Title: Non equilibrium thermodynamic of gravitational screens

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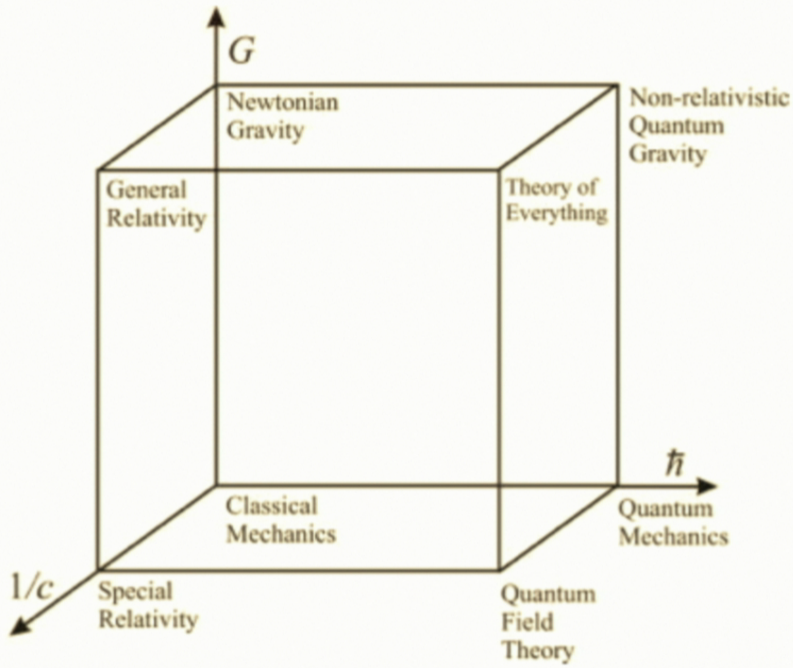
Abstract: In this talk I will review the evidence for a mysterious and deep relationship between gravitational dynamics and thermodynamics. I will show how we can extend this connection to non equilibrium thermodynamics. Using the fact that the gravitational equations are fundamentally holographic, we express them in a way that shows a deep connection between gravity and the dynamics of viscous bubbles. We will explore some aspects of this surprising correspondence.

Non eq Thermodynamics of gravitational screens

Laurent Freidel PI.
Perimeter 14

with Yuki Yokokura
arXiv:1312.1538, 1403...

Bronstein Cube



- What can be the relation between Quantum gravity and fluid mechanics? or non eq thermodynamic?

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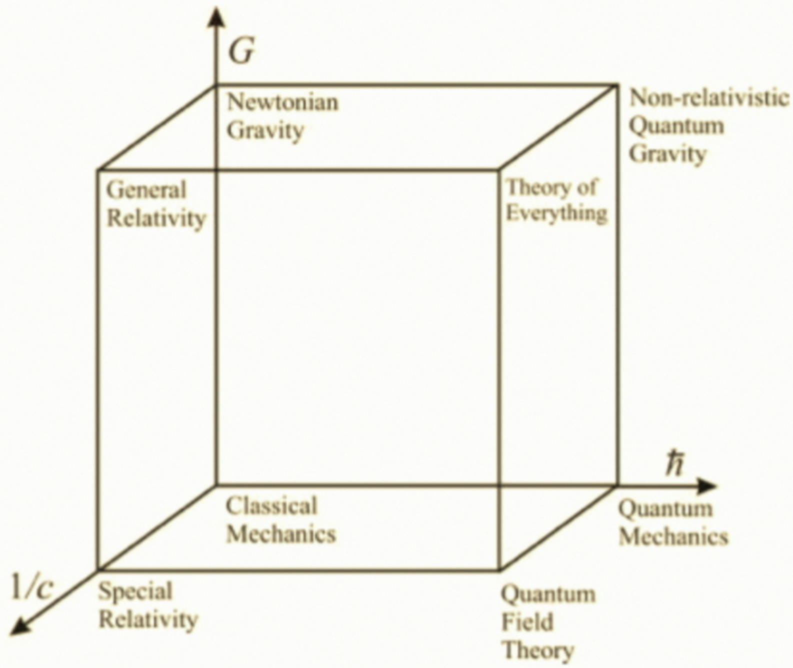

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Analogy Gravity-Thermodyamics

- There seems to be lots of evidence of a correspondence between Black Hole physics and eq. thermodynamic.
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- Is it just an analogy or is there a deeper correspondence?
- I want to give here evidence for a deeper correspondence that extend to non eq. thermodynamics ?

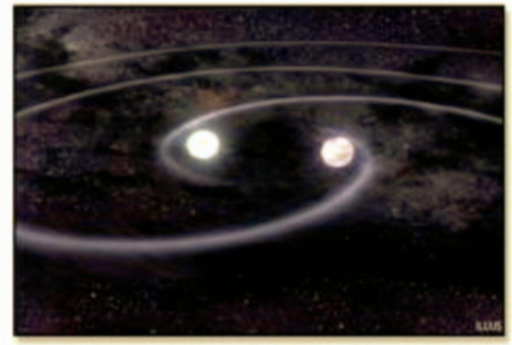
Such a correspondence can

- Provide a beautiful/holographic physical picture of gravity
- Gives a clue on quantum gravity constituents
- Allow to do gravity experiment in the lab

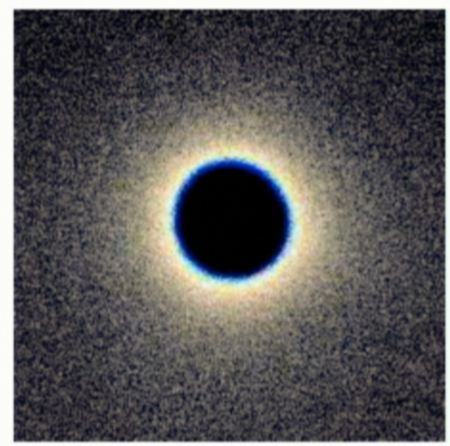
Black Hole primer

- collapsing phase: orbital decay
  gravitational radiation, merger
- A black hole horizon forms
- gravitational emission: ringing down
- settled in a static BH configuration
- BH have no hair: simple description, all information that fall in is forgotten classically

