Title: The Status of Black Hole Binary Simulations

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Abstract: The initial gold rush of exploration into new regions of parameter space has slowed significantly. While our ability to simulate larger spins and more extreme mass ratios has continued to improve, much of the recent progress in numerical relativity has centered on improvements in methodology, in condensing and interpreting an ever-growing body of numerical results, and in incorporating matter into the numerical simulations. In this review, I will summarize the recent progress in this field, focusing on novel results in the simulation of black hole binaries, with some discussion of novel applications of those results to data analysis.

The status of black hole binary simulations

Sean McWilliams
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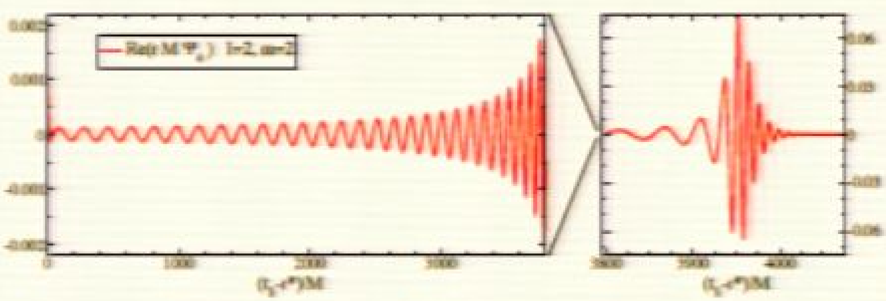
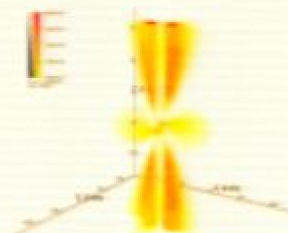




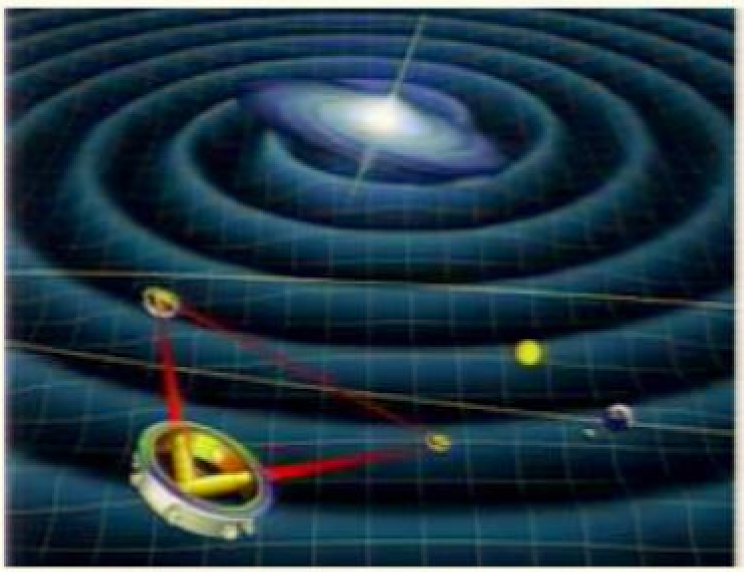
NRDA2010
Perimeter Institute
Waterloo, Ontario, Canada
June 24 2010

Outline of talk

- A brief introduction of numerical relativity methodology
- The current state-of-the-art of black hole binary (BHB) simulations
    - in vacuum
    - with matter
    - novel methodology
- A tip-of-the-iceberg look at data analysis/astronomy applications
- Conclusions and questions

Numerical relativity in a nutshell

Few exact analytic solutions are available in GR - the ($N > 1$) body problem is not one of them. During the inspiral, perturbative approximations (e.g. post-Newtonian) can be applied. Approaching merger, such approximations break down, and the full nonlinear Einstein equations need to be solved numerically.



$$ds^2 = g_{ab} dx^a dx^b$$

Einstein equations couple spacetime curvature to the energy-momentum of matter:

$$G_{ab} = 8\pi T_{ab},$$

NB: $T_{ab} = 0$ is highly nontrivial: satisfied by BHBs in vacuum emitting gravitational waves!

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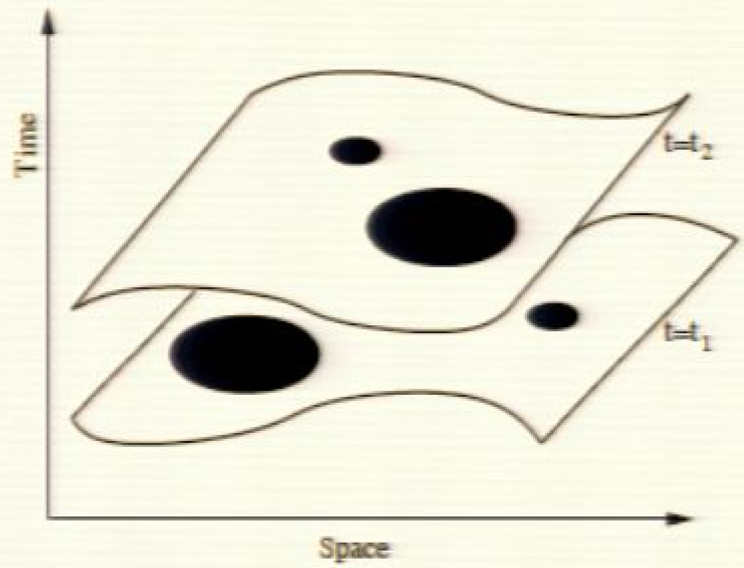

- Split Einstein equations into 3+1: space+time
- Choose some $t = \mathrm{const}$ hypersurface of spacetime
- Specify data in some gauge for two BHs in orbit, with or without matter
- Evolve

It's that easy!

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- Need a 3+1 decomposition that is well-posed and stable
  - Freedom to choose variables and gauge, need to pick a "good" gauge
  - BSSN or harmonic formulations most common, but they come in different flavors
- Need to evolve a pair of physical singularities
  - can excise them by placing a boundary inside the horizon (causally disconnected if no superluminal modes)
  - can treat them as "moving punctures" by choice of gauge
- Disparate scales - BH near-zone resolution $\ll$ wavezone scale
- No surefire way to specify correct initial data for a desired system

It's **NOT** that easy!

State of the art – summary of vacuum results

Superlative	Value	Sim. details	Reference
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Smallest mass ratio	$q = 1/10$	$a_{1,2} = 0$	[Gonzalez 2009
			[Lousto 2010]*
Largest recoil	10000 km/s	"superkick", $e > 1$	[Healy 2009]
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Most energetic	$E_{rad}/M = 0.14$	$q = 1$, $a_{1,2} = 0$, $e \gg 1$	[Sperhake 2008]

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32 cycles - Caltech/Cornell (Scheel et al 2009)

- Equal mass, nonspinning binary
- Uses SpEC (spectral methods) with 1st order harmonic formulation of 3+1, yields smallest numerical error
- See Uli Sperhake's talk at 5:10 today for unequal mass
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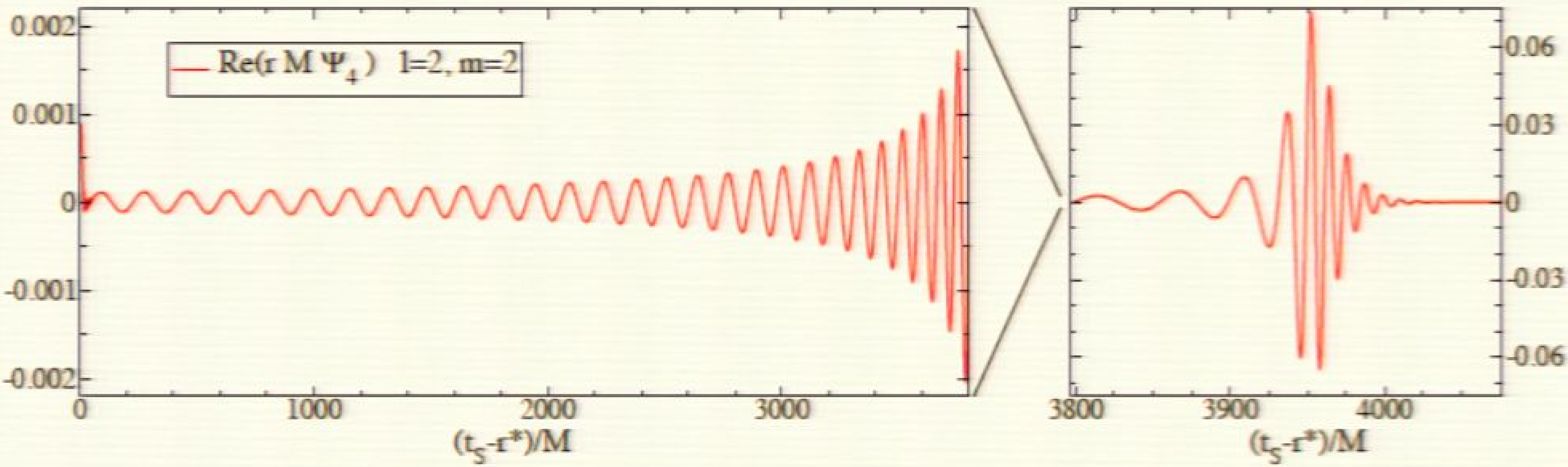

