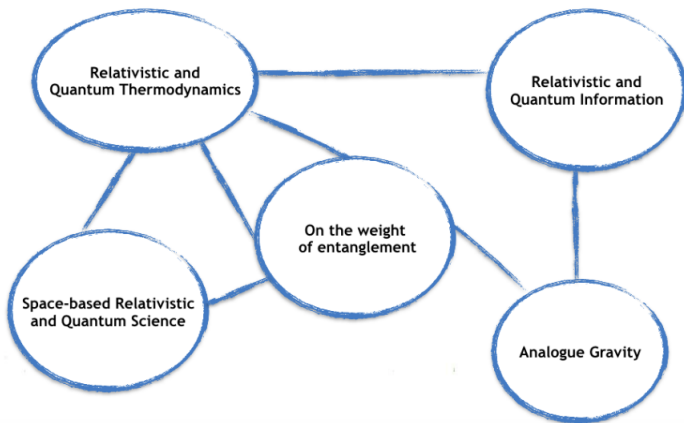# Self gravity affects quantum states

David Edward Bruschi

Institute for Quantum Computing Analytics (PGI-12)
Forschungszentrum Jülich
Germany

VIII.IX.MMXXI

Einstein gravity

We know that **ALL ENERGY GRAVITATES**.

Einstein gravity

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Einstein equations

$$G_{\mu\nu} = \kappa\, T_{\mu\nu}.$$

These equations have been highly successful in providing many predictions.

Successes

- Precession of orbits;
- Bending of light;
- Black Holes;
- Penrose process;
- Gravitational waves;
- Cosmology.

Difficulties

- Rotation curves of galaxies;
- Nonlinearity of equations;
- Gravitation of quantum objects;
- Quantum nature of gravity;
- Fundamental or emergent theory?

Einstein gravity extended

We know that **ALL ENERGY GRAVITATES**.

Semiclassical gravity

$$G_{\mu\nu} = \kappa \left\langle : \hat{T}_{\mu\nu} : \right\rangle$$

$\hat{T}_{\mu\nu}$: stress-energy tensor for quantum field. $: \cdot :$ is normal ordering.

Successes

- Takes into account (somehow) backreaction;

- ...

Problems

- Fluctuations of stress energy tensor big/huge;

- Curved spacetime: inconsistent renormalisation procedures;

- "Strange" predictions for gravitational fields of superpositions;

- ...

Experiments at the overlap of relativity/quantum phys.

Planning

There are plans to try to test the gravitational field of small quantum objects that can be found in quantum states.

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Experiments of interest

- Spontaneous WF collapse;
- Gravitational decoherence;
- Superposition of masses;
- Optomechanical systems;
- Space based tests;
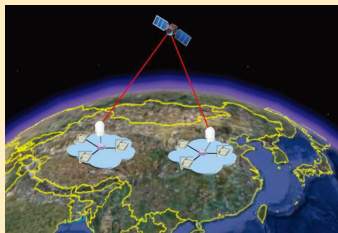- Atom Interferometry;
- More?

One setup

Figure: Micius satellite CAS

Quantum Information (QI) and Thermodynamics (QT)

Quantum Information

Allows us to connect concepts such as entropy and quantum correlations.

Quantum Thermodynamics

QT investigates thermodynamics far from thermodynamic limit.
Regime of interest: where fluctuations around the mean are important;

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- Small (quantum) constituents;
- Few (e.g ONE) systems;
- Concepts of energy and work not unique;
- Fluctuation relations;
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Applications
- Quantum chemistry;
- Quantum refrigerators;
- Fundamental physics;
- Connections to Information Theory;
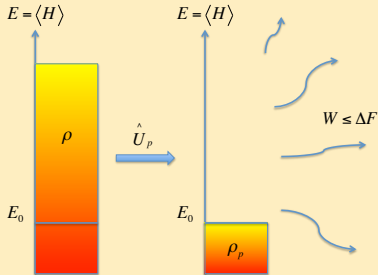- ...

Quantum Thermodynamics (QT)

Resources

State $\hat{\rho}$. Unitaries $\hat{U}$. Then, exists $\hat{U}_p$: $\hat{\rho}_p = \hat{U}_p^\dagger \, \hat{\rho} \, \hat{U}_p$. And, $\hat{\rho}_p$ is "passive".

