# Beyond binary black holes

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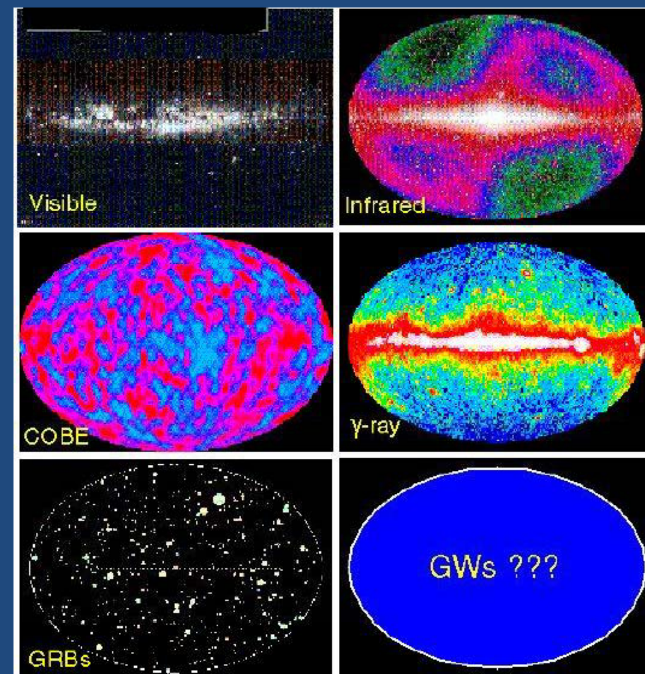
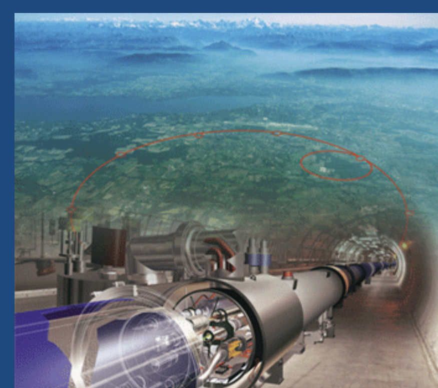
# *New facilities, opportunities & challenges to understand our universe*


LIGO

LHC

# *Why care about gravity?*

- After all … gravity is weak…..

| Interaction | Strength | Acts on | Carried by | Quant. theory |
|---|---|---|---|---|
| Strong (short ranged) | 10 | Quarks | Color | OK |
| E&M (long ranged) | $10^{-2}$ | Charged particles | Electric charges/fields | OK |
| Weak (short ranged) | $10^{-13}$ | Quarks, leptons | Flavor charge | OK |
| Gravitational (long ranged) | $10^{-40}$ | All particles | Graviton? | …? |

Gravity… by far the coolest interaction…

- *Dominates over large distances (cosmology)*
- *Modifies the nature of the spacetime (eg. Around black holes)*
- *Mediates the most efficient conversion mechanisms from mass to energy*
- *And we haven't a clue of what goes on below very small scales*

# *What do we know? (when do we know?...)*

- Linearized theory
  - Post Newtonian expansion ($v \rightarrow 0$, $M/D \rightarrow 0$) reasonable good handling to some given orders. *[at least enough for $200 GPSs....]*
  - Perturbations over fixed backgrounds. Good handling to 1st order in special cases, iffy from there on....

- Non-linear theory
  - Global stability of flat spacetime understood in 1990 [Christodoulou-Klainerman, also Lindblad-Rodnianski 05].

- We'd like to know
  - Behavior around highly dynamical, strongly gravitating cases ($v \rightarrow c$, $M/D \sim 1$).
  - Behavior close to singularities, connection to quantum gravity ideas
  - *Role in astrophysical phenomena*.

Where to look for signatures of strong gravity?

- Astrophysical systems containing BHs, Neutron stars.
- Cosmological consequences of early universe scenarios
- Highly energetic configurations in the lab (assuming some flavors of string theory is correct).

All require understanding the solution of Einstein equations.

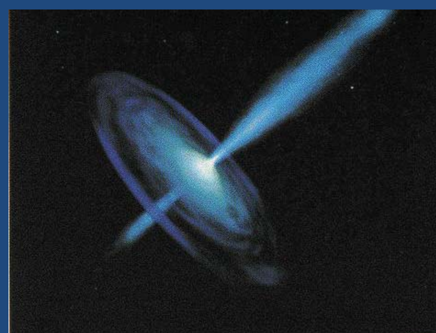
- *Non-linear, highly involved, constrained, PDE system.*
- *Many different length scales involved.*
- *Physics (2 d.o.f) 'hidden' in many variables.*
- *Singularities mark the demise of the theory, and we want to look 'close' to them.*

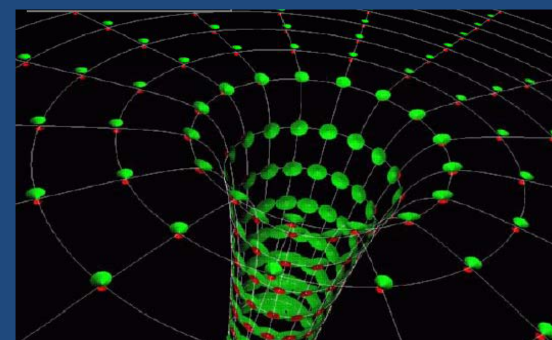
Numerical simulations only road to make head-ways.

- To obtain particular solutions
- To gain insights which can be exploited at the analytical level.

# *Two 'frontiers'*

- GR in 'practical' context. Astrophysics
  - Describe accurately signals expected from sources likely to be detected. Gravitational Wave Astronomy.
  - Understand observed phenomena; e.g. gamma-ray bursts.



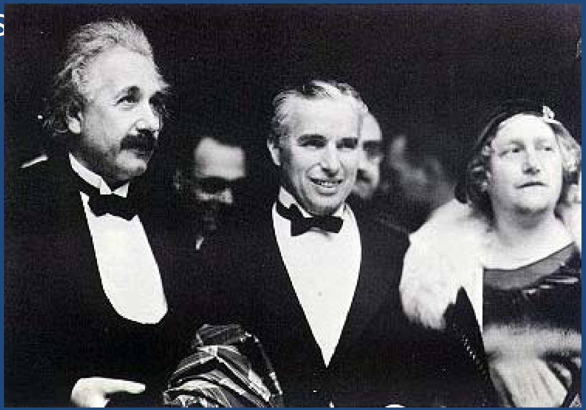


- Classical limit of prospective quantum gravity theories
  - Understand theories arising from quantum gravity efforts.
  - Deduce observable consequences

