TaylorEt GW templates & Jena's SAPE

Achamveedu Gopakumar

TPI, FSU-Jena

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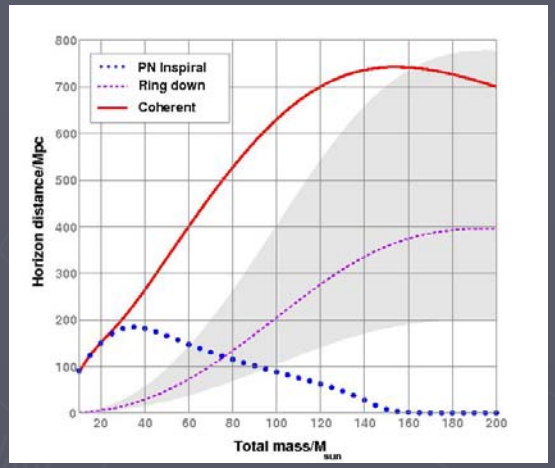
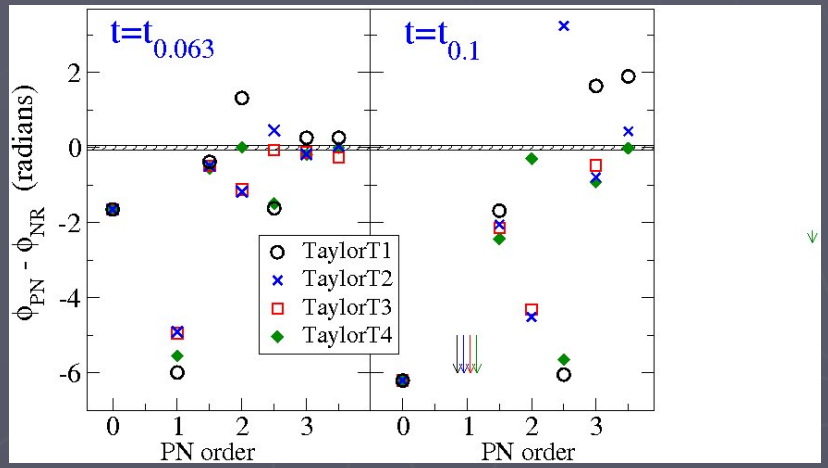
Coalescing black hole binaries:
the most promising sources



Ajith et.al (2007)



Boyle et.al (2007)

- GW data analysts, PN & NR advocates are working closely
- GW Astronomy with LISA in 10-15 years ???
- A close look @ PN & NR-based h(t) is not a bad idea !!

PN & NR-based h(t): ?

- The usual PN-accurate search templates model GWs from compact binaries inspiralling under various prescriptions for radiation reaction along exact circular orbits !

- NR-based h(t) have tiny eccentricities even near the LSO; but they still agree with PN-accurate h(t) !!!

- Do I/you need to think about these issues ?
  YES/NO

LAL PN approximants :I

- Inspiral GWs from non-spinning compact binaries are being searched using several types of PN approximants : (Damour, Iyer & Sathyaprakash 2001)

These PN approximants require

- 3PN accurate orbital energy E (x); Damour, Jarnowski & Schäfer (2001)

  $x = (G\, m\, \omega / c^3)^{2/3}$ ω : the orbital angular frequency

- 3.5PN accurate GW luminosity L(x); Blanchet et al. 2002 & 2005

- Restricted PN waveforms: $h(t) \sim x(t) \cos 2\varphi(t)$

LAL approximants: II

- TaylorT1 approximant (Damour, Iyer & Sathyaprakash 2001)

  $h(t) \sim x(t) \cos 2\varphi(t)$

  $d\varphi/dt = x^{3/2}/m;\ dx/dt = -L(x)/\ dE/dx$

- To construct TaylorT1 3.5PN search templates,
  use 3.5PN accurate L(x) & 3PN accurate E(x)

- PN-accurate approximants T1..T4, P1,P2 & F2 require
  $x = (m\omega)^{2/3}$ variable : $d\varphi/dt = \omega$

- Inspiral is along exact PN-independent circular orbit !!

