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Quantum gravity Phenomenology with and without Lorentz violation

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SISSA — ma per seguir virtute e canoscenza

INFN — Istituto Nazionale di Fisica Nucleare

John Templeton Foundation

What is Quantum gravity Phenomenology?

Old "dogma": you shall not access any quantum gravity effect as this would require experiments at the Planck scale!

This has changed in the last two decades, as several proposal for mesoscopic QG effects have been proposed.

- After several decades of efforts we have nowadays several workable quantum gravity theories and various scenarios for how the continuous and semi-classical limit are reached within them
- I.e. we have for the first time a chance to ask the hard questions about how and what we can probe of the fabric of spacetime.
- Missing a definitive scenario for the continuum limit of QG, we can try to categorise what can go wrong in our certainties...

Let's see where this goes...

QG phenomenology a la carte

ex pluribus quattuor

Broken or deformed Symmetries

- Lorentz
- Translations
- SUSY (still missing obs. evidence so far)
- Diffeomorphism (e.g. strong bounds from pulsar timing Donoghue et al. PhysRevD.81.084059. See also Bluhm talk)

Locality

- QG induced non-locality
- Uncertainty Principle->GUP (no strong constraints)
- Non-commutative geometries

Dimensions

- Extra dimensions (still missing obs. evidence so far)
- Dimensional reduction in QG (early universe?)

QG Modified gravitational dynamics

- E.g. Bouncing Universes
- Regular Black holes.

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Dynamical frameworks for LIV

Frameworks for preferred frame effects

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

EFT+LV

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

Non EFT proposals:
Spacetime foam models
DSR/Relative Locality

SME: local EFT with LIV
Non-renormalizable ops,
CPT ever or odd
(no anisotropic scaling),
(UV LIV – QG inspired LIV)

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

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

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

(Colladay-Kosteleky 1998, Colemann-Glashow 1998)

E.g. QED, rot. inv.dim 5 operators

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

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

(Myers-Pospelov 2003)

EFT with Lorentz breaking Ops.
Matter Sector Constraints

Terrestrial tests:

Penning traps
Clock comparison experiments
Cavity experiments
Spin polarised torsion balance
Neutral mesons
Slow atoms recoils

Astrophysical tests:

Cosmological variation of couplings, CMB
Cumulative effects in astrophysics
Anomalous threshold reactions
Shift of standard thresholds reactions with new threshold phenomenology
LV induced decays not characterised by a threshold
Reactions affected by "speeds limits"

$$E_\gamma^2 = k^2 + \xi_\pm^{(n)} \frac{k^n}{M_{pl}^{n-2}} \qquad \text{photons}$$

$$E_{matter}^2 = m^2 + p^2 + \eta_\pm^{(n)} \frac{p^n}{M_{pl}^{n-2}} \qquad \text{leptons/hadrons} ,$$

SL, CQG Topic Review 2013

where, in EFT, $\xi^{(n)} \equiv \xi_+^{(n)} = (-)^n \xi_-^{(n)}$ and $\eta^{(n)} \equiv \eta_+^{(n)} = (-)^n \eta_-^{(n)}$.

Table 2 Summary of typical strengths of the available constrains on the SME at different orders.

Order	photon	e^-/e^+	Hadrons	Neutrinos[a]
n=2	N.A.	$O(10^{-13})$	$O(10^{-27})$	$O(10^{-8})$
n=3	$O(10^{-14})$ (GRB)	$O(10^{-16})$ (CR)	$O(10^{-14})$ (CR)	$O(30)$
n=4	$O(10^{-8})$ (CR)	$O(10^{-8})$ (CR)	$O(10^{-6})$ (CR)	$O(10^{-4})^*$ (CR)

GRB=gamma rays burst, CR=cosmic rays

[a] From neutrino oscillations we have constraints on the difference of LV 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.

