

Title: Possible strategies for the search for quantum gravity induced effects

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Abstract: We investigate the abstract features of the abstract, and find an abstractly abstracted abstract. We investigate the abstract features of the abstract, and find an abstractly abstracted abstract. We investigate the abstract features of the abstract, and find an abstractly abstracted abstract. We investigate the abstract features of the abstract, and find an abstractly abstracted abstract.

# The need for experiments

Today's standard theories and standard space-time notion as derived from observations of 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"><li>• Incompatibility of quantum theory and General Relativity</li><li>• Problem of time</li><li>• Occurrence of singularities</li></ul>	Unification of all interactions

Need of modifications of standard theories, but standard theories derived from observations  
⇒ need for domain of experience, observations,  
measurements

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# Outline

## ① The situation of standard physics

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- 1 The situation of standard physics
- 2 The search for Quantum Gravity effects: General remarks

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  - The generalized Dirac equation
  - LLI and UFF
  - Tests of basic principles
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  - Active and passive charges
  - Test of standard Maxwell equations

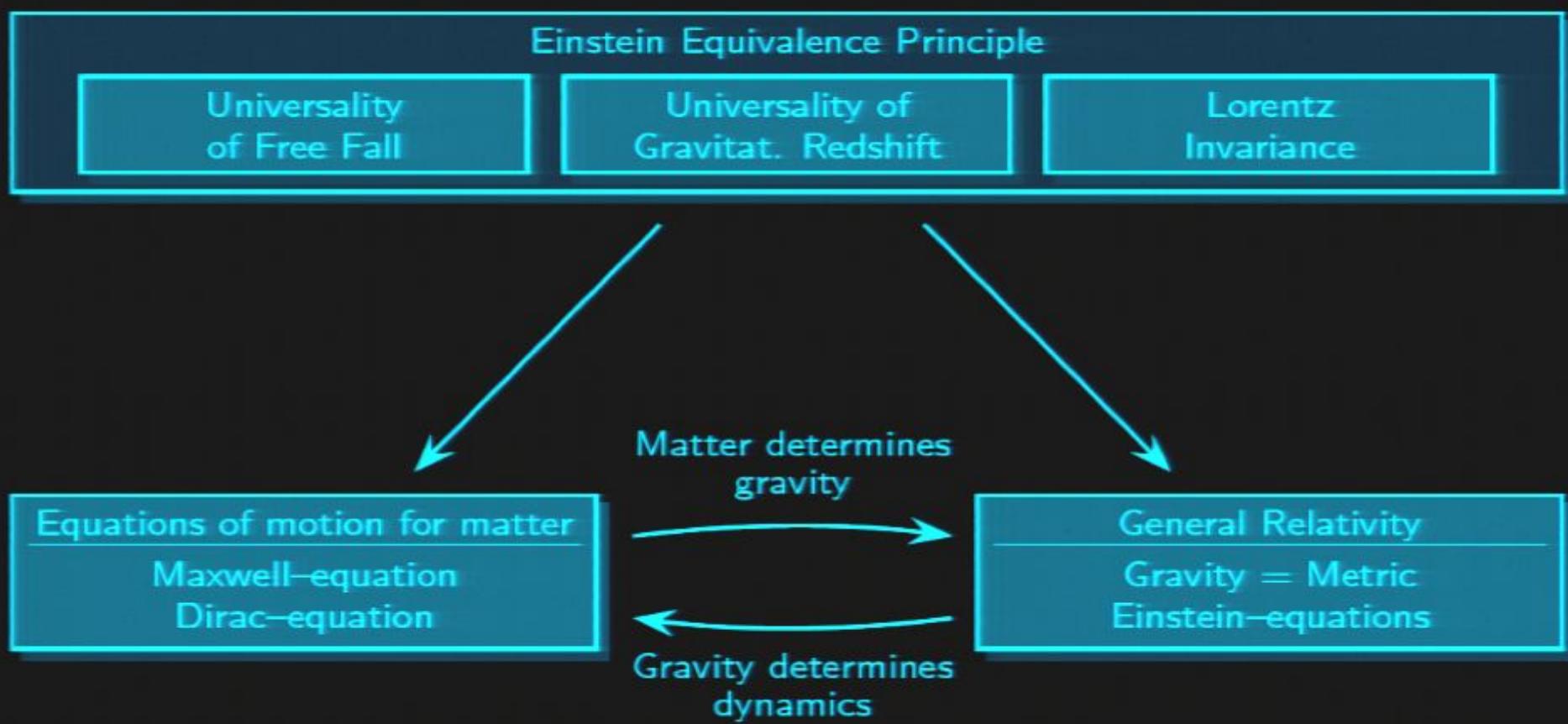
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# Structure of standard physics



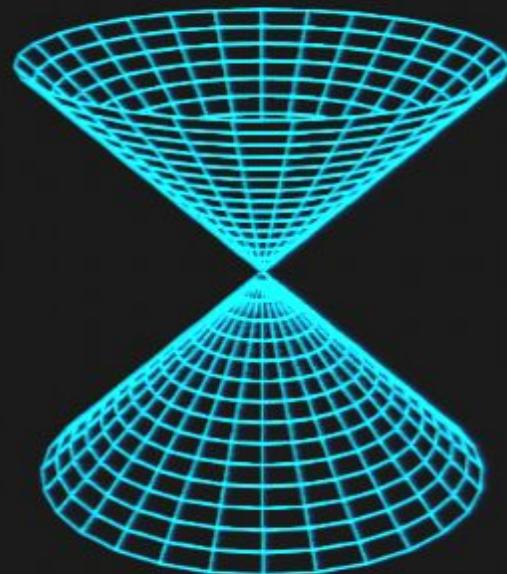
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All aspects of Lorentz invariance are experimentally well tested and confirmed

## Foundations

## Postulates

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



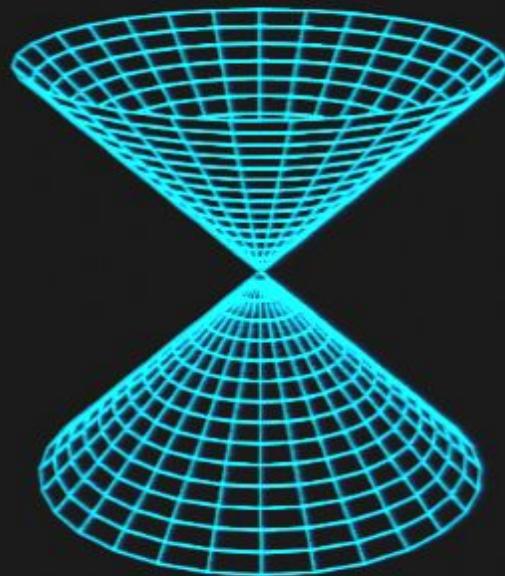
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## Tests

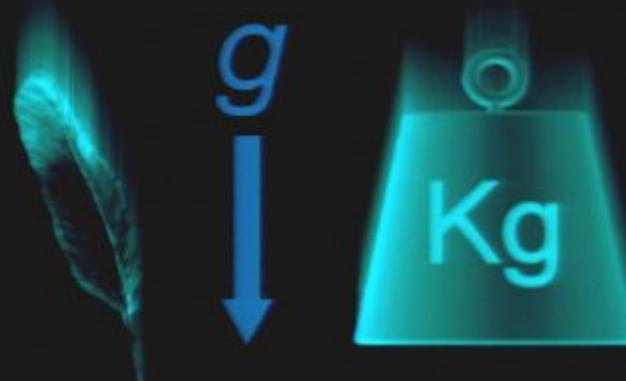
- Independence of  $c$  from velocity of the source
- Universality of  $c$
- Isotropy of  $c$
- Independence of  $c$  from velocity of the laboratory
- Time dilation
- Isotropy of physics (Hughes–Drever experiments)
- Independence of physics from the velocity of the laboratory

# The present situation

Many aspects of the Universality of Free Fall are experimentally well tested and confirmed

## Postulate

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

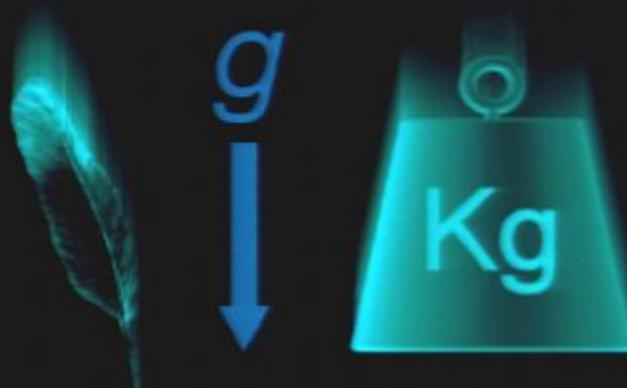


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## Tests

UFF for

- Neutral bulk matter
- Charged particles
- Particles with spin

No test so far for

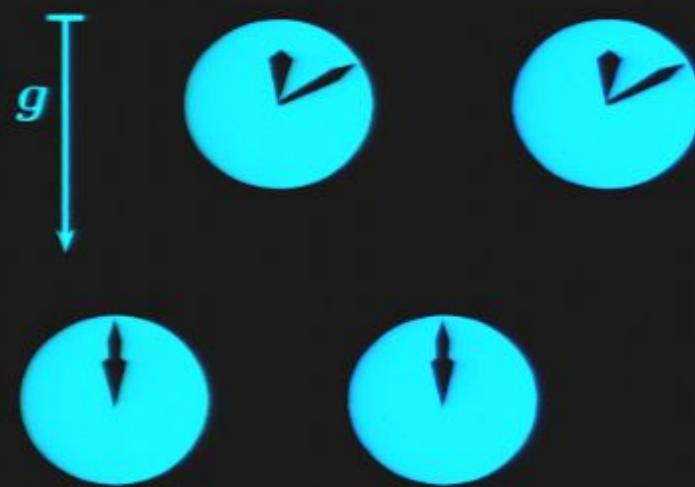
- Anti particles

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Many aspects of the Universality of the Gravitational Redshift are experimentally well tested and confirmed

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In a gravitational field all clocks behave in the same way

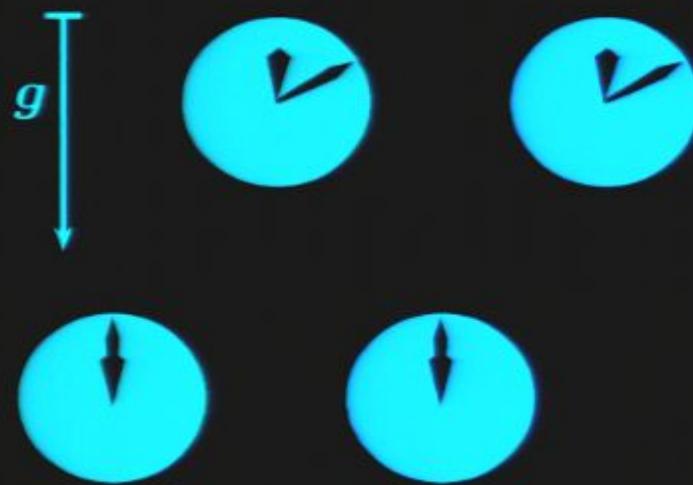


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## Tests

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 Einstein Equivalence Principle

Point particle

# The Einstein Equivalence Principle



# The Einstein Equivalence Principle

Point particle

EEP

Geodesic equation  
in Riemann space 1

Spin-1/2 particle

# The Einstein Equivalence Principle

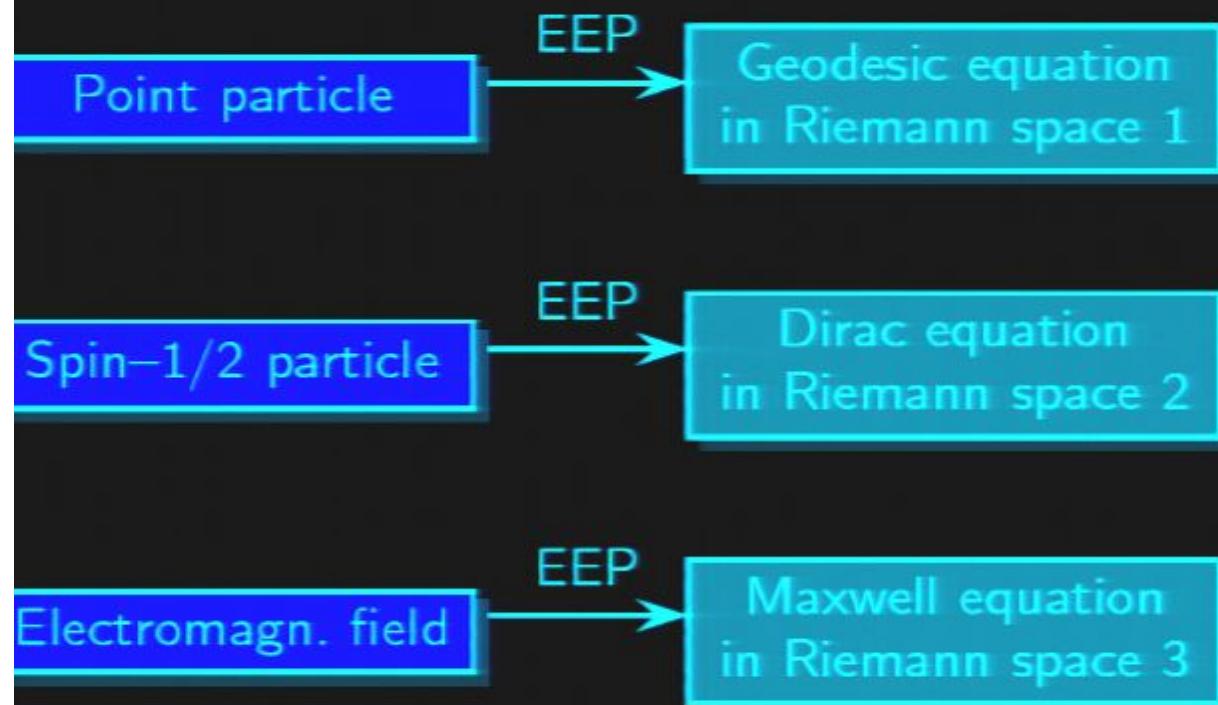


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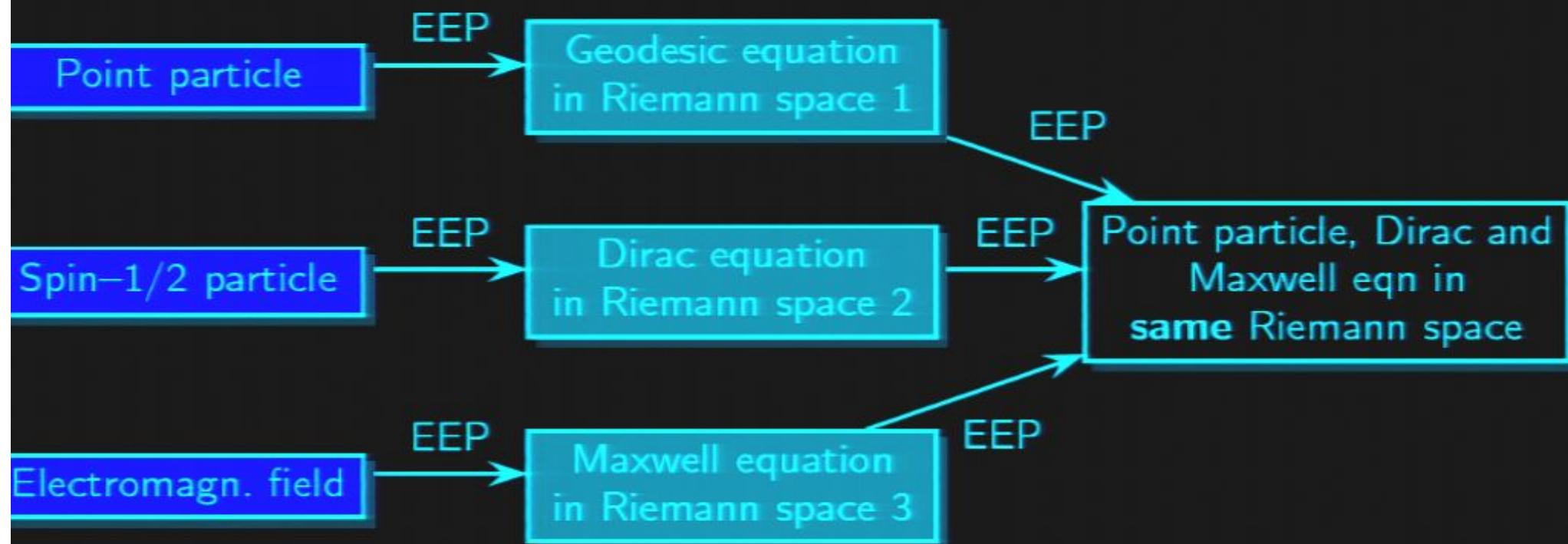


