

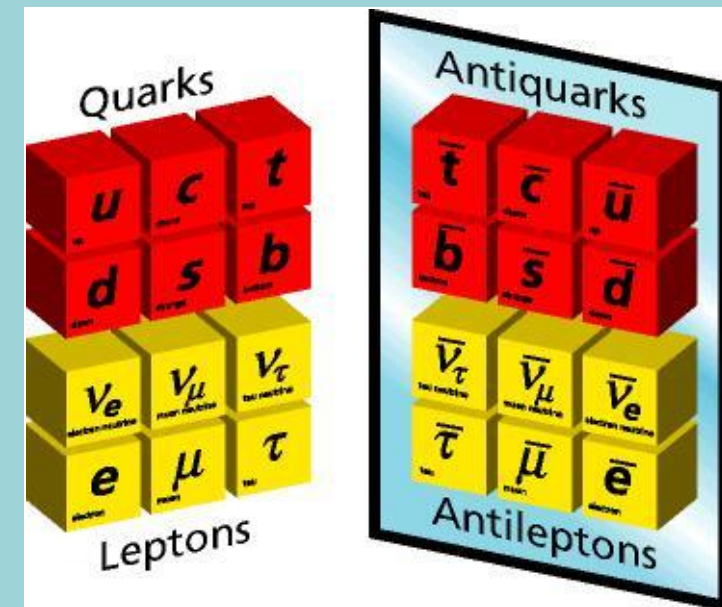
Antimatter Gravitation and Fundamental Laws

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- Antimatter: the Cosmic Mystery
- Fundamental Laws and Antimatter
- Gravitational Measurements



Antimatter: the Cosmic Mystery

Fundamental (2023) Physics and the Universe

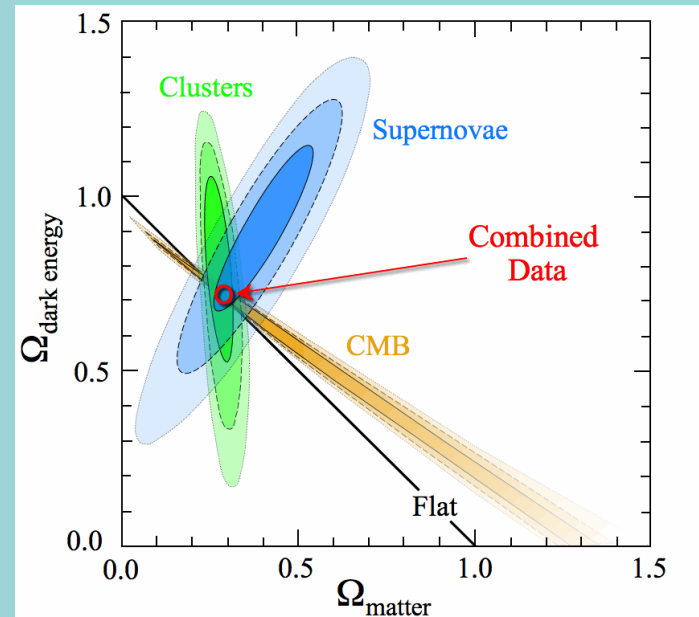
Known fundamental particles
(and their interactions)

Cosmological ingredients
Dark Matter, Dark Energy

The Standard Model of Particle Physics

FERMIONS (matter particles)			BOSONS (force carriers)	
QUARKS	u up	c charm	t top	g gluon
	d down	s strange	b bottom	H Higgs boson
	e electron	μ muon	τ tau	γ photon
LEPTONS	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z^0 Z boson
				W^\pm W boson

sciencealert



Not fully confirmed **Λ -CDM Model**

- Standard Model Quantum Physics
- Friedmann Models (General Relativity)
- Inflation (new Physics)

Note: a question mark!

How do the early structures seen by J Webb and ALMA fit into the picture?