Warning
GZK ISSUE!
$p+\gamma_{CMB} \to p+\pi^0$
$p+\gamma_{CMB} \to n+\pi^+$

Furthermore puzzling cut off above 2 PeV in UHE neutrinos at IceCube maybe consistent with p^4 LIV at $M_{LIV} \sim 10^{15}$ GeV. F.W. Stecker, S.T. Scully, SL, D. Mattingly. JCAP 2015

LIV constraints with Gravitational Waves

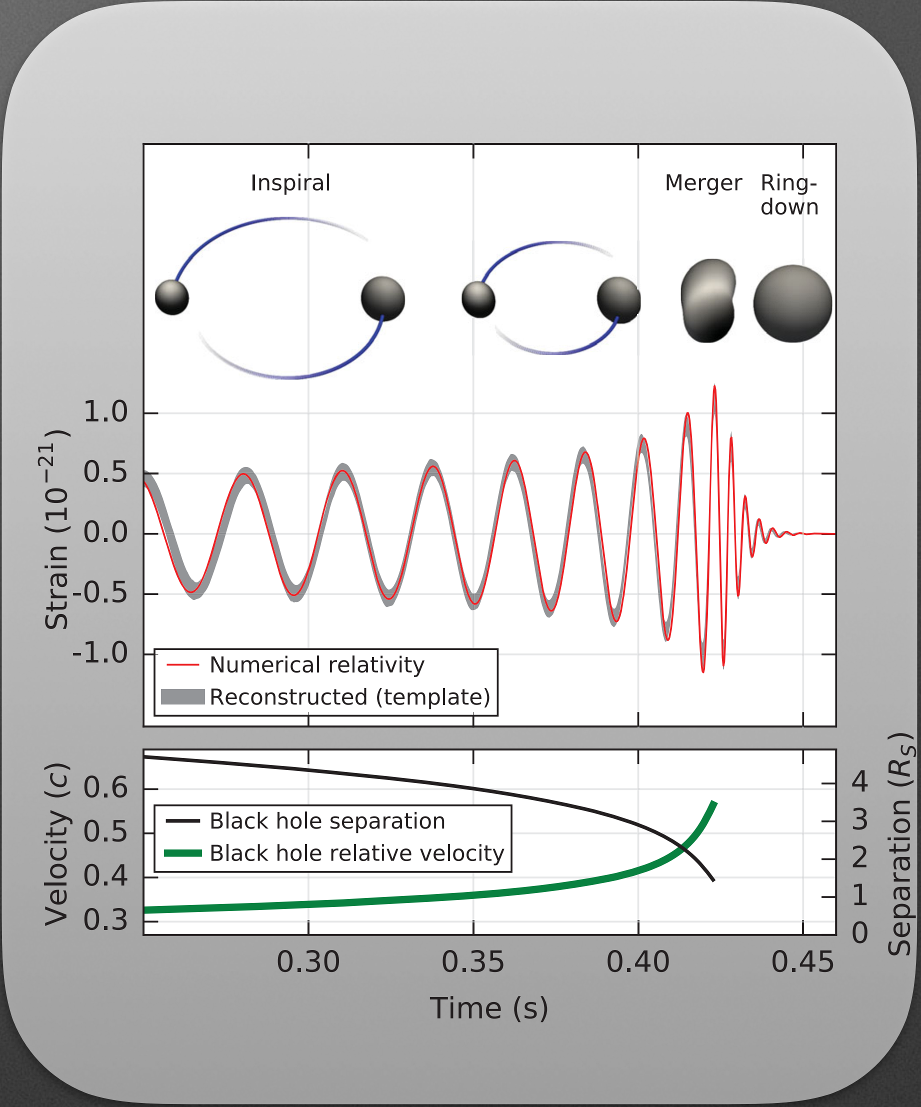
- GW speed vs Light or Neutrino speed measurement (e.g. supernova, GRB, neutron binaries merging) could provide crucial test for low energy LIV. Presently we know from binary pulsars $\Delta c/c < 1\%$

- to avoid gravy-Cherenkov for UHECR one has the conservative bound $(c_{light} - c_{grav})/c_{light} < 10^{-15}$

  - Together with time of arrival of GW150914 at the two LIGO detectors one then gets $0 \lesssim (c_{grav} - c_{light})/c_{light} \lesssim 0.7$.

- E.g. if faint GRB detection almost simultaneous and co-local to GW150914 would be robust then $(c_{grav} - c_{light})/c_{light} < 10^{-17}$ (Ellis et al. arXiv:1602.04764).

- Future Tests: polarisation constraints extra DOF in GW (e.g. Spin 0,1 modes in LIV gravity), test nature of Horizon via ringdown or event horizon telescope



This is the dawn of a new channel also for QG phenomenology!

Breakdown of translations in discrete QG: The CAUSET case study

1. Treat massive particles as point particles
2. Particle can only hop from point to point on a causal set.

SPACETIME PACHINKO!