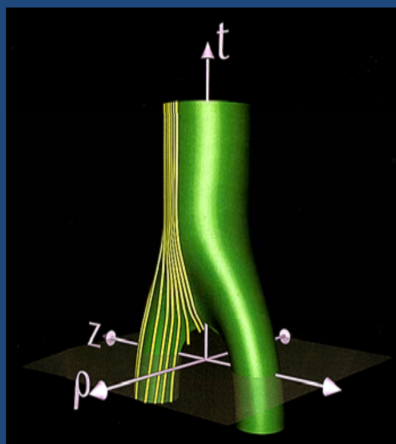
# *Astro-frontier*

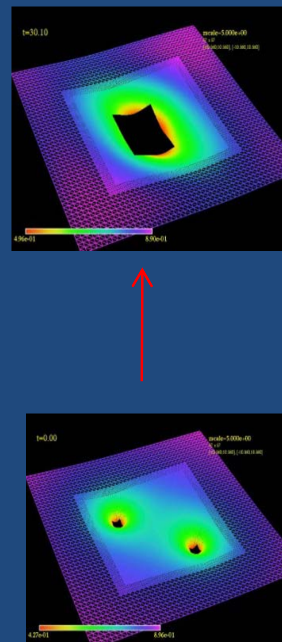
- Black holes
  - end point of sufficiently massive stars collapsing
  - end product of collisions of neutron stars
  - Ruled by null rays (limit of those that reach to infinity)
  - Can have  max. angular momentum or something nasty happens
  - Can not bifurcate unless something 'nasty' happens
  - They're stable, if perturbed, they ring-down to a BH


- How do we see them?
  - Effects on neighboring matter → EM, neutrino radiation. Eg  Gamma ray bursts
  - Effects on the fabric of spacetime → Gravitational Waves
    - Even with strong sources (collisions) GWs  are quite weak, detectors alone have a hard time to catch the waves
    - Even when 'caught', we need to interpret signals and extract physical information.
    - Can we expect surprises?

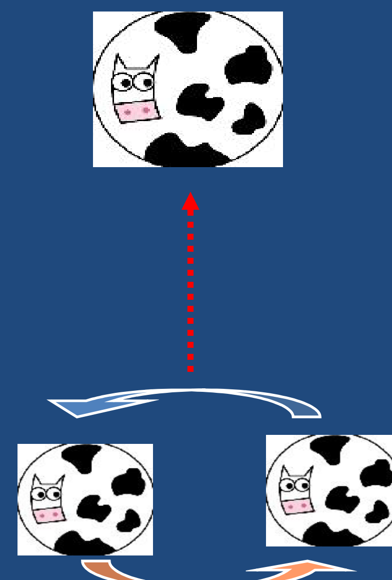


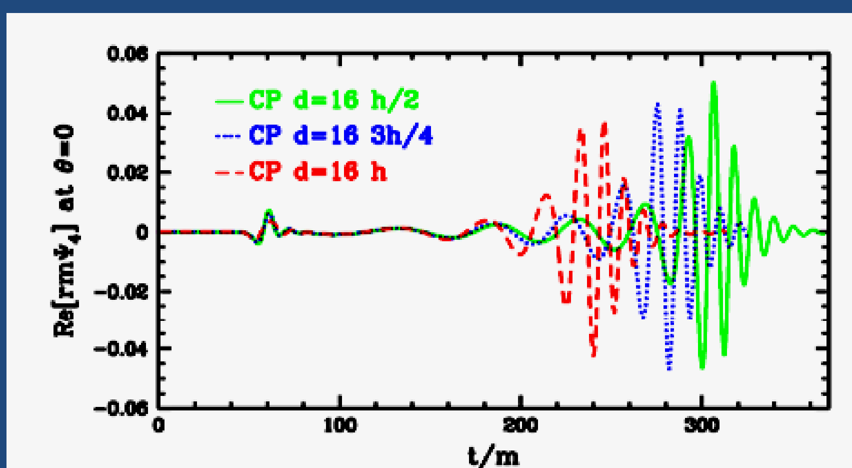
# Leading candidate: colliding black holes



Essentially no suprises. Waves smoothly transitioning from chirp to quasinormal ringing





# *Estimating the final outcome*

- Early epoch: 2 bodies orbiting, physics captured via PostNewtonian effects. Internal structure doesn't matter
- Lat e epoch: given total mass & angular momentum, can express the soln in terms of damped harmonics.

- Early –to– late recipe: Mix Newtonian analysis with a pinch of General Relativity ([Buonnano,Kidder,LL 07])

$$L(M,a) = L_{orb} + S_1 + S_2$$

  - M. sum of individual masses.
  - $L_{orb}$ from the reduced 2-body problem in a Kerr black hole at the innermost stable circular orbit. It depends on *M,a*

# Is this it?

- Yes & no...
  - Much work ahead to map out signals for detection/analysis efforts
  - ‘strange’ configurations to probe particular aspects of the theory (e.g. naked singularities, high-speed collisions)
  - However… with only one dissipative mechanism not many possibilities left out. Unlikely path to surprises…

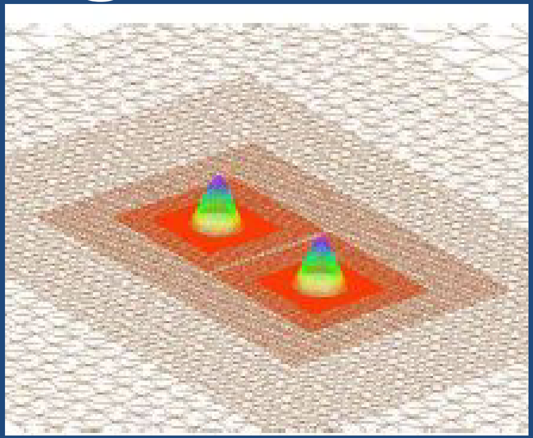
- Call it quits in 4D?... No way!
  - GR role in spectacular phenomena: gamma ray bursts, supernovae, etc.
  - More than one ‘dissipative’ channel → requires richer, more complex simulations.
    - GR, hydrodynamics, magnetic fields, radiation transport, nuclear physics…..
  - Dump the Prius, get a BH! Efficiencies ~ 0.5 for M → energy

# Binary neutron stars

- Almost as compact as BHs.
- Lower masses than BHs → merge frequencies beyond current LIGO. Though advanced LIGO could see the merger itself
- Possible (short) gamma ray burst central engine (together with BH-NS).
- Can lead to an accreting BH system.
- Lots of ingredients required for a complete description of the problem
  - Equation of state? One reason to understand this system
  - Magnetic fields included. E.g. pulsars
  - Radiation transport.
  - Produce observable both gravitational and electromagnetic signals!

