

Cold atoms in gravity and microgravity for fundamental physics

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Outline

1 Introduction

- Universality principles
- Need for Quantum Gravity
- Drop tower experiments
- Science questions



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- Spreading of wave packets
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- Self gravitating quantum systems
- Semiclassical Einstein equations
- Modified dispersion relations



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Universality principles

- Gravity acts on all kinds of matter
- Gravity acts on all kinds of matter in the same way
- Gravity acts on all kinds of clocks
- Gravity acts on all kinds of clocks in the same way
- Gravity is created from all kinds of matter
- Gravity is created from all kinds of matter in the same way



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gravity \Leftrightarrow universality principles \Leftrightarrow gravity = geometry

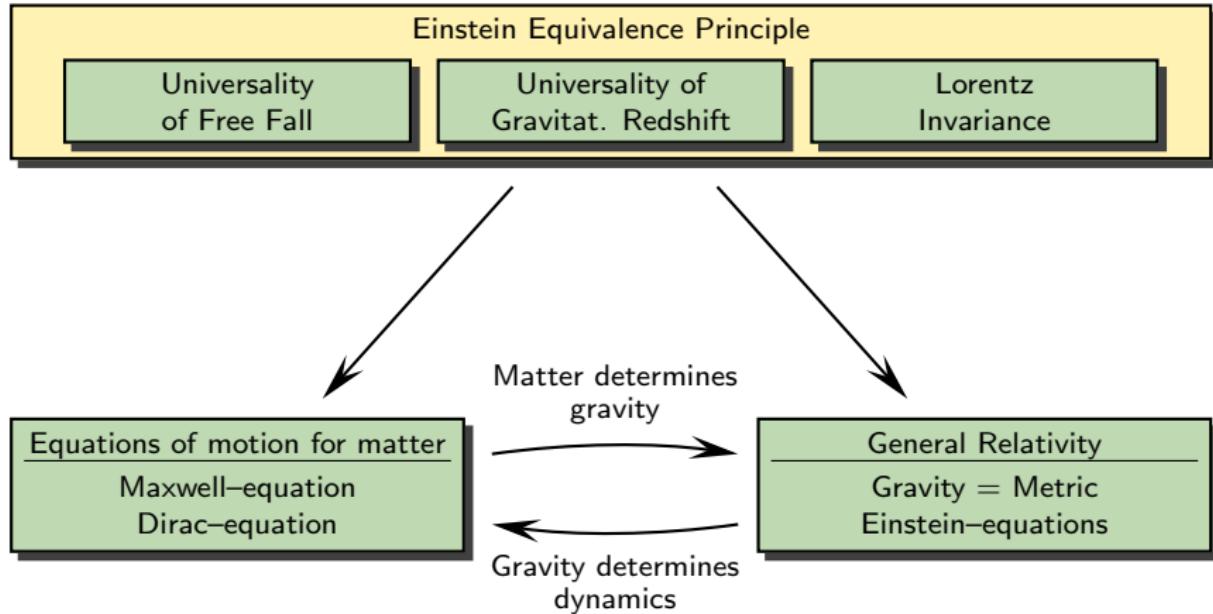
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gravity \Leftrightarrow universality principles \Leftrightarrow gravity = geometry

It is a miracle that these universality principles hold with the present high experimental accuracy

Structure of standard physics



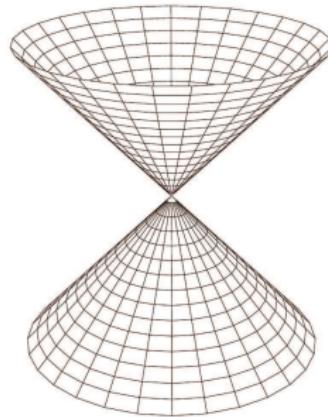
The present situation

All aspects of Lorentz invariance are experimentally well tested and confirmed

Foundations

Postulates

- $c = \text{const}$
- Principle of Relativity



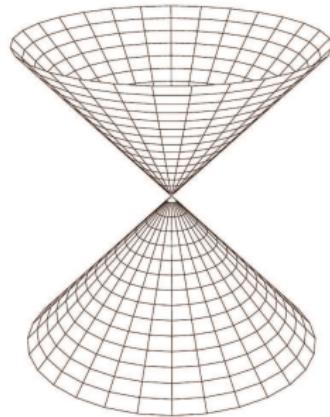
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Tests

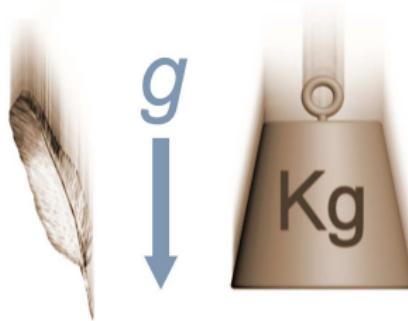
- Independence of c from velocity of the source
- Universality of c
- Isotropy of c
- Independence of c from velocity of the laboratory
- Time dilation
- Isotropy of physics (Hughes–Drever experiments)
- Independence of physics from the velocity of the laboratory

The present situation

Many aspects of the Universality of Free Fall (= Weak Equivalence Principle) are experimentally well tested and confirmed

Postulate

In a gravitational field all
structureless test particles fall in
the same way

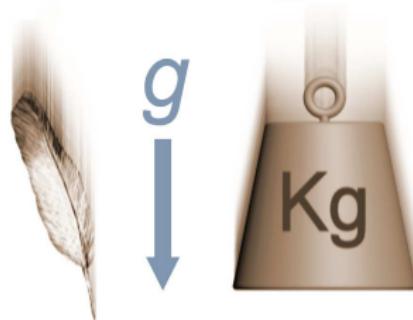


The present situation

Many aspects of the Universality of Free Fall (= Weak Equivalence Principle) are experimentally well tested and confirmed

Postulate

In a gravitational field all structureless test particles fall in the same way



Tests

UFF for

- Neutral bulk matter
- Charged particles
- Particles with spin

No test so far for

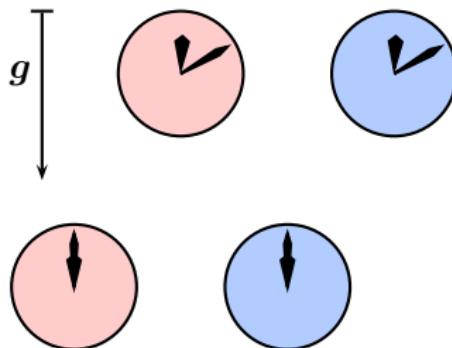
- Anti particles

The present situation

Many aspects of the Universality of the Gravitational Redshift (= Local Position Invariance) are experimentally well tested and confirmed

Postulate

In a gravitational field all clocks behave in the same way

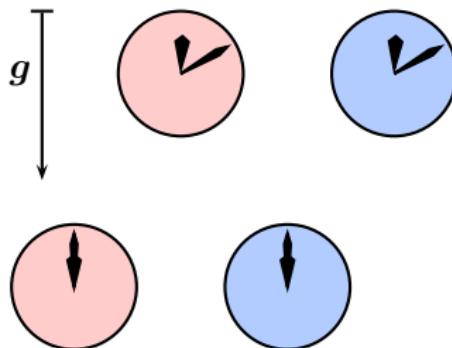


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Tests

UGR for

- Atomic clocks: electronic
- Atomic clocks: hyperfine
- Molecular clocks: vibrational
- Molecular clocks: rotational
- Resonators
- Nuclear transitions

No test so far for

- Anti clocks

The present situation

All predictions of General Relativity are experimentally well tested and confirmed

Foundations

The Einstein Equivalence Principle

- Universality of Free Fall
- Universality of Gravitational Redshift
- Local Lorentz Invariance



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Implication

Gravity is a metrical theory

Ehlers, Pirani & Schild 1972

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Implication

Gravity is a metrical theory

Predictions for metrical theory

- Solar system effects
 - Perihelion shift
 - Gravitational redshift
 - Deflection of light
 - Gravitational time delay
 - Lense–Thirring effect
 - Schiff effect
- Strong gravitational fields
 - Binary systems
 - Black holes
- Gravitational waves



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General Relativity

Schiff's conjecture

The importance of the Universality of Free Fall: Schiff's conjecture

UFF implies the EEP, or: Violation of LLI or LPI implies violation of UFF

UFF is a universal tool to look for violations of standard physics

In reply to the Schiff conjecture: Ni, PRL 1977

Theorem: In a neutral system which Lagrangian density is given by

$$\mathcal{L} = -\frac{1}{16\pi} \Lambda^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma} - A_\mu j^\mu \sqrt{-g} - \sum_i m_i \frac{ds_i}{dt} \delta(x - x_i)$$

the UFF holds if and only if

$$\Lambda^{\mu\nu\rho\sigma} = \sqrt{-g} \left(\frac{1}{2} (g^{\mu\rho} g^{\nu\sigma} - g^{\mu\sigma} g^{\nu\rho}) + \phi \epsilon^{\mu\nu\rho\sigma} \right),$$

ϕ pseudoscalar field (axion)

Only small loophole \Rightarrow UFF still is most important principle

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Quantum gravity

Incompatibilities

- All standard quantization schemes not applicable
- The problem of time

Time in quantum theory } incompatible { Time in General Relativity
external variable dynamical variable

Quantum gravity

Incompatibilities

- All standard quantization schemes not applicable
- The problem of time

$$\left. \begin{array}{c} \text{Time in quantum theory} \\ \text{external variable} \end{array} \right\} \qquad \xleftrightarrow{\text{incompatible}} \qquad \left\{ \begin{array}{c} \text{Time in General Relativity} \\ \text{dynamical variable} \end{array} \right.$$

Further reasons for a need of Quantum Gravity

- If matter is quantized, then the interaction has to be quantized, too (Bohr, Rosenfeld)
- Singularities – black holes
 - Classical GR: singularity theorems
 - Quantization circumvents breakdown of physics in the early universe and in black holes

The description of physics is not yet complete

Today's standard theories and standard space-time notion as explored by point particles, light rays, and fields

Frame theories	Interactions
Quantum theory	Electrodynamics
Special Relativity	Gravity
General Relativity	Weak interaction
Statistical mechanics	Strong interaction
Problems	Wish
<ul style="list-style-type: none">• Incompatibility of quantum theory and General Relativity• Problem of time• Occurrence of singularities	Unification of all interactions

Need of modifications of standard theories, but standard theories derived from universality principles

⇒ need for **more precise** measurements, **other** observations



Implications of a new theory

Unresolved fundamental inconsistency

- ⇒ Standard physics cannot be completely correct
- ⇒ There have to be modifications to standard physics

Modifications on the effective level

- ⇒ Modifications in Maxwell, Dirac, Einstein equations
- ⇒ Violation of Einstein Equivalence Principle
- ⇒ Search for violations of the Einstein Equivalence Principle



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- ⇒ **Search for violations of the Einstein Equivalence Principle**

Modifications on the quantum level

Modified notion of space-time (e.g. space-time fluctuations)

But: space-time is explored by particles, photons, ...

- ⇒ Modified space-time properties result in modified equations of motion ⇒
Search for violation of the Einstein Equivalence Principle
- ⇒ **Search for fundamental noise, decoherence, non-conserved probability, ...**

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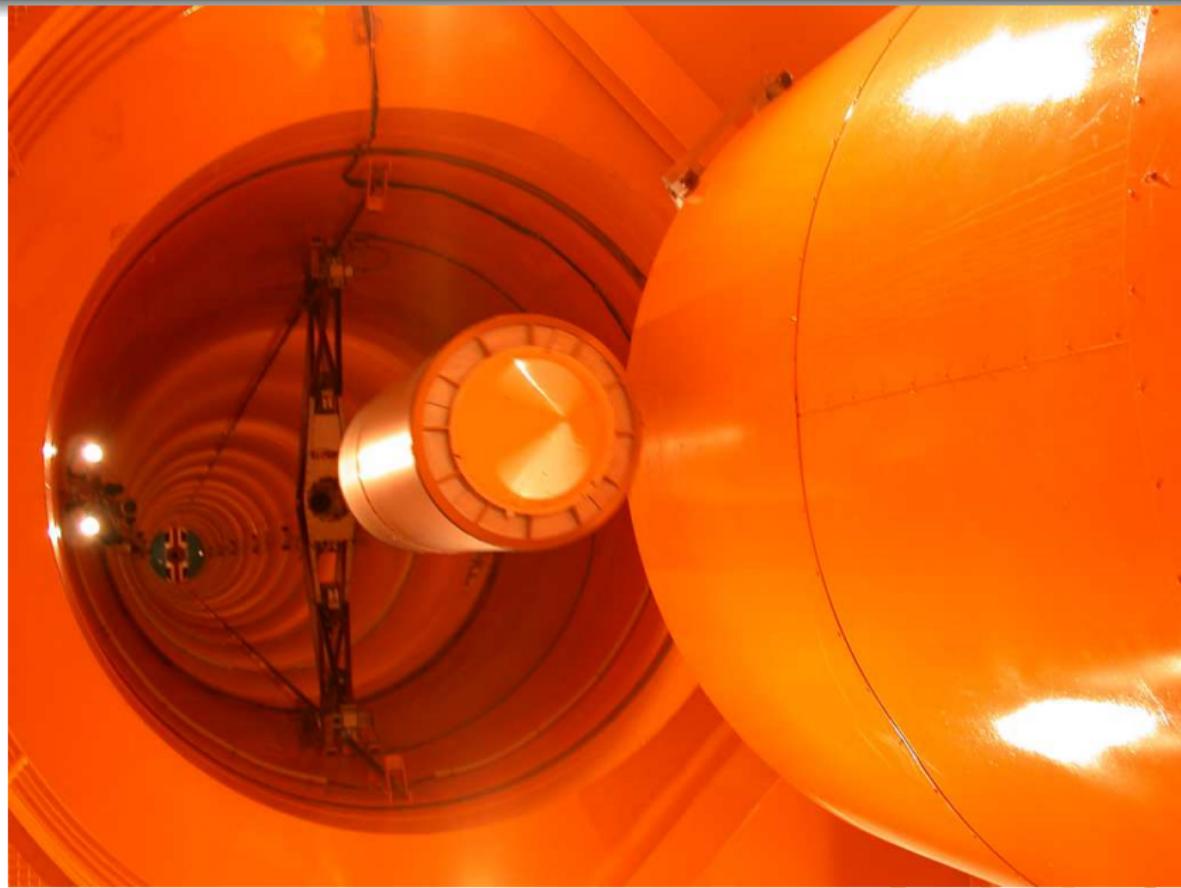
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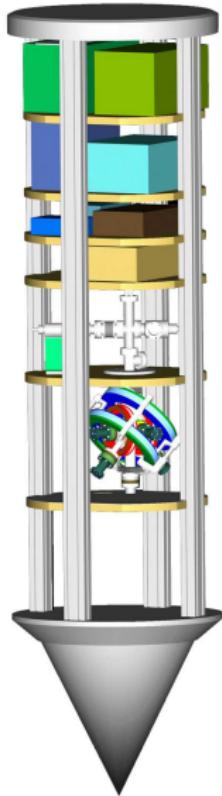
The Bremen drop tower



