Quantum gravity Phenomenology: from cold atoms to astroparticle physics, and back...

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What next - Fisica Fondamentale

The unhappy relativist and the power of analogies...

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Nonetheless both the puzzling Universe emerging from cosmological observations and the difficulties in developing a full quantum gravity theory in absence of experimental guidance are baffling us.

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- In simple terms, analogy is used to highlight a point of similarity by comparing two things that are similar to each other in some sense.

- Freud said that an analogy won't settle an argument, but a good one may surely help to clarify the issues...

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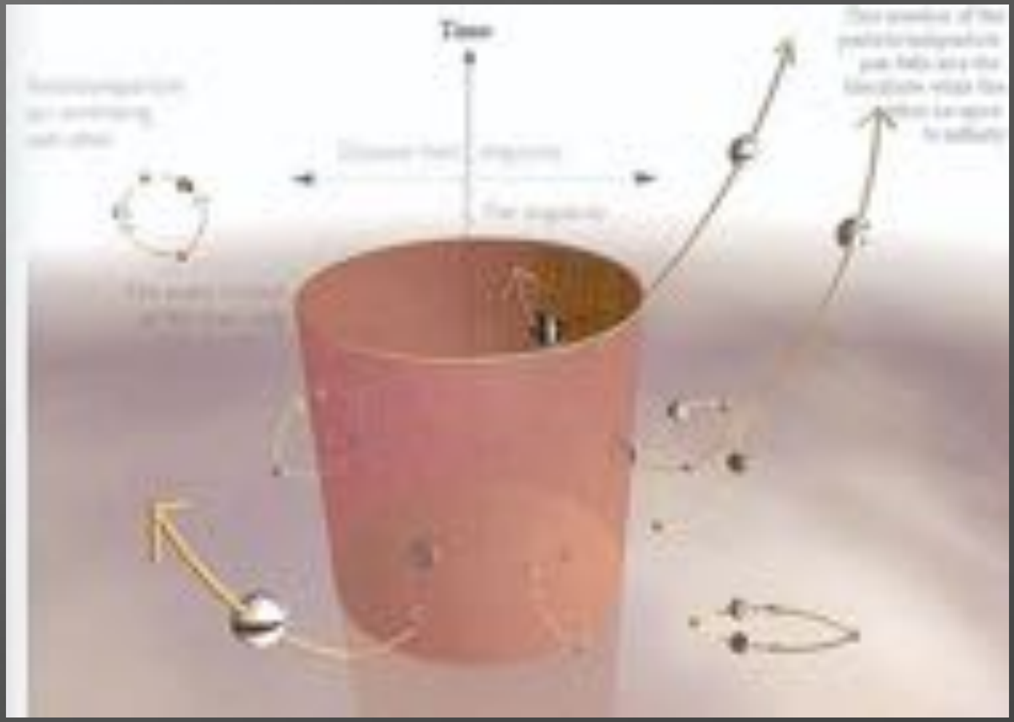
Even just the second achievement would be valuable in gravitation theory nowadays… let’s take Black Hole thermodynamics as a concrete example…

BH thermodynamics in a nutshell

LAW	THERMODYNAMICS	BLACK HOLES
0	T=constant at thermodynamic equilibrium	κ=constant on the event horizon of a stationary BH
1	$\delta E = T\delta S + P\delta V$	$\delta M = \kappa/2\pi\ \delta A + \Omega\delta J$
2	$\delta S \geq 0$	$\delta A \geq 0$
3	Impossible to obtain T=0	Impossible to obtain κ=0

(Bardeen, Bekenstein, Carter, Christodoulou, Hawking, Ruffini ('73-'75))

κ= surface gravity=1/4M for Schwartzschild BH. Ω= BH angular velocity.
J= angular momentum. A= event horizon area.



$$T = \frac{\hbar\kappa}{2\pi k_B c}, \quad S = \frac{A}{4 l_{Pl}^2}, \quad E = Mc^2, \quad l_{Pl} = \sqrt{\frac{\hbar G}{c^3}}$$

Open Questions

How did GR know about Hawking radiation?

BH laws = GR theorems Hawking radiation = QFT in Curved Spacetime calculation

Information Loss?

Pure state apparently goes into a Mixed state

Ultra high energy particles?

Tracing back in time Hawking quanta lead to exponentially increasing frequencies. Transplanckian origin of Hawking quanta inconsistent with QFT in CS approximation!

Can we test at least some of these features?

Using analogies: Black holes without General relativity

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Monticello dam, Napa County, California

A moving fluid will drag sound pulses along with it

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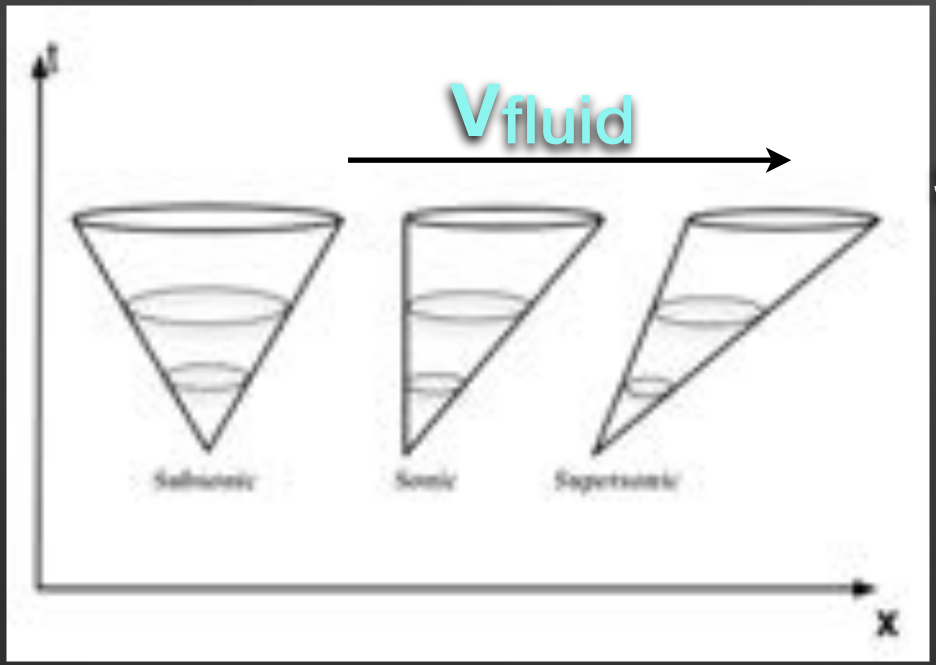
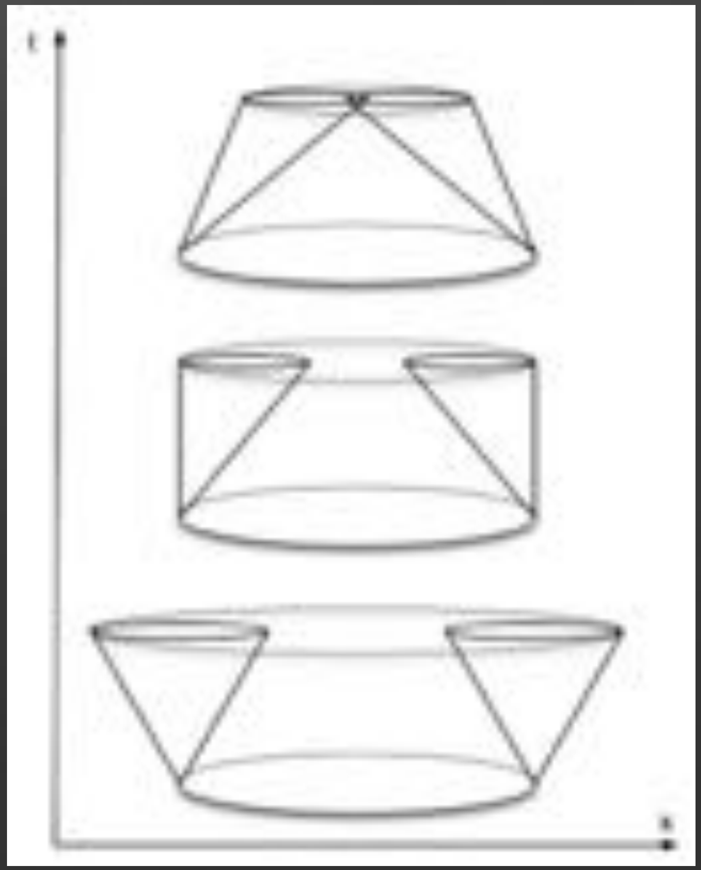


A moving fluid will tip the "sound cones" as it moves. Supersonic flow will tip the cone past the vertical.

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



Using analogies: Black holes without General relativity

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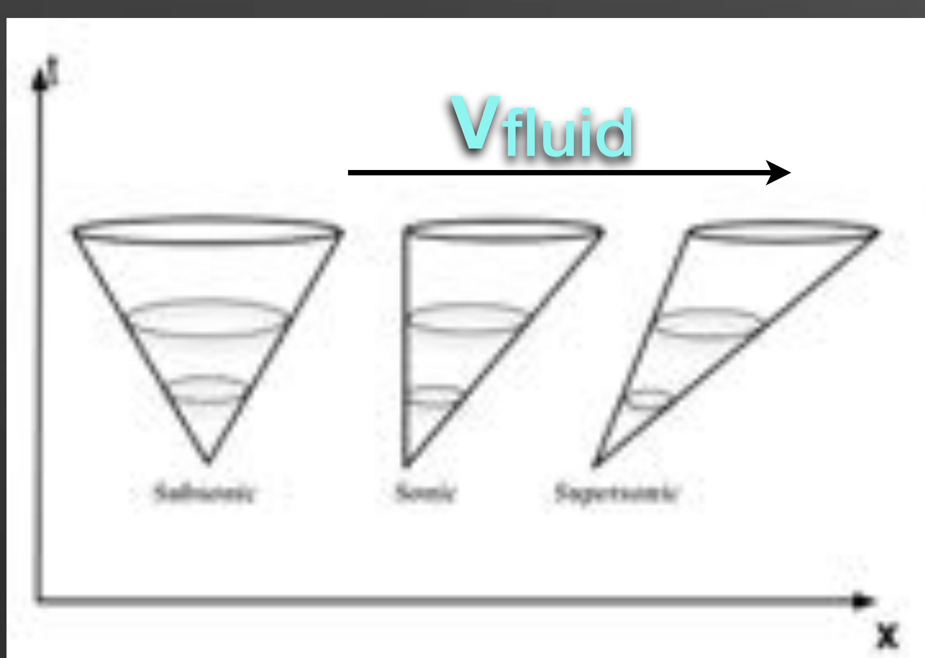

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Is this just a qualitative analogy?

Unruh ’81, Visser ’93
But see also White ‘73

The example: Acoustic 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

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

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

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

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This is the same equation as for a scalar field moving in curved spacetime.
Waves can indeed feel a "dumb hole" after all!

Analogue models of gravity

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

- Dielectric media
- Acoustic in moving fluids
- Gravity waves
- High-refractive index dielectric fluids: “slow light”
- Optic Fibers analogues
- Quasi-particle excitations: fermionic or bosonic quasi-particles in He3
- Non-linear electrodynamics
- “Solid states black holes”
- Perturbation in Bose-Einstein condensates
- Graphene
- Many more…

Review: C.Barcelo, S.L and M.Visser, “Analogue gravity” Living Rev.Rel.8,12 (2005-2011).

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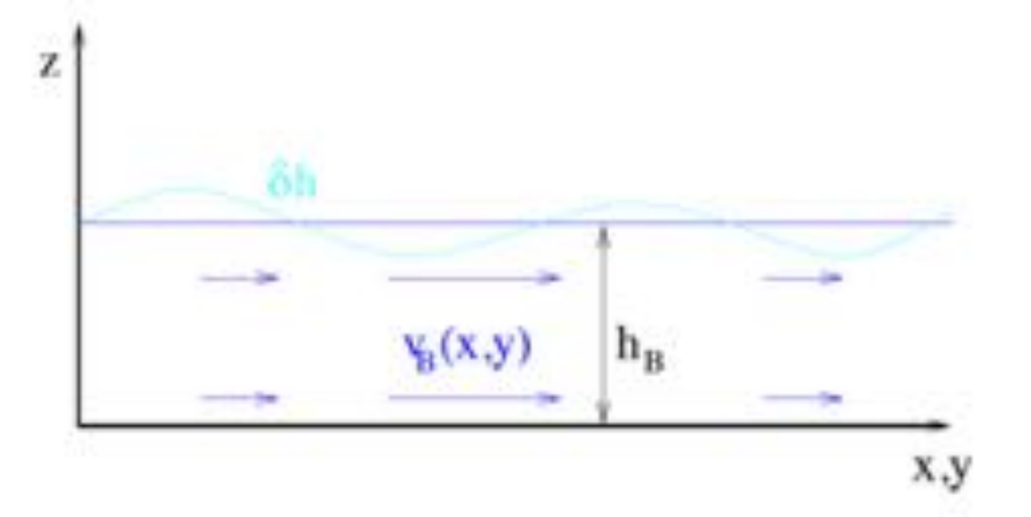
Let’s review respectively a classical and a quantum analogue system

Review: C.Barcelo, S.L and M.Visser, “Analogue gravity” Living Rev.Rel.8,12 (2005-2011).

Classical analogues: Gravity waves

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



Let's consider an inviscid, irrotational flow of a barotropic fluid under the influence of gravity. The Bernoulli's equation reads

$$\partial_t \phi + \frac{1}{2}(\nabla\phi)^2 = -\frac{p}{\rho} - gz - V_{\|}.$$

Here ρ is the density of the fluid, p its pressure, g the gravitational acceleration and $V_{\|}$ a potential associated with some external force necessary to establish an horizontal flow in the fluid which we call $v_B^{\|}$. Boundary conditions: pressure at the surface and vertical velocity at the flat bottom, vanish.