Matter-Antimatter Asymmetry Generation

Generally accepted Baryogenesis scheme

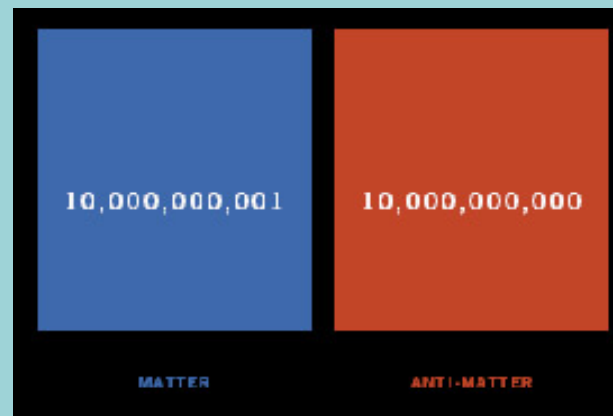
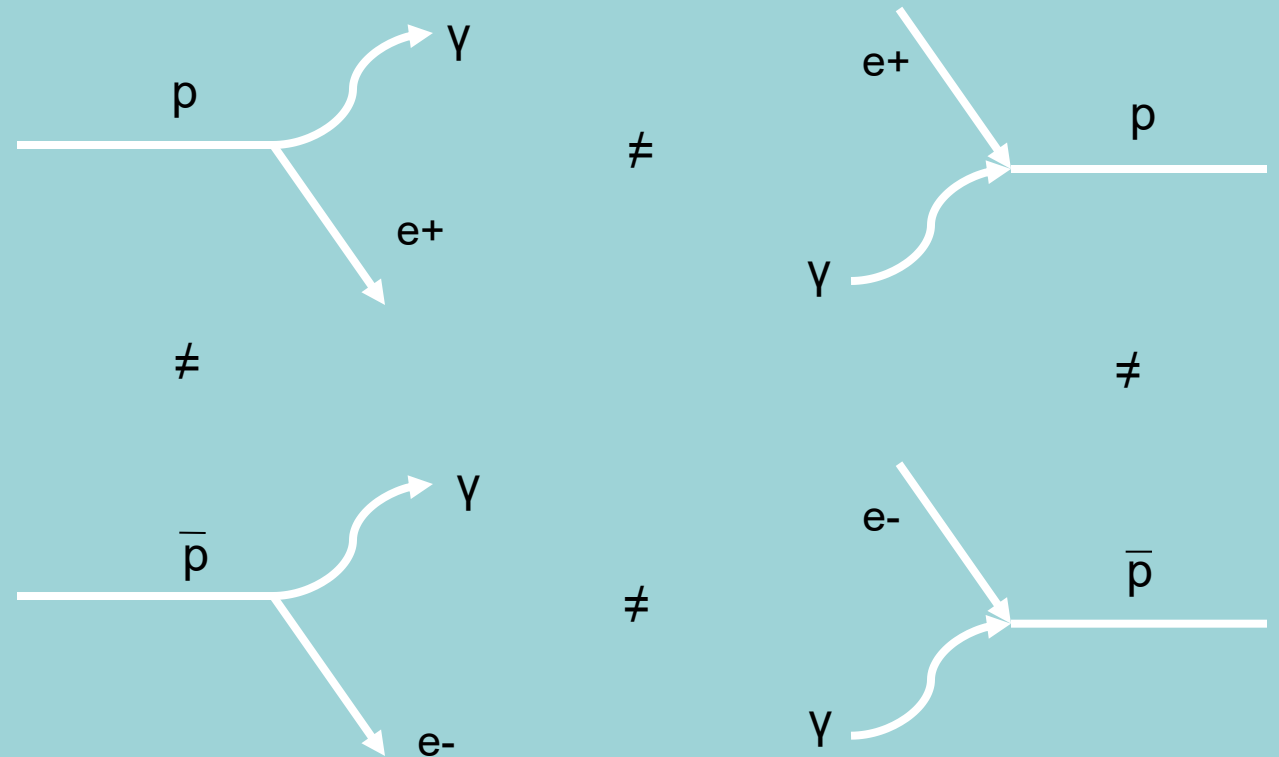
- Baryon Number Violation
- CP Violation
- Out of Equilibrium

Sakharov conditions

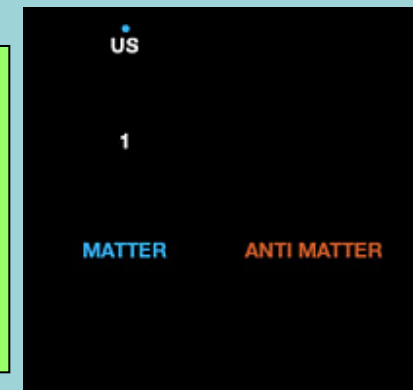
CP Violation in the Standard Model

- Baryogenesis
- Leptogenesis

Insufficient to explain the asymmetry \rightarrow CPT violation?



