Title: Analogue gravity as a toy model of emergent spacetime: three small lessons

Speakers: Stefano Liberati

Series: Quantum Gravity

Date: April 07, 2022 - 9:30 AM

URL: https://pirsa.org/22040106

Abstract: The analogue gravity framework uses condensed matter systems to simulate phenomena characteristics of quantum field theory in curved spacetimes (e.g. cosmological particle production or black hole evaporation). In this seminar, I will review the state of this field and explore its extension towards the simulation of the emergent spacetime paradigm. In doing so I will discuss three lessons that we can draw from this framework about long standing puzzles in black hole thermodynamics and cosmology.

Zoom Link: https://pitp.zoom.us/j/98714282554?pwd=QnAxRkk4SVg0TnVneDFySFJYTDJoQT09

Stefano Liberati

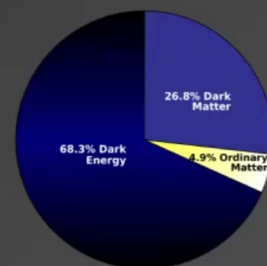
Analogue gravity as a toy model of emergent spacetime: three small lessons

Talk @

GR, a beautiful but weird theory...

Albeit we "use" GR everyday (e.g. GPS) still it has some tantalising features and it has proved very hard to fully merge with QM.

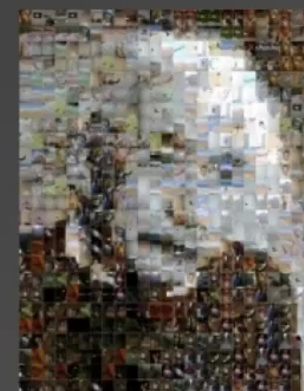
- Singularities and Horizon thermodynamics
- Critical phenomena in gravitational collapse
- The "dark ingredients" of our universe?
- AdS/CFT duality, holographic behaviour
- Faster than light and Time travel solutions
- Gravity/fluid duality
- thermodynamic interpretation of Einstein equations
- Entropic force interpretation of gravity
- Spacetime thermodynamics: Einstein equation as an equation of state (irreversible terms)



Emergent Spacetimes?

Emergent gravity idea: the metric or the connections are not fundamental object but collective variables of more fundamental discrete/quantum structures. Gravitons would be more like phonons than true elementary particles...

- GR ⇒ Hydrodynamics
- Metric as a collective variable
- All the sub-Planckian physics is low energy physics
- Spacetime as a condensate of some more fundamental objects
- Spacetime symmetries as emergent symmetries
- Singularities as phase transitions (Big Bang as geometrogenesis)
- Cosmological constant as deviation from the real ground state



- Many QG proposals are nowadays resorting to emergent gravity scenarios. E.g.
  - Causal sets
  - Quantum graphity models
  - Group field theories
  - AdS/CFT scenarios where the CFT is considered primary
  - For me: Any QG approach where the underlying quantum/discrete structure is not a mere regulator and gravitons are collective excitations of this substratum.
    - The emergent spacetime paradigm is not an alternative to teh quantum gravity one, but refers to the way classical/continuuum spacetime is recovered in a given QG model.

Condensed matter analogues of gravity are actually realisable settings where many these ideas can be directly tested

W.G. Unruh Phys Rev Lett 46 1351 (1981)
But see also White '73

WHAT IS ANALOGUE GRAVITY?

Continuity $\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v}) = 0$ Euler $\rho \frac{d\vec{v}}{dt} \equiv \rho \left[\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla) \vec{v} \right] = -\vec{\nabla} p - \rho \vec{\nabla} \Phi + \vec{f}_{\text{viscosity}}$

External Forces $\vec{f}_{\text{viscosity}} = +\eta \nabla^2 \vec{v} + \left(\zeta + \frac{1}{3} \eta \right) \vec{\nabla} \left(\vec{\nabla} \cdot \vec{v} \right)$

$p =$ pressure, $\eta =$ dynamic viscosity, $\zeta =$ bulk viscosity,

$\Phi =$ potential of external driving force (gravity included)

Basic Assumptions

$\vec{\nabla} \times \vec{v} = \vec{0}$ $\vec{v} = \vec{\nabla} \psi$ $\rho = \rho(p)$ $c_s^2 = \frac{dp}{d\rho}$

IDEAL PERFECT FLUID
Irrotational Flow
Barotropic
Viscosity free flow

Linearize the above Eq.s around some background

$$\rho(t,x) = \rho_0(t,x) + \varepsilon \rho_1(t,x)$$
$$p(t,x) = p_0(t,x) + \varepsilon p_1(t,x)$$
$$\psi(t,x) = \psi_0(t,x) + \varepsilon \psi_1(t,x)$$

And combine then so to get a second order field equation

$$\frac{\partial}{\partial t} \left(c_s^{-2} \rho_0 \left(\frac{\partial \psi_1}{\partial t} + \vec{v}_0 \cdot \nabla \psi_1 \right) \right) = \nabla \cdot \left(\rho_0 \nabla \psi_1 - c_s^{-2} \rho_0 \vec{v}_0 \left(\frac{\partial \psi_1}{\partial t} + \vec{v}_0 \cdot \nabla \psi_1 \right) \right)$$

This looks messy but if we introduce the "acoustic metric"

$$g_{\mu\nu} \equiv \frac{\rho_0}{c_s} \begin{bmatrix} -\left(c_s^2 - v_0^2 \right) & -v_0^j \\ -v_0^i & \delta_{ij} \end{bmatrix}$$

We get

$$\Delta \psi_1 \equiv \frac{1}{\sqrt{-g}} \partial_\mu \left(\sqrt{-g} g^{\mu\nu} \partial_\nu \psi_1 \right) = 0$$

W.G. Unruh Phys Rev Lett 46 1351 (1981)
But see also White '73

What is analogue gravity?

Continuity $\frac{\partial\rho}{\partial t}+\vec{\nabla}\cdot(\rho\vec{v})=0$ Euler $\rho\frac{d\vec{v}}{dt}\equiv\rho\left[\frac{\partial\vec{v}}{\partial t}+(\vec{v}\cdot\nabla)\vec{v}\right]=-\vec{\nabla}p-\rho\vec{\nabla}\Phi+\vec{f}_{\text{viscosity}}$

External Forces $\vec{f}_{\text{viscosity}}=+\eta\nabla^2\vec{v}+\left(\zeta+\frac{1}{3}\eta\right)\vec{\nabla}(\vec{\nabla}\cdot\vec{v})$

$p=$ pressure, $\eta=$ dynamic viscosity, $\zeta=$ bulk viscosity,

$\Phi=$ potential of external driving force (gravity included)

Basic Assumptions

$\vec{\nabla}\times\vec{v}=\vec{0}$ $\vec{v}=\vec{\nabla}\psi$ $\rho=\rho(p)$ $c_s^2=\frac{dp}{d\rho}$

IDEAL PERFECT FLUID
Irrotational Flow
Barotropic
Viscosity free flow

Linearize the above Eq.s around some background

$$\rho(t,x)=\rho_0(t,x)+\varepsilon\rho_1(t,x)$$
$$p(t,x)=p_0(t,x)+\varepsilon p_1(t,x)$$
$$\psi(t,x)=\psi_0(t,x)+\varepsilon\psi_1(t,x)$$

And combine then so to get a second order field equation

$$\frac{\partial}{\partial t}\left(c_s^{-2}\rho_0\left(\frac{\partial\psi_1}{\partial t}+\vec{v}_0\cdot\nabla\psi_1\right)\right)=\nabla\cdot\left(\rho_0\nabla\psi_1-c_s^{-2}\rho_0\vec{v}_0\left(\frac{\partial\psi_1}{\partial t}+\vec{v}_0\cdot\nabla\psi_1\right)\right)$$

This looks messy but if we introduce the "acoustic metric"

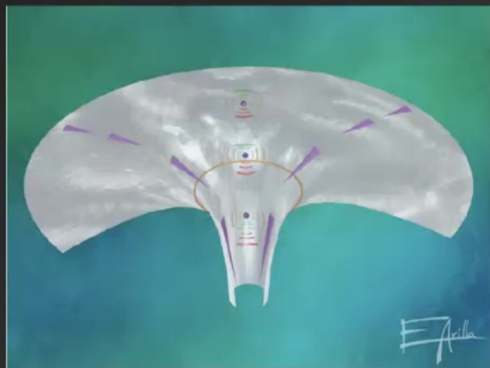
$$g_{\mu\nu}\equiv\frac{\rho_0}{c_s}\begin{bmatrix}-(c_s^2-v_0^2) & -v_0^j\\ -v_0^i & \delta_{ij}\end{bmatrix}$$

