

Title: Emergent spacetimes

Date: Nov 06, 2008 02:00 PM

URL: <http://pirsa.org/08110042>

Abstract: We discuss the possibility that spacetime geometry may be an emergent phenomenon. This idea has been motivated by the Analogue Gravity programme. An '\(e\)'ffective gravitational field' dominates the kinematics of small perturbations in an Analogue Model. In these models there is no obvious connection between the '\(g\)'ravitational' field tensor and the Einstein equations, as the emergent spacetime geometry arises as a consequence of linearising around some classical field. After a brief introduction on this topic, we present our recent contributions to the field.

PI-2008



New



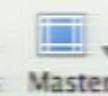
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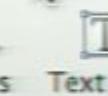
View



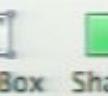
Themes



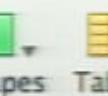
Masters



Text Box



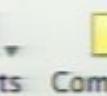
Shapes



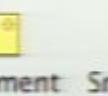
Table



Charts



Comment



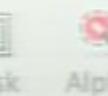
Smart Builds



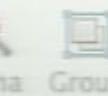
Mask



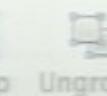
Alpha



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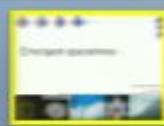


Ungroup



Format

Slides



1



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Emergent spacetimes

By Silke Weinfurter
and collaborators:

Matt Visser, Stefano Liberati, Piyush Jain, Angiea White, Crispin Gardiner and Bill Unruh



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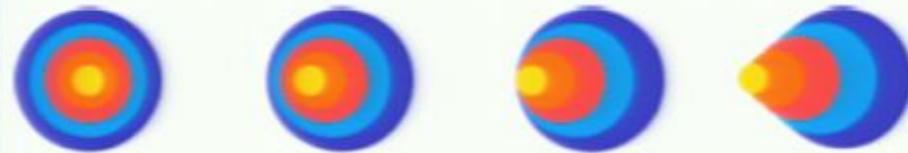


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Spacetime geometry and general relativity



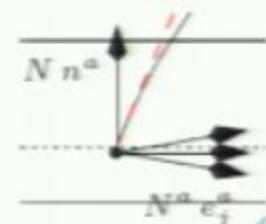
A world full of effective spacetimes



Concept of emergence



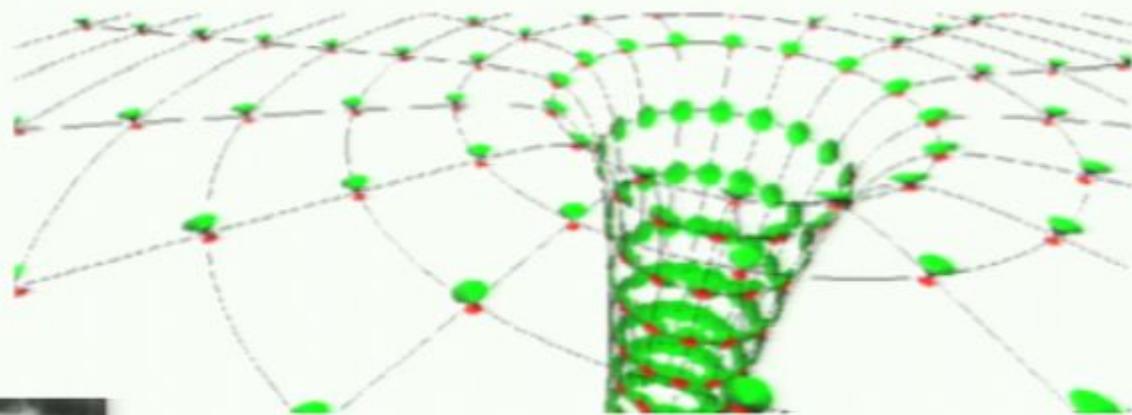
Emergent spacetimes bearing gifts:



....



From emergent spacetimes to emergent gravity...?



Spacetime geometry and general relativity



Spacetime geometry

Einstein: Gravity a consequence of spacetime geometry!

space (**d**) + time (**1**) \hookrightarrow spacetime (**d+1**)

Geometry of spacetime:

$$g_{ab} = g_{ab}(t, \mathbf{r})$$

$$g_{ab} = \begin{bmatrix} g_{00} & g_{01} & g_{02} & g_{03} \\ g_{01} & g_{11} & g_{12} & g_{13} \\ g_{02} & g_{12} & g_{22} & g_{23} \\ g_{03} & g_{13} & g_{23} & g_{33} \end{bmatrix}$$

($n+1$)/2 independent components (without dynamical equations)

In general relativity *free particles* are *freely falling* particles - no external force but remain under the influence of the spacetime geometry. The kinematical equations of motion for free test particles following geodesics:

$$s_{AB} = \int_A^B ds = \int_A^B [-g_{ab} dx^a dx^b]^{1/2}$$

Einstein field equations

$$G_{ab} = 8\pi G_N T_{ab}$$

General relativity also identifies (in a coordinate covariant manner) density and flux of energy and momentum in the n dimensional spacetime as the source of the gravitational field g_{ab} :

Einstein tensor: $G_{ab} = R_{ab} - \frac{1}{2}R g_{ab}$

Tress-energy tensor: $T^{ab} = \begin{bmatrix} \text{energy density} & \text{energy fluxes} \\ \hline \text{momentum densities} & \text{stress tensor} \end{bmatrix}$

Spacetime and gravity

Einstein
dynamics:

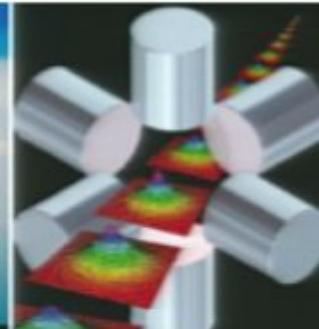
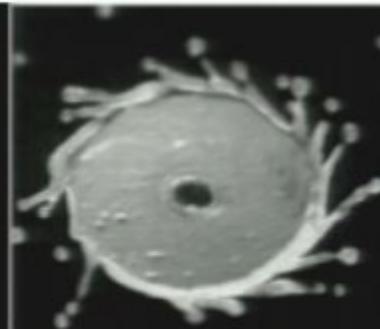
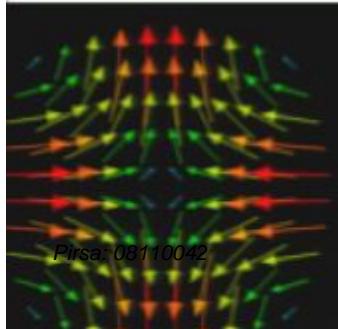
$$G_{ab} = 8\pi G_N T_{ab}$$



Broad class of systems with ***completely*** different dynamics:
electromagnetic waveguide, fluids, ultra-cold gas of Bosons and Fermions;



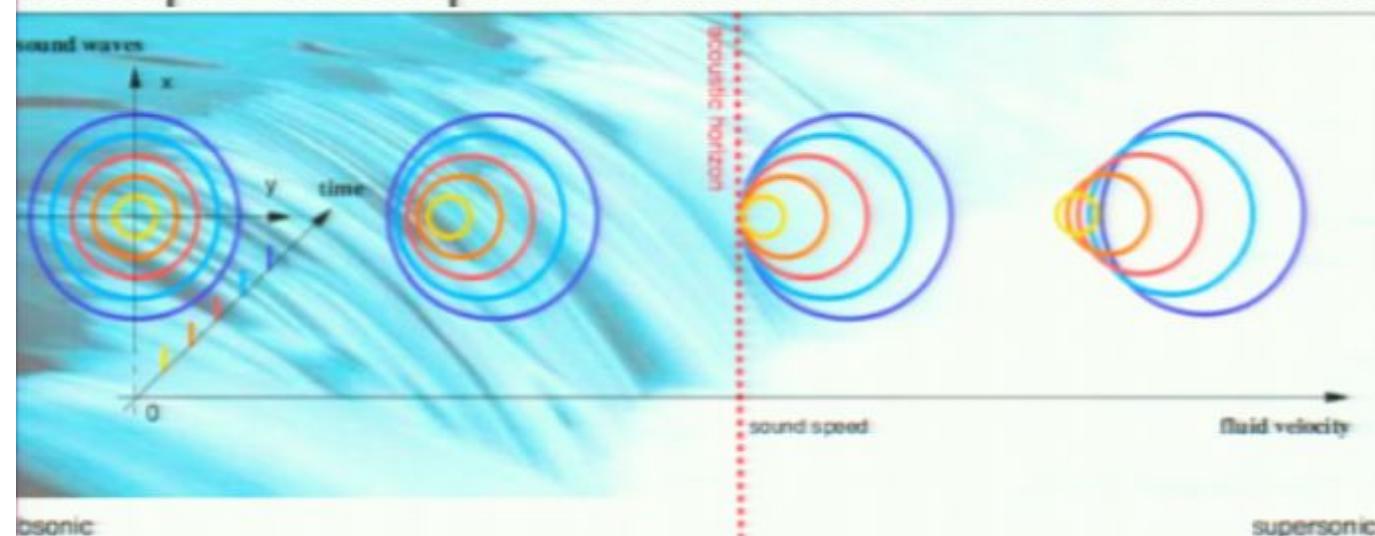
A world full of effective spacetimes





The first analogue model:

A simple example: Sound waves in a fluid flow



Exact analogy to a massless minimally coupled scalar field in an effective curved spacetime:

$$g_{ab} \propto \begin{bmatrix} -(c^2 - v^2) & -v_j \\ -v_i & \delta_{ij} \end{bmatrix}$$

The kinematic equations for small - classical or quantum - perturbations (i.e., sound waves) in barotropic, invicid and irrotational fluid are given by

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$$\frac{1}{\sqrt{-g}} \partial_a (\sqrt{-g} g^{ab} \partial_b \phi) = 0$$

PHYSICAL REVIEW
LETTERS

VOLUME 46

25 MAY 1981

NUMBER 21

Experimental Black-Hole Evaporation?

W. G. Unruh

Department of Physics, University of British Columbia, Vancouver, British Columbia V6T 1Z1

(Received 8 December 1980)

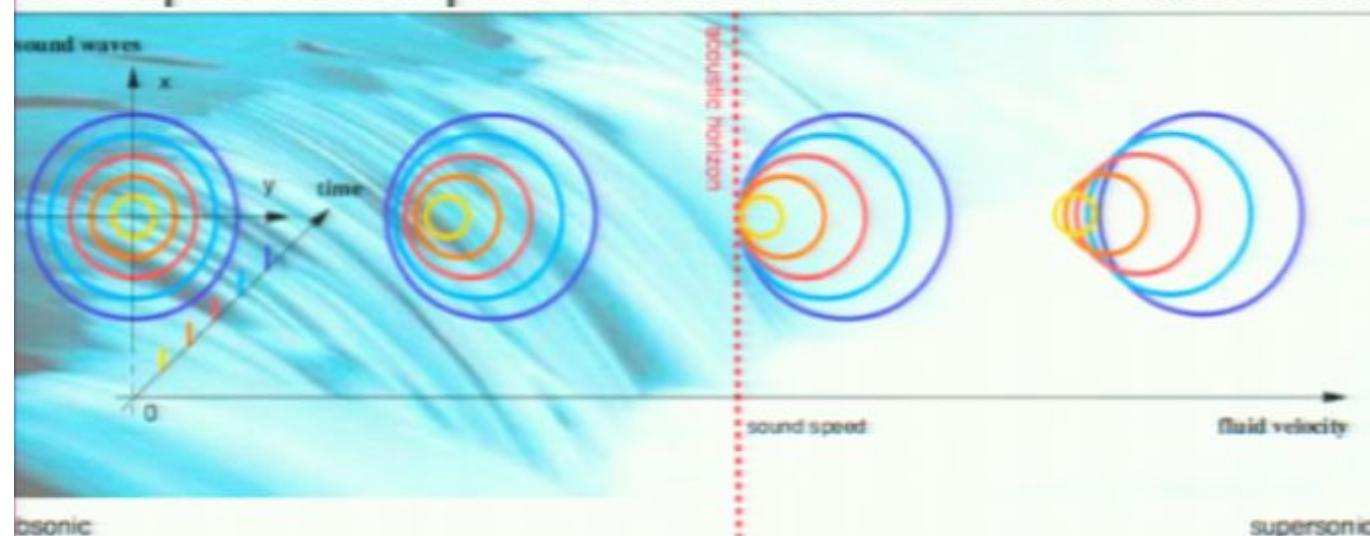
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It is shown that the same arguments which lead to black-hole evaporation also predict that a thermal emission of particles from a black hole can be observed near the event horizon.



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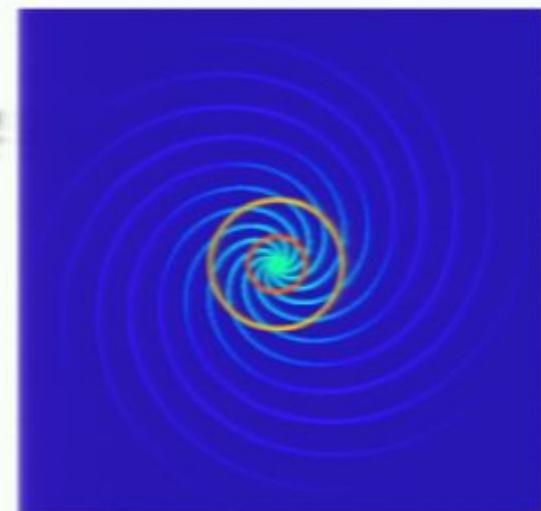




Acoustic Kerr black hole

task:

Can we use a fluid to mimic a Kerr black hole?



problems:

Physical acoustics only for wavelength with:

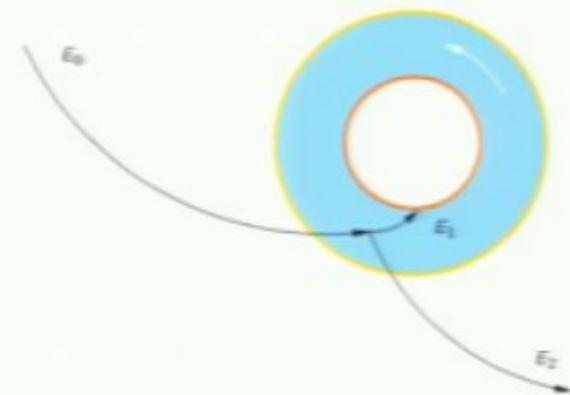
$$c k \gg ||\tilde{\nabla} \times \tilde{v}||$$

Only 1 degrees of freedom for acoustic spacetime

Conformal flatness of spatial slice in acoustic metric

relevance: Penrose process; Superradiant Scattering; Hawking radiation

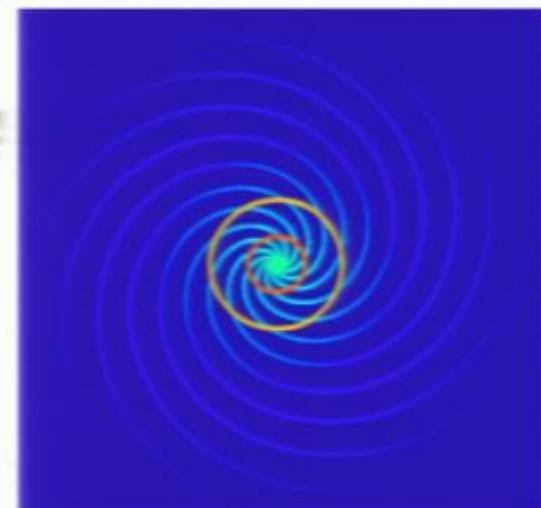
results: The equatorial slice through a rotating Kerr black hole is formally equivalent to geometry felt by phonons



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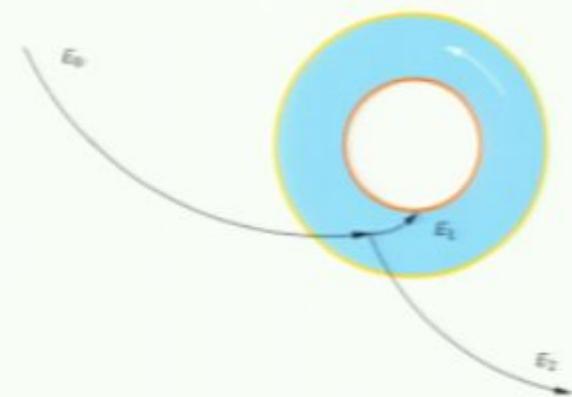
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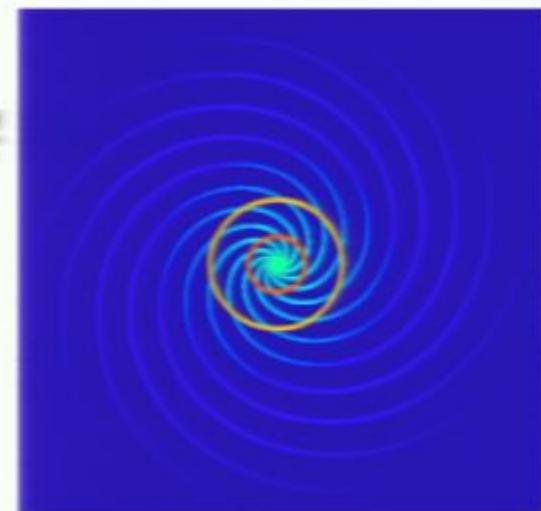


$$g_{ab} = \begin{pmatrix} c^2 - v^2 & -v \\ -v & (p+1) \end{pmatrix}$$

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Physical acoustics only for wavelength with:

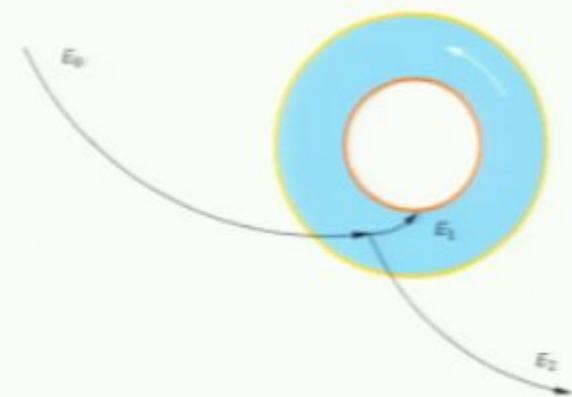
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Natural occurrence...?



A chalkboard featuring a graph of a function labeled n_r and a handwritten equation for the metric tensor component g_{ab} .

The graph shows a curve starting at a point on the vertical axis and decreasing towards the right.

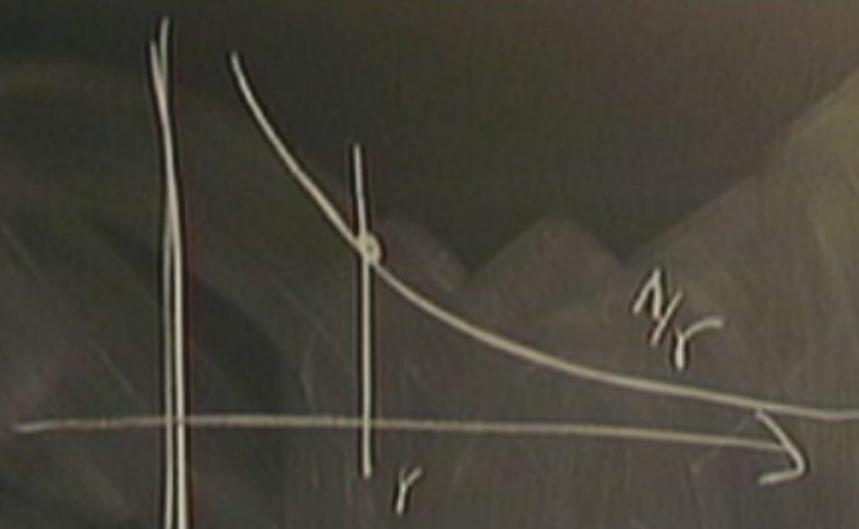
The handwritten equation is:

$$g_{ab} = \begin{pmatrix} c^2 - v^2 & -v \\ -v & 1 \end{pmatrix}$$

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A chalkboard featuring a graph on the left and a complex mathematical equation on the right. The graph shows a horizontal axis with two vertical tick marks. A curve starts at the origin, rises to a peak, and then descends. The peak is labeled with the Greek letter π . Below the curve, there is some handwritten text that appears to be $b =$. To the right of the graph is a large, complex equation involving variables C^2 , v^2 , v' , and v'' . The equation is enclosed in parentheses and includes a term with a denominator of $v^2 - v'^2$.

$$\left(\frac{C^2 - v^2}{v^2 - v'^2} - v' \right)$$



A diagram of a hyperbolic paraboloid surface, often called a saddle shape. It is drawn with a grid of curves. A vertical axis is labeled r , and a horizontal axis is labeled θ . A point on the surface is marked with a dot.

$$g_{ab} = \begin{pmatrix} c^2 - v^2 & -v \\ -v & 1 \end{pmatrix}$$

Natural occurrence of acoustic bh

▶ Sound of superradiance?

