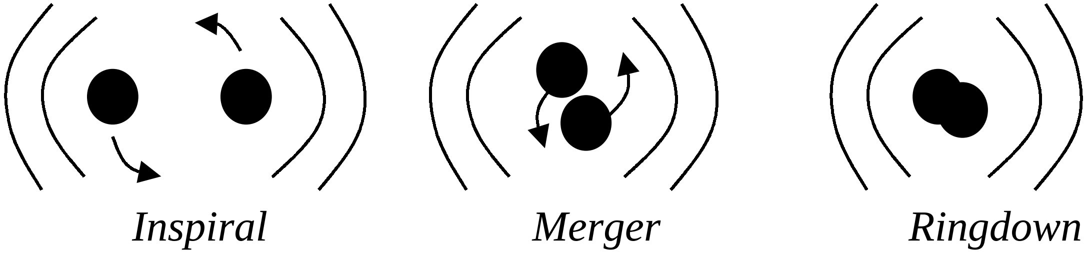
Merger phase simulations of binary-systems: status

- Waveforms – today
- *BH-BH*
- *BH-NS*
- NS-NS
- Main difficulties/unknowns
- Outlook *(for some of the problems)*
  - Computational/analytical sides

Luis Lehner UBC → LSU

LIGO-G020166-00-Z

Waveforms…



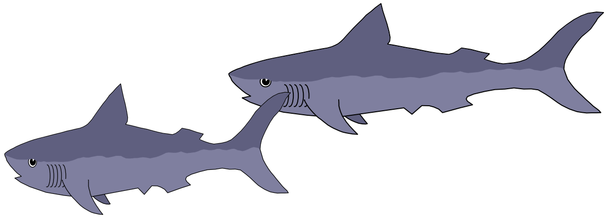
?

Binary Simulations: Key issues

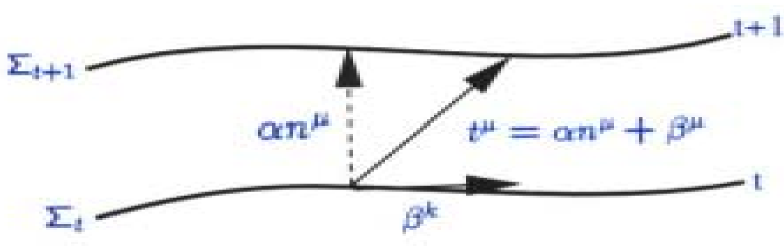
- ***Formulation and discretization of equations of motion***
- ***Singularity and/or fluid handling***
- ***Coordinates?***
- ***Computational demands***
- ***Tie-in to observations (gravitational wave extraction…we're working with a deadline!)***