Analogous to equilibrium state

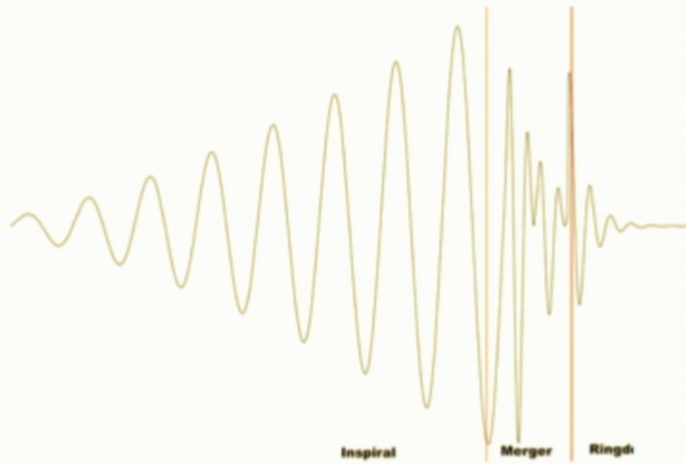


GSFC/D. Berry



Gravitational waves

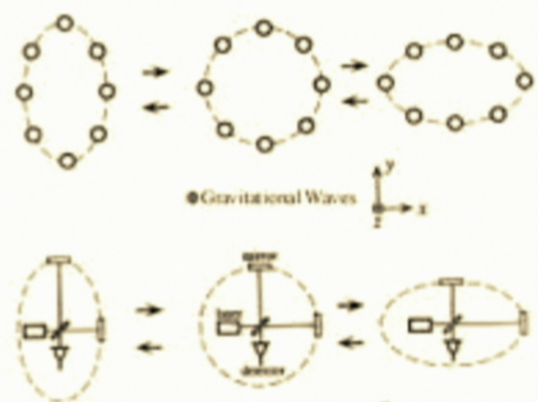
•Every perturbation of a Black hole finally settle down to a static spherically symmetric configuration.



inspiral, merger, ringdown

effect of gravity wave
on a ring of particle

shear: σ ellipse rate of change



Black Hole perturbation

- Every perturbation of a Black hole finally settles down to a static spherically symmetric configuration.

- Analogous to the statement that any non equilibrium system finally settle down to an equilibrium configuration

- Is the ringing down of BH the same as the process of relaxation to equilibrium?

- Can we understand the production of gravitational wave as entropy production mechanism?

- Can we understand this process quasi locally?

Thermostatic Laws of Black Hole

A neutral BH is characterised by its Mass, Angular momenta and its Area (M, J, A)

- BH are at equilibrium: Temperature = cste

- First law $$dM = \frac{\kappa}{2\pi}\frac{dA}{4G} + \Omega dJ$$

- Second Law $$\frac{dA}{dt} > 0$$

- If we identify Entropy = $\dfrac{A}{4G\hbar}$

Bardeen, Carter, Hawking

- Temperature = $\dfrac{\hbar\kappa}{2\pi}$ ← surface acceleration

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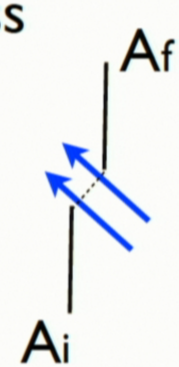
First Law

$$dM = \frac{\kappa}{2\pi}\frac{dA}{4G} + \Omega dJ$$

Bekenstein

Initial derivation: compare 2 different space-times
with different values of mass, angular momenta, charge

Physical derivation as a process:
Compare 2 different state of the BH at different time and
see how the mass changes under a process
that do not produce gravitational waves.



Carter, Jacobson, Sorkin, ...

Generalised Second Law

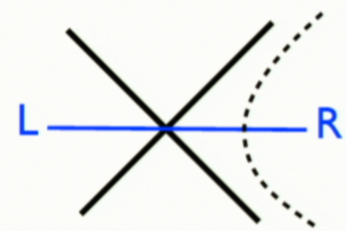
The total entropy of matter outside black hole plus the sum of black areas never decrease.

$$\delta S_{matter} + \frac{\delta A}{4G} \geq 0$$

Bekenstein,...

At the quantum level a Black hole radiate at a temperature proportional to its radial acceleration. Similarly an accelerated observer experience a thermal flux prop to its acceleration

Hawking, Unruh



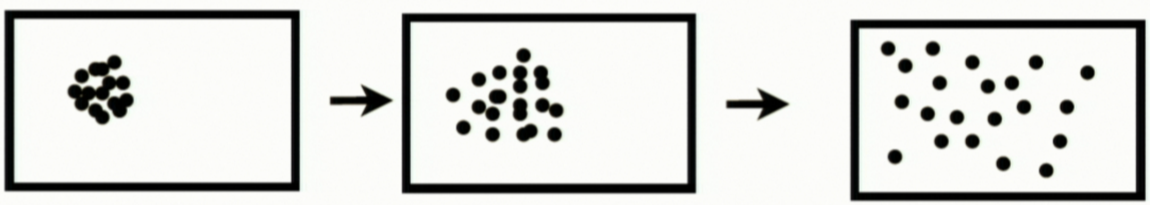
Due to vaccua entanglement

Going out of equilibrium

•Out of equilibrium= Entropy production
Can we understand gravitational evolution as entropy production happening in a physical system?

•What is the entropy of gravitational system?
A for BH but in general?

Time evolution of non gravitational system



low entropy high entropy

WMAP, Planck satellite puzzle: Early universe
= Perfect Black body

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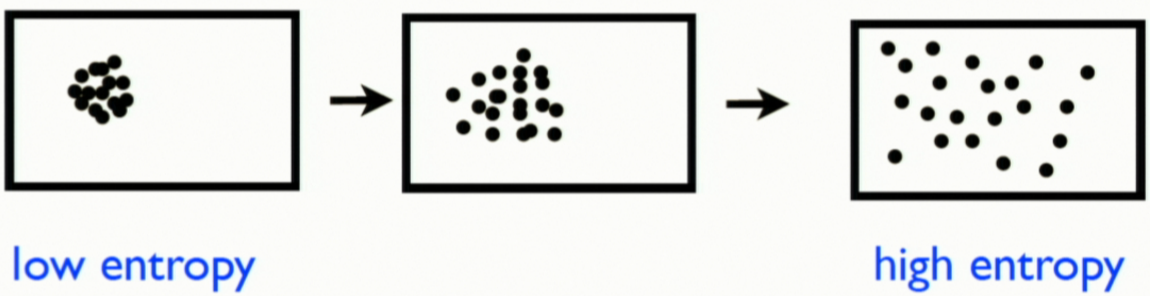

