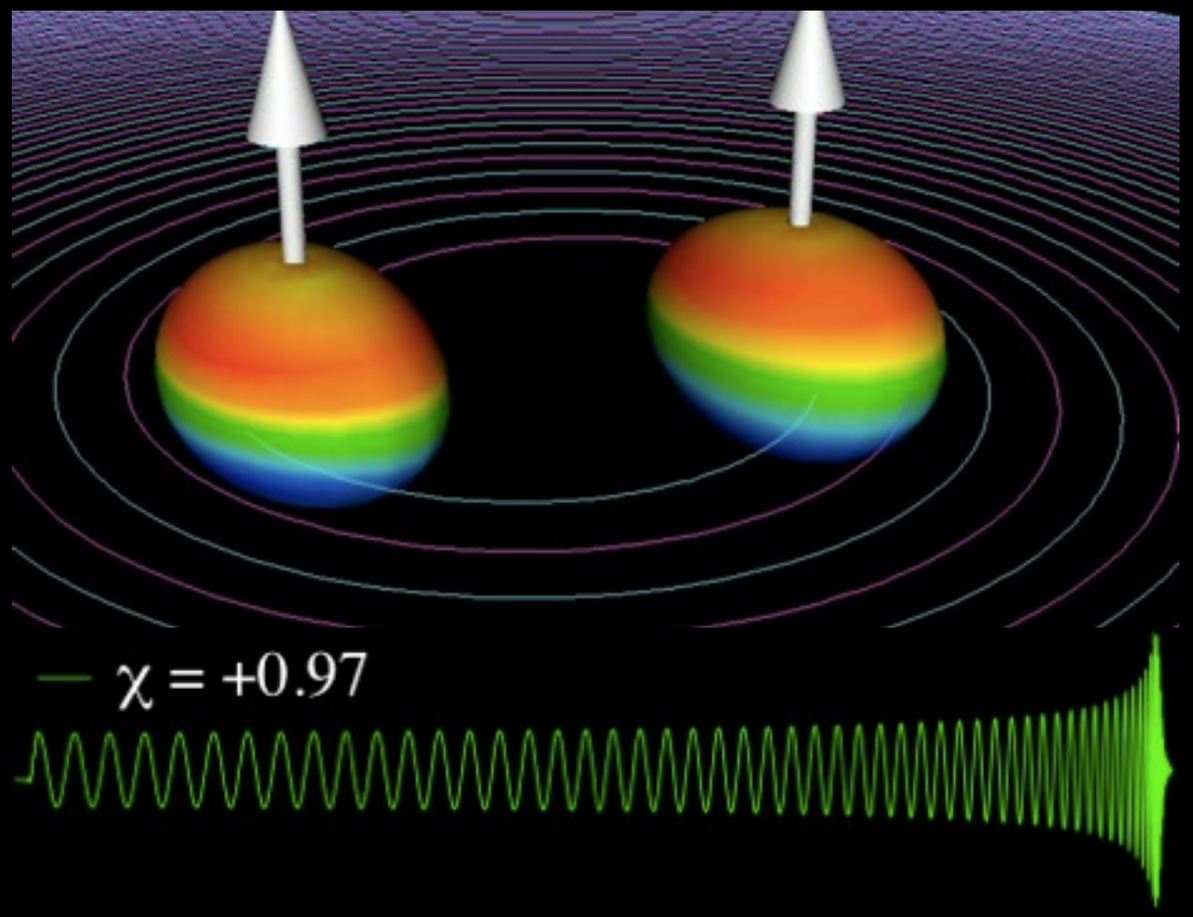
Numerical simulations of binary black holes in the presence of spins



Geoffrey Lovelace
Gravitational Wave Physics and Astronomy Center
California State University, Fullerton
July 31, 2012

Outline

- Background & motivation
  - Spinning black holes
  - Gravitational waves (GW) from binary black holes (BBHs)
  - Modeling spinning BBHs using numerical simulations
- Results so far: some highlights
- Challenge: apply to GW data analysis
  - For best possible model waveforms, simulations must be
    - Extreme: capable of very high black-hole spin
    - Generic: handle misaligned spins & precession, unequal masses, unequal spins, extreme spins
    - Efficient: sufficiently long, accurate, & inexpensive

Spinning black holes

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- Black holes
  - Region of warped spacetime
  - Horizon: surface of black hole

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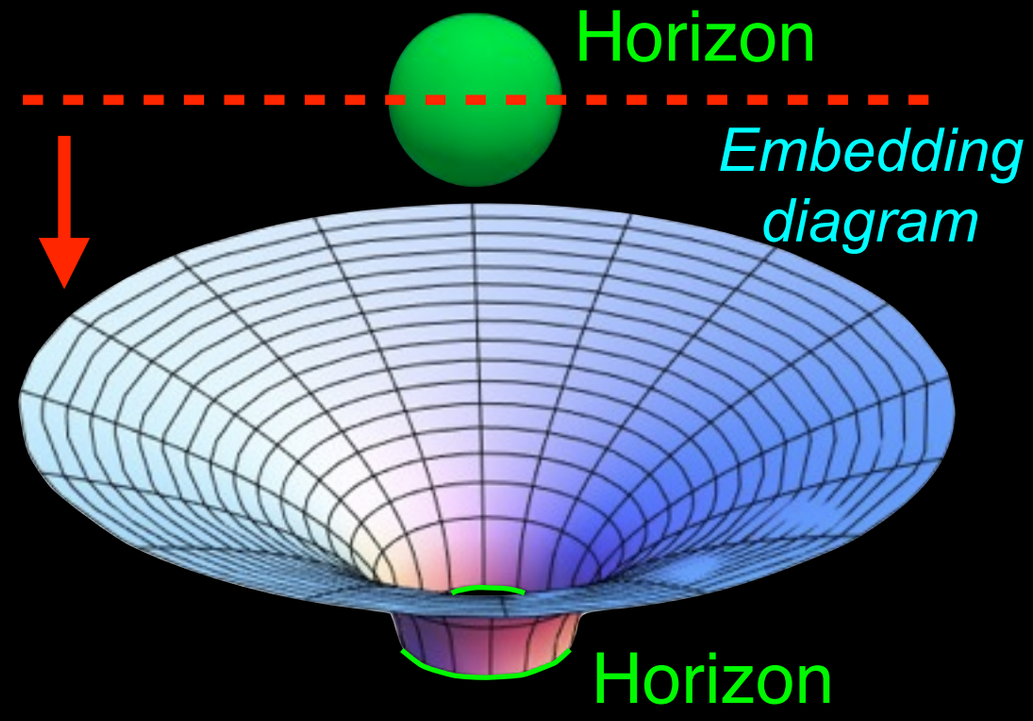

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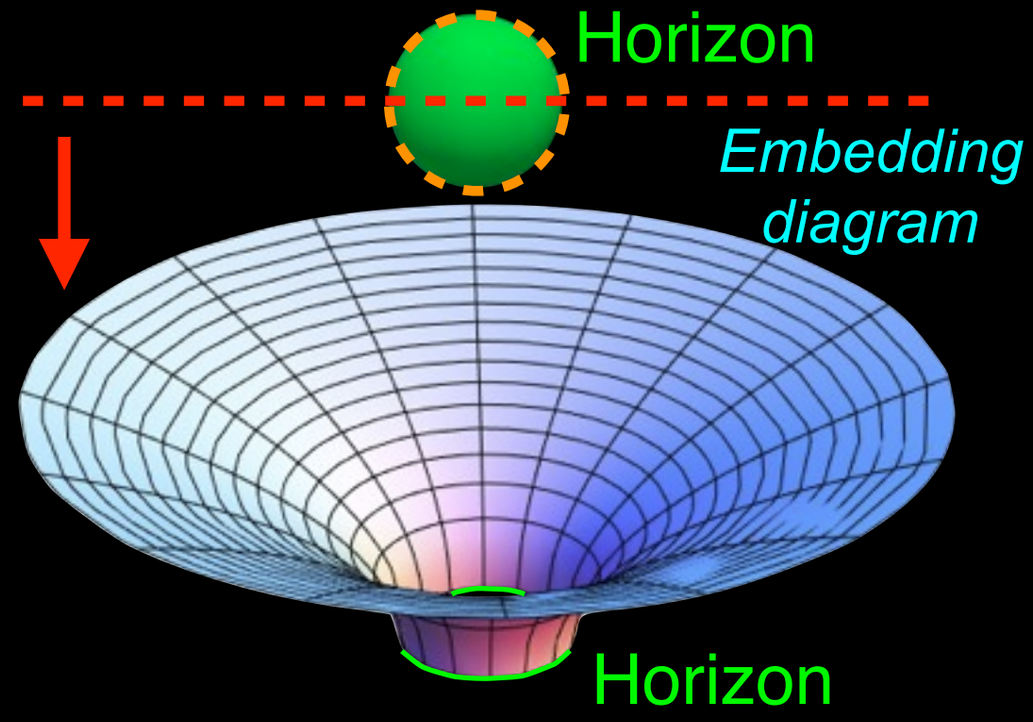

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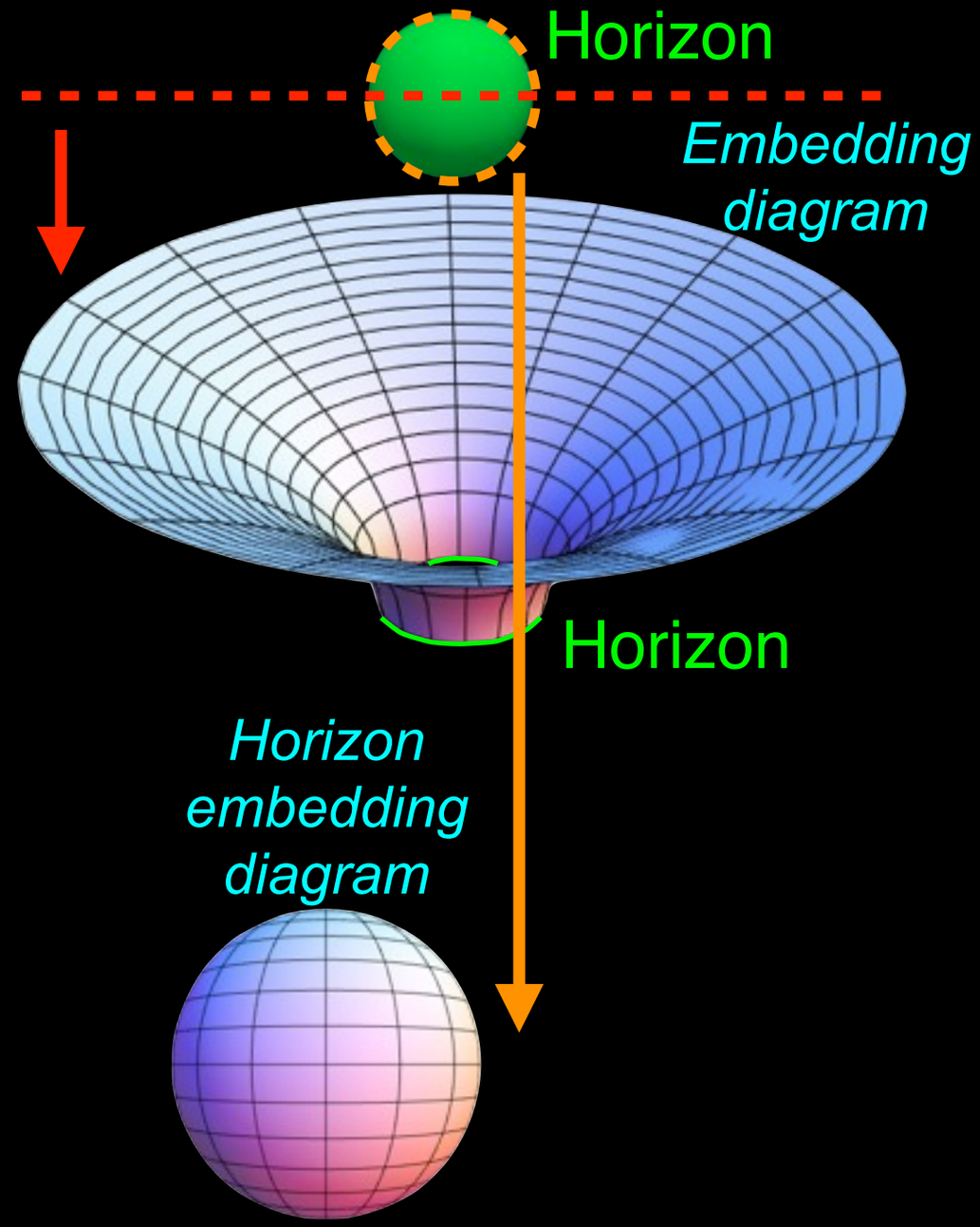

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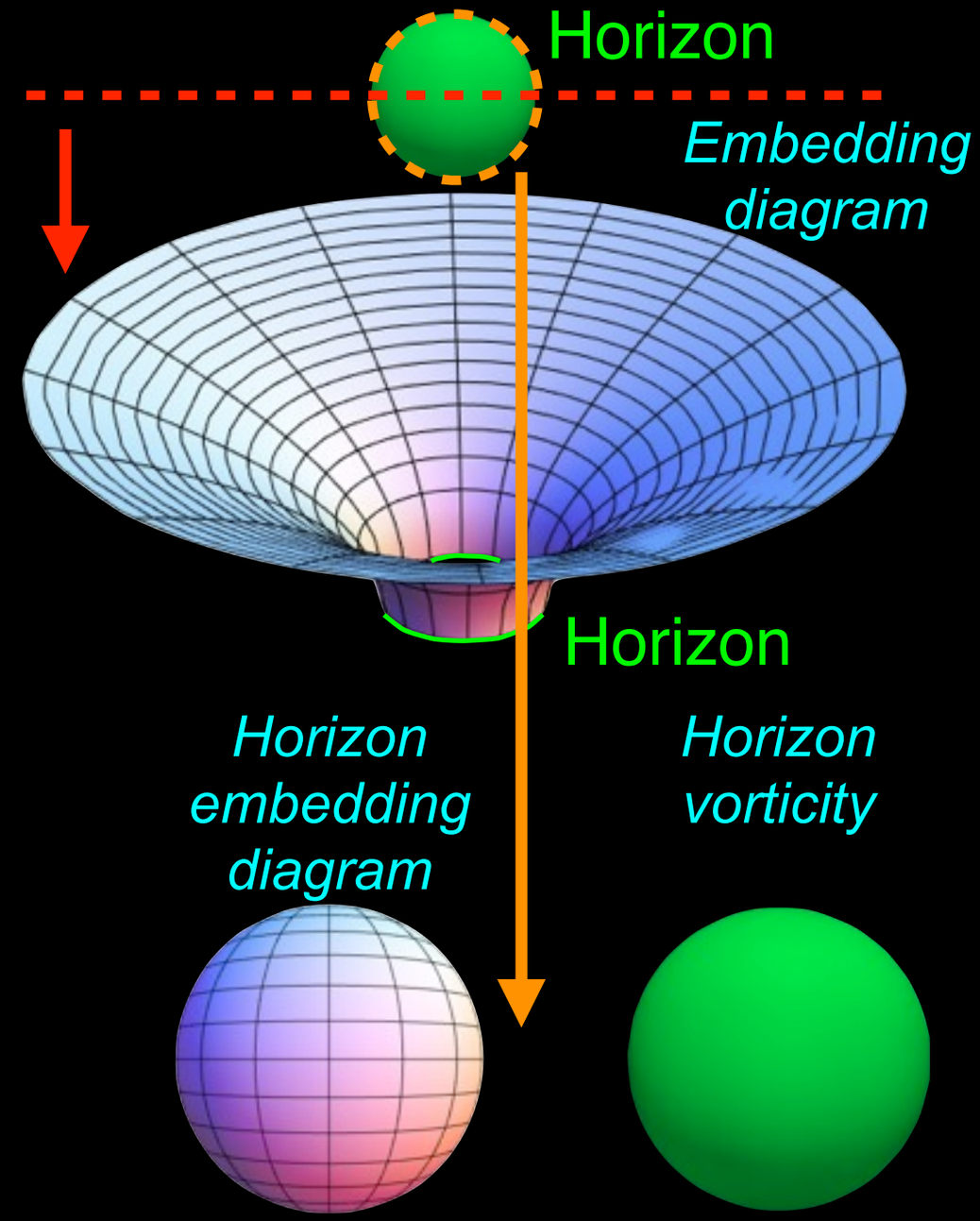

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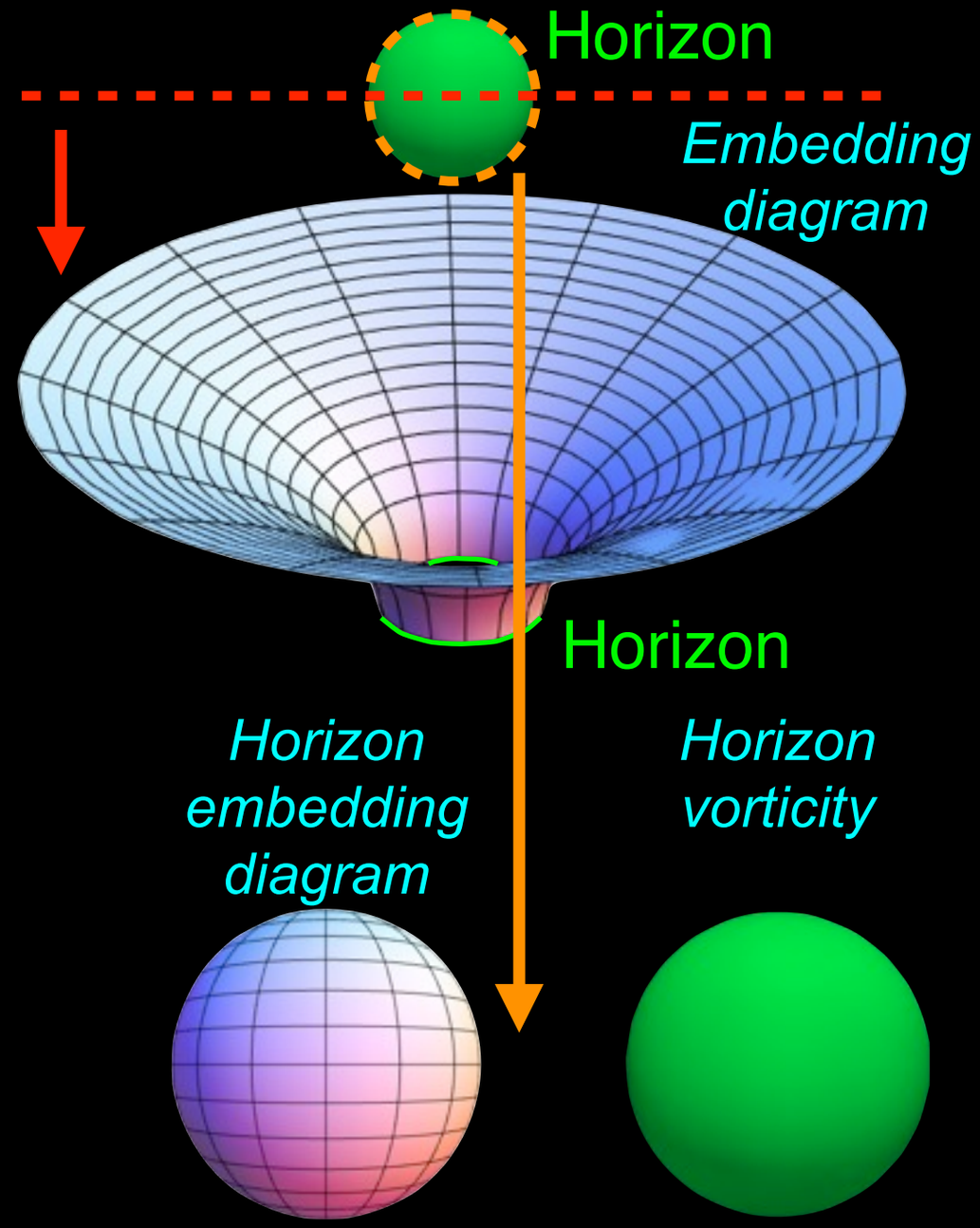

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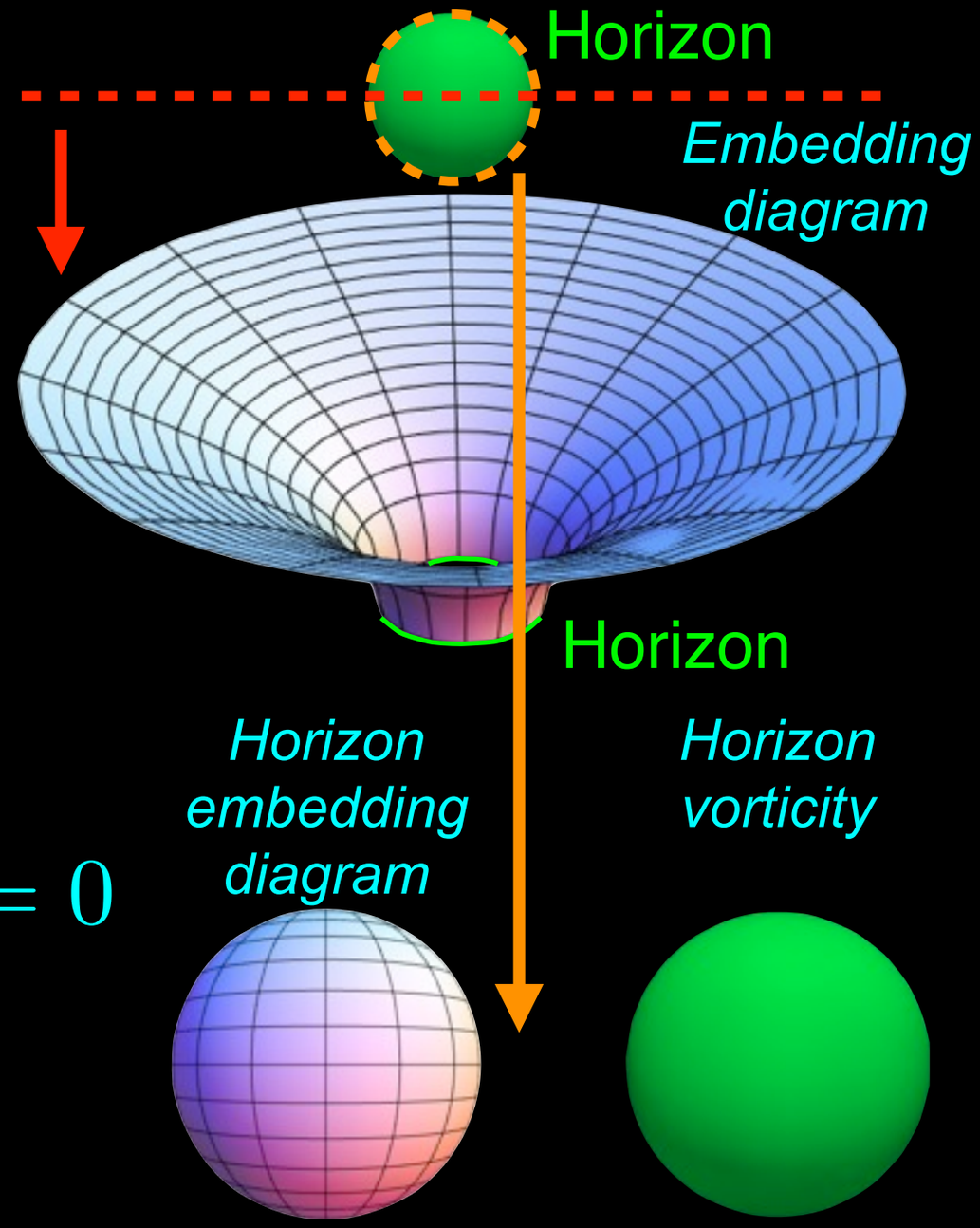

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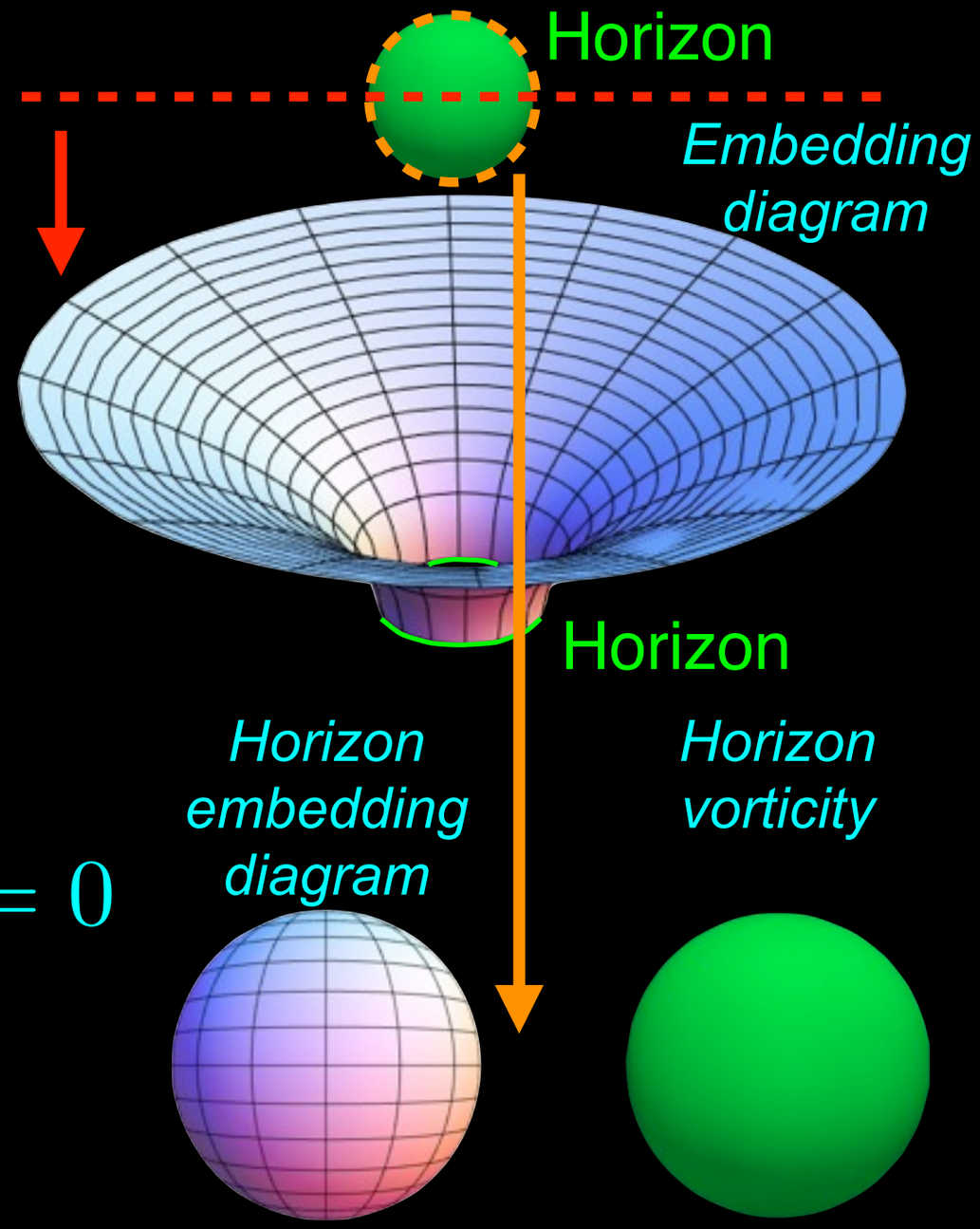

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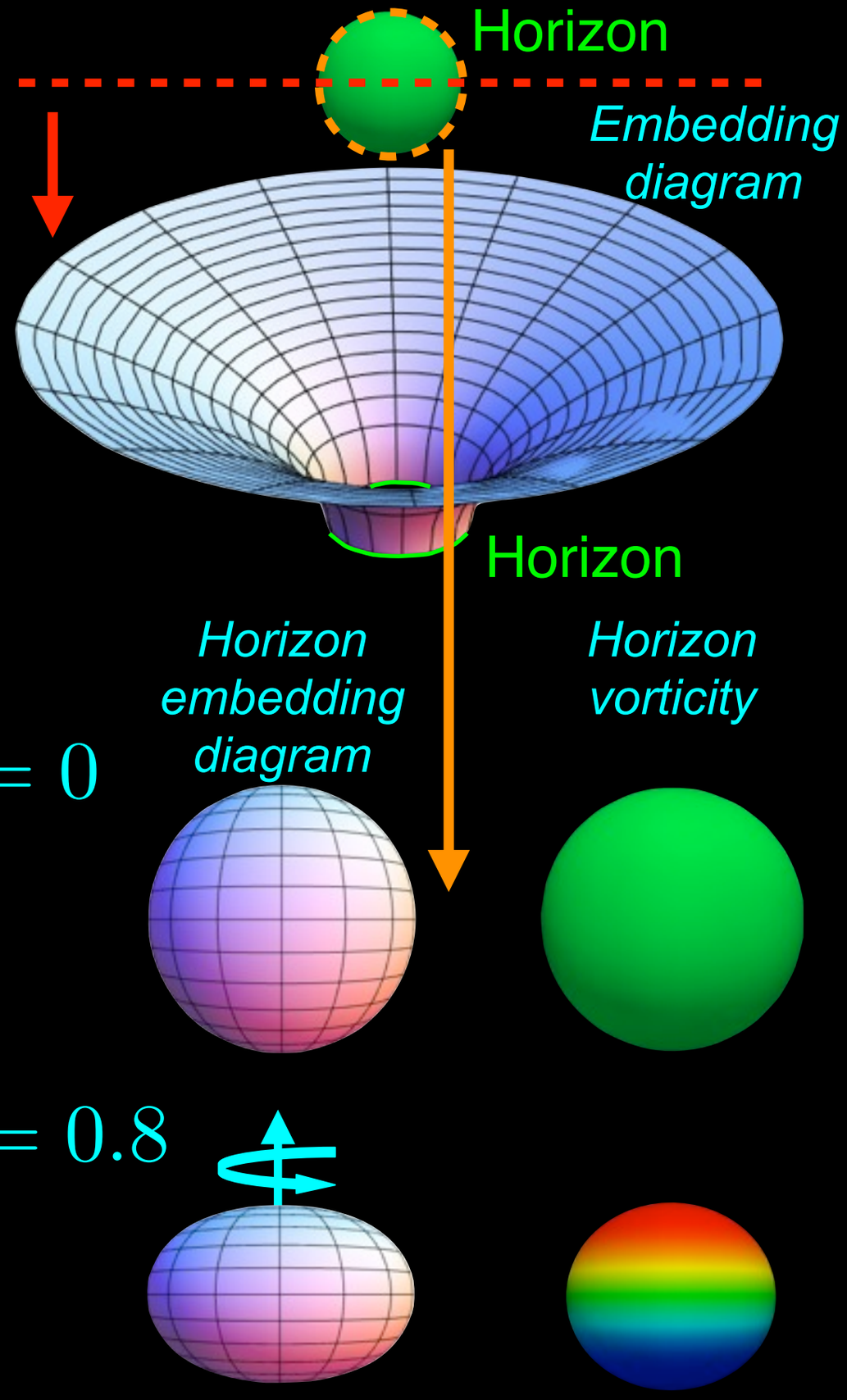