Then for the perturbation one has

$$\partial_t\, \delta\phi + \mathbf{v}_{\mathrm{B}}^{\|} \cdot \boldsymbol{\nabla}_{\|}\delta\phi = -\frac{\delta p}{\rho}.$$

Expanding the perturbations in a Taylor series

$$\delta\phi = \sum_{n=0}^{\infty} \frac{z^n}{n!}\, \delta\phi_n(x, y),$$

and using the continuity equation one finds that in the long wavelength limit (shallow basin) surface wave propagate on an effective geometry

$$\mathrm{d}s^2 = \frac{1}{c^2}\left[-(c^2 - v_{\mathrm{B}}^{\|2})\,\mathrm{d}t^2 - 2\mathbf{v}_{\mathrm{B}}^{\|}\cdot \mathbf{dx}\,\mathrm{d}t + \mathbf{dx}\cdot\mathbf{dx}\right]$$

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

Badulin (1983)

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

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

Accidentally this analogue gravity formalism can be used to describe focussing of Tsunami waves by submarine mountains as analogue gravitational lensing (M. Berry ~2005-2007)

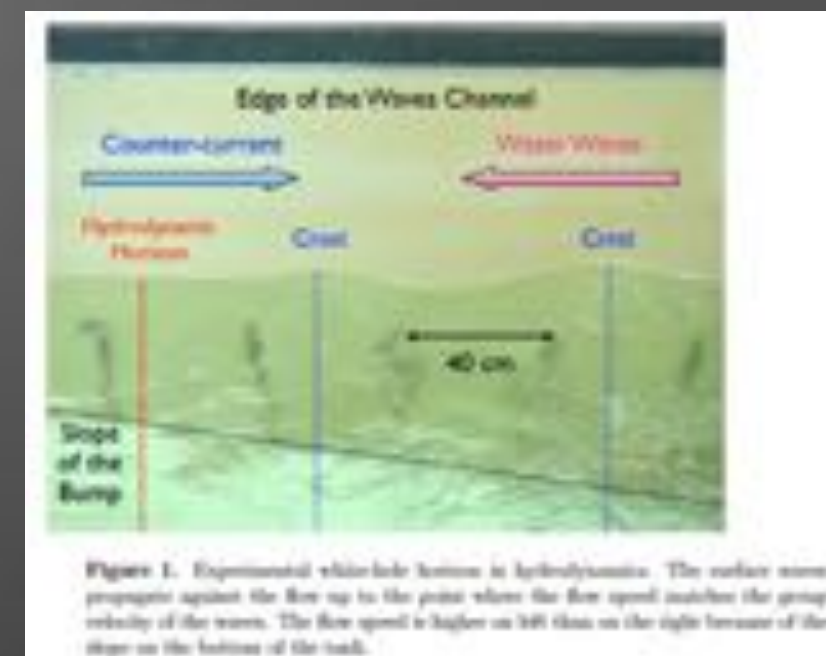
Gravity waves Experiments

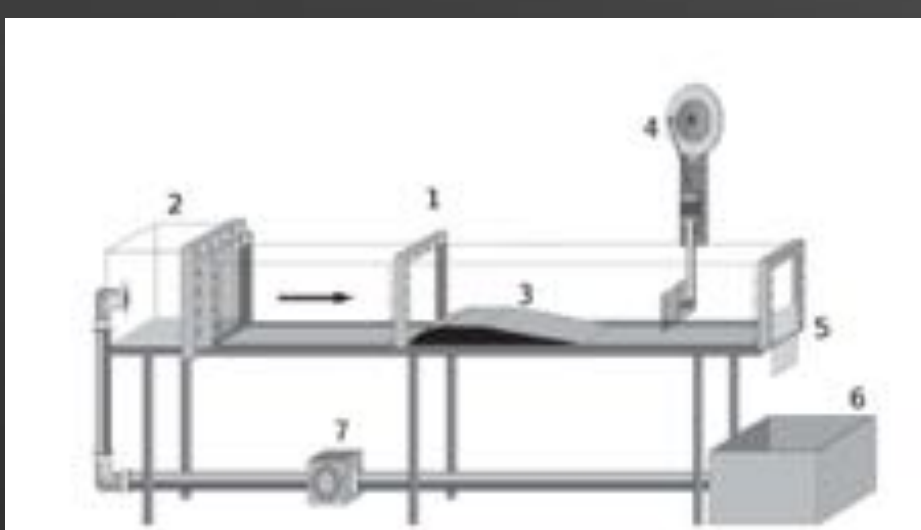
The entire previous analysis can be generalized to the case in which the bottom of the basin is not flat, and the background flow not purely horizontal

Some experimental applications

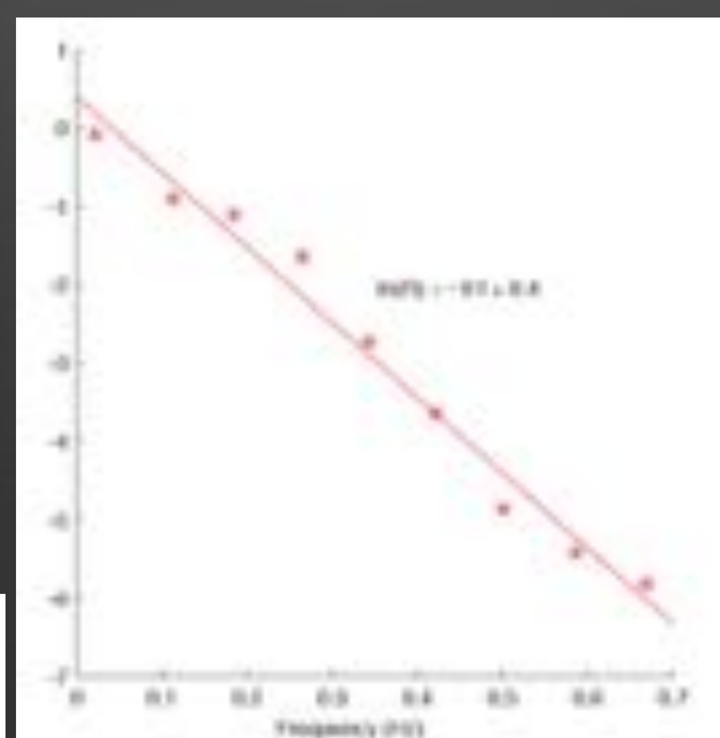
First direct observation of negative-frequency waves converted from positive-frequency waves in a moving medium with analogue WH. Rousseaux et al. New J.Phys.10:053015,2008

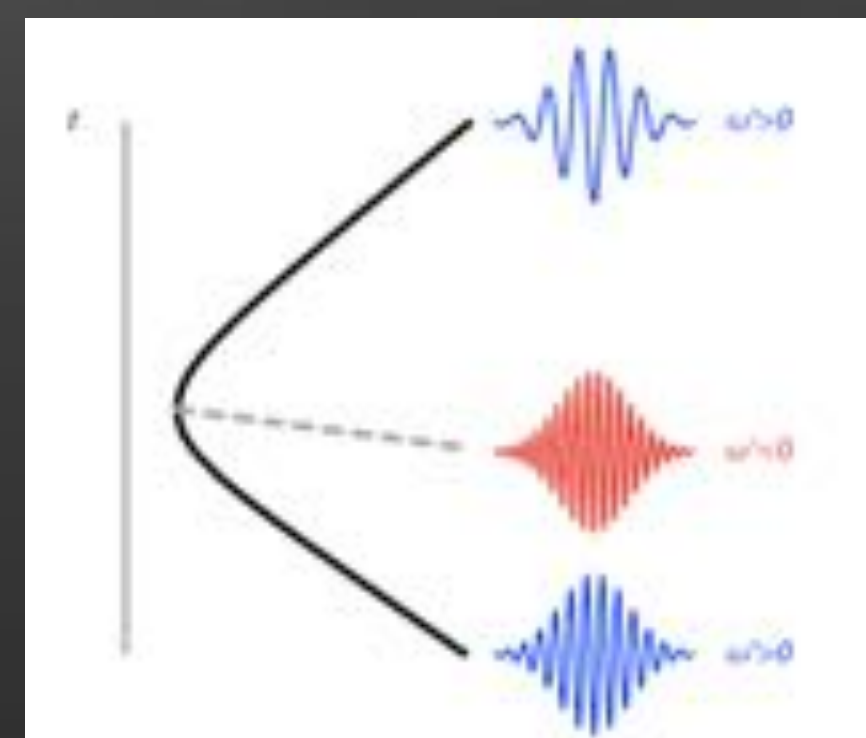
HR mode conversion at white hole horizon has been detected in a shallow water basin!
S.Weinfurtner, E.W. Tedford, M. C. J. Penrice, W. G. Unruh, and G. A. Lawrence. Phys.Rev.Lett. 106 (2011) 021302
But see however F. Michel, R.Parentani. e-Print: arXiv:1404.7482 for alternative interpretation





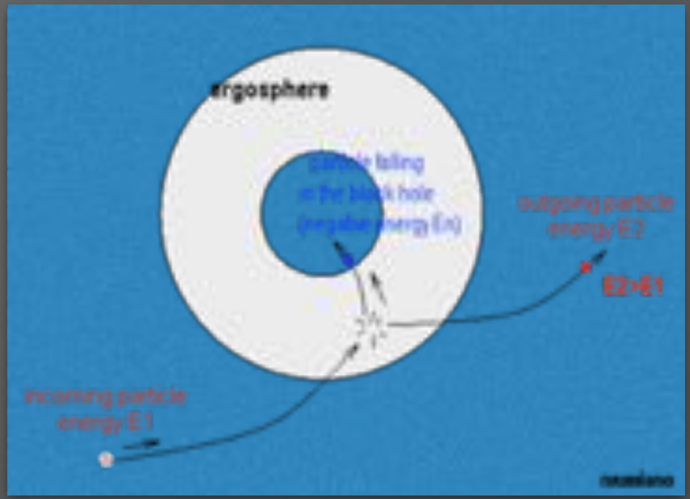
$$R = \frac{|\beta_f|^2}{|\alpha_f|^2} = \exp\left(\frac{-4\pi^2 f}{g_H}\right)$$





Analogue spacetime Maelstroms

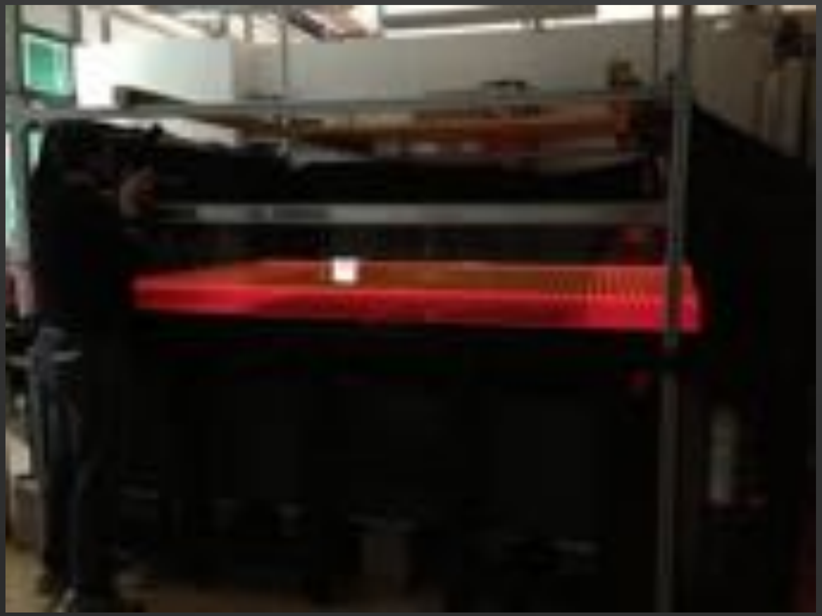
A special characteristic of rotating black holes is the so called Ergoregion surrounding the event horizon.
This ergoregion is a region of spacetime from which one can still escape by spiralling out of it but in it the frame dragging is so strong that it is impossible to remain at a fixed position.

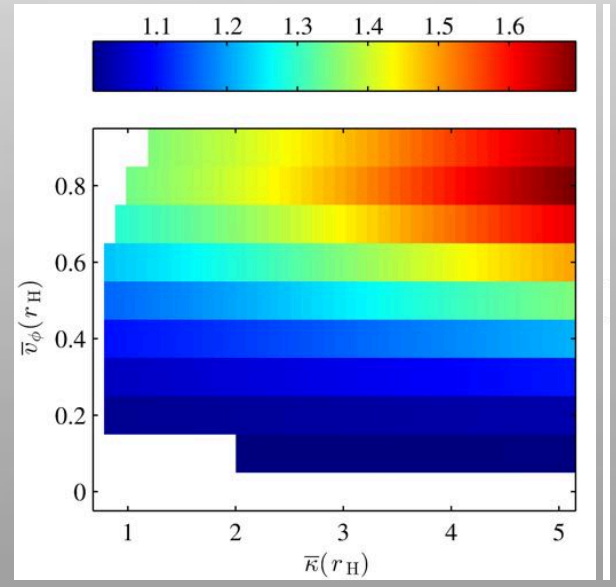


In a BH ergoregion an object moving in them can have an energy as defined at infinity which is negative!
Hence by carefully throwing something into an ergoregion one can extract energy from it.
This energy is subtracted of course from the rotational energy of the BH.
This mechanism is at the base of energy extraction from rotating BHs.

SISSA-Nottingham experiment: an analogue of superradiant scattering (PI: S. Weinfurtner)

Mauricio Richartz, Angus Prain, SL, Silke Weinfurtner.
Class.Quant.Grav. 30 (2013) 085009 and arXiv:1411.1662

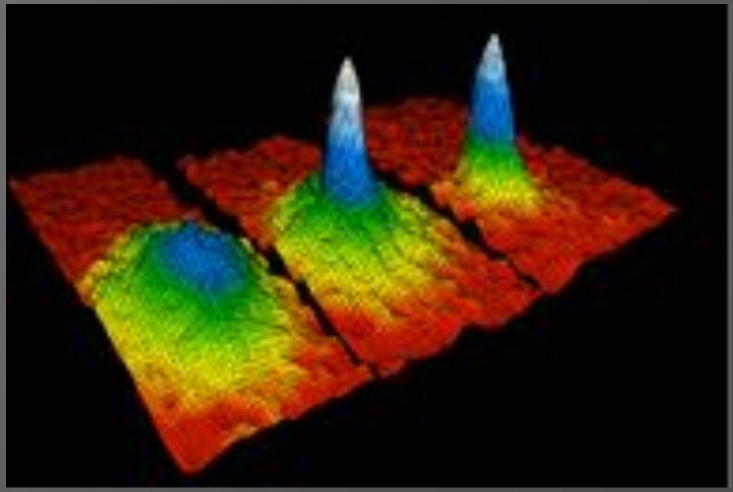




(a) Maximum reflection coefficient $|\mathcal{R}_{\max}|^2$.