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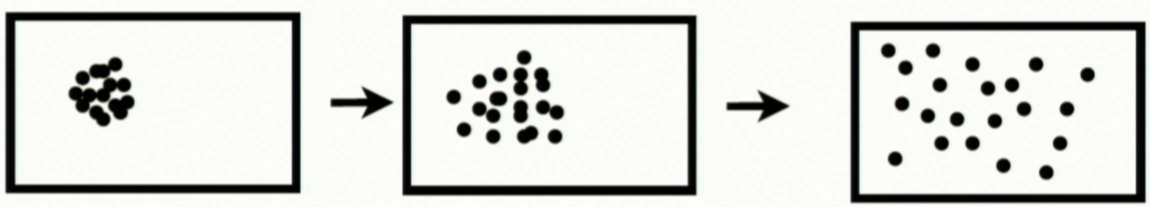

low entropy   high entropy

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Going out of equilibrium

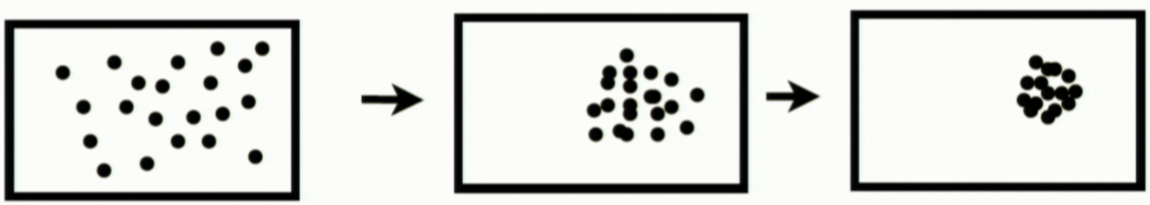
- Is A really an entropy?
- Out of equilibrium= Entropy production

can we understand this process happening in a physical system?

- What is the entropy of gravitational system?

Time evolution of gravitational system

Penrose

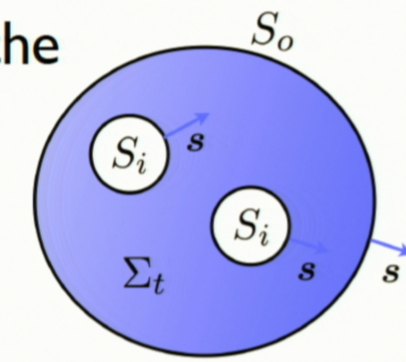


low gravitational waves

high gravitational waves

The set up

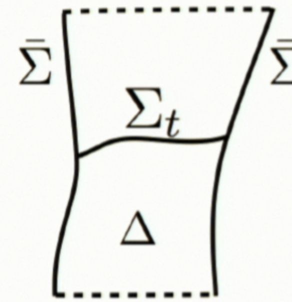
• We want to provide a quasi-local description of gravitational physics without refereeing to the end of time or space



• We chose a domain, the boundary of this domain is the screen.

chose a notion of time : a foliation.
And a preferred field of Eulerian observers.

Time flow $\boldsymbol{t} = t^\mu \partial_\mu$ foliation normal to T=cste



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screen= generalised observer

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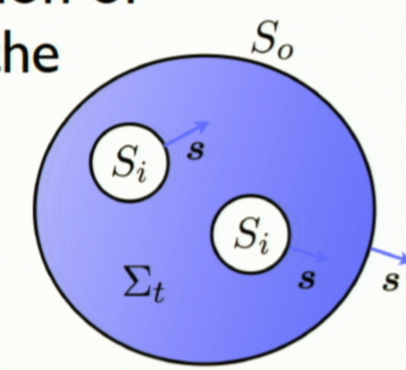

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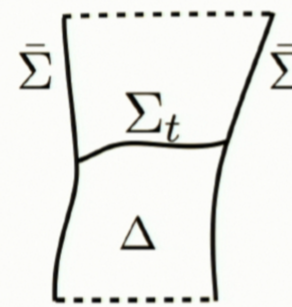

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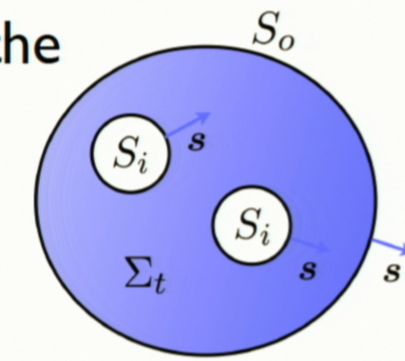

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Punch-Line:

• The gravitational dynamics of the region inside the screen is entirely encoded in its 2d boundary.
It is equivalent to the non equilibrium dynamics of a 2d, viscous bubble, in the presence of newtonian gravity.

Damour, Price, Thorne,... Membrane paradigm

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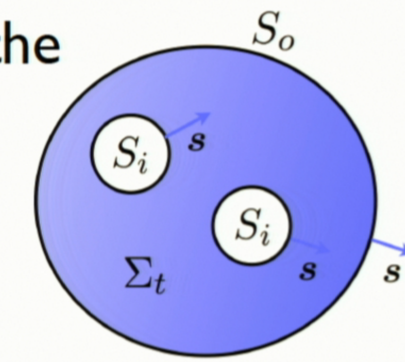

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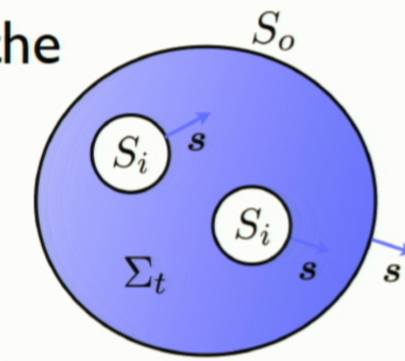

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- The gravitational dynamics of the region inside the screen is entirely encoded in its 2d boundary.
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- This correspondence relies on the fact that a gravitational screen possess a surface tension σ and an internal energy ϵ

Gravity is Holographic

- One of the key element of theory of gravity is the principle of equivalence
- We can always locally eliminate the gravitational field.
- Let compute the total (gravitational + matter) energy of a gravitational system in a region R (canonical energy)

$\partial R = S$

In a usual physical system

$$H = H_R + H_S$$

H_R: Bulk

H_S: Boundary

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Usual notion of energy is valid only if we can neglect the gravitational contribution

Gravity is impossible to screen.

Idea: matter energy = Work ; Gravitational energy = heat

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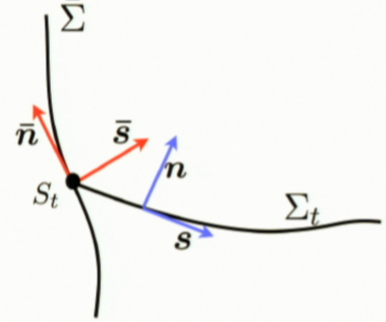
because time is immaterial in gravity

- The total energy of the system contained inside the screen is given by a boundary term given by a mass term characterised by a surface acceleration σ_t and an angular momenta

$$H_t = M_t + \varphi \cdot \boldsymbol{J}$$



Mass $$M_t \equiv \int_S \sqrt{q}\sigma_{\hat{t}}$$

Surface tension σ_t: average of the radial acceleration of the screen compared to Eulerian and freely falling observers.

