# Work is the source of gravity

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Department of Physics
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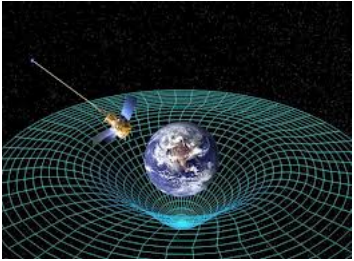
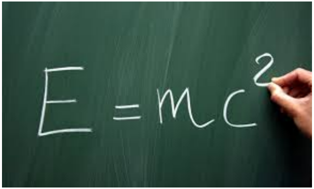
XXII August MMXVII

# The standard theory of gravity

We know that...






... **ENERGY GRAVITATES**.

# Einstein gravity

## 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;
- Existence of Black Holes;
- Penrose process;
- Gravitational waves;
- Big Bang;
- ...

## Problems

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

# Einstein gravity extended

## 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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## Experiments of interest

- Spontaneous WF collapse;
- Gravitational decoherence;
- Superposition of masses;
- Optomechanical systems;
- Space based tests;
- Atom Interferometry;
- Angelo Bassi's talk...

## One setup

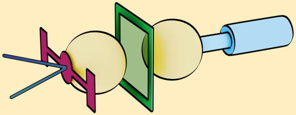

Figure: Class. Quantum Grav. 33 (2016) 125031

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- 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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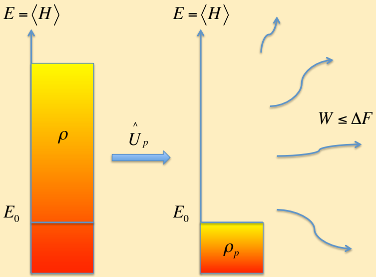

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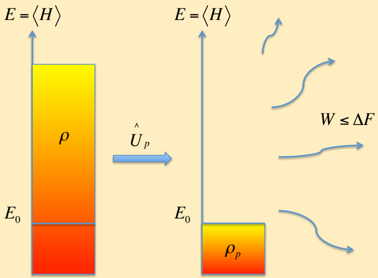


## Applications (PRE 91, 032118 (2015))

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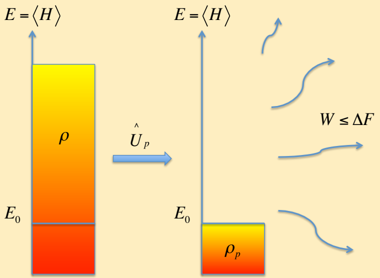


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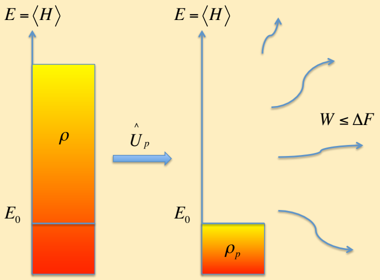


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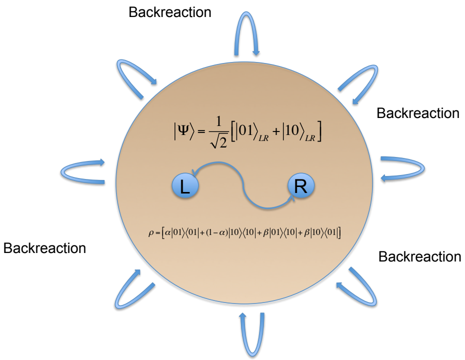
- Conclusion:
  Correlations must "carry energy".