Quantum analogue models: BEC

A BEC is quantum system of N interacting bosons in which most of them lie in the same single-particle quantum state
($T<T_c \sim 100$ nK, $N_{atoms} \sim 10^5 \div 10^6$)



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

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

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

(a=s-wave scattering length)

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

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

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

Note that: $\underbrace{\hat{\Psi}|0\rangle = 0}_{\text{atomic Fock vacuum}}$ $\qquad$ $\underbrace{\hat{\Psi}|\Omega\rangle \neq 0}_{\text{ground state}}$

Bose-Einstein condensate: an example of analogue emergent spacetime

By direct substitution of this ansatz in the above equation one gets

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

Background dynamics

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

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
The second one encodes the dynamics for the quantum excitations

The equations are coupled via the so called anomalous mass m̃ and density ñ. Which we shall neglect for the moment…

Acoustic metric

Let's consider quantum perturbations over the BEC background and adopt the "quantum acoustic representation"

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

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 D2 is a represents a second-order differential operator: the linearized quantum potential

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

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

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

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

This is an inherently quantum systems and as such is a good analogue for testing QFT in curved spacetime phenomena. But…

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Lessons

The collective excitations (phonons) of the BEC propagate on a Lorentzian spacetime determined by the background velocity and density

- The atomic physics enters only in determining the fundamental constants of the low energy phenomenology (e.g. speed of sound c_s=analogue speed of light)
- The Lorentz symmetry of the phononic theory is an accidental symmetry, it is not fundamental as the true theory is non-relativistic.

This is an inherently quantum systems and as such is a good analogue for testing QFT in curved spacetime phenomena. But…

Acoustic Lorentz invariance breaking in BEC analogue gravity

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 (experimentally observed) 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"
$\lambda_C=h/(2m_{c_s})=\pi\xi$ with ξ=healing length of BEC=1/(8πρa)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 (breakdown of the continuous medium approximation) $\omega \approx (\hbar^2 k^2)/(2m)$

Robustness of Hawking radiation in Black hole analogues

It turned out that Hawking Radiation is robust against LIV (see e.g. Parentani and collaborators recent papers), however you get (controllable) instabilities such as “black hole laser effect” (superluminal relation in compact supersonic region)

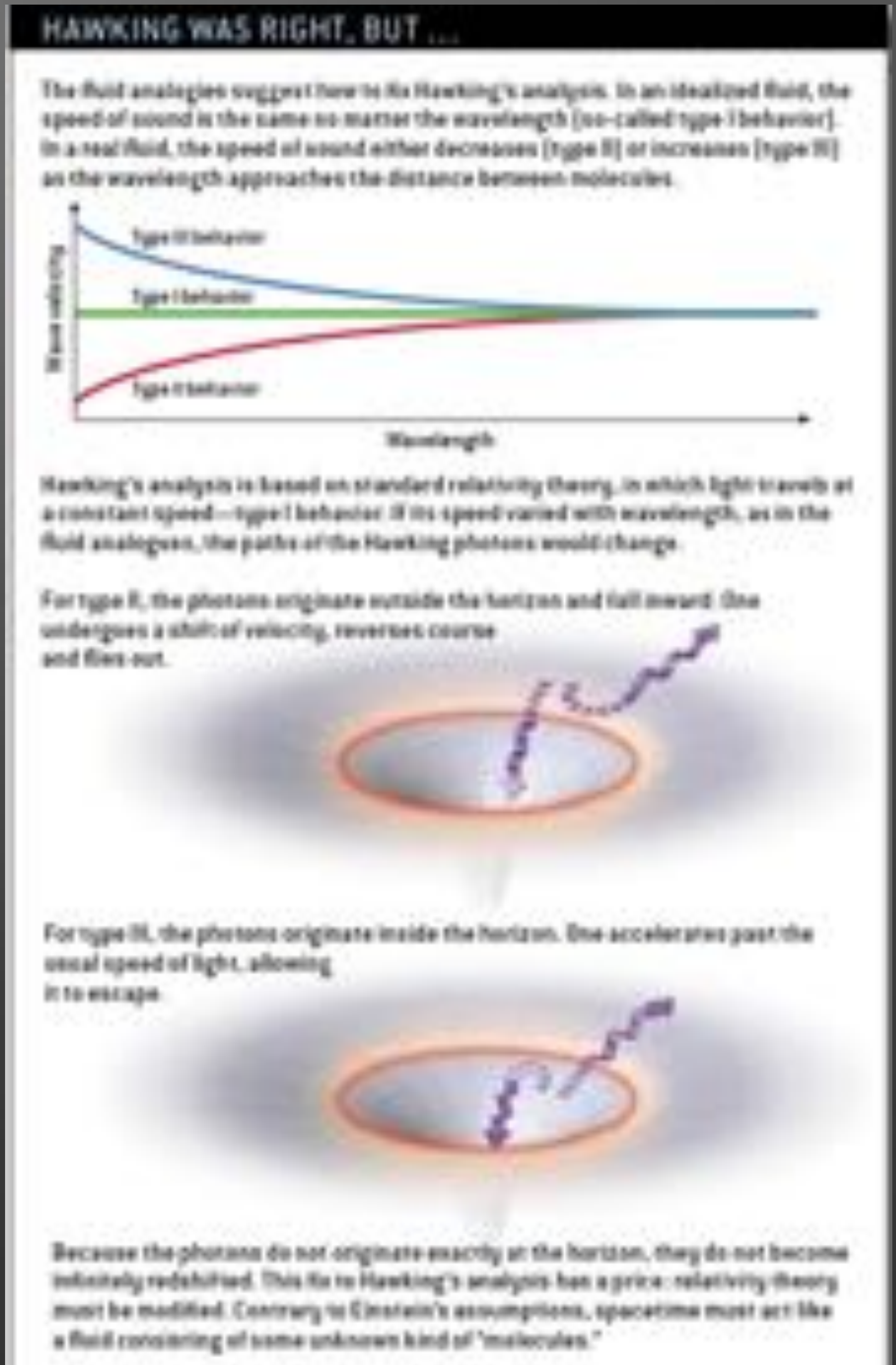
Some facts:

In static spacetimes Hawking radiation robustness is generally assured if there is a separation of scales: $\kappa_{BH} << \Lambda$ where Λ is parametrically related to the UV LIV scale.

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: the horizon becomes thick

White hole-Cauchy horizons UV instabilities are regularised by LIV although at the price of new, slow, IR instabilities (undulation).

WH show HR as time reversed BH HR. Two main differences w.r.t BH: Hawking quanta have high wavevectors even when the Hawking temperature is low, and the entangled partners propagate on the same side of the horizon (inside for superluminal, outside for subluminal dispersion).

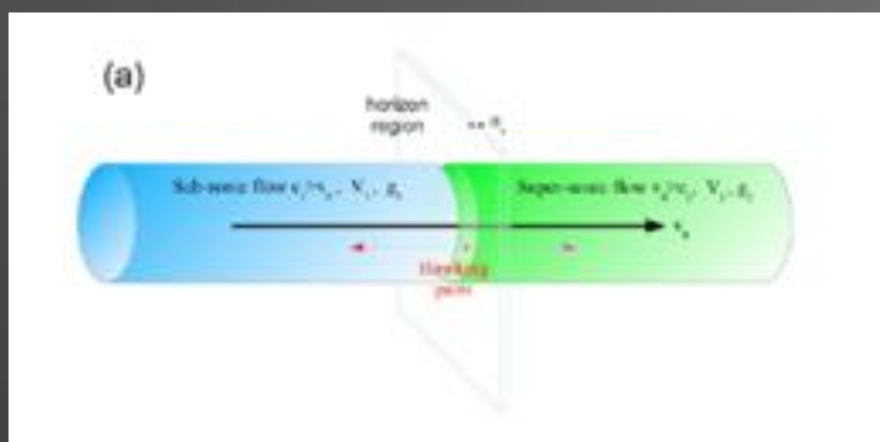


From Jacobson-Parentani: Sci. Am. 2005

Hunting Hawking radiation in BEC

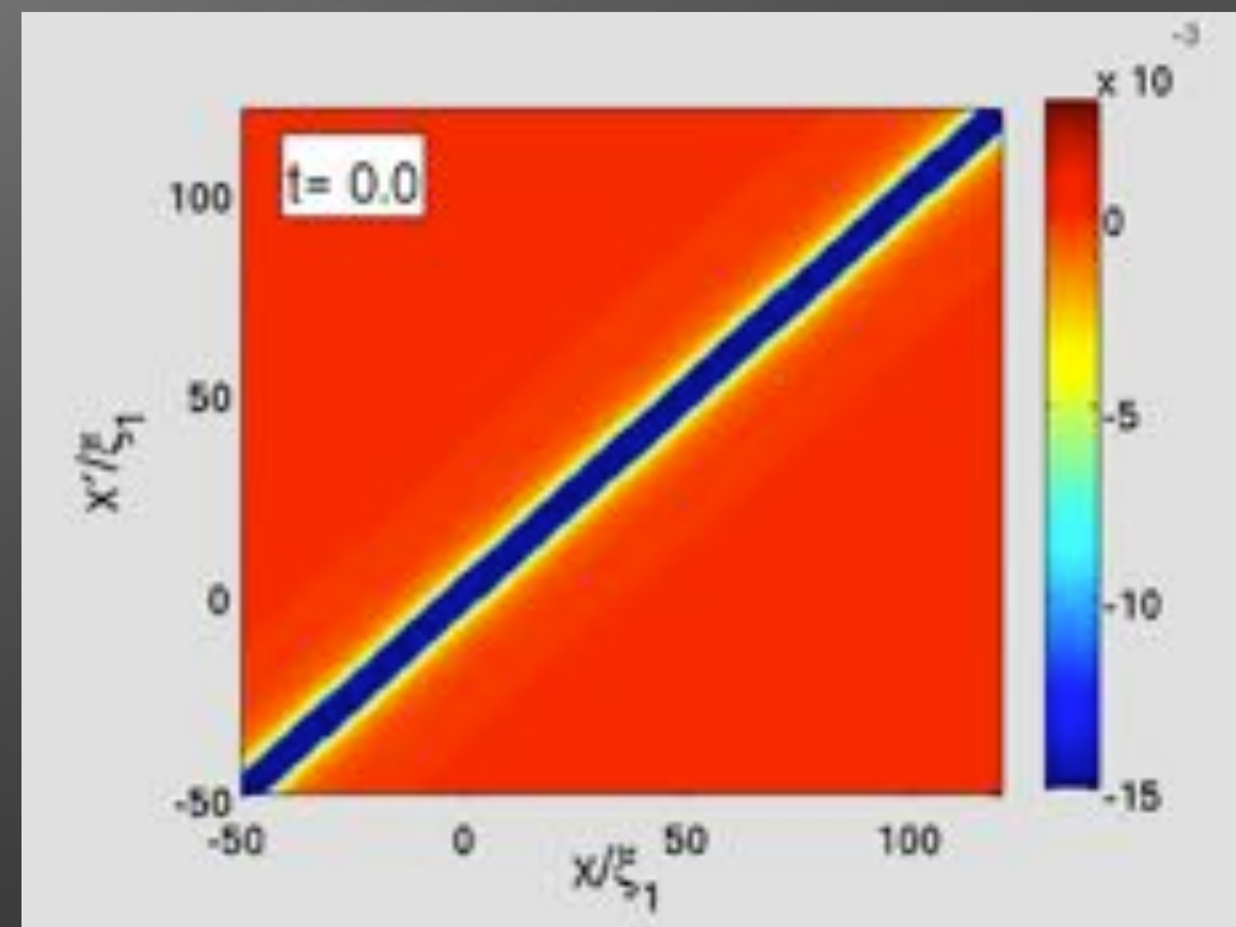
We saw that Hawking radiation is a very faint phenomenon. How can we “see it”?

Idea: use a Feshbach resonance to control the scattering length and hence the speed of sound, in order to create an analogue black hole than look for density-density correlates between Hawking radiation pairs of quanta.



