Recess is over!
Understanding gravity in strong regimes in time for observations

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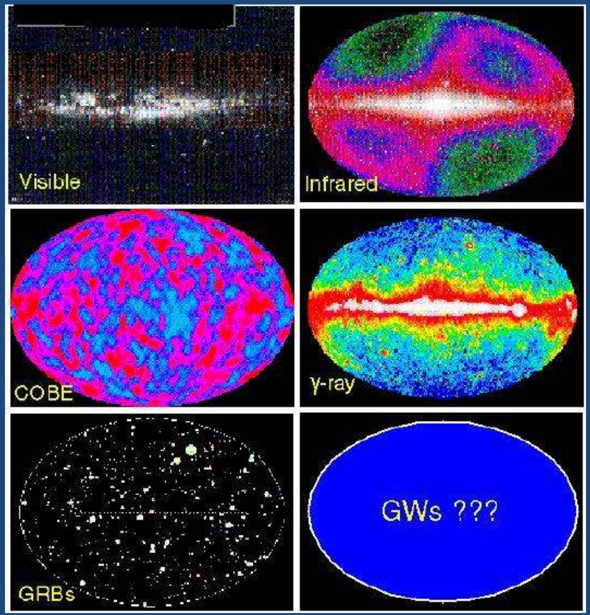
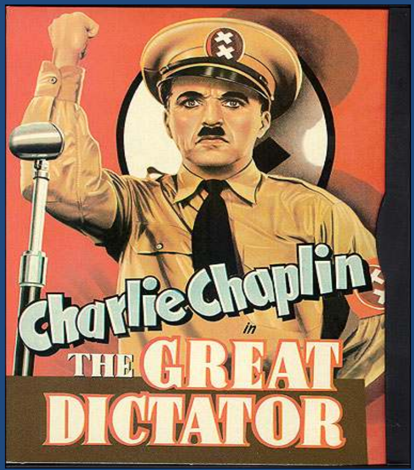
NSF

- From our naked eye, to highly sophisticated observatories we’ve been gathering ‘light’ to peek out there…
  - This light is produced by charged particles oscillating, which produce variations in the electromagnetic field, which propagate through the space(time) towards us

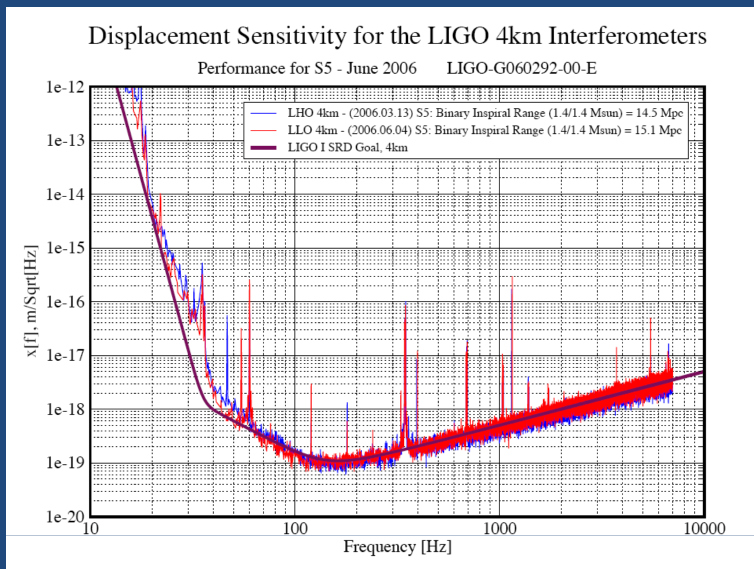
- This isn’t all we get… we might ‘feel’ variations of the spacetime itself. *Gravity waves. What do they have to say?*

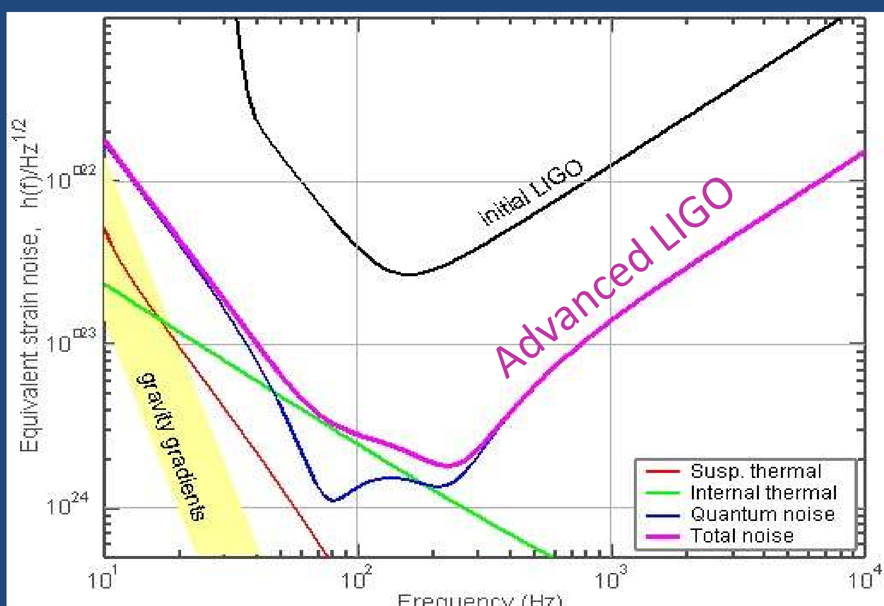




detectors…

LIGO
GEO600
TAMA
VIRGO
AIGO
Global Distribution of Major Inteferometer Sites
TAMA
GEO
VIRGO
LIGO
Hanford
LIGO
Livingston



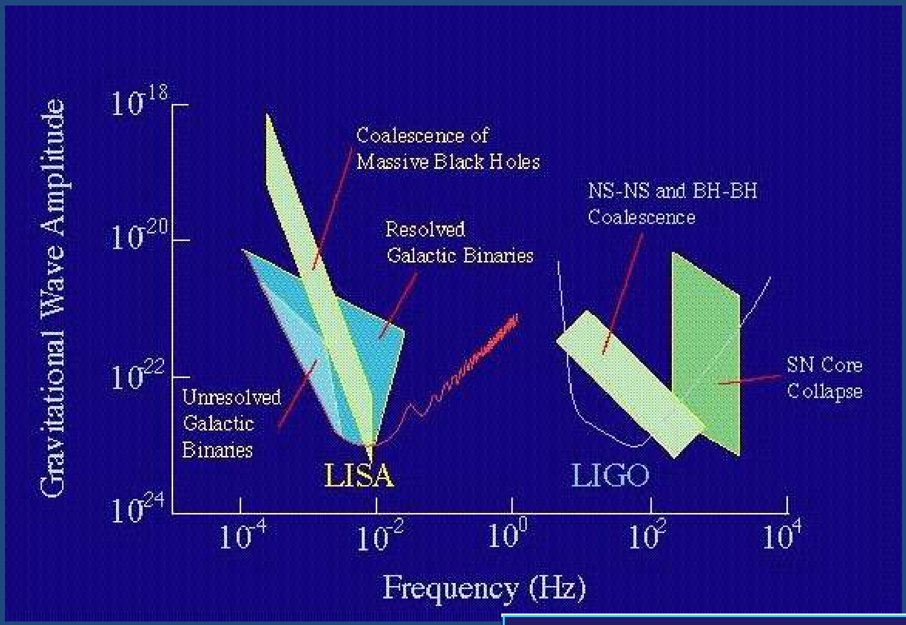


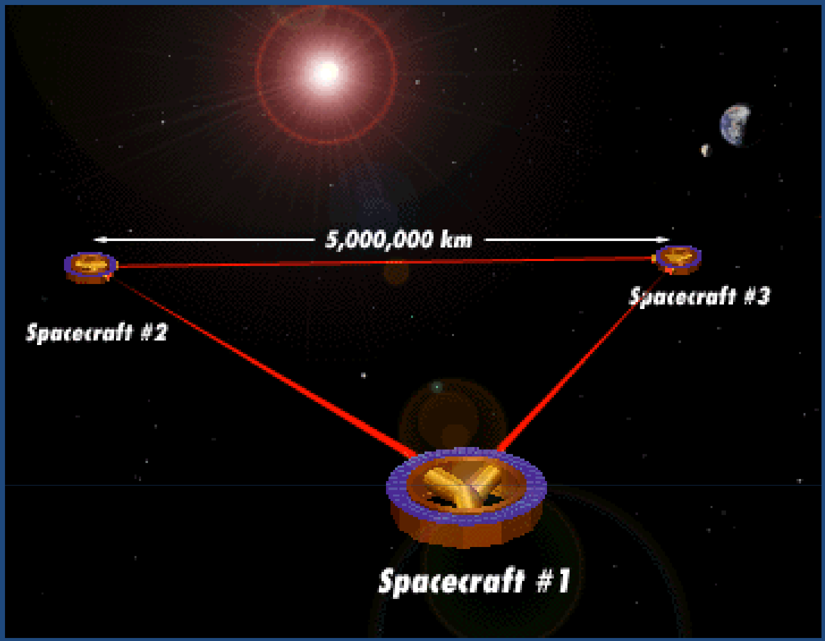
- **Neutron Star Binaries:**
  Initial LIGO: ~10-20 Mpc →
  Advanced LIGO: ~200 Mpc
  Most likely(?) rate: ~20/yr

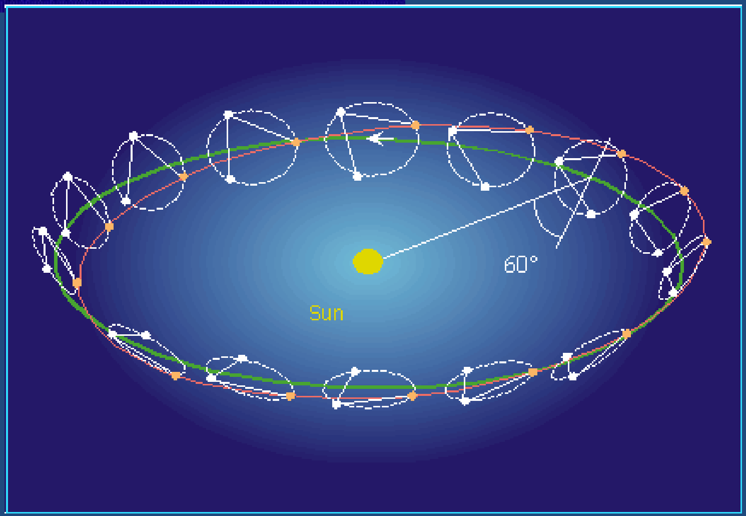
LIGO Scientific Collaboration

- Australian Consortium for Interferometric Gravitational Astronomy
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Sturt Univ.
- Columbia University
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd University
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Leibniz Universität Hannover
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola University New Orleans
- University of Maryland
- Max Planck Institute for Grav Physics
- University of Michigan
- University of Minnesota
- The University of Mississippi
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University
- National Astronomical Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washington