F. Dowker, J. Henson and R. D. Sorkin, Quantum gravity phenomenology, Lorentz invariance and discreteness, Mod. Phys. Lett. A 19, 1829 (2004).

See also similar ideas by S. Hossenfelder, Phys.Rev. D88 (2013) no.12, 124031 Phys.Rev. D88 (2013) no.12, 124030

You then get Lorentz-invariant momentum space diffusion of initial distribution ρ

$$\frac{\partial \rho}{\partial \tau} = k \nabla_p^2 \rho - \frac{1}{mc^2} p^\mu \frac{\partial}{\partial x^\mu} \rho$$

The problem with this diffusion in momentum space is basically that cold stuff becomes rapidly hot. Even assuming this applies only to elementary particles you get strong bounds from cosmology.

N.Kaloper and D.Mattingly, Phys. Rev. D 74, 106001 (2006).
strong bounds from relic neutrinos not violating bounds on hot DM.
Similar bounds also for photons w.r.t. CMB (Philipot, Dowker, Sorkin, Phys. Rev. D 79, 124047 (2009).)

$$k < 10^{-61} \mathrm{GeV}^3$$

Hence

1. If discreteness scale is Planck then you need anomalous suppression of diffusion
2. or Particles are not point-like but they feel an “averaged spacetime”
3. or CAUSET and discrete models must be endowed with an extra, mesoscopic, scale other than the discreteness one

Remarkably, points 2) and 3) lead in CAUSET to non-local EFT scenarios…

Non-local D'Alambertians

Let us focus on free particles non-locality

$$\Box \to f(\Box)$$

Generic expectation if you want to introduce length or energy scale in flat spacetime KG equation without giving up Lorentz invariance.

Causal Set Theory $$\Box_\rho \approx \Box + \frac{\alpha}{\sqrt{\rho}}\Box^2 + \frac{\beta}{\sqrt{\rho}}\Box^2 \ln\left(\frac{\gamma}{\rho}\Box^2\right) + \dots \qquad \rho = 1/\ell_{\rm nl}^4$$

String Field Theory $$\Box \to (\Box + m^2)\exp^{\frac{\Box + m^2}{\Lambda^2}} \qquad \Lambda = 1/\ell_{\rm nl}$$

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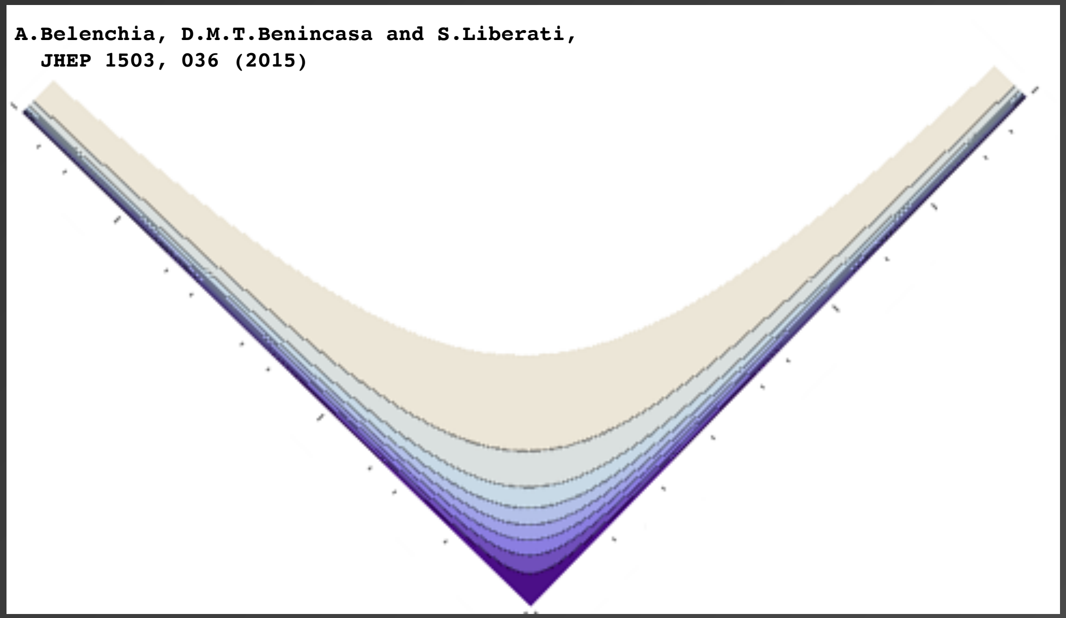
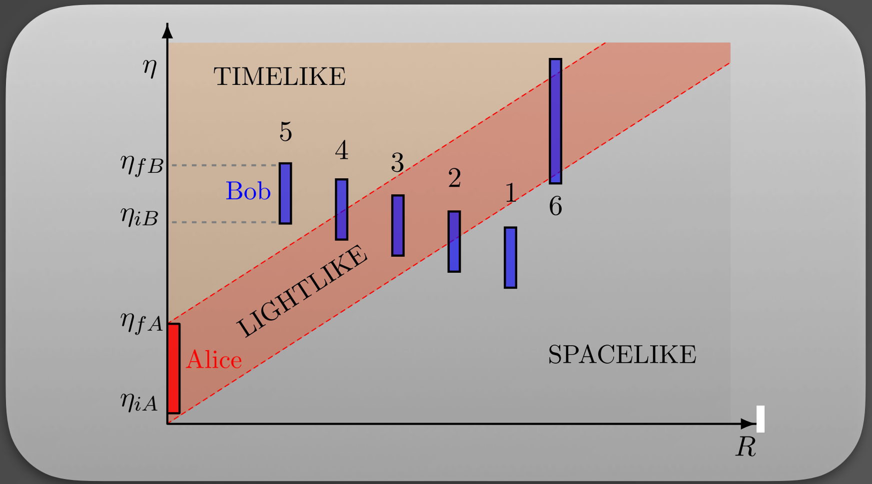
A typical signature of non-analytic non-local propagators are violations of the Huygen principle (e.g. CAUSET): The propagator of massless particles can have support inside the light cone in 3+1