Idea: A tornado is a violently rotating column of air, and outside its core it is a perfect example of an irrotational vortex: $v \propto 1/r$

Problem: The highest wind speeds recorded do not exceed 150 m/s (about 0.5 Mach), due to different physics in the core of the vortex: $v \propto r$

Possibility of supersonic wind flows in tornados..?



Natural occurrence of acoustic bh

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Possibility of supersonic wind flows in tornados..?



Shallow water waves - theory

Gravity wave analogs of black holes

Authors: Ralf Schützhold, William G. Unruh

Journal-ref: Phys.Rev. D66 (2002) 044019

Propagation of ripples in a basin filled with liquid is governed by

$$ds^2 = \frac{1}{c^2} [-(c^2 - (\vec{v}_B^{\parallel})^2) dt^2 - 2 \vec{v}_B^{\parallel} \cdot d\vec{x} dt + d\vec{x}^T \cdot d\vec{x}]$$

velocity parallel to the basin

Advantage: Extreme ease with which one can adjust the velocity of the surface waves

$$c^2 = g h_B$$



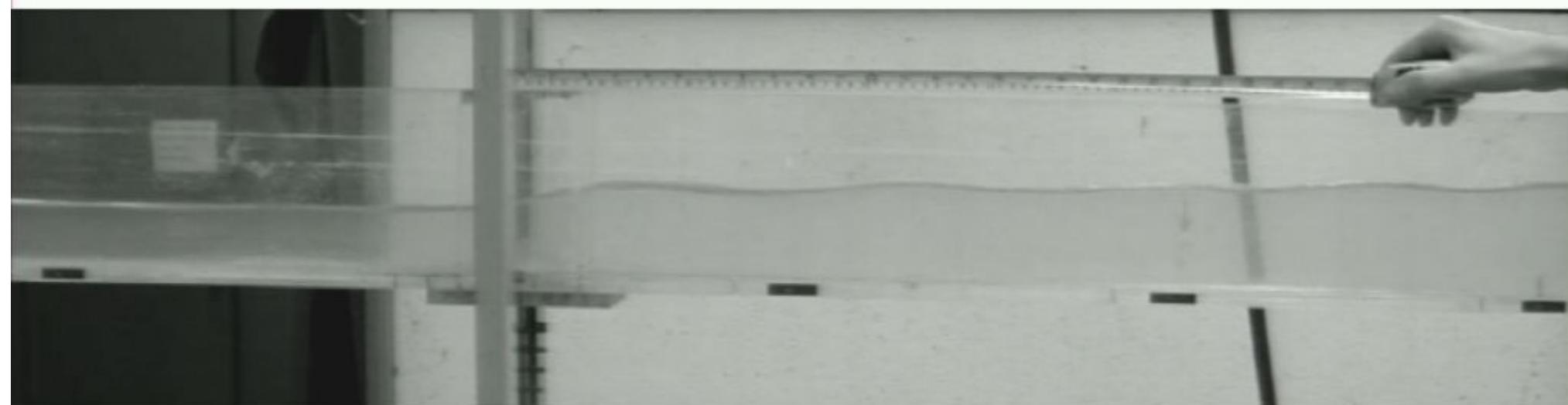
Via the depth of the basin!

Shallow water waves - experiment

Dumb holes: analogues for black holes Dumb holes: analogues for black holes

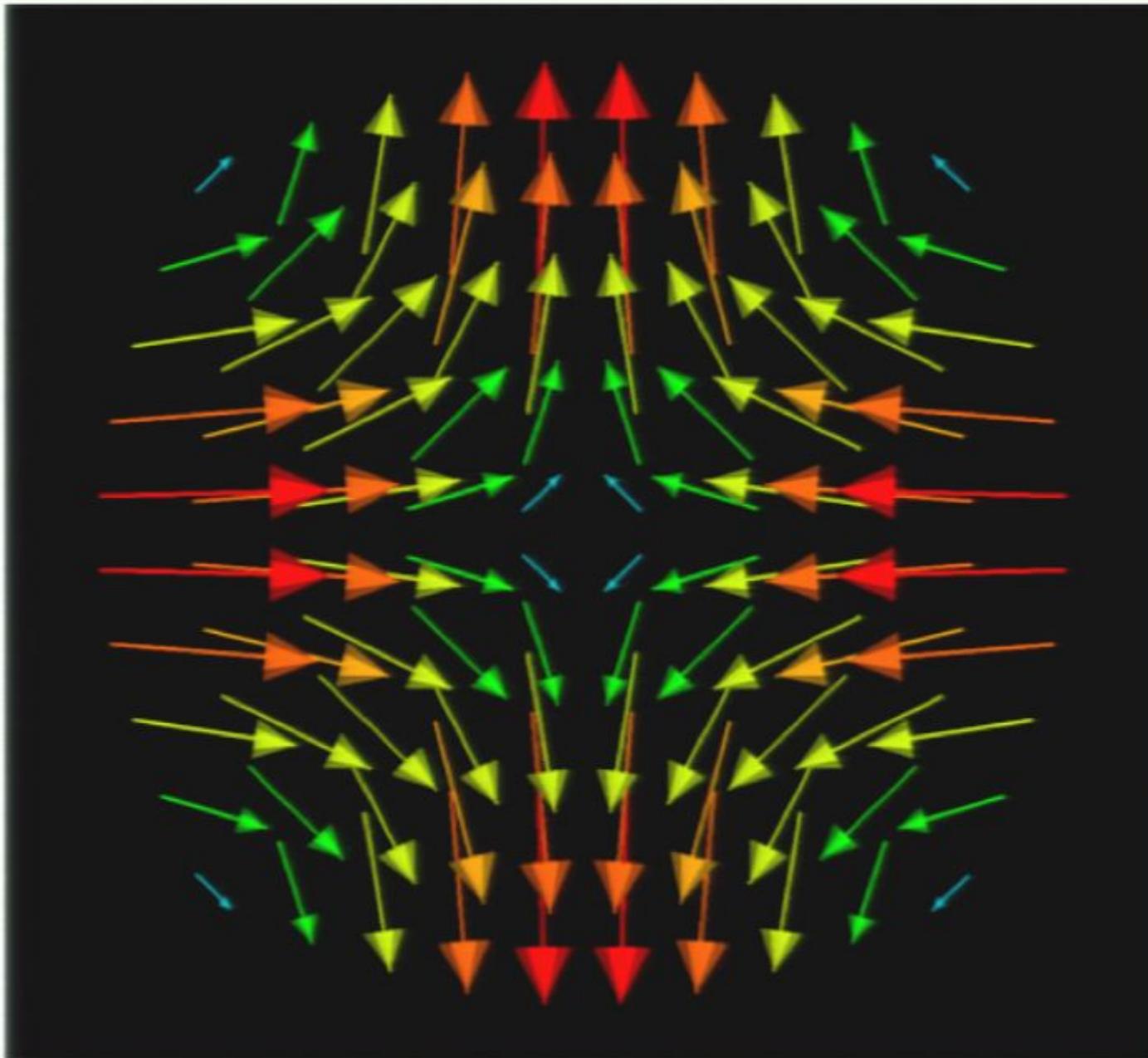
Authors: William G. Unruh

Journal-ref: Phil. Trans. R. Soc. A 366 (2008) 2905--2913



flow direction

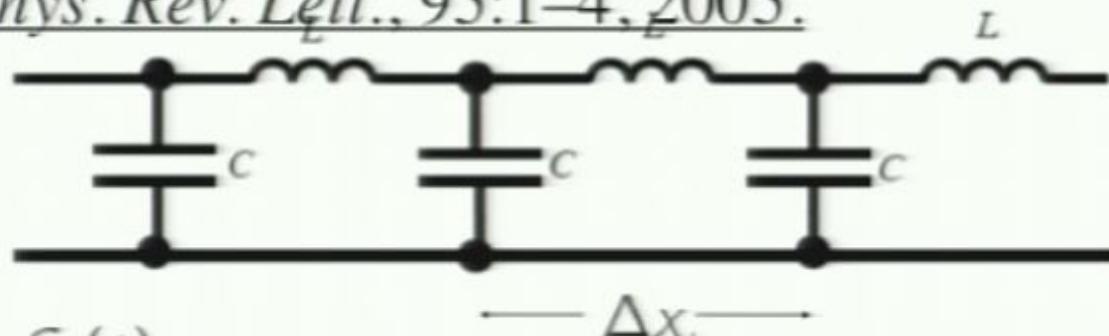
Figure 1. The left-to-right flow is ‘supersonic’ (faster than the velocity of low-wavenumber gravity waves) to the left of the stanchions and ‘subsonic’ to the right. The jump in average level at the ‘white hole’ horizon (where the decreasing velocity of the fluid just equals the velocity of gravity waves) can be regarded as a zero-wavenumber wave impinging on the white hole from the right. The undulating wave (which camps out due to the viscosity of the water) going off to the right has zero-phase velocity, but a non-zero group velocity, carrying energy away from the white hole horizon. Quantum mechanically, this would mean that the radiation from a white hole horizon would not be thermal around zero wavenumber, but rather would be a non-thermal, high-frequency



Electromagnetic wave guide - lattice structure

Manipulating electromagnetic waves in a wave-guide so that they experience an effective curved spacetime in the form of a (2+1) dimensional Painleve-Gullstrand-Lemaitre geometry.

L. Schuetzhold and W. Unruh. *Phys. Rev. Lett.*, 95:1–4, 2005.



Wave-guide consists
of a ladder circuit with:
time-dependent capacitance $C_n(t)$

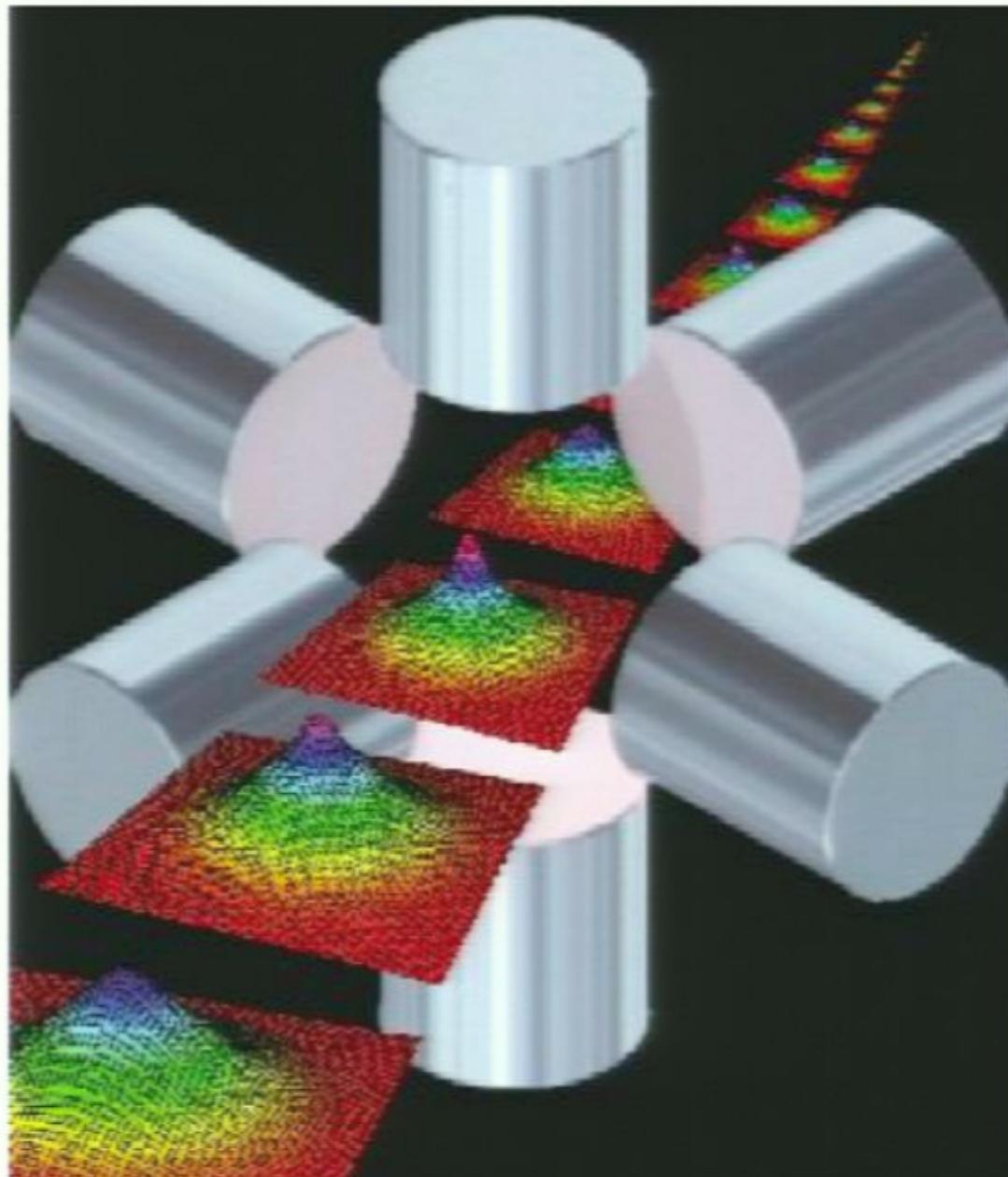
coil in each loop has constant inductance $L_n = L = \text{constant}$.
current in each circuit is given by I_n ,

effective potential A_n , such that $I_n = A_{n+1} - A_n$.

or wave-length $\lambda \gg \Delta x$ the discreteness of the x-axis is negligibly small, hence $A_n \rightarrow A(x)$:

$$(\partial_t + v \partial_x) \frac{1}{c^2} (\partial_t + v \partial_x) - \partial_x^2] A(x) = 0 \quad \text{where}$$

Bose-Einstein condensate - a quantum model

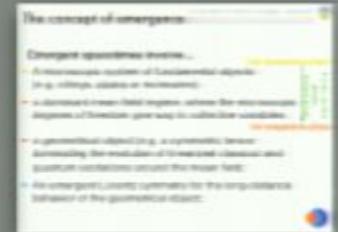
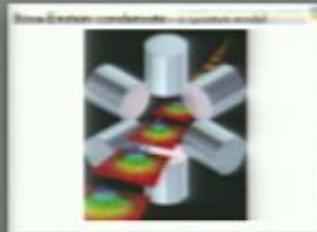




Concept of emergence



Concept of emergence



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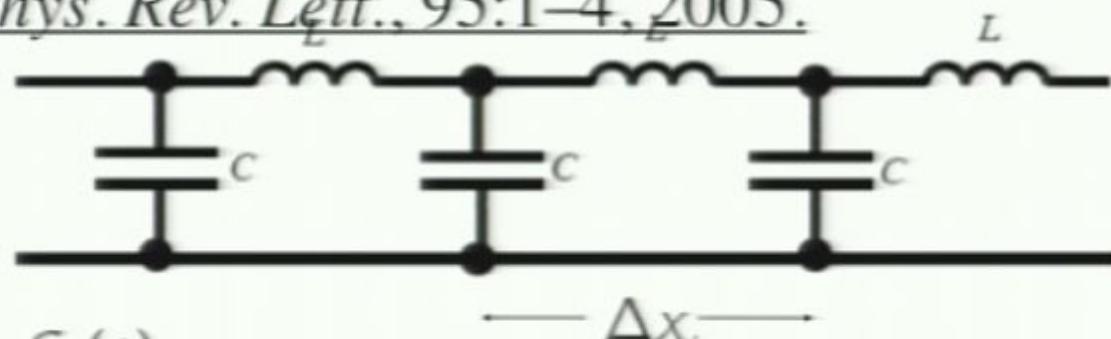


Concept of emergence

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The concept of emergence

Emergent spacetimes involve...

- ▶ A microscopic system of fundamental objects (e.g. strings, atoms or molecules);
- ▶ a dominant mean field regime, where the microscopic degrees of freedom give way to collective variables;
- ▶ a geometrical object (e.g. a symmetric tensor dominating the evolution of linearized classical and quantum excitations around the mean field);
- ▶ An emergent Lorentz symmetry for the long-distance behavior of the geometrical object;

high temperature phase

first-order
phase
transition

low temperature phase



Example BEC [microscopic degrees of freedom]

Emergent spacetimes from Bose-gas

- A microscopic system of fundamental objects:
ultra-cold dilute gas of weakly interacting Bosons

Microscopic theory well understood:

$$\hat{H} = \int d\mathbf{x} \left(-\hat{\Psi}^\dagger \frac{\hbar^2}{2m} \nabla^2 \hat{\Psi} + \hat{\Psi}^\dagger V_{\text{ext}} \hat{\Psi} + \frac{U}{2} \hat{\Psi}^\dagger \hat{\Psi}^\dagger \hat{\Psi} \hat{\Psi} \right)$$

SO(2) – symmetry

$$\hat{\Psi} \rightarrow \hat{\Psi}^* = \hat{\Psi} \exp(i\alpha)$$

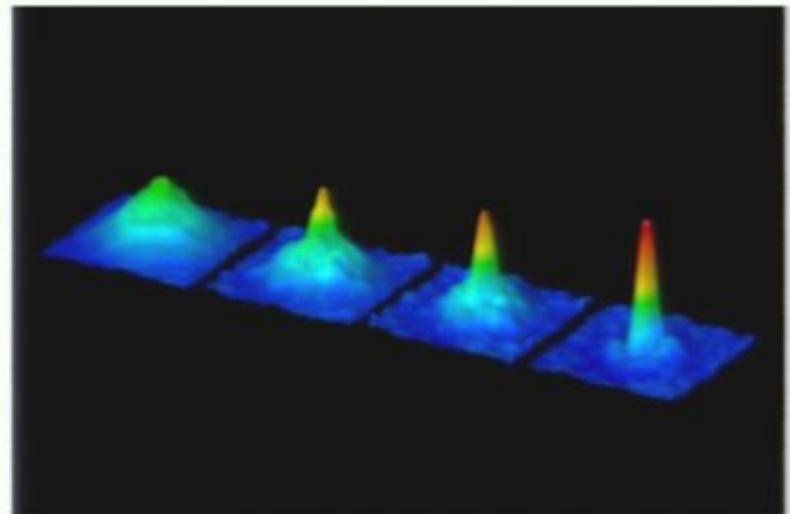


Example BEC [macroscopic variables]

[Emergent spacetimes from Bose-gas](#)

► A dominant mean field regime:

Bose-Einstein condensate



Spontaneous symmetry breaking:

$$\langle \hat{\Psi}(t, \mathbf{x}) \rangle = \psi(t, \mathbf{x}) = \sqrt{n_0(t, \mathbf{x})} \exp(i\phi_0(t, \mathbf{x})) \neq 0$$



Example BEC [geometrical object]

[Emergent spacetimes from Bose-gas](#)

Small perturbations - linear in density and phase - in the macroscopic mean-field emerging from an ultra-cold weakly interacting gas of bosons are inner observers experiencing an effective spacetime geometry,

$$\frac{1}{\sqrt{|\det(g_{ab})|}} \partial_a \left(\sqrt{|\det(g_{ab})|} g^{ab} \partial_b \hat{\phi} \right) = 0$$

where

$$g_{ab} = \left(\frac{c_0}{U/\hbar} \right)^{\frac{2}{d-1}} \begin{bmatrix} - (c_0^2 - v^2) & -v_x & -v_y & -v_z \\ -v_x & 1 & 0 & 0 \\ -v_y & 0 & 1 & 0 \\ -v_z & 0 & 0 & 1 \end{bmatrix};$$



Example BEC [Emergent Lorentz symmetry]

Emergent spacetimes from Bose-gas

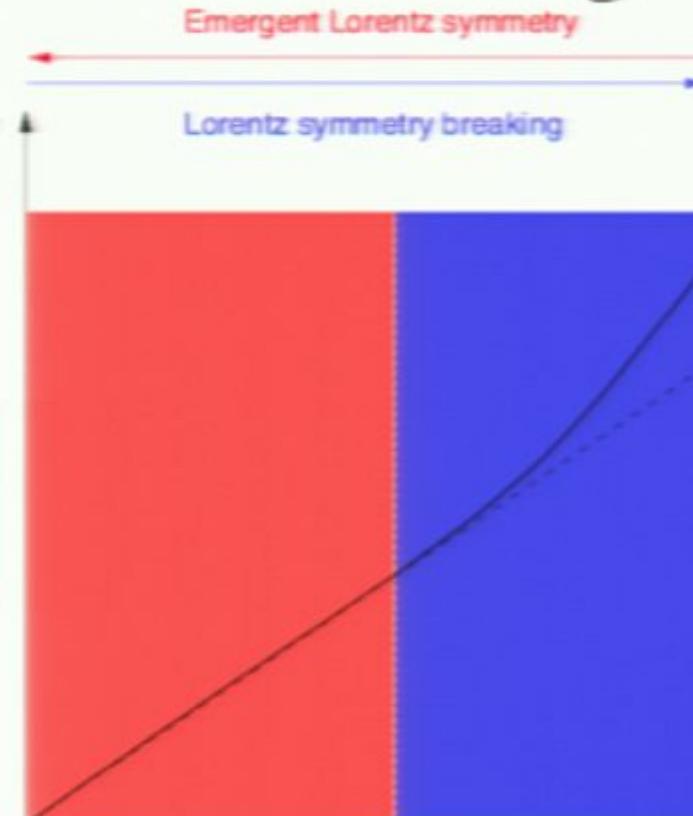
- An emergent Lorentz symmetry:

Bogoliubov dispersion relation for excitations

$$\omega_k^2 = c_0^2 k^2 + \left(\frac{\hbar}{2}\right)^2 k^4$$

Macroscopic variables

$$\omega_k \approx c_0 k$$



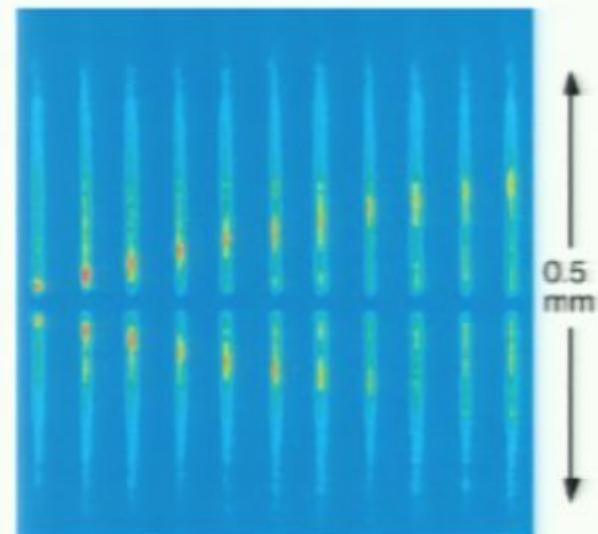
Microscopic variables

$$\omega_k \approx \frac{\hbar}{2m} k^2$$

On inner and out observer and absolute

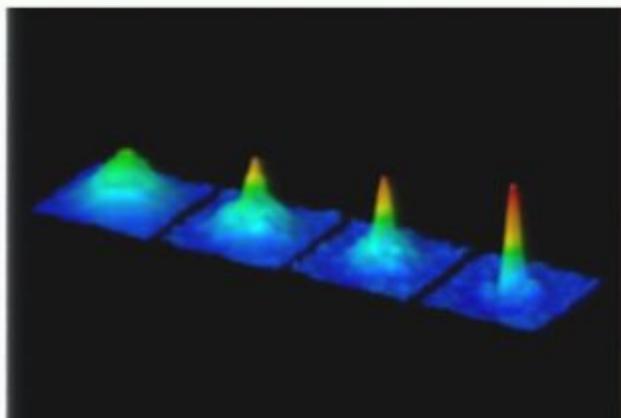
Inner observer:

Small excitations in the system experience an effective spacetime geometry represented by the macroscopic mean-field variables!

$$[\hat{\theta}(t, \mathbf{x}), \hat{\Pi}_{\hat{\theta}}(t, \mathbf{x}')] = i\delta(\mathbf{x} - \mathbf{x}')$$


Outer observer:

Live in the preferred frame - the laboratory frame, such that the condensate parameters are functions of lab-time (absolute time).