Density-Density correlation function

$$G^{(2)}(x,x') = \frac{\langle : n(x)\, n(x') : \rangle}{\langle n(x) \rangle \, \langle n(x') \rangle}$$



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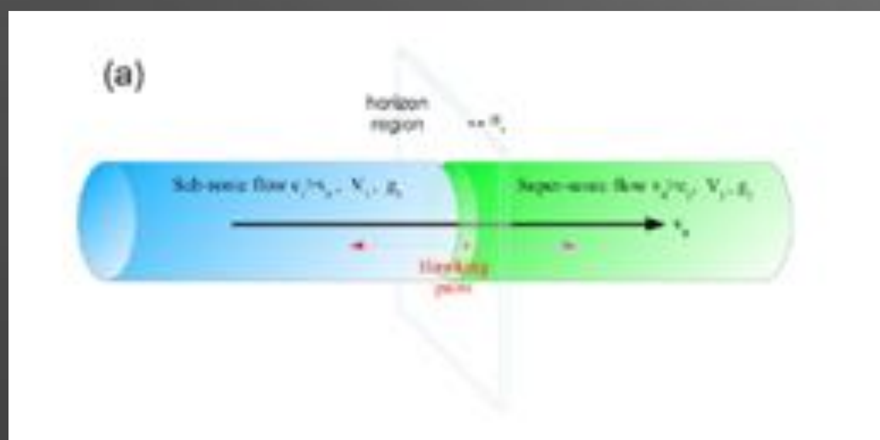

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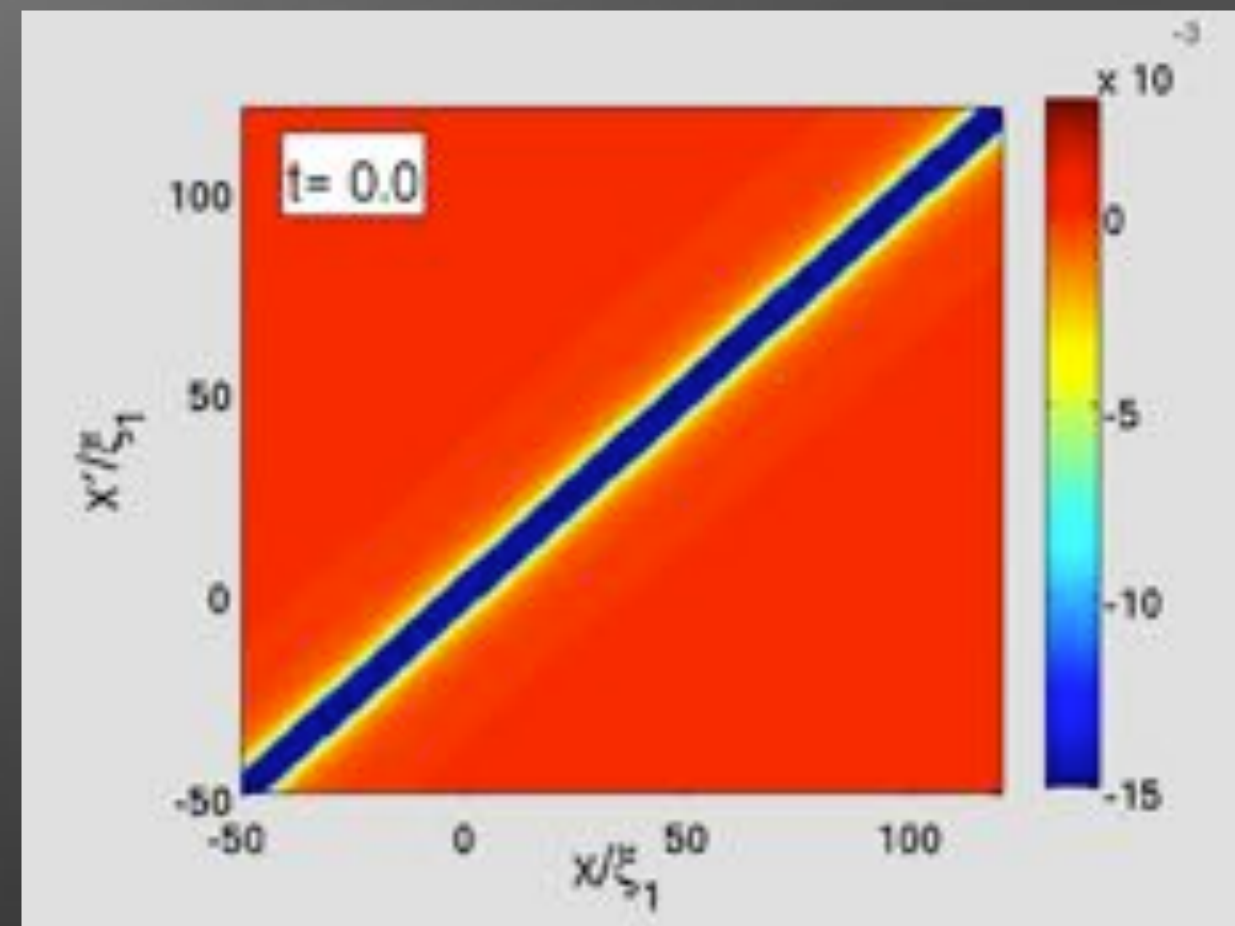

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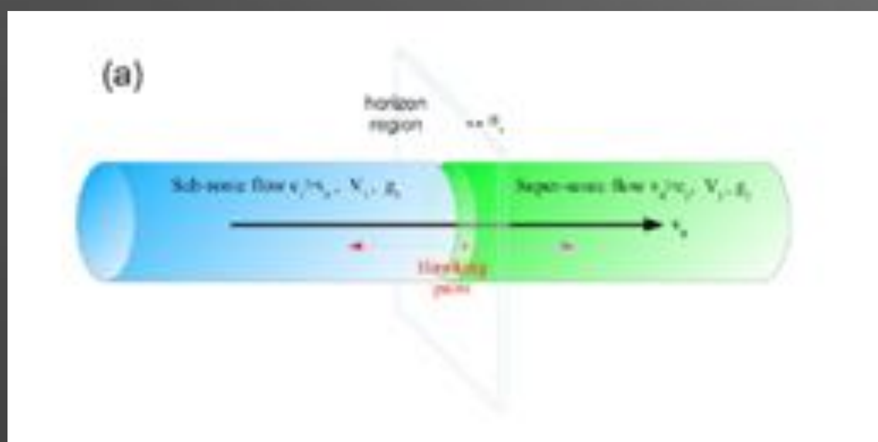

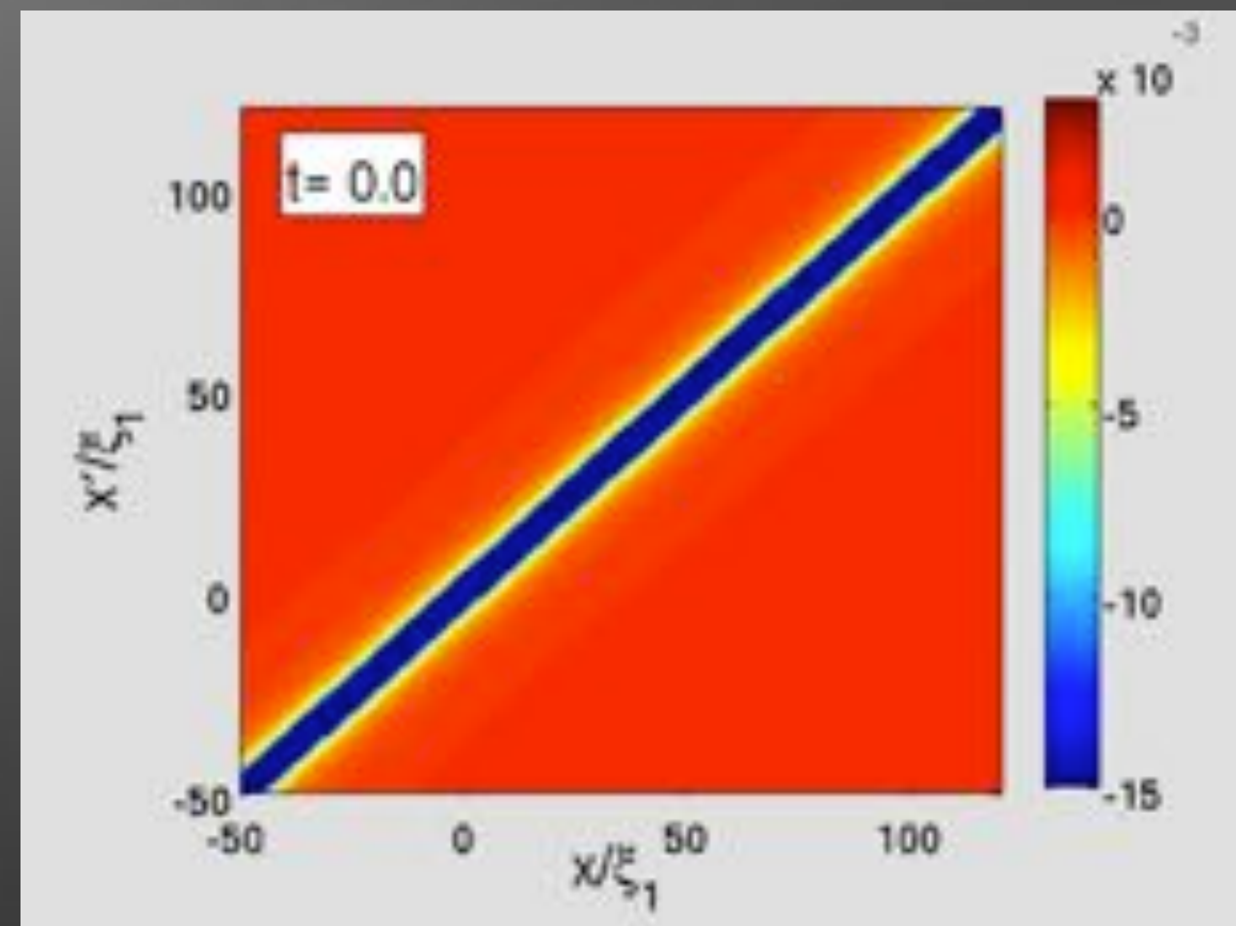

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June 2009: First claim BEC-BH realized!
A sonic black hole in a density-inverted Bose-Einstein condensate.
Unfortunately it was too short living...
O.Lahav et al. arXiv:0906.1337. More efforts undergoing now.

Are we close to the first detection of analogue Hawking radiation?

Indirect Detection of Hawking radiation: the Laser effect in BEC

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

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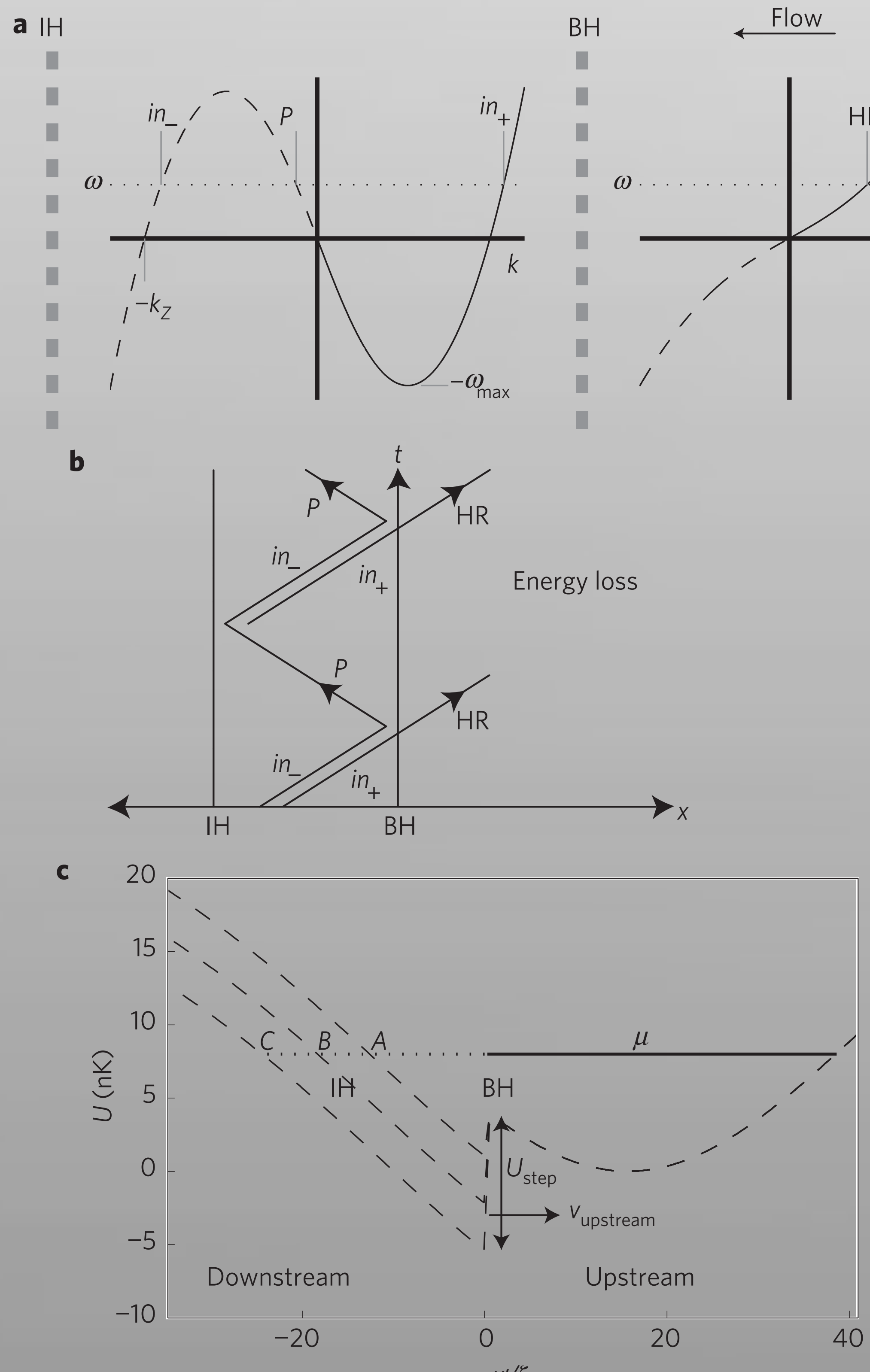

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- Corley-Jacobson (1999) qualitatively predict self amplification of Hawking modes with compact ergoregion. (Superluminal Dispersion relation in Supersonic region)
- Finazzi-Parentani (2010) discuss analytical/ numerical solutions in BEC and show duality (Superliminal->Subluminal, Supersonic->Subsonic region)
- Lahav et al.: First short living Analogue BH in BEC.
- J. Steinhauer. First Observation of the Laser Effect (2014). Nature Physics.