- ***Turn-around time for tests too long!***

- ***Shortage of personnel***
  - ***(5 candidates for ~15 PD jobs!)***



Eqns: 3+1 approach



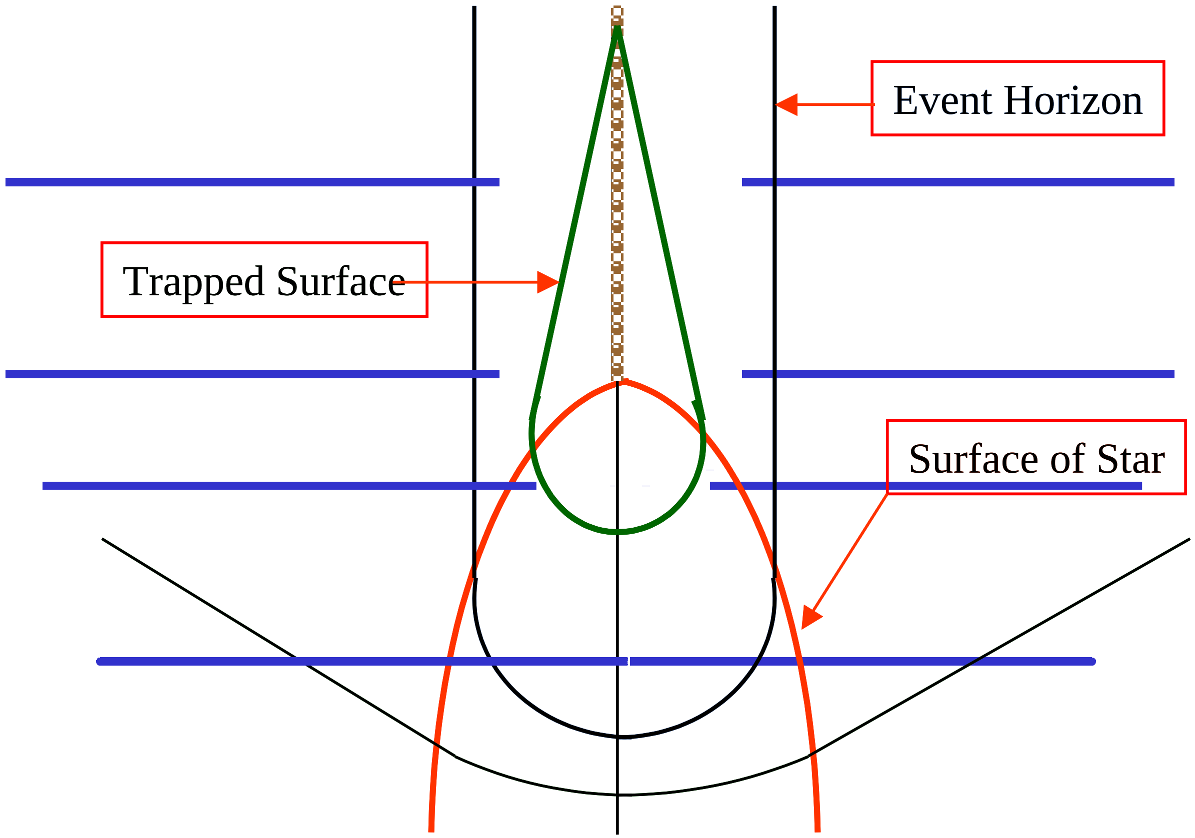
$$\partial_t^2 g_{ij} = g^{kl} \partial_{kl}^2 g_{ij} + F(S)$$
$$C_a(g) = 0$$
$$S = \{\alpha, \beta^i, g_{kl}, derivs(S)\}$$

- Several Flavors: *ADM; BSSN; EC*, …
  - ADM: Geometrical: ‘oldest’…
  - BSSN: ‘gauge’ separating: very popular, close to ADM
  - Hyperbolic: well posedness and cleaner boundary treament
- Coordinate conditions defined by α, β^i
- ID needs to satisfy constraints.

$$\begin{aligned} R + K^2 - K_{ij}K^{ij} &= 0 \\ D^j(K_{ij} - g_{ij}K) &= 0 \end{aligned}$$

Singularity handling

- ‘singularity excision’



Coordinates?

- ‘mere’ labels. Can be chosen arbitrarily
- Affect metric form

$$ds^2 = -dt^2 + dx^2 + dy^2$$

$$ds^2 = -dt^2 + dr^2 + r^2 d\theta^2$$

Flat spacetime!, just in different coordinates: Cartesian, cylindrical

- ‘co-moving’ coordinates considerably simplify the description
  - Generally requires ‘knowledge’ of dynamics
- Avoid ‘coordinate singularities’ (eg. same point with different coordinate labels)
- Require compatibility with ‘singularity excision’