State of the art – Smallest mass ratio

$q = 1/10$ - Gonzalez, Sperhake, and Bruegmann 2009

- Nonspinning, completed 3 orbits
- Uses BAM (finite difference) with modified BSSN formulation of 3+1
- Verified kick formula at very small $\eta = m_1 m_2 / M^2 = 0.083$
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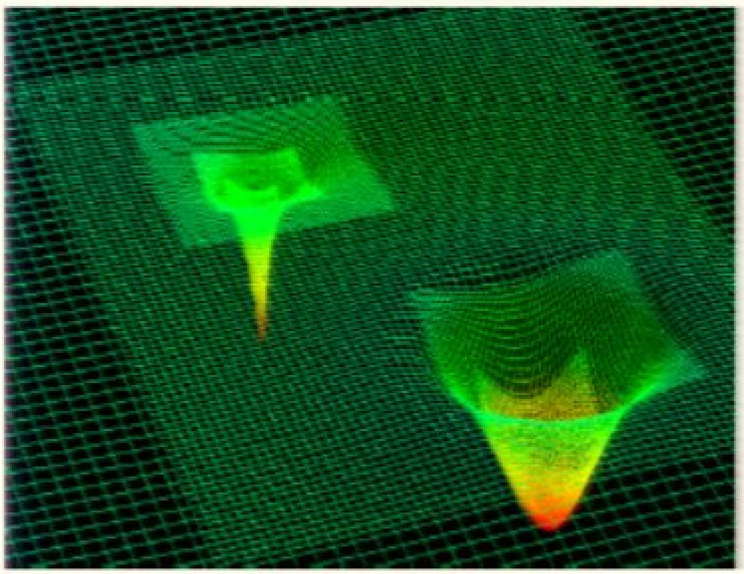

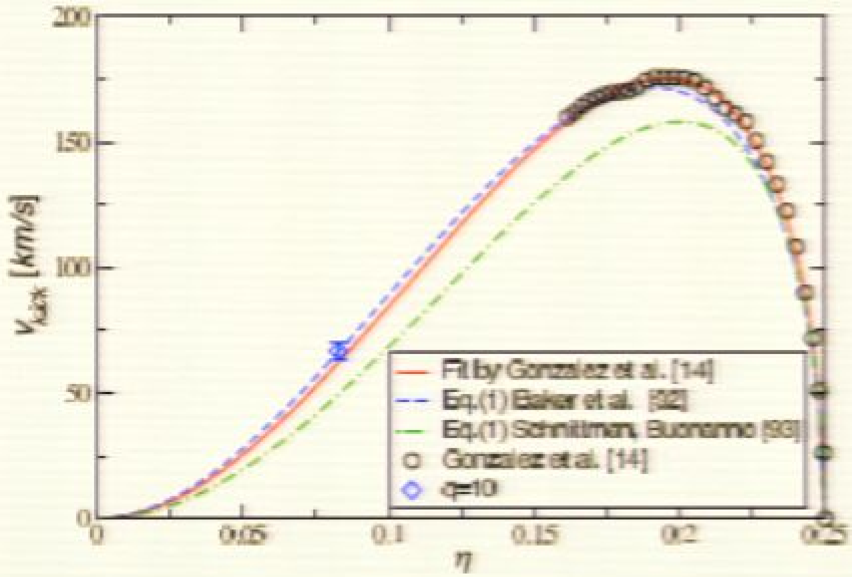

State of the art – Largest recoil

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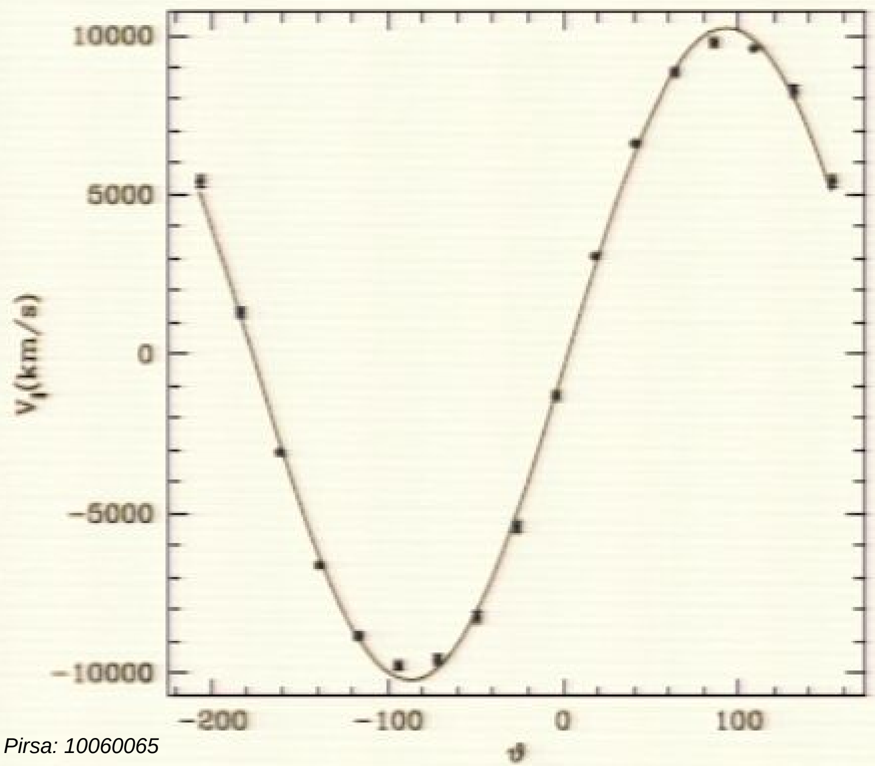
- Healy et al 2009
- *may* happen for stellar BHs, never for supermassive



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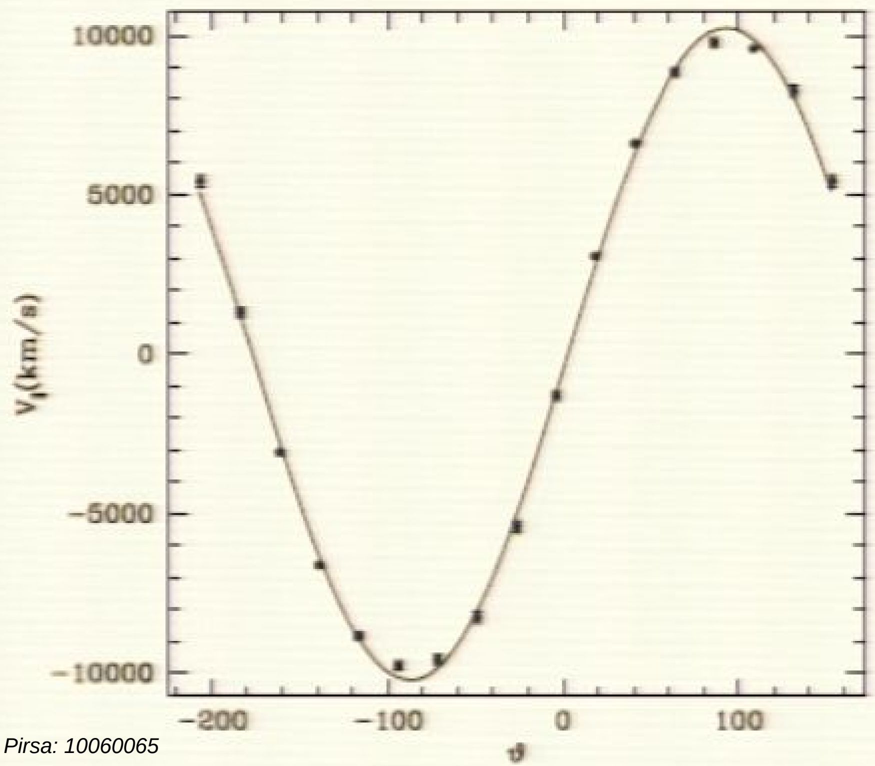