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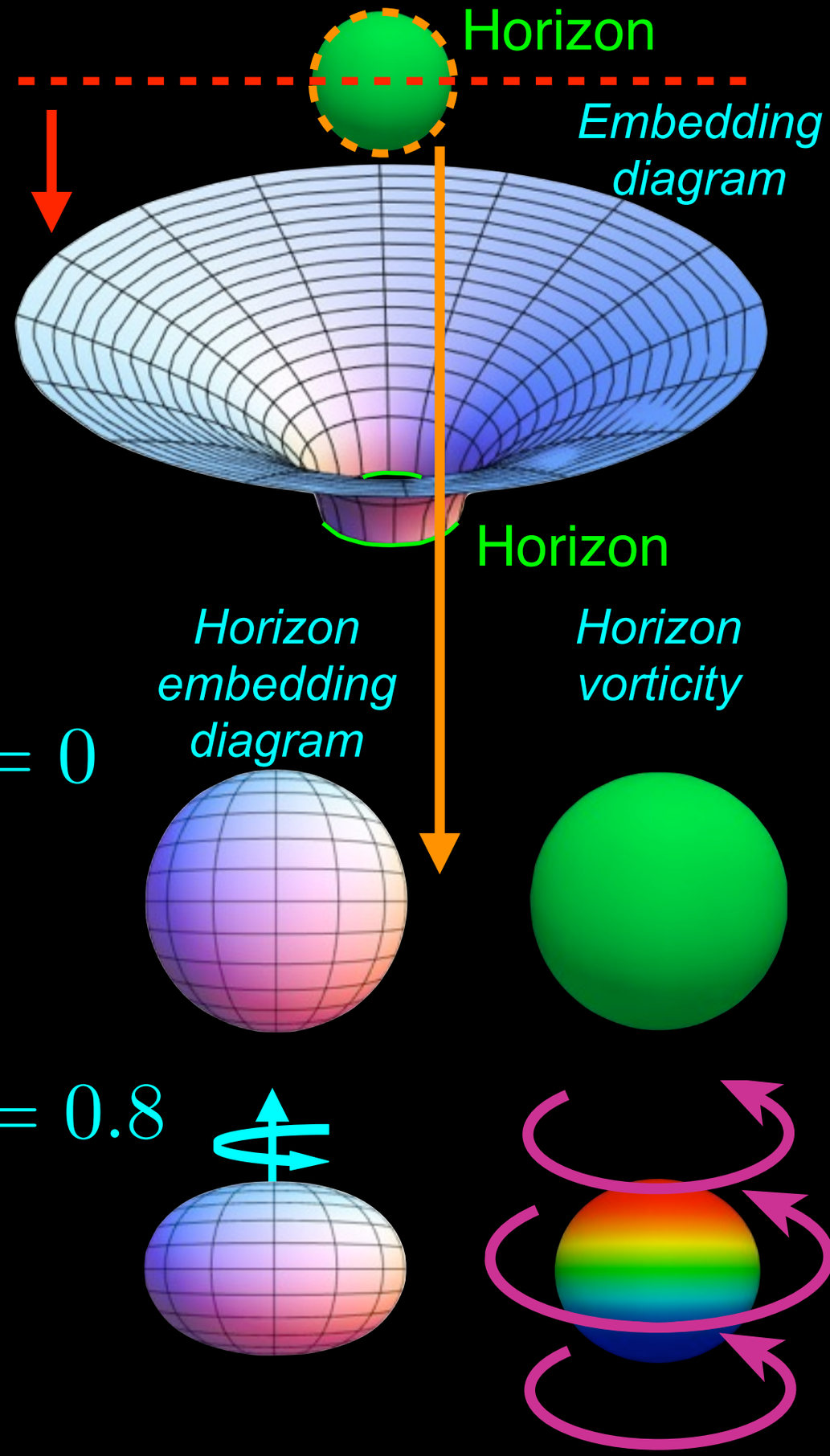

Observing black holes

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Images courtesy NASA

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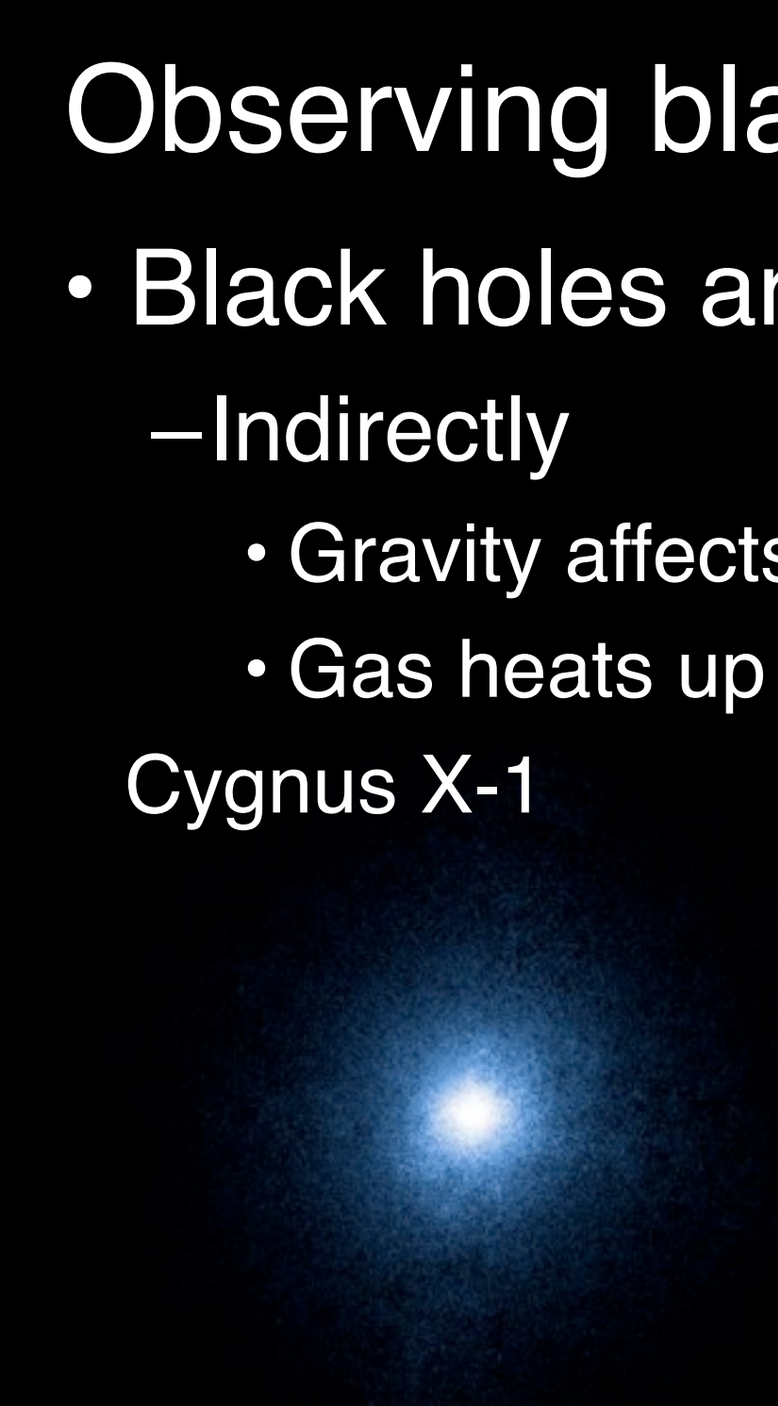

First candidate black hole discovered

$M/M_{\rm sun} \approx 15$

$\chi \gtrsim 0.95$ — Gou *et al.* (2011)

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Black hole at center of our galaxy

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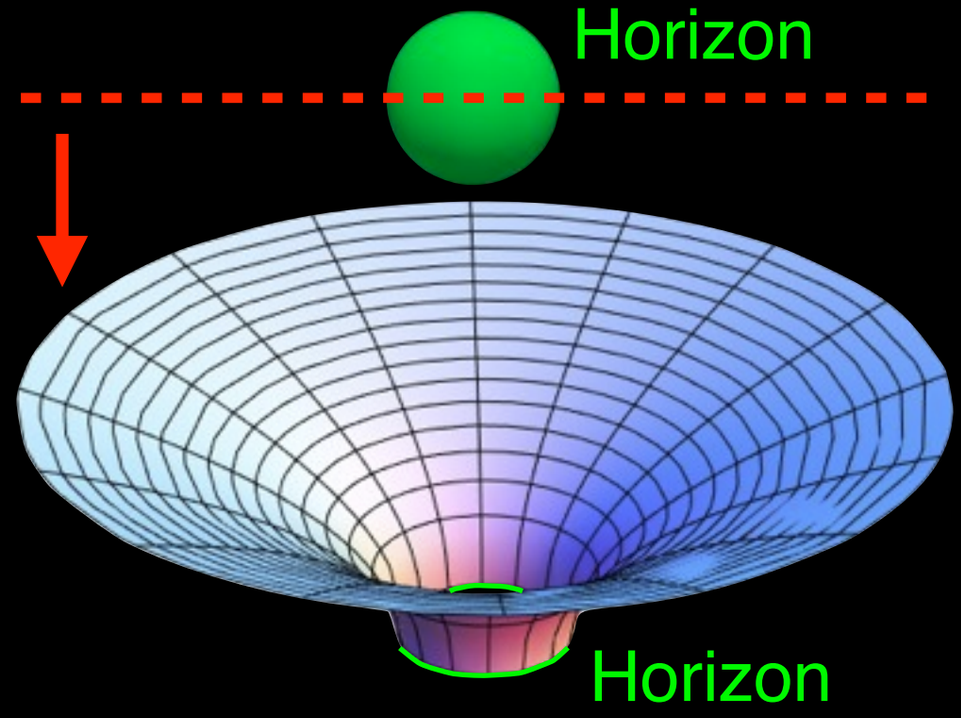
  - Directly: *waves of gravity* from colliding black holes

Black holes & grav. waves



Black holes & grav. waves

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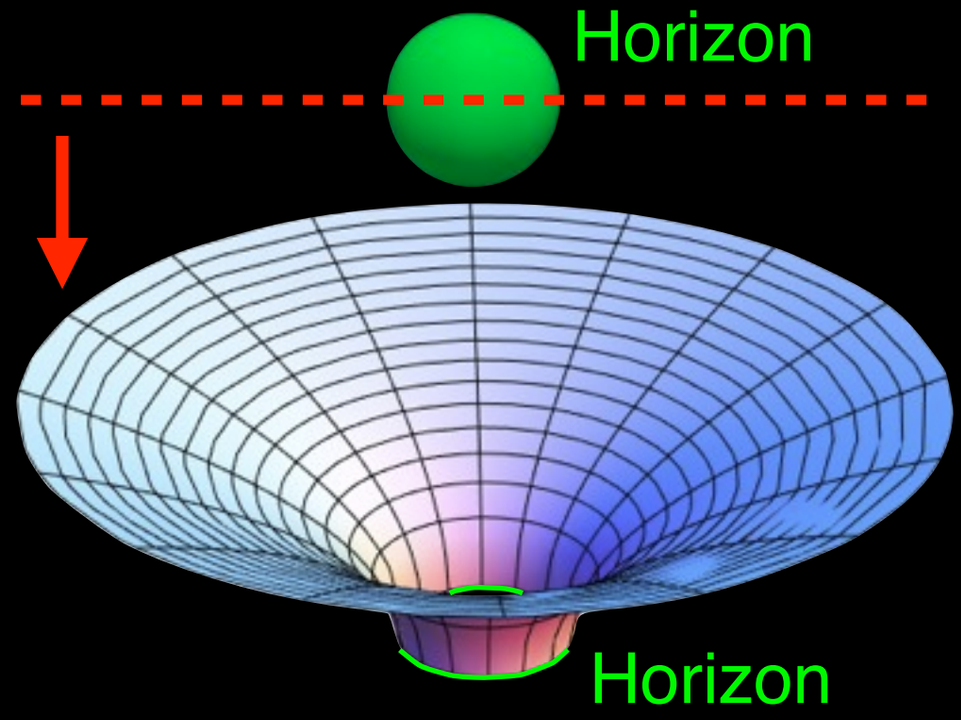

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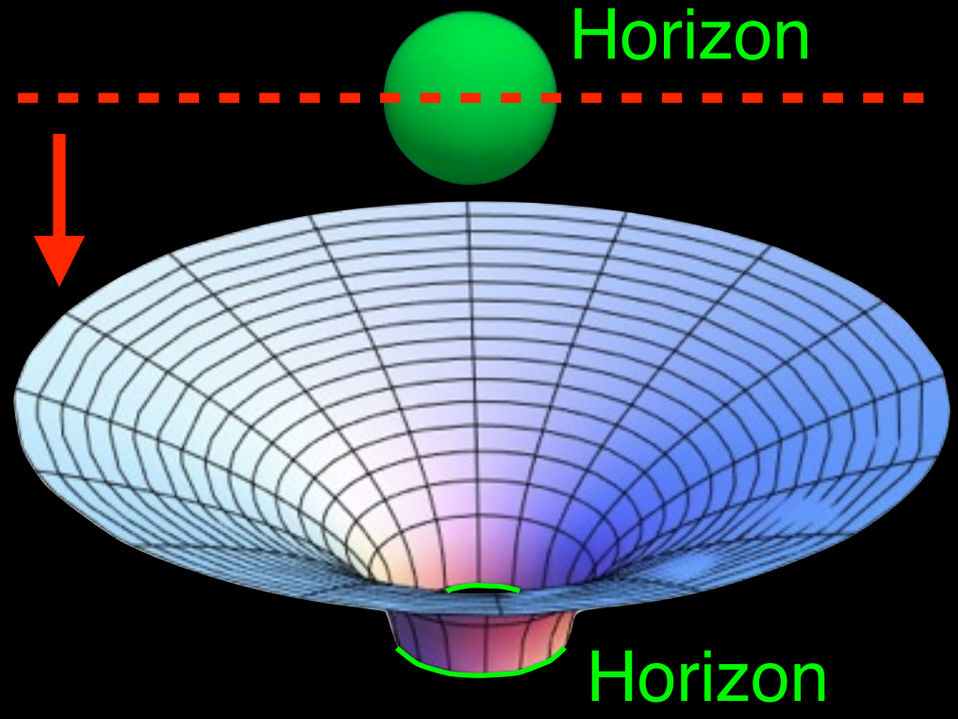

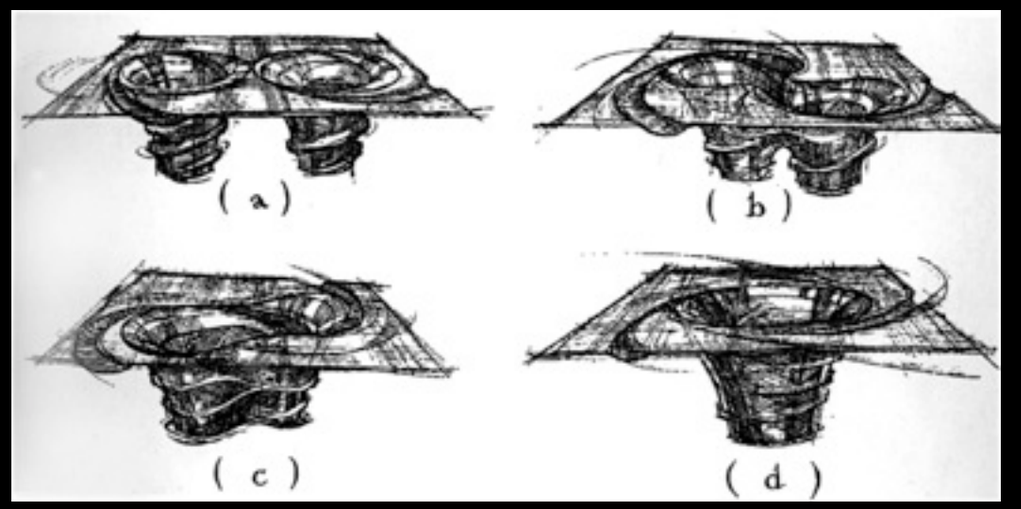

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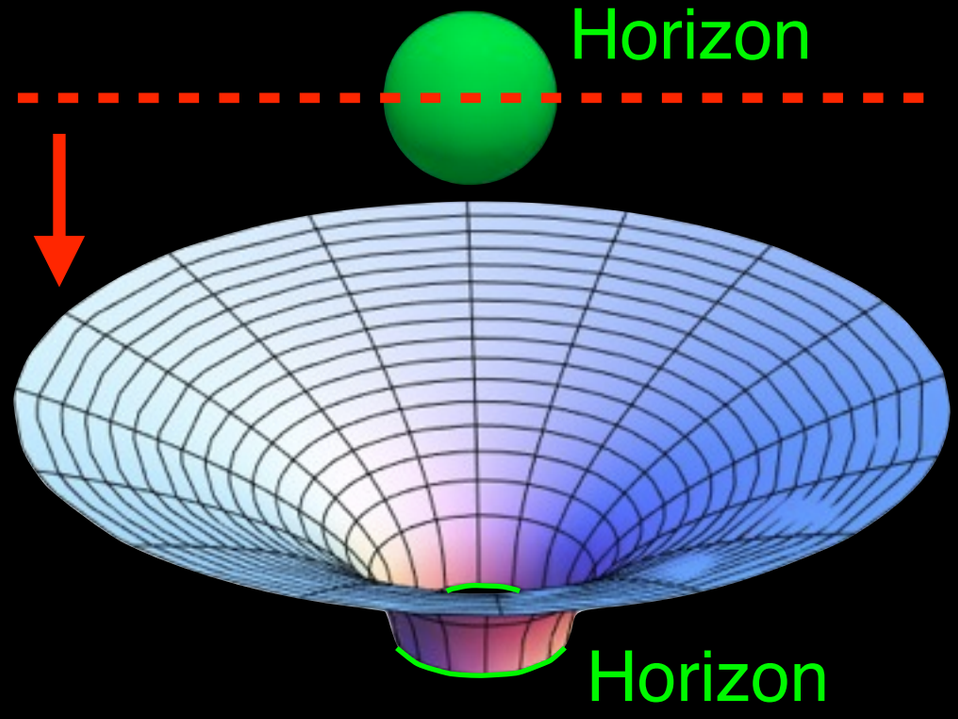

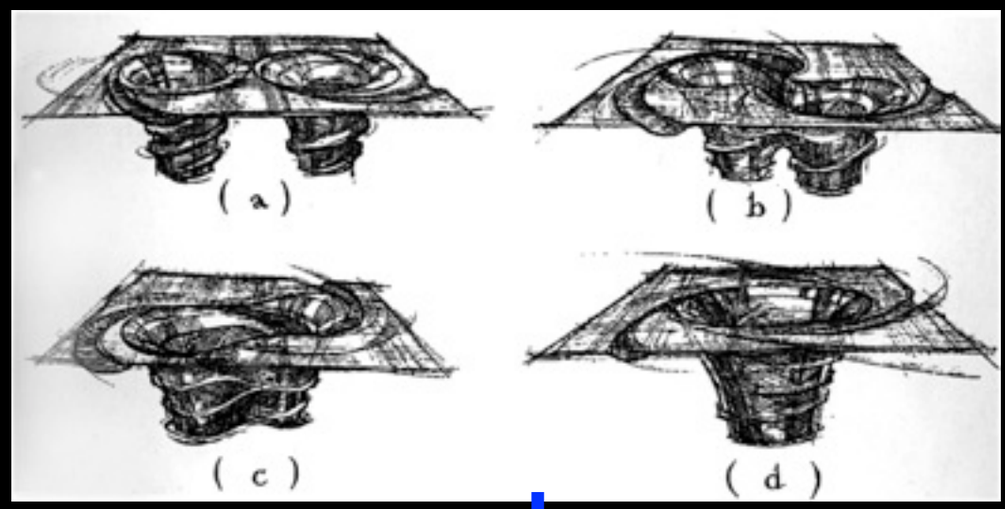

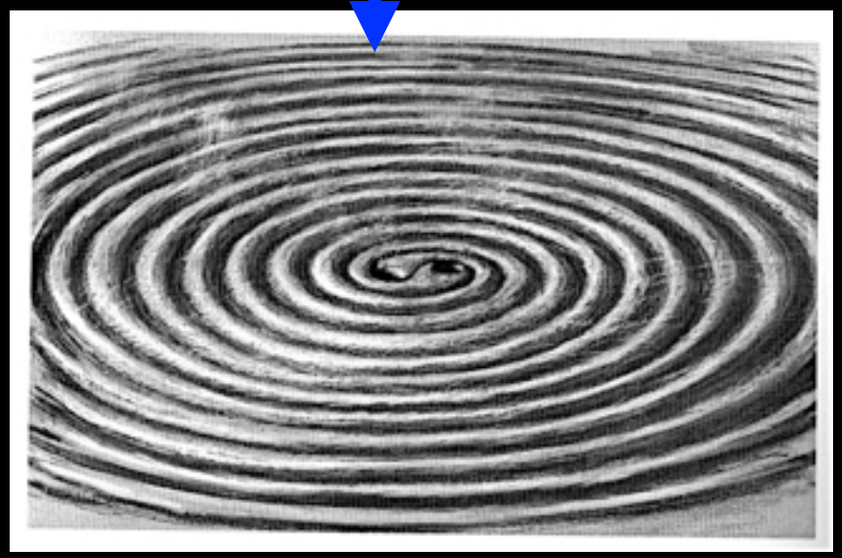

Black holes & grav. waves

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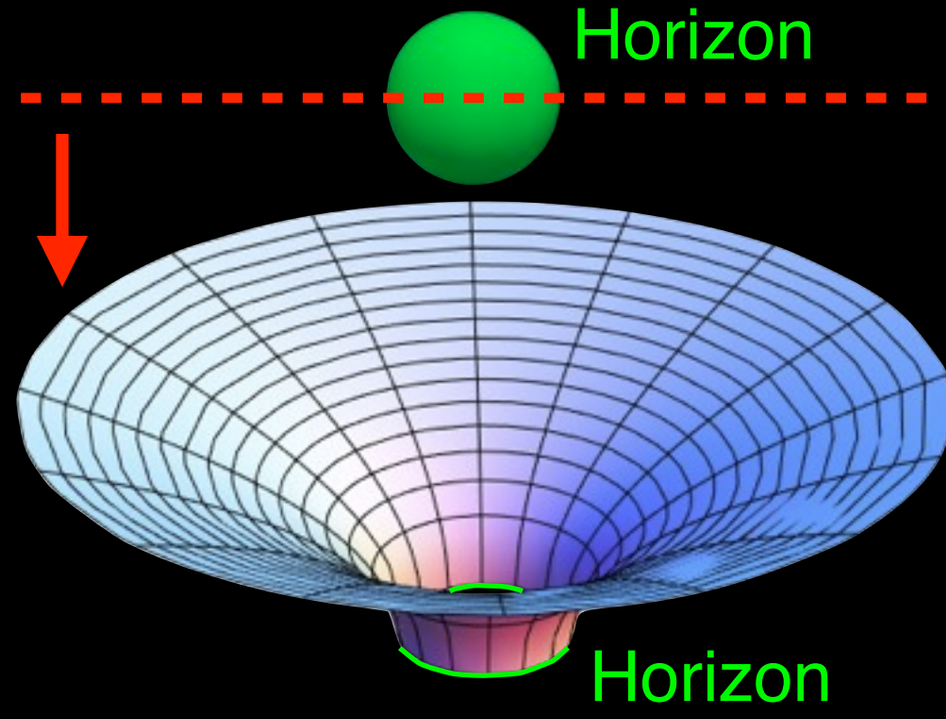
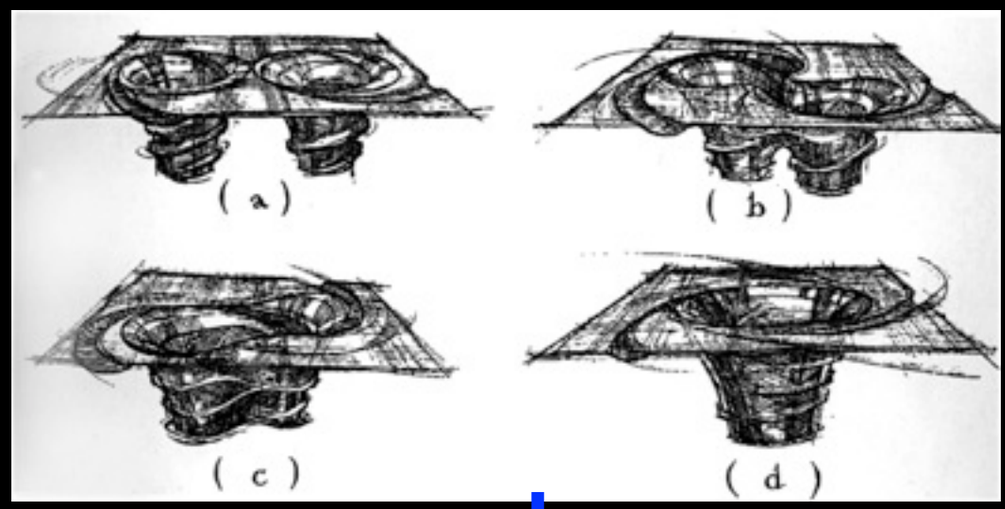
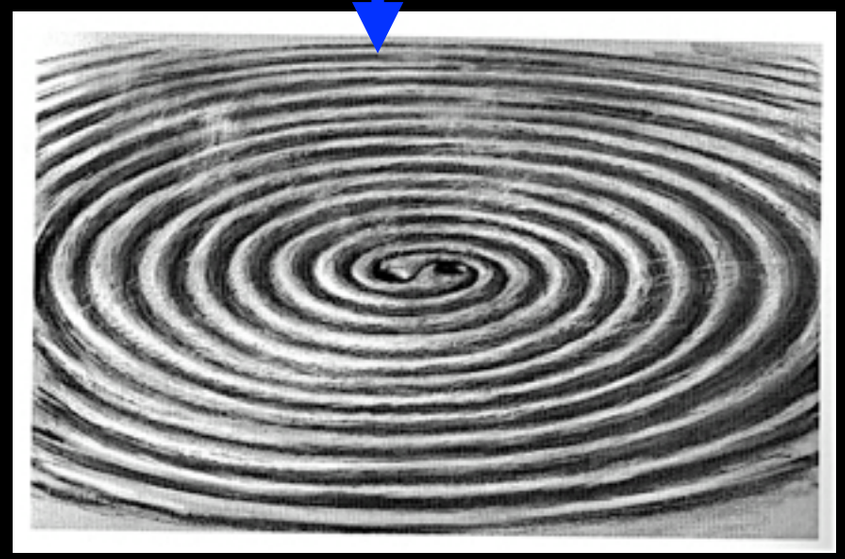
    - Radiate ~10% of mass (vs. ~0.5% nuclear fusion) as *gravitational waves (GW)*

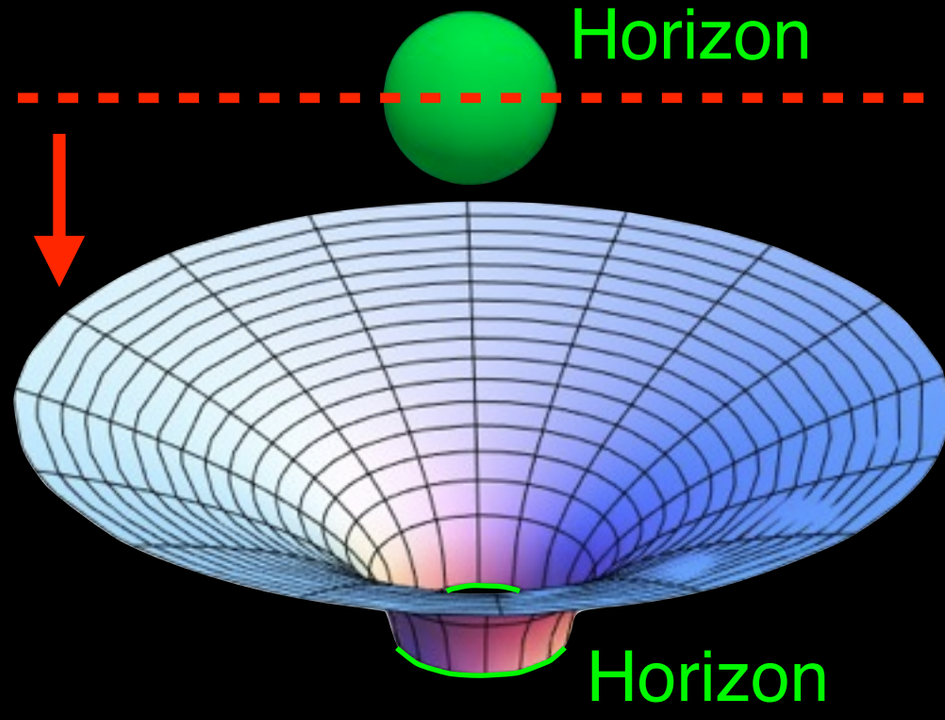


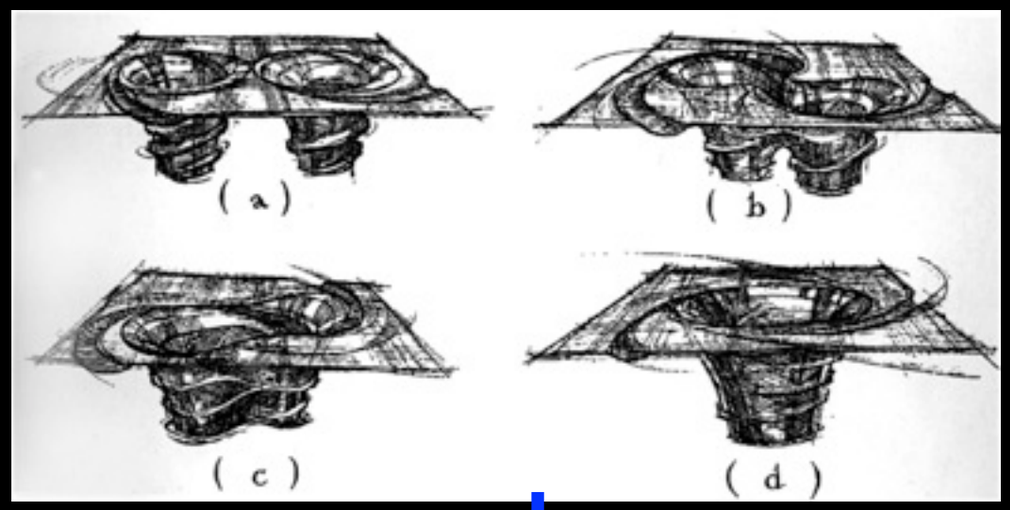


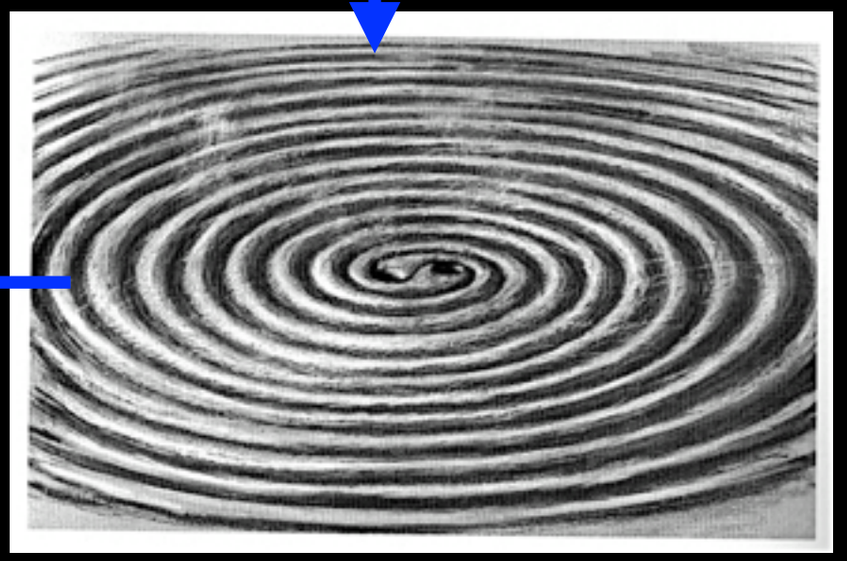


Black holes & grav. waves

- Coalescing black holes
  - Most violent events in universe
    - Radiate ~10% of mass (vs. ~0.5% nuclear fusion) as *gravitational waves (GW)*
  - Waves weak at earth
    - Need accurate GW predictions
      - To find GW in noisy detector data
      - To estimate source properties







GW vary 4km arm length by 10^{-18} m = 0.1% atomic nucleus

Images courtesy LIGO, Kip Thorne

Colliding black holes

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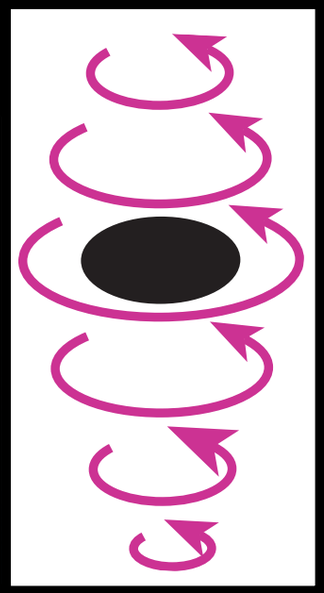

Images courtesy Kip Thorne

  - –History: black hole solutions
    - 1915: GR, Spherical black hole
    - 1963: Rotating black hole