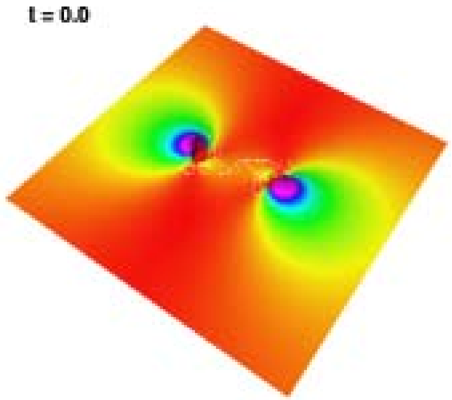
Cost of 'typical simulation'…

- RHS' ~ 10^3 ops
- Vars ~ 10^1- 10^2
- Resolution per wavelength 20 pts (ε~10%); 64 pts (ε ~1%)
  - Δx ~ M/6
- Evol time ~10^3 M
- Boundaries? 'as far as possible' [System in a Box!…*approximation* to the 'target system']
  - Cost for T=10^3M, OB=50M ~10^{17} Flops!!!
  - (Note: cheaper for spectral methods iif smooth enough solutions!)

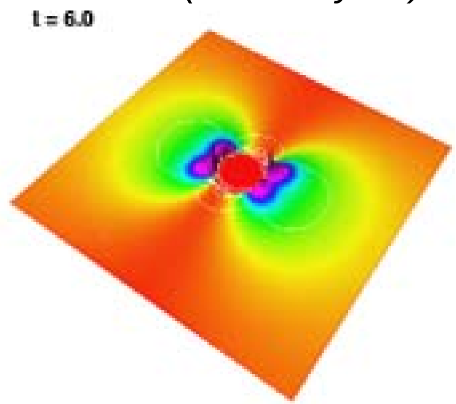
- *Note:*
  - *Twice the resolution?. Multiply by 16*
  - *Move boundaries 10 x farther ? Multiply by 10^3!*

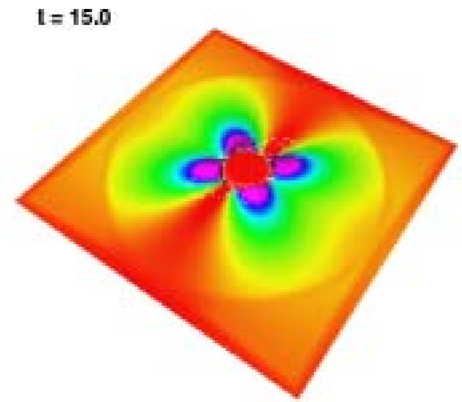
BH-BH (~2000 | UT-Pitt-PSU / AEI)

- Preliminary *(quite naïve)* binary black hole runs



Mesh size of order 100 x 100 x 100; other calculations approaching 400 x 400 x 400 (100 Gbyte!)





Single component of 3-metric on 2-D slice through grid is visualized, black hole excision techniques employed

- The good: Can handle 2 BH → BH
- The bad & the ugly: Still lots of problems.
  - Stability (2BH T<30M || 1BH T<100M);
  - *Equations; coordinates; accuracy; boundaries*

Regroup & revise

- Simplified problems:
  - 3D single (slightly perturbed) black holes [AEI,PSU, Cornell, UT,UIUC…]
  - 2D greatly perturbed bh's [UBC,LIU-BYU]
- Worrying about outer boundary issues!
  - 'outgoing wave' conditions [UIUC, AEI, WashU, PSU, UBC…]
  - Constraint enforcing boundary conditions [Pitt,LSU,Cornell-Caltech]
  - Compactification [UBC,Oakland]
- Coordinate issues
  - Pressing on singularity 'freezing' coordinates * [AEI...]
- black hole excision issues
  - Simpler if *
  - Dealing with moving boundaries
    - 3D a few points for ~ 40M [PSU,UT...]
    - 2D hundreds of points 'forever' [UBC]

- Stability?
  - Formulation suitability
    - Hyperbolic formulations [Cornell-Caltech,LSU,UT…]
    - Influence of non-principal part of the equations [LSU-UBC,Caltech,...]
    - Modifying rhs’s with constraints [UBC,PSU,UIUC,AEI…]
  - Numerical algorithms
    - Wave-equation based not necessarily good! [LSU,...]
    - Dissipation needed [UBC,LSU]
    - Special handling at excision bdries [AEI,UIUC,…]
  - Resolution!
    - AMR [UBC,NASA,WashU…]

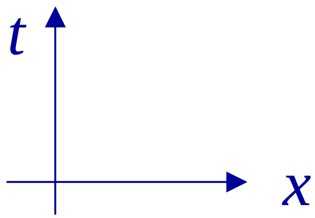
Note: these issues are all intertwined!