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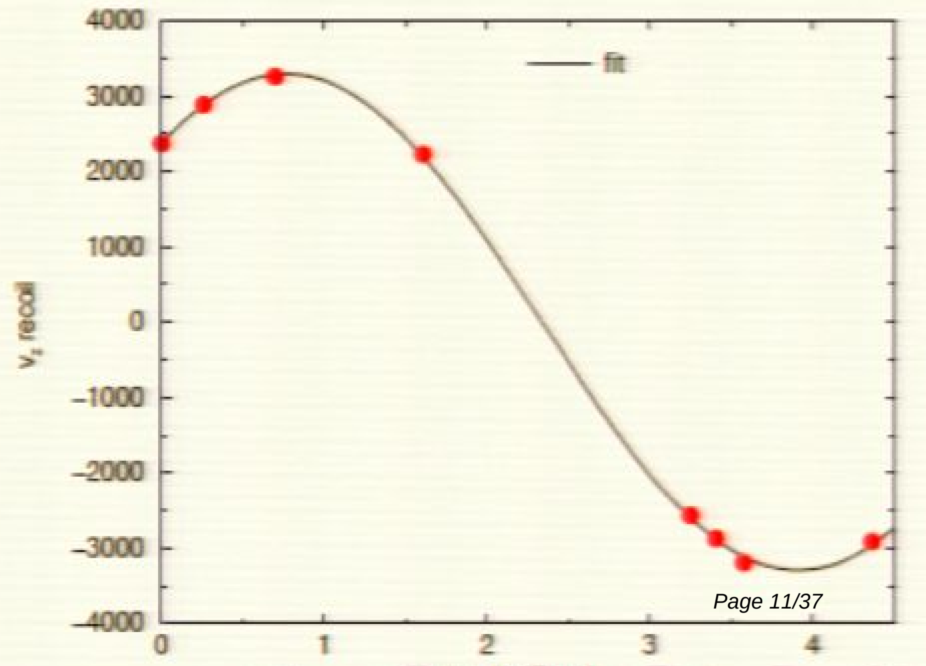

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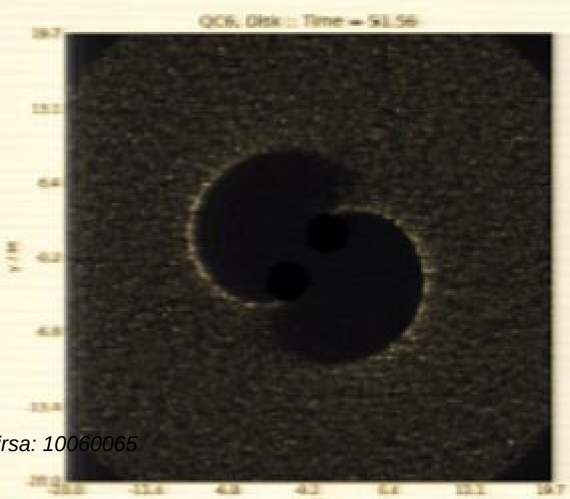
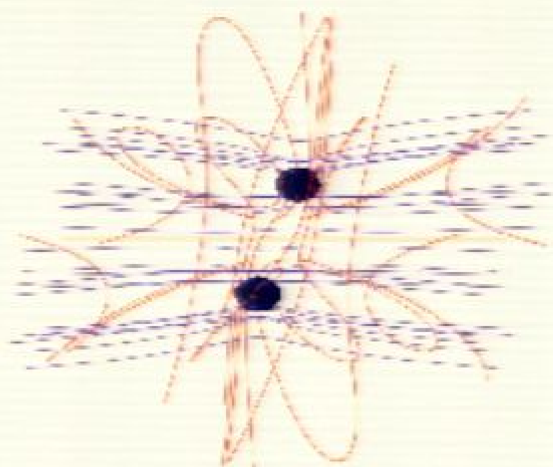
- Analytic models that include merger-ringdown tuned to simulations are becoming ubiquitous (Buonanno et al 2007, Baker et al 2008, Ajith et al 2009, Sturani et al 2010, Santamaria et al 2010...)
  - Talks similarly ubiquitous – see Sturani, Barausse, Pan, and Ohme tomorrow 4:30-5:50, Kelly et al poster
- Methods to measure (Mroué et al 2010) and mitigate eccentricity (Buonanno et al, in preparation) being actively developed, motivated by NR-AR.

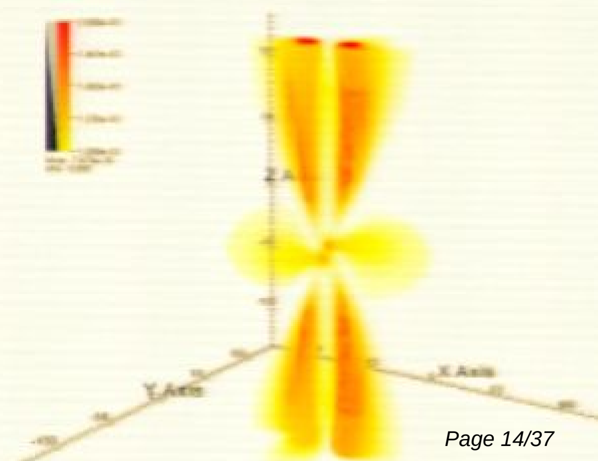
State of the art – matter summary

Since the last NRDA, 3 groups have incorporated matter into BHB simulation, 2 including E&M. Several other groups are developing those capabilities.

- van Meter et al 2009 traced geodesics in BHB spacetime, suggesting a possible EM signature of merger
- Bode et al 2010 incorporated hydrodynamics into BHB spacetime, evolving a neutral gas surrounding the binary
- Palenzuela et al 2009 and 2010a and Mösta et al 2010 evolved the Einstein-Maxwell equations for an EM field in a BHB spacetime
- Palenzuela et al 2010b incorporated plasma and showed the emission of dual jets, even for a nonspinning BHB