We get

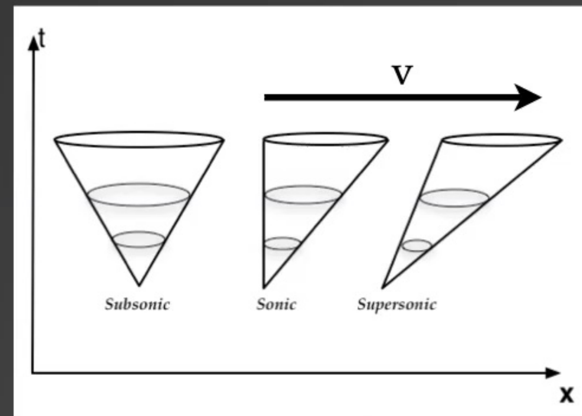
$$\Delta\psi_1\equiv\frac{1}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}g^{\mu\nu}\partial_\nu\psi_1\right)=0$$

This is the same equation as for a scalar field moving in curved spacetime, possibility to simulate FRW and Black Holes!
Analysis can be generalised to relativistic fluids=>Disformal geometries

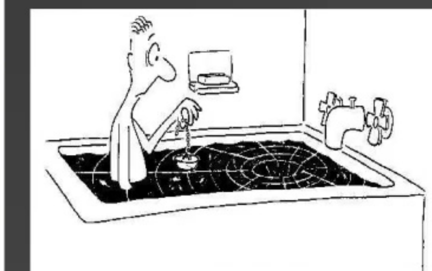
Analogue Black holes



A moving fluid will tip the "sound cones" as it moves.
Supersonic flow will tip the cone past the vertical.

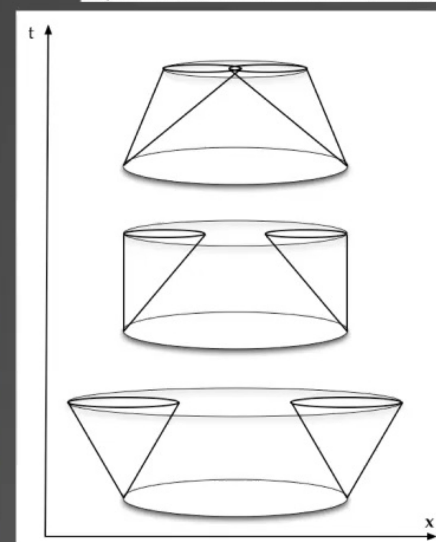


GR	Hydrodynamics
Ergoregion	Any region of supersonic flow Es: steady flow $g_{\mu\nu}(\partial/\partial t)^{\mu}(\partial/\partial t)^{\nu} \Rightarrow$ $g_{tt} = -[c_s^2 - v^2]$
Trapped Surface	Any closed two-surface where the fluid velocity is everywhere inward-pointing and the normal component of the fluid velocity is always greater than the speed of sound
Future Event Horizon	Boundary of the region from which null geodesics (phonons) cannot escape.
Surface Gravity	$g_H = \frac{1}{2}\left\lvert \frac{\partial}{\partial n}\left(c_s^2 - v_\perp^2\right)\right\rvert$



M. Visser, CQG. 15 (6): 1767-1791. (1998).

A moving fluid can form "trapped regions" when supersonic flow will tip the cone past the vertical.



If the field propagating on these black holes can be quantised we should expect analogue Hawking radiation and its puzzles…

Analogue models of gravity beyond acoustics

See e.g. C.Barcelo, S.L and M.Visser, "Analogue gravity" Living Rev.Rel.8,12 (2005-2011).

An analogue system of gravity is a generic dynamical system where the propagation of linearised perturbations can be described via hyperbolic equations of motion on some curved spacetime possibly characterized be one single metric element for all the perturbations.

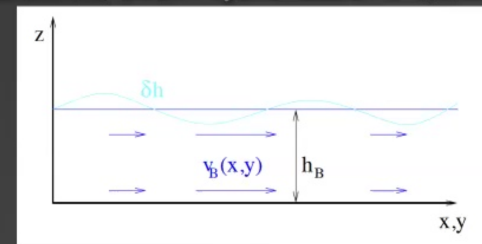
Analogue models

- Gravity waves in shallow basins (Rousseaux, Unruh-Schutzhold, Weinfurtner…)
- High-refractive index dielectric fluids: "slow light"
- Optic Fibers analogues (Philbin, Faccio, Leonhardt…)
- Quasi-particle excitations: fermionic or bosonic quasi-particles in He3 (Volovik)
- Non-linear electrodynamics
- "Solid states black holes"
- Perturbation in Bose-Einstein condensates (Garay et al, Barcelo et al, Fischer et al., Parentani et al, Carusotto et al., Steinhauer, etc…)
- Graphene

The use of Analogue gravity (AG) as a model of classical/quantum field theory in Curved spacetimes has been fundamental for understanding and reproducing phenomena of field theory on curved spacetime.

Classical analogues: e.g. Gravity waves

Schutzhold, Unruh. Phys.Rev.D66:044019,2002.



Let's consider gravity waves on an inviscid, irrotational flow of a barotropic fluid under the influence of gravity. The Bernoulli's and continuity equations imply that in the long wavelength limit (shallow basin) surface wave propagate on an effective geometry

$$ds^2 = \frac{1}{c^2}\left[-(c^2 - v_B^{\|2})\,dt^2 - 2\mathbf{v}_B^{\|}\cdot \mathbf{dx}\,dt + \mathbf{dx}\cdot\mathbf{dx}\right]$$

where $c \equiv \sqrt{g h_B}$.

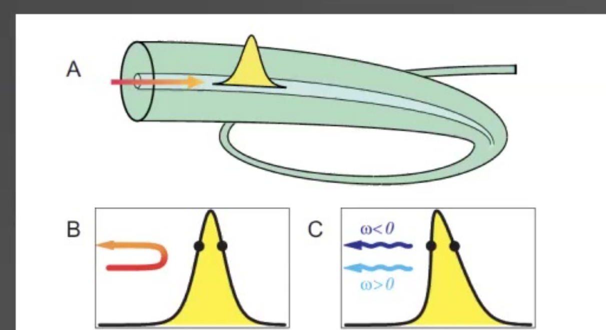
$$\omega = \mathbf{v}\cdot\mathbf{k} \pm \sqrt{\left(gk + \frac{\sigma}{\rho}k^3\right)\tanh(kh)}$$

Badulin (1983)

For arbitrary wavelength the dispersion relation is non-relativistic and goes from linear to "subluminal" to "superluminal".

Quantum analogues: e.g Fiber optics analogues

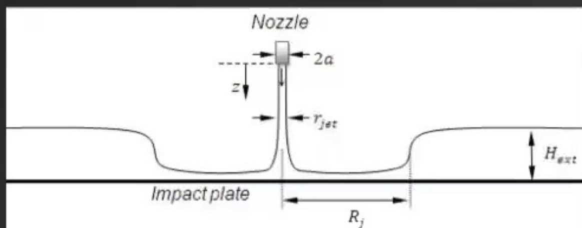
- Original idea: send non-dispersive pulses (solitons) through a optical fiber. Each pulse modifies the optical properties of the fiber due to the Kerr effect:
- the effective refractive index of the fiber, n_0, gains an additional contribution δn that is proportional to the instantaneous pulse intensity I at position z and time t.
- launch a continuous wave of light, a probe, that follows the pulse with slightly higher group velocity, attempting to overtake it
- As the probe approaches the pulse it slows down so much so that for some frequency it cannot "enter" the pulse. The rear front acts like a white horizon.
- Similarly probe light insight the pulse cannot escape from it, so the front of the pulse acts like a black horizon.



MAKE YOUR OWN WHITE HOLE AT HOME!

Basic setup: A liquid is pumped through a nozzle and the fluid jet impacts vertically onto a horizontal plate.

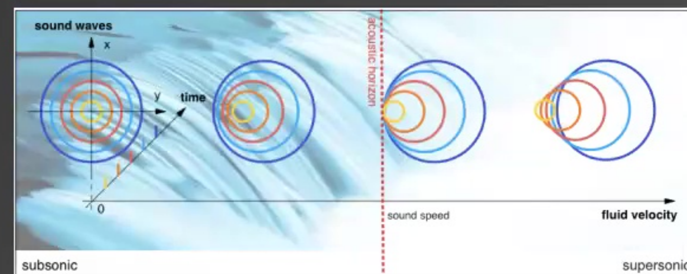
Reproducible at home in your kitchen sink!



where $c \equiv \sqrt{g h_{\mathrm{B}}}$.