Possibly very relevant for relativistic quantum information tests as detectors can influence each other at timelike separations

Opportunity for Phenomenology?

R. H. Jonsson, E. Martin-Martinez, and A. Kempf, Phys.Rev.Lett. 114, 110505 (2015). Ana Blasco, Luis J. Garay, Mercedes Martin-Benito, Eduardo Martin-Martinez. Phys.Rev.Lett. 114 (2015) 14, 141103

Testing non-local EFT with optomechanical oscillators

A. Belenchia, D. Benincasa, SL, F. Marin, F. Marino, A. Ortolan.
Phys.Rev.Lett. 116 (2016) no.16, 161303

E.g. let’s consider its non-relativistic limit of a non-local KG with analytic f(□).

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

$$\mathcal{S} = i\hbar\frac{\partial}{\partial t} + \frac{\hbar^2}{2m}\nabla^2,$$

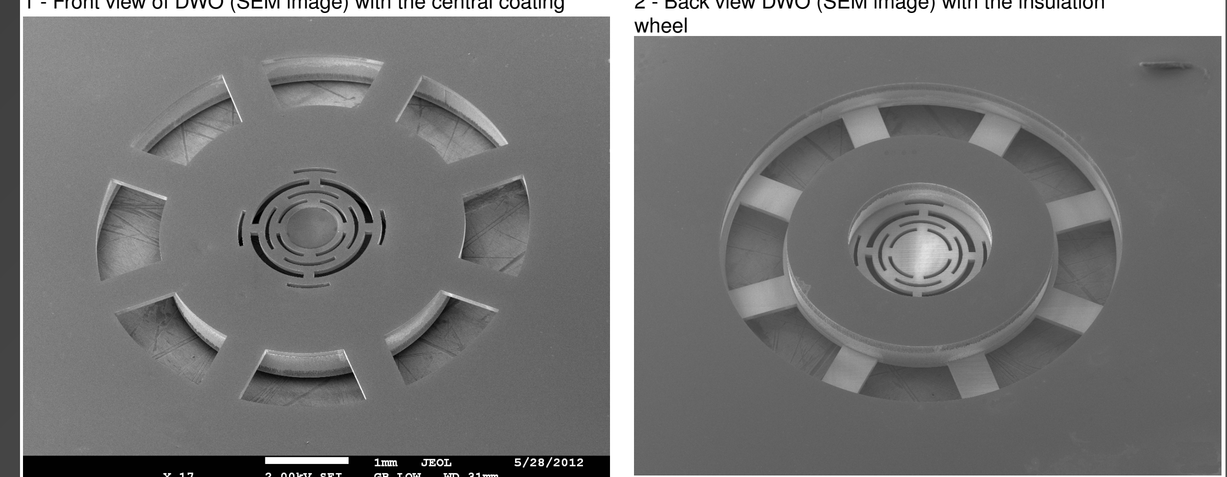
So we get $(\mathcal{S}_{NL} - V)\,\phi(t,x) = 0.$

Where can be test this?