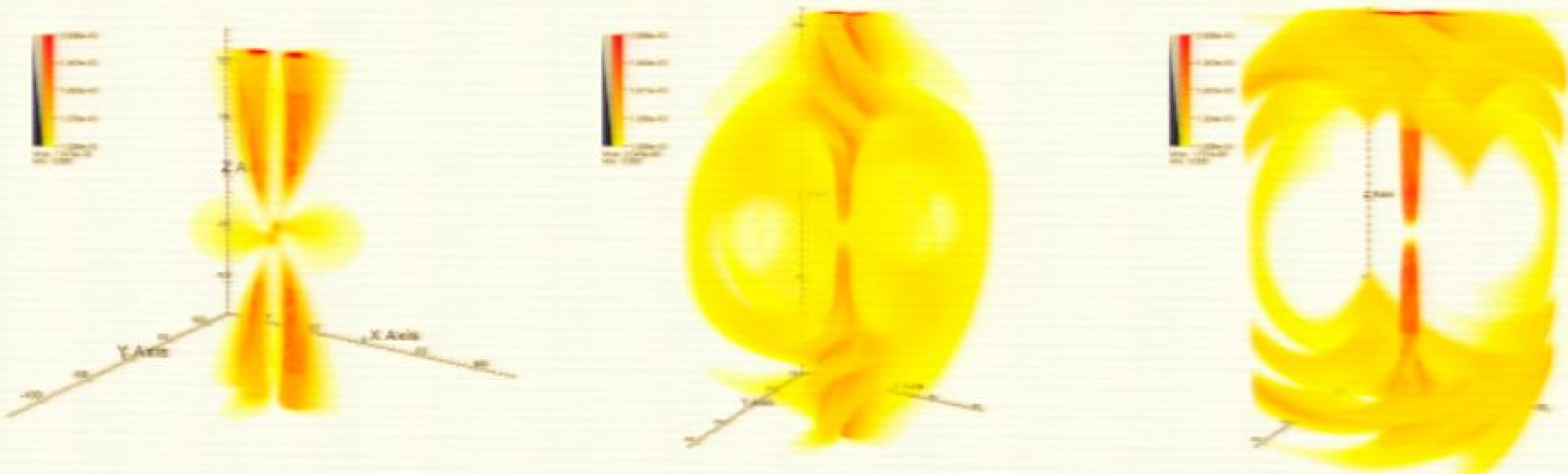






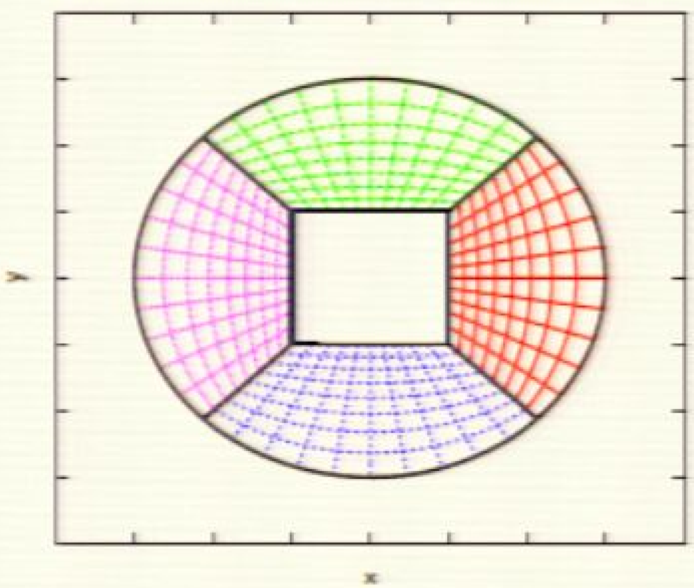
State of the art – dual jets

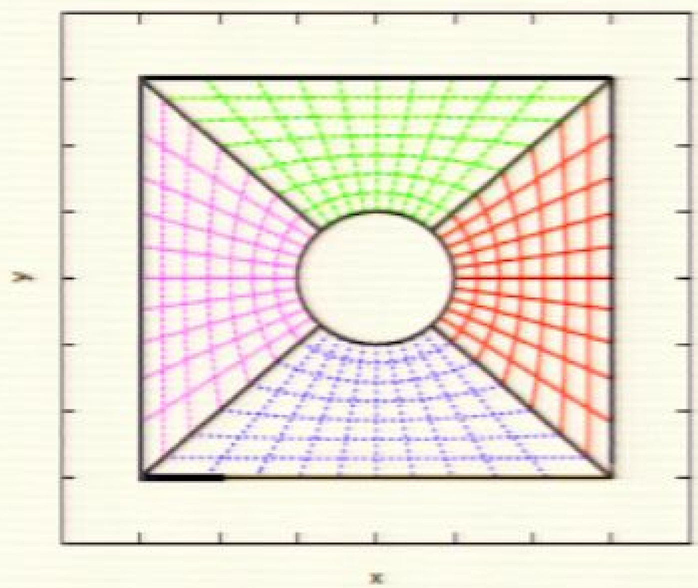
- Palenzuela, Lehner, and Liebling 2010
- Force-free assumption: magnetic pressure $\gg$ gas pressure
- Find dual jets for a *nonspinning* BHB – not typical Blandford-Znajek mechanism



State of the art – methodology – multipatch

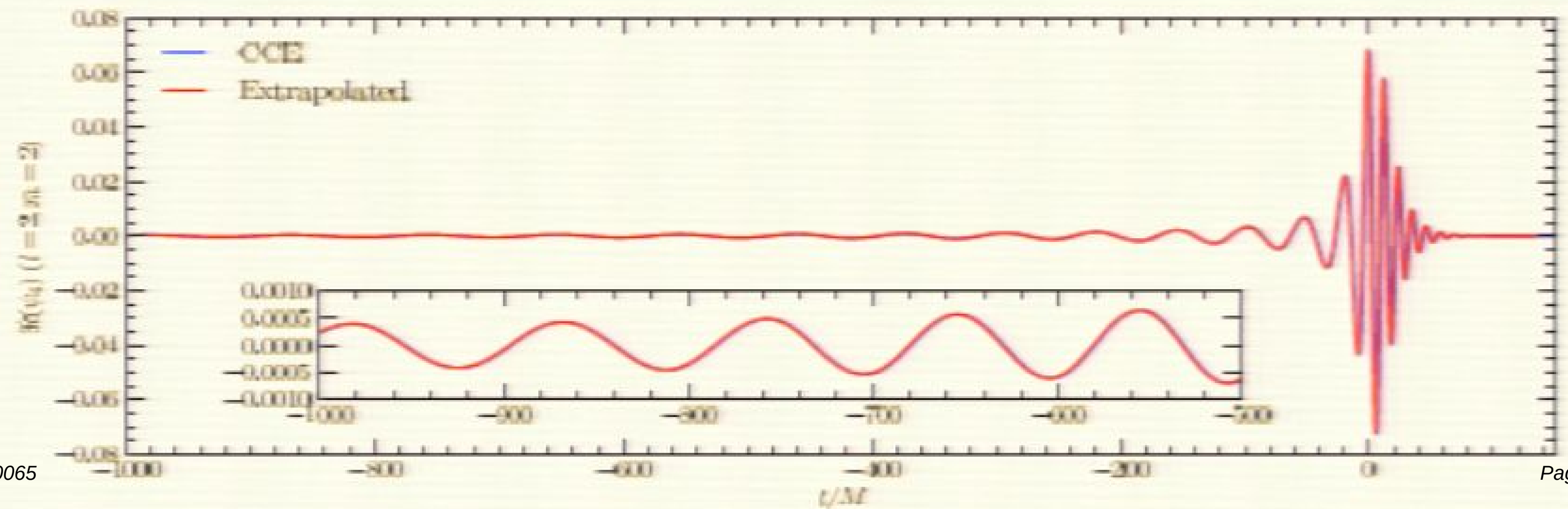
- Pazos et al 2009, Pollney et al 2009
- Greater freedom to tailor grid to geometry of the problem
- Waveforms don't gain any angular structure as $r \to \infty$
- Multipatch facilitates an extension of the grid with only radial elements ($\mathcal{O}(N)$ instead of $\mathcal{O}(N^3)$)





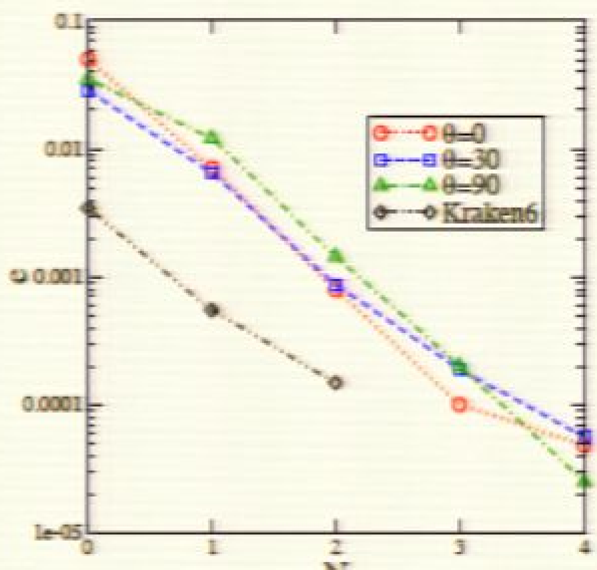
State of the art – methodology – Cauchy characteristic extraction

- Reisswig et al 2010
- Waveform extraction occurs at future null infinity (can also be done by compactifying, see Zenginoglu and Tiglio)
- Confirms that the practice of extracting at finite radii and extrapolating is reliable
- See Maria Babuic's poster



State of the art – methodology – reducing eccentricity

- Not as trivial as you might think - Kepler's law won't help you
- There are several approaches
  - Historically, quasi-circular ($\dot{r} = 0$) orbits were used, but this is no longer good enough "out of the box"
  - Can improve substantially by iterating on p_ϕ ($e < 10^{-5}$ in [Pfeiffer et al 2007, Boyle et al 2007])
  - Alternatively, can integrate PN equations of motion for 1000s of orbits
- Things get messier with spin (especially anti-aligned)
- Recent NR-AR efforts have focused on mitigating e in generic binaries – and are succeeding (Mroué et al, ongoing CITA/UMD effort)