And may be to space... LISA







Gravity… < 1915

Newtonian Gravity

- Absolute reference frame, preferred time

$$\nabla^2 \Phi = 4\pi\rho$$

Gravitational Potential $\Longleftrightarrow$ Matter

- 1 Elliptic equation to solve (with well defined rhs)
- Potential Φ defined on an Euclidean manifold
  - Newtonian spacetime (E^3, Φ) [Distances: $ds^2 = dx^2 + dy^2$]
- ‘Signals’ propagate at *infinite* speed
- Trajectories determined by forces
- Gravity is a force field

Einstein's theory

$$G_{\mu\nu} = \kappa T_{\mu\nu}$$

Geometry of spacetime ⟷ Matter/Energy

- System of ten partial differential equations that yields the *spacetime geometry*.
- Geometry encoded in $g_{ab.}$ Spacetime ($\mathcal{M}$, g_{ab}).(unique geometry, g_{ab} not quite unique)

[redacted]

[redacted]

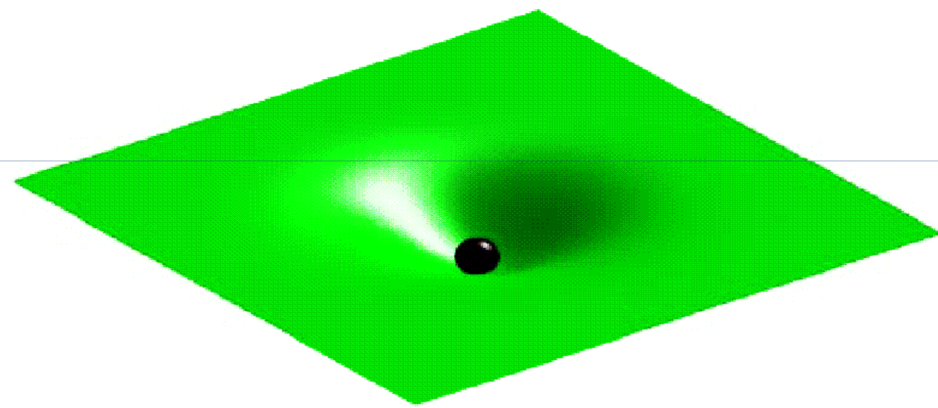
Flat spacetime!, just in different coordinates: Cartesian, cylindrical

  - A metric allows us to measure distances.
  - Fields determine a Lorentzian metric.

- 'Signals' propagate at the speed of light → wave smell…
  - Move the earth… the moon will feel it 1.3 secs later

Einstein's theory cont.

- Trajectories 'straightest paths' on curved manifold
- Matter/Energy curves spacetime and that in turn affects trajectories in it. For example:
  - Precession of Mercury's orbit
  - Deflection of light around the Sun



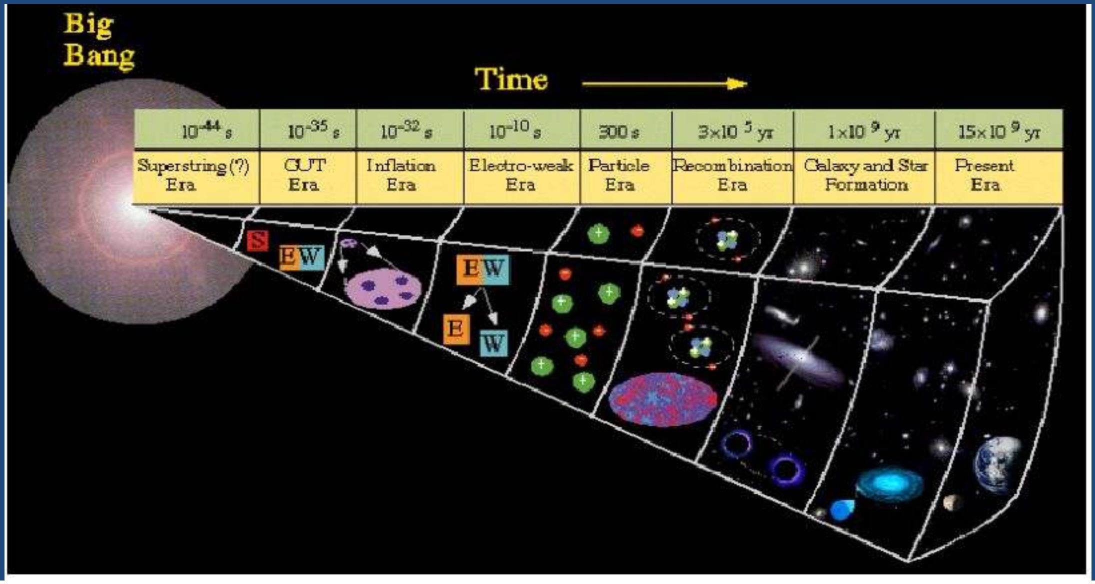
Spacetime grips mass, telling it how to move, and mass grips spacetime, telling it how to curve. – J. A. Wheeler

Gravity is a *manifestation* of the geometry

$$G_{\mu\nu} = \kappa T_{\mu\nu}$$ ← *This is a mess!*

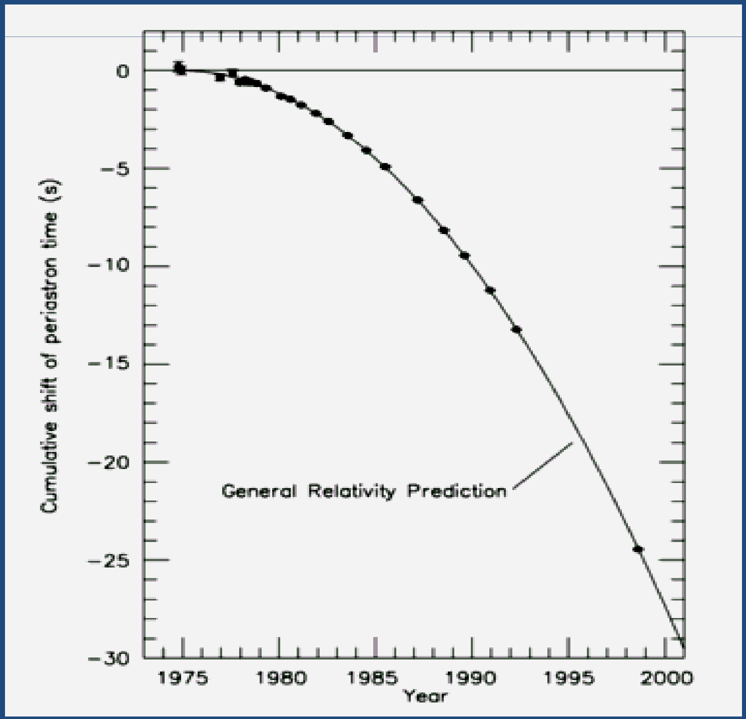
Gravitational 'vs' electromagnetic waves

Oscillations of the spacetime itself	Oscillations of EM fields propagating through spacetime
Coherent emission by bulk motion of matter & energy	Incoherent superposition of waves from molecules, atoms and particles
Freqs ~ 1kHz and down by 20 orders	Freqs ~ 1Mhz and up by 20 orders
Basically unscattered	Strongly interacting with matter between source & detector
observable falls as 1/r	Most observables $1/r^2$
10^{-43} secs after BB	After decoupling: 10^5yrs after BB



Are they for real?

- Extremely weak, not yet measured directly
  - Predicted in the theory by 1916 (and even Einstein doubted them!)
  - Experimental search ~ 1970 by Joseph Weber (bar detectors) + plans for interferometers by Ray Weiss (~78).
  - Taylor & Hulse measure variation in period of pulsar (pulsar 1913+16) in 1974. Excellent agreement with the prediction of G.R. (Nobel prize in 1993).



- Want to detect gravitational waves and understand what produced them
  - In many cases, there will not be an observable counterpart (e.g. Not beamed to us, black holes…)

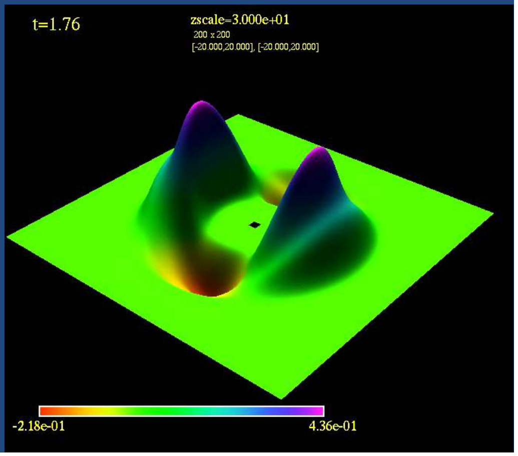
- Understand you must what you can see not…

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 good enough for $100 GPSs….]*
  - Perturbations over fixed backgrounds. Good handling to 1st order in special cases, iffy from there on….

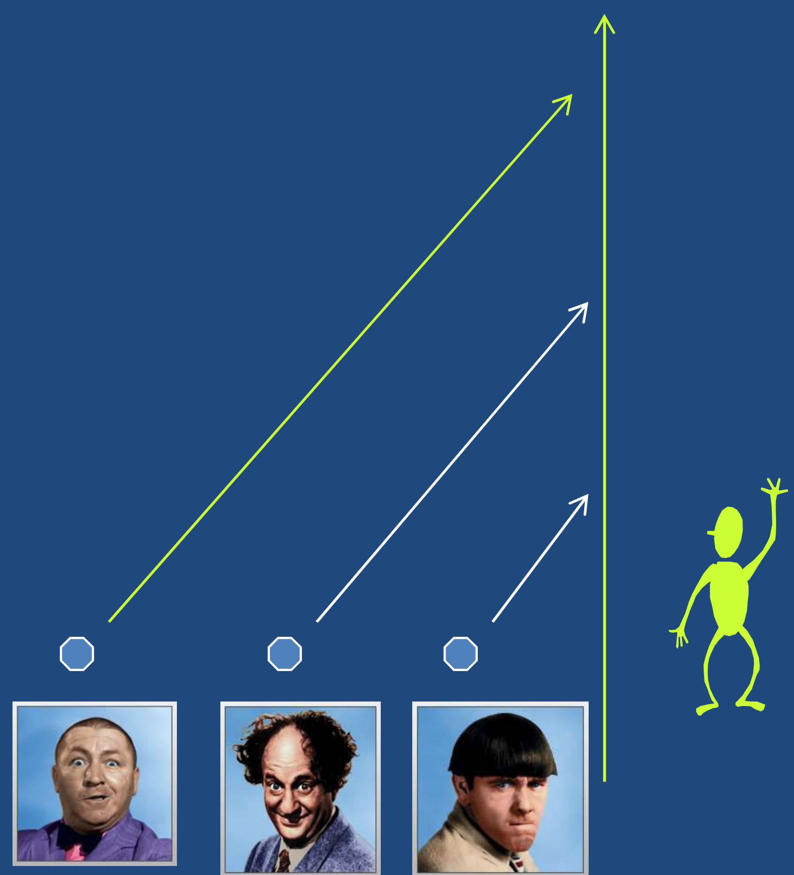
- Non-linear theory
  - Global stability of flat spacetime understood in 1990 [Christodoulou-Klainerman, also Lindblad-Rodnianski 05].