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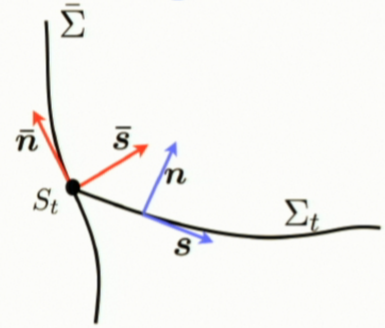

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Surface Tension

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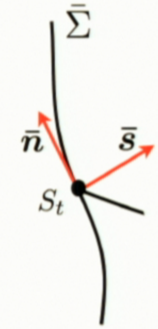
Agree with
Komar mass if Killing,
ADM mass if infinity,
Bondi energy if null infty,
Newtonian mass in the limit.

surface tension= total radial acceleration

$$\sigma_{\boldsymbol{t}} = \frac{1}{8\pi G}\left(\boldsymbol{a}_{\bar{\boldsymbol{s}}}^{Screen} + \boldsymbol{a}_{\bar{\boldsymbol{s}}}^{Static}\right)$$

it slides and boosts



$\sigma > 0$ outer screen

~ Newton Gauss law $a_r^{Newton} = \frac{GM}{r^2}$

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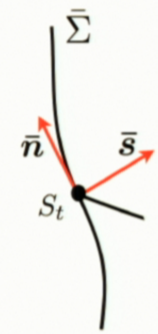

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ThermoStatic?

$$M_{\boldsymbol{t}} \equiv \int_S \sqrt{q}\,\sigma_{\hat{\boldsymbol{t}}}$$

- What does it means Physically for the screen to possess a surface tension?

- What about internal energy?

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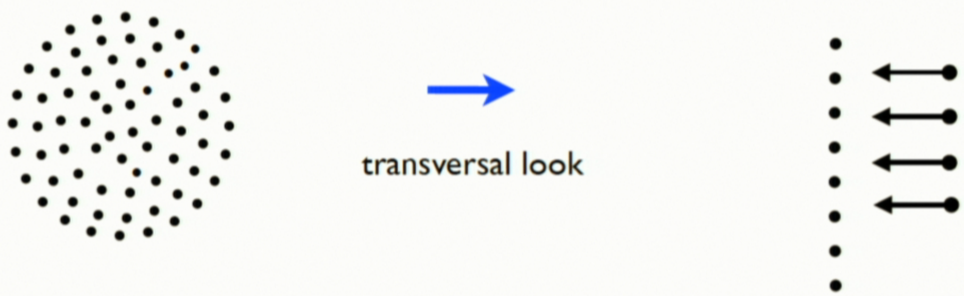
Simplest expression of Einstein Equation

Can we express Einstein equation in plain english without any complicated geometrical notion? J. Baez, L.F

- By the equivalence principle we can define the notion of a freely falling frame where locally no gravity is felt

1-Consider an array of freeling falling test particles initially at rest in this frame forming a small area:

2-Send some energy through it



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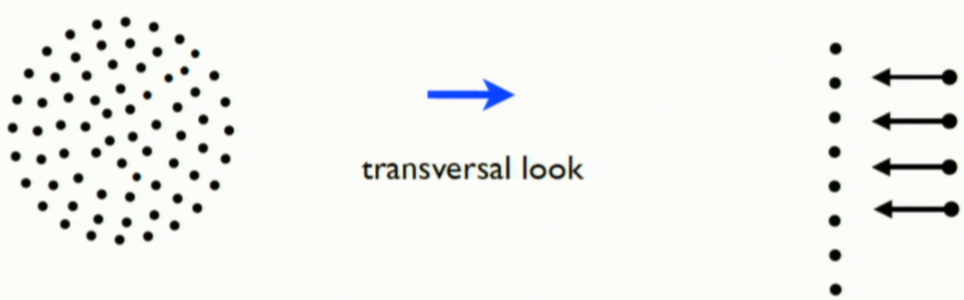
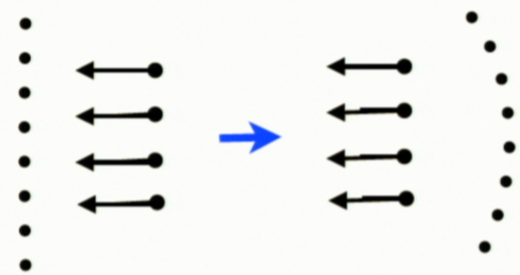


“Everything is linear to first order”

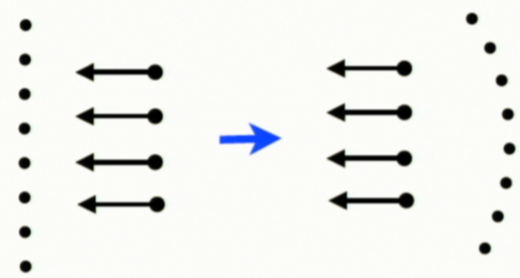


at first order the change of shape is a change in curvature of the curve $1/R$

another orthogonal transversal look $1/R'$

By isotropy the change of shape of the area is characterised by the curvature $\theta = 1/R + 1/R'$

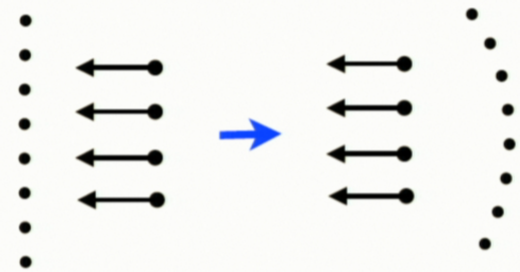
Einstein Equation in plain english



The rate of change of curvature is proportional to the flow of transverse momenta, with the same negative proportionality coefficient for all inertial observers.

gravity is attractive

Einstein Equation in plain english



Rate of change of curvature = $-8\pi G$ flow of transverse momenta

gravity is attractive

$$\leftrightarrow \qquad \partial_t \theta = -(8\pi G)\int_S T_{rt}$$

$$\leftrightarrow \qquad G_{ab} = 8\pi G T_{ab} + \Lambda g_{ab}$$

for all screens

Einstein eq. is equ. to energy conservation $\quad \delta\epsilon = \delta E_{matter}$ internal energy

$$\epsilon = -\frac{\theta_r}{8\pi G}$$

Dynamics

- The system is characterised by its boundary density of M, J, A

$\partial R = S$

- The dynamics is characterized by the evolution of Mass, angular momenta, and Hawking entropy production

$$\dot{S}_H \equiv \int_S \sqrt{q}\theta_t = \dot{A}$$

θ_t expansion along t

- In general M, J, A are not conserved due to matter and gravity wave flowing out of the screen.