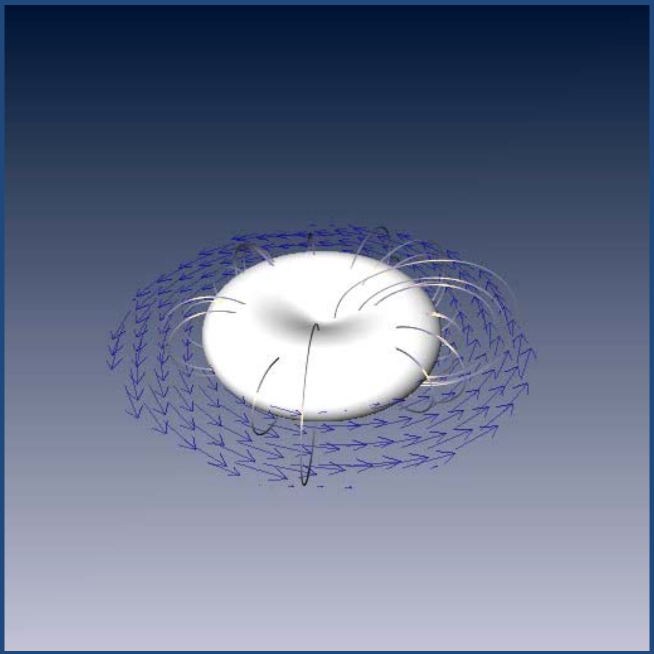
  - Challenge: put all this in a (super-duper) computer…

# Putting (some) pieces together



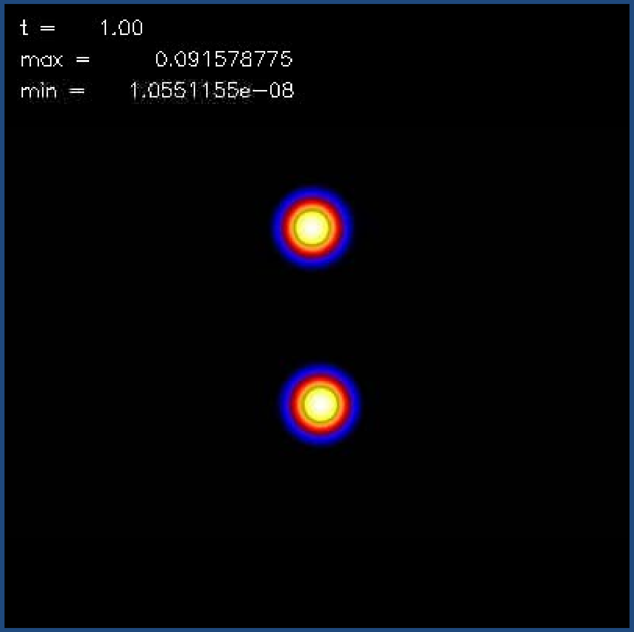
- Infrastructure that implements grid adaptivity and parallelization
- General Relativity + Hydrodynamics + Magnetic fields (ideal MHD)

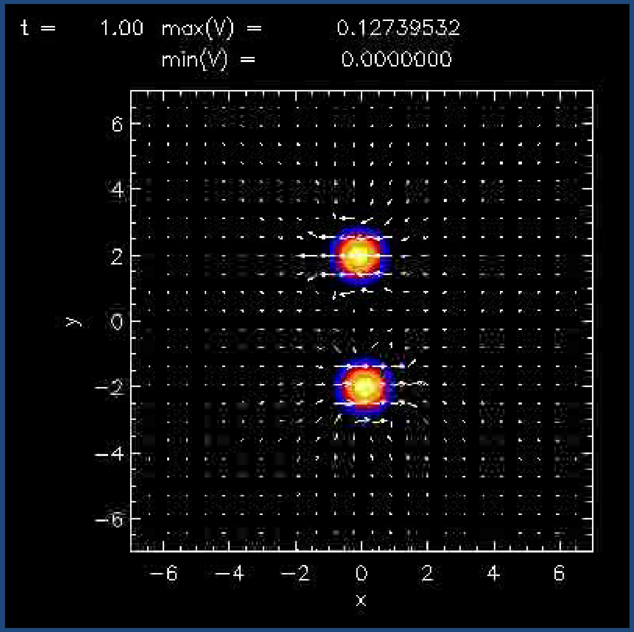
- Dissipation mechanisms:
  - Gravitational waves
  - internal fluid dynamics
  - Magnetic field effects (e.g. redistribution of angular momentum)

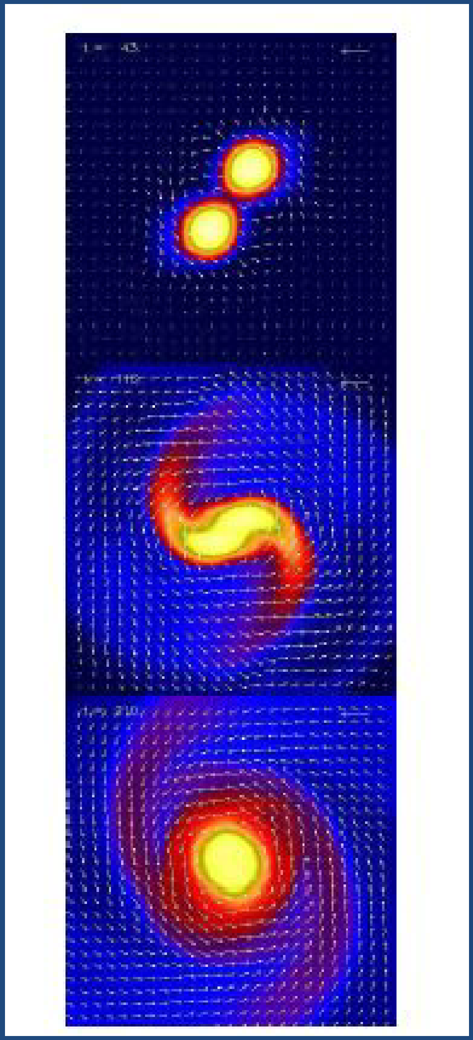


[Anderson,Hirschmann,LL,Liebling,Neilsen,Palenzuela]

