On the weight of entanglement

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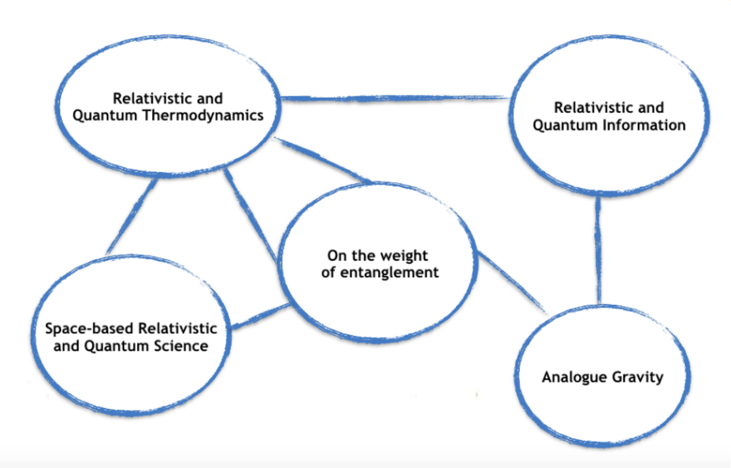
Relativistic and
Quantum Thermodynamics
Relativistic and
Quantum Information
On the weight
of entanglement
Space-based Relativistic
and Quantum Science
Analogue Gravity

Einstein gravity

We know that **ALL ENERGY GRAVITATES**.

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Einstein equations

$$G_{\mu\nu} = \frac{8\,\pi\,G}{c^4}\,R_{\mu\nu}\,.$$

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

$$G_{\mu\nu} = \frac{8\,\pi\,G}{c^4}\,\langle:\,\hat{T}_{\mu\nu}\,:\rangle$$

$\hat{T}_{\mu\nu}$: 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;
- ...

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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

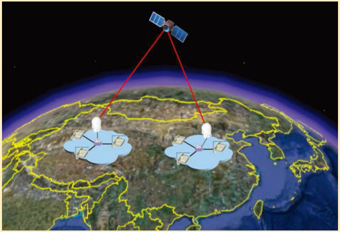

Figure: Micius satellite CAS

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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Features

- 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 "unique".

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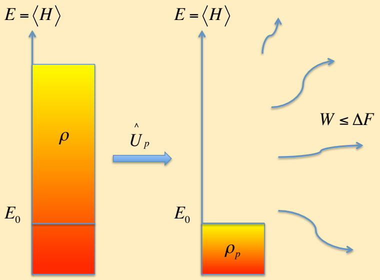

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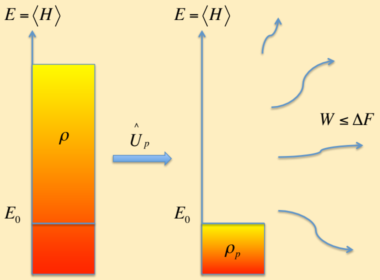

Applications (PRE 91, 032118 (2015))

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

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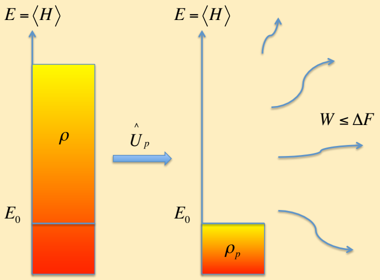

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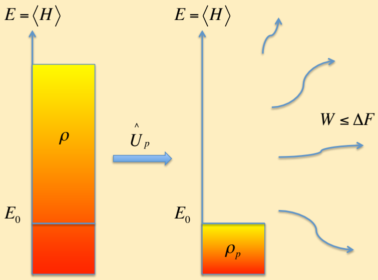

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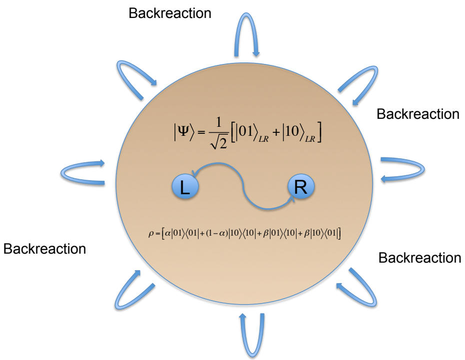
- Conclusion: Correlations must "carry energy".

Role of corrleations

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

Employing semiclassical gravity: **entanglement has a weight**.

We find $G_{\beta}^{(1)} \propto \beta$, 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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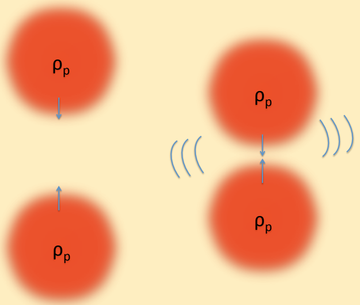

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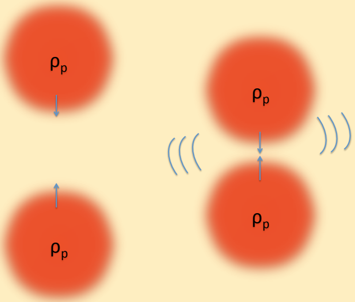