Semi-classical quantum geometry

C. Barcelo, S. Liberati, and M. Visser. Analog gravity from field theory normal modes?
Class. Quant. Grav., 18:3595–3610, 2001.

*Effective curved-spacetime quantum field theory
 description of the linearization process:*

Small perturbations around some background solution $\phi_0(t, x)$

$$\phi(t, x) = \phi_0(t, x) + \epsilon \phi_1(t, x) + \frac{\epsilon^2}{2} \phi_2(t, x)$$

In a generic Lagrangian $\mathcal{L}(\partial_a \phi, \phi)$, depending only on a single Scalar field and its first derivatives yields an effective

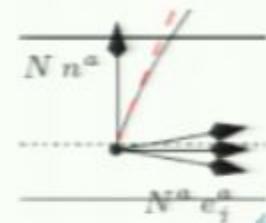
Spacetime geometry

$$g_{ab}(\phi_0) = \left[-\det \left(\frac{\partial^2 \mathcal{L}}{\partial(\partial_a \phi) \partial(\partial_b \phi)} \right) \right]^{\frac{1}{d-1}} \Big|_{\phi_0} \left(\frac{\partial^2 \mathcal{L}}{\partial(\partial_a \phi) \partial(\partial_b \phi)} \right)^{-1} \Big|_{\phi_0}$$

For the classical/ quantum fluctuations. The equation of Motion for small perturbations around the background Are then given by $(\Delta_{g(\phi_0)} - V(\phi_0)) \phi_1 = 0$



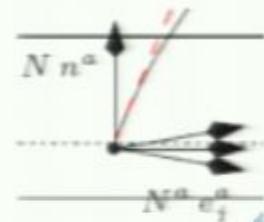
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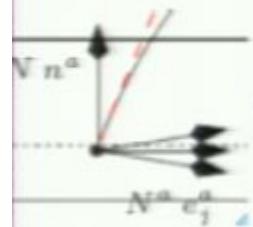
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Emergent spacetimes bearing gifts:



....



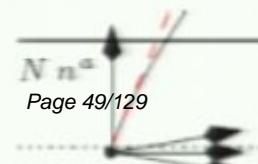
Signature of spacetime

Signature of spacetime - why $(-, +, +, +)$?

- Signature of spacetime is a certain pattern of Eigenvalues of the metric tensor at each point of the manifold [Lorentzian $(-, +, +, +)$ or Riemannian $(+, +, +, +)$]
- Spacetime foliation into non-intersecting spacelike hypersurfaces (Lapse and Shift)
- Kinematics of signature change (Lapse is a non-dynamical variable)

C. Teitelboim, "The Hamiltonian Structure Of Space-Time", General Relativity and Gravitation 1 (1981) 195–225.

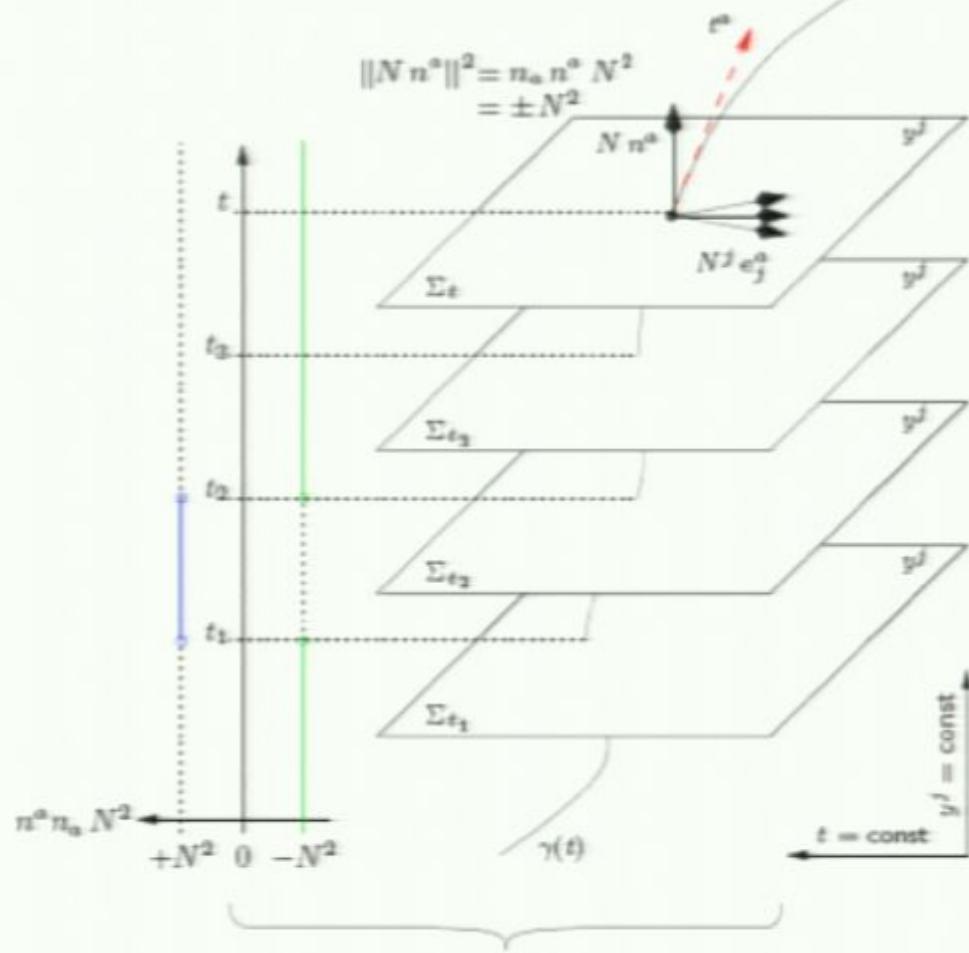
- There is no driving mechanism within GR that drives changes in the signature of the geometry...



Signature of spacetime - what is it really?

- Spacetime foliation into non-intersecting spacelike hypersurfaces (Lapse and Shift)

$$ds^2 = g_{ab} dx^a dx^b = (n^a n_a) N^2 dt^2 + h_{ij} (dy^i + N^i dt) (dy^j + N^j dt)$$

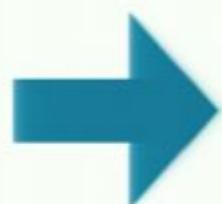


BEC: Interactions \rightarrow spacetime signature

$$\vec{v} \rightarrow \vec{0}$$

$$U \rightarrow U(t)$$

$$c_0^2 \rightarrow c(t)^2$$



$$g_{ab} = \left(\frac{c(t)}{U(t)/\hbar} \right)^{\frac{2}{d-1}} \begin{bmatrix} -c(t)^2 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$c_0^2 = \frac{n_0(t, \mathbf{x}) U(t)}{m}$$

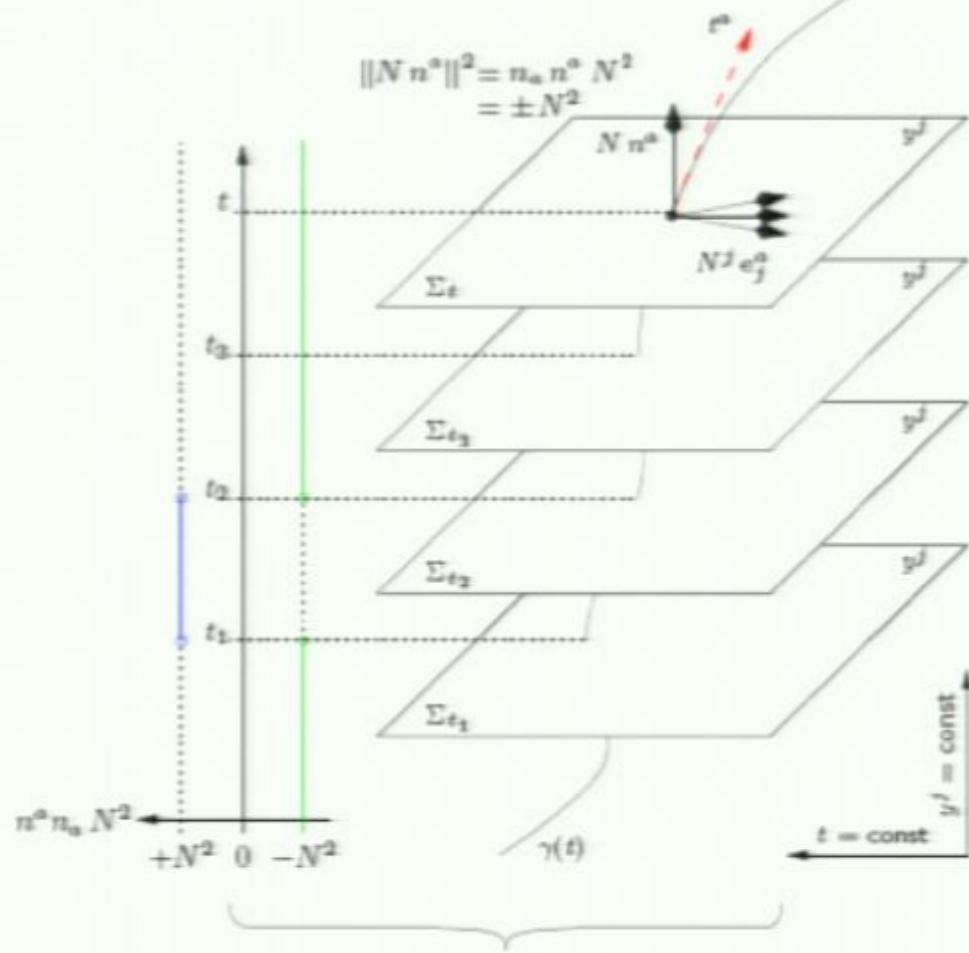
$$\begin{array}{ll} U > 0 \\ U < 0 \end{array}$$

repulsive;
attractive.

Signature of spacetime - what is it really?

- ▶ Spacetime foliation into non-intersecting spacelike hypersurfaces (Lapse and Shift)

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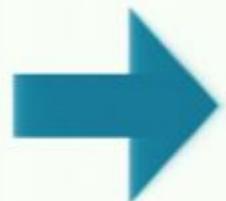


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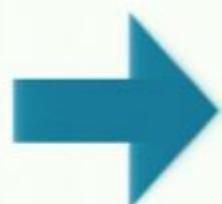
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$U > 0$ repulsive;
 $U < 0$ attractive.

$$g_{ab} \sim \begin{bmatrix} -c(t)^2 & 0 & 0 & 0 \\ 0 & +1 & 0 & 0 \\ 0 & 0 & +1 & 0 \\ 0 & 0 & 0 & +1 \end{bmatrix}$$

$$g_{ab} \sim \begin{bmatrix} +c(t)^2 & 0 & 0 & 0 \\ 0 & +1 & 0 & 0 \\ 0 & 0 & +1 & 0 \\ 0 & 0 & 0 & +1 \end{bmatrix}$$

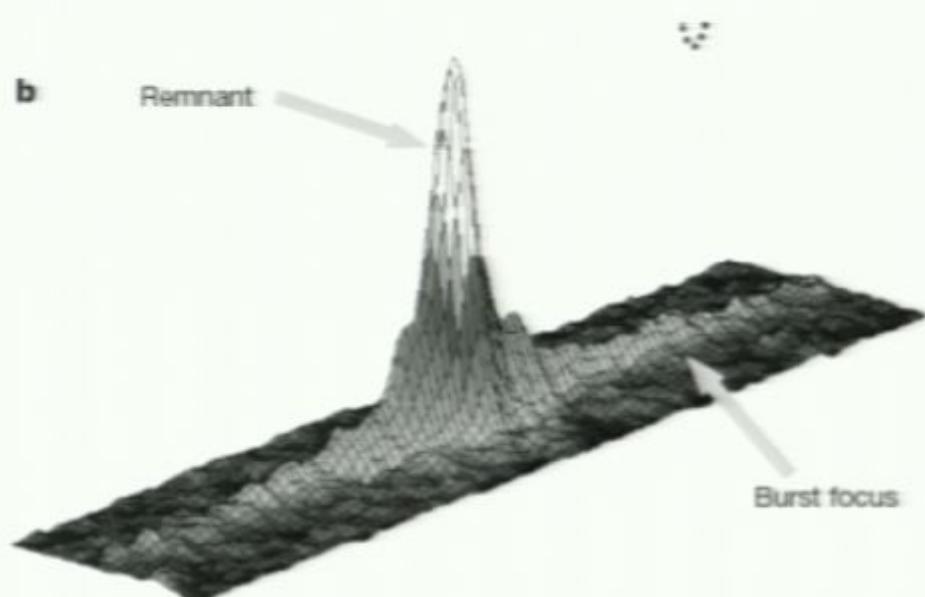
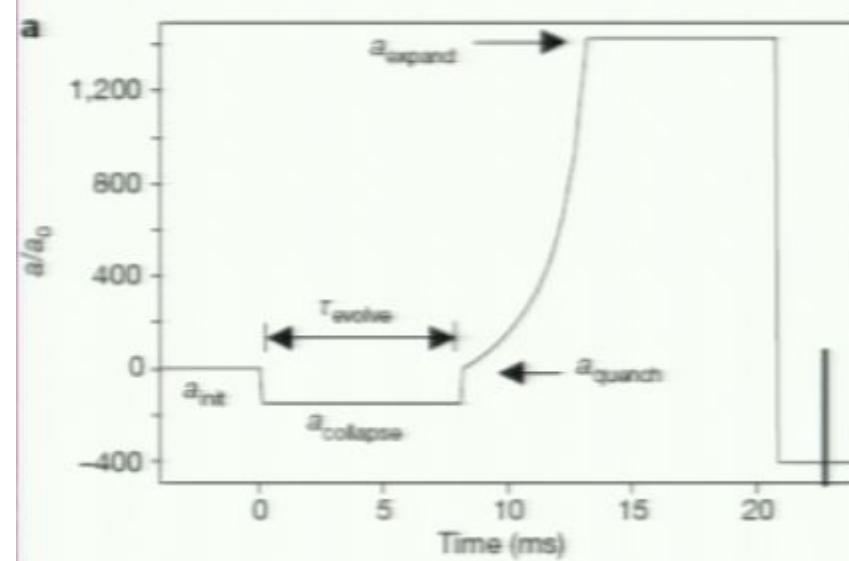
Daily signature change events...

Dynamics of collapsing and exploding Bose–Einstein condensates

NATURE | VOL 412 | 19 JULY 2001

Elizabeth A. Donley*, Neil R. Claussen*, Simon L. Cornish*, Jacob L. Roberts*, Eric A. Cornell*† & Carl E. Wieman*

The bosenova experiment:



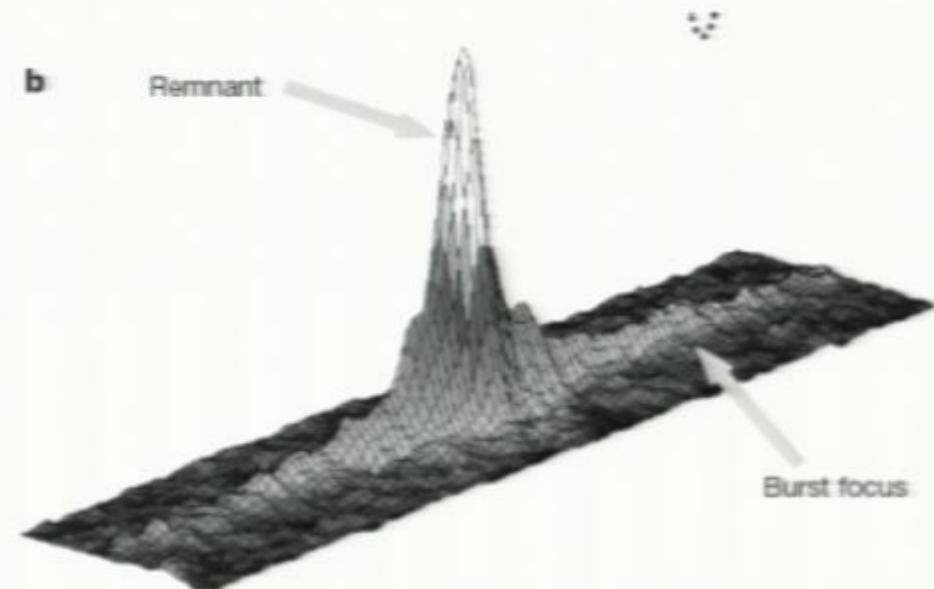
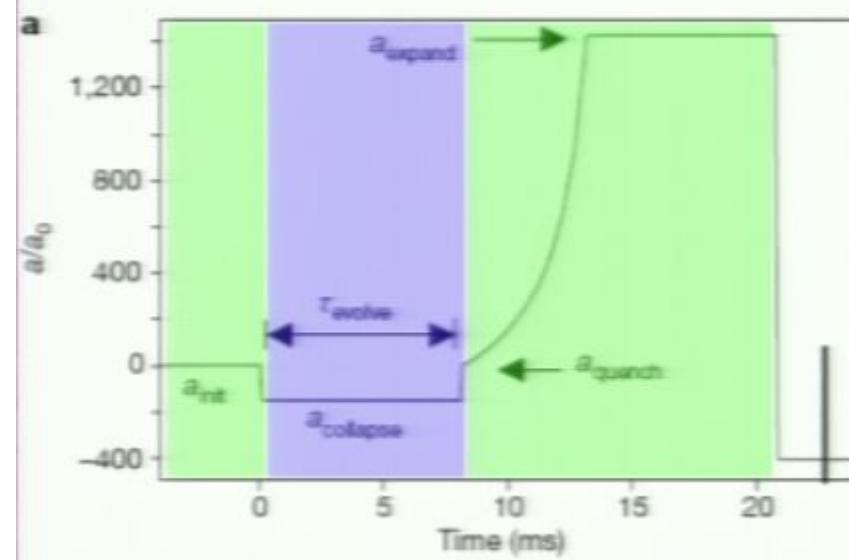
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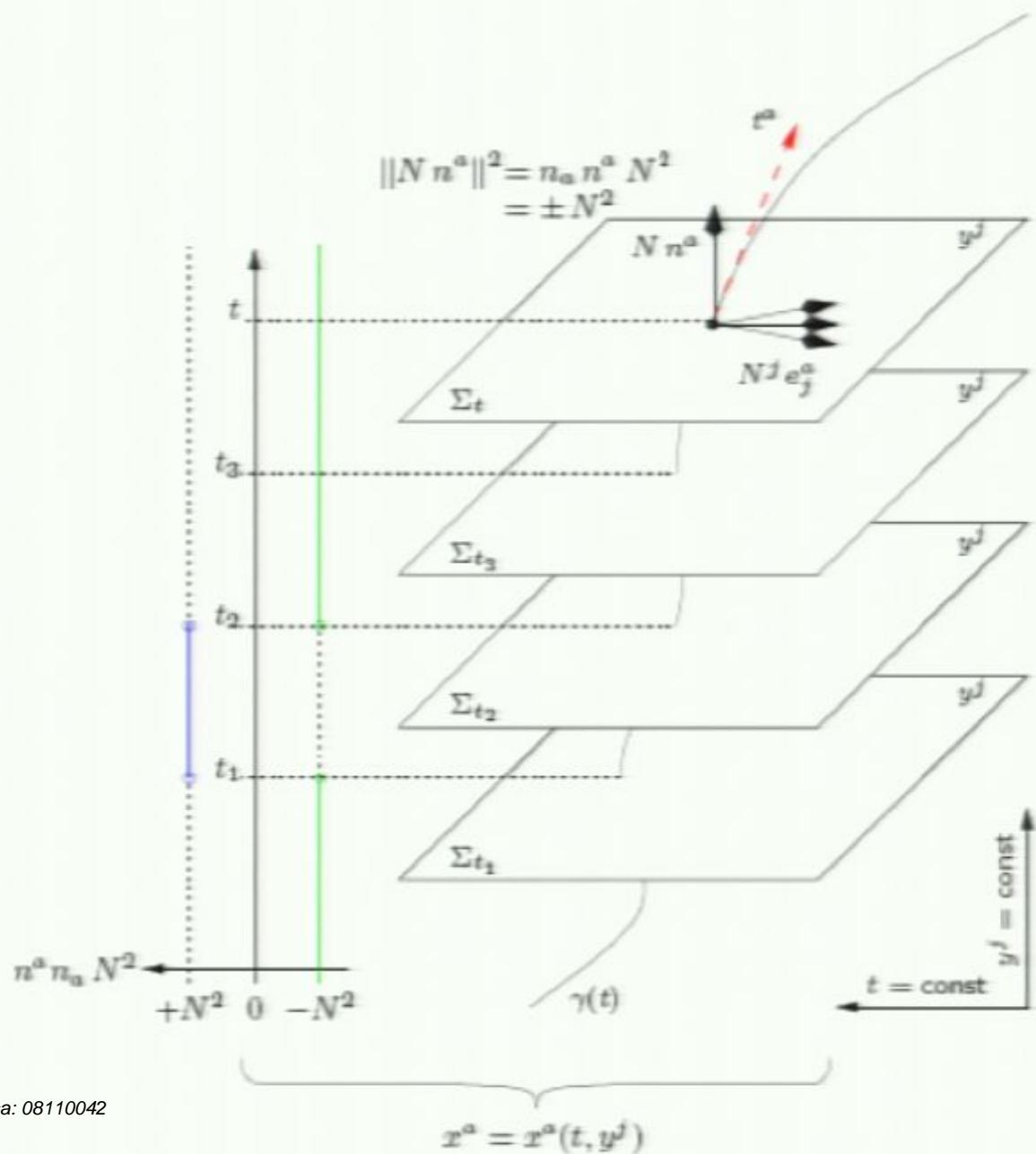
Lorentzian signature