# Dynamics (no B)

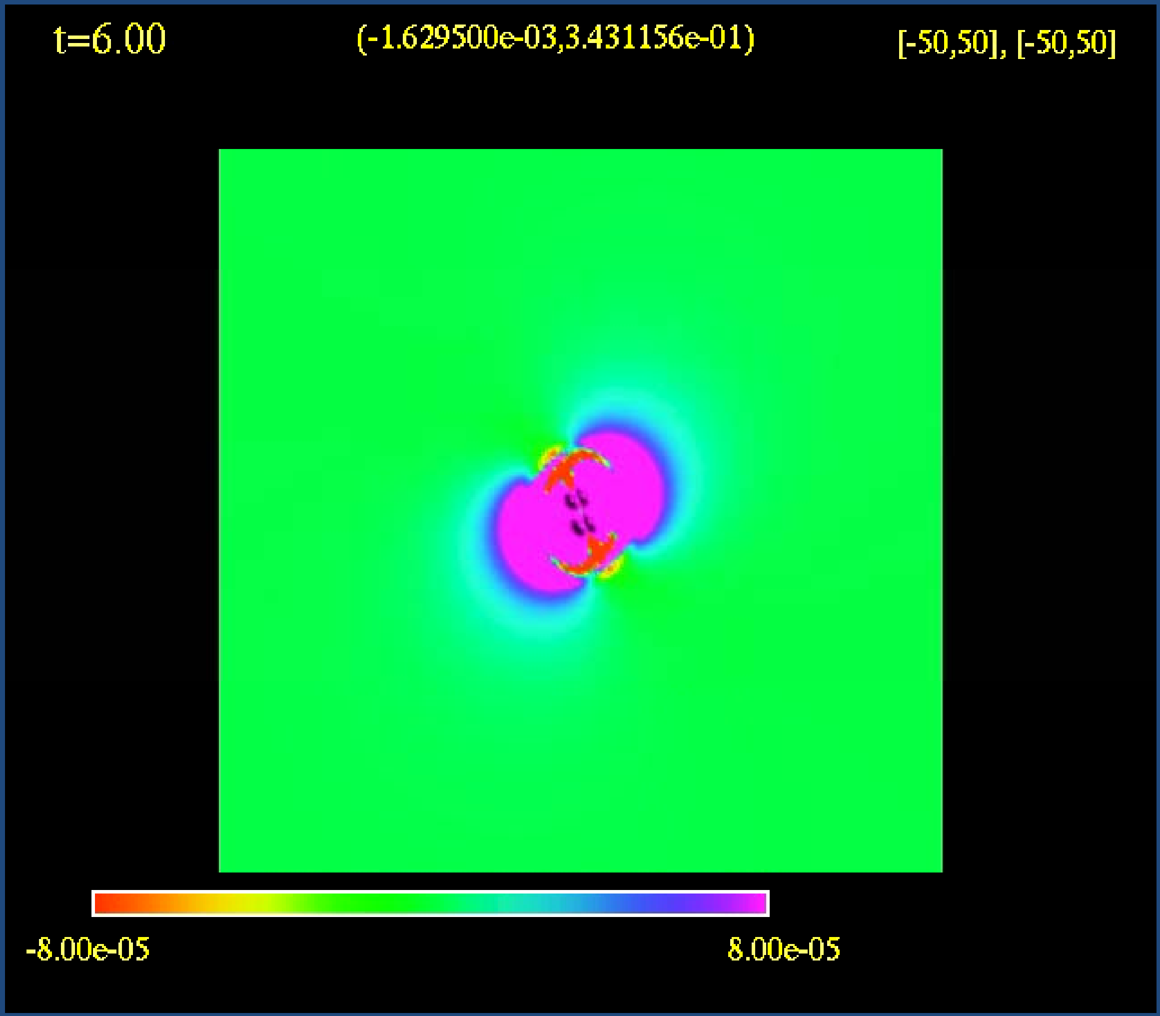


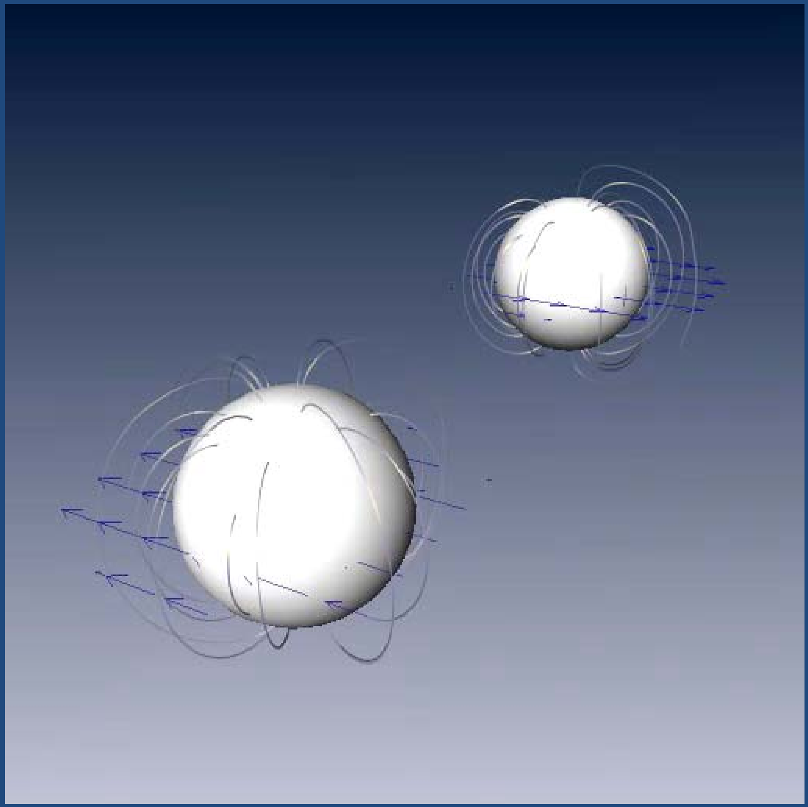



- (THIS) Merger leads to a differentially rotating star, massive enough to collapse, but has too much angular momentum!. Radiates excess and forms a BH
- However… differential rotation would feed magnetic instabilities….