- Unbalance created within the first 10^{-12} s of Universal Time
- One part out of 10^{10}
- The subsequent annihilation generated a matter-only Universe



Fundamental Laws and Antimatter

Laws relating Particles (Matter) to
Antiparticles (Antimatter)

Einstein Equivalence
Principle (EEP)

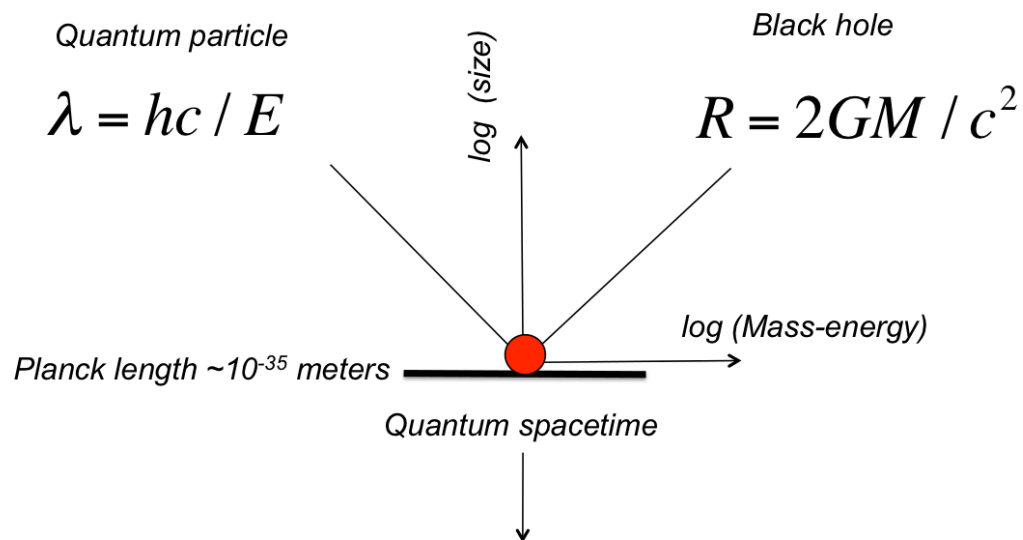
- Weak Equivalence Principle
- Local Position Invariance
- Strong Equivalence Principle

In a classical theory of Gravitation

CPT Theorem

- Lorentz-invariant QFT
- Flat spacetime

Only a Quantum meaning



Quantity	Expression	Metric value	Name
Length (L)	$l_P = \sqrt{\frac{\hbar G}{c^3}}$	1.616×10^{-35} m	Planck length
Mass (M)	$m_P = \sqrt{\frac{\hbar c}{G}}$	2.176×10^{-8} kg	Planck mass
Time (T)	$t_P = \sqrt{\frac{\hbar G}{c^5}}$	5.391×10^{-44} s	Planck time
Temperature (Θ)	$T_P = \sqrt{\frac{\hbar c^5}{G k_B^2}}$	1.417×10^{32} K	Planck temperature

Particles and Antiparticles

Dynamical meaning

$$F = m_I a$$

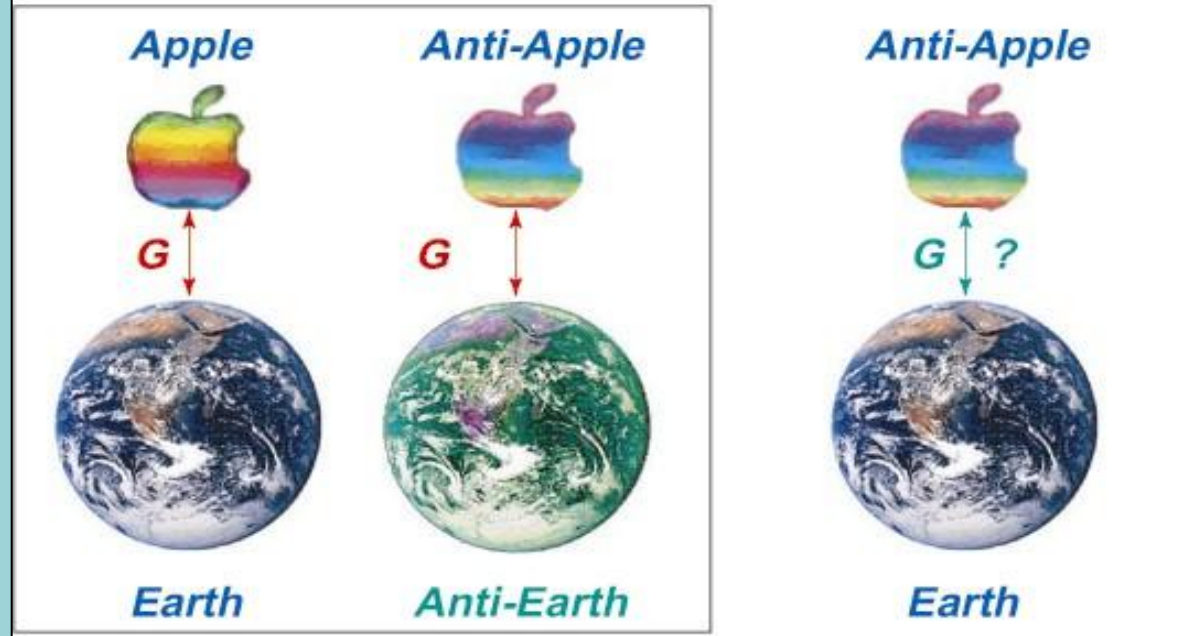
The gravitational «charge»