Electromagn. field

# The Einstein Equivalence Principle



# The Einstein Equivalence Principle



# The present situation

All predictions of Einstein's 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



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## Implication

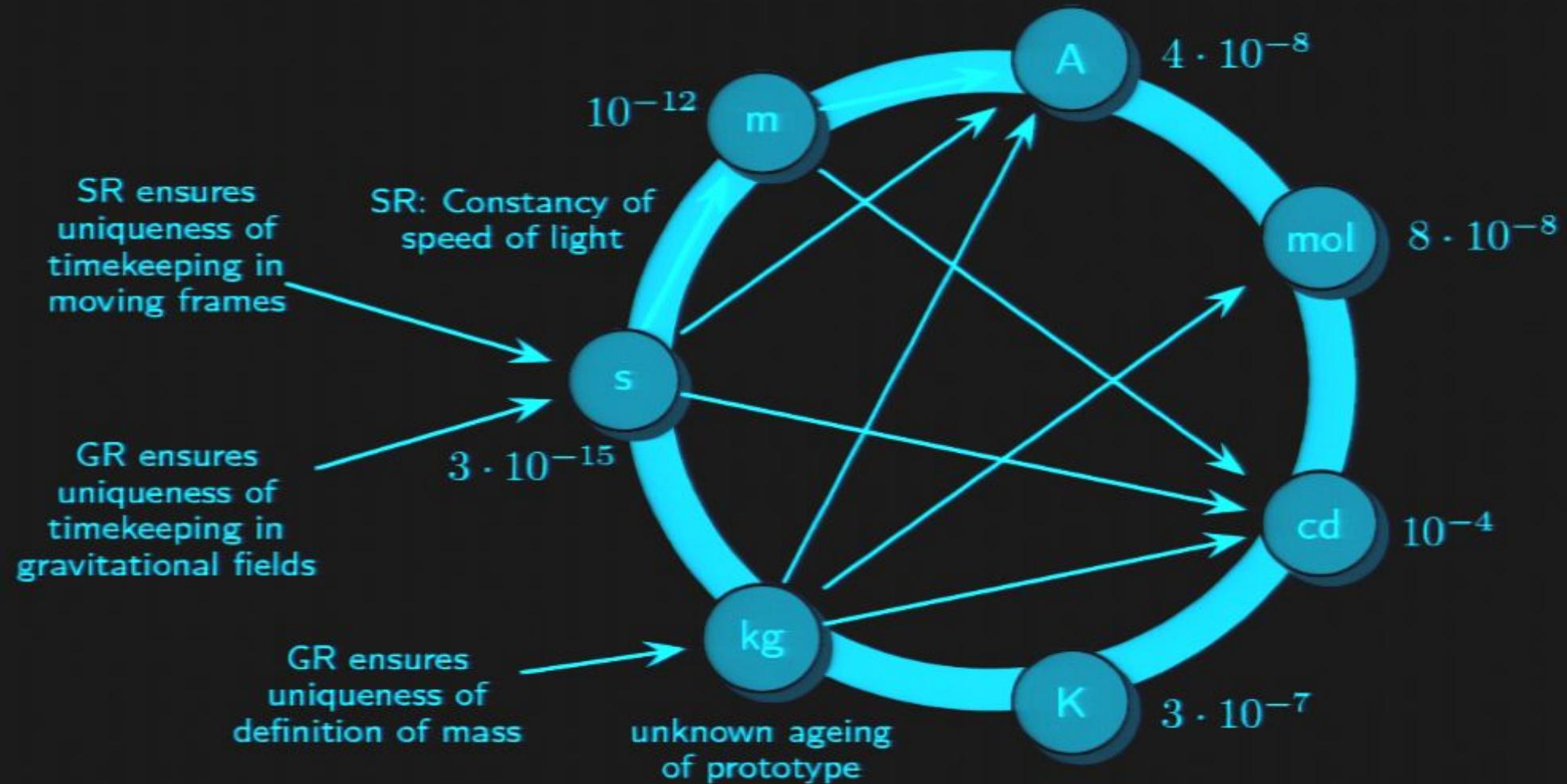
Gravity is a metrical theory



## 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
- Cosmology

# Application: Metrology





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## Implications of a new theory

Unresolved fundamental inconsistency

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

Ordinary modifications (on classical level)

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

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Other modifications (on 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 fundamental noise, decoherence, non-conserved probability, ...

(only later it might be useful to assign certain effects to space-time properties)

# Hierarchy of theories

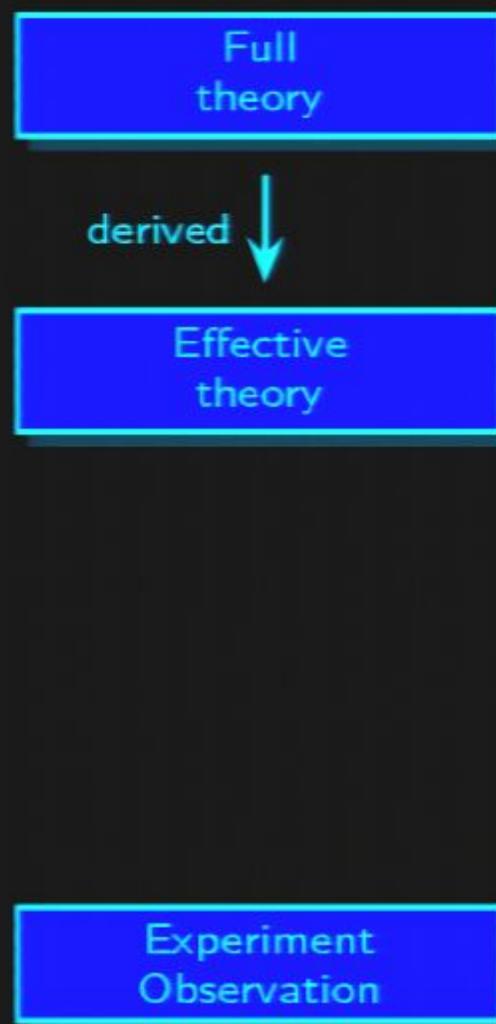
Full  
theory

Quantum Gravity

Experiment  
Observation

Clock readout  
Interference fringes  
acceleration  
counting events

# Hierarchy of theories

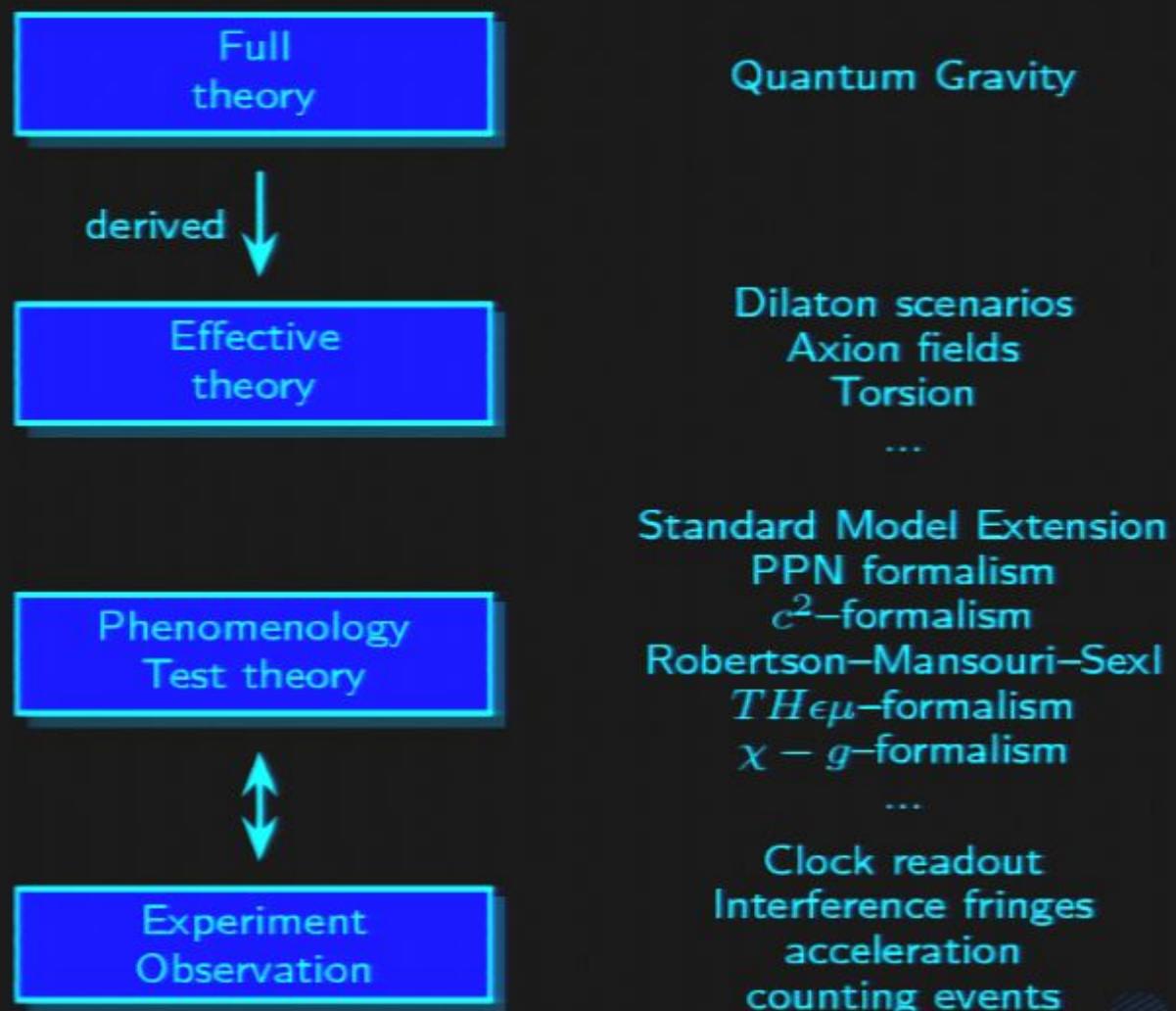


Quantum Gravity

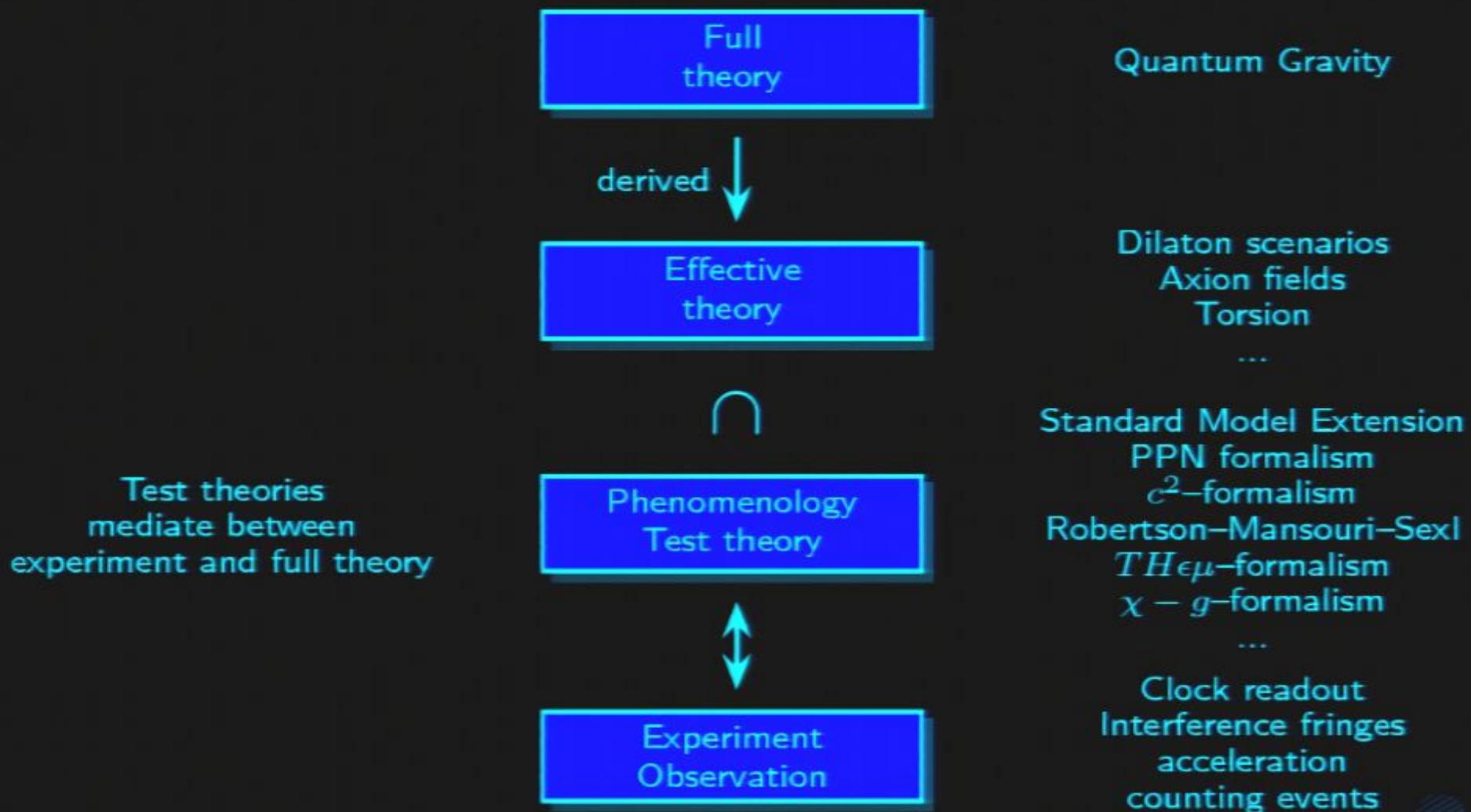
Dilaton scenarios  
Axion fields  
Torsion  
...

Clock readout  
Interference fringes  
acceleration  
counting events  
...