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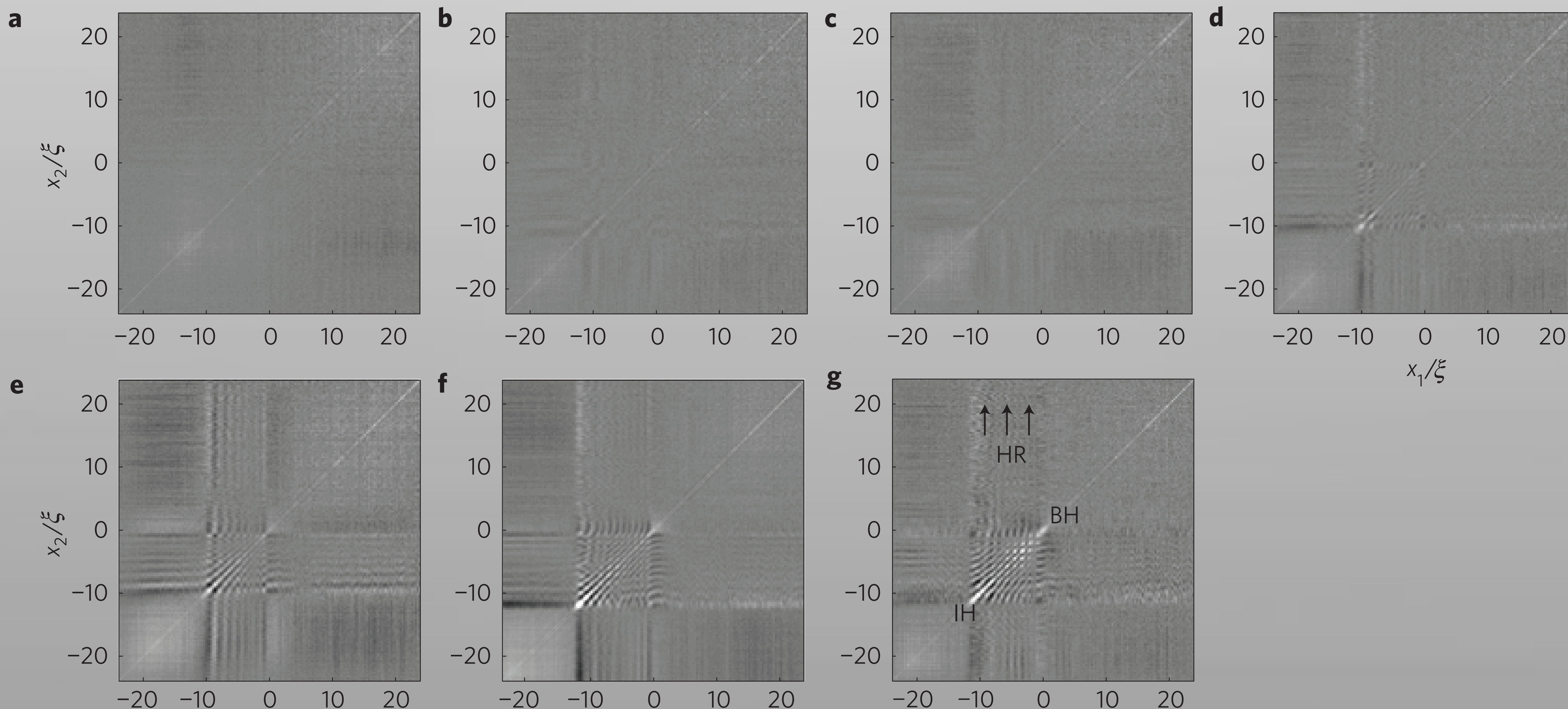

From Analogue Models to Astroparticle Physics

We have seen how condensed matter analogues can be fruitfully used in order to test several ideas related to

- quantum field theory in curved spacetime effects
- and the UV behaviour of an emergent classical spacetime (e.g. UV Lorentz breaking)

But can we test these scenarios in “real life”?

Lorentz violation: a first glimpse of QG?

Suggestions for Lorentz violation searches (at low or high energies) came from several QG models:

- String field theory, tensor VEVs (Kostelecky-Samuel 1989, ...)
- Cosmological varying moduli (Damour-Polyakov 1994)
- Spacetime foam scenarios (Ellis, Mavromatos, Nanopoulos 1992, Amelino-Camelia et al. 1997-1998)
- Some semiclassical spin-network calculations in Loop QG (Gambini-Pullin 1999)
- Einstein-Aether Gravity (Gasperini 1987, Jacobson-Mattingly 2000, …)
- Some non-commutative geometry calculations (Carroll et al. 2001)
- Some brane-world backgrounds (Burgess et al. 2002)
- Ghost condensate in EFT (Cheng, Luty, Mukohyama, Thaler 2006)
- Horava-Lifshiftz Gravity (Horava 2009, …)

Many of the aforementioned QG models have been shown to lead to modified dispersion relations like those encountered in condensed matter analogues

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$$E^2 = p^2 + m^2 + M\eta^{(1)}|p| + \eta^{(2)}p^2 + \eta^{(3)}|p|^3/M \ldots$$

Dynamical frameworks for LIV

Missing a definitive QG candidate able to provide definitive sub-Planckian predictions
different general dynamical framework have been proposed
Many of the aforementioned QG models have been shown to lead to modified dispersion relations but we need also a dynamical framework

Frameworks for preferred frame effects

See e.g. SL. CQG Topic Review (2013)

See e.g. Amelino-Camelia. Living Reviews of Relativity

EFT+LV

Non EFT proposals:
E.g. Non-critical Strings
Spacetime foam models

Minimal Standard Model Extension
Renormalizable ops.
(IR LIV - LI SSB)

local EFT with LIV
Non-renormalizable ops,
CPT ever or odd
(no anisotropic scaling),

NOTE: CPT violation implies Lorentz violation but LV does not imply CPT violation in local EFT.
"Anti-CPT" theorem (Greenberg 2002).
So one can catalogue LIV by behaviour under CPT

E.g. QED, rot. Inv. dim 3,4 operators

electrons $\quad E^2 = m^2 + p^2 + f_e^{(1)} p + f_e^{(2)} p^2$

photons $\quad \omega^2 = \left(1 + f_\gamma^{(2)}\right) k^2$

(Colladay-Kosteleky 1998, Colemann-Glashow 1998)

E.g. QED, dim 5 operators

electrons $\quad E^2 = m^2 + p^2 + \eta_\pm^{(3)} (E^3/M_{\rm Pl})$

photons $\quad \omega^2 = k^2 \pm \xi(\omega^3/M_{\rm Pl})$

(Myers-Pospelov 2003)

[Collins et al. PRL93 (2004),
[Iengo, Russo, Serone (2009)]
Belenchia, Gambassi, SL: in Preparation

An open problem: the un-naturalness of small LV in EFT

Dim 3,4 operators are tightly constrained: $O(10^{-46})$, $O(10^{-27})$. This is why much attention was focused on dim 5 and higher operators (which are already Planck suppressed).

However if one postulates classically a dispersion relation with only naively (no anisotropic scaling) non-renormalizable operators (i.e. terms $\eta^{(n)}p^n/M_{Pl}^{n-2}$ with $n \geq 3$ and $\eta^{(n)} \approx O(1)$ in disp.rel.) then

Radiative (loop) corrections involve integration up to the natural cutoff M_{Pl} will generate the terms associated to renormalizable operators ($\eta^{(1)} p M_{Pl}, \eta^{(2)} p^2$) which are observationally very constrained.

This is THE main problem with UV Lorentz breaking!

Note: Analogue gravity toy model of a Custodial Symmetry protection from IR LIV was shown in SL, Weinfurtner, Visser. Phys. Rev. Lett. 96, 151301 (2006).

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One needs another scale other from E_{LIV}
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So far main candidate SUSY but needs E_{SUSY} not too high.

E.g. gr-qc/0402028 (Myers-Pospelov) or
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E.g. Horava gravity coupled to LI Standard Model: Pospelov & Shang arXiv.org/1010.5249v2

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Models with strong coupling at high energies improving RG flow a la Nielsen. Pujolas et al.

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But let's see what we can say "order by order" for the moment…

Constraints on QED dim 5 CPT Odd QED extension

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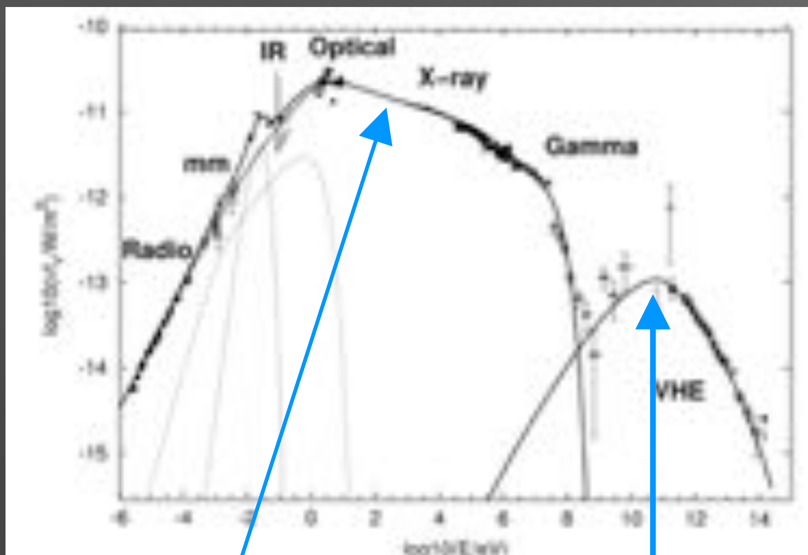
photons $\omega^2 = k^2 \pm \xi(k^3/M_{\mathrm{Pl}})$



Synchrotron

Inverse Compton

L.Maccione, SL, A.Celotti and J.G.Kirk: JCAP 0710 013 (2007)
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The Crab nebula a supernova remnant (1054 A.D.) distance ~1.9 kpc from Earth.
Spectrum (and other SNR) well explained by synchrotron self-Compton (SSC)
Electrons are accelerated to very high energies at pulsar: in LI QED $\gamma_e \approx 10^9 \div 10^{10}$
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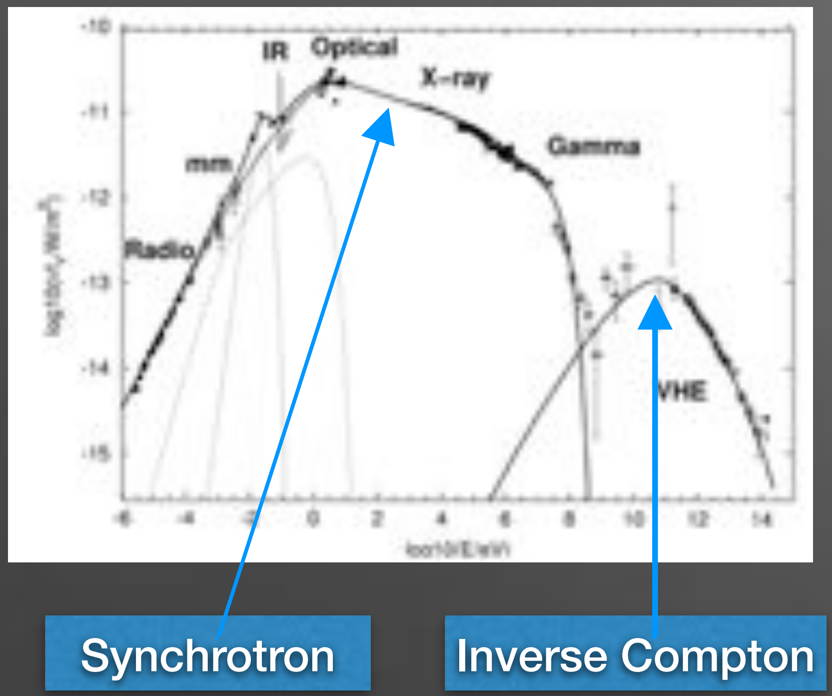

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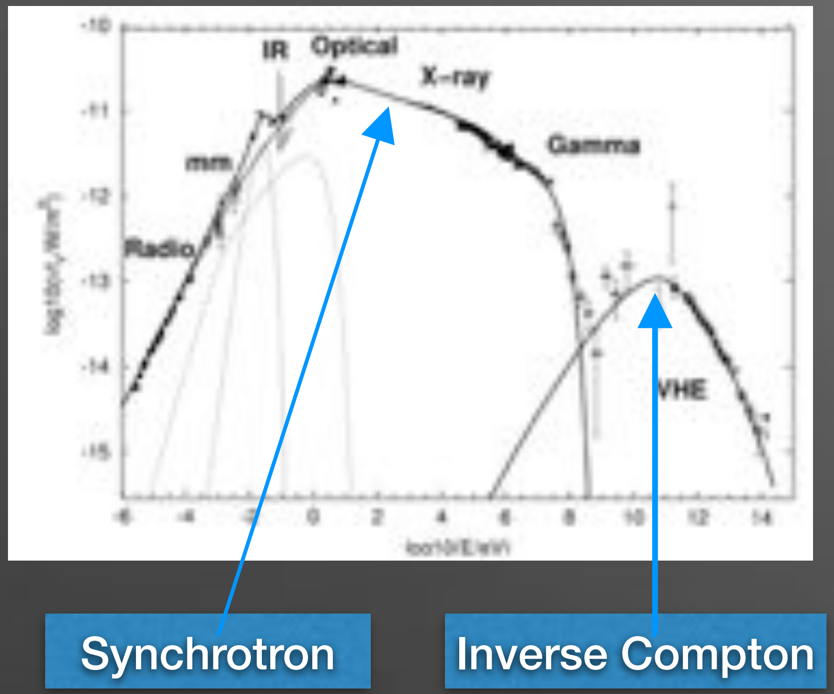

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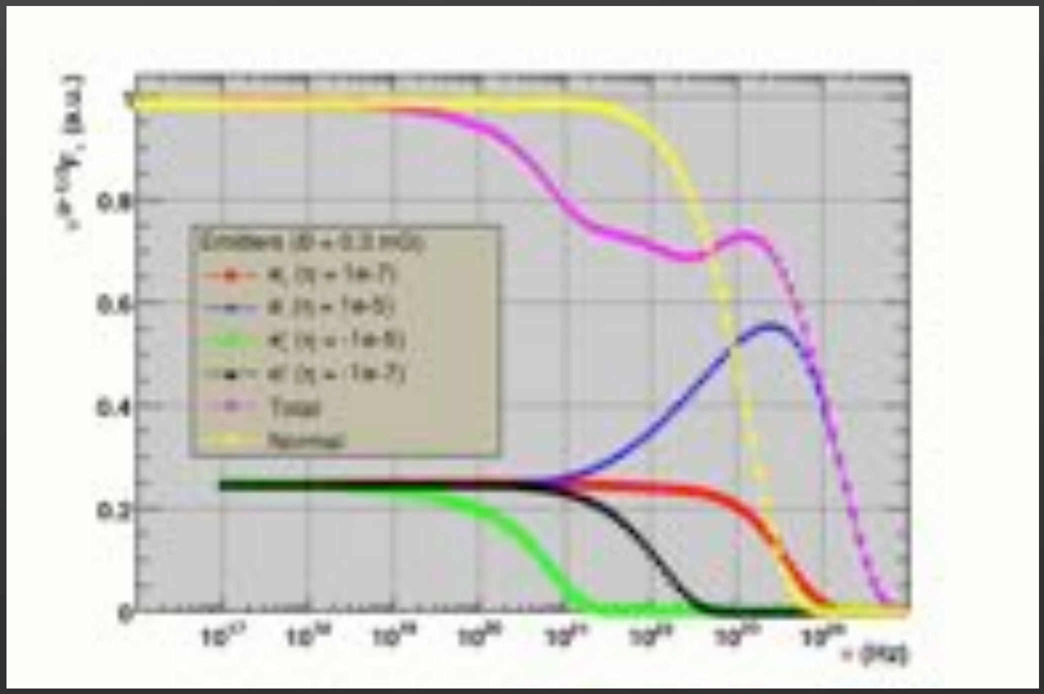
Spectrum very well know via EGRET, now AGILE+FERMI