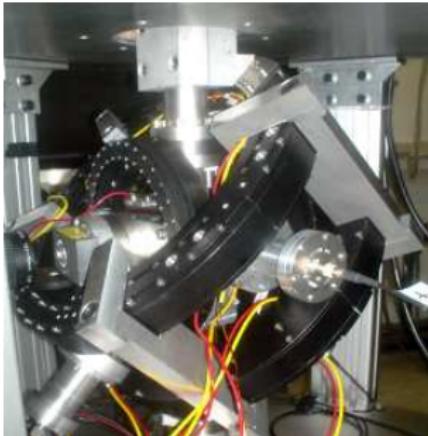
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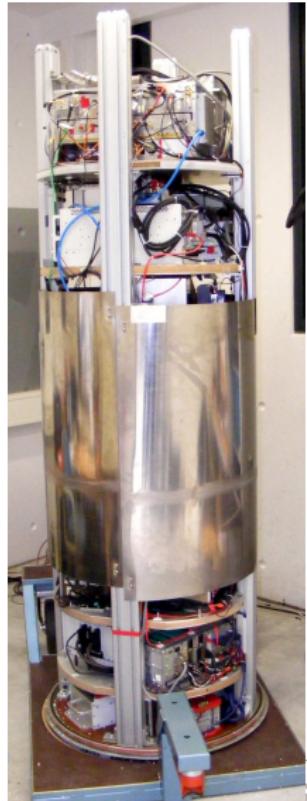
BEC in microgravity



design of capsule

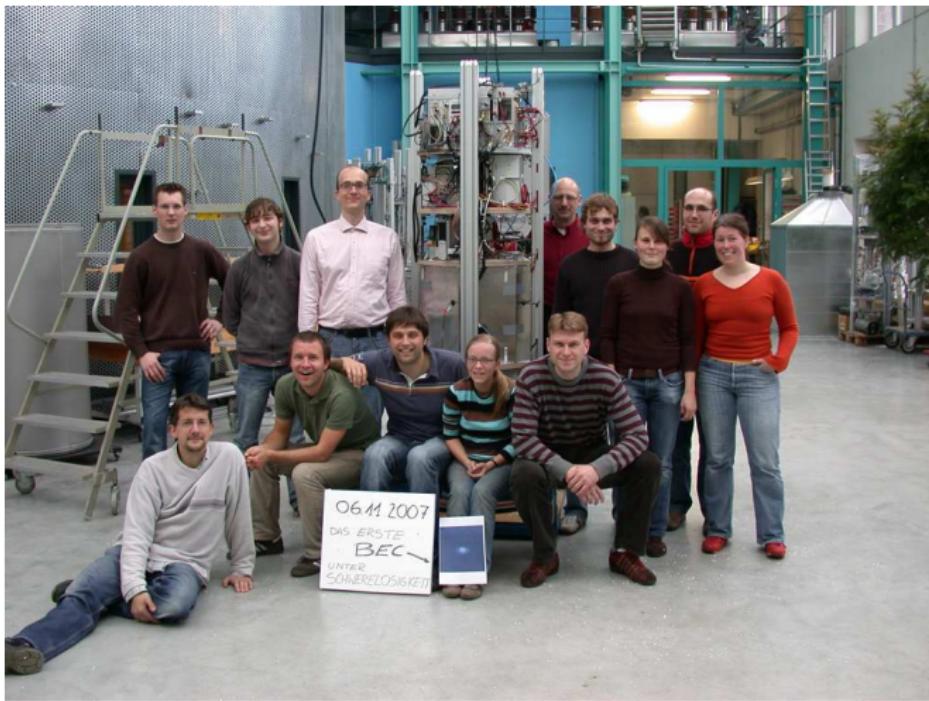


vacuum chamber



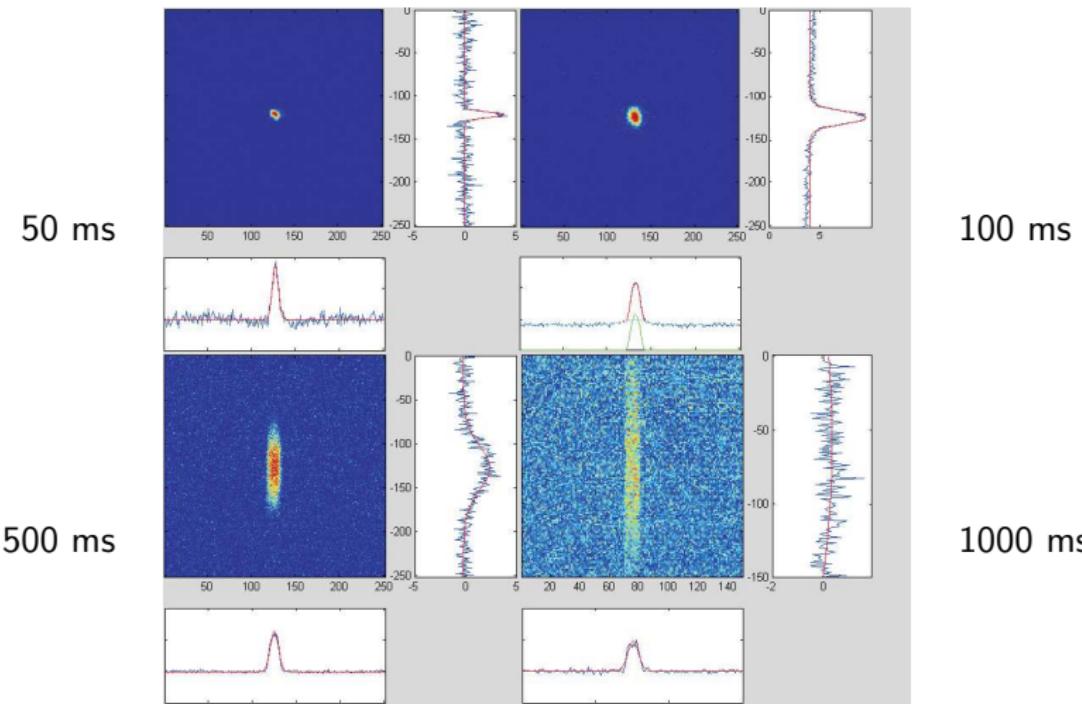
capsule

First BEC in microgravity / extended free fall



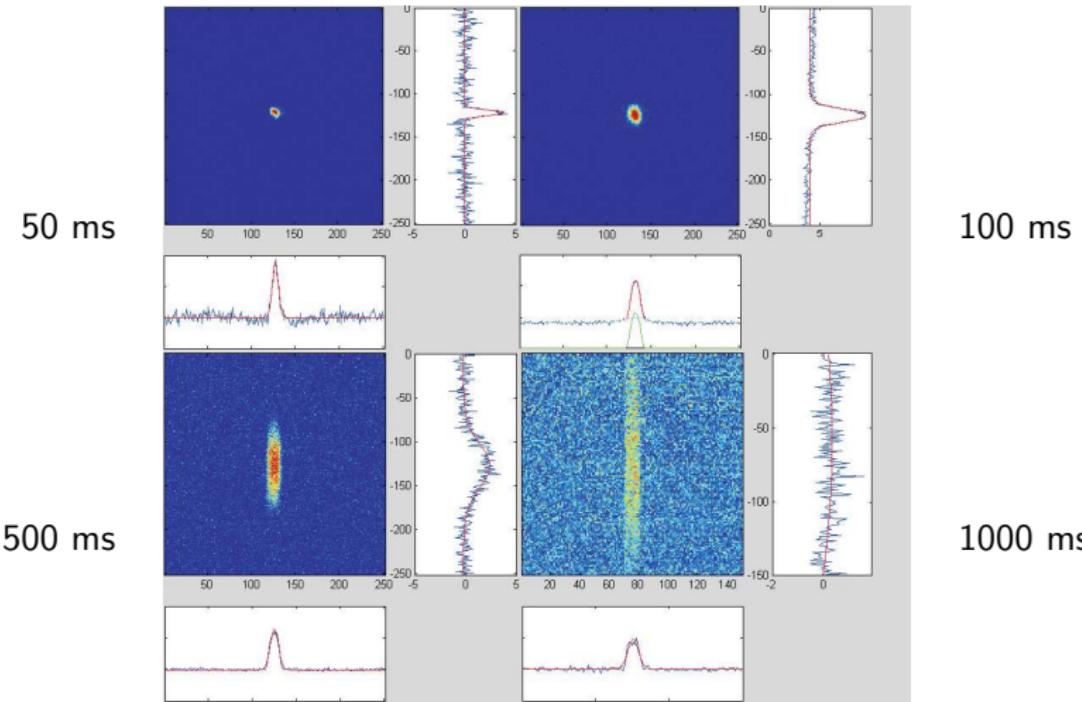
LU Hannover, ZARM, MPQ Munich, U Hamburg, HU Berlin, U Ulm

BEC in microgravity – long free evolution



10^4 atoms, 1 s free evolution time (not possible on ground)
van Zoest et al, Science 2010

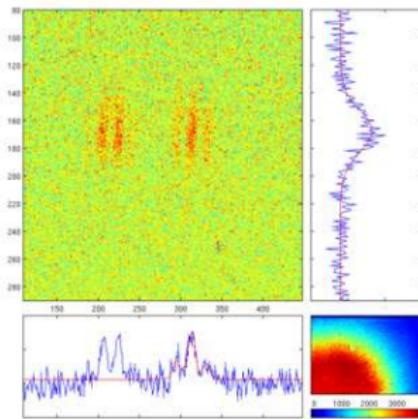
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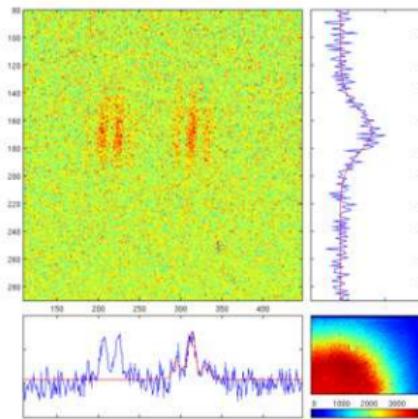
Interference

Interference for long time of flight (at the moment > 0.5 s)



Interference

Interference for long time of flight (at the moment > 0.5 s)



Capability for long time observations of ultracold atoms

- BEC
- Phase shift
- Probability distribution

BEC in free fall

- Status

- More than 350 drops
- BEC is created regularly
- Extremely robust (survives $\sim 50\text{ g}$)

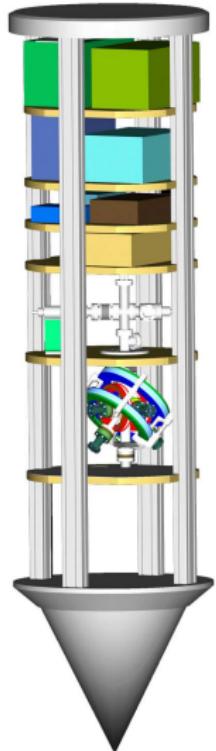
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- Ongoing work

- PRIMUS (PRäzisions–Interferometrie mit Materiewellen Unter Schwerelosigkeit)
- FOKUS (FaserOptischer FrequenzKamm Unter Schwerelosigkeit)

- In future

- Fundamental Physics experiments
- Drop tower — sounding rocket — ISS — satellite
- Inertial sensors
- High precision clocks



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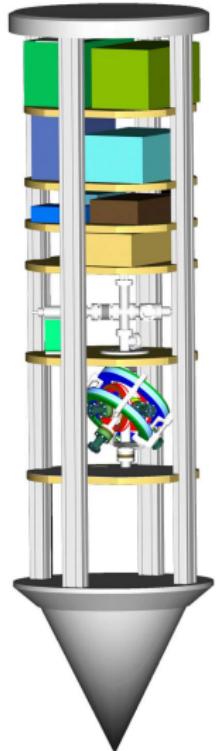
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Advantages of microgravity

Long free evolution time of quantum systems \Rightarrow better sensitivity to many quantum effects

- Acceleration

$$i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m} \Delta \phi + m \mathbf{g} \cdot \mathbf{x} \psi \quad \Rightarrow \quad \delta \phi = \mathbf{k} \cdot \mathbf{g} T^2$$

- Rotation

$$i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m} \Delta \phi + \boldsymbol{\omega} \cdot \mathbf{L} \psi \quad \Rightarrow \quad \delta \phi = \mathbf{k} \cdot (\boldsymbol{\omega} \times \langle \mathbf{v} \rangle) T^2$$

- Search for decoherence
- Search for nonlinearities
- ...

Most effects scale with time

$$i\hbar \frac{\partial \psi}{\partial t} = H(p) \psi \quad \Rightarrow \quad \delta \phi = \frac{1}{\hbar} (H(p') - H(p)) T$$

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Today's science quests

Science

- Gravitational physics
 - Equivalence principle
 - Clocks in gravitational fields
 - Non–Newton gravitational force
- Quantum physics
 - Decoherence – measurement problem, quantum–to–classical transition
 - Linearity
 - Entanglement
- Quantum gravity
 - Modified dispersion
 - Self–gravity
 - Semiclassical Einstein equations

Applications

- Geodesy
- Clocks



Possible experiments with cold atoms

Application of cold atoms for fundamental physics research

- **Test of quantum principles**

- Testing linearity of quantum mechanics
- Search for fundamental decoherence
- Measuring wave packet spreading
- Study of the measurement process
- Order of equations of motion

- **Quantum test of gravity principles**

- Quantum test of UFF
- Quantum test of UFF with atoms with spin, charge
- Test of UFF for rotation
- Testing relativistic effects
- Giant hydrogen atom
- Gravity trampoline

- **Combined tests (towards quantum gravity)**

- Investigation of self gravity
- Test of semiclassical Einstein equations
- Search for modified dispersion relation

Quantum measurement schemes

- Interference experiments
 - Interference pattern — phase shift — external interactions
 - Visibility — (de)coherence
- Energy levels (corresponds to clocks) — internal interactions
- Time-of-flight measurements — spatial evolution of quantum state