Pirsa: 08110042

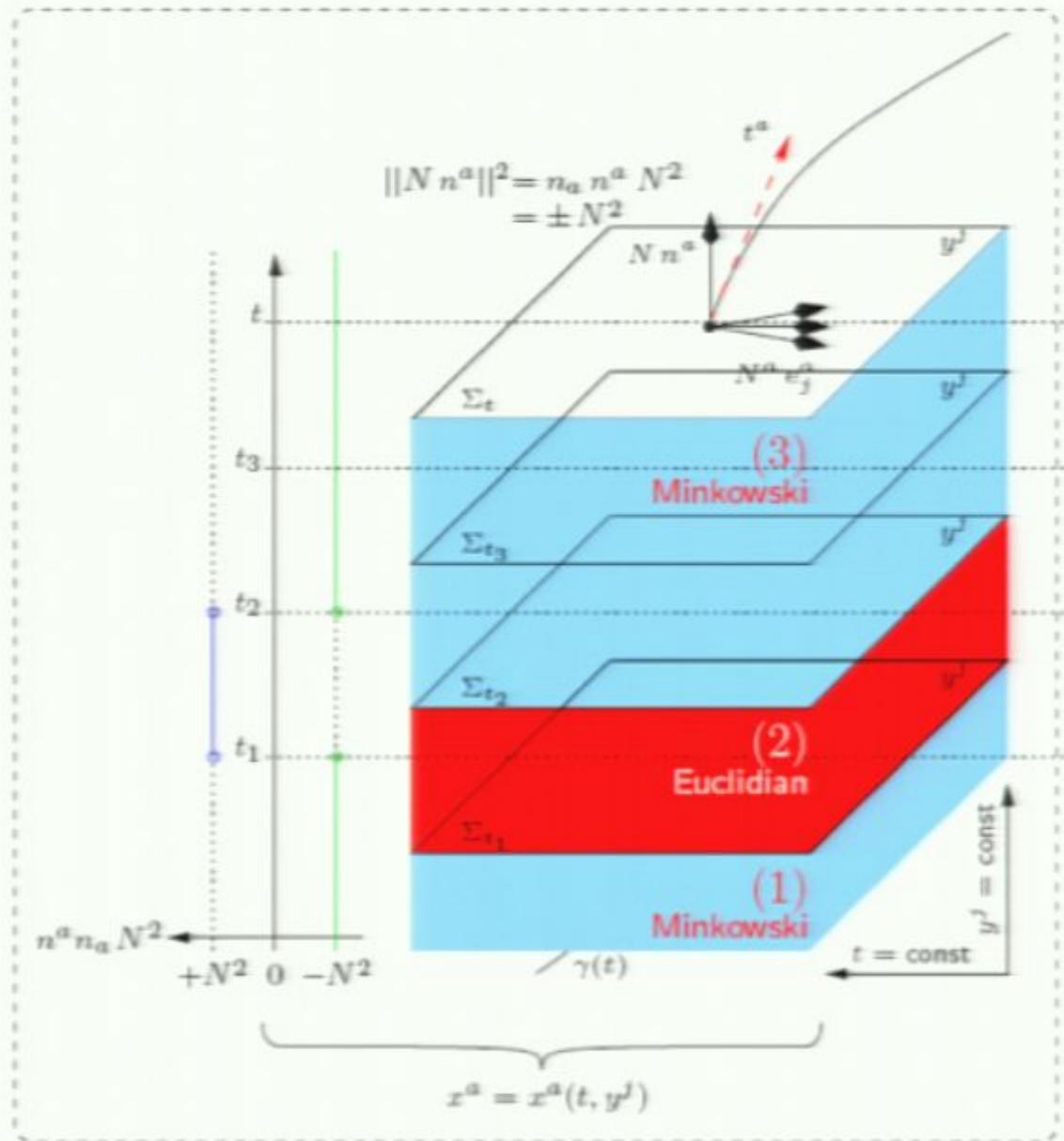
Riemannian signature

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Quantum field theory on Riemannian manifolds



Quantum field theory on Riemannian manifolds



Quantum field theory on Riemannian manifolds

Physical grasp on quantum field on Riemannian manifolds –
super-Hubble horizon modes in cosmology:

Mechanism responsible for enormous particle production works
analogous to cosmological particle production during inflation:

$$\ddot{v}_k(t) + \Omega_{\text{eff}}^2 v_k(t) = 0,$$

$$\Omega_{\text{flat}}^2 = - \left(\frac{k^2}{A} + m^2 \right)$$



Daily signature change events...

Can we understand the bosenova experiment via the emergent spacetime programme?

Early Universe Quantum Processes in BEC Collapse Experiments

E. A. Calzetta¹ and B. L. Hu² *

¹Departamento de Fisica, FCEyN Universidad de Buenos Aires Ciudad Universitaria, 1428 Buenos Aires, Argentina

²Department of Physics, University of Maryland, College Park, MD 20742, USA

(March 11, 2005)

- *Invited Talk presented at the Peyresq Meetings of Gravitation and Cosmology, 2003. To appear in Int. J. Theor. Phys.*

Main Theme We show that in the collapse of a Bose-Einstein condensate (BEC)¹ certain processes involved and mechanisms at work share a common origin with corresponding quantum field processes in the early universe such as particle creation, structure formation and spinodal instability. Phenomena associated with the controlled BEC collapse observed in the experiment of Donley et al [2] (they call it ‘Bose-Nova’, see also [3]) such as the appearance of bursts and jets can be explained as a consequence of the squeezing and amplification of quantum fluctuations above the condensate by the dynamics of the condensate. Using the

Need to understand particle production process via sudden variations in atomic-interactions...

Quantum field theory on Riemannian manifolds

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$$\ddot{\chi}_k(t) + \left(\frac{k^2}{e^{2Ht}} + m^2 - \frac{d^2 H^2}{4} \right) \dot{\chi}_k(t) = 0$$

$$m < d \frac{H}{2}$$

$$k < k_{\text{HubbleHorizon}}$$

$$\ddot{v}_k(t) + \Omega_{\text{eff}}^2 v_k(t) = 0,$$

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frozen modes

$$\ddot{v}_k(t) + \Omega_{\text{eff}}^2 v_k(t) = 0,$$

$$\Omega_{\text{flat}}^2 = - \left(\frac{k^2}{A} + m^2 \right)$$

all modes are *frozen*

Trans-Planckian beats signature

hydrodynamic approximation: Variations in the kinetic energy of the condensate are considered to be negligible, compared to the internal potential energy of the Bosons.

$$\frac{\hbar^2}{2m} \frac{\nabla^2 \sqrt{n_0 + \hat{n}}}{\sqrt{n_0 + \hat{n}}} \ll U$$

$$\hat{H} = \int dx \left(-\hat{\Psi}^\dagger \frac{\hbar^2}{2m} \nabla^2 \hat{\Psi} + \hat{\Psi}^\dagger V_{ext} \hat{\Psi} + \frac{U}{2} \hat{\Psi}^\dagger \hat{\Psi}^\dagger \hat{\Psi} \hat{\Psi} \right)$$

Keeping quantum pressure term leads to “effective interaction” seen by inner observer:

$$U = U - \frac{\hbar^2}{4mn_0} \left\{ \frac{(\nabla n_0)^2 - (\nabla^2 n_0)n_0}{n_0^2} - \frac{\nabla n_0}{n_0^2} \nabla + \nabla^2 \right\}$$



harmonic trap

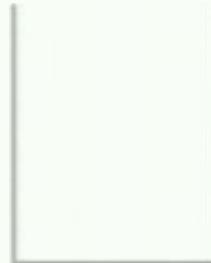
[position dependent sound speed]



condensate in box

[uniform number density]

Trans-Planckian beats signature



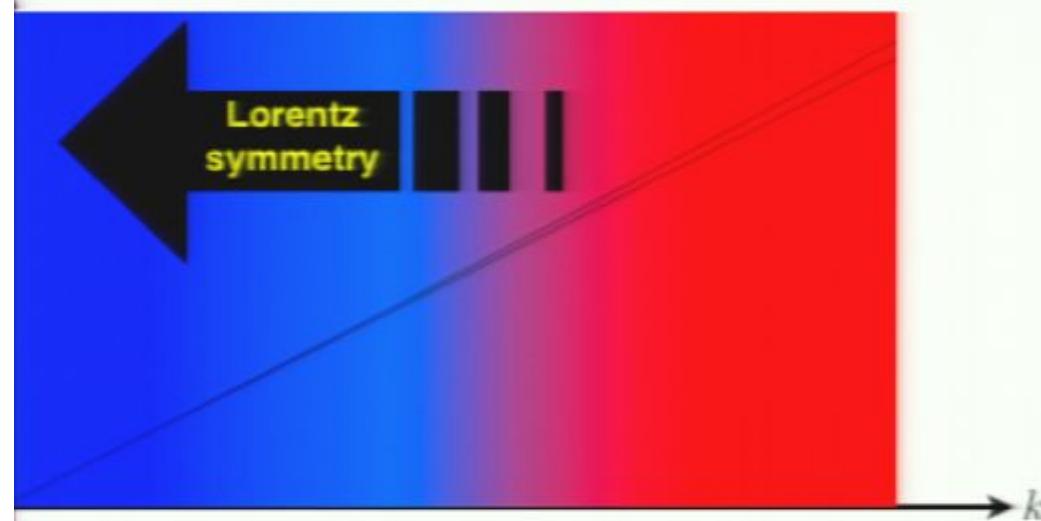
$$\mathcal{U} = U - \frac{\hbar^2}{4mn_0} \left\{ \frac{(\nabla n_0)^2 - (\nabla^2 n_0)n_0}{n_0^2} - \frac{\nabla n_0}{n_0^2} \nabla + \nabla^2 \right\} \longrightarrow \mathcal{U} = U - \frac{\hbar^2}{4mn_0} \nabla^2.$$

$$c^2(U) = \frac{n_0 U}{m} \rightarrow c_k^2(\mathcal{U}) = c^2(U) + \left(\frac{\hbar}{2m} \right)^2 k^2$$

condensate in box

[uniform number density]

$$\omega_k^2 = c(t) k^2 + \left(\frac{\hbar}{2m} \right)^2 k^4$$

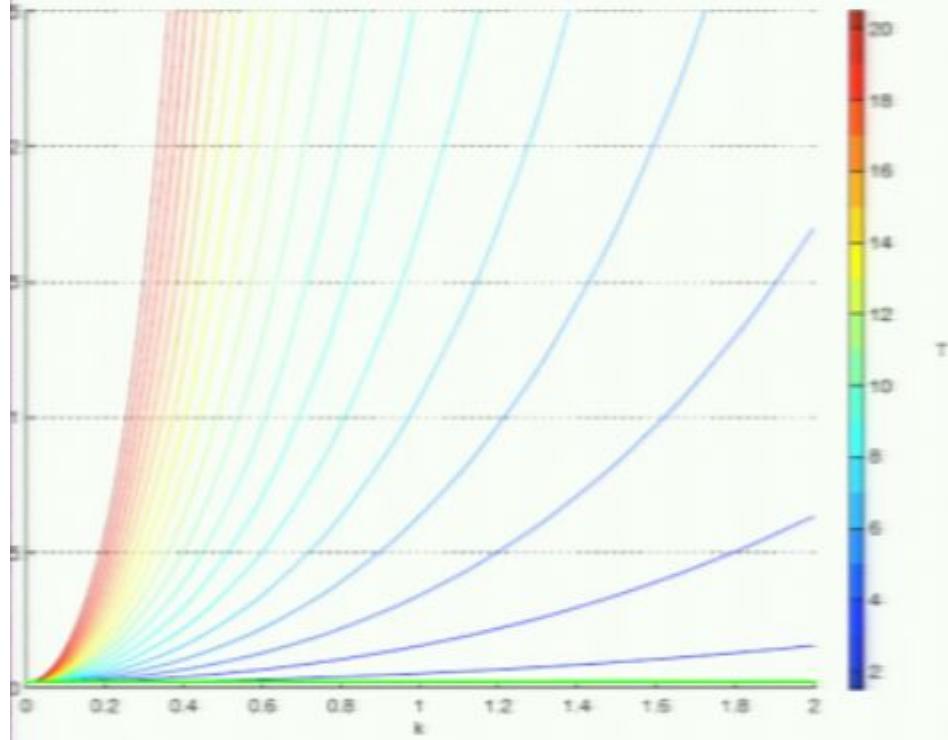


healing length:

$$\xi^2(t) = \left(\frac{\epsilon_{qp}}{c(t)} \right)^2 = \left(\frac{\hbar/2m}{c(t)} \right)^2$$

Trans-Planckian beats signature

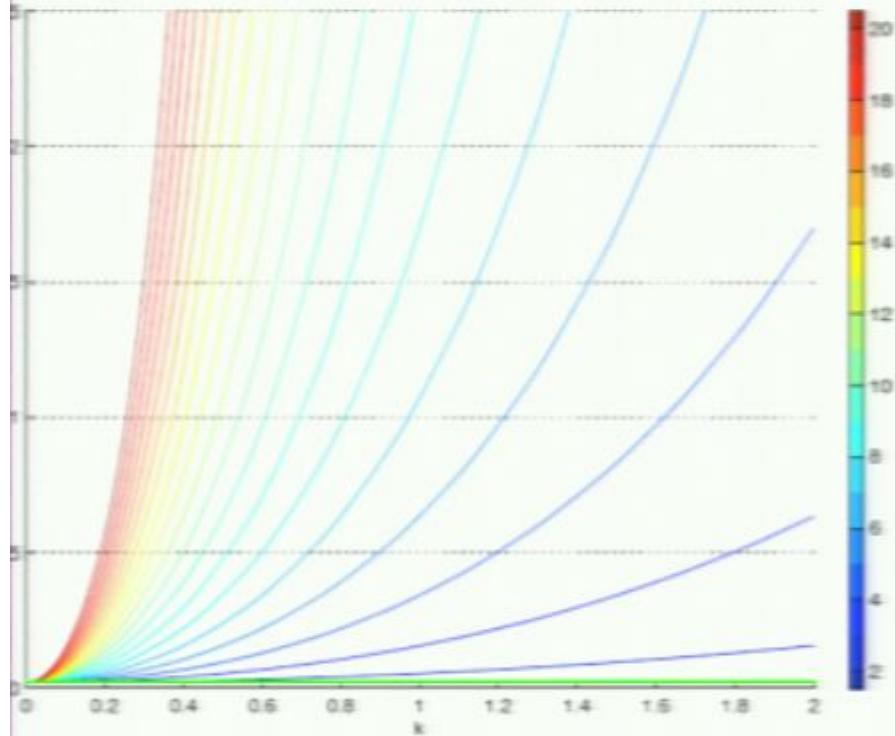
hydrodynamic
approximation



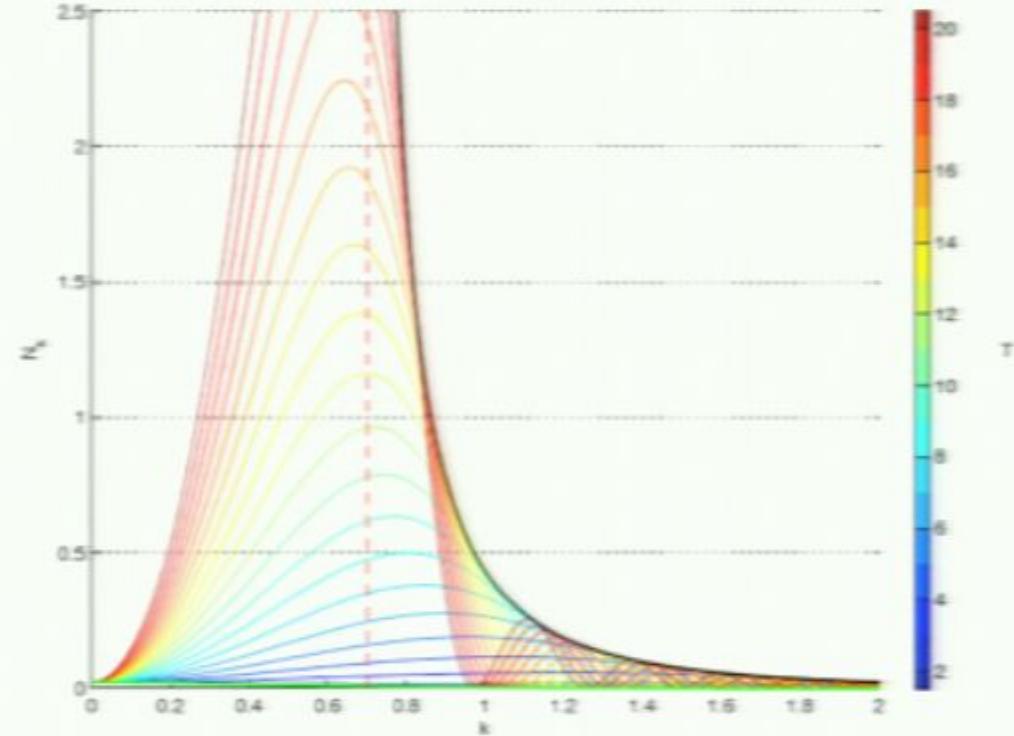
Number of quasiparticles
infinite!?