- 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*.



What we knew about BHs…

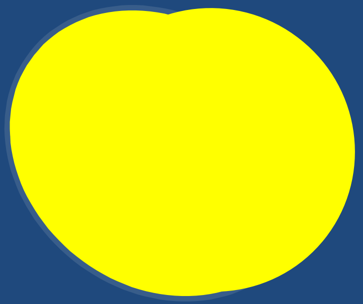
- Vacuum soln of Einstein eqns, end point of collapse, by-product of collisions, etc.
- Blackness?: 'Causal signals' can't propagate from the inside of some region (causal signals take 'forever' to leave the region, boundary = BH surface = Event Horizon)

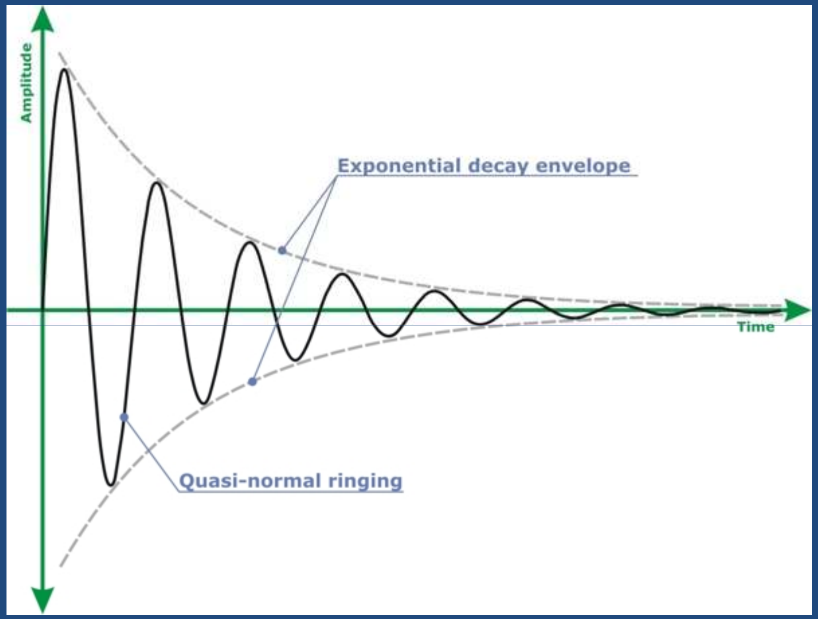


What we knew about BHs…

- Vacuum soln of Einstein eqns
- Blackness?: 'Causal signals' can't propagate from the inside of some region (causal signals take 'forever' to leave the region, boundary = BH surface = Event Horizon)

- They are ‘stable’ (are they always? … higher dims…)





They're simple….

- If all transients take place, they'd go to a simple time-independent state.
- Characterized by 2 quantities! M, a
  – No matter what produced them!

They're powerful….

- Extreme 'dragging' around rotating black holes.

- Energy extraction from a rotating black hole, most efficient way to convert matter into energy! (~10%!)
  - Eg. Penrose and Blandford-Znajeck processes.

Orbits around BHs and Kepler's problem…..

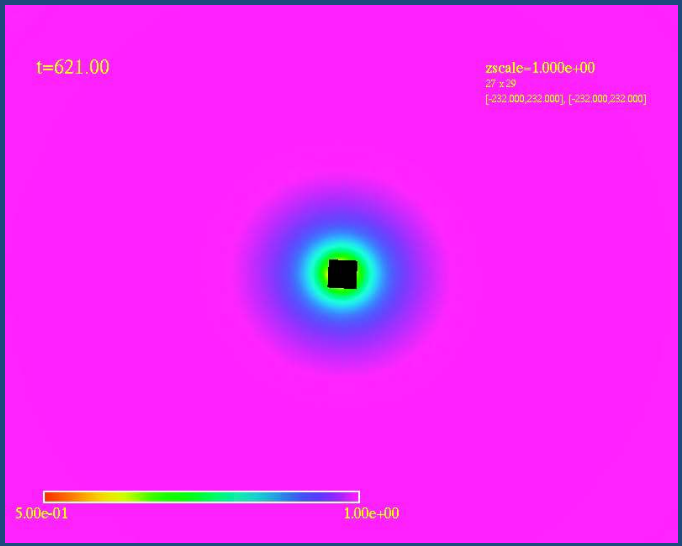
- For 'large' distances… leading behavior just as in Newtonian theory
  - However, beyond it, orbits 'shrink' due to the emission of GWs

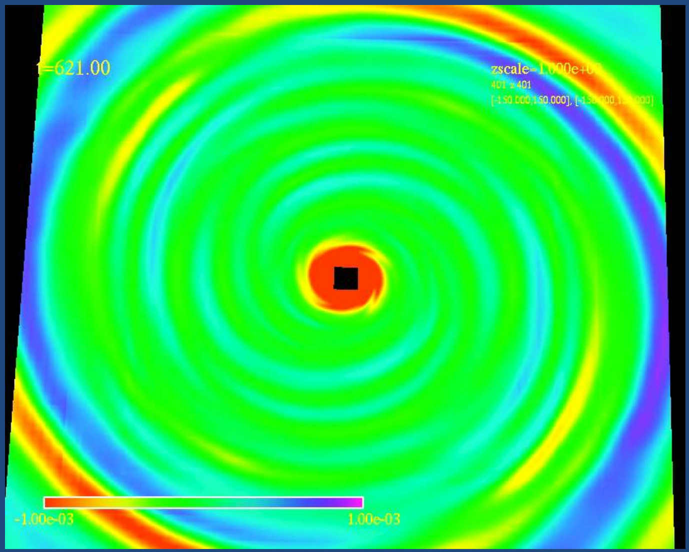
- For $r < r_{BH}$, well… we die…

- For $r_{BH} < r < r_{ISCO}$
  - No stable circular orbits even at leading order

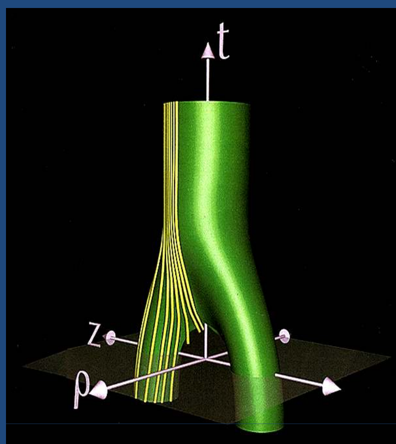
But beyond that?

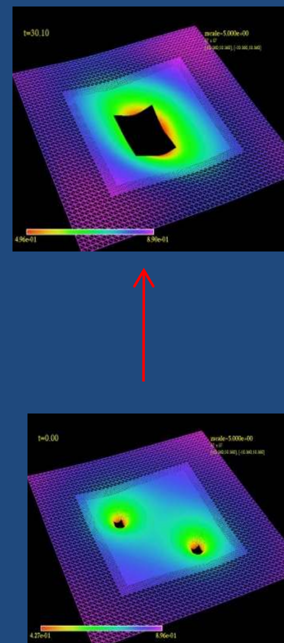
- Not much was known until recently…
- Large computer simulations required to study the system
  - Run on supercomputers
  - Dealing with a messy system of equations



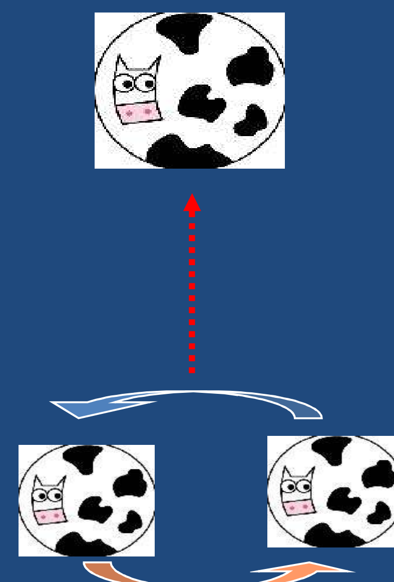


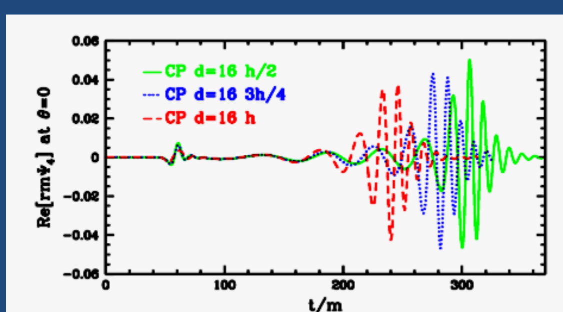
In the end… the picture turned out quite simple

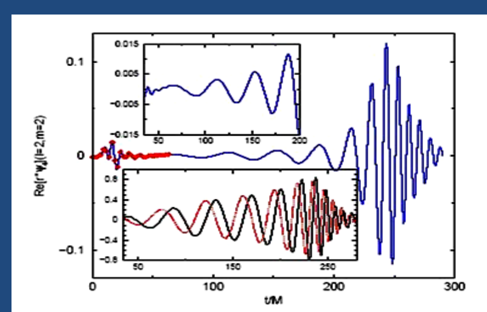




Essentially no suprises.
Waves smoothly transitioning from chirp to quasinormal ringing





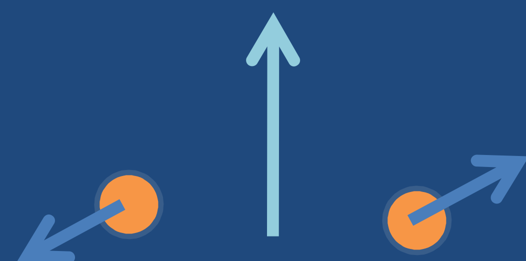


[Pretorius 06, everyone else shortly after]

But what's the scoop?

- Radiation: convert ~ 5% of total intial mass and angular momentum. (can be higher for 'tuned' collisions)

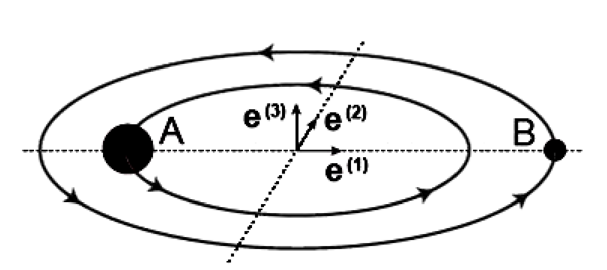
- Asymmetric scenarios give rise to kicks, these can be as large as 3-4 10^3 km/s! (claim Quasar SDSS J092712.65+294344.0)
  - Yet… these need some tweaking.



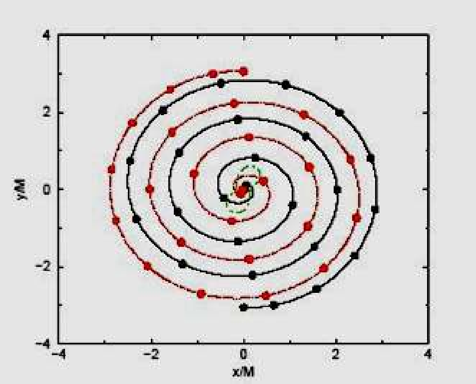
  - A few 100s km/s more typical.