Colliding black holes

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  - –History: black hole solutions
    - 1915: GR, Spherical black hole
    - 1963: Rotating black hole
    - 2005: First inspiral,
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      (only possible via
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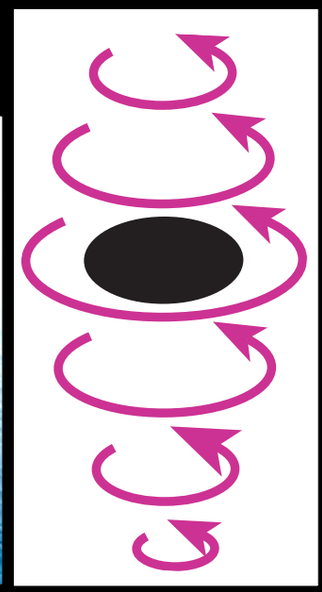
      Pretorius, PRL **95**,
      121101 (2005)

Single black hole



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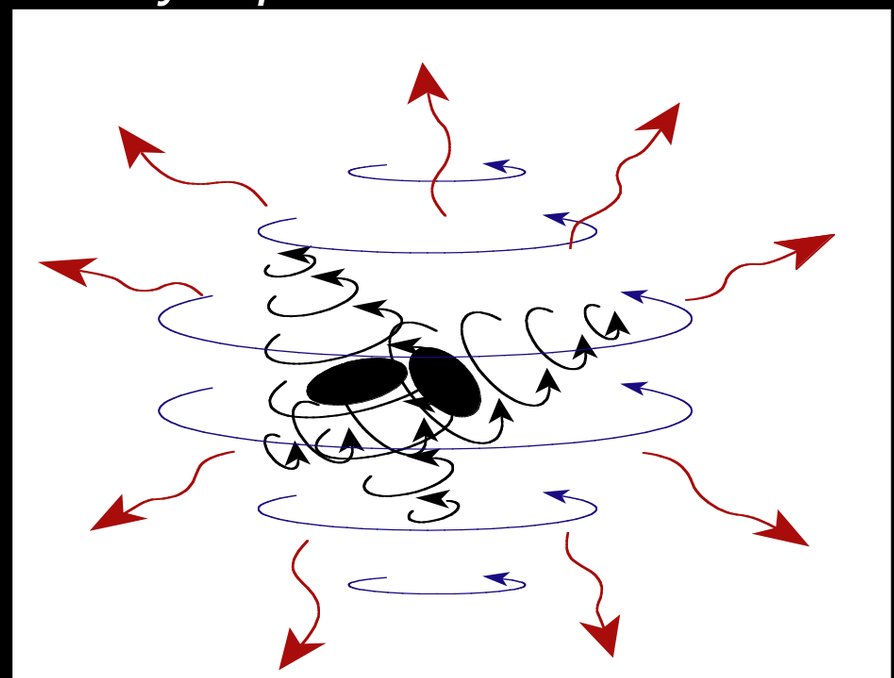

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Simulating colliding black holes

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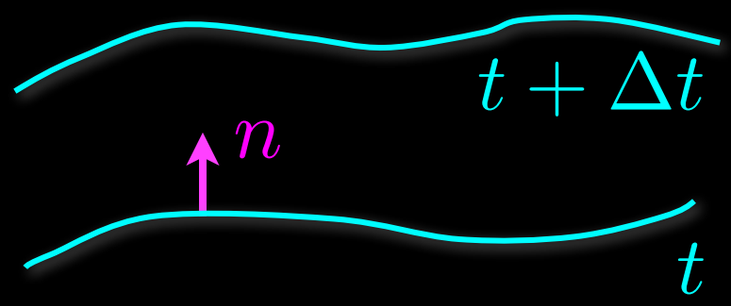

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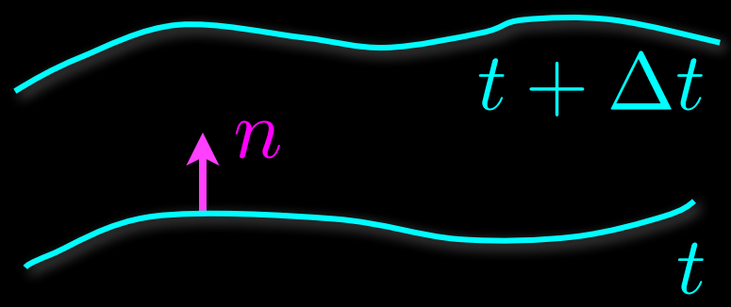

Simulating colliding black holes

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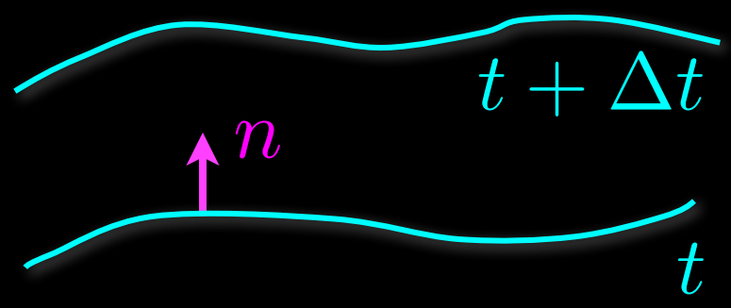
  - Must satisfy constraints



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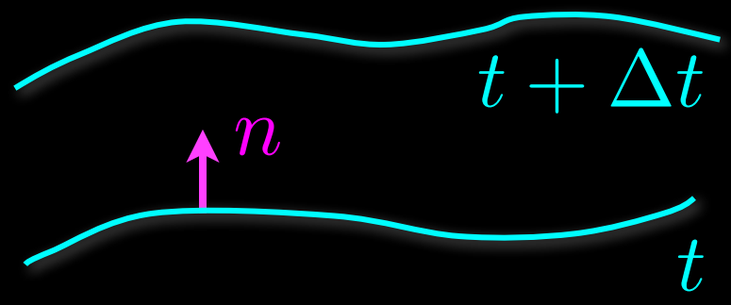

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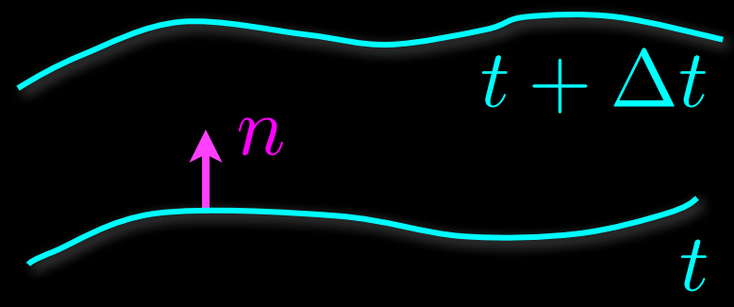

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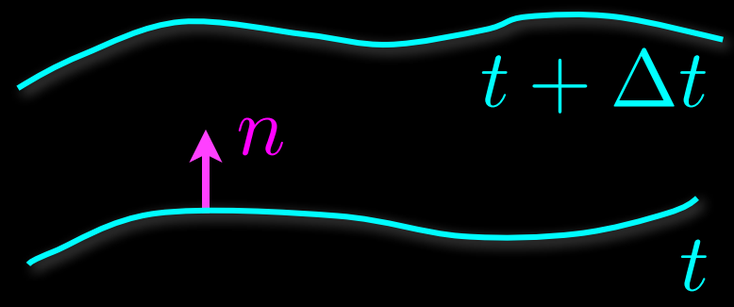

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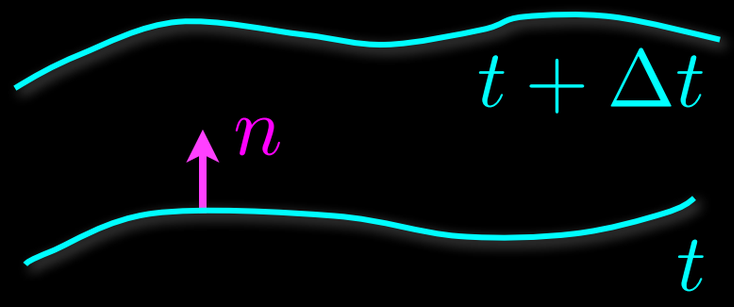

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  - –Step from current time to next time
  - –Challenges
    - Constraints must stay satisfied
    - Coordinates must be well behaved
    - Remove singularities
    - Boundary conditions
    - Computational cost

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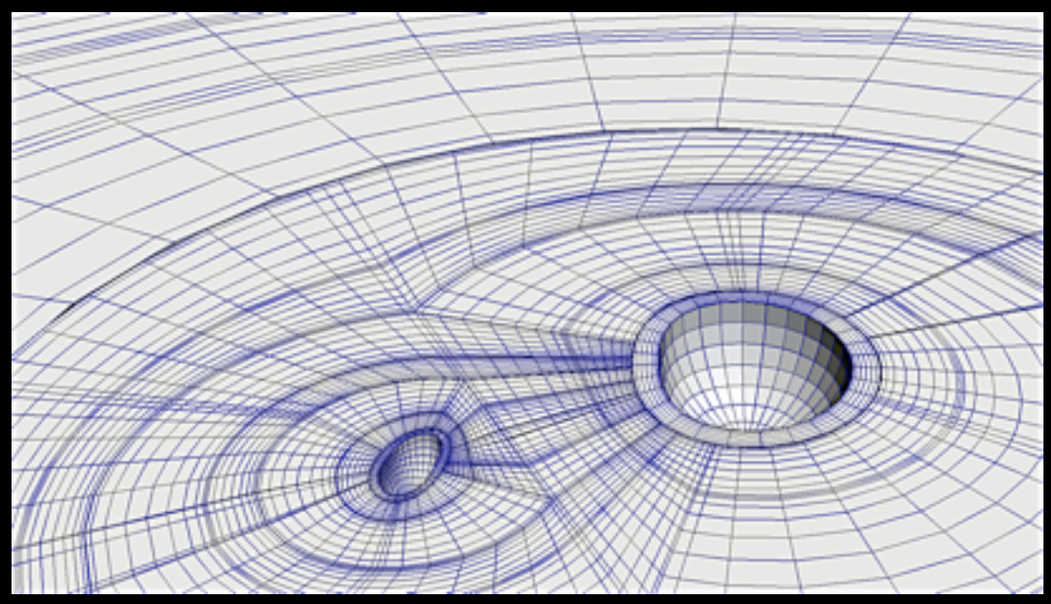

Simulation methods

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Evolution	BSSNOK evolution eqs.	Generalized harmonic evolution eqs.
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	Moving puncture	Excision
Codes	BAM, Hahndol, LazEv, Lean, Llama, MayaKranc, UIUC	SpEC

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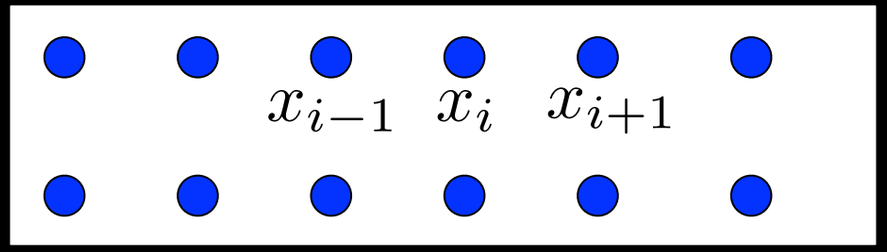

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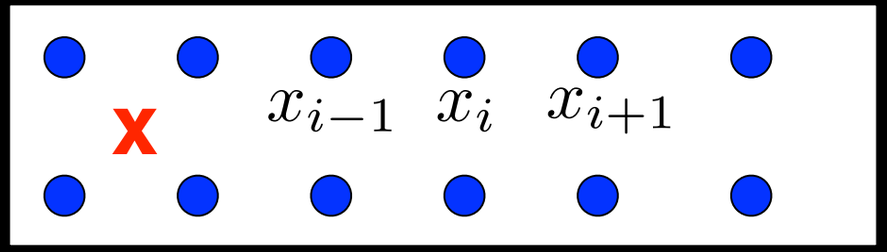

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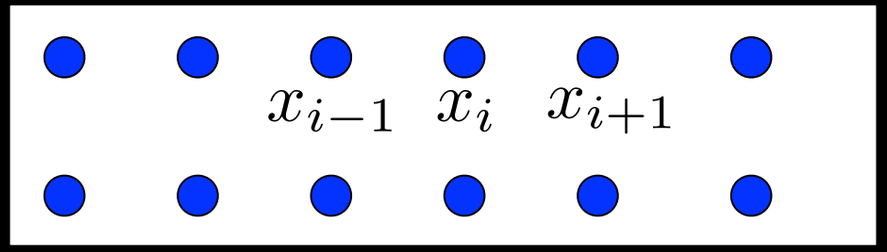

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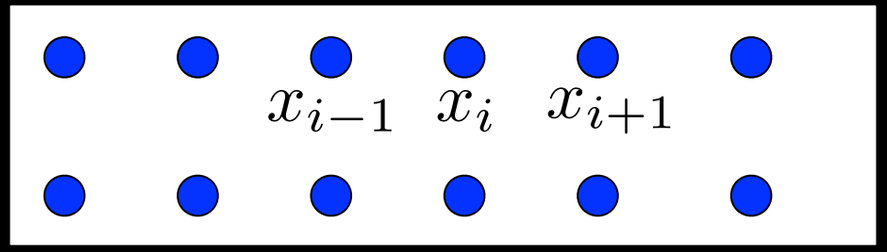

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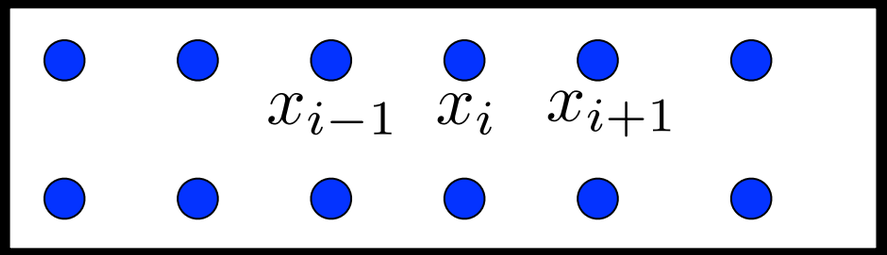

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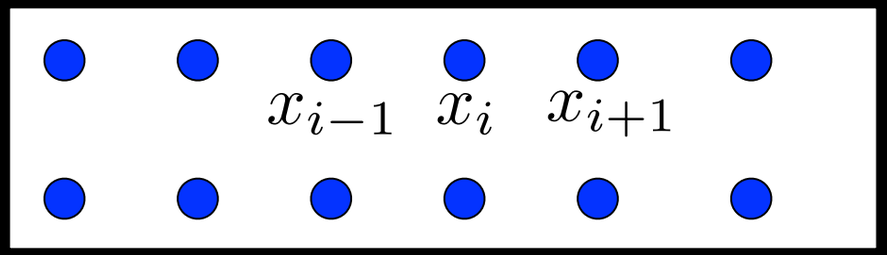

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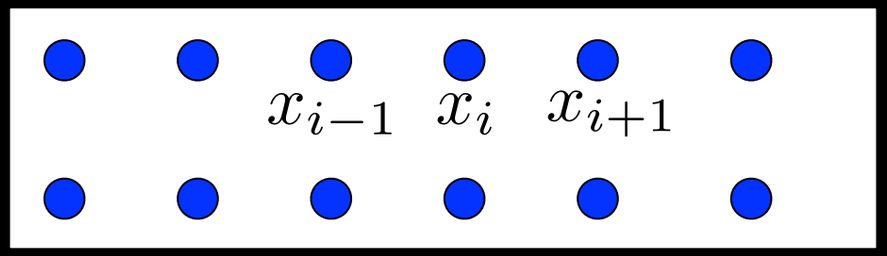

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Advantages	Robust, open-source frameworks, many more simulations so far	High accuracy at lower cost, longer simulations, very high black-hole spins

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Some results

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- Orbital hangup

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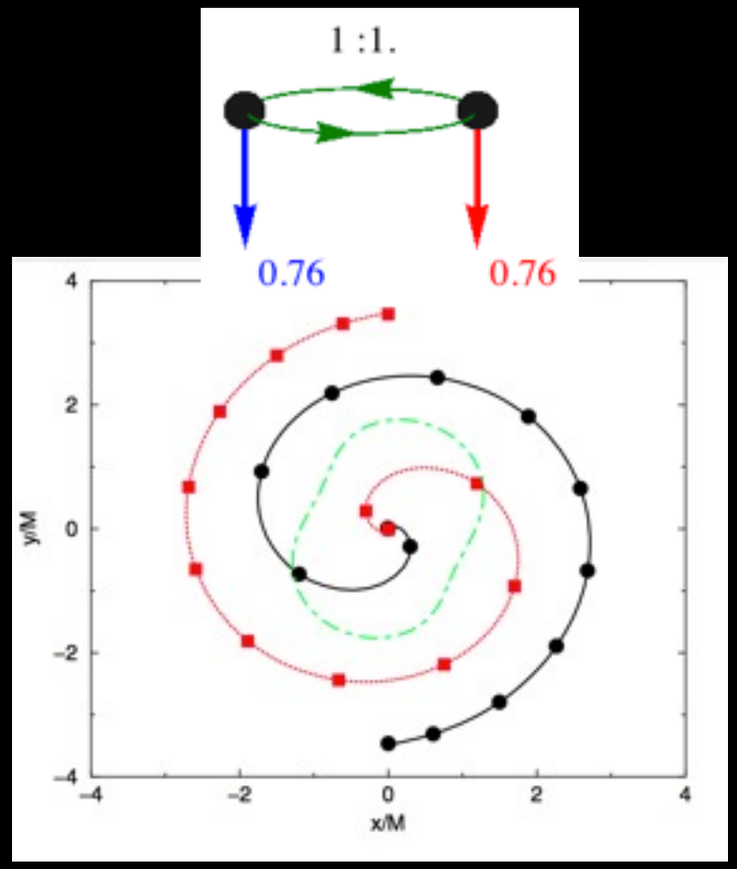

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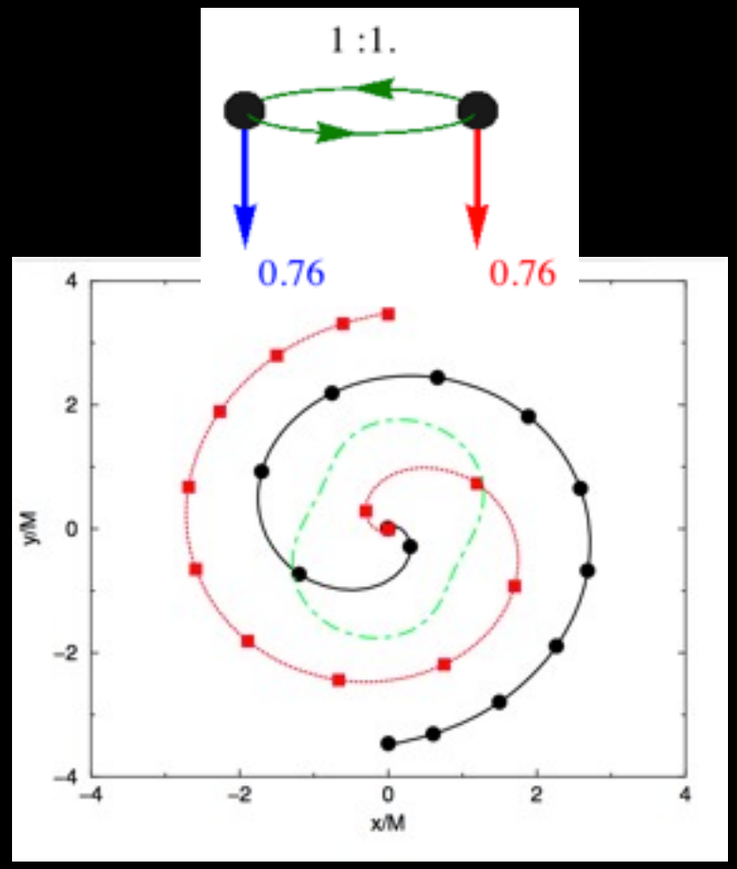

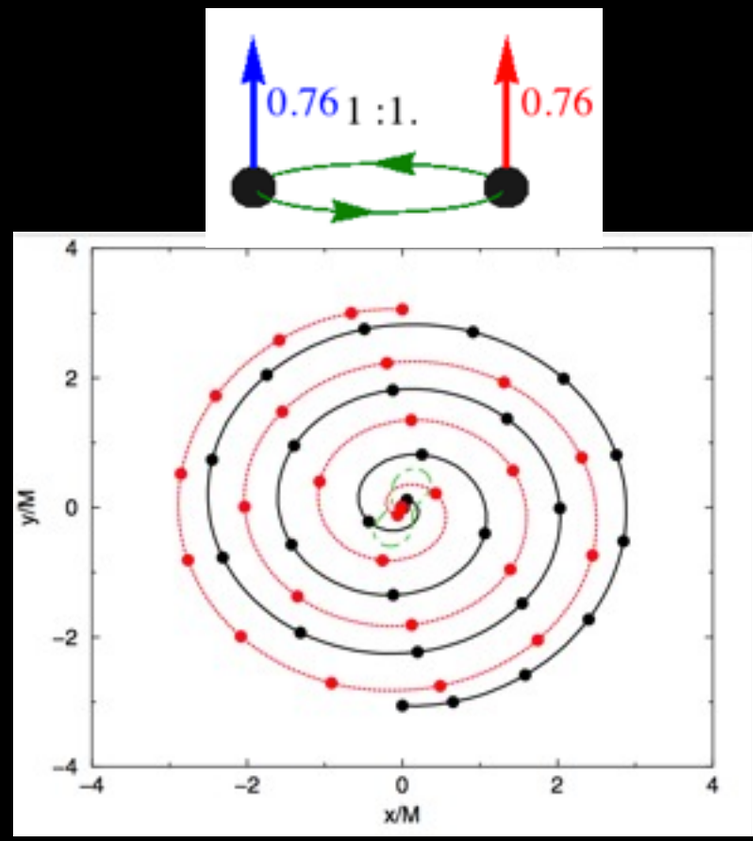

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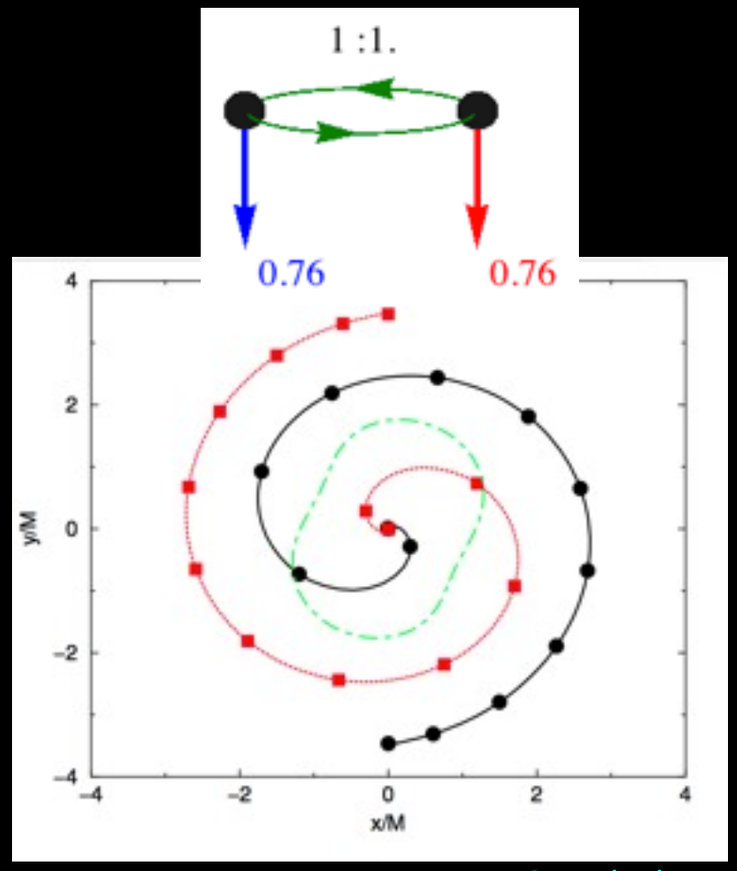
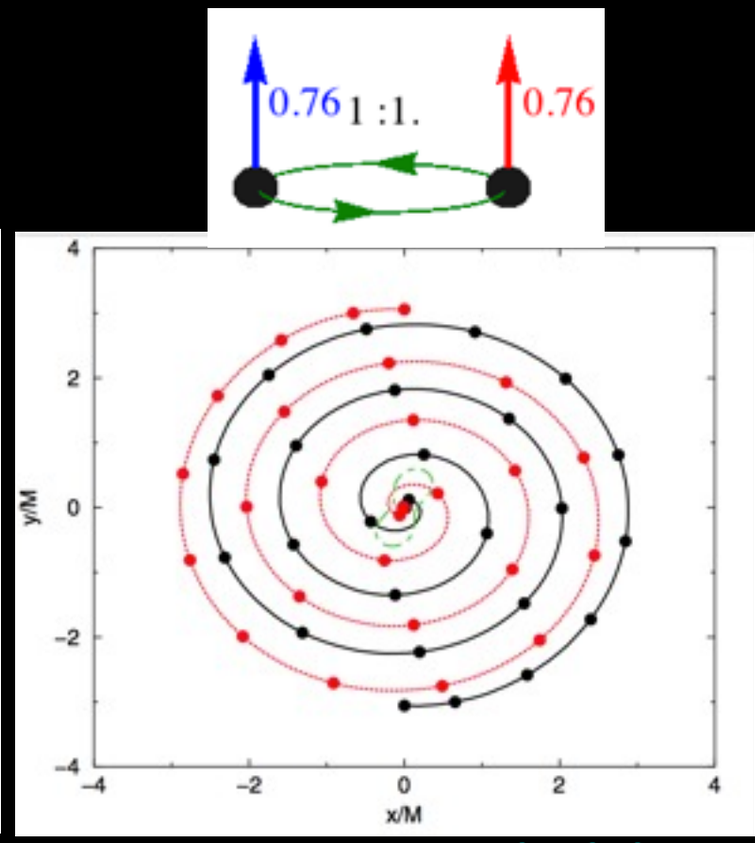


$\chi_{\rm final} = +0.44$



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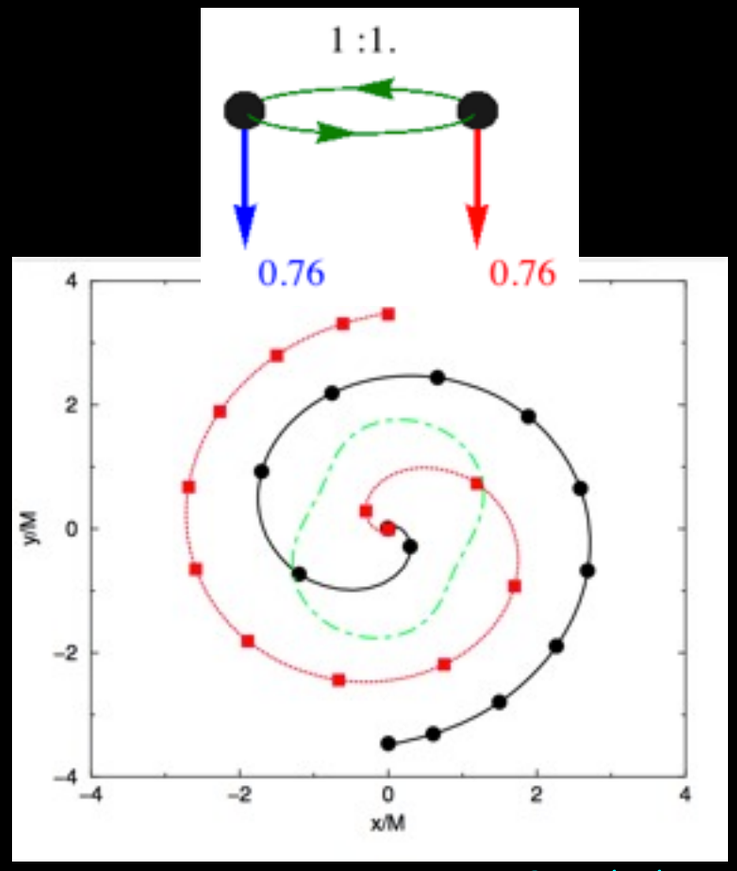

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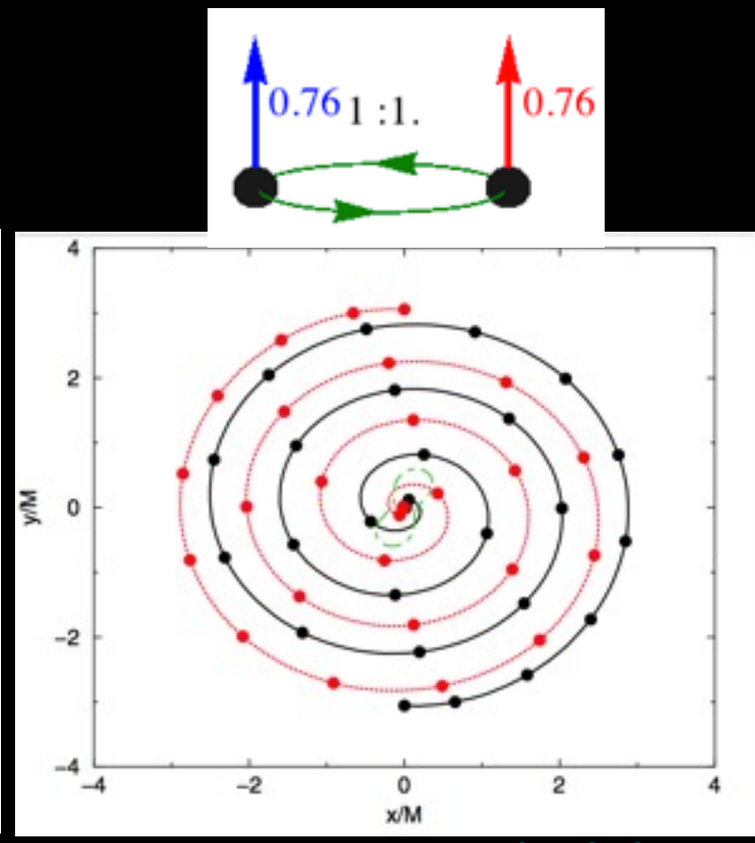

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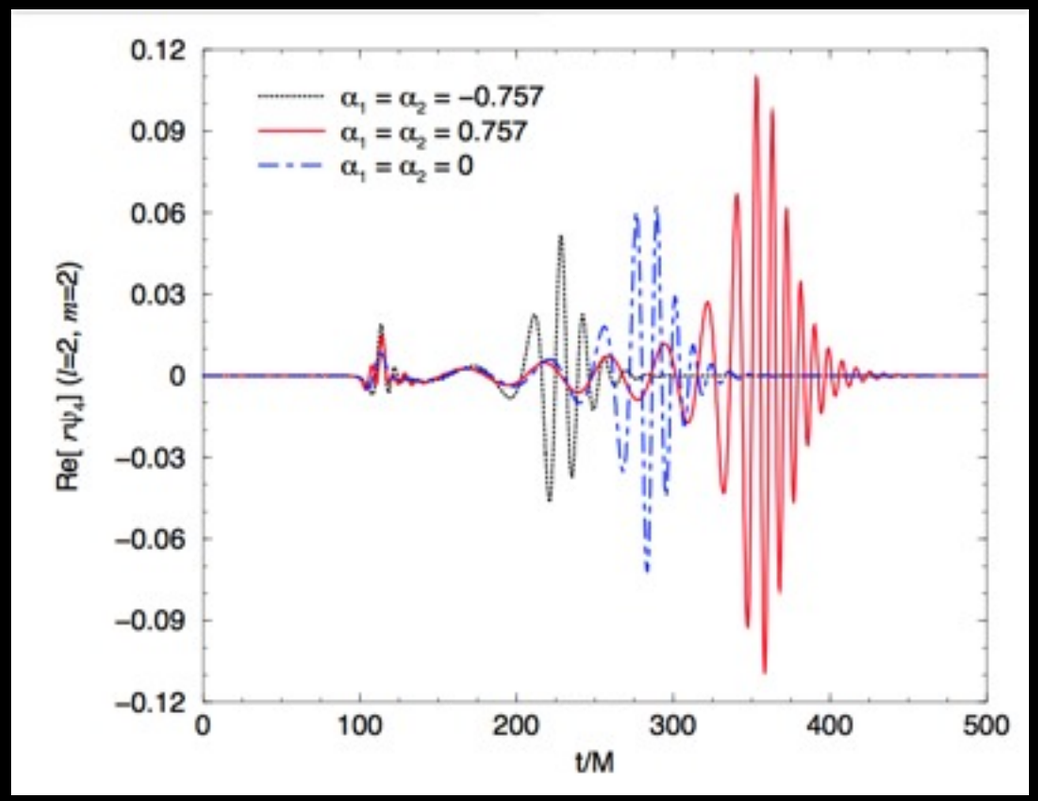
Figure by Campanelli appearing in Centrella et al, RMP **82**, 3069 (2010).