Experiment/observations vs theory

time

trajectory/positions

energy

phase shift

fringe visibility

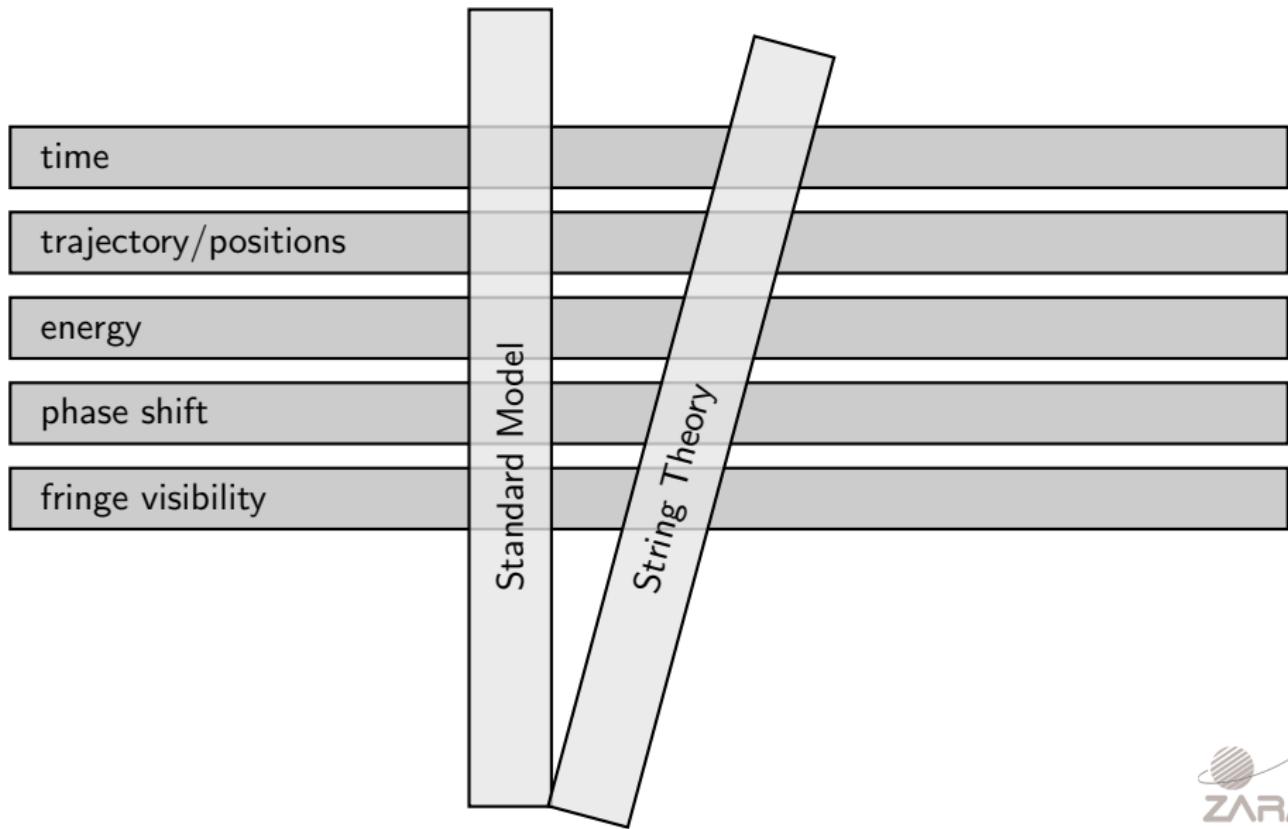


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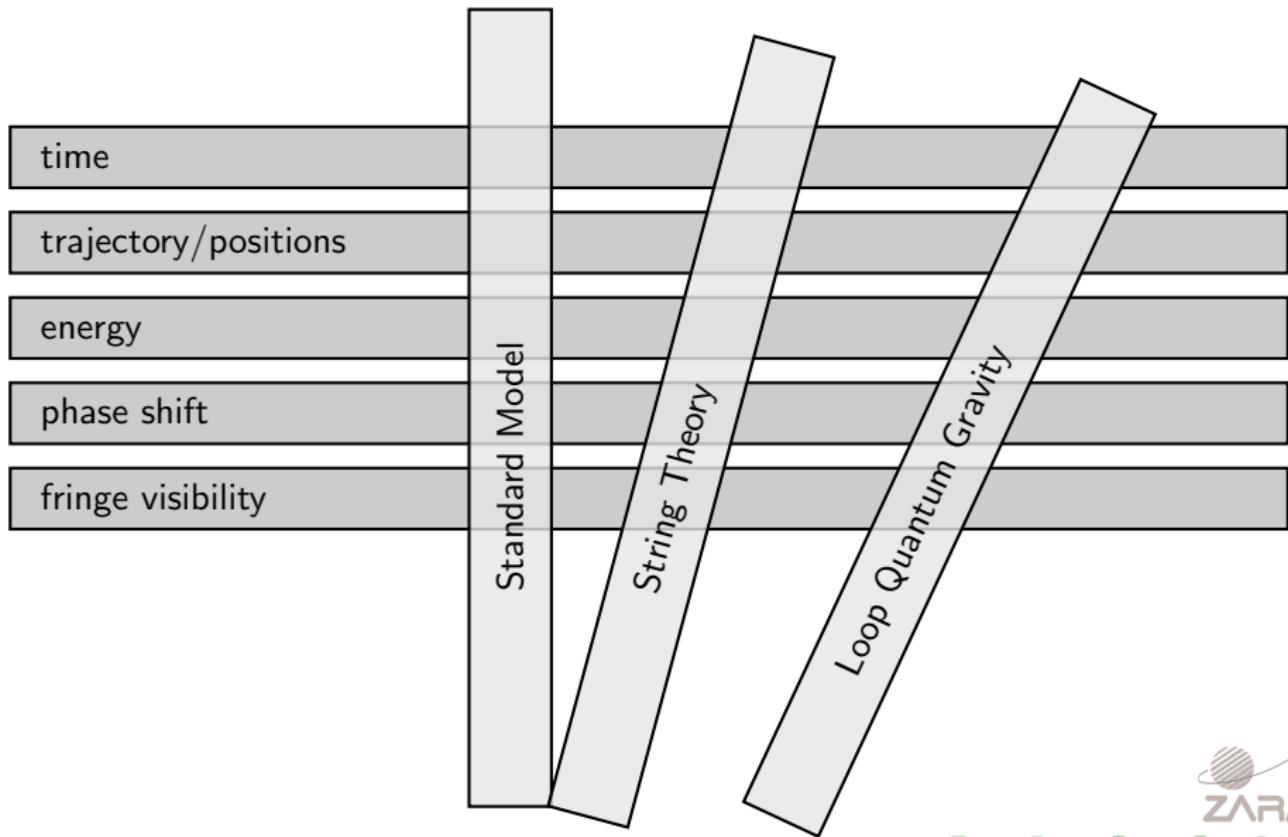
	Standard Model
time	
trajectory/positions	
energy	
phase shift	
fringe visibility	



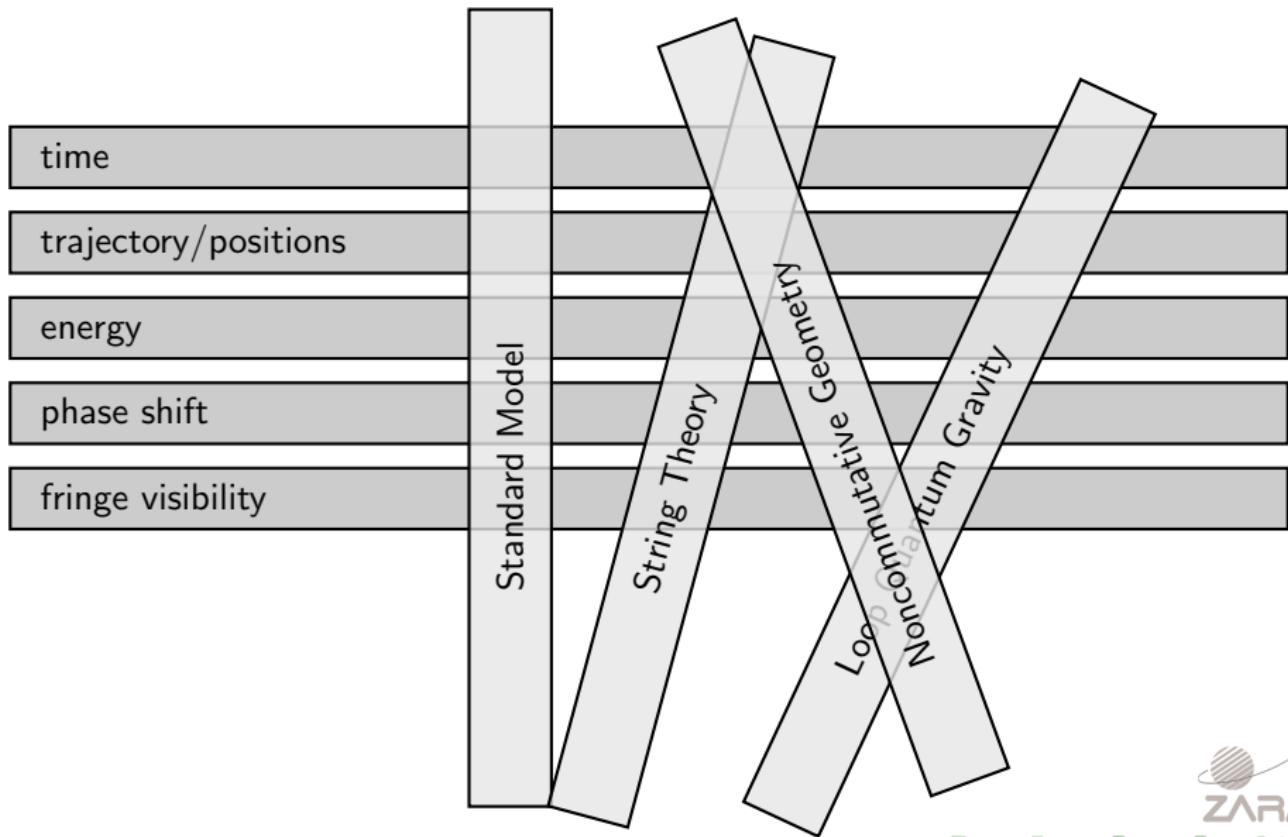
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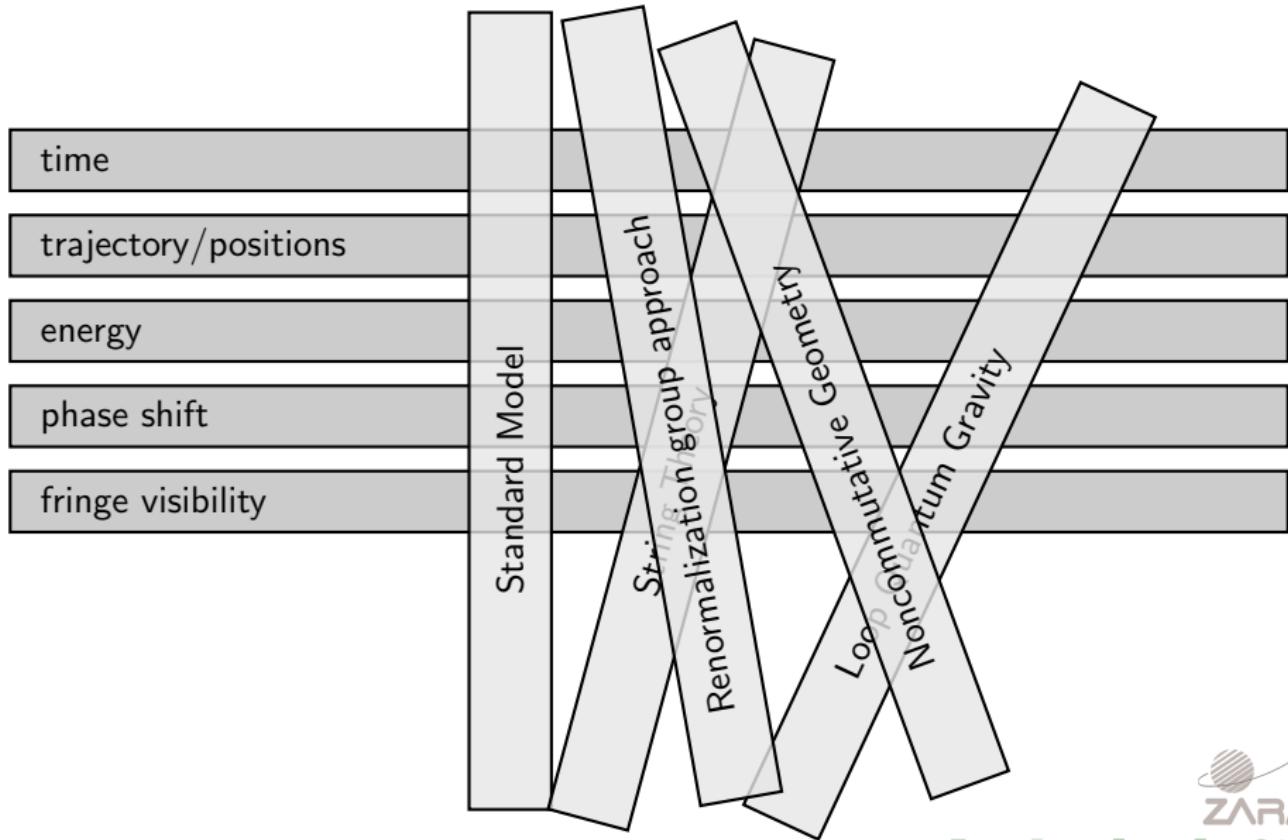
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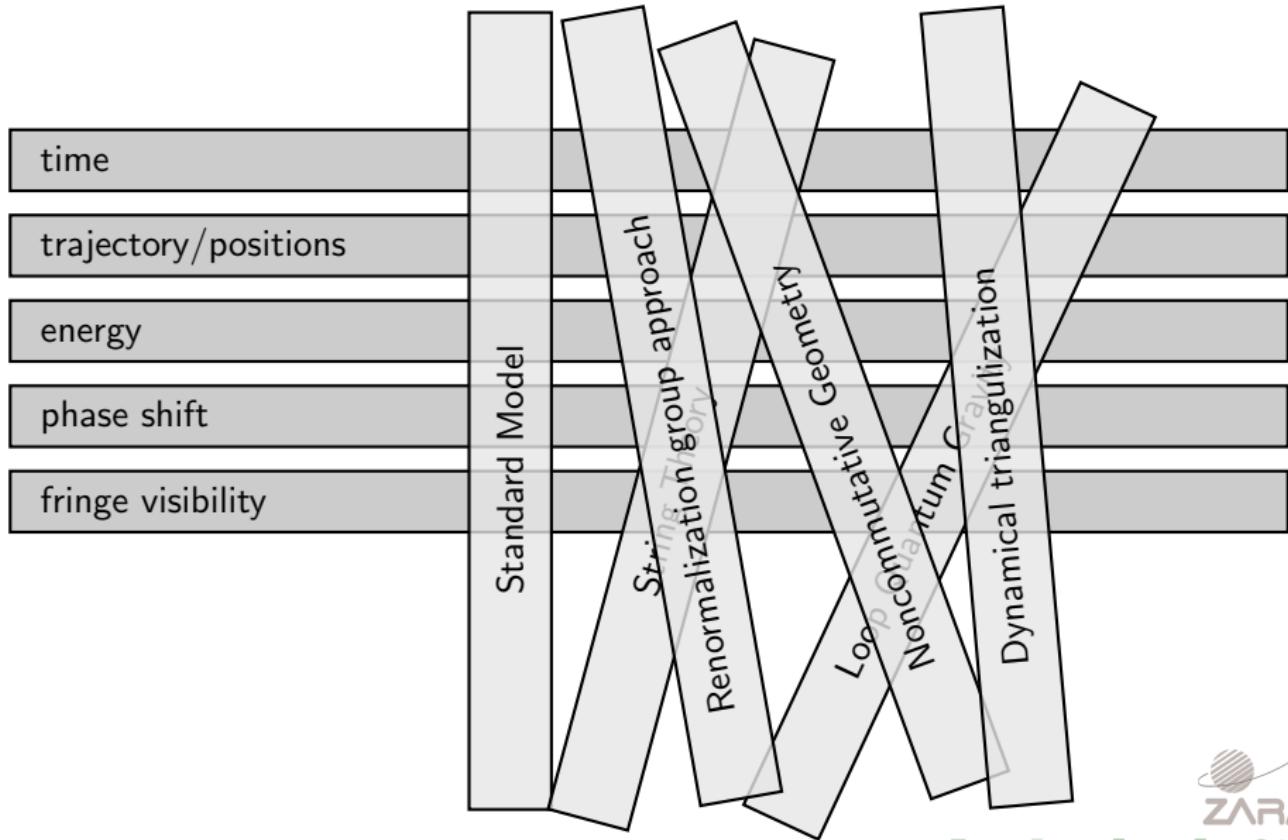
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Decoherence