- As interesting as these might be… back of the envelope arguments do go a long way.

Estimating the final outcome



- Early epoch: 2 bodies orbiting, physics captured via PostNewtonian effects. Internal structure doesn't matter



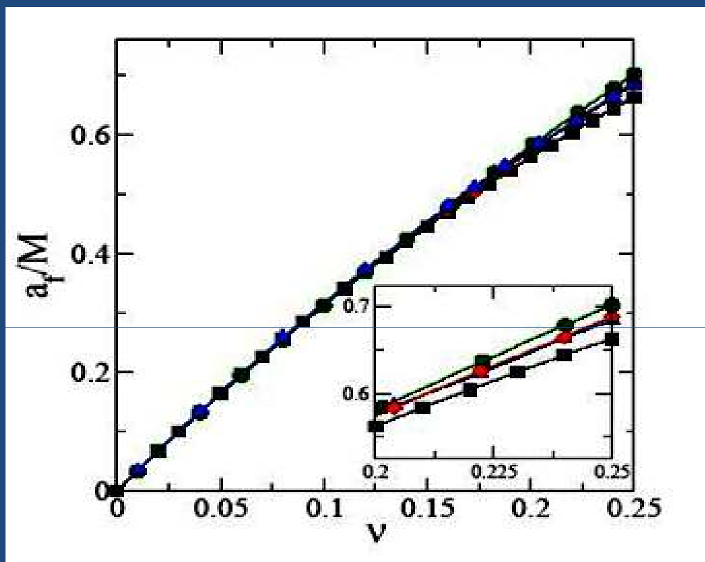
- Late epoch: given total mass & angular momentum, can express the soln in terms of damped harmonics.

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

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

  – 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*

Does this work?



Case [Reference]	a_f/M	ι(deg)	a_f/M	ι(deg)
C_1 [31]	0.67	-	0.66	0
C_2 [31]	0.72	-	0.71	23
C_3 [31]	0.68	-	0.66	0
C_4 [31]	0.73	-	0.71	23
C_5 [31]	0.64	-	0.61	34
C_6 [31]	0.81	-	0.82	14
C_7 [31]	0.80	-	0.82	14
C_8 [31]	0.80	-	0.82	14
SP_3 [8]	0.72	18	0.70	21
SP_4 [8]	0.81	10	0.80	13
SP_6 [32]	0.50	33	0.48	35

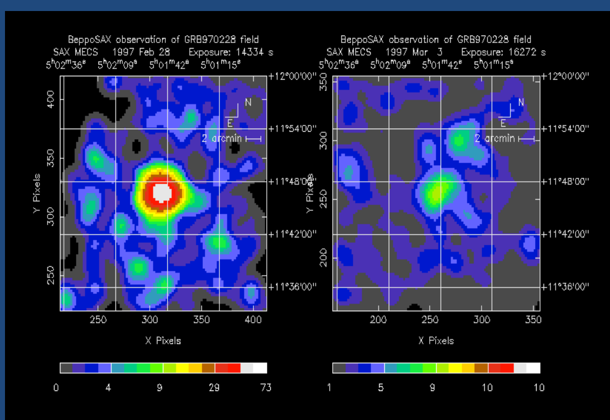
For ‘broad’ purposes:

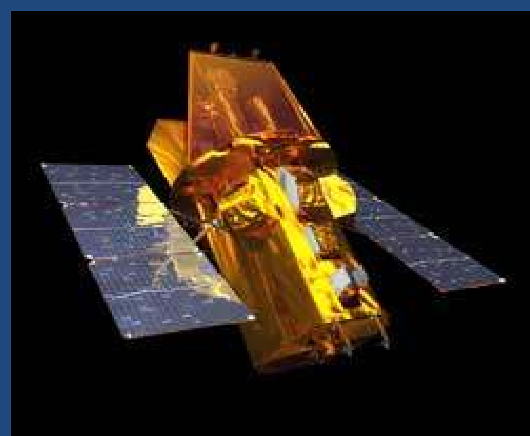
PostNewtonian + Particle on a BH spacetime + Quasinormal modes is enough

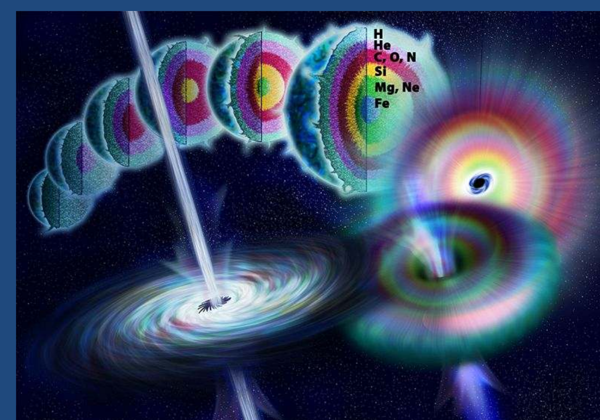
Yet… delicate measures require much more accuracy… work to come

There is certainly a lot more….

- Many other systems of interest:
  - Binary neutron stars
  - Black hole-neutron stars
  - BHs and effects on surrounding disks
- These might have electromagnetic counterparts. Furthermore, they are key ingredients for already observed phenomena.







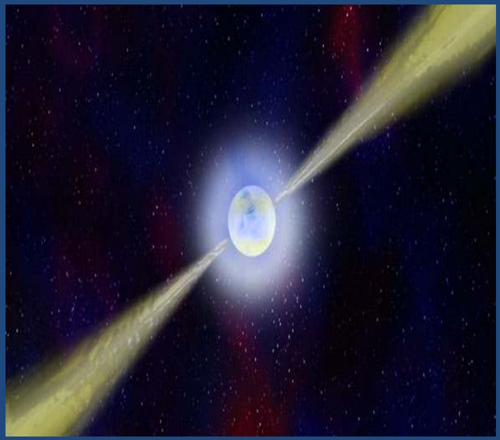
NS-NS

- For grav waves.
  - Early pre-merger stages: PN is good enough
  - Late pre-merger: careful, internal structure may play a role
  - Merger, postmerger: prompt vs. delayed collapse to a BH and other features, we could use to determine eqn of state.
  - *Can different effects be disentangled?*

- Beyond these, other key qns
  - Does the merger give rise to a BH with sizeable disk?, what is its final spin, magnetic field strength etc?
  - How long does the hypermassive star exists before collapsing?
  - *All these connect directly with short GRBs models*

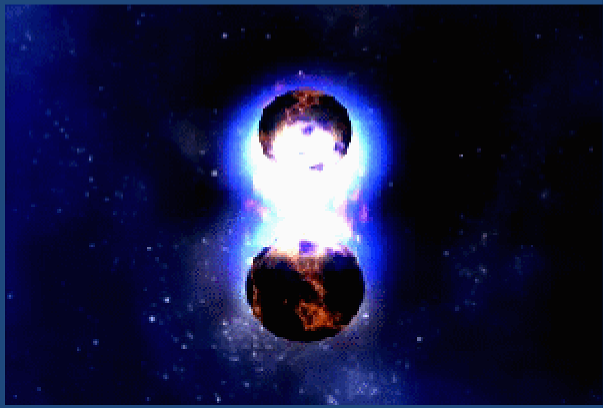
Initial configuration. (Not ‘too physical’…)

- Equal non-rotating polytropes to represent the stars (Γ=2). (R_s=16.26km, M~0.9 M_O)



- Poloidal seed magnetic fields, antialigned with orbital angular momentum in each star. B ~ 9 10^{15} G

- Initial separation ~ 4 R_s



- Grid : [-100R_s , 100R_s]; up to 7 levels of refinement Δ_{min}=0.46km. Gravitational waves extracted well within the wave zone.

Dynamics: Pre-Merger

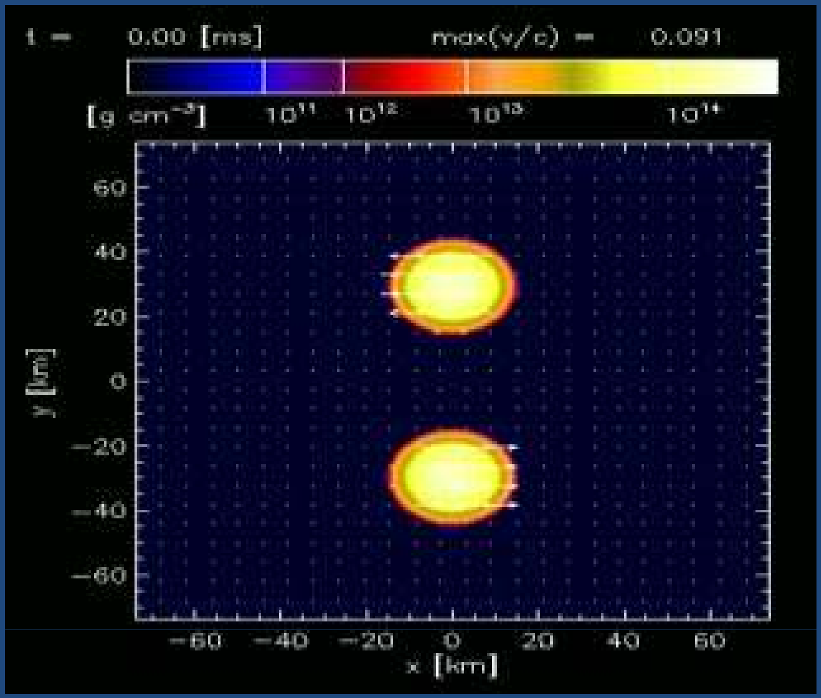
- Early dynamics should be mostly insensitive to magnetic fields. To zeroth order

$$F_G \sim \frac{m_1 m_2}{r^2}; F_M \sim \frac{\mu_1 \mu_2}{r^4}$$

- To higher order, essentially a spin-spin PN interaction calculation, overall, expect at most 2% cycle difference as long as point-particle approximation holds if fields stay < 10^{16}G. [Ioka-Taniguchi 00]

$$N_{mag} \sim 610^{-3}\left(\frac{H_1}{10^{16} G}\right)\left(\frac{H_2}{10^{16} G}\right)\left(\frac{m_1+m_2}{2.8 M_\Theta}\right)^{-13/3} (\pi m_{tot} f)\Big|_{f_{\min}}^{f_{\max}}$$