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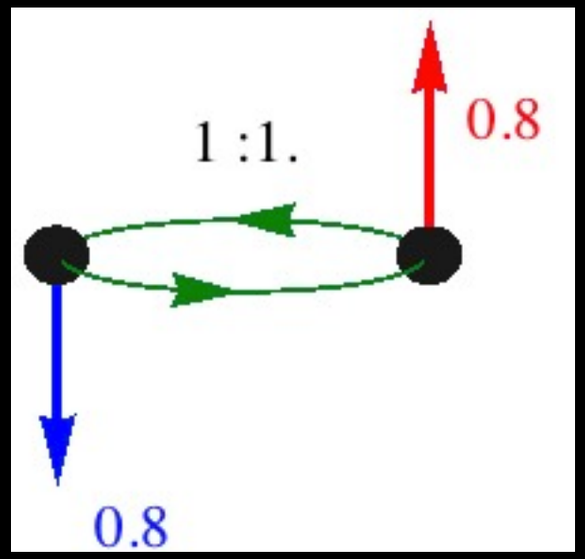
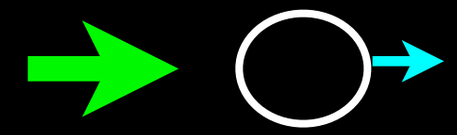


$v \approx 400$ km/s



Herrmann et al, APJ **661**, 430 (2007)

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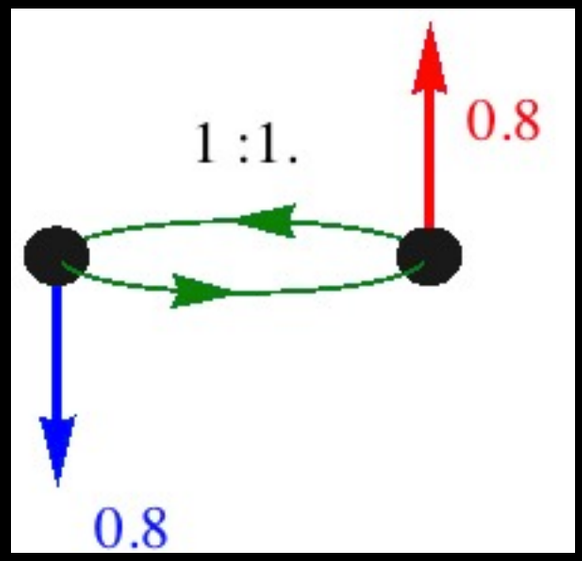

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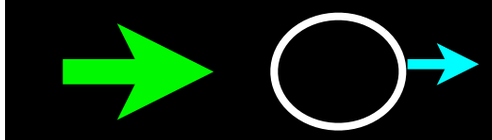

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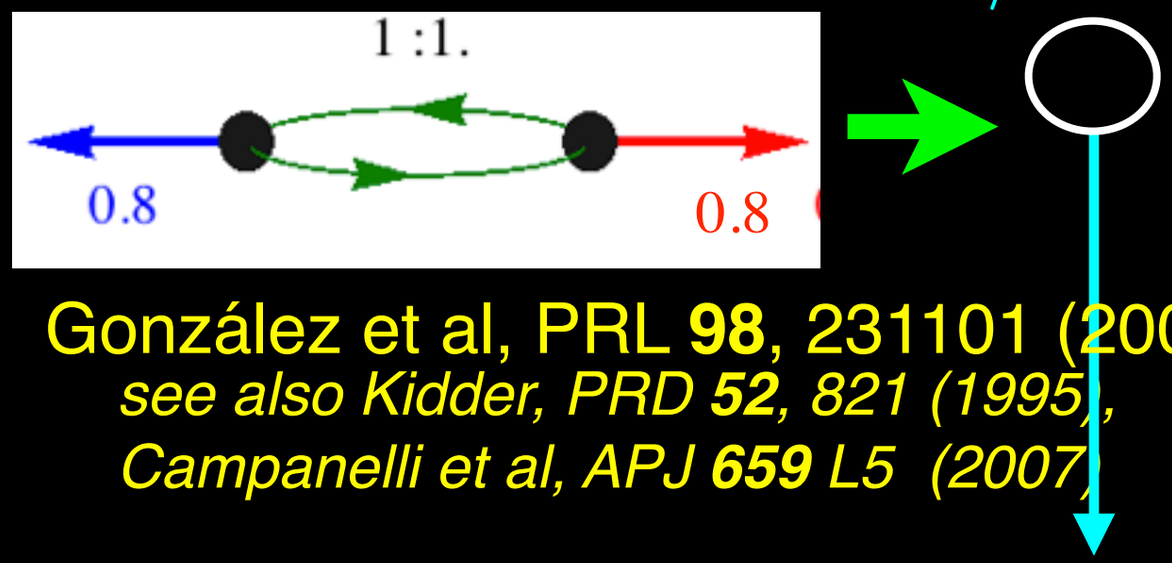

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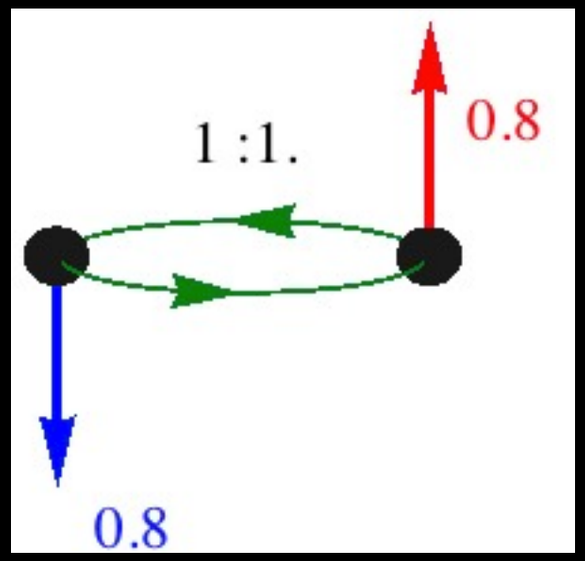

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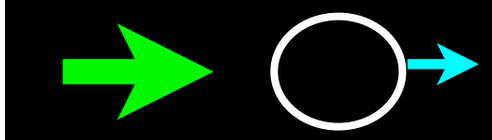

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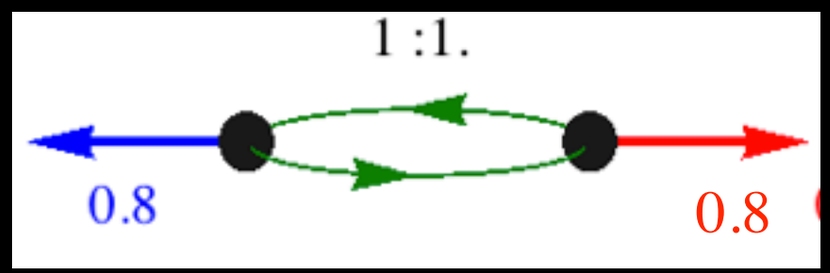

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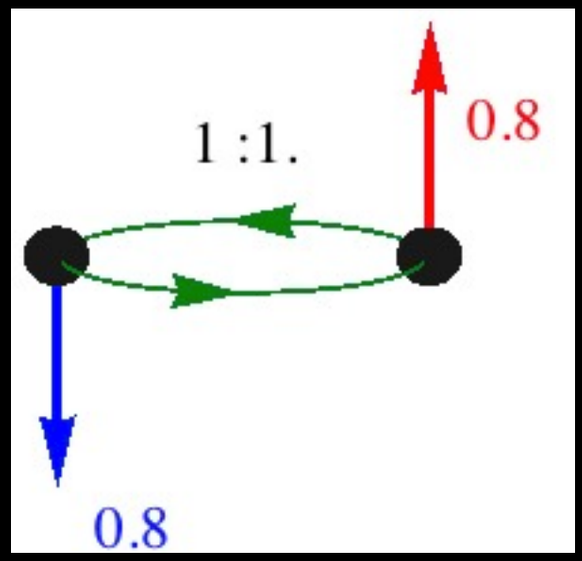

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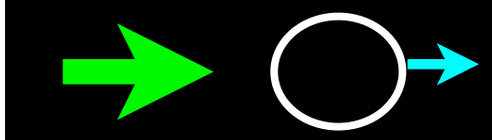

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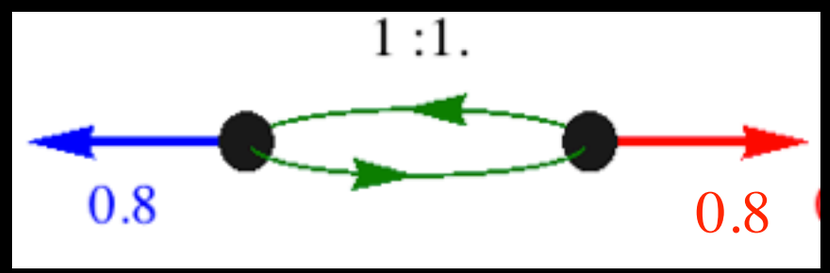

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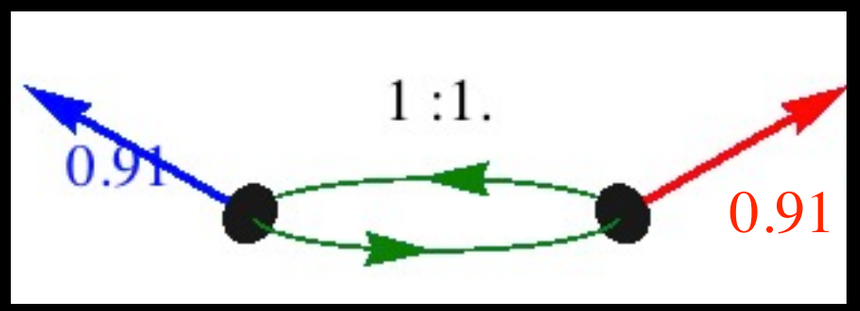

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Lousto & Zlochower,
PRL **107**, 231102 (2011)

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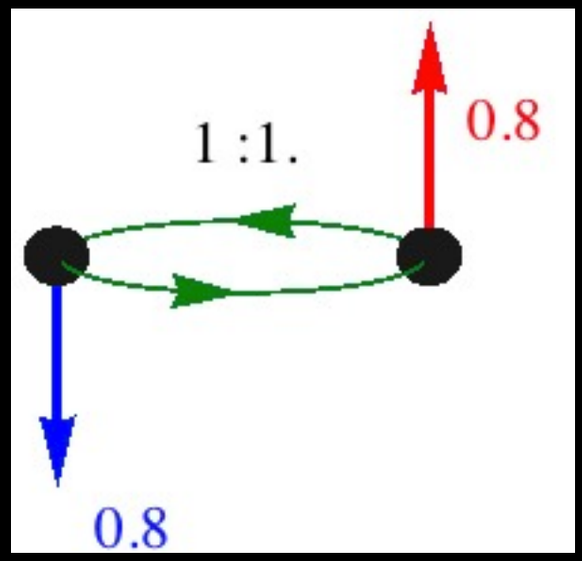

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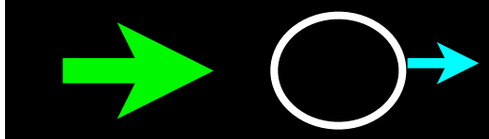

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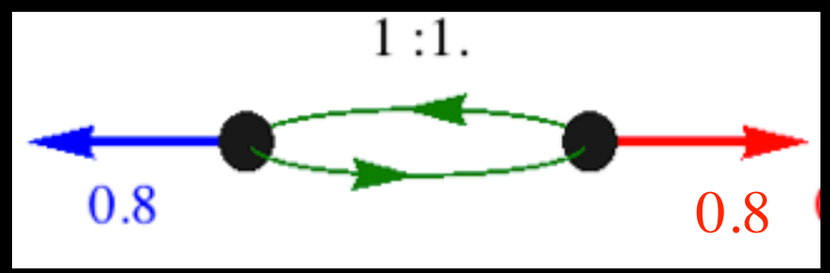

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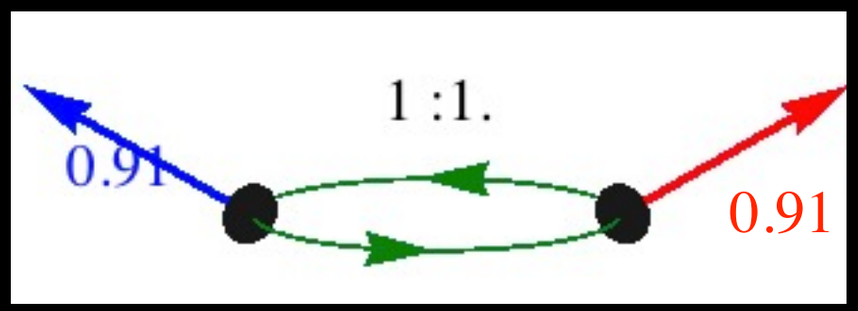

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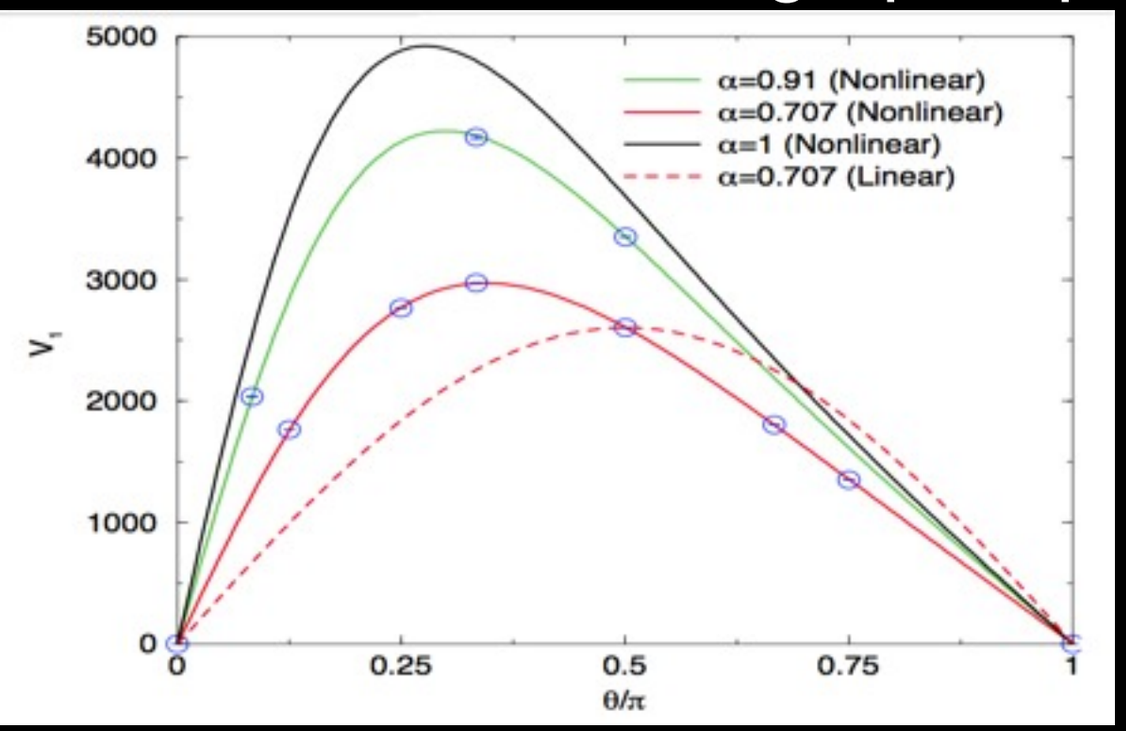

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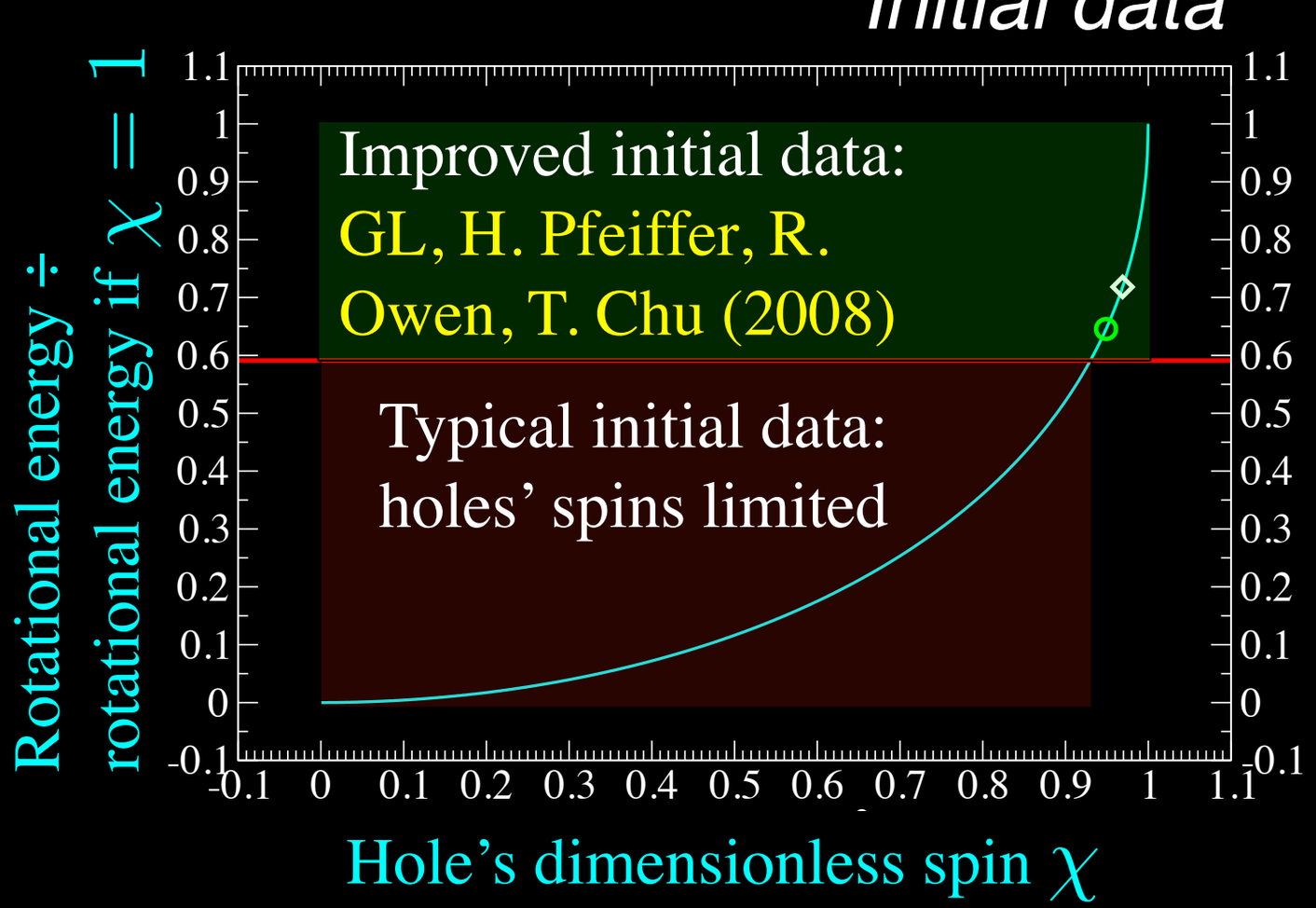

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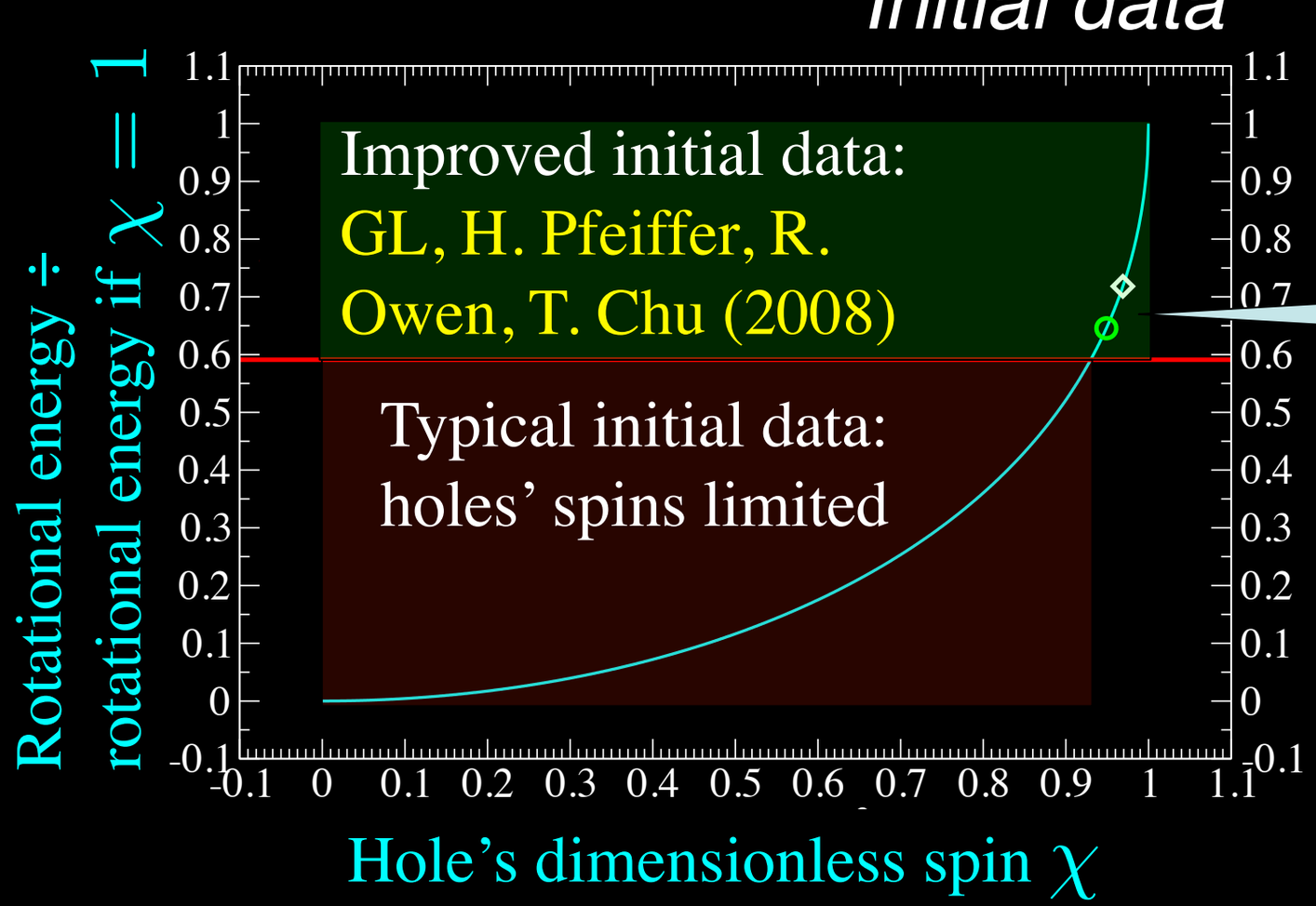

Highest black-hole spins simulated to date (only to exceed the "typical" ("Bowen-York") initial-data limit

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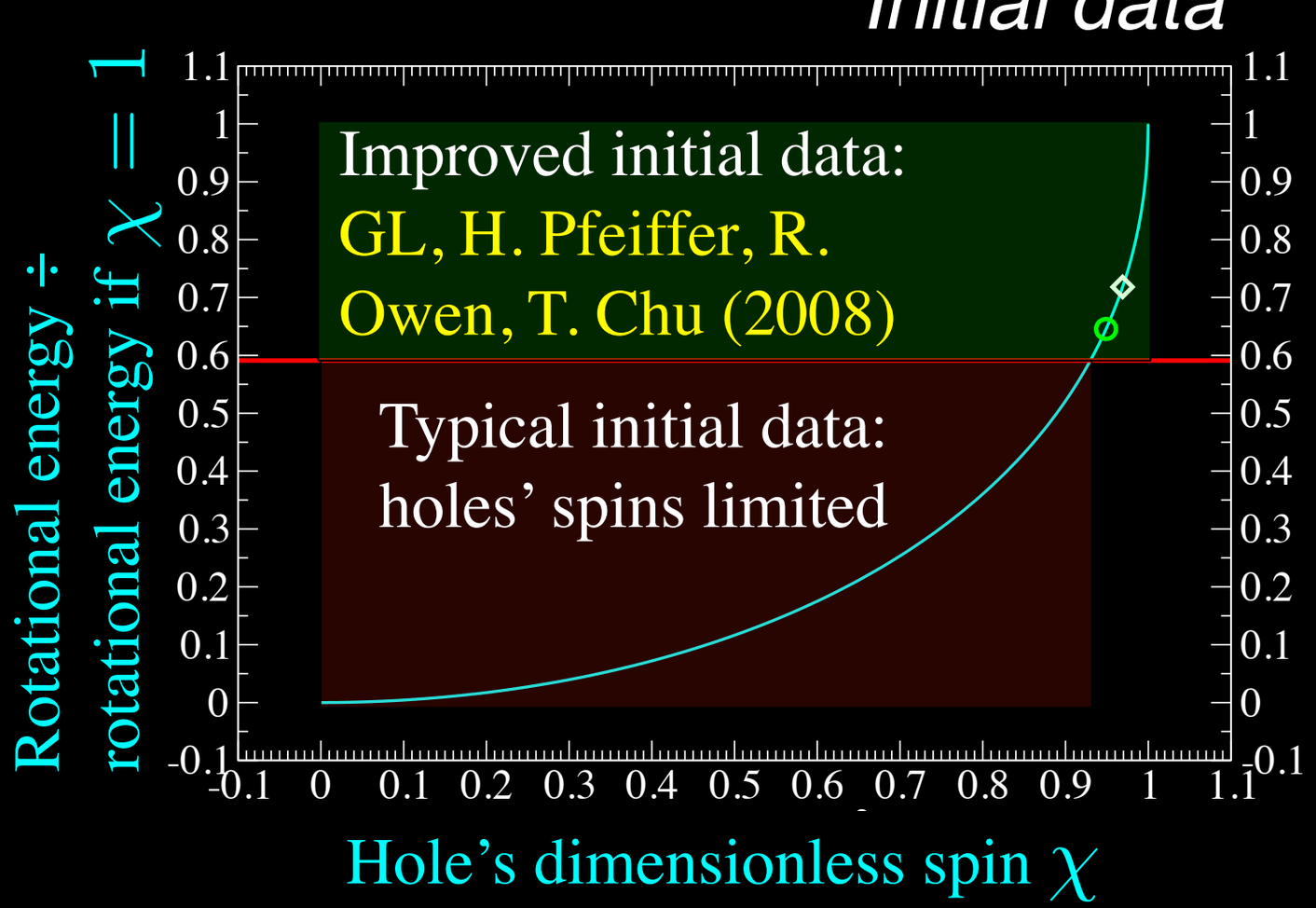

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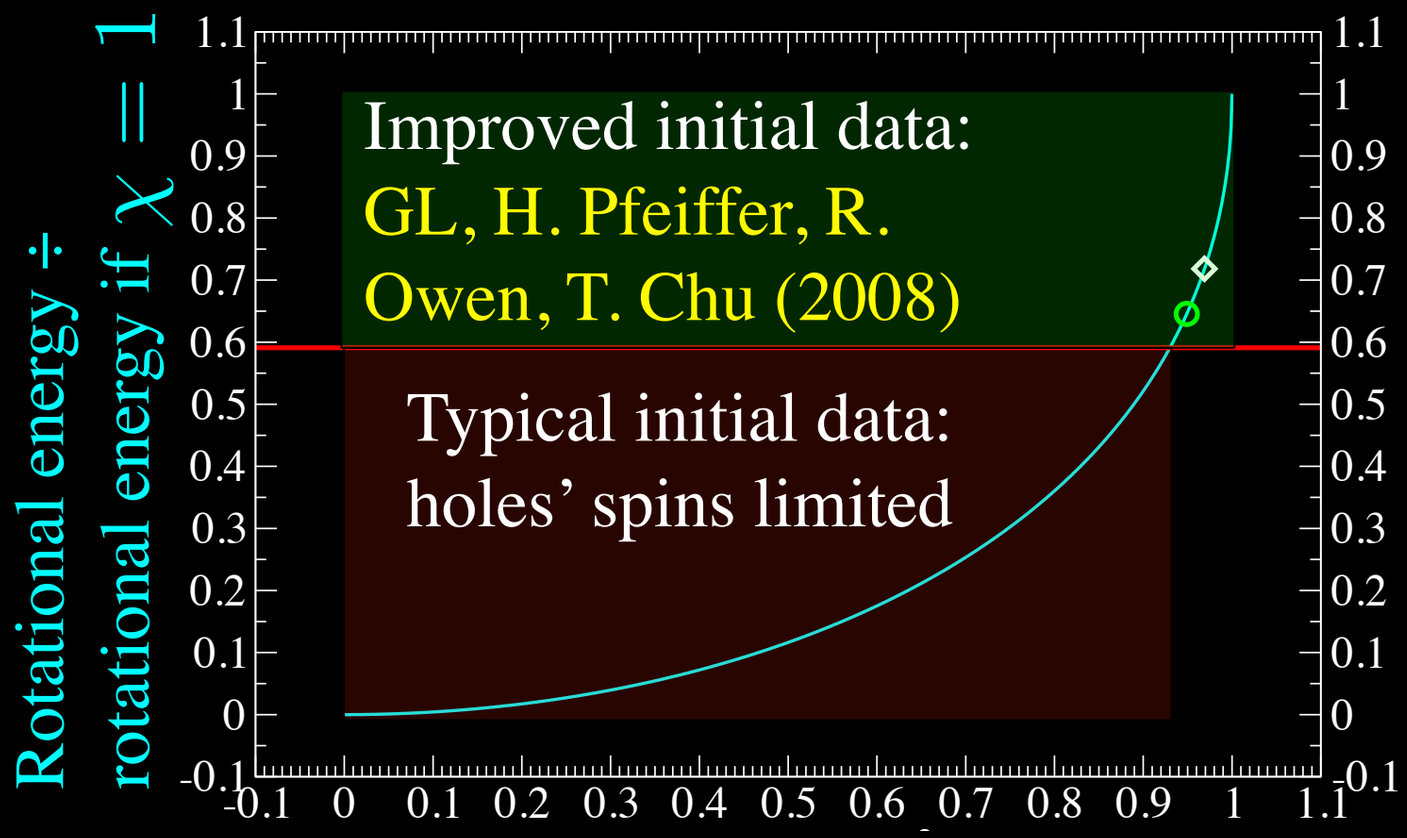