TaylorEt h(t)

TaylorEt approximant : I

- A new class of GW search templates is proposed that model GWs from compact binaries inspiralling under PN -accurate radiation reaction along PN-accurate circular orbits !(gr-qc/0712.3737)

- It explicitly takes into account the fact that the advance of periastron, appearing even at 1PN, is NOT ZERO even when eccentricity is ZERO

- It is termed TaylorEt approximant & it does NOT require x variable

TaylorEt approximant: II

- TaylorEt approximant at 3.5PN order

$$h(t) \sim \xi(t) \cos 2\varphi(t)$$

$$\frac{d\varphi}{dt} = \xi^{3/2}\{1 + .. \xi + .. \xi^{2} + .. \xi^{3}\}$$

$$\frac{d\xi}{dt} = \frac{64\,\eta}{5\,m}\xi^{5}\{1 + .. \xi + .. \xi^{3/2} + ..+ .. \xi^{7/2}\}$$

- $\xi = -\frac{2E}{\mu}$ (dimensionless orbital binding energy)

Equal emphasis to the conservative & reactive phase evolution

TaylorEt approximant: III

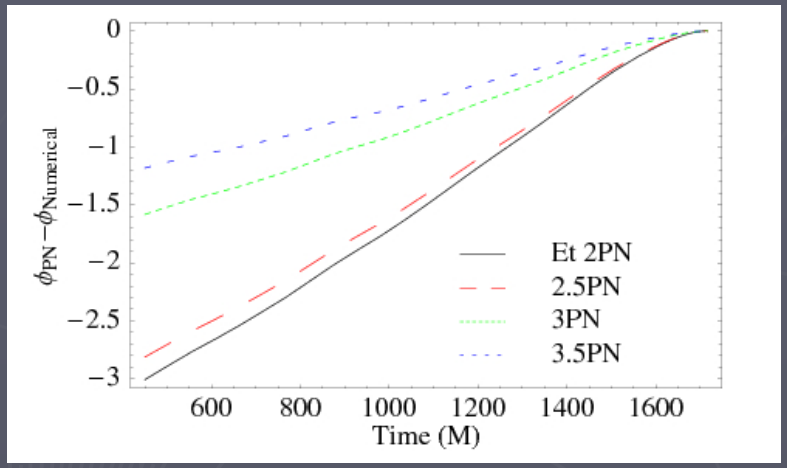
- Approximants where inspiral is along PN-accurate circular orbits should be more efficient in capturing GWs from compact binaries having tiny orbital eccentricities M.Tessmer & AG, gr-qc/0712.3199

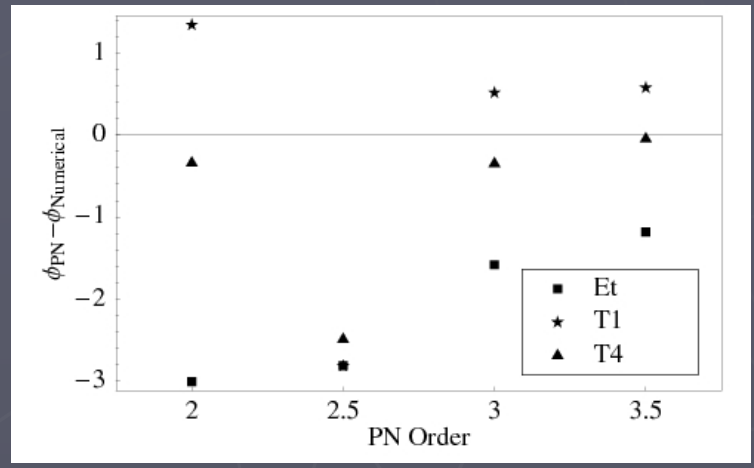
- GW phasing for eccentric binaries requires that compact binaries inspiral along precessing (PN- accurate) eccentric orbits (Damour, AG & Iyer 2004)

- In a given GW frequency window, TaylorEt provides more N_{GW} than TaylorT1..T4 at a given reactive PN order

N_{GW} decreases monotonically as the reactive PN order is increased !