Trans-Planckian beats signature

hydrodynamic
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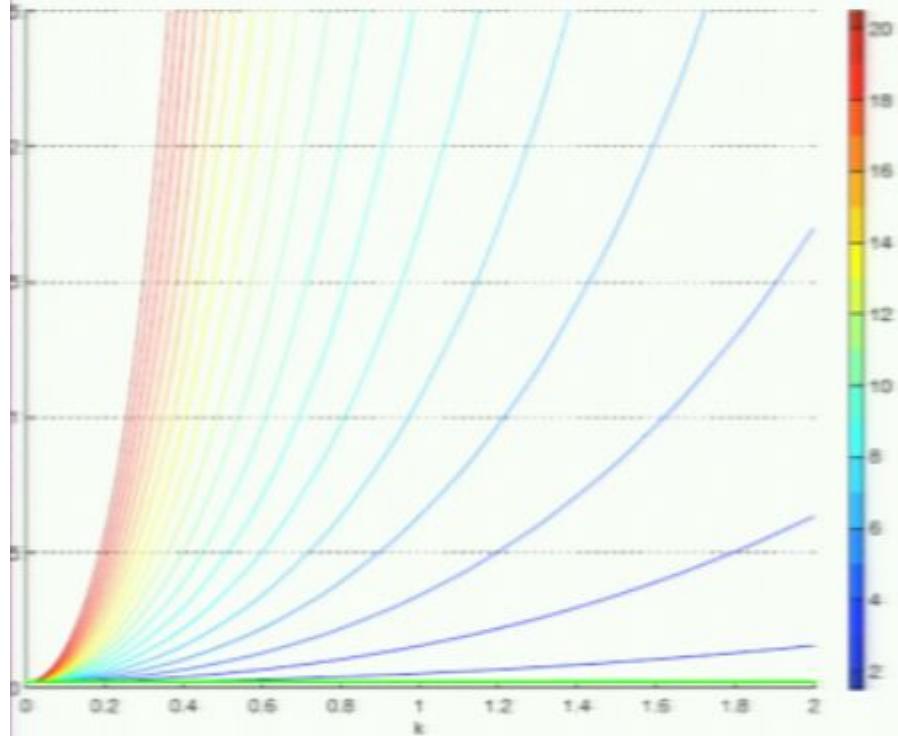


modified hydrodynamics
[including quantum pressure effects]

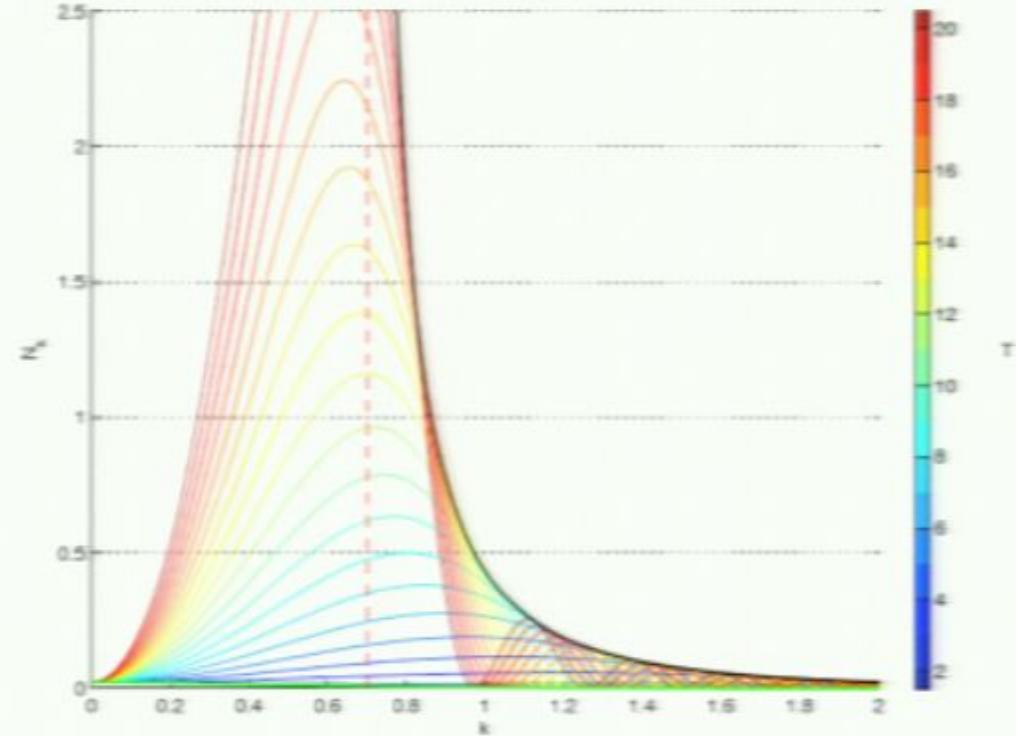


Trans-Planckian beats signature

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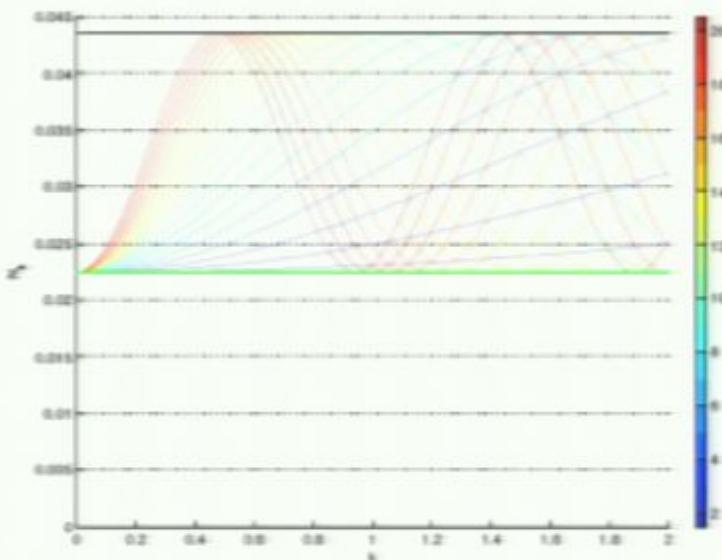


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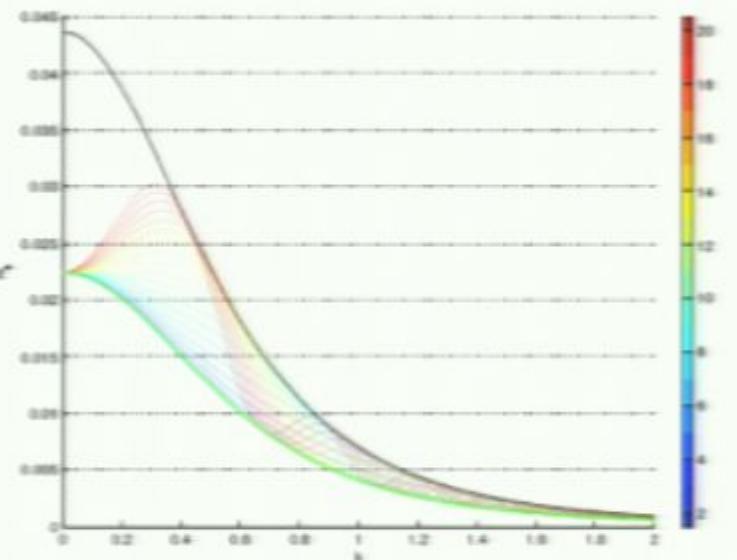


$$\mathcal{U}|_{\nabla \rightarrow -ik} \rightarrow U_k = \textcolor{blue}{U} + \frac{\hbar^2}{4mn_0} k^2$$

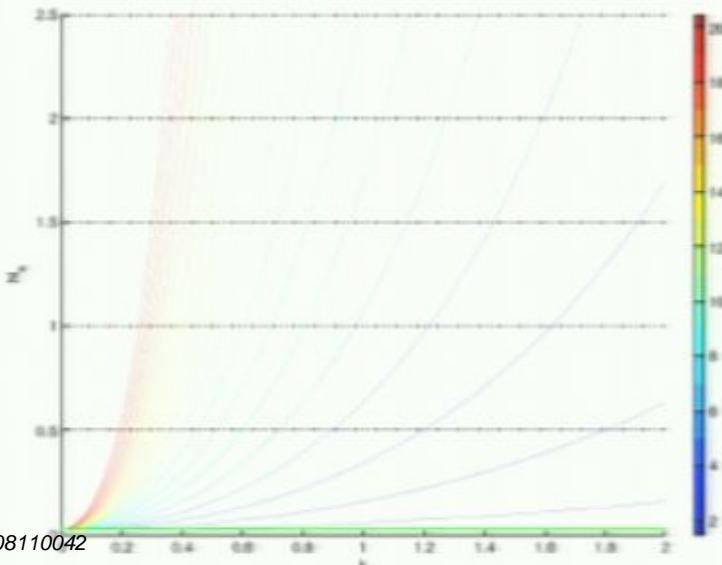
Trans-Planckian beats signature



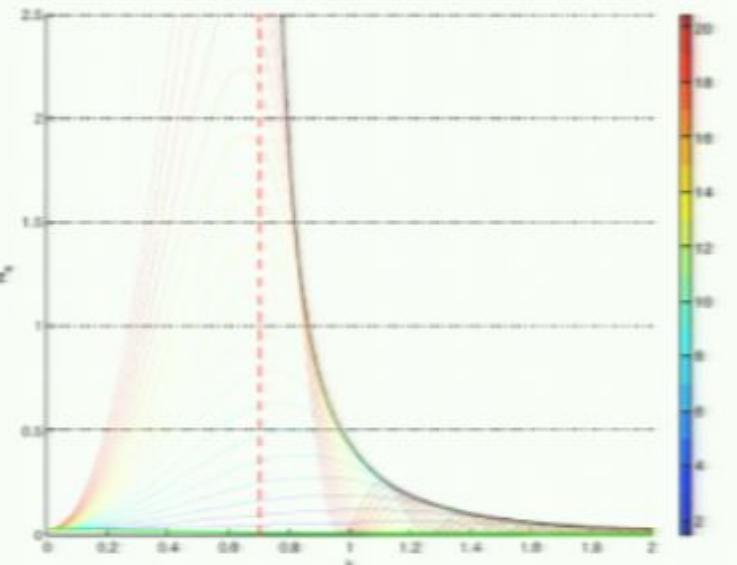
(a) Hydrodynamic limit; L-L-L.



(b) Microscopic corrections; L-L-L.

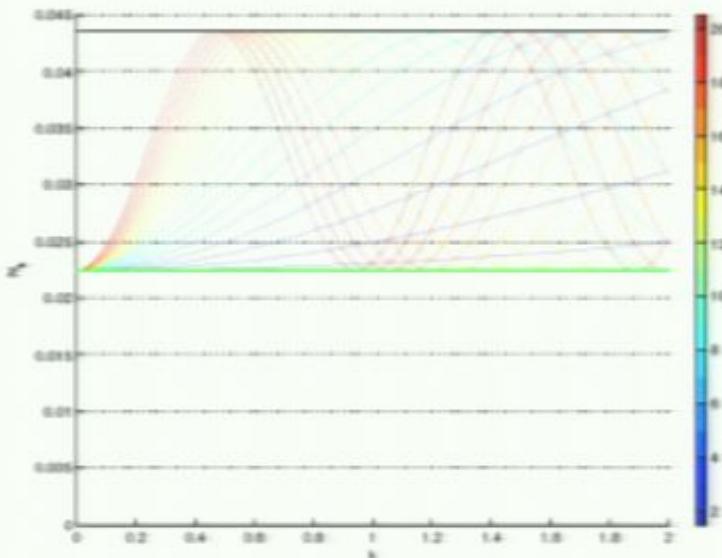


(c) Hydrodynamic limit; L-E-L.

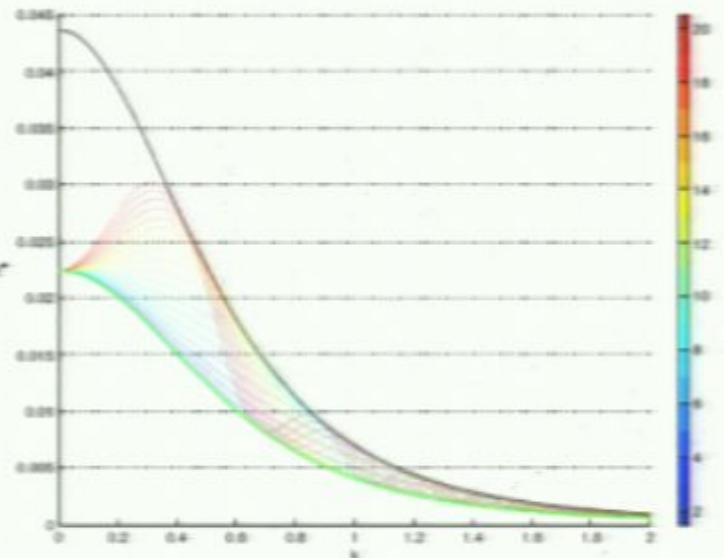


(d) Microscopic corrections; L-E-L.

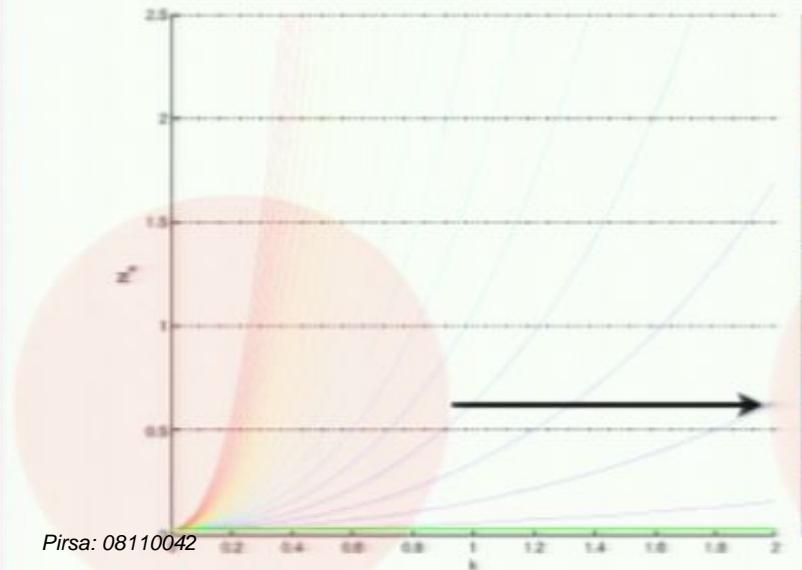
Trans-Planckian beats signature



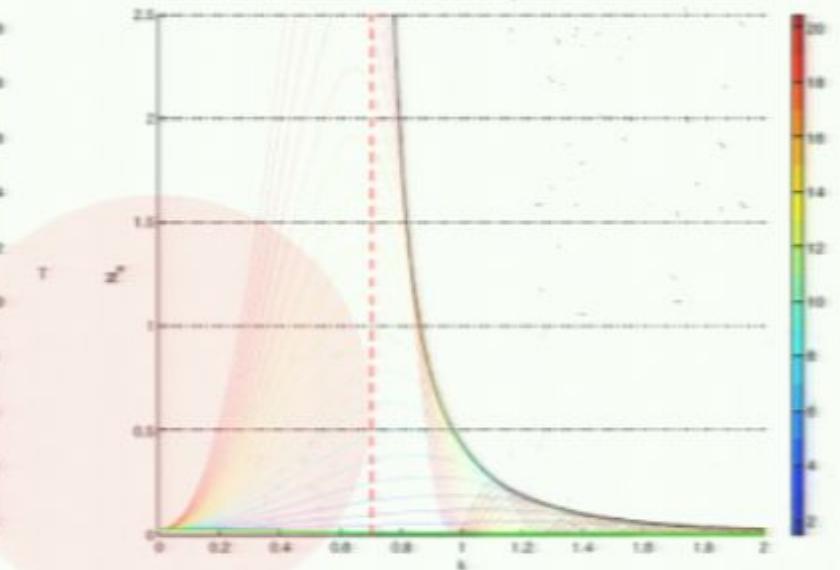
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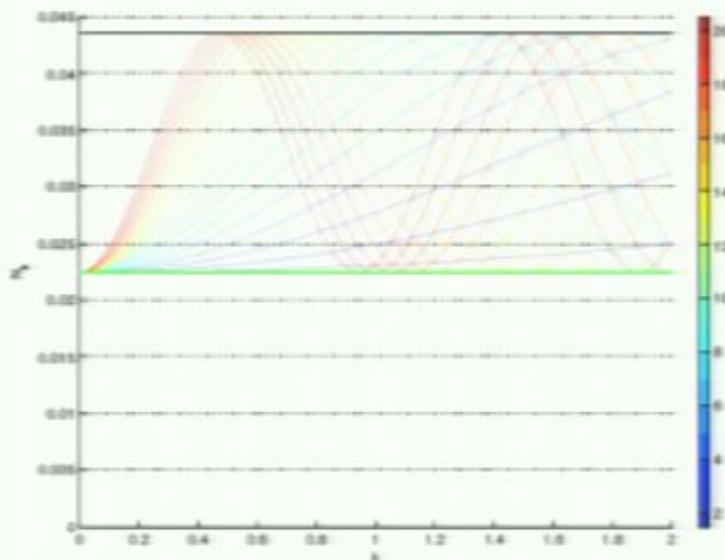


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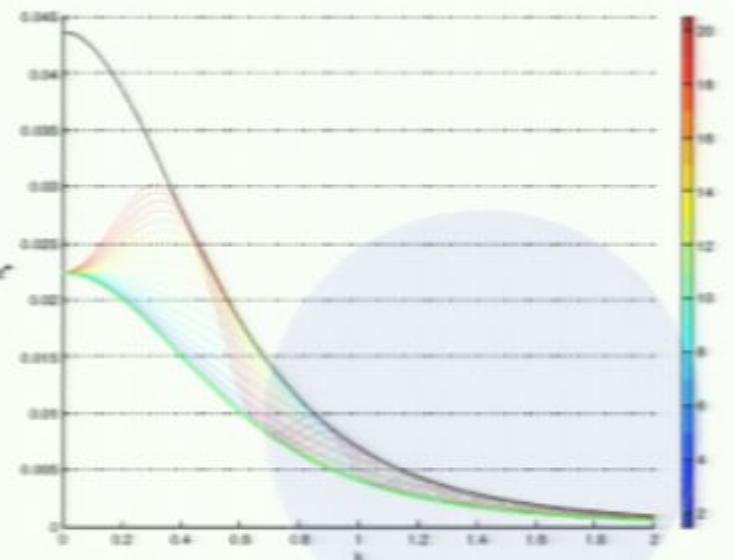


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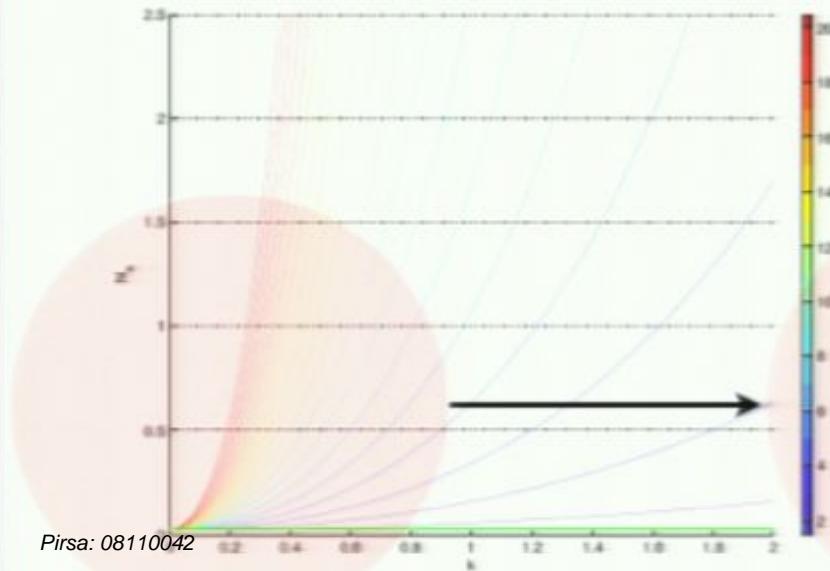
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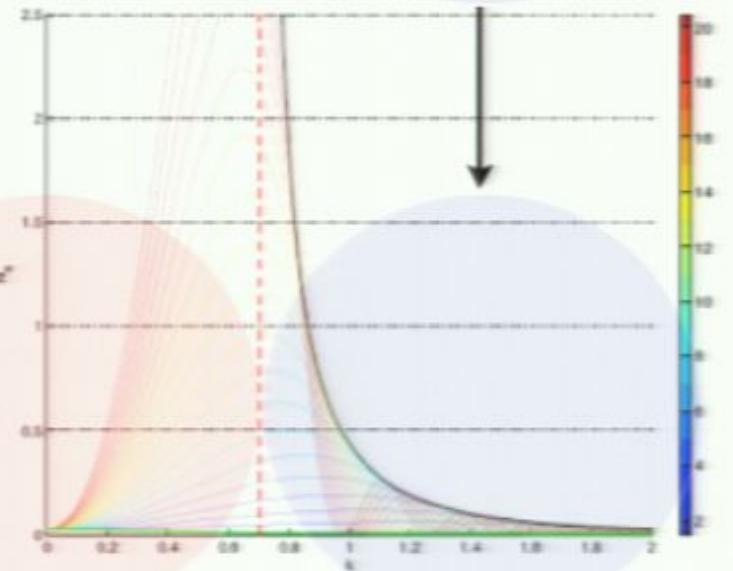
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Trans-Planckian beats signature - but why?