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Dynamics

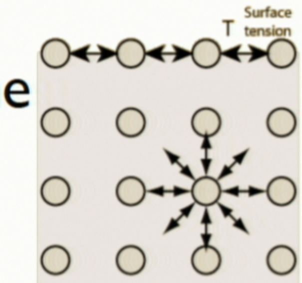
• The non conservation of M,J,A can be written entirely from a 2d perspective !

• It is equivalent to the non equilibrium dynamics of a 2d, viscous bubble, in the presence newtonian gravity.

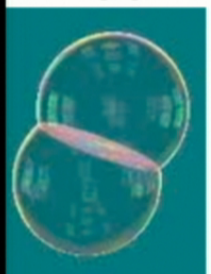
What are the equations characterizing this physics?

Surface tension

Surface tension is due to the polarisability of the constituents.



σ is the energy that needs to be supplied to increase the area by one unit



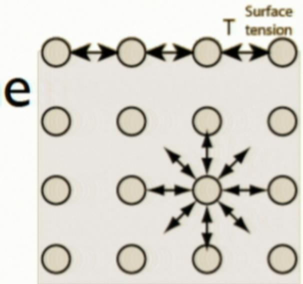
$$\delta W = \sigma \delta A$$

It acts as a negative 2d pressure $\sigma = -p_{2d}$

It is responsible for the physics of drops, droplets, bubbles, foams, evaporation, wetting phenomena and capillarity adhesion...

P. G. de Gennes,...

Surface tension



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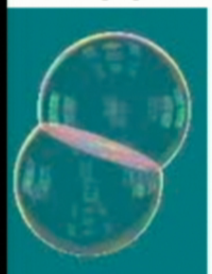

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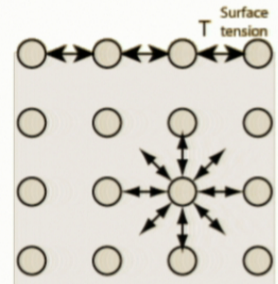
Young Laplace equation



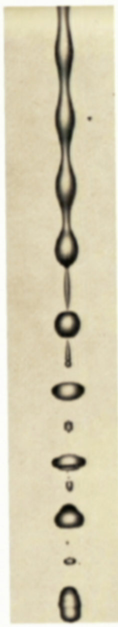
static

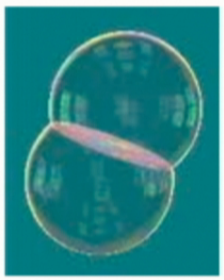
$$\boxed{\sigma\theta_r = -\Delta P}$$

surface tension

$$\Delta P = (P_{out} - P_{in})$$

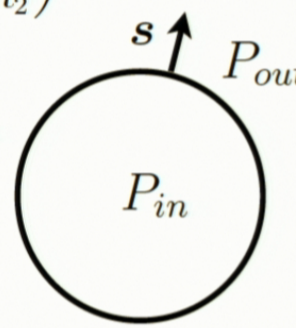
Curvature $\theta_r = \nabla_a s^a = \left(\frac{1}{R_1} + \frac{1}{R_2}\right)$

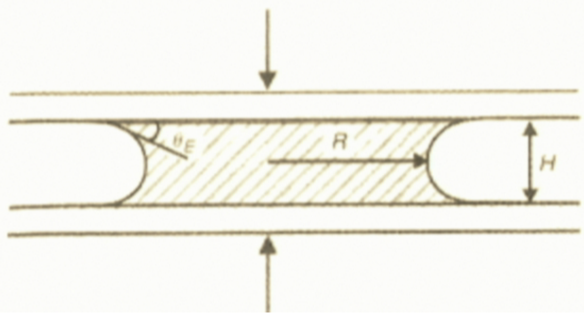




over pressure inside bubbles

$$\theta_r > 0$$



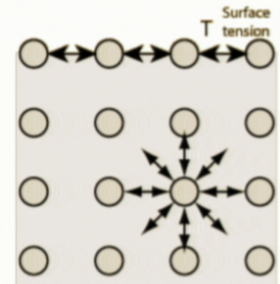


$$\theta_r < 0$$

Capillary adhesion

Plateau-Rayleigh instability

Young Laplace equation

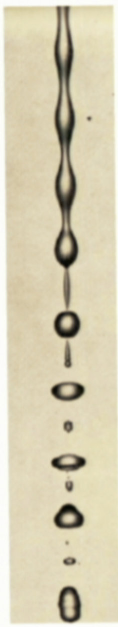


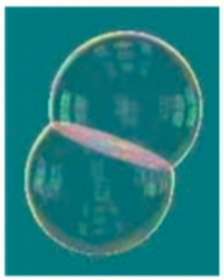
static $\boxed{\sigma\theta_r = -\Delta P}$

surface tension

$$\Delta P = (P_{out} - P_{in})$$

Curvature $\theta_r = \nabla_a s^a = \left(\frac{1}{R_1} + \frac{1}{R_2}\right)$





over pressure inside bubbles

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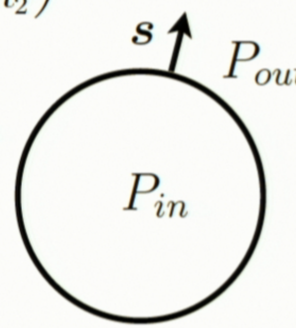

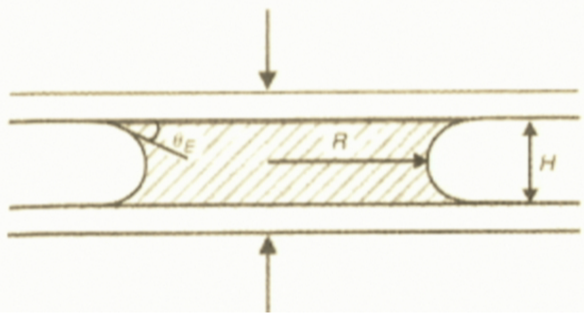

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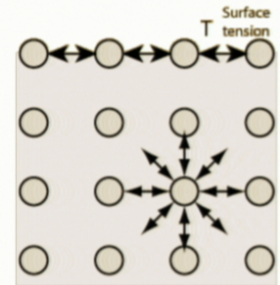