$$F = -G m_G M_G / r^2$$

According to the WEP

$$m_I = m_G$$

CPT Symmetric Situation



CPT Theorem

$$m_I = \bar{m}_I$$

$$m_G = m_I = \bar{m}_I ? \bar{m}_G$$

Which means that

$$m_G \neq \bar{m}_G$$

Would not necessarily mean that
CPT is broken

$$m_G \neq \bar{m}_G$$

Means that either CPT or the WEP are
broken at the particle level

Theoretical framework: Standard Model Extension : D. Colladay, V. Kostelecký, Phys Rev D **55 (1997) 6760**

Fundamental (2025) Physics

$$\mathcal{L} = \mathcal{L}_{\text{EH}} + \mathcal{L}_{\text{SM}}$$

General Relativity

Standard Model

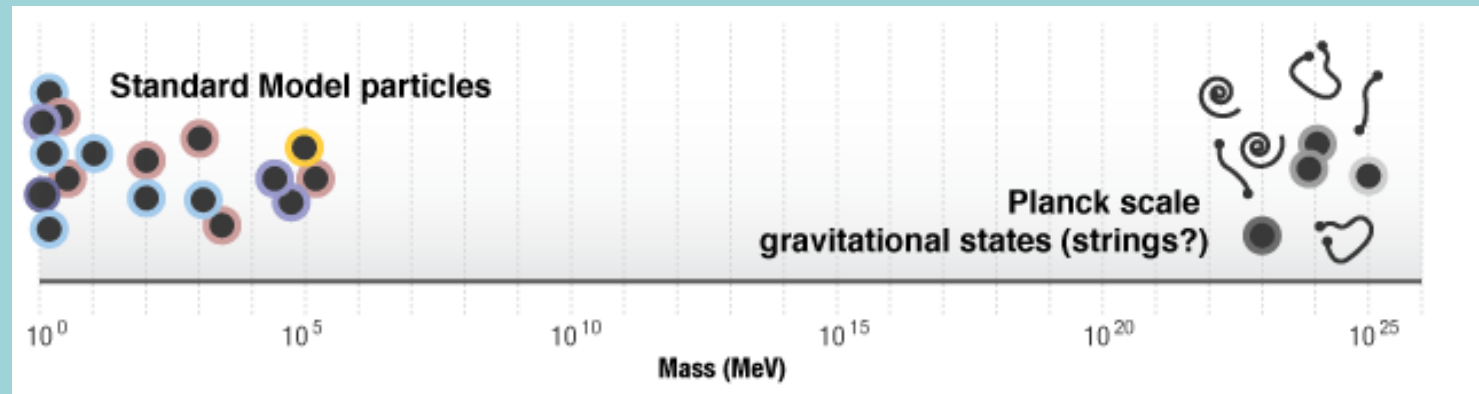
Curvature scalar R
Metrics $g(x)$
(Classical Matter Fields)

Quark, Lepton fields
Gauge Bosons Fields
Higgs Field
(in a fixed $g = \eta$)