HUMOR

Heisenberg Uncertainty Measured with Opto-mechanical Resonators (LENS - Florence, Italy)

Designed to test generalised uncertainty principle
Macroscopic harmonic oscillator.
$m \sim 10^{-11} / 10^{-5}$ Kg $\quad \omega \sim 10^{+5} / 10^{+3}$ Hz



1 - Front view of DWO (SEM image) with the central coating
2 - Back view DWO (SEM image) with the insulation wheel

In order to solve the non-local Schroedinger, one needs to adopt a perturbative expansion around a “local” Sch. solution

$$\phi = \phi_0 + \sum_{n=1}^{\infty} \epsilon^n \psi_n$$

With ϵ the small dimensionless parameter for this problem.

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

And at the lowest order we can solve

$$\left(i\hbar\partial_t + \frac{\hbar^2}{2m}\partial^2_{xx}\right)\psi + \epsilon a_2\left(\frac{-2}{\hbar\omega}\right)\mathcal{S}^2\psi = \frac{1}{2}m\omega^2 x^2\psi.$$

Spontaneous squeezing from non-locality

Results

$$\langle x\rangle = \sqrt{2}\alpha\cos(t)\left(1+\frac{1}{4}\epsilon\alpha^2 a_2\left[\cos(2t)-1\right]\right)+\mathcal{O}(\epsilon^2),$$

$$\langle p\rangle = \sqrt{2}\alpha\sin(t)\left(1+\frac{1}{4}\epsilon\, a_2\;\left[\alpha^2(7+3\cos(2t))-2\right]\right)+\mathcal{O}(\epsilon^2),$$

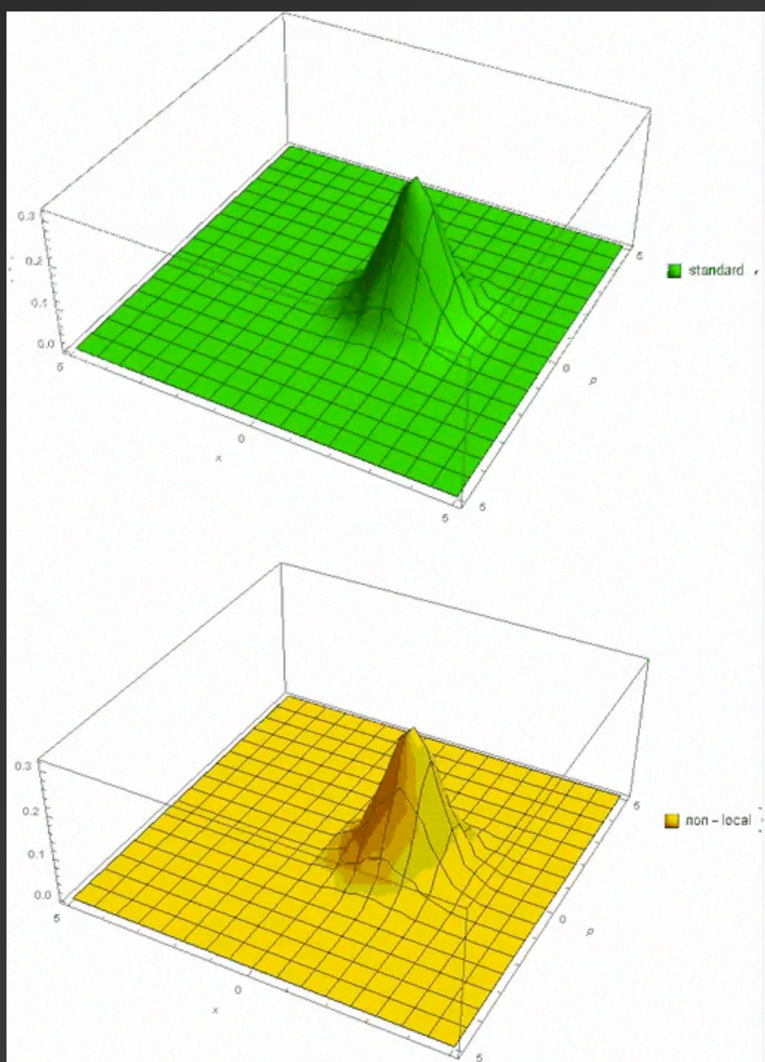
$$\mathrm{Var}(x) = \frac{1}{2}\left(1-\epsilon a_2\left[(6\alpha^2-1)\sin^2(t)\right]\right)+\mathcal{O}(\epsilon^2),$$