# Hierarchy of theories



# Hierarchy of theories



# The role of test theories

Test theories generalize specific “predictions”

## Noncommutative theory

- Noncommutativity → non-locality → higher derivatives in field equations → anomalous dispersion  
⇒ all implications of anomalous dispersion
- $[x^\mu, x^\nu] = i\theta^{\mu\nu}$  → preferred directions → violation of Lorentz invariance

## String theory

- Low energy limit → scalar-tensor theory → additional scalar field couples differently to various matter fields → violation of UUF, UGR  
⇒ general scalar tensor theories
- Scheme with symmetry breaking → breaking of Lorentz invariance

# The role of test theories

## Canonical/loop quantum gravity

- Fluctuating metric → non-unitary terms in effective Schrödinger equation  
⇒ general non-unitarity
- Fluctuating metric → anomalous inertial properties
- In quasiclassical limit higher order and non-linear terms appear  
⇒ general higher order theories ⇒ anomalous dispersion  
⇒ general non-linearities

Since there is no complete theory available (no mapping between theoretical notions and observed quantities), "predictions" can serve just as hints to the possible structure of effects

Examples ....

# Predictions from loop quantum gravity

## Modified Maxwell equations

Gambini & Pullin 1999

$$\begin{aligned}\partial_t \mathbf{E} &= -\nabla \times \mathbf{B} + 2\chi l_P \nabla^2 \mathbf{B} \\ \partial_t \mathbf{B} &= \nabla \times \mathbf{E} - 2\chi l_P \nabla^2 \mathbf{E}.\end{aligned}$$

Alfaro, Morales-Tecotl & Urrutia 2002

$$\begin{aligned}0 &= \nabla \times \mathbf{B} - \partial_t \mathbf{E} + \vartheta_1 \nabla \times \mathbf{B} + \vartheta_2 \Delta(\nabla \times \mathbf{B}) + \vartheta_3 \Delta \mathbf{B} + \vartheta_4 \nabla \times (B^2 \mathbf{B}) + \dots \\ 0 &= \nabla \times \mathbf{E} + \partial_t \mathbf{B} + \vartheta_1 \nabla \times \mathbf{E} + \vartheta_2 \Delta(\nabla \times \mathbf{E}) + \vartheta_3 \Delta \mathbf{E} + \dots,\end{aligned}$$

## Modified Dirac equation

Alfaro, Morales-Tecotl & Urrutia 2002

$$i\tilde{\gamma}^a \partial_a \psi - \tilde{m} \psi - \tilde{\gamma}^{ab} \partial_a \partial_b \psi = 0,$$

## Predictions from string theory

### Modified Maxwell equations

Ellis, Mavromatos & Nanopoulos 1999

$$\begin{aligned}\nabla \cdot \mathbf{E} + \bar{\mathbf{u}} \cdot \partial_t \mathbf{E} &= 0 & \nabla \cdot \mathbf{B} &= 0 \\ \nabla \times \mathbf{B} - (1 - \bar{u}^2) \partial_t \mathbf{E} + \bar{\mathbf{u}} \times \partial_t \mathbf{B} + (\bar{\mathbf{u}} \cdot \nabla) \mathbf{E} &= 0 & \nabla \times \mathbf{E} &= -\partial_t \mathbf{B},\end{aligned}$$

### Modified Dirac equation

Ellis et al 2000

$$i\gamma^a \partial_a \psi - \bar{u}^a \gamma^0 i \partial_a \psi - m \psi = 0$$

# 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)

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

$\varphi$  = dilaton field

$\varphi_0$  = 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:  $\gamma$ -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

$$\begin{aligned}\frac{\nu_{AA'}(r)}{\nu_{BB'}(r)} &= \frac{F(Z_A e^2(\varphi))}{F(Z_B e^2(\varphi))} \\ \delta \ln e^2 &= -2.5 \cdot 10^{-2} \alpha_{\text{had}}^2 \delta U(t) - 4.7 \cdot 10^{-3} \alpha_{\text{had}}^2 H_0 \delta t\end{aligned}$$

# "Predictions"

Effect	dilaton	cosmon	varying $e$
UFF — $\eta$	$10^{-13}$	$10^{-14}$	$< 10^{-13}$
UGR	$10^{-18}$	$10^{-18}$	
PPN — $\gamma$	$10^{-5}$		
PPN — $\beta$	$10^{-9}$		
$\dot{\alpha}/\alpha$	$10^{-21} \text{ y}^{-1}$		

Damour and Polyakov 1994, Damour, Piazza, and Veneziano 2002

Wetterich 2002, 2003

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Sandwick et al 2000

## On the present status of "predictions"

- Specific predictions are not important
- "Predictions" open the door to a whole range of effects
- Then test theories take over the description of experiments

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# Test theories

## Further reasons for using test theories

- Parametrization and identification of possible violation
- Quantification of degree of validity
- Different (!) experiments can be compared

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## Dynamical test theories

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|---------------------------|-------------------------|
| • $c^2$ –formalism        | 1 parameter             |
| • $\chi - g$ –formalism   | 19 parameter            |
| • Extended Standard Model | $19 + n_{48}$ parameter |
| • PPN–formalism           | 10 parameter            |

One needs as many tests as there are parameters



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### Dynamical test theories are superior

# Test theories, Phenomenology

Phenomenology = Generalizations of Maxwell and Dirac equations

$$4\pi j^\mu = \eta^{\mu\rho}\eta^{\nu\sigma}\partial_\nu F_{\rho\sigma}$$

$$0 = i\gamma^a D_a \psi + m\psi$$

with

$$\gamma^a \gamma^b + \gamma^b \gamma^a = 2\eta^{ab}$$

- Standard equations

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with

$$\gamma^a \gamma^b + \gamma^b \gamma^a = 2\eta^{ab} +$$

- Standard equations
- Particular case: Standard Model Extension
- More general cases with charge non-conservation  $\dot{Q} \neq 0 \leftrightarrow \dot{\alpha} \neq 0$
- Higher derivative models

# Possible effects

## Possible geometry relevant effects

- Anisotropic speed of light
- Anisotropy in quantum fields
- Violation of UFF, UGR
- Birefringence
- Anomalous spin-coupling
- Anomalous coupling of charge
- Anomalous dispersion
- Newton / Coulomb potential
- Nonlinearities
- Charge non-conservation
- Active – passive mass and charge

## Other possible effects

- Decoherence
- Modified interference
- Non-localities
- Non-unitarity

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## Structure of parameters

- Usually: parameters are assumed to be constant
- In unification scenarios: parameters depend on time and position, through one or more fields (dilaton, cosmon) → scalar-tensor theories

# The magnitude of Quantum Gravity effects

Typical laboratory energies  $\sim 1$  eV  
QG energy scale  $\sim E_{\text{Planck}} \sim 10^{28}$  eV }  $\Rightarrow$  Expectation:  
QG effects in laboratory  $\sim 10^{-28}$

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- $E_{\text{QG}} \sim E_{\text{Planck}}$  is just a hypothesis until now,  $E_{\text{QG}}$  might be smaller
  - QG effects in “large extra dimensions”: deviations from Newton’s law
  - String-theory-motivated “dilaton scenarios” (DPV 2002): UFF may be violated at  $10^{-13}$  level, and  $|\gamma - 1| \sim 10^{-5}$
  - Low-energy data suggest that electroweak and strong interactions unify at GUT energy scale of  $\sim 10^{16}$  GeV, perhaps also gravity would be of the same strength as the other interactions at that scale

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  - Sensitivity of some clock–comparison experiments is amplified by  $m_p c^2/(h\nu) \sim 10^{18}$  ( $\nu = \text{clock frequency}$ ,  $m_p = \text{the proton mass}$ )

# The magnitude of Quantum Gravity effects

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- Some laboratory experiments (grav. wave interferometers) may reach  $10^{-28}$

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Comparison: high energy cosmic ray observation  $\leftrightarrow$  low energy laboratory exp.



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Standard physics experimentally well proven for standard energy, velocity, distance, ...

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- Dark energy, dark matter, Pioneer anomaly related to large distances
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Extreme long timescales:

- Search for space-time fluctuations in terms of  $1/f$ -noise
- Time dependence of constants

Extreme short timescales. Short time scales  $\leftrightarrow$  large energies

# First BEC in microgravity / extended free fall



Campus of University of Bremen



# First BEC in microgravity / extended free fall



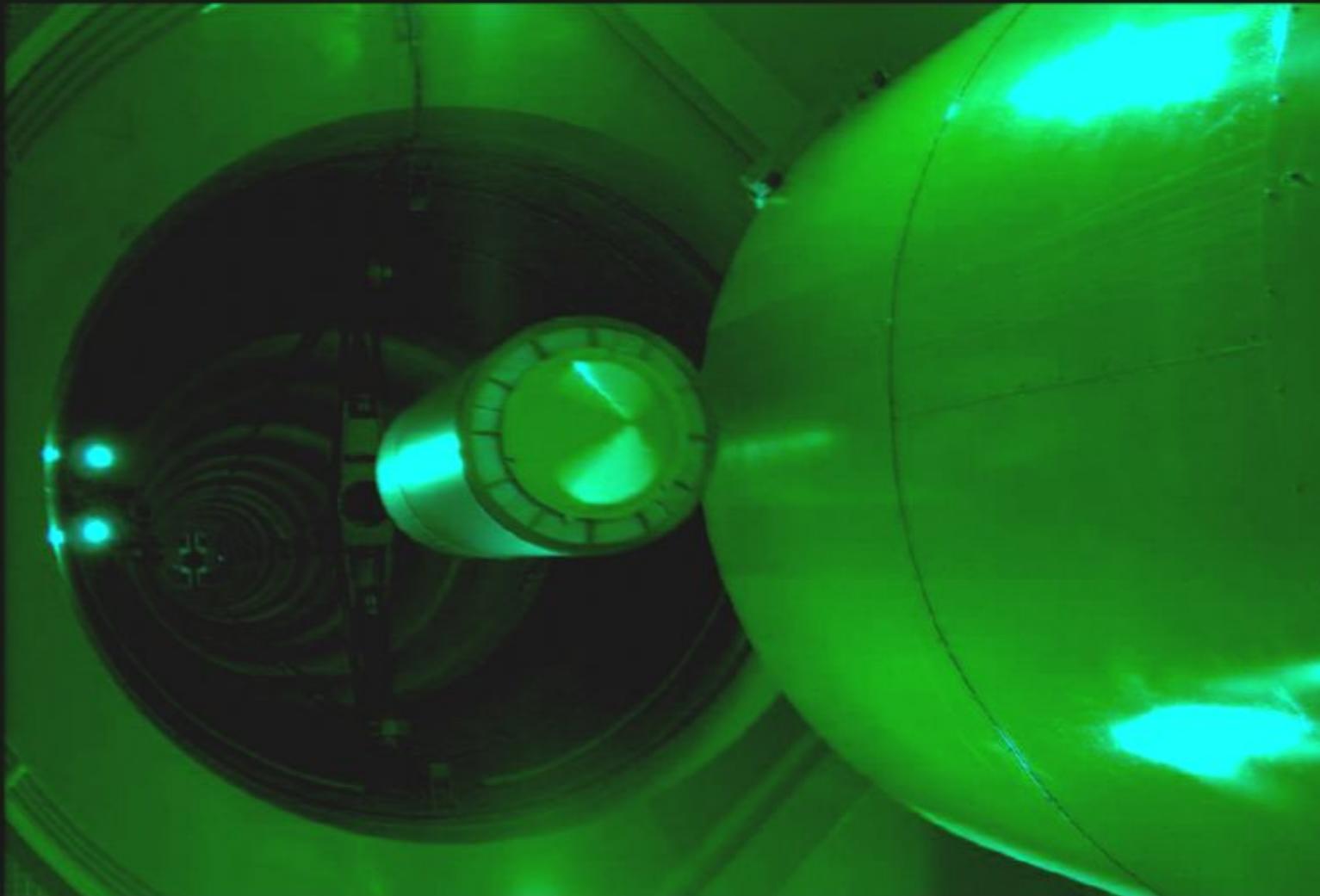
Tower 146 m

drop tube  
110 m

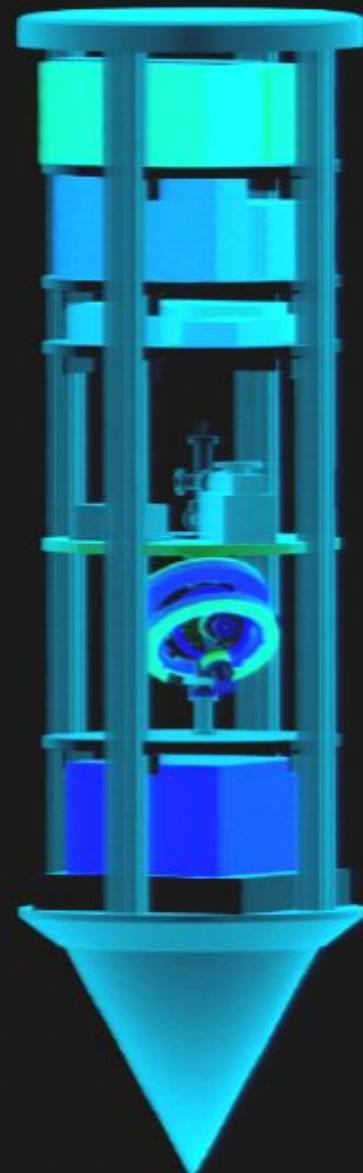
free fall time  
= 4.7 s

deceleration  
 $\sim 30\ g$

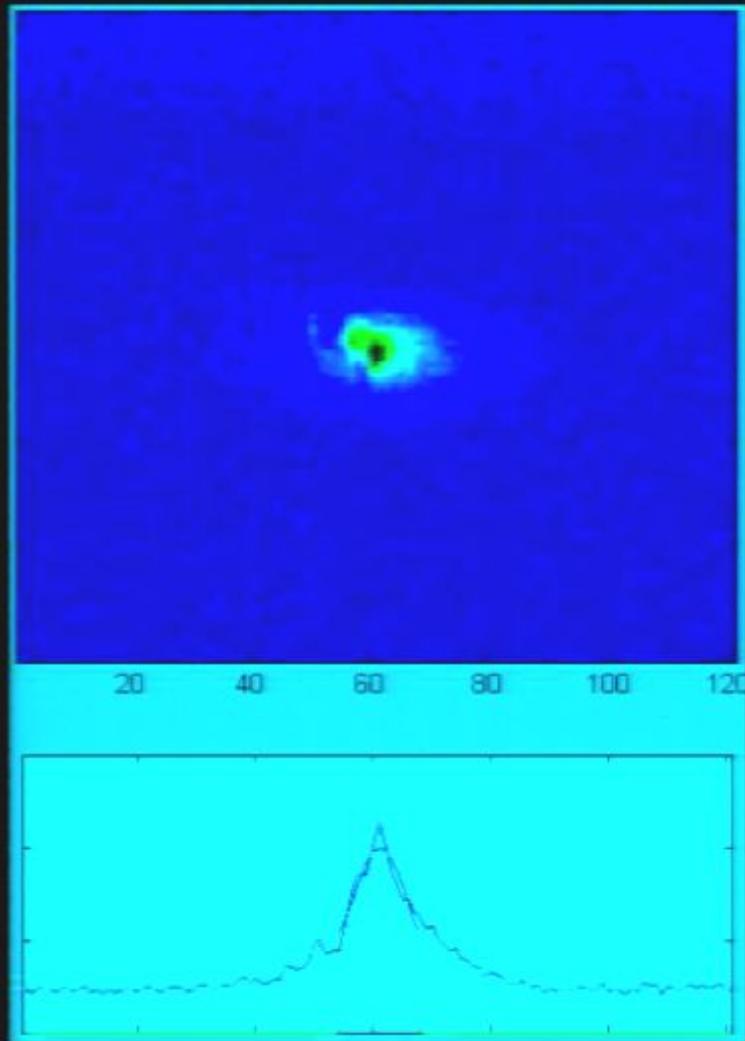
## First BEC in microgravity / extended free fall