Hierarchy Problem

Cosmological Constant Problem

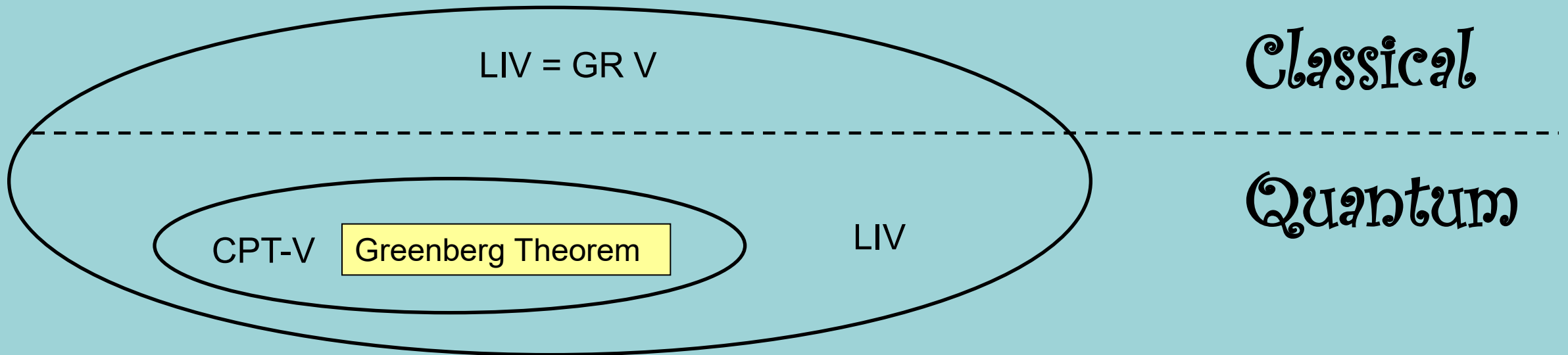
Lack of SUSY (DM?) Particles



Standard Model Extension

$$\mathcal{L} = \mathcal{L}_{\text{EH}} + \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{LIV}}$$

Main mechanism: Lorentz Invariance Violation (LIV) \rightarrow CPT and GR Violation



Is Lorentz Invariance Violation reasonable? \rightarrow Yes, based on general properties of Planck scale
How? \rightarrow Typically by means of static background fields due to the presence of a non-trivial vacuum state

LIV → Spacetime operators (parametrized as a power of the mass)

$$\mathcal{L} = \mathcal{L}_{\text{EH}} + \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{LIV}}$$

LIV terms up to some
mass dimension
If $d < 5 \rightarrow$ mSME

A fermion in the (flat spacetime) SME :

$$(i\gamma^\mu D_\mu - m_e - \boxed{a_\mu^e \gamma^\mu - b_\mu^e \gamma_5 \gamma^\mu} - \boxed{\frac{1}{2}H_{\mu\nu}^e \sigma^{\mu\nu} + ic_{\mu\nu}^e \gamma^\mu D^\nu + id_{\mu\nu}^e \gamma_5 \gamma^\mu D^\nu})\psi = 0.$$

CPT & LORENTZ
VIOLATION

Standard Model + LIV, no
gravity, a fermion

LIV coefficients depend
on the specific particle!

LORENTZ VIOLATION

D. Colladay and V.A. Kostelecky, PRD 55, 6760 (1997)

Gravitating Matter/Antimatter Systems in the Standard Model Extension

V.A. Kostelecký and A. Vargas, Phys. Rev. D 92
(2015) 056002

$$m_i^B = m^B + \sum_w \frac{5}{3} (N^w + N^{\bar{w}}) m^w c^w$$

a^w CPT-odd

c^w CPT-even

$$m_g^B = m^B + \sum_w \left[(N^w + N^{\bar{w}}) m^w c^w + 2\alpha (N^w + N^{\bar{w}}) a^w \right]$$

$$\alpha = \frac{1}{3} m^w c^w$$

$$m_i = m_g \quad (\text{matter})$$

Anti-Hydrogen

$$\frac{\delta g}{g} = \frac{2}{m} \sum_w \left(\alpha a^w + \frac{1}{3} m^w c^w \right)$$