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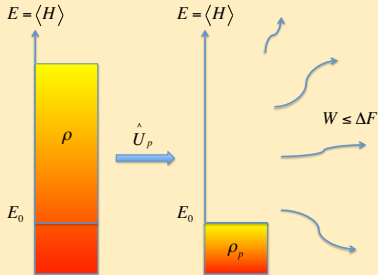
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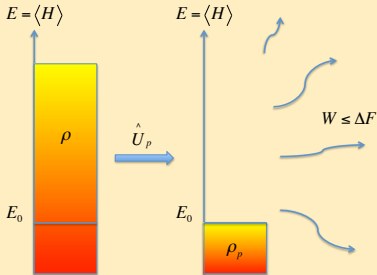
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Applications (PRE 91, 032118 (2015))

- Correlations $\mathcal{I}_{AB}$ give work (W) $\Leftrightarrow$ work (W) gives correlations $\mathcal{I}_{AB}$.

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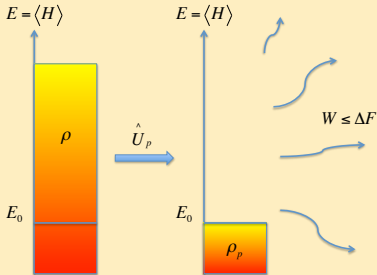
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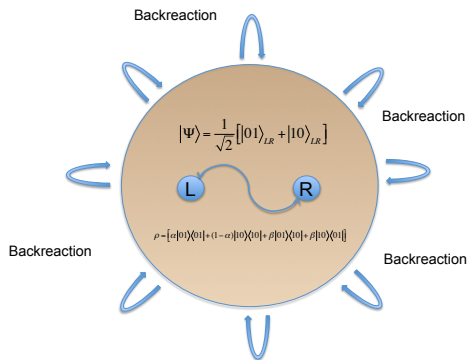
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- Conclusion: Correlations must "carry energy".

Role of corrleations

On the weight of entanglement (Physics Letters B 54, 182-186 (2016))

Employing semiclassical gravity: "entanglement has a weight".
We find $G^{(1)}_\beta \propto \beta$, where $G^{(1)}$ is correction to flat Einstein tensor.
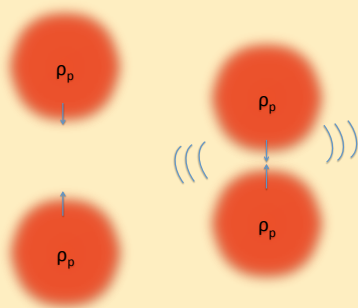
A gedankenexperiment

The weight of a passive state

$$\hat{\rho} \xrightarrow{U} \hat{\rho}_p, \qquad \mathrm{Tr}(\hat{H}_0 \, \hat{\rho}_p) = E_0.$$

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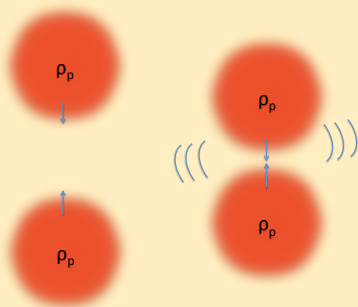

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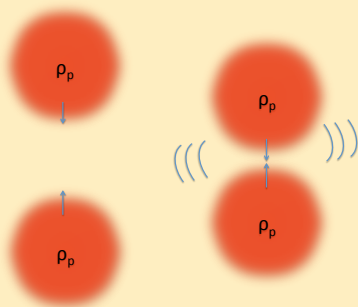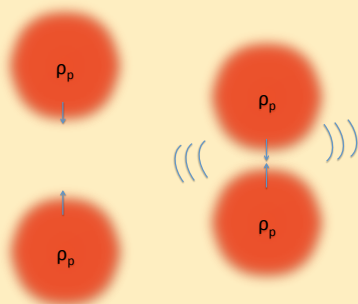
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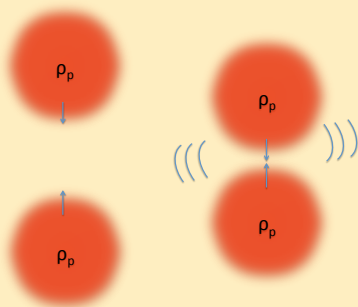- (Also if GR dof in passive state);
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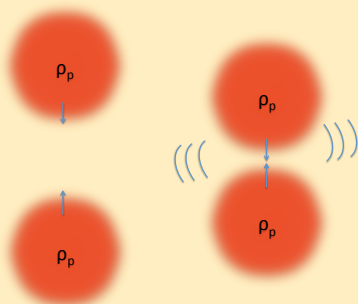
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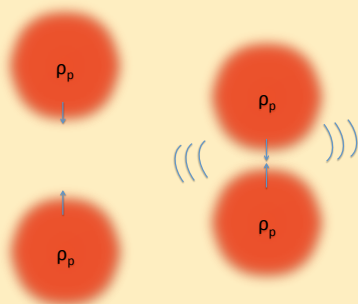