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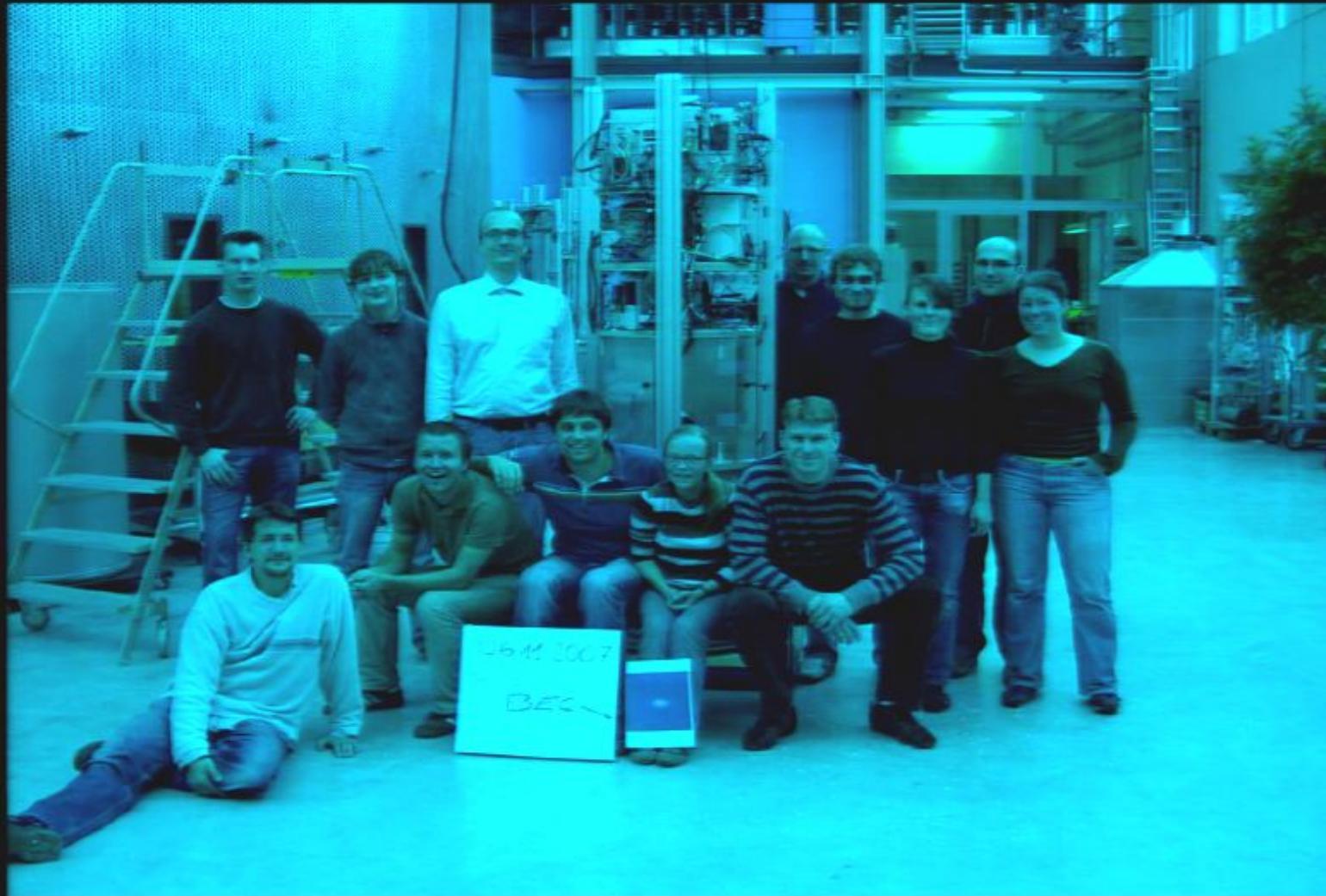
## First BEC in microgravity / extended free fall



BEC in free fall may become colder than today's 500 fK (Ketterle)

aim 1 fK

# First BEC in microgravity / extended free fall



## What is a violation of EEP, what is a QG effect?

Assume we observe a new effect which is not included present standard theory

- if the effect can be shielded  $\Rightarrow$  new interaction and no geometry, no gravity
- if the effect is universal w.r.t. mass or spin  $\Rightarrow$  part of geometry  $\Rightarrow$  modified space-time property, modified gravity
- identification of part of geometry difficult. Example: torsion

### Violation of LLI

- Finsler metric (difficult to obtain with present particles – needs more complicated structure)
- LLI violation usually through bi-metric theory (metric for Maxwell, metric for Dirac)

### Violation of UFF

- only charged particles, always electromagnetic fields: one never can observe UFF, it is only in the equations
- apparent violation in scalar-tensor theories: no violation at fundamental level, always violation at observational level. Question: uniqueness of description at fundamental level?

# Outline

- 1 The situation of standard physics
- 2 The search for Quantum Gravity effects: General remarks
- 3 Tests of Lorentz invariance
- 4 Tests of General Relativity
- 5 Tests of the matter sector / Test of Quantum Theory
  - The generalized Dirac equation
  - LLI and UFF
  - Tests of basic principles
  - Space-time fluctuations
- 6 Photon sector
  - Tests of basic principles
  - Space-time fluctuations
  - Active and passive charges
  - Test of standard Maxwell equations
- 7 Unexplained observations
- 8 Conclusion and outlook

# Postulates

## Postulates of SR

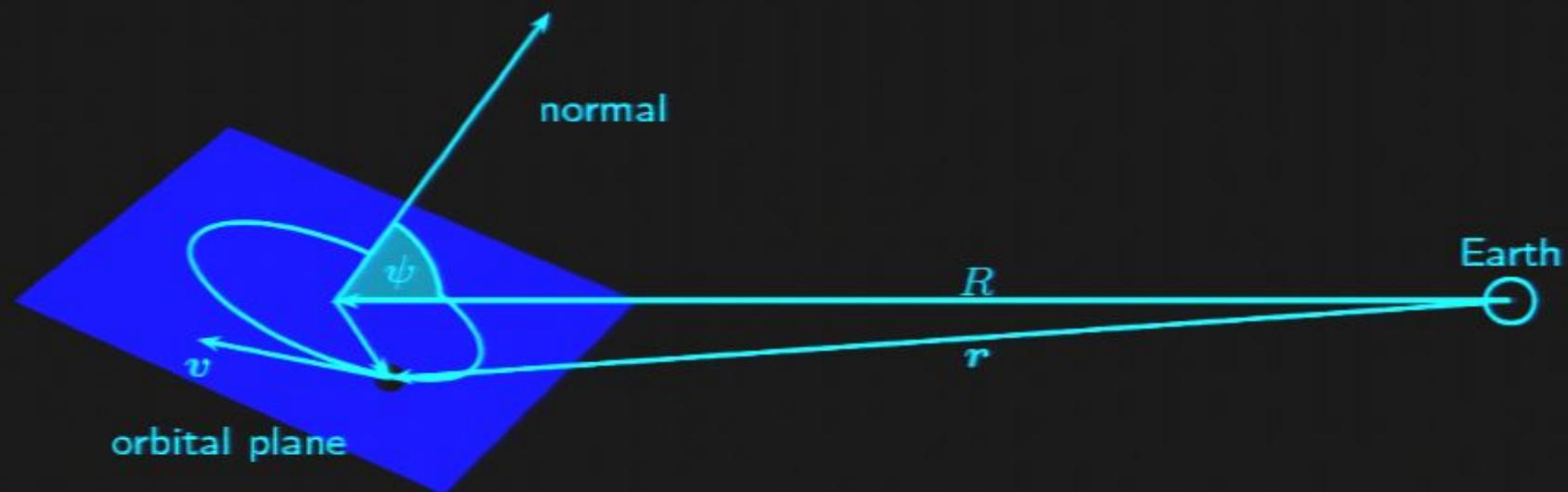
Postulate 1: The velocity of light is constant.

Postulate 2: The relativity principle.

## The meaning of the postulates

- $c$  does not depend on
  - the velocity of the source  $\Rightarrow$  **uniqueness** of  $c$
  - the velocity of the observer
  - the direction of propagation
  - its frequency and polarization
- The meaning of  $c$ 
  - For all particles the velocity of light is the limiting velocity
$$c = c_+ = c_- = c_\nu = v_p^{\max} = v_e^{\max} = v_{\text{grav}}$$
  - $c$  is universal and can, thus, be interpreted as geometry
- **All** physics is the same in **all** inertial systems
  - Experimental results do not depend on the orientation of the laboratory
  - Experimental results do not depend on the velocity of the laboratory

# Independence of $c$ from the velocity of the source



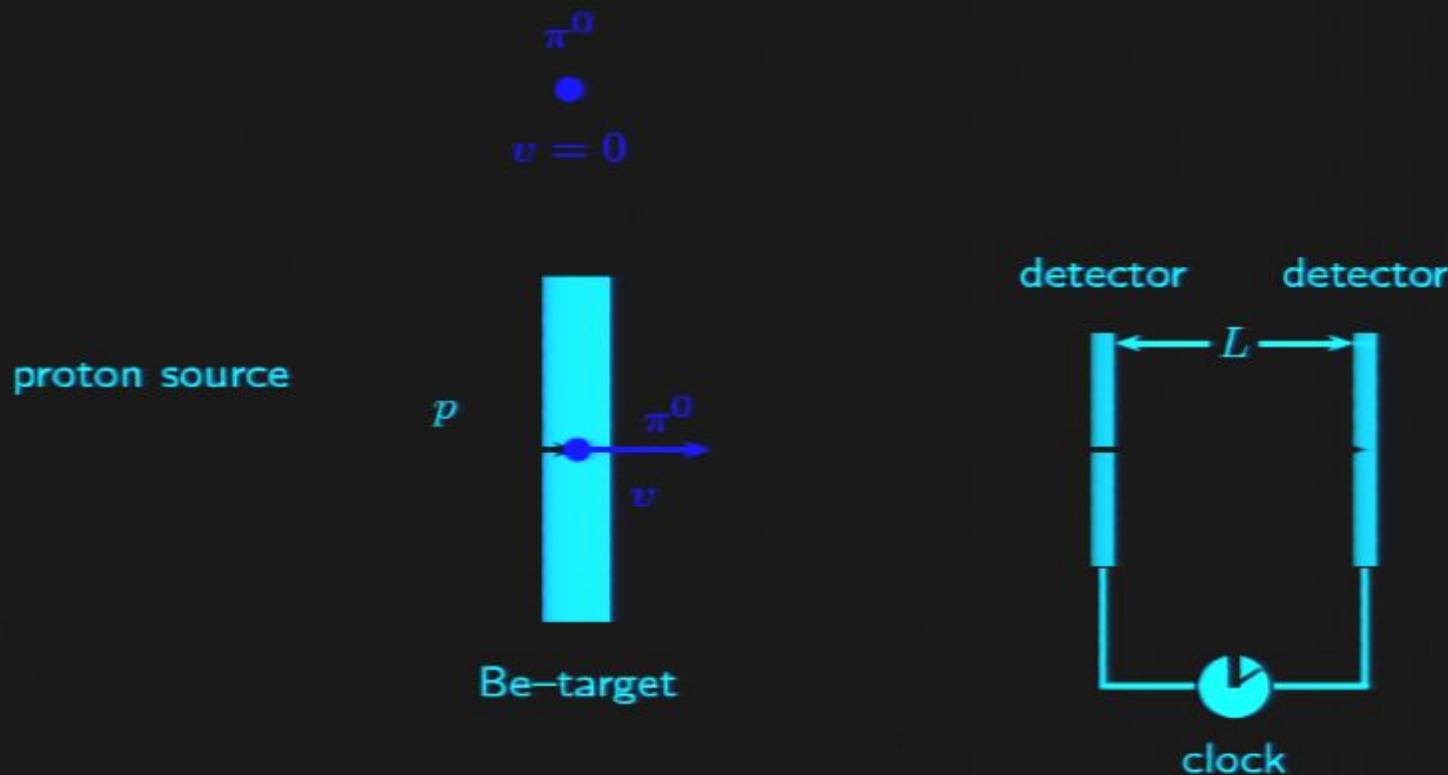
## Description and result (Brecher 1977)

- Model  $c' = c + \kappa v$
- Time of flight consideration: May happen
  - Reversal of chronological order (one light ray may overtake the other)
  - Multiple images
  - ...
- Result  $|\kappa| \leq 10^{-11}$

# Independence of $c$ from the velocity of the source

$$\begin{array}{c} \pi^0 \\ \bullet \\ v = 0 \end{array}$$

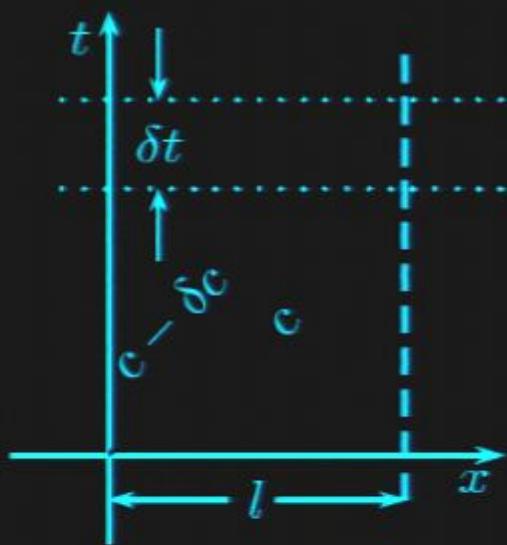
# Independence of $c$ from the velocity of the source



## Description and result (Alväger et al 1964)

- Model  $c' = c + \kappa v$
- Result  $|\kappa| \leq 10^{-6}$  at  $v = 0.99975c$

# Tests of the universality of $c$



Polarization / dispersion of light

Method: Comparison of arrival times of light with different polarization / different frequency from distant galaxies

## Result

Carrol, Field and Jackiw 1992, Kauffmann and Haugan 1995, Kostelecky and Mathews 2002

$$\left| \frac{c_+ - c_-}{c_+} \right| \leq 10^{-32}$$

Schafer 1999, Biller 1999

$$\left| \frac{c_\nu - c_{\nu'}}{c_\nu} \right| \leq 6 \cdot 10^{-21}$$

# Tests of the universality of $c$

Velocity of neutrinos

Method: Comparison of arrival times of photons and neutrinos from supernova SN1987a