# 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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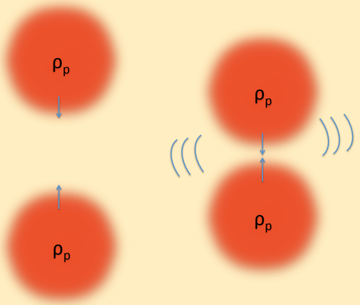

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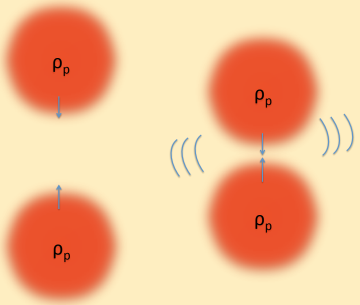


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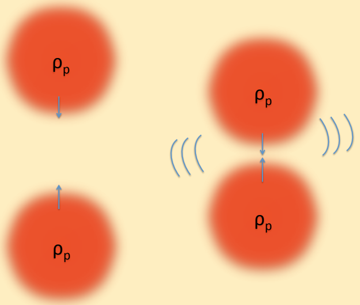


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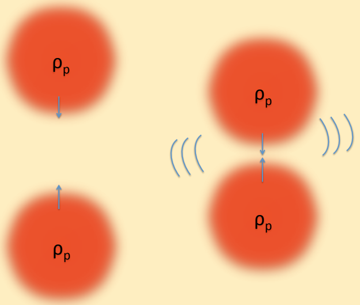


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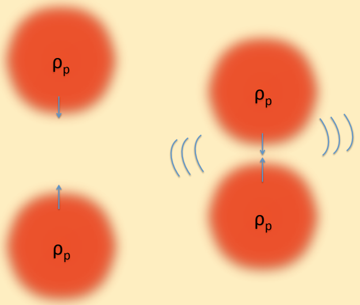


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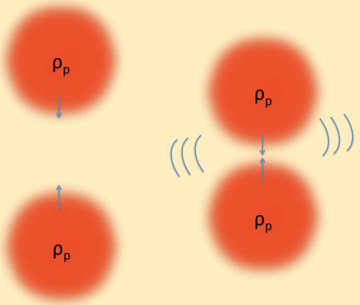


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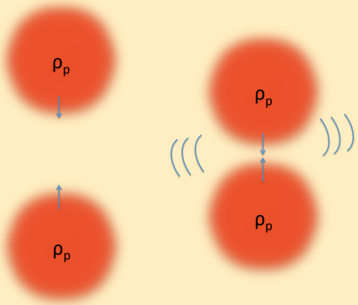


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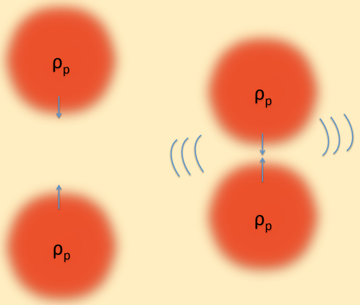


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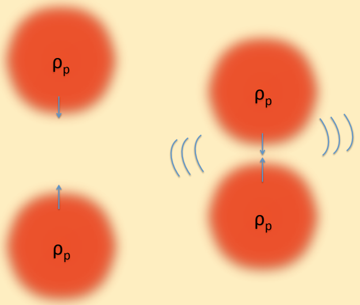


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- Something is wrong;

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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

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**N.B.**

Classical states (should) have very little (if not vanishing) zero point energy.

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- 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 beacuse the "change of observer" does not add energy to the observed system (which is in the vacuum state).

# Time evolution without by work (arXiv:1702.05450)

## Time evolution

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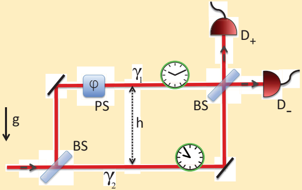


Figure: CQG 29, 224010 (2012)

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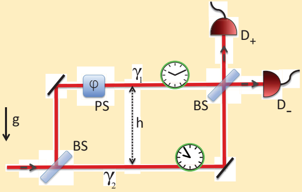


Figure: CQG 29, 224010 (2012)

## 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:

- Discussed open issues at the overlap of gravity and quantum theory;
- Looked into novel approaches to understanding energy and entropy in quantum systems;
- Thought about peculiar gedanken experiments;
- Found some subtle inconsistencies;
- Proposed alternative source of gravity: extractible energy;
- Discussed implications;
- Open directions.

# Acknowledgments

Thank you.