TaylorEt approximant : IV



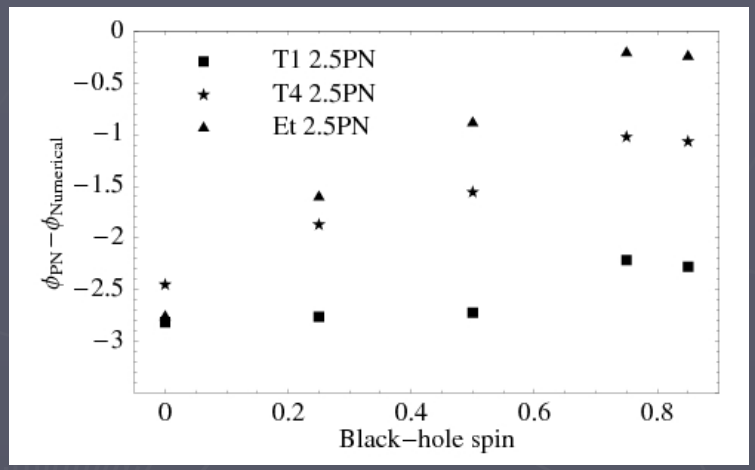


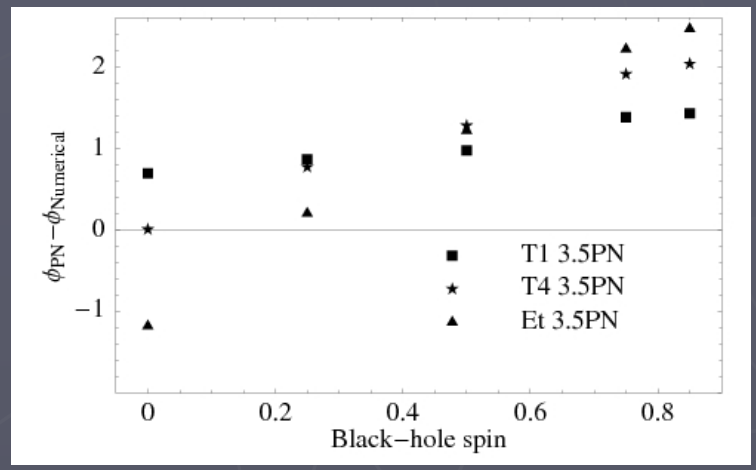
- A comparison of GW phase evolutions under NR & PN descriptions : equal mass non-spinning BBHs

NR simulation last ~ 9 orbits till the Last Stable Orbit

- Monotonic convergence to exact GW phase evolution in GR is only exhibited by TaylorEt approximant ! gr-qc/0712.3737

TaylorEt GW templates: V





- A comparison of GW phase evolutions under NR & PN descriptions : equal mass spinning BBHs

  NR simulation last ~ 10 GW cycles till $(m\,\omega)_{GW} = 0.1$

- To 2.5PN order, PN & NR descriptions are dealing with BLACK-HOLES ! The above analysis is fully trustable only to 2.5PN order !!

- *We considered only the orbital hang-up configuration*
  gr-qc/07123787 (M. Hannam, et al.)

TaylorEt GW templates: VI

- Recently, we performed detailed Fitting Factor computations relevant for LIGO, Virgo & A-LIGO involving TaylorEt h(t) & x-based templates
  S. Bose, A.G & M. Tessmer (LIGO-T080142-00-Z)

- It may not be a bad idea to allow
  $m_1 m_2 / (m_1 + m_2)^2 > 0.25$
  in current x-based templates

- We are only beginning to probe various consequences of TaylorEt h(t)

Why new approximants should capture GWs efficiently from compact binaries

having tiny orbital eccentricities ?