One ansatz

$$i\hbar \frac{\partial}{\partial t} \psi = -\frac{\hbar^2}{2m} \Delta \psi + i\gamma \psi, \quad \gamma \in \mathbb{R}$$

Discussed for

- Path integral quantization of GR (Ellis et al, NPB 1984), comparison with neutron interferometry (visibility) $\gamma \leq 2 \cdot 10^{-21}$ GeV
- Canonical quantization of GR (Kiefer, PRD 1994)
- Space–time fluctuations minimally coupled to Klein–Gordon

$$H = \frac{1}{2m} (\delta^{ij} + \tilde{\alpha}^{ij} + \gamma^{ij}(t)) p_i p_j$$

- constant $\tilde{\alpha}^{ij}$ related to Universality of Free Fall (see later)
- fluctuating γ^{ij} gives decoherence
- Noise model: white noise (can be easily generalized)

(Breuer, Göklü & C.L. 2009)

Experiments should be 5 orders of magnitude better with atomic interferometry

Decoherence

The model

- model as above

$$H = \frac{1}{2m} (\delta^{ij} + \tilde{\alpha}^{ij} + \gamma^{ij}(t)) p_i p_j$$

- discuss now the influence of γ^{ij} and neglect $\tilde{\alpha}^{ij}$
- neglect small x-dependence

Noise model

- isotropic fluctuations $\gamma^{ij}(t) = \sigma \delta^{ij} \xi(t)$
- white noise $\langle \xi(t) \rangle = 0, \langle \xi(t) \xi(t') \rangle = \delta(t - t')$
- $\text{dim} \sigma^2 = \text{time} = \tau_c$
- practically no influence from colored noise
- $\gamma^{ij}(t)$ random process



Decoherence

Master equation

- stochastic Schrödinger equation in interaction picture

$$i\hbar \frac{d}{dt} |\tilde{\psi}\rangle = \tilde{H}_\gamma |\tilde{\psi}\rangle, \quad \tilde{H} = e^{\frac{i}{\hbar} H_0 t} H_\gamma e^{-\frac{i}{\hbar} H_0 t}$$

with random Hamiltonian \tilde{H}_γ with $\langle \tilde{H}_\gamma \rangle_t = 0$

- averaging over fluctuations \Rightarrow averaged density matrix

$$\tilde{\rho}(t) = \langle | \tilde{\psi} \rangle \langle \tilde{\psi} | \rangle$$

- master equation for averaged density matrix to second order in the fluctuations

$$i\hbar \frac{d}{dt} \tilde{\rho} = -\frac{i}{\hbar} \int_0^t \langle [\tilde{H}_\gamma(t), [\tilde{H}_\gamma(t'), \tilde{\rho}(t)]] \rangle dt'$$



Decoherence

Markovian master equation

- in Schrödinger picture

$$i\hbar \frac{d}{dt} \rho(t) = [H_0, \rho(t)] + i\hbar(\mathcal{D}\rho)(t)$$

with

$$(\mathcal{D}\rho)(t) = -\frac{1}{2}[V, [V, \rho(t)]] \quad \text{with} \quad V = \frac{\sqrt{\tau_c}}{\hbar} \frac{p^2}{2m}$$

- master equation is in Lindblad form \Rightarrow defines a completely positive quantum-dynamical semigroup
- energy is conserved (different from Wang et al, QCG 2006 based on primary state diffusion Percival & Strunz, PRAL 1997)
- \mathcal{D} is the dissipator

Decoherence

Decoherence time

- solution of master equation in momentum space

$$\rho(p, p', t) = \exp\left(-\frac{i}{\hbar}\Delta E t - \frac{(\Delta E)^2 \tau_c}{2\hbar^2} t\right) \rho(p, p', 0)$$

decoherence time

$$\tau_D = \frac{2\hbar^2}{(\Delta E)^2 \tau_c} = 2 \left(\frac{\hbar}{\Delta E \tau_c} \right)^2 \tau_c$$

- for $\tau_c = t_{\text{Planck}}$

$$\tau_D = \frac{10^{13} \text{ s}}{(\Delta E/\text{eV})^2}$$

- too large for being observable
- may change for BECs

(Breuer, Göklü & C.L. 2009)



Outline

1 Introduction

- Universality principles
- Need for Quantum Gravity
- Drop tower experiments
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2 Quantum experiments

- Decoherence
- **Spreading of wave packets**
- Superposition principle

3 Gravity experiments

- Testing the equivalence principle in the quantum domain
- Particles with degrees of freedom
- Gravitational eigenstates

4 Search for Quantum gravity

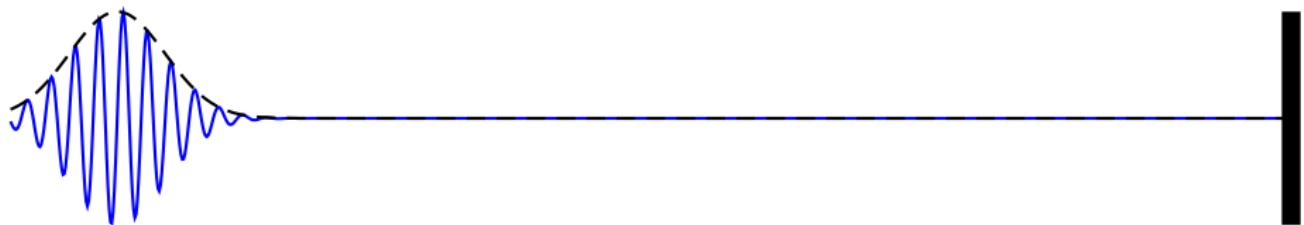
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6 Summary and Outlook

Spreading of wave packets

Spreading of wave packet: envelope = probability density



Standard spreading for Gaussian initial wave packet

$$\langle x^2(t) \rangle = \sigma^2(0) + \frac{\hbar^2}{4m^2\sigma^2(0)}t^2$$

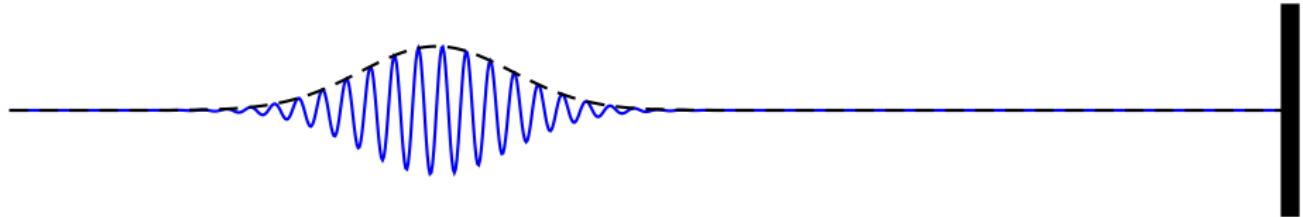
General modifications

$$\langle x^2(t) \rangle = \sigma^2(0) + s_1 t + \frac{\hbar^2}{4m^2\sigma^2(0)}t^2 + s_3 t^3 + s_4 t^4 + \dots$$

Spreading of wave packets does not necessarily modify spatial coherence

Spreading of wave packets

Spreading of wave packet: envelope = probability density



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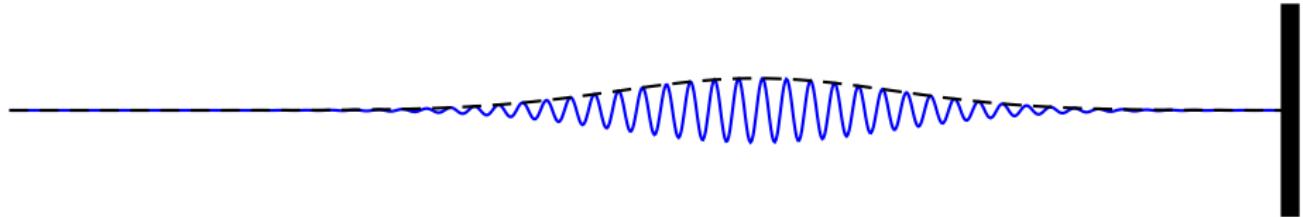
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Spreading of wave packets does not necessarily modify spatial coherence

Spreading of wave packets

Model

- Klein–Gordon coupled to space–time fluctuations

$$H = H_0 + V(x), \quad V(x) = \mathcal{O}(h\partial\partial h, \partial h\partial h)$$

- V is Gaussian random function

$$\langle V(x) \rangle = 0, \quad \langle V(x), V(x') \rangle = V_0^2 \delta(t - t') g(\mathbf{x} - \mathbf{x}')$$

long calculations ...

(Göklü, C.L., Camacho & Macias, CQG 2009)

The spreading

for Gaussian correlation and Gaussian initial wave packet

$$\langle x^2(t) \rangle = \underbrace{\sigma^2 + \frac{\hbar^2}{4m^2\sigma^2(0)}t^2}_{\text{free evolution}} + \underbrace{\frac{5V_0^2}{\sqrt{2\pi}m^2a^7}t^3}_{\text{superdiffusion}}$$

effect becomes more pronounced for large t — need of cold atoms

Spreading of wave packets

- No dedicated experiment until now
- Proposed measurement scheme: time-of-flight measurement
- Effect scales with time: should be very good for cold atoms



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Superposition principle

General non-linear Schrödinger equation

$$i\frac{\partial\psi}{\partial t} = -\frac{1}{2m}\Delta\psi + F(\psi^*\psi)\psi$$

Separability of quantum systems: non-linear Schrödinger equation of
Bialnicki-Birula PRL 1977; Shimony, PRA 1978

$$i\frac{\partial\psi}{\partial t} = -\frac{1}{2m}\Delta\psi + \textcolor{red}{a} [\ln(b\psi^*\psi)] \psi$$



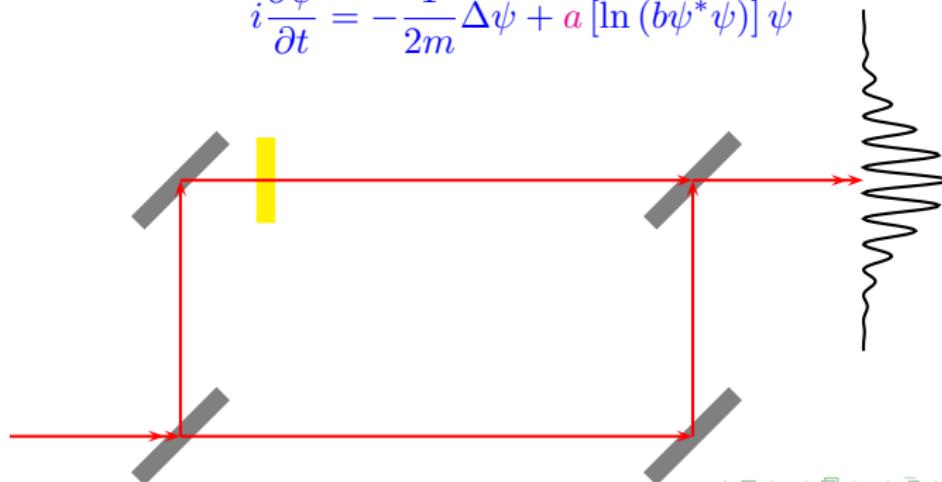
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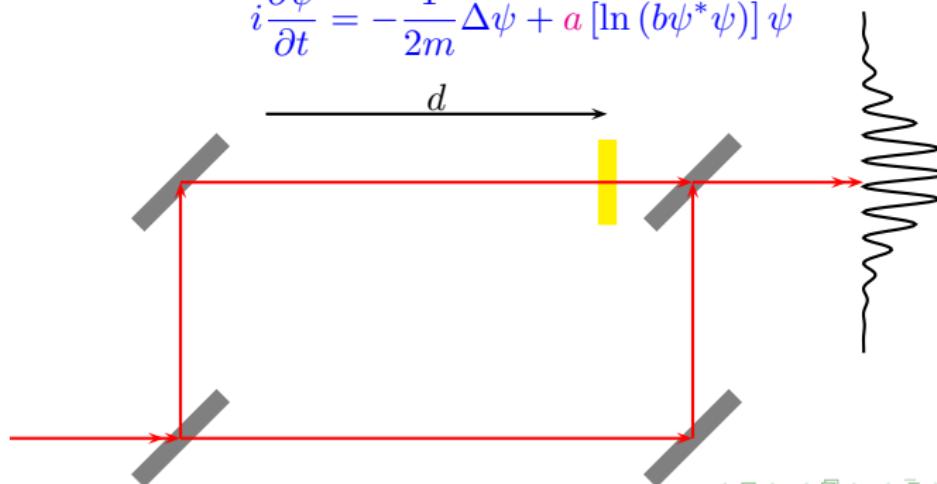
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$$i \frac{\partial \psi}{\partial t} = -\frac{1}{2m} \Delta \psi + a [\ln(b \psi^* \psi)] \psi$$



Superposition principle

phase shift:

$$\delta\phi = \frac{\Delta t}{\hbar} (F(|\varphi|^2) - F(\alpha^2|\varphi|^2))$$

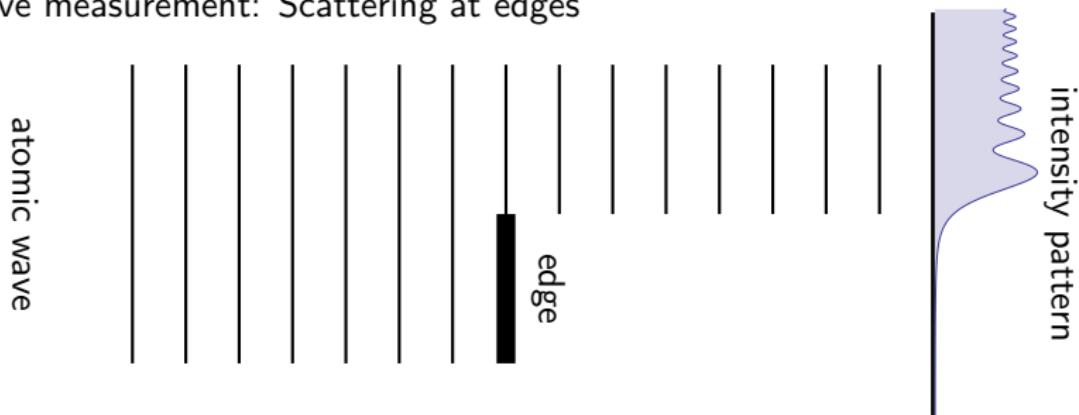
α = intensity attenuation.