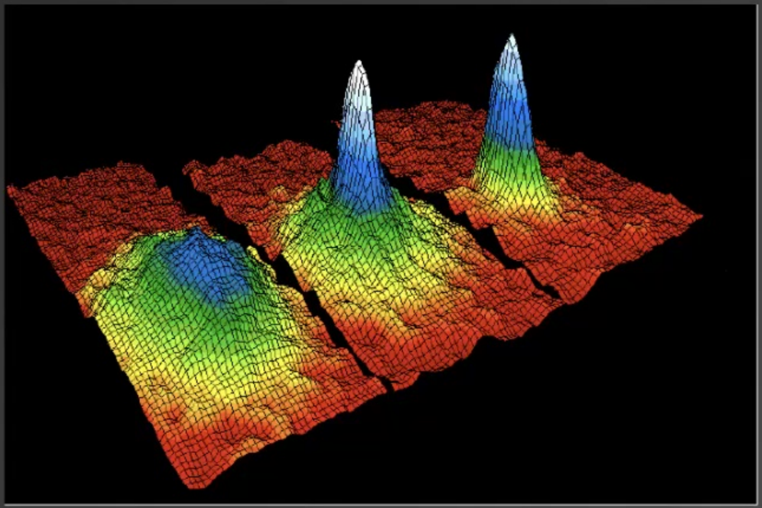
A white hole is the time-reversal of a black hole.
Something in which nothing can enter and all has to exit

G. Jannes, R. Piquet, P. Maissa, C. Mathis, G. Rousseaux. Phys.Rev. E83 (2011) 056312
Hydraulic Jump experiment figures from G.Jannes, Germain Rousseaux: arXiv:1203.6505



Measurements of the Mach angle θ, sinθ=c/v, confirm the presence of the supersonic region and white hole. A needle is placed inside the flow at varying distances from the centre of the jump.

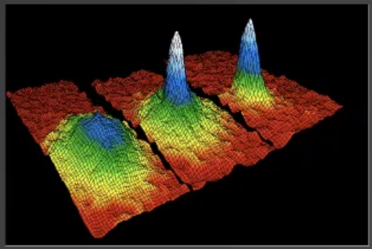
(a) Mach cone near the centre of the jump. (b) Mach cone near the edge of the jump. (c) The Mach cone disappears just outside the jump



Analogue gravity in Bose-Eistein condensates

A CONCRETE EXAMPLE: BEC ANALOGUE GRAVITY

A BEC is quantum system of N interacting bosons in which most of them lie in the same single-particle quantum state ($T<T_c\sim100$ nK, $N_{atoms}\sim10^5\div10^6$)



It is described by a many-body Hamiltonian which in the limit of dilute condensates gives a non-linear Schrödinger equation

$$i\hbar\frac{\partial}{\partial t}\hat{\Psi} = -\frac{\hbar^2}{2m}\nabla^2\hat{\Psi} - \mu\hat{\Psi} + \kappa|\hat{\Psi}|^2\hat{\Psi}.$$

(a=s-wave scattering length)

$$\kappa(a) = \frac{4\pi a\hbar^2}{m}.$$

This is still a very complicate system, so let's adopt a mean field approximation

Mean field approximation: $\hat{\Psi}(t,\mathbf{x}) = \psi(t,\mathbf{x}) + \hat{\chi}(t,\mathbf{x})$ where $|\psi(t,\mathbf{x})|^2 = n_c(t,\mathbf{x}) = N/V$

$\psi(t,\mathbf{x}) = \langle\hat{\Psi}(t,\mathbf{x})\rangle$ = classical wave function of the BEC , $\hat{\chi}(t,\mathbf{x})$ = excited atoms

Note that: $\hat{\Psi}|0\rangle = 0$ (atomic Fock vacuum) $\hat{\Psi}|\Omega\rangle \neq 0$ (ground state)

The ground state is the vacuum for the collective excitations of the condensate (quasi-particles) but this an inequivalent state w.r.t. the atomic vacuum. They are linked by Bogoliubov transformations.

Bose-Einstein condensate: an example of analogue emergent spacetime

By direct substitution of the mean field ansatz in the non-linear Schrödinger equation gives

$$i\hbar \frac{\partial}{\partial t}\psi(t,\mathbf{x}) = \left(-\frac{\hbar^2}{2m}\nabla^2 - \mu + \kappa|\psi|^2\right)\psi + 2\kappa\left(\tilde{n}\psi + \tilde{m}\psi^*\right)$$

Background dynamics (neglecting depletion terms the Gross-Pitaevski equation)

$$i\hbar \frac{\partial}{\partial t}\widehat{\chi} = \left(-\frac{\hbar^2}{2m}\nabla^2 - \mu + 2\kappa n_T\right)\widehat{\chi} + \kappa m_T\,\widehat{\chi}^\dagger$$

Excitations dynamics

$$n_c \equiv |\psi(t,\mathbf{x})|^2; \qquad m_c \equiv \psi^2(t,\mathbf{x});$$
$$\tilde{n} \equiv \langle\widehat{\chi}^\dagger\widehat{\chi}\rangle; \qquad \tilde{m} \equiv \langle\widehat{\chi}\widehat{\chi}\rangle;$$
$$n_T = n_c + \tilde{n}; \qquad m_T = m_c + \tilde{m}.$$

These are the so called Bogoliubov-de Gennes equations
The first one encodes the BEC background dynamics including the back reaction of quantum excitations.
The second one encodes the dynamics for the quantum excitations

The equations are coupled via the so called anomalous mass $\tilde{m}$ and density ñ. Which we shall neglect for the moment…

Let's consider quantum perturbations over the BEC background and adopt the "quantum acoustic representation" (Bogoliubov transformation)

$$\widehat{\chi}(t,\mathbf{x}) = e^{-i\theta/\hbar}\left(\frac{1}{2\sqrt{n_c}}\,\widehat{n}_1 - i\frac{\sqrt{n_c}}{\hbar}\,\widehat{\theta}_1\right)$$

For the perturbations one gets the system of equations

$$\partial_t\widehat{n}_1 + \frac{1}{m}\nabla\cdot\left(\widehat{n}_1\,\nabla\theta + n_c\,\nabla\widehat{\theta}_1\right) = 0,$$
$$\partial_t\widehat{\theta}_1 + \frac{1}{m}\nabla\theta\cdot\nabla\widehat{\theta}_1 + \kappa(a)\,n_1 - \frac{\hbar^2}{2m}\,D_2\widehat{n}_1 = 0.$$

Where D_2 is a represents a second-order differential operator: the linearized quantum potential

$$D_2\,\widehat{n}_1 \equiv -\frac{1}{2}n_c^{-3/2}\left[\nabla^2(n_c^{+1/2})\right]\widehat{n}_1 + \frac{1}{2}n_c^{-1/2}\,\nabla^2(n_c^{-1/2}\,\widehat{n}_1).$$

Acoustic metric and the fate of Lorentz invariance

For very long wavelengths the terms coming from the linearized quantum potential D_2 can be neglected.

$$\Delta\theta_1 \equiv \frac{1}{\sqrt{-g}}\,\partial_\mu\left(\sqrt{-g}\,g^{\mu\nu}\,\partial_\nu\right)\widehat{\theta}_1 = 0,$$

The so obtained metric is again the acoustic metric

$$c_s = \frac{\hbar}{m}\sqrt{4\pi\rho a}$$

$$g_{\mu\nu}(t,\mathbf{x}) \equiv \frac{c_s}{\lambda}\begin{bmatrix} -\left(c_s^{\,2}-\mathrm{v}_0^2\right) & \vdots & -(\mathrm{v}_0)_j \\ \cdots & \cdot & \cdots \\ -(\mathrm{v}_0)_i & \vdots & \delta_{ij}\end{bmatrix} = \frac{n_0}{c_s m}\begin{bmatrix} -\left(c_s^{\,2}-\mathrm{v}_0^2\right) & \vdots & -(\mathrm{v}_0)_j \\ \cdots & \cdot & \cdots \\ -(\mathrm{v}_0)_i & \vdots & \delta_{ij}\end{bmatrix}$$

If instead of neglecting the quantum potential we adopt the eikonal approximation (high-momentum approximation) we find, as expected, deviations from the Lorentz invariant physics of the low energy phonons.