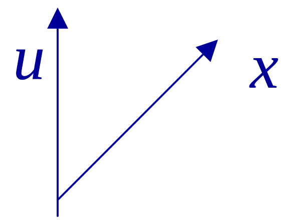
NS-NS

- Freq. too high for LIGO…
  - but can help to put error bars on perturbative methods
- Simulations of merging NS on their way
  - Able to follow for a few orbits [Japan-UIUC,WashU]
  - Fluid treatment with: (a) artificial dissipation, (b) high resolution shock handling schemes
- Rough waveforms obtained.
- Much larger parameter space!
  - eqn of state
- *Good eqns of state?*
- *Are the results robust for different ones?*

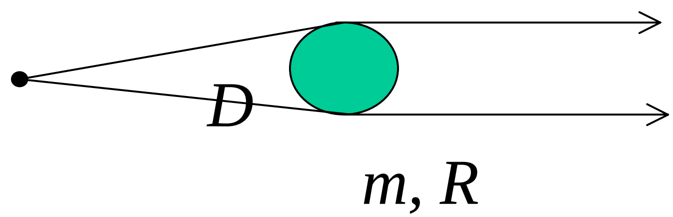
BH-NS

- Not as agressively pursued
  - But combination of NS-NS & BH-BH simulations should make this straightforward
  - Alternative: use ‘characteristic’ formulation [Pitt-UBC-UNISA]





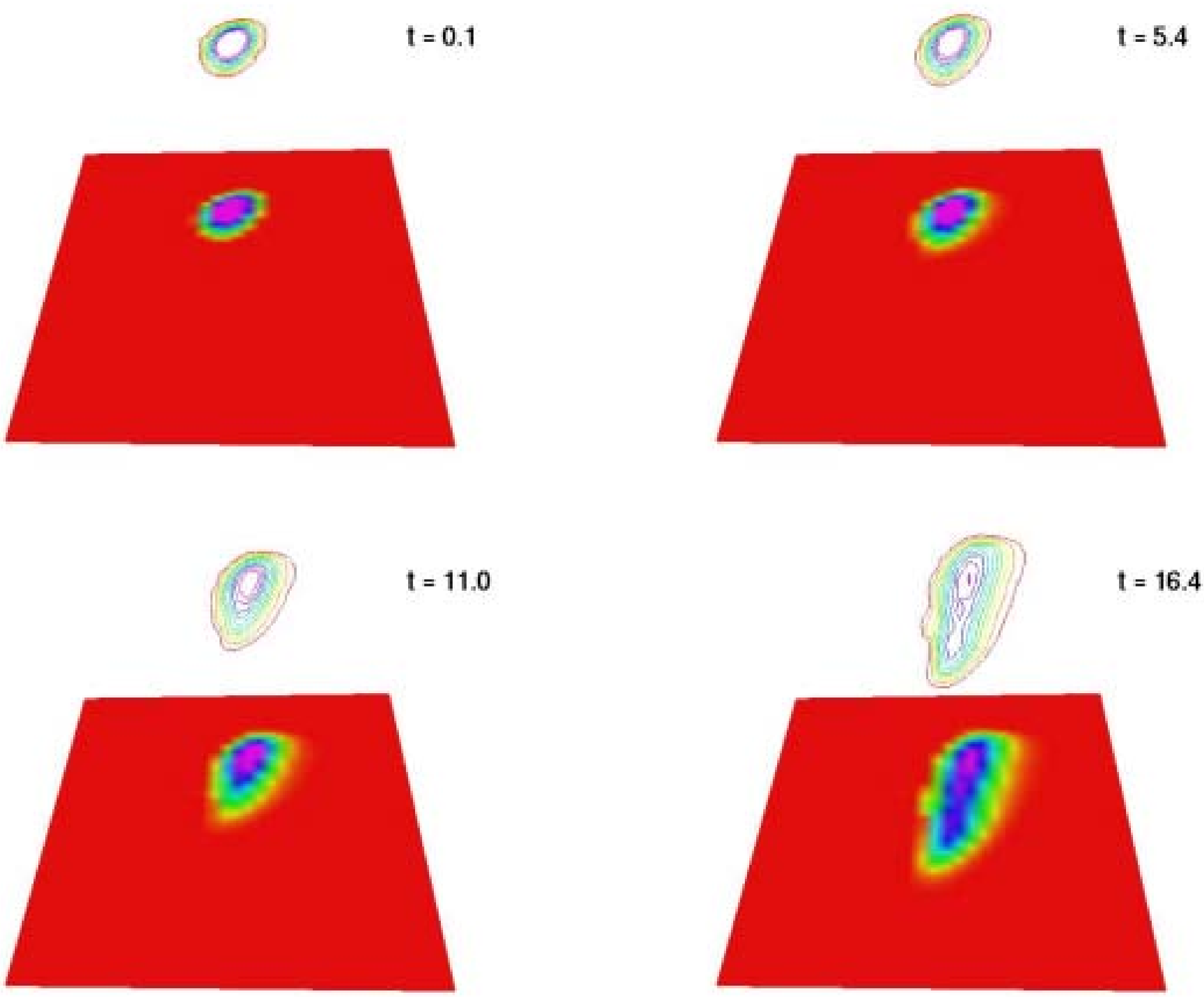
- Restricted parameter space, but single bh’s evolved forever.