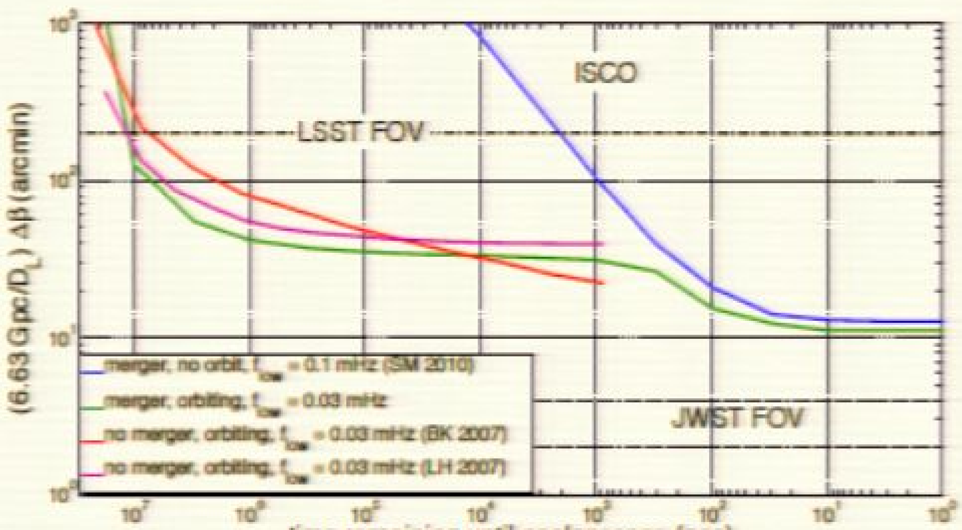


Data analysis – FAQ

- How much of the black-hole binary parameter space has been sampled?
  - Lots, but sparsely. NB: need a *model* to span parameter space, not a template bank of simulations
- How many cycles are needed? How does that depend on parameters?
  - Ask Mark Hannam at 4:50
- What accuracy is needed?
  - Depends on detector
- How well do results from different codes compare?
  - Quite well – see the Samurai project
- How close to merger can we trust PN and EOB models?
  - Depends on parameters, but closer than thought pre-2006 – no "IBBH" problem (yet)
- How much will BHB merger waveforms help in detecting GWs? in measuring source parameters?
  - Merger dominates SNR... period (Baker et al 2006, STM et al 2010). Parameter estimation is more subtle, but signs point to "a lot" (STM et al 2009, Ajith and Bose 2009)

Using mergers to probe dark energy

- Mergers are critical for detection (STM et al 2010) and important for parameter estimation (STM et al 2009, Ajith and Bose 2009)
- Ground-based detectors can localize source to < 1 sq. deg. with mergers
  - Sources are detectable to $z < 1$ (Baker et al 2007)
  - Combined with a large FOV EM survey, could do cosmography to $z < 1$
- LISA can localize to $\mathcal{O}(10)$ sq. arcmin, and measure luminosity distance beyond current weak lensing limits.
- With either a small error box or an EM counterpart (see BHB with matter), can do cosmography as far away as EM observation can be made.
- Sky information from merger is *o*rthogonal to that from orbital modulation



Conclusions

- Progress in vacuum BHB simulations continues (albeit at a more modest pace than $\sim$ 2006-2008)
- Significant progress has been made in employing the body of available waveforms to address general questions about mergers
- Tremendous progress has occurred over the last year in incorporating matter and EM fields in BHB simulations
- Methodological advances continue, enabling greater efficiency and accuracy
- BHB simulations are actively being exploited to address data analysis questions, and can address critical questions from astronomy

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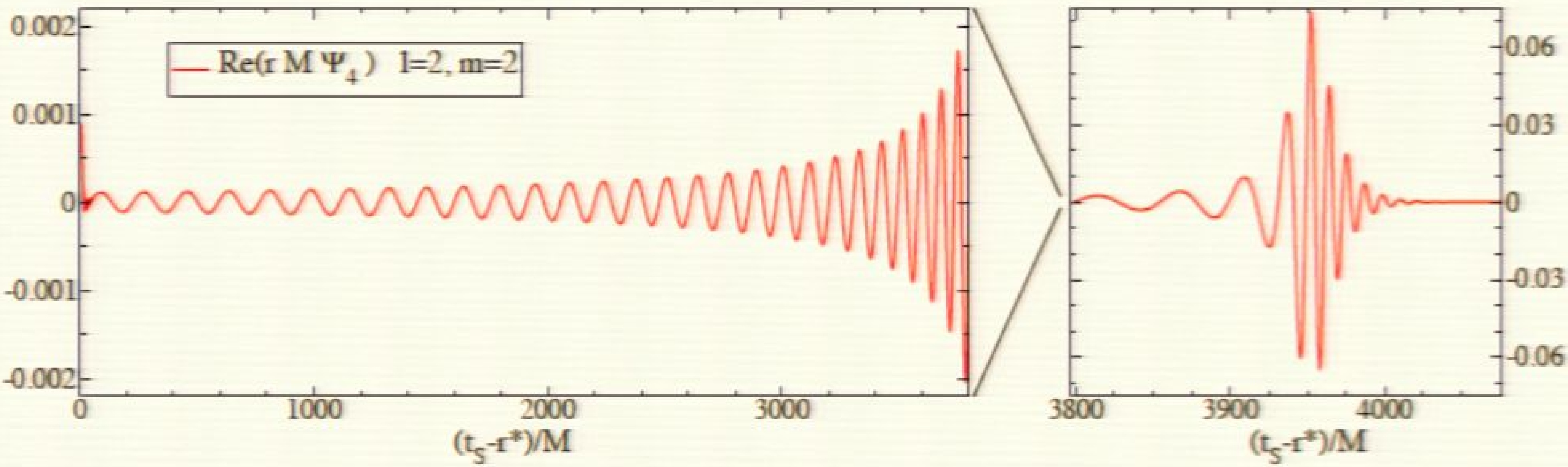

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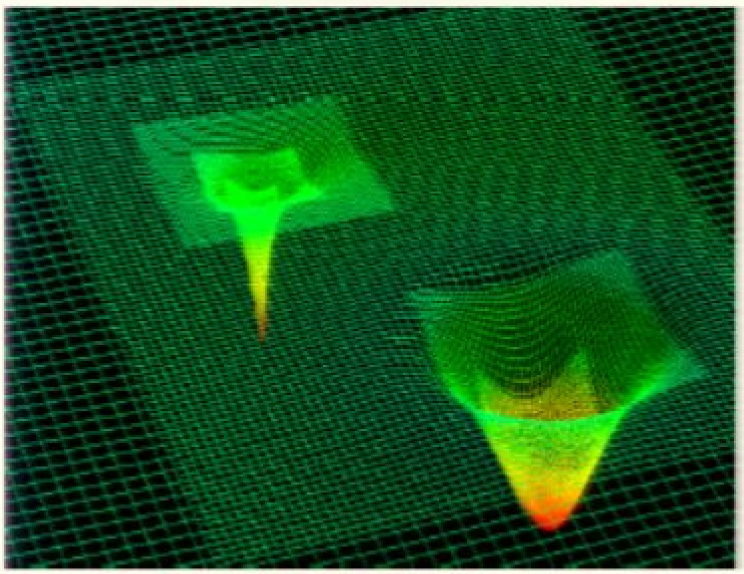