# waves

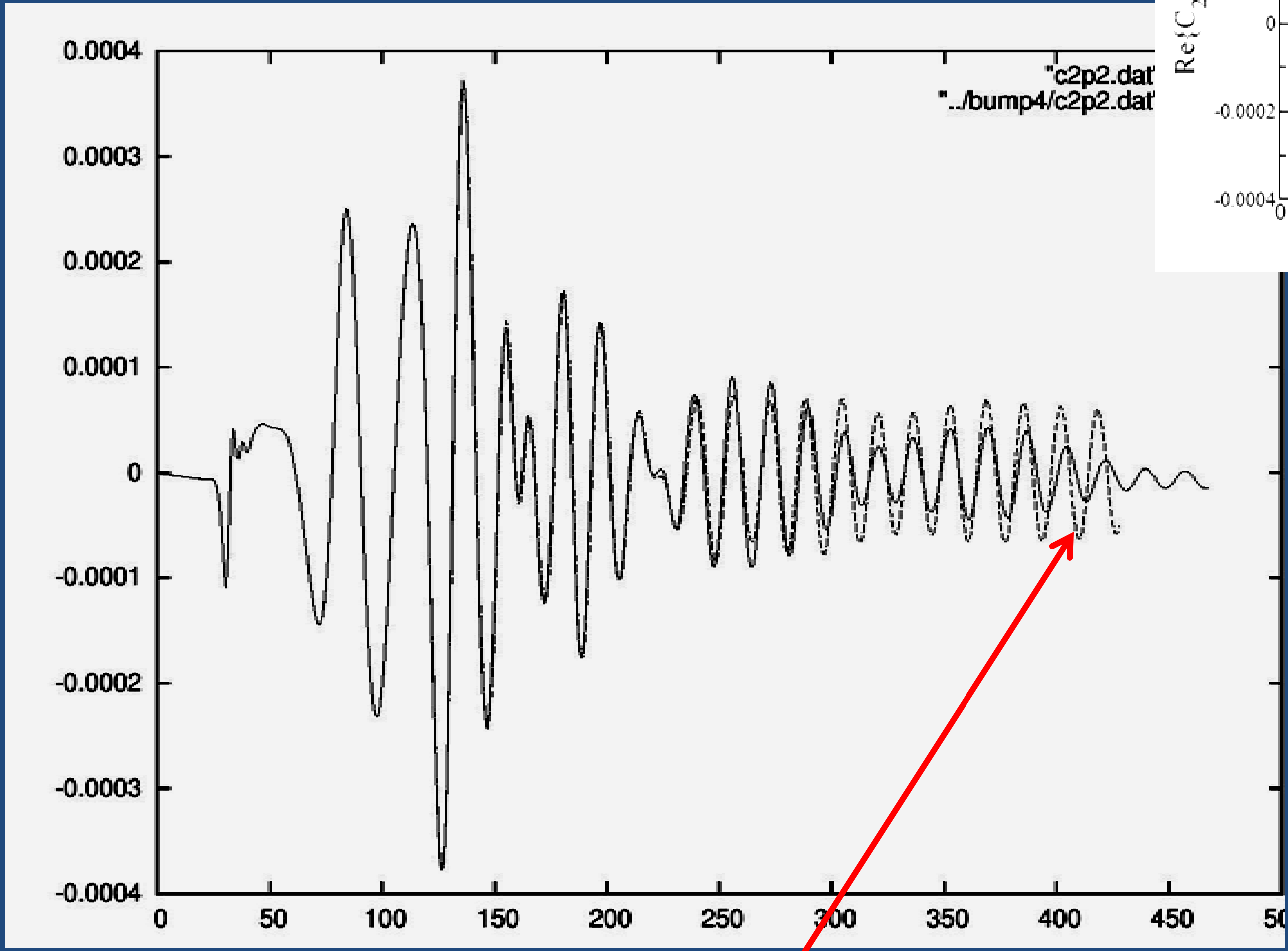


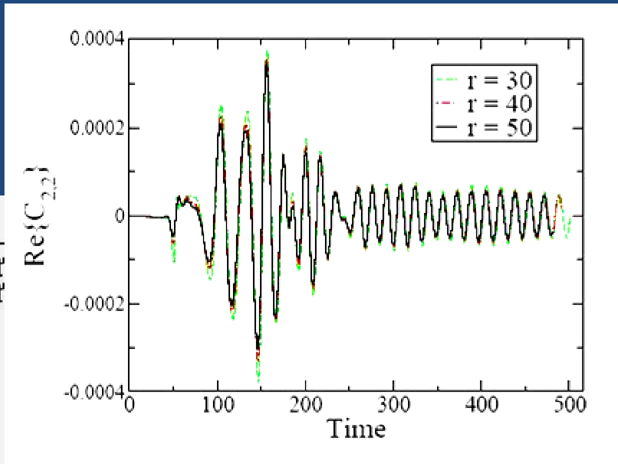
# Dynamics (B)



movie

# Grav waves




No magnetic field

- Piece-meal approach has given different fields key clues into the behavior of many systems

- However richer phenomenology leads to different outcomes, depending on the goal this might be crucial

- Obvious time-invariant statement of the day:

  *‘As computers become more powerful, our description will become more realistic*’

# Going up in dims

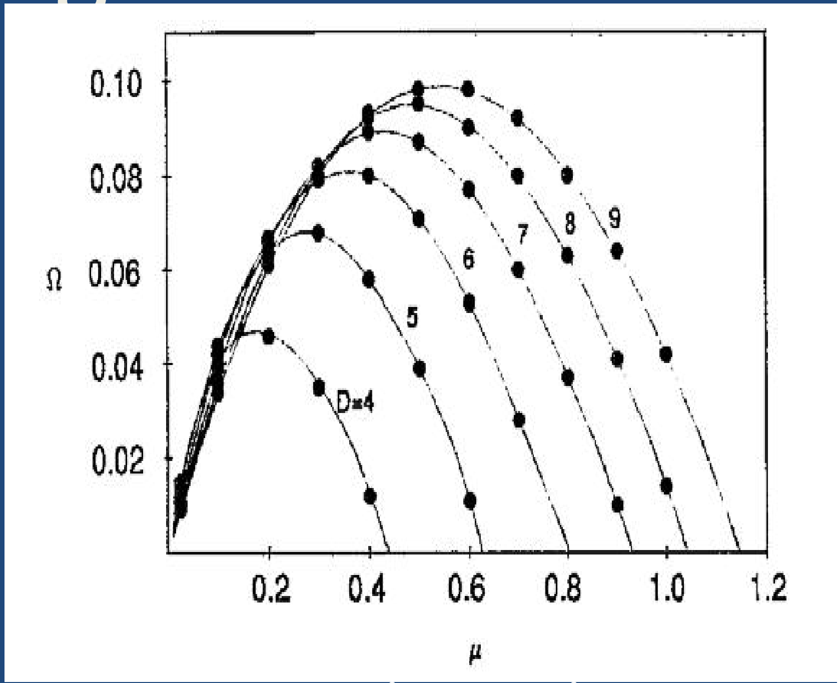
- Beyond GWs, Astro and fundamental questions in 4D, NR can help in searches for Quant. Grav theories (at a very very very humble level)
  - Take classical limit and analyze what's there
  - Loop quantum gravity → GR in 4D
  - String theory → GR in higher dims coupled with extra fields.

  - Latter case… warning… better knock down lots of dims through symmetry considerations. As in 4D, black holes are handy…

- Features of these black objects?
  - Singularity inside at the classical level (OK)
  - Can not bifurcate unless a naked singularity shows up (OK)
  - Unique in spherical symmetry (NO!, wait what sphere?)

  - Natural questions!
    - *What are the possible solutions?*
    - *are those stable?*
    - *What's their role (e.g. in black hole information paradox, stability of spacetimes)*

# Black strings

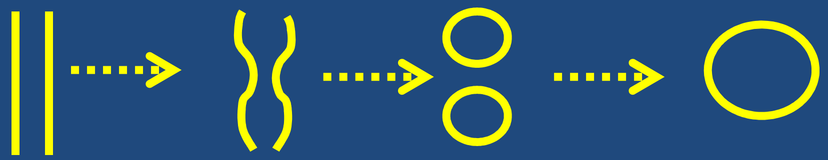



1.- Contain singularities
2.- Ruled by null-rays
3.- Non-unique even in spherical symm

Stability?