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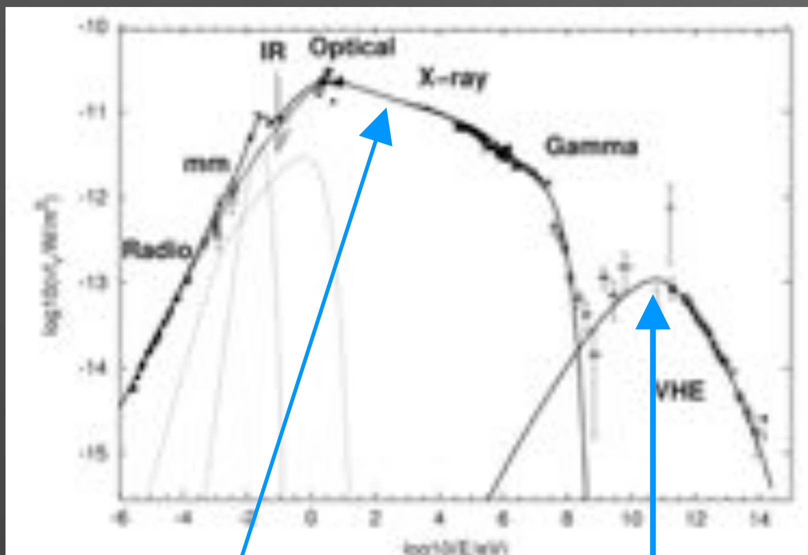

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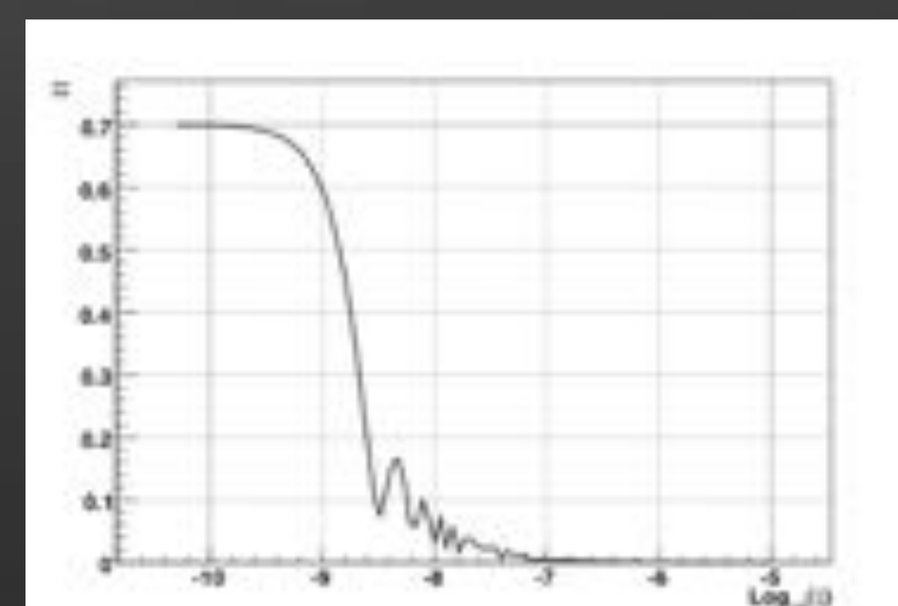
The polarization of the synchrotron spectrum is strongly affected by LIV: there is a rotation of the angle of linear polarization with different rates at different energies. Strong, LIV induced, depolarization effect.

$$\Delta\theta = \xi \left(k_2^2 - k_1^2\right) d/2M, \quad (\text{where } d = \text{distance source-detector})$$

Polarization recently accurately measured by INTEGRAL mission: 40±3% linear polarization in the 100 keV - 1 MeV band + angle θobs= (123±1.5)° from the North



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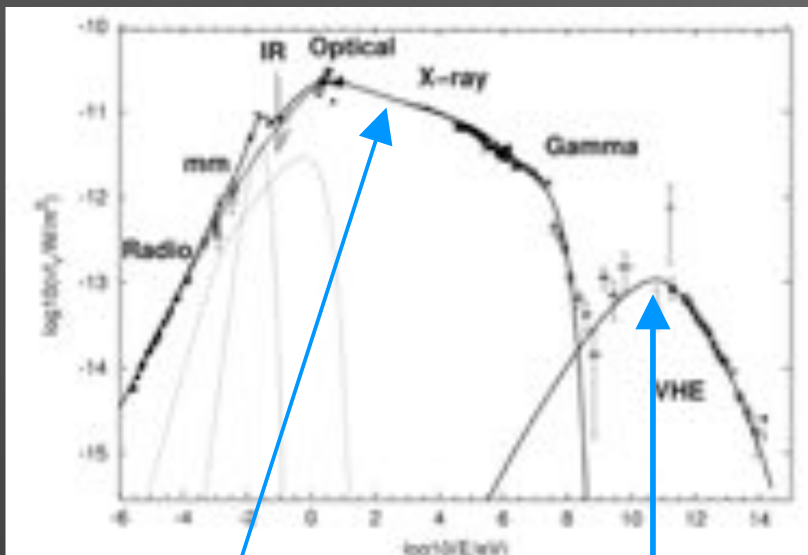

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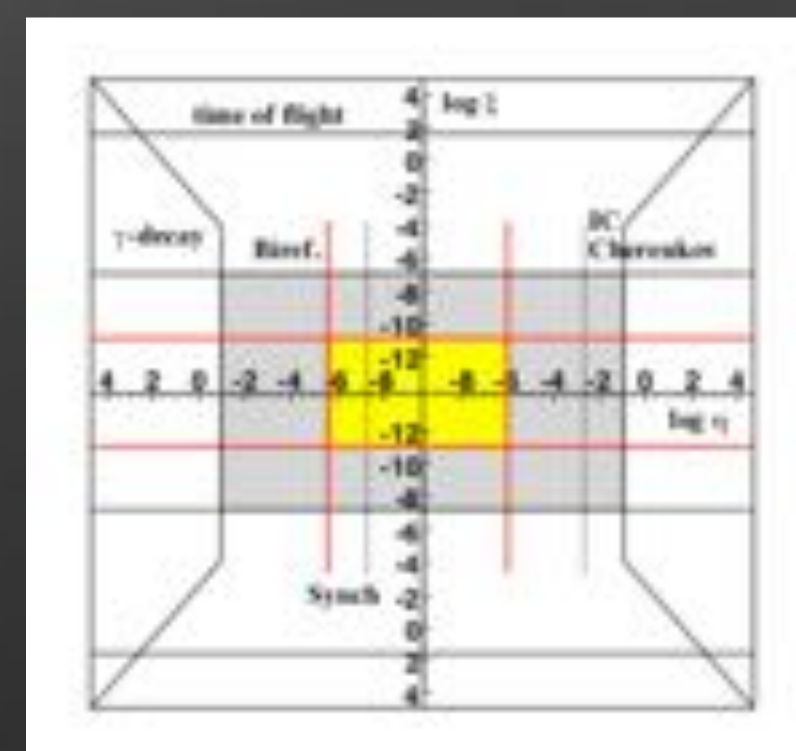
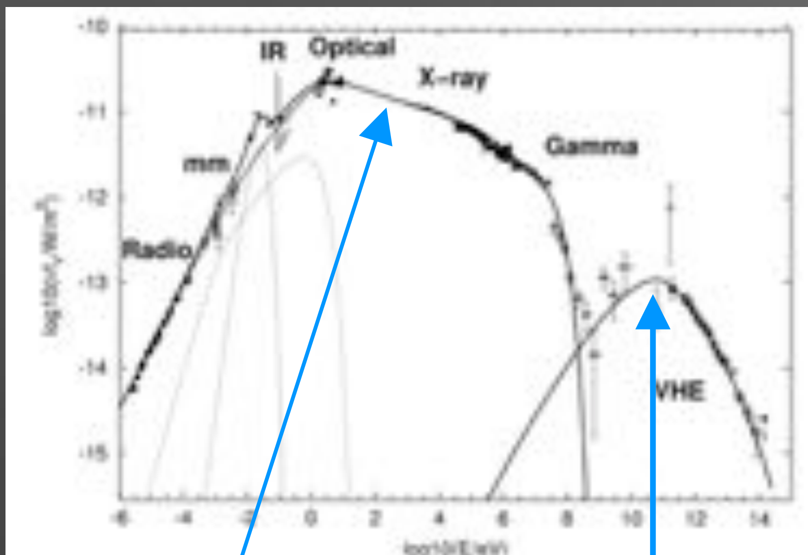


Constraints on QED dim 5 CPT Odd QED extension

electrons $E^2 = m^2 + p^2 + \eta_{\pm}(p^3/M_{\mathrm{Pl}})$

photons $\omega^2 = k^2 \pm \xi(k^3/M_{\mathrm{Pl}})$



Synchrotron

Inverse Compton

L.Maccione, SL, A.Celotti and J.G.Kirk: JCAP 0710 013 (2007)
L.Maccione, SL, A.Celotti and J.G.Kirk, P. Ubertini:Phys.Rev.D78:103003 (2008)

The Crab nebula a supernova remnant (1054 A.D.) distance ~1.9 kpc from Earth.
Spectrum (and other SNR) well explained by synchrotron self-Compton (SSC)
Electrons are accelerated to very high energies at pulsar: in LI QED $\gamma_e \approx 10^9 \div 10^{10}$
High energy electrons emit synchrotron radiation
Synchrotron photons undergo inverse Compton with the high energy electrons

Currently the best two test come from the measurement of the spectrum and polarization of Crab synchrotron emission.

The synchrotron spectrum is strongly affected by LIV: maximum gamma factor for subliminal leptons and vacuum Cherekov limit for superluminal ones (there are both electrons and positrons and they have opposite η).
Spectrum very well know via EGRET, now AGILE+FERMI

The polarization of the synchrotron spectrum is strongly affected by LIV: there is a rotation of the angle of linear polarization with different rates at different energies. Strong, LIV induced, depolarization effect.

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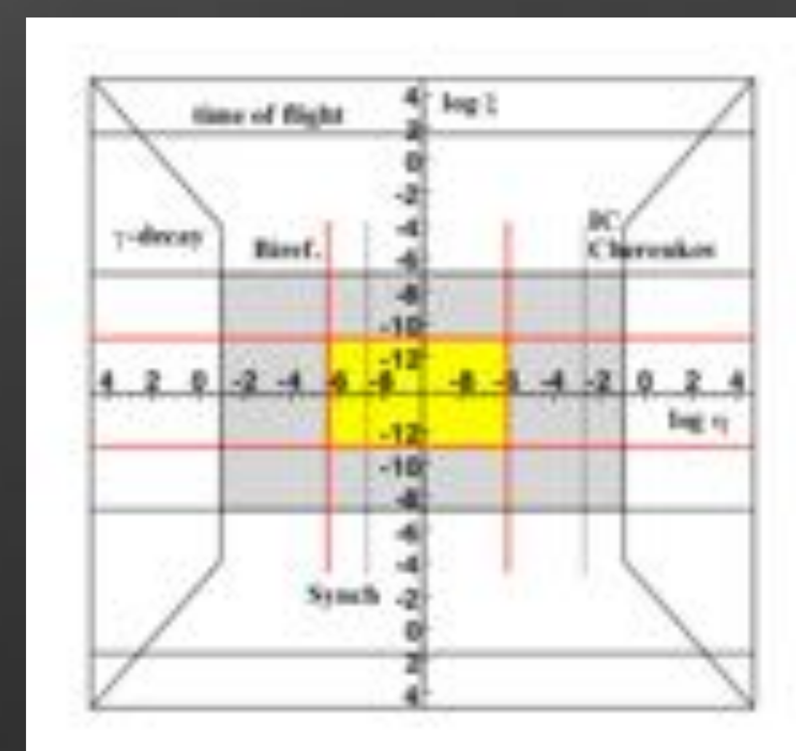

Galaverni, Sigl, arXiv:0708.1737. PRL
Maccione, SL, arXiv:0805.2548. JCAP

Constraints on dim 5-6 CPT even LV QED

$$\begin{aligned} \omega^2 &= k^2 + \xi\, k^4/M_{\rm Pl}^2 \\ E_\pm^2 &= p^2 + m_e^2 + \eta_\pm\, p^4/M_{\rm Pl}^2 \\ \text{where} \quad \pm &= \text{opposite helicity states} \end{aligned}$$

In this case we need ultra high energies:
p_{crit} for e^-~100 PeV

Cosmic Rays Photo pion production:
The Greisen-Zatsepin-Kuzmin effect

$$p + \gamma \to p + \pi^0 (n + \pi^+) \qquad E_{\rm th} = \frac{2 m_p m_\pi + m_\pi^2}{4\epsilon} \sim 4 \cdot 10^{19}\ \text{eV}$$