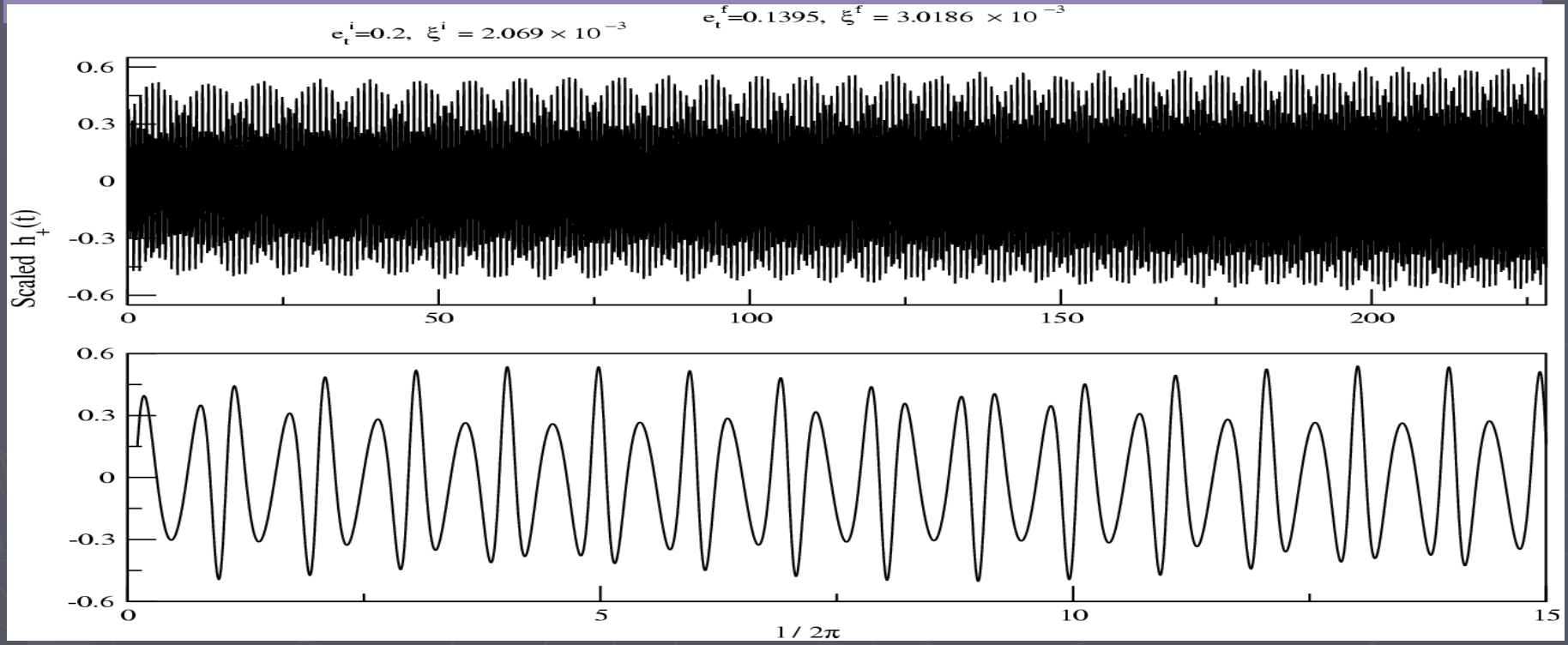
GW templates: I

- Highly accurate & efficient *ready-to-use* GW templates for compact binaries of arbitrary mass ratio moving in inspiralling eccentric orbits are being computed in Jena

- We adapted an approach of T. Damour that gave the heavily employed *timing formula* for relativistic binary pulsars