Let's do quantum gravity phenomenology, in the sense of an ultra-high energy breakdown of Lorentz symmetry

T. Jacobson, "Black hole evaporation and ultrashort distances", Phys. Rev. D 44 (1991) 1731

$$\Delta_{d+1}\phi - F(-\Delta_d)\phi = m^2\phi$$

where



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Δ_{d+1} is the spacetime D'Alembertian

$$\Delta_{d+1}\phi = \frac{1}{\sqrt{-g_{d+1}}}\partial_a(\sqrt{-g_{d+1}}g^{ab}\partial_b\phi)$$

Δ_d is a purely spatial D'Alembertian

$$\Delta_d\phi = \frac{1}{\sqrt{g_d}}\partial_i(\sqrt{g_d}g^{ij}\partial_j\phi)$$



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$$\bar{\omega}_{\text{effective}}^2 = \epsilon A^d [m^2 + F(k^2/A) + k^2/A]$$

$$\beta \approx i \sinh \left\{ \int_E \sqrt{m^2 + k^2/A + F(k^2/A)} A^{d/2} d\bar{t} \right\}$$



Trans-Planckian beats signature

Particle production in *real* world with naive LIV terms:

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Particle production in analogue *world* - a BEC - with quantum pressure correction to the mean-field:

$$\beta \approx i \sin \left\{ \int_E \sqrt{B m^2 + \varepsilon_{qp}^2 k^4 + B k^2/A} A^{d/2} d\bar{t} \right\}$$



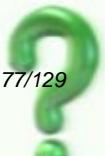


Conclusions for signature change events

quantum modes on a Riemannian manifold have like super-
bubble horizon modes during inflation

> Explains particle production

Signature change events in the *real* universe show serious
problems: driving the production of an infinite number of
particle, with infinite energy, which are not removed by
dimension, rest mass, or even reasonable sub-class of LIV



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problems: driving the production of an infinite number of
particle, with infinite energy, which are not removed by
dimension, rest mass, or even reasonable sub-class of LIV

If there is a way to drive sig. change events within the
realm QG, there should be a mechanism to regularize the
infinities..! (Analogue to the situation in the BEC)



Quantum gravity phenomenology

Quantum gravity phenomenology [LIV]

QGP: Summarizes all possible **phenomenological consequences from quantum gravity**. While different quantum gravity candidates may have completely distinct physical motivation, they can yield similar observable consequences, e.g. **Lorentz symmetry breaking at high energies**.

- 1) Presense of a preferred frame;
- 2) All frames equal, but transformation laws between frames are modified.



Analogue Lorentz symmetry breaking

Symmetry breaking mechanism in different analogue models lead to model-specific modifications:

Bose-Einstein condensate: $\omega_k^2 = c_0^2 k^2 + \epsilon_{qp}^2 k^4$

Electromagnetic waveguide: $\omega_k^2 = \frac{4}{LC} \sin^2\left(\frac{k \Delta x}{2}\right) \approx c^2 k^2 - \frac{\Delta x^4}{12LC} k^4$.

Despite all fundamental differences similar modifications:

$$\Delta\omega_k^2 \sim \pm k^4.$$

Any emergent spacetimes based on analogue models per definition have a preferred frame: The external observer.





Generating a mass and Goldstone's theorem

[*] Back to the equation of motion -

Can we extend the class of fields...

[*] Goldstone's theorem -

Spontaneous symmetry breaking...

[*] Mass generating mechanism -

Explicit symmetry breaking...



Goldstone's theorem...

“... whenever a continuous symmetry is spontaneously broken, massless fields, known as Nambu-Goldstone bosons, emerge.” [Quantum Field Theory in a Nutshell, A. Zee]

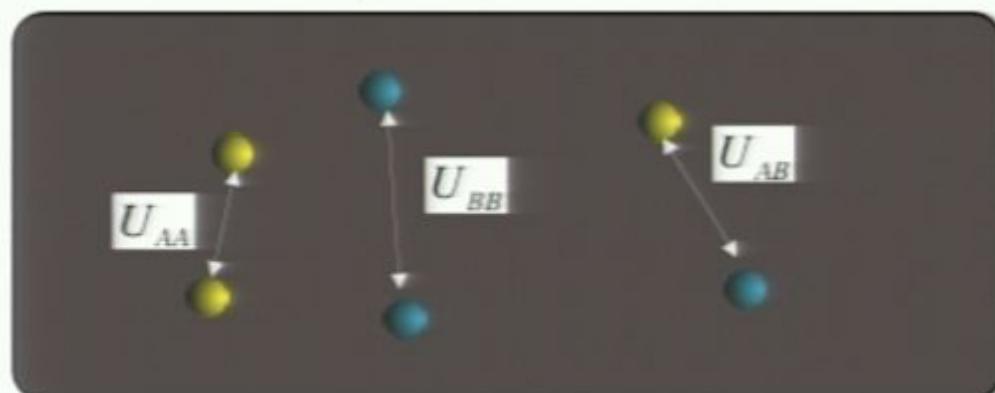
Per definition Bose-Einstein condensation always (spontaneously) breaks $SO(2)$ symmetry of many-body Hamiltonian!!!

$$\hat{H} = \int d\mathbf{x} \left(-\hat{\Psi}^\dagger \frac{\hbar^2}{2m} \nabla^2 \hat{\Psi} + \hat{\Psi}^\dagger V_{\text{ext}} \hat{\Psi} + \frac{U}{2} \hat{\Psi}^\dagger \hat{\Psi}^\dagger \hat{\Psi} \hat{\Psi} \right)$$



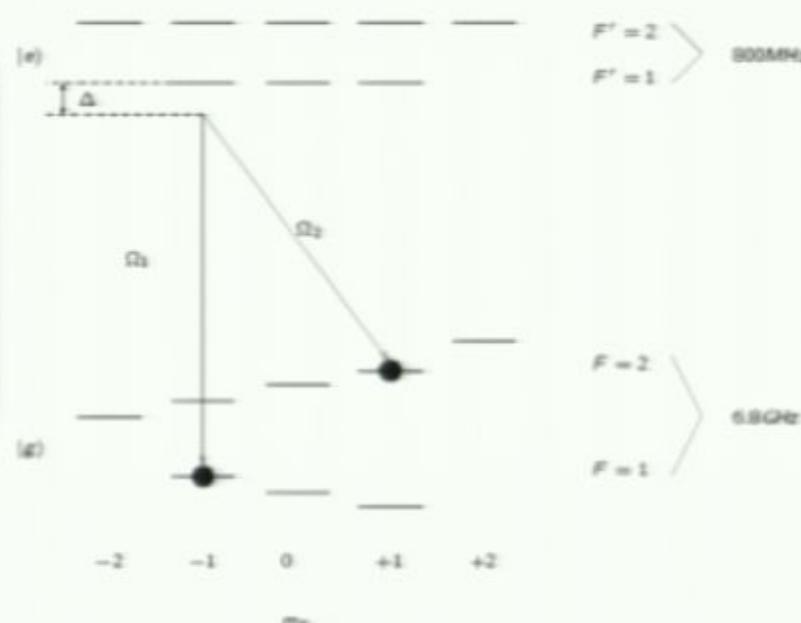
Mass generating mechanism - all about symmetries

M. Visser and S. W. Phys. Rev., D72:044020, 2005.



Explicit symmetry breaking through transitions in a 2-component system

$$\hat{H} = \int d\mathbf{r} \left\{ \sum_{i=1,2} \left(-\hat{\Psi}_i^\dagger \frac{\hbar^2 \nabla^2}{2m_i} \hat{\Psi}_i + \hat{\Psi}_i^\dagger V_{ext,i}(\mathbf{r}) \hat{\Psi}_i \right) + \frac{1}{2} \sum_{i,j=1,2} \left(U_{ij} \hat{\Psi}_i^\dagger \hat{\Psi}_j^\dagger \hat{\Psi}_i \hat{\Psi}_j + \lambda \hat{\Psi}_i^\dagger (\sigma_x)_{ij} \hat{\Psi}_j \right) \right\}$$



$$SO(2)_A \times SO(2)_B \rightarrow SO(2)_{AB}$$

$$\theta_A \rightarrow \tilde{\theta}_A = \theta_A \exp(+i\alpha) \quad \theta_B \rightarrow \tilde{\theta}_B = \theta_B \exp(-i\alpha)$$

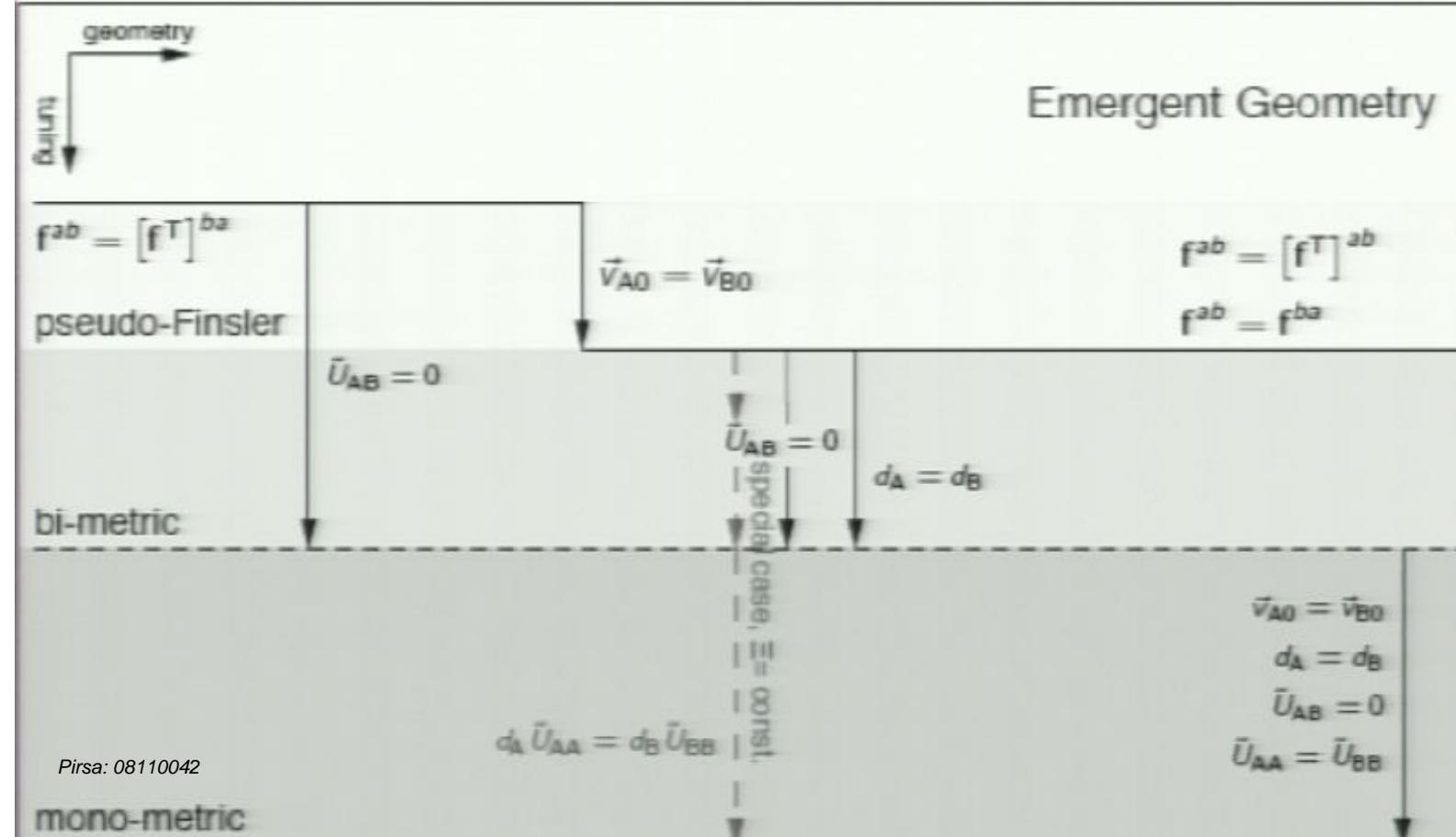
However, the fundamental Hamiltonian of the two-component system is a functional of $\vec{\theta} = (\theta_A, \theta_B)$. In the absence of transitions between the two fields the Hamiltonian exhibits an extra $SO(2)$ symmetry under which $\vec{\theta}$ transforms as a 2-component vector. This symmetry is explicitly broken for interacting fields, so that $SO(2)_A \times SO(2)_B \rightarrow SO(2)_{AB}$. The coupled system is only invariant under simultaneous transformations of the form $\theta_A \rightarrow \tilde{\theta}_A = \theta_A \exp(+i\alpha)$, and $\theta_B \rightarrow \tilde{\theta}_B = \theta_B \exp(-i\alpha)$. Thus the spontaneous symmetry breaking during the Bose-Einstein condensation relates to $SO(2)_{AB}$, in *Pirsa: 08110042* individual symmetries. Altogether, linearizing around both fields yields two excitations, where one has to be a "Nambu-Goldstone Boson" (i.e., a zero-mass excitation), while there are no constraints on the mass of the second quasi-particle.



Mono-metricity

More complicated hyperbolic wave equation: $\partial_a (f^{ab} \partial_b \bar{\theta}) + (\Lambda + K) \bar{\theta} + \frac{1}{2} \{ \Gamma^a \partial_a \bar{\theta} + \partial_a (\Gamma^a \bar{\theta}) \} = 0$

$$f^{ab} = \begin{bmatrix} \Xi_{11}^{-1} \left(\begin{array}{c|c} -1 & -\vec{v}_{A0}^T \\ \hline -\vec{v}_{A0} & \frac{d_a}{\Xi_{11}^{-1}} \delta_{ij} - \vec{v}_{A0} \vec{v}_{A0}^T \end{array} \right) & \Xi_{12}^{-1} \left(\begin{array}{c|c} 1 & \vec{v}_{B0}^T \\ \hline \vec{v}_{A0} & \vec{v}_{A0} \vec{v}_{B0}^T \end{array} \right) \\ \hline \Xi_{21}^{-1} \left(\begin{array}{c|c} 1 & \vec{v}_{A0}^T \\ \hline \vec{v}_{B0} & \vec{v}_{B0} \vec{v}_{A0}^T \end{array} \right) & \Xi_{22}^{-1} \left(\begin{array}{c|c} -1 & -\vec{v}_{B0}^T \\ \hline -\vec{v}_{B0} & \frac{d_a}{\Xi_{22}^{-1}} \delta_{ij} - \vec{v}_{B0} \vec{v}_{B0}^T \end{array} \right) \end{bmatrix} \quad f^{ab} \sim \sqrt{-g} g^{ab}$$

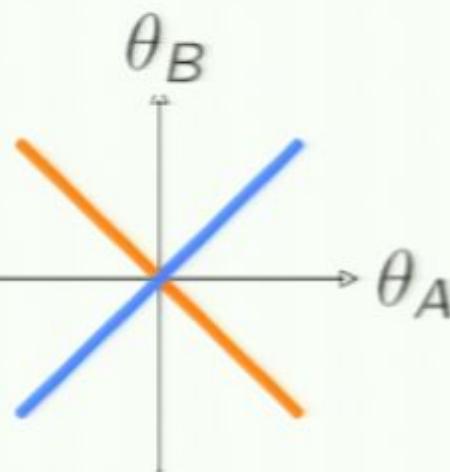


Emergent massive fields

$$\frac{1}{\sqrt{-g_{I/II}}} \partial_a \left\{ \sqrt{-g_{I/II}} (g_{I/II})^{ab} \partial_b \tilde{\theta}_{I/II} \right\} + \omega_{I/II}^2 \tilde{\theta}_{I/II} = 0$$

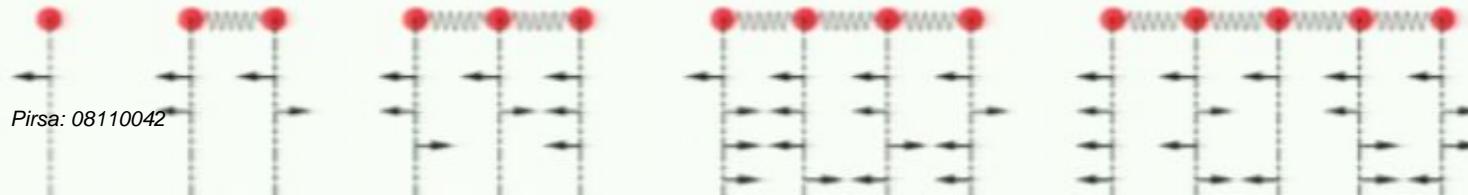
the acoustic metrics are given by

$$(g_{I/II})_{ab} \propto \begin{bmatrix} -(c^2 - v_0^2) & -v_0^T \\ -v_0 & I_{d \times d} \end{bmatrix}$$



In-phase perturbation (= mass zero particle): $\omega_I^2 = 0$

Anti-phase perturbation (= mass non-zero particle): $\omega_{II}^2 \propto \lambda \neq 0$



Bogoliubov dispersion relation for 2-comp. sys.

$$\omega_k^2 = \omega_0^2 + (1 + \eta_2) c^2 k^2 + \eta_4 \left(\frac{\hbar}{M_{LIV}} \right)^2 k^4 + \dots$$



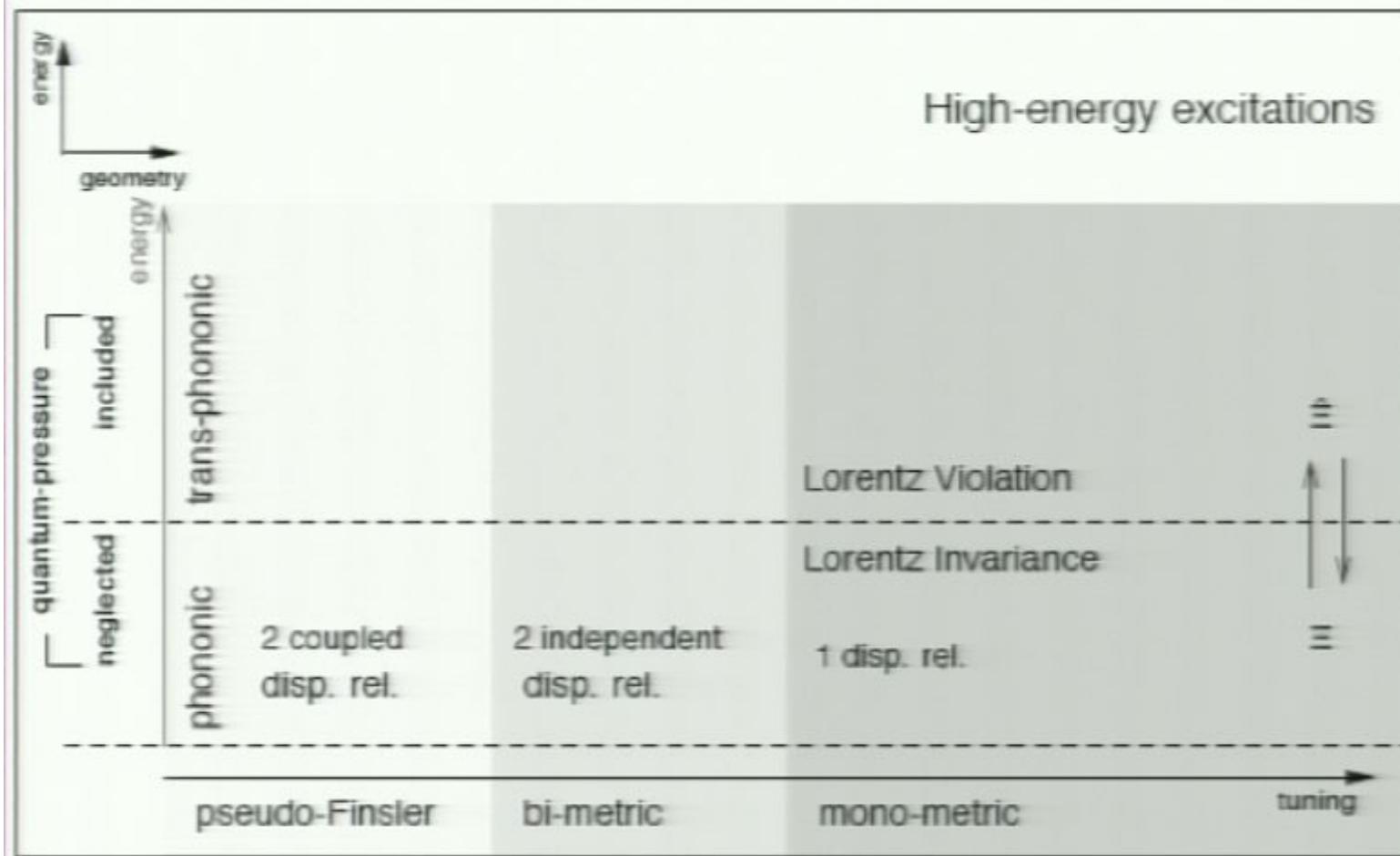
$$\eta_{4,X} \approx 1; \quad X = I, II$$

$$\eta_{2,X} \approx \left(\frac{m_X}{M_{\text{eff}}} \right)^2 = \left(\frac{\text{mass scale of quasiparticle}}{\text{effective Planck scale}} \right)^2; \quad X = I, II$$



Collective excitations + microscopic fingerprints

Beyond the hydrodynamic approximation...