Test with neutron interferometry ([Shull et al, PRL 1980](#))

- result: $a \leq 3.4 \cdot 10^{-13}$ eV
- atomic interferometry in microgravity should lead to 6 orders of magnitude improvement (for 1 s flight)
- from energy levels: $a \leq 4 \cdot 10^{-10}$ eV

Superposition principle

Alternative measurement: Scattering at edges



- yields best estimates for neutrons: $\alpha \leq 3 \cdot 10^{-15}$ eV
 - depends on velocity of particles → **should be better for atoms by many orders of magnitude**
 - Van der Waals, Casimir forces etc. should be included in calculation, and parameters determined by independent experiments, or by scattering at edges made of different materials



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Tests of UFF

1 Tests with bulk matter

Method	Grav field	Accuracy	Experiment
Torsion pendulum	Sun	$\eta \leq 2 \cdot 10^{-13}$	Adelberger 2006

2 Tests with quantum matter

Method	Grav field	Accuracy	Experiment
Atom interferometry	Earth	$\eta \leq 10^{-9}$	Chu, Peters 1999
		$\eta \leq 10^{-7}$	Fray et al 2004

3 Gravitational self energy

Method	Grav field	Accuracy	Experiment
Torsion pendulum and LLR	Sun	$\eta \leq 1.3 \cdot 10^{-3}$	Baessler et al 1999

Tests of UFF

4 Charged particles

Method	Grav field	Accuracy	Experiment
Free fall of electron	Earth	$\eta \leq 10^{-1}$	Witteborn & Fairbank 1967

5 Particles with spin

Method	Grav field	Accuracy	Experiment
Weighting polarized bodies	Earth	$\eta \leq 10^{-8}$	Hsie et al 1989

6 Anti-particles

Method	Grav field	Accuracy	Experiment
Free fall of anti-Hydrogen	Earth	$\eta \leq 10^{-3} - 10^{-5}$	(estimate)

Types of tests

- **Free fall test with classical bulk matter**

Kuroda & Mio $\eta \leq 10^{-9}$

MICROSCOPE $\eta \leq 10^{-15}$

- **Torsion pendulum test with bulk matter**

Schlamminger, Gundlach, Adelberger $\eta \leq 10^{-13}$

Gundlach: After next ten years improvement by a factor 2 ... 5

- **Free fall test with quantum matter and bulk matter**

Peters, Chu $\eta \leq 10^{-9}$

- **Free fall test with quantum matter**

Fray, Weitz, Haensch $\eta \leq 10^{-5}$

Spin \leftrightarrow quantum matter



Types of tests

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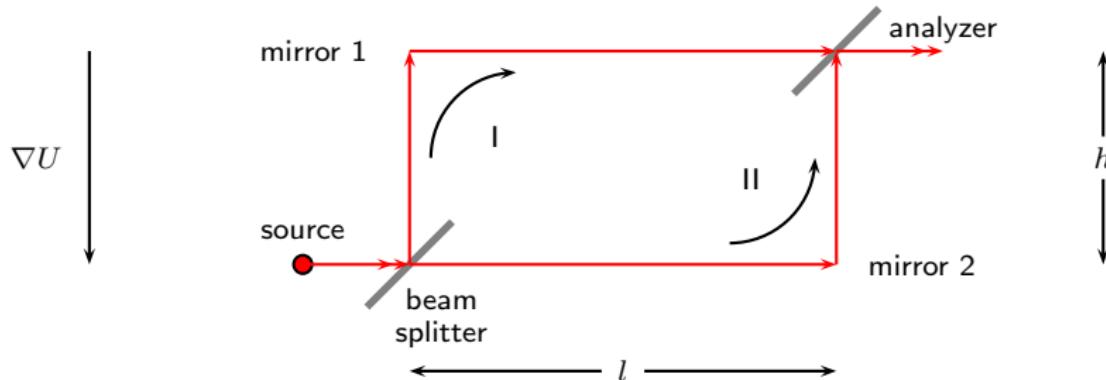


- **Free fall test with quantum matter**

Fray, Weitz, Haensch $\eta \leq 10^{-5}$

Spin \leftrightarrow quantum matter

Interference: The general phase shift



Phase shift

$$\Delta\phi = \oint p$$

integration along classical trajectory

Universality of Free Fall in interferometry

- For standard gravitational acceleration: atom interferometry ([Bordé 1989](#))

$$\delta\phi = \mathbf{k} \cdot \mathbf{g} T^2$$

- Universality of Free Fall exactly fulfilled
- Also holds for neutron interferometry $\delta\phi = \mathbf{C} \cdot \mathbf{g} T^2$ ([C.L., GRG 1996](#))
- UFF also valid for nonlinear Schrödinger equation in general ([Chen & Liu, PRL 1976](#))
- Violation of UFF

$$i\hbar \frac{\partial}{\partial t} \psi = -\frac{\hbar^2}{2m_i} \Delta \psi + m_g U \psi \quad \Rightarrow \quad \delta\phi = \frac{m_g}{m_i} \mathbf{k} \cdot \mathbf{g} T^2$$

Models violating the UFF

- Dilaton scenarios (Damour & Polyakov 2003, 2004, Damour, Piazza & Veneziano, PRL 2002, PRD 2002)
- Quintessence, cosmon field (Wetterich PLB 203)
- Scattering of D -branes at massive particles leads to a particle dependent influence on its mean motion \Rightarrow violation of UFF at 10^{-18} level (Ellis et al 2003)
- Varying e models Bekenstein
- From Klein–Gordon in fluctuating space-time: Schrödinger equation in gravitational field

$$i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m} (\delta^{ij} + \alpha^{ij}) \partial_i \partial_j \phi + mU\psi$$

α^{ij} depends on atomic species and noise scenario (see later, Göklü & C.L., CQG 2009)

Scalar tensor theories

Effective Lagrangian

From string theory: effective Lagrangian for gravity with long-ranged dilaton-like scalar field (Damour et al 1993, 1994, 2002)

$$\begin{aligned} L_{\text{eff}} = & \frac{1}{16\pi G} R(g) - \frac{1}{8\pi G} g^{\mu\nu} D_\mu \varphi D_\nu \varphi - \frac{1}{4e^2(\varphi)} F_{\mu\nu} F^{\mu\nu} \\ & - \sum_A (\bar{\psi}_A \gamma^\mu (D_\mu - iA_\mu) \psi_A + m_A(\varphi) \bar{\psi}_A \psi_A) \end{aligned}$$

φ = dilaton field

φ_0 = vacuum expectation value given by cosmological evolution

Parameters depending on dilaton field:

- mass of fermion
- coupling to electromagnetic field
- energy levels of atoms

Scalar tensor theories

Strengths of couplings

- Strength of coupling of dilaton to mass m_A : $\alpha_A = \frac{\partial \ln m_A(\varphi)}{\partial \varphi} \Big|_{\varphi=\varphi_0}$
- Strength of coupling of dilaton to electromagnetism: $\alpha_{\text{em}} = \frac{\partial e^2(\varphi)}{\partial \varphi} \Big|_{\varphi=\varphi_0}$
- Energy differences: $\alpha_{AA'} = \frac{\partial E_{AA'}(\varphi)}{\partial \varphi} \Big|_{\varphi=\varphi_0}$

Gravitational constant

One obtains a composition-dependent gravitational constant:

$$\text{Acceleration of test body 1 by body 2: } a_1 = \frac{(m_g)_1}{(m_i)_1} \frac{G(m_g)_2}{r_{12}^2} = G_{12} \frac{(m_g)_2}{r_{12}^2}$$

$$\text{Then } G_{12} = G \frac{(m_g)_1}{(m_i)_1} \frac{(m_g)_2}{(m_i)_2} \approx G (1 + \alpha_1 \alpha_2)$$

Scalar tensor theories

Consequences

UFF: $\eta = \frac{a_A - a_B}{\frac{1}{2}(a_A + a_B)} = \frac{G_{13} - G_{23}}{\frac{1}{2}(G_{13} + G_{23})} \approx (\alpha_A - \alpha_B) \alpha_E \approx -5 \cdot 10^{-5} \alpha_{\text{had}}^2$

PPN: γ -parameter: $\gamma - 1 = -2 \frac{\alpha_{\text{had}}^2}{1 + \alpha_{\text{had}}^2}$

Redshift: $\frac{\nu_{AA'}(r_1)}{\nu_{AA'}(r_2)} \approx 1 + (1 + \alpha_{AA'} \alpha_E) \frac{U_E(r_2) - U_E(r_1)}{c^2}$

UGR: Comparison of two different clocks at same position: Time dependence

$$\frac{\nu_{AA'}(r)}{\nu_{BB'}(r)} = \frac{F(Z_A e^2(\varphi))}{F(Z_B e^2(\varphi))}$$

$$\delta \ln e^2 = -2.5 \cdot 10^{-2} \alpha_{\text{had}}^2 \delta U(t) - 4.7 \cdot 10^{-3} \alpha_{\text{had}}^2 H_0 \delta t$$

Scalar tensor theories

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"Predictions"

Quintessence (Wetterich 2003)

- Cosmologically given dynamics of scalar field = quintessence
 - relation of quintessence to observations
- ⇒ predictions of violation of UFF of order 10^{-14}

String theory (Ellis et al 2003)

Scattering of D -branes at massive particles leads to particle-dependent influence on its mean motion ⇒ violation of UFF at the 10^{-18} level.

Effect	dilaton	cosmon	varying e	string
UFF — η	10^{-13}	10^{-14}	$< 10^{-13}$	$< 10^{-18}$
UGR	10^{-18}	10^{-18}		
PPN — γ	10^{-5}			
PPN — β	10^{-9}			
$\dot{\alpha}/\alpha$	10^{-21} y^{-1}			



Some history of space–time fluctuations I

Space–time foam, fuzzy space–time, space–time fluctuations
 Goes back to Hawking 1973, Bekenstein 1975, Wheeler 1982

- **Ellis, Hagelin, Nanopoulos & Srednicki, NPB 1984** decoherence due to fluctuating metric, neutron interferometry
- **Kiefer & Singh, PRD 1994** modified Schrödinger equation
- **Percival & Strunz, PRAL 2000** Influence of stochastic metric fluctuations on atom interferometry
- **Power & Percival, PRAL 2000** Decoherence of wave packets from conformal space–time fluctuations, modified Schrödinger equation for density matrix
- **Amelino–Camelia, PRD 2000** Saleker–Wigner argument, random–walk, modified dispersion
 yields general Brownian motion ansatz $S_{\text{sf}}^{(\alpha,\gamma)}(\nu) = \zeta \frac{\Lambda}{c} \left(\frac{l_{\text{Planck}}}{\Lambda} \right)^\alpha \left(\frac{\nu}{c/\Lambda} \right)^\gamma$
- **Ng & van Dam 2000** Distance measurement by clocks (based on Saleker–Wigner argument) $\delta g \sim (l_{\text{Planck}}/l)^{\frac{2}{3}}$



Some history of space–time fluctuations II

- **Ng 2002** Holographic principle $(l/\delta l)^3 \leq (l_{\text{Planck}}/l) \Rightarrow \delta g \sim (l_{\text{Planck}}/l)^{\frac{2}{3}}$.
Idea: holographic principle follows from space–time fluctuations
Relation to quantum computing
Influence on dispersion relations, decoherence of light phase, UHECR,
non-locality, ...
- **Hu & Verdaguer 2002, 2008** Axiomatic approach: Einstein–Langevin
equations, application to backreaction problems and black hole fluctuations
- **Ford 2003 – 2008** No specific model, luminosity fluctuations, line
broadening, angular blurring, black hole fluctuations
- **Aloisio, Galante, Grillo, Liberati, Lucio & Mendez 2006** no specific
scenario, relation to modified dispersion
- **Wang, Bonifacio, Bingham & Mendonca, CQG 2006; CQG 2009**
Conformal fluctuations and decoherence of quantum particle, effect for very
large masses $\sim 10^{19}$ a.m.u.
- **Hogan, PRD 2008** Holographic noise in GEO600

The basic equations

The model

- Klein–Gordon equation

$$g^{\mu\nu} D_\mu D_\nu \varphi + m^2 \varphi = 0, \quad D = \partial + \{ \cdot \cdot \}$$

- Fluctuating metric

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \quad |h_{\mu\nu}| \ll 1$$

- noise

$$\langle h_{\mu\nu}(x) \rangle_{\text{st}} = \gamma_{\mu\nu}, \quad \delta^{\rho\sigma} \langle h_{\mu\rho}(x) h_{\nu\sigma}(x) \rangle_{\text{st}} = \sigma_{\mu\nu}^2$$

- small amplitude of fluctuations
- frequency might be large, wavelength might be small
- $\langle \cdot \rangle_{\text{st}}$ = averaging over a space–time volume
- we do not require the $h_{\mu\nu}$ to obey a wave equation

The basic equations

Approximations

- Weak field up to second order $\tilde{h}^{\mu\nu} = h^{\mu\rho}h_{\rho}^{\nu}$
- Relativistic approximation of metric and quantum field (á la Kiefer & Singh, PRD 1994)

$$\begin{aligned} H\psi &= -((^3)g)^{\frac{1}{4}} \frac{\hbar^2}{2m} \Delta_{\text{cov}} \left(((^3)g)^{-\frac{1}{4}} \psi' \right) + \frac{m}{2} \left(\tilde{h}_{(0)}^{00} - h_{(0)}^{00} \right) \psi \\ &\quad - \frac{1}{2} \left\{ i\hbar\partial_i, h_{(1)}^{i0} - \tilde{h}_{(1)}^{i0} \right\} \psi \end{aligned}$$

manifest hermitean w.r.t. flat scalar product

- only second order terms do not vanish by averaging
- Dirac equation

Short wavelength

Spatial average

- spatial average

$$\langle A\psi \rangle_s(x) := \frac{1}{V_x} \int_{V_x} A(y)\psi(y)d^3y$$

- short wavelength of fluctuations: V small
- spatial average of Schrödinger equation

$$H = \frac{1}{2m} (\delta^{ij} + \alpha^{ij}(x)) p_i p_j + \alpha_0$$

with $\alpha(x) = \langle \tilde{h}^{ij} - h^{ij} \rangle_s(x)$

- $\alpha^{ij}(x)$: small variation w.r.t. x , fluctuations w.r.t. t .
- decompose $\alpha^{ij}(x) = \tilde{\alpha}^{ij}(x) + \gamma^{ij}(x)$ with $\langle \gamma^{ij} \rangle_t = 0$
- $\tilde{\alpha}^{ij}(x)$ acts like an anomalous inertial mass tensor