- Black string perturbations admit exponential growth for $L > L_c$ (Gregory-Laflamme)
- Entropy $S_{BS} < S_{BH}$ (for a given M)

Conjecture: Black strings will bifurcate

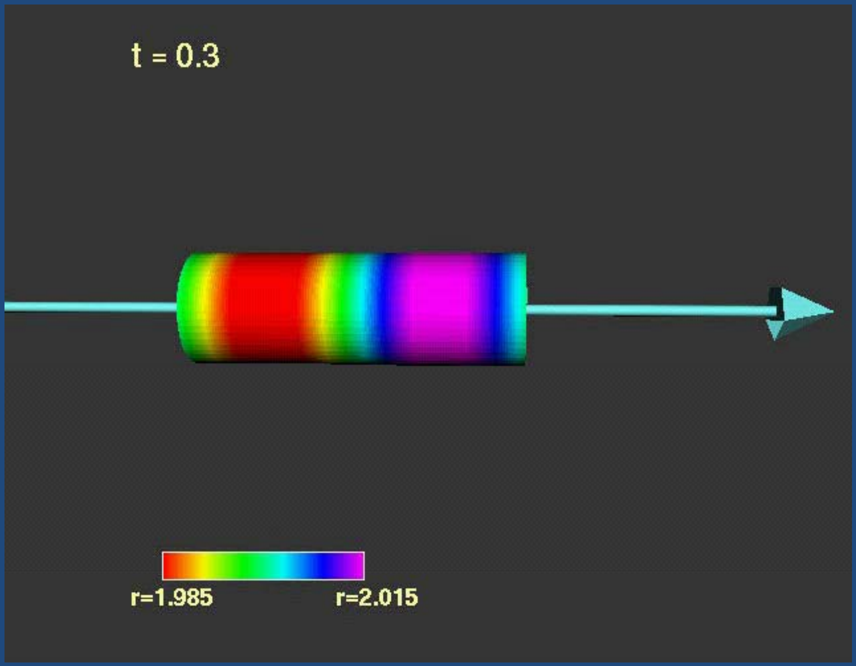


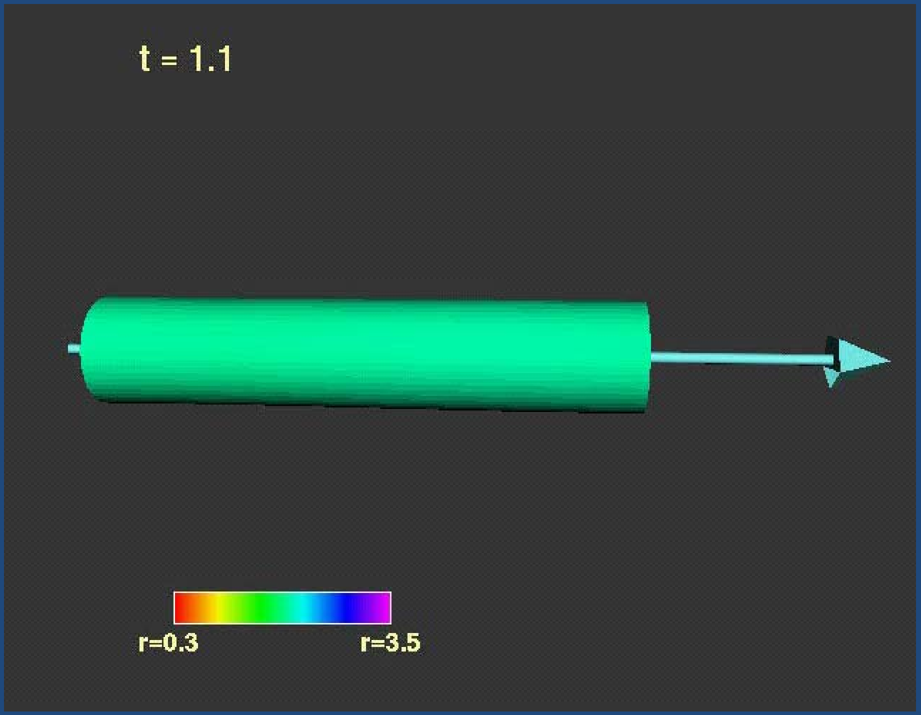
- Conjecture used in many scenarios
    - Density of states from Ads/CFT correspondence
    - Discussions of BH on brane worlds. BH in matrix theory, etc

## Recent developments

- Horowitz-Maeda, can't bifurcate in finite time. *Conjecture: will 'settle' to a non-uniform stationary soln*
- Wiseman: stationary solns which are not the Horowitz-Maeda ones (too little entropy)
- Kol: Transition from black string to BH through a conical singularity