As long as PN approx holds, this should be fine…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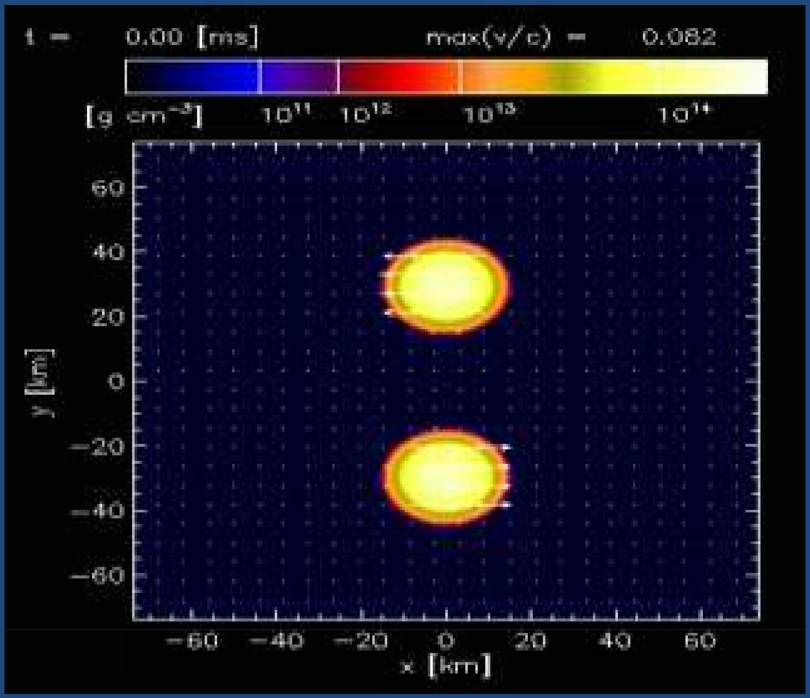
max(v/c) = 0.091
[g cm⁻³] 10¹¹ 10¹² 10¹³ 10¹⁴
y [km]
x [km]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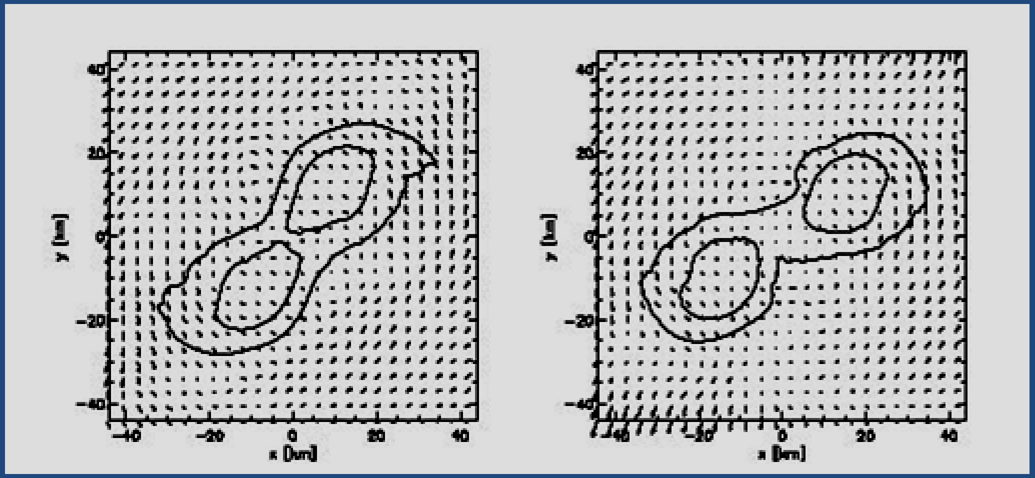
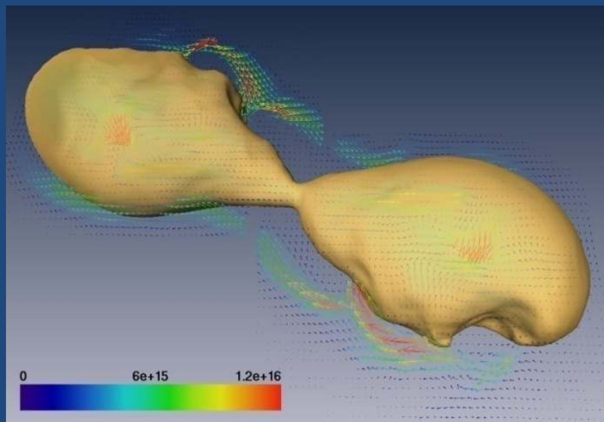
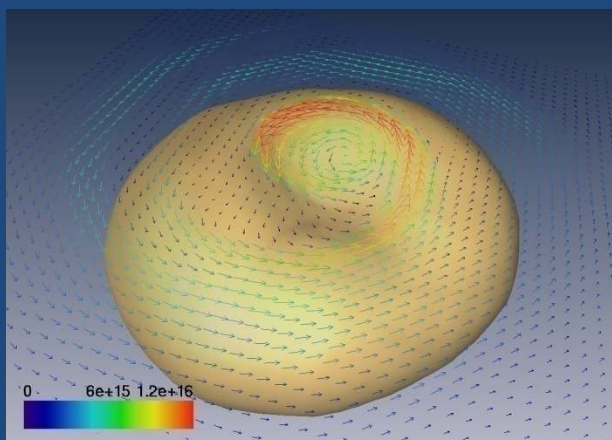
max(v/c) = 0.082
[g cm⁻³] 10¹¹ 10¹² 10¹³ 10¹⁴
y [km]
x [km]

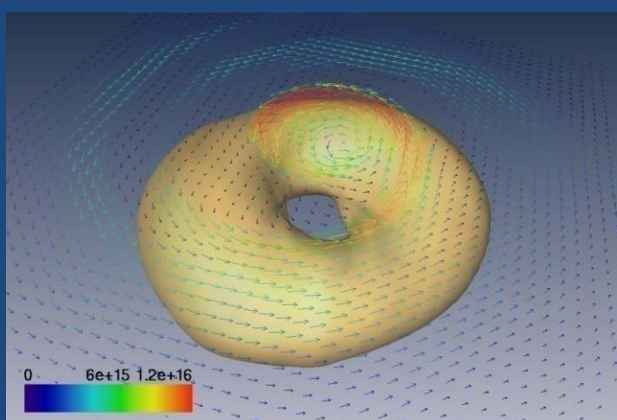

y [km]
x [km]



$\rho=10^{14}\,g/cm^{3}$



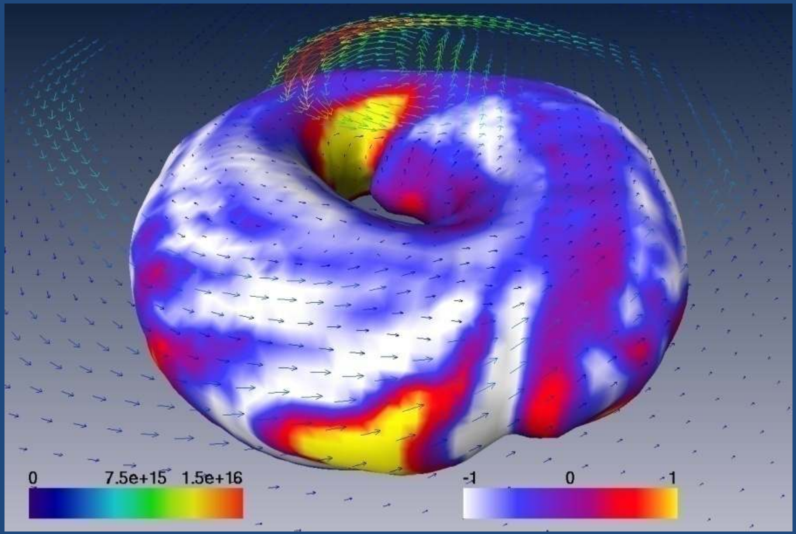
$\rho=8\ 10^{13}\,g/cm^{3}$



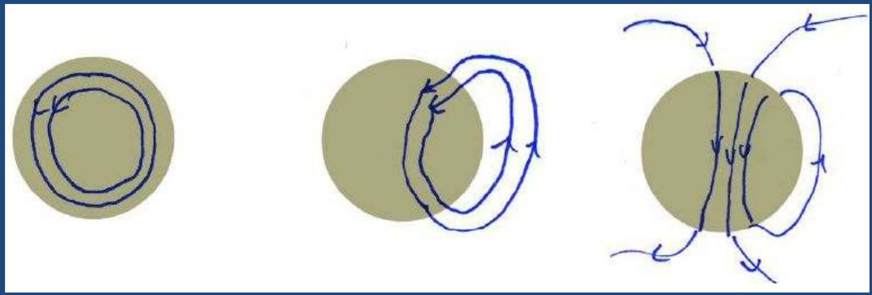
$\rho=10^{14}\,g/cm^{3}$

- K-H instability, shear energy into magnetic fields which grow ~ 1 order of magnitude. Growth saturates ~ Alfven time-scale
- Hypermassive star differentially rotating at rates different from the non-magnetized case