GZK photons are pair produced by decay of π_0 produced in GZK process

The Greisen-Zatsepin-Kuzmin
effect and secondary production

$$p + \gamma \to N + \pi \quad \begin{cases} \pi^0 \to \gamma\gamma \\ \pi^\pm \to \mu\nu_\mu \to e\,\nu_\mu \bar{\nu}_\mu \nu_e \end{cases}$$

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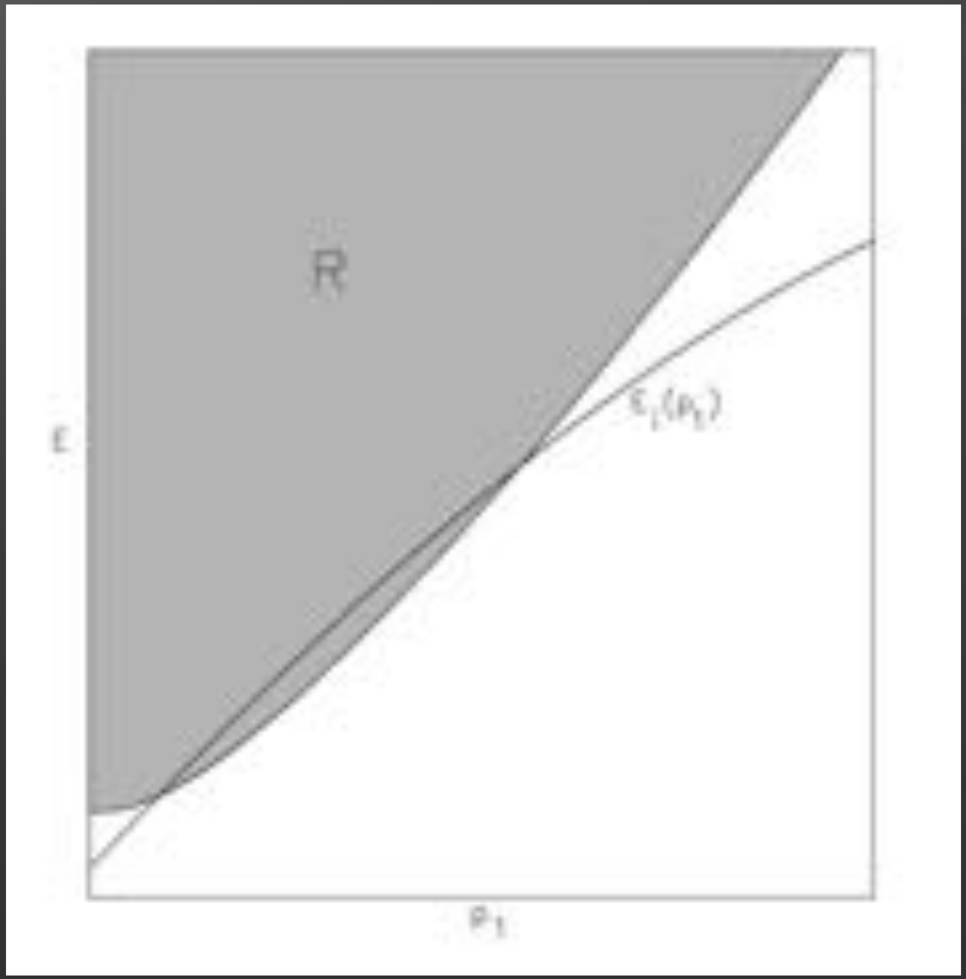

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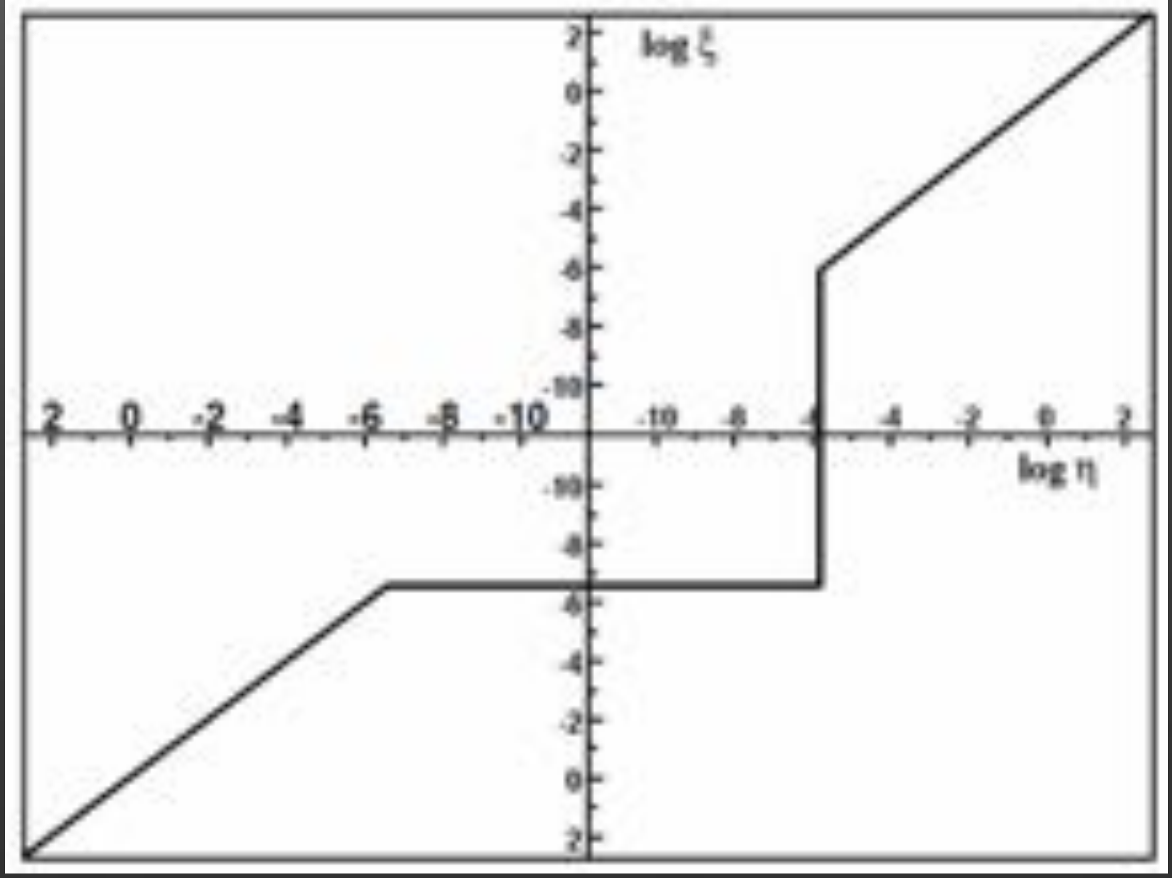

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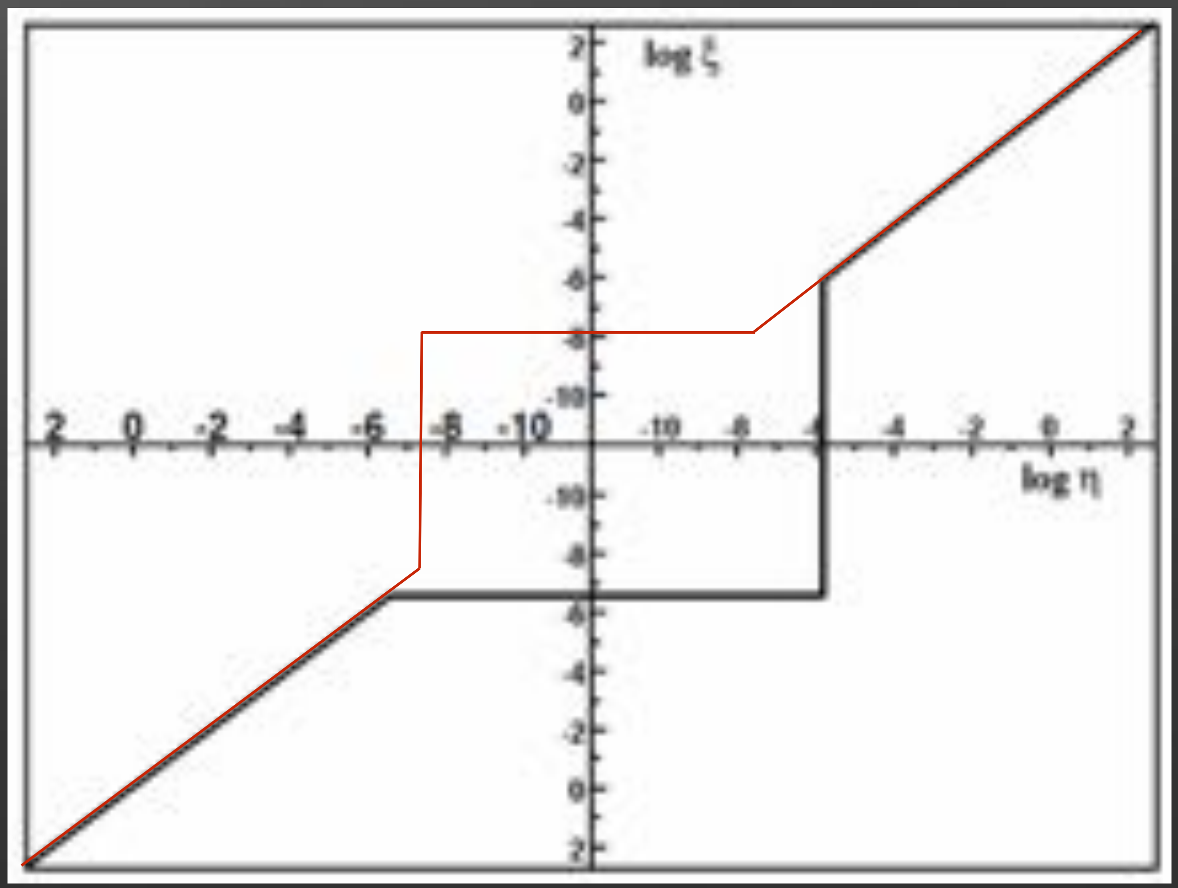
LIV strongly affects the threshold of this process: lower and also upper thresholds.
If $k_{up} < 10^{20}$ eV then photon fraction in UHECR much larger than present upper limits
LIV also introduces competitive processes: γ-decay
If photons above 10^{19} eV are detected then γ-decay threshold > 10^{19} eV



Testing Lorentz violations: end of the story?

Order	photon	e^-/e^+	Protrons	Neutrinos[a]
n=2	N.A.	$O(10^{-16})$	$O(10^{-20})$ (CR)	$O(10^{-8} \div 10^{-10})$
n=3	$O(10^{-16})$ (GRB)	$O(10^{-16})$ (CR)	$O(10^{-14})$ (CR)	$O(40)$
n=4	$O(10^{-8})$ (CR)	$O(10^{-8})$ (CR)	$O(10^{-6})$ (CR)	$O(10^{-7})^*$ (CR)

Table 2. Summary of typical strengths of the available constrains on the SME at different n orders for rotational invariant, neutrino flavour independent LIV operators. GRB=gamma rays burst, CR=cosmic rays. [a] From neutrino oscillations we have constraints on the difference of LIV coefficients of different flavors up to $O(10^{-28})$ on dim 4, $O(10^{-8})$ and expected up to $O(10^{-14})$ on dim 5 (ICE3), expected up to $O(10^{-4})$ on dim 6 op. * Expected constraint from future experiments.

QG phenomenology of Lorentz and CPT violations is a a success story in physics. We have gone in few years (1997->2010) from almost no tests to tight, robust constraints on EFT models.

Chances are high that improving observations in HE astrophysics will strengthen these constraints in a near future… If there is Lorentz violation, and it is described by the same modified dispersion relation at all energies then its scales seems required to be well beyond the Planck scale…

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Should we conclude that we have deviations from Special Relativity enough?
Mission Accomplished?

Not quite…

Caveat: A potential problem with the UHECR data?

- With increased statistics the composition of UHECR beyond 10^{19} eV seems more and more dominated by iron ions rather than protons at AUGER. But Telescope Array (TA) in Utah is instead Ok with purely proton composition. Are we really seeing the GZK?
- With improved statistic the correlated AUGER UHECR-AGN events have decreased from 70% to 40%: large deflections? i.e. heavy (high Z) ions?
- Also no evidence at the TA for AGN correlation. But some hint of correlation with LLS for E>57 EeV
- Ions do photodisintegration rather than the GZK reaction, this may generate much less protons which are able to create pions via GZK and hence UHE photons.
- Have we really seen the GZK cutoff? See e.g. arXiv:1408.5213.
- If not all the constraints on dim 6 CPT even operators would not be robust…
- Furthermore puzzling cut off above 2 PeV in UHE neutrinos at IceCube maybe consistent with p^4 LIV: F.W. Stecker, S.T. Scully, SL, D. Mattingly. JCAP 2015

What next?

Analogue gravity

- Definitive direct detection of Analogue Hawking Radiation in quantum system
- Further theoretical exploration as toy models of emergent gravity

Tests of Lorentz Violations

- We need better data from UHECR and Cosmogenic Neutrinos to constraint $O(k^4)$
- Also the gravity sector needs more exploration: missing test of LIV in gravity beyond 10^{-2} eV

Other mesoscopic physics without Lorentz violation?

- We do have concrete QG models of emergent gravity like Causal Sets or String Field Theory or Loop Quantum Gravity which generically seem to predict exact Lorentz invariance below the Planck scale in spite of (fundamental or quantum) discreteness at the price to introduce non-local EFT.

Conjecture: Discreetness + Lorentz Invariance = Non-Locality

Examples

Causal Set Theory

$$\Box_\rho \approx \Box + \frac{\alpha}{\sqrt{\rho}}\Box^2 + \frac{\beta}{\sqrt{\rho}}\Box^2 \ln\left(\frac{\gamma}{\rho}\Box^2\right) + \dots$$

String Field Theory

$$\Box \to (\Box + m^2)\exp\frac{\Box+m^2}{\Lambda^2}$$

These theories involve a very subtle phenomenology very hard to constraint, still they do show novelties, e.g. breakdown of the Huygens principle in 4D.