E.g. the dispersion relation for the BEC quasi-particles is

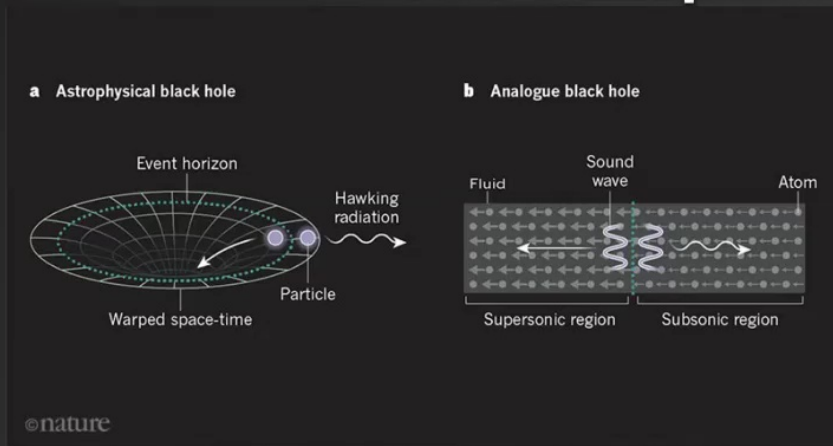
$$\omega^2 = c_s^2 k^2 + \left(\frac{\hbar}{2m}\right)^2 k^4$$

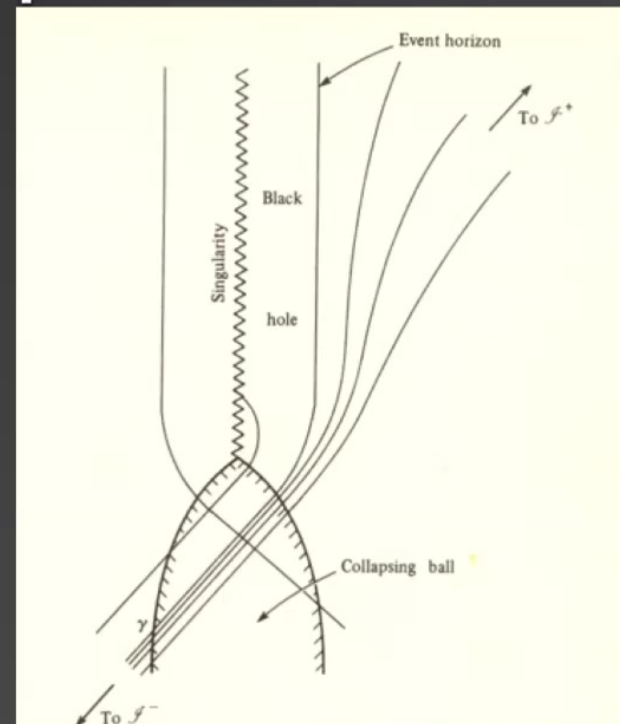
This (Bogoliubov) dispersion relation actually interpolates between two different regimes depending on the value of the fluctuations wavelength $\lambda=2\pi/|k|$ with respect to the "acoustic Planck wavelength"

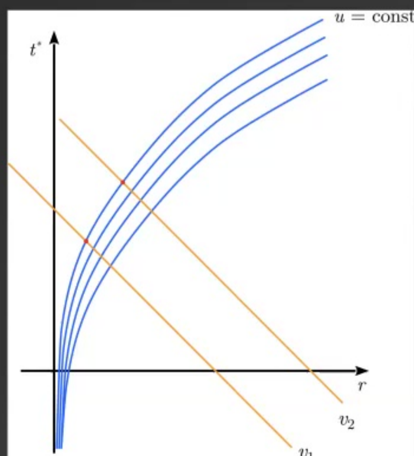
- $\lambda_C=h/(2m_{cs})=\pi\xi$ with ξ=healing length of BEC=$1/(8\pi\varrho a)1/2$
- For $\lambda \gg \lambda_C$ one gets the standard phonon dispersion relation $\omega\approx c|k|$
- For $\lambda \ll \lambda_C$ one gets instead the dispersion relation for an individual gas particle $\omega\approx(\hbar^2k^2)/(2m)$ (breakdown of the continuous medium approximation)
- So there is a Lorentz invariance violation (LIV) in the UV

<u>So AG systems are able to simulate classical and/or quantum Field Theory over a curved spacetime albeit the analogue metric field equations will not be described by the Einstein equations</u>

The transplanckian problem







$$\Delta v = v_2 - v_1 > 0$$

$$\frac{\omega_{\rm p}(v_1)}{\omega_{\rm p}(v_2)} \simeq e^{\kappa \Delta v}$$

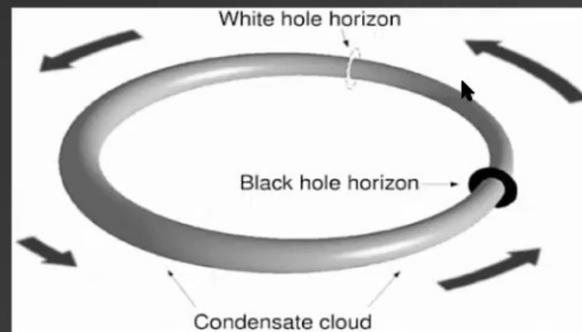
$$kT_H = \frac{\hbar}{2\pi} \left. \frac{\partial |c - v|}{\partial n} \right|_H ,$$

Hawking radiation is based on the extrapolation of standard QFT in CS up to transplanckian frequencies.
It seems to relate far UV physics to IR at infinity.
Question: is HR robust against UV physics features?

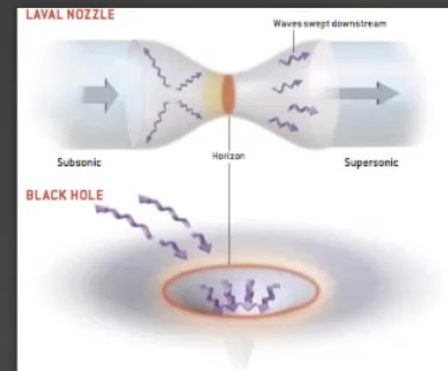
This transplanckian problem was initially <u>the main motivation</u> for the Analogue gravity program: T. Jacobson Phys Rev D44 (1991), W.G. Unruh Phys.Rev.D 51 (1995)

BHs in BEC

GR	Hydrodynamics
Ergoregion	Any region of supersonic flow Es: steady flow $g_{\mu\nu}\left(\partial/\partial t\right)^{\mu}\left(\partial/\partial t\right)^{\nu} \Rightarrow$ $g_{tt} = -\left[c_s^2 - v^2\right]$
Trapped Surface	Any closed two-surface where the fluid velocity is everywhere inward-pointing and the normal component of the fluid velocity is always greater than the speed of sound
Future Event Horizon	Boundary of the region from which null geodesics (phonons) cannot escape.
Surface Gravity	$g_H = \frac{1}{2}\left|\frac{\partial}{\partial n}\left(c_s^2 - v_\perp^2\right)\right|$



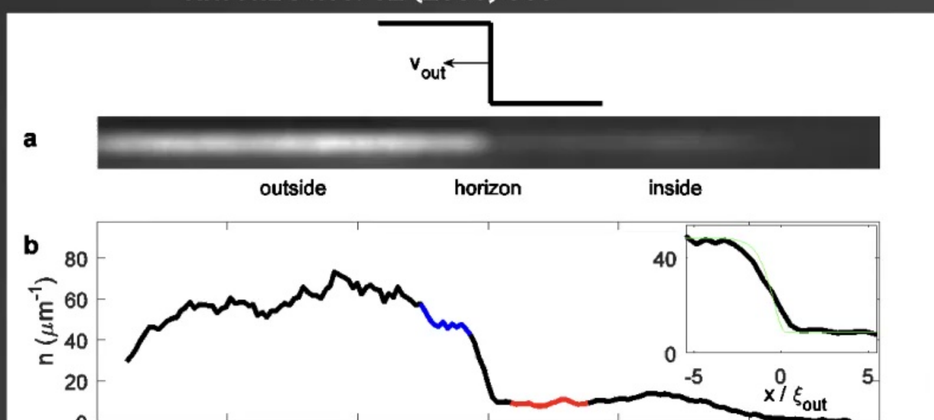
L.J. Garay, J.R. Anglin, J.I. Cirac, P. Zoller.
Phys.Rev.Lett. 85 (2000) 4643-4647
Phys.Rev. A63 (2001) 023611



Carlos Barcelo, SL, Matt Visser.
Int.J.Mod.Phys. A18 (2003) 3735.

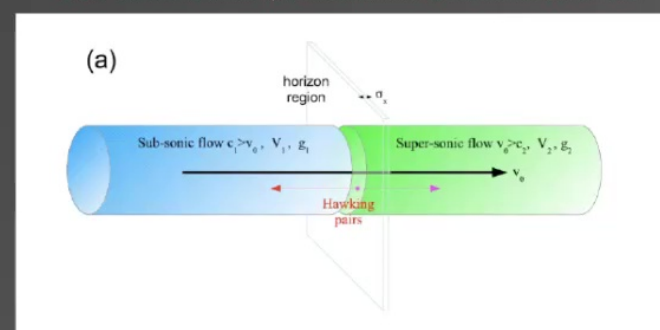
Use a sweeping one step potential to generate a BEC "waterfall".