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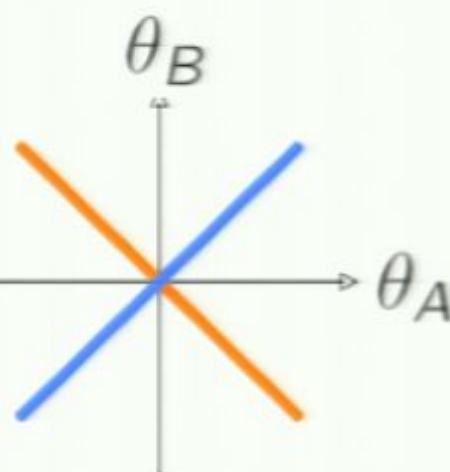


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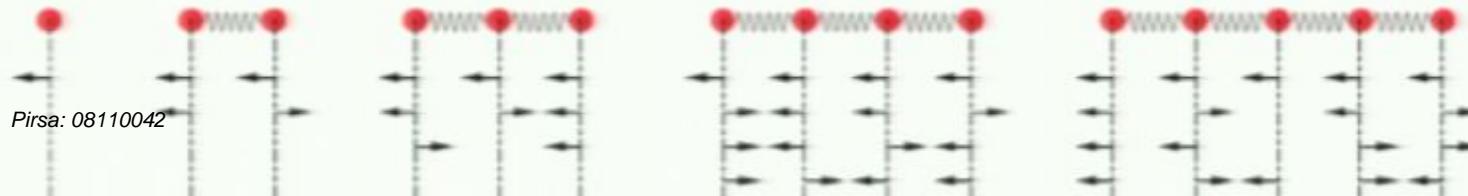
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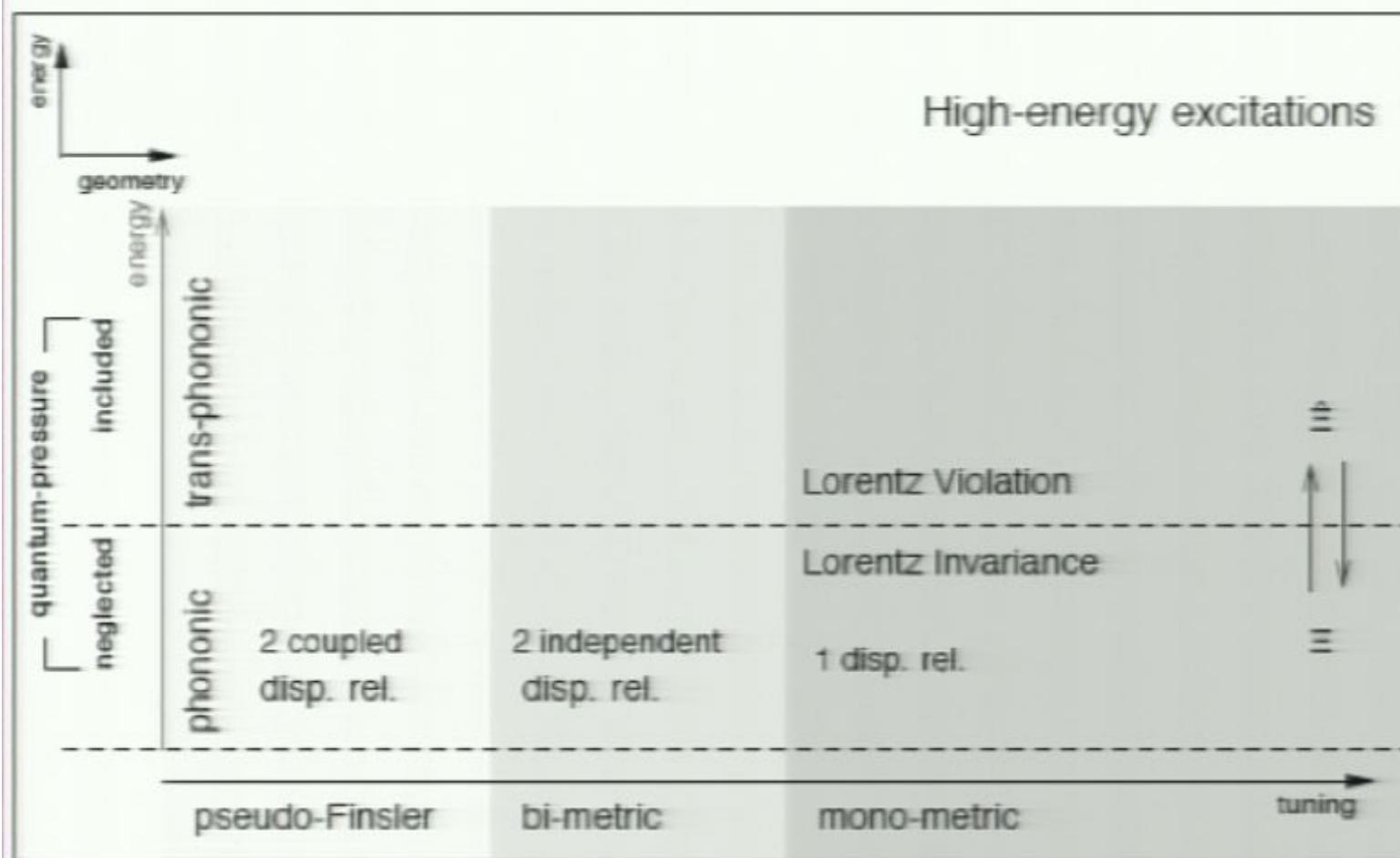
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Naturalness problem in emergent spacetime

Dispersion relation obtained from our CMS has the form:

$$\omega^2 = \omega_0^2 + (1 + \eta_2) c^2 k^2 + \eta_4 \left(\frac{\hbar}{M_{\text{LIV}}} \right)^2 k^4 + \dots$$

CPT invariant (LIV in the boost subgroup)

has the form as suggested in many (non-renormalizable) effective field theory approaches

natural suppression of low-order modifications in our model!

$$\begin{aligned} \eta_{2,\text{I/II}} &\approx \left(\frac{m_{\text{I/II}}}{M_{\text{LIV}}} \right)^2 = \left(\frac{\text{quasiparticle mass}}{\text{effective Planck scale}} \right)^2; \\ \eta_{4,\text{I/II}} &\approx 1; \end{aligned}$$

analogue LIV scale is given by the microscopic variables: $M_{\text{LIV}} = \sqrt{m_A m_B}$

not a tree-level result. results directly computed from fundamental Hamiltonian

η_4 -coefficients are different for $m_A \neq m_B$



Cosmolgoy



Cosmolgoy

The image shows a grey navigation bar with three white rectangular windows containing text and small icons. On the far left is a left-pointing arrow. In the center is a window with the number 54 highlighted in a light blue box. On the far right is a right-pointing arrow. The windows contain the following text:

53

Naturality problem in emergent spacetime
Dipendra Patel's connection from our CMS has the form:
$$\omega = \omega_0 + \omega_1 \exp(-\frac{1}{2} \int d^4x \sqrt{-g} R) \left(\frac{\partial}{\partial t} - \frac{1}{2} \nabla^2 \right)^2 dt$$

This is a very interesting result. It is also very similar to the one I obtained in my paper.
I am curious if there is any other way to obtain this result.

54

Comments

55

On robustness
Robustness (against reasonable modifications of spacetime field) –
Check in emergent spacetime
P. C. W. Davies and S. Aspinwall (arXiv:hep-th/0207001)
Emergent spacetime – robust against reasonable modifications of spacetime field
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Emergent spacetime – robust against reasonable modifications of spacetime field
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Cosmolgoy



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PI-2008

New Play View Themes Masters Text Box Shapes Table Charts Comment Smart Builds Mask Alpha Group Ungroup

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Slides

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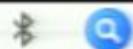
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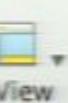
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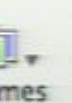
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View



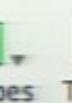
Themes



Masters



Text Box



Shapes



Table



Charts



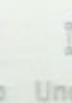
Comment



Smart Builds



Mask



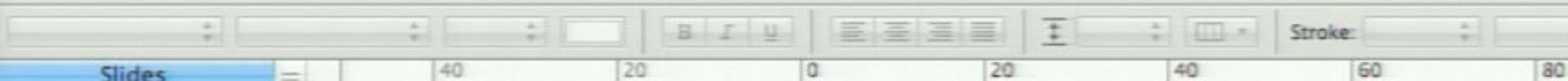
Alpha



Group



Ungroup



Slides

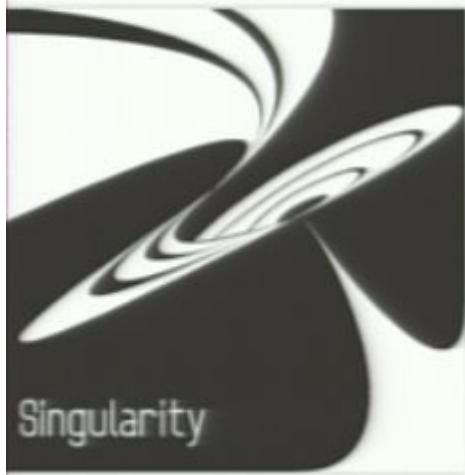
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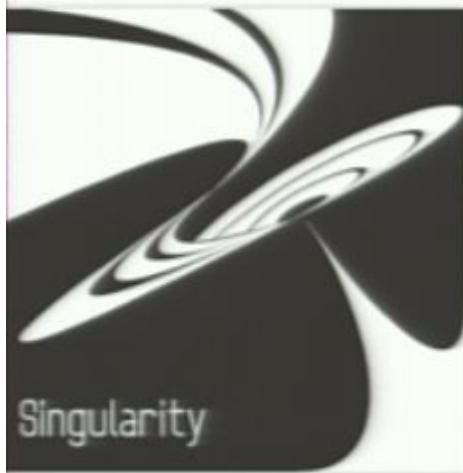


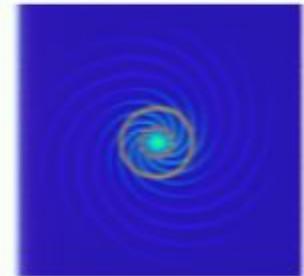
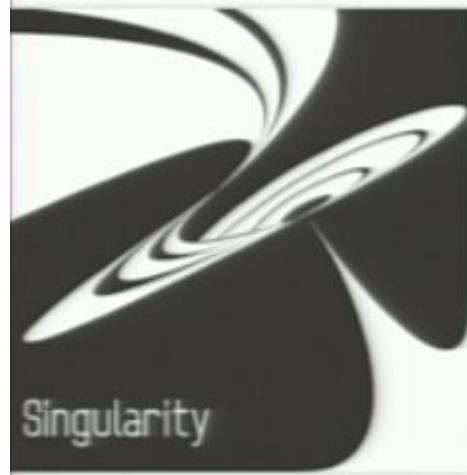
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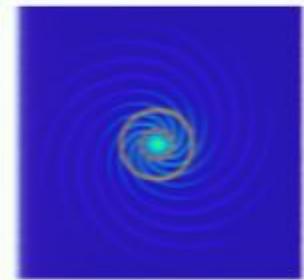
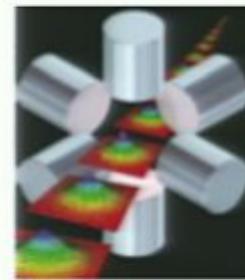
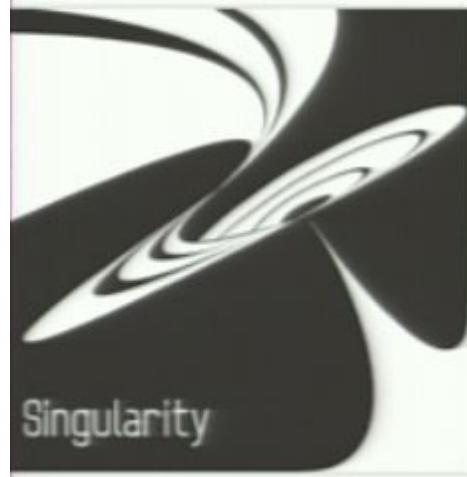
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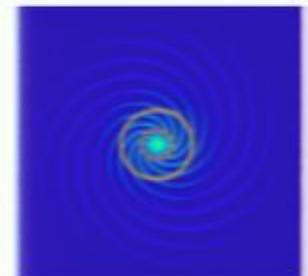
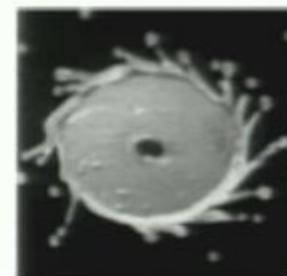
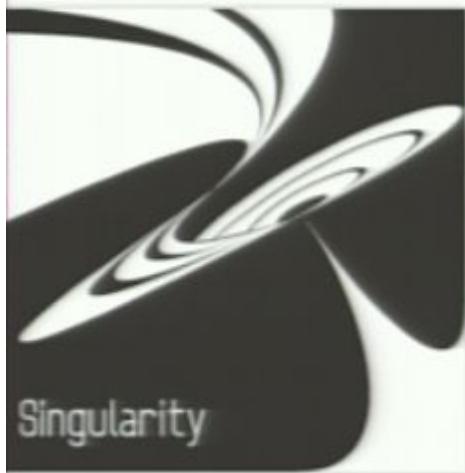


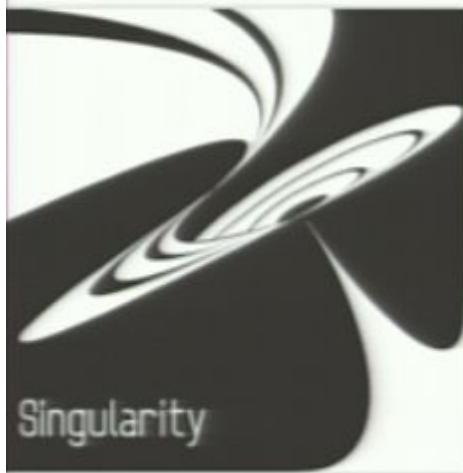








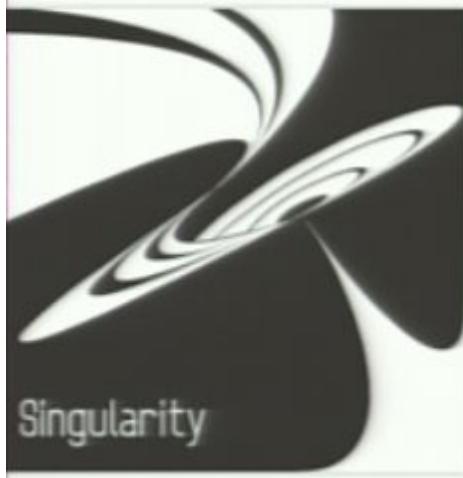




“Black Hole” Nucleation in a Splash of Milk

Laurent Courbin¹, James C. Bird¹, Andrew Belmonte²
& Howard A. Stone¹

1. School of Engineering and Applied Sciences, Harvard University, USA
2. W. G. Pritchard Labs, Dept of Mathematics, Penn State University, USA



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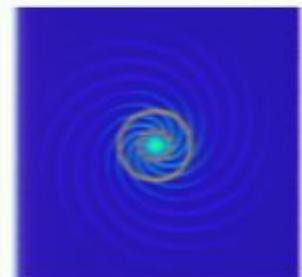
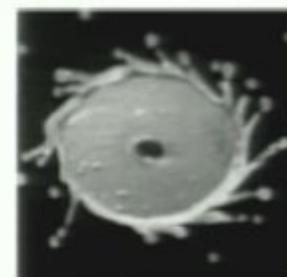
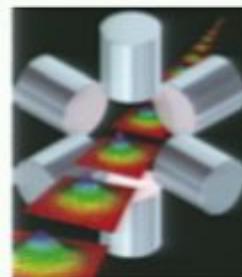
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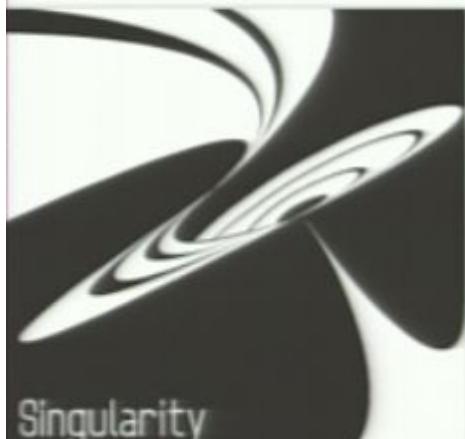
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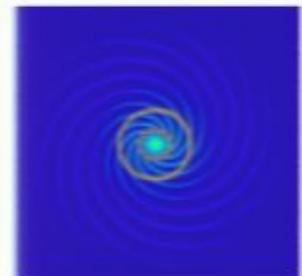
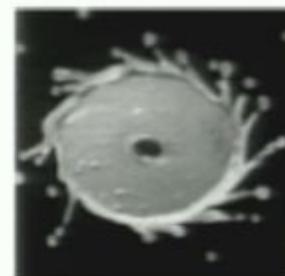
Singularity



The bouncing of a fluid droplet off of a hydrophobic surface is well known.



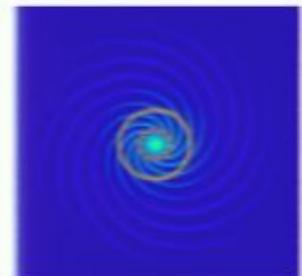
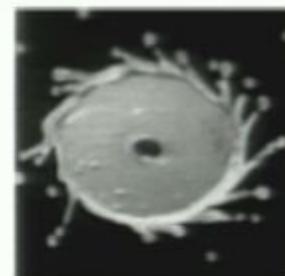
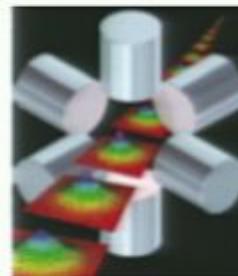
Singularity



The bouncing of a fluid droplet off of a hydrophobic surface is well known. Here we use rotational effects to spread out the droplet during the bounce, leading to a variety of new effects.