T. Damour, A.G, C.Königsdörffer, B.R. Iyer, M. Tessmer,…

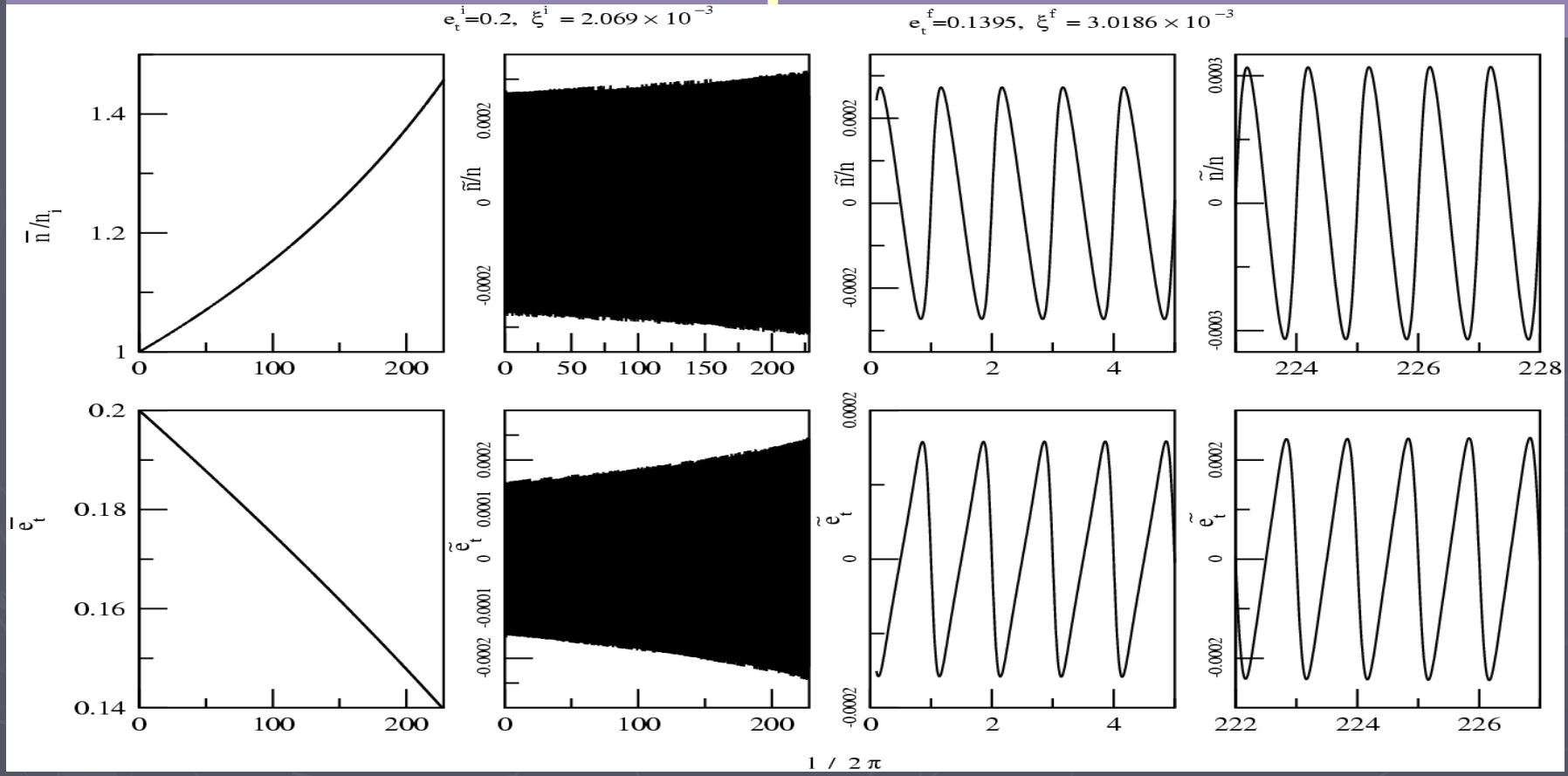
GW templates: II



- ✓ Plots of $h_+(t)$ showing 3 relevant time scales

orbital evolution is NOT adiabatic
fully 3.5PN accurate in orbital dynamics

GW templates: III



- ✓ Quasi periodic variations in orbital elements
- ✓ We can handle arbitrary eccentricities

Eccentric h(t) for LIGO-VIRGO ? : I

- PSR 1913+16 => compact binaries will have e $\sim 10^{-6}$ by the time GWs from similar systems enter LIGO/VIRGO bandwidth

- Therefore, currently, GW DA community is ONLY looking for ICBs in quasi circular orbits using TaylorT1… templates

$$d\,\varphi / d\,t = x^{3/2}/m; \quad x = (m\,\omega)^{2/3}$$

- GW data analysts also refer to a paper by Martel & Poisson (2000) to justify why they ignore eccentric binaries..