Result

Longo 1987, Stodolsky 1988

$$\left| \frac{c - v_\nu}{c} \right| \leq 10^{-8}$$

Limiting velocity of protons

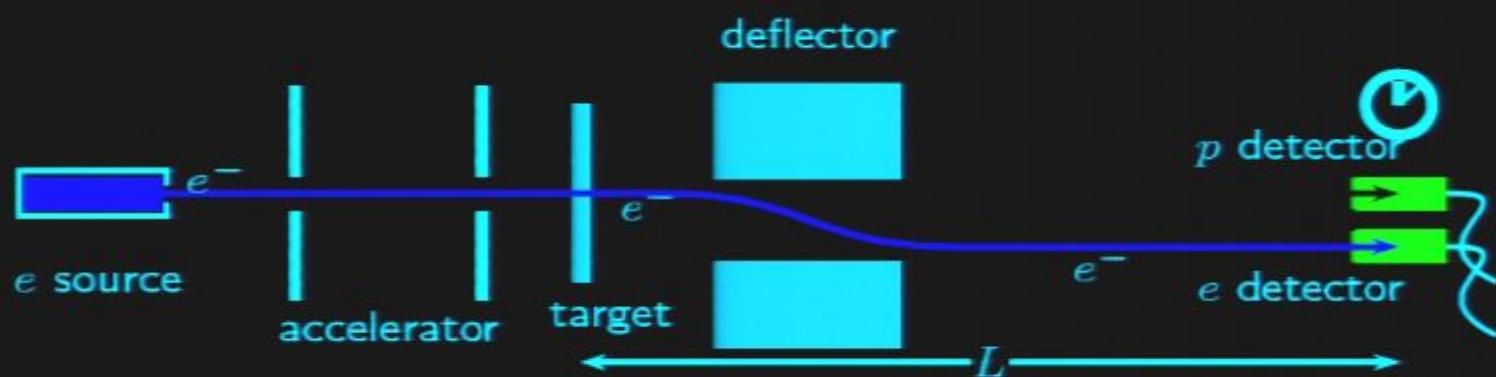
Result

Coleman and Glashow 1998

$$\left| \frac{v_p^{\max} - c}{c} \right| \leq 10^{-21}$$

# Tests of the universality of $c$

Limiting velocity of electrons



Result

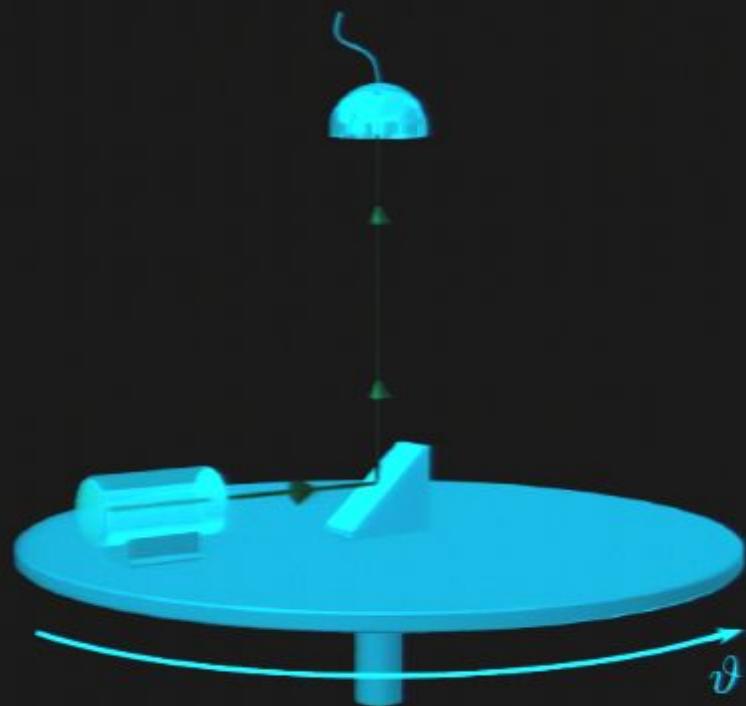
Giugossian et al 1965

$$\left| \frac{v_e^{\max} - c}{c} \right| \leq 10^{-6}$$

Other tests by Brown et al 1963, Alspector et al 1976, Kalbfleisch et al 1976 with result of same order of accuracy

# Test of isotropy of $c$

- Interference experiment – Michelson–Morley ....
- Measuring frequency of light in rotating resonator



## Model independent description

- Light wave  

$$\varphi = A e^{i(k_+ \cdot x - \omega t)} + B e^{i(k_- \cdot x - \omega t)}$$
- Dispersion relation  $\omega = k_{\pm} c_{\pm}$
- Boundary conditions
- Effective: 2-way velocity of light

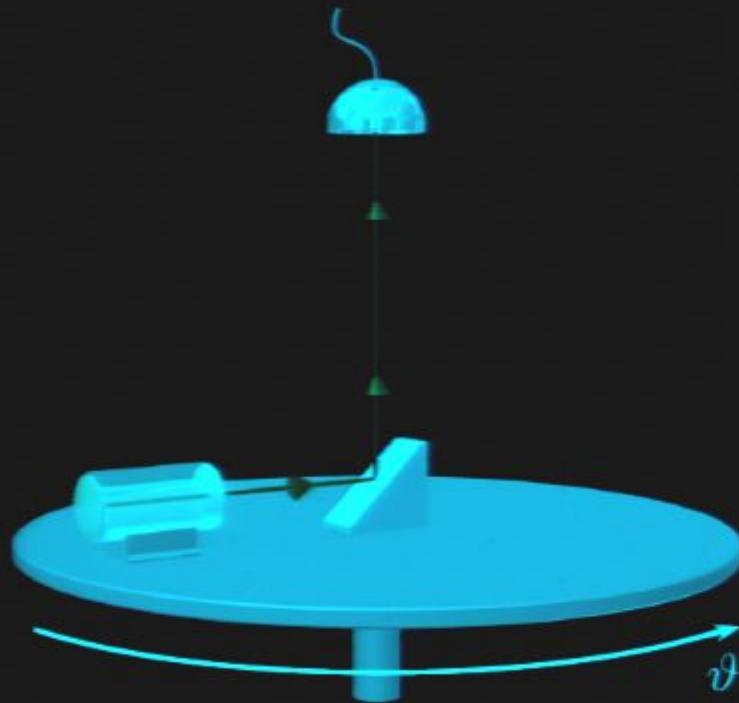
$$\frac{2}{c} = \frac{1}{c_+} + \frac{1}{c_-}$$

- Observable frequency

$$\nu = \frac{m}{2L} c$$

# Test of isotropy of $c$

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## Result

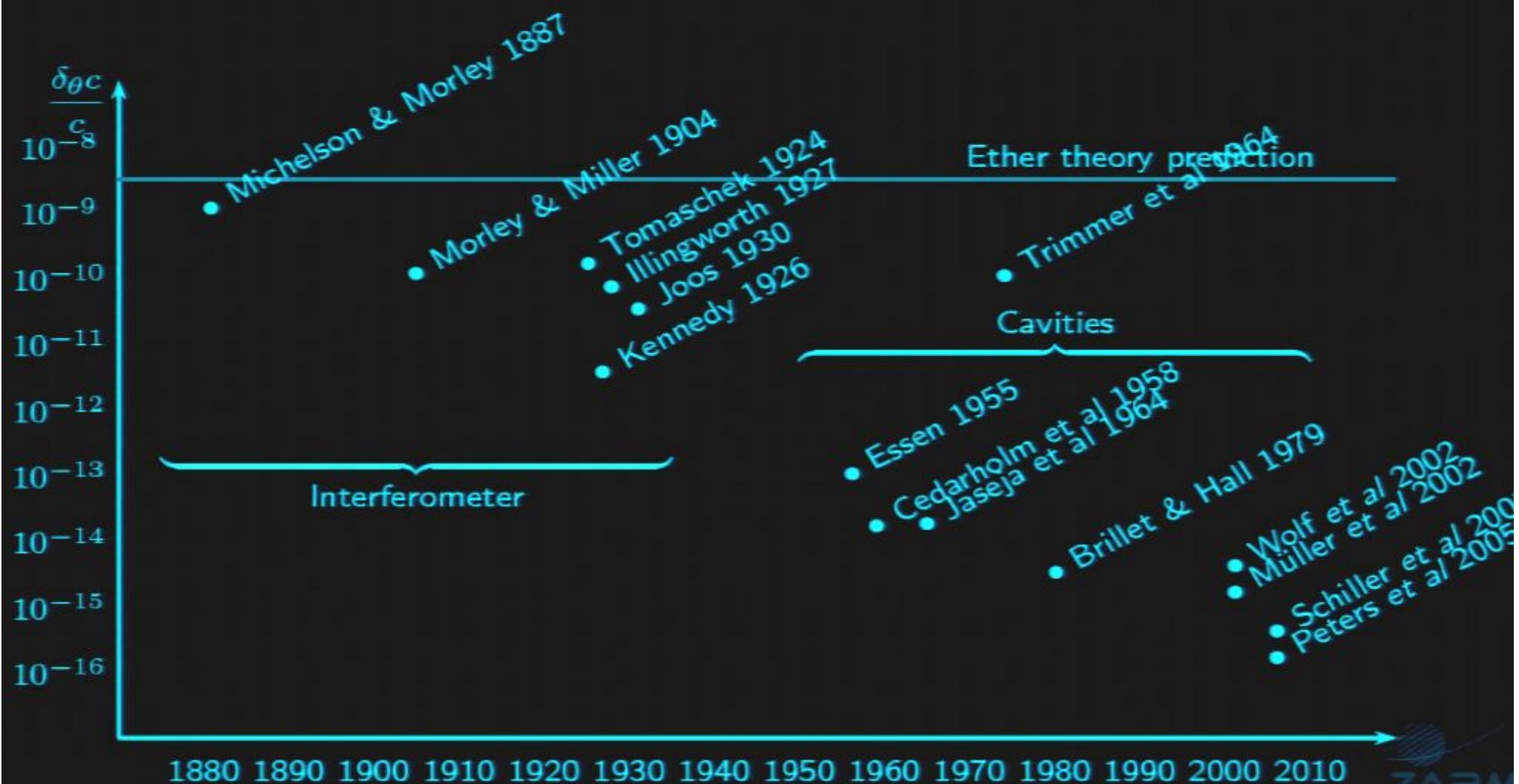
- Herrmann, Peters et al 2005
- Cryogenic resonators, one rotating, one fixed
- Result

$$\left| \frac{\Delta_\theta c}{c} \right| \leq (2.5 \pm 4) \cdot 10^{-16}$$

## Interpretation (Müller et al 2004)

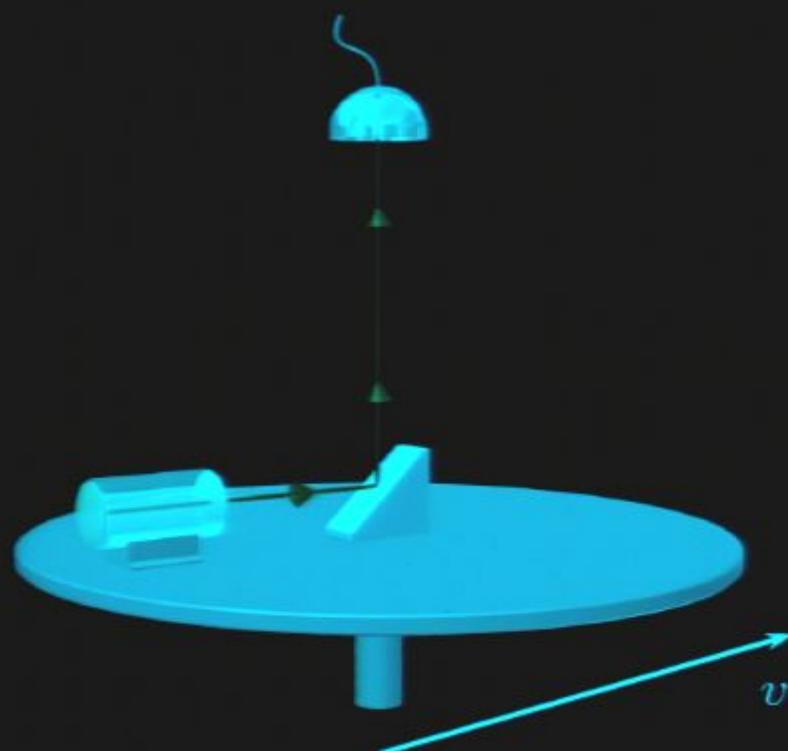
- Velocity of light
- Electron properties (in  $L$ )

# Summary: Test of isotropy of $c$



# Test of independence of $c$ from laboratory velocity

- Interference experiment – Kennedy–Thorndike ....
- Measuring frequency of light in moving resonator



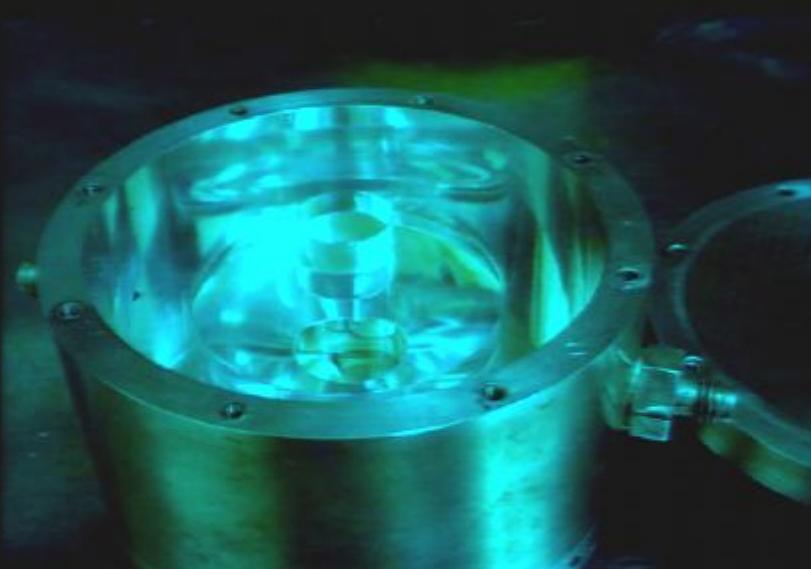
## Model independent description

- Same description as above
- Observable frequency

$$\nu = \frac{m}{2L}c$$

# Test of independence of $c$ from laboratory velocity

## Cavity-clock comparison

 $p = 5$  $m = 3$  $p = 5$  $m = 30$  $p = 5$  $m = 100$ 

**Whispering gallery modes**

### Method and result

- Wolf et al 2004
- Whispering gallery modes
- Comparison with H-maser
- Result

$$\left| \frac{\Delta_v c}{c} \right| \leq (4.5 \pm 4.5) \cdot 10^{-16}$$

- $\delta v \leftrightarrow$  rotation of Earth

# Hughes–Drever experiments

The model

Modified Schrödinger equation

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

Leads to a splitting of the Zeeman singlett

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## Experiments

experiment	method	estimate
Hughes et al 1960	NMR with ${}^7\text{Li}$	$ \alpha^{ij}  \leq 10^{-20}$
Drever 1961	NMR with ${}^7\text{Li}$	$ \alpha^{ij}  \leq 2 \times 10^{-23}$
Prestage et al. 1985	NMR with ${}^9\text{Be}^+$	$ \alpha^{ij}  \leq$
Lamoreaux et al. 1986, 1989, 1990	NMR with ${}^{201}\text{Hg}$	$ \alpha^{ij}  \leq 2 \times 10^{-28}$
Chupp et al 1989	NMR with ${}^{21}\text{Ne}$	$ \alpha^{ij}  \leq 5 \times 10^{-30}$