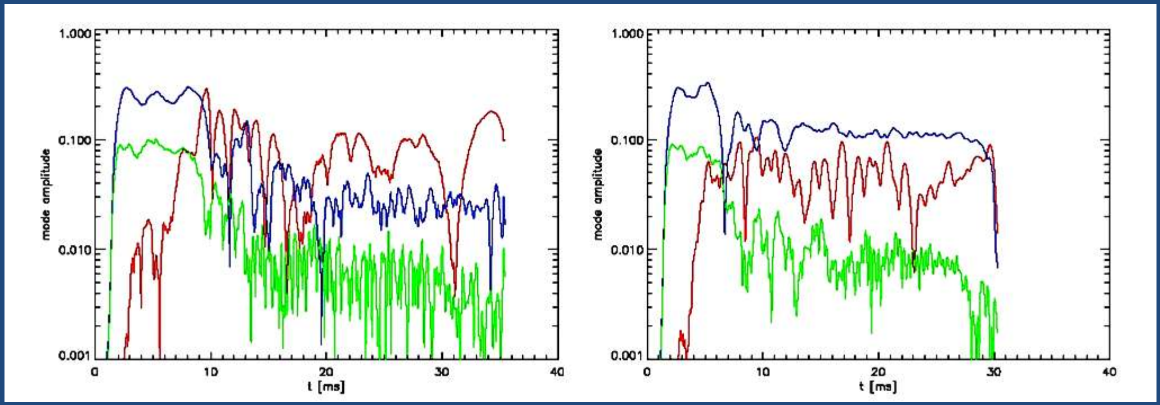
Less obvious effects



Magnetic Buoyancy

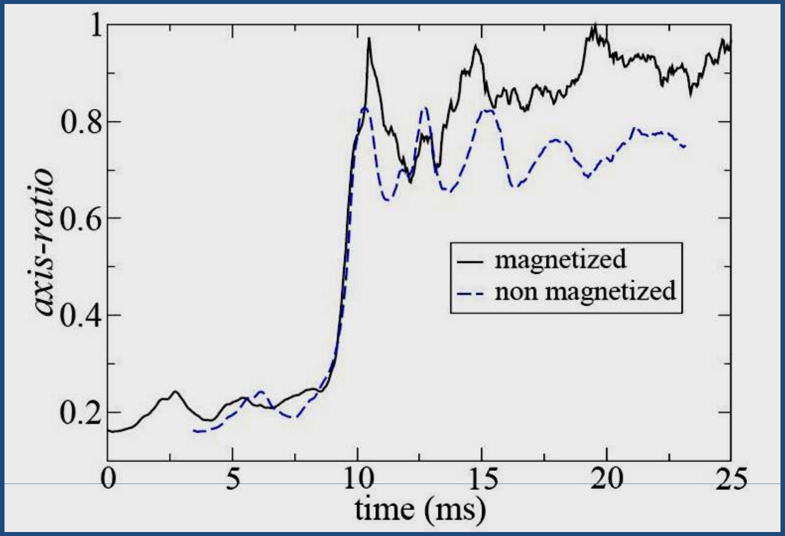


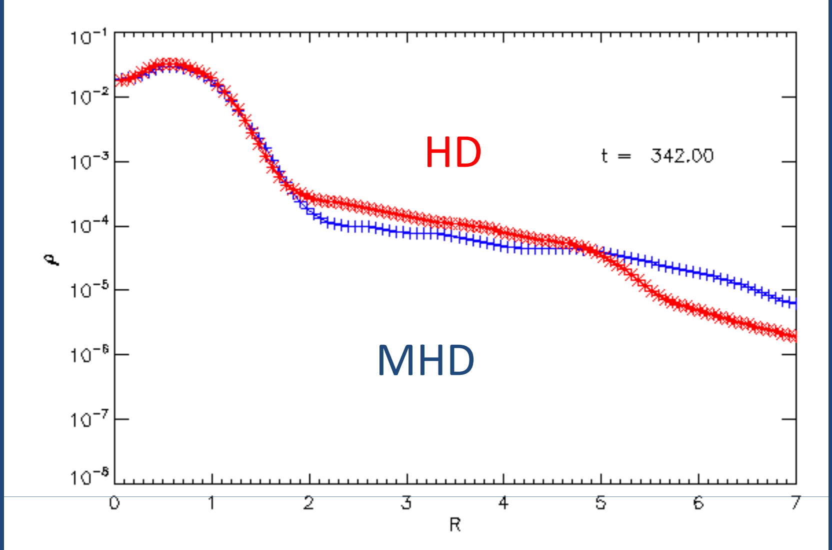
Ruderman-Kluzniak
B ~ 10^{17}G

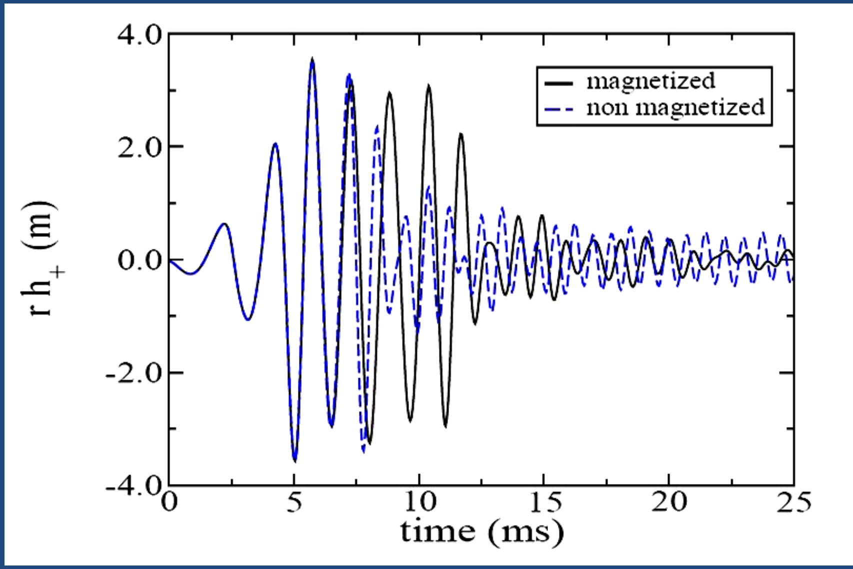


l = 2 decreasing consistently with gravitational wave emission rate
l = 4 'Cartesian grid' induced remains under control throughout
l = 1 mode growing, consistent with Tayler's instabilty (magnetic field)

‘bulk’ dynamics & consequences







Amplitudes ~
Consistent with noise level
to 2-4Mpc in current LIGO

Matches:

- 0.98 to t=7.5ms
- 0.63 to t= 12.5ms
- 0.59 to t=25ms

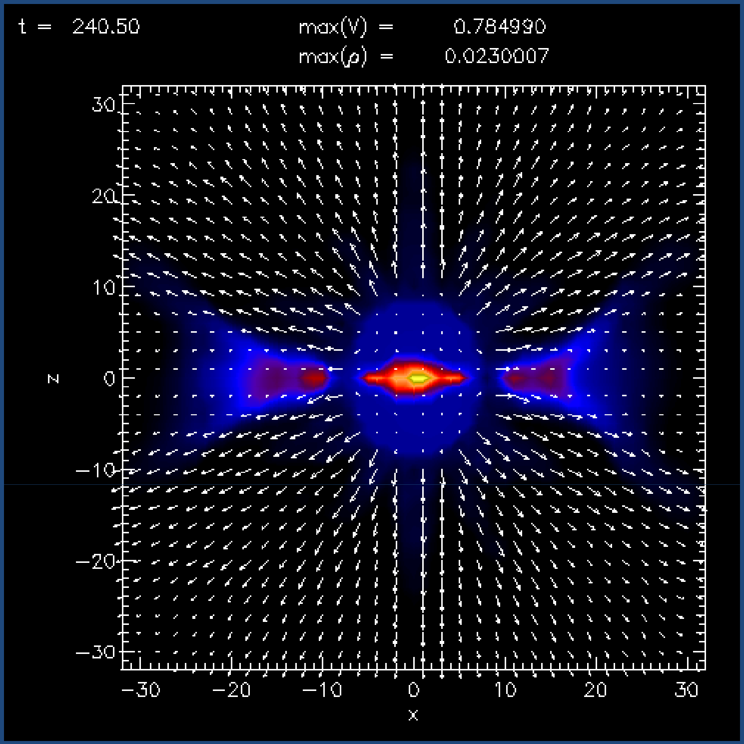
[related to Price-Rosswog 06]

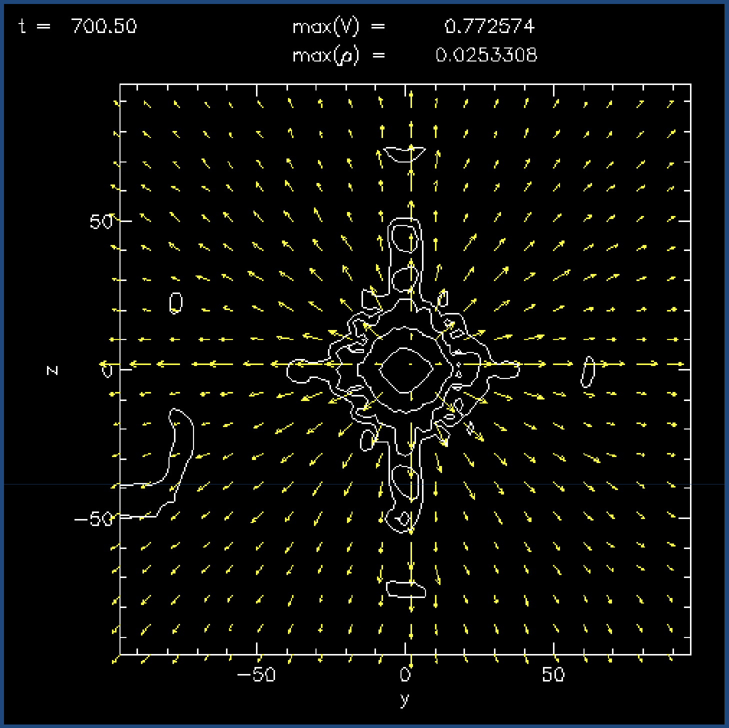
What's the scoop?

- First… take everything with a warning…
  - We've only taken the first steps.
    - Eqn of states? Magnetic fields? Neutrinos? Different configurations…
- For current LIGO, merger takes place beyond most sensitive area ☺
- For advanced LIGO, this isn't the case! Furthermore, they need info now as it could be tunable ☹
- Picture emerging is that eqn of state, better be pinned down prior to merger, post-merger can give ideas of magnetic field strengths… (can neutrinos mess it up?)

- Is this all?...

Other hints...

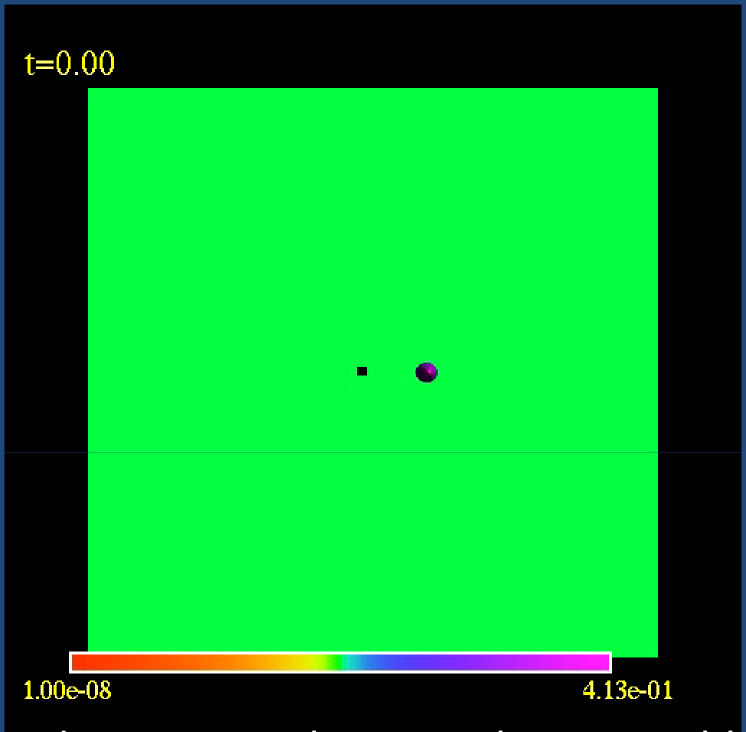




- Could these induce asymmetric bubbles? [Bucciantini et. al.]
- how about long-term behavior of the disk? Other models will need to take over [Metzger et.al.]

as opposed to BH-BH case, too early to hand it over....

BH-NS



[Anderson,LL,Neilsen,Hirschmann,Liebling]

Disruption of NS

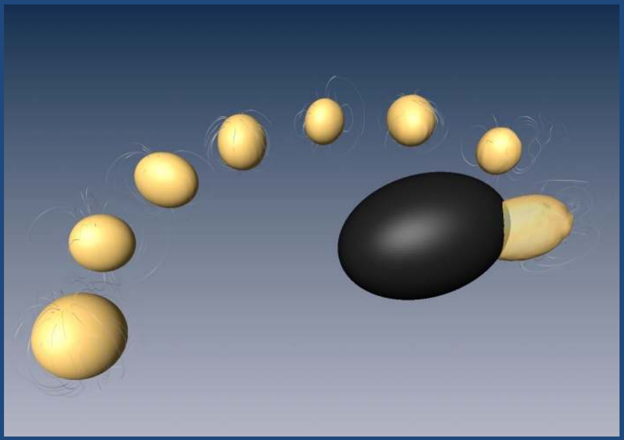
↓

Shut off of GWs

↓

when → star radius

Size of disk → GRB candidate?