Sentitive to six parameter

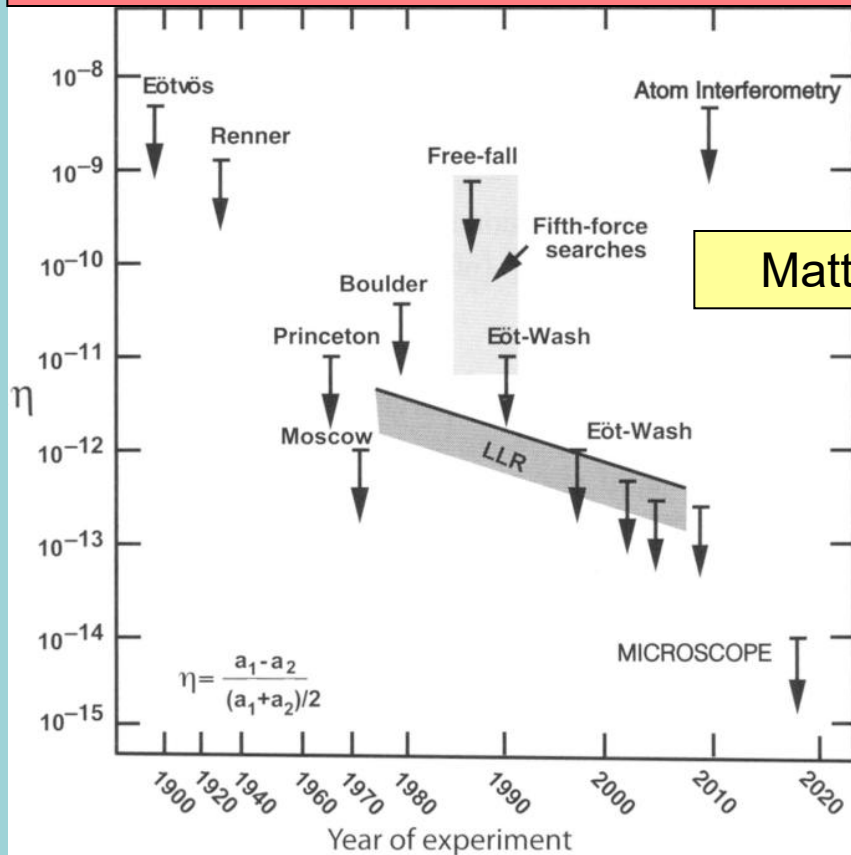
Positronium

$$\frac{\delta g}{g} = \frac{8}{3} c^e$$

Sentitive to one parameter

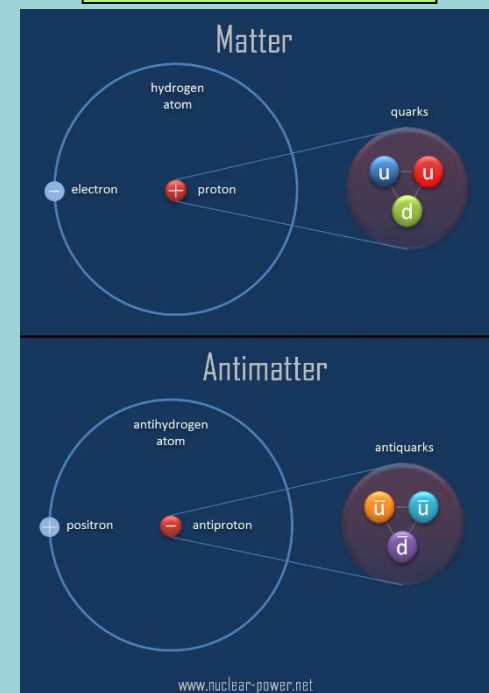
Gravitational Measurements

Tests of the Einstein Equivalence Principle

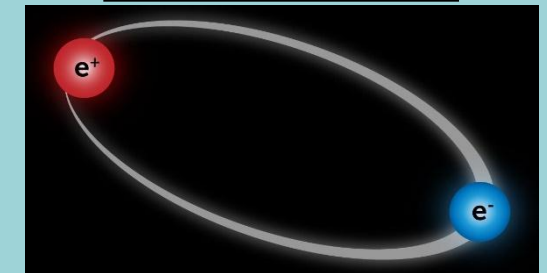


Antimatter ?