Differently from UV Lorentz breaking physics it will be here a matter of PRECISION instead of HIGH ENERGIES…

Non-local Schrödinger equation

Let's consider a non-local Klein-Gordon field equation e.g. from String Field theory

$$\underbrace{(\frac{1}{c^2}\partial_t^2 - \nabla_x^2 + \frac{m^2c^2}{\hbar^2})}_{\mathcal{KG}} Exp\left[\frac{\frac{1}{c^2}\partial_t^2 - \nabla_x^2 + \frac{m^2c^2}{\hbar^2}}{\Lambda^2}\right]\psi(t,x) = 0,$$

Disclaimer
Work in Progress!

Then let's consider its non-relativistic limit. One get's

$$\sum_{n=0}^{\infty} \underbrace{\frac{1}{n!}\left(-\frac{2m}{\hbar^2}\right)^n \frac{1}{\Lambda^{2(n-1)}}}_{a_n} \frac{1}{\Lambda^2}\mathcal{S}^{n+1} \equiv \mathcal{S}_{NL}.$$

where

$$\mathcal{S} \equiv i\hbar\partial_t + \frac{\hbar^2}{2m}\nabla_x^2,$$

So we get

$$(\mathcal{S}_{NL} - V)\,\phi(t,x) = 0.$$

In order to solve this one needs to adopt a perturbative expansion around a "local" Sch. solution $\phi = \phi_0 + \epsilon\phi_1,$

The first order perturbation solves

$$(\mathcal{S} - V)\phi_1 = \underbrace{-\mathcal{D}\phi_0}_{\mathcal{J}(t,x)},$$

where

$$\mathcal{J} = -\sum_{n=2}^{\infty} a_{n-1}\mathcal{S}^n\phi_0 = -\sum_{n=2}^{\infty} a_{n-1} f\,[n]\,,$$

$$f\,[n] = \phi_0 \sum_{k=0}^{n}\binom{n}{k}(i\hbar)^k\left(\frac{\hbar^2}{2m}\right)^{n-k} B^k A^{n-k} H_{2(n-k)}(\sqrt{A}x) = \phi_0 A^n \sum_{k=0}^{n}\binom{n}{k}\frac{1}{2^{n-k}} H_{2(n-k)}(\sqrt{\frac{m\omega}{2\hbar}}x). \tag{15}$$

where here $A = \frac{\hbar\omega}{2}$.

While complicated, this equation can now be solved numerically in order to extract the first deviation from the standard evolution as dictated by the local Schrödinger equation.

What is a good quantum system to test this?

Testing non-local EFT with macroscopic quantum objects?

$$\epsilon = \frac{m\omega}{\hbar\Lambda^2}$$

Suppose

$$m = 1\mu g = 10^{-9} Kg$$

and

$$\omega \approx 5 \cdot 10^4 Hz.$$

Then our parameter will be

$$\epsilon \approx 5 \cdot 10^{29} l_{nl}^2$$

that means

$$\epsilon \ll 1 \Leftrightarrow l_{nl} \ll \sqrt{2} \cdot 10^{-14} m$$

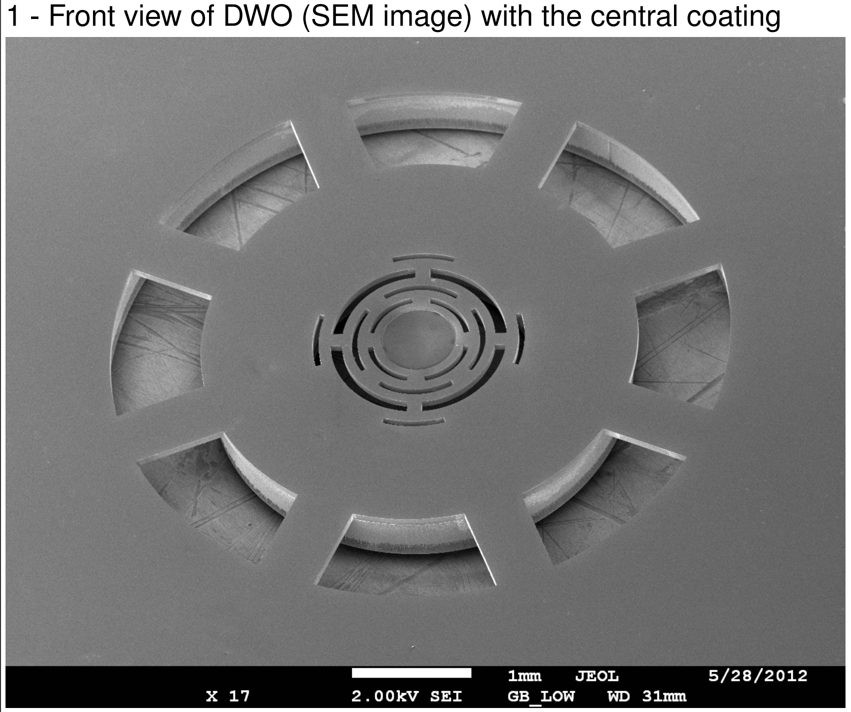
The expansion is justified for small ε but for it to be within experimental reach one wants macroscopic quantum objects.
Best case scenario: macroscopic quantum oscillators? (or alternative lighter but better developed BEC?)

HUMOR

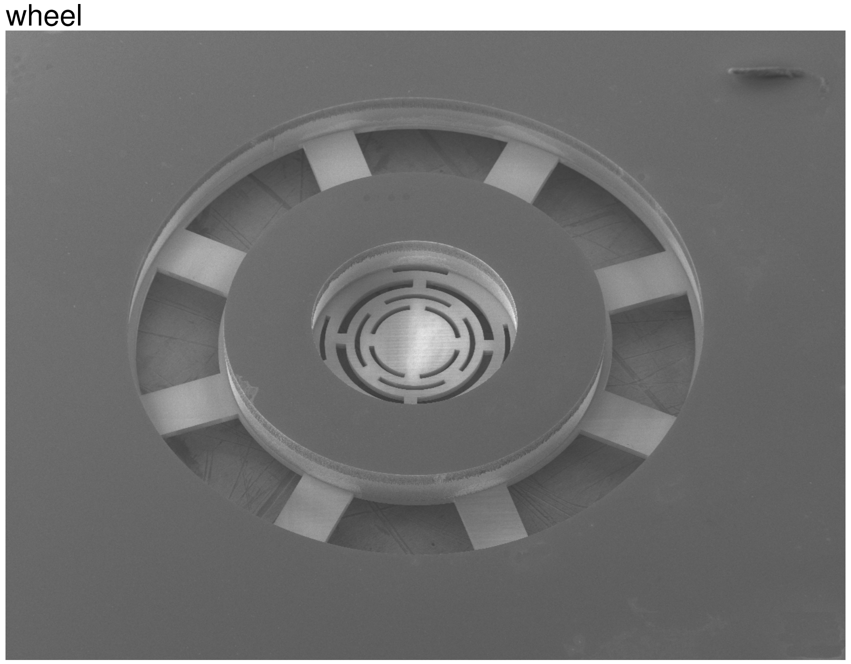
Heisenberg Uncertainty Measured with Opto-mechanical Resonators

Collaboration SISSA gravity group with with F. Marin, F. Marino, A. Ortolan.

1 - Front view of DWO (SEM image) with the central coating



2 - Back view DWO (SEM image) with the insulation wheel



Determine evolution of

$$\langle x \rangle = \langle \psi | \, x \, | \psi \rangle$$

$$\langle x^2 \rangle$$ and correlators...

See
F. Marin talk...

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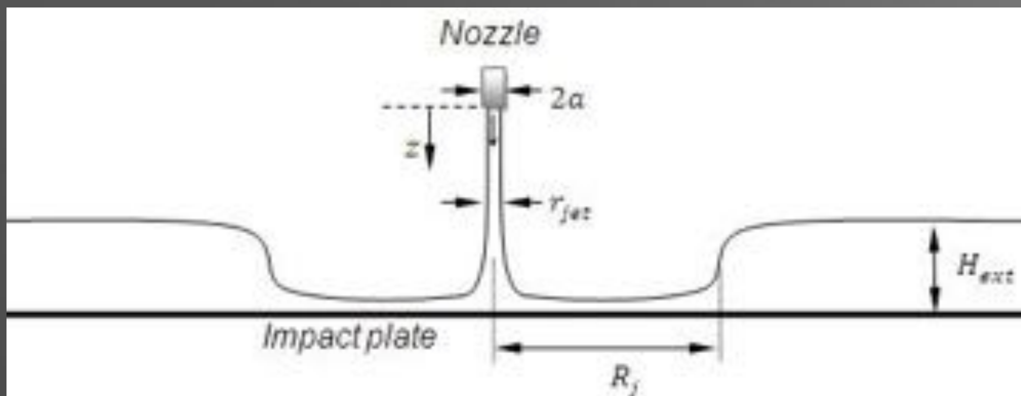
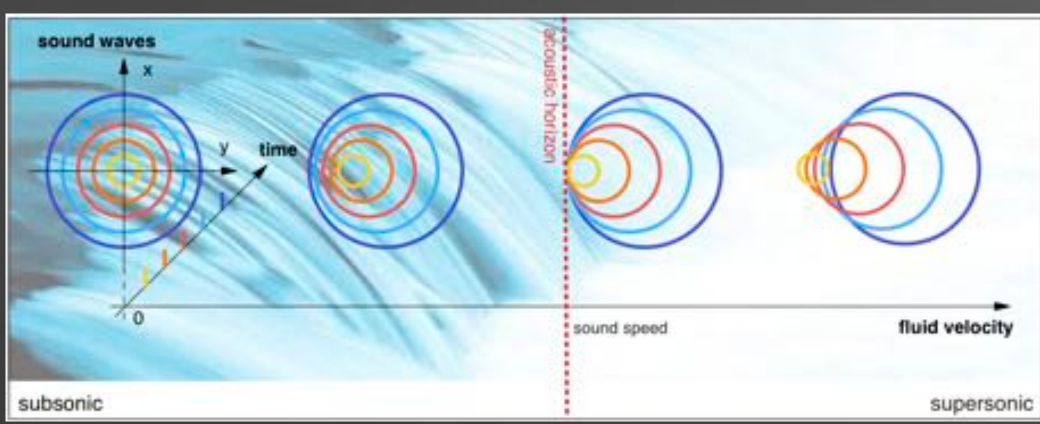
"I think that in the discussion of natural problems we ought to begin not with the Scriptures, but with experiments and demonstrations."
Galileo Galilei

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

Circular Hydraulic Jump gravity waves

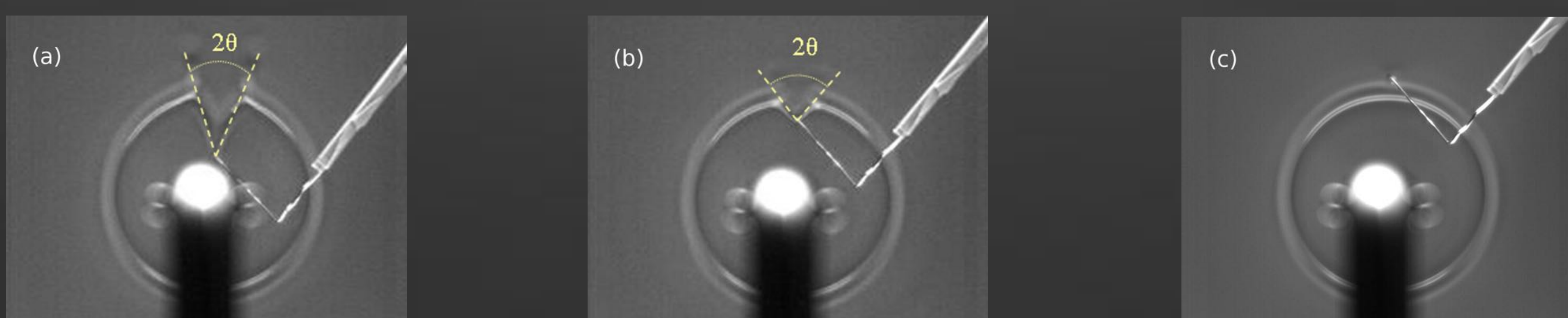


Basic setup: A liquid is pumped through a nozzle and the fluid jet impacts vertically onto a horizontal plate. Reproducible at home in your kitchen sink.



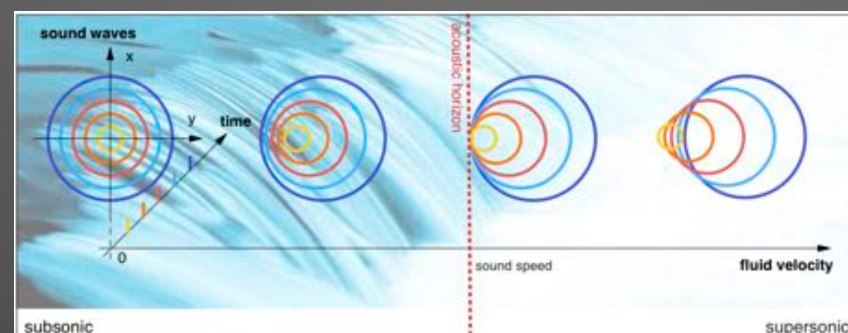
A white hole is the time-reversal of a black hole. Something in which nothing can enter and all has to exit

Measurements of the Mach angle θ 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

Make your own white hole at home!



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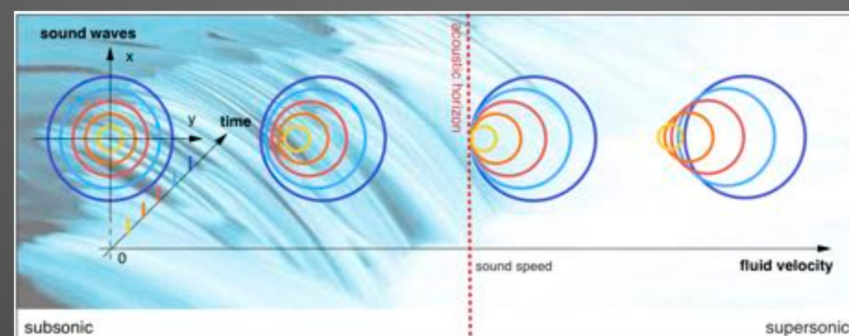

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