- Need to address significantly different computational issues

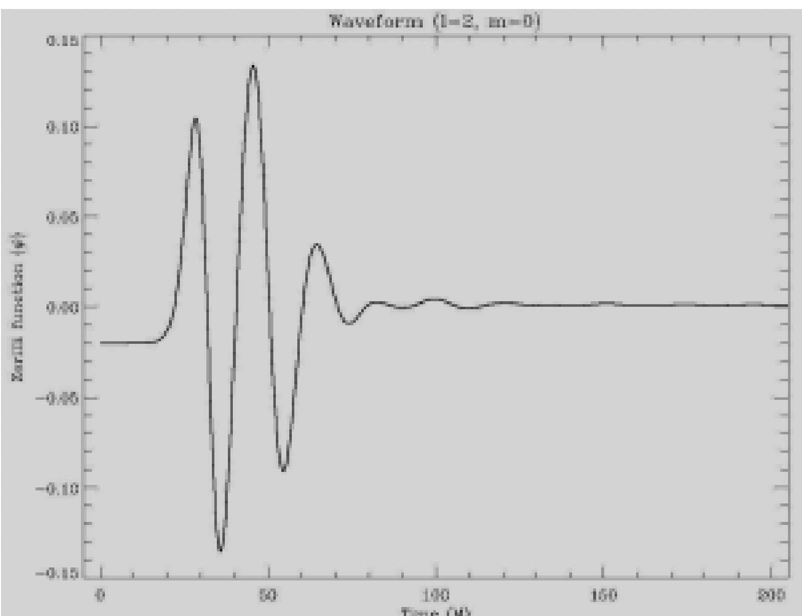
- Targeting BH-NS and SMBH-compact object systems

Density(r,q=const,p)