Jeff Steinhauer
Nature Phys. 12 (2016) 959

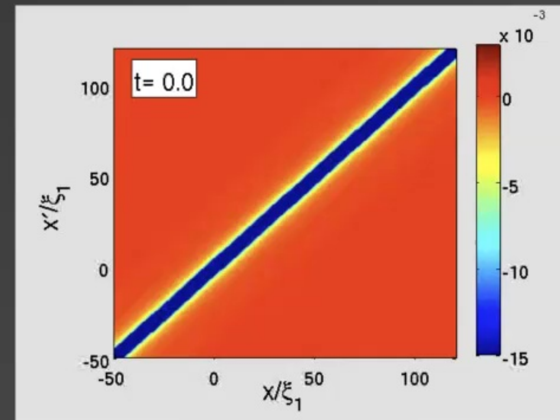


Use a Feshbach resonance to control the scattering length and hence the speed of sound, in order to create an analogue

Carusotto, Fagnocchi, Recati, Balbinot, Fabbri.
New J. Phys.10, 103001 (2008)
See also Macher, Parentani: arXiv:0905.3634



Hawking radiation in Black hole analogues: Observation in BEC



Detection via density-density correlations

$$S_0\langle \hat{b}_{\rm H}\hat{b}_{\rm P}\rangle = \sqrt{\frac{\xi_{\rm out}\xi_{\rm in}}{L_{\rm out}L_{\rm in}}}\int {\rm d}x\,{\rm d}x' e^{ik_{\rm H}x}e^{ik_{\rm P}x'}G^{(2)}(x,x')$$

HAWKING-PARTNERS CORRELATORS

$$G^{(2)}(x,x') = \sqrt{\xi_{\rm out}\xi_{\rm in}/n_{\rm out}n_{\rm in}}\,\langle\delta n(x)\delta n(x')\rangle$$

DENSITY-DENSITY CORRELATORS

HAWKING RADIATION SIGNATURE IN DENSITY-DENSITY CORRELATION.
BEC SIMULATION.
CARUSOTTO, FAGNOCCHI, RECATI, BALBINOT, FABBRI.
NEW J. PHYS.10, 103001 (2008)

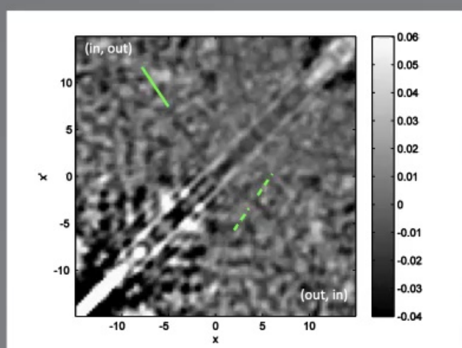
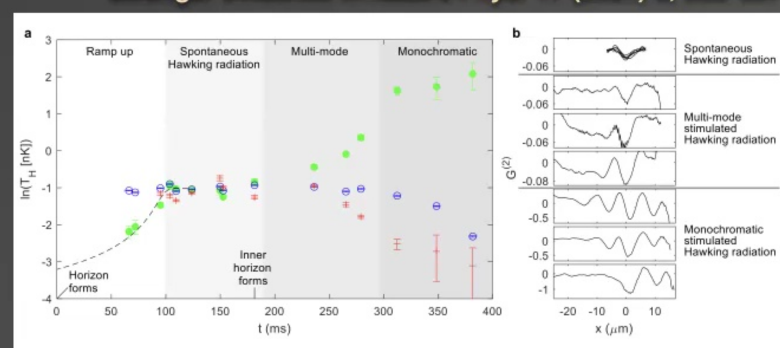


Fig. 3. Observation of Hawking/partner pairs. The horizon is at the origin. The dark bands emanating from the horizon are the correlations between the Hawking and partner particles. The solid line shows the angle of equal times from the horizon, found in Fig. 4. The Fourier transform along the dashed line measures the entanglement of the Hawking pairs.

First claim of Hawking detection (J. Steinhauer. 2015)
Nature 569, 7758 (2019) 688-691 and
Stronger evidence in *Nature Phys.* 17 (2021) 3, 362-367



Robustness of Hawking radiation in Black hole analogues: Theory

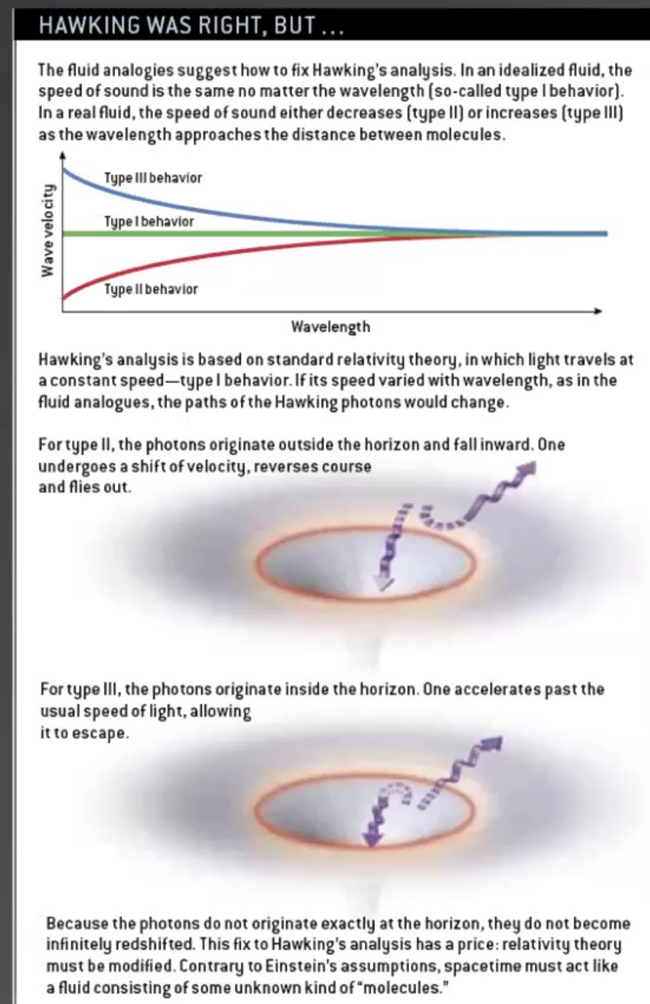
$$\omega^2 = c_s^2 \left(k^2 \pm \frac{k^4}{K^2} \right)$$

It turned out that Hawking Radiation is robust against LIV (see e.g. Parentani et al. papers), however you also can get (controllable) instabilities such as "black hole laser effect" due to the modified dispersion relation
(see e.g. Jacobson-Corley and Parentani-Finazzi.)

Some lessons:

- In static spacetimes Hawking radiation robustness is generally assured if there is a separation of scales: $\kappa_{BH} << \Lambda$ where $\Lambda = K \cdot F(v_{asym})$ for superluminal disp.rel. (For subliminal $|v_{asym}| < \kappa_{BH}/K$). Indeed T_{BH} is in this case constant for a wide range of wavenumbers k in spite of the modified dispersion relation.
- Key point for HR is also vacuum condition at particle creation region for freely falling observers (which are carrying with them the preferred frame associated to LIV)
- the quantity that really fixes the Hawking temperature is an average of the spatial derivative of the velocity profile on a region across the horizon whose size is related to the UV LIV scale: <u>the horizon becomes thick</u>

NOTE: WHAT MAKES THEORETICAL AND EXPERIMENTAL WORK ON HAWKING RADIATION VALUABLE IN ANALOGUE GRAVITY IS NOT JUST THE FINAL DETECTION, BUT THE UNDERSTANDING OF HOW AND IN WHICH SENSE HR IS ROBUST AGAINST THE UV PHYSICS.
BUT CAN WE GO BEYOND THIS?



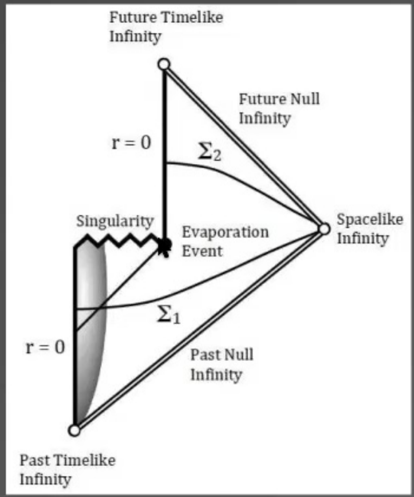
From Jacobson-Parentani: Sci. Am. 2005

The Information non-loss in BEC issue

Analogue gravity in BEC introduces a classical background (the wave function of the condensate, the expectation value of a quantum operator on a quasi-coherent state) and describe the propagation of quantum fields (the quasi-particles) over it. In this sense it is the analogue of QFT in a curved spacetime.