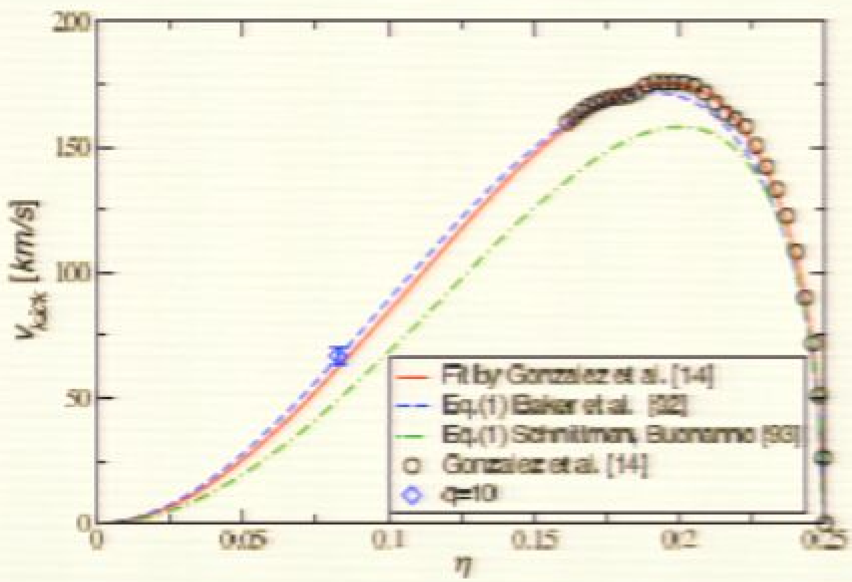

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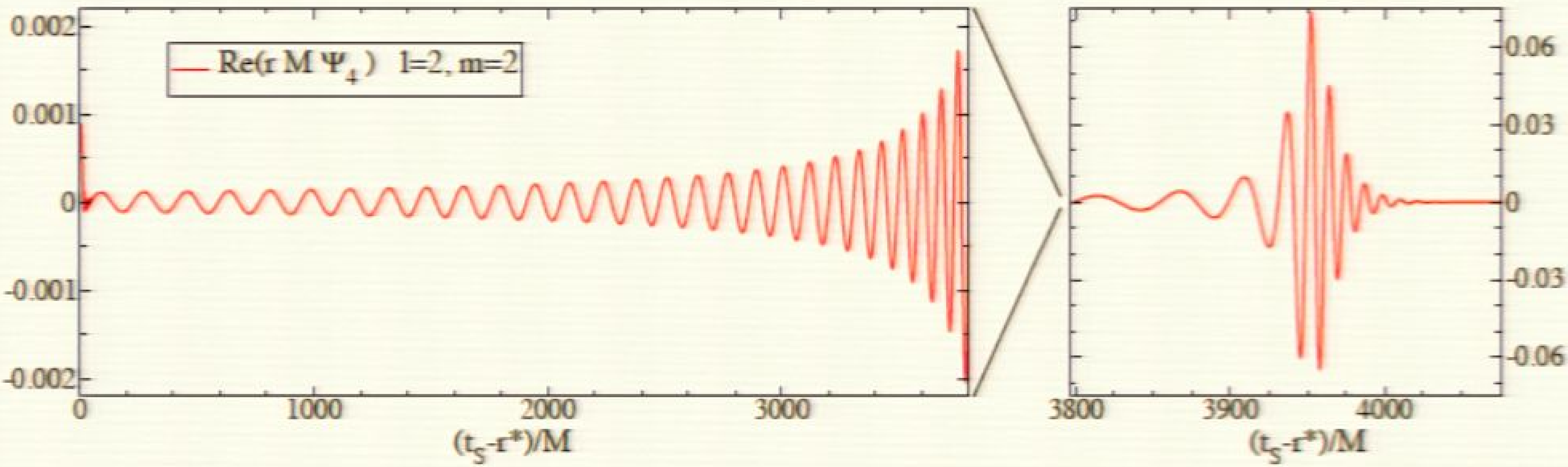

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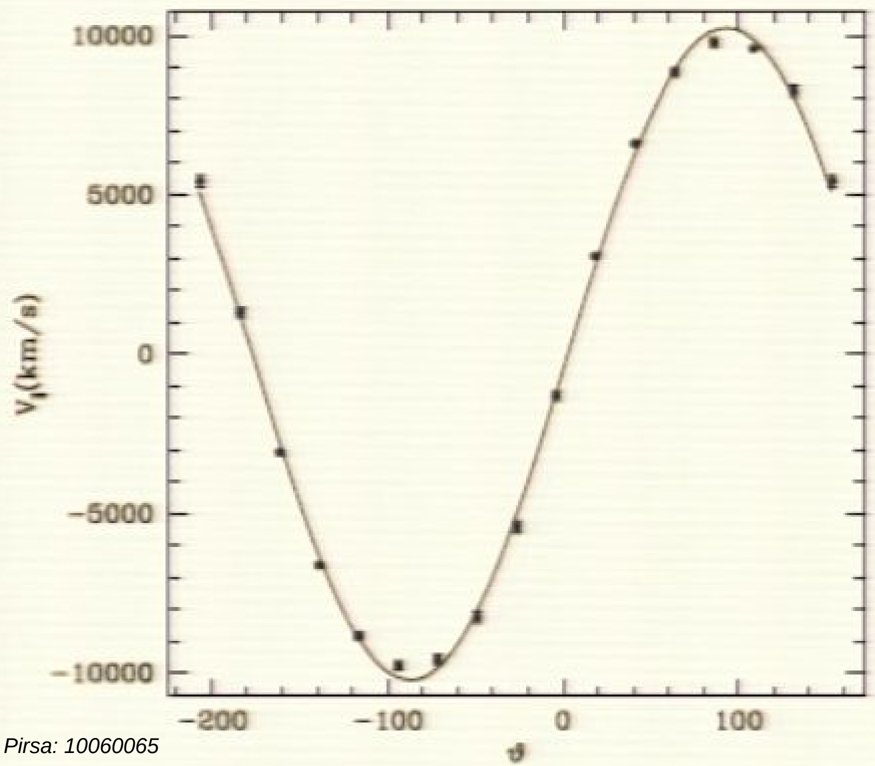

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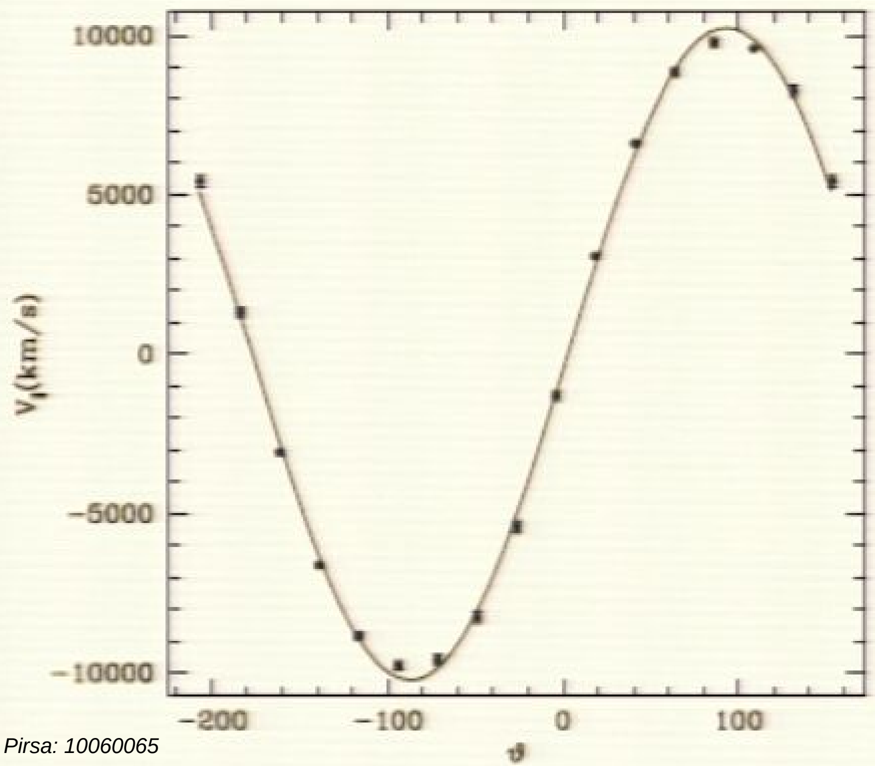