# Methods for testing time-dilation

General: Comparison of identical clocks in different motion

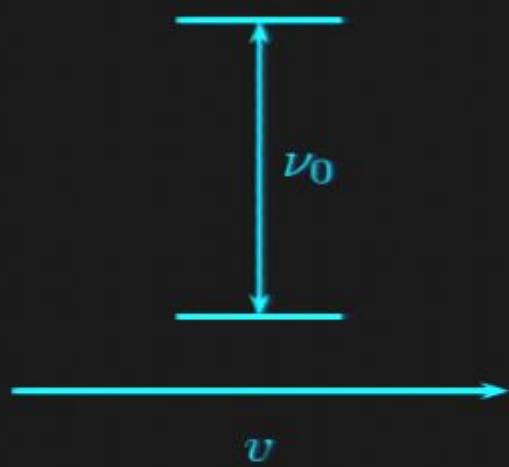
- Transport of macroscopic clocks
- Photon absorption / emission
- Two-photon absorption
- Rotor experiments
- Saturation spectroscopy
- Particle decay

# Test of time-dilation: Transport of clocks

The Experiment by Hafele and Keating 1968



# Test of time-dilation: Photon emission / absorption



## Description

- Doppler effect

$$\nu_{\pm} = \frac{1}{\sqrt{1-v^2}} (1 \pm v) \nu_0$$

## Description

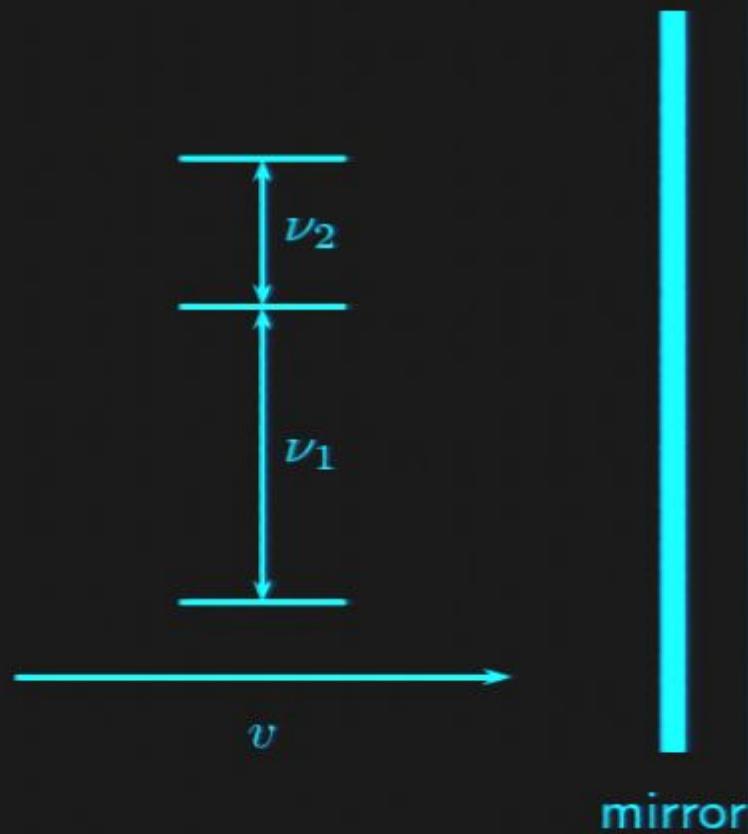
- Simple consequence

$$\nu_0^2 = \nu_+ \nu_-$$

- independent of synchronization
- Experiments

- Ives & Stilwell 1938
- Otting 1939
- Pound & Rebka 1960
- Mandelberg & Witten 1962
- Olin 1973
- Junckar 1985
- MacArthur 1986
- Gwinner et al 2002
- Saathoff et al 2004
- Reinhard et al 2007

# Test of time-dilation: 2 Photon absorption



## Description

- Resonance condition for  $v = 0$

$$2\nu_{\text{laser}}^{v=0} = \nu_1 + \nu_2$$

- Resonance condition for  $v \neq 0$

$$\nu_1 = \nu_+ = \nu_{\text{laser}}^v (1 + v) \sqrt{1 - v^2}$$

$$\nu_2 = \nu_- = \nu_{\text{laser}}^v (1 - v) \sqrt{1 - v^2}$$

- Consequence

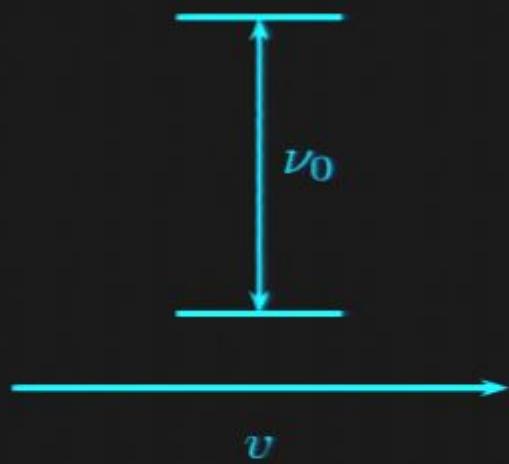
$$\nu_{\text{laser}}^{v=0} = \nu_{\text{laser}}^v \sqrt{1 - v^2}$$

with

$$v = \frac{\nu_+ - \nu_-}{\nu_+ + \nu_-}$$

- No need of synchronization

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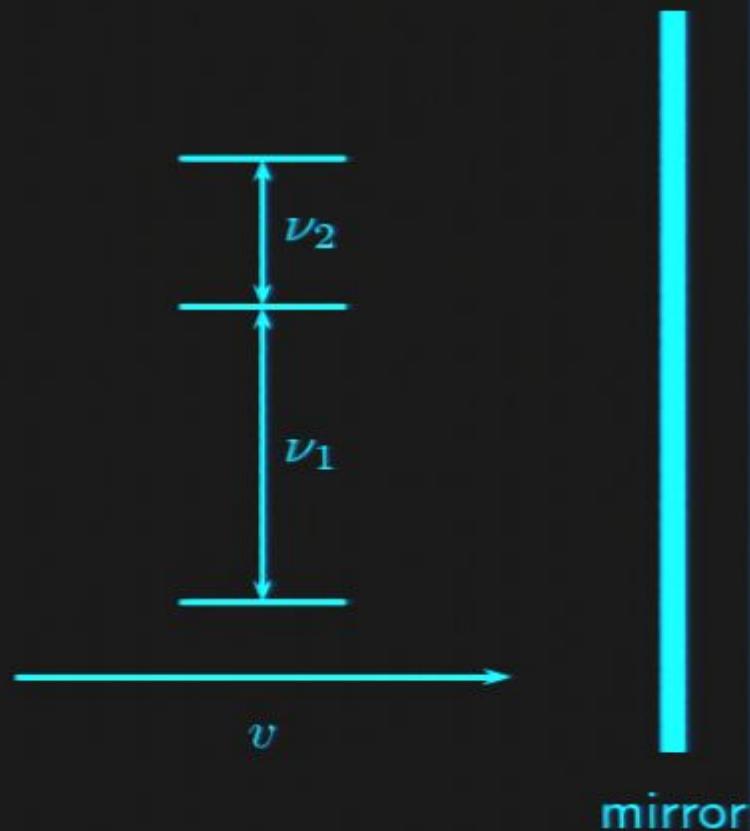
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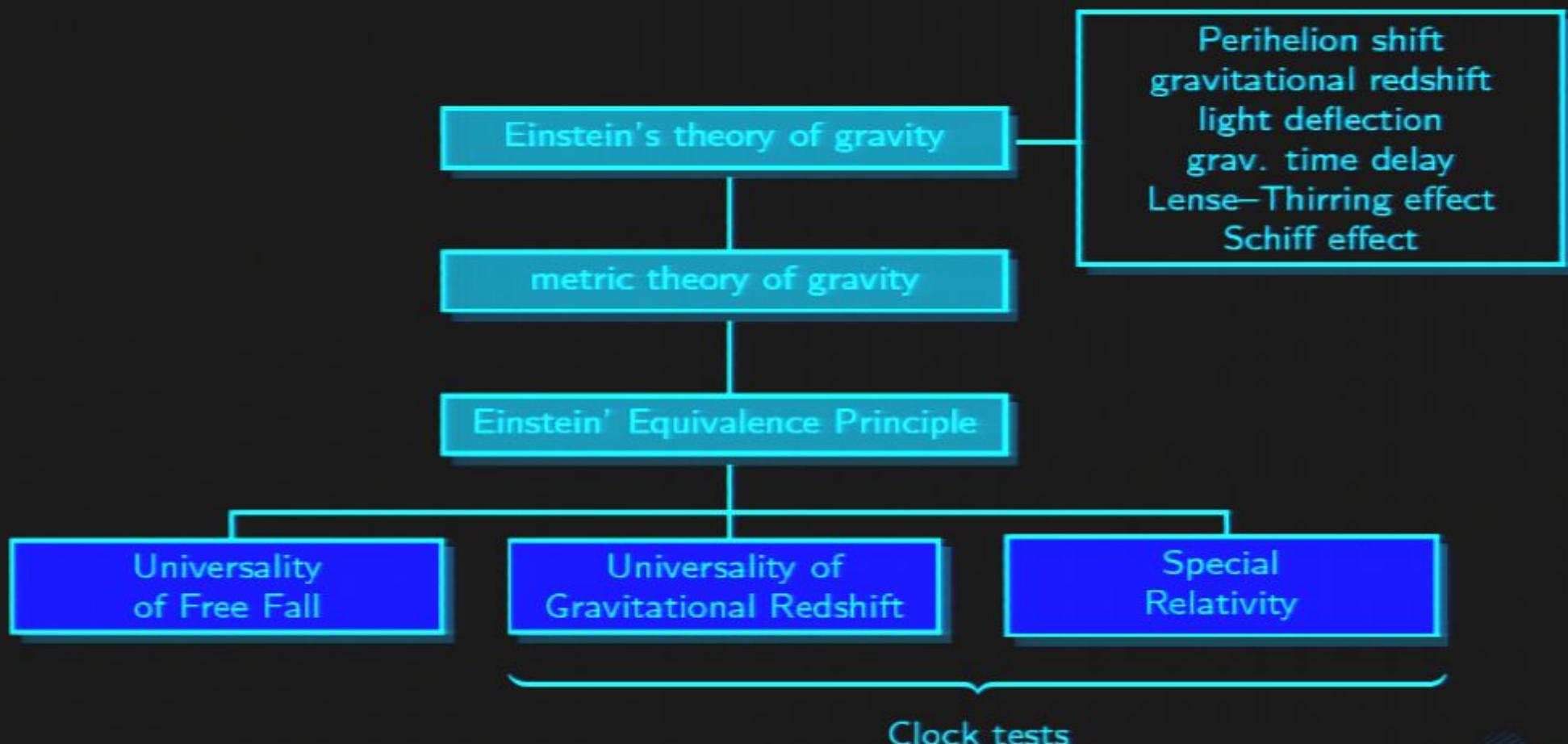
- No need of synchronization

## Further tests

- Time dilation with saturation spectroscopy
- Rotor time dilation experiments
- Sagnac effect
- Experiments testing  $E = mc^2$
- ...

- Tests of local Lorentz invariance
  - Space-time fluctuations
  - Active and passive charges
  - Test of standard Maxwell equations
- Unexplained observations
- Conclusion and outlook

# The structure of GR



# Description of tests of the Universality of Free Fall

## Haugan formalism

- Ansatz: Hamiltonian

$$E = mc^2 + \frac{1}{2}m \left( \delta_{ij} + \frac{\delta m_{ij}}{m} \right) v^i v^j + m \left( \delta_{ij} + \frac{\delta m_{gij}}{m} \right) U^{ij}(\vec{x})$$

- Canonical equations

$$a^i = \delta^{ij} \partial_j U + \frac{\delta m^{ij}}{m} \partial_j U + \delta^{ij} \frac{\delta m_{gkl}}{m} \partial_j U^{kl}(\vec{x}),$$

- For diagonal mass tensors  $\delta m_{ij} = m_i \delta_{ij}$ ,  $\delta m_{gij} = m_g \delta_{ij}$ :

$$a^i = \delta^{ij} \frac{m_g}{m_i} \partial_j U$$

- Comparison of acceleration of two different particles: Eötvös coefficient

$$\eta = \frac{a_2 - a_1}{\frac{1}{2}(a_2 + a_1)} = \frac{(m_g/m_i)_2 - (m_g/m_i)_1}{\frac{1}{2}((m_g/m_i)_2 + (m_g/m_i)_1)}$$

# Description of tests of the Universality of Free Fall

## Particles with spin

- Ansatz: Hamiltonian

$$\begin{aligned} i \frac{\partial}{\partial t} \varphi = & -\frac{1}{2m} \left( \delta^{ij} - \frac{\delta m_i^{ij}}{m} - \frac{\delta \bar{m}_{ik}^{ij} \sigma^k}{m} \right) \partial_i \partial_j \varphi + \left( c_D A_j^i + \frac{1}{m} a_j^i \right) \sigma^j i \partial_i \varphi \\ & + \left[ m U(\mathbf{x}) + \mathbf{C} \cdot \boldsymbol{\sigma} m U(\mathbf{x}) + \delta m_{gij} U^{ij}(\mathbf{x}) \right. \\ & \quad \left. + c_D \mathbf{T} \cdot \boldsymbol{\sigma} + mc_D^2 \mathbf{B} \cdot \boldsymbol{\sigma} \right] \varphi \end{aligned}$$

- Canonical equations

$$a^i = \delta^{ij} \partial_j U + \left[ \frac{\delta m_i^{ij}}{m} + 2 \left( \frac{\delta \bar{m}_{ik}^{ij}}{m} + \delta^{ij} C_k \right) S^k \right] \partial_j U + \delta^{ij} \frac{\delta m_{gkl}}{m} \partial_j U^{kl}(\vec{x})$$

## Spin-dependent forces

# Tests of UFF

## Tests with classical bulk matter

Method	Grav field	Accuracy	Experiment
Pendula	Earth	$\eta \leq 10^{-3}$	Newton 1686
Pendula	Earth	$\eta \leq 2 \cdot 10^{-5}$	Bessel 1832
Torsion balance	Sun	$\eta \leq 5 \cdot 10^{-8}$	Eötvös, Pekar, Fekete 1922
Pendula	Earth	$\eta \leq 10^{-5}$	Potter 1932, 1927
Torsion balance	Sun	$\eta \leq 10^{-11}$	Roll, Krotkov, Dicke 1964
Torsion balance	Sun	$\eta \leq 2 \cdot 10^{-12}$	Braginski, Panov 1972
Free Fall	Earth	$\eta \leq 5 \cdot 10^{-10}$	Niebauer, Hughes, Faller 1987
Free Fall	Earth	$\eta \leq 2 \cdot 10^{-10}$	Kuroda & Mio 1989, 1990
Torsion balance	Sun	$\eta \leq 10^{-12}$	Adelberger et al. 1994
Torsion balance	Sun	$\eta \leq 5 \cdot 10^{-13}$	Adelberger et al 2002
Earth-Moon motion future	Sun	$\eta \leq 5 \cdot 10^{-13}$	Williams et al. 1996
Free fall in orbit	Earth	$\eta \leq 10^{-15}$	MICROSCOPE 2011
Free fall in orbit	Earth	$\eta \leq 10^{-17}$	GG 2015+
Free fall in orbit	Earth	$\eta \leq 10^{-18}$	STEP 2015+

# Tests of UFF

## Tests with quantum matter

Method	Grav field	Accuracy	Experiment
Free fall neutron	Earth	$\eta \leq 5 \cdot 10^{-4}$	Koester
Atom interferometry	Earth	$\eta \leq 10^{-9}$	Chu, Peters 1999

## Gravitational self energy

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

## Charged particles

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

## Particles with spin

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

# UFF and charge

## Standard theory

- In standard theory from ordinary coupling:  $a^\mu = \alpha \lambda_C c R^{\mu}{}_{\nu} v^\nu$