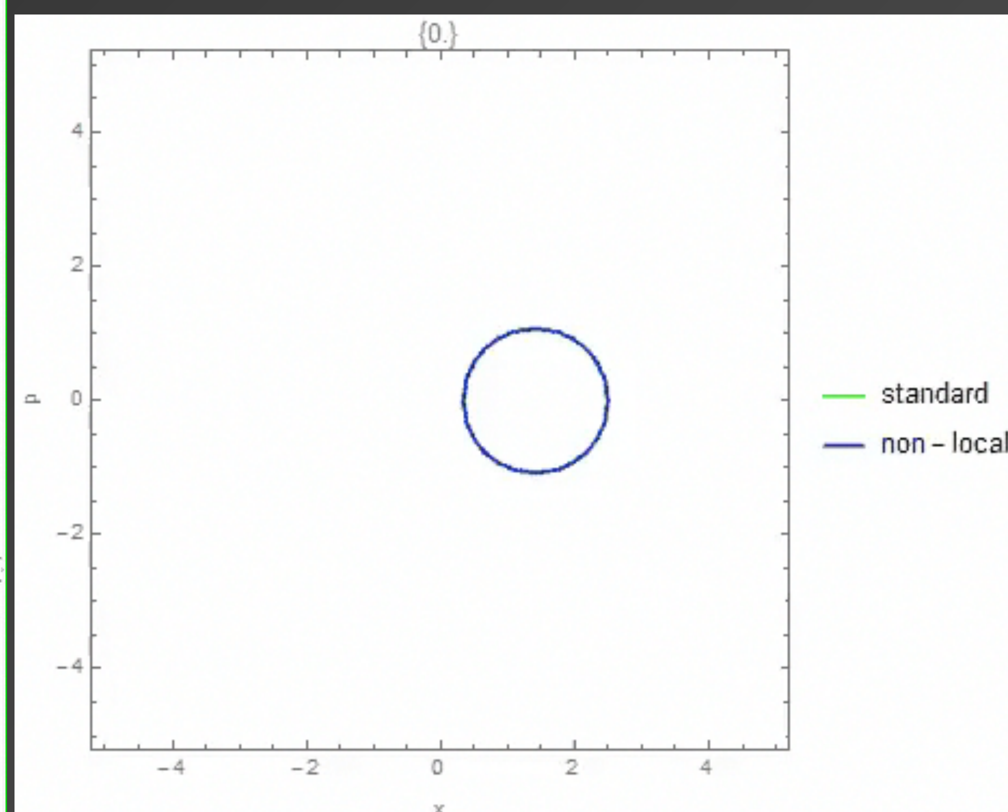
$$\mathrm{Var}(p) = \frac{1}{2}\left(1+\epsilon a_2\left[(6\alpha^2-1)\sin^2(t))\right]\right)+\mathcal{O}(\epsilon^2).$$

Let's consider Wigner quasi probability distribution for a coherent state of our quantum harmonic oscillator,

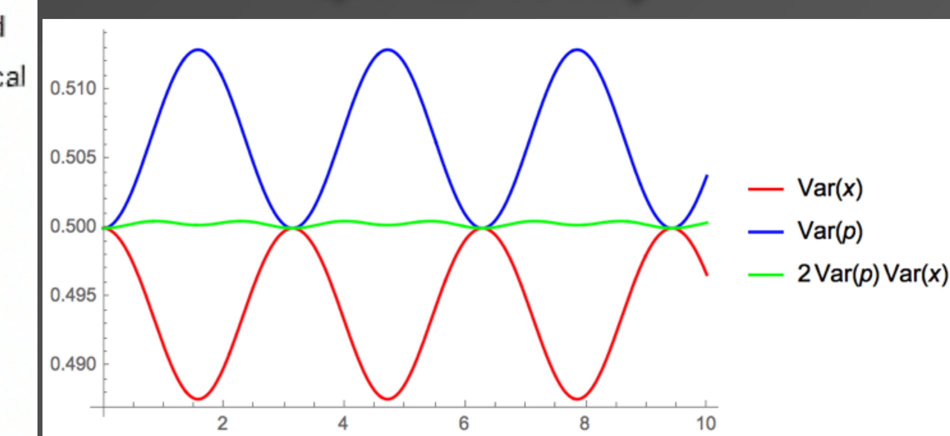
$$P(x,p;t)\frac{1}{\pi}\int_{-\infty}^{\infty}\mathrm{dy}\;\phi(x+y,t)^*\phi(x-y,t)\;e^{2ipy}$$