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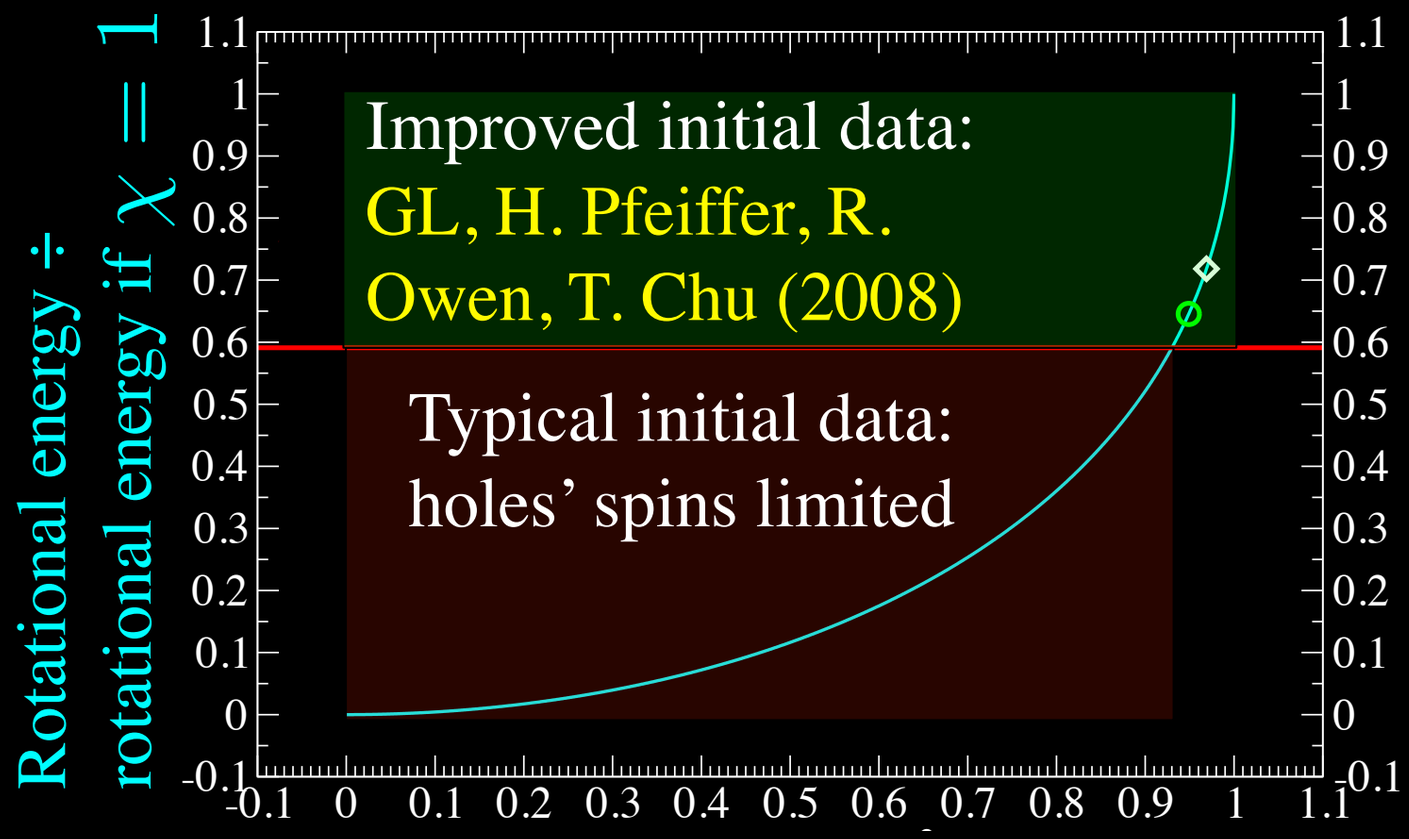

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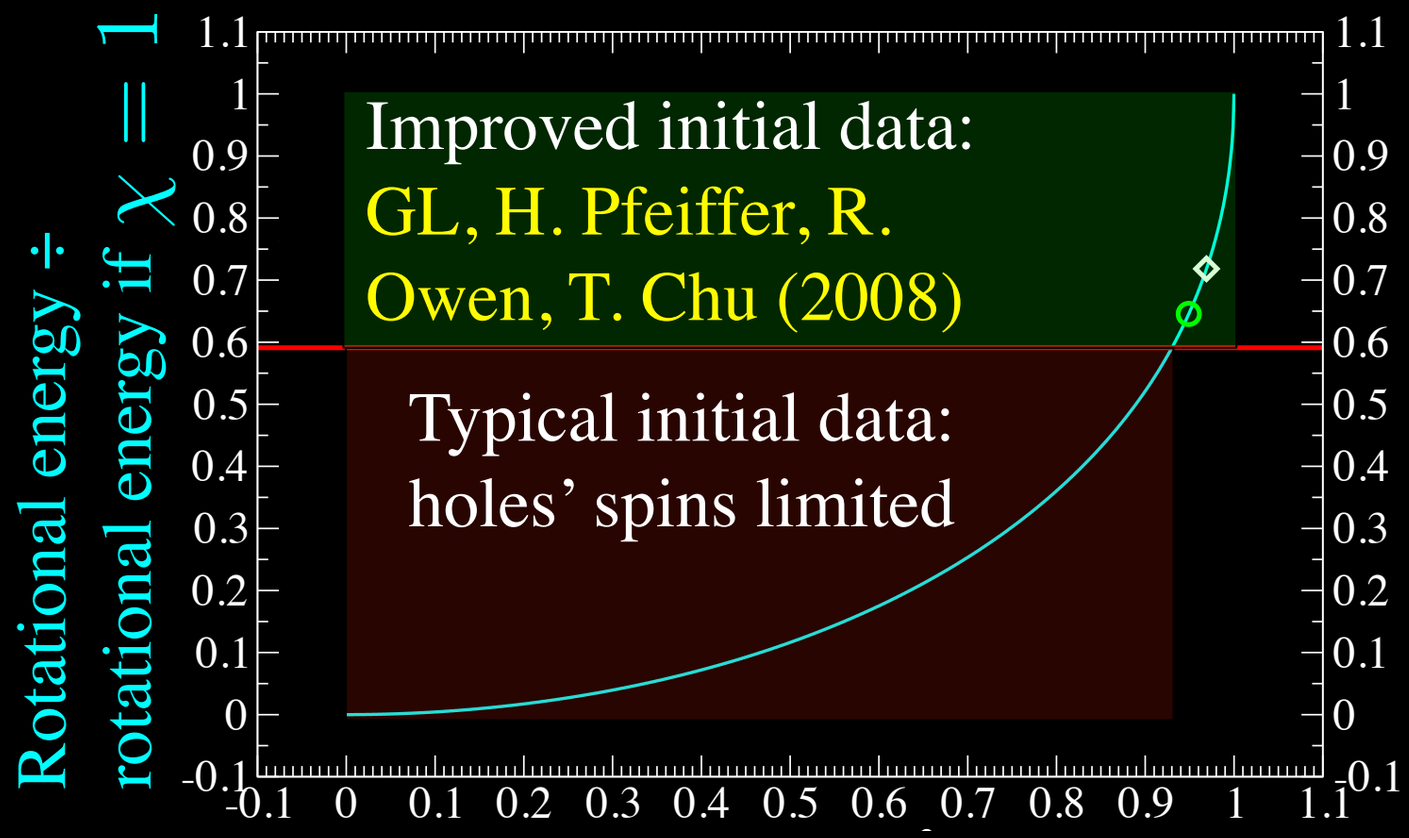

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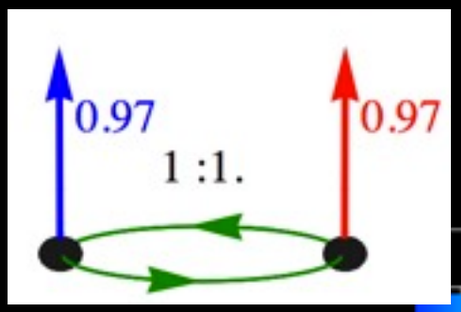

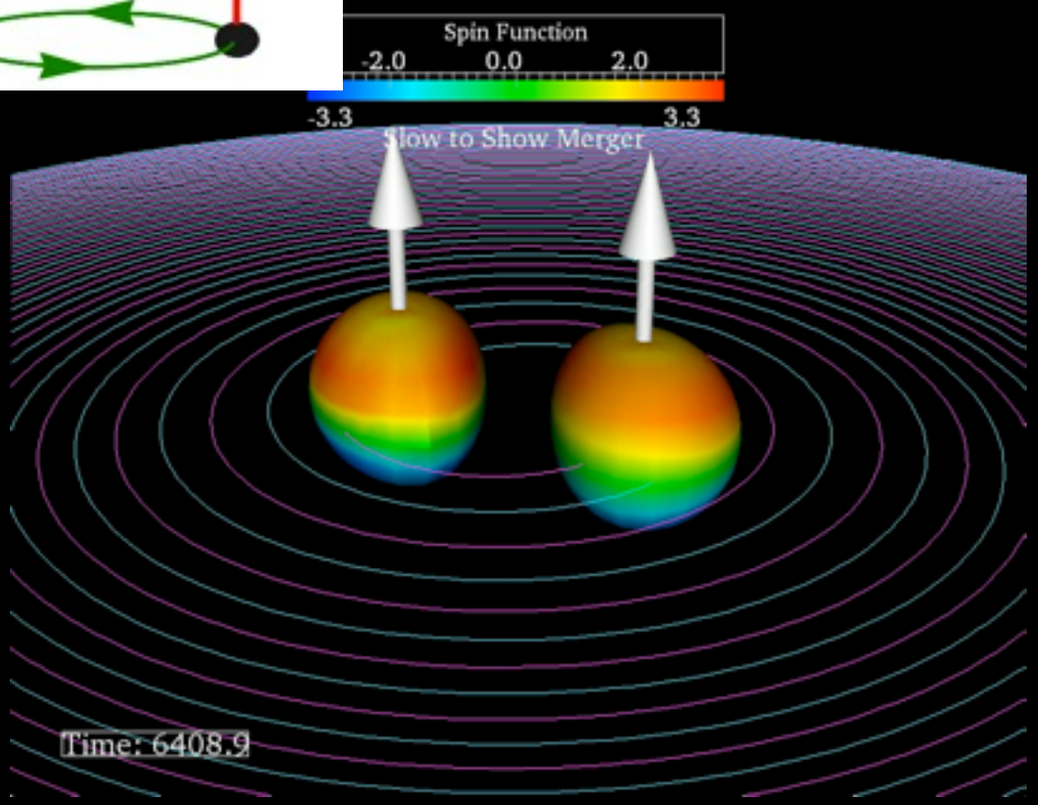

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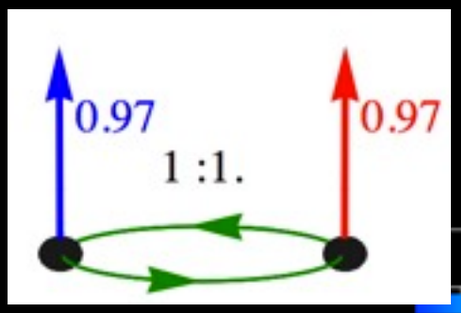
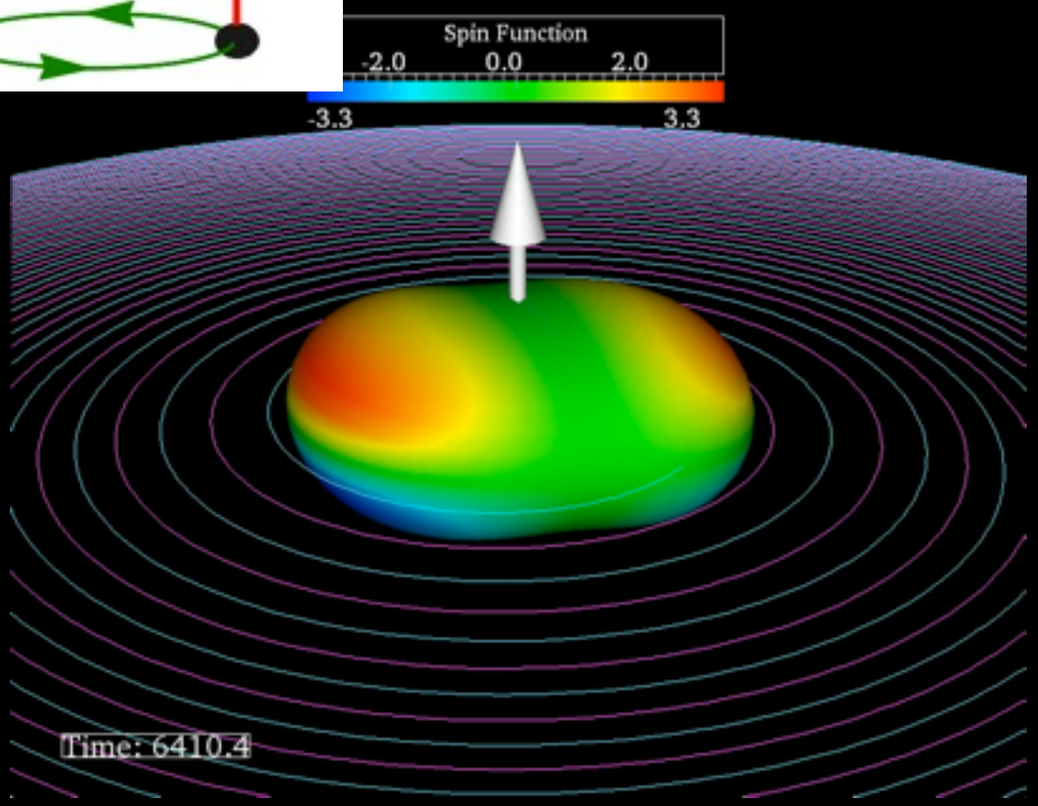
GL, Boyle, Scheel, Szilágyi, CQG **29**, 045003 (2012)





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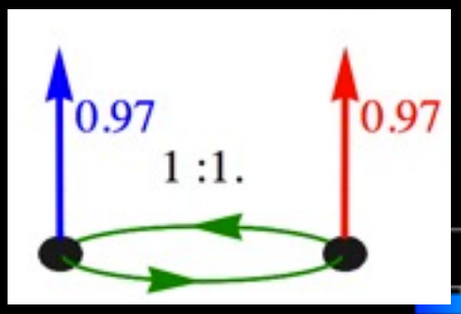

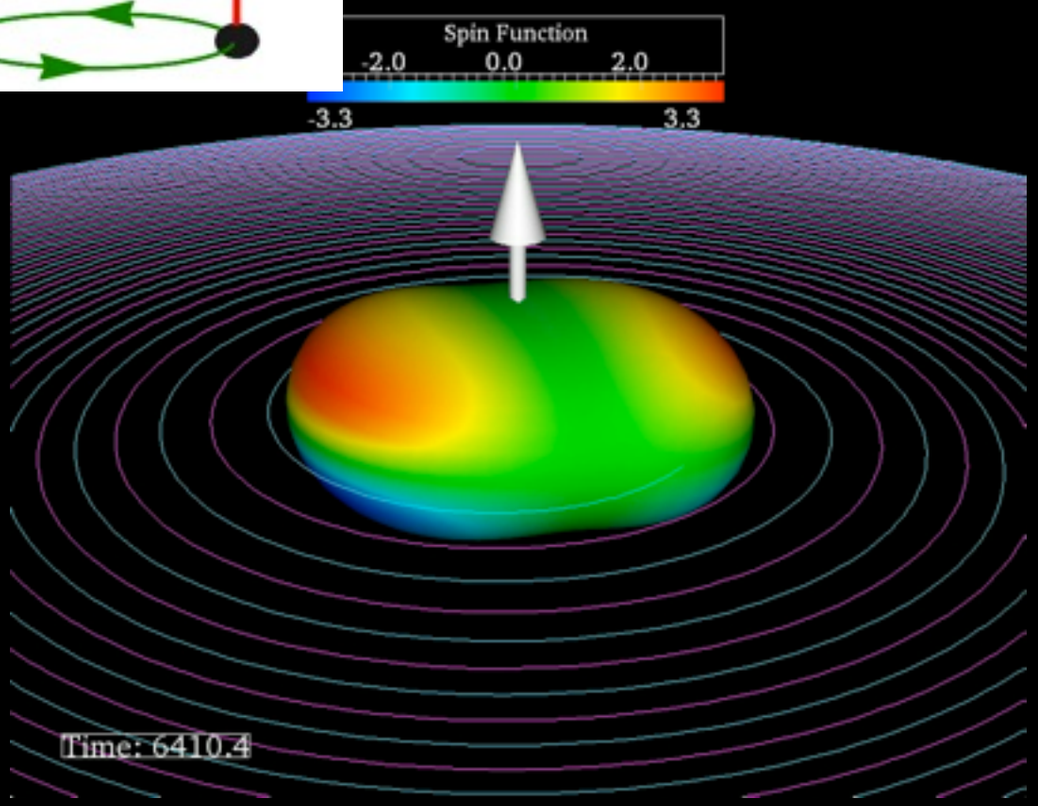

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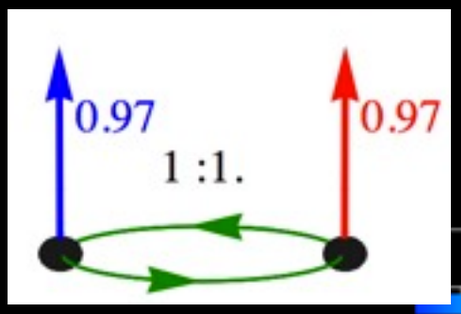

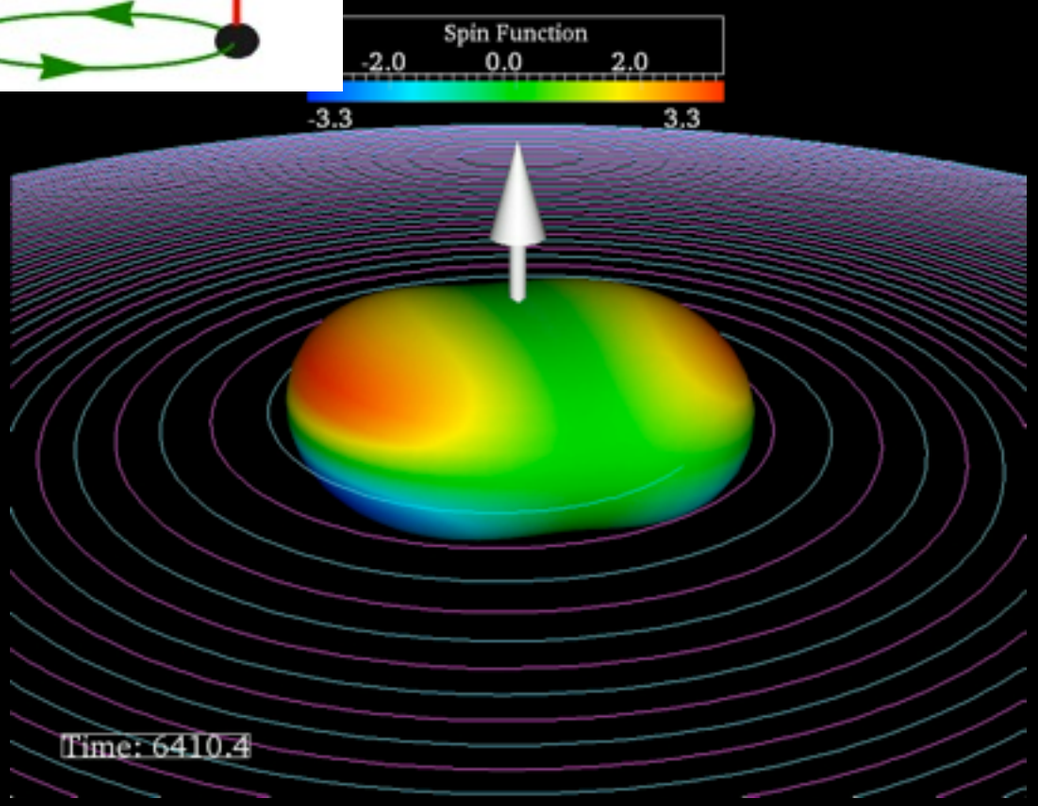

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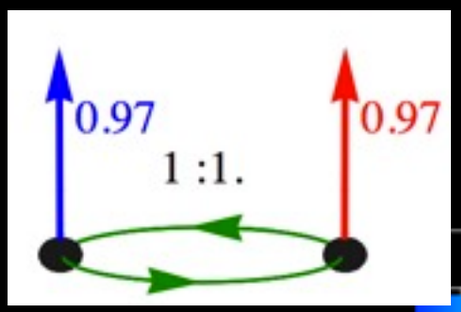

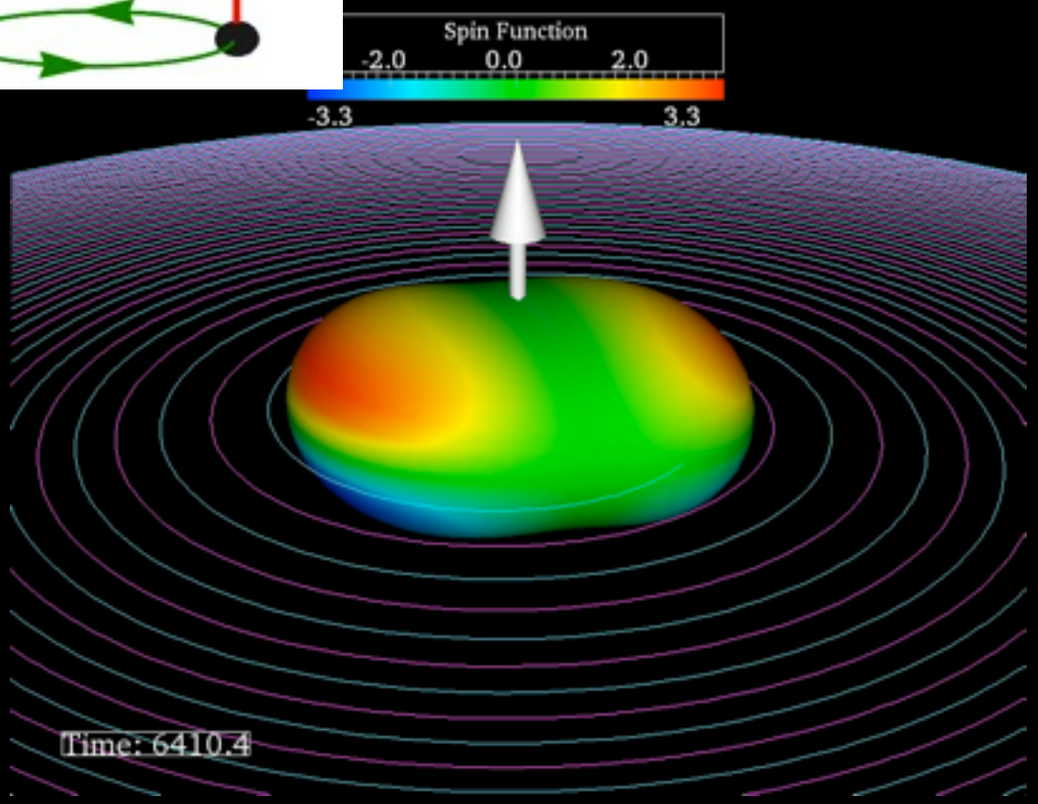

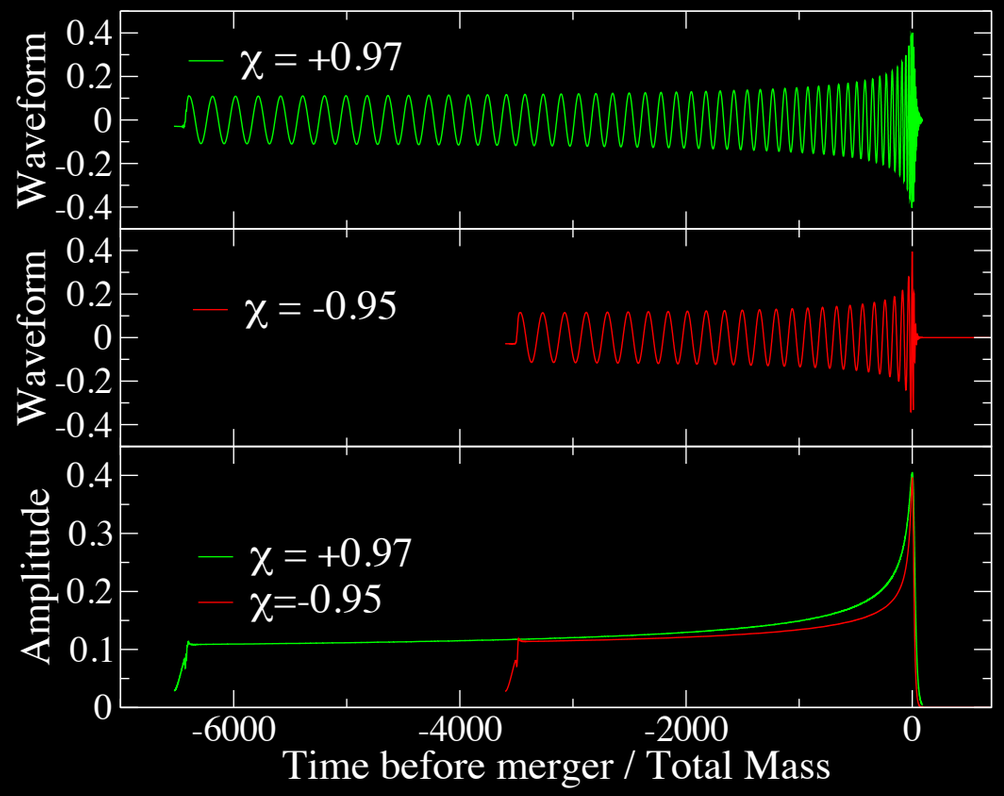

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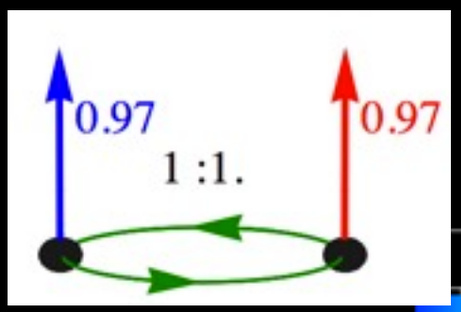

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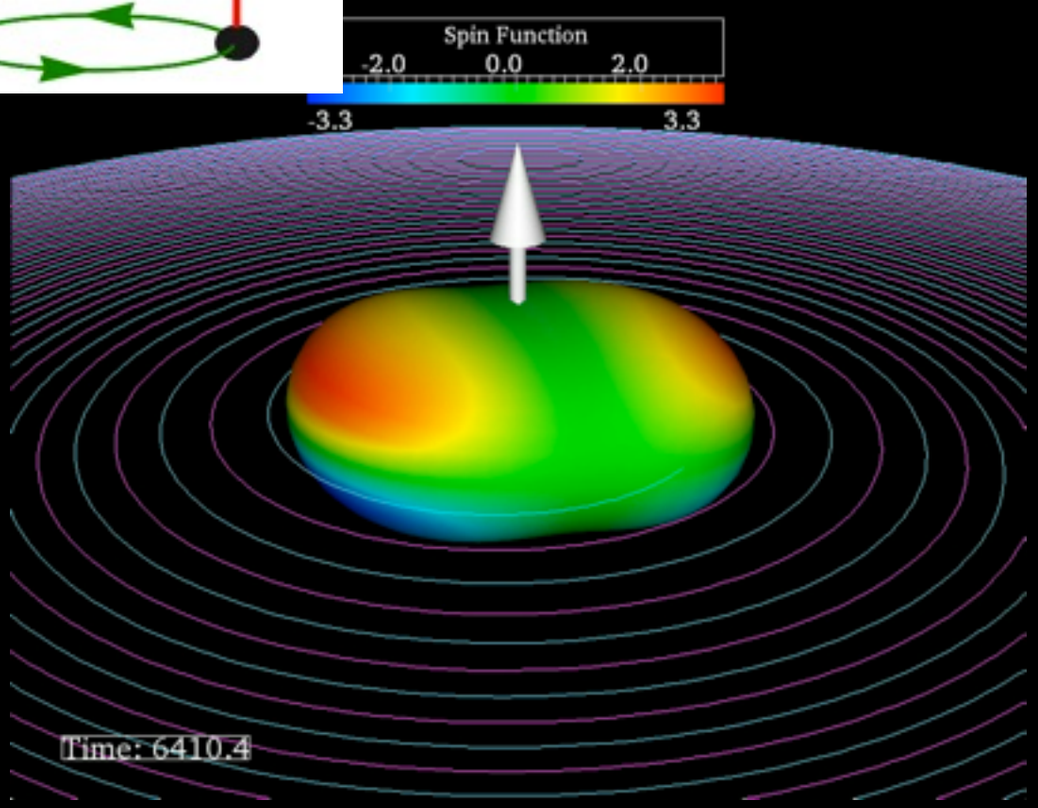

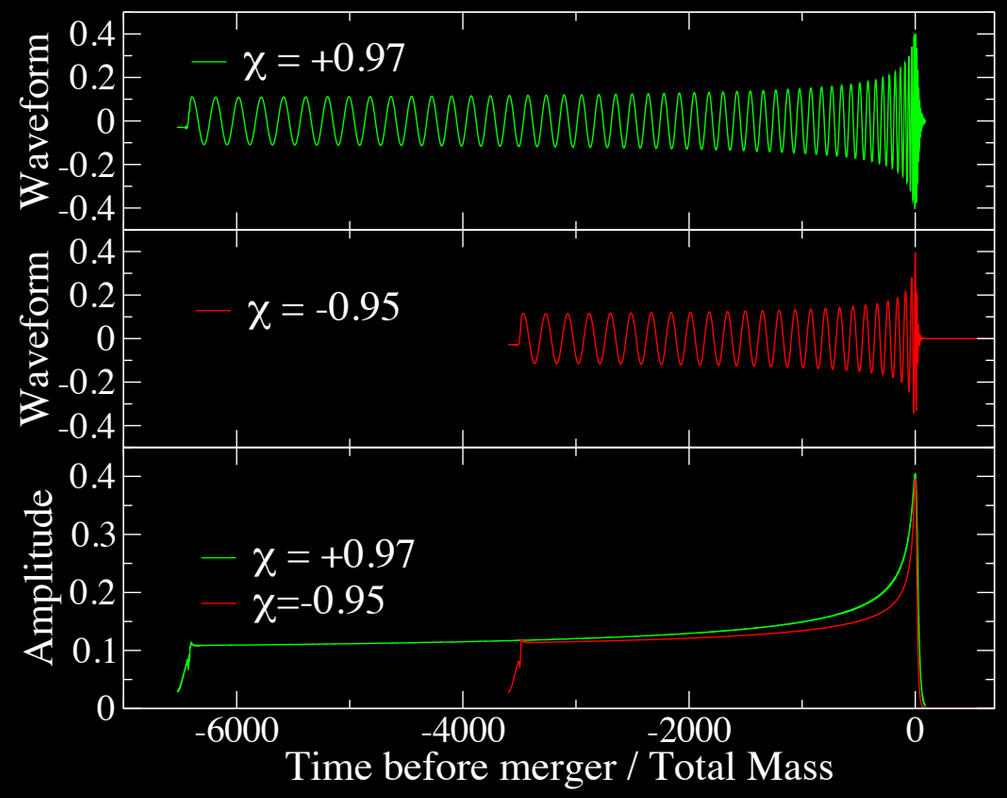

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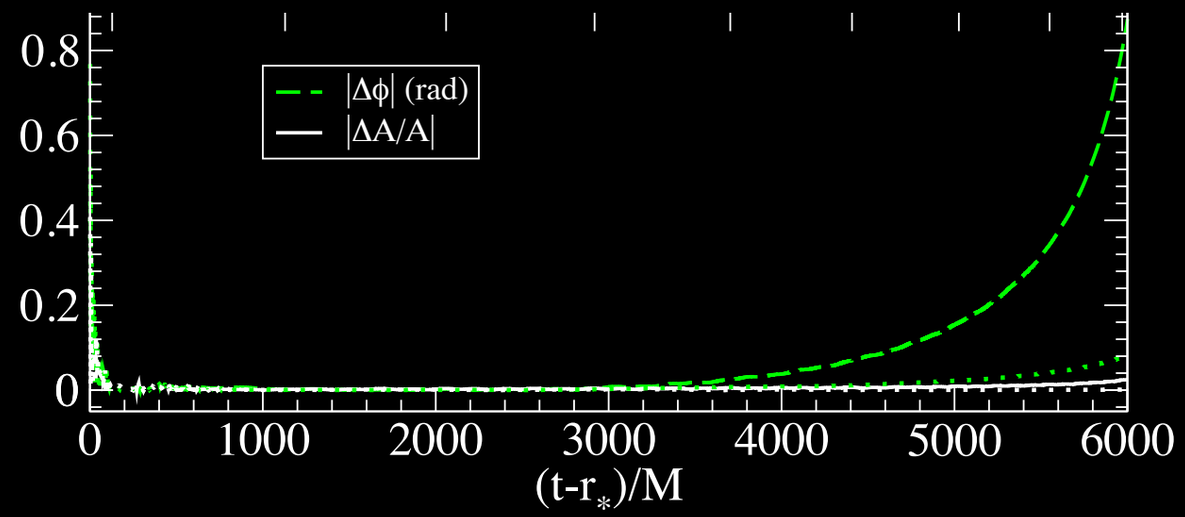