Eccentric h(t) for LIGO-VIRGO ? : II

- Martel & Poisson argued that GW templates (TaylorT1/T4) should be quite efficient in extracting GWs from even mildly eccentric compact binaries

- MP modeled GWs originating from compact binaries in exact (Newtonian) eccentric orbits, perturbed by quadrupolar (2.5PN) radiation reaction contributions & used TaylorT1 templates

- Tessemer & AG argued that above analysis requires a detailed look !!

  gr-qc/0712.3199

Eccentric h(t) for LIGO-VIRGO ? : III

- While modeling astrophysical GWs from eccentric binaries, influenced by GW radiation reaction entering at 2.5PN order, we need to include periastron (secular) effects appearing at 1PN & 2PN orders..

- MP ignored secular 1PN & 2PN effects, while we (TG) included it correctly using Damour, AG & Iyer 2004

- We demonstrated that TaylorT1/T4, completely adiabatic & non-adiabatic circular templates (AIRS 2004) having Newtonian RR are highly inefficient in capturing DGI eccentric h(t) also having Newtonian accurate RR !!

Eccentric h(t) for LIGO-VIRGO ? : IV

- TaylorEt templates model GWs inspiralling under GW radiation reaction along PN accurate circular orbits
- Therefore, TaylorEt can capture GWs from eccentric binaries & we demonstrated it
- Recall TaylorT1..T4 templates model GWs inspiralling under GW radiation reaction along exact (PN independent) circular orbits

This is why secular phase evolution starts at 2.5PN order

LISA Templates

LISA will require these templates to hear GWs from

- ✓ Galactic Stellar mass compact binaries
- ✓ Intermediate mass BH binaries
- ✓ Super massive BH binaries

Current eccentricity related projects

Efforts are ongoing in Jena

- To improve TG07 work by improving DGI 2004: 3PN conservative & 2PN reactive dynamics.. Extending TaylorEt h(t) for eccentric cases..
- To probe data analysis issues, relevant both for ground and space based GW detectors with Prof. Bose & collaborators
- To include certain spin effects
- To compare GW phase evolution for eccentric binaries with NR group @ Jena

Semi-Analytic Puncture evolution (SAPE)

SAPE: II

- It is possible to derive a Hamiltonian that describes orbiting Brill-Linquist black-holes within well-defined truncations to Einstein Field Equations

- Skeleton Hamiltonian that describes conservative orbital dynamics of binary non-spinning punctures

Faye, Jaranowski & Schäfer 2004

SAPE: III

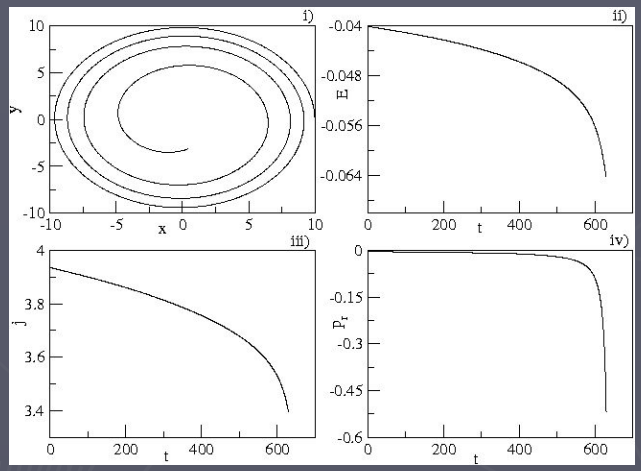
- We (AG & G. Schäfer) incorporated in a transparent Hamiltonian way the effects of gravitational radiation reaction onto the conservative H_{Sk}