and confront its evolution for a coherent state (easier to experimental realise than the ground state) in the case of ***S*** and ***S***+ε***S***^{2}





The Coherent state Wigner function shows a periodic almost perfect squeezing.
Very difficult to produce spontaneously…



Current best bounds on the non-locality scale by comparing nonlocal relativistic EFTs to the 8 TeV LHC data $l_{nl} \leq 10^{-19}$m

Forecast with experiment in preparation (in absence of periodic squeezing) imply $l_{nl} \leq 10^{-29}$m !

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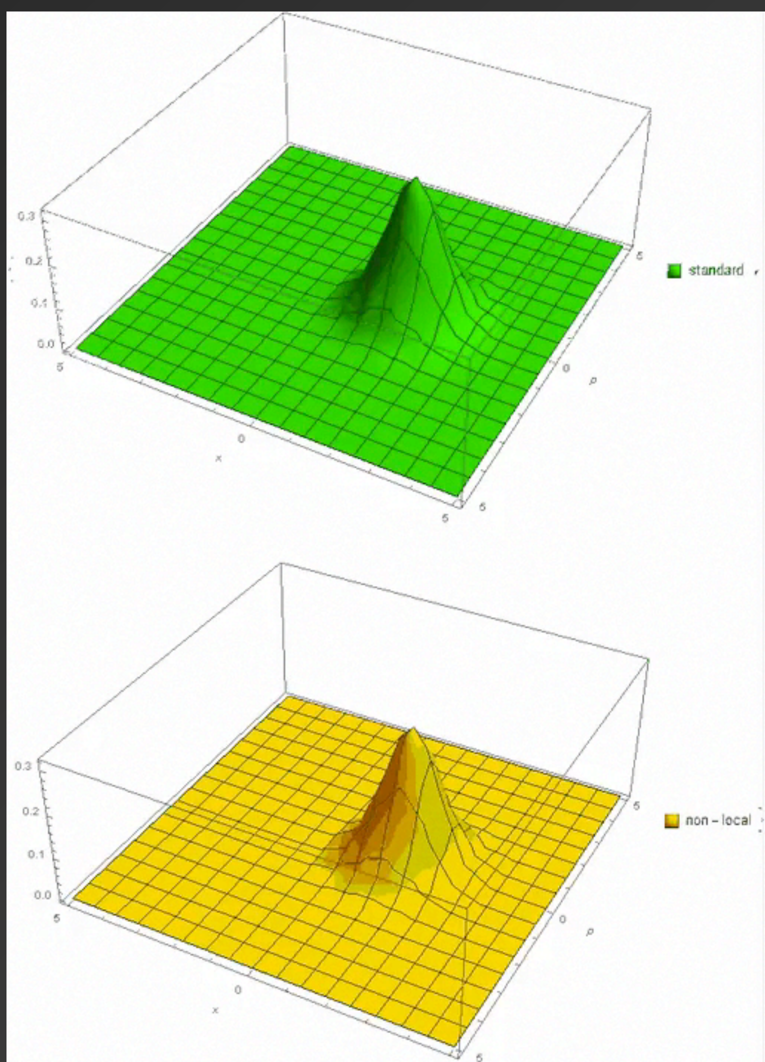