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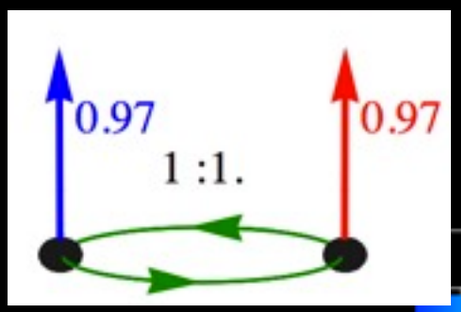

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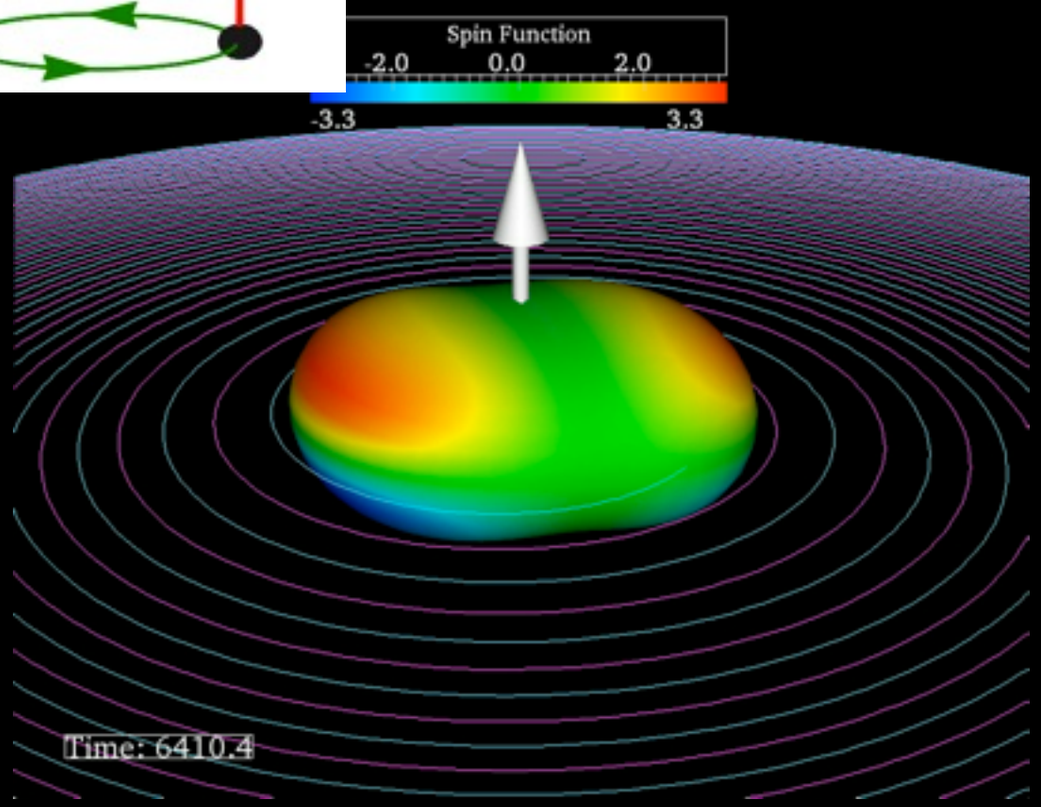

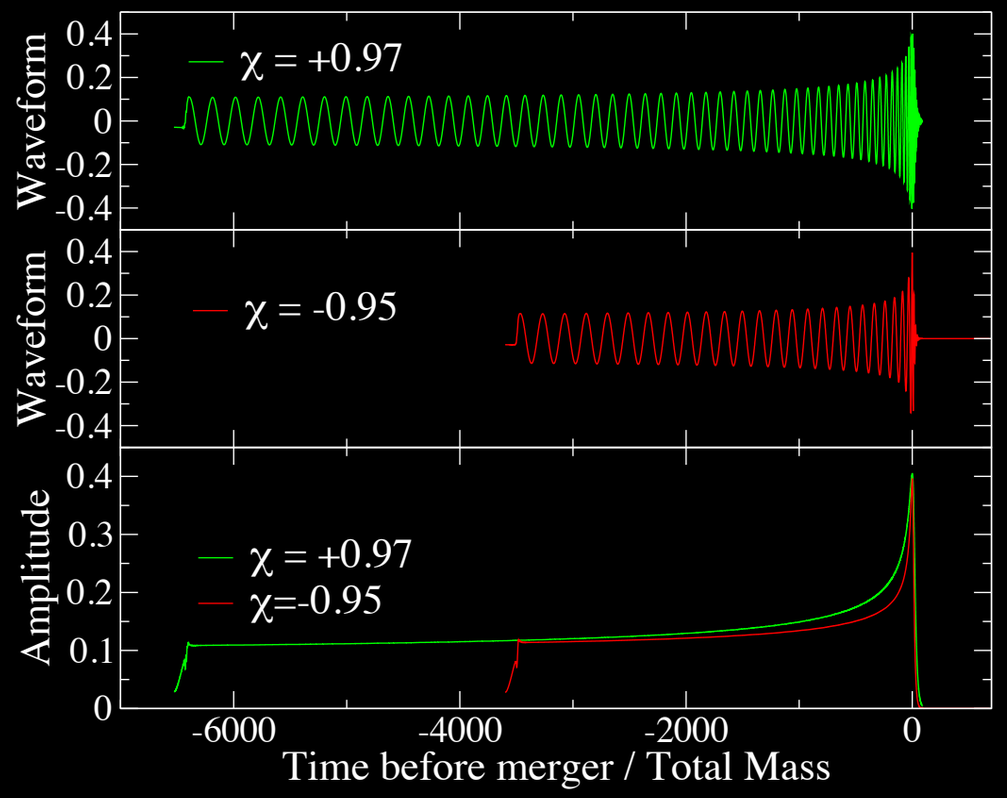

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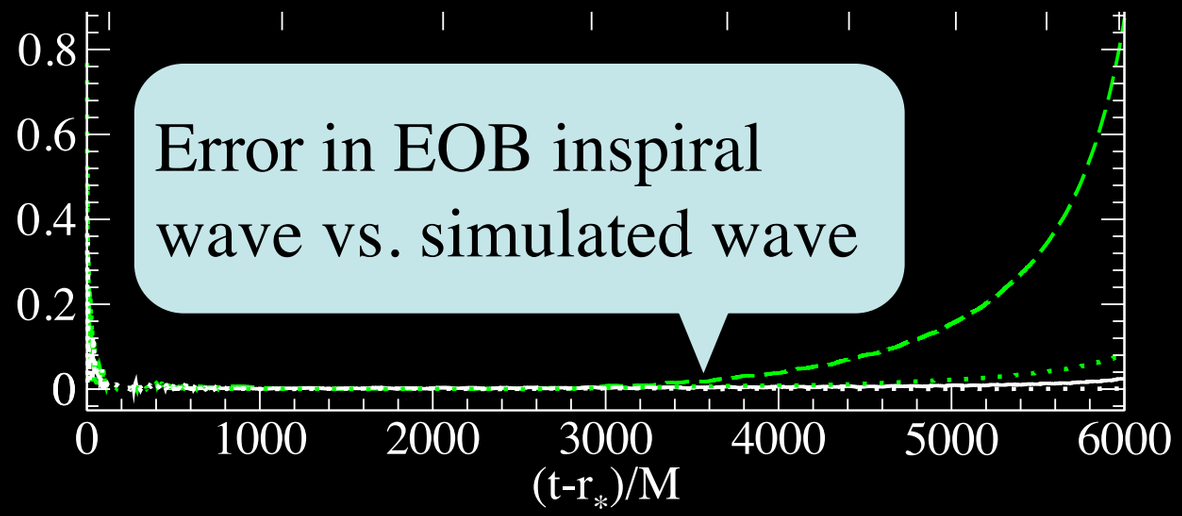

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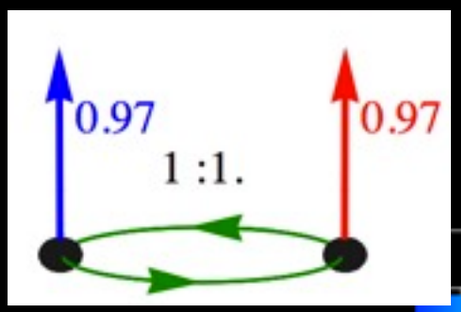

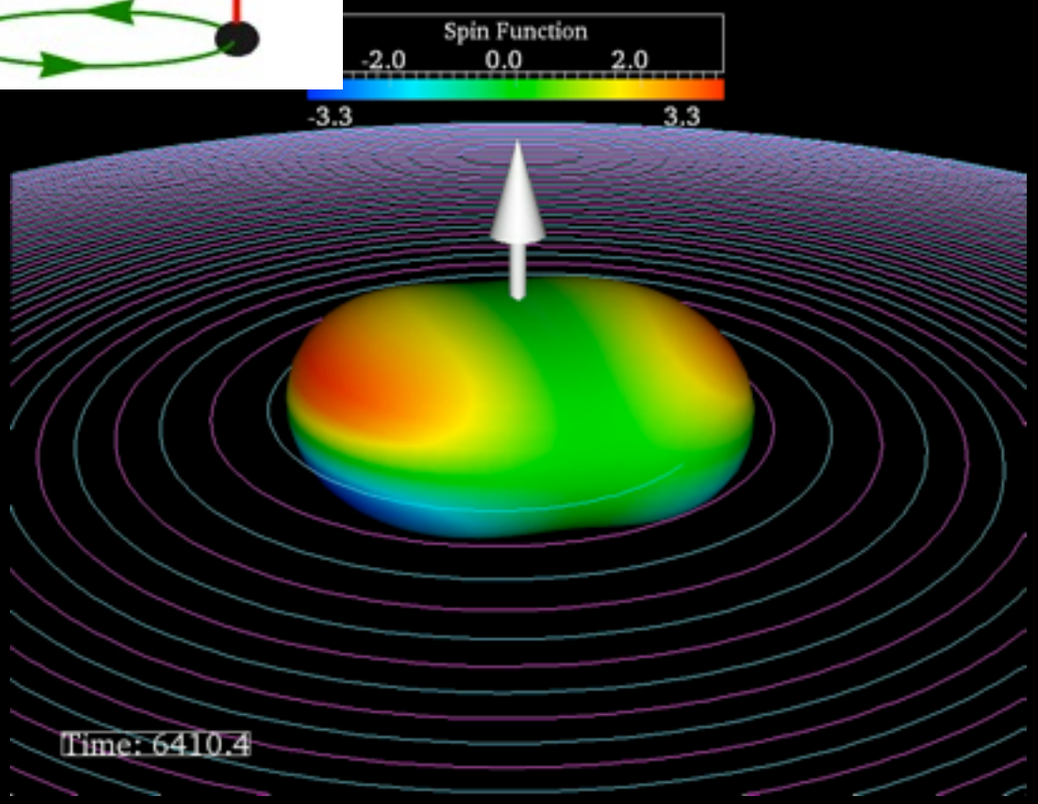

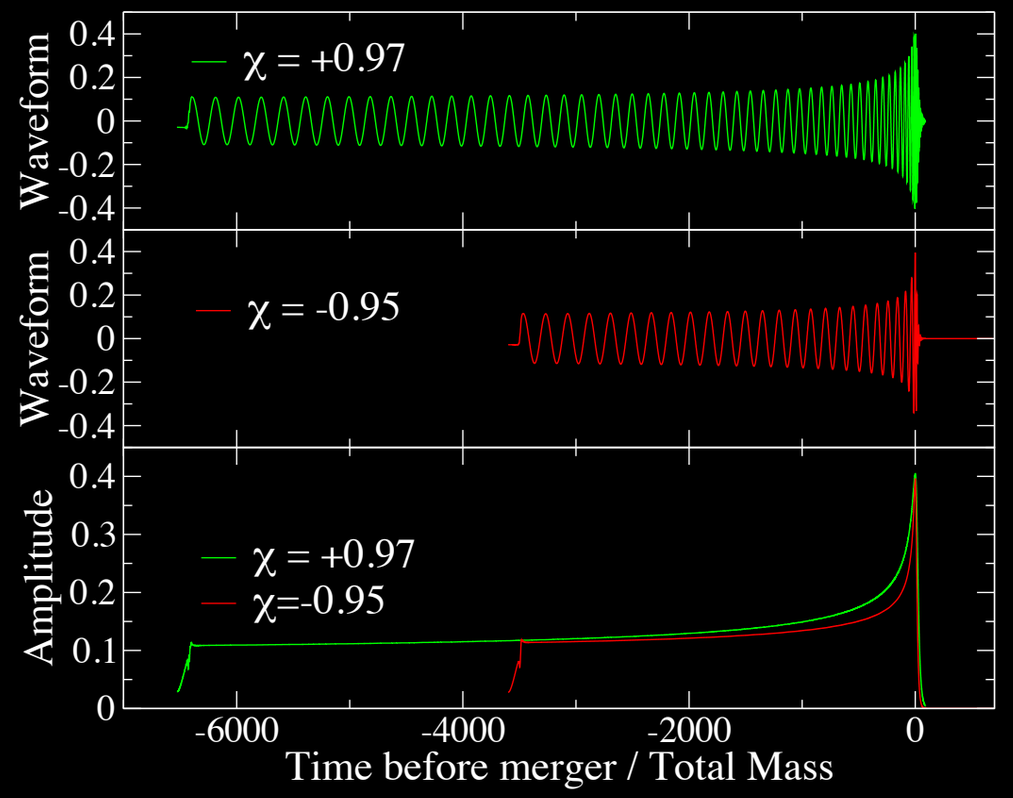

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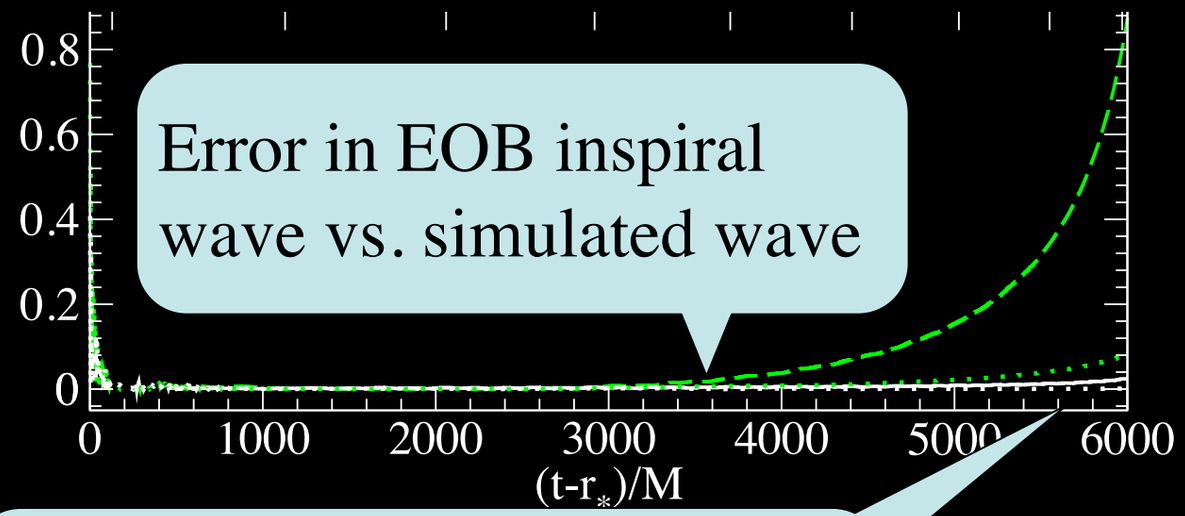

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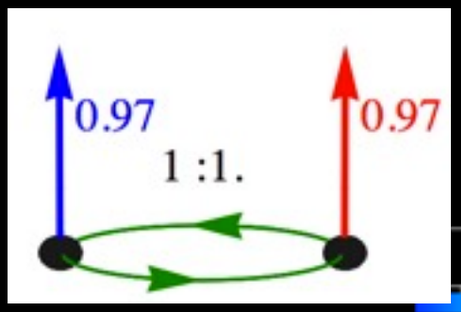

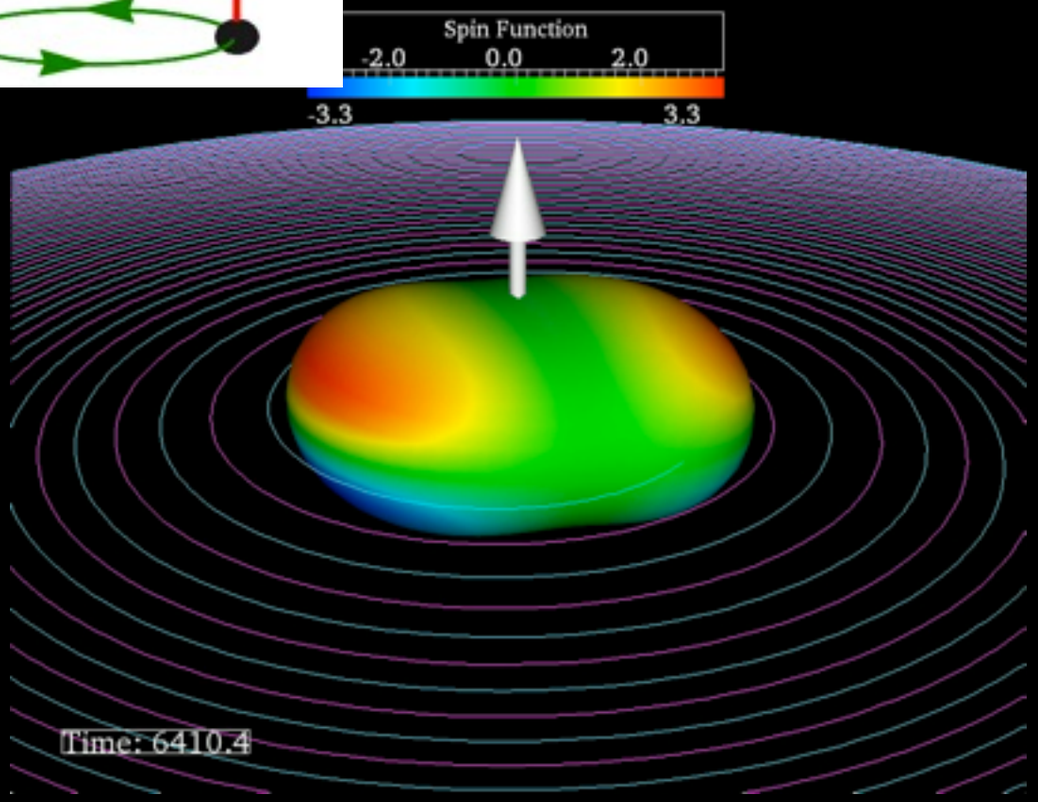

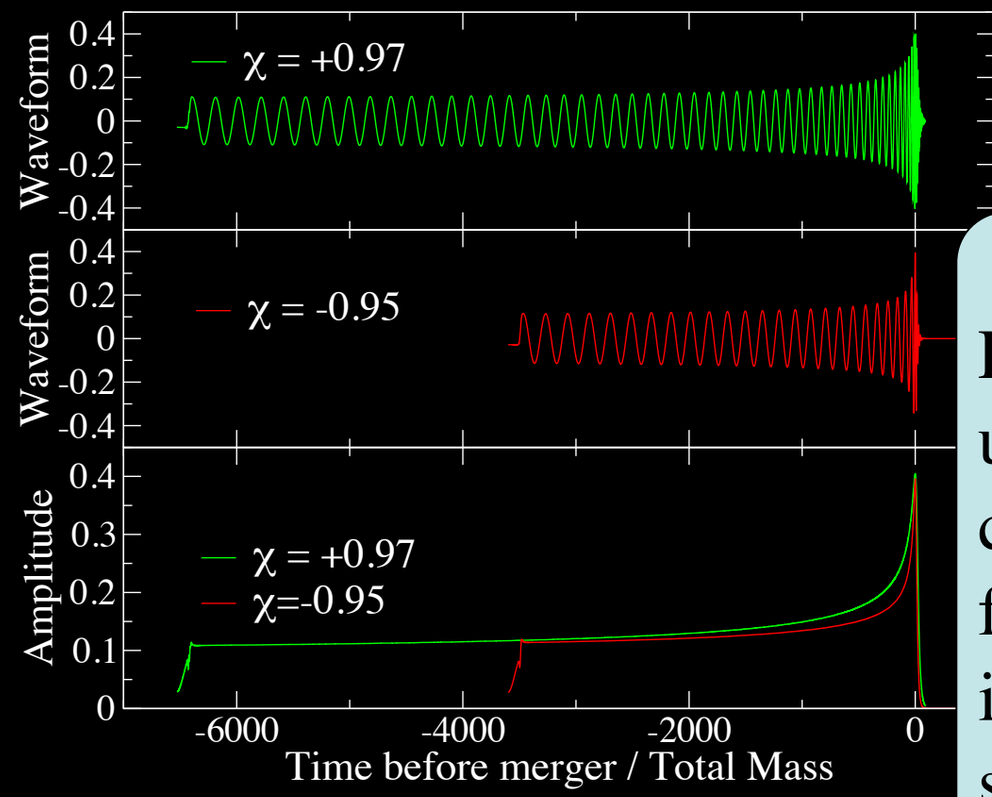

EOB unreliable currently for merger if aligned spin $\chi \gtrsim 0.7$

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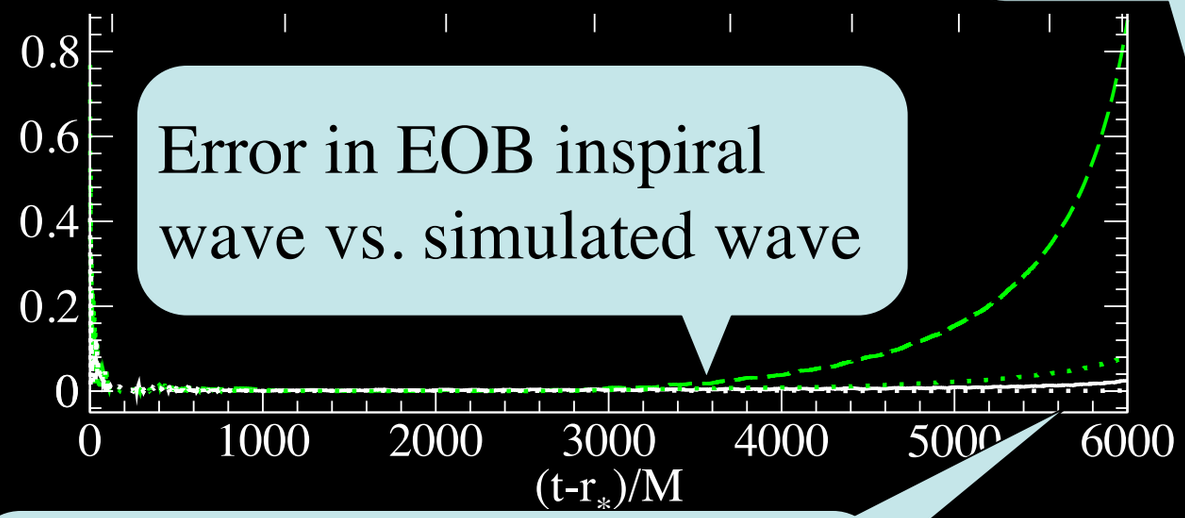

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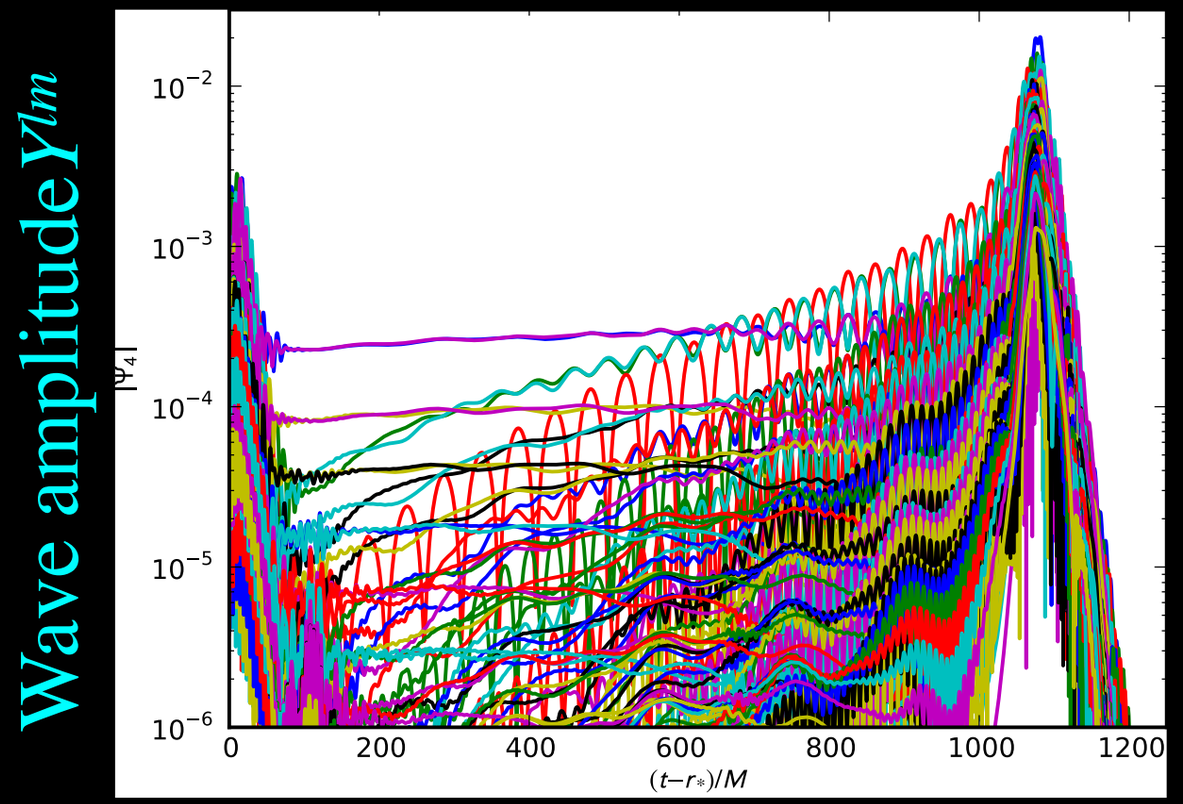
Figure courtesy M. Boyle & L. Kidder



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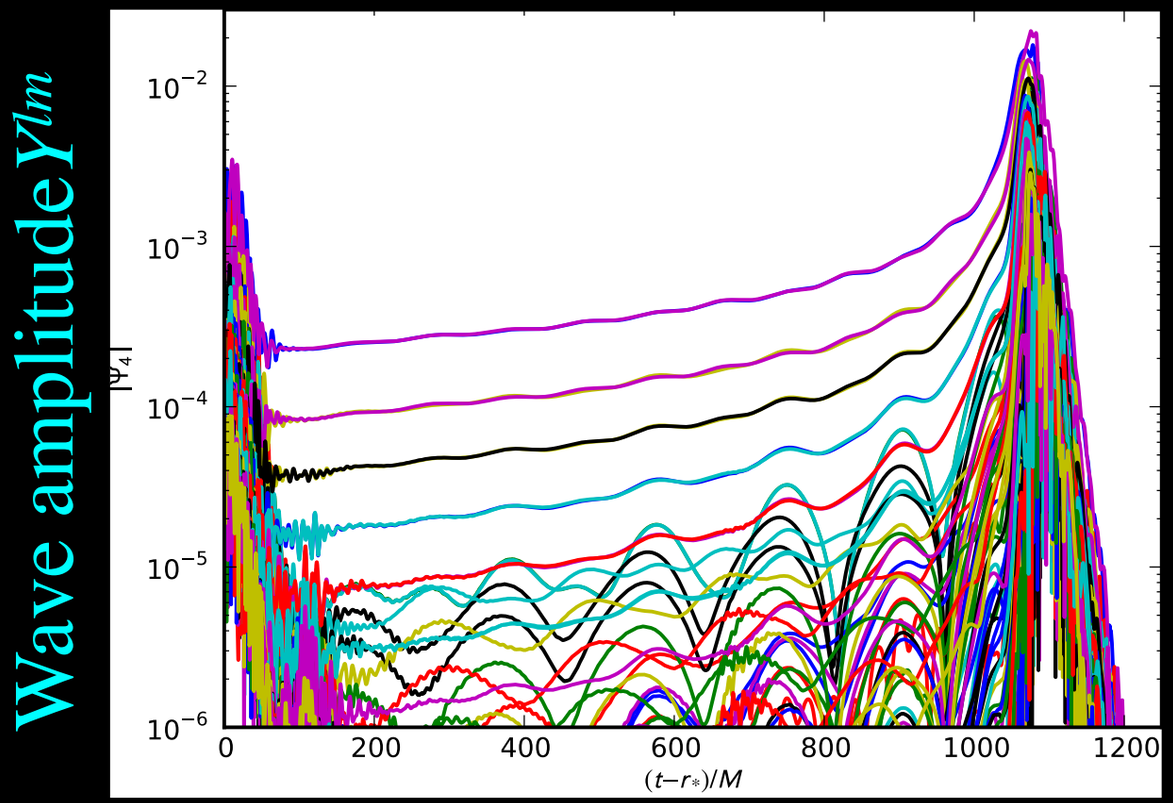
Radiation-aligned frame
Schmidt et al, PRD **84**, 024046 (2011)
O'Shaughnessy et al,
PRD **84**, 124002 (2011)

Figure courtesy M. Boyle & L. Kidder



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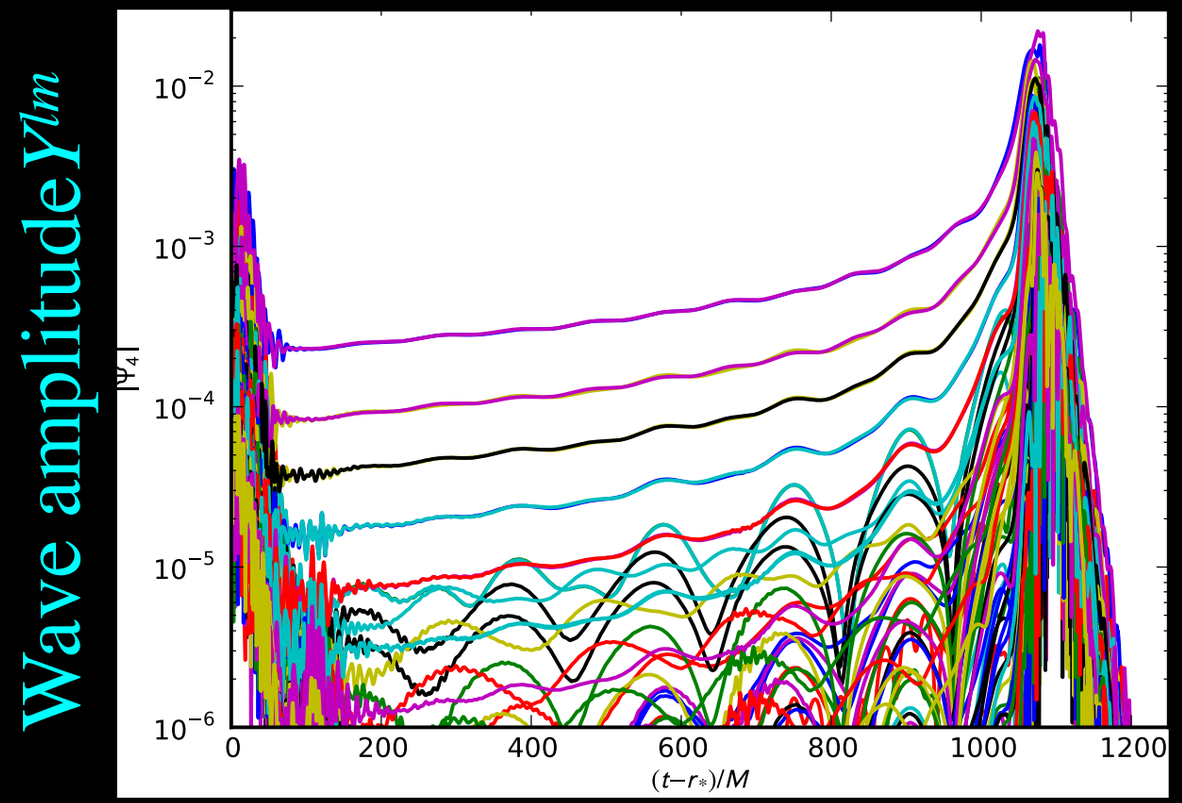