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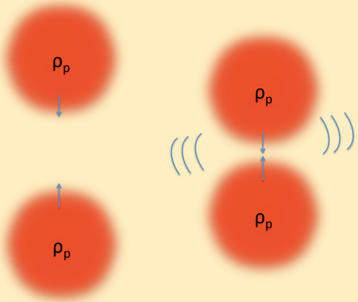

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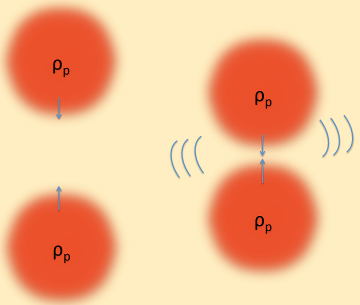

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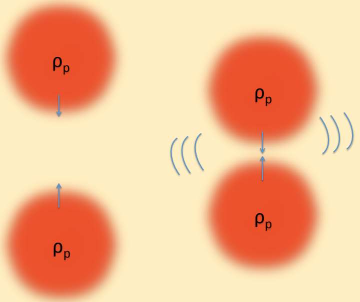

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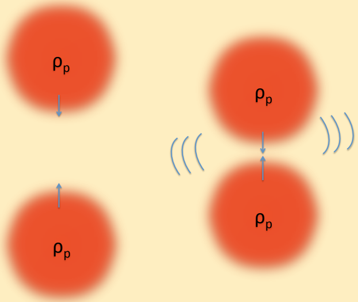

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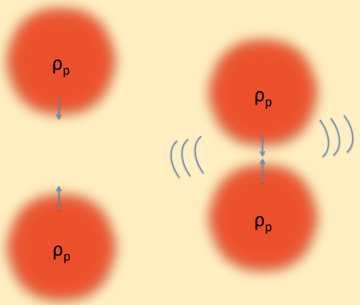

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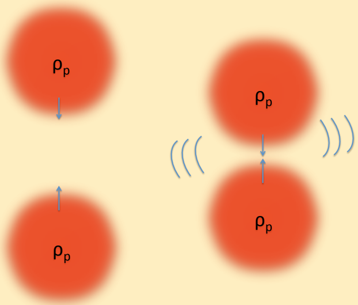

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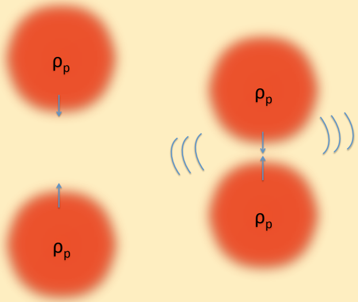

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- Employable energy= work;
- Something is wrong;
- (Also if GR dof in passive state);

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Only extractible energy gravitates.

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New proposal

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However:

- "Automatically renormalises" the vacuum energy;
- Provides physical mechanism to justify "renormalisation" of vacuum energy;
- Requires change in (possibly all) standard eq.s (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 (initial paper) required infinite acceleration times (infinite fuel).
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The theory...

... "correctly" predicts that these highly entangled (squeezed) states cannot gravitate/be detected beacuse the "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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The modified Heisenberg equation

$$\dot{A} = \frac{i}{\hbar}[H, A] - \frac{i}{\hbar}[U_p^\dagger \, H \, U_p, A] + \frac{\partial A}{\partial t}.$$

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- $|\psi\rangle = \cos\theta\,|0\rangle + \sin\theta\,|1\rangle$;
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"Novel" time evolution

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- $p_{|0\rangle} = \cos^2\theta - \cos^2\theta\,\cos^2(\sin\theta\,\frac{E_1}{\hbar}\,t)$
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Testing in experiments (AoP 394, 155-161 (2018))

An experimental proposal

- Use highly entangled quantum state;
- Use Mach-Zender interferometer with arms at different heights;
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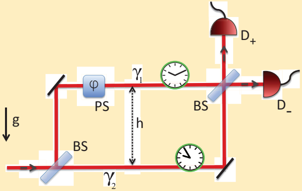

Figure: CQG 29, 224010 (2012)

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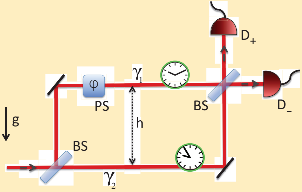

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- $|\psi\rangle = \frac{1}{\sqrt{2}}[|N0\rangle + |0N\rangle]$;
- $\dot{\rho} = \frac{i}{\hbar}[H, \rho] - \frac{i}{\hbar}[U_p^\dagger\, H\, U_p, \rho]$;
- $p_{|N0\rangle} = \frac{1}{2}[1 + \frac{r_s}{r_E}\frac{h}{r_E}\sin^2(\frac{N\,\omega_0\,t}{2})]$;
  $p_{|0N\rangle} = \frac{1}{2}[1 - \frac{r_s}{r_E}\frac{h}{r_E}\sin^2(\frac{N\,\omega_0\,t}{2})]$;
- 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:

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- Proposed that only extractible energy gravitates;
- Modified time evolution to be compatible with new proposal;
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Then:

- Applications include single mode cases and two mode cases;
- Predictions are very different from the standard Heisenberg case;
- More advanced mathematical tools can be used to propose better models;
- Experiments can be potentially done with current technology;
- More work to come...

Acknowledgments: U. des Saarlandes and U. of Vienna

Хвала

PLB 54, 182-186 (2016) — arXiv:1701.00699 — AoP 394, 155-161 (2018)