Space-time fluctuations

Fluctuation model

- $\alpha^{ij} \leftrightarrow$ spectral noise density of fluctuations
- particular model:

$$\tilde{\alpha}^{ij}(x) = \frac{1}{V_x} \int_{V_x} \tilde{h}^{ij}(\mathbf{x}, t) d^3\mathbf{x} = \frac{1}{V_x} \int_{1/V_x} (S^2(\mathbf{k}, t))^{ij} d^3\mathbf{k}$$

- model: power law spectral noise density

$$(S^2(\mathbf{k}, t))^{ij} = (S_{0n}^2)^{ij} |\mathbf{k}|^n \quad \xrightarrow{\text{integration}} \quad \alpha^{ij}(x) = (S_{0n}^2)^{ij} \lambda_p^{-(6+n)}$$

with $\dim(S_{0n}^2)^{ij} = \text{length}^{3+\frac{n}{2}}$

- $V_x \sim \lambda_p^3$
- $\lambda_p = \text{invariant length scale of quantum object} = \lambda_{\text{Compton}}$
- $\lambda_p = \text{de Broglie wave length}$
- $\lambda_p = \text{geometric extension } l_p \text{ of quantum object (Bohr radius of atom)}$

Space-time fluctuations

Fluctuation model

- assumption: $S_{0n} \sim l_{\text{Planck}}^{3+\frac{n}{2}}$, then

$$\alpha^{ij}(x) \sim \left(\frac{l_{\text{Planck}}}{l_p} \right)^\beta a^{ij}(x), \quad \beta = 6 + n, \quad a^{ij}(x) = \mathcal{O}(1)$$

- effective Hamiltonian

$$H = \frac{1}{2m} \left(\delta^{ij} + \left(\frac{l_{\text{Planck}}}{l_p} \right)^\beta a^{ij}(x) \right) p_i p_j = \frac{1}{2m} \left(\delta^{ij} + \frac{\delta m^{ij}(x)}{m} \right) p_i p_j$$

δm^{ij} = anomalous inertial mass tensor, depends on particle

- δm^{ij} leads to violation of Universality of Free Fall

- $\beta = \frac{1}{2}$ \leftrightarrow random walk
- $\beta = \frac{2}{3}$ \leftrightarrow holographic noise



Result

Result

Metric fluctuations \Rightarrow anomalous inertial mass \rightarrow **apparent** violation of UFF

- Alternative route for violation of UFF and LLI
- Need of quantum tests
- No difference for particles and antiparticles

Example

For Cesium and Hydrogen and geometric extension of atoms

$$\eta_{\beta=1} = 10^{-20}, \quad \eta_{\beta=2/3} = 10^{-15}, \quad \eta_{\beta=1/2} = 10^{-12}$$

Accuracy 10^{-15} is planned for the next years

(Göklü & C.L. CQG 2008, also Jaekel & Reynaud, 2002)



Universality of gravitomagnetic coupling

- Sagnac effect

$$\delta\phi = k \cdot (\mathbf{v} \times \boldsymbol{\Omega})$$

- Schiff effect (gravitomagnetic effect of gyroscopes)

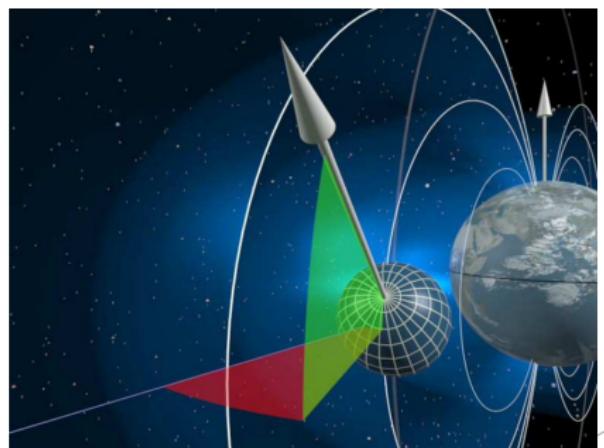
$$\boldsymbol{\Omega} = \nabla \times \mathbf{h}, \quad ds^2 = g_{00}dt^2 + h_idtdx^i + g_{ij}dx^i dx^j$$

- UFF for gravitomagnetism

$$\delta\phi = (1 + \kappa) k \cdot (\mathbf{v} \times (\nabla \times \mathbf{h}))$$

κ may depend on particle

- Example: Particle with spin in Riemann–Cartan space–time
- Recent analysis by Ni, PRL 2011 related to GP-B (universality of parallel displacement)



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UFF and charge

Standard theory

- In standard theory from ordinary coupling (deWitt & Brehme, AP 1968)

$$a^\mu = \alpha \lambda_C R^\mu{}_\nu v^\nu \sim 10^{-35} \text{ m/s}^2$$

Anomalous coupling

- Anomalous coupling (Dittus, C.L., Selig, GRG 2004)

$$H = \frac{\mathbf{p}^2}{2m} + mU(\mathbf{x}) + \kappa e U(\mathbf{x}) = \frac{\mathbf{p}^2}{2m} + m \left(1 + \kappa \frac{e}{m}\right) U(\mathbf{x}).$$

- Charge dependent anomalous gravitational mass
 - Can be generalized to charge dependent anomalous inertial mass (e.g. Rohrlich 2000)
- ⇒ Charge dependent Eötvös factor
- It is possible to choose κ 's such that for neutral composite matter UFF is fulfilled while for **isolated charges** UFF is violated

UFF and spin

Standard theory

- In standard theory from ordinary coupling: $a^\mu = \lambda_C R^\mu{}_{\nu\rho\sigma} v^\nu S^{\rho\sigma} \Rightarrow$ violation of UFF at the order 10^{-20} m/s², beyond experiment

Anomalous coupling

- Speculations: violation P , C , and T symmetry in gravitational fields ([Leitner & Okubo 1964](#), [Moody & Wilczek 1974](#)) suggest

$$V(r) = U(r) [1 + A_1(\boldsymbol{\sigma}_1 \pm \boldsymbol{\sigma}_2) \cdot \hat{\mathbf{r}} + A_2(\boldsymbol{\sigma}_1 \times \boldsymbol{\sigma}_2) \cdot \hat{\mathbf{r}}]$$

- One body (e.g., the Earth) is unpolarized →

$$V(r) = U(r) (1 + A\boldsymbol{\sigma} \cdot \hat{\mathbf{r}})$$

Hyperfine splittings of H ground state: $A_p \leq 10^{-11}$, $A_e \leq 10^{-7}$

- [Hari Dass 1976, 1977](#), includes velocity of the particles

$$V(r) = U_0(r) [1 + A_1 \boldsymbol{\sigma} \cdot \hat{\mathbf{r}} + A_2 \boldsymbol{\sigma} \cdot \frac{\mathbf{v}}{c} + A_3 \hat{\mathbf{r}} \cdot (\boldsymbol{\sigma} \times \frac{\mathbf{v}}{c})]$$

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- **Gravitational eigenstates**

4 Search for Quantum gravity

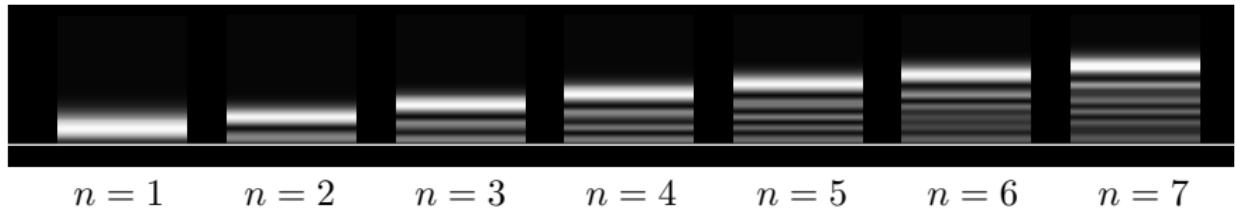
- Self gravitating quantum systems
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5 On redshift experiments

6 Summary and Outlook

BEC in GOST

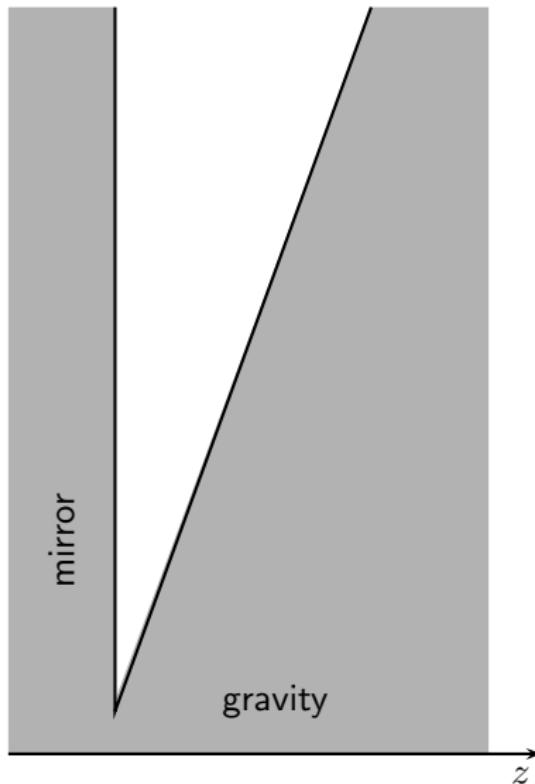
- BEC in gravito-optical surface trap
- Boundary conditions $\psi = 0$ for $z = 0$
- Spacing of maxima of wave functions $\sim 1/g$



nonlinear boundary value problem
(Marojevic, in preparation)

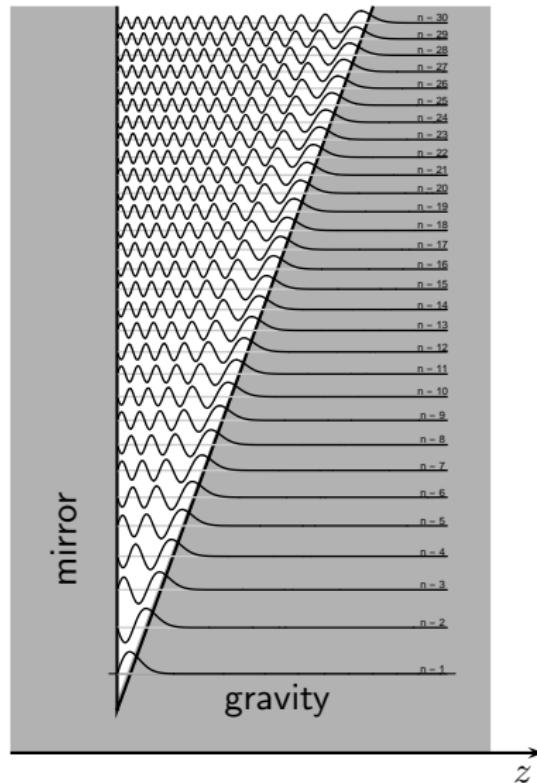
Neutron eigenstates

Potential



Neutron eigenstates

Potential

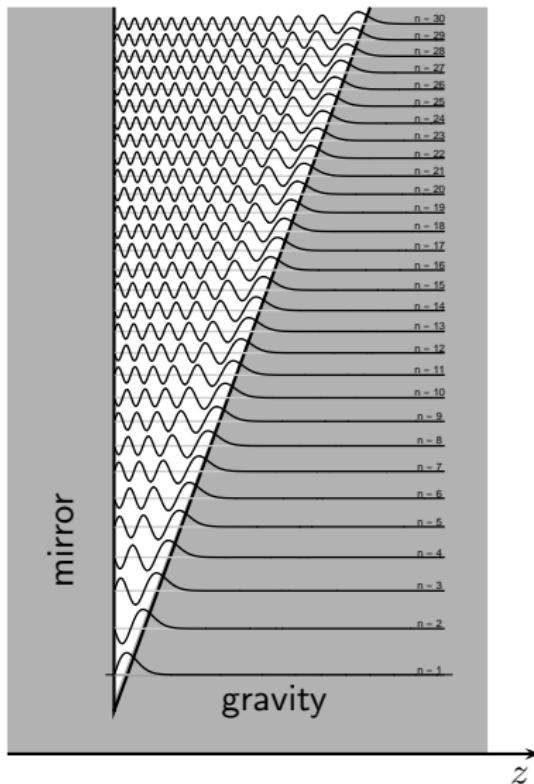


Süßmann 1965, Landau–Lifshitz



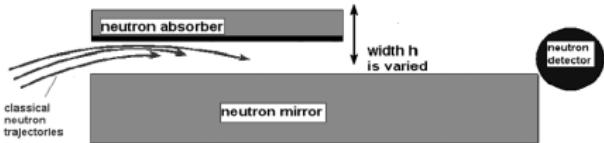
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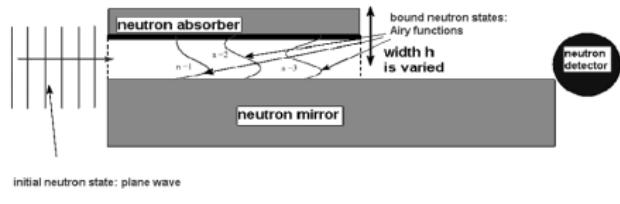


experimental setup

Classical View



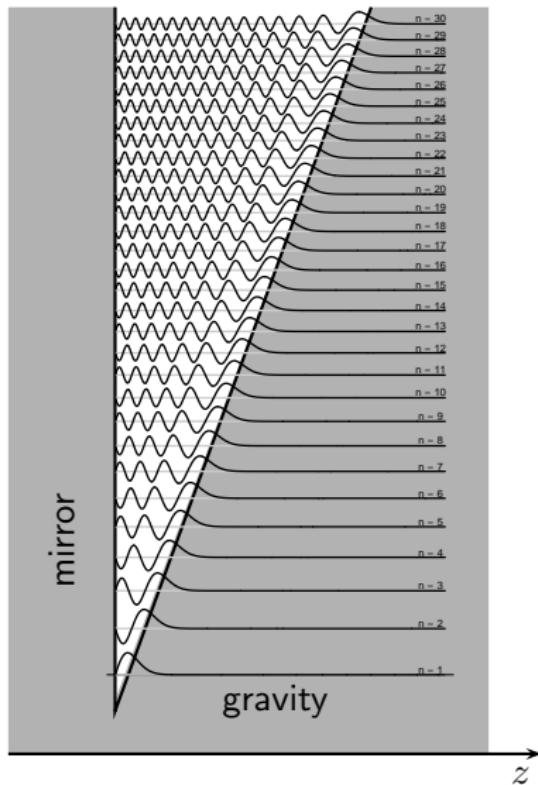
Quantum View



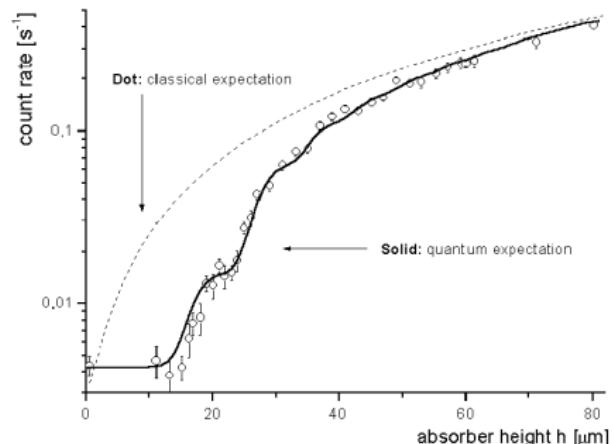
Süßmann 1965, Landau–Lifshitz

Neutron eigenstates

Potential



measurement



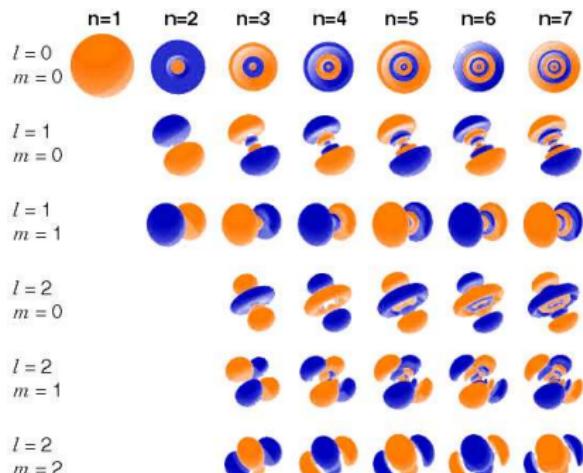
Süßmann 1965, Landau–Lifshitz
Nesvizhevsky et al, Nature 2002