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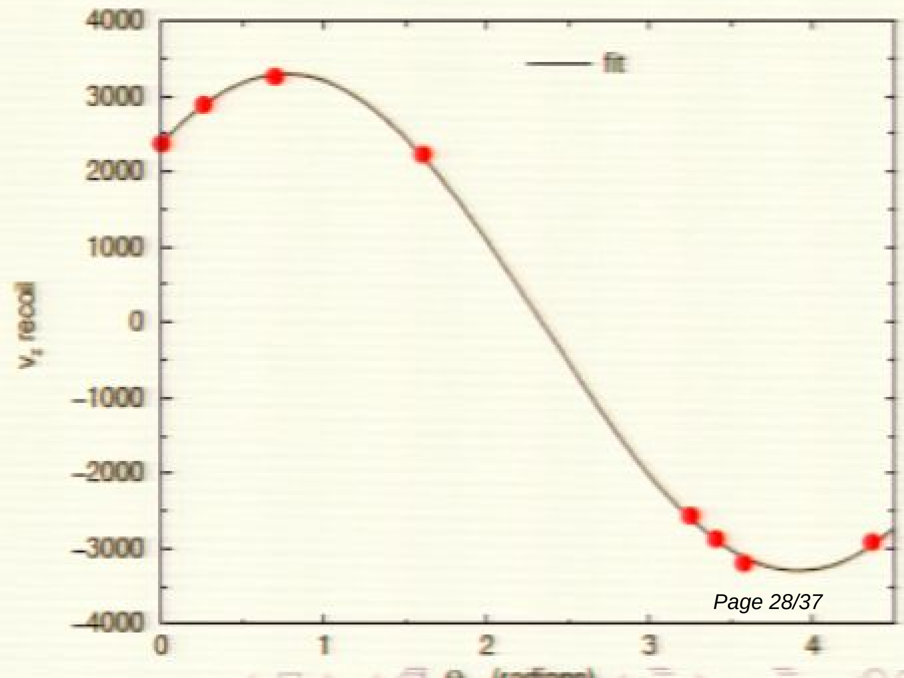

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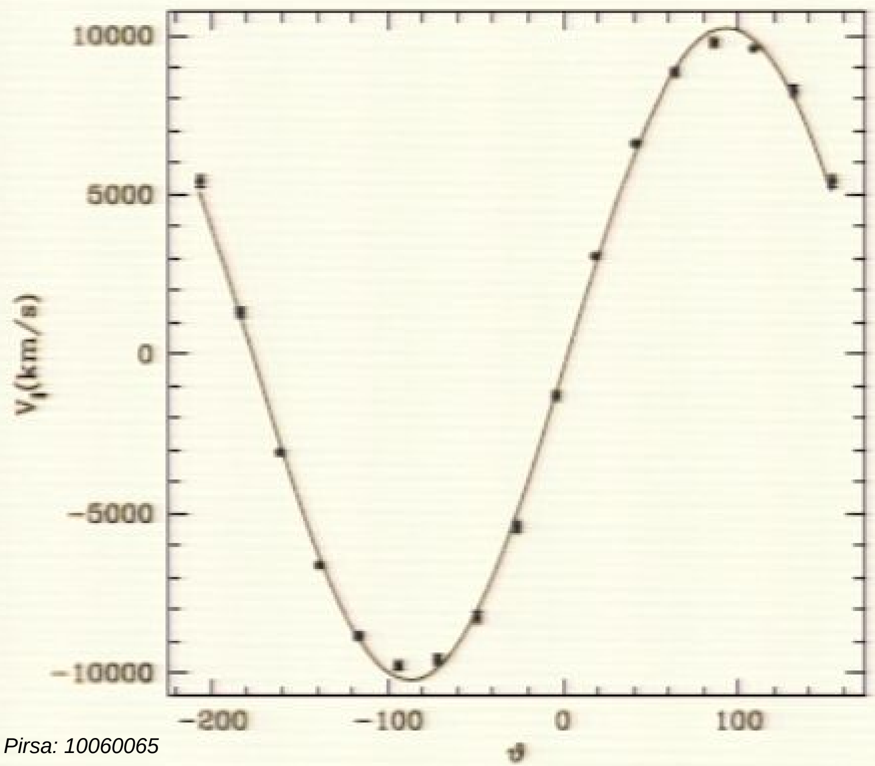

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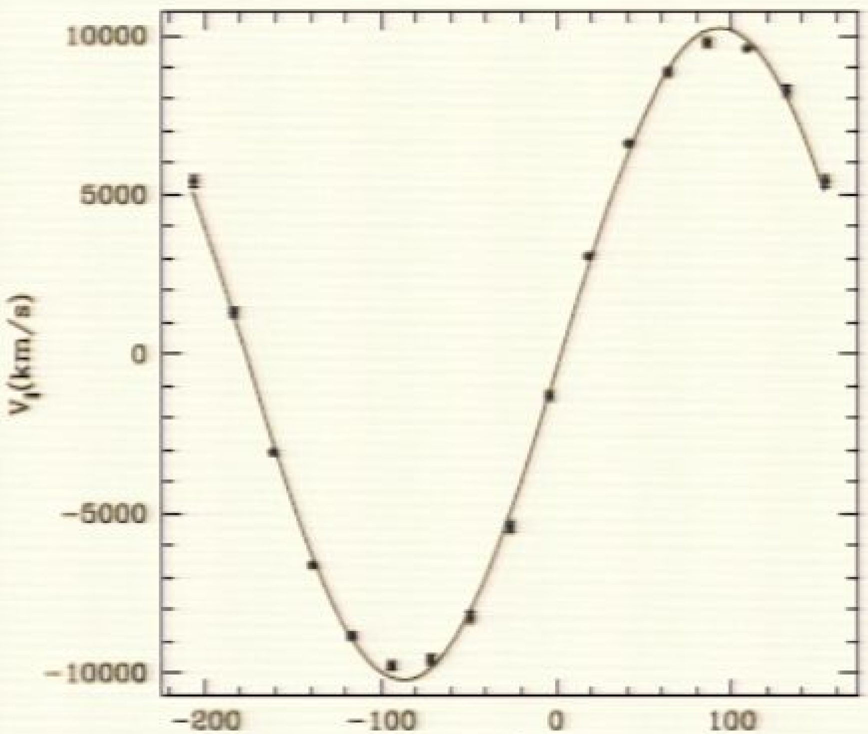

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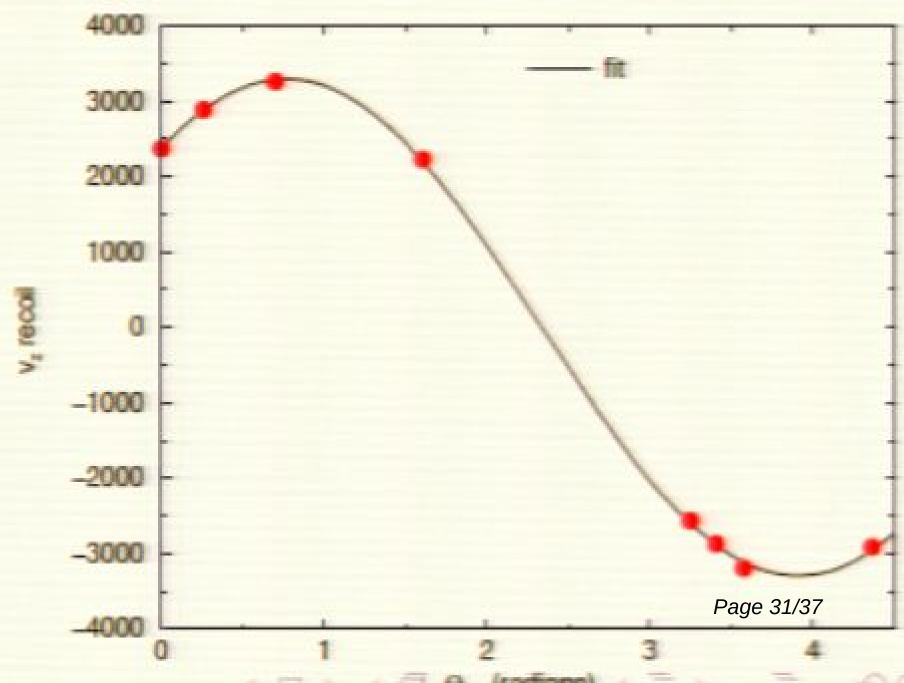