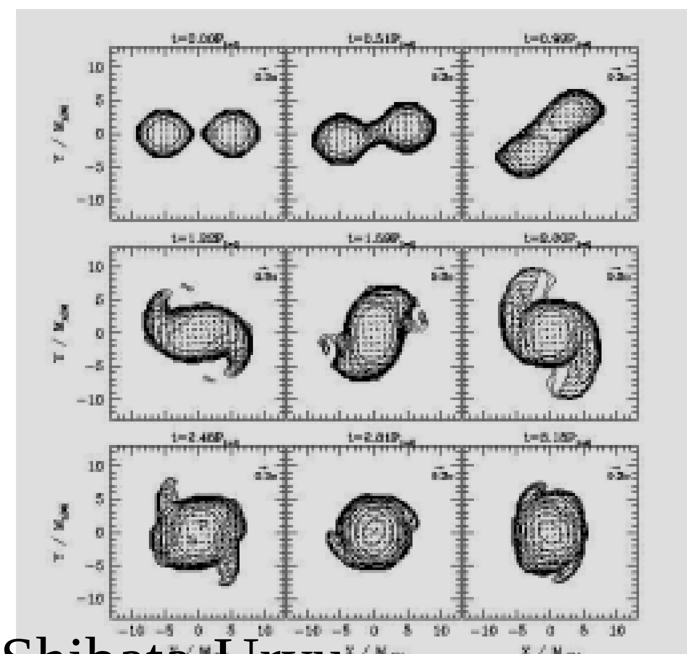


Today: hopeful signs!

- Past 2 years
  - 3D single black hole evolutions pushed by 1-2 orders of magnitude in the past 2 years!
  - 3D binary black holes pushed to ~100M’s
  - 2D simulations (basically) stable (unlimited evolutions)
  - A few orbits of NS-NS systems.

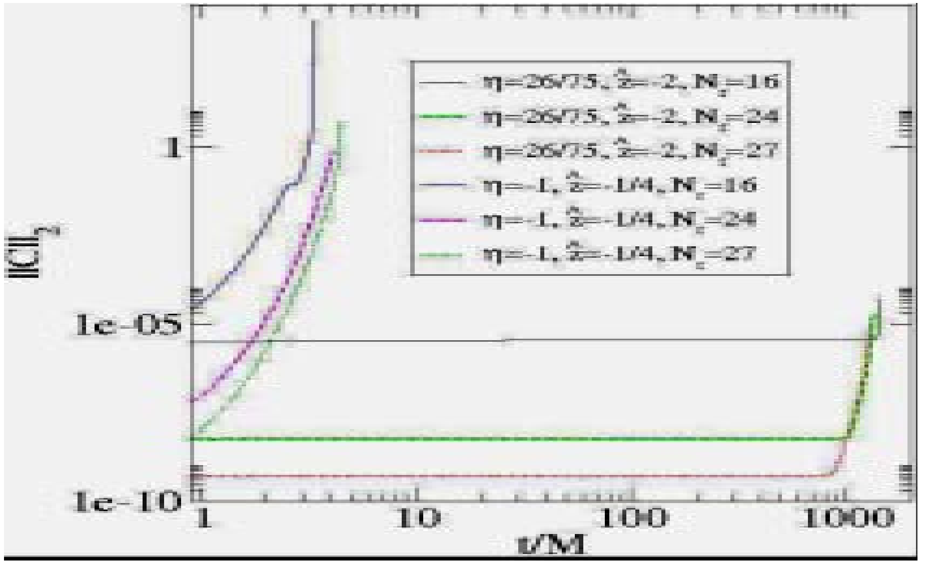


AEI



Shibata-Uryu

- Better understanding of :
  - Formulations, influence of non-linear terms (mathematical knowledge limited)
  - Boundary conditions
  - Moving boundaries