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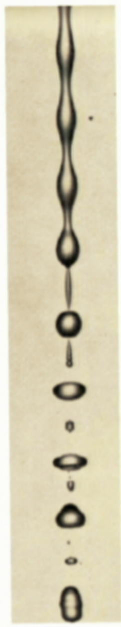

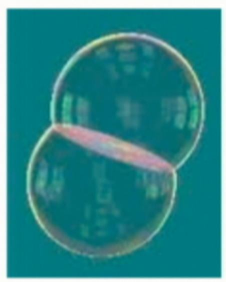

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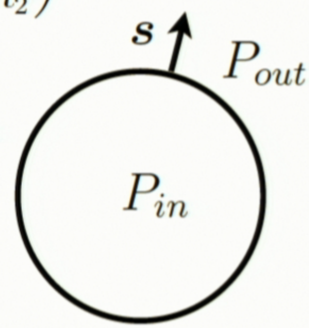

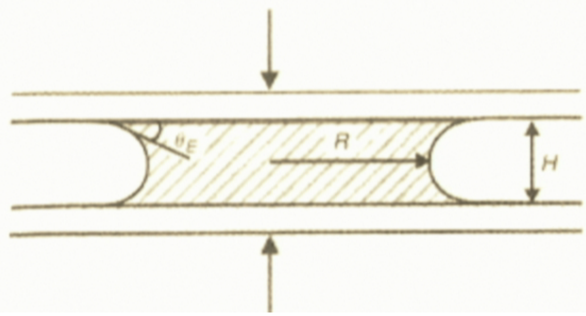

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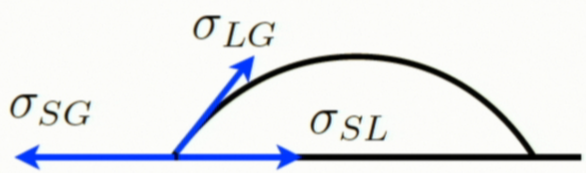
Wetting

A liquid spread if it is less polarisable than the solid

Total wetting

$$S = \sigma_{SG} - (\sigma_{SL} + \sigma_{LG}) > 0$$

partial wetting

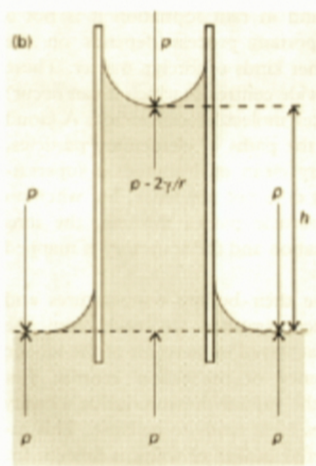


$$\boxed{\sigma_{LG} \cos\theta = \sigma_{SG} - \sigma_{SL}}$$

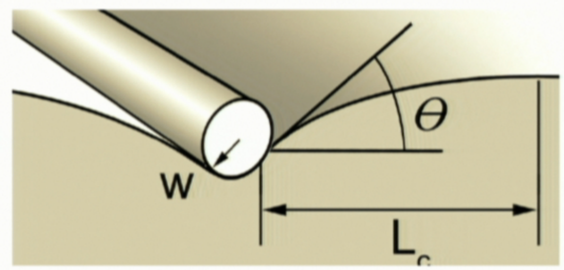
Young-Dupre

capillary rise

$$h = \frac{2\sigma}{\rho R g}$$



Floating rod



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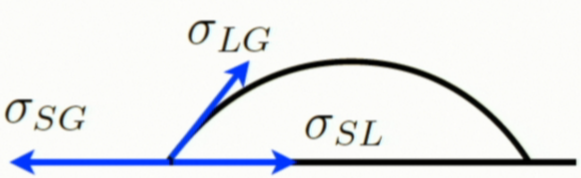

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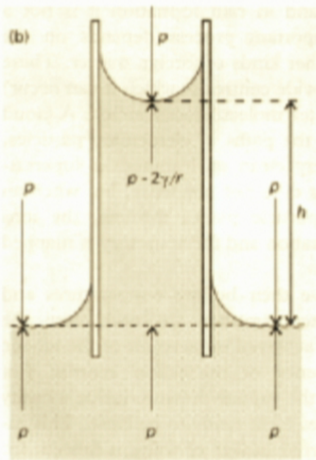

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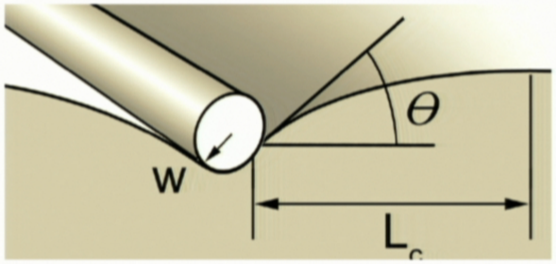
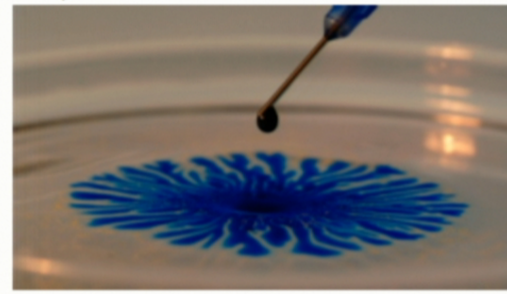


Marangoni Flow

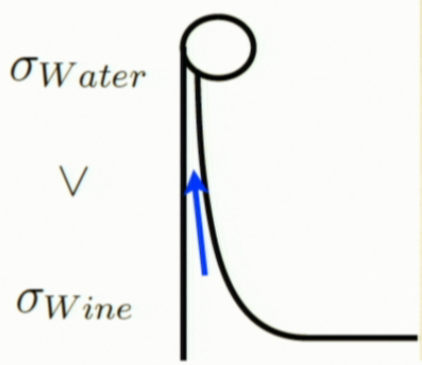
A gradient of surface tension drive a flow in the interface toward High tension. $p = -\sigma$