Giant hydrogen atom

- Spherically symmetric gravitating mass of 1 g
- Bohr radius ~ 1 mm
- Corresponds to Rydberg energy of 10^{-35} J $\leftrightarrow 10^{-12}$ K
- Today $T \sim 10^{-9}$ K

Study of

- Quantum mechanics of the hydrogen atom on macroscopical scales (observation of states, transitions, Rydberg states, quantum-to-classical transition)
- Study of measurement process
- Gravitational atom
- Influence of nonlinearity



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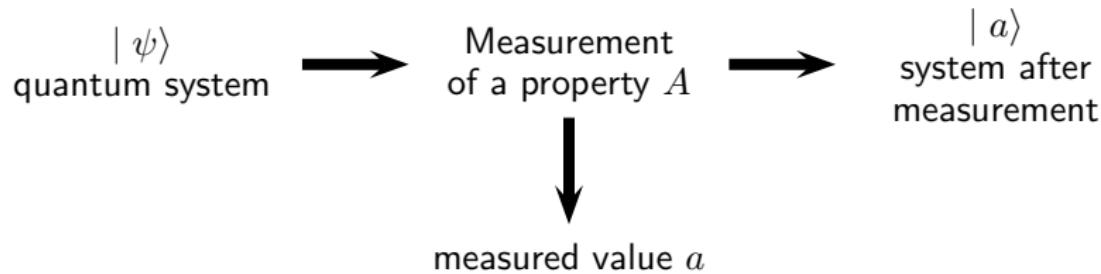
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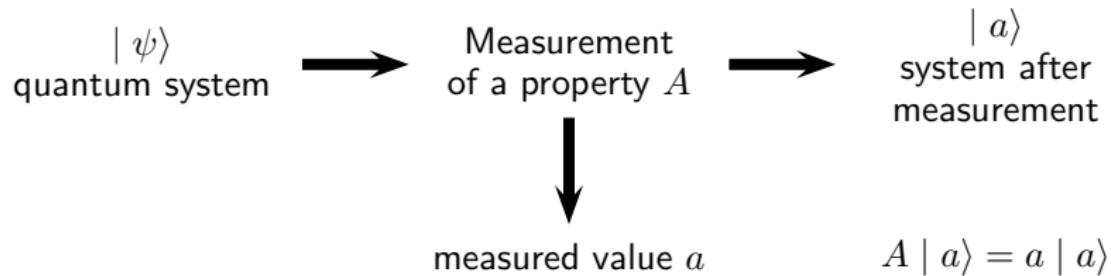
Self gravity

Problem: Quantum measurement problem



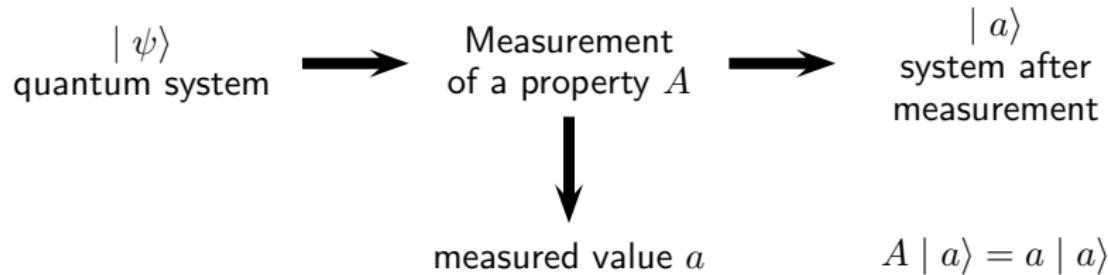
Self gravity

Problem: Quantum measurement problem



Self gravity

Problem: Quantum measurement problem



What is the state reduction $|\psi\rangle \rightarrow |a\rangle$

- Is it a formal mapping in Hilbert space? (Measurement postulate)
- Or does the reduction of the quantum state really occurs?

Self gravity in fluids

One idea (Penrose): Self gravity

- Standard interpretation: Schrödinger field \leftrightarrow particle \leftrightarrow no internal structure
- Quantum field interpreted as “fluid”: gravitational interaction between constituents
- Self–gravitating fluid:

$$0 = \dot{\rho} + \nabla(\rho v)$$

$$0 = \rho(\partial_t v + (v \cdot \nabla)v) + \frac{\rho}{m} \nabla U$$

$$\Delta U = 4\pi G\rho$$

Introduces additional **nonlinearity** and **nonlocality**

Self gravity in quantum systems

- Non-relativistic self gravity

$$i\hbar\dot{\psi} = -\frac{\hbar^2}{2m}\Delta\phi + mU\psi, \quad \Delta U = 4\pi G\bar{\psi}\psi$$

Newton–Schrödinger equations

- Relativistic self gravity (Boson stars)

$$0 = \square\psi + m^2\psi + V(\psi), \quad R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \kappa T_{\mu\nu}(\psi)$$

Einstein–Klein-Gordon equations

Is beyond standard quantum theory!

Gives coupling between G and \hbar characteristic for Quantum Gravity

Self gravity in quantum systems

First remarks and questions:

- Do such objects really exist? Are there solutions of these equations?
 - Spherically symmetric solutions
 - Axially symmetric solutions
 - Solutions stable?
- Nonlinearity: no dispersion – one single solution
- After measurement (= interaction of two systems) there also should be one single state: **realization of state reduction**
- Dynamical behaviour of such solutions? Superposition? Limit of standard quantum mechanics?

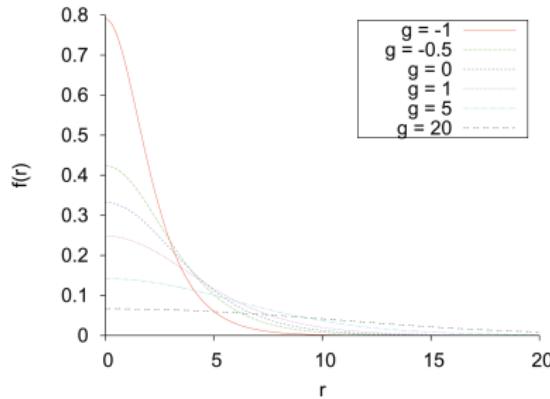
For BECs in microgravity with long evolution time:

- Experimental realization of self–gravitating BECs (needs high density)
 - Spherically symmetric configurations
 - Rotating configurations
- Interference of two self–gravitating objects: dynamical problem — should reflect the measurement process

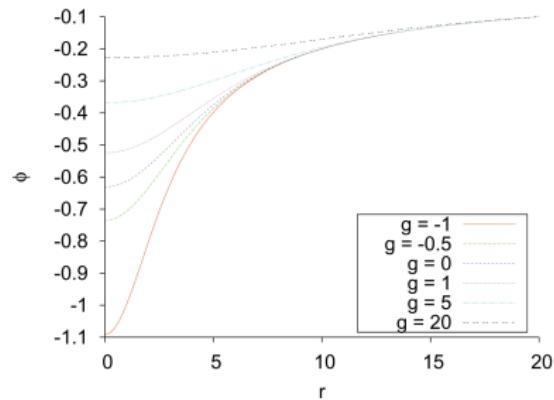


Self gravity in quantum systems

Schroven, bachelor thesis 2011, Chavenais, PRD 2011: Solutions for self-gravitating BECs exist (numerical)



wave function



gravitational potential

Work in progress: states for different discrete energy eigenvalues, rotating self-gravitating BECs (quantum analogues of rotating Lichtenberg's "figures of equilibrium" = ideal fluid stars)

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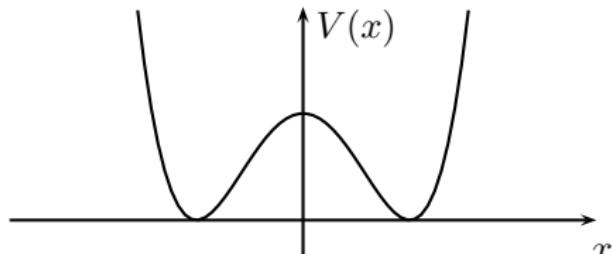
6 Summary and Outlook

Semiclassical Einstein equations

Semiclassical Einstein equations

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \kappa \langle \psi | \hat{T}_{\mu\nu} | \psi \rangle$$

Symmetrized and antisymmetrized states in double-well potential



$$| \psi_{\pm} \rangle = \frac{1}{\sqrt{2}} (| \psi_1 \rangle \pm | \psi_2 \rangle)$$

- Symmetrized and antisymmetrized states have same spatial density
 $\| |\psi_+\rangle \| = \| |\psi_-\rangle \|$
- Symmetrized and antisymmetrized states create different gravitational field:
 $\langle \psi_+ | \hat{T}_{\mu\nu} | \psi_+ \rangle \neq \langle \psi_- | \hat{T}_{\mu\nu} | \psi_- \rangle$
- Gravitational field can be probed by slow atoms ($v \sim 1 \text{ mm/s}$)

(Peres & Lindner, PRA 2004, Castin & Weiss, PRL 2008)

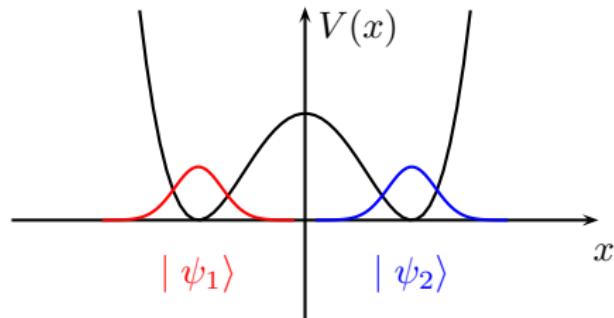
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• Modified dispersion relations

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6 Summary and Outlook

Modified dispersion relations

dispersion relation = energy–momentum relation = frequency–wave vector relation

$$E = E(p)$$

- standard non-relativistic dispersion relation

$$E = \frac{p^2}{2m}$$

- standard relativistic dispersion relation

$$E = \sqrt{m^2 c^4 + p^2 c^2} = mc^2 + \frac{p^2}{2m} + \dots$$

- modified dispersion relation

$$E^2 = m^2 c^4 + p^2 c^2 + e(p) \quad \Leftrightarrow \quad E = mc^2 + \frac{p^2}{2m} + e'(p) + \dots$$

linear effects : large for small $p \leftrightarrow$ low temperatures



Atom interferometry with modified dispersion relation

recoil shift for quantum system described by Hamiltonian H

$$\delta\phi = \frac{1}{\hbar} (H(p + \hbar k) - H(p)) \Delta t = \frac{1}{\hbar} (H(\hbar k) + h(\hbar k, p)) \Delta t$$

polynomial Hamiltonian

$$H(p) = mc^2 + \frac{p^2}{2m} + \frac{1}{2m_{\text{Pl}}} \left(\xi_1 mcp + \xi_2 p^2 + \xi_3 \frac{p^3}{mc} + \dots \right)$$

recoil shift

$$\delta\phi = \underbrace{\left(\frac{\hbar k^2}{2m} + \xi_1 \frac{mck}{2m_{\text{Pl}}} \right) \Delta t}_{\text{recoil shift}} + \underbrace{\left(1 + 2\xi_2 \frac{m}{m_{\text{Pl}}} + \frac{3}{2} \xi_3 \frac{p}{m_{\text{Pl}}c} \right) \frac{pk}{m} \Delta t}_{\text{Doppler shift}}$$

reanalysis of experiment $\xi_1 \leq 10$ and $\xi_2 \leq 10^9$

Amelino-Camelia, C.L., Mercati & Tino, PRL 2009
 also Amelino-Camelia & C.L., CQG 2004



BEC with modified dispersion relation

Polynomial dispersion relation

- MDR

$$E = \frac{p^2}{2m} + \eta \frac{p^4}{4m^2 E_{\text{QG}}} + \dots,$$

- equation of state

$$\frac{p}{kT} = \frac{1}{\lambda^3} \left(g_{\frac{5}{2}}(z) - \frac{15}{8} \eta \frac{kT}{E_{\text{QG}}} g_{\frac{7}{2}}(z) \right)$$

$$\frac{N - N_0}{V} = \frac{1}{\lambda^3} \left(g_{\frac{3}{2}}(z) - \frac{15}{8} \eta \frac{kT}{E_{\text{QG}}} g_{\frac{5}{2}}(z) \right)$$

- BEC exists, modified critical temperature

$$T_c = \frac{\hbar^2}{2\pi m k} \left(\frac{N}{V \zeta(\frac{3}{2})} \right)^{\frac{2}{3}} \left(1 + \frac{5}{4} \eta \frac{k}{E_{\text{QG}}} \frac{\zeta(\frac{5}{2})}{\zeta(\frac{3}{2})} \frac{\hbar^2}{2\pi m k} \left(\frac{N}{V \zeta(\frac{3}{2})} \right)^{\frac{2}{3}} \right)$$

BEC with modified dispersion relation

Polynomial dispersion relation with linear term

- MDR

$$E = \eta p + \frac{p^2}{2m} + \dots$$

- equation of state (for rectangular trap)

$$\begin{aligned}\frac{p}{kT} &= \frac{1}{\lambda^3} g_{\frac{5}{2}}(z) \pm kT \left(\frac{2m}{h^2}\right)^{\frac{3}{2}} \sqrt{2m} \eta g_2(z) \\ \frac{N - N_0}{V} &= \frac{1}{\lambda^3} g_{\frac{3}{2}}(z) \mp kT \frac{2}{h^3} \sqrt{2m} \eta g_1(z)\end{aligned}$$

since $g_1(z) = \ln(1 - z)$ not bound for $z \rightarrow 1$: no BEC

can this really rule out linear terms?