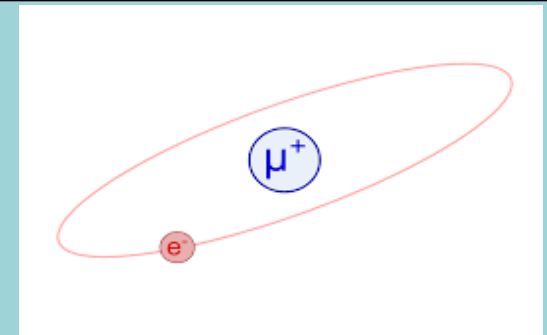
Anti-Hydrogen



Positronium

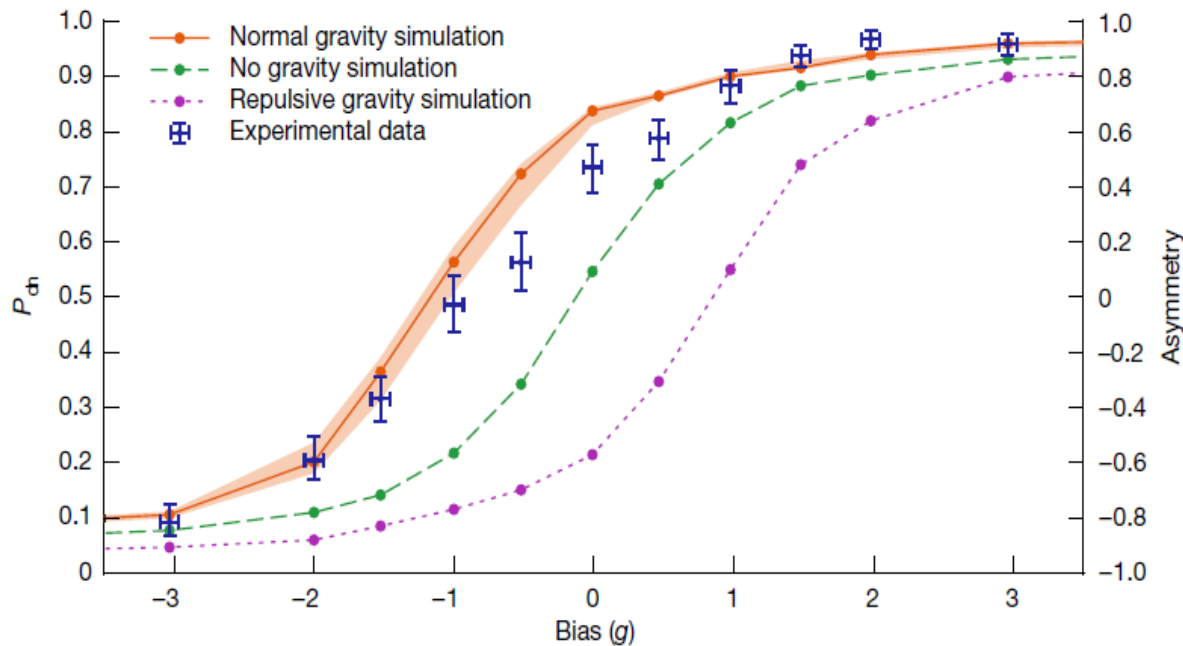


Muonium (Mu-atom, please)

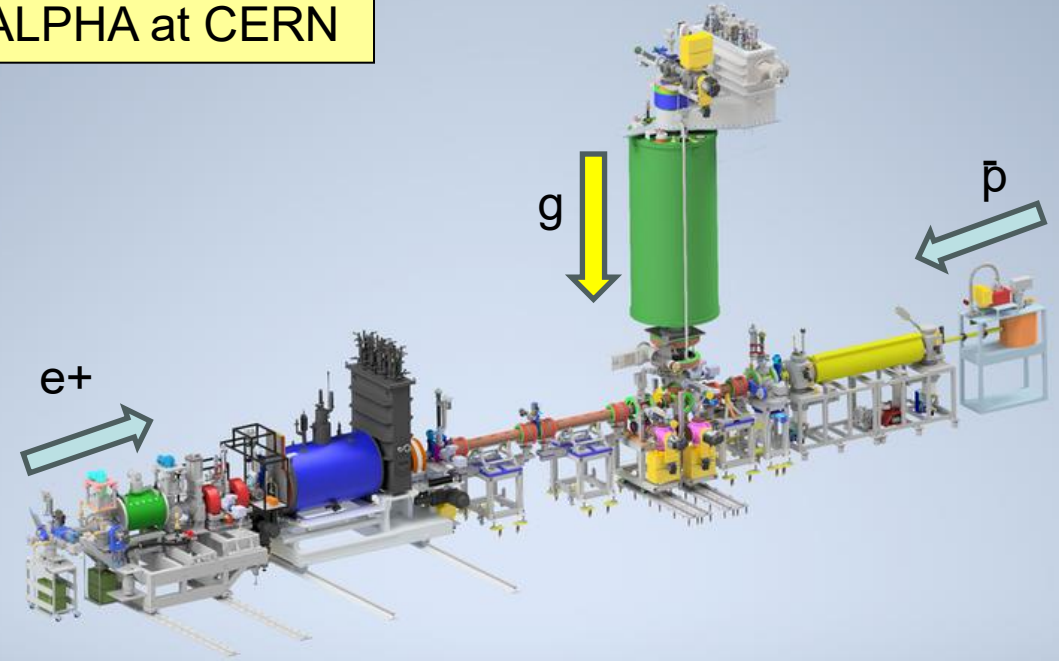


Anti-Hydrogen first measurement

Nature 621 (2023) 716
**Observation of the effect of gravity
on the motion of antimatter**
ALPHA Collaboration