However, nothing forbids in analogue gravity to simulate singularities (as a regions where the hydrodynamic approximation does not hold) and even an evaporation process

But from the point of view of BEC the singularity is at most a region where the hydrodynamical limit is not legitimate
<u>Hence the analogue evaporation process must be unitary preserving.</u>
(if one does not “kicks out atoms”).



But then in this cases how the evolution is held unitary?

It seems that a necessary step is to be able to retain a quantum description of the whole condensate (in a number conserving ansatz) in order to not have an obvious loss of information at the analogue singularity…

I.e. we need to go beyond the mean field approx $\phi(x) = \langle \phi(x) \rangle + \delta\phi(x)$

SL, G. Tricella, A. Trombettoni
Entropy 2019, 21, 940;

Beyond Bogoliubov: Natural Orbitals

Indeed, the condensation phenomenon can be also defined considering the properties of the 2-point correlation functions: a method allowing to retain the information about the quantum nature of the atoms in the BEC.

The 2-point correlation function being Hermitian can be diagonalised in a basis of orthonormal functions f_I which are known as natural orbitals (Penrose-Osanger 1954) .

$$\left\langle \phi^{\dagger}(x)\,\phi(y)\right\rangle = \sum_I \langle N_I\rangle\, \overline{f_I}(x)\, f_I(y)\,,$$

$$\int \mathrm{d}x\, \overline{f_I}(x)\, f_J(x) = \delta_{IJ}\,.$$

- For a time-dependent Hamiltonian the natural orbitals are also time-dependent
- The natural orbitals define a complete basis for the 1-particle Hilbert space and can be used to define destruction and creation operators.

$$a_I = \int \mathrm{d}x\, \overline{f_I}(x)\, \phi(x)\,,$$

$$\left[a_I, a_J^{\dagger}\right] = \delta_{IJ}\,, \qquad \left[a_I, a_J\right] = 0\,,$$

$$N_I = a_I^{\dagger} a_I\,.$$

- The eigenvalues $\langle N_I\rangle$ are the occupation numbers of these wave functions (whose sum = N_{tot}).
- The state is called "condensate" when $N_0 >> N_I$.
- For a perfect condensation (no depletion) ===>

$$\begin{aligned} f_0(x) &= \langle N_0\rangle^{-1/2}\langle\phi(x)\rangle\,,\\ \langle N_0\rangle &= \int \mathrm{d}y\, \overline{\langle\phi(y)\rangle}\,\langle\phi(y)\rangle\\ \langle N_{I\neq 0}\rangle &= 0\,. \end{aligned}$$

$$\begin{aligned} \phi(x) &= \phi_0(x) + \phi_1(x)\\ &= f_0(x)\, a_0 + \sum_I f_I(x)\, a_I \end{aligned}$$

It is possible to show that neglecting the depletion the GP is recovered with $\langle\varphi\rangle$ replaced by $\langle N_0\rangle^{1/2} f_0(x)$.
Hence, it can be shown that Analogue gravity continues to hold also in this formalism.
Taking into account the depletion terms also the BdG equation can be recovered (neglecting suppressed terms)

$$i\partial_t\left(\langle N_0\rangle^{1/2} f_0(x)\right) = -\frac{\nabla^2}{2m}\left(\langle N_0\rangle^{1/2} f_0(x)\right) + \lambda\,\langle N_0\rangle^{3/2}\,\overline{f_0}(x)\, f_0(x)\, f_0(x) \;+\text{depletion terms}$$

Furthermore this is still true if one adopts a Number-conserving formalism involving modified ladder operators

$$\alpha_I = N_0^{-1/2} a_0^{\dagger} a_I$$

Analogue Cosmological particle creation

Hawking radiation is hard!

So let's consider Cosmological particle creation: much easier but still captures the basic physics.
We simulate that with a tunable interaction (change of the scattering length e.g. via Feshbach resonance) but imposing the conservation of the total number of atoms (number conserving formalism)

$$g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = -\mathrm{d}\tau^2 + a^2\delta_{ij}\mathrm{d}x^i\mathrm{d}x^j\,, \qquad a(\tau(t)) = \left(\frac{\rho_0}{m\lambda(t)}\right)^{1/4}\frac{1}{C}\,, \qquad \mathrm{d}\tau = \frac{\rho_0}{ma(\tau(t))}\frac{1}{C^2}\mathrm{d}t\,,$$

As usual we can consider an expansion localised in time and compare the expansion in the far past/future

$$\theta_k(t\to-\infty) = \frac{1}{\mathcal{N}_k}\left(e^{-i\omega_k t}c_k + e^{i\omega_k t}c^\dagger_{-k}\right) \qquad \theta_k(t\to+\infty) = \frac{1}{\mathcal{N}'_k}\left(e^{-i\omega'_k t}c'_k + e^{i\omega'_k t}c'^\dagger_{-k}\right)$$

$$c'_k = \cosh\Theta_k c_k + \sinh\Theta_k e^{i\psi_k}c^\dagger_{-k}$$

We take the initial state to be the quasi-particle vacuum
At late times the two point correlators of number-conserving operators describing atomic excitations then become (quasi-particle ops and number conserving ops are related via a Bogoliubov transformation)

$$\left\langle \delta\phi^\dagger_k(t)\,\delta\phi_k(t)\right\rangle = \frac{\frac{k^2}{2m}+\lambda'\rho_0}{2\omega'_k}\cosh(2\Theta_k) - \frac{1}{2} + \frac{\lambda'\rho_0\sinh(2\Theta_k)}{2\omega'_k}\cos\left(2\omega'_k t - \varphi_k\right)\,. \qquad \omega'_k = \sqrt{\frac{k^2}{2m}\left(\frac{k^2}{2m}+2\lambda'\rho_0\right)}.$$

Even assuming that the backreaction of the quasi-particles on the condensate is negligible, the first term above shows that the mechanism of extraction of atoms from the condensate fraction is effective and increases the depletion.
This is a consequence of us imposing the conservation of the atom number.
Quasiparticle creation removes atoms from the condensate N_0 phase to the excitations N_I

PARTICLE CREATION IN NUMBER CONSERVING FORMALISM

- The Out state and the IN state are related by a Bogoliubov transformation that can be associated to a squeezing operator that acts on the whole Hilbert space not just on the one of the quasi-particles

$$S^\dagger c_k S = c'_k = \cosh\Theta_k c_k + \sinh\Theta_k e^{i\varphi_k} c^\dagger_{-k}$$

- The scattering operator of the quasi-particle pairs is particularly simple and takes the peculiar expression that is required for producing squeezed states.

$$S = \exp\left(\frac{1}{2}\sum_{k\neq 0}\left(-e^{-i\varphi_k}c_k c_{-k} + e^{i\varphi_k}c_k^\dagger c_{-k}^\dagger\right)\Theta_k\right).$$

- The time-independent operators c_k depend also on the condensate operator a_0 and can be defined as compositions of number-conserving atom operators $\delta\varphi_k(t)$ and $\delta\varphi_{-}{}^{\dagger}{}_{k}(t)$

- This dynamics produces (at any time) non-zero ($1/N_0$ supppressed) correlators between the condensate atoms and the quasi-particles

$$\langle c_k c_{k'} N_0\rangle - \langle c_k c_{k'}\rangle\langle N_0\rangle = -\sum_q \left(\langle c_k c_{k'}\delta\phi_q^\dagger\delta\phi_q\rangle - \langle c_k c_{k'}\rangle\langle\delta\phi_q^\dagger\delta\phi_q\rangle\right) + \langle c_k c_{k'} N\rangle - \langle c_k c_{k'}\rangle\langle N\rangle$$

- This is because the operators a_0 and $a_0^\dagger$ do not commute with the creation of pairs of quasi-particles $c^\dagger_k c^\dagger_{-k}$, which is described by the combination of the operators $\delta\varphi^\dagger_k\delta\varphi_k$, $\delta\varphi^\dagger_k\delta\varphi^\dagger_{-k}$ and $\delta\varphi_k\delta\varphi_{-k}$

$$\left(\delta\phi_k^\dagger\delta\phi_k\right)a_0^\dagger = a_0^\dagger\left(\delta\phi_k^\dagger\delta\phi_k\right),$$

$$\left(\delta\phi_k^\dagger\delta\phi_{-k}^\dagger\right)^n a_0^\dagger = a_0^\dagger\left(\delta\phi_k^\dagger\delta\phi_{-k}^\dagger\right)^n\left(\frac{N_0+1}{N_0+1-2n}\right)^{1/2},$$

$$\left(\delta\phi_k\delta\phi_{-k}\right)^n a_0^\dagger = a_0^\dagger\left(\delta\phi_k\delta\phi_{-k}\right)^n\left(\frac{N_0+1}{N_0+1+2n}\right)^{1/2}.$$