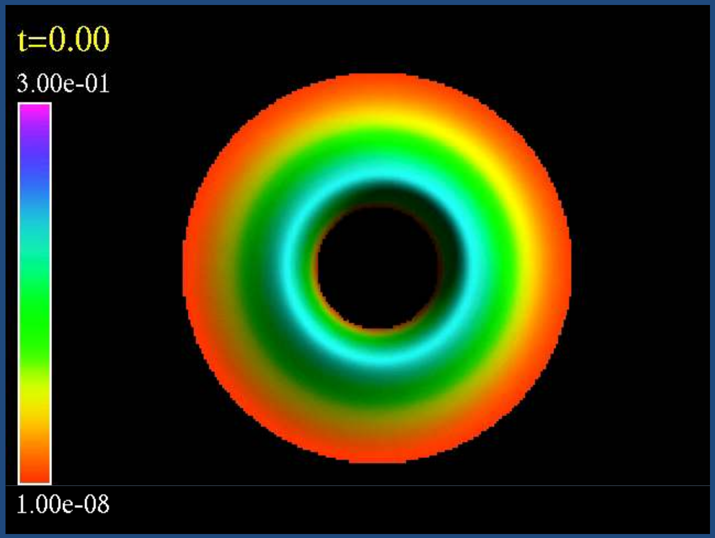


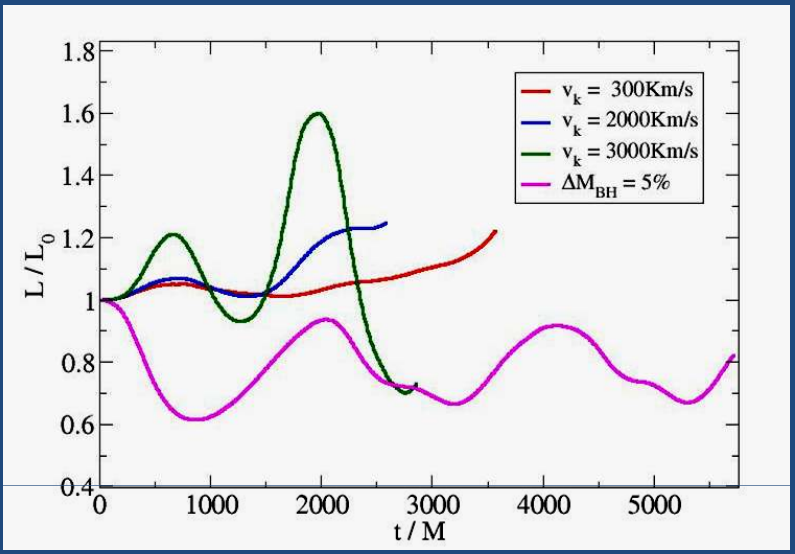
Magnetic fields not strongly affecting things for a=0.
Significant disks require high spins [Etienne et.al, Shibata etal, us].
Spin value of final BH could tell the systems apart (NS-NS, BH-NS)

Back to binary black holes

- In galaxy mergers → Binary black hole collisions surrounded by a circumbinary disk
  - Impact of BHs on the disk?
  - Impact of disk on possible effects around BHs?

‘kicked black holes’ retaliate





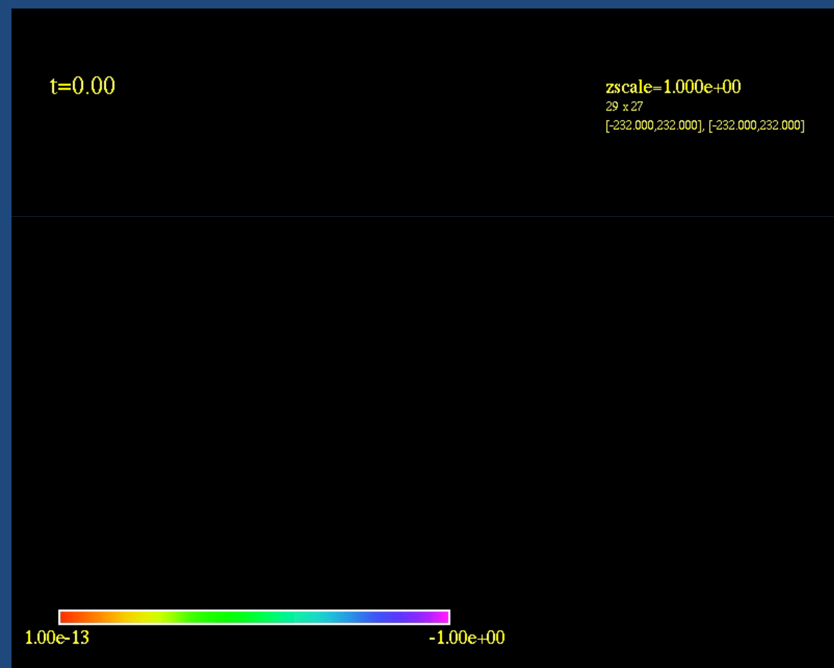
[Megevand,LL,Neilsen,Liebling]

GW Signals associated with the kick process will come before the electromagnetic ones, another tantalizing prospect to combine both efforts. [Milosavljevic-Phinney 05]

- EM signals? Shock energies damped onto the disk, from there on… take your pick…
  - Lipai et. al. : prompt and in the UV
  - Bonning et. al. : delayed and in soft Xrays
  - Phinney et. al. : not kicks but mass reduction, significant output
  - O’Neil et. Al. : not kicks but mass reduction, lowering of luminosity

Stirred, not mixed: ‘B-Z’ for binaries

- Energy extraction in a spinning BH can power jets,etc. Can binaries add to the mix?
- Ingredients: GR + Maxwell Eqns (ElectroVac)



Enhancement of E&M fields during merger epoch… BZ on steroids?

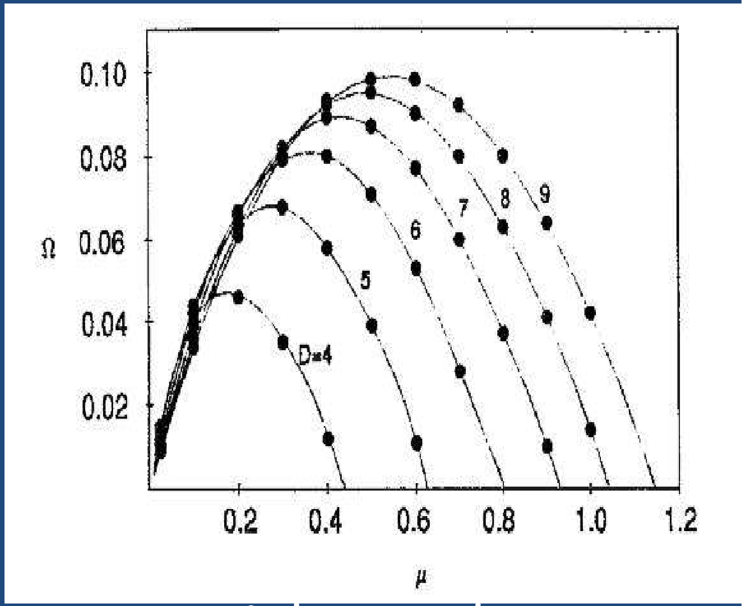
outlook

- Gravitational waves are still the unheard audio-track, it promises to be pretty darn good, community willing to pay the price.
- Experimental status is very good. Target sensitivity for LIGO reached.
- Adv LIGO in good shape and LISA plans on the way (?).
- Theoretical status is 'under control' for LIGO sources, not for LISA!
  - PN + Num Rel (or alternatives) + Quasinormal modes complete the description for binary black holes. Other sources on the way
  - SMBH + small object. Conceptual issues remain, crucial to separate the see of signals (LISA)
- In many cases, will get info out of phenomena without optic counterpart.
- In others, there will be optical counterpart, and combination should tell a nice story (eg. Gamma ray bursts). Collaborations and 'early warnings', etc.

- Undoubtedly, the full movie will be great, expect surprises as everytime a new instrument came along. *Do we have some in store?*

Black holes can misbehave! (in higher dims)

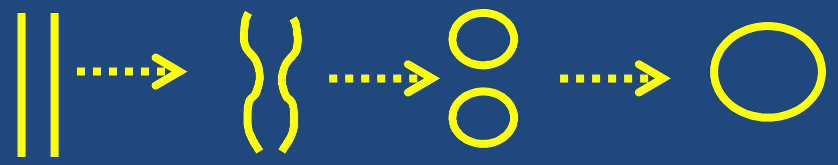
1.- Contain singularities
2.- Ruled by null-rays
3.- Non-unique even in spherical symm



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

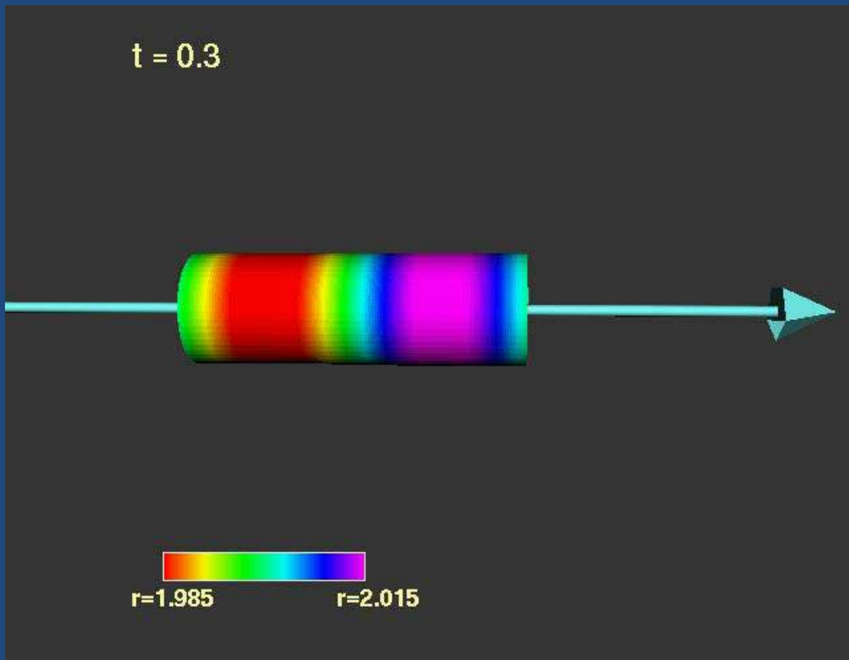


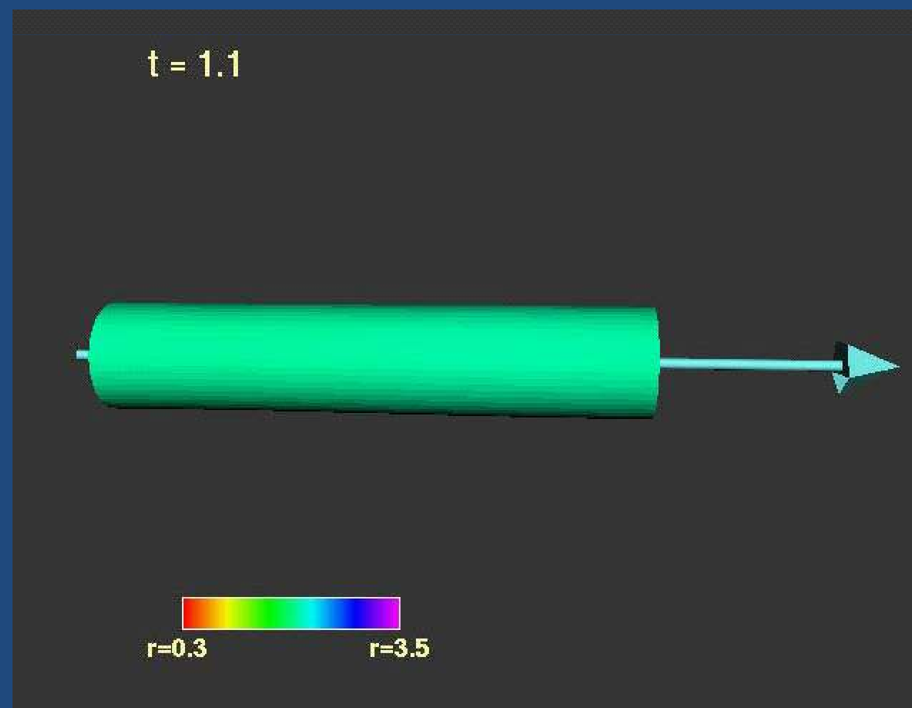
- Conjecture used in many scenarios
    - Density of states from Ads/CFT correspondence
    - Discussions of BH on brane worlds. BH in matrix theory, etc