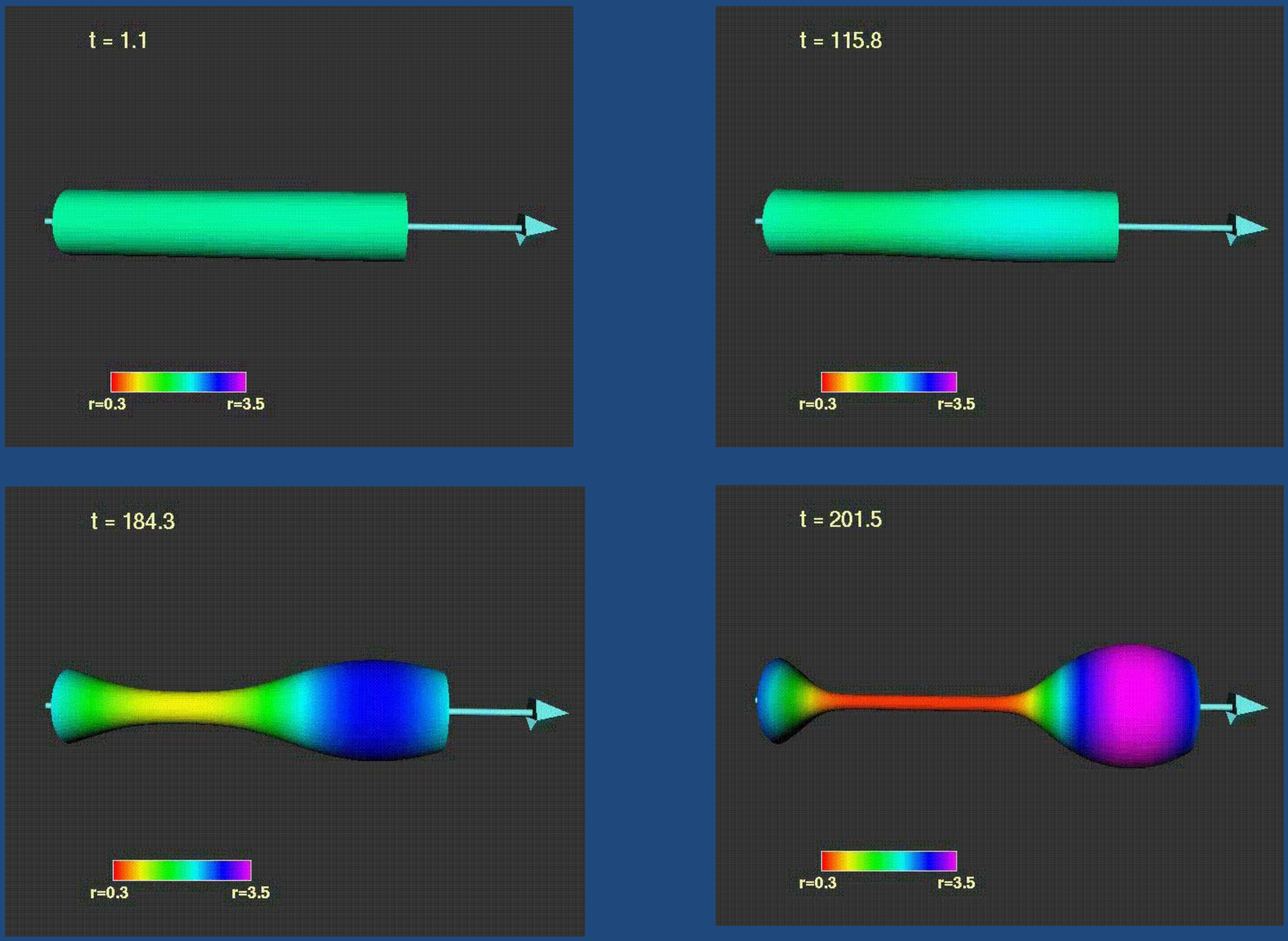
- Qns:
    - *What is the final solution of a perturbed black string?*
    - *Can it bifurcate in 'infinite time'?*
    - *Are Wiseman's solns, physically relevant?*



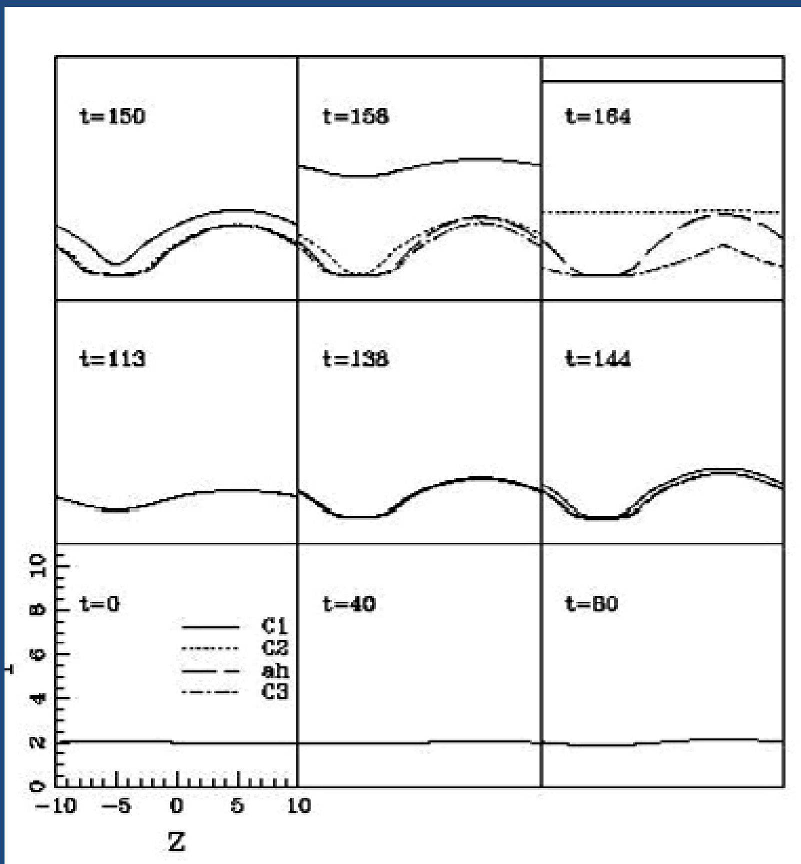




[Choptuik,LL,Olabarrieta,Pretorius,Villegas 03]