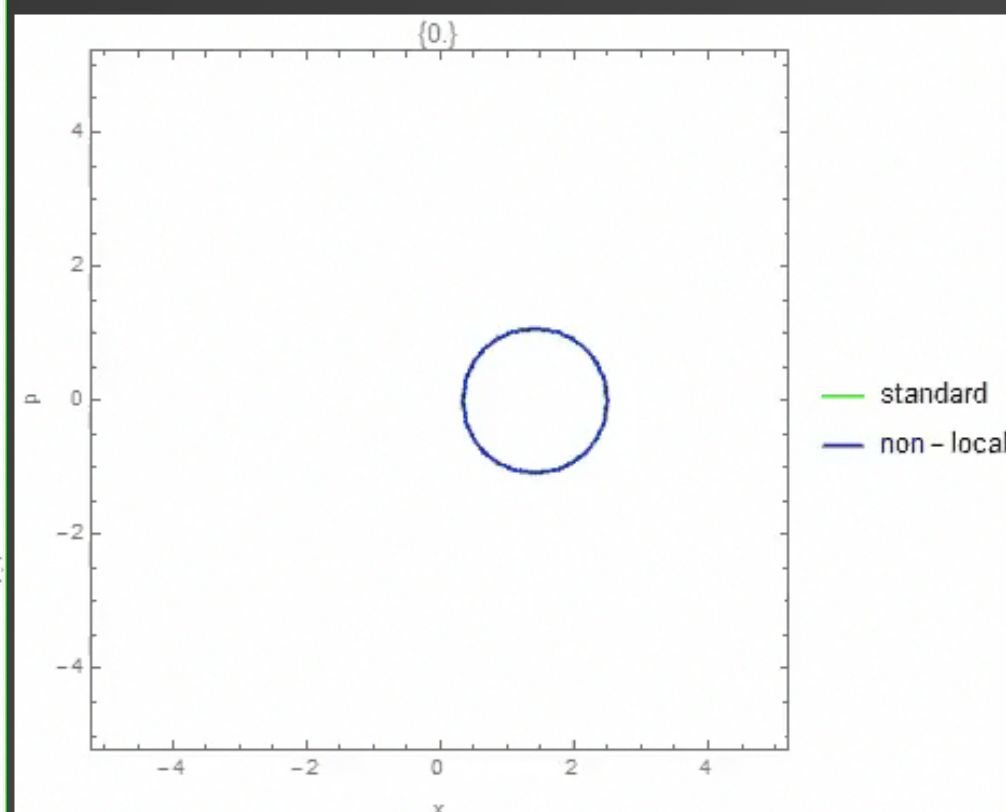

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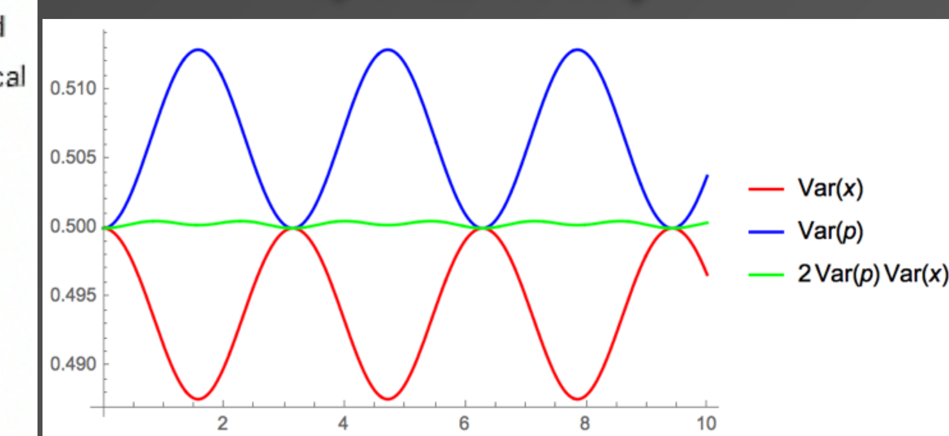

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Conclusions

Broken or deformed Symmetries

- SUSY- So far no evidence at LHC
- Lorentz - Ok Matter but n=4 needs GZK, more to do on Gravitational sector. Good perspectives
- Translations - Done
- Deformed Relativity? We need to understand it better!

Locality

- QG induced non-locality Work in progress New link with Relativistic Quantum Informations techniques

Dimensions

- Extra dimensions - No evidence yet
- Dimensional reduction in QG - Only early Universe test? We need better ideas.

Modified gravitational dynamics

- Bouncing Universes
- Regular Black holes. Work in progress. New link with BH imaging (EHT) and GW physics.

QG phenomenology is evolving and developing into several ramifications. A closer link with QG models is needed but a consistent landscape seems to be emerging as well as links with Relativistic Quantum Information Techniques. There is much more to come...

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The surface of the Earth is the shore of the cosmic ocean...Recently, we've waded a little way out, maybe ankle-deep, and the water seems inviting... (Carl Sagan)