## Anomalous coupling

- Anomalous coupling (on non-relativistic level)

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

- Charge dependent anomalous gravitational mass tensor
- Can be generalized to charge dependent anomalous inertial mass tensor (e.g. Rohrlich 2000)
- ⇒ Charge dependent Eötvös factor
- It is possible to choose  $\kappa$ '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/s<sup>2</sup>, 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  $\rightarrow$

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

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

$$V(r) = U_0(r) \left[ 1 + B_1 \boldsymbol{\sigma} \cdot \hat{\mathbf{r}} + B_2 \boldsymbol{\sigma} \cdot \frac{\mathbf{v}}{c} + B_3 \hat{\mathbf{r}} \cdot \left( \boldsymbol{\sigma} \times \frac{\mathbf{v}}{c} \right) \right]$$

# Spin–spin interactions

## The model

direct spin–spin interaction between electrons  $V = \alpha_s \frac{\mu_e \sigma \cdot \mu_e \sigma}{r}$

## The experiments

Method	Accuracy	Experiment
Molecular spectra	$\alpha \leq 5 \times 10^{-5}$	Ramsey 1979
NMR	$\alpha \leq 10^{-10}$	Aleksandrov et al. (1983)
NMR	$\alpha \leq 10^{-10}$	Anselm & Neronov 1985
torsion pendulum	$\alpha_s \leq 3 \times 10^{-10}$	Graham & Newman 1985
induced ferromagnetism	$\alpha_s \leq 5 \times 10^{-14}$	Vorobyov & Gitarts 1988
induced ferromagnetism	$\alpha_s \leq 8.5 \times 10^{-15}$	Bobrakov et al 1991
		Hawkins 1989
torsion balance	$\alpha_s \leq 9 \times 10^{-12}$	Ritter et al. 1990
torsion balance	$\alpha_s \leq 1.5 \times 10^{-12}$	Pan, Ni & Chen 1992
induced paramagnetism	$\alpha_s \leq 5 \times 10^{-14}$	Chui & Ni 1993
induced paramagnetism	$\alpha_s \leq 1.2 \times 10^{-14}$	Ni et al. 1994

# Spin-mass interactions

## The model

$$V = \boldsymbol{\sigma} \cdot \boldsymbol{r}$$

## The experiments

Method	Accuracy	Experiment
weight of pol. bulk matter	$\eta \leq 10^{-8}$	Hsieh et al 1989
torsion balance	$\frac{g_s g_p}{4\pi\hbar c} \leq 3 \times 10^{-27}$	Ritter et al 1993
NMR experiments	$\approx 31 \text{ Hz}$	Velyukhov 1968
proton magnetometer	$\leq 0.3 \text{ Hz}$	Young 1969
ground-state hyperfine separation in deuteron	$\delta\nu < 10^{-4} \text{ Hz}$ $D \leq 6.7 \times 10^{-8} \text{ kg}^{-1}$	Wineland & Ramsey 1978
NMR	$D(^9\text{Be}) \leq 9.0 \times 10^{-9} \text{ kg}^{-1}$ $D(e) \leq 4.5 \times 10^{-5} \text{ kg}^{-1}$ $D(n) \leq 2.7 \times 10^{-8} \text{ kg}^{-1}$	Wineland et al. 1991
nuclear spin precession	$D(n) \leq 1.7 \times 10^{-9} \text{ kg}^{-1}$	Venema et al. 1992
comparison of frequencies of Hg and Cs magnetom.	$\frac{g_s g_p}{\hbar c}(e) \leq 2.3 \times 10^{-29},$ $\frac{g_s g_p}{\hbar c}(n) \leq 3.6 \times 10^{-29}$	Youdin et al. 1996

# Spin–velocity interactions

## The model

$$V = \boldsymbol{\sigma} \cdot \boldsymbol{v}$$

## The experiments

Method	Accuracy	Experiment
torsion pendulum	$\delta E \leq 4.5 \times 10^{-11} \text{ eV}$	Phillips & Woolum 1969
torsion pendulum	$\delta E \leq 8.5 \times 10^{-18} \text{ eV}$	Phillips 1987
relative frequency of Hg and Cs magnetometers	$\kappa(e) \leq 2 \times 10^{-4} \text{ Hz}$ , $\kappa(n) \leq 1.1 \times 10^{-7} \text{ Hz}$	Berglund et al. 1995
torsion pendulum		Ni et al 1999

# Active and passive mass

Gravitationally bound two-body system (Bondi, RMP 1957)

$$m_{1i}\ddot{\mathbf{x}}_1 = m_{1p}m_{2a}\frac{\mathbf{x}_2 - \mathbf{x}_1}{|\mathbf{x}_2 - \mathbf{x}_1|^3}, \quad m_{2i}\ddot{\mathbf{x}}_2 = m_{2p}m_{1a}\frac{\mathbf{x}_1 - \mathbf{x}_2}{|\mathbf{x}_1 - \mathbf{x}_2|^3}$$

Unequal active and passive masses  $\Rightarrow$  self-acceleration of center of mass

$$\ddot{\mathbf{X}} = \frac{m_{1p}m_{2p}}{M_i}\bar{C}_{21}\frac{\mathbf{x}}{|\mathbf{x}|^3}, \quad \bar{C}_{21} = \frac{m_{2a}}{m_{2p}} - \frac{m_{1a}}{m_{1p}}.$$

$\bar{C}_{21} = 0$ : ratio of the active and passive masses are equal for both particles.  
 Dynamics of relative coordinate

$$\ddot{\mathbf{x}} = -\frac{m_{1p}m_{2p}}{m_{1i}m_{2i}} \left( m_{1i}\frac{m_{1a}}{m_{1p}} + m_{2i}\frac{m_{2a}}{m_{2p}} \right) \frac{\mathbf{x}}{|\mathbf{x}|^3}.$$

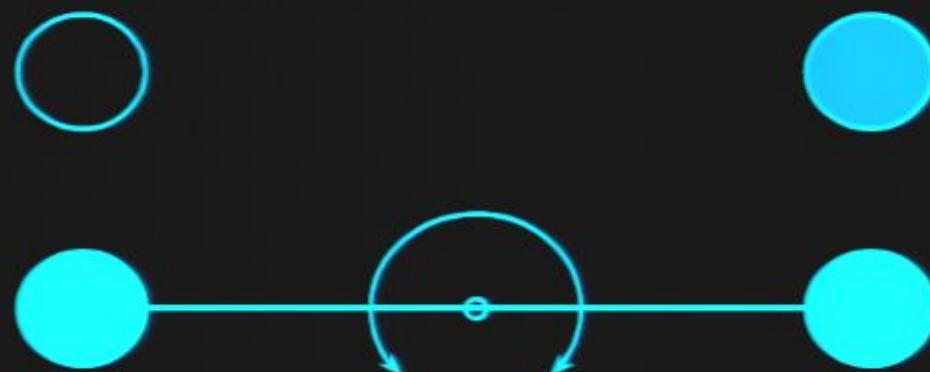
# Experiment testing $m_{\text{ga}} = m_{\text{gp}}$

Measurement of relative acceleration

Step 1: Take two masses with  $m_{\text{pg}2} = m_{\text{ag}2}$  (equal weight)

Step 2: Test active equality of these two masses with torsion balance

Experimental setup: Torsion balance with equal passive masses reacting on and  $m_{\text{ag}2}$



No effect has been seen:  $C_{12} \leq 5 \cdot 10^{-5}$   
 Kreuzer, PR 1868

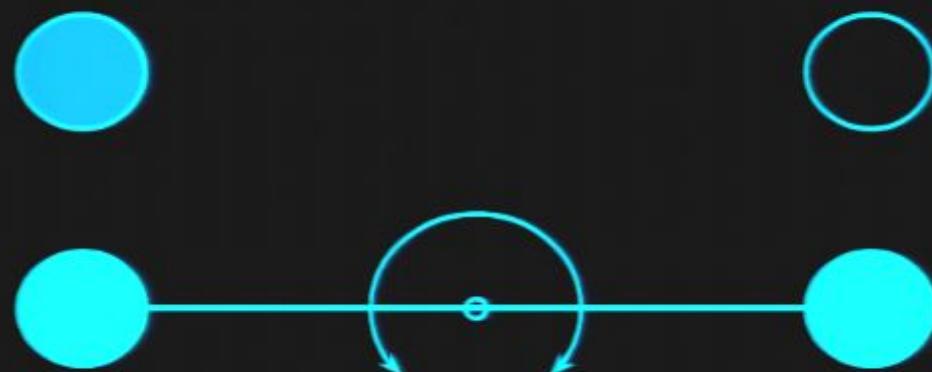
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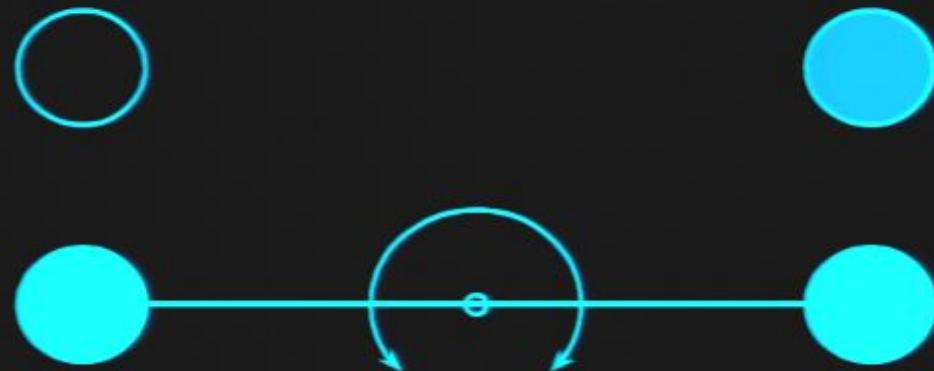
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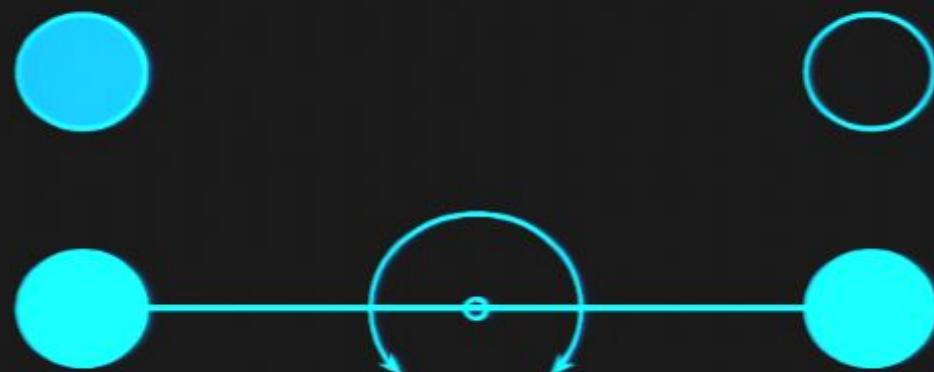
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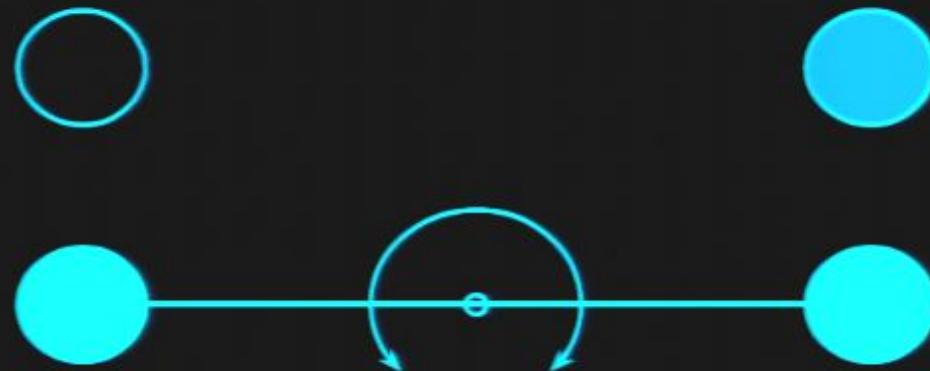
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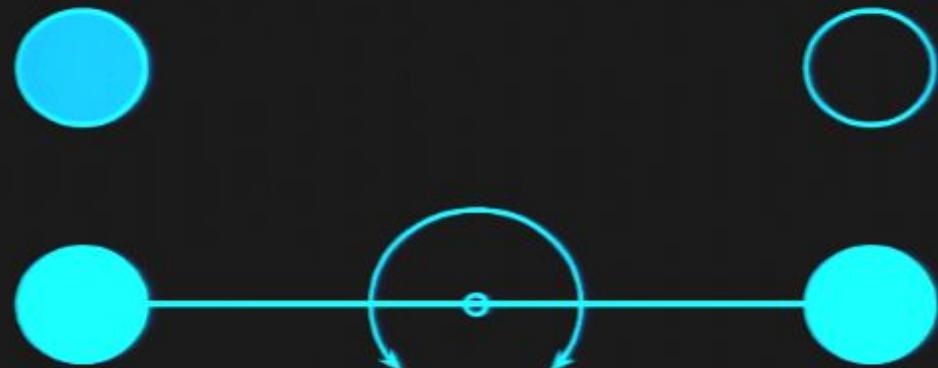
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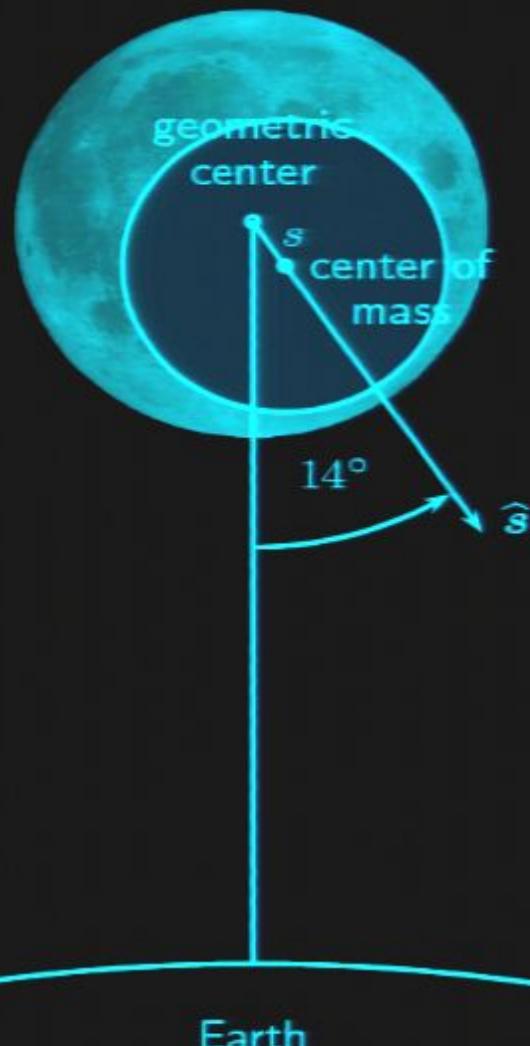
Measurement of center-of-mass acceleration