ALPHA at CERN



Escape curve from the ALPHA-g
magnetic system compared to simulations

$$(0.75 \pm 0.13 \text{ (statistical + systematic)} \pm 0.16 \text{ (simulation)}) g$$

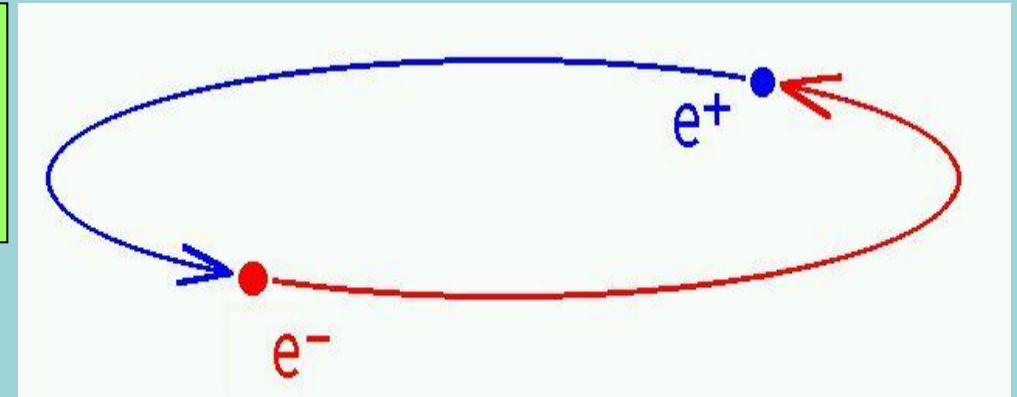
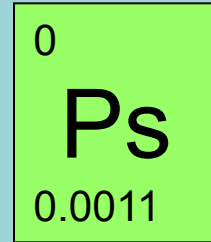
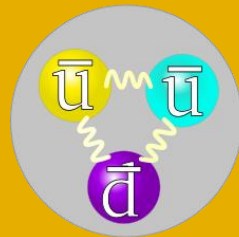
Compatible with g

Positronium

Why Positronium (as complementary to anti-H)?

- Anti-H is not an elementary particle (not even the antiproton is)
- Ps is made of two fundamental fermions, directly appearing in the Standard Model Lagrangian
- Most of the mass of the antiproton is not “constituent mass”

$$m(\bar{p}) = m(\text{quarks}) + m(\text{colorfield}) \\ \cong 15 \text{ MeV} + m(\text{colorfield})$$

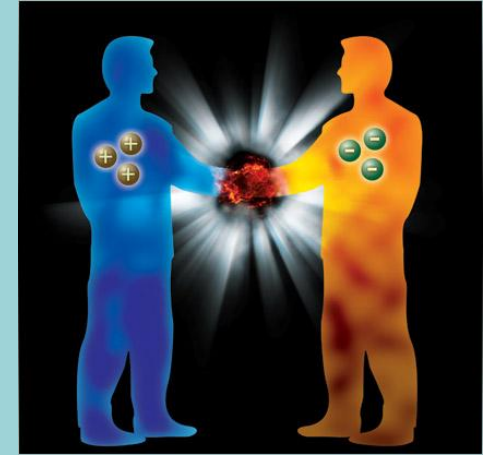


QUPLAS : Positron Interferometry
and Positronium Gravitation
(in construction)

A conclusion

Research on Antimatter Gravitation at Low Energy :

- Deals with Fundamental Laws
- Studies the interplay between Quantum Physics and Gravitation
- Could (help to) solve a Cosmic Mystery...and...
- Anti-hydrogen first measurement!



“Nature is in some sense, the Gospel and preach loudly creative power, wisdom and greatness of God.”

Mikhail Vasilevich Lomonosov



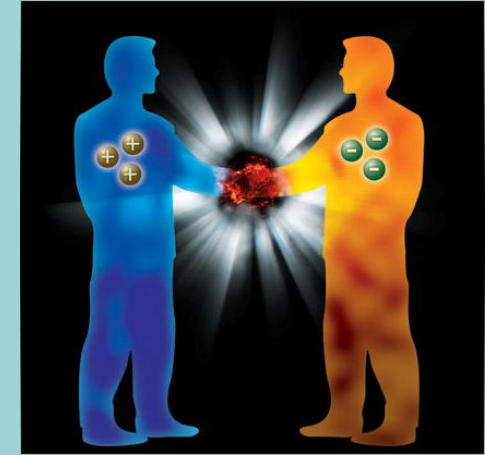
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Спасибо за
внимание !