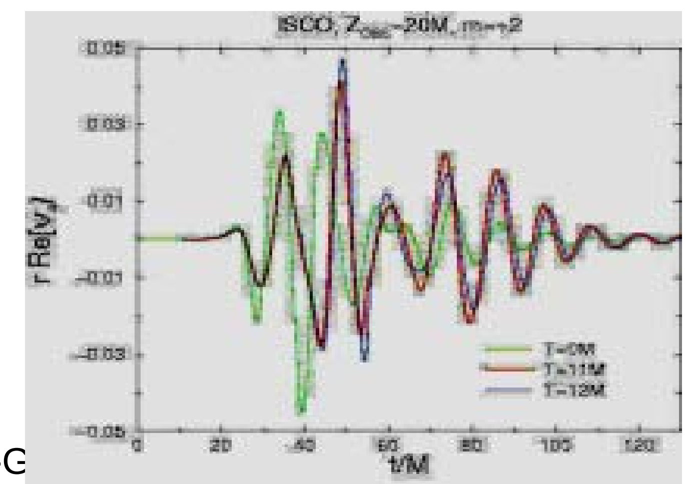
- Computers getting more powerful, and learning how to get the ‘most’ out of them.
  - Cactus, Paramesh, Kelp, etc.etc

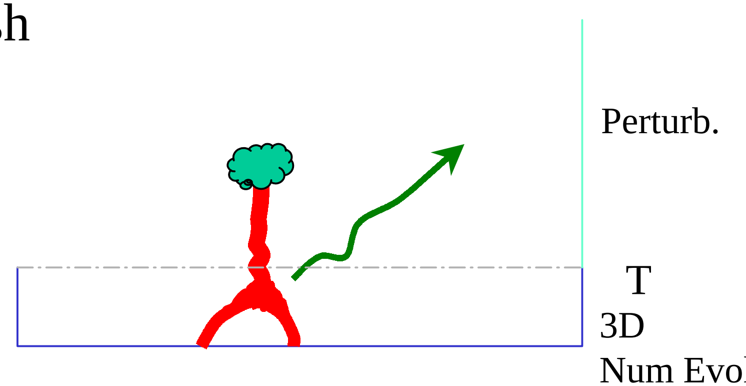
Missing links (practically)…

- ‘realistic’ initial data
  - PN,
  - Quasi-equilibrium,
  - IBBH

→*Right ‘metric’ information seed for elliptic ID solvers. Inner boundaries?*

- Post-merger treatment
  - CLAP, Lazarus, direct match to QNM (need good parameter estimation of final object, isolated horizons?)
  - Can even be used to ‘cheat’ the crash