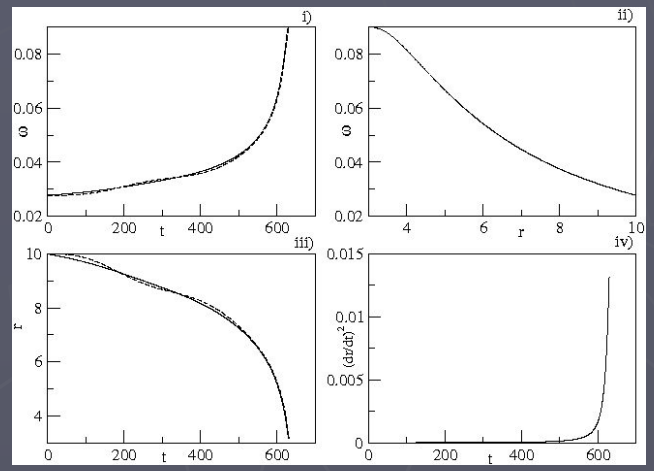
- This is how we obtained a Semi-Analytic Puncture Evolution (SAPE)
  AG & G. Schäfer (2008)

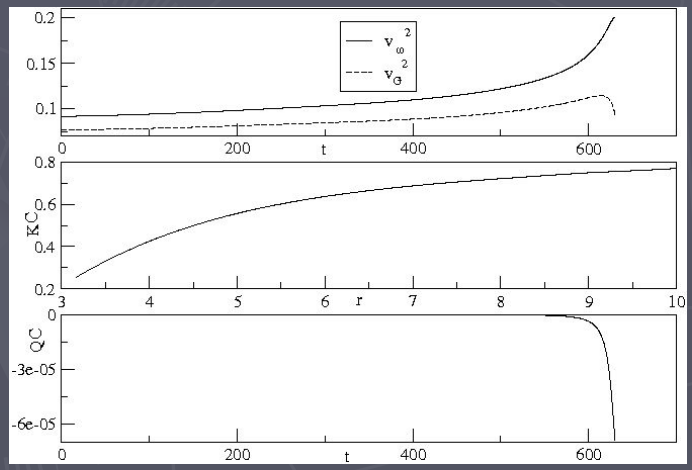
- SAPE shares many features with the puncture evolution in GR, pursued by many NR groups

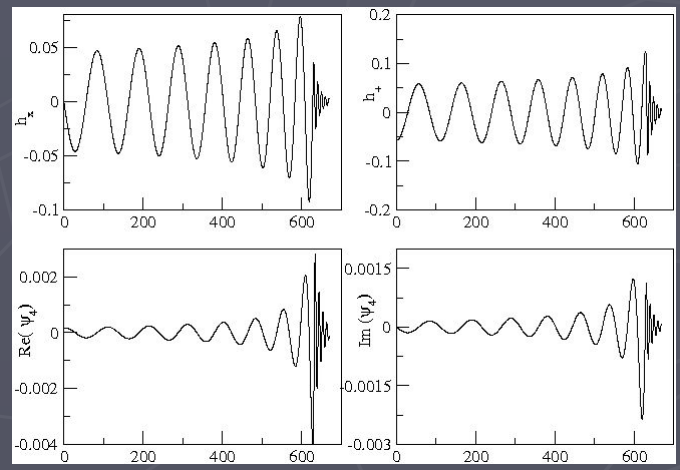
- Therefore, we should be able to probe ***the physics*** behind the recent NR advances

Various Facets of SAPE









SAPE: Plans

- Accurate comparisons with NR & PN evolutions
- For dirty MBH mergers !!
- It should be useful to construct EMRI/IMRI h(t)
  LISA astronomers want to `hear' EMRI/IMRI h(t)
- BBH merger movies in SAPE without supercomputers !

Conclusions

- We are taking a close look @ PN-accurate & NR-based h(t)

- There are few more interesting issues to be sorted out !!