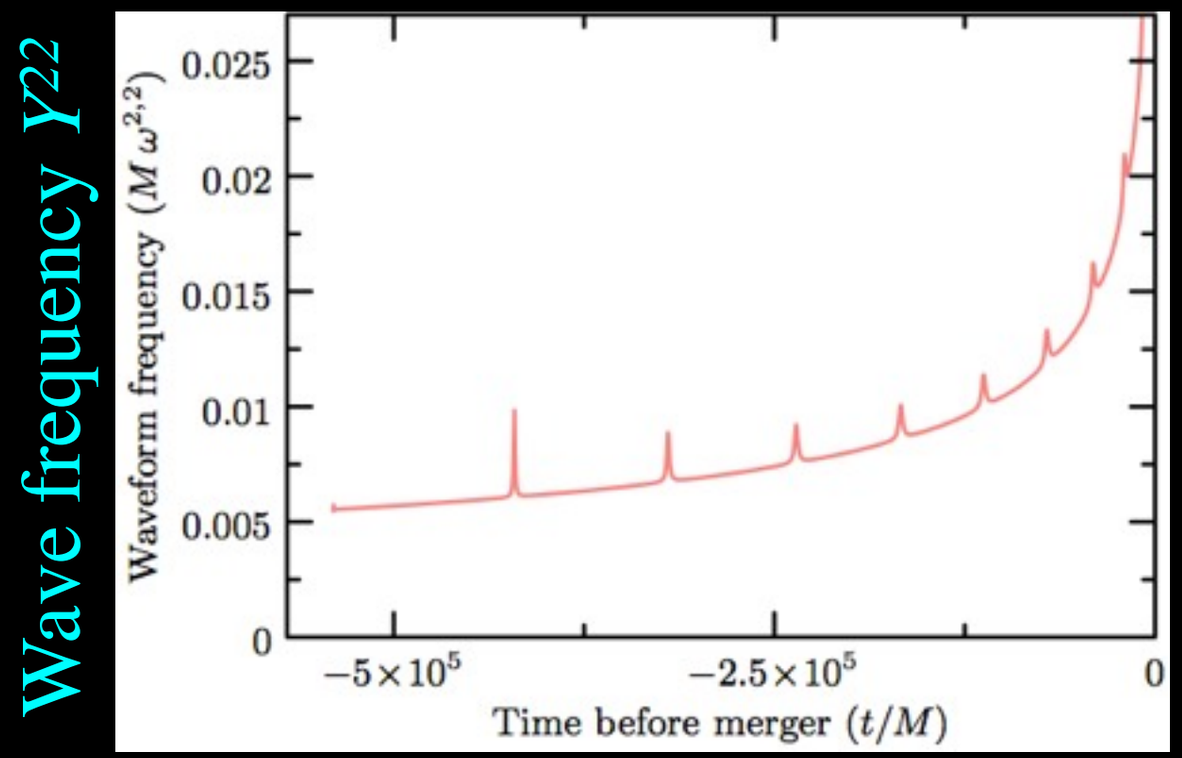

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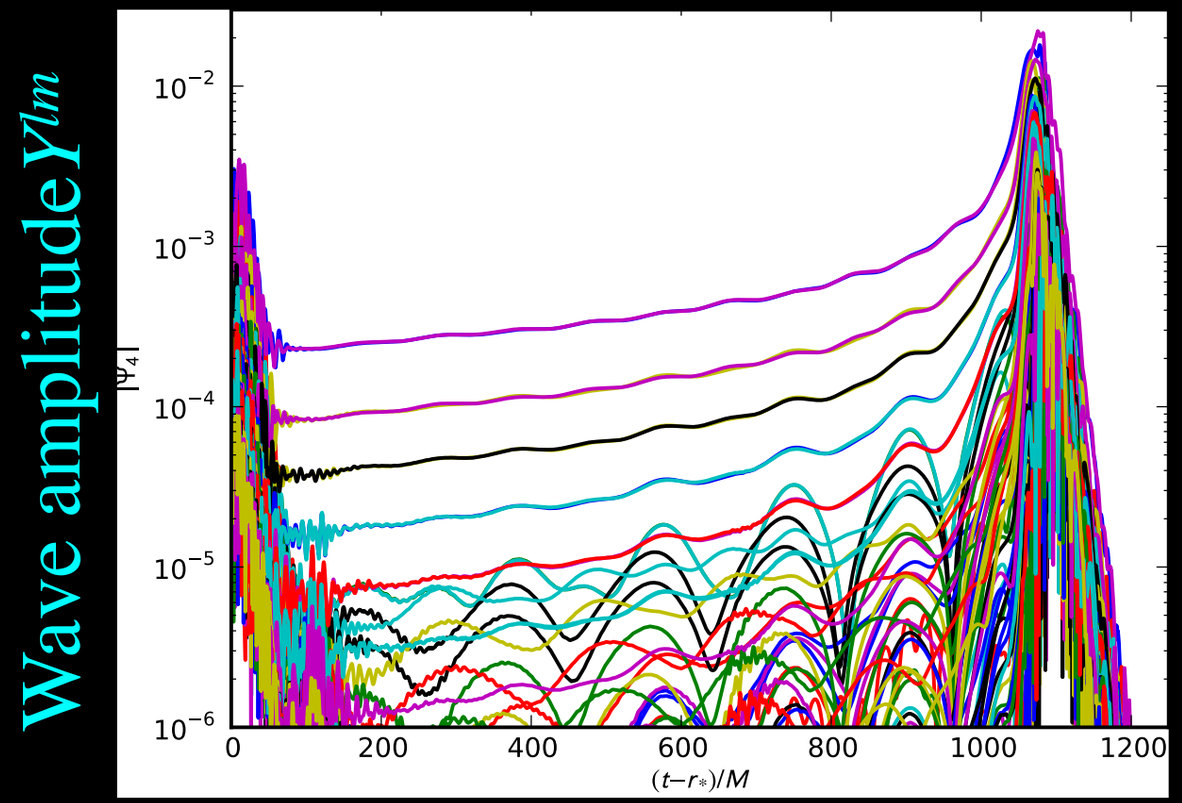

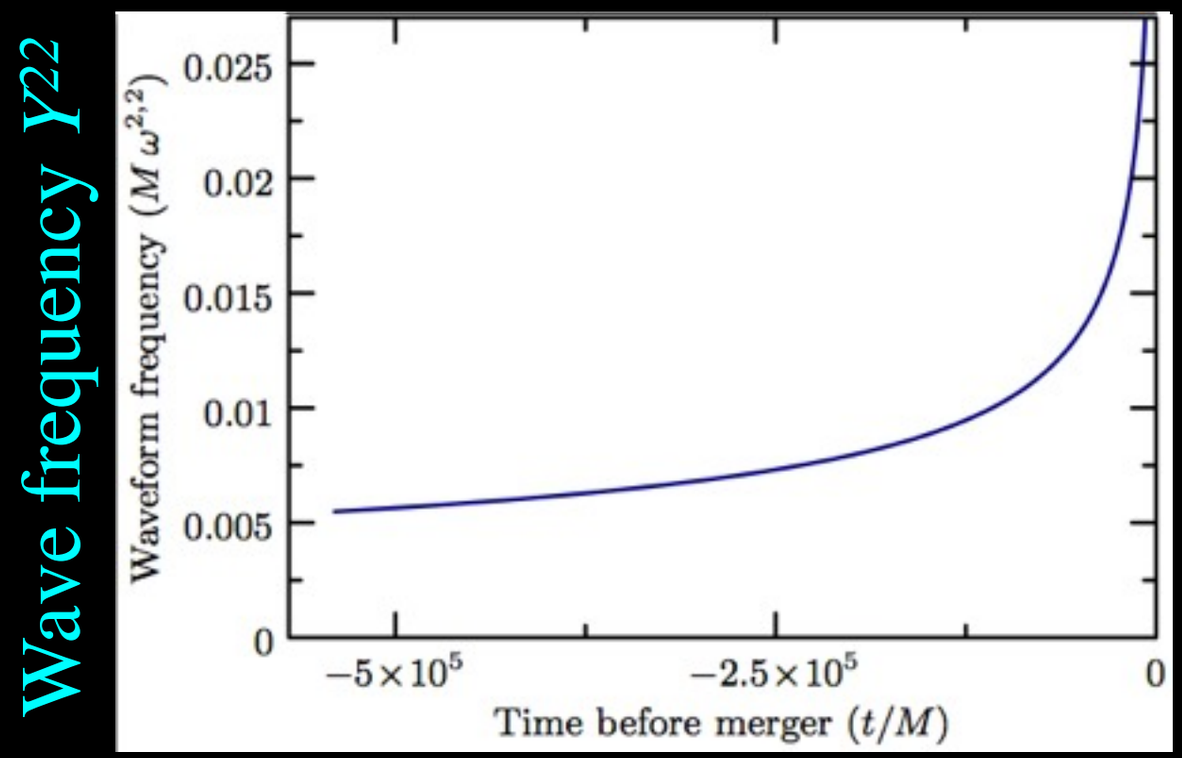

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Approximate mapping of precessing inspiral waveforms to non-precessing
Schmidt et al, (2012), arXiv:1207.3088

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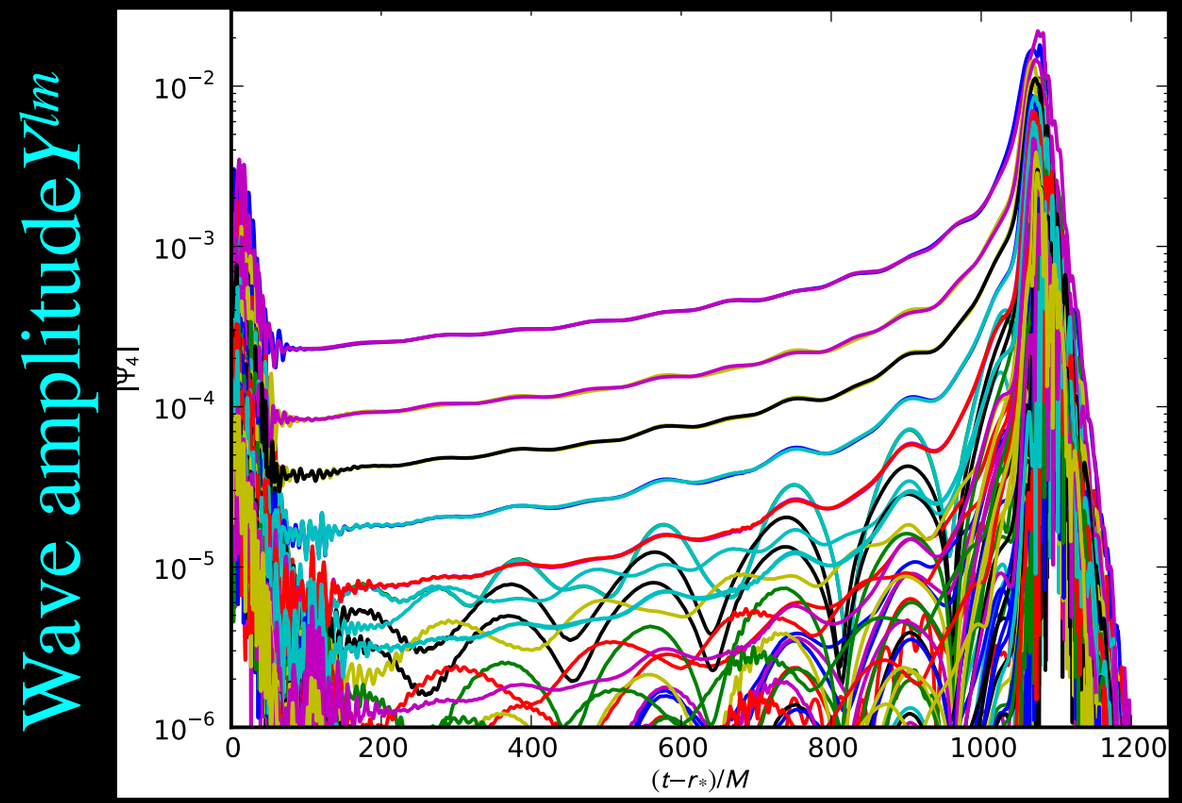

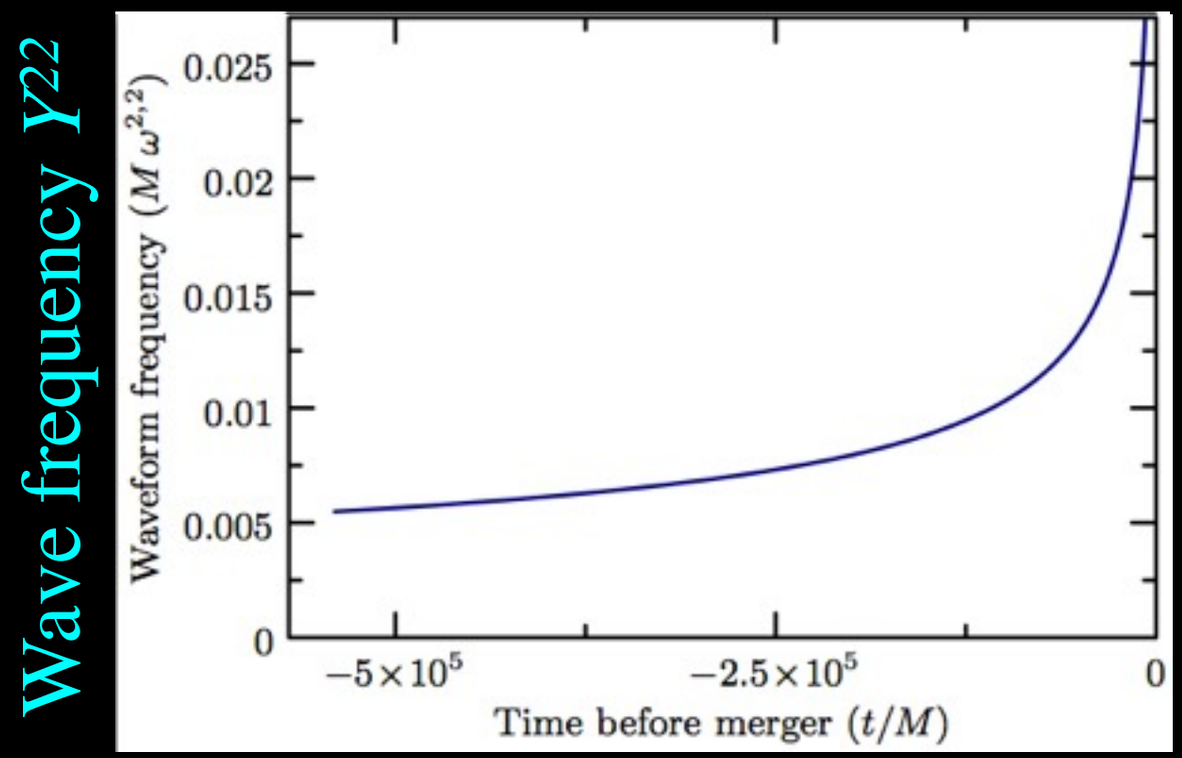

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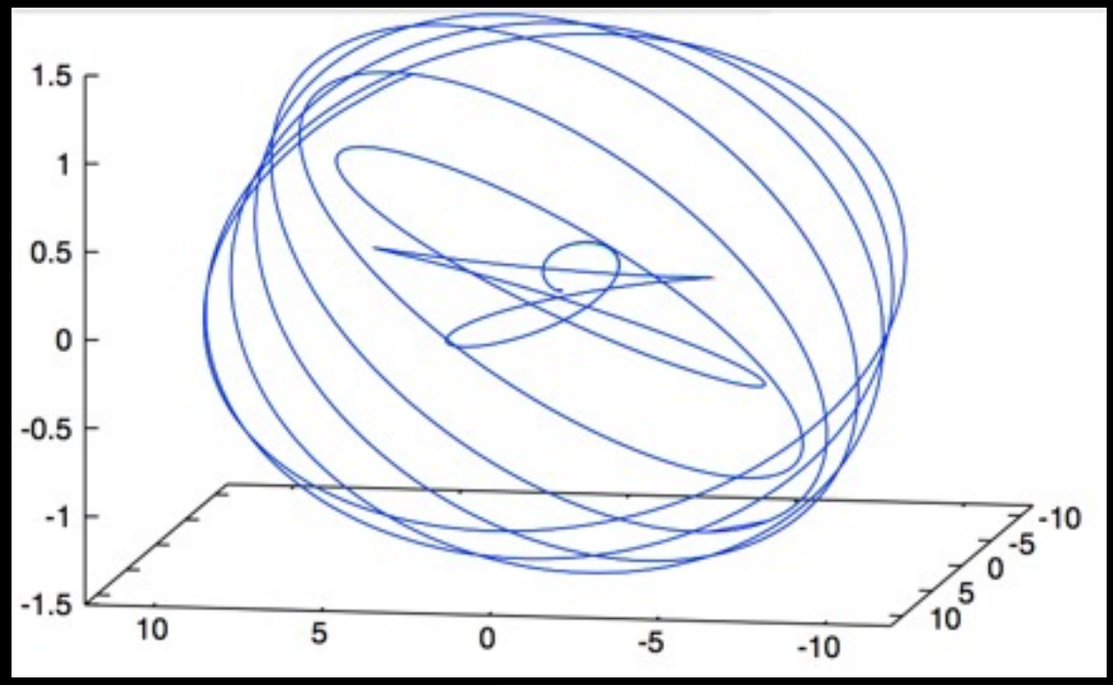
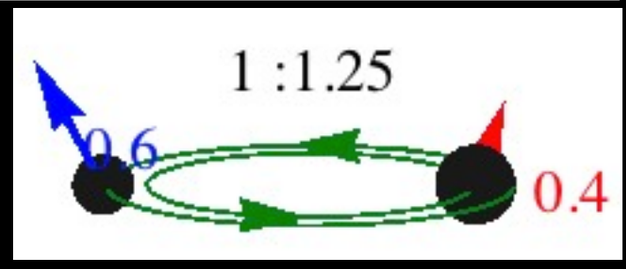


Campanelli et al, PRD **79**, 084010 (2009)



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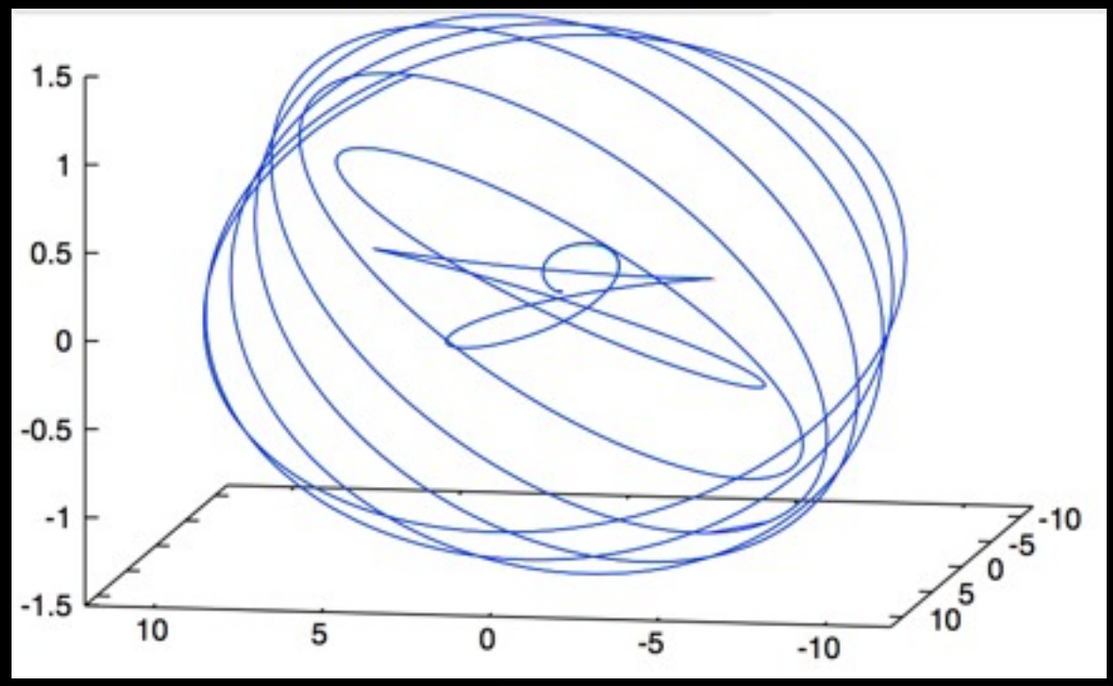

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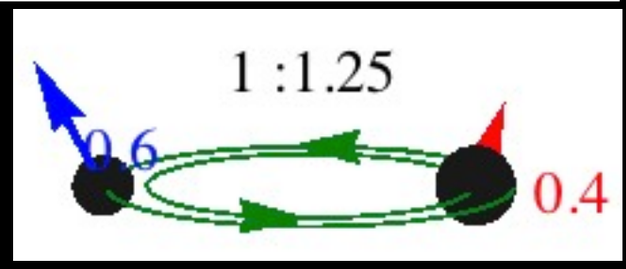
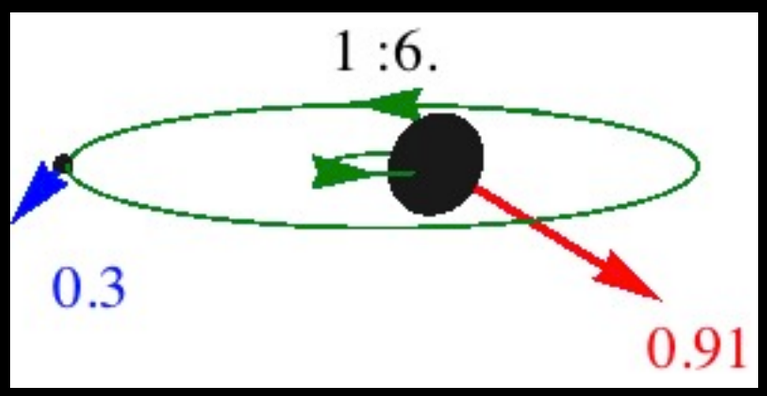


SXS (black-holes.org) collaboration in preparation



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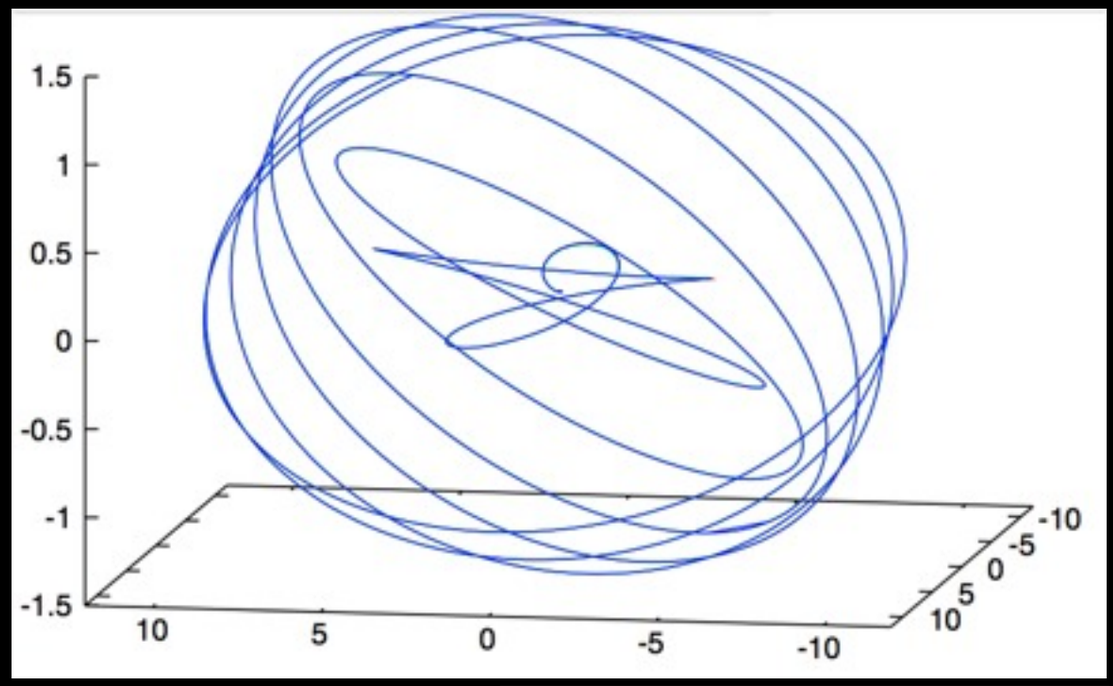

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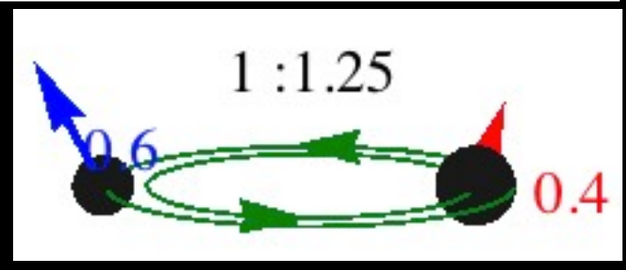

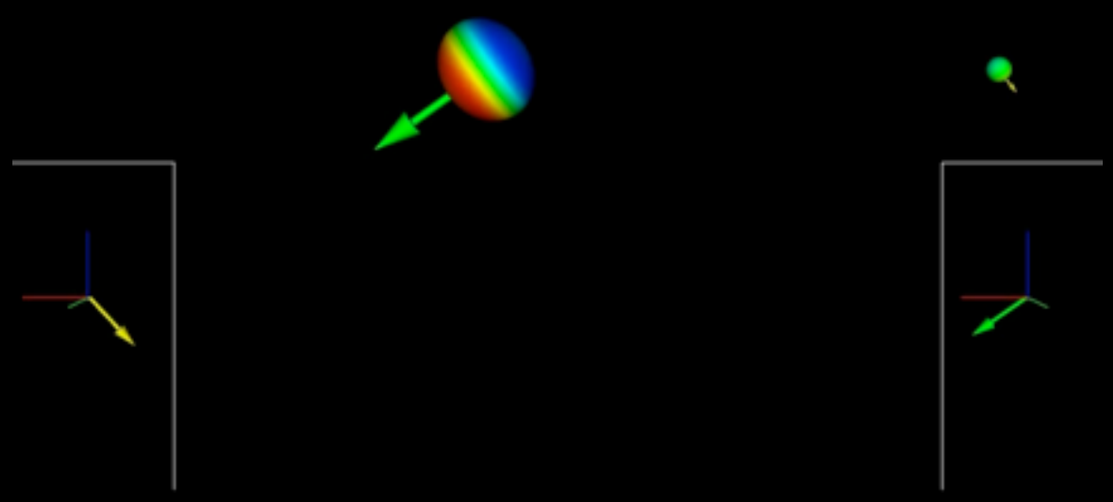

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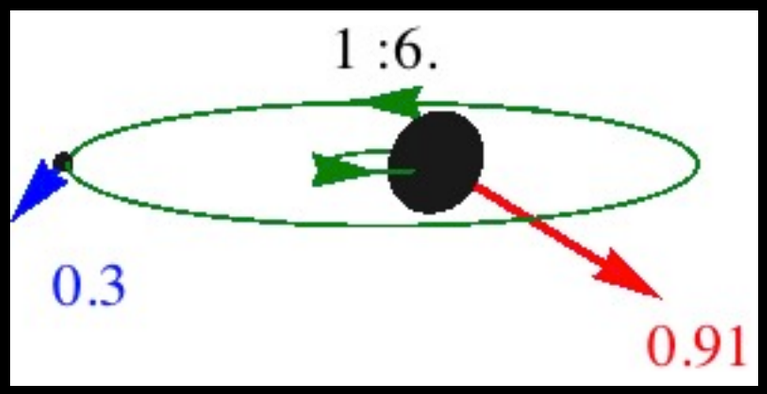

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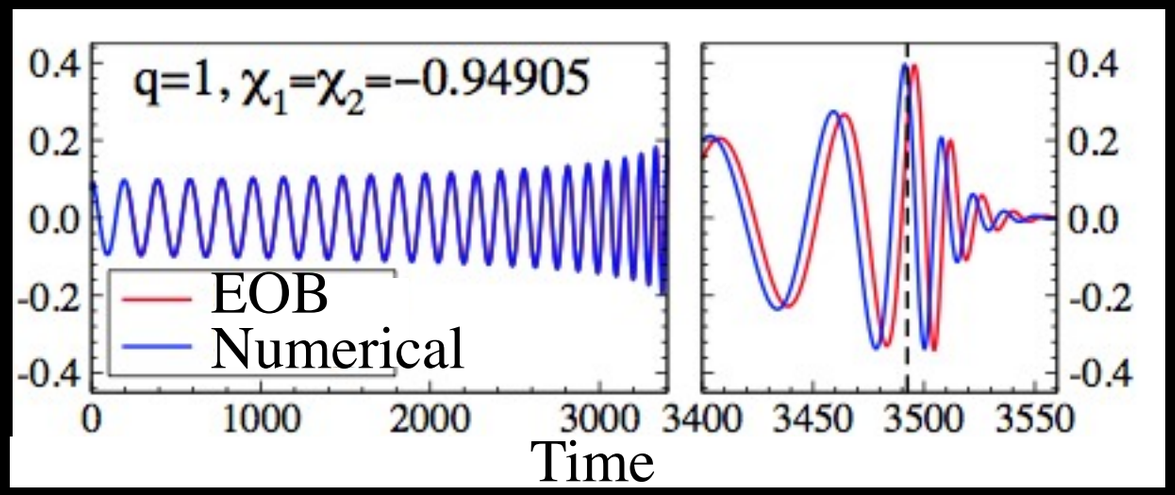

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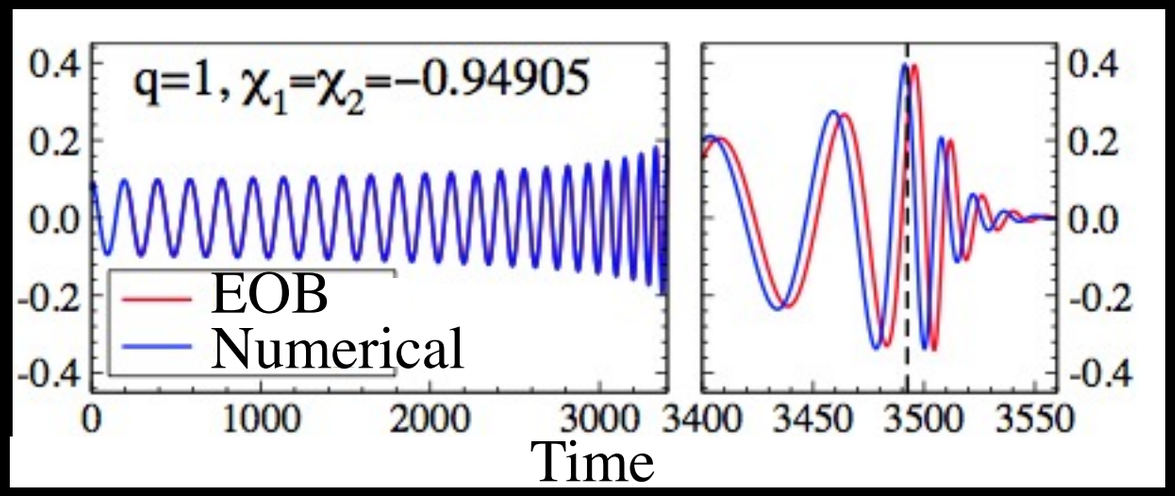

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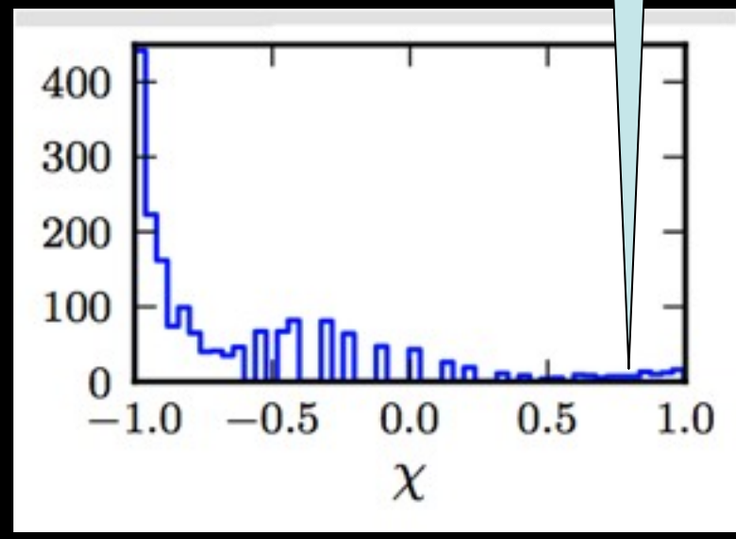