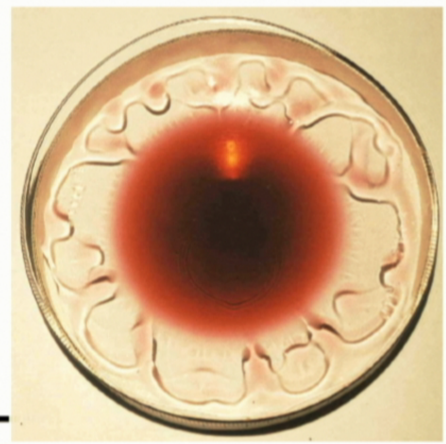
created by heat, surfactant, concentration,

$$\dot{\pi} = \nabla\sigma + f_a$$

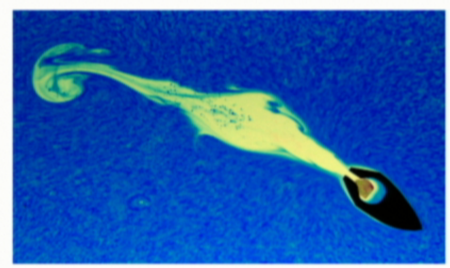


Tears of wine





Soap boat



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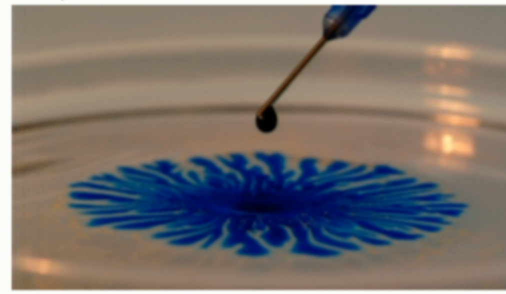

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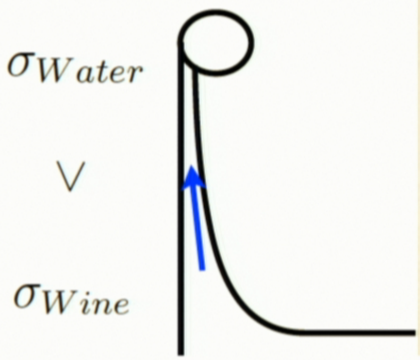

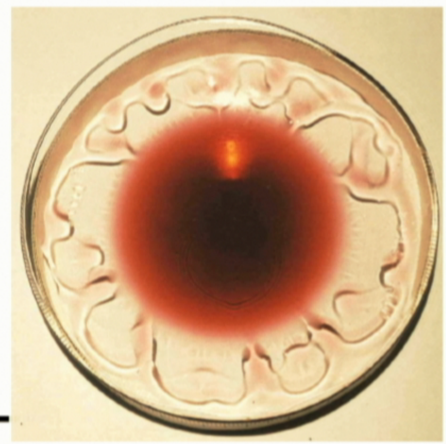

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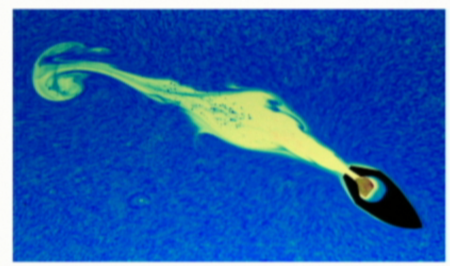

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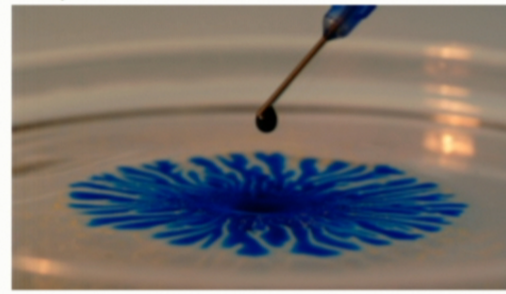

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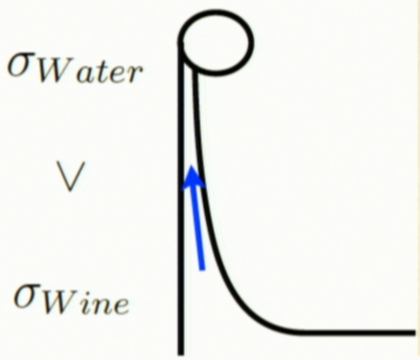

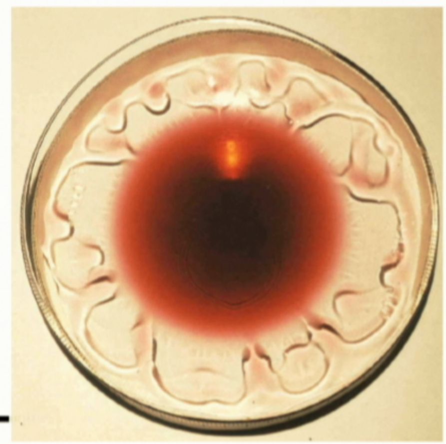

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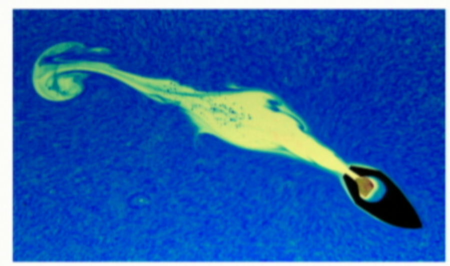
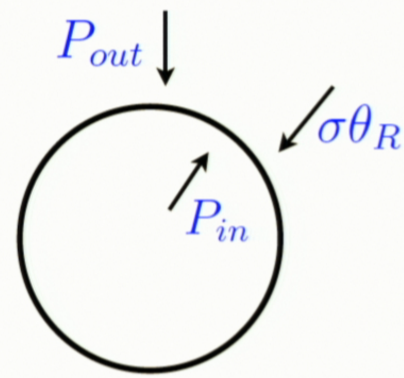


Rayleigh-Plesset eq

This is the equation that dominates the physics of cavitation and boiling: nucleation and expansion of bubbles

$$\rho(R\ddot{R} + \frac{3}{2}\dot{R}^2) = -(\sigma\theta_R + P_{out} - P_{in})$$



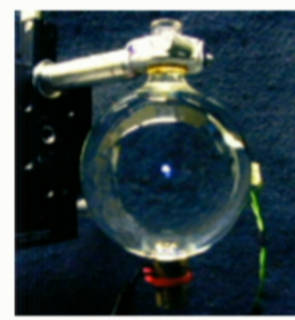
vapor gaz

$$P_{in} = P_V + \frac{P_0}{R^3}$$

Cavitation: nucleation in a liquid when the pressure falls below the vapor pressure