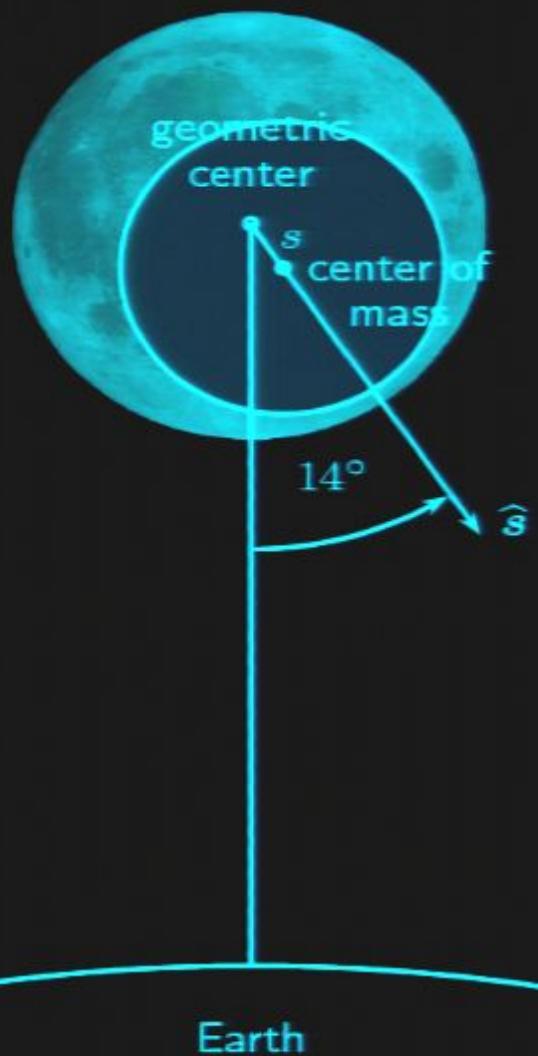
Earth

# Experiment testing $m_{ga} = m_{gp}$

Measurement of center-of-mass acceleration



# Experiment testing $m_{\text{ga}} = m_{\text{gp}}$



Measurement of center-of-mass acceleration

$$\frac{\mathbf{F}_{\text{self}}}{F_{\text{EM}}} = C_{\text{Al-Fe}} \frac{M_{\text{M}}}{M_{\oplus}} \frac{r_{\text{EM}}^2}{r_{\text{M}}^2} \frac{\mathbf{s}}{r_{\text{M}}} \frac{\rho}{\Delta\rho} \hat{\mathbf{s}}$$

Effect of tangential force: increase of orbital angular velocity

$$\frac{\Delta\omega}{\omega} = 6\pi \frac{F_{\text{self}}}{F_{\text{EM}}} \sin 14^\circ \text{ per month}$$

From LLR  $\frac{\Delta\omega}{\omega} \leq 10^{-12}$  per month

$$\Rightarrow C_{\text{Al-Fe}} \leq 7 \cdot 10^{-13}$$

Bartlett & van Buren PRL 1986  
significant improvement with new  
LLR data possible

# MOdified Newtonian Dynamics

## MOND ansatz

Modification of Newton's second law = modification of relation between applied force and resulting acceleration (Milgrom)

$$m\ddot{\mathbf{x}} = \mathbf{F} \quad \longrightarrow \quad m\ddot{\mathbf{x}}\mu(|\ddot{\mathbf{x}}|/a_0) = \mathbf{F}$$

with function

$$\mu(x) = \begin{cases} 1 & \text{for } |\ddot{\mathbf{x}}| \gg a_0 \\ x & \text{for } |\ddot{\mathbf{x}}| \ll a_0 \end{cases}$$

## For Newtonian gravity

Newtonian force  $\mathbf{F} = m\nabla U$

- large accelerations / large forces  $\ddot{\mathbf{x}} = \nabla U$
- small accelerations / small forces  $\ddot{\mathbf{x}}|\ddot{\mathbf{x}}| = a_0 \nabla U \rightarrow |\ddot{\mathbf{x}}| = \sqrt{a_0 |\nabla U|}$

reproduces many galactic rotation curves – may also reproduce dynamics of galactic clusters

# Testing MOND

## Torsion balance

Gundlach et al PRL 2007

- transcribes acceleration into torque (for hollow cylinder with radius  $R$ ):  

$$\tau = \frac{I}{R} a \mu(a/a_0)$$
- takes  $r\ddot{\theta} = a$  as acceleration
- no deviation from Newton's second law down to  $a \sim 10^{-14} \text{ m/s}^2$

My problem: is it allowed to separate components?

Earlier experiment by Abramovici and Vager PRD 86

## Free fall experiment

Ignatiev PRL 2007

Free fall with respect to galaxy:

MOND-situation possible on Earth once a year for 0.1 s within 10 cm

# Tests of the Universality of Gravitational Redshift

## Description

- Gravitational redshift

$$\nu(x_1) = \left(1 - (1 + \alpha_{\text{clock}}) \frac{U(x_1) - U(x_0)}{c^2}\right) \nu(x_0)$$

may depend on used clock

- Comparison of two colocated clocks

$$\frac{\nu_1(x_1)}{\nu_2(x_1)} \approx \left(1 - (\alpha_{\text{clock}2} - \alpha_{\text{clock}1}) \frac{U(x_1) - U(x_0)}{c^2}\right) \frac{\nu_1(x_0)}{\nu_2(x_0)}.$$

- Null test
- Tested quantity:  $\alpha_{\text{clock}2} - \alpha_{\text{clock}1}$
- Need of large differences in the gravitational potential

# Clocks

- Atomic clocks
  - based on principal transitions
  - based on fine structure
  - based on hyperfine transitions
- Molecular clocks
  - based on rotational transitions
  - based in vibrational transitions
- Light clocks
- Gravitational clocks
  - planetary motion
  - binary systems
- Rotation
  - Earth
  - pulsars
- Decay of particles

All based on physical principles, laws.

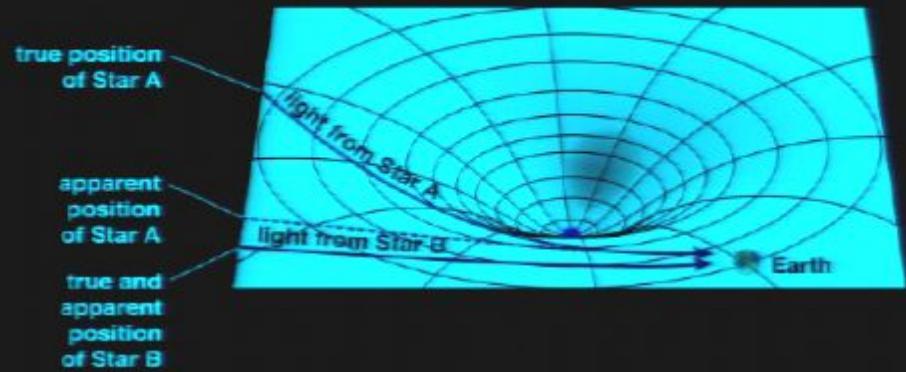
# Tests of predictions – measurement of PPN parameters

## Metric

$$g_{00} = -1 + 2\alpha \frac{U}{c^2} - 2\beta \frac{U^2}{c^4}$$

$$g_i := g_{0i} = 4\mu \frac{(\mathbf{J} \times \mathbf{r})_i}{c^3 r^3}$$

$$g_{ij} = (1 + 2\gamma) \frac{U}{c^2}$$



## Standard tests

Test	Experiment	Parameter
Gravitational redshift	GP-A	$ \alpha_{\text{H-maser}} - 1  \leq 1.4 \cdot 10^{-4}$
Perihelion shift	Astrophys. observation	$\left  \frac{2(\alpha+\gamma)-\beta}{3} - 1 \right  \leq 10^{-4}$
Light deflection	VLBI	$ \gamma - 1  \leq 10^{-4}$
Gravitational time delay	Cassini	$ \gamma - 1  \leq 2 \cdot 10^{-5}$
Lense-Thirring	LAGEOS	$\sim 10\%$
Schiff	GP-B	$\sim 0.5\% \text{ (expected)}$

# Modified Newton potential

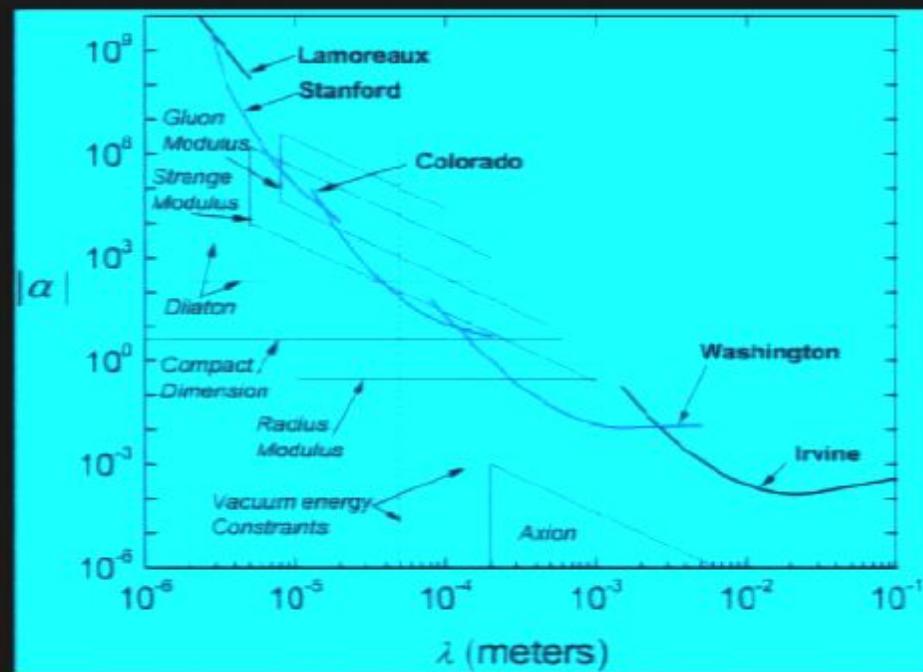
## Prediction

- Higher dimensional theories
- Moduli
- Axion
- Effective potential in Loop QG  
e.g. Bjerrum-Bohr, Donoghue, Holstein 2003

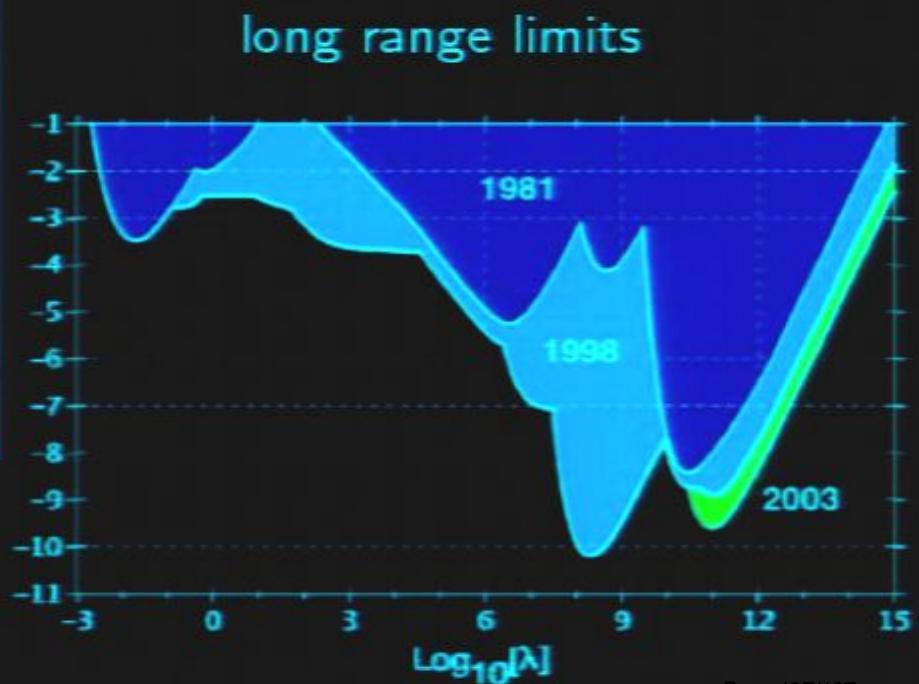
$$V(r) = -\frac{GM_1M_2}{r} \left( 1 + 3\frac{G(M_1 + M_2)}{r} + \frac{41}{10\pi} \frac{G\hbar}{r^2} \right)$$

# Test of Newton potential

$$U = \frac{GM}{r} \left( 1 + e^{-r/\lambda} \right)$$



short range limits



# Outline

- 1 The situation of standard physics
- 2 The search for Quantum Gravity effects: General remarks
- 3 Tests of Lorentz invariance
- 4 Tests of General Relativity
- 5 Tests of the matter sector / Test of Quantum Theory
  - The generalized Dirac equation
  - LLI and UFF
  - Tests of basic principles
  - Space-time fluctuations
- 6 Photon sector
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  - Active and passive charges
  - Test of standard Maxwell equations
- 7 Unexplained observations
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## The model

1st order linear Maxwell equations (CL, Macias, Müller, PRD 2005)

$$\partial_\nu F^{\mu\nu} + k^{\mu\nu\rho\sigma} \partial_\nu F_{\rho\sigma} + k^{\mu\rho\sigma} F_{\rho\sigma} = 4\pi j^\mu$$

## Axion and charge non-conservation

- $k^{[\mu\rho\sigma]}$  axion. Carroll, Fields and Jackiw 1990
- tensor and trace part of  $k^{\mu\rho\sigma}$ : charge non-conservation. Only tested through  $\dot{\alpha}$ , smaller than  $10^{-16} \text{ y}^{-1}$ . (CL & Haugan, PLA 2001)

## Interpretation of anisotropy in Maxwell equations

### Frame

$$4\pi j^\mu = \partial_\nu (\eta^{\mu\rho} \eta^{\nu\sigma} F_{\rho\sigma} + \lambda^{\mu\nu\rho\sigma} F_{\rho\sigma})$$

Theorem: No birefringence  $\Rightarrow$  then there exists a unique Riemannian metric (no Finsler extension possible, CL & Hehl, PRD 2004)

$\Rightarrow$  anisotropy in electromagnetic sector cannot exist by itself but only through comparison with the matter sector. We always test bi-metricity.

Applies to Michelson–Morley experiments, Kennedy–Thorndike, ...

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# Conclusion and outlook

## What can we expect from the future?

Isotropy of  $c$ : Near future  $10^{-18}$ , in space  $10^{-20}$

UFF: MICROSCOPE 2009  $10^{-15}$ , later ( $> 2015$ ) STEP  $10^{-18}$

Free-fall tests with anti-H

PPN  $\gamma$ : In space Gaja, LATOR, ASTROD  $10^{-9}$

PPN  $\beta$ : In space ASTROD  $10^{-9}$ , improvement of LLR

UGR: Near future:

- PHARAO/ACES clocks in space with  $10^{-16}$  stability
- Optical clocks with  $10^{-18}$  stability ( $\leftrightarrow$  Doppler shift of continental drift)
- Possible in space SPACETIME, OPTIS: UGR test with  $10^{-10}$
- Anti-H-clocks with same precision as H-clocks

BEC: Near future: 1 fK; improvements for atomic interferometry

Gravity at large distances: Near future: (Re-)analysis of Pioneer data, far future: new improved mission



# Conclusion and outlook

## What can we expect from the future?

Condensed matter: Postponed: Test of renormalization group theory.

UHECR: New detectors in Argentina, etc.

Atom interferometry:  $\alpha$  to  $10^{-10}$  accuracy

## General statements

- All kinds of experiments have to be improved
- Progress also important for daily life technology
- No preference for astrophysical tests
- Until now only 9 years of dedicated search for QG effects .....

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## Personal view

- most simple beyond-Einstein scenario: Scalar field: Violation of UFF, UGR, time-dependence of constants
- soon \*much better clocks available