MAIN LESSONS

- As expected when describing the particle creation on the full Fock space (condensate+QP), there isn't any unitarity breaking, and the purity of the state is preserved.
- The particle creation unavoidably creates entanglement of the quasi-particles with the atoms in the condensate: even if the initial state factories the final one won't

IN $$\sum_N \frac{e^{-N/2}}{\sqrt{N!}} |N;\varnothing\rangle_{qp} \approx |\langle N\rangle\rangle_{mf} \otimes |\varnothing\rangle_{qp\,Boq}\,,$$

OUT $$\sum_N \frac{e^{-N/2}}{\sqrt{N!}} \sum_{lr} a'_{lr} \left(1+\mathcal{O}\left(N^{-1}\right)\right) |N-l-r,l,r\rangle_a \neq |\langle N\rangle\rangle_{mf} \otimes \sum_{lr} a'_{lr} |l,r\rangle_{a\,Bog}\,.$$

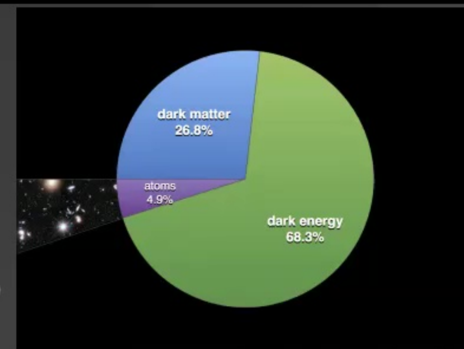
- In cases such as the cosmological particle creation, where the phenomenon happens on the whole spacetime, N_0 is the (large) number of atoms in the whole condensate, and thus the correlations between the substratum and the quasi-particles are negligible.

- In the GR black hole case, we expect a finite region of spacetime to be associated to the particle creation, thus in the analogy N_0 is not only finite but decreases as a consequence of the evaporation making the correlators between geometry and Hawking quanta more and more non-negligible at late stages of the BH evaporation.
- The back reaction shrinks the horizon and reproduces this behaviour also in some acoustic black holes (SL, G. Tricella, A. Trombettoni. *Appl.Sciences* 10 (2020) 24, 8868 • e-Print: 2010.09966 [gr-qc])

- The Bogoliubov approximation corresponds to taking the quantum degrees of freedom of the geometry as classical. This is not per se a unitarity violating operation. Indeed, the operator so recovered is still a unitarity preserving squeezing one: it is the usual squeezing operator relating In and Out vacua in QFT on CS.

- However, the two descriptions are no longer practically equivalent when a region of quantum gravitational evolution is somehow simulated (analogue singularity or end of evaporation of even regular BH).

The cosmological constant problem



Approximately 68% of the cosmic pie is made of Dark energy.
An homogeneously distributed cosmological fluid which makes the universe expand faster and faster.

The simplest explanation is a cosmological Constant induced by the vacuum energy associated to quantum fields

$$H = \hbar \sum_k^{\infty} \omega_k \left(a_k^{\dagger} a_k + \frac{1}{2} \right) \qquad E_{vac} = \langle 0 | H | 0 \rangle = \hbar \sum_k^{\infty} \frac{k}{2} = \infty$$

Natural to cut off at the Planck scale but then one gets $\rho_{VAC} \sim (M_{PL})^4$
120 orders of magnitude larger than the observed cosmological constant!

There is apparently a similar problem in Analogue gravity

$$H_{\text{phon}} = \hbar \sum_k^{\infty} \omega_k \left(a_k^{\dagger} a_i + \frac{1}{2} \right) \qquad E_{vac} = \langle \Omega | H_{\text{phon}} | \Omega \rangle$$

Ground state: no phonons

Not knowing about the physics beyond the "healing scale" we would cut-off the system at ξ=healing length of BEC and hence get a huge cosmological constant=$(1/\xi)^4$ V

A toy model for emergent gravity: non-relativistic BEC

So let's go back to the mean field approximation of BEC and focus on the BdG equation for the background:

F. Girelli, S.L.,L.Sindoni
Phys.Rev.D78:084013,2008

$$i\hbar\frac{\partial}{\partial t}\psi(t,\mathbf{x}) = \left(-\frac{\hbar^2}{2m}\nabla^2 + V_{\mathrm{ext}}(\mathbf{x}) + \kappa n_c\right)\psi(t,\mathbf{x}) + \kappa\left(2\tilde{n}\psi(t,\mathbf{x}) + \tilde{m}\psi(t,\mathbf{x})\right)$$

- Can this be encoding some form of gravitational dynamics?
- If yes it must be some form of Newtonian gravity (non relativistic equation)
- But, in order to have any chance to see this, we need to have some massive field

Non-relativistic BEC gravitational potential

So we would now like to cast the equation for the a stationary, homogeneous, condensate background in a Poisson-like form with the quasi-particles moving accordingly to the analogue gravitational potential.

$$\vec{F} = \vec{a} = -\mathcal{M}\vec{\nabla}\Phi_{\rm grav}$$

$$\left(\nabla^2 - \frac{1}{L^2}\right)\Phi_{\rm grav} = 4\pi G_{\rm N}\rho + \Lambda$$

where L ⇒ range of the gravitational interaction, G_N ⇒ analogue G Newton,

Λ ⇒ analogue cosmological constant

Results

1. It is possible to show by looking at the Newtonian limit of the acoustic geometry that the gravitational potential is encoded in density perturbations
2. By adopting the ansatz $\psi = \left(\frac{\mu+\lambda}{\kappa}\right)^{1/2}(1+u(\mathrm{x}))$ $\quad \eta_{\mu\nu} + h_{\mu\nu}, \qquad h_{00} \propto u(x)$

and looking at the Hamiltonian for the quasi-particles in the non relativistic limit, one can actually show that the analogue of the gravitational potential is

$$\Phi_{grav}(\mathrm{x}) = \frac{(\mu+4\lambda)(\mu+2\lambda)}{2\lambda m}u(\mathrm{x})$$

NON-RELATIVISTIC BEC: EMERGENT NEWTONIAN GRAVITY

Let's consider the equation for a static background with a source term.
The latter is given partly by a localized quasi-particle plus a vacuum contribution due to the unavoidable presence/backreaction of excited atoms above the condensate

$$\left(\frac{\hbar^2}{2m}\nabla^2 - 2(\mu+\lambda)\right) u(\mathrm{x}) = 2\kappa\left(\bar{n}(\mathrm{x}) + \frac{1}{2}\bar{m}(\mathrm{x})\right) + 2\kappa\left(\tilde{n}_0 + \frac{1}{2}\tilde{m}_0\right)$$

where $\bar{n}(\mathrm{x}) = \tilde{n}(\mathrm{x}) - \tilde{n}_0, \qquad \bar{m}(\mathrm{x}) = \tilde{m}(\mathrm{x}) - \tilde{m}_0$

and $\tilde{n}_0 = \langle 0|\hat{\chi}^\dagger(\mathrm{x})\hat{\chi}(\mathrm{x})|0\rangle, \qquad \tilde{m}_0 = \langle 0|\hat{\chi}(\mathrm{x})\hat{\chi}(\mathrm{x})|0\rangle$

are the quasi-particle vacuum backreaction terms

Now, knowing what is the analogue gravitational potential, this can be cast in the form of a generalized Poisson equation with a (negative) cosmological constant.

$$\left(\nabla^2 - \frac{1}{L^2}\right)\Phi_{grav} = 4\pi G_N \rho_{\mathrm{matter}} + \Lambda,$$

where

$$\rho_{\mathrm{matter}}(\mathrm{x}) = \left(\bar{n}(\mathrm{x}) + \frac{1}{2}\bar{m}(\mathrm{x})\right) \qquad G_N \equiv \frac{\kappa(\mu+4\lambda)(\mu+2\lambda)^2}{4\pi\hbar^2 m\lambda^{3/2}(\mu+\lambda)^{1/2}}$$

$$\Lambda \equiv \frac{2\kappa(\mu+4\lambda)(\mu+2\lambda)}{\hbar^2\lambda}\left(\tilde{n}_0 + \frac{1}{2}\tilde{m}_0\right), \qquad L^2 \equiv \frac{\hbar^2}{4m(\mu+\lambda)}$$

WEIGHTING LAMBDA...

$$\mathcal{E}_\Lambda = \frac{\Lambda c_s^4}{4\pi G_{\mathrm{N}}}, \quad \mathcal{E}_{\mathrm{P}} = \frac{c_s^7}{\hbar G_{\mathrm{N}}^2}, \quad \Longrightarrow \quad \frac{\mathcal{E}_\Lambda}{\mathcal{E}_{\mathrm{P}}} \propto \rho_0 a^3 \left(\frac{\lambda}{g\rho_0}\right)^{-5/2}.$$

The cosmological constant scale is suppressed by a small number (the dilution factor $\rho a^3 \ll 1$) w.r.t. the analogue/emergent Planck scale!