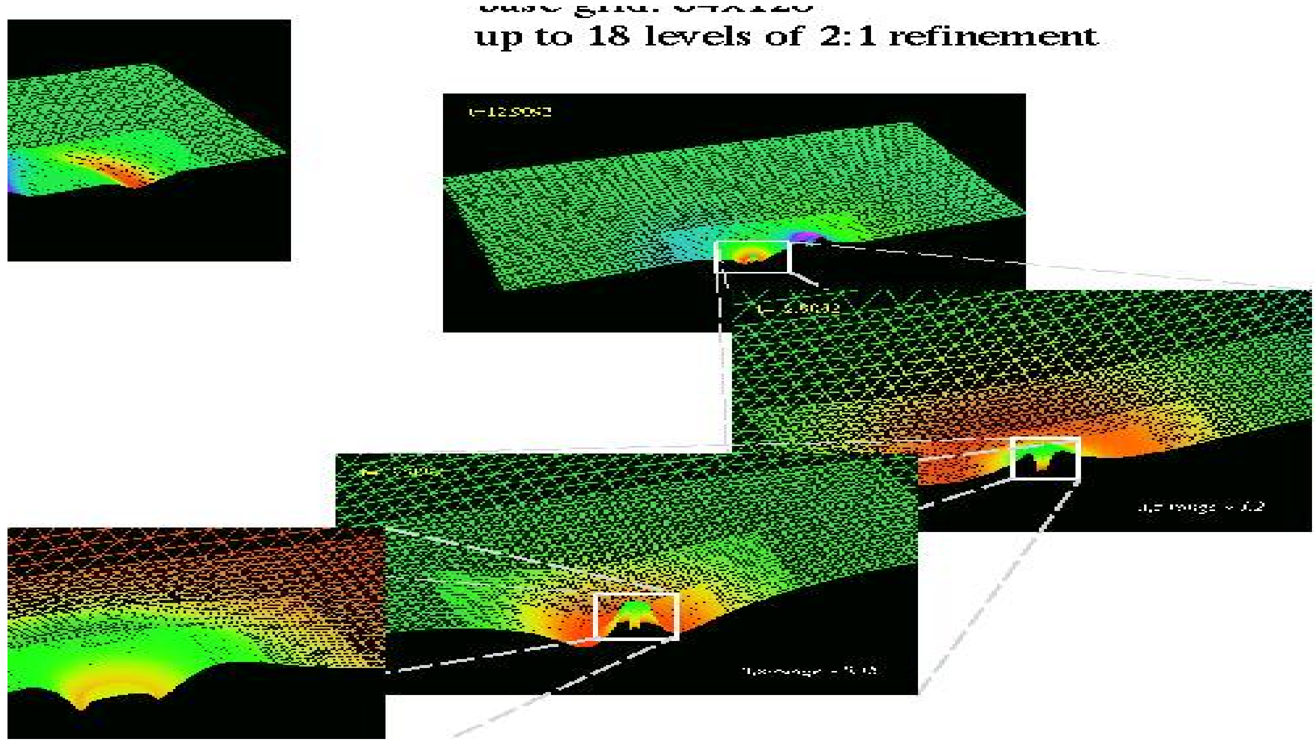


Baker, Bruegmann, Campanelli, Lousto

More missing links…

- Resolution
  - Adaptive/fixed mesh refinement

2D Physics
UBC-LIU-BYU
3D Testing:
NASA
WashU-AEI

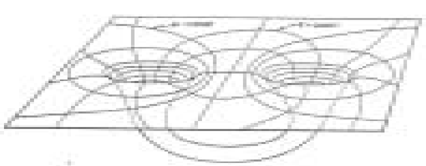


- Needs to work on:
  - What's the 'acceptable' error for data analysis? [25% total??]
  - What's the expected configuration sample? (need feed-back from simulations themselves!, but… astrophysically relevant parameter space is huge!!!)

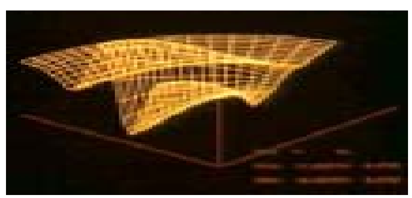
Pushing Further?

- *lots of activities!*
  - Mexican workshop (06/02)
  - Caltech waveform simulations workshop (06/02-06/03 ? 04)
  - Cargese school (07/02)
  - ITP compact object simulations (05-07/03)
- *Computational power…*

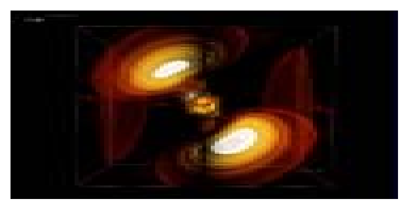
300X **30,000X**



1963
Hahn & Lindquist
IBM 7090
One Processor
Each 0.2 Mflops
3 Hours



1977
Eppley & Smarr
CDC 7600
One Processor
Each 35 Mflops
5 Hours



1999
Seidel & Suen, et al.
SGI Origin
256 Processors
Each 500 Mflops
40 Hours

‘cheaper’ machines
Procs now ~2Gflops

Qn: ‘when do you expect waveforms’

- *Answers:*
  - *2 yrs*
  - *5 yrs*
  - *take the 5th*
  - *Are you nuts?!*

“whoever burned his tongue with milk,
will cry at the sight of a cow….”

- Detection info (we could all get away with murder ...)
- GW analysis info (significant new challenges ahead for all!)