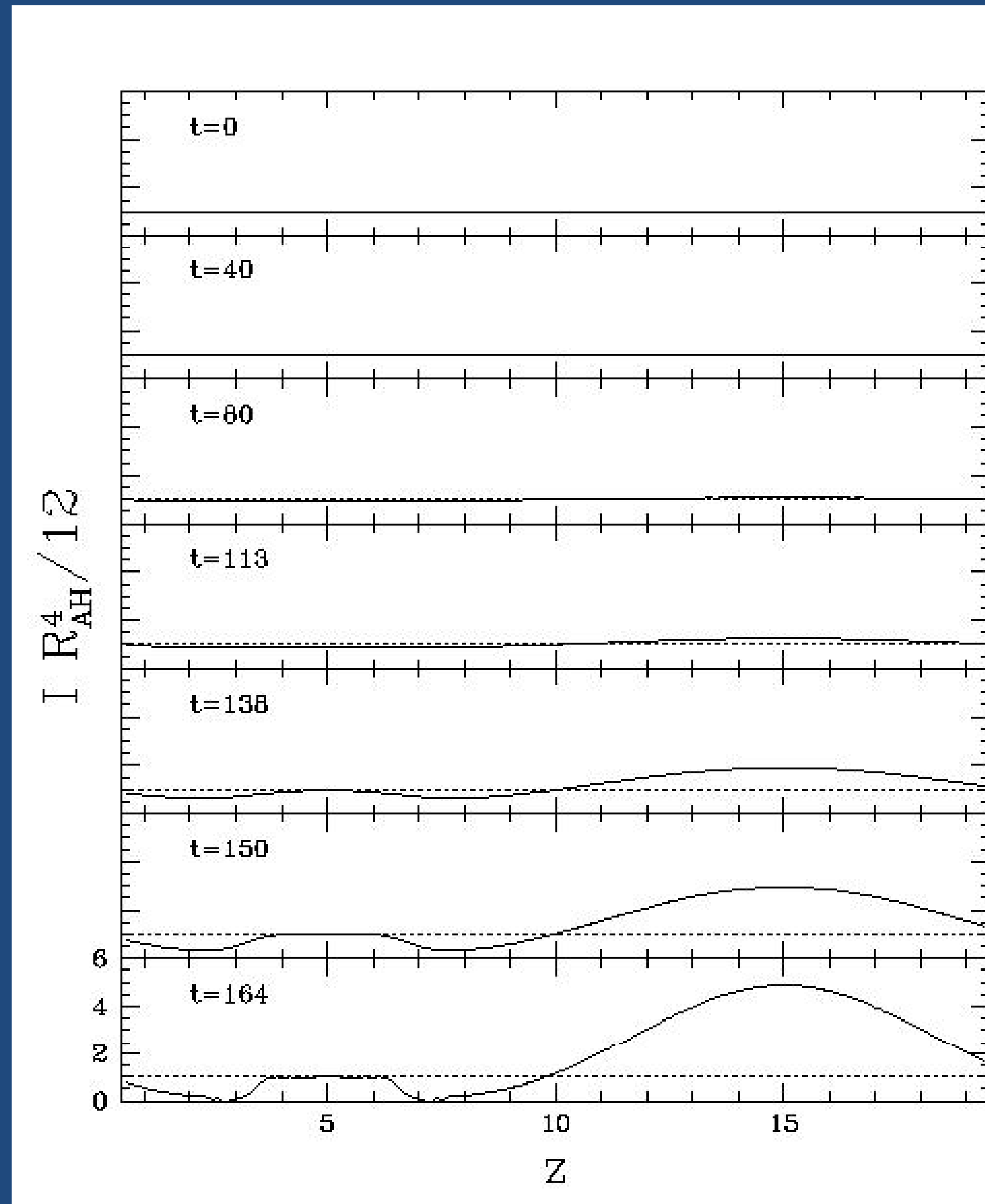
# Super-critical case

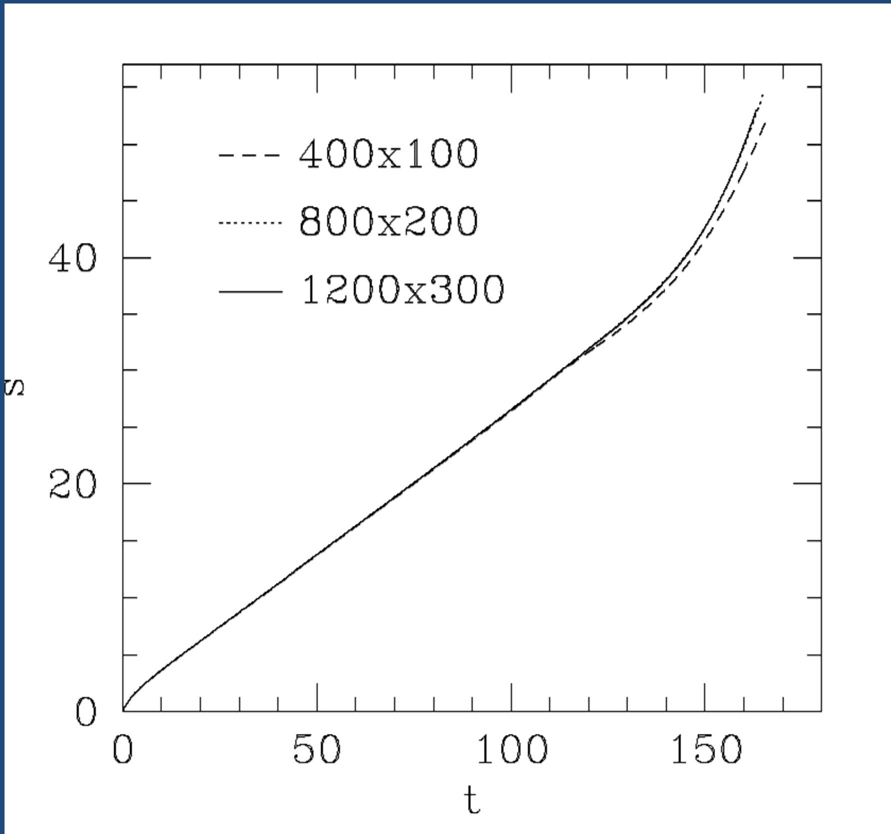


## ‘Event’ horizon



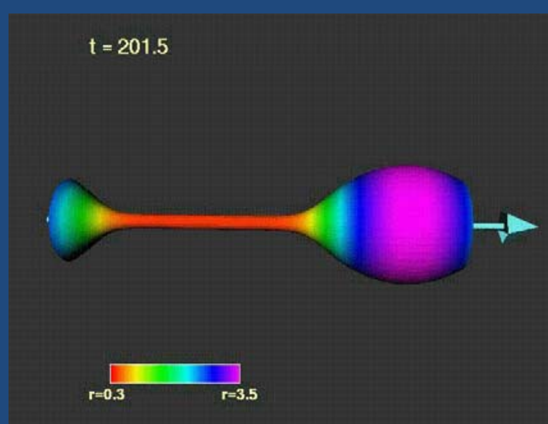

## Curvature

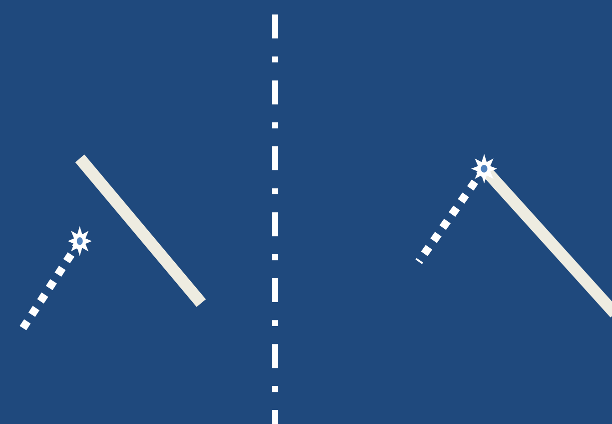





- Affine time, $\lambda = e^s$ growing exponentially ($\sim 10^{22}$)
- "bifurcation" in infinite affine time certainly possible
- 'cascade' of unstable strings also possible

[Garfinkle-LL-Pretorius]



- Where are we?
  - Still not know what the final fate is.
  - Dynamical process takes a long time to progress to highly distorted scenarios.
  - More systems found in recent years whose dynamics is strongly linked to the black string (black saturns,highly spinning black holes, black branes, etc).

- Ongoing project to decipher it… keep posted

# Final words

- Role of gravity in astrophysical systems being understood. While not significant suprises may arise gravitational dissipation competition with other process need be considered.

- Surprises still might lurke around, both in 4D and higher dimensional scenarios. These require strong fields/dynamics, which in turn requires simulations

- Definitively in the right time to attempt this!