Bubble chamber

sonoluminescence:
Smallest Black body
10^4 K, 0.1micron



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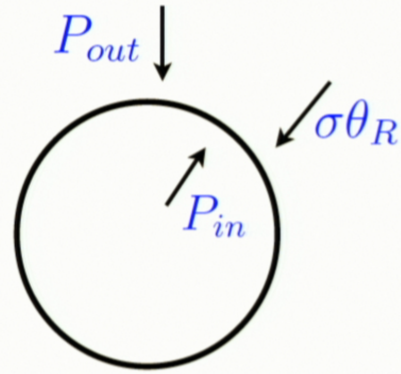

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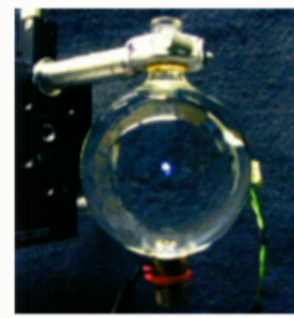

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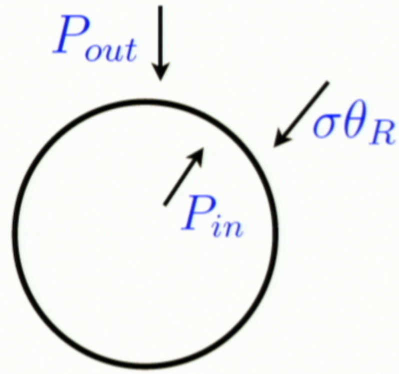

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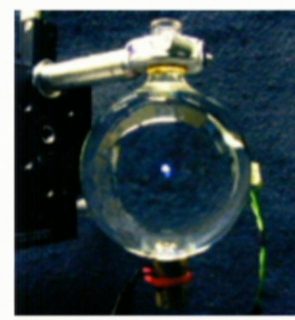

Viscous flow

When the fluid is a general viscous fluid the bulk entropy production rate do not vanish

A general fluid is characterised by:

its viscous stress tensor Θ_{AB} force

its rate of strain tensor $\Delta_{AB} \equiv \partial_{(A} v_{B)}$ flux

For a one component fluid in a closed box the entropy production rate is given by Flux x Force

$\beta = 1/T$

$$\boxed{T\dot{s} = \boldsymbol{\Delta} : \boldsymbol{\Theta} + \boldsymbol{q} \cdot \mathbf{d}\beta} \quad > 0 \quad = \text{2nd Law}$$

The nature of the fluid is encoded in the constituent equation: $\Theta(\Delta, \dot{\Delta}, \ddot{\Delta}, \cdots)$

Newtonian fluid = Hydrodynamics $\boldsymbol{\Theta} = \nu\Delta + \xi\delta$

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Dynamics

- The non conservation of M,J,A can be written entirely from a 2d perspective !
- It is equivalent to the non equilibrium dynamics of a 2d, viscous bubble, in the presence newtonian gravity.

$\dot{J}_t \rightarrow$ Cauchy equation: Conservation of momenta

$$\boxed{\frac{\mathrm{d}\boldsymbol{\pi}}{\mathrm{d}t} + \delta\boldsymbol{\pi} = -\boldsymbol{\nabla}p + \boldsymbol{\partial}\cdot\boldsymbol{\Theta} + \boldsymbol{f}}$$

momenta | comp factor | surf tension = neg pressure | viscous stress | external force

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$\dot{J}_t$ → Cauchy equation: Conservation of momenta

$\dot{M}_t$ → First law: Conservation of energy

$\dot{S}_H$ → Dynamical Young-Laplace equation

These equations are equivalent to the gravity equations on the screen:

$$G_{sA} = 8\pi G T_{sA}, \quad G_{sn} = 8\pi G T_{sn}, \quad G_{ss} = 8\pi G T_{ss}.$$

First Law and Gravity

Within our correspondence we can write the first law of thermodynamics for a general screen as follows

$$\boxed{\delta U = \sigma \delta A + T \delta S + \delta E_{\text{Mat}} + \delta E_{\text{Newt}}}$$

$8\pi G = 1$

Internal energy: $U \equiv -\int_S \sqrt{q}\theta_r$

$\epsilon = -\theta_r$

2d pressure,
-surf. tension: $\sigma = a_r$

$\delta E = \int_{t_0}^{t_1} \dot{E} \mathrm{d}t$

Matter flow: $\dot{E}_{\text{Mat}} = \int_S \sqrt{q} T_{\boldsymbol{rt}}$

Newton flow: $\dot{E}_{\text{Newt}} = \int_S \sqrt{q} \epsilon \dot{\phi}$

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Rate of Strain $\boldsymbol{\Delta} = \boldsymbol{\Theta_t}$ Stress $\boldsymbol{\Theta} = \boldsymbol{q}\theta_r - \boldsymbol{\Theta_r}$

Force = flow in radial direction!

Fluid entropy production = gravitational waves!

Thermo		⟷	Gravity	
p	internal pressure	⟷	radial acceleration	$\sigma_{\boldsymbol{t}}$
ΔP	External pressure	⟷	radial pressure	$T_{\boldsymbol{ss}}$
ϵ	internal energy	⟷	radial expansion	$-\theta_{\boldsymbol{s}}$
$\dot{E}$	Ext entropy rate	⟷	momenta flux	$T_{\boldsymbol{ns}}$
	Rate of strain $\Sigma_{AB} = \partial_A v_B$	⟷	temporal extrinsic curv $\Theta_{\boldsymbol{n}AB} = \nabla_A n_B$	
Δ_{AB}	viscous stress	⟷	radial extrinsic curv $\widehat{\Theta}_{\boldsymbol{s}AB} = \nabla_A s_B - q_{AB}\theta_{\boldsymbol{s}}$	
π_A	momenta	⟷	normal form	$\boldsymbol{s}\cdot\nabla_A \boldsymbol{n}$
	velocity	...		

Summary

• We have seen that due to its holographic nature gravity in a box can be equivalently described in terms of its boundary: the screen

• A screen possess a surface tension and an internal energy

• From the screen point of view Einstein laws are rephrased as fundamental laws of thermodynamic plus a fundamental law of evolution for the Hawking entropy rate

• The evolution for the hawking entropy rate is a bulk equation that can equation can also be interpreted as a Dynamical Young-Laplace equation for the screen in space.

Conclusion

- This brings new lights on the nature of gravity, a new point of view on non equilibrium physics and new questions:

- We have two different notion of entropy: Hawking and the viscous fluid, they agree near equilibrium (no grav wave) but are they the same in non eq regime?

- Is there a principle in thermo that determine the evolution of entropy production rate? e.g max entropy rate principle

- A change of screen is a change of constitutive law. Can we model realistic system with a gravity screen?

- Clues about quantum gravity? Dissipation = Fluctuation

- Is it useful? Ringing down of Black hole

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