,\ 0°$, and a spin-flip of $\Delta\beta = 55°,\ 25°,\ 0°$, respectively.

Mass ratio dependence of spin-flip angle



In the majority of cases it happens during the inspiral!

Gergely, Biermann, Caramete, arXiv: 1005.2287 (2010)

Figure 2. The spin-flip angle $\sigma_{\min}$ as function of the relative orientation of the spin and orbital angular momentum $\alpha+\beta$ (a constant during inspiral), and mass ratio ν. For a given mass ratio the spin-flip angle has a maximum shifted from $\pi/2$ towards the anti-aligned configurations. The mass ratios $\nu = 1$; $1/3$; $1/30$ and $1/1000$ are located on the $\log\nu^{-1}$ axis at 0; 1.09; 3.40 and 6.91, respectively, confirming the prediction, that a significant spin-flip will happen in the mass ratio range $\nu \in (1/30, 1/3)$. For mass ratios smaller than $1/100$ the spin does not flip at all, as the infalling SMBH acts as a test particle.

Summary

- Galactic SMBH statistics indicate the typical mass ratio of 1:3 to 1:30 in mergers (1:10 representative)
- In this mass range, during the inspiral

  i. The orbital momentum of the binary dominates at the beginning, while the spin of the bigger BH dominates at the end, very little orbital momentum being left before the merger

  ii. The spin turns into the direction of the original total angular momentum → spin-flip

  iii. Spin precession causes a super-wind, sweeping out the base of the jets, in accordance with observations

  iv. Magnitude of spins unchanged → can stay high

- The mass quadrupole is at least as much important as the spin-spin (more important at unequal masses)
- Parameter estimation techniques should take this into consideration