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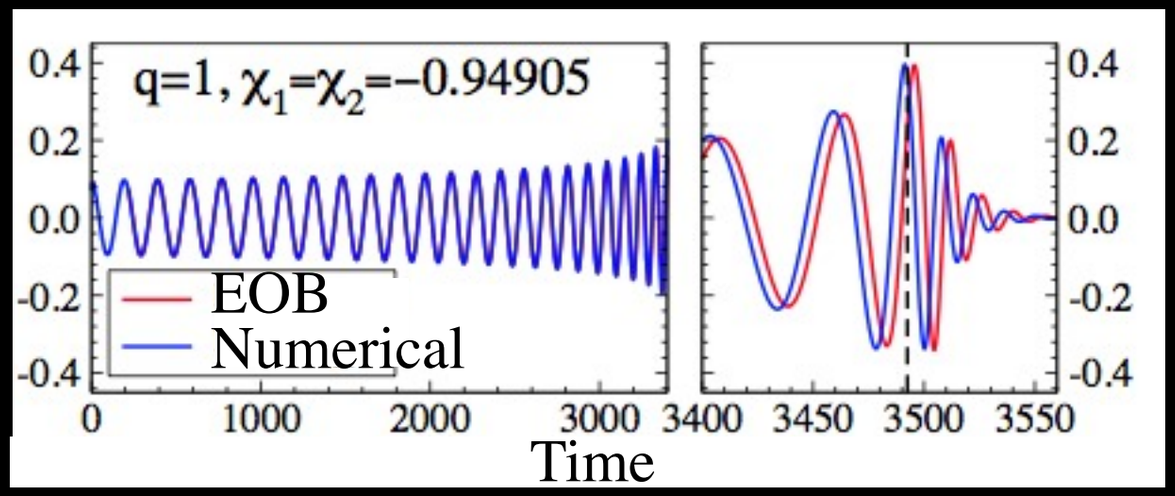
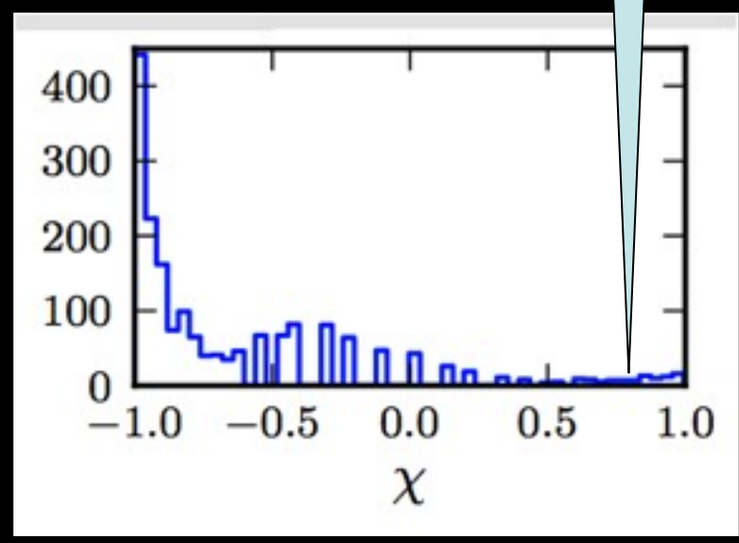
  - –How many waveforms?
    - Uncertain, but guess $O\left(10^3\right)$



elements chosen by R.B. for equal-, aligned-spin post-Newtonian waves



Applying simulations to GW data analysis

- Hybrid waveforms

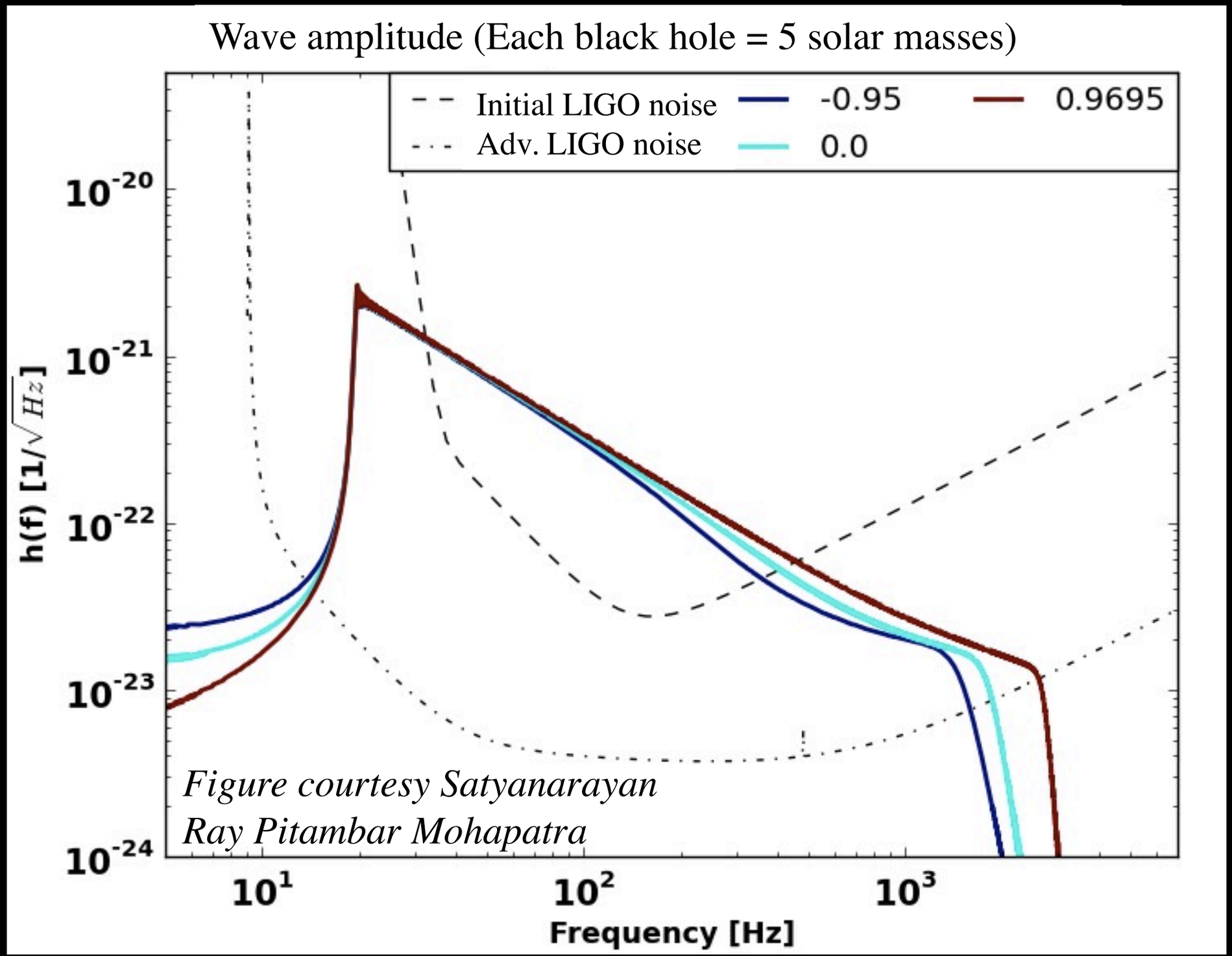


Figure courtesy Satyanarayan Ray Pitambar Mohapatra

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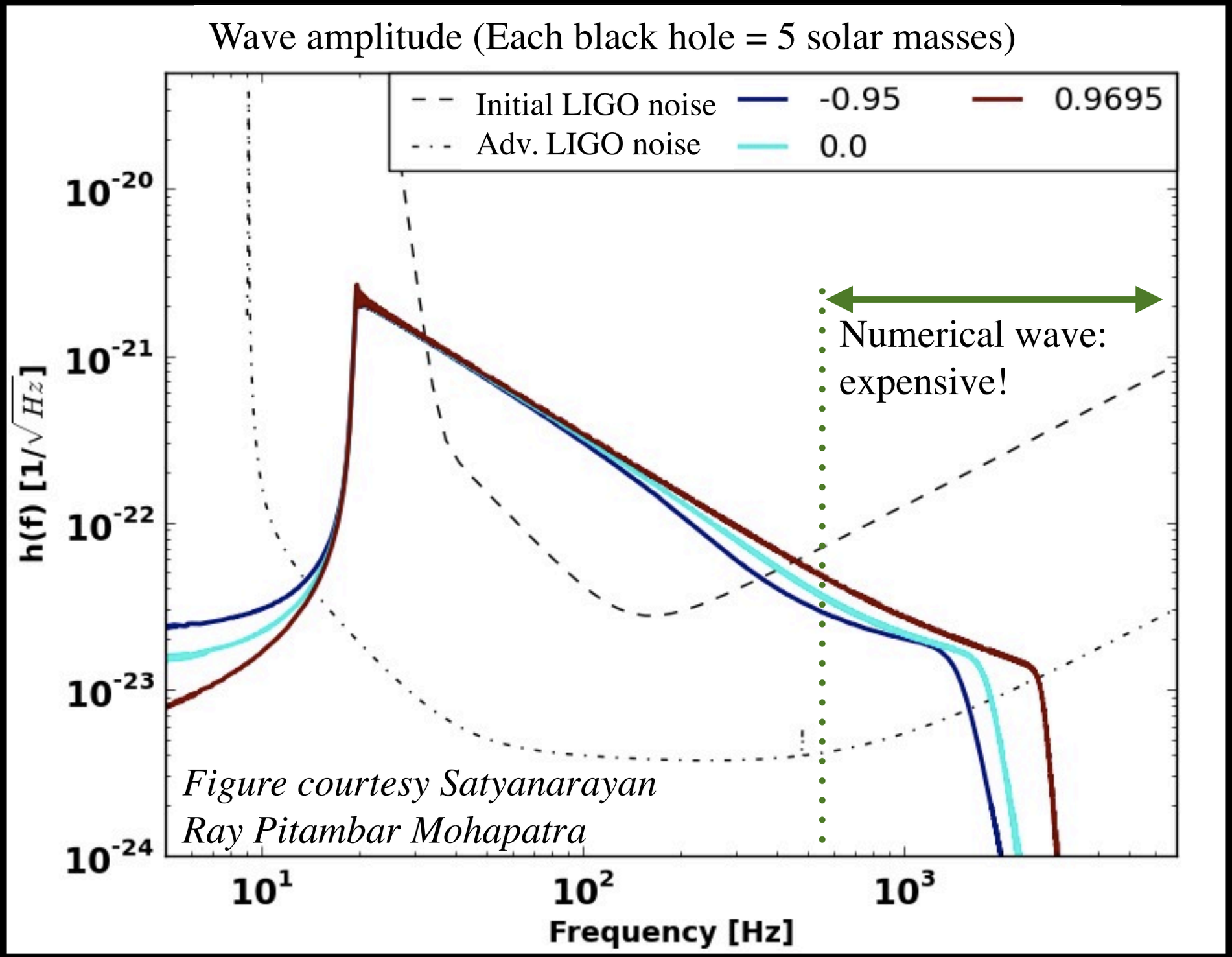

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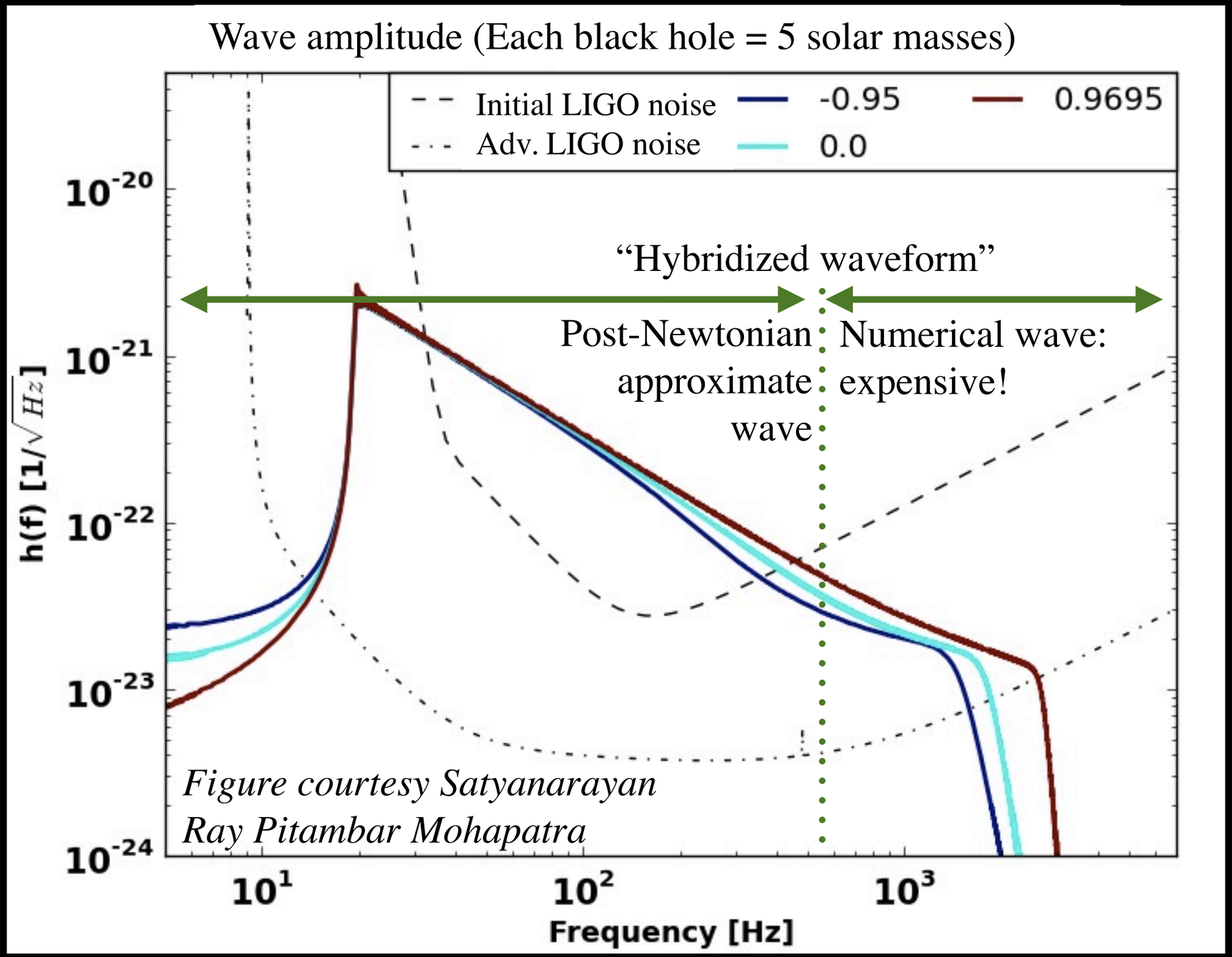

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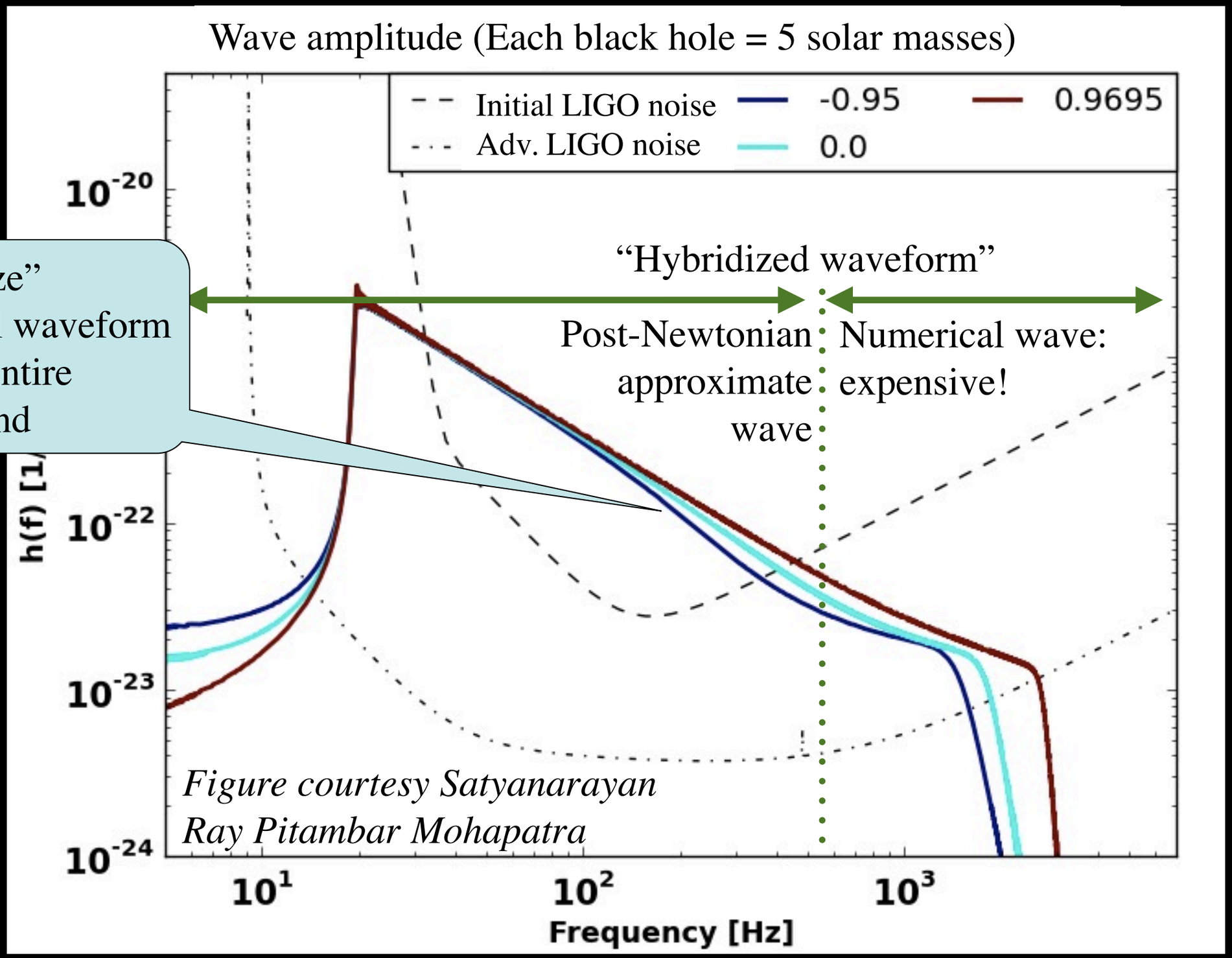

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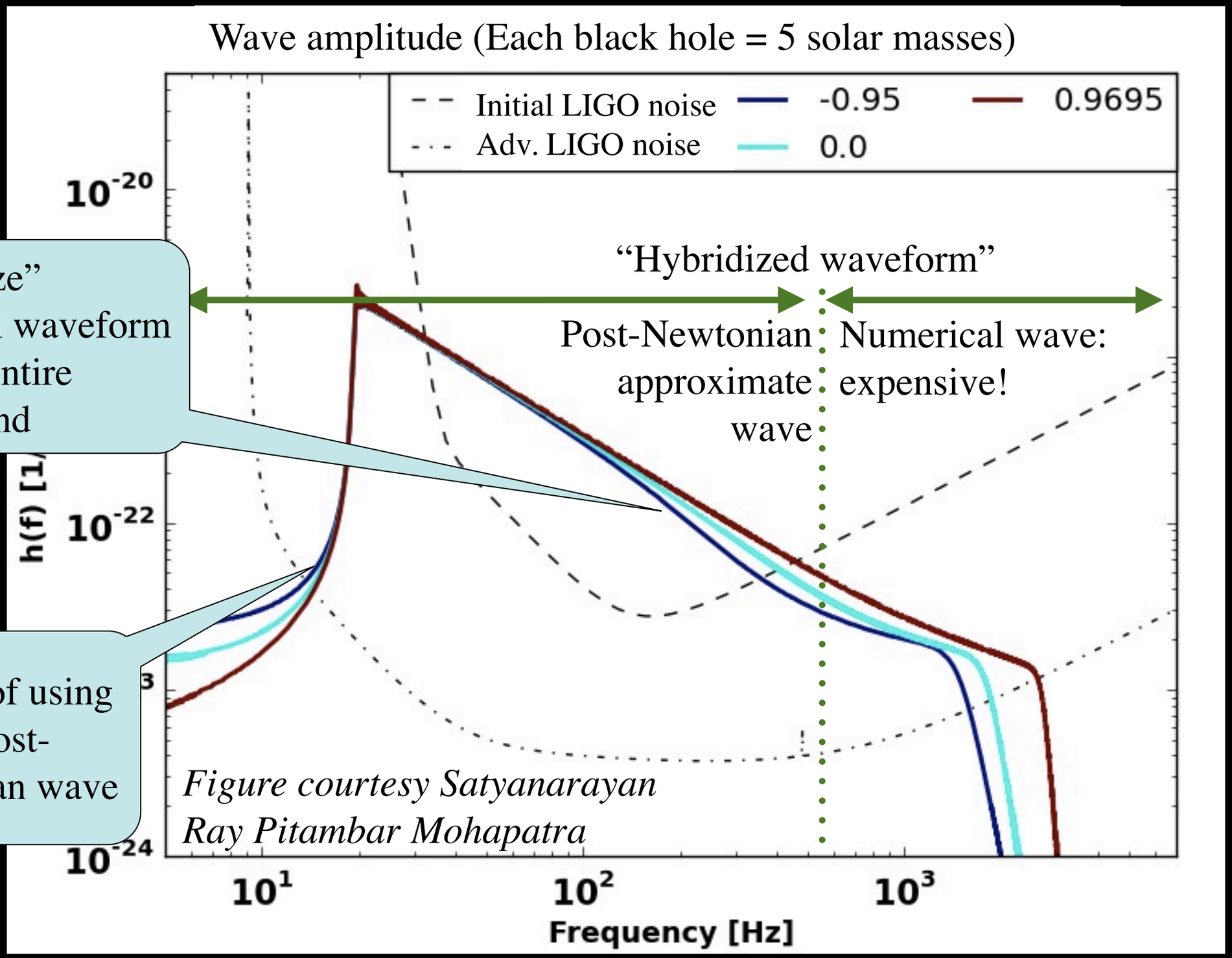

Numerical INjection Analysis (NINJA)

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- NINJA-2 project goals
  - Inject contributed numerical waveforms into LIGO data
  - Search for injected waveforms

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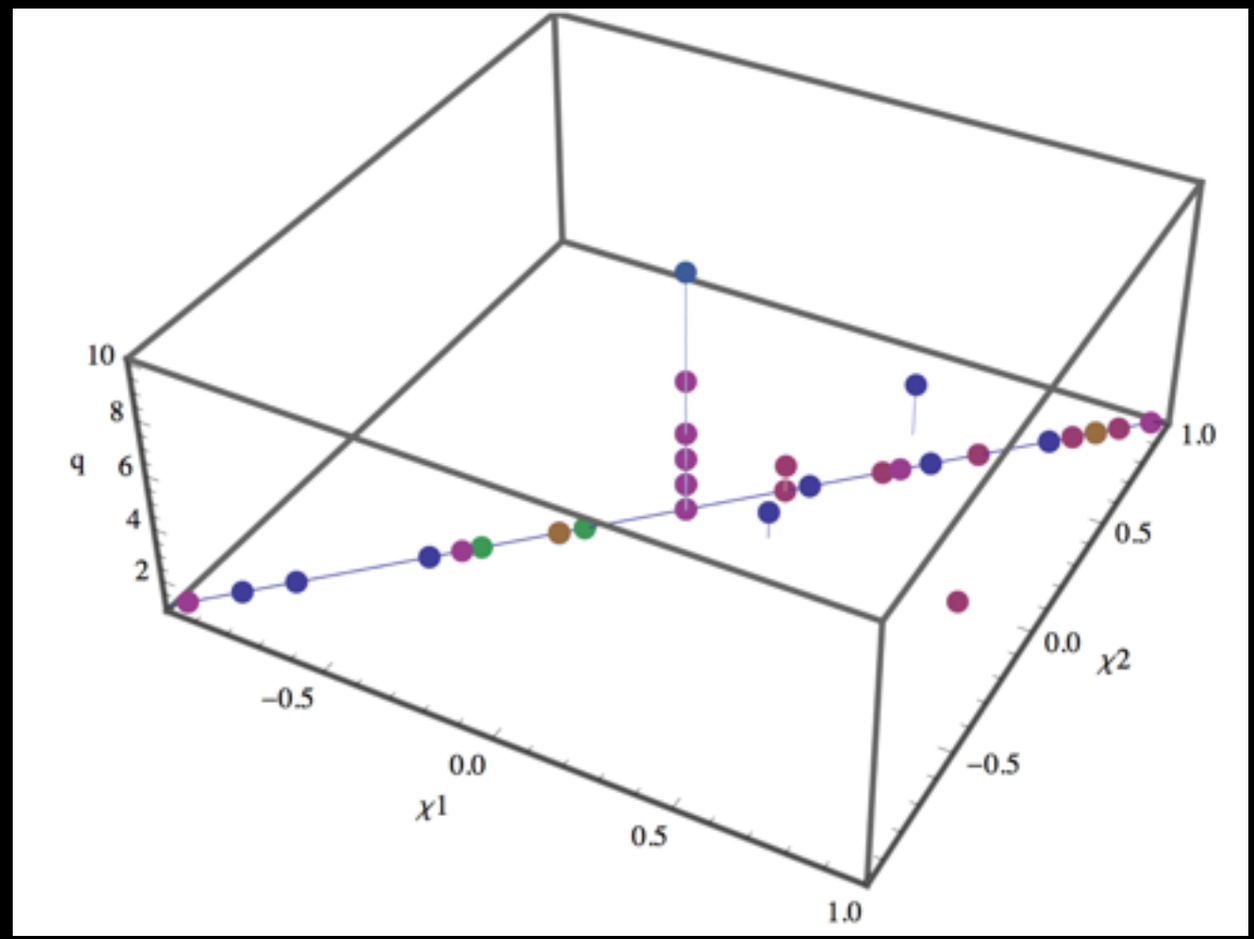
- NINJA-2 project goals
  - Inject contributed numerical waveforms into LIGO data
  - Search for injected waveforms
- Current status
  - Catalog contains 63 hybrid waveforms
    - Mostly unequal mass
    - No precession (i.e. spin aligned with orbital ang. momentum)
  - Catalog paper on arXiv (public release coming soon)
  - Now injecting waveforms & searching for them



Ajith *et al* (2012), arXiv:1201.5319
see also poster by Thilina Dayanga

Numerical Relativity / Analytical Relativity (NRAR)

precessing
not precessing

Numerical Relativity / Analytical Relativity (NRAR)

- NRAR project goals
  - Simulate new waveforms, including precession
  - Use numerical waveforms to calibrate approximate, analytic waveform templates

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Numerical Relativity / Analytical Relativity (NRAR)

- NRAR project goals
  - Simulate new waveforms, including precession
  - Use numerical waveforms to calibrate approximate, analytic waveform templates
- Current status
  - 35 waveforms
  - Moderate mass ratios & spins, some precession
  - Catalog not yet complete

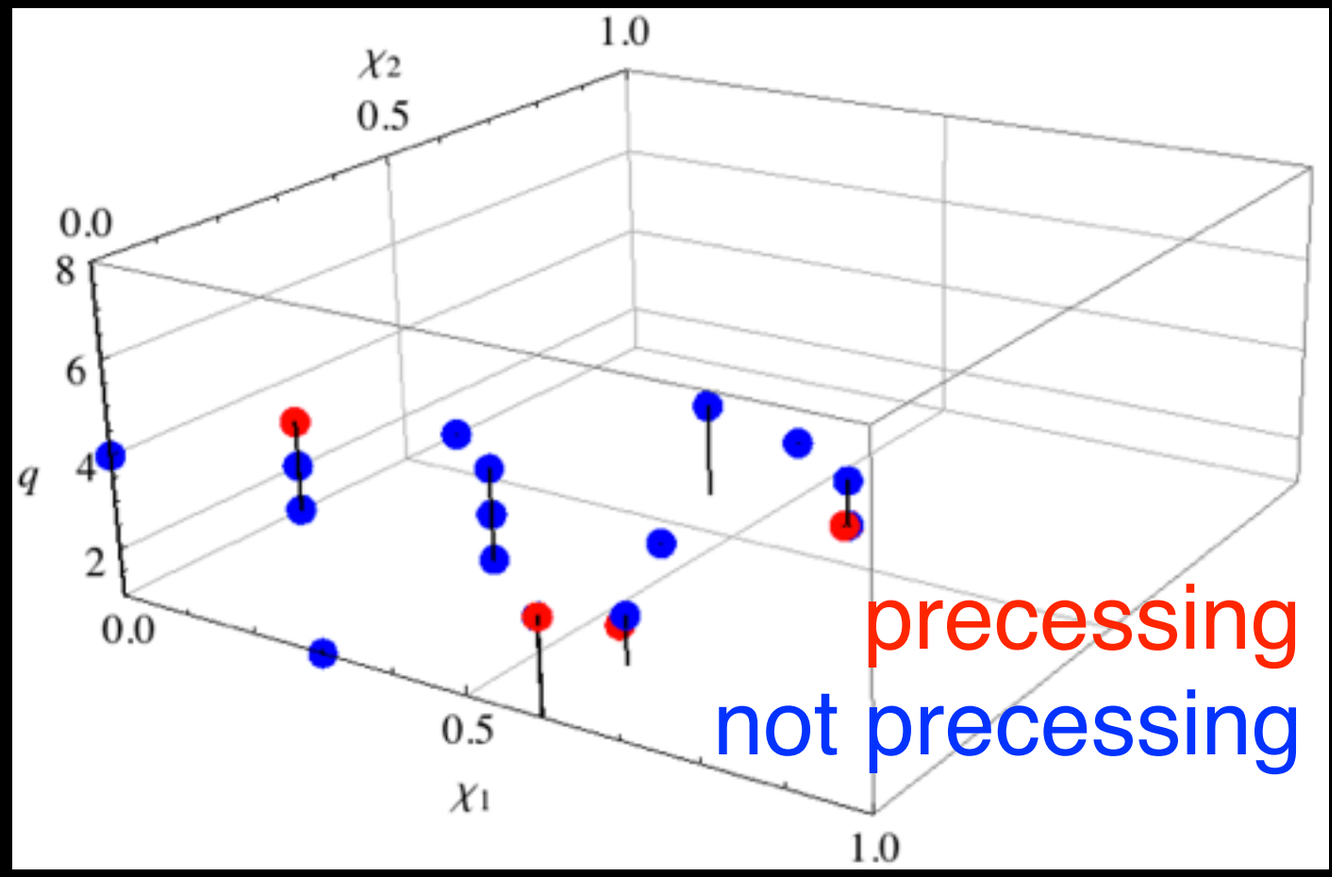

Figure courtesy NRAR project
see also talk by Yi Pan Thursday, 11:00AM

Efficiency

Efficiency

- Cost

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  - Typical cost per simulation

	CPU hours	Wallclock time
Puncture codes	O(100k cpu hours)	O(months)
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    - New methods needed

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Hannam et al, PRD **82**, 124052, (2010)
Damour et al, PRD **83**, 024006 (2011)
Ohme et al, PRD **84**, 064029 (2011)
MacDonald et al, CQG **28,** 134002 (2011)
Boyle, PRD **84**, 064013 (2011)

- Accuracy & length
  - Parameter estimation
    - Much longer waveforms than common today
    - Better post-Newtonian for better hybrid waveforms

See also talk by Sascha Husa (Thursday, 12:00PM)

Summary & questions

- Summary
  - Spinning BBH important GW sources for LIGO
  - Considerable progress so far
  - Challenges remain
    - Goal: for GW data analysis, need large number of generic waveforms & extreme waveforms
      - Also need improved approximate, analytic models (post-Newtonian, EOB)
    - Goal: greatly reduce computational cost
- Some questions
  - Priorities: what simulations most useful for data analysis?
  - Production: biggest obstacles to large GW catalogs, including precessing waveforms?