Black holes and membranes: From jets to violation of cosmic censorship

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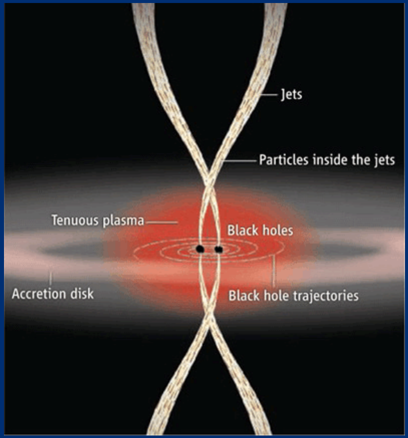
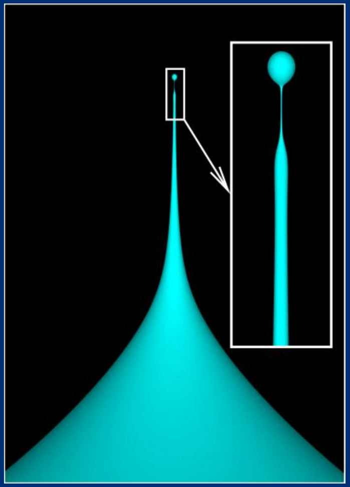
Outline:
2 fronts for black holes and ‘membranes’



- Astro:
  Jets from binary black holes
  (a new twist on an old story)
  [Science V329, 927 (2010),PRD V82, 044045 (2010),PNAS 2011]



- Black hole stability in higher dims:
  Violating cosmic censorship and then some
  (resolution to a few old questions)
  [PRL V105, 101102 (2010)]

In both cases, strong gravity/high dynamics require full GR (at least)
→ Numerical simulations needed.

Membranes, then and now

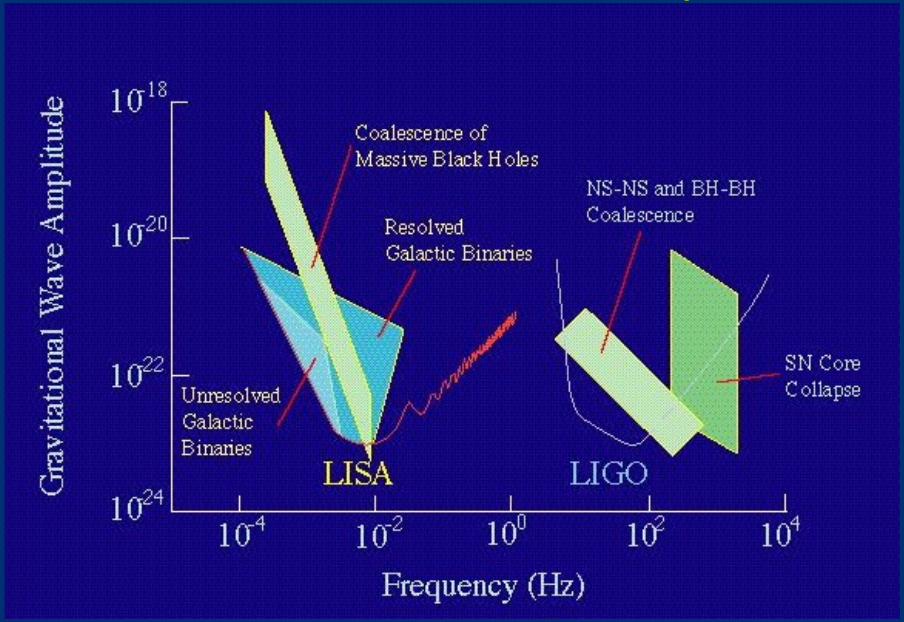
- Membrane paradigm (80s): [Damour,Thorne,McDonnald,Price]
  - Dynamics of a "stretched horizon" is governed by the Navier-Stokes equations for a relativistic fluid with very low shear-viscosity $\sigma = 1/16\pi$
  - Electrodynamics behavior of ''stretched horizon'' understood as a (poor) conductor with resistance $R = 1/4\pi$

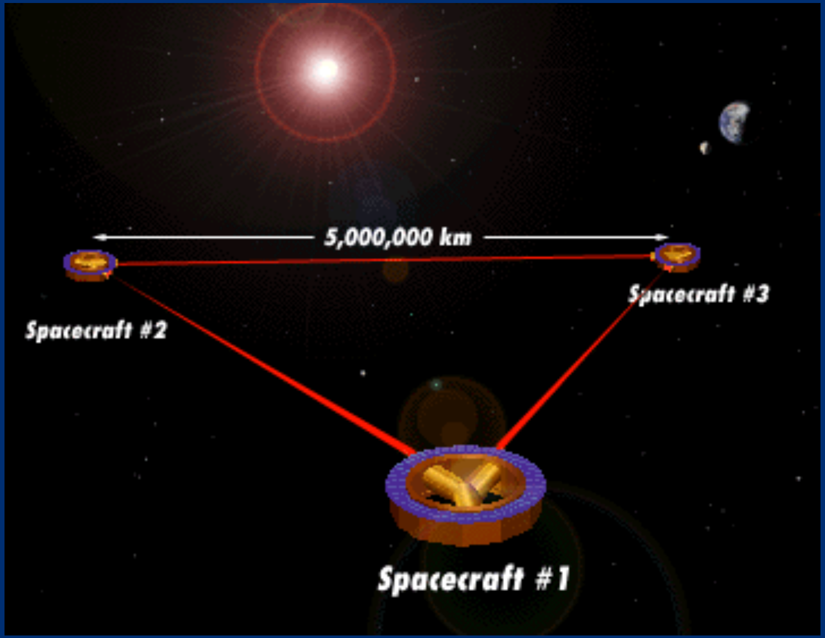
- Recently, within the context of AdS/CFT [Bhattacharyya et al.;Bredberg et.al.] and also AF [Emparan et al]
  - 'Formal' expansion, recasting Einstein Eqns as Navier-Stokes eqns + 'extrinsic' eqns governing given timelike surfaces [for a particular fluid]

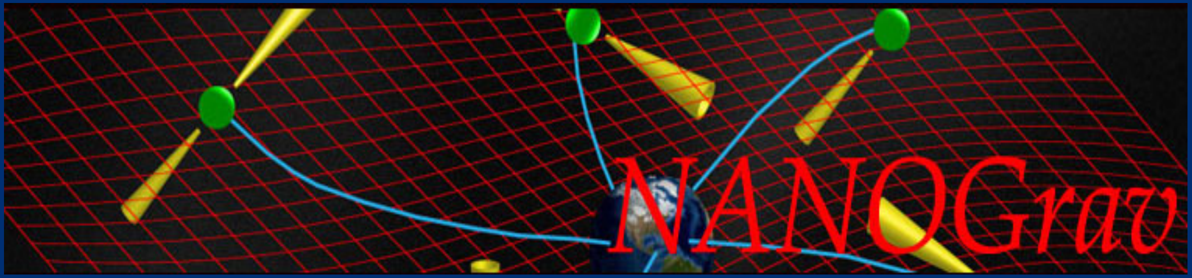
Analogies, if trusted can be used to obtain a natural handling of some problems and perhaps speculate/guess interesting behaviors

GWs and 2(?) detectors… LISA &PTA

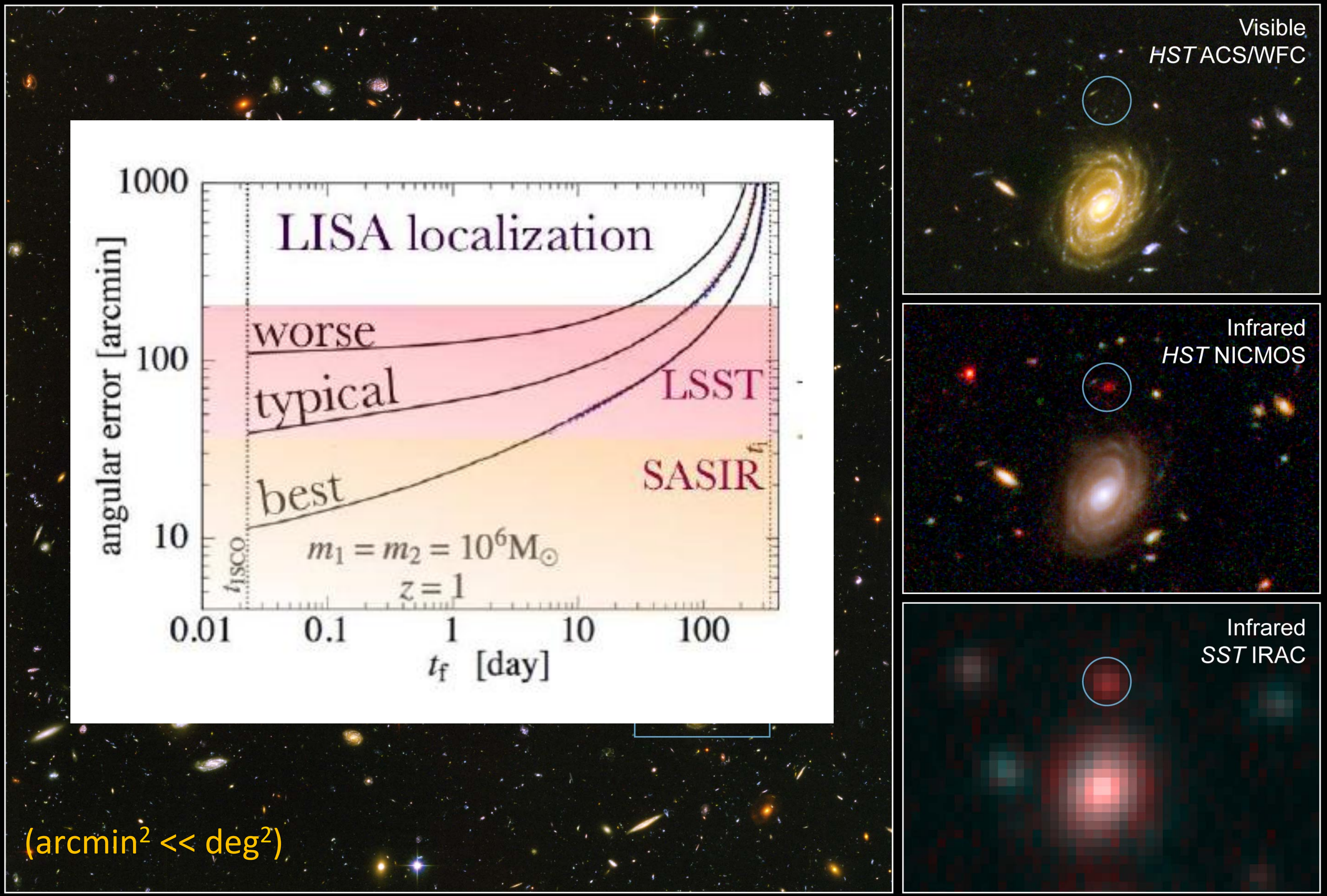
(see talks by:Thorne, Schutz,Whitcomb)







BBH waveforms for both these options are under control
-- in the process, interesting physics dug out (eg. energetics, recoils, etc)