<u>Recent developments</u>

- 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

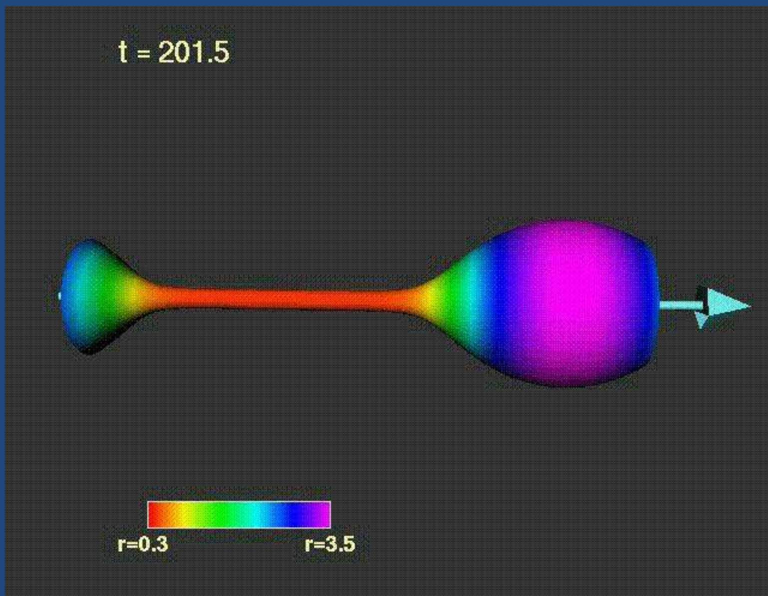
- Qns:
    - *What is the final solution of a perturbed black string?*
    - *Can it bifurcate in 'infinite time'?*

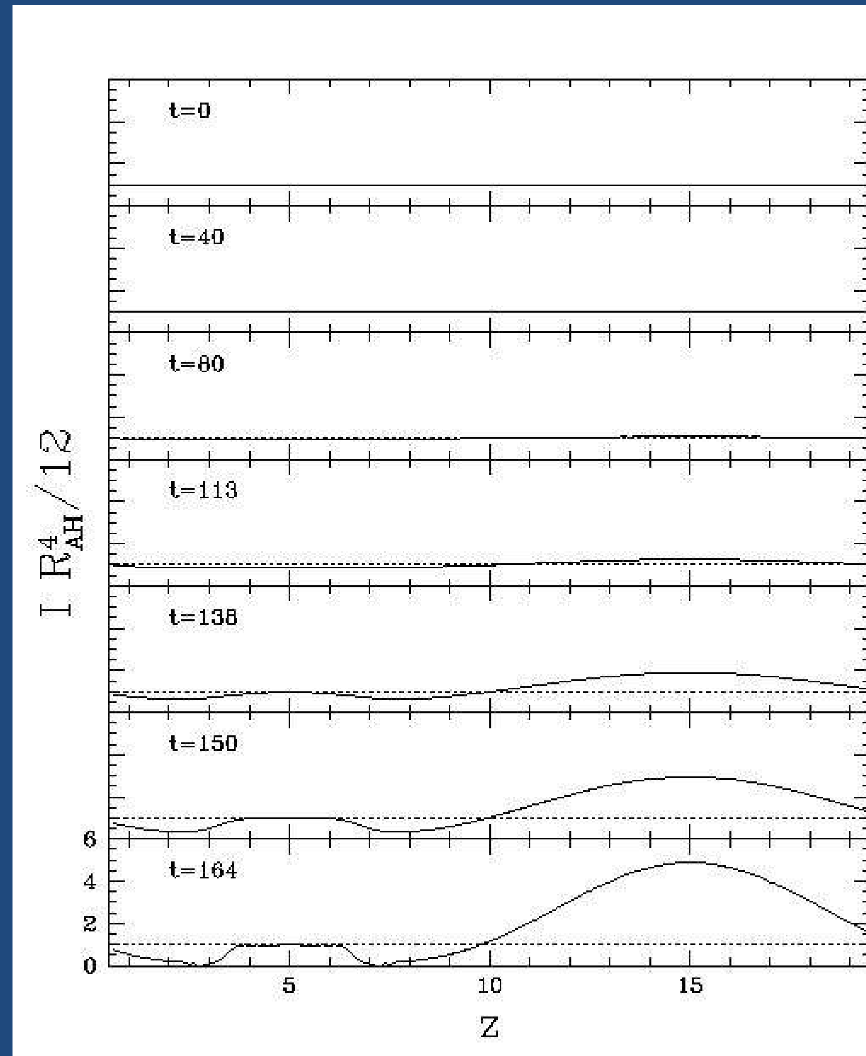




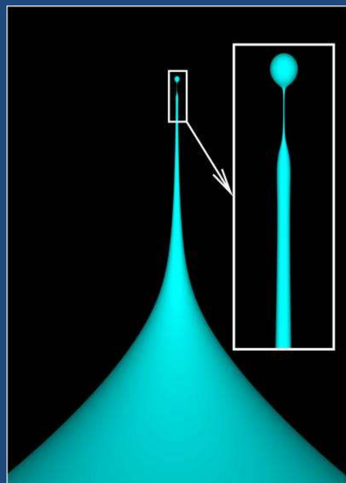
[Choptuik,LL,Olabarrieta,Pretorius,Villegas 03]

Curvature





Cascading effect possible? Have we seen this before???



Satellite formation and merging

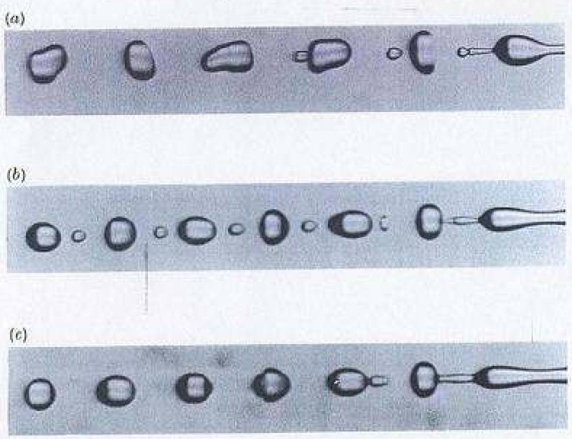
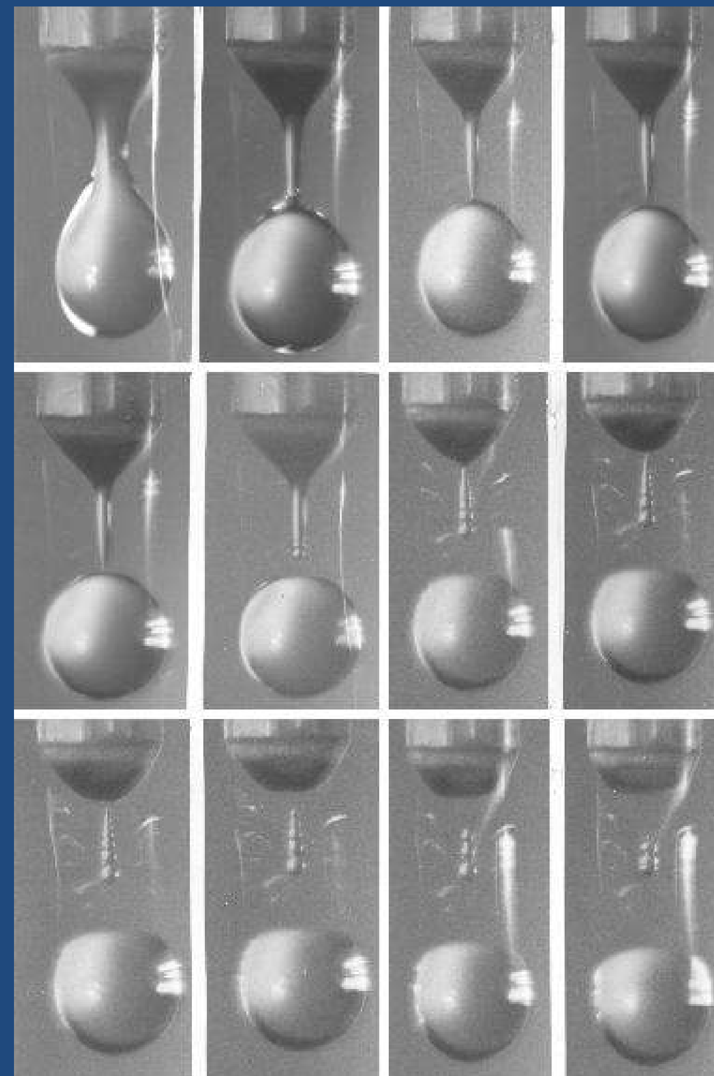


Figure 8. Medium-wavelength Rayleigh breakup. (a) Rear merge satellite ($D = 0.34$ mm, $We = 27.3$, $\lambda/D = 5.7$ and $A = 50$ V). (b) Stable satellite ($D = 0.27$ mm, $We = 30.6$, $\lambda/D = 5.9$ and $A = 70$ V). (c) Forward merge satellite ($D = 0.27$ mm, $We = 30.6$, $\lambda/D = 5.9$ and $A = 85$ V).



And BH super-radiance?

- Dumb holes ← → Black hole association (Unruh)
- Inspiraling water down the drain, induced metric ~ Kerr BH, water drain crests can be explained as a super-radiance effect [Unruh-Schutzhold]

Perhaps a surprise will be to get a better appreciation of our bathtubs ☺