Singularity

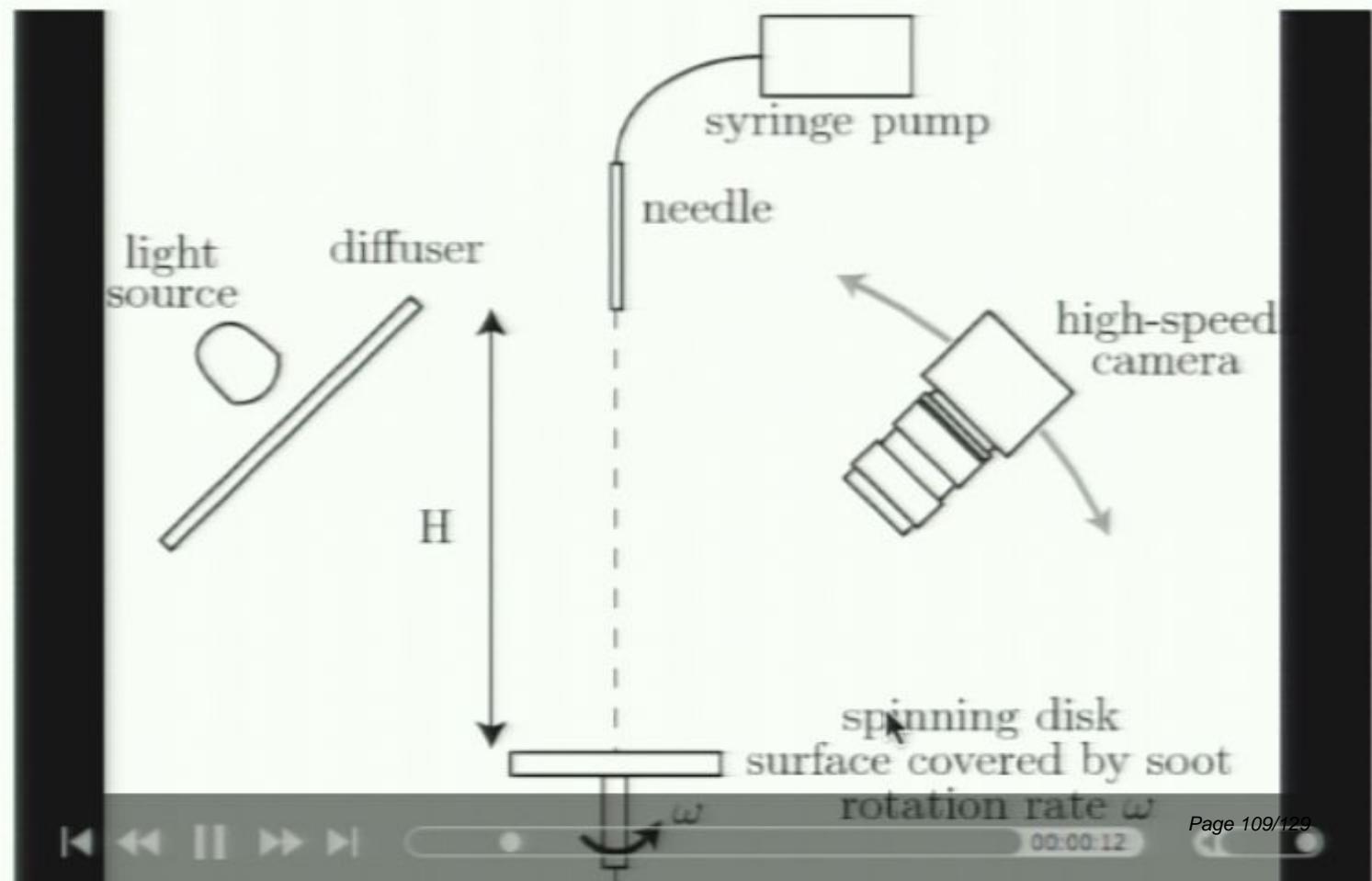
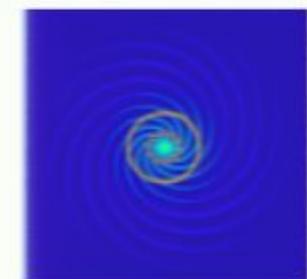
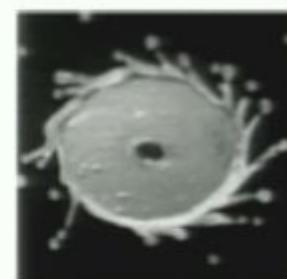
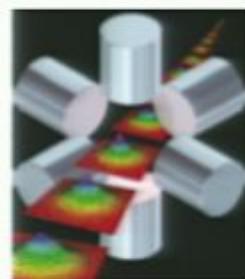


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Experimental set-up

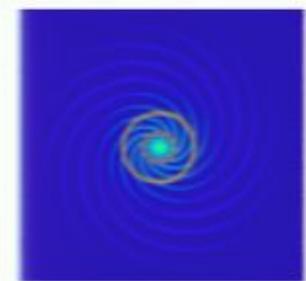
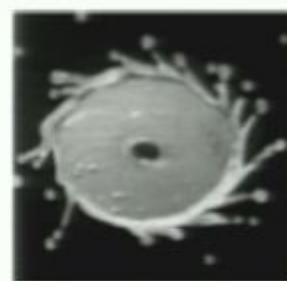


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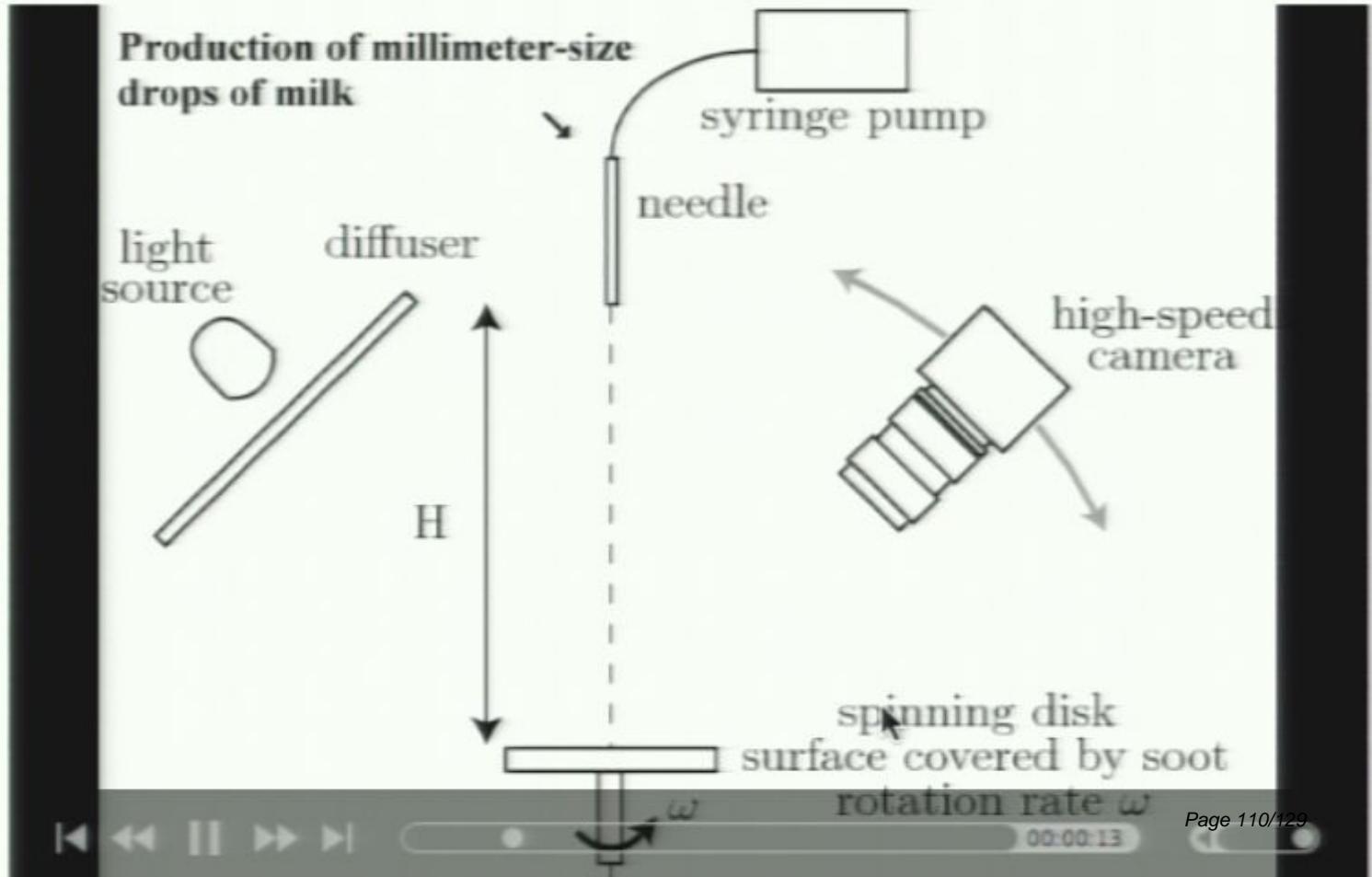




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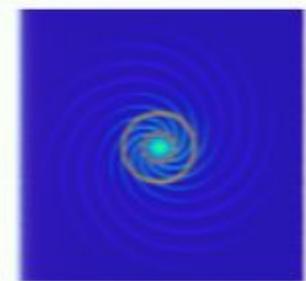
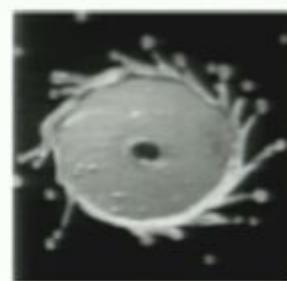
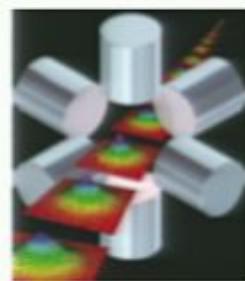


Production of millimeter-size drops of milk

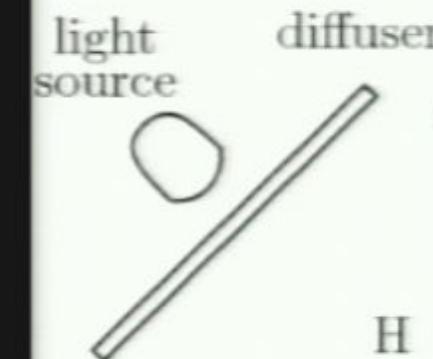




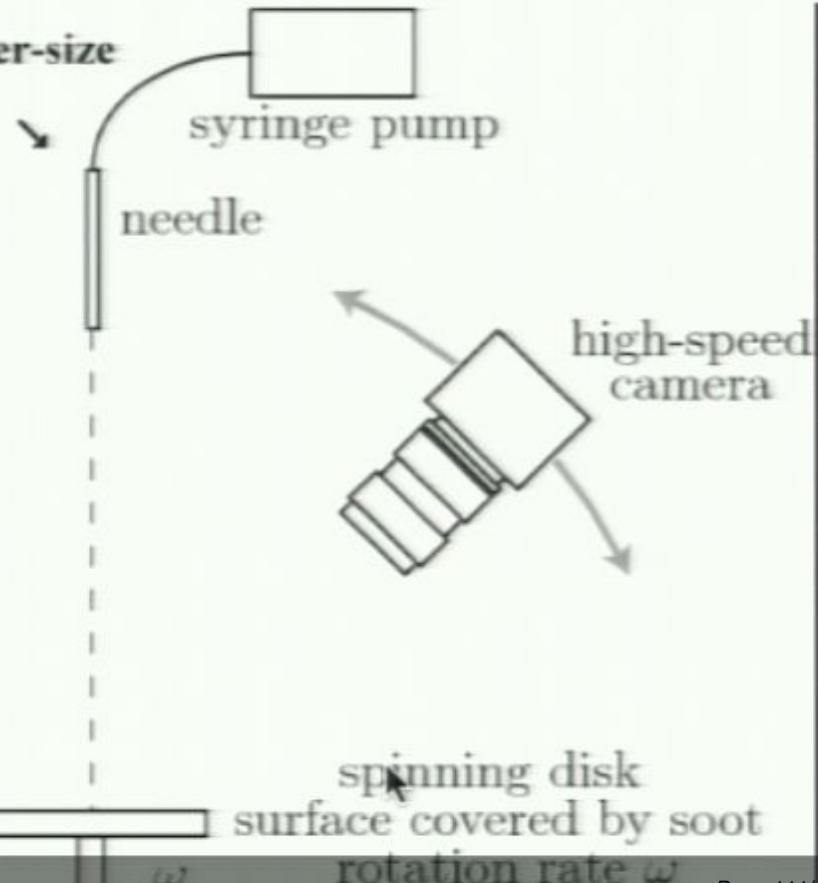
Singularity



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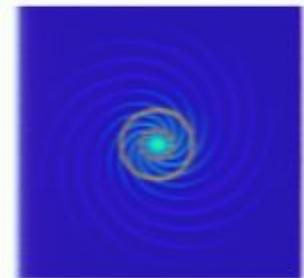
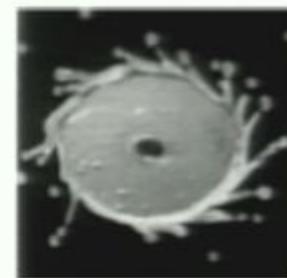
 H

$H = 2\text{-}20 \text{ cm}$
 $\omega = 50\text{-}700 \text{ rad/s}$





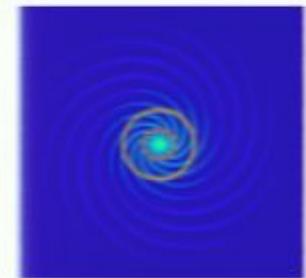
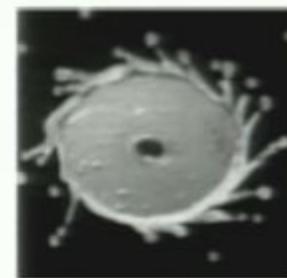
Singularity

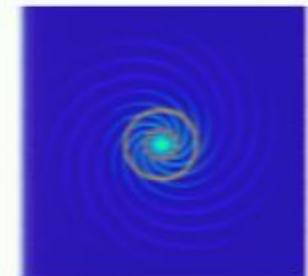
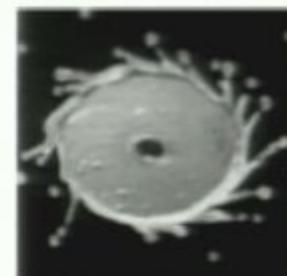
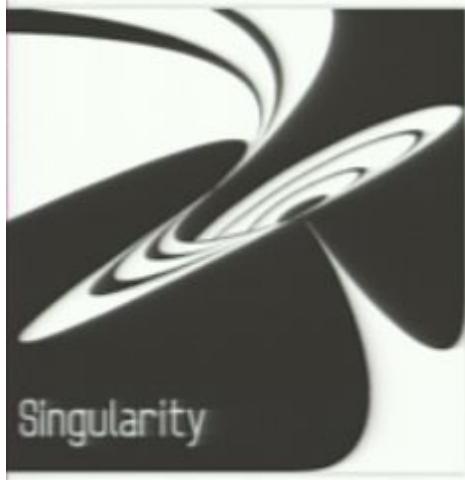


Statics



Singularity





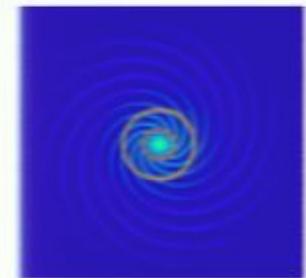
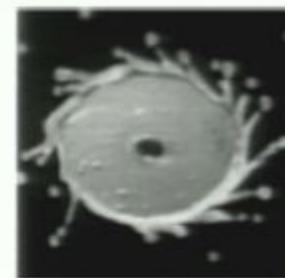
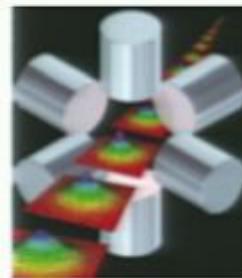
Nearly spherical millimeter-size drop of milk ↗

The disk surface covered by soot exhibits superhydrophobicity ↗





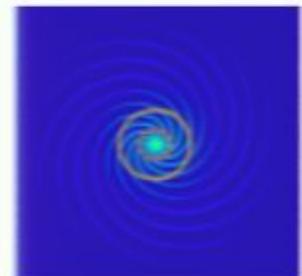
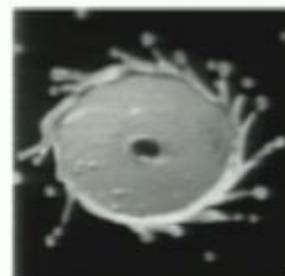
Singularity



Impact dynamics



Singularity

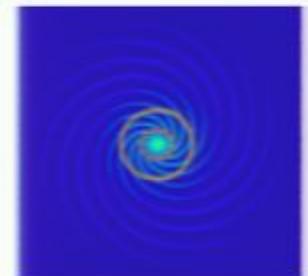
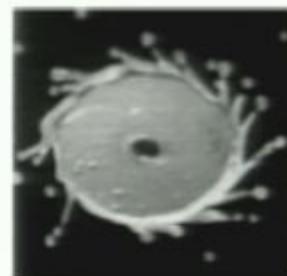


Small H and ω

Bouncing



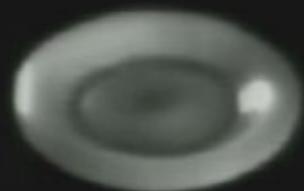
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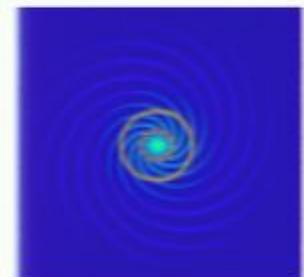
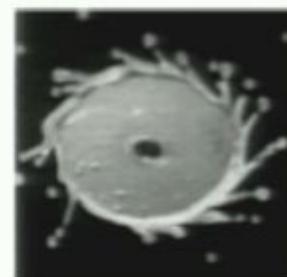
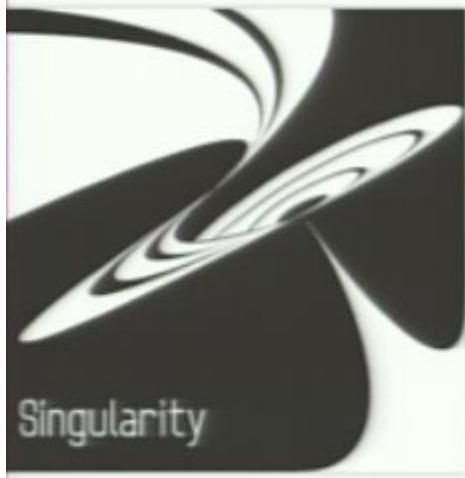


20.75 ms

$H = 37 \text{ mm}$
 $\omega = 79 \text{ rad/s}$

The drop retracts





40.25 ms

$H = 37 \text{ mm}$
 $\omega = 79 \text{ rad/s}$

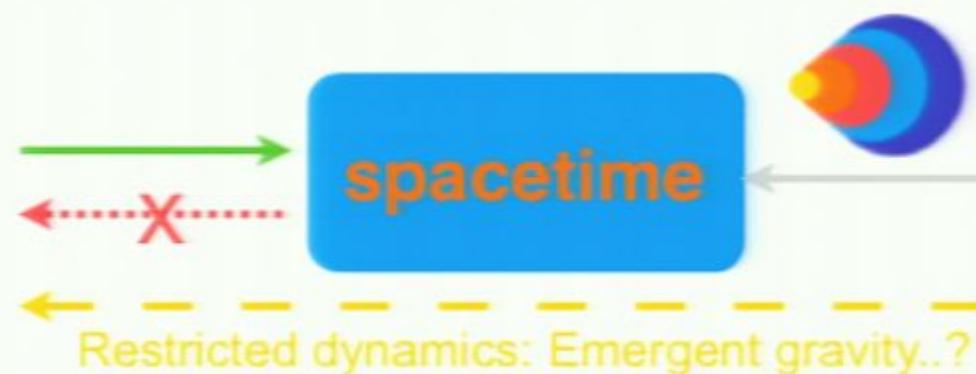
A video frame showing a fluid drop on a surface. The drop has retracted and is now a small, vertical column of liquid. The text "The drop retracts and rebounds" is overlaid on the left side of the frame. In the center, there is a large, semi-transparent letter "i". A cursor arrow is visible in the bottom right corner. At the very bottom, there is a control bar with arrows for navigation and a progress bar indicating "00:00:37".

The drop retracts
and rebounds

Emergent gravity

Einstein
dynamics:

$$G_{ab} = 8\pi G_N T_{ab}$$



Broad class of systems with ***completely*** different dynamics:
electromagnetic waveguide, fluids, ultra-cold gas of Bosons and Fermions;

Emergent gravity

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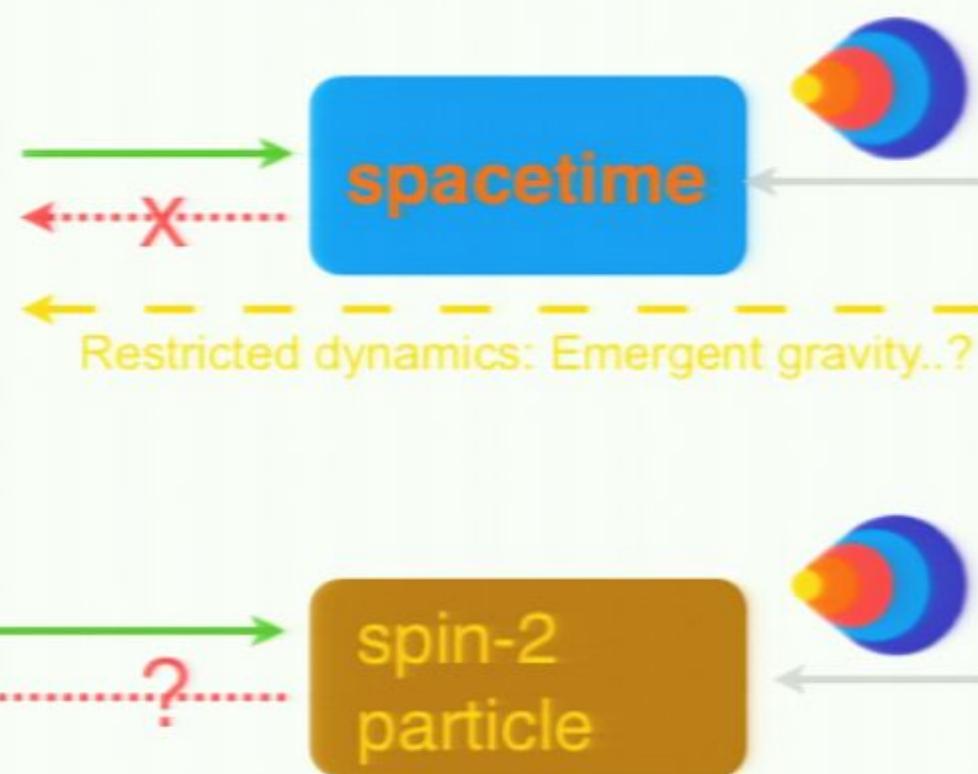


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(1+4) dimensional quantum Hall effect, quantum rotor model;

Emergent gravity

Einstein dynamics:

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spacetime

**spin-2
particle**

Restricted dynamics: Emergent gravity..?

Broad class of systems with **completely** different dynamics:

electromagnetic waveguide, fluids, ultra-cold gas of Bosons and Fermions;

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