BEC with modified dispersion relation

Polynomial dispersion relation with linear term

- MDR

$$E = \eta p + \frac{p^2}{2m} + \dots$$

- for harmonic trap and small number of atoms (Grossmann & Holthaus, PLA 1995; Haugerud, Haugset & Ravidal, PLA 1997)

$$N - N_0 = \left(\frac{kT}{\hbar\omega} \right)^3 g_3(z) + \frac{3}{2} \left(\frac{kT}{\hbar\omega} \right)^2 \left(1 + \frac{1}{3} \frac{m\eta^2}{\hbar\omega} \right) g_2(z) + \frac{3}{4} \frac{kT}{m\hbar\omega} \frac{\eta^2}{\hbar\omega} g_1(z)$$

since $g_1(z)$ not bound for $z \rightarrow 1$: no BEC

can this really rule out linear terms?

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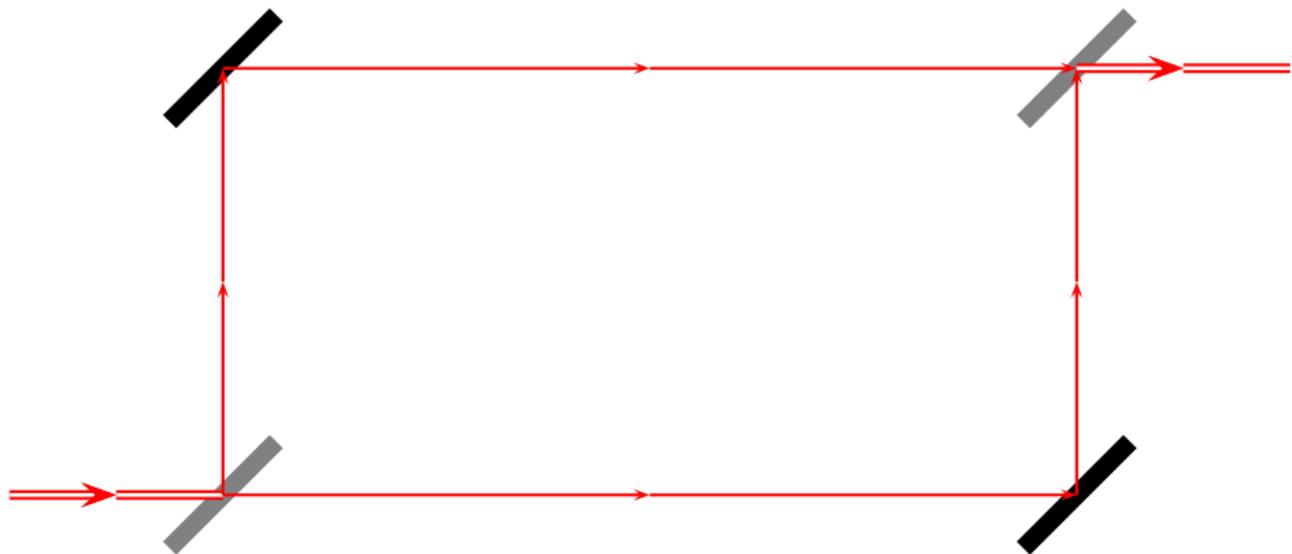
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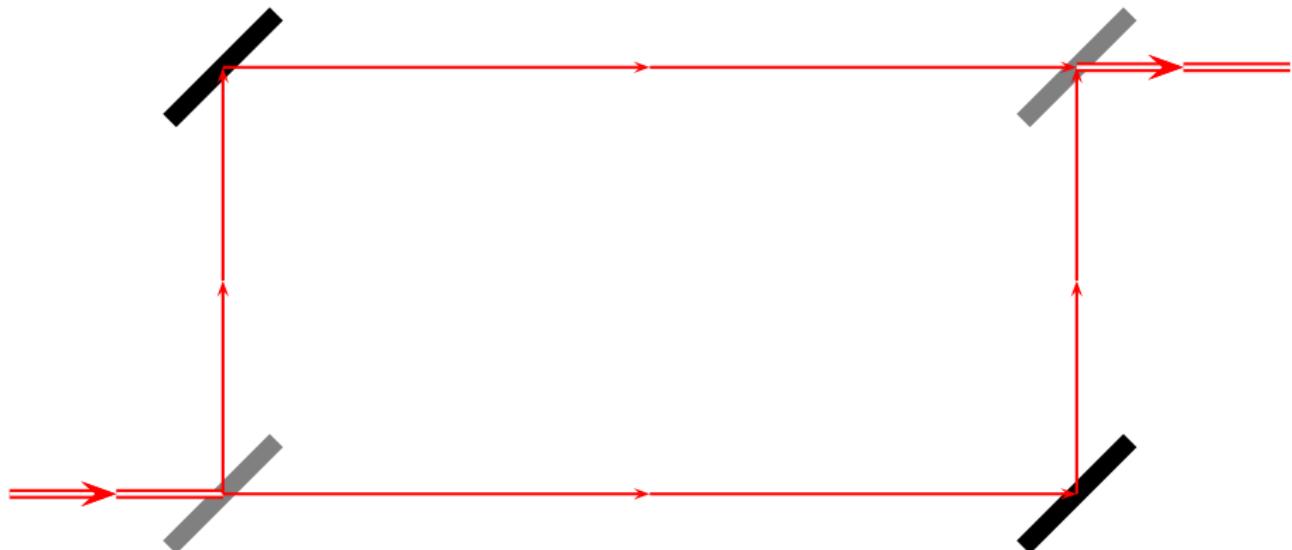
5 On redshift experiments

6 Summary and Outlook

The redshift in neutron and atomic interferometry



The redshift in neutron and atomic interferometry



$$\omega_{\text{Compton}} = \frac{mc^2}{\hbar}$$

The redshift in neutron and atomic interferometry



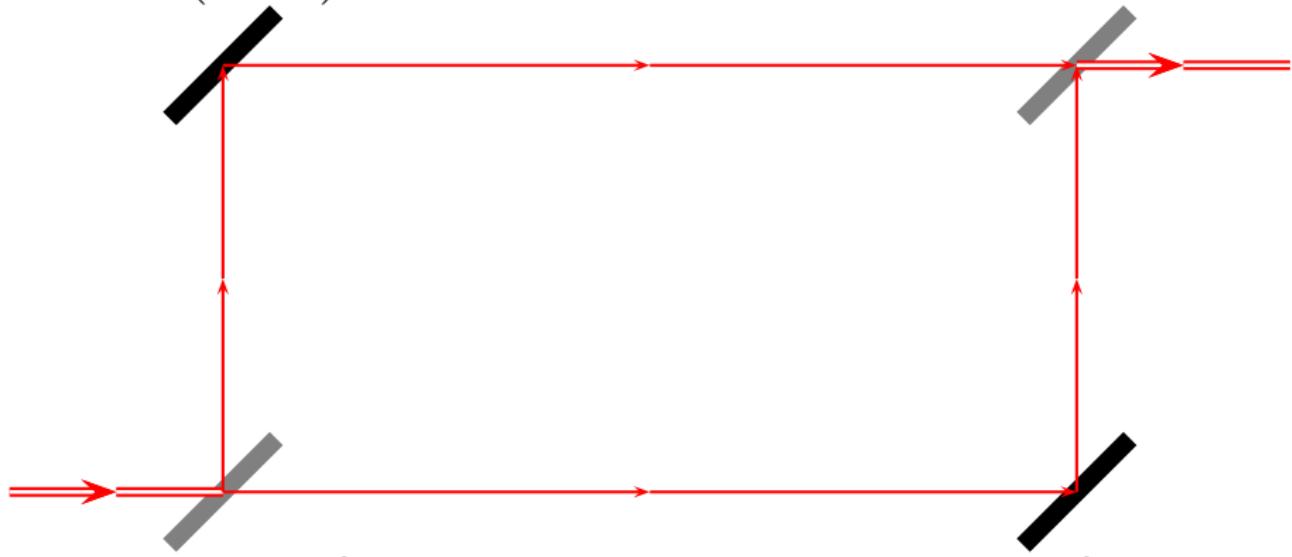
$$\omega_{\text{Compton}} = \frac{mc^2}{\hbar}$$

$$\frac{mc^2}{\hbar} T$$



The redshift in neutron and atomic interferometry

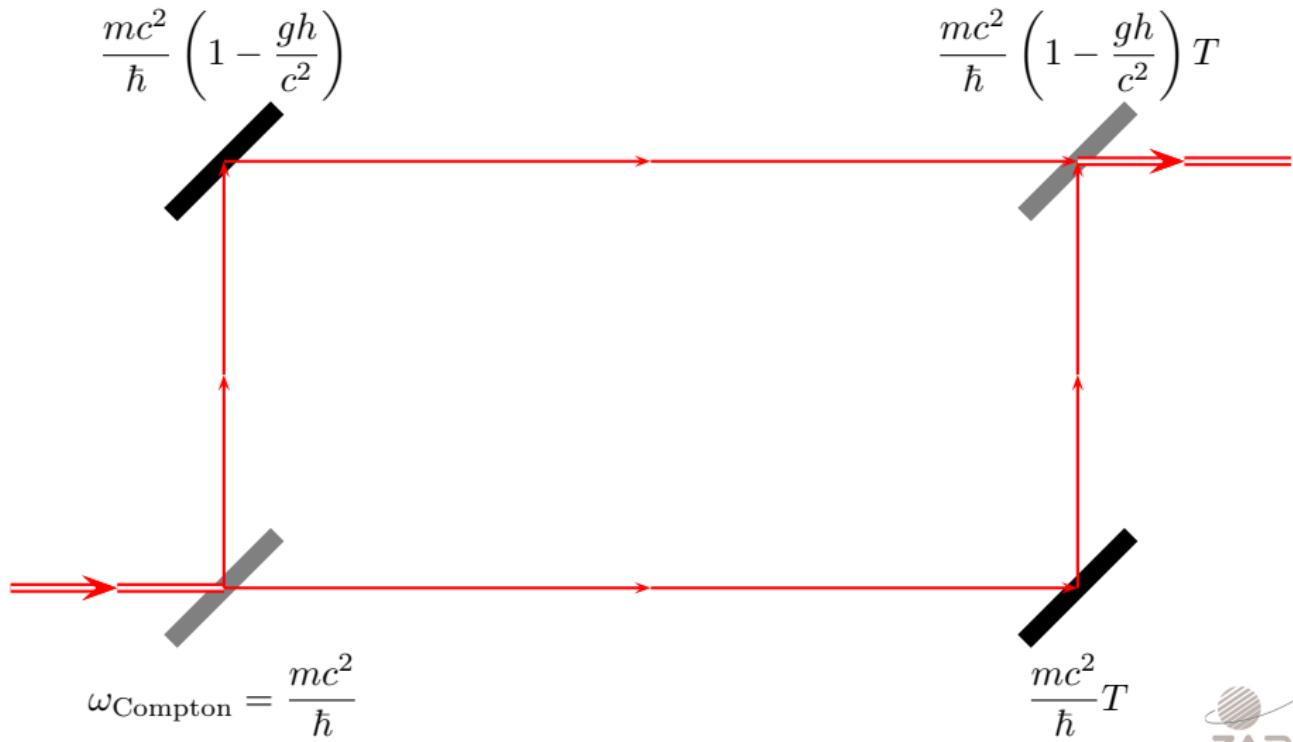
$$\frac{mc^2}{\hbar} \left(1 - \frac{gh}{c^2} \right)$$



$$\omega_{\text{Compton}} = \frac{mc^2}{\hbar}$$

$$\frac{mc^2}{\hbar} T$$

The redshift in neutron and atomic interferometry



The redshift in neutron and atomic interferometry

Phase difference

$$\delta\phi = \frac{mc^2}{\hbar} \left(1 - \frac{gh}{c^2}\right) T - \frac{mc^2}{\hbar} T = -\frac{mc^2}{\hbar} \frac{gh}{c^2} T$$

height given by

$$h = \Delta v \quad T' = \frac{\hbar k}{m} T'$$

then

$$\delta\phi = -kgTT' \stackrel{*}{=} -gkT^2$$

The redshift in neutron and atomic interferometry

Phase difference

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height given by – or T given by

$$h = \Delta v \quad T' = \frac{\hbar k}{m} T' \quad \text{or} \quad T = \frac{l}{v}$$

then

$$\delta\phi = -kgTT' \stackrel{*}{=} -gkT^2 \quad \text{or} \quad \delta\phi = -\frac{mghl}{\hbar v}$$

The redshift in neutron and atomic interferometry

Phase difference

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then

$$\delta\phi = -kgTT' \stackrel{*}{=} -gkT^2 \quad \text{or} \quad \delta\phi = -\frac{mghl}{\hbar v}$$

Same result from

$$i\hbar\partial_t\psi = -\frac{\hbar^2}{2m}\Delta\psi - m\mathbf{g} \cdot \mathbf{x}\psi$$

and plane wave ansatz, Fourier, π - and $\frac{\pi}{2}$ -pulses, ... , exact result

The redshift in neutron and atomic interferometry

- ω_{Compton} is no clock
- k no wave vector related to ω_{Compton}
- ω_{Compton} is related to an atom or molecule or (operational?)
- two ways to derive the effect:
 - needs c "in between"
 - no c needed: simpler theory
- reasoning does not depend on the various contributions to the phase shift

The redshift in neutron and atomic interferometry

- with modified redshift $1 + \frac{\Delta U}{c^2} \rightarrow 1 + \kappa \frac{\Delta U}{c^2}$
- usually κ depends on used clock (Hg, H, Cs, ...) (has to be calculated)
- our κ couples / is related to ω_{Compton} (**but is no clock !!!**)
- implies $g \rightarrow \kappa g$
- phase shift

$$\delta\phi = -\kappa g k T^2$$

- phase shift for testing the equality of m_i and m_g

$$\delta\phi = -\frac{m_g}{m_i} g k T^2$$

- accuracies
 - redshift experiments $|\kappa| \leq 10^{-5}$
 - UFF experiments $\left| \frac{m_g}{m_i} \right| \leq 10^{-9}$ or 10^{-13}
- ⇒ UFF experiments constrain κ better than UGR experiments

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Summary

- There are many gravity related experiments for cold atom benefiting from microgravity
- New parameter range not accessible in Earth bound lab
- Drop tower, rocket, ISS, spacecraft
- Many experiments in fundamental physics

Outlook

- Working on these ideas
 - Finding analytical solutions
 - Numerical solutions
 - Investigating better experiments
- Developing new ideas
 - Simulations of black holes (analogue gravity)
 - Simulation of Hawking radiation
 - Testing Newton's laws (order of equation of motion, actio = reactio, active and passive charge/mass)
 - Finsler geometry and temperature-dependent violation of UFF
- Practical applications
 - Geodesy
 - Clocks in space (Timing formula)
- Proposal STE–QUEST

The end

Thank you

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- Center of excellence QUEST