- The (negative) cosmological constant is not the cut-offed phonons vacuum energy, neither it is the atoms grand canonical energy density *h*, or energy density *ε=h+μρ*
- It is just related to the subdominat second order correction to these latter quantities due to quantum depletion (the part related to the excitations) and its scale is the healing scale.
- There could be no a priori reason why the cosmological constant should be computed as the zero-point energy of the system: *its computation must inevitably pass through the derivation of Einstein equations emerging from the underlying microscopic system.*

S. Finazzi, S. Liberati and L. Sindoni, Phys. Rev. Lett. 108, 071101 (2012)

- THE ENERGY SCALE OF Λ CAN BE SEVERAL ORDERS OF MAGNITUDE SMALLER THAN ALL THE OTHER ENERGY SCALES FOR THE PRESENCE OF A VERY SMALL NUMBER, NONPERTURBATIVE IN ORIGIN, WHICH CANNOT BE COMPUTED WITHIN THE FRAMEWORK OF AN EFT DEALING ONLY WITH THE EMERGENT DEGREES OF FREEDOM (I.E., SEMICLASSICAL GRAVITY).

EMERGENT GRAVITY IN RELATIVISTIC BEC

Belenchia, SL, Mohd: arXiv:1407.7896
Phys.Rev. D90 (2014) 10, 104015

$$\mathcal{L}_{\rm eff} = -\eta^{\mu\nu}\partial_\mu\phi^*\partial_\nu\phi - m^2\phi^*\phi - \lambda(\phi^*\phi)^2 + \mu^2\phi^*\phi + i\mu(\phi^*\partial_t\phi - \phi\partial_t\phi^*)$$

$$g_{\mu\nu} = \frac{c}{c_s}\left[\eta_{\mu\nu} + \left(1 - \frac{c_s^2}{c^2}\right)\frac{v_\mu v_\nu}{c^2}\right]$$

IN THIS CASE THERE IS A MASSLESS MODE WITH ACOUSTIC LORENTZ INVARIANCE PROPAGATING ON A DISFORMAL GEOMETRY AT LONG WAVELENGTHS. AT SHORT WAVELENGTH THIS BECAME SA RELATIVISTIC ATOM IN MINKOWSKI (LLI WITH C). AT INTERMEDIATE WAVELENGTHS THERE IS A RAINBOW SPACETIME.

LET US AGAIN DECOMPOSE Φ AS $\Phi = \Phi_0(1 + \Psi)$, WHERE Φ_0 IS THE CONDENSED PART OF THE FIELD ($\langle\Phi\rangle = \Phi_0$) AND Ψ IS THE FRACTIONAL FLUCTUATION WHICH CAN BE WRITTEN IN TERMS OF ITS REAL AND IMAGINARY PARTS $\Psi = \Psi_1 + i\Psi_2$

CRUCIAL POINT: IN SOME SUITABLE REGIME (NEUTRAL BACKGROUND FIELD, c_s=C) YOU CAN COMPLETELY MASK THE LORENTZ BREAKING. IN THIS REGIME ONE FINDS

Excitations Eq.

$$\Box_g\psi_1 - 4\lambda\psi_1 = 0,$$

$g_{\mu\nu} = \phi^2{}_0\eta_{\mu\nu}$ $\quad$ $\Box_g\psi_2 = 0.$

Background Eq.

$$R_g - \frac{m^2}{\phi^2} + \Lambda = \langle T_{\rm qp}\rangle, \qquad R_g = -6\frac{\Box\varphi_0}{\varphi_0^3}$$

$$\langle T_{\rm qp}\rangle := -12\lambda\left[3\langle\psi_1^2\rangle + \langle\psi_2^2\rangle\right],$$

FOR m->0 (BEC still allowed by non zero chemical potential μ)
EQUIVALENT TO EINSTEIN-FOKKER EQUATION OF NORDSTRÖM GRAVITY!

$$R + \Lambda = 24\pi G_{\rm N}\,T,$$

NORDSTRÖM GRAVITY (1913) IS THE ONLY OTHER THEORY IN 3+1 DIMENSIONS WHICH SATISFIES THE STRONG EQUIVALENCE PRINCIPLE. HOWEVER, IT IS NOT TRULY BACKGROUND INDEPENDENT (FIXED MINKOWSKI CAUSAL STRUCTURE)

$$\langle T\rangle = -\frac{\Lambda}{6}\left[3\langle\psi_1^2\rangle + \langle\psi_2^2\rangle\right] = -2\lambda\left[3\langle\psi_1^2\rangle + \langle\psi_2^2\rangle\right] = 6\langle T_{qp}\rangle. \qquad \Lambda \equiv 12\lambda\frac{\mu^2}{c^2\hbar} = 12\lambda\frac{M_{\rm P}^2c^2}{4\pi\hbar}. \qquad G_{\rm N}^{\rm eft} = G/4\pi = \hbar c^5/(4\pi\mu^2)$$

$$M_{\rm Pl} = \mu\sqrt{4\pi}/c^2 \qquad \frac{\epsilon_\Lambda}{\epsilon_P} \simeq \frac{\lambda\hbar^2c^2}{\mu^2} \quad \text{SMALL}$$

THE "BARE" Λ IS IN THIS CASE SMALL AND POSITIVE BUT IT WILL GENERICALLY RECEIVE A (NEGATIVE) CORRECTION FROM THE FRACTION OF ATOMS IN THE NON-CONDENSATE PHASE, THE DEPLETION FACTOR.

What next?

This is all interesting but is clearly open to several criticisms:

1. In the non-relativistic BEC you get only Newtonian gravity+Lorentz breaking
2. In the relativistic case, fine tuning of the system gives you Nordstrom gravity which is remarkable but it is still "just" scalar gravity+it is not really background independent

How can we go beyond?
We can bring forward to hints...

Marolf's theorem (Phys.Rev.Lett. 114 (2015) no.3, 031104): Emergence of Gravity a la Analogue Model+ background independence requires kinematical non-locality (different microcausality) to start with...

What next?

This is all interesting but is clearly open to several criticisms:

1. In the non-relativistic BEC you get only Newtonian gravity+Lorentz breaking
2. In the relativistic case, fine tuning of the system gives you Nordstrom gravity which is remarkable but it is still "just" scalar gravity+it is not really background independent

How can we go beyond?
We can bring forward to hints...

Marolf's theorem (Phys.Rev.Lett. 114 (2015) no.3, 031104): Emergence of Gravity a la Analogue Model+ background independence requires kinematical non-locality (different microcausality) to start with...

Is non-locality a key ingredient to emerge spacetime and diffeo invariance? (surely it seems an alternative to Lorentz breaking: see eg. Causet example)

Closing

- (historic) Lesson 1: Hawking radiation is UV robust
- Lesson 2: Info Loss problem in BH could be an artefact of neglecting gravity Hilbert space in semiclassical gravity. In emergent gravity scenarios matter and gravity must come from the same microstructure.
- Lesson 3: In emergent gravity scenarios Λ must be derived by gravitodynamics equations, not using IR EFT.

- Many other issues could be addressed still: e.g. how and where the particle production happens at the atomic level, what is the interpretation of the quasi-particle entanglement (EPR) at the microscopic scale? etc...

Closing

- (historic) Lesson 1: Hawking radiation is UV robust
- Lesson 2: Info Loss problem in BH could be an artefact of neglecting gravity Hilbert space in semiclassical gravity. In emergent gravity scenarios matter and gravity must come from the same microstructure.
- Lesson 3: In emergent gravity scenarios Λ must be derived by gravitodynamics equations, not using IR EFT.

- Many other issues could be addressed still: e.g. how and where the particle production happens at the atomic level, what is the interpretation of the quasi-particle entanglement (EPR) at the microscopic scale? etc...

So Analogue gravity can provide not only theoretical understanding and experimental tests of field theory in curved spacetime

It can also be a toy model of emergent spacetime and an be an effective tool to rephrase/better understand in this framework longstanding problems.

Analogue gravity lessons seems far from over...

And I cherish more than anything else the Analogies, my most trustworthy masters. They know all the secrets of Nature, and they ought least to be neglected in Geometry.

Johannes Kepler