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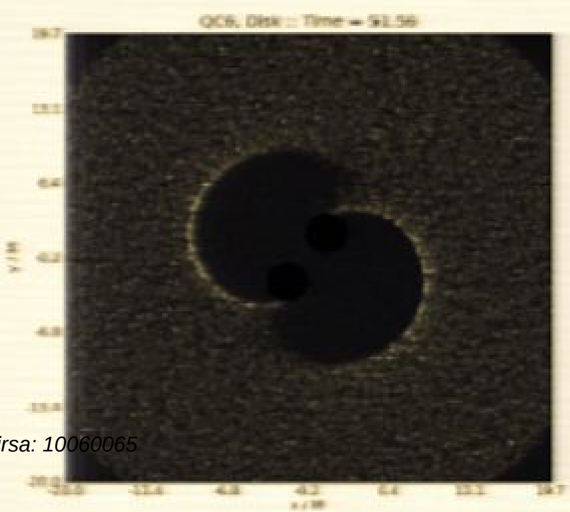
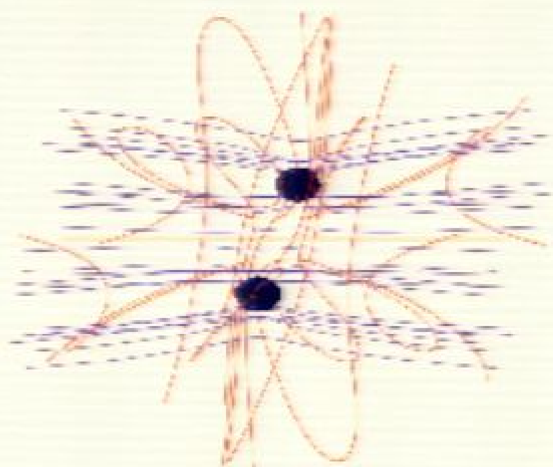
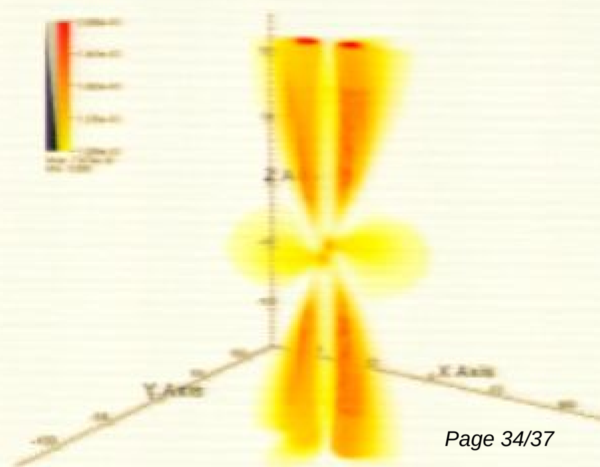
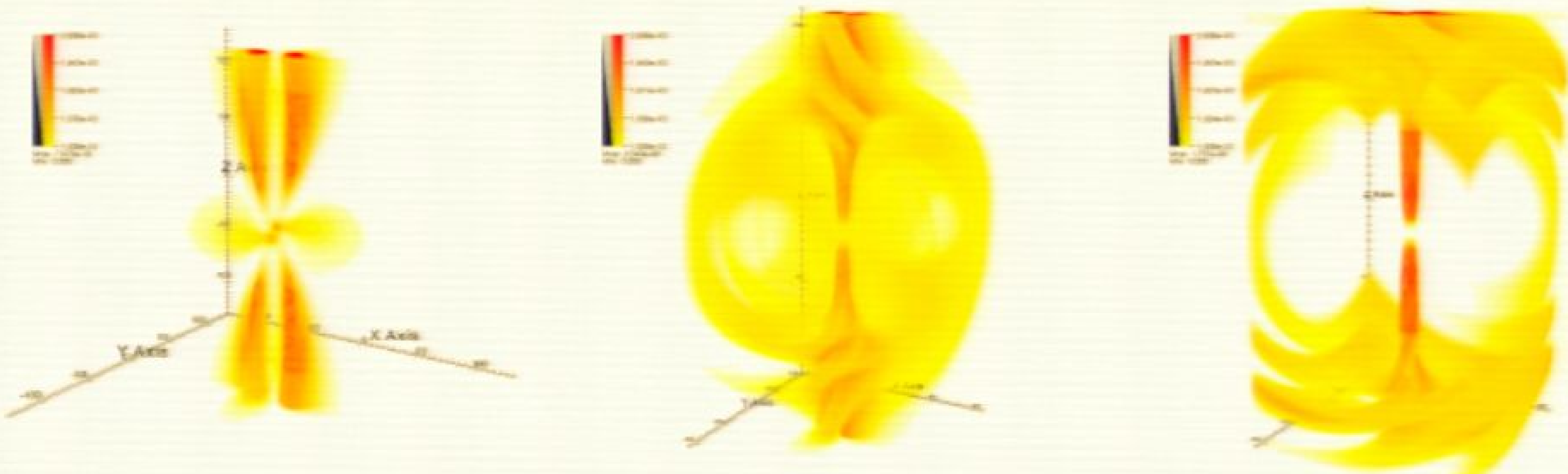






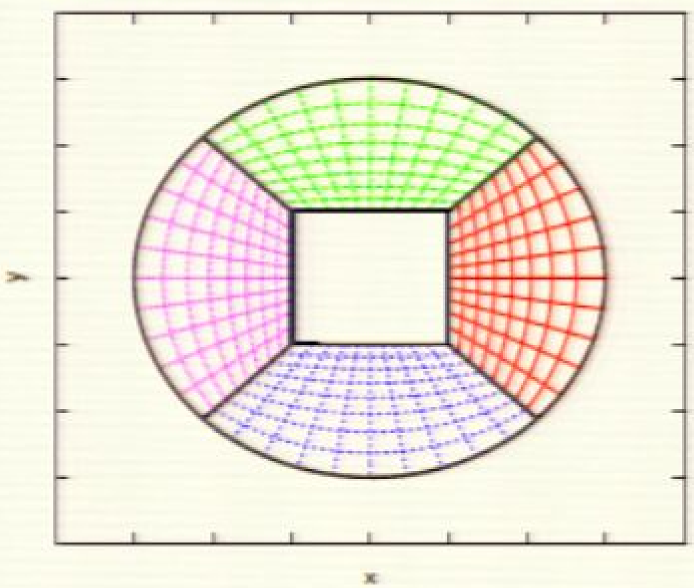
State of the art – dual jets

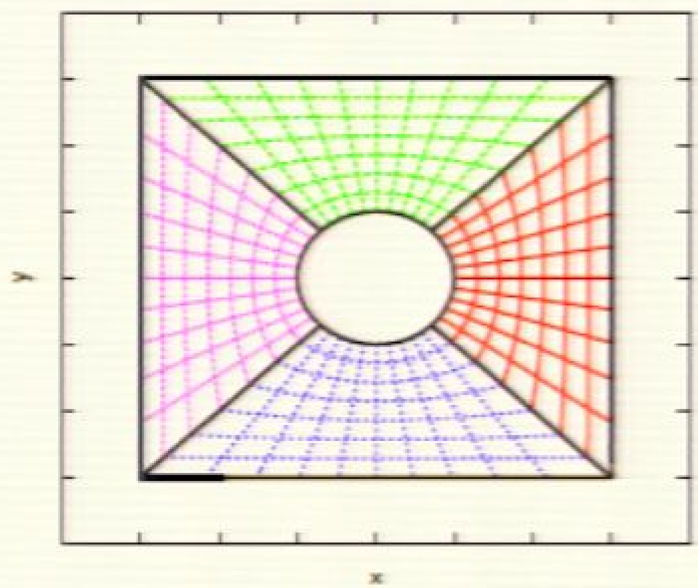
- Palenzuela, Lehner, and Liebling 2010
- Force-free assumption: magnetic pressure ≫ gas pressure
- Find dual jets for a *nonspinning* BHB – not typical Blandford-Znajek mechanism



State of the art – methodology – multipatch

- Pazos et al 2009, Pollney et al 2009
- Greater freedom to tailor grid to geometry of the problem
- Waveforms don't gain any angular structure as $r \to \infty$
- Multipatch facilitates an extension of the grid with only radial elements ($\mathcal{O}(N)$ instead of $\mathcal{O}(N^3)$)





State of the art – methodology – Cauchy characteristic extraction

- Reisswig et al 2010
- Waveform extraction occurs at future null infinity (can also be done by compactifying, see Zenginoglu and Tiglio)
- Confirms that the practice of extracting at finite radii and extrapolating is reliable
- See Maria Babuic's poster