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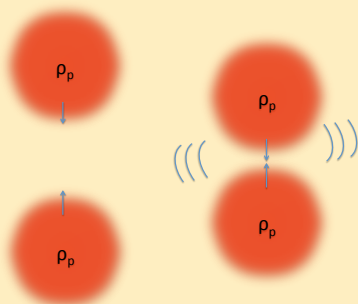

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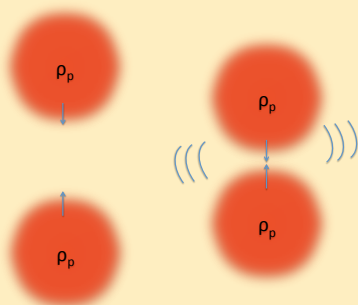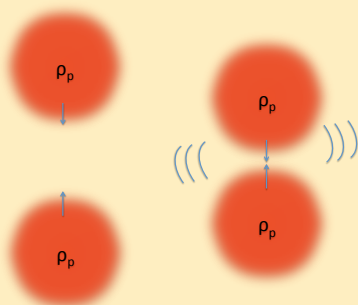

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New proposal

The field equations of Nature need to take into account the fact that it is extractible work that determines gravity, not the "whole amount of energy".

However: this might require to change other fundamental equations (i.e., Heisenberg eq.).

Features of the proposal I

Clarification

Passive state $\hat{\rho}_p$ is vacuum state of full theory (including gravity part).

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N.B.

Classical states: little/vanishing zero point energy compared to total one.

Features of the proposal II

Considerations on known effects in QFT

- Unruh effect: theoretically requires infinite acceleration times (i.e., infinite fuel).

- Schwarzschild BH evaporation: evaporates forever as seen by somebody sitting at infinity (i.e., infinite energy).

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Considerations on known effects in QFT

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- Non-trivial Bogoliubov transf. between vacua (entangled states).

The proposal...

... predicts that these highly ideal scenarios should be "trivial" beacuse the unitary transformation involved ("change of observer") does not add energy to the observed system (which is in the vacuum state).

Time evolution by work (AoP 394, 155-161 (2018))

Time evolution

- Time evolution is typically "driven" by Hamiltonian.

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- $\Rightarrow$ time evolution cannot be driven by Hamiltonian

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- $|\psi\rangle = \cos\theta \, |0\rangle + \sin\theta \, |1\rangle$;
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An experimental proposal

- Use highly entangled quantum state;
- Use Mach-Zender interferometer with arms at different heights;
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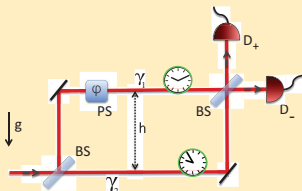- Use new time evolution equation.

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Figure: CQG 29, 224010 (2012)

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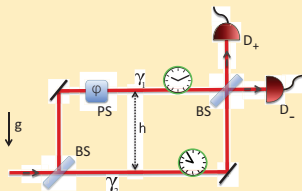- Use new time evolution equation.

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Heisenberg evolution

- $|\psi\rangle = \frac{1}{\sqrt{2}} [|N0\rangle + |0N\rangle]$;

- $\dot{\rho} = \frac{i}{\hbar}[H, \rho] - \frac{i}{\hbar}[U_p^\dagger H U_p, \rho]$;

- $p_{|N0\rangle} = \frac{1}{2}[1 + \frac{r_s}{r_E}\frac{h}{r_E}\sin^2(\frac{N\omega_0 t}{2})]$;
  $p_{|0N\rangle} = \frac{1}{2}[1 - \frac{r_s}{r_E}\frac{h}{r_E}\sin^2(\frac{N\omega_0 t}{2})]$;

- Note: $\frac{r_s}{r_E}\frac{h}{r_E} \sim \frac{g\,h}{c^2}$;

- Note: $\frac{r_s}{r_E}\frac{h}{r_E} \sim h \times 10^{-16}$.

Conclusions

We have:

- Studied role of quantum correlations/entanglement in gravitating quantum systems;

- Proposed that only extractible energy gravitates;

- Modified time evolution to be compatible with new proposal

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- Studied role of quantum correlations/entanglement in gravitating quantum systems;

- Proposed that only extractible energy gravitates;

- Modified time evolution to be compatible with new proposal

Then:

- Applications include localized scenarios, as well as global ones;

- Predictions are (very) different from the standard known theories;

- More advanced mathematical tools can be used to propose better models;

- Experiments can be potentially done with current technology;

- More work to come...

Acknowledgments

Grazie