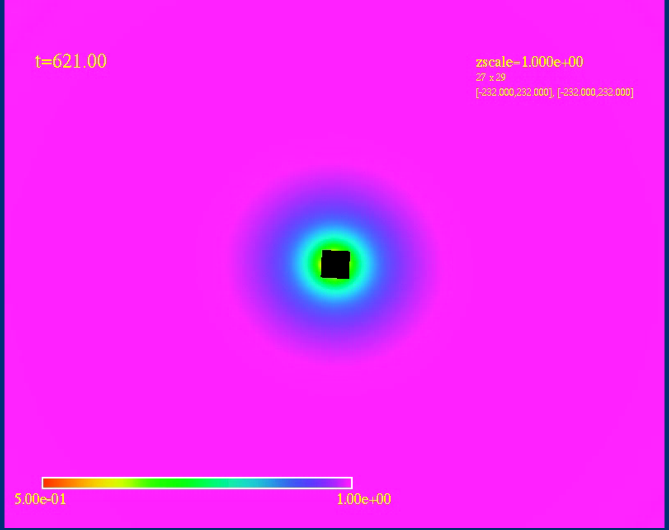


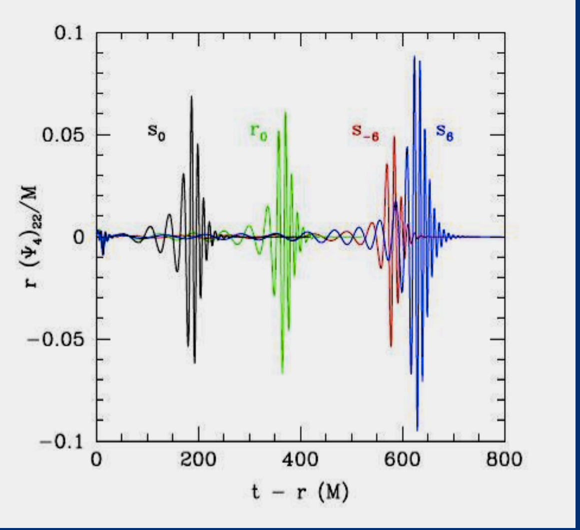
Distant Galaxy in the Hubble Ultra Deep Field • HUDF-JD2

Hubble Space Telescope ▪ ACS/ WFC

NASA, ESA, and B. Mobasher (STScI/ESA)

STScI-PRC05-28





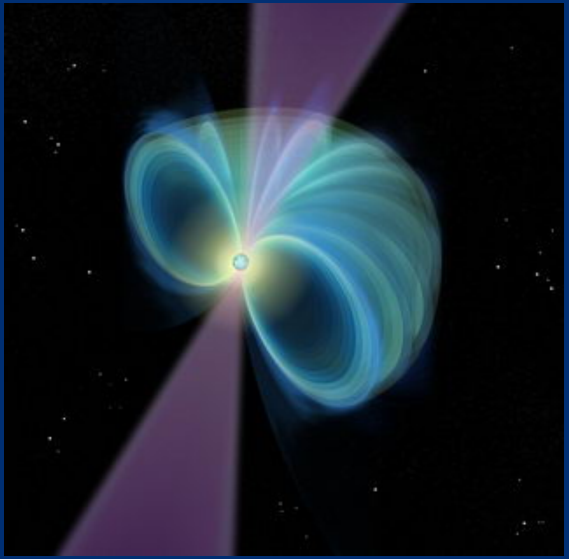
- Can we get bhs to do more? (recall $L_{GW} \sim 10^{23} L_{sun}$)
  - Can the merger dynamics give rise to observable electromagnetic counterparts?
    - Going deeper into the physics of different systems
    - Aid in the detection (localization) of the source
    - Confronting gravitational and electromagnetic based knowledge. Ie. Luminosity distance vs redshift diagram.

    *lots of activity in the past few years on this front, still in early stages though.
  - Need to understand what can produce the counterparts

[work with Palenzuela,Liebling, also Neilsen,Anderson,Hirschmann,Thompson, Hanna]

Where to we go from here?

- Need to find what's the right model
  - microphysics, EM fields, what's outside compact objects? (This is tough, but nature doesn't care what we think…)
- So… let's start simple… consider a star and its dipole… Pulsars radiate….. Dipole radiation?



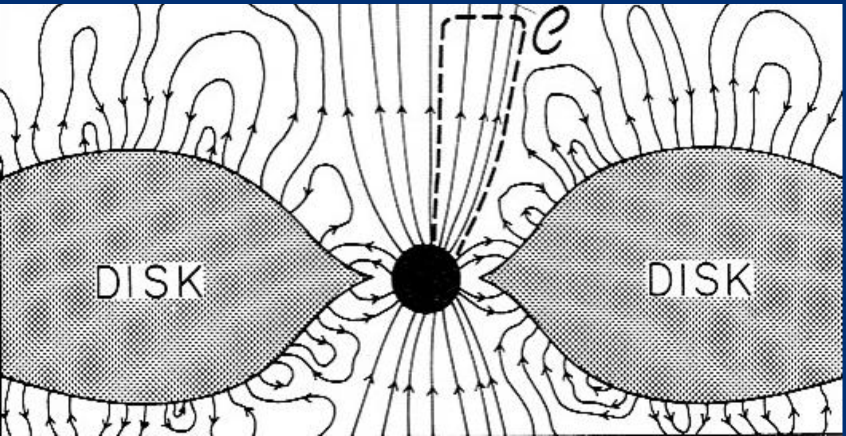
$L \sim B^2 \Omega^4 R^6 \sin(x)^2$

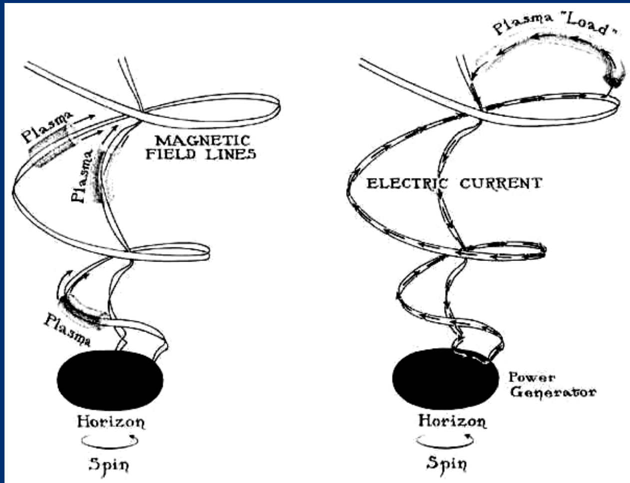
(but this isn't right,
$L \sim B^2 \Omega^4 R^6 [1+\sin(x)^2]$
Spitkovsky 2006

Binary black holes as blenders.
A new spin on an old story

How does the curvature/dynamics influence EM fields?

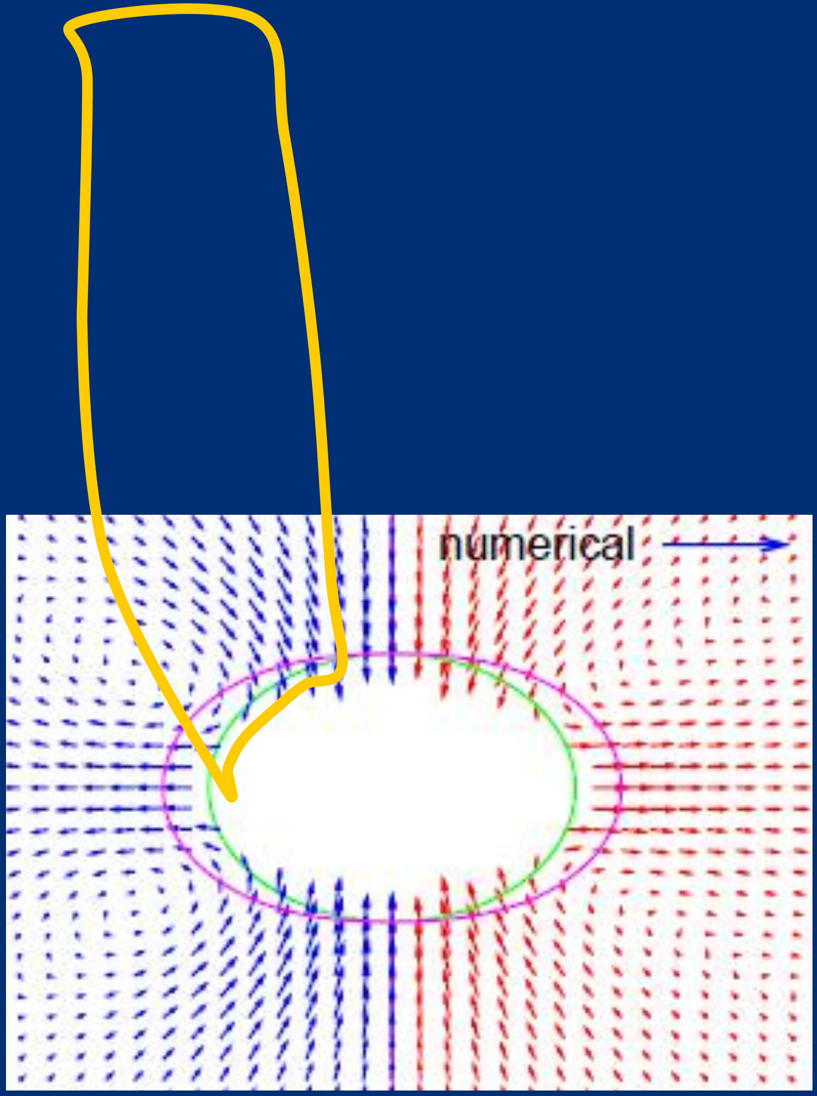
- Blandford-Znajek. Emmision mechamism for Kerr bh's surrounded by magnetic fields (anchored by an accretion disk)
- Stray charges accelerate→ photons → pair production → cascade. BH becomes surrounded by a tenuous conducting plasma with little inertia
- Blandford-Znajek: BH acquires and induced charge distribution, bh rotation provides an EMF with $V \sim B\, a \rightarrow L \sim (Ba)^2$





[Goldreich-Julian, Blandford-Znajek]

Basic picture from the membrane paradigm



BH: (poor) conductor

Battery: Black hole' s rotation

Plasma to close the circuit

Far load: to dissipate energy

$L \sim B^2 a^2$

However, this is just a picture, does it hold ? Need full solution to compare against

Approach: Force-free electrodynamics

$$\nabla_a T^{ab} = 0 \quad \rightarrow \quad \nabla_a T^{ab}_{(fluid)} = -\nabla_a T^{ab}_{(em)} = -F^{ab} J_a$$

$$\text{if} \quad \rho, P << B^2 \quad \text{then} \quad \nabla_a T^{ab}_{(fluid)} << \; F^{ab} J_a \approx 0$$

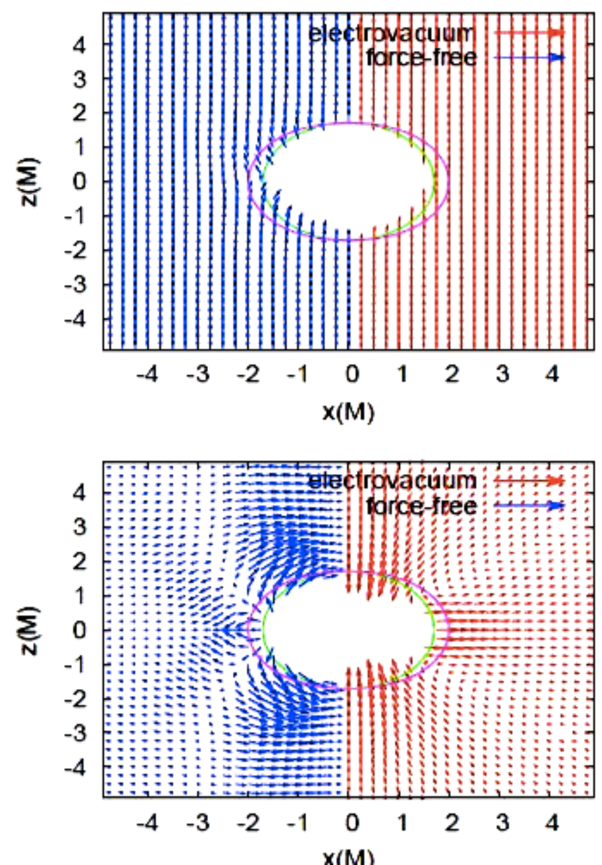
$$q\,\mathbf{E} + \mathbf{J} \times \mathbf{B} = 0 \;\rightarrow\; E \cdot B = 0 \text{ , and non-zero J}$$

System can thus be studied in an ``effective way"

- plasma supplies charges/currents and enforce E.B = 0

- furthermore, fields can carry charged particles, and establish a circuit

Need to solve this problem, what can we expect that is interesting/relevant? -- and, can we guess what to expect?



- *IF* analogy can be pushed further, there is little special about BH's rotation, any relative motion of conductor wrt ambient magnetic field would give and EMF

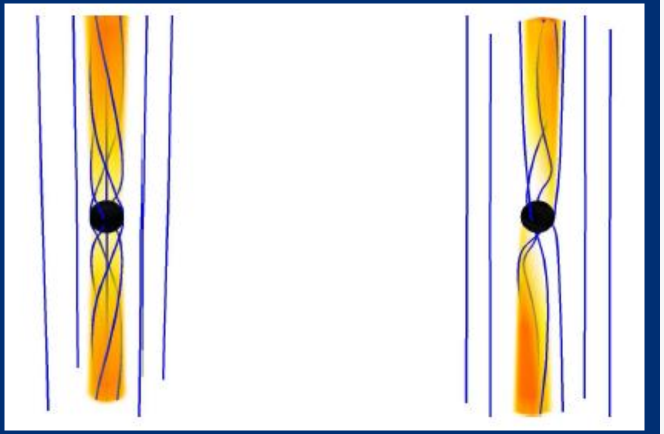
- SMBH merger will give such scenarios
  - Prior to merger, 2 bhs orbital motion inside the circumbinary disk region
  - After merger final BH rotates, but also might have a velocity due to recoil

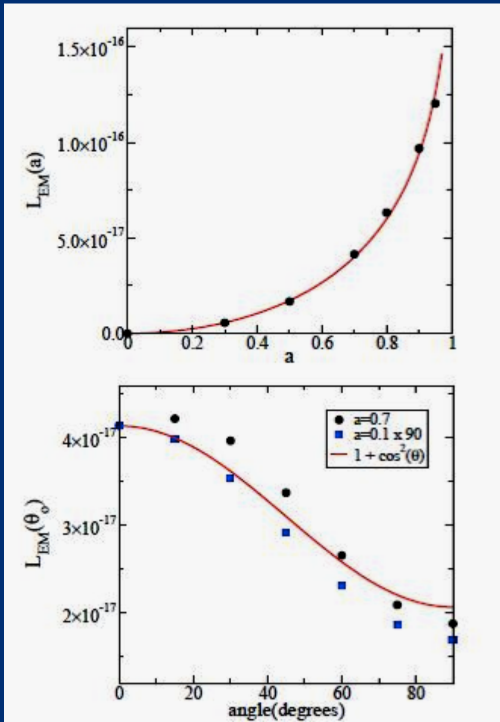
- Can this intuition be confirmed? And connection further exploited?

• we knew. $L \sim B^2 \; a^2$ in the aligned case [finer version Tchechovskoy,Narayan,McKinney 2010].

• For misaligned case?
  • Poynting flux still there, along B
  • $L \sim B^2 \; a^2 \; (1 + \cos^2)$

  (can be predicted using Damour 74 + mp!)

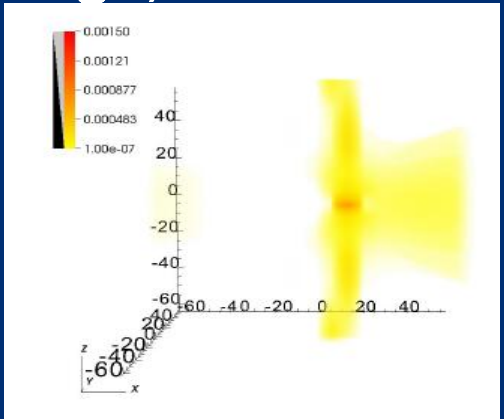




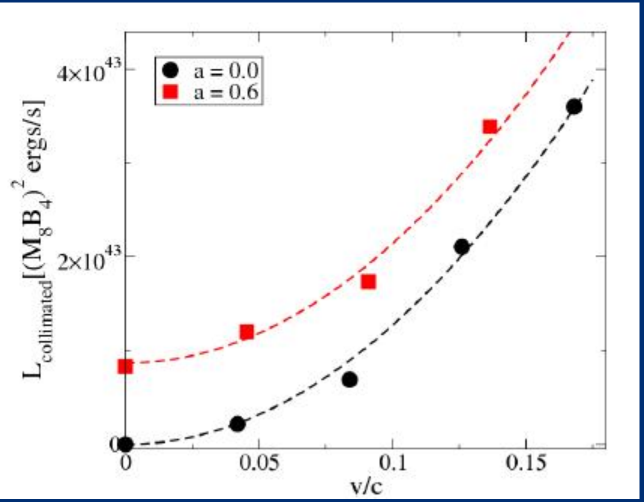
[Palenzuela,Garret,LL,Liebling, PRD 2010]

What if it moves?

- E.g. after black holes merge, individual black holes prior to merger.



- Where from? From membrane paradigm → BH is a conductor. If moving through a B field, induce E ~ v x B → EMF=V ~ (vB) ; L ~ V^2

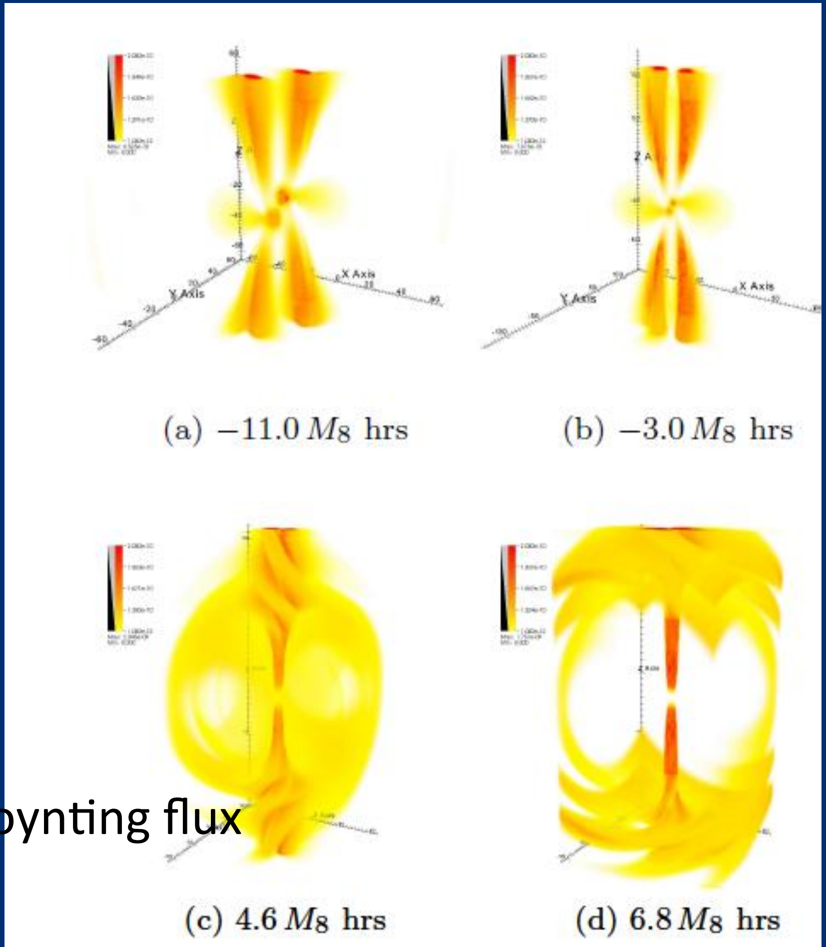


- Thus, L ~ B^2v^2

(Can be predicted using theory of satellite propulsion Drell,Foley,Rudderman 65!)

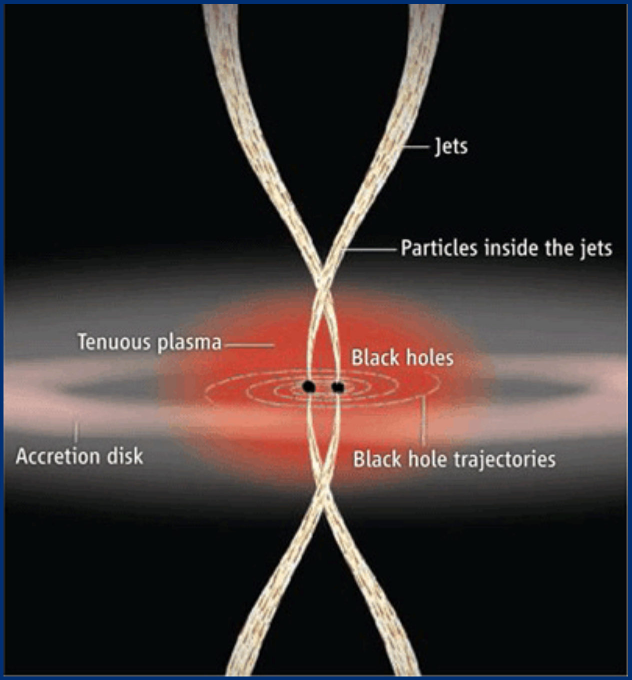
Onto the binary case

- Orbit → Black holes move through B. Hall effect analogue.
- As in previous cases, 'circuit' can be established due to charge separation
- Thus, expect Poynting flux through orbiting stages. Also contribution from standard BZ .

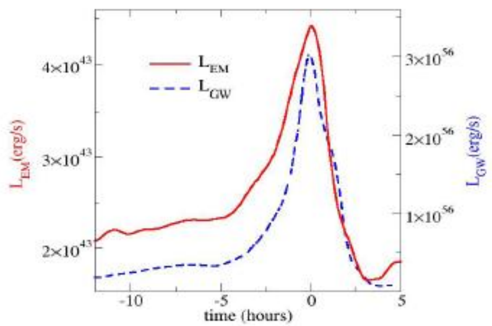


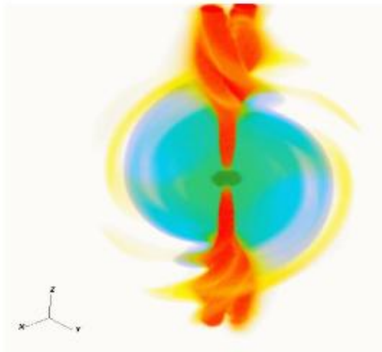
(a) $-11.0\, M_8$ hrs (b) $-3.0\, M_8$ hrs

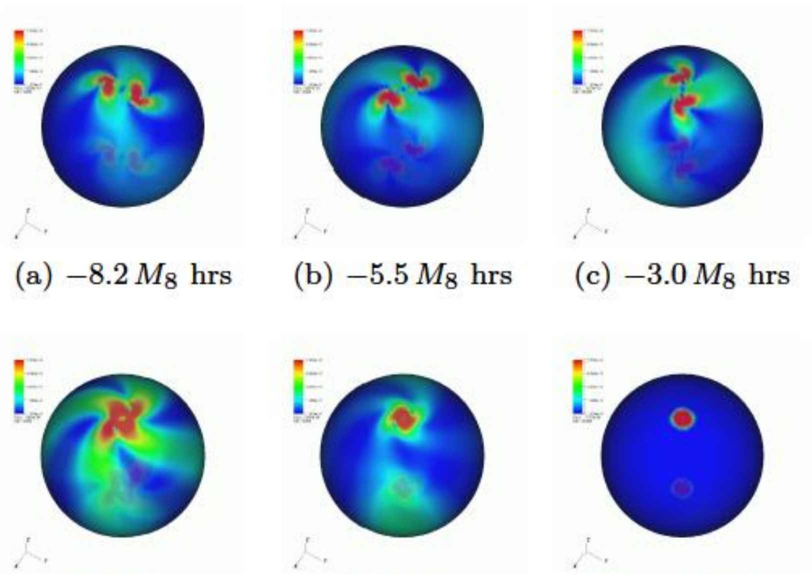
(c) $4.6\, M_8$ hrs (d) $6.8\, M_8$ hrs



[Palenzuela,LL,Liebling , Science 2010]



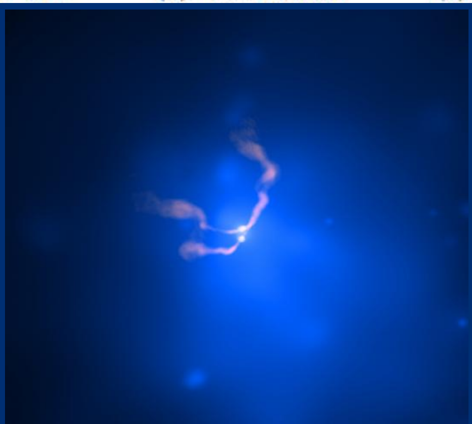




(a) $-8.2\,M_8$ hrs (b) $-5.5\,M_8$ hrs (c) $-3.0\,M_8$ hrs

(d) $2.0\,M_8$ hrs (e) $4.6\,M_8$ hrs (f) $6.8\,M_8$ hrs

•



Putting all together:

$L \sim (1\,[a/0.6]^2 + 100\,v^2)\,10^{43}$ ergs $[M_8\,B_4]^2$

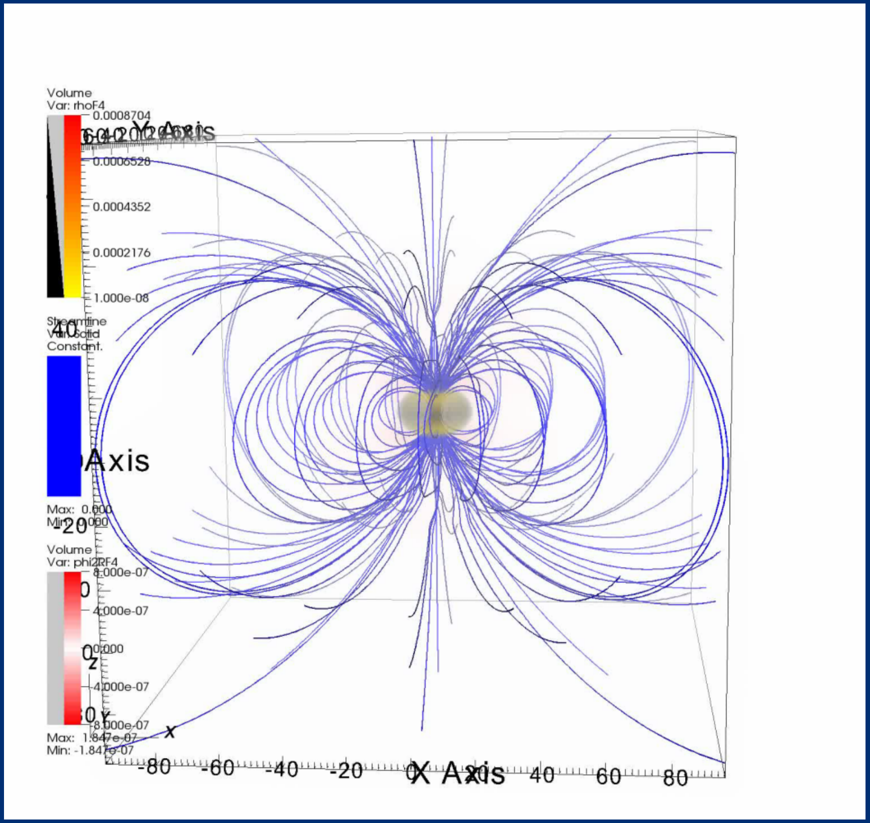
* *EM flux acts as a "spacetime tracer"*
* *Can exploit 'standard' BBH results to predict much of the EM flux behavior*

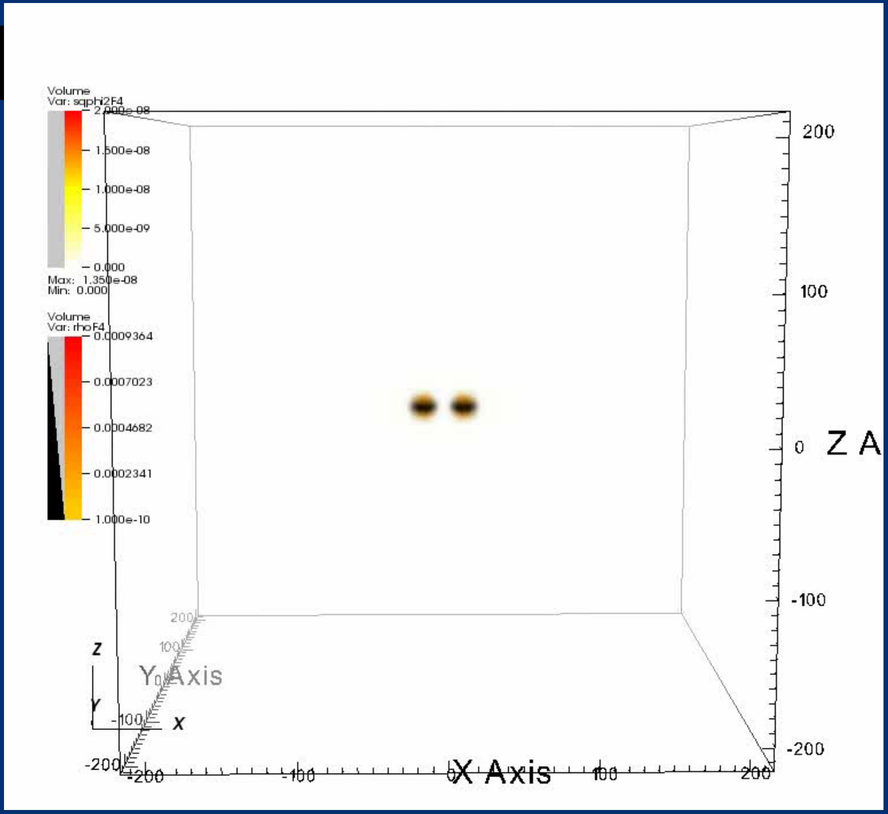
Multimessenger? : LISA & PTA for gravity waves

EM observations? For 10^4G, $10^8 M_O$ flux ~ $10^{43\text{-}44}$ ergs. IF Poynting flux energy efficiently transferred to observable emissions, interesting pre/post merger observations possible; to z=1 ?

How about Ligo/Virgo sources?

[LL,Palenzuela,Liebling,Thopmson,Hanna, arxiv 1112.2622]





Single NS collapsing:

-- Cons of flux B ~ $1/R^2$
-- Cons of ang mom, Ω ~ $1/R^2$
-- Pulsar spindown → L ~ $1/R^6$

(see talks by Shibata, Bhattacharya)

Binary NS

-- Magnetosphere interactions: field direction → reconnections prior to merger
-- B strength enhancement by collision
-- unavoidable collapse to a BH
-- field reordering in disk, wind on disk, etc

Stability of (higher dimensional) BHs

[work with F. Pretorius]

if cosmic censorship holds → an observer does not need quantum gravity….

If unstable → naked singularity? → violation of cosmic censorship. Is it generic?

--in 4D: examples are either non-generic or requiring 'unphysical' matter

- At the gravity level alone, D=4 is special, but how special?
  - Beyond behavior of orbits and no "Kerr-bound", there are richer geometries in higher dimensional Ricci-flat Lorentzian manifolds, in particular the zoo of "black objects" - black spheres, rings, strings, saturns, drops, …

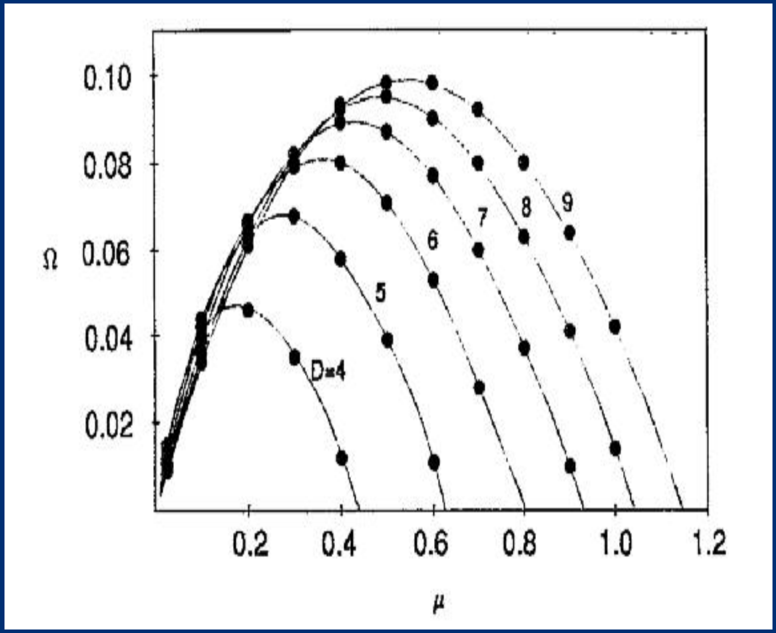
- If string theory is providing the correct path to a consistent theory of nature valid at Planck scales, the universe is fundamentally higher dimensional

- Lots of examples on (holographic) correspondences of string theory (AdS/CFT in particular) to describe many aspects of conventional non-gravitational 4D physical processes in terms of higher dimensional gravity
  - superconductors, superfluidity, quark-gluon plasmas, etc.
  - interestingly, the gravitational dual to these processes studied to date involves *black holes*

(see talks by Horowitz-Minwalla)

BHs in higher dims: come Black strings

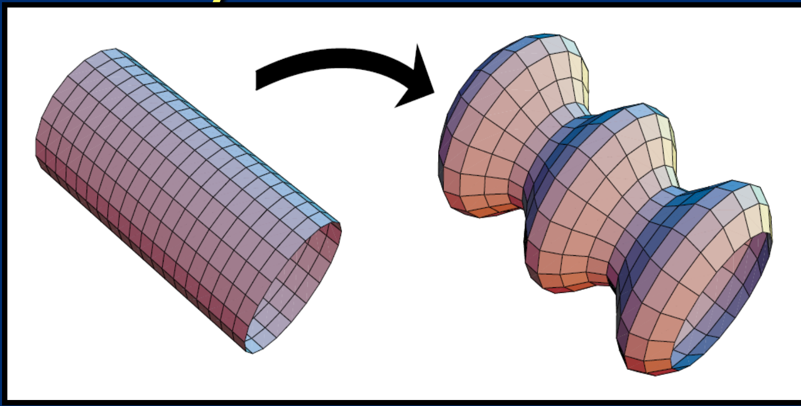
1.- Contain singularities
2.- Ruled by null-rays
3.- Non-unique even in spherical symmetry



Stability? (Gregory-Laflamme 93)

- Black string perturbations admit exponential growth for $L > L_c$ ($L_c \sim 14.3m$)

End-state of the instability?

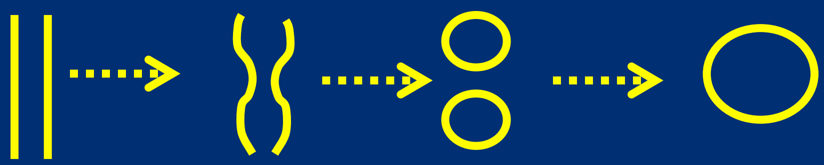


- Entropic argument:
  - above a similar critical wavelength L_c the total *area/length* of a sequence of 5D hyper-spherical black holes, each a distance L_c apart, is *greater* than a 5D black string with the *same* total mass/length ($M=mL$):

$$\frac{A_{BH}}{A_{BS}} = \sqrt{\frac{8}{27\pi}\frac{L}{m}} \Rightarrow L_c = \frac{27\pi}{8} m \approx 10.6m$$

Image from:
R. Gregory and R. Laflamme,
Nucl.Phys.B428 (1994)

Conjecture: Black strings will bifurcate

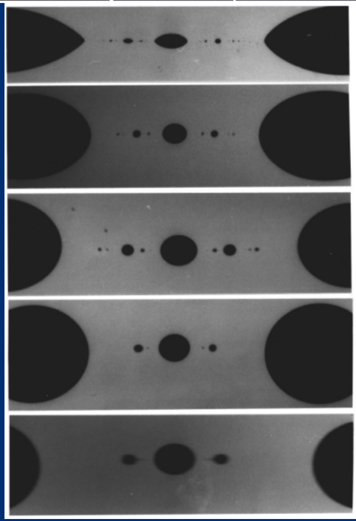


- But, this cannot happen without the appearance of a naked singularity (the "no-bifurcation" theorems still hold in 5D) → a *generic* example of cosmic censorship violation in higher dimensional gravity

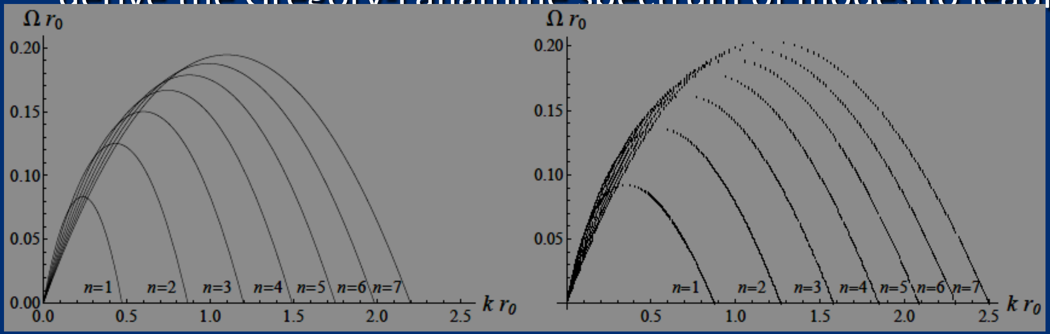
What is the end-state of the system?

- Horowitz and Maeda *[PRL 87, 131301 (2001)]* proved that black string horizons cannot shrink to zero cross-sectional radius in *finite affine time* of the generators of the horizon
  - based on this, they conjectured the end-state would be a new, static, non-uniform solution with the same topology as the black string
  - this spurred a search for such solutions; a couple were found *[S. S. Gubser, CQG. 19, 4825 (2002), T. Wiseman, CQG. 20, 1137 (2003), E. Sorkin, PRD74:104027 (2006)]*; however, these solutions have less entropy (area) than the uniform black string, so could not be the end-state of the GL instability
- Also, other more radical conjectures (e.g. spacetime collapses on itself)
- 2003… Numerical attempt. Didn't resolve it

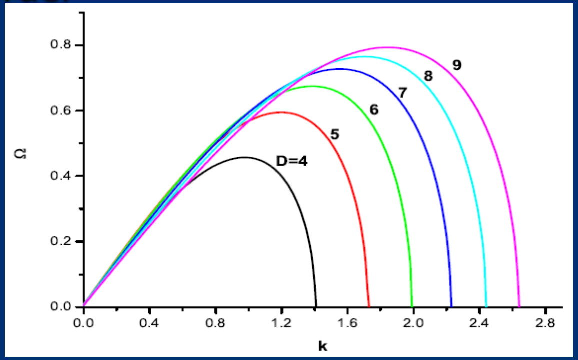
What in the world is the end-state of the instability?



- Further (anecdotal) evidence in favor of the pinch-off scenario gathered in the form of various correspondences between equations governing viscous hydrodynamics and horizon dynamics
  - the membrane paradigm *[Damour; Thorne, Price, Macdonald, Eds. (1986)]* ➔Navier-Stokes equations.
  - Cardoso and Dias *[PRL 96 (2006)] (right figure)* showed that the spectrum of unstable modes of a cylindrical flow of fluid with surface tension, subject to the Rayleigh-Plateau instability, was quantitatively similar to that of black strings
  - more recently developed frameworks *[Bhattacharya et al., JHEP 02 (2008), R. Emparan et al. JHEP 03 (2010)]* established similar relationships; *[J. Camps et al., arxiv:1003.3636 (2010)] (left figures)* used the "black folds" approach to re-derive the Gregory-Laflamme spectrum of modes to leading order



unstable sound waves in effective black string fluid (left) compared to GL modes (right)



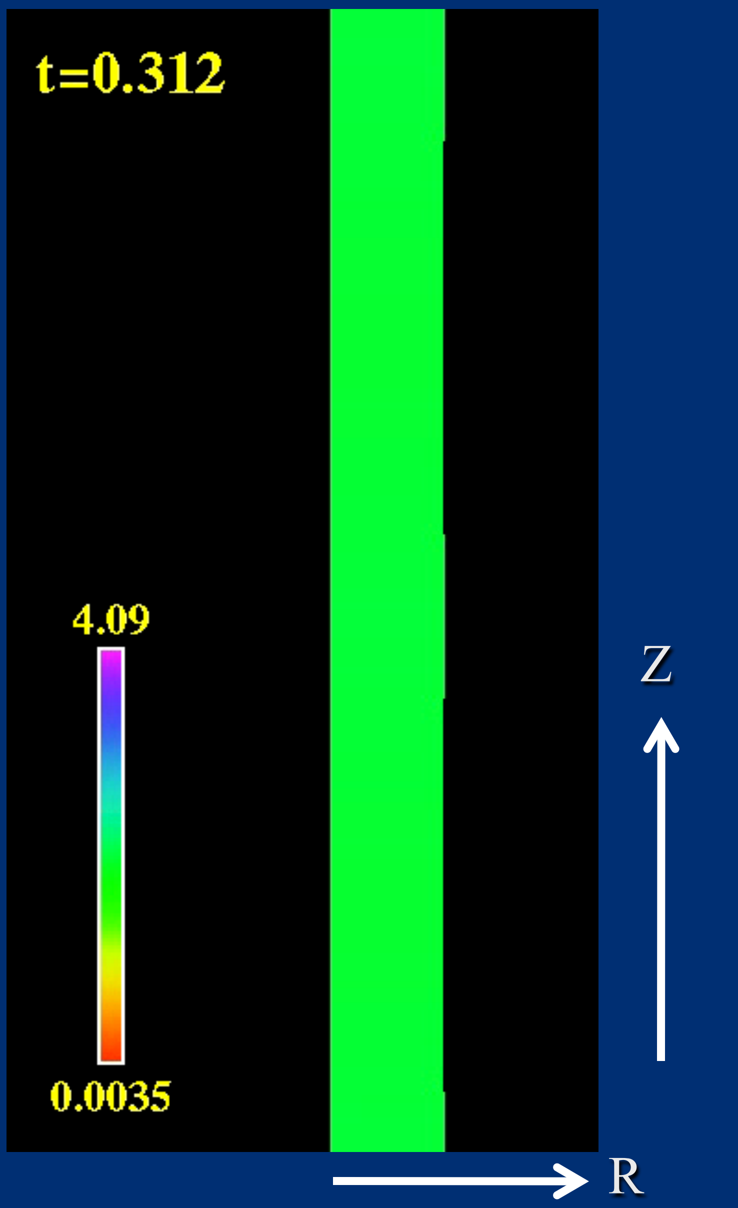
Rayleigh-Plateau analogue

Sealing the fate…..

- New numerical study…
- map the geometric 1D shape of each *t=x=y=constant* slice of the apparent horizon to a flat *(R,Z)* Euclidean space; i.e. in parametric form

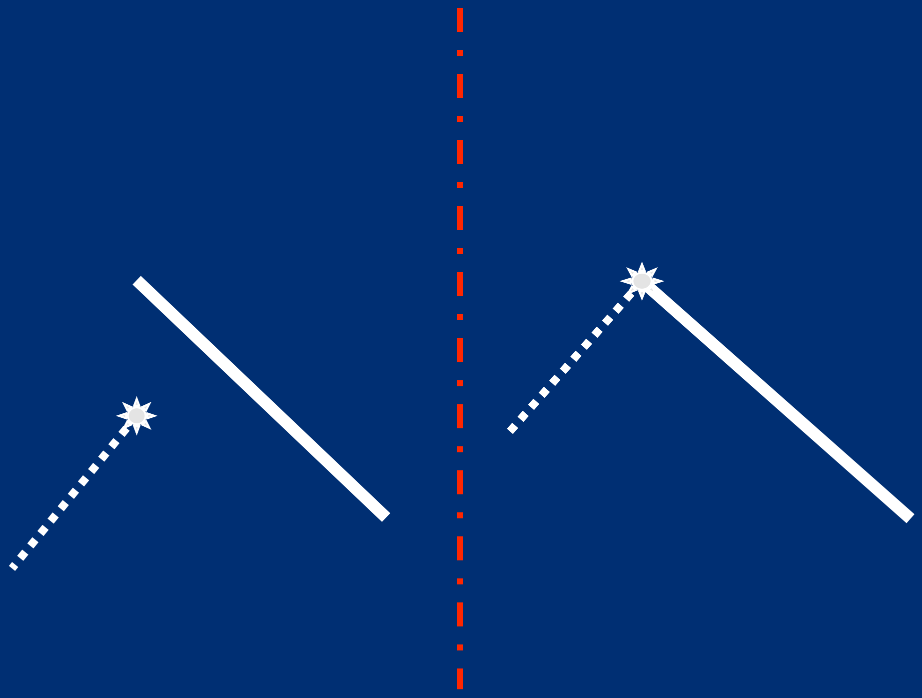
$$(R,Z) = \big(R(\xi), Z(\xi)\big)$$

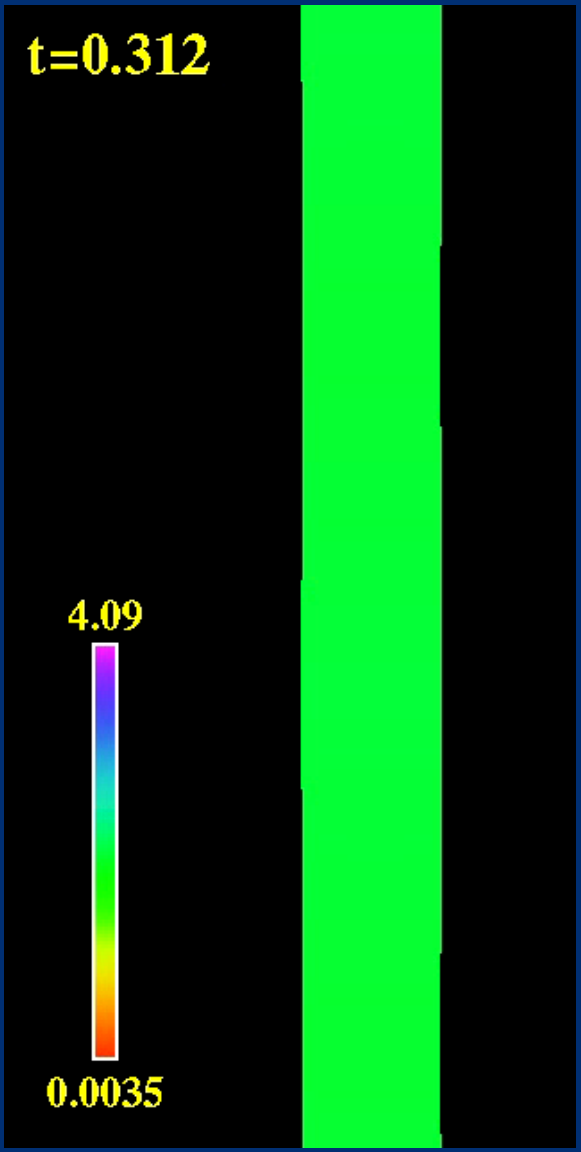
- $R(\xi)$ is the areal radius of that point on the horizon, and $Z(\xi)$ is defined so that the proper length of the curve in the flat space is identical to that of the corresponding curve in the physical geometry
- the movie shows this curve spun around $R=0$ to form a surface for visual aid
- color is mapped to R
- (note that time is "slowing down" !)



zooming in, affine time

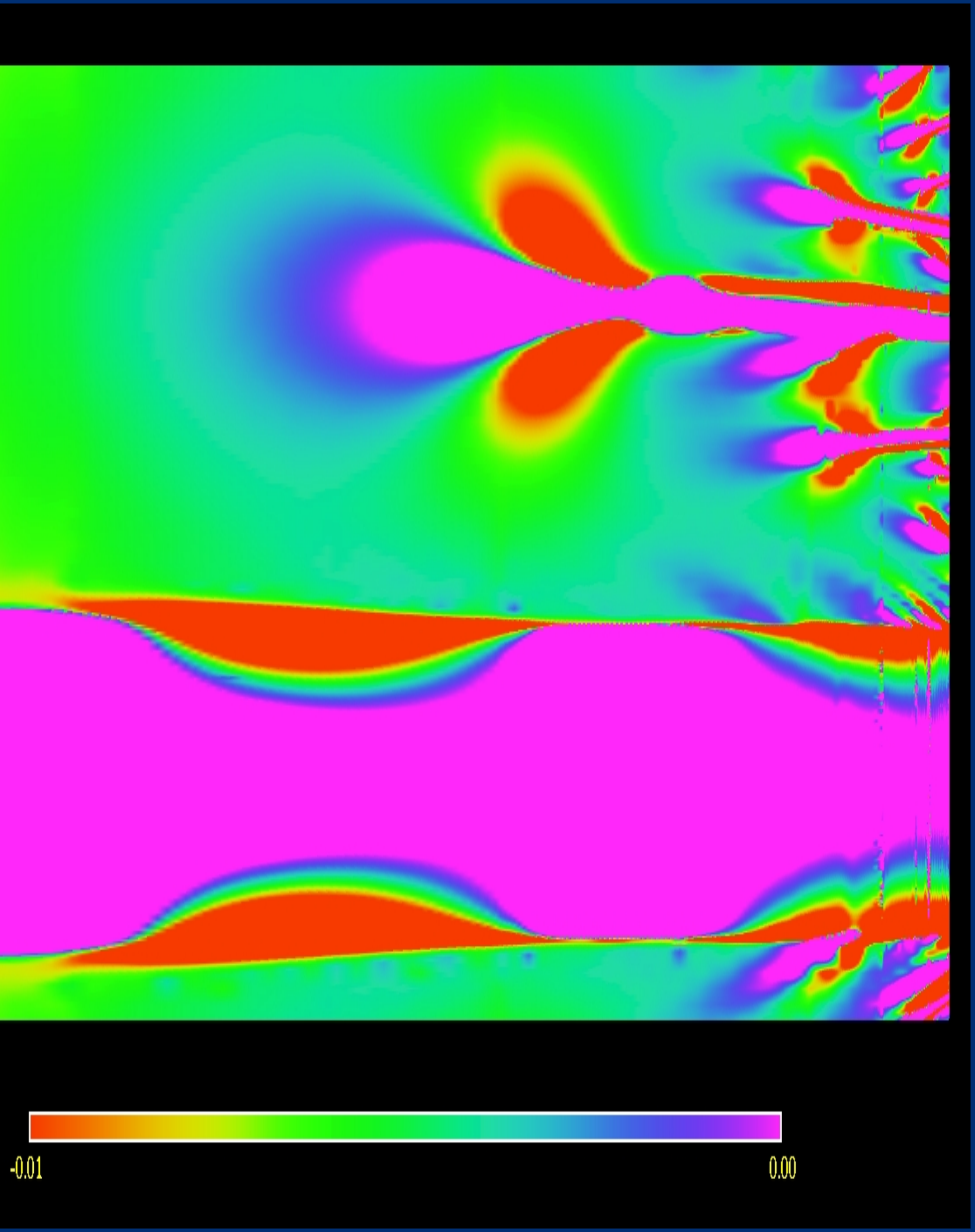
- *NO tension with Horowitz-Maeda result*
  affine time → infnity
  $\lambda \sim m\, e^{40}$ (at t~165m already)





What is it? …let’ s check some more…

AH behavior..



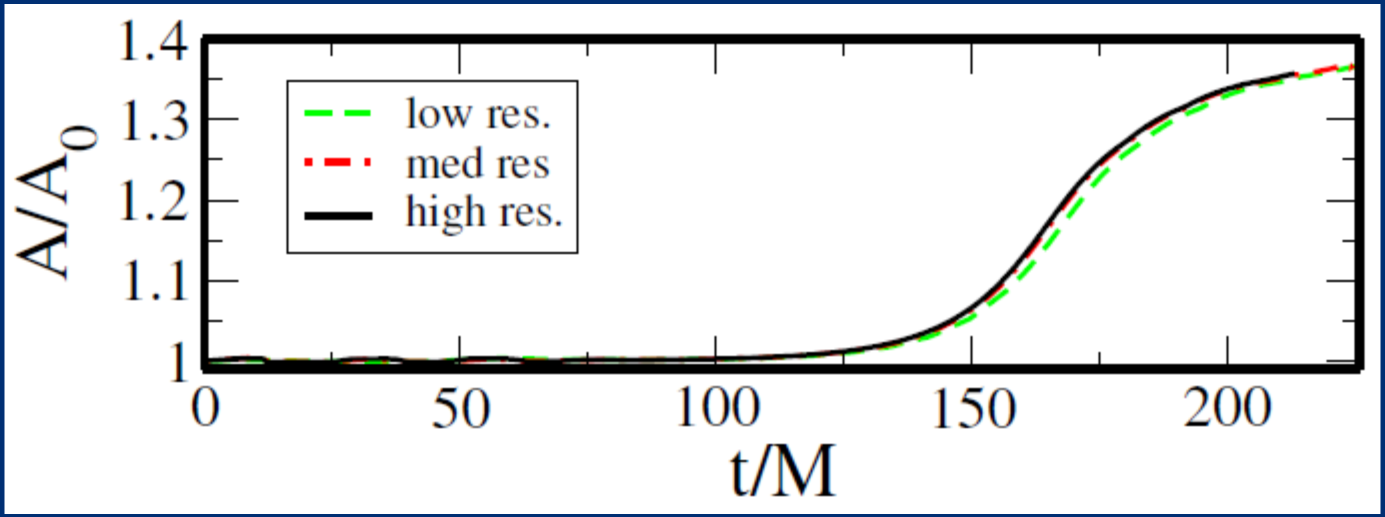
Hausdorff dimension?

$$L(t) = (t_c - t)^{(1-d)}$$

$d \sim 1.05$

(i.e. simple fractal structure)

Apparent Horizon Area



- Resolutions chosen via specification of the maximum estimated truncation error τ, from τ_0, $\tau_0/8$ to $\tau_0/64$ ("low" to "high")
- For this configuration, ignoring the (small amount of) energy from the initial perturbation, a sequence of spherical black holes (one per period) with the same energy as the initial string has an area

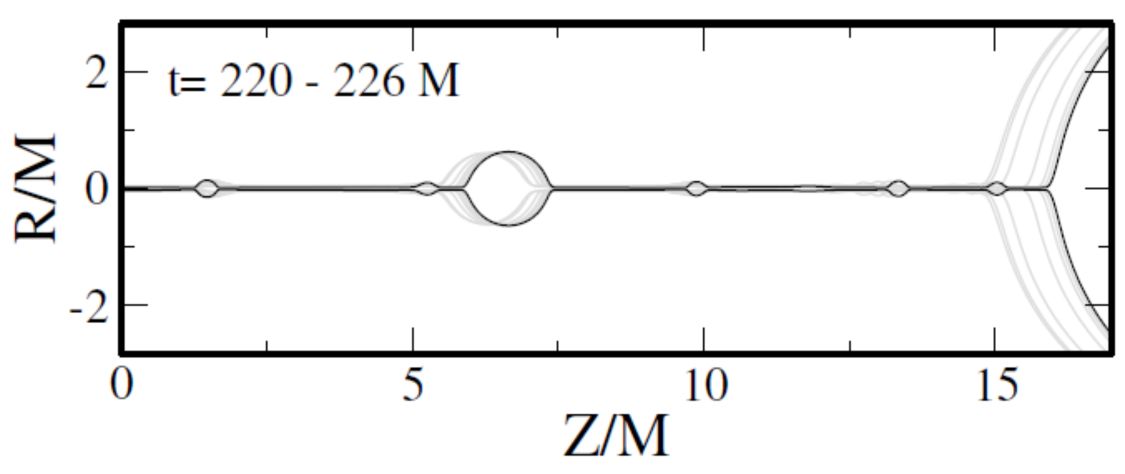
$$A_{BH}/A_{BS} = 1.374$$

The lowest resolution simulation, which has run the longest in physical time, has reached a value

$$A/A_0(t = t_{end}) \approx 1.369 \pm 0.005$$

- This is consistent with the argument that the dynamics of the instability is such as to saturate the entropy of the spacetime. "No mass is left behind"

Apparent Horizon Dynamics



- At late times the horizon certainly *looks* like it can be described as a sequence of spherical black holes connected by string segments; to quantify this a bit, we evaluate the following curvature invariants on the horizon:

$$I = R_{abcd}R^{abcd}; \;\; J = R_{abcd}R^{cdef}R_{ef}{}^{ab}$$

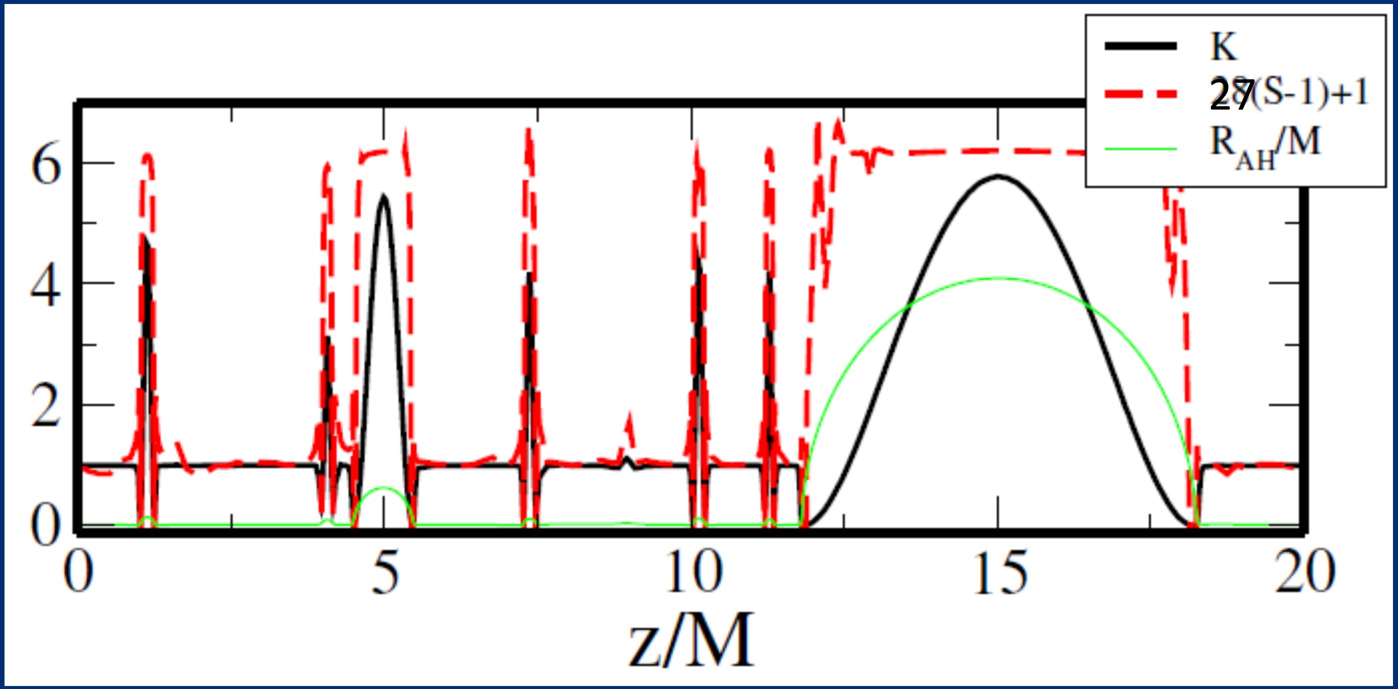
and construct the following dimensionless scalars

$$K = IR_{AH}^4/12; \;\; S = 12J^2I^{-3}$$

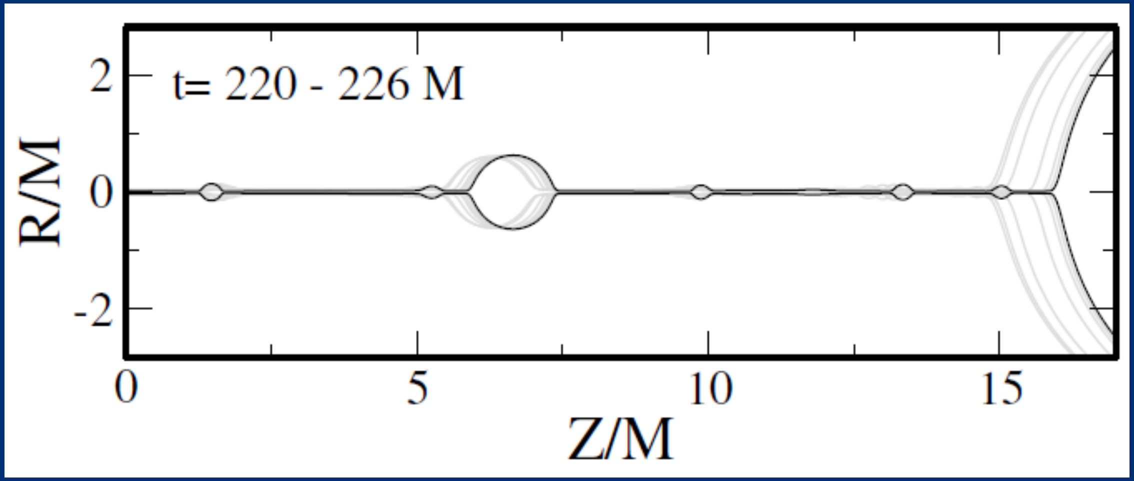
which evaluate to the following for the exact black sphere/black string solutions

$$K_{BH} = 6; \;\; 27(S_{BH} - 1) + 1 = 6 \qquad K_{BS} = 1; \;\; 27(S_{BS} - 1) + 1 = 1$$

Apparent Horizon Dynamics



Invariants above evaluated on the apparent horizon at the last time step of the (medium resolution) simulation depicted to right



Properties of satellites and string-segments

- Therefore, the spheres-connected-by-string-segments interpretation seems reasonable. With that interpretation, and that evolution proceeds through a sequence of unstable epochs, we extract the following properties from the horizon:

Gen.	t_i/M	n_s	$R_{s,i}/M$	$R_{AH,f}/M$	$L_{s,i}/R_{s,i}$
1	118.1 ± 0.5	1	2.00	$4.09 \pm 0.5\%$	10.0
2	203.1 ± 0.5	1	$0.148 \pm 1\%$	$0.63 \pm 2\%$	$105 \pm 1\%$
3	223 ± 2	> 1	$0.05 \pm 20\%$	$0.1 - 0.2$	$\approx 10^2$
4	≈ 227	$> 1(?)$	≈ 0.02	?	$\approx 10^2$

Gen: generation number

t_i: time of initial satellite formation (defined to be time when the areal radius has grown to 1.5 times that of the surrounding string-segment)

n_s: number of satellites that form

$R_{s,i}$: radius of local string segment

$R_{AH,f}$: radius of satellites by the time the simulation was stopped

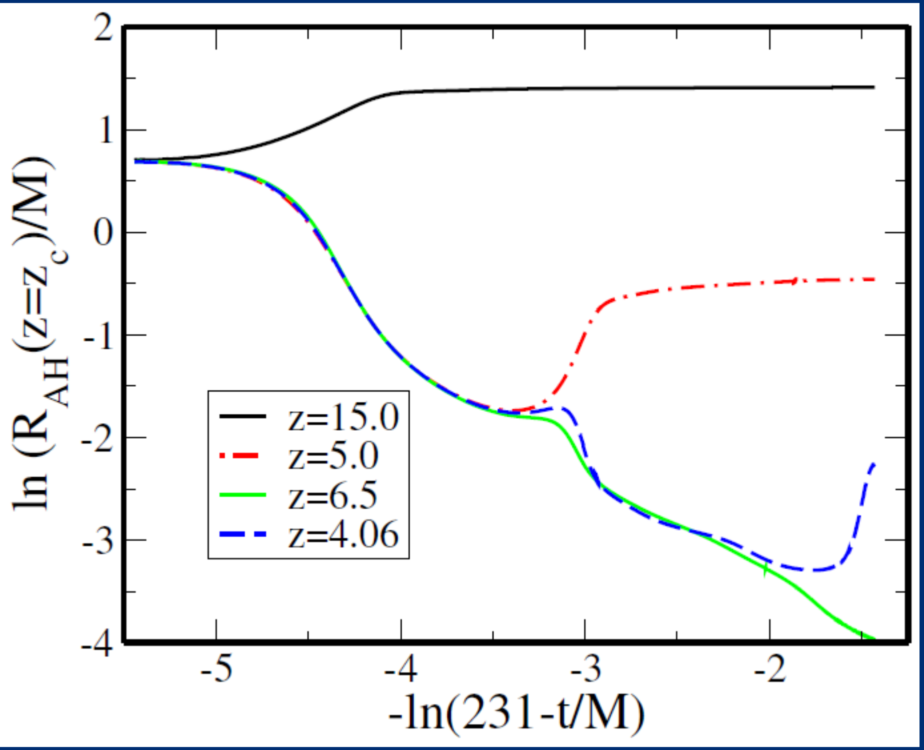
L_{si}/R_{si}: Ratio of length to radius of local string-segment (GL critical ratio ~ 7.2)

Properties of satellites and string-segments

- The dynamics of the apparent horizon also suggests that the instability unfolds in a self-similar manner; if so, transforming to logarithmic coordinates in space and time should reveal this more clearly
- The following shows $R_{AH}(t,w=const.)$ at points (roughly coinciding) with the eventual maxima of satellites, and one representative point that is still string-like near the end of the simulation
- Guess at "pinch-off time" by assuming the time scale for each later generation is a constant fraction X of the preceding one, with the exception of the first generation, whose time scale is controlled by the initial data:

$$\Delta T \sim T_0 + \sum_{i=0}^{\infty} T_1 X^i = T_0 + \frac{T_1}{1-X}$$

from the data in the table, we get $\Delta T \sim 231M$



Consequences/provocations…

- If Cosmic censorship valid: spacetime accessible to observers does not need QG. Otherwise, QG is required to provide the complete observable solution

  GL instability shows CS can be violated ‘generically’ in higher dims (note: many BHs show this instability. Eg. Myers-Perry BHs)

- For this case (and a number of others that can be mapped to it)
  - Naked singularity has 0 mass. Local spacetime would behave as a Hawking evaporating BH (unless higher curvature corrections kick in)
  - Fluid analogue: nothing drastic takes place at pinch off, 2nd solution (bubbles) proceed smoothly → nothing drastic expected in the spacetime
  - Thus, while formally QG is needed, in practical terms not so much → observer does not need to care about quantum gravity

Properties of satellites and string-segments

- In a fluid with tension, the shrinking neck region exhibits a scaling solution of the form *[Eggers, PRL 71 (1993); Miyamoto, JHEP 1010 (2010)]*

$$r \propto (t_0 - t)$$

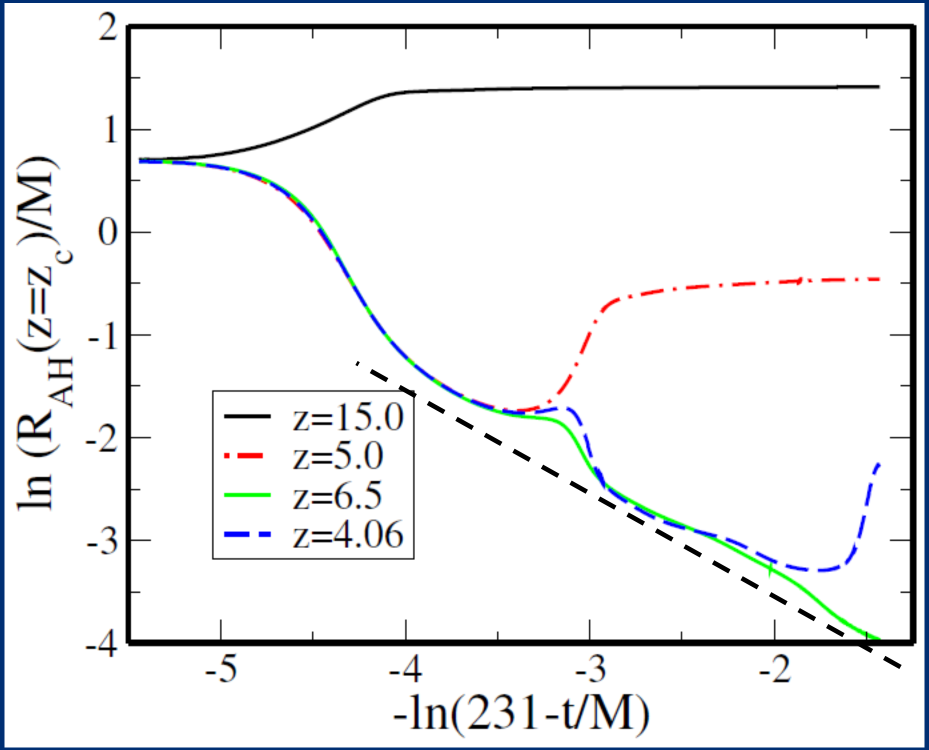
or in logarithmic coordinates

$$\frac{d \ln r}{d(-\ln(t_0 - t))} = -1$$

where t_0 is the pinch-off time

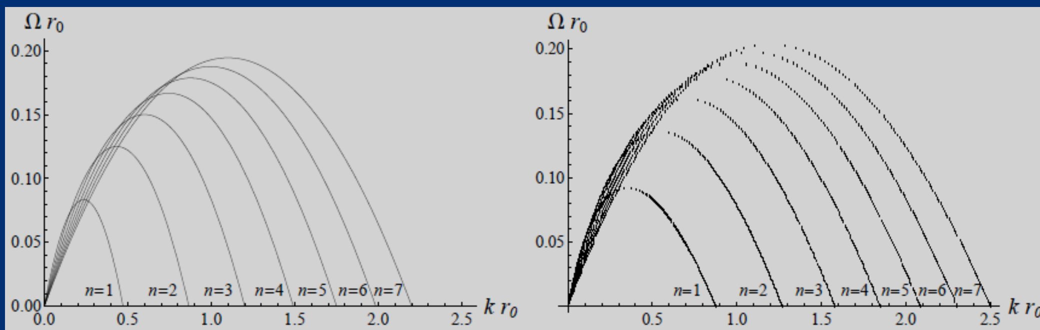
- The dashed line overlayed on the figure has slope ~-1
  - on average seems behavior of thinning string segment seems consistent with a self-similar pinch-off

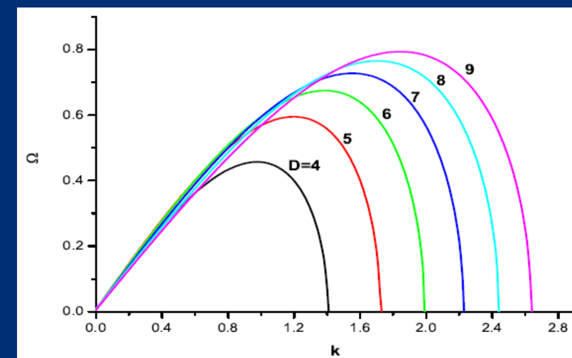
– *This is the good news…though…*



Not quite the same….

- Rayleigh-Plateau dispersion relation $\Omega \sim \lambda^{-1/2}$
- Gregory-Laflamme dispersion relation $\Omega \sim \lambda^{-1}$





- BUT, ‘cascade’ behavior is ‘mid-wavelength’ driven

- Curiously (i) → 2nd order expansion in λ, with ‘just’ intrinsic eqns, turns Ω around [Camps, Emparan]
- Curiously (ii) → 1st order expansion in λ , with both intrinsic and extrinsic equations turns around & looks a lot more like RP in derivation.

Final comments

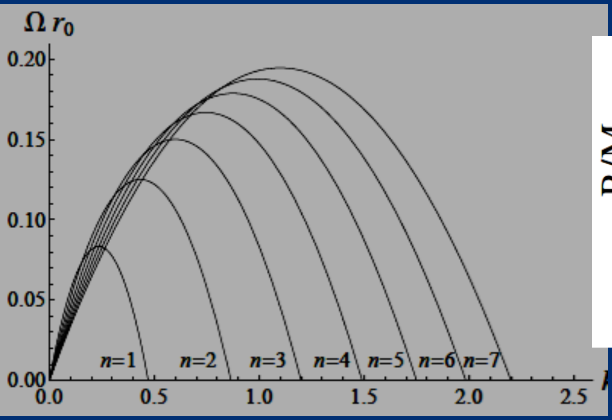
- As for final state: extrapolating from the first few generations, pinch-off will be reached in finite asymptotic time, at which time (classically) infinite geometric curvature will be revealed to the exterior universe

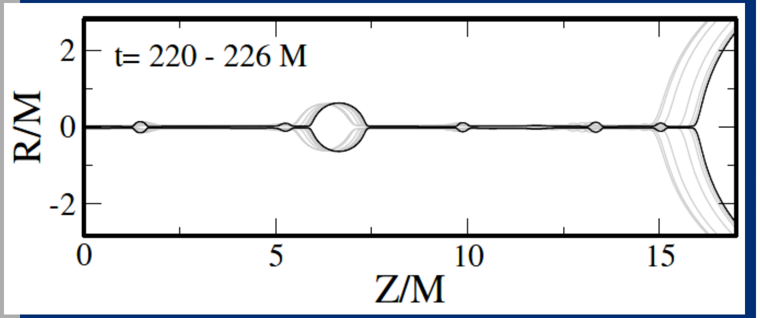
- this is then an example in 5D Einstein gravity (and also other dimensions where black holes exhibit similar instabilities) where generic violation of cosmic censorship occurs.

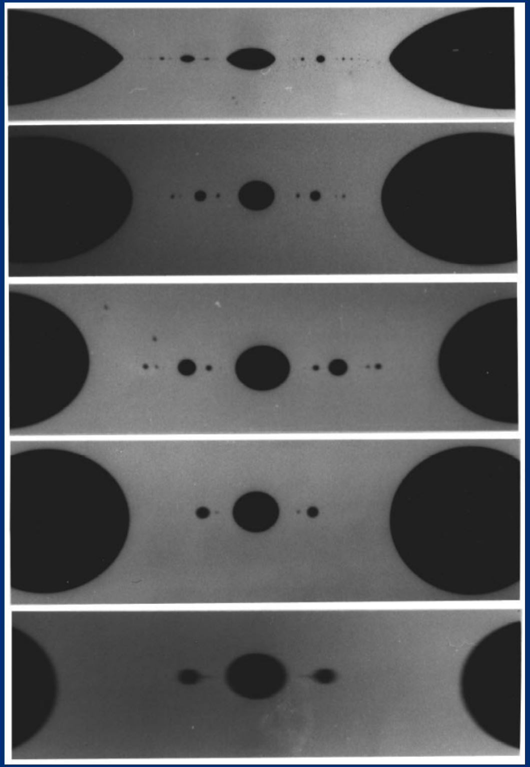
- As for full solution: the "true" end-state will thus require some theory of quantum gravity to extend spacetime beyond the pinch-off

- As for membrane connection: see how far the hydrodynamic analogy can be extended. Can further connections be uncovered/tested?

- Next steps: Understand behavior from:
  - a purely gravity point of view: Thinning/bulging behavior
  - a dynamical p.o.v : NOT a 'competition of modes'

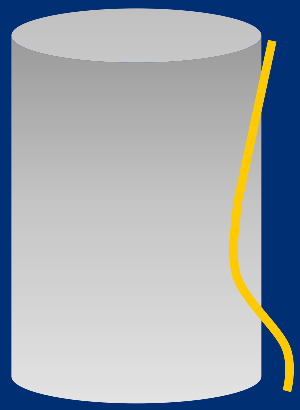






Fluid / black fold

- Rayleigh-Plateau instability:



- Fluid : Navier-Stokes + cont eqns
  $\delta u^i{}_{,t} = -1/\rho\ \delta p_{,i}$
  $\delta u^r{}_{,r} + \delta u^r/r + \delta u^z = 0$
- Interface: stress balance at interface:
  $p + dp = \sigma$ Div n

- "Membrane paradigm" (e.g. 'blackfolds' [Emparan,Harmark,Niarchos,Obers;Bhattacharyya,Hubeny,Minwalla,Rangami]
- Captures 'long-wavelength' dynamics of black branes in far zone $R>>r_o$
- Einstein Eqns: $D_a T^{ab}=0$; $T^{ab}K_{ab}{}^A = 0$
  $T_{ab} = (e+P)\ u_a\ u_b + P\ h_{ab}$
  $e \sim (n+1)\ r_o{}^n$; $P \sim -e/(n+1)$

Interestingly, extrinsic eqns:
$(e\ X_{,tt} + P\ X_{,ii}) = 0 \Rightarrow \sigma \sim 1/(n+1)$?

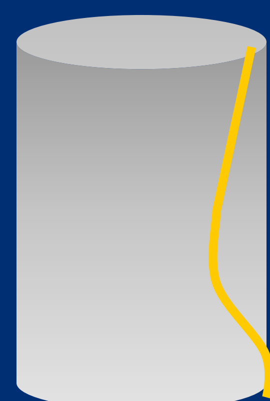
What in the world is the end-state of the instability?
Help from outside? Guidance from analogy

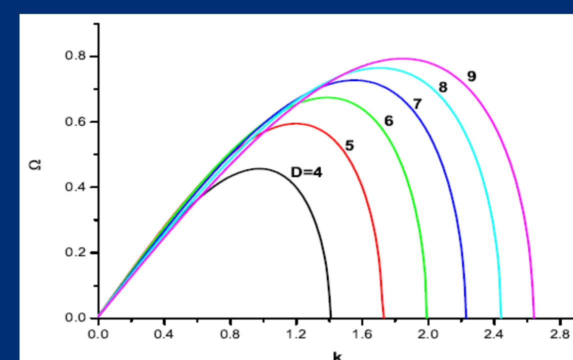
- Unstable fluid streams generically break up
  - For the Rayleigh-Plateau instability surface area is also the key explaining why one would expect a long-wavelength instability leading to pinch-off : above a critical length a sequence of spherical droplets has lower energy (due to surface tension) than a cylinder with the same volume/length

- Fluid : Navier-Stokes + cont eqns

  $\delta u^i{}_{,t} = -1/\rho \, \delta p_{,i}$

  $\delta u^r{}_{,r} + \delta u^r/r + \delta u^z = 0$





- Interface: stress balance at interface:

  $p + dp = \sigma \, \mathrm{Div} \, n